From few-body to many-body systems

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KVI-CART, University of Groningen

« Future directions for nuclear structure and reaction theories:
Ab initio approaches for 2020 »

FUSTIPEN, GANIL, France

March 17, 2016

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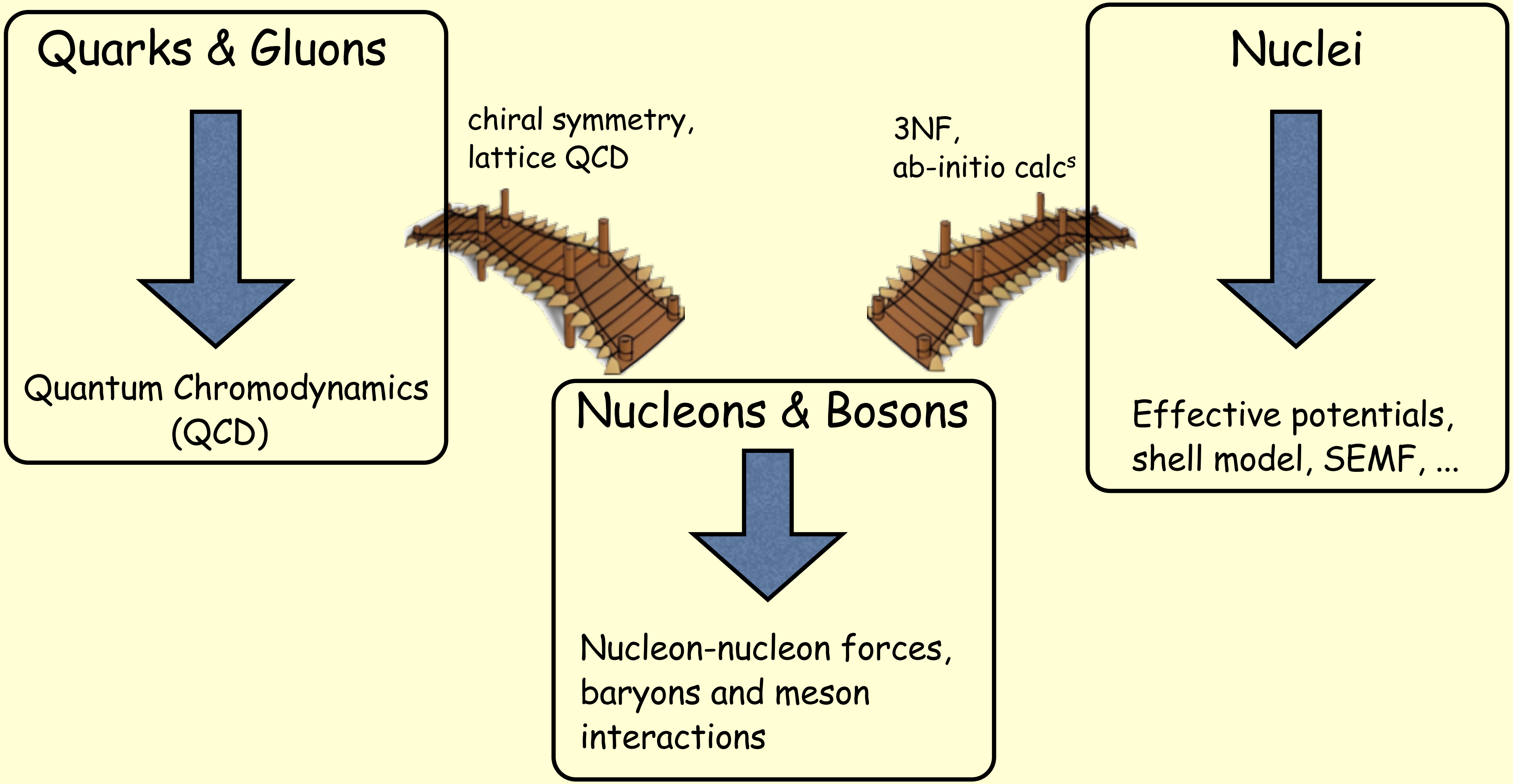
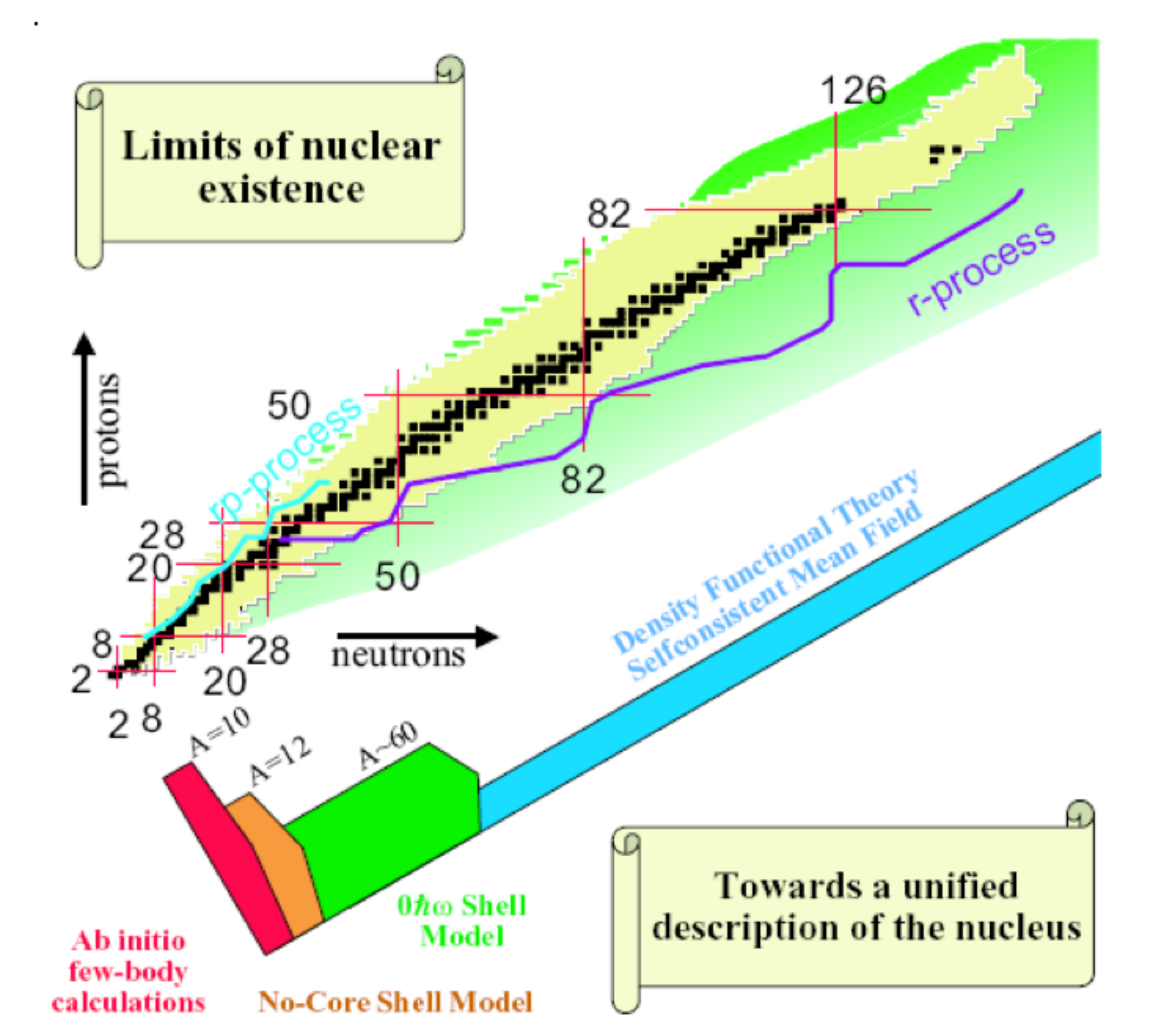
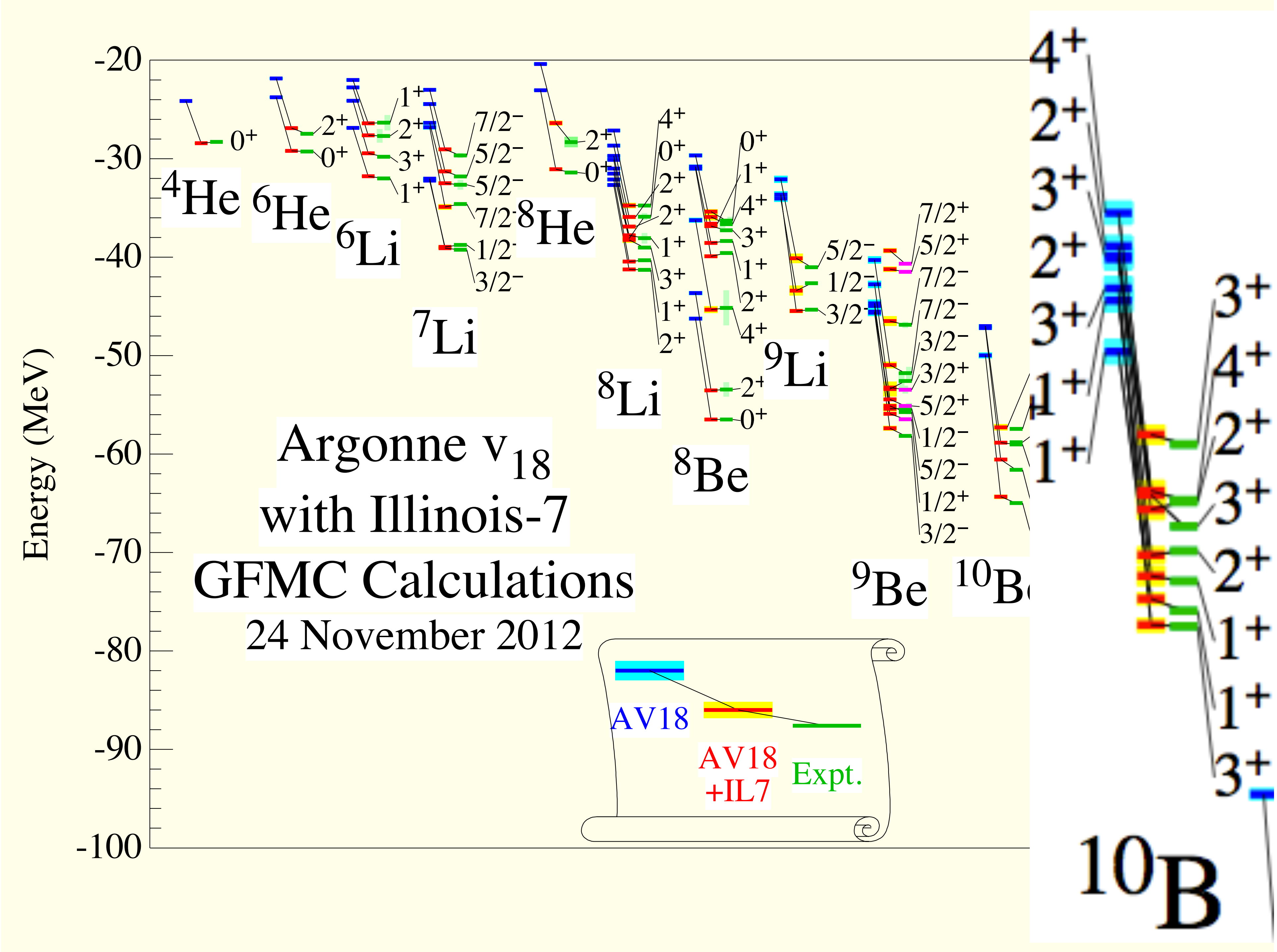
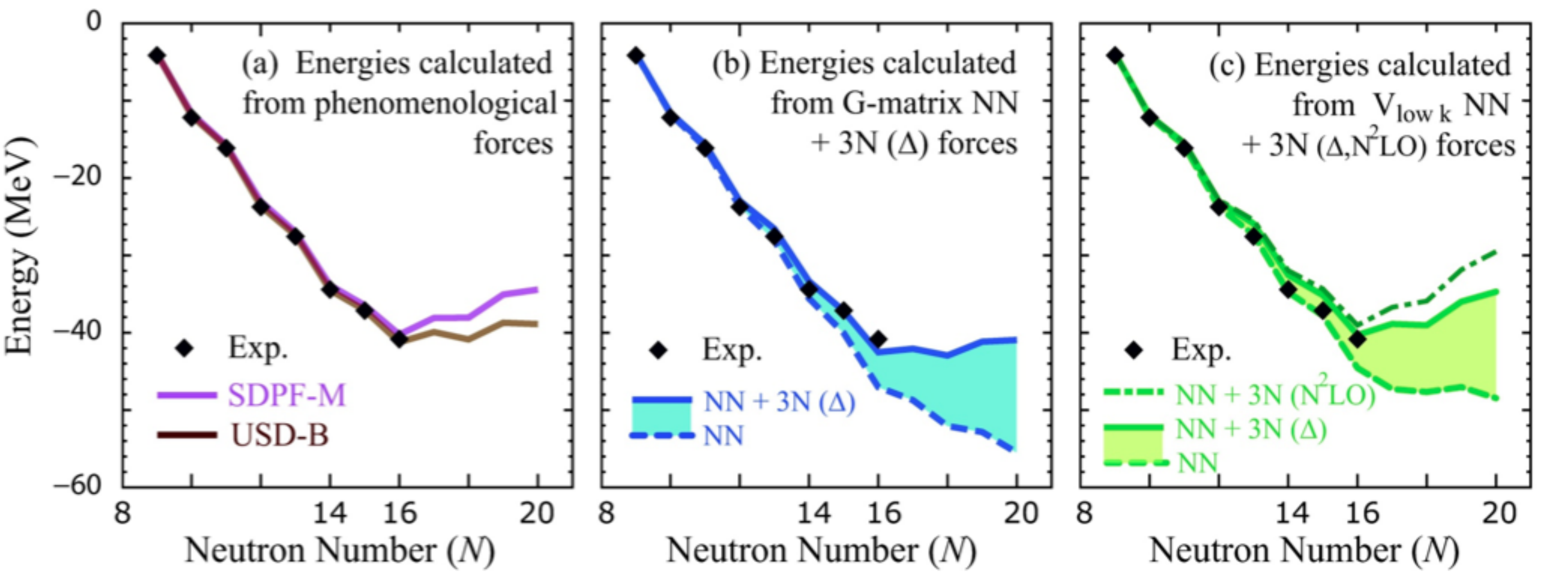

Quarks & Gluons
Quantum Chromodynamics
(QCD)
chiral symmetry,
lattice QCD
Nucleons & Bosons
Nucleon-nucleon forces,
baryons and meson
interactions
3NF,
ab-initio calcs
Nuclei
Effective potentials,
shell model, SEMF, ...


Limits of nuclear existence
126
82
50
rp-process
r-process
protons
28
20
8
2
2 8
20
28
50
82
neutrons
Density Functional Theory
Selfconsistent Mean Field
A=10
A=12
A~60
Ab initio few-body calculations
No-Core Shell Model
0ħω Shell Model
Towards a unified description of the nucleus


Energy (MeV)
-20
-30
-40
-50
-60
-70
-80
-90
-100
4He
6He
6Li
7Li
8He
8Li
8Be
9Li
9Be
10Be
10B
Argonne v18
with Illinois-7
GFMC Calculations
24 November 2012
AV18
AV18
+IL7
Expt.
0+
2+
0+
1+
2+
3+
1+
7/2−
5/2−
5/2−
7/2−
1/2−
3/2−
2+
0+
4+
0+
2+
2+
1+
3+
1+
2+
0+
1+
4+
3+
1+
2+
4+
2+
0+
5/2−
1/2−
3/2−
7/2+
5/2+
7/2−
7/2−
3/2−
3/2+
5/2+
1/2−
5/2−
1/2+
3/2−
4+
2+
3+
2+
3+
1+
1+
3+
4+
2+
3+
2+
1+
1+
3+

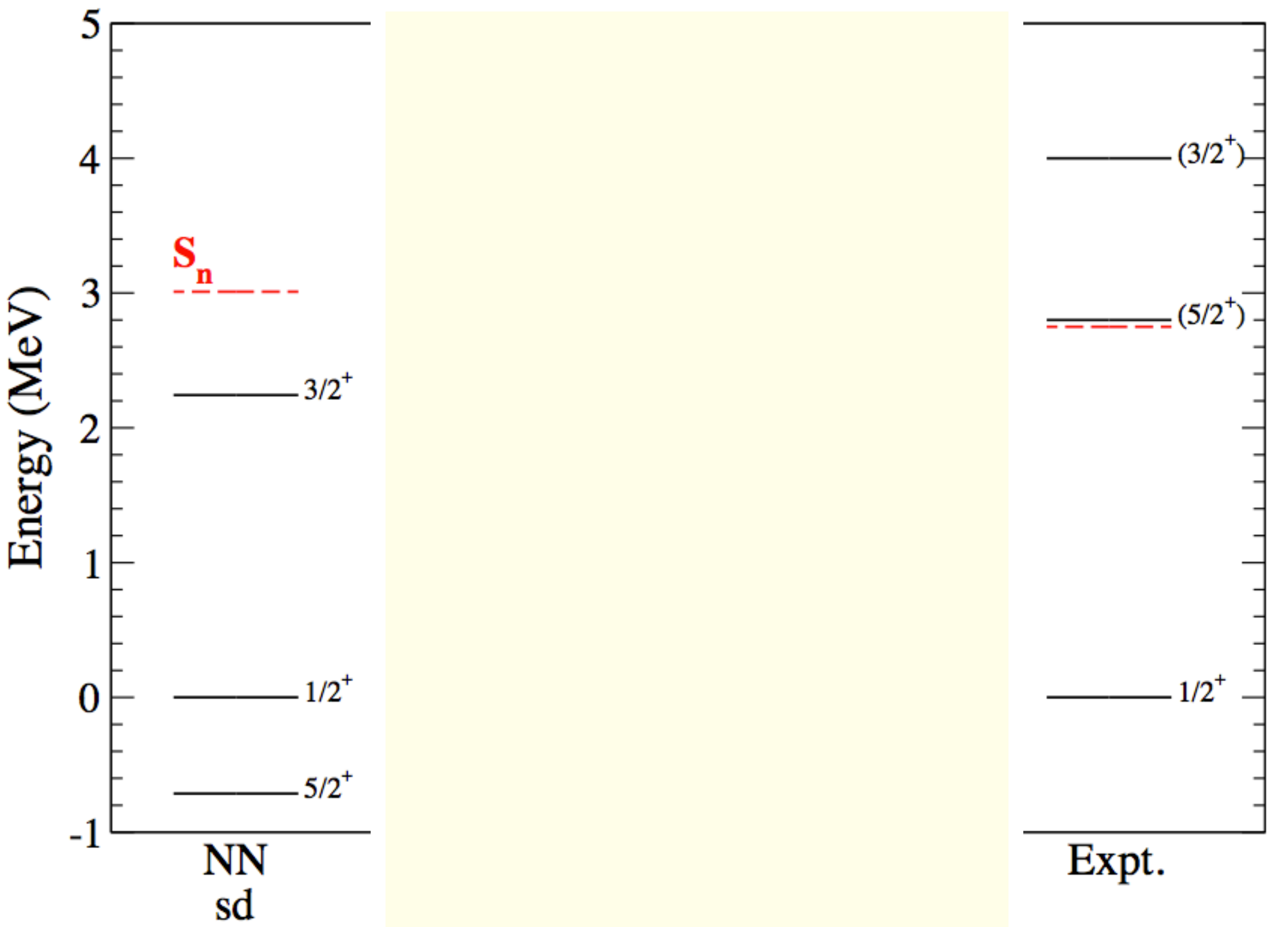
Binding Energies of Oxygen Isotopes



Otsuka, Suzuki, Holt, Schwenk, Akaishi, PRL 105, 032501 (2010)

^{23}O

5/2$^+$, 3/2$^+$ indicate position of $d_{5/2}$ and $d_{3/2}$ orbits

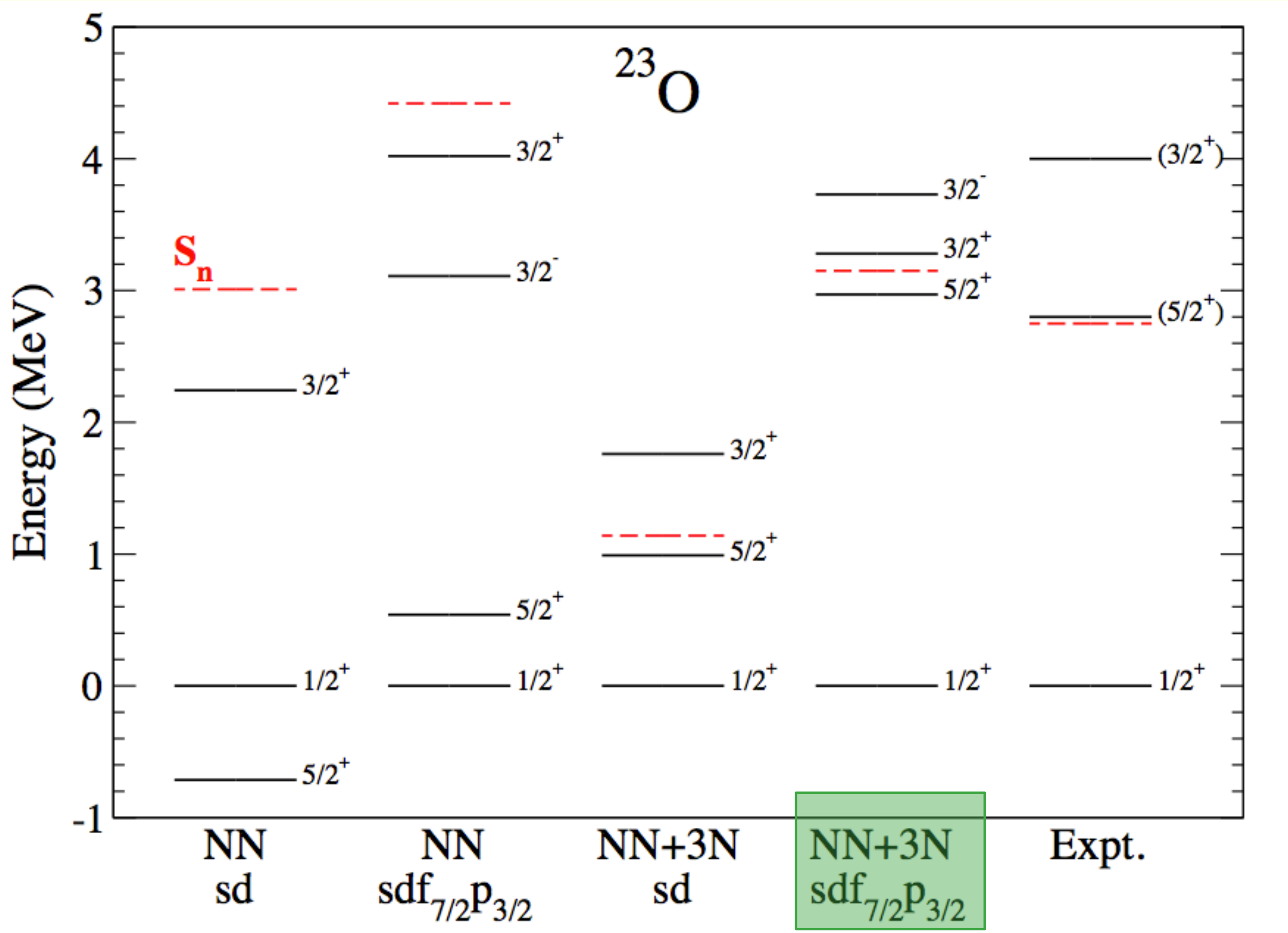


sd-shell NN-only
Wrong ground state!
5/2$^+$ much too low
3/2$^+$ bound

Holt et al., EPJ A49, 39 (2013)

^{23}O

5/2$^+$, 3/2$^+$ indicate position of $d_{5/2}$ and $d_{3/2}$ orbits



sd-shell NN-only
Wrong ground state!
5/2$^+$ much too low
3/2$^+$ bound

Microscopic NN+3N
Great improvements in extended valence space!

Holt et al., EPJ A49, 39 (2013)

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Ground-state energies

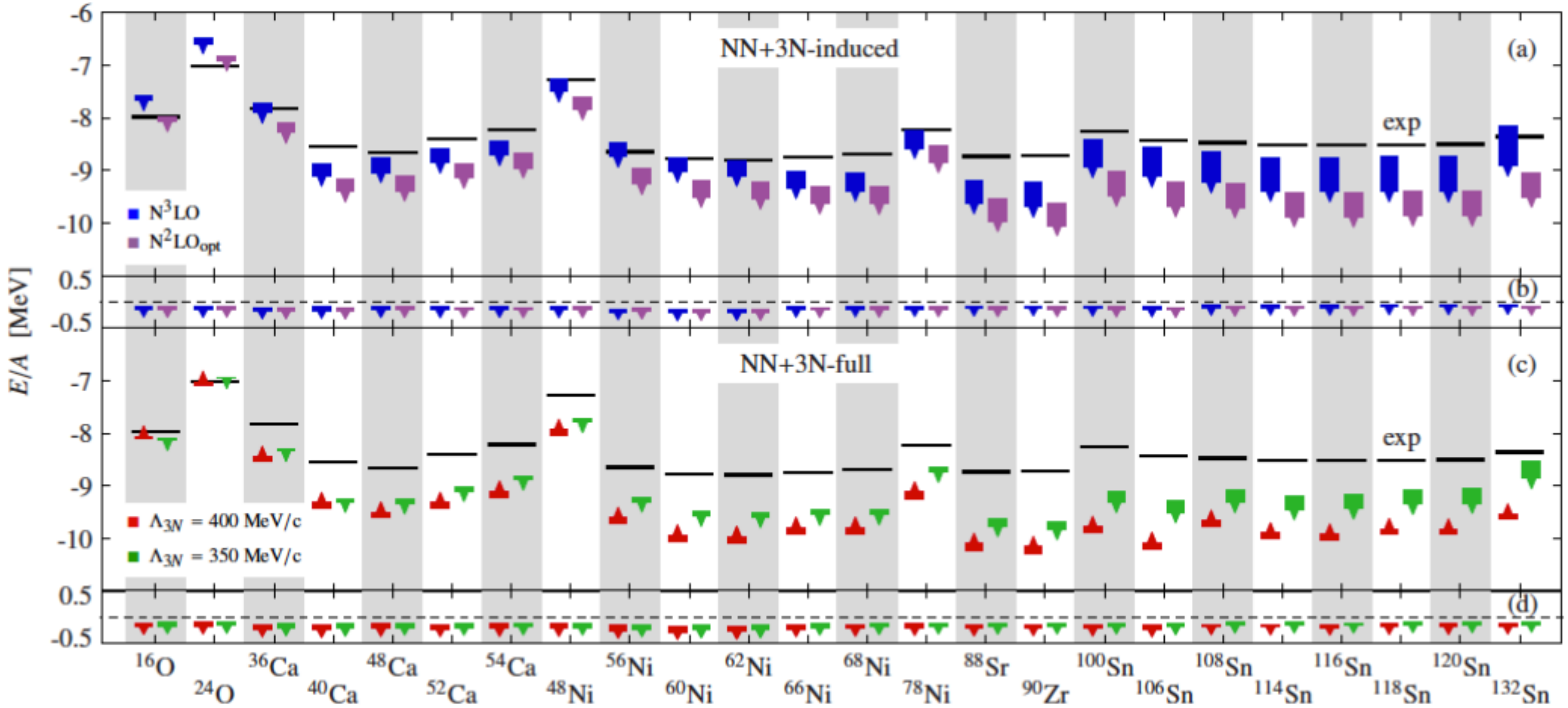
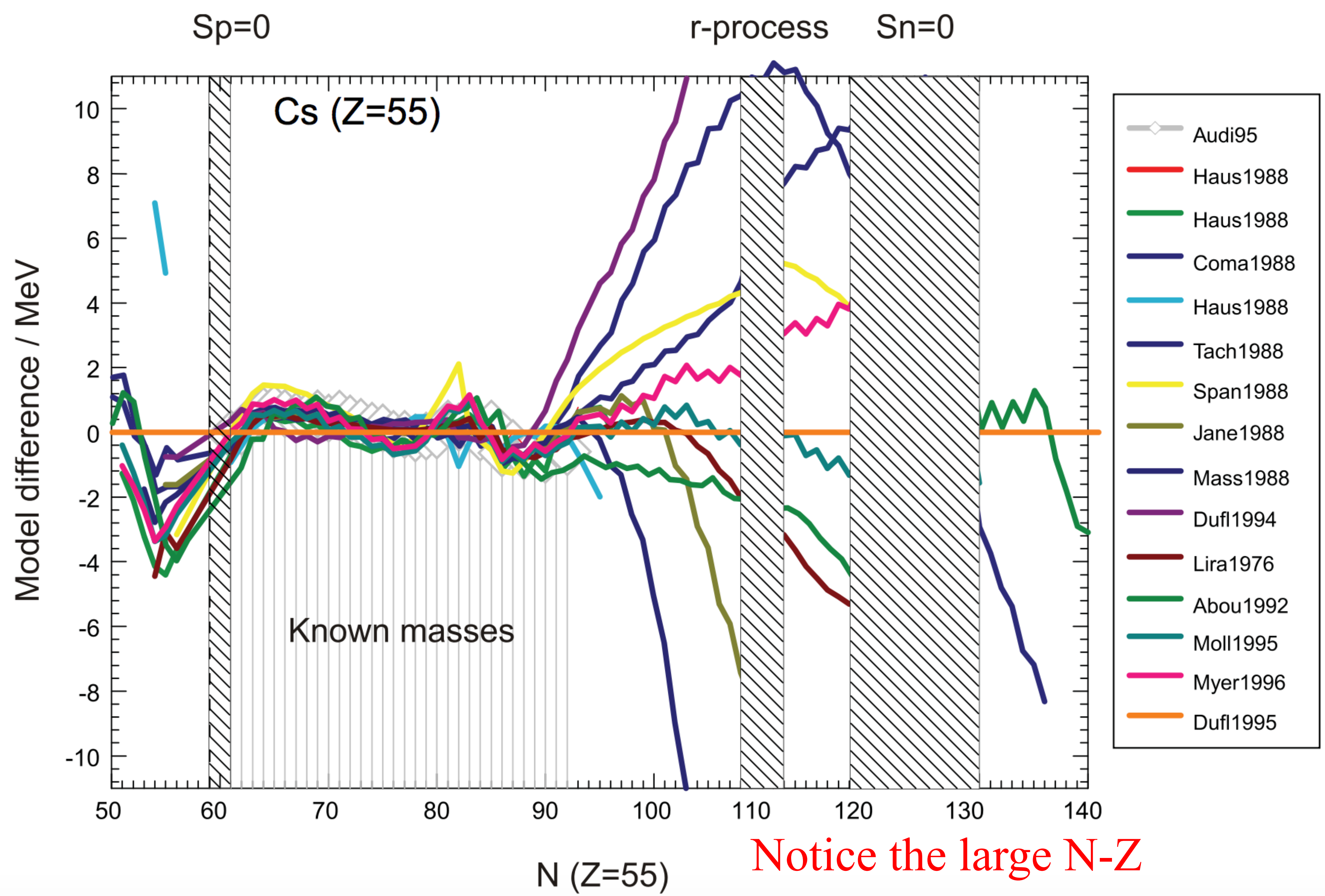


FIG. 5: (Color online) Ground-state energies from CR-CC(2,3) for (a) the *NN*+3*N*-induced Hamiltonian starting from the N^{3}LO and N^{2}LO-optimized *NN* interaction and (c) the *NN*+3*N*-full Hamiltonian with Λ_{3N} = 400 MeV/c and Λ_{3N} = 350 MeV/c. The boxes represent the spread of the results from $\alpha = 0.04$ fm^4 to $\alpha = 0.08$ fm^4, and the tip points into the direction of smaller values of α. Also shown are the contributions of the CR-CC(2,3) triples correction to the (b) *NN*+3*N*-induced and (d) *NN*+3*N*-full results. All results employ $\hbar\Omega$ = 24 MeV and 3*N* interactions with E_{3max} = 18 in NO2B approximation and full inclusion of the 3*N* interaction in CCSD up to E_{3max} = 12. Experimental binding energies [32] are shown as black bars.

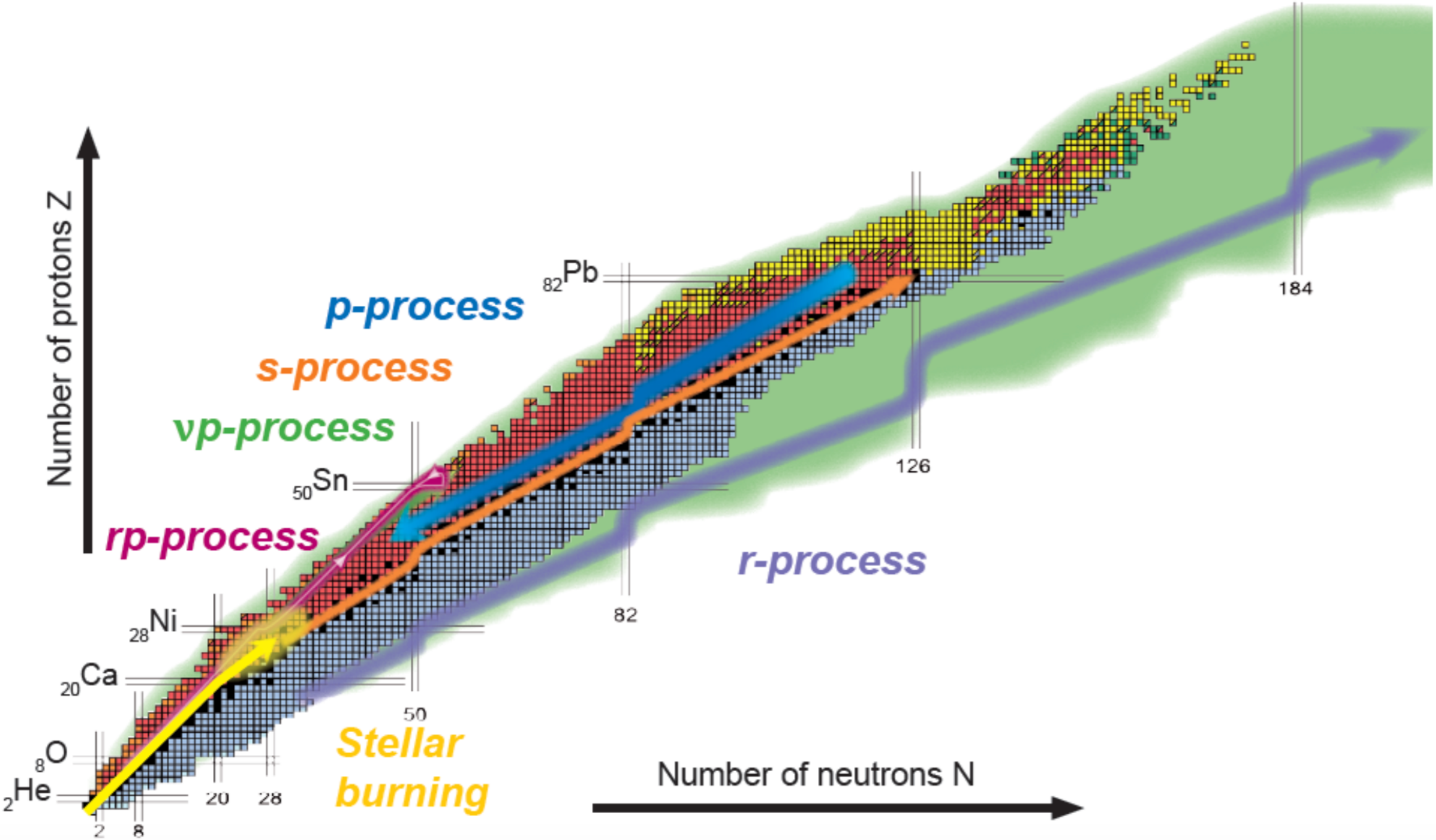
S. Binder et al., Phys. Lett. B 736, 119 (2014),

Model differences

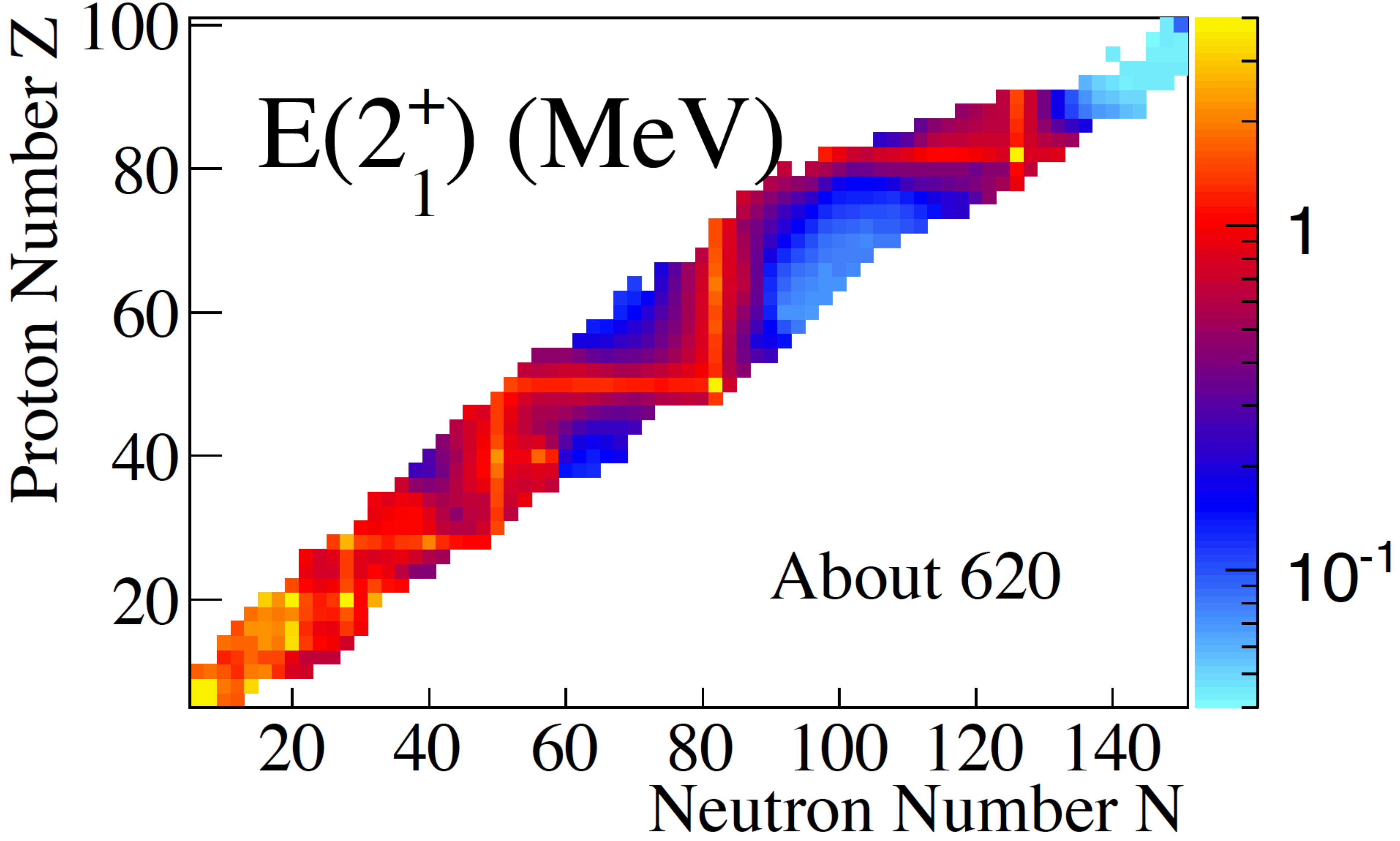


Notice the large N-Z

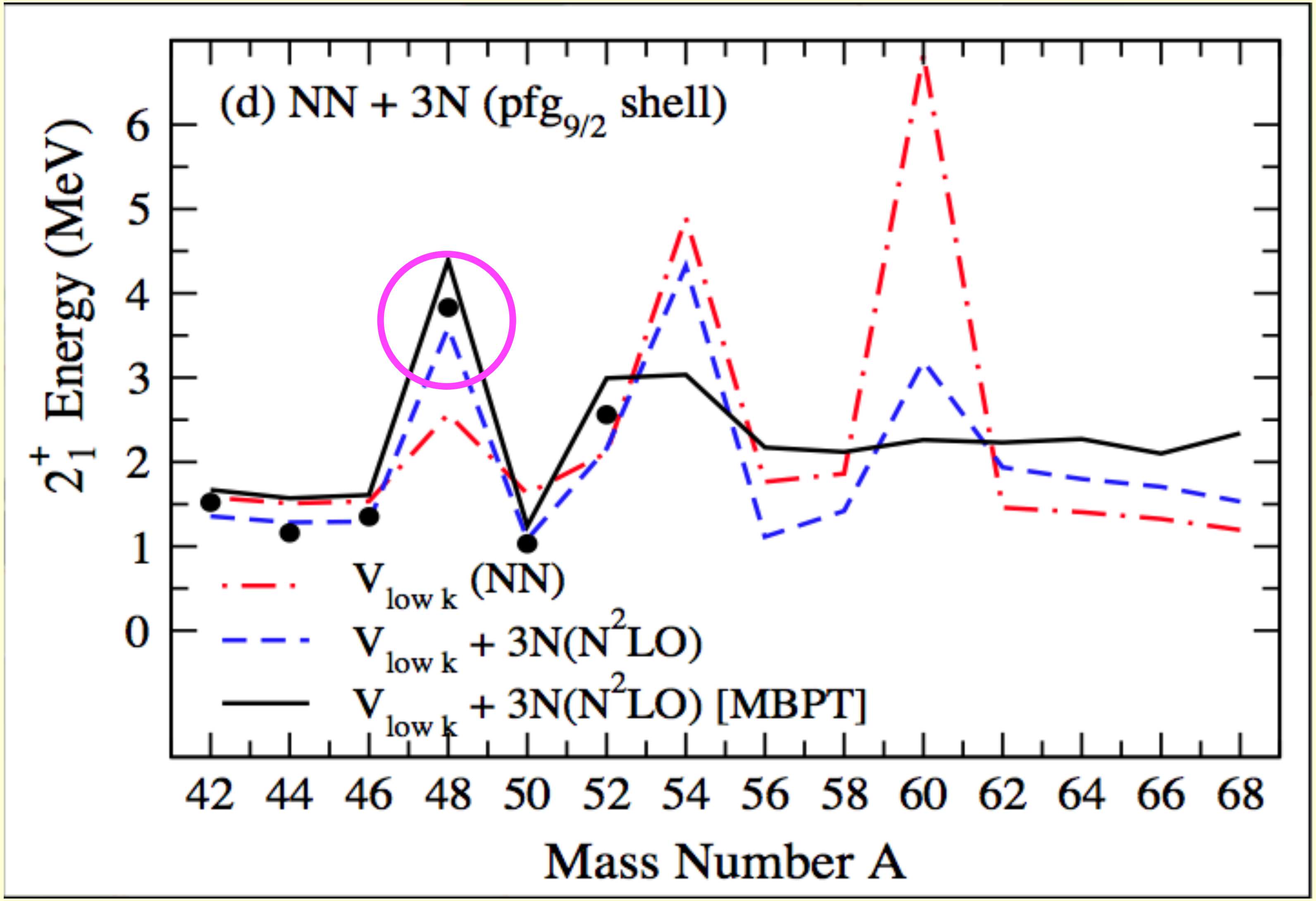
Nuclear and astrophysics meet



Energy of the 2^+



N=28 magic number in Calcium



Holt, Otsuka, Schwenk and Suzuki, J. Phys. G39, 085111 (2012)

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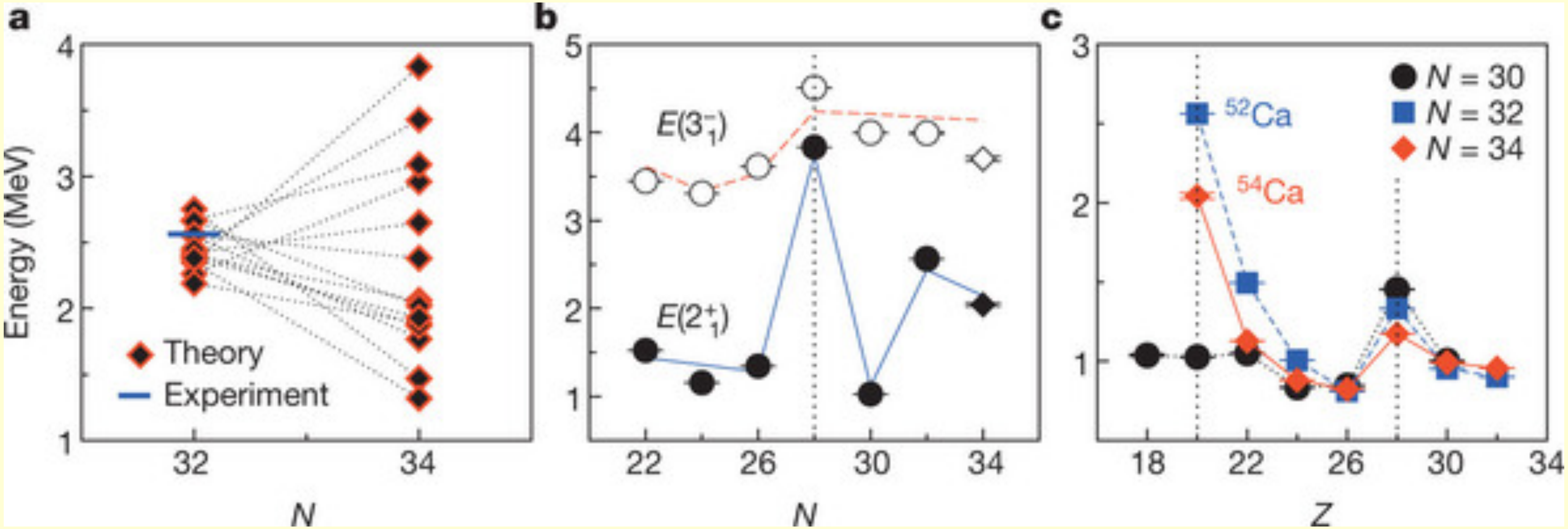
Medium heavy elements



Nature **502**, 207–210 (10 October 2013)

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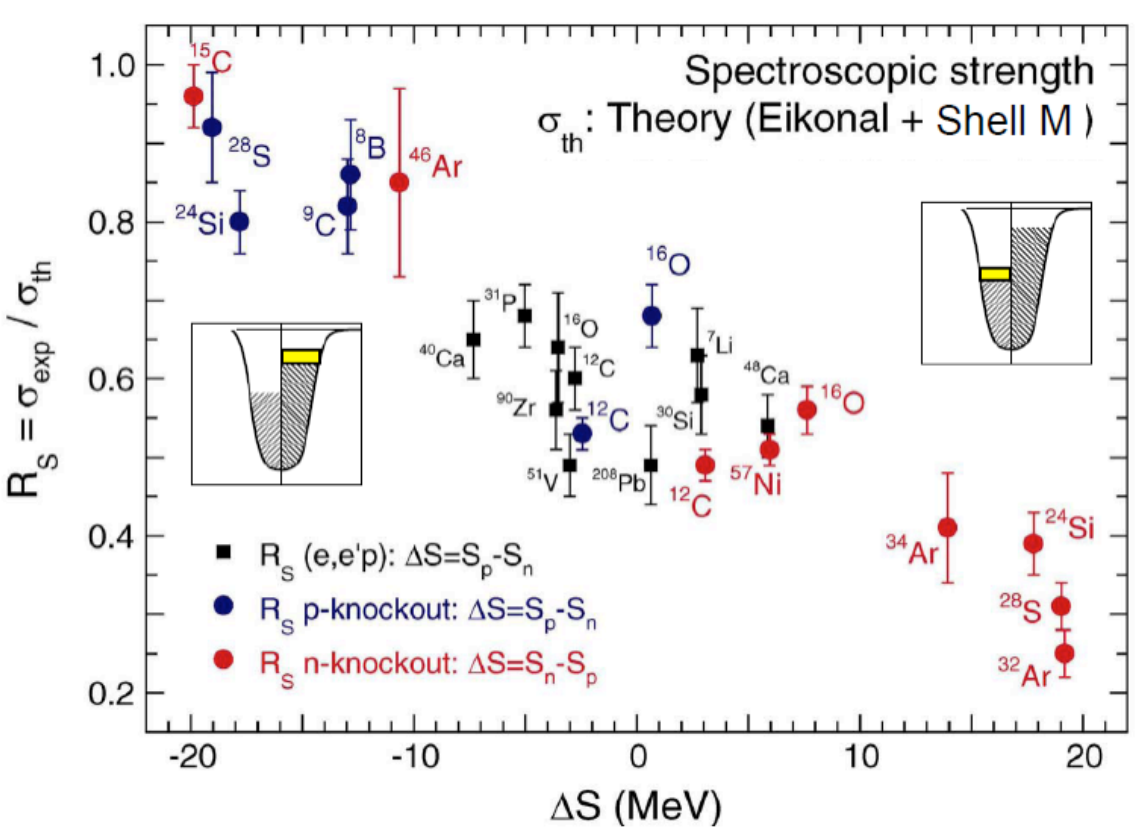
Spectroscopic factors for neutron-proton asymmetric nuclei

weakly bound nucleons

strongly bound nucleons



?

Origin unclear

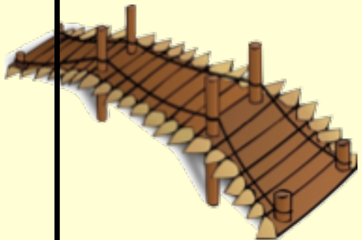
isospin dependence of correlations ?

Figure from Alexandra Gade, Phys. Rev. C 77, 044306 (2008)

Quarks & Gluons

Quantum Chromodynamics (QCD)

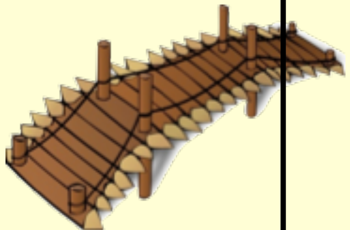
chiral symmetry, lattice QCD



Nucleons & Bosons

Nucleon-nucleon forces, baryons and meson interactions

3NF, ab-initio calc^s

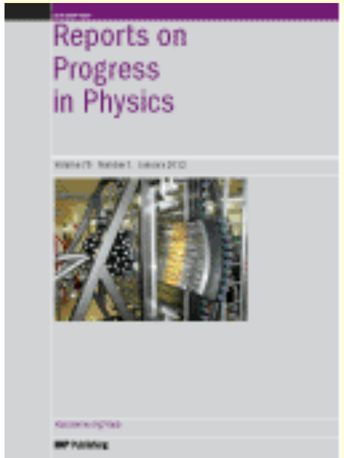


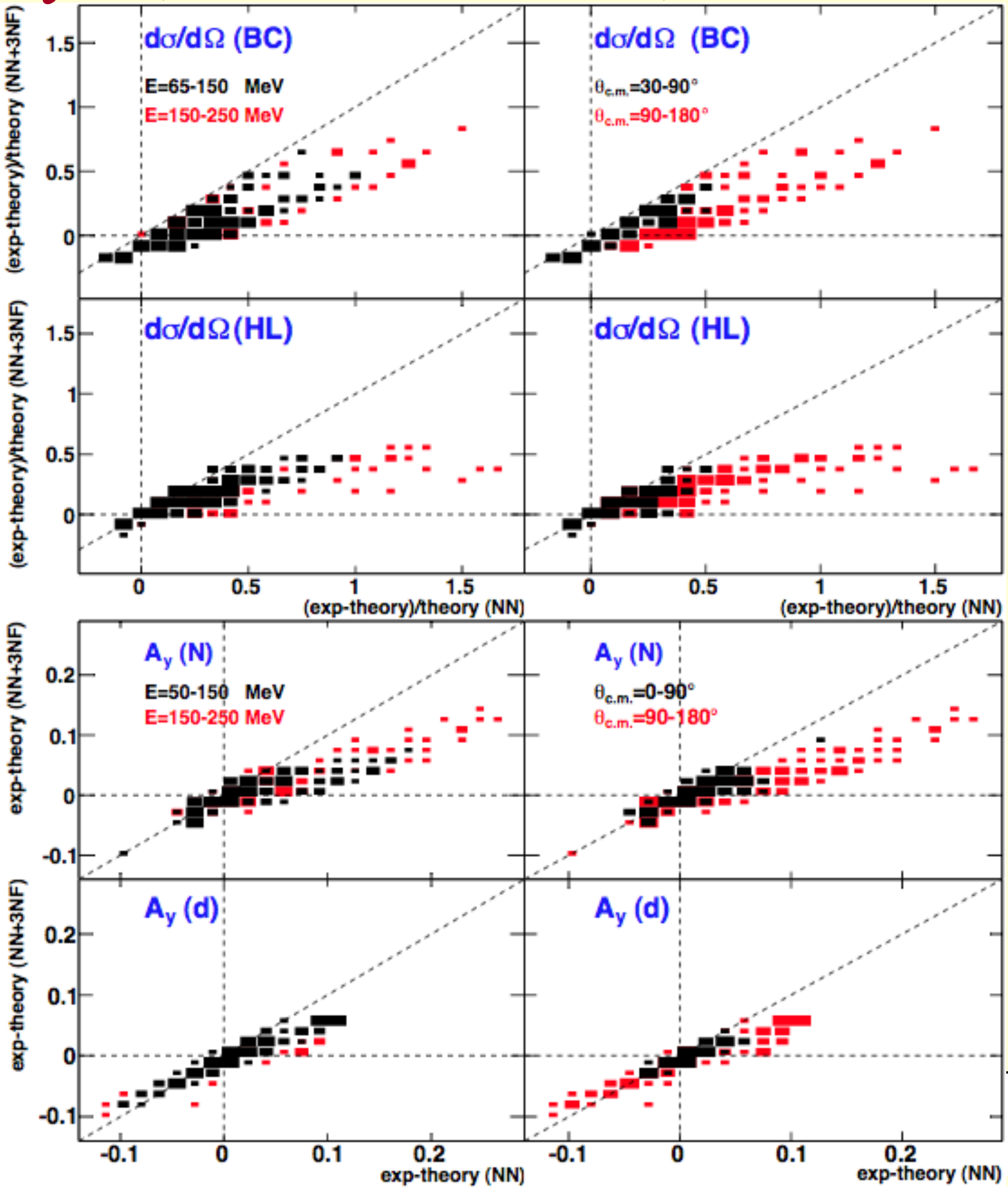
Nuclei

Effective potentials, shell model, SEMF, ...

Global Analysis, Elastic channel, 50-250 MeV/nucleon

NK et al., Reports on Progress in Physics 75, 016301 (2012)





$$\vec{p}+d \rightarrow p+d$$

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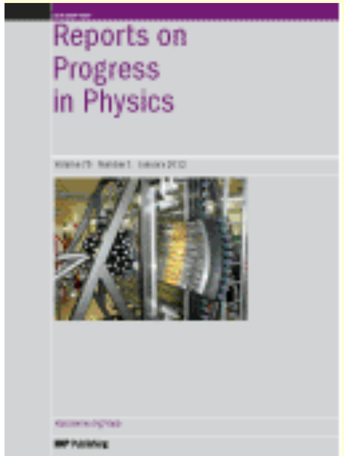
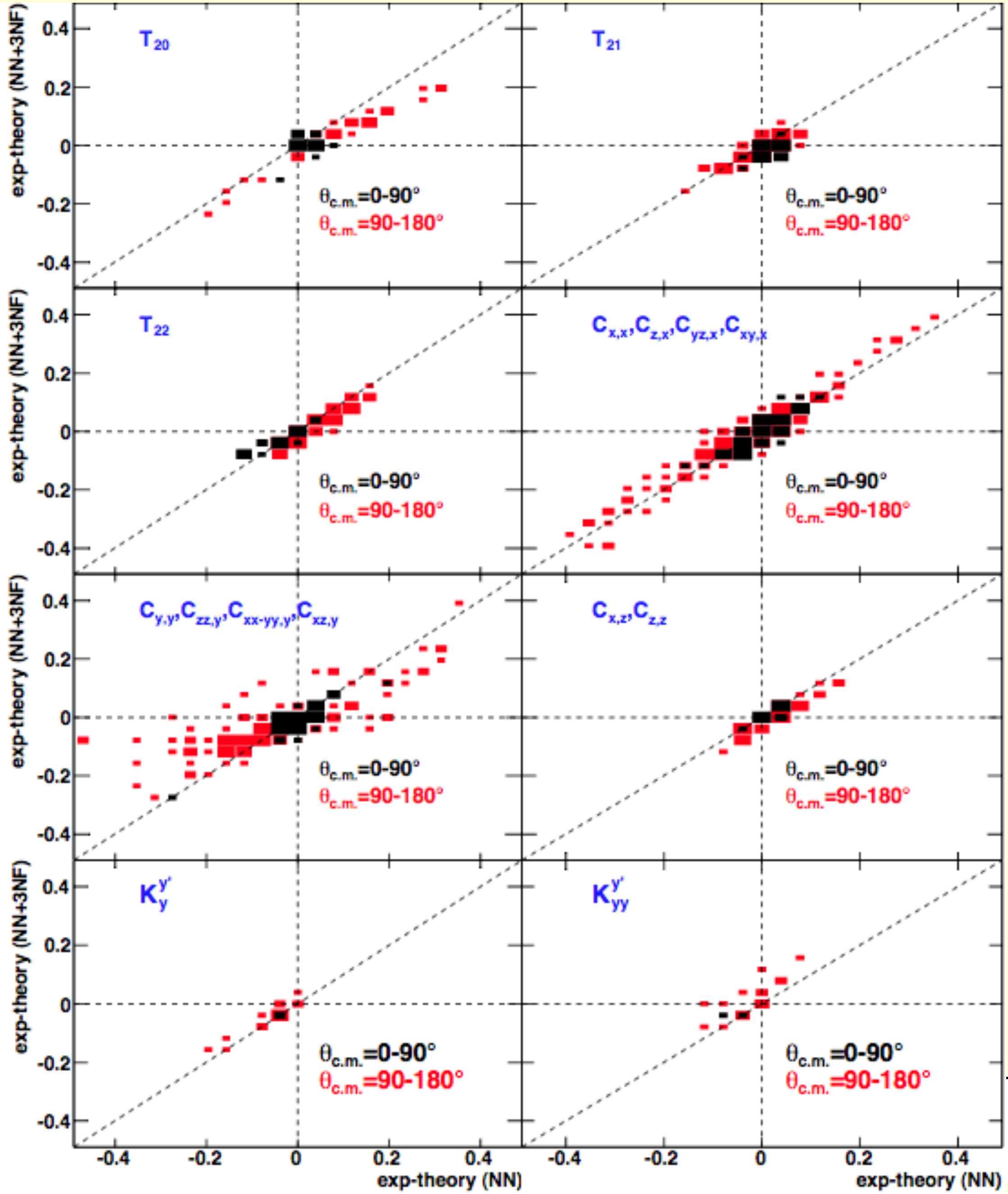
Global Analysis, Elastic channel, 50-250 MeV/nucleon

NK et al., Reports on Progress in Physics 75, 016301 (2012)





$\vec{p} + d \rightarrow p + d$

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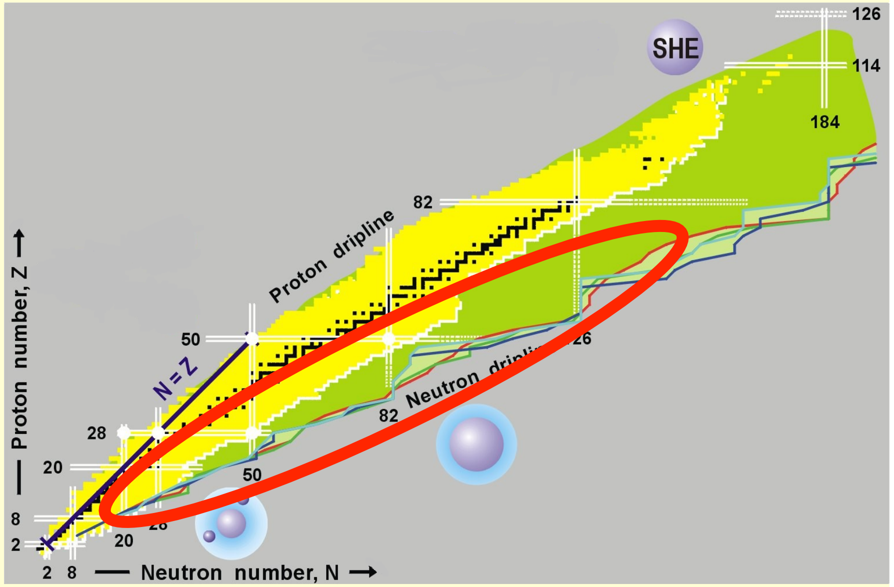
Main Physics Goals in Nuclear Structure

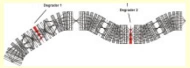


physics interest:

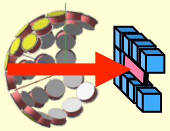
- matter distributions (halo, skin…)
- single-particle structure evolution (new magic numbers, new shell gaps, spetroscopic factors)
- NN correlations, pairing and clusterization phenomena
- new collective modes (different deformations for p and n, giant resonance strength)
- parameters of the nuclear equation of state
- in-medium interactions in asymmetric and low-density matter
- astrophysical r and rp processes, understanding of supernovae

Complementarity of NUSTAR experiments

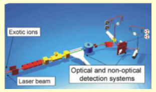
Super-FRS



HISPEC/ DESPEC

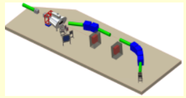


LASPEC

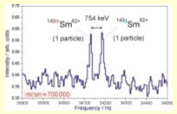


MATS

R3B

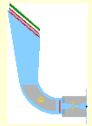


ILIMA



SHE

ELISE

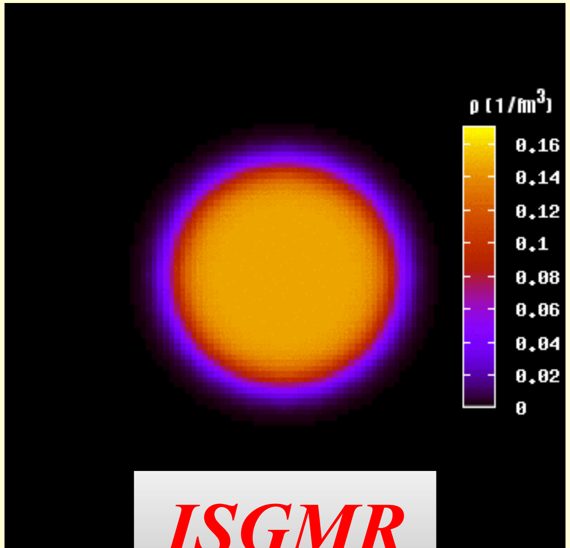


EXL

	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISe	EXL
Masses		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	dressed ions, µs...s			resonance width, decay up to 100ns	bare ions, ms…years	µs...days		
Matter radii	interaction x-section				interaction x-section				matter densitiy distribution
Charge radii	charge-changing cross sections		mean square radii		charge-changing cross sections			charge density distribution	
Single-particle structure	high resolution, angular momentum	high-resolution particle and γ-ray spectroscopy	magnetic moments, nucl. spins	evolution of shell str., pairing int., valence nucl.	quasi-free knockout, short-range and tensor	evolution of shell closures, pairing corr.	shell structure of SHEs		low momentum transfers
Collective behavior		electromag. transitions	quadrupole moments	halo structure	dipole response	changes in deformation		electromag. transitions	monopole resonance
EoS					polarizability, neutron skin			neutron skin ➔	neturon skin, Compressibility
Exotic Systems	bound mesons, hypernuclei, nucleon res.								

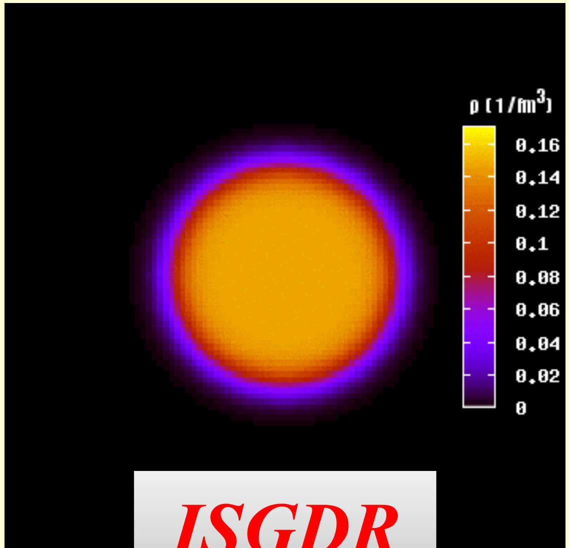
Giant Resonances

Collective oscillations of all neutrons and all protons in a nucleus in phase (isoscalar) or out of phase (isovector)



ISGMR

Breathing Mode



ISGDR

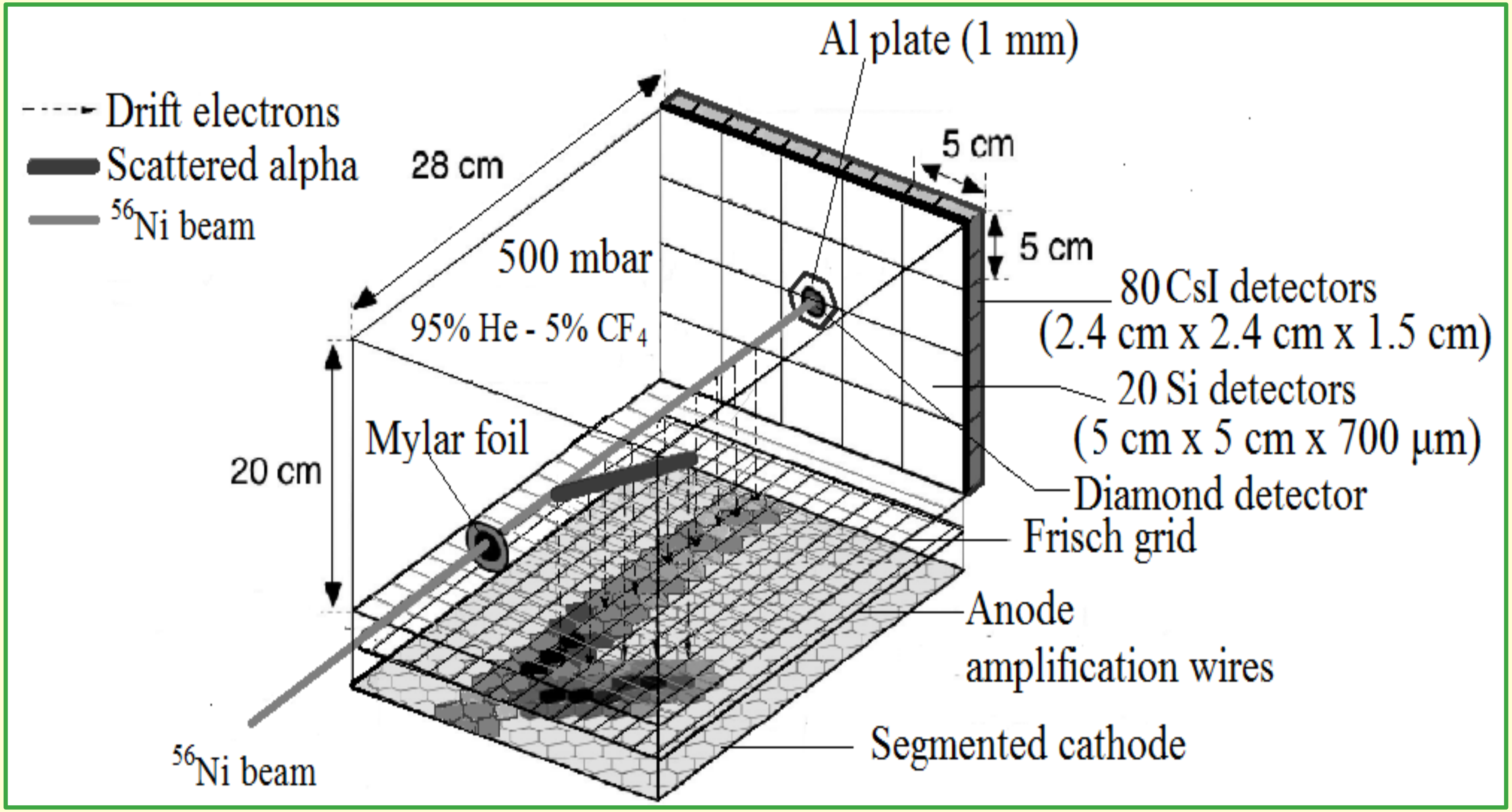
Squeezing Mode

ISGQR

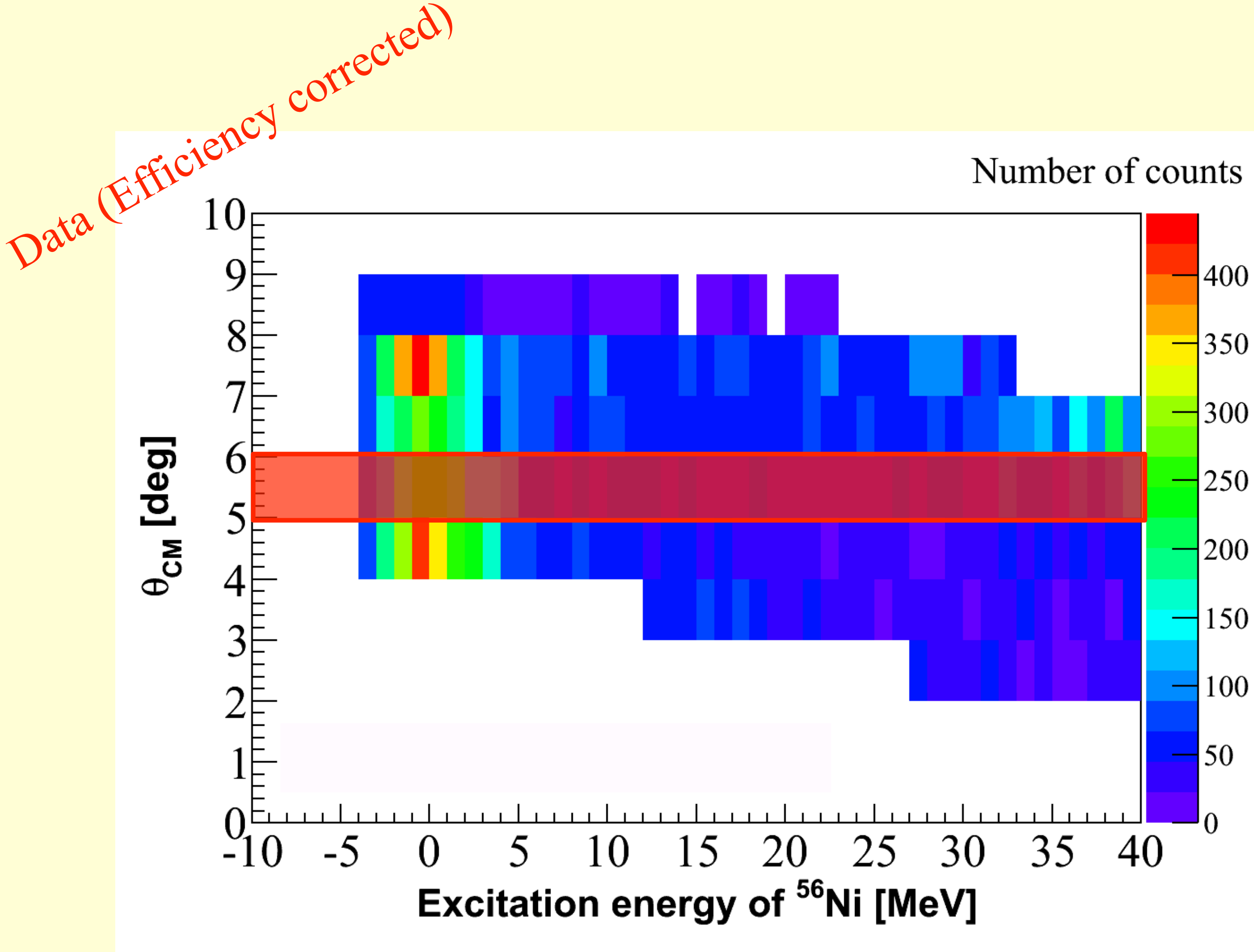
No Density Variation
Shape Change

M. Itoh

Schematic view of MAYA active target detector



Peak fitting method



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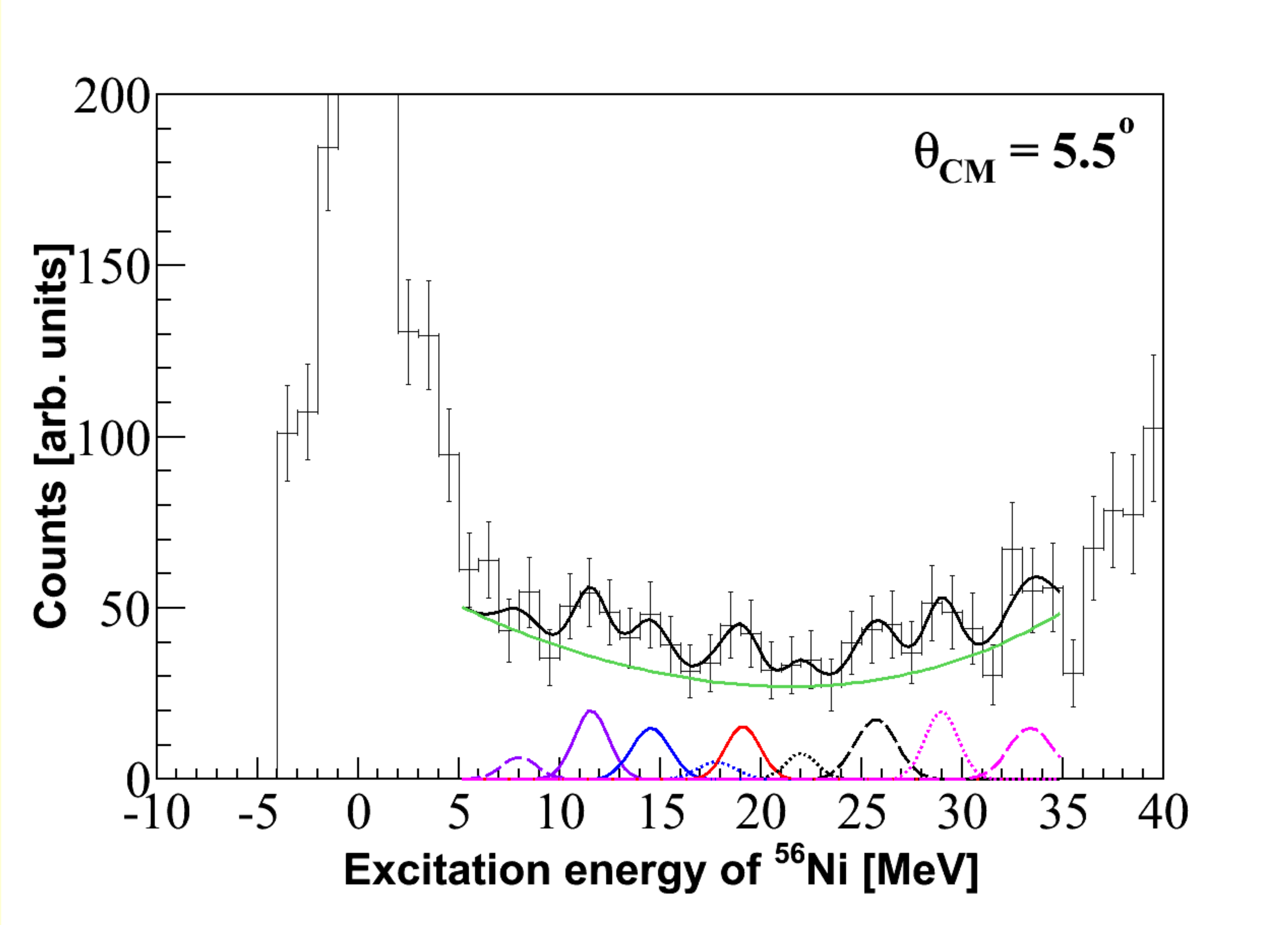
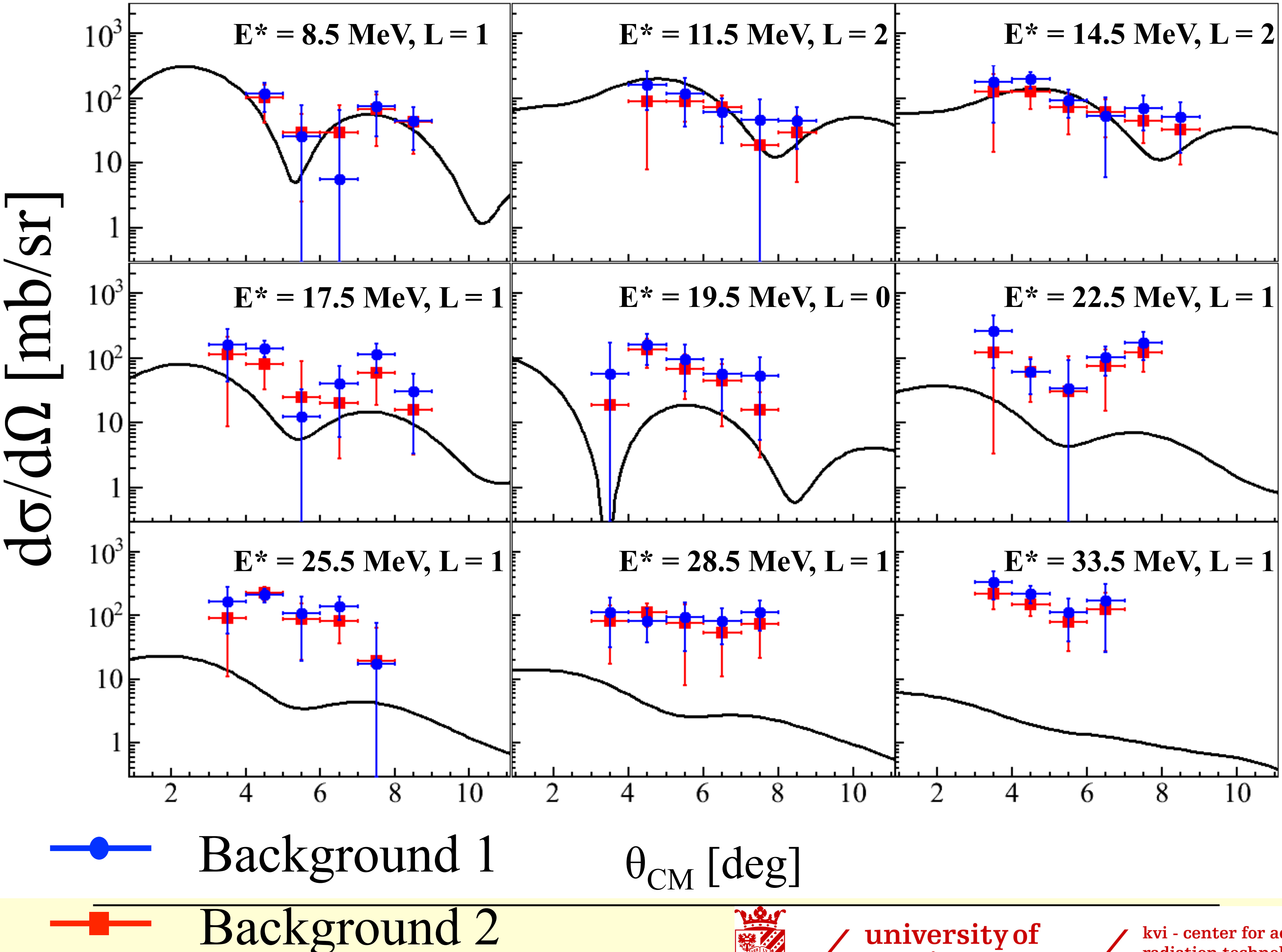
Excitation energy of ^{56}Ni at θ_{CM}=5.5°, S. Bagchi





S. Bagchi et al., Phys. Lett. B751, 371 (2015)

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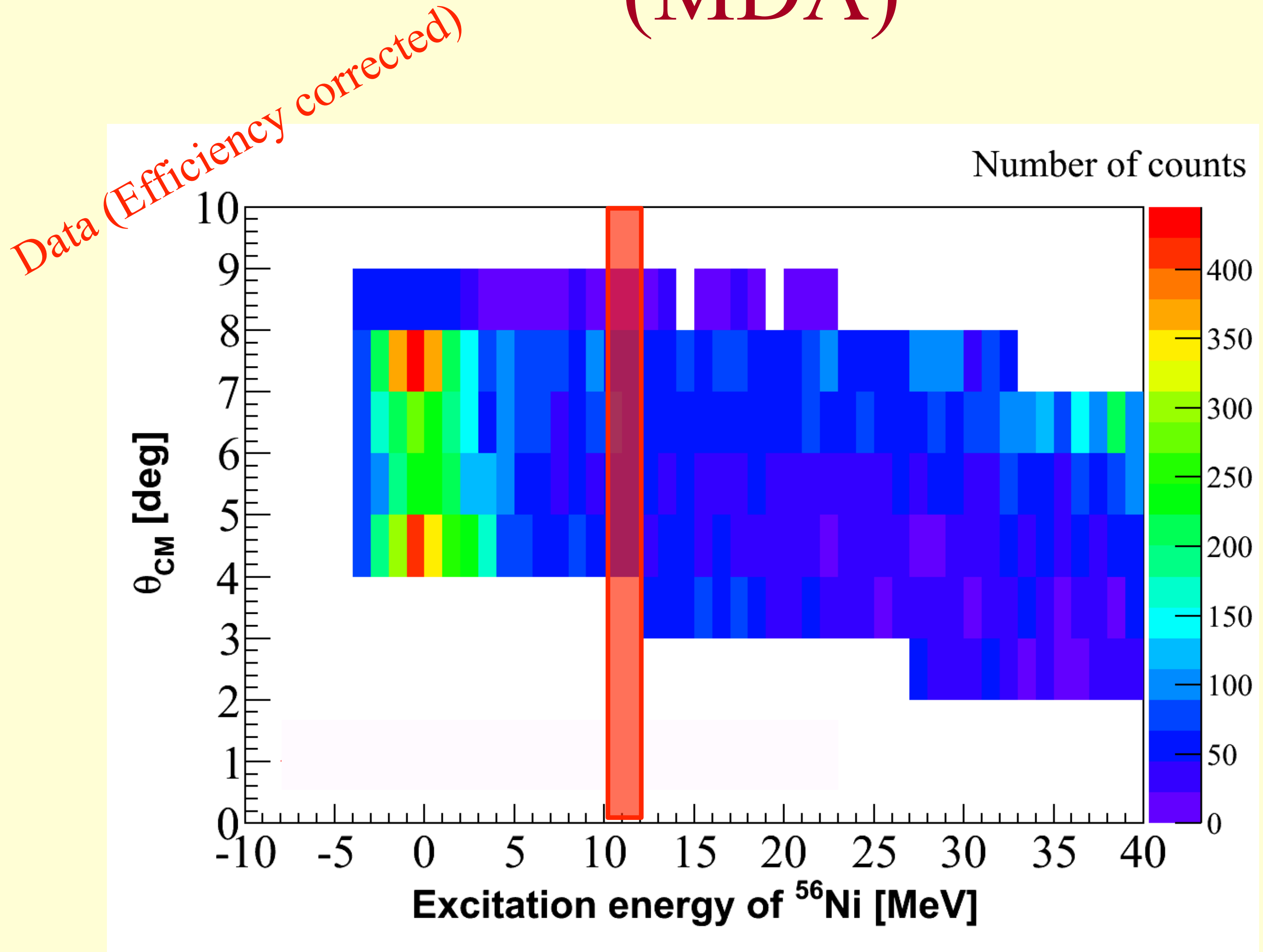
Multipole Decomposition Analysis (MDA)



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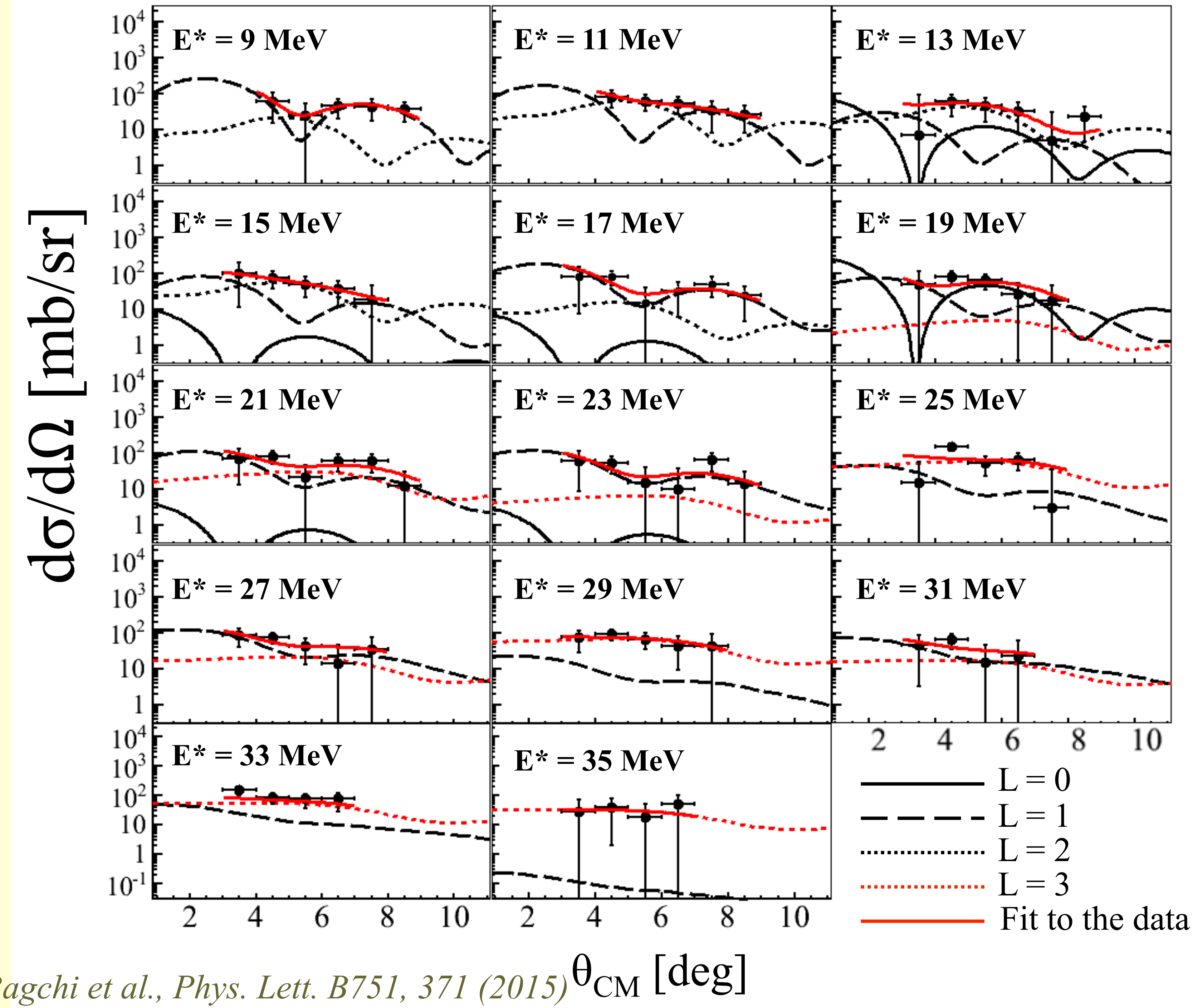

S. Bagchi et al., Phys. Lett. B751, 371 (2015)

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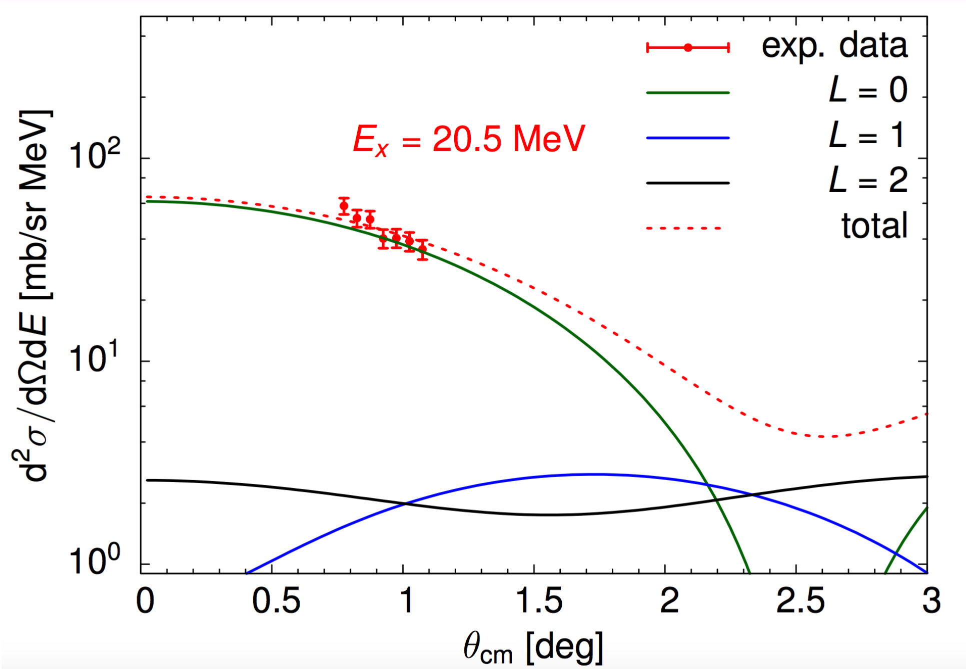
Summary of all Ni isotopes for ISGMR

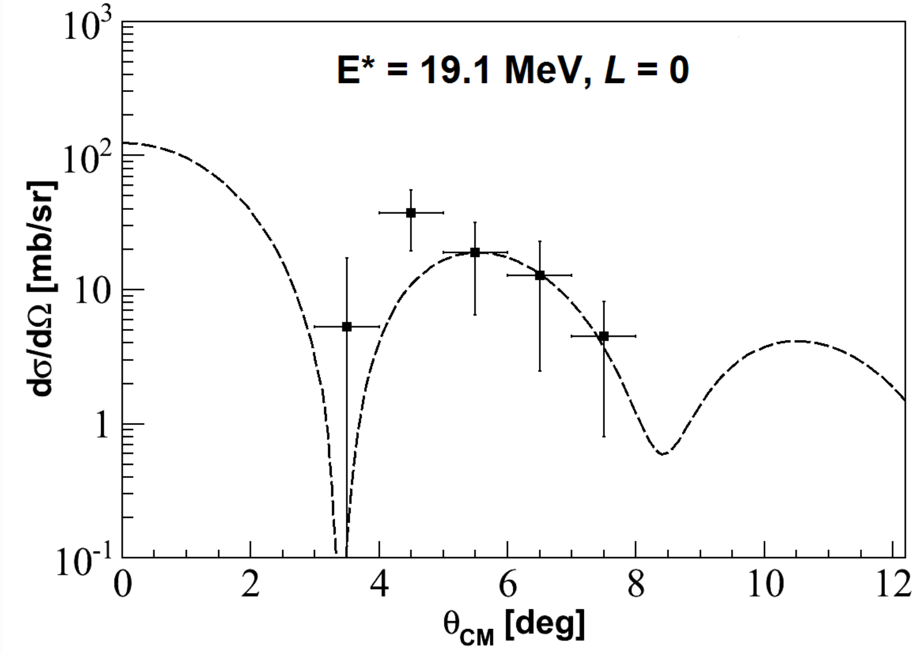
L = 0, T = 0 (ISGMR)

Reaction	Gaussian fitting E* [MeV]	Gaussian fitting FWHM [MeV]	MDA E* [MeV]	MDA Width (rms) [MeV]
$^{56}Ni(\alpha,\alpha')^{56}Ni^*$ (this work)	19.1 ± 0.5	2.0 ± 0.3	18.4 ± 1.8	2.0 ± 1.2
$^{56}Ni(d,d')^{56}Ni^*$	19.5 ± 0.3	5.2	19.3 ± 0.5	2.3
$^{58}Ni(\alpha,\alpha')^{58}Ni^*$	18.43 ± 0.15	7.41 ± 0.13	$19.2^{+0.44}_{-0.19}$	$4.89^{+1.05}_{-0.31}$
$^{58}Ni(\alpha,\alpha')^{58}Ni^*$	-	-	$19.9^{+0.7}_{-0.8}$	-
$^{60}Ni(\alpha,\alpha')^{60}Ni^*$	17.62 ± 0.15	7.55 ± 0.13	$18.04^{+0.35}_{-0.23}$	$4.5^{+0.97}_{-0.22}$
$^{68}Ni(\alpha,\alpha')^{68}Ni^*$	21.1 ± 1.9	1.3 ± 1.0	23.4	6.5

S. Bagchi et al., Phys. Lett. B751, 371 (2015)

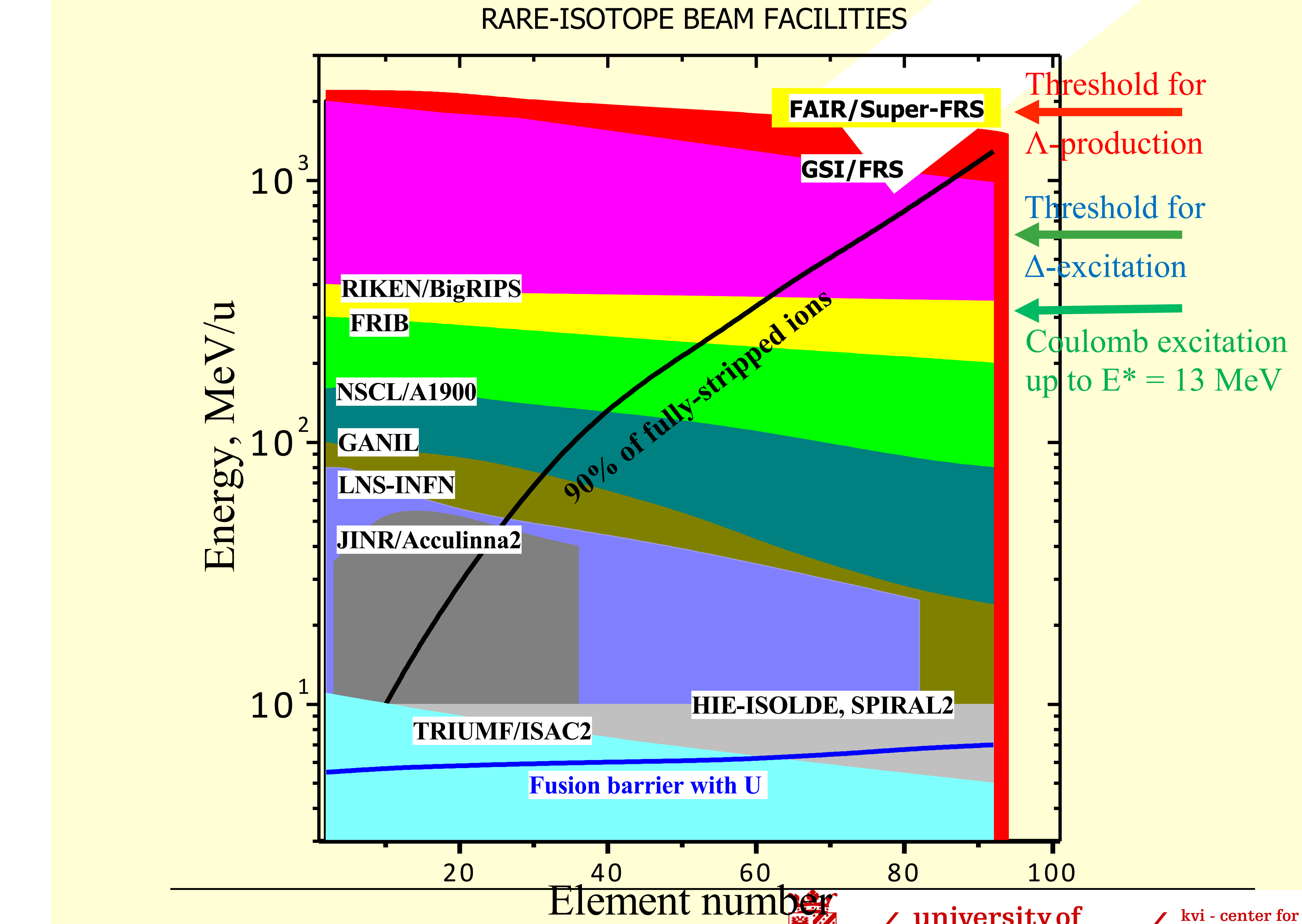
Monopole mode in ^{58}Ni and ^{56}Ni: ring vs. active target



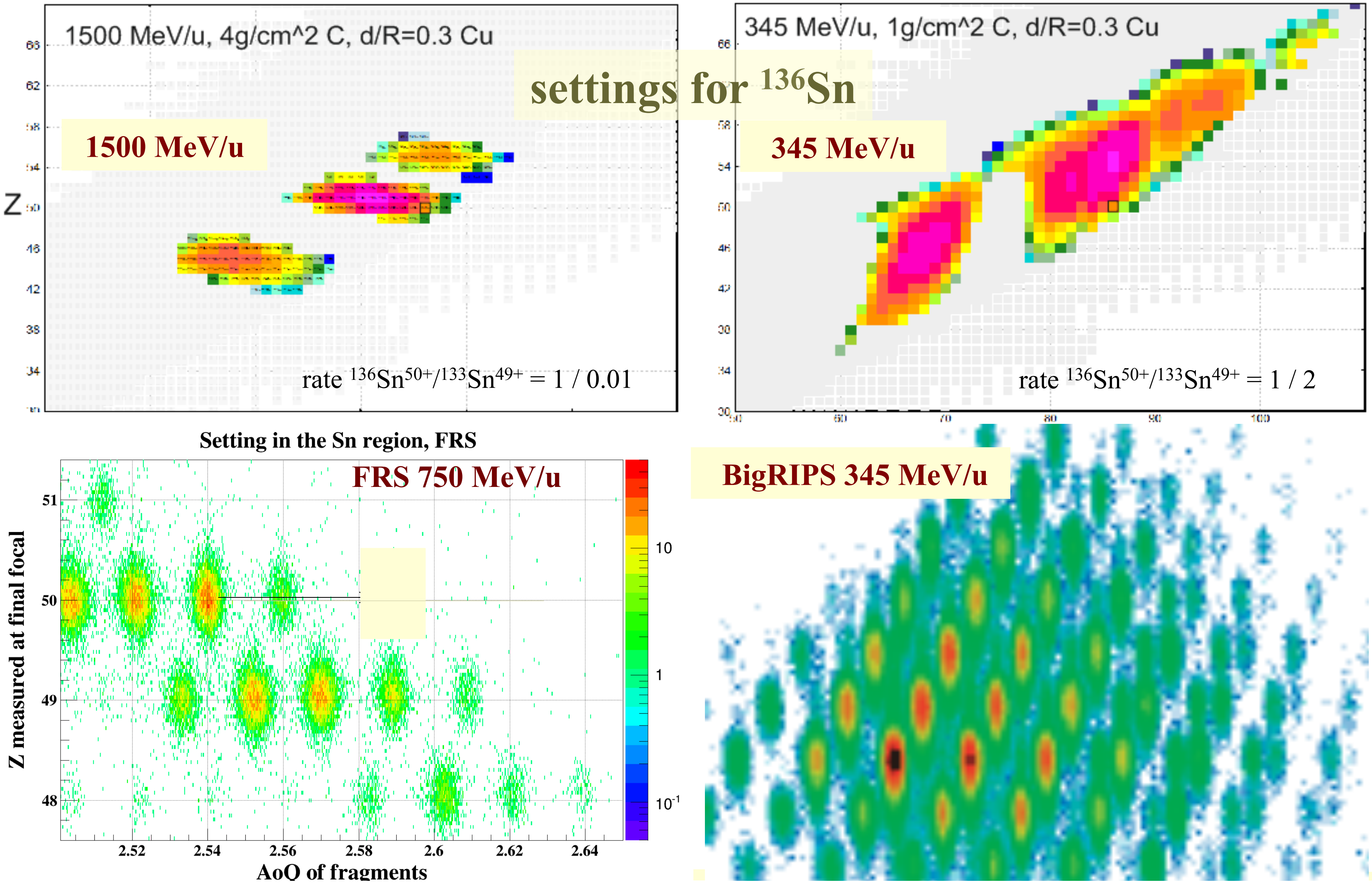


^{58}Ni

^{56}Ni


RARE-ISOTOPE BEAM FACILITIES
FAIR/Super-FRS
GSI/FRS
RIKEN/BigRIPS
FRIB
NSCL/A1900
GANIL
LNS-INFN
JINR/Acculinna2
HIE-ISOLDE, SPIRAL2
TRIUMF/ISAC2
Fusion barrier with U
90% of fully-stripped ions
Threshold for
Λ-production
Threshold for
Δ-excitation
Coulomb excitation
up to E* = 13 MeV
Energy, MeV/u
Element number
10^3
10^2
10^1
20
40
60
80
100

Charge-separation capability for different Energies



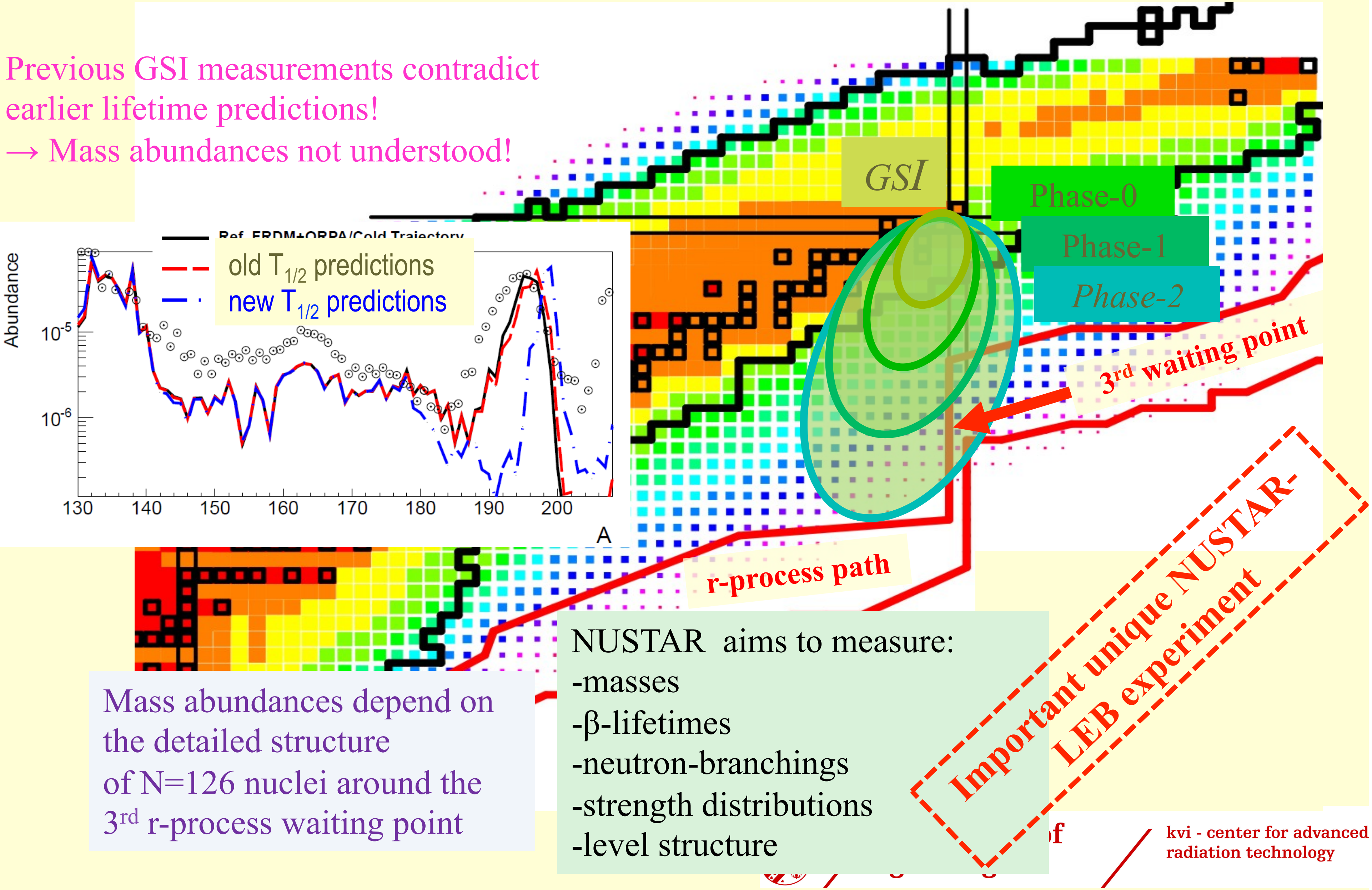
What are the highlights of NUSTAR Phase 1 program?

- Understanding the 3rd r-process peak by means of comprehensive measurements of masses, lifetimes, neutron branchings, dipole strength, and level structure along the N=126 isotones;
- Equation of State (EoS) of asymmetric matter by means of measuring the dipole polarizability and neutron skin thicknesses of tin isotopes with N larger than 82 (in combination with the results of the first highlight);
- Exotic hypernuclei with very large N/Z asymmetry.

Phase 1 Physics with HISPEC/DESPEC:

r-process nuclei at N=126

Previous GSI measurements contradict earlier lifetime predictions!
→ Mass abundances not understood!



Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

NUSTAR aims to measure:
- masses
- β-lifetimes
- neutron-branchings
- strength distributions
- level structure

Important unique NUSTAR-LEB experiment

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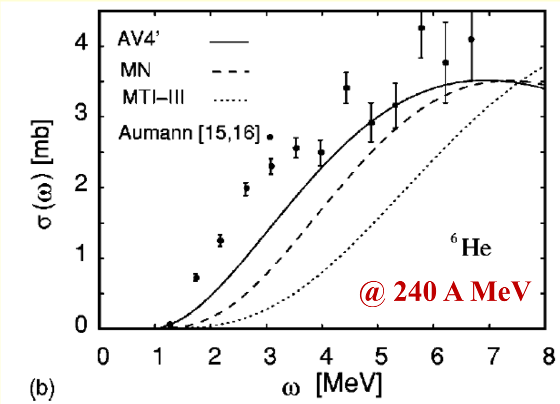
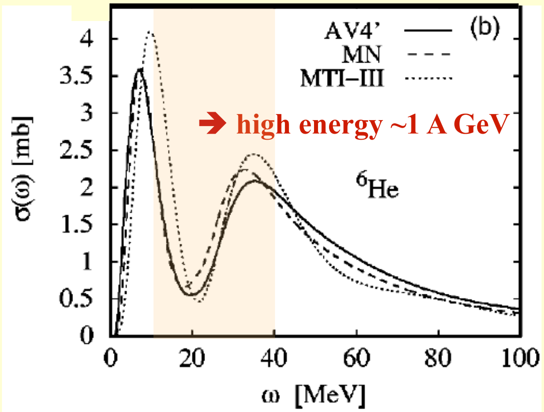
Phase 1 Physics with R3B setup:

Dipole strength Distributions in heavy neutron-rich nuclei

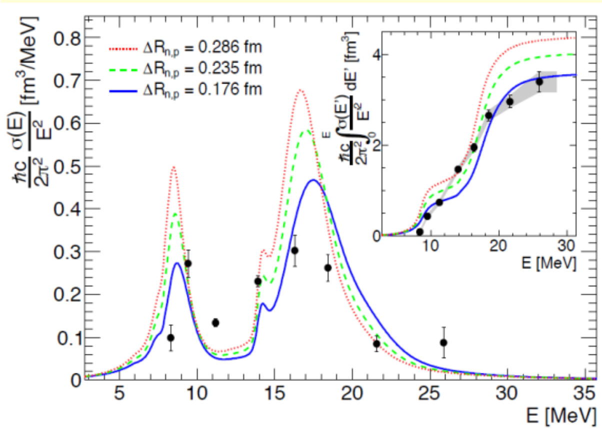
- core vs. neutron skins & halos → density / asymmetry





S. Bacca et al.
PRL **89** (2002) 052502
PRC **69** (2004) 057001

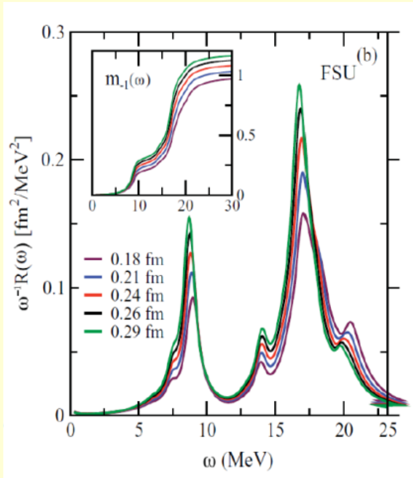
- access to EoS (e.g. neutron star) & low lying E1 strength (r-process)



$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma(E)}{E^2}dE$$

D. Rossi et al.
PRL **111** (2013) 242503

skin thickness ^{68}**Ni**
0.175(21) fm



Pb chain &
N=126 isotones

~1 A GeV →
bare ions
Fragment
identification

J. Piekarewicz, PRC **83** (2011) 034319

Conclusions

✧ Many-body theories have come a long way. These days, they can work with chiral nuclear forces as well. 3NF should be better understood though. New reaction theories based on these new developments should now be worked on.

Conclusions

- ✧ Many-body theories have come a long way. These days, they can work with chiral nuclear forces as well. 3NF should be better understood though. New reaction theories based on these new developments should now be worked on.
- ✧ Light hadron scattering can be used at low momentum transfers to probe fundamental properties of nuclei such as density distributions, compressibility and in general collective properties, beta-decay rates etc. Equation of state of asymmetric matter is highly desired.

Conclusions

✧Many-body theories have come a long way. These days, they can work with chiral nuclear forces as well. 3NF should be better understood though. New reaction theories based on these new developments should now be worked on.

✧Light hadron scattering can be used at low momentum transfers to probe fundamental properties of nuclei such as density distributions, compressibility and in general collective properties, beta-decay rates etc. Equation of state of asymmetric matter is highly desired.

✧NOTE: I could only show a small subset of all nuclear-structure activities around the world.

Thank you!