“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

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School of Physics and Astronomy
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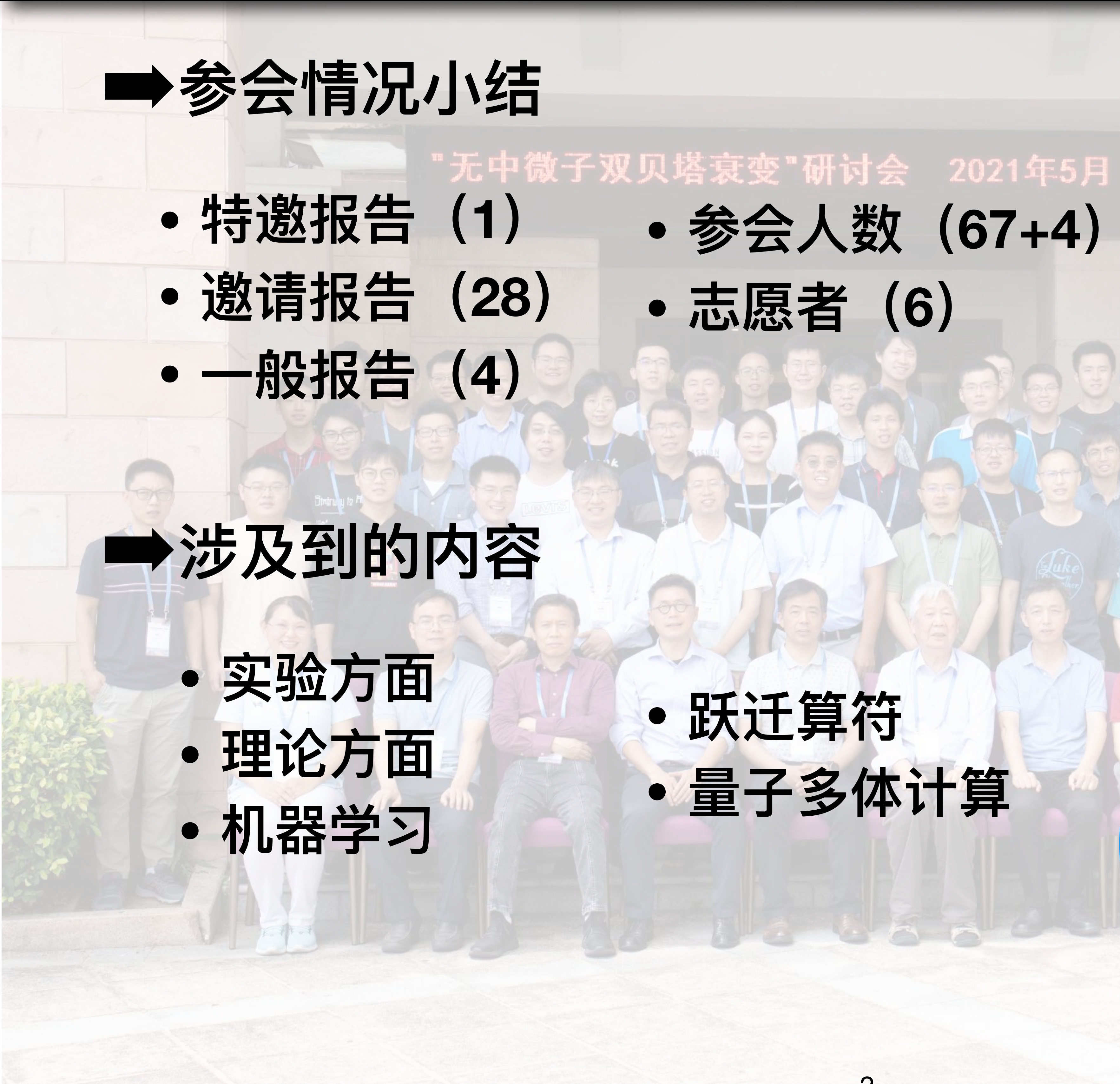
组委会：安振东、焦长峰、李宁、肖翔、尧江明、张鹏鸣

2021年5月23日

Summary

➡参会情况小结



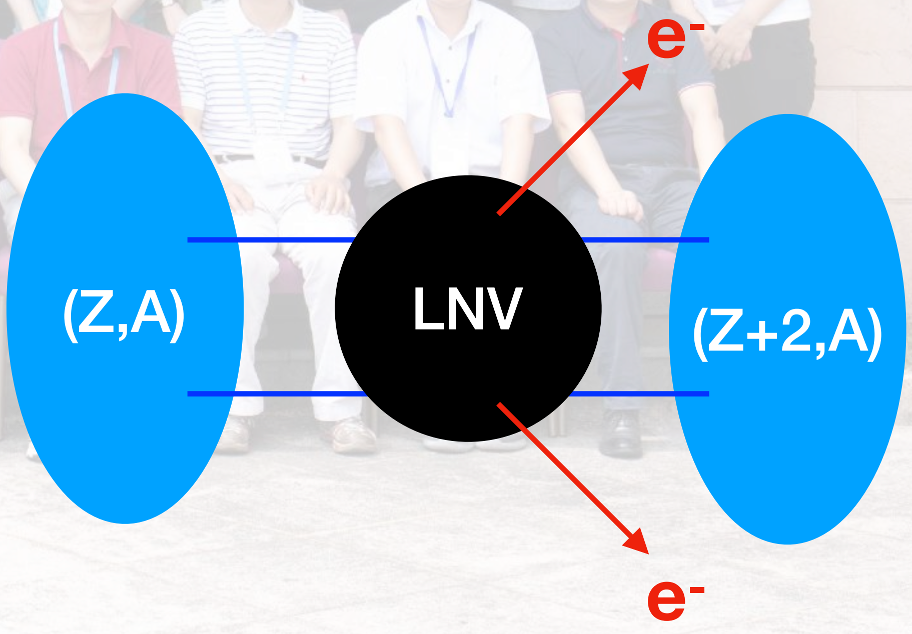
- 特邀报告（1）
- 邀请报告（28）
- 一般报告（4）

- 参会人数（67+4）
- 志愿者（6）

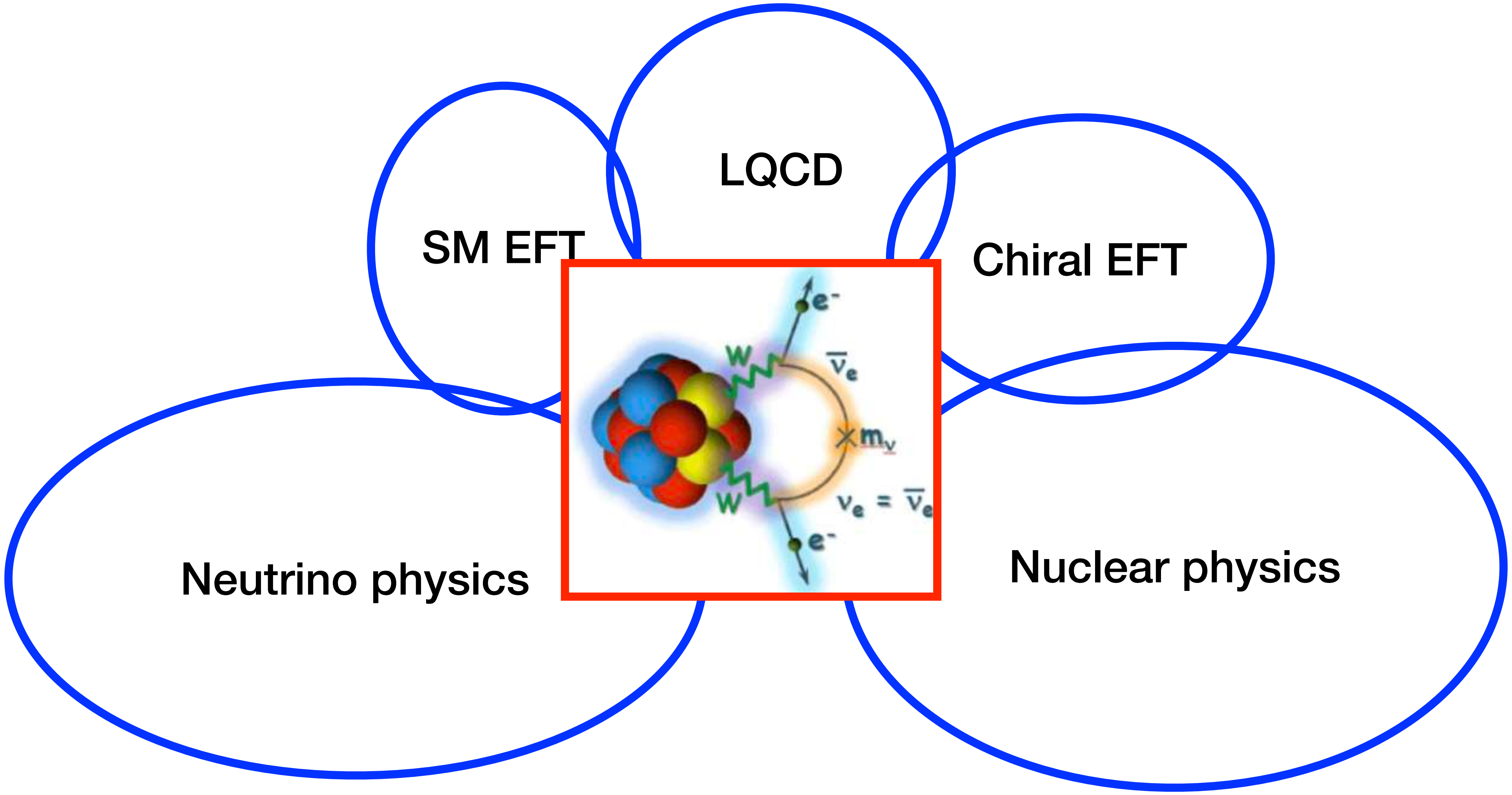
➡涉及到的内容

- 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

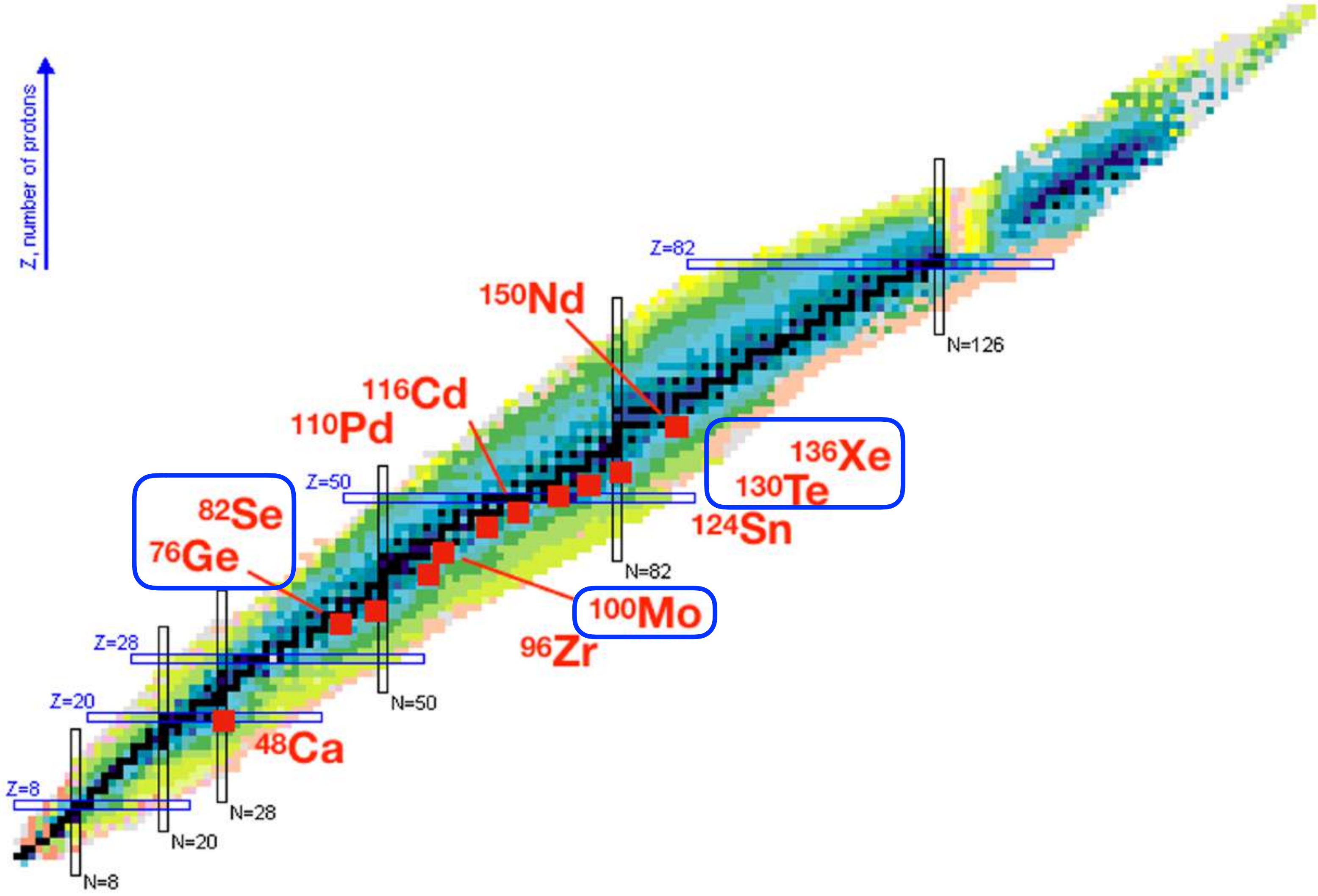


- Neutrino physics
- Status and plans of 0νββ decay experiments
- LNV operators from Standard Model EFT
- Perspectives from lattice QCD
- Nuclear potentials and effective transition operators in chiral EFT
- Nuclear ab initio methods
- Nuclear shell models and energy density functionals
- Mean-field 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）**

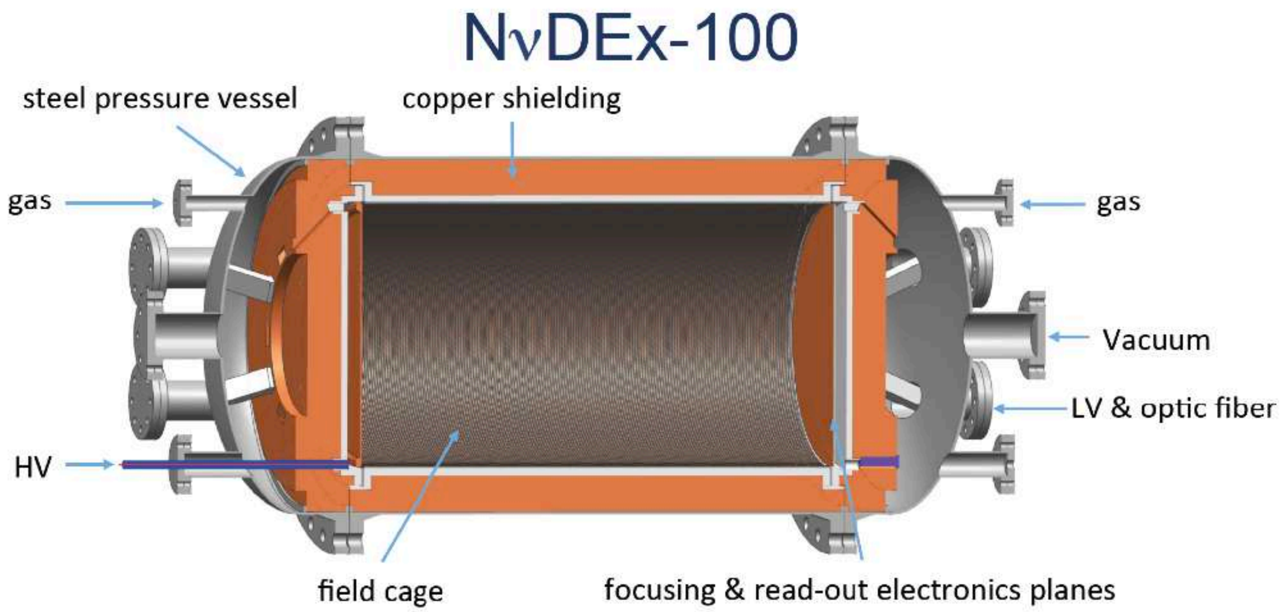
  （韩柯、王少博）

- **^{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)**

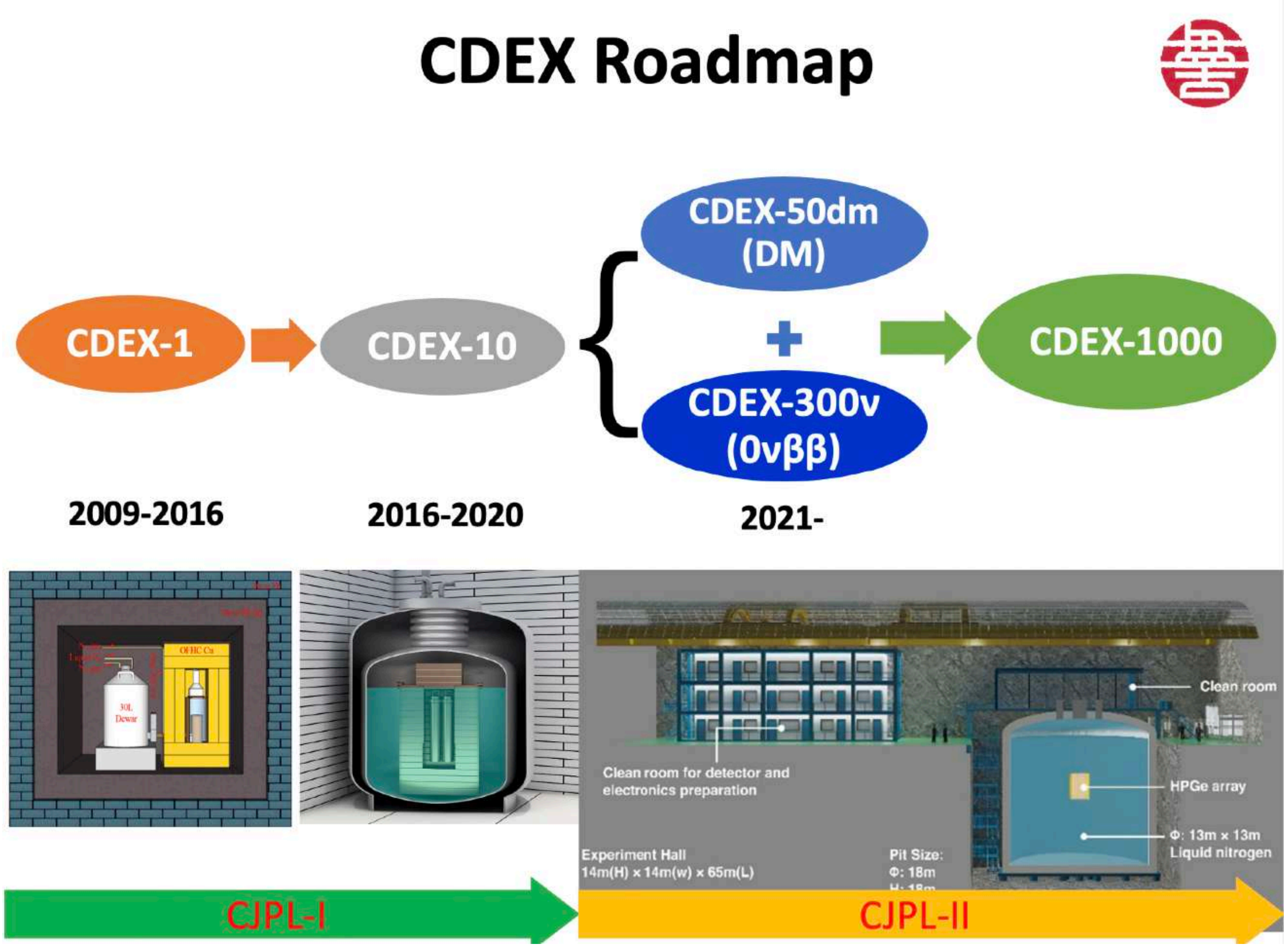


- 2021年：
  - 验证Topmetal芯片读出：达到~1%能量分辨率
  - 完成高压气腔和气体系统
- 2022年：
  - 完成100-kg级实验地面样机：TPC场笼、读出平面
  - 测试长期运行气体安全性
  - 完成本底研究，为地下实验样机研制做准备
- 2022年底：白皮书
- 希望~2023年，开始在CJPL进行地下实验样机研制

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）**



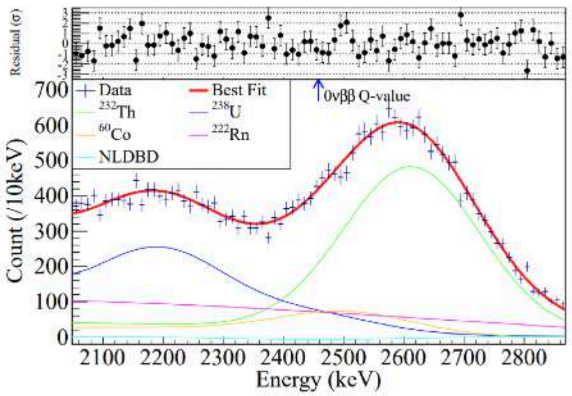
Summary

▸ 实验方面

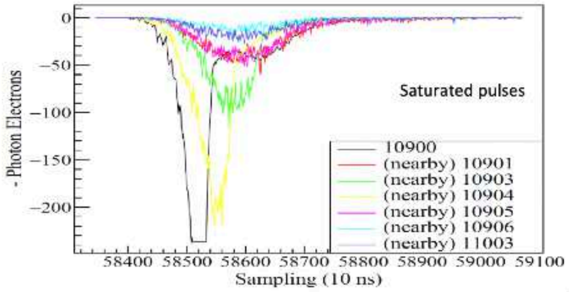
- **PandaX-II 实验、PandaX/PandaX-xT 实验** (韩柯、王少博)

PandaX-II 实验寻找0νββ

- 半衰期下限为2.4×10²³ 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

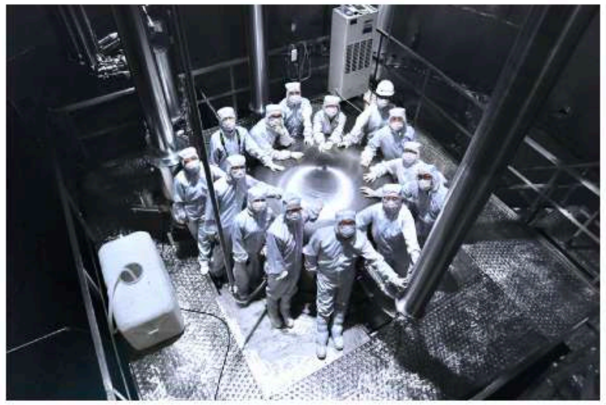


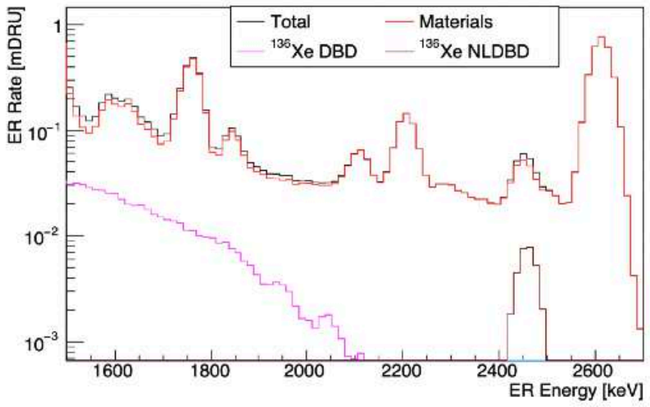
Chinese Physics C 43, 113001 (2019)



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10²⁵yr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



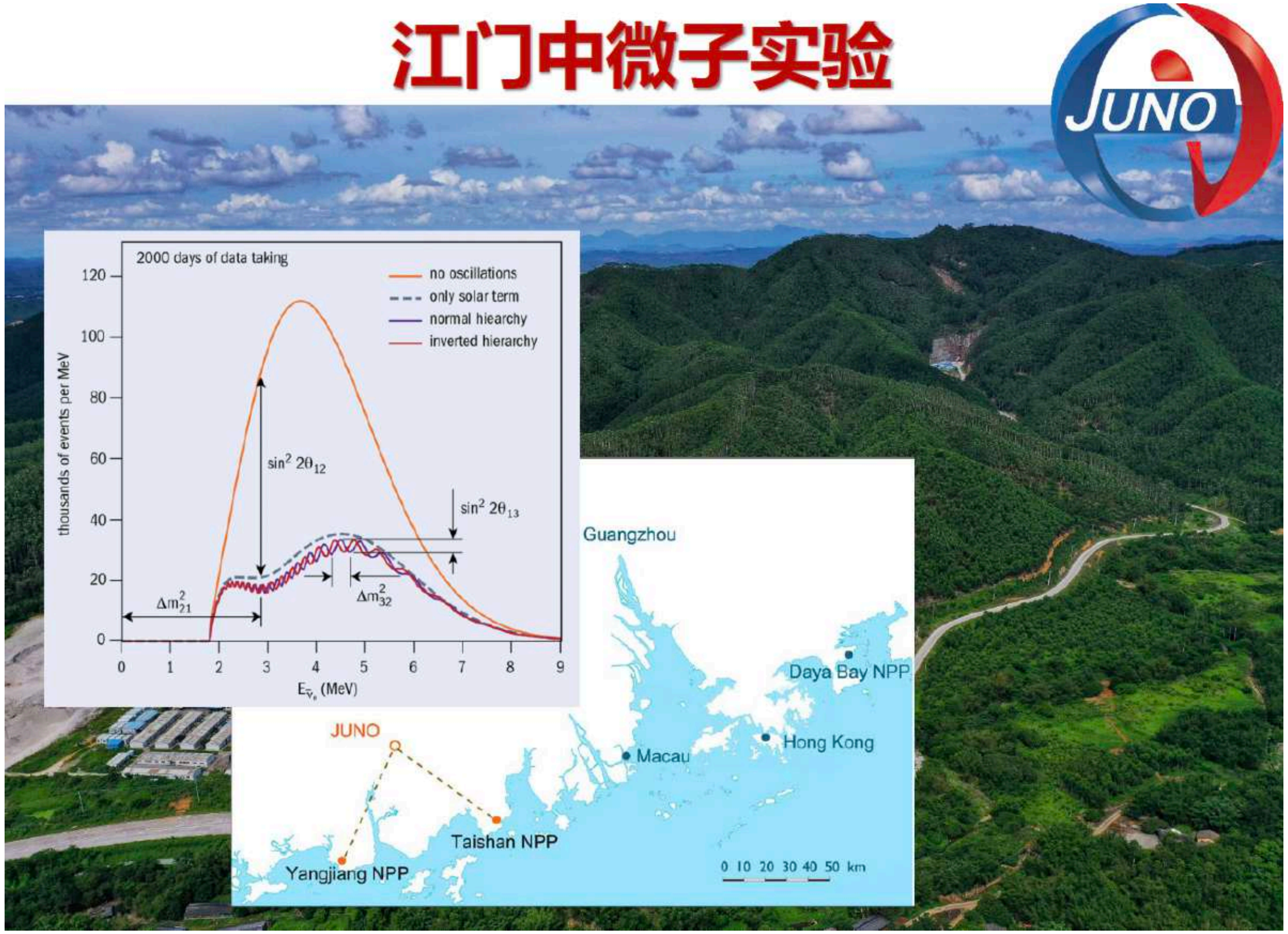


Summary

▶ 实验方面

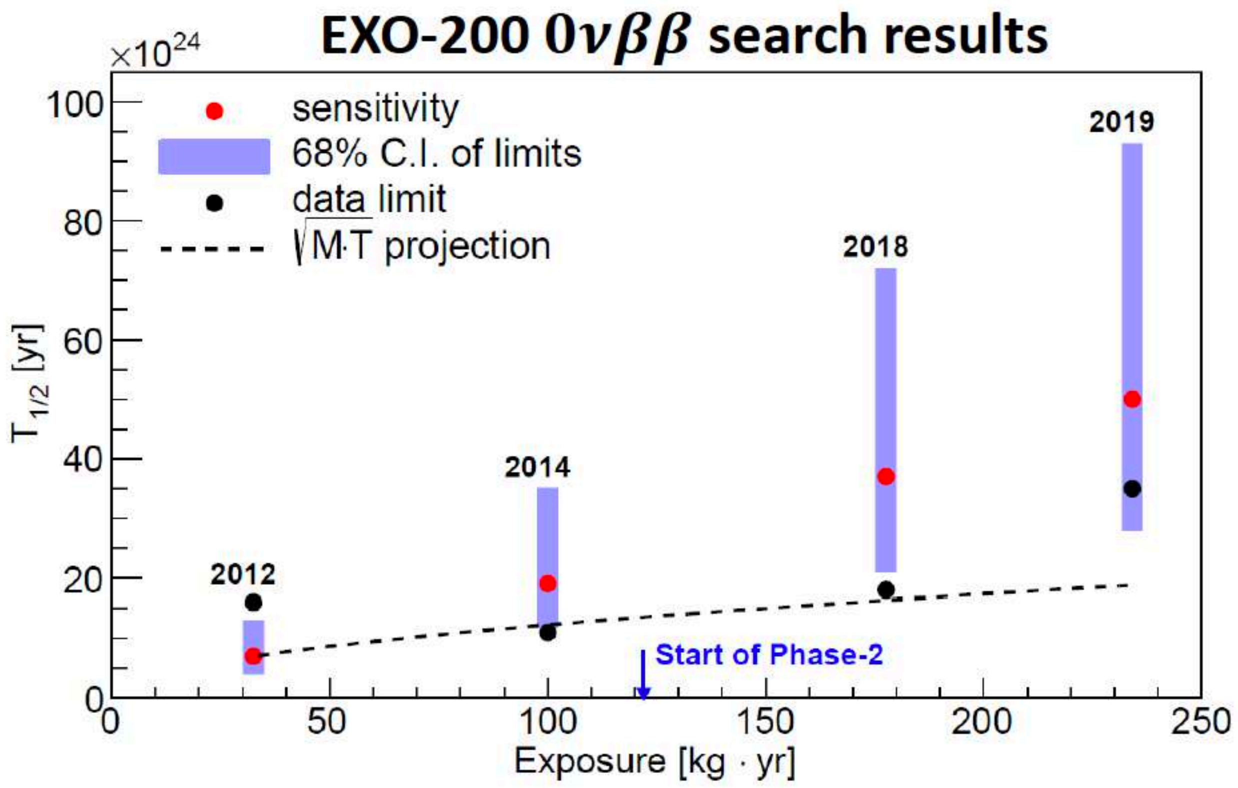
- **2030年，计划将JUNO改造为$0\nu\beta\beta$实验，用百吨量级^{130}Te，将灵敏度再提高>20倍，$|m_{\beta\beta}|$灵敏度逼近meV**

(温良剑）

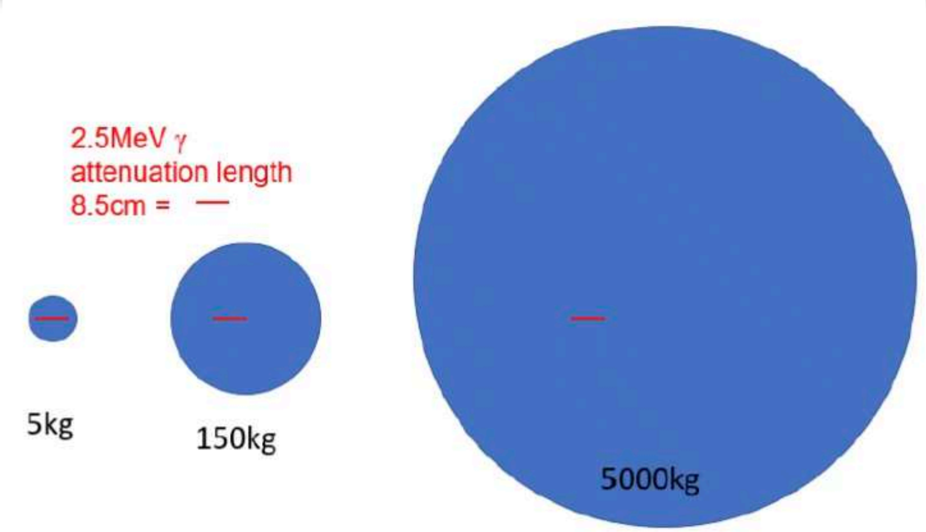


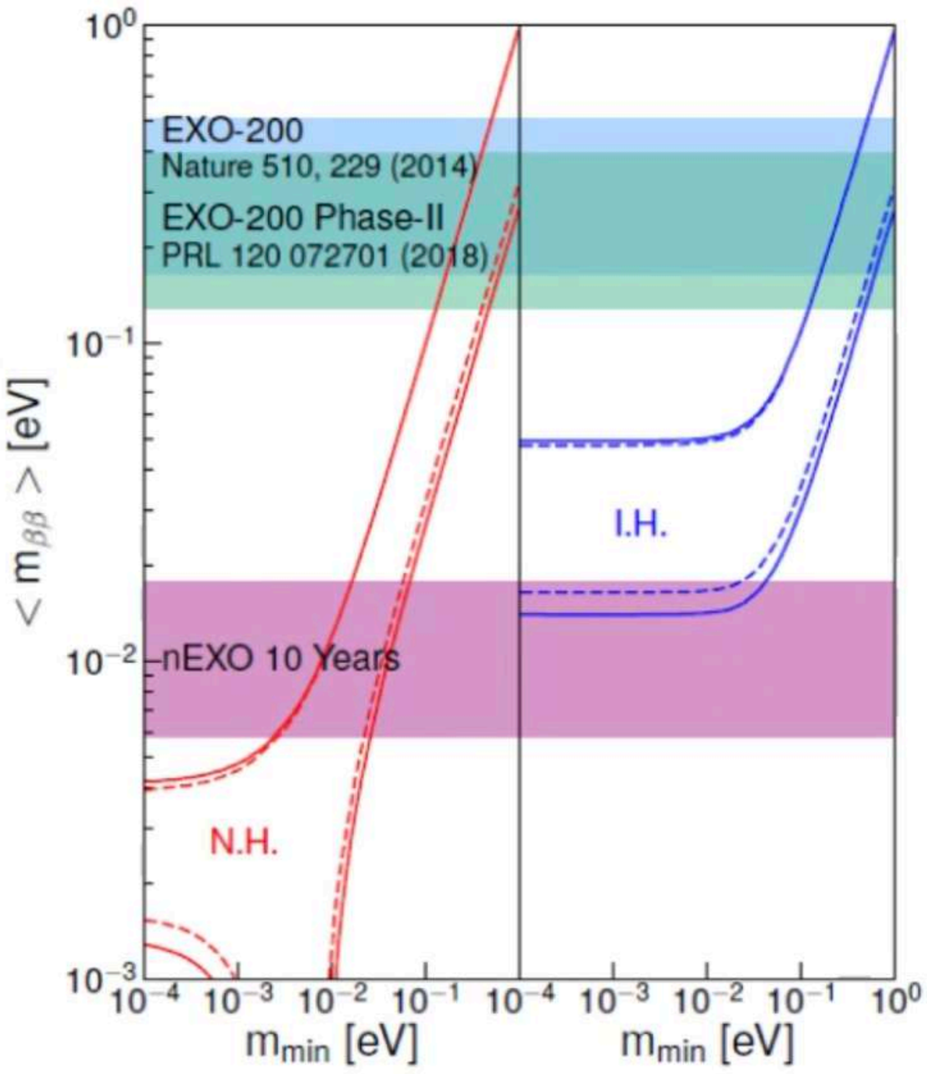
Summary

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



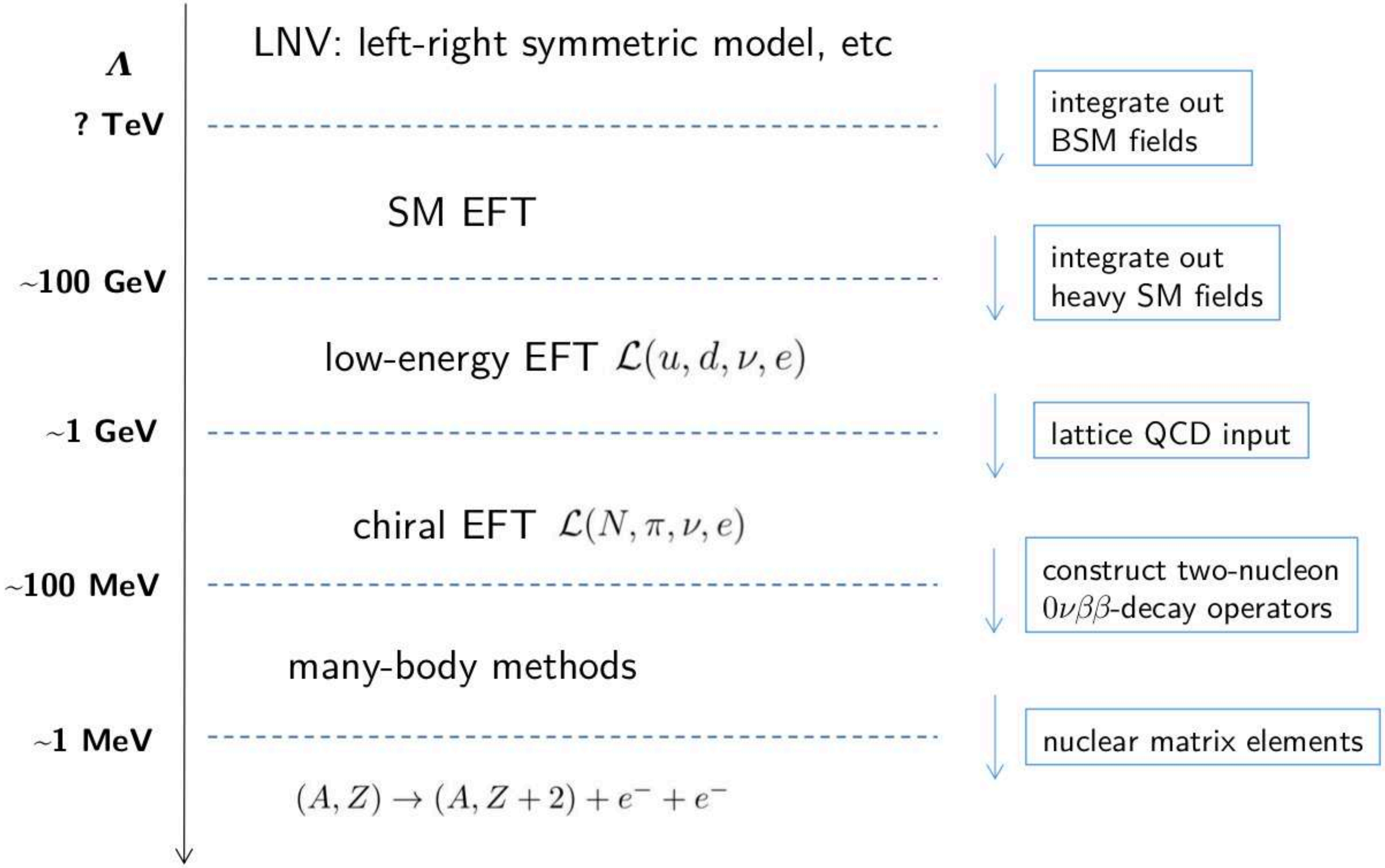
2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys.Rev.Lett. 123 (2019) no.16, 161802





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

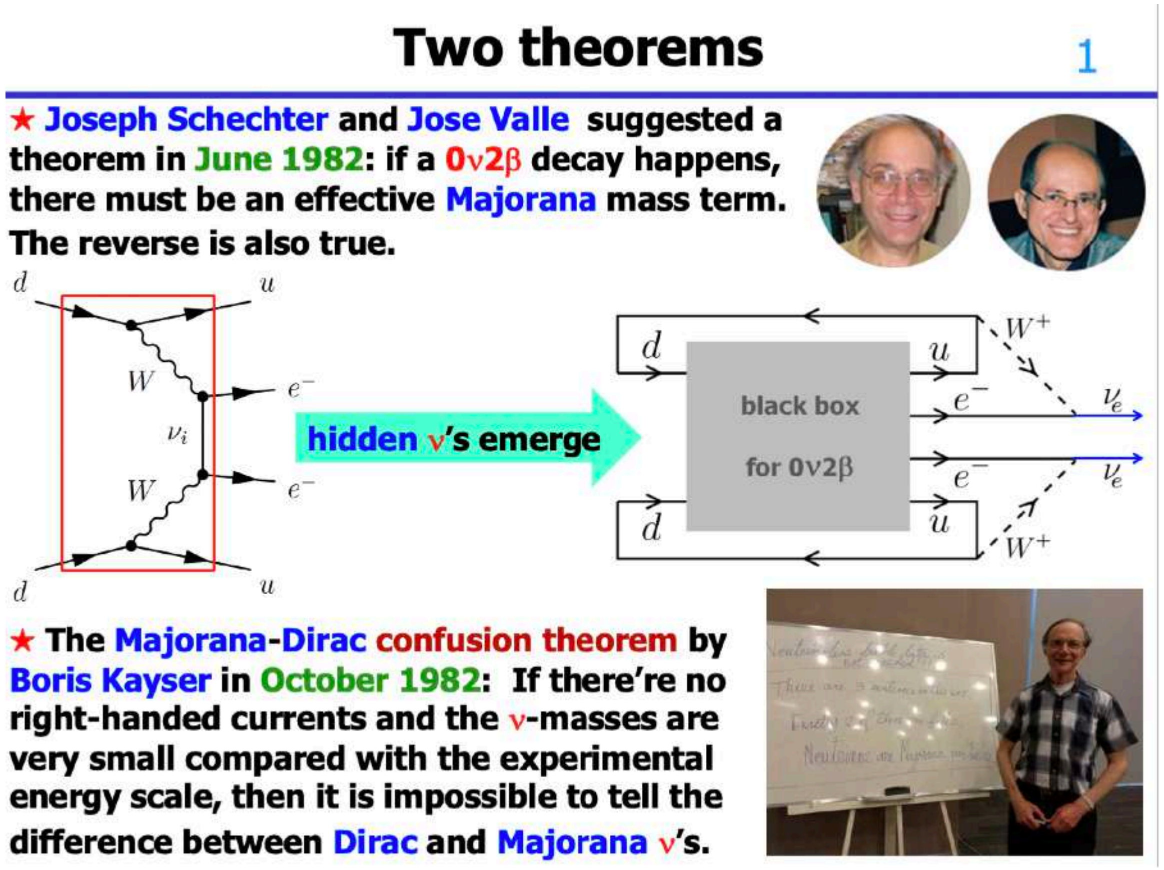
  （赵鹏巍、吕炳楠、高早春、刘朗、李剑、耿晶）
- 机器学习在核物理中的应用 （庞龙刚）

Summary

▶ **理论方面**

▶ **中微子物理 （质量起源）（邢志忠、周顺、李玉峰）**

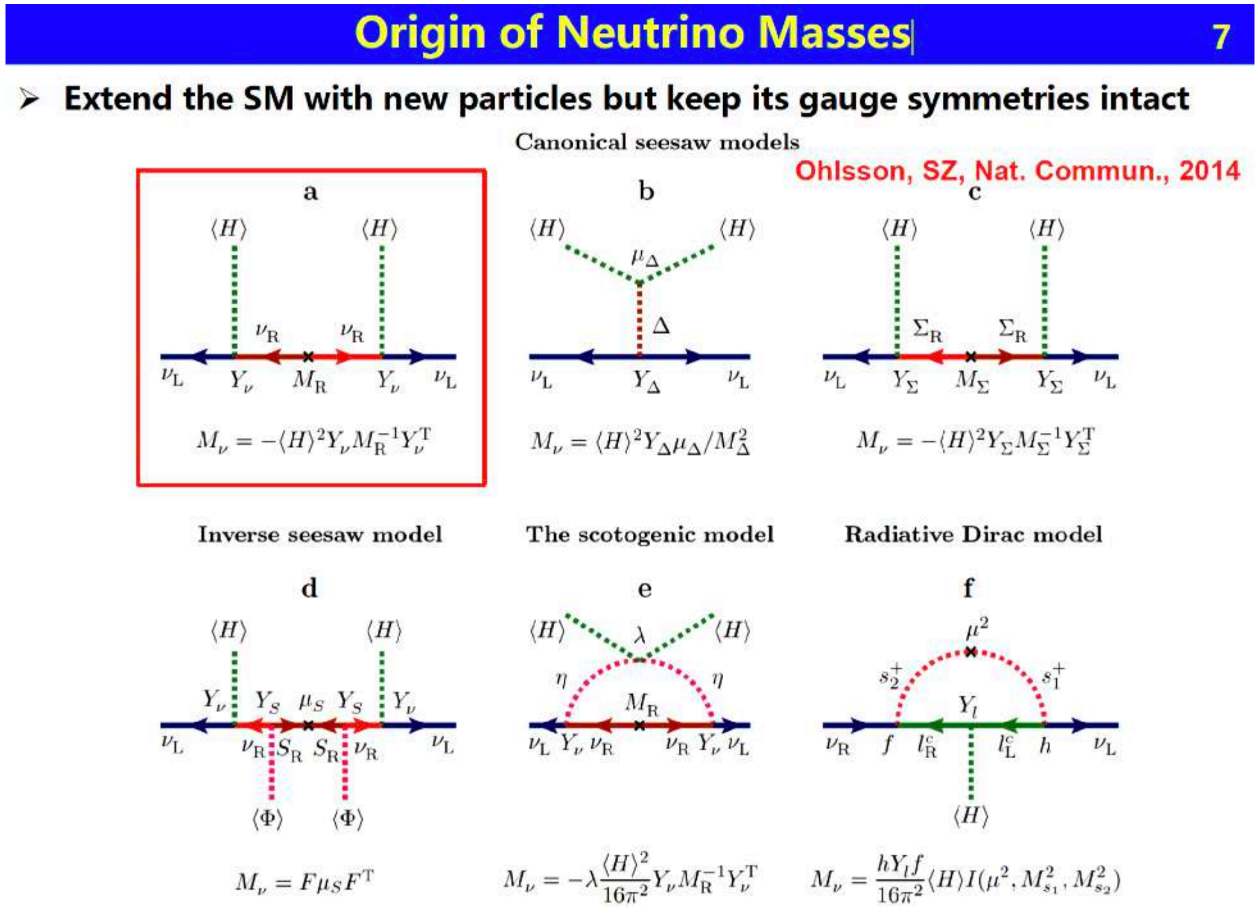
- **A brief history: ideas and facts oscillated**
- **Salient properties of Majorana neutrinos**



Two theorems

★ **Joseph Schechter** and **Jose Valle** suggested a theorem in **June 1982**: if a **0ν2β** decay happens, there must be an effective **Majorana** mass term. The reverse is also true.

★ The **Majorana-Dirac confusion theorem** by **Boris Kayser** in **October 1982**: If there're no right-handed currents and the ν-masses are very small compared with the experimental energy scale, then it is impossible to tell the difference between **Dirac** and **Majorana** ν's.



Origin of Neutrino Masses

➢ **Extend the SM with new particles but keep its gauge symmetries intact**

Canonical seesaw models

Ohlsson, SZ, Nat. Commun., 2014

$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$

$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$

$M_\nu = -\langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$

Inverse seesaw model

The scotogenic model

Radiative Dirac model

$M_\nu = F \mu_S F^T$

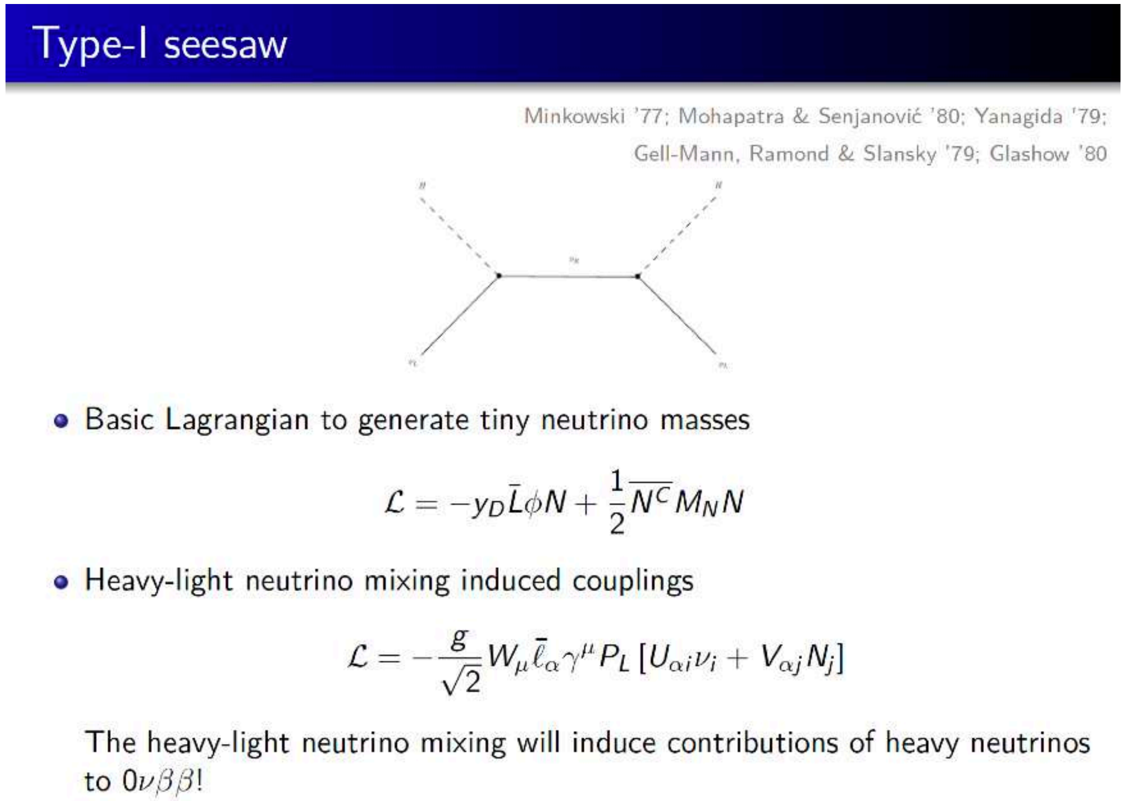
$M_\nu = -\lambda \frac{\langle H\rangle^2}{16\pi^2} Y_\nu M_R^{-1} Y_\nu^T$

$M_\nu = \frac{h Y_l f}{16\pi^2} \langle H\rangle I(\mu^2, M_{s_1}^2, M_{s_2}^2)$

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

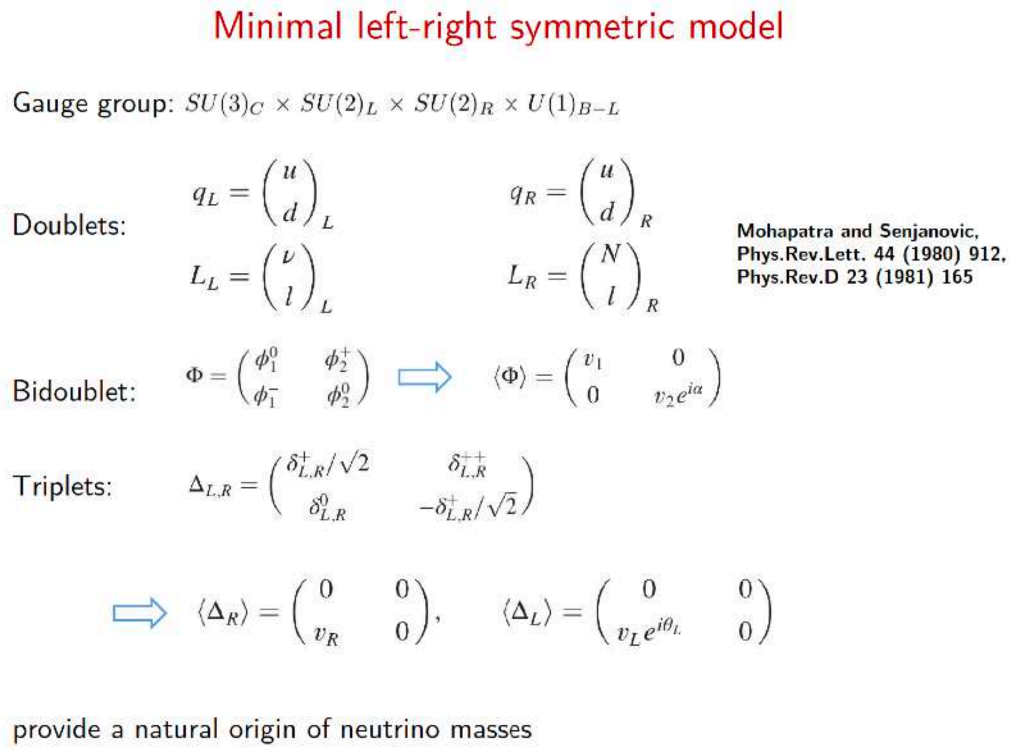
- Basic Lagrangian to generate tiny neutrino masses

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

- 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:
$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$$
$$L_L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L \qquad L_R = \begin{pmatrix} N \\ l \end{pmatrix}_R$$

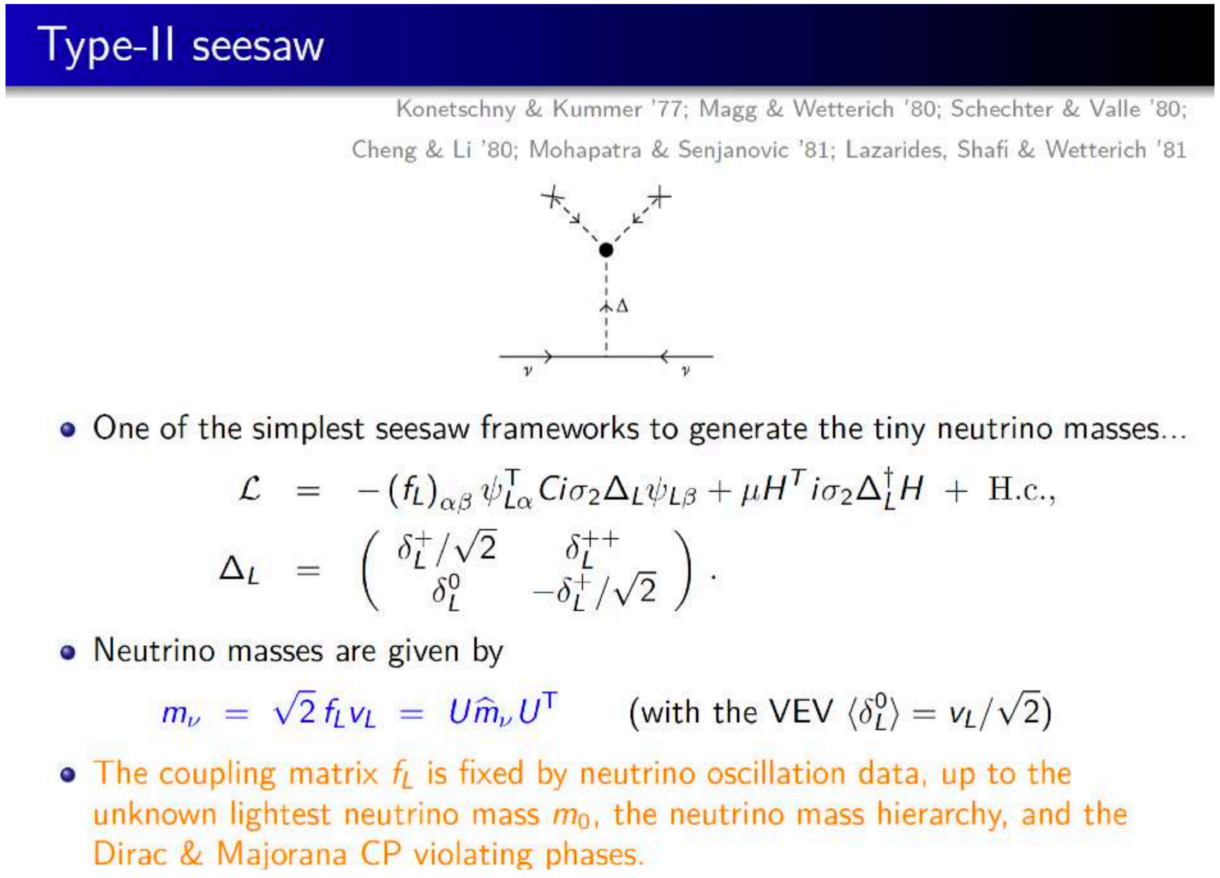
Mohapatra and Senjanovic,
Phys.Rev.Lett. 44 (1980) 912,
Phys.Rev.D 23 (1981) 165

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

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

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...

$$\mathcal{L} = -(f_L)_{\alpha\beta}\, \psi_{L\alpha}^T C i\sigma_2 \Delta_L \psi_{L\beta} + \mu H^T i\sigma_2 \Delta_L^\dagger H + \text{H.c.},$$
$$\Delta_L = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}.$$

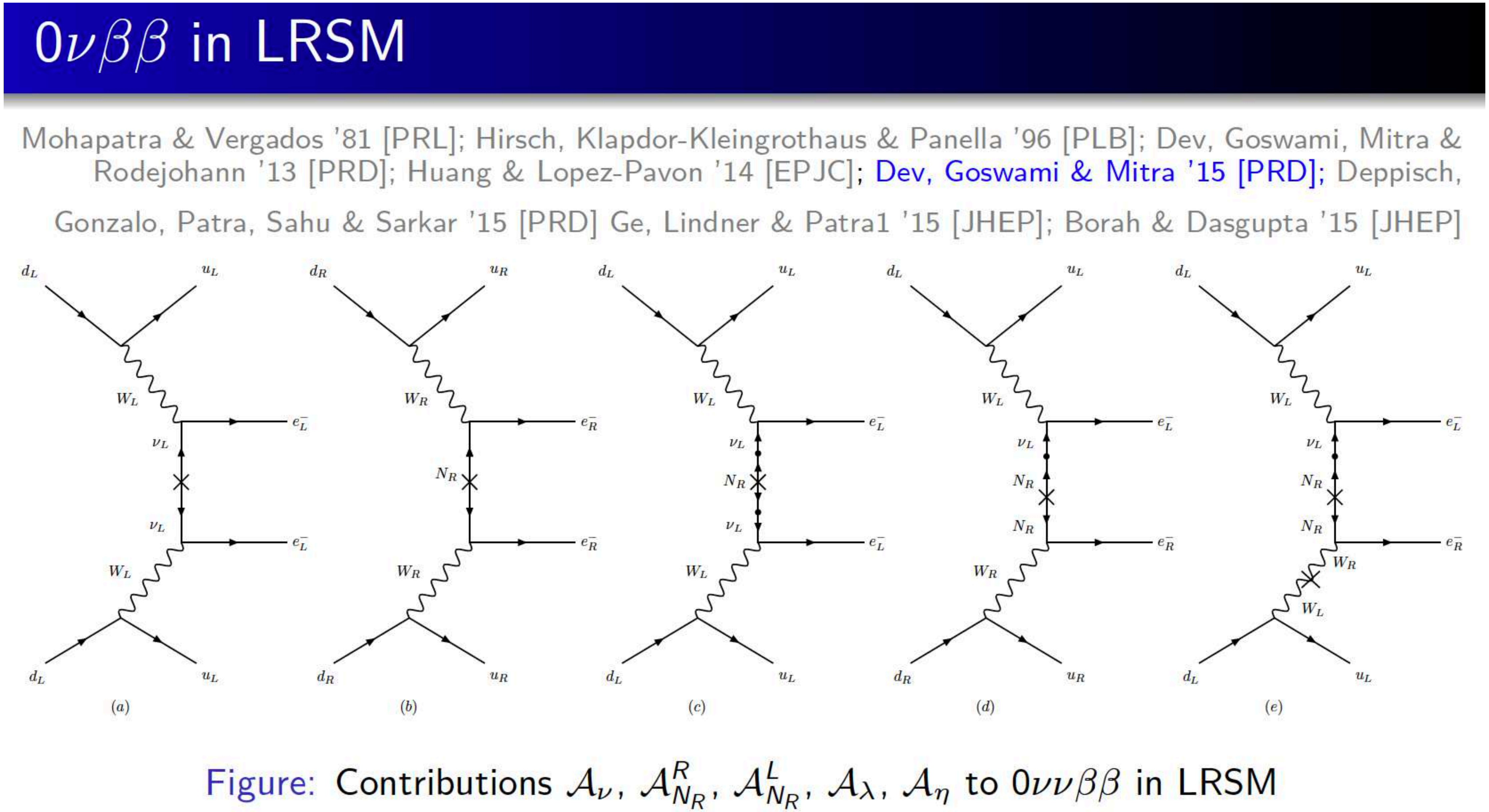
- Neutrino masses are given by

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

- 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）**



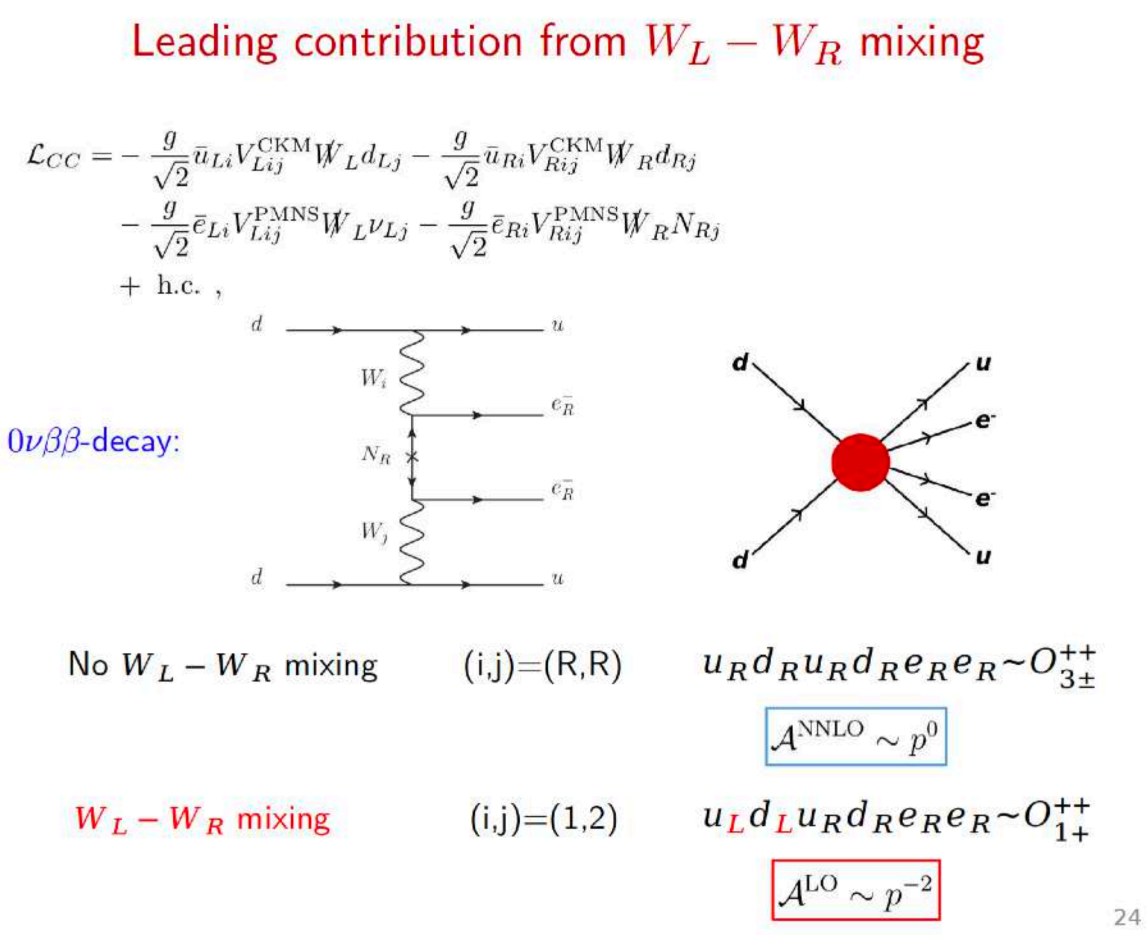
$0\nu\beta\beta$ in LRSM

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

Summary

- **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

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\bar{u}_{Li}V^{\rm CKM}_{Lij}\not{W}_L d_{Lj} - \frac{g}{\sqrt{2}}\bar{u}_{Ri}V^{\rm CKM}_{Rij}\not{W}_R d_{Rj} - \frac{g}{\sqrt{2}}\bar{e}_{Li}V^{\rm PMNS}_{Lij}\not{W}_L \nu_{Lj} - \frac{g}{\sqrt{2}}\bar{e}_{Ri}V^{\rm PMNS}_{Rij}\not{W}_R N_{Rj} + \text{h.c.}\,,$$

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

No $W_L - W_R$ mixing　(i,j)=(R,R)　$u_R d_R u_R d_R e_R e_R \sim O^{++}_{3\pm}$

$\boxed{\mathcal{A}^{\rm NNLO} \sim p^0}$

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

$\boxed{\mathcal{A}^{\rm LO} \sim p^{-2}}$

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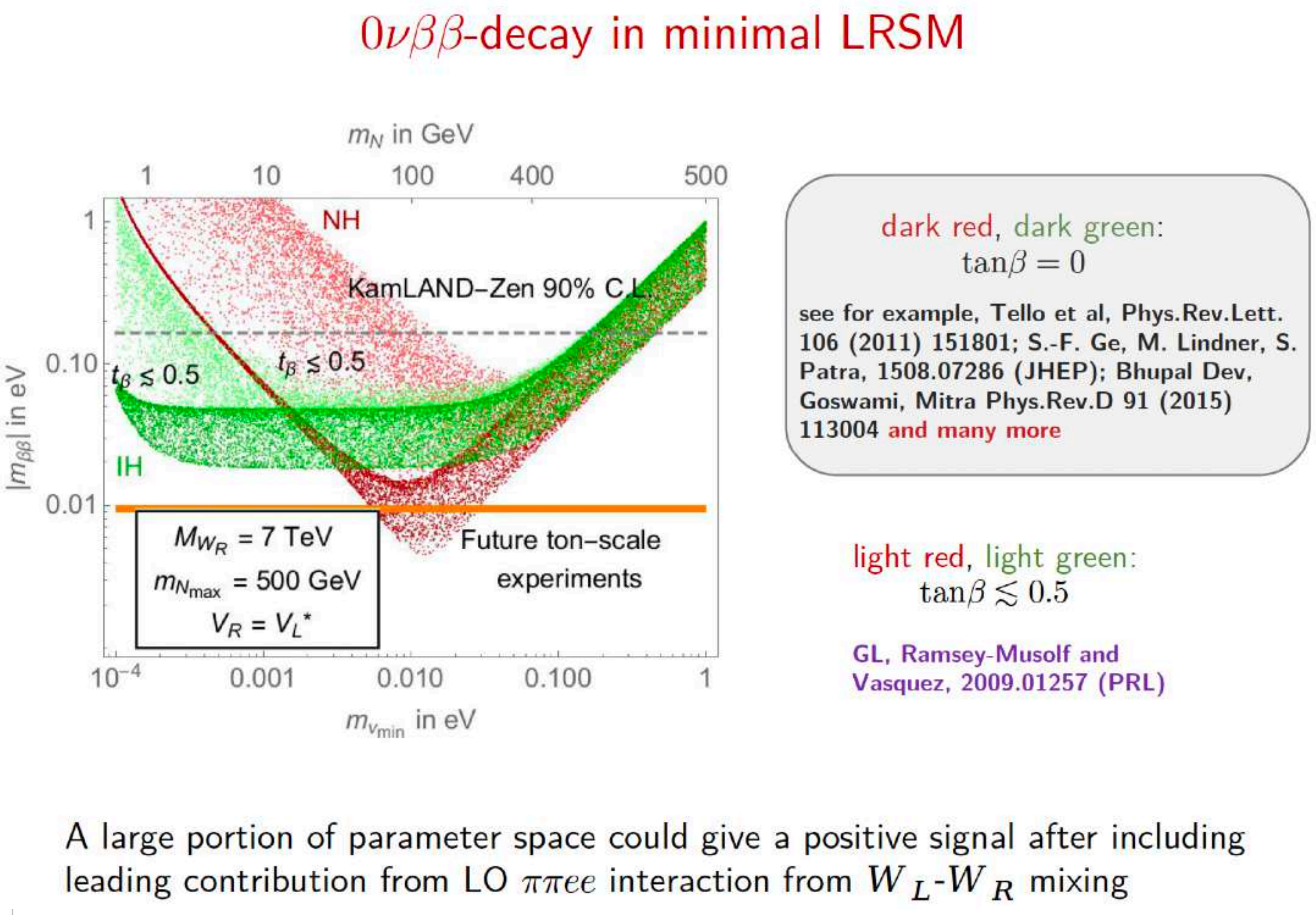


$0\nu\beta\beta$-decay in minimal LRSM

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

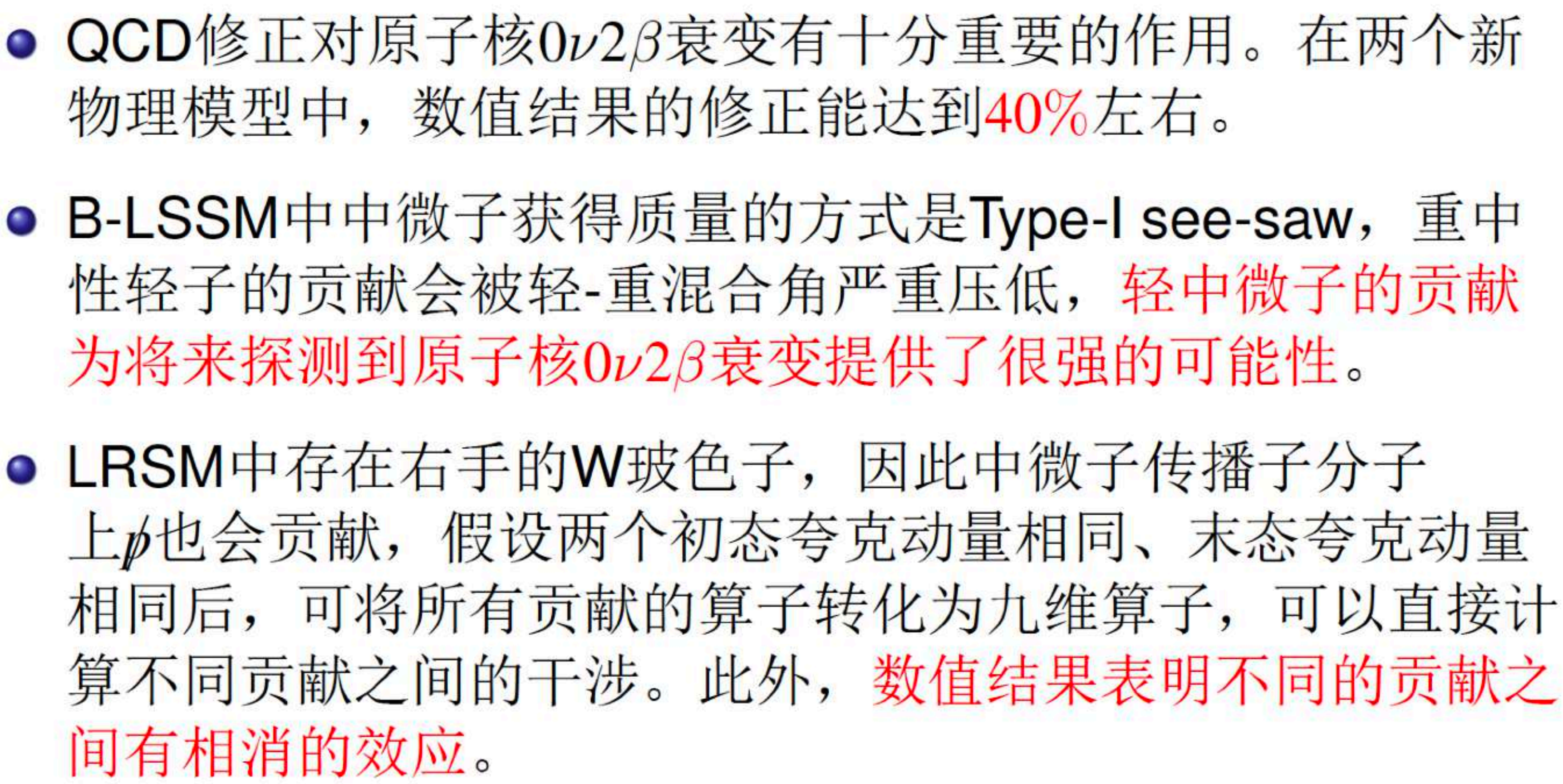
light red, light green:
$\tan\beta \lesssim 0.5$

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

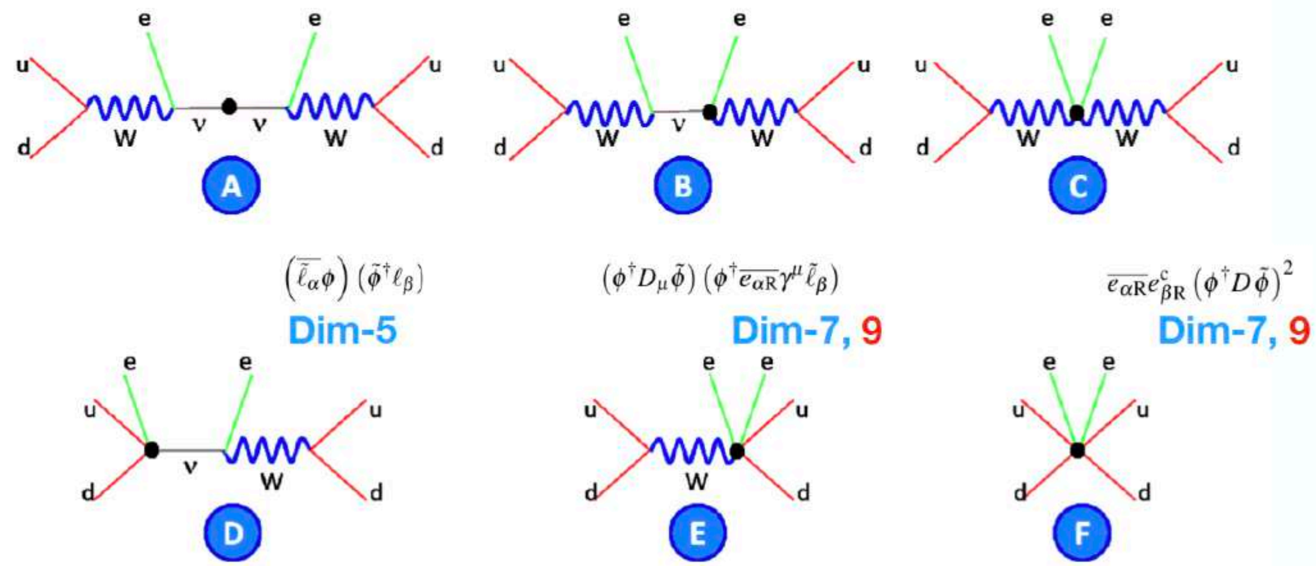
- **理论方面**
  - **轻子数破坏（LNV）有效场论**

    （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:



$\left(\overline{\tilde{\ell}_\alpha}\phi\right)\left(\tilde{\phi}^\dagger\ell_\beta\right)$ Dim-5

$\left(\phi^\dagger D_\mu\tilde{\phi}\right)\left(\phi^\dagger\overline{e_{\alpha\mathrm{R}}}\gamma^\mu\tilde{\ell}_\beta\right)$ Dim-7, 9

$\overline{e_{\alpha\mathrm{R}}}e^c_{\beta\mathrm{R}}\left(\phi^\dagger D\tilde{\phi}\right)^2$ Dim-7, 9

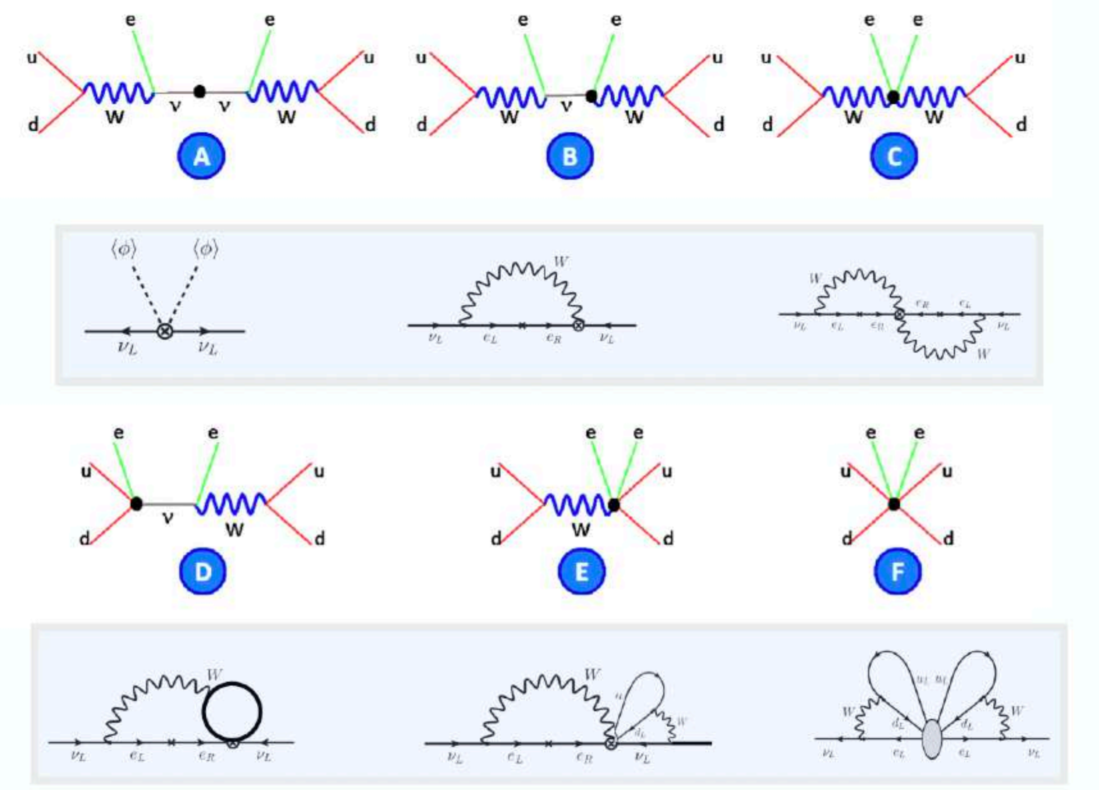
Dim-7, 9

Dim-9

Dim-9

Not complete

Neutrino Masses and 0vbb



Summary

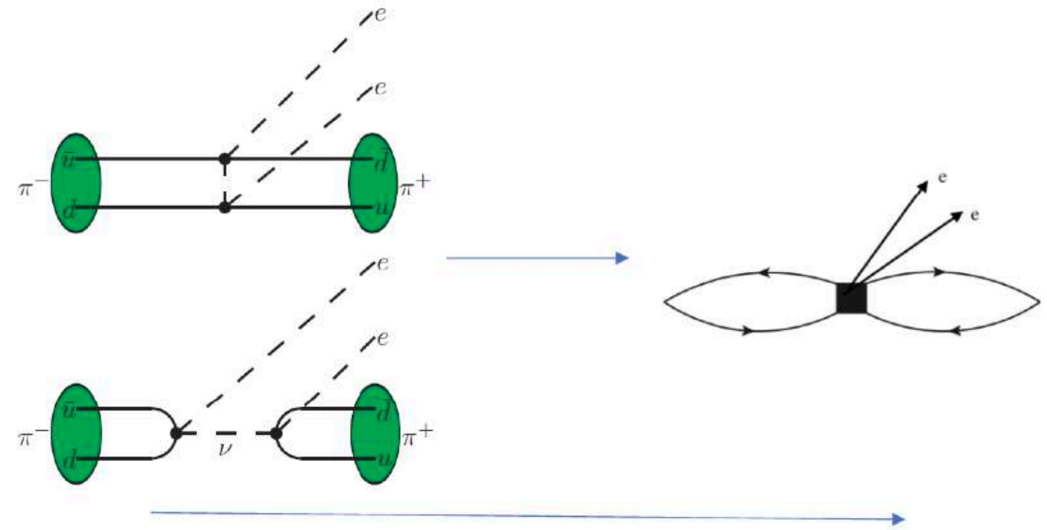
- **理论方面**
  - **轻子数破坏（LNV）有效场论**

    (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

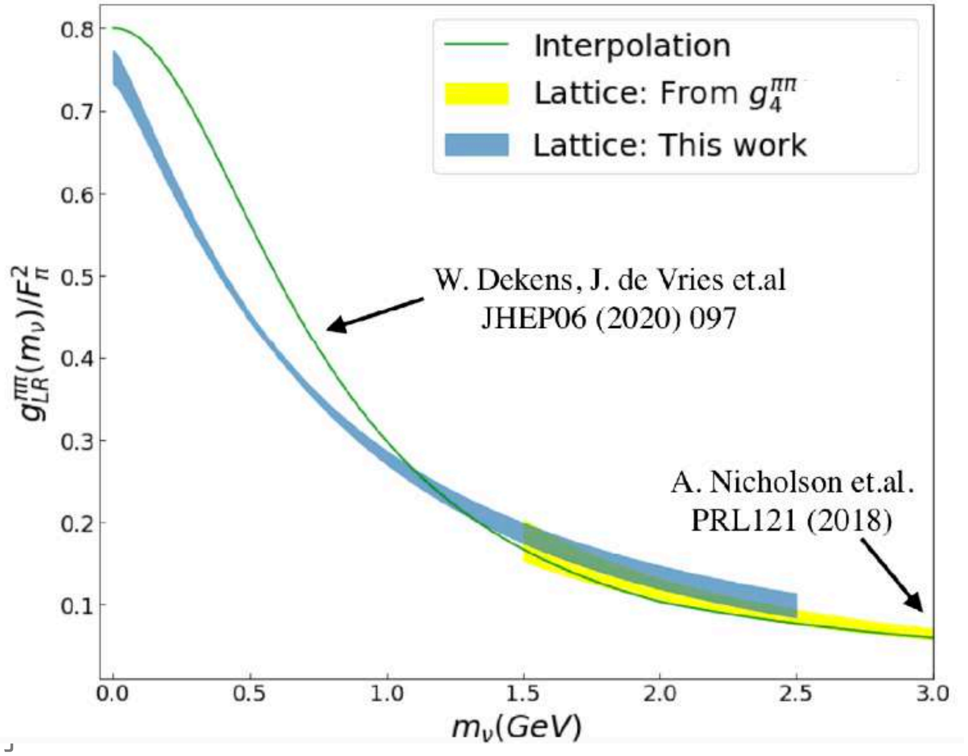
Summary

- **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]

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

Lattice calculation yields (statistical error only)

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

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

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

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

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

Lattice calculation yields (statistical + systematical errors)

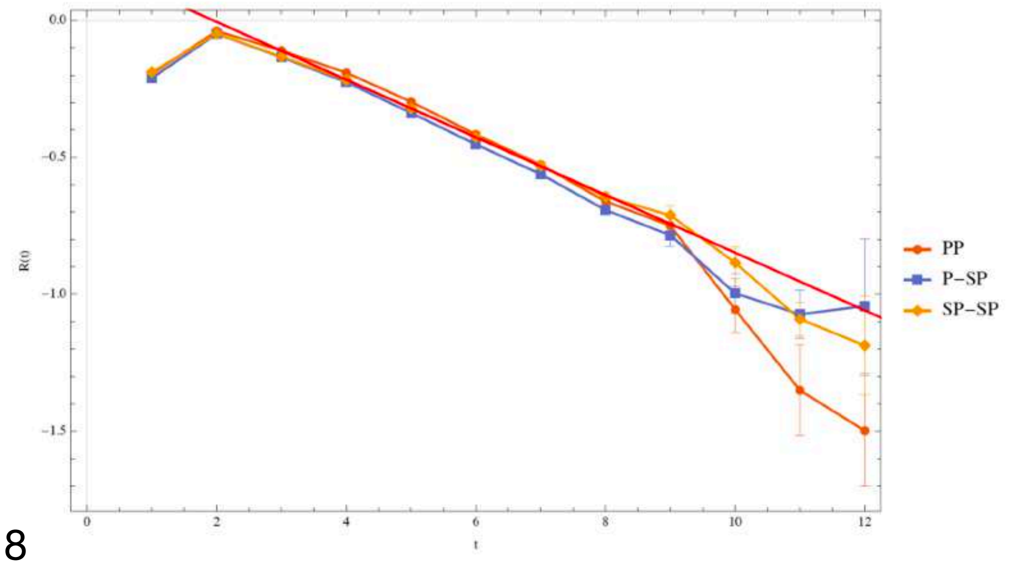
$$\frac{\mathcal{A}(\pi^-\to\pi^+ ee)}{2F_\pi^2\, T_{\rm lept}} = 1.105(3)(7) \quad\Rightarrow\quad g_\nu^{\pi\pi}(m_\rho) = -10.9(3)(7)$$

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: $nn \to ppee$

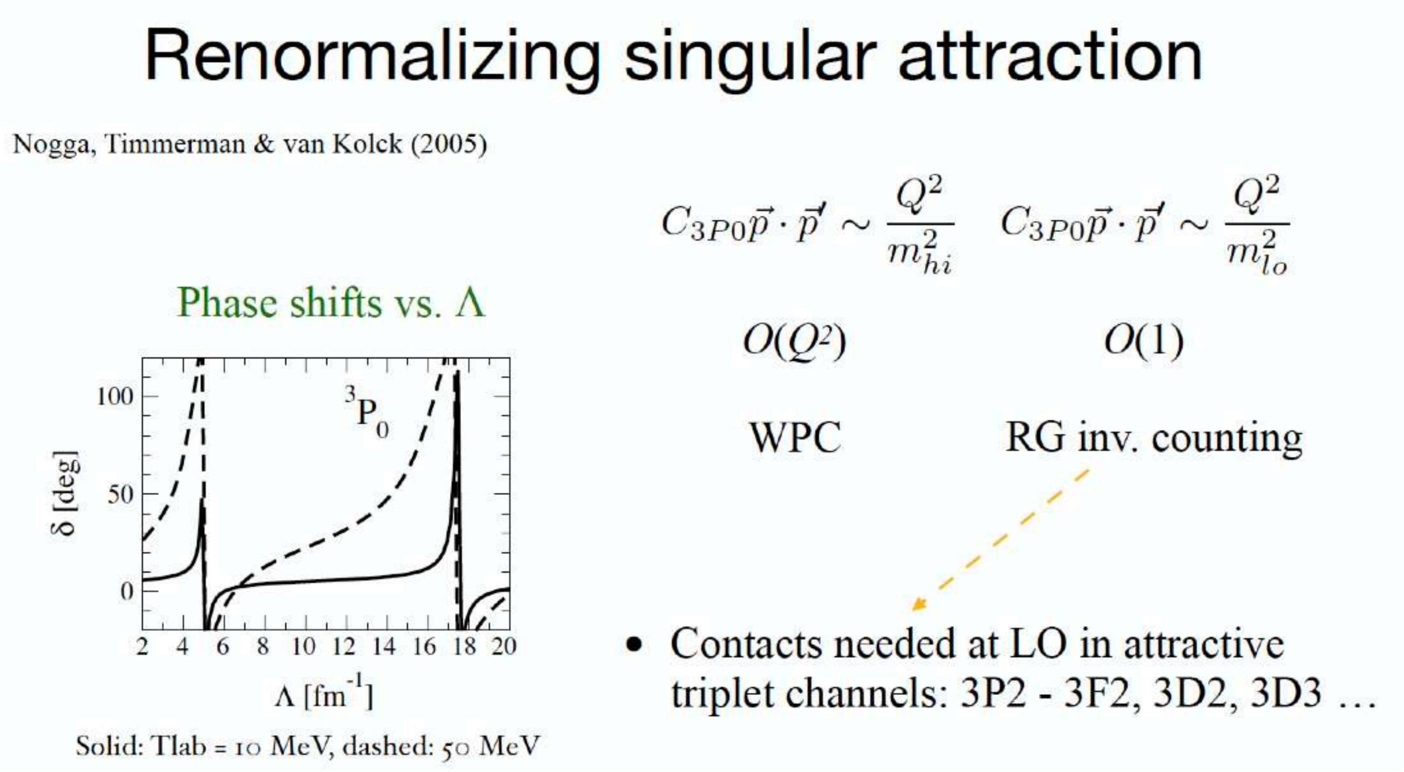


Summary

- **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

$C_{3P0}\vec{p}\cdot\vec{p}' \sim \frac{Q^2}{m_{hi}^2}$　　$C_{3P0}\vec{p}\cdot\vec{p}' \sim \frac{Q^2}{m_{lo}^2}$

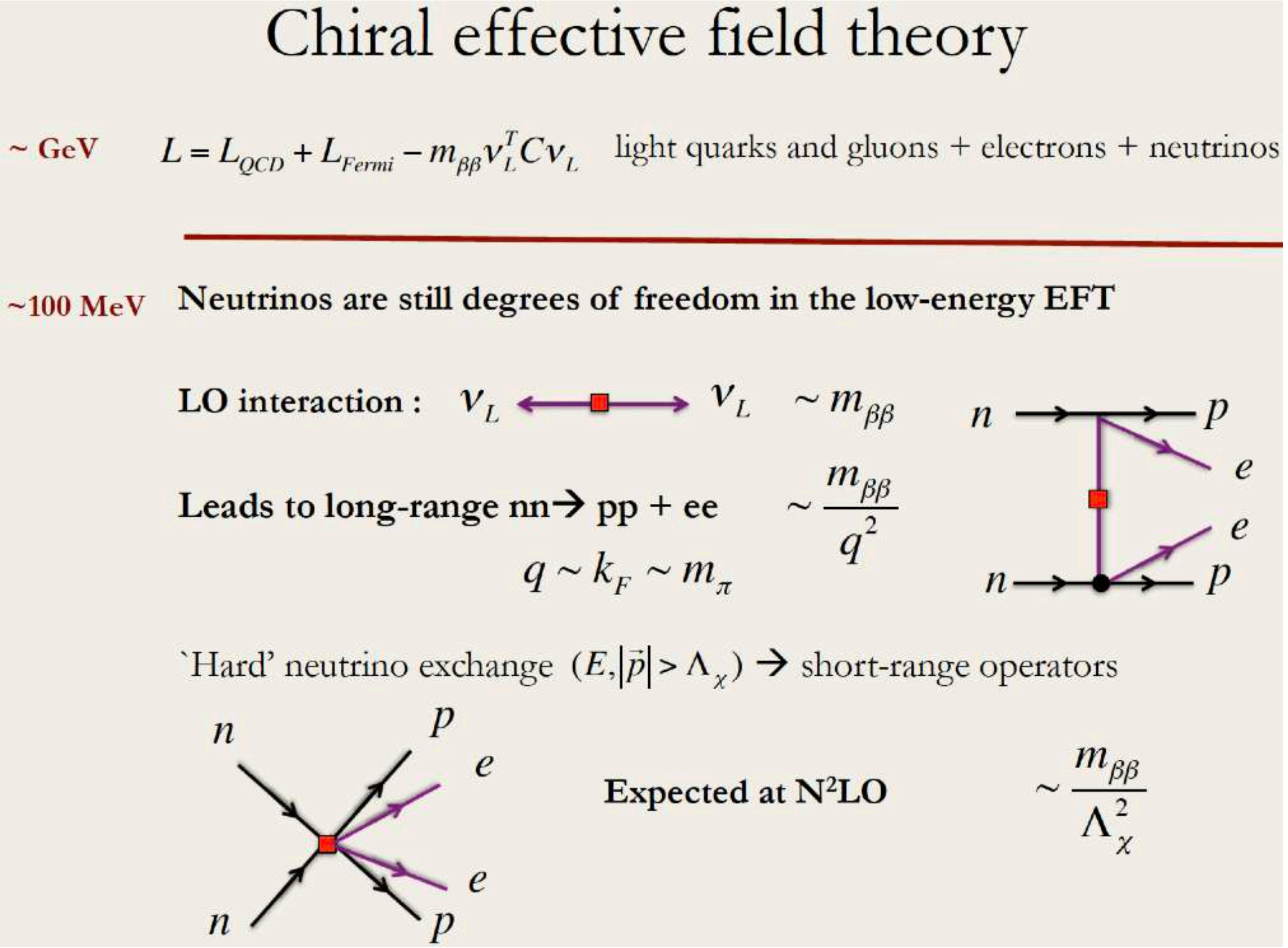
$O(Q^2)$　　$O(1)$

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 : ν_L ⟷ ν_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

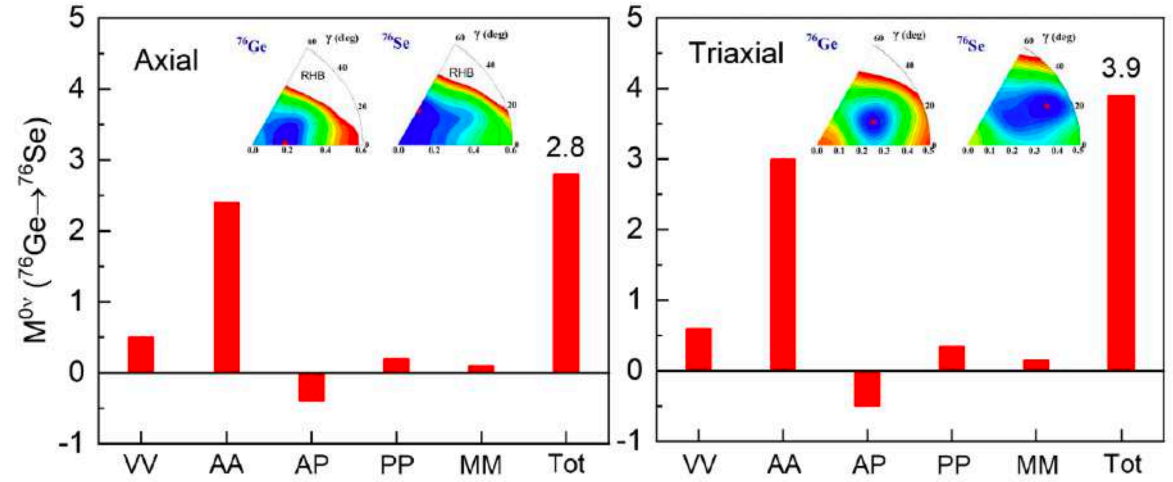
Expected at N²LO　$\sim \frac{m_{\beta\beta}}{\Lambda_\chi^2}$

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）

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%

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 $|\Phi_\kappa\rangle \in \{|\Phi_0\rangle, \hat{\beta}^\dagger_{\nu_i}\hat{\beta}^\dagger_{\nu_j}|\Phi_0\rangle, \hat{\beta}^\dagger_{\pi_i}\hat{\beta}^\dagger_{\pi_j}|\Phi_0\rangle\}$

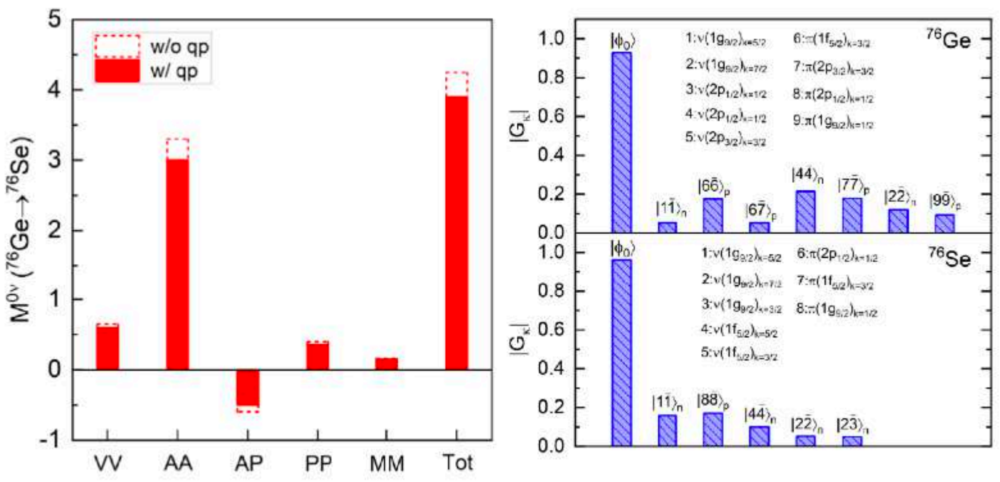
$$|\Phi_0\rangle = \prod_{k>0} \hat{\beta}_k |0\rangle, \quad \begin{pmatrix} h_D - \lambda & \Delta \\ -\Delta^* & -h^*_D + \lambda \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

□ 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 $\hat{\rho}_{ji}$ 的二阶偏导求得，无任何可调参数

核矩阵元：准粒子组态混合效应



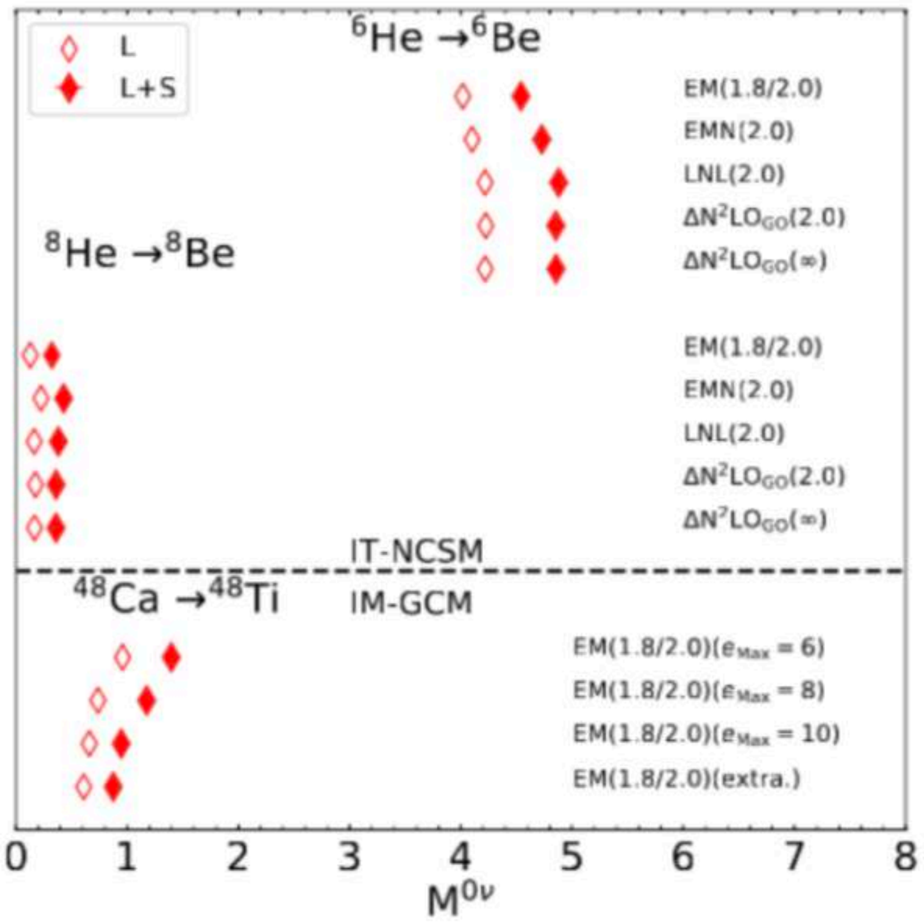
原子核	核矩阵元	
	考虑组态混合	不考虑组态混合
^{76}Ge	3.90	4.25

- ✓ 考虑准粒子组态混合，核矩阵元值从 4.25 降低至 3.90

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）

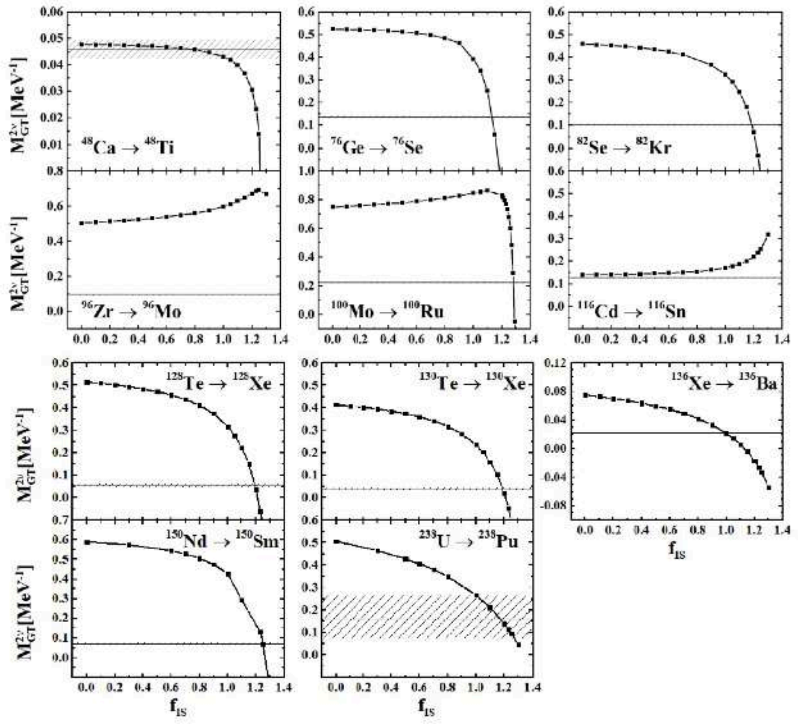


“标准”机制下短程耦合效应

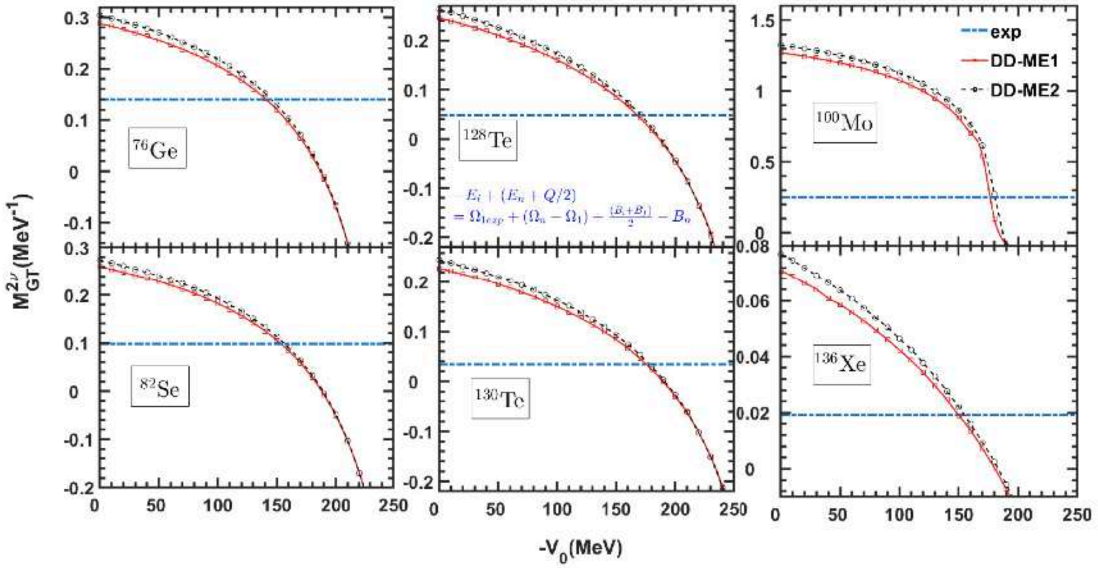
NME of 2νββ

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

Skyrme QRPA



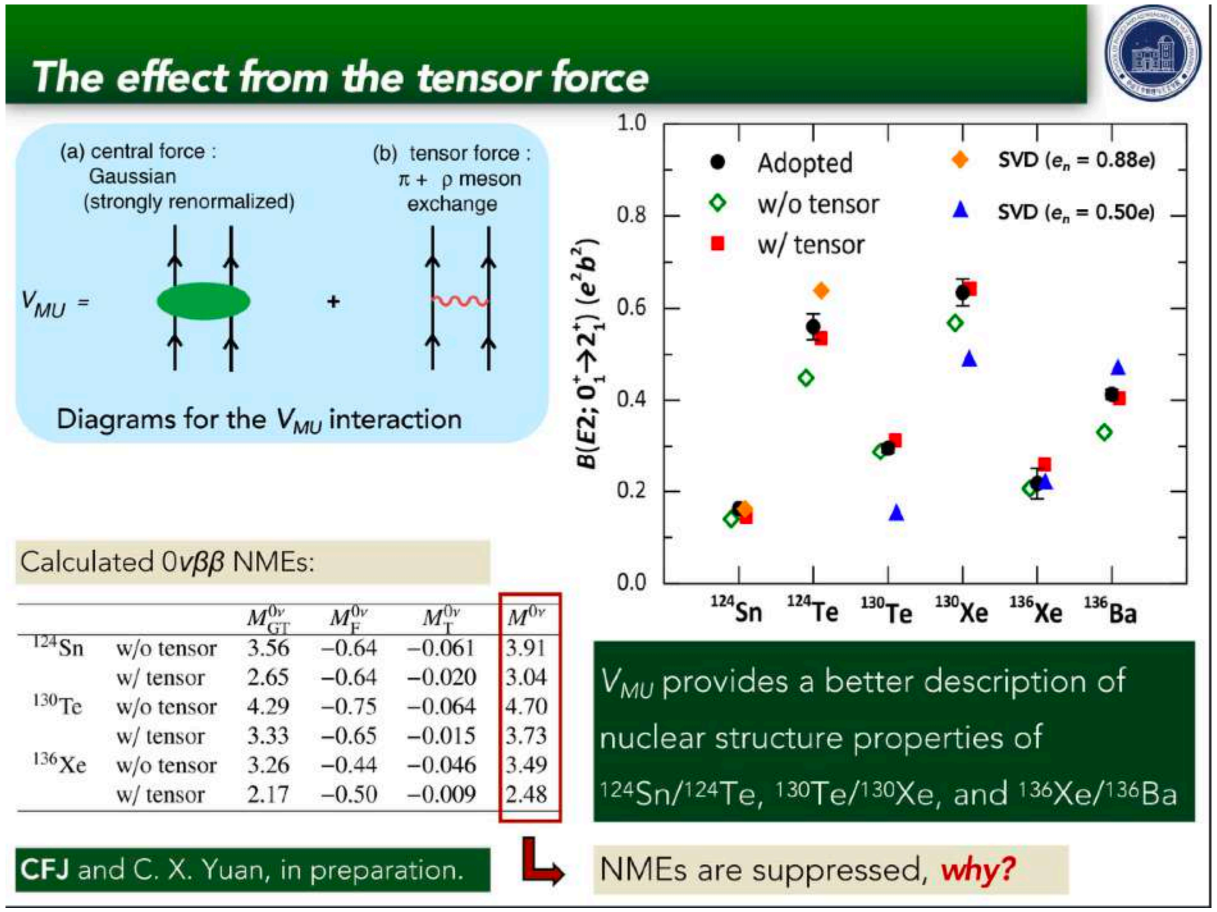
relativistic QRPA



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）



The effect from the tensor force

Diagrams for the V_{MU} interaction

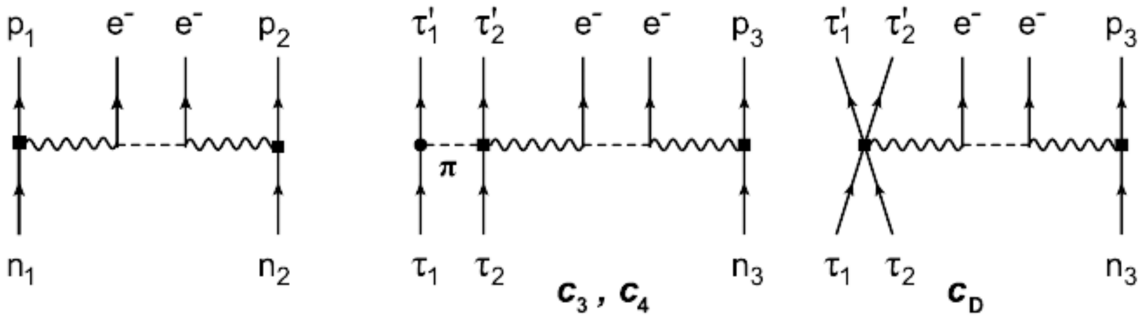
Calculated $0\nu\beta\beta$ NMEs:

		$M^{0\nu}_{GT}$	$M^{0\nu}_{F}$	$M^{0\nu}_{T}$	$M^{0\nu}$
^{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

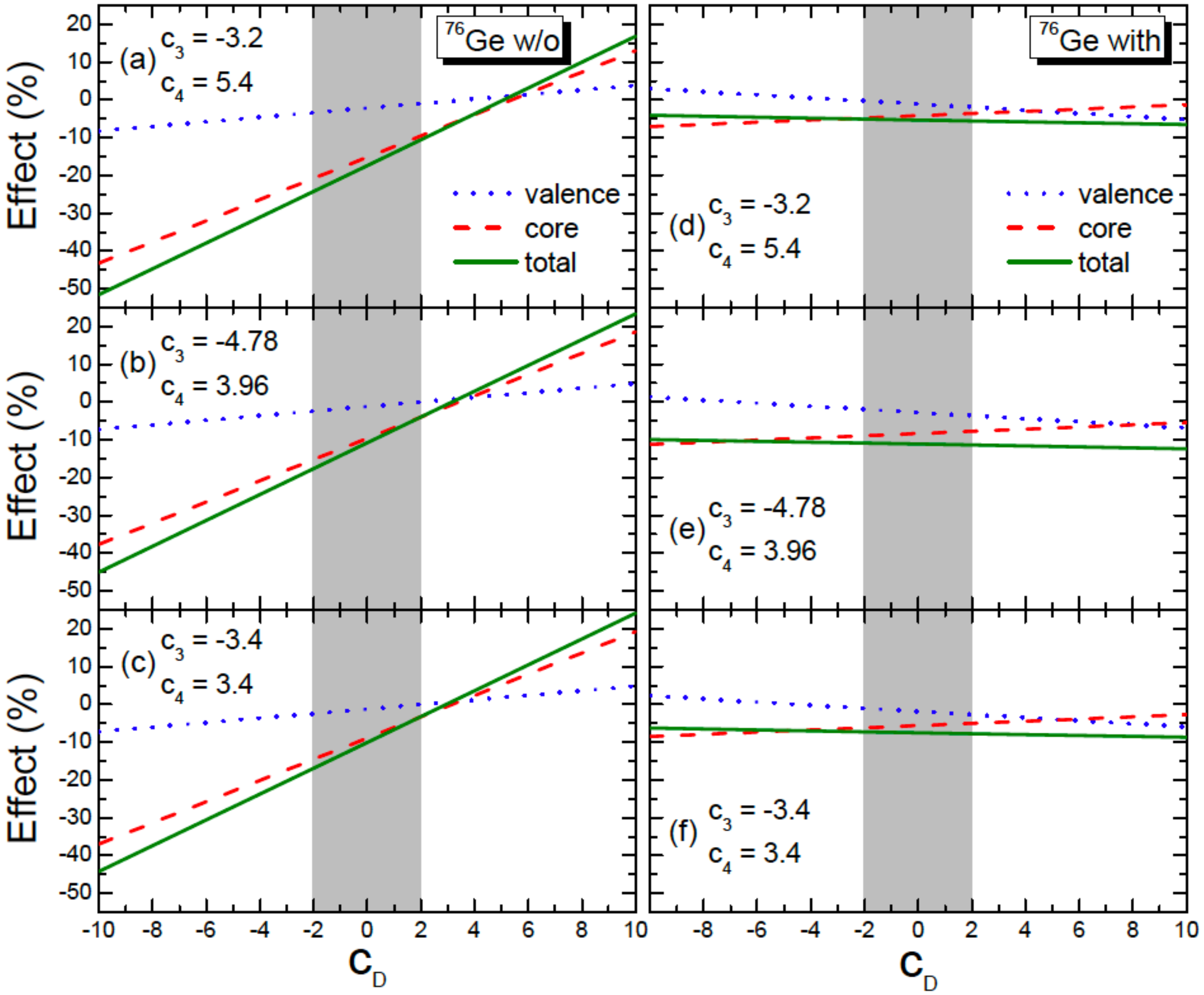
CFJ and C. X. Yuan, in preparation.

NMEs are suppressed, *why?*



(a) Double 1-body

(b) 1-body plus 2-body

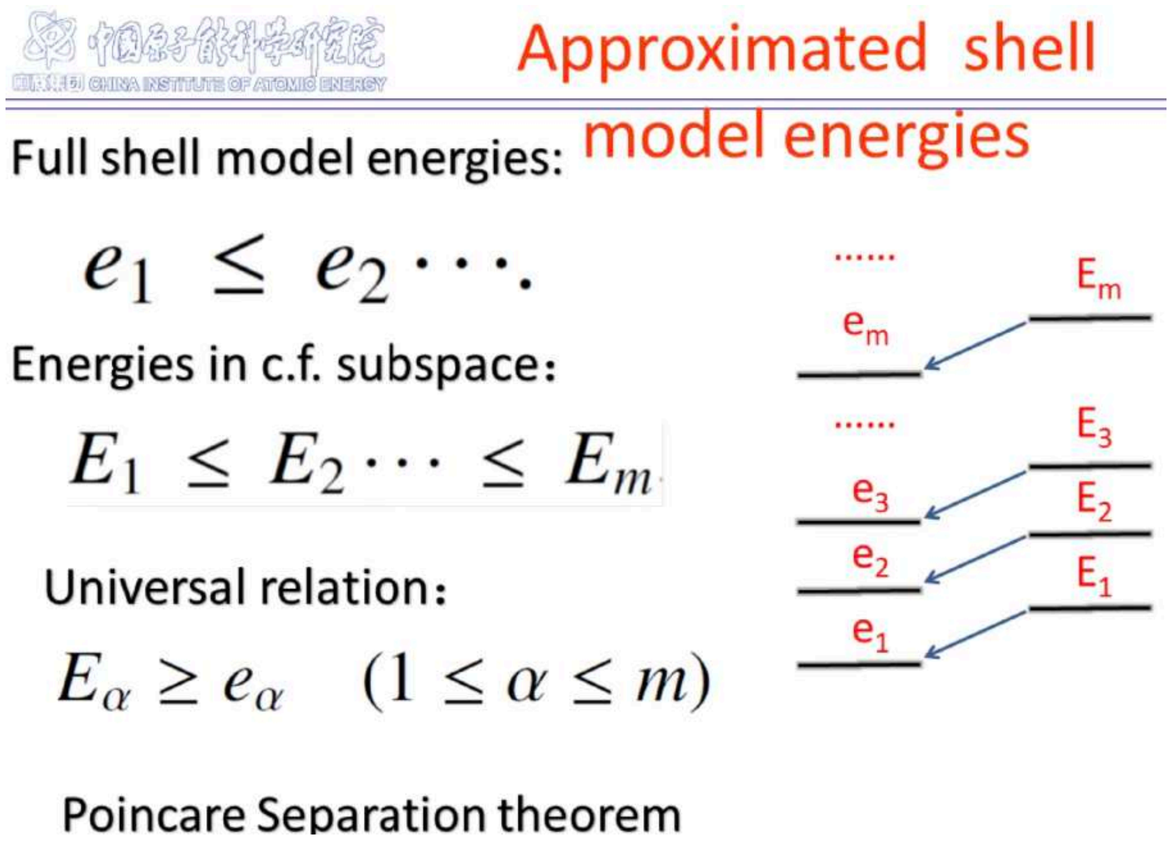


Summary

- **理论方面**
  - **原子核结构**

（赵鹏巍、吕炳楠、高早春、刘朗、李剑、耿晶）

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



Approximated shell model energies

Full shell model energies:

$$e_1 \le e_2 \cdots .$$

Energies in c.f. subspace:

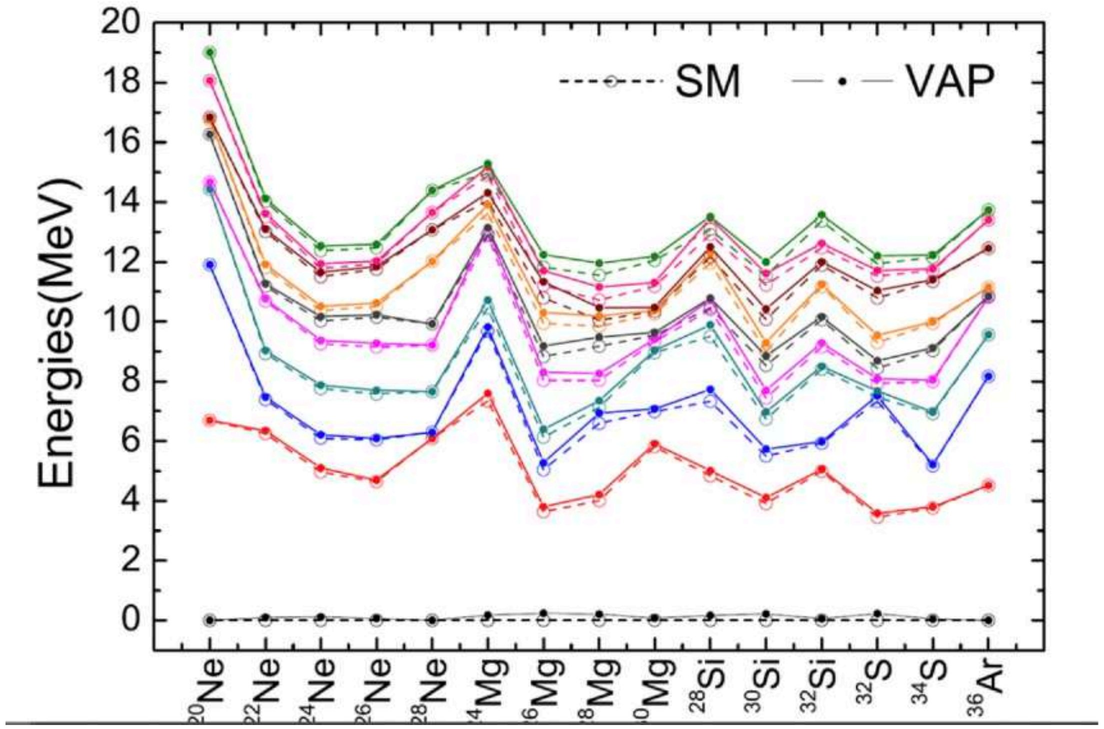
$$E_1 \le E_2 \cdots \le E_m$$

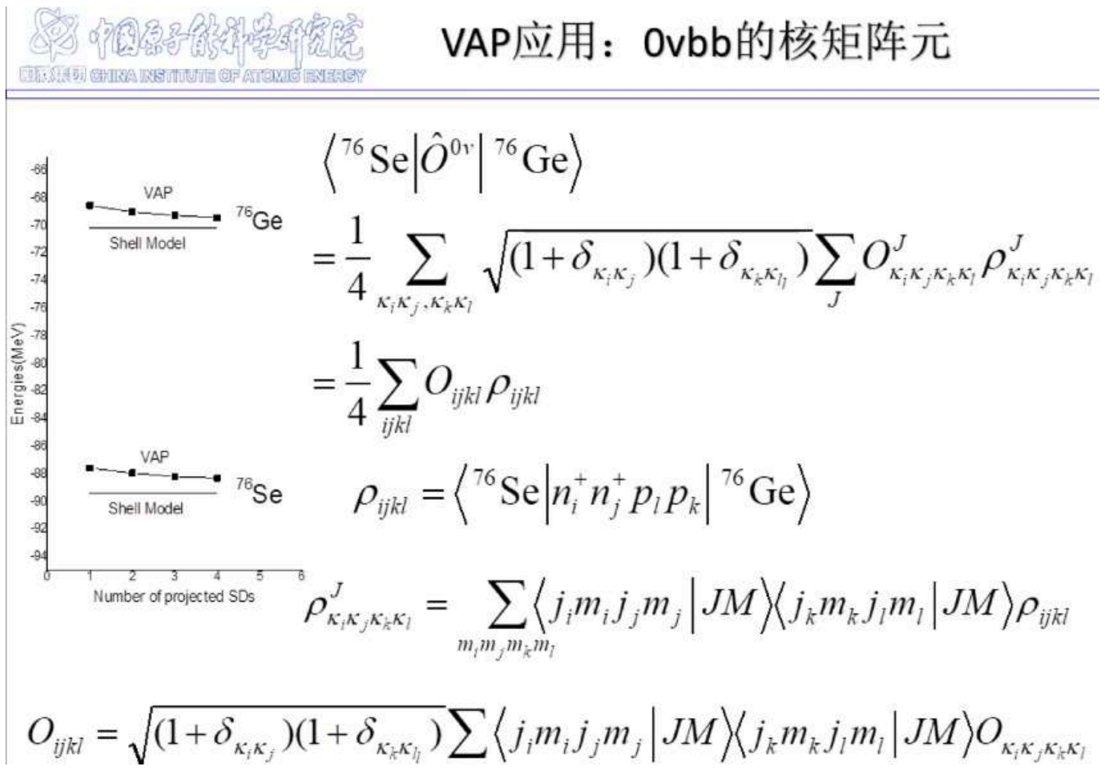
Universal relation:

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

Poincare Separation theorem

VAP（多个低激发态同时取极值）





VAP应用：0vbb的核矩阵元

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

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

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

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

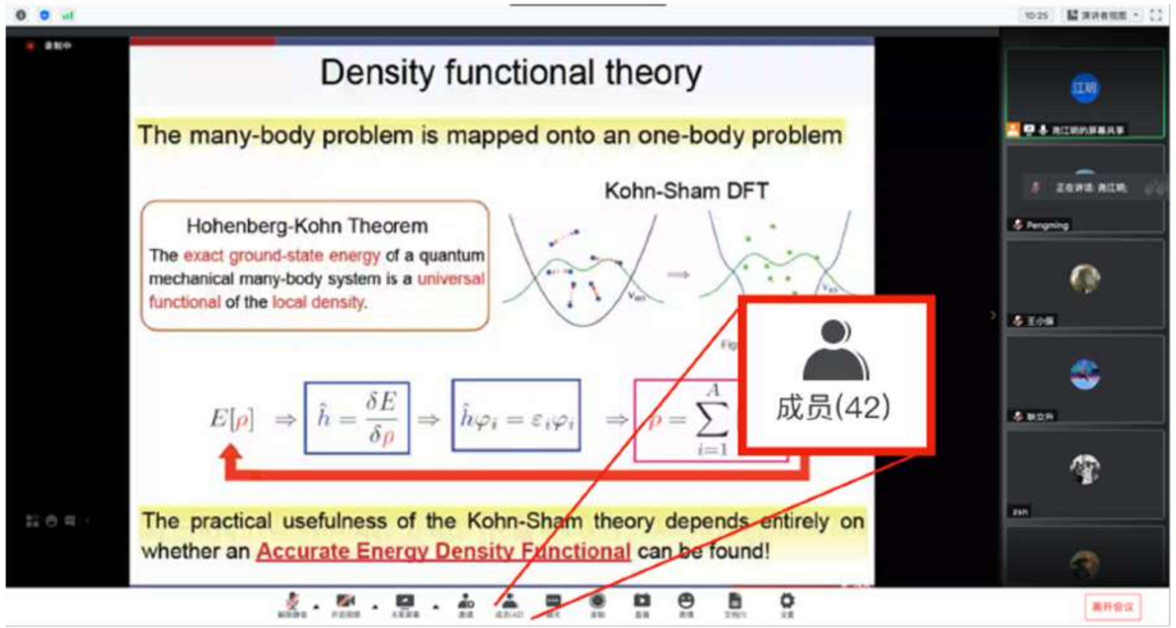
$$\rho^J_{\kappa_i\kappa_j\kappa_k\kappa_l}=\sum_{m_im_jm_km_l}\langle j_im_ij_jm_j|JM\rangle\langle j_km_kj_lm_l|JM\rangle\rho_{ijkl}$$

$$O_{ijkl}=\sqrt{(1+\delta_{\kappa_i\kappa_j})(1+\delta_{\kappa_k\kappa_l})}\sum\langle j_im_ij_jm_j|JM\rangle\langle j_km_kj_lm_l|JM\rangle O_{\kappa_i\kappa_j\kappa_k\kappa_l}$$

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）



Density functional theory

The many-body problem is mapped onto an one-body problem

Hohenberg-Kohn Theorem

The exact ground-state energy of a quantum mechanical many-body system is a universal functional of the local density.

Kohn-Sham DFT

$$E[\rho] \Rightarrow \hat{h} = \frac{\delta E}{\delta \rho} \Rightarrow \hat{h}\varphi_i = \varepsilon_i \varphi_i \Rightarrow \rho = \sum_{i=1}^{A} \ldots$$

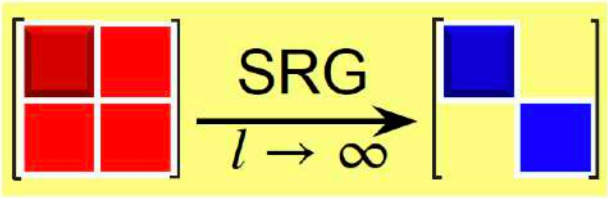
成员(42)

The practical usefulness of the Kohn-Sham theory depends entirely on whether an Accurate Energy Density Functional can be found!

Similarity Renormalization Group

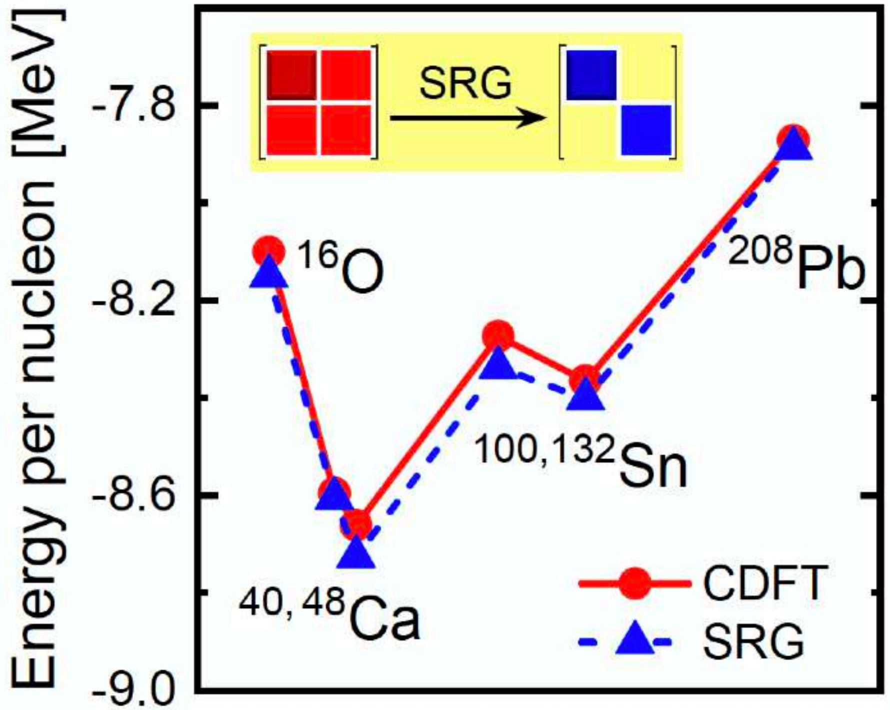
Relativistic Kohn-Sham Equation: Dirac Equation

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



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

Toward a bridge between relativistic and nonrelativistic DFT



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

Summary

- **理论方面**
  - **原子核结构**

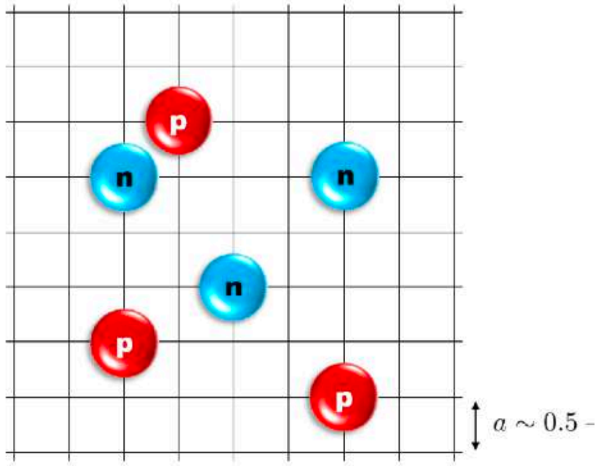
（赵鹏巍、吕炳楠、高早春、刘朗、李剑、耿晶）

Quantum many-body problem can be solved on a lattice

Lattice QCD, Hubbard model, Cold atoms...

Lattice EFT = Chiral EFT + Lattice + Monte Carlo

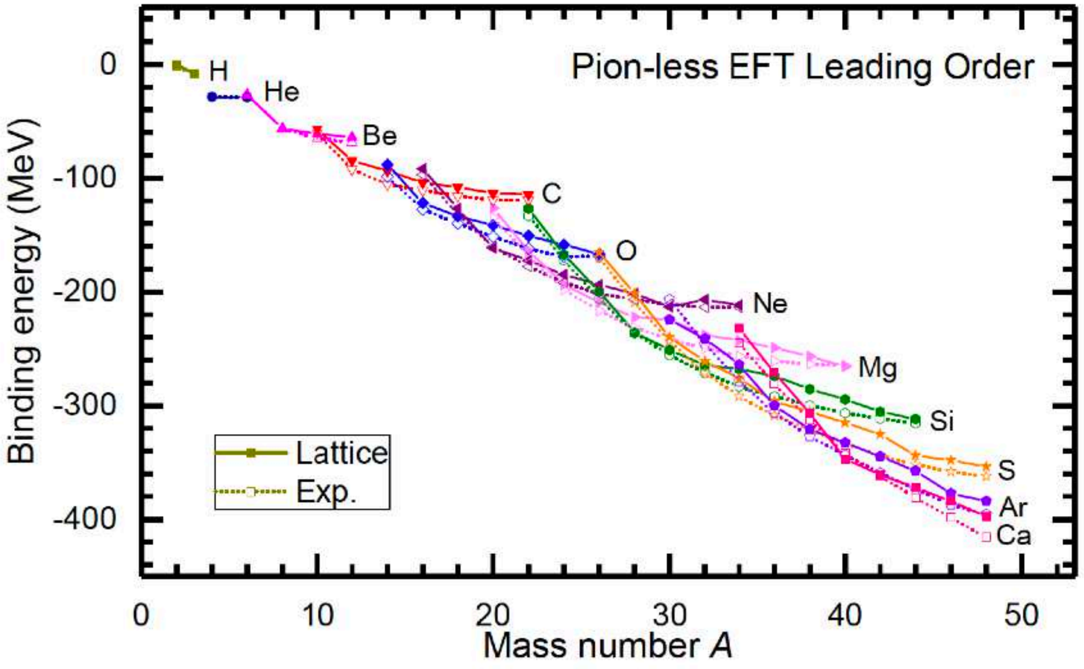
- Discretized chiral EFT
- Lattice spacing $a \sim 1$ fm
- Lattice imposes a momentum cutoff $\Lambda = \pi\hbar/a \sim 600$ MeV
- Exact method, polynomial scaling ($\sim A^2$)



Lattice adapted for nucleus

How many free parameters are essential for a proper nuclear force?

Answer: 4, Strength, Range, Three-body, Locality



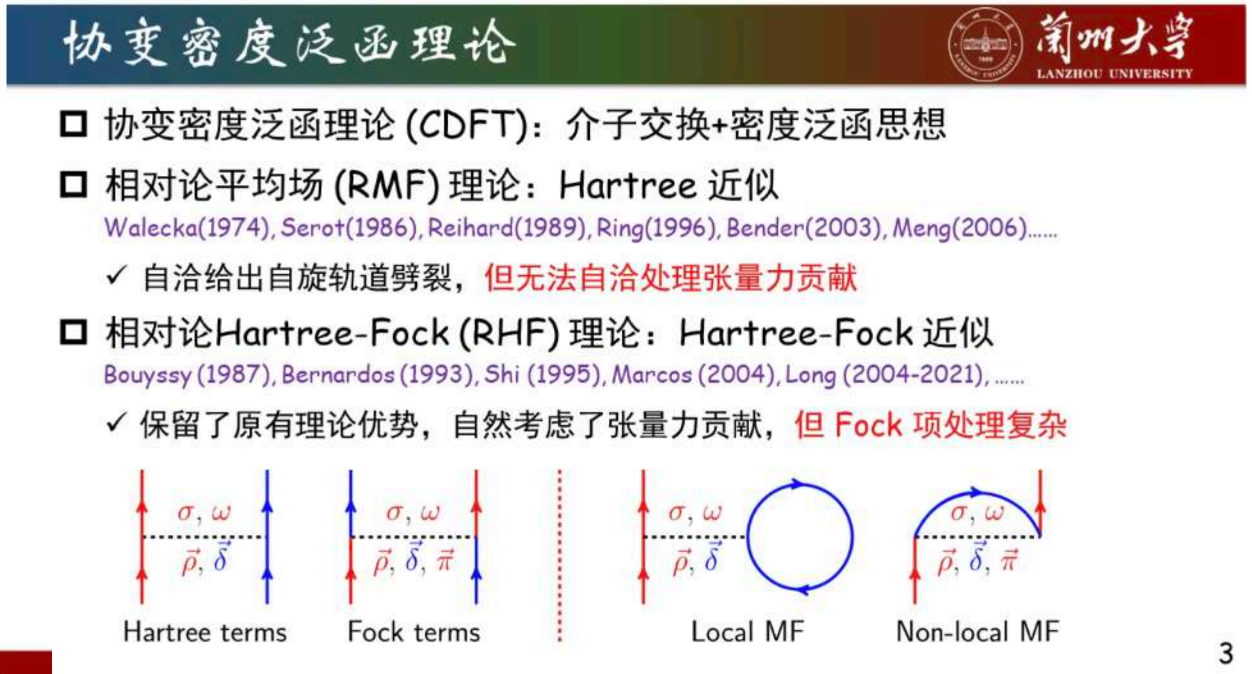
B.L., Ning Li, Elhatisari, Lee, Epelbaum, Meißner, PLB 797, 134863 (2019)

- 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

兰州大学 LANZHOU UNIVERSITY

□ 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

3

轴对称形变的RHF理论发展

兰州大学 LANZHOU UNIVERSITY

RHF

□ 柱坐标空间

传播子展开项积分收敛缓慢

Xiang, Doctor theis

□ 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)

□ 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)

RMF

□ 柱坐标空间

Lee (1986) , Furnstahl (1988) , Zhou (2000)

□ 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) …

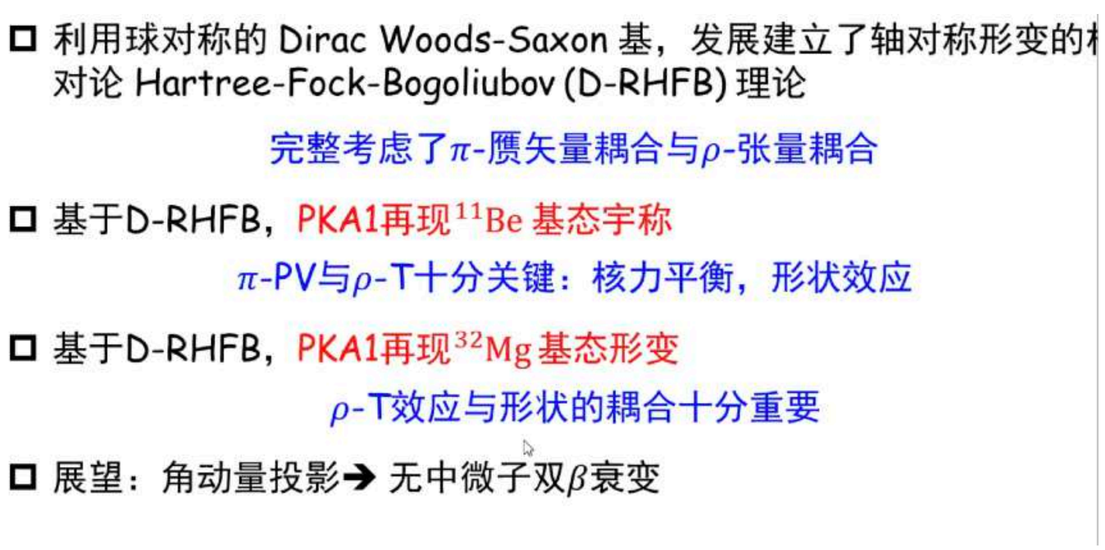
□ Dirac Woods-Saxon (DWS) 基

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
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

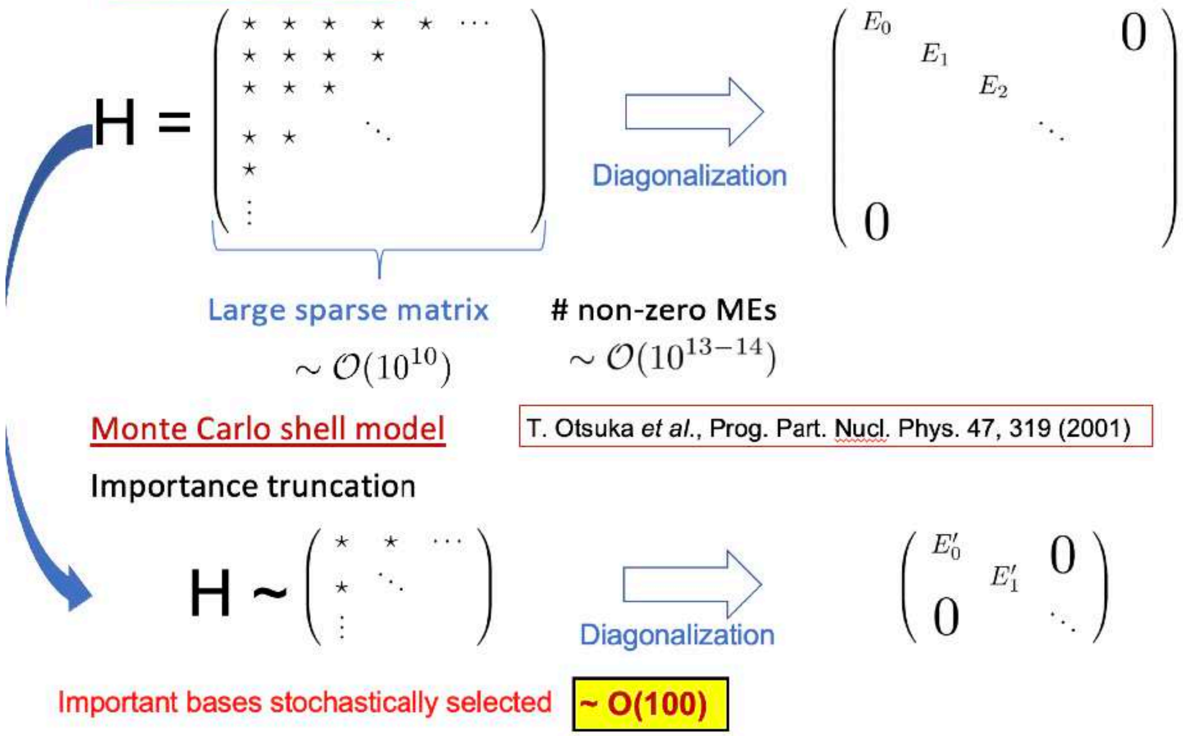
□ 展望：角动量投影➔ 无中微子双β衰变

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）

Dimension of H matrix for MCSM



Standard shell model

$H = \begin{pmatrix} \star & \star & \star & \star & \star & \cdots \\ \star & \star & \star & \star & & \\ \star & \star & \star & & & \\ \star & \star & & \ddots & & \\ \star & & & & & \\ \vdots & & & & & \end{pmatrix} \xrightarrow{\text{Diagonalization}} \begin{pmatrix} E_0 & & & 0 \\ & E_1 & & \\ & & E_2 & \\ 0 & & & \ddots \end{pmatrix}$

Large sparse matrix $\sim \mathcal{O}(10^{10})$

non-zero MEs $\sim \mathcal{O}(10^{13-14})$

T. Otsuka *et al.*, Prog. Part. Nucl. Phys. 47, 319 (2001)

Monte Carlo shell model

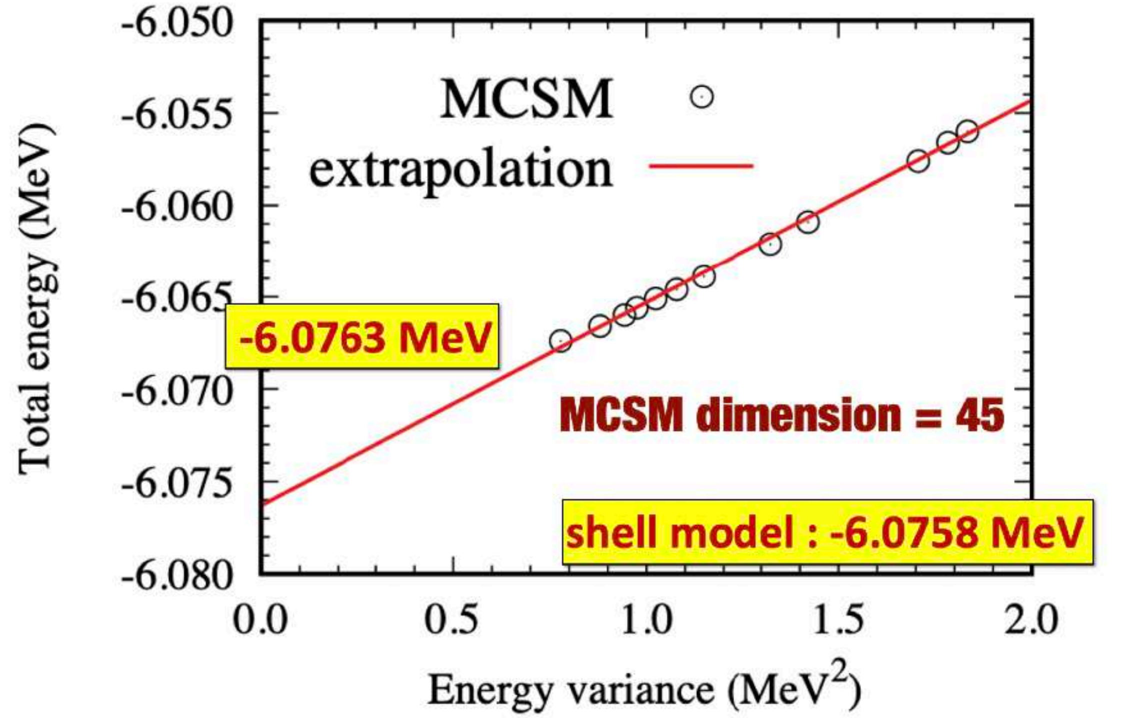
Importance truncation

$H \sim \begin{pmatrix} \star & \star & \cdots \\ \star & \ddots & \\ \vdots & & \end{pmatrix} \xrightarrow{\text{Diagonalization}} \begin{pmatrix} E'_0 & & 0 \\ & E'_1 & \\ 0 & & \ddots \end{pmatrix}$

Important bases stochastically selected **~ O(100)**

MCSM extrapolation: ^{3}H

Model space: e_{max}=3 (4 major shells) **interaction: V_{UCOM}(N^3LO)**



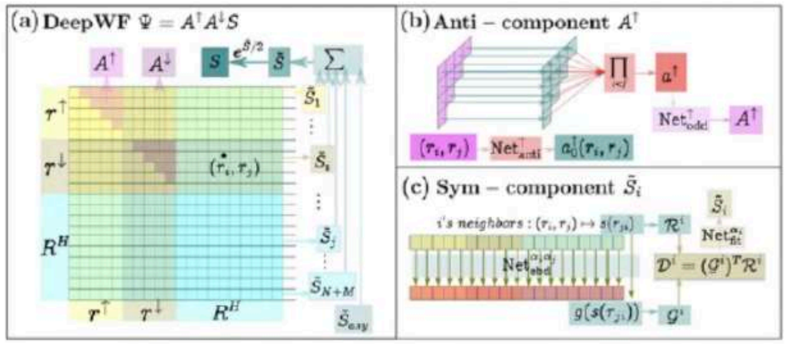
Summary

- **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



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

$$a^{\uparrow}\left(\boldsymbol{r}^{\uparrow}\right) = \prod_{1\le i<j\le N_{\uparrow}} a_0^{\uparrow}\left(\boldsymbol{r}_i,\boldsymbol{r}_j\right)$$

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

$$a_0^{\uparrow}\left(\boldsymbol{r}_i,\boldsymbol{r}_j\right) = \mathrm{Net}^{\uparrow}_{\mathrm{anti}}\left(\boldsymbol{r}_i,\boldsymbol{r}_j,|r_{ji}|\right) - \mathrm{Net}^{\uparrow}_{\mathrm{anti}}\left(\boldsymbol{r}_j,\boldsymbol{r}_i,|r_{ji}|\right)$$

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

Summary

- ▸ **机器学习 (庞龙刚)**

Nuclear properties
+
Transition operators

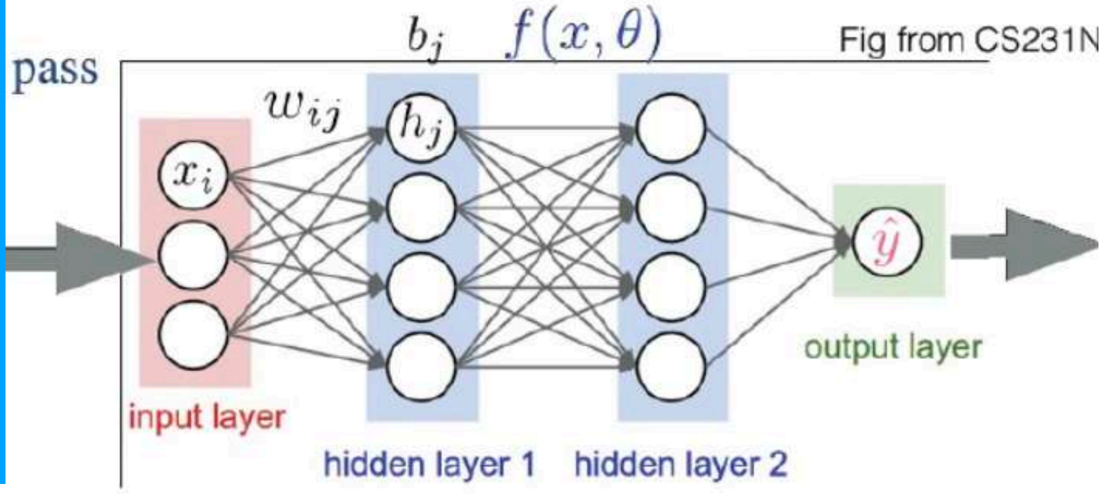
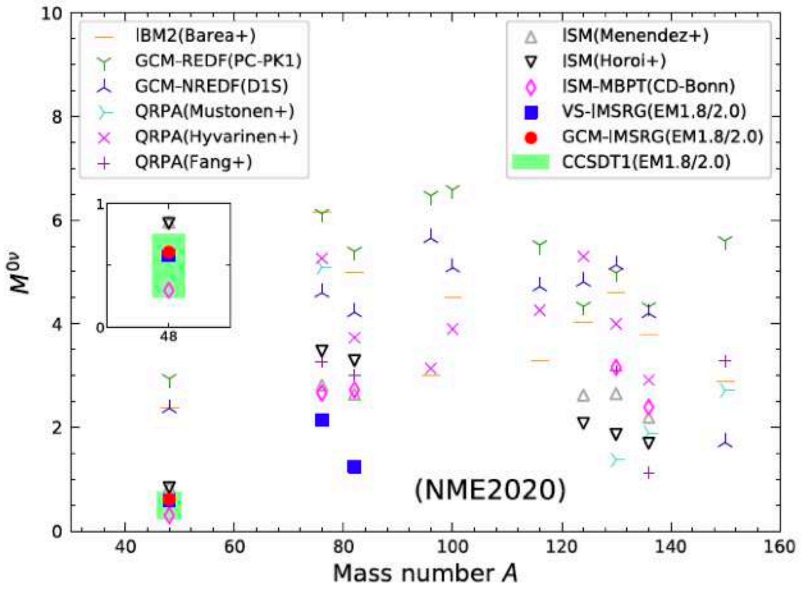
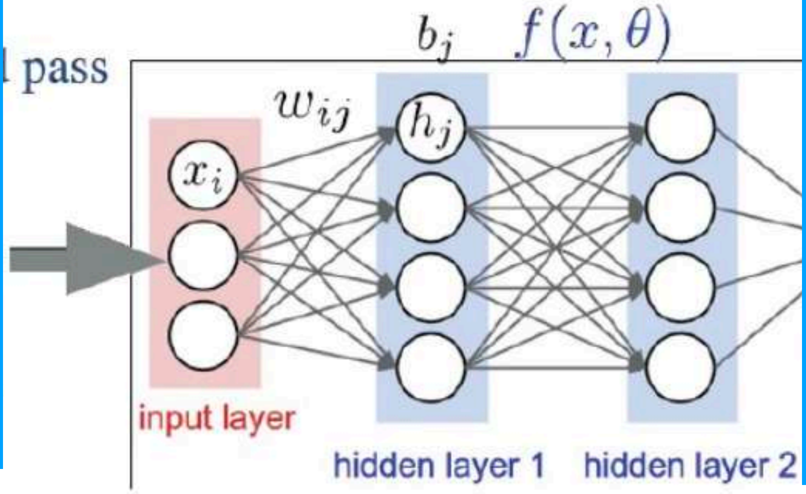


Fig from CS231N

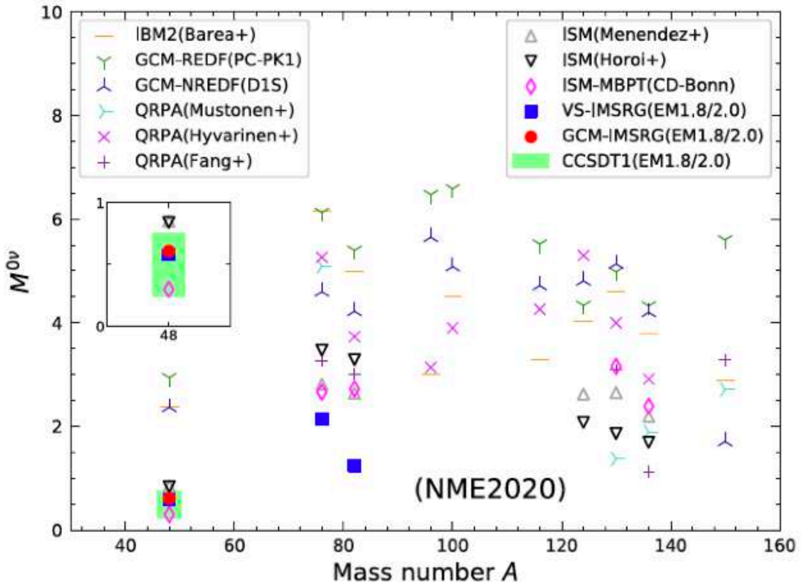


(N,Z,H)



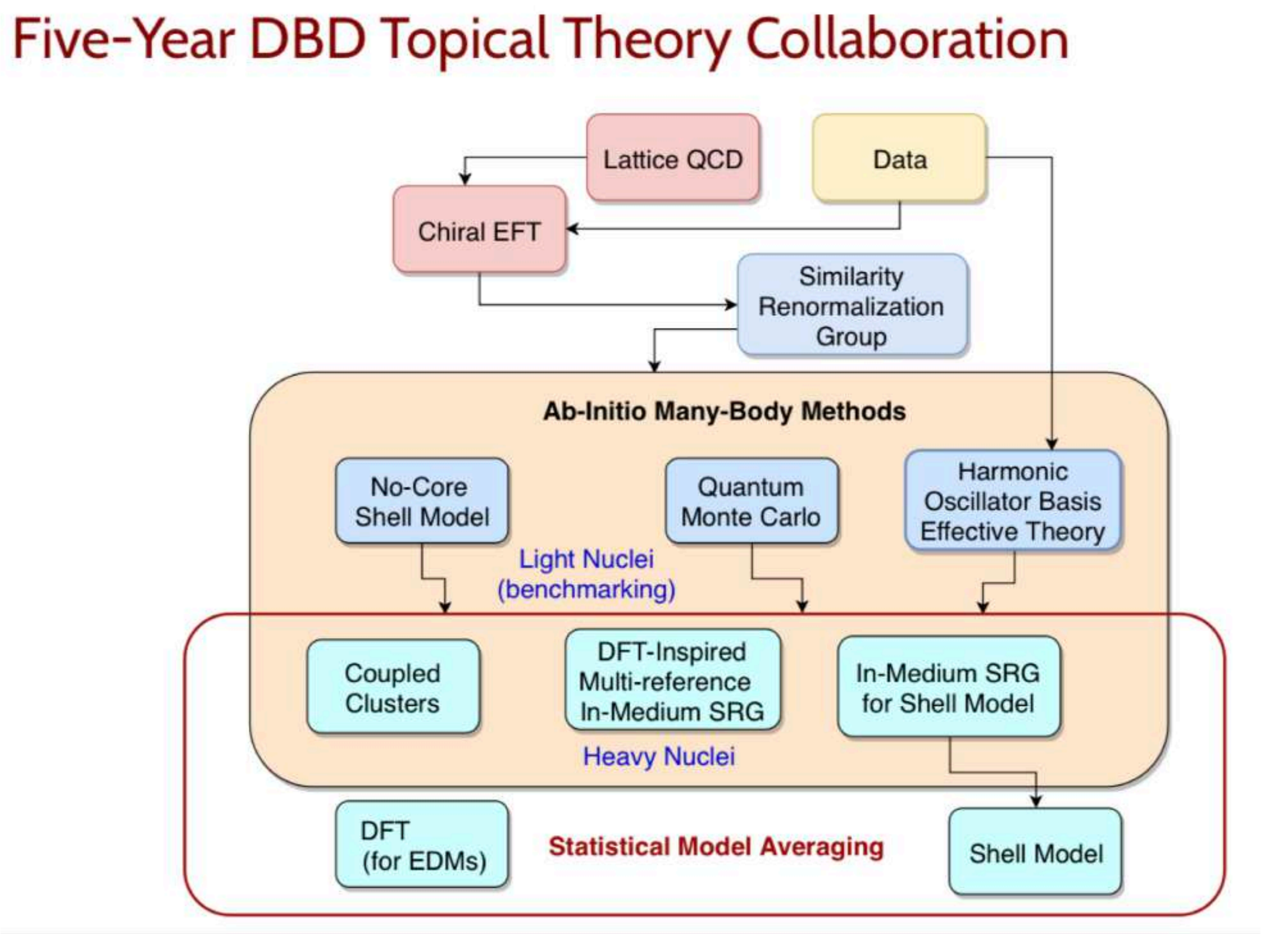
Ground state w.f.s of many-body systems

NLDBD operator



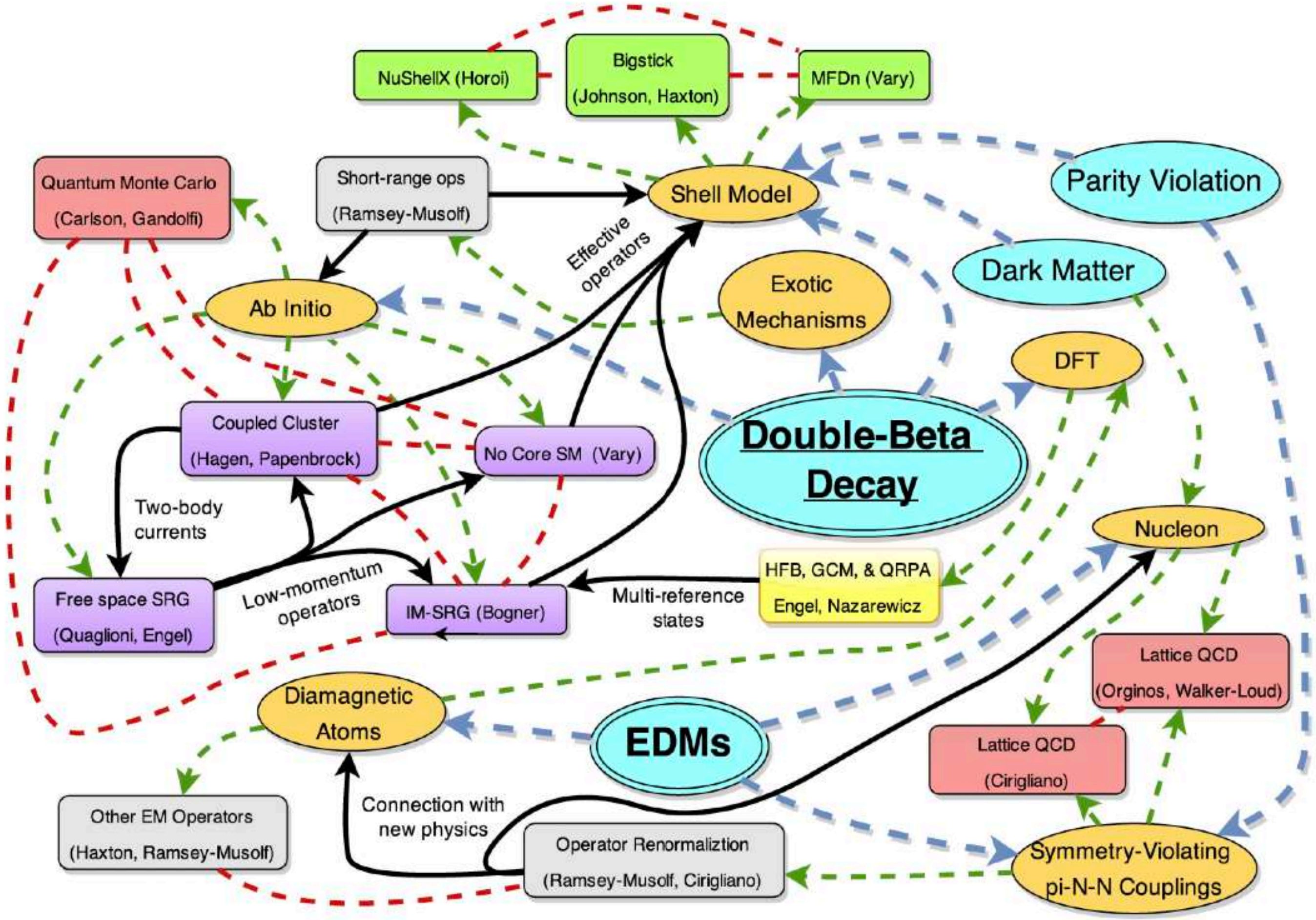
An introduction to US DBD Topic Collaboration

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



Five-Year DBD Topical Theory Collaboration

Lattice QCD
Data
Chiral EFT
Similarity Renormalization Group
Ab-Initio Many-Body Methods
No-Core Shell Model
Quantum Monte Carlo
Harmonic Oscillator Basis Effective Theory
Light Nuclei (benchmarking)
Coupled Clusters
DFT-Inspired Multi-reference In-Medium SRG
In-Medium SRG for Shell Model
Heavy Nuclei
DFT (for EDMs)
Statistical Model Averaging
Shell Model



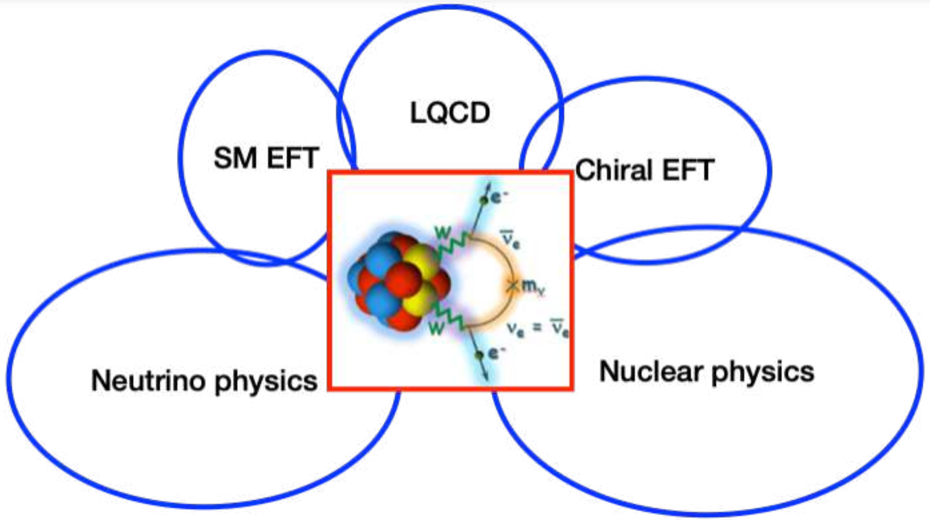
NuShellX (Horoi)
Bigstick (Johnson, Haxton)
MFDn (Vary)
Quantum Monte Carlo (Carlson, Gandolfi)
Short-range ops (Ramsey-Musolf)
Shell Model
Parity Violation
Effective operators
Ab Initio
Exotic Mechanisms
Dark Matter
DFT
Coupled Cluster (Hagen, Papenbrock)
No Core SM (Vary)
Double-Beta Decay
Two-body currents
Nucleon
Free space SRG (Quaglioni, Engel)
Low-momentum operators
IM-SRG (Bogner)
Multi-reference states
HFB, GCM, & QRPA Engel, Nazarewicz
Lattice QCD (Orginos, Walker-Loud)
Diamagnetic Atoms
EDMs
Lattice QCD (Cirigliano)
Other EM Operators (Haxton, Ramsey-Musolf)
Connection with new physics
Operator Renormaliztion (Ramsey-Musolf, Cirigliano)
Symmetry-Violating pi-N-N Couplings

From Jon Engel

U.S. DEPARTMENT OF ENERGY | Office of Science

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”

“无中微子双贝塔衰变”研讨会（系列）

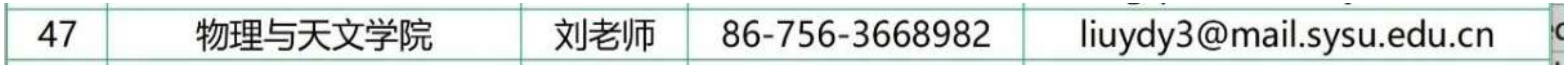
下次研讨会

- 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

论坛时间
2021年7月2-4日

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，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

肖翔 焦长峰 尧江明 李宁
安振东
2021 年 5 月 珠海