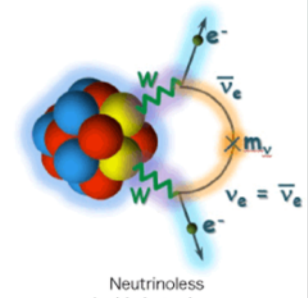
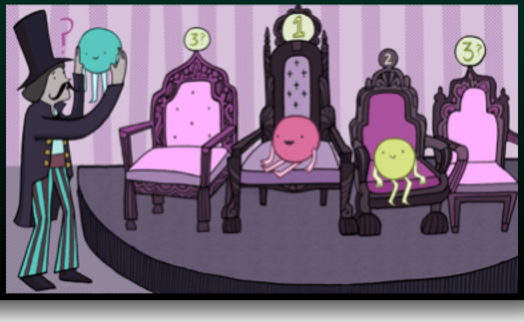


$0\nu\beta\beta$衰变矩阵元的从头计算

—从核衰变到中微子质量



Neutrinoless double beta decay



$T^{1/2}>10^{26}$ yr

$m_{\beta\beta}<0.1$ eV

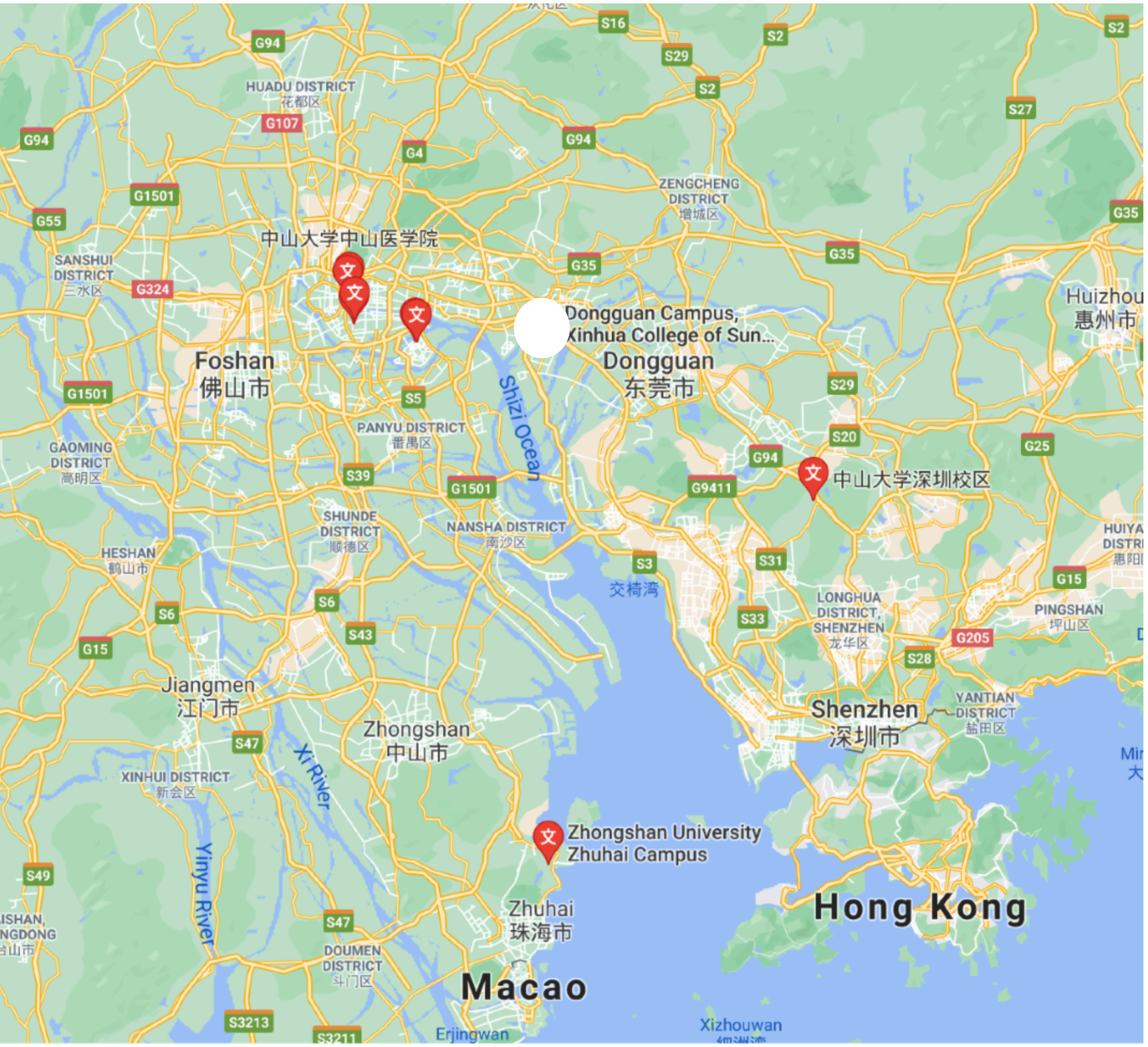
尧江明
中山大学物理与天文学院
School of Physics and Astronomy
Sun Yat-sen University

天津

南开大学物理科学学院

2021年6月1日

中山大学-3校区5校园



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

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

全国院系调整，中山大学天文系以及天文台师生员工，整体迁入南京大学

2013.12

成立天文与空间科学研究院，复办天文学科

2015.9

成立物理与天文学院

2016.4

成立天琴中心

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

中山大学-物理与天文学院

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

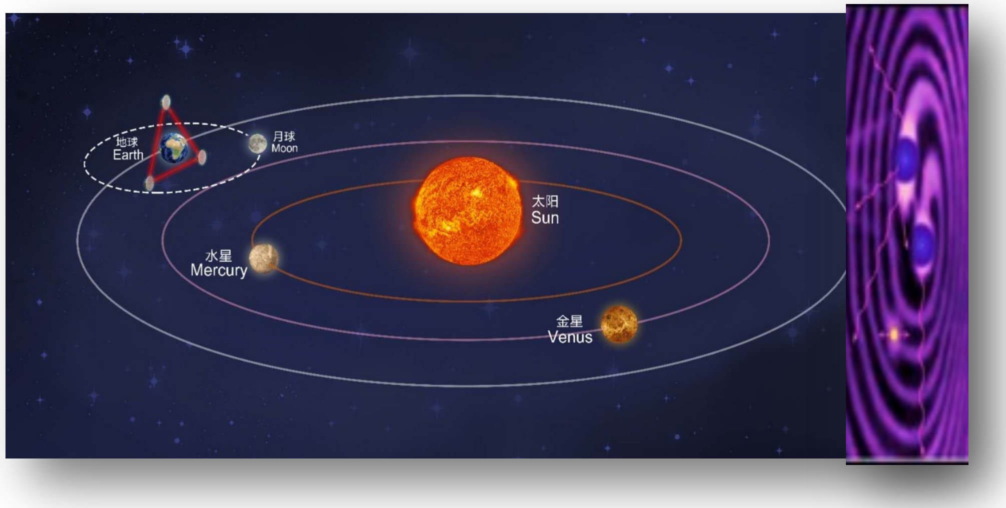
发展4个研究团队

中山大学-物理与天文学院

团队	专任教师	专职+博后	团队主要研究方向
天琴	26	15	引力波科学与数据处理分析、空间引力波探测方案概念性研究、惯性基准及无拖曳控制技术、星间激光干涉测量技术、科学卫星及编队、地月/地卫激光
天文	27	15	恒星与行星物理、星系与宇宙学、高能天体物理、引力波多信使天文学、天体测量和天体力学、天文观测技术与方法、微重力流体、空间科学仪器和技
理论物理	10	2	宇宙学、引力理论、量子场论、弦论、粒子物理与核物理、粒子天体物理、量子物理
量子物理	18	9	人工量子体系及其调控、原子分子光物理、冷原子物理、量子光学、精密光谱学、量子精密测量与传感、量子计算、量子模拟、量子通信等
总计	81	41	

中山大学-天琴计划团队

◆ 建设空间引力波探测天文台 ~2035

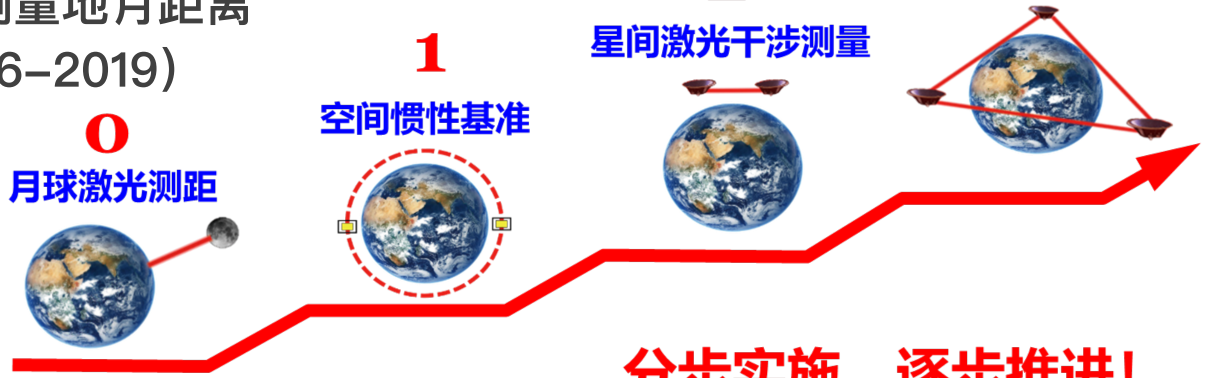


揭秘天琴一号

首次实现地月测量 为引力波探测打基础

录上次播放时间 01:07 从头观看 会，明年起北京将取消高速费起步价，客车、货车均按照实际行驶里程精确收费。

◆ 天琴计划0123 路线图



“天琴二号”试验卫星
(2025)

待开展：
✓天琴三号（天琴）

“天琴一号”试验卫星
(2019)

激光测量地月距离
（2016–2019）

0
月球激光测距

1
空间惯性基准

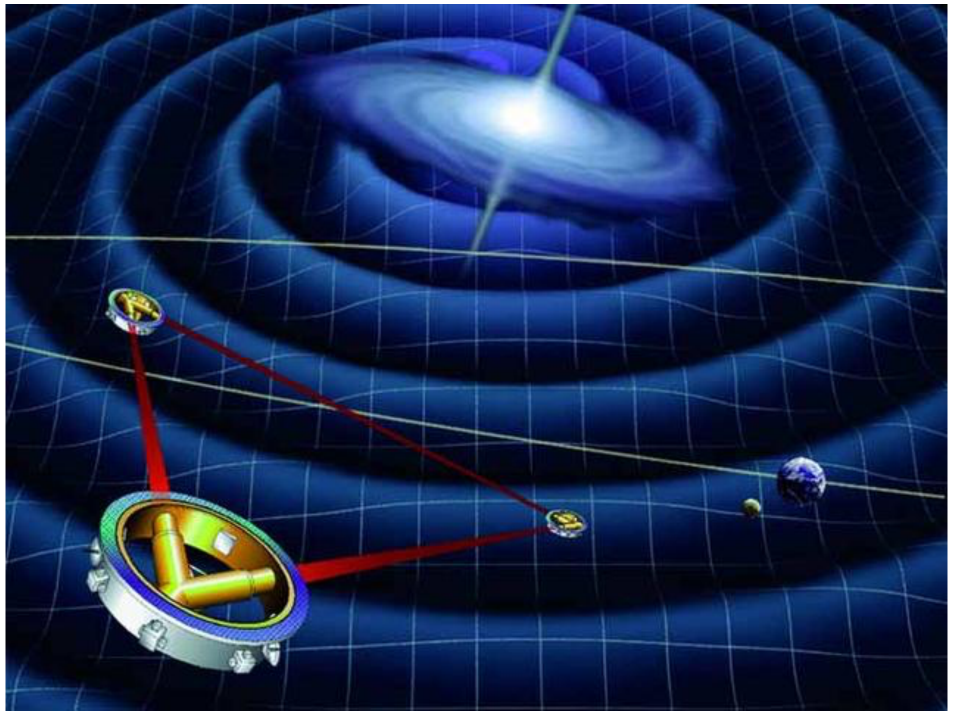
2
星间激光干涉测量

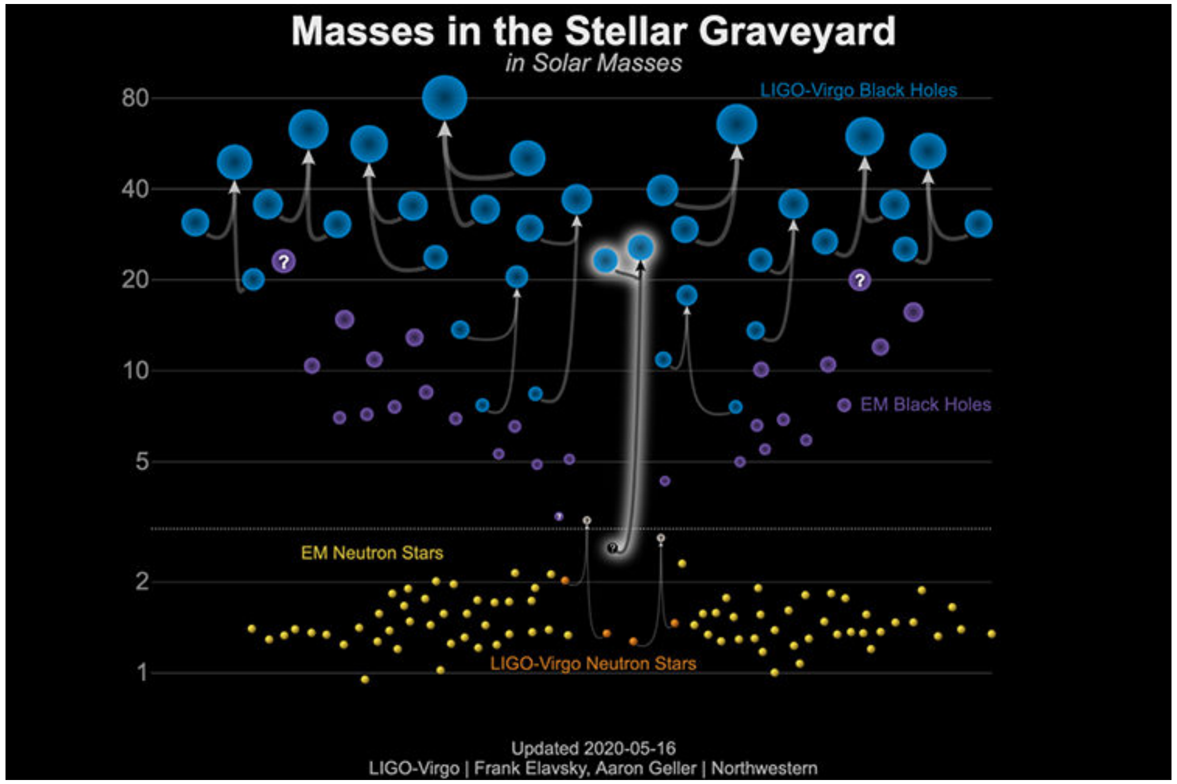
3
空间引力波探测

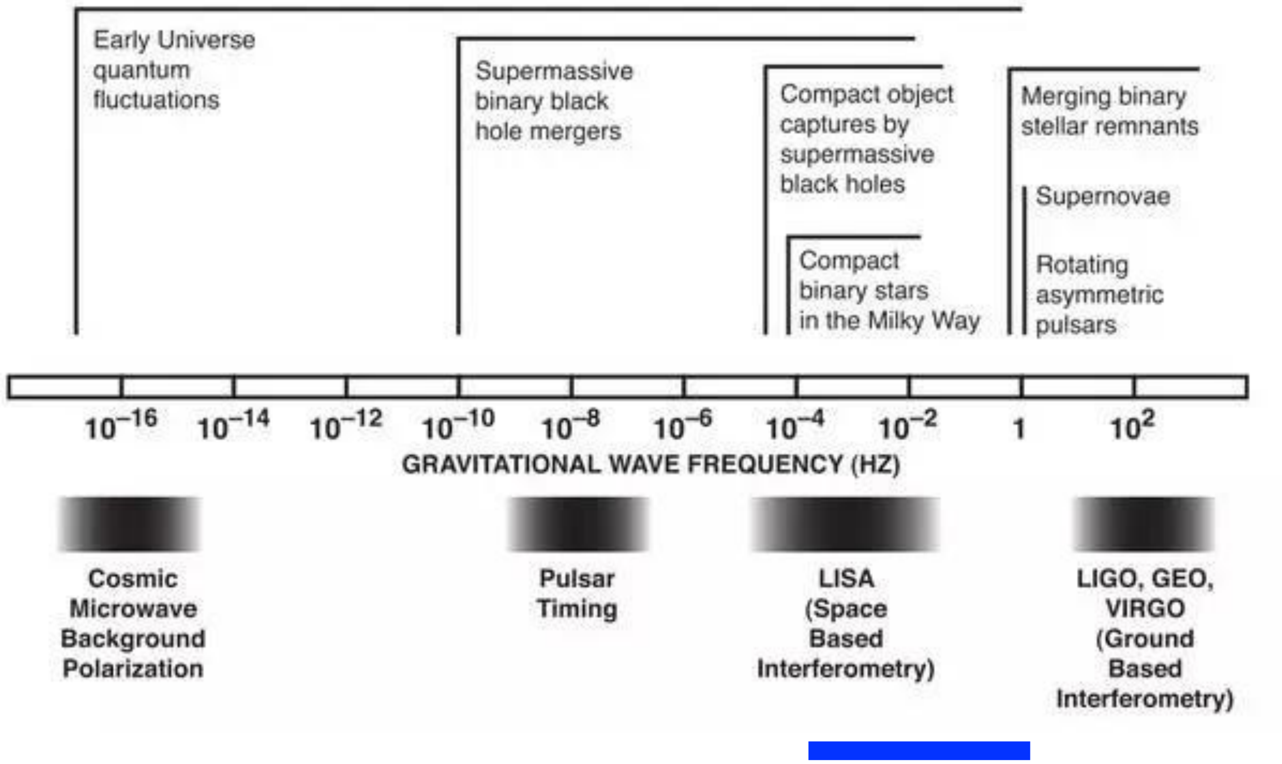
分步实施，逐步推进！

“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）；

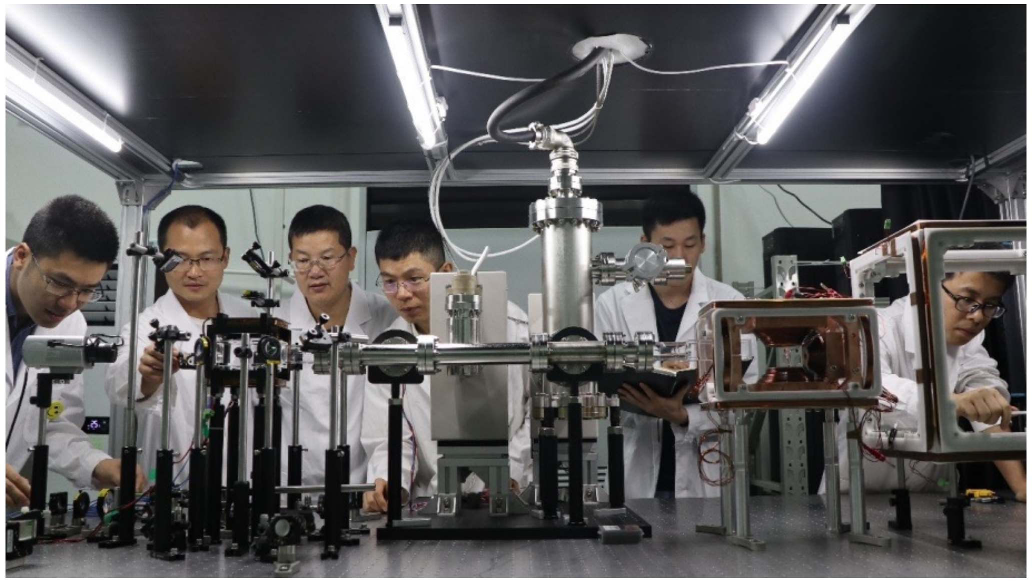
② **实测天文学**（恒星物理、天体化学，原子分子天文学等）；

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

广东省量子精密测量与传感重点实验室



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）

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

师资（5+5+2）相对薄弱，
需要更多优秀人才加入。

中山大学-国际青年学者论坛

中山大学第十二届国际青年学者论坛诚邀全球英才…

报名方式

手机端：请关注微信公众号“中山大学人才发展办公室”，点击菜单栏“招贤纳士”中“我要报名”跳转至报名系统，或扫描下方二维码。

欢迎推荐优秀的博士后、博士毕业生！

Outline

✦ Introduction to $0\nu\beta\beta$ decay

- Significance
- Status

✦ Advances in (ab initio) modeling NME of $0\nu\beta\beta$ decay

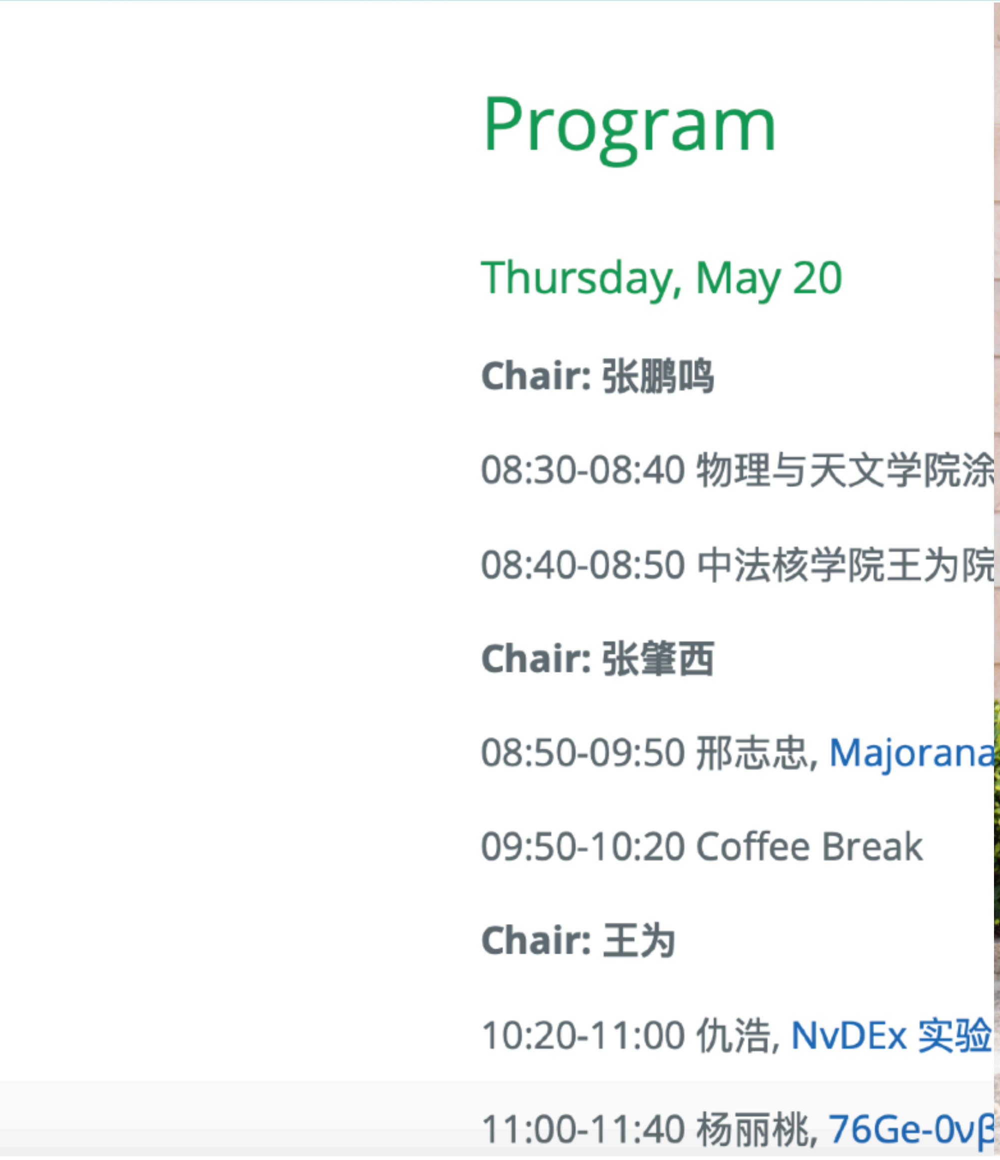
- Challenges
- Achievements

✦ Summary and Outlook

Contents can be found in the talks …

Workshop on neutrinoless double beta decay, May 19-23, 2021 SYSU (Zhuhai)

https://nldbd-china.github.io



Program

Thursday, May 20

Chair: 张鹏鸣

08:30-08:40 物理与天文学院涂

08:40-08:50 中法核学院王为院

Chair: 张肇西

08:50-09:50 邢志忠, Majorana

09:50-10:20 Coffee Break

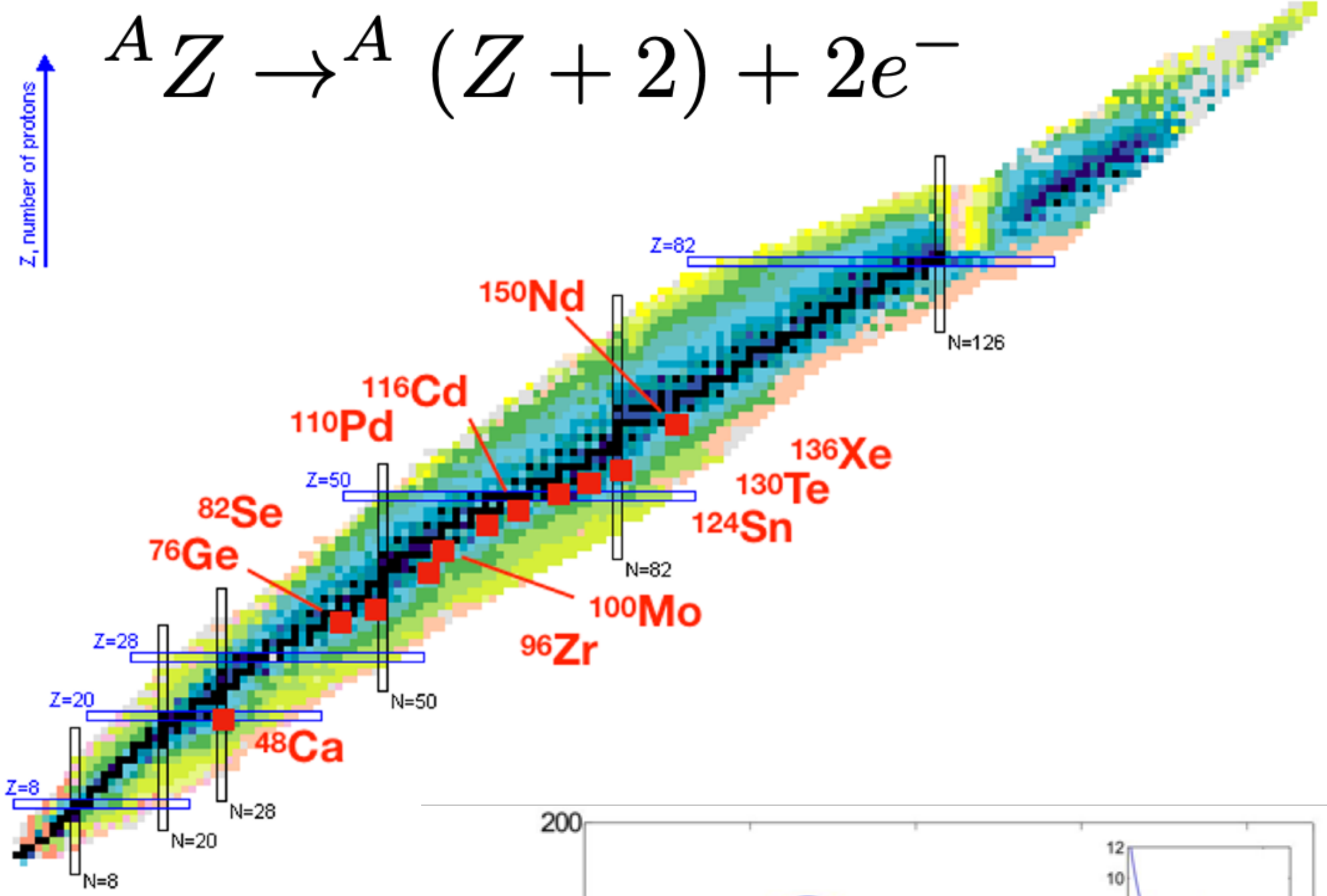
Chair: 王为

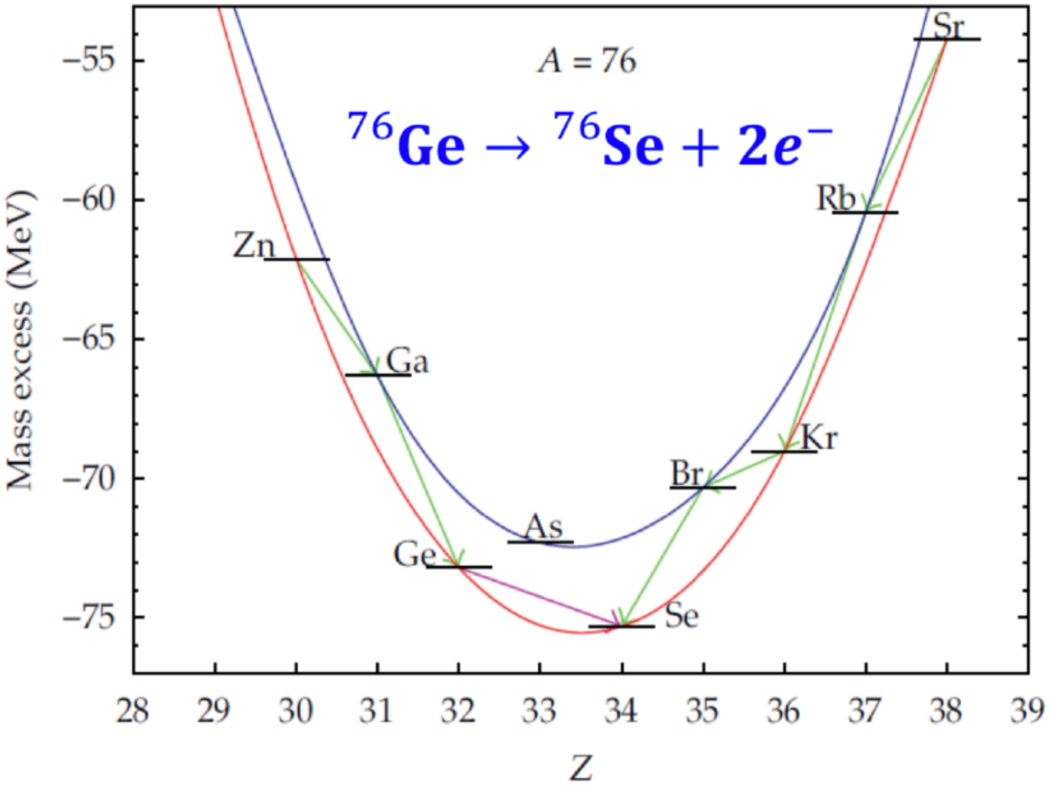
10:20-11:00 仇浩, NvDEx 实验

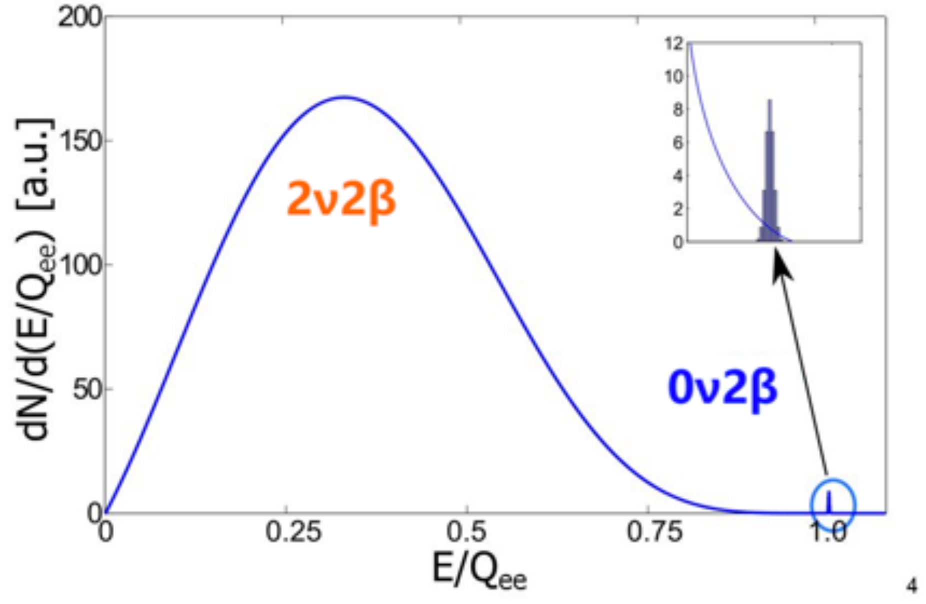
11:00-11:40 杨丽桃, 76Ge-0vβ

What is $0\nu\beta\beta$ decay?

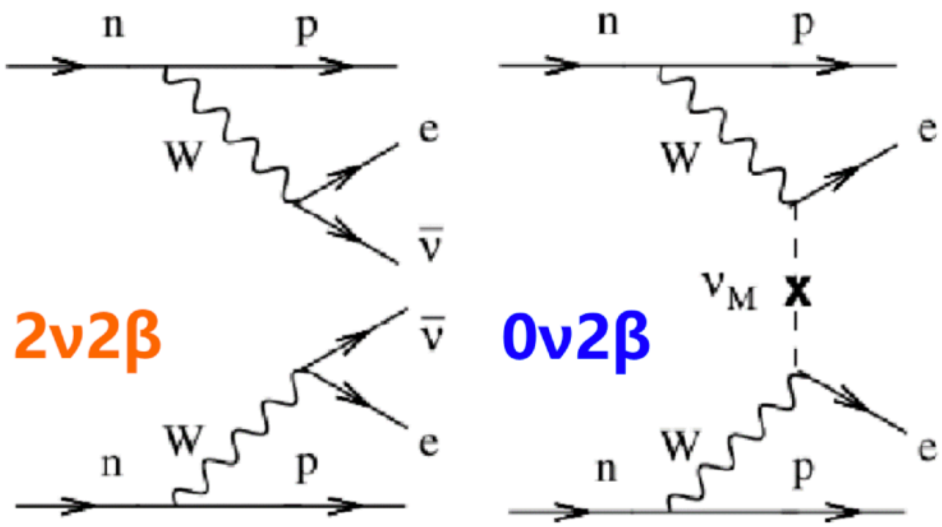
$$^{A}Z \to {}^{A}(Z+2) + 2e^-$$







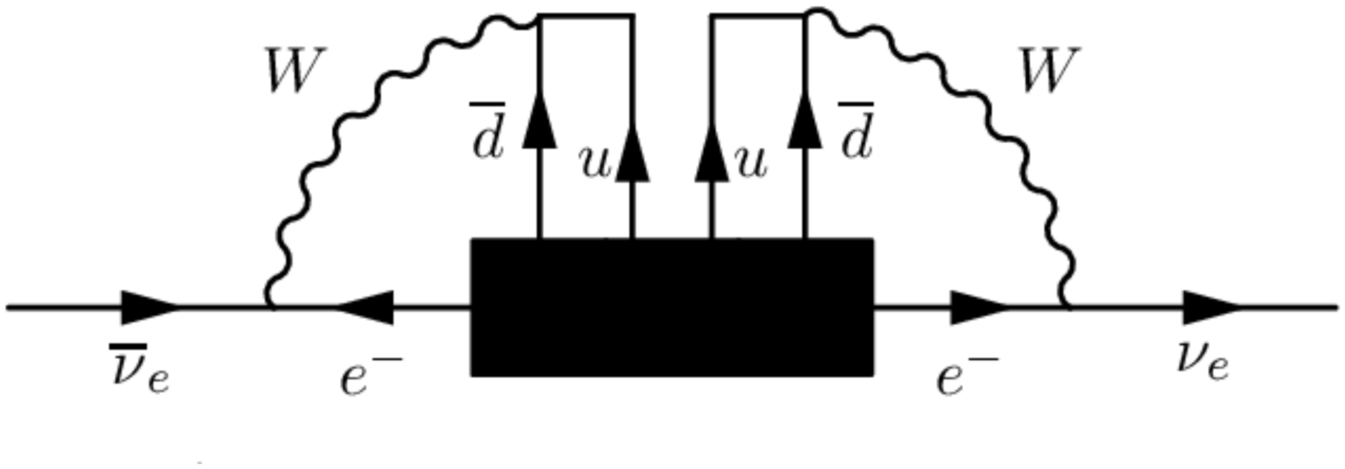
Sum of 2e energy



- Maria Goeppert-Mayer(1935): $2\nu\beta\beta$ decay
- Ettore Majorana (1937): neutrino=anti-neutrino
- Wendell Furry(1939): $0\nu\beta\beta$ decay $T^{0\nu}_{1/2} \sim 10^{-5} T^{2\nu}_{1/2}$

Why $0\nu\beta\beta$ decay?

Schechter-Valle Theorem (1982):
If the 0νββ decay happens, there must exist an effective Majorana neutrino mass term.



Even though this mass is too small to explain neutrino oscillation data.

$$\boxed{\delta m_\nu \lesssim O(10^{-28}\,\mathrm{eV})}$$

Duerr, Lindner, Merle, JHEP, 2011;
Liu, Zhang, Zhou, PLB, 2016

Significance

- Nature of neutrinos: Majorana or Dirac
- Lepton-number-violation process (implication for matter-antimatter asymmetry)
- Effective neutrino mass

$$[T^{0\nu}_{1/2}]^{-1} = g_A^4 G_{0\nu} \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2 \left|M^{0\nu}\right|^2$$

$$\langle m_{\beta\beta}\rangle = \sum_{j=1}^{3} U_{ej}^2 m_j = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-2\delta)}$$

$$|\nu_\alpha\rangle = \sum_{j=1}^{3} U^*_{\alpha j}\,|\nu_j\rangle\,,$$

Flavor
(e,mu,tau)

Mass
(1,2,3)

Why $0\nu\beta\beta$ decay?

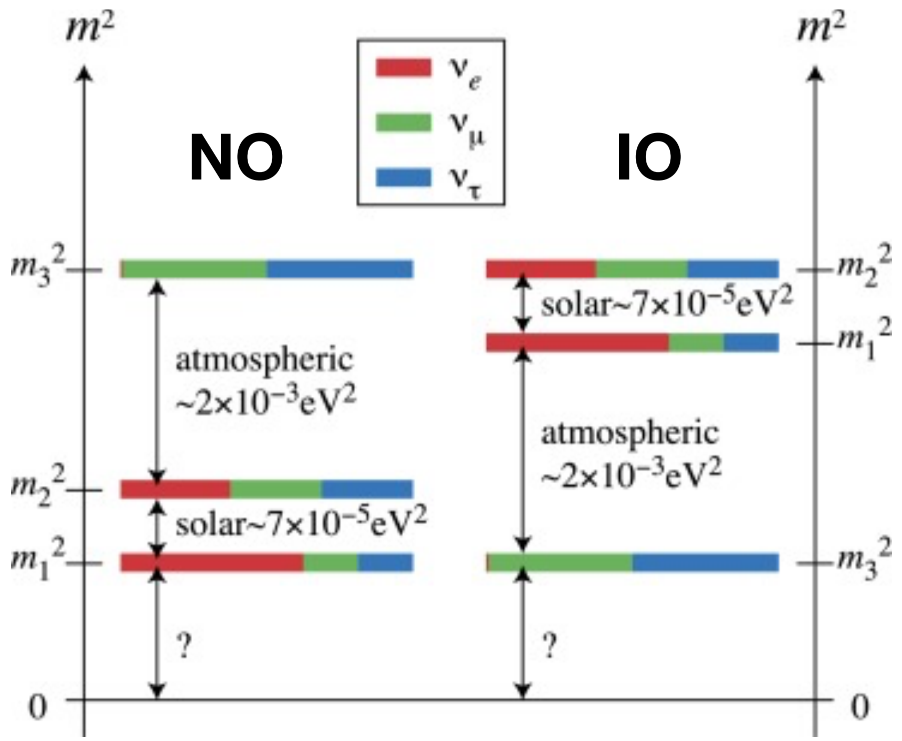
Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$
\begin{aligned}
U &= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathcal{P}
\end{aligned}
$$

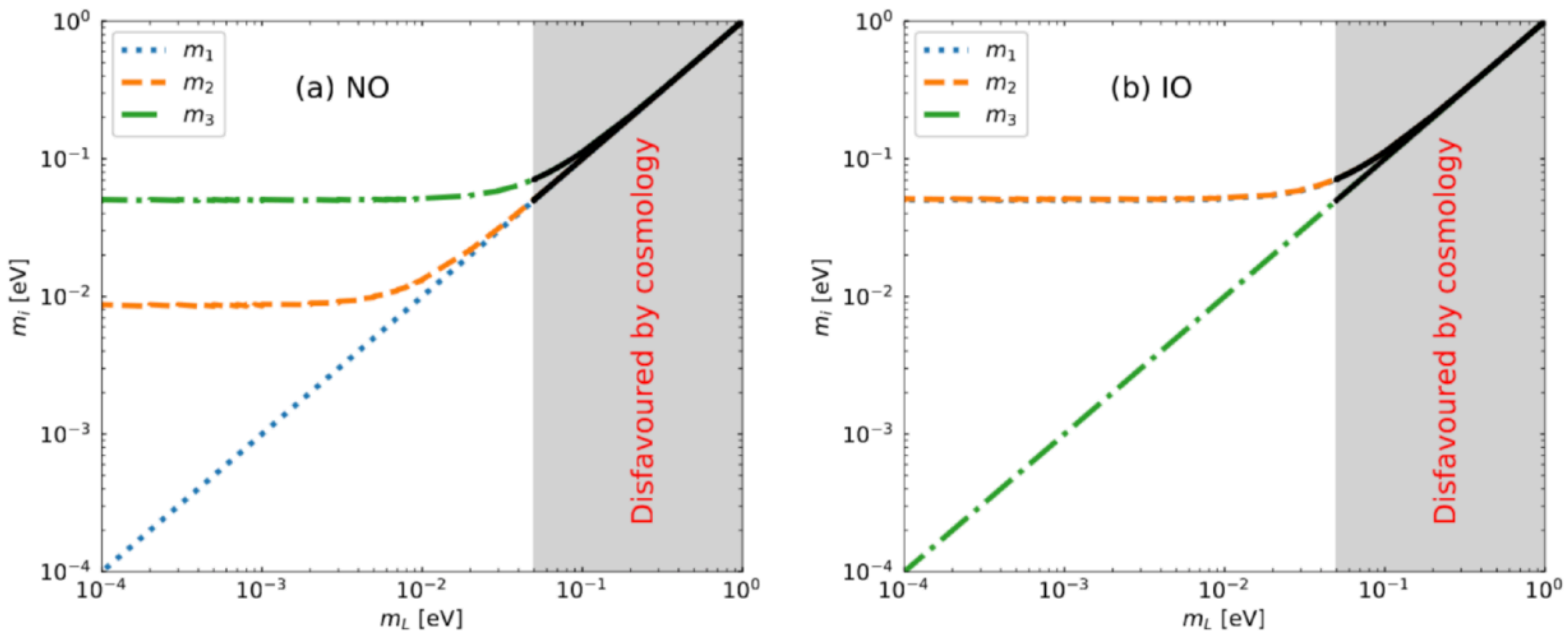
Current information on neutrino parameters from neutrino oscillation measurements

$$
\begin{aligned}
0.250 \leq & s_{12}^2(0.297) \leq 0.354, \\
0.0190 \leq & s_{13}^2(0.0215) \leq 0.0240, \\
6.93 \times 10^{-5}\mathrm{eV}^2 \leq & \Delta m_{21}^2(7.37 \times 10^{-5}\mathrm{eV}^2) \leq 7.96 \times 10^{-5}\mathrm{eV}^2, \\
2.45 \times 10^{-3}\mathrm{eV}^2 \leq & \Delta m_{31}^2(2.56 \times 10^{-3}\mathrm{eV}^2) \leq 2.69 \times 10^{-3}\mathrm{eV}^2.
\end{aligned}
$$

Two potential mass orderings of neutrinos: normal ordering or inverted ordering?



Stephen F.King,PLB(2016)

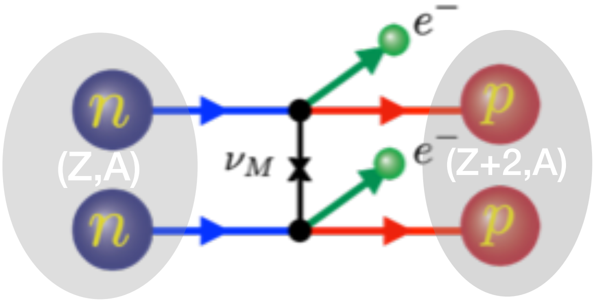


Why $0\nu\beta\beta$ decay important for neutrino physics?

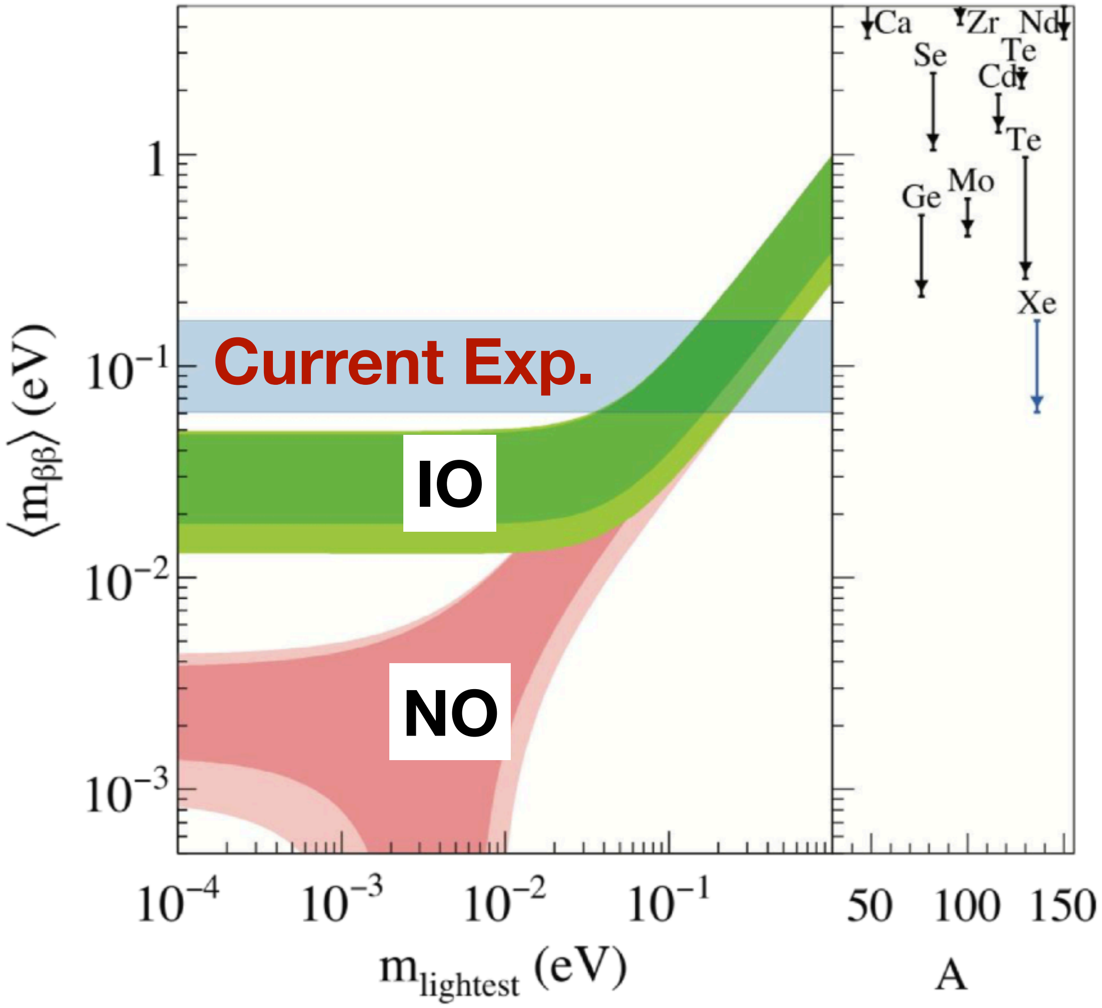
If the 0νββ decay is observed, the neutrino mass (hierarchy) can be determined, assuming the “standard” mechanism of exchange light Majorana neutrino,

$$[T^{0\nu}_{1/2}]^{-1} = g_A^4 G_{0\nu} \left| \frac{\langle m_{\beta\beta} \rangle}{m_e} \right|^2 |M^{0\nu}|^2$$

$$\langle m_{\beta\beta} \rangle = \sum_{j=1}^{3} U_{ej}^2 m_j = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-2\delta)}$$

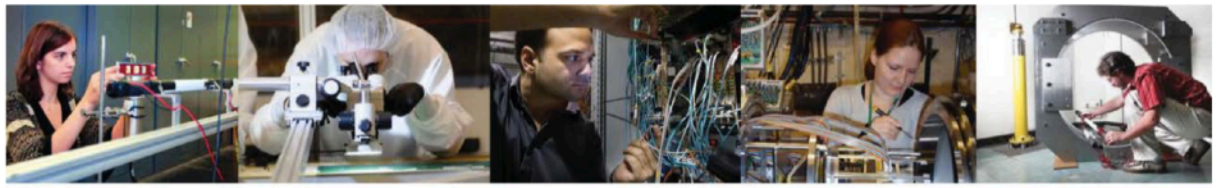


“standard” mechanism



Race to $0\nu\beta\beta$ decay

A priority for US nuclear physics



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

RECOMMENDATION II:
"The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.
"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

INITIATIVE B:
"We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC."

US DOE has scheduled a portfolio review of DBD in July 2021

国内正在/计划开展的相关实验

学术引领系列

中国学科发展战略

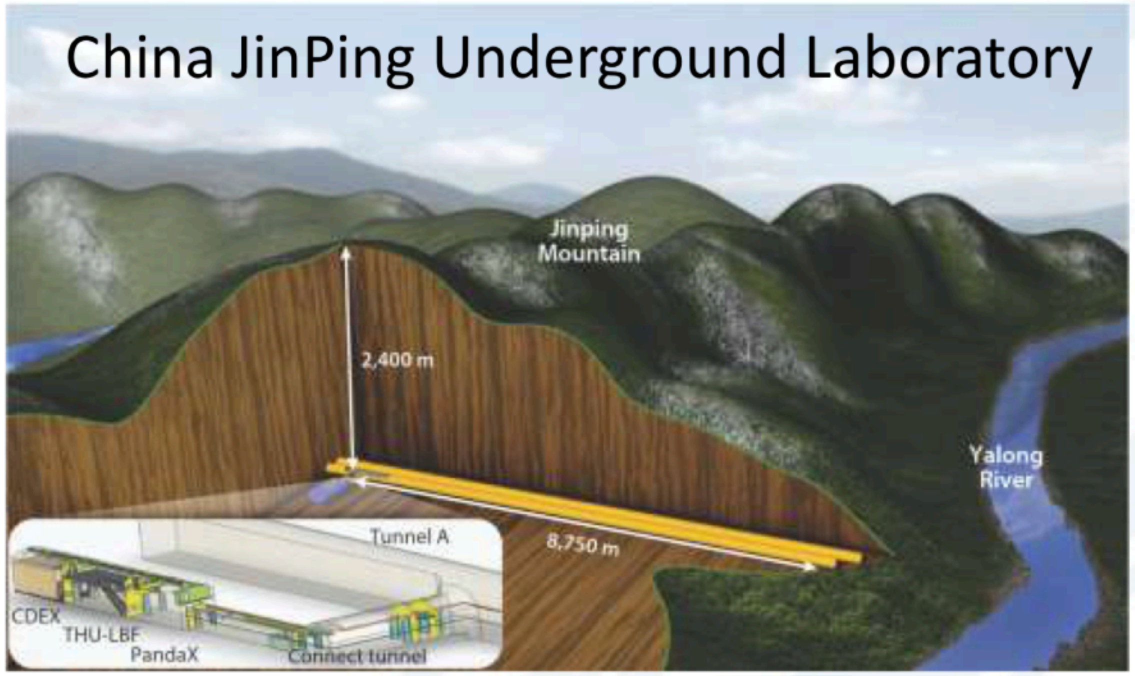
国家科学思想库

无中微子双贝塔衰变实验

中国科学院

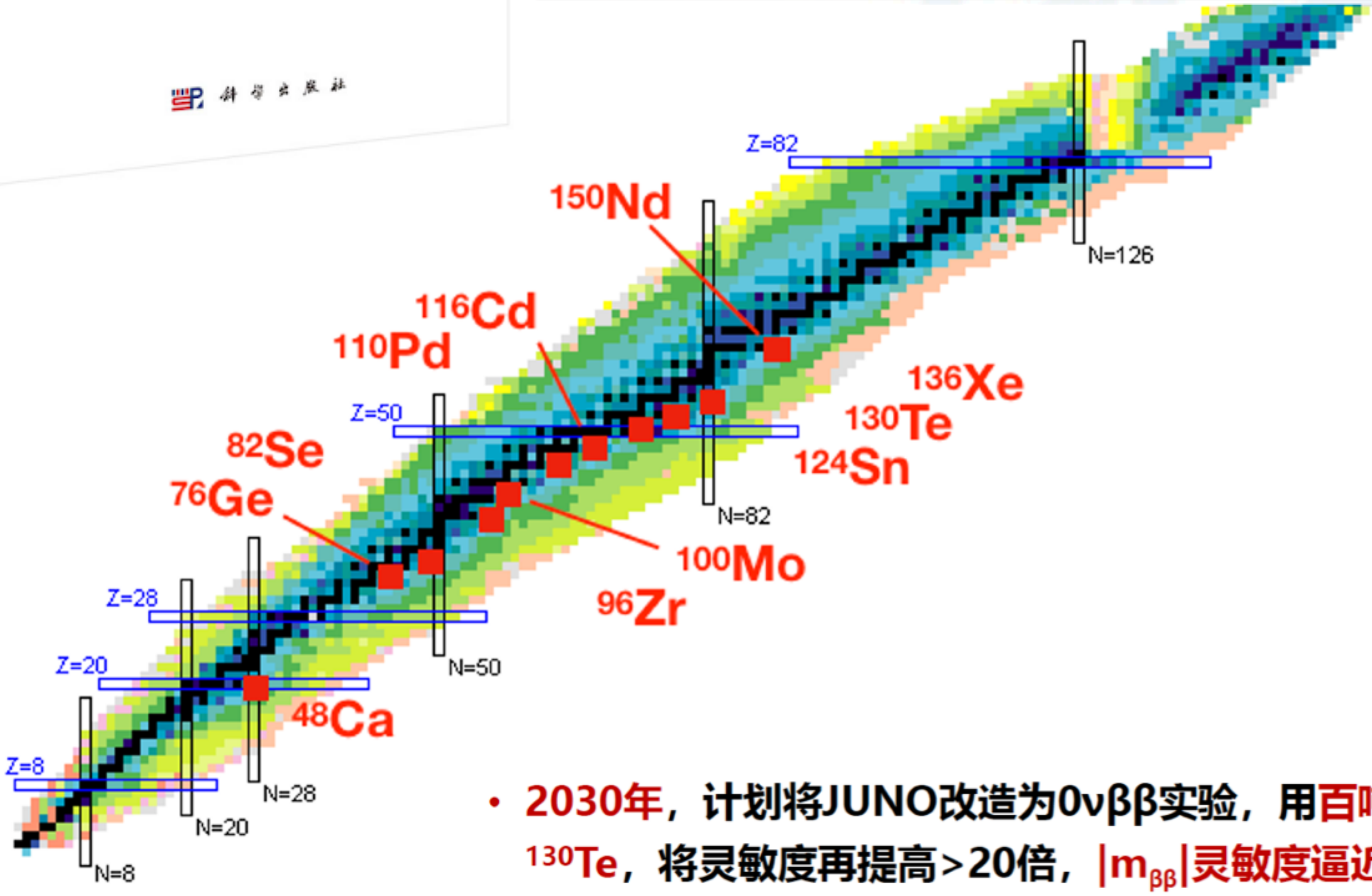
科学出版社

(2020)


China JinPing Underground Laboratory

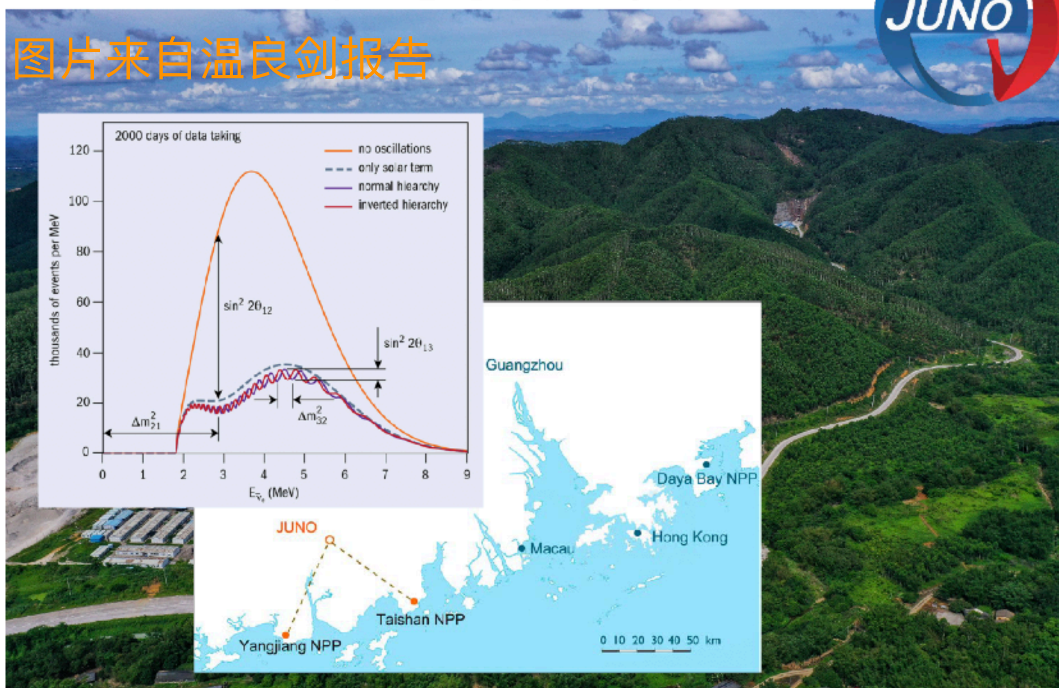
国内实验合作组

- ► ^{76}Ge （CDEX-300）
- ► ^{82}Se （NνDEx）
- ► ^{100}Mo (CUPID-China)
- ► ^{136}Xe （PandaX-4T）
- ► ^{136}Xe或^{130}Te (JUNO-0$\nu\beta\beta$)

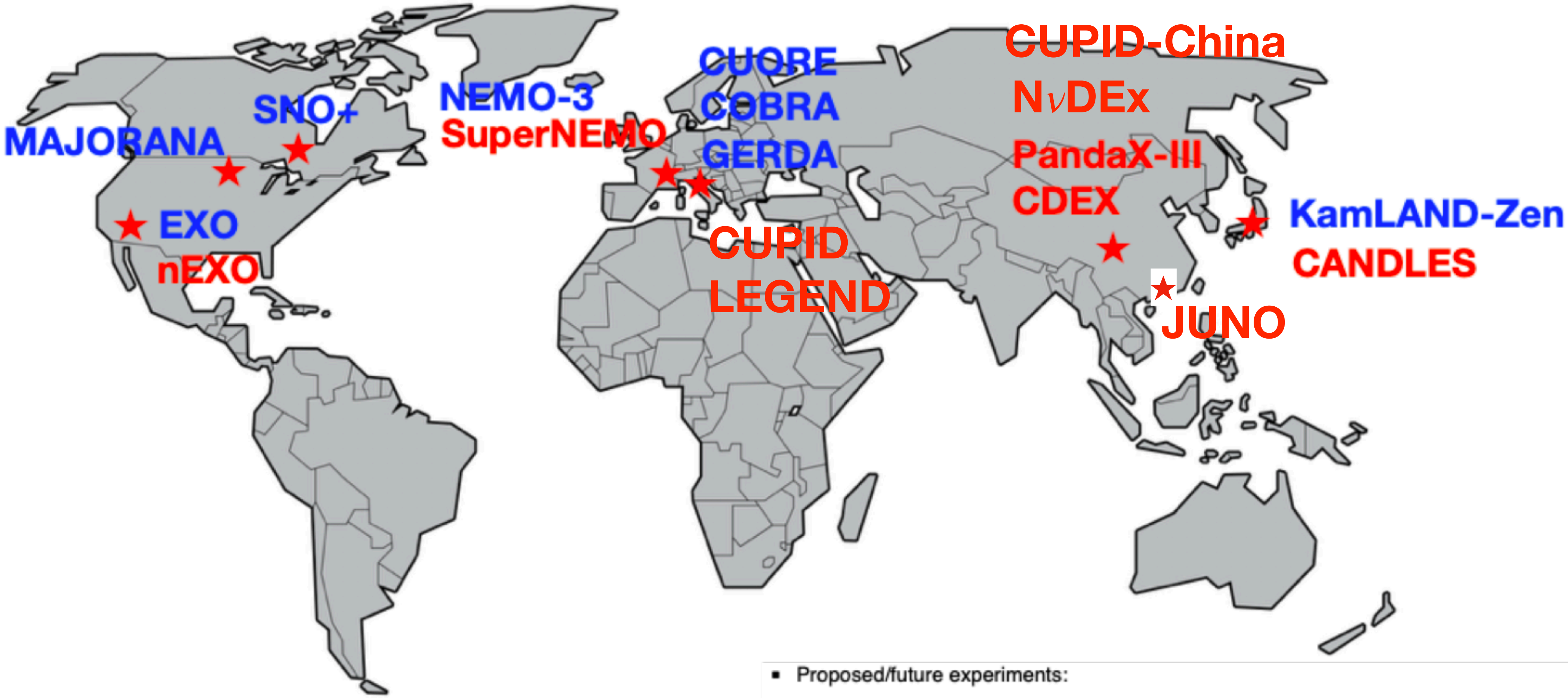


- 2030年，计划将JUNO改造为0νββ实验，用百吨量级^{130}Te，将灵敏度再提高>20倍，$|m_{\beta\beta}|$灵敏度逼近meV

江门中微子实验


图片来自温良剑报告

Current status of experimental searches



- Experiments taking data as of November 2017:
  - COBRA, ^{116}Cd in room temperature CdZnTe crystals
  - CUORE, ^{130}Te in ultracold TeO_2 crystals
  - EXO, a ^{136}Xe and ^{134}Xe search
  - GERDA, a ^{76}Ge detector
  - KamLAND-Zen, a ^{136}Xe search. Data collection from 2011.[21]
  - MAJORANA, using high purity ^{76}Ge p-type point-contact detectors.[22]

source: https://en.wikipedia.org/wiki/Double_beta_decay

- Proposed/future experiments:
  - CANDLES, ^{48}Ca in CaF_2, at Kamioka Observatory
  - MOON, developing ^{100}Mo detectors
  - AMoRE, ^{100}Mo enriched $CaMoO_4$ crystals at YangYang underground laboratory[23]
  - nEXO, using liquid ^{136}Xe in a time projection chamber [24]
  - LEGEND, Neutrinoless Double-beta Decay of ^{76}Ge.
  - LUMINEU, exploring ^{100}Mo enriched $ZnMoO_4$ crystals at LSM, France.
  - NEXT, a Xenon TPC. NEXT-DEMO ran and NEXT-100 will run in 2016.
  - SNO+, a liquid scintillator, will study ^{130}Te
  - SuperNEMO, a NEMO upgrade, will study ^{82}Se
  - TIN.TIN, a ^{124}Sn detector at INO
  - PandaX-III, an experiment with 200 kg to 1000 kg of 90% enriched ^{136}Xe

Current status of experimental searches

Isotope	Experiment	Exposure (kg yr)	Average half-life sensitivity (10^{25} y)	Half-life limit (10^{25} y) 90% C.L.	Effective mass limit (meV) Range from NME*	Reference
^{76}Ge	GERDA	127.2	18	> 18	< 79−180	Agostini et al. PRL 125, 252502 (2020)
	MJD	26.0	4.8	> 2.7	< 200-433	Alvis et al. Phys Rev C 100, 025501 (2019)
^{130}Te	CUORE	288	2.8	> 2.2	< 90-305	Adams et al. arXiv:2104.06906 (2021)
^{136}Xe	EXO-200	234.1	5.0	> 3.5	< 93-286	Anton et al. PRL 123, 161802 (2019)
	KamLAND-ZEN	504	5.6	> 10.7	< 60-161	Gando et al., PRL 117, 082503 (2016)

$T^{1/2}>10^{26}$ yr $m_{\beta\beta}<0.1$ eV

Slide from M. Dolinski

Next-generation tonne-scale experiments

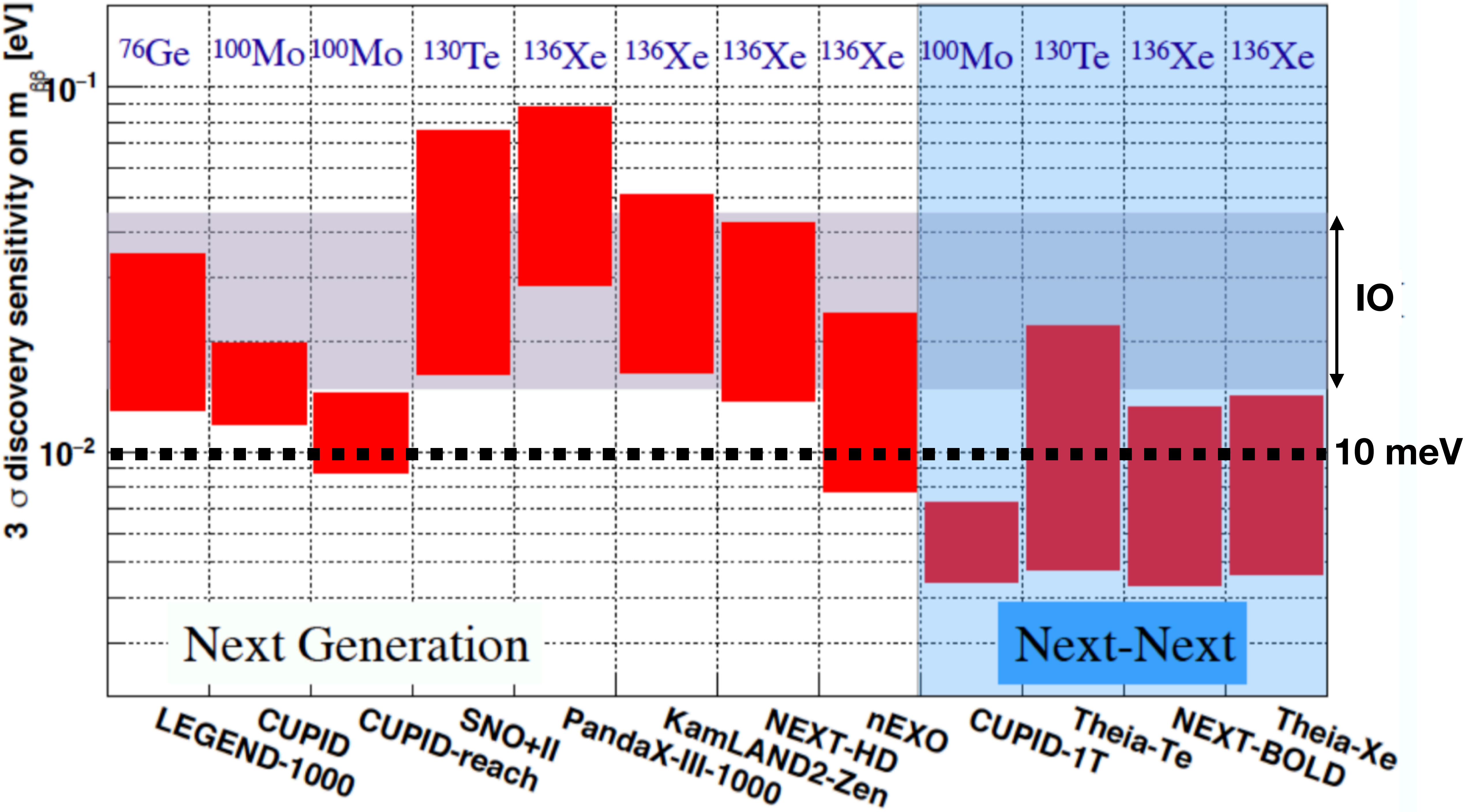
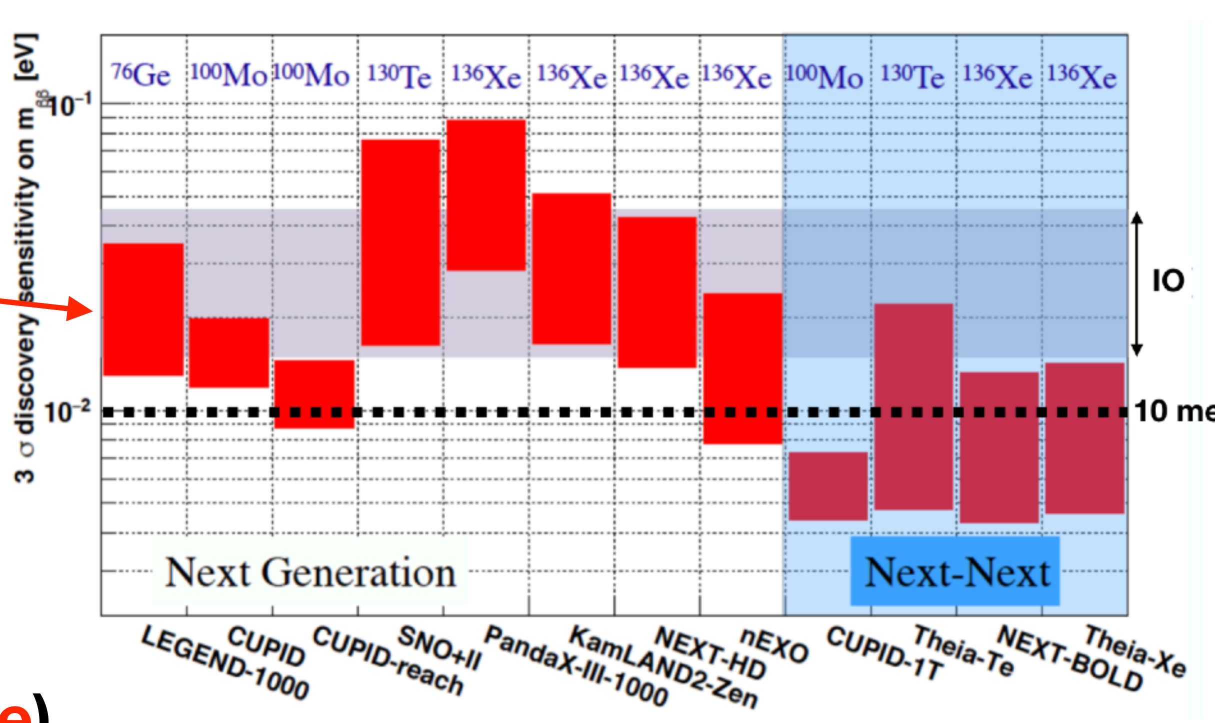


Figure from G. Benato, Y.G. Kolomensky
Methodology from Phys. Rev. D96, 053001 (2017)

Why the NME of $0\nu\beta\beta$ decay?

$$[T^{0\nu}_{1/2}]^{-1} = g_A^4 G_{0\nu} \left| \frac{\langle m_{\beta\beta} \rangle}{m_e} \right|^2 \boxed{|M^{0\nu}|^2}$$

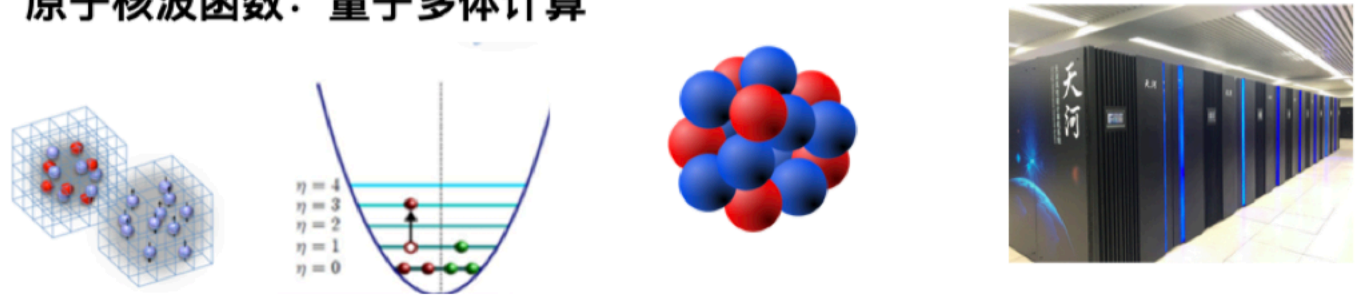
Large uncertainty due to the discrepancy in the NMEs by diff. nuclear models.



$$M^{0\nu} = \langle \Psi_F | \hat{O}^{0\nu} | \Psi_I \rangle$$

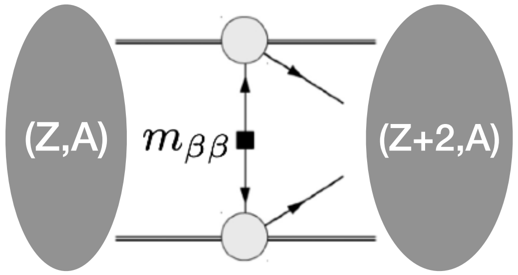
- **Nuclear many-body calculations (challenge)**

原子核波函数：量子多体计算

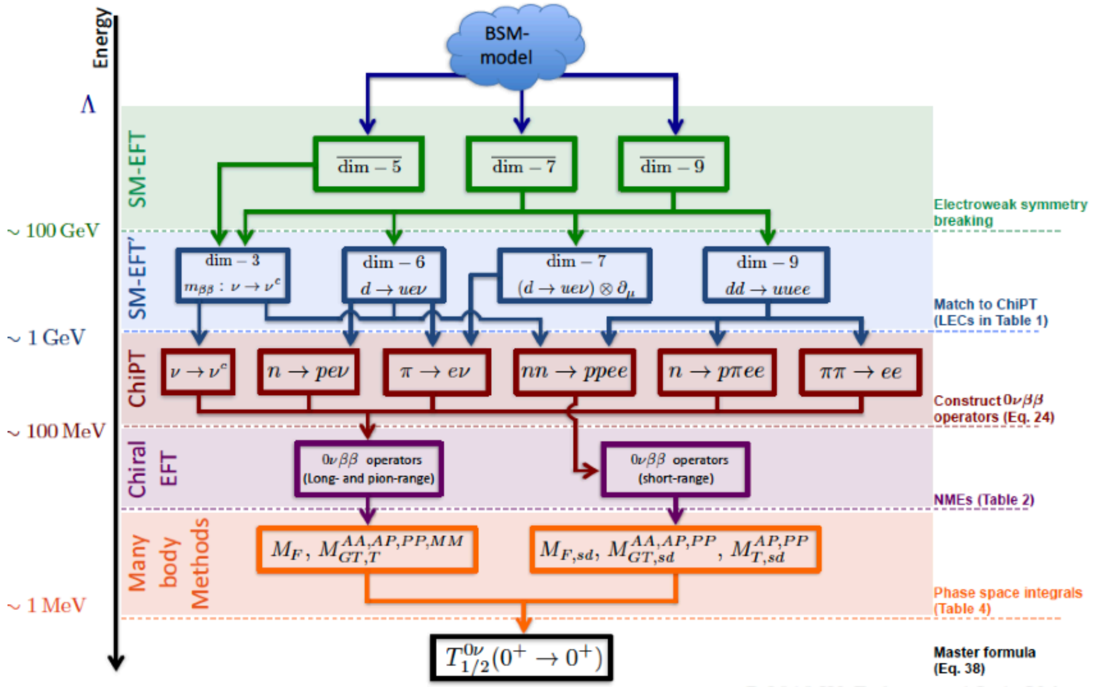


- **Lepton-number-violating (LNV) mechanism**

“Low-energy” effective operators in the “standard” mechanism

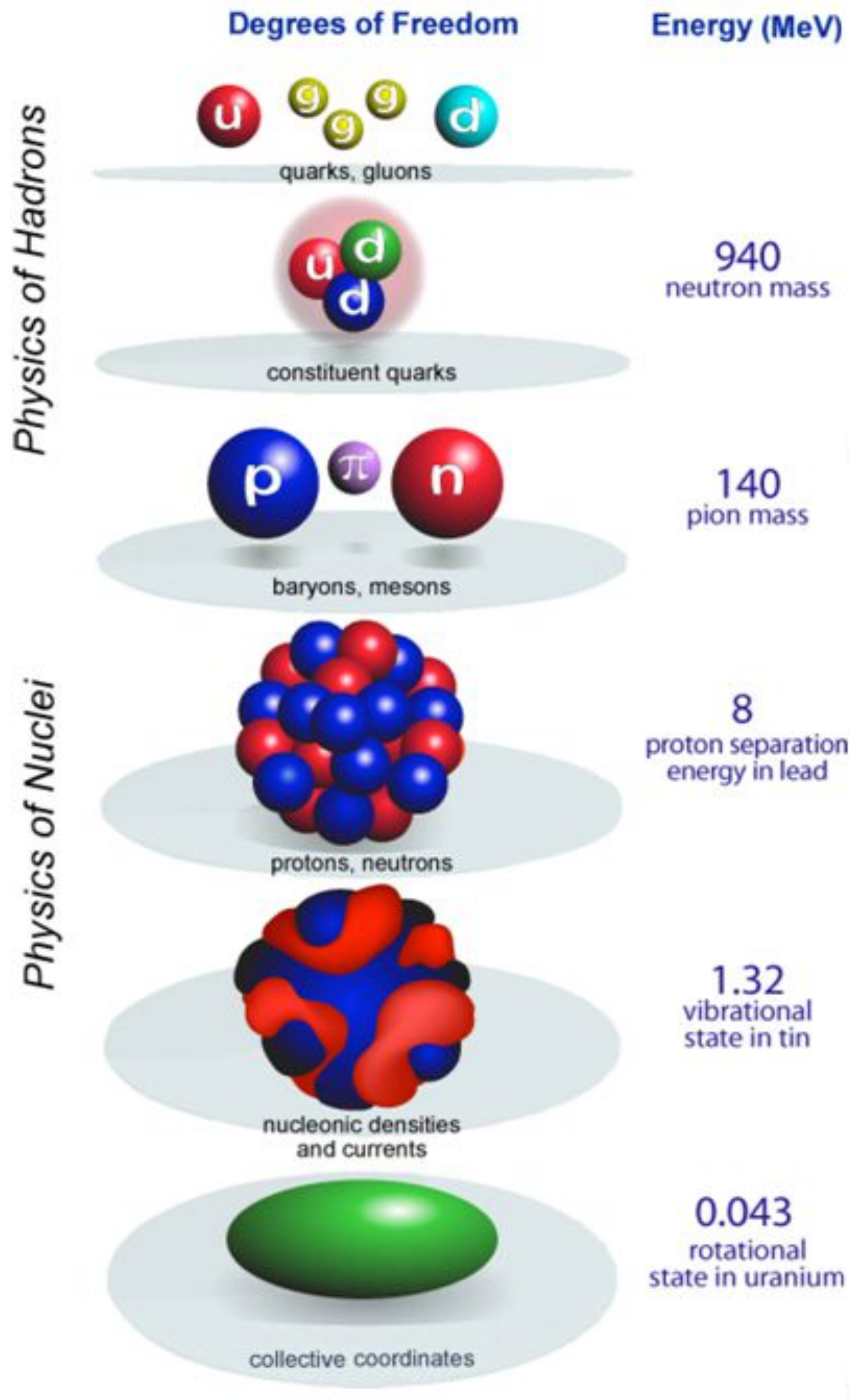


Effective Field Theories for $0\nu\beta\beta$



©2018 W. Dekens and J. de Vries

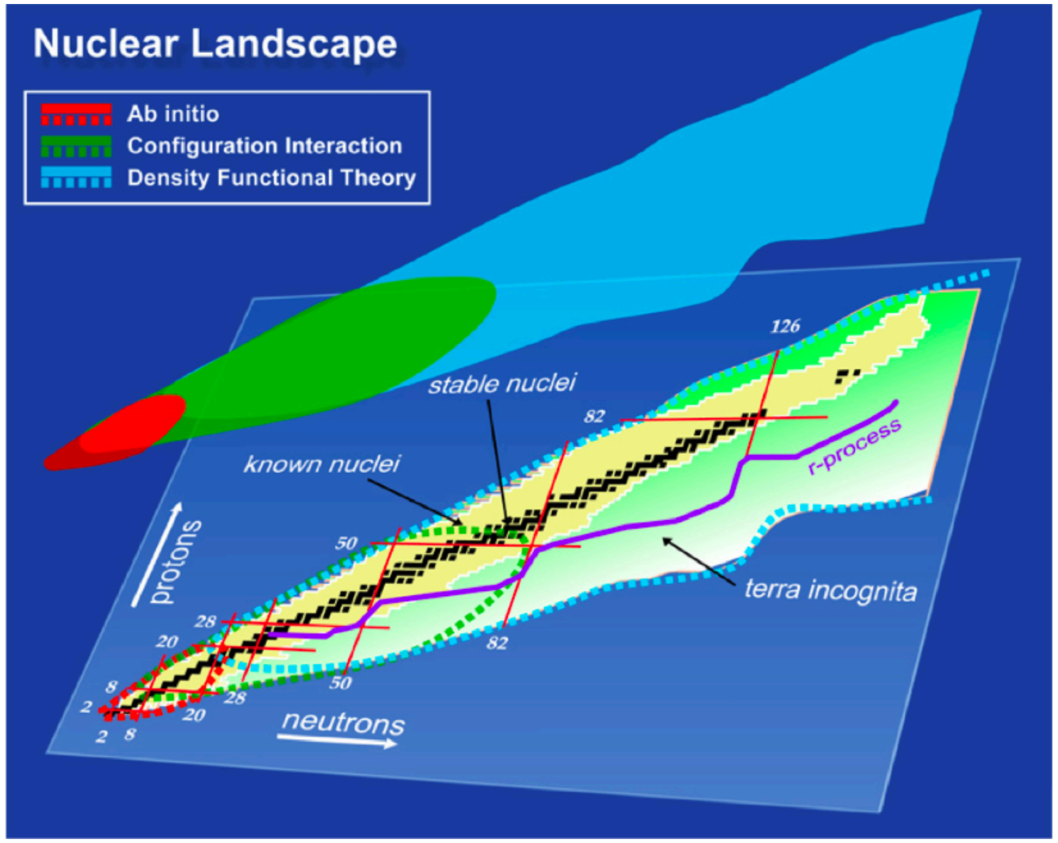
How to modeling atomic nuclei?



multi-faceted nuclei

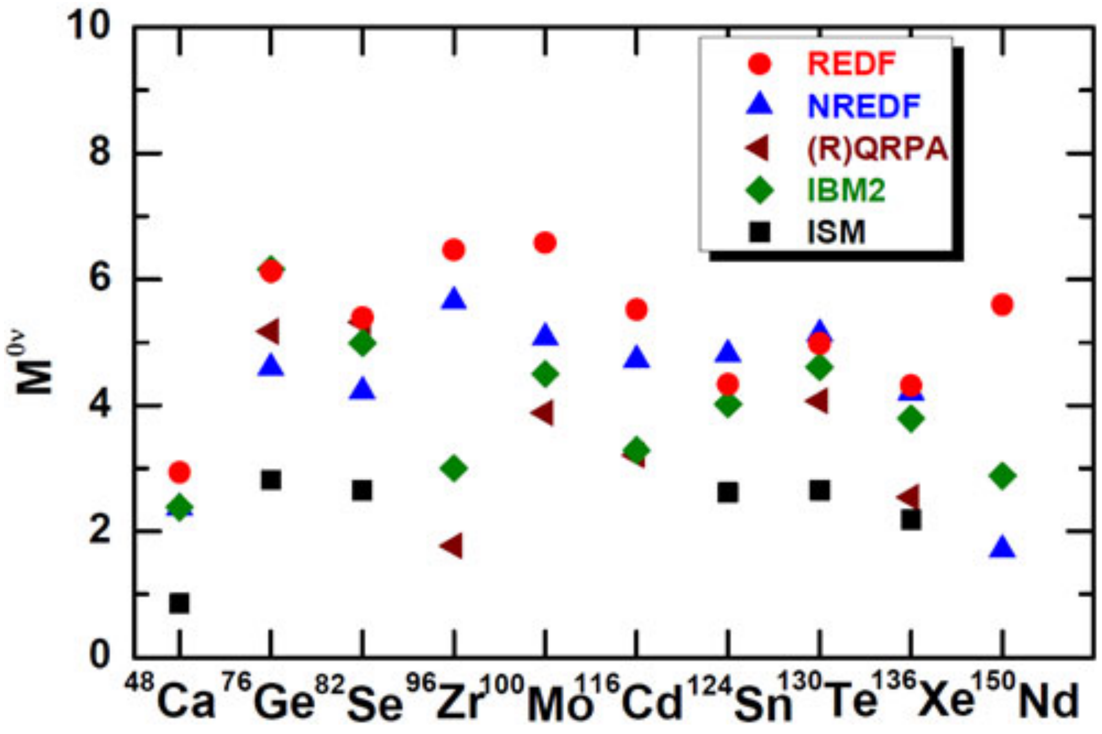
- **Nuclear many-body calculations (challenge)**

✓ Ab initio methods
✓ Configuration-interaction shell-models
✓ Nuclear energy density functionals
✓ Collective models
✓ …



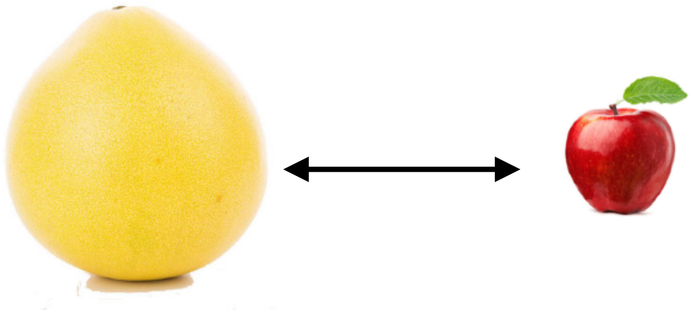
The Frontiers of Nuclear Science: A Long-Range Plan, 2007.

Nuclear Matrix Elements of $0\nu\beta\beta$ in phenomenological models



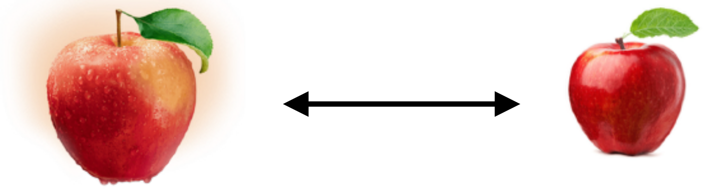
Current situation:

- ▸ **Differ by a factor up to 3**
- ▸ **Difficult to trace the origin of the discrepancies**
  - Different effective interactions
  - Different many-body truncations (approximation)



Ongoing efforts :

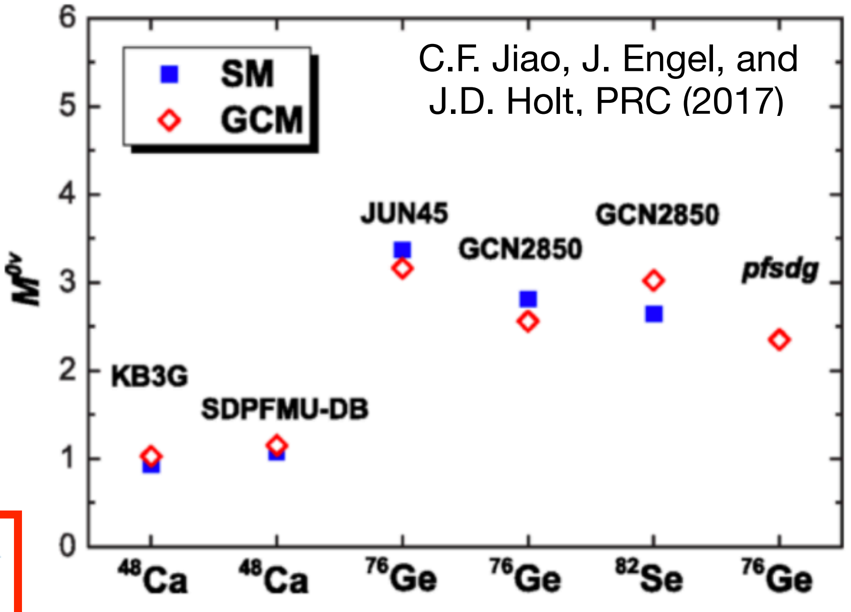
- ▸ **Understand/Reduce the discrepancy among various phenomenological models**
  - Same interactions, different many-body methods
  - Same many-body methods, different interactions



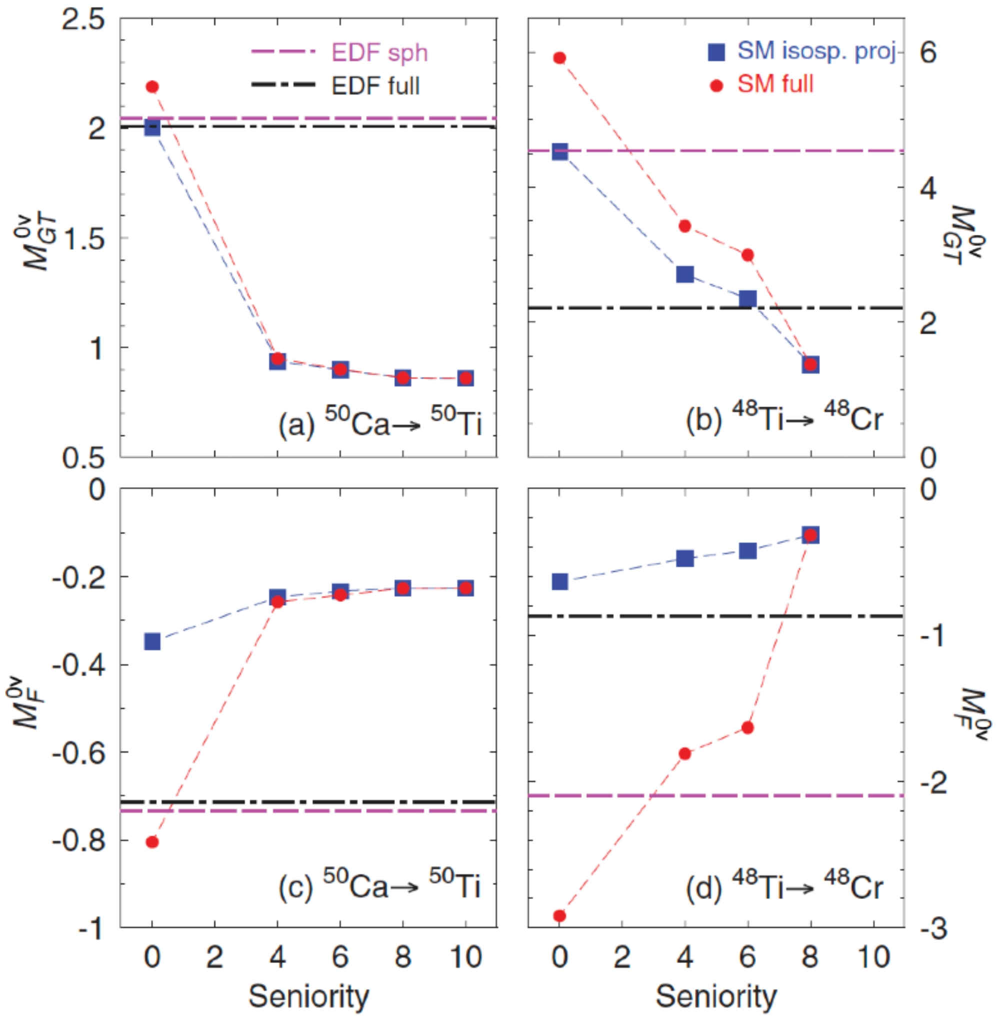
Understanding the existing discrepancy

- **Identify relevant degrees of freedom for 0νββ decay**
  - higher seniority components
  - Iso-scalar pairing
  - Shape mismatching

-> quenches NME

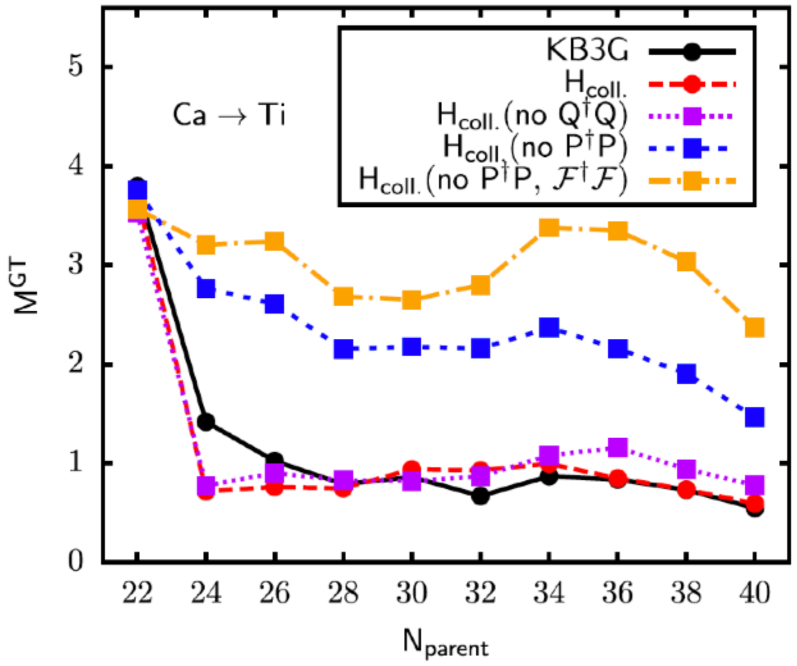


C.F. Jiao, J. Engel, and J.D. Holt, PRC (2017)

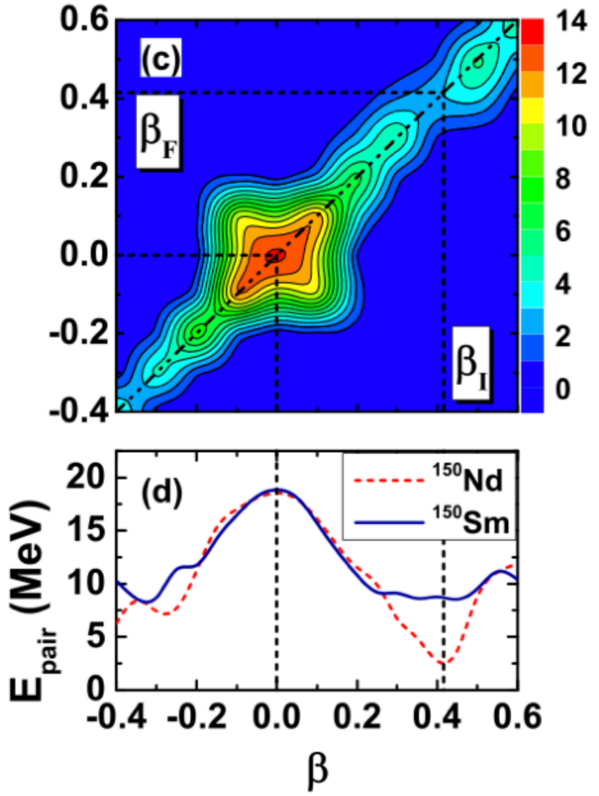


J. Menéndez et al., PRC (2014)

$$H = h_0 - \sum_{\mu=-1}^{1} g_\mu^{T=1}\, S_\mu^\dagger S_\mu - \frac{\chi}{2}\sum_{K=-2}^{2} Q_{2K}^\dagger Q_{2K} - g^{T=0}\sum_{\nu=-1}^{1} P_\nu^\dagger P_\nu + g_{ph}\sum_{\mu,\nu=-1}^{1} \mathcal{F}_\nu^{\mu\dagger}\mathcal{F}_\nu^{\mu}\,,$$



J. Menéndez et al., PRC (2016)

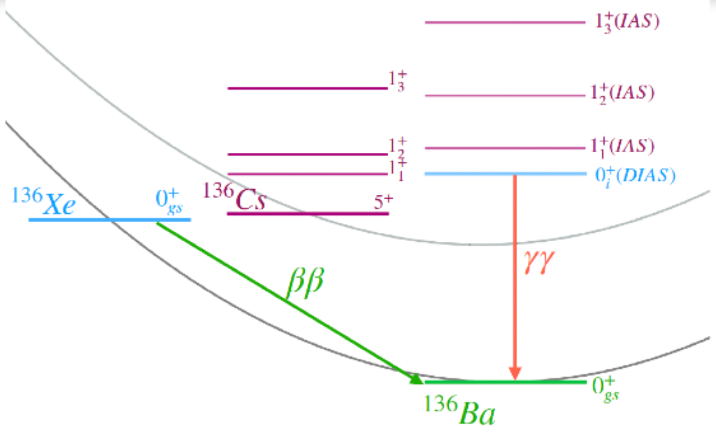


L.S. Song, JMY, P. Ring, J. Meng, PRC(2014)

Recent progresses in phenom. studies

- Correlation between diff. quantities

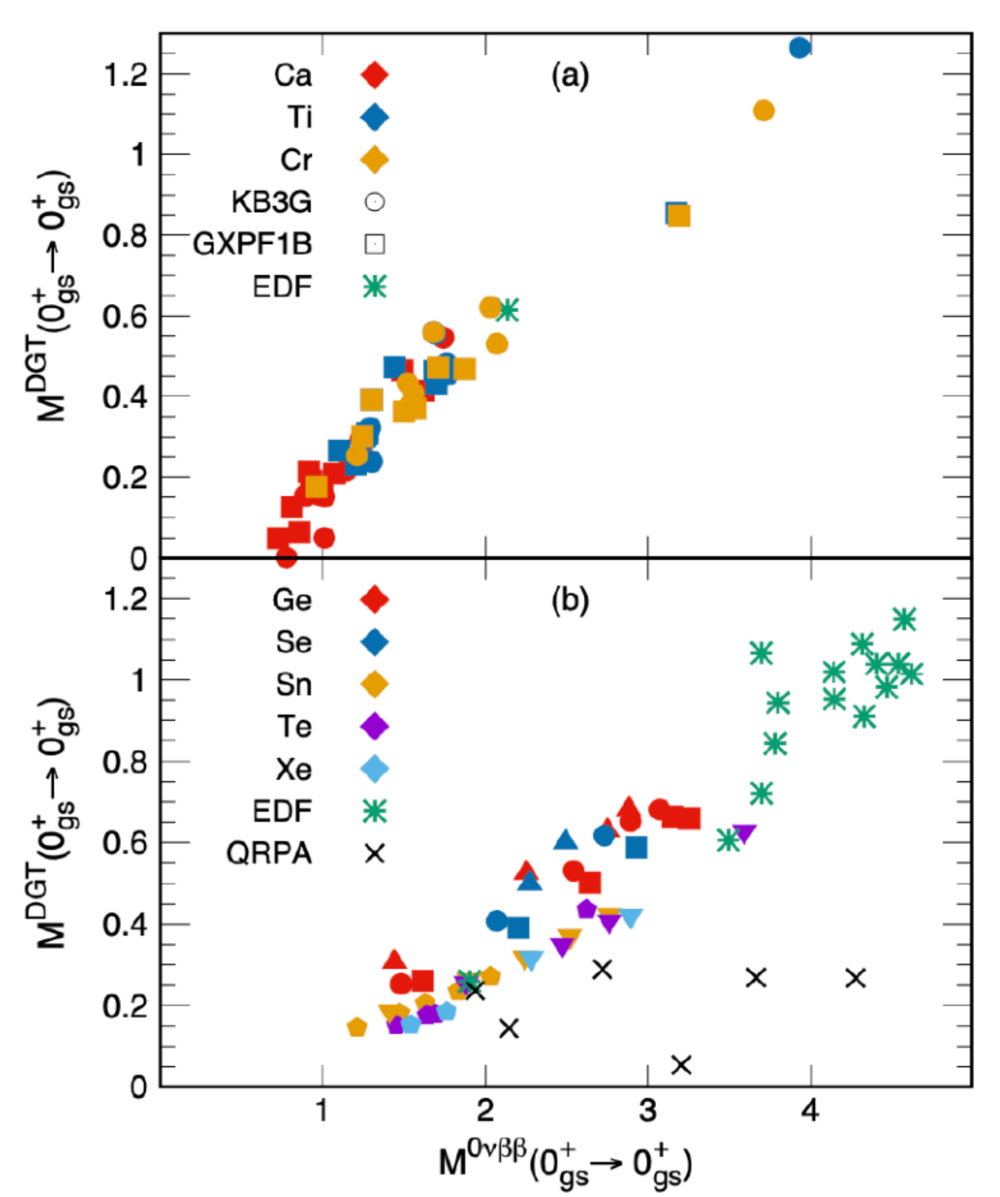
DGT: $|\langle 0^+_{gs,f}|| \sum_{j,k} [\sigma_j\tau_j^- \times \sigma_k\tau_k^-]^0 || 0^+_{gs,i}\rangle|$

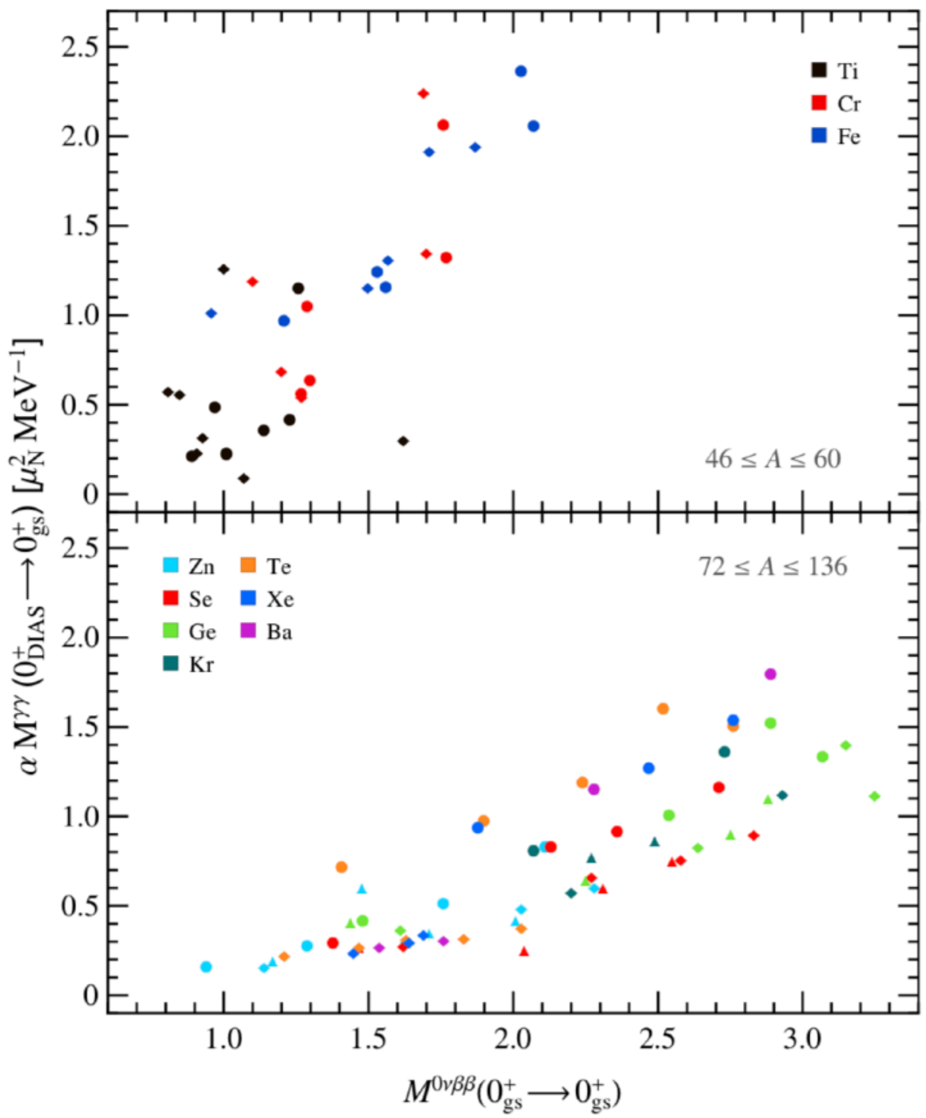


$|0^+(DIAS)\rangle = \frac{T_-T_-}{N_f}|0^+_{gs}(\beta\beta_{emiter})\rangle$

N. Shimizu, J. Menéndez and K. Yako, PRL(2018)

B. Romeo, J. Menéndez, C. Peña (2021)



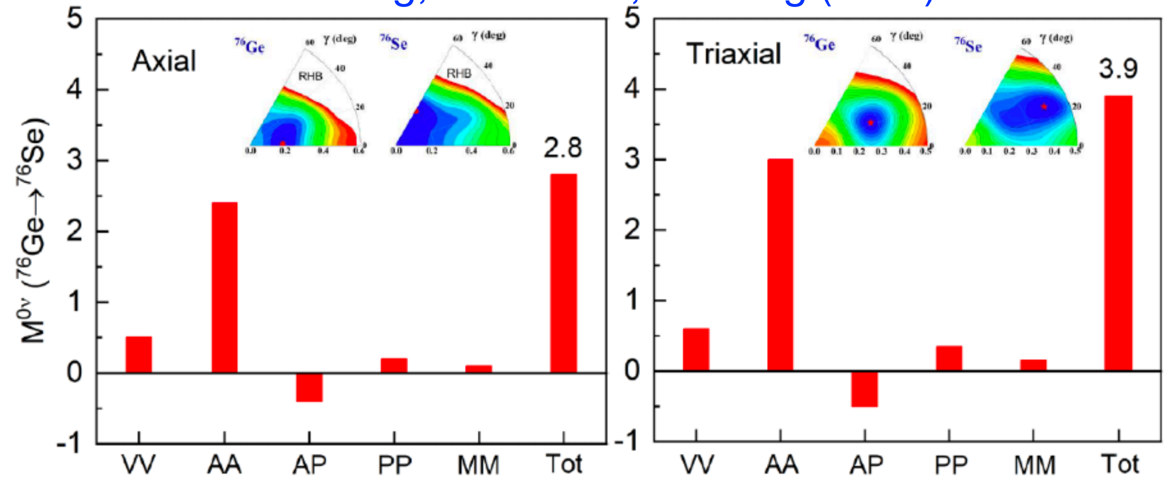


Recent progresses in phenom. studies

- Impact of higher-order deformation (triaxial)

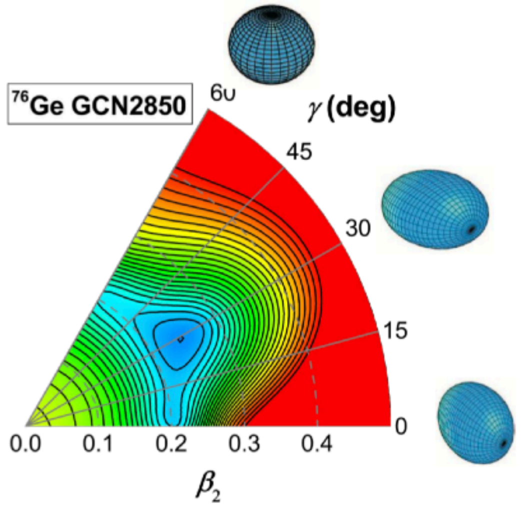
核矩阵元：三轴形变效应

Y.K. Wang, P.W. Zhao, J. Meng (2021)



- ✓ 轴矢耦合道贡献的核矩阵元值约占总核矩阵元值的 85%，赝标和弱磁耦合项的贡献约为10%
- ✓ 考虑三轴形变自由度，核矩阵元值从 2.8 增加到 3.9，增幅约 39%

Triaxial deformation



	GCN2850	JUN45
Axial GCM	2.93	3.51
Triaxial GCM	2.56	3.16
Exact	2.81 [6]	3.37 [35]

~10% reduced if triaxial-shape fluctuation is included.

CFJ, J. Engel, and J.D. Holt, PRC 96, 054310 (2017)

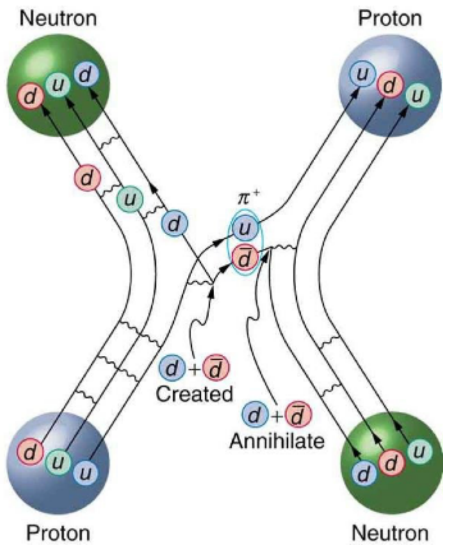
Comparing apples to oranges?

- Ongoing efforts…
  - Variation after projection (VAP) (Z.C. Gao, etc)
  - QRPA (D.L. Fang, C.L. Bai, Y.F. Niu, etc)
  - Nucleon-pairing-approximation (NPA) (B.C. He, S.Y. Zhang, Y. A. Luo, etc)
  - …

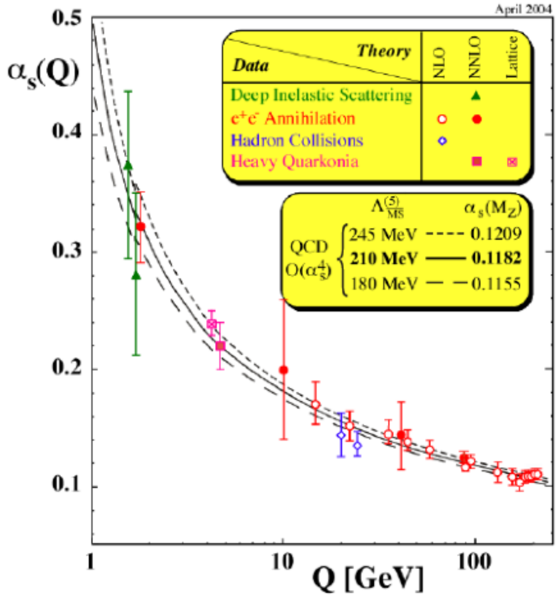
Nuclear Matrix Elements of $0\nu\beta\beta$ at the Crossroads

Modeling atomic nuclei from first principles?

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



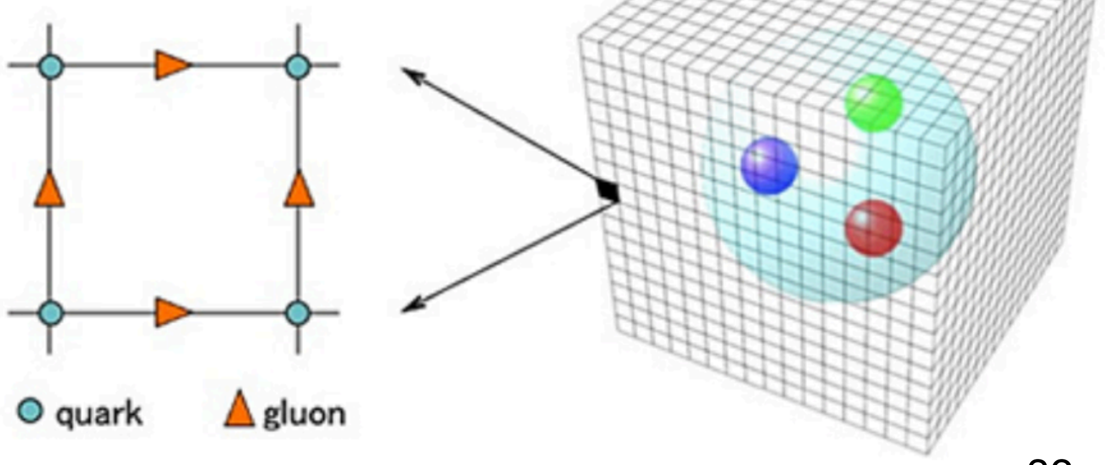
Quark and gluons: Non-perturbative nature of strong interaction in the low-energy regime relevant to nuclear physics



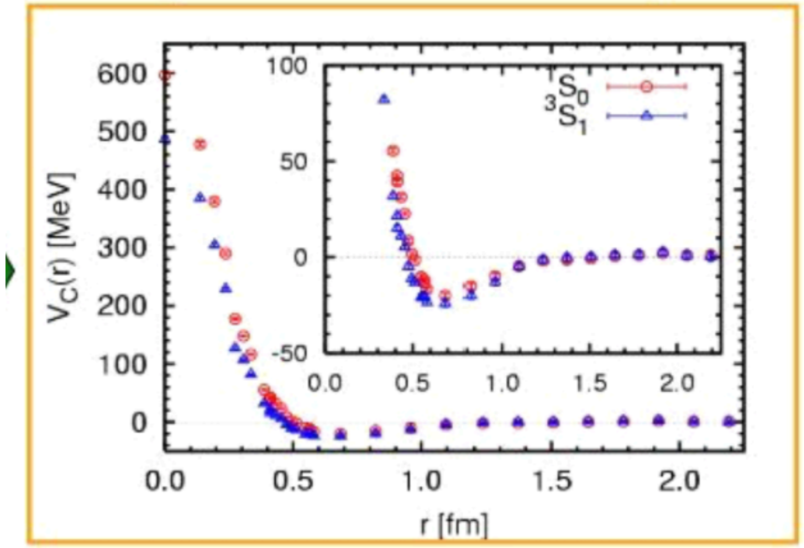
- Nuclear force from Lattice QCD (**infancy**)

QCD Lagrangian

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



Computation challenge at physical pion mass



HAL QCD collaboration

Ishii-Aoki-Hatsuda, PRL99(2007)022001

Ab initio modeling of nuclear $0\nu\beta\beta$ decays

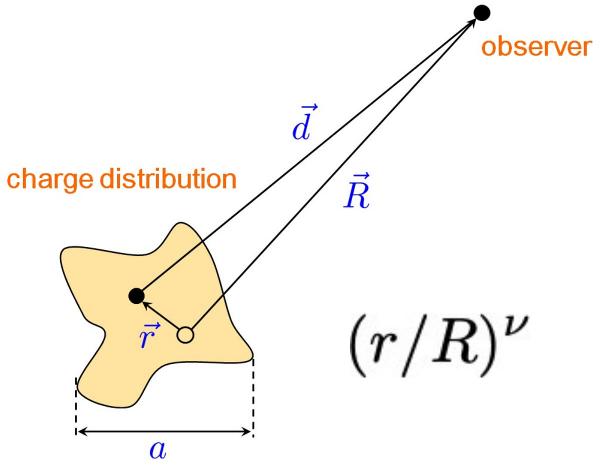
Our goal is to provide ab initio calculations of the NMEs (personally):

- in nuclear many-body methods with **controllable approximations**
- using **nuclear interactions and weak transition operators derived consistently** from an (chiral) EFT
- with the feature of **order-by-order convergence**.

Clarifications (Three Not Necessaries):

- **Nuclear many-body methods** not necessary to be full configuration-interaction
- **Nuclear force** not necessary to be derived directly from QCD in terms of (q,g)
- **LNV transition operator** not necessary to be derived directly from a fundamental theory (if any)

How to determine the potential V(R) if the charge distribution is unknown?



$(r/R)^\nu$

$$\int d^3r\,\frac{\rho(\vec{r})}{|\vec{R}-\vec{r}|} = \frac{q}{R} + \frac{1}{R^3}\sum_i R_i P_i + \frac{1}{6R^5}\sum_{ij}(3R_iR_j - \delta_{ij}R^2)Q_{ij} + \dots$$

LO NLO N²LO

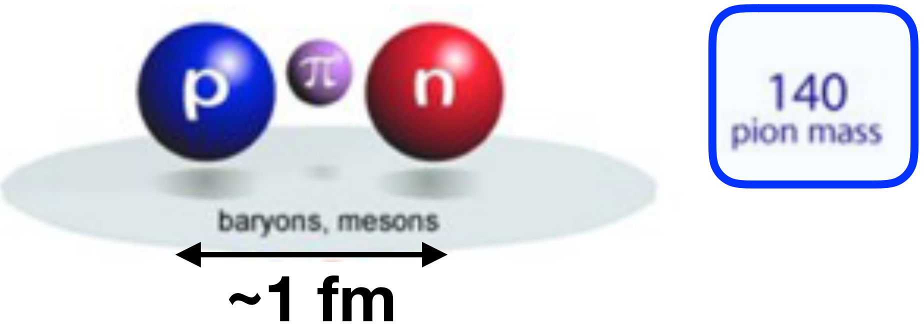
The result is systematically improvable

$$q = \int d^3r\,\rho(\vec{r}), \qquad P_i = \int d^3r\,\rho(\vec{r})\,r_i, \qquad Q_{ij} = \int d^3r\,\rho(\vec{r})(3r_ir_j - \delta_{ij}r^2)$$

Nuclear force from chiral EFT

- Nuclear force from the chiral EFT

d.o.f.: nucleons and pions



Weinberg's power counting:

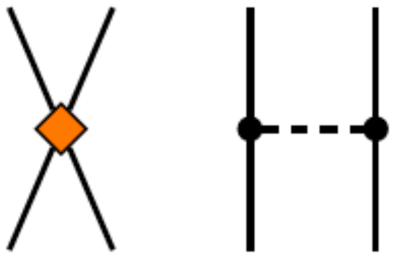
$$(Q/\Lambda_\chi)^\nu$$

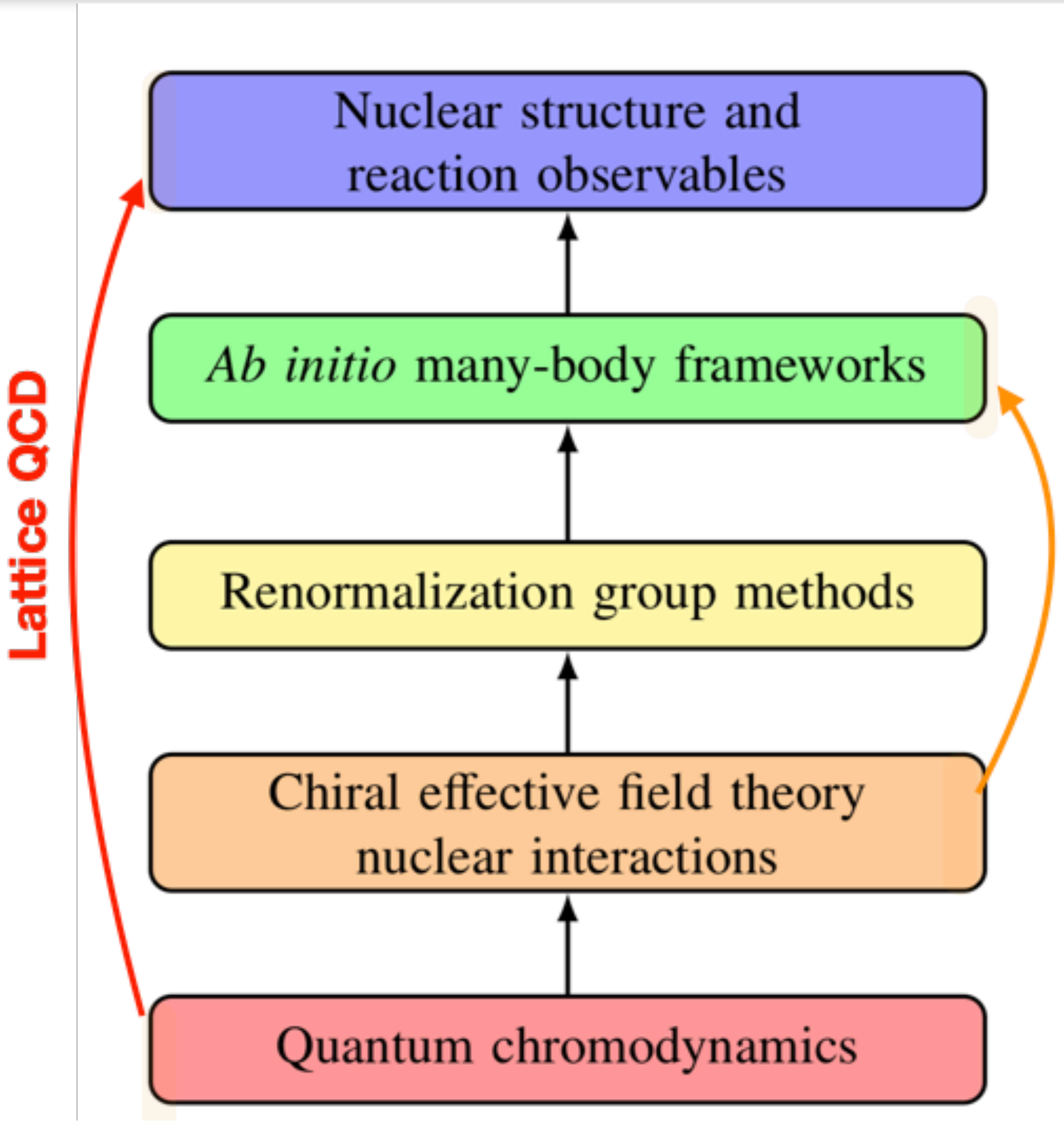
chiral-symmetry-breaking hard scale (~700 MeV)

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

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

LO





Nuclear structure and reaction observables

Ab initio many-body frameworks

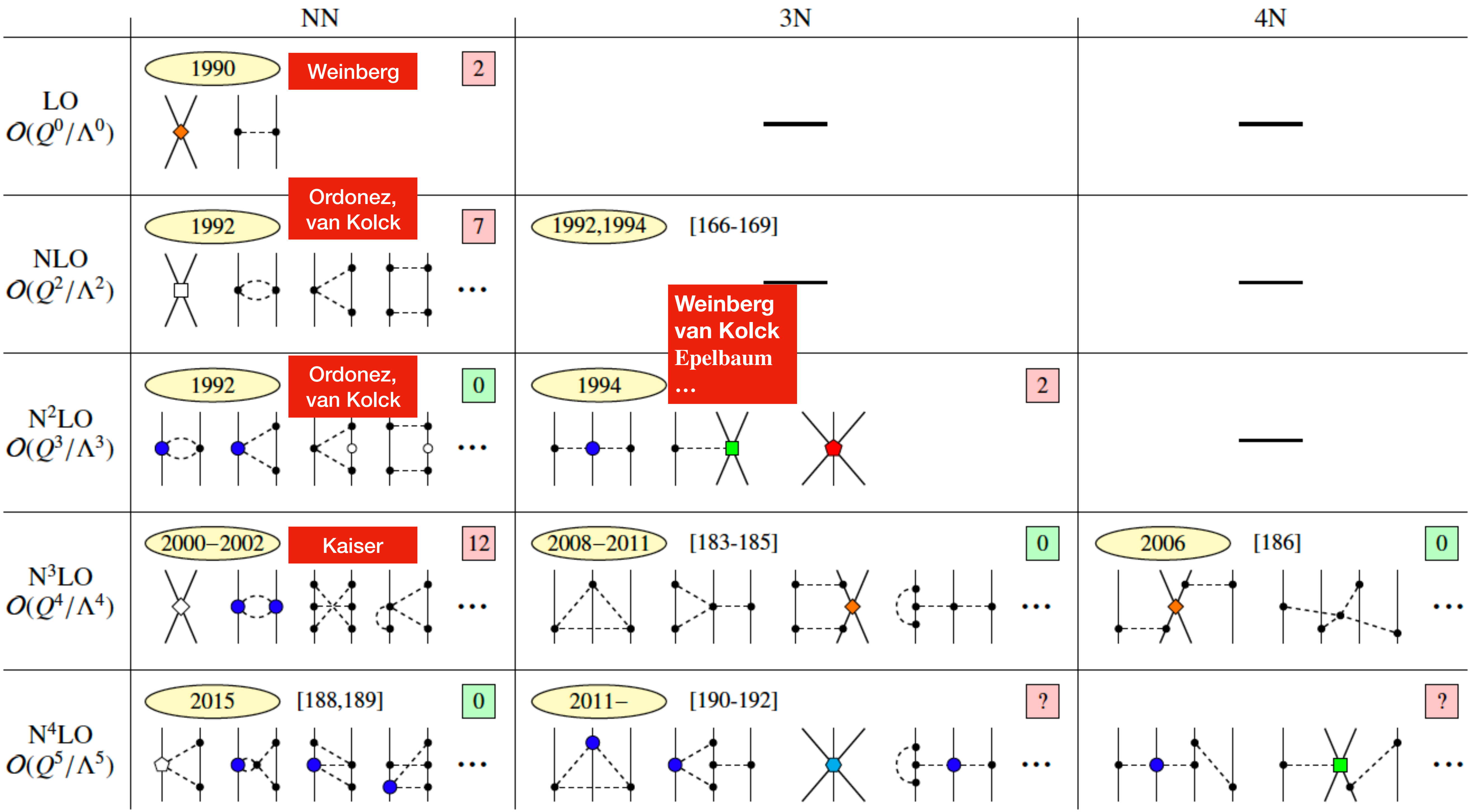
Renormalization group methods

Chiral effective field theory nuclear interactions

Quantum chromodynamics

K. Hebeler, Phys. Rep. 890, 1 (2020)

Nuclear force from chiral EFT



	NN	3N	4N
LO $\mathcal{O}(Q^0/\Lambda^0)$	1990 **Weinberg** 2	—	—
NLO $\mathcal{O}(Q^2/\Lambda^2)$	1992 **Ordonez, van Kolck** 7	1992,1994 [166-169] —	—
N^{2}LO $\mathcal{O}(Q^3/\Lambda^3)$	1992 **Ordonez, van Kolck** 0	**Weinberg** **van Kolck** **Epelbaum** **…** 1994 2	—
N^{3}LO $\mathcal{O}(Q^4/\Lambda^4)$	2000–2002 **Kaiser** 12	2008–2011 [183-185] 0	2006 [186] 0
N^{4}LO $\mathcal{O}(Q^5/\Lambda^5)$	2015 [188,189] 0	2011– [190-192] ?	?

K. Hebeler, Phys. Rep. 890, 1 (2020)

ab initio many-body frameworks

- **Quantum Monte Carlo methods**

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

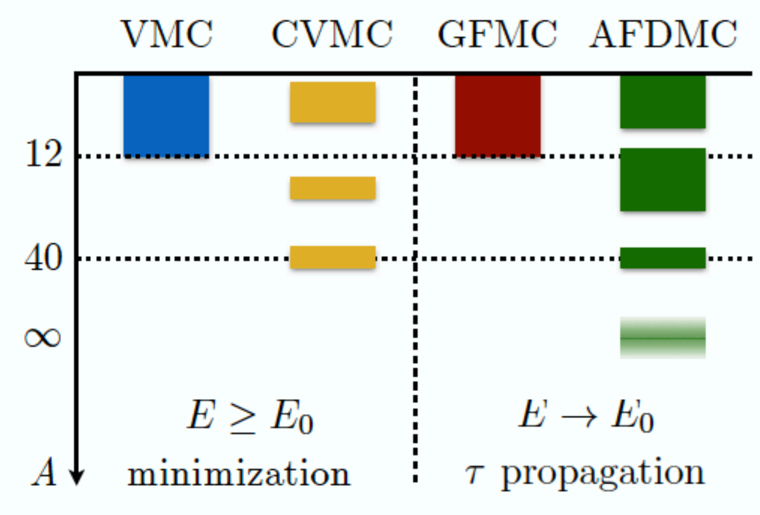
  J. Carlson et al., RMP 87, 1067 (2015)

  Variational Monte Carlo (VMC)

  Green's function Monte Carlo (GFMC)

  Auxiliary-field diffusion Monte Carlo (AFDMC)

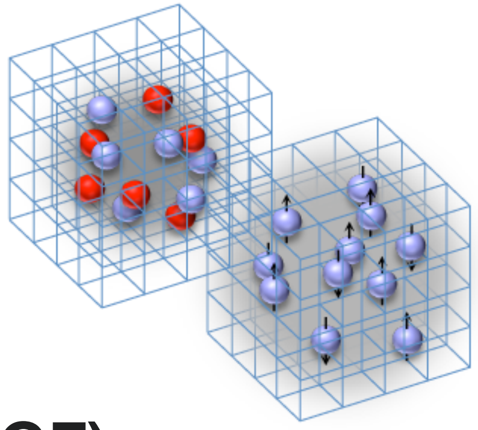
credit: D. Lonardoni



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

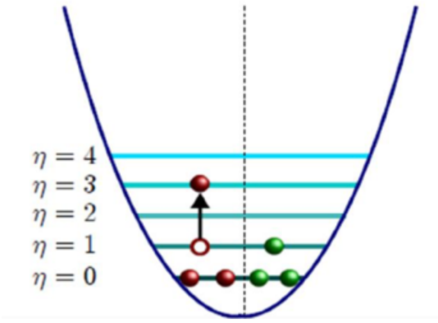
- **Lattice effective field theory (LEFT)**

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



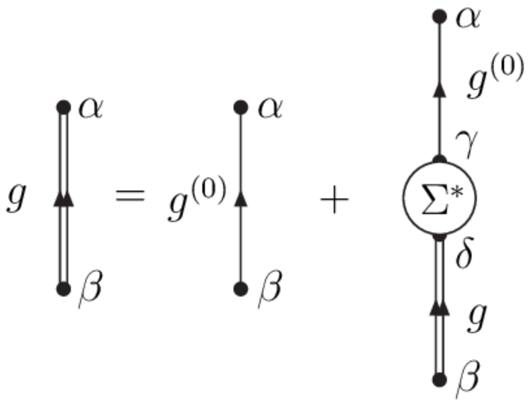
- **No-core shell model (NCSM)**

  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)

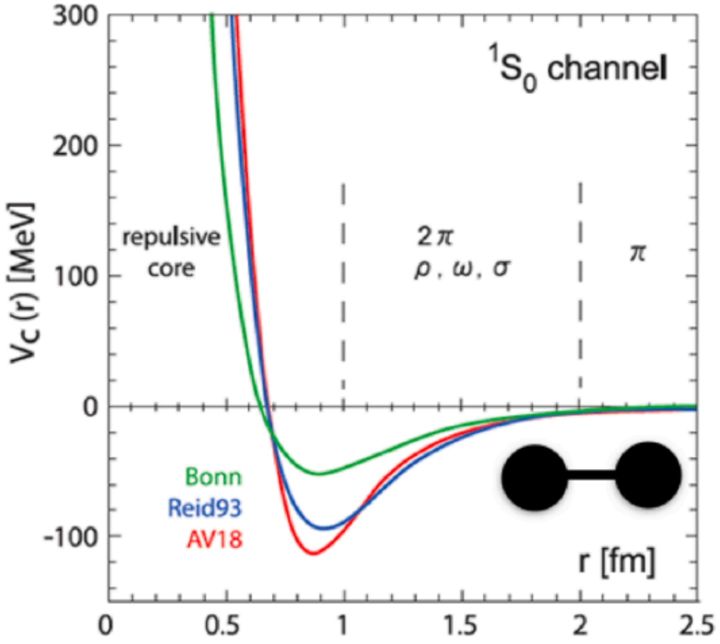
- **In-medium similarity renormalization group (IM-SRG)**

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

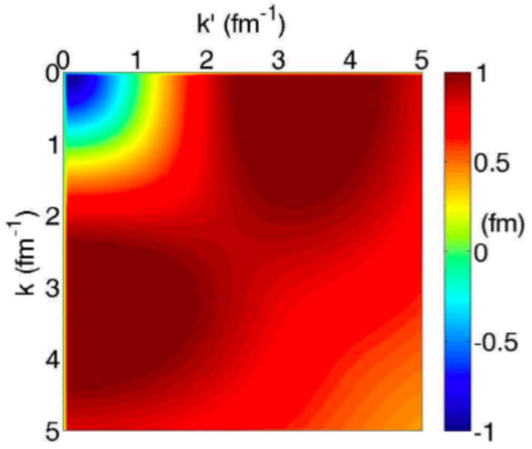
- MBPT, (R)BHF,...

孟杰、许甫荣、胡金牛、申时行等

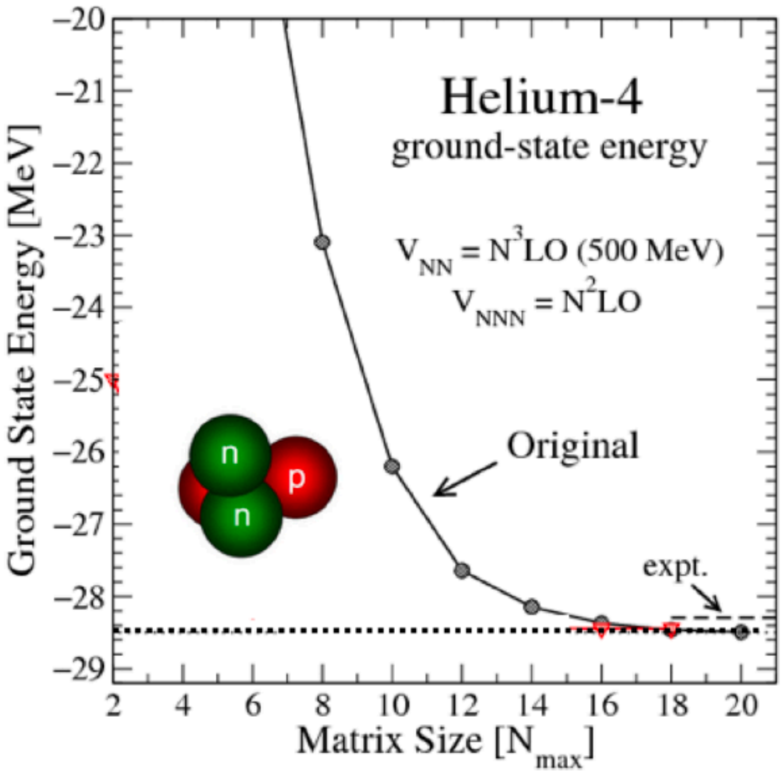
Realistic nuclear force: challenge



$$V_{\ell=0}(k,k') = \int d^3 r j_0(kr) V(r) j_0(k'r)$$



S. Bogner et al., PPNP (2010)

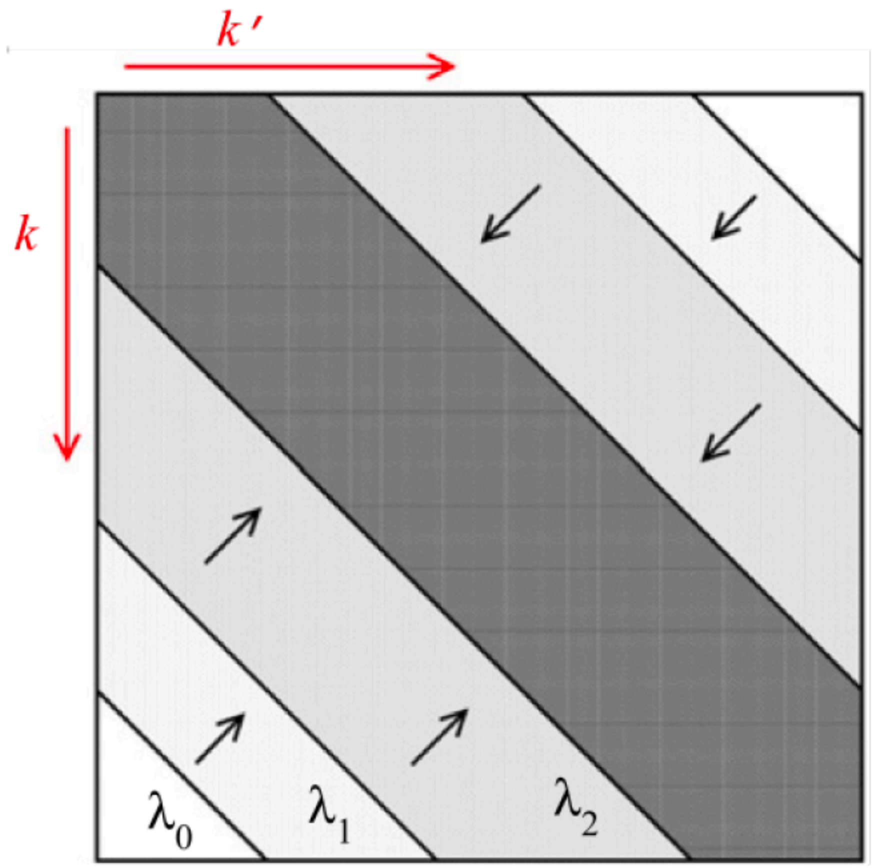


- Repulsive core & strong tensor force => low and high k modes strongly coupled by the interaction
- non-perturbative, poorly convergent basis expansions (cutoff Λ, No. of s.p. states D)

$$Dim(H) \sim \frac{D!}{(D-A)!A!}, \quad D \sim \Lambda^3 A \quad A \sim R^3$$

For $\Lambda = 4.0\ \mathrm{fm}^{-1}$, $A = 16$, $Dim(H) \sim 10^{14}$.

Realistic nuclear force: SRG



The flow parameter s is usually replaced with $\lambda = s^{-1/4}$ with units of fm^{-1}.

S. K. Bogner, R. J. Furnstahl, and R. J. Perry (2007)

- Apply unitary transformations to Hamiltonian

$$H_s = U_s H U_s^\dagger \equiv T_{\mathrm{rel}} + V_s \tag{1}$$

- Flow equation

$$\frac{dH_s}{ds} = [\eta_s, H_s], \tag{2}$$

where the generator η_s is chosen to diagonalize $H(s)$ in the eigenbasis of T_{rel},

$$\eta_s = [T_{\mathrm{rel}}, H_s] \tag{3}$$

$$\frac{dV_s(k,k')}{ds} = -(k^2 - k'^2)V_s(k,k') + \frac{2}{\pi}\int_0^\infty q^2 dq (k^2 + k'^2 - 2q^2) V_s(k,q) V_s(q,k')$$

Realistic nuclear force: SRG

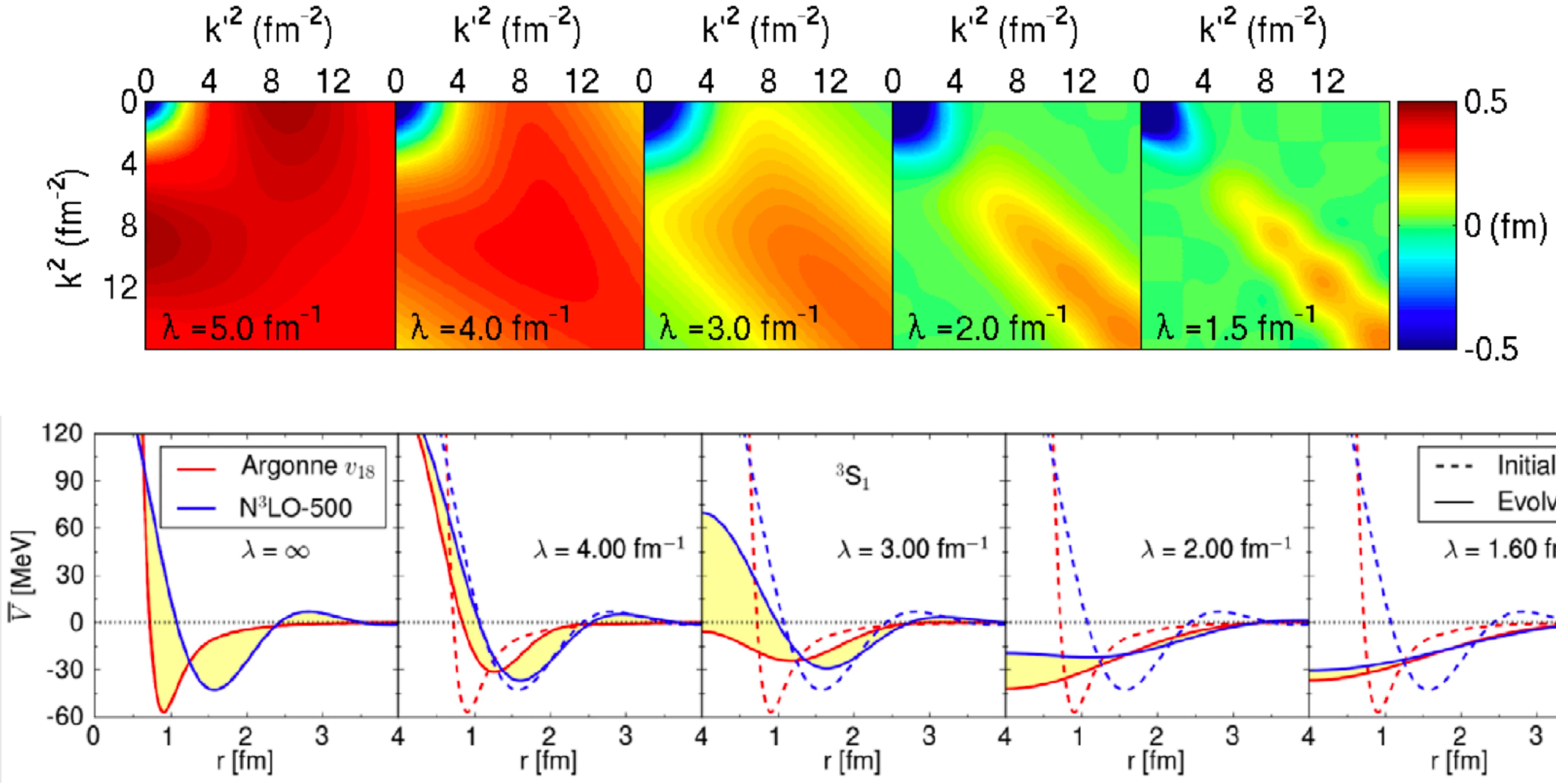


Figure: Local projection of AV18 and N^{3}LO(500 MeV) potentials $V(r)$ in $^3S_1$ channel.

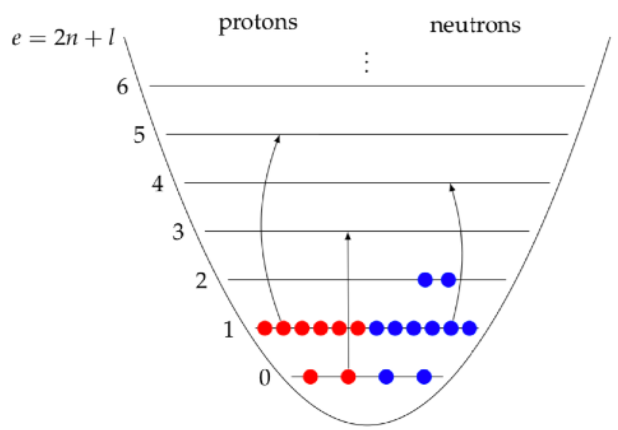
- "Hard core" disappears in the softened interactions

S. K. Bogner et al. (2010); Wendt et al. (2012)

NCSM: exponential growth of the model space

- The A-body Schroedinger equation

$$H|\Psi\rangle = E|\Psi\rangle,$$



- The wave function is expanded in terms of many-body basis states

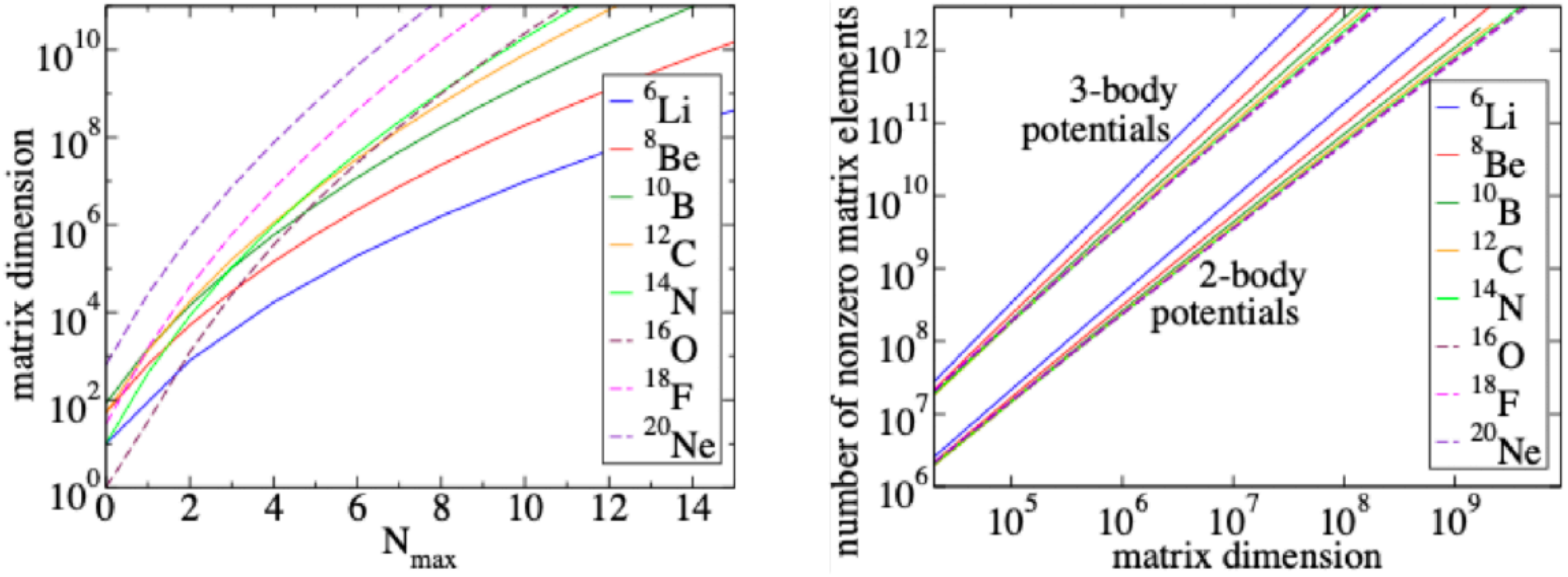
$$|\Psi\rangle = \sum_{\mu} c_{\mu}|\Phi_{\mu}\rangle,$$

where c_μ is to be determined from the diagonalization of the H. $|\Phi_\mu\rangle$ is a Slater Determinant of single-particle states occupied by the nucleons.

Dimension:

$$D \sim \binom{\Omega_\pi}{N_\pi}\binom{\Omega_\nu}{N_\nu}$$

Computation challenge



from: C. Yang, H. M. Aktulga, P. Maris, E. Ng, J. Vary, Proceedings of NTSE-2013

In-medium similarity renormalization group (IMSRG)

- A set of continuous unitary transformations onto the Hamiltonian

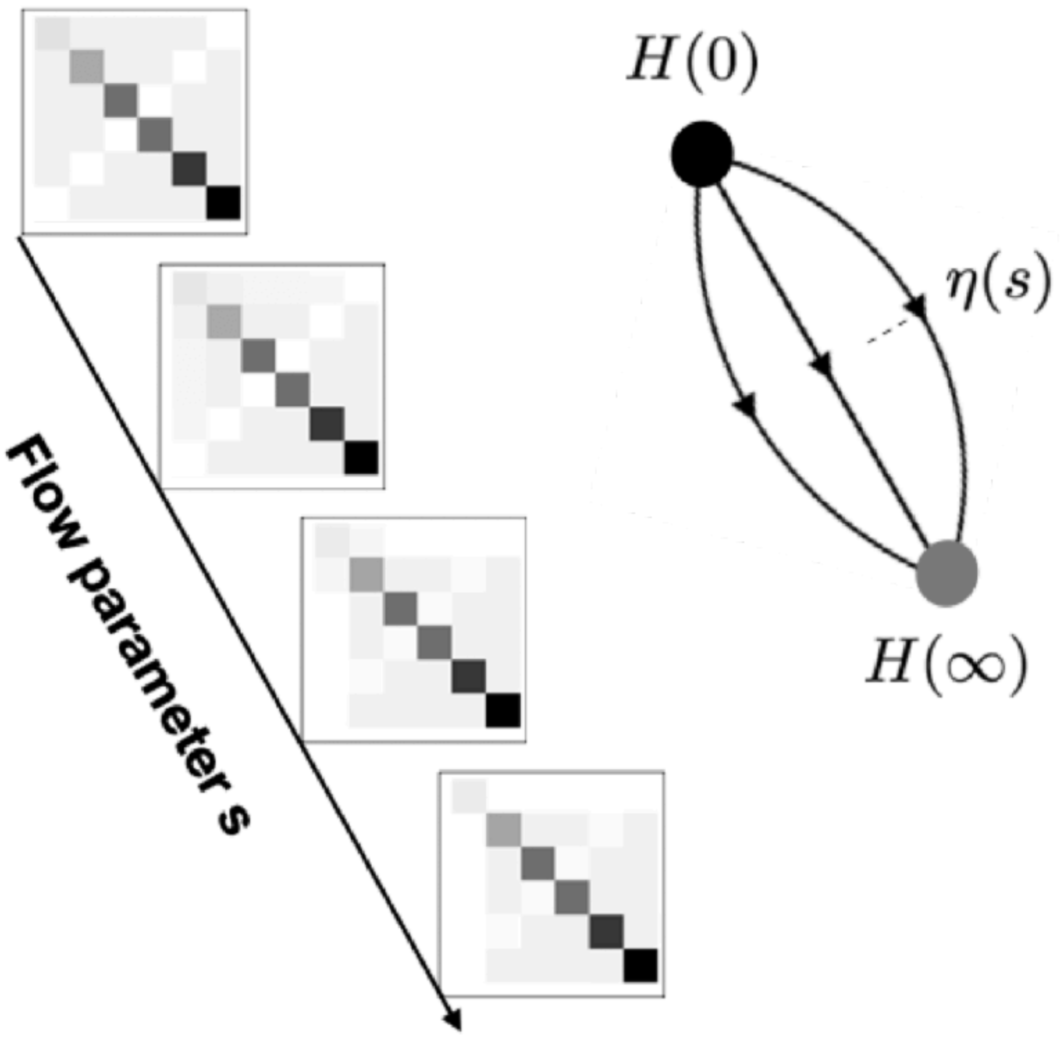
$$H(s) = U(s) H_0 U^\dagger(s)$$

- Flow equation for the Hamiltonian

$$\frac{dH(s)}{ds} = [\eta(s), H(s)]$$

where the $\eta(s) = \frac{dU(s)}{ds} U^\dagger(s)$ is the so-called generator chosen to decouple a given reference state from its excitations.

- Computation complexity scales polynomially with nuclear size

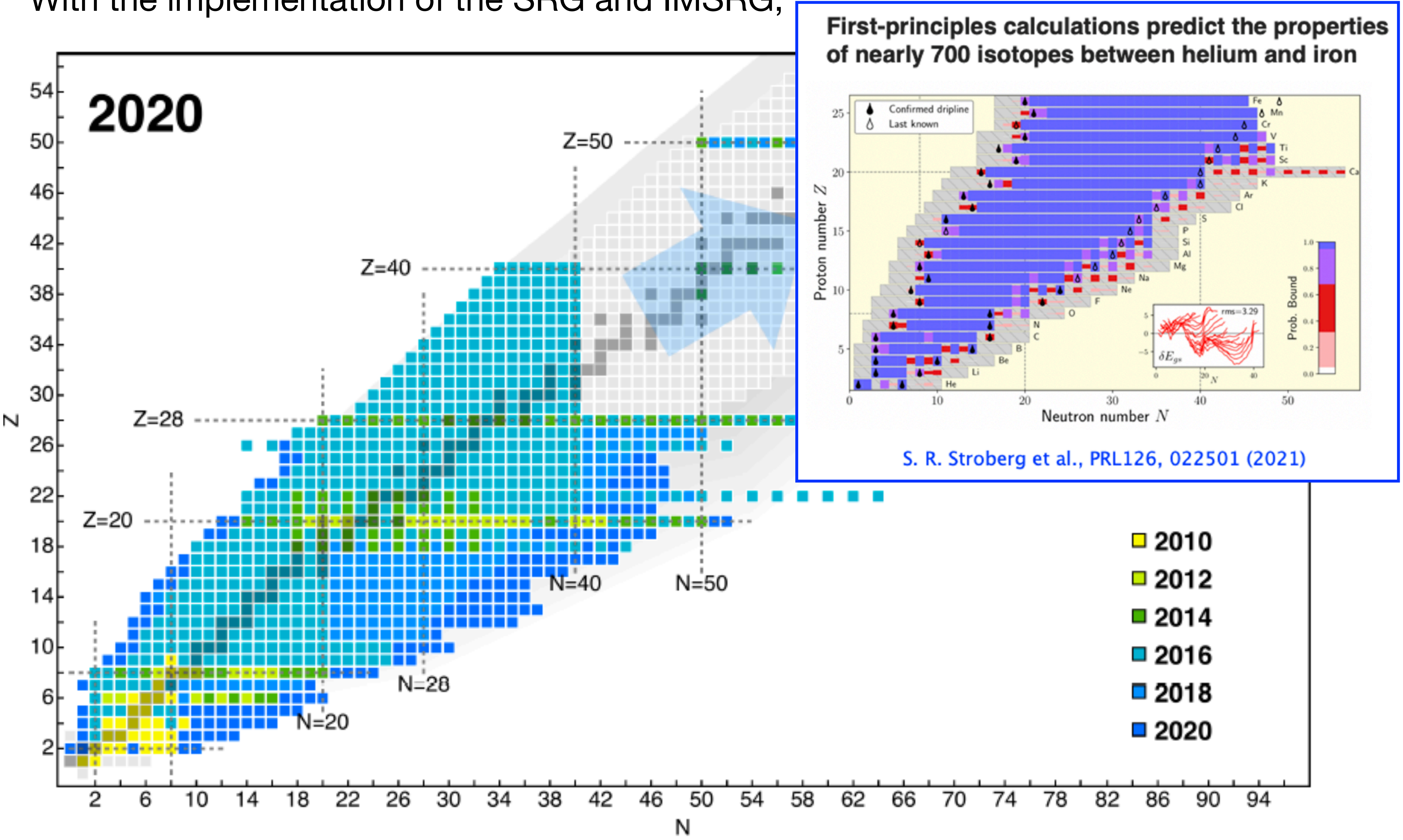


Tsukiyama, Bogner, and Schwenk (2011)
Hergert, Bogner, Morris, Schwenk, Tsukiyama (2016)

Not necessary to construct the H matrix elements in many-body basis !

Achievements of ab initio calculations for nuclei

With the implementation of the SRG and IMSRG,



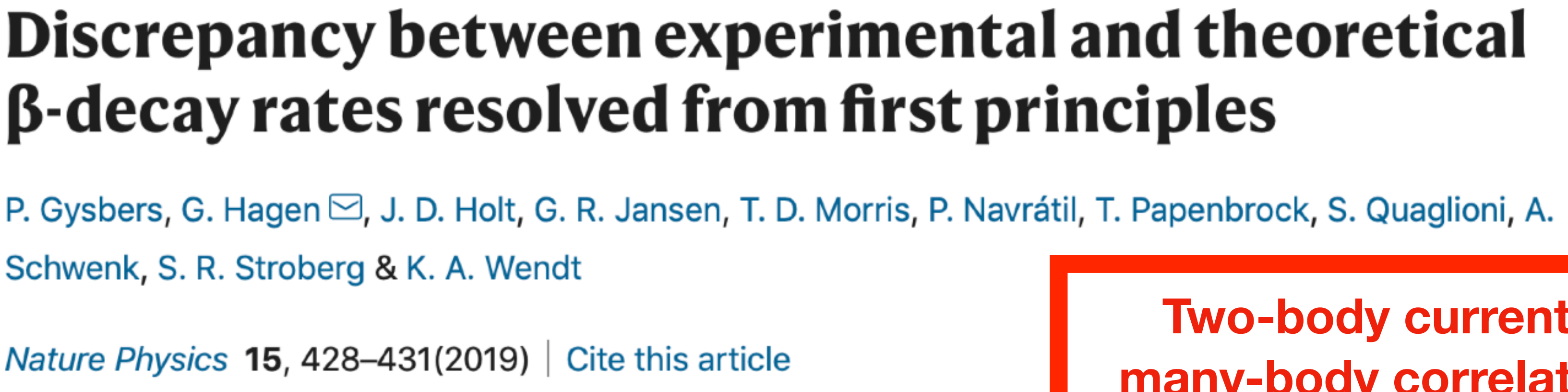
First-principles calculations predict the properties of nearly 700 isotopes between helium and iron

S. R. Stroberg et al., PRL126, 022501 (2021)

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

ab initio calculations of nuclear single-beta decay

g_A quenching in GT transition

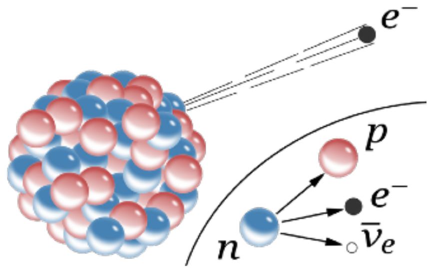


Discrepancy between experimental and theoretical β-decay rates resolved from first principles

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

Two-body currents+ many-body correlations

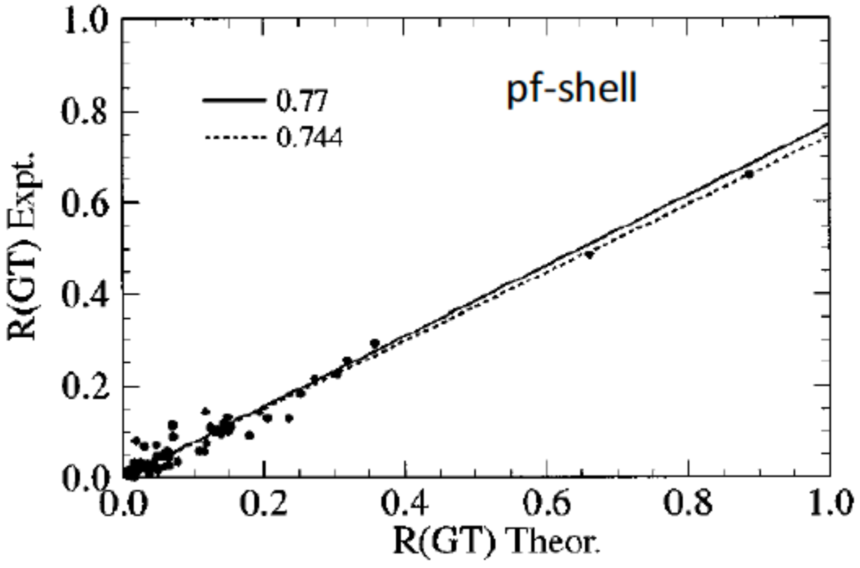


- The half-life of single-beta decay

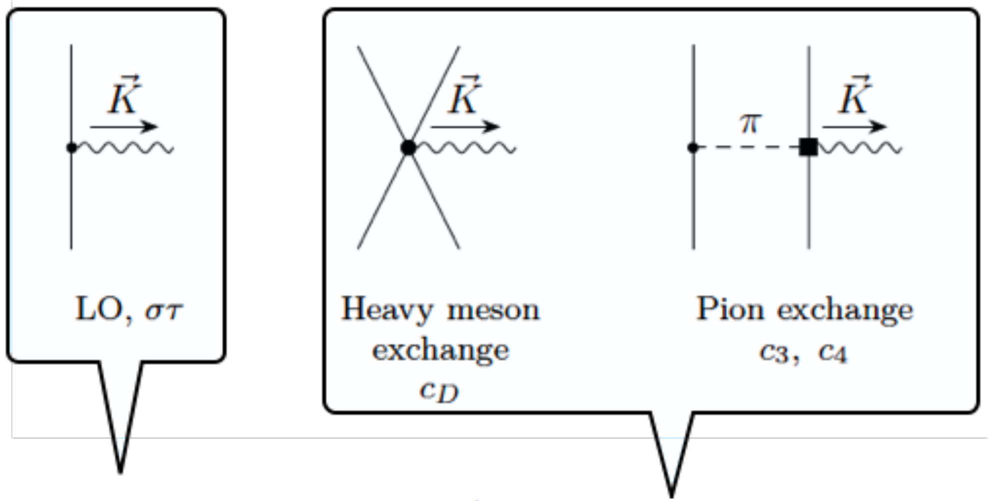
$$t_{1/2} = \frac{\kappa}{f_0(B_F + B_{\rm GT})},$$

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

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



- charge-changing axial-vector current



$$\vec{J}^A(\vec{K}) = \sum_j \imath g_A \boldsymbol{\sigma}_j \boldsymbol{\tau}_j^{\pm} e^{\imath \vec{K}\cdot\vec{r}_j}\,.$$

2B currents

Park, T.-S. et al. Phys. Rev. C 67, 055206 (2003)

- GT transition operator

$$O_{\rm GT} = O_{\sigma\tau}^{1b} + O_{\rm 2BC}^{2b}.$$

ab initio calculations of nuclear single-beta decay

g_A quenching in GT transition

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

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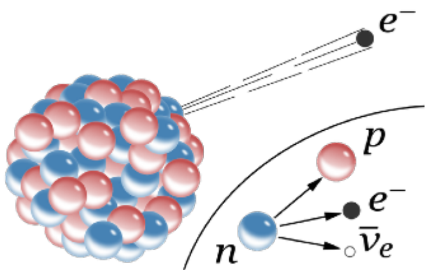
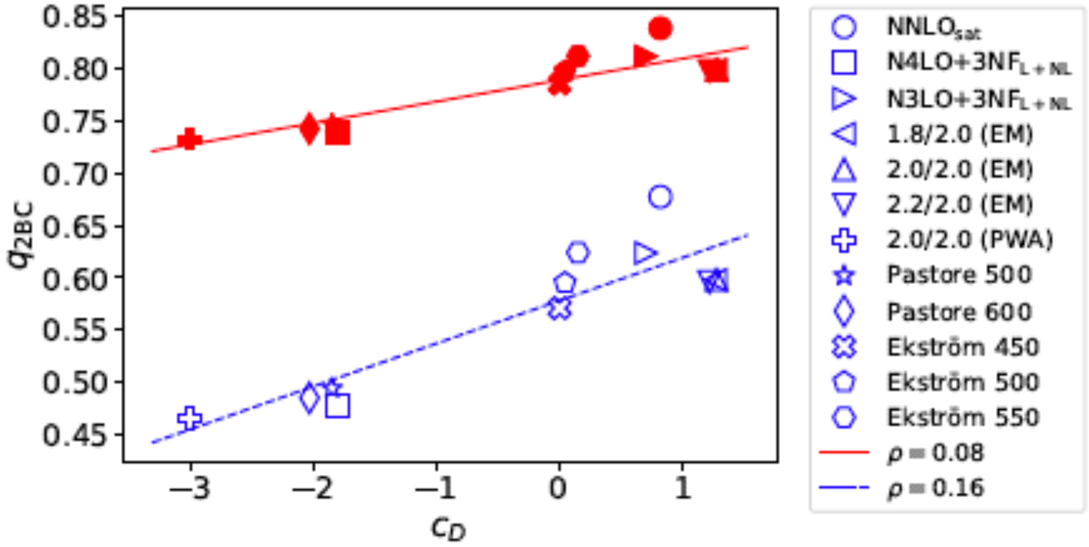
Two-body currents+ many-body correlations

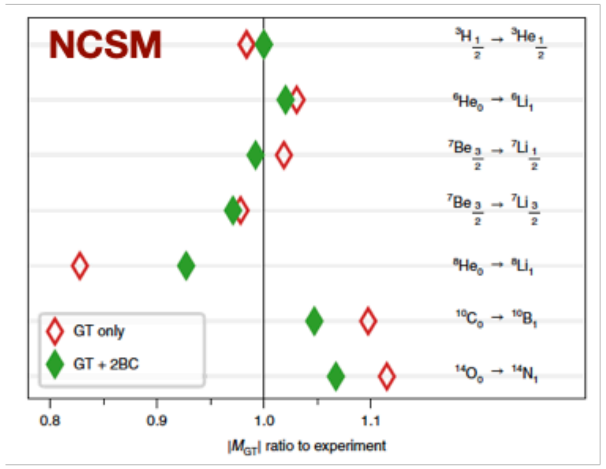


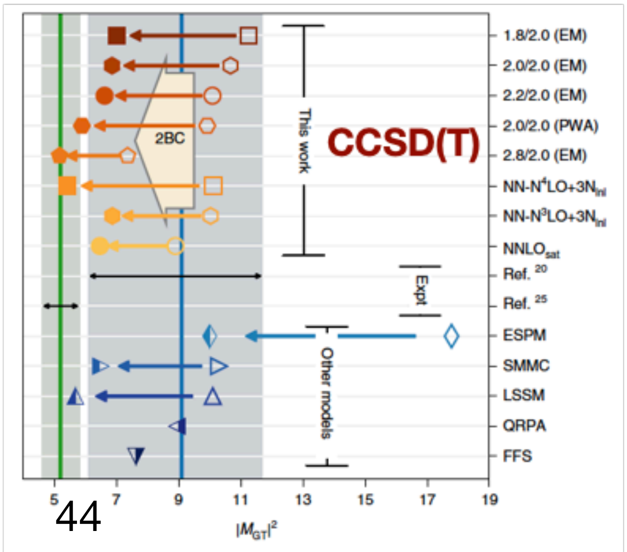
- **Intuitive picture**

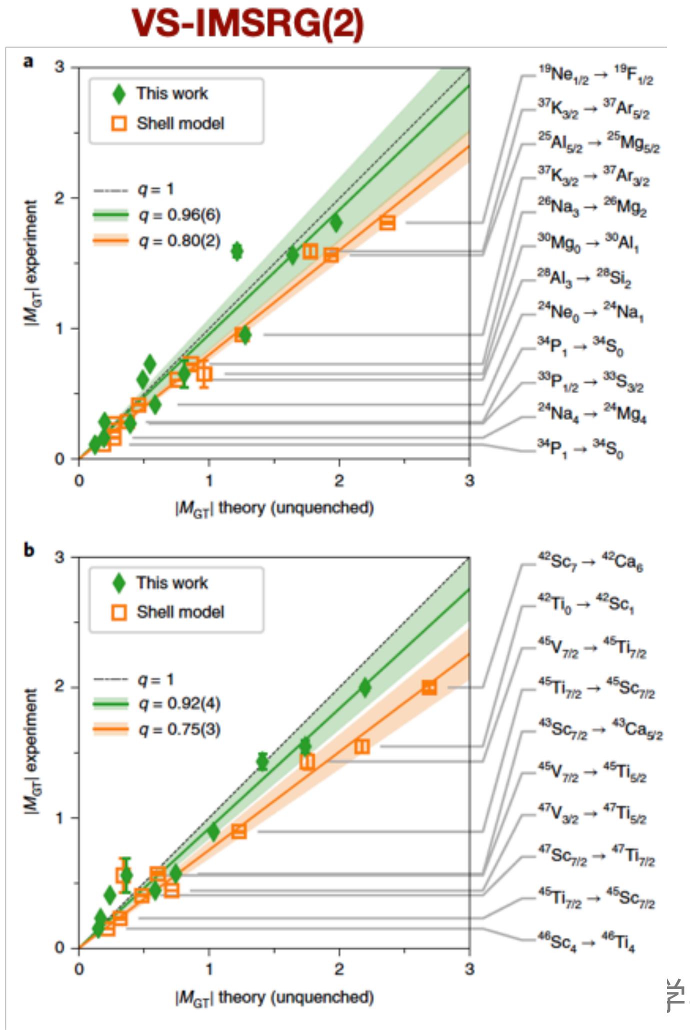
Normal-ordering the 2BC w.r.t nuclear matter of two diff. density rho.



- **Ab initio calculations**







Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

☑ Ab initio calculations of $0\nu\beta\beta$-decay candidate nuclei and corresponding NME of the decays

- ✓ **In-medium similarity renormalization group (IMSRG)+Generator coordinate method (GCM)**

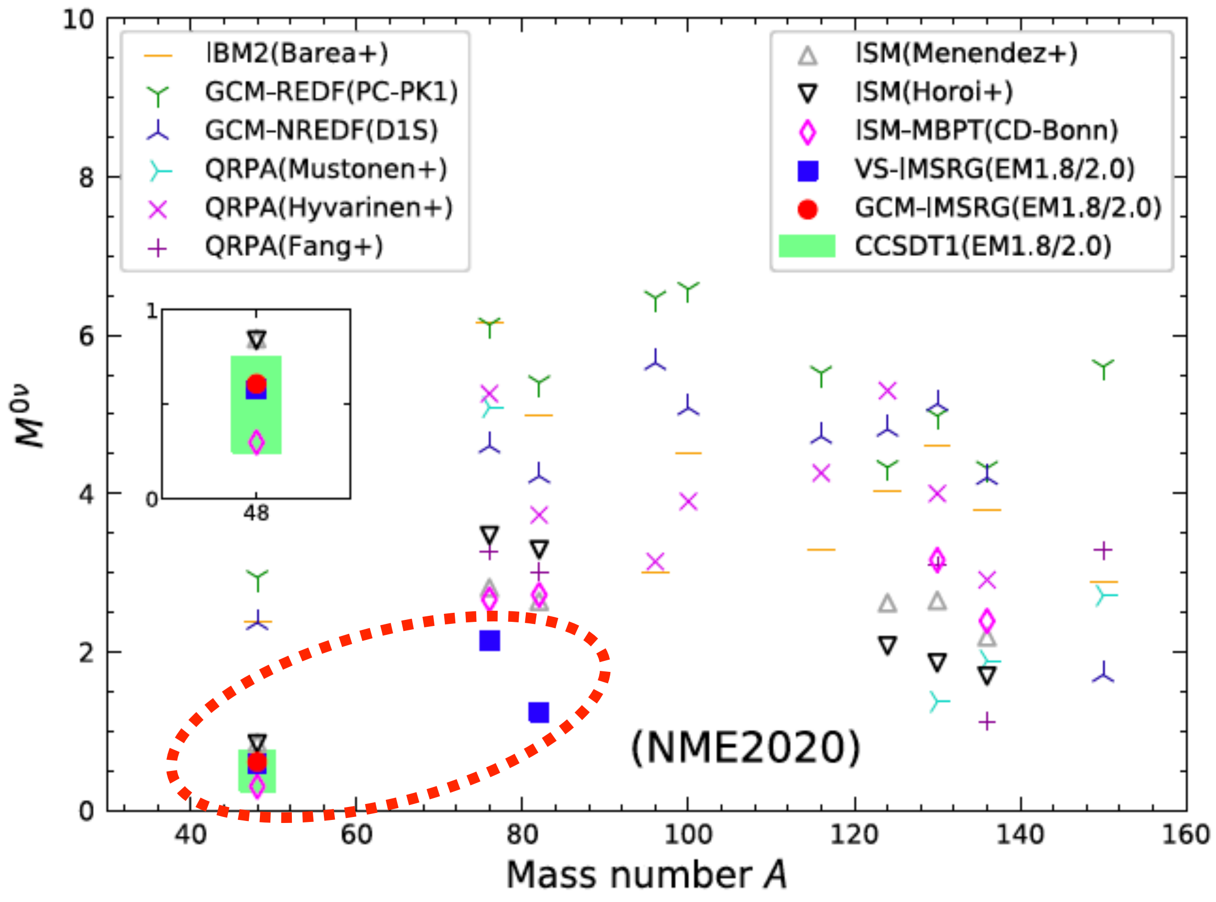
  JMY et al., PRL124, 232501 (2020)

- ✓ **Valence-space IMSRG+ interacting-shell-model (ISM)**

  A. Belley et al., PRL126, 042502 (2021)

- ✓ **Coupled cluster (CC)**

  S. Novario et al., PRL126, 182502 (2021)



JMY, Science Bulletin (2021)

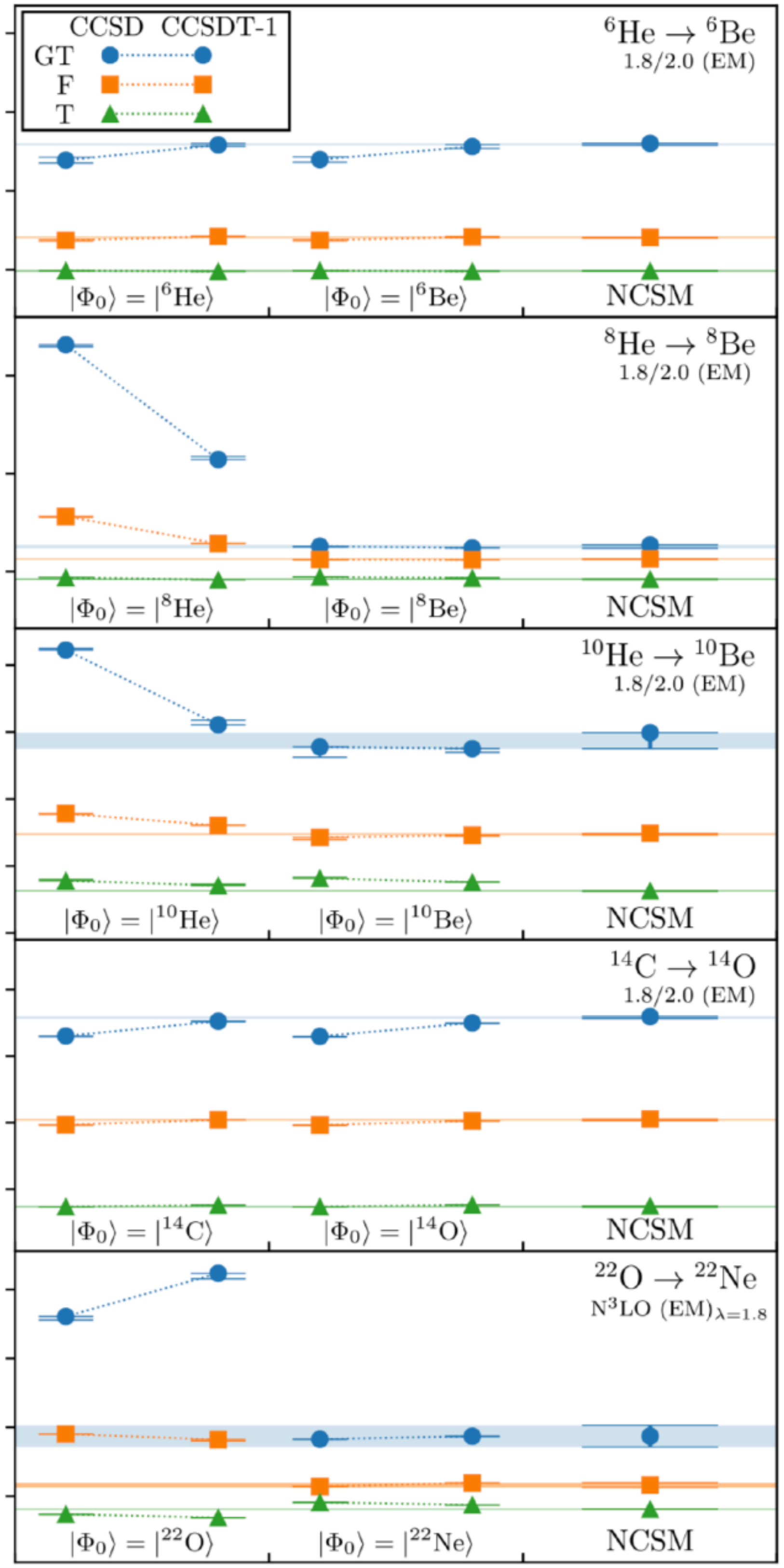
The NMEs by the three ab-initio methods consistently **smaller** than other phenomenological methods.

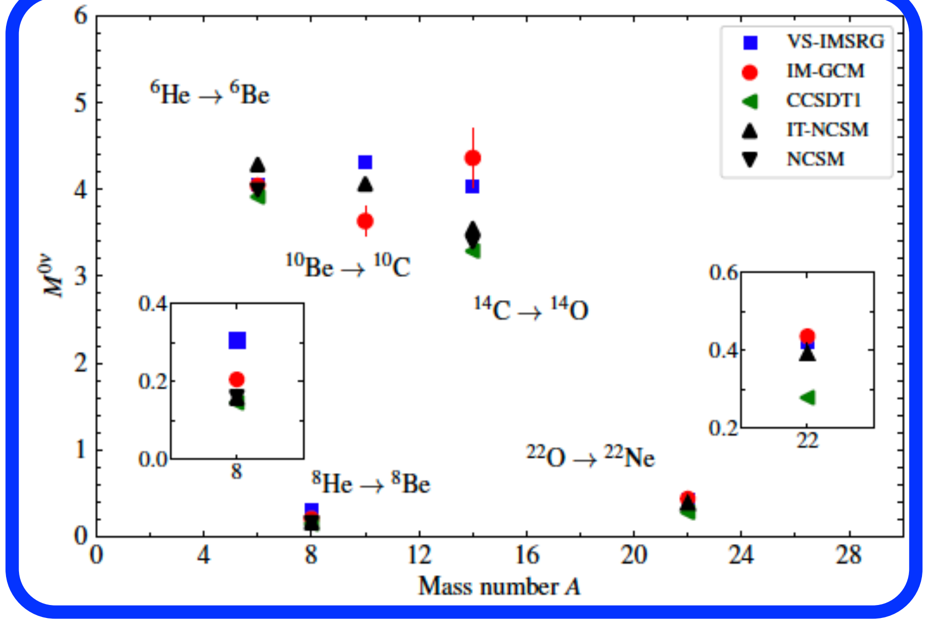
Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

☑ Benchmark calculations for light nuclei for which (quasi)-exact solution is possible

cross-checking among different models

- ✓ Quantum Monte Carlo vs **shell model**
  X. Wang et al., PLB 798, 134974 (2019)
- ✓ NCSM vs IMSRG
  R. A. M. Basili et al., PRC102, 014302 (2020).
- ✓ NCSM vs CC
  S. Novario et al., PRL126, 182502 (2021)
- ✓ NCSM vs IT-NCSM vs CC vs VS-IMSRG vs IM-GCM
  JMY et al., PRC103, 014315 (2021)





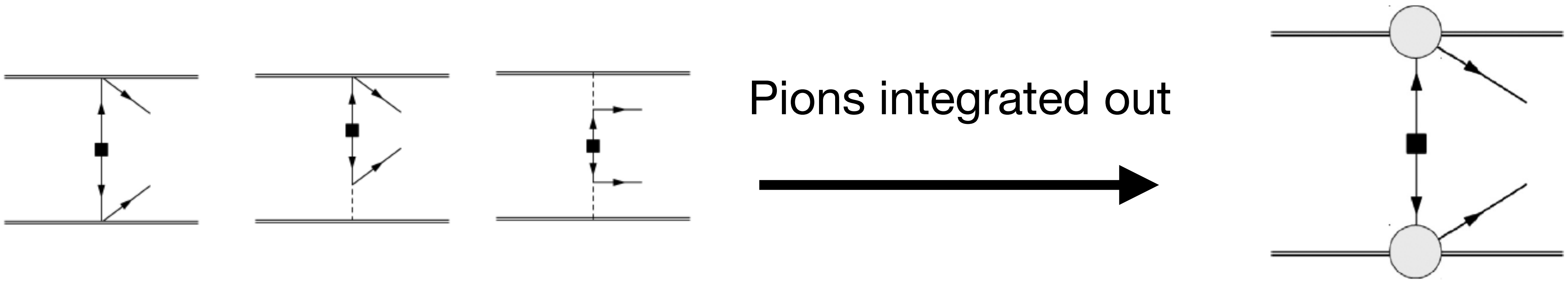
Advances in ab initio modeling of 0$\nu\beta\beta$-decay NME

☐ The 0$\nu\beta\beta$-decay in chiral EFT based on the “standard” mechanism of light Majorana neutrino exchange V. Cirigliano et al., PRC97, 065501 (2018)

✓ **Chiral expansion of neutrino potentials**

$$V_\nu = \sum_{a\neq b}\left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \cdots\right).$$

LO



Pions integrated out

$$V_{\nu,0}^{(a,b)} = \tau^{(a)+}\tau^{(b)+}\frac{1}{\mathbf{q}^2}\left\{1 - g_A^2 \times \left[\boldsymbol{\sigma}^{(a)}\cdot\boldsymbol{\sigma}^{(b)} - \boldsymbol{\sigma}^{(a)}\cdot\mathbf{q}\,\boldsymbol{\sigma}^{(b)}\cdot\mathbf{q}\,\frac{2m_\pi^2+\mathbf{q}^2}{\left(\mathbf{q}^2+m_\pi^2\right)^2}\right]\right\}$$

Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

✓ Chiral expansion of neutrino potentials

V. Cirigliano et al., PRC97, 065501 (2018)

$$V_\nu = \sum_{a\neq b}\left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \cdots\right).$$

N²LO

- **N²LO contributions to single-nucleon currents are usually taken into account by introducing dipole form factors,**

$$V_{\nu,0}^{(a,b)} = \tau^{(a)+}\tau^{(b)+}\frac{1}{\mathbf{q}^2}g_A^2\{h_F(\mathbf{q}^2)/g_A^2 - \boldsymbol{\sigma}^{(a)}\cdot\boldsymbol{\sigma}^{(b)}\,h_{\mathrm{GT}}(\mathbf{q}^2) - S^{(ab)}\,h_T(\mathbf{q}^2)\},$$

dipole form factors

$$g_V(q) = g_V\left(1+\frac{q^2}{\Lambda_V^2}\right)^{-2}, \qquad g_A(q) = g_A\left(1+\frac{q^2}{\Lambda_A^2}\right)^{-2},$$

$$g_M(q) = (1+\kappa_1)g_V(q), \qquad g_P(q) = -\frac{2m_N g_A(q)}{q^2+m_\pi^2}.$$

- **Genuine N²LO contributions from loops corrections to the LO diagram (induce short-range neutrino potential) are NOT considered yet**

$$V_{\nu,2}^{(a,b)} = \tau^{(a)+}\tau^{(b)+} \times \left(\mathcal{V}_{VV}^{(a,b)} + \mathcal{V}_{\mathrm{AA}}^{(a,b)} + \tilde{\mathcal{V}}_{\mathrm{AA}}^{(a,b)}\ln\frac{m_\pi^2}{\mu_{\mathrm{us}}^2} + \mathcal{V}_{CT}^{(a,b)}\right).$$

CT at N²LO

$$\mathcal{V}_{CT}^{(a,b)} = \frac{g_A^2}{(4\pi F_\pi)^2}\frac{\boldsymbol{\sigma}^{(a)}\cdot\mathbf{q}\,\boldsymbol{\sigma}^{(b)}\cdot\mathbf{q}}{m_\pi^2}\left[\frac{5}{6}g_\nu^{\pi\pi}\frac{\hat{q}}{(1+\hat{q})^2} - g_\nu^{\pi N}\frac{1}{1+\hat{q}}\right] - \boxed{\frac{2g_\nu^{\mathrm{NN}}}{(4\pi F_\pi)^2}\mathbf{1}^{(a)}\times\mathbf{1}^{(b)}}$$

Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

- **Transition amplitude of the process (LO)** $nn \to pp + e^- e^-$

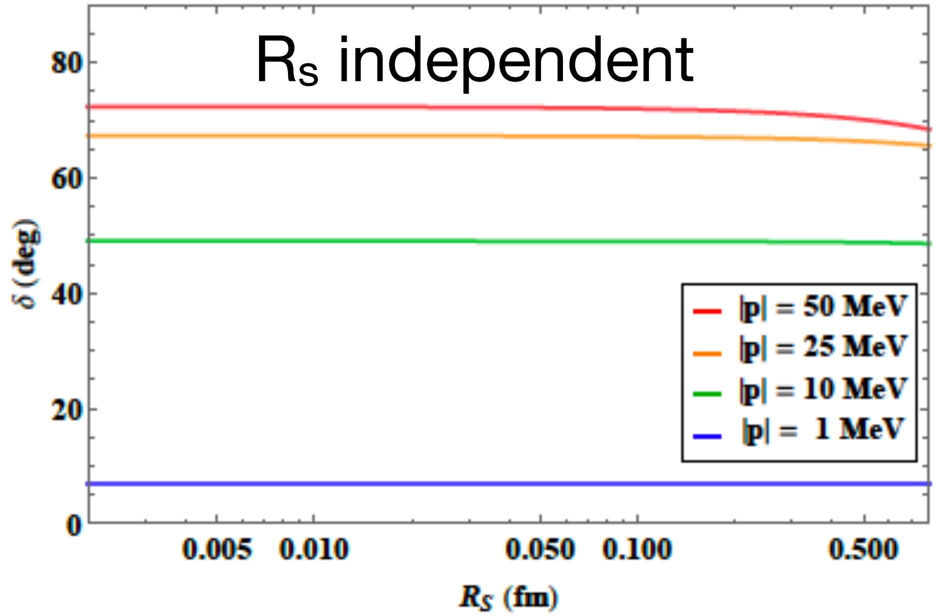
V. Cirigliano et al., PRL120, 202001 (2018); PRC97,065501 (2019)

$$V_0(\mathbf{q}) = \tilde{C} + V_\pi(\mathbf{q}), \qquad V_\pi(\mathbf{q}) = -\frac{g_A^2}{4F_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2+m_\pi^2},$$

The contact nuclear potential is regularized as

$$\tilde{C}\delta^{(3)}(\mathbf{r}) \to \frac{\tilde{C}(R_S)}{(\sqrt{\pi}R_S)^3}\exp\left(-\frac{r^2}{R_S^2}\right) \equiv \tilde{C}(R_S)\delta^{(3)}_{R_S}(\mathbf{r}),$$

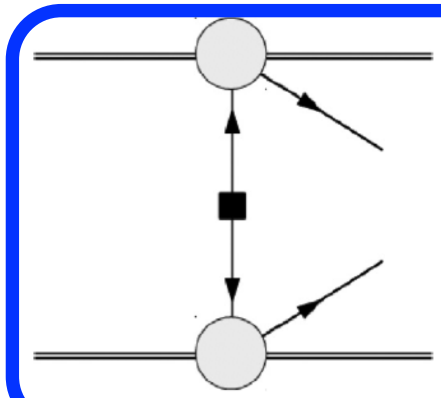
The LEC C(R) is adjusted to reproduce the np-scattering length for a given Rs.



Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

- **Transition amplitude of the process (LO)** $nn \to pp + e^- e^-$

V. Cirigliano et al., PRL120, 202001 (2018); PRC97,065501 (2019)



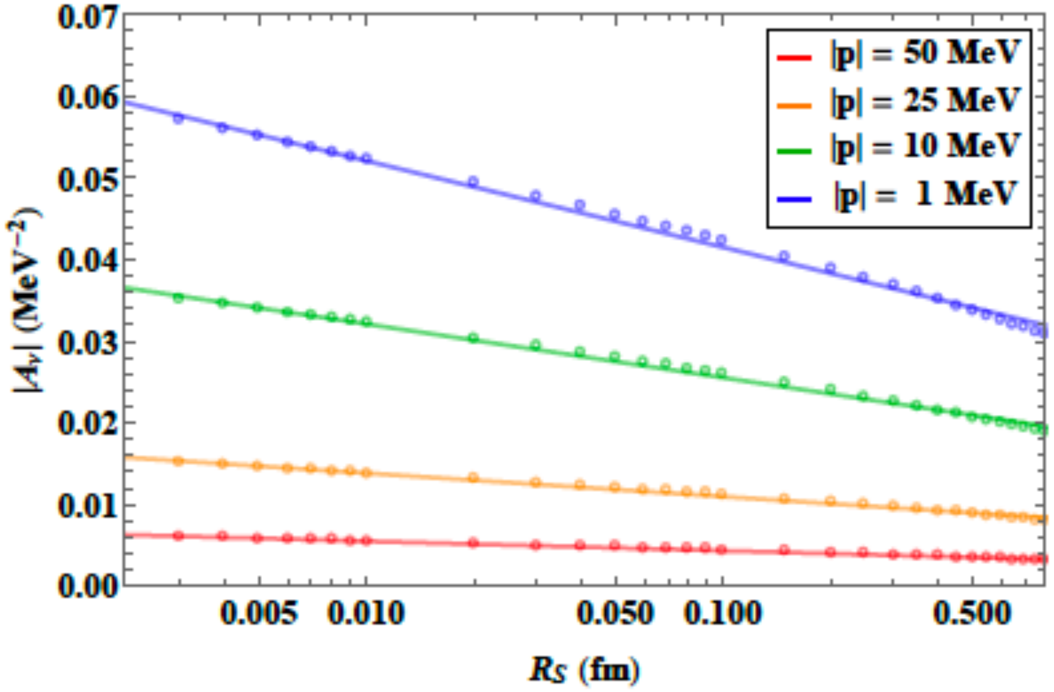
$$V_{\nu,0}(\mathbf{q}) = \tau^{(1)+}\tau^{(2)+}\frac{1}{\mathbf{q}^2}\left(1 - g_A^2\boldsymbol{\sigma}^{(1)}\cdot\boldsymbol{\sigma}^{(2)} + g_A^2\boldsymbol{\sigma}^{(1)}\cdot\mathbf{q}\,\boldsymbol{\sigma}^{(2)}\cdot\mathbf{q}\,\frac{2m_\pi^2+\mathbf{q}^2}{(\mathbf{q}^2+m_\pi^2)^2}\right),$$

$$\mathcal{A}_\nu(E,E') = -\langle\Psi_{pp}(E')|V_{\nu\,\mathrm{L}}^{^1S_0}|\Psi_{nn}(E)\rangle$$

$$E = \mathrm{p}^2/m_n \text{ and } E' = \mathrm{p}'^2/m_p$$

$$E' = E + 2(m_n - m_p - m_e)$$

$$|\mathrm{p}'| = \sqrt{\mathrm{p}^2 + 2m_N(m_n - m_p - m_e)},$$



Lines fitted to $\mathcal{A}_\nu = a + b\ln R_S$

logarithmic dependence on R_S

The transition amplitude is regulator dependent! Needs a counter term (contact operator) at LO in order to ensure renormalizability.

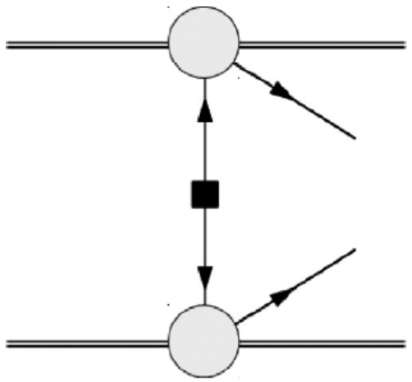
Violation of power counting?

Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

- **Necessary of introducing a contact term at LO** $nn \to pp + e^- e^-$

V. Cirigliano et al., PRL120, 202001 (2018); PRC97,065501 (2019)

A missing piece



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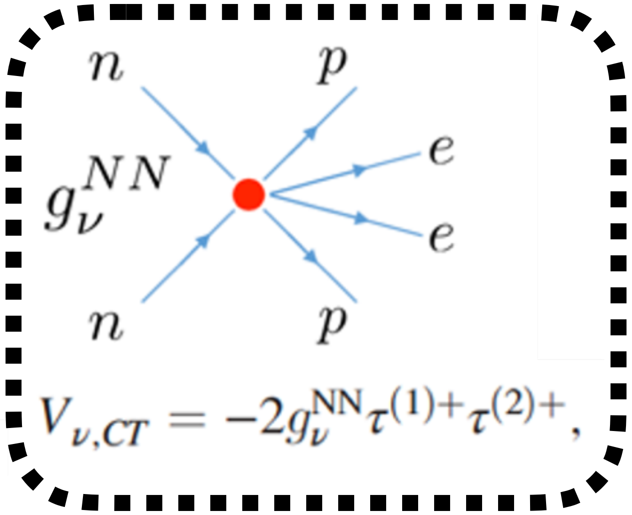
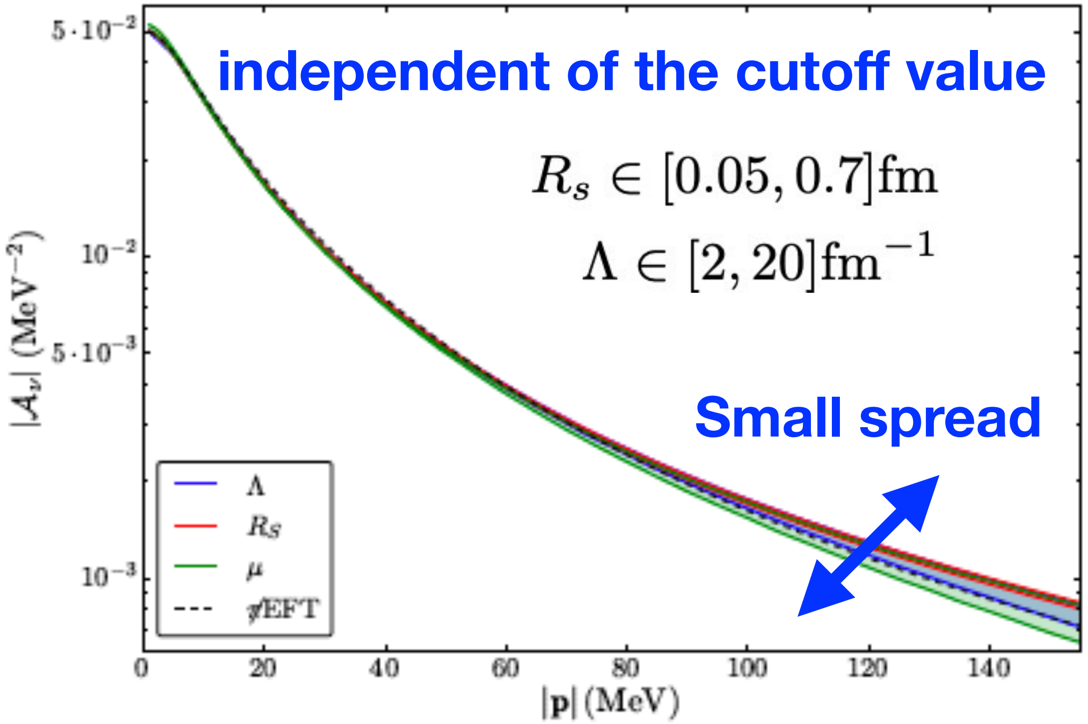


$$V_{\nu,CT} = -2 g_\nu^{\mathrm{NN}} \tau^{(1)+} \tau^{(2)+},$$

Total transition amplitude $\mathcal{A}(p,p') = \mathcal{A}_L(p,p') - 2g\mathcal{A}_S(p,p').$

Fitted to an arbitrary value

$$\mathcal{A}_\nu(|\mathbf{p}| = 1\,\mathrm{MeV},\ |\mathbf{p}'| = 38\,\mathrm{MeV})\, e^{-i(\delta_{^1S_0}(E)+\delta_{^1S_0}(E'))} = -0.05\,\mathrm{MeV}^{-2}$$



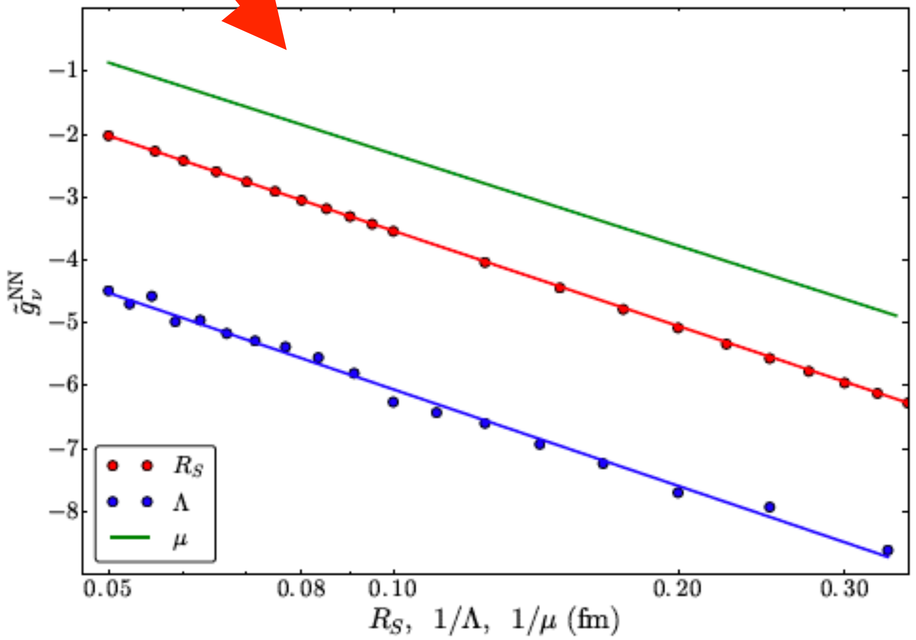
independent of the cutoff value

$R_s \in [0.05, 0.7]$fm

$\Lambda \in [2, 20]\mathrm{fm}^{-1}$

Small spread

LEC



Determination of the leading-order contact operator

- The LEC should be fitted to **data** or the LD+SD **amplitude by Lattice QCD**

Light-Neutrino Exchange and Long-Distance Contributions to $0\nu2\beta$ Decays: An Exploratory Study on $\pi\pi \to ee$

Xu Feng, Lu-Chang Jin, Xin-Yu Tuo, and Shi-Cheng Xia
Phys. Rev. Lett. **122**, 022001 – Published 15 January 2019

LQCD: $$\left.\frac{\mathcal{A}(\pi\pi \to ee)}{F_\pi^2 T_{\text{lept}}}\right|_{m_\pi=140\ \text{MeV}} = 1.820(6)$$

$$T_{\text{lept}} = 4G_F^2 V_{ud}^2 m_{\beta\beta} \bar{u}_L(p_1) u_L^c(p_2).$$

discrepancy might be from

- lattice artifacts and finite-volume effects
- LO chiral expansion error

Chiral EFT(LO): $$\mathcal{A}^{\text{LO}}(\pi\pi \to ee) = 2F_\pi^2 T_{\text{lept}}$$

Path from Lattice QCD to the Short-Distance Contribution to $0\nu\beta\beta$ Decay with a Light Majorana Neutrino

Zohreh Davoudi and Saurabh V. Kadam
Phys. Rev. Lett. **126**, 152003 (2021) – Published 16 April 2021

Providing a framework to match the total transition amplitude of the nn→ppe-e- process from the calculations of both **lattice QCD** and **chiral effective field theory**.

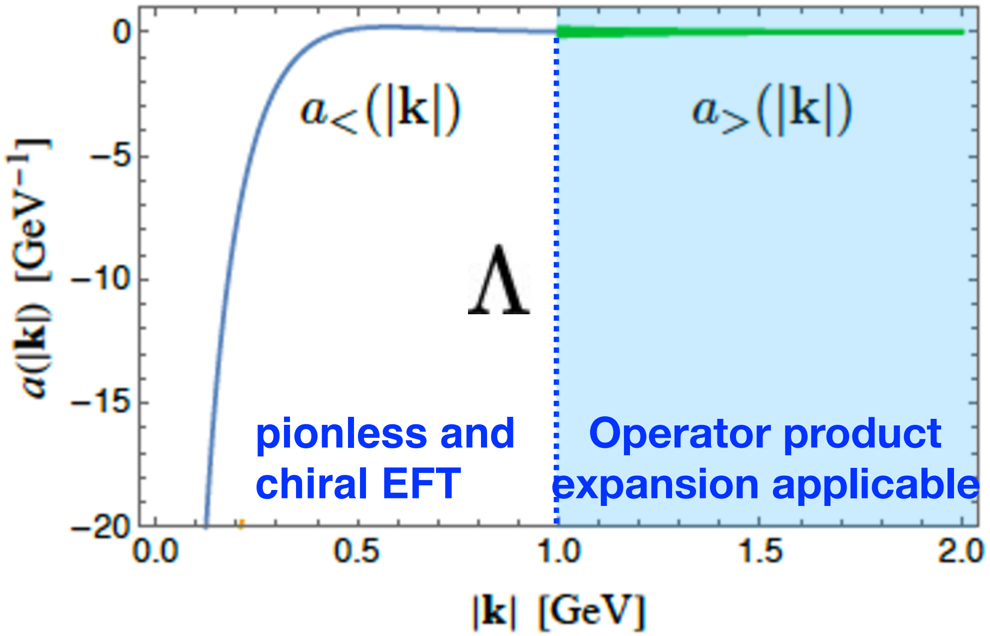
Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

- **Determination of the LEC for the contact term**

Toward Complete Leading-Order Predictions for Neutrinoless Double β Decay

Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Martin Hoferichter, and Emanuele Mereghetti

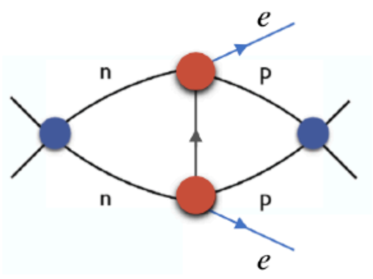
Phys. Rev. Lett. **126**, 172002 (2021) – Published 30 April 2021



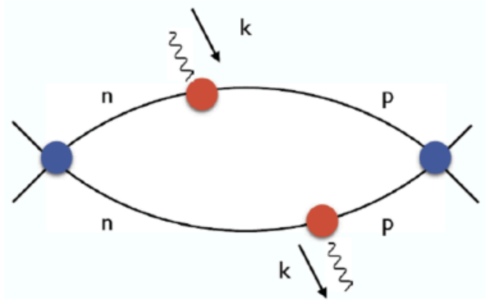
- **Cottingham formula** W.N. Cottingham, Ann. Phys. 25, 424 (1963)

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4}\frac{g_{\mu\nu}}{k^2+i\epsilon}\int d^4x\, e^{ik\cdot x}\langle pp|T\{j_{\rm w}^\mu(x)j_{\rm w}^\nu(0)\}|nn\rangle$$

$$\mathcal{A}_\nu =$$



$$\propto \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2+i\epsilon}$$



forward Compton amplitude

$$\mathcal{A}_\nu^{\rm full} = \int_0^\infty d|\mathbf{k}|\; a^{\rm full}(|\mathbf{k}|) = \mathcal{A}^< + \mathcal{A}^>\,,$$

$$\mathcal{A}^< = \int_0^\Lambda d|\mathbf{k}|\; a_<(|\mathbf{k}|)\,,$$

$$\mathcal{A}^> = \int_\Lambda^\infty d|\mathbf{k}|\; a_>(|\mathbf{k}|)\,,$$

- **Synthetic datum**

$$\mathcal{A}_\nu(|\mathbf{p}|,|\mathbf{p}'|)\times e^{-i(\delta_{{}^1S_0}(|\mathbf{p}|)+\delta_{{}^1S_0}(|\mathbf{p}'|))} = -\left(2.271 - 0.075\,\tilde{\mathcal{C}}_1(4\,M_\pi)\right)\times 10^{-2}\,\mathrm{MeV}^{-2}$$

$$\boxed{|\mathbf{p}| = 25\,\mathrm{MeV}\;\;(|\mathbf{p}'| = 30\,\mathrm{MeV})} \qquad = -1.95(5)_{\tilde{\mathcal{C}}_1}\times 10^{-2}\,\mathrm{MeV}^{-2}\,,$$

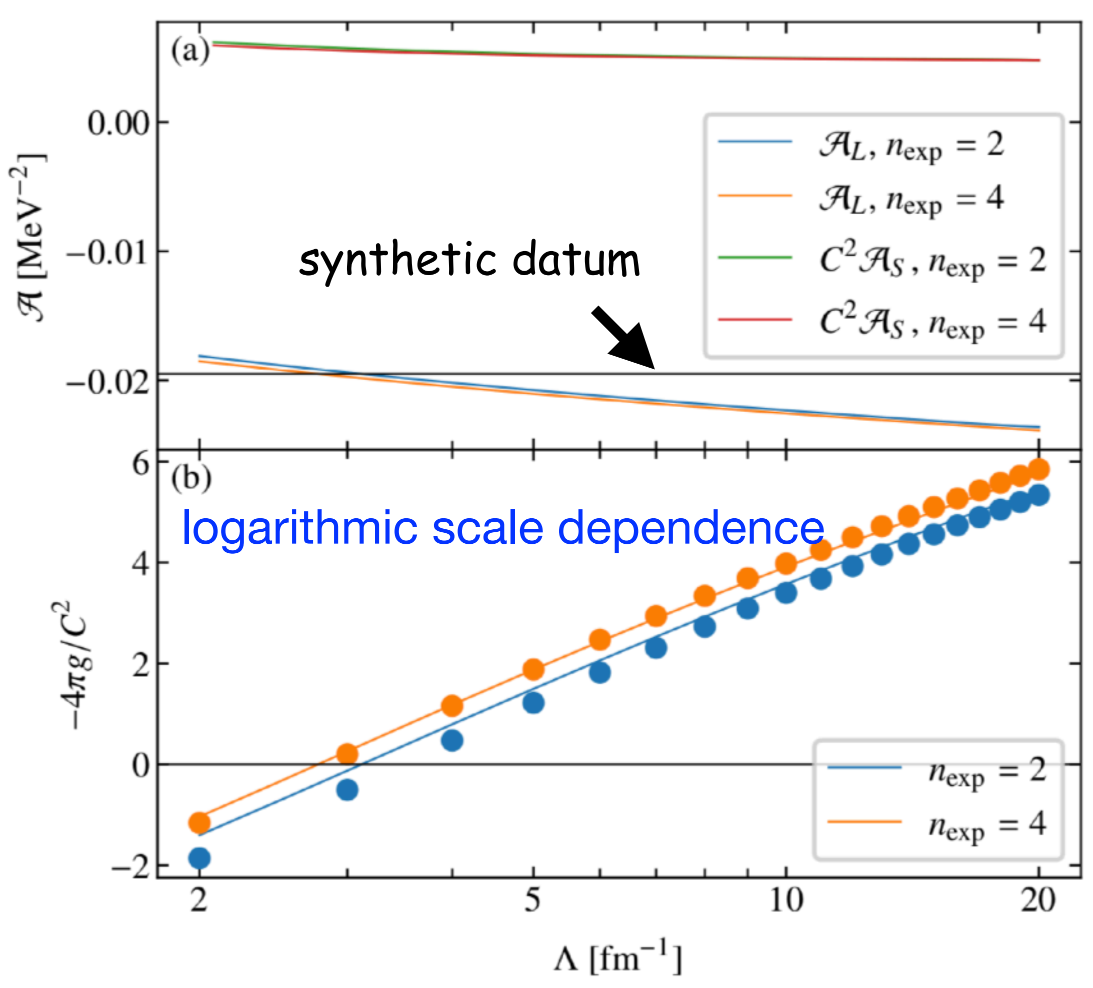
Uncertainty from the estimate of the **inelastic** contributions

The amplitude is observable and thus scheme independent.

Determination of the leading-order contact operator

- **Contribution of the contact term to the NME of finite nuclei**

$$\mathcal{A}(p,p') = \mathcal{A}_L(p,p') - 2g\mathcal{A}_S(p,p').$$

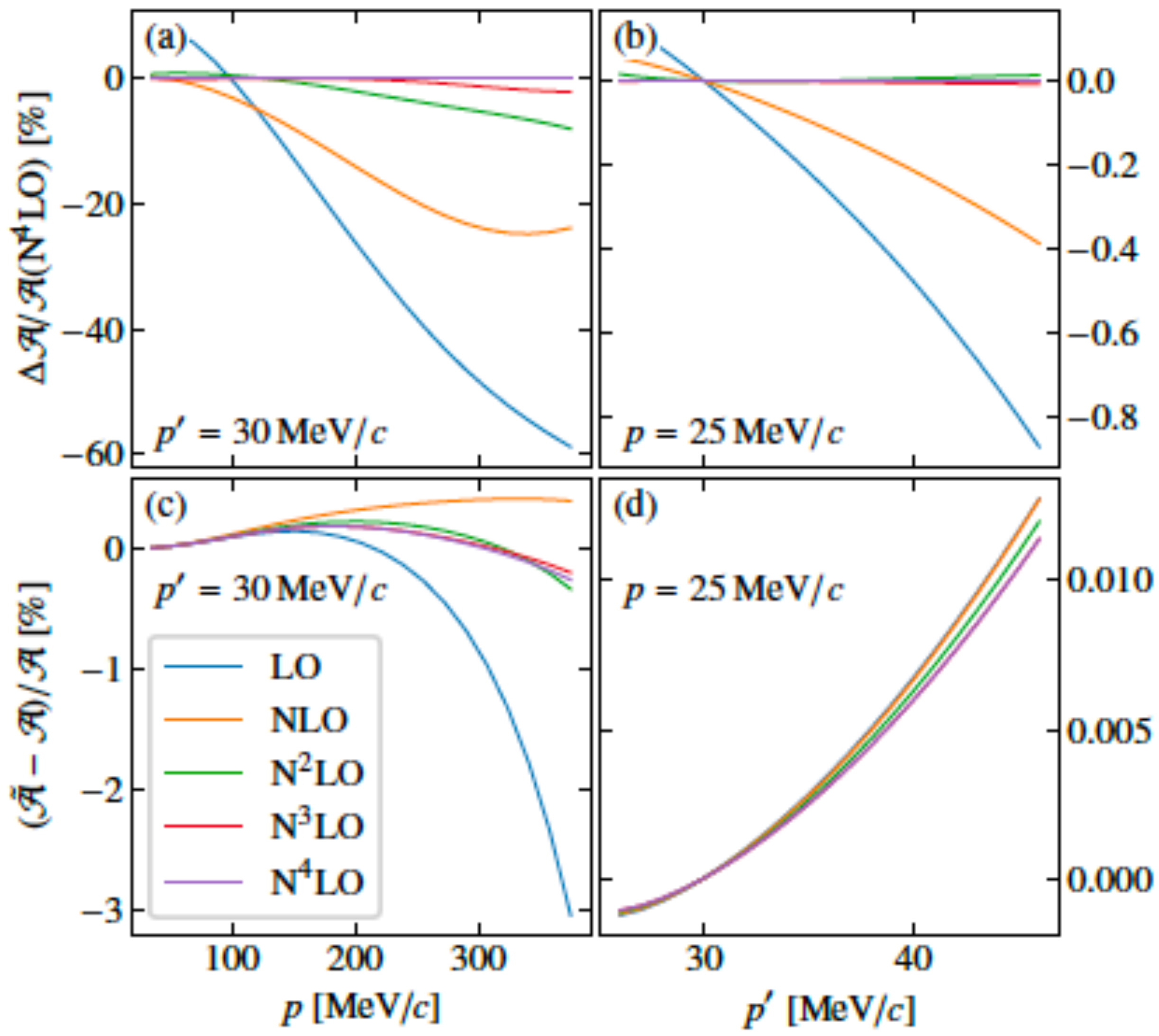


synthetic datum

logarithmic scale dependence

The dimensionless LEC C is adjusted to reproduce the neutron–proton scattering length $a_{np}=-23.74$ fm.

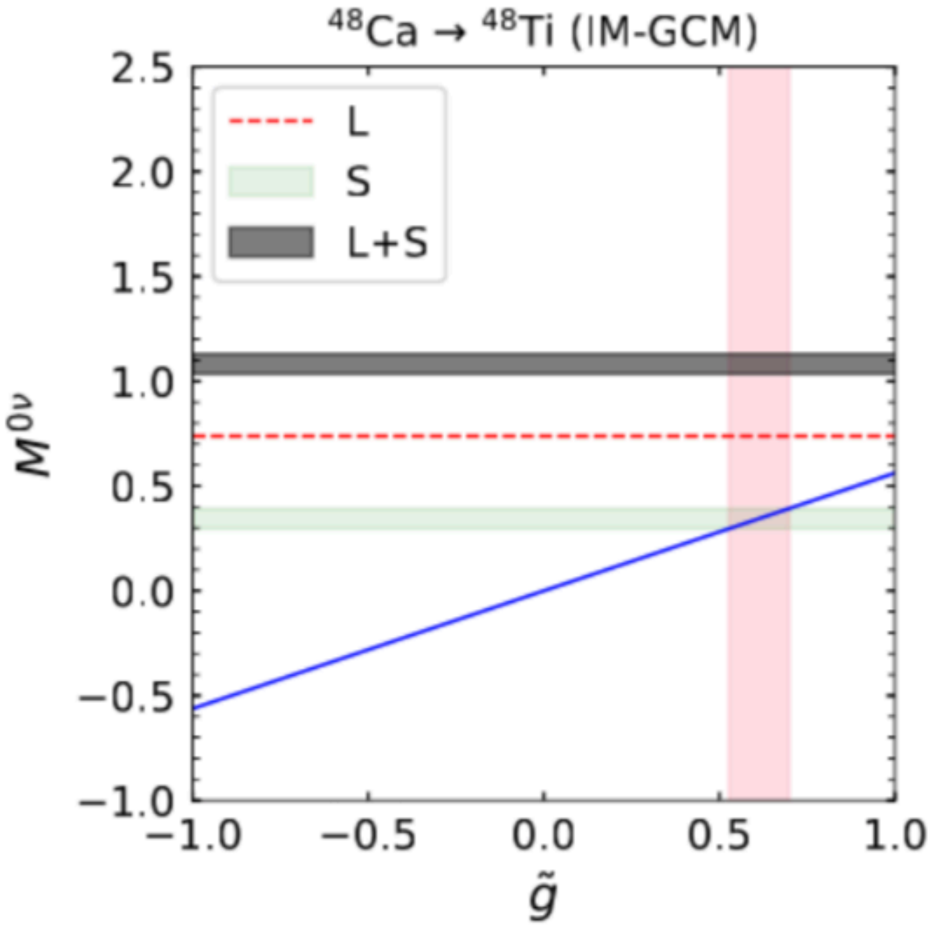
- Chiral expansion order of the nuclear interaction (not transition operator)
- LO and N^{2}LO (partial) neutrino potential

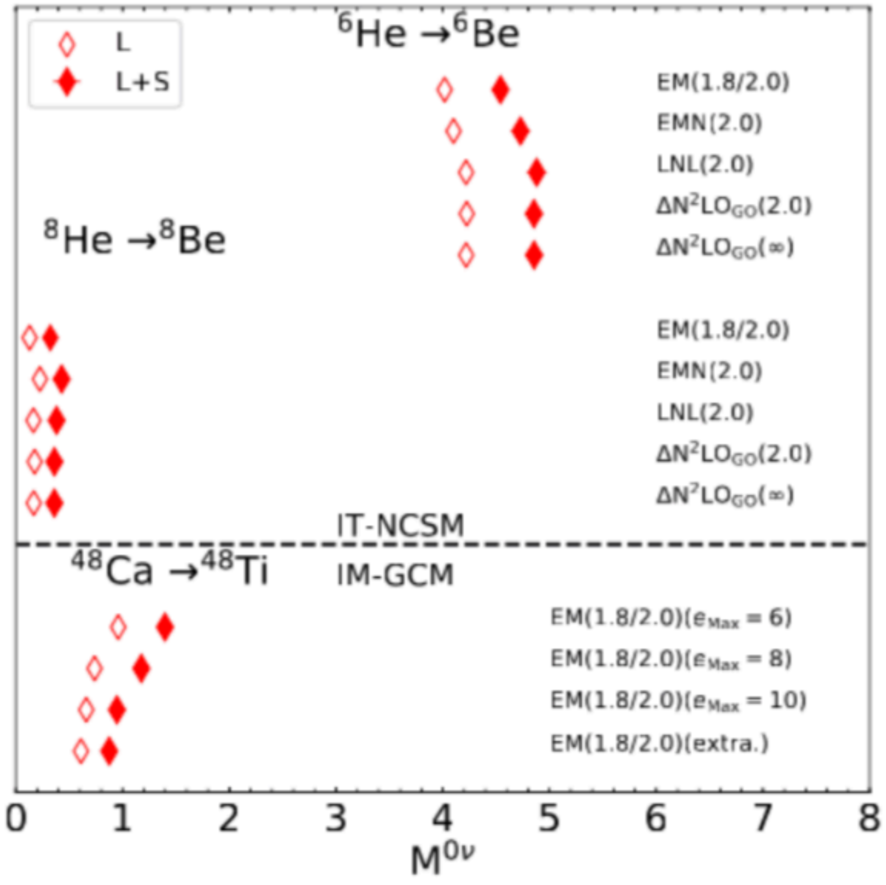


R. Wirth, JMY, H. Hergert, arXiv:2105.05415 [nucl-th]

Determination of the leading-order contact operator

- **The contribution of the contact term to the NME**

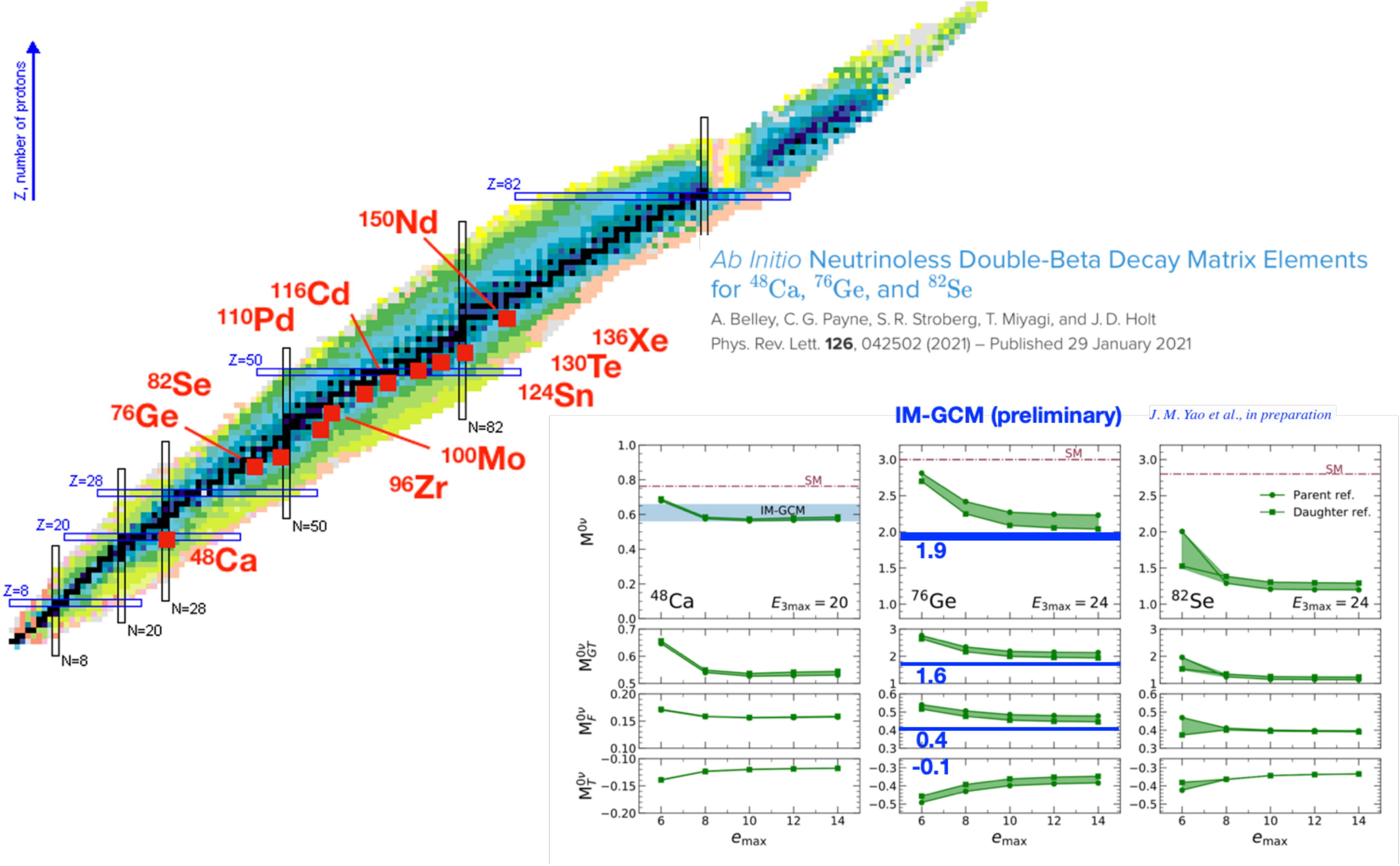




- The contact term **enhances the NME for ^{48}Ca by 43(7)%**, the uncertainty is propagated only from the synthetic datum.
- An important positive message for planning and interpreting future experiments.

\R. Wirth, JMY, H. Hergert, arXiv:2105.05415 [nucl-th]

Extension to heavier $0\nu\beta\beta$ candidates



Ab Initio Neutrinoless Double-Beta Decay Matrix Elements for ^{48}Ca, ^{76}Ge, and ^{82}Se

A. Belley, C. G. Payne, S. R. Stroberg, T. Miyagi, and J. D. Holt

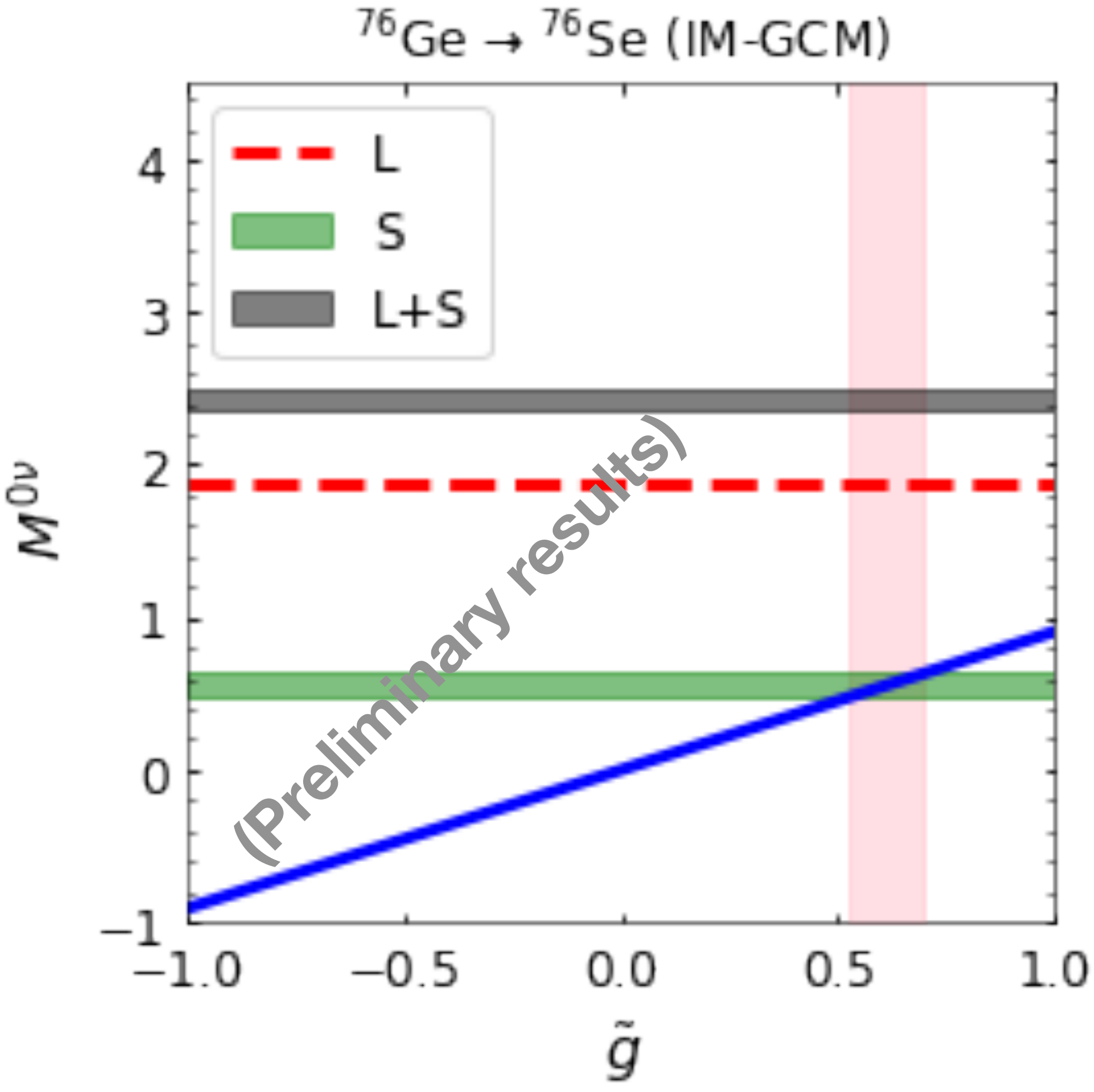
Phys. Rev. Lett. **126**, 042502 (2021) – Published 29 January 2021

IM-GCM (preliminary)

J. M. Yao et al., in preparation

Extension to heavier $0\nu\beta\beta$ candidates

- **The contribution of the contact term to the NME**



$$e_{\mathrm{Max}} = 8, \hbar\omega = 12 \text{ MeV}$$

The contact term **enhances the NME for ^{76}Ge by 29(5)% !**

JMY et al., in preparation

Summary and outlook

✦ Take-away messages

- Experimental searches of $0\nu\beta\beta$ decay are pushing up to **tonne-scale detectors** with the half-life sensitivity up to **10^{28} years**.
- The **NMEs** by phenomenological models **differ by a factor up to three**. It is a challenge to reduce the discrepancy.
- Significant advances in ab initio modeling of atomic nuclei.

From light to medium-mass nuclei, close-shell to open-shell nuclei, spherical to deformed nuclei.

- Ab initio calculation of the NMEs of candidate nuclei with both long- and short-range operators are within reach.

✓ The leading-order short-range operator generally enhances the NME in the ab initio calculations using a chiral nuclear force with low-energy scale regulator.
✓ Ready to compute the NME of heavier candidate nuclei.

Summary and outlook

✦ Outlook (TODO LIST)

- **Standard mechanism:** trans. operators derived consist. from EFT)
- **Other mechanisms:** heavy-particle exch., Left-Right mixing, etc.
- **Uncertainty Quantification:** Truncation error in both nuclear interactions and many-body methods, IMSRG(3)
- **Building an emulator for the NME**: Machine learning?

Fortunately, we are hitting the road …

Missing many pieces?

Collaborators and acknowledgement

Collaborators

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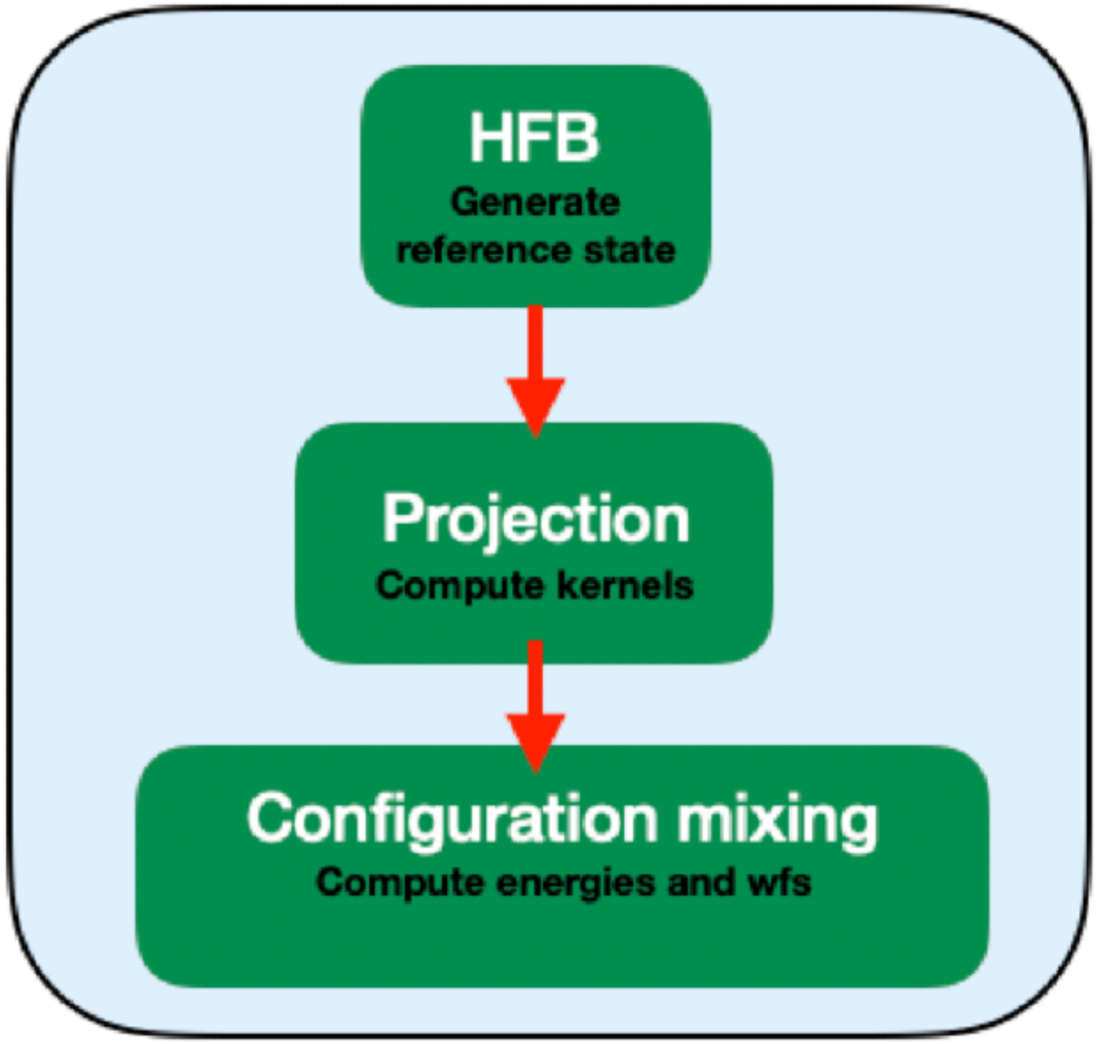
- J. Meng, L. S. Song, Peking University, China
- P. Ring,Technical University of Munich, Germany
- K. Hagino, Kyoto University, Japan
- **R. Wirth, H. Hergert**, Michigan State University, USA
- **J. Engel, A. Marquez Romero**, UNC-CH, USA
- **A. Belley, T. Miyagi, C. G. Payne, J. D. Holt**,TRIUMF,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

Thank you for your attention!

Generator coordinate method (GCM) in a nutshell



HFB
Generate reference state

Projection
Compute kernels

Configuration mixing
Compute energies and wfs

- The trial wave function of a GCM state

$$|\Phi^{JNZ\cdots}\rangle = \sum_{Q} F_Q^{JNZ} \hat{P}^J \hat{P}^N \hat{P}^Z \cdots |\Phi_Q\rangle$$

$|\Phi_Q\rangle$ are a set of HFB wave functions from constraint calculations, Q is the so-called generator coordinate.

- The mixing weight F_Q^{JNZ} is determined from the Hill-Wheeler-Griffin equation:

$$\sum_{Q'} \left[H^{JNZ}(Q, Q') - E^J N^{JNZ}(Q, Q') \right] F_{Q'}^{JNZ} = 0$$

Features (pros) of GCM

– The Hilbert space in which the H will be diagonalized is defined by the Q.
Many-body correlations are controlled by the Q

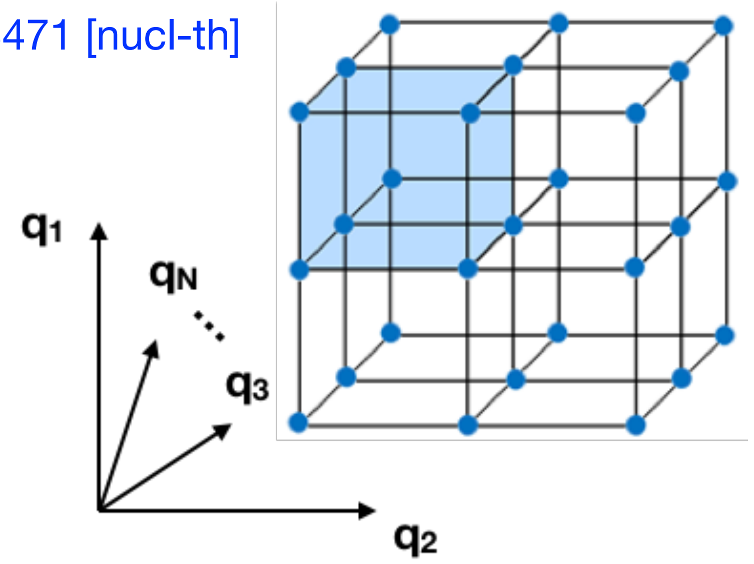
– The Q is chosen as (collective) degrees of freedom relevant to the physics.

– Dimension of the space in GCM is generally much smaller than full CI calculations.

Optimization of GCM

"dimensionality curse" in GCM

A.M. Romero, J. Engel, JMY, arXiv:2105.03471 [nucl-th]

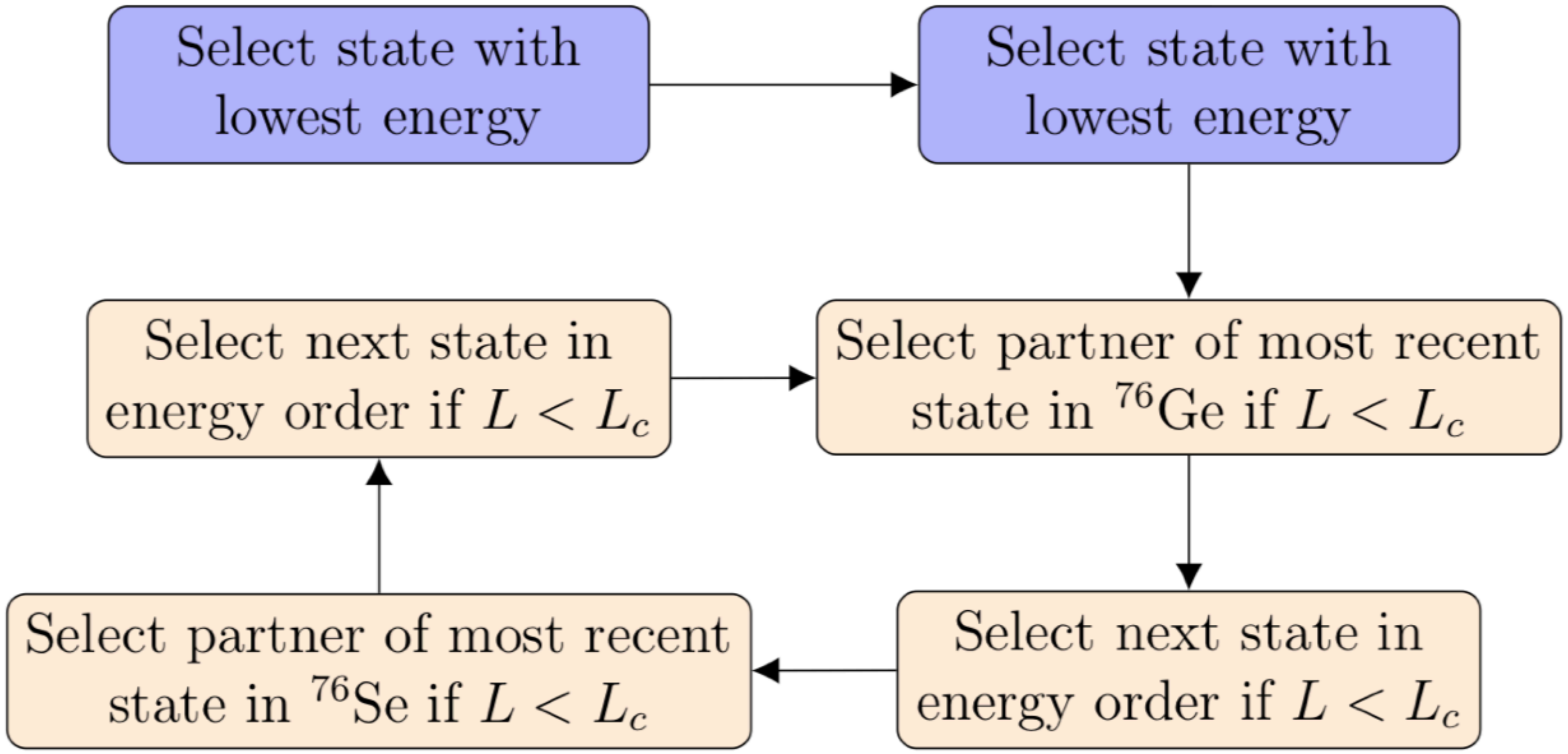


N dimensional collective space $Q=(q_1,q_2,\ldots,q_N)$

- energy-transition-orthogonality procedure (ENTROP)

^{76}Ge

^{76}Se



Select state with lowest energy

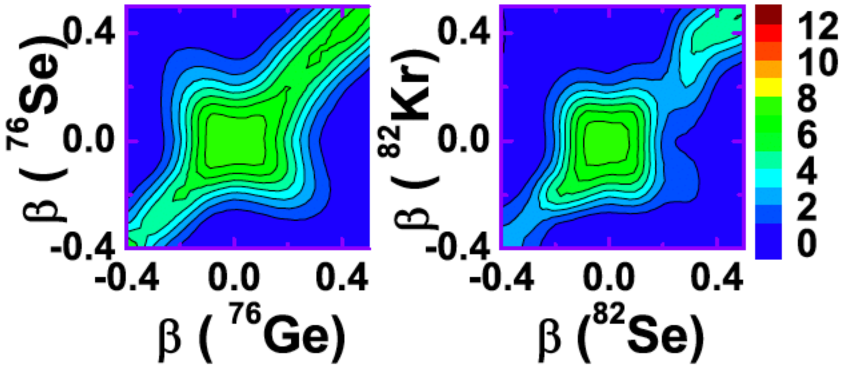
Select state with lowest energy

Select partner of most recent state in ^{76}Ge if $L < L_c$

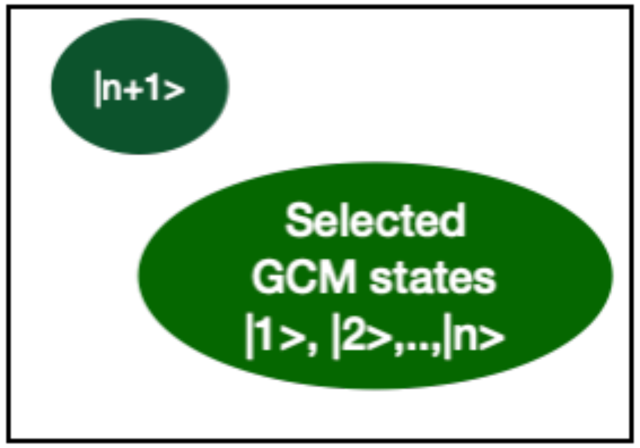
Select next state in energy order if $L < L_c$

Select partner of most recent state in ^{76}Se if $L < L_c$

Select next state in energy order if $L < L_c$



JMY, L. S. Song, K. Hagino, P. Ring, and J. Meng PRC91, 024316 (2015)



$$\boxed{L = \frac{\langle n+1|P^{(n)}|n+1\rangle}{\langle n+1|n+1\rangle}}$$

$$P^{(n)}|n+1\rangle = \sum_{i=1}^{n} \alpha_i^{(n)}|i\rangle,$$

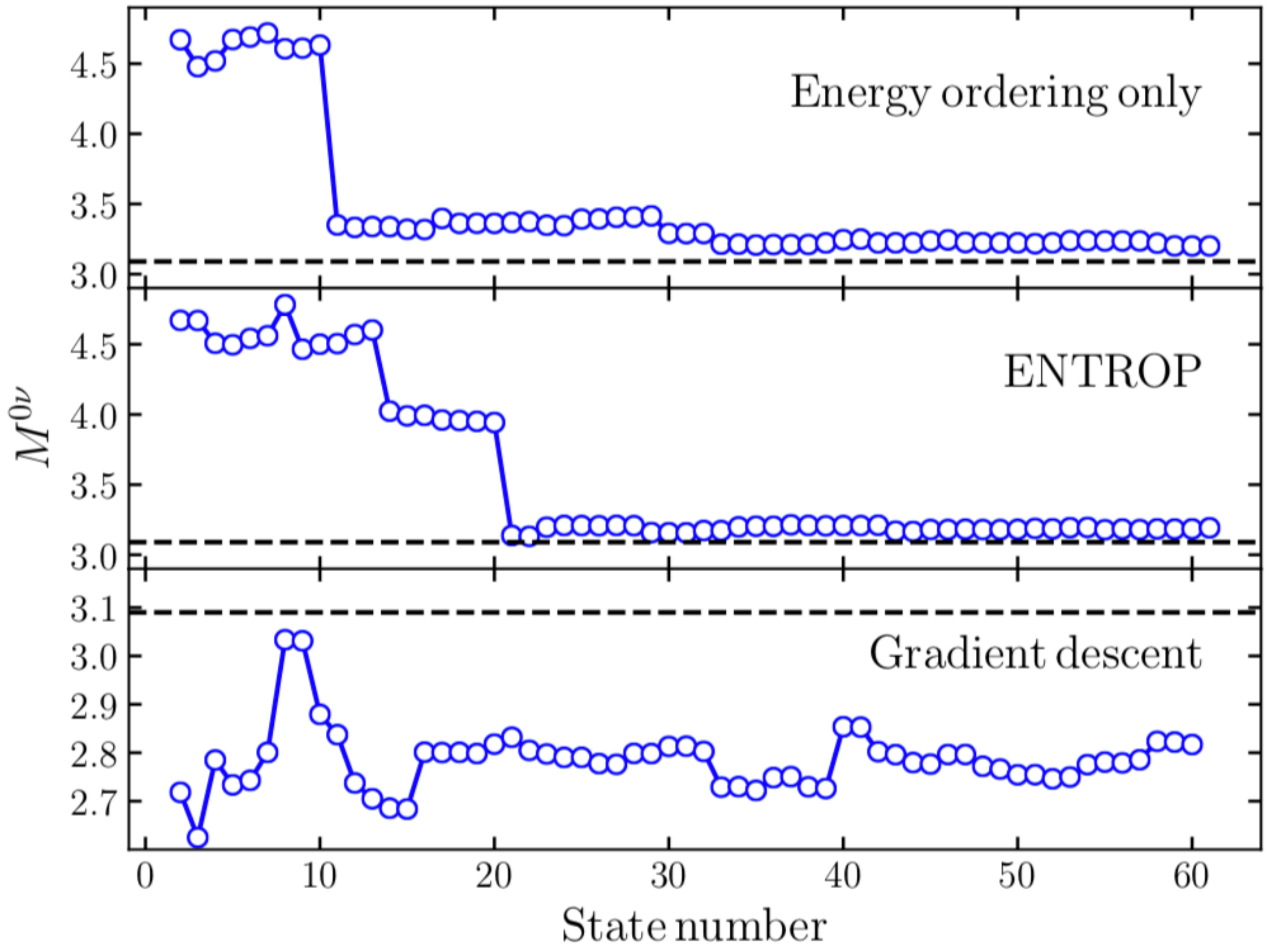
L: a measure if the model space is complete or not.

Optimization of GCM

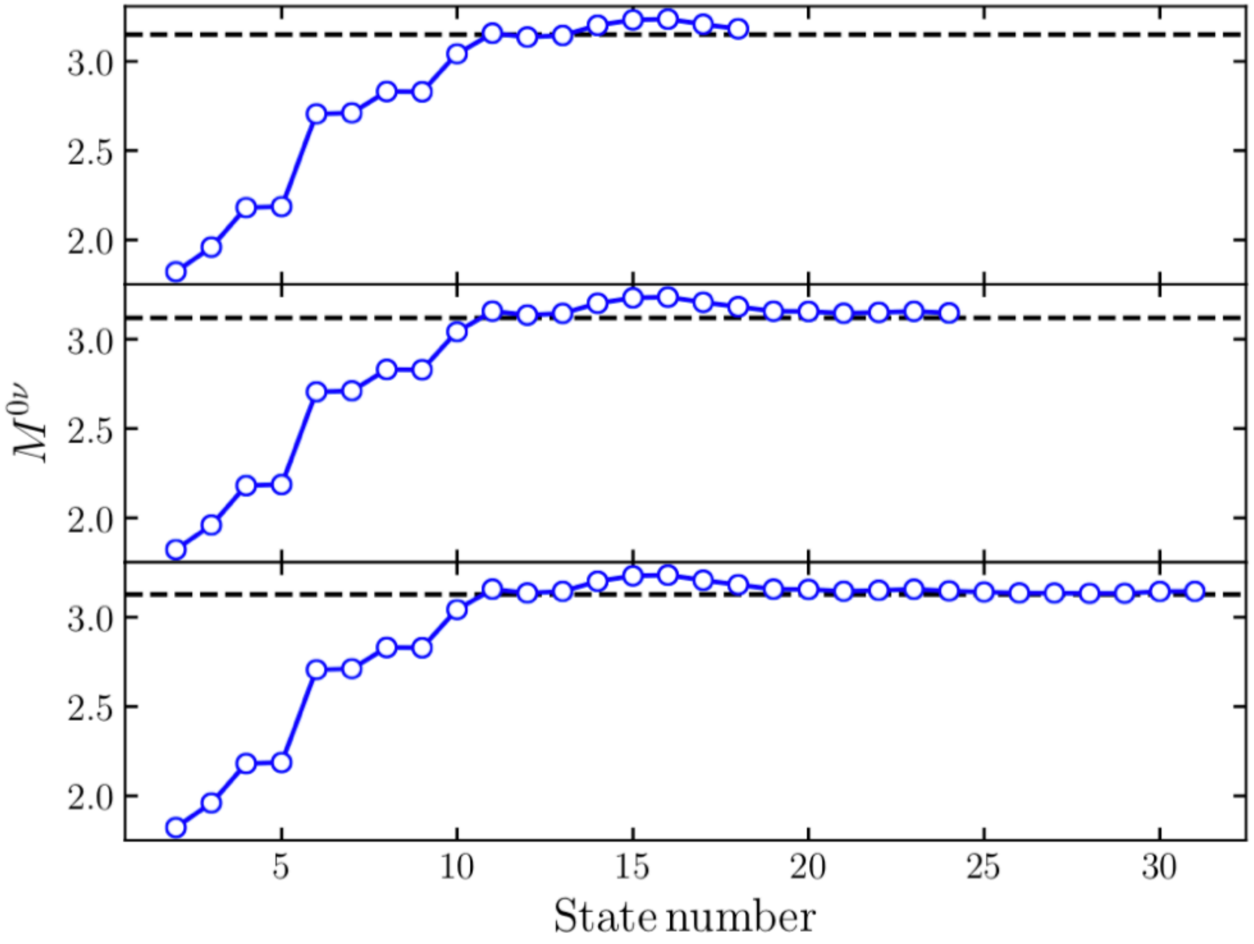
“dimensionality curse” in GCM A.M. Romero, J. Engel, JMY, arXiv:2105.03471 [nucl-th]

N dimensional collective space $Q=(q_1,q_2,\ldots,q_N)$

- energy-transition-orthogonality procedure (ENTROP)



GCM with shell-model interaction GCN2850



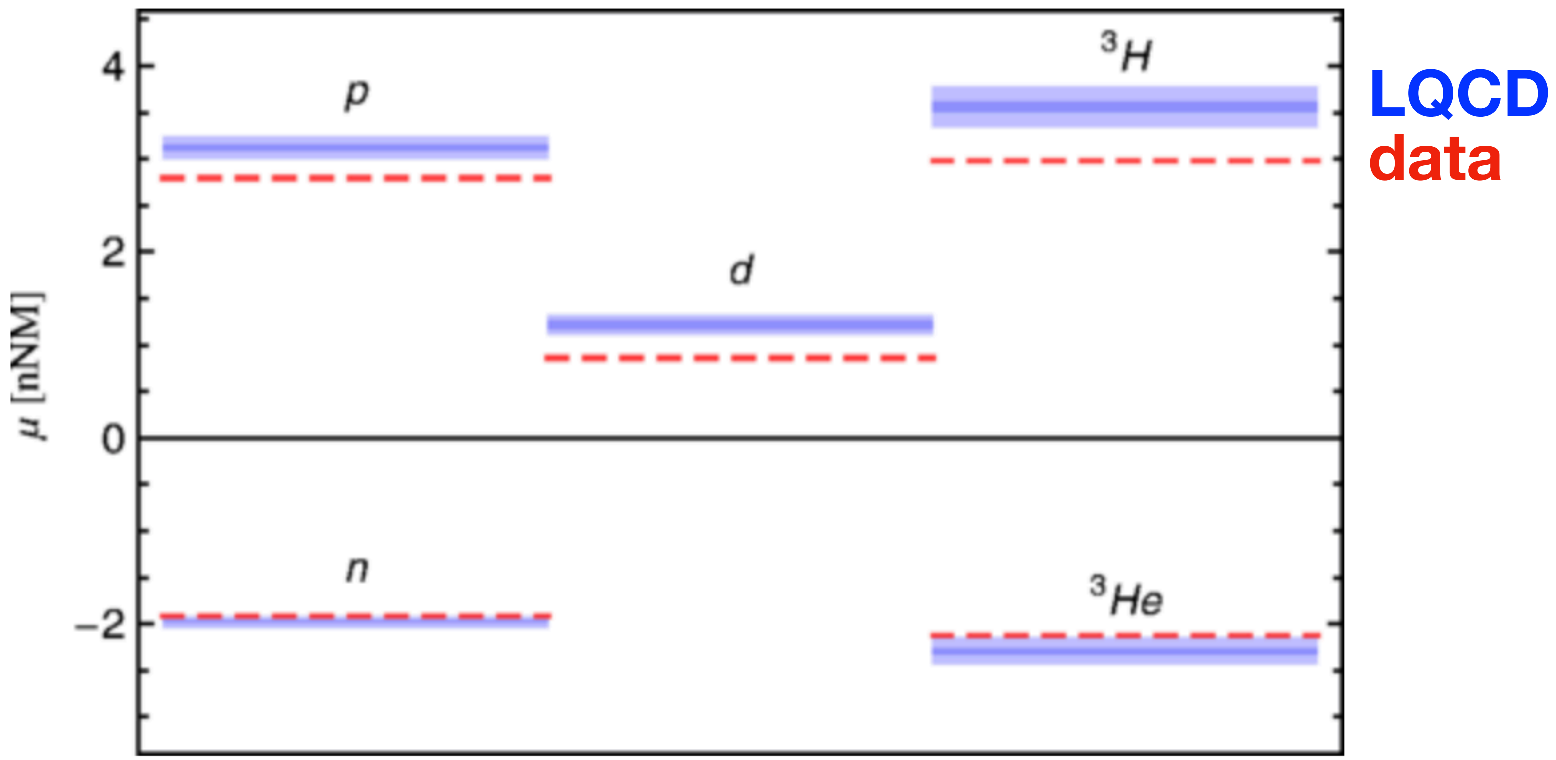
IM-GCM with a chiral nuclear force (eMax=6)

Lattice QCD for nuclear structure

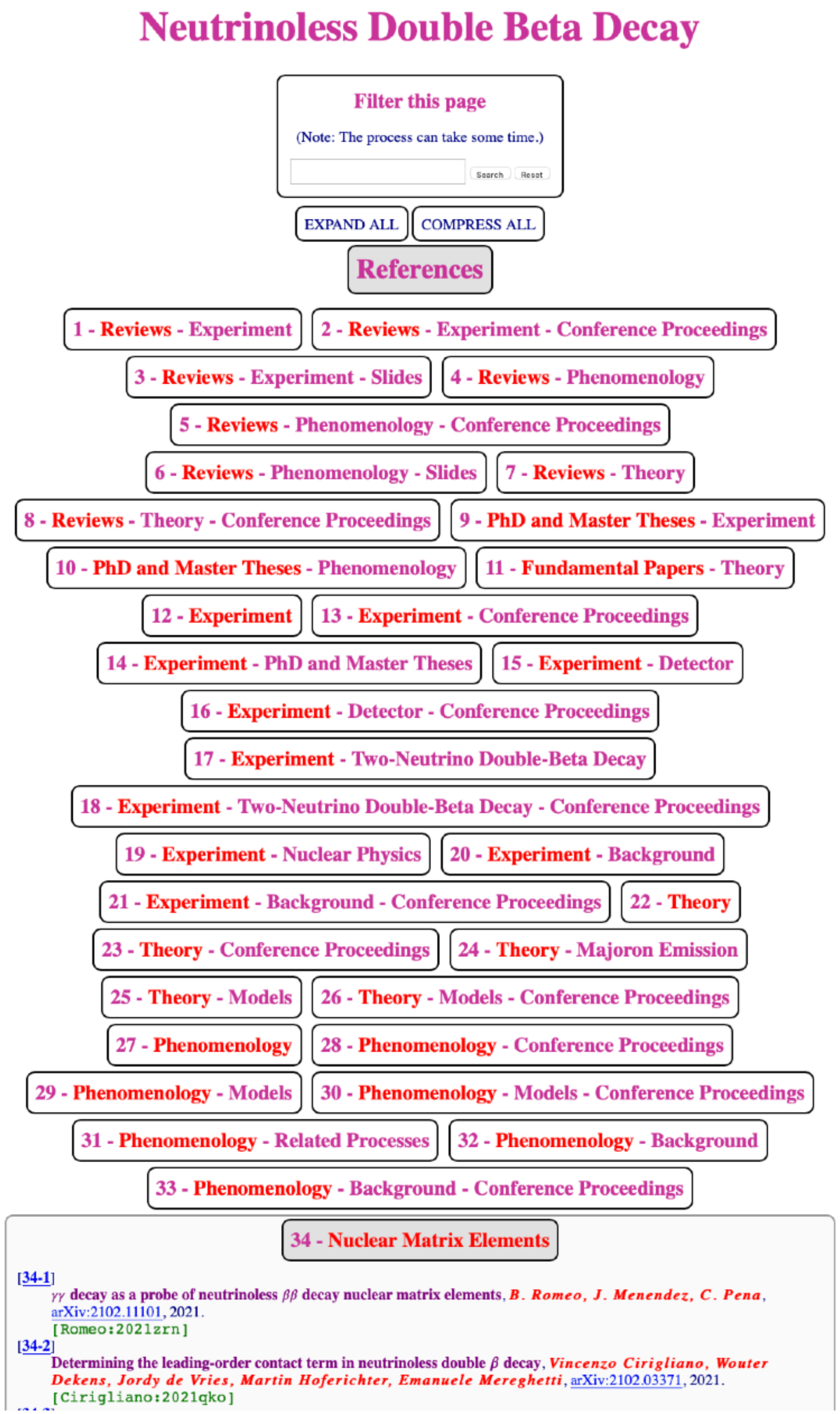
Magnetic Moments of Light Nuclei from Lattice Quantum Chromodynamics

S. R. Beane, E. Chang, S. Cohen, W. Detmold, H. W. Lin, K. Orginos, A. Parreño, M. J. Savage, and B. C. Tiburzi
(NPLQCD Collaboration)
Phys. Rev. Lett. **113**, 252001 – Published 16 December 2014

$m_\pi \sim 800\text{MeV},$



Advances in the studies of $0\nu\beta\beta$ decay


Neutrinoless Double Beta Decay

References

1 - Reviews - Experiment

2 - Reviews - Experiment - Conference Proceedings

3 - Reviews - Experiment - Slides

4 - Reviews - Phenomenology

5 - Reviews - Phenomenology - Conference Proceedings

6 - Reviews - Phenomenology - Slides

7 - Reviews - Theory

8 - Reviews - Theory - Conference Proceedings

9 - PhD and Master Theses - Experiment

10 - PhD and Master Theses - Phenomenology

11 - Fundamental Papers - Theory

12 - Experiment

13 - Experiment - Conference Proceedings

14 - Experiment - PhD and Master Theses

15 - Experiment - Detector

16 - Experiment - Detector - Conference Proceedings

17 - Experiment - Two-Neutrino Double-Beta Decay

18 - Experiment - Two-Neutrino Double-Beta Decay - Conference Proceedings

19 - Experiment - Nuclear Physics

20 - Experiment - Background

21 - Experiment - Background - Conference Proceedings

22 - Theory

23 - Theory - Conference Proceedings

24 - Theory - Majoron Emission

25 - Theory - Models

26 - Theory - Models - Conference Proceedings

27 - Phenomenology

28 - Phenomenology - Conference Proceedings

29 - Phenomenology - Models

30 - Phenomenology - Models - Conference Proceedings

31 - Phenomenology - Related Processes

32 - Phenomenology - Background

33 - Phenomenology - Background - Conference Proceedings

34 - Nuclear Matrix Elements

[34-1]
$\gamma\gamma$ decay as a probe of neutrinoless $\beta\beta$ decay nuclear matrix elements, *B. Romeo, J. Menendez, C. Pena*, arXiv:2102.11101, 2021.
`[Romeo:2021zrn]`

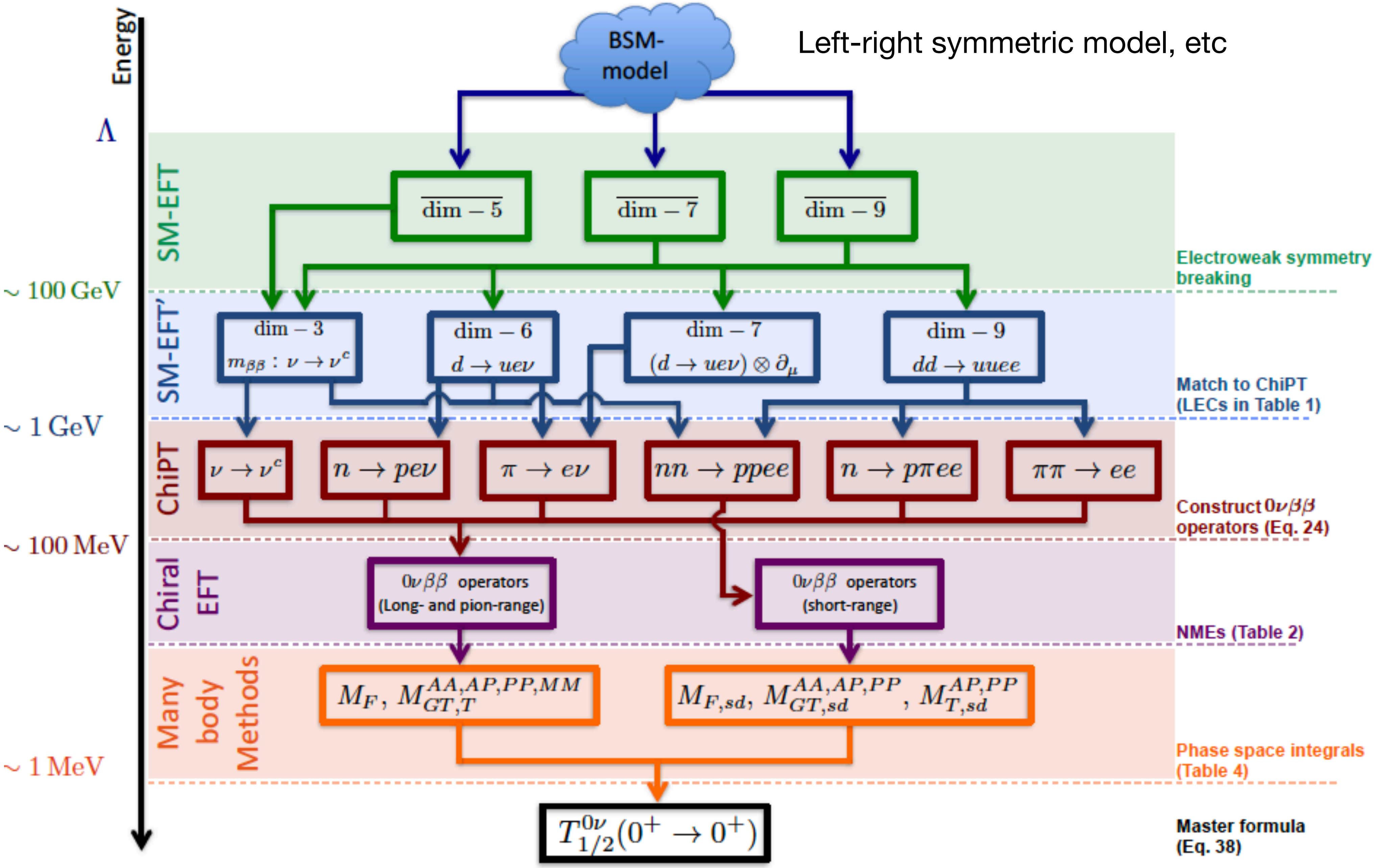
[34-2]
Determining the leading-order contact term in neutrinoless double β decay, *Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Martin Hoferichter, Emanuele Mereghetti*, arXiv:2102.03371, 2021.
`[Cirigliano:2021qko]`

http://www.nu.to.infn.it/Neutrino_Double_Beta_Decay/

What is $0\nu\beta\beta$ decay?

Effective Field Theories for $0\nu\beta\beta$

top-down: Integrate out and matching/running



Left-right symmetric model, etc

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