From Halo EFT to Reaction EFT

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U.S. DEPARTMENT OF ENERGY | Office of Science

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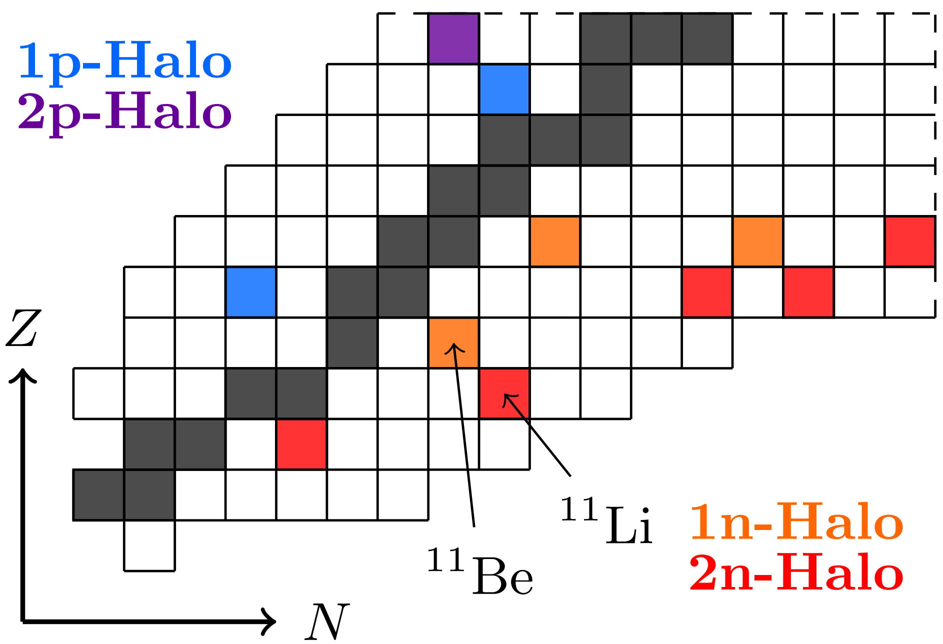
Outlook

- What is Halo EFT
- Examples
- Frontiers in Halo EFT:
  - D-wave systems
  - Transfer reactions
- Outlook

What is Halo EFT

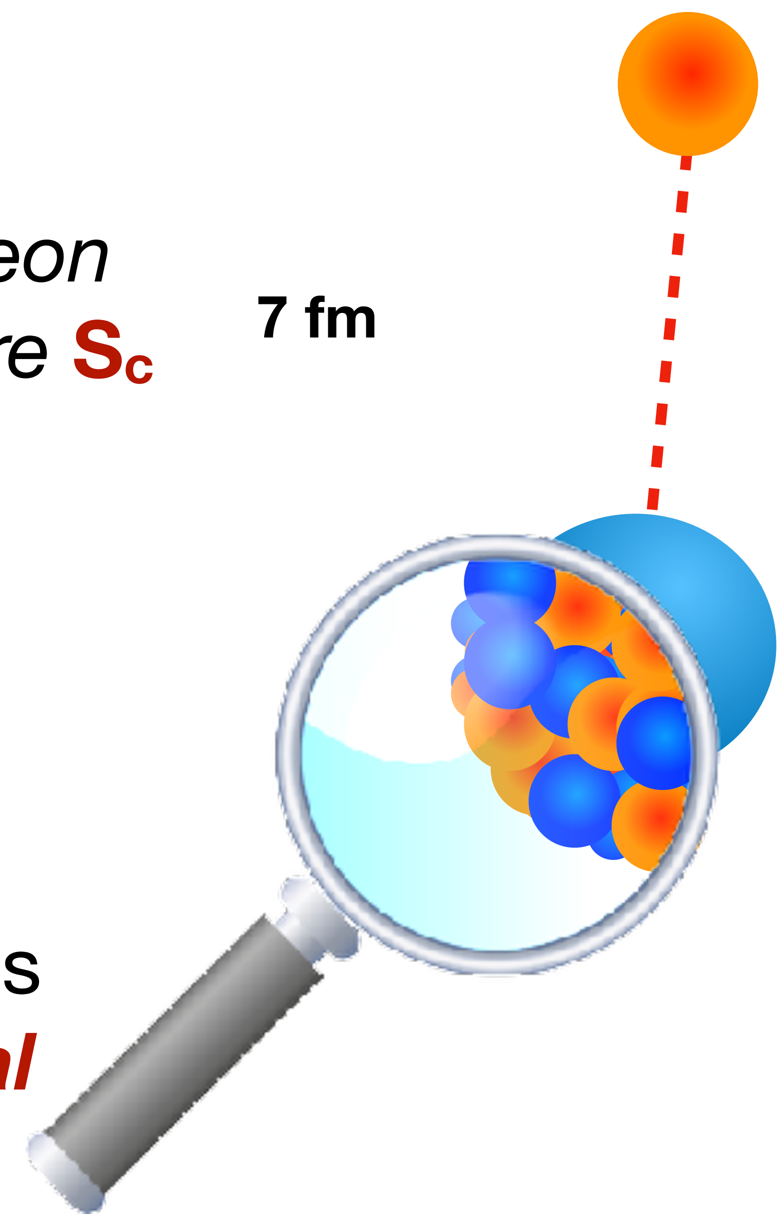
- Halo EFT is designed for weakly bound nuclei
- degrees of freedom are
  - tightly bound nucleus (e.g. alpha-particle)
  - weakly bound nucleons (protons or neutrons)
- Halo nuclei are emergent degrees of freedom along the driplines
- Nucleons can be in different partial waves with the *core* nucleus



Bertulani, Hammer, van Kolck 2002, Bedaque, Hammer, van Kolck 2003

Separation of scales

- Application of halo EFT guided by separation of 2 scales, e.g.
  - 1-nucleon separation energy of *halo nucleon* **S_h** divided by 1-nucleon separation of *core* **S_c**
  - *core radius* **R_c** divided by *halo radius* **R_h**
- core appears structureless at low energies
- can be applied to any system that possesses such a scale separation: **not only *traditional* halo nuclei**



Formulation of EFT

- Express interactions as contact interactions (no exchange particles)
- use quantum field theory (whenever possible) for calculations
- *S-wave:* 1 parameter at LO (one-nucleon separation energy, effective range parameters, …)
- higher partial waves: depends on power counting

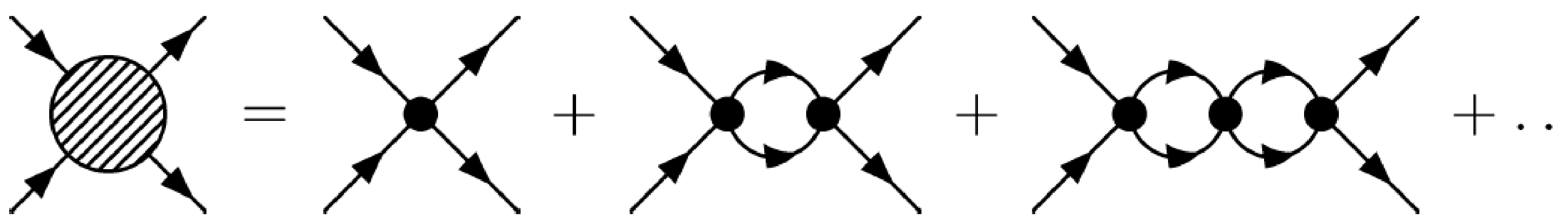
Beryllium Lagrangian as example

$$
\begin{aligned}
\mathcal{L} = {} & c^\dagger\left(i\partial_t + \frac{\nabla^2}{2M}\right)c + n^\dagger\left(i\partial_t + \frac{\nabla^2}{2m}\right)n \\
& + \sigma^\dagger\left[\eta_0\left(i\partial_t + \frac{\nabla^2}{2M_{nc}}\right) + \Delta_0\right]\sigma \\
& + \pi_j^\dagger\left[\eta_1\left(i\partial_t + \frac{\nabla^2}{2M_{nc}}\right) + \Delta_1\right]\pi_j \\
& - g_0\left[\sigma n^\dagger c^\dagger + \sigma^\dagger n c\right] \\
& + \frac{i g_1}{2}\left[\pi_j^\dagger (c \overleftrightarrow{\nabla}_j n) - (c^\dagger \overleftrightarrow{\nabla}_j n^\dagger)\pi_j\right] + \ldots.
\end{aligned}
$$

Hammer & Phillips 2011

Practical matters

- Calculate diagrams directly with quantum field theory (propagators & vertices)

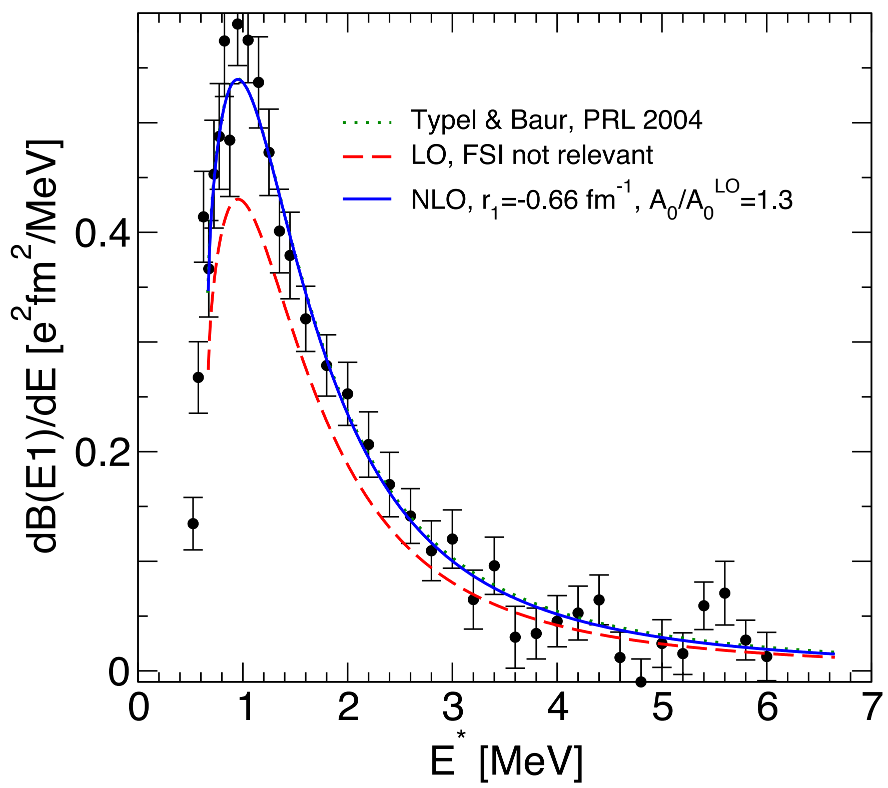


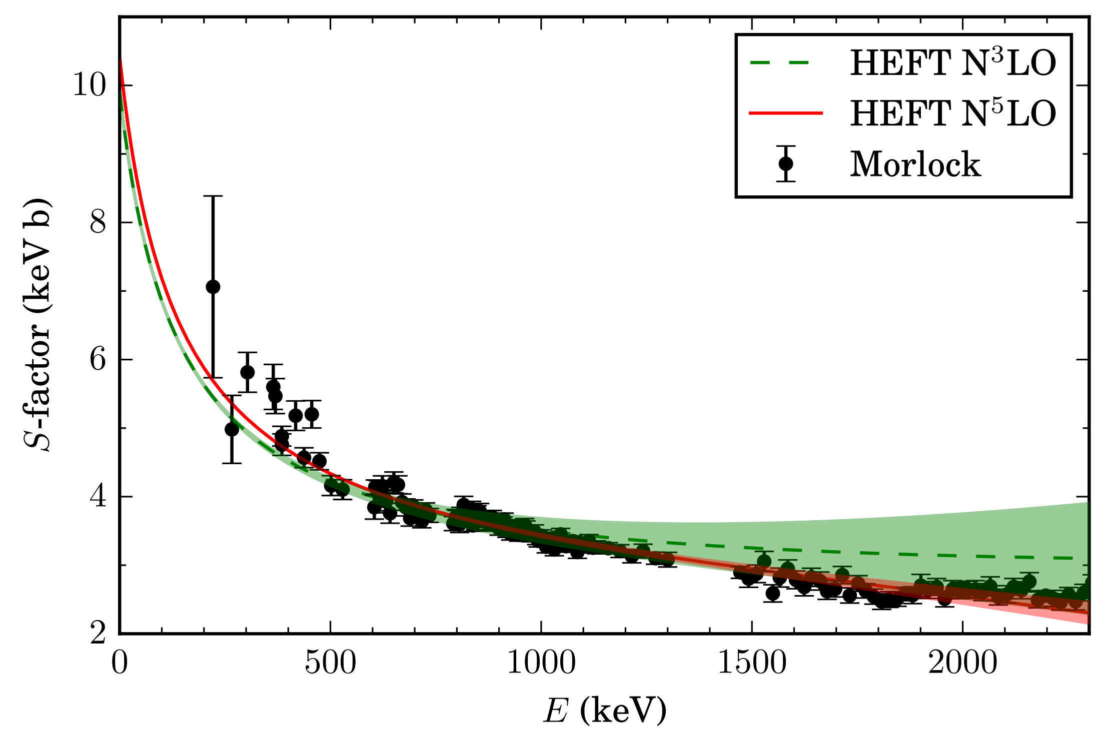
- Parameters in Lagrangian (interaction) are fixed from observables, e.g. binding energies, phaseshifts, effective range parameters

$$k \cot \delta = -\frac{1}{a} + \frac{r}{2} k^2 + ...$$

Halo EFT Applications

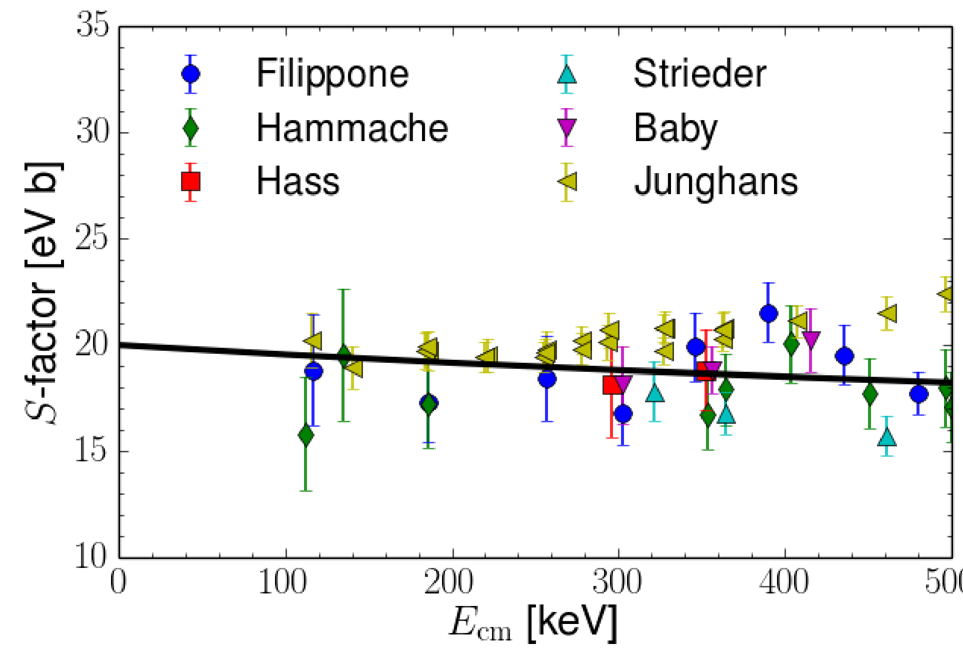
- Neutron halo nuclei:
  - Beryllium-11 (Hammer & Phillips)
  - Helium-6 (Ji, Elster & Phillips)
  - Carbon-22 (Acharya, Ji & Phillips)
- Proton halo nuclei:
  - Fluorine-17 (Ryberg, Forssen, Hammer & LP)

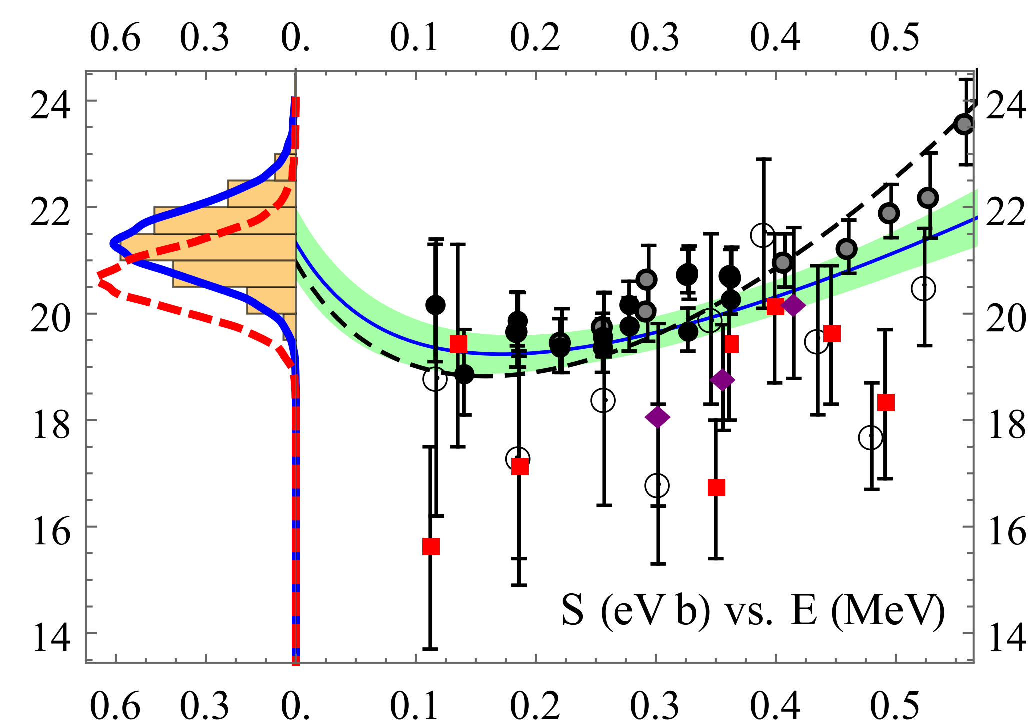




Combine ab initio w/ Halo EFT

- ab initio can provide input parameters:
- proton-capture on Beryllium-7 [Ryberg, Hammer, Forssen & LP 2014, Zhang, Nollett & Phillips 2014 & 2015]
- Calcium-62 halo [Hagen, Hagen, Hammer & LP 2014]





EFT Frontier:
D-wave halos

Braun, Hammer, Roth 2018

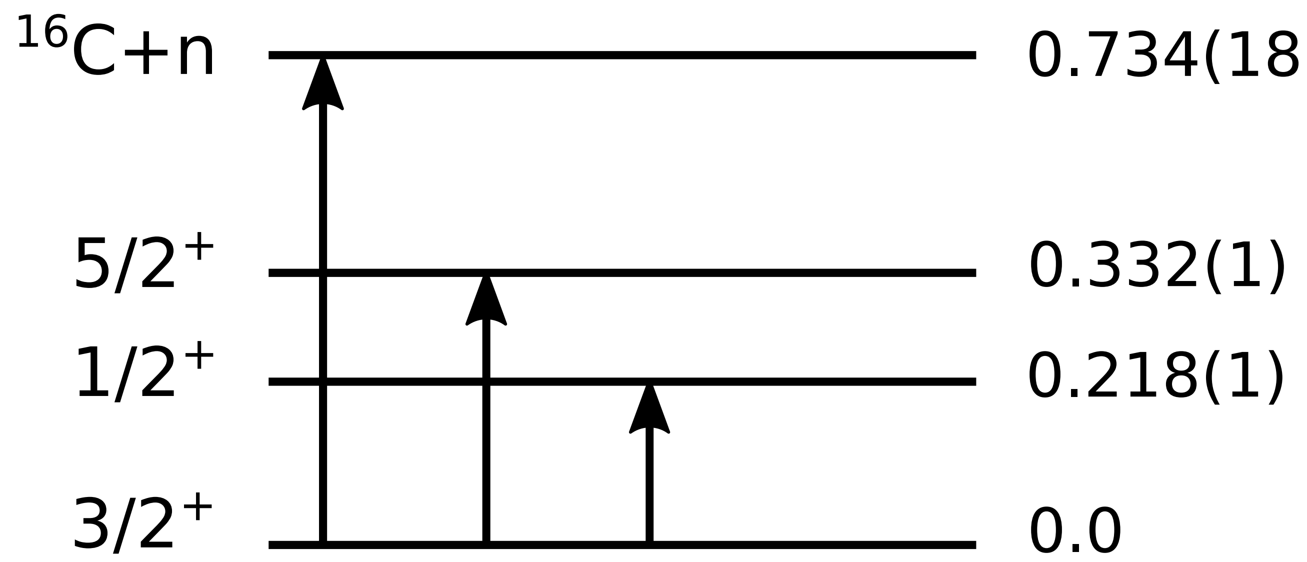
- *non-traditional* halos - **guidance by scale separation**
- proposed power counting requires 2 counterterms (data points) at leading order, different scaling estimates for effective range parameters
- electromagnetic properties of Carbon-15 states (form factors, E2 transition)
- universal correlations

Carbon-17

Braun, Hammer, LP 2018

- Carbon-17 has 3 weakly bound states

- excitation energy of Carbon-16 is 1.8 MeV



➡ use EFT to describe this system

- system hard for ab initio approaches (calculations exist w/ IT-NCSM)

E2 Transitions in C17

- M1 and E2 transitions possible between states in this system
- E2 transitions

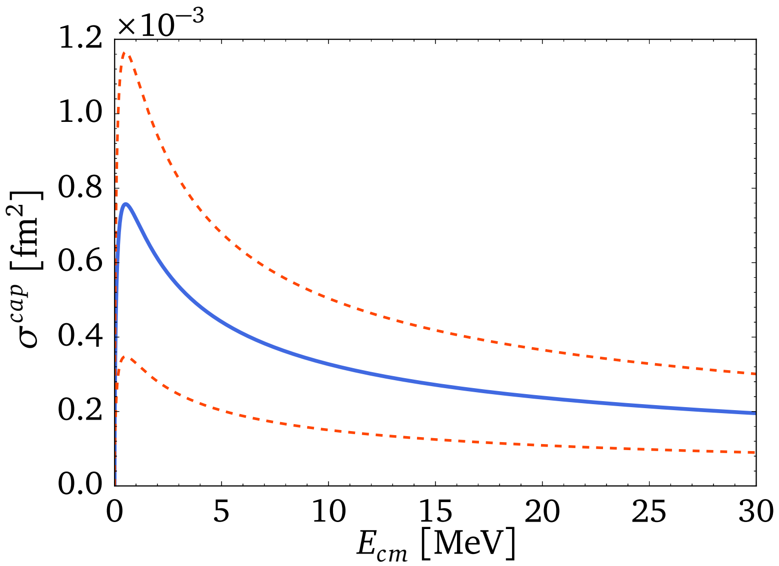
$$\mathrm{B(E2:}\ 1/2^+ \to 5/2^+) = -\frac{4}{5\pi}\frac{Z_{eff}^2 e^2}{r_{2'} + \mathcal{P}_{2'}\gamma_{2'}^2}\ \gamma_0\ \left[\frac{3\gamma_0^2 + 9\gamma_0\gamma_{2'} + 8\gamma_{2'}^2}{(\gamma_0+\gamma_{2'})^3}\right]^2,$$

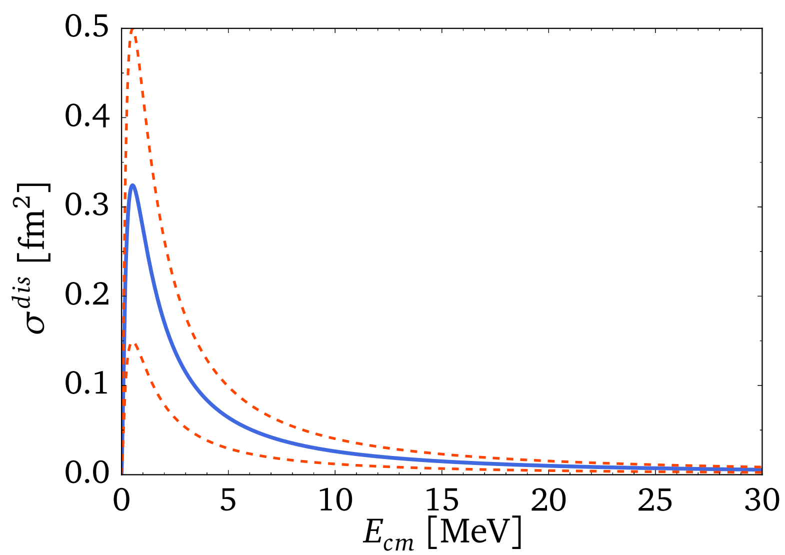
$$\mathrm{B(E2:}\ 1/2^+ \to 3/2^+) = -\frac{8}{15\pi}\frac{Z_{eff}^2 e^2}{r_2 + \mathcal{P}_2\gamma_2^2}\ \gamma_0\ \left[\frac{3\gamma_0^2 + 9\gamma_0\gamma_2 + 8\gamma_2^2}{(\gamma_0+\gamma_2)^3}\right]^2.$$

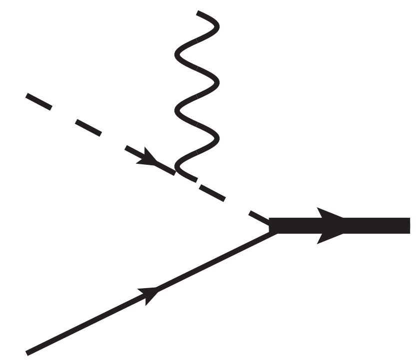
- depend on 2 binding energies & 1 combination of ERE parameters
- **Opportunity** for ab initio or shell model calculations

Capture reactions w/ C17

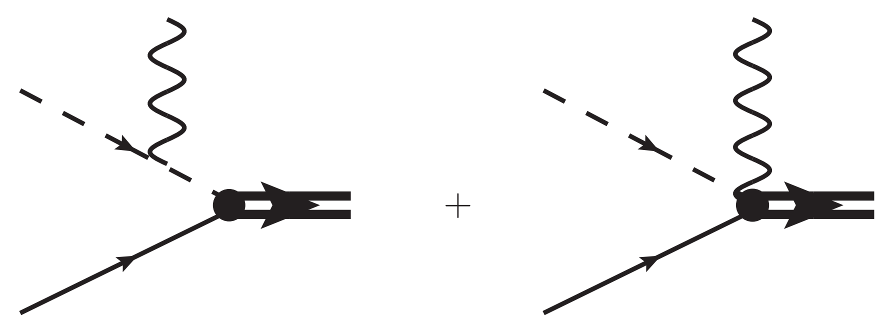
- E1 capture and photodisassociation into S-wave







- E1 capture into D-wave states



$$\sigma^{cap} = \frac{\alpha Z_{eff}^2}{-r_2 - \mathcal{P}_2\gamma_2^2}\frac{32\pi p}{3m_R^2}\frac{\left(5\gamma_2^4 + 11p^4 + 14\gamma_2^2 p^2\right)}{\left(\gamma_2^2 + p^2\right)}\,.$$

- prefactor as before

M1 Transitions:

- M1 transitions measured and calculated (Smalley et al. 2017)
- zero at leading order in Halo EFT
- counterterm has to be fitted, for example

$$\mathrm{B}(\mathrm{M1:}\ 1/2^+ \to 3/2^+) \quad = \quad -\frac{1}{4\pi}\frac{\gamma_0}{r_2 + \mathcal{P}_2\gamma_2^2}\left(\tilde{L}_{M1}^{\sigma d}\right)^2 \mu_N^2$$

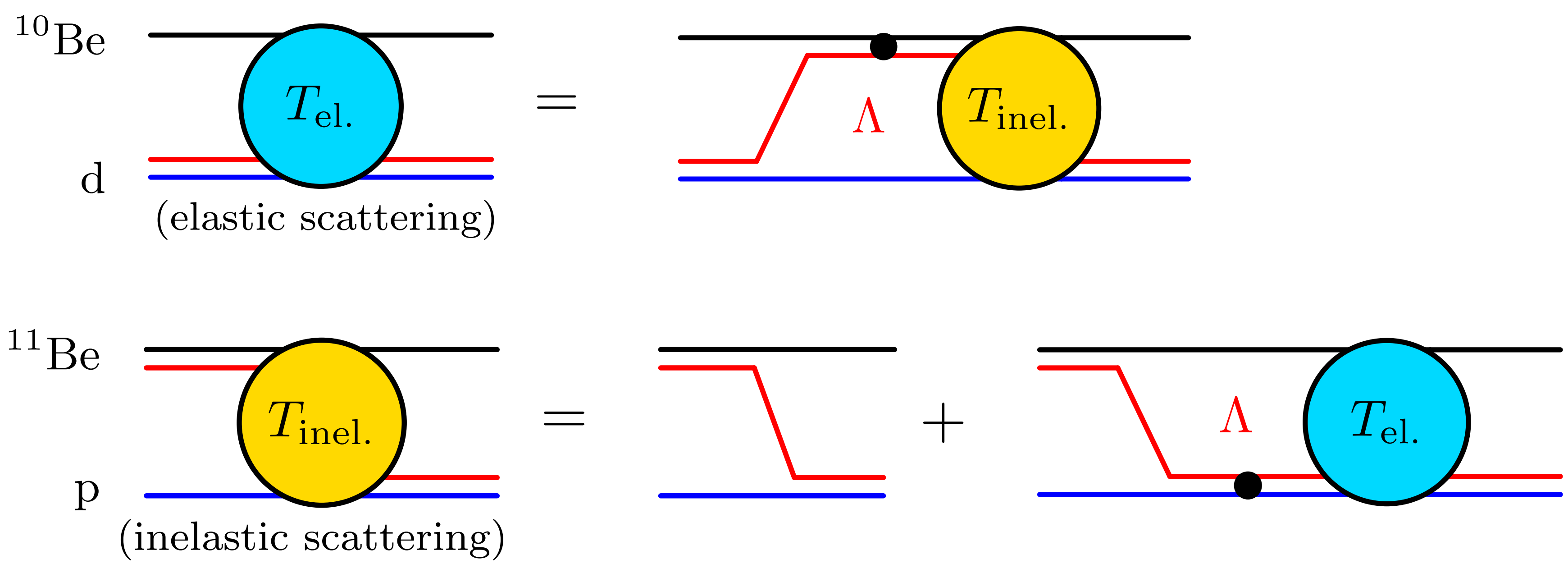
- **order of magnitude estimate**

$$\mathrm{B}(\mathrm{E2:}\ 1/2^+ \to 3/2^+) \approx 3 \times 10^{-2}\ e^2\mathrm{fm}^4$$

EFT Frontier:
Transfer Reactions

w/ Schmidt, Hammer

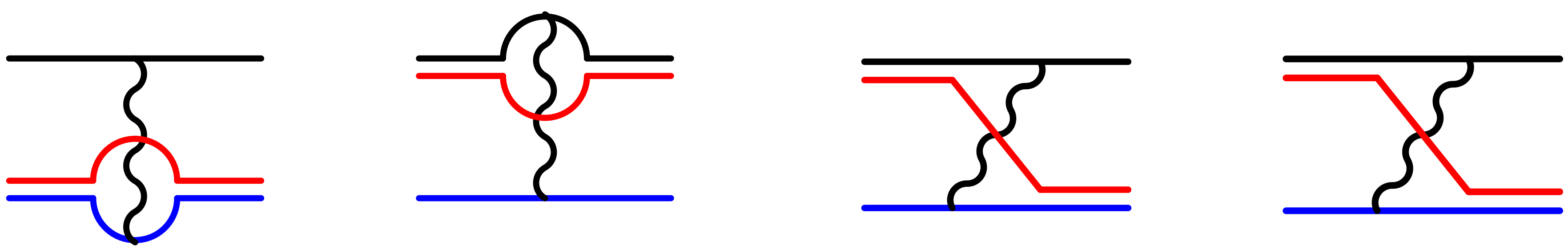
- Consider now neutron-transfer reactions in halo EFT
- use ^{10}Be(p,d)^{11}Be as first application
- Diagrammatics lead to coupled integral equation (w/o Coulomb)



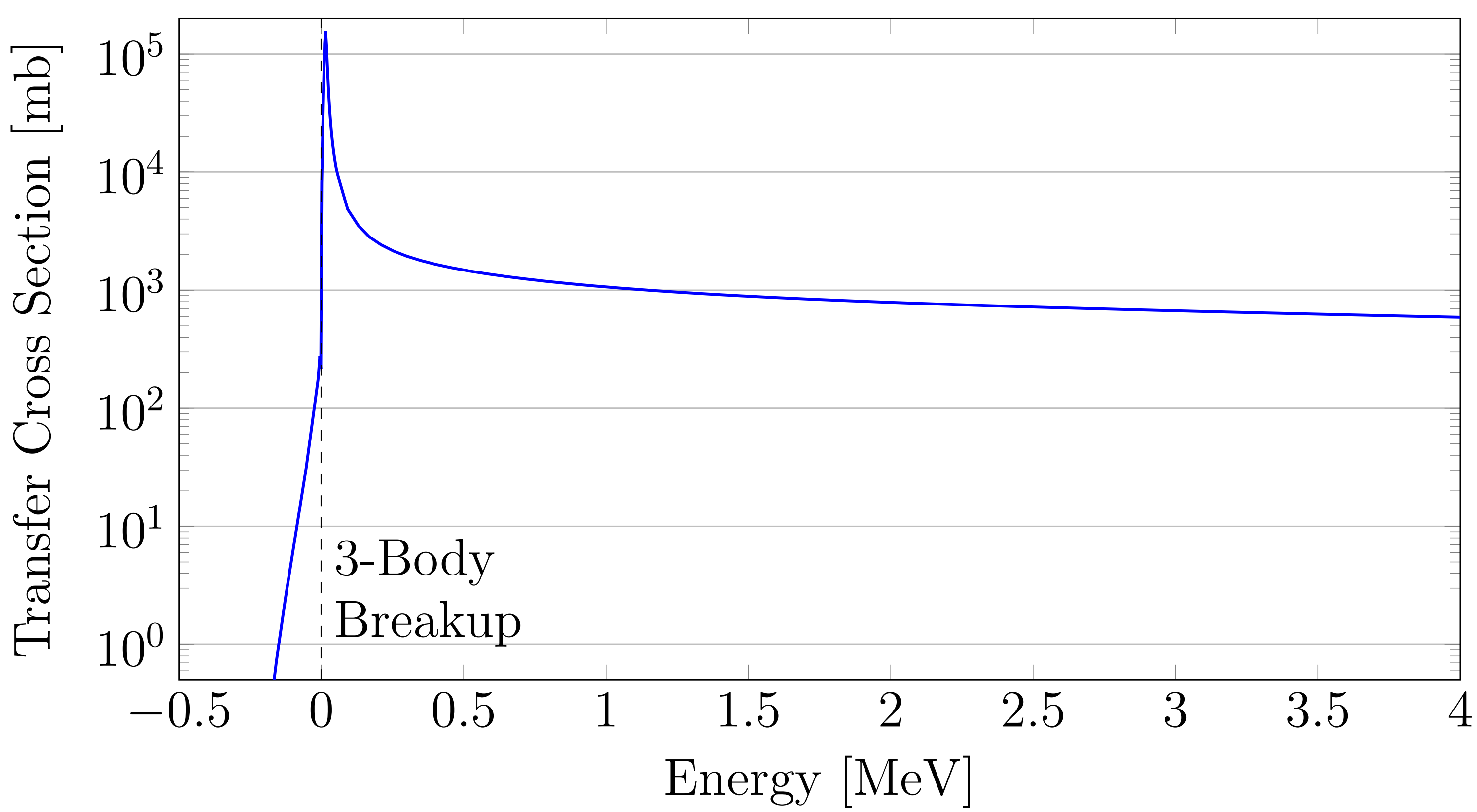
- Faddeev equation for contact interactions (more complete dynamics than CDCC)

Observables

- adapt König et al. and include Coulomb into integral equation



- calculate transfer cross section



Outlook

- Halo EFT is considering more systems now (S-wave, P-wave, D-wave)
- **Only prerequisite for application is scale separation!**
- Observables are parameterized in terms of measurable parameters
- More counterterms in halos w/ higher partial waves but ab initio can help (NCSM, Coupled Cluster, IM SRG)
- Continuum accessible: capture reactions, transfer reactions/ optical potentials
- inelastic channels through *open EFT* (optical potentials)

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