25th European Conference on Few-Body Problems in Physics

Electroweak properties of nuclei in chiral effective field theory

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Collaborators

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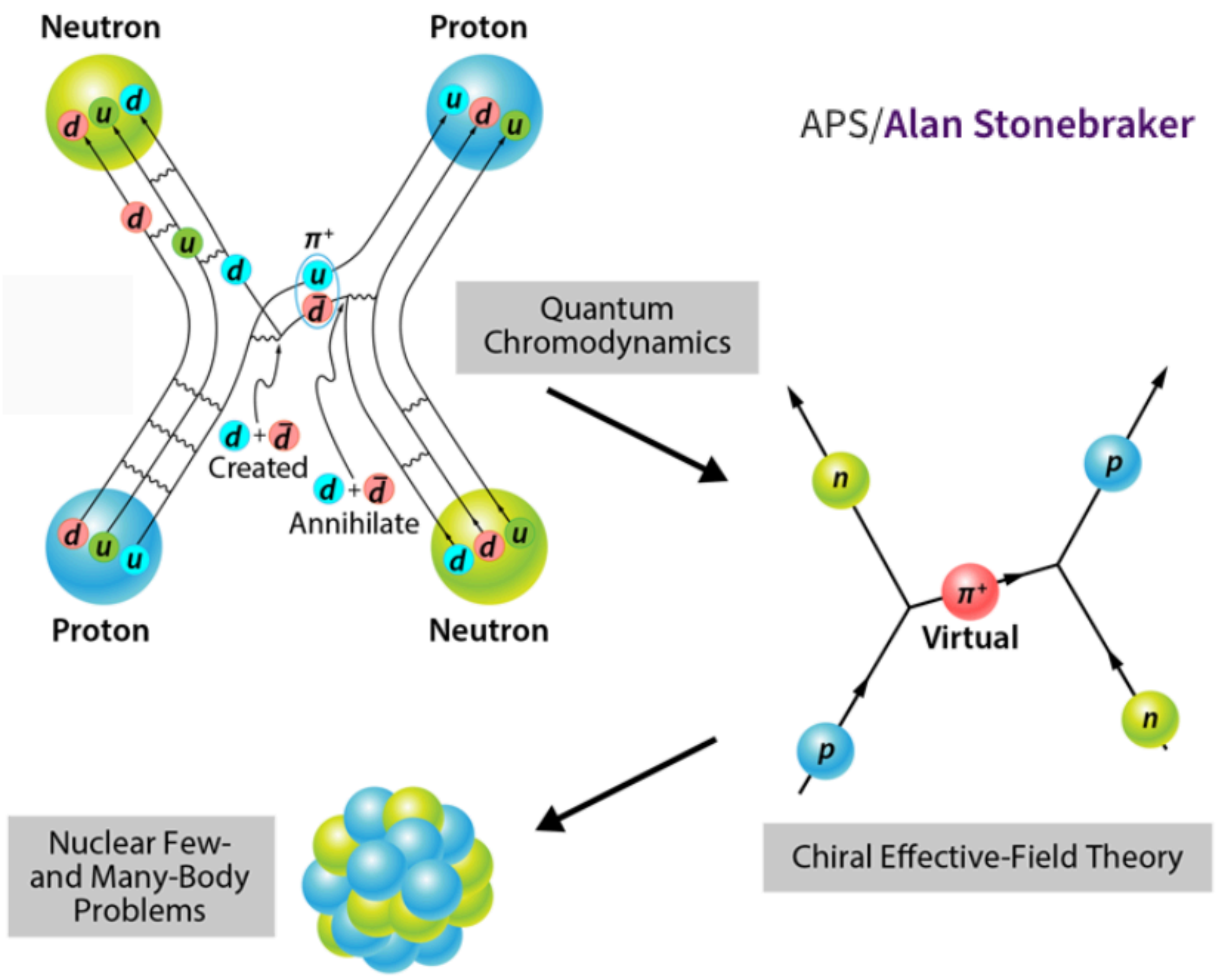
Outline

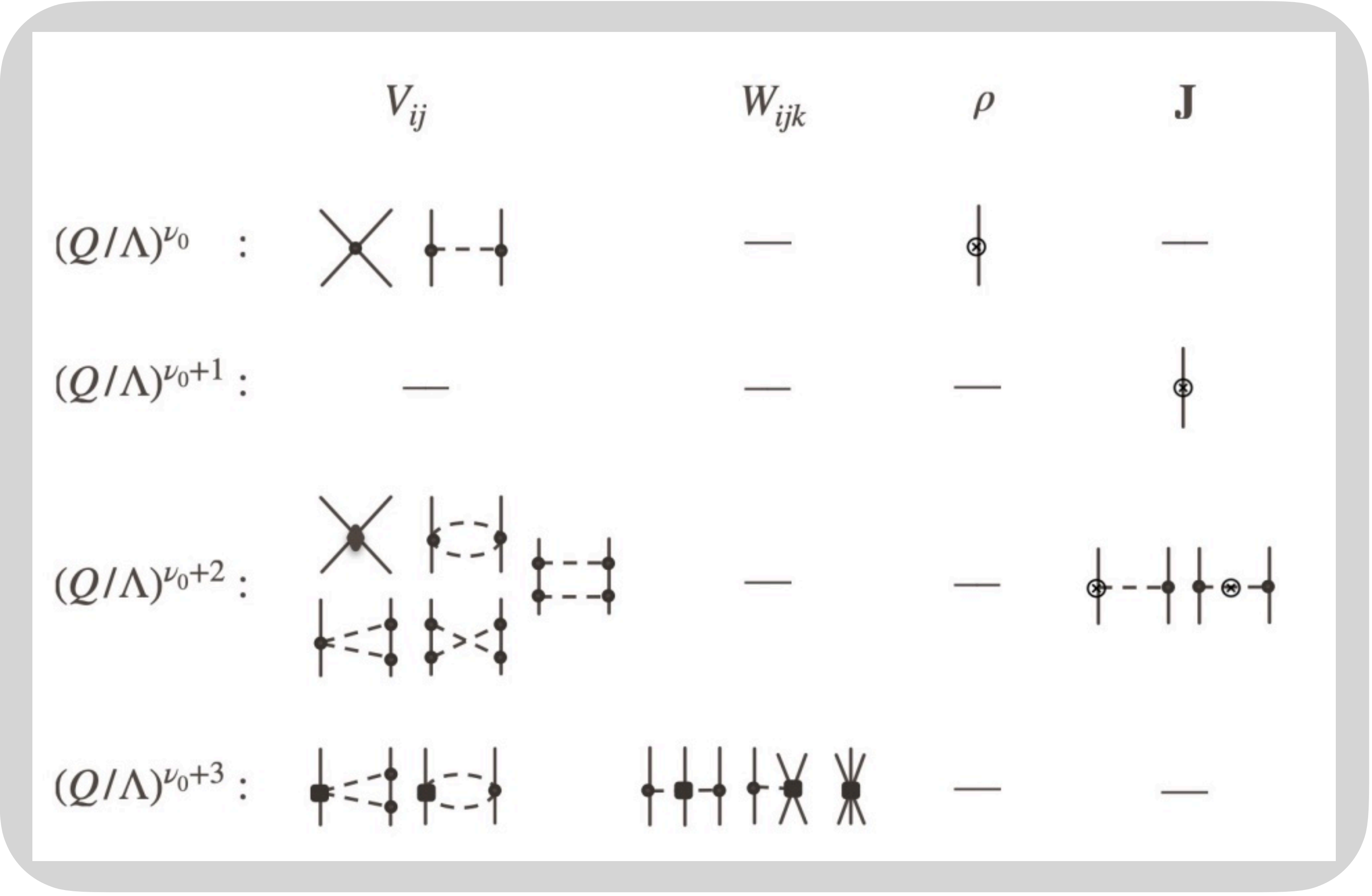
- Chiral effective field theory (χEFT) and EFT truncation errors
- The $np \to d\gamma$ reaction in big-bang nucleosynthesis (BBN)
- The proton-proton fusion reaction and the standard solar model
- Few-body inputs to magnetic dipole excitation of $^{48}\mathrm{Ca}$

Chiral effective field theory (χEFT)

Weinberg, Epelbaum, Krebs, Meissner, van Kolck, Schiavilla, Pastore, Machleidt, Entem, Ekström, Piarulli, Kaplan, Savage, Wise,…

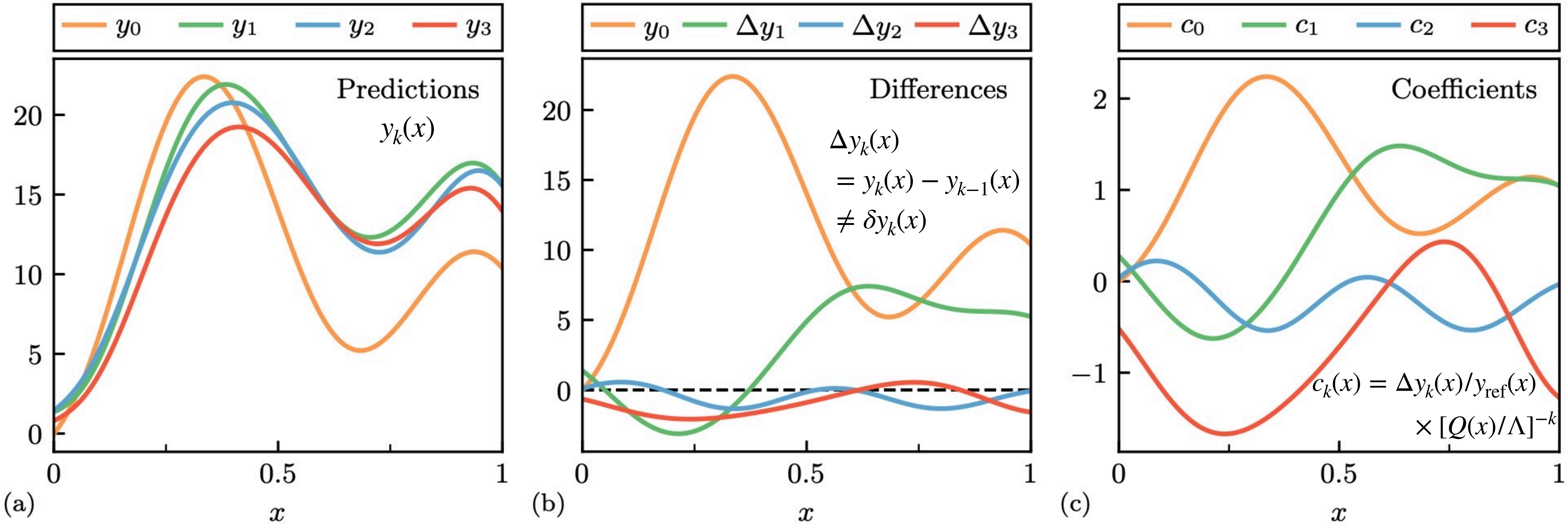
- Quantum Chromodynamics (QCD) is intractable at nuclear energies except for the simplest systems
- Work with nucleons; interactions $(V_{ij}, W_{ijk}\ldots)$ and currents $(\rho, \mathbf{J})$ that couple to external (electroweak, dark…) sources from χEFT
- Order-by-order expansion of Standard Model interactions in powers of Q/Λ
- Valid at low momenta Q below $\Lambda \sim 700\ \mathrm{MeV}$
- Underlying quark-gluon physics shows up as values of low-energy constants, which are fit to data (NN, πN, nuclei, nuclear matter)
- Theory uncertainty from the neglected higher-order terms can be estimated





EFT truncation errors

Melendez et al., Phys. Rev. C ***100*** *(2019) 044001*



- For any observable $y(x)$, we perform order-by-order calculation to obtain $y_0, y_1, \ldots, y_n$.
- Need to estimate the error δy_n from neglecting higher-order terms. Naively, one can expect that $\delta y_n / y \sim (Q/\Lambda)^{n+1}$.
- A better estimate of δy_n is obtained by using the calculated orders $y_0, y_1, \ldots, y_n$ as "data".

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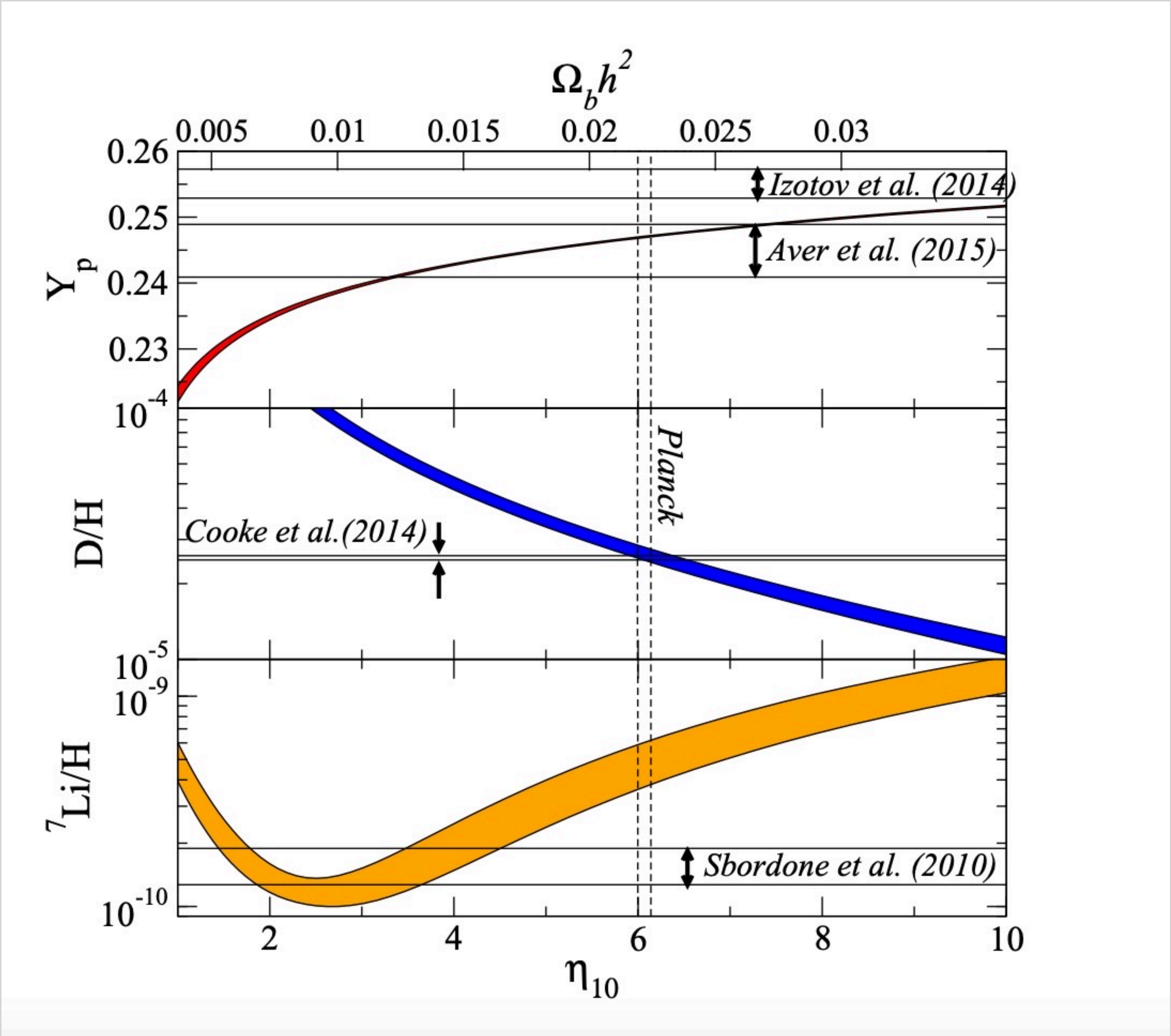
The $np \to d\gamma$ reaction in BBN

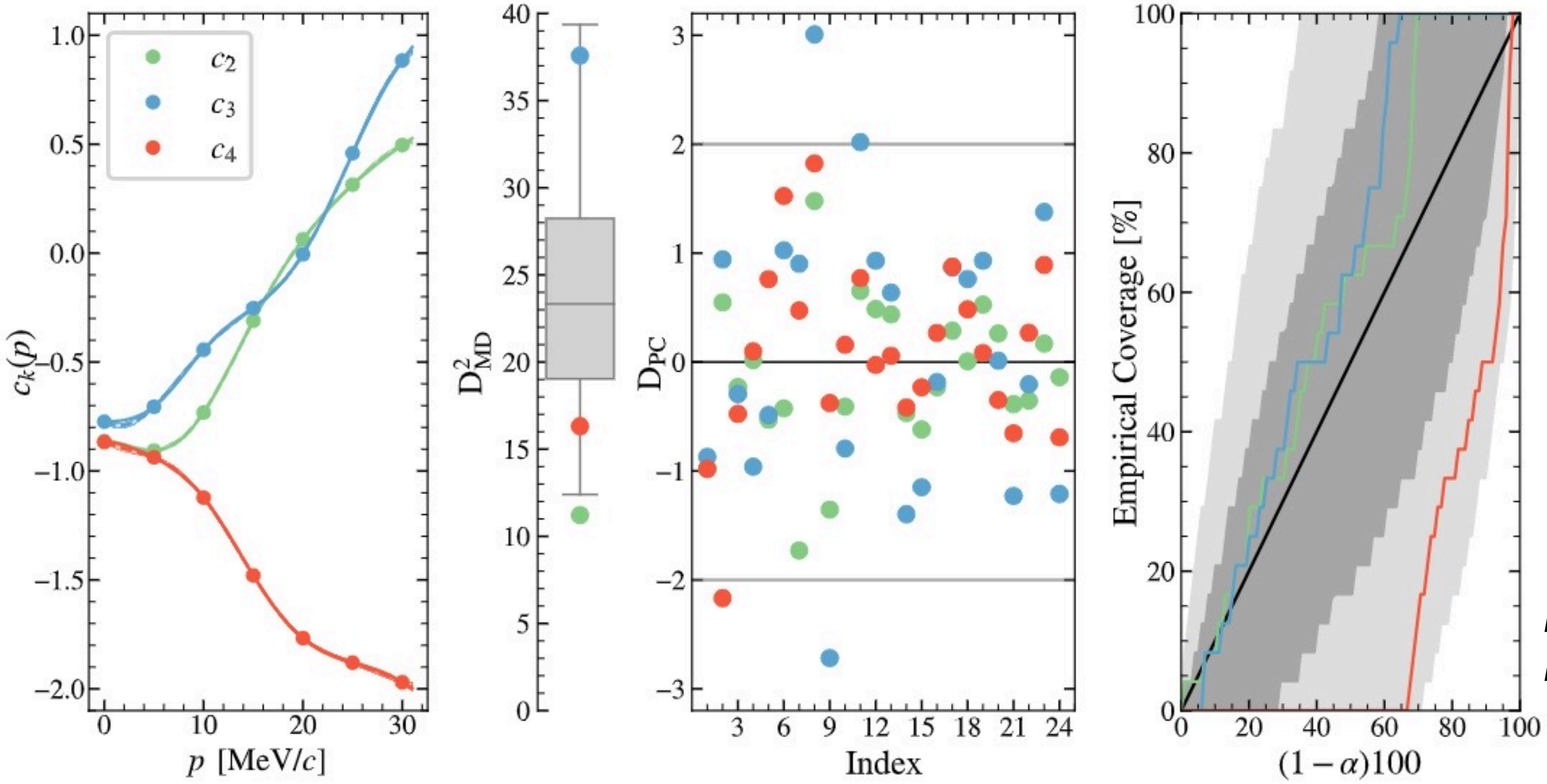
- Agreement between cosmic microwave anisotropies, spectroscopy of metal poor stars, and nuclear reaction rates constrain new physics candidates in cosmology and particle physics
- D/H is the most powerful constraint
- Rates of deuteron-burning reactions are now the dominant uncertainty source for nuclear physics
- Constraints on the production reaction $np \to d\gamma$ are almost entirely from theoretical calculations
- Modern BBN network simulations use Pionless EFT results† as input

†G Rupak, Nucl. Phys. A **678** (2000) 405



Nakamura et al., Int. J. Mod. Phys. E **26** (2017) 17410003

The BUQEYE χEFT error model[†] for $np \to d\gamma$



BA and S Bacca,
Phys. Lett. B ***827*** *(2022) 137011*

- Assume $c_n(p)$ are random draws from a Gaussian Process (GP) $\Leftrightarrow \{c_n(p_i)\}$ follow a multivariate Gaussian distribution $\forall \{p_i\}$.
- Calibrate the GP [*i.e.* mean $\mu(p)$ and covariance $K(p,p')$] by fitting to calculated $c_{0,1,\ldots,n}(p)$ using Bayesian methodology.
- Validate the GP model using statistical diagnostic criteria.
- Use the calibrated GP to obtain a prediction for the truncation error $\delta y_n = y_{\rm ref} \sum_{k=n+1}^{\infty} c_k(p)\,(Q/\Lambda)^k$ [also a GP!].

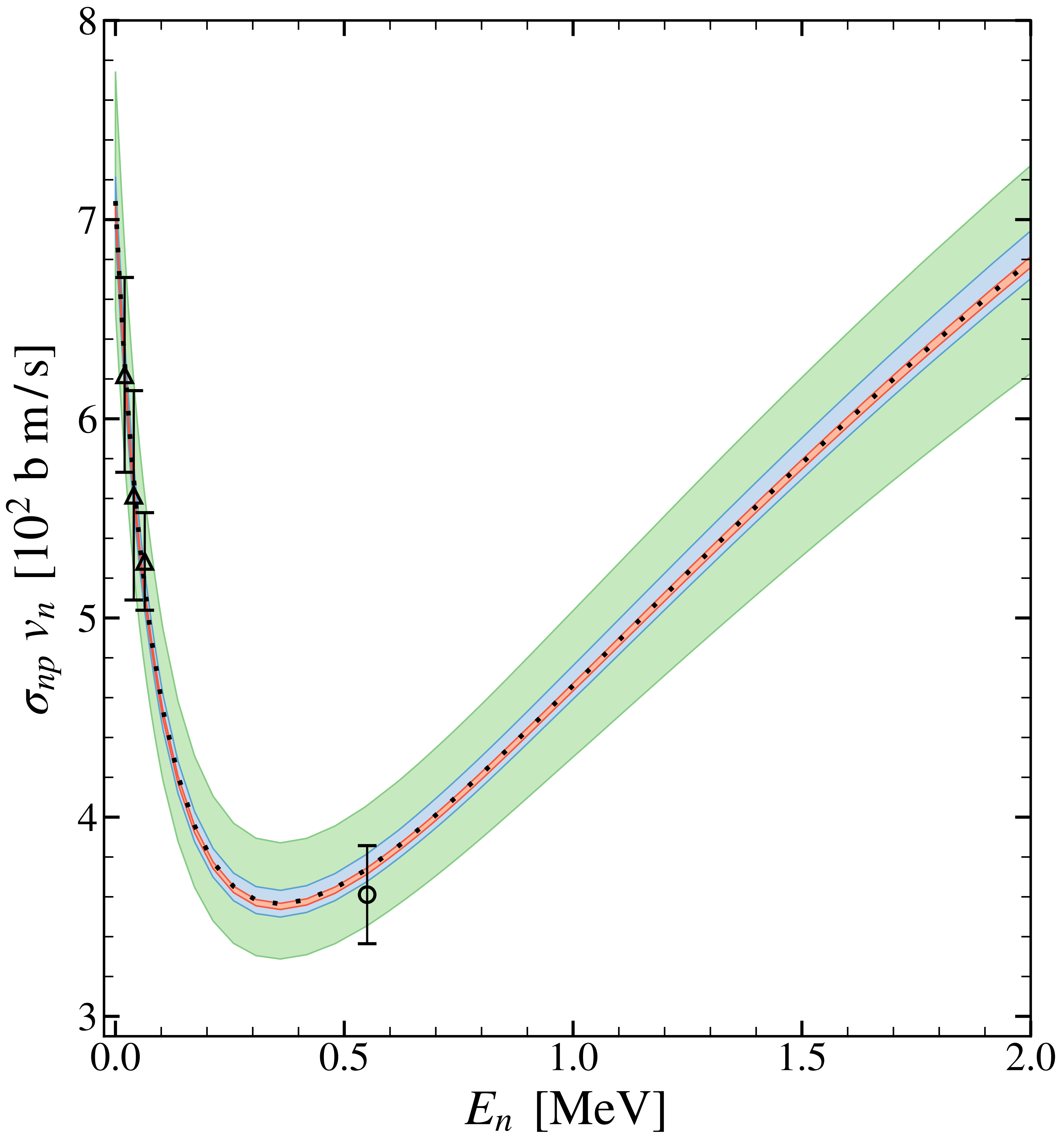
[†]*Melendez et al., Phys. Rev. C* **100** (2019) 044001

Posterior predictive distribution for $\sigma_{np \to d\gamma}$

- Extracted 95% Bayesian credible intervals for the $np \to d\gamma$ rate at BBN kinematics
- Only includes uncertainty from truncating the potential V_{ij} at N3LO
- Current $\mathbf{J}$ fixed at N2LO and truncation error not included—previous attempts to fit subleading pion-exchange and contact N3LO currents yielded unnatural values of LECs
- Recent progress by *A Gnech et al.*† will allow us to include N3LO currents (~1% in the BBN regime)
- Will provide most up-to-date rates for BBN simulations

†*Alex's talk at Monday Parallel Session: NN and Currents*

BA and S Bacca, Phys. Lett. B ***827*** *(2022) 137011*



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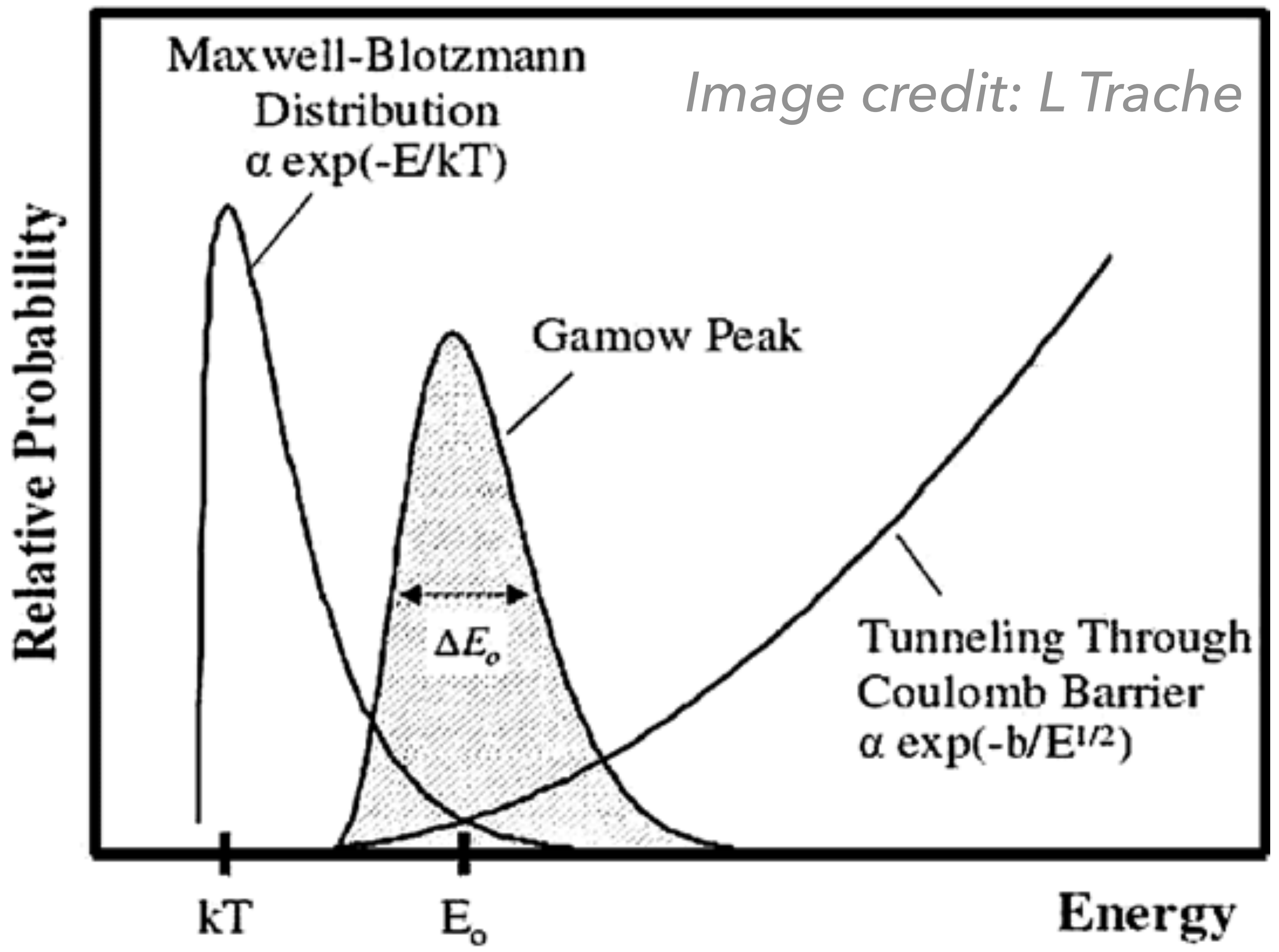
$p + p \rightarrow d + e^+ + \nu_e$ and the standard solar model (SSM)

- Stellar nucleosynthesis begins with conversion of H to He
- Proceeds through the pp chains in 1st and lighter 2nd/3rd generation stars such as the Sun
- The pp fusion reaction is the first and the slowest/rate-determining step
- Not feasible to measure the rate at energies relevant for astrophysics



- Nuclear theory provides inputs to stellar models ← $S_{pp}(E) = \exp[2\pi\eta]\, E\, \sigma_{pp}(E)$
- SSM had a "solar neutrino problem" ← **Resolved by (and partly led to) the detection of neutrino oscillations** 
- SSM now has a "solar composition problem" ← **Larger $S_{pp}(E)$ supports higher photospheric metallicity**

$$S_{pp}(E) \propto \int d\Phi \left| \langle \psi_f | \mathbf{J}^{(A)}_{1B} + \mathbf{J}^{(A)}_{2B} | \psi_i \rangle \right|^2$$

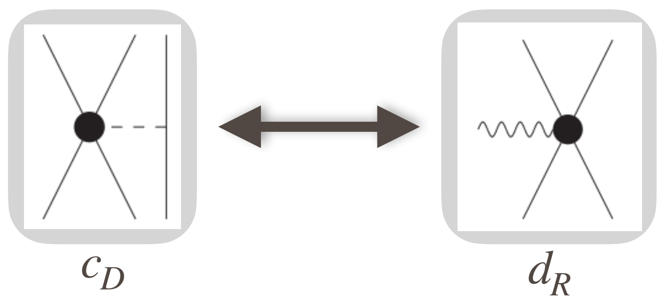
- $\mathbf{J}^{(A)}_{2B}$ contribution ~1%; needs to be calibrated; not included in older calculations[1]—including it by fitting to tritium β decay significantly reduced the spread between models[2]

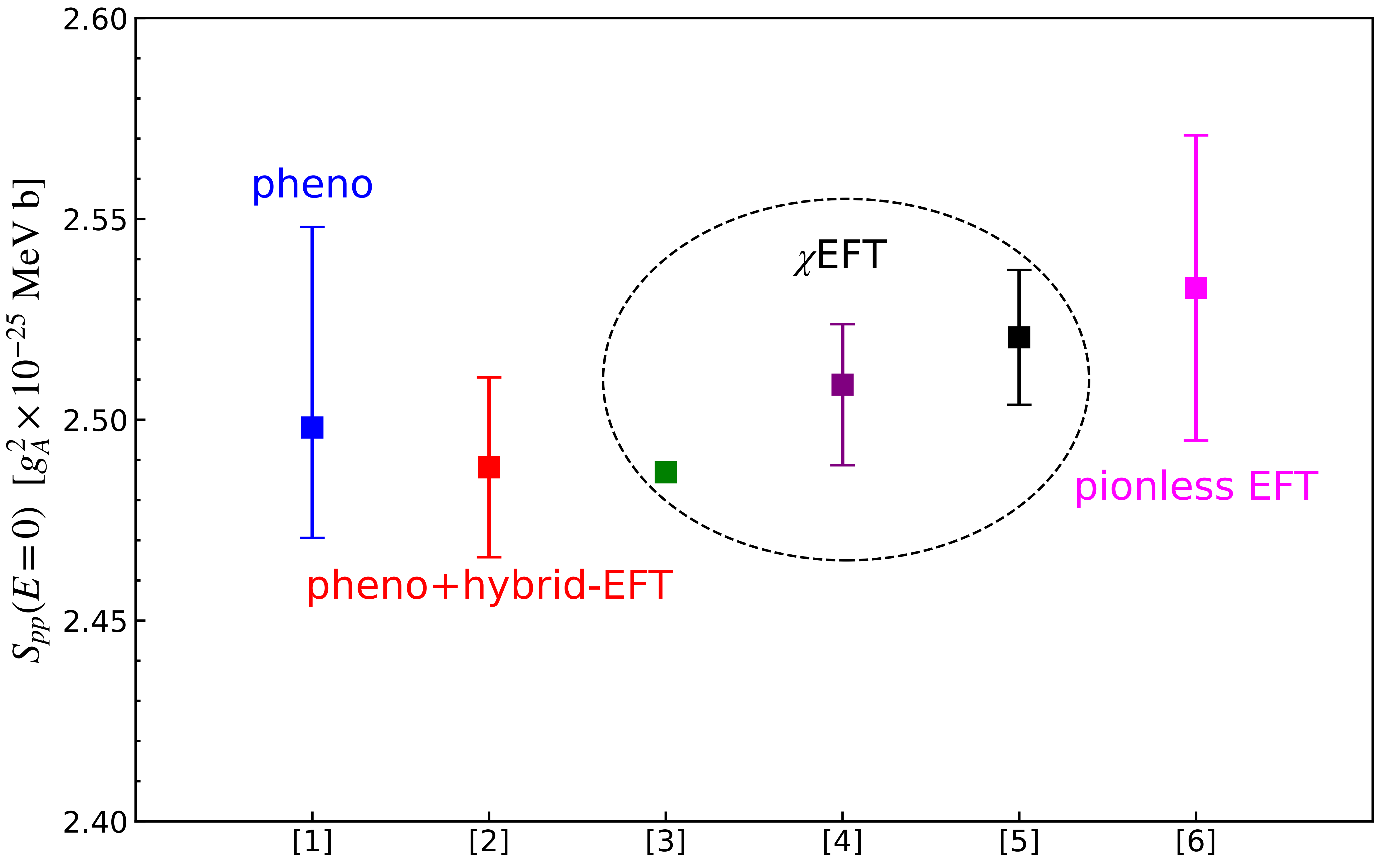
- In χEFT, the unconstrained part of $\mathbf{J}^{(A)}_{2B}$—the LEC d_R—is related to the 3-nucleon force parameter c_D by:
$$d_R = -\frac{m_N}{4 g_A \Lambda_\chi} c_D + \frac{m_N}{3} c_3 + \frac{2m_N}{3} c_4 + \frac{1}{6}$$

- Early χEFT calculations[3,4] suffered from error in $d_R - c_D$ relation that circulated widely in literature; fixed in [5]

- Eliminating finite-volume effects[7] in [3] leads to agreement between [3] and [4] (see [5])

- Recent comprehensive analysis[5] of uncertainties (using different variants of χEFT, propagating errors from few-body fits, fitting to Nd scattering versus tritium β decay…) will inform new recommendations[8]





[1] *Adelberger et al. [SF I], Rev. Mod. Phys.* ***70*** *(1998) 1265*

[2] *Adelberger et al. [SF II], Rev. Mod. Phys.* ***83*** *(2011) 195*

[3] *Marcucci et al., Phys. Rev. Lett.* ***110*** *(2013) 192503; Erratum: Ibid 123 (2019) 019901*

[4] *BA et al., Phys. Lett. B* ***760*** *(2016) 584*

[5] *BA , Marcucci and Platter, J. Phys. G: Nucl. Part. Phys.* ***50*** *(2023) 095102*

[6] *De-Leon and Gazit, arXiv:2207.10176 [nucl-th]*

[7] *BA et al., Phys. Rev. C* ***95*** *(2017) 031301*

[8] *BA et al. [SF III], Rev. Mod. Phys., In Preparation*

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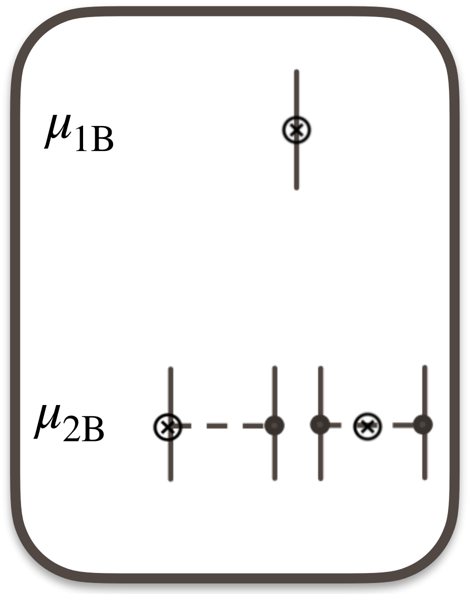
Magnetic dipole $(M1)$ excitation of $^{48}\mathrm{Ca}$

- Magnetic transitions in $^{48}\mathrm{Ca}$ and neighbors are important for understanding the Fe-Ni creation phase of stellar evolution

- $\mu_p \approx 2.79\mu_N,\ \mu_n \approx -1.91\mu_N \Rightarrow$ the 1-body $M1$ and GT operators are closely related:

$$\boldsymbol{\mu}_{1\mathrm{B}} = \sum_{i=1}^{A} \mu_n \boldsymbol{\sigma}_i \frac{1+\tau_i^{(z)}}{2} + (\boldsymbol{l}_i + \mu_p \boldsymbol{\sigma}_i)\frac{1-\tau_i^{(z)}}{2}, \quad \hat{O}_{1\mathrm{B}}^{GT} = \sum_{i=1}^{A} \boldsymbol{\sigma}_i \boldsymbol{\tau}_i$$



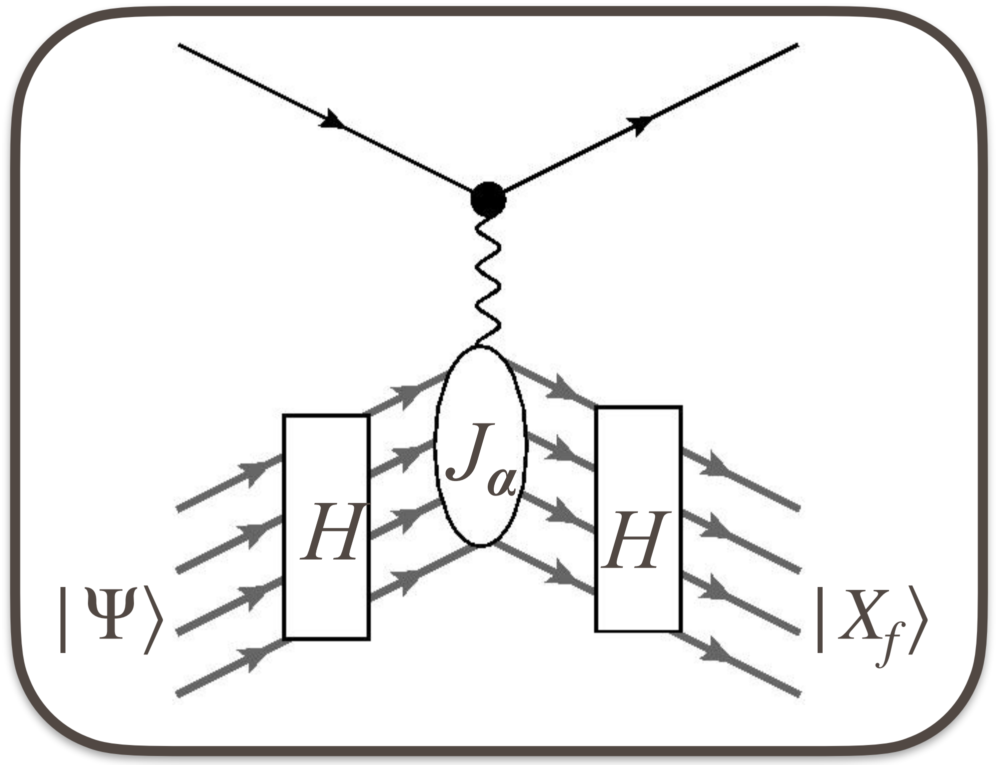
- Measurements of $M1$ transition strengths $B(M1)$ thus constrain neutrino transport and ν-process nucleosynthesis in supernovae

- What will happen to this $M1$-GT connection when 2-body current effects are included?

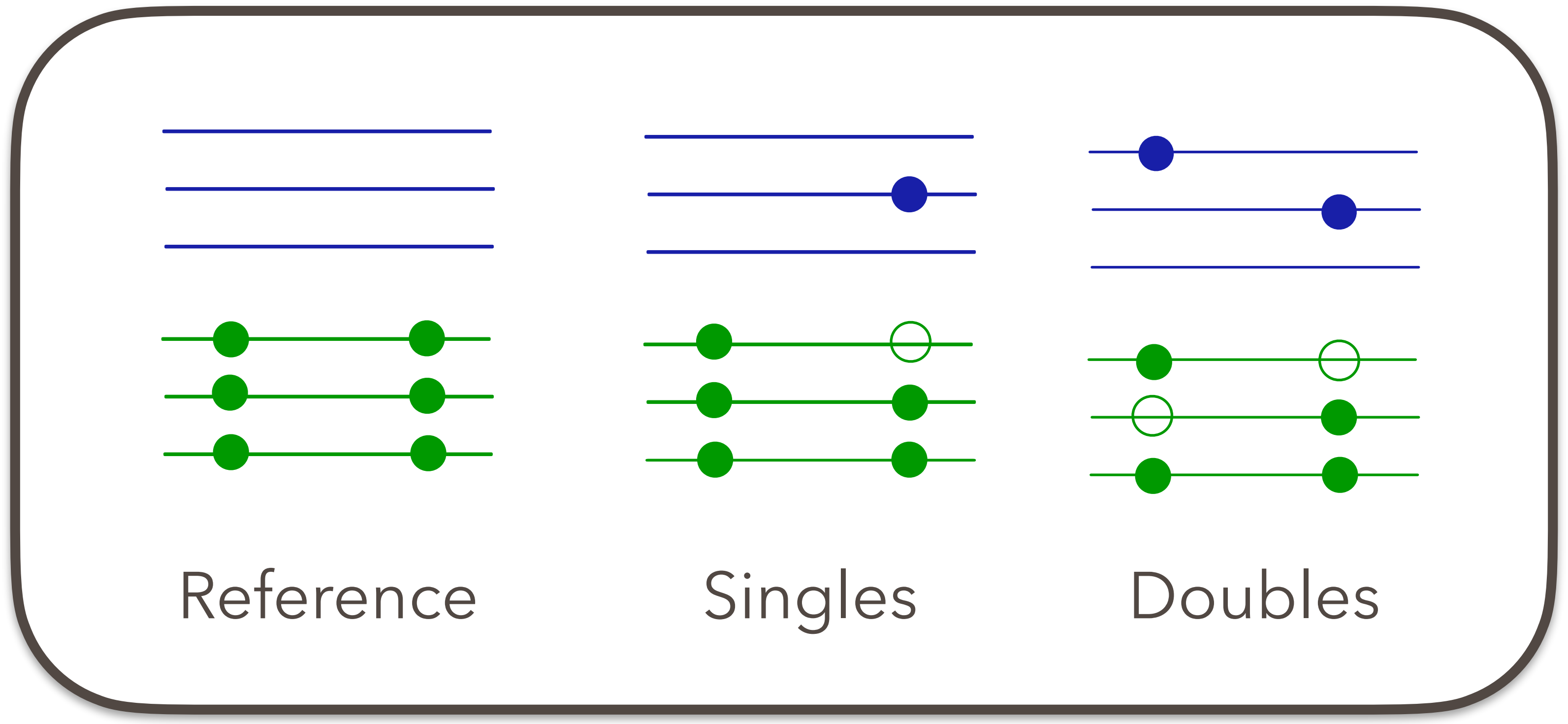
- Is $B(M1)$ “quenched” (i.e. lowered) by 2-body currents?

Few-body inputs to many-body computations: coupled-cluster (CC) theory†

Koester, Kümmel, Bartlett, Papenbrock, Dean, Hagen, …



- CC theory used few-body inputs (NN+3N interactions, 1-body and 2-body currents) to solve the nuclear many body problem



- Approaches the exact solution of the many-body Schrödinger equation through particle-hole excitations around a reference Slater determinant

- Allows us to choose the reference state, go higher in particle-hole expansion …

Milestone

Ab initio coupled-cluster approach to nuclear structure with modern nucleon-nucleon interactions

G. Hagen, T. Papenbrock, D. J. Dean, and M. Hjorth-Jensen
Phys. Rev. C **82**, 034330 – Published 30 September 2010

An article within the collection: *Physical Review C* 50th Anniversary Milestones

† *J E Sobczyk's talk at today's Parallel Session: Few- and many-body systems*

$M1$ transition in ^{48}Ca: status of experiments

- Large $B(M1: 0^+ \rightarrow 1^+)$ is expected in ^{48}Ca due to strong $\nu 1f_{7/2} \rightarrow \nu 1f_{5/2}$ excitation—ESPM predicts 11.96 μ_N^2

- Darmstadt group's experiments have found a much smaller value of $B(M1: 0^+ \rightarrow 1^+)$

- Quenching of $B(GT)$ has been offered as argument to support the notion that $B(M1)$ is strongly quenched (q.f. = 0.75), consistent with Darmstadt group's experiments

- A TUNL experiment at HIγS found a larger value

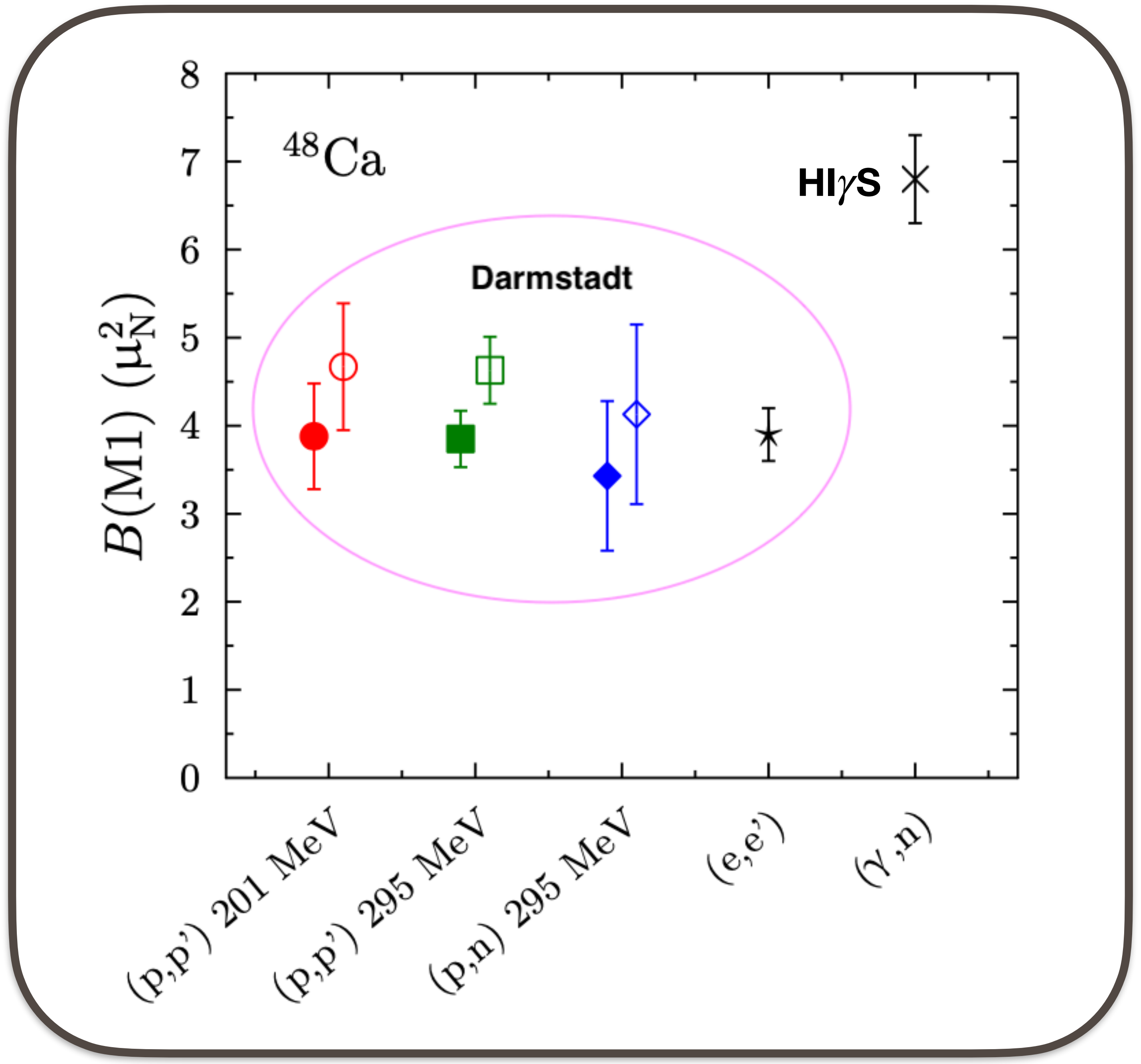
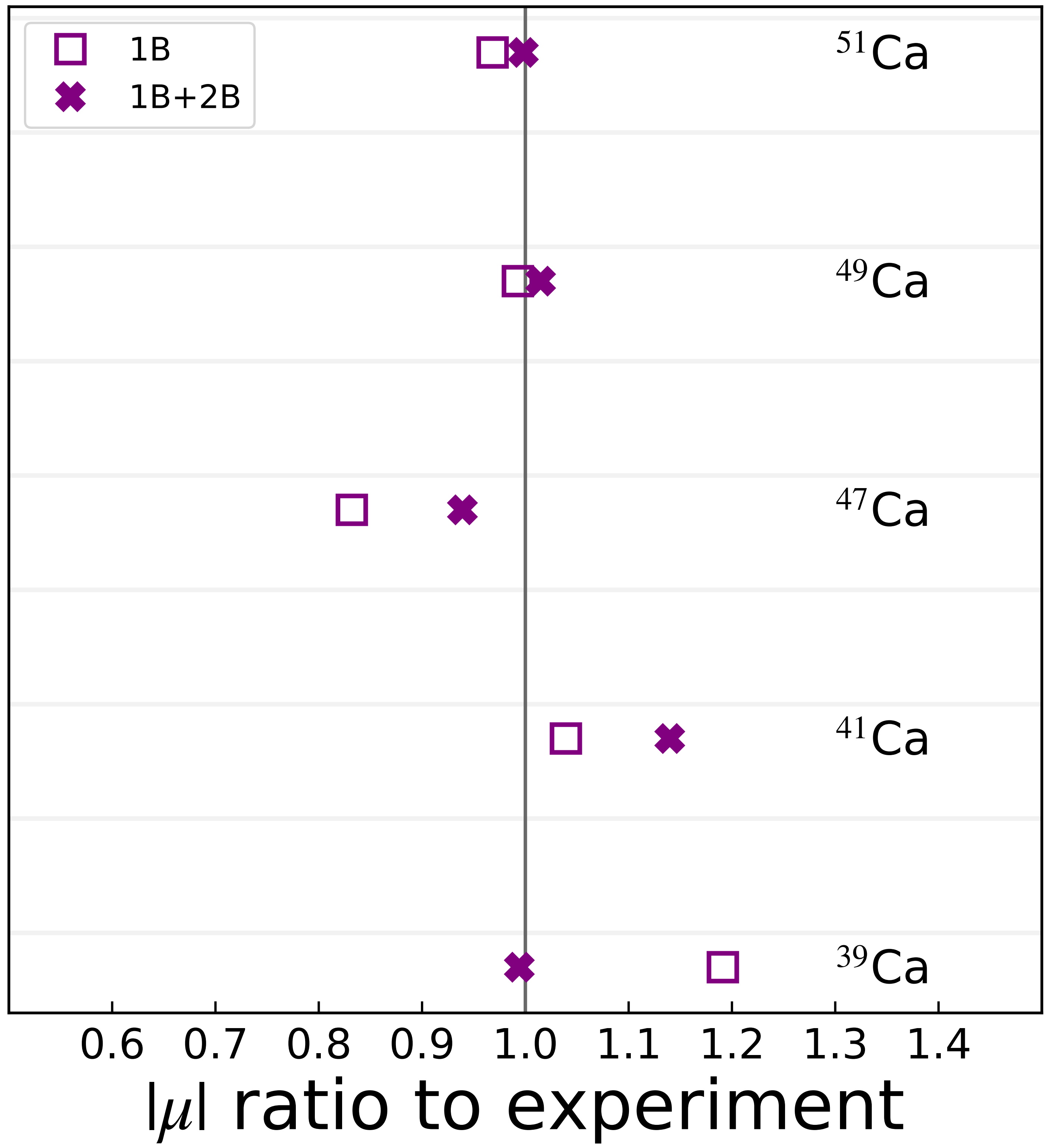


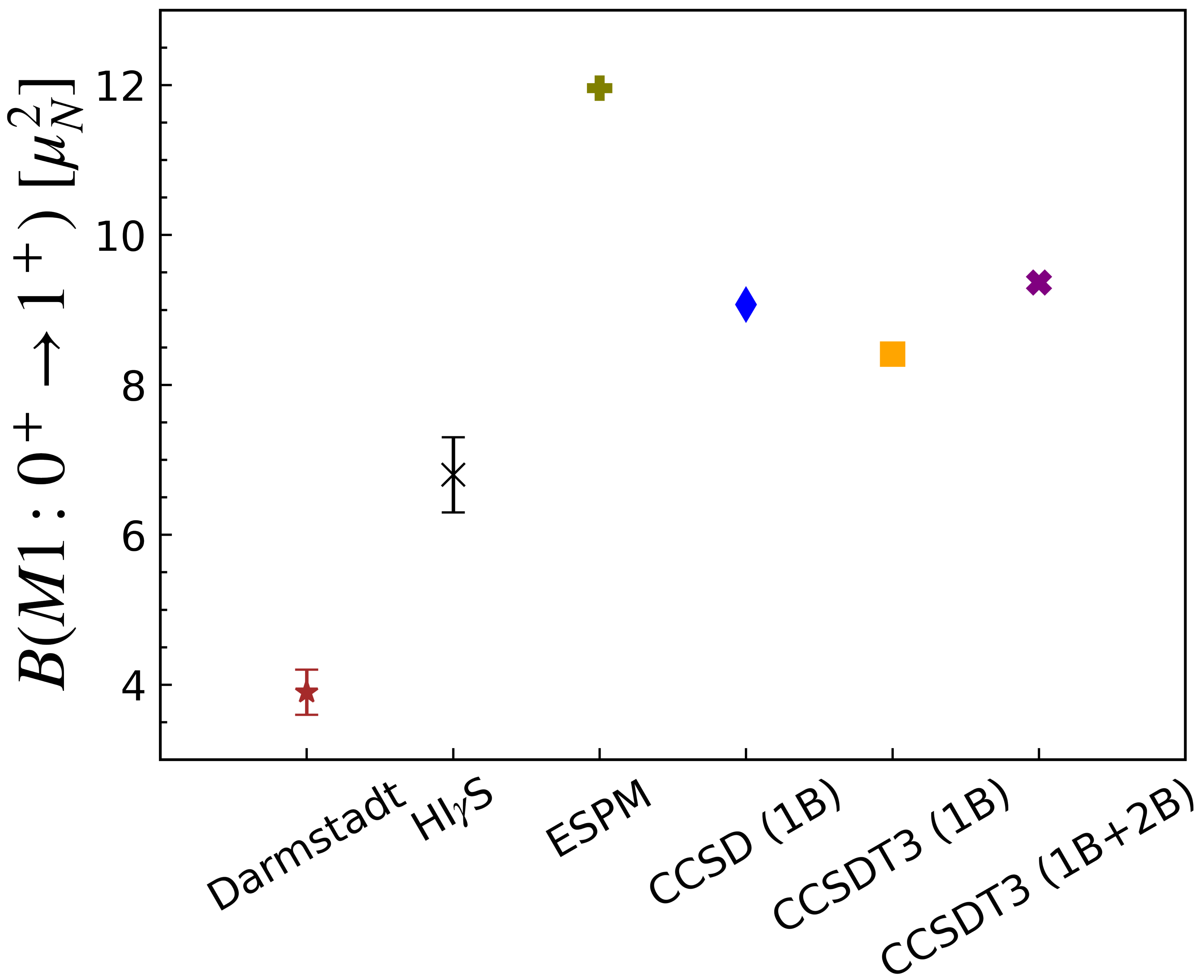
*Figure adapted from PRC **93** (2016) 041302(R)

Ground state $M1$ moments in Ca isotopes



Overall, 2B currents lead to improved description of magnetic moments

$B(M1)$ in $^{48}\mathrm{Ca}$



Instead of quenching, 2B currents lead to a small enhancement in $B(M1)$

Conclusions and Outlook

- χEFT can provide reliable predictions for nuclear electroweak processes, along with rigorous uncertainty estimates
- Reliable values with uncertainties are useful, especially for quantities that are important in astrophysical environments but can not be measured in the lab with sufficient accuracy/precision
- Gaussian Process error model performs well for χEFT computations of $np \to d\gamma$ rate at BBN energies; higher-order currents are needed and we are working on those
- New result for $S_{pp}(E)$ from χEFT with updated inputs and corrections is higher that prior recommendations but consistent within estimated errors
- Theory is closer to TUNL (γ, n) than with Darmstadt (e, e') experiment for $M1$ transition in ^{48}Ca; we are working on uncertainty estimates

Thank you!