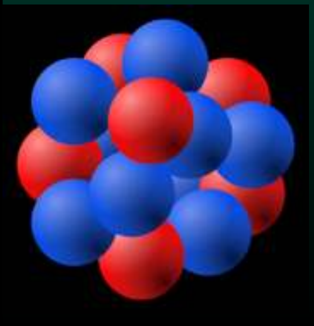


# 原子核物理的从头计算
# —从原子核到中子星



$10^{-15}$ m

$10^{4}$ m


尧江明

中山大学物理与天文学院

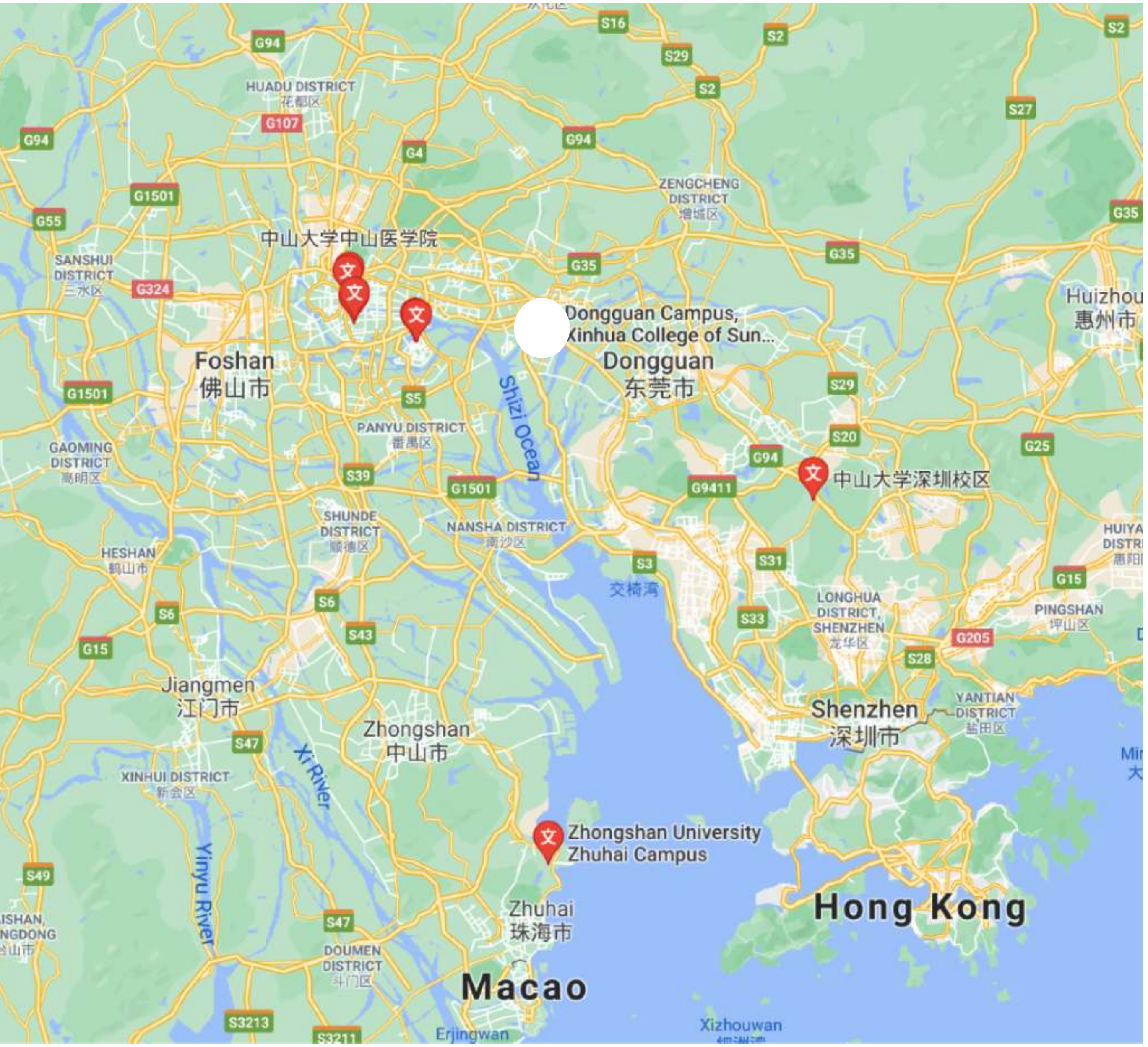
School of Physics and Astronomy

Sun Yat-sen University


江西 南昌

2021年4月27日

# 中山大学-五个校区




## 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。

## 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。

# 中山大学-珠海校区

# 中山大学-珠海校区


2015年，罗俊院士在中山大学提出“天琴计划”空间引力波探测大科学工程计划，标志着引力波探测重新在中山大学起航。

# 中山大学-物理与天文学院

**1927**

**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

**1929**

**建立中山大学天文台（国内第二座现代天文台）**

**1952**

**中山大学天文系和天文台迁至南京大学**

**2013.12**

**天文与空间科学研究院成立复办天文学科**

**2015.9**

**物理与天文学院成立**

**2016.4**

**天琴中心成立**

**2019.12**

**复办天文系**

**2020.9**

**成立中国空间站工程巡天望远镜粤港澳大湾区科学中心**

深空

物理学

天文学

理论物理

量子物理

引力物理

天体物理

物理与天文学院

引领1个 学 科 群

支撑2个一级学科

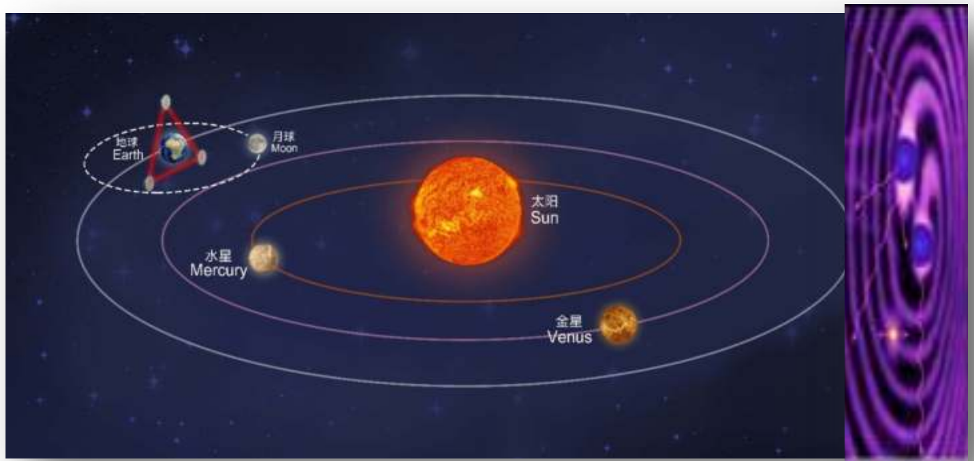
发展4个研究团队

# 中山大学-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 | |

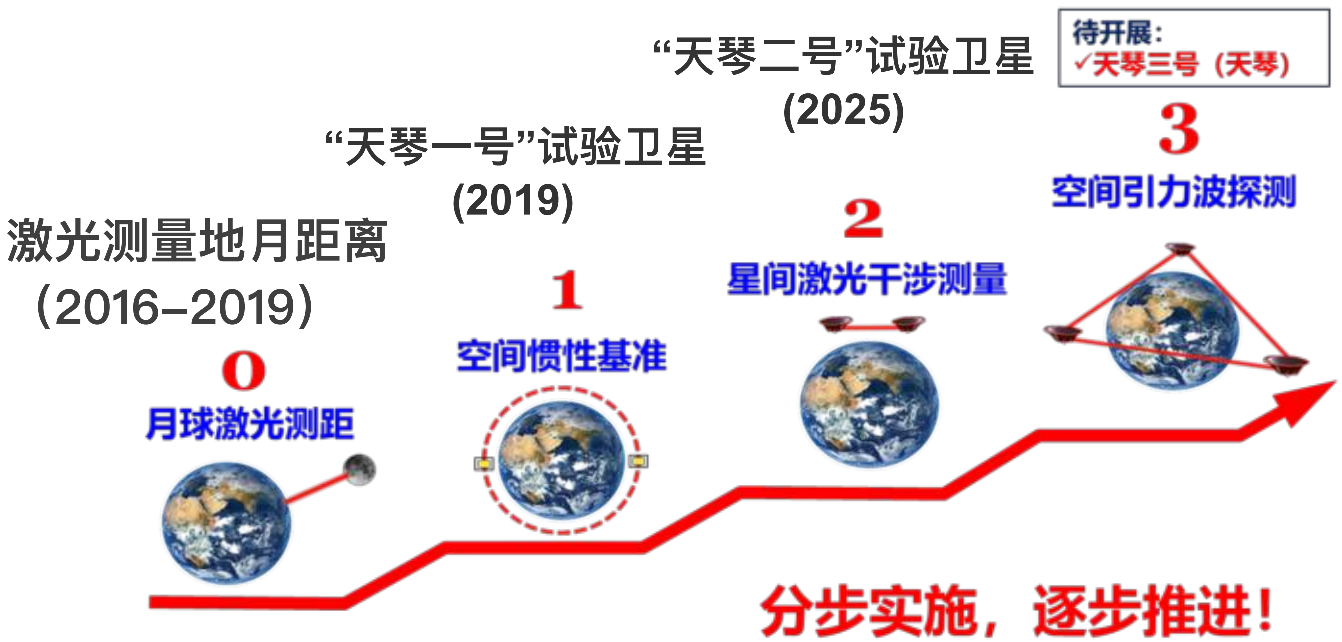
# 中山大学-天琴计划团队

◆ **建设空间引力波探测天文台 ~2035**



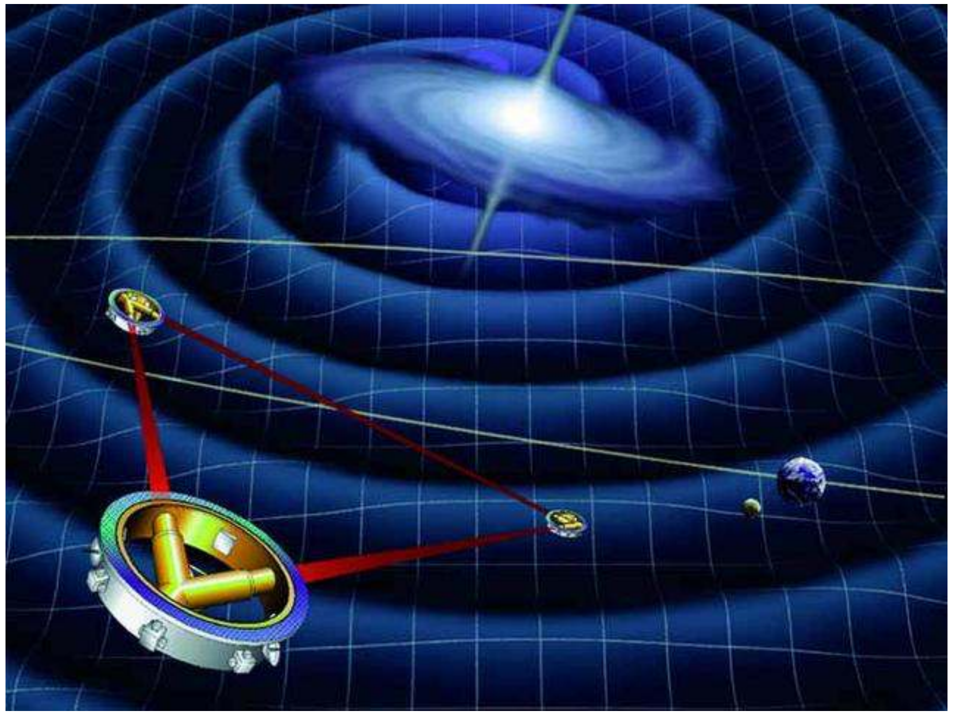


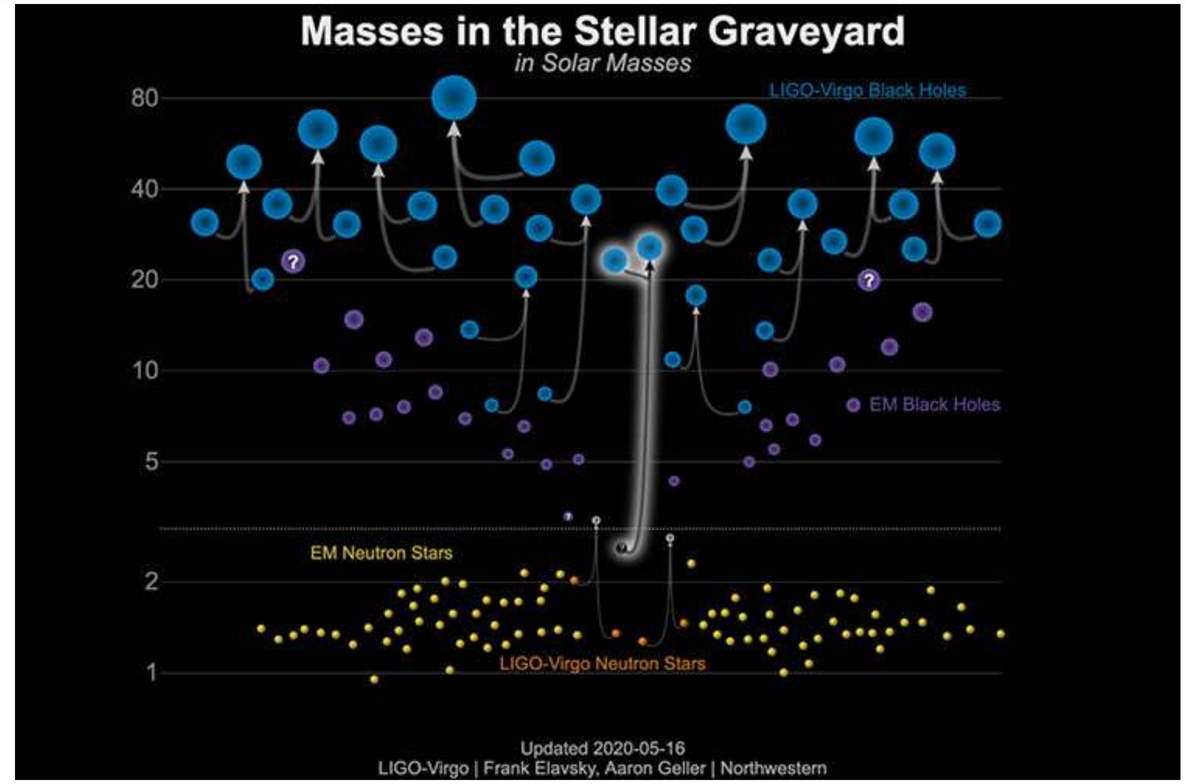
◆ **天琴计划0123 路线图**

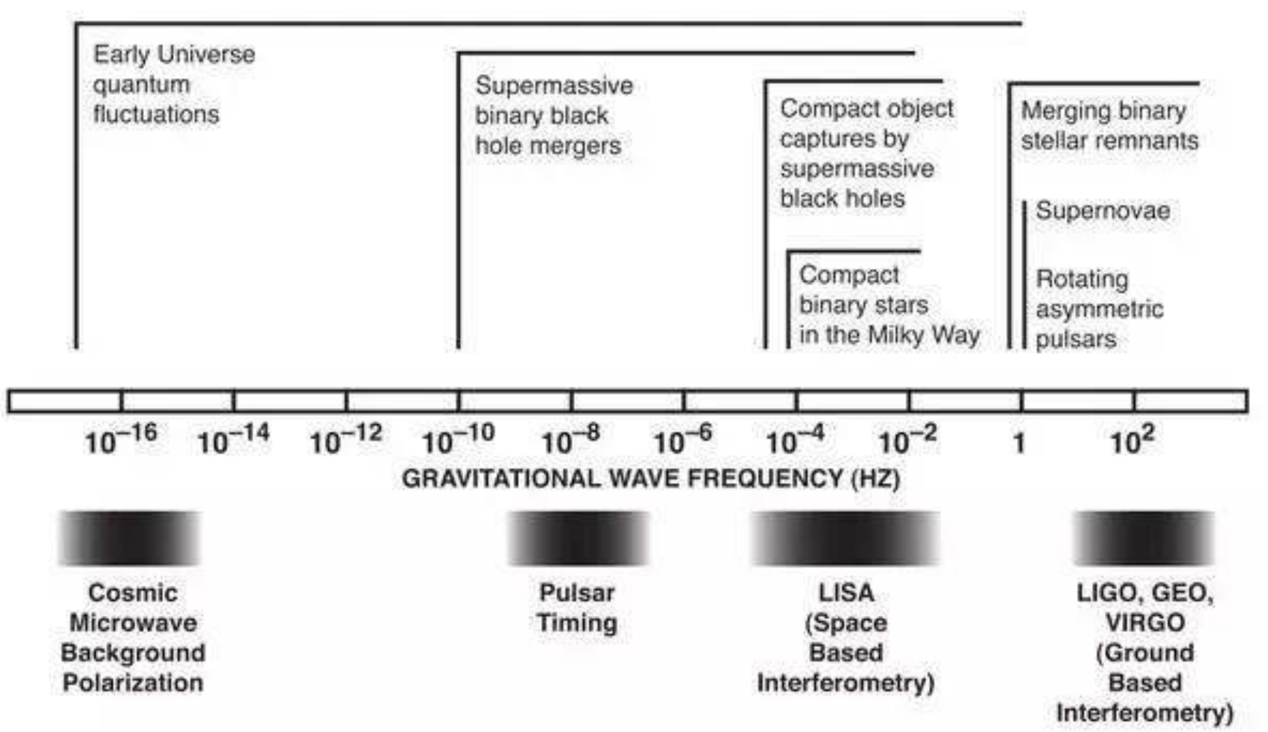



“天琴一号”卫星2019年12月20日

# 中山大学-天琴计划团队





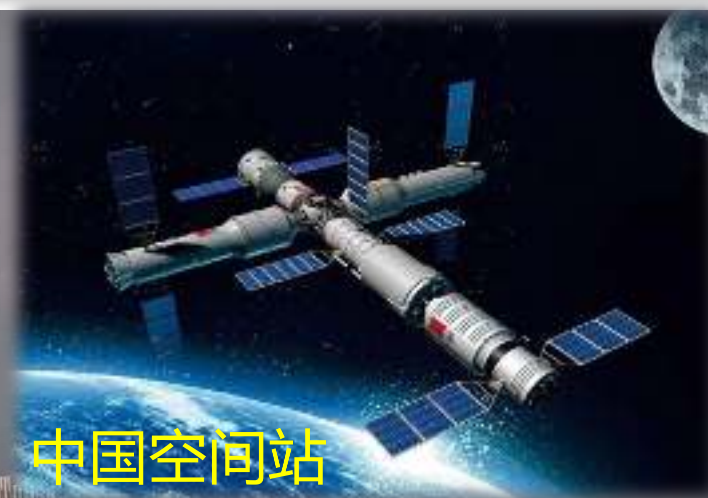




天琴计划

天琴将打开0.1mHz~1Hz频段的引力波的探测窗口，主要探测对象包括了

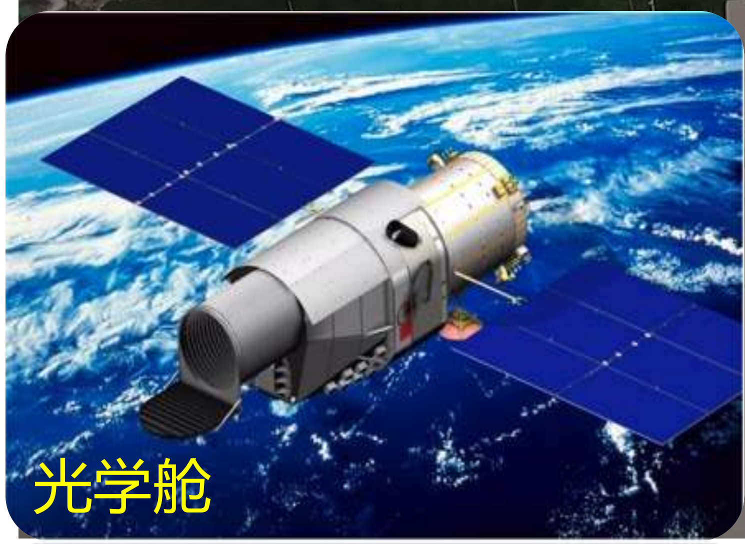
- 几倍太阳质量的恒星级黑洞
- 上千万倍太阳质量的大质量黑洞
- 致密双星
- 以及源于早期宇宙的引力波等。

# 中山大学-巡天中心


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




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）

# 中山大学-量子物理团队

量子工程与精密测量团队

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、非平衡量子动力学、集体量子现象、量子输运、量子人工智能等）。

量子信息与测控团队

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

# 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**

**引力理论**（孙佳睿、苗荣欣）
黑洞、全息、量子引力

**宇宙学**（高显、王爽）
修改引力、引力波理论、暗能量

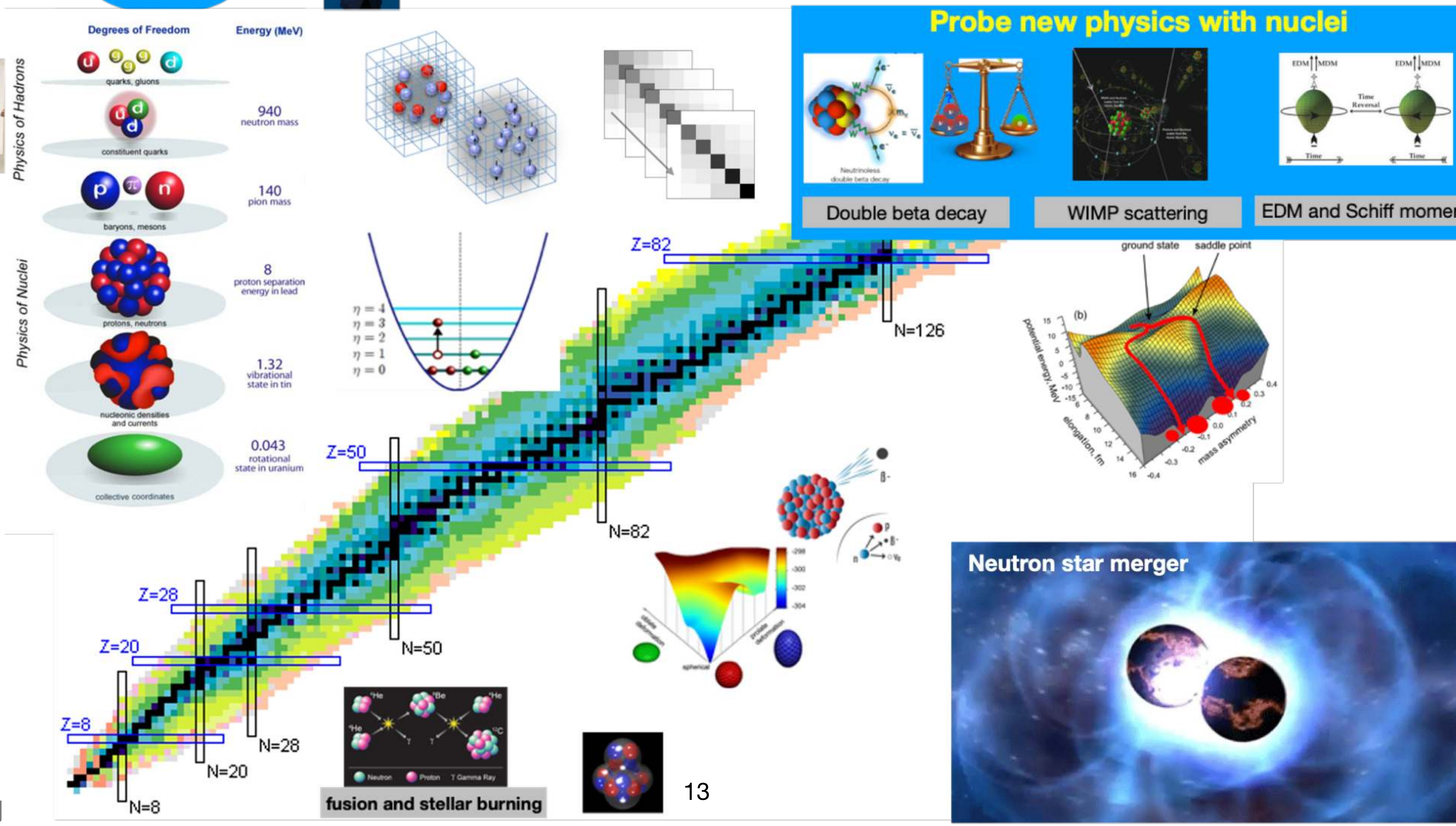
**引力波物理**

**粒子物理**（张鹏鸣、 Ivanov、罗峰）
暗物质、新物理引力波信号

**核物理**（林树、尧江明、焦长峰）
核天体物理、原子核结构与衰变

# 中山大学-“原子核理论与核天体物理课题组”

核结构与衰变



**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）、出版物或原创性工作成果材料的复印件（自愿提供）；

**坚持英语学习、参加学科竞赛、加入科研团队**

## 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**

# Outline

## ✦ Introduction

New opportunities and challenges in nuclear physics

## ✦ Advances in modeling atomic nuclei

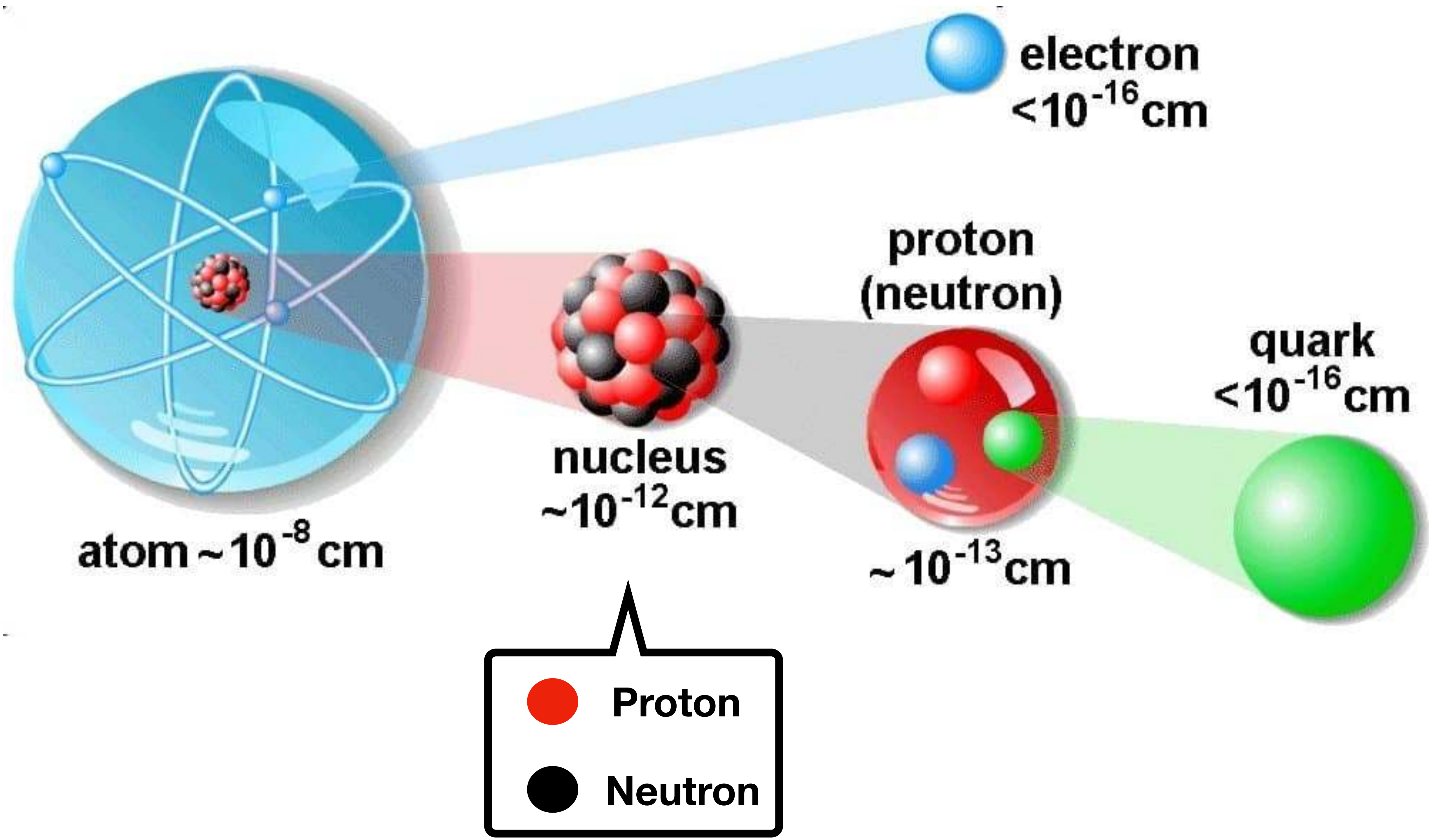
- **Nuclear (covariant) energy density functional theory**
- **Nuclear ab initio methods**

Nuclear structure and weak decays

Neutron-star matter

## ✦ Summary and Outlook

# Atomic nucleus: core of matter

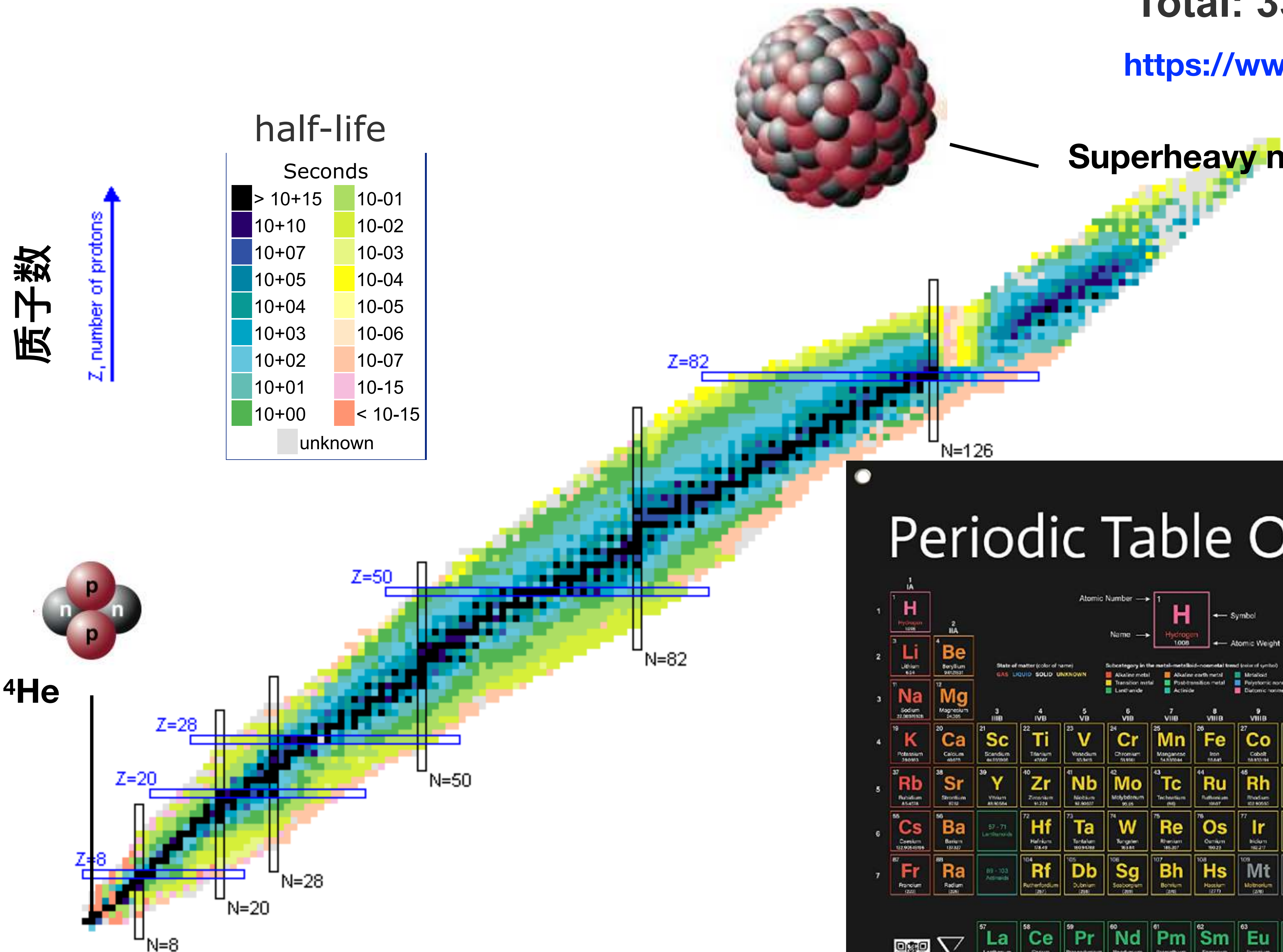


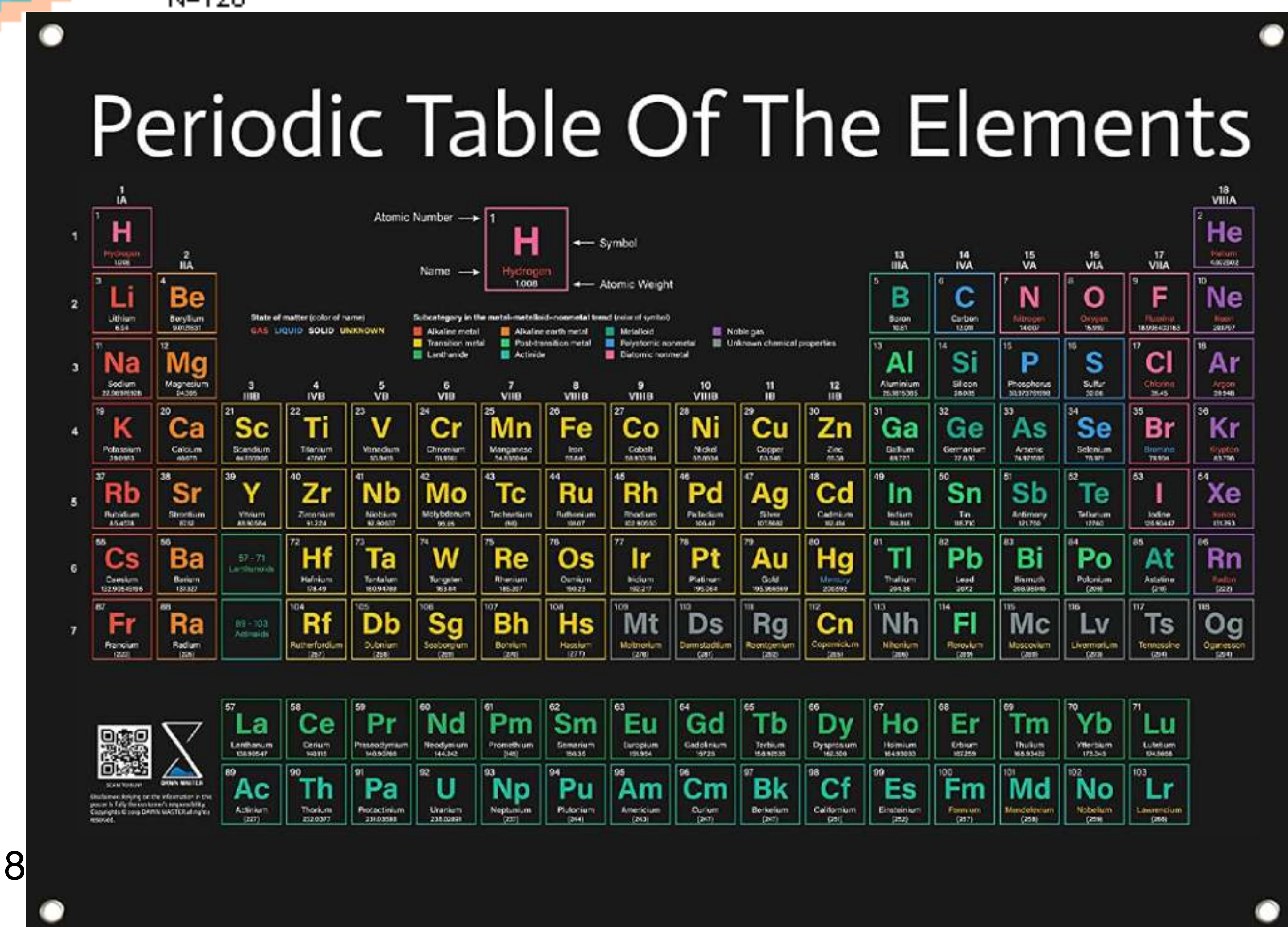
# Structure of atomic nuclei

**Total: 3386 known nuclei**

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

**Superheavy nuclei**






尧江明

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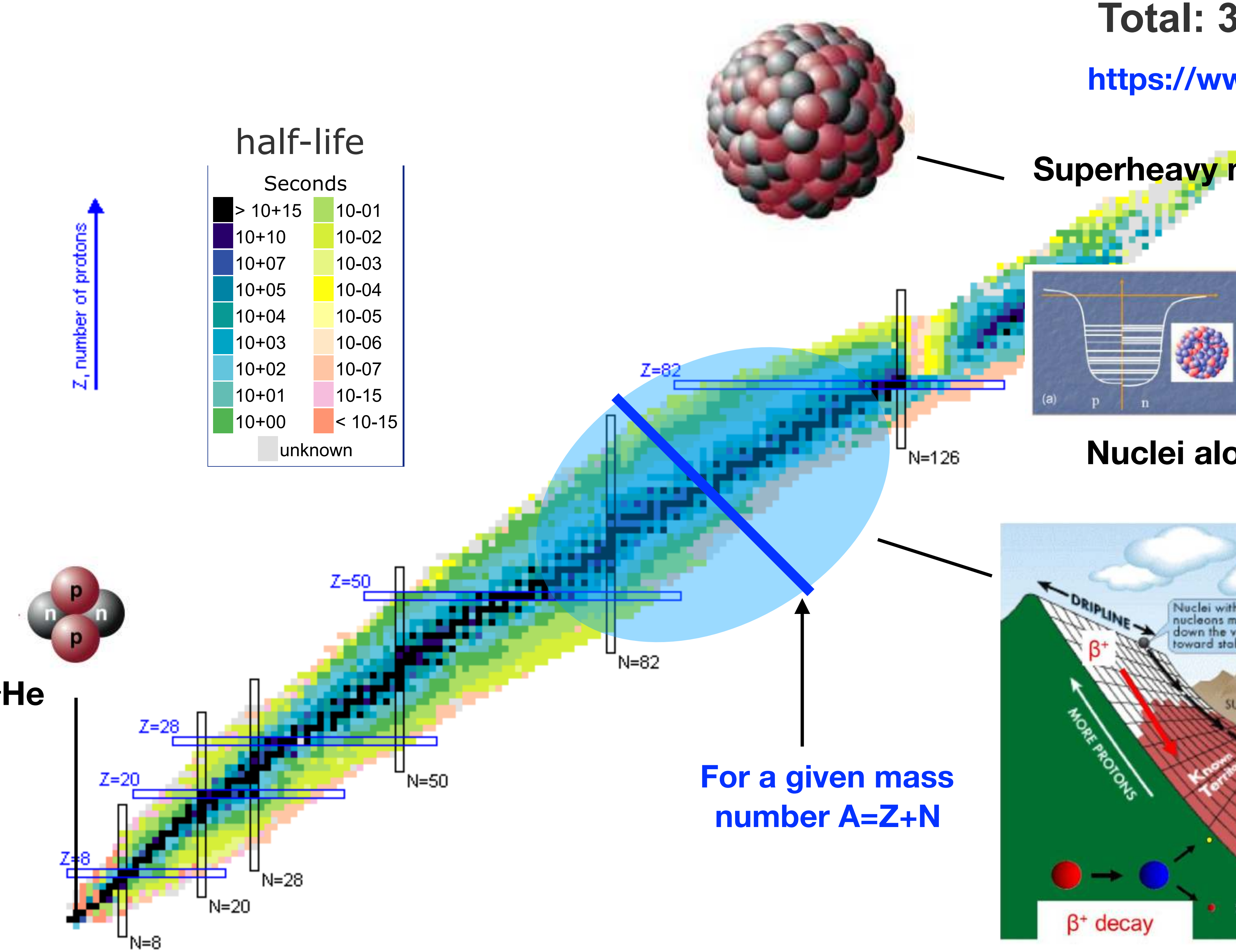
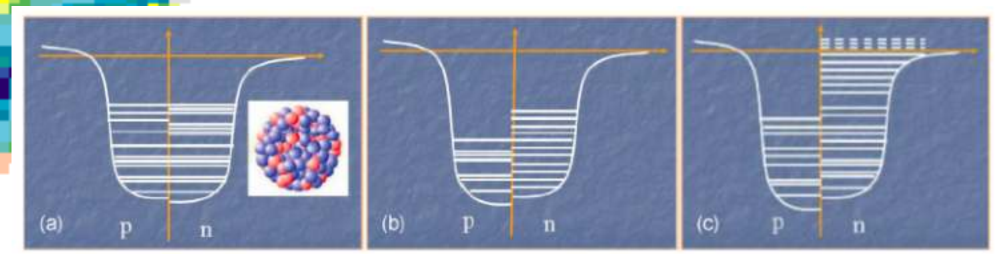
**Superheavy nuclei**

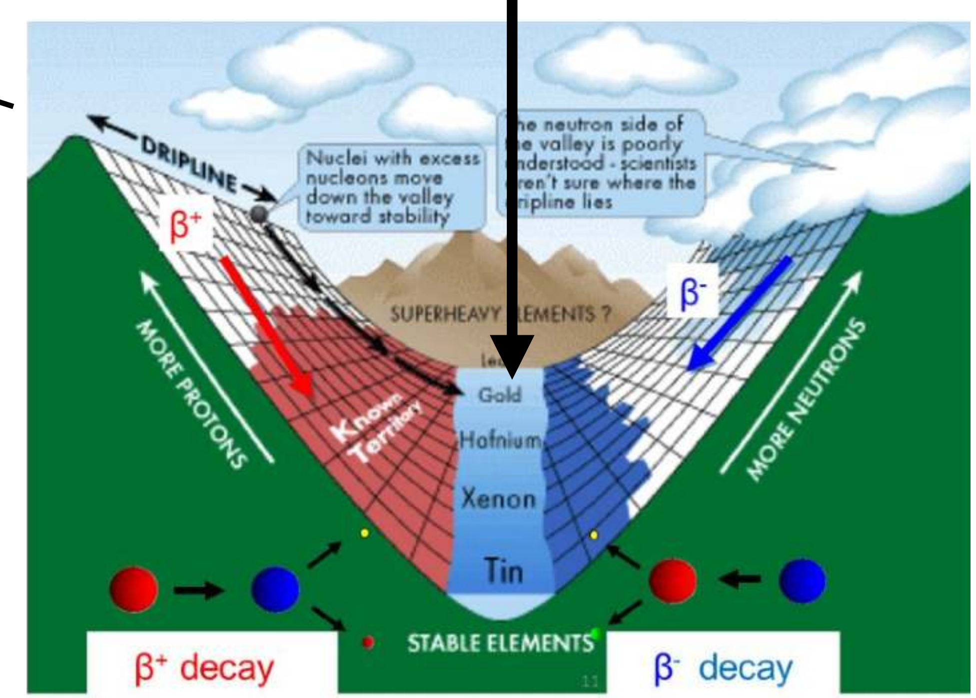



$^4$He




**Nuclei along valley of stability**

**For a given mass number A=Z+N**

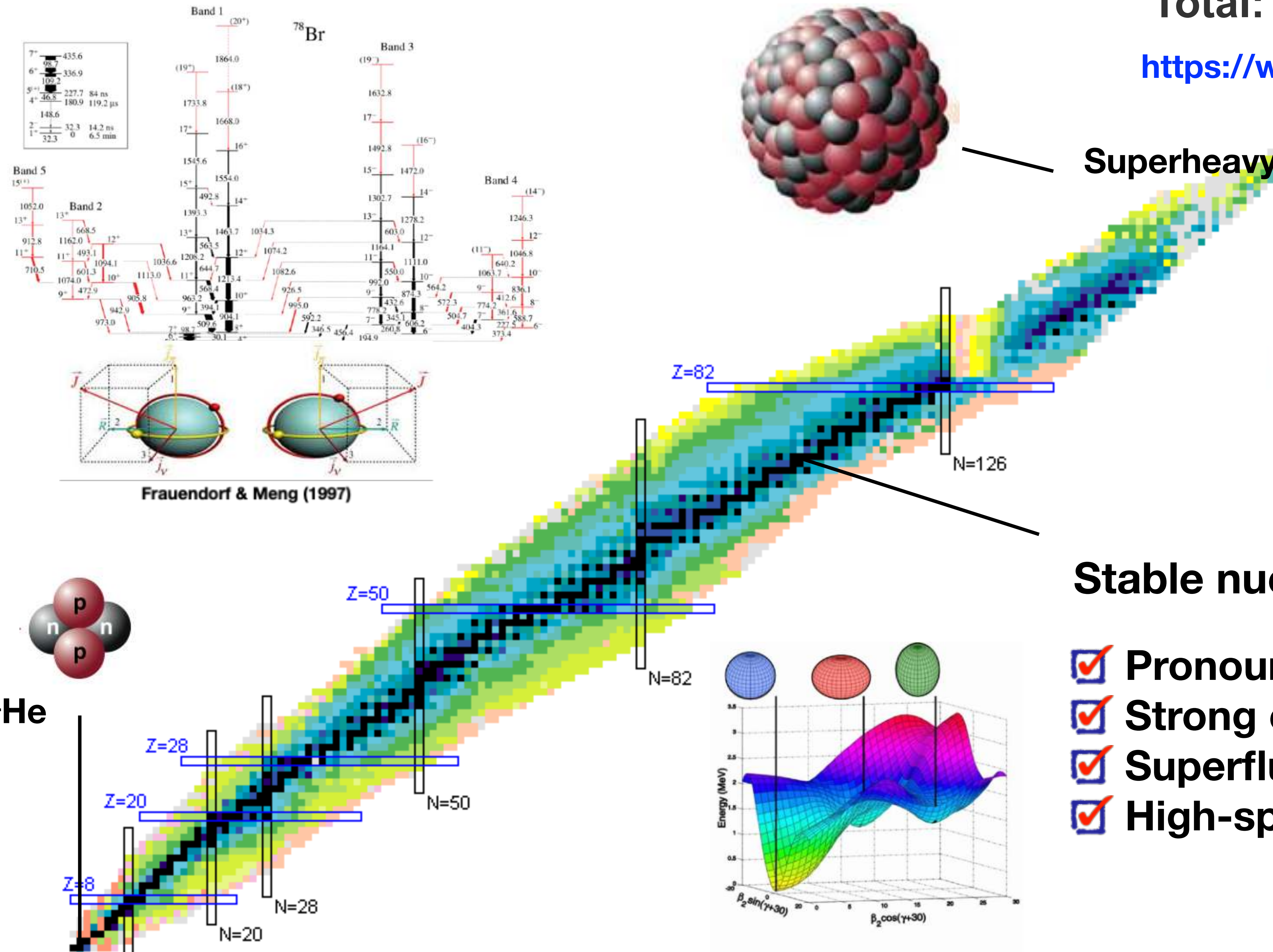



**E ~ Z**

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

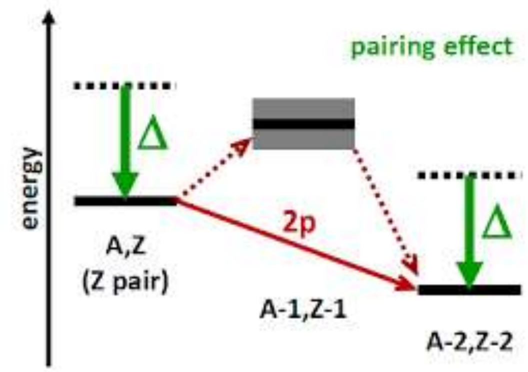
**Total: 3386 known nuclei**

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



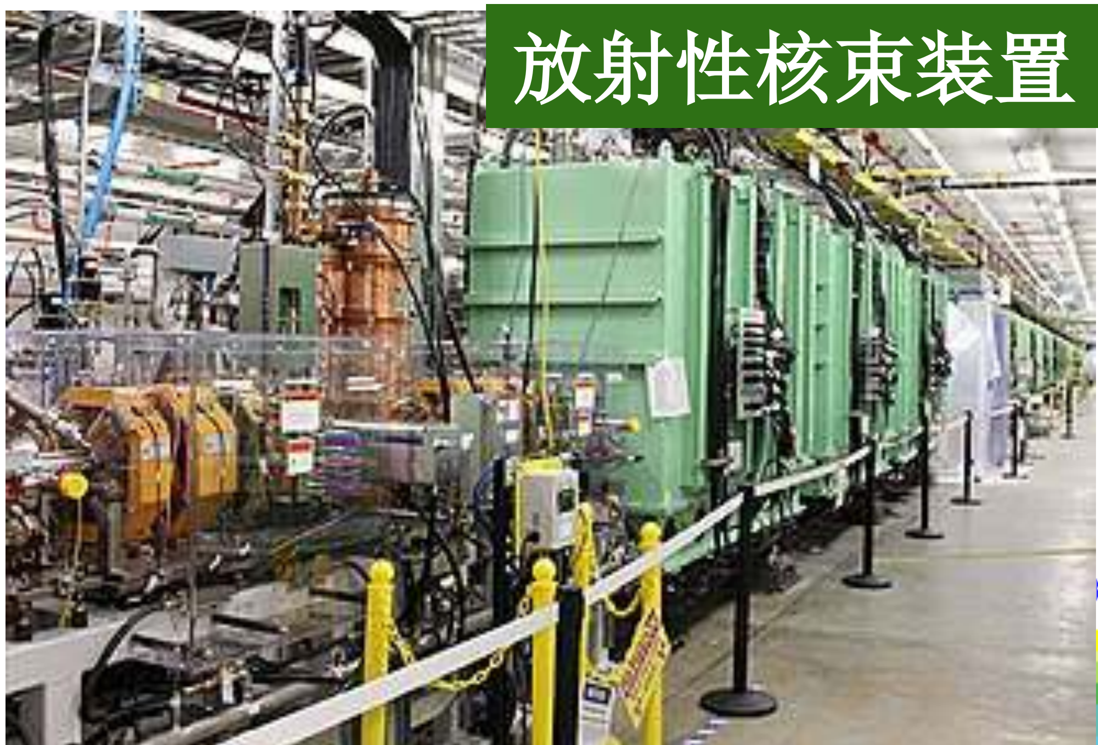

Potential Energy Surface for $^{186}$Pb

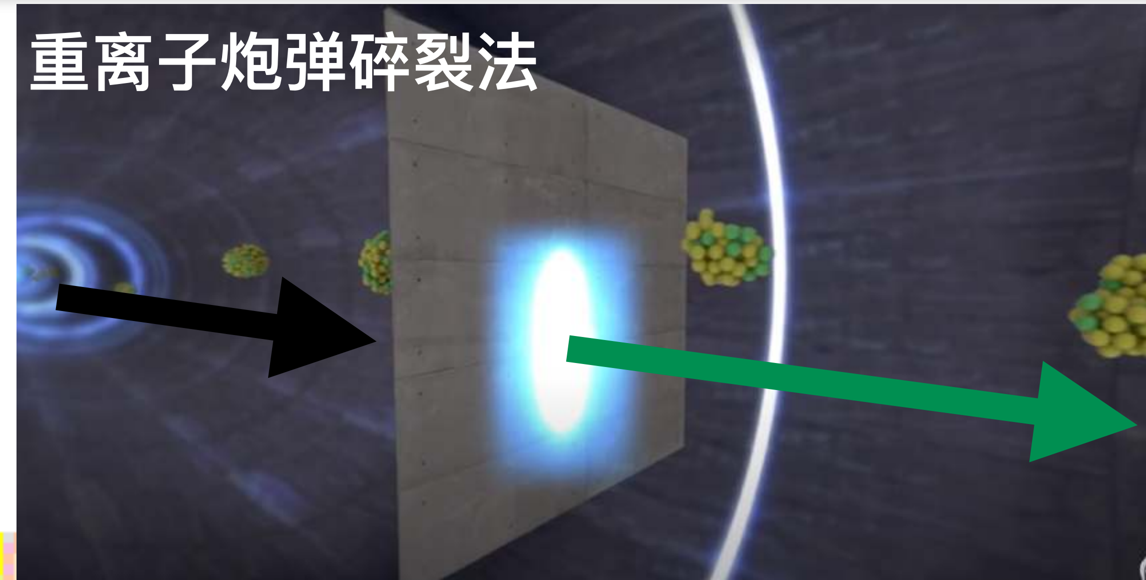
A. Andreyev et al., Nature 405 (2000) 430

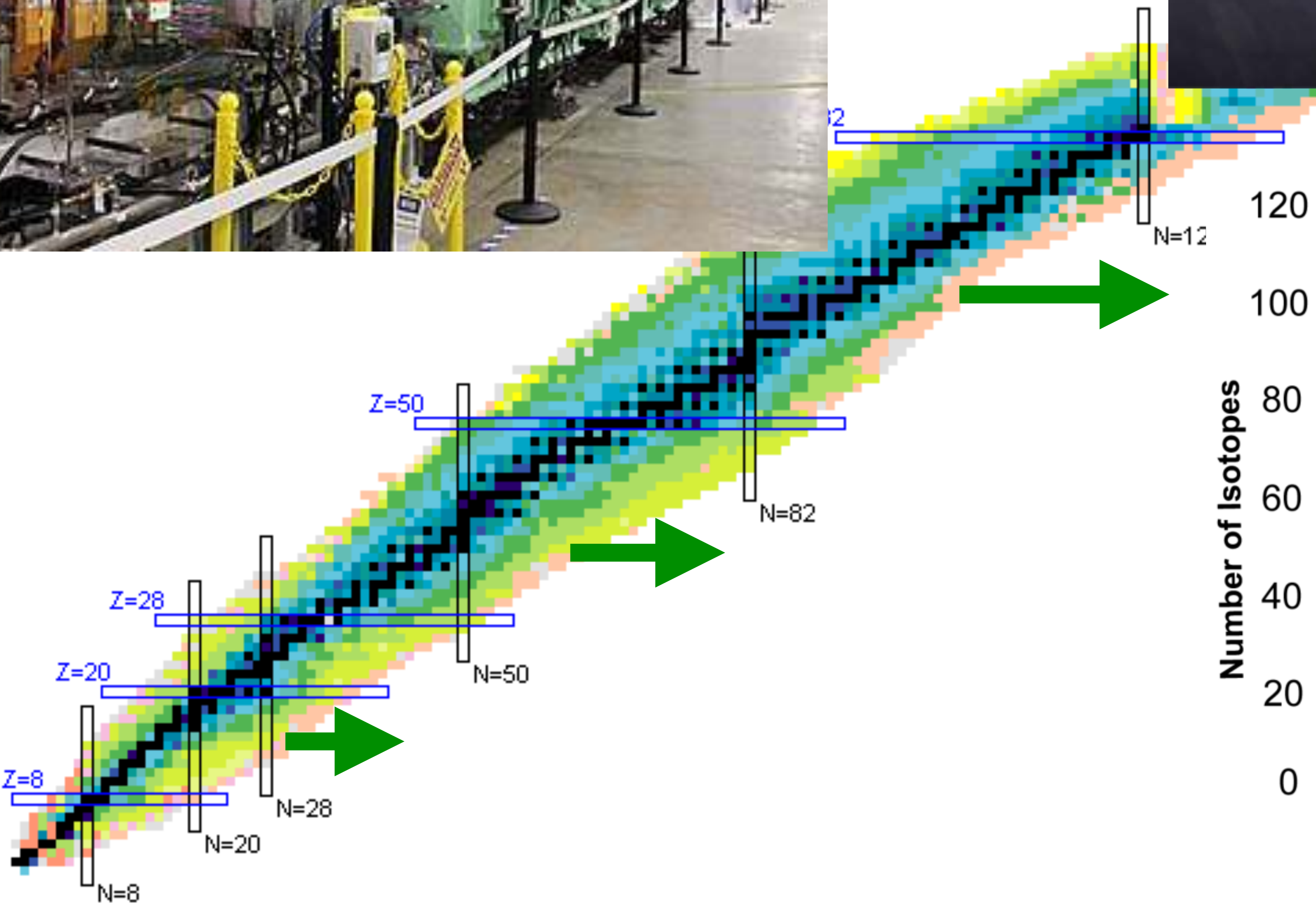


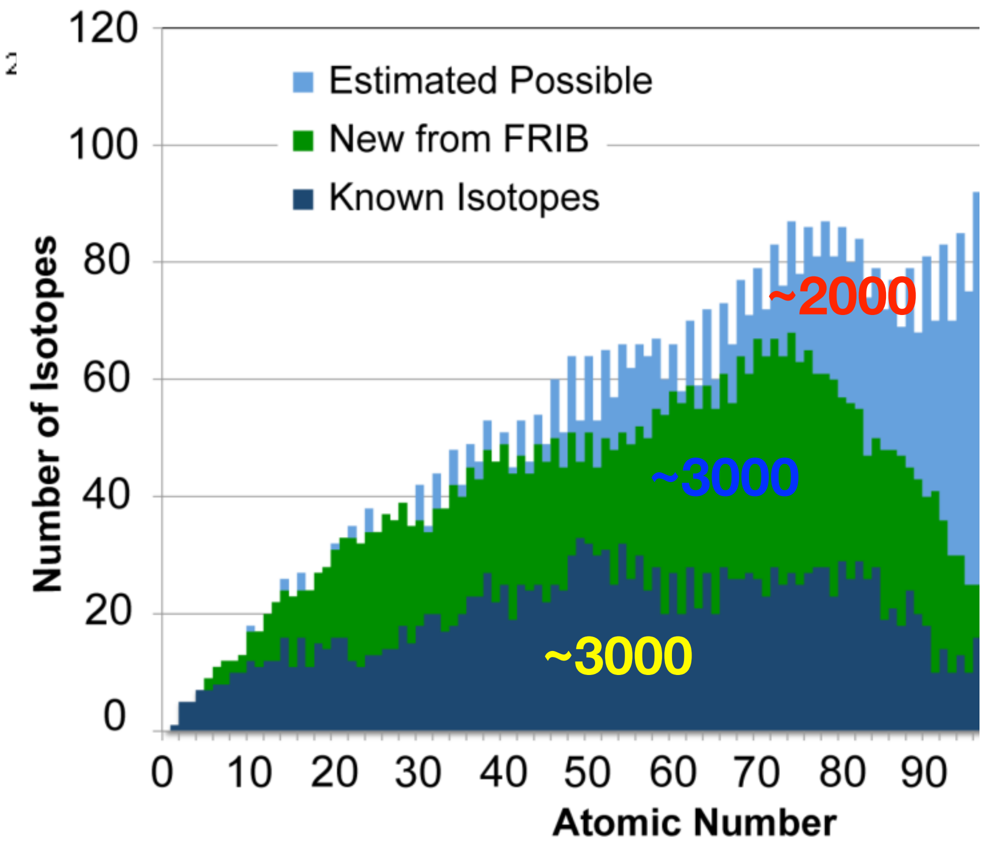

- ☑ Pronounced shell structure
- ☑ Strong collectivity/shapes
- ☑ Superfluidity
- ☑ High-spin states

# Structure of atomic nuclei




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

# Structure of atomic nuclei

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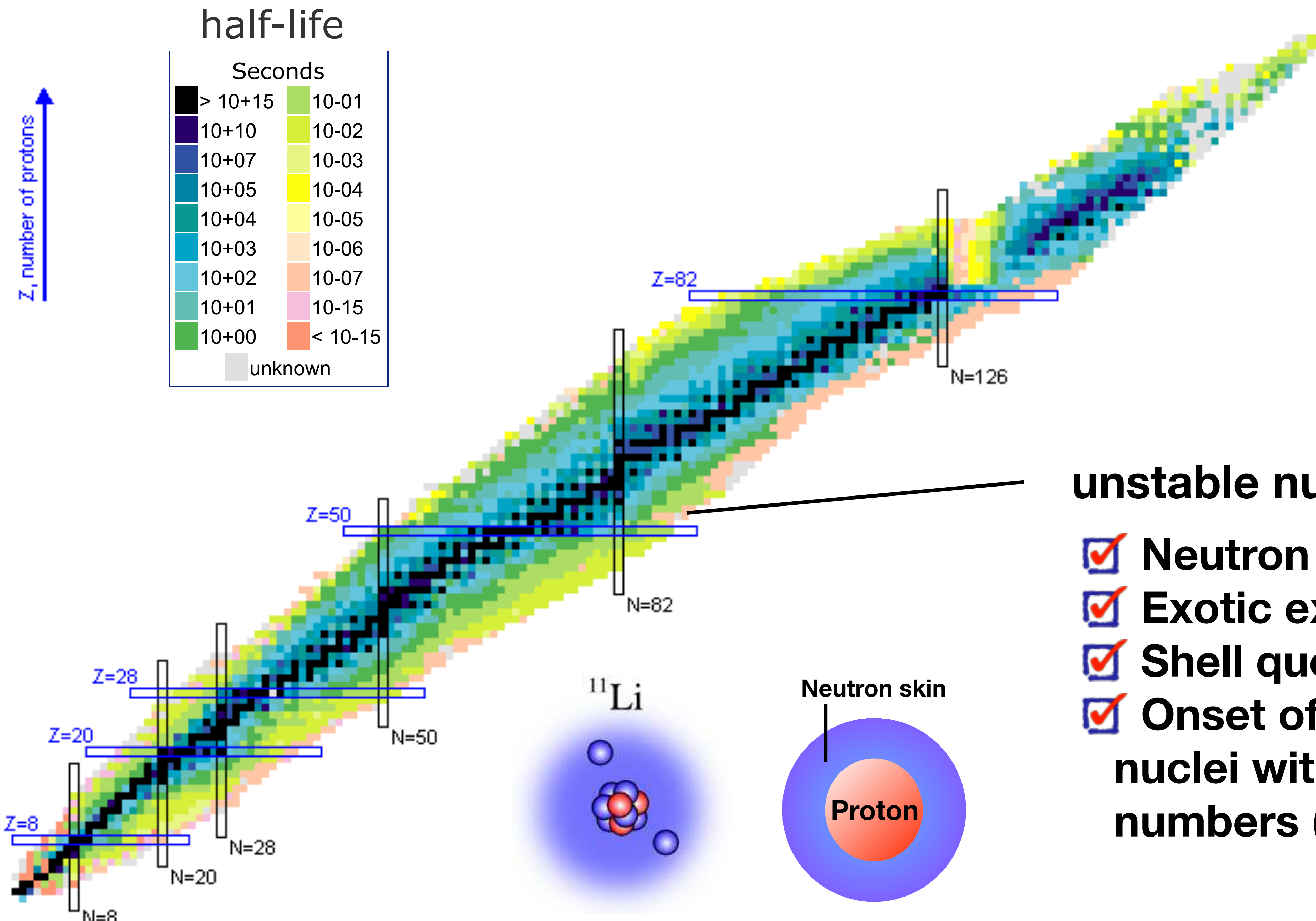
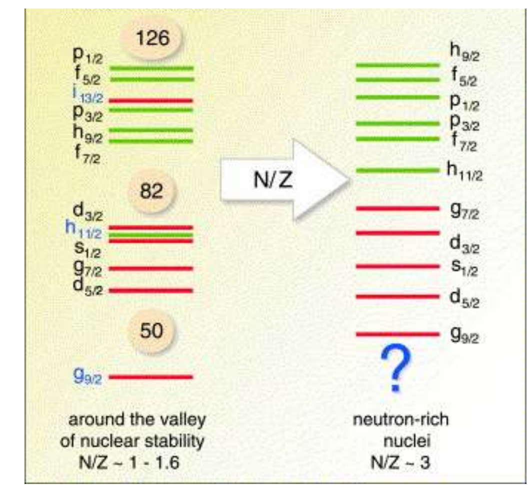
https://www.nndc.bnl.gov/nudat2/



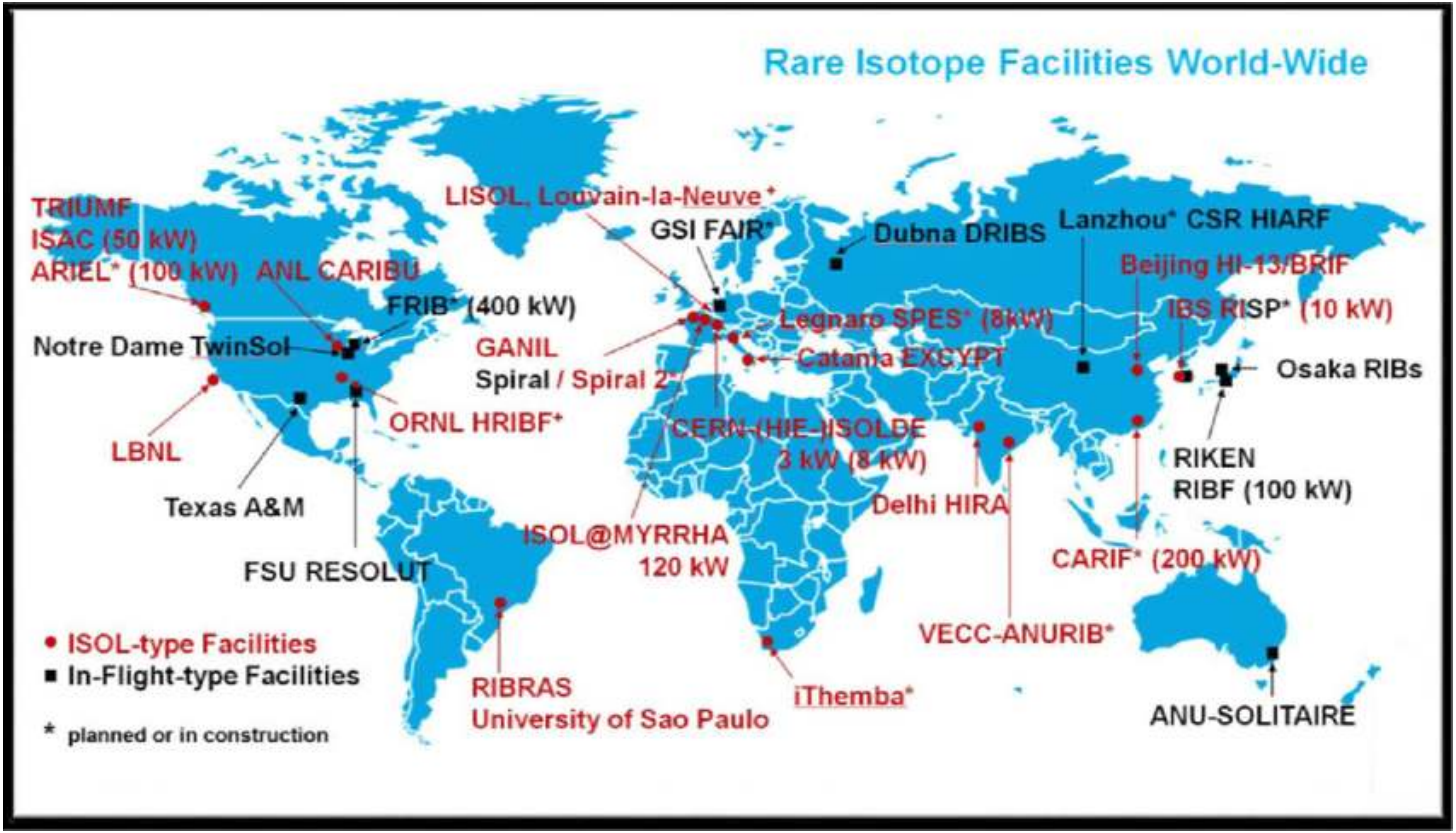

**unstable nuclei ~3000**

- ☑ **Neutron halo/skin**
- ☑ **Exotic excitation modes**
- ☑ **Shell quenching**
- ☑ **Onset of large collectivity at nuclei with traditional magic numbers (island of inversion)**

**Neutron halo**

**Interplay: continuum, pairing and collectivity**

# 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?

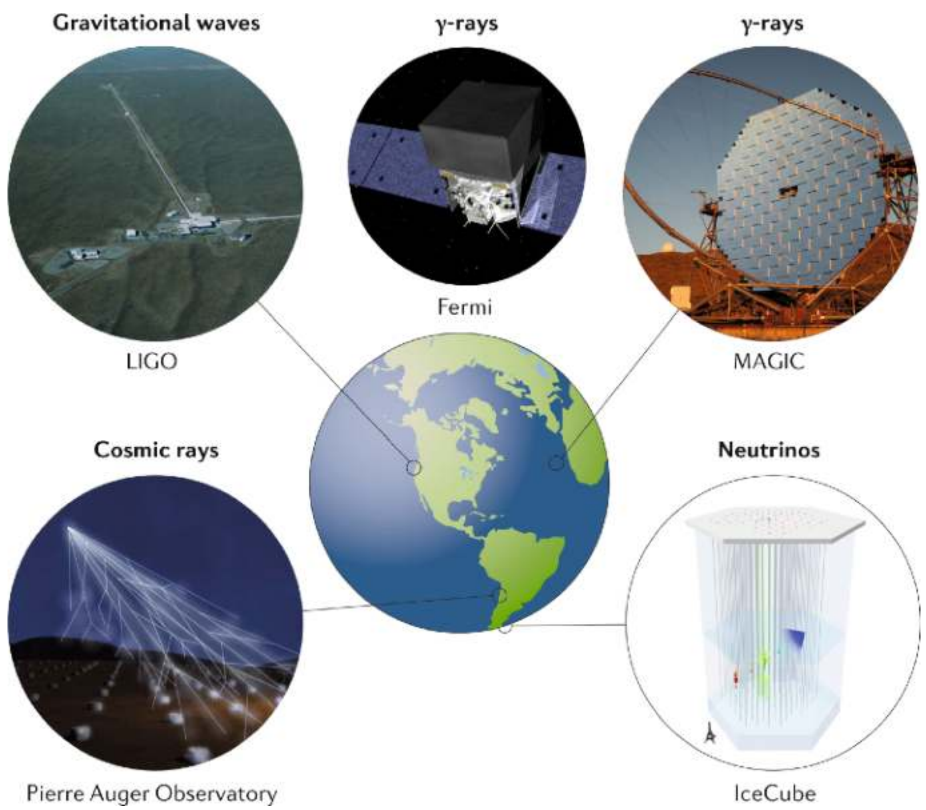
— How were the elements from carbon to uranium created?

— How is energy generated in stars and stellar explosions?

— What is the behavior of stars and supernovae?

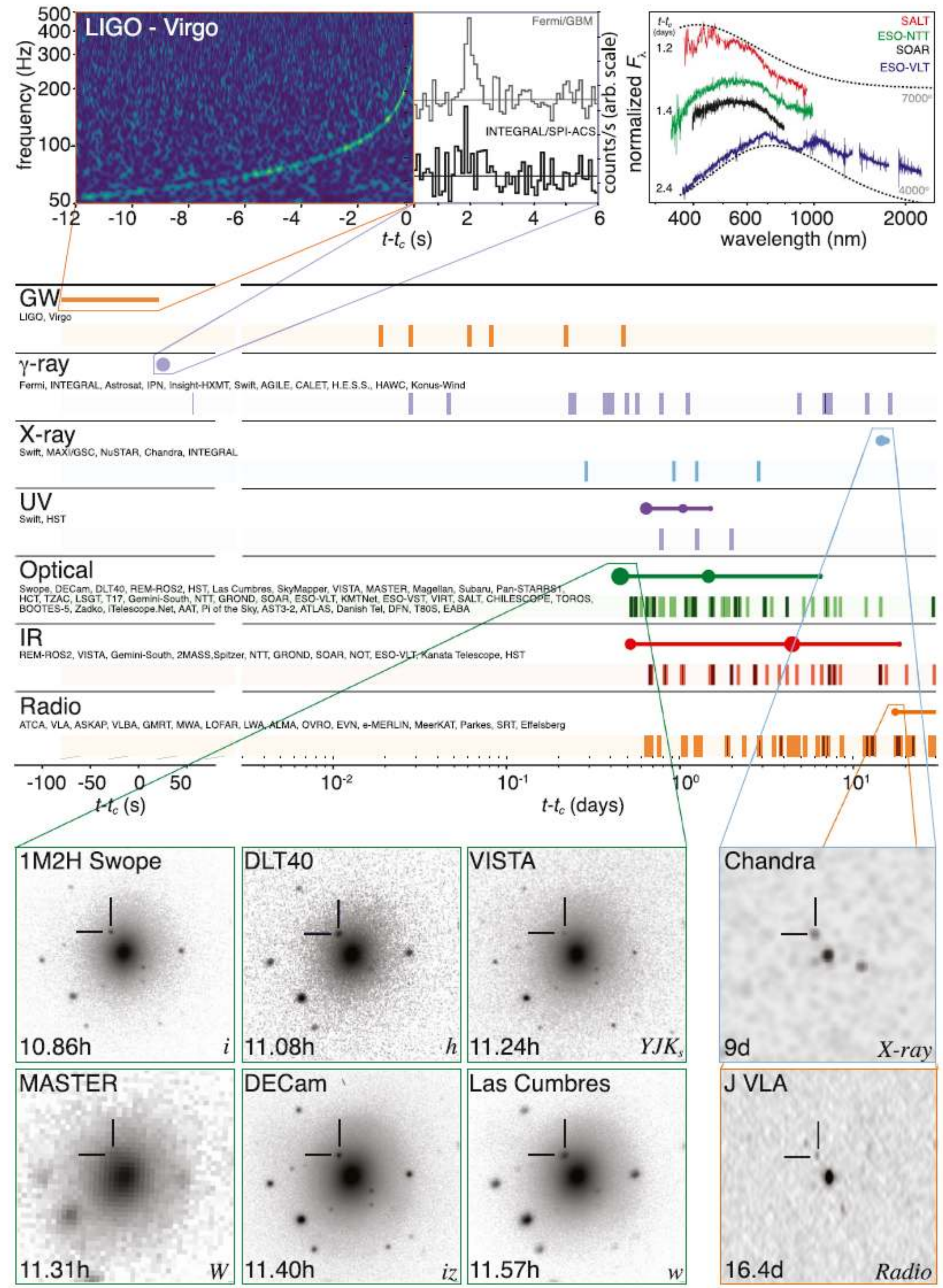
# Nuclear physics in the era of multi-messenger astronomy

Multi-messenger Observations of a Binary Neutron Star Merger*





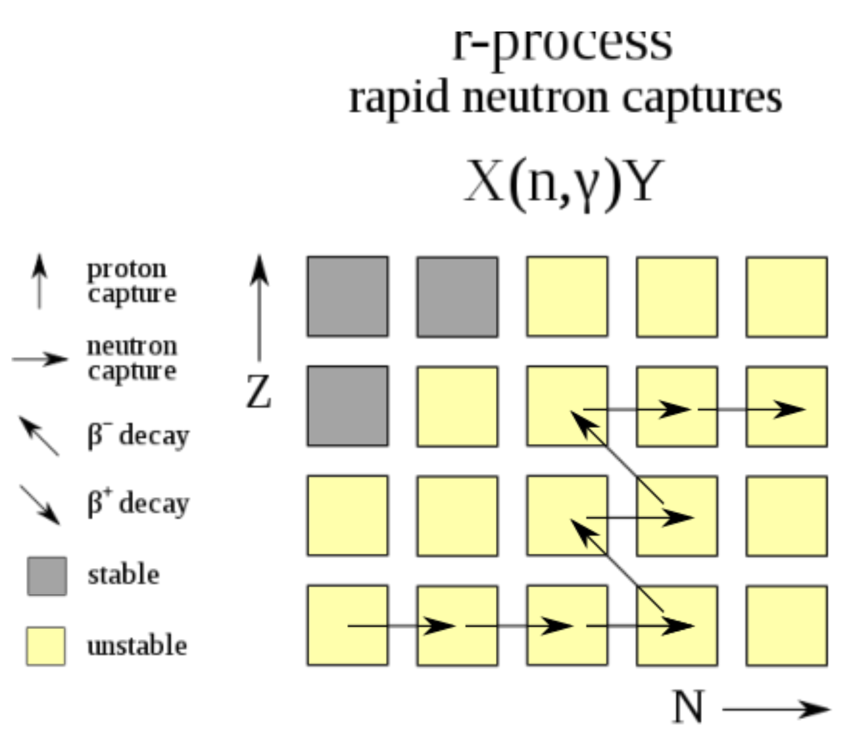
**B. P. Abbott et al., Astrophys. J. 848, L12 (2017).**

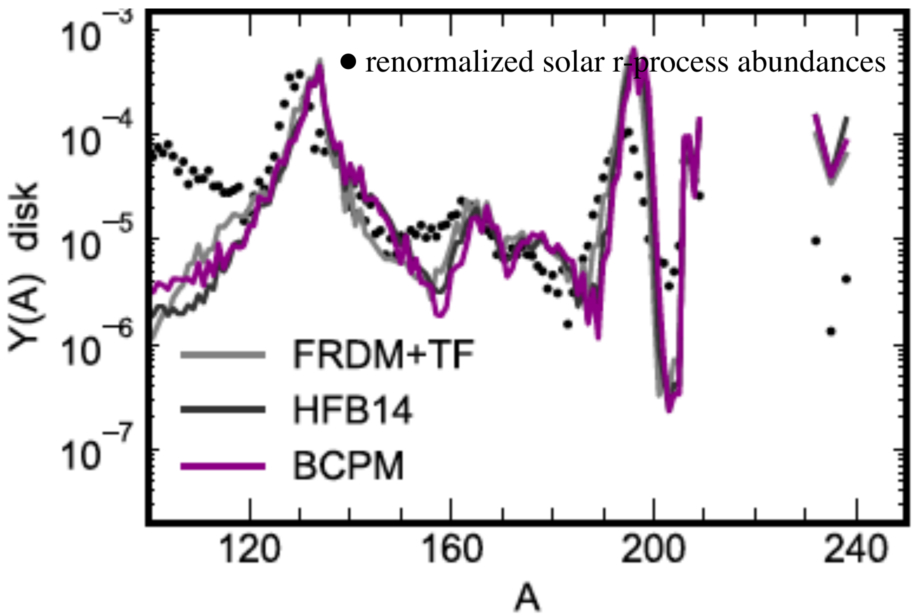


**GW170817**: gravitational wave signal and its associated AT 2017gfo electromagnetic (EM) counterpart provided the first evidence that **r-process nucleosynthesis** occurs in neutron star mergers.


**kilonova** (decay of heavy r-process nuclei)

**What is the origin of elements heavier than iron?**



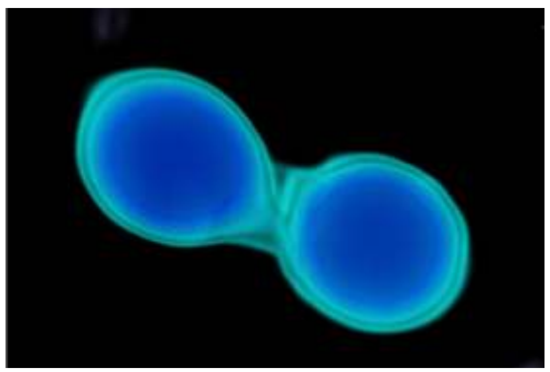



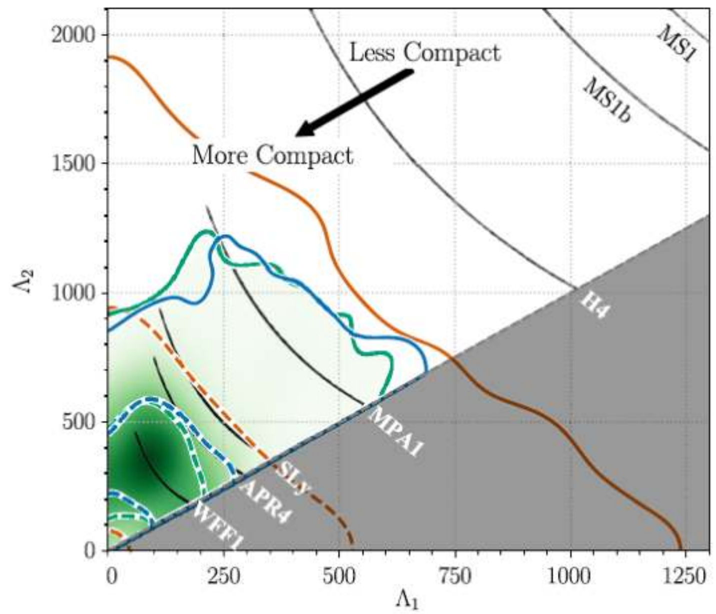

Samuel A. Giuliani et al., PRC102, 045804 (2020)

# Nuclear physics in astronomy (neutron stars)

**GW170817: Measurements of Neutron Star Radii and Equation of State**

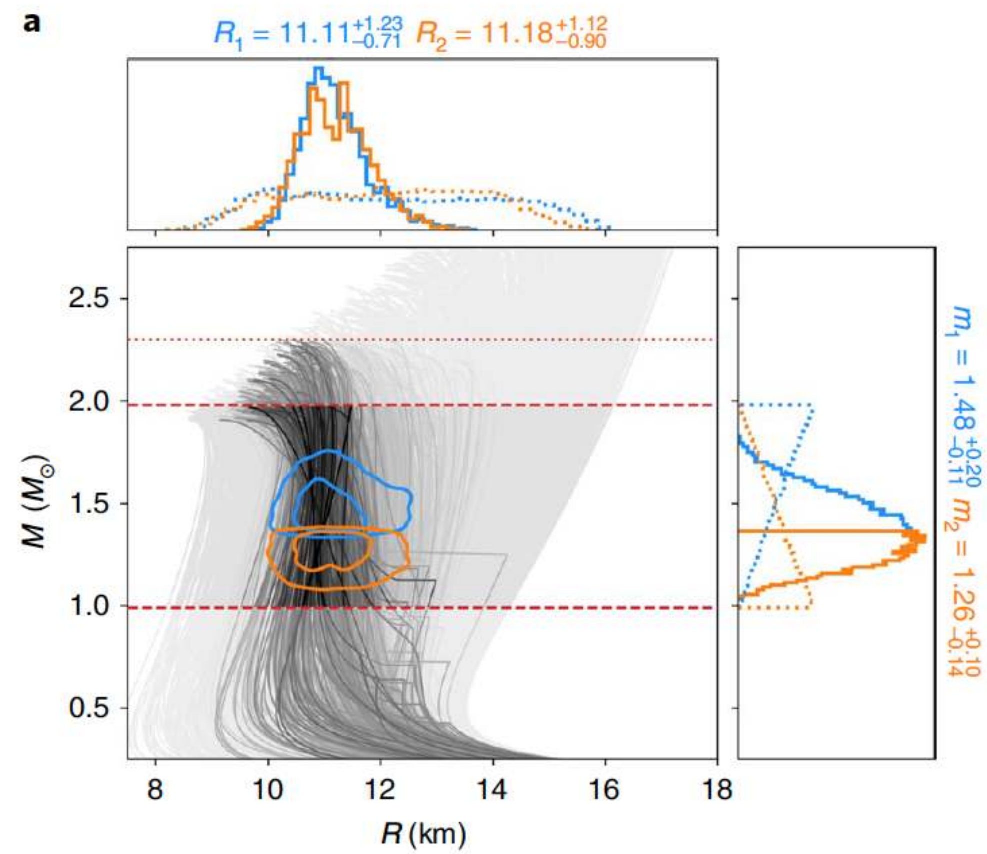
B. P. Abbott et al., PRL121, 161101 (2018)






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

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




## Tidal deformation (潮汐形变)

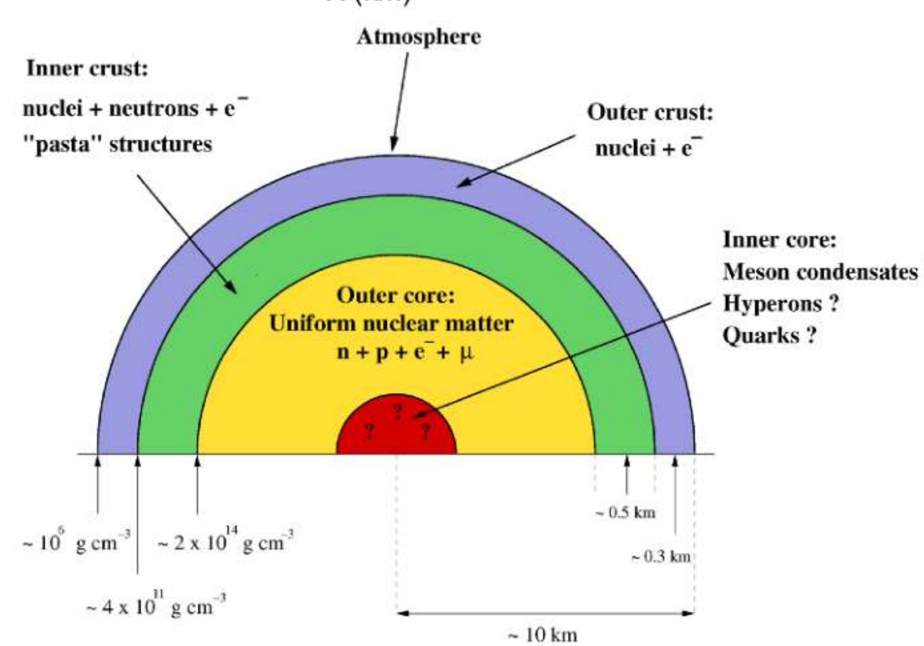
- ☑ **enhances GW emission**
- ☑ **accelerates the decay of the quasicircular inspiral**

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



# Constrain Nuclear physics from neutron stars

**Neutron stars as windows into ultra-dense matter**

Credit to J. Holt

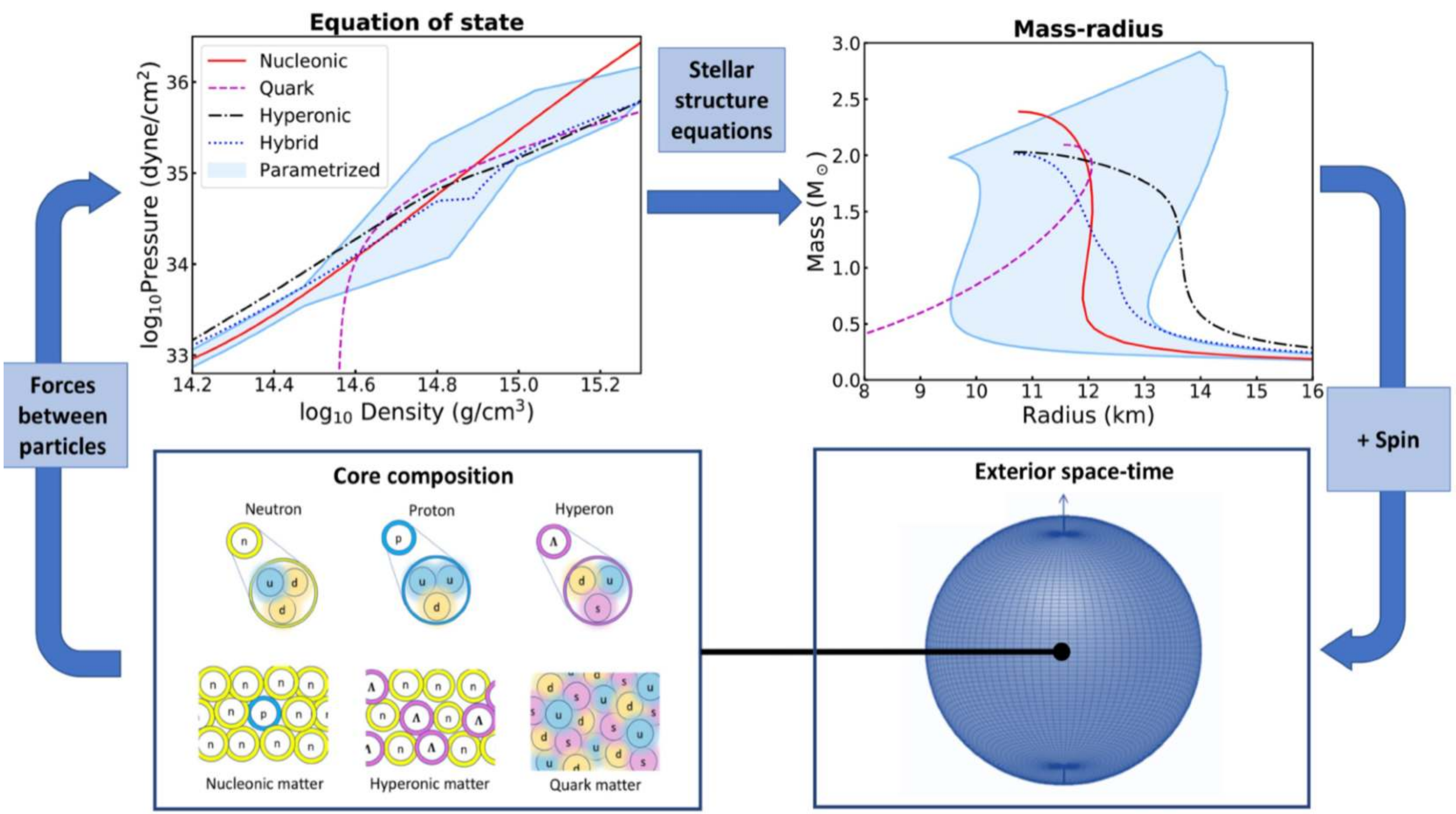
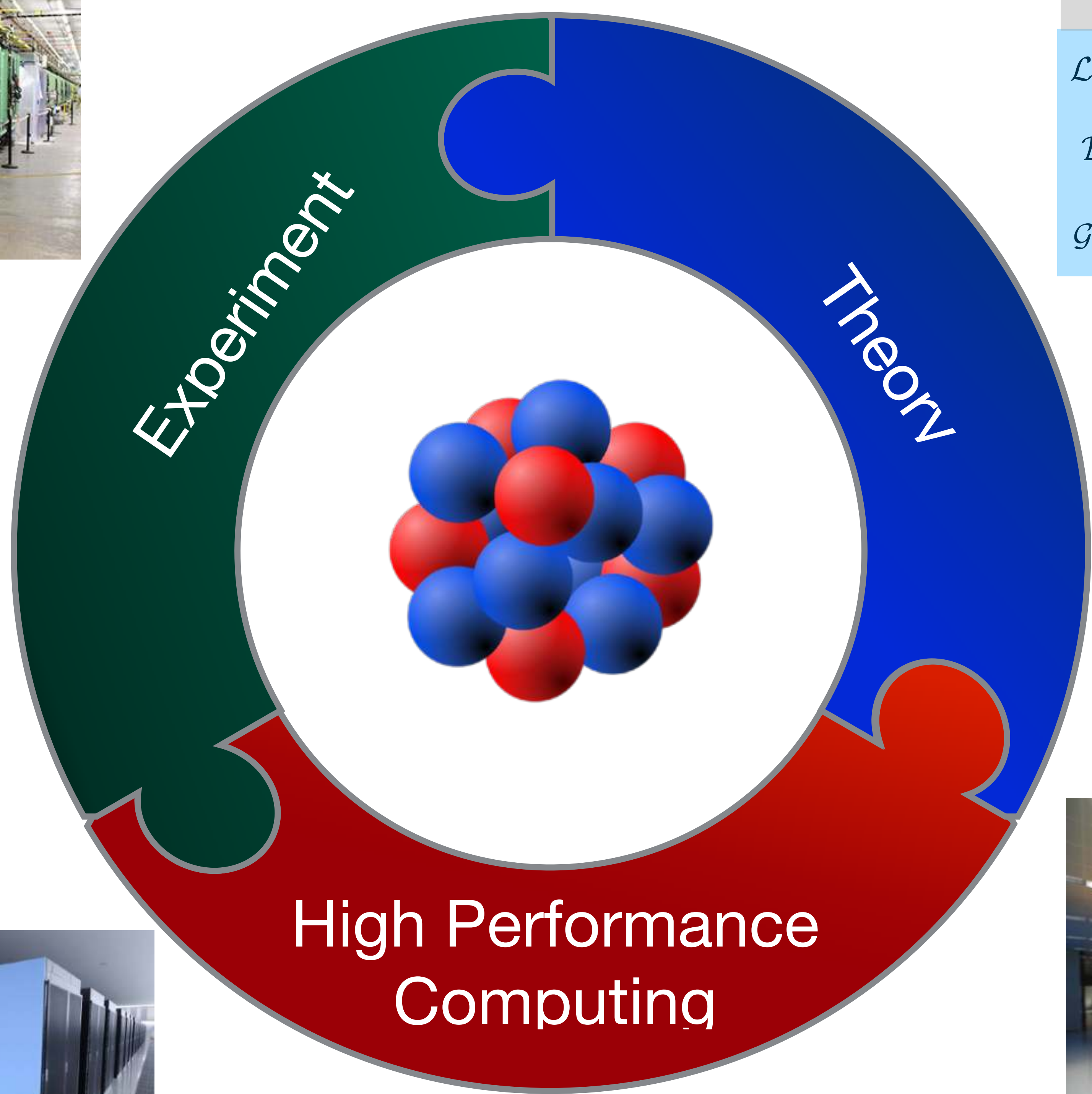



Figure adapted from A. Watts

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

# The “three horses” in nuclear physics research




Quantum Chromodynamics

$$\mathcal{L}_{\rm QCD} = \bar{q}(i\gamma^\mu \mathcal{D}_\mu - \mathcal{M})q - \frac{1}{4}\mathcal{G}_{\mu\nu,a}\mathcal{G}^{\mu\nu}_a$$

$$\mathcal{D}_\mu = \partial_\mu - ig\frac{\lambda_a}{2}\mathcal{A}_{\mu,a}$$

$$\mathcal{G}_{\mu\nu,a} = \partial_\mu \mathcal{A}_{\nu,a} - \partial_\nu \mathcal{A}_{\mu,a} + g f_{abc}\mathcal{A}_{\mu,b}\mathcal{A}_{\nu,c}$$

# Outline

## ✦ Introduction

New opportunities and challenges in nuclear physics

## ✦ Advances in modeling atomic nuclei

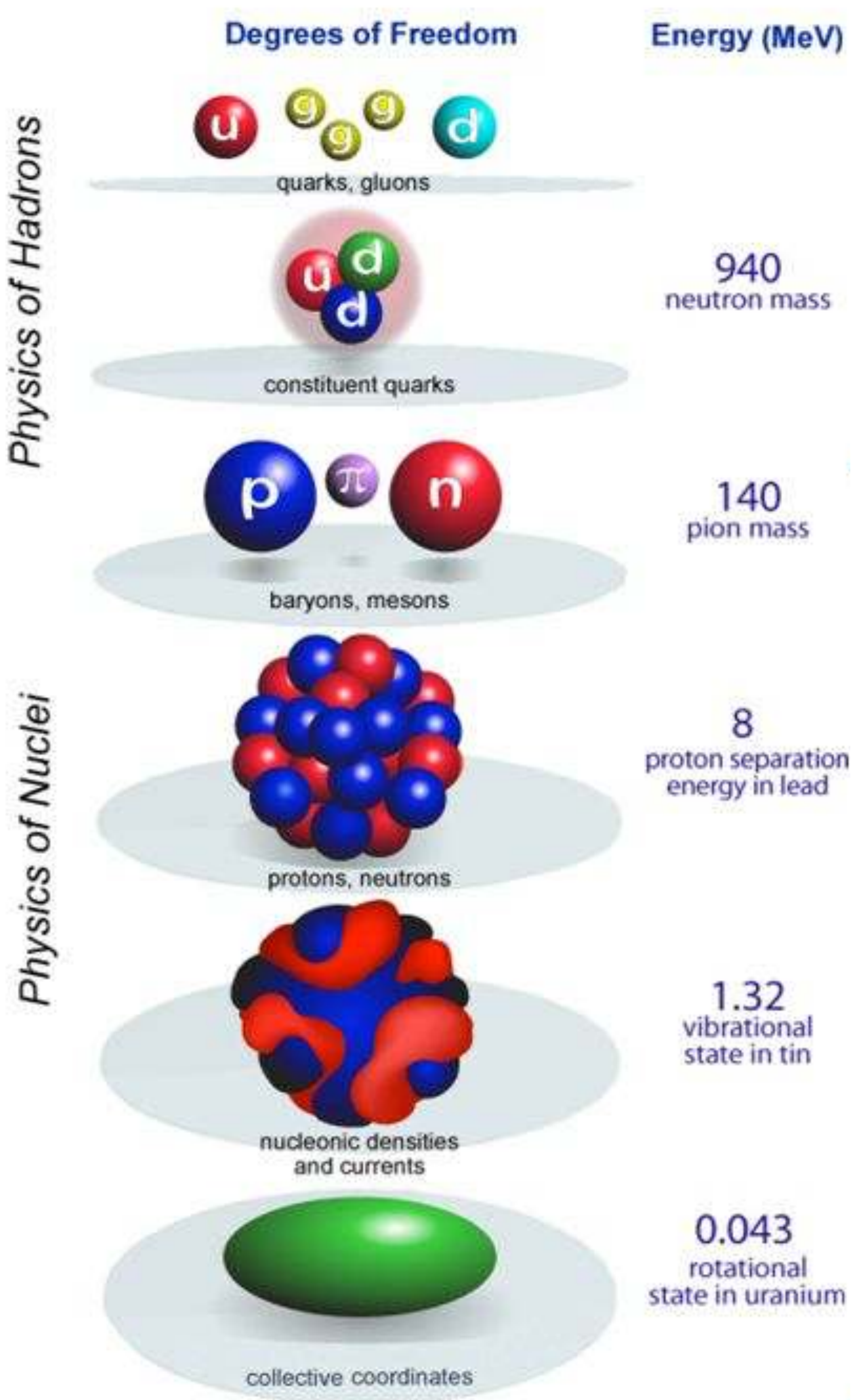
- Nuclear (covariant) energy density functional theory
- Nuclear ab initio methods

Nuclear structure and weak decays

Neutron-star matter

## ✦ Summary and Outlook

# How to modeling atomic nuclei?




**multi-faceted nuclei**

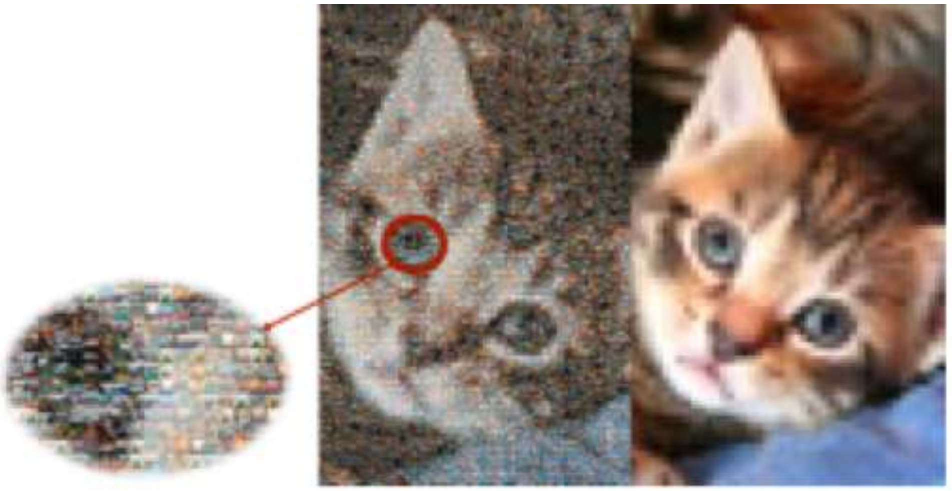
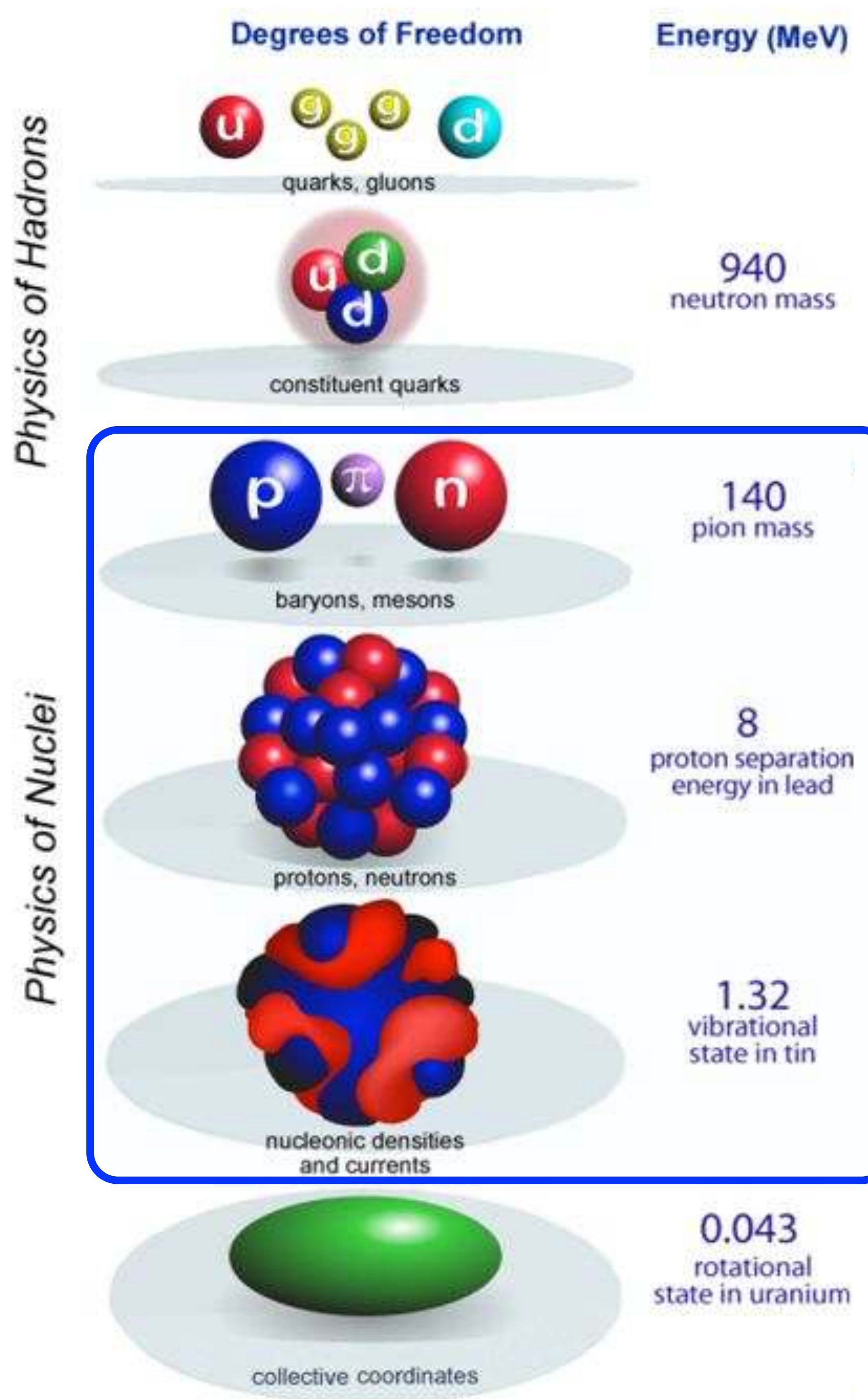


**Image with different resolutions**

# How to modeling atomic nuclei?




**multi-faceted nuclei**

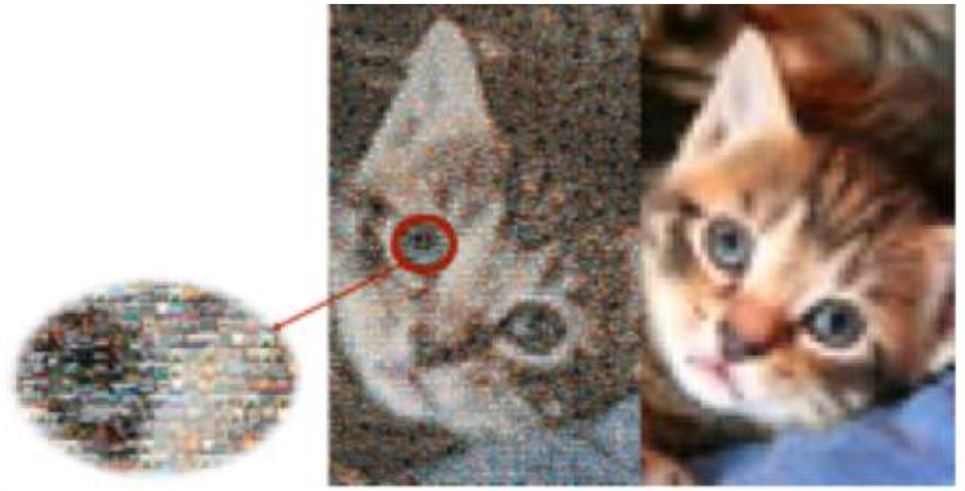
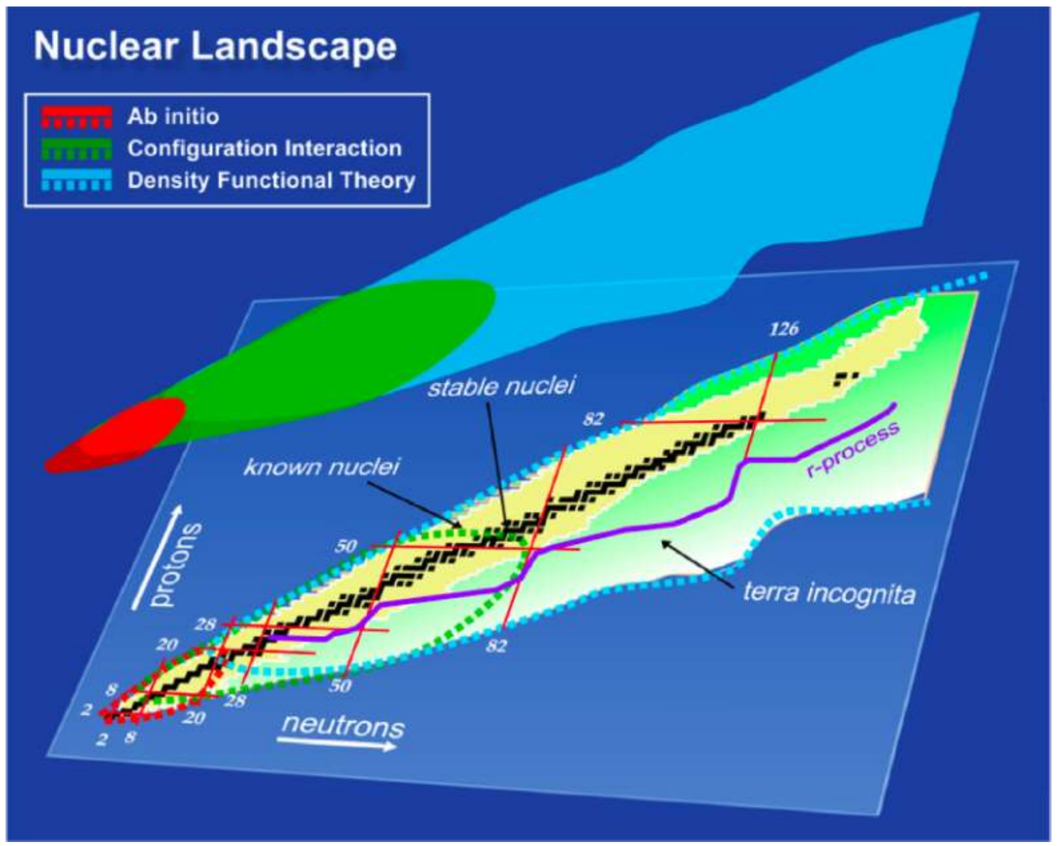


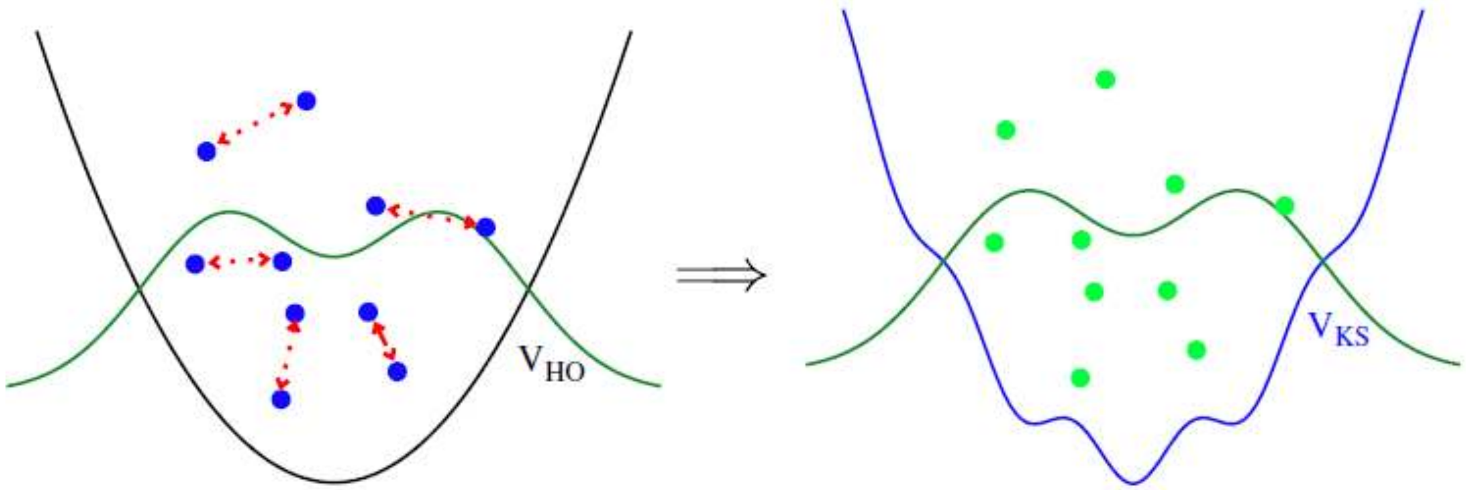
**Image with different resolutions**

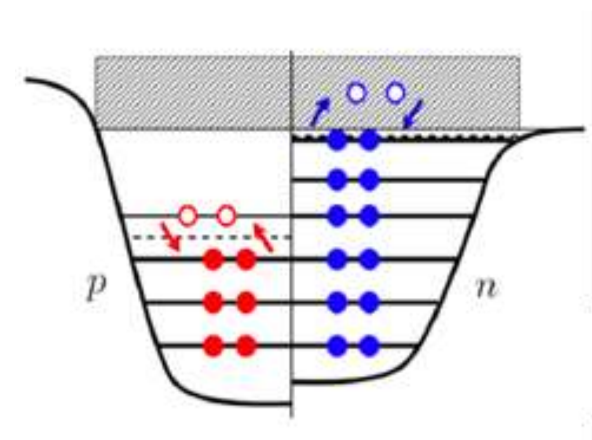



**The Frontiers of Nuclear Science: A Long-Range Plan, 2007.**

# Nuclear (covariant) energy density functional theory

**Mean-field approximation: (HF/DFT)**




**Many-body problem**

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

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

**One-body problem**

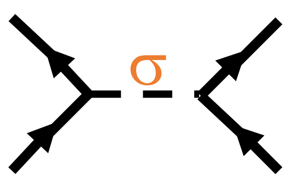
$$\left\{-\frac{1}{2M}\nabla^2 + u(\mathbf{r}) - \epsilon_i\right\}\varphi_i(\mathbf{r}) = 0$$

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

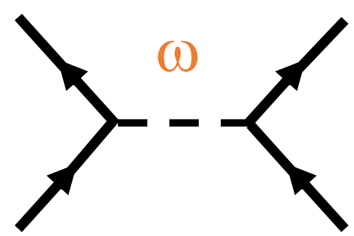
- ✓ Ingredients of n and p density/current, pairing density, etc.
- ✓ Universal and unified description of nuclear structure and reaction, relevant information (mass, beta decay, etc) for nucleosynthesis.

# Nuclear (covariant) energy density functional theory

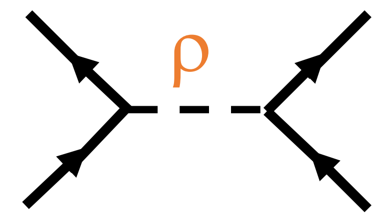
Nucleons are coupled by exchange of mesons via an effective Lagrangian




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




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




$(J^{\pi}\ T)=(1^{-}1)$

Sigma-meson:
attractive scalar field

Omega-meson:
Short-range repulsive

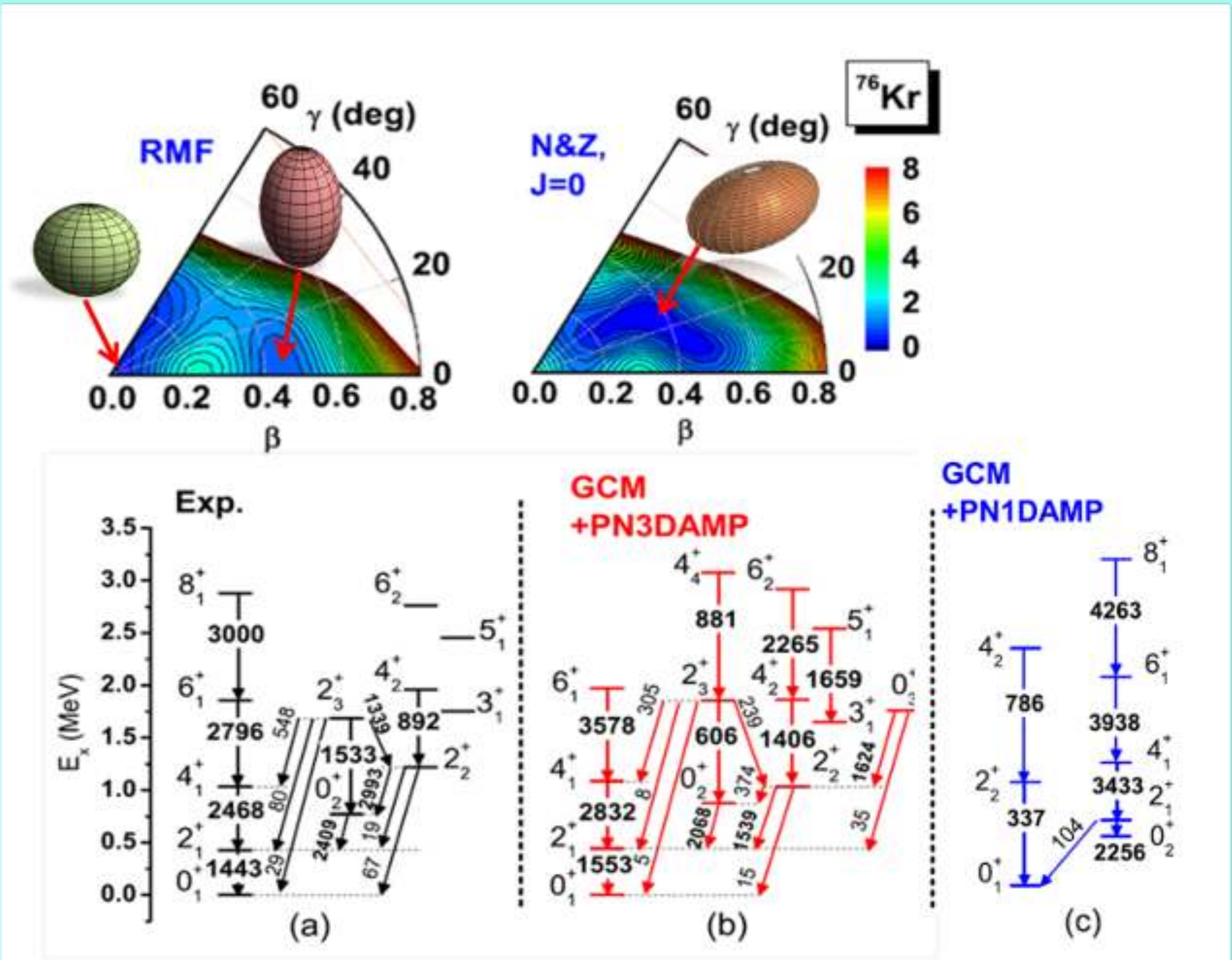
$$S(r) = g_{\sigma}\sigma(\boldsymbol{r})$$

$$V(r) = g_{\omega}\omega^{0}(\boldsymbol{r}) + g_{\rho}\tau_{3}\rho^{0}(\boldsymbol{r}) + e\frac{1-\tau_{3}}{2}A^{0}(\boldsymbol{r})$$


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

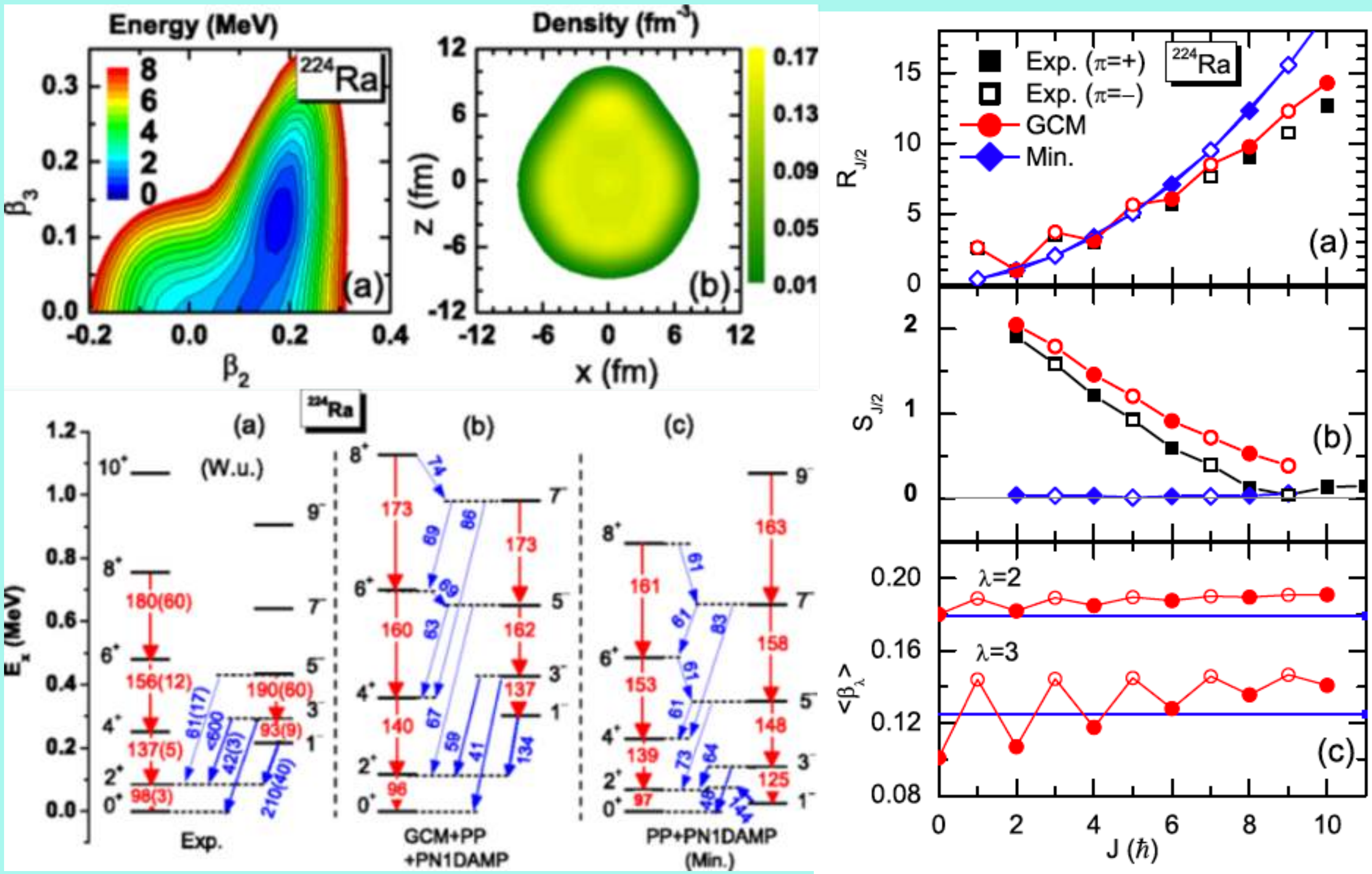



Results of $^{76}$Kr from MR-CDFT calculation.
[JMY, K.Hagino, Z.P. Li, J. Meng, P. Ring, Phys.Rev.C (2014)]

- 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.

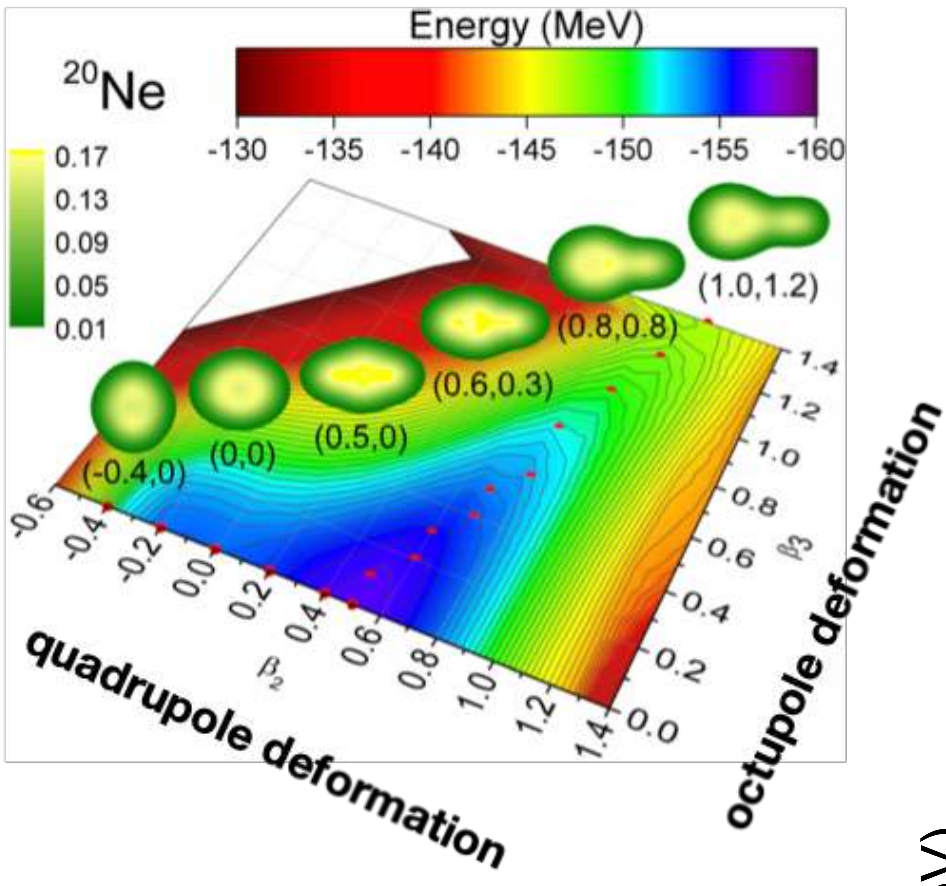
# Nuclear (covariant) energy density functional theory

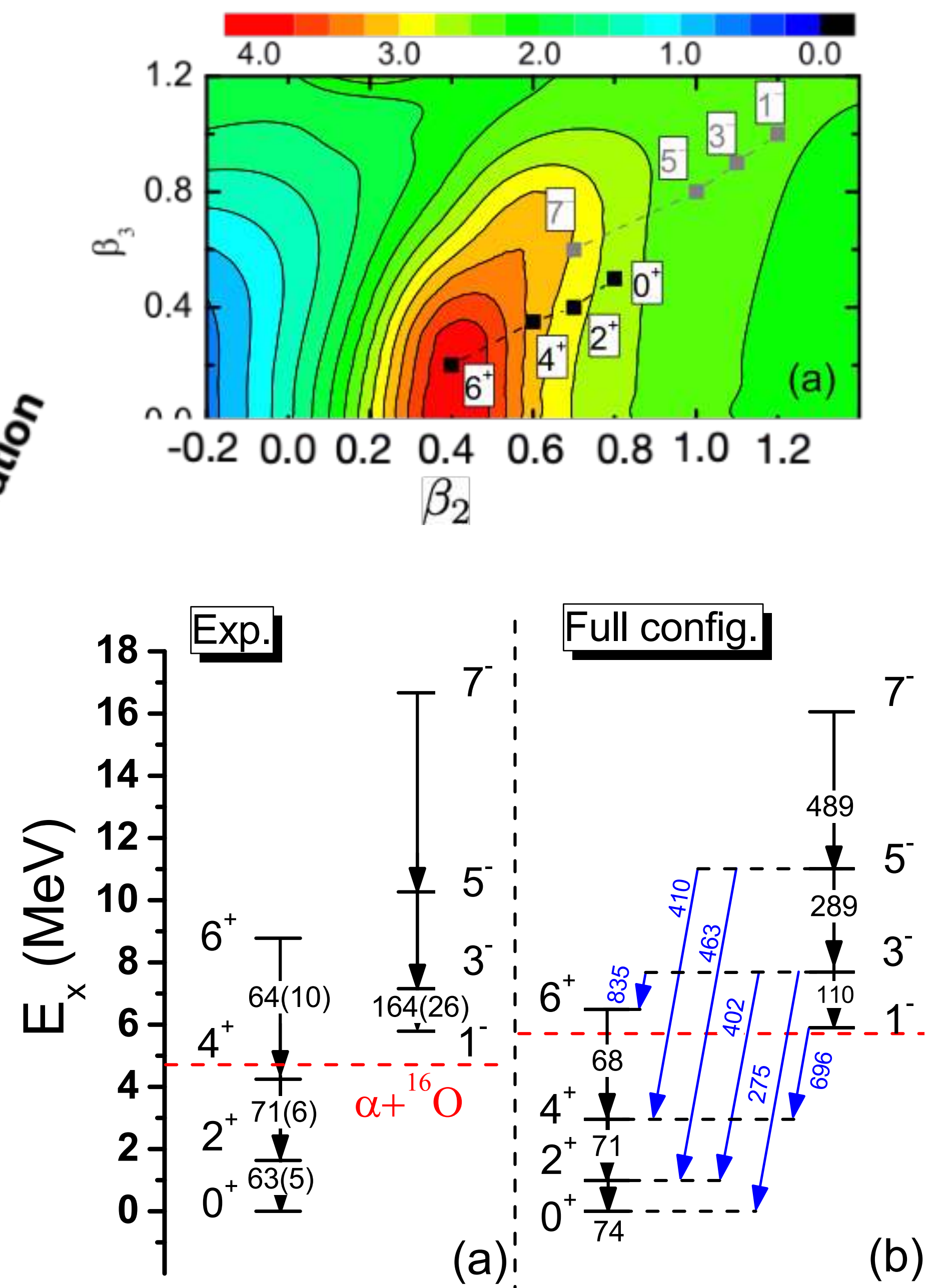
## ✦ From octuple vibration to octuple rotation excitations

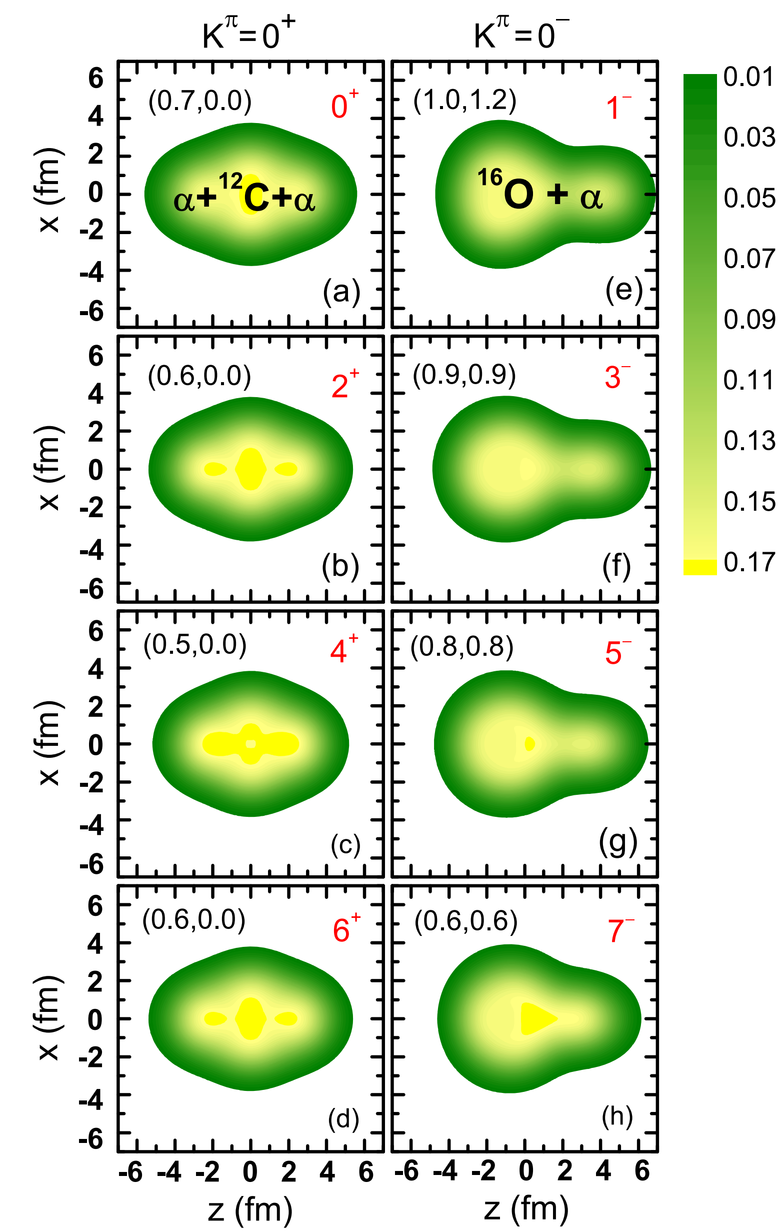



Results of $^{224}$Ra from MR-CDFT calculation.
[JMY, E.F. Zhou, Z.P. Li, Phys. Rev.C (2015)]

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

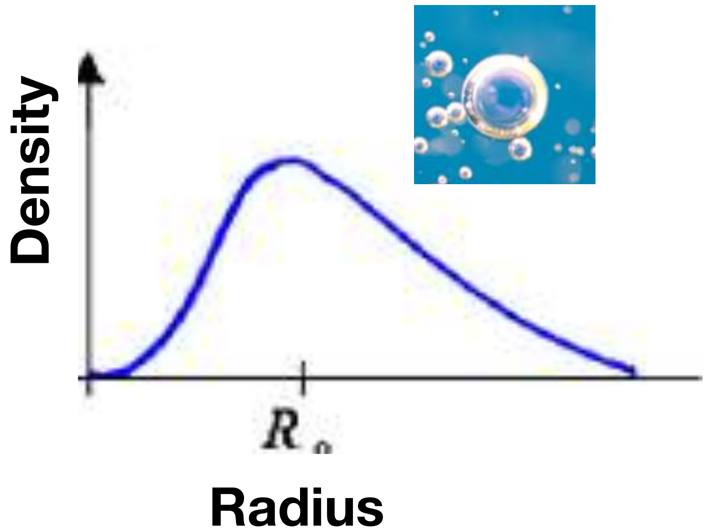



E.F. Zhou, JMY, Z.P. Li, J. Meng, P. Ring, PLB (2016)

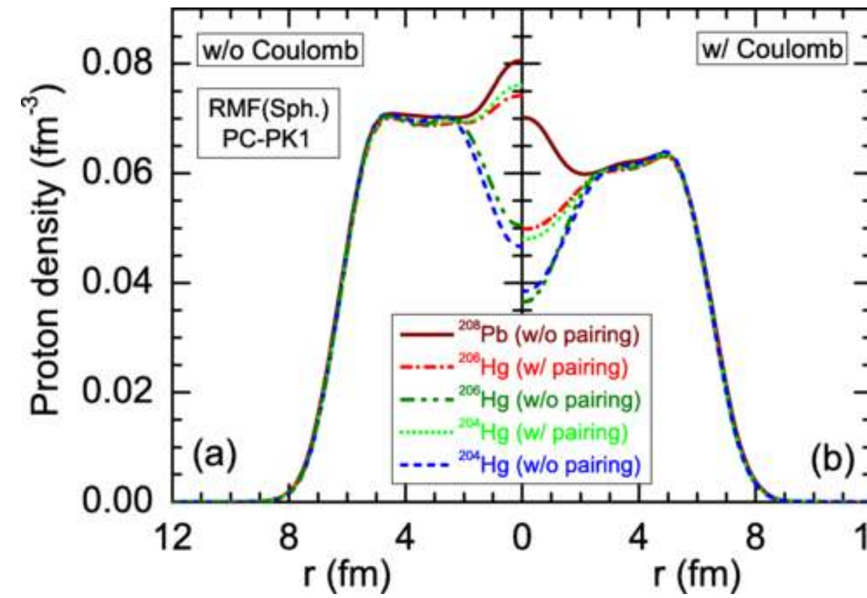
# Semi-bubble structure in atomic nuclei



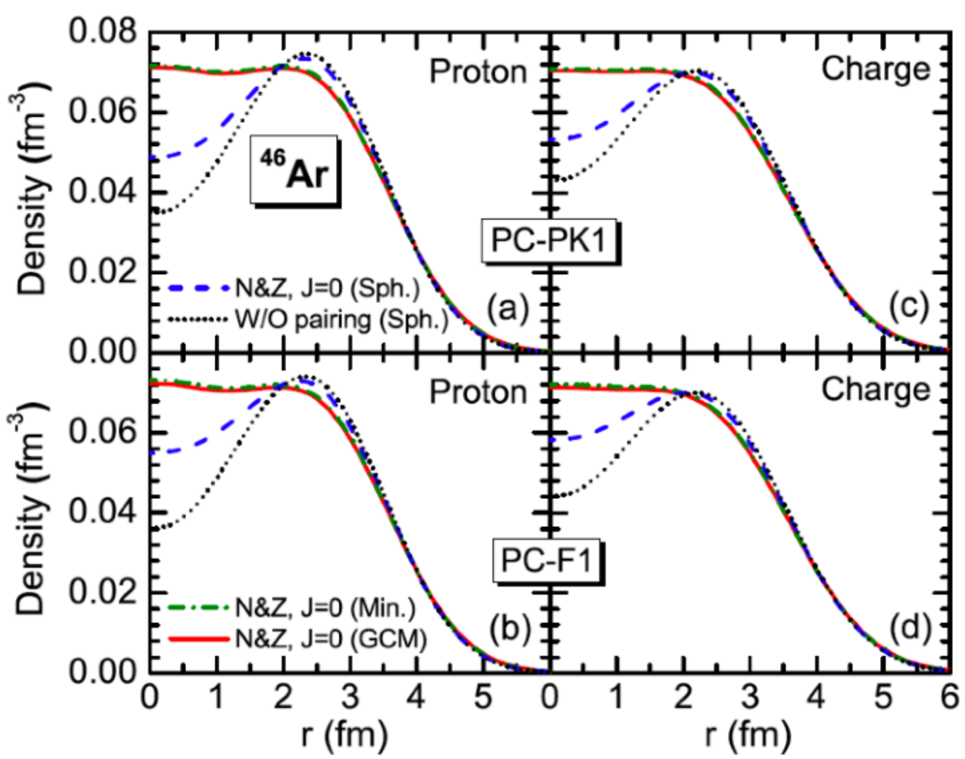

**Favor bubble:**
Quantum and Coulomb repulsion

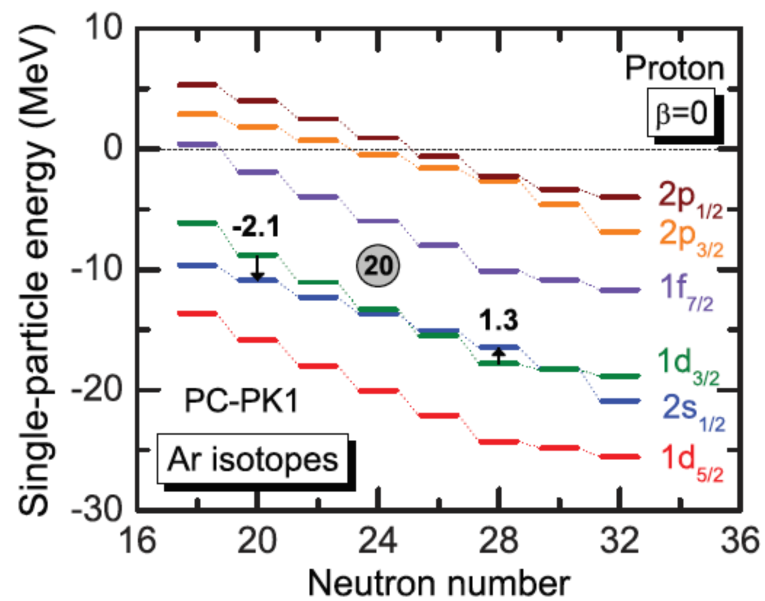
**Anti-bubble effect:**
pairing correlation and shape-mixing

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

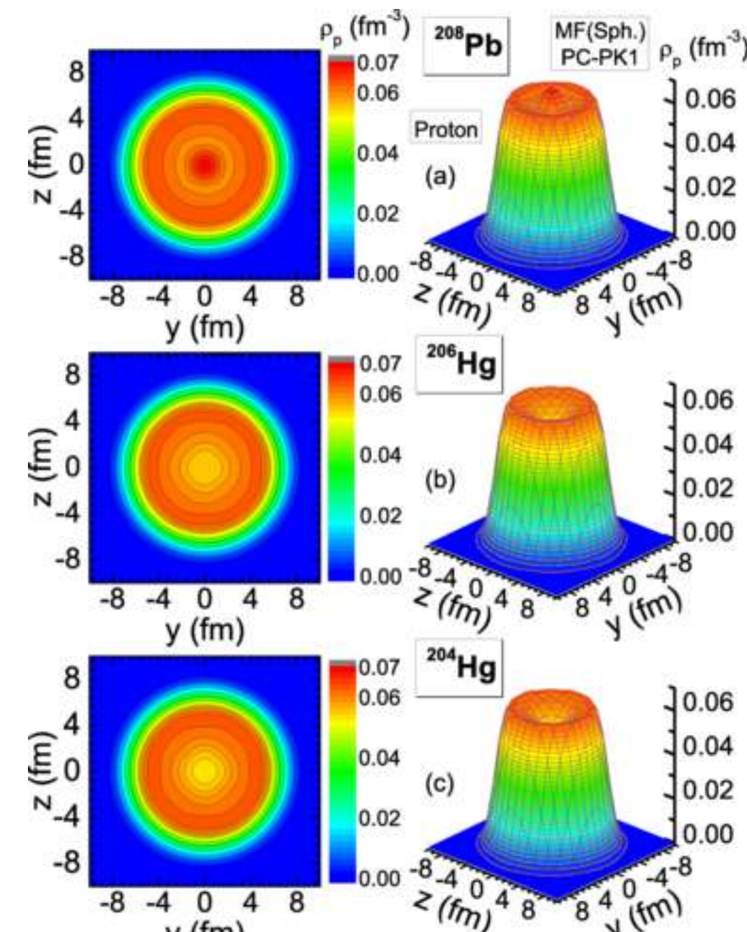



**Formation of proton bubble: depopulation of $2s_{1/2}$ orbit**

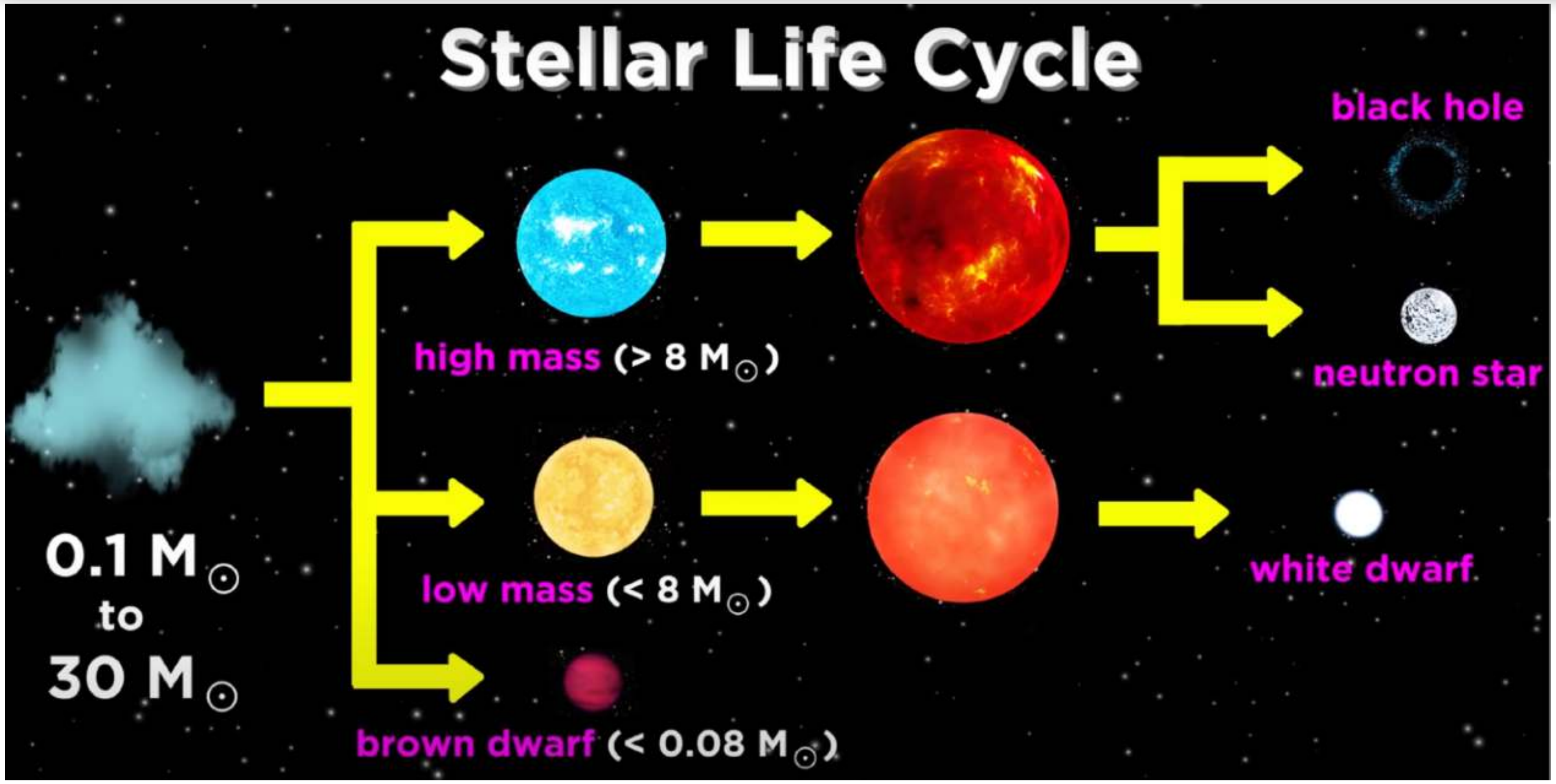



X.Y.Wu, JMY, Z.P. Li, Phys.Rev.C (2014)



# Neutron stars

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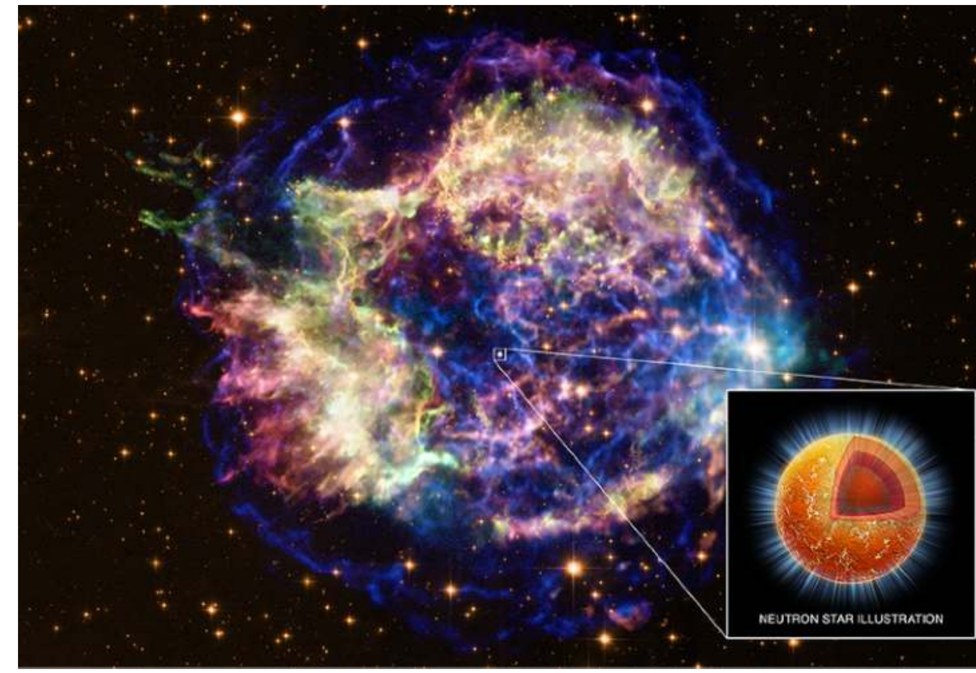
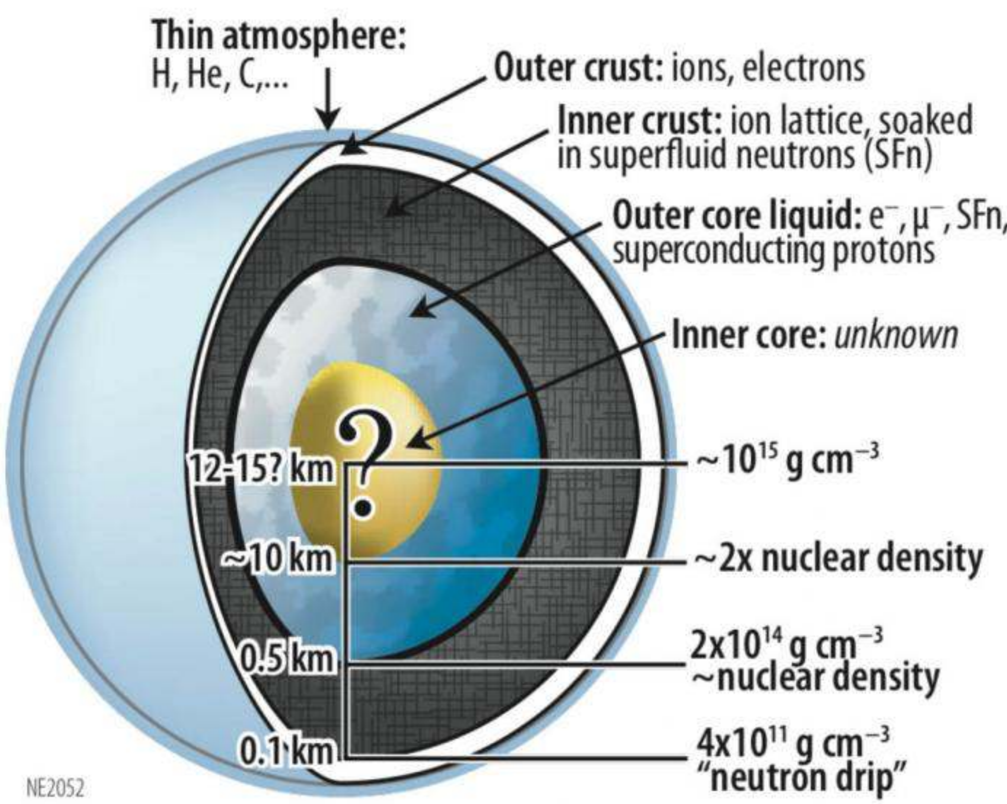
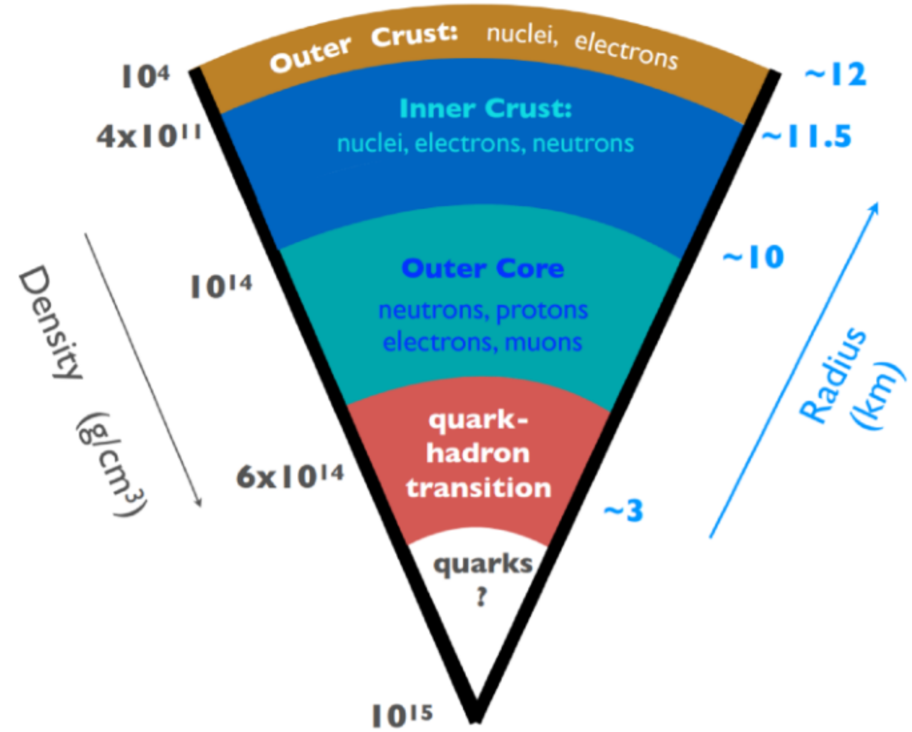


# Neutron stars

Tolman-Oppenheimer-Volkoff Equation

Probe the equation of state of ultra dense matter

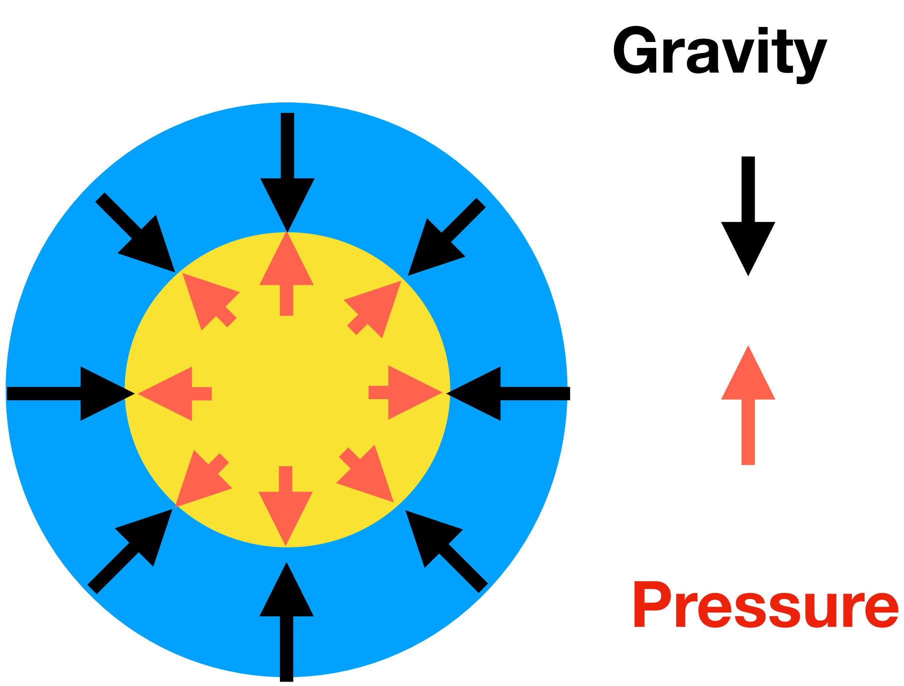
- for the interior of a spherical, static, relativistic star

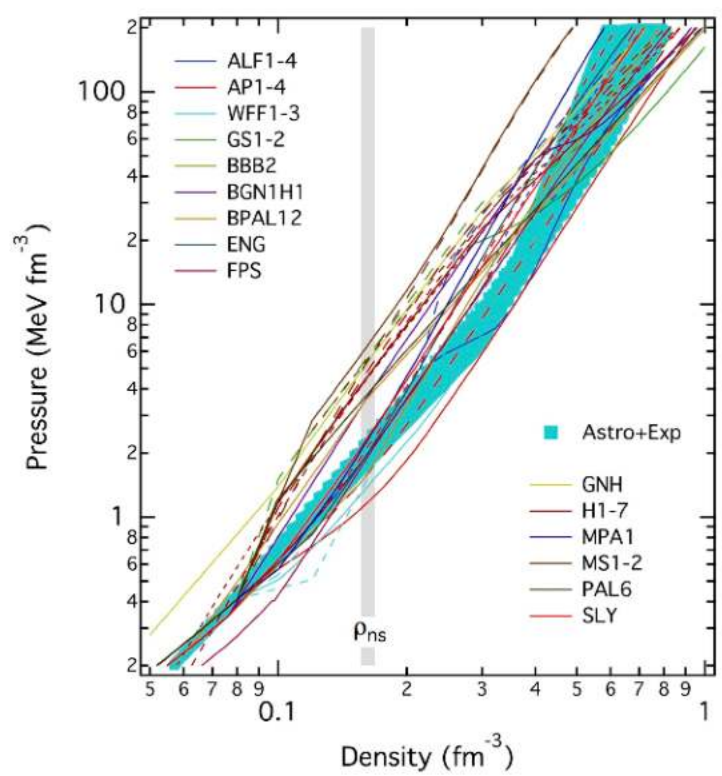
$$\frac{dp}{dr} = -\varepsilon(r)\frac{Gm(r)}{r^2}\left[1+\frac{p(r)}{\varepsilon(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{m(r)}\right]\left[1-\frac{2Gm(r)}{r}\right]^{-1}$$

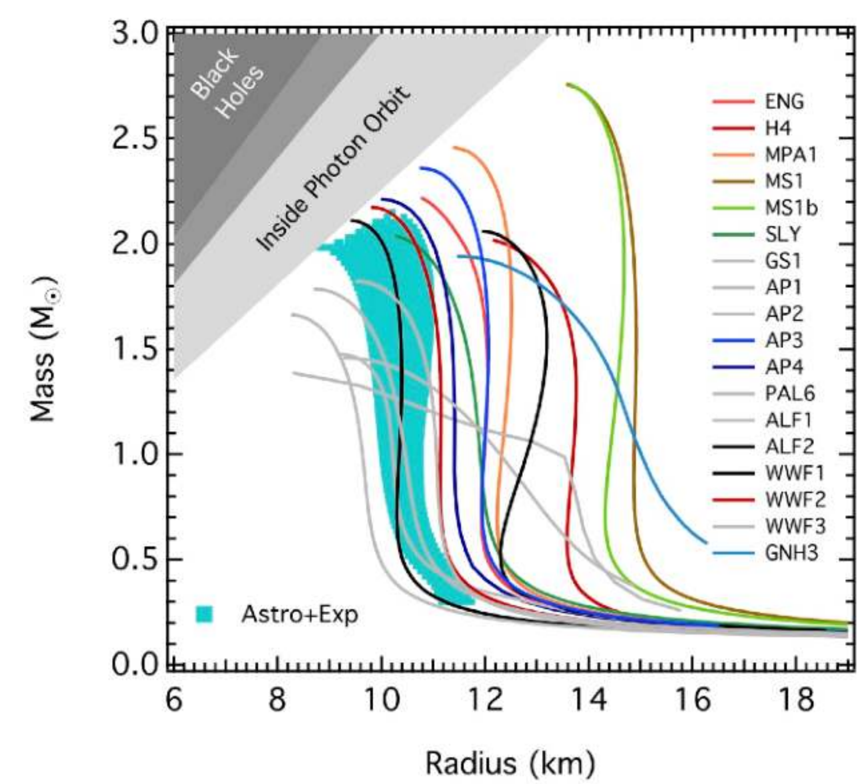
where the enclosed mass is defined as

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

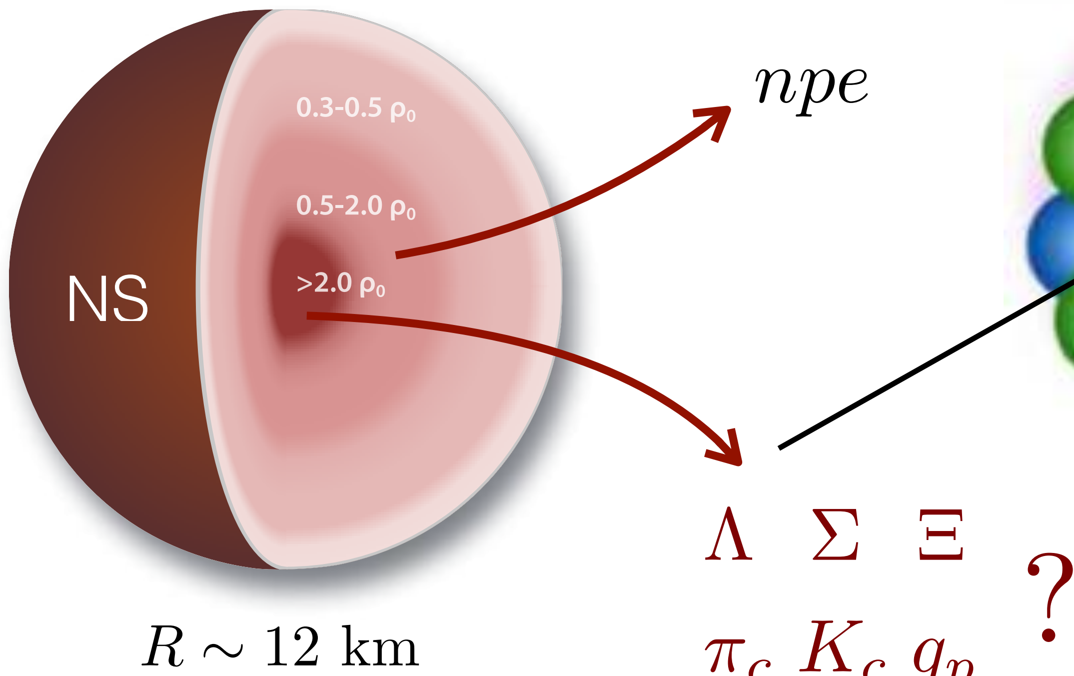
- **Gravity** tries to push the star into a black hole
- **Pressure** of strongly interacting neutrons resists the gravity

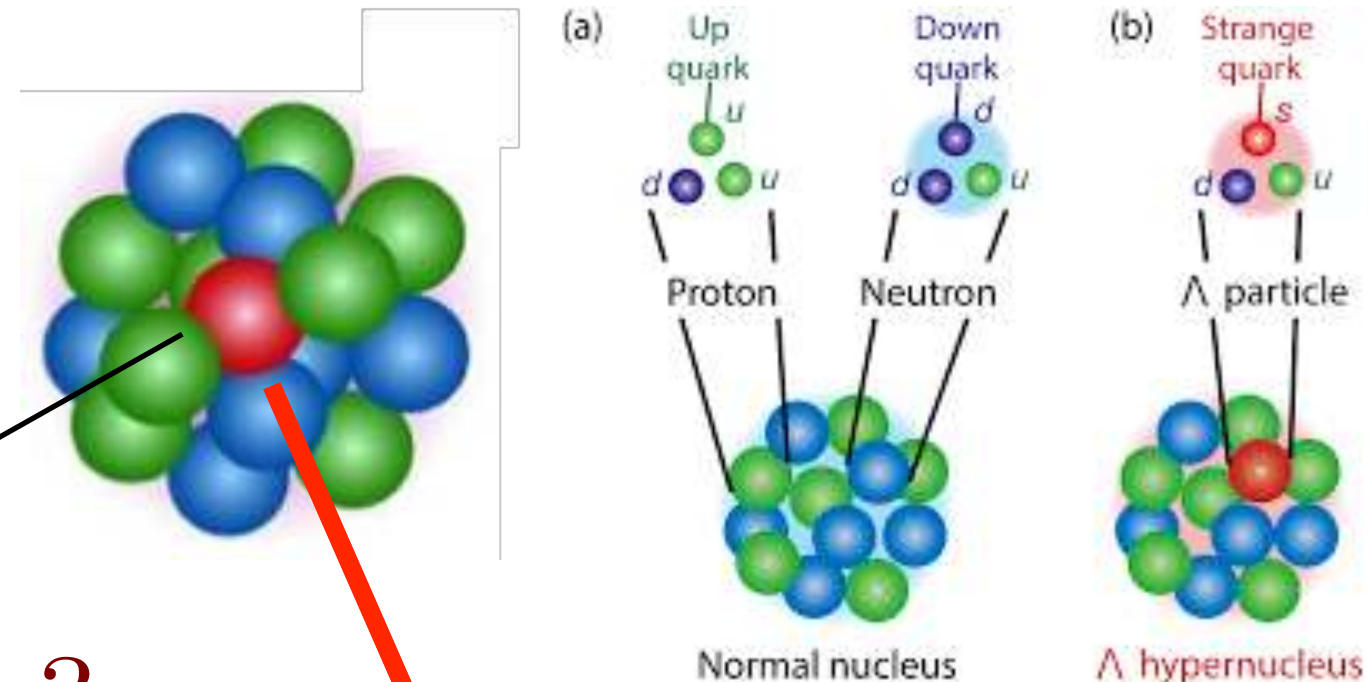


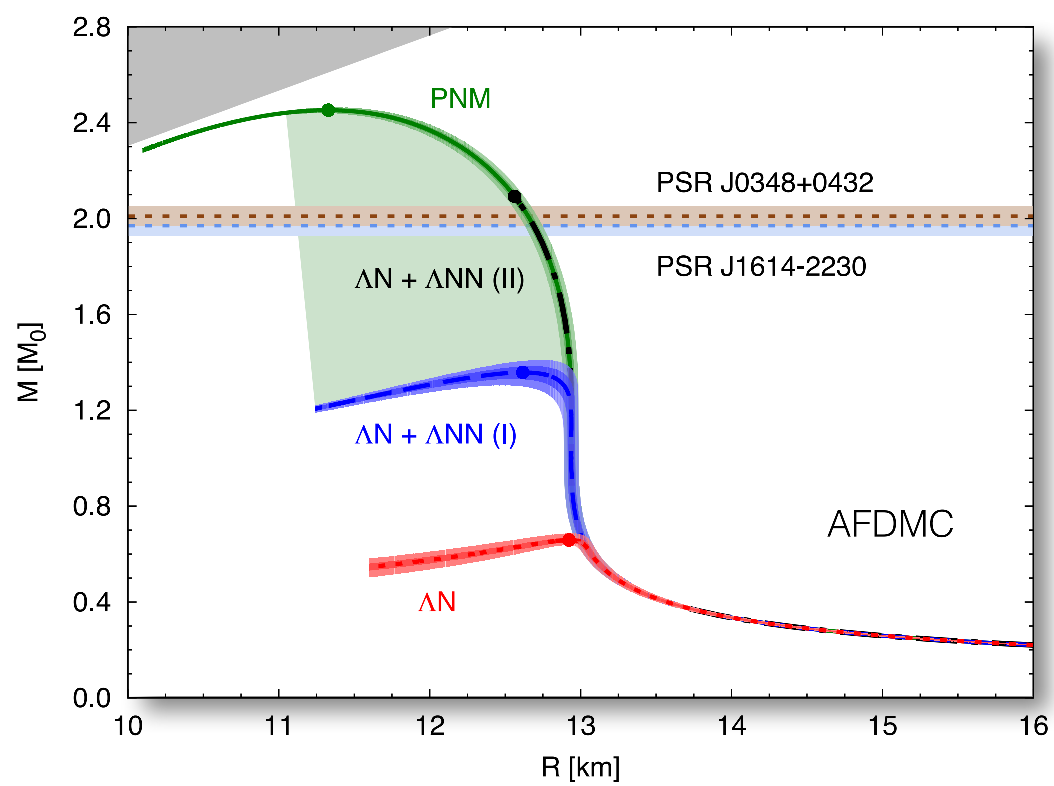



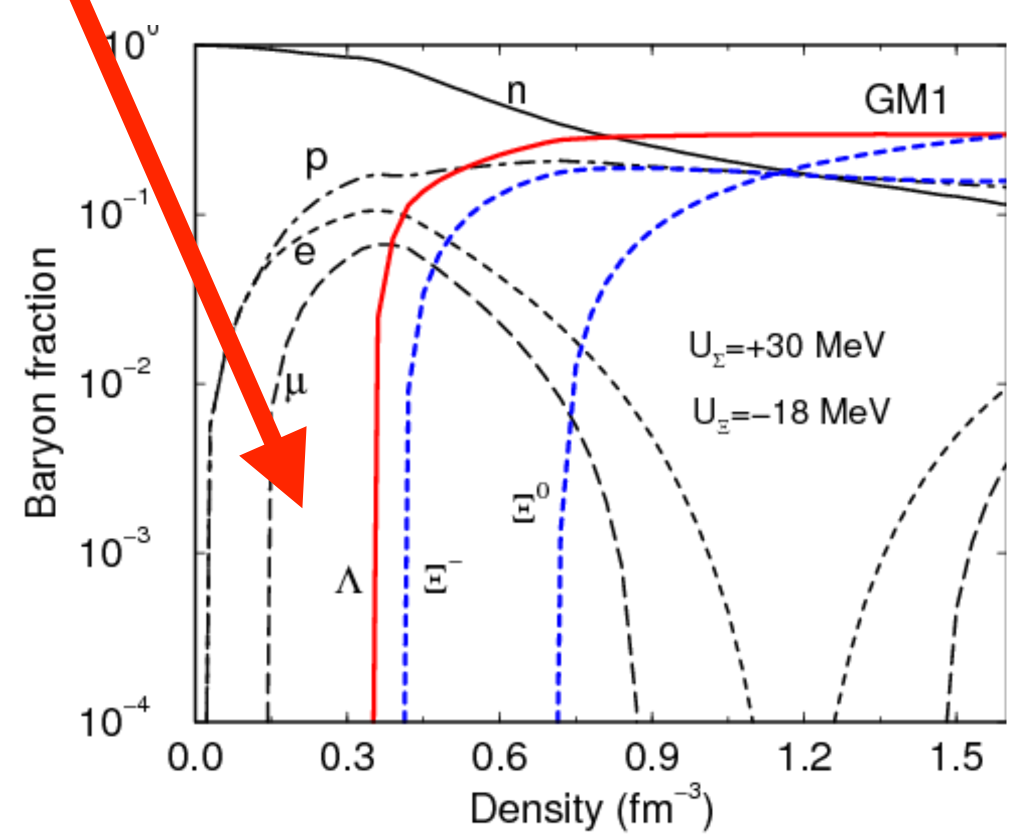
# Neutron star matter (hyperon puzzle)




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

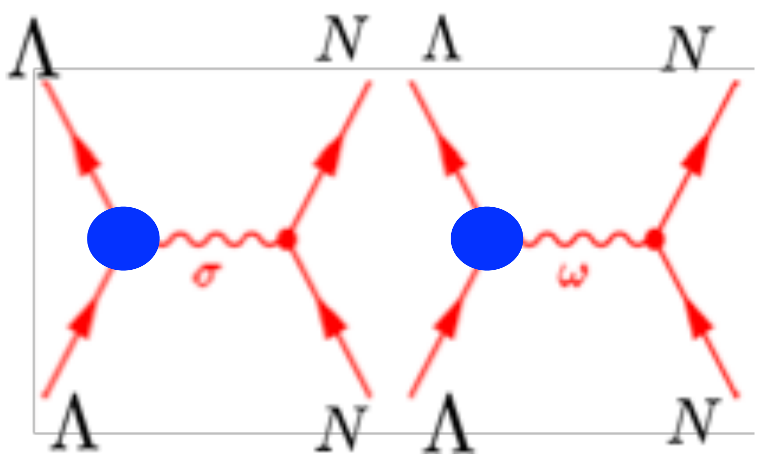



J. Schaffner and I. N. Mishustin (1996)

# Neutron star matter (hyperon puzzle)

## Covariant energy density functional theory for NN/YN interactions

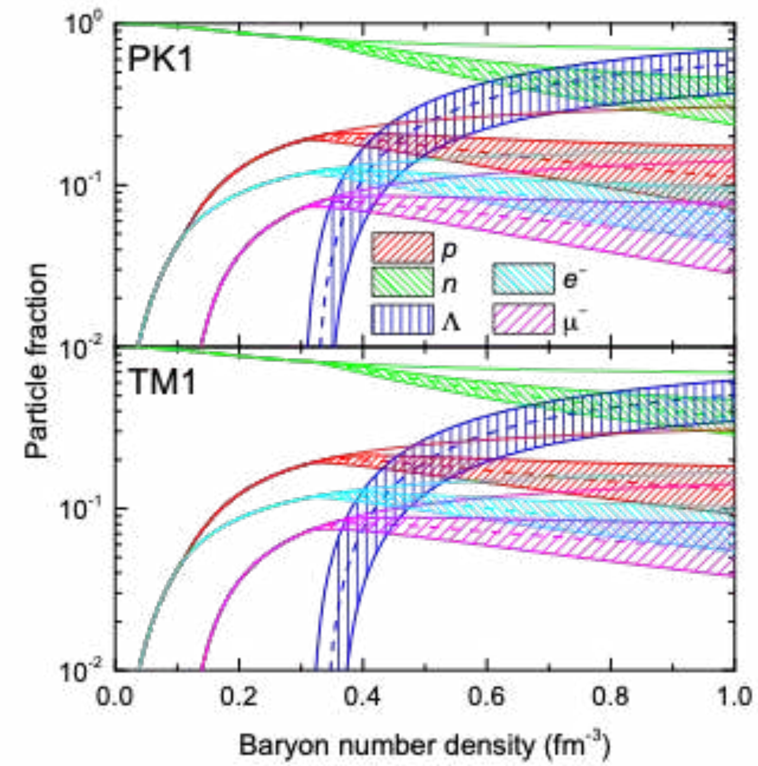
The coupling strengths in **hyperon-nucleon** interaction are often fitted to **hyperon binding energies**

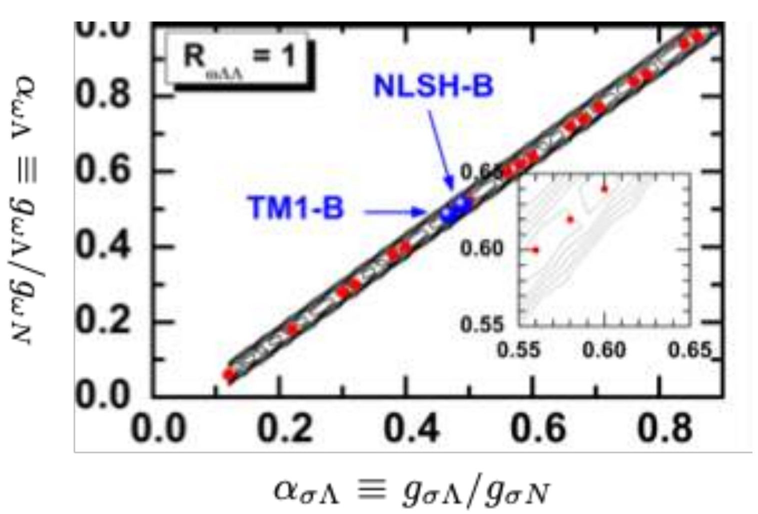


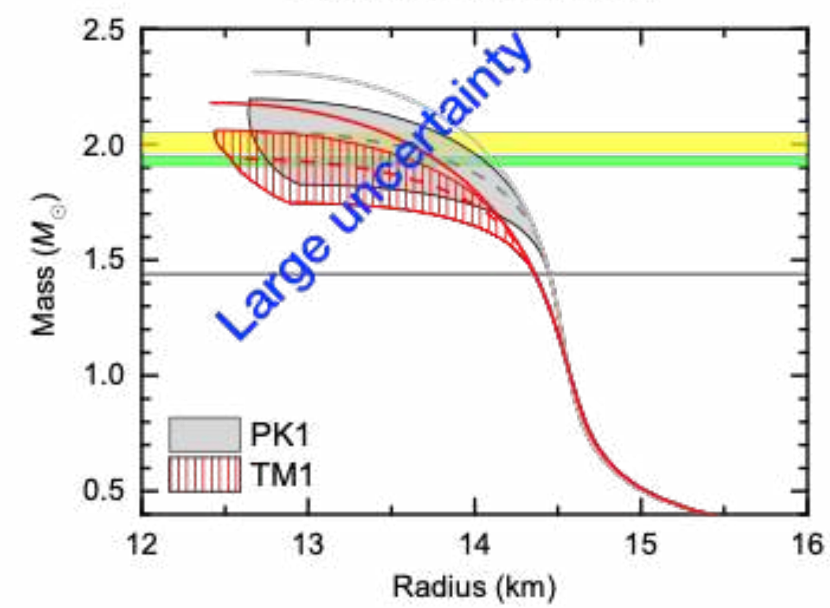

**parameters**

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

**Fitted to Lambda separable energy**



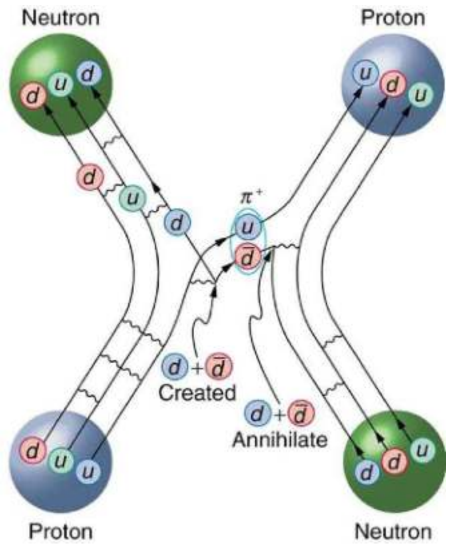




T. T. Sun, C. J. Xia, S. S. Zhang, M.S. Smith (2018)

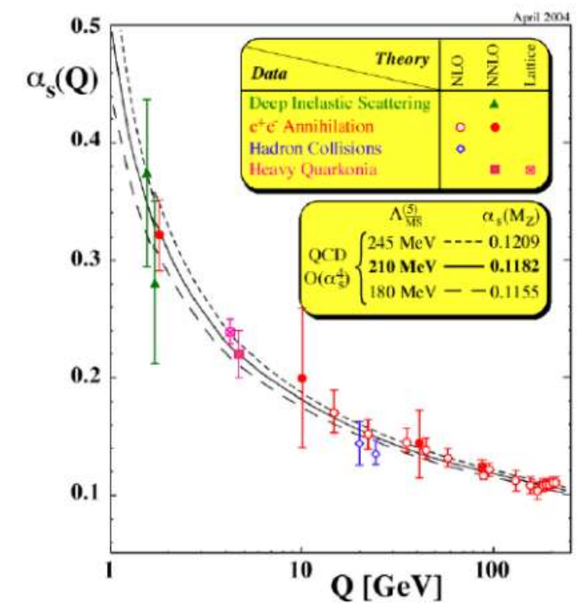
**Parameters are NOT uniquely determined.**
**More data on YN interactions are required.**

# Modeling atomic nuclei from first principles?

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



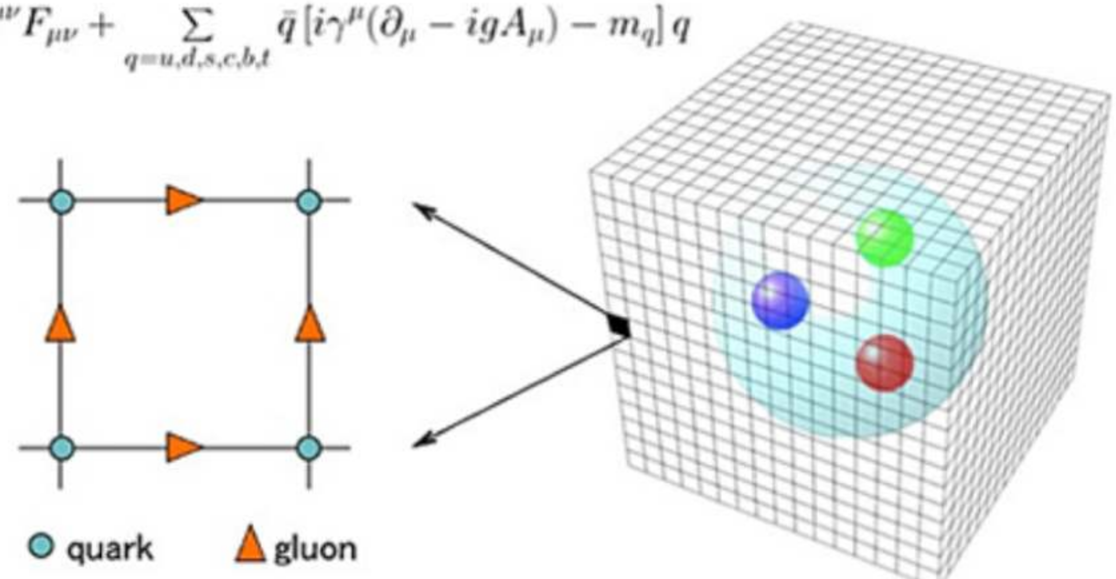

Non-perturbative nature of strong interaction at low-energy regime

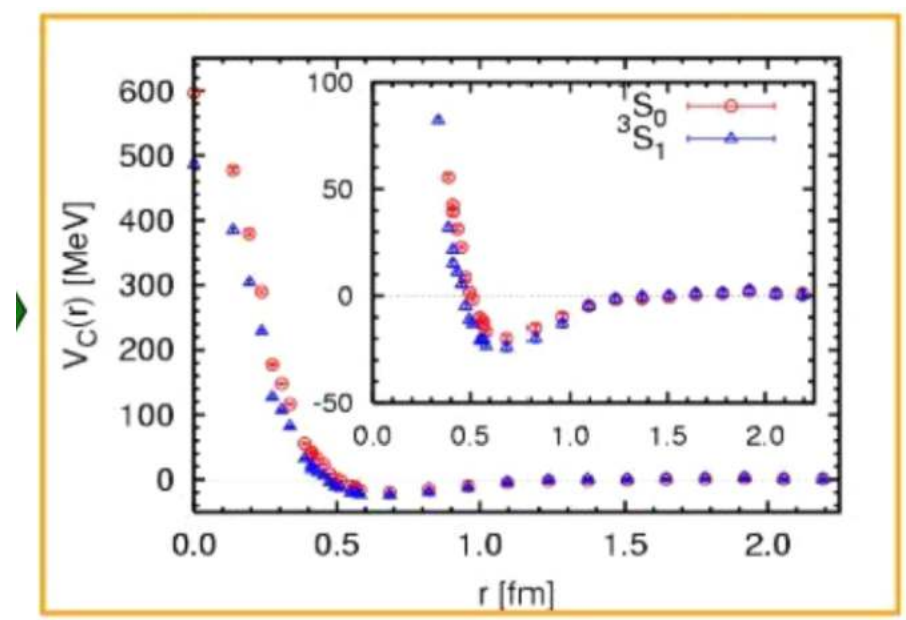



- Nuclear force from Lattice QCD

QCD Lagrangian

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

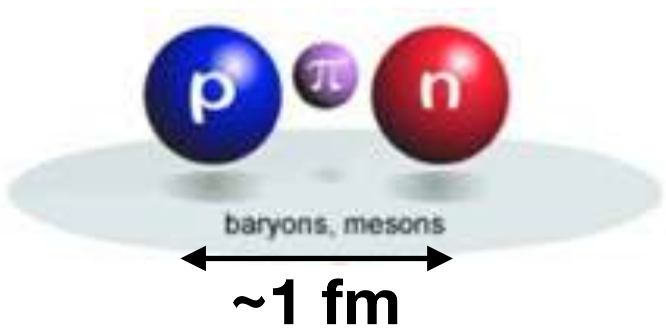



Ishii-Aoki-Hatsuda, PRL99(2007)022001

# Modeling atomic nuclei from first principles?

- Nuclear force from chiral EFT



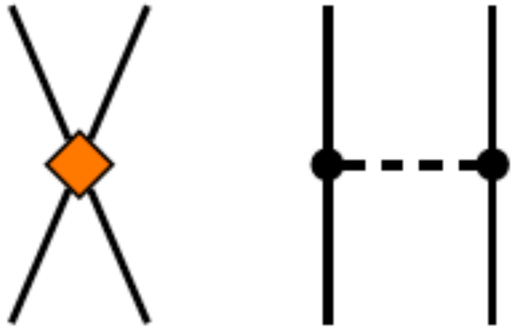


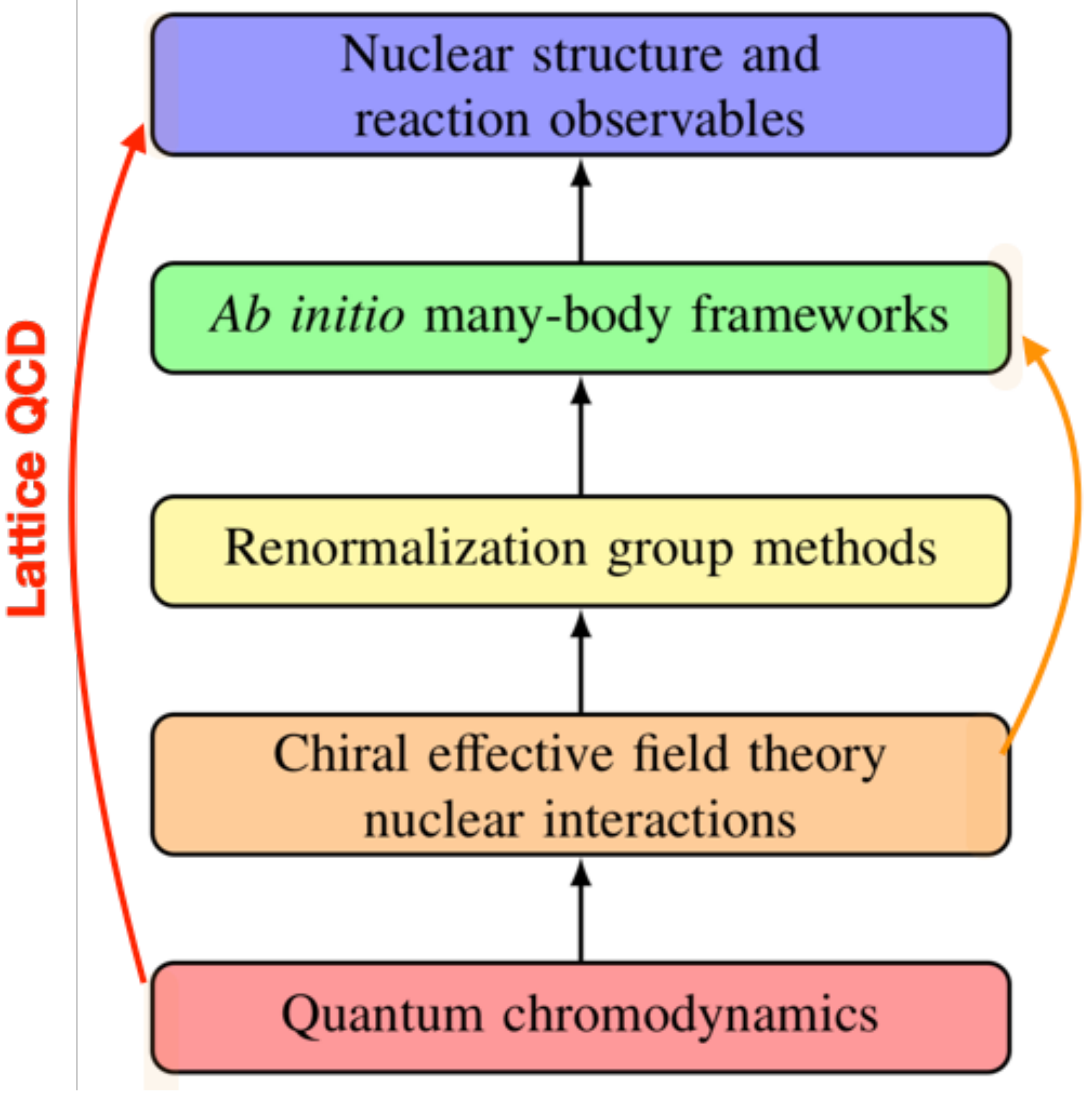
Weinberg's power counting:

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

chiral-symmetry-breaking (hard) scale (~700 MeV)

soft scale associated with external momenta, pion mass (~140 MeV)

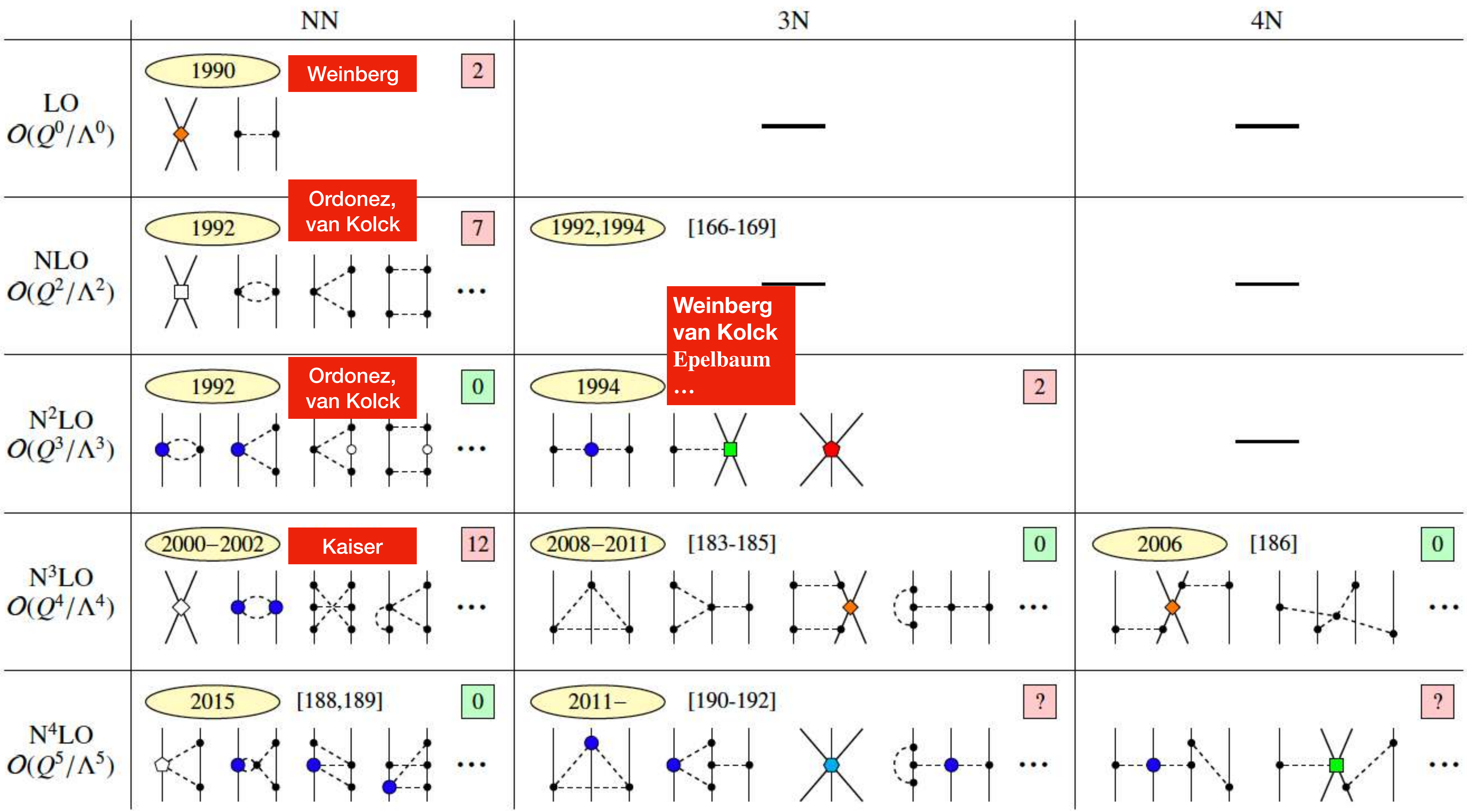





K. Hebeler, Phys. Rep. 890(2021)1

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

# Nuclear force from chiral EFT




K. Hebeler, arXiv:2002.09548 [nucl-th]

# ab initio many-body frameworks

- **Quantum Monte Carlo methods**

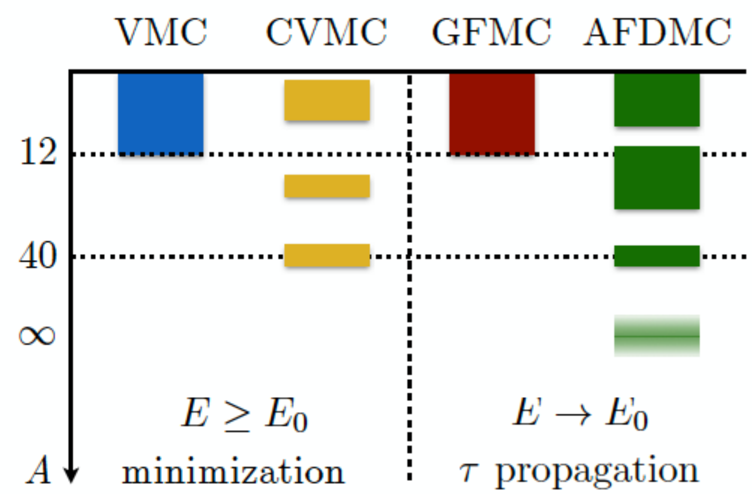
  credit: D. Lonardoni

  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)

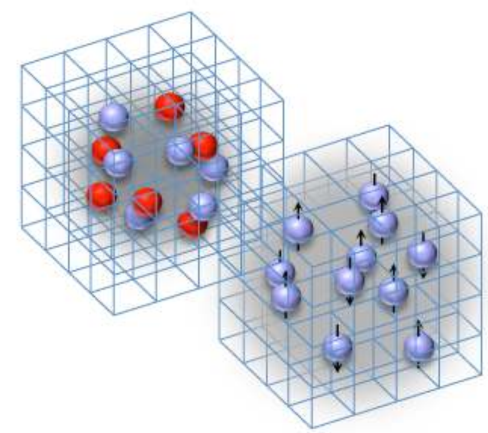
  Auxiliary-field diffusion Monte Carlo (AFDMC)

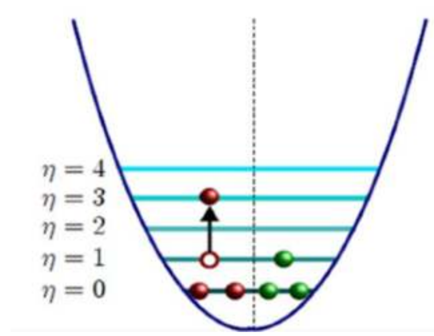



| | | |
|---|---|---|
| (C)VMC<br>GFMC<br>AFDMC | light systems | $A \leq 12$ |
| CVMC<br>AFDMC | light to medium-mass nuclei | $A \sim 50$ |
| AFDMC | infinite matter | $A \to \infty$ |

- **Lattice effective field theory (EFT)**

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



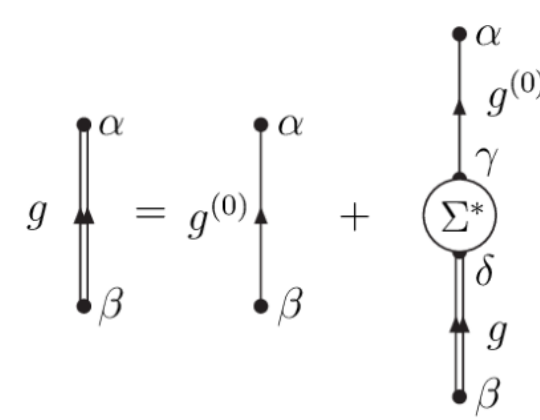



- **No-core shell model (NCSM)**

  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,...

# ab initio calculations for nuclei: nuclear masses

Featured in Physics

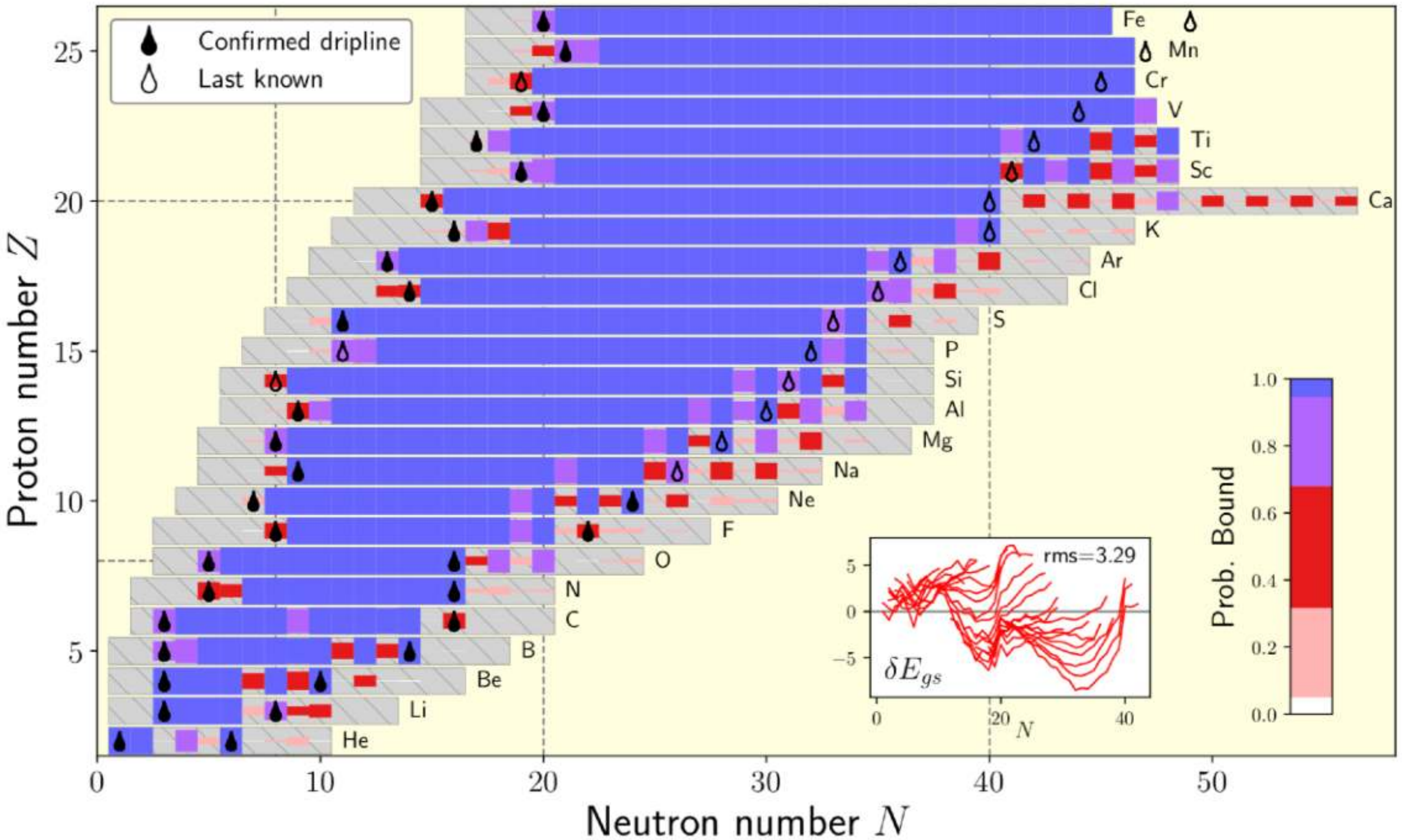
Editors' Suggestion

## *Ab Initio* Limits of Atomic Nuclei

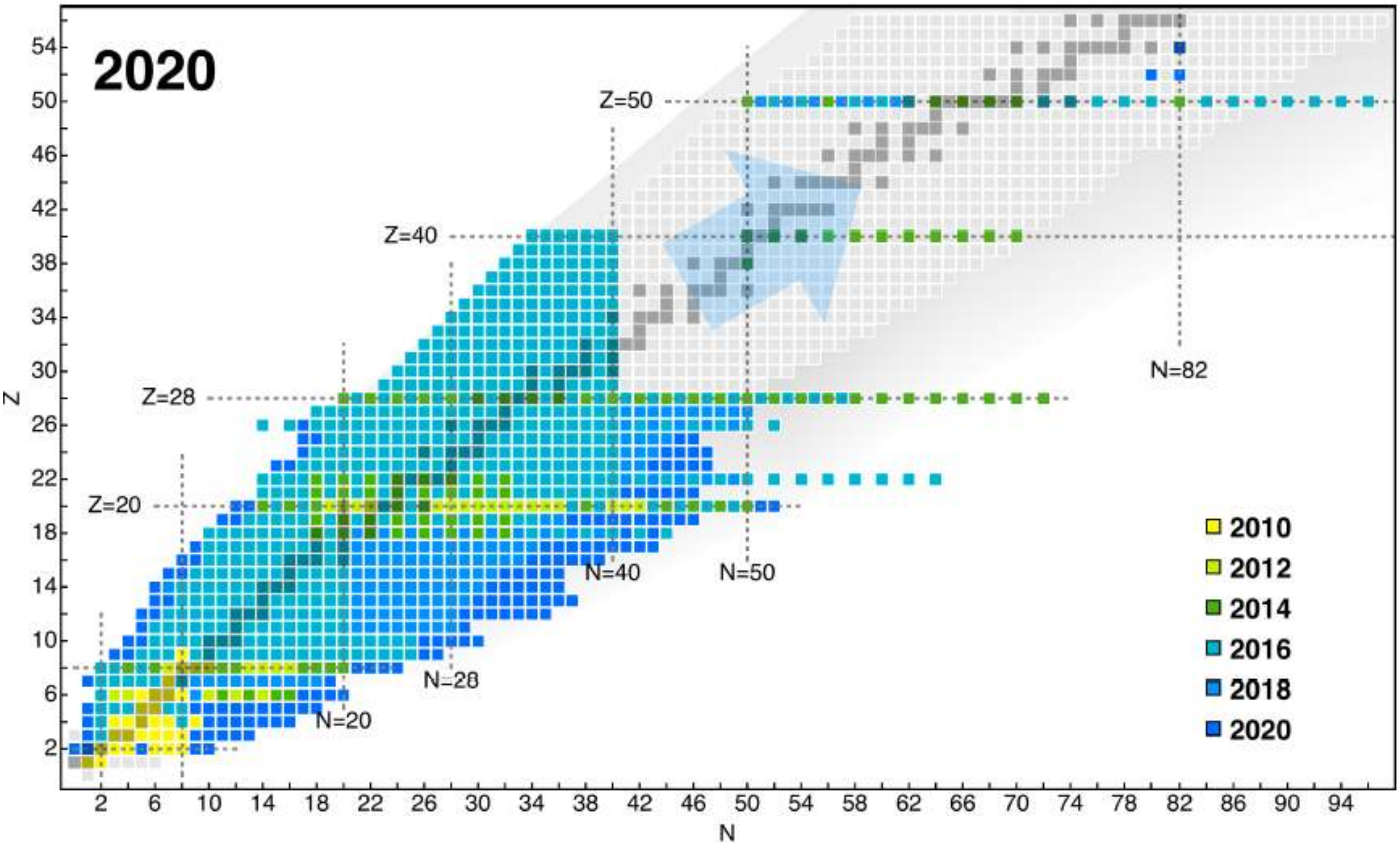
S. R. Stroberg, J. D. Holt, A. Schwenk, and J. Simonis

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



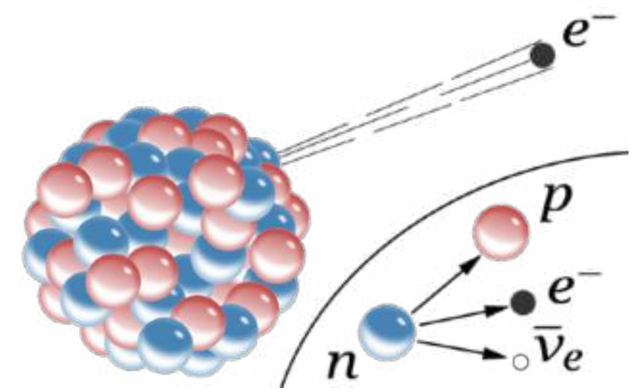

H. Hergert, Front. Phys. 8, 379 (2020)

# 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



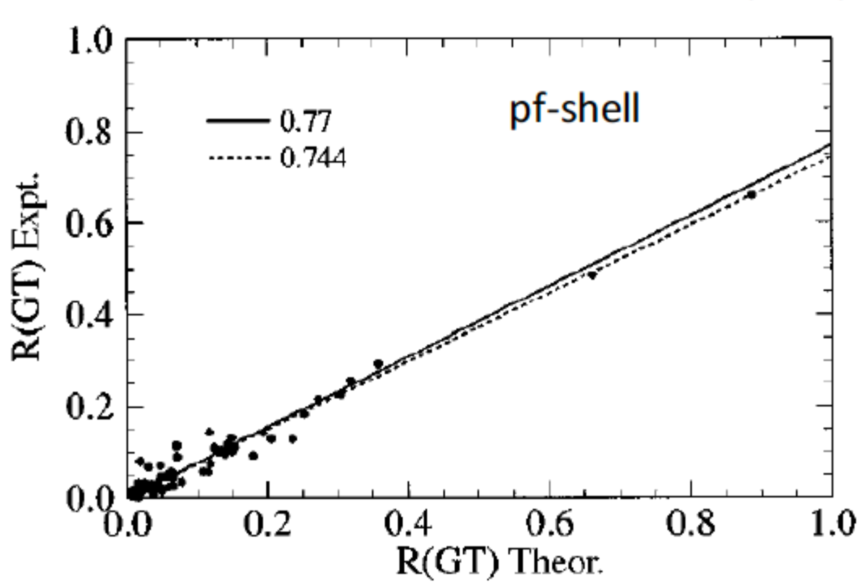

The half-life of nuclear single-beta decay

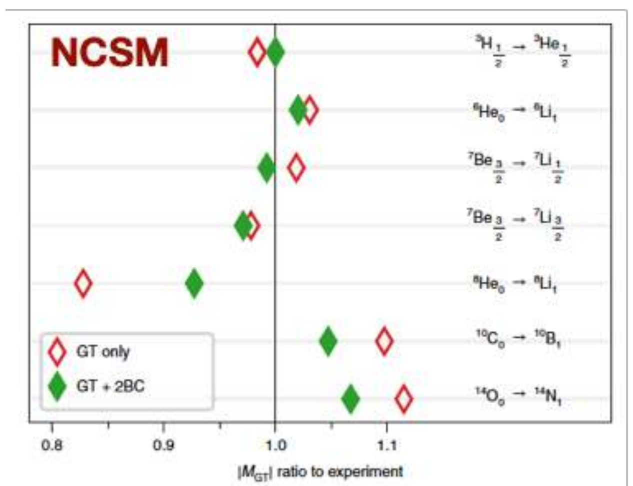
**Two-body currents+ many-body correlations**

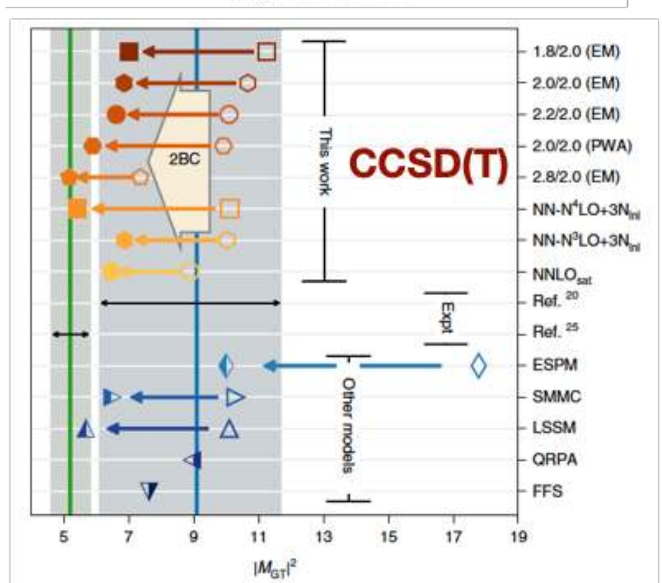
$$t_{1/2} = \frac{\kappa}{f_0(B_F + B_{\rm GT})},$$

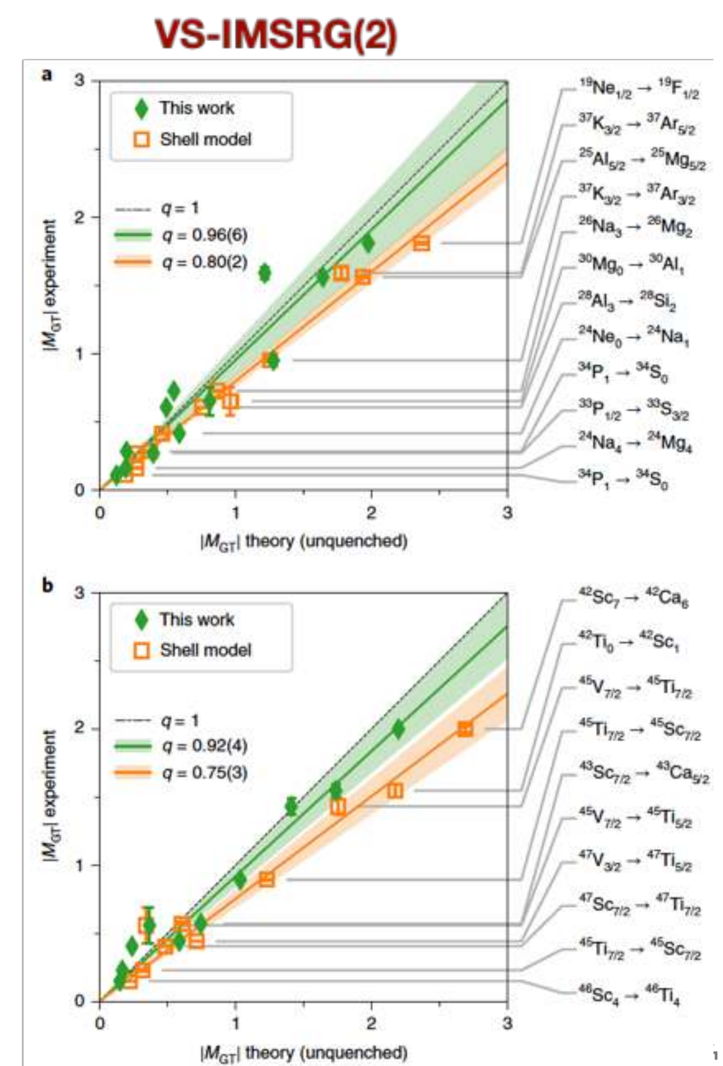
$$B_F = \frac{g_V^2}{2J_i+1}|M_F|^2, \quad B_{\rm GT} = \frac{g_A^2}{2J_i+1}|M_{\rm GT}|^2$$

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




尧江明

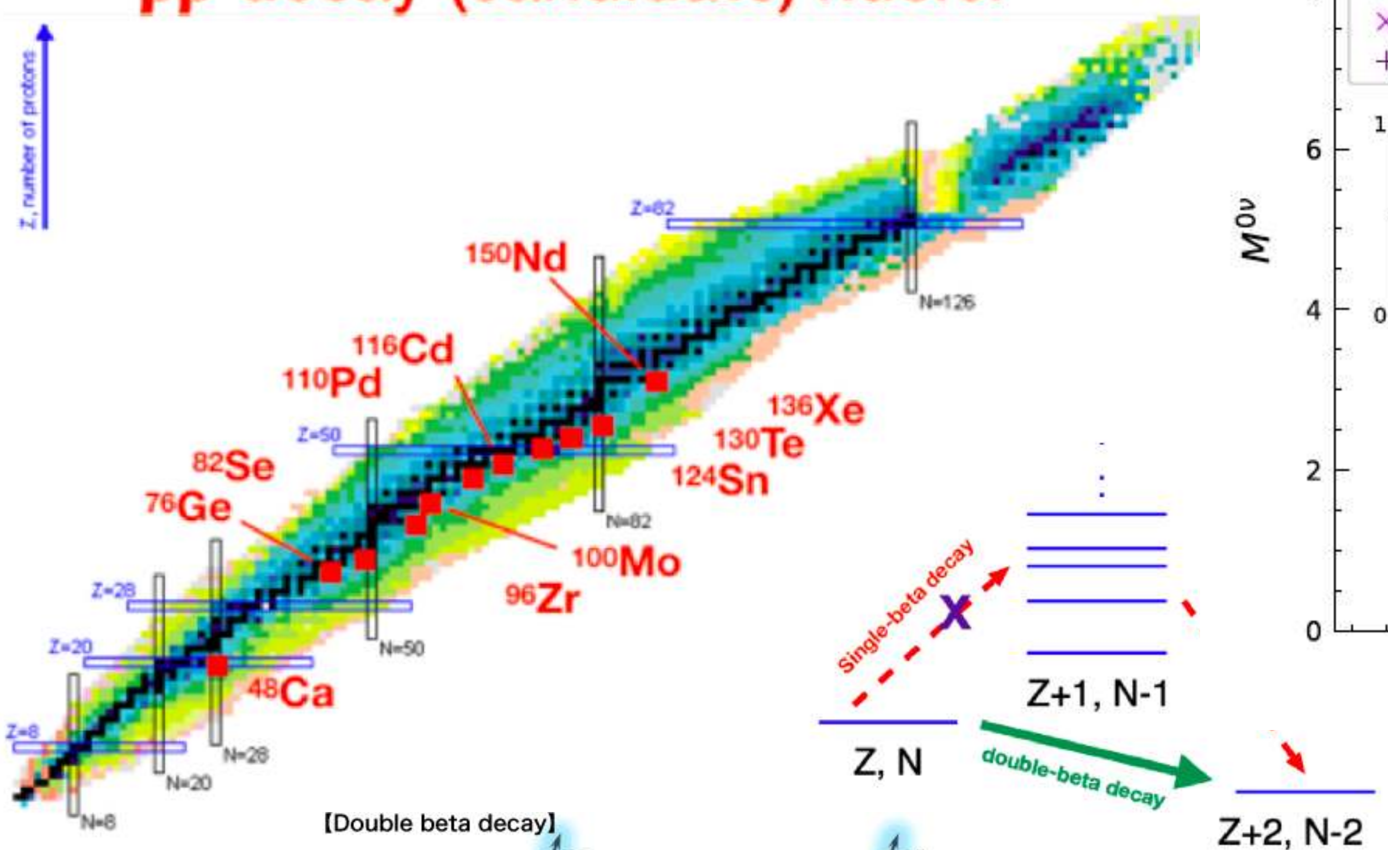
# ab initio calculations for nuclei: double-beta decay

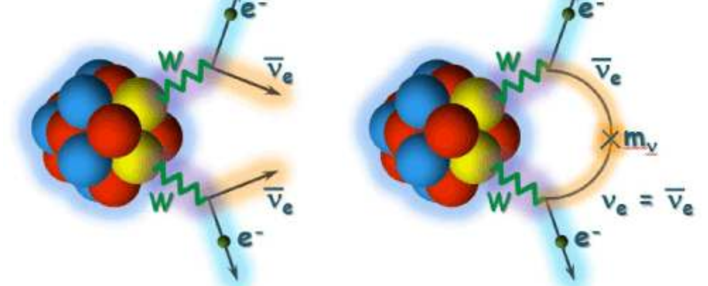
NSCL FRIB

## *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

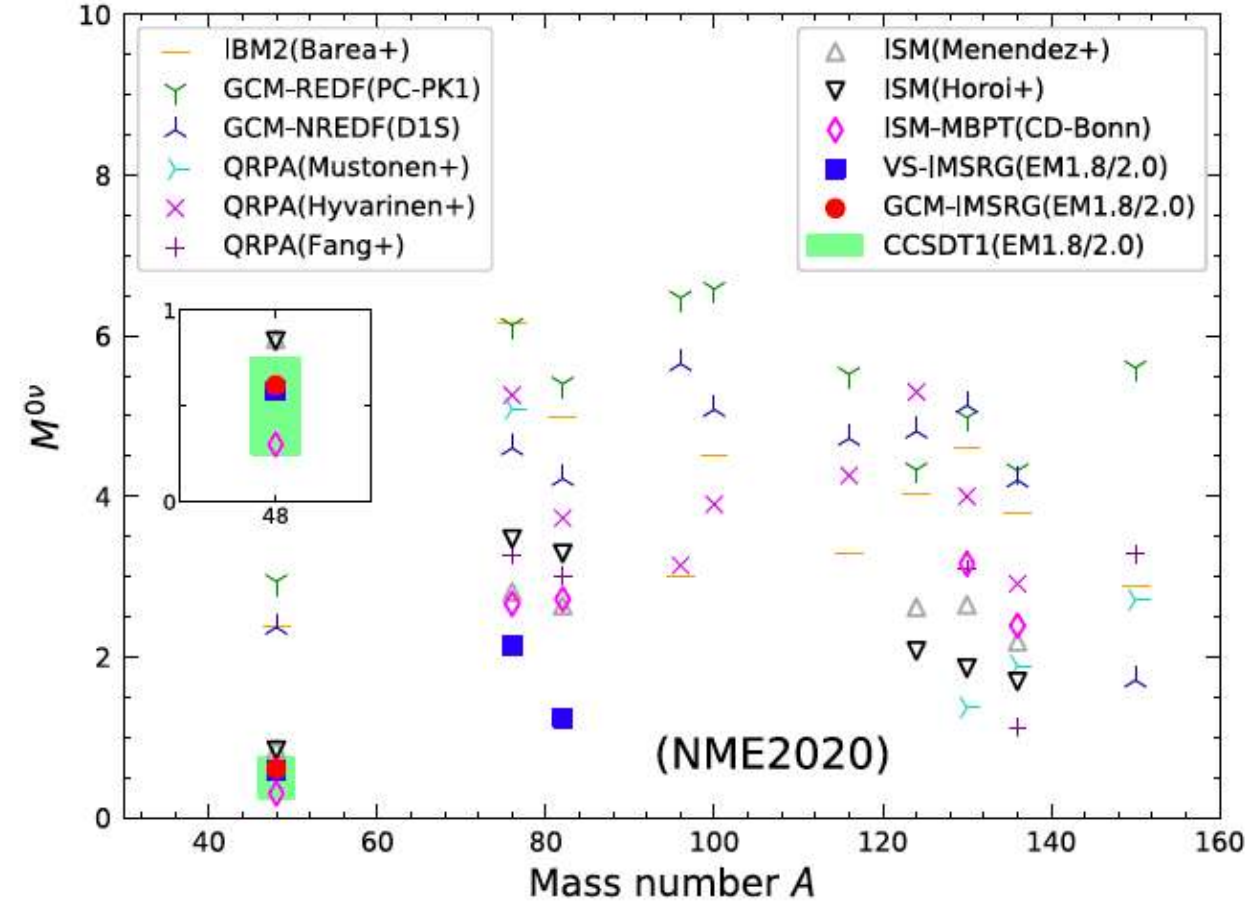
ββ decay (candidate) nuclei




Double beta decay which emits anti-neutrinos

Neutrinoless double beta decay

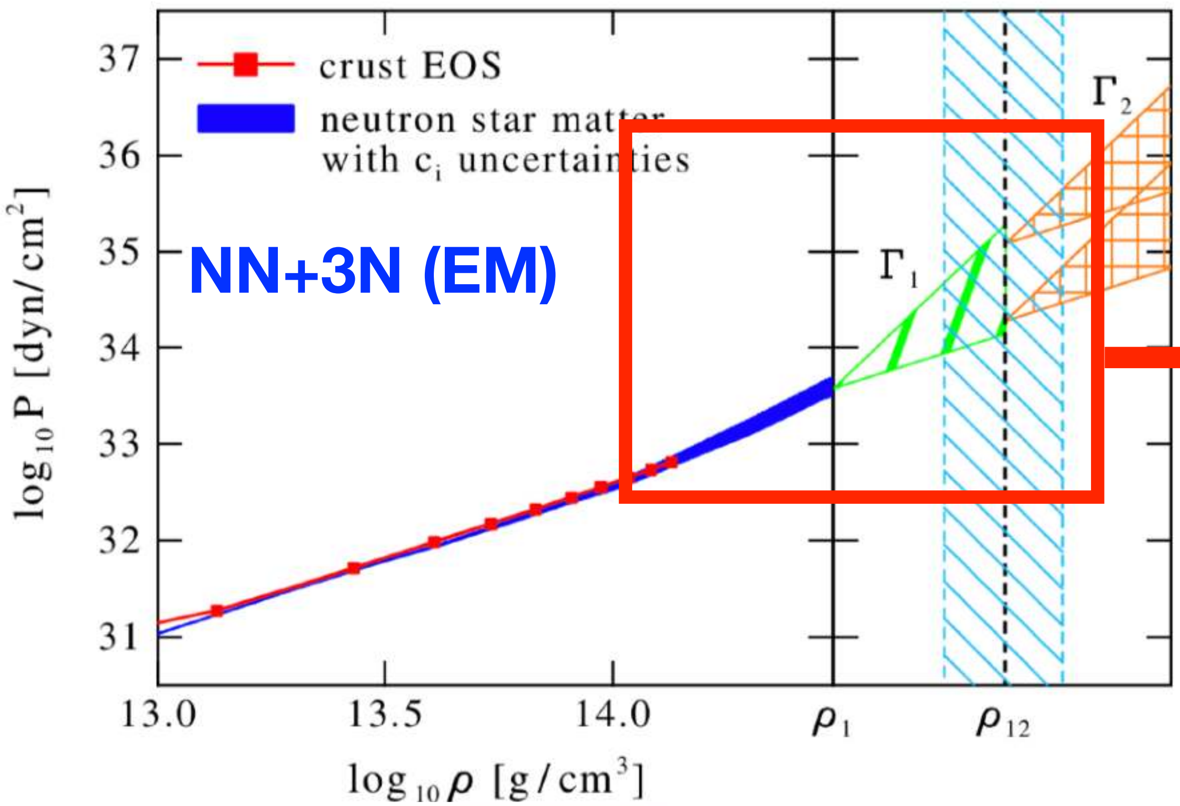



JMY, Science Bulletin (2021)

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

# ab initio calculations for neutron star matter

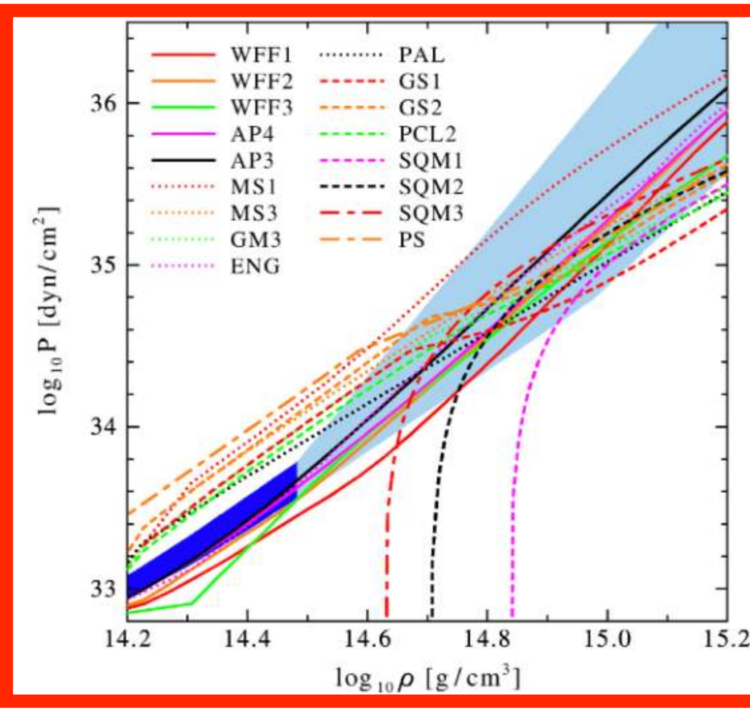
## Constraints on Neutron Star Radii Based on Chiral Effective Field Theory Interactions

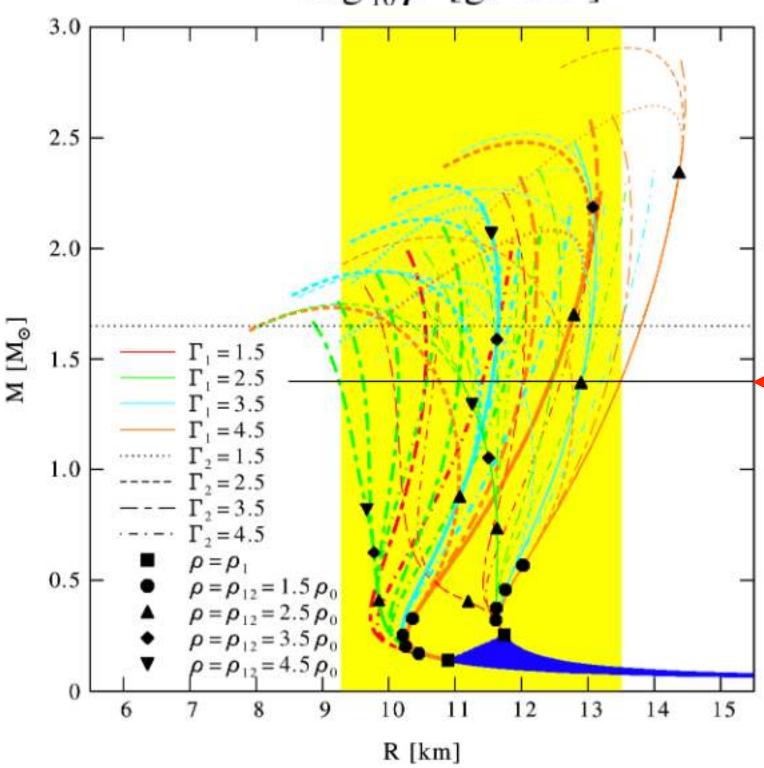



piecewise polytropes

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

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




$1.4 M_\odot$

$R = 9.3–13.5$ 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

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

x: Proton fraction

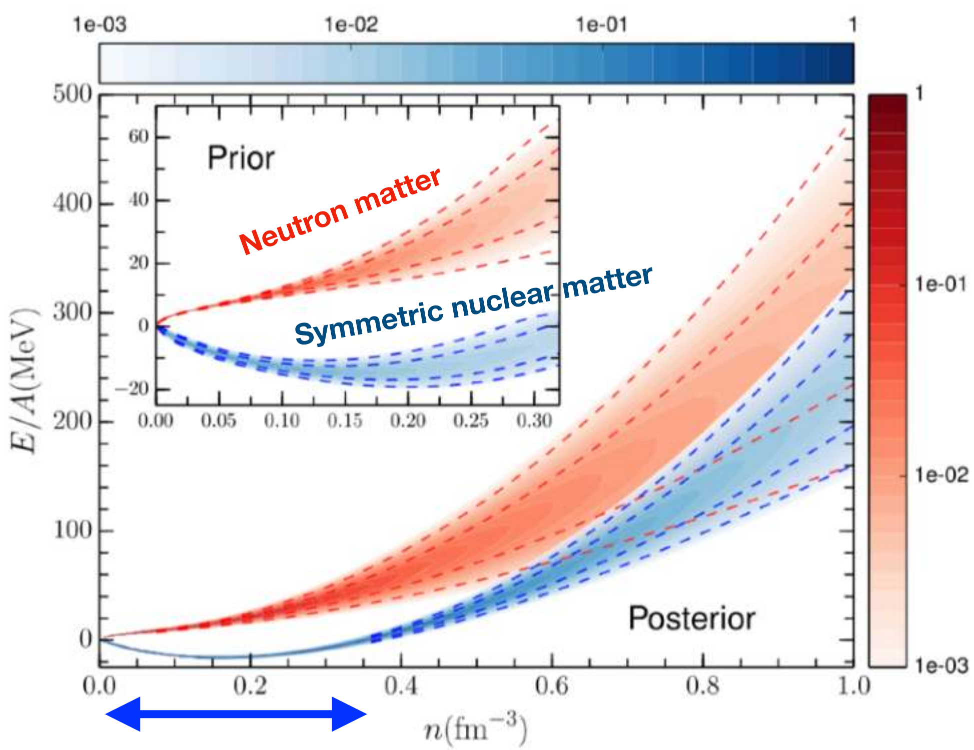
$f_n(n)$: $\sum_{i=0}^{3} b_i n^{(2+i/3)}$ $\quad$ $f_s(n)$: $\sum_{i=0}^{3} a_i n^{(2+i/3)}$,

- Bayes' Theorem: $P(\vec{a}|data) \sim P(data|\vec{a})P(\vec{a})$

Posterior

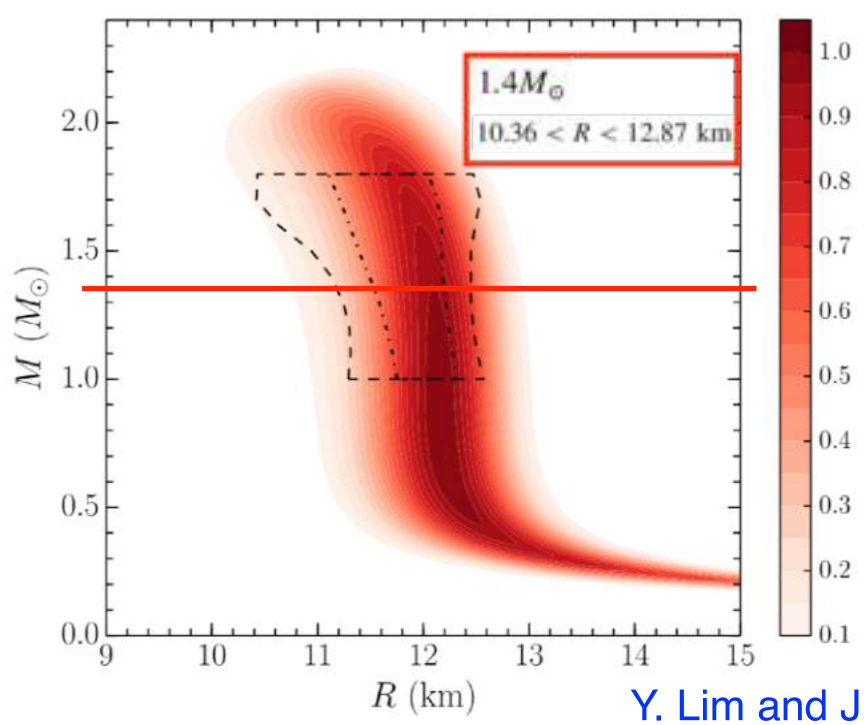
Likelihood of data given a probability distribution for $\vec{a}$

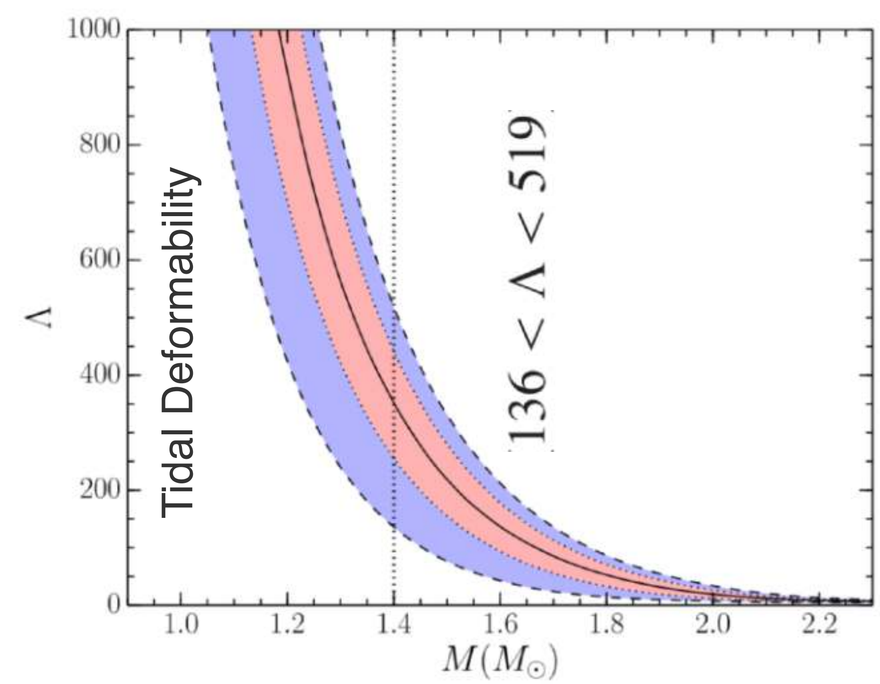
Beliefs about parameters $\vec{a}$ before measurements




✦ 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




Y. Lim and J.W. Holt, Phys. Rev. Lett. **121**, 062701 (2018)

# 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

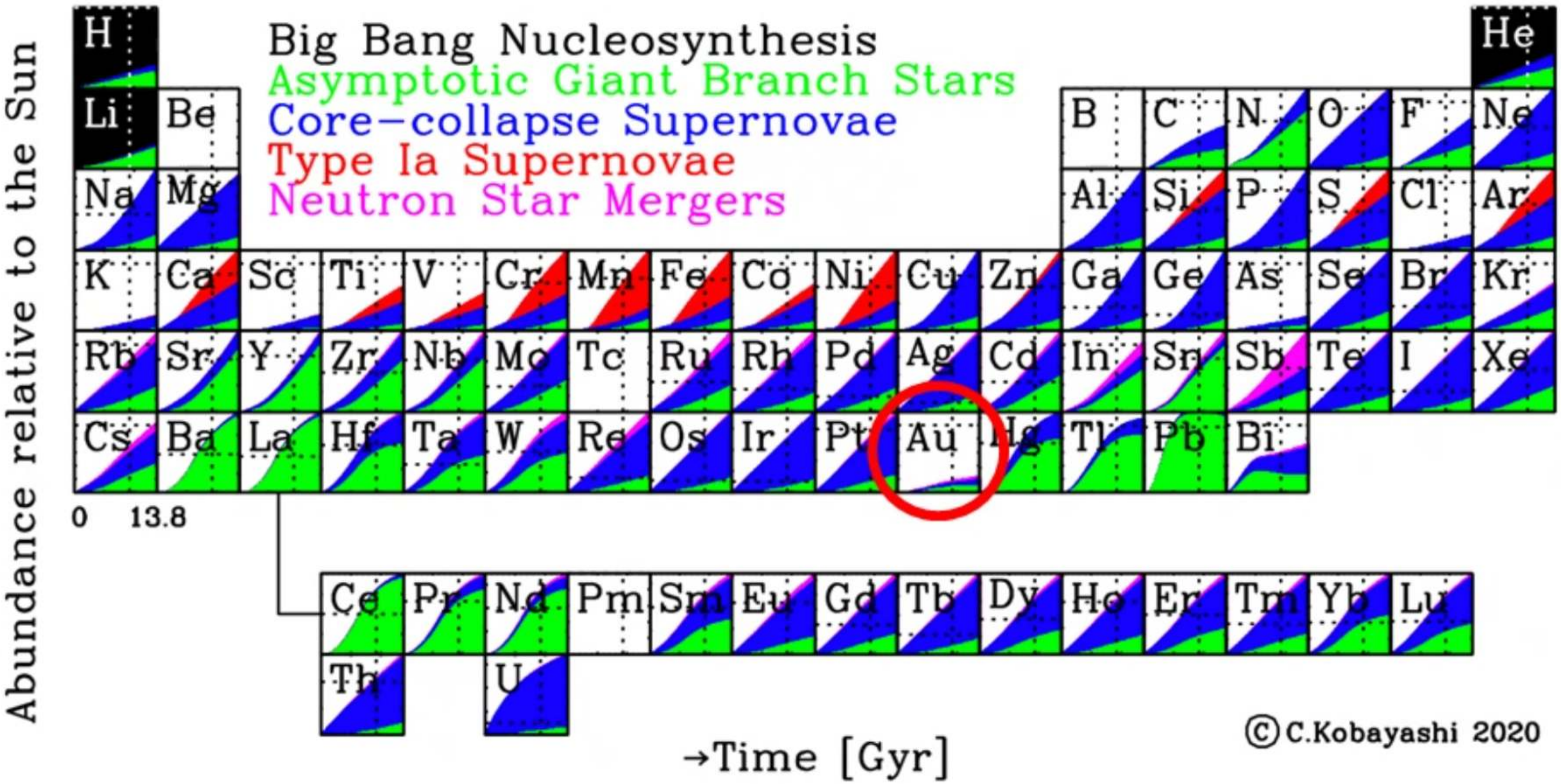
# Collaborators and acknowledgement

## 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**

# GW170817双中子星并合产生约300倍地球重量的黄金！




**The Astrophysical Journal 900 (2020) 179**