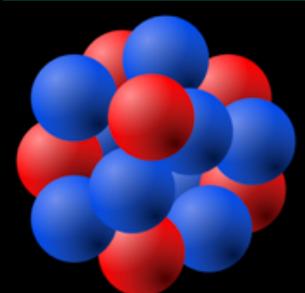




原子核物理的从头计算 —从原子核到中子星



10^{-15} m



江西 南昌

尧江明
中山大学物理与天文学院
School of Physics and Astronomy
Sun Yat-sen University

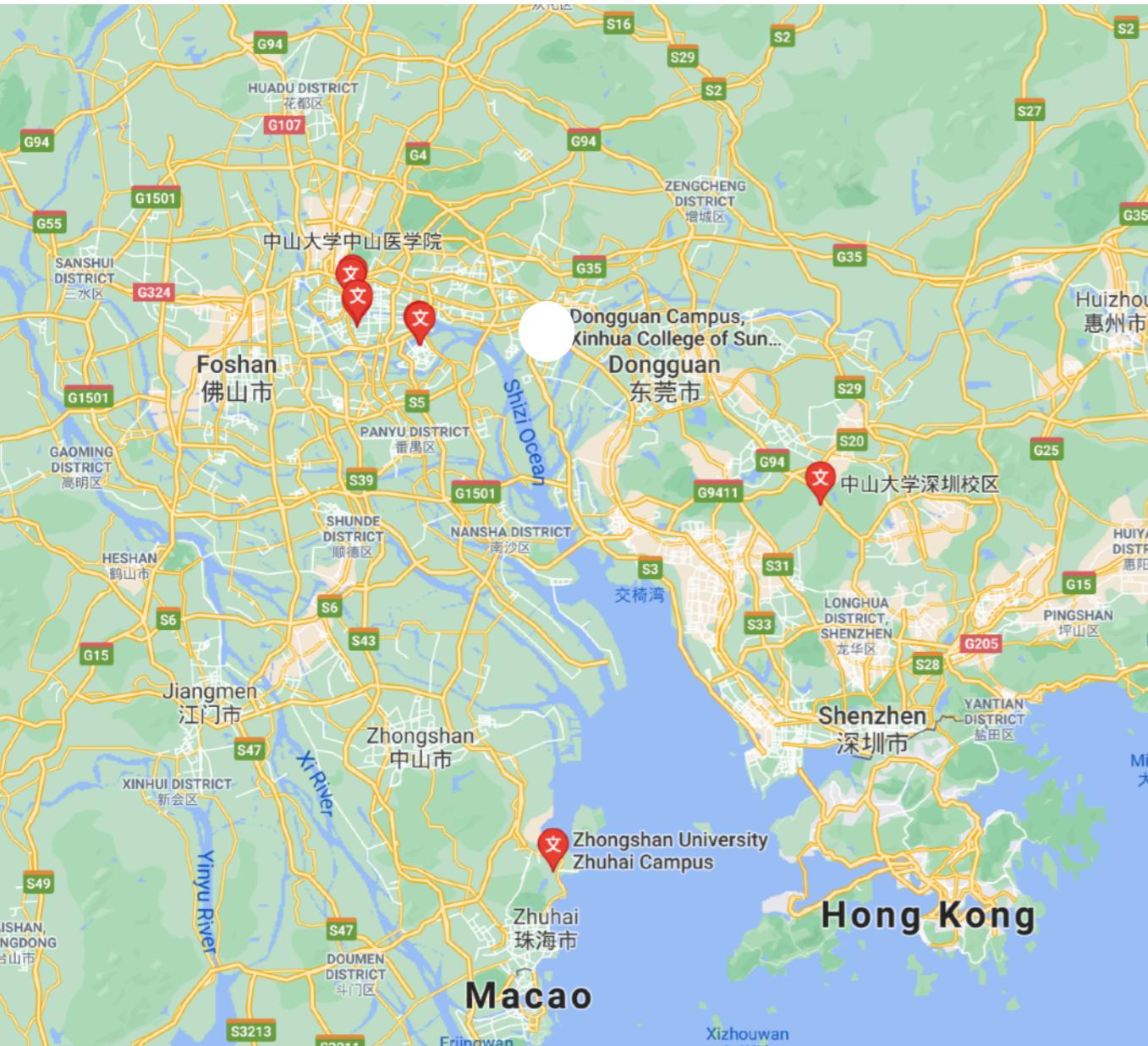
10^3 m



2021年4月27日



中山大学-五个校区



珠海校区

中国语言文学系（珠海）、历史学系（珠海）、哲学系（珠海）、国际金融学院、国际翻译学院、国际关系学院、旅游学院、数学学院（珠海）、**物理与天文学院**、大气科学学院、海洋科学学院、地球科学与工程学院、化学工程与技术学院、海洋工程与技术学院、**中法核工程与技术学院**、土木工程学院、微电子科学与技术学院、测绘科学与技术学院。

广州校区北校园

中山医学院、光华口腔医学院、公共卫生学院、护理学院。

广州校区南校园

中国语言文学系、历史学系、哲学系、社会学与人类学学院、博雅学院、岭南学院、外国语学院、马克思主义学院、数学学院、**物理学院**、地理科学与规划学院、生命科学院、逸仙学院、体育部、艺术学院。

广州校区东校园

法学院、政治与公共事务管理学院、管理学院、心理学系、传播与设计学院、资讯管理学院、工学院、化学学院、材料科学与工程学院、电子与信息工程学院、数据科学与计算机学院（软件学院）、国家保密学院、网络安全学院、环境科学与工程学院、系统科学与工程学院、药学院。

深圳校区

医学院、公共卫生学院（深圳）、药学院（深圳）、材料学院、生物医学工程学院、电子与通信工程学院、智能工程学院、航空航天学院、农学院、生态学院。



中山大学-珠海校区





中山大学-珠海校区





中山大学-物理与天文学院

建立中国第一个天文系

张云（里昂大学博士，曾任校长）
建立国内高校首个天文学系

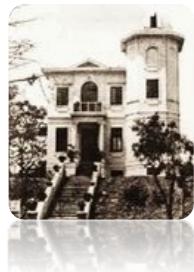


中山大学天文
系和天文台迁
至南京大学

1927

1952

2013.12



建立中山大学
天文台
(国内第二座
现代天文台)



天文与空间科
学研究院成立
复办天文学科



物理与天文学院
成立

2015.9



天琴中心
成立

2019.12



成立中国空间站工
程巡天望远镜粤港澳
大湾区科学中心

江西师范大学

尧江明



深空



物理学



天文学

理论
物理

量子
物理

引力
物理

天体
物理

引领**1**个学科群

支撑**2**个一级学科

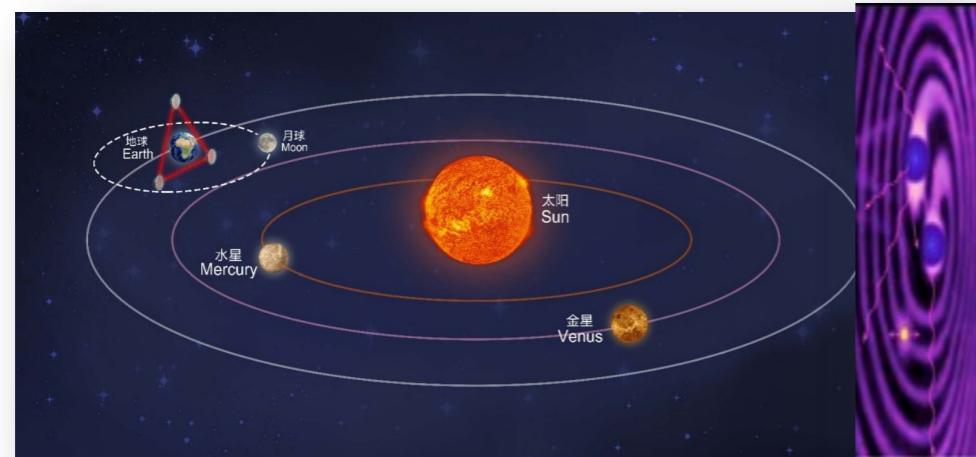
发展**4**个研究团队

物理与天文学院

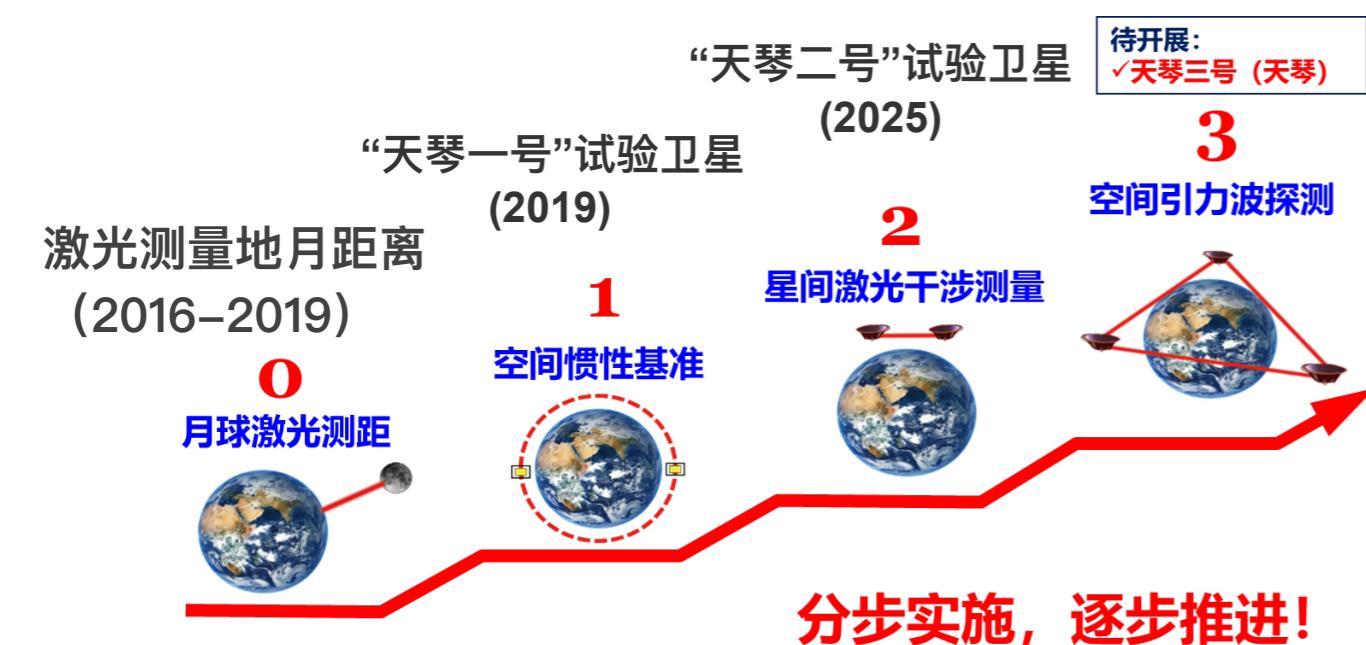


团队	教师人数	专职+博后	团队主要研究方向
理论物理	10	4	宇宙学、引力理论、粒子物理和核物理
量子1	9	10	超冷原子与离子，量子精密测量，量子模拟，低维量子材料，拓扑量子物态，机器学习在量子科学的应用，精密光学成像
量子2	7	1	超冷原子；囚禁离子；里德堡原子为主的量子信息处理；单光子为主的弱光测控技术和激光技术为主的强光测控技术
天文	25	20	星系宇宙学，恒星与行星科学，高能天体物理
天琴	22	14	引力波理论与数据，空间惯性基准，星间激光干涉测量，引力波卫星平台
总计	73	49	

◆ 建设空间引力波探测天文台 ~2035

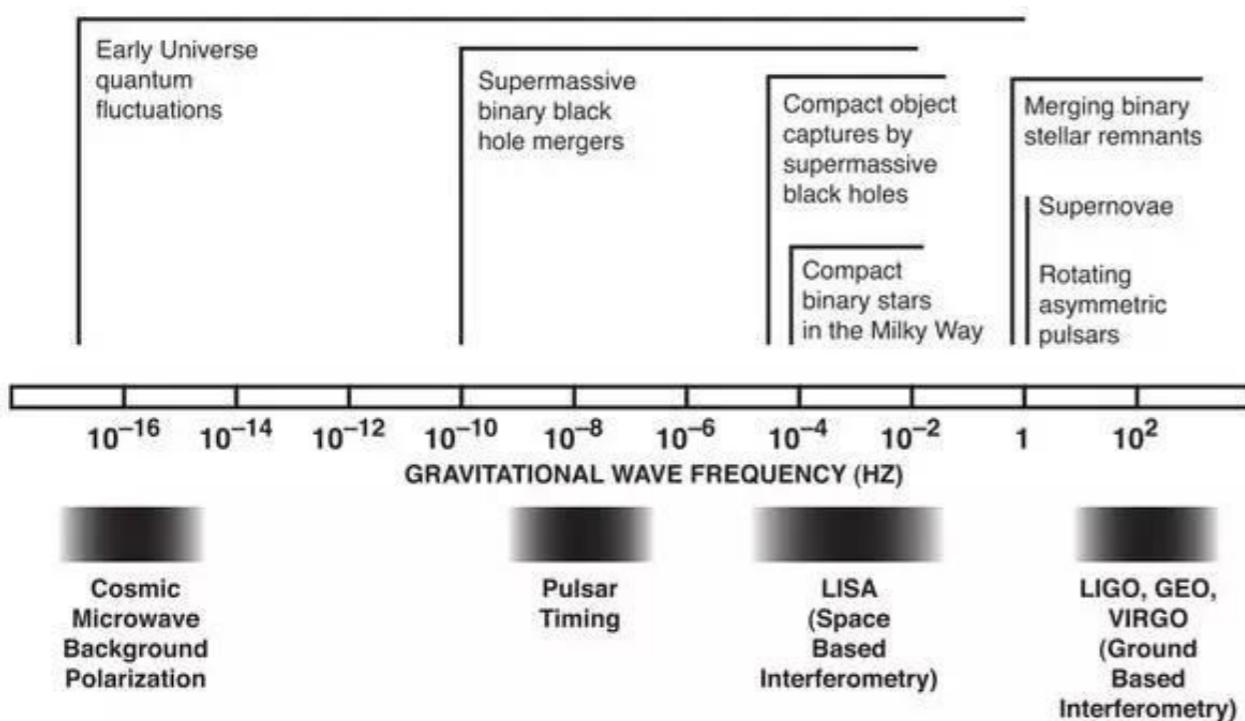
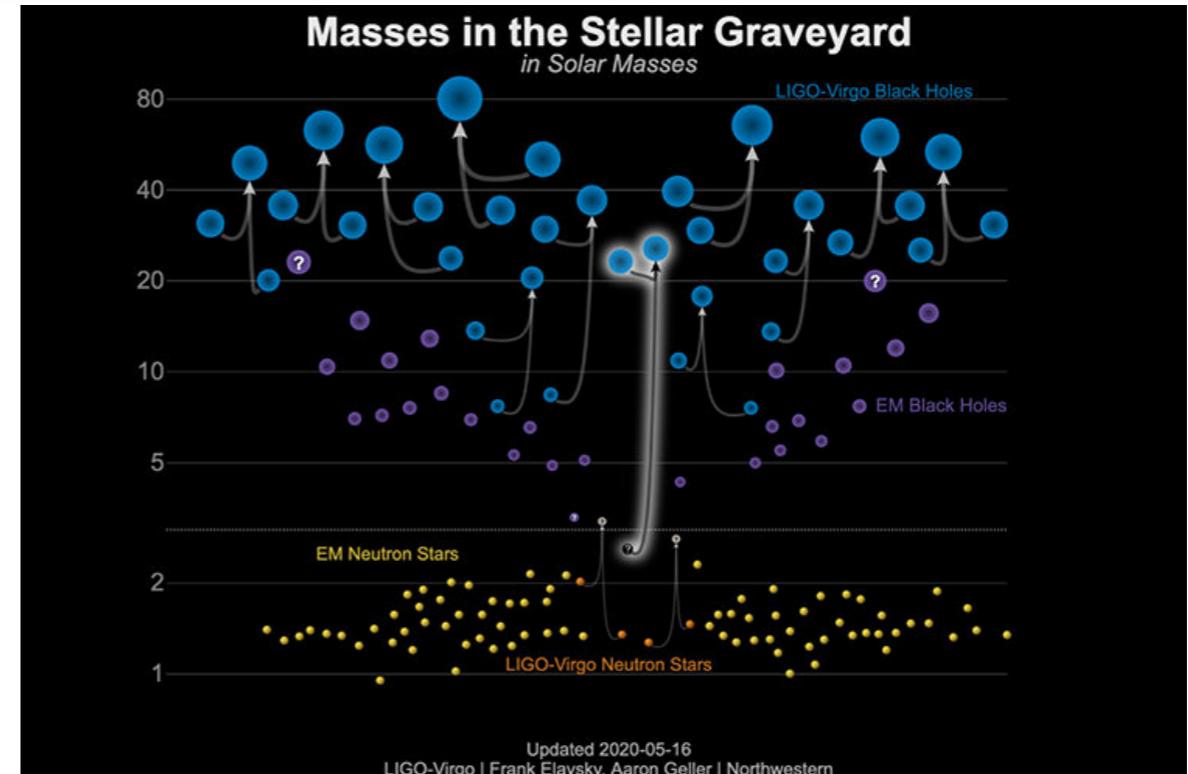
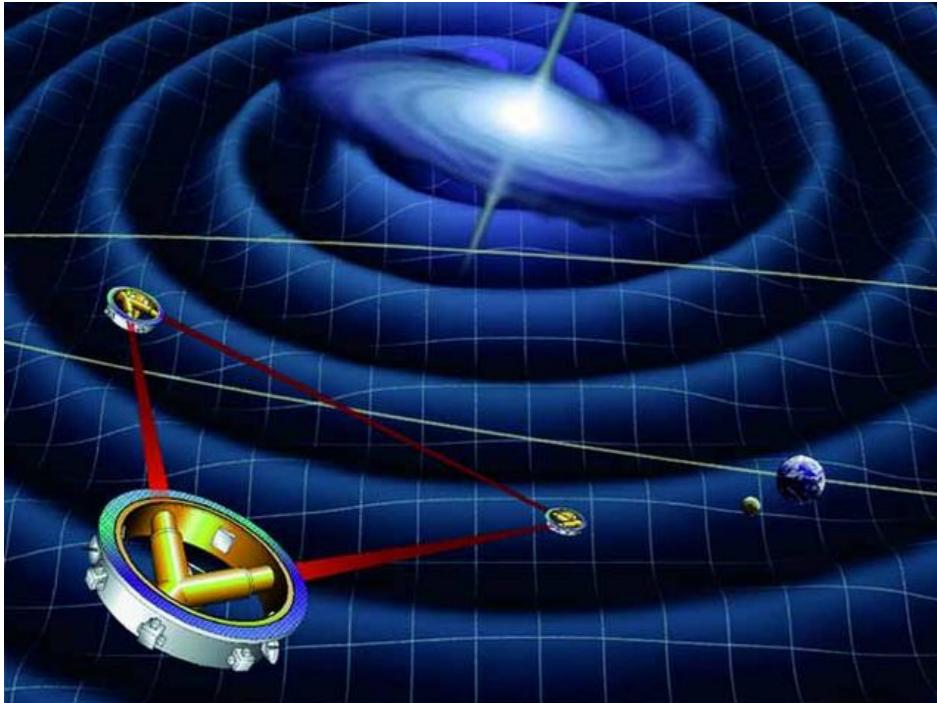


◆ 天琴计划0123 路线图



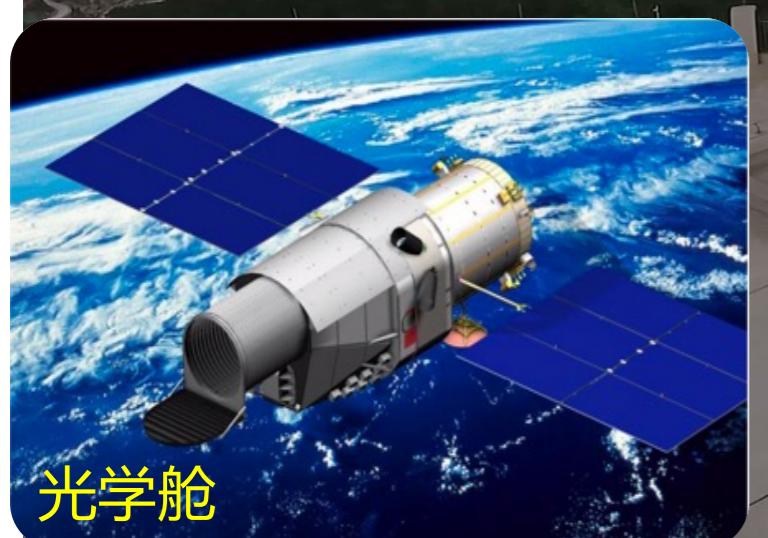
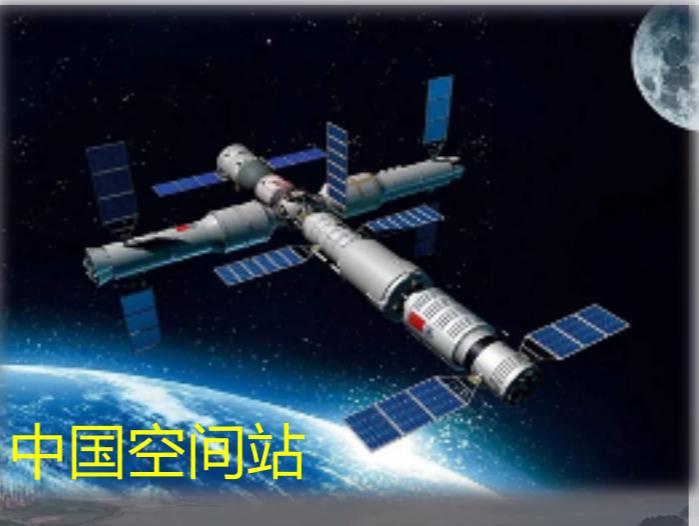
“天琴一号”卫星2019年12月20日

中山大学-天琴计划团队



天琴计划

中山大学-巡天中心



① 计算天体物理（以天河二号为计算平台开展宇宙学、宇宙大尺度结构、星系形成、行星形成等）；

② 实测天文学（恒星物理、天体化学，原子分子天文学等）；

③ 高能天体物理（以天琴计划为引导的引力波天文学、多信使天文学、致密天体研究等）；

④ 行星物理（面向国家深空探测战略需求的行星科学基础和应用研究）

巡天中心是发挥好中国空间站巡天空间望远镜挖掘科学价值的研究实体，按照载人航天工程“三步走”战略，中国空间站将于2022年前后完成在轨建造，之后将发射巡天空间望远镜。

中国空间站工程
巡天望远镜粤港澳
大湾区科学中心



中山大学-量子物理团队



- ① 量子工程与量子模拟（冷原子（离子）的制备与操控、冷原子（离子）量子模拟、低维量子材料的光电操控等）；
- ② 量子精密测量与量子传感器件（量子精密测量理论、冷原子精密重力测量、高精度冷原子（离子）光钟、电磁场灵敏探测等）；
- ③ 多体量子物理与量子动力学（冷原子物理、量子材料、量子光子学、量子关联与量子相变、拓扑物态与拓扑相变、非平衡量子力学、集体量子现象、量子输运、量子人工智能等）。

量子工程与精密测量团队



- ① 超冷原子量子模拟与测控（原子气体玻色-爱因斯坦凝聚和费米凝聚、强相互作用量子气体、同核与异核分子量子气体、原子气体的偶极相互作用和人工规范场，原子光子混合干涉仪，冷原子短程力精密测量等）
- ② 囚禁离子量子计算与测控（模块化囚禁离子量子计算，离子光子量子纠缠网络、离子与自发辐射光子量子界面、囚禁离子洛伦兹对称性测量，囚禁离子陀螺仪等）
- ③ 飞秒光梳量子测控与精密光谱（光梳超快控制量子体系，红外和紫外宽光谱精密光梳，双光梳光谱技术，精密宽光谱分子光谱，光梳光谱和波长调制光谱的远程大气遥感等）
- ④ 激光量子相干控制（相干拉曼散射合成飞秒光梳，非线性光子远距离遥感成像，多光子量子相干控制，便携式光学和原子传感平台等）
- ⑤ 原子、光子、固体比特混合量子网络（单光子波长转换技术、混合量子网络的纠缠与不确定性检验、原子比特与固体比特纠缠等）

广东省量子精密测量与传感重点实验室

量子信息与测控团队

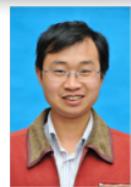


中山大学-理论物理团队

方向：引力、宇宙学、粒子物理与核物理



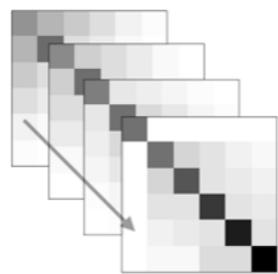
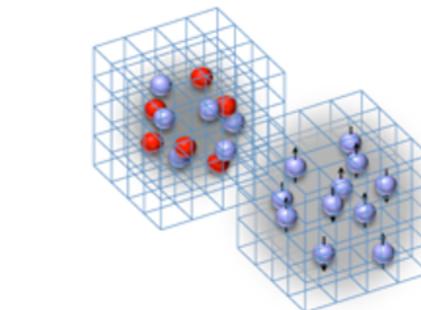
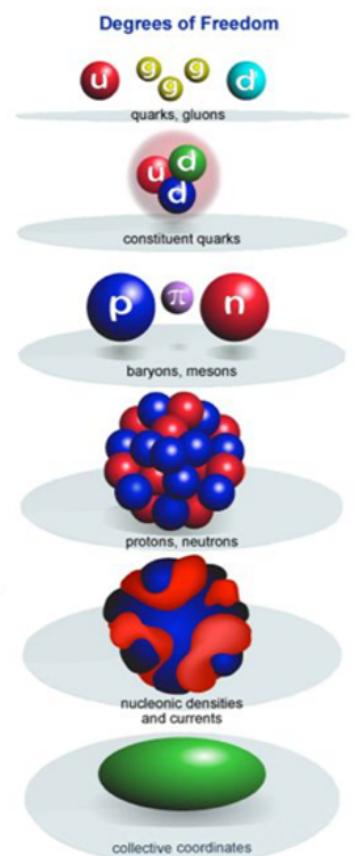
中山大学-“原子核理论与核天体物理课题组”



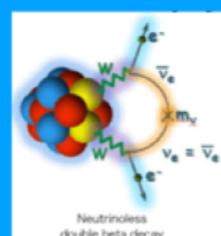
核结构与衰变



Physics of Hadrons



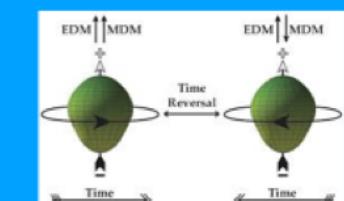
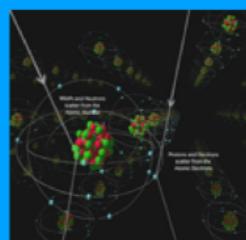
Probe new physics with nuclei



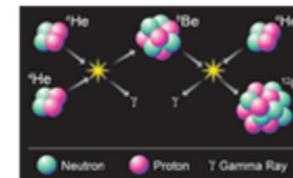
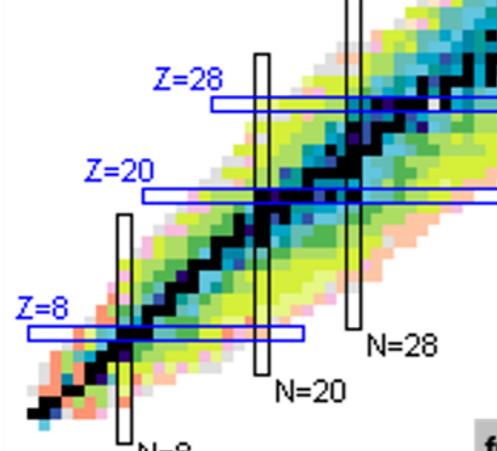
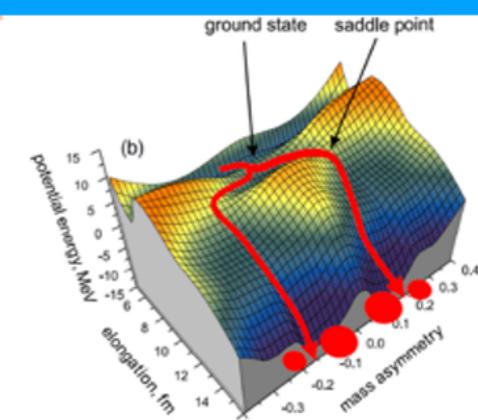
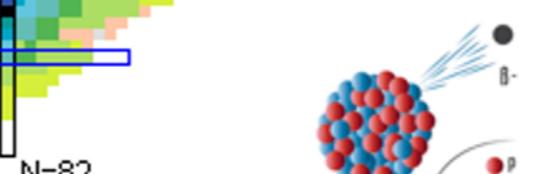
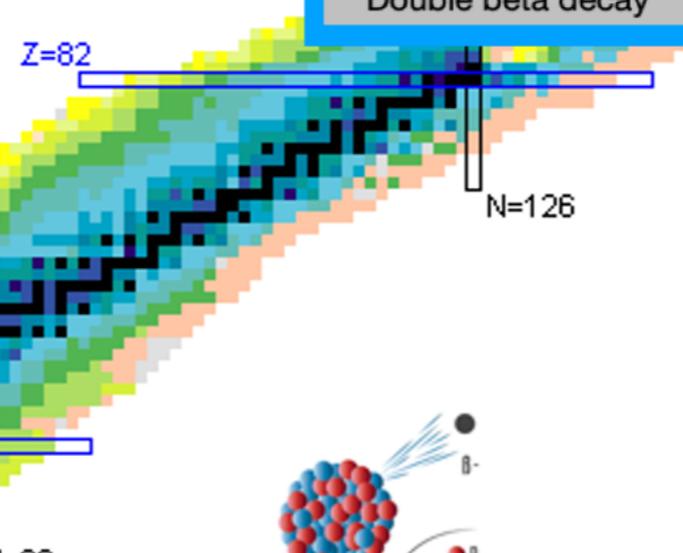
Double beta decay



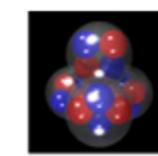
WIMP scattering



EDM and Schiff moment



fusion and stellar burning



13





中山大学-物理与天文学院（研究生招生）

硕士招生

中山大学物理与天文学院2020年全国优秀大学生云夏令营活动公告

二、参与报名

(一) 接受报名专业和项目类别

物理学：理论物理方向（硕博士项目）

原子与分子物理方向（硕博士项目）

精密测量物理方向（硕博士项目）

天文学：天体物理方向（目前仅招硕士研究生）

理论物理（含天文学）方向（硕博士项目）

(二) 申请资格

- 1.拥护中国共产党的领导，遵纪守法，品德良好，学风端正，身心健康；
- 2.全国各高等院校本科三年级在校生（2021年夏季应届毕业生）；
- 3.学习成绩优秀，英语水平良好，英语过六级（425分）同学优先；
- 4.对物理学、天文学有浓厚兴趣，有较强的创新意识、创新能力和专业能力，有从事学术研究工作的强烈意愿；
- 5.有意向报读物理与天文学院研究生的学生。

(三) 申请材料

1. 前三年（或两年半）成绩单（有学校教务部门公章）与总评成绩排名证明（有学校教务部门公章）；由于疫情，成绩单和成绩排名原件可以学院盖章或者学生系统打印等复印件扫描的电子版。等疫情过后，再按照要求补充该项报考材料。
- 2.学生证（将个人信息页和注册信息页复印在1张A4纸上）及身份证复印件（将正反面复印在1张A4纸上）；
- 3.全国大学英语六级考试成绩单复印件或TOEFL成绩、GRE/GMAT成绩等体现自身英语水平的证明材料复印件；
4. 获奖证书复印件1份（限填5项）；
- 5.体现自身学术水平的代表性学术论文（其中已发表论文提供期刊目录、论文首页，未正式发表论文提供单页摘要）、出版物或原创性研究成果材料的复印件（自愿提供）；

**坚持英语学习、
参加学科竞赛、
加入科研团队**



中山大学-物理与天文学院（研究生招生）

博士招生

物理与天文学院 2021 年招收博士研究生实行以综合素质能力考核为基础的“申请-考核”制招生方式。申请人须按照中山大学 2021 年博士研究生招生章程和物理与天文学院的相关要求进行报名并提交申请材料。

一、申请条件

(一) 遵守中华人民共和国宪法和法律，道德品行良好，身体和心理健康状况符合国家和中山大学的规定。

(二) 已获硕士学位者及应届硕士毕业生(最迟须于入学前取得硕士学位)。

(三) 申请人持境外获得的学历证书报考，须通过教育部留学服务中心认证，资格审查时须提交认证报告(最迟须于录取前提交)。

(四) 有两名与本学科有关的副教授(或相当职称)以上的专家推荐。

(五) 具有浓厚的学术研究兴趣，具备较强的科研能力。

(六) 英语水平满足以下条件中的一项：(1) 发表过英文的专业性学术论文，(2) 通过大学英语六级考试或者新托福成绩 ≥ 90 分(老托福成绩 ≥ 580 分)，或者雅思成绩 ≥ 6.0 分。如

不能满足以上条件，仅通过国家大学英语四级考试，可书面

**坚持英语学习、
发表专业论文**



◆ Introduction

New opportunities and challenges in nuclear physics

◆ Advances in modeling atomic nuclei

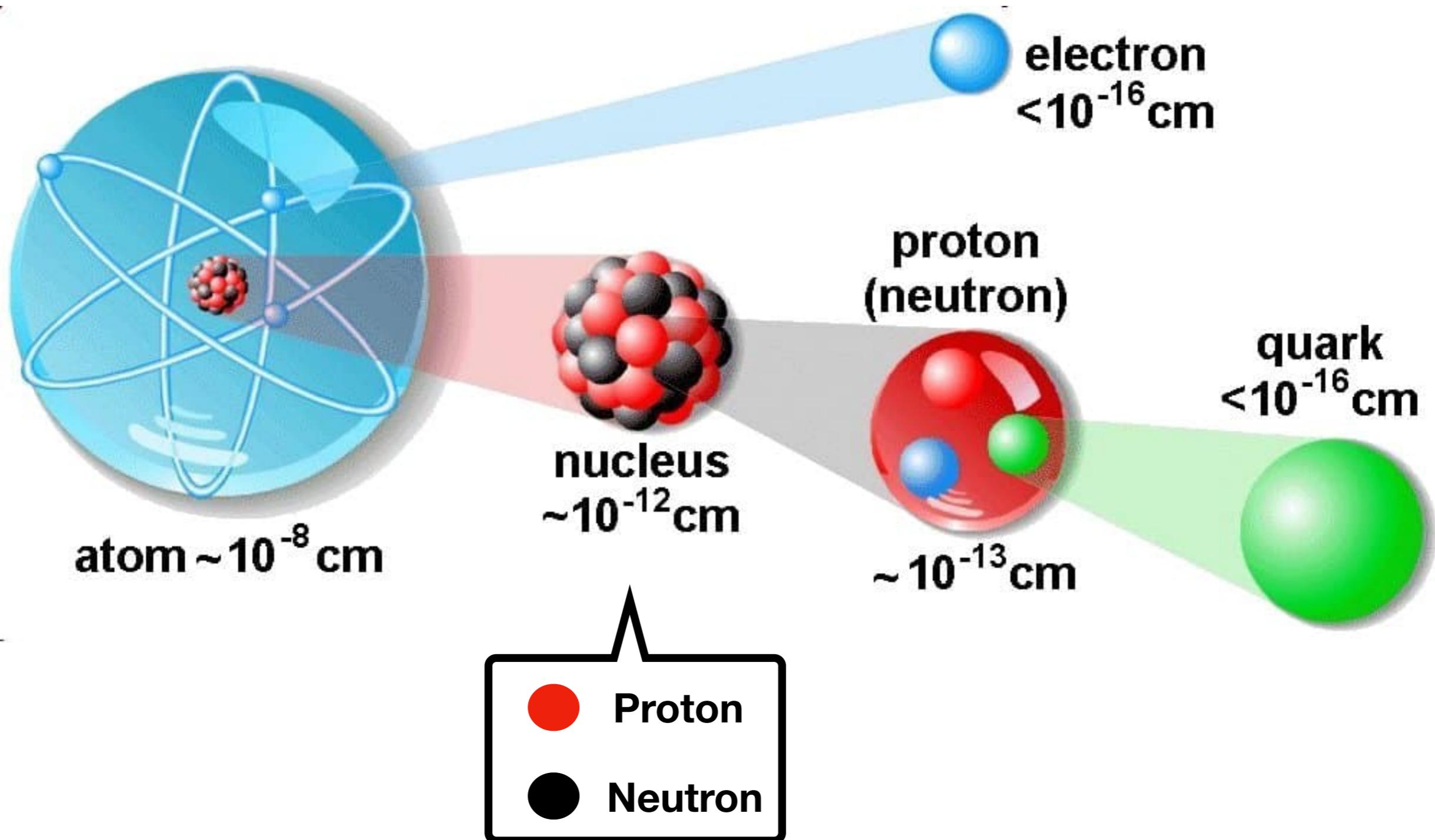
- ▶ Nuclear (covariant) energy density functional theory
- ▶ Nuclear ab initio methods

Nuclear structure and weak decays

Neutron-star matter

◆ Summary and Outlook

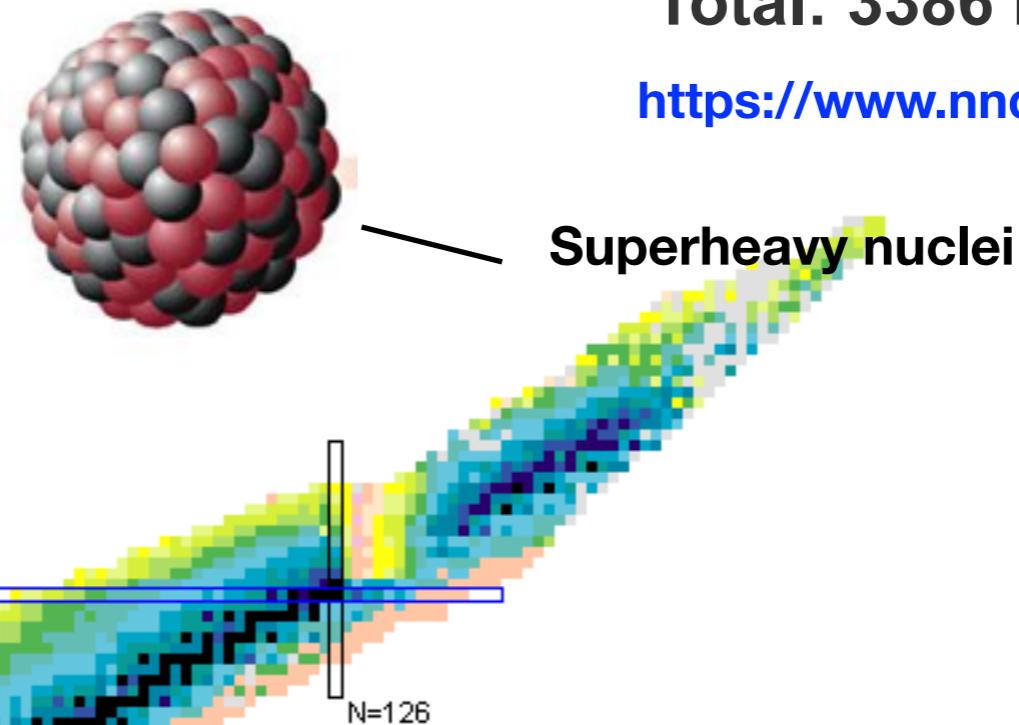
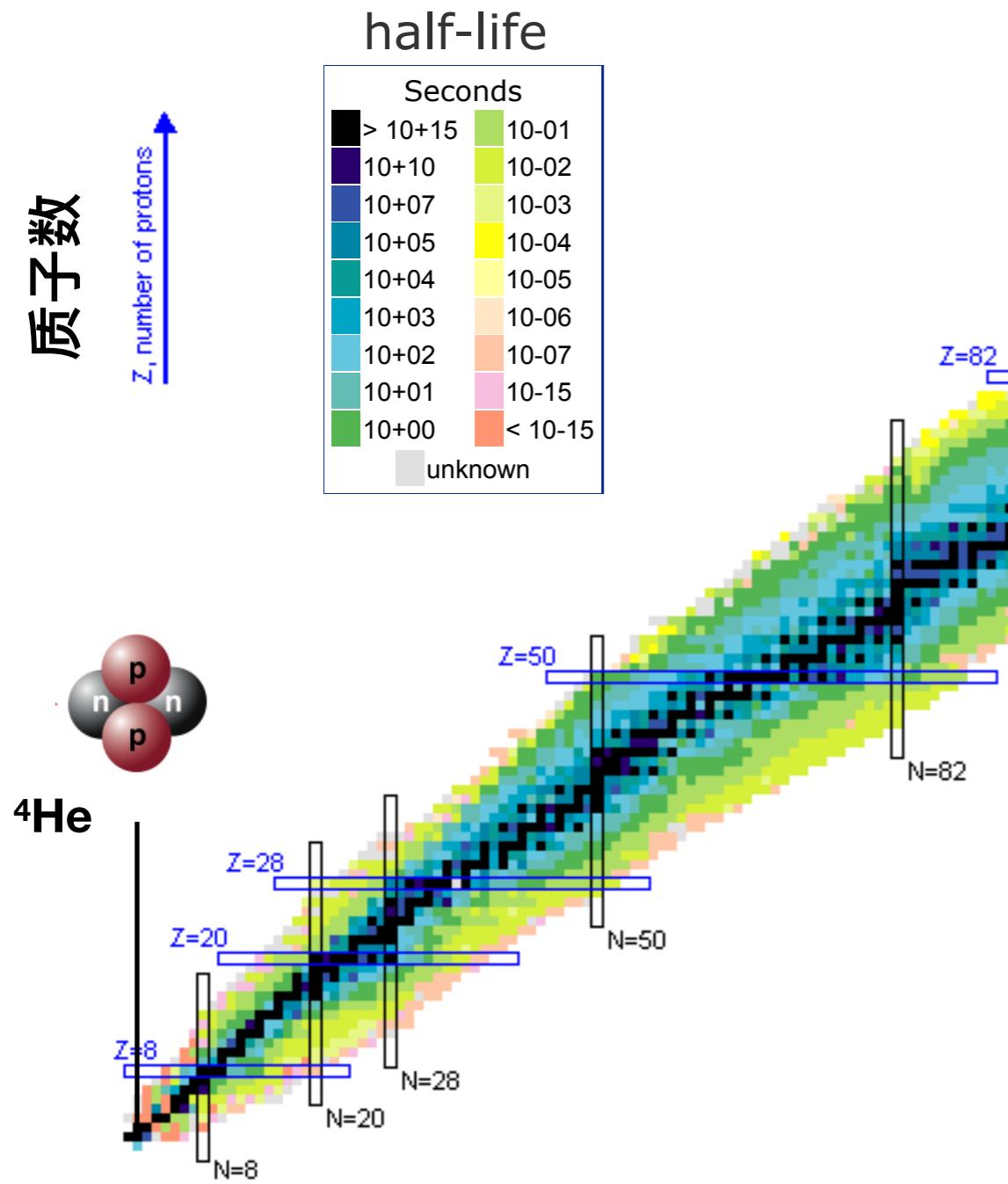
Atomic nucleus: core of matter



Structure of atomic nuclei

Total: 3386 known nuclei

<https://www.nndc.bnl.gov/nudat2/>



Periodic Table Of The Elements

Atomic Number → 1

Name → H

Symbol → Hydrogen

Atomic Weight → 1.008

State of matter (color of name)

Subcategory in the metal-metallloid-nonmetal trend (color of symbol)

Alkaline metal Alkaline earth metal Post-transition metal Noble gas

Transition metal Post-transition metal Polyatomic nonmetal Unknown chemical properties

Lanthanide Actinide Diatomic nonmetal

1	IA	H	Hydrogen	1.008	GAS	Alkaline metal	Hydrogen
2	IIA	Be	Beryllium	9.01289	LIQUID	Alkaline earth metal	Boron
3	III	Li	Lithium	6.94	SOLID	Scandium	Carbon
4	IVB	Mg	Magnesium	24.315	UNKNOWN	Titanium	Nitrogen
5	V	K	Potassium	39.0983		Vvanadium	Oxygen
6	VIIB	Ca	Calcium	40.078		Chromium	Fluorine
7	VIB	Sc	Scandium	44.9590		Manganese	Neon
8	VIII	Ti	Titanium	47.98		Iron	Argon
9	VIII	V	Vanadium	50.951		Cobalt	
10	VIII	Cr	Chromium	51.981		Nickel	
11	IB	Mn	Manganese	54.9384		Copper	
12	IIB	Fe	Iron	55.845		Zinc	
13	IIIA	Co	Cobalt	58.9514		Aluminum	
14	IVA	Ni	Nickel	58.6934		Silicon	
15	VIA	Cu	Copper	63.546		Phosphorus	
16	VIIA	Zn	Zinc	65.45		Sulfur	
17	VIIA	Al	Aluminum	26.9815385		Chlorine	
18	VIIA	Si	Silicon	28.085		Ar	
19	VIIA	Ge	Germanium	72.63			
20	VIIA	As	Arsenic	74.91965			
21	VIIA	P	Phosphorus	30.9707599			
22	VIIA	S	Sulfur	32.06			
23	VIIA	Cl	Chlorine	35.45			
24	VIIA	Ar	Argon	39.948			
25	VIIA	Br	Bromine	79.904			
26	VIIA	Kr	Krypton	83.774			
27	VIIA	I	Iodine	126.90447			
28	VIIA	Xe	Xenon	131.951			
29	VIIA	At	Astatine	210.0			
30	VIIA	Rn	Radon	222.0			
31	VIIA	Tl	Thallium	204.38			
32	VIIA	Pb	Lead	207.2			
33	VIIA	Bi	Bismuth	208.9594			
34	VIIA	Po	Po	209.0			
35	VIIA	At	Astatine	210.0			
36	VIIA	Rn	Radon	222.0			
37	VIIA	Fr	Francium	223.0			
38	VIIA	Ra	Radium	226.0			
39	VIIA	Ac	Actinium	227.0			
40	VIIA	Th	Thorium	232.037			
41	VIIA	Pa	Protactinium	231.03588			
42	VIIA	U	Uranium	234.03628			
43	VIIA	Np	Neptunium	237.0			
44	VIIA	Pu	Plutonium	244.0			
45	VIIA	Am	Americium	243.0			
46	VIIA	Cm	Curium	247.0			
47	VIIA	Bk	Berkelium	249.0			
48	VIIA	Cf	Californium	251.0			
49	VIIA	Es	Einsteinium	252.0			
50	VIIA	Fm	Fermium	257.0			
51	VIIA	Md	Mendelevium	258.0			
52	VIIA	No	Nobelium	259.0			
53	VIIA	Lr	Lawrencium	256.0			
54	VIIA	Ts	Ts	254.0			
55	VIIA	Og	Oganesson	254.0			

SCANNABLE QR CODE

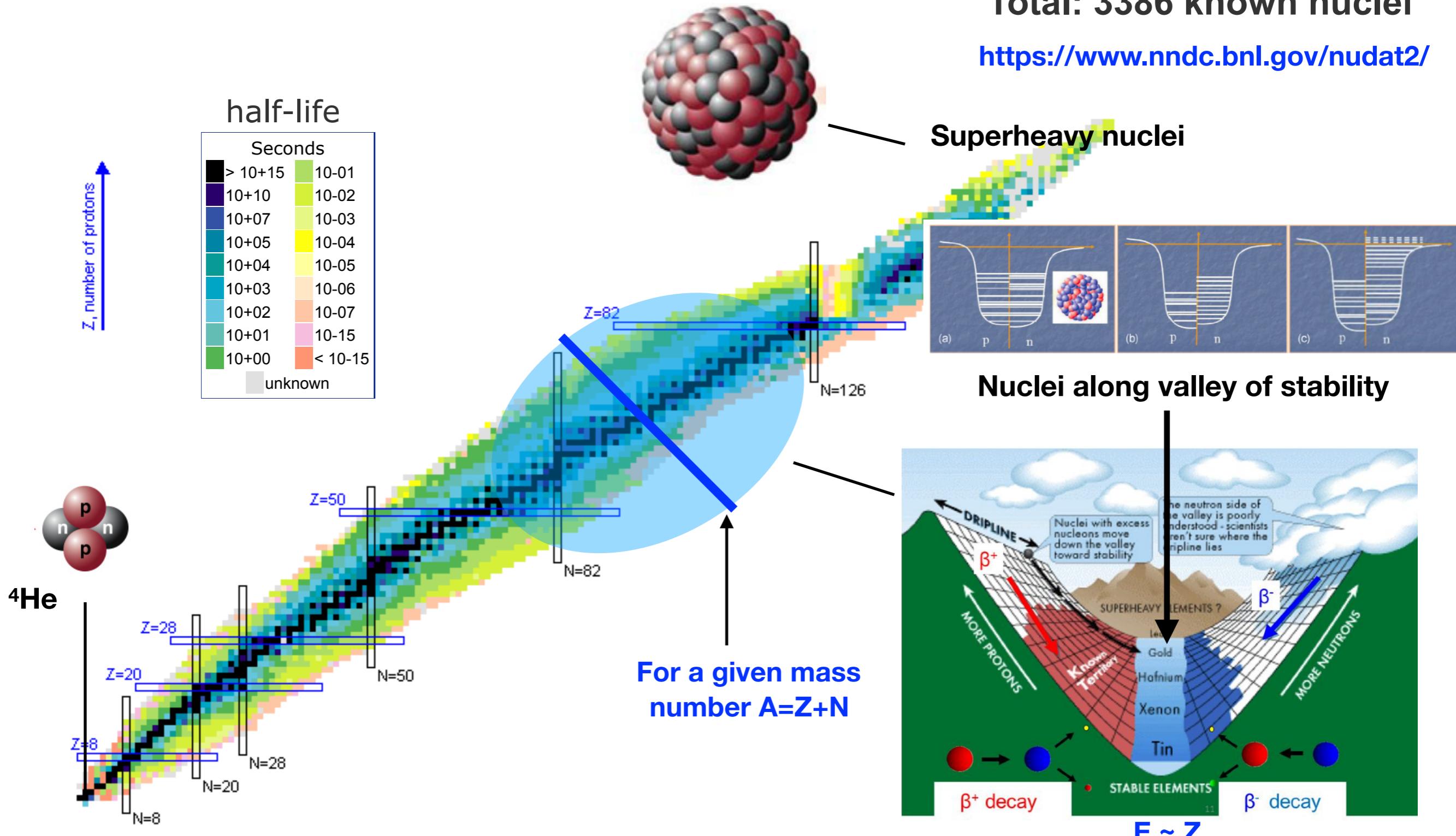
DATA BY DR. WALTER BRÜgel

Copyright © 2019 DR. WALTER BRÜGEL. All rights reserved.

Structure of atomic nuclei

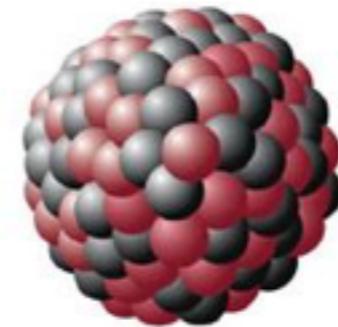
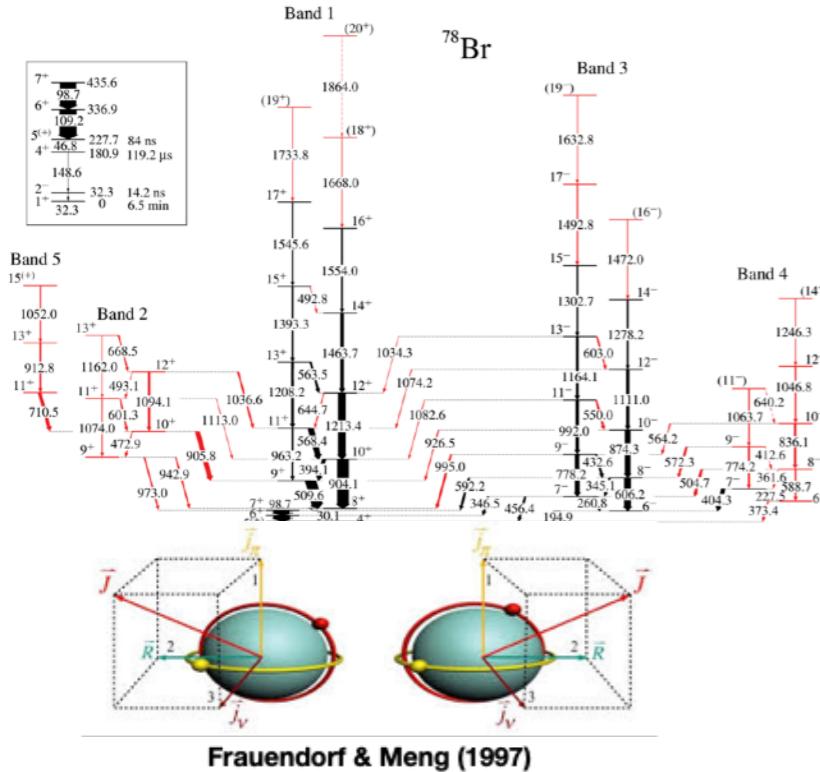
Total: 3386 known nuclei

<https://www.nndc.bnl.gov/nudat2/>



Structure of atomic nuclei

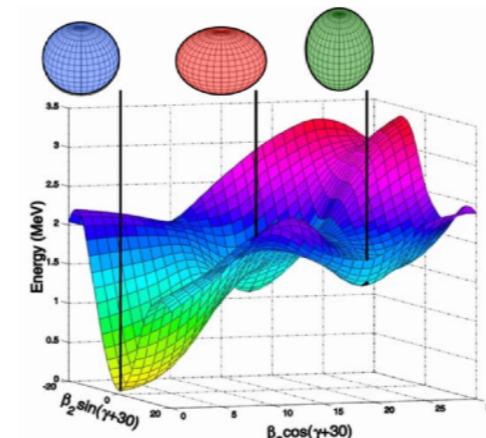
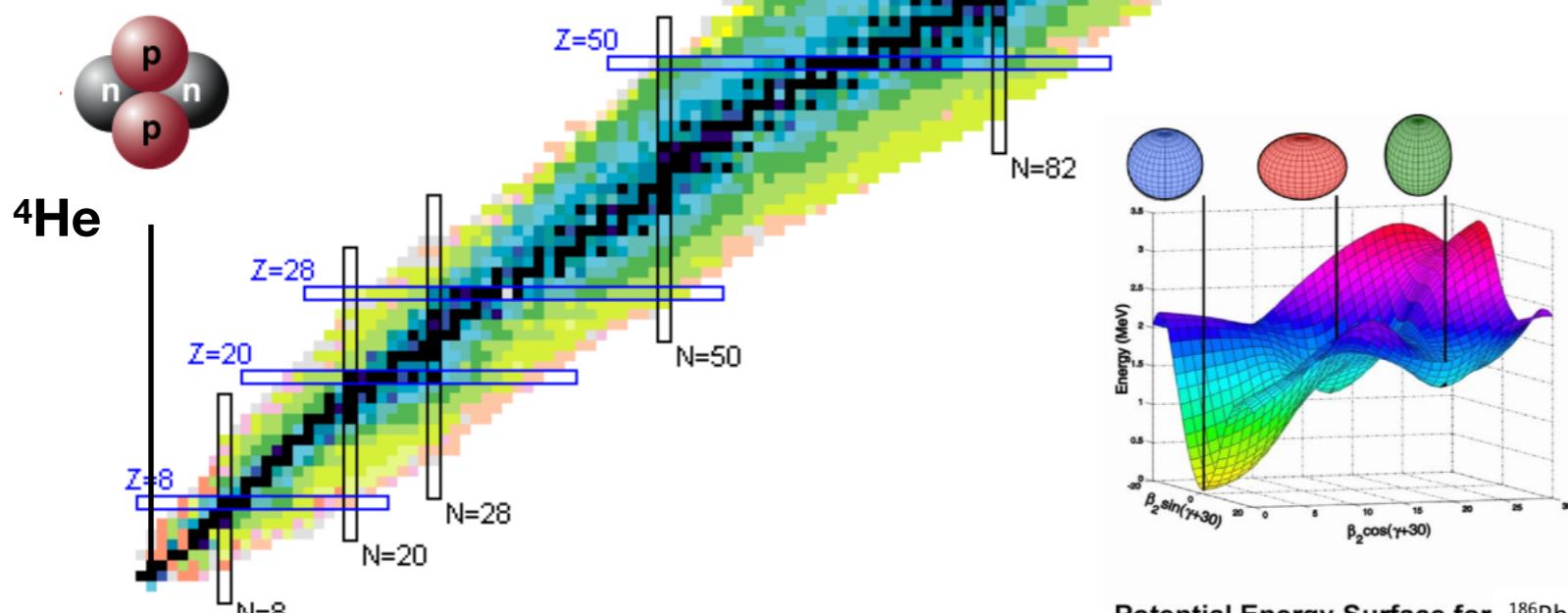
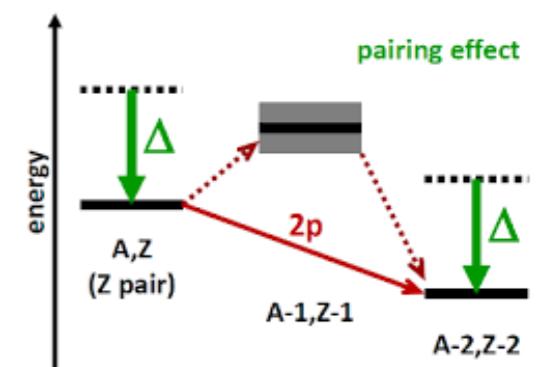
C. Liu et al., PRL116, 112501 (2016)



Total: 3386 known nuclei

<https://www.nndc.bnl.gov/nudat2/>

Superheavy nuclei

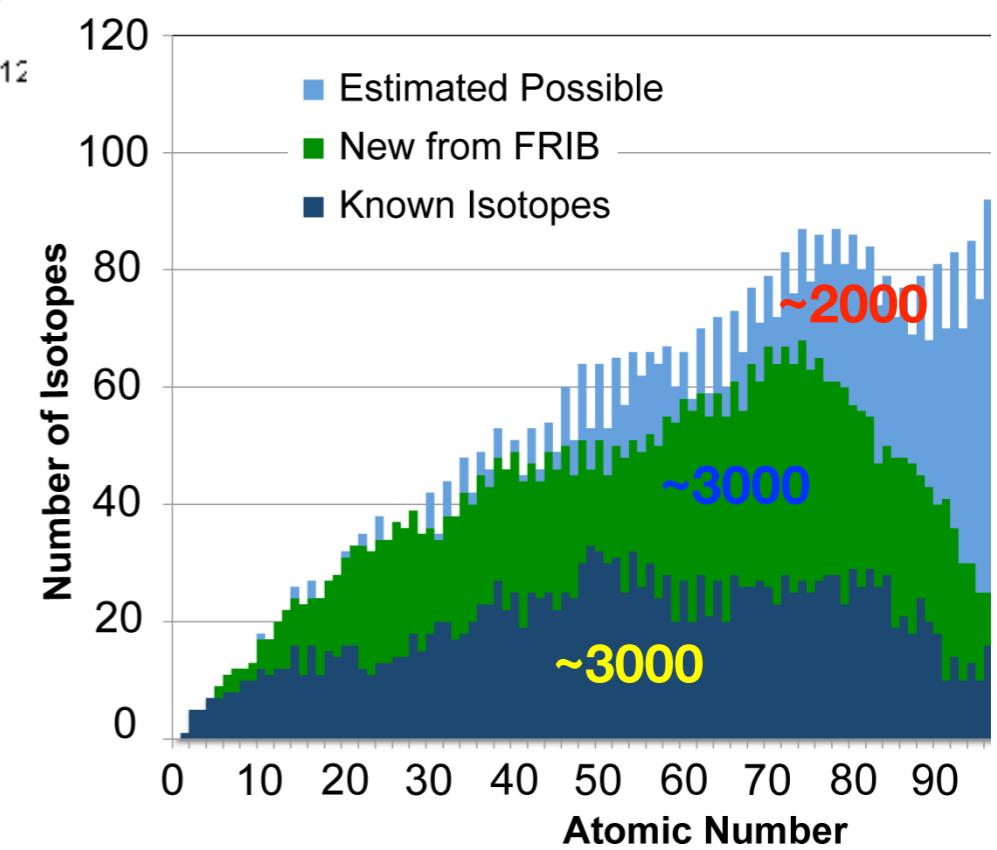
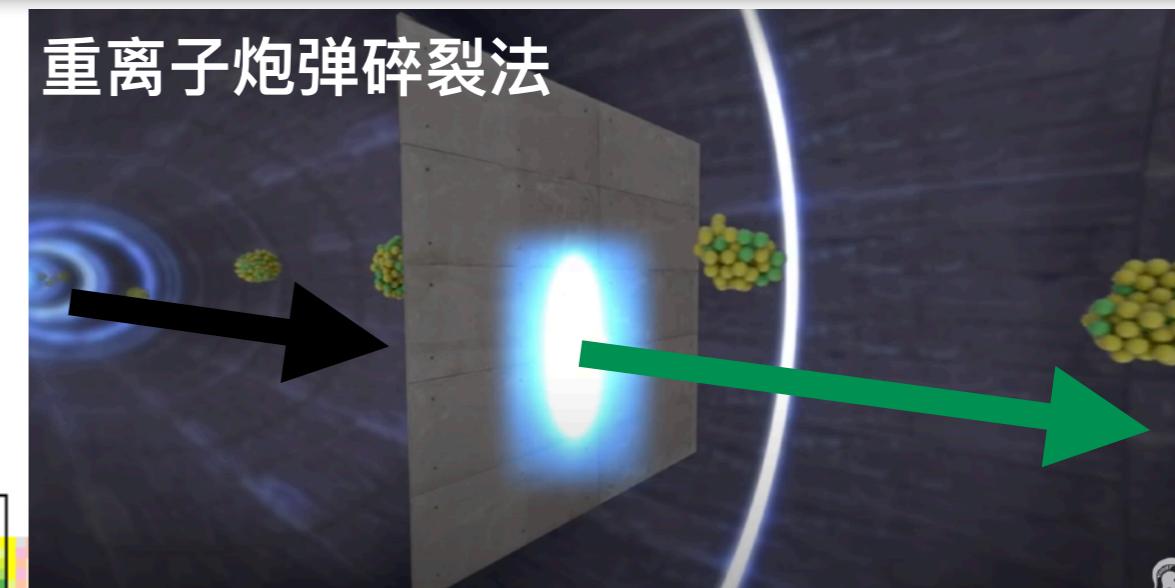
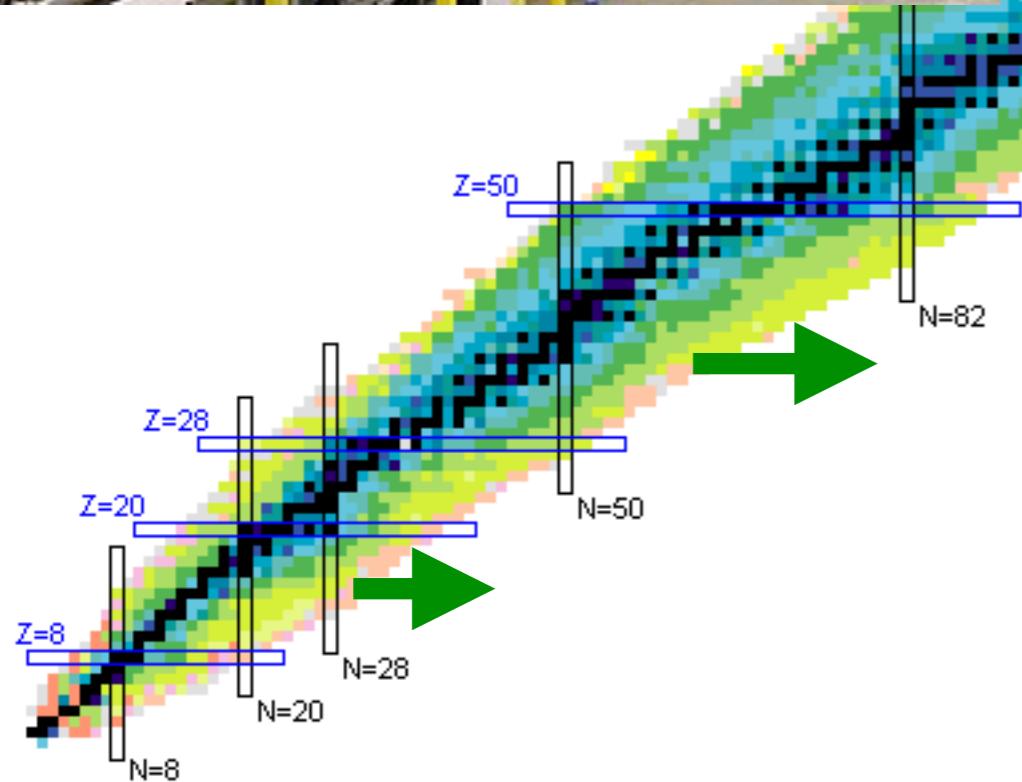
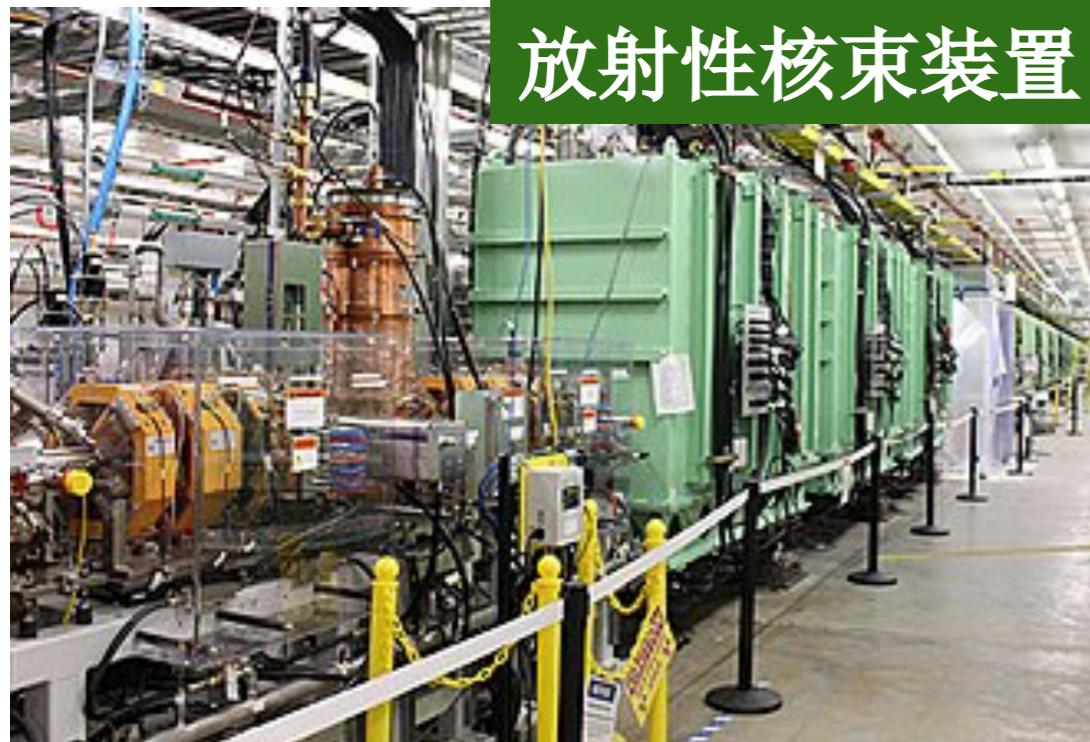


A. Andreyev et al., Nature 405 (2000) 430

Stable nuclei <300

- Pronounced shell structure
- Strong collectivity/shapes
- Superfluidity
- High-spin states

Structure of atomic nuclei

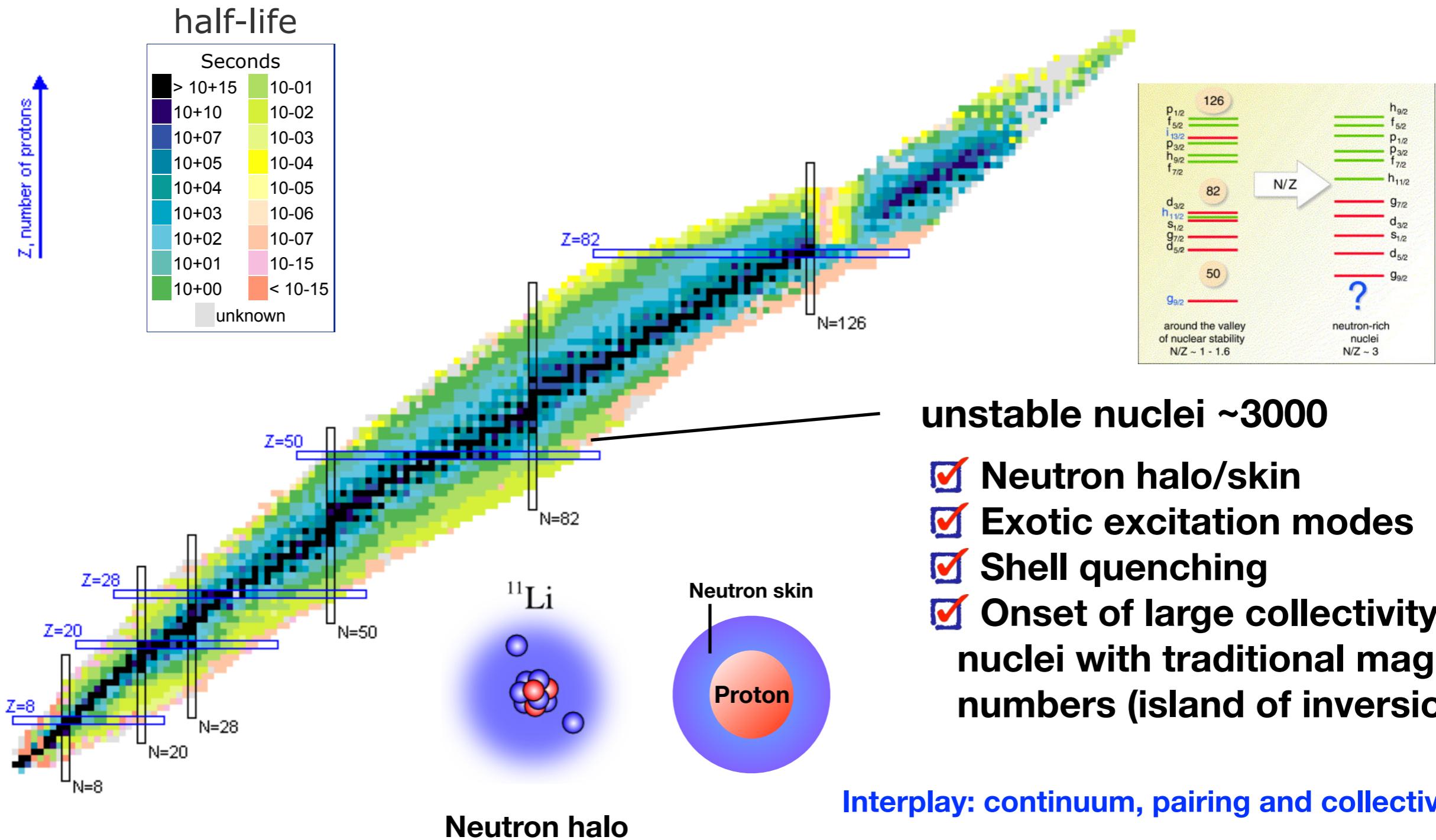


A.B. BALANTEKIN et al., Mod. Phys. Lett. A (2014)

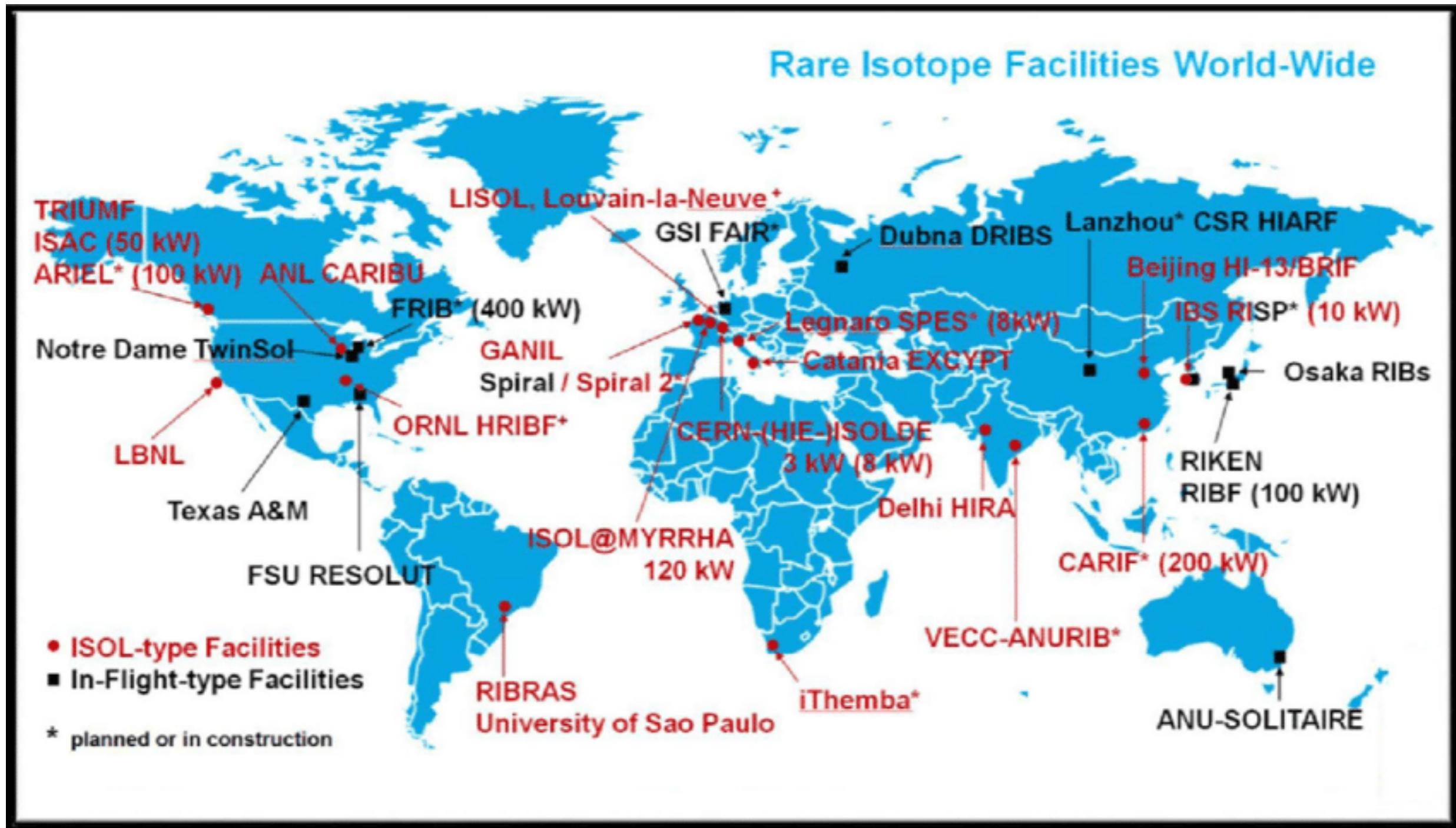
Structure of atomic nuclei

Total: 3386 known nuclei

<https://www.nndc.bnl.gov/nudat2/>



Rare isotope facilities



CARIF: China advanced rare ion beam facility

Nuclear facilities in China (中国核物理大科学装置)

兰州重离子加速器与冷却储存环装置 (HIRFL-CSR)



广东惠州 - 强流重离子加速器装置 (HIAF)



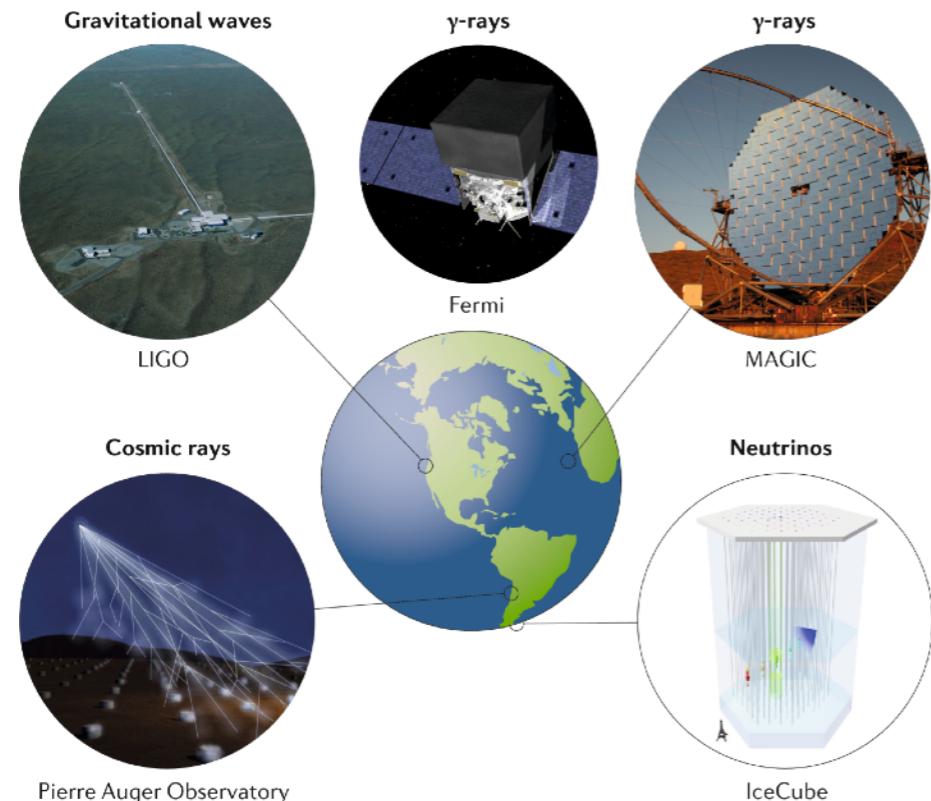
Nuclear physics at HIAF

- What are the limits to nuclear existence?
- What are new forms of nuclear matter far from stability?
- How about the quantum levels far from stability?
- What are new forms of collective motion far from stability?
- What dynamical symmetries appear in exotic nuclei?
- How were the elements from carbon to uranium created?
- How is energy generated in stars and stellar explosions?
- What is the behavior of stars and supernovae?

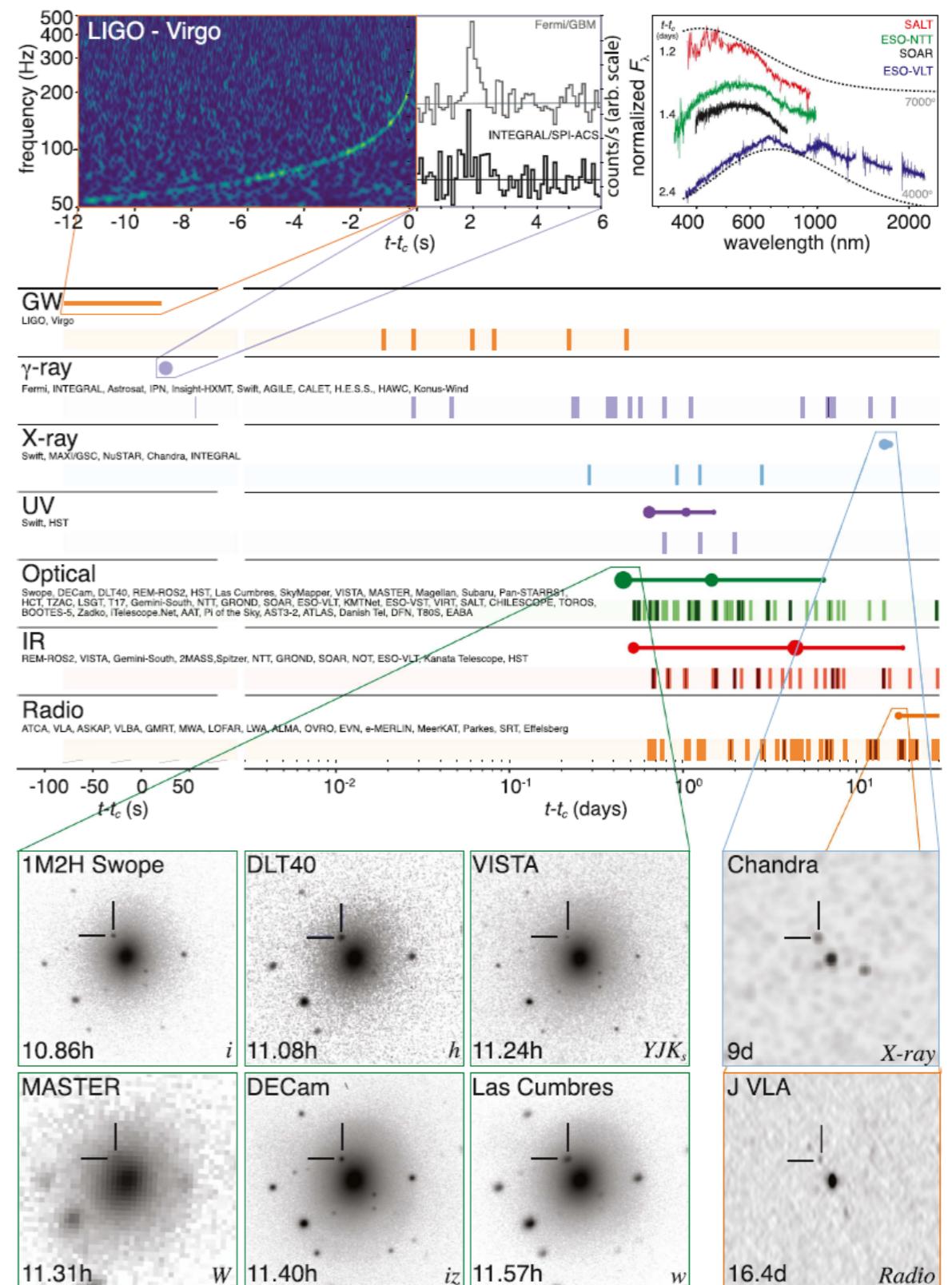


Nuclear physics in the era of multi-messenger astronomy

Multi-messenger Observations of a Binary Neutron Star Merger*



B. P. Abbott et al., *Astrophys. J.* 848, L12 (2017).



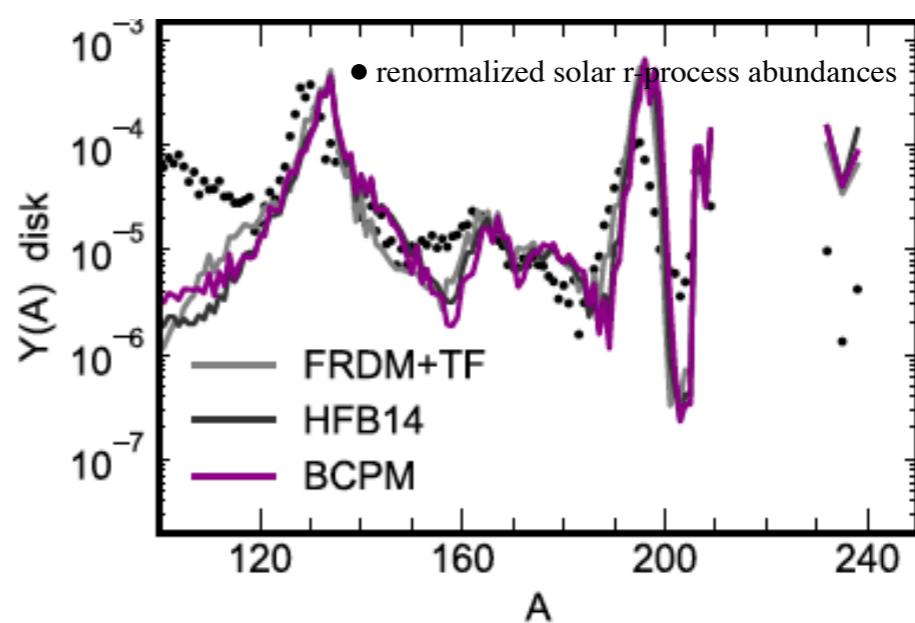
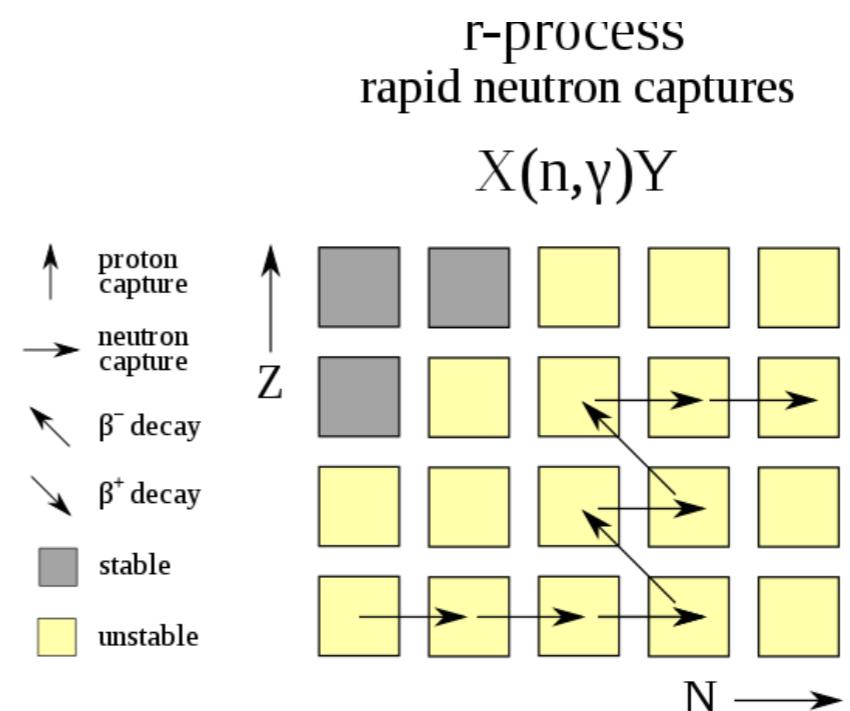
Nuclear physics in astronomy (nucleosynthesis)

GW170817: gravitational wave signal and its associated AT 2017gfo electromagnetic (EM) counterpart provided the first evidence that **r-process nucleosynthesis** occurs in neutron star mergers.



kilonova (decay of heavy r-process nuclei)

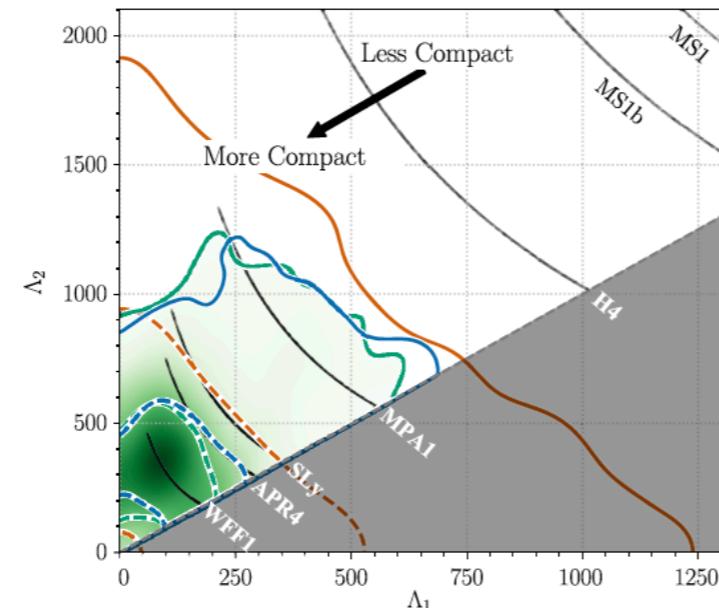
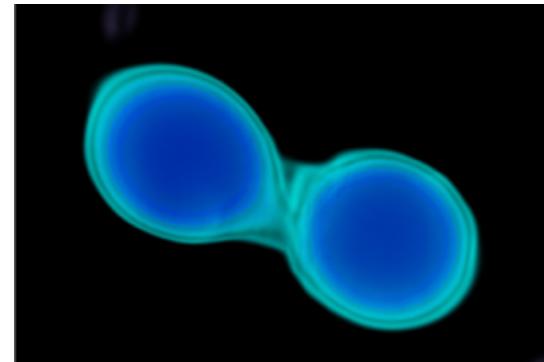
What is the origin of elements heavier than iron?



Nuclear physics in astronomy (neutron stars)

GW170817: Measurements of Neutron Star Radii and Equation of State

B. P. Abbott et al.. PRL121. 161101 (2018)



Tidal deformation (潮汐形变)

- enhances GW emission
- accelerates the decay of the quasicircular inspiral

The leading-order contribution is proportional to each star's **tidal deformability parameter**,

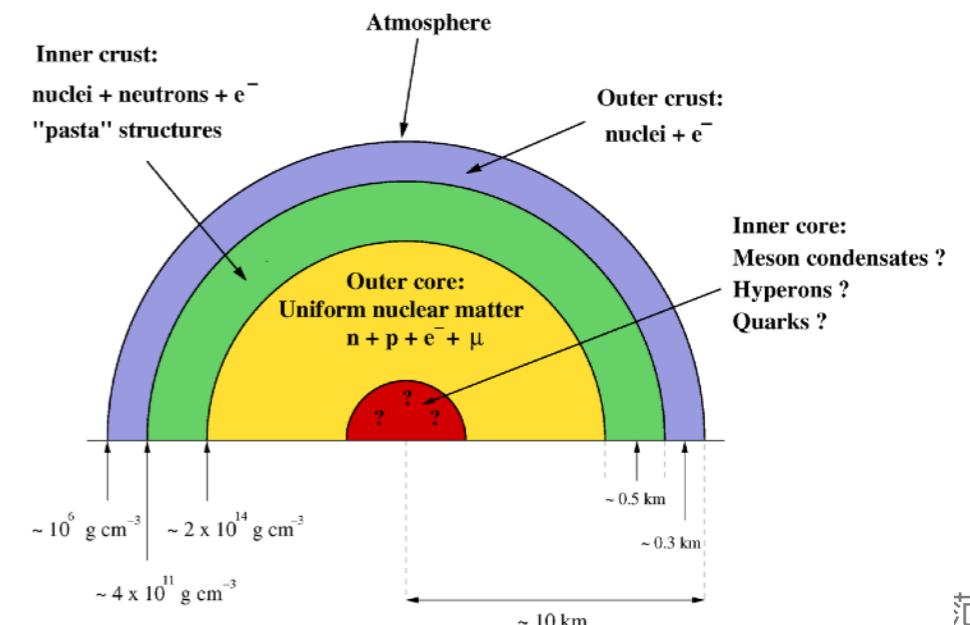
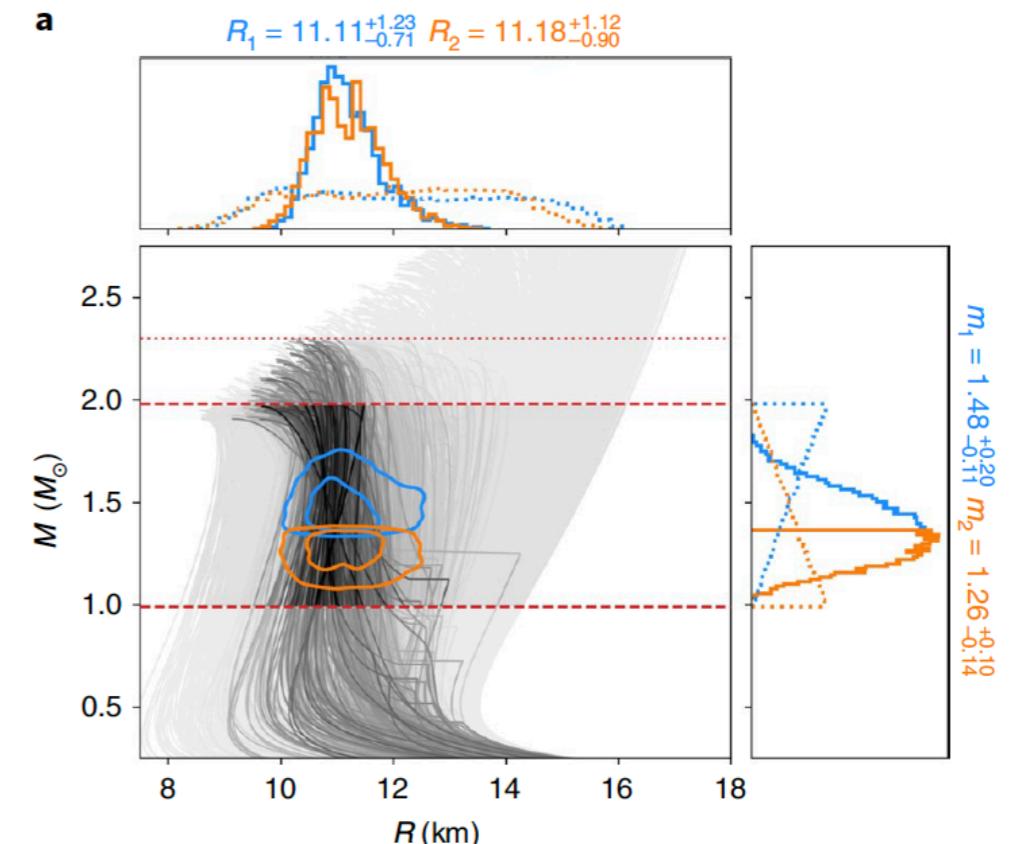
$$\bar{\Lambda} = \Lambda/M^5 = 2k_2/(3C^5),$$

with $C \equiv M/R$ denoting the compactness of the configuration.

T. Hinderer (2008) *Astrophys. J.* **677** 1216–20

Stringent constraints on neutron-star radii from multimessenger observations and nuclear theory

Collin D. Capano et al.. Nature Astronomy 4. 625 (2020)



Constrain Nuclear physics from neutron stars



Neutron stars as windows into ultra-dense matter

Credit to J. Holt

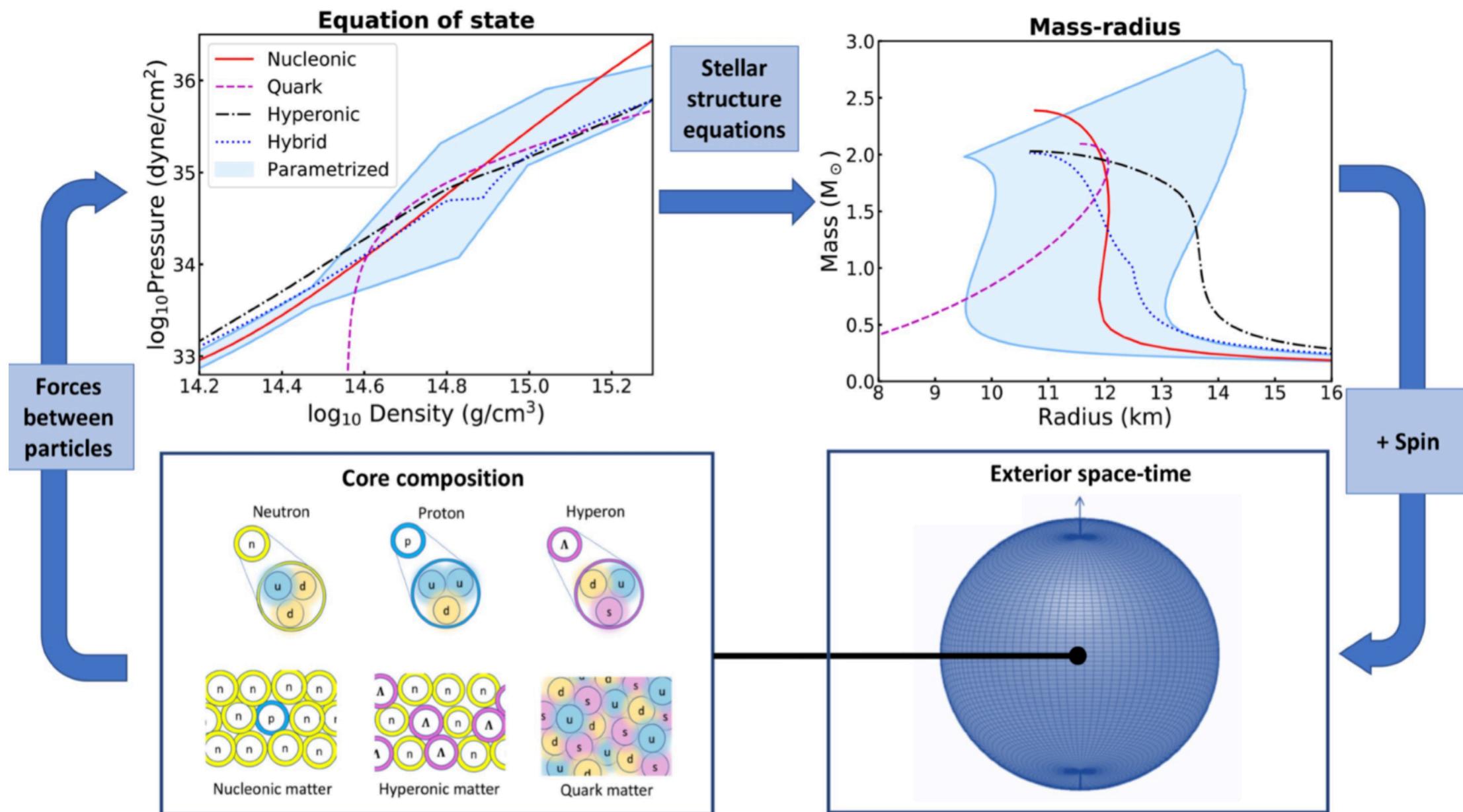
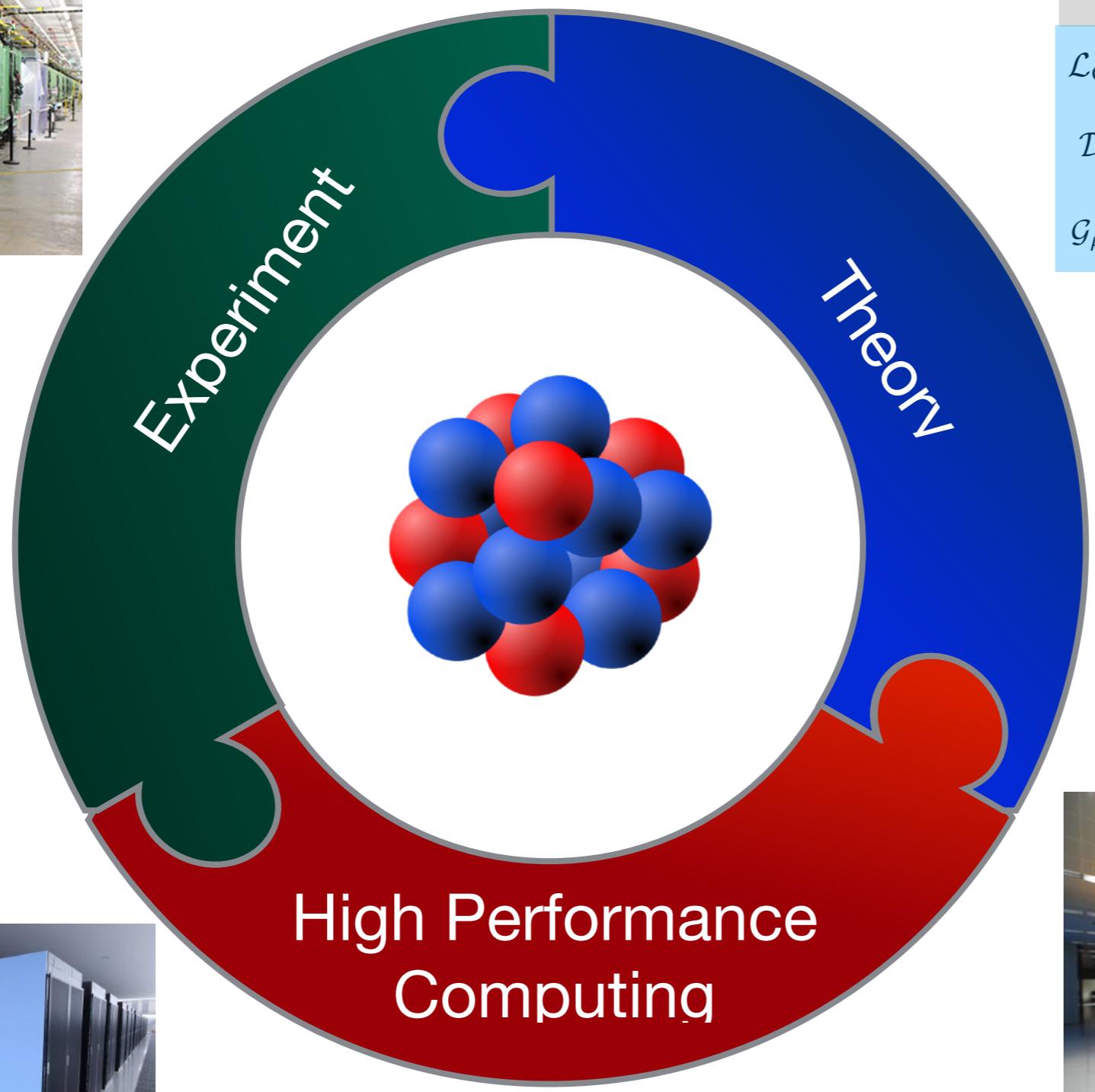
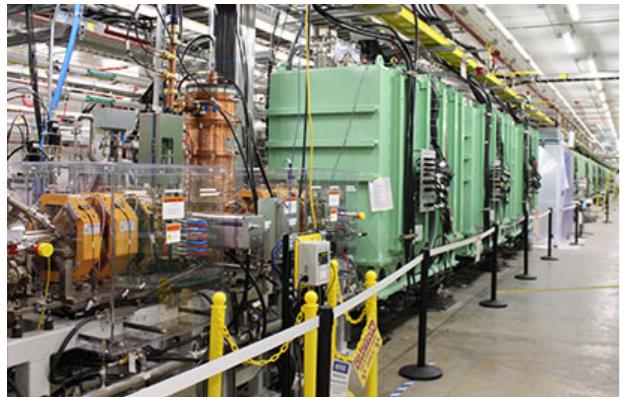


Figure adapted from A. Watts

- Recent review article: Drischler, Holt & Wellenhofer, Ann. Rev. Nucl. Part. Sci. (2021)

The “three horses” in nuclear physics research



Quantum Chromodynamics

$$\mathcal{L}_{\text{QCD}} = \bar{q}(i\gamma^\mu \mathcal{D}_\mu - \mathcal{M})q - \frac{1}{4}\mathcal{G}_{\mu\nu,a}\mathcal{G}_a^{\mu\nu}$$
$$\mathcal{D}_\mu = \partial_\mu - ig\frac{\lambda_a}{2}\mathcal{A}_{\mu,a}$$
$$\mathcal{G}_{\mu\nu,a} = \partial_\mu\mathcal{A}_{\nu,a} - \partial_\nu\mathcal{A}_{\mu,a} + g f_{abc}\mathcal{A}_{\mu,b}\mathcal{A}_{\nu,c}$$



◆ Introduction

New opportunities and challenges in nuclear physics

◆ Advances in modeling atomic nuclei

- ▶ Nuclear (covariant) energy density functional theory
- ▶ Nuclear ab initio methods

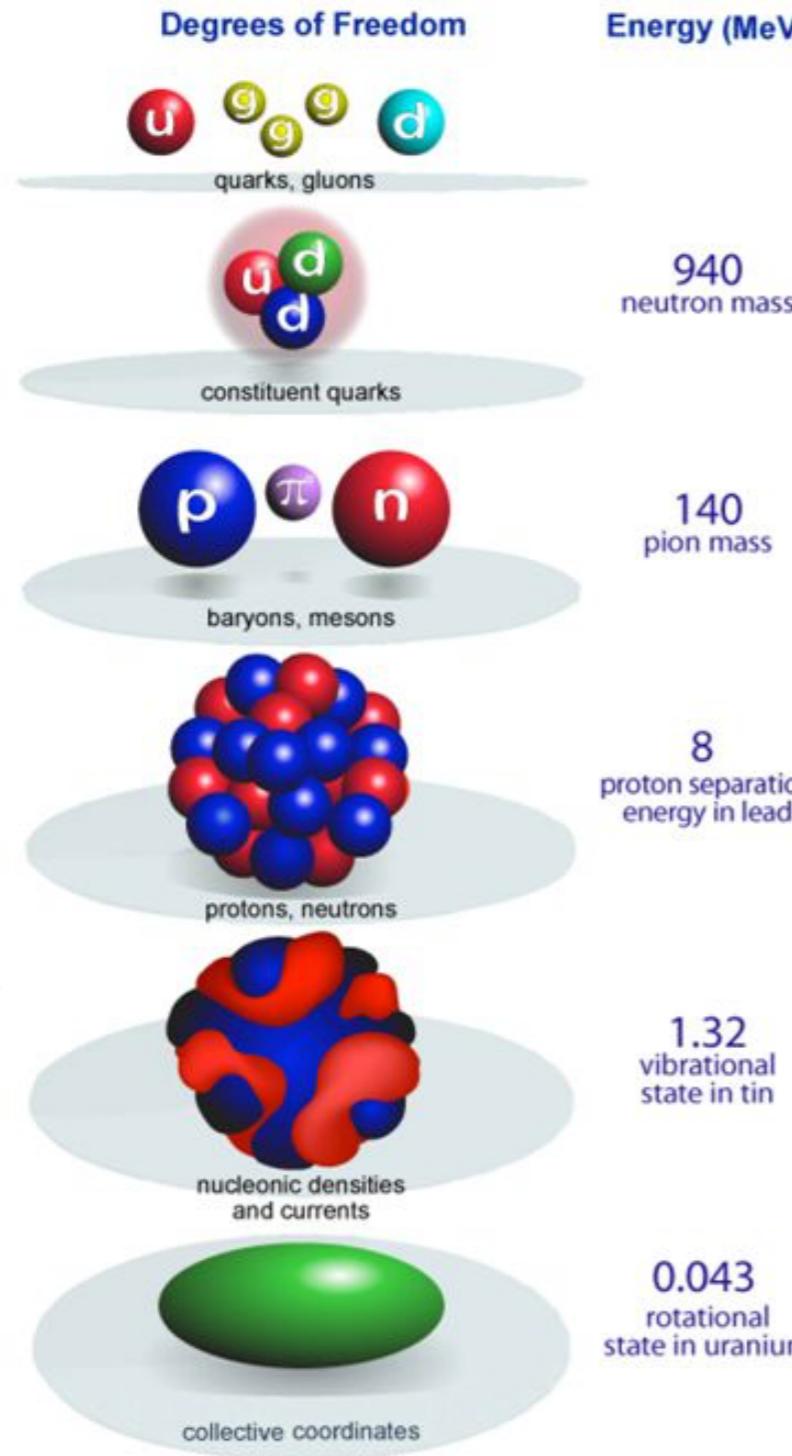
Nuclear structure and weak decays

Neutron-star matter

◆ Summary and Outlook

How to modeling atomic nuclei?

Physics of Hadrons



multi-faceted nuclei

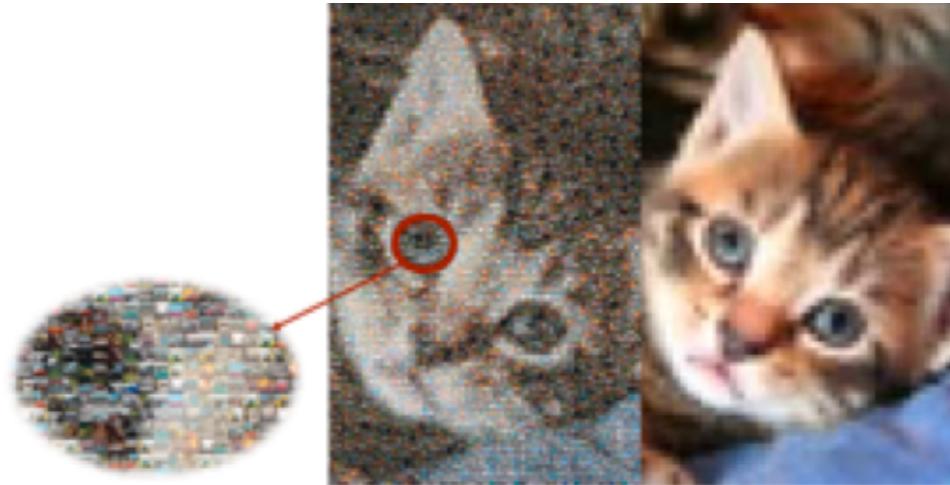


Image with different resolutions

How to modeling atomic nuclei?

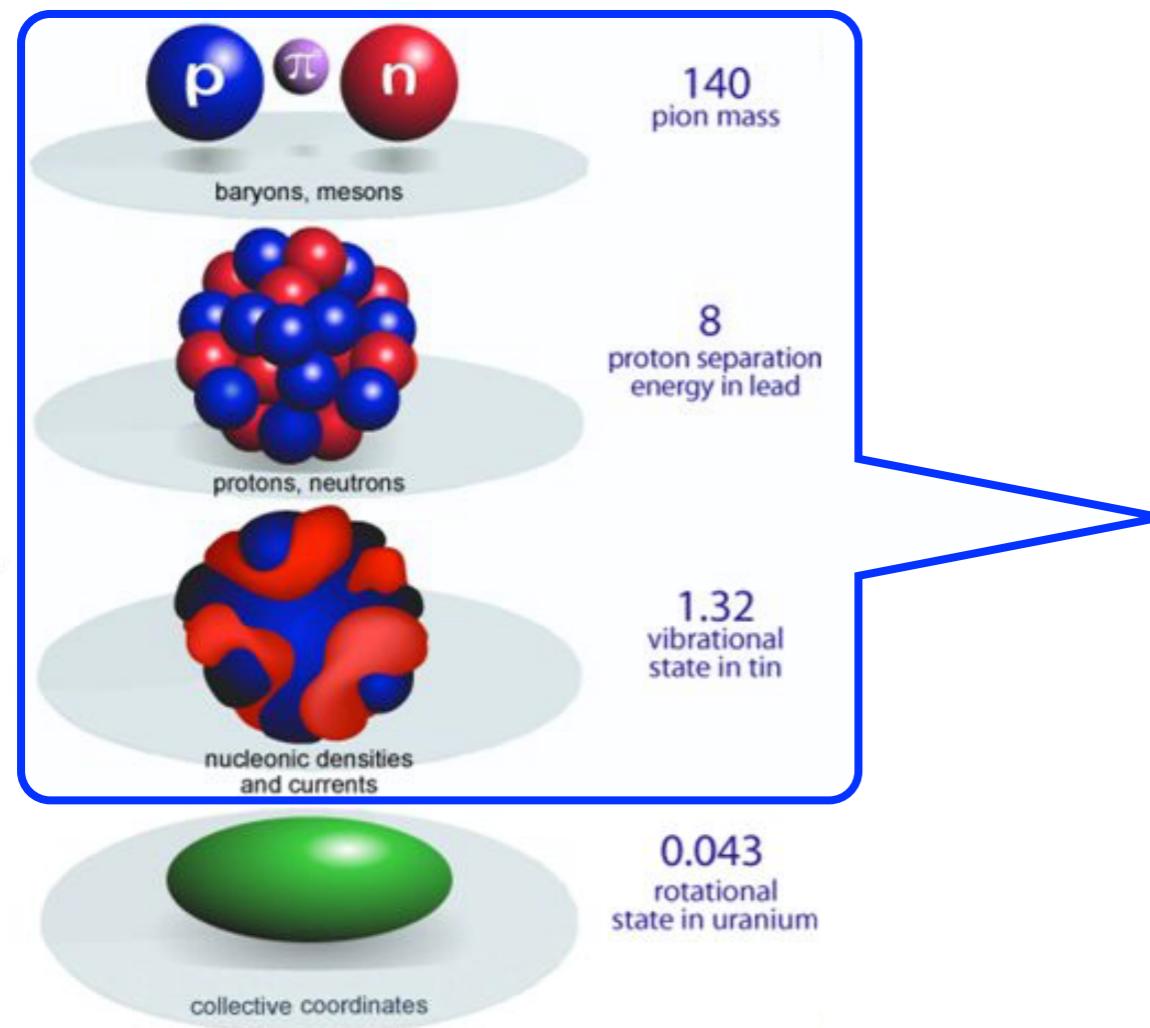
Physics of Hadrons



Energy (MeV)

940 neutron mass

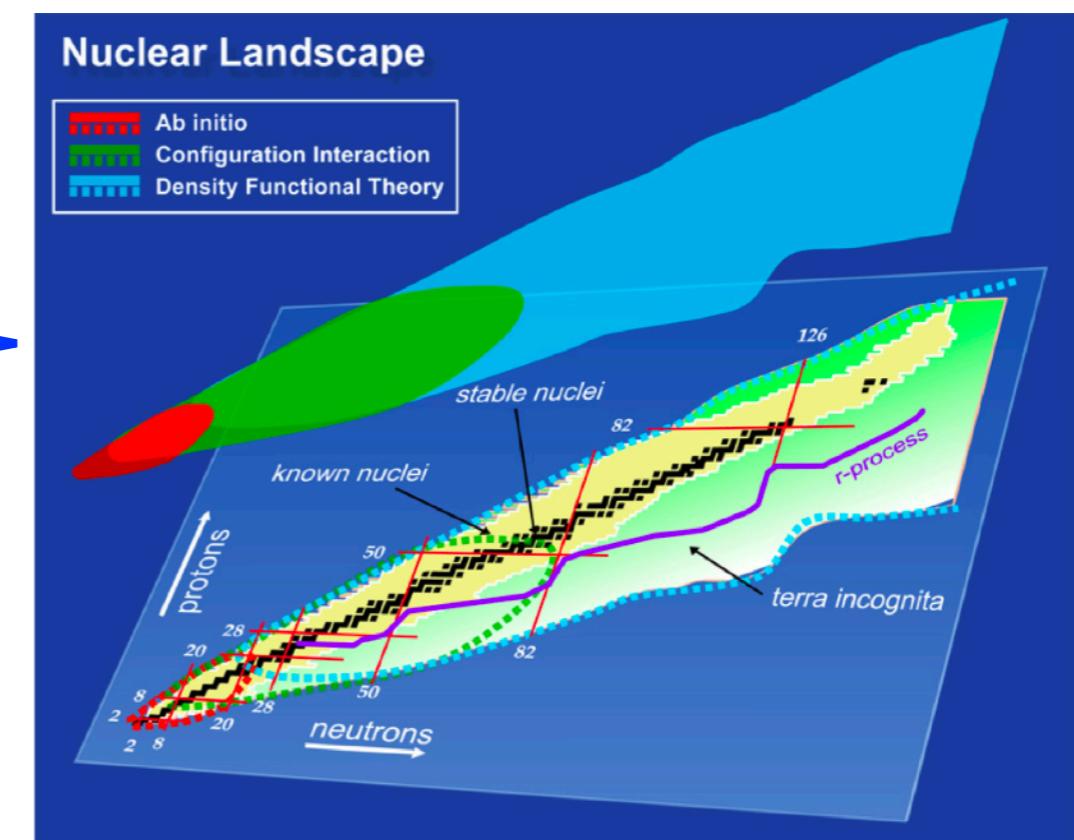
Physics of Nuclei



multi-faceted nuclei



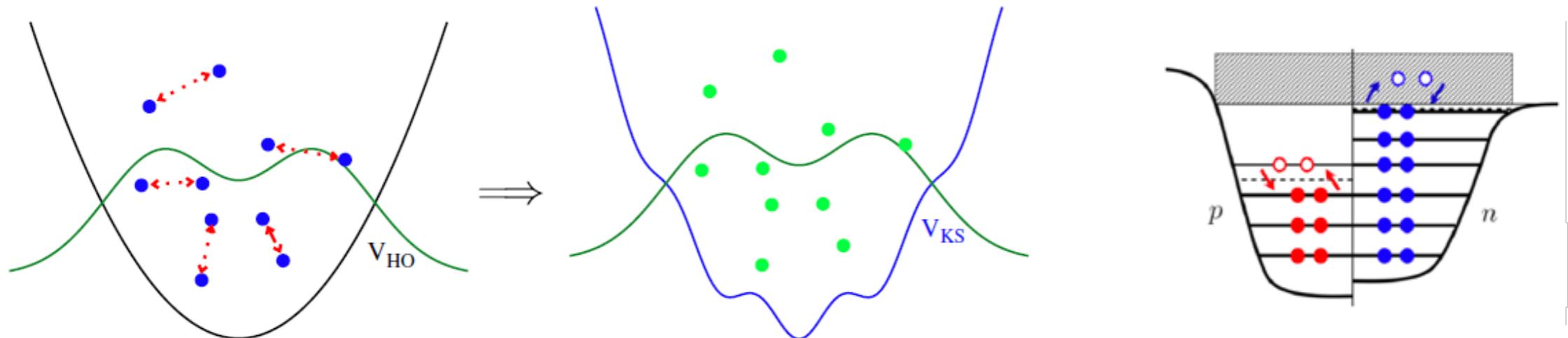
Image with different resolutions



The Frontiers of Nuclear Science: A Long-Range Plan, 2007.

Nuclear (covariant) energy density functional theory

Mean-field approximation: (HF/DFT)



Many-body problem

$$\hat{H}\Psi(x_1, x_2, \dots, x_N) = E\Psi(x_1, x_2, \dots, x_N)$$

$$\hat{H} = \sum_i^N t_i + \sum_{i < j} V_{ij} + \text{many-body forces}$$

One-body problem

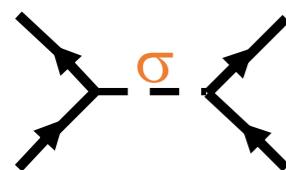
$$\left\{ -\frac{1}{2M} \nabla^2 + u(\mathbf{r}) - \epsilon_i \right\} \varphi_i(\mathbf{r}) = 0$$

$$\hat{H} = \sum_i^N (t_i + U_i) + \left(\sum_{i < j} V_{ij} - \sum_i^N U_i \right)$$

- ✓ Ingredients of n and p density/current, pairing density, etc.
- ✓ Universal and unified description of nuclear structure and reaction, relevant information (mass, beta decay, etc) for nucleosynthesis.

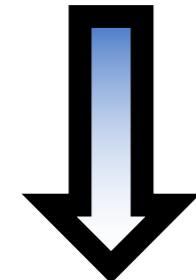
Nuclear (covariant) energy density functional theory

Nucleons are coupled by exchange of mesons via an effective Lagrangian

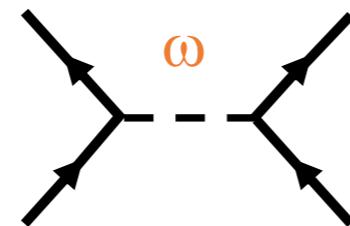


$$(J^\pi T) = (0^+0)$$

Sigma-meson:
attractive scalar field

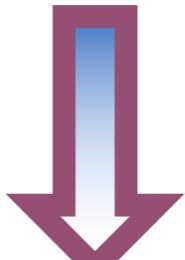


$$S(r) = g_\sigma \sigma(r)$$



$$(J^\pi T) = (1^-0)$$

Omega-meson:
Short-range repulsive



$$V(r) = g_\omega \omega^0(r) + g_\rho \tau_3 \rho^0(r) + e \frac{1 - \tau_3}{2} A^0(r)$$

Serot & Walecka, Adv. Nucl. Phys. 16 (86) 1

Reinhard, Rep. Prog. Phys. 52 (89) 439

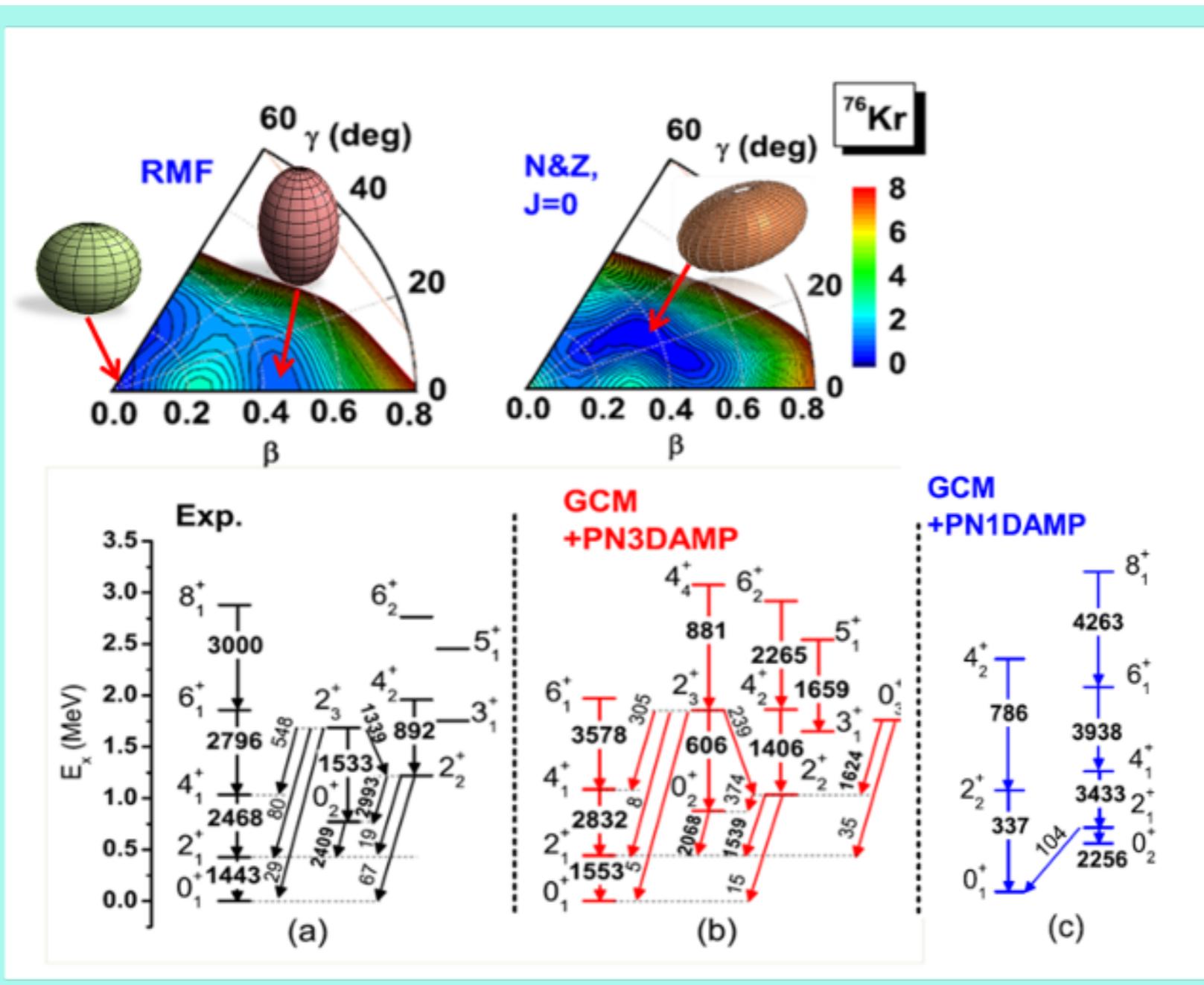
Ring, Prog. Part. Nucl. Phys. 37 (96) 193

Meng, Toki, Zhou, Zhang, Long & Geng, Prog. Part. Nucl. Phys. 2006

...

Nuclear (covariant) energy density functional theory

◆ Triaxiality in low-lying states of ^{76}Kr

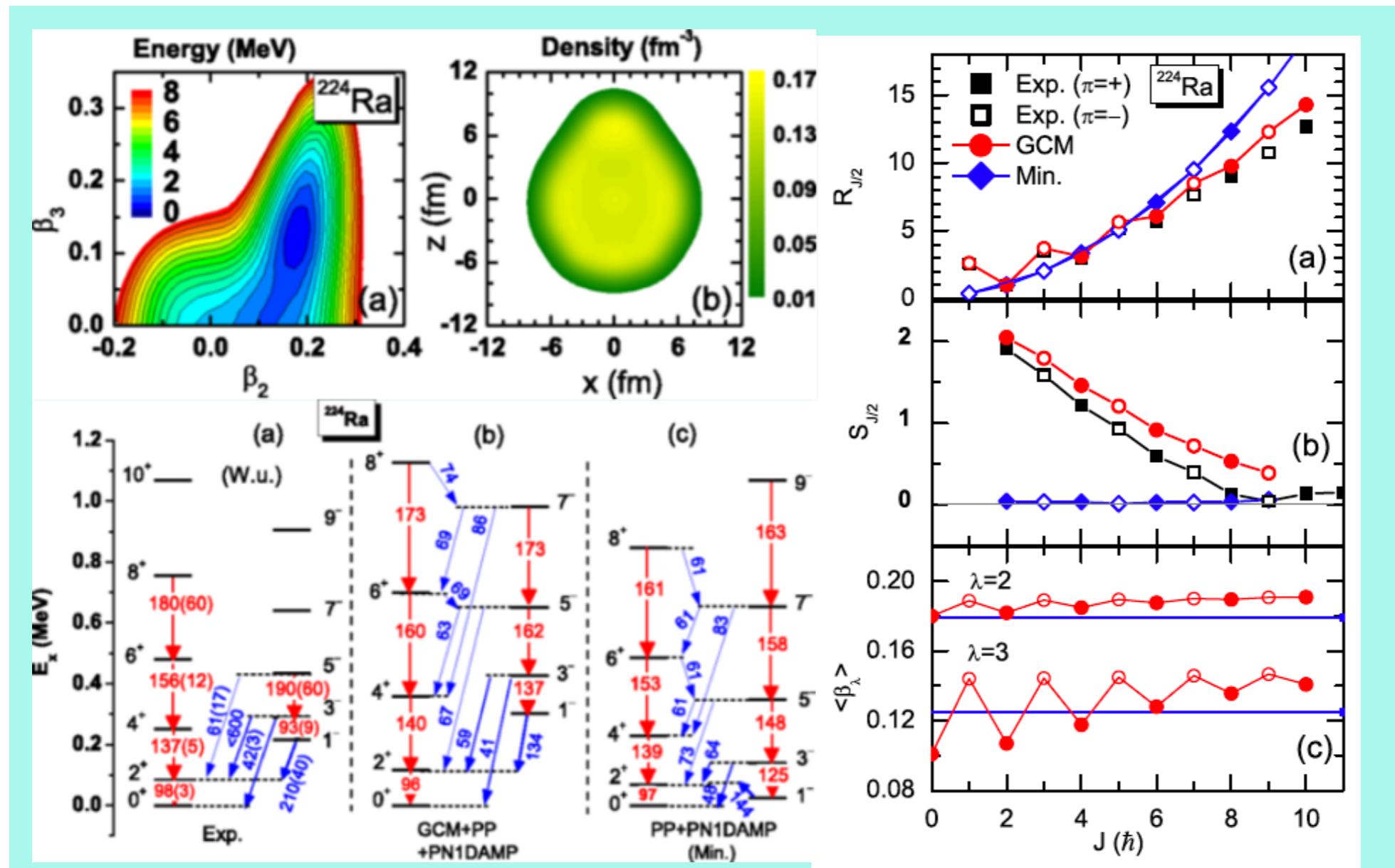


Results of ^{76}Kr from MR-CDFT calculation.
 [JMY, K.Hagino, Z.P. Li, J. Meng, P. Ring, Phys.Rev.C (2014)]

- AMP changes significantly the PES.
- The gamma deformation dof connecting weakly oblate deformed energy minimum with strongly prolate deformed energy minimum.
- The spectrum can only be reproduced with the inclusion of triaxially deformed states.

Nuclear (covariant) energy density functional theory

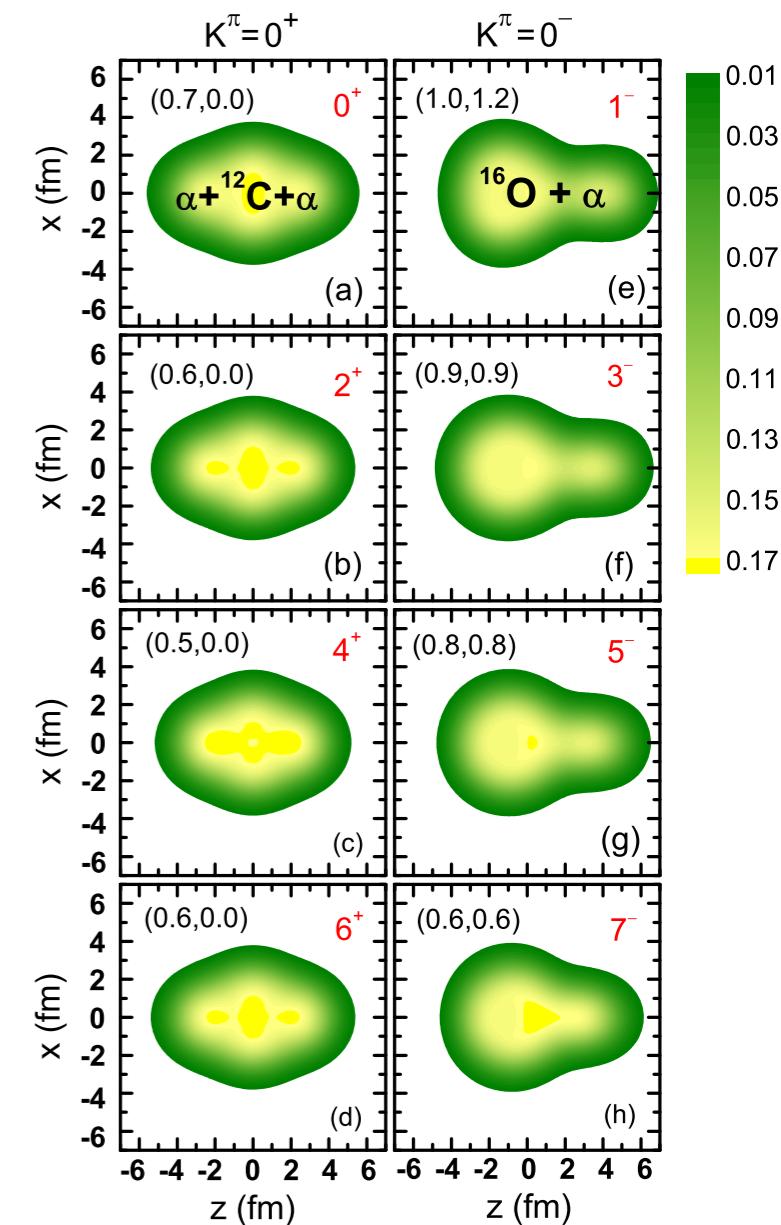
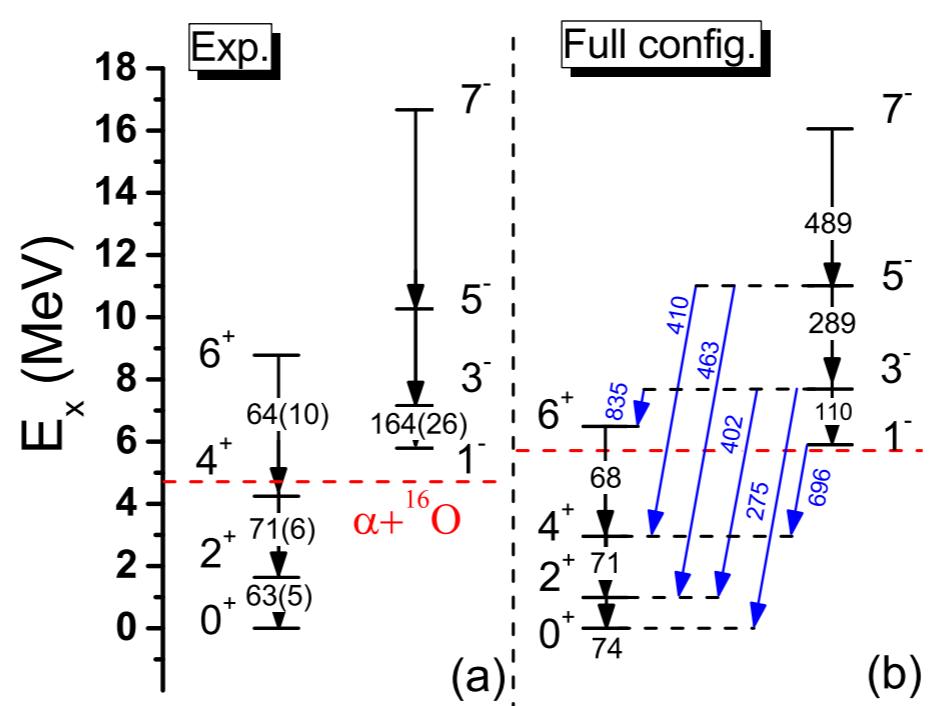
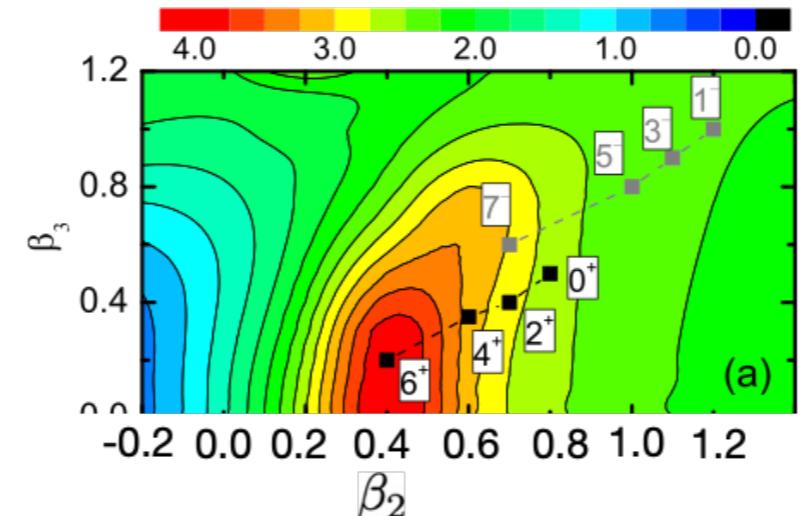
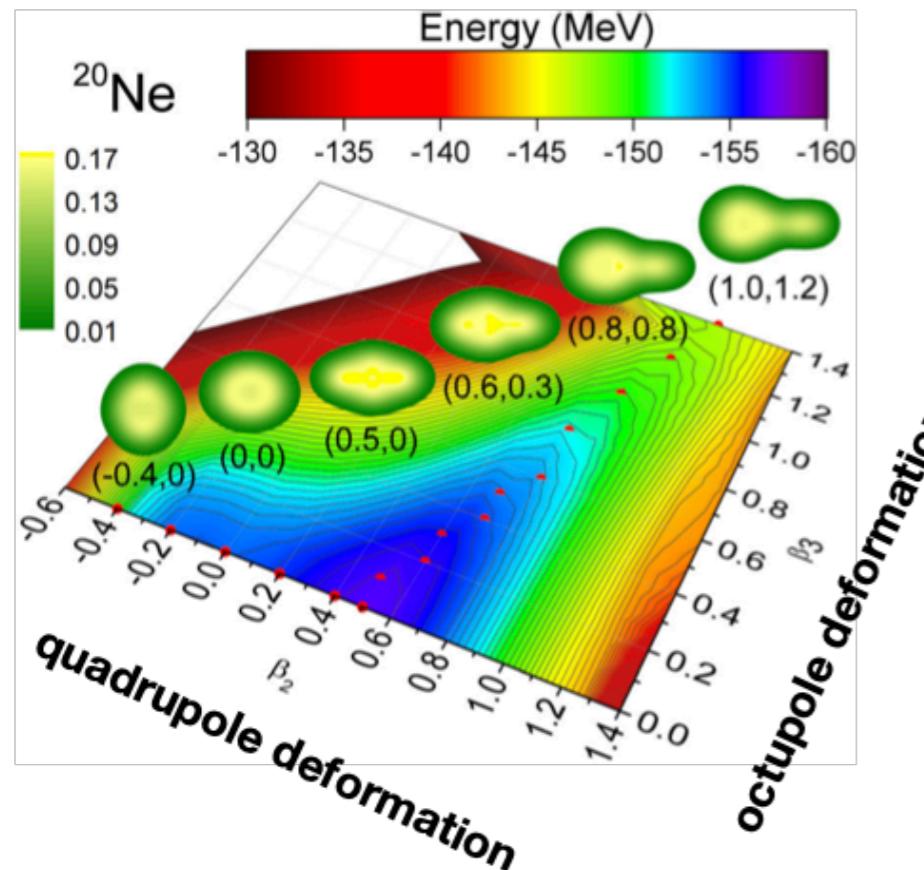
◆ From octupole vibration to octupole rotation excitations



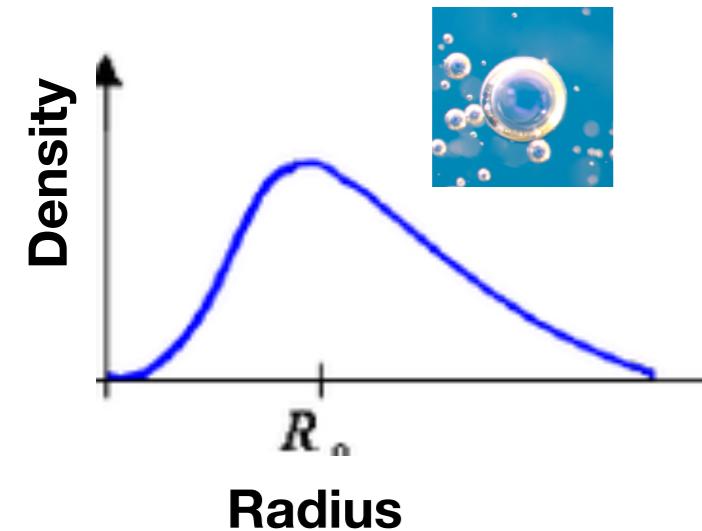
Results of ^{224}Ra from MR-CDFT calculation.
 [JMY, E.F. Zhou, Z.P. Li, Phys. Rev.C (2015)]

Molecular-like clustering structure

A rotation-induced dissolution of ${}^4\text{He}+{}^{16}\text{O}$ molecular-like structure



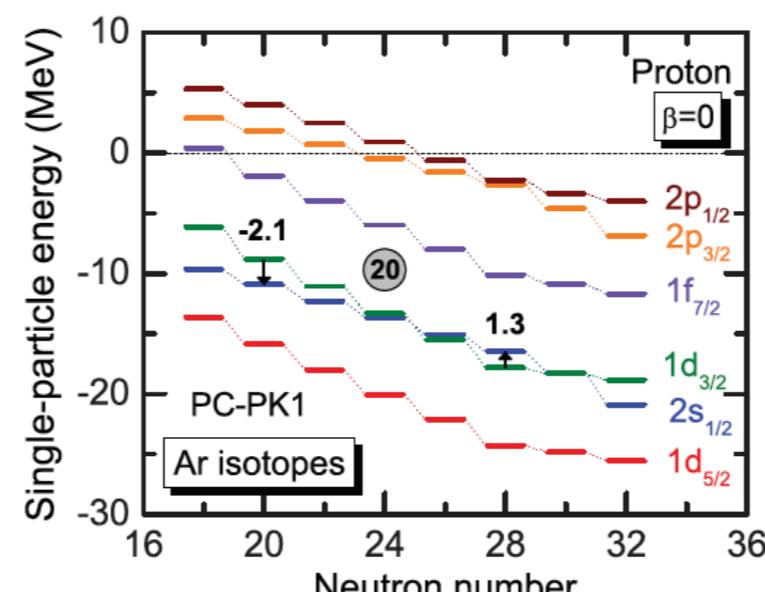
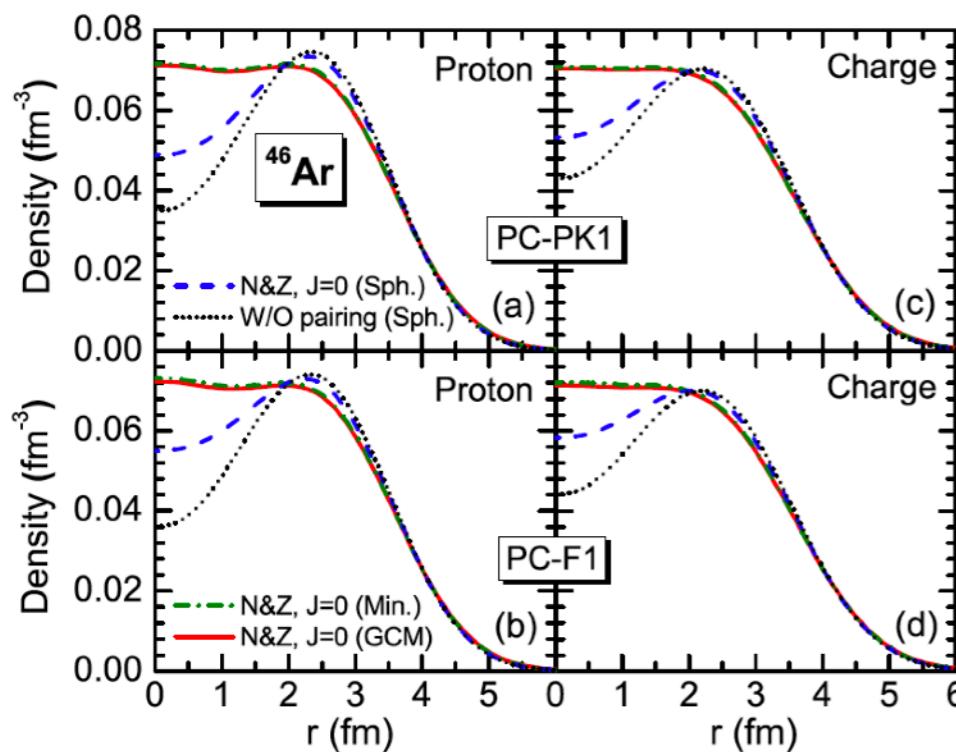
Semi-bubble structure in atomic nuclei



Favor bubble:
Quantum and Coulomb repulsion

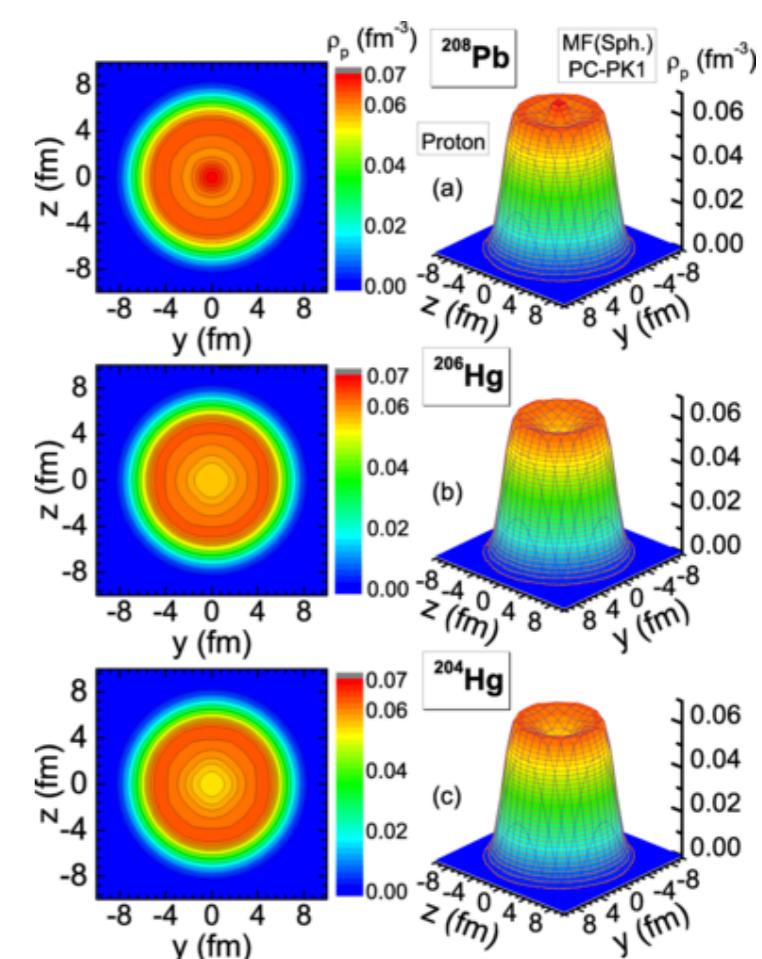
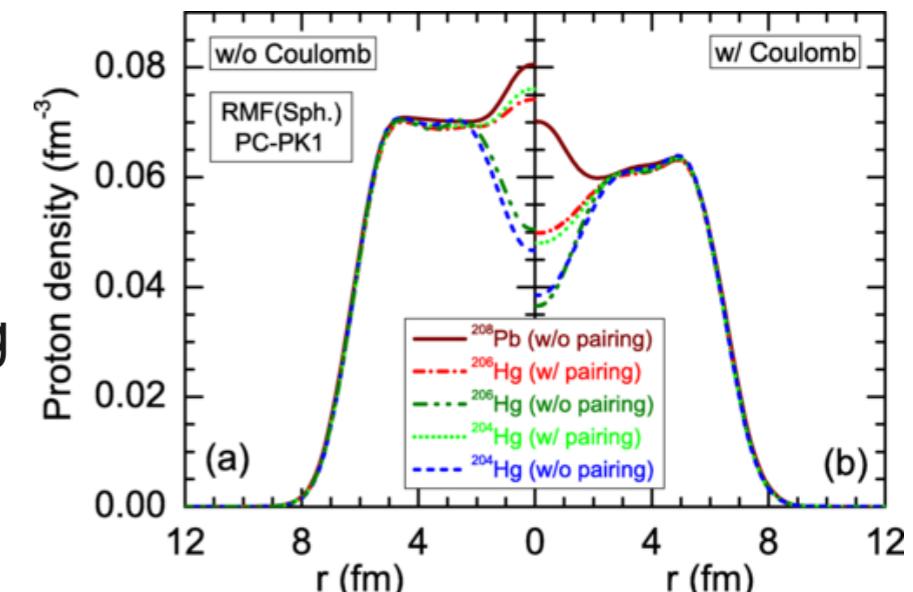
Anti-bubble effect:
pairing correlation and shape-mixing

Formation of proton bubble: depopulation of $2s_{1/2}$ orbit

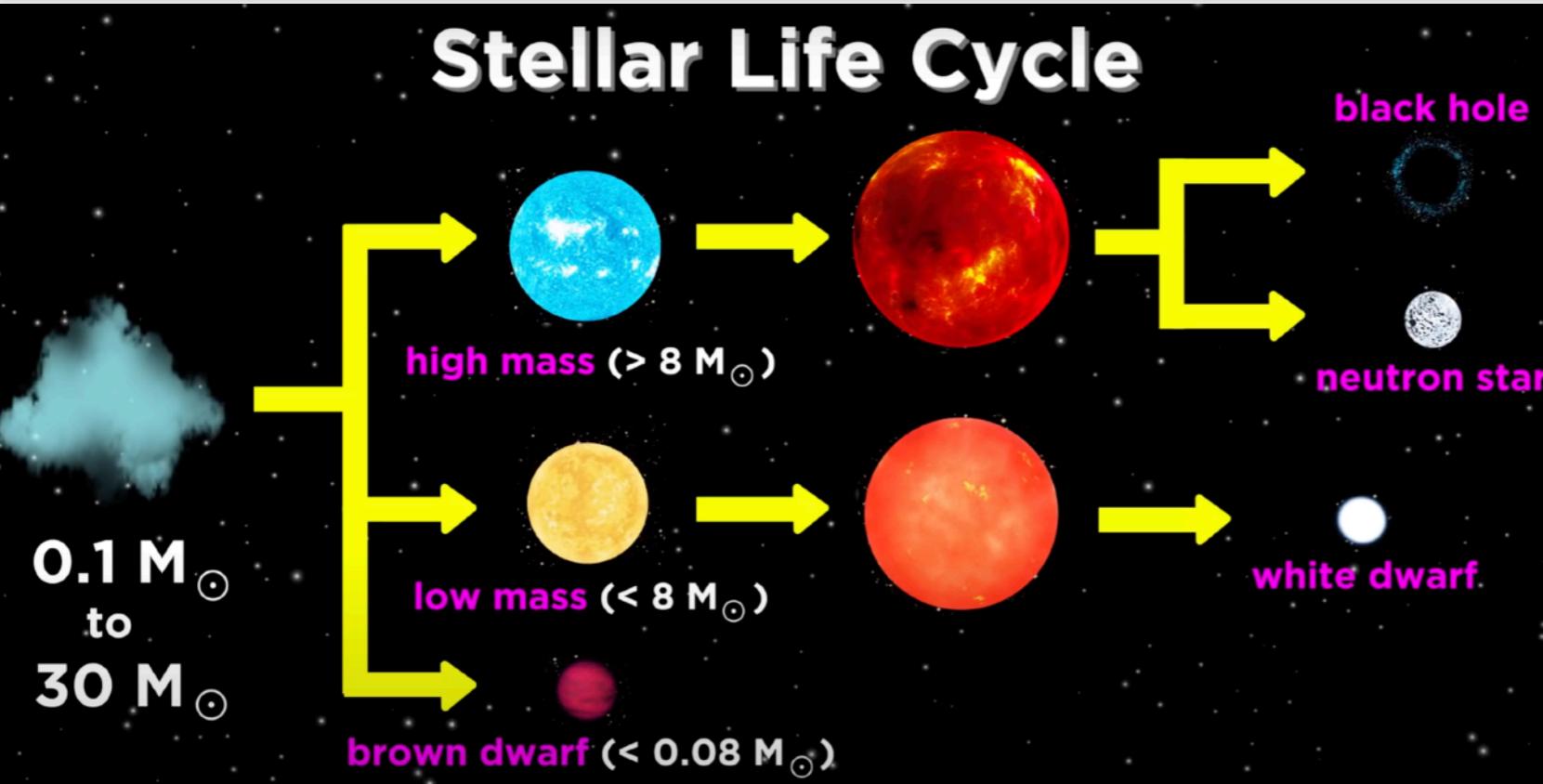


X.Y.Wu, JMY, Z.P. Li, Phys.Rev.C (2014)

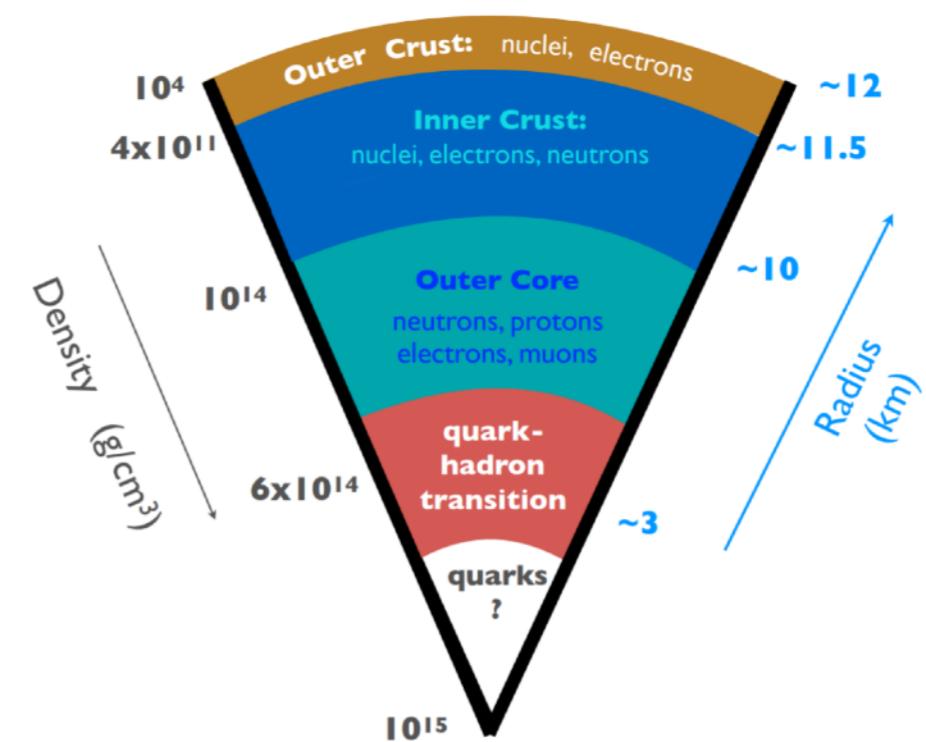
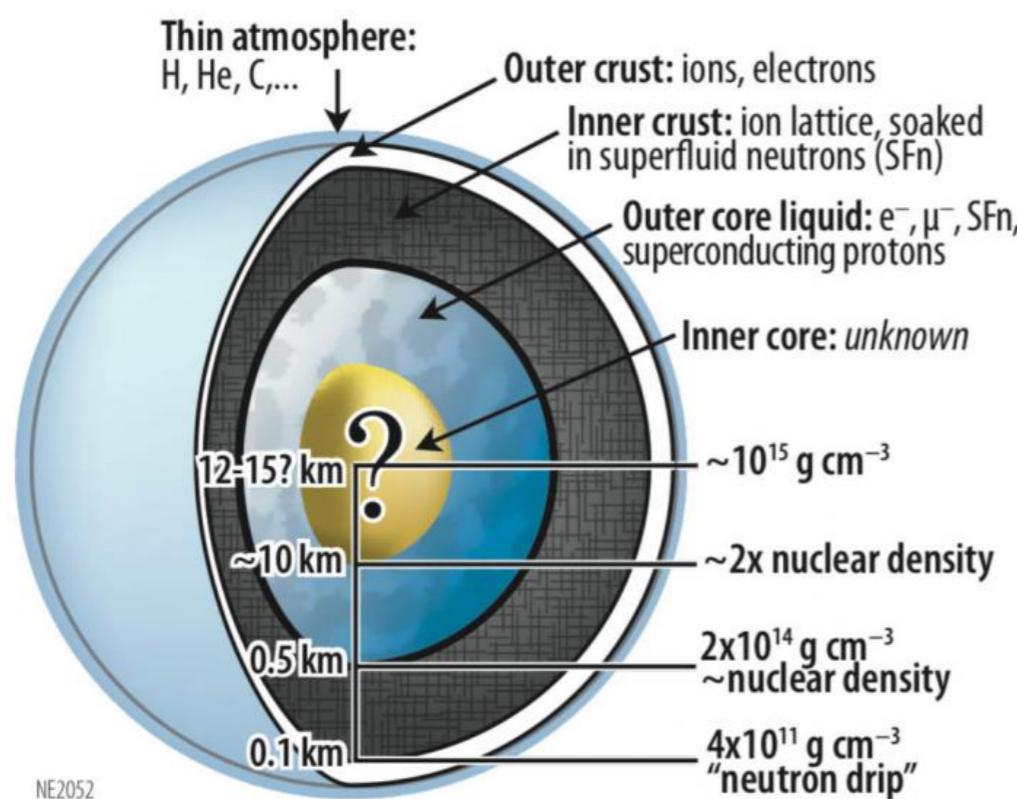
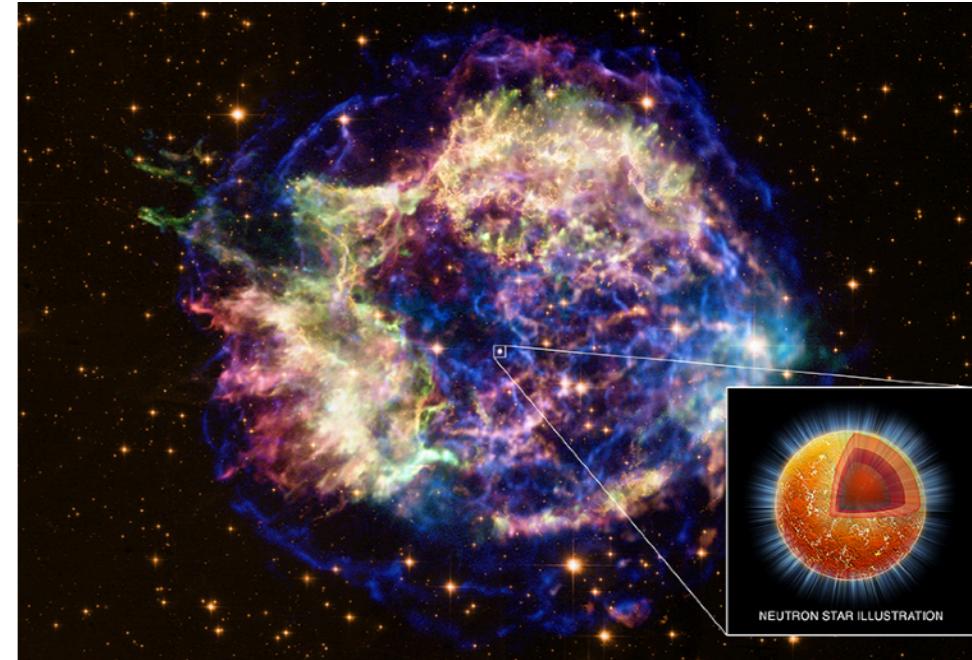
X. Y. Wu, J. Xiang, Phys.Rev.C 98 (2018)



Neutron stars



蟹状星云



Neutron stars

Tolman-Oppenheimer-Volkoff Equation

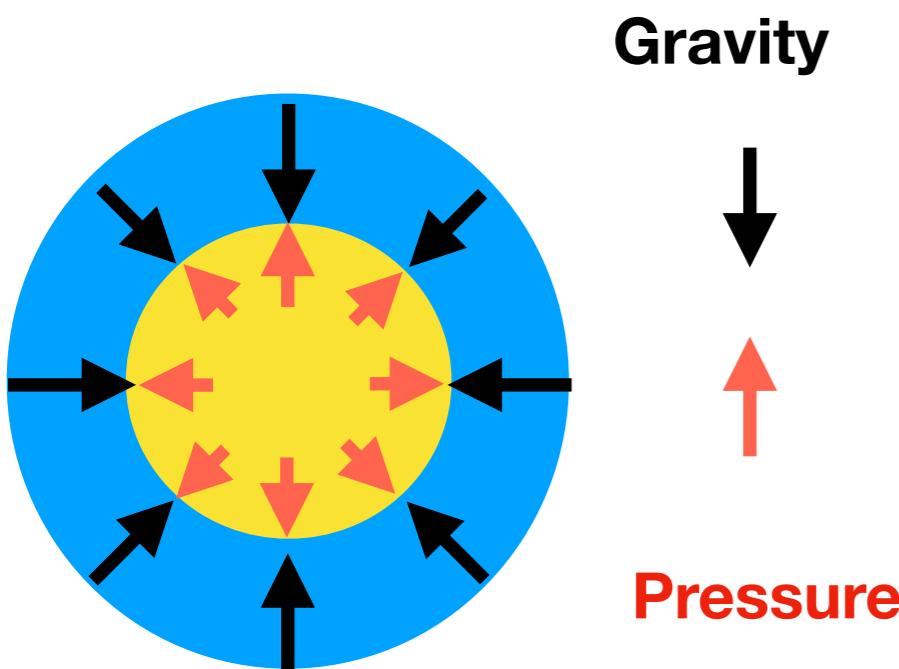
Probe the equation of state of ultra dense matter

- for the interior of a spherical, static, relativistic star

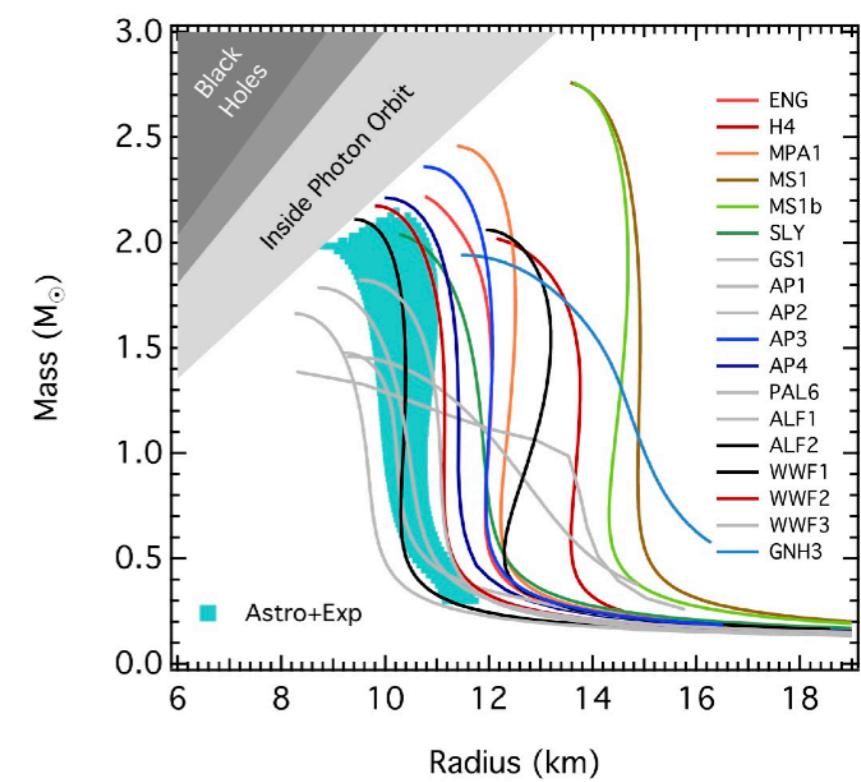
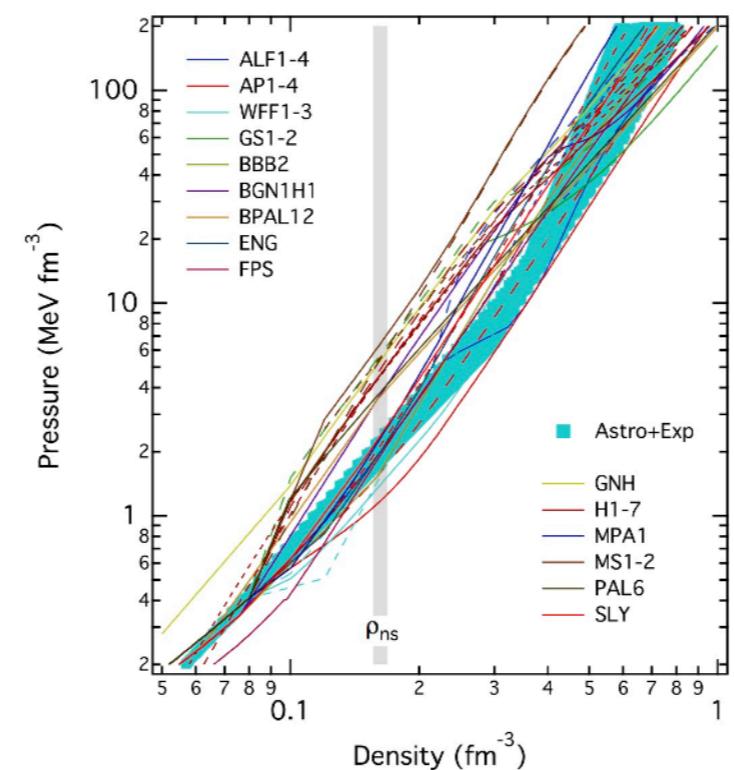
$$\frac{dp}{dr} = -\varepsilon(r) \frac{Gm(r)}{r^2} \left[1 + \frac{p(r)}{\varepsilon(r)} \right] \left[1 + \frac{4\pi r^3 p(r)}{m(r)} \right] \left[1 - \frac{2Gm(r)}{r} \right]^{-1}$$

where the enclosed mass is defined as

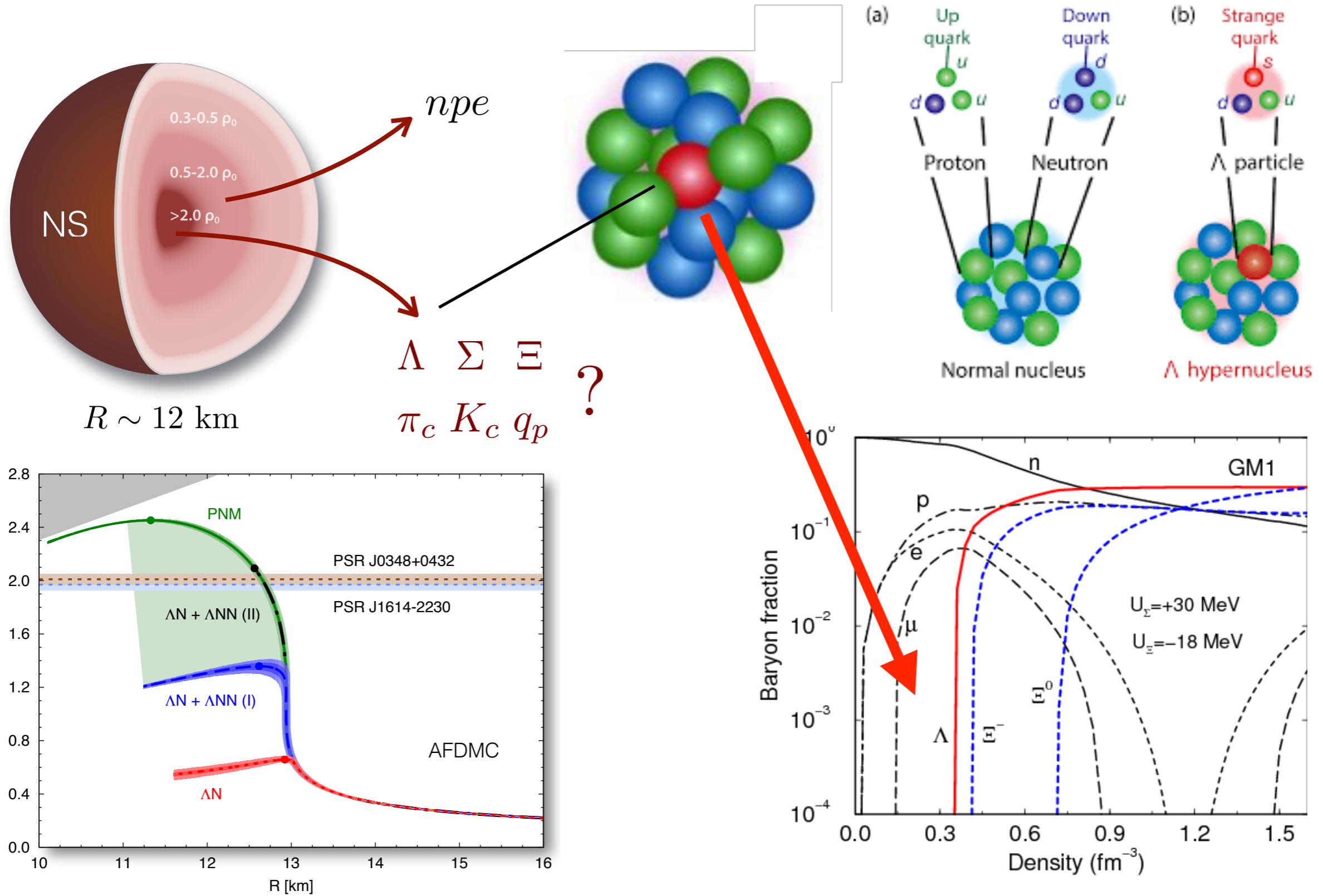
$$m(r) \equiv 4\pi \int_0^r \varepsilon(r) r^2 dr$$



- Gravity** tries to push the star into a black hole
- Pressure** of strongly interacting neutrons resists the gravity



Neutron star matter (hyperon puzzle)



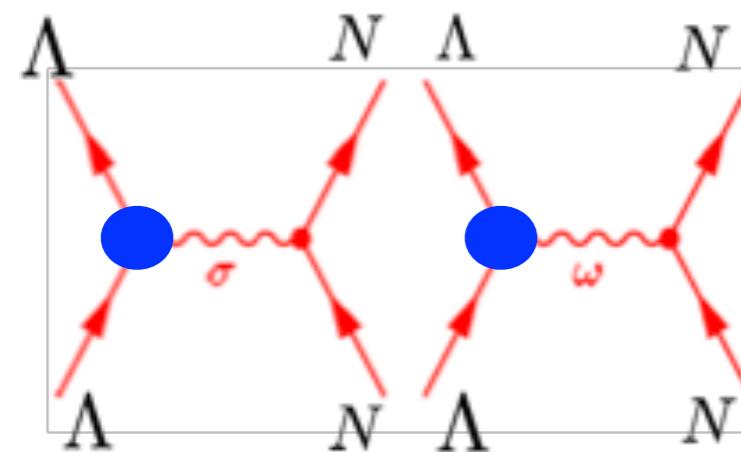
D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva (2015)

J. Schaffner and I. N. Mishustin (1996)

Neutron star matter (hyperon puzzle)

Covariant energy density functional theory for NN/YN interactions

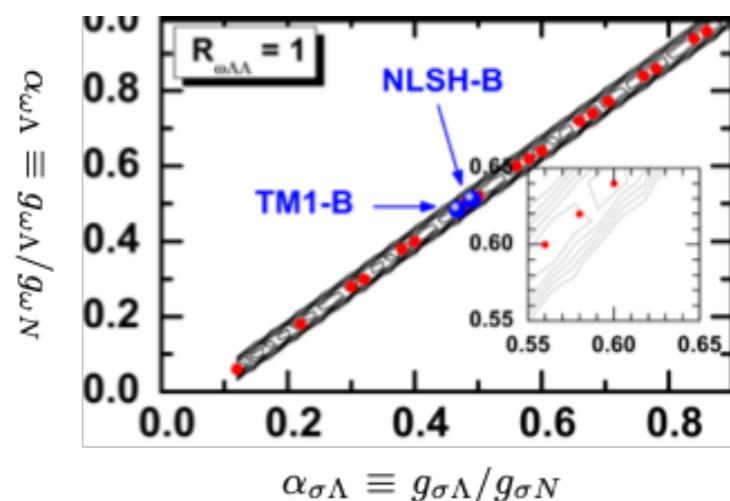
The coupling strengths in **hyperon-nucleon** interaction
are often fitted to **hyperon binding energies**



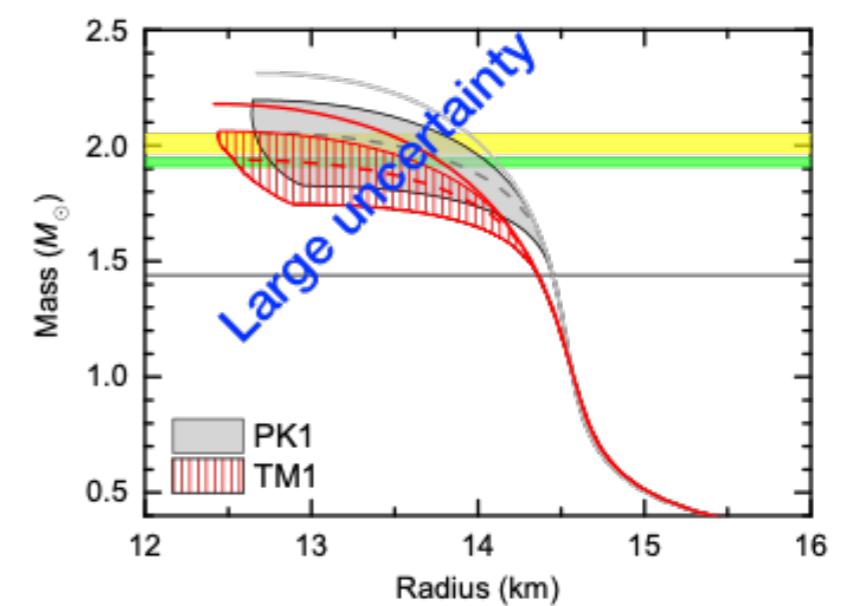
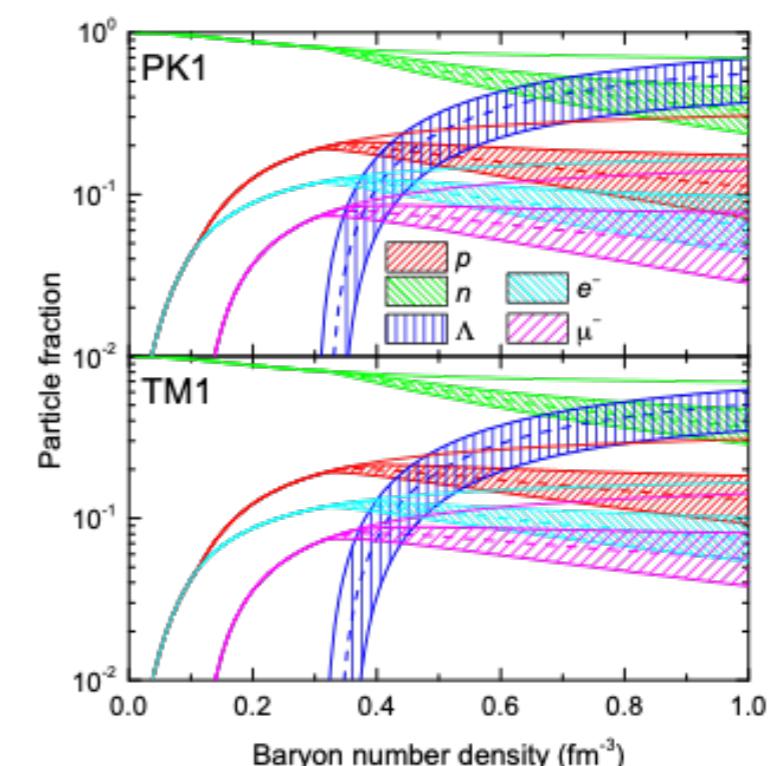
parameters

$$g_{\sigma\Lambda} \quad g_{\omega\Lambda}$$

Fitted to Lambda
separable energy



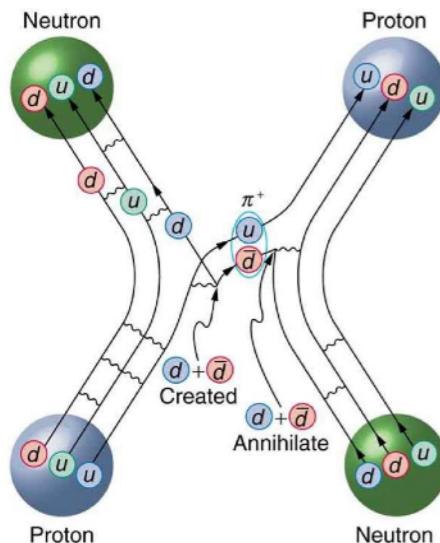
Parameters are NOT uniquely determined.
More data on YN interactions are required.



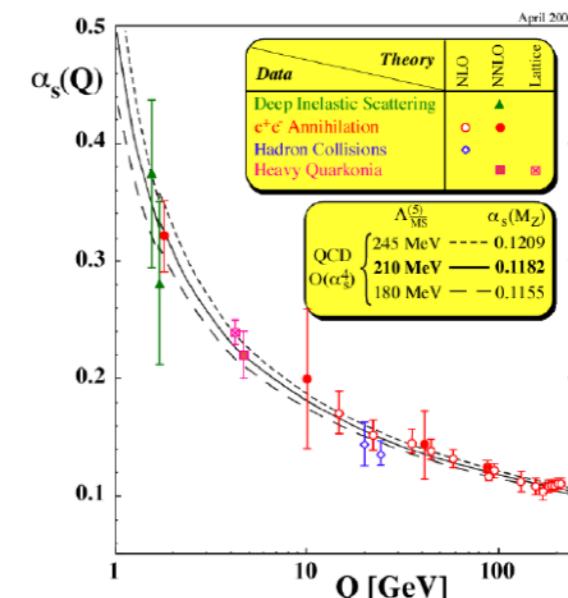
T. T. Sun, C. J. Xia, S. S. Zhang, M.S. Smith (2018)

Modeling atomic nuclei from first principles?

- Construction of nuclear force from QCD (**difficult**)



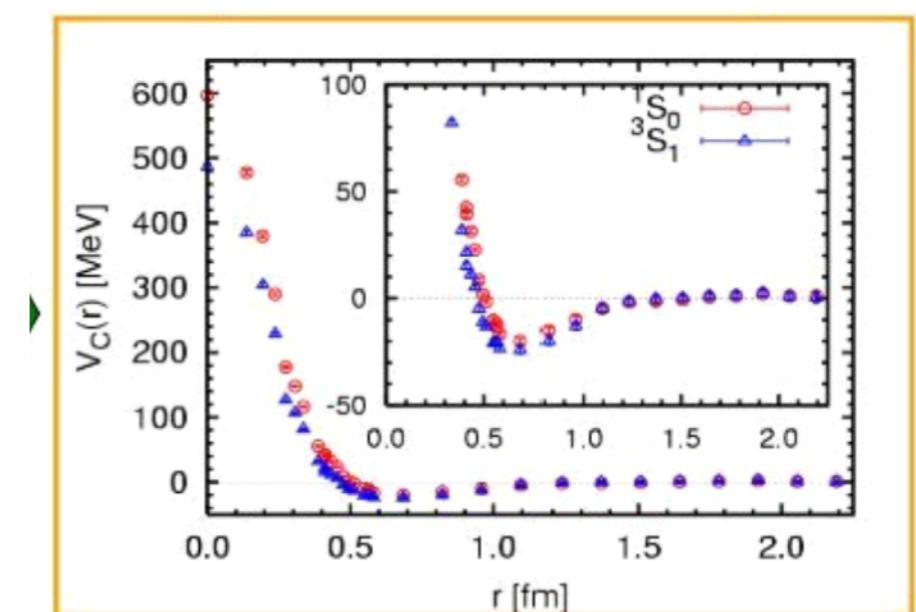
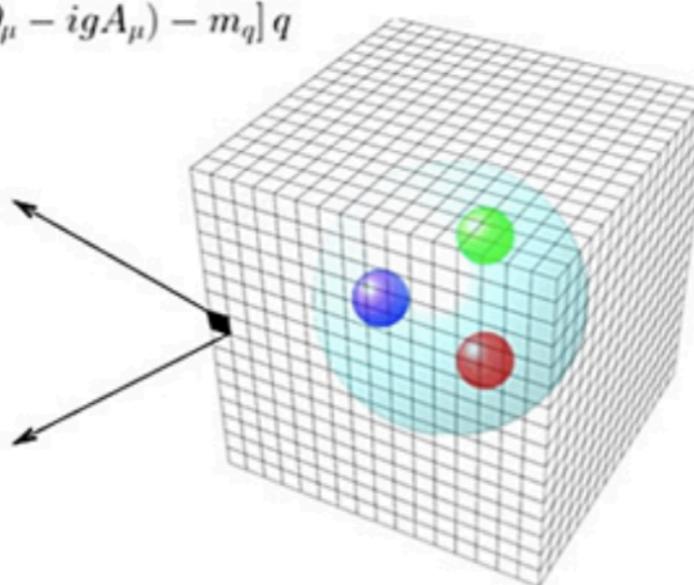
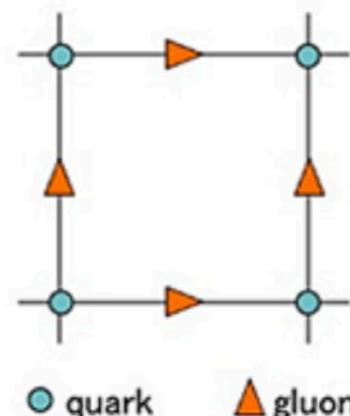
Non-perturbative nature
of strong interaction at
low-energy regime



- Nuclear force from Lattice QCD

QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q}[i\gamma^\mu(\partial_\mu - igA_\mu) - m_q]q$$

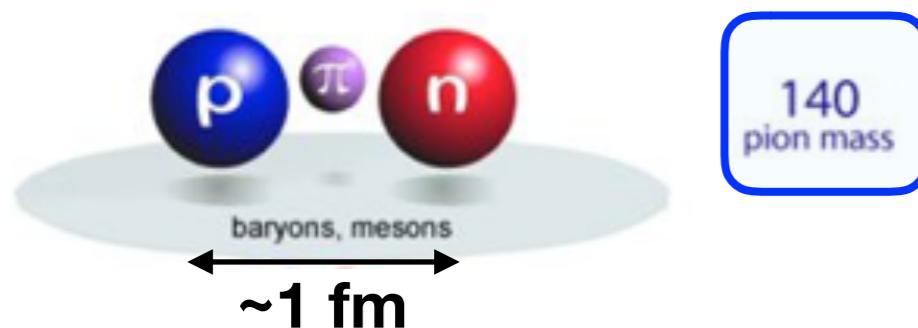


Ishii-Aoki-Hatsuda,
PRL99(2007)022001

Modeling atomic nuclei from first principles?



- Nuclear force from chiral EFT

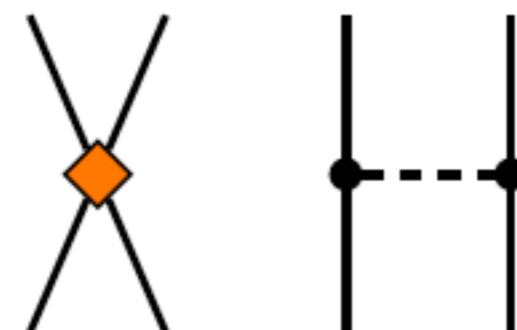


Weinberg's power counting:

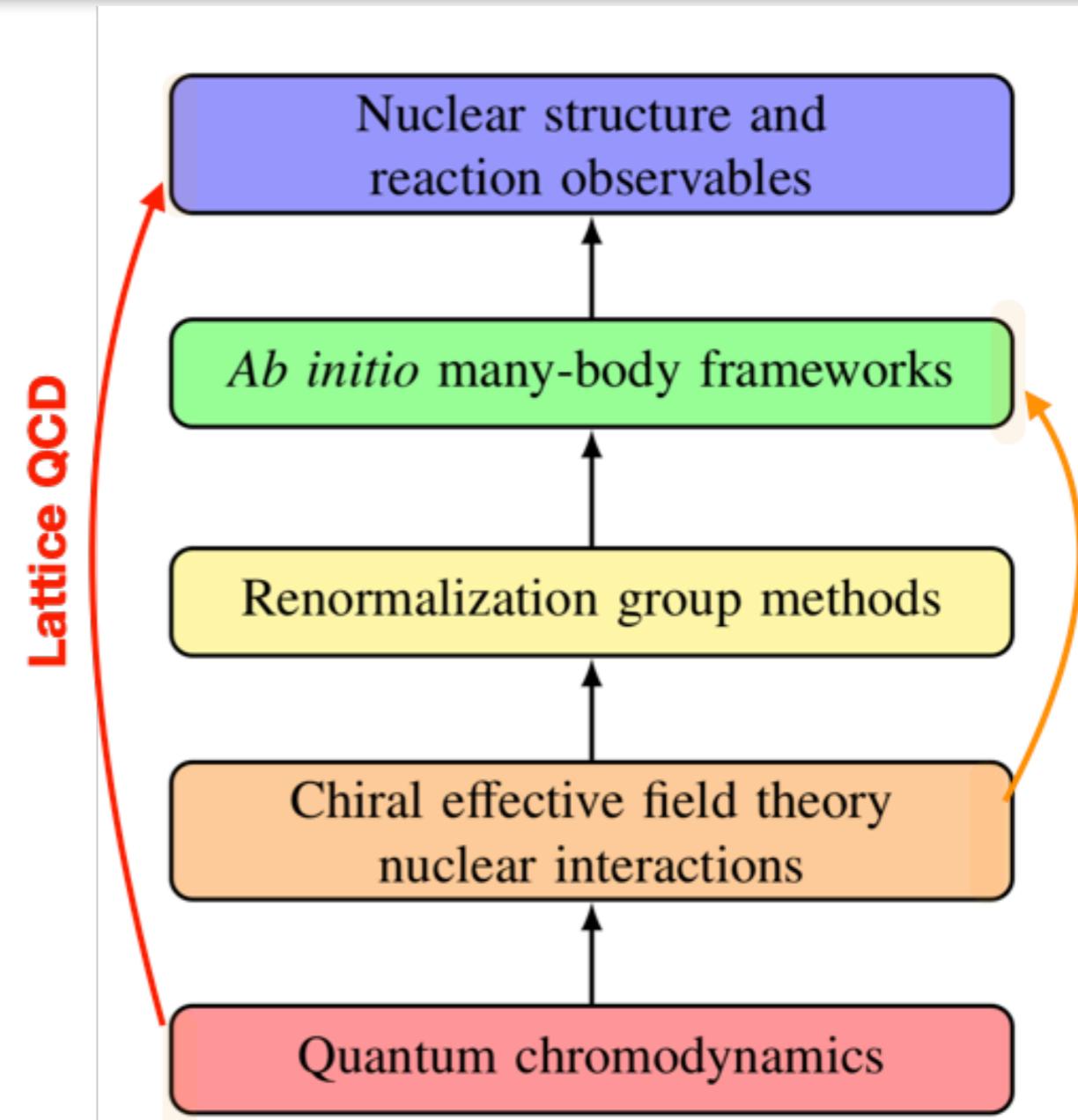
$$(Q/\Lambda_\chi)^\nu$$

chiral-symmetry-breaking (hard) scale ($\sim 700 \text{ MeV}$)

soft scale associated with external momenta, pion mass ($\sim 140 \text{ MeV}$)

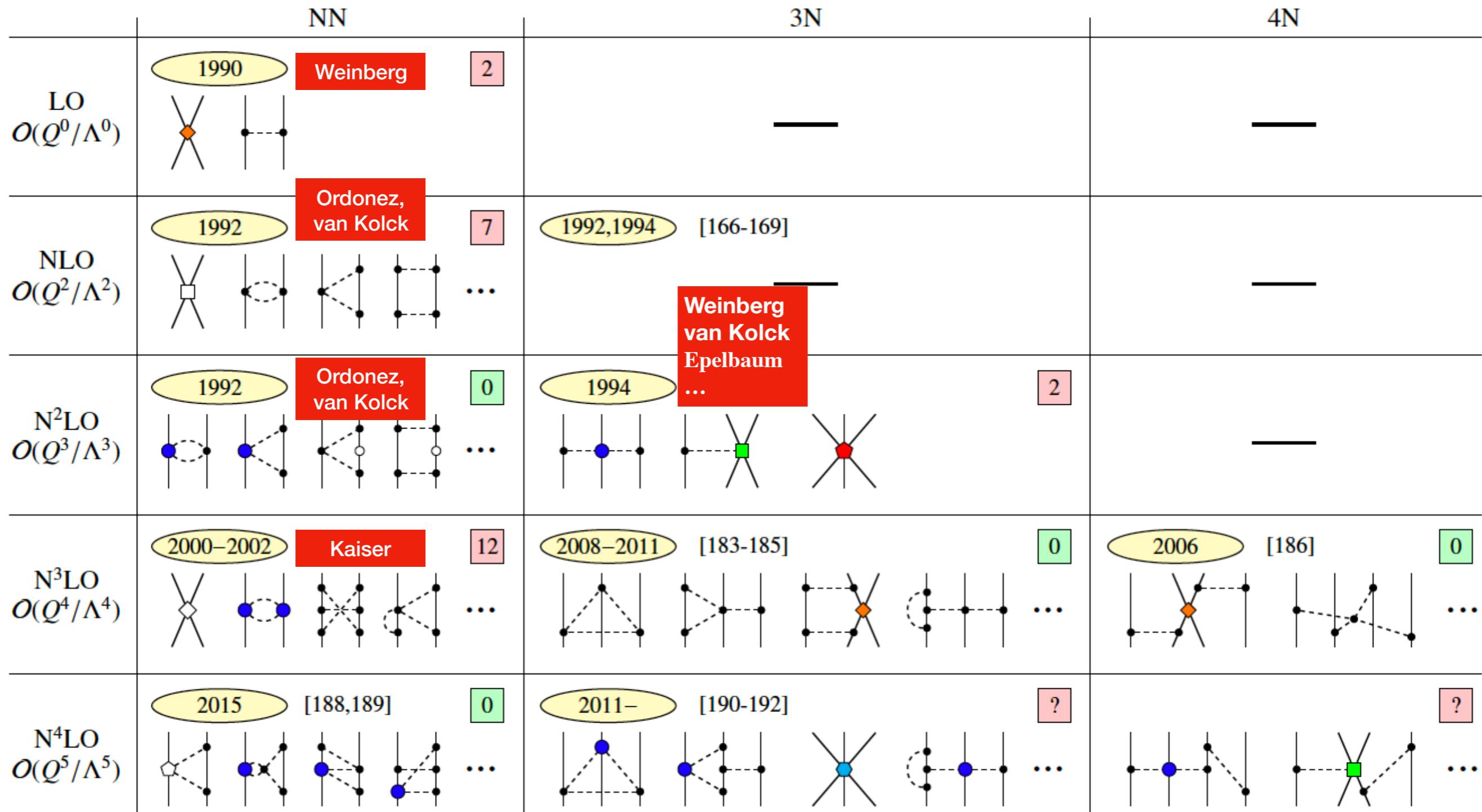


S. Weinberg, PLB251, 288 (1990)
S. Weinberg, NPB 363, 3 (1991)



K. Hebeler, Phys. Rep. 890(2021)1

Nuclear force from chiral EFT



ab initio many-body frameworks



• Quantum Monte Carlo methods

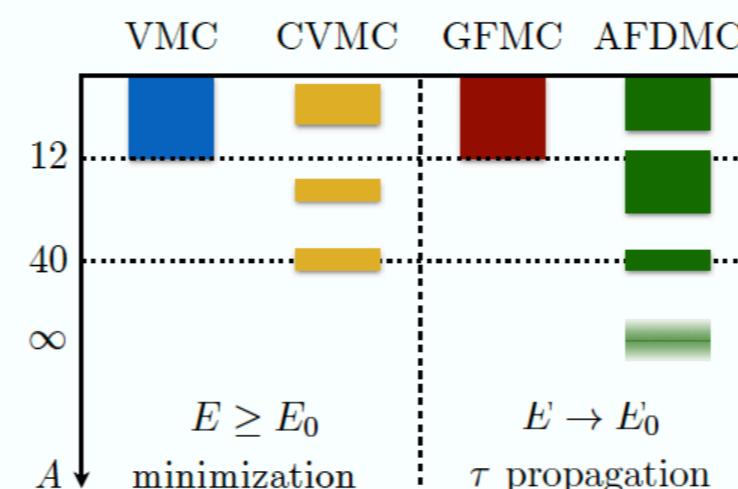
Pieper, S.C.; Wiringa, R.B. (2001)

J. Carlson et al., RMP 87, 1067 (2015)

Variational Monte Carlo (VMC)

Green's function Monte Carlo (GFMC)

Auxiliary-field diffusion Monte Carlo (AFDMC)



credit: D. Lonardoni

(C)VMC

GFMC

AFDMC

CVMC

AFDMC

AFDMC

light systems

$A \leq 12$

light to medium-mass nuclei

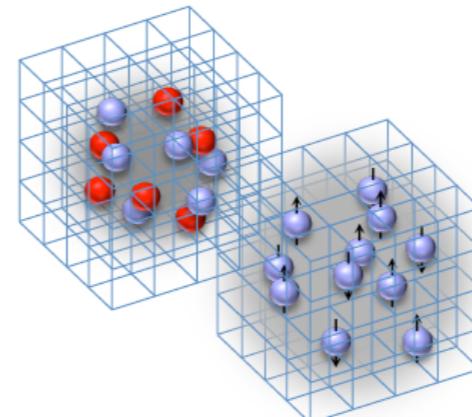
$A \sim 50$

infinite matter

$A \rightarrow \infty$

• Lattice effective field theory (EFT)

D. Lee, Prog. Part. Nucl. Phys. 63, 117 (2009)



• No-core shell model (NCSM)

Barrett, Navrátil, Vary, Prog. Part. Nucl. Phys. 69, 131 (2013)

• Self-consistent Green's function (SCGF)

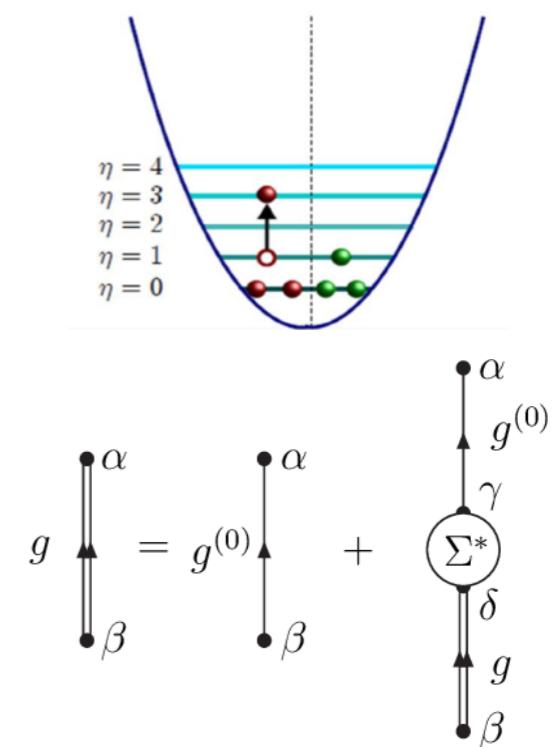
V. Somà, Frontiers in Physics 8, 340 (2020)

• Coupled cluster (CC)

G. Hagen, T. Papenbrock, M. Hjorth-Jensen, and D. J. Dean, Rep. Prog. Phys. 77, 096302 (2014)

• In-medium similarity renormalization group (IM-SRG)

H. Hergert, S. K. Bogner, T. D. Morris, A. Schwenk, and K. Tsukiyama, Phys. Rep. 621, 165 (2016)



• MBPT, (R)BHF,...

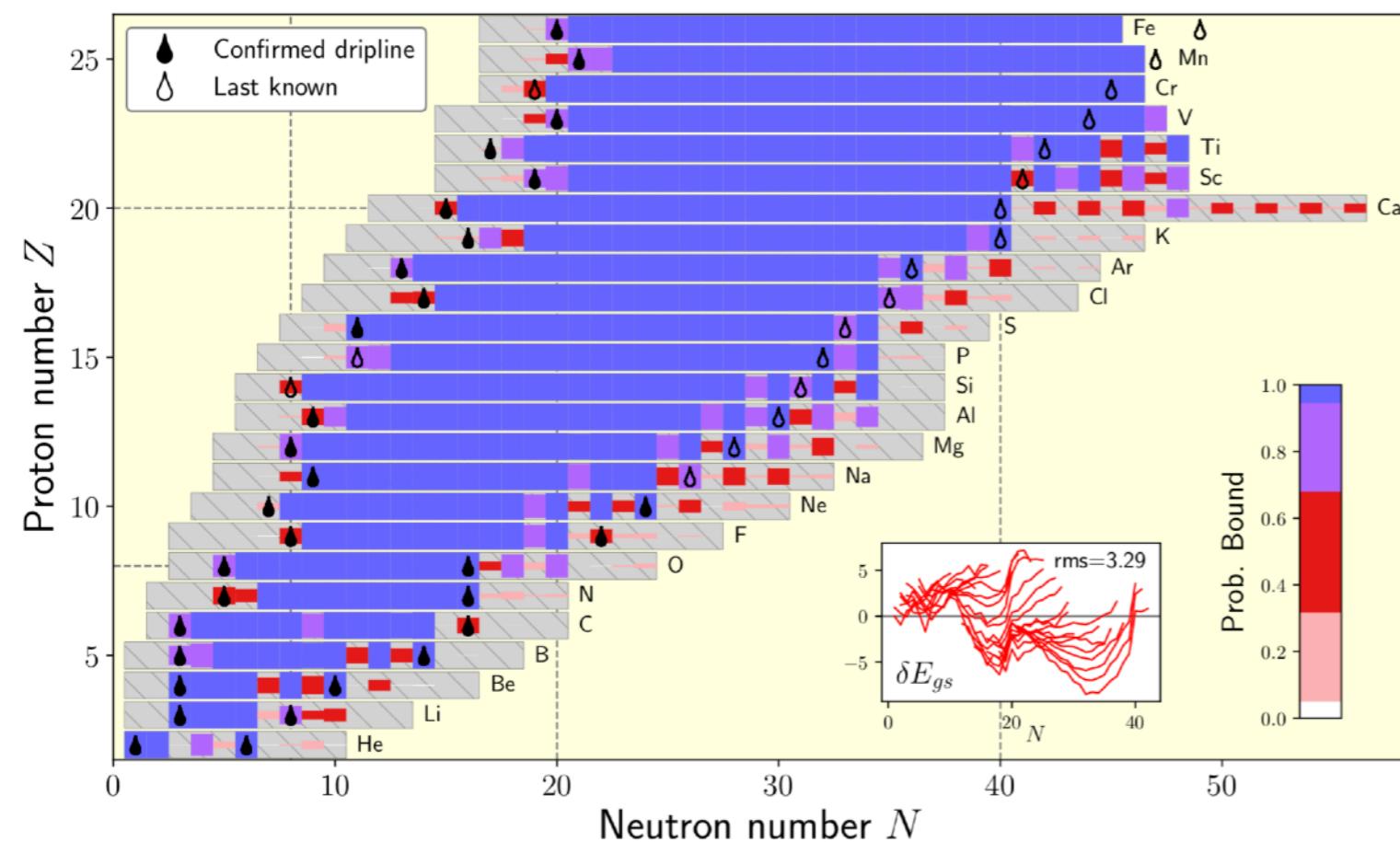
Featured in Physics

Editors' Suggestion

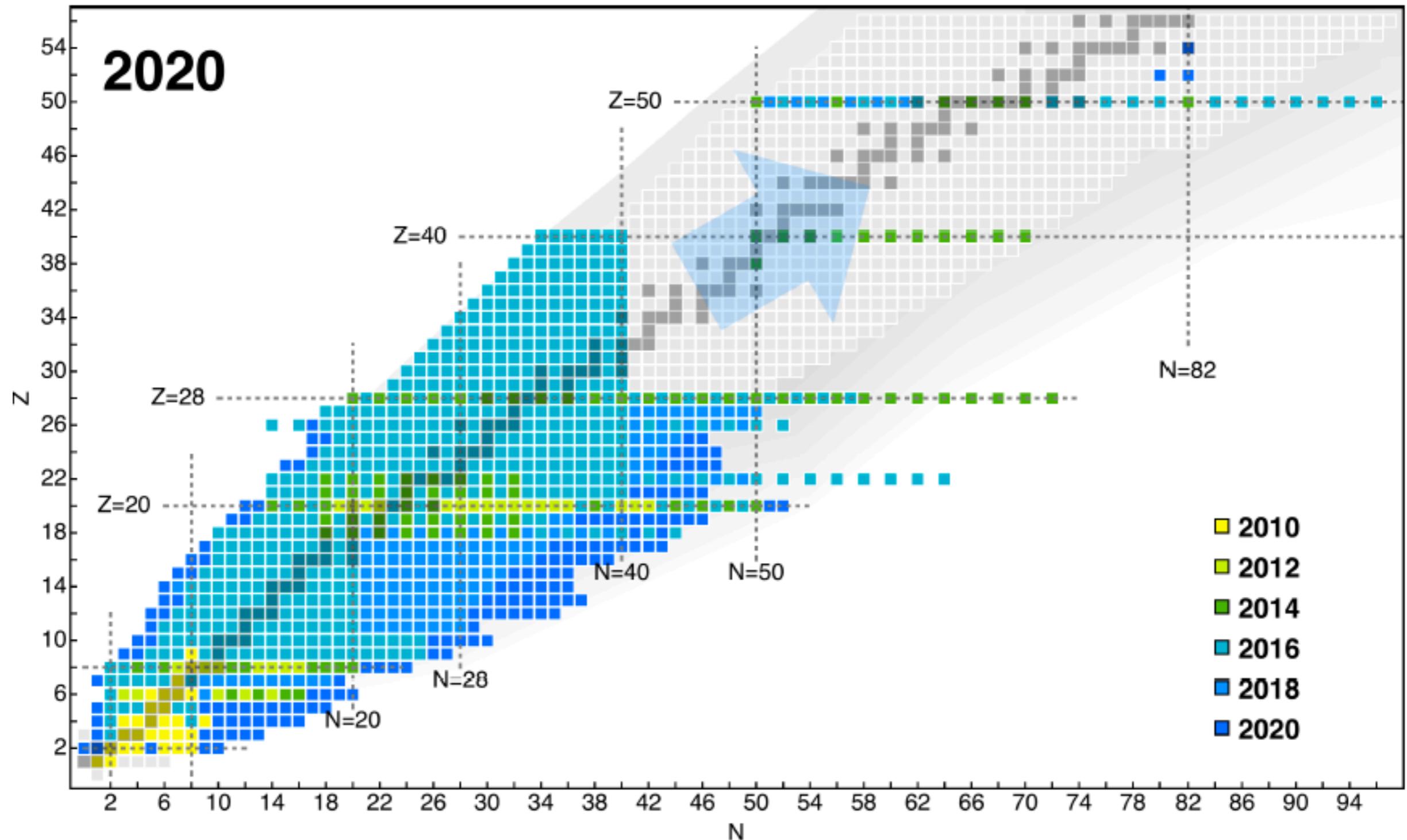
Ab Initio Limits of Atomic Nuclei

S. R. Stroberg, J. D. Holt, A. Schwenk, and J. Simonis
Phys. Rev. Lett. **126**, 022501 – Published 12 January 2021

**First-principles calculations predict the properties
of nearly 700 isotopes between helium and iron**



Achievements of ab initio calculations for nuclei



ab initio calculations for nuclei: single-beta decay

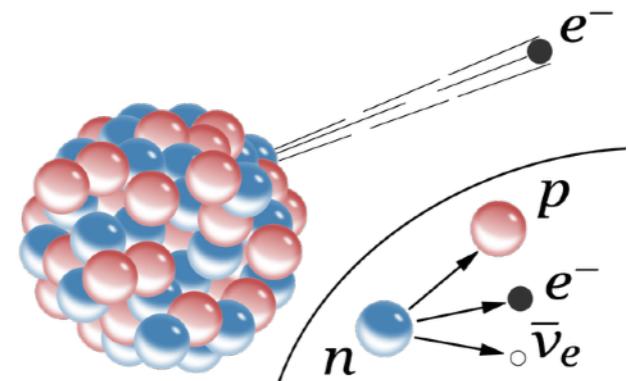


Discrepancy between experimental and theoretical β -decay rates resolved from first principles

P. Gysbers, G. Hagen , J. D. Holt, G. R. Jansen, T. D. Morris, P. Navrátil, T. Papenbrock, S. Quaglioni, A. Schwenk, S. R. Stroberg & K. A. Wendt

Nature Physics **15**, 428–431(2019) | [Cite this article](#)

The half-life of nuclear single-beta decay

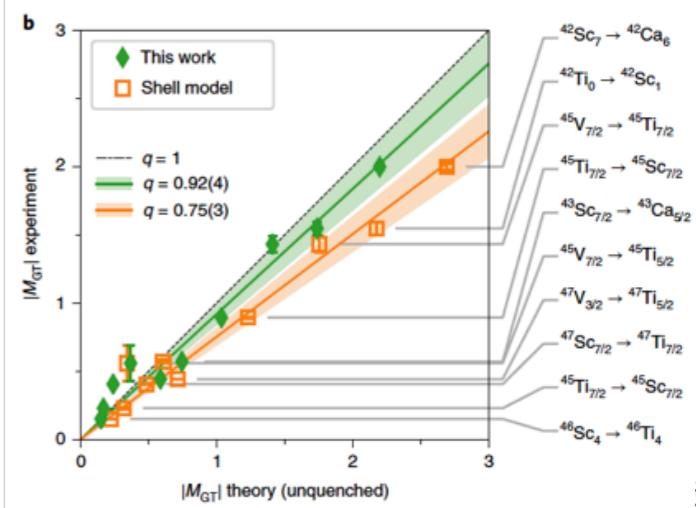
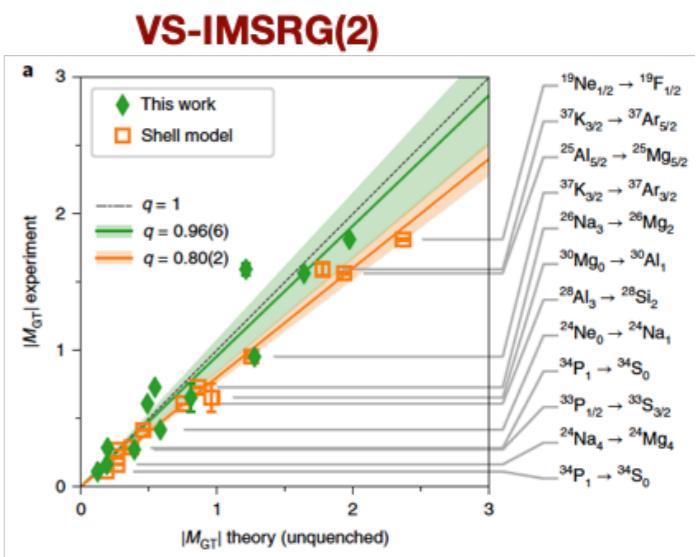
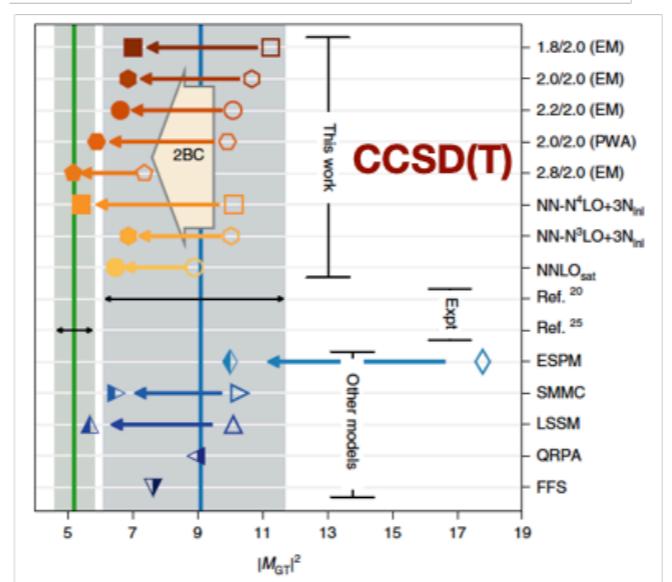
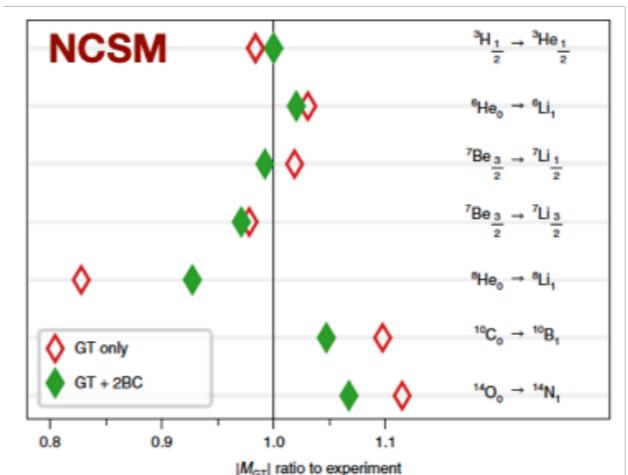
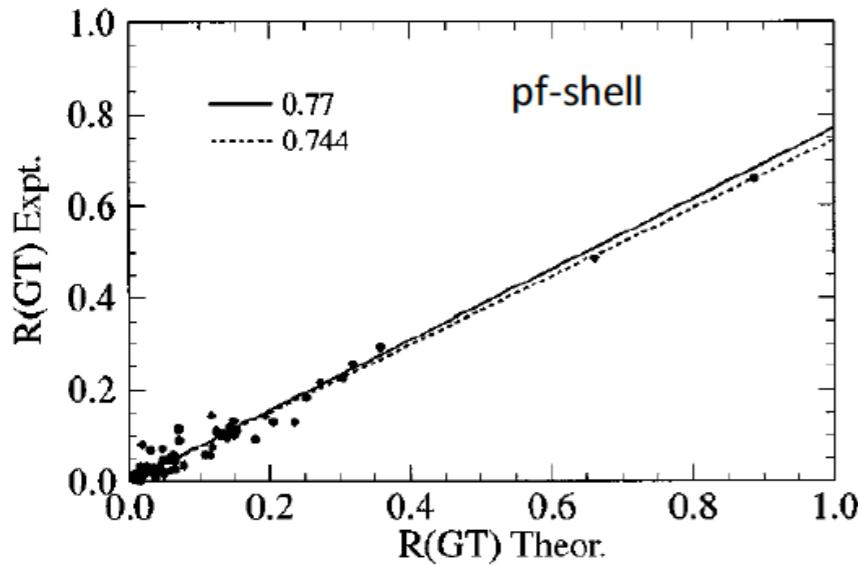


Two-body currents+
many-body correlations

$$t_{1/2} = \frac{\kappa}{f_0(B_F + B_{GT})},$$

$$B_F = \frac{g_V^2}{2J_i + 1} |M_F|^2, \quad B_{GT} = \frac{g_A^2}{2J_i + 1} |M_{GT}|^2$$

G. Martinez-Pinedo et al, PRC **53**, R2602 (1996)

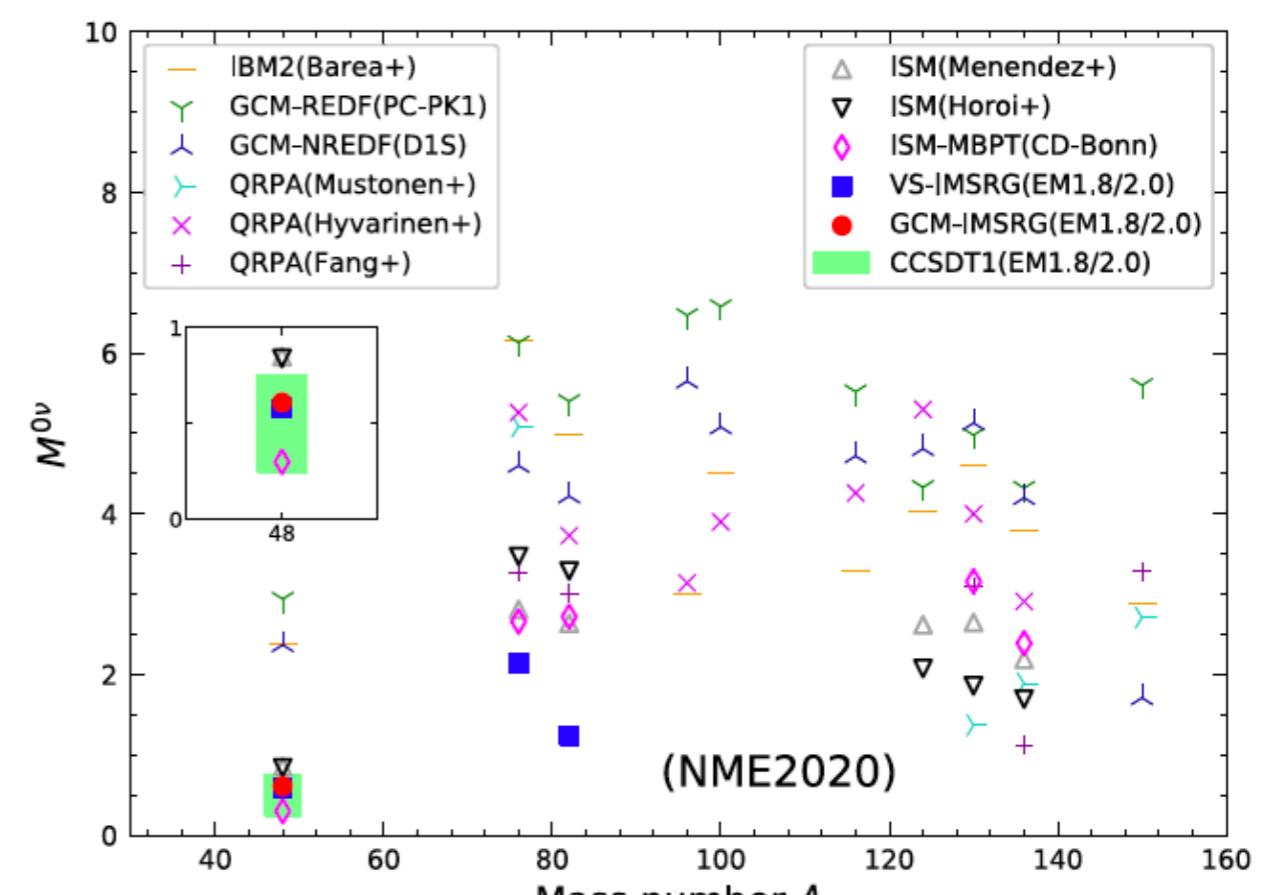
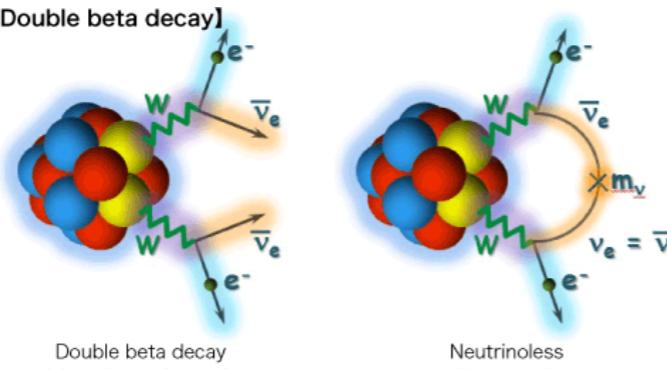
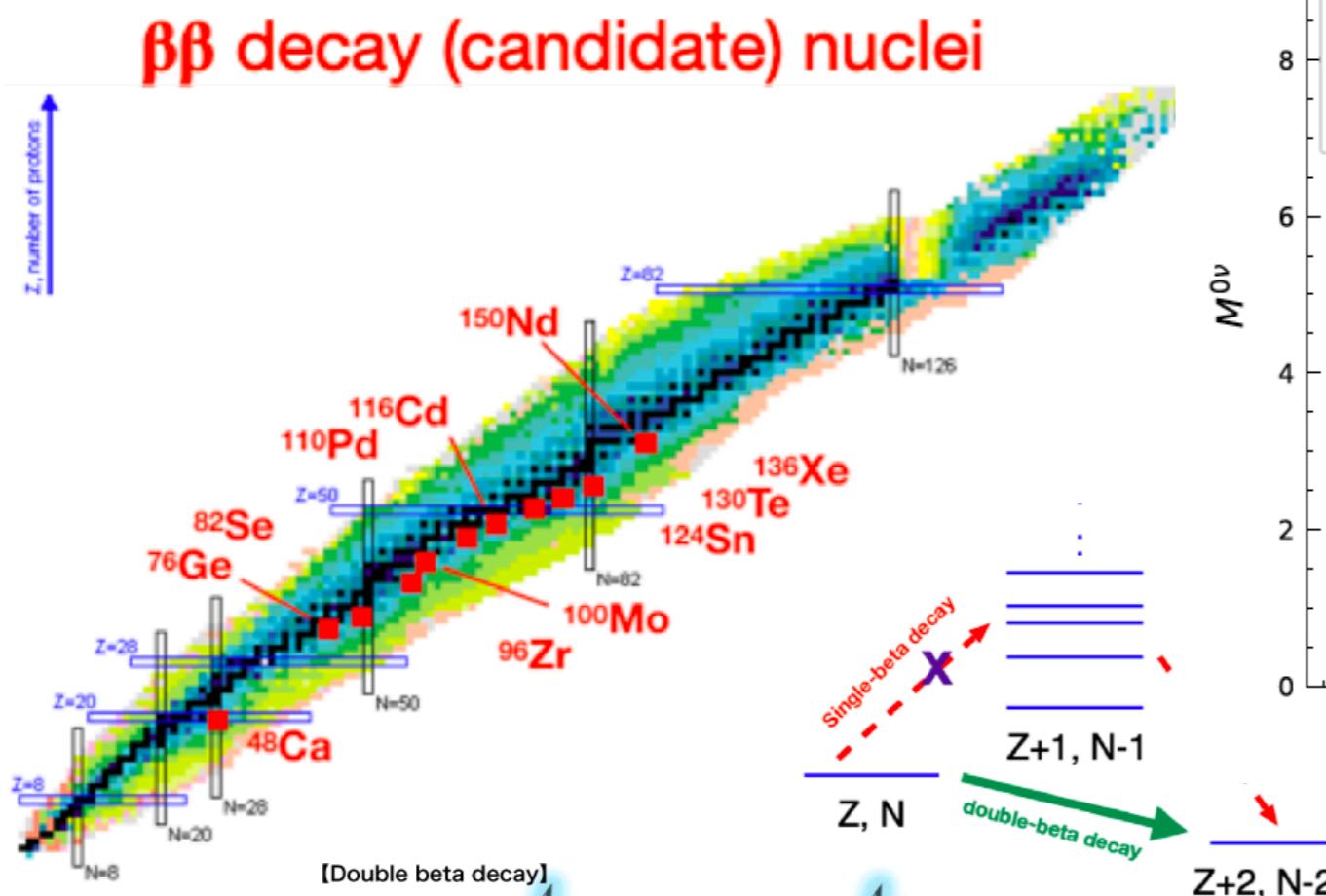


ab initio calculations for nuclei: double-beta decay



Ab Initio Treatment of Collective Correlations and the Neutrinoless Double Beta Decay of ^{48}Ca

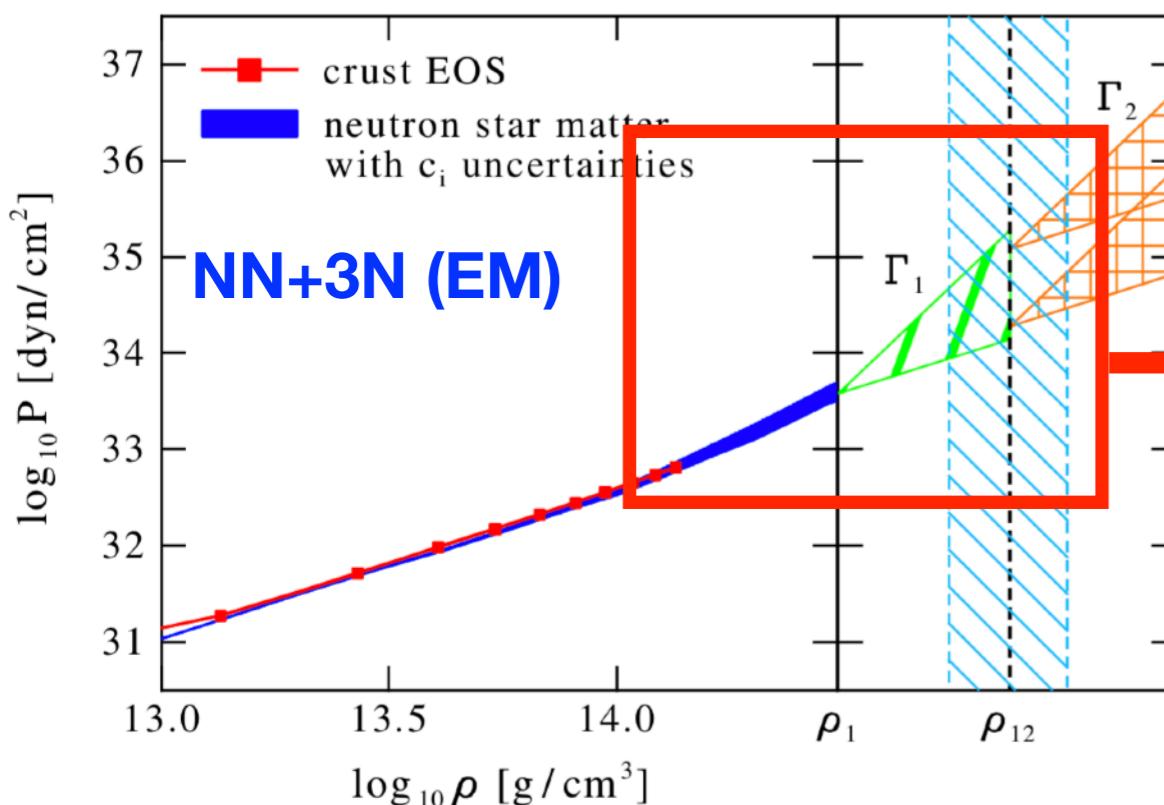
J. M. Yao, B. Bally, J. Engel, R. Wirth, T. R. Rodríguez, and H. Hergert
 Phys. Rev. Lett. **124**, 232501 – Published 11 June 2020



JMY, Science Bulletin (2021)

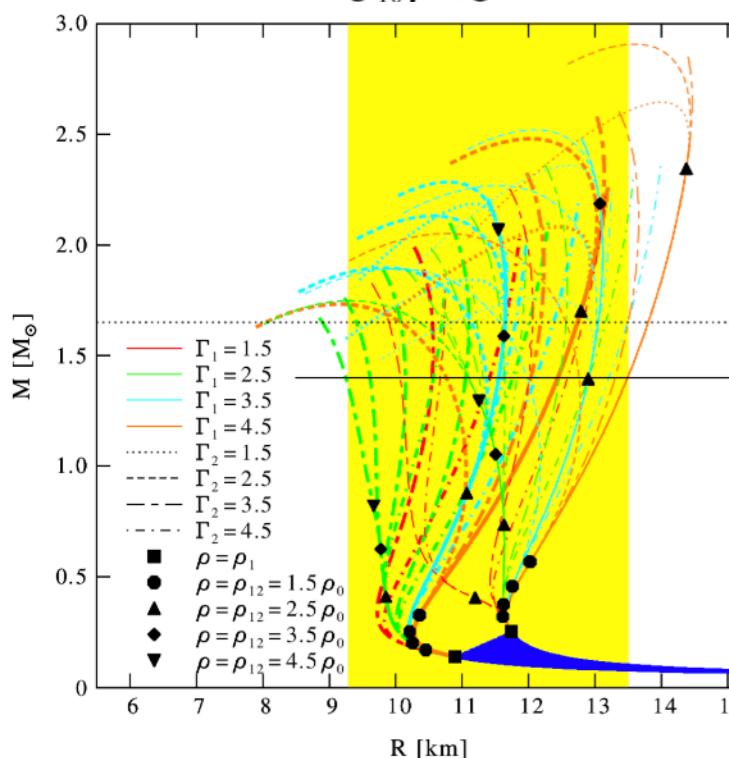
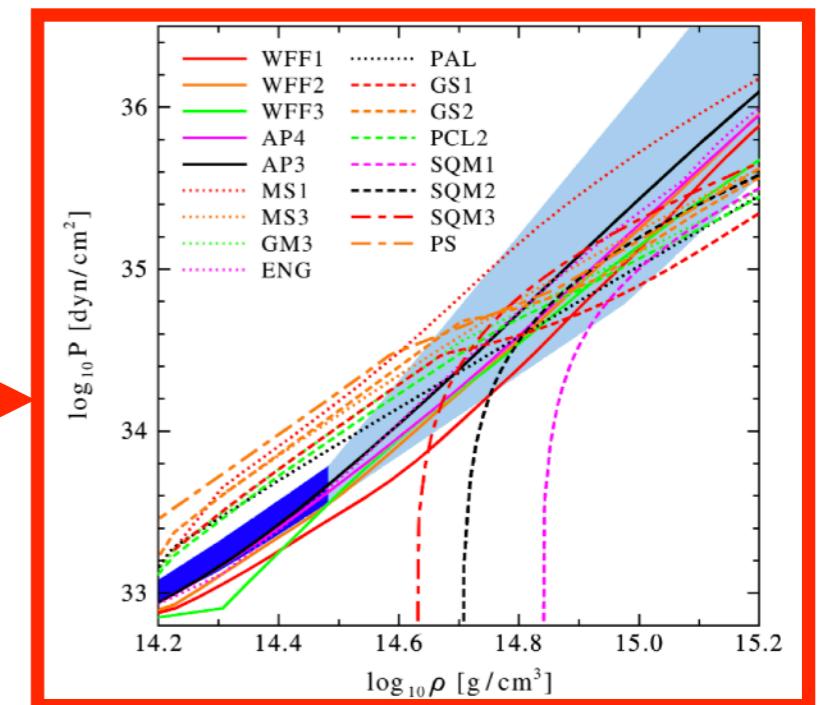
$$[T_{1/2}^{0\nu}]^{-1} = g_A^4 G_{0\nu} \left| \frac{\langle m_{\beta\beta} \rangle}{m_e} \right|^2 |M^{0\nu}|^2, \quad \langle m_{\beta\beta} \rangle = \left| \sum_{i=1,2,3} U_{ei}^2 m_i \right|$$

Constraints on Neutron Star Radii Based on Chiral Effective Field Theory Interactions



piecewise
polytropes

$$P(\rho) = \kappa_1 \rho^{\Gamma_1}$$

$$P(\rho) = \kappa_2 \rho^{\Gamma_2}$$


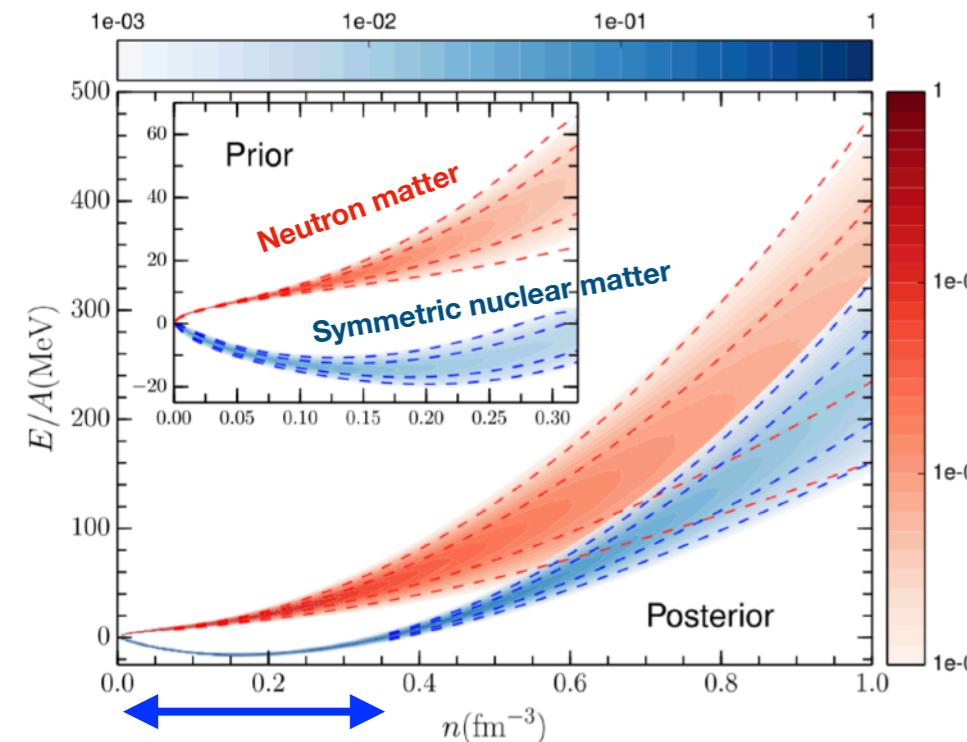
$1.4M_\odot$
 $R = 9.3\text{--}13.5 \text{ km}$

K. Hebeler, J. M. Lattimer, C. J. Pethick, and A. Schwenk
Phys. Rev. Lett. **105**, 161102 (2010)

Use ab initio calculations as constraints



Neutron Star Tidal Deformabilities Constrained by Nuclear Theory and Experiment



$$\mathcal{E}(n, x) = \frac{1}{2m} \tau_n + \frac{1}{2m} \tau_p + (1 - 2x)^2 f_n(n) + [1 - (1 - 2x)^2] f_s(n),$$

$$\sum_{i=0}^3 b_i n^{(2+i/3)}$$

$$\sum_{i=0}^3 a_i n^{(2+i/3)},$$

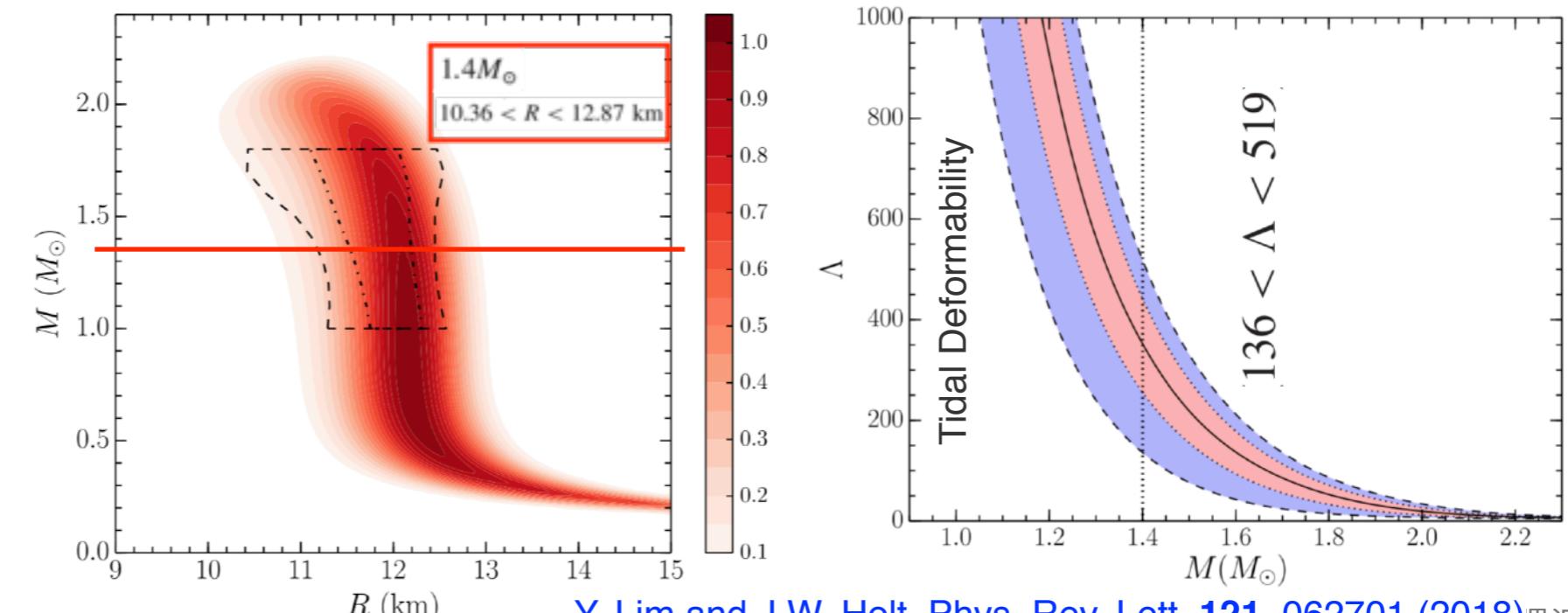
▪ Bayes' Theorem: $P(\vec{a}|data) \sim \frac{P(data|\vec{a})}{\text{Beliefs about parameters } \vec{a}} P(\vec{a})$

Posterior

Likelihood of data given a probability distribution for \vec{a}

Beliefs about parameters \vec{a} before measurements

- ◆ Determine prior probability distributions for a_i and b_i with the EOS by chiral EFT up to $2n_0$
- ◆ The posterior distributions are determined by empirical information of nuclear matter





Summary and outlook

- **Many new exciting opportunities in nuclear physics**

Facilities for Rare Isotope Beams: Neutron-rich nuclei

Multi-messenger astronomy: nucleosynthesis and neutron stars

New physics probes: neutrinoless double beta decay, WIMP, etc

- **Significant advances in modeling of atomic nuclei**

Beyond mean-field (covariant) EDFs: collective excitations, decays, etc.

Chiral EFT: an elegant framework to derive nuclear forces

Ab initio many-body frameworks: MC, Lattice EFT, CC, IMSRG, MBPT, etc.

- **Outlook**

Uncertainty Quantification: Truncation error in both nuclear interactions and many-body methods

Machine learning and quantum computing: application to nuclear structure and reaction



Collaborators and acknowledgement

Collaborators

- N. Li, C.F. Jiao, Sun Yat-sen University, China
- Z.P.Li, L. J. Wang, Southwest University, China
- X.Y. Wu, Jiangxi Normal University, China
- J. Meng, L. S. Song, Peking University, China
- R. Wirth, H. Hergert, Michigan State University, USA
- J. Engel, A. Marquez Romero, UNC-CH, USA
- A. Belley, T. Miyagi, C. G. Payne, J. D. Holt, TRIUMF, Canada
- P. Ring, Technical University of Munich, Germany
- B. Bally, Tomás R. Rodríguez, Universidad Autónoma de Madrid, Spain
- and more ...

Thank you for your attention