Neutrinoless ββ Decay Nuclear Matrix Elements from an Approximation to IMSRG(3)

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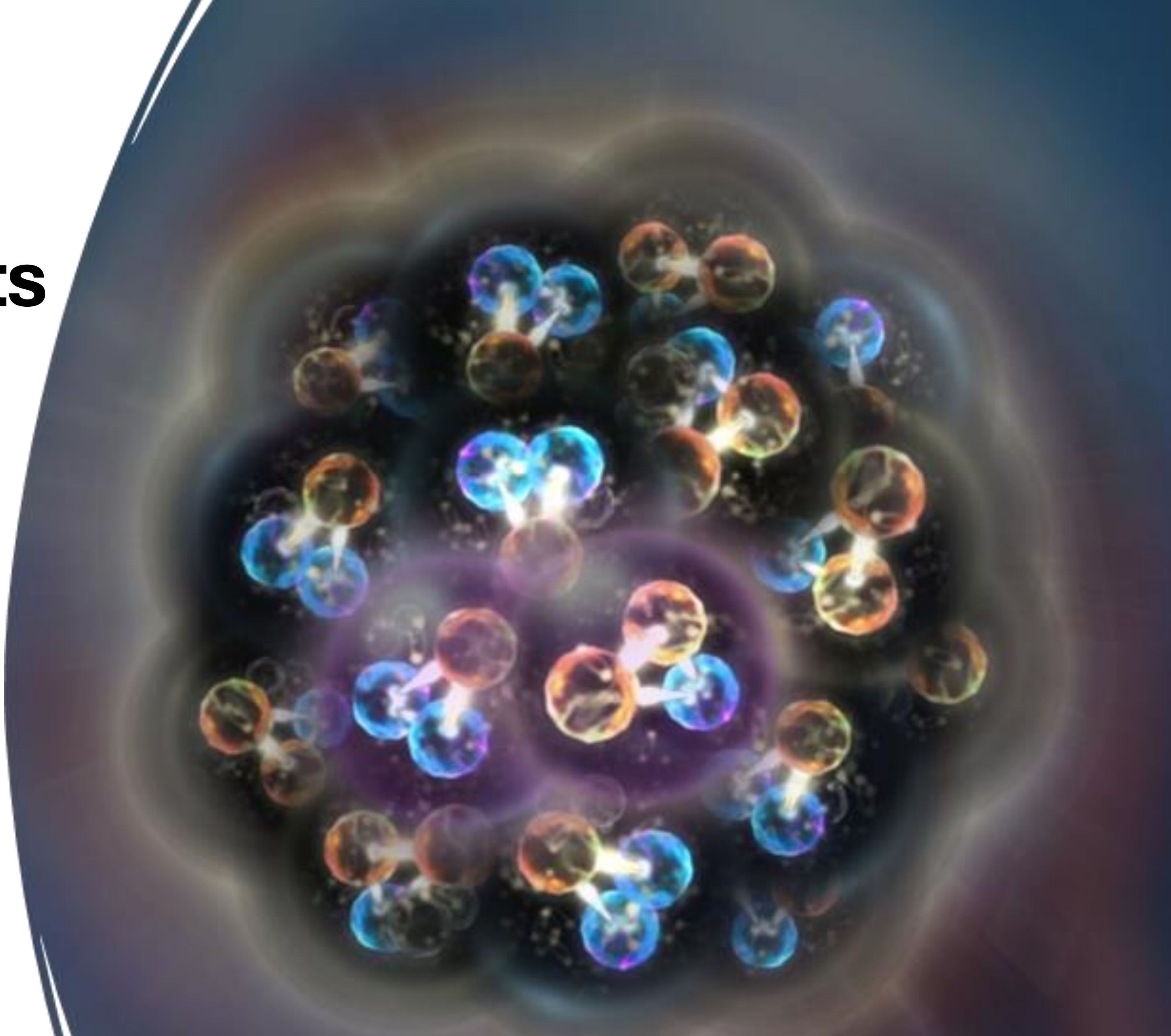
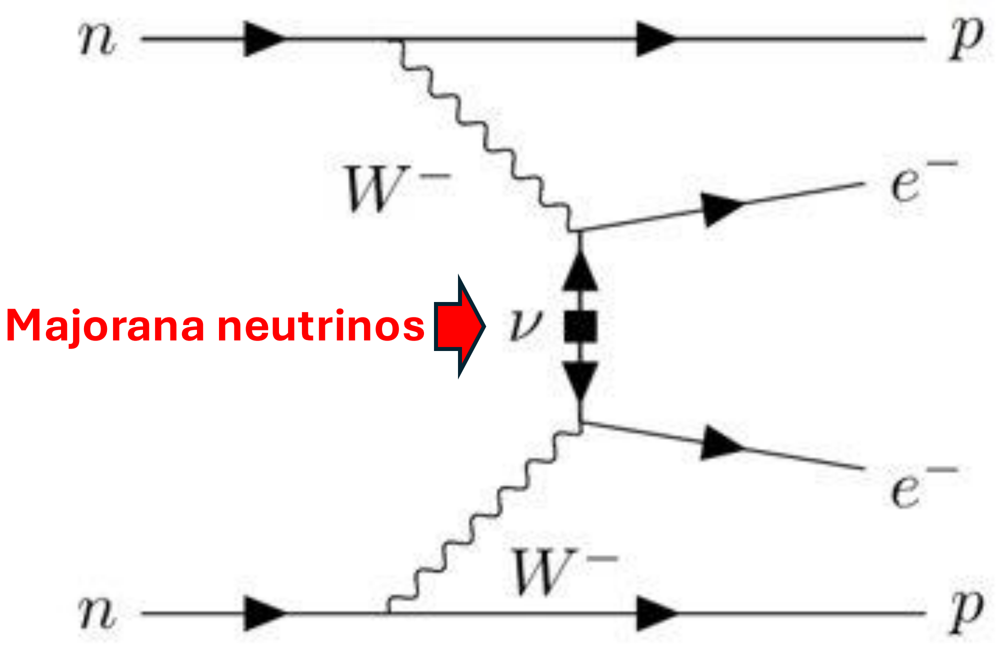


Collaborators: Bingcheng He, Ragnar Stroberg, Antoine Belley, Jason Holt

Neutrinonless double-beta decay

<u>0vββ probes:</u>

- Majorana/Dirac nature of neutrinos
- Lepton-number violation
    - ➢ Baryon asymmetry of universe
- Absolute neutrino mass scale
- Exotic BSM mechanisms
    - ➢ Heavy neutrinos? Seesaw mechanisms? Sterile neutrinos?

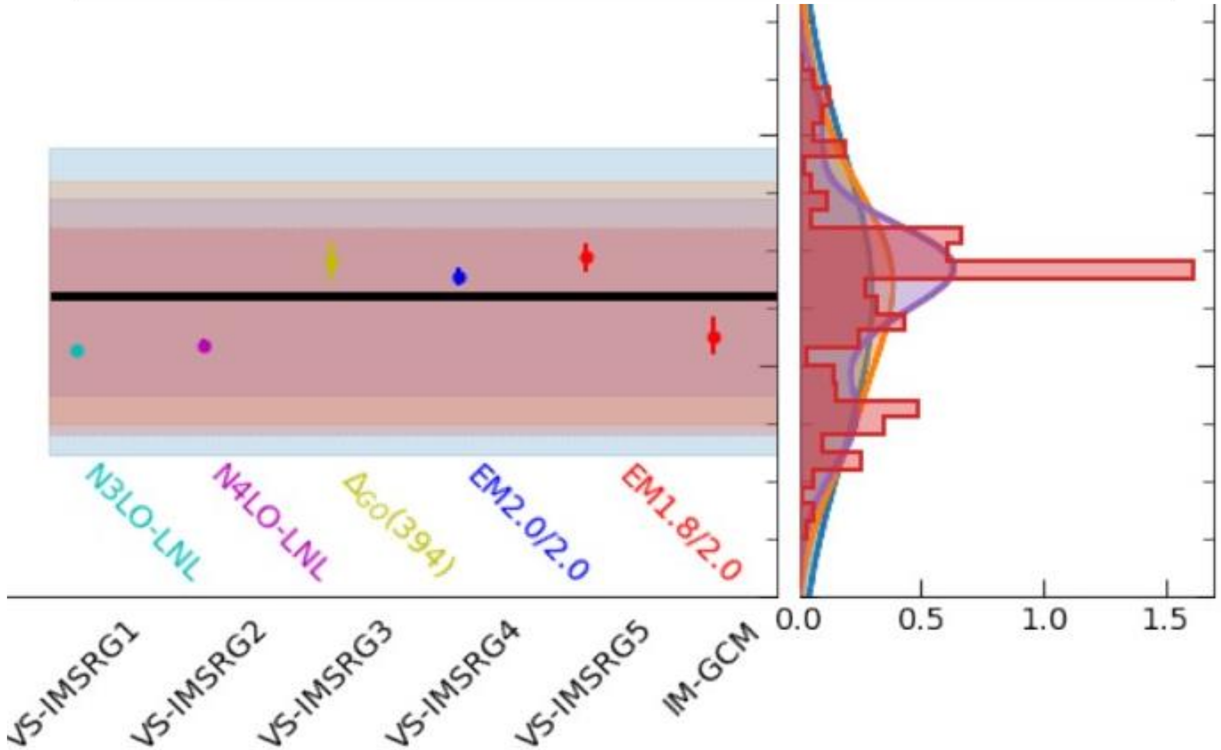


$$\left[T_{1/2}^{0\nu}\right]_{\text{light}}^{-1} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left| \frac{\langle m_{\beta\beta} \rangle}{m_e} \right|^2$$

Many-body uncertainty in nuclear matrix elements

TABLE I. **The recommended value for the total NME of $0\nu\beta\beta$ decay in ^{76}Ge, together with the uncertainties from different sources.**

$M^{0\nu}$	ϵ_{LEC}	$\epsilon_{\chi EFT}$	ϵ_{MBT}	ϵ_{OP}	ϵ_{EM}
$2.60^{+1.28}_{-1.36}$	0.75	0.3	0.88	0.47	<0.06



A. Belley et al., PRL 132 (2024)

(Using IMSRG(2))

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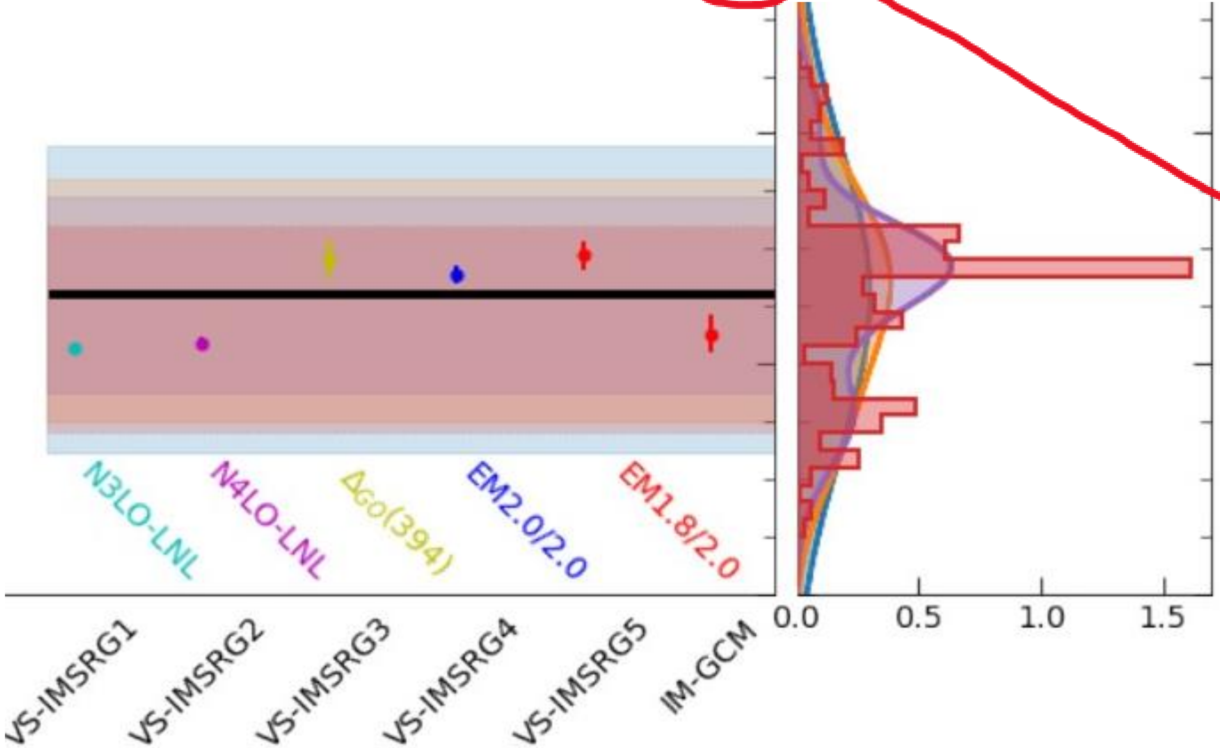
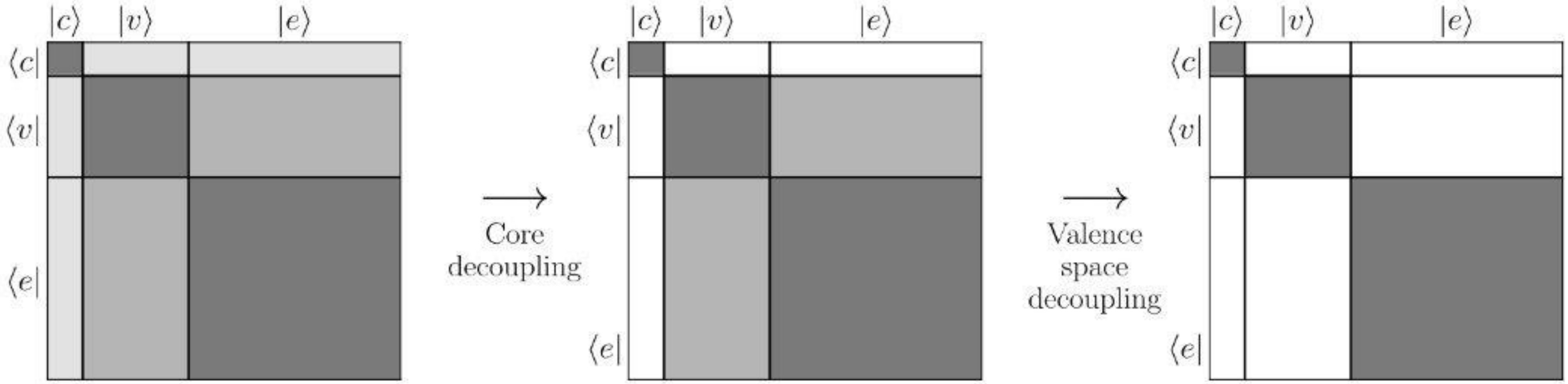


A. Belley et al., PRL 132 (2024)

Many-body uncertainty is quite large!

(Using IMSRG(2))

Many-body error in the IMSRG



$$H(s) = e^{\Omega(s)} H(0) e^{-\Omega(s)} = \sum_{k=0}^{\infty} \frac{1}{k!} [\Omega(s), H(0)]^{(k)} = H + [\Omega, H] + \frac{1}{2}[\Omega, [\Omega, H]] + \cdots$$

During SRG flow, nested commutators generate **higher-body** operators

Higher-body operator suppression

Apply Wick's theorem:

$$\langle\Psi|\, a^\dagger a^\dagger a^\dagger aaa \,|\Psi\rangle \sim A^3 + A^2 \langle\Psi|{:}a^\dagger a{:}|\Psi\rangle + A \langle\Psi|{:}a^\dagger a^\dagger aa{:}|\Psi\rangle + \langle\Psi|{:}a^\dagger a^\dagger a^\dagger aaa{:}|\Psi\rangle$$

$$\sim A^3 \left(1 + \frac{N_{\mathrm{q}}}{A} + \frac{N_{\mathrm{q}}^2}{A^2} + \frac{N_{\mathrm{q}}^3}{A^3}\right)$$

Higher-body operator suppression

Apply Wick's theorem:

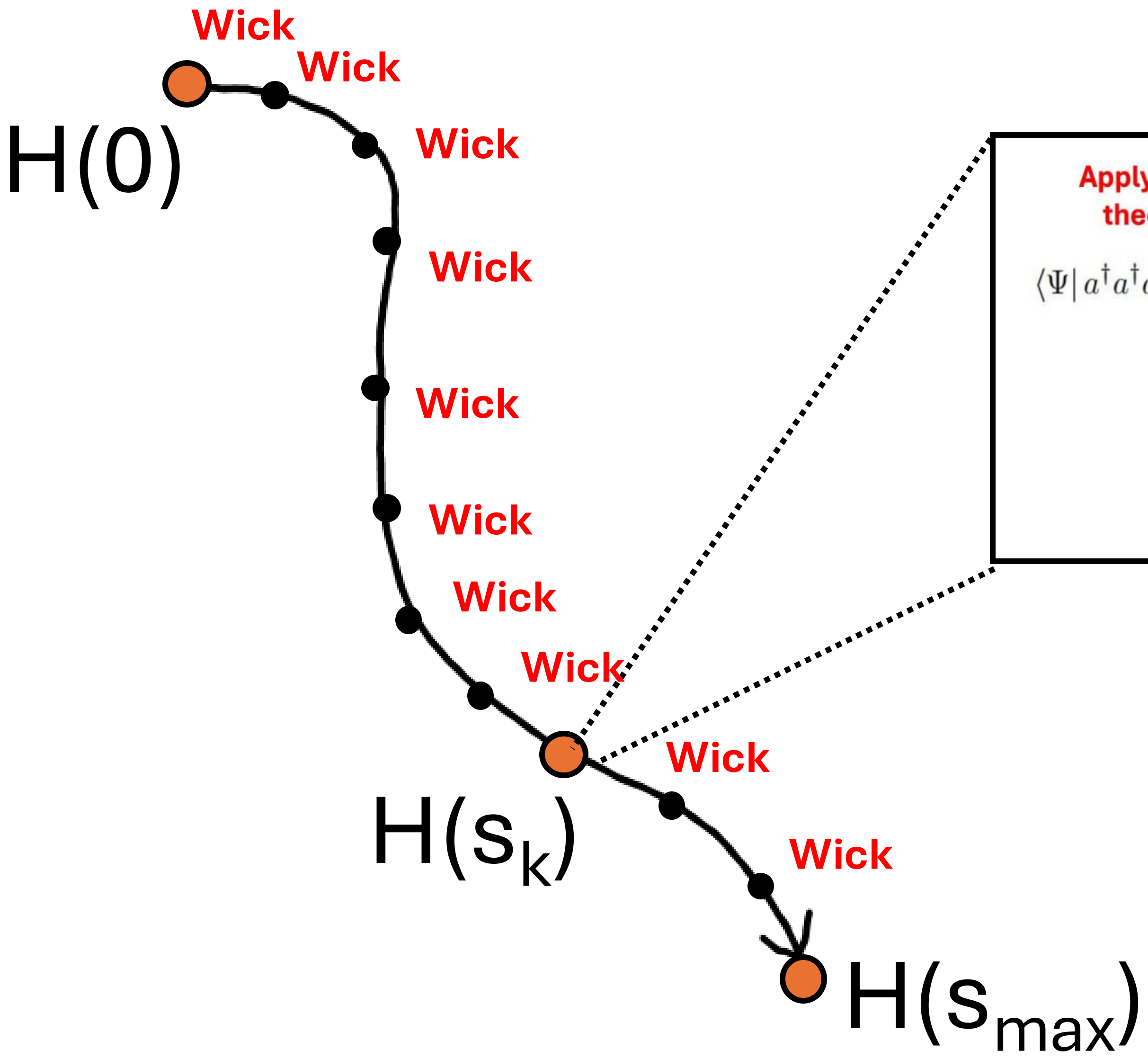
0-body, 1-body, 2-body, 3-body

$$\langle\Psi|\, a^\dagger a^\dagger a^\dagger aaa\,|\Psi\rangle \sim A^3 + A^2 \langle\Psi|:a^\dagger a:|\Psi\rangle + A \langle\Psi|:a^\dagger a^\dagger aa:|\Psi\rangle + \langle\Psi|:a^\dagger a^\dagger a^\dagger aaa:|\Psi\rangle$$

$$\sim A^3 \left(1 + \frac{N_{\mathrm{q}}}{A} + \frac{N_{\mathrm{q}}^2}{A^2} + \frac{N_{\mathrm{q}}^3}{A^3}\right)$$

Higher-body contributions suppressed by powers of N_q/A

But we apply Wick's theorem many times....



Apply Wick's theorem:

0-body | 1-body | 2-body | 3-body

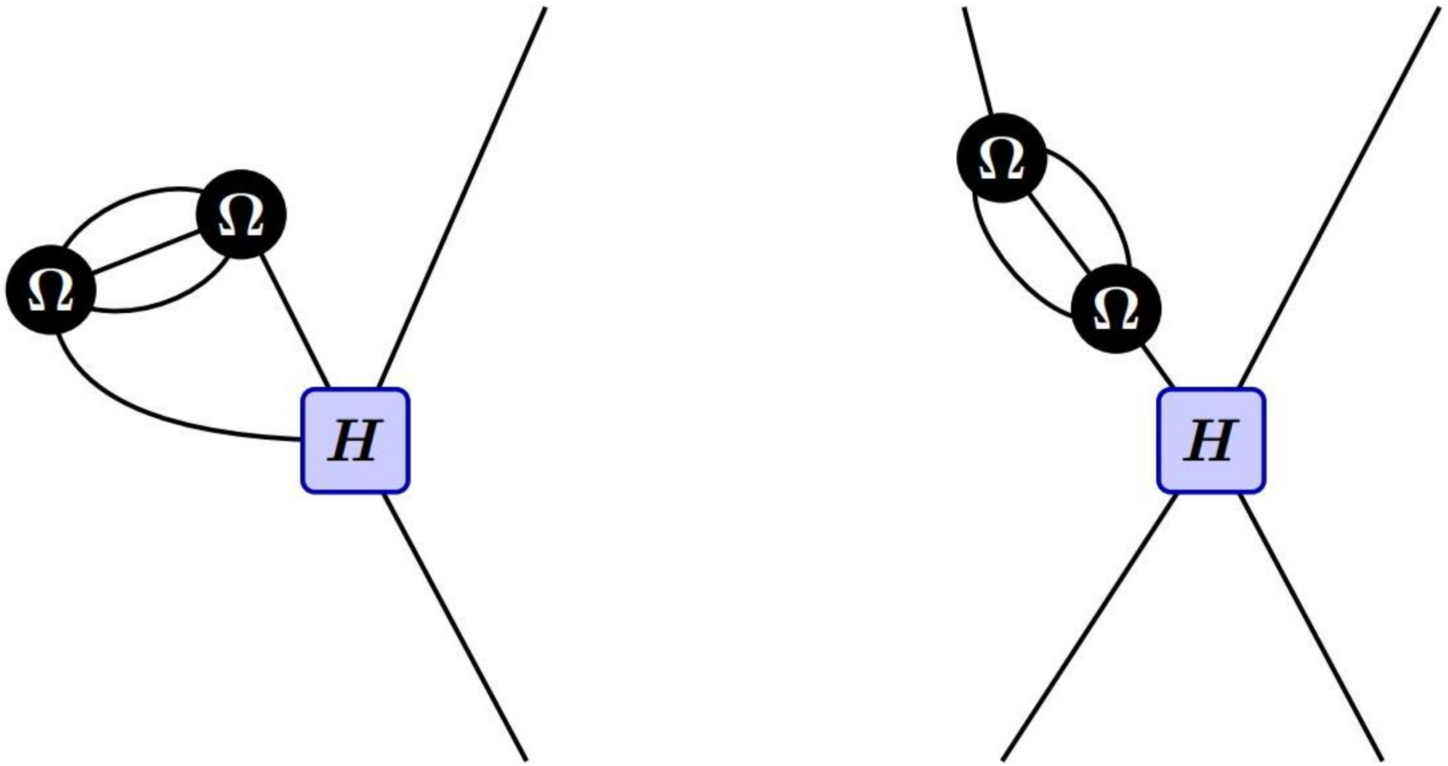
$$\langle\Psi|\, a^\dagger a^\dagger a^\dagger aaa \,|\Psi\rangle \sim A^3 + A^2 \langle\Psi|:a^\dagger a:|\Psi\rangle + A \langle\Psi|:a^\dagger a^\dagger aa:|\Psi\rangle + \langle\Psi|:a^\dagger a^\dagger a^\dagger aaa:|\Psi\rangle$$

$$\sim A^3 \left(1 + \frac{N_{\mathrm{sp}}}{A} + \frac{N_{\mathrm{sp}}^2}{A^2} + \frac{N_{\mathrm{sp}}^3}{A^3}\right)$$

Higher-body contributions suppressed by powers of N_{sp}/A

IMSRG(3f2)

- Takes into account induced 3-body operators that contract back to 1- and 2-body operators during the flow.
- Commutators are factorized to get ~IMSRG(2) scaling



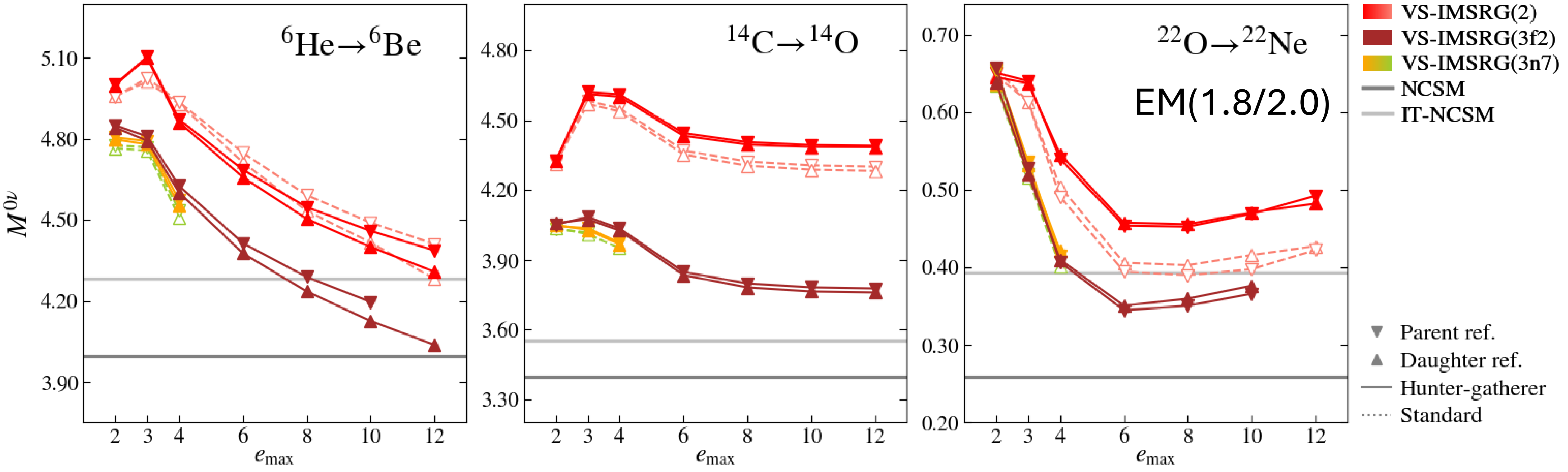
(b) $[\Omega_{2b}, [\Omega_{2b}, H_{2b}]_{3b}]_{1b}$ (c) $[\Omega_{2b}, [\Omega_{2b}, H_{2b}]_{3b}]_{2b}$

IMSRG(2) → IMSRG(3f2) → IMSRG(3n7) → IMSRG(3)

→ **Accuracy** →

VS-IMSRG Benchmark in light nuclei

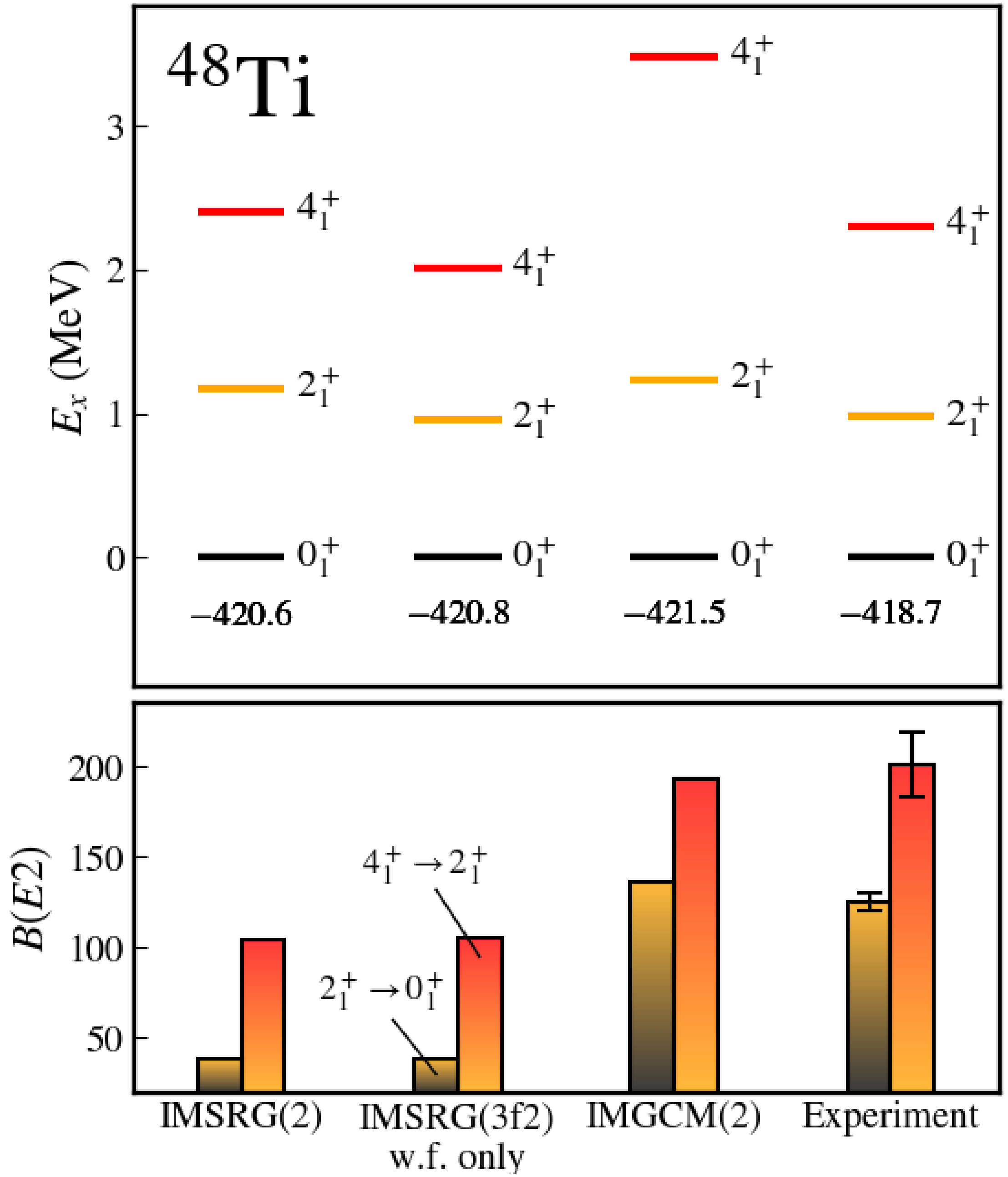
NCSM NMEs from J.M. Yao, A. Belley, et al
Phys. Rev. C 103, 014315 (2021).



Takeaways:

- ✓ IMSRG(3f2) matches IMSRG(3n7).
- ✓ IMSRG(3f2) closer to NCSM.
- ✓ Magnus splitting scheme dependence reduced at IMSRG(3) level

Will the IMSRG(3f2) be enough for $0\nu\beta\beta$?



How do we know we're not in B(E2) territory?

Good spectra

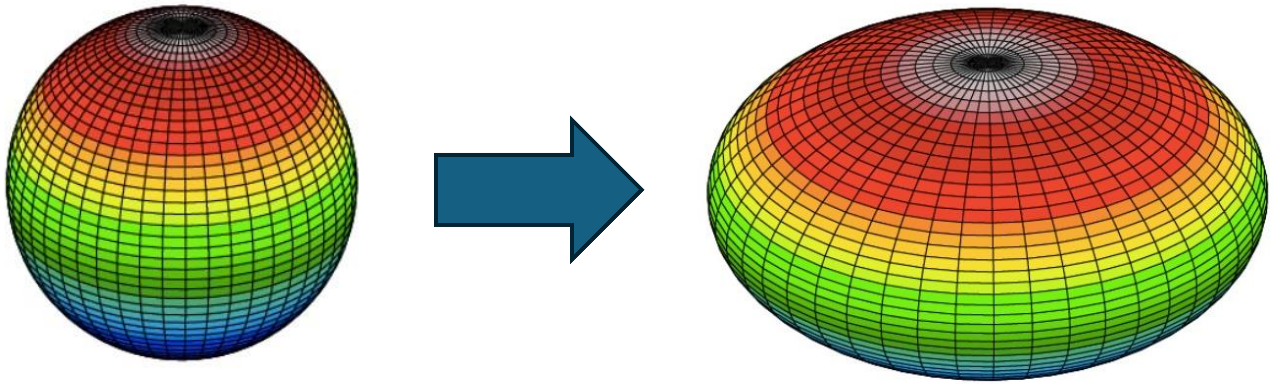
Poor B(E2)s...

Hamiltonian with a quadrupole term

$$H = H_{\text{EM}}^{1.8/2.0} - \chi Q \cdot Q$$

Increasing quadrupole–quadrupole interaction strength χ lowers energy of states with larger intrinsic quadrupole moments, favoring less spherical configurations

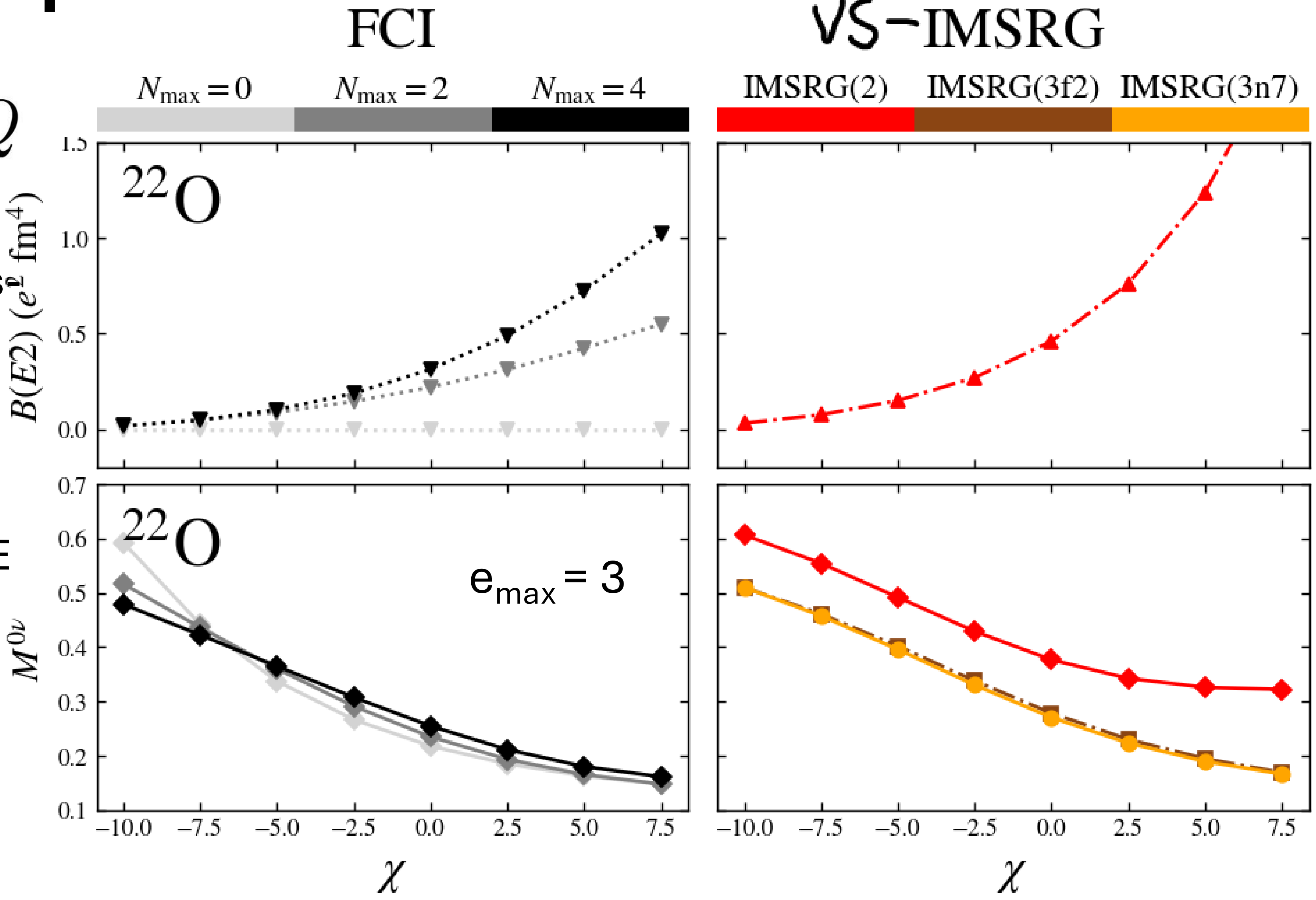
$$Q_{2\mu} = \sum_i e_i r_i^2 Y_{2\mu}(\hat{r}_i)$$



B(E2) vs NME response

$$H = H_{\text{EM}}^{1.8/2.0} - \chi Q \cdot Q$$

- B(E2) requires more cross-shell excitations when deformation is larger, whereas NMEs do not (100% vs. 5% diff).
- IMSRG(3f2) captures NME response well!



Next steps

- Reproduce deformation-sensitivity plot in a deformed nucleus (^{20}Ne) as a final benchmark
- Now with a better understanding of reliability of IMSRG(3f2), calculate NMEs in medium-mass isotopes
- Use results for many-body uncertainty quantification

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