“无中微子双贝塔衰变”研讨会 2021年5月19-23日 珠海

Workshop on “Neutrinoless double beta decay” Summary, outlook, and acknowledgement

尧江明

中山大学物理与天文学院

School of Physics and Astronomy

Sun Yat-sen University

组委会：安振东、焦长峰、李宁、肖翔、尧江明、张鹏鸣

2021年5月23日

Summary

➡参会情况小结

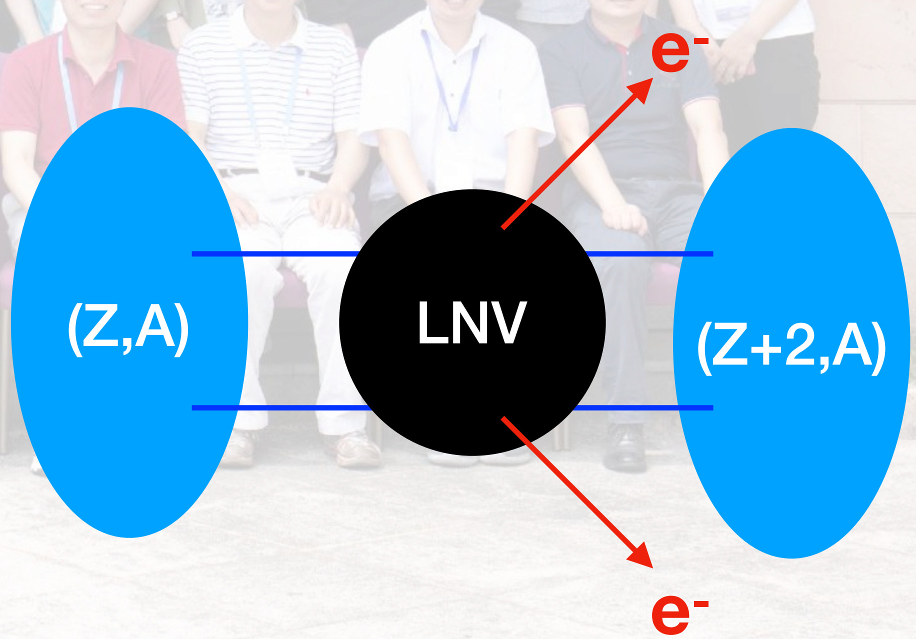
- 特邀报告（1）
- 邀请报告（28）
- 一般报告（4）

- 参会人数（67+4）
- 志愿者（6）

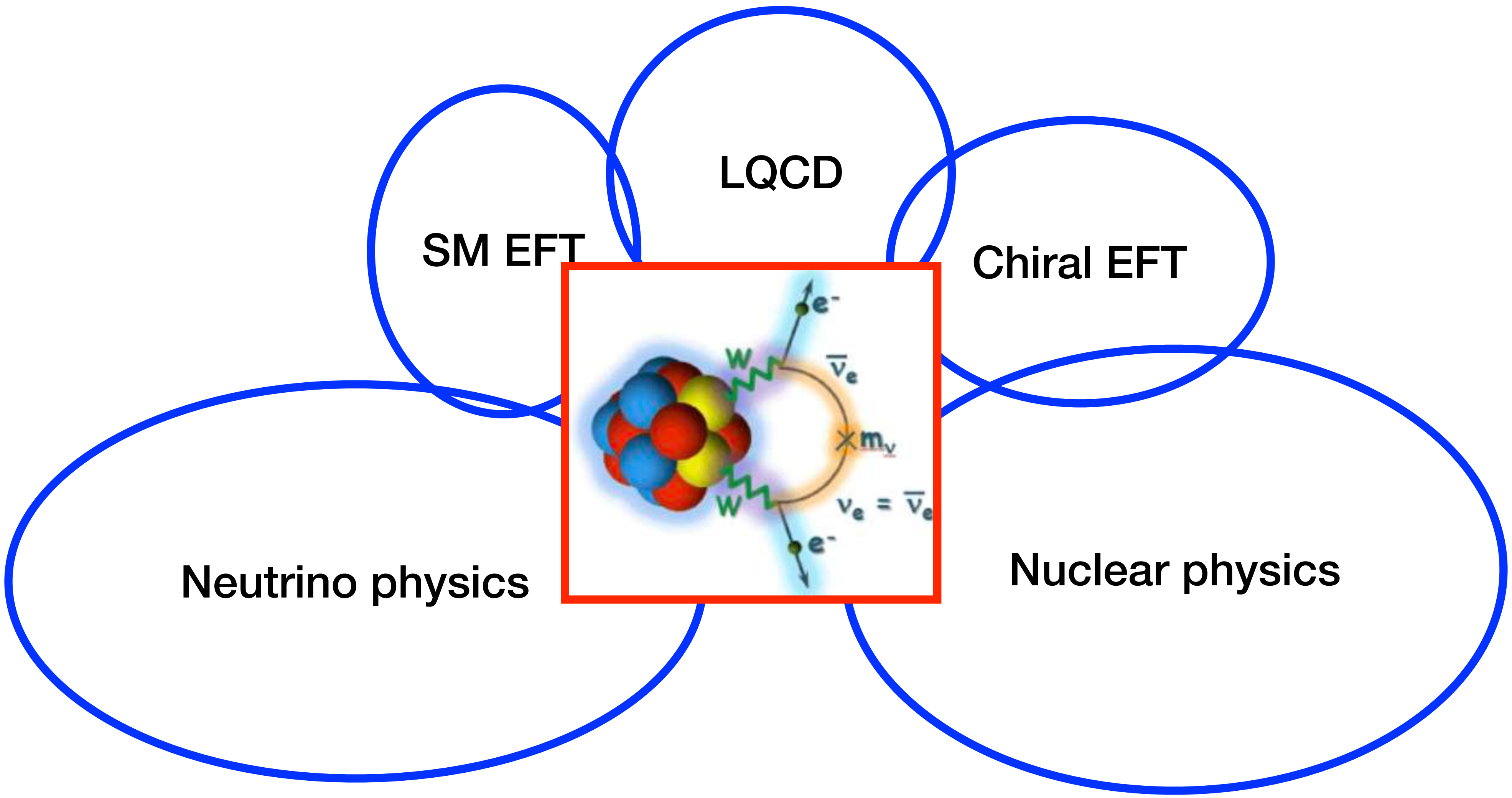
➡涉及到的内容

- 实验方面
- 理论方面
- 机器学习

- 跃迁算符
- 量子多体计算



Explore new/neutrino physics with atomic nuclei

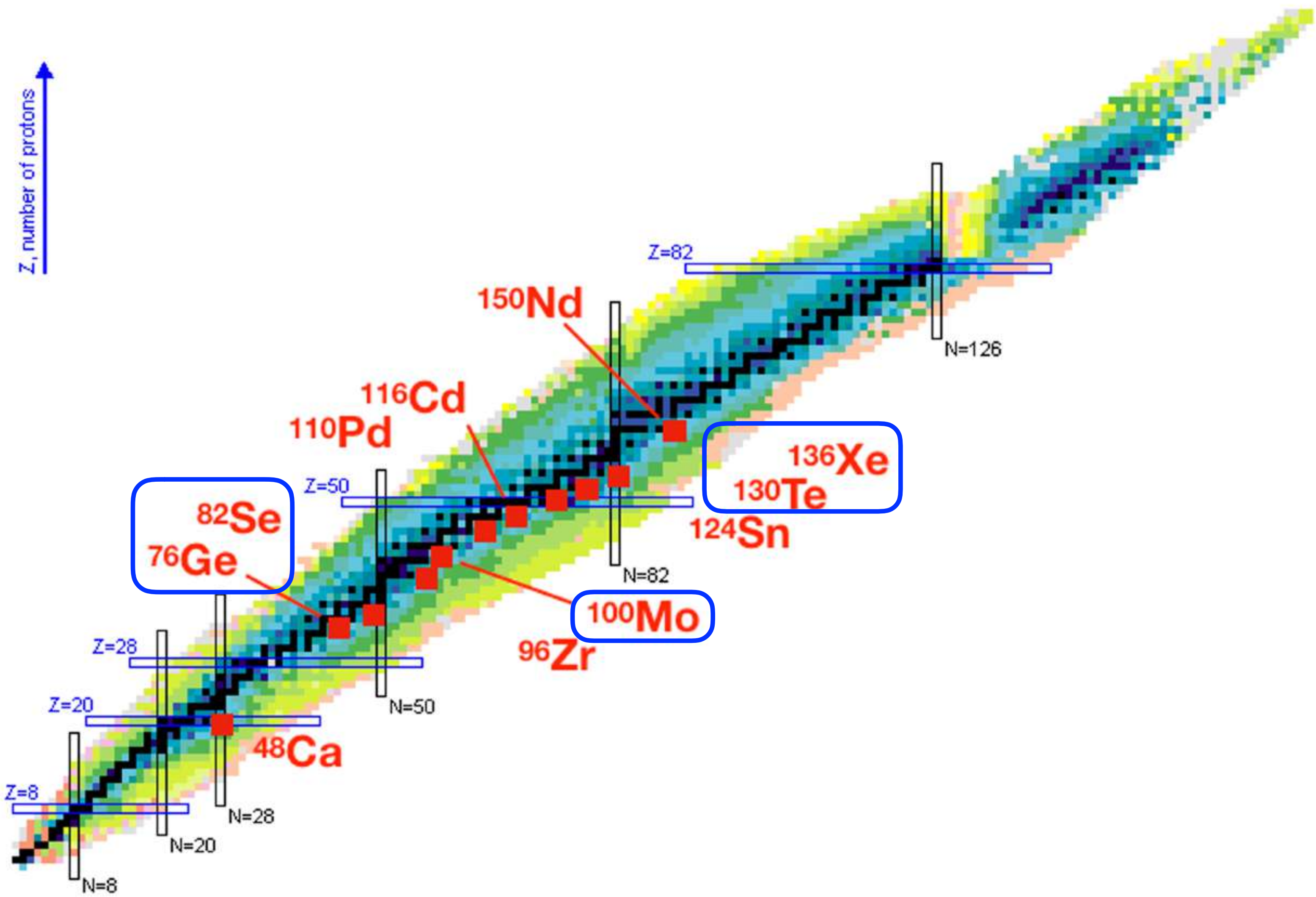


- Neutrino physics
- Status and plans of 0νββ decay experiments
- LNV operators from Standard Model EFT
- Perspectives from lattice QCD
- Nuclear potentials and effective transition operators in chiral EFT
- Nuclear ab initio methods
- Nuclear shell models and energy density functionals
- Mean-field and beyond approaches (QRPA, PHFB, GCM, etc.)
- Application of machine learning in nuclear physics

Here are the (tentative) questions to be discussed in the workshop:
- What is the challenge and perspective on 0νββ decay search (in China)?
- What level of precision is required for the NMEs from experimental design?
- How other mechanisms contribute to the 0νββ decay?
- How to determine the LECs in the effective transition operators?
- How much should gA be quenched in 0νββ decay?
- How to reduce the discrepancy among different model predictions?
- How to quantify theoretical uncertainty in the predicted NMEs of each model?
- How can we exploit machine learning techniques in the determination of NMEs?

Summary

- ▶ 实验方面



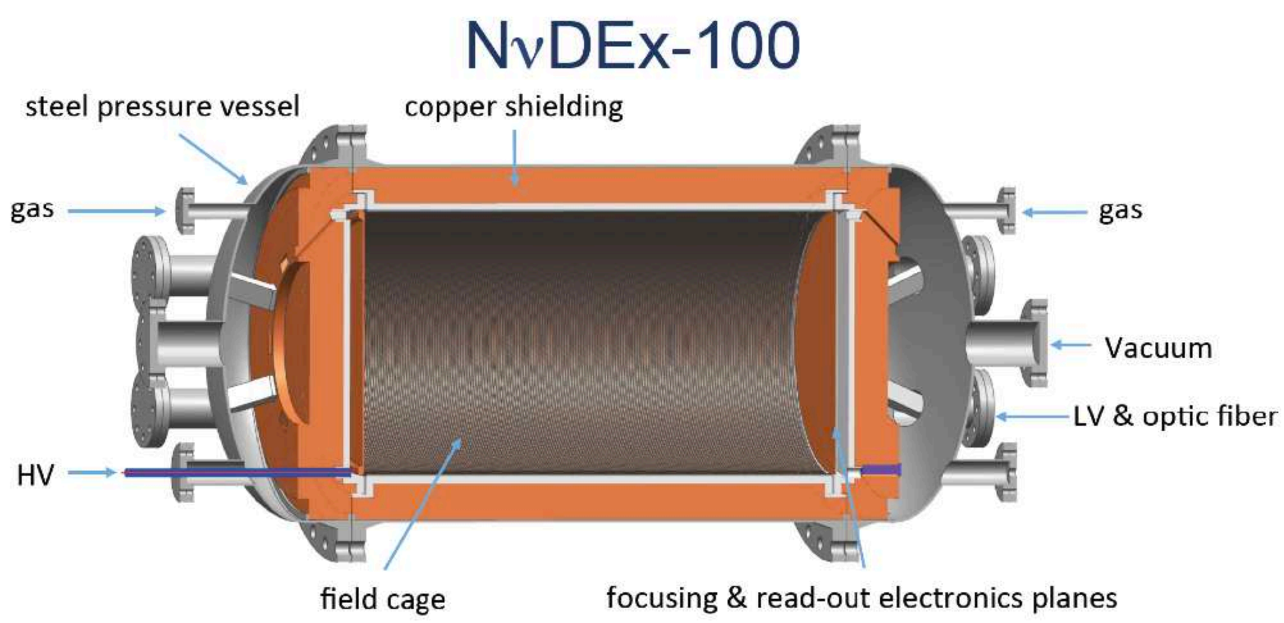
✳本底反应测量(安振东)

- ▶ ^{76}Ge （CDEX）
  （杨丽桃）
- ▶ ^{82}Se （NνDEx）
  （仇浩）
- ▶ ^{100}Mo (CUPID-China)
  （薛明萱）
- ▶ ^{136}Xe或^{130}Te (JUNO-0$\nu\beta\beta$)
  (温良剑/李高嵩）
- ▶ ^{136}Xe （PandaX-4T）
  （韩柯、王少博）
- ▶ ^{136}Xe（nEXO）(李高嵩)

Summary

▸ **实验方面**

- **NvDEx实验概念以及NvDEx-100地面样机进展** **(仇浩)**

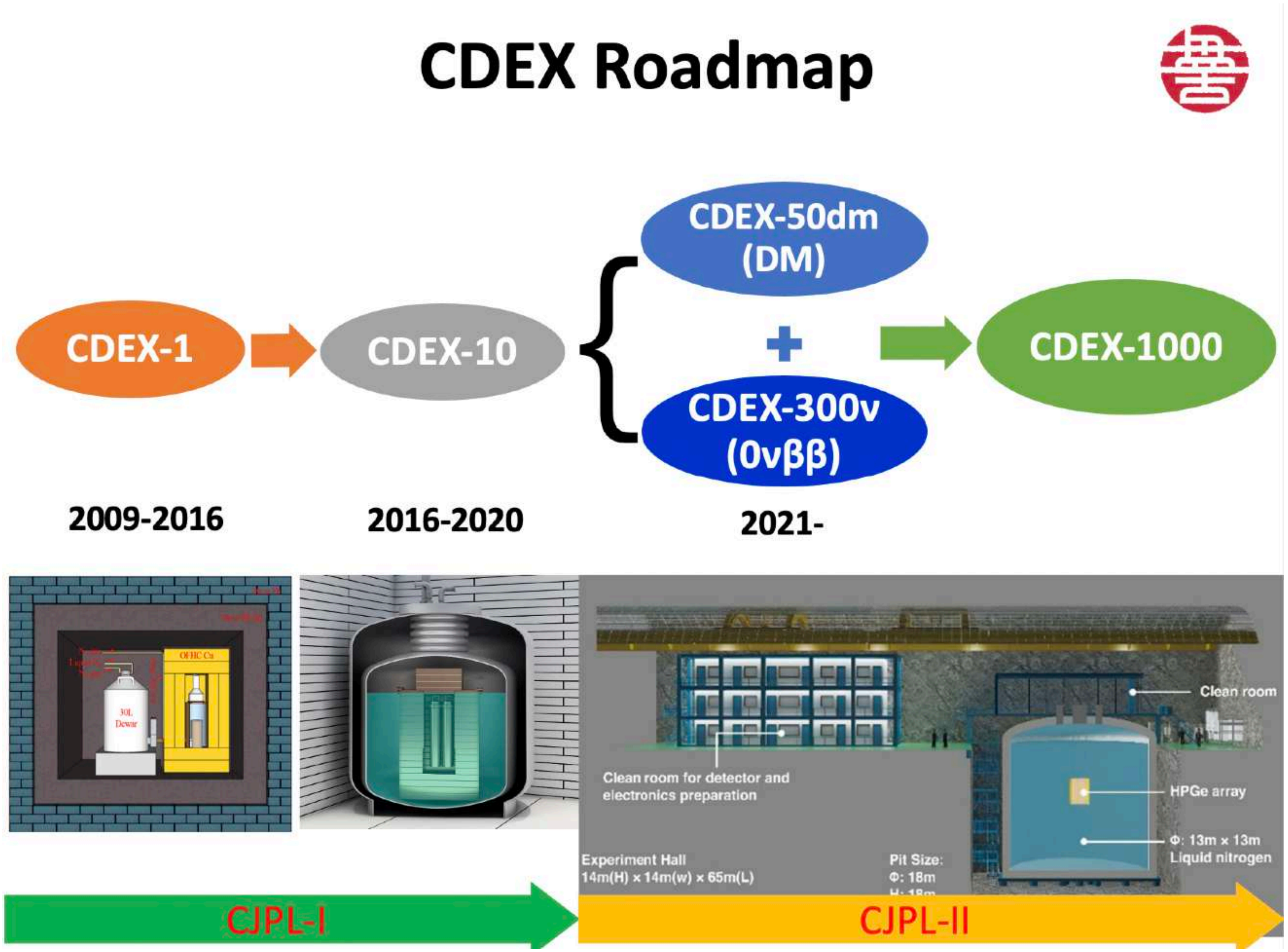


- 2021年：
  - 验证Topmetal芯片读出：达到~1%能量分辨率
  - 完成高压气腔和气体系统
- 2022年：
  - 完成100-kg级实验地面样机：TPC场笼、读出平面
  - 测试长期运行气体安全性
  - 完成本底研究，为地下实验样机研制做准备
- 2022年底：白皮书
- 希望~2023年，开始在CJPL进行地下实验样机研制

Summary

▶ **实验方面**

- **CDEX合作组启动CDEX-300ν实验，开展300kg量级富集锗探测器实验系统建设（杨丽桃）**



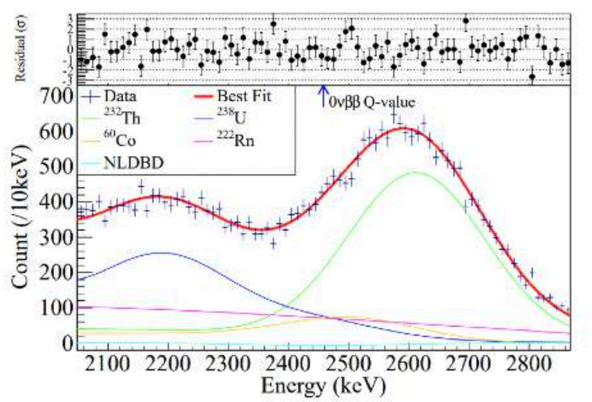
Summary

▶ 实验方面

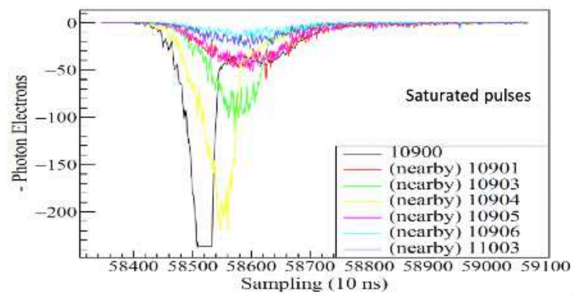
- **PandaX-II 实验、PandaX/PandaX-xT 实验** **(韩柯、王少博)**

PandaX-II 实验寻找0νββ

- 半衰期下限为2.4×10^{23} yr at 90% CL，对应的中微子马约拉纳有效质量上限1.3-3.5 eV
- 首个利用双相自然氙实验探测器给出0νββ 结果
- 验证了此类实验在寻找0νββ 上的可行性
- 面临的主要挑战：MeV宽能谱范围内的本底水平和探测器的能量分辨率

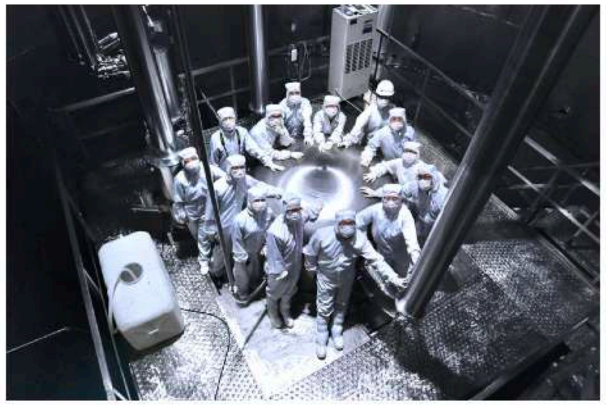


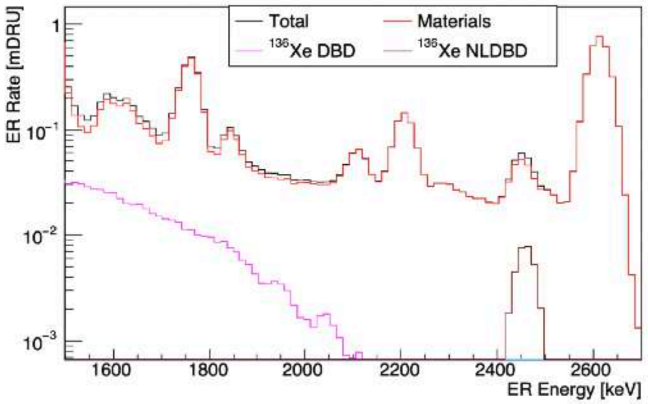
Chinese Physics C 43, 113001 (2019)



PandaX-4T 实验寻找 0νββ

- PandaX-4T探测器灵敏体积内含有350 公斤氙-136
- 材料的放射源是本底的主要来源
- 0νββ 探测灵敏度接近EXO-200的10^{25}yr水平，中微子马约拉纳有效质量上限0.2-0.5eV
- 为下一代PandaX-xT实验平台提供参考



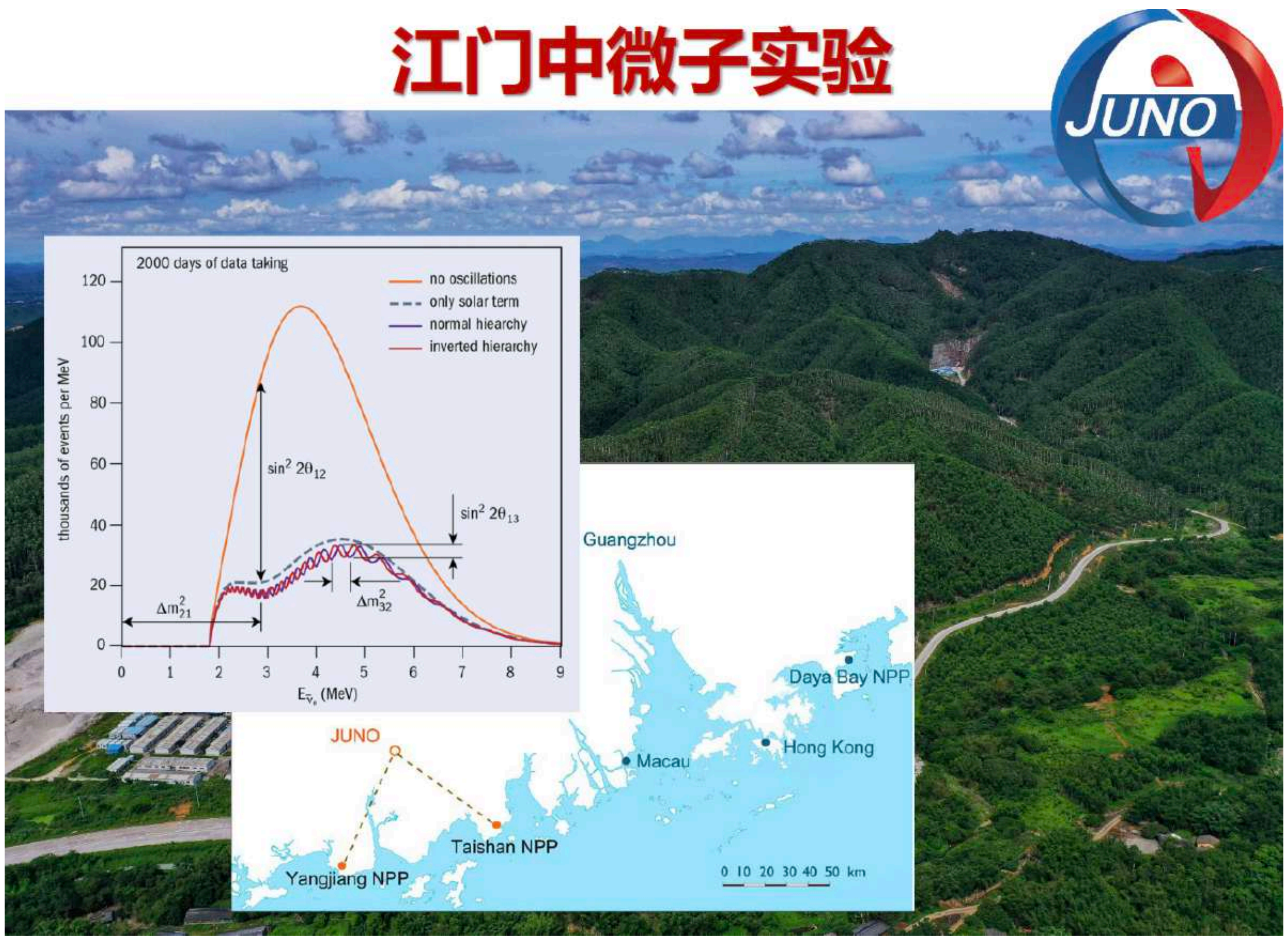


Summary

▸ 实验方面

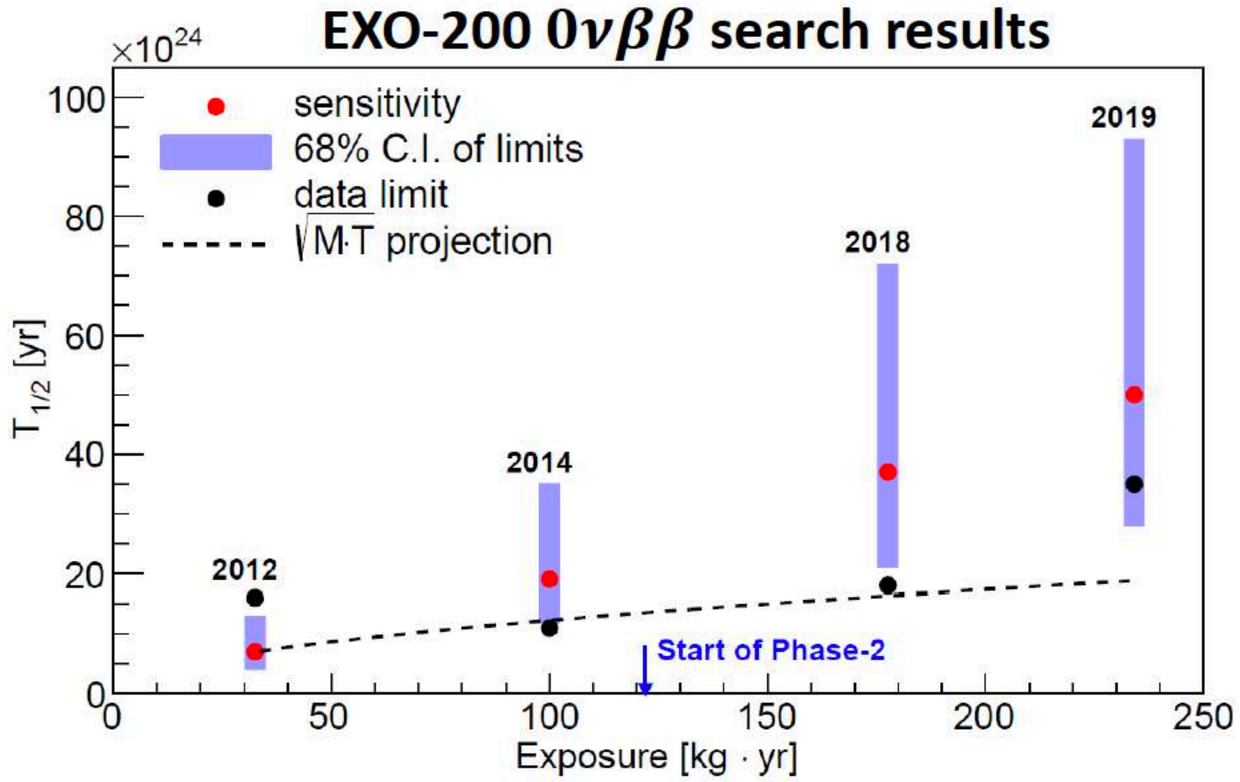
- **2030年，计划将JUNO改造为0νββ实验，用百吨量级 ^{130}Te，将灵敏度再提高>20倍，$|m_{\beta\beta}|$灵敏度逼近meV**

(温良剑)

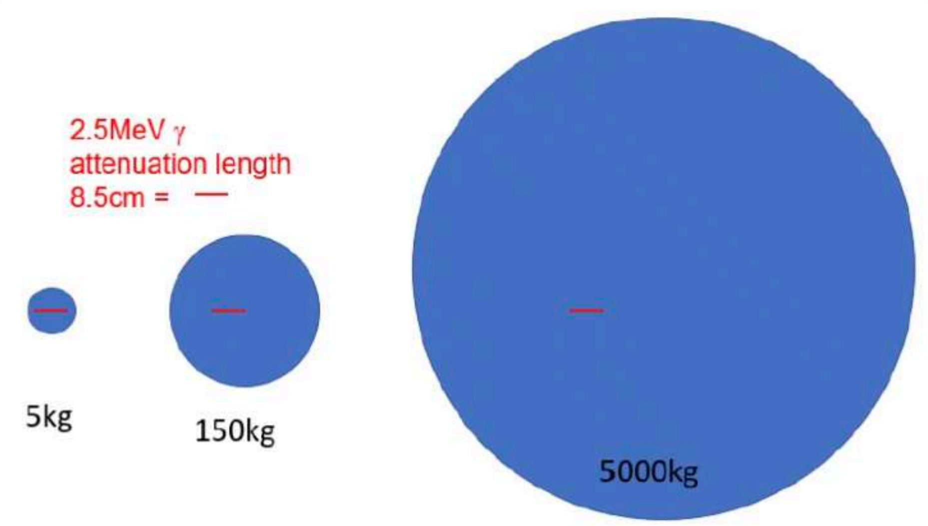


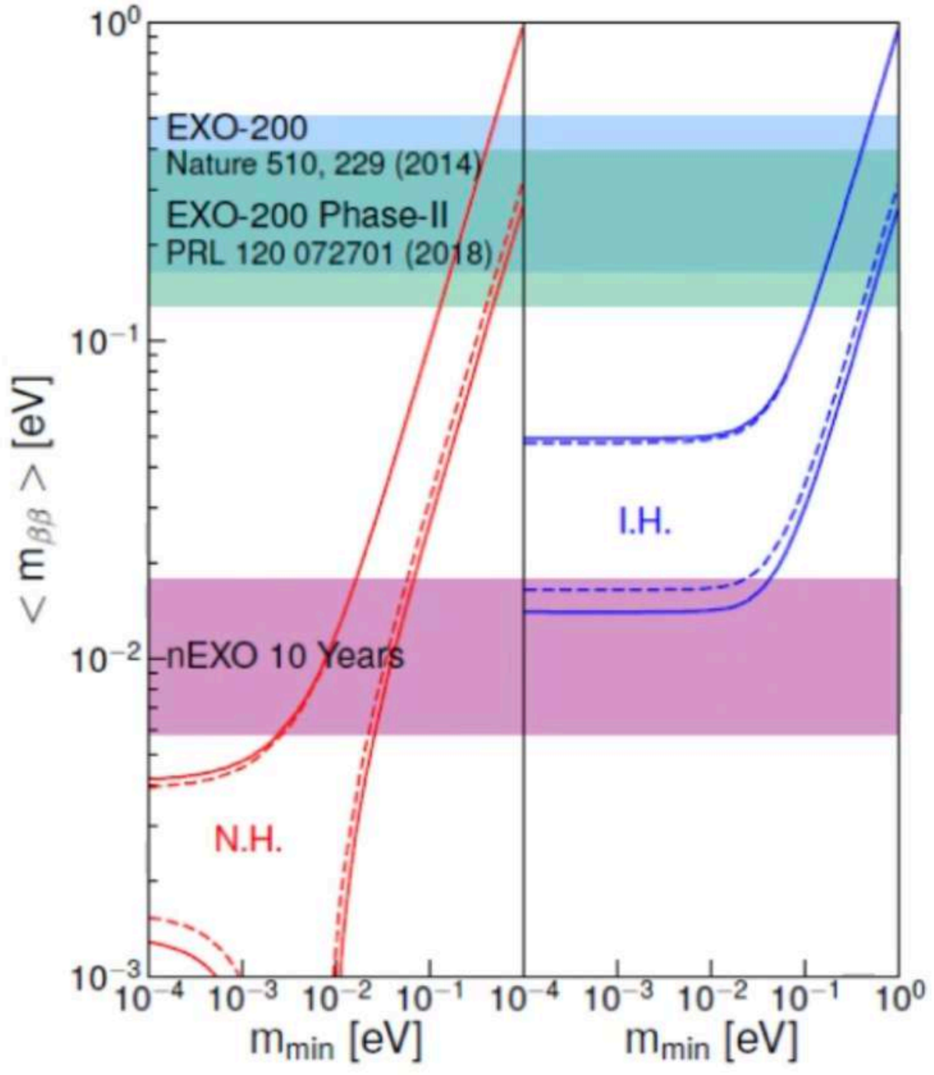
Summary

- ▸ **实验方面**
  - **from EXO-200 to nEXO** （李高嵩）



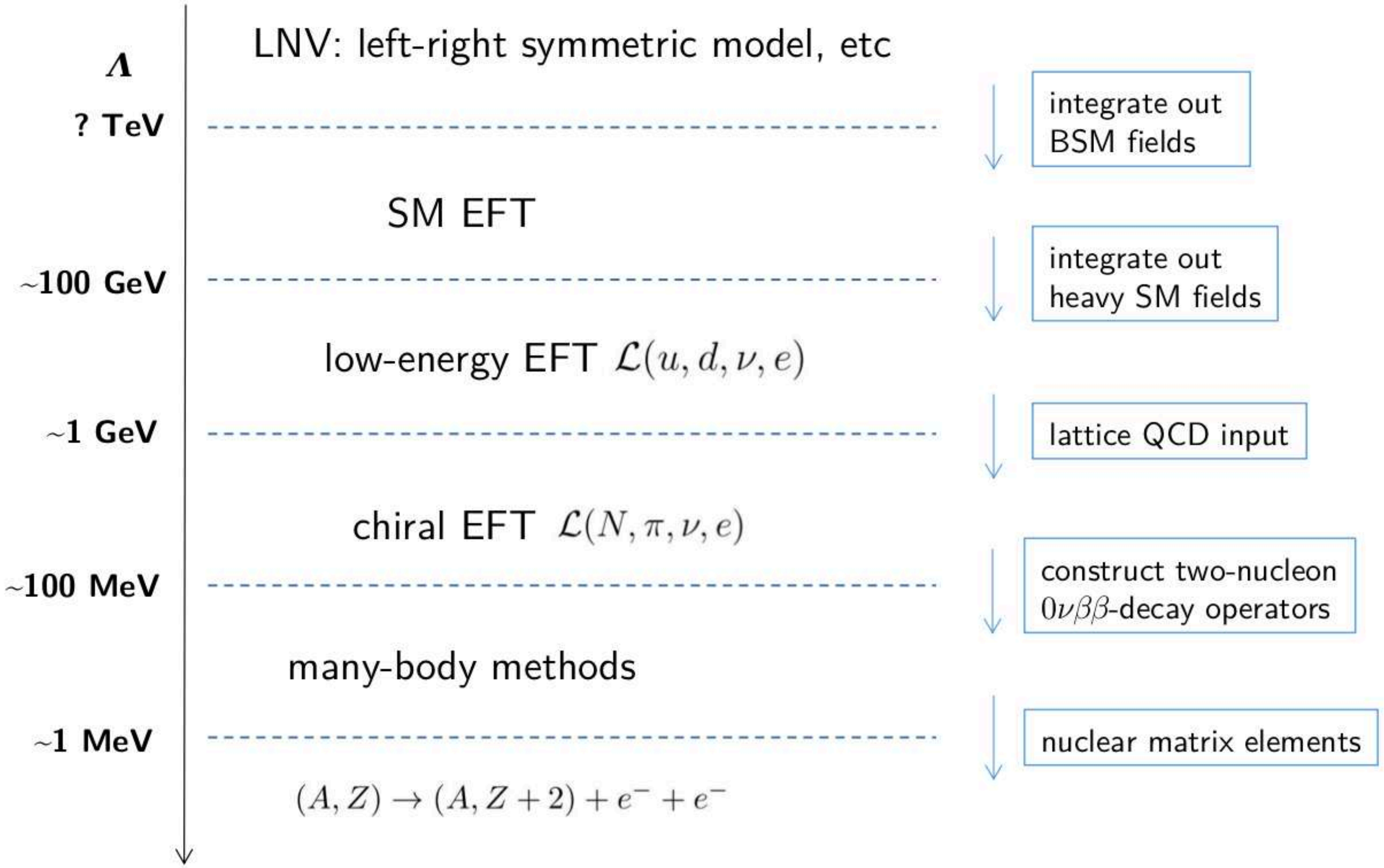
2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys.Rev.Lett. 123 (2019) no.16, 161802





Summary

Figure Credit to G. Li



- 中微子物理 （质量起源）（邢志忠、周顺、李玉峰）
- 非标准衰变机制

  （李刚、张永超、杨金磊）
- 轻子数破坏（LNV）有效场论

  （于江浩、王昊琳）
- 格点QCD（冯旭）
- 核物理中的（手征）有效场论

  （耿立升、龙炳蔚）
- 原子核矩阵元计算

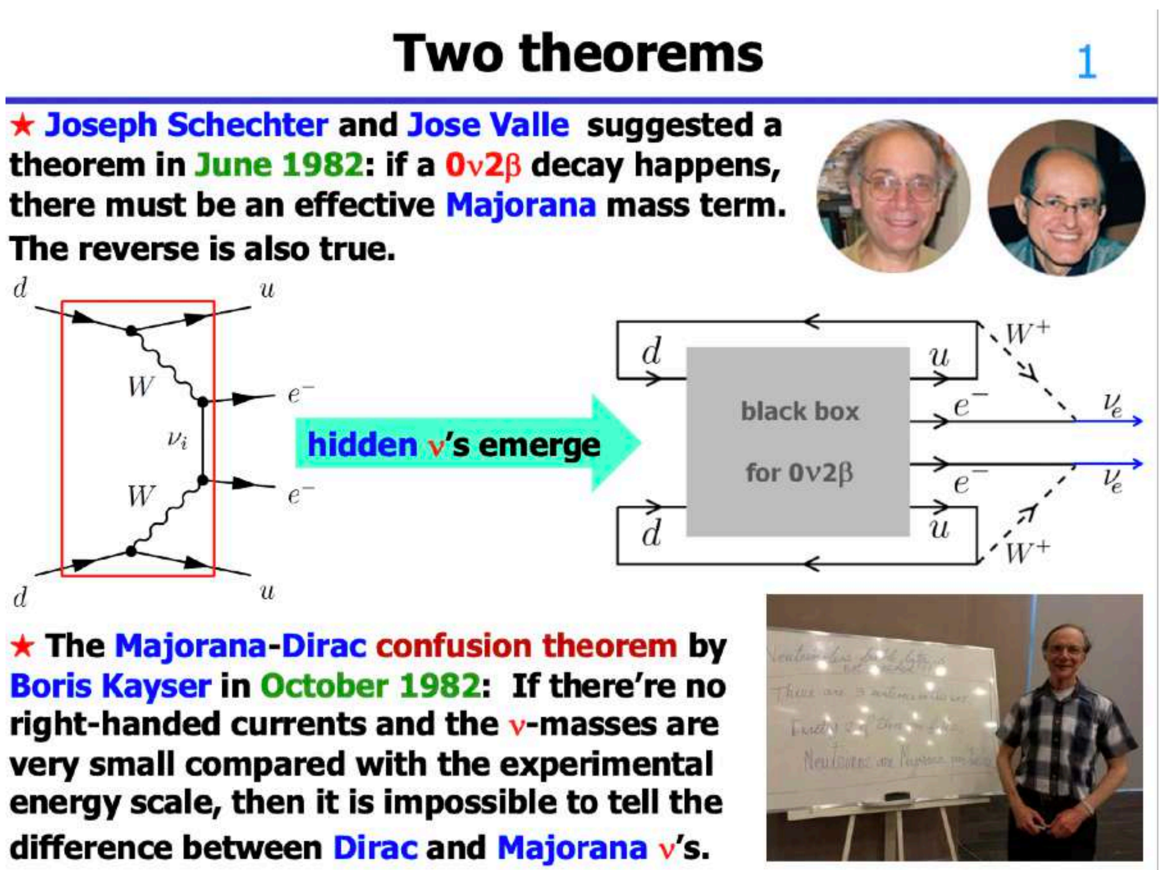
  （房栋梁、尧江明、牛一菲、王小保、焦长峰、王龙军、王亚坤）
- 原子核结构

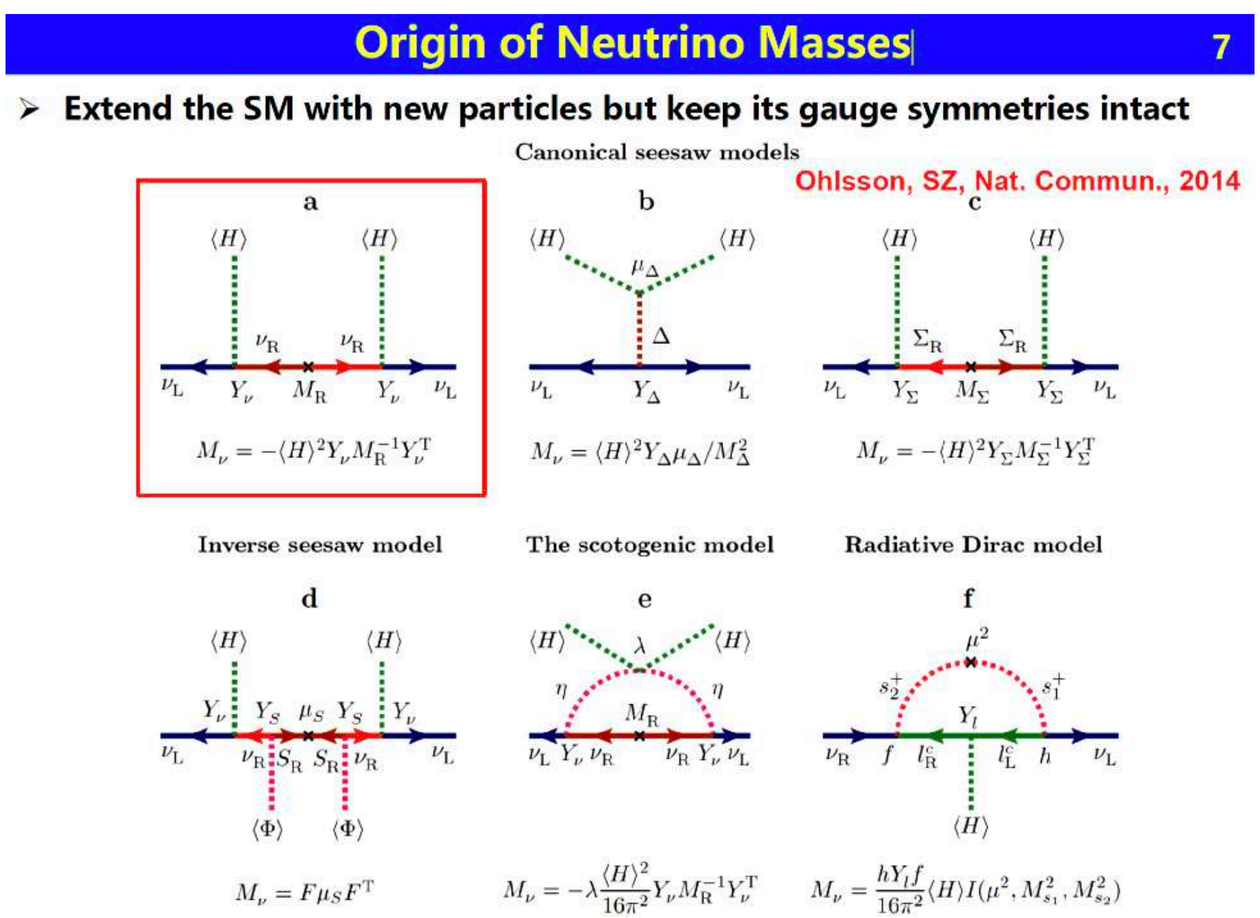
  （赵鹏巍、吕炳楠、高早春、刘朗、李剑、耿晶）
- 机器学习在核物理中的应用 （庞龙刚）

Summary

- 理论方面
  - 中微子物理 （质量起源）（邢志忠、周顺、李玉峰）

- **A brief history: ideas and facts oscillated**
- **Salient properties of Majorana neutrinos**





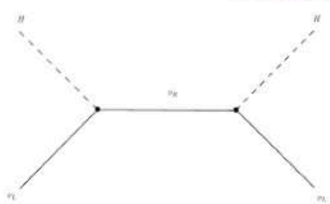
Summary

- **理论方面**
  - **非标准衰变机制　（李刚、张永超、杨金磊）**

Seesaw mechanisms and left-right symmetric model

Type-I seesaw

Minkowski '77; Mohapatra & Senjanović '80; Yanagida '79;
Gell-Mann, Ramond & Slansky '79; Glashow '80



- Basic Lagrangian to generate tiny neutrino masses

$$\mathcal{L} = -y_D \bar{L}\phi N + \frac{1}{2}\overline{N^C} M_N N$$

- Heavy-light neutrino mixing induced couplings

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W_\mu \bar{\ell}_\alpha \gamma^\mu P_L \left[U_{\alpha i}\nu_i + V_{\alpha j} N_j\right]$$

The heavy-light neutrino mixing will induce contributions of heavy neutrinos to $0\nu\beta\beta$!

Minimal left-right symmetric model

Gauge group: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Doublets: $q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$ $\quad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$

$L_L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L$ $\quad L_R = \begin{pmatrix} N \\ l \end{pmatrix}_R$

Mohapatra and Senjanovic,
Phys.Rev.Lett. 44 (1980) 912,
Phys.Rev.D 23 (1981) 165

Bidoublet: $\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow \langle\Phi\rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}$

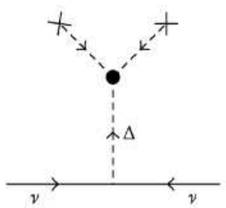
Triplets: $\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix}$

$$\Rightarrow \langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \quad \langle\Delta_L\rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

provide a natural origin of neutrino masses

Type-II seesaw

Konetschny & Kummer '77; Magg & Wetterich '80; Schechter & Valle '80;
Cheng & Li '80; Mohapatra & Senjanovic '81; Lazarides, Shafi & Wetterich '81



- One of the simplest seesaw frameworks to generate the tiny neutrino masses...

$$\mathcal{L} = -(f_L)_{\alpha\beta}\psi^T_{L\alpha} C i\sigma_2 \Delta_L \psi_{L\beta} + \mu H^T i\sigma_2 \Delta_L^\dagger H + \text{H.c.},$$

$$\Delta_L = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}.$$

- Neutrino masses are given by

$$m_\nu = \sqrt{2} f_L v_L = U \widehat{m}_\nu U^T \qquad (\text{with the VEV } \langle\delta_L^0\rangle = v_L/\sqrt{2})$$

- The coupling matrix f_L is fixed by neutrino oscillation data, up to the unknown lightest neutrino mass m_0, the neutrino mass hierarchy, and the Dirac & Majorana CP violating phases.

Summary

- **理论方面**
  - **非标准衰变机制　　（李刚、张永超、杨金磊）**

$0\nu\beta\beta$ in LRSM

Mohapatra & Vergados '81 [PRL]; Hirsch, Klapdor-Kleingrothaus & Panella '96 [PLB]; Dev, Goswami, Mitra & Rodejohann '13 [PRD]; Huang & Lopez-Pavon '14 [EPJC]; Dev, Goswami & Mitra '15 [PRD]; Deppisch, Gonzalo, Patra, Sahu & Sarkar '15 [PRD] Ge, Lindner & Patra1 '15 [JHEP]; Borah & Dasgupta '15 [JHEP]

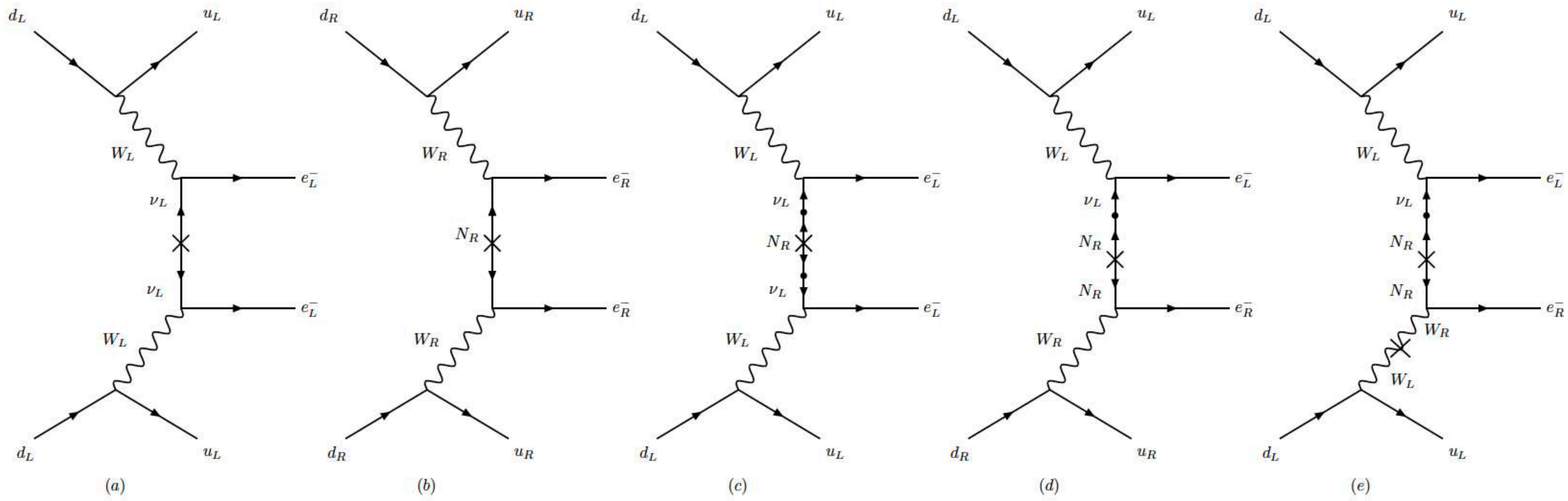


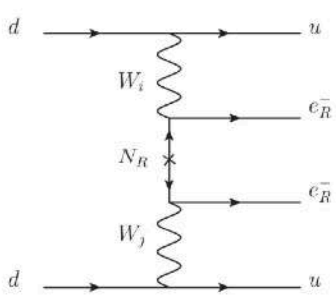
Figure: Contributions $\mathcal{A}_\nu$, $\mathcal{A}^R_{N_R}$, $\mathcal{A}^L_{N_R}$, $\mathcal{A}_\lambda$, $\mathcal{A}_\eta$ to $0\nu\nu\beta\beta$ in LRSM

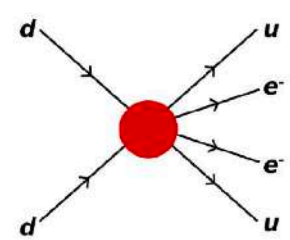
- **理论方面**
  - **非标准衰变机制　（李刚、张永超、杨金磊）**

Leading contribution from $W_L - W_R$ mixing

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\bar{u}_{Li}V^{\text{CKM}}_{Lij}W_L d_{Lj} - \frac{g}{\sqrt{2}}\bar{u}_{Ri}V^{\text{CKM}}_{Rij}W_R d_{Rj} - \frac{g}{\sqrt{2}}\bar{e}_{Li}V^{\text{PMNS}}_{Lij}W_L \nu_{Lj} - \frac{g}{\sqrt{2}}\bar{e}_{Ri}V^{\text{PMNS}}_{Rij}W_R N_{Rj} + \text{h.c.}\,,$$

$0\nu\beta\beta$-decay:





No $W_L - W_R$ mixing　(i,j)=(R,R)　$u_R d_R u_R d_R e_R e_R \sim O^{++}_{3\pm}$　$\boxed{\mathcal{A}^{\text{NNLO}} \sim p^0}$

$W_L - W_R$ mixing　(i,j)=(1,2)　$u_L d_L u_R d_R e_R e_R \sim O^{++}_{1+}$　$\boxed{\mathcal{A}^{\text{LO}} \sim p^{-2}}$

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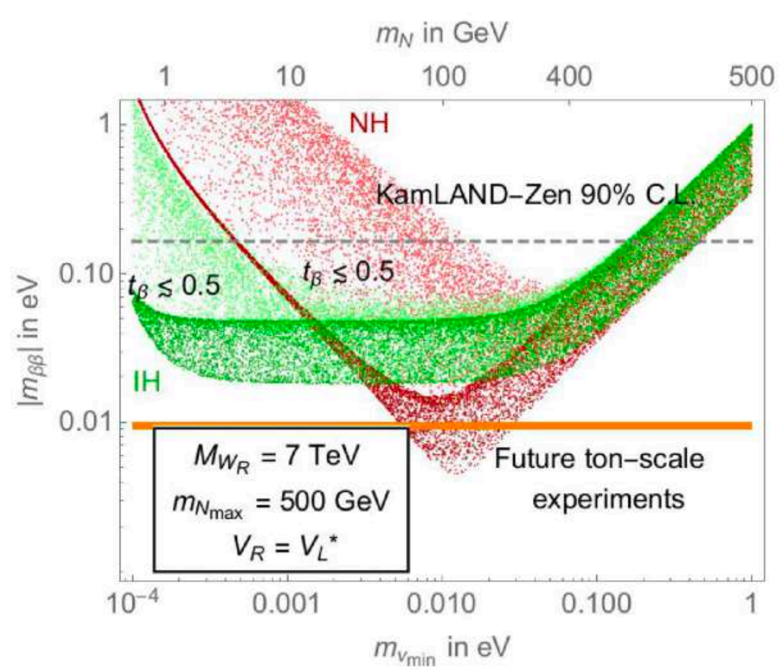
$0\nu\beta\beta$-decay in minimal LRSM



dark red, dark green:
$\tan\beta = 0$

see for example, Tello et al, Phys.Rev.Lett. 106 (2011) 151801; S.-F. Ge, M. Lindner, S. Patra, 1508.07286 (JHEP); Bhupal Dev, Goswami, Mitra Phys.Rev.D 91 (2015) 113004 and many more

light red, light green:
$\tan\beta \lesssim 0.5$

GL, Ramsey-Musolf and Vasquez, 2009.01257 (PRL)

A large portion of parameter space could give a positive signal after including leading contribution from LO $\pi\pi ee$ interaction from W_L-W_R mixing

Summary

- **理论方面**
  - **非标准衰变机制　（李刚、张永超、杨金磊）**
    - QCD修正对原子核$0\nu2\beta$衰变有十分重要的作用。在两个新物理模型中，数值结果的修正能达到40%左右。
    - B-LSSM中中微子获得质量的方式是Type-I see-saw，重中性轻子的贡献会被轻-重混合角严重压低，轻中微子的贡献为将来探测到原子核$0\nu2\beta$衰变提供了很强的可能性。
    - LRSM中存在右手的W玻色子，因此中微子传播子分子上$\not{p}$也会贡献，假设两个初态夸克动量相同、末态夸克动量相同后，可将所有贡献的算子转化为九维算子，可以直接计算不同贡献之间的干涉。此外，数值结果表明不同的贡献之间有相消的效应。

Summary

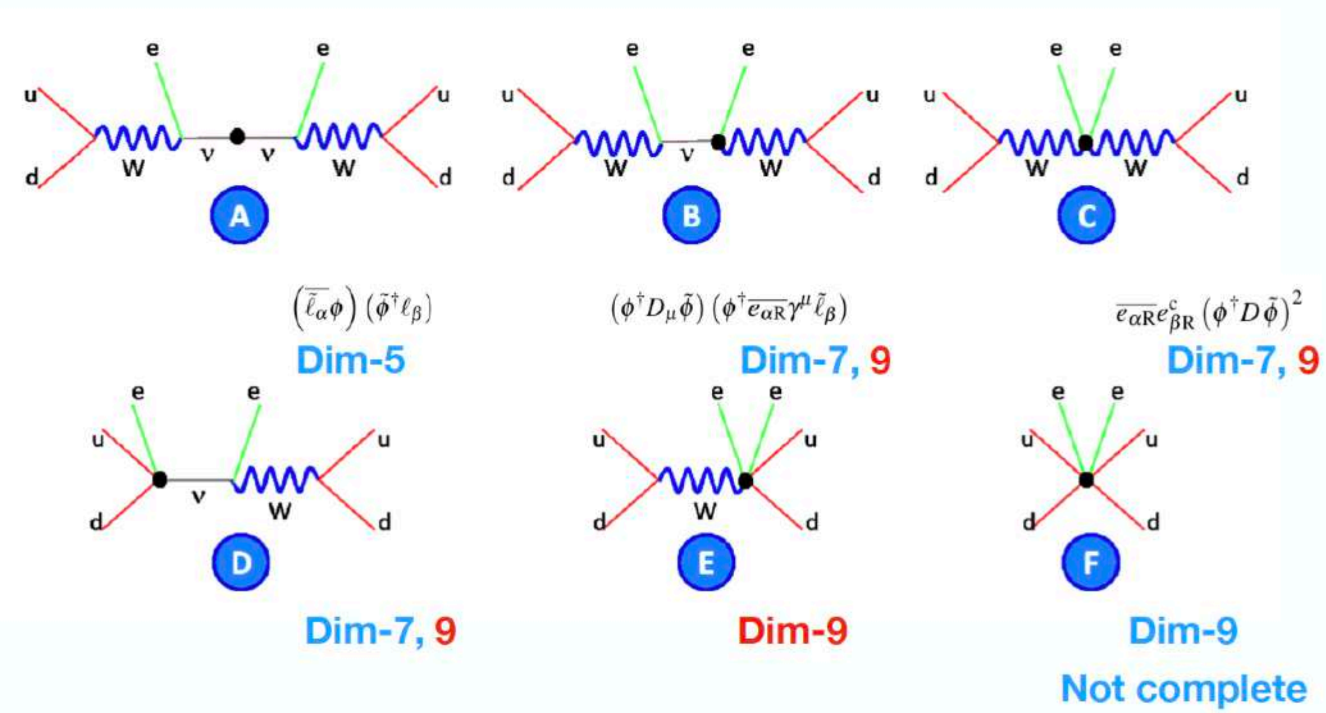
- **理论方面**
  - **轻子数破坏（LNV）有效场论**

    （于江浩、王昊琳）

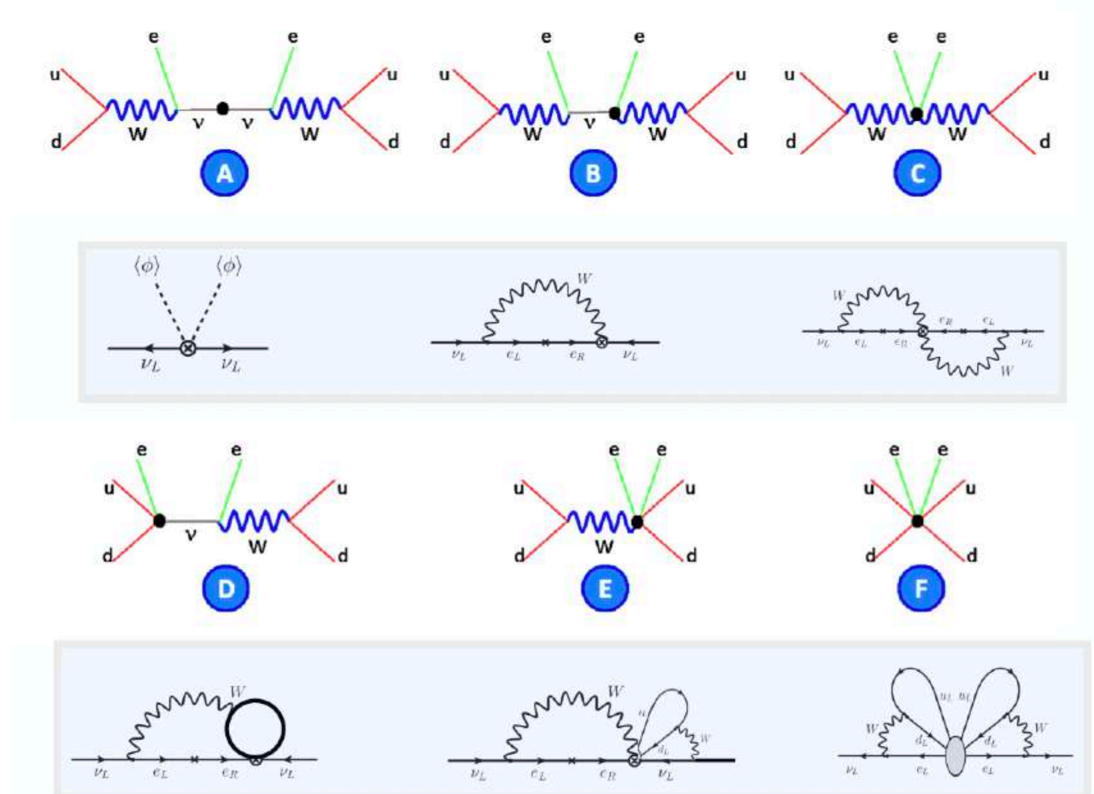
- 0vbb involves in many scales: SMEFT, LEFT, ChiEFT
- The complete bases just written down recently 2020 - 2021
- The formalism needs to be extended in each EFT levels

0vbb Related Operators

Relate to SMEFT unbroken operators:



Neutrino Masses and 0vbb



Summary

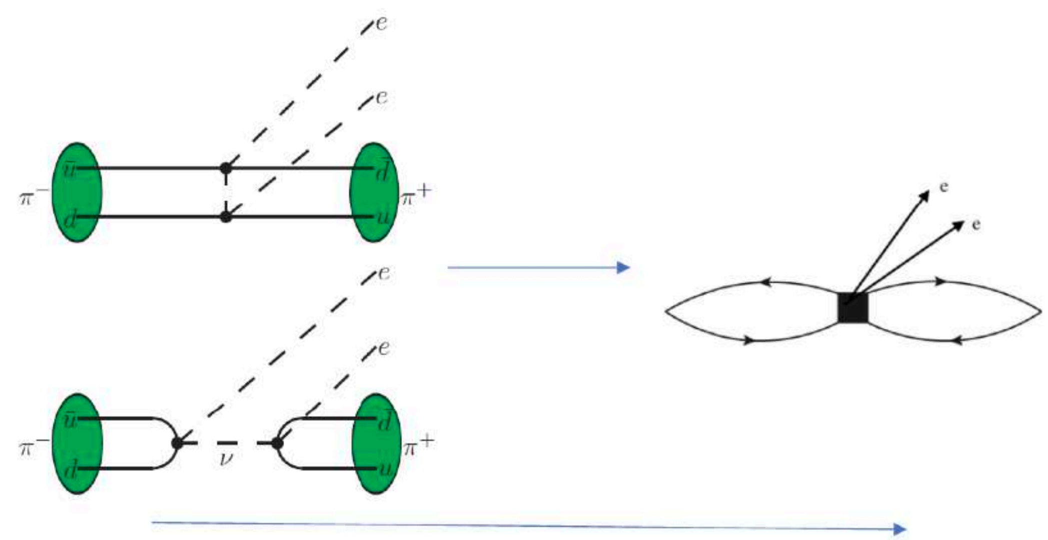
- **理论方面**
  - **轻子数破坏（LNV）有效场论**

    (于江浩、王昊琳)

    - We studied the LNV process in the series of EFTs
    - Matching and running are done between different EFTs
    - These studies are complementary to $0\nu\beta\beta$
    - We systematically include the potential LNV sources
    - The uncertainties can be systematically estimated

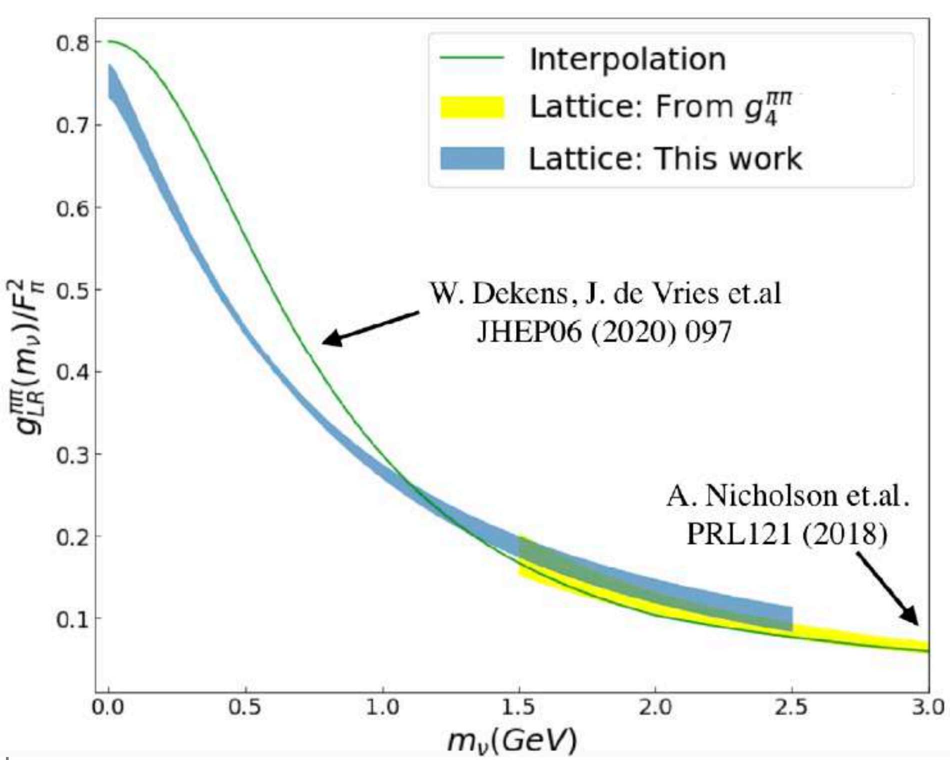
Summary

- ▸ **理论方面**
  - ▸ **格点QCD（冯旭）**



Increase the mass of the neutrino

Project lead by Xin-Yu Tuo



Chiral perturbation theory for $\pi^-\pi^- \to ee$

[Cirigliano, Dekens, Mereghetti, Walker-Loud, PRC97 (2018) 065501]

$$\frac{\mathcal{A}(\pi^-\pi^- \to ee)}{2F_\pi^2 T_{\text{lept}}} = 1 - \frac{m_\pi^2}{(4\pi F_\pi)^2}\left(3\log\frac{\mu^2}{m_\pi^2} + \frac{7}{2} + \frac{\pi^2}{4} + \frac{5}{6}g_\nu^{\pi\pi}(\mu)\right)$$

Lattice calculation yields (statistical error only)

[XF, L. Jin, X. Tuo, S. Xia, PRL122 (2019) 022001]

$$\frac{\mathcal{A}(\pi\pi \to ee)}{2F_\pi^2 T_{\text{lept}}} = 0.910(3) \quad \Rightarrow \quad g_\nu^{\pi\pi}(m_\rho) = -12.0(3)$$

Chiral perturbation theory for $\pi^- \to \pi^+ ee$

[X. Tuo, XF, L. Jin, PRD100 (2019) 094511]

$$\frac{\mathcal{A}(\pi^- \to \pi^+ ee)}{2F_\pi^2 T_{\text{lept}}} = 1 + \frac{m_\pi^2}{(4\pi F_\pi)^2}\left(3\log\frac{\mu^2}{m_\pi^2} + 6 + \frac{5}{6}g_\nu^{\pi\pi}(\mu)\right)$$

Lattice calculation yields (statistical + systematical errors)

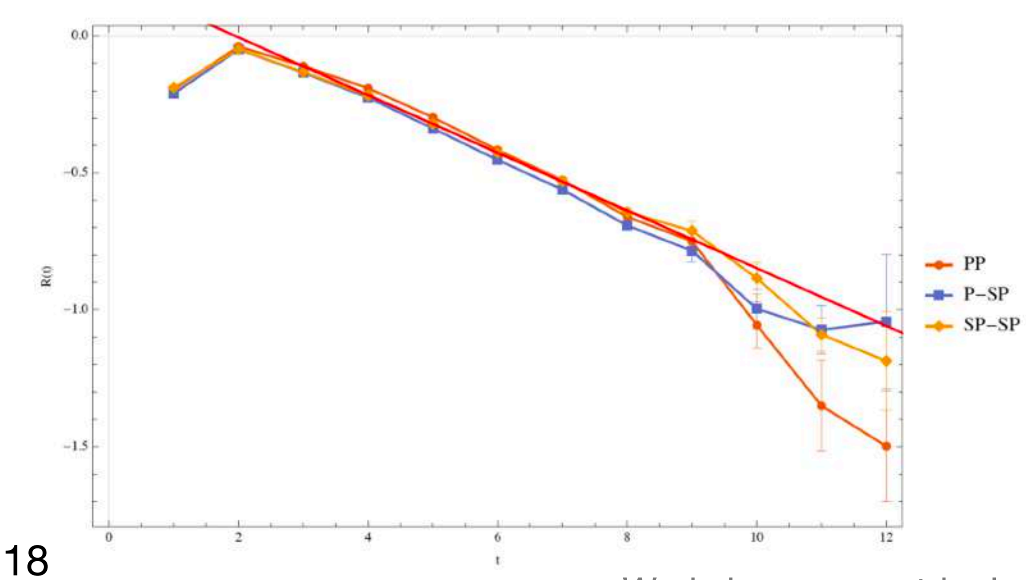
$$\frac{\mathcal{A}(\pi^- \to \pi^+ ee)}{2F_\pi^2 T_{\text{lept}}} = 1.105(3)(7) \quad \Rightarrow \quad g_\nu^{\pi\pi}(m_\rho) = -10.9(3)(7)$$

Also $g_\nu^{\pi\pi}(m_\rho) = -10.8(1)(5)$ [W. Detmold, D. Murphy, arXiv:2004.07404]

$nn \to ppee$ decay amplitude

Project lead by Zi-Yu Wang

$0\nu2\beta$ decay: $nn \to ppee$



Summary

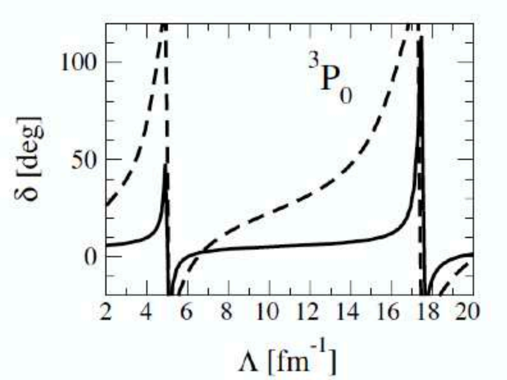
- **理论方面**
  - **核物理中的（手征）有效场论**
    （耿立升、龙炳蔚）

相对论手征核力： 参数更少?

Renormalizing singular attraction

Nogga, Timmerman & van Kolck (2005)

Phase shifts vs. Λ



Solid: Tlab = 10 MeV, dashed: 50 MeV

$C_{3P0}\vec{p}\cdot\vec{p}' \sim \frac{Q^2}{m_{hi}^2}$	$C_{3P0}\vec{p}\cdot\vec{p}' \sim \frac{Q^2}{m_{lo}^2}$
$O(Q^2)$	$O(1)$
WPC	RG inv. counting

- Contacts needed at LO in attractive triplet channels: 3P2 - 3F2, 3D2, 3D3 …

Power Counting change?

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

Chiral effective field theory

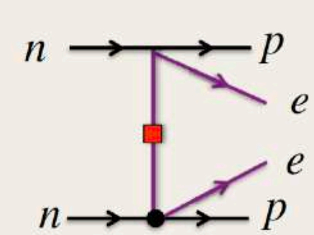
~ GeV $L = L_{QCD} + L_{Fermi} - m_{\beta\beta}\nu_L^T C \nu_L$ light quarks and gluons + electrons + neutrinos

~100 MeV **Neutrinos are still degrees of freedom in the low-energy EFT**

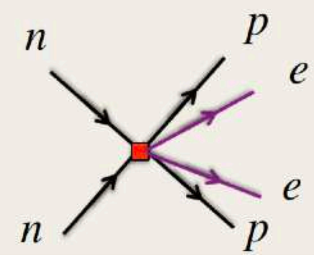
LO interaction : $\nu_L \longleftrightarrow \nu_L$ $\sim m_{\beta\beta}$

Leads to long-range nn→ pp + ee $\sim \frac{m_{\beta\beta}}{q^2}$

$q \sim k_F \sim m_\pi$



\`Hard' neutrino exchange $(E,|\vec{p}| > \Lambda_\chi)$ → short-range operators



Expected at N²LO $\sim \frac{m_{\beta\beta}}{\Lambda_\chi^2}$

Summary

▸ **理论方面**

▸ **原子核矩阵元计算**

（房栋梁、王亚坤、尧江明、牛一菲、王小保、焦长峰、王龙军、高早春）

CI-PDFT多体波函数

- CI-PDFT 框架下的核多体波函数：

$$|\Psi_{IM}\rangle = \sum_{K\kappa} F^{I}_{K\kappa} \hat{P}^{I}_{MK} |\Phi_\kappa\rangle$$

- 三维角动量投影算符 $\hat{P}^{I}_{MK}$：

$$\hat{P}^{I}_{MK} = \frac{2I+1}{8\pi^2} \int d\Omega D^{I*}_{MK}(\Omega)\hat{R}(\Omega)$$

- 内禀波函数 $|\Phi_\kappa\rangle \in \{|\Phi_0\rangle, \hat{\beta}^\dagger_{\nu_i}\hat{\beta}^\dagger_{\nu_j}|\Phi_0\rangle, \hat{\beta}^\dagger_{\pi_i}\hat{\beta}^\dagger_{\pi_j}|\Phi_0\rangle\}$

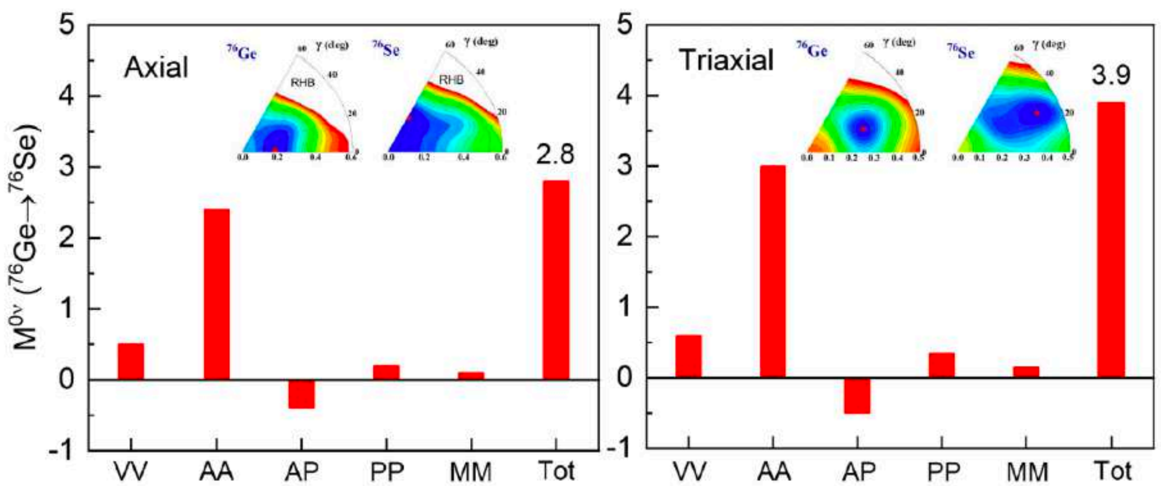
$$|\Phi_0\rangle = \prod_{k>0} \hat{\beta}_k |0\rangle, \quad \begin{pmatrix} h_D - \lambda & \Delta \\ -\Delta^* & -h^*_D + \lambda \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

- 变分参数 $F^{I}_{K\kappa}$ 求解：

$$\sum_{K'\kappa'} \{\langle \Phi_\kappa | \hat{H} \hat{P}^{I}_{KK'} | \Phi_{\kappa'} \rangle - E^I \langle \Phi_\kappa | \hat{P}^{I}_{KK'} | \Phi_{\kappa'} \rangle\} F^{I}_{K'\kappa'} = 0$$

$\hat{H}$ 通过密度泛函对密度矩阵 ρ_{ji} 的二阶偏导求得，无任何可调参数

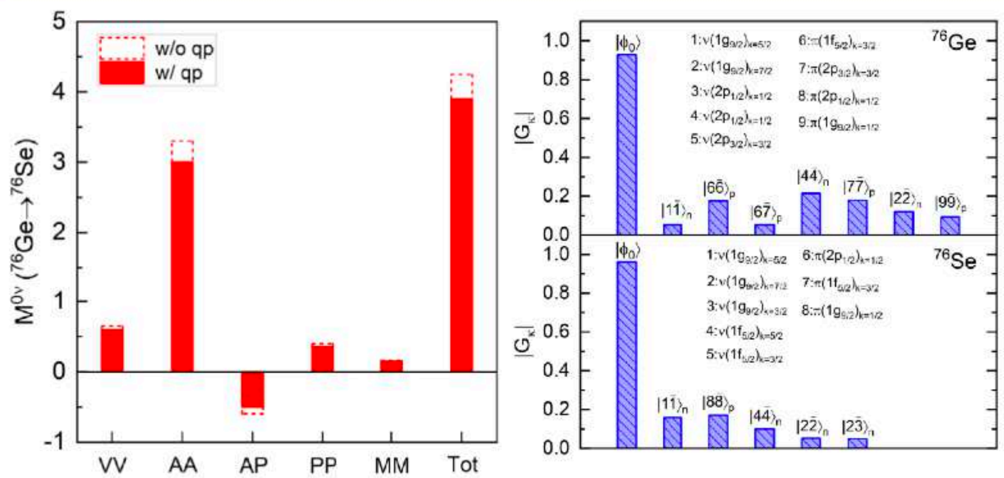
核矩阵元：三轴形变效应



✓ 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%

核矩阵元：准粒子组态混合效应

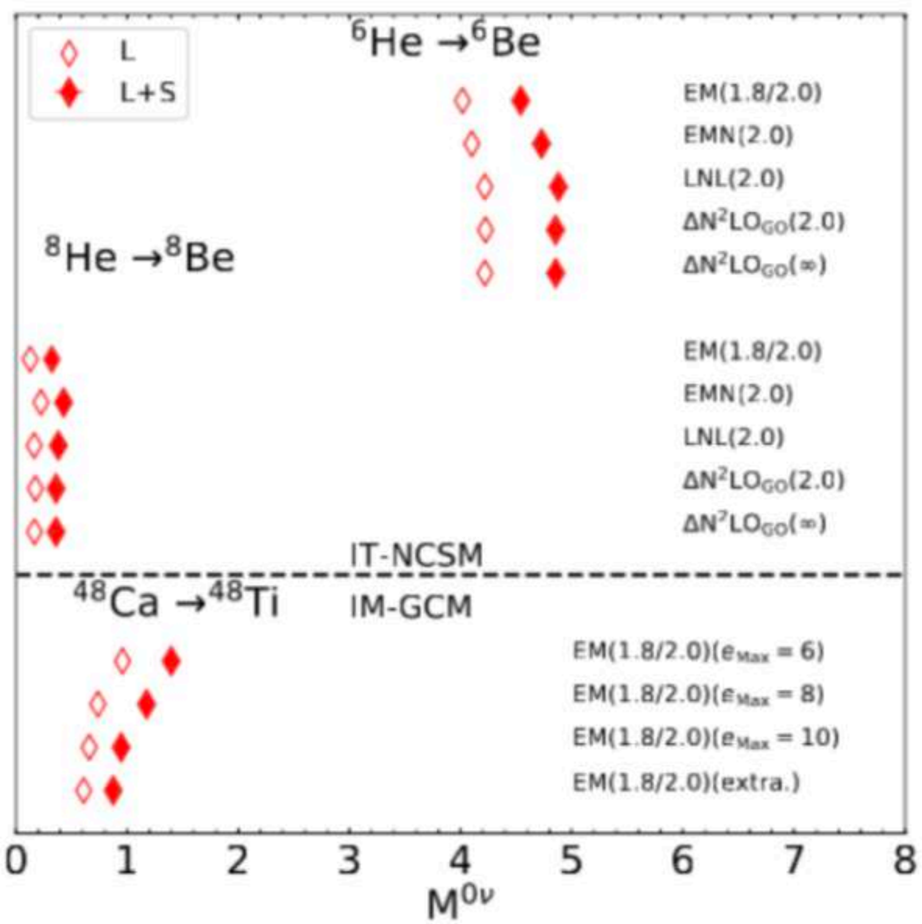


原子核	核矩阵元	
	考虑组态混合	不考虑组态混合
^{76}Ge	3.90	4.25

✓ 考虑准粒子组态混合，核矩阵元值从 4.25 降低至 3.90

- ▶ **理论方面**
  - ▶ **原子核矩阵元计算**

（房栋梁、王亚坤、尧江明、牛一菲、王小保、焦长峰、王龙军、高早春）

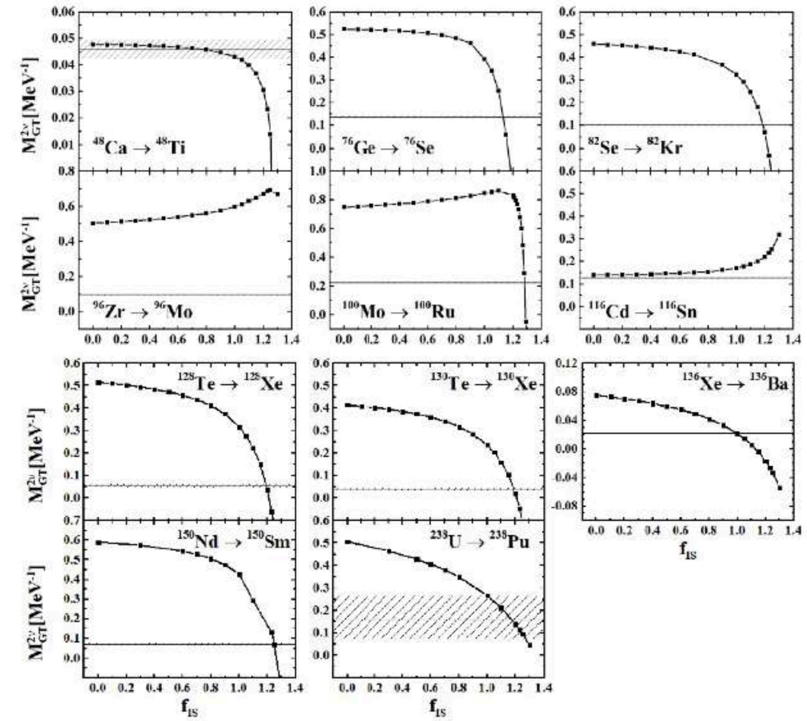


“标准”机制下短程耦合效应

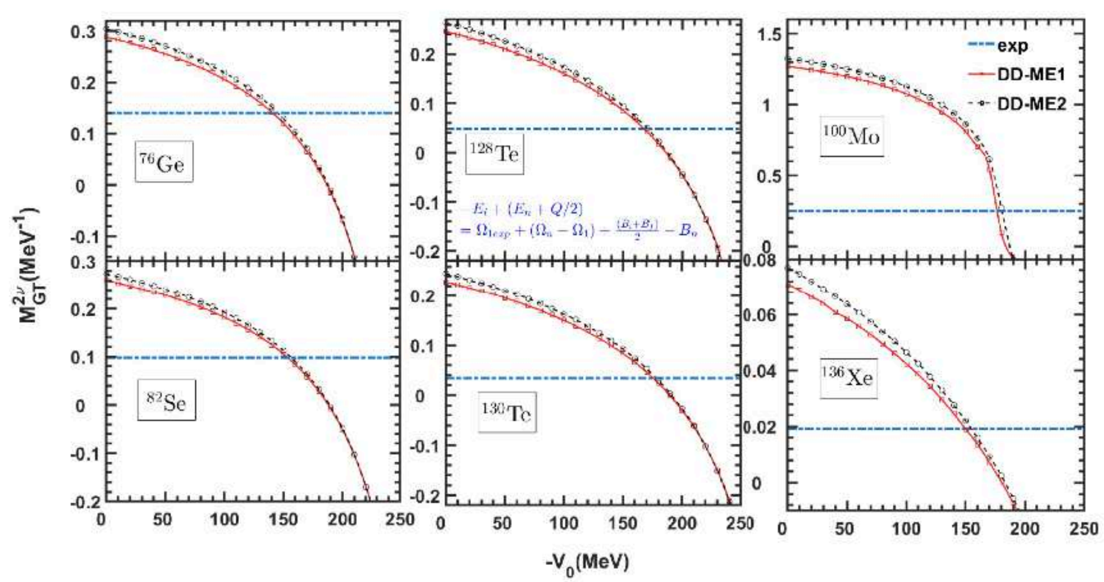
NME of $2\nu\beta\beta$

- **Dependence of NME on isoscalar pairing strength**

Skyrme QRPA



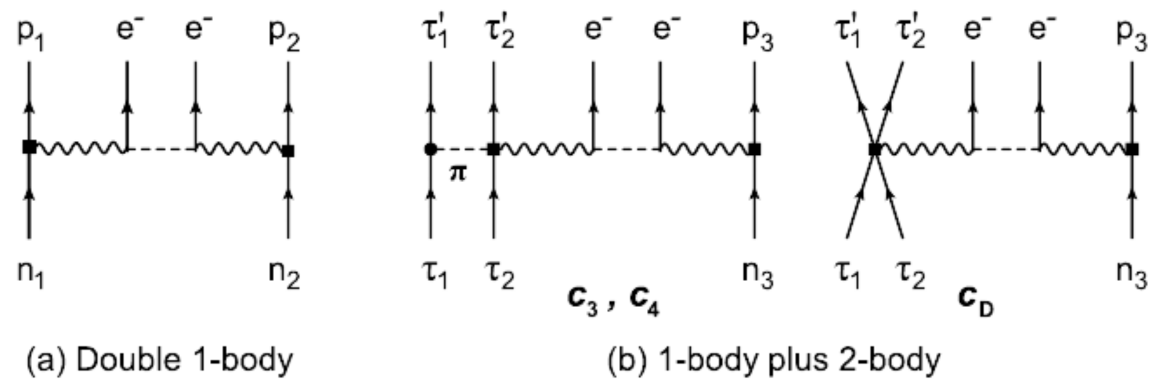
relativistic QRPA

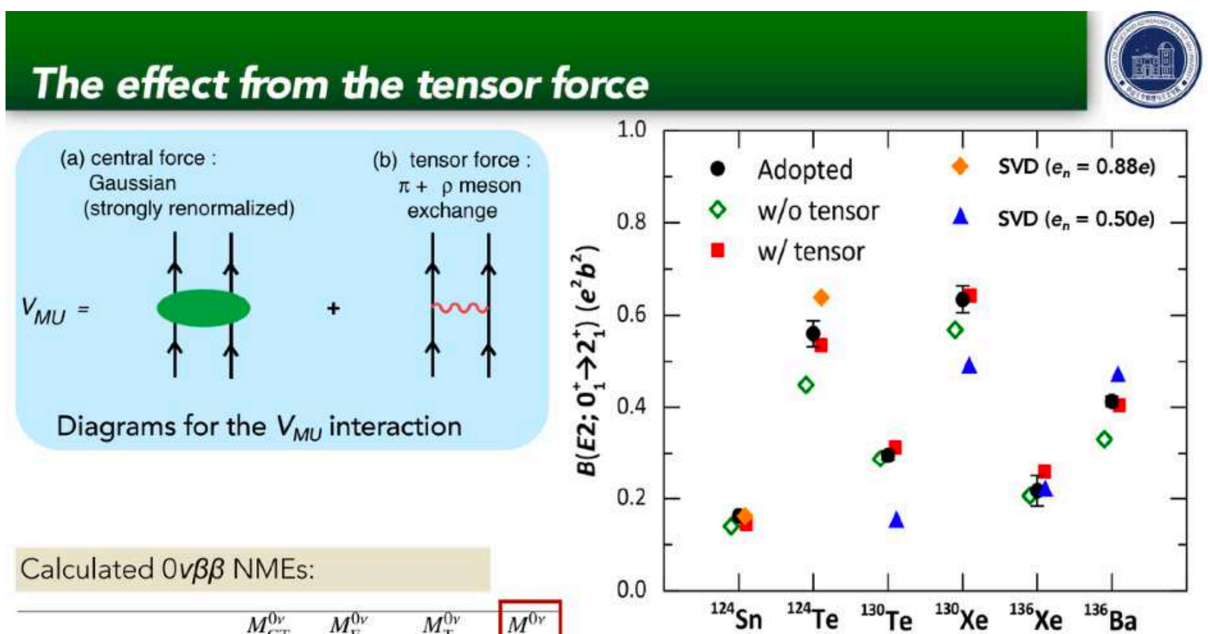


Summary

- **理论方面**
  - **原子核矩阵元计算**

（房栋梁、王亚坤、尧江明、牛一菲、王小保、焦长峰、王龙军、高早春）





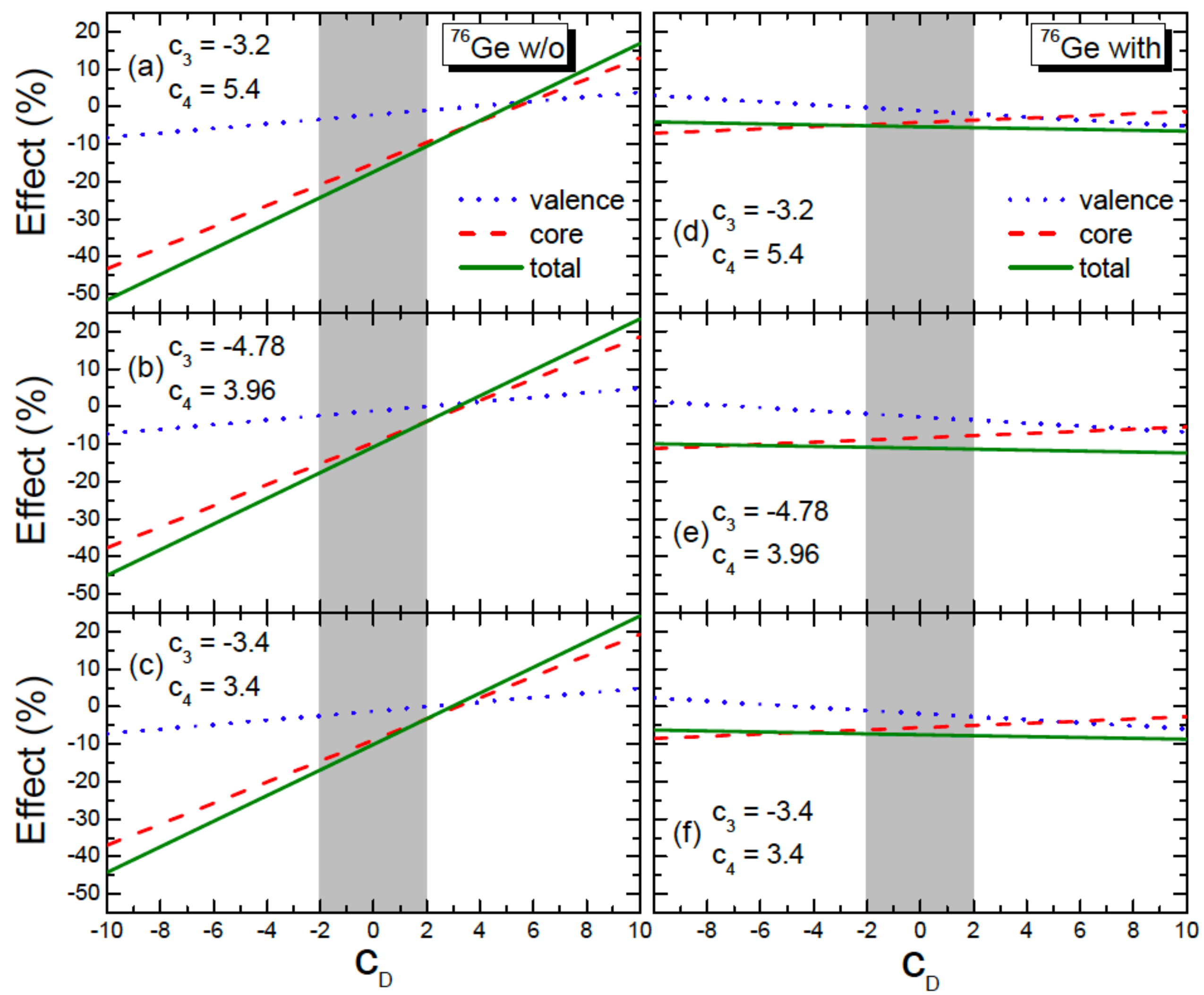
Calculated $0\nu\beta\beta$ NMEs:

		$M^{0\nu}_{GT}$	$M^{0\nu}_{F}$	$M^{0\nu}_{T}$	$M^{0\nu}$
^{124}Sn	w/o tensor	3.56	−0.64	−0.061	3.91
	w/ tensor	2.65	−0.64	−0.020	3.04
^{130}Te	w/o tensor	4.29	−0.75	−0.064	4.70
	w/ tensor	3.33	−0.65	−0.015	3.73
^{136}Xe	w/o tensor	3.26	−0.44	−0.046	3.49
	w/ tensor	2.17	−0.50	−0.009	2.48

V_{MU} provides a better description of nuclear structure properties of ^{124}Sn/^{124}Te, ^{130}Te/^{130}Xe, and ^{136}Xe/^{136}Ba

CFJ and C. X. Yuan, in preparation.

NMEs are suppressed, *why?*

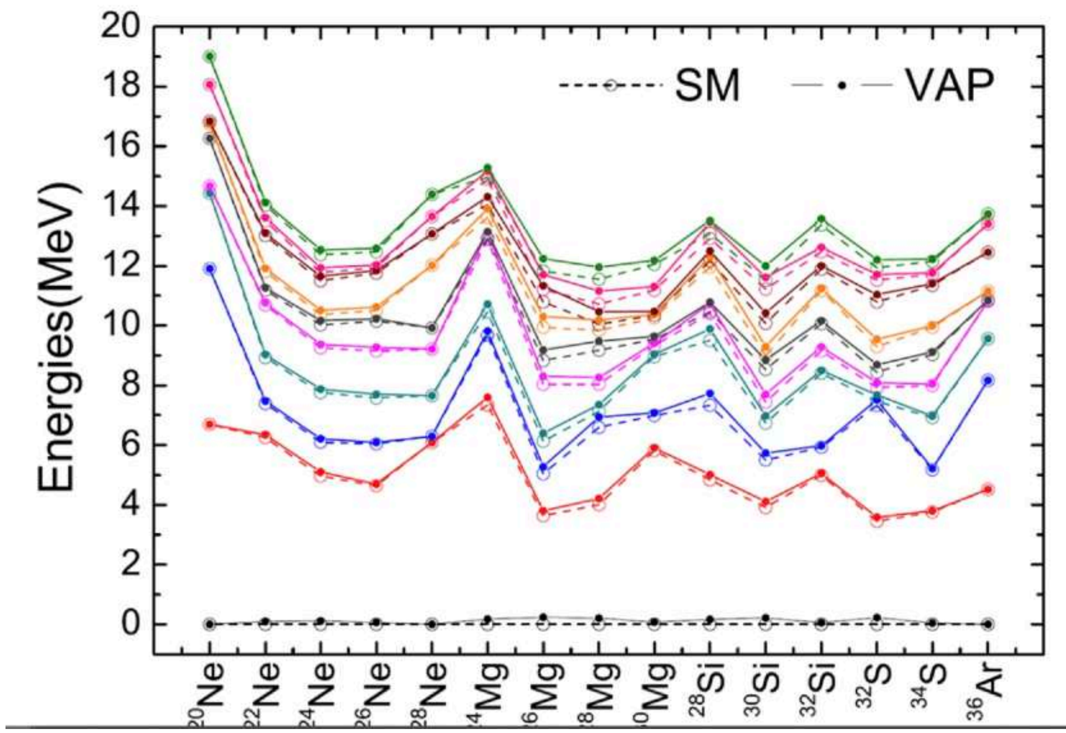


Summary

▸ **理论方面**

▸ **原子核结构**

（赵鹏巍、吕炳楠、高早春、刘朗、李剑、耿晶）



$$\langle \Psi(N-2, Z+2) | \hat{O}^{0\nu} | \Psi(N, Z) \rangle$$

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

Approximated shell model energies

Full shell model energies:

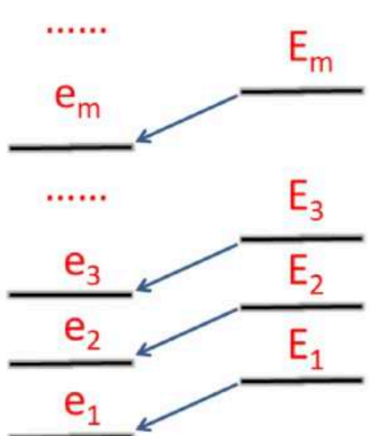
$$e_1 \le e_2 \cdots.$$

Energies in c.f. subspace:

$$E_1 \le E_2 \cdots \le E_m$$

Universal relation:

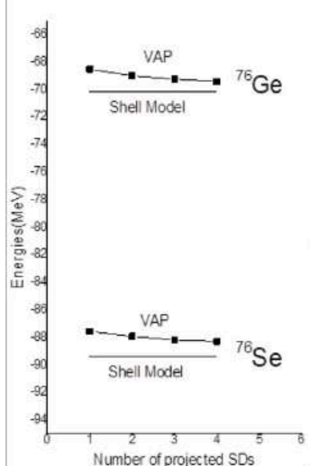
$$E_\alpha \ge e_\alpha \quad (1 \le \alpha \le m)$$



Poincare Separation theorem

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY

VAP应用：0vbb的核矩阵元



$$\langle {}^{76}\mathrm{Se} | \hat{O}^{0\nu} | {}^{76}\mathrm{Ge} \rangle$$

$$= \frac{1}{4} \sum_{\kappa_i\kappa_j, \kappa_k\kappa_l} \sqrt{(1+\delta_{\kappa_i\kappa_j})(1+\delta_{\kappa_k\kappa_{l_l}})} \sum_J O^J_{\kappa_i\kappa_j\kappa_k\kappa_l} \rho^J_{\kappa_i\kappa_j\kappa_k\kappa_l}$$

$$= \frac{1}{4} \sum_{ijkl} O_{ijkl} \rho_{ijkl}$$

$$\rho_{ijkl} = \langle {}^{76}\mathrm{Se} | n_i^+ n_j^+ p_l p_k | {}^{76}\mathrm{Ge} \rangle$$

$$\rho^J_{\kappa_i\kappa_j\kappa_k\kappa_l} = \sum_{m_i m_j m_k m_l} \langle j_i m_i j_j m_j | JM \rangle \langle j_k m_k j_l m_l | JM \rangle \rho_{ijkl}$$

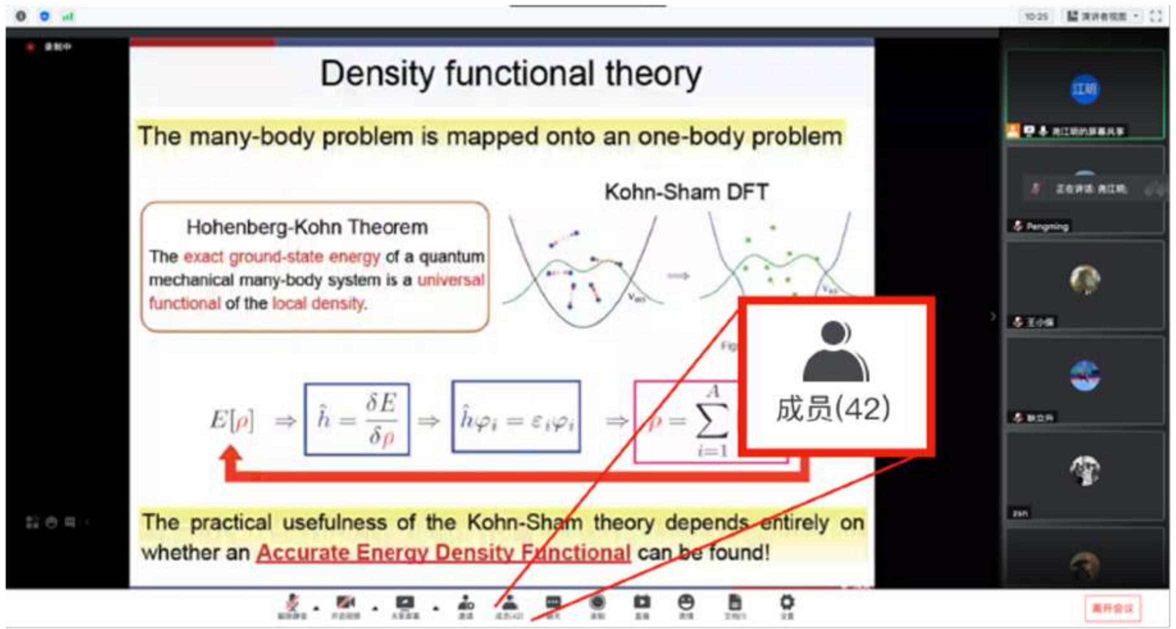
$$O_{ijkl} = \sqrt{(1+\delta_{\kappa_i\kappa_j})(1+\delta_{\kappa_k\kappa_{l_l}})} \sum \langle j_i m_i j_j m_j | JM \rangle \langle j_k m_k j_l m_l | JM \rangle O_{\kappa_i\kappa_j\kappa_k\kappa_l}$$

VAP（多个低激发态同时取极值）

Summary

- **理论方面**
  - **原子核结构**

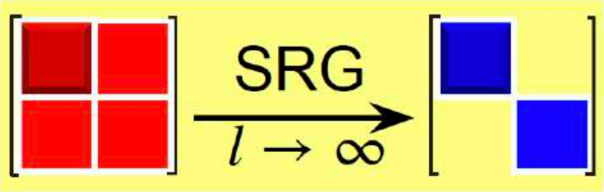
  （赵鹏巍、吕炳楠、高早春、刘朗、李剑、耿晶）



Similarity Renormalization Group

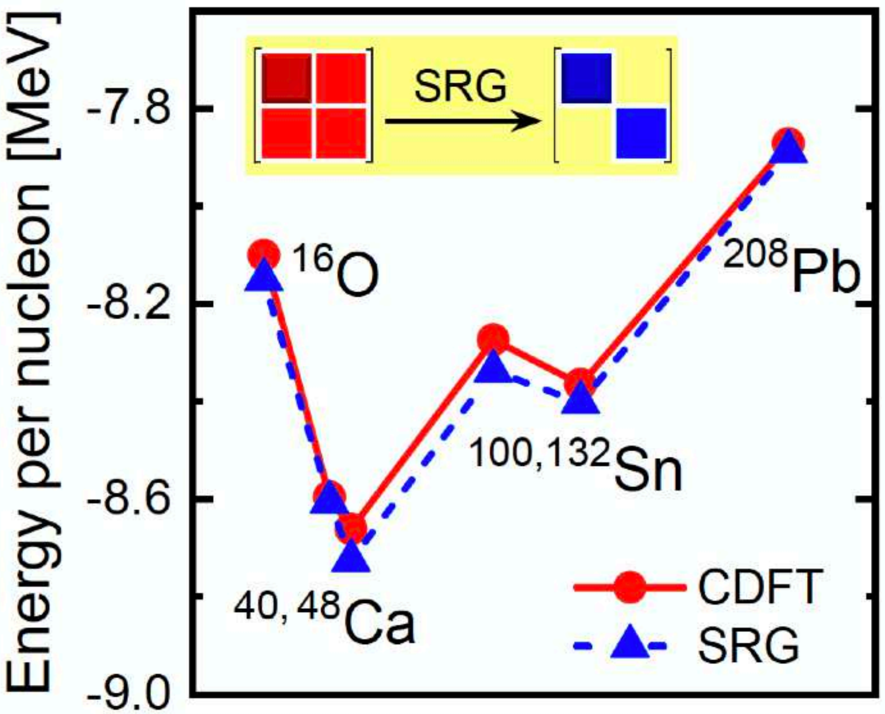
Relativistic Kohn-Sham Equation: Dirac Equation

$$\begin{pmatrix} m+V+S & \boldsymbol{\sigma}\cdot\boldsymbol{p} \\ \boldsymbol{\sigma}\cdot\boldsymbol{p} & -m+V-S \end{pmatrix}\begin{pmatrix} f \\ g \end{pmatrix} = \varepsilon \begin{pmatrix} f \\ g \end{pmatrix}$$



$$\frac{dH(l)}{dl} = [\eta(l), H(l)], \quad \eta(l) = [\beta, H(l)]$$

Toward a bridge between relativistic and nonrelativistic DFT



Ren, PWZ, Phys. Rev. C, 102, 021301(R) (2020) Editors' Suggestion

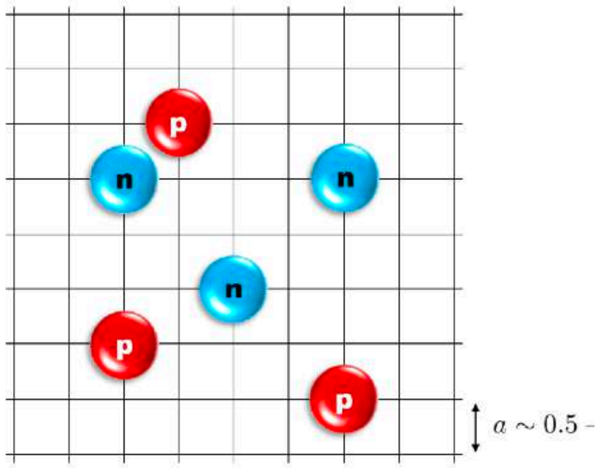
- **理论方面**
  - **原子核结构**

（赵鹏巍、吕炳楠、高早春、刘朗、李剑、耿晶）

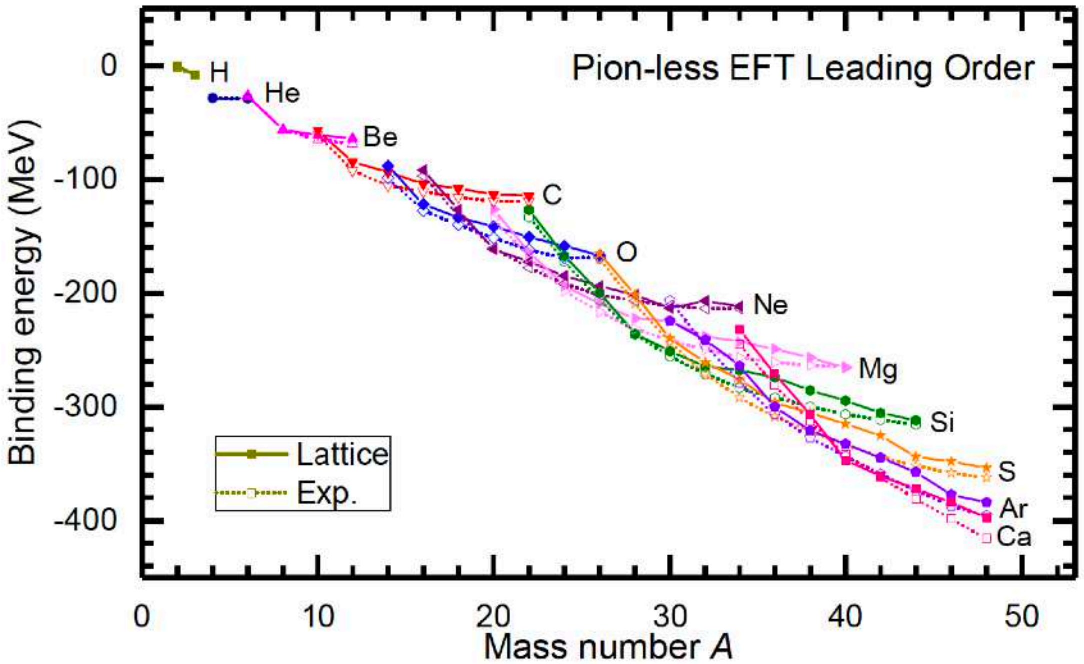
How many free parameters are essential for a proper nuclear force?
Answer: 4, Strength, Range, Three-body, Locality

Quantum many-body problem can be solved on a lattice
Lattice QCD, Hubbard model, Cold atoms...
Lattice EFT = Chiral EFT + Lattice + Monte Carlo

- Discretized chiral EFT
- Lattice spacing $a \sim 1$ fm
- Lattice imposes a momentum cutoff $\Lambda = \pi\hbar/a \sim 600$ MeV
- Exact method, polynomial scaling ($\sim A^2$)



Lattice adapted for nucleus



B.L., Ning Li, Elhatisari, Lee, Epelbaum, Meißner, PLB 797, 134863 (2019)

- Future projects: $0\nu\beta\beta$ calculations, independent of other *ab initio* methods, reduce systematic errors. Possible connection with Lattice QCD.

Summary

- **理论方面**
  - **原子核结构**

（赵鹏巍、吕炳楠、高早春、刘朗、李剑、耿晶）

协变密度泛函理论

□ 协变密度泛函理论 (CDFT)：介子交换+密度泛函思想

□ 相对论平均场 (RMF) 理论：Hartree 近似

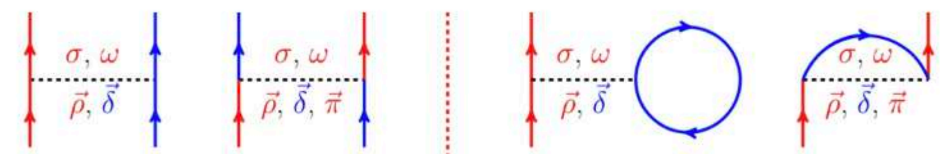
Walecka(1974), Serot(1986), Reihard(1989), Ring(1996), Bender(2003), Meng(2006)......

✓ 自洽给出自旋轨道劈裂，但无法自洽处理张量力贡献

□ 相对论Hartree-Fock (RHF) 理论：Hartree-Fock 近似

Bouyssy (1987), Bernardos (1993), Shi (1995), Marcos (2004), Long (2004-2021), ...

✓ 保留了原有理论优势，自然考虑了张量力贡献，但 Fock 项处理复杂



Hartree terms　Fock terms　Local MF　Non-local MF

3

轴对称形变的RHF理论发展

RHF	RMF
□ 柱坐标空间 传播子展开项积分收敛缓慢 Xiang, Doctor theis	□ 柱坐标空间 Lee (1986) , Furnstahl (1988) , Zhou (2000)
□ 谐振子基：波函数与平均场 波函数渐进行为，重排项处理 J.P. Ebran, et al, PRC.83,064323 (2011)	□ 谐振子基 不能给出合理的波函数渐进行为 Pannert (1987), Price (1987) , Gambhi (1990), Lalazissis (1999) , Vretenar (1999) ...
□ 球对称的 DWS 基：波函数 轴对称形变 RHF 理论：张量力 Geng, Xiang, Sun, Long PRC.101,064302 (2020)	□ Dirac Woods-Saxon (DWS) 基 合理的波函数渐进行为　Zhou (2003) Zhou (2006, 2010) , Li (2012) , Chen (2012)

形变不稳定核 —Bogoliubov 变换 / DWS 基展开→ 轴对称形变的相对论 Hartree-Fock-Bogoliubov (D-RHFB) 理论

4

□ 利用球对称的 Dirac Woods-Saxon 基，发展建立了轴对称形变的相对论 Hartree-Fock-Bogoliubov (D-RHFB) 理论

完整考虑了π-赝矢量耦合与ρ-张量耦合

□ 基于D-RHFB，PKA1再现^{11}Be 基态宇称

π-PV与ρ-T十分关键：核力平衡，形状效应

□ 基于D-RHFB，PKA1再现^{32}Mg 基态形变

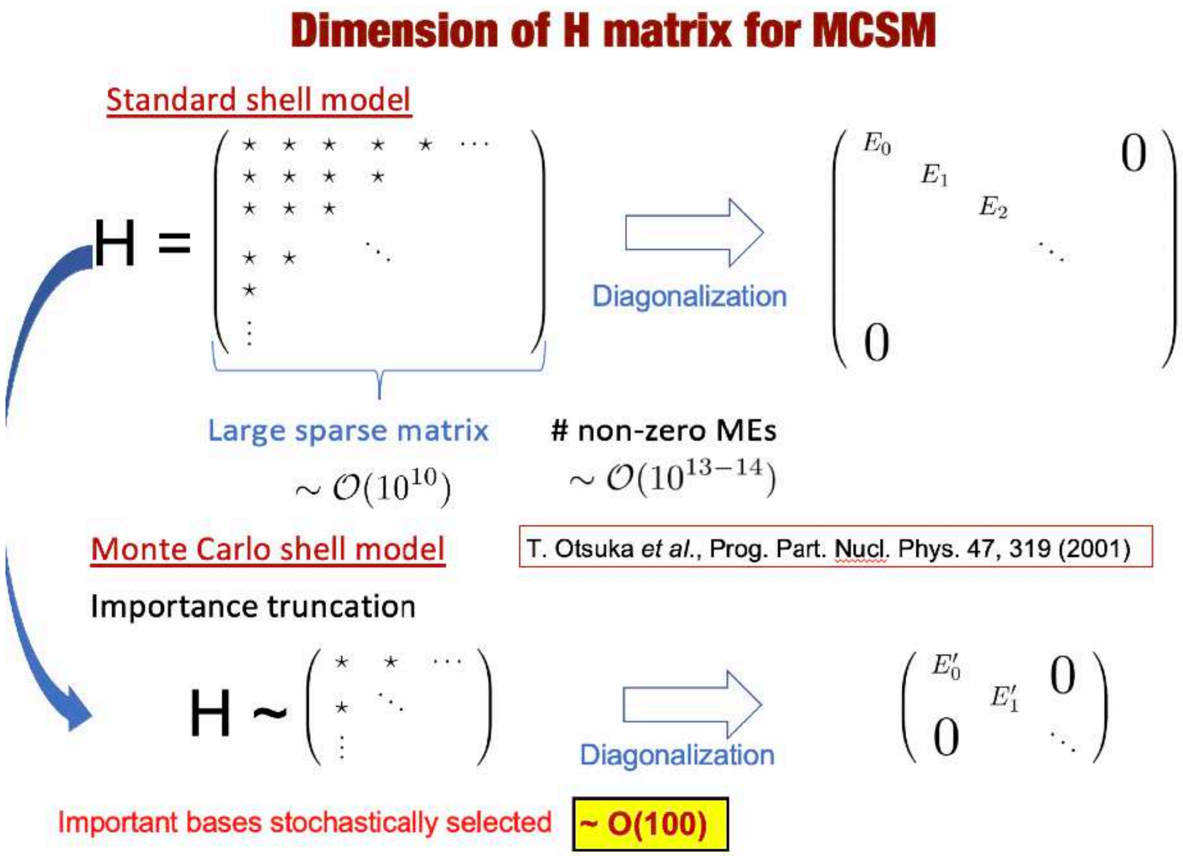
ρ-T效应与形状的耦合十分重要

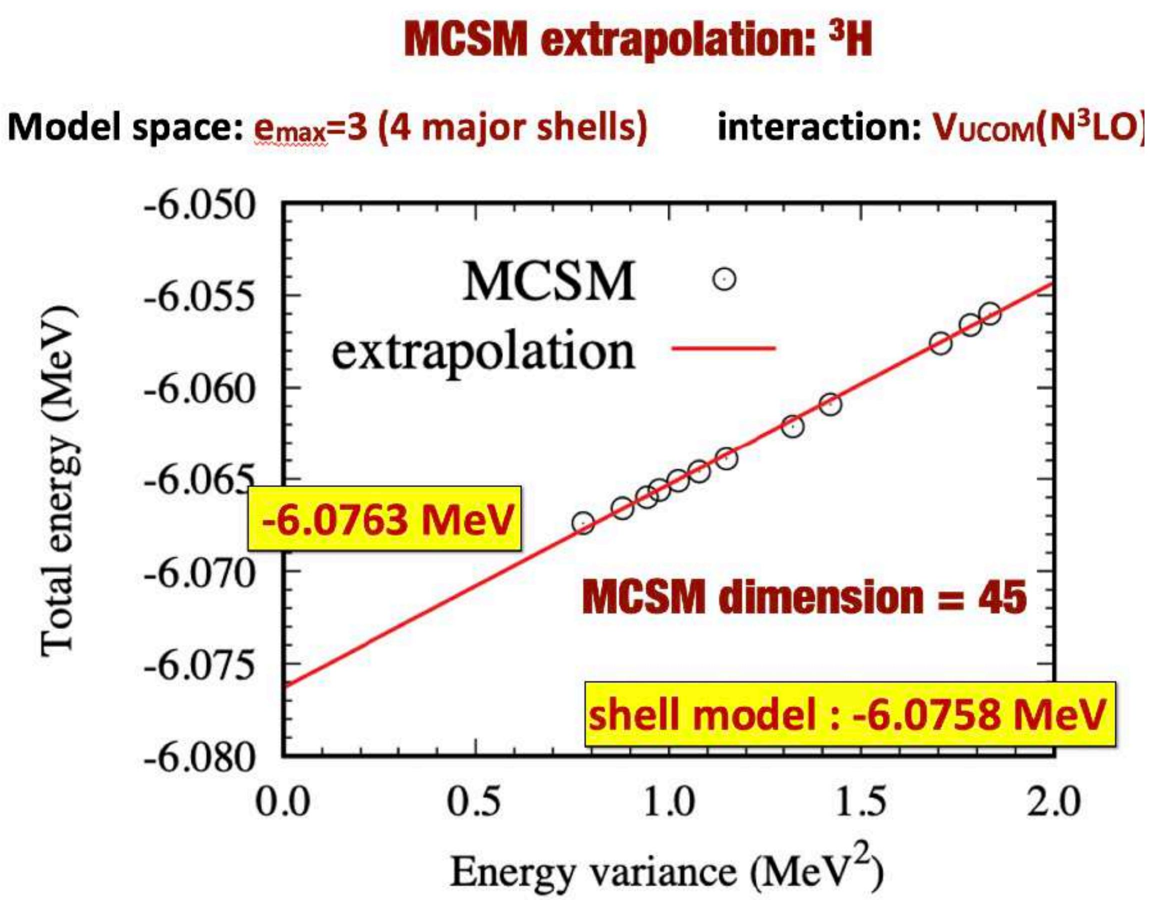
□ 展望：角动量投影➔ 无中微子双β衰变

Summary

- **理论方面**
  - **原子核结构**

（赵鹏巍、吕炳楠、高早春、刘朗、李剑、耿晶）



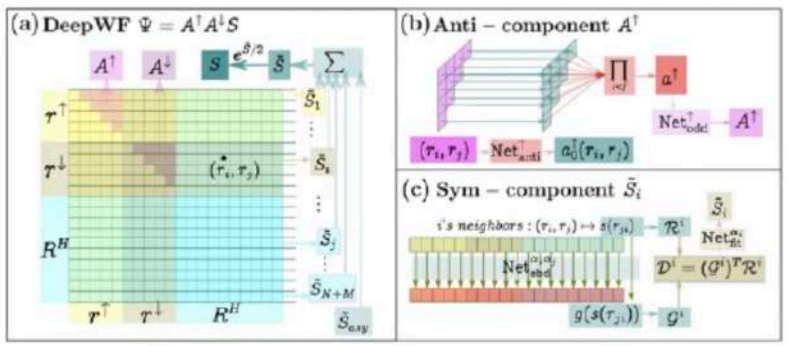


- **机器学习　(庞龙刚)**

DeepWF: anti-symmetric trial wave-function using neural network

Solving many-electron Schrödinger equation using deep neural network

JiequnHan LinfengZhang WeinanE



$$\Psi(\boldsymbol{r};\boldsymbol{R}) = S(\boldsymbol{r};\boldsymbol{R})A^{\uparrow}\left(\boldsymbol{r}^{\uparrow}\right)A^{\downarrow}\left(\boldsymbol{r}^{\downarrow}\right)$$

$$\boldsymbol{a}^{\uparrow}\left(\boldsymbol{r}^{\uparrow}\right) = \prod_{1\le i<j\le N_{\uparrow}} \boldsymbol{a}_0^{\uparrow}\left(\boldsymbol{r}_i,\boldsymbol{r}_j\right)$$

Build physical a prior into the neural network, e.g., anti-symmetric, vortical free, divergence free, translational invariant (equivalent), rotational symmetry

$$\boldsymbol{a}_0^{\uparrow}\left(\boldsymbol{r}_i,\boldsymbol{r}_j\right) = \mathrm{Net}_{\mathrm{anti}}^{\uparrow}\left(\boldsymbol{r}_i,\boldsymbol{r}_j,|r_{ji}|\right) - \mathrm{Net}_{\mathrm{anti}}^{\uparrow}\left(\boldsymbol{r}_j,\boldsymbol{r}_i,|r_{ji}|\right)$$

Fermi-Net:

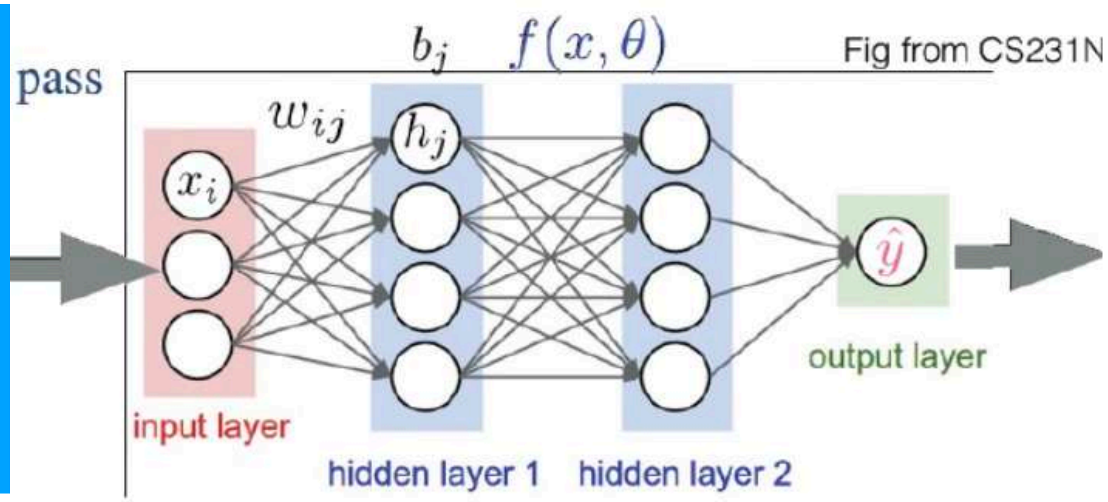
***Ab initio* solution of the many-electron Schrödinger equation with deep neural networks**

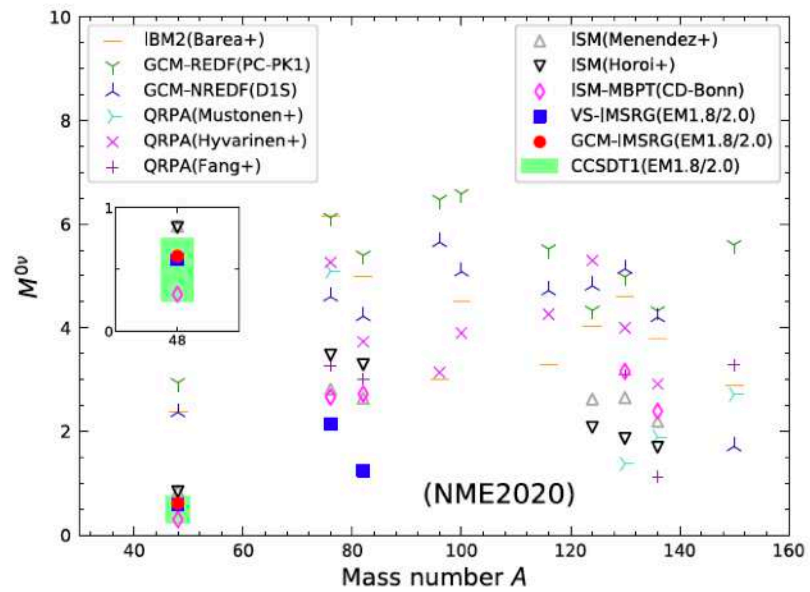
David Pfau,[*,†] James S. Spencer,[*] and Alexander G. D. G. Matthews
DeepMind, 6 Pancras Square, London N1C 4AG, United Kingdom

W. M. C. Foulkes
Department of Physics, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom

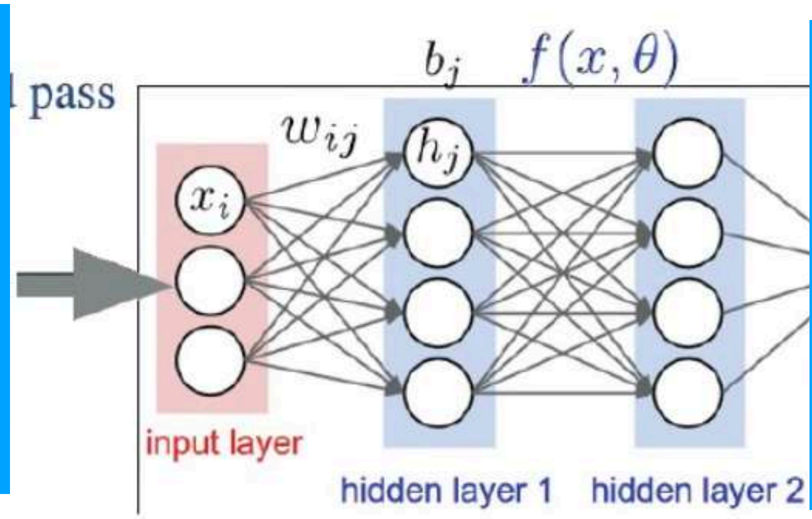
- ▸ **机器学习　(庞龙刚)**

Nuclear properties + Transition operators



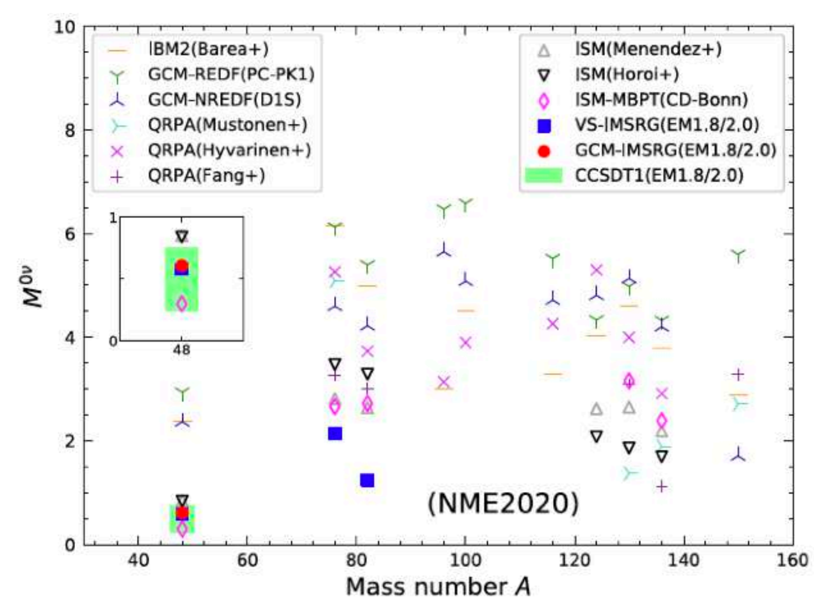


(N,Z,H)



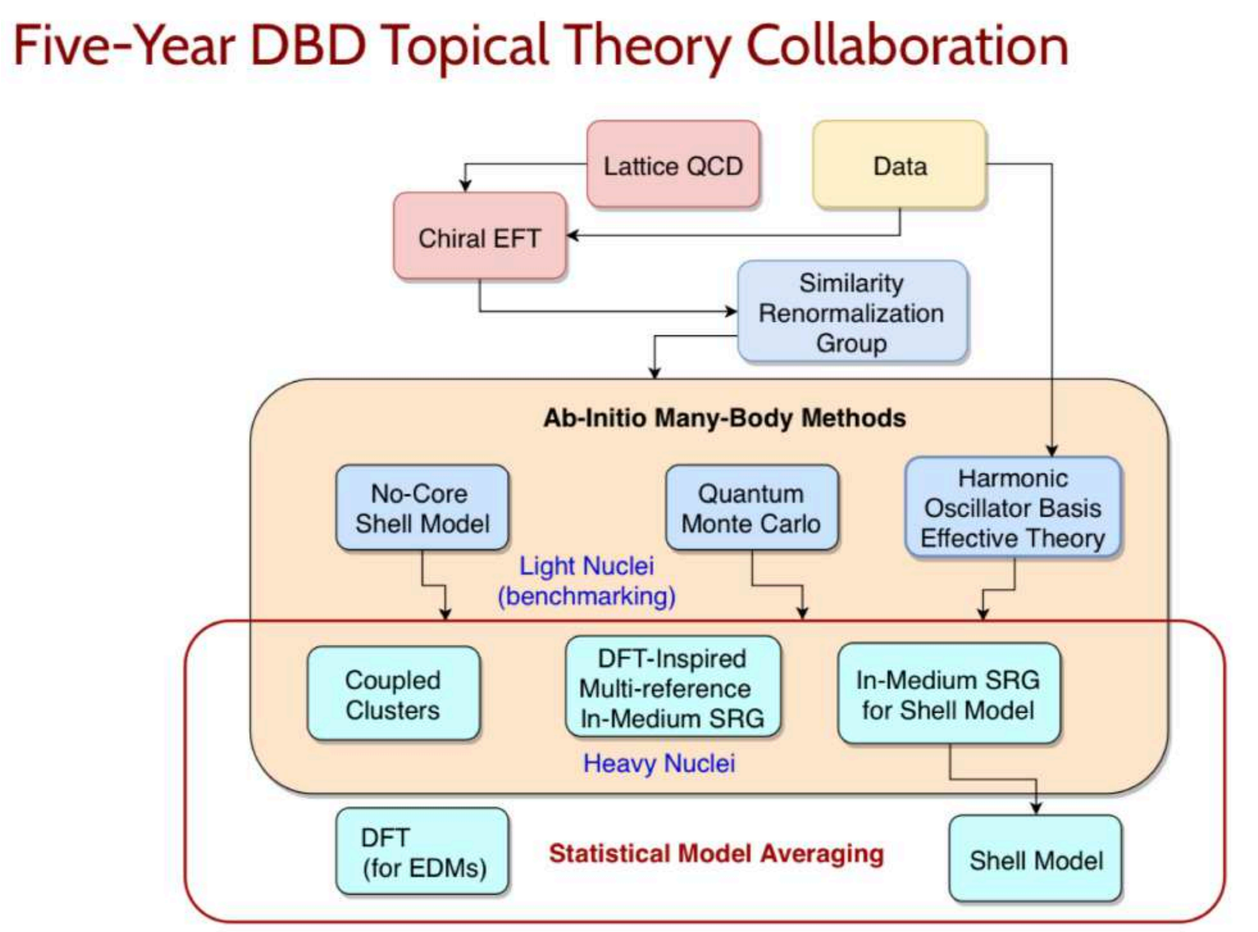
Ground state w.f.s of many-body systems

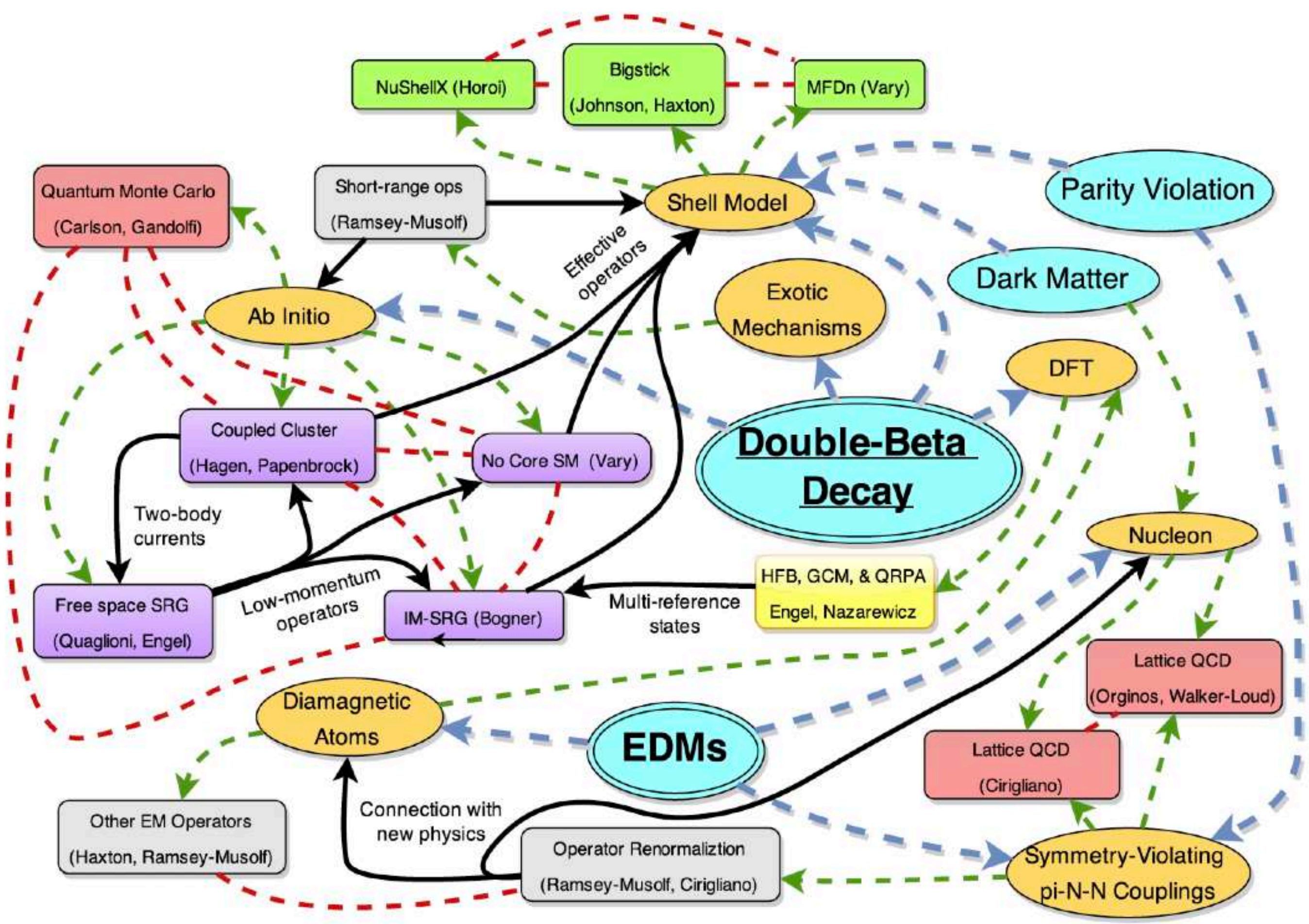
NLDBD operator



An introduction to US DBD Topic Collaboration

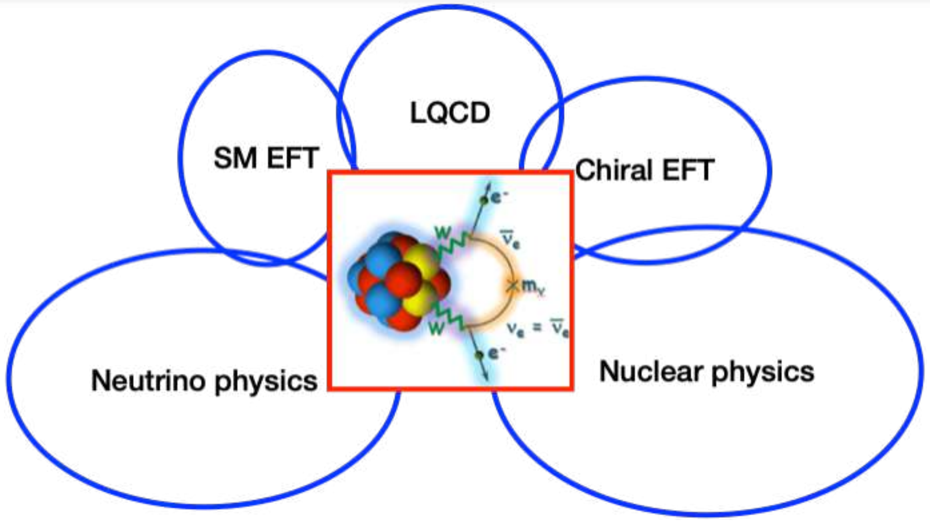
Nuclear Theory for ββ-decay and Fundamental Symmetries (2016-2021)





From Jon Engel

CHINA Neutrino-Nuclei Collaboration?



Long-term collaboration on "Explore new/neutrino physics with atomic nuclei"

- **目的**

  从不同能标共同研究无中微子双贝塔衰变及相关物理 (0$\nu\beta\beta$, EDM, WIMP, νN-scattering, etc)

- **合作形式 （针对几个不同课题建立稳定的合作关系）**

- **资源（超算平台、网站？）**

"Rome is not built in one day"

下次研讨会

- 举办地 （继续在珠海？）
- 时间 （冬季？）
- 主办单位：高能物理学会、核物理学会?
- 承办单位： （继续中大？）

中山大学第十二届国际青年学者论坛诚邀全球英才参加

日 程	时 间（暂定）	举办地点
大会主论坛	2021年7月3日	珠海
分论坛	2021年7月2-4日	广州/珠海/深圳

47	物理与天文学院	刘老师	86-756-3668982	liuydy3@mail.sysu.edu.cn

致谢

- 所有参会人员
- 组织委员会成员以及志愿者

刘贝，赵鹏程，张馨，周千诚，王新宇，钟福铖 （中山大学）

吴先业（江西师大），张馨（华中科技大学）

- 特别感谢会议秘书 袁彬 老师

谢谢！


荣誉证书

HONORARY CREDENTIAL

袁 彬 老师：

感谢您为 2021 年“无中微子双贝塔衰变”研讨会在中山大学珠海校区顺利举办所做出的重要贡献。

特发此证，以示纪念。

“无中微子双贝塔衰变”研讨会组织委员会

安振东，焦长峰，李宁，肖翔，尧江明，张鹏鸣

2021 年 5 月 珠海