Experiments with Rare Isotopes
- Recent (selected) Highlights -

R. Kanungo
Saint Mary's University & TRIUMF , Canada

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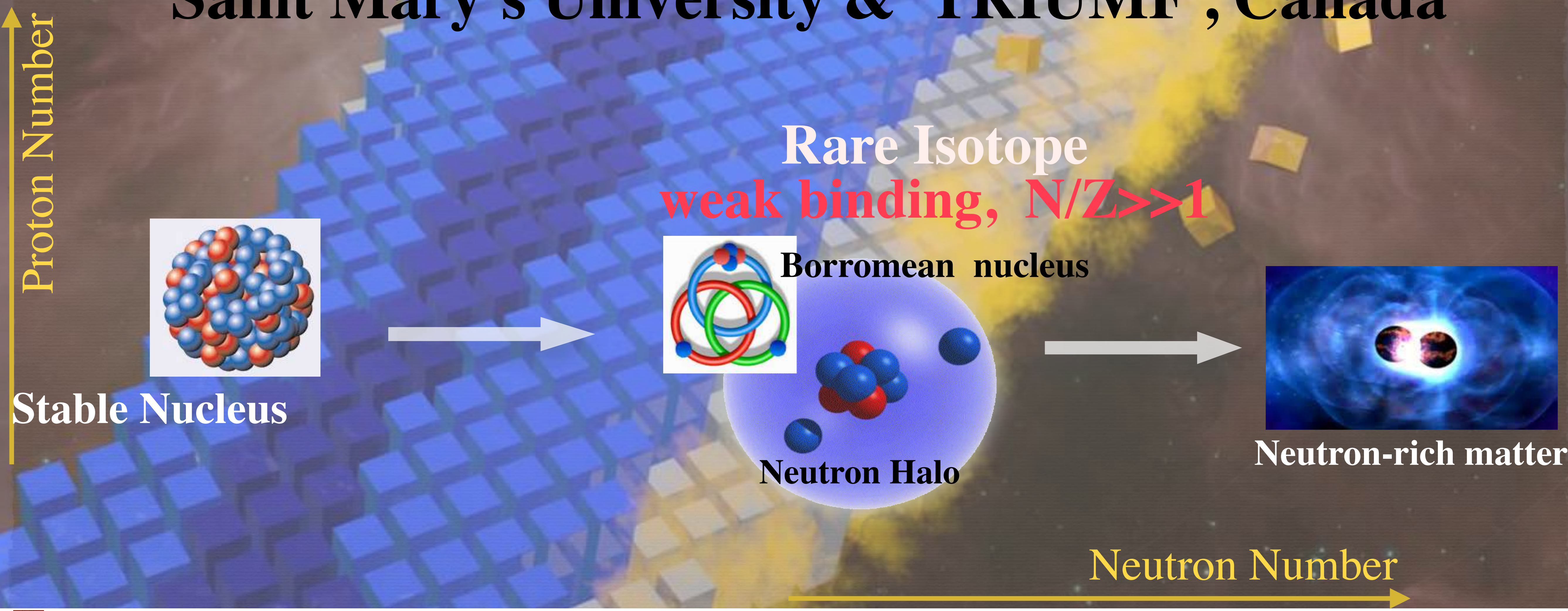


Why explore the rare isotopes ?

- **What new features emerge with neutron-proton asymmetry ?**

  New structures - Halo, Skin
  New Excitation modes
  Change of shells

- **What is the nature of the nuclear force ?**

  Tensor force
  Three-body force
  Pairing Interaction

- **How do rare isotopes shape our Universe ?**

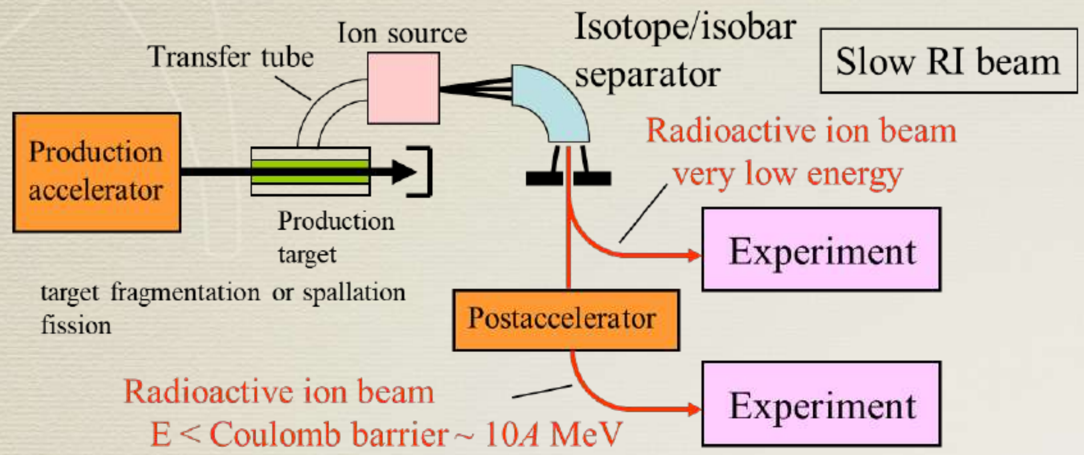
  Nucleosynthesis *(Talk : Hendrik Schatz)*
  Structure information needed to constrain reaction rates
  Equation of state of asymmetric nuclear matter

- **Rare isotopes test fundamental symmetries**

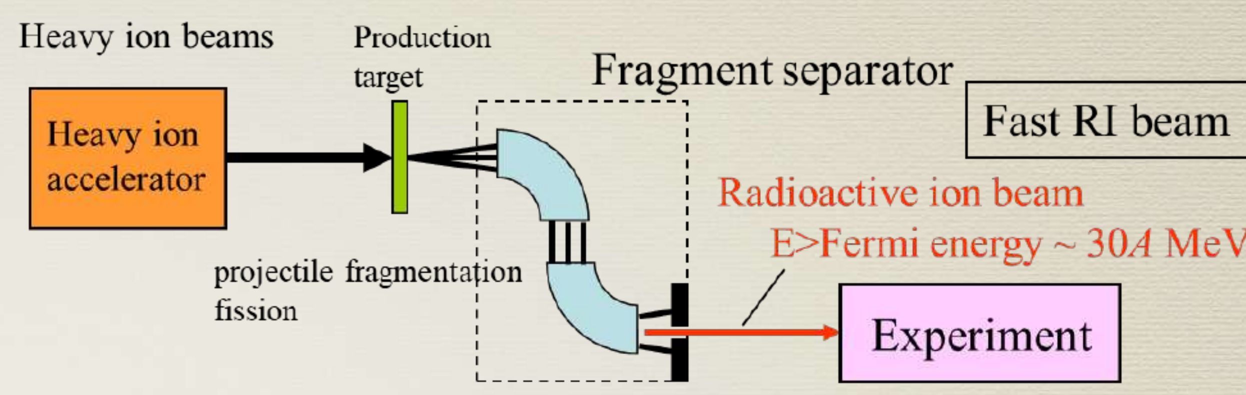
Rare Isotopes Facilities

Isotope Separator Online (ISOL)

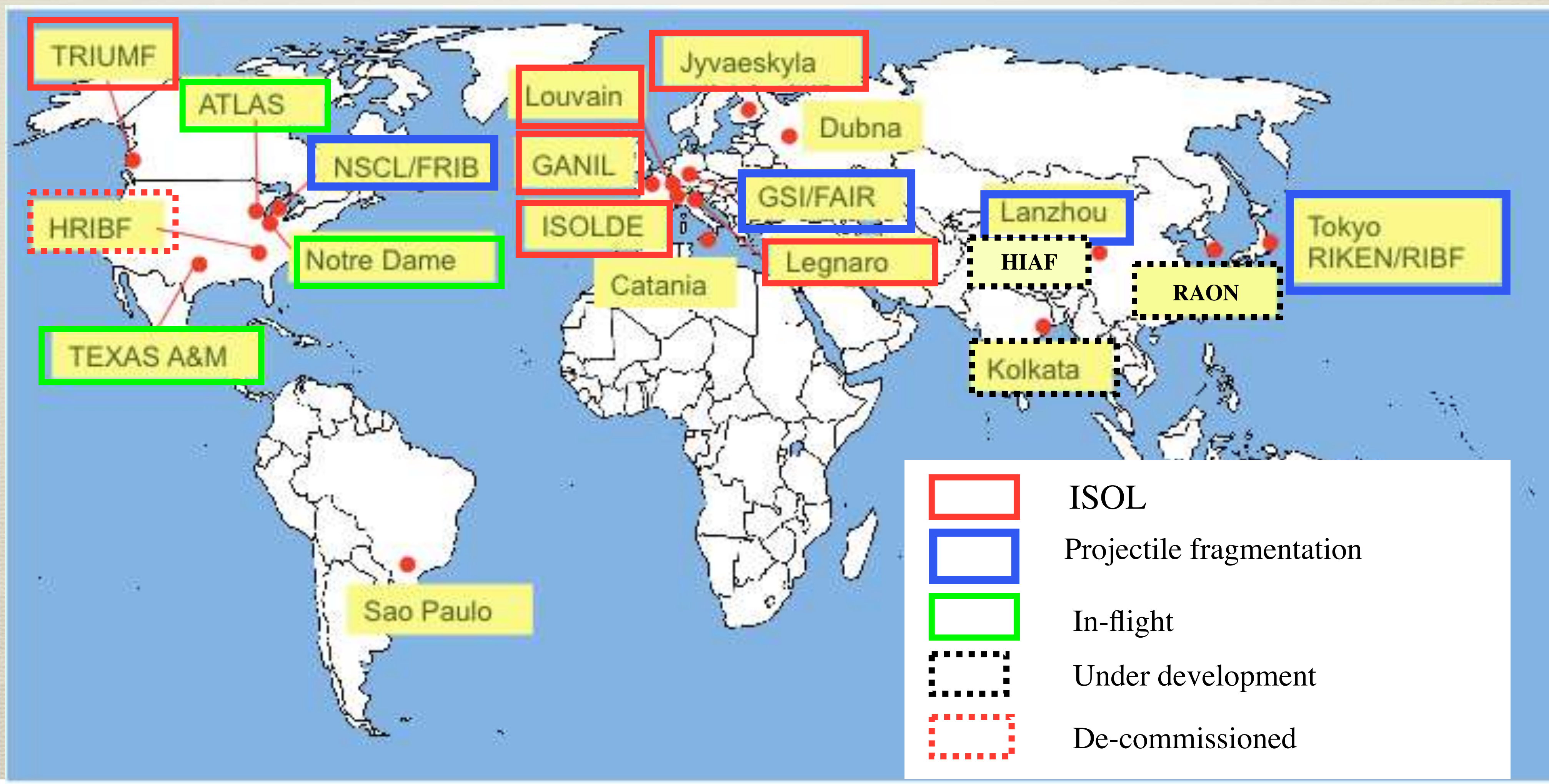
ISOL facility



In-flight - Projectile Fragmentation



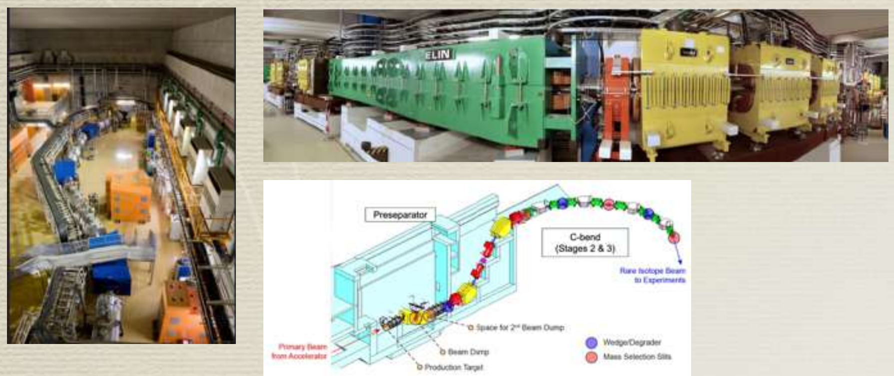
Courtesy : H. Sakurai



State-of-the-art instruments peek into rare isotpes

Fragment Separators

BigRIPS (RIKEN), FRS (GSI), ARIS+A1900 (FRIB)



Mass Measurements

Penning Traps: TITAN (TRIUMF), ISOLTRAP (CERN), CPT (ANL), LEBIT(FRIB), JYFLTRAP (Jyväskylä)

MR-TOF : RIKEN, GSI, TRIUMF

Storage Ring: ESR (GSI), Rare-RI Ring (RIKEN), HIRFL-CSR (Lanzhou)

High Rigidity Spectrometers & Mass Separators

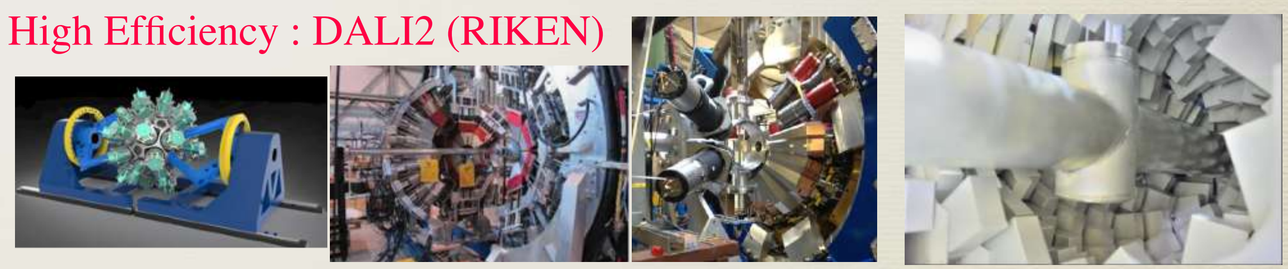
High Rigidity Spectrometers : SAMURAI (RIKEN), GLAD-R^{3}B (GSI/ FAIR), S800 (FRIB)

Mass Separators/Spectrometers : DRAGON, EMMA (TRIUMF), SECAR (FRIB), SHARAQ (RIKEN)

γ- spectroscopy

High Resolution : GRETINA/GRETA, CLARION (USA), AGATA (Europe), GRIFFIN, TIGRESS (Canada)

High Efficiency : DALI2 (RIKEN)



High Luminosity Targets

Active Targets : MAYA,ACTAR (GANIL), AT-TPC (FRIB), TEXAT (TAMU), SpecMAT (Leuven), MAIKo (Kyoto/RCNP)

Solid H_2 Target : IRIS (TRIUMF)

Liquid H_2 Target : MINOS (RIKEN)

High resolution charged particle spectroscopy

HELIOS (ANL), Isolde Solenoidal Spectrometer (CERN), SOLARIS (FRIB)

Neutron detectors

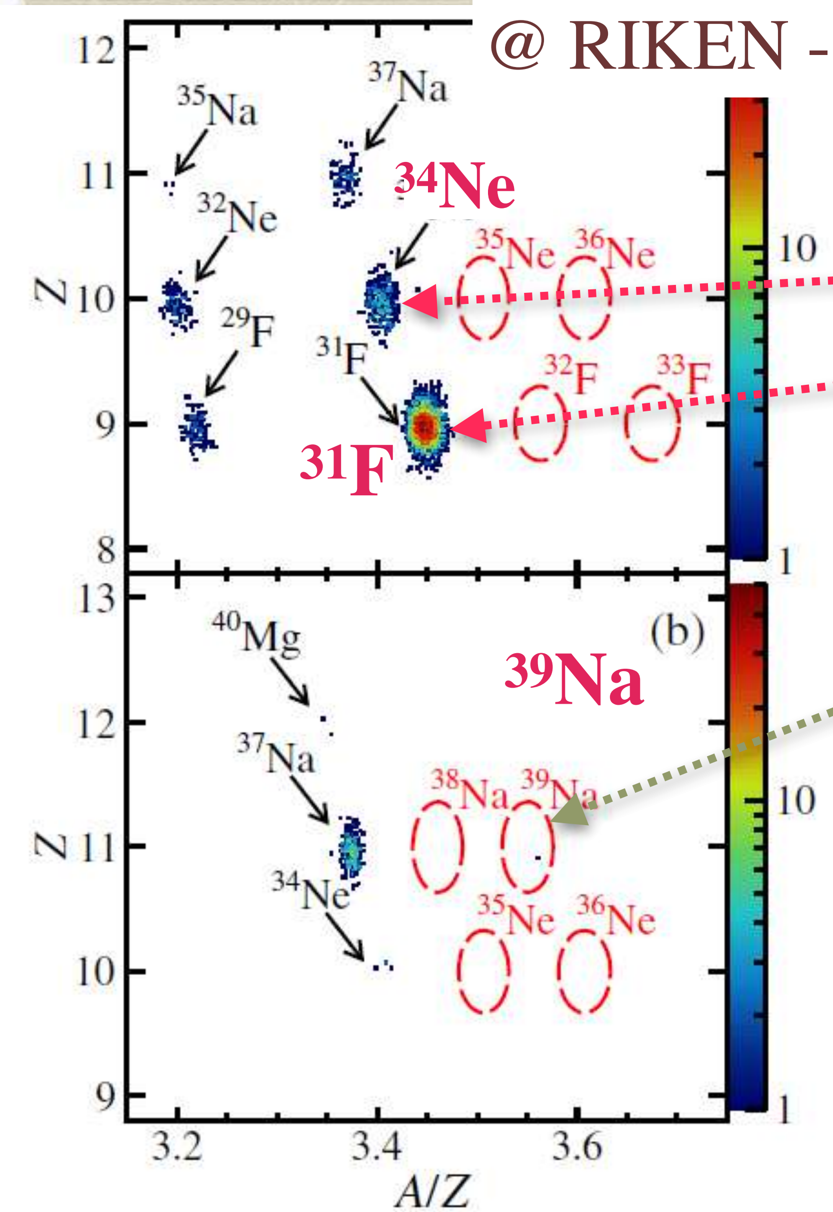
MoNA (FRIB), NeuLAND (GSI), NEBULA (RIKEN), BELEN (Europe), VANDLE (FRIB), DESCANT (TRIUMF), TexNEUT (TAMU)

Laser Spectroscopy

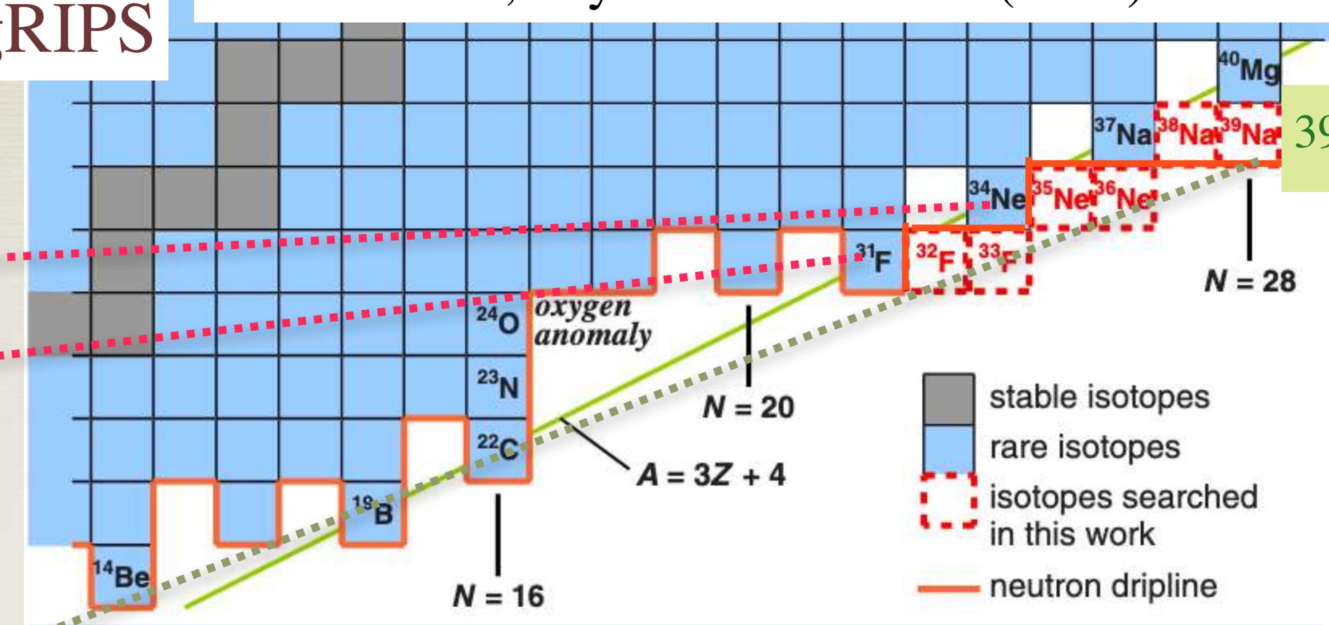
COLLAPS, CRIS (CERN), BECOLA (FRIB)

Hunt for the nuclear landscape boundary

@ RIKEN - BigRIPS



D. Ahn *et al*., Phys. Rev. Lett. 123 (2019) 212501

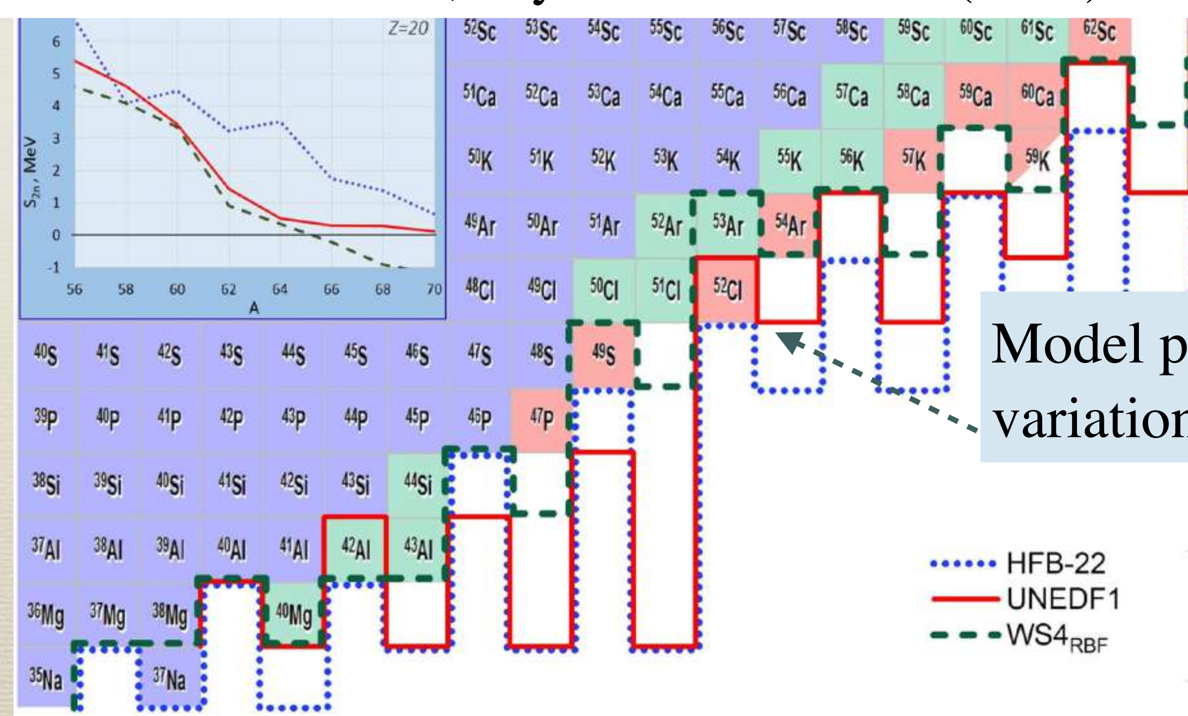


^{39}Na is bound !

Neutron drip-line established for F and Ne

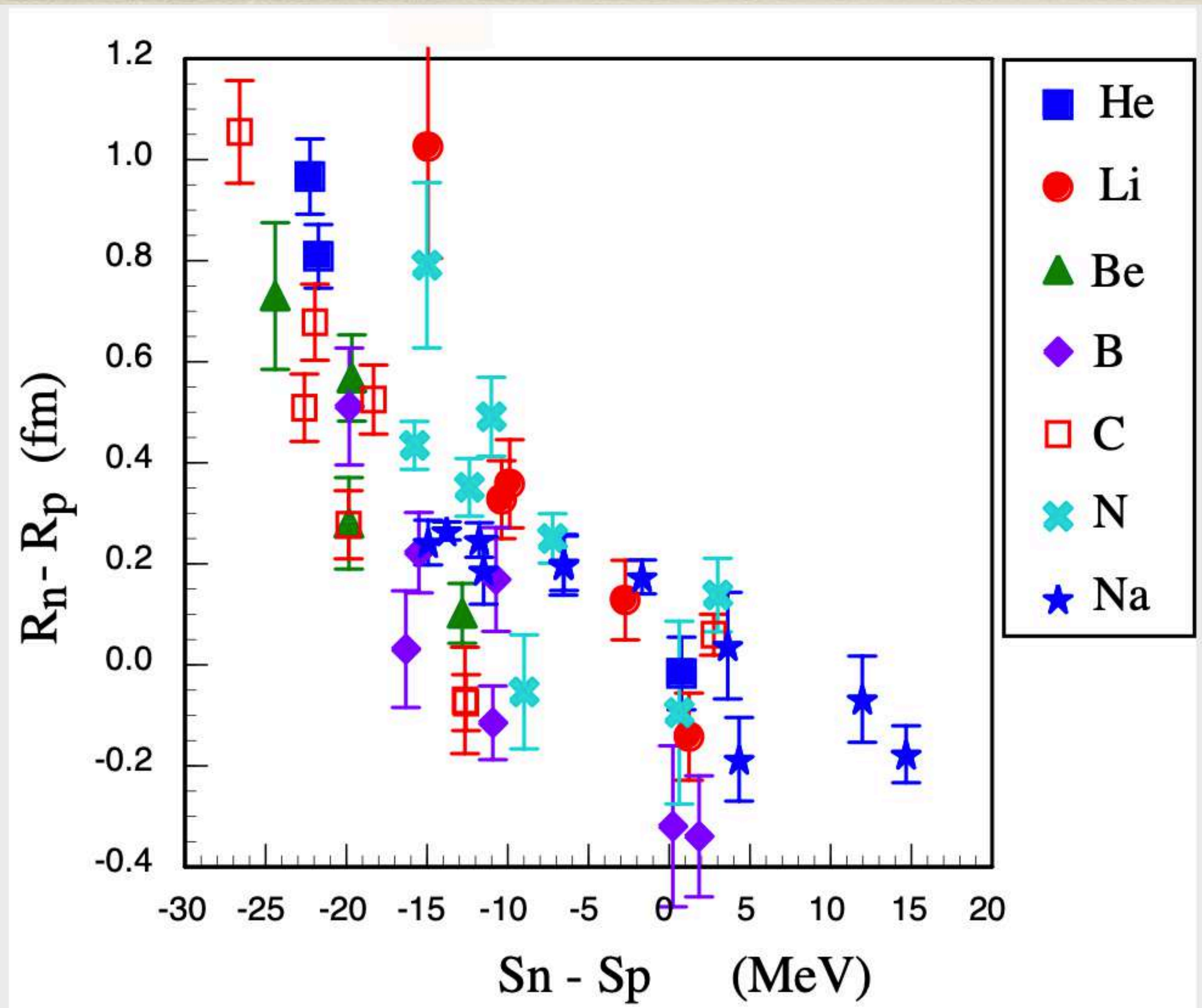
Drip line @ ^{31}F signals it is deformed

O. B. Tarasov *et al*., Phys. Rev. Lett. 121 (2018) 022501



Model predictions have a wide variation in predicting the drip-line

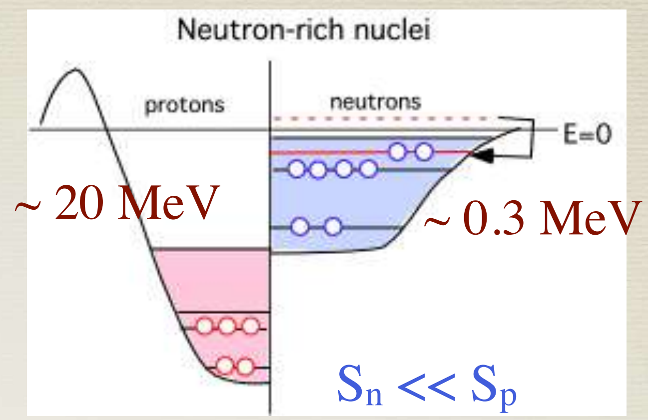
Neutron balloon in neutron-rich nuclei



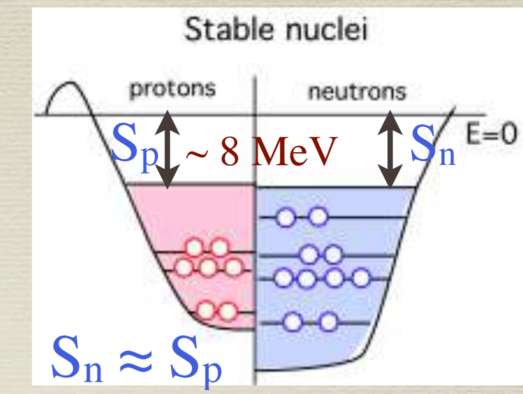
Neutron-rich nuclei

Stable nuclei

N/Z >> 1

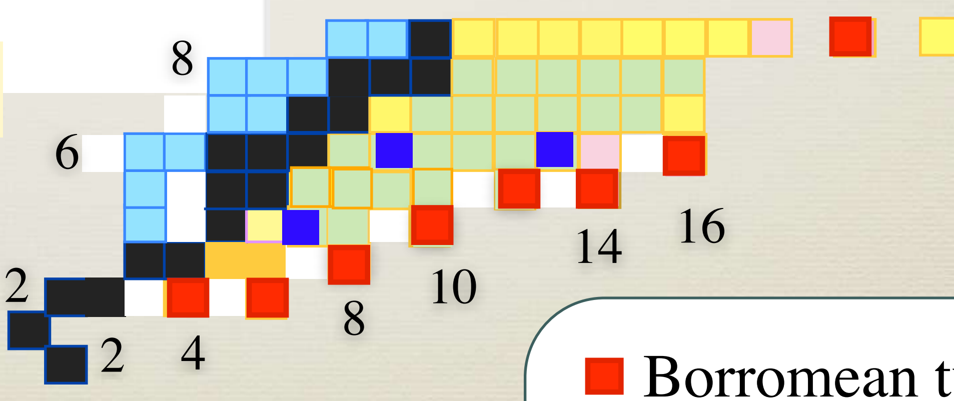


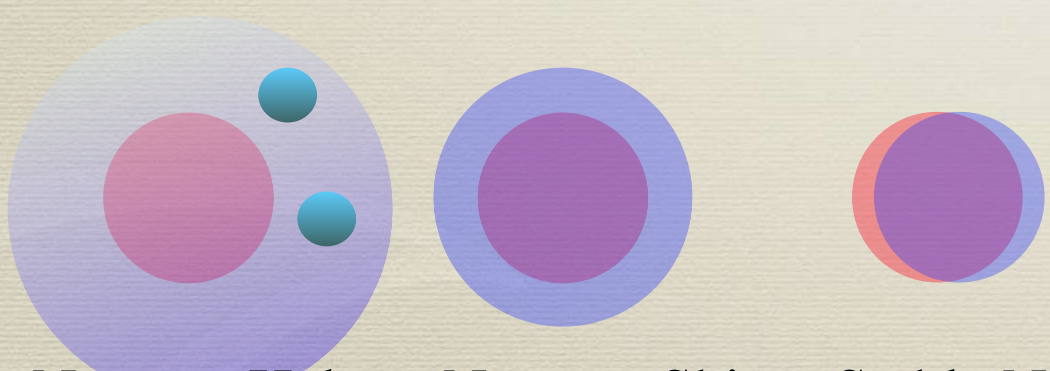
N/Z ~ 1-1.5



Fermi-levels of neutrons and protons are similar.

- Weak binding & *n-p* Fermi level difference



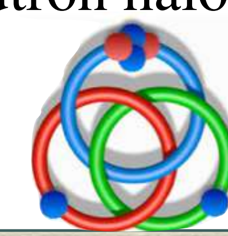


Neutron Halo Neutron Skin Stable Nucleus

Borromean two-neutron halos

Core+n+n

One-neutron halos

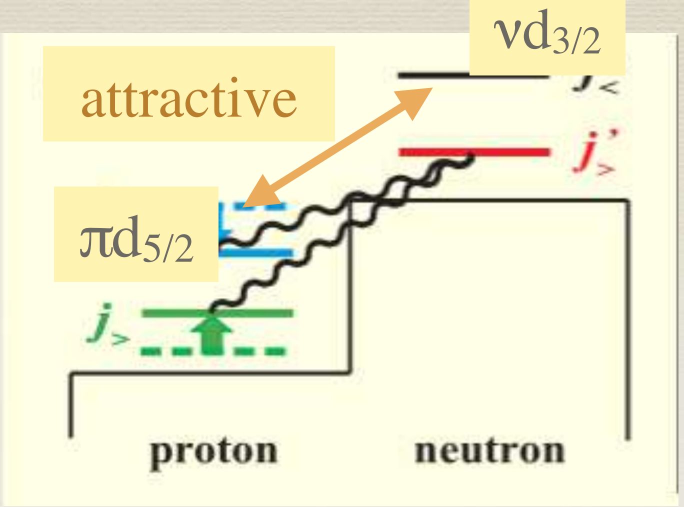


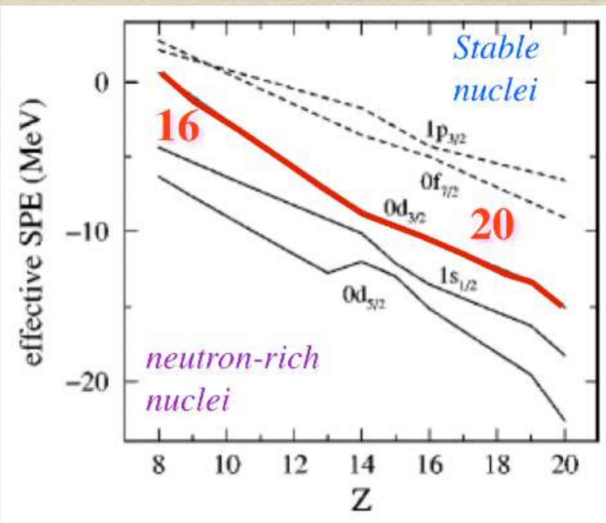
Exotic phenomena & nuclear force

❖ Tensor force

p(j< = *l*-1/2) - n(j>=*l*+1/2) attractive
p(j> =*l*+1/2) - n(j> =*l*+1/2) repulsive

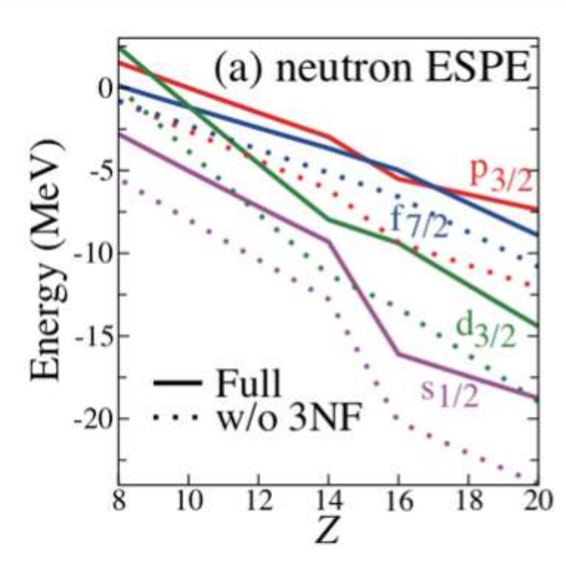
T. Otsuka *et al*., Phys. Rev. Lett. 2005





❖ Three-nucleon force

N = 20



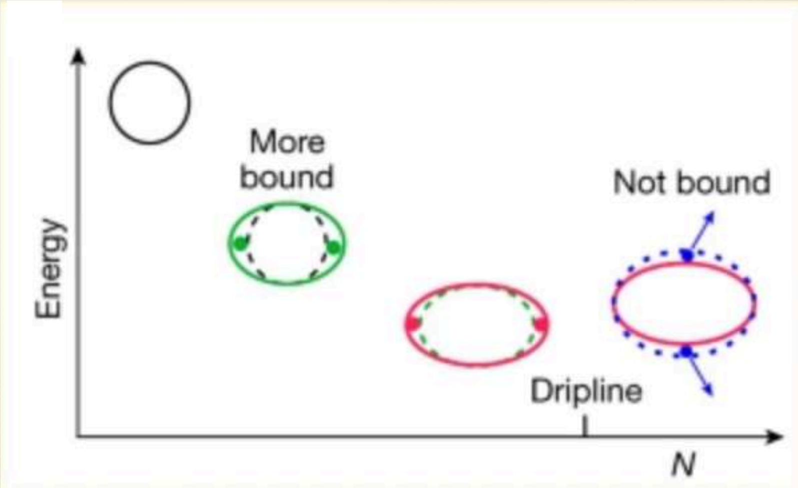
N. Tsunoda *et al*., Phys. Rev. C (R) 2017

Neutron drip-line in O isotopes

❖ Deformation

N. Tsunoda, T. Otsuka, K. Takayanagi *et al*., Nature, 2020

F to Mg : Strongly correlated valence neutrons -> ellipsoidal shape saturation marks the drip-line



❖ Pairing Interaction

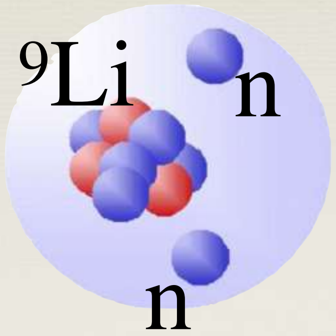
Neutron Halo features &
Disappearance of known nuclear shell gaps

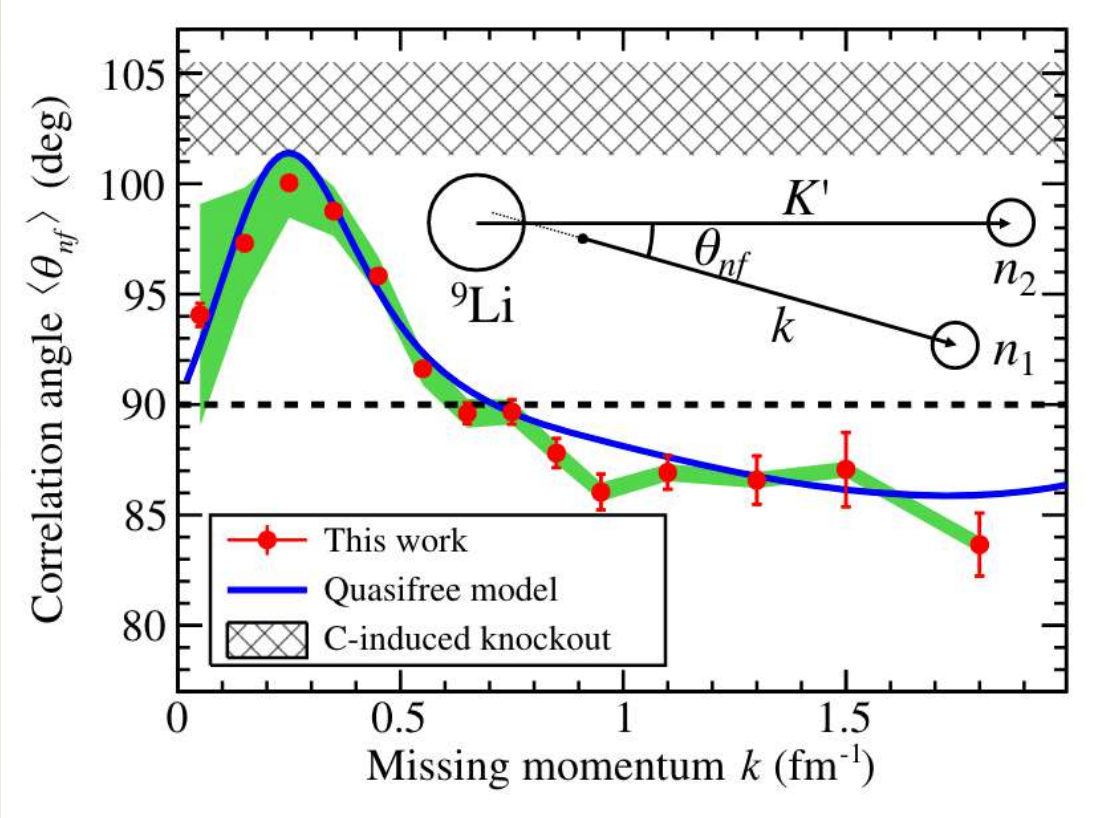
^{11}Li : Halo n-n correlation

@ RIKEN-SAMURAI E/A = 246 MeV

^{11}Li(p, pn)^{10}Li

Y. Kubota, A. Corsi, G. Authelet *et al.*, Phys. Rev. Lett. 125 (2020) 252501





Di-neutron localized at the surface
i.e. *Core - nn distance* of ~ 3.6 fm

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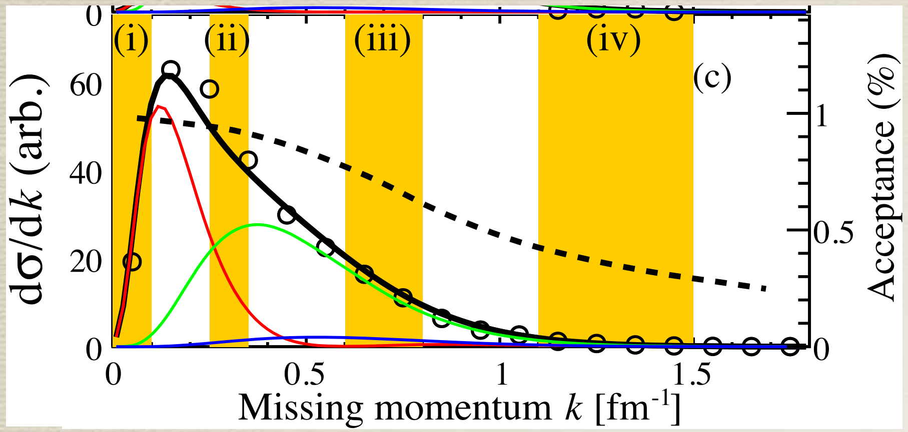
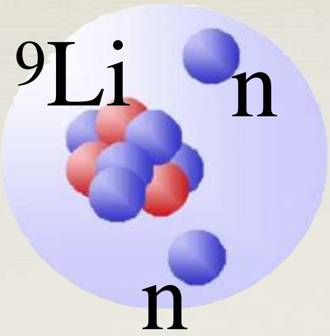
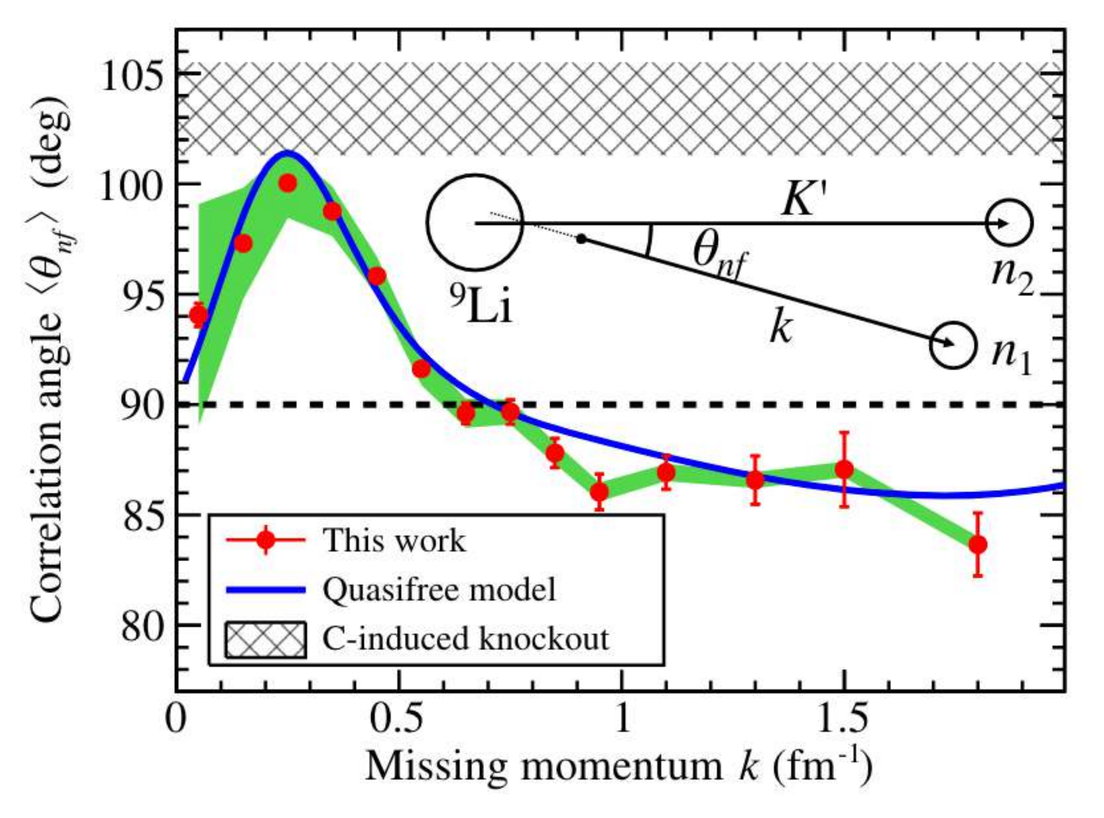


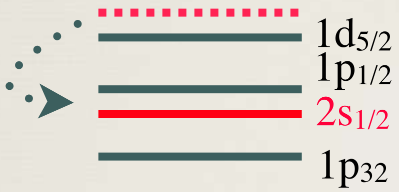




$2s_{1/2}$: 35(4)%

$1p_{1/2}$: 59(1)%

$1d_{5/2}$: 6(4)%



N = 8 shell vanishes

Di-neutron localized at the surface
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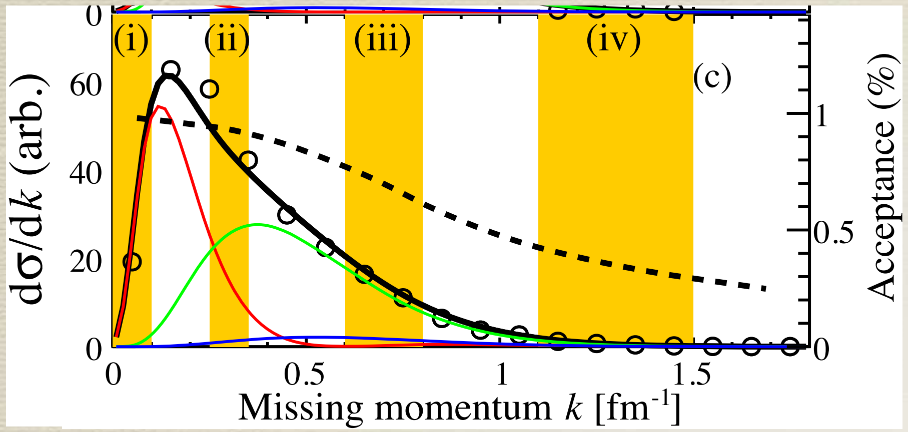

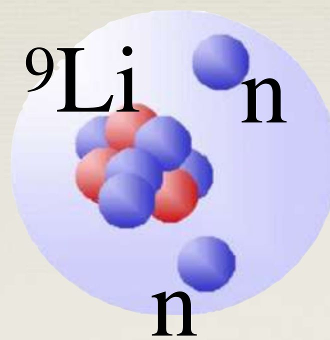

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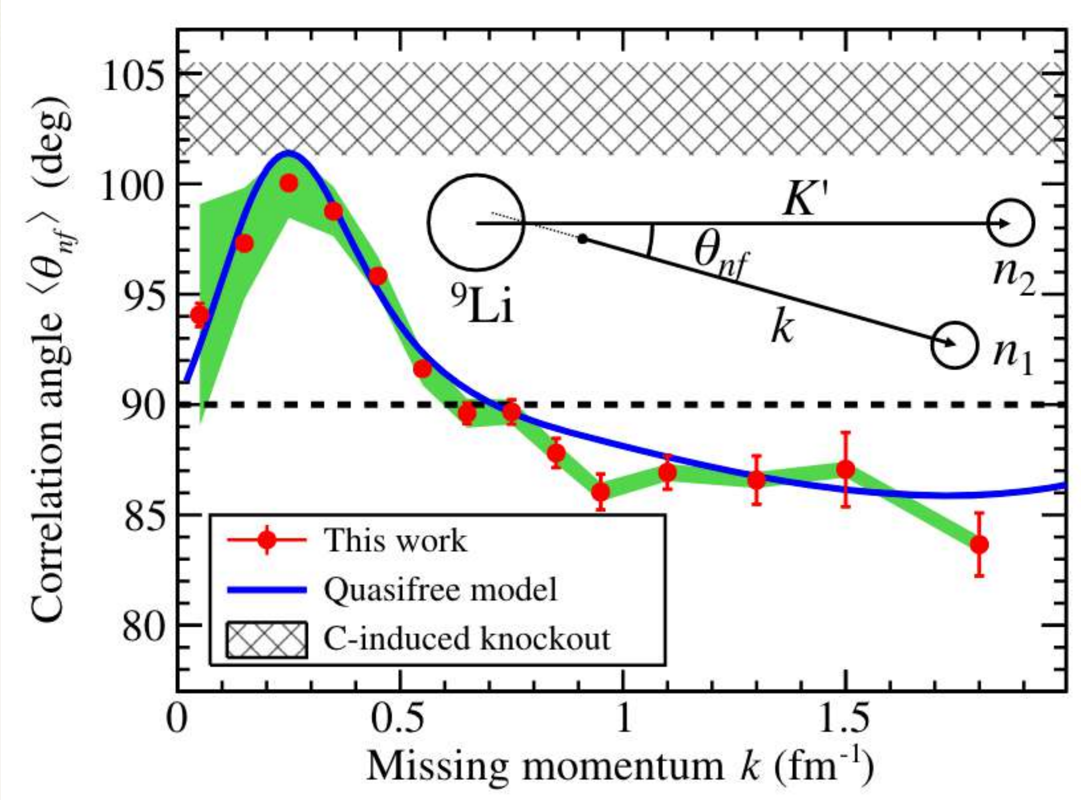

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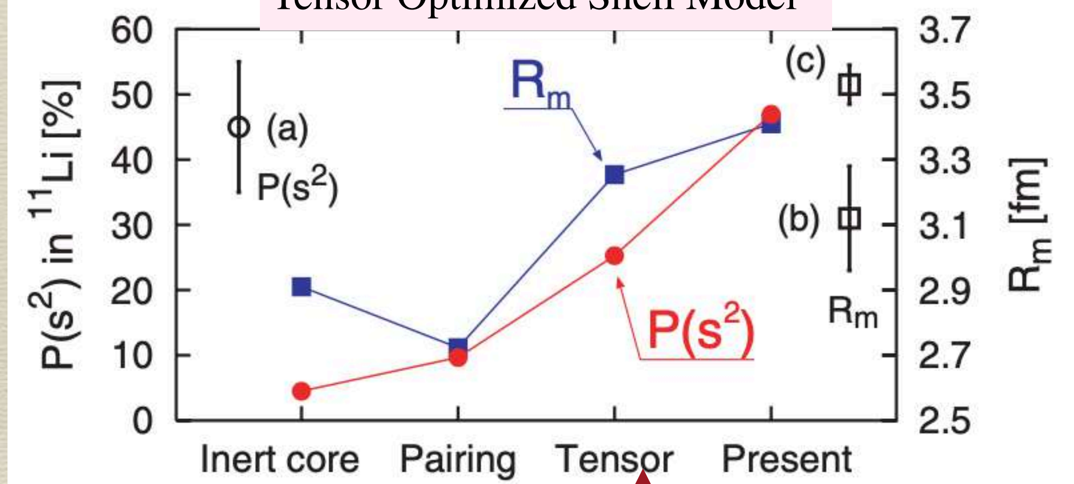
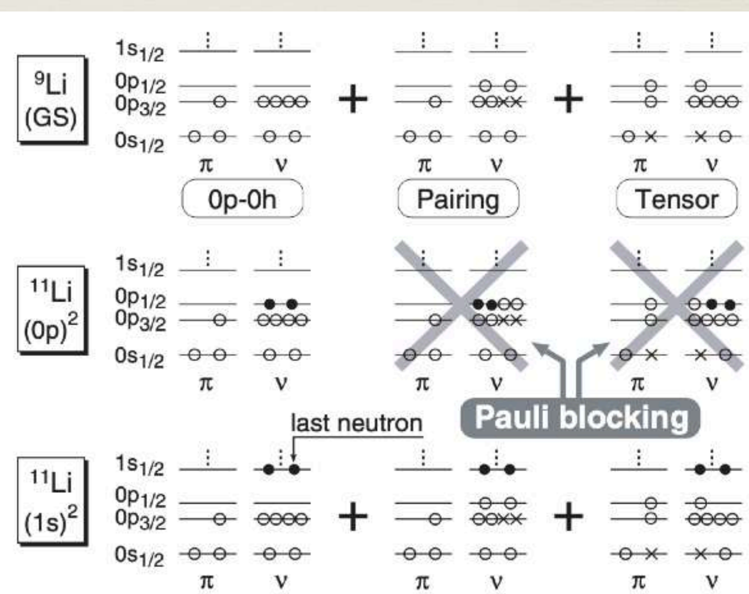
i.e. *Core - nn distance* of ~ 3.6 fm

Tensor Optimized Shell Model



T. Myo *et al.*, PRC (2007)

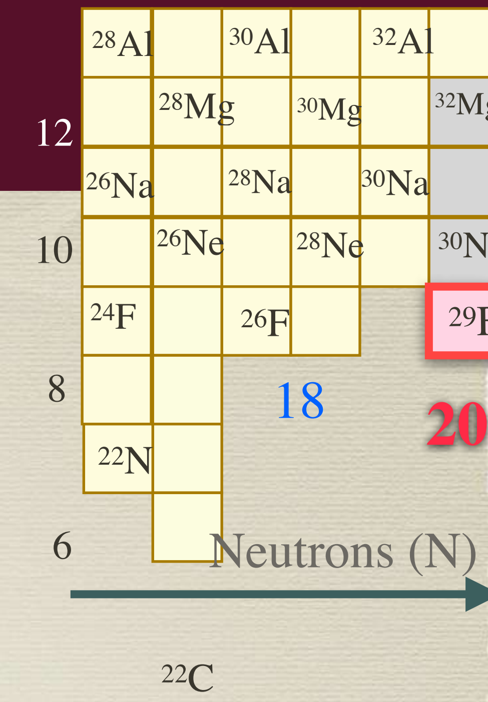
$2s_{1/2}$ lowering : predicted due to Tensor force - 2π exchange



^{29}F : Borromean Neutron halo

@ RIKEN-BigRIPS+ZDS

S_{2n} = 1.4(6) MeV

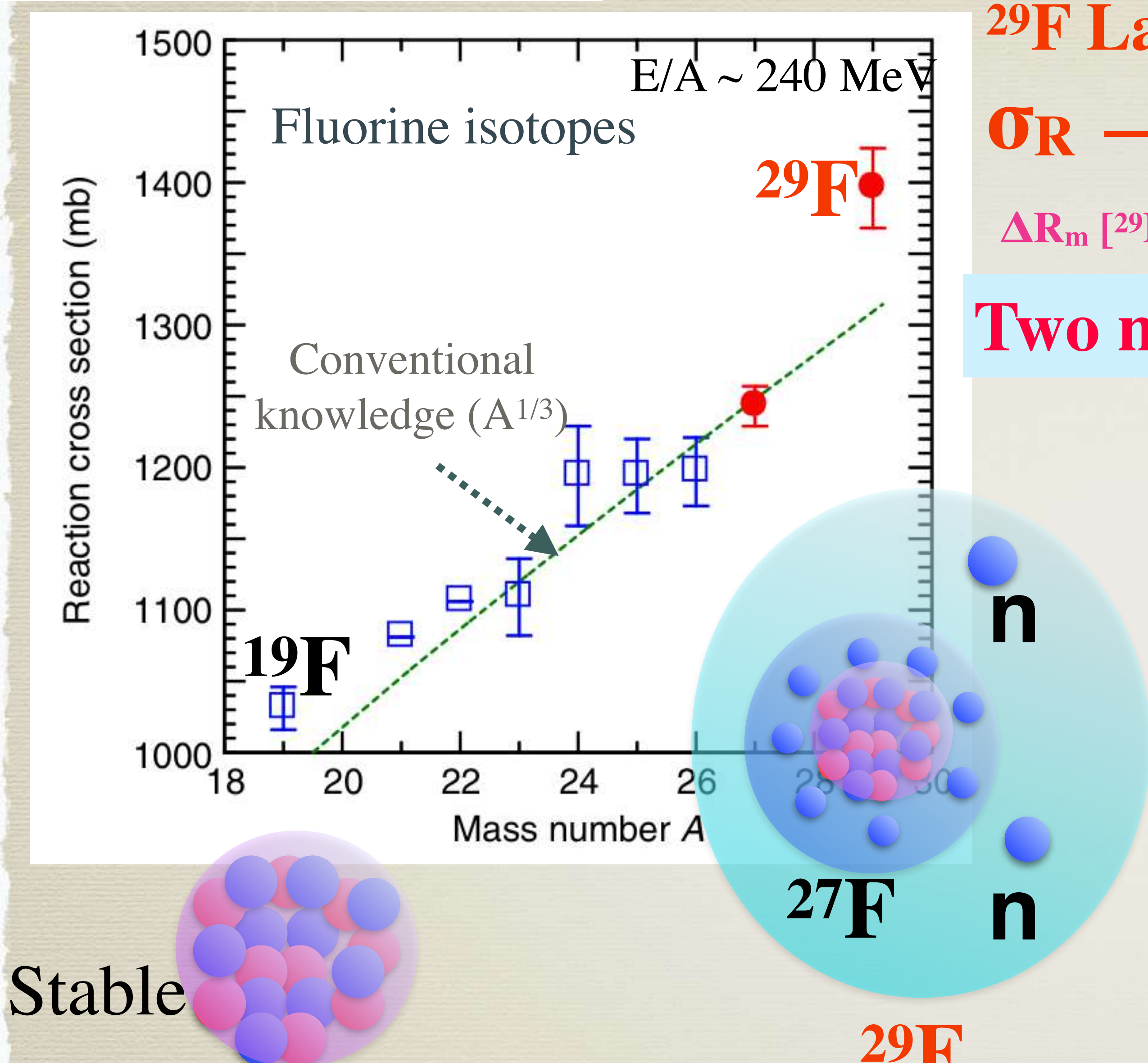


^{29}F Large increase in

σ_R —> matter radius

ΔR_m [^{29}F - ^{27}F] ~ 0.39(18) fm

Two neutron halo



Stable

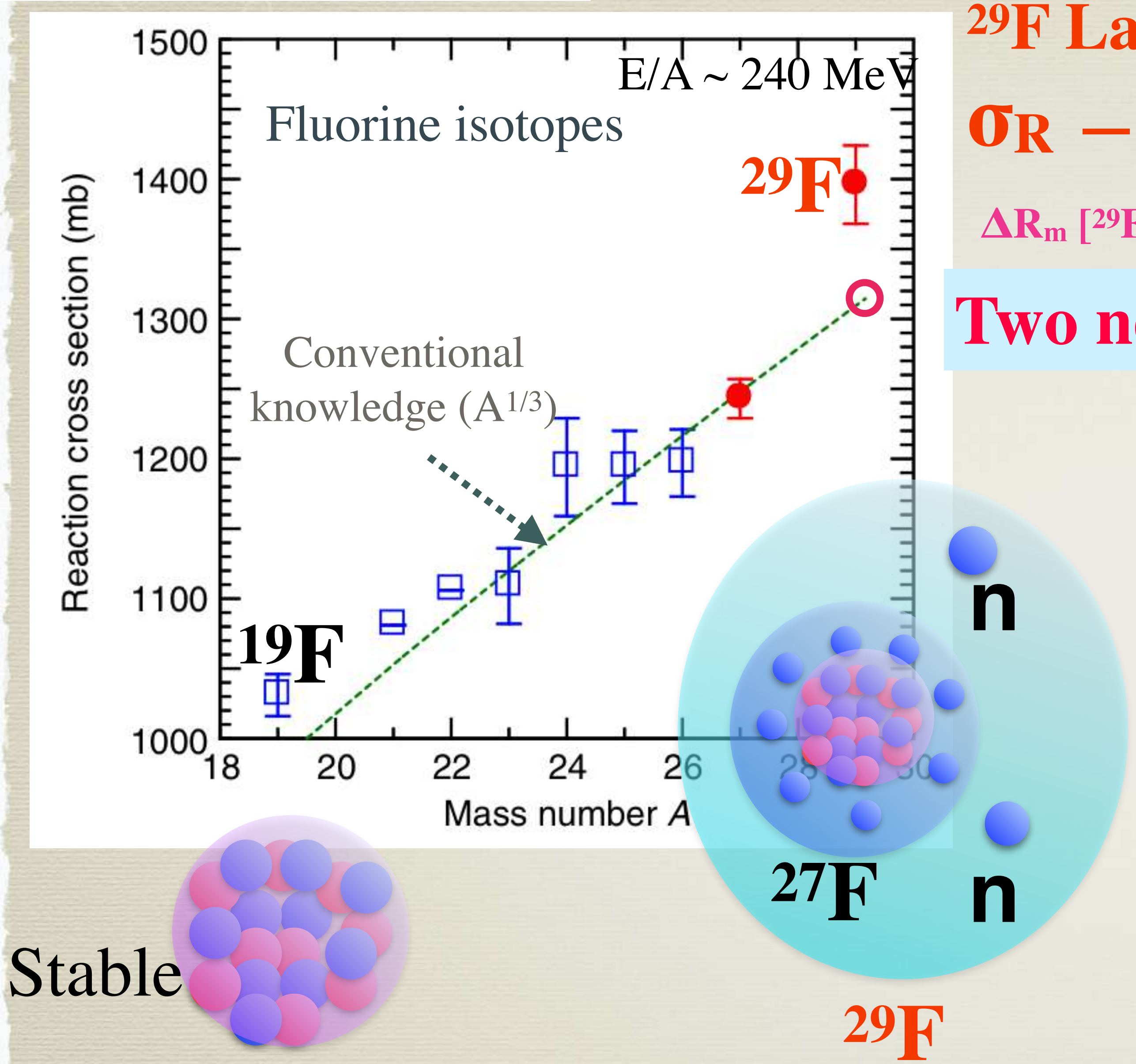
^{29}F

S. Bagchi et al., Phys. Rev. Lett. 124 (2020) 222504

□ A. Honma et al., JPS Proc. 14 (2017) 021010

^{29}F : Borromean Neutron halo

@ RIKEN-BigRIPS+ZDS



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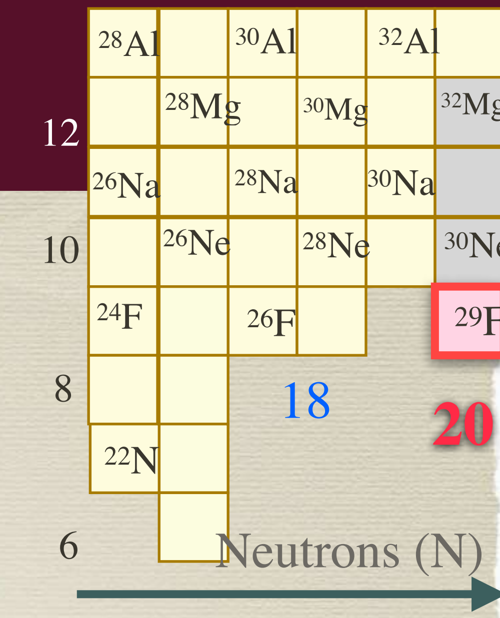

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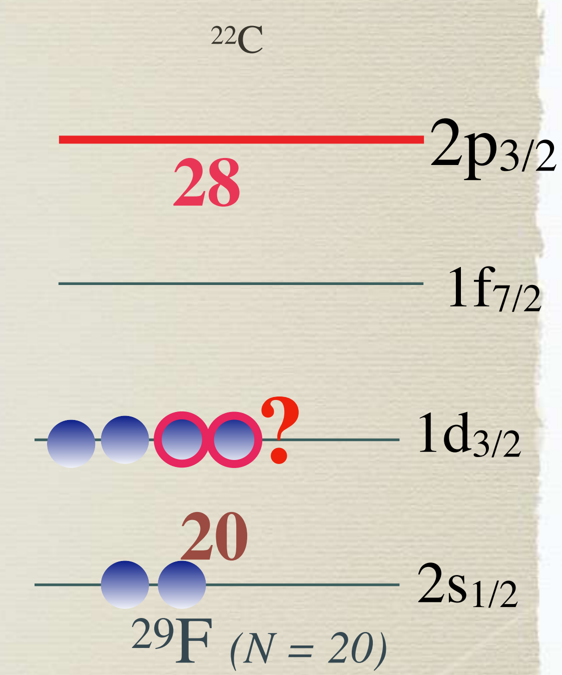

S. Bagchi et al., Phys. Rev. Lett. 124 (2020) 222504

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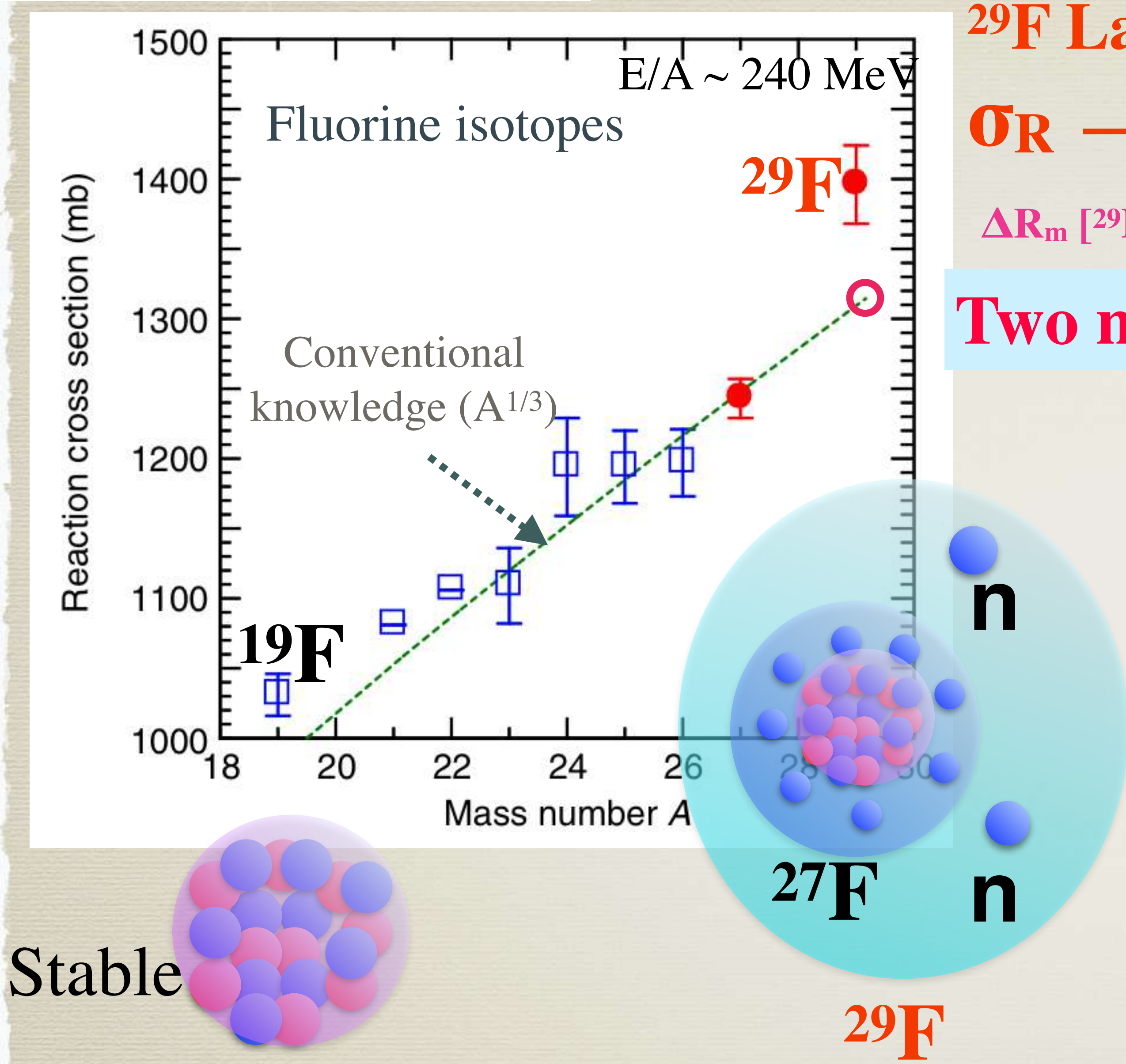

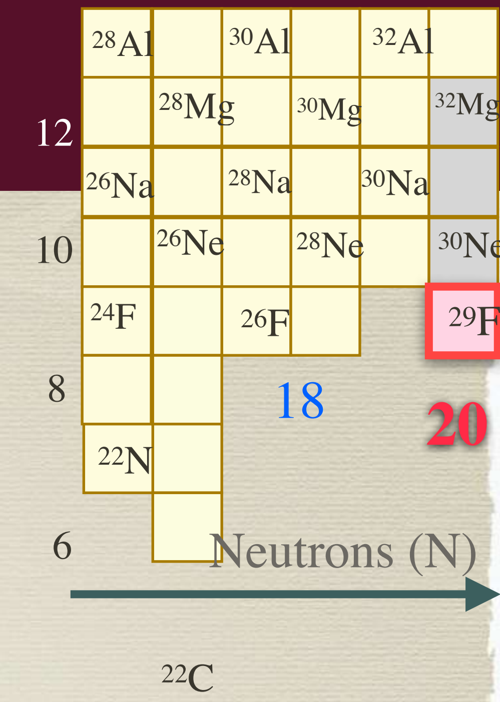

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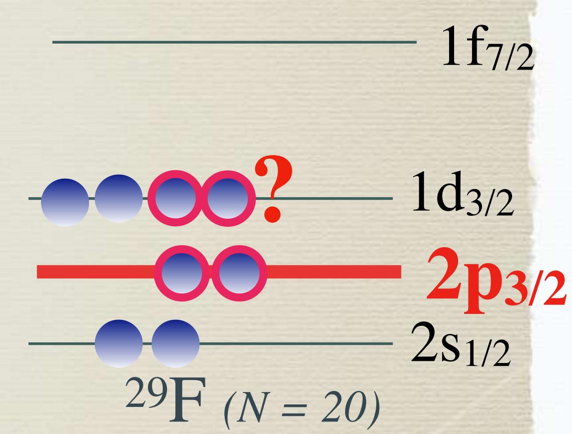
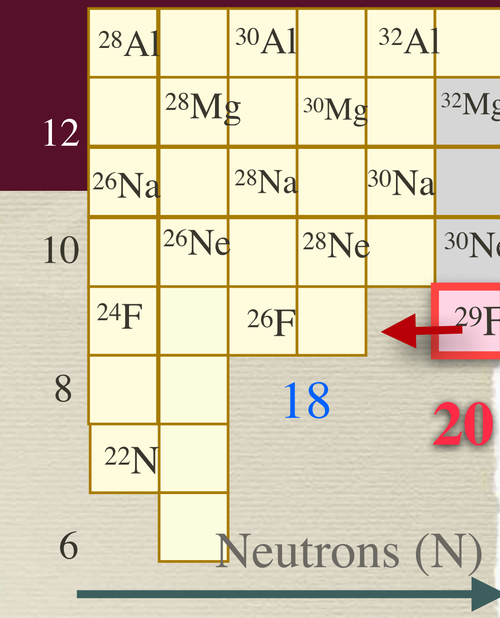


S. Bagchi et al., Phys. Rev. Lett. 124 (2020) 222504

□ A. Homma et al., JPS Proc. 14 (2017) 021010

^{29}F : Borromean Neutron halo



@ RIKEN-BigRIPS+ZDS

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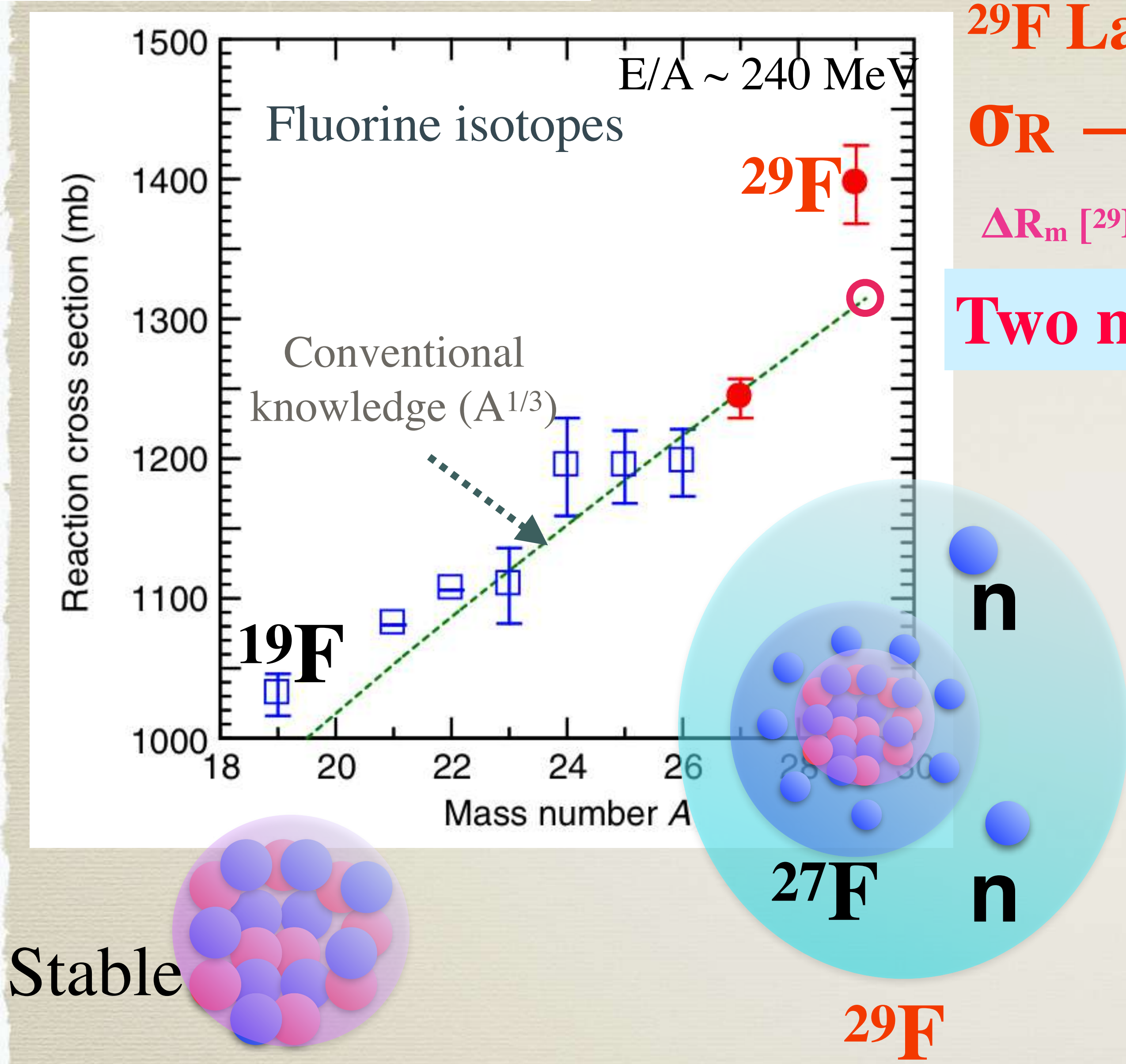
ΔR_m [^{29}F - ^{27}F] ~ 0.39(18) fm

Two neutron halo

^{22}C

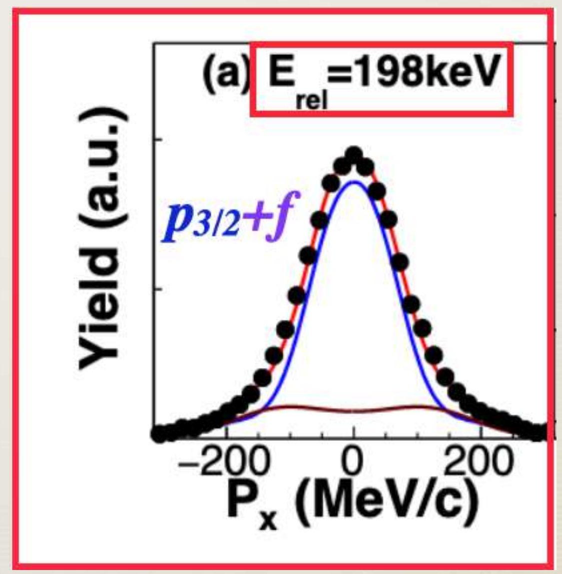


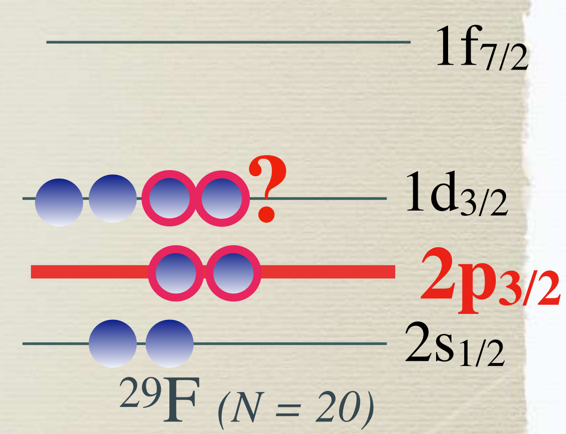
S. Bagchi et al., Phys. Rev. Lett. 124 (2020) 222504

A. Honma et al., JPS Proc. 14 (2017) 021010

@ RIKEN-SAMURAI

^{29}F ⟶ ^{28}F*

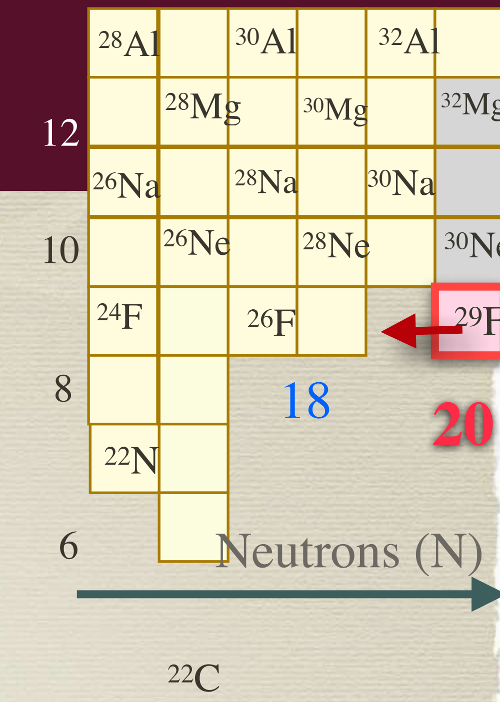




Narrow momentum distribution —> $2p_{3/2}$ orbital

A. Revel et al., Phys. Rev. Lett. 124 (2020) 152502

^{29}F : Borromean Neutron halo



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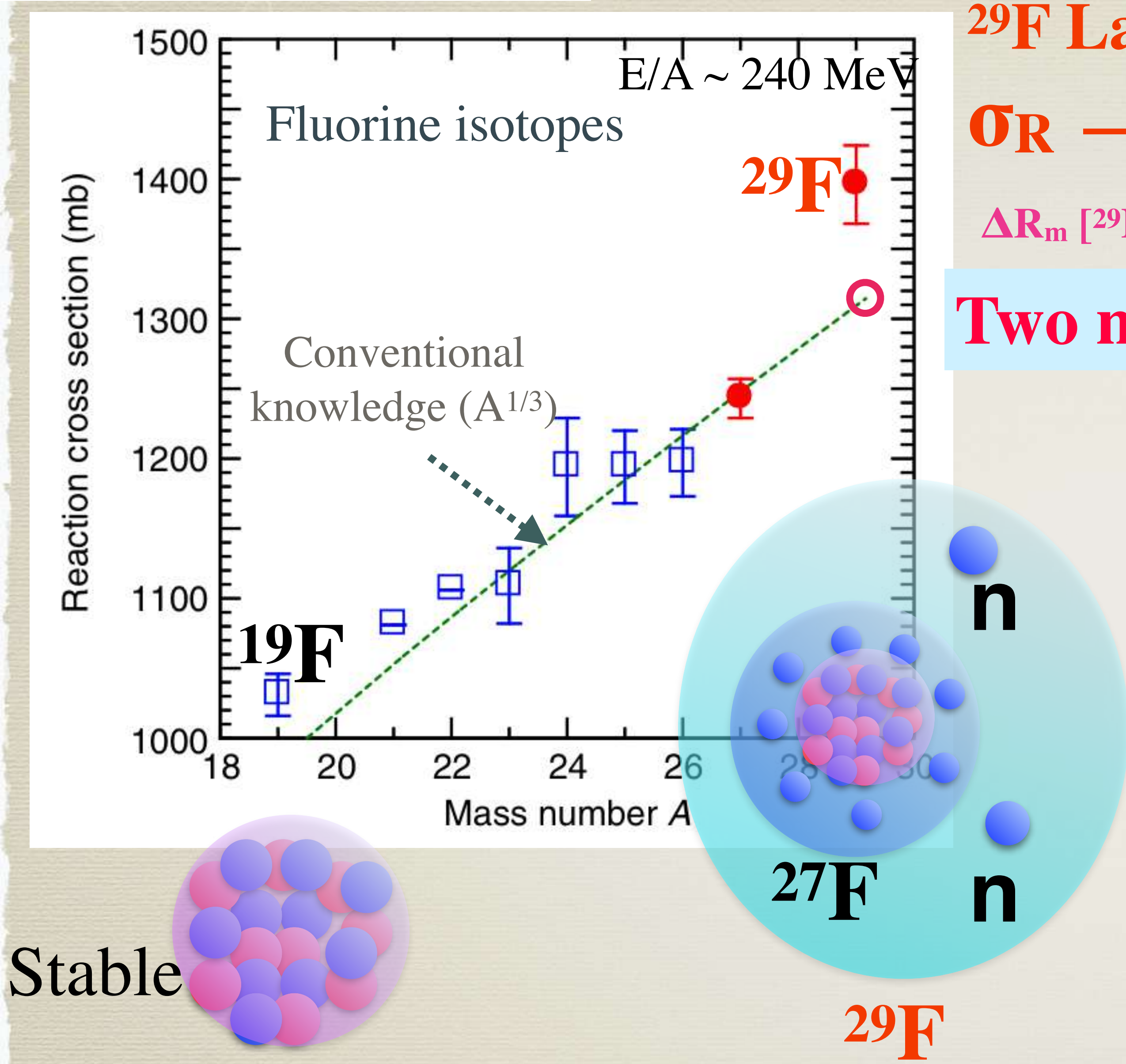

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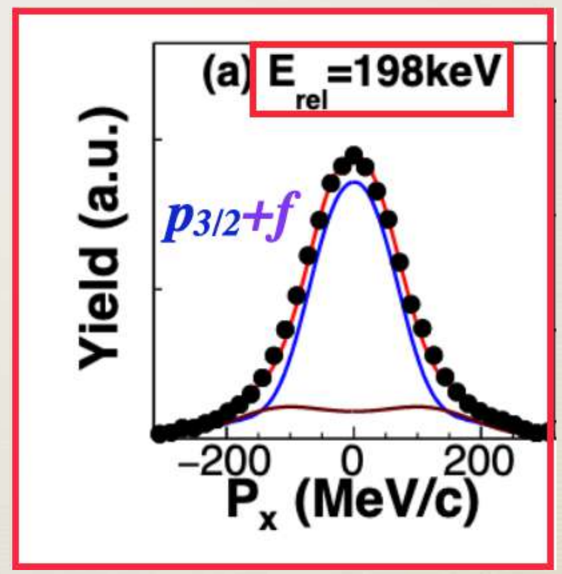
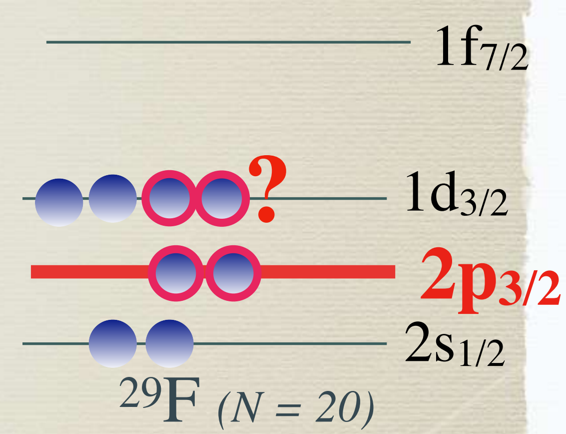




S. Bagchi et al., Phys. Rev. Lett. 124 (2020) 222504

Narrow momentum distribution —> $2p_{3/2}$ orbital

□ A. Honma et al., JPS Proc. 14 (2017) 021010

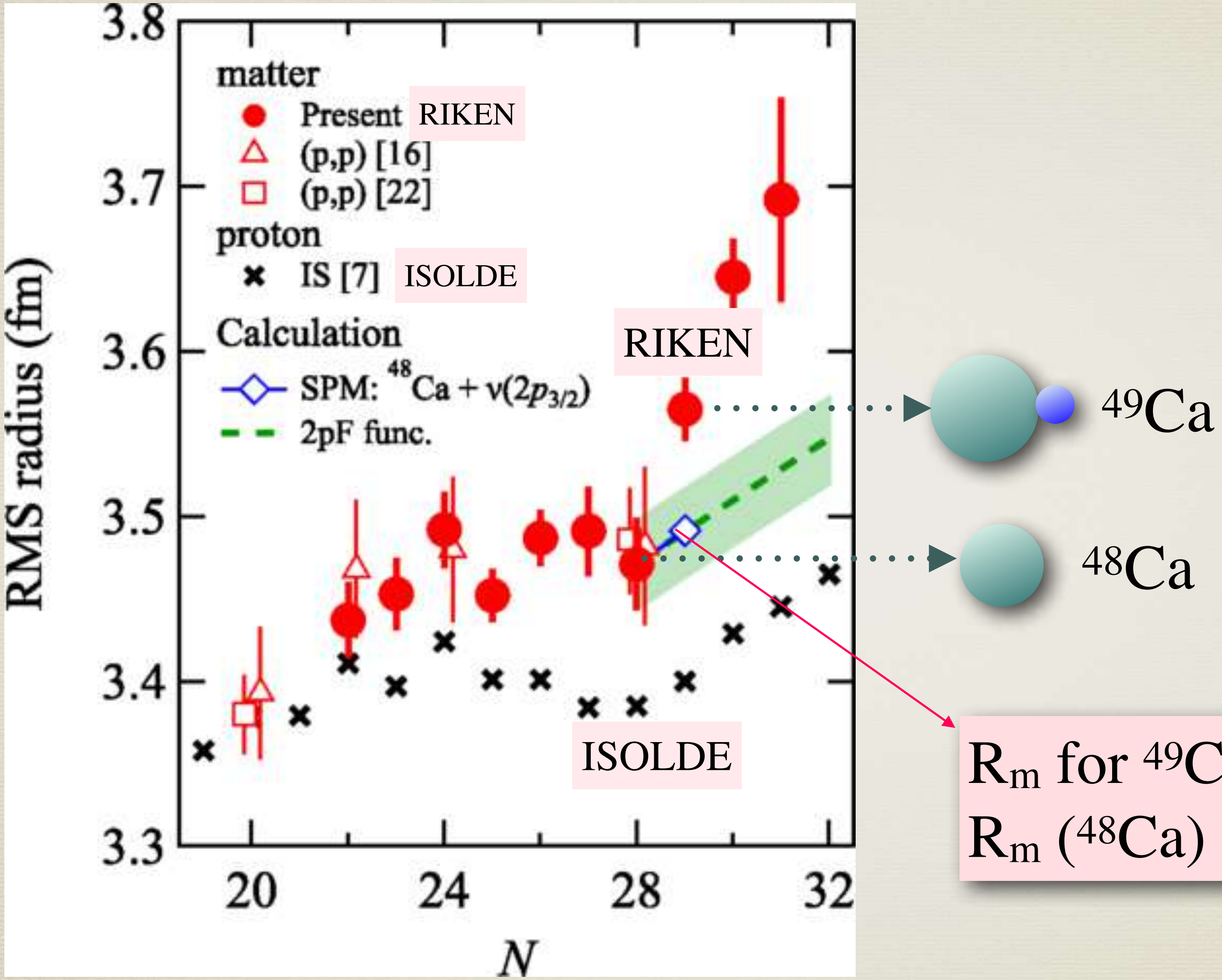
A. Revel et al., Phys. Rev. Lett. 124 (2020) 152502

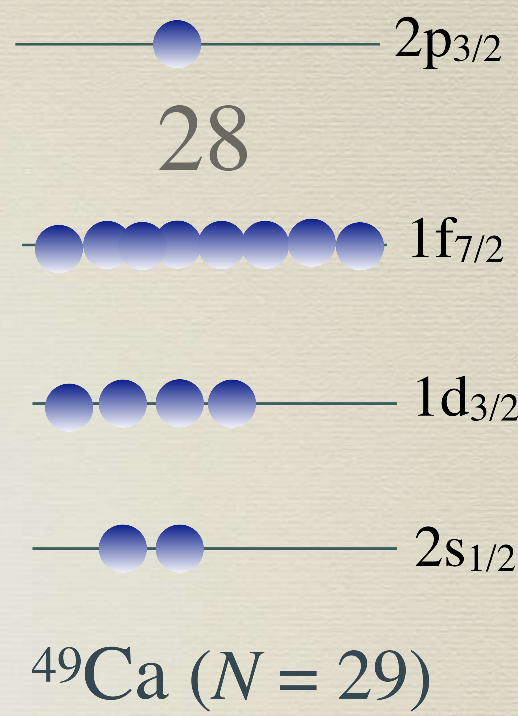
N = 20, 28 shells vanish in a Borromean halo

Enlarged size of Ca isotopes beyond $N = 28$

@ RIKEN - BigRIPS

M. Tanaka, M. Takechi, A. Homma *et al*., Phys. Rev. Lett. 124 (2020) 102501





R_m for ^{49}Ca is not explained by R_m (^{48}Ca) + n ($2p_{3/2}$)

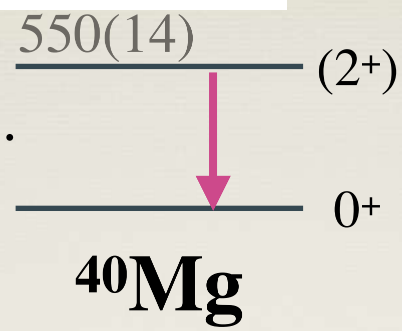
Dip in the proton distribution radius for ^{48}Ca shows $N = 28$ is closed shell

The ^{48}Ca core is enlarged in neutron-rich Ca isotopes : *p - n* attractive force

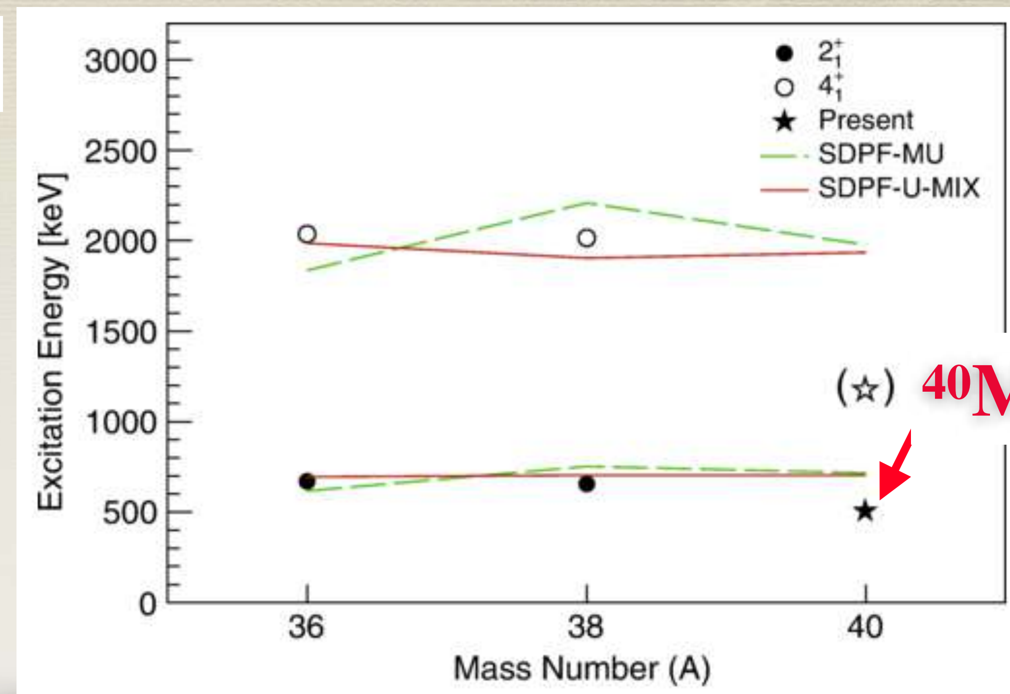
$N = 28$ shell closure breakdown

^{41}Al ⟶ ^{40}Mg* @ RIKEN - BigRIPS & DALI2

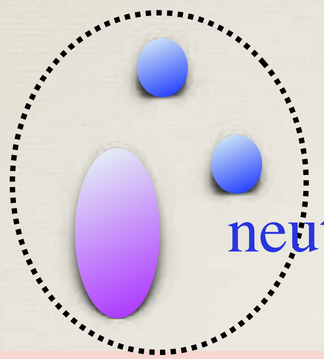
H. L. Crawford et al., Phys. Rev. Lett. 122 (2019) 052501



(2+) Excited state energy decreases in ^{40}Mg.

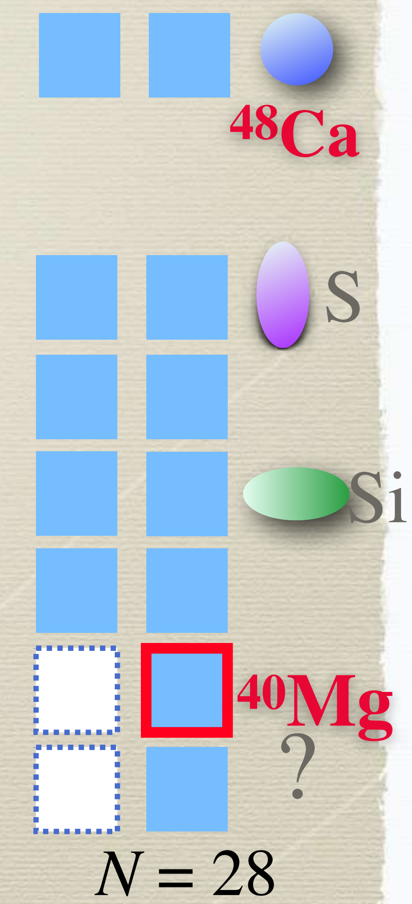


Not explained by shell model interactions



neutron in $p_{3/2}$?

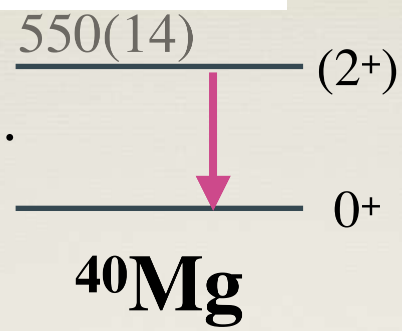
***N* = 28 shell gap disappears in ^{40}Mg.**
Is ^{40}Mg a Borromean halo ?



N = 28 shell closure breakdown

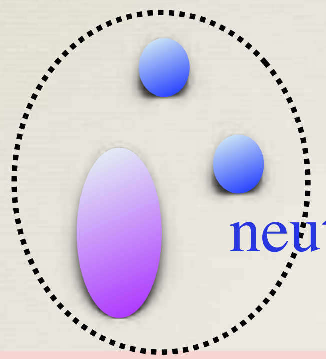
^{41}Al ⟶ ^{40}Mg* @ RIKEN - BigRIPS & DALI2

H. L. Crawford et al., Phys. Rev. Lett. 122 (2019) 052501

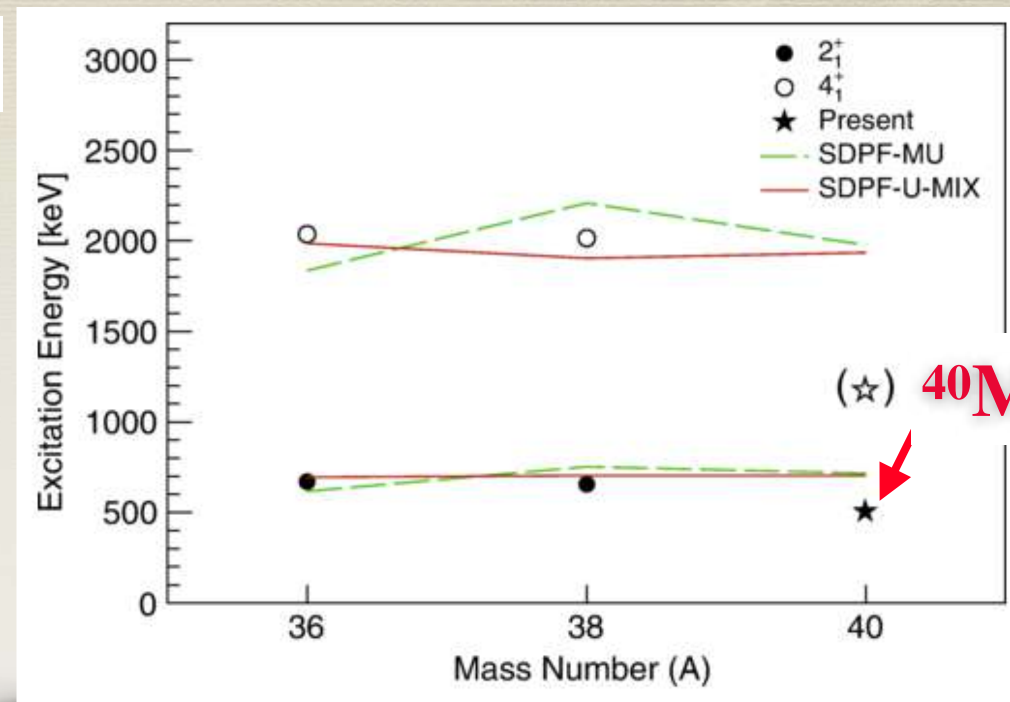


(2+) Excited state energy decreases in ^{40}Mg.

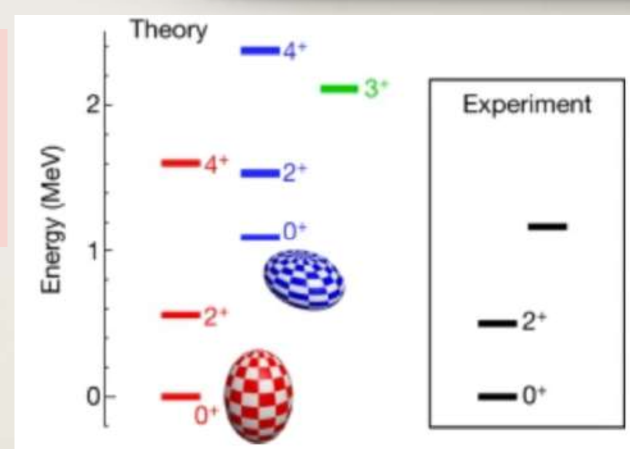
Not explained by shell model interactions



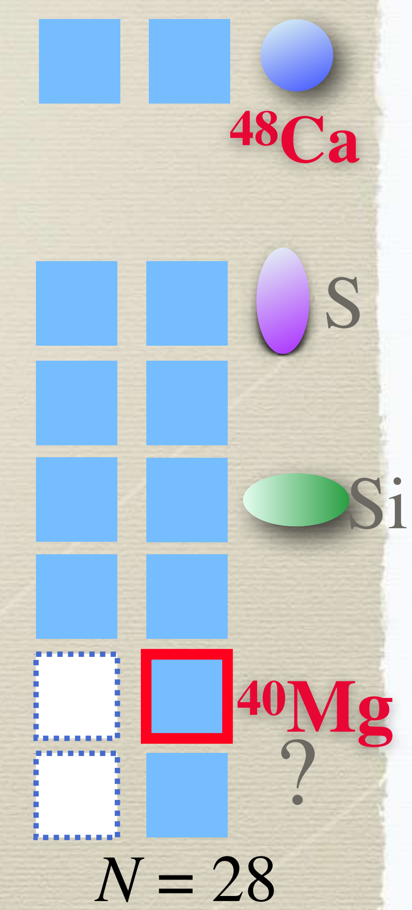
neutron in $p_{3/2}$?



***N* = 28 shell gap disappears in ^{40}Mg.**
Is ^{40}Mg a Borromean halo ?



N. Tsunoda, et al., Nature, 2020



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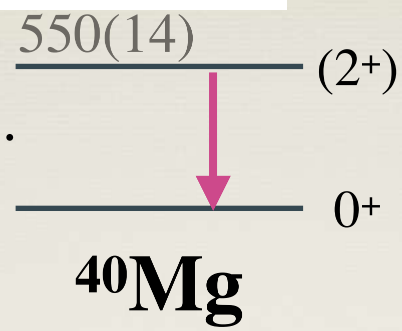
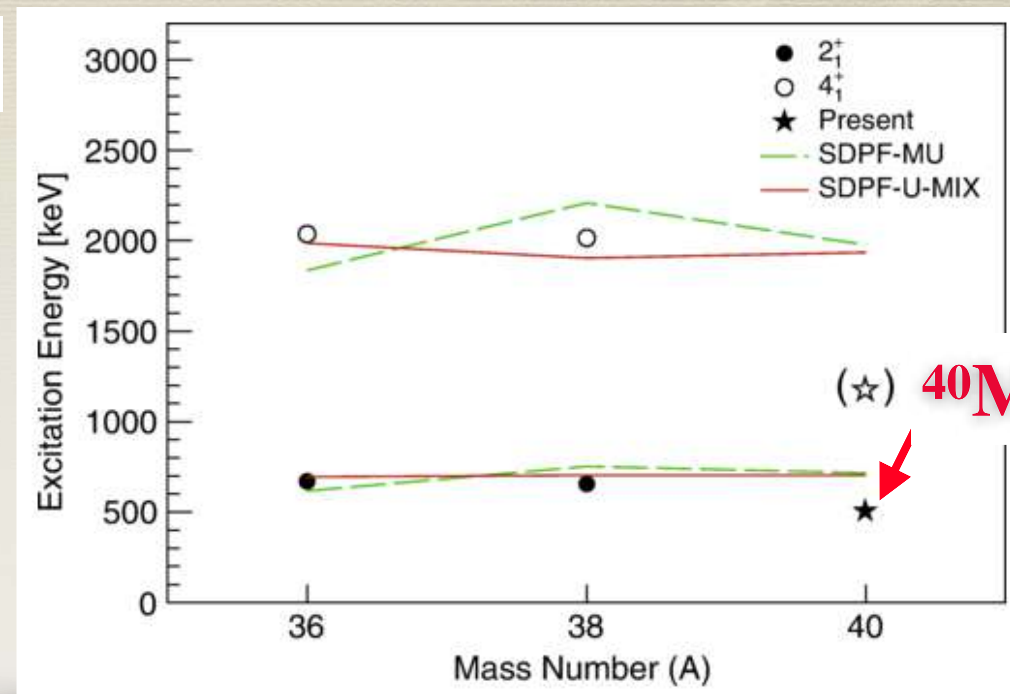
^{41}Al ⟶ ^{40}Mg* @ RIKEN - BigRIPS & DALI2

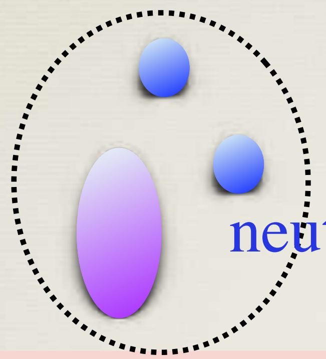
H. L. Crawford et al., Phys. Rev. Lett. 122 (2019) 052501





(2+) Excited state energy decreases in ^{40}Mg.

Not explained by shell model interactions



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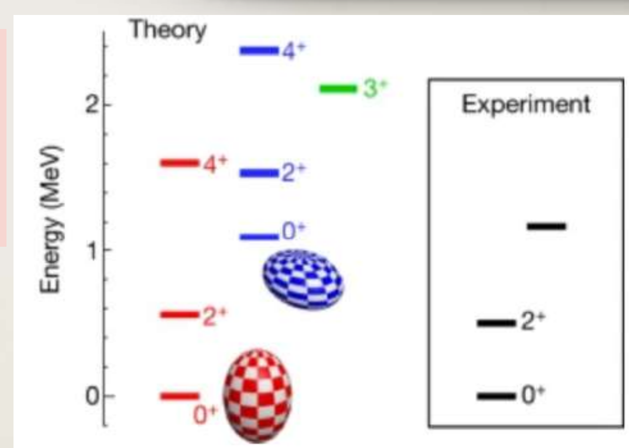


N. Tsunoda, et al., Nature, 2020

^{43}S (^{43}S*m) + ^{209}Bi (Coulex) @ NSCL - CAESAR

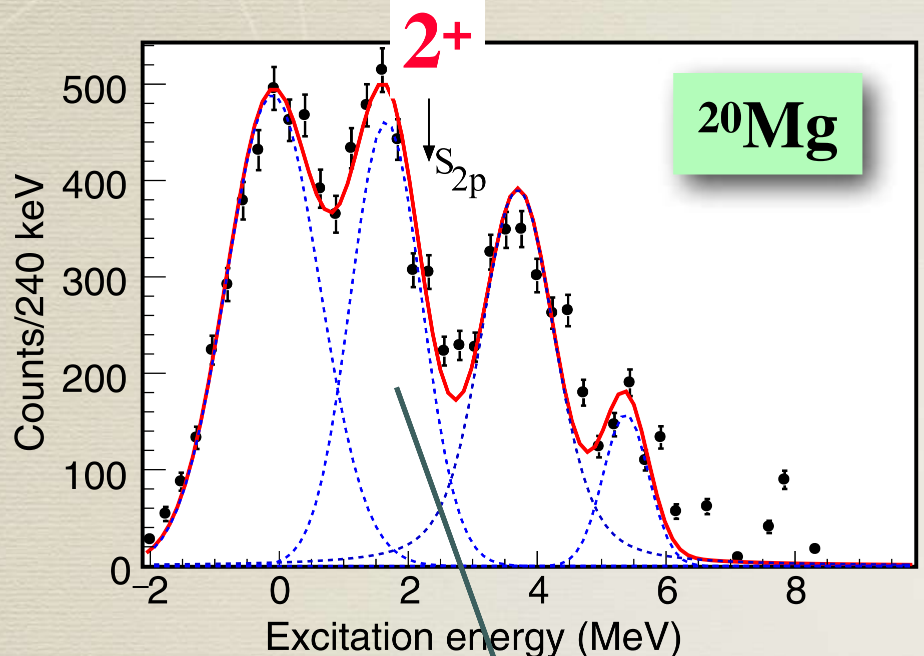
B. Longfellow, D. Weisshaar, A. Gade et al., Phys. Rev. Lett. 125 (2020) 232501

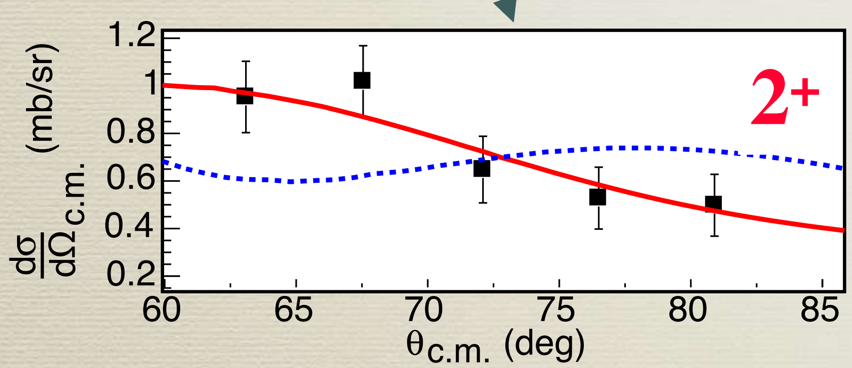
Shape co-existence in ^{43}S - degeneracy of $2p_{3/2}$ and $1f_{7/2}$ orbitals

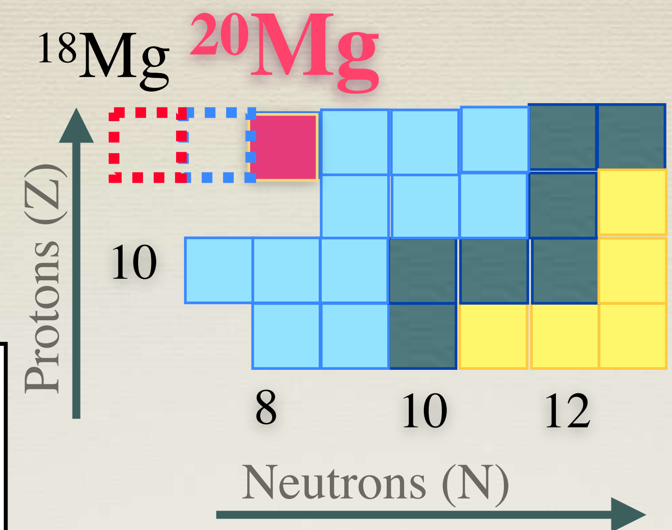
N = 8 vanishing @ Proton Drip Line ?

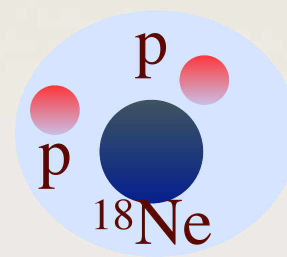
@ TRIUMF - IRIS

J.S. Randhawa, R.K., M. Holl et al.
Phys. Rev. C 99 (2019) 021301(R)



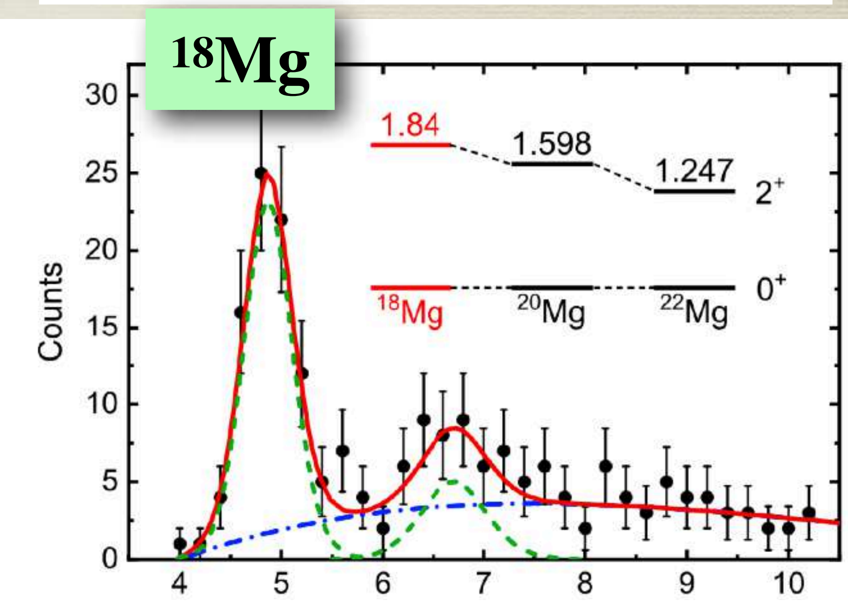






@ NSCL- HiRA

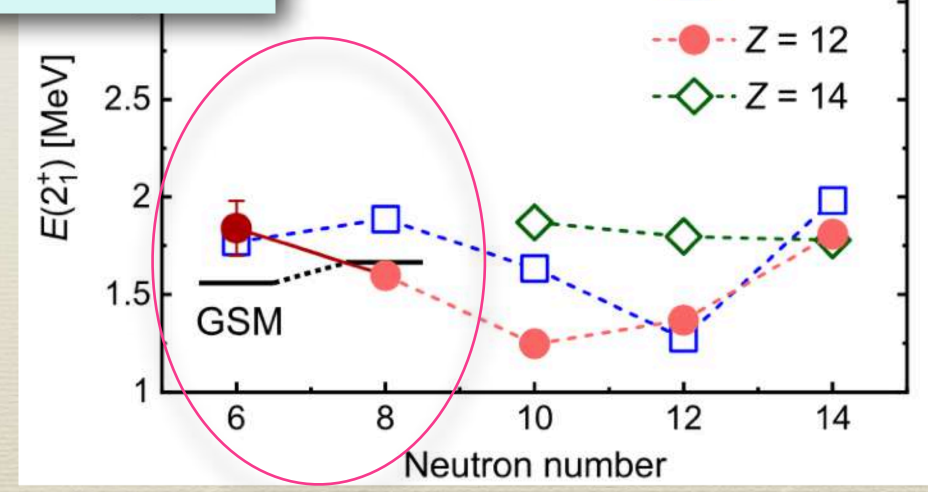
Y. Jin, C.Y. Niu, K.W. Brown *et al.*
Phys. Rev. Lett. 127 (2021) 262502



^{14}O + 4p invariant mass (MeV)

N = 10 Higher 2^+ excitation energy than *N* = 8

Challenge for theory



N = 8 Large quadrupole deformation $\beta = 0.44(4)$

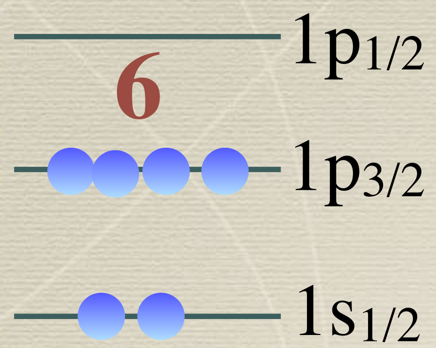
_N_ = 8 shell gap quenching hinted at the proton drip-line ***from large deformation & lower energy of excited state***

New shell gaps

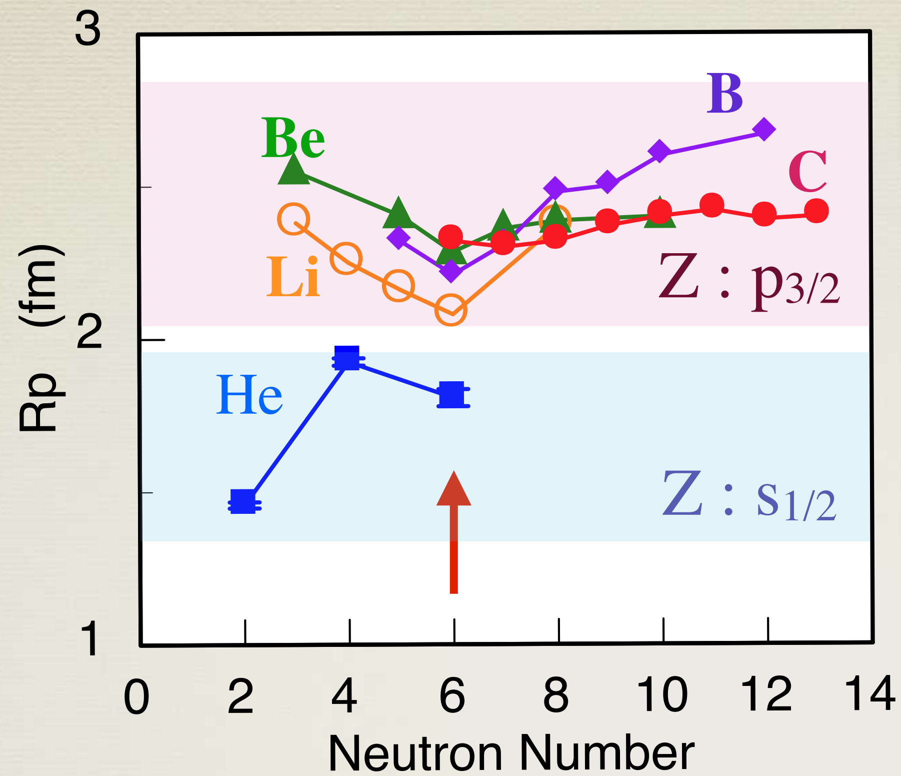
^{8}He : N = 6 new sub-shell

@ TRIUMF - IRIS

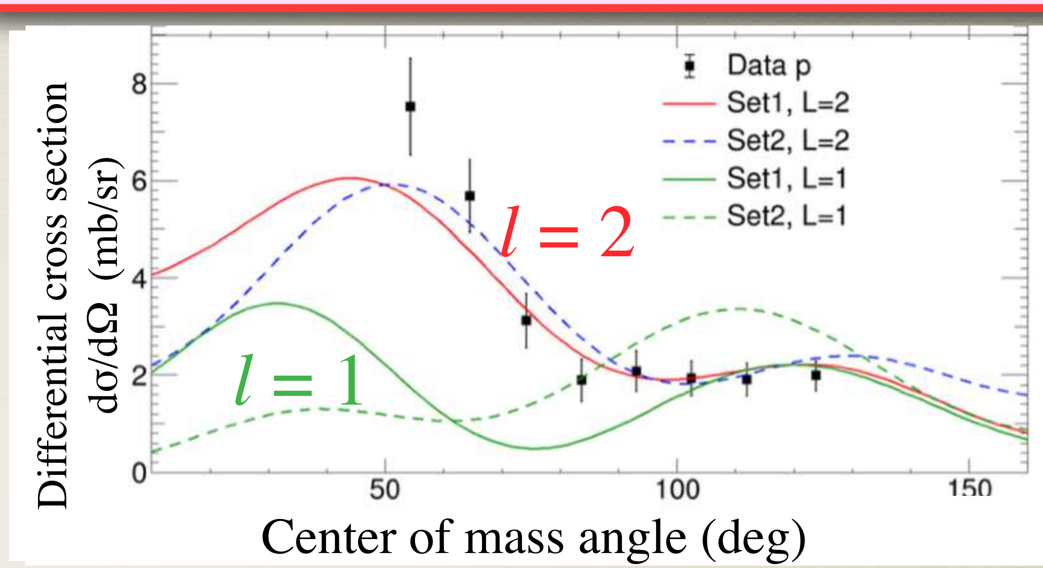
M. Holl, R.K., Z.H, Sun *et al*. Phys. Lett. B 822 (2021) 135748



Dip in R_p : Closed shell N = 6

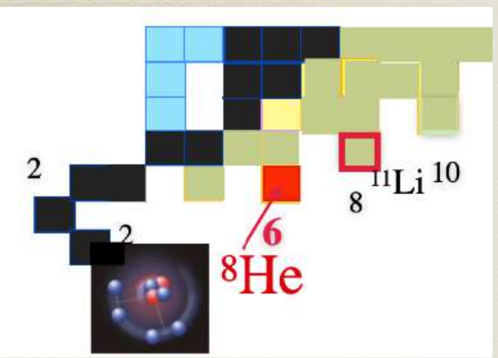


Doubly Magic - but deformed !



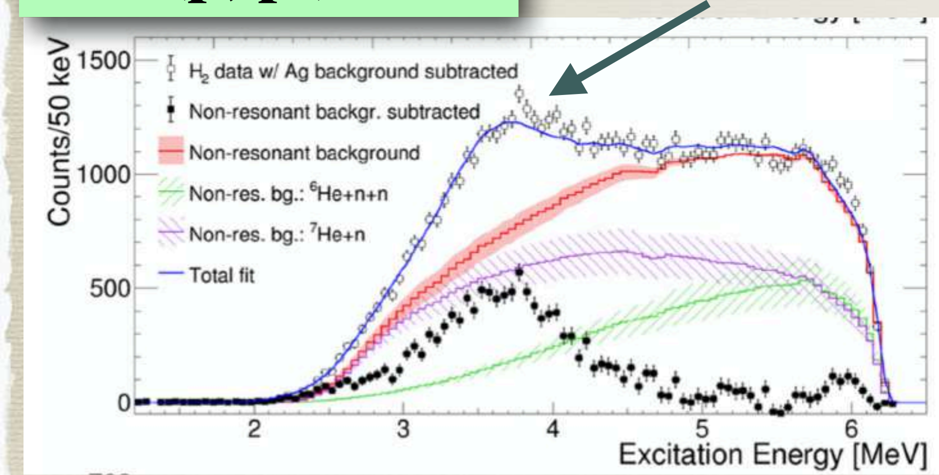
- **Resonance (2+) shows deformation**

$\beta_2 = 0.40 \pm 0.03$



^{8}He(p, p')^{8}He*

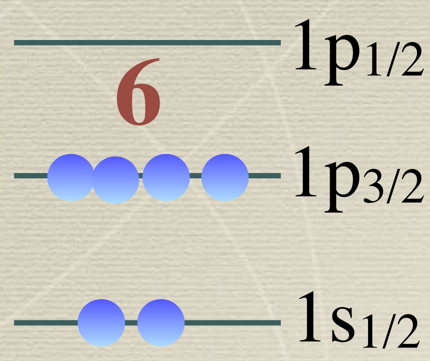
High Excitation energy ~ Ex ~ 3.5 MeV : closed shell N = 6



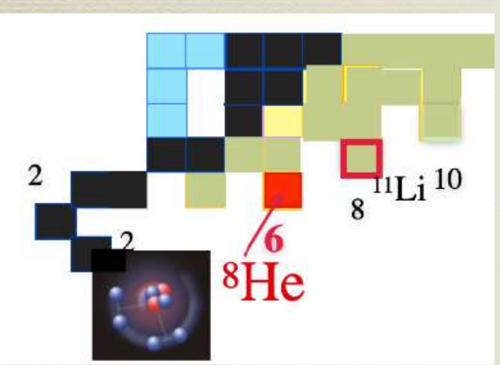
^{8}He : N = 6 new sub-shell

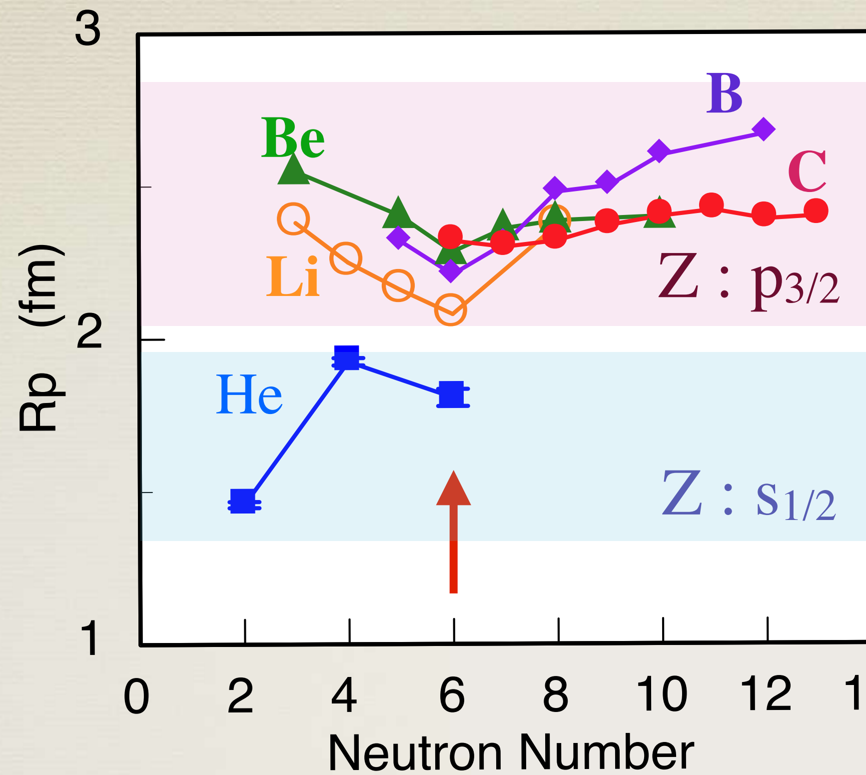
@ TRIUMF - IRIS

M. Holl, R.K., Z.H, Sun *et al*. Phys. Lett. B 822 (2021) 135748

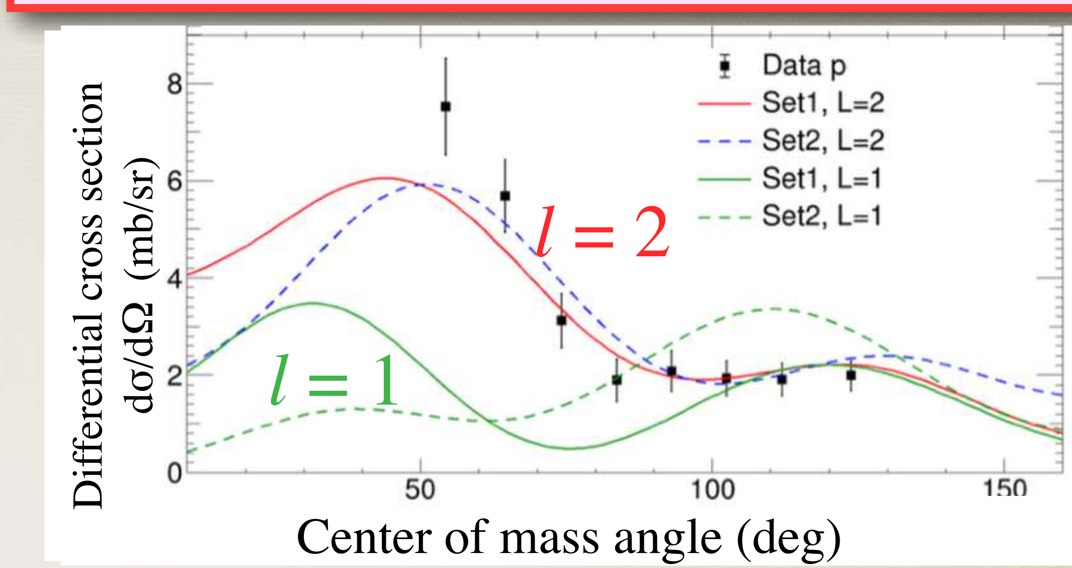


Dip in R_p : Closed shell N = 6





Doubly Magic - but deformed !



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^{8}He(p, p')^{8}He*

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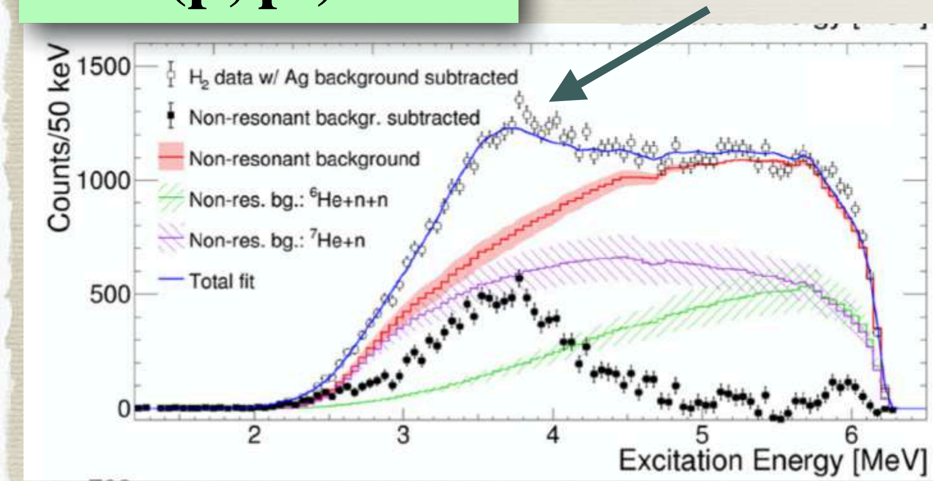


No Core Shell Model with chiral force consistent with experimental observations

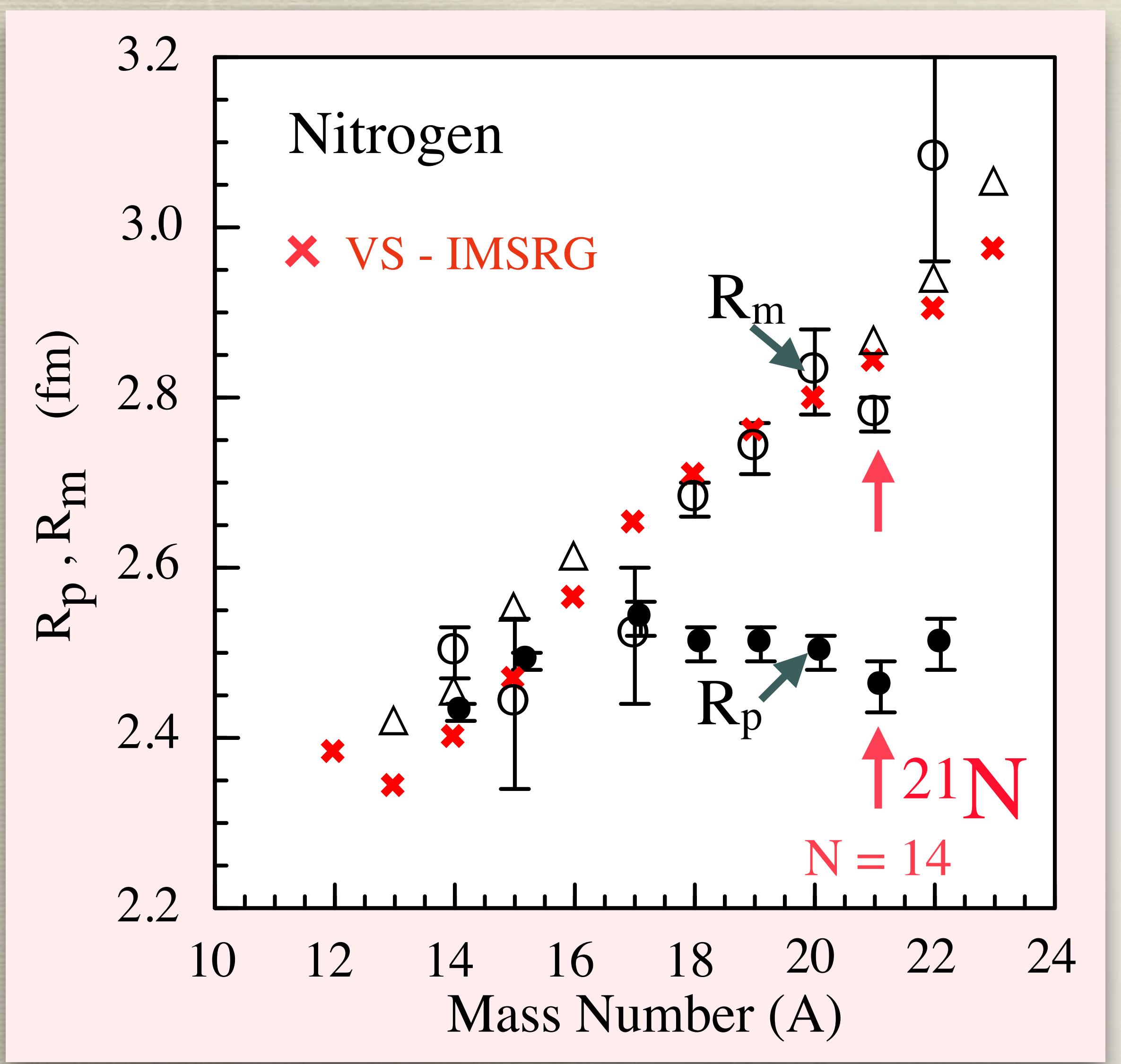
^{8}He (2+) : **Qn = 6.15 efm^2**, Qp = 0.60 efm^2

^{8}He : spherical in protons and deformed in neutrons

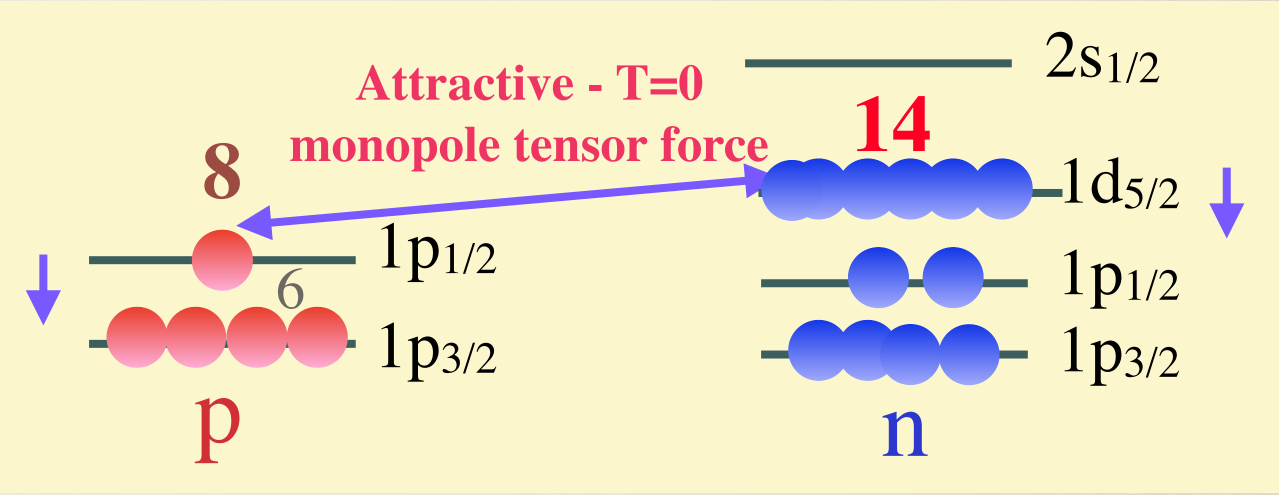
$N = 14$ new sub-shell

@ GSI - FRS

S. Bagchi, R.K., W. Horiuchi *et al*. Phys. Lett. B 790 (2019) 251



^{21}N : Dip in R_p and R_m directly shows effect of tensor force



Proton $p_{1/2}$ more strongly bound -> Smaller R_p. &
***Z* = 6 gap reduced**

Neutron $d_{5/2}$ more strongly bound -> Smaller R_m. &
new gap @ *N* = 14

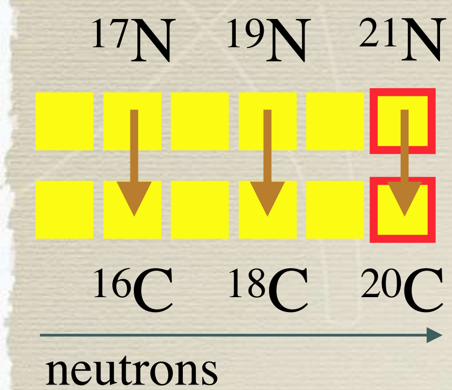
Dip in proton distribution radius shows new sub-shell gap @ *N* = 14

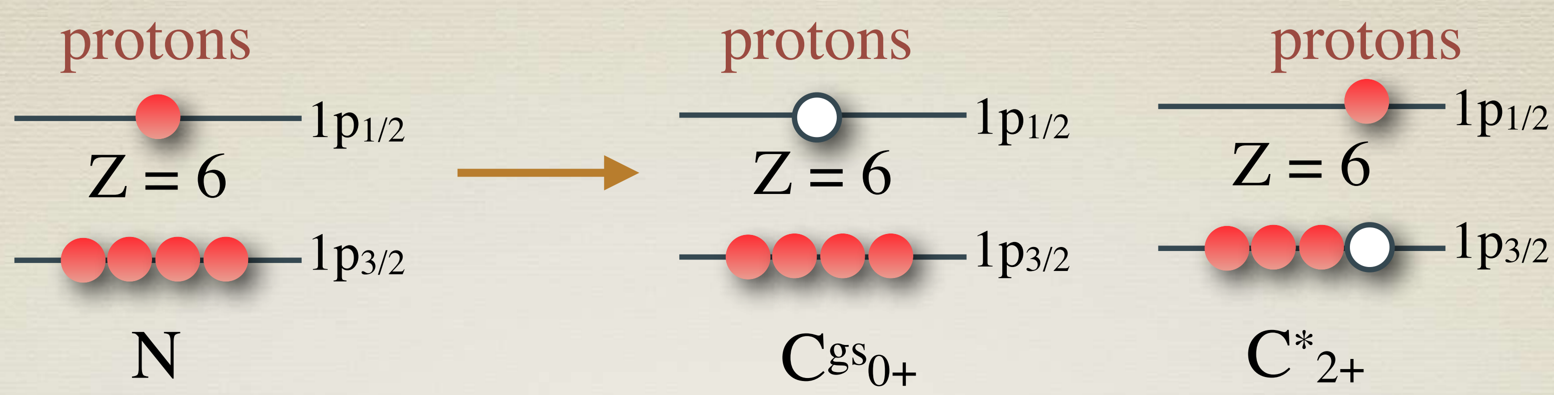
Quenching of proton sub-shell *Z* = 6

@ GSI - R^{3}B/LAND

^{A}N(p, 2p)$^{A-1}$C

I. Syndicus, M. Petri, A.O. Macchiavelli *et al*. Phys. Lett. B 809 (2020) 135748



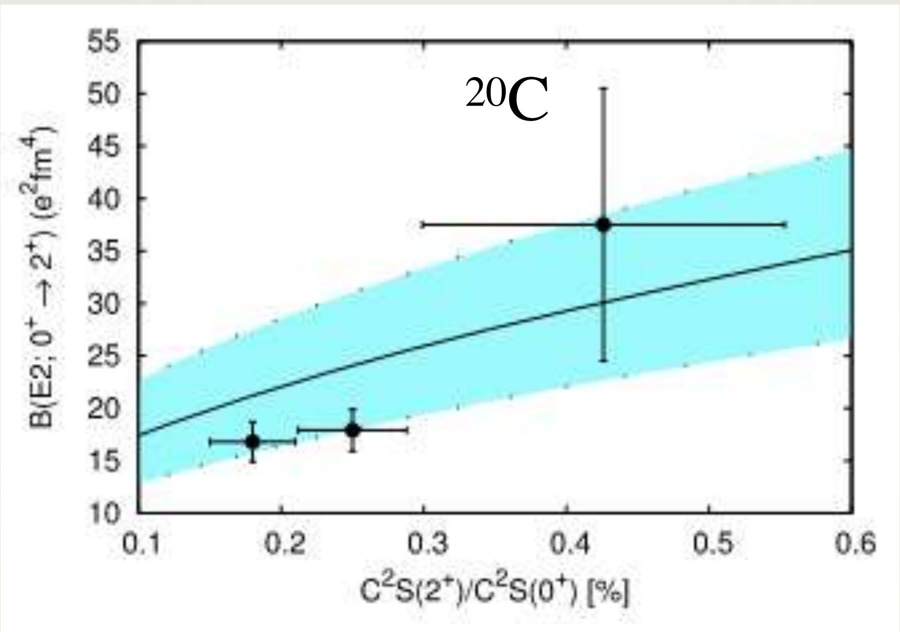


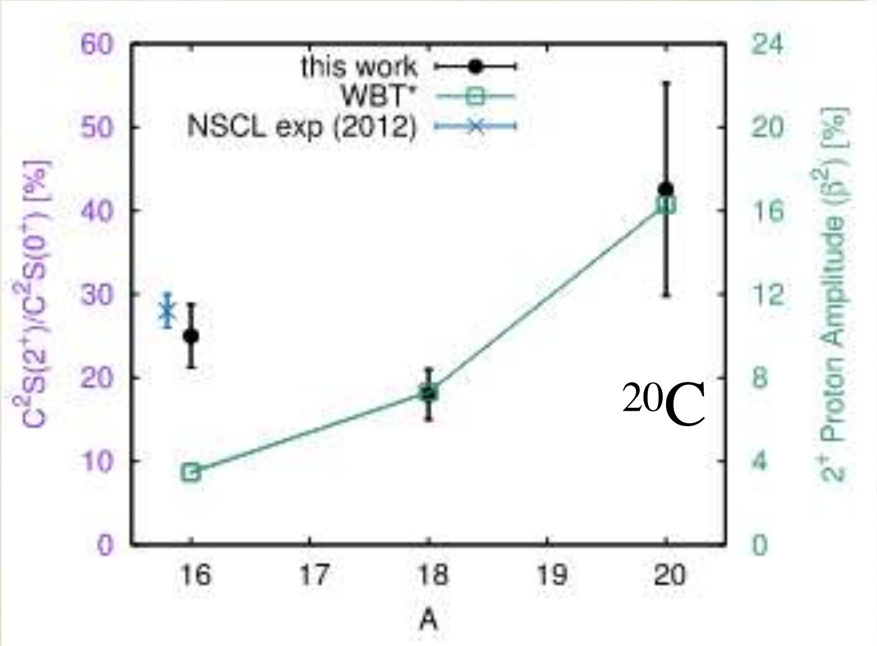
$$|2_1^+;\ ^{A-1}\mathrm{C}\rangle \approx \alpha|\nu\,(sd)^n;\ J=2\rangle \otimes |\pi\,(p_{3/2})^4;\ J=0\rangle$$

proton excitation component: 2+ $+\beta|\nu\,(sd)^n;\ J=0\rangle \otimes |\pi\,(p_{3/2})^3(p_{1/2})^1;\ J=2\rangle$

Large quadrupole deformation -> [B(E2)] in ^{20}C

Deformation in ^{20}C correlated to proton excitation contribution

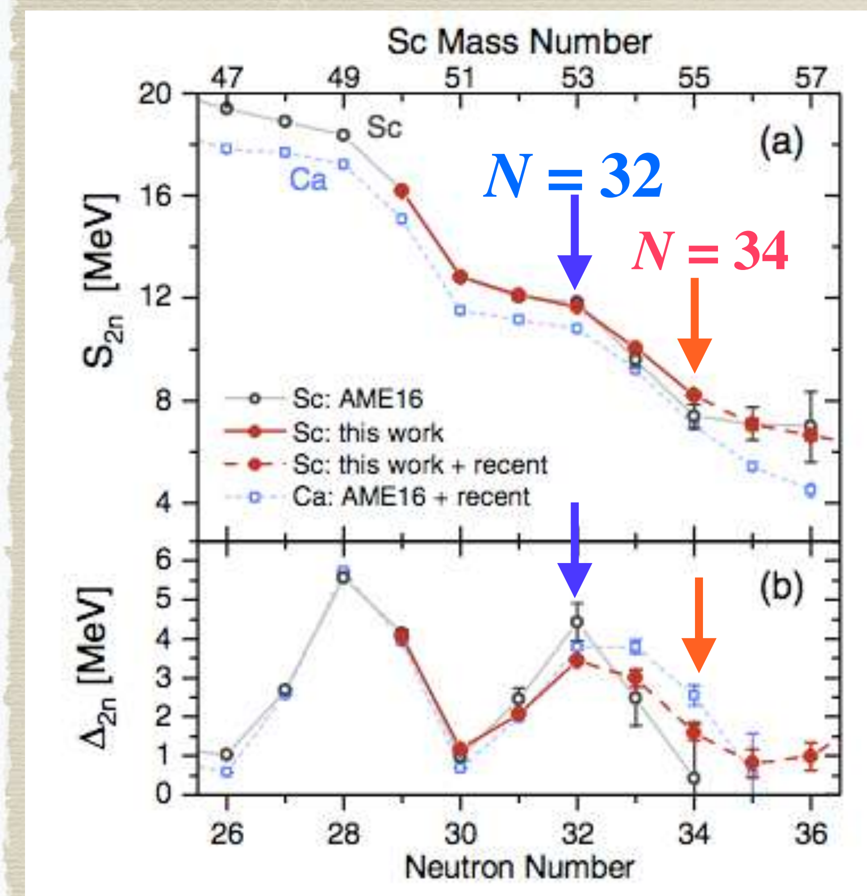


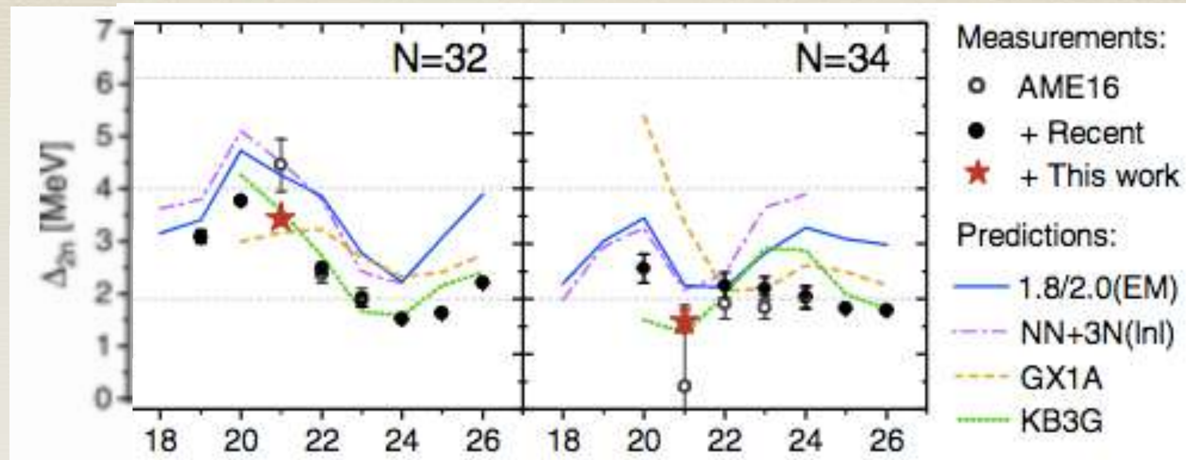


Hint of reduction in the *Z* = 6 sub-shell gap in neutron-rich nuclei

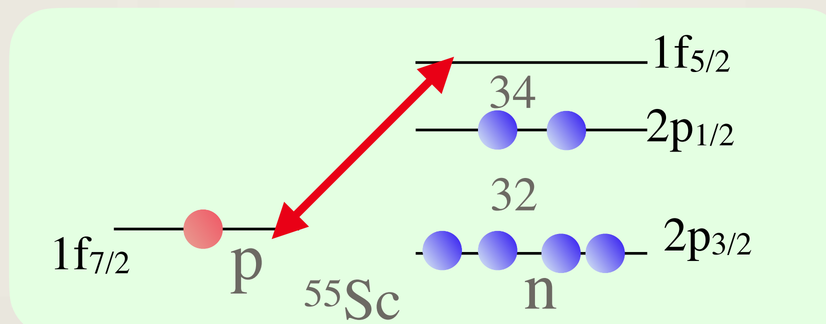
New shells $N = 32, 34$ $^{50-53}Sc$ @ NSCL - LEBIT $^{54-55}Sc$ @ TRIUMF - TITAN

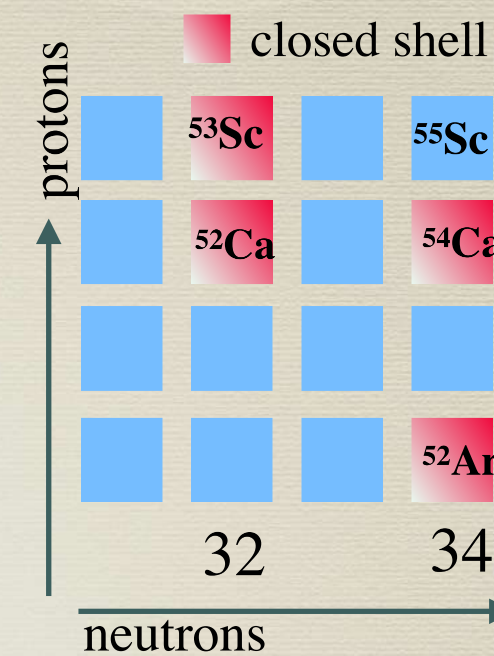
E. Leistenschneider, E. Dunling, G. Bollen *et al*. Phys. Rev. Lett. 126 (2021) 042501





Theory predictions have large variation for N = 34



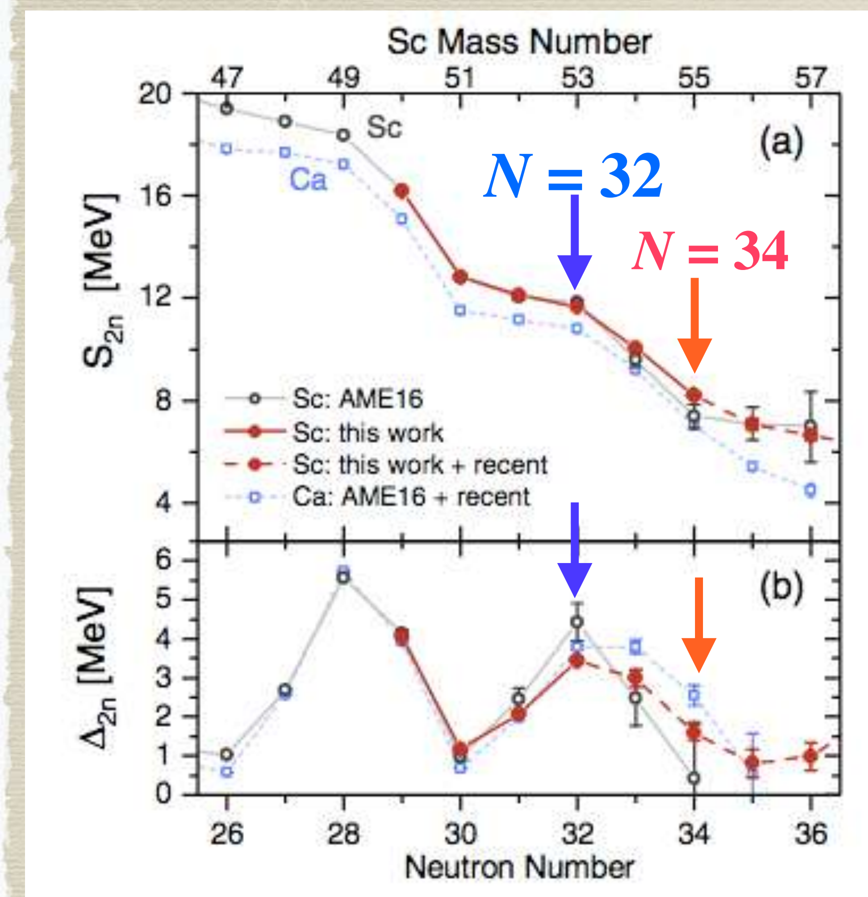


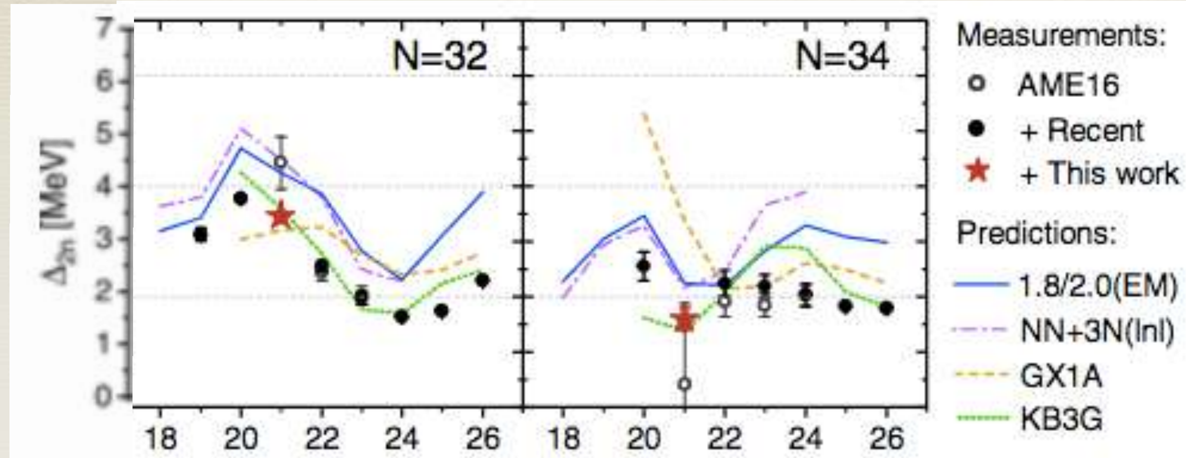
***N* = 32 shell gap seen in ^{53}Sc.**

No signature of *N* = 34 shell gap in ^{55}Sc

New shells $N = 32, 34$ $^{50\text{-}53}$Sc @ NSCL - LEBIT $^{54\text{-}55}$Sc @ TRIUMF - TITAN

E. Leistenschneider, E. Dunling, G. Bollen *et al*. Phys. Rev. Lett. 126 (2021) 042501





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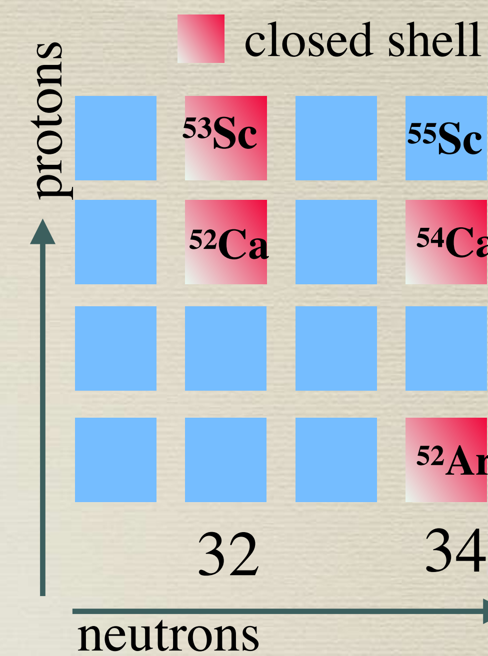
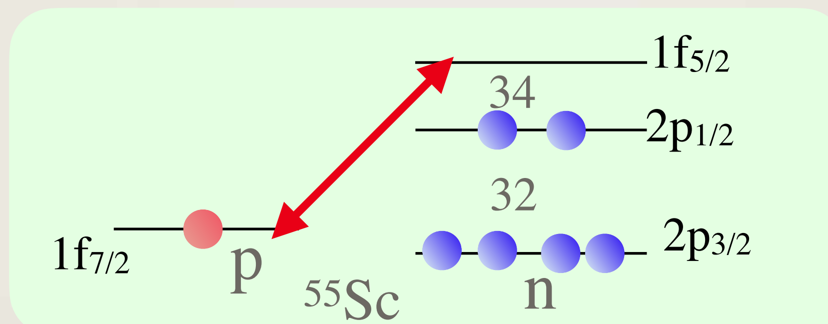


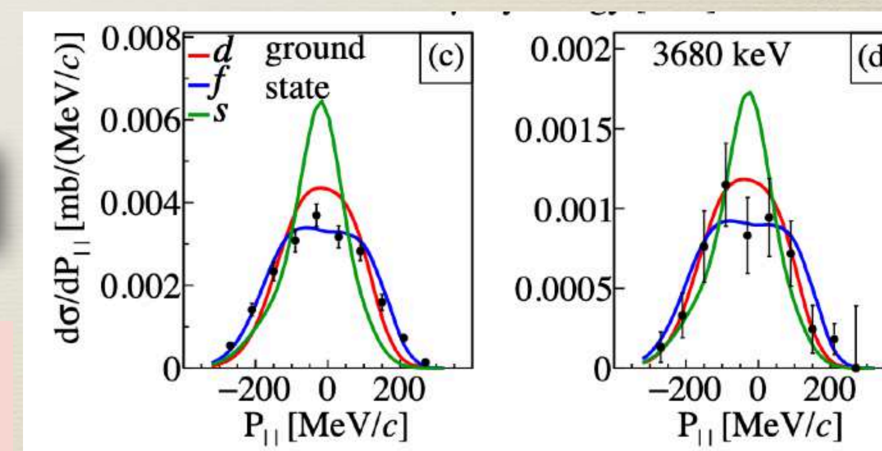


^{54}Ca @ RIBF - BigRIPS

N = 32 shell gap seen in ^{53}Sc.

No signature of N = 34 shell gap in ^{55}Sc

^{55}Sc$(p, 2p)^{54}$Ca



$1f_{7/2}$ proton removal from ^{55}Sc dominantly populates ^{54}Ca$_{gs.}$: Pairing force effect

$$C^2S_{g.s.} = (\alpha_{0p0h}\beta_{0p0h} + \alpha_{2p2h}\beta_{2p2h})^2.$$

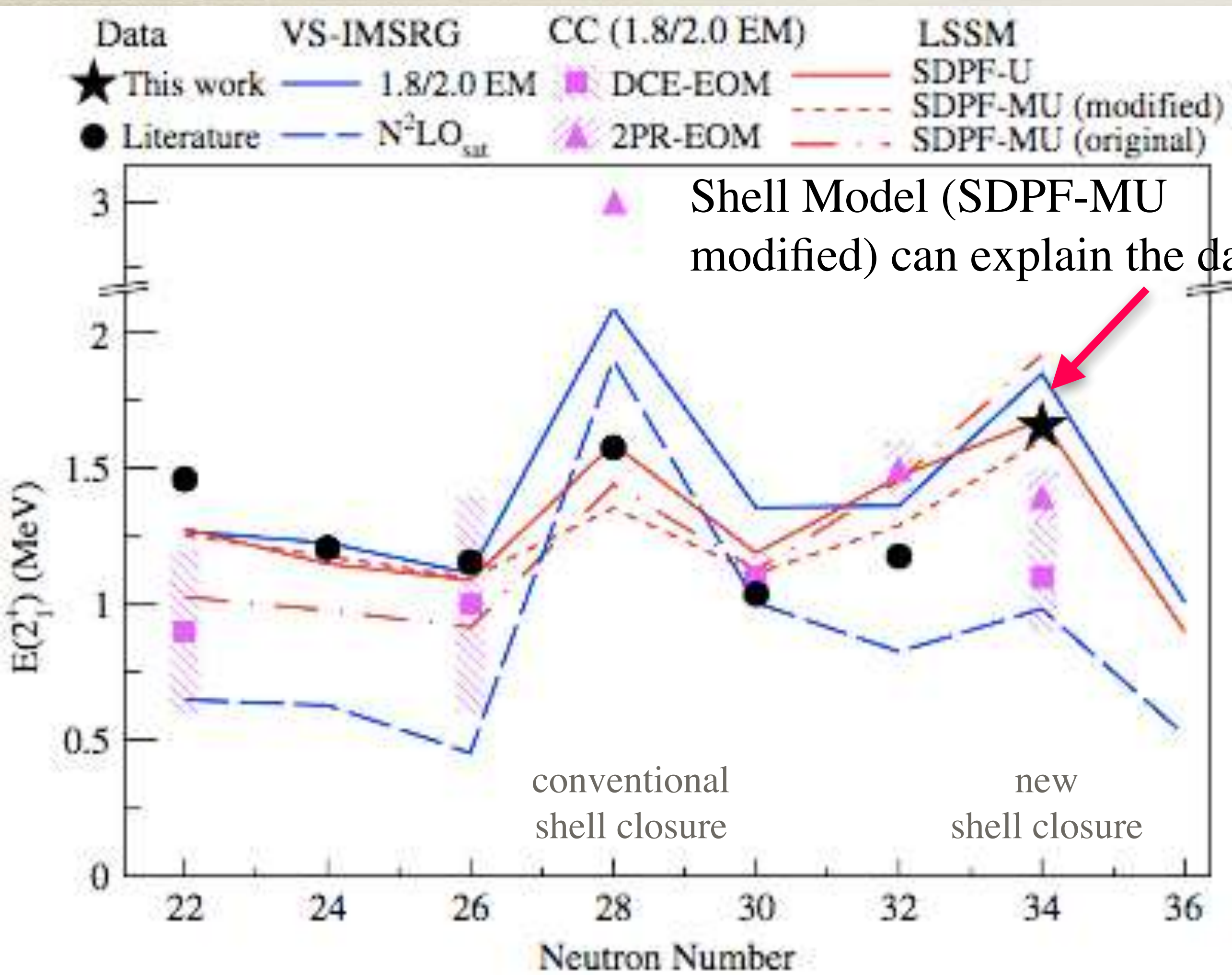
F. Browne, S. Chen, P. Doornenbal et al., Phys. Rev. Lett. 126 (2021) 252501

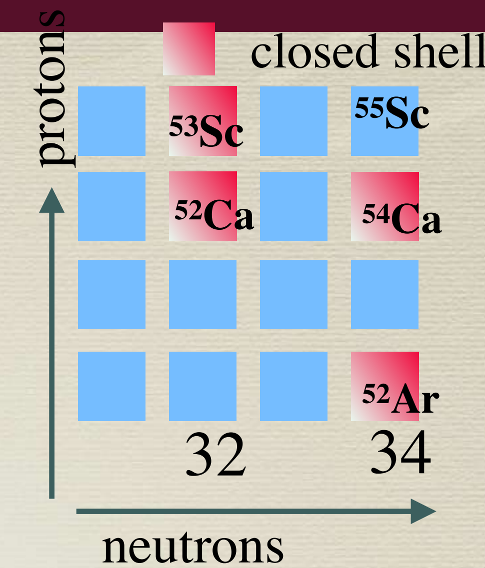
New shells $N = 32, 34$ ^{52}Ar

@ RIBF - MINOS+SAMURAI

H. Liu, A. Obertelli, P. Doornenbal et al., Phys. Rev. Lett. 122 (2019) 072502.

$^{53}K(p,2p)^{52}Ar$





N = 32 does not show closed shell behaviour

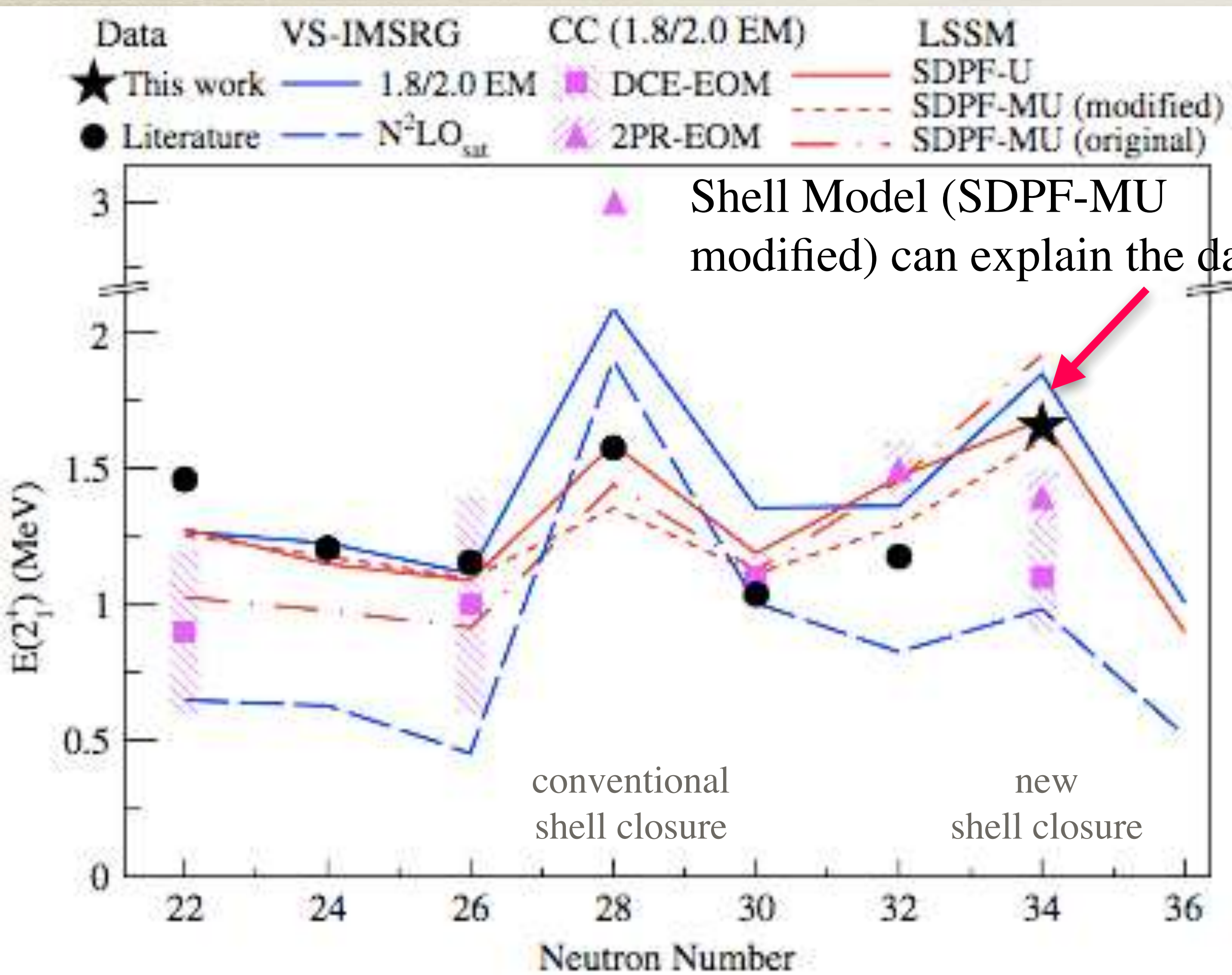
***N* = 34 shell gap seen in ^{52}Ar from the high excitation energy**

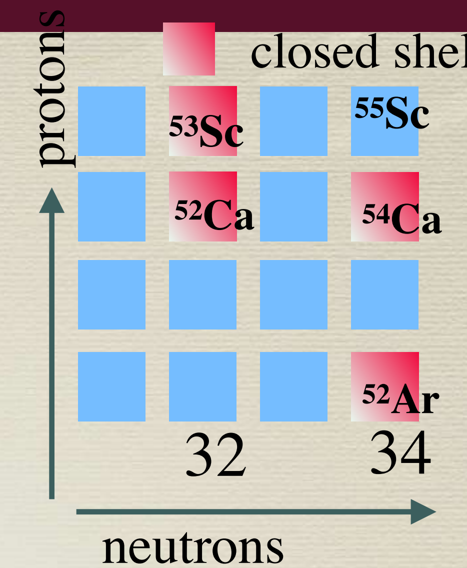
New shells $N = 32, 34$ ^{52}Ar

@ RIBF - MINOS+SAMURAI

H. Liu, A. Obertelli, P. Doornenbal et al., Phys. Rev. Lett. 122 (2019) 072502.

^{53}K(p,2p)^{52}Ar





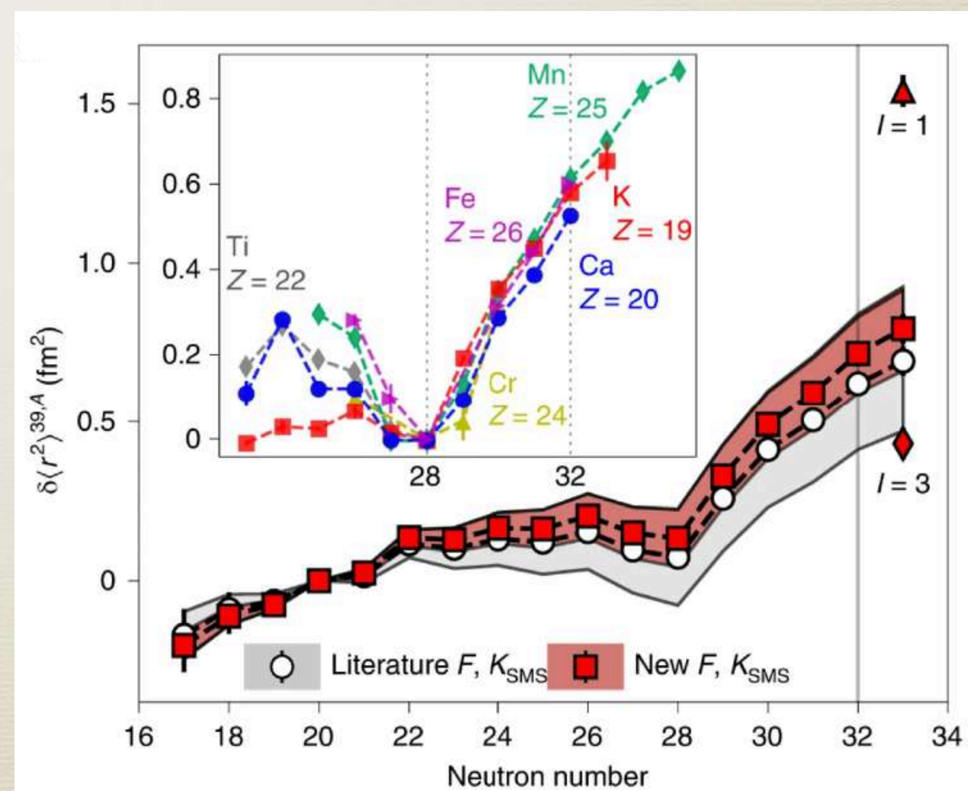
$N = 32$ does not show closed shell behaviour

$N = 34$ shell gap seen in ^{52}Ar from the high excitation energy

Charge Radius

@ ISOLDE - CRIS

A. Koszorus, et al., Nature 17 (2021) 439

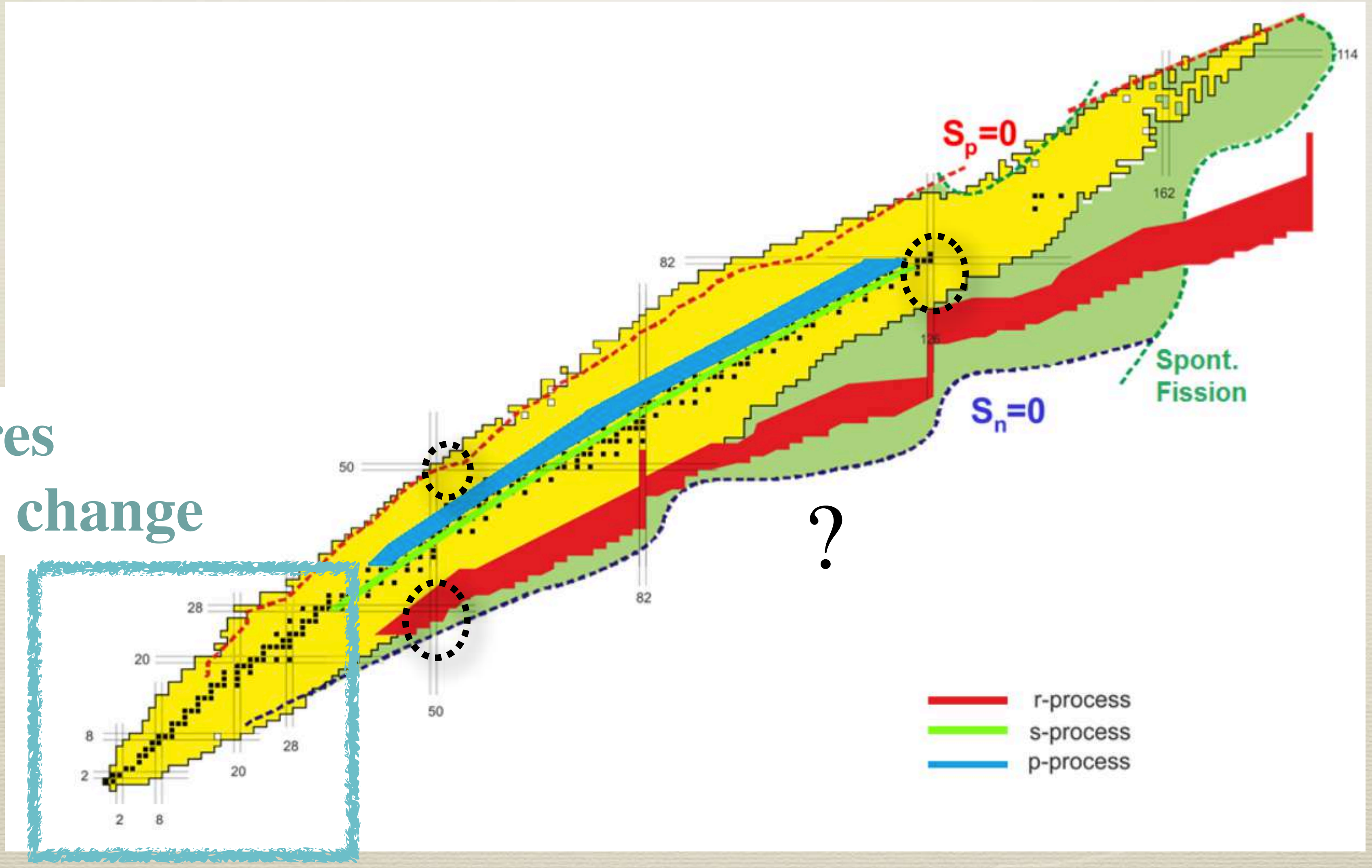


Charge radius does not show dip @ N = 32

Nuclear structure and shell evolution impacts heavy element synthesis

N = 50 & 126 conventional shells

Shell closures observed to change



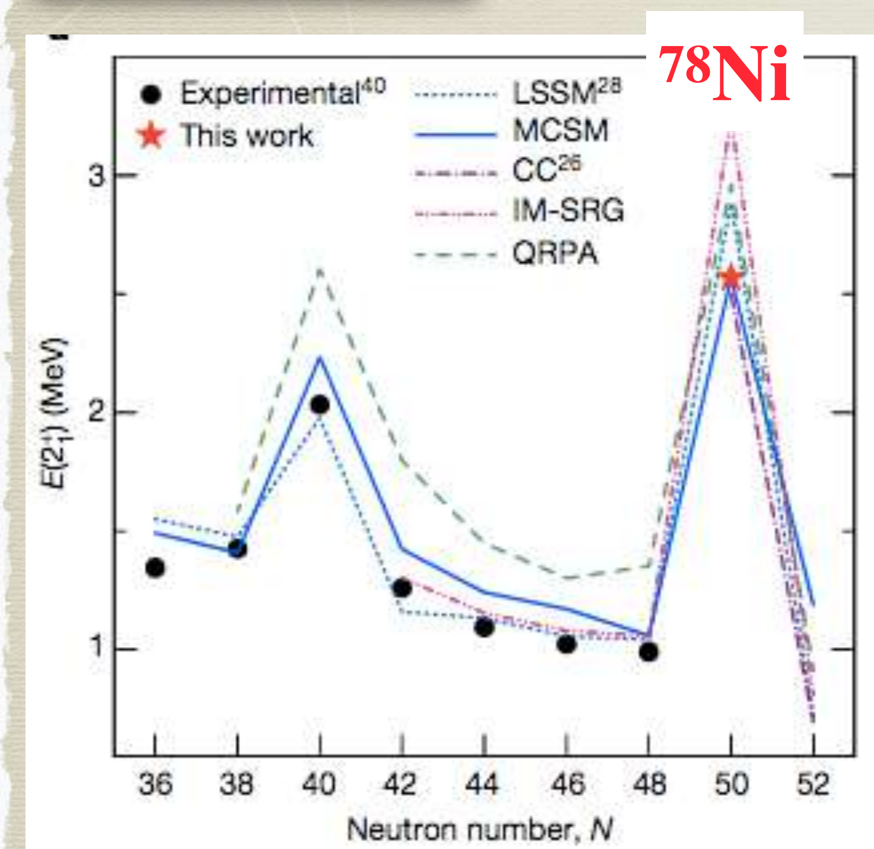
Doubly magic ^{78}Ni (N = 50)

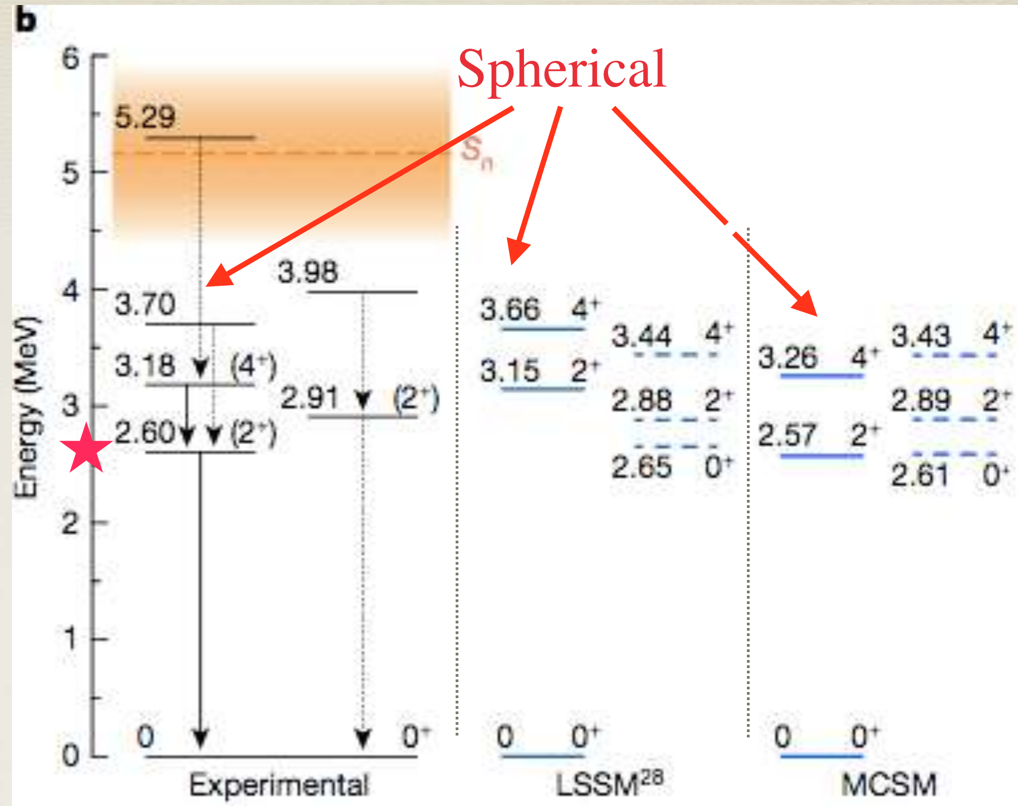
@ RIKEN - BigRIPS

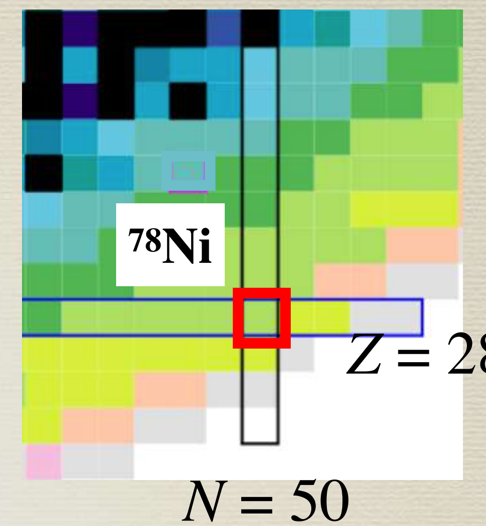
^{80}Zn(p, 3p)^{78}Ni

R. Taniuchi, C. Santamaria, P. Doornenbal *et al*. Nature 569 (2019) 53

^{79}Cu(p, 2p)^{78}Ni







High excitation energy of first 2+ state : N = 50 closed shell

Second 2+ state located close to first 2+ state : Close lying spherical and deformed configurations

Calculations with three nucleon force explain data

^{78}Ni is doubly magic - N = 50 shell closure persists

Doubly magic ^{78}Ni ($N = 50$)

@ RIKEN - BigRIPS

^{80}Zn(p, 3p)^{78}Ni

R. Taniuchi, C. Santamaria, P. Doornenbal *et al*. Nature 569 (2019) 53

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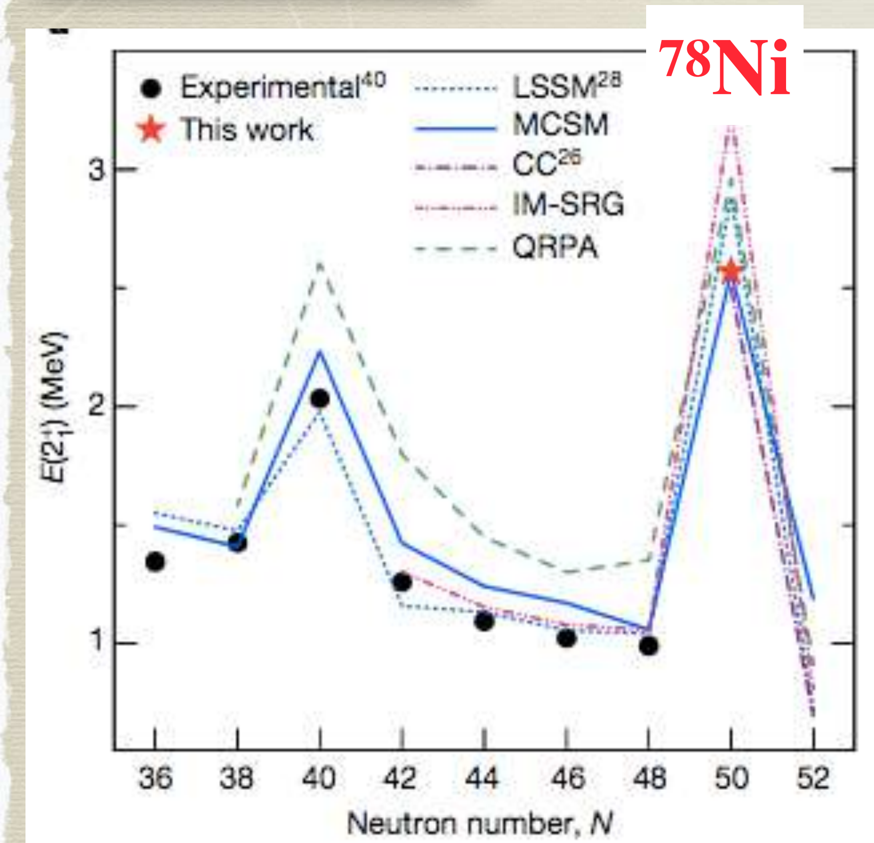
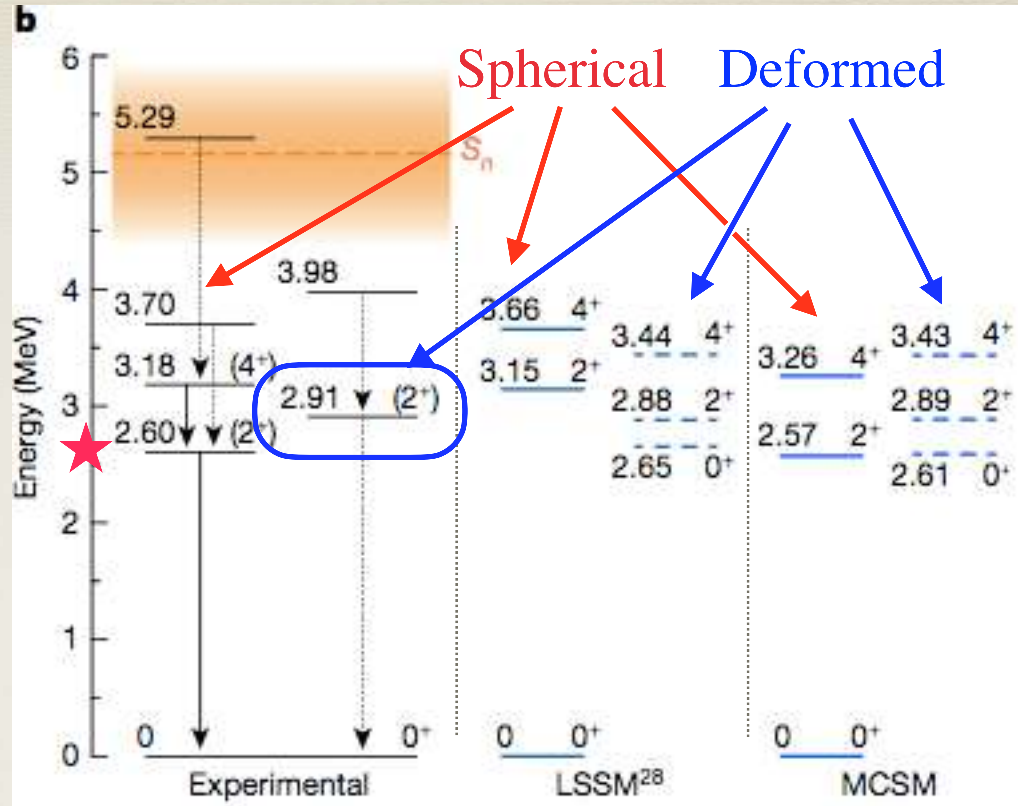
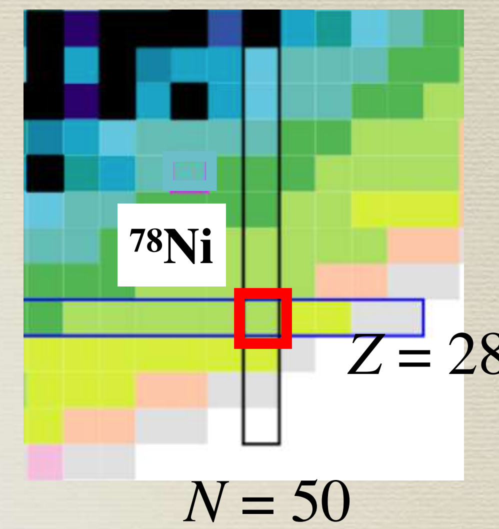


High excitation energy of first 2+ state : $N = 50$ closed shell



Second 2+ state located close to first 2+ state : Close lying spherical and deformed configurations



Calculations with three nucleon force explain data

^{78}Ni is doubly magic - $N = 50$ shell closure persists

$N = 50$ shell gap quenching beyond ^{78}Ni hinted - competing deformed & spherical shapes

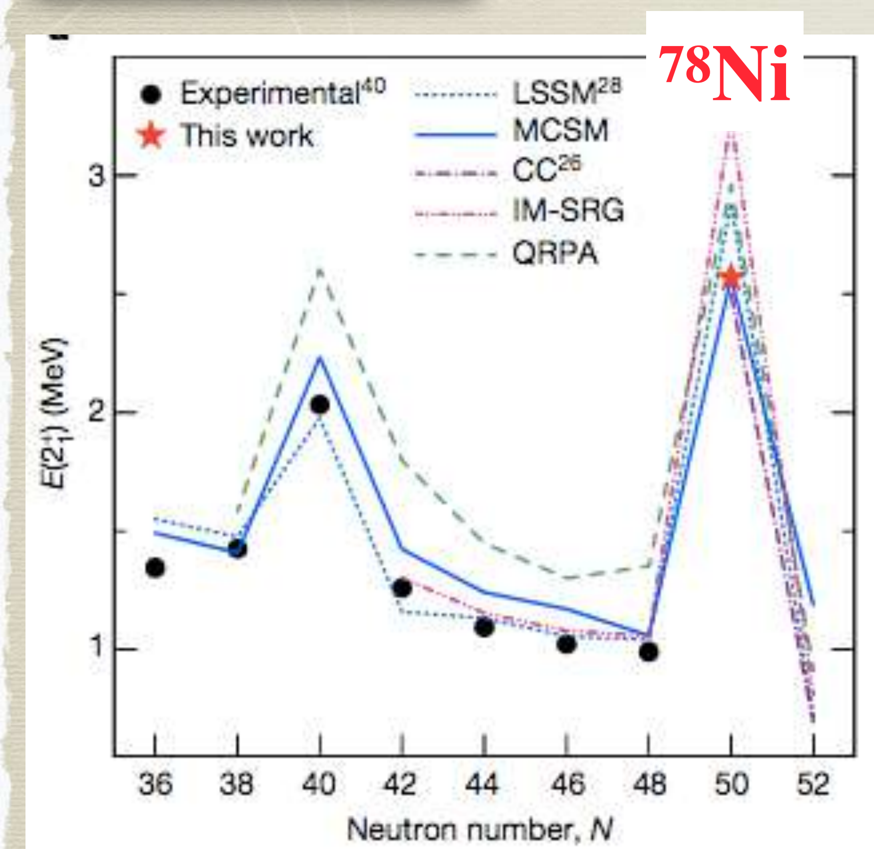
Doubly magic ^{78}Ni ($N = 50$)

@ RIKEN - BigRIPS

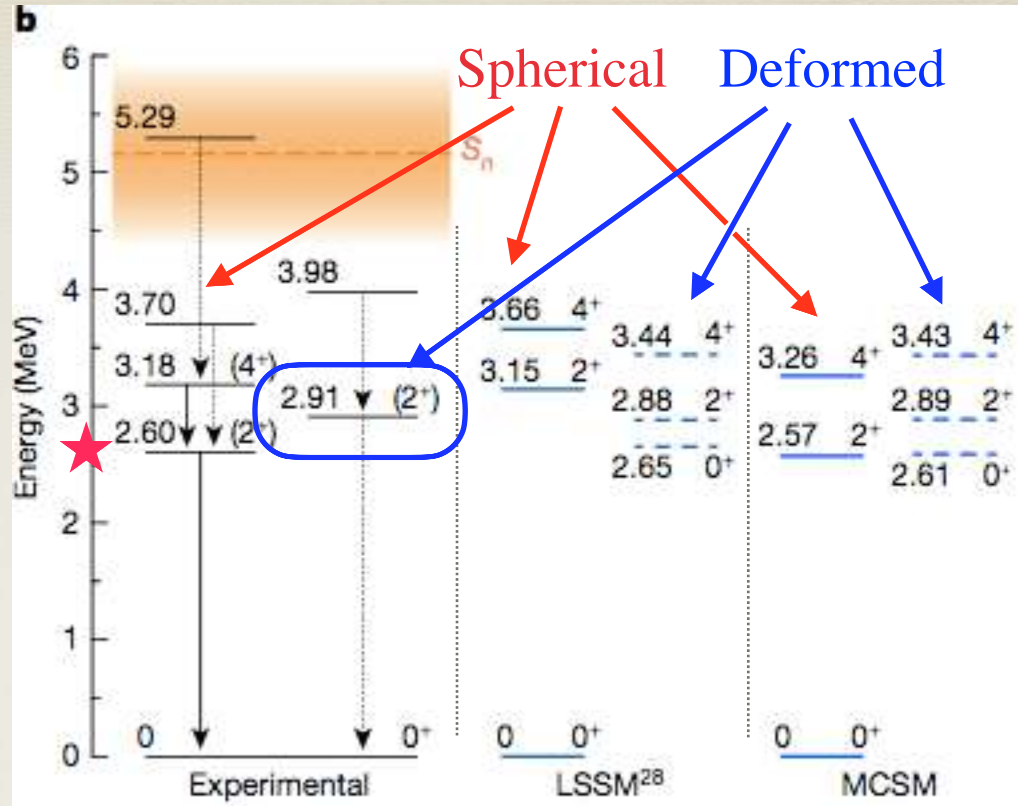
^{80}Zn(p, 3p)^{78}Ni

^{79}Cu(p, 2p)^{78}Ni

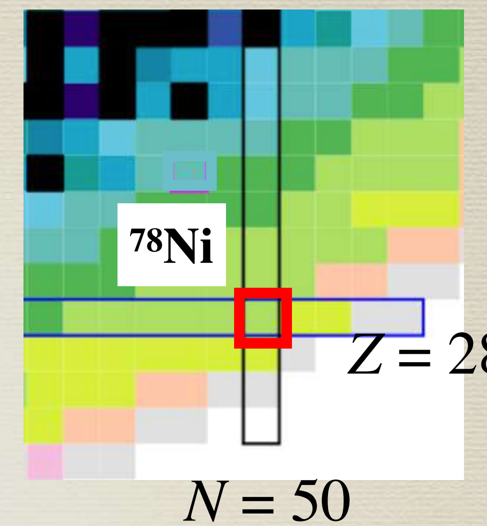
R. Taniuchi, C. Santamaria, P. Doornenbal *et al*. Nature 569 (2019) 53



High excitation energy of first 2+ state : $N = 50$ closed shell



Second 2+ state located close to first 2+ state : Close lying spherical and deformed configurations



Calculations with three nucleon force explain data

^{78}Ni is doubly magic - $N = 50$ shell closure persists

$N = 50$ shell gap quenching beyond ^{78}Ni hinted - competing deformed & spherical shapes

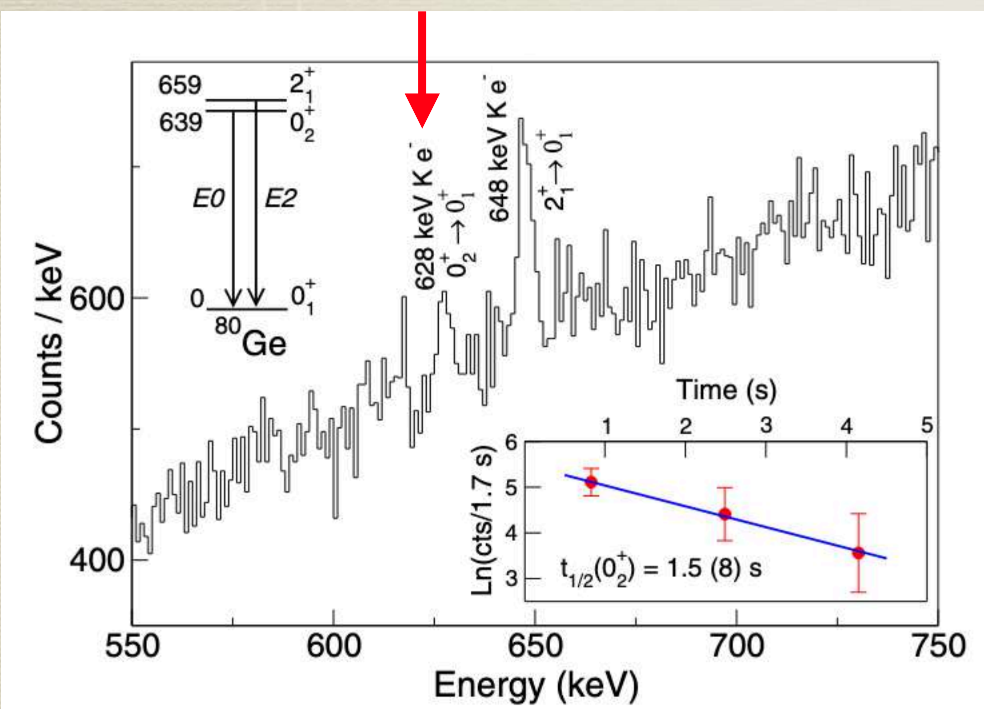
Future studies on ^{76}Fe and ^{74}Cr needed to search for erosion for $N = 50$ shell gap

^{80}Ge ($N = 48$) : Shape coexistence or not ? controversy resolved

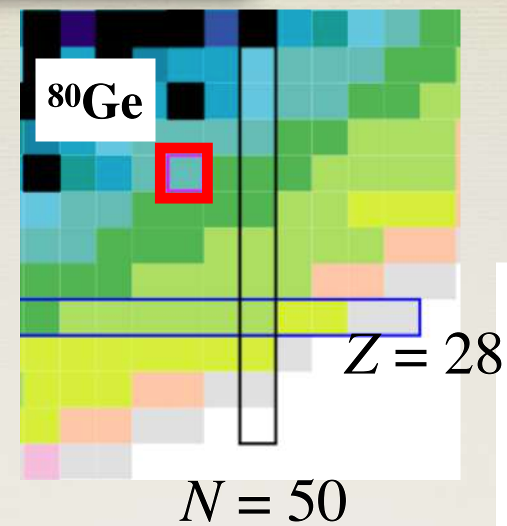
^{80}Ga β^- decay

@ ALTO

A. Gottardo et al., Phys. Rev. Lett. 116 (2016) 182501

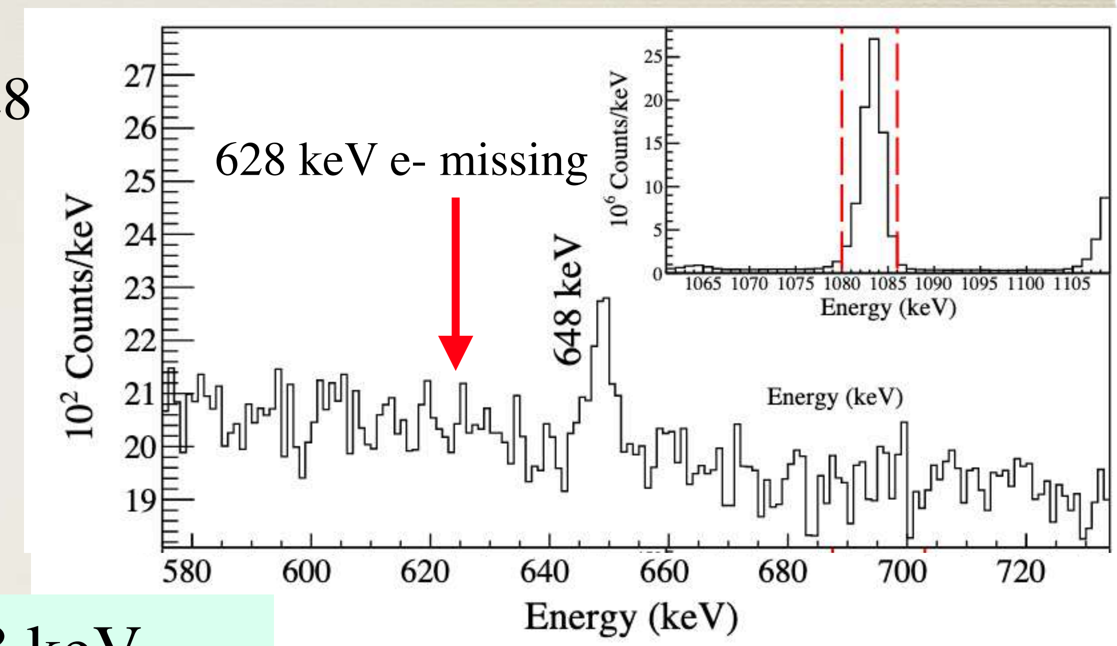


0_2^+ state @ 639 keV below 2+ state reported as evidence of shape coexistence

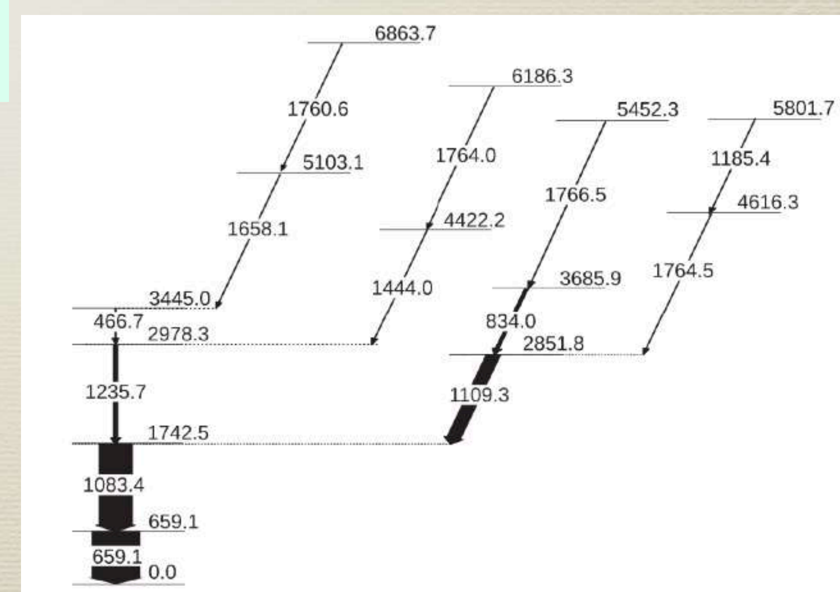


@ TRIUMF - GRIFFIN

F. Garcia et al., Phys. Rev. Lett. 125 (2020) 172501



0_2^+ : 638 keV state not found !



No shape coexistence in ^{80}Ge

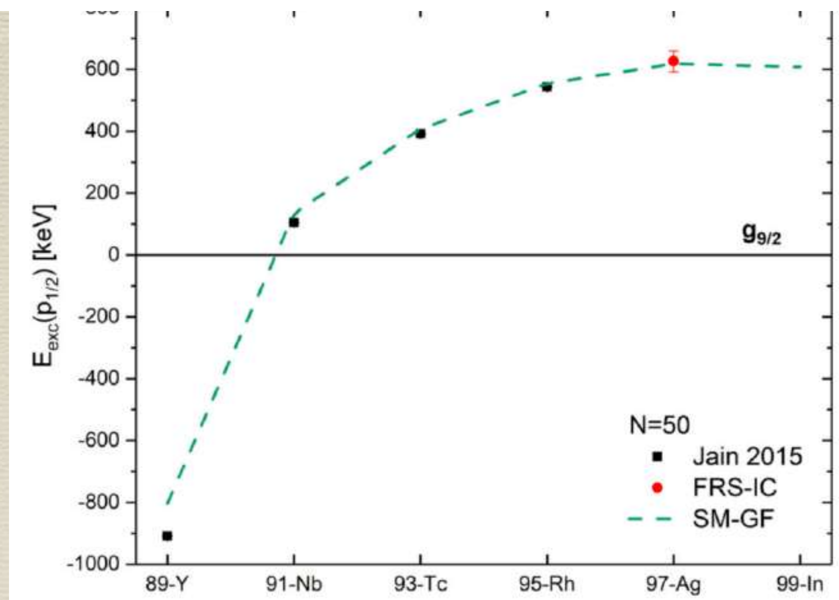
Isomer states found around ^{100}Sn

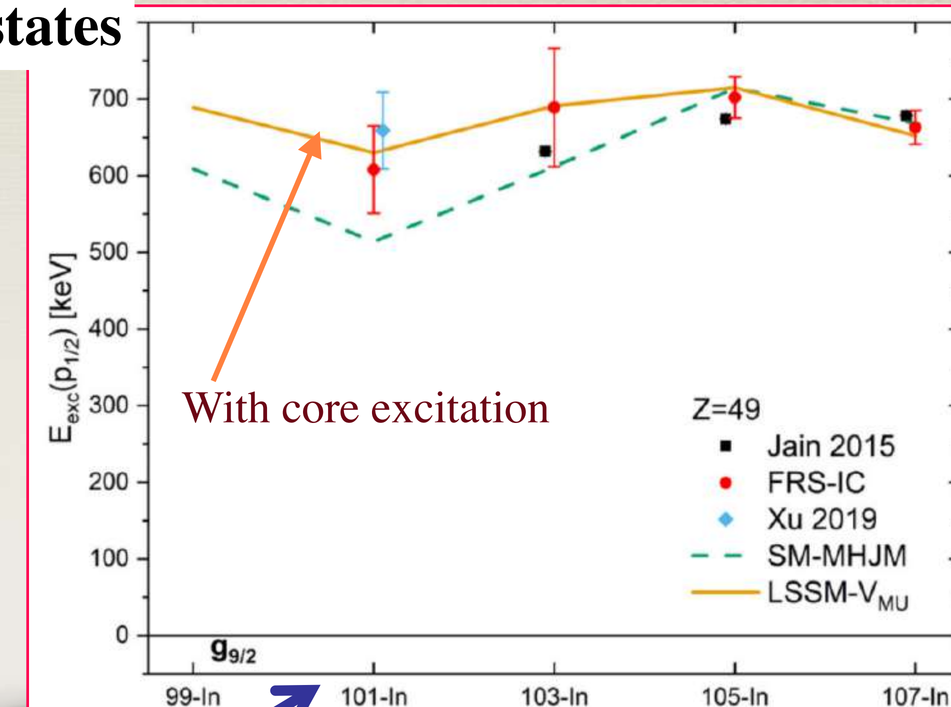
@ GSI - FRS Ion Catcher & MR-TOF

N = *Z* = 50 region

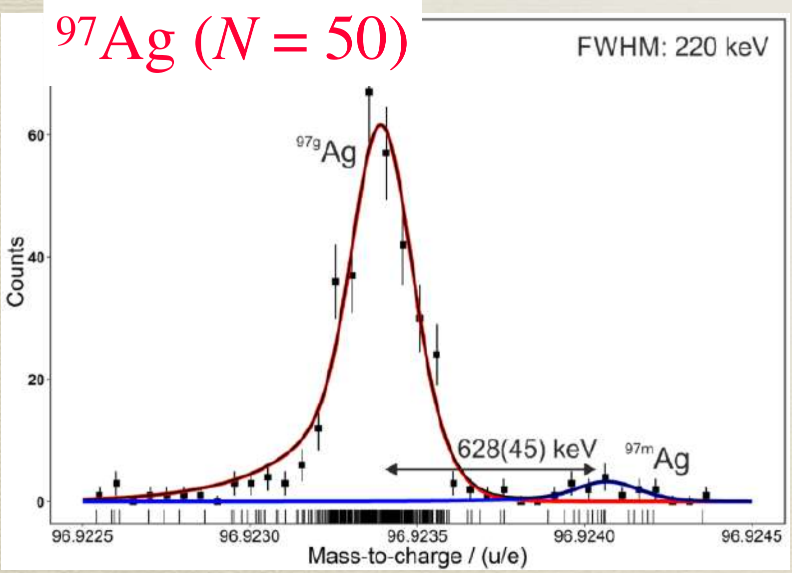
C. Homung *et al*. Phys. Lett. B 802 (2020) 135200

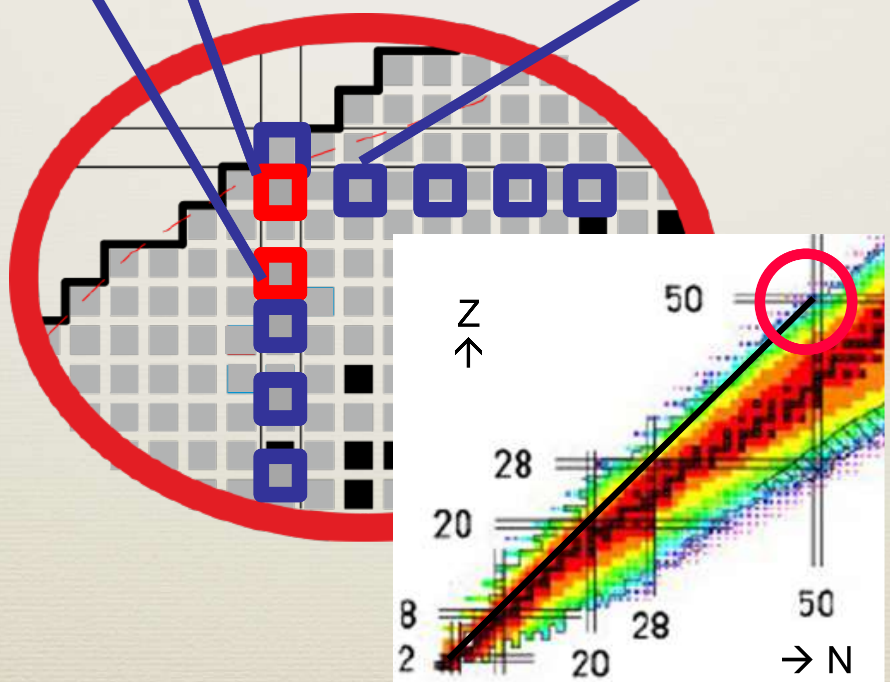
High precision mass measurements identify isomeric states



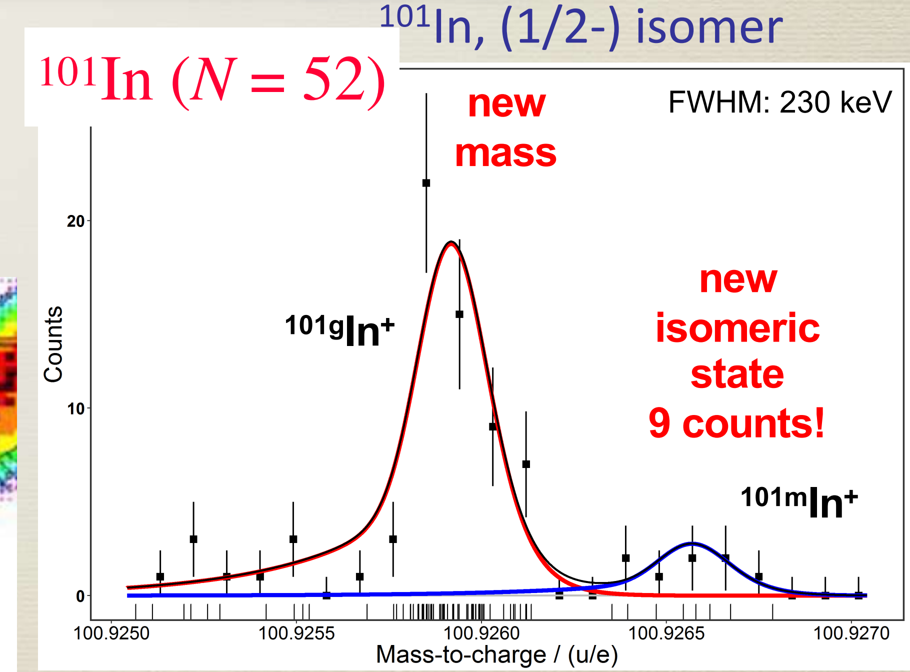


^{97}Ag, new (1/2-) isomer





^{101}In, (1/2-) isomer



Courtesy : T. Dickel

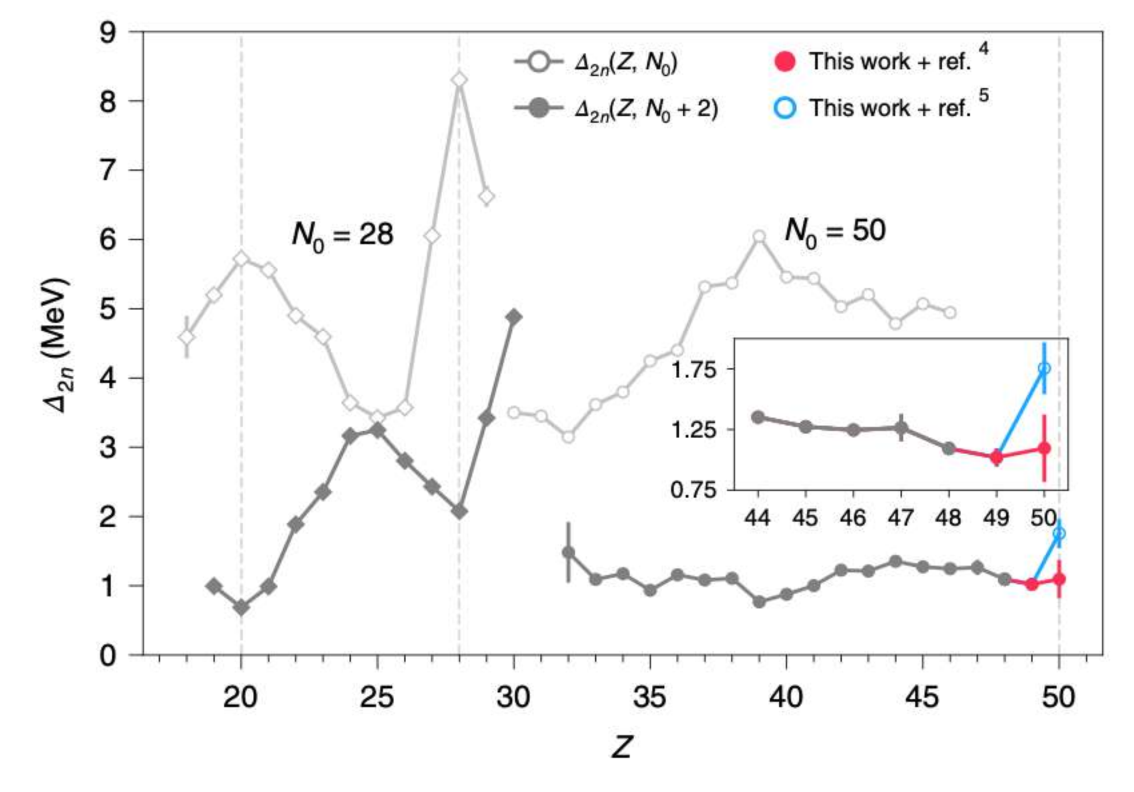
Data shows the need for core excitation across *N* = 50 : Large Scale Shell model calculations

Mass $^{99-101}$In *towards ^{100}Sn*

@ ISOLDE - ISOLTRAP & MR-TOF

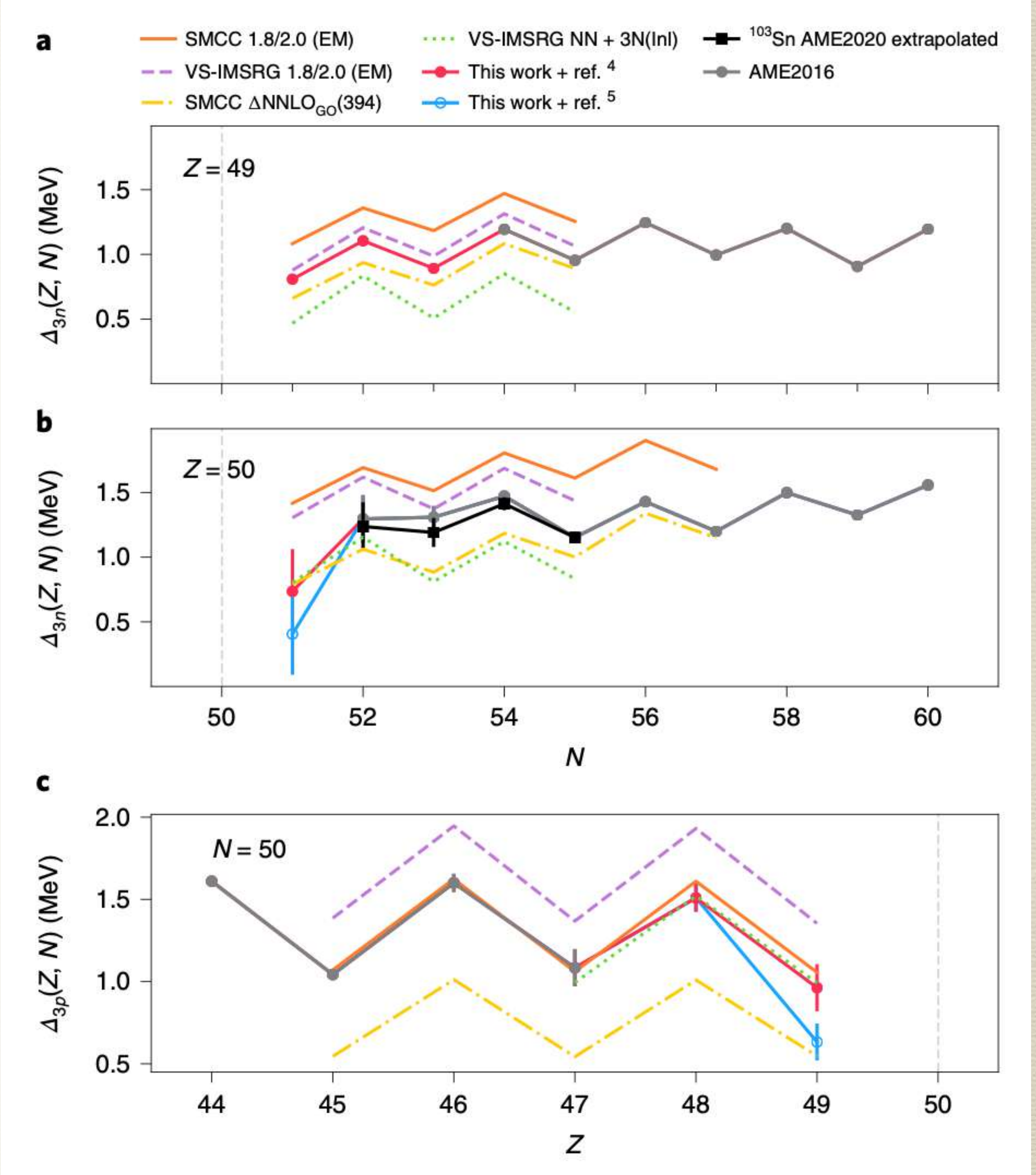
N = Z = 50 region

M. Mougeot et al., Nat. Phys. 17 (2021) 1099



$$\Delta_{2n}(Z,N_0) = M_E(Z,N_0-2) - 2M_E(Z,N_0) + M_E(Z,N_0+2)$$

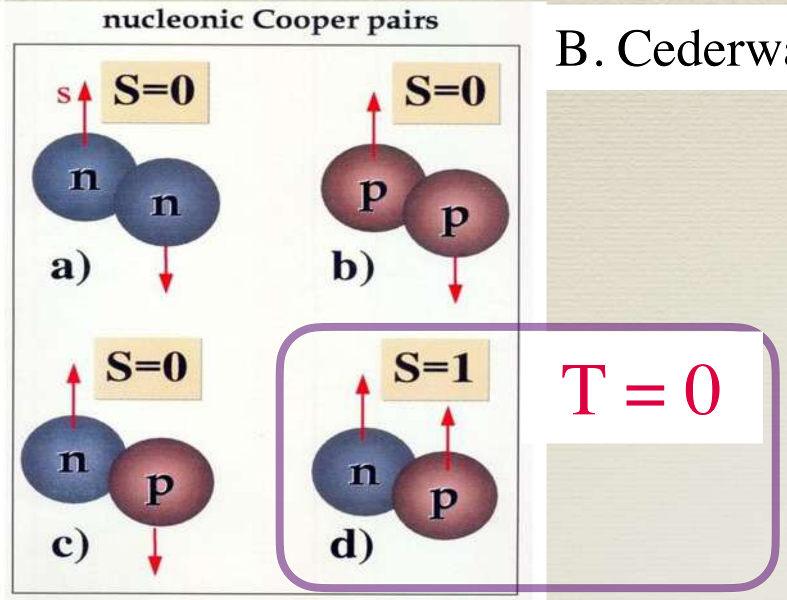
High precision mass measurements show trend of shell closure towards *N = Z* = 50



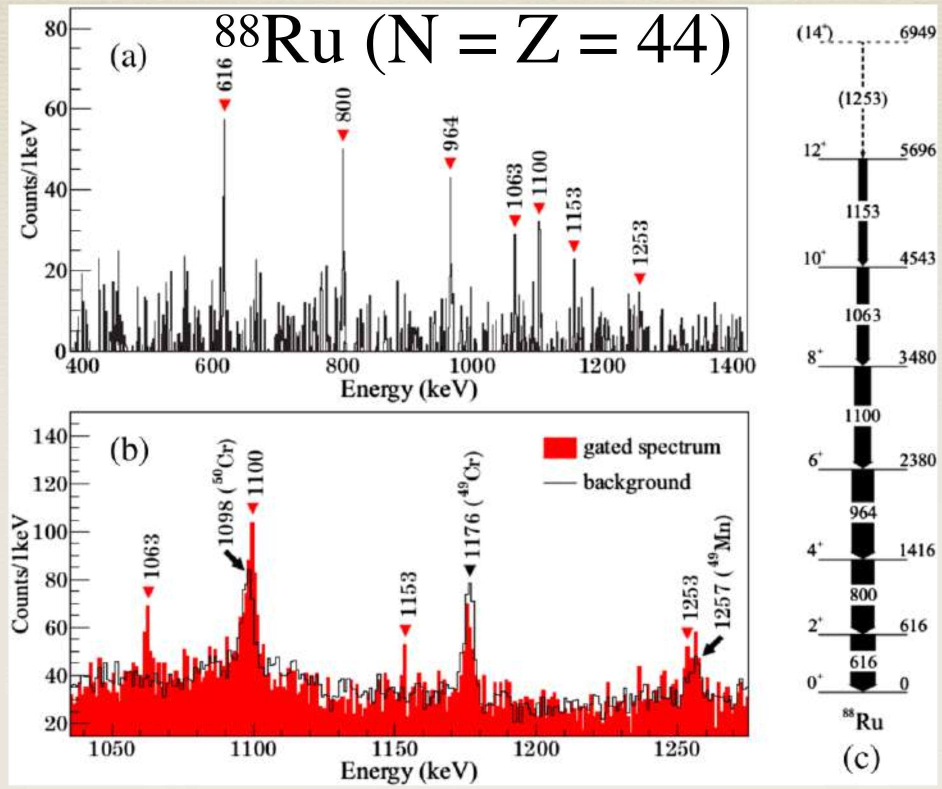
Ab initio predictions of odd-even staggering overall align well with data.

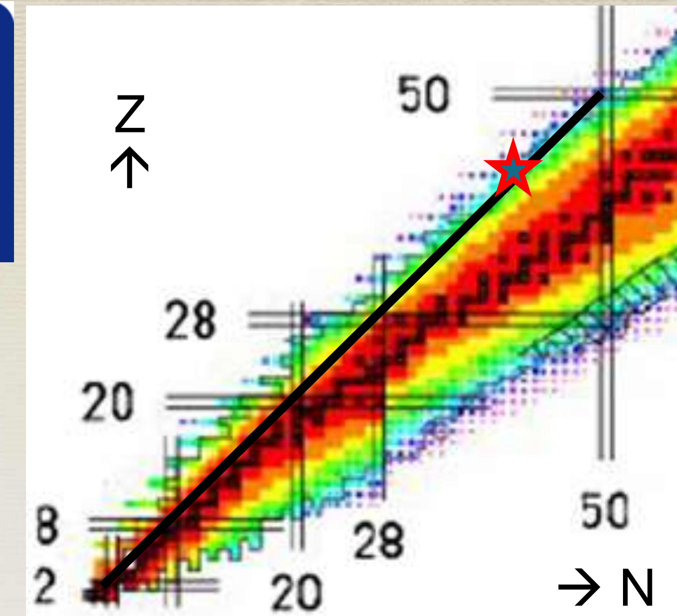
$N = Z$: Neutron-Proton (p-n) Isoscalar Pairing

@ GA NIL - AGATA



B. Cederwall *et al*. Phys. Rev. Lett. 124 (2020) 062501

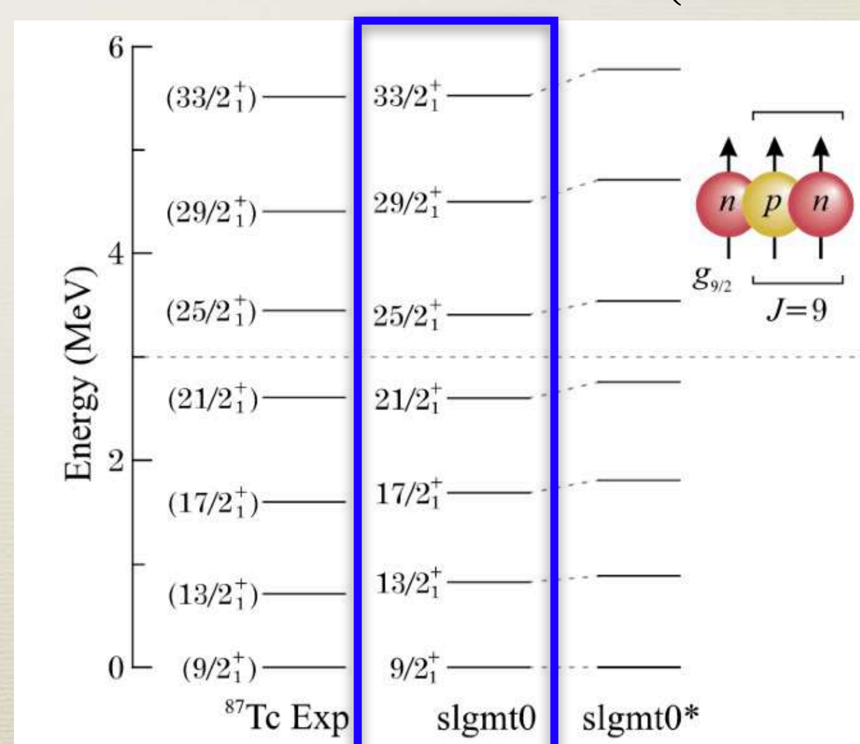




^{87}Tc (N = 44, Z = 43)

X. Liu *et al*. Phys. Rev. C Lett. 104 (2021) L021302

^{56}Fe(^{36}Fe, 2n1p)^{87}Tc

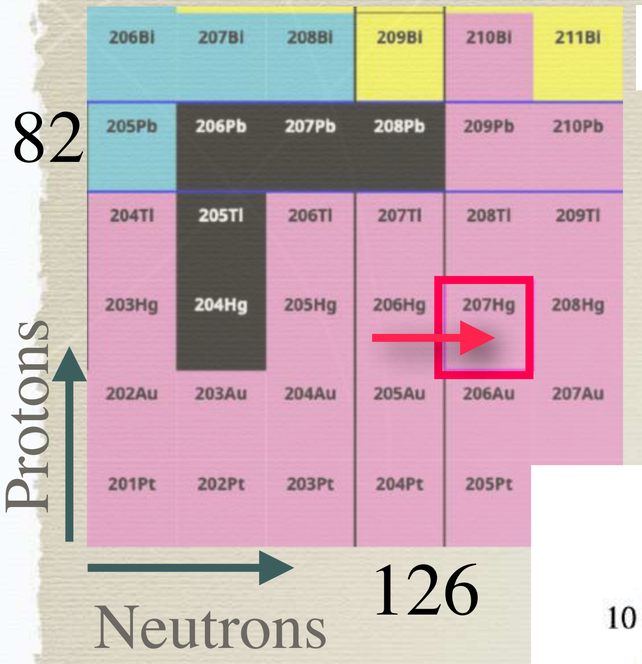


Observed rotation spectrum supports predictions with strong n-p pairing (T= 0) correlation

Shell structure beyond $N = 126$

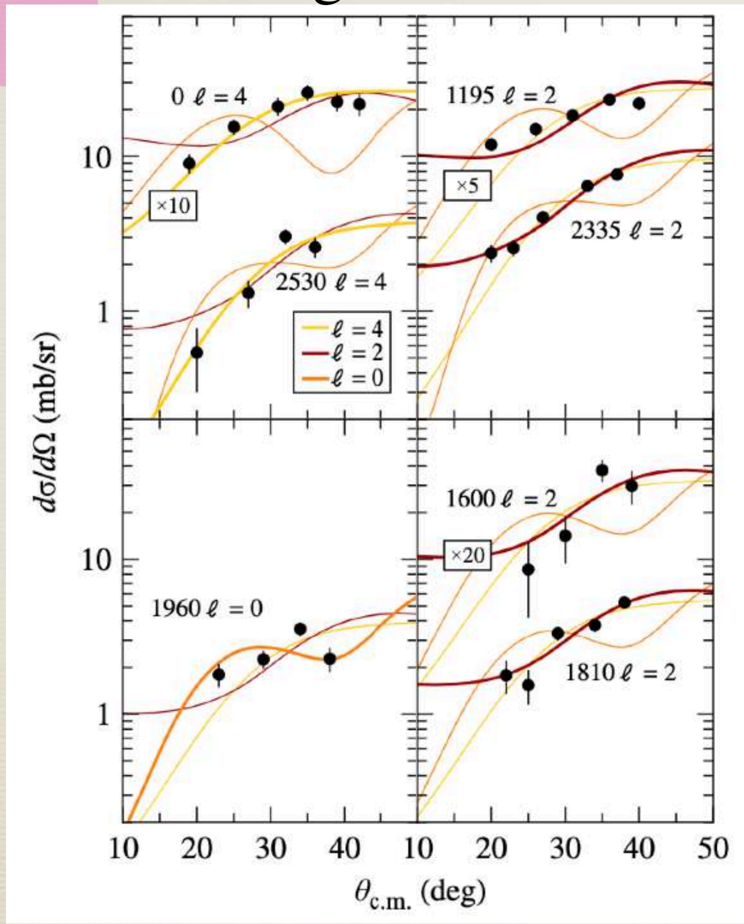
@ ISOLDE - Solenoidal Spectrometer

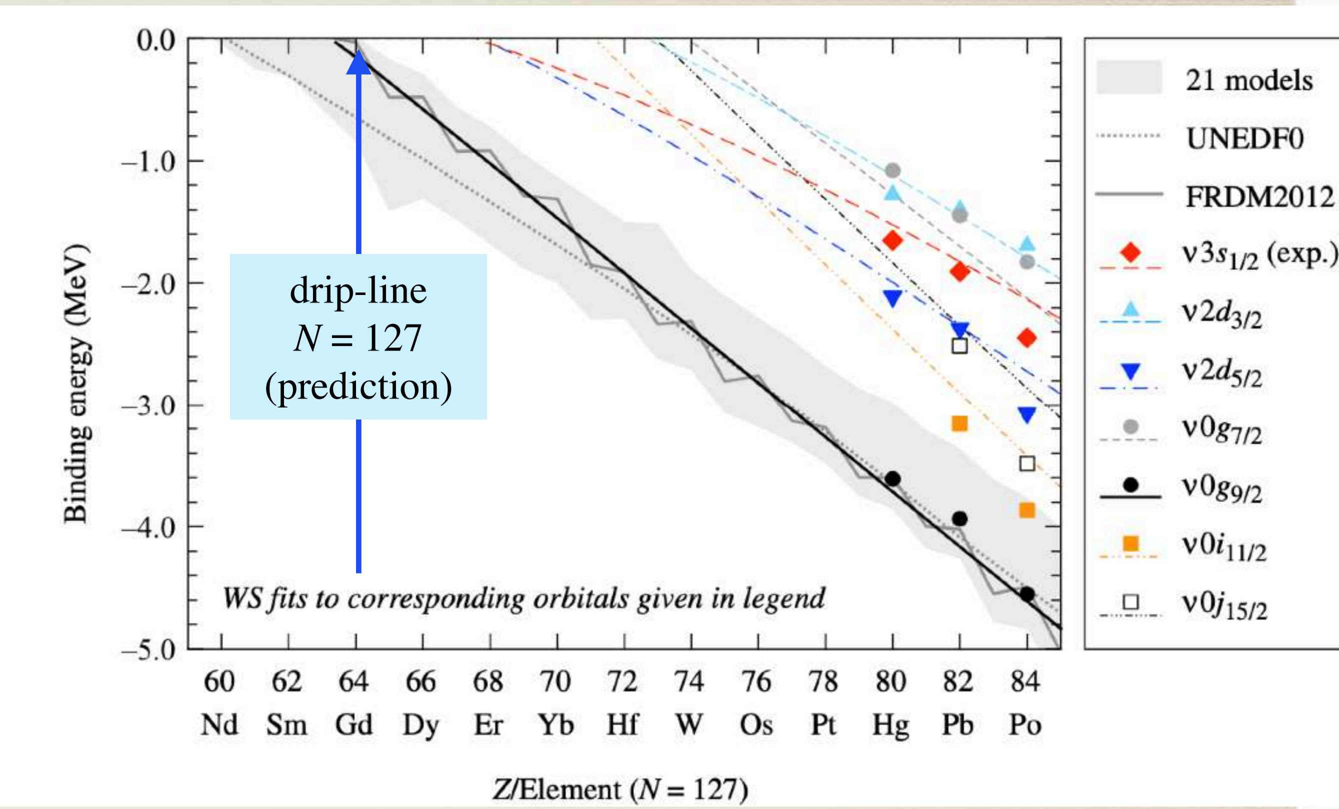
T.L. Tang, B.P. Kay, C.R. Hofmann *et al*. Phys. Rev. Lett. 124 (2020) 062502



$^{206}Hg(d, p)^{207}Hg$

^{207}Hg excited states





^{207}Hg states show normal shell configuration. Binding energy aligns with predictions.

$Z = 64$ predicted to be the drip line of $N = 127$.

r-process neutron capture improbable with low angular momentum orbitals being unbound

Assumption : $N = 126$ shell closure persists. Future experiments will inform on this.

Unbound Nuclei - open quantum systems

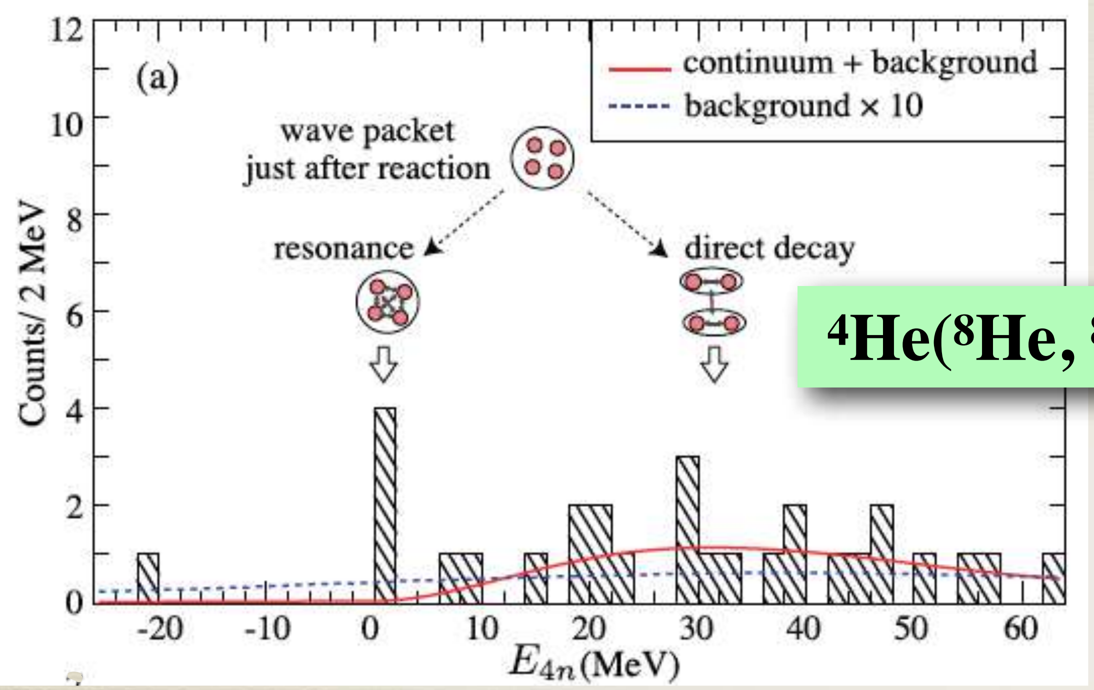
The hunt for tetraneutron

@ RIKEN - SHARAQ

K. Kisamori, S. Shimoura, H. Miya *et al.*, Phys. Rev. Lett. 116 (2016) 052501

^1n ^4n

The first result of ^{4}**n** from SHARAQ



$^4He(^8He, ^8Be)^4n$

Resonance reported ~ 1 MeV

Theoretical Predictions

- Hiyama et al. No
  (too strong 3N force is needed)
- Shirokov et al. Yes
  (NSCM with JISP16 interaction)
- Gandolfi et al. Yes
  (QMC with chiral interaction)

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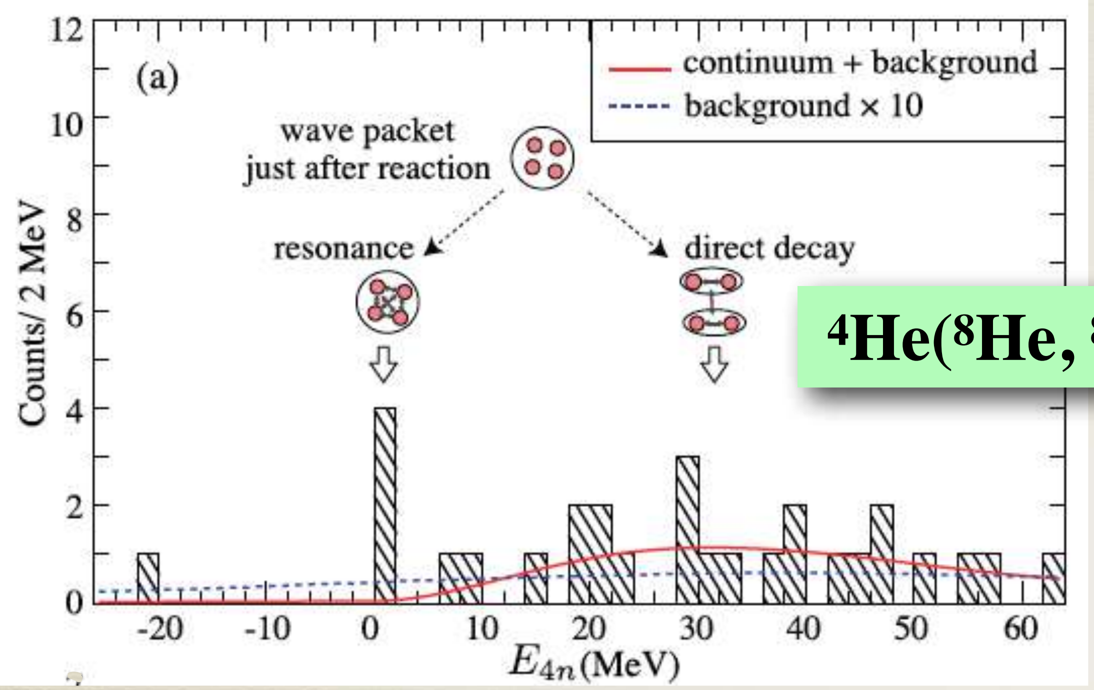

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The question is still open on the existence of narrow resonance for tetraneutron

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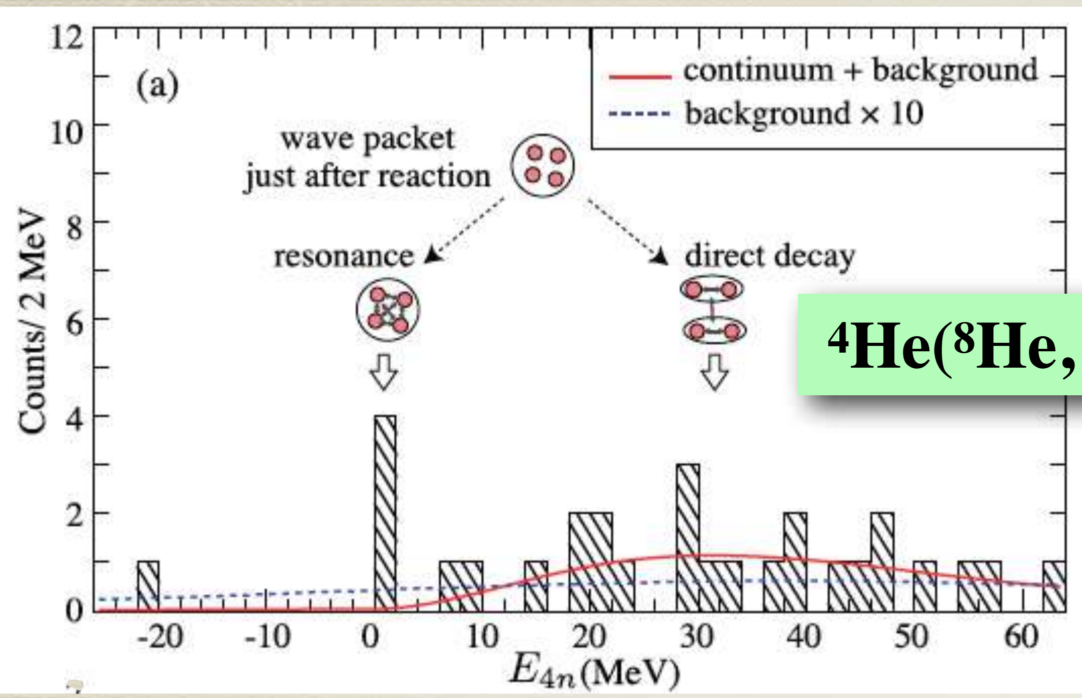

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New Experiments to study exotic system @ RIKEN – RIBF

SHARAQ

- Shimoura et al.
  Revisit $^{4}He(^{8}He,^{8}Be)$ ^{4}**n**
- Miki et al.
  $^{3}H(^{3}H,^{3}He)$ ^{3}**n**

SAMURAI

- Rossi et al.
  $^{8}He(p,p\alpha)$ ^{4}**n**
- Yang and Marques at al.
  $^{8}He(p,2p)$ ^{7}**H**→t+ ^{4}**n**
- Beaumel et al.
  $^{14}Be(p, p\alpha)$ ^{6}n+α

Courtesy : H. Sakurai

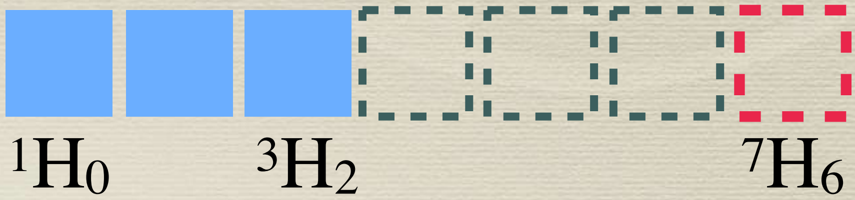
The question is still open on the existence of narrow resonance for tetraneutron

Superheavy hydrogen ^7H

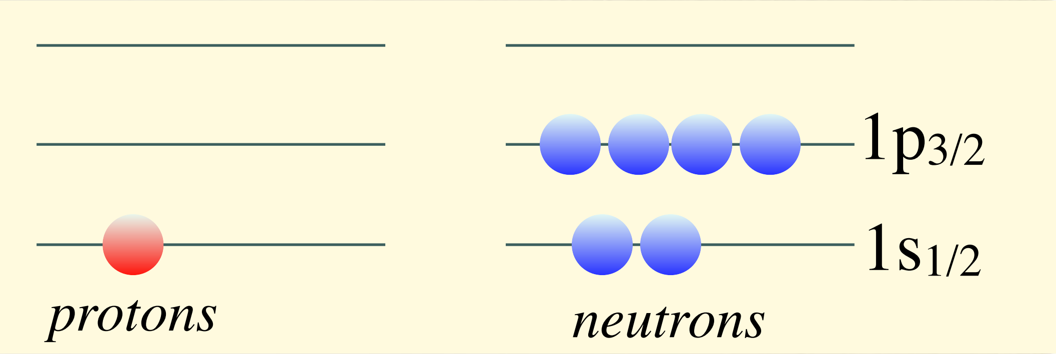
@ GANIL - MAYA

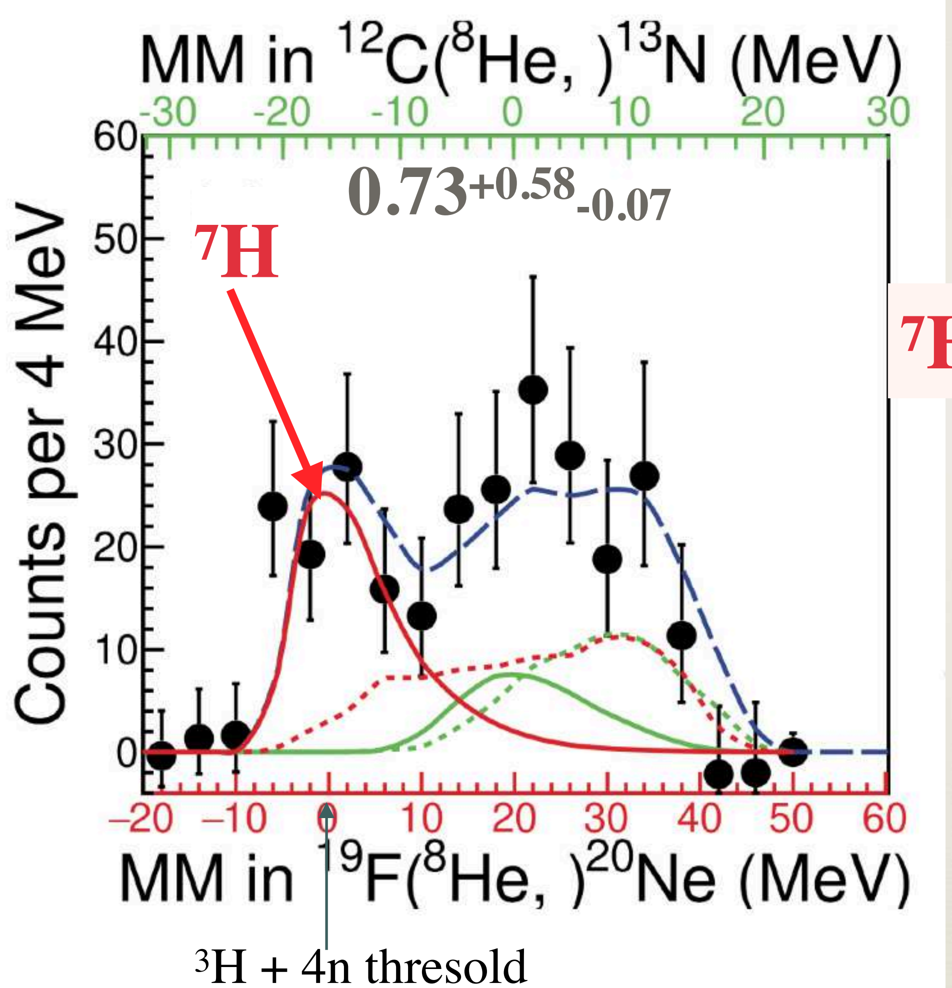
M. Cammano, T. Roger, T. Moro *et al*. Phys. Lett. B 829 (2022) 137067

Active Target gas He + CF_4



$^{12}C(^8He, ^7H)^{13}N$ **$^{19}F(^8He, ^7H)^{20}Ne$**

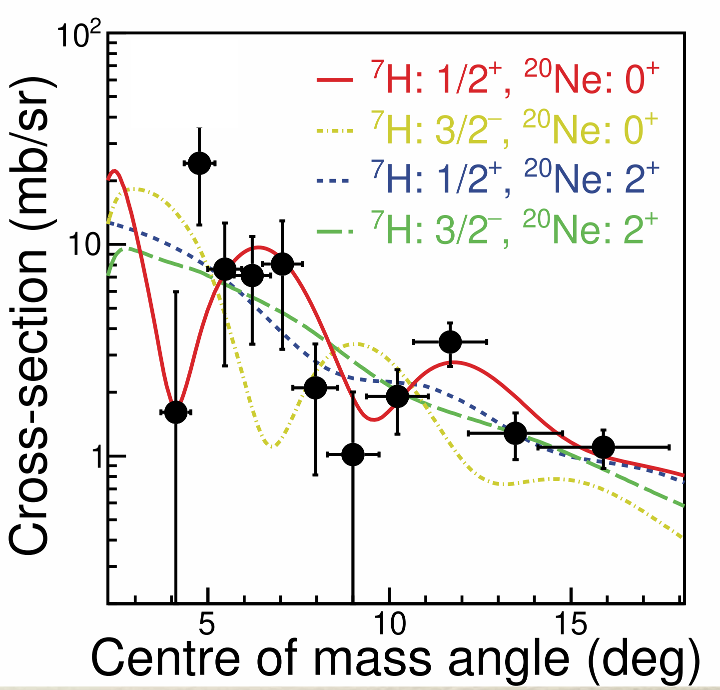




Excitation energy ^7H

^7H Resonance energy

$0.73^{+0.58}_{-0.07}$ MeV



Resonance spin : 1/2+ !

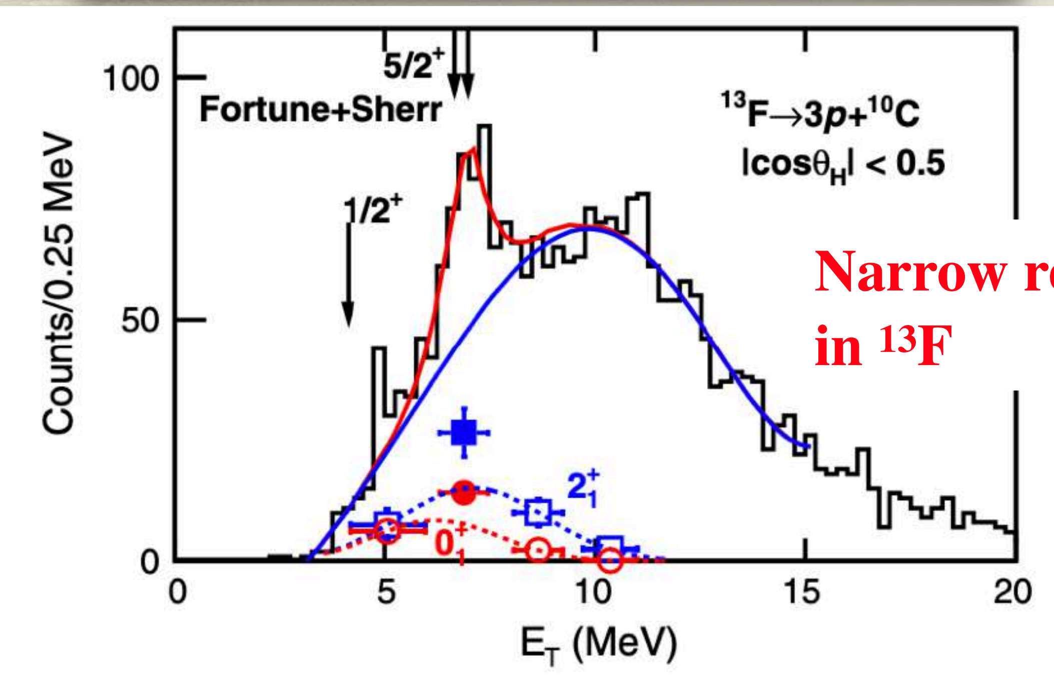
^7H resonance observed ~ 0.7 MeV. ^3H + 4n structure deduced.

Beyond the proton drip-line ^{13}F, ^{11}O

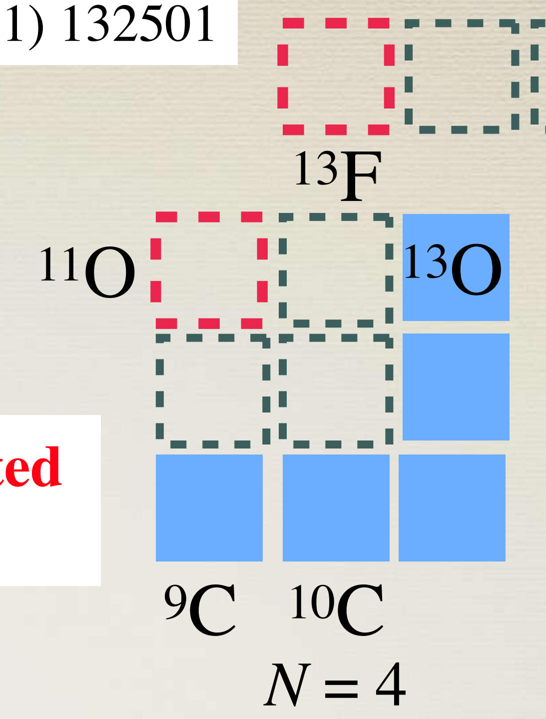
@ NSCL - HIRA

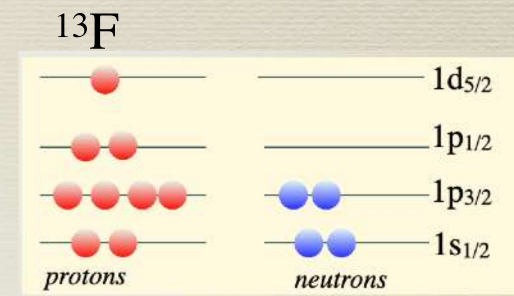
R.J. Charity, T.B. Webb, J.M. Elson *et al*. Phys. Rev. Lett. 126 (2021) 132501

^{13}O+^{9}Be —> ^{13}F*(= ^{10}C + 3p)



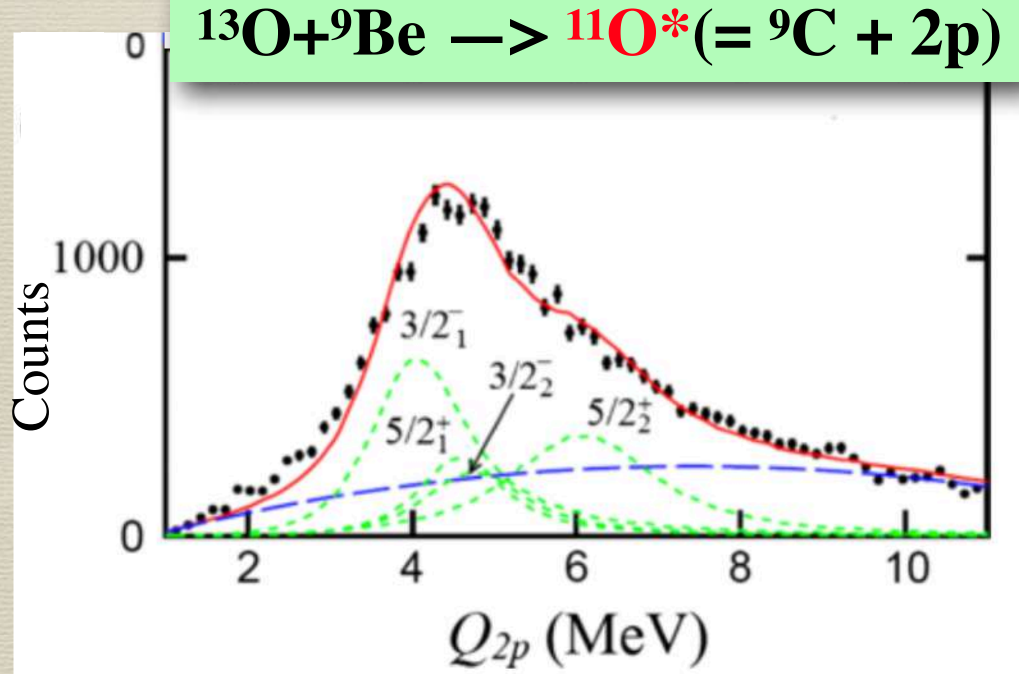
Narrow resonance sighted in ^{13}F

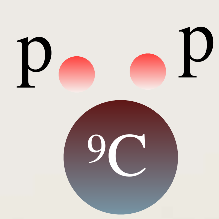




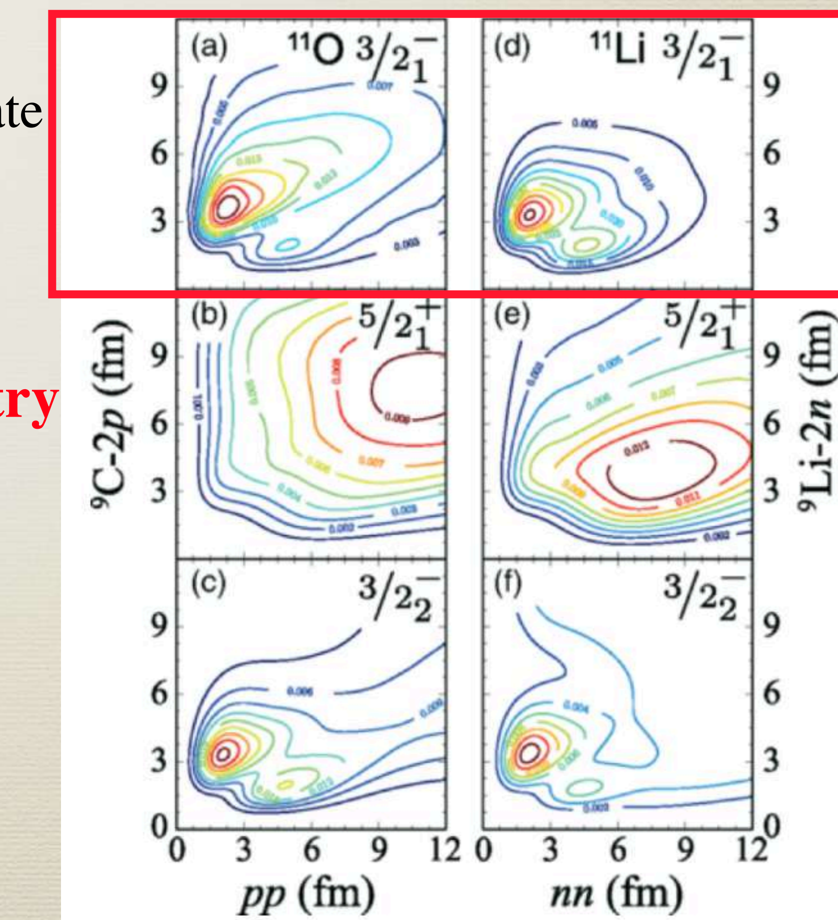
T. Webb *et al*. Phys. Rev. Lett. 122 (2019) 122501

^{13}O+^{9}Be —> ^{11}O*(= ^{9}C + 2p)





ground state



^{11}O is mirror to ^{11}Li

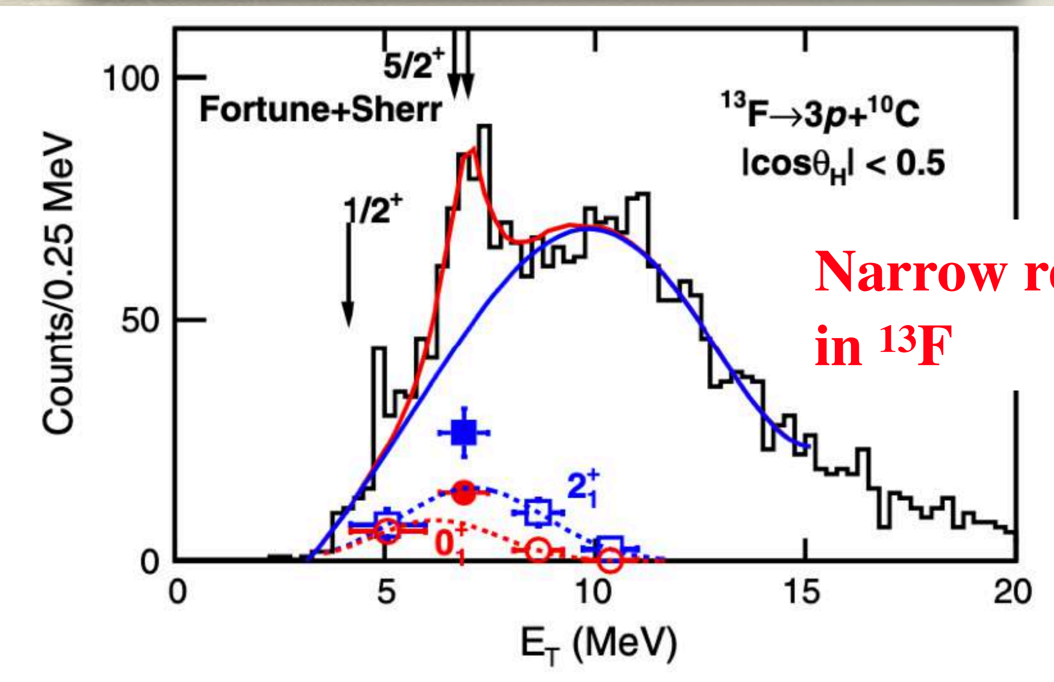
Very small isospin asymmetry seen between ^{11}O and ^{11}Li

Beyond the proton drip-line ^{13}F, ^{11}O

@ NSCL - HIRA

R.J. Charity, T.B. Webb, J.M. Elson *et al*. Phys. Rev. Lett. 126 (2021) 132501

$^{13}O+^{9}Be \longrightarrow$ $^{13}F^{*}$(= ^{10}C + 3p)



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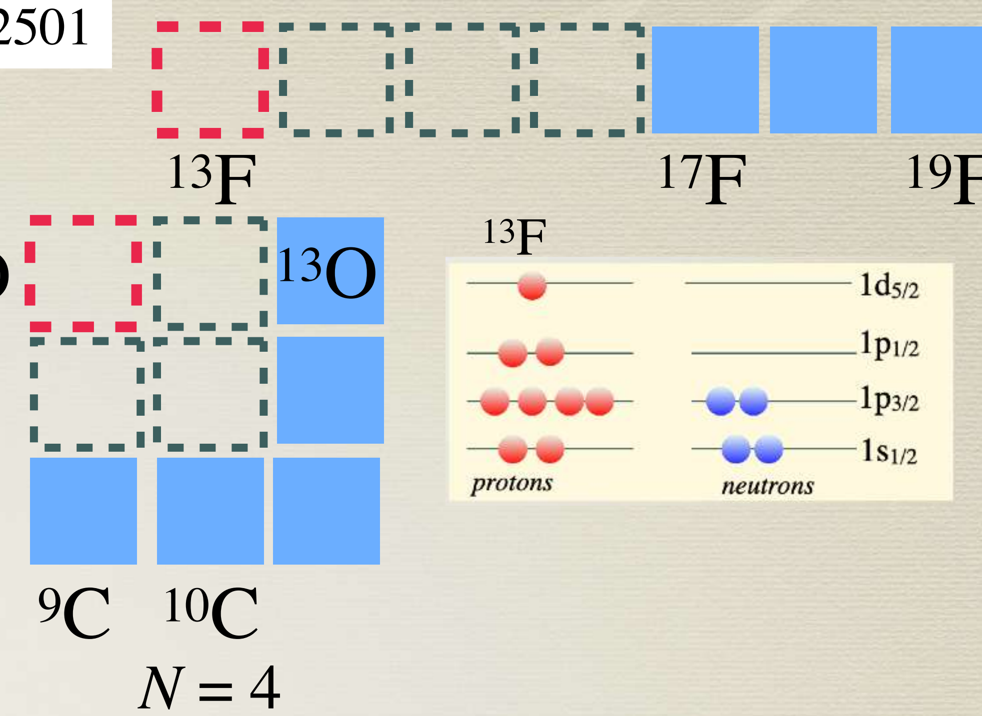
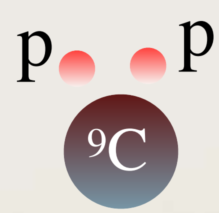
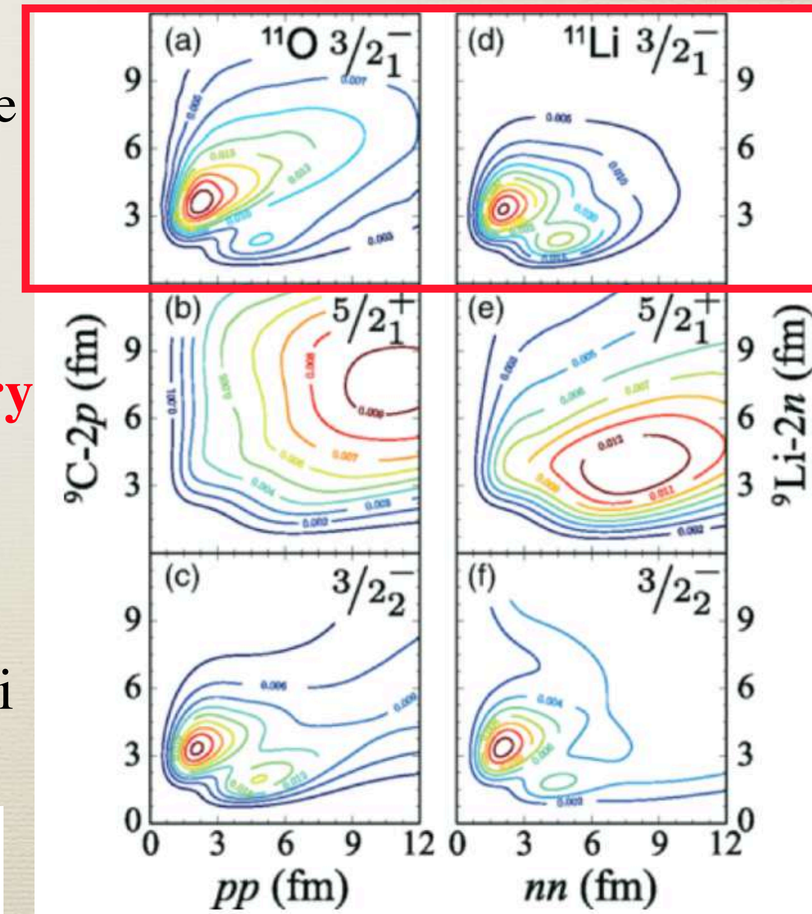




ground state



T. Webb *et al*. Phys. Rev. Lett. 122 (2019) 122501

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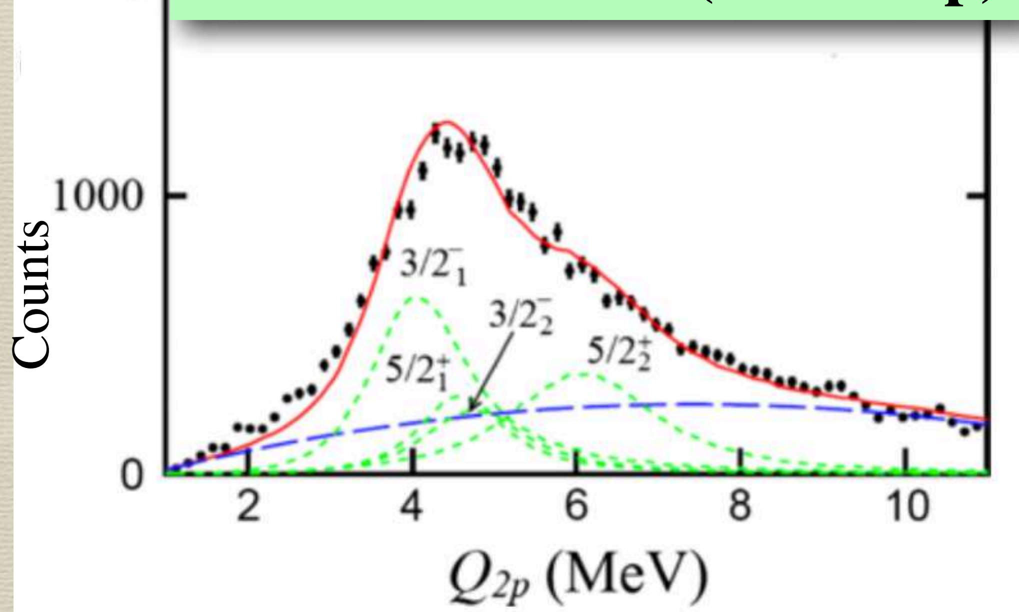

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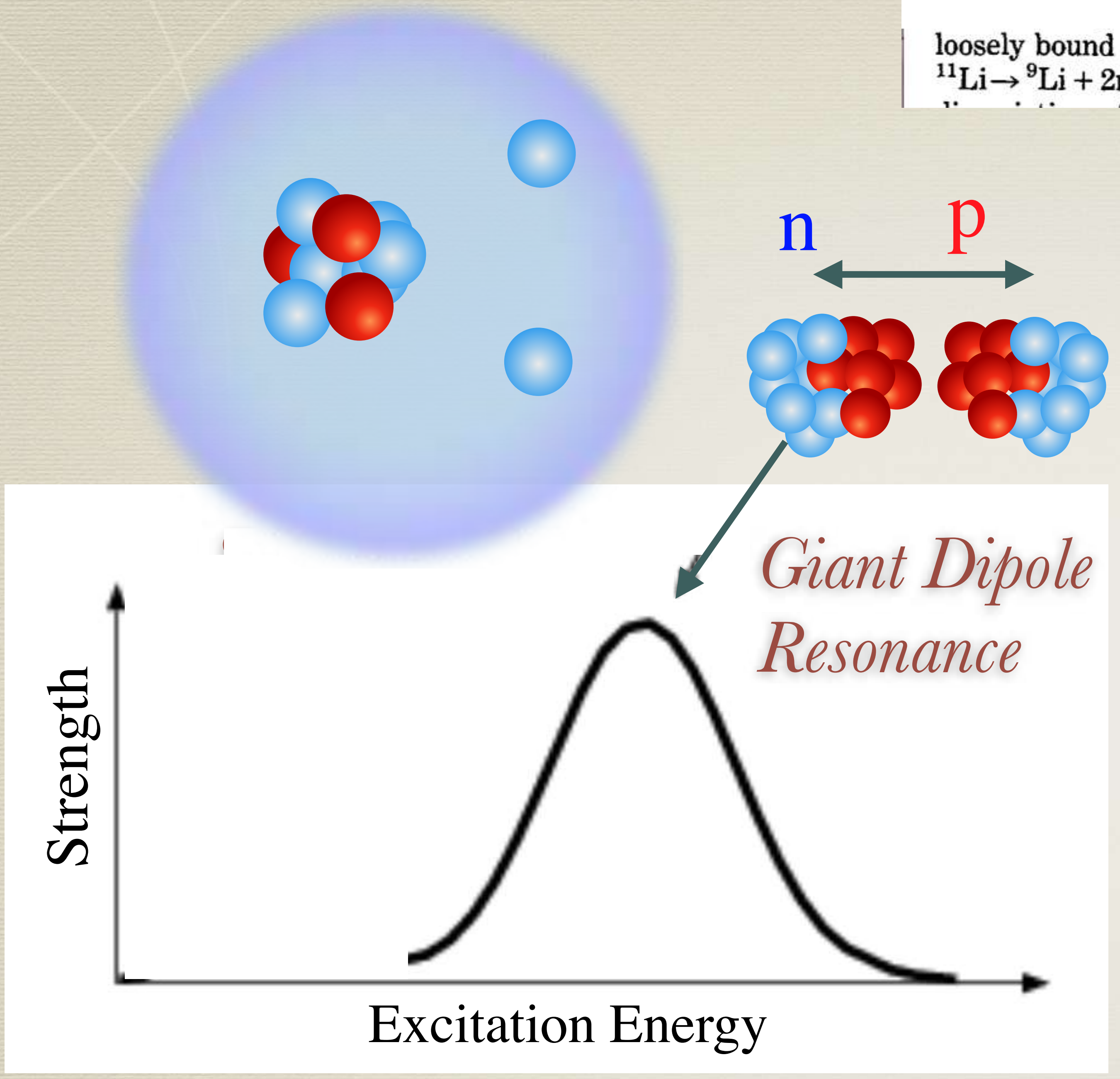
Shape changes in mirror nuclei ^{70}Kr & ^{70}Se

K. Wimmer, W. Korten, P. Doornenbal *et al*. Phys. Rev. Lett. 126 (2021) 072501

Effects of neutron skin

Equation of state of asymmetric nuclear matter

Neutron skin/halo oscillation



it is tempting to speculate that a loosely bound nucleus such as ^{11}Li will have a soft electric-dipole mode so that the reaction $^{11}Li \to {}^{9}Li + 2n$ can be excited in Coulomb collisions at relatively low energy.

(Non-resonant) dipole (E1) enhancement due halo density tail.

Soft dipole resonance

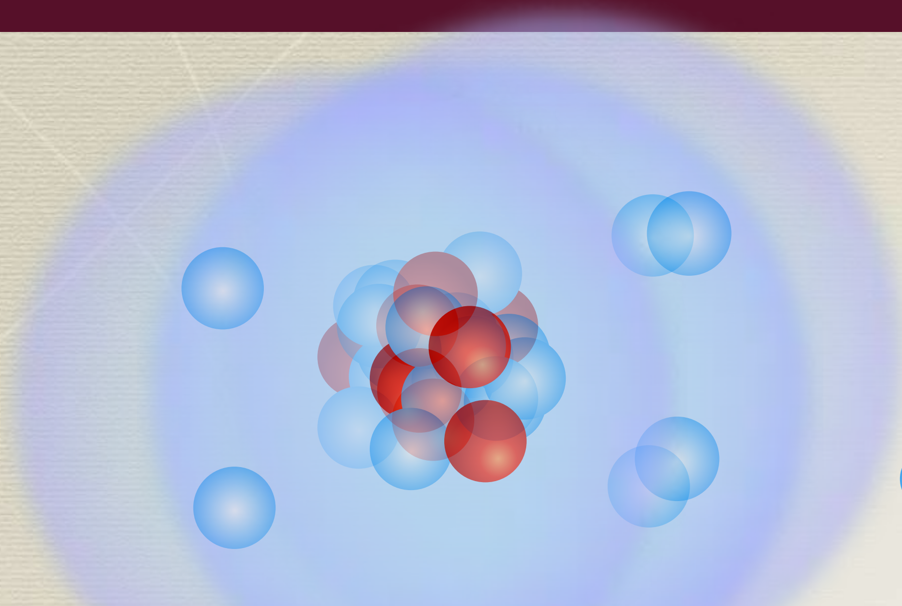
Halo oscillation

"Pygmy" dipole resonance

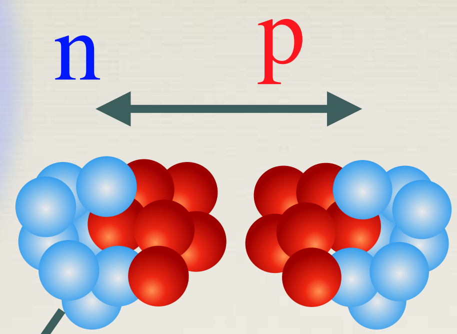
Neutron skin oscillation

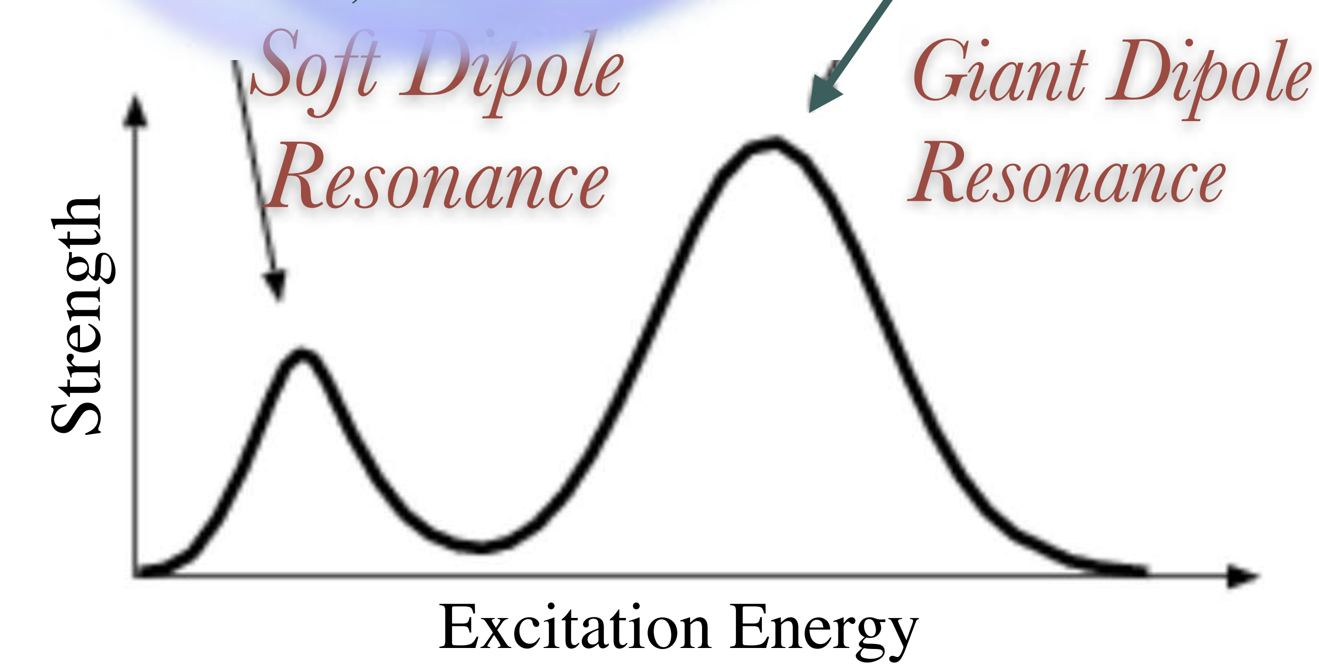
(traditionally oscillation of neutrons outside N = Z core)

Neutron skin/halo oscillation



K. Ikeda, 1992





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G. Hansen and B. Jonson, 1987

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(traditionally oscillation of neutrons outside N = Z core)

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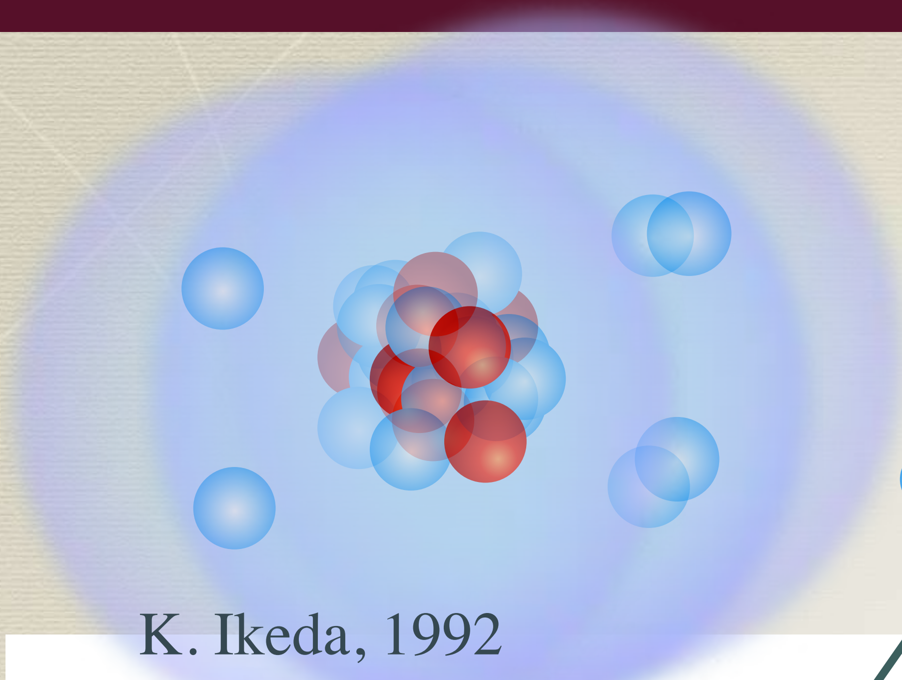

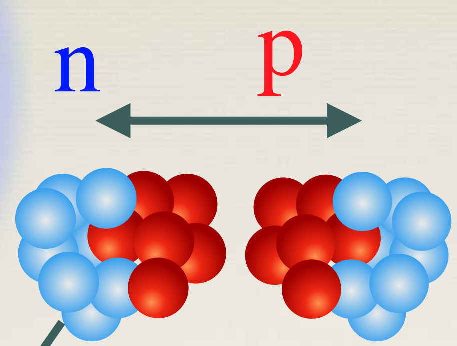

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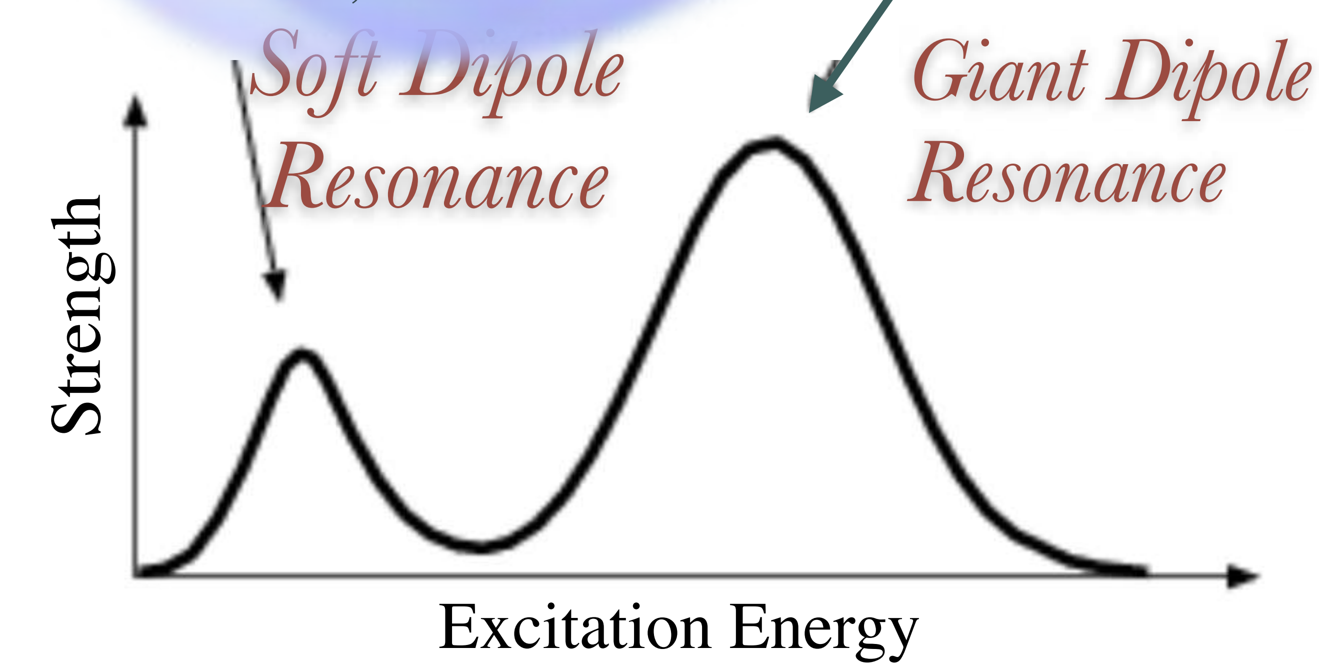

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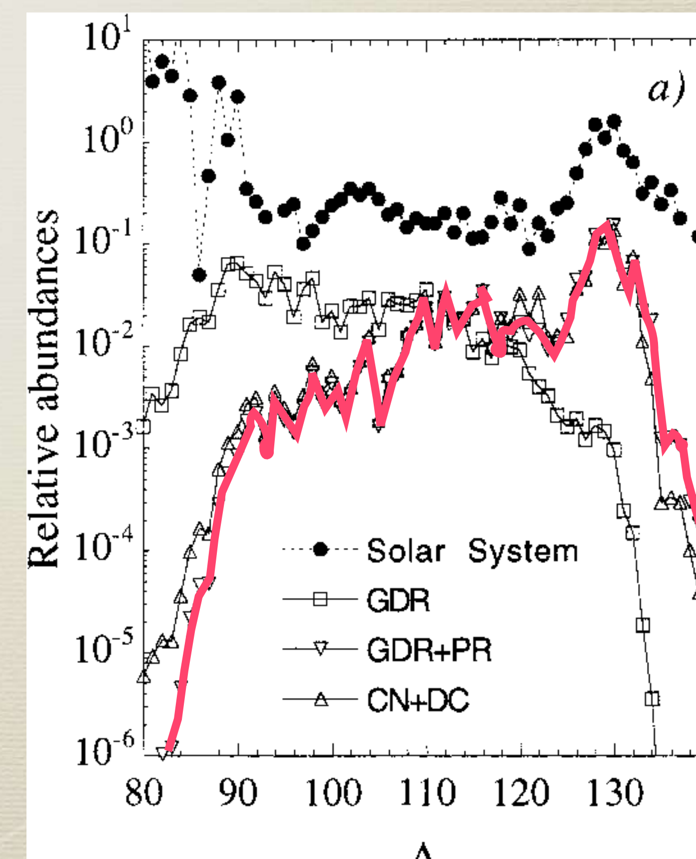
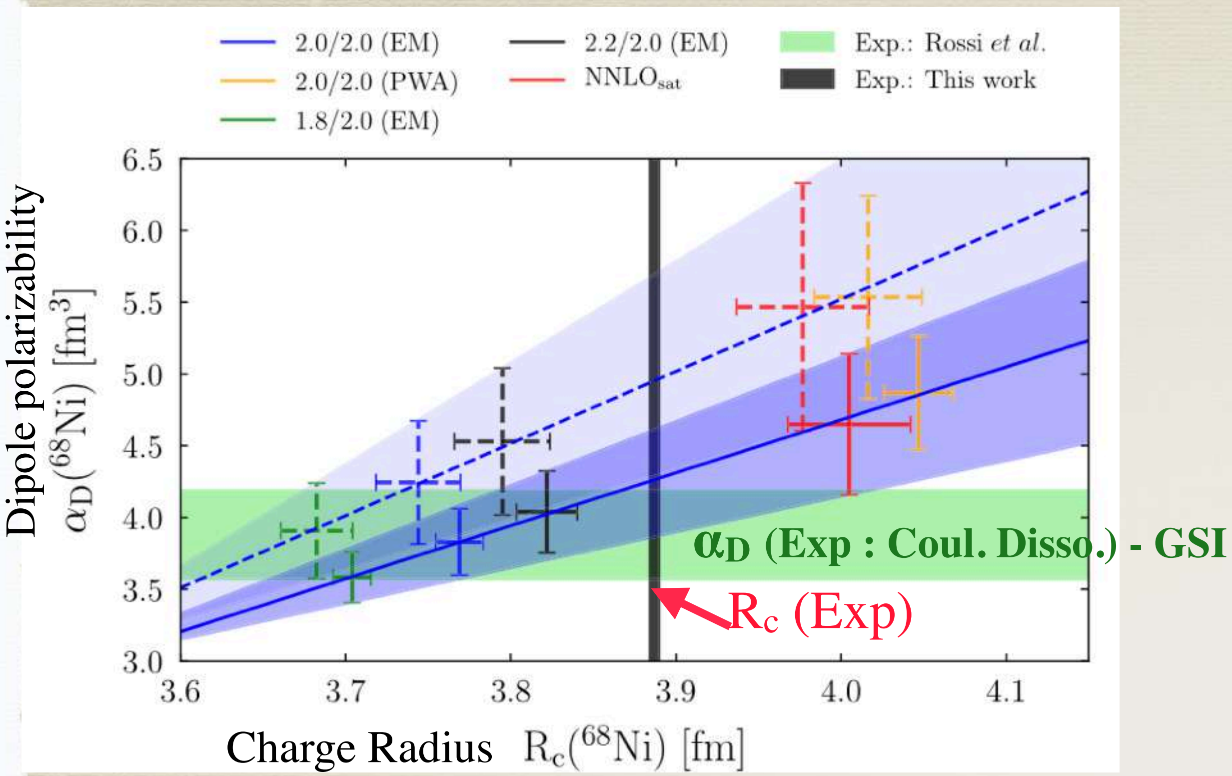


Low-energy dipole resonances (~ 1 -2 MeV above S_n) can enhance neutron capture rates in *r* -process

S. Goriely, '2001

Charge radius ^{68}Ni ($N = 40$) @ ISOLDE - COLLAPS

S. Kaufmann, J. Simonis, S. Bacca *et al*. Phys. Rev. Lett. 124 (2020) 132502



Measured charge radius : challenge for chiral interactions

***Ab initio* calculations show a correlation between dipole polarizability and charge radius. 3p-3h correlation explains α_D & R_c.**

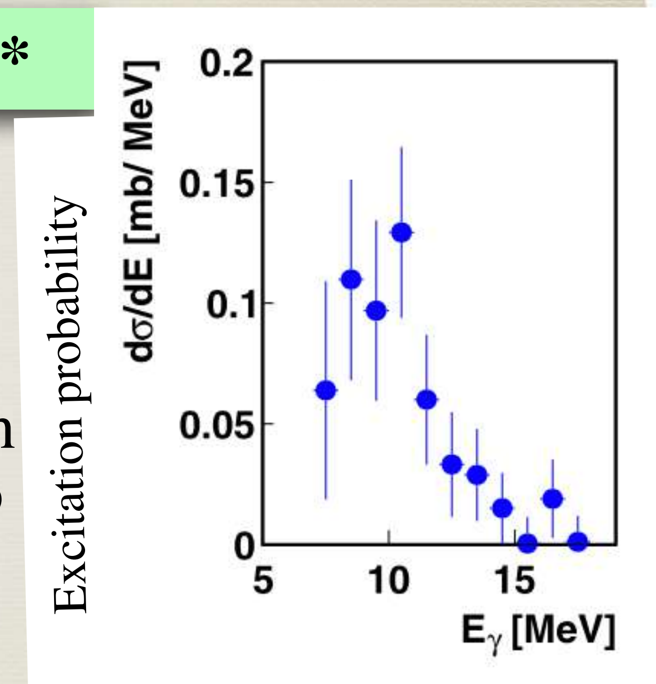
Pygmy dipole ^{68}Ni @ INFN - LNS

N.S. Martorana, G. Cardella, E.G. Lanza *et al*. Phys. Lett. B 782 (2018) 112

^{68}Ni + ^{12}C —> ^{68}Ni*

Isoscalar pygmy dipole ~ 10 MeV.

Consistent energy with Coulomb excitation @ GSI - LAND



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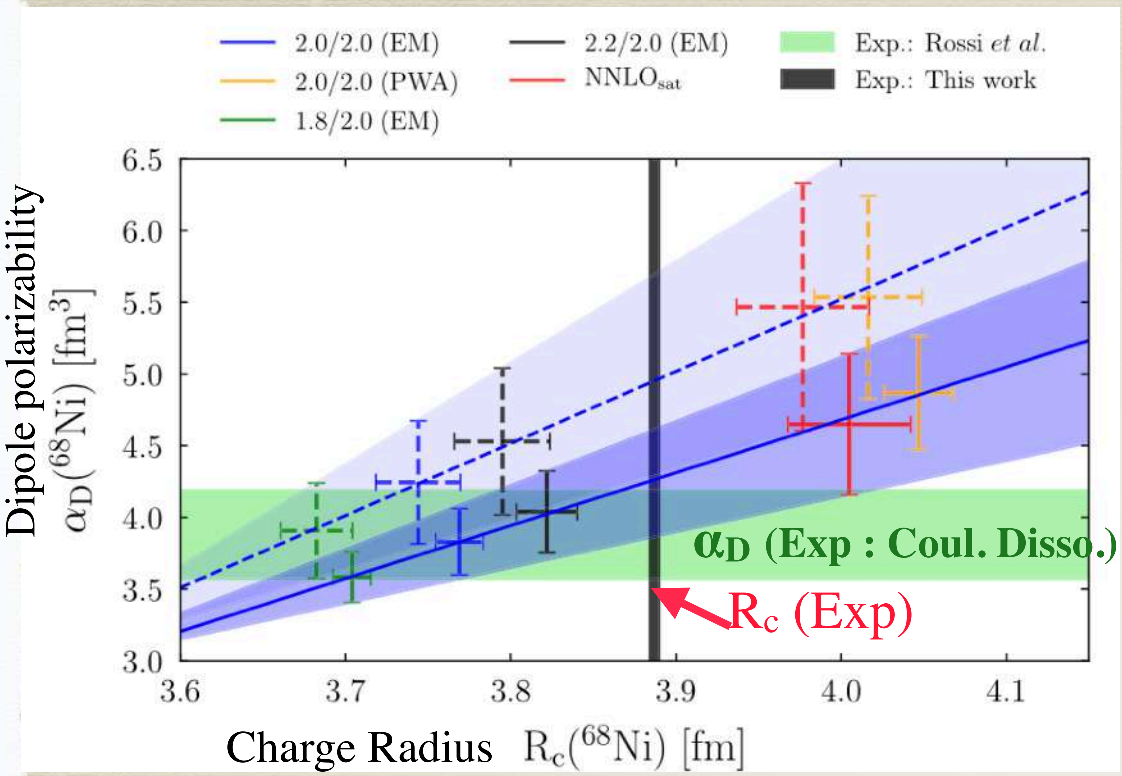
S. Kaufmann, J. Simonis, S. Bacca *et al*. Phys. Rev. Lett. 124 (2020) 132502



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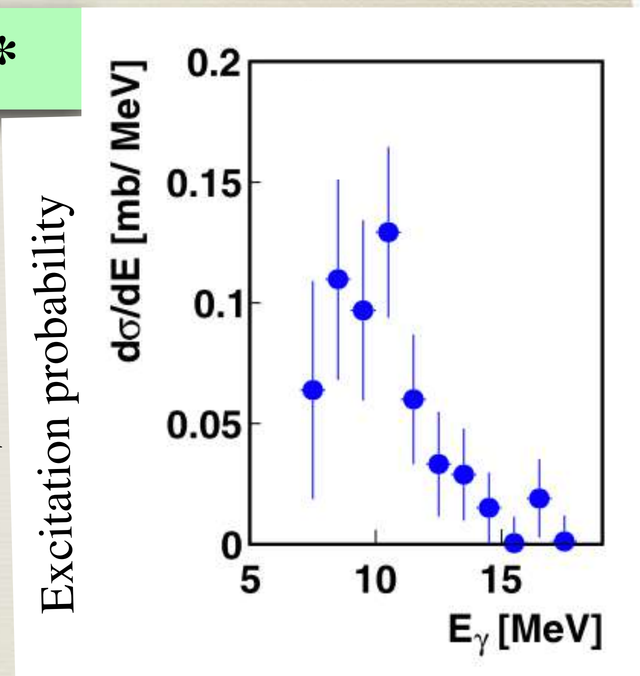


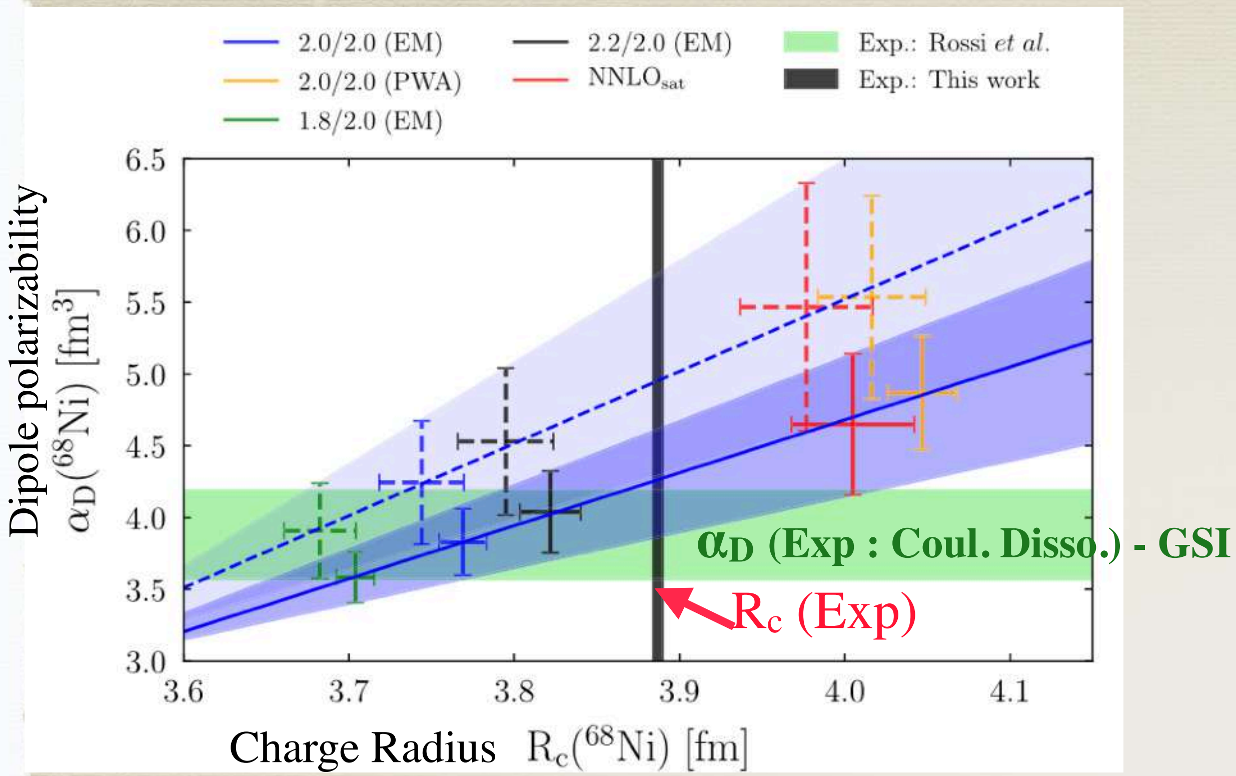
Dipole Strength ^{62,64}Fe ($N = 36,38$) @ GSI - AGATA

R. Avigo, O. Wieland, A. Bracco *et al*. Phys. Lett. B 811 (2020) 135951

E1 strength at high Eγ increases with increasing neutron number and has complex 3p-3h structure

Charge radius ^{68}Ni ($N = 40$) @ ISOLDE - COLLAPS

S. Kaufmann, J. Simonis, S. Bacca *et al*. Phys. Rev. Lett. 124 (2020) 132502



Measured charge radius : challenge for chiral interactions

***Ab initio* calculations show a correlation between dipole polarizability and charge radius. 3p-3h correlation explains α_D & R_c.**

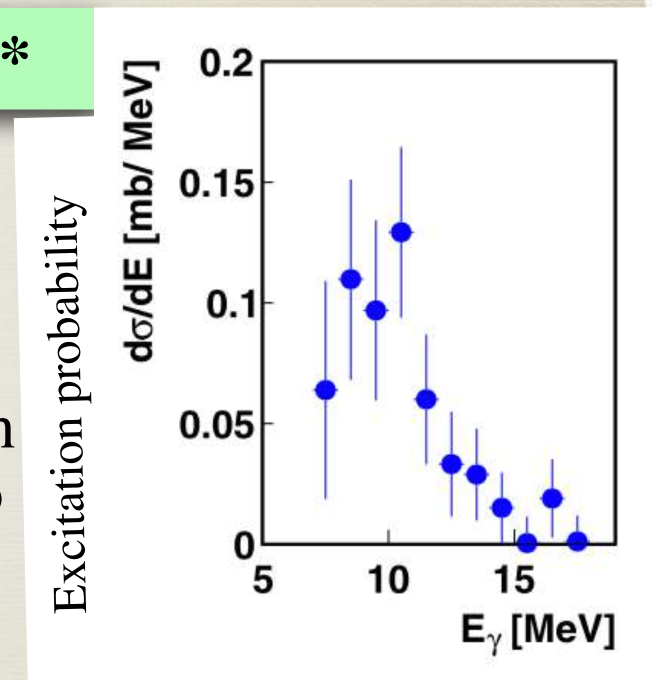
Pygmy dipole ^{68}Ni @ INFN - LNS

N.S. Martorana, G. Cardella, E.G. Lanza *et al*. Phys. Lett. B 782 (2018) 112

^{68}Ni + ^{12}C —> ^{68}Ni*

Isoscalar pygmy dipole ~ 10 MeV.

Consistent energy with Coulomb excitation @ GSI - LAND



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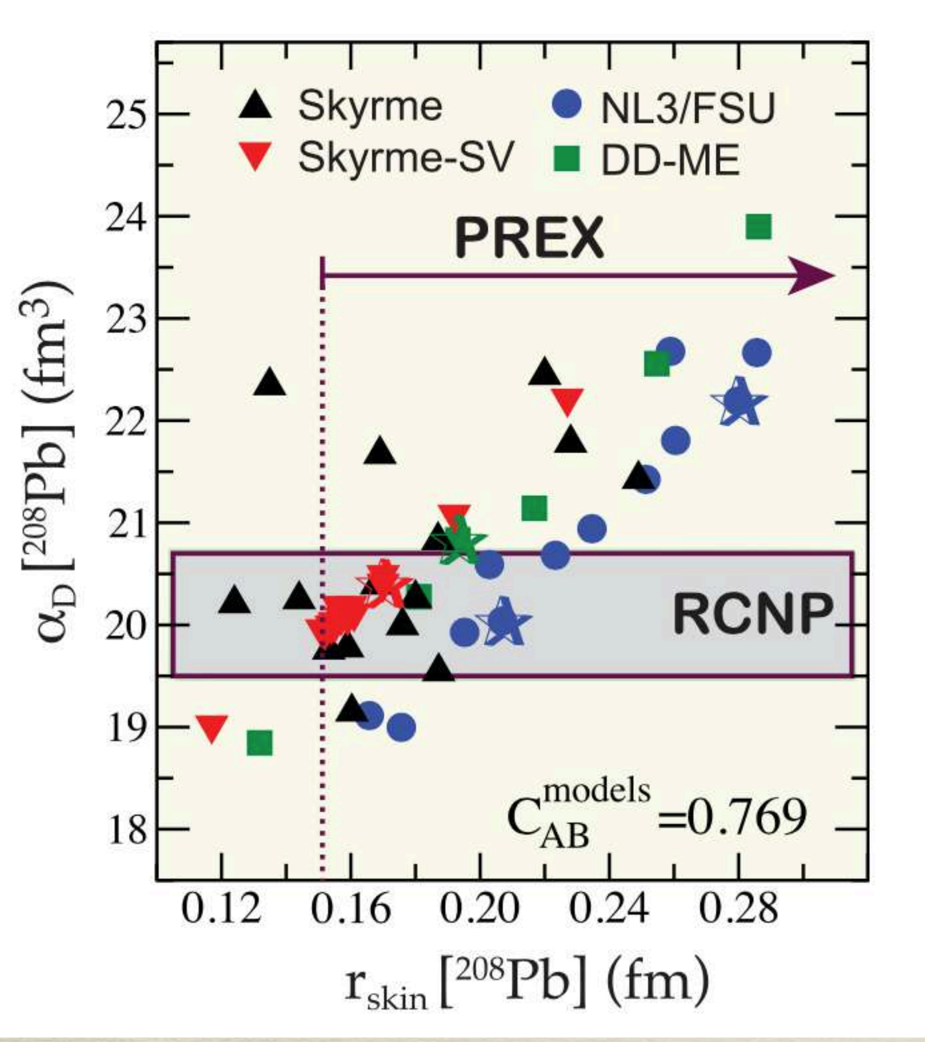
Low-energy dipole resonances in neutron-rich heavy nuclei yet to be found

Dipole polarizability & neutron skin

Dipole polarizability (α_D)

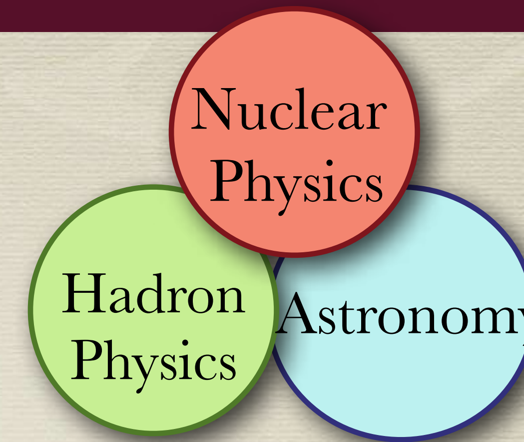
$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}}{E_x^2} dE_x = \frac{8\pi}{9} \int \frac{B(E1)}{E_x} dE_x$$



J. Piekarewicz (2012)

Neutron skin : bridge from neutron-rich nuclei to neutron stars

Equation of state of asymmetric nuclear matter



PREX, CREX

NICER

$$e(\rho,\delta) = e(\rho,0) + c_{\rm sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) \qquad \delta = \frac{\rho_n - \rho_p}{\rho}$$

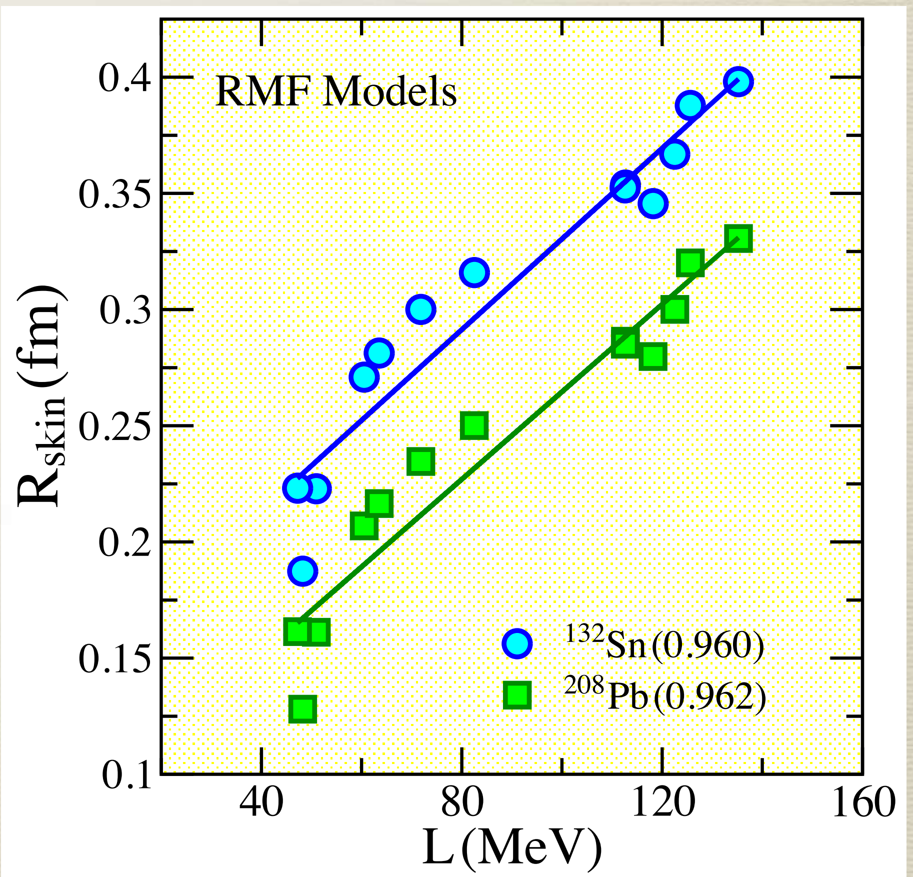
e = energy per particle

Symmetry Energy is poorly constrained

$$c_{\rm sym}(\rho) = J - L\epsilon + \tfrac{1}{2}K_{\rm sym}\epsilon^2 + \mathcal{O}(\epsilon^3) \qquad \epsilon = (\rho_0 - \rho)/(3\rho_0)$$

$$L = 3\rho\,\partial c_{\rm sym}(\rho)/\partial\rho|_{\rho_0}$$

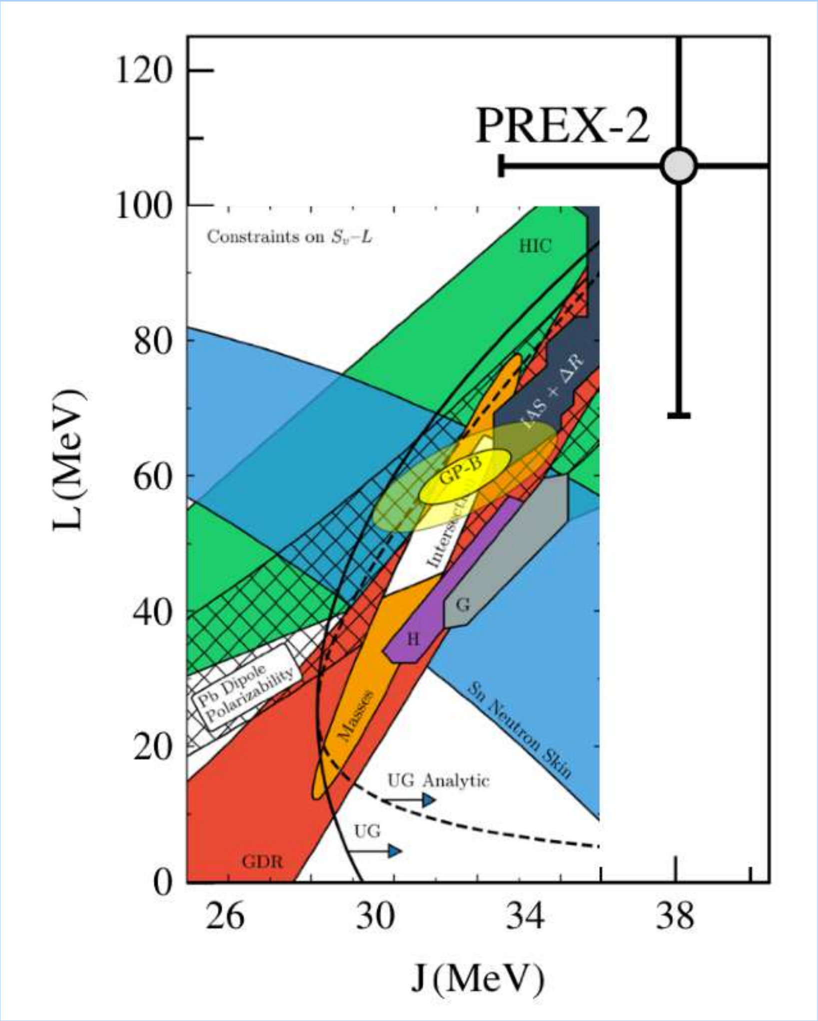
Neutron skin is strongly correlated with *L*



J. Piekarewicz

Neutron skin (PREX & CREX @ JLab) : Symmetry energy

Parity violating electron scattering



Reed et al., PRL (2021)

PREX value of neutron skin of 208Pb is higher than other measurements

↓

Higher value of *L* - Stiffer EOS

D. Adhikari *et al*., Phys. Rev. Lett. 126 (2021) 172502

Neutron skin (PREX & CREX @ JLab) : Symmetry energy

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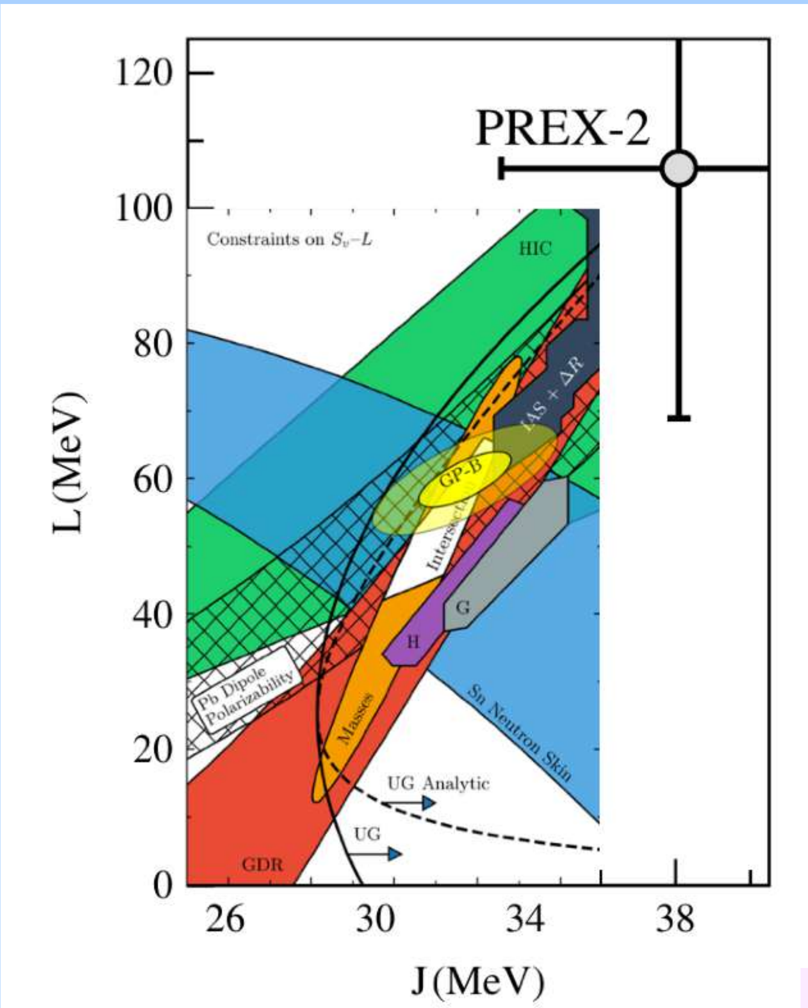

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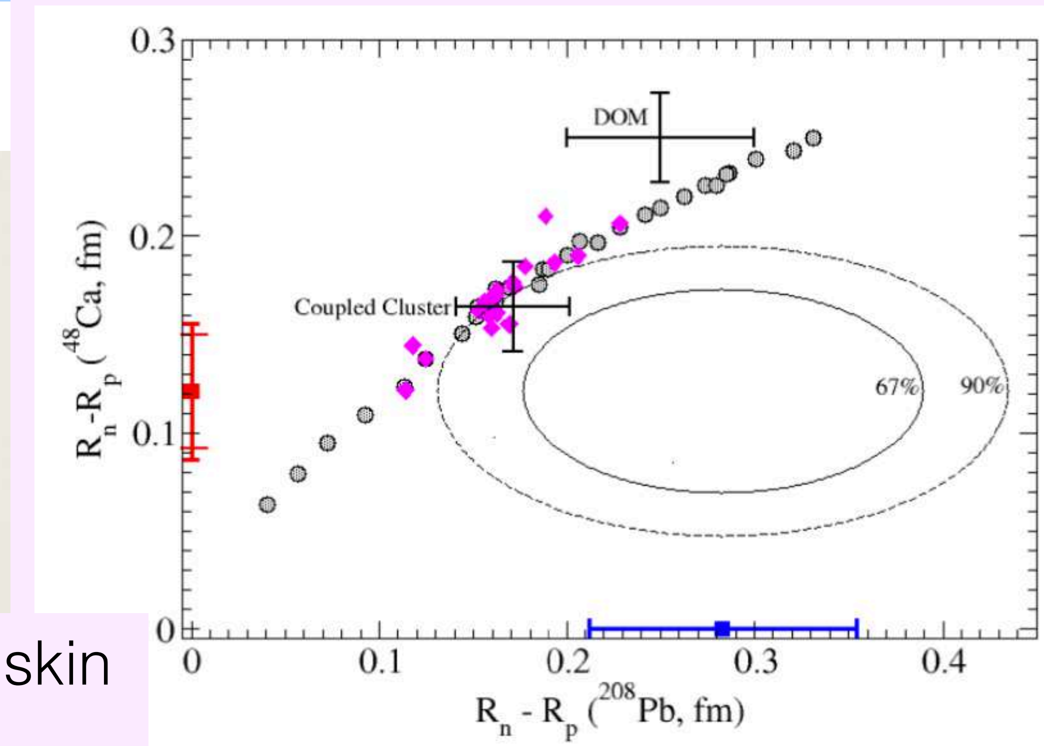


D. Adhikari *et al*., arXiv:2205.11593v1

CREX finds thin neutron skin

↓

Lower value of *L*

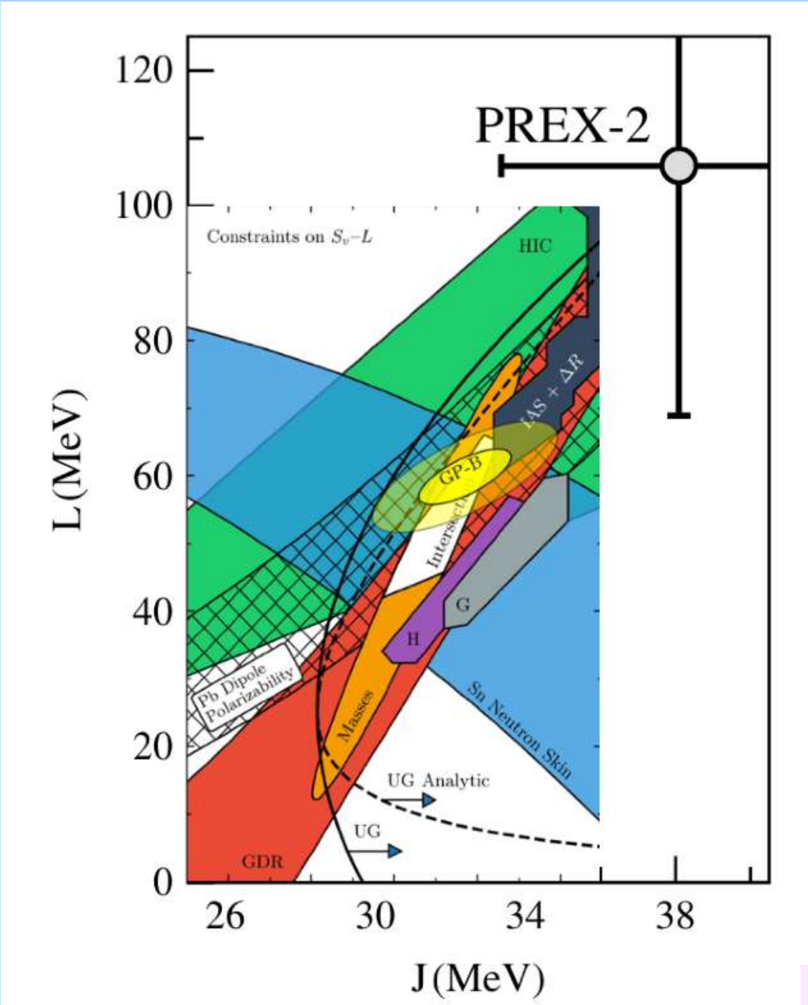
^{48}Ca neutron skin

Dipole Polarizability
Reaction Cross Section
CREX

} Agree

Neutron skin (PREX & CREX @ JLab) : Symmetry energy

Parity violating electron scattering



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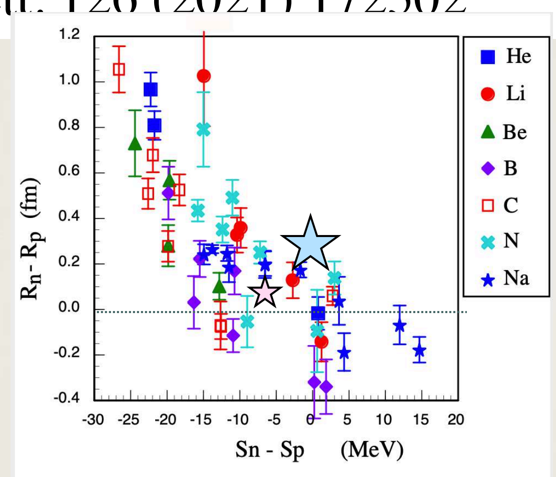
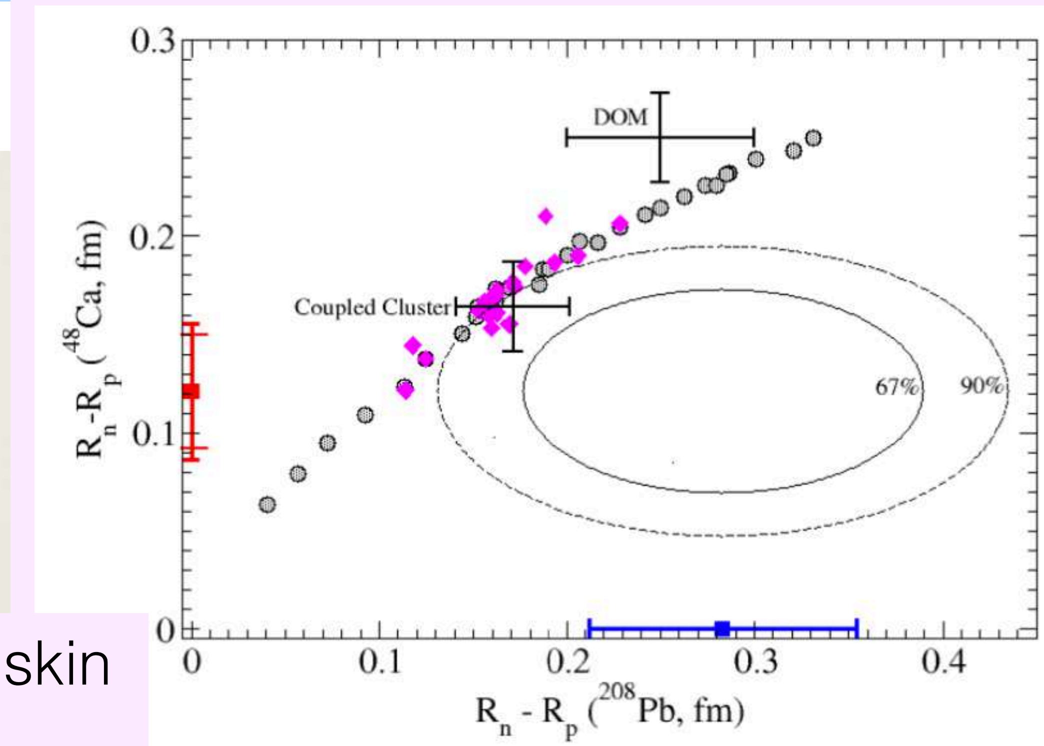
D. Adhikari *et al*., Phys. Rev. Lett. 126 (2021) 172502





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Dipole Polarizability
Reaction Cross Section
CREX
} Agree

Rare isotopes with thicker skins will be more sensitive constraints on 'L'

Heavy Ion Collision : Symmetry energy

@ RIKEN - SAMURAI (SπRIT TPC)

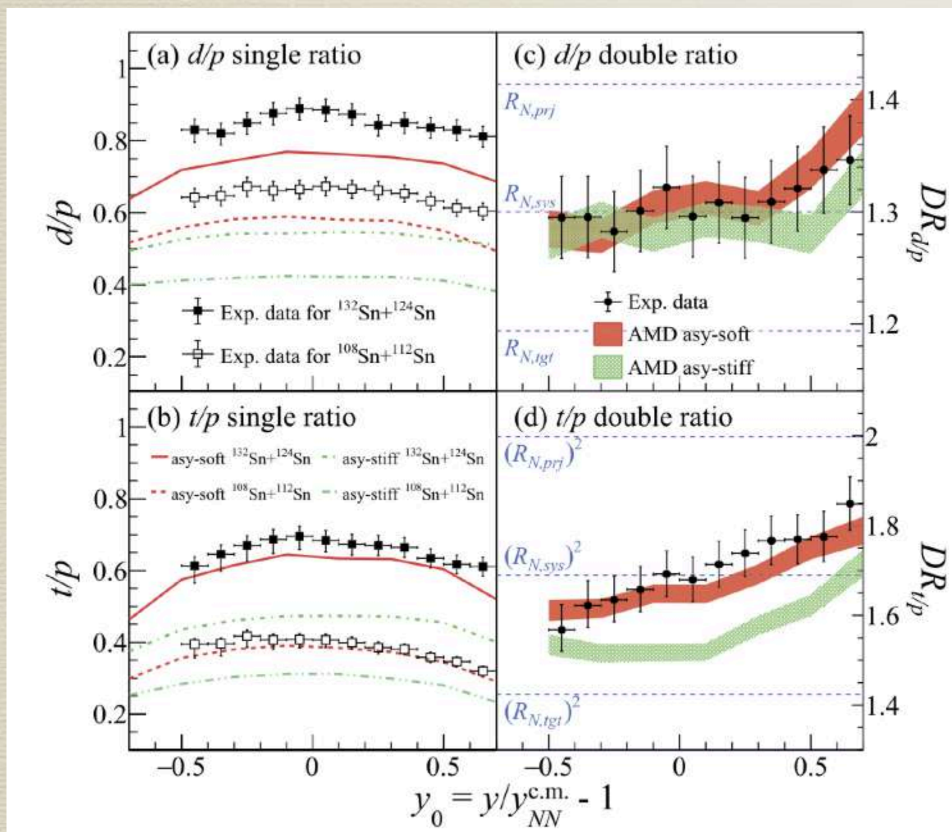
Symmetry energy constraint at supra-saturation density

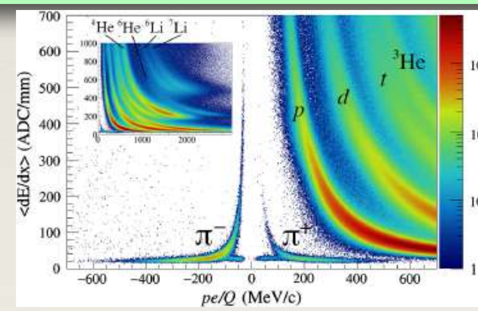
M. Kaneko et al., Phys. Lett. B. 822 (2021) 136681

G. Jhang et al., Phys. Lett. B. 813 (2021) 136016

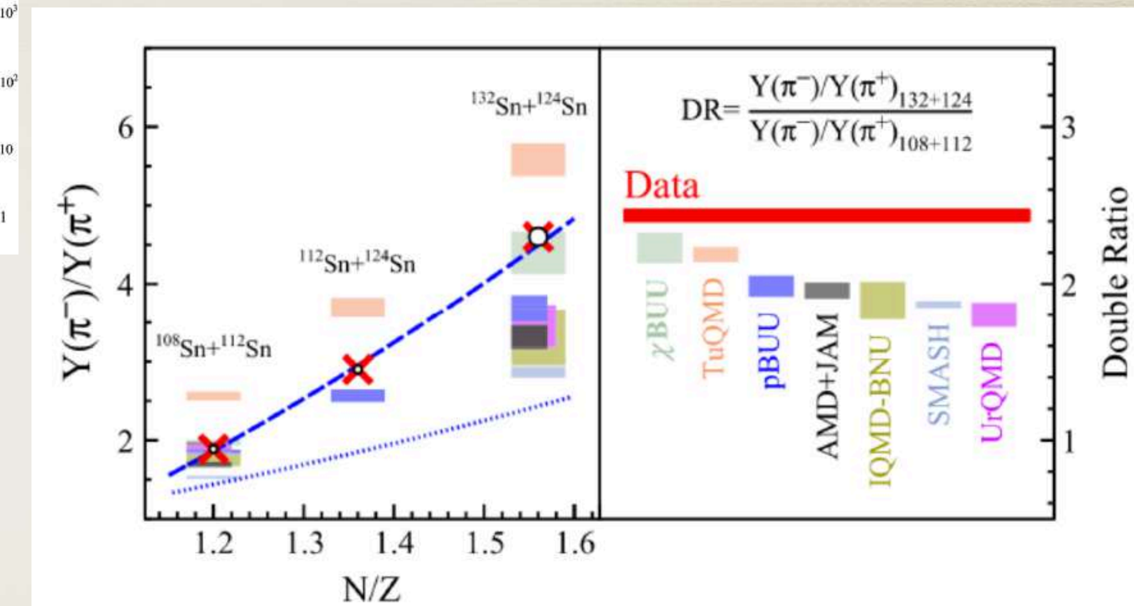
^{132}Sn + ^{124}Sn & ^{108}Sn + ^{112}Sn

p, d, t





π^+, π^-



Small variation in predicted ratio for large (stiff) and small (soft) values of *L*.

$$DR_{d/p} = \frac{d/p\left({}^{132}\mathrm{Sn}+{}^{124}\mathrm{Sn}\right)}{d/p\left({}^{108}\mathrm{Sn}+{}^{112}\mathrm{Sn}\right)}, \quad DR_{t/p} = \frac{t/p\left({}^{132}\mathrm{Sn}+{}^{124}\mathrm{Sn}\right)}{t/p\left({}^{108}\mathrm{Sn}+{}^{112}\mathrm{Sn}\right)}$$

Measured Double Ratio *t/p* agrees with AMD predictions of soft EOS (*L* ~ 46 MeV)

The differences of transport models make it difficult to place a constraint on *L*.

Summary & Outlook

Rare Isotopes are enabling to unveil the unknown fundamentals of visible matter in the Universe

❖ Exotic forms of nuclei - unique quantum systems emerge far from the valley of stability

- Do nuclear halos occur in heavy nuclei?
- What new features of nucleon-nucleon pairing correlation emerge in neutron-rich nuclei?
- What new phenomena surface with nuclear halo & skin?
- Electron - RI Scattering

❖ Nuclear shells are mutating

- How do nuclear change in heavy nuclei?
- What is their influence on heavy element synthesis?
- What features of the nuclear force drive the shell evolution?

❖ Neutron rich nuclei bring laboratory access to study behaviour of neutron-rich matter (EOS)

- Connecting neutron skin driven effects to constrain EOS of asymmetric nuclear matter

❖ Constraining the nuclear force - defining from first principles : Excited States and Radii

- Dynamical reaction probes

❖ Search for new physics - fundamental symmetries in nature (not covered)

- Radioactive Molecules as probes of symmetry violation
- Electric Dipole Moment measurements (Ra, Rn)
- Beta - neutrino correlation
- Unitarity of the CKM matrix element

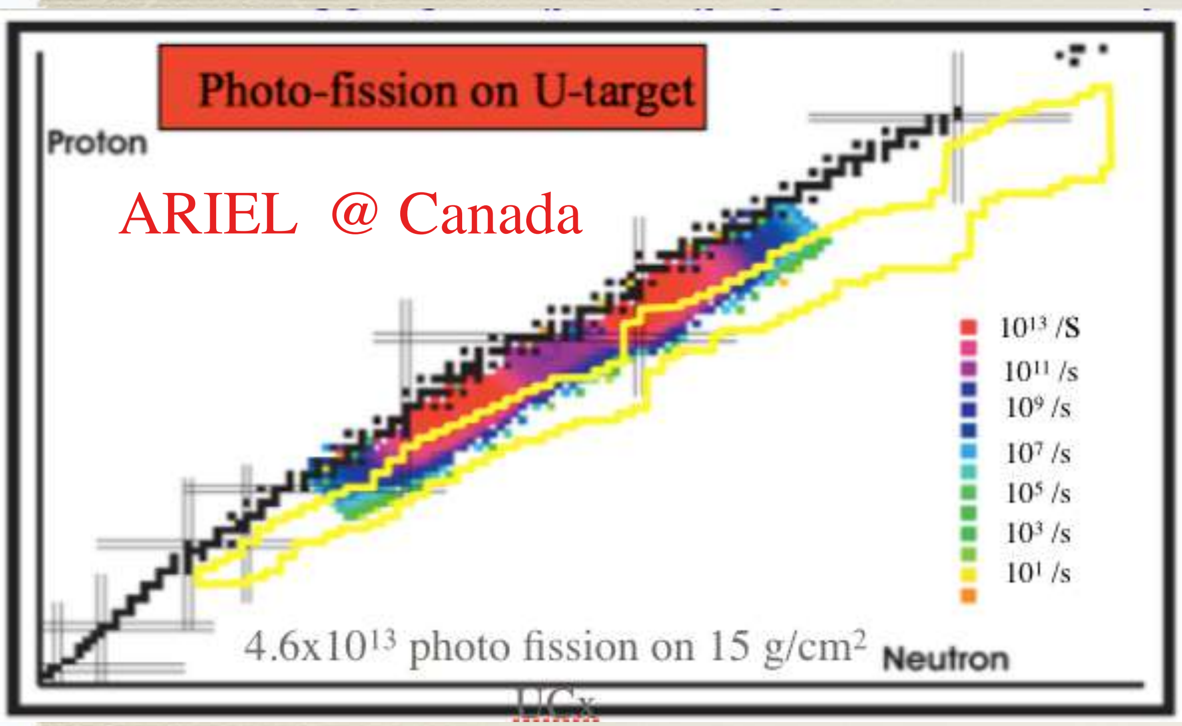
❖ Rare strange matter : RI Hypernuclei (not covered)

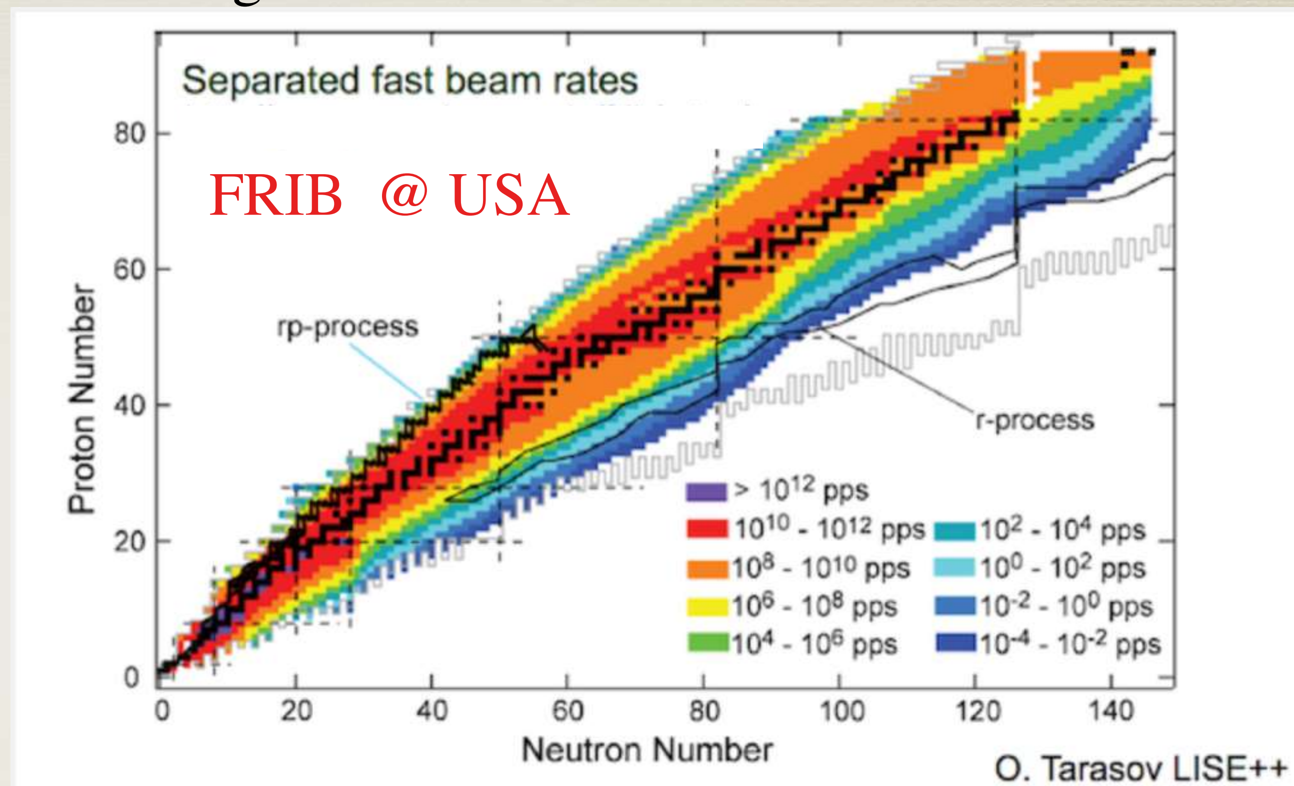
Summary & Outlook

An era of new discoveries awaits in the horizon

New generation facilities bring access to rare isotopes in colliding stars

ISOL *North America* In-flight





- Masses & Half-lives
- Decay spectroscopy
- Charged particle spectroscopy - shell structure
- Safe Coulex - shell structure
- Direct capture

- New isotope search
- Masses, Half-lives, Radii, Decay & In-beam γ spectroscop
- Knockout, Coulomb Disso. - shell structure
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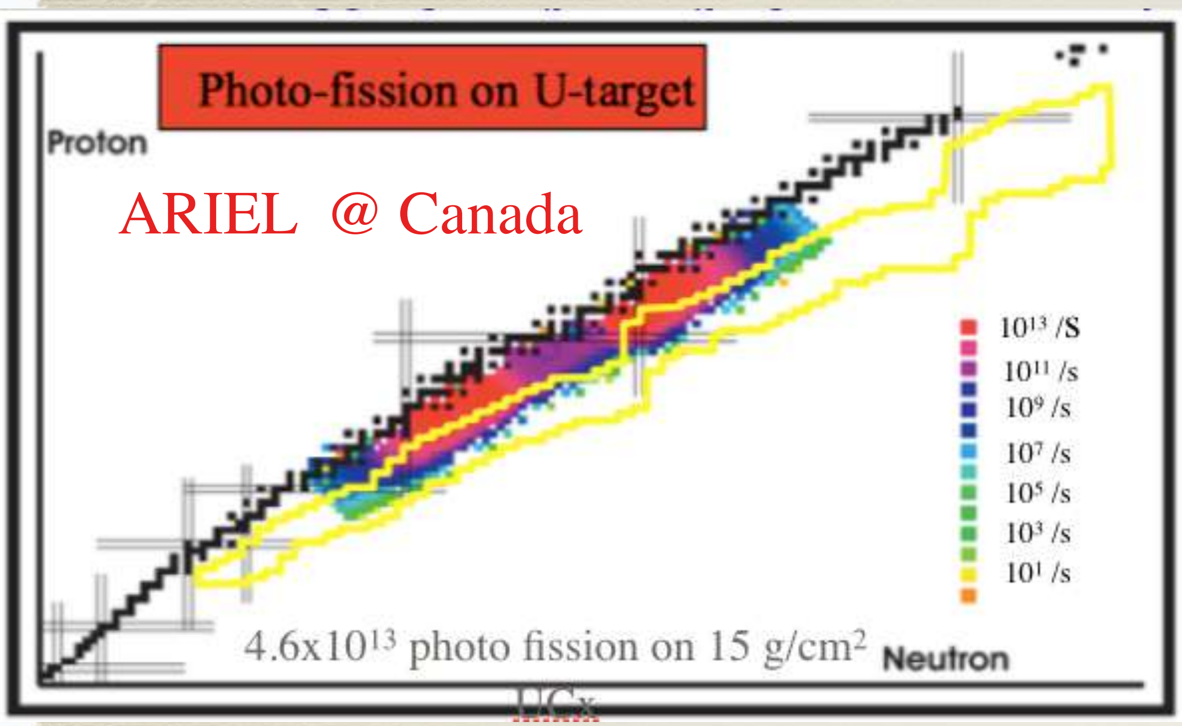

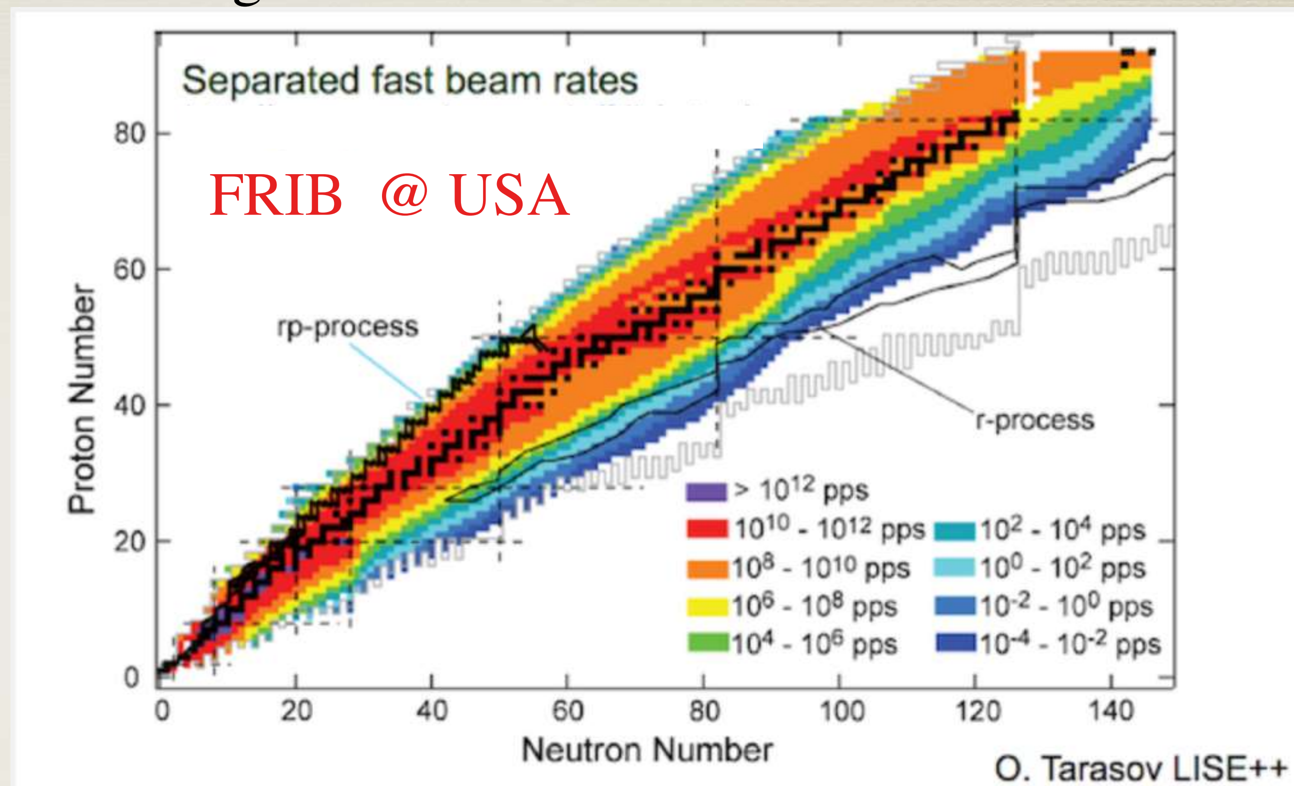

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Thanks : RI Beam Facilities and the funding agencies for enabling the discoveries.

P. Roussel-Chomaz, T. Dickel, P. Doornenbal, G. Neyens, H. Sakurai, C. Scheidenberger

Thank you for your attention