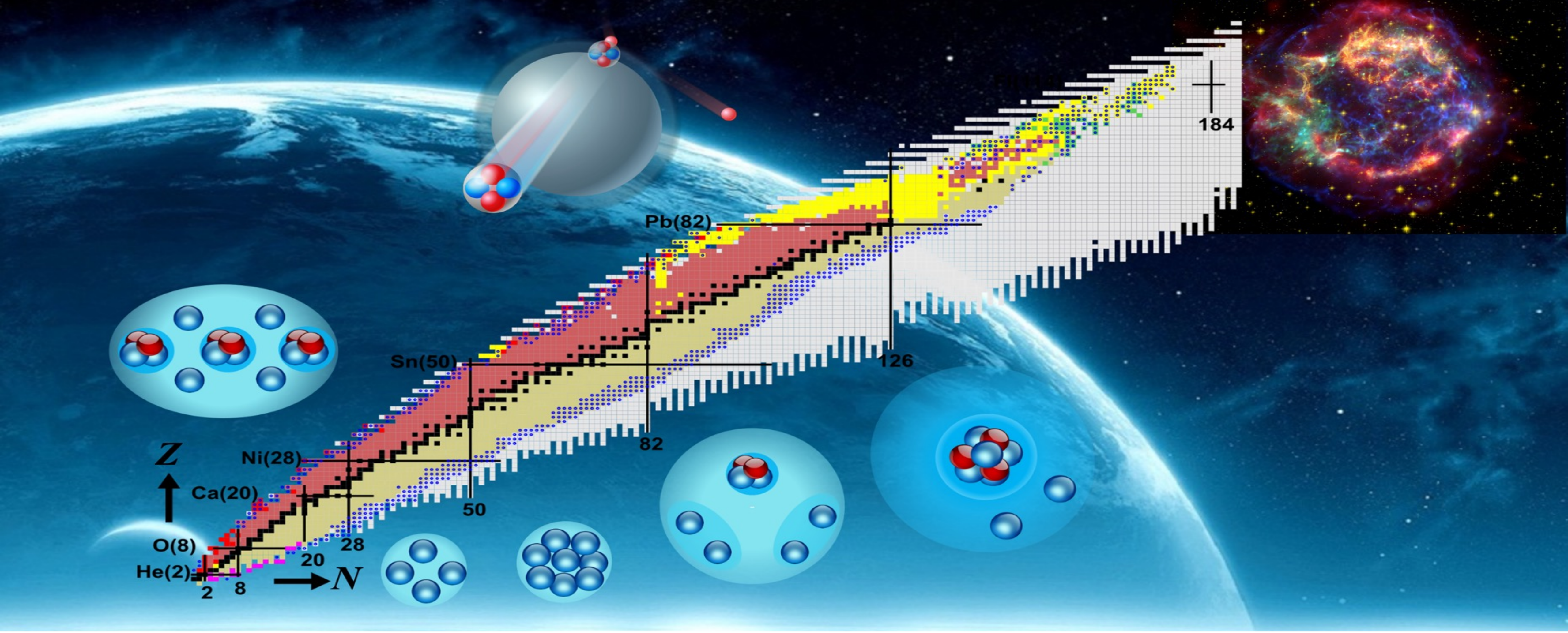


A wonderworld of atomic nuclei: from tiny to infinity

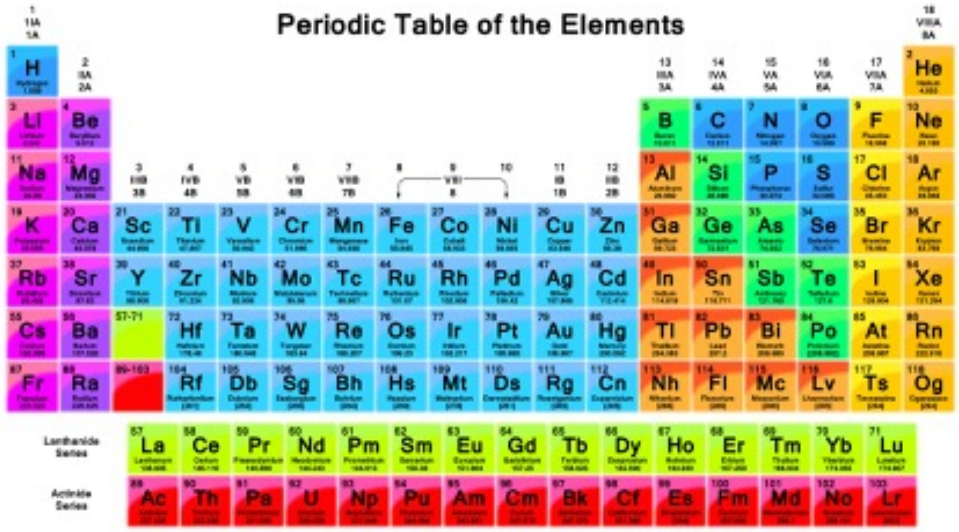
Zaihong Yang (Peking University)

2024 Nishina School，RIKEN Nishina Center，Wako, 2024 07-08

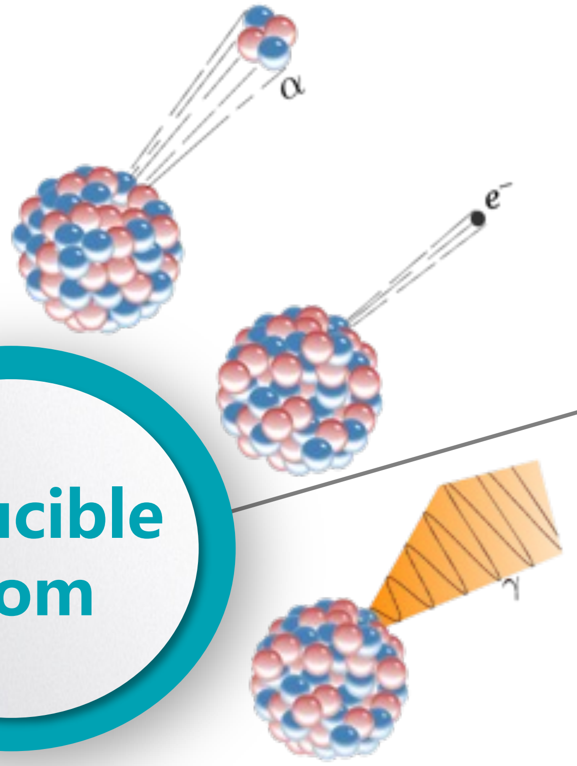
Outline

- ✓ Introduction: basics about the structure of nucleus
- ✓ Clustering in nuclear systems
- ✓ Halo and neutron correlations
- ✓ Summary and Perspective

The heart of atom: Atomic Nucleus



- Atomic theory of Dalton (1808)
- Mendeleev's periodic table (1869)

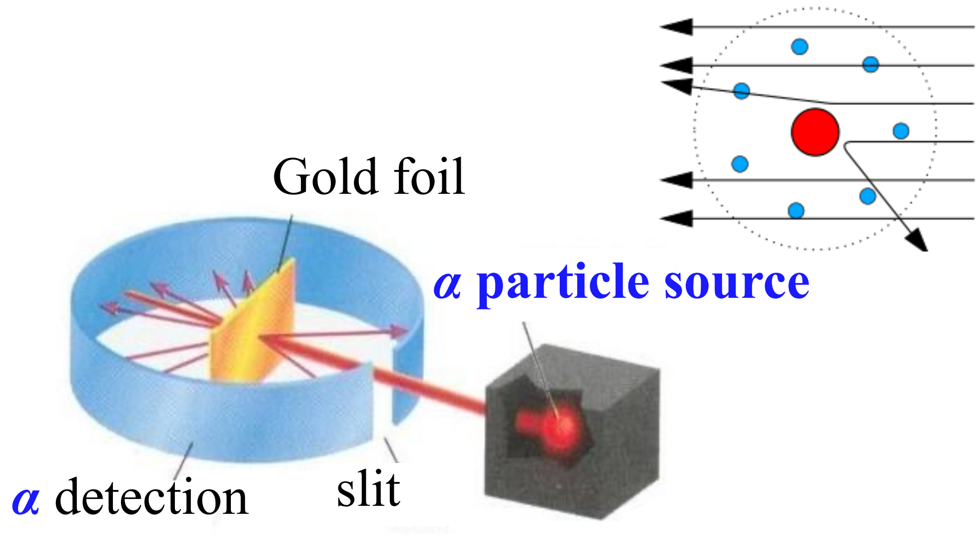


Reducible Atom

Atom

- Discovery of X-ray (Roentgen, 1895, Nobel-1901）
- Discovery of electron (Thomson, 1897, Nobel-1906）
- Discovery of Radioactivity (Becquerel/ Pierre Curie/ Marie Curie/ Rutherford, 1896~, Nobel-1903/-1908)

The heart of atom: Atomic Nucleus

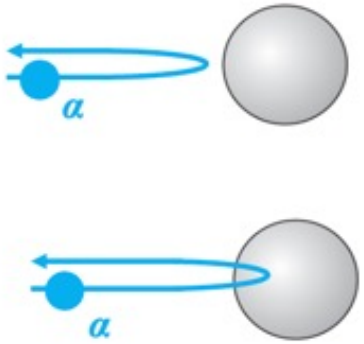


- **Rutherford scattering experiment (~1909)**

"Measure" the size of nucleus

Head-on collision
→ closest distance r_d

$$E_k = \frac{1}{2} m_\alpha v^2 = \frac{e^2}{4\pi\epsilon_0} \frac{Z_\alpha Z}{r_d}$$



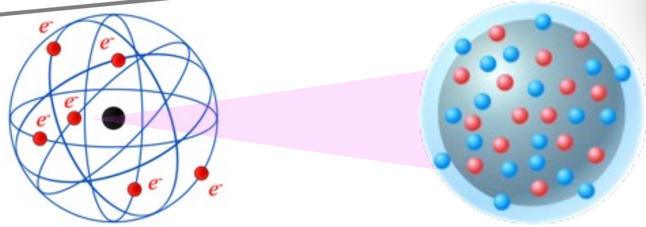
Discovery of proton (Rutherford, 1914)

$$^{14}N + \alpha \longrightarrow {}^{17}O + p$$

Discovery of neutron (Chadwick,1932)

$$^{9}Be + \alpha \longrightarrow {}^{12}C + n$$

(Atomic) Nucleus

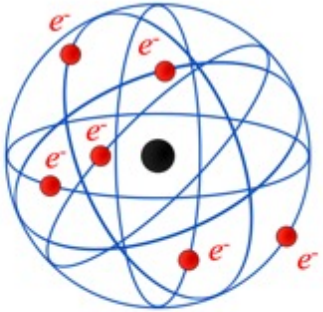


(~10^{-10}m) (~10^{-15}m)

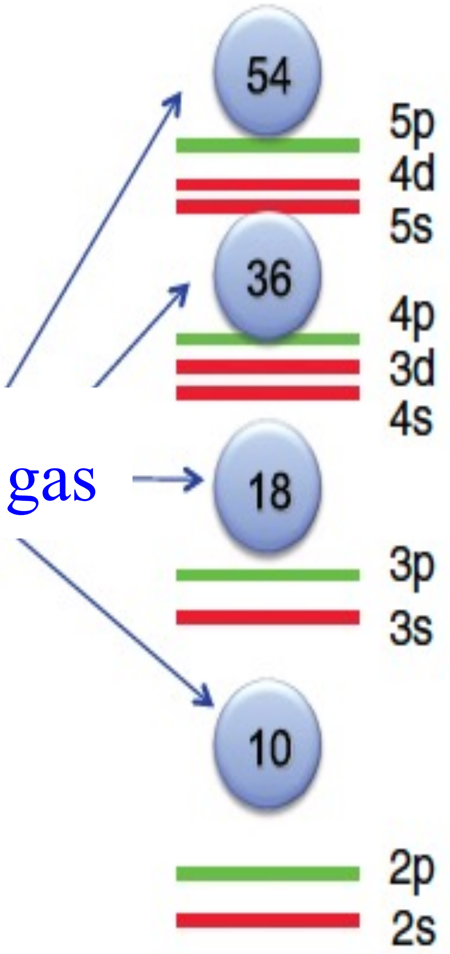
Nuclear reaction as a probe for nuclear structure

What is the structure of the nucleus?

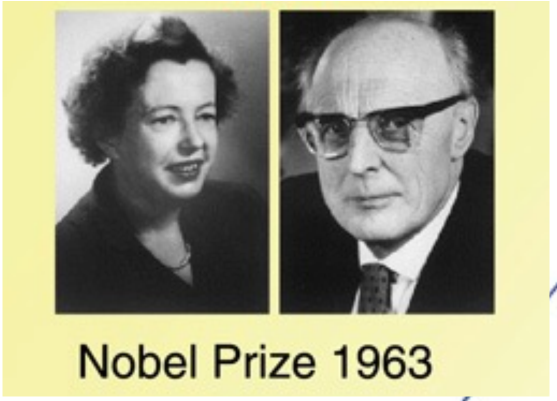
Shell structure of atom



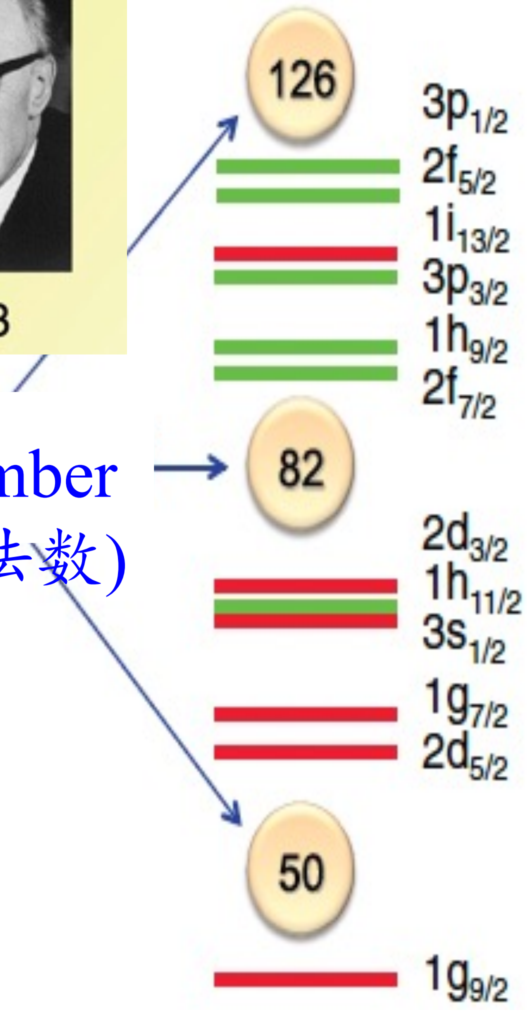
Nobel gas

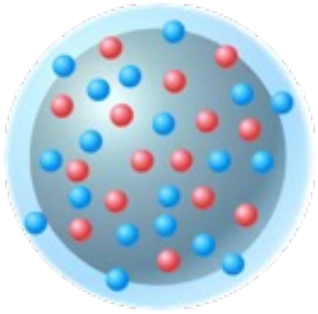


Shell structure of nucleus

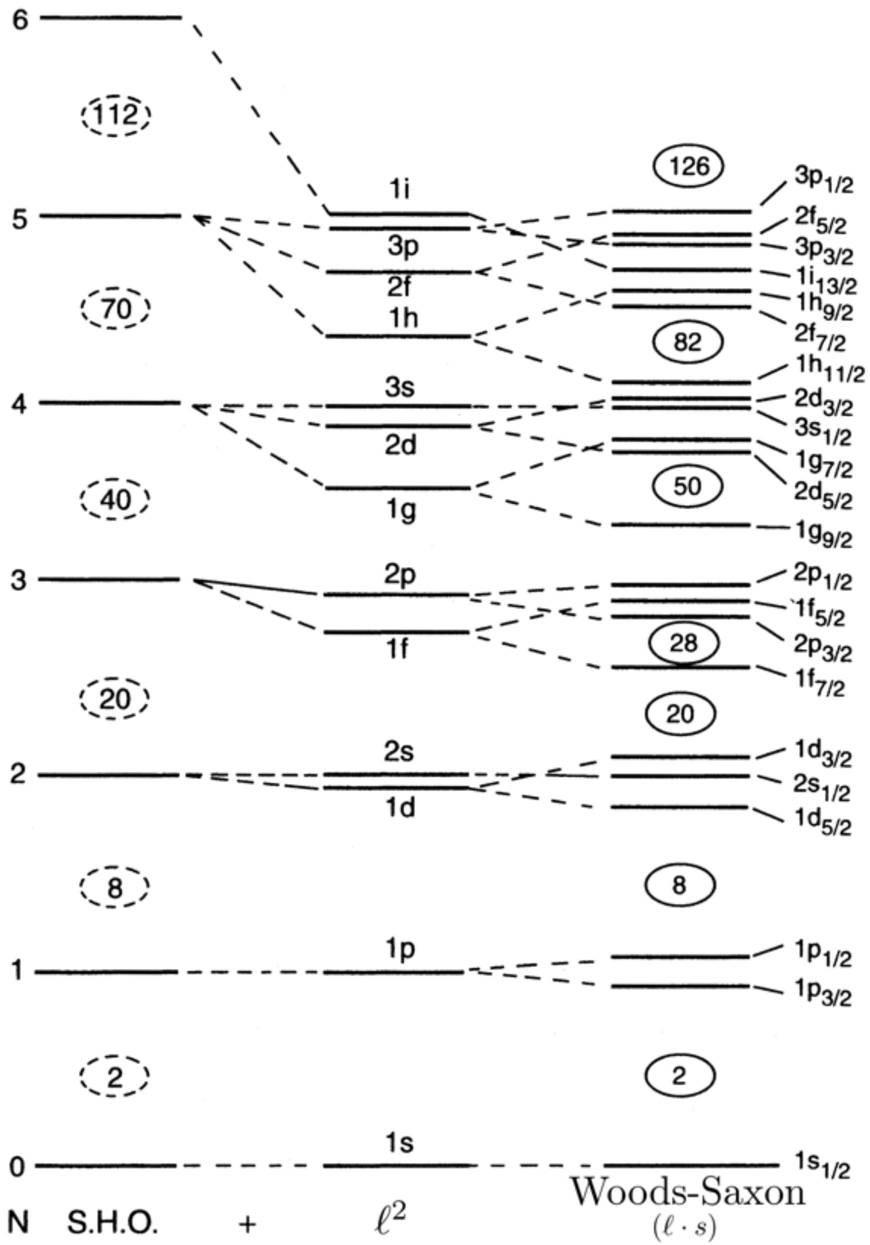


Magic number
(幻数/魔法数)

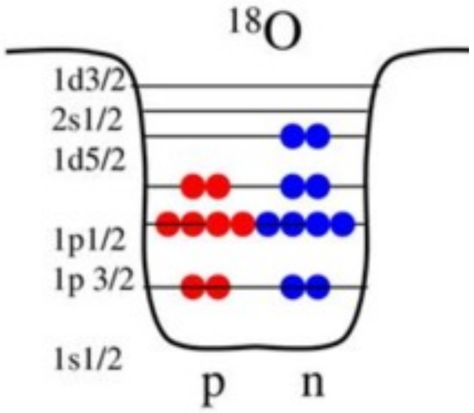




Single-particle levels and shell structure

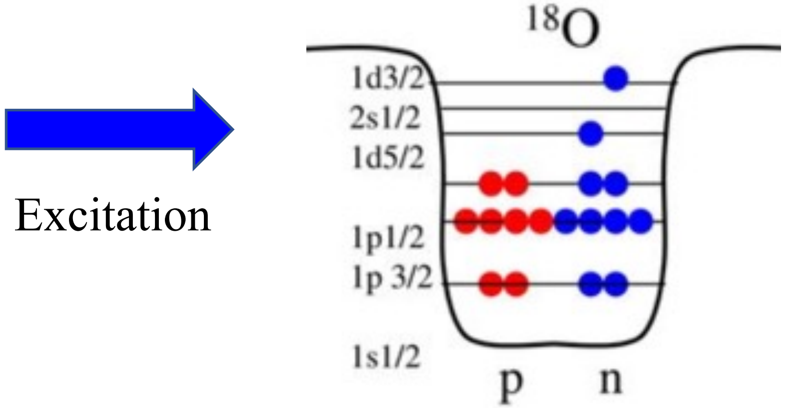


Ground state

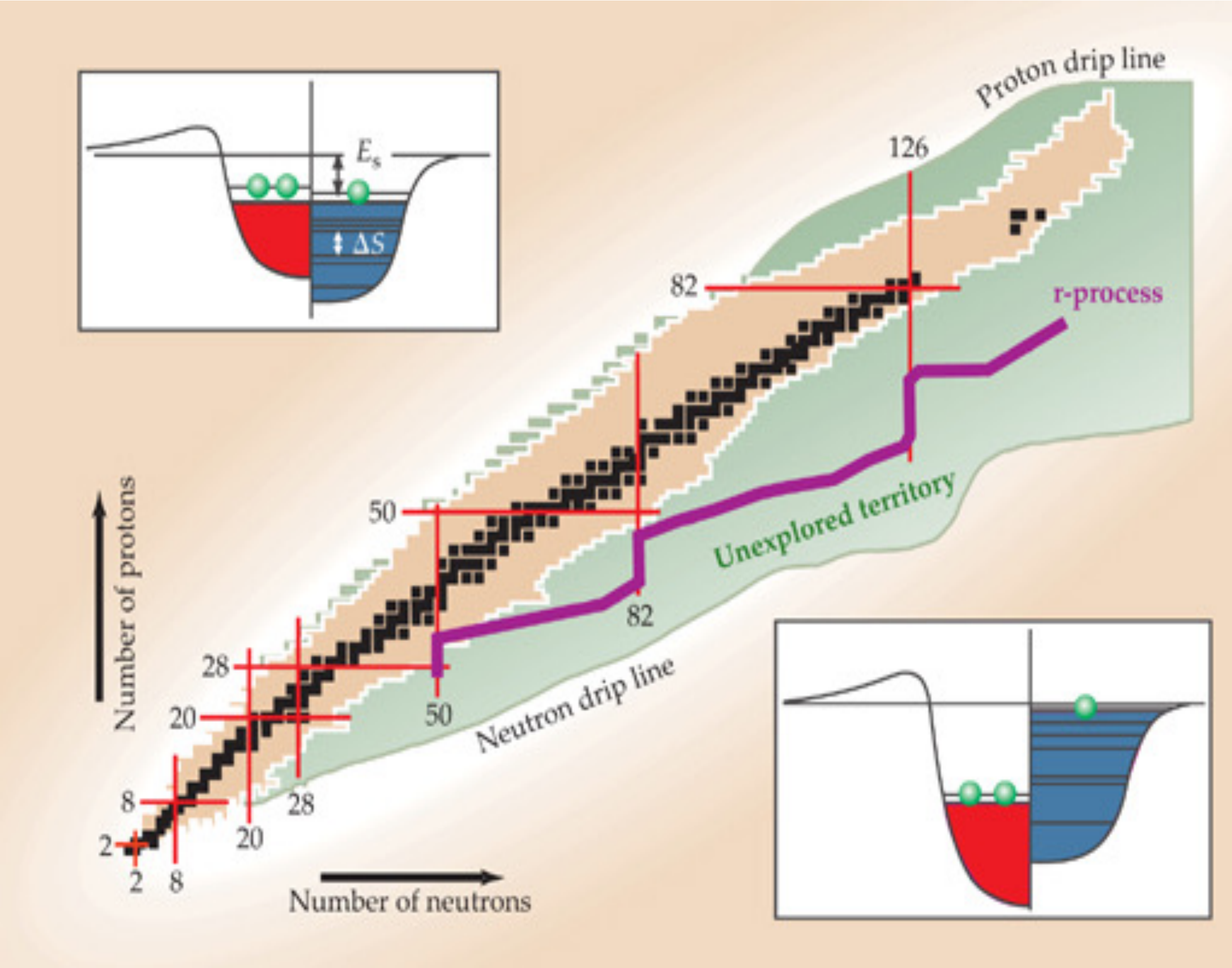


Excitation

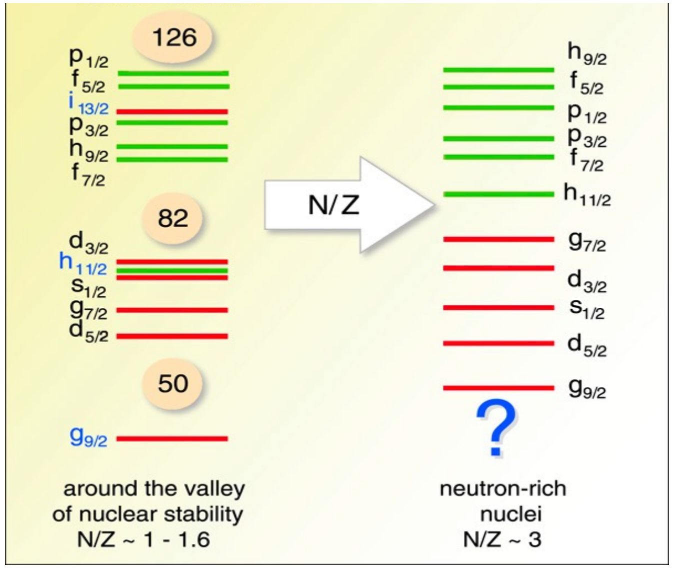
Excited state



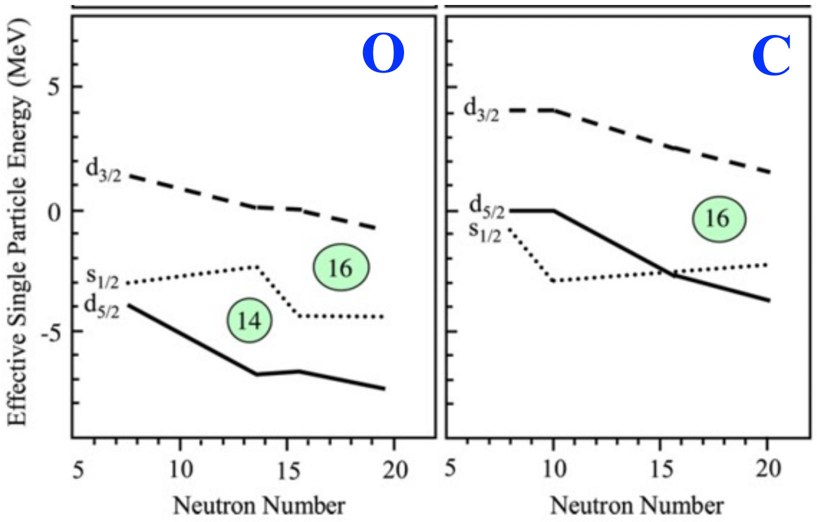
Evolution of the shell structure and new magic numbers



Otsuka et al. RMP92(20)015002



Sorlin et al. PPNP 61(2008)602



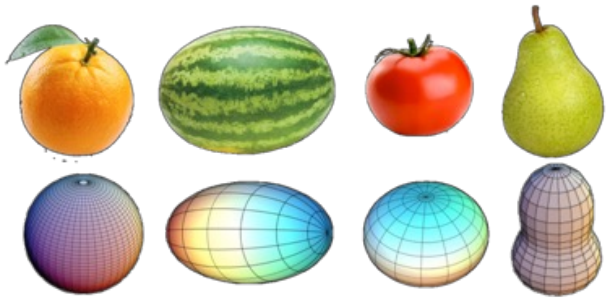
- ✓ Change of density distribution
- ✓ Continuum coupling (from closed- to open-quantum systems)
- ✓ …

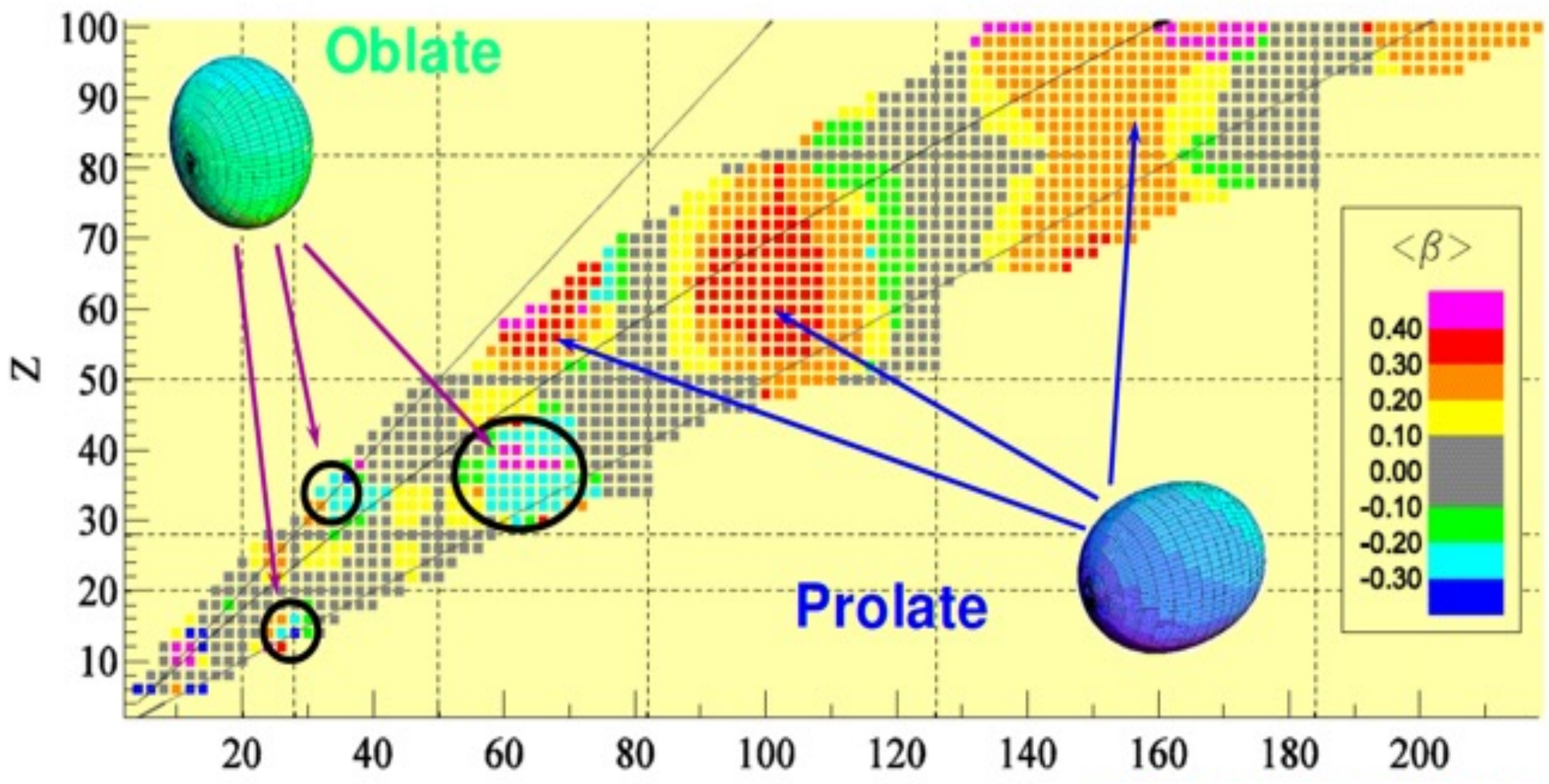
Shapes and Collective excitation

- ✓ Description of “shape”:

$$R(\theta,\phi) = R_0\left[1+\sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda} a_{\lambda,\mu}Y_{\lambda\mu}(\theta,\phi)\right]$$

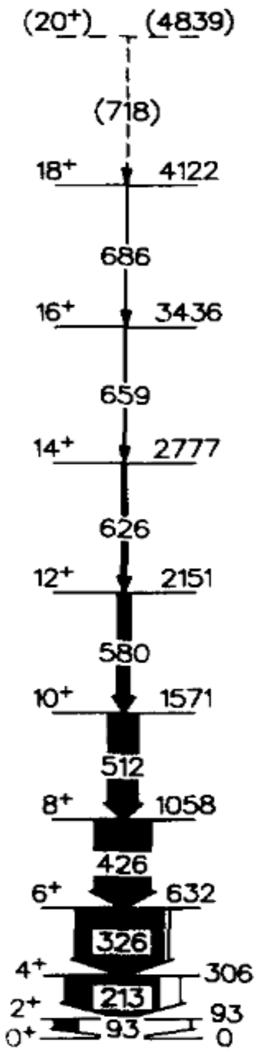
- ✓ Nuclei are not always spherical.

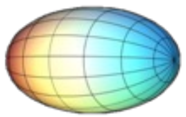




E. Clément INTC-P-216 CERN-INTC (2006)

Rotations of deformed nuclei



^{178}Hf 

Mmullins et al. PLB393(97)279

✓ Check the E_x systematics

- Experimental data

J^π	0^+	2^+	4^+	6^+	8^+
$E_x\ (kev)$	0	93.2	306.6	632.2	1058.6
$E_{J\pi}/E_{2+}$	0.00	1.00	3.29	6.78	11.36

- Predictions of a simple rotor model: $E_x \sim J(J+1)\frac{\hbar^2}{2I}$

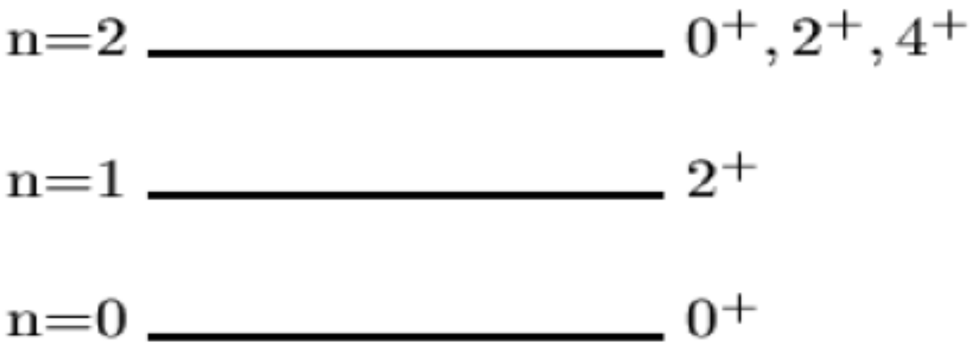
J^π	0^+	2^+	4^+	6^+	8^+
$E_x\ (kev)$	0	$6\frac{\hbar^2}{2J}$	$20\frac{\hbar^2}{2J}$	$42\frac{\hbar^2}{2J}$	$72\frac{\hbar^2}{2J}$
$E_{J\pi}/E_{2+}$	0.00	1.00	3.33	7.00	12.00

E_{4+}/E_{2+} =3.33 for a rotor

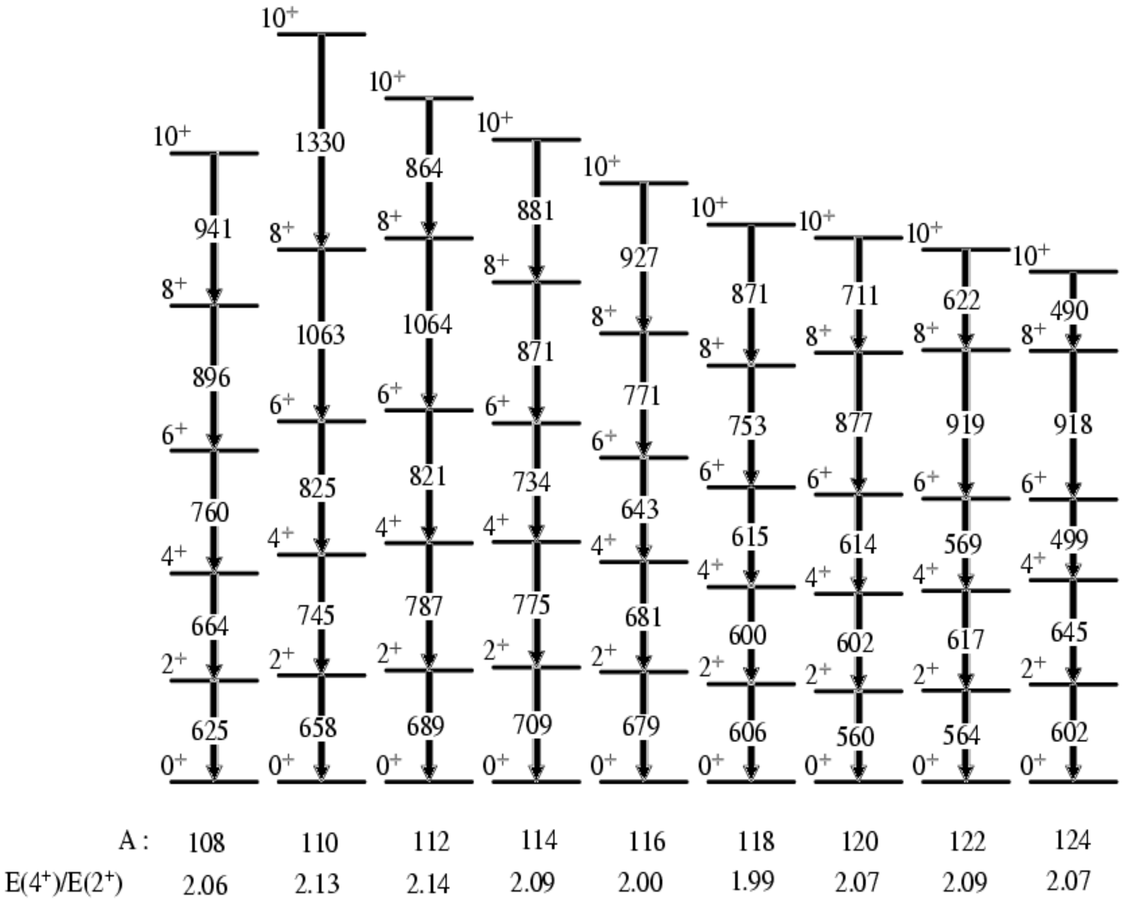
Vibrations of (nearly) spherical nuclei

✓ Excitation energy described by phonons

E_{4+}/E_{2+} =2 for vibrator

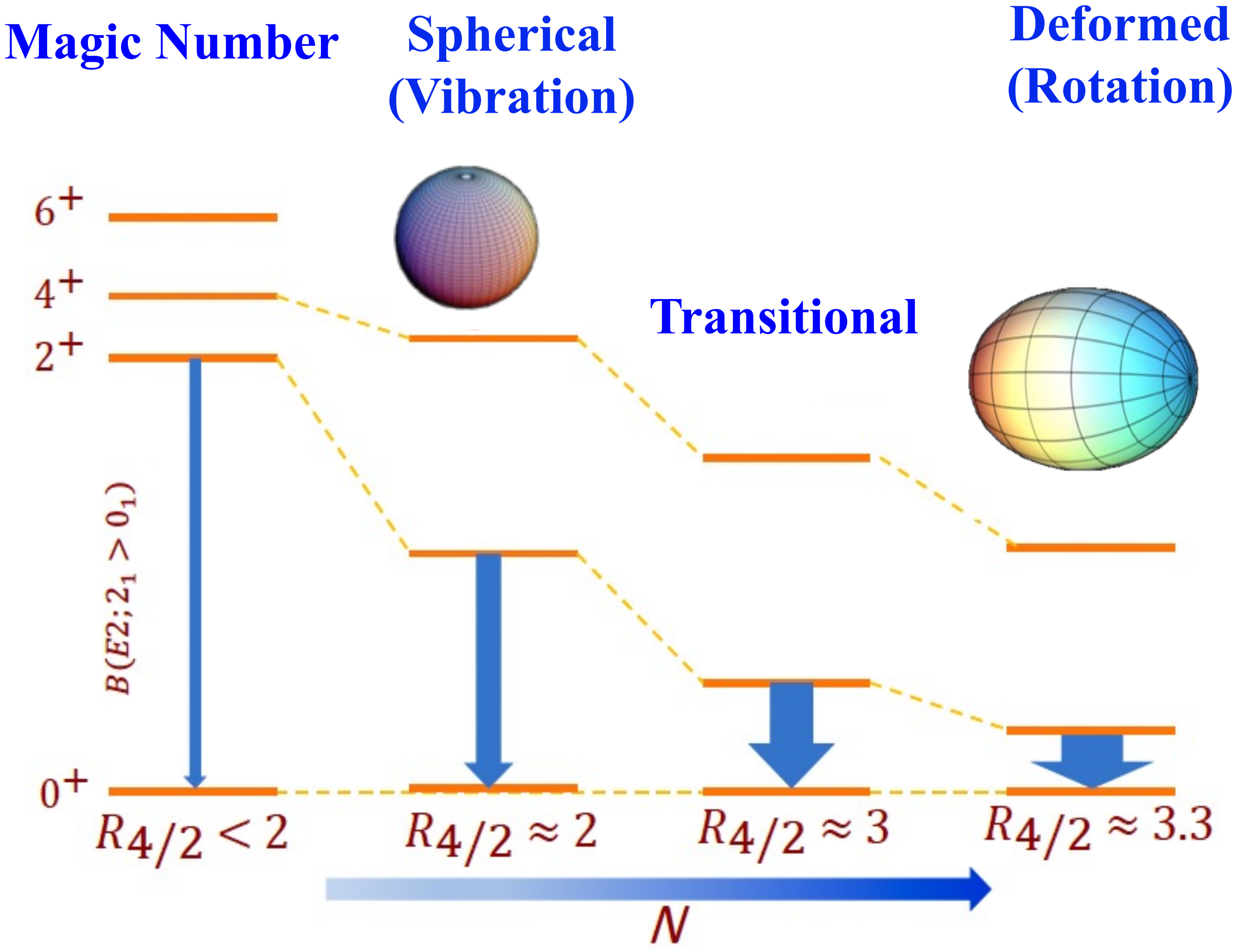


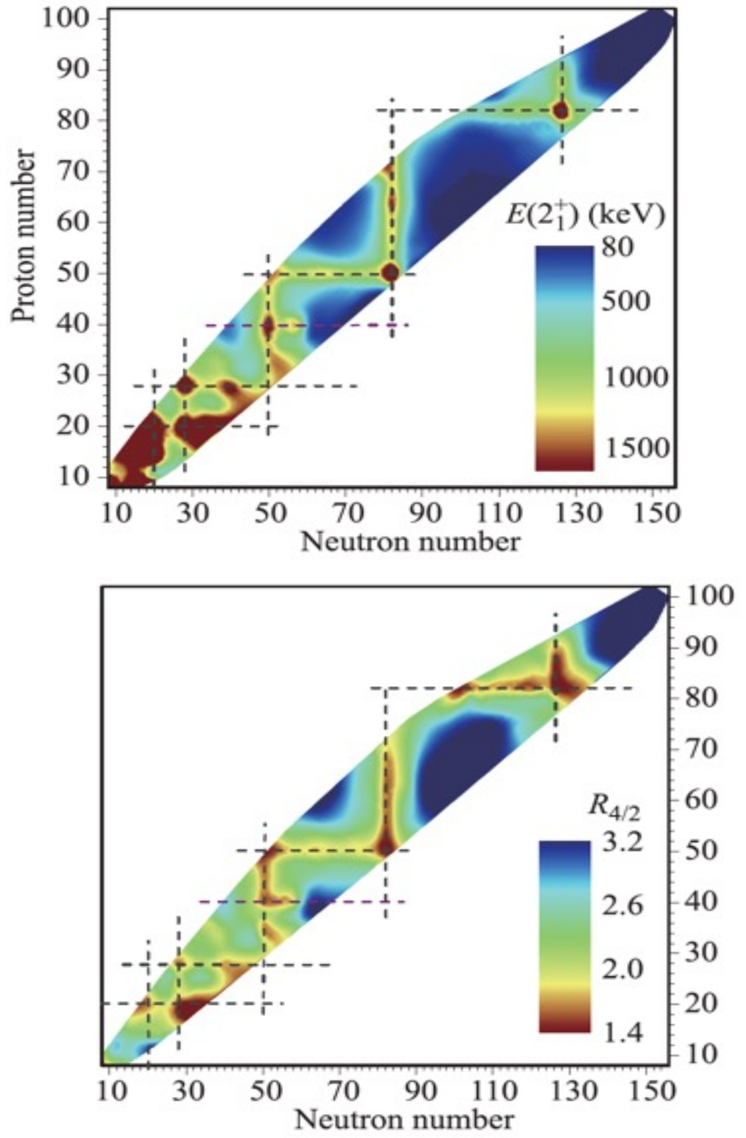
Te Isotopes (Z=52)



Evolution of shell structure and shape

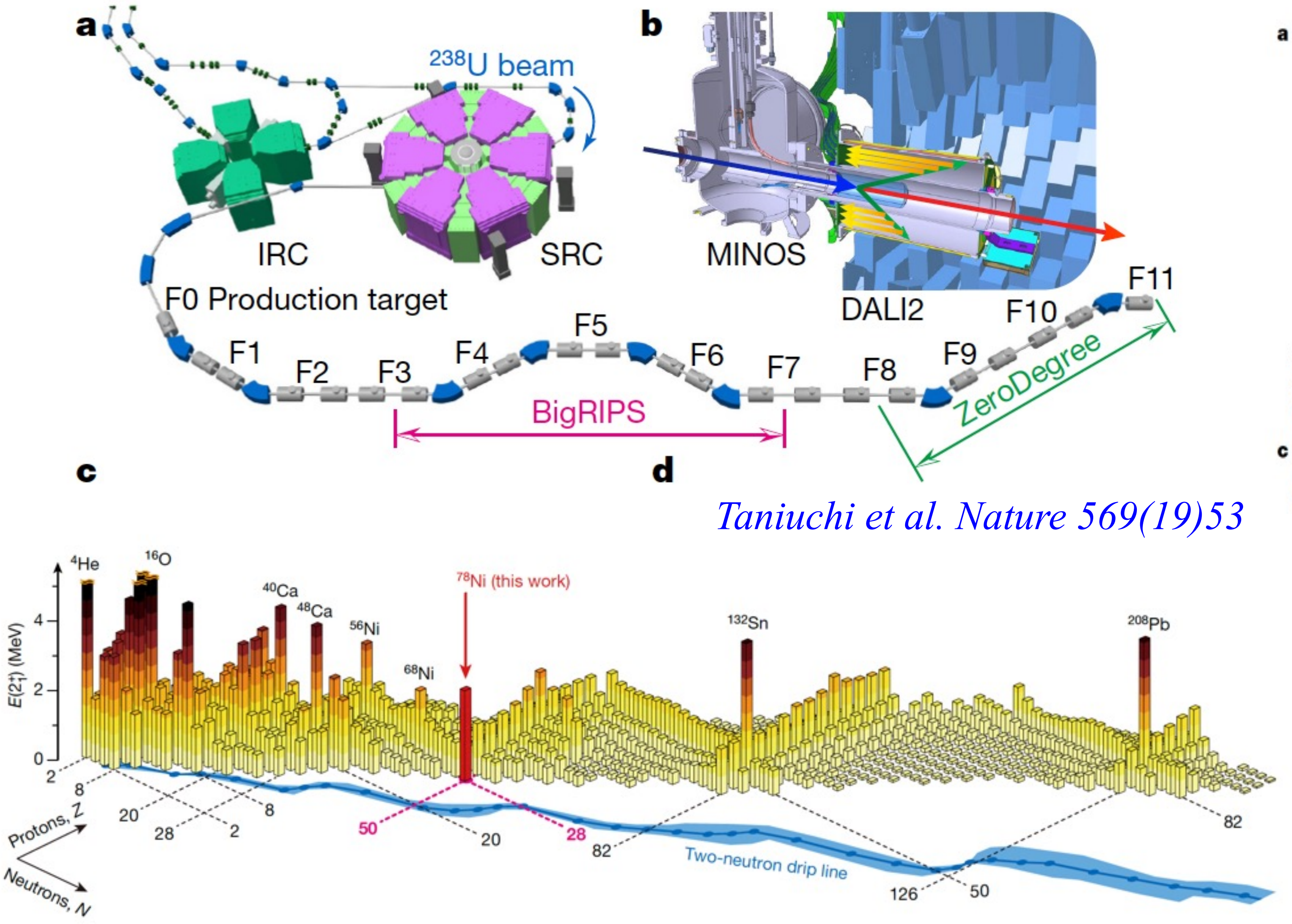
R. F. Casten. Frontiers of Physics, 13(2018)132104



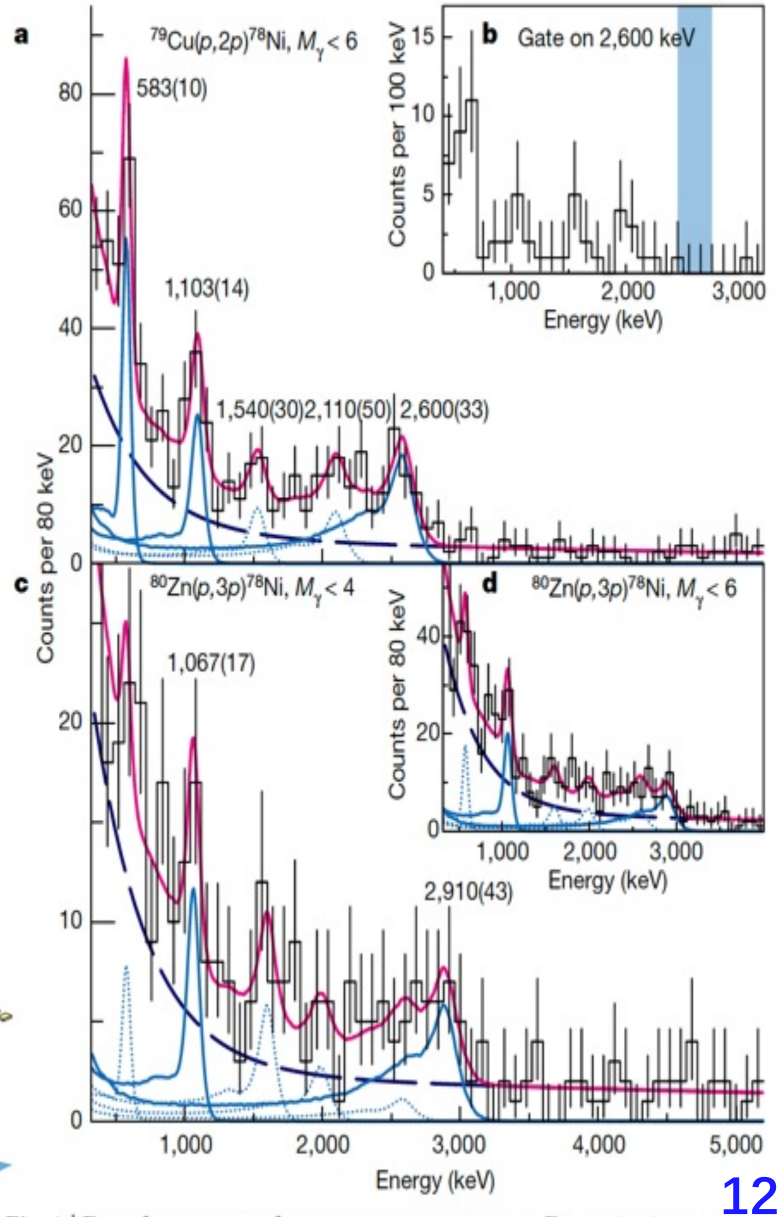


E_{2+} *and* E_{4+}/E_{2+} : indicator for the evolution of shell structure and shape.

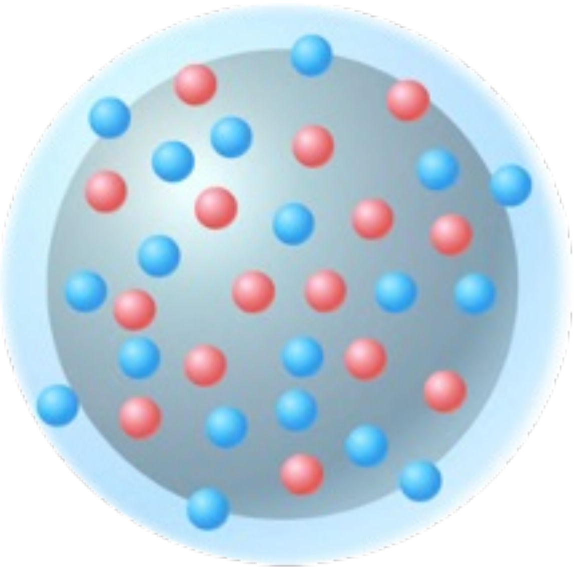
^{78}Ni: Magicity from in-beam γ-ray spectroscopy @RIBF

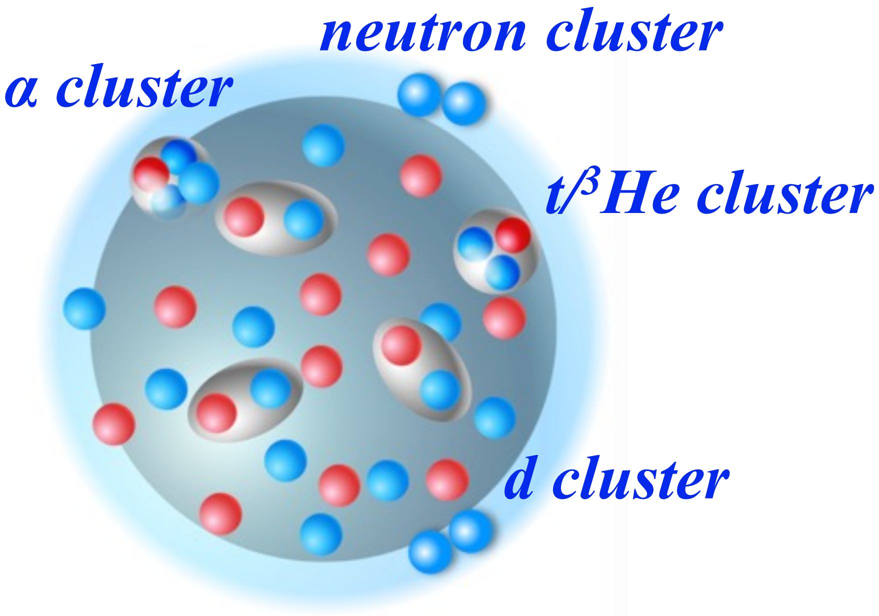


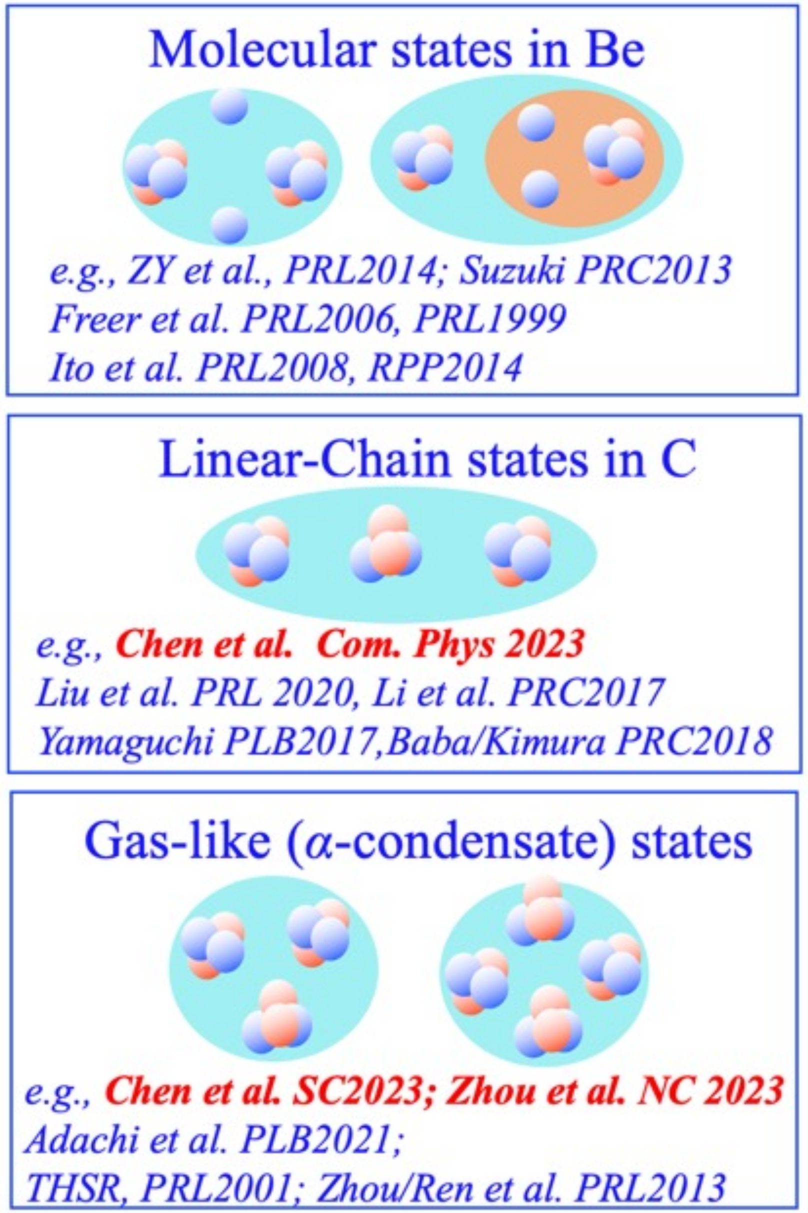
Taniuchi et al. Nature 569(19)53



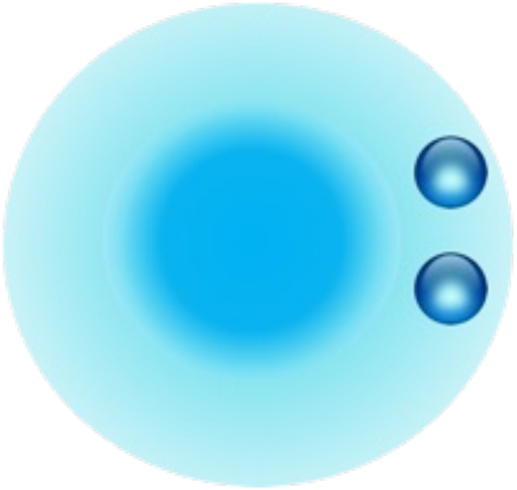
Non-uniformity in the nucleus: clustering



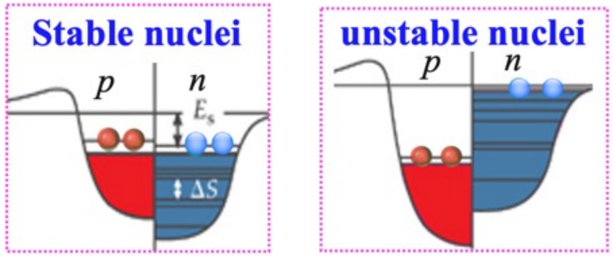


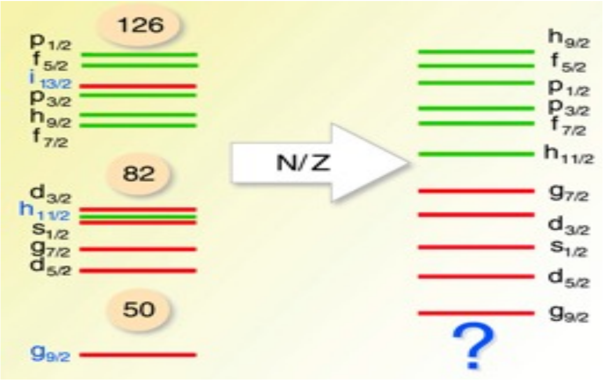


Neutron halo

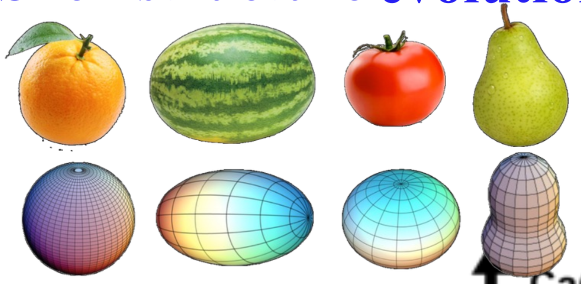


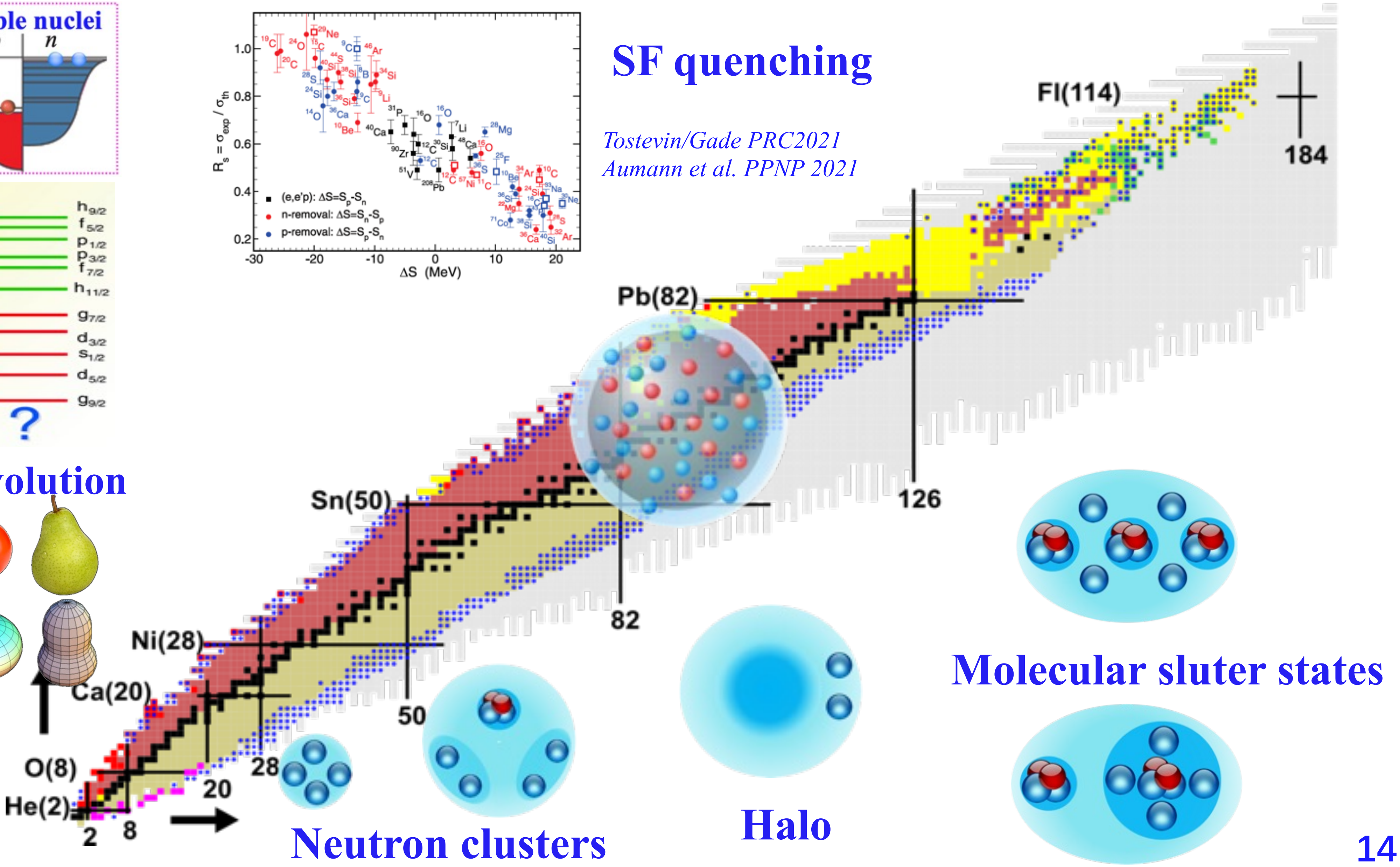
What is the structure of (unstable) nuclei?



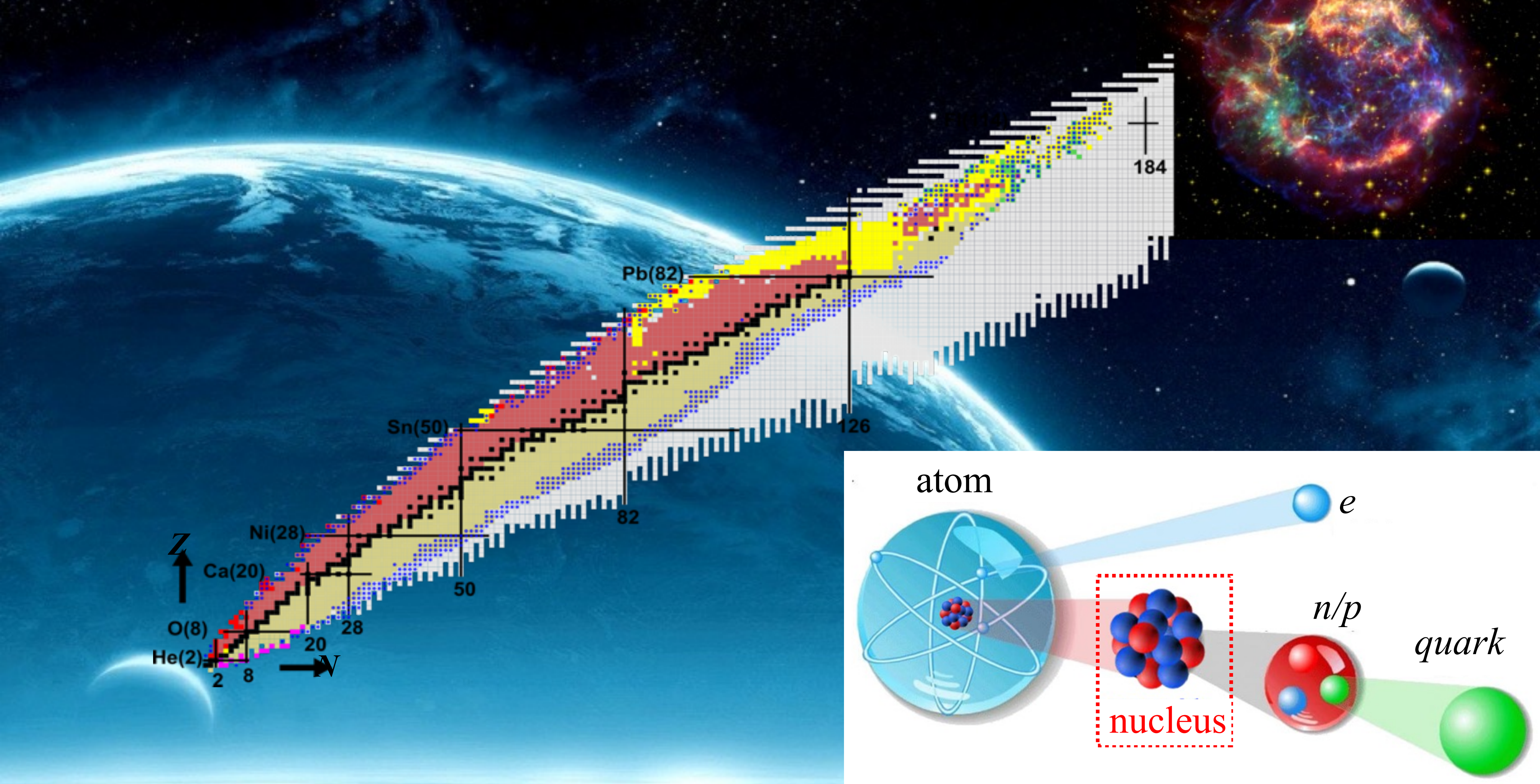


Shell structure evolution



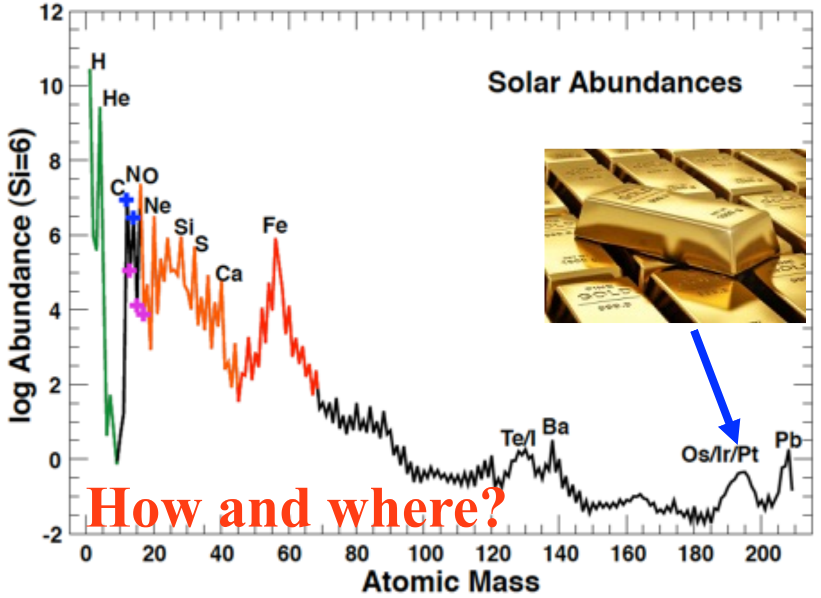


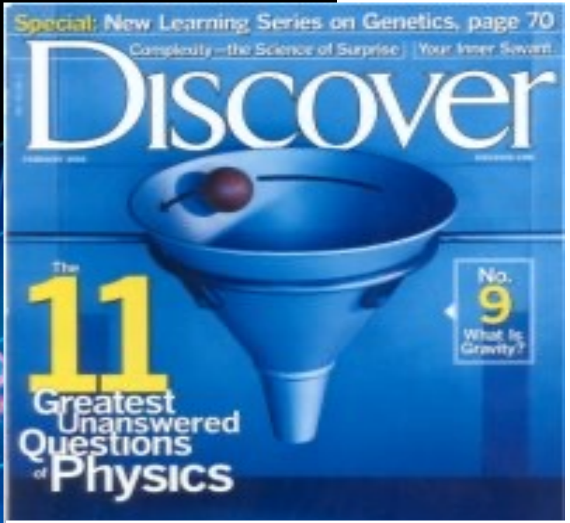
Nucleus: from tiny to infinity



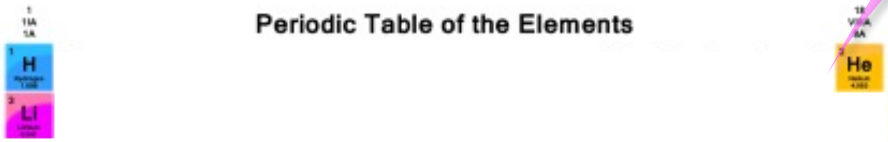
The Origin of (heavy) elements?

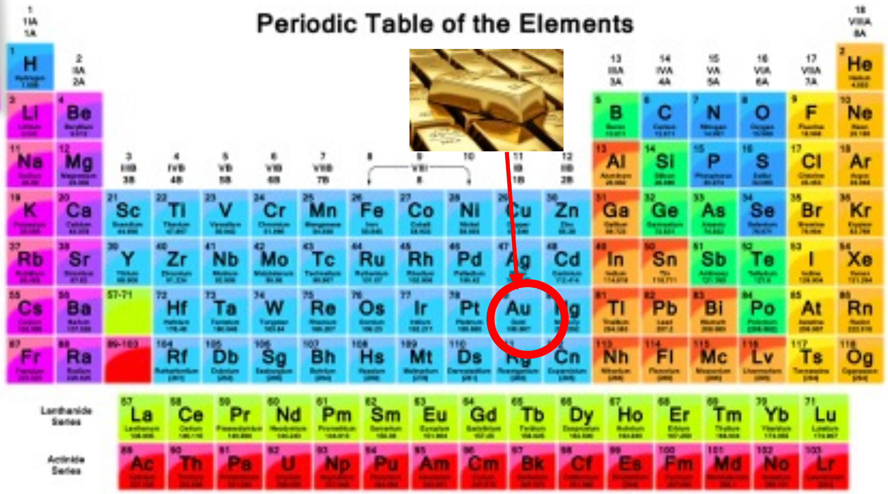
Alchemy（錬金術）





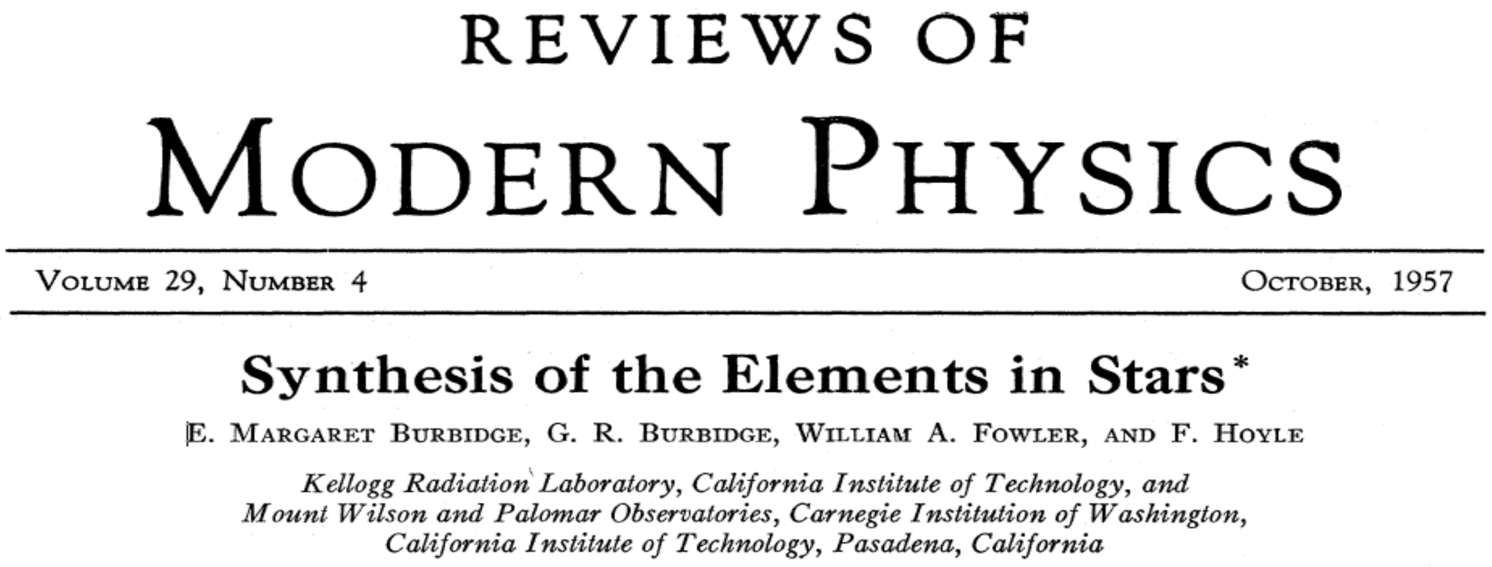
(3)How were the heavy elements from iron to uranium made?





Long history of understanding energy generation of the sun

- ✓ 1928, G.Gamow: tunneling effect
- ✓ Rutherford’s work on nuclear transmutations (1919~): energy may be generated from nuclear reactions in stars
- ✓ 1938, Bethe and Critchfield: “formation of deuterons by proton combination” (H burning)
- ✓ 1938/1939, Weizaecker and Bethe: CNO cycle
- ✓ 1946, Hoyle: nuclear reactions in genesis of the chemical elements
- ✓ 1950s, essential framework of stellar nucleosynthesis (B2FH)


REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

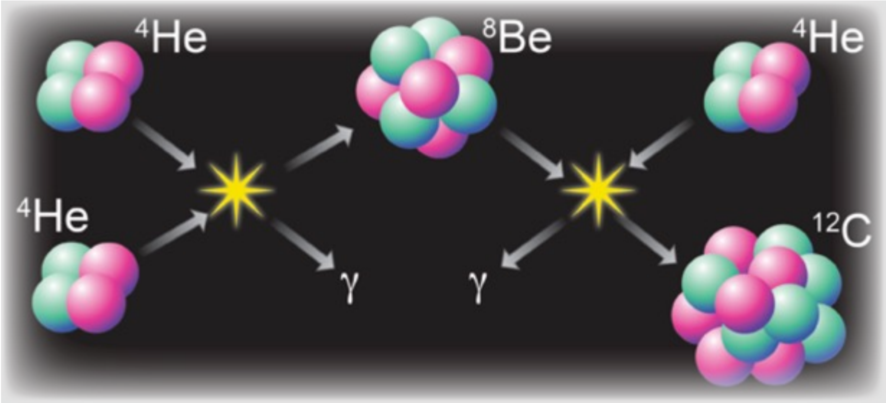
Synthesis of the Elements in Stars*

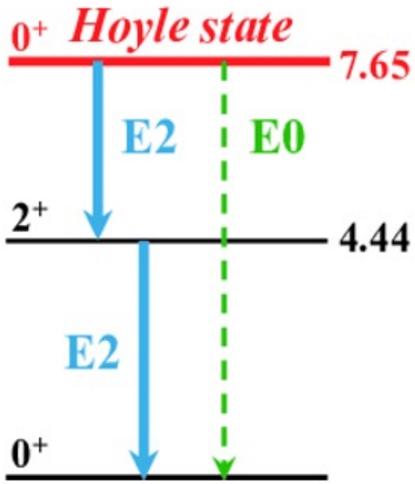
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

Helium Burning $3\alpha \to {}^{12}C$ and the Hoyle state

- ✓ No long-lived nuclei with A=5 and A=8
- ✓ Direct 3-α capture Rate is too low to explain the ^{12}C abundance





Hoyle, APJ Suppl.1(54)121

- ✓ The 3α (resonant) reaction rate is : $r_{3\alpha} = \rho^2 N_A^2 Y_{^8\mathrm{Be}} Y_\alpha \langle\sigma v\rangle_{^8\mathrm{Be}+\alpha}$

(narrow resonant state)

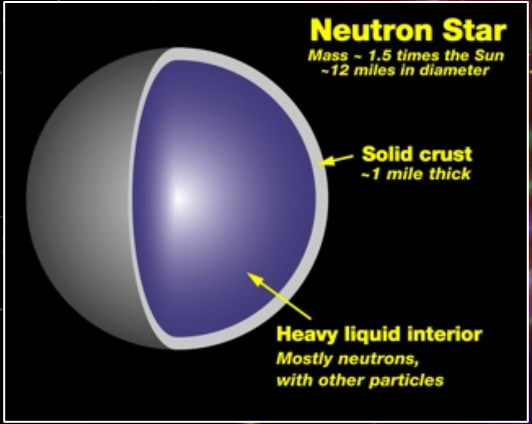
$$\langle\sigma v\rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 (\omega\gamma)_r \exp\left(-\frac{E_r}{kT}\right) \qquad \omega\gamma = \frac{\Gamma_\alpha \Gamma_\gamma}{\Gamma}$$

$$r_{3\alpha \to {}^{12}C} = \rho^3 N_A^3 \frac{Y_\alpha^3}{2} 3^{3/2} \left(\frac{2\pi\hbar^2}{M_\alpha kT}\right)^3 f\omega \frac{\Gamma_\alpha \Gamma_\gamma}{\Gamma\hbar} \exp\left(-\frac{Q}{kT}\right) \qquad Q_{3\alpha} = 380 keV$$

Neutron star and dense matter

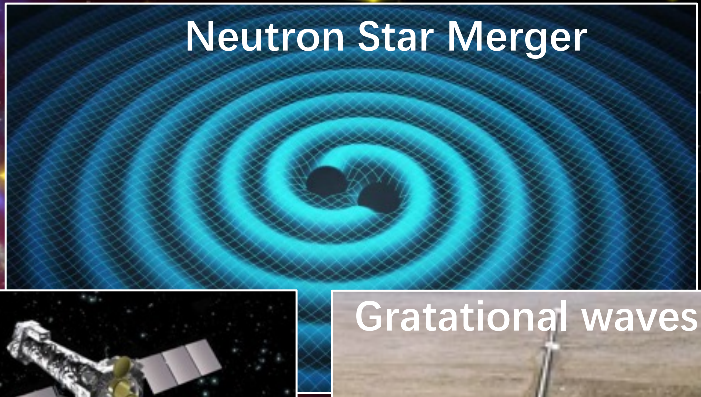
- -Equation of state of nuclear matter?
- -Phases of dense nuclear matter?
- -Elements created in supernovae?
- -Elements ejected in neutron star mergers

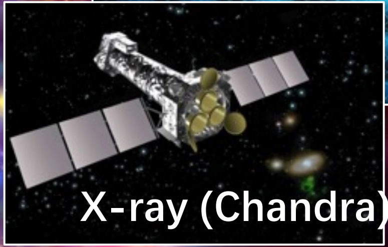
Neutron Stars



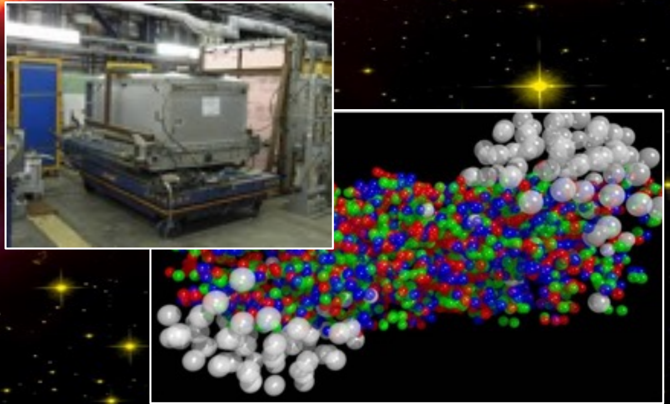
RIB reactions

Astrophysical observations

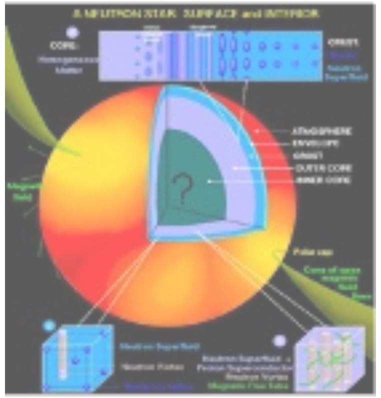




Heavy Ion Collisions



EoS： from nucleus to neutron stars



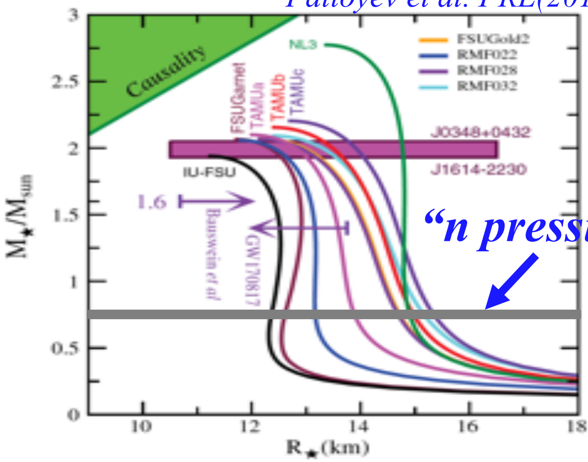
In Heaven

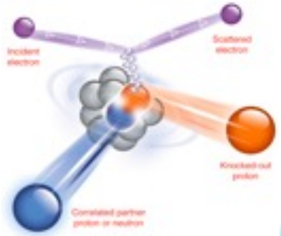
Neutron star

- ✓ *EoS + General relativity*
- ✓ *Merger*
- ✓ *Cold dense matter*

Mass-radius relation

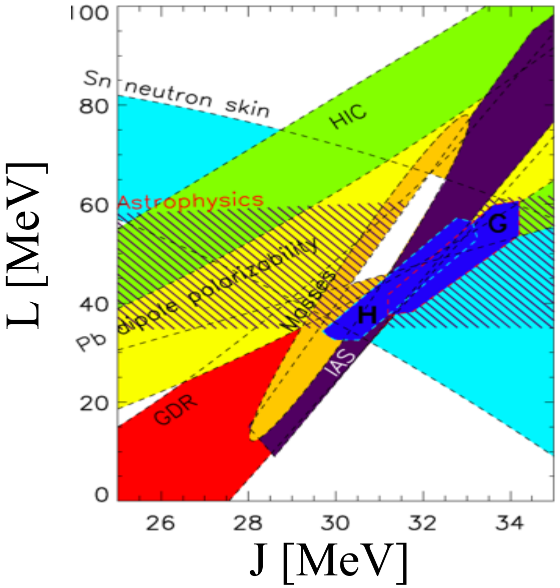
Fattoyev et al. PRL(2018)





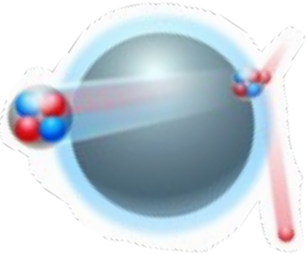
Nuclar matter EoS

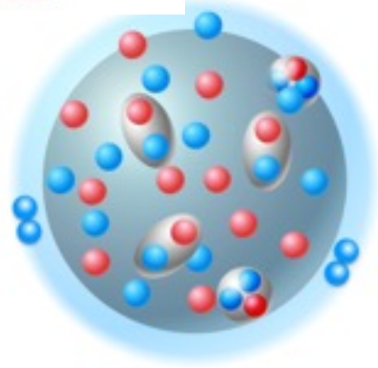
Roca-Maza, PPNP(2018)



Better constraints

- ✓ *More (accurate) data*
- ✓ *Nuclear interactions*
- ✓ *Correlations and clusters*





On Earth

EoS： from nucleus to neutron stars

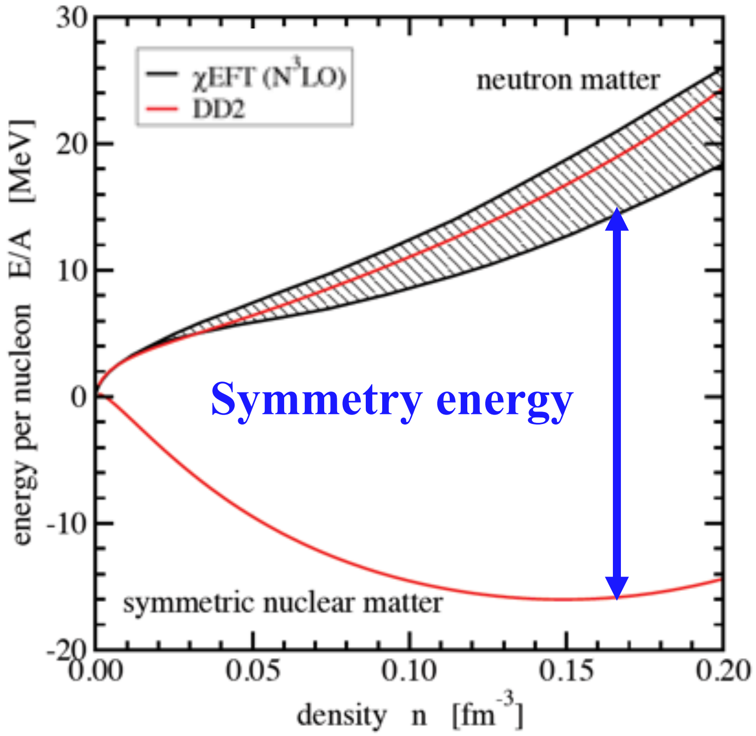
- ✓ **Nuclear matter equation of state (EoS)**

$$\frac{E}{A}(\rho,\delta)=\frac{E}{A}(\rho,0)+S(\rho)\,\delta^2+\ \ldots \qquad \rho(r)=\rho_n(r)+\rho_p(r) \qquad \delta(r)=\frac{\rho_n(r)-\rho_p(r)}{\rho_n(r)+\rho_p(r)}$$

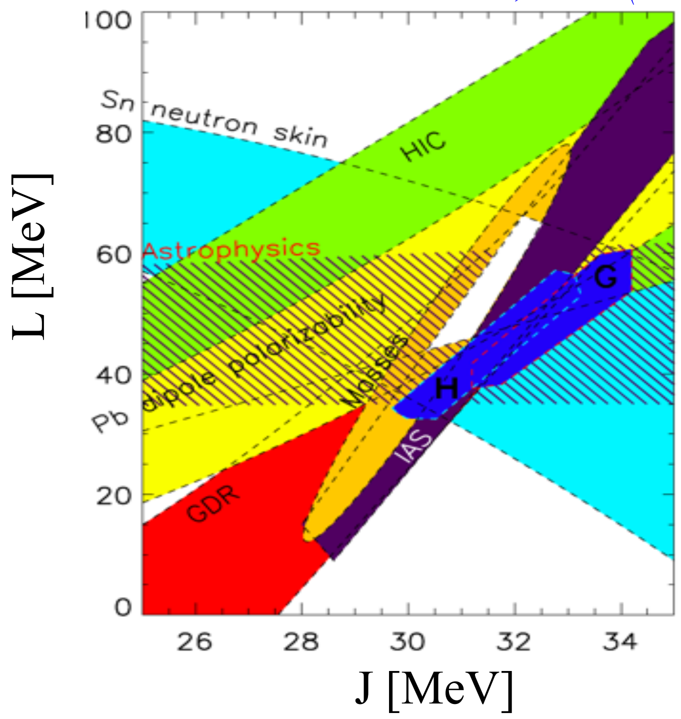
- ✓ **Symmetry energy**

Slope parameter

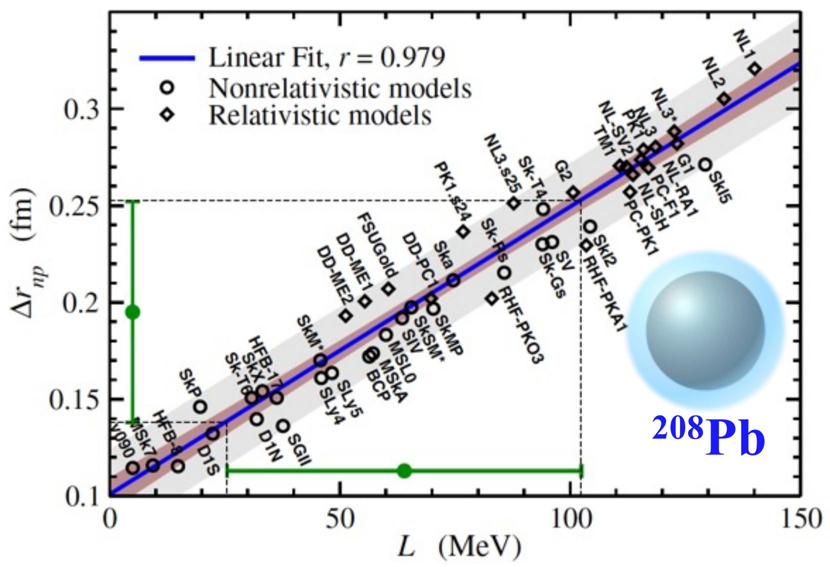
$$S(\rho)=J+\frac{L}{3\rho_0}(\rho-\rho_0)+\frac{K_{sym}}{18\rho_0}(\rho-\rho_0)^2+\ \ldots$$



Roca-Maza, PPNP(2018)

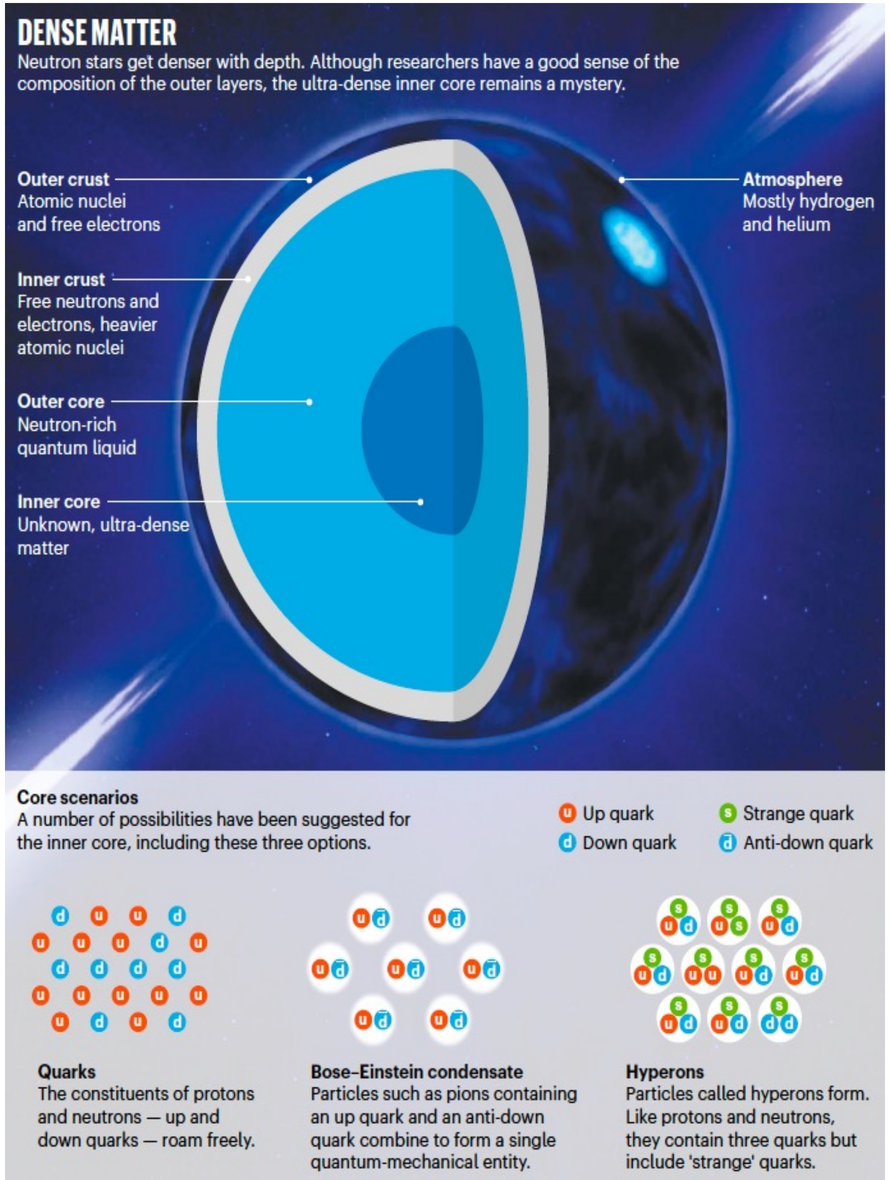


n-skin Δ_{np} ~L



Roca-Maza, PRL (2001)

EoS： from nucleus to neutron stars



- ✓ Born in the core-collapse supernova of massive stars.
- ✓ Typical mass: ~1.4 $M_\odot$
- ✓ Typical size: radius ~10 km

Tolman-Oppenheimer-Volkoff (TOV) equations with parameters of Nuclear EoS

$$\frac{dp}{dr} = -G\frac{\varepsilon m}{r^2}\left(1+\frac{p}{\varepsilon}\right)\left(1+\frac{4\pi p r^3}{m}\right)\left(1-\frac{2Gm}{r}\right)^{-1}$$

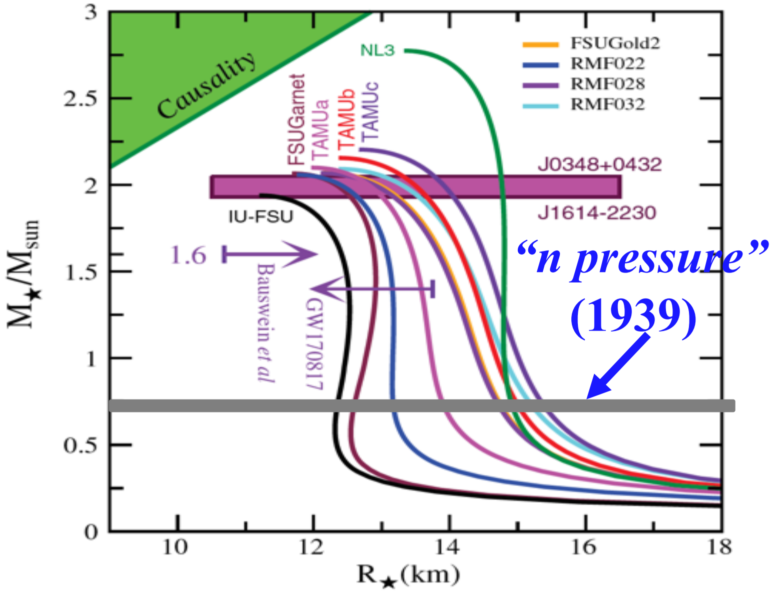
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon ,$$

-G is the gravitational constant

-*p* is pressure and *ε* is energy density

Mass-radius relation

Fattoyev et al. PRL(2018)

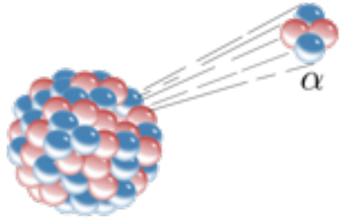


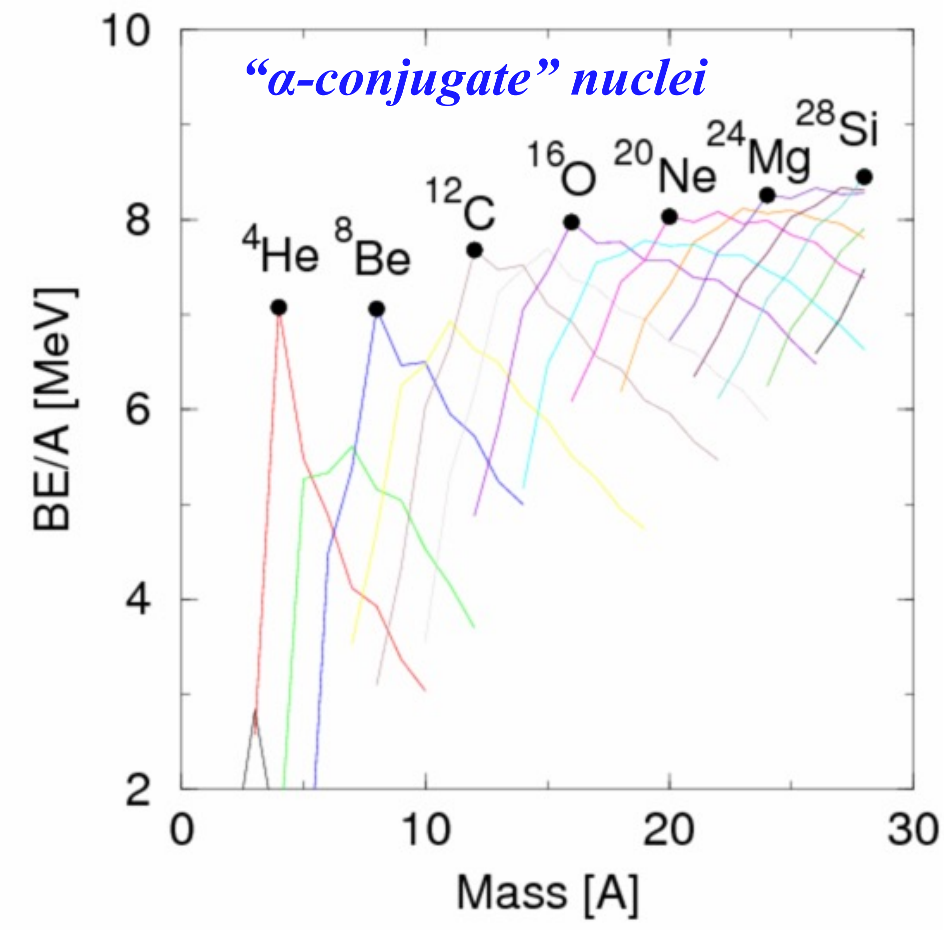
Outline

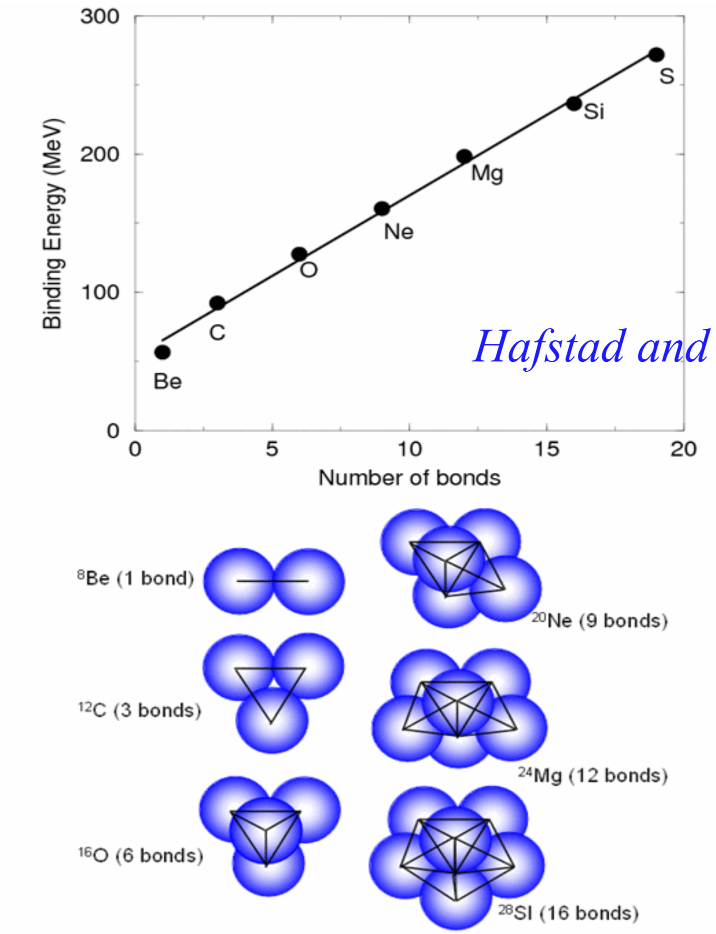
- ✓ Introduction: basics about the structure of nucleus
- ✓ Clustering in nuclear systems
- ✓ Halo and neutron correlations
- ✓ Summary and Perspective

“α particle” nuclei in 1930s

- ✓ Alpha radioactivity: 1890s
- ✓ Alpha decay model (quantum tunneling): Gamow, 1928
- ✓ Discovery of the neutron: 1932, Chadwick







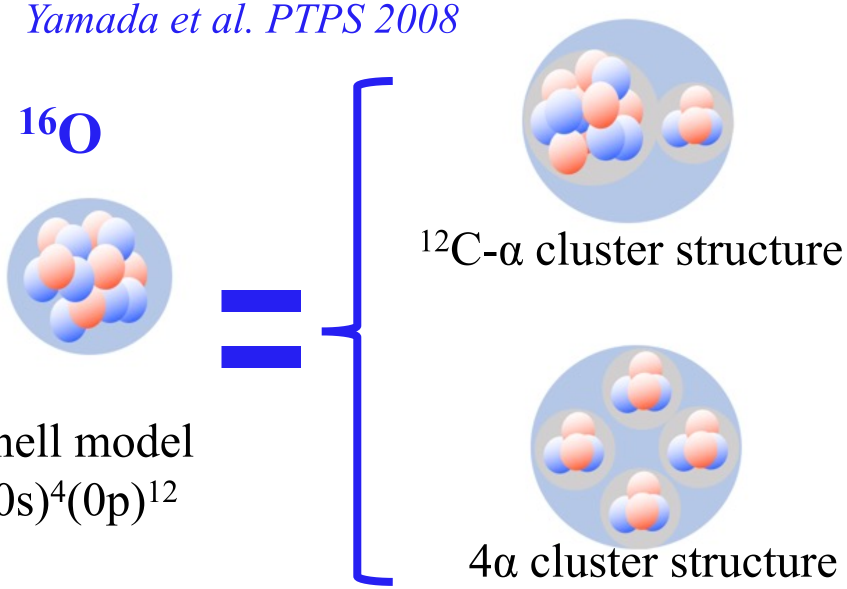
Hafstad and Teller, PR 1938

Coexistence of clustering and non-clustering structures

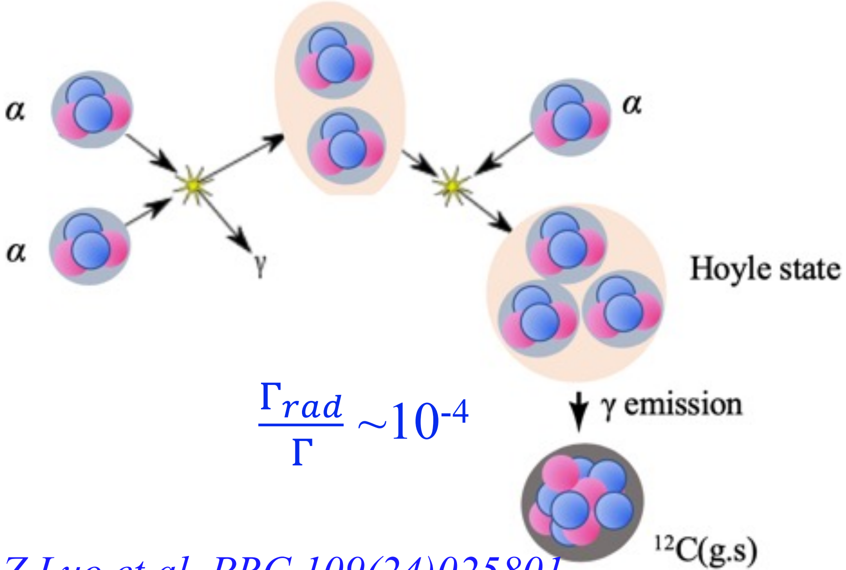
Duality of nuclear WF

✓ Bayman-Bohr theorem *Nucl. Phys. 1958*

Yamada et al. PTPS 2008



The Hoyle state



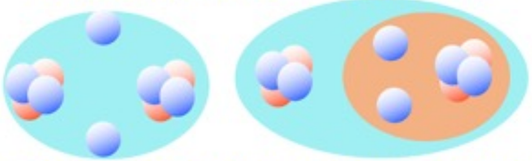
$\frac{\Gamma_{rad}}{\Gamma} \sim 10^{-4}$

Z.Luo et al. PRC 109(24)025801

Freer et al. PPNP78(14)1

Cluster structures in excited states of light nuclei

Molecular states in Be



e.g., ZY et al., PRL2014; Suzuki PRC2013
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Linear-Chain states in C

*e.g., **Chen et al. Com. Phys 2023***
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Gas-like (α-condensate) states

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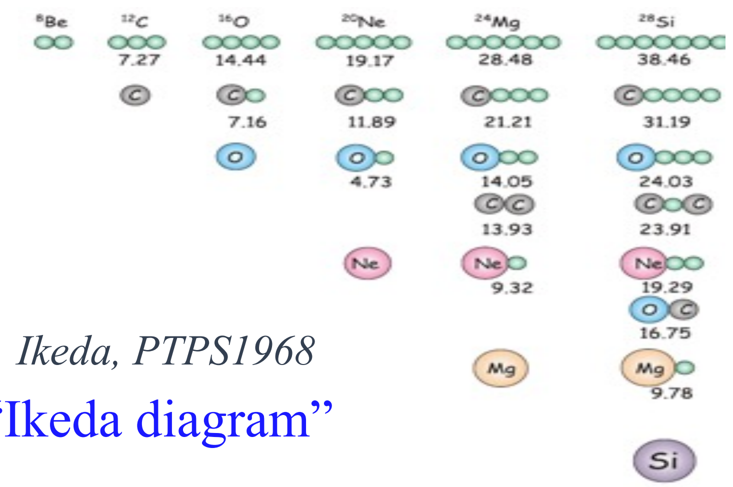
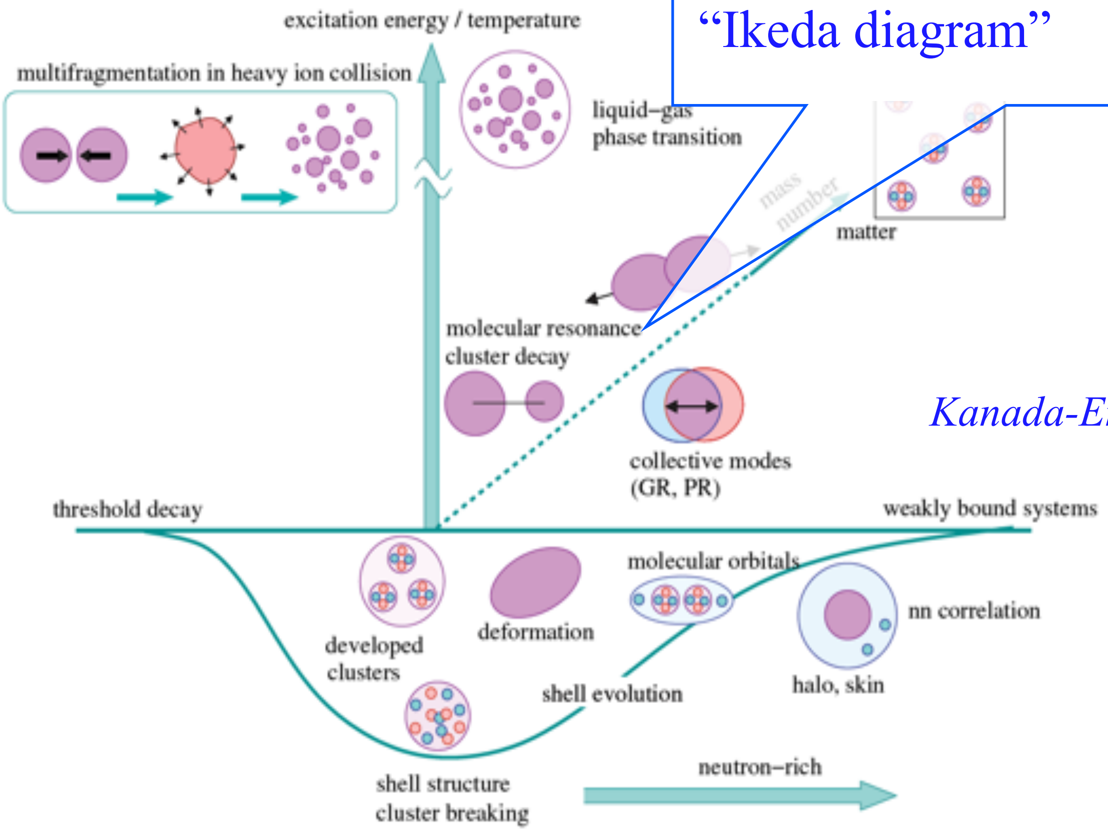


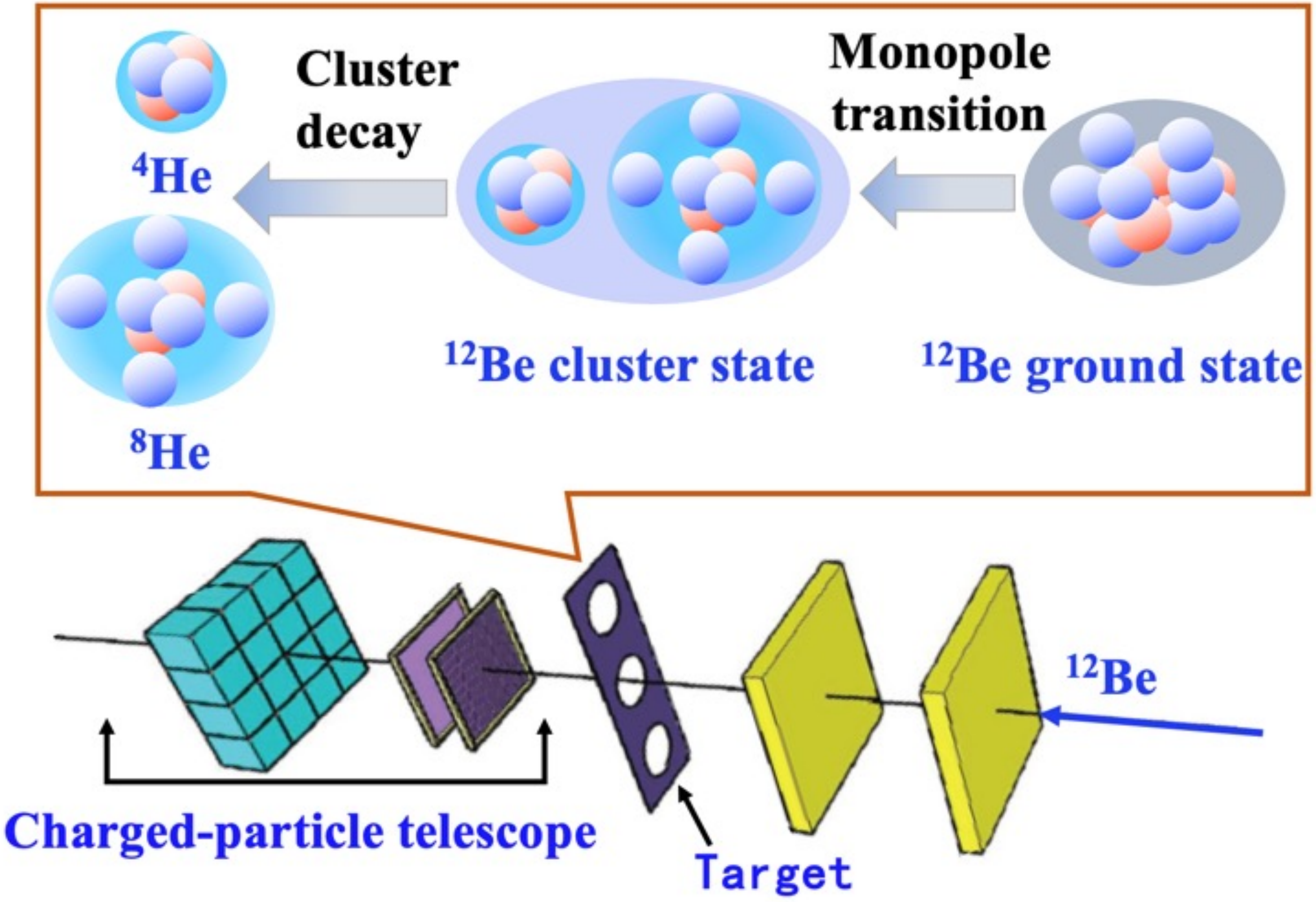
Ikeda, PTPS1968
"Ikeda diagram"



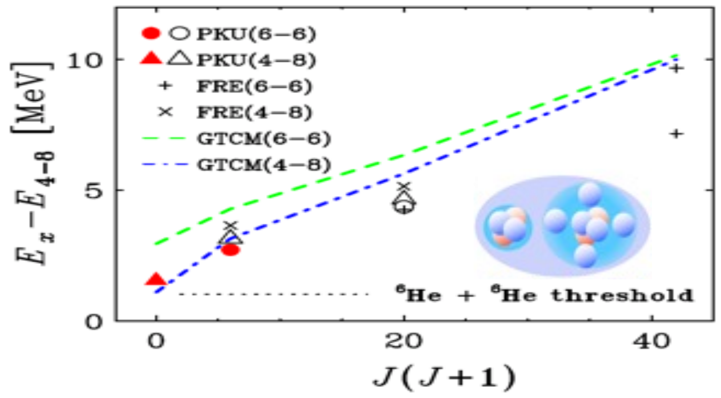
Kanada-Enyo, PTEP 2012

e. g.： Molecular cluster structure in ^{12}Be

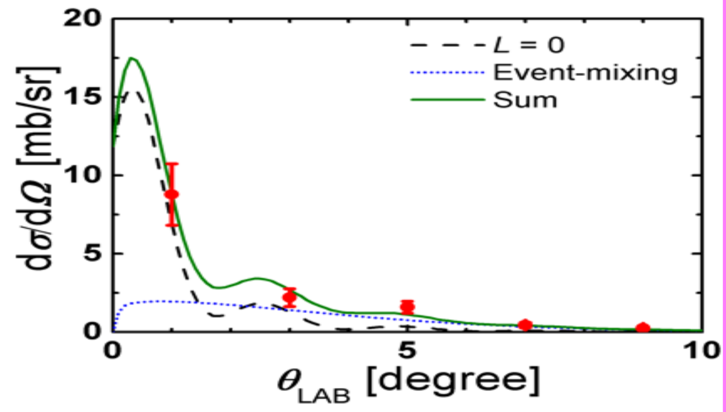
@HIRFL-RIBLL1 beamline（IMP, Lanzhou, China）



Cluster rotational band



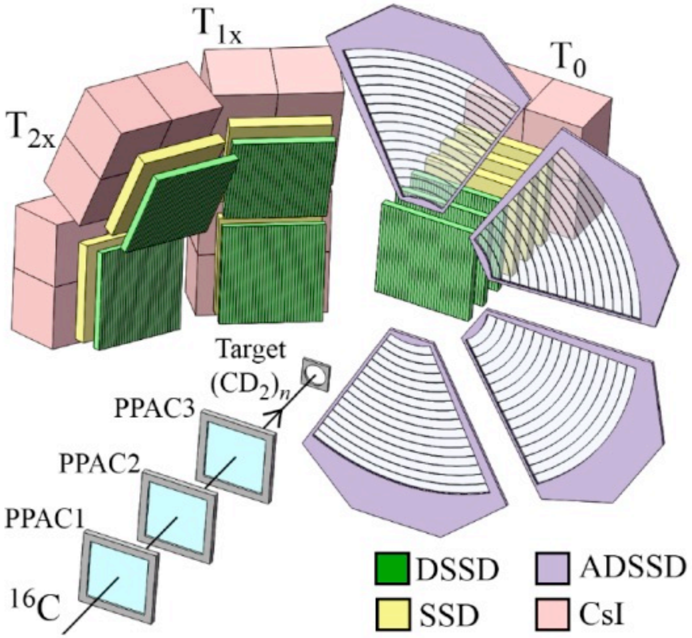
Enhanced M(IS) strength

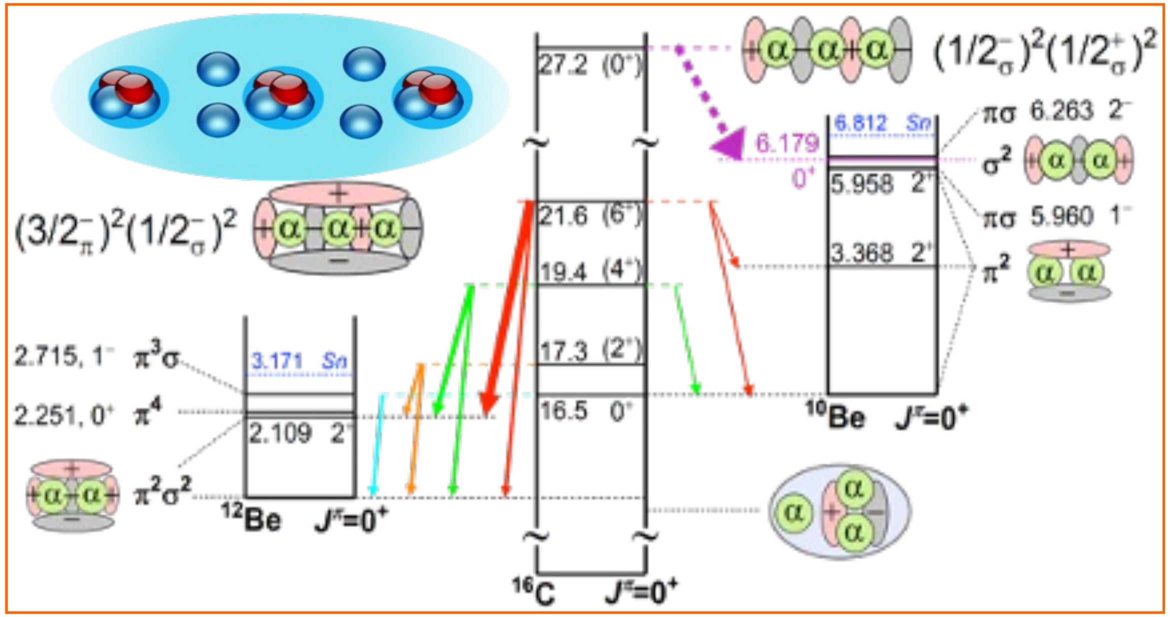


ZHY et al. PRL112(14)162501;PRC91(14)024304

e. g.： Linear-chain cluster structure in C

@HIRFL-RIBLL1 beamline（IMP, Lanzhou, China）





PHYSICAL REVIEW C **105**, 044302 (2022)

Observation of the $\pi^2\sigma^2$-bond linear-chain molecular structure in ^{16}C

J. X. Han,[1] Y. Liu,[1,2,*] Y. L. Ye,[1,†] J. L. Lou,[1] X. F. Yang,[1] T. Baba,[3] M. Kimura,[4] B. Yang,[1] Z. H. Li,[1] Q. T. Li,[1] J. Y. Xu,[1] Y. C. Ge,[1] H. Hua,[1] Z. H. Yang,[5] J. S. Wang,[6,7] Y. Y. Yang,[7] P. Ma,[7] Z. Bai,[7] Q. Hu,[7] W. Liu,[1] K. Ma,[1] L. C. Tao,[1] Y. Jiang,[1] L. Y. Hu,[8] H. L. Zang,[1] J. Feng,[1] H. Y. Wu,[1] S. W. Bai,[1] G. Li,[1] H. Z. Yu,[1] S. W. Huang,[1] Z. Q. Chen,[1] X. H. Sun,[1] J. J. Li,[1] Z. W. Tan,[1] Z. H. Gao,[7] F. F. Duan,[7] J. H. Tan,[8] S. Q. Sun,[8] and Y. S. Song[8]

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

PHYSICAL REVIEW LETTERS **124**, 192501 (2020)

Positive-Parity Linear-Chain Molecular Band in ^{16}C

Y. Liu,[1] Y. L. Ye,[1,*] J. L. Lou,[1] X. F. Yang,[1] T. Baba,[2] M. Kimura,[3] B. Yang,[1] Z. H. Li,[1] Q. T. Li,[1] J. Y. Xu,[1] Y. C. Ge,[1] H. Hua,[1] J. S. Wang,[4,5] Y. Y. Yang,[5] P. Ma,[5] Z. Bai,[5] Q. Hu,[5] W. Liu,[1] K. Ma,[1] L. C. Tao,[1] Y. Jiang,[1] L. Y. Hu,[6] H. L. Zang,[1] J. Feng,[1] H. Y. Wu,[1] J. X. Han,[1] S. W. Bai,[1] G. Li,[1] H. Z. Yu,[1] S. W. Huang,[1] Z. Q. Chen,[1] X. H. Sun,[1] J. J. Li,[1] Z. W. Tan,[1] Z. H. Gao,[5] F. F. Duan,[5] J. H. Tan,[6] S. Q. Sun,[6] and Y. S. Song[6]

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[2]*Kitami Institute of Technology, 090-8507 Kitami, Japan*
[3]*Department of Physics, Hokkaido University, 060-0810 Sapporo, Japan*
[4]*School of Science, Huzhou University, Huzhou 313000, China*
[5]*Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, China*
[6]*Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin 150001, China*

RAPID COMMUNICATIONS

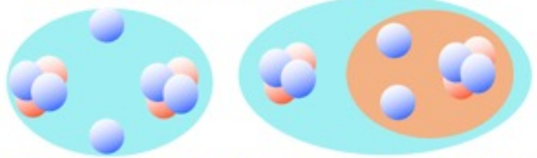
PHYSICAL REVIEW C **95**, 021303(R) (2017)

Selective decay from a candidate of the σ-bond linear-chain state in ^{14}C

J. Li,[1] Y. L. Ye,[1,*] Z. H. Li,[1] C. J. Lin,[2] Q. T. Li,[1] Y. C. Ge,[1] J. L. Lou,[1] Z. Y. Tian,[1] W. Jiang,[1] Z. H. Yang,[3] J. Feng,[1] P. J. Li,[1] J. Chen,[1] Q. Liu,[1] H. L. Zang,[1] B. Yang,[1] Y. Zhang,[1] Z. Q. Chen,[1] Y. Liu,[1] X. H. Sun,[1] J. Ma,[1] H. M. Jia,[2] X. X. Xu,[2] L. Yang,[2] N. R. Ma,[2] and L. J. Sun[2]

Cluster structures of light nuclei

Molecular states in Be



e.g., ZY et al., PRL2014; Suzuki PRC2013
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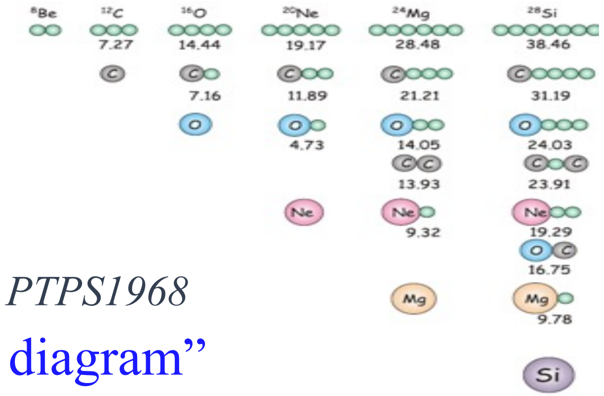
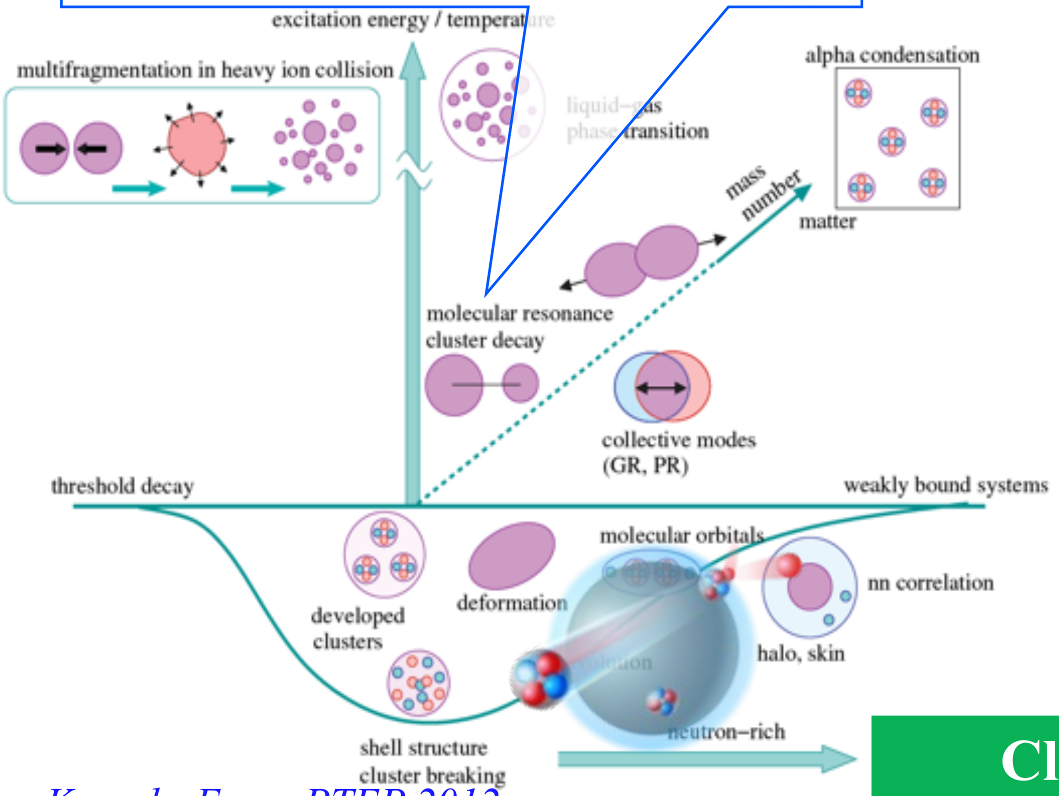
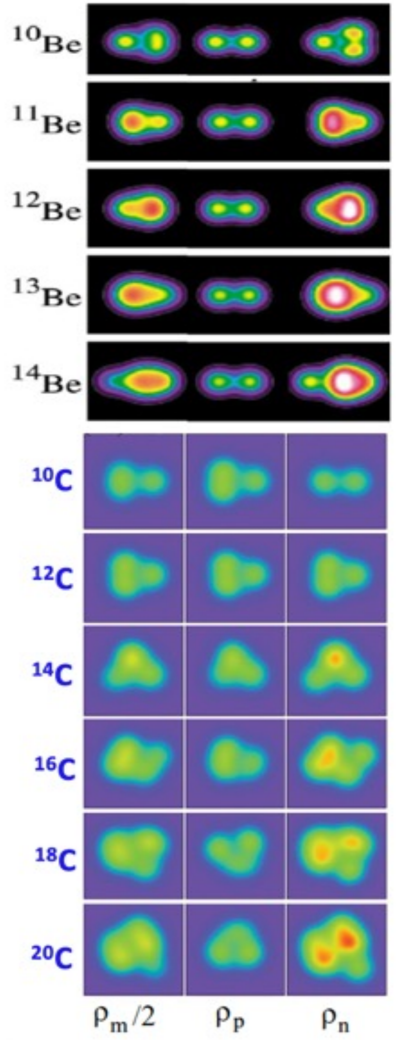


Ikeda, PTPS1968
"Ikeda diagram"



Kanada-Enyo, PTEP 2012

Y. Kanada-Enyo, et al., C. R. Physique 2003

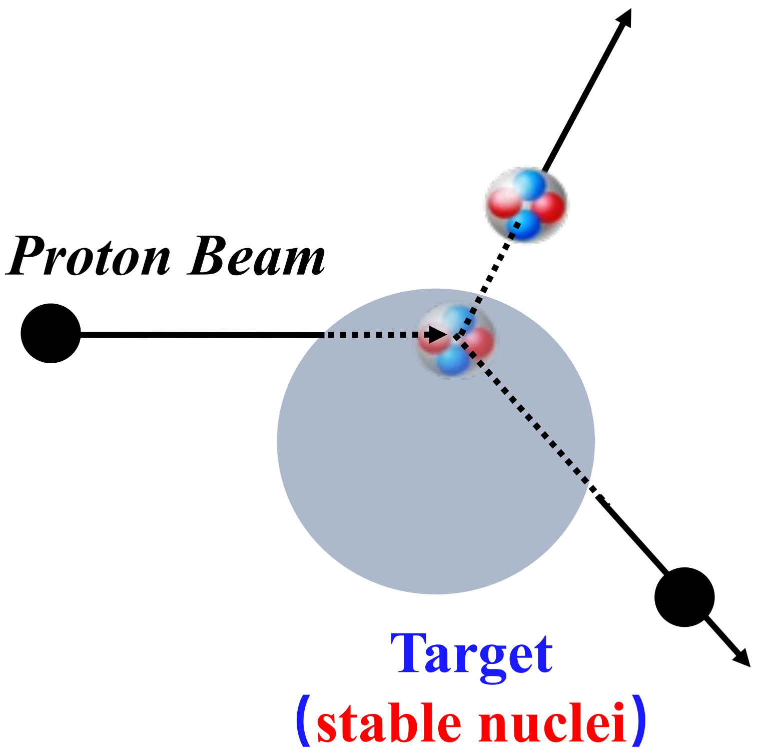


Cluster knockout

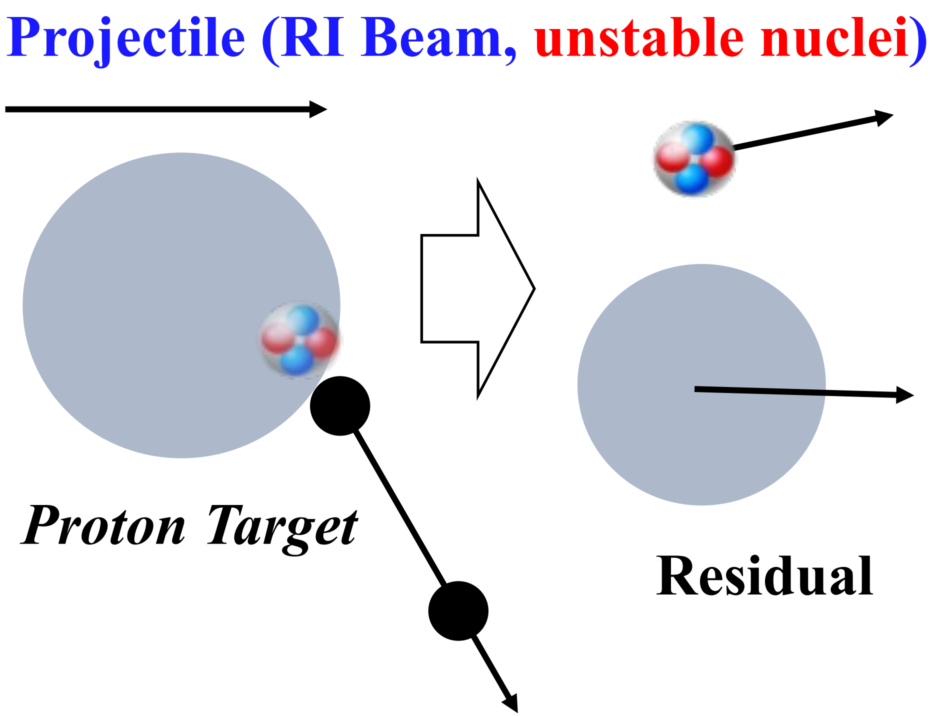
(*p*,*pα*) : a probe for clusters in ground state

- ✓ Cluster structure in excited states: one can measure cluster decay fragments
- ✓ Clusters in *g.s*: quasi-free (*p*,*pα*) [~ several hundred MeV/u] *Yoshida, PRC2016/PRC2018/PRC2019*

Normal kinematics



Inverse kinematics



($p,p\alpha$)： a probe for clusters in ground state

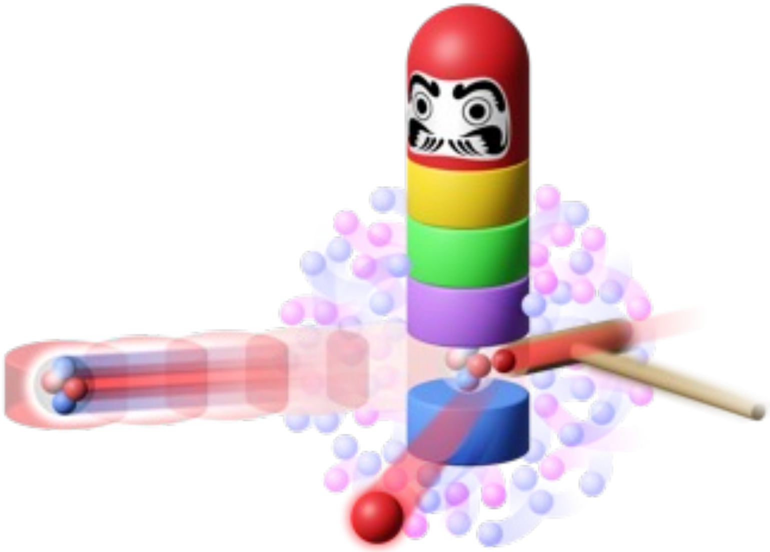
- ✓In1970s and 1980s: with light stable nuclei like ^{7}Li/^{9}Be/^{12}C.
- ✓Analysis of triple differential cross sections utilizing DWIA

$$\frac{d^3\sigma}{dE_1^{L}d\Omega_1^{L}d\Omega_2^{L}} = S_\alpha F_{\rm kin} C_0 \sum_m \left| \bar{T}^{nljm}_{\boldsymbol{K}_0\boldsymbol{K}_1\boldsymbol{K}_2} \right|^2$$

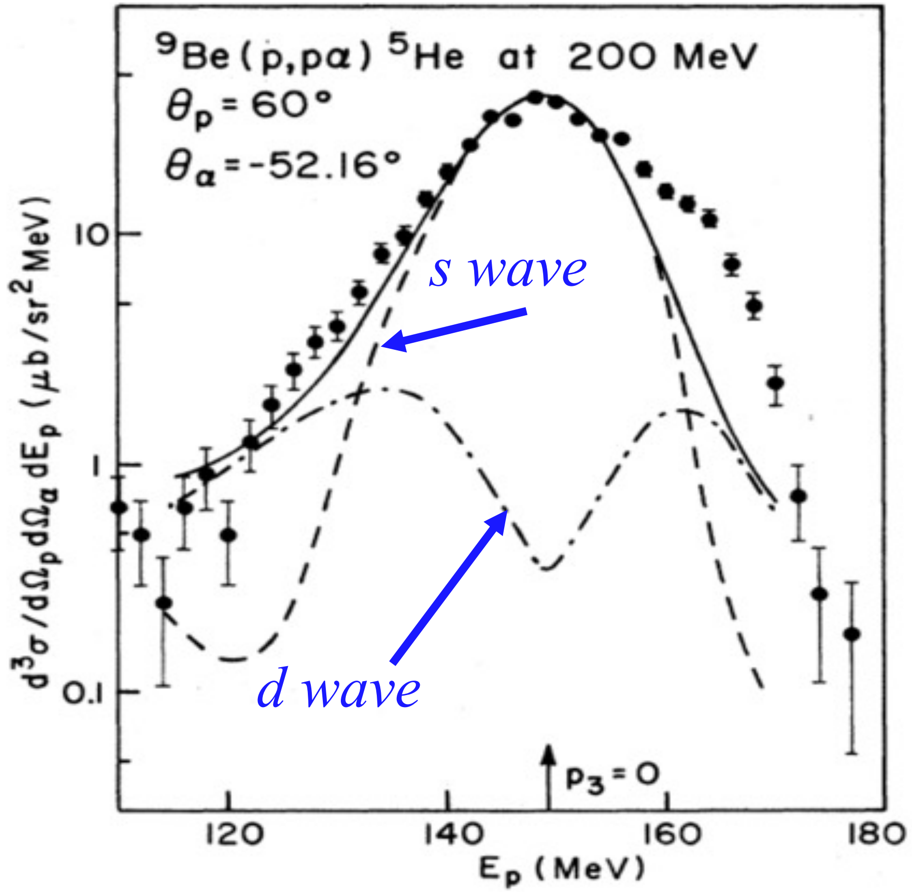
- ✓Recent theoretical development for ($p,p\alpha$) (*Ogata et al.)*

Lyu, et al., PRC2018; Yoshida et al. PRC2019;Taniguchi et al. PRC2021

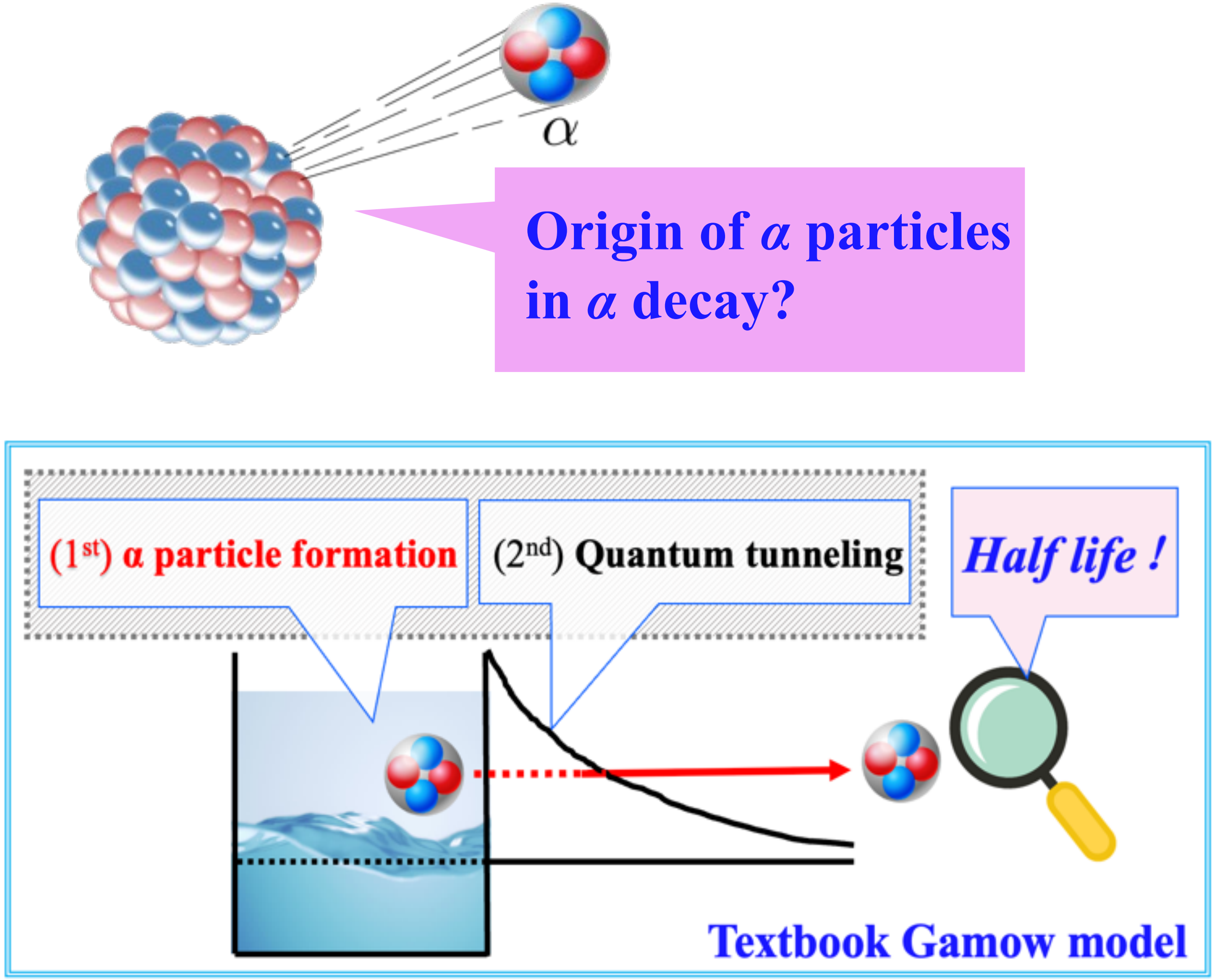
Nadasen et al. PRC1989
Chan and Roos PRC1977;
Carey et al. PRC1981



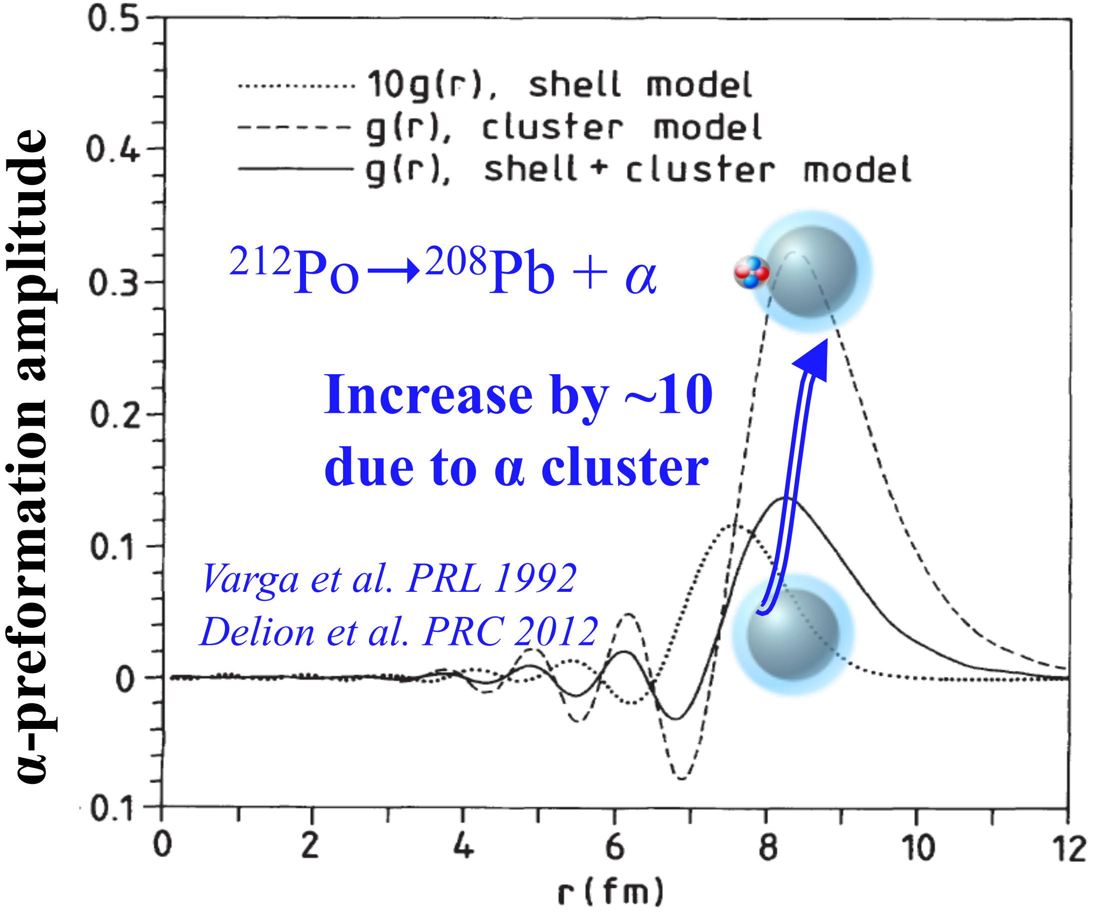
quasi-free knockout with large momentum transfer



Heavy nuclei: α preformation in α decay?



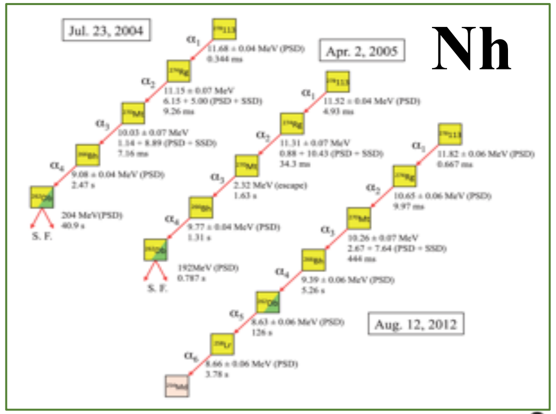
α decay half life: $T_{1/2} = \frac{\hbar \ln 2}{\Gamma_\alpha}, \Gamma_\alpha \propto |g(r)|^2$



✓Theoretical calculations

e.g. Xu/Ren et al. PRC93(16)011306; PRC104(21)034302
J.M.Dong et al. PLB813(21) 136063

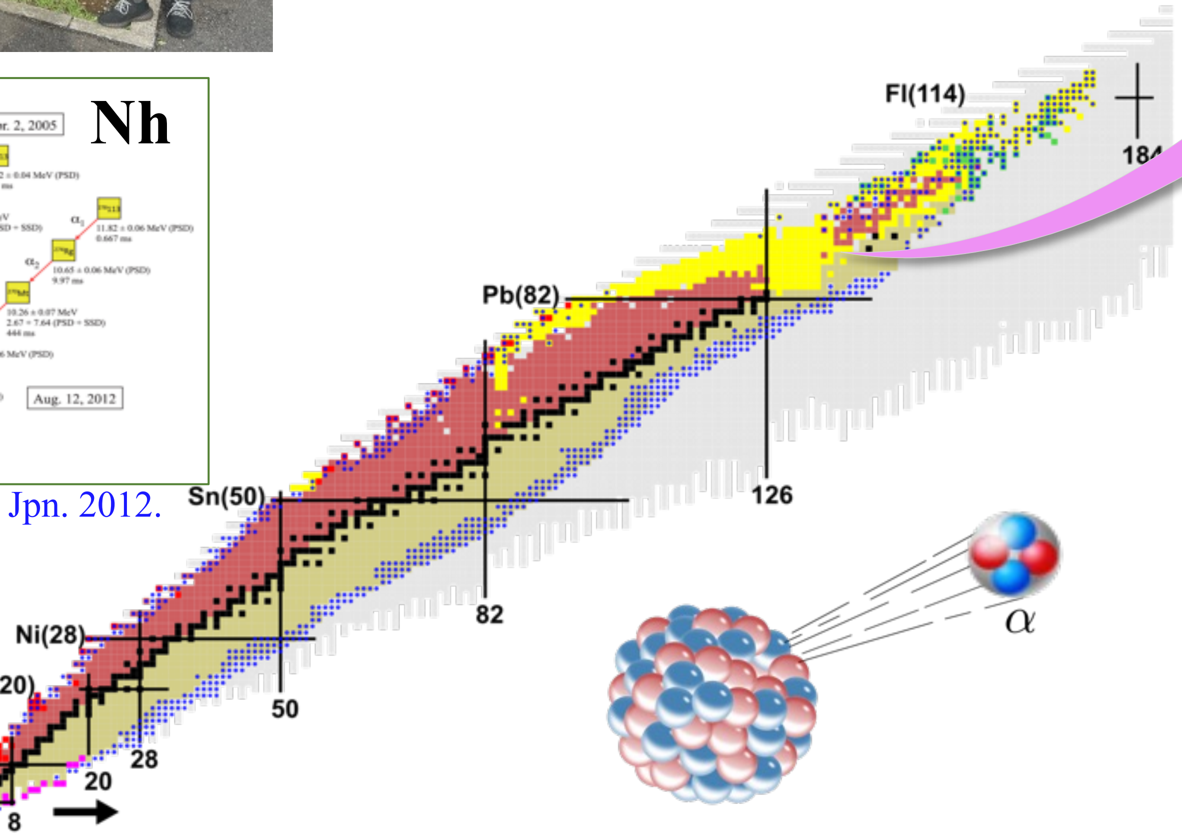
α decay in heavy and superheavy nuclei

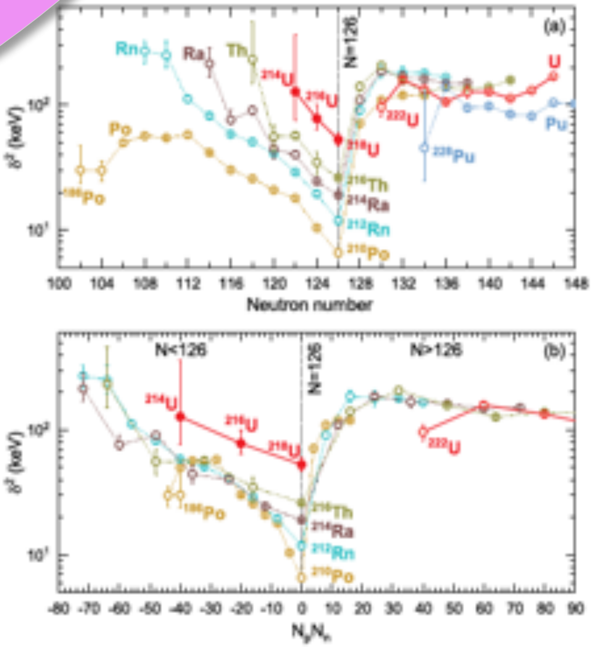


Morita et al., JPS. Jpn. 2012.

Z=119? Z=120?

"Island of stability"

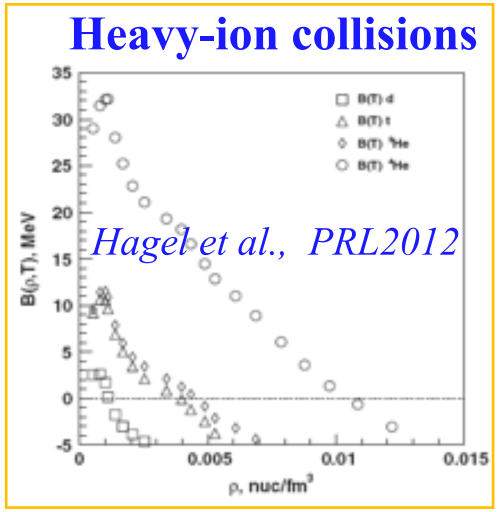


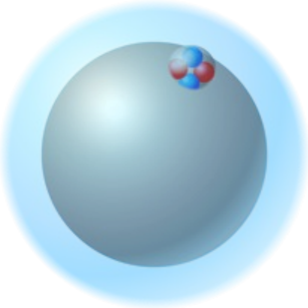


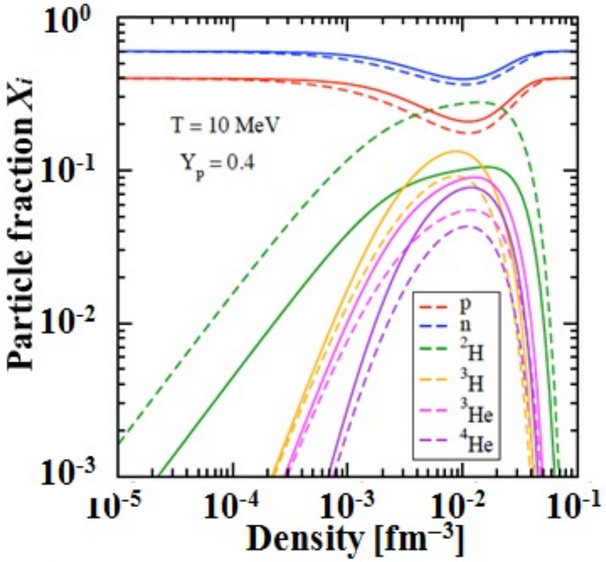
Zhang et al. PRL 2021

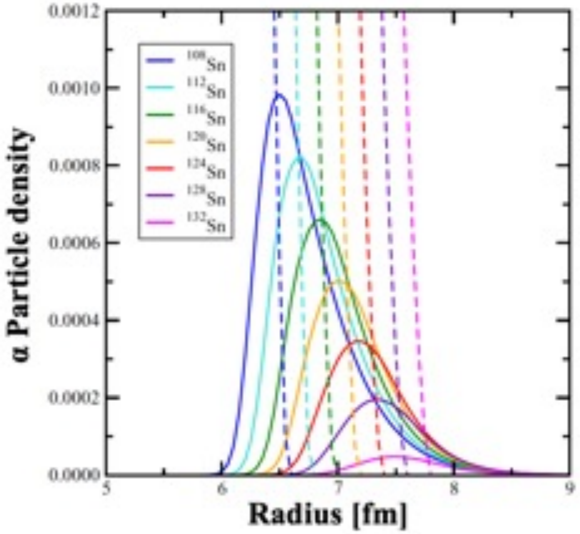
Nuclear matter: Impact of clustering on EoS

✓ Theoretical predictions of α clusters in low-density environments like the surface of heavy nuclei:



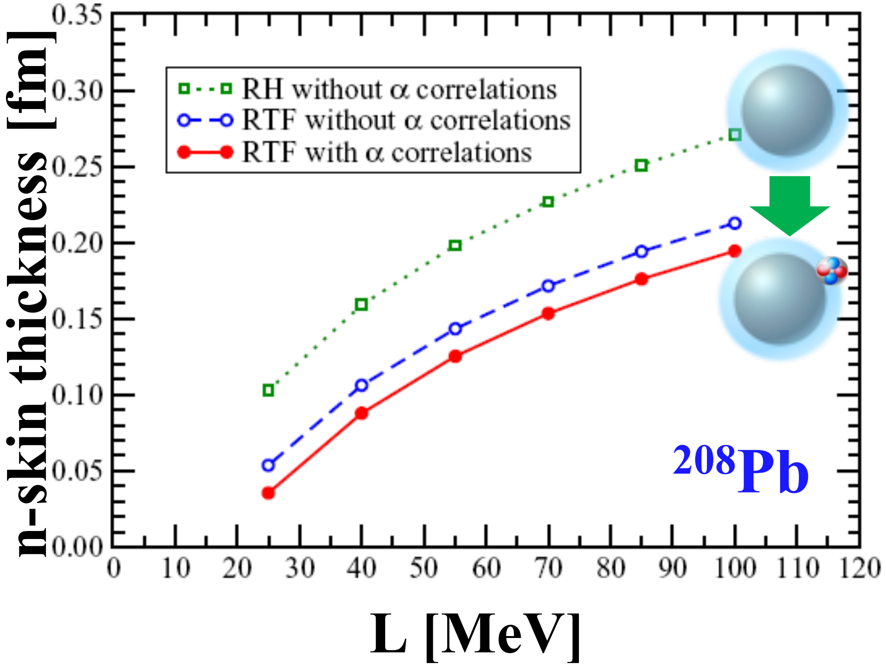






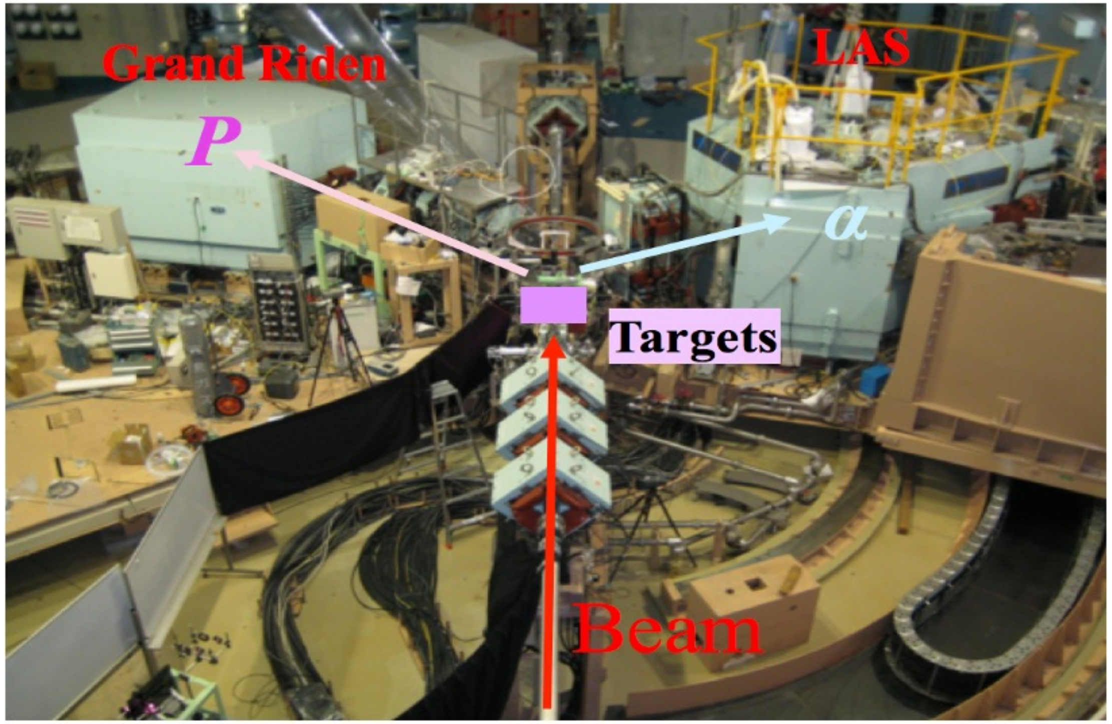
Typel, PRC89(2014) 064321,PRC 81(2010) 015803

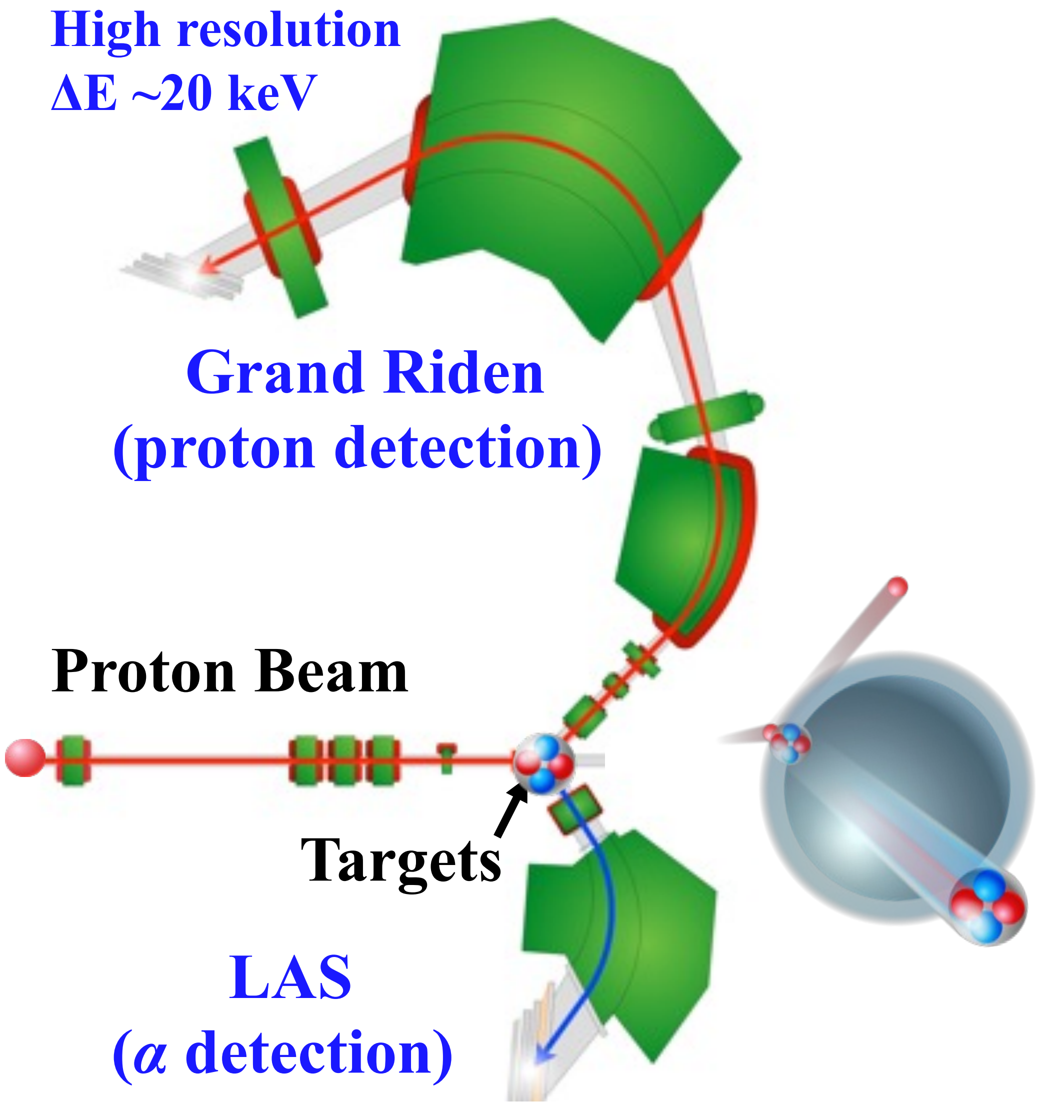
α cluster suppress *n* skin



Quasi-free (*p,pα*) at RCNP (Osaka/Japan)

- ✓ **Beam:** 392 MeV proton, ~100 pnA
- ✓ **Targets:** ^{112,116,120,124}Sn (~40 mg/cm^2)

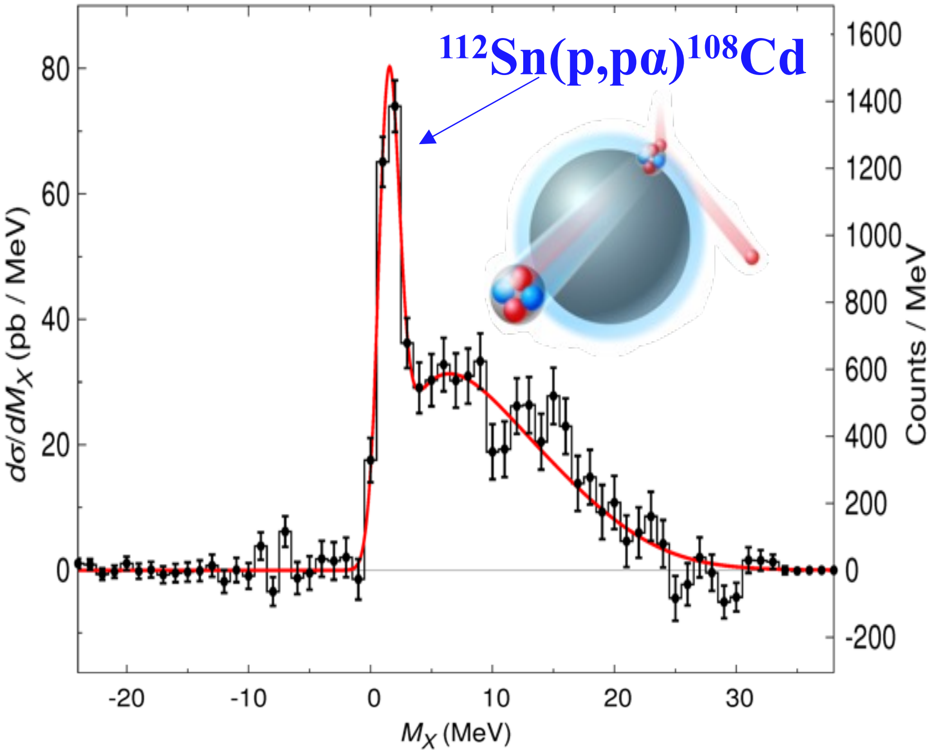




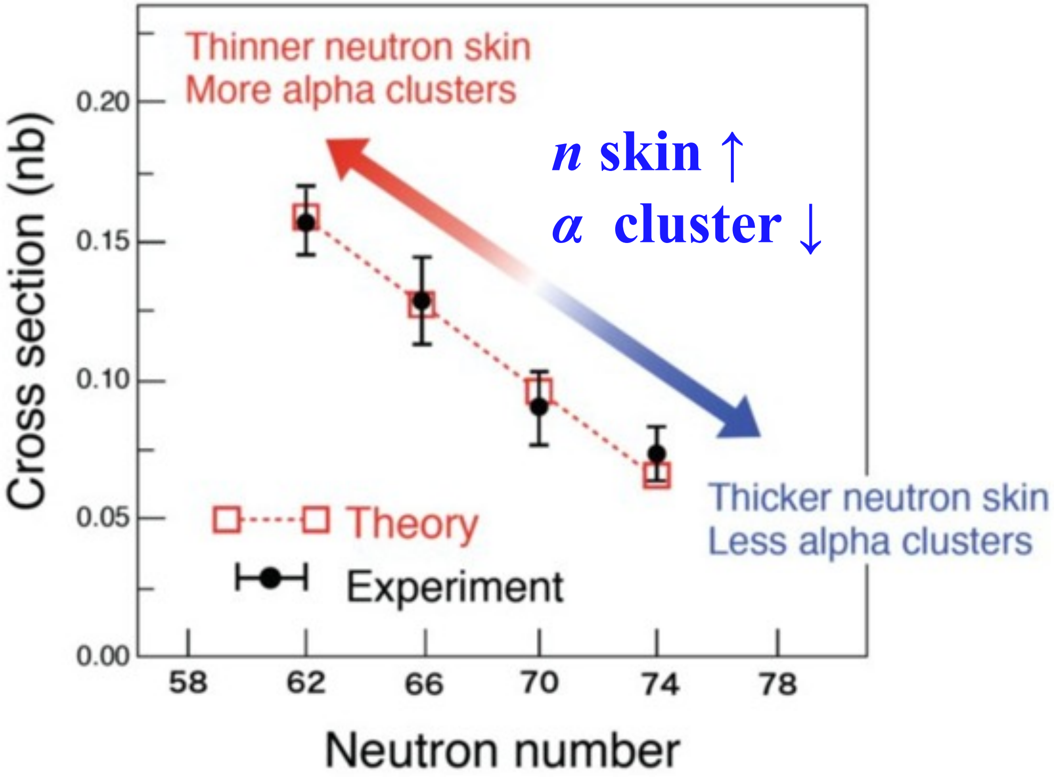
knockout α clusters from heavy nuclei $^{112-124}Sn$

Tanaka, Yang et al. Science 371, 260–264 (2021)

α separation energy spectrum



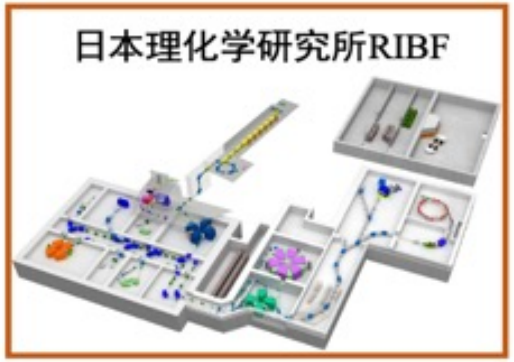
α cluster knockout reaction

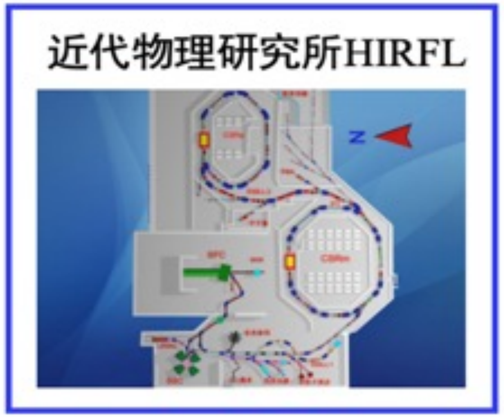


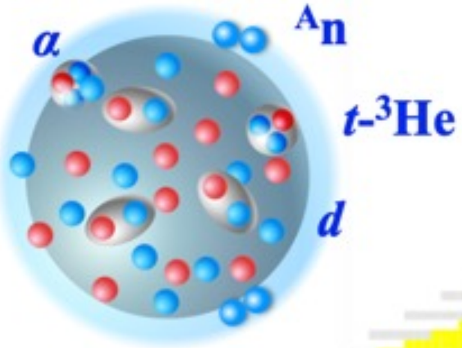
- ✓ E_{sep} Peak clearly observed for all Sn isotope $^{112,116,120,124}Sn$.
- ✓ Reaction Theory: Distorted-Wave Eikonal Approximation
  - ✓ α-cluster wave function from gRDF
  - ✓ Distortion effect considered

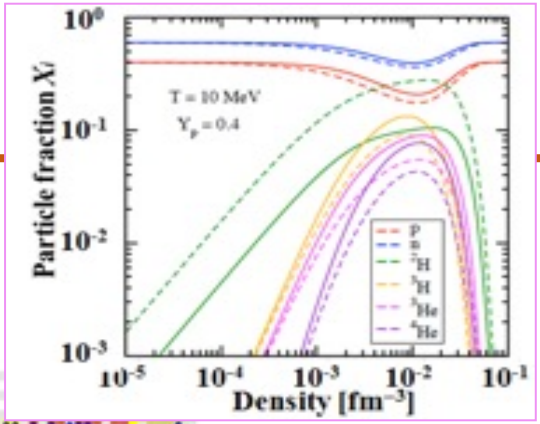
What's next： More Cluster, More exotic

- ✓ **More exotic nuclei, more types of cluster (*α*, *t*, ^{3}He, *d*)**

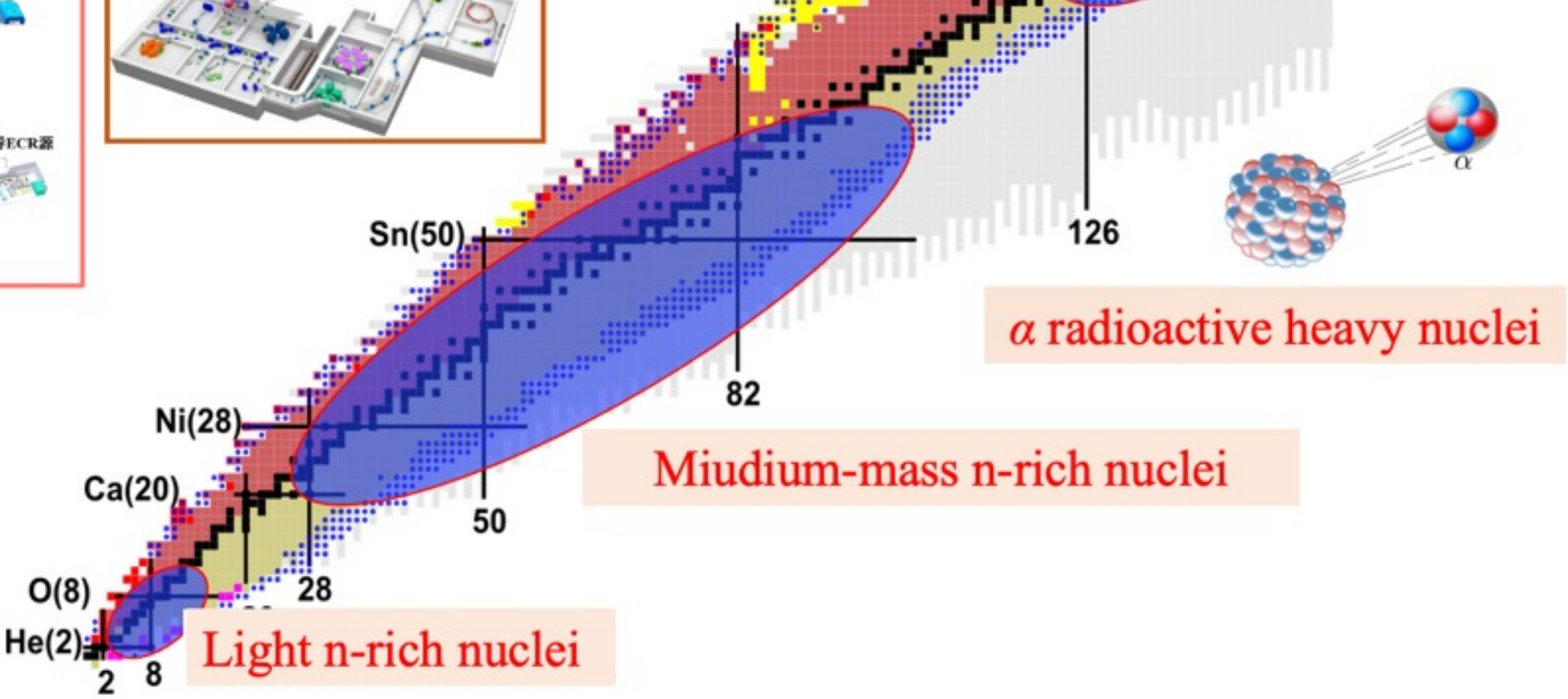








Typel PRC2010; Zhang PRC2017



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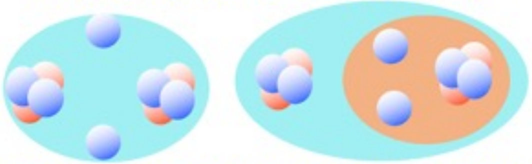

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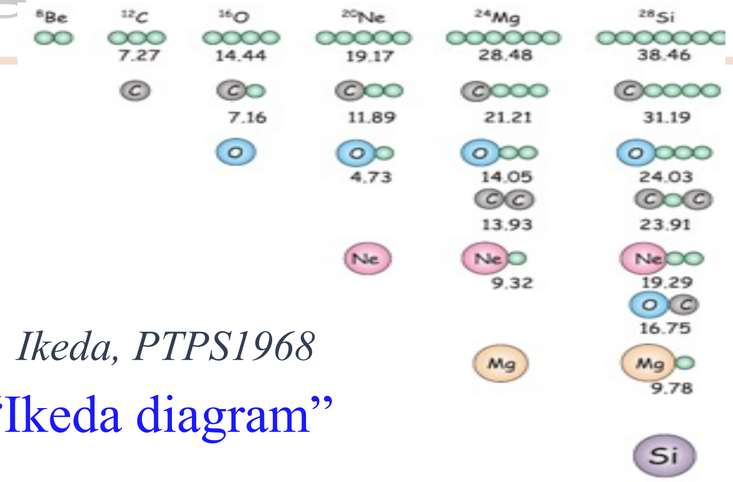
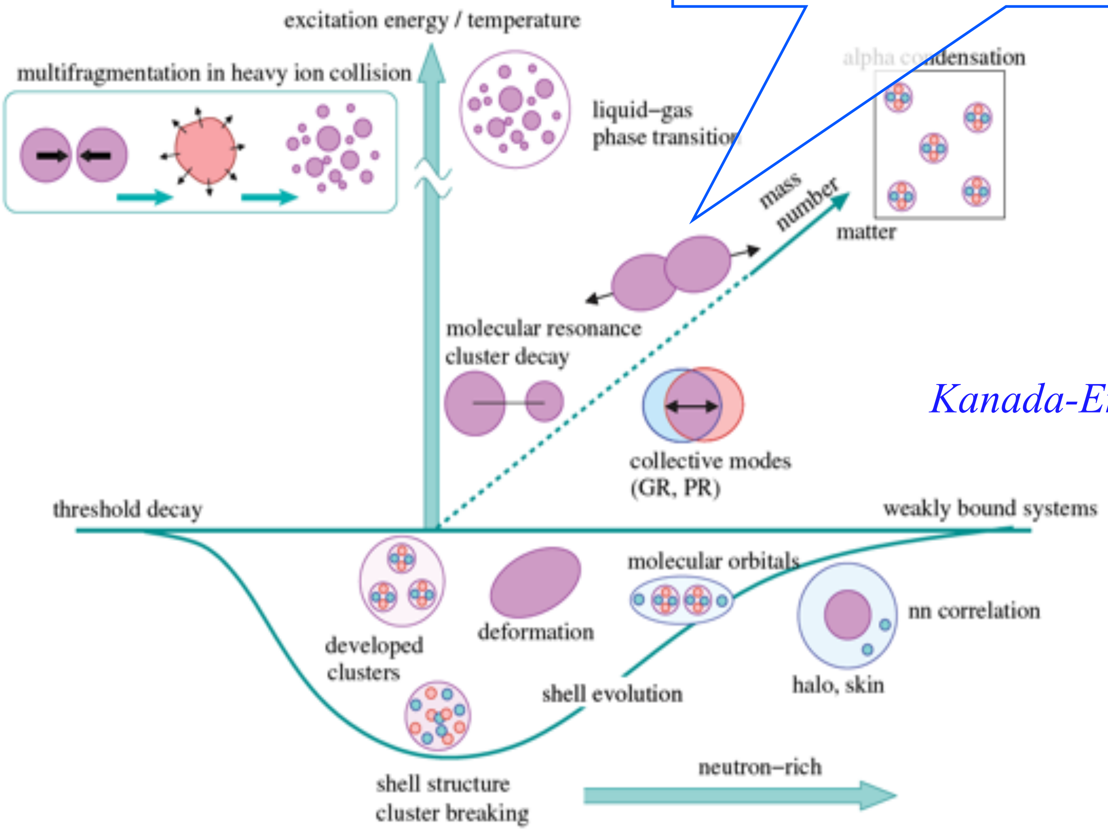


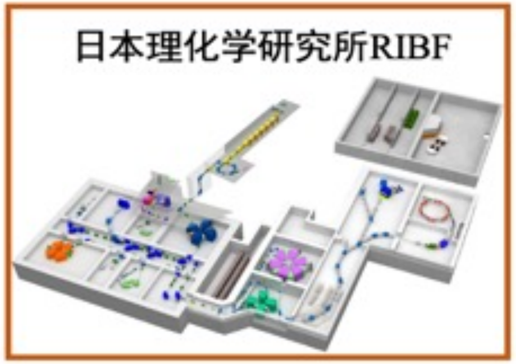
Ikeda, PTPS1968

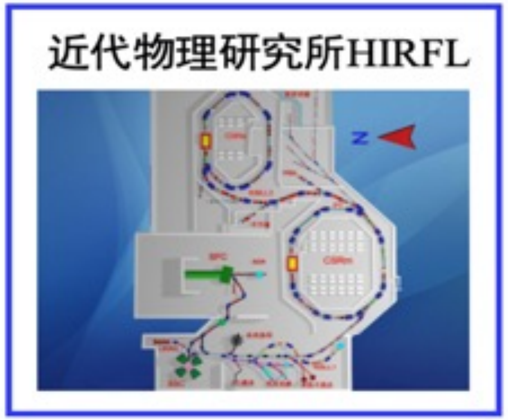
“Ikeda diagram”

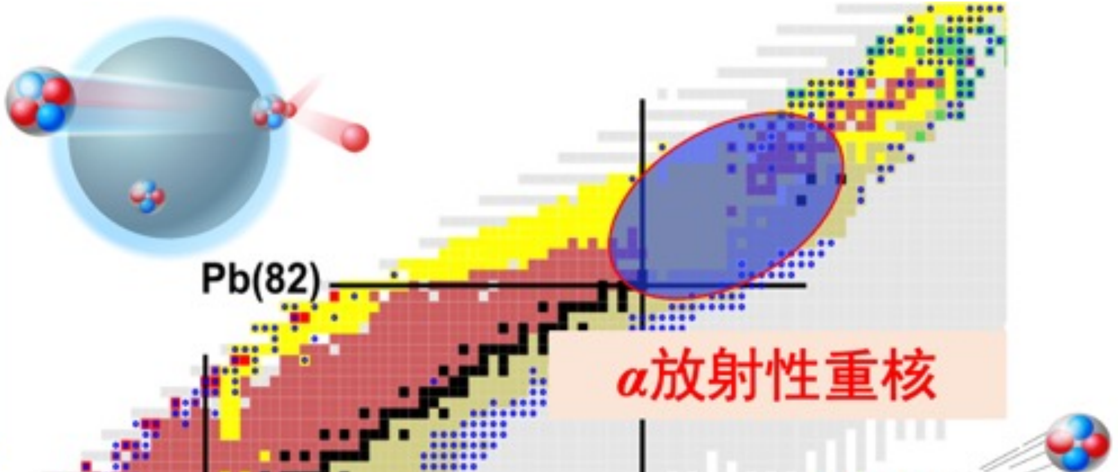
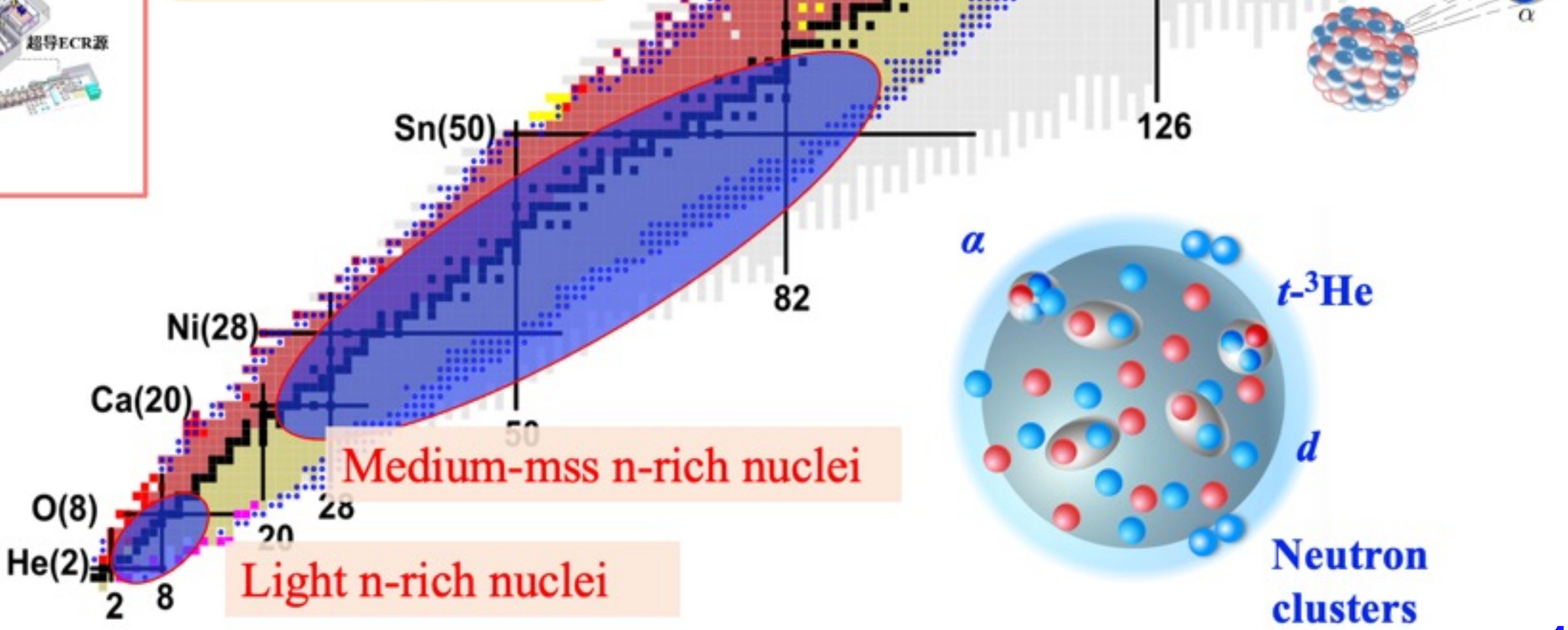


Kanada-Enyo, PTEP 2012

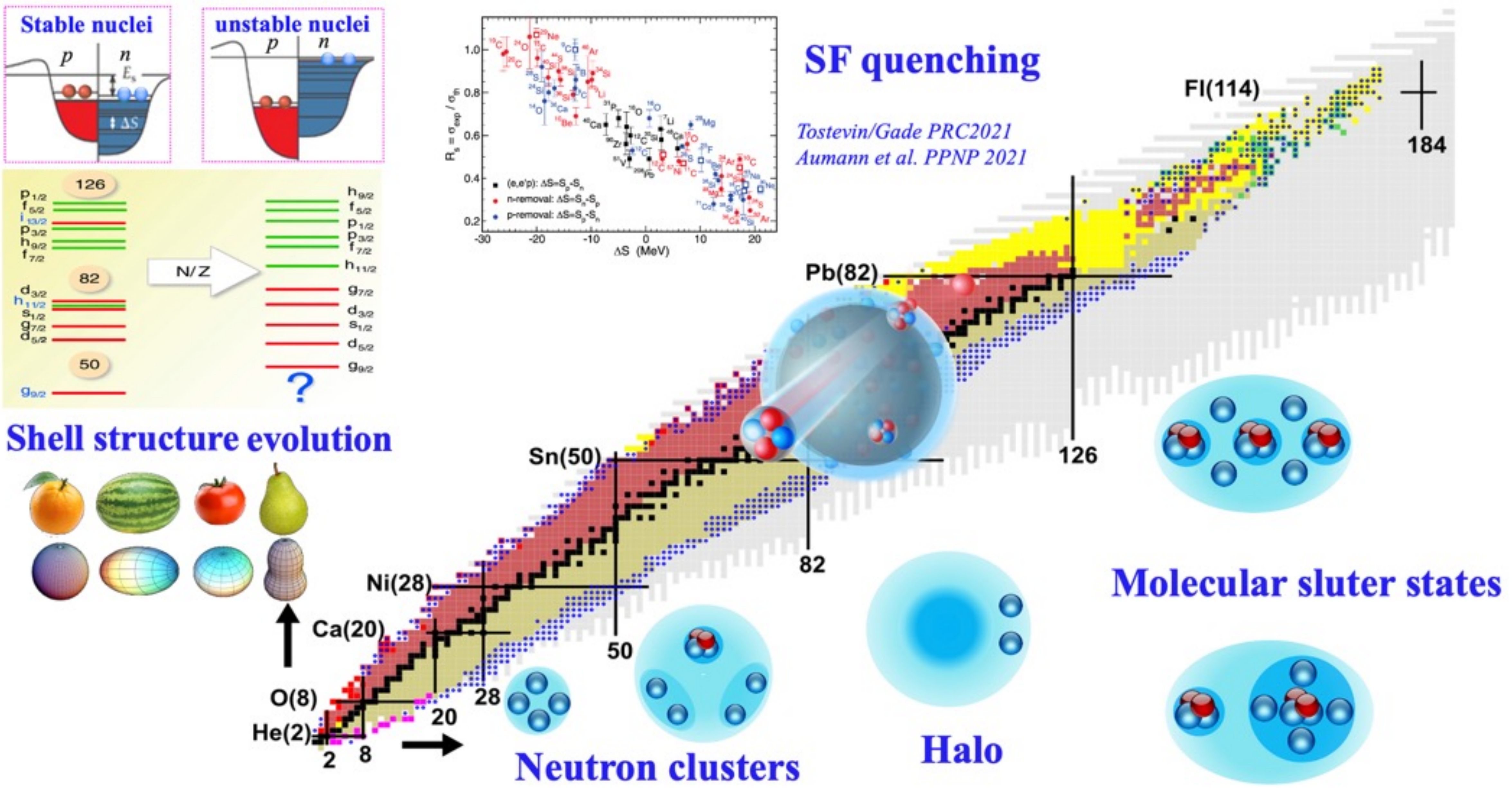
Cluster structure in ground states probed by knockout reaciton



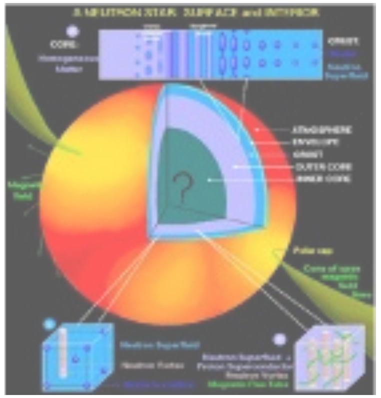


What is the structure of (unstable) nuclei?



Exotic neutron-rich nuclei: a bridge to the neutron star



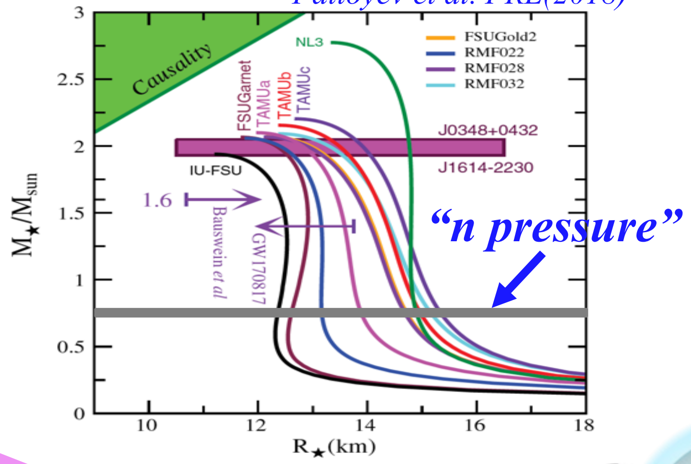
Neutron star

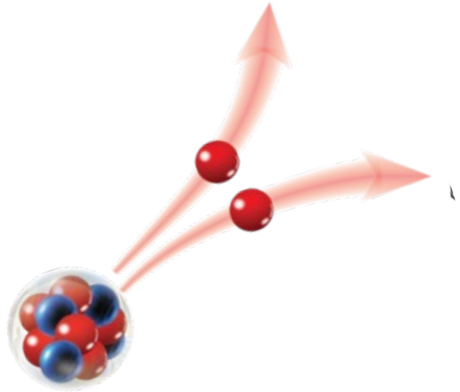
- ✓ *EoS + General relativity*
- ✓ *Merger*
- ✓ *Cold dense matter*

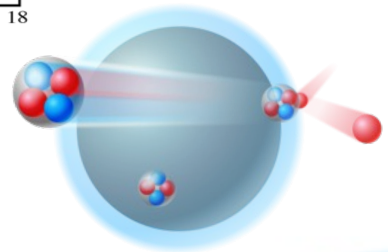
In Heaven

Mass-radius relation

Fattoyev et al. PRL(2018)

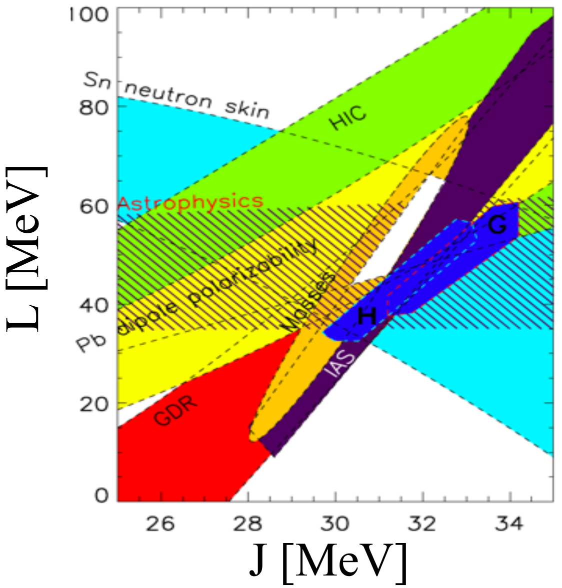






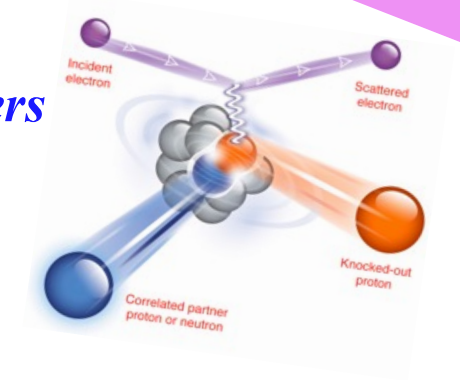
Nuclear matter EoS

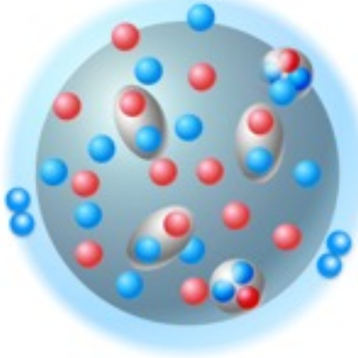
Roca-Maza, PPNP(2018)



Better constraints

- ✓ *More (accurate) data*
- ✓ *Nuclear interactions*
- ✓ *Correlations and clusters*

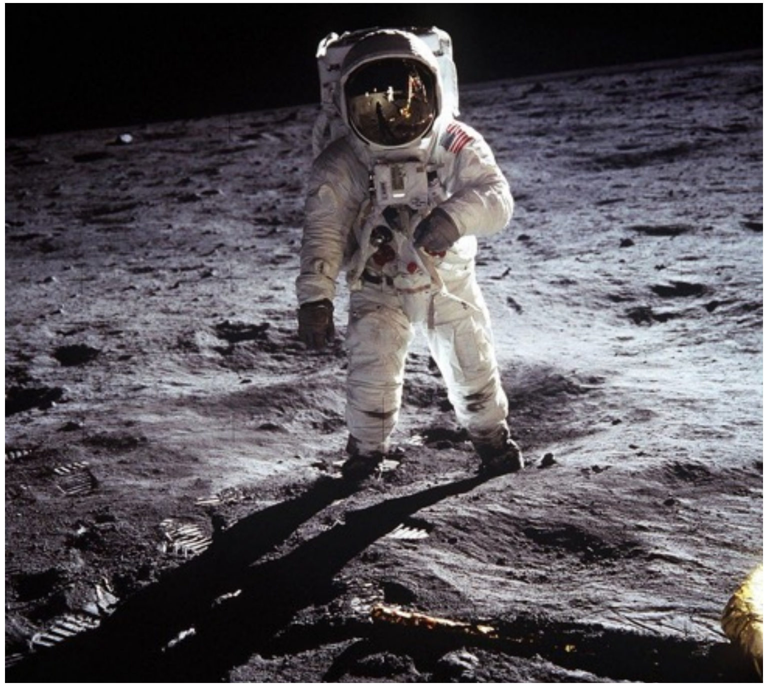




On Earth

A wonderworld of atomic nuclei: from tiny to infinity

- ✓ Introduction
- ✓ Clustering in nuclear systems
- ✓ Halo and neutron correlations
- ✓ Summary and Perspective



"That's one small step for man. One giant leap for mankind."
-Neil Armstrong, July, 1969, Moon.

Thank you!