中性子過剰原子核の存在限界とその新しい原理
~核力に基づく大規模計算による解析

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素粒子・原子核・宇宙「京からポスト京に向けて」
シンポジウム
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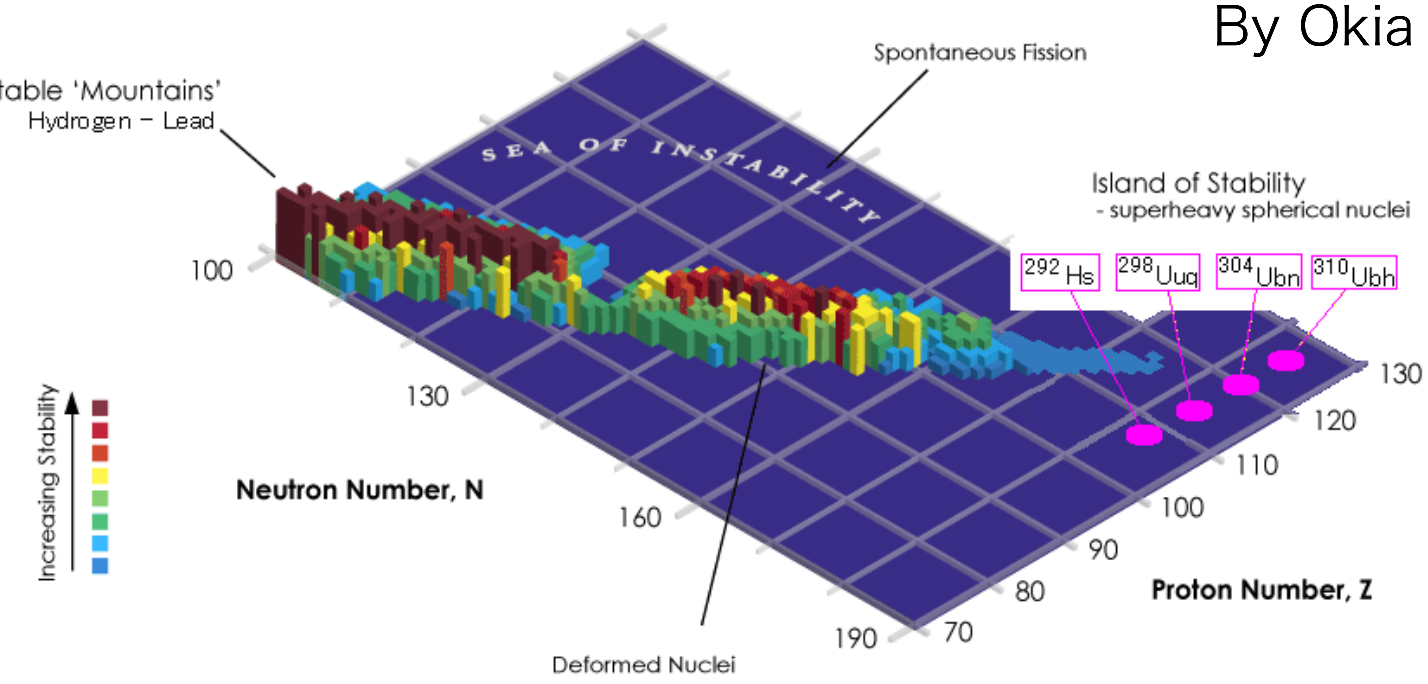
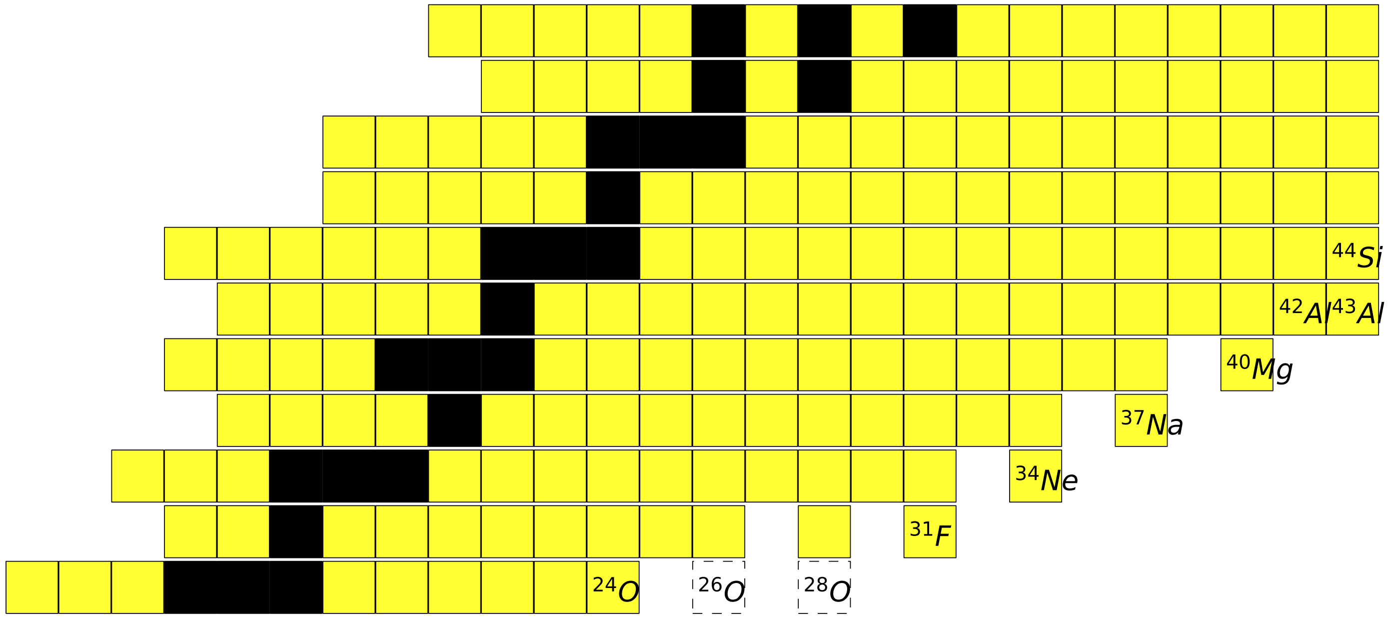
物質の存在限界

By Okia (Wikipedia)

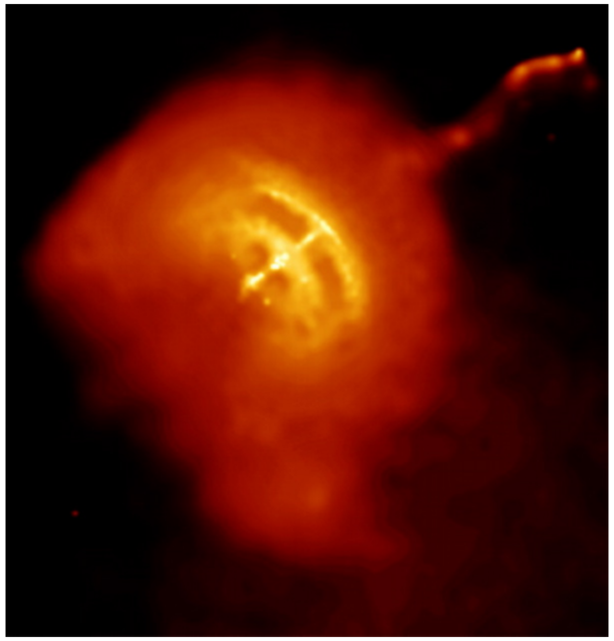
安定の島



原子核のドリップライン

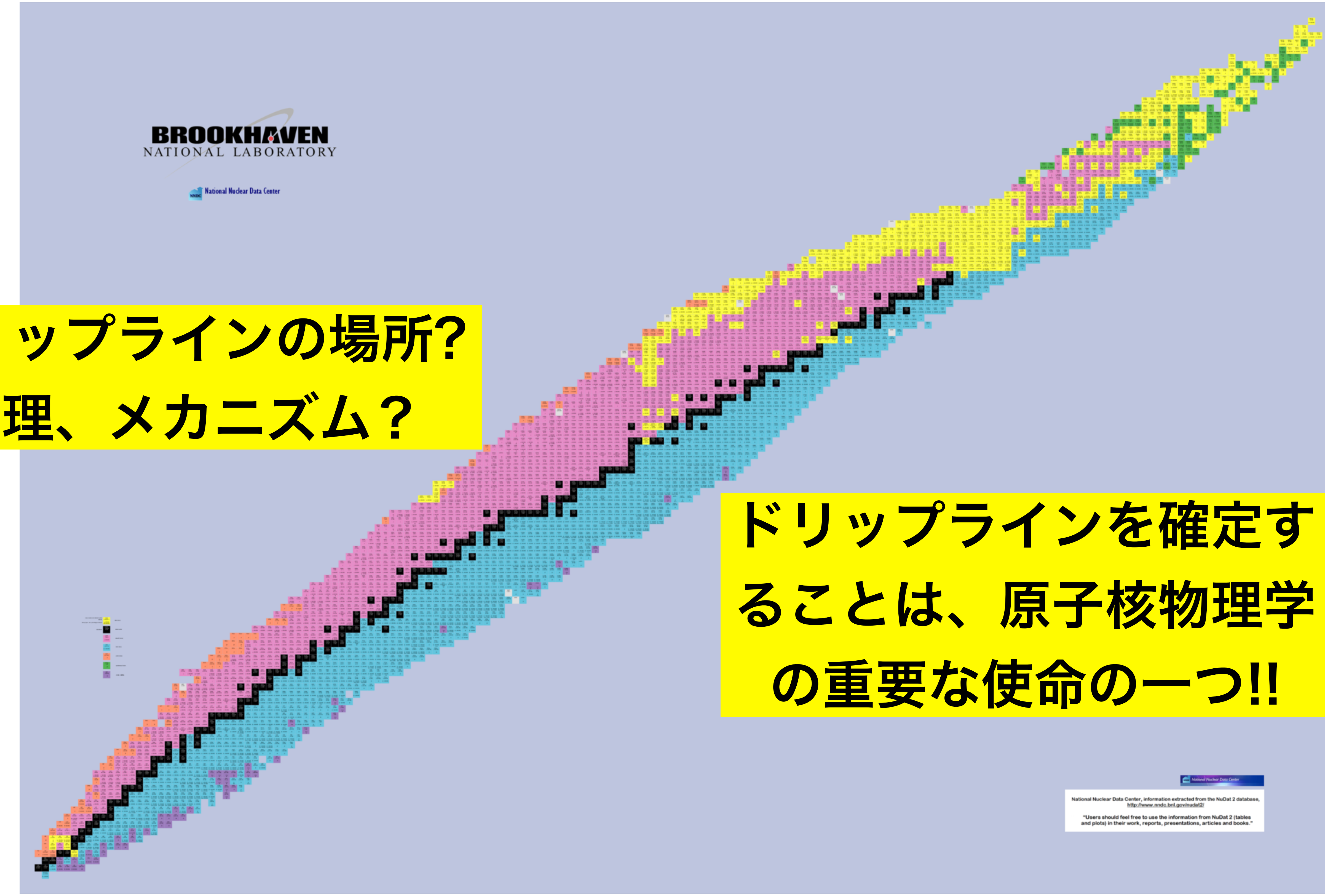


中性子星



By NASA/CXC/PSU/G.Pavlov et al.

物質の存在限界

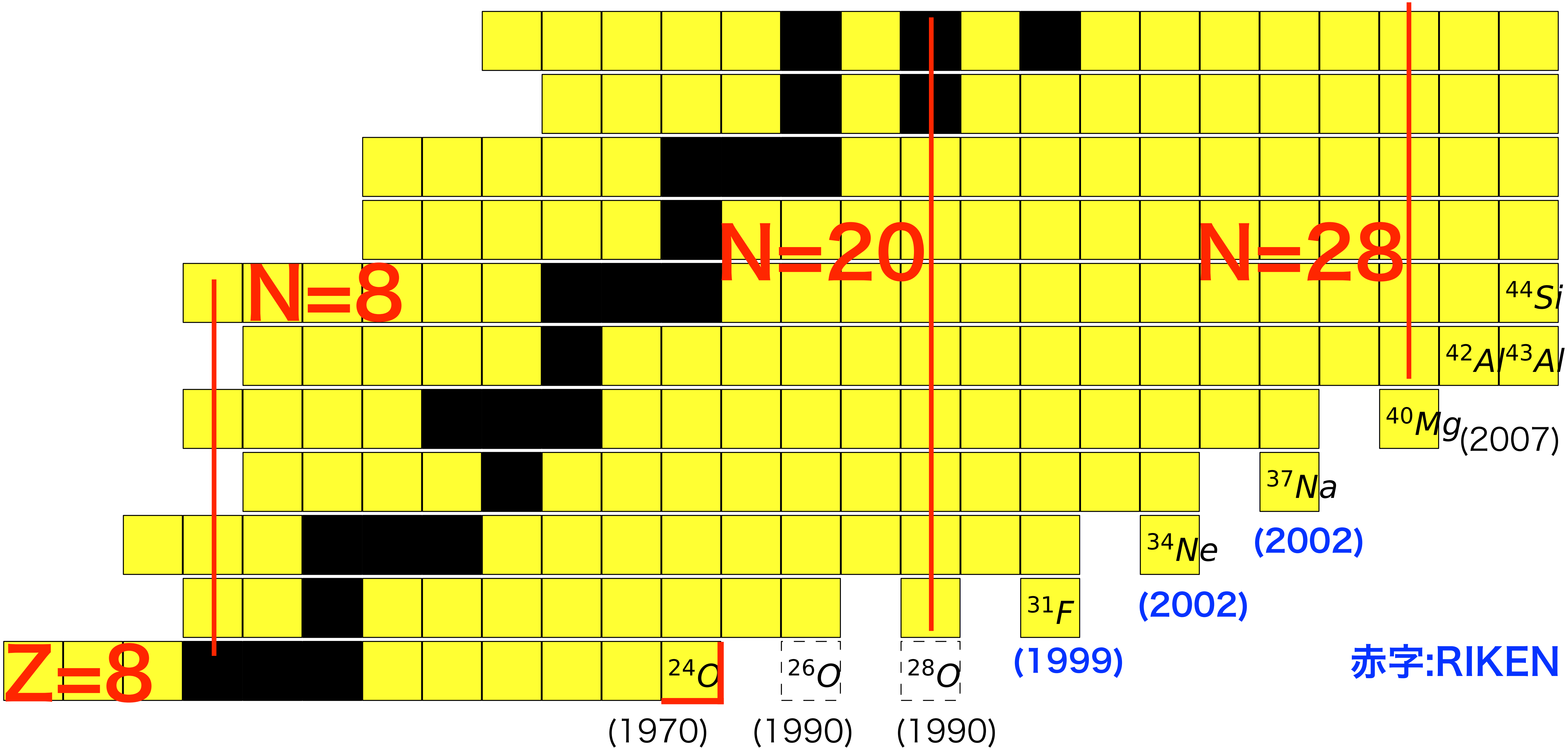


ドリップラインの場所?
原理、メカニズム？

ドリップラインを確定することは、原子核物理学の重要な使命の一つ!!

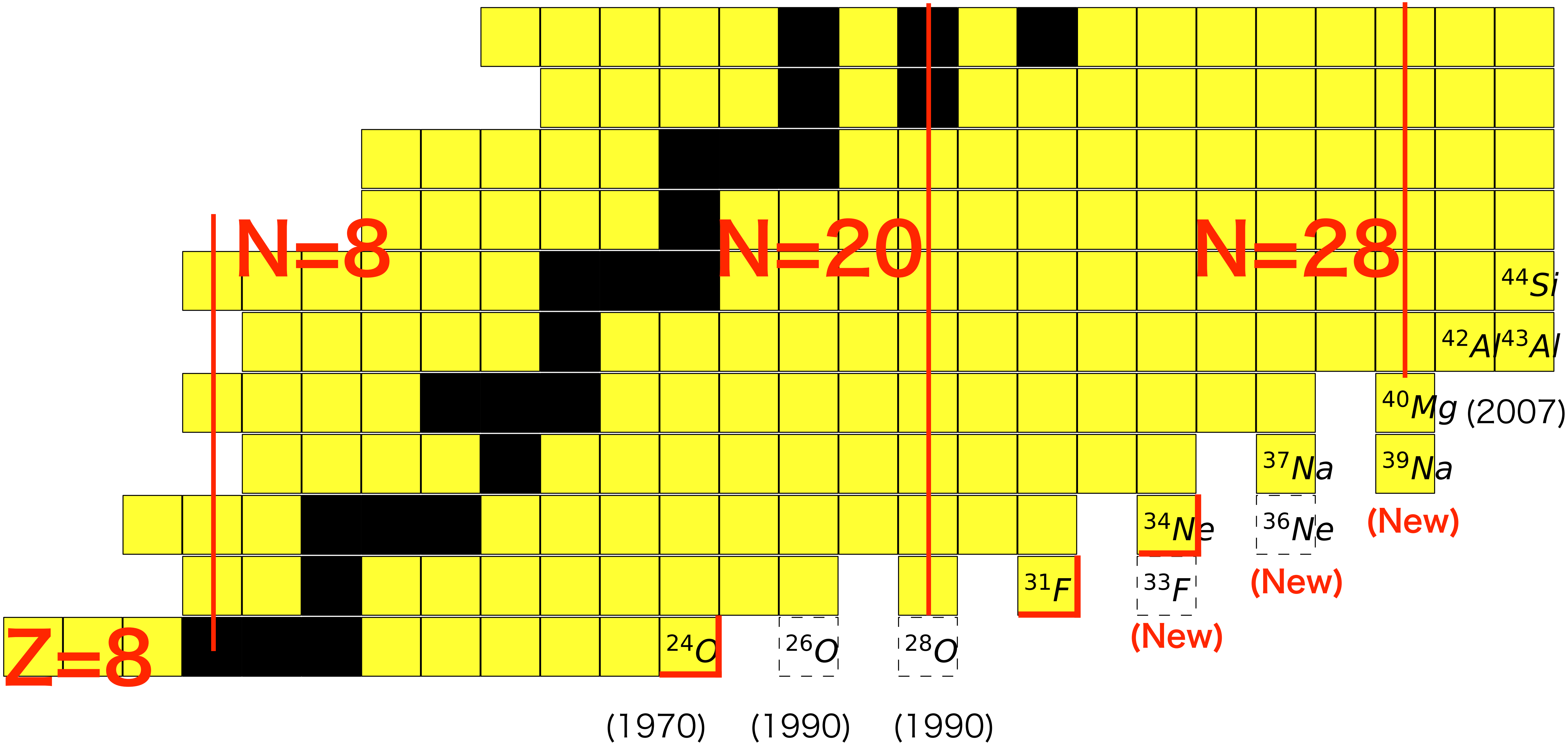
By The viewer - National Nuclear Data Center

加速器実験で測れるドリップライン (少し前)



- ドリップラインが確定ているのはOまで(軽い核のみ)
- F 以降はこの時点でまだ不明

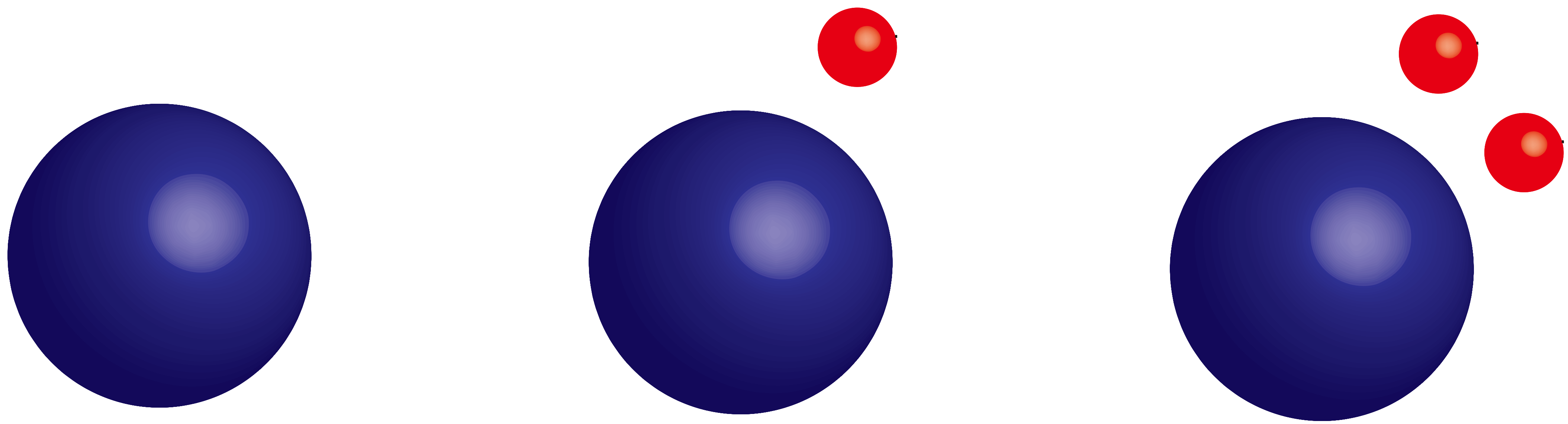
加速器実験で測れるドリップライン (現在)



- F/Ne のドリップラインが確定 (^{31}F, ^{34}Ne)
- ^{39}Na の存在を確認 (ドリップラインはまだ不明)
- Mg 以降は次世代の実験
- Mechanism?

中性子ドリップライン

E(Z, N) : 結合エネルギー



E(Z, N)　　E(Z, N+1)　　E(Z, N+2)

E(Z, N) < E(Z, N+1,2) => (Z, N+1,2) は **bound**

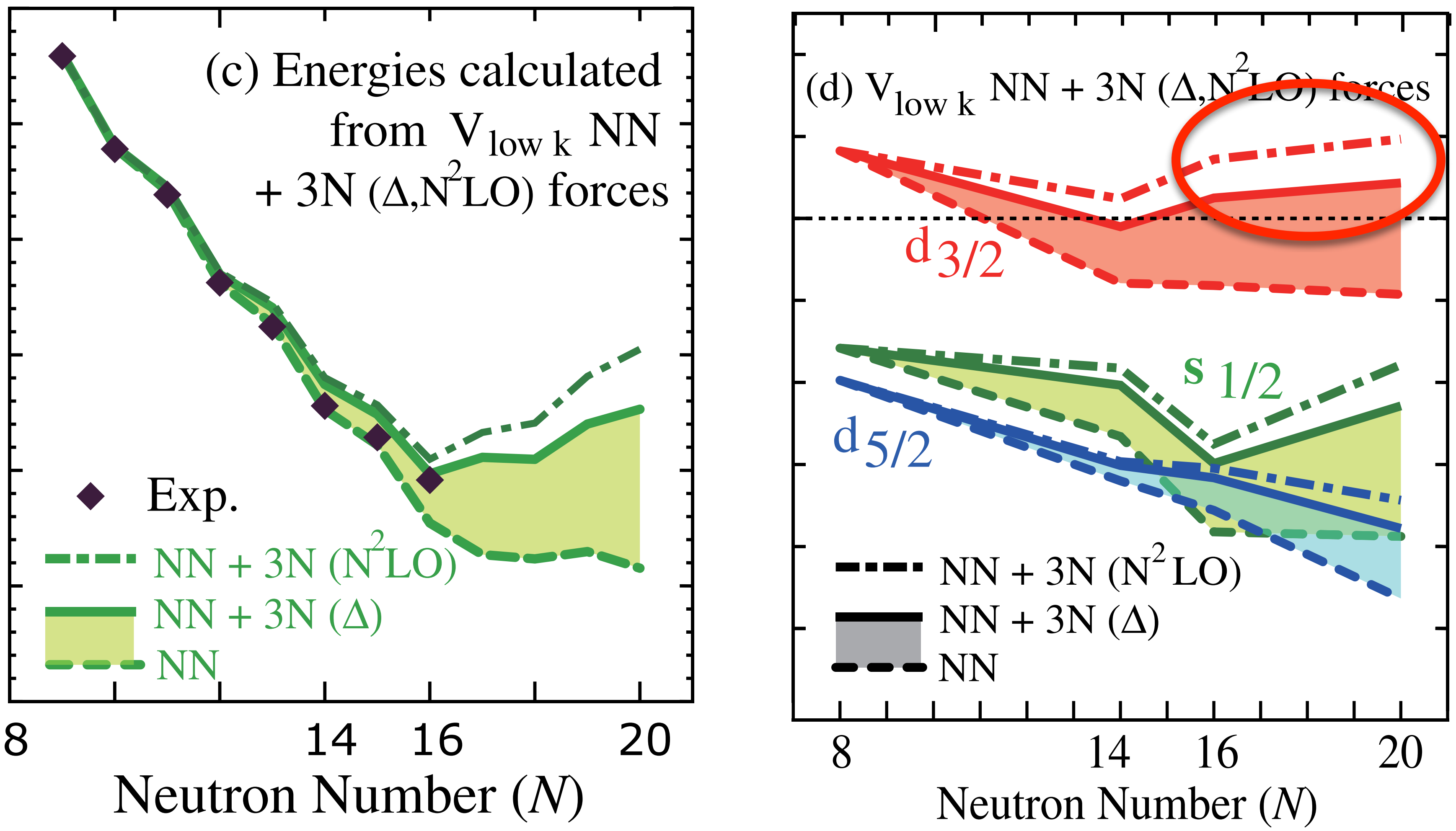
E(Z, N) > E(Z, N+1,2) => (Z, N+1,2) は **unbound**

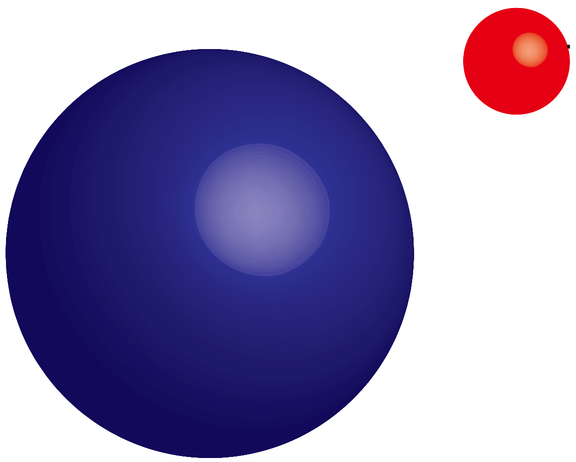
1つ、または2つ粒子を足した時、結合エネルギーを稼げるか?

一般的な中性子ドリップラインの説明

Oxygen(Z=8) case

T. Otsuka et al., Phys. Rev. Lett. 105, 032501 (2010).

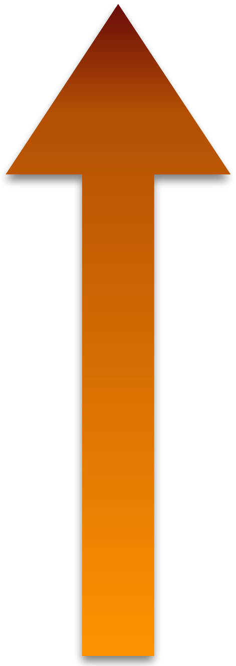




ESPE mostly determines drip line

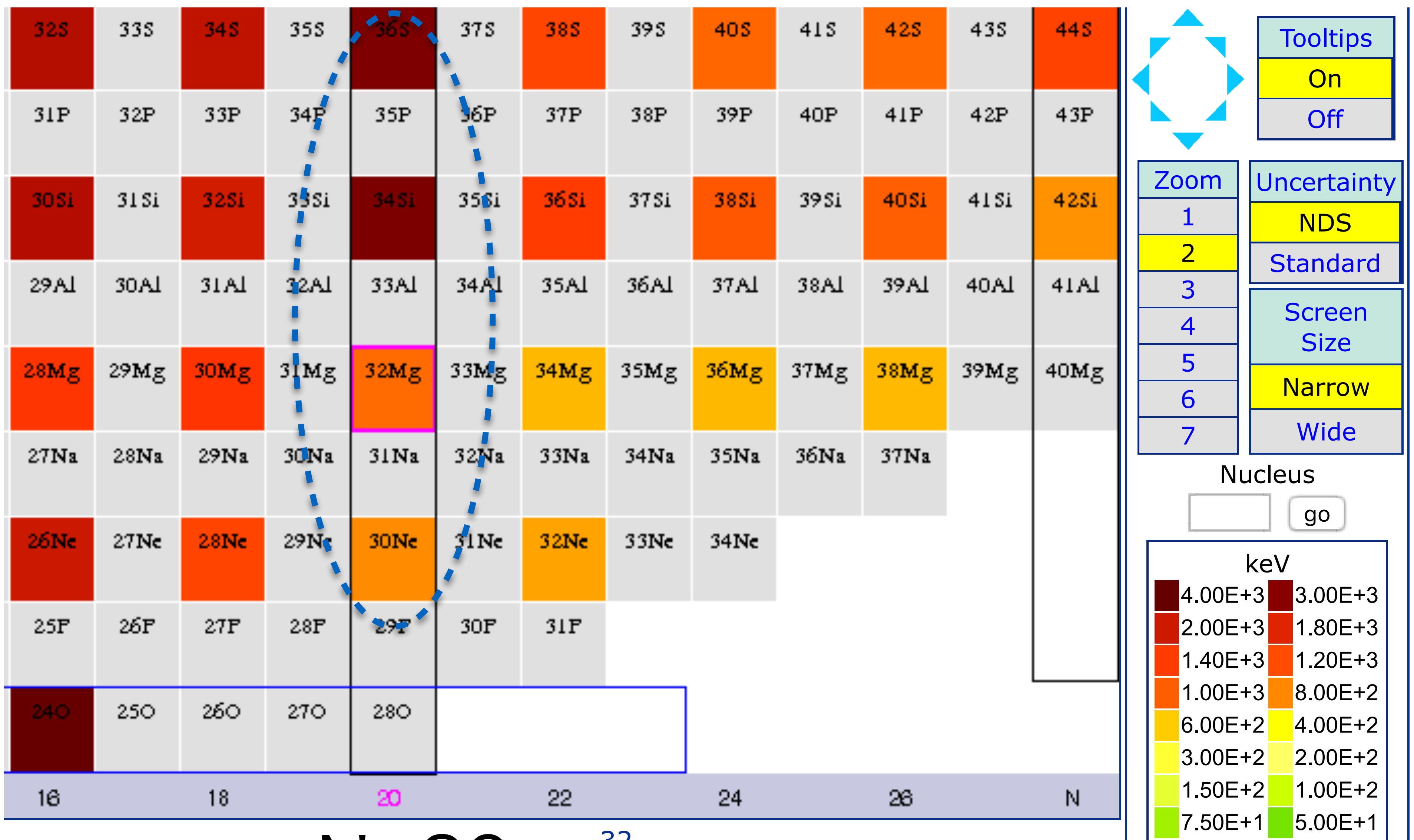
Neutron-rich nuclei~ island of inversion

shell gap



breaking of shell gap

http://www.nndc.bnl.gov/nudat2/reCenter.jsp?z=12&n=20

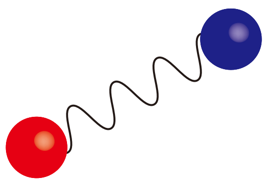


N=20

- E(2+)~1 MeV on N=20 indicate **breaking** of major shell gap
- Unified treatment of beyond and below the N=20 gap is necessary

Original Hamiltonian

$$H = T + \sum_{i,j=1}^{N} V_{NN} + \sum_{i,j,k}^{N} V_{NNN}$$



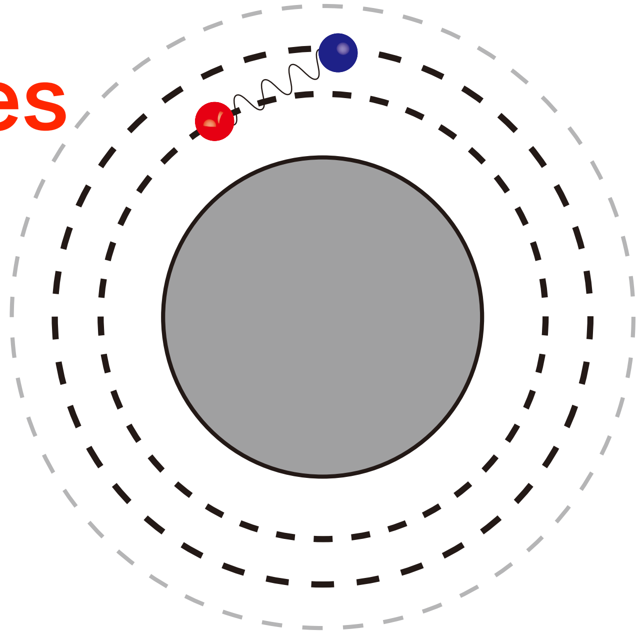
Shell model Hamiltonian

Single particle energies

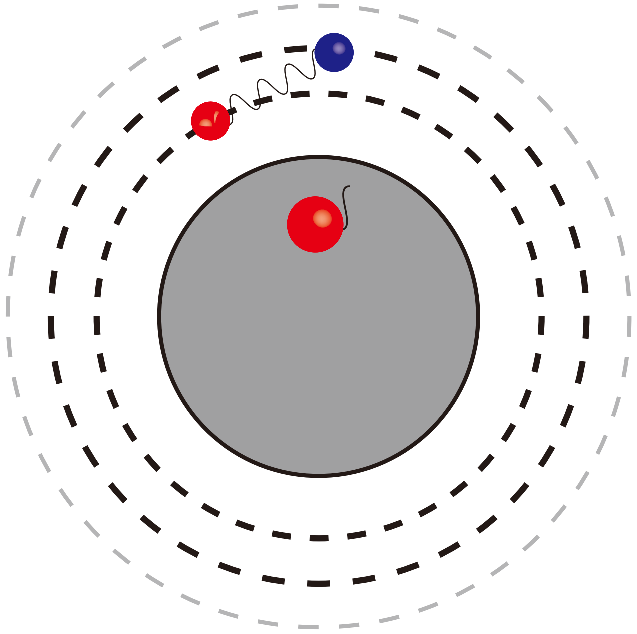
$$H = \sum_{i} \epsilon_i a_i^\dagger a_i + \sum_{ijkl} V_{ij,kl}\, a_i^\dagger a_j^\dagger a_l a_k .$$

Two-body matrix elemetns

NN force

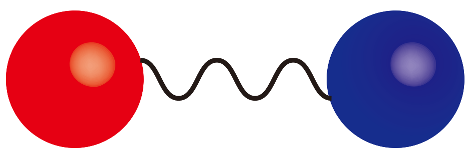


effective NN from 3N

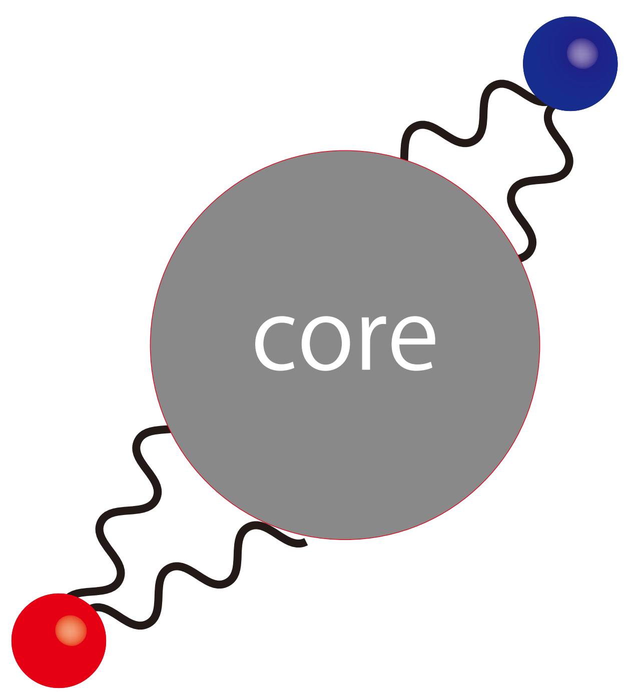


Effective interaction

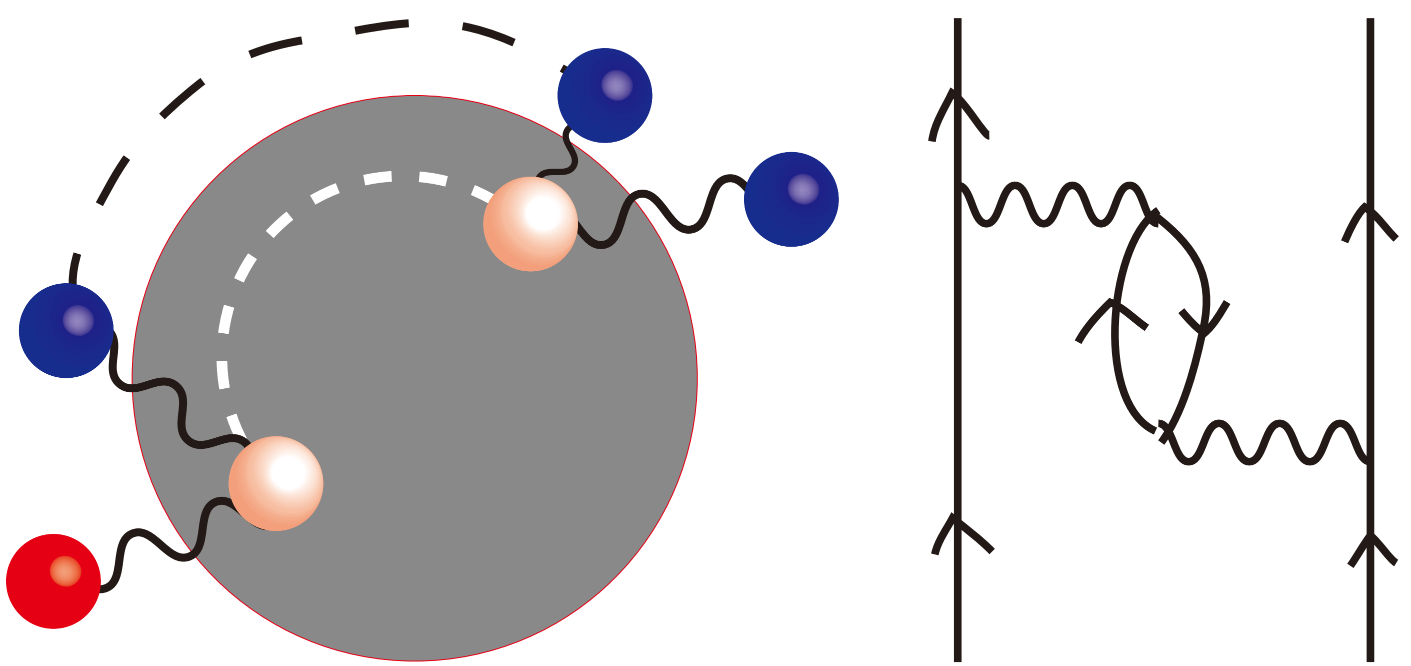
Nuclear force in vacuum



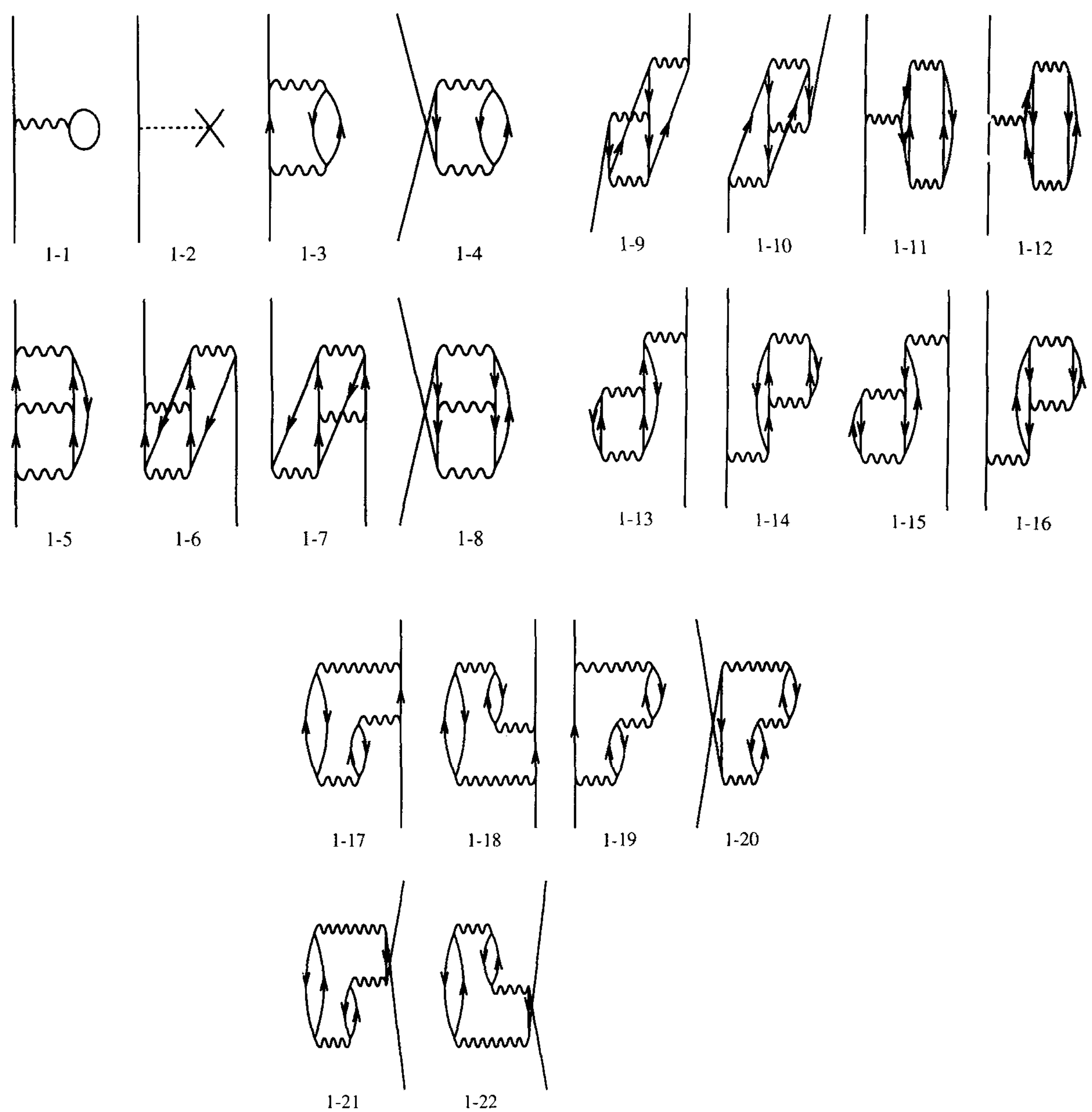
Medium effect

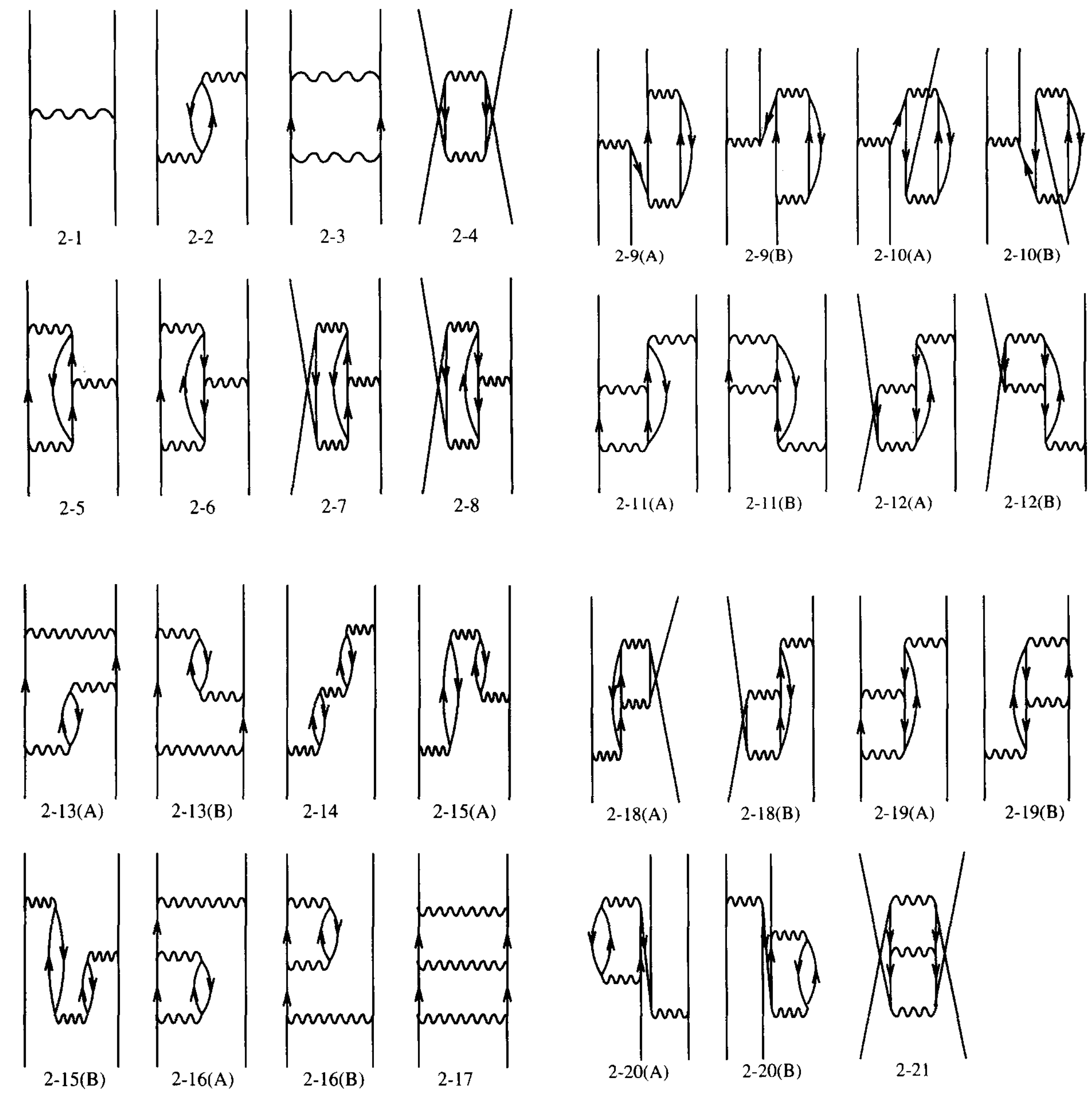


Core polarization (3p1h)



Many-body perturbation theory





Extended KK method and conventional KK method

EKK method

New parameter E (arbitrary parameter)

$$H = H_0' + V'$$
$$= \begin{pmatrix} E & 0 \\ 0 & QH_0Q \end{pmatrix} + \begin{pmatrix} P\tilde{H}P & PVQ \\ QVP & QVQ \end{pmatrix},$$

$$H_{\rm BH}(E) = PHP + PVQ\frac{1}{E - QHQ}QVP.$$

$$\tilde{H}_{\rm eff}^{(n)} = \tilde{H}_{\rm BH}(E) + \sum_{k=1}^{\infty} \hat{Q}_k(E)\{\tilde{H}_{\rm eff}^{(n-1)}\}^k.$$

KK method (conventional)

$$H = H_0 + V$$
$$= \begin{pmatrix} PH_0P & 0 \\ 0 & QH_0Q \end{pmatrix} + \begin{pmatrix} PVP & PVQ \\ QVP & QVQ \end{pmatrix}$$

$$\hat{Q}(E) = PVP + PVQ\frac{1}{E - QHQ}QVP$$

$$V_{\rm eff}^{(n)} = \hat{Q}(\epsilon_0) + \sum_{k=1}^{\infty} \hat{Q}_k(\epsilon_0)\{V_{\rm eff}^{(n-1)}\}^k.$$

- **EKK method enable us to construct effective interaction for multi-major shell**

N. Tsunoda, K. Takayanagi, M. Hjorth-Jensen, and T. Otsuka, Phys. Rev. C 89, 024313 (2014).

K. Takayanagi, Annals of Physics 350, 501 (2014).

K. Takayanagi, Nucl. Phys. A 852, 61 (2011).

EEdf1 interaction

- Effective interaction for **island of inversion**
- Effective interaction designed for **sd+pf** shell
- TBMEs are determined by **EKK method**
- Effective 2NF from **3NF**(Fujita-Miyazawa type) force is added
- SPEs are fitted to experimental data

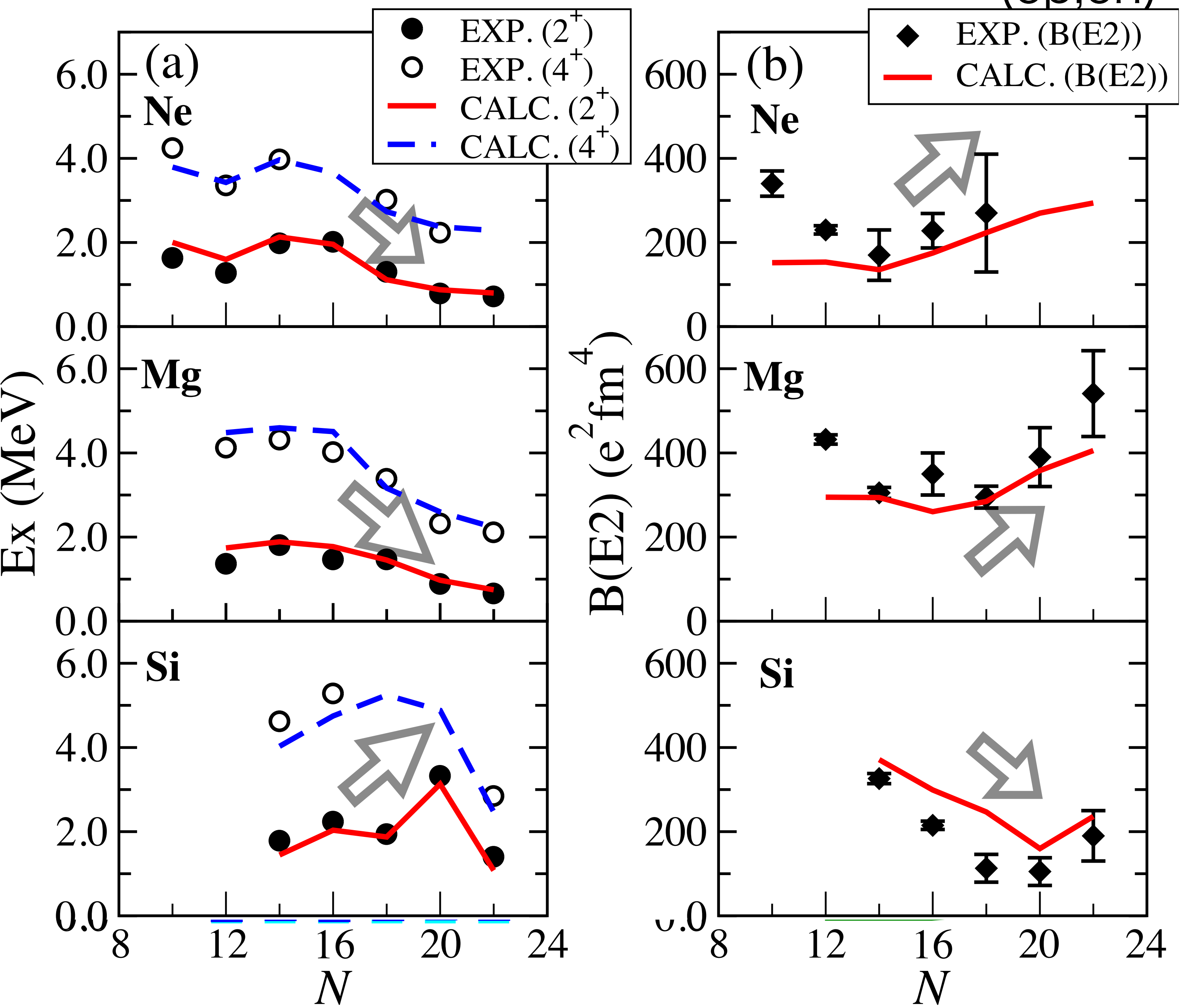
Shell structure in "island of inversion"

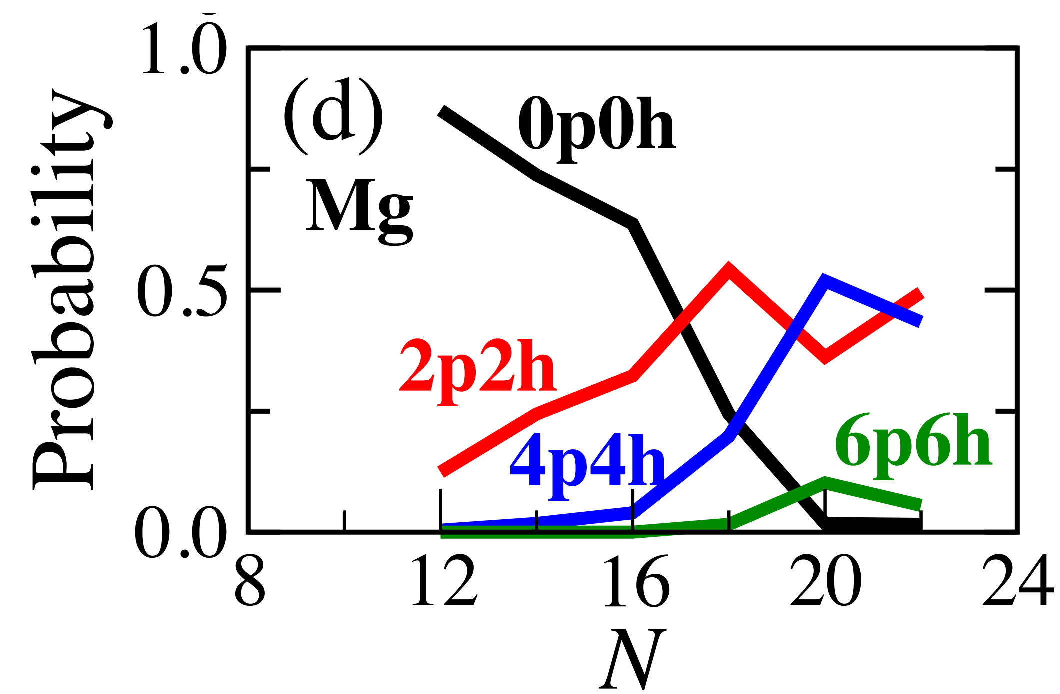
EEdf1

Effective charges

(ep,en)=(1.25, 0.25)

N.T, et al. Phys. Rev. C 95, 021304 (20





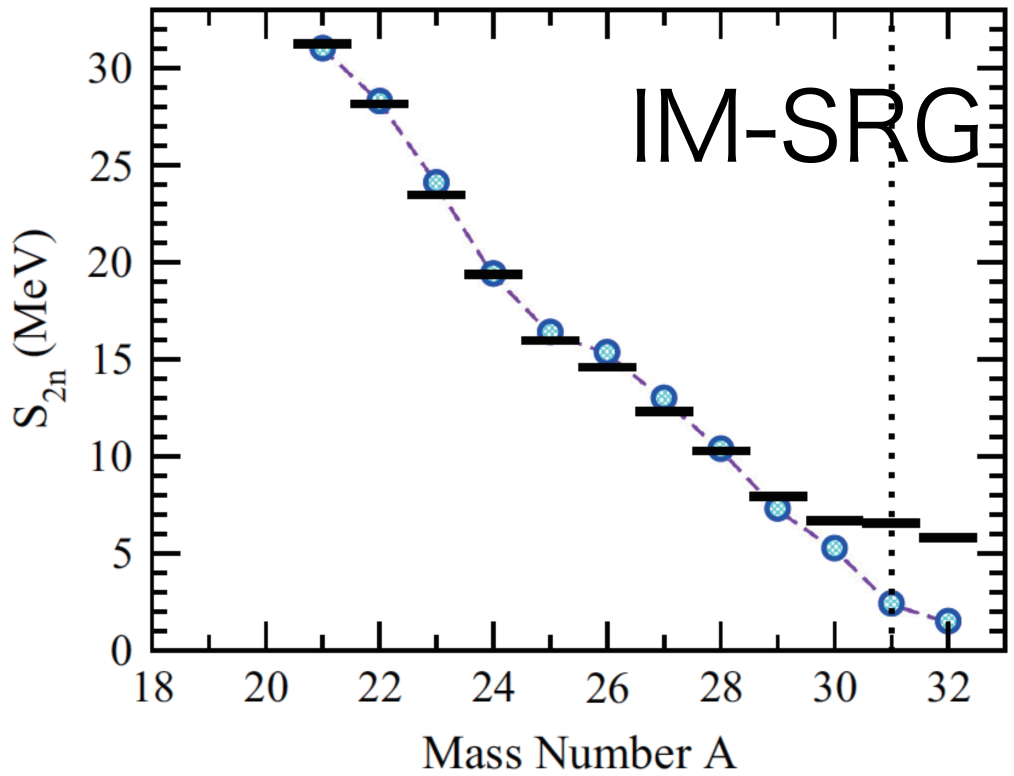
Similar ph excitation pattern to:

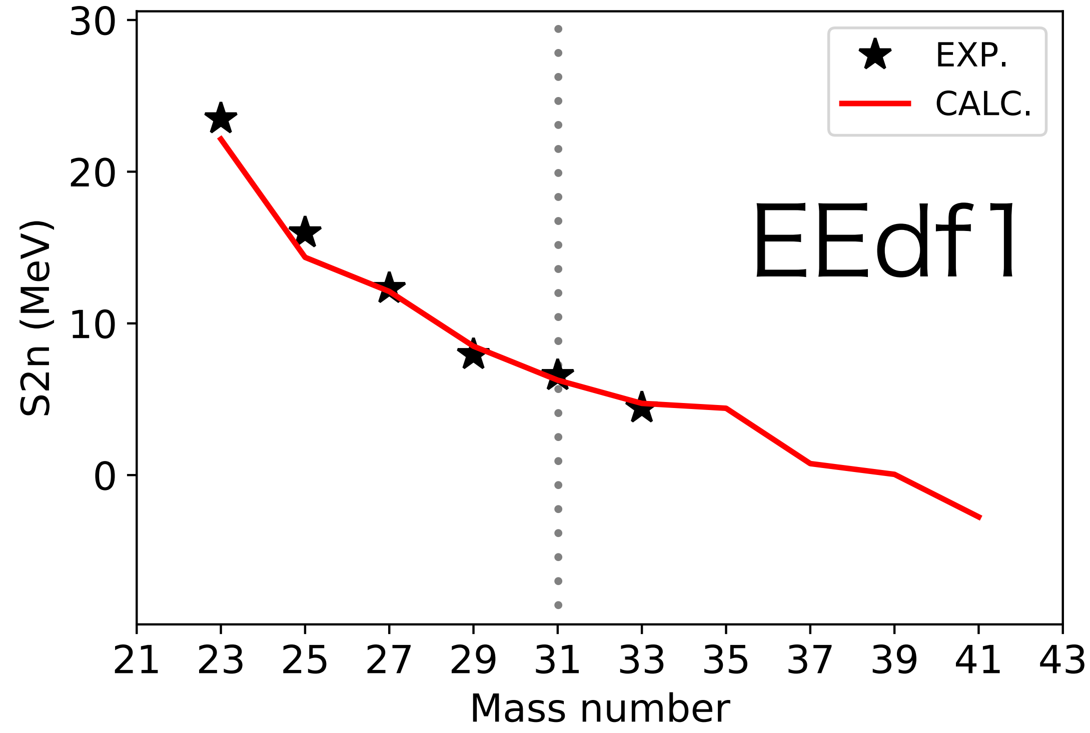
A. O. Macchiavelli, et al., Phys. Rev. C 94, 051303 (2016).

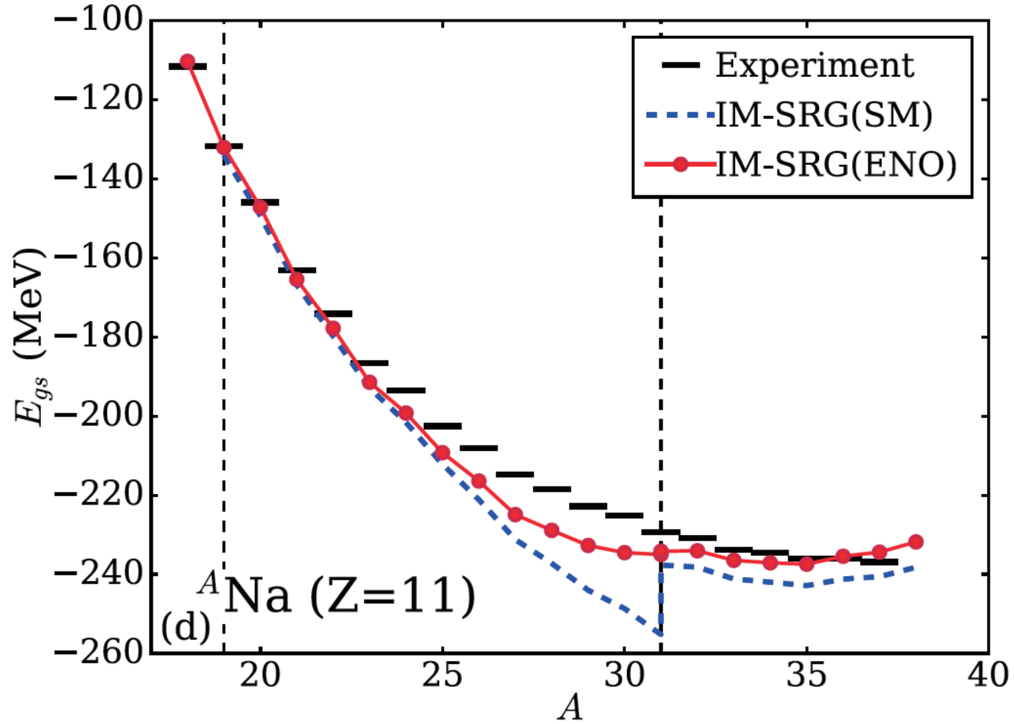
For larger N, we are now working on…

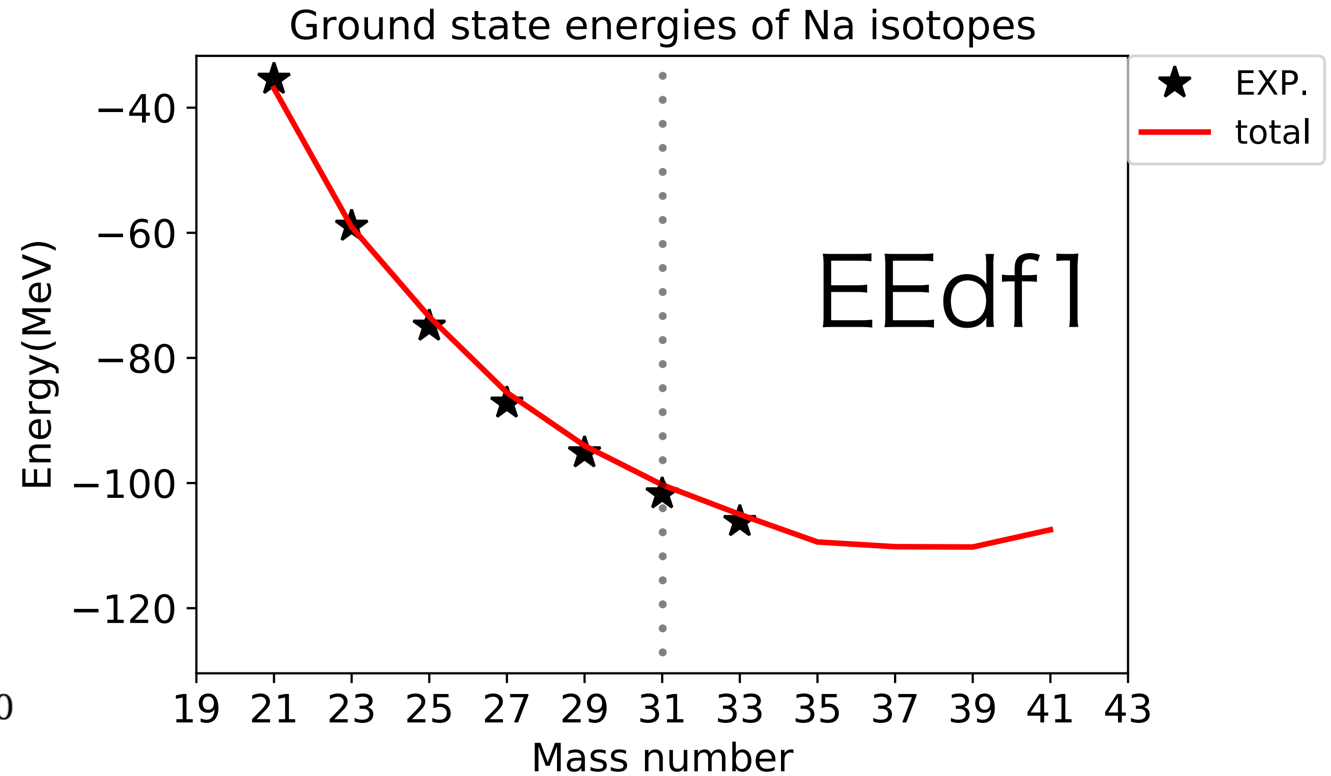
(e.g. 40Mg 2+ by Crawford's talk)

Comparison to ab initio calculations









S. R. Stroberg, et al., Phys. Rev. Lett. 118, 032502 (2017).

J. Simonis, et al., Phys. Rev. C 96, 014303 (2017).

その他最新の実験との比較

- ^{27}Ne C. Leolius et al., accepted to PRL
- ^{30}Mg B. Fernandez-Domınguez et al., PLB **779**, 124(2018)
- ^{31}Na, ^{31}Mg H. Nishibata et al., 論文投稿中
- ^{32}Ne I. Murray et al., PRC accepted(2019)
- ^{34}Ne, ^{39}Na Deuksoon Ahn et al., 論文準備中
- ^{34}Al Z. Xu et al. PLB **782**, 619(2018)

Comparisons to experimental data are successful !

Anatomy of interaction

bare SPE $\sum \epsilon_i a_i^+ a_i$

monopole $\sum_{i,j} V^{ab}_{\rm mono} a_i^+ a_j^+ a_j a_i$ $\quad V^{ab}_{\rm mono} = \sum_J \frac{(2J+1)\langle ab|V|ab\rangle_J}{2J+1}$

pairing J=0 (monopole removed)

multipole other (QQ etc.)

Anatomy of interaction

bare and effective SPE

bare SPE $\sum \epsilon_i a_i^+ a_i$

monopole $\sum_{i,j} V_{\rm mono}^{ab} a_i^+ a_j^+ a_j a_i$ $V_{\rm mono}^{ab} = \sum_J \frac{(2J+1)\langle ab|V|ab\rangle_J}{2J+1}$

pairing J=0 (monopole removed)

multipole other (QQ etc.)

Anatomy of interaction

bare and effective SPE

bare SPE $\sum \epsilon_i a_i^+ a_i$

monopole $\sum_{i,j} V^{ab}_{\mathrm{mono}} a_i^+ a_j^+ a_j a_i$ $V^{ab}_{\mathrm{mono}} = \sum_J \frac{(2J+1)\langle ab|V|ab\rangle_J}{2J+1}$

correlation

pairing J=0 (monopole removed)

multipole other (QQ etc.)

Anatomy of interaction

bare and effective SPE

bare SPE $\sum \epsilon_i a_i^+ a_i$

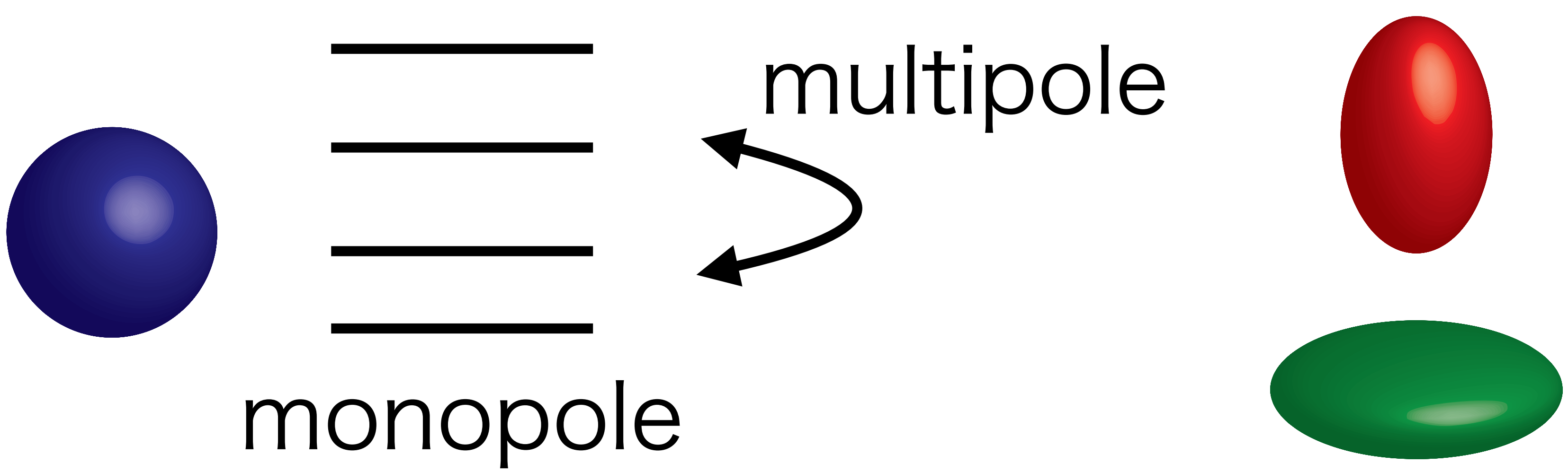
monopole $\sum_{i,j} V_{\text{mono}}^{ab} a_i^+ a_j^+ a_j a_i$ $\quad V_{\text{mono}}^{ab} = \sum_J \frac{(2J+1)\langle ab|V|ab\rangle_J}{2J+1}$

correlation

pairing J=0 (monopole removed)

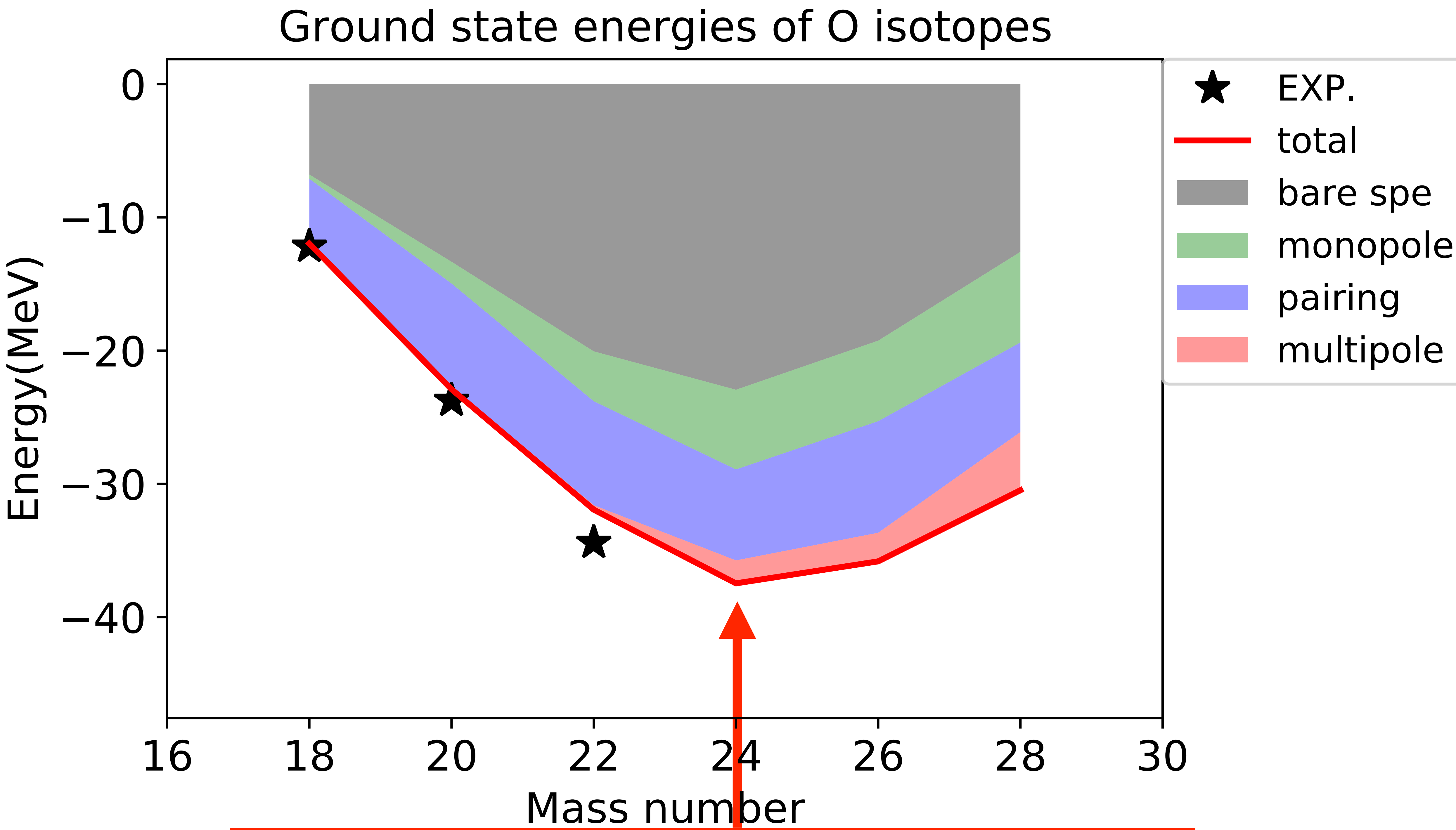
including deformation

multipole other (QQ etc.)



O isotope (Z=8)

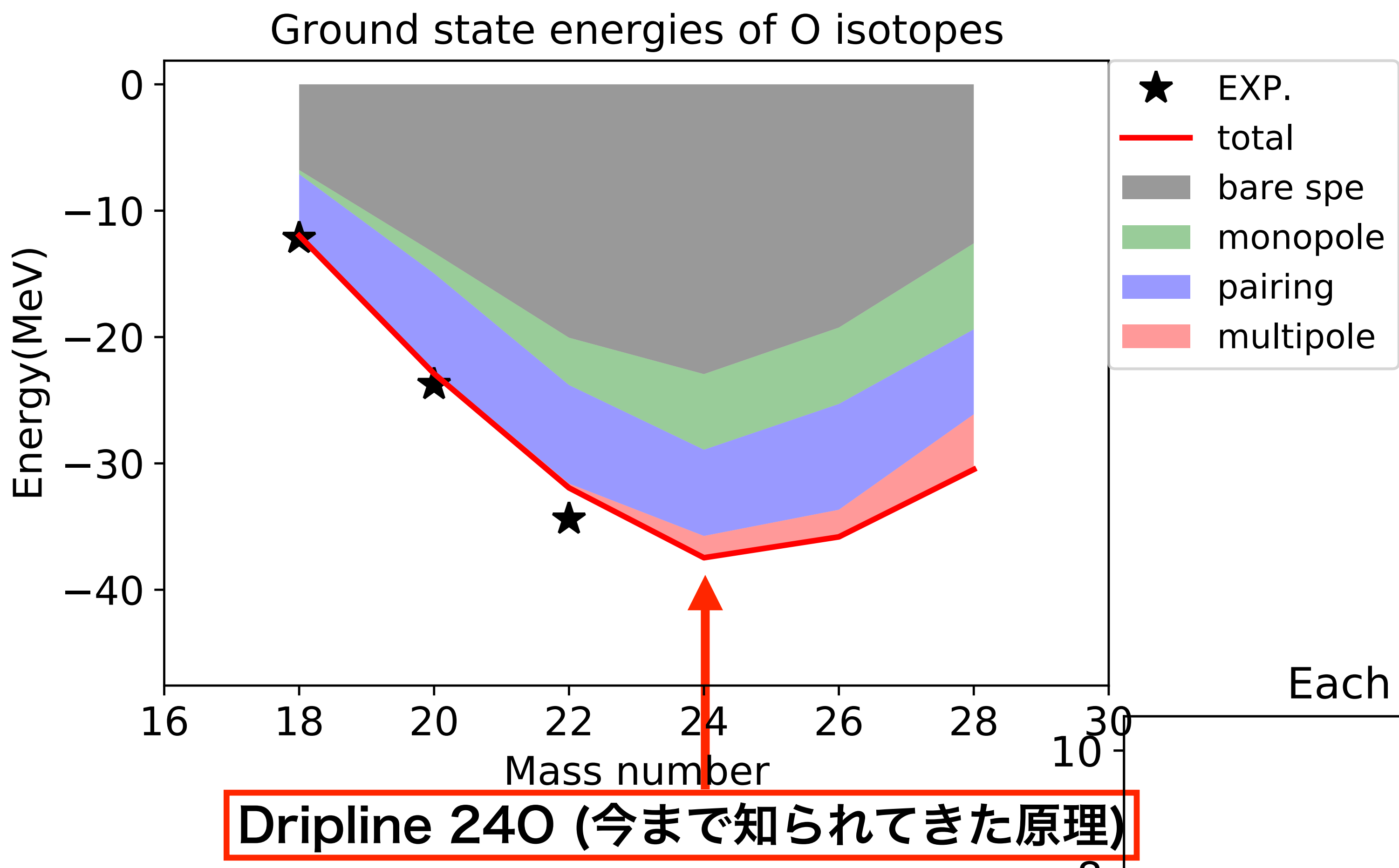
(all the SPEs shifted by 0.9 MeV)

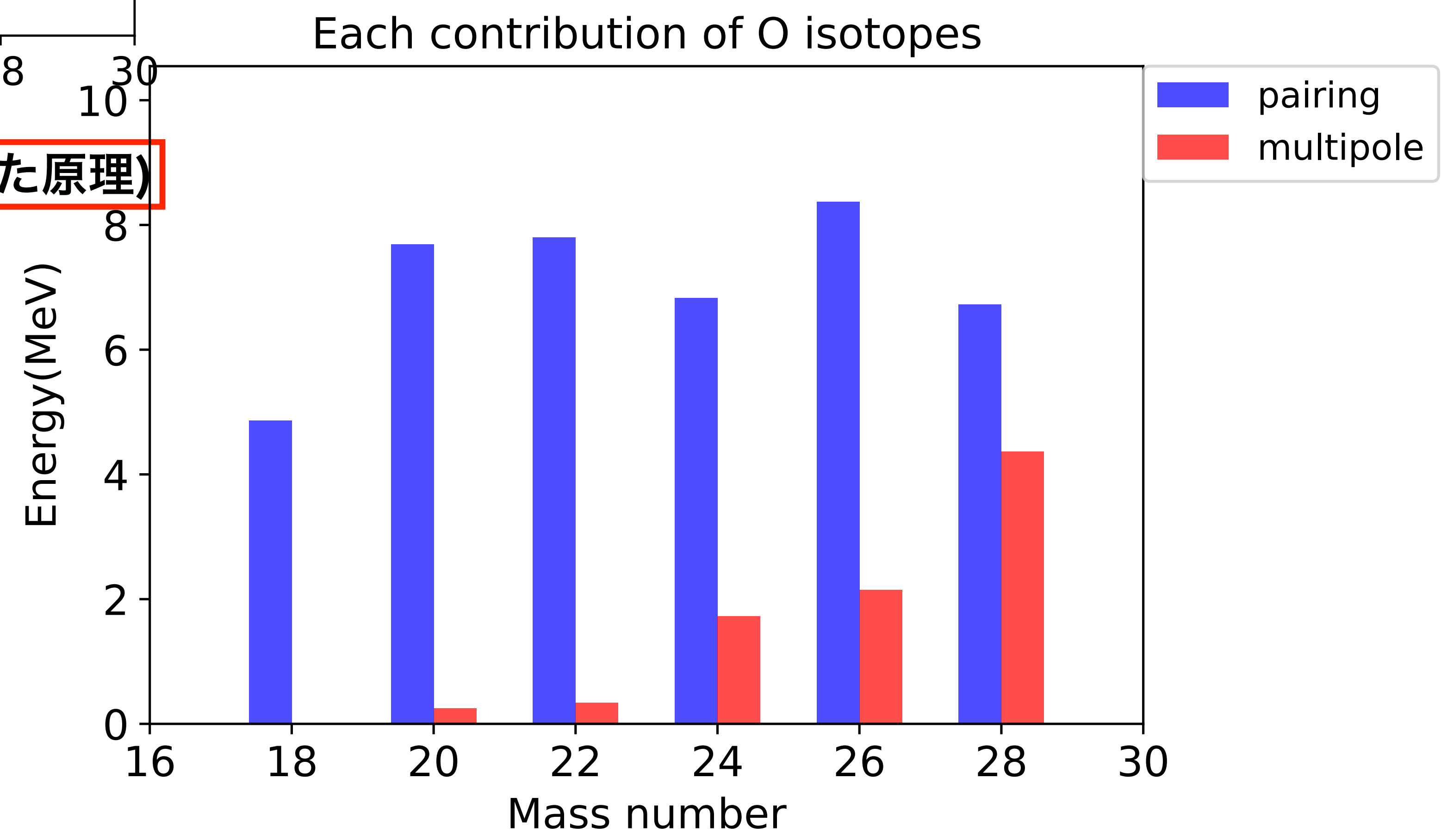


Dripline 24O (今まで知られてきた原理)

O isotope (Z=8)

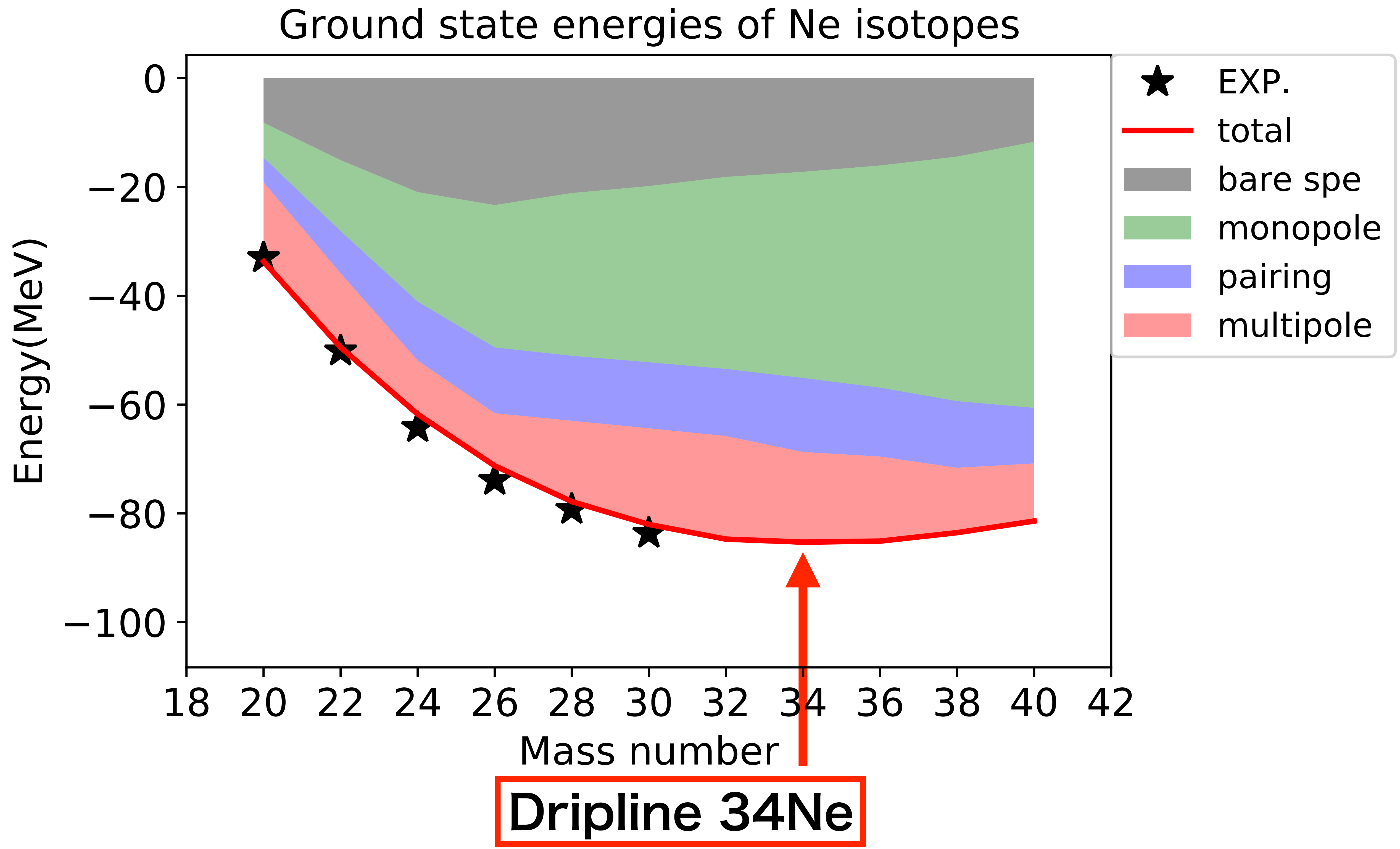
(all the SPEs shifted by 0.9 MeV)





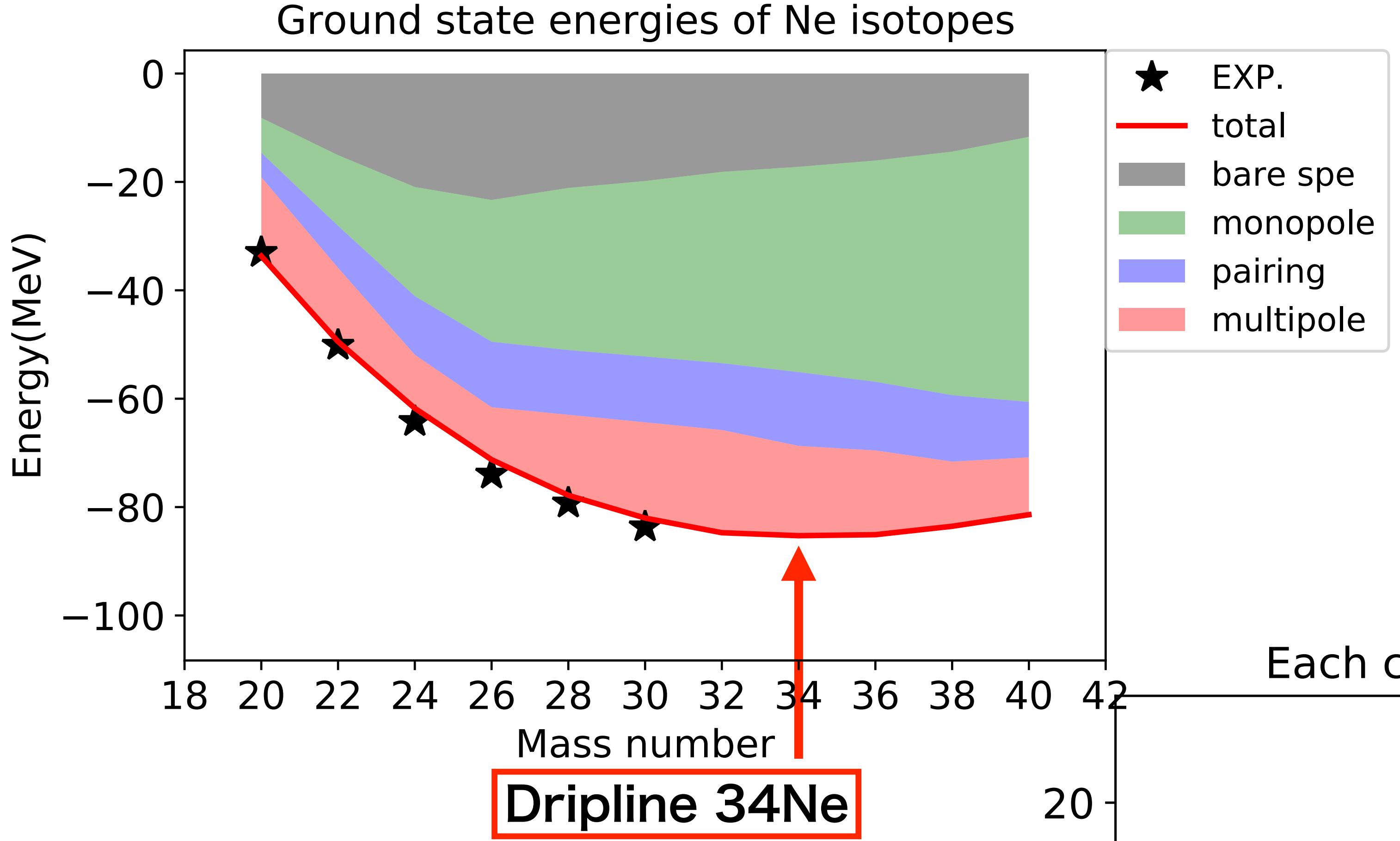
Ne isotope (Z=10)

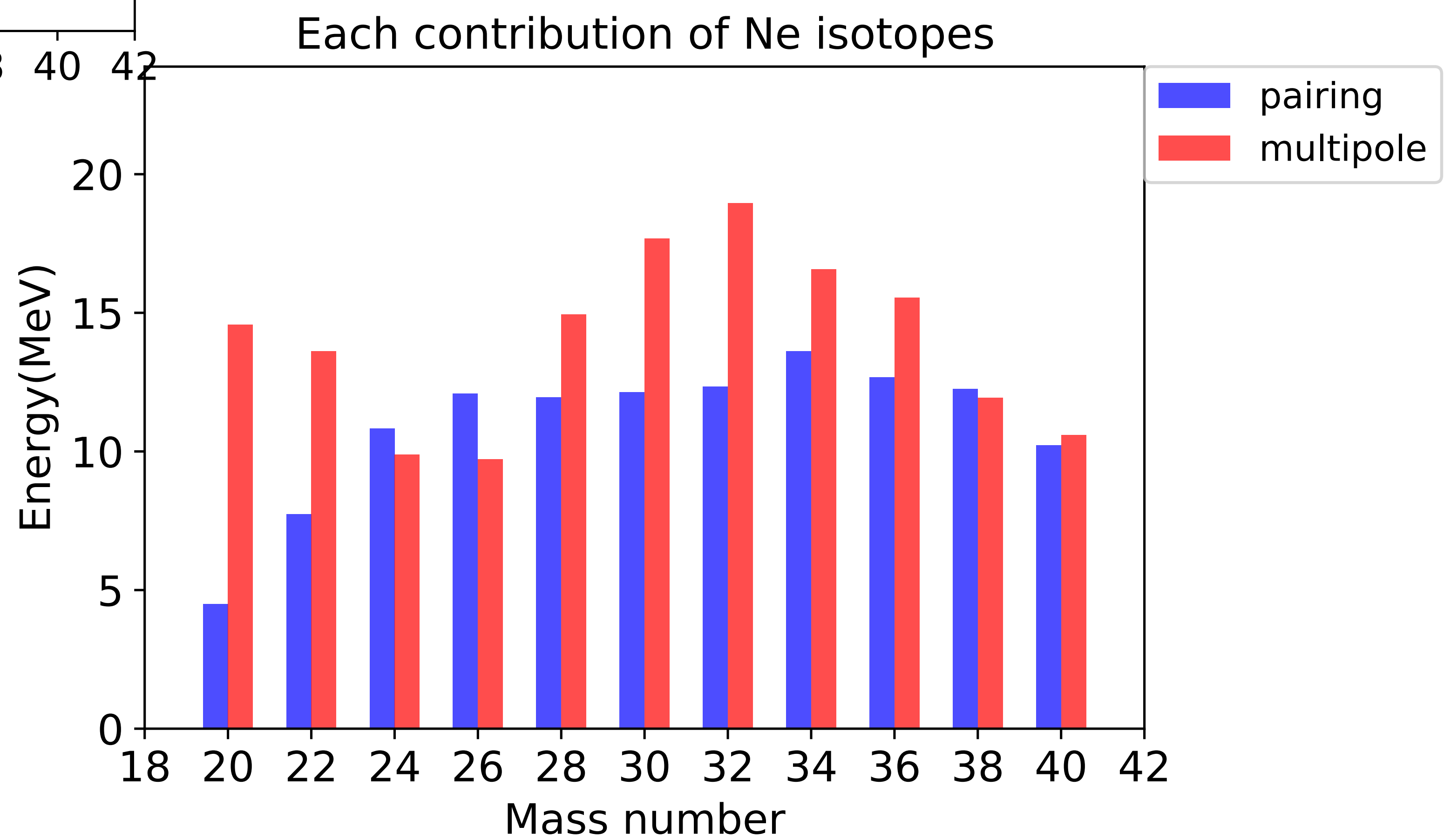
(all the SPEs shifted by 0.9 MeV)



Ne isotope (Z=10)

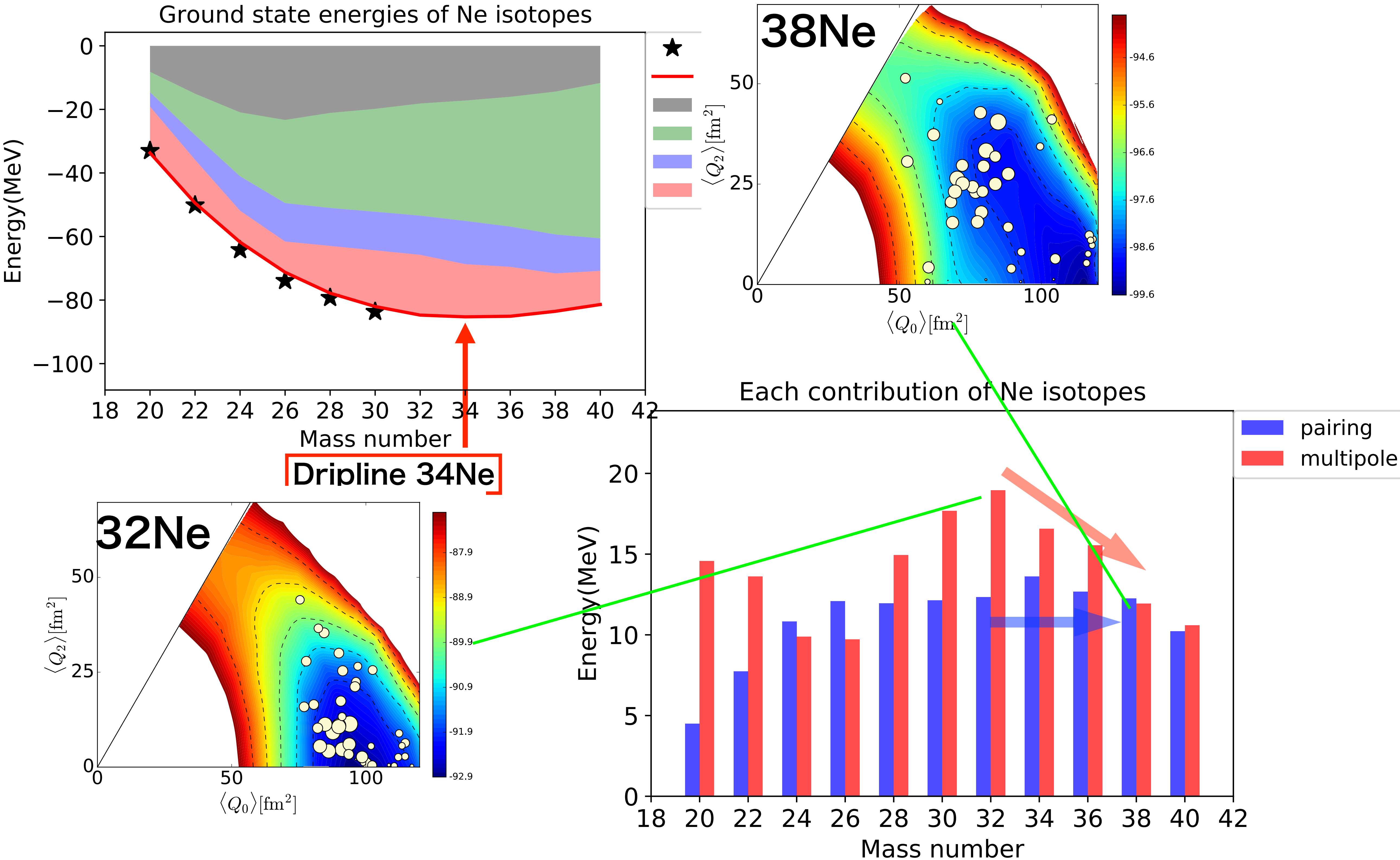
(all the SPEs shifted by 0.9 MeV)



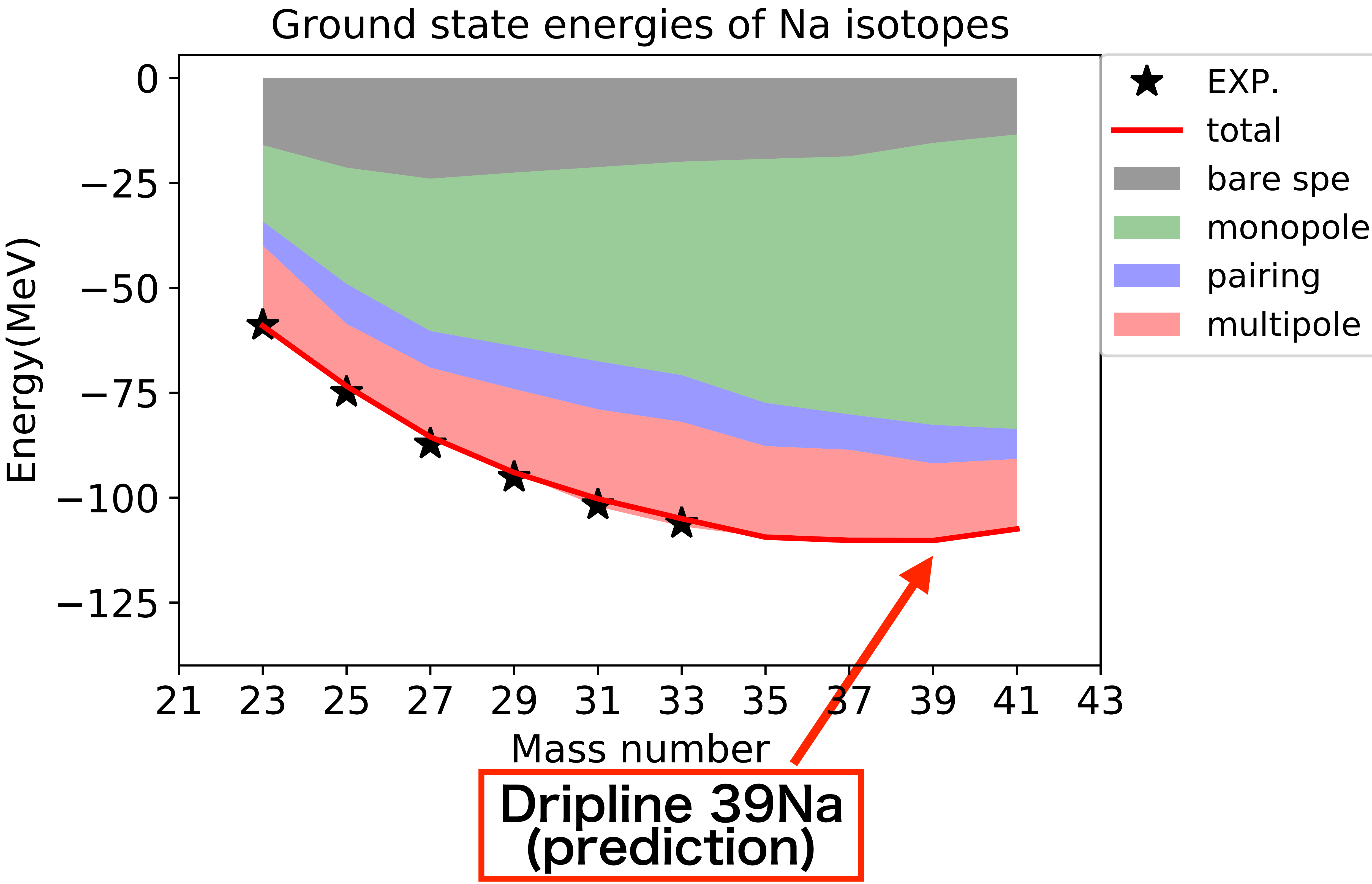


Ne isotope (Z=10)

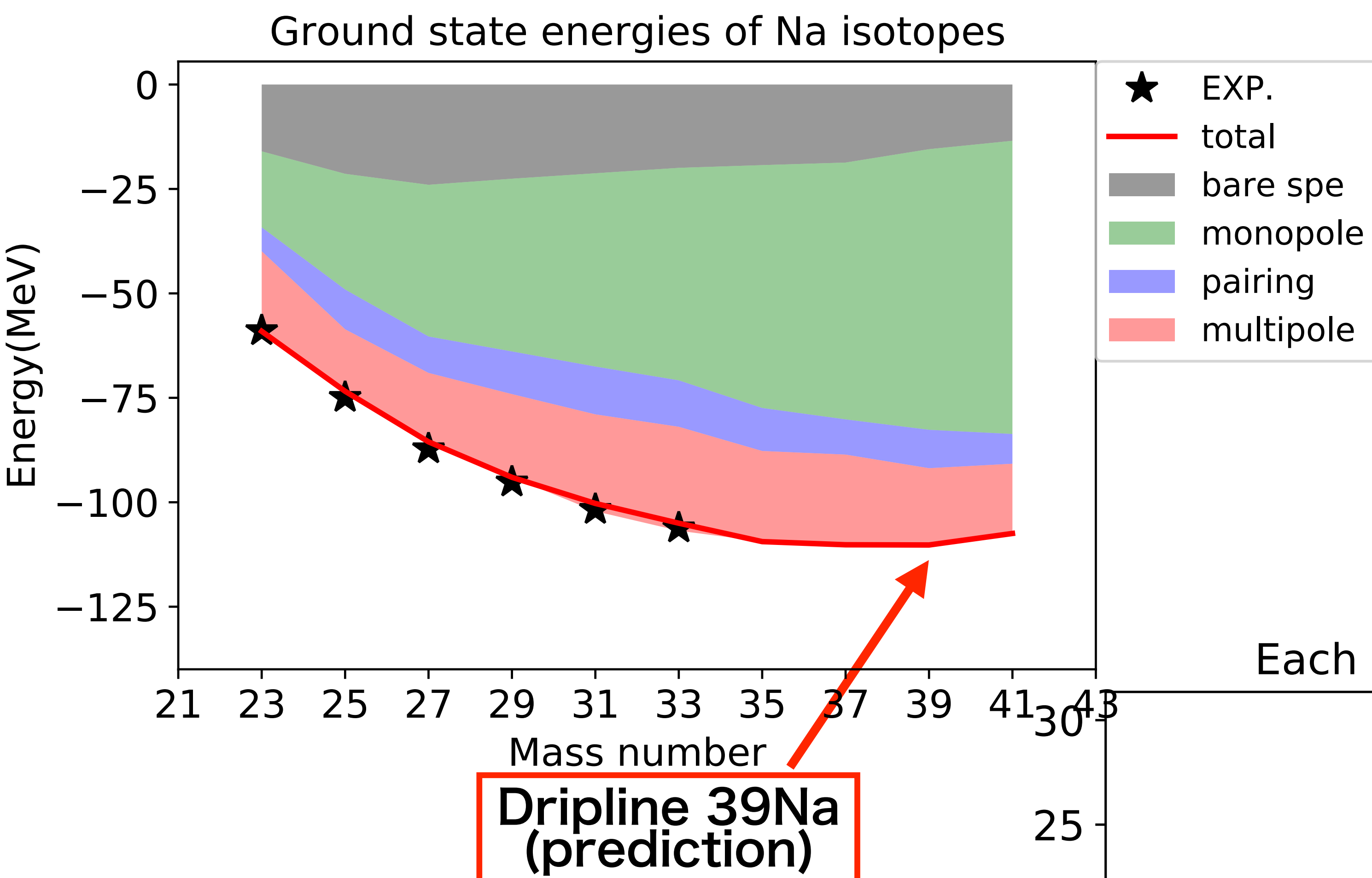
(all the SPEs shifted by 0.9 MeV)

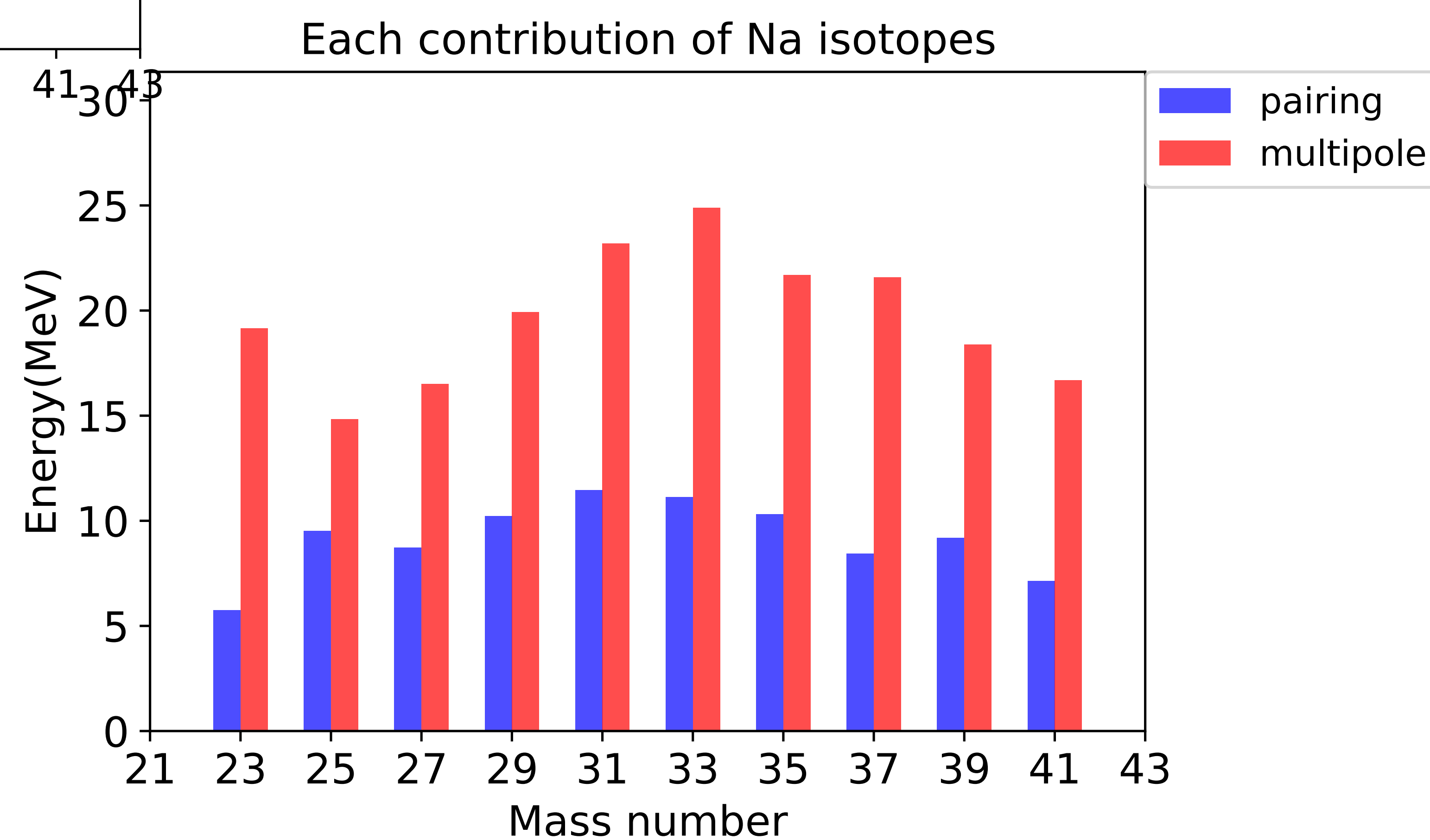


Na isotope (Z=11)

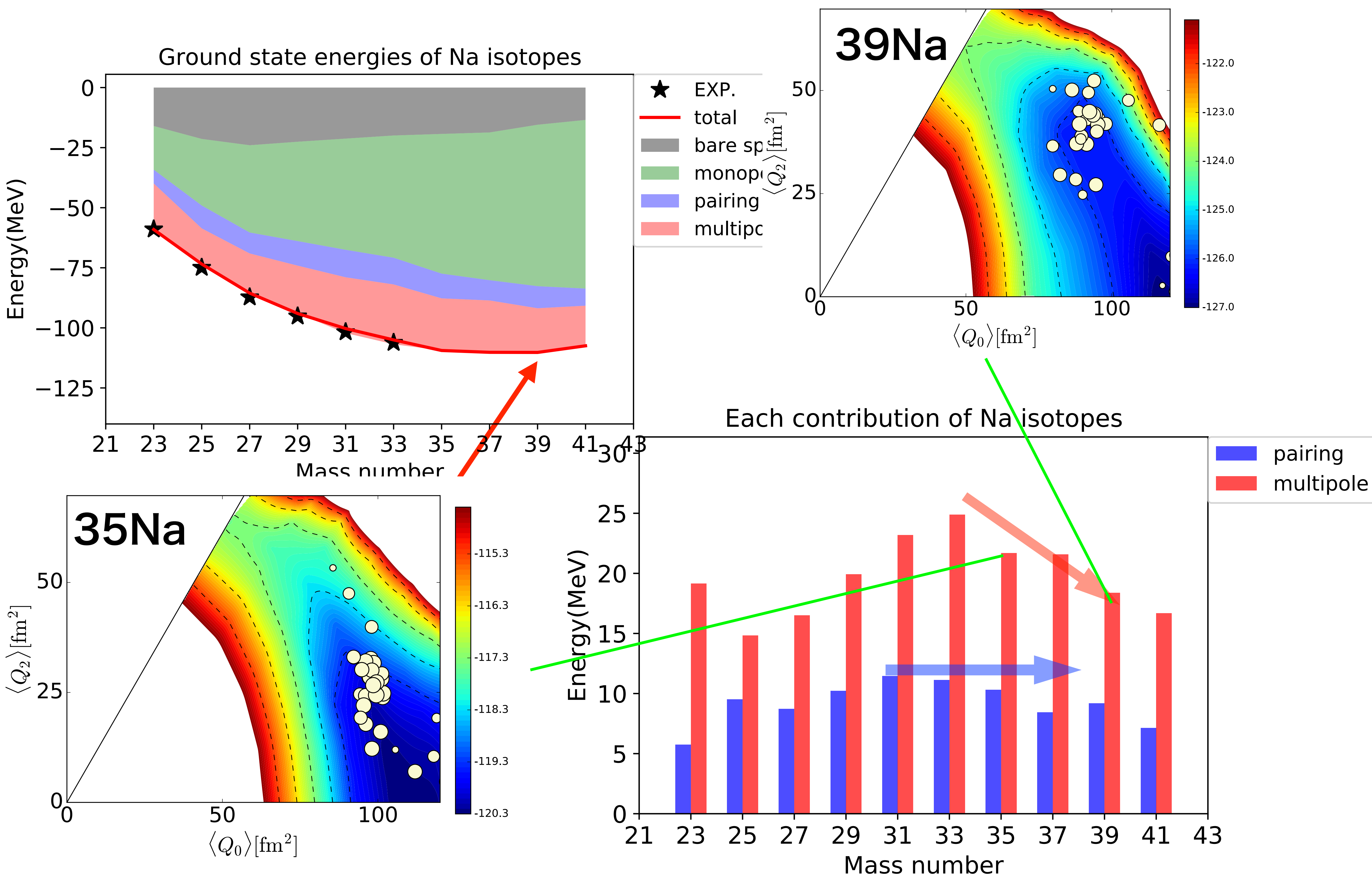


Na isotope (Z=11)

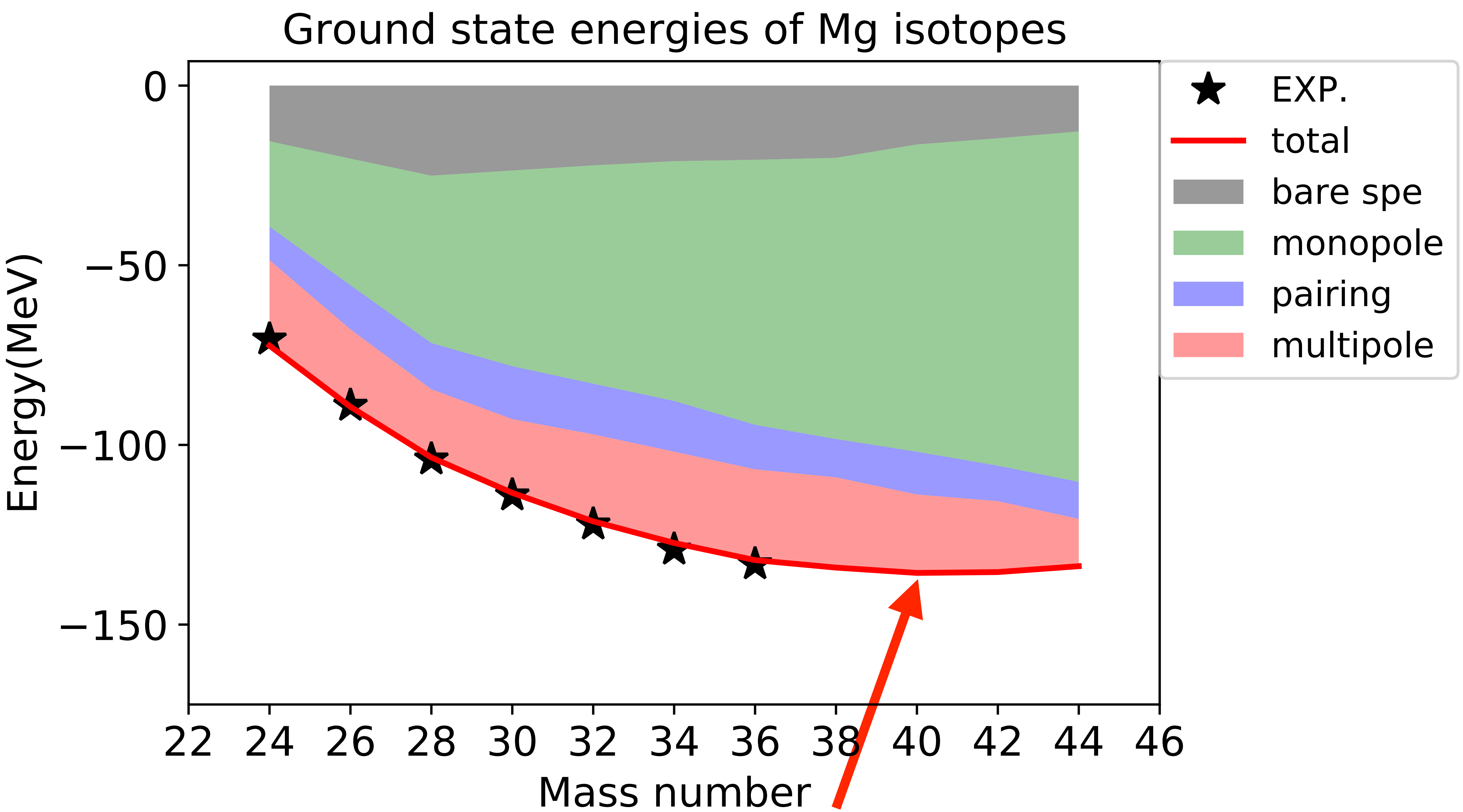




Na isotope (Z=11)

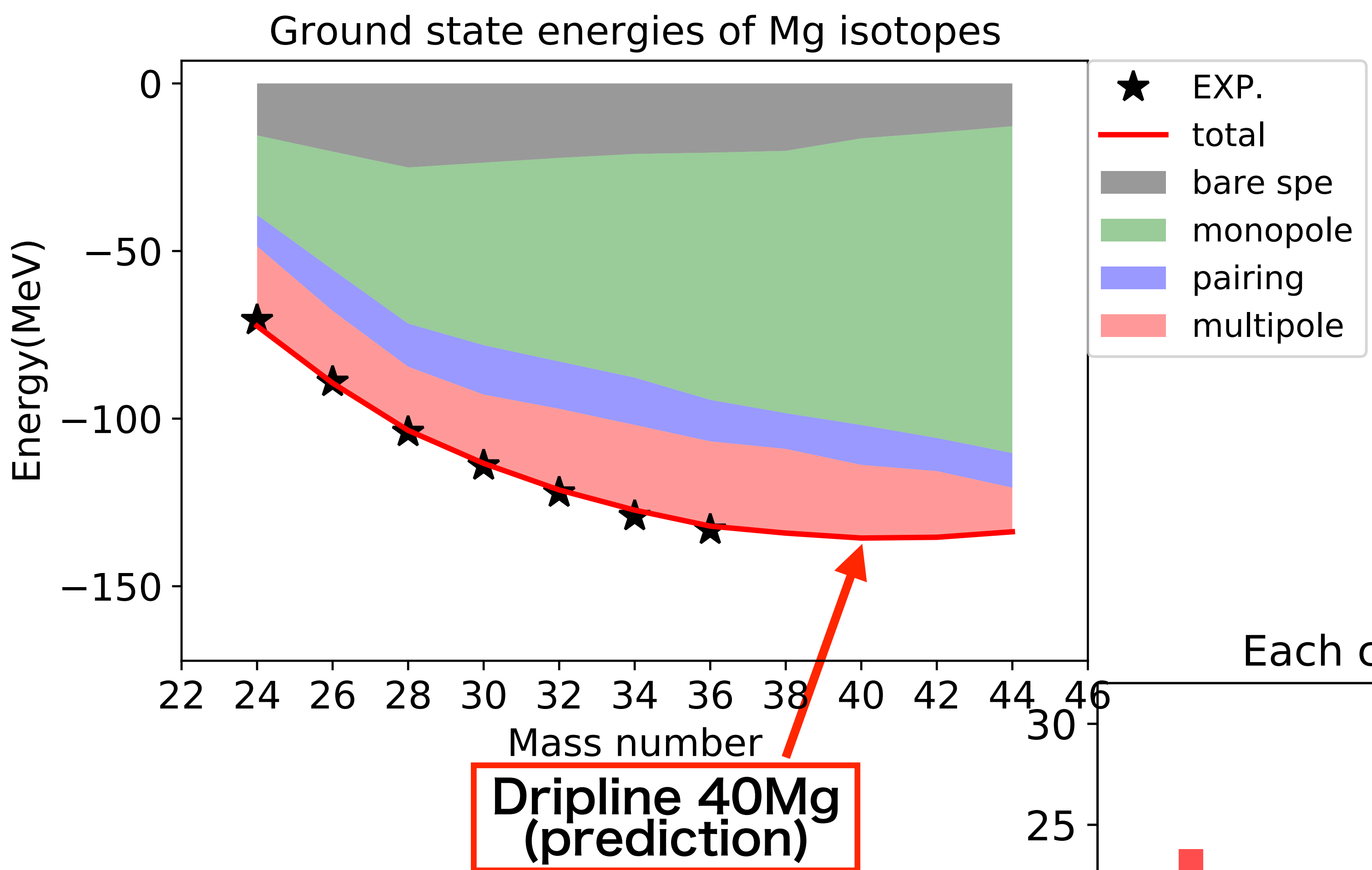


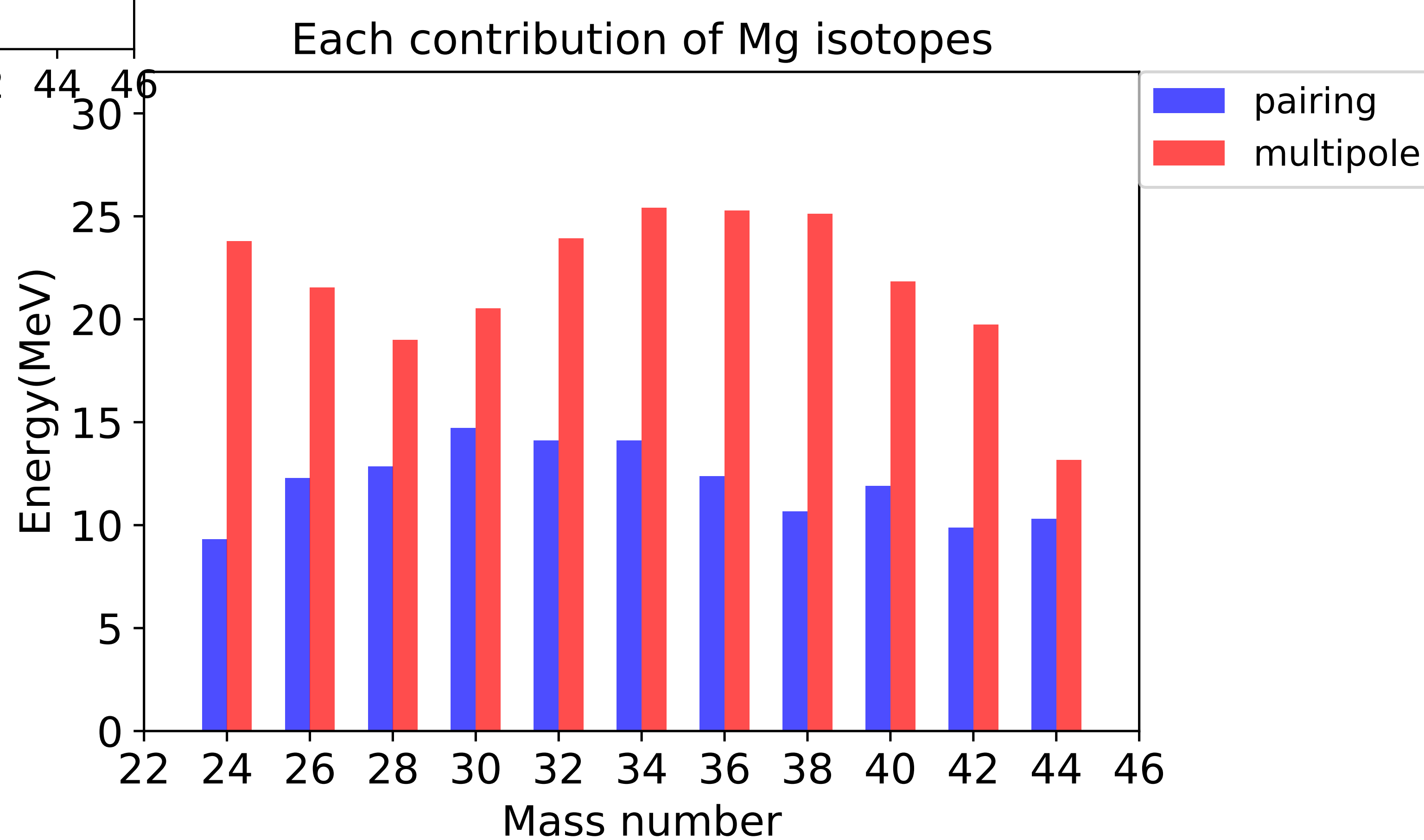
Mg isotope (Z=12)



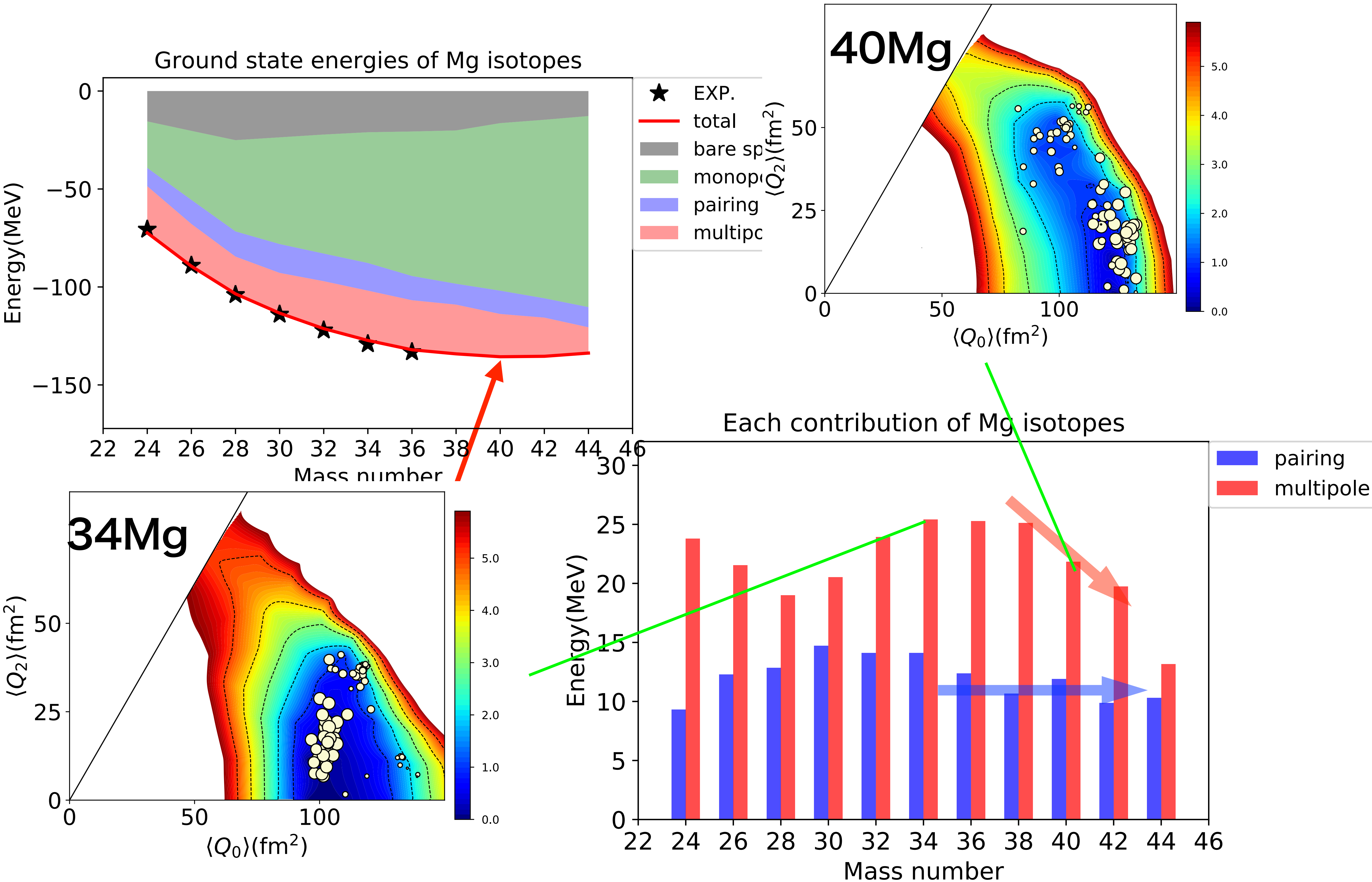
Dripline 40Mg (prediction)

Mg isotope (Z=12)

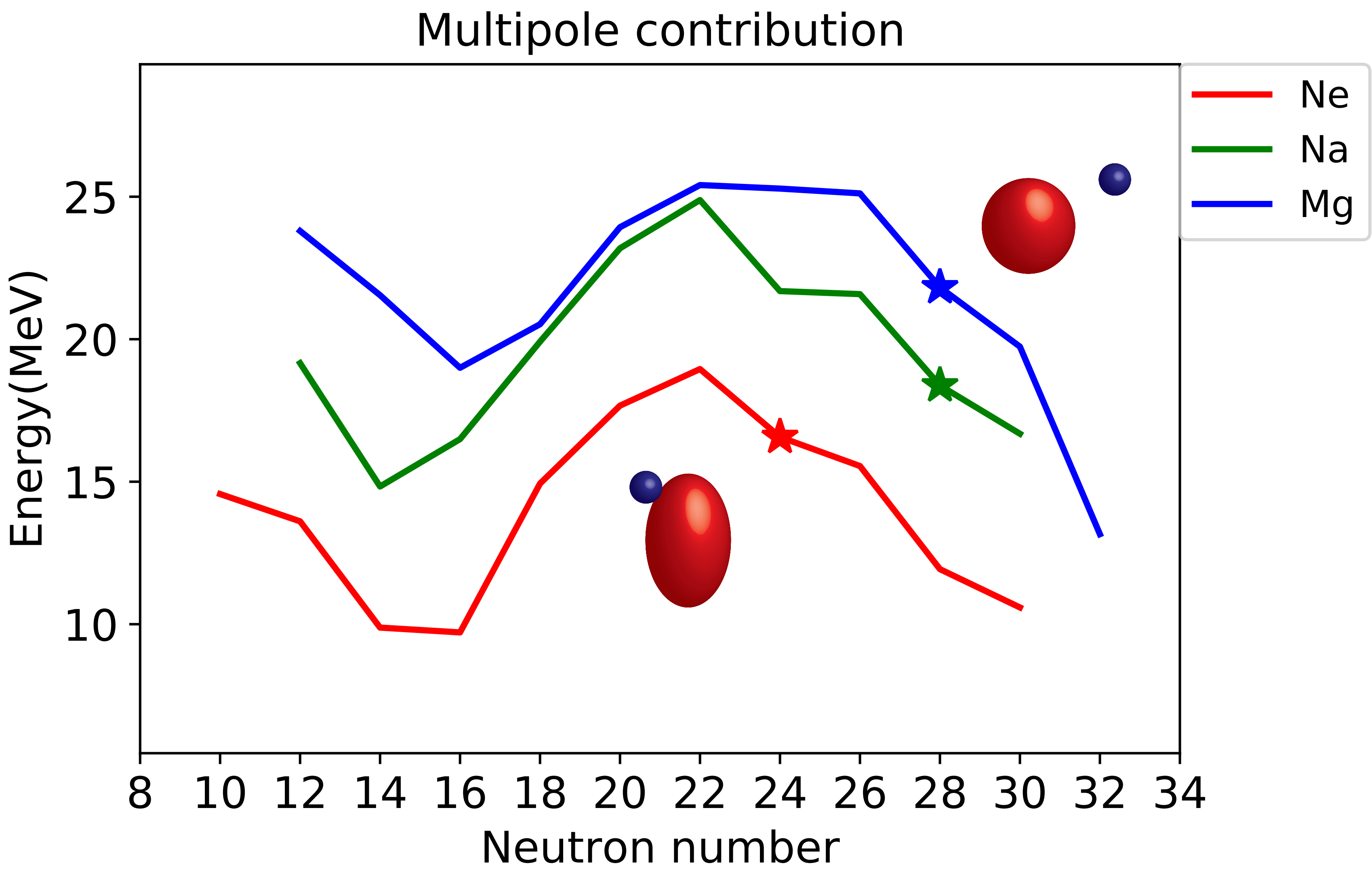




Mg isotope (Z=12)



Multipole contribution (変形の効果)



A new mechanism of dripline

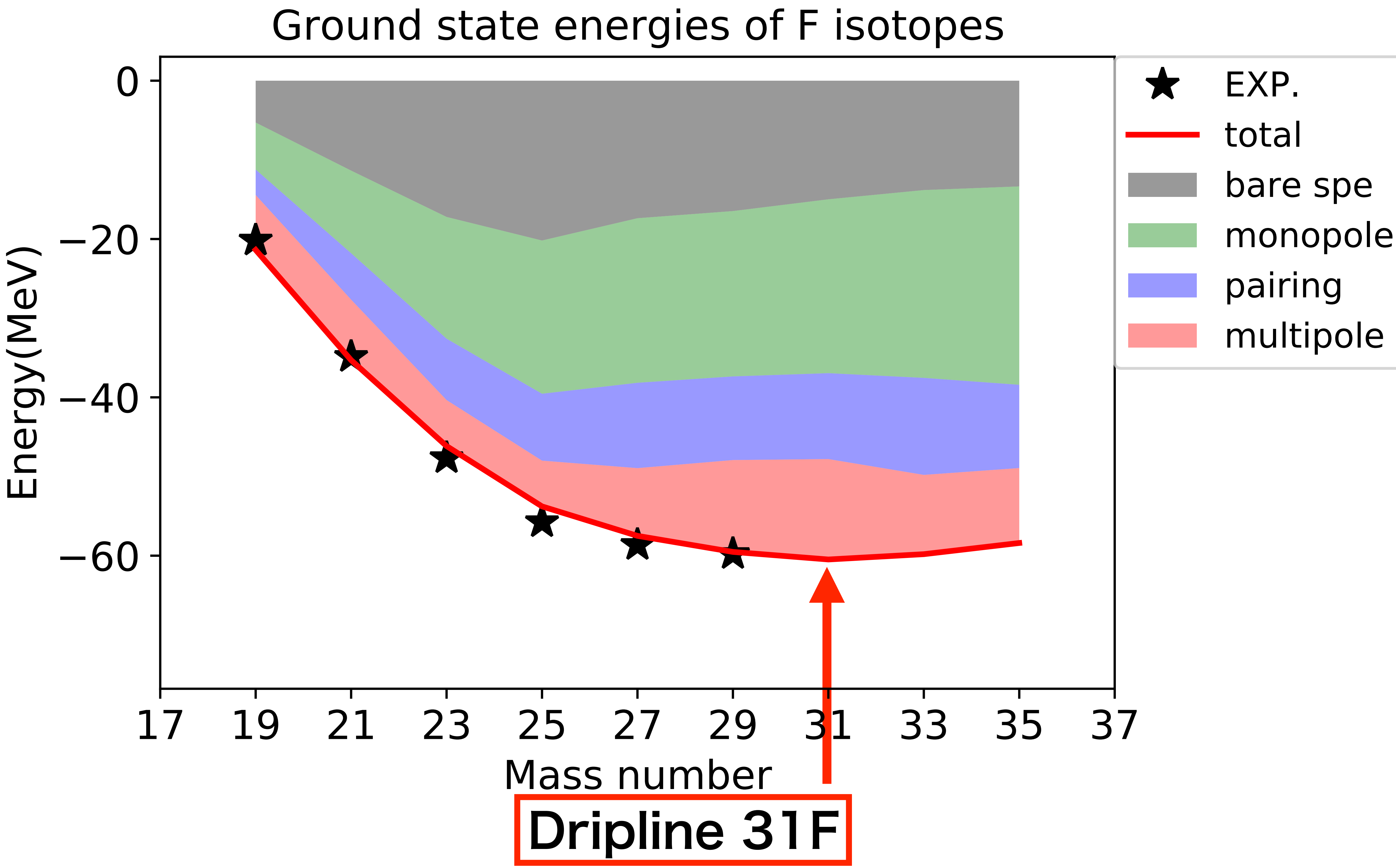
==> **competition** between EPSE and Deformation

negative ESPE but less deformation energy

粒子をくっつけると、変形エネルギーが減ってしまい、束縛できない

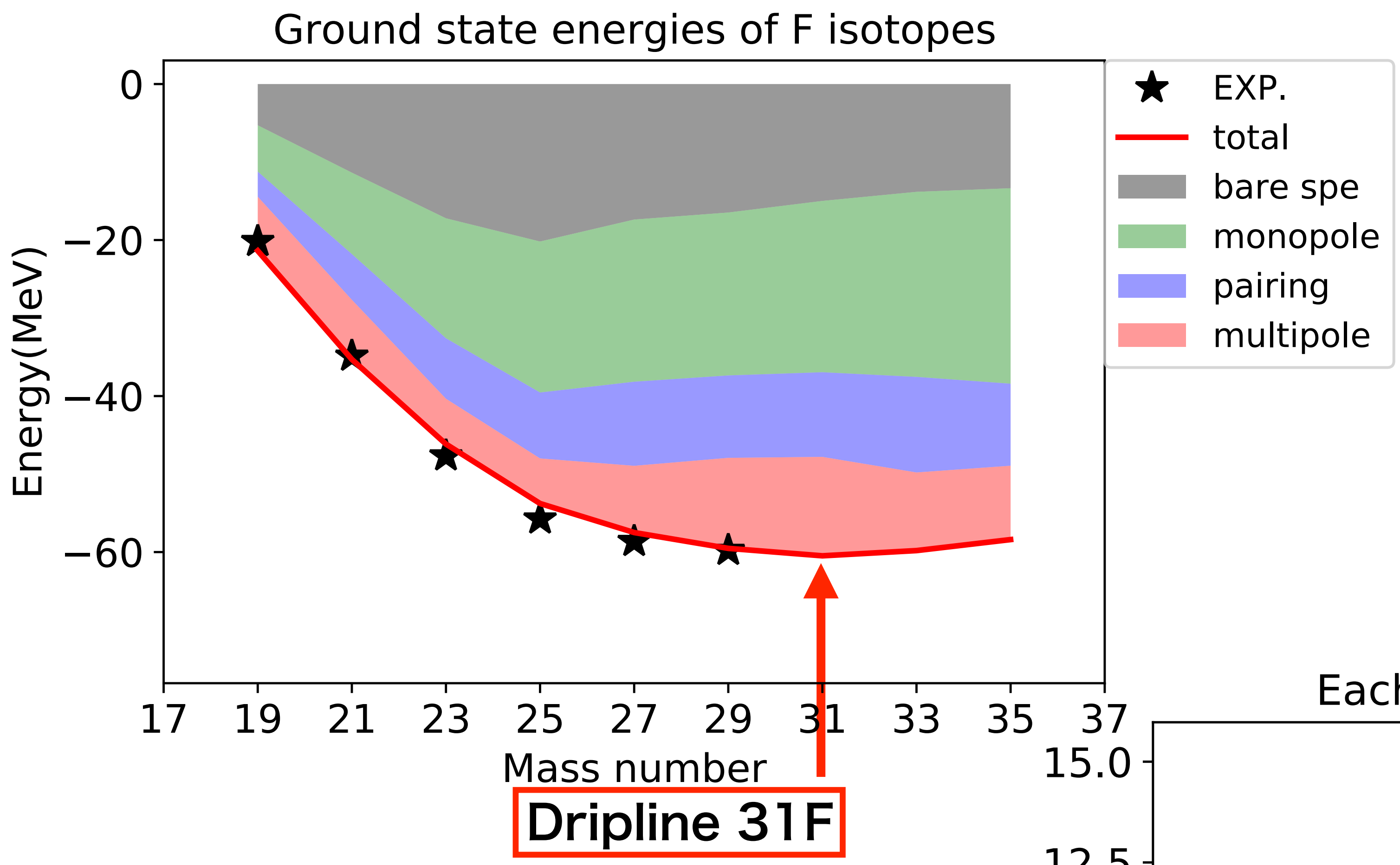
F isotope (二つの原理の切り替わり Z=9)

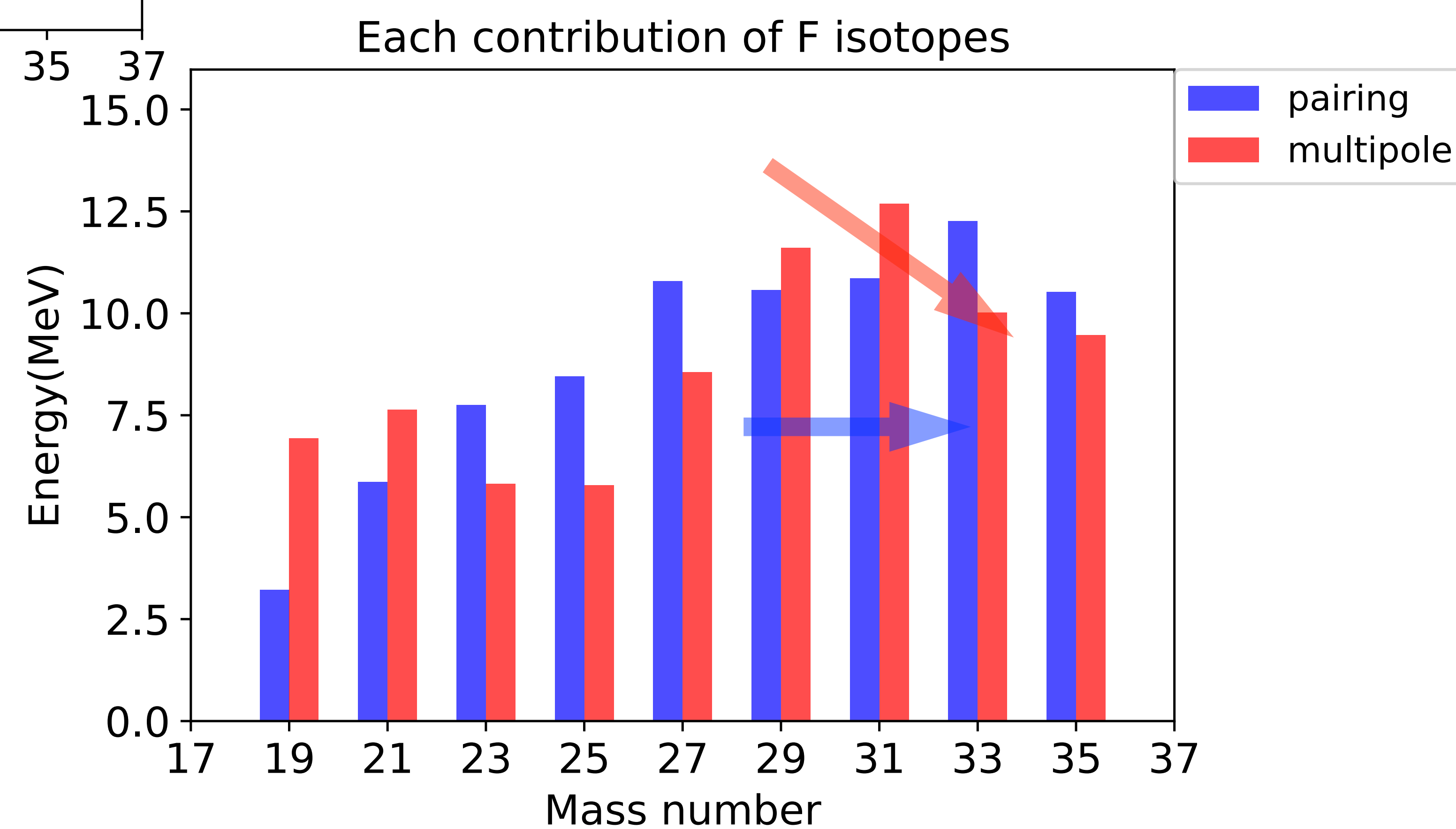
(all the SPEs shifted by 0.9 MeV)



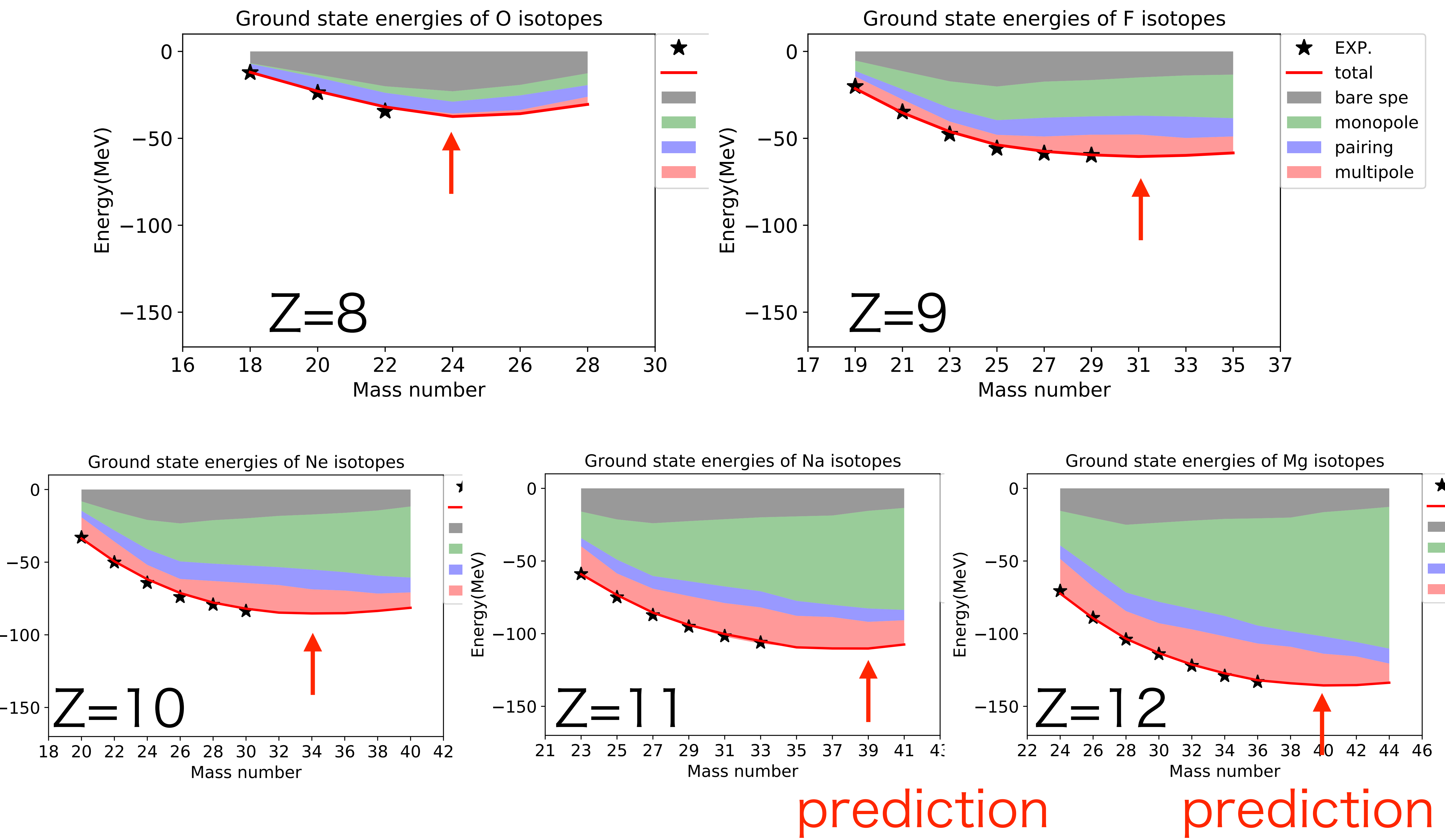
F isotope (二つの原理の切り替わり Z=9)

(all the SPEs shifted by 0.9 MeV)





All isotopes



Conclusion

- ドリップラインの解析は原子核物理にとって重要な使命
- 「京」を用いたZ=8-12のドリップラインの理論的解析
- 実験との一致
- 新しいドリップラインの原理の発見
- Ne、Na、Mg のドリップラインは**変形エネルギー**が小さくなることによって出現 (Oの場合には、変形エネルギーではなく、ナイーブなsingle particle energy によってドリップラインが決定されることと対照的)

collaborators

- Takaharu Otsuka
- Noritaka Shimizu
- Kazuo Takayanagi
- Morten Hjorth-Jensen
- Toshio Suzuki
- DeukSoon Ahn (and her collaborators)
- Hiroki Nishibata (and his collaborators)
- B. Fernández-Domínguez (and her collaborators)
- Ian Murray (and his colloborators)