Frontiers in Nuclear Theory: From Light Nuclei to Astrophysics

Sonia Bacca

CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

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TRIUMF

American Physical Society - North West Section Meeting

May 14-16 2009

University of British Columbia, Vancouver

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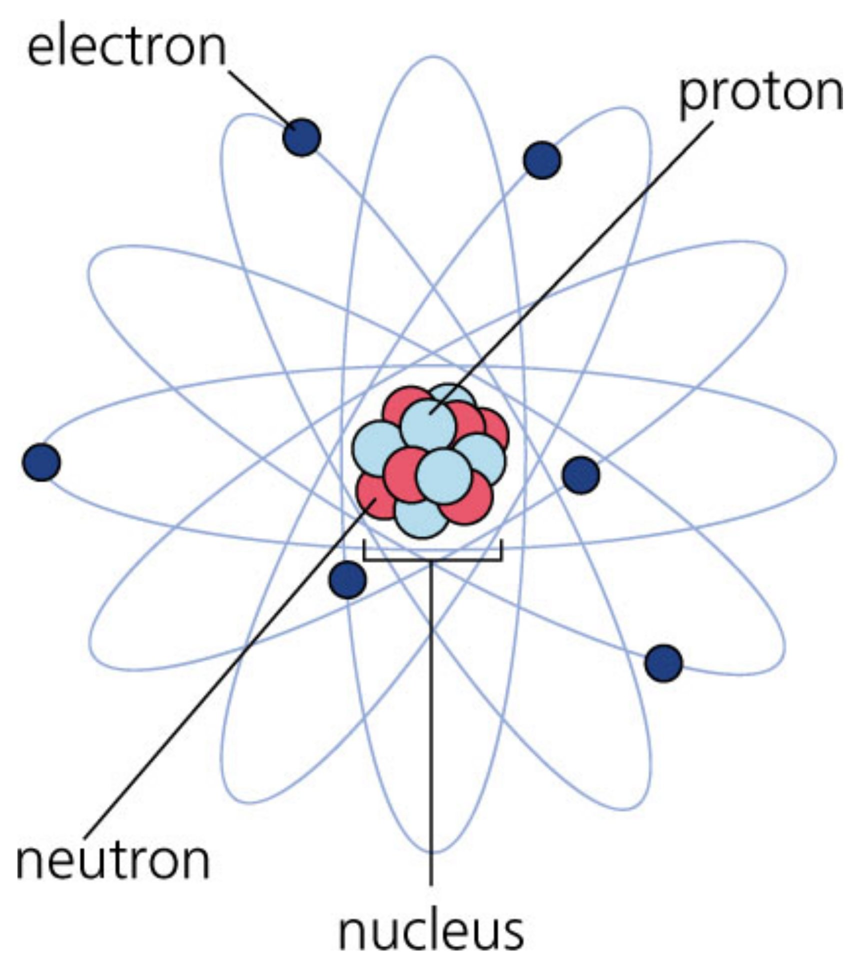

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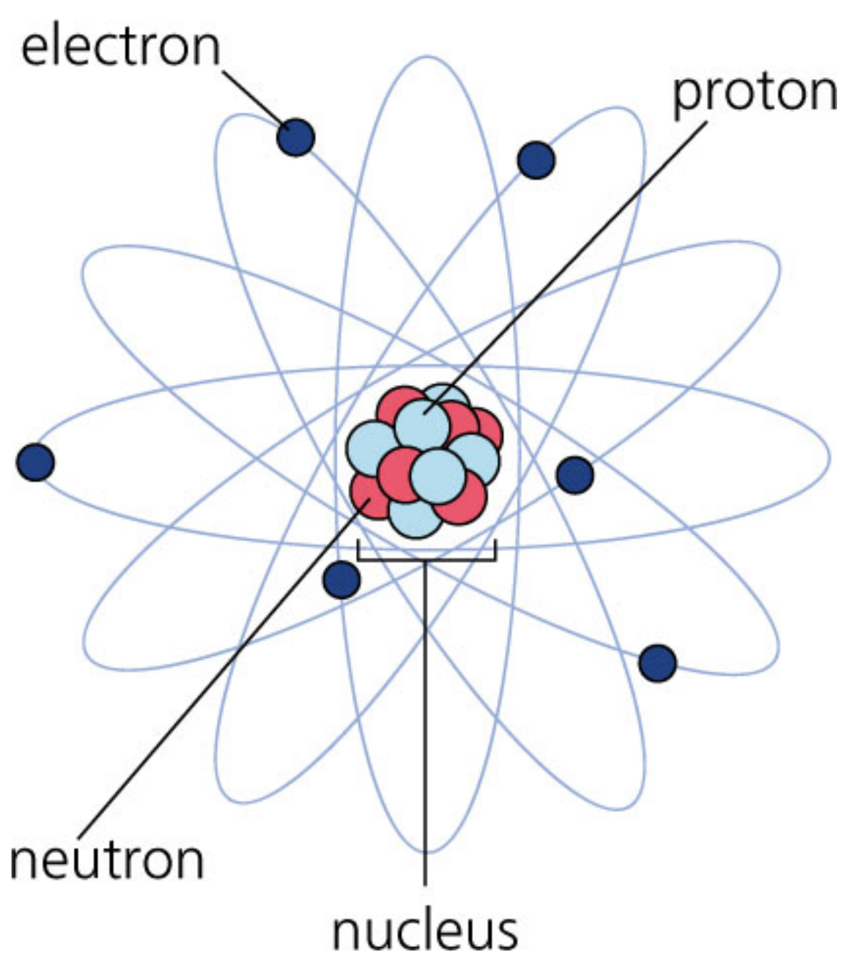


What is Nuclear Physics?

"Nuclear Physics is the field of physics that studies the building blocks and interactions in atomic nuclei" ✓

- It is a science build on a strong connection between theory and experiment

- It has also many interesting applications that influence and improve our daily life:

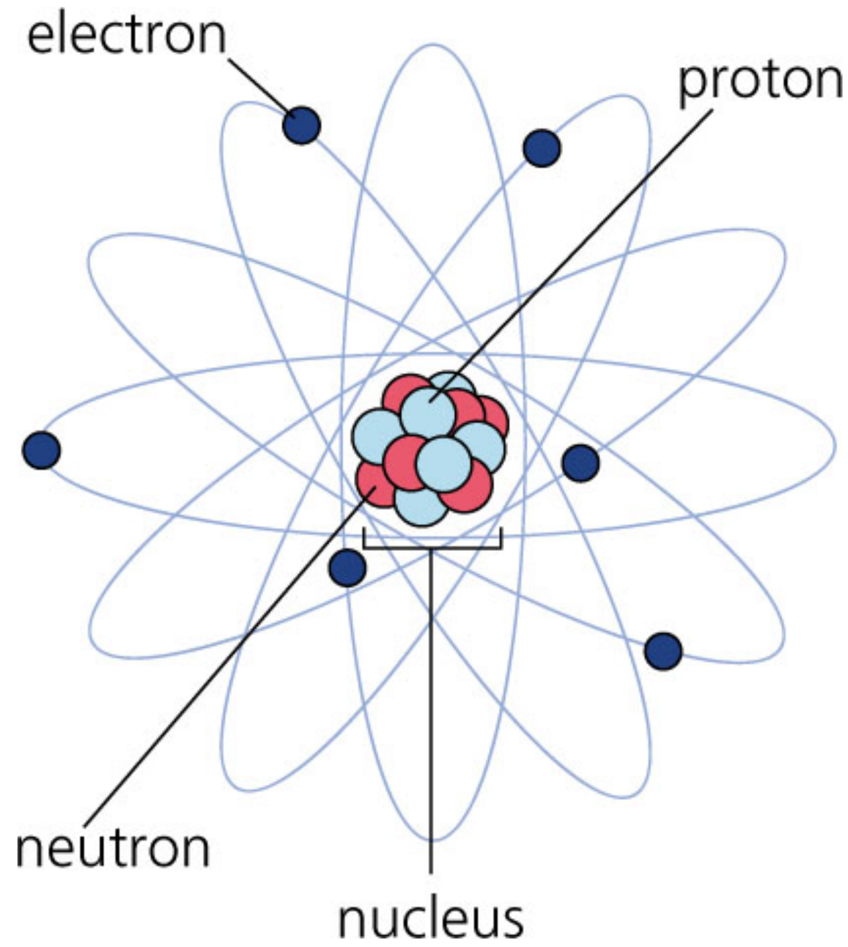
  ★ nuclear medicine (radiopharmaceuticals)

  ★ hadron therapy (cure of cancer)

  ★ engineering materials (ion implantation)

  ★ archaeology (carbon dating)

...



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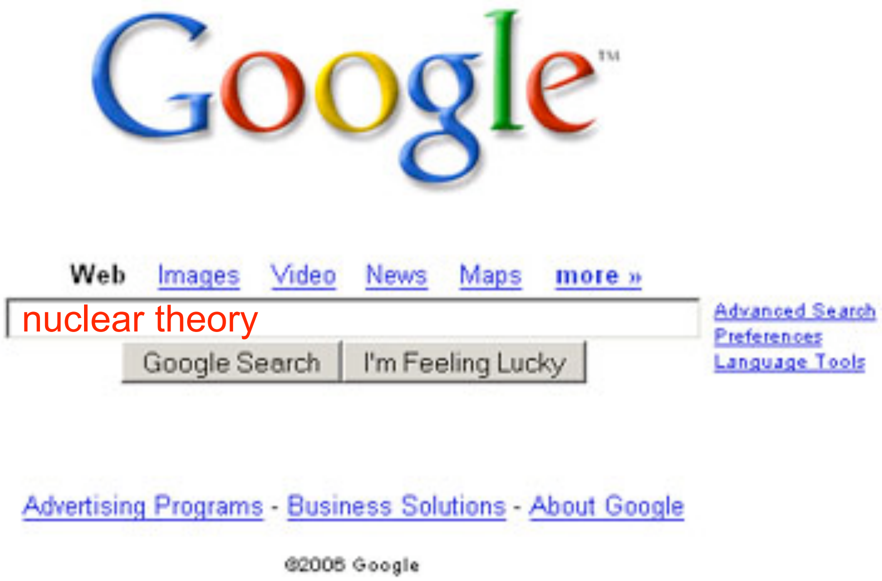

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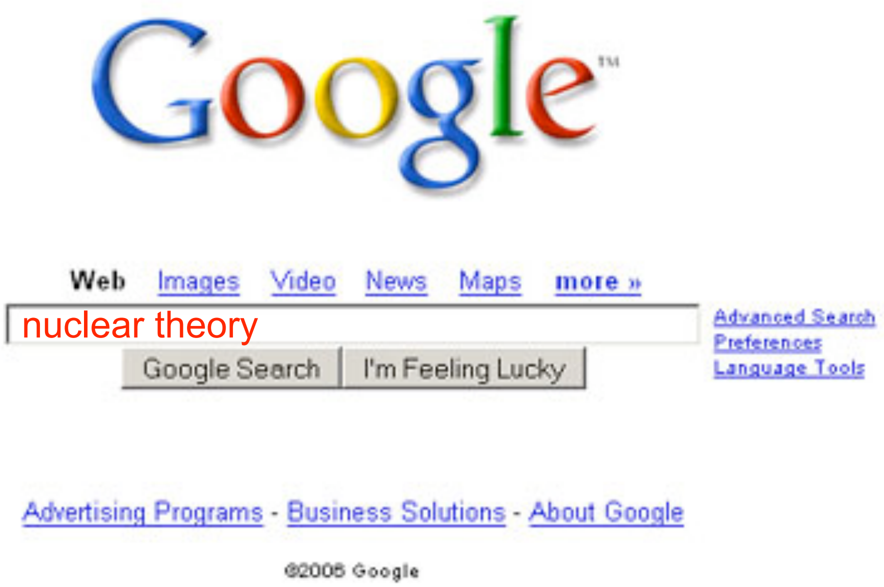

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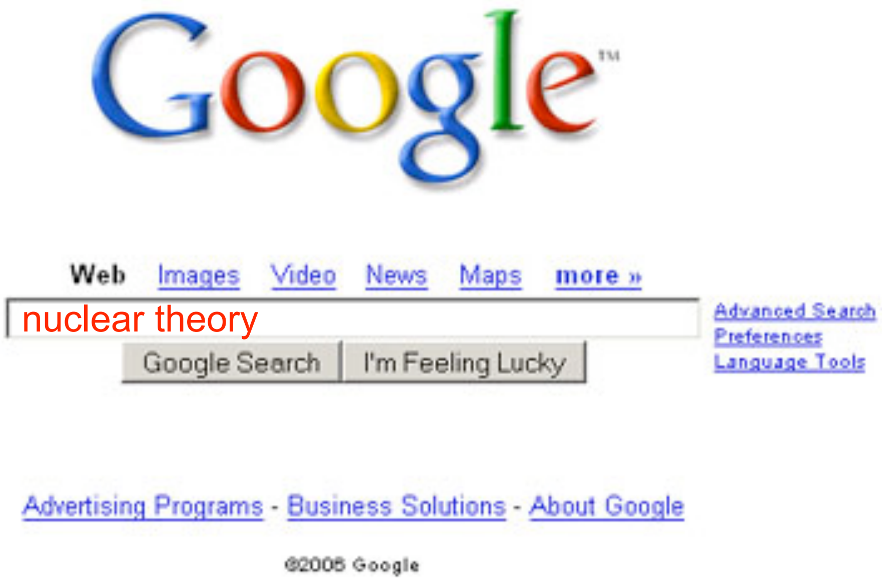

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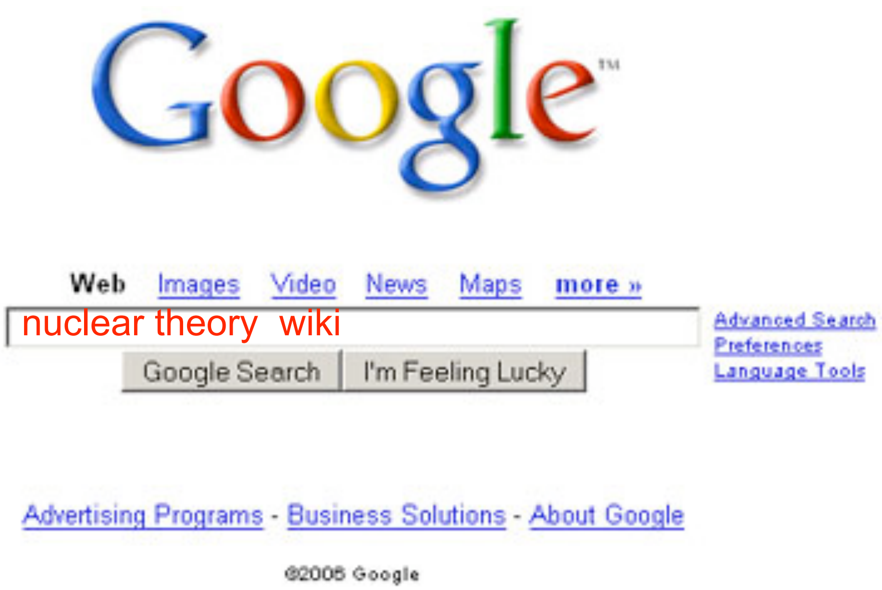

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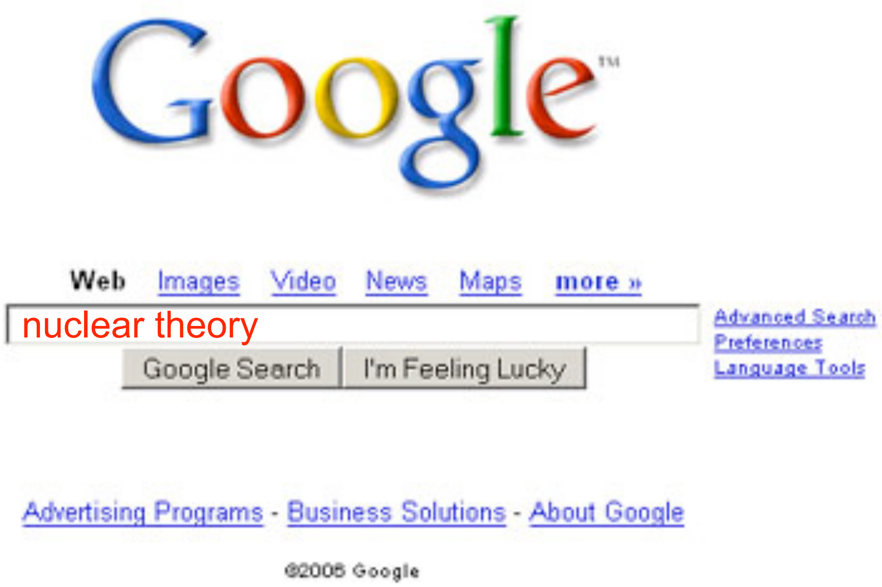

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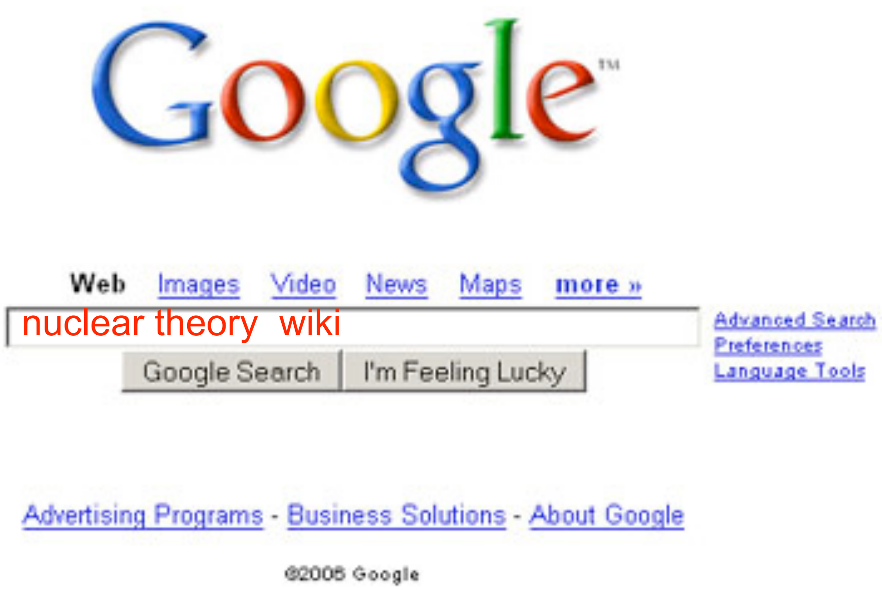

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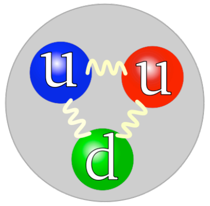
★ What is the interaction that binds nucleons together?
What is its relation to Quantum Chromo Dynamics?



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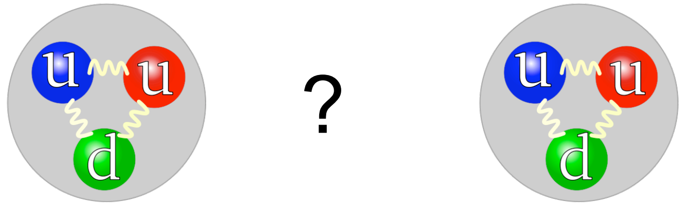

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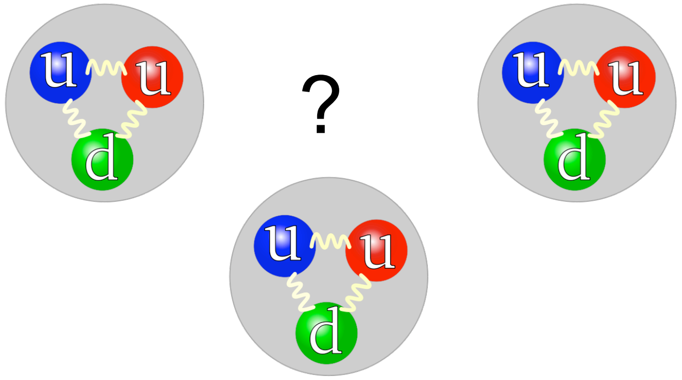

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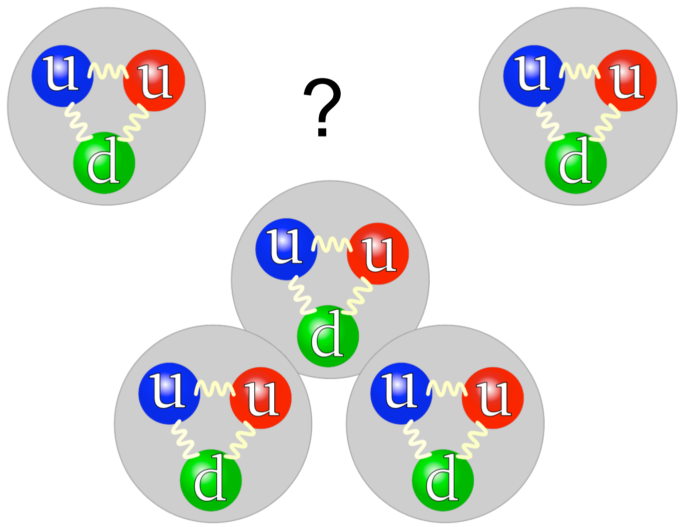

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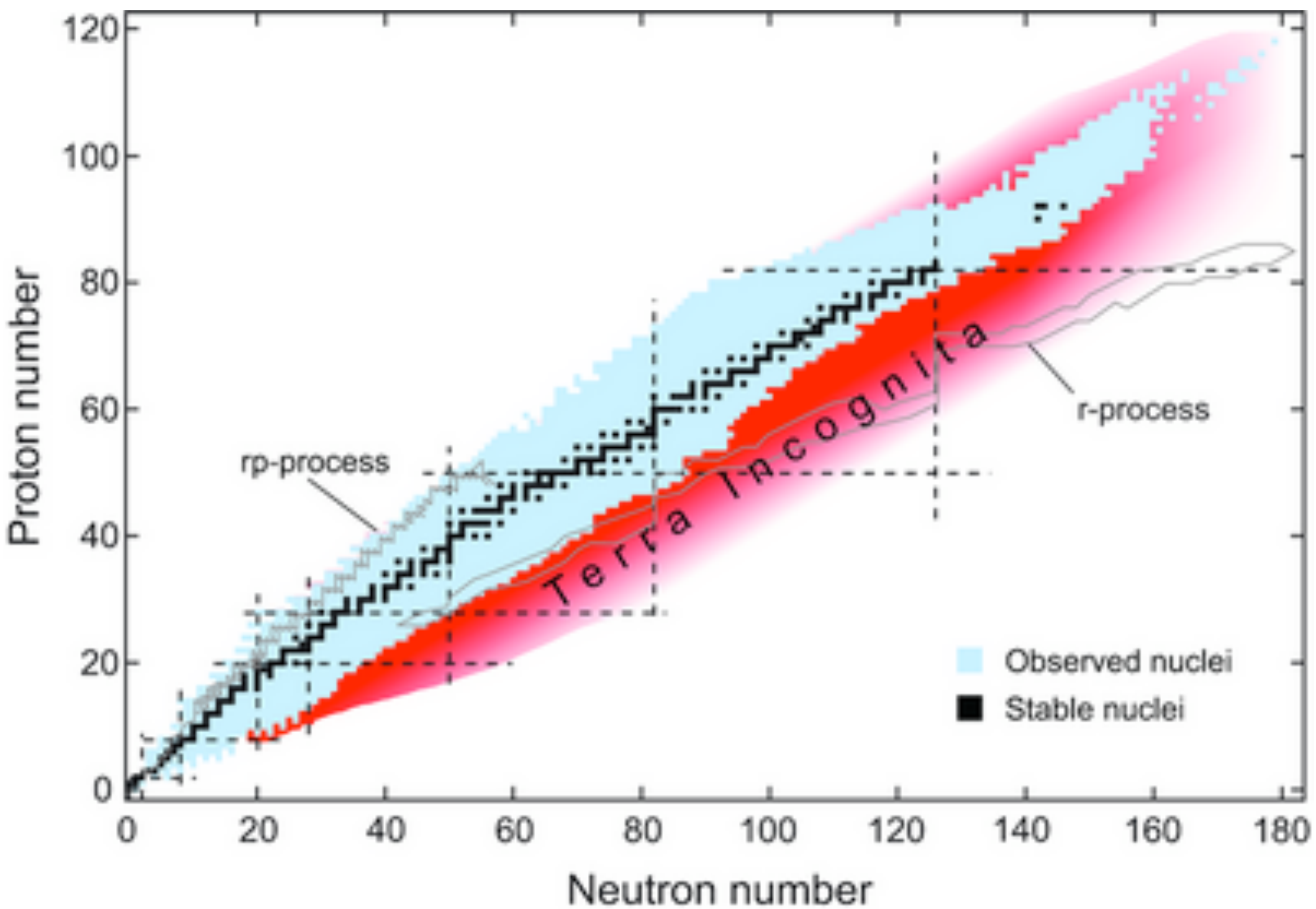

★ How happens that protons and neutrons are bound into stable and rare isotopes?
What are the limits of their existence?

★ How did the nucleosynthesis of elements occur?
Big Bang Nucleosynthesis
r-process ...

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What are the interesting questions we try to answer?

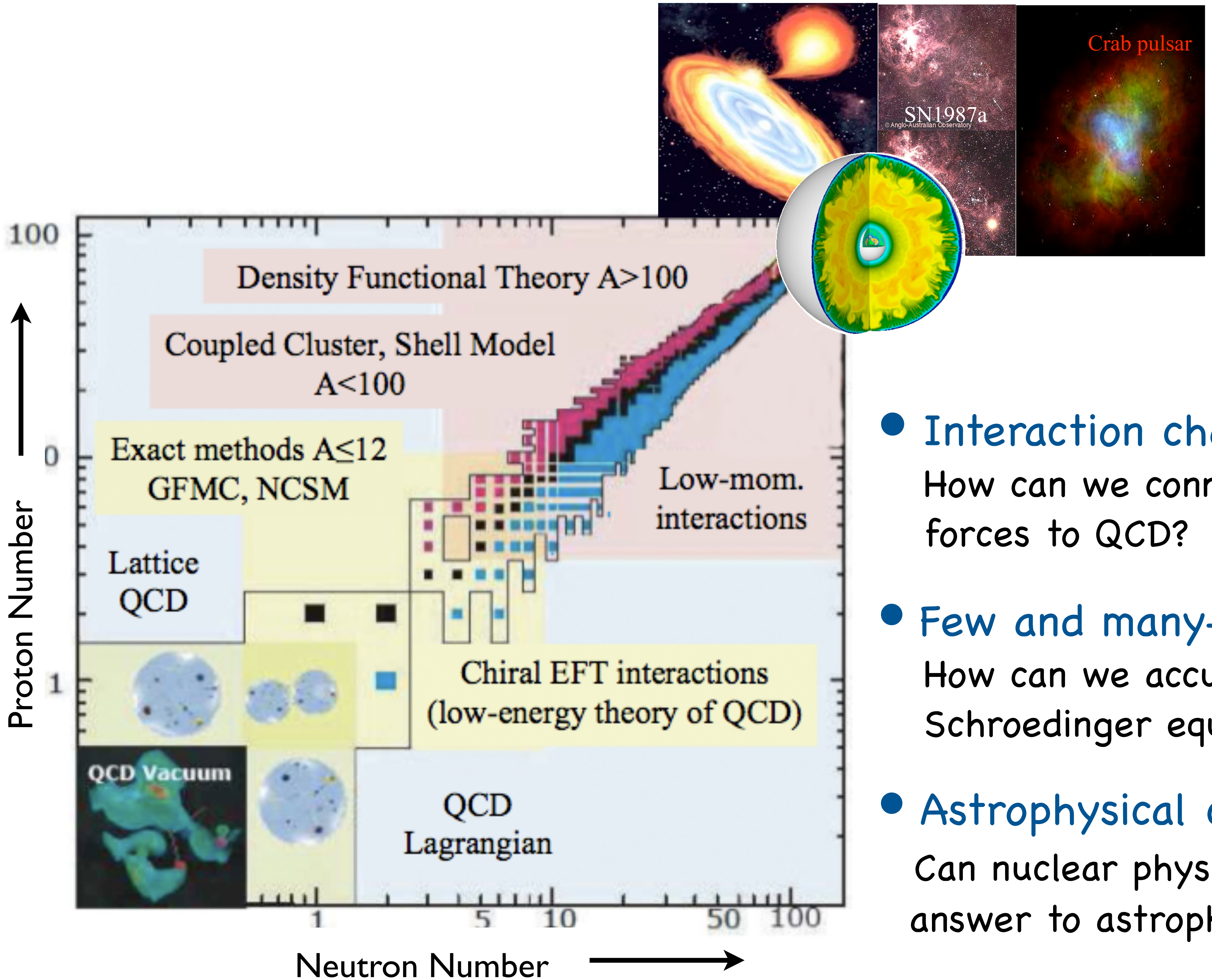
★ What is the nature of neutron stars?

★ What are the nuclear reactions that drive supernovae explosions?

before

after

Frontiers in Nuclear Theory

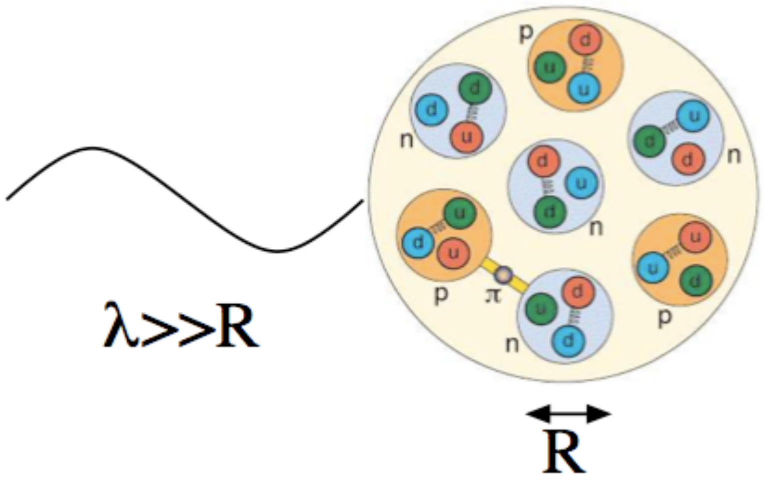


- **Interaction challenges**
  How can we connect nuclear forces to QCD?
- **Few and many-body challenges**
  How can we accurately solve the Schroedinger equation?
- **Astrophysical challenges**
  Can nuclear physics provide an answer to astrophysical questions?

Interaction challenges

The Chiral Effective Field Theory Approach

Separation of scales $\frac{1}{\lambda} = Q \ll \Lambda_{\rm b} = \frac{1}{R}$



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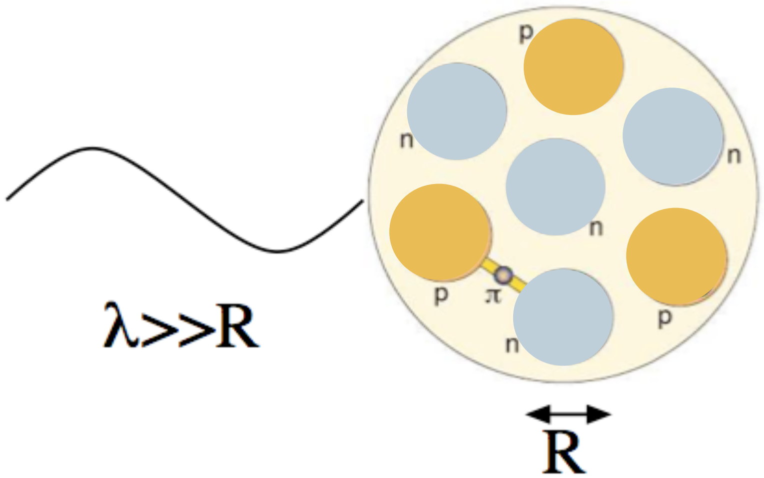

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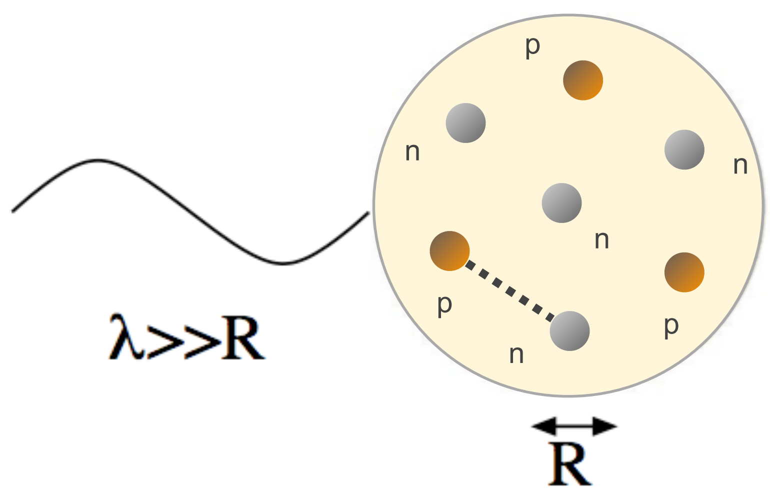

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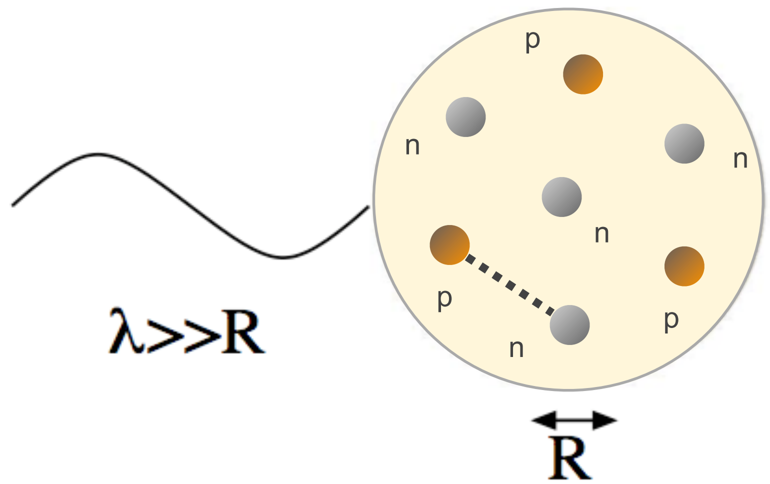

Limited resolution at low energy
expand in powers $\frac{Q}{\Lambda_b}$

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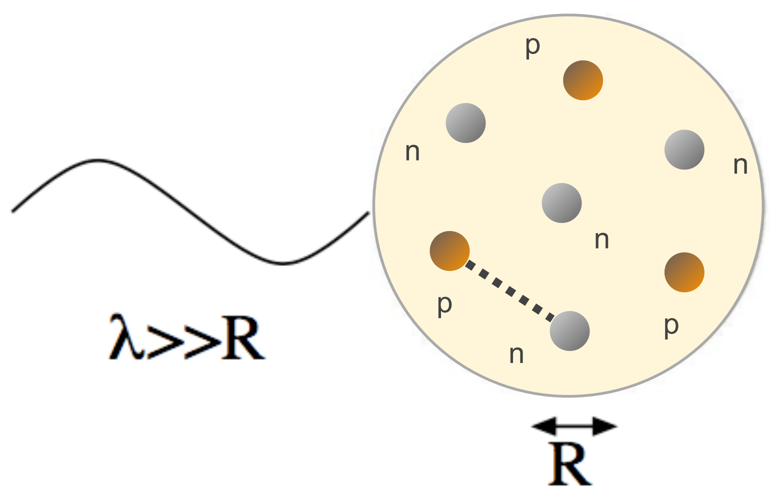

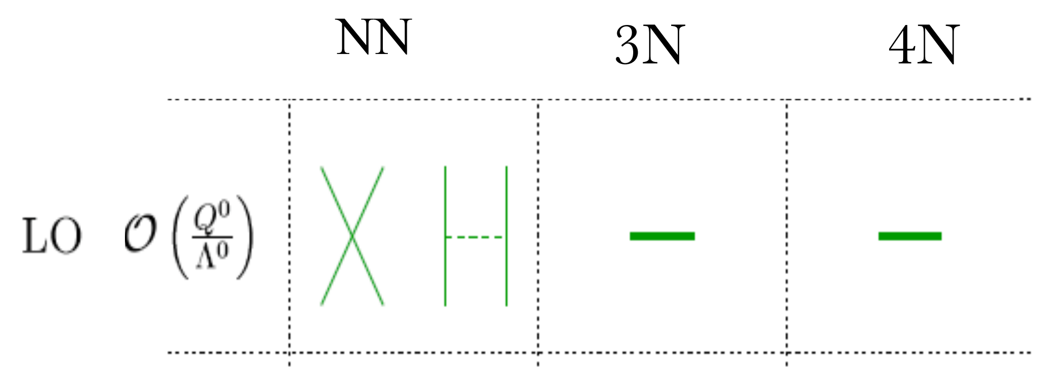

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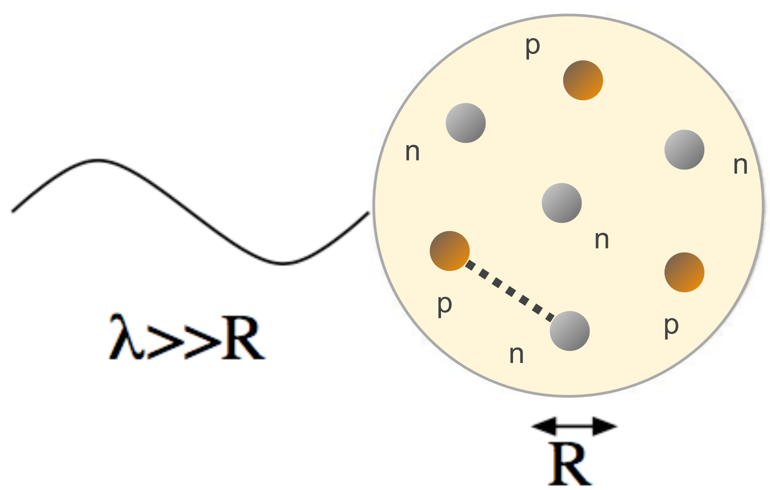

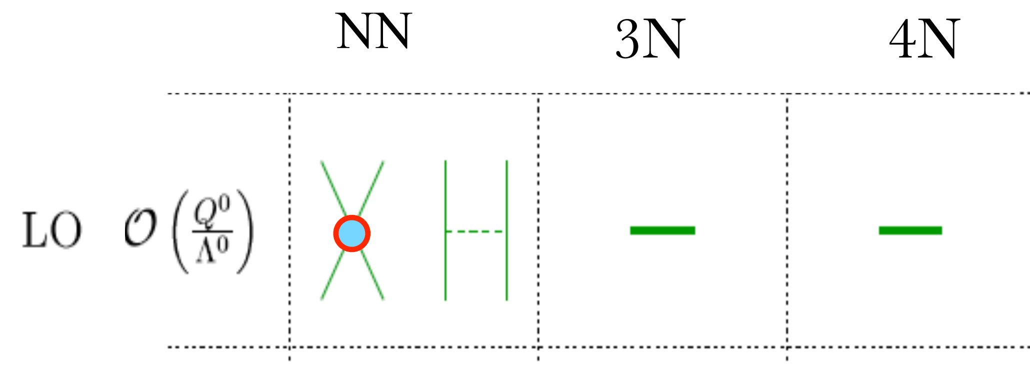

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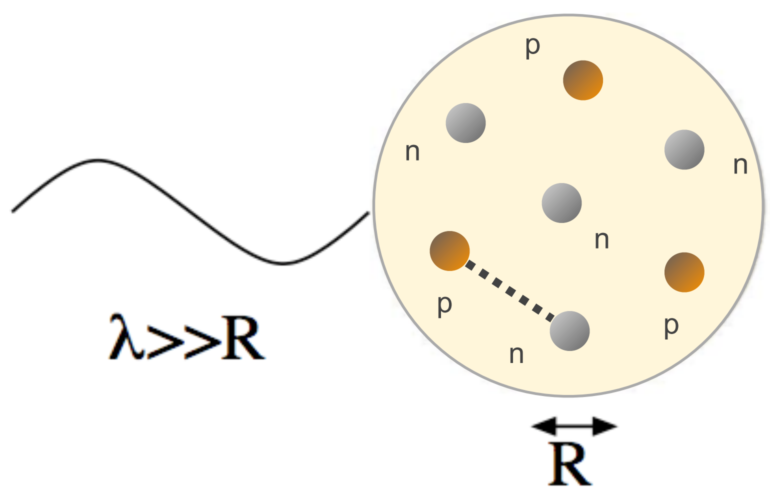

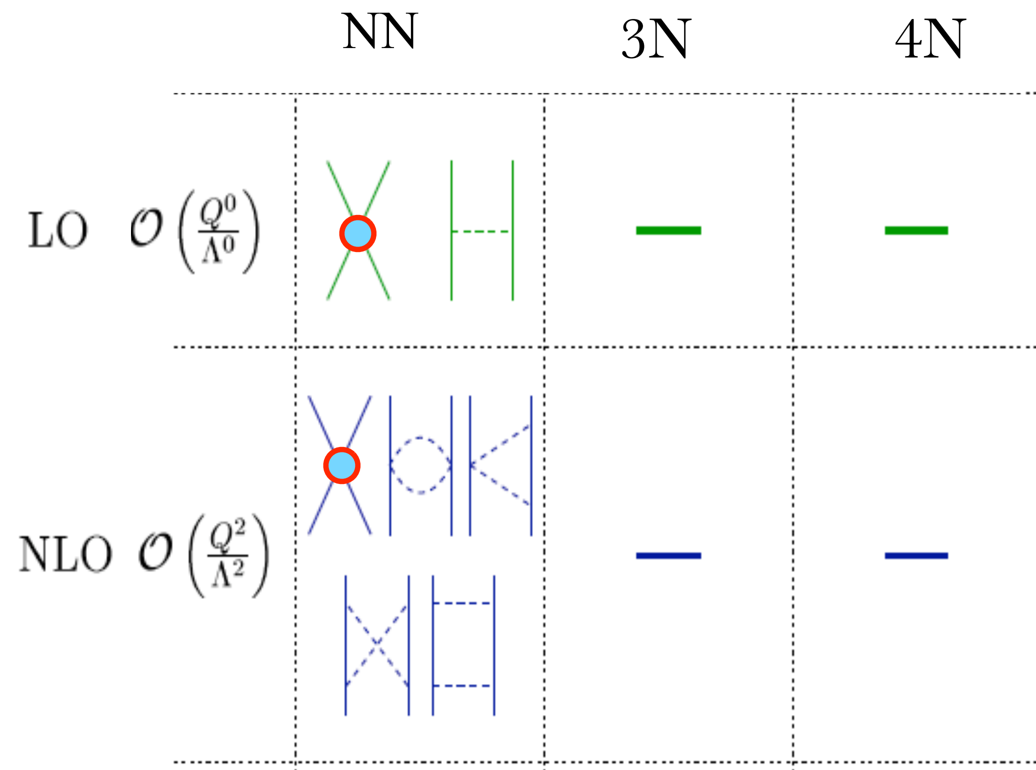

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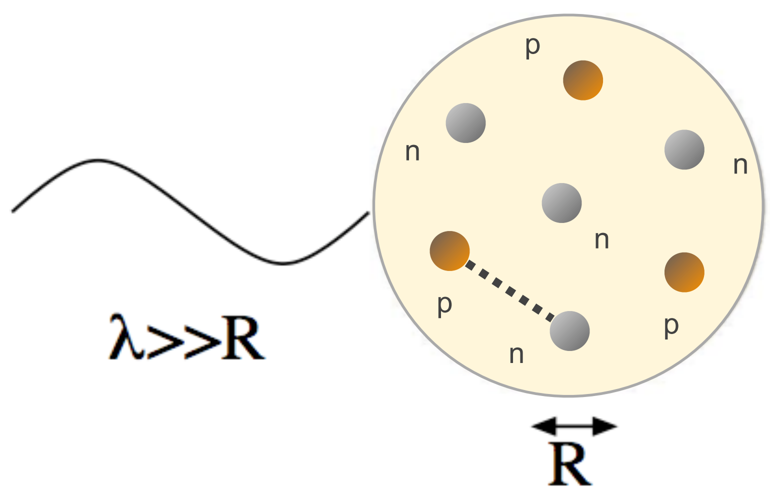

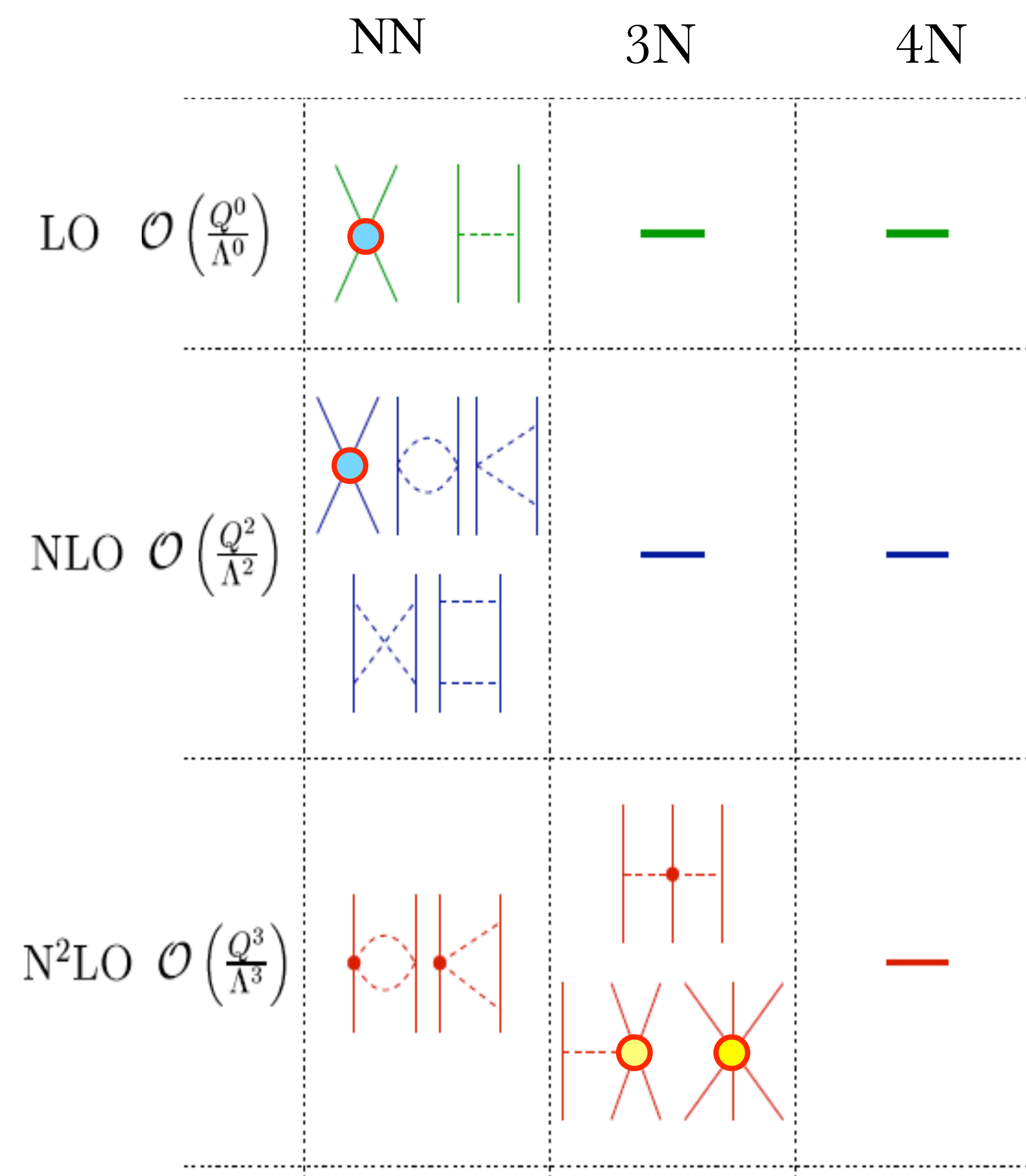

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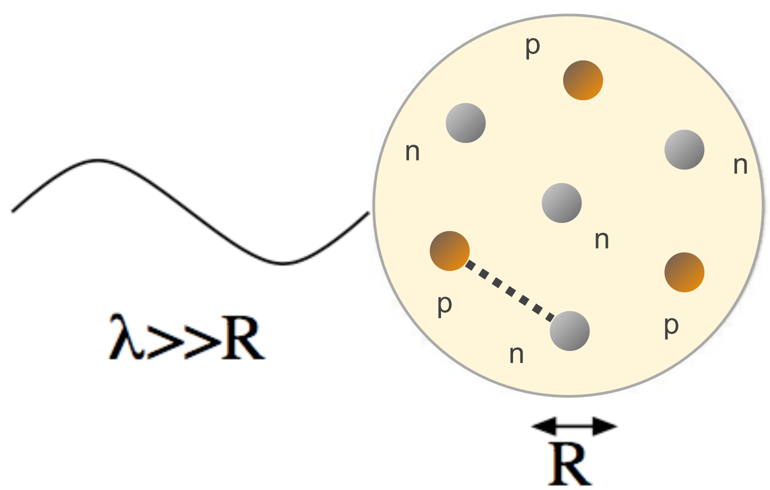

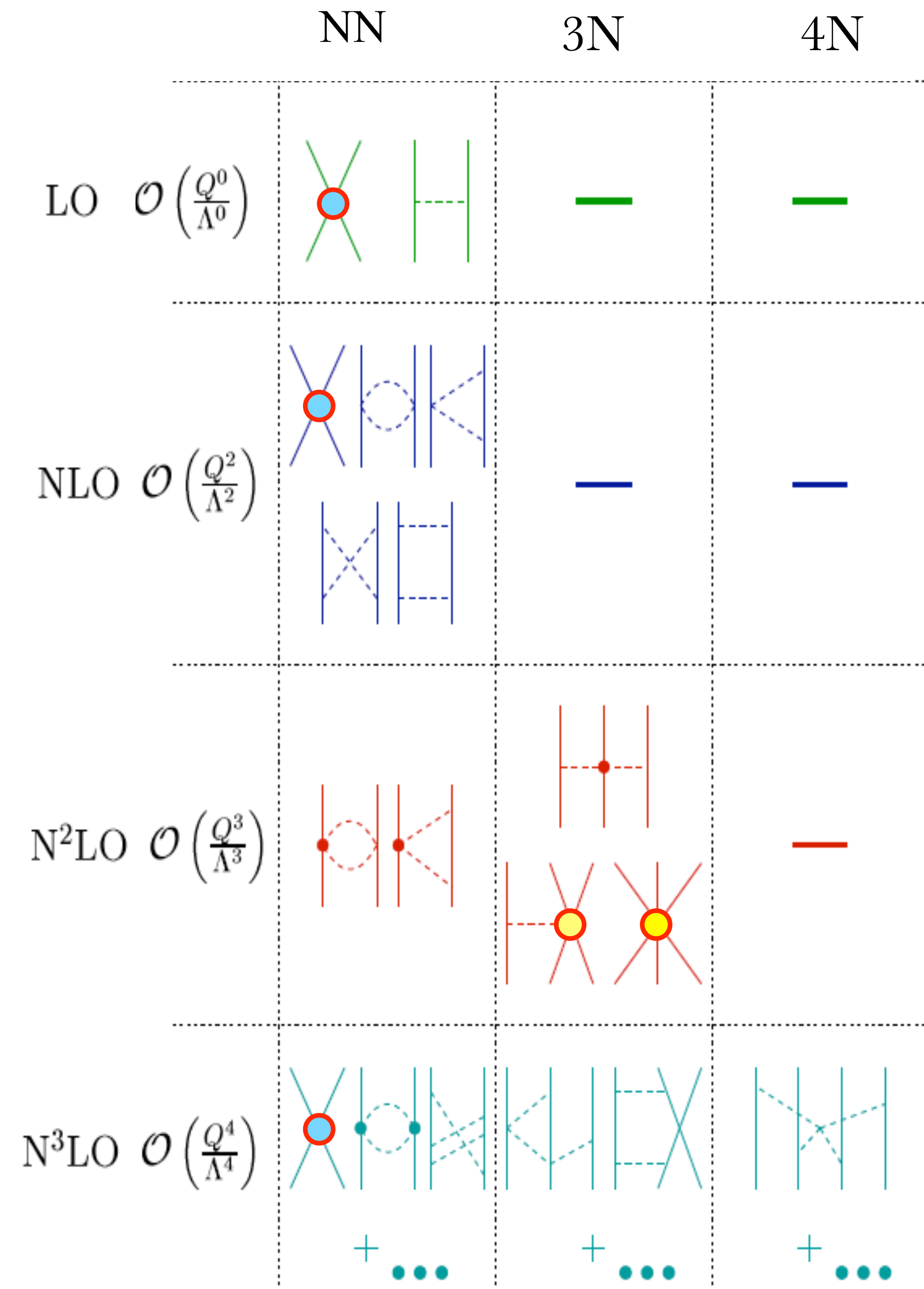

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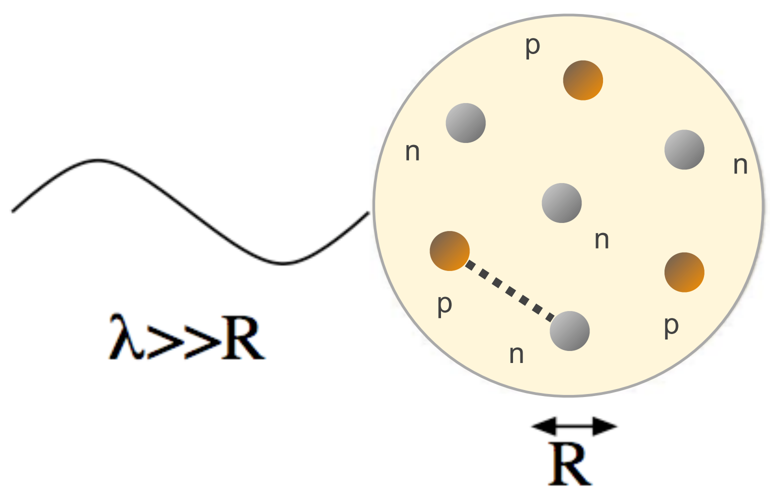

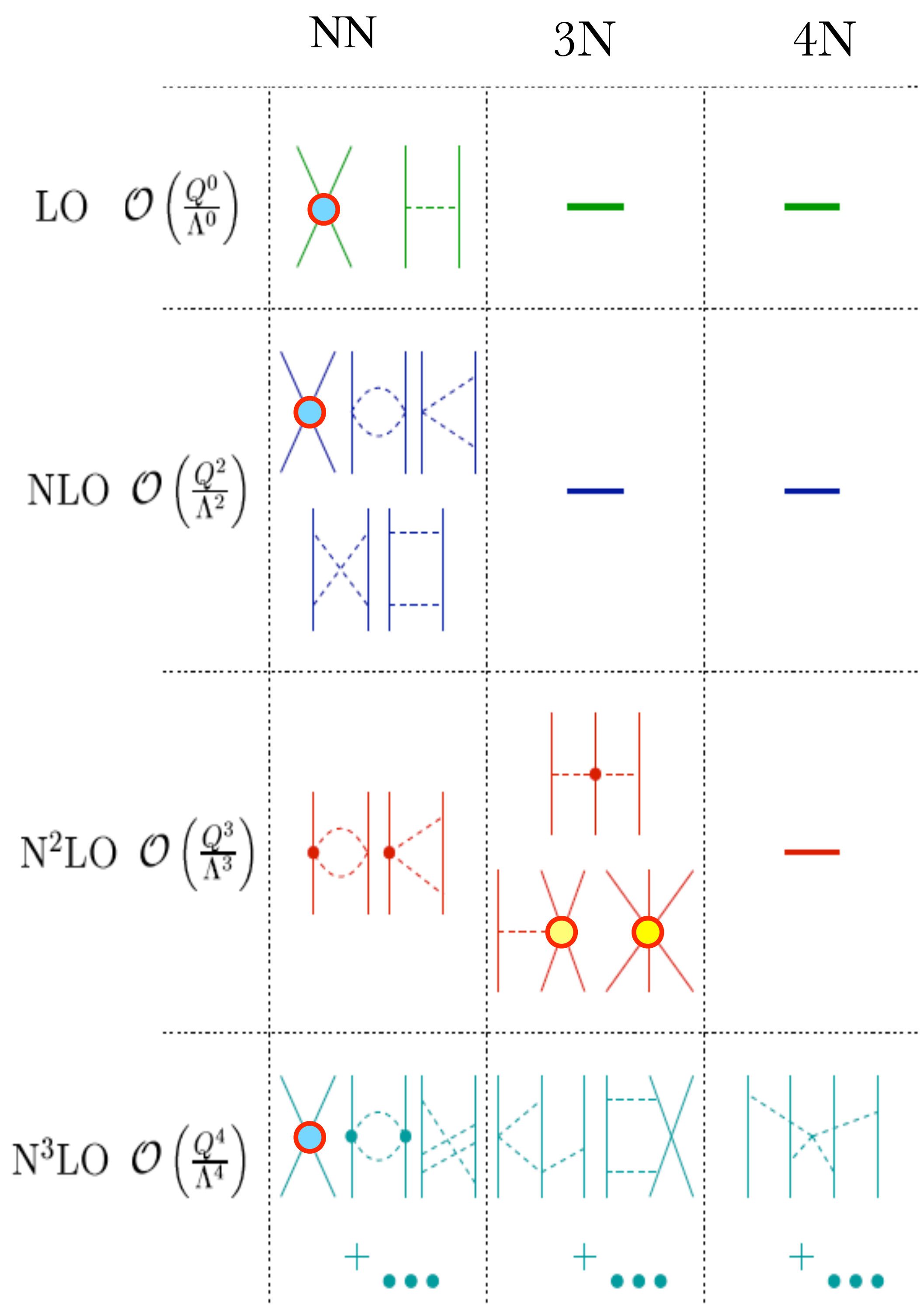

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Systematic and can provide error estimates

Interaction challenges

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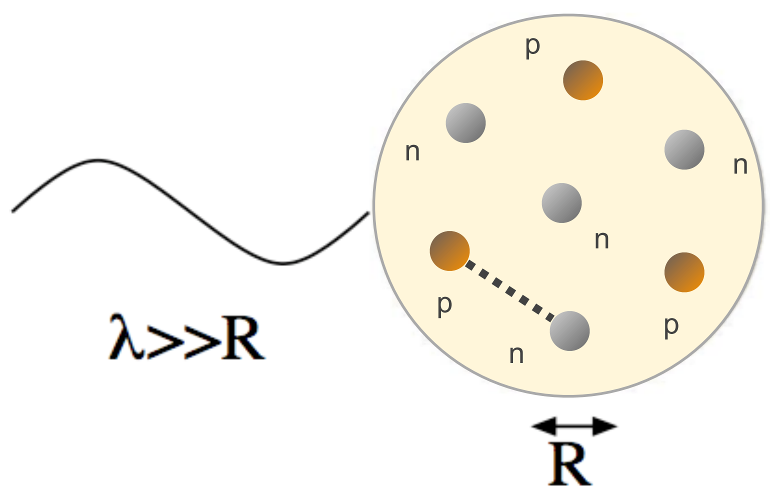
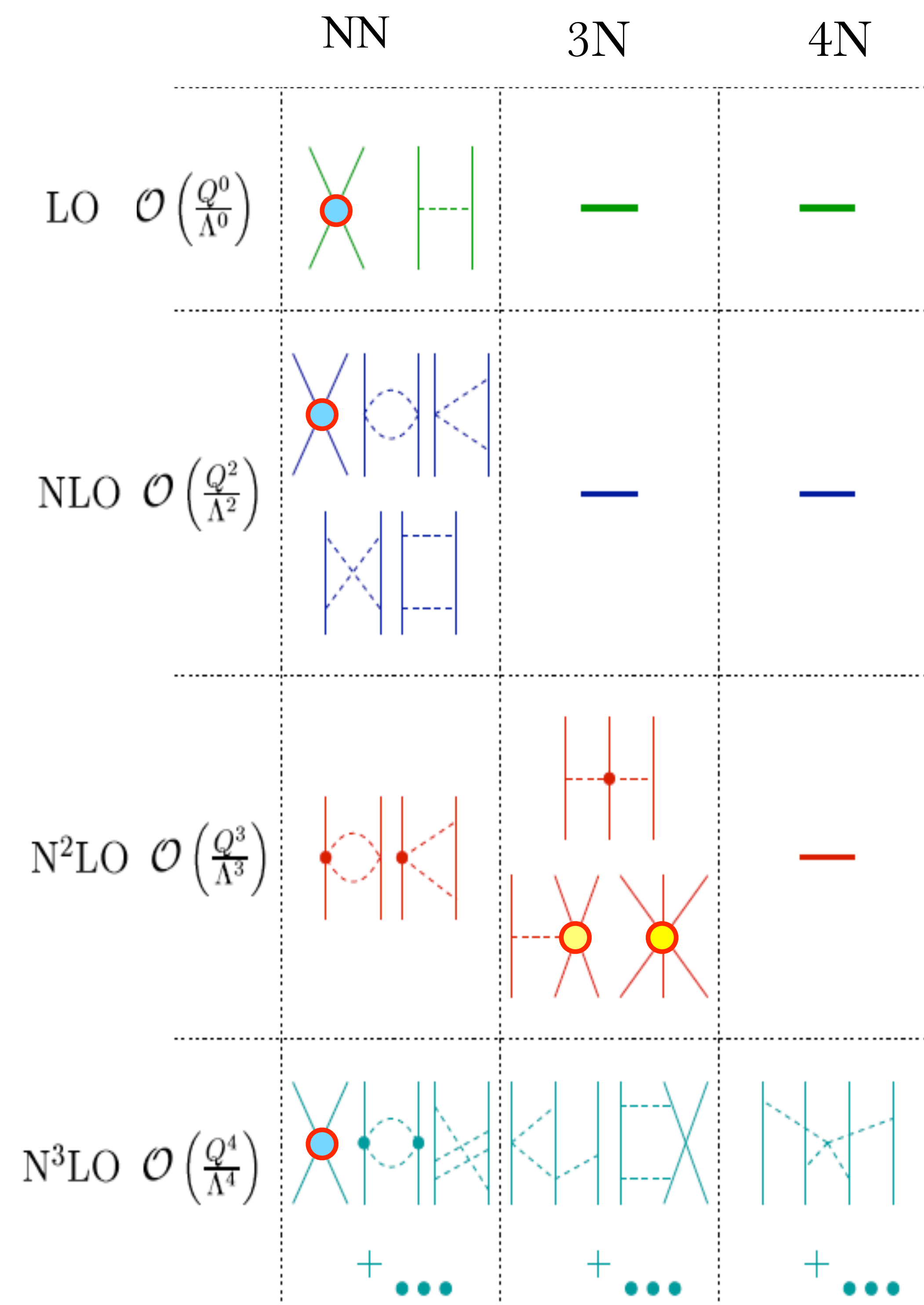




Limited resolution at low energy
expand in powers $\frac{Q}{\Lambda_b}$

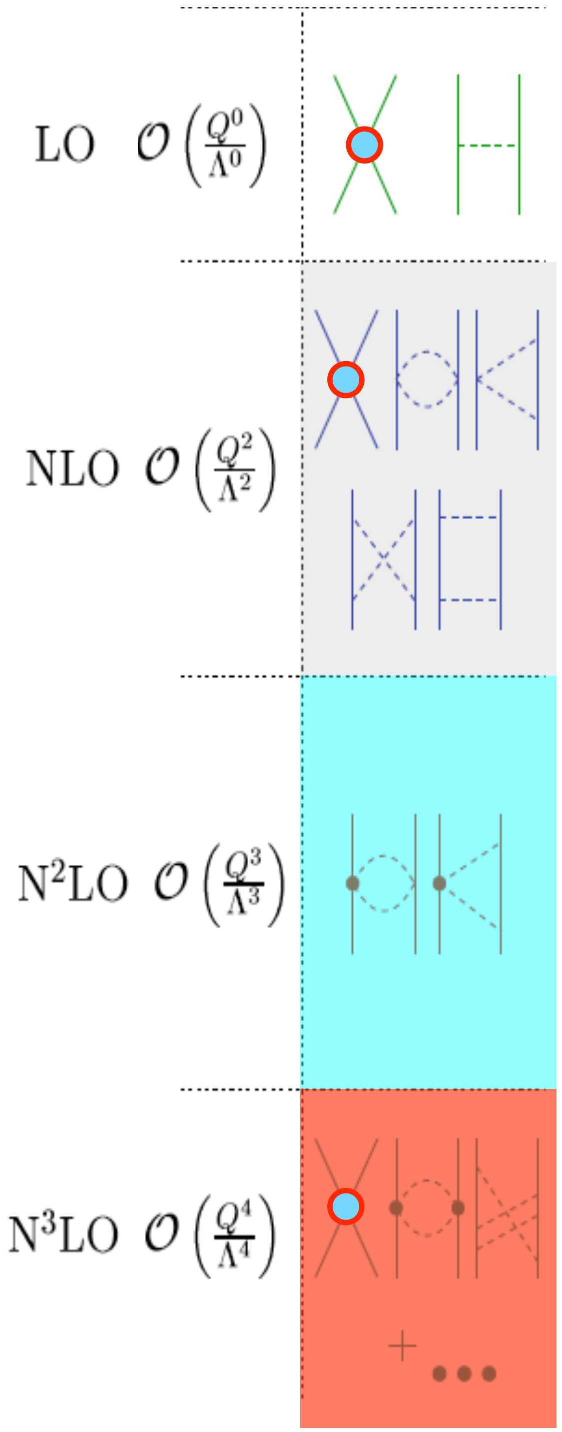
Systematic and can provide error estimates

Details of short distance physics not resolved,
but captured in short range couplings
➡ fit to experiment

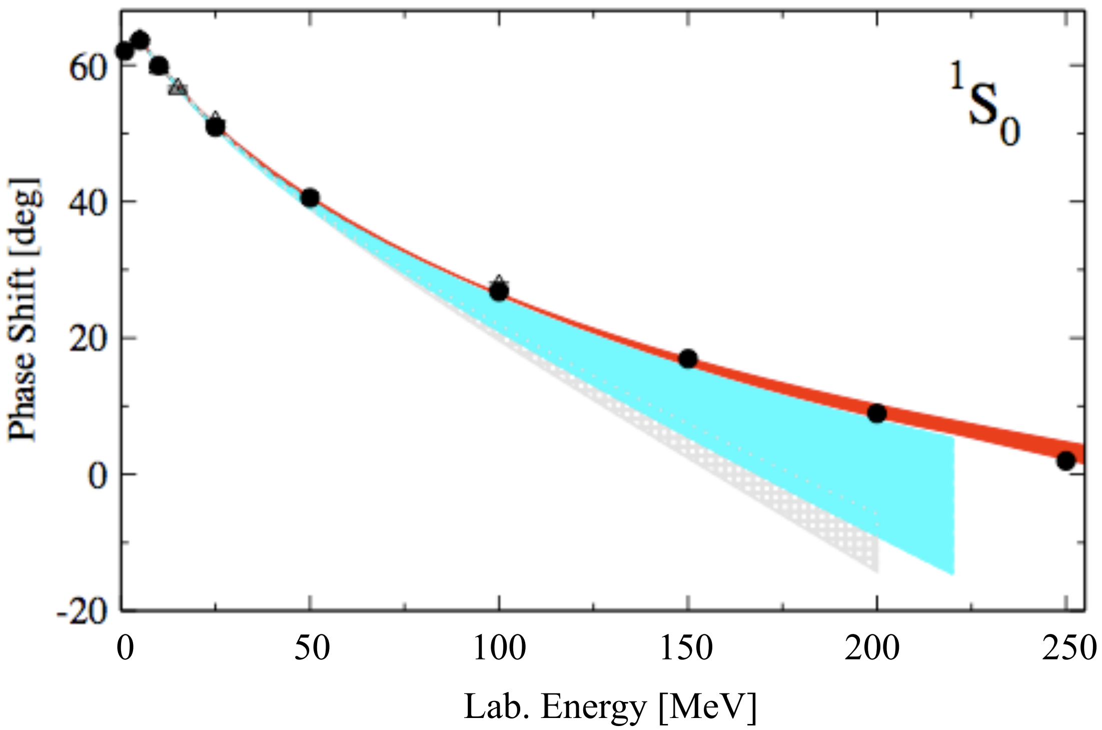
Interaction challenges

The Chiral Effective Field Theory Approach

- NN Sector -



coupling constants fitted to NN scattering phase-shifts



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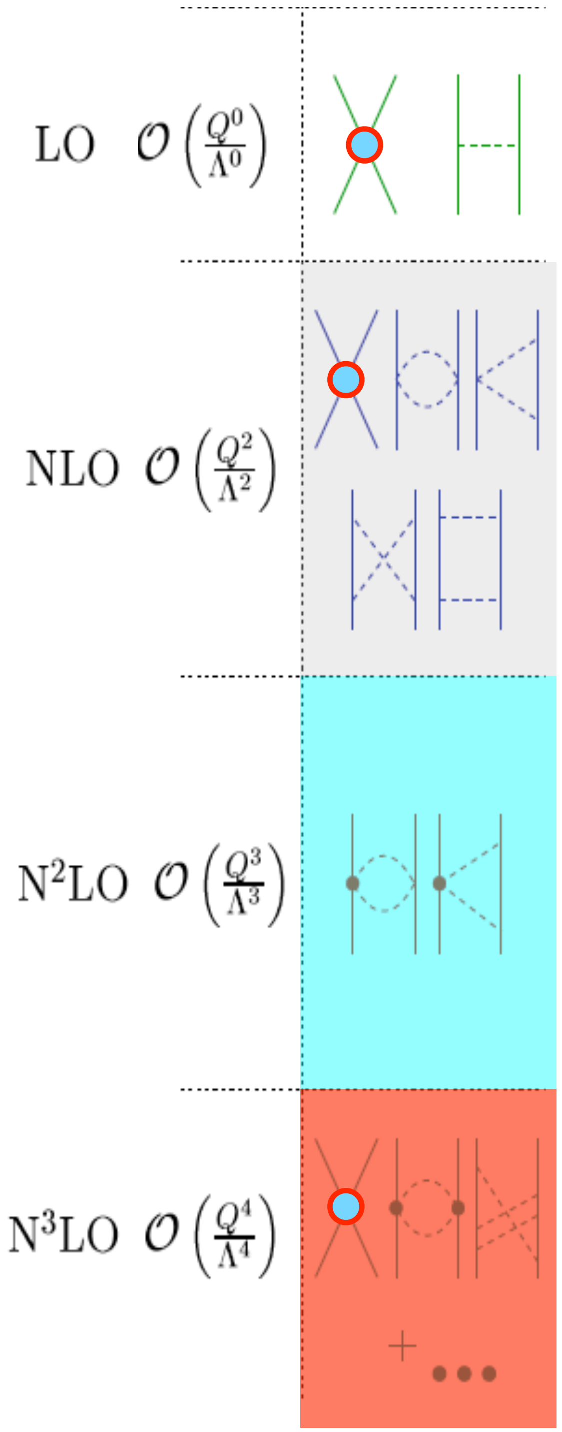

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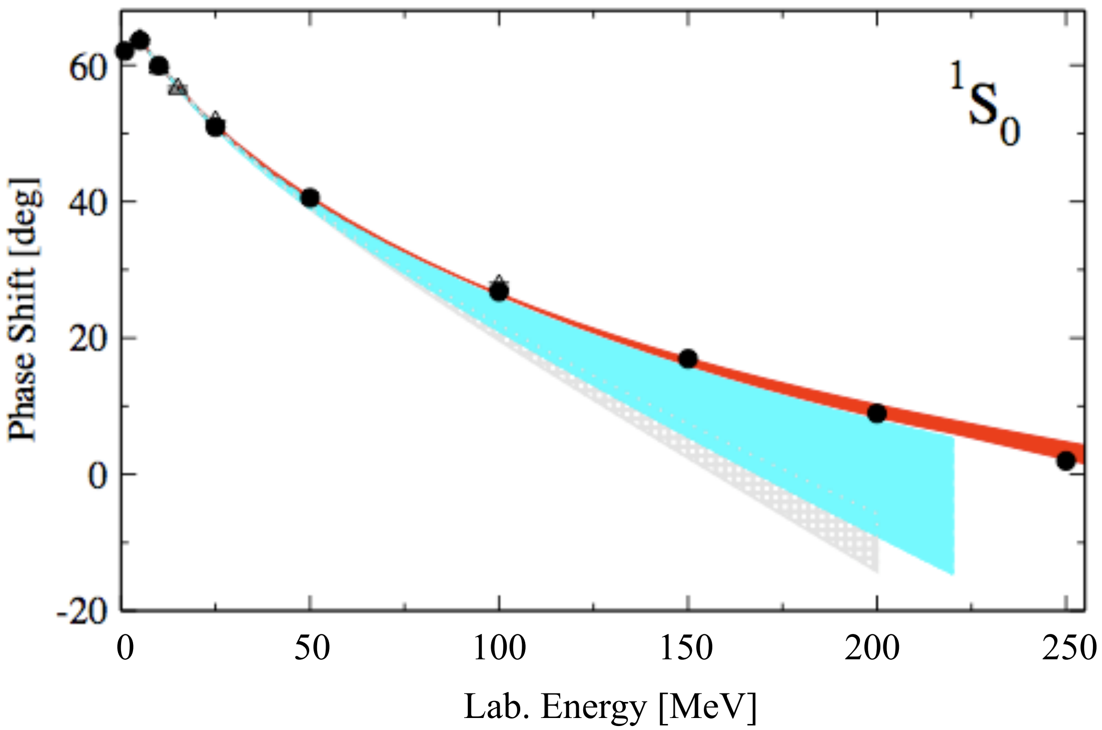

We have a resolution dependence!

Coupling constants run with the resolution scale Λ

Interaction challenges

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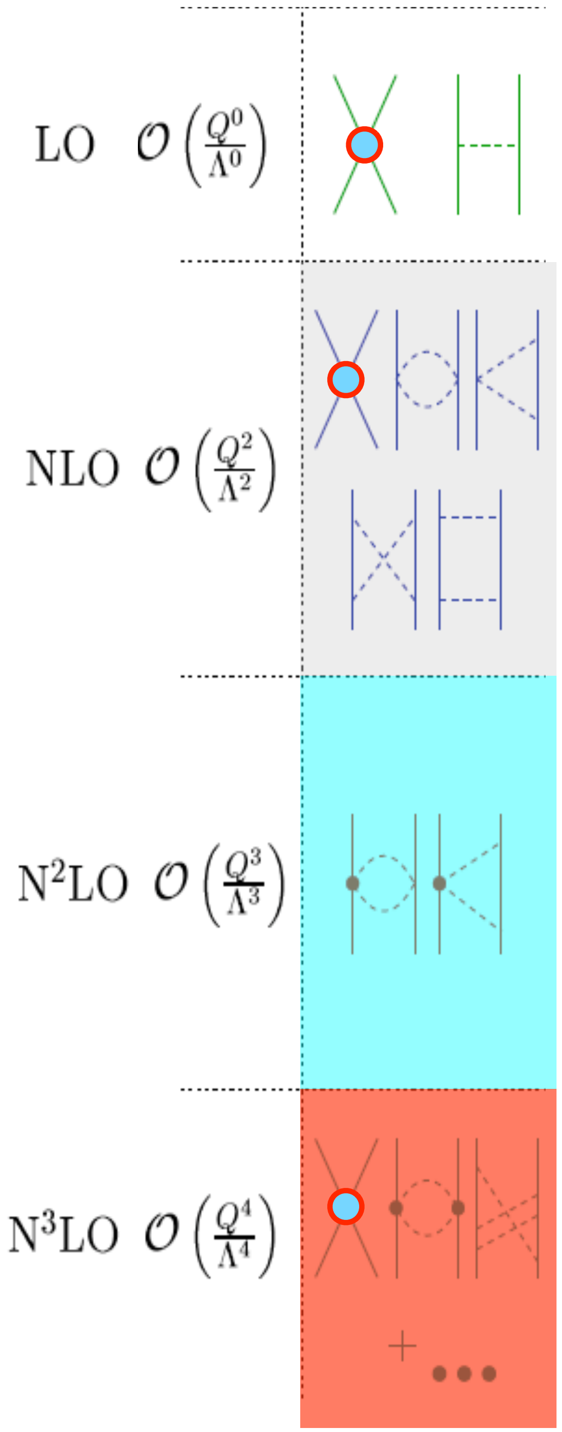

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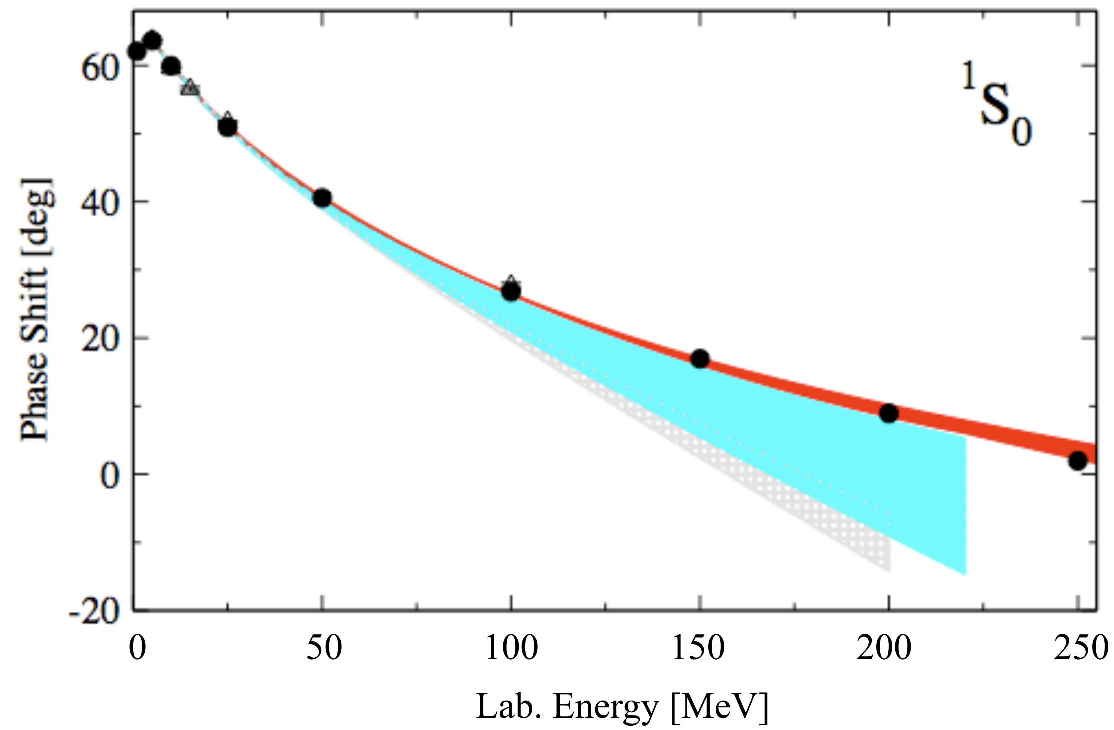

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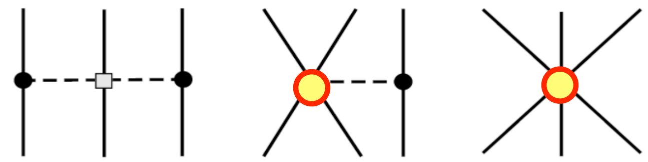
The dependence on the cutoff leads to different potentials, but observables should be cutoff independent

Interaction challenges

The Chiral Effective Field Theory Approach

- 3N Sector -

N^2LO



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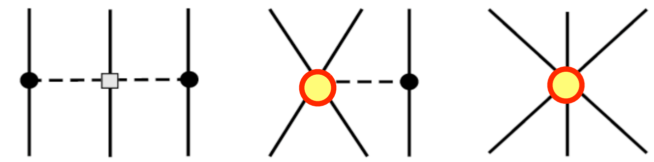
N^{2}LO 

- What is its origin? Nucleons are effective degrees of freedom

Interaction challenges

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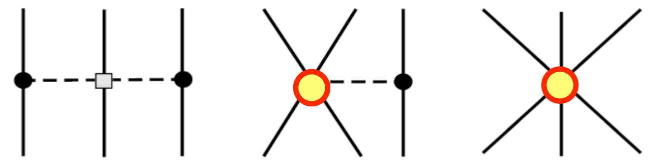
N^{2}LO 

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"The three-body force is a force that does not exist in a two-nucleon system, but appears in a system with three objects or more" $A \geq 3$

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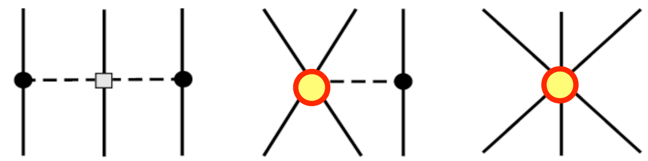
N^{2}LO 

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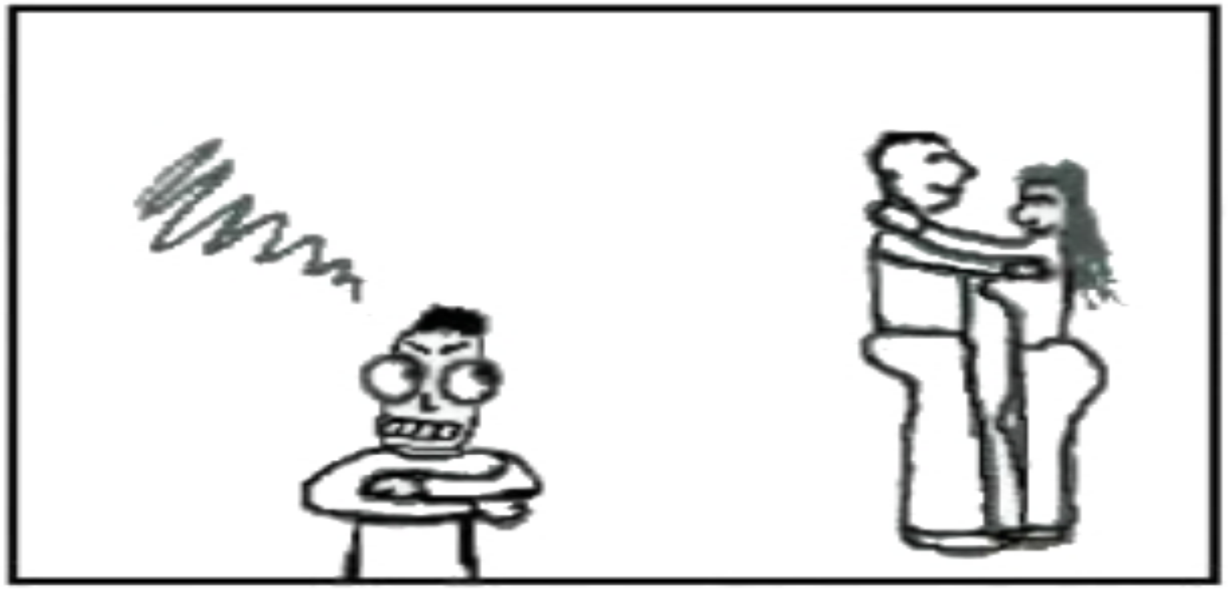
As an analogy, if we identify objects with human beings and forces with emotions, then jealousy is a good example of a three-body force: it is not felt as long as two-person are acting, but it shows up as soon as a third person enters the scene.



From N. Kalantar, FM50

Interaction challenges

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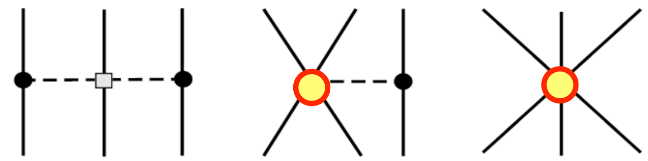
N^{2}LO  $A \geq 3$

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Interaction challenges

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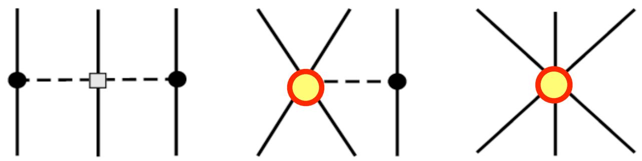
N^2LO  $A \geq 3$

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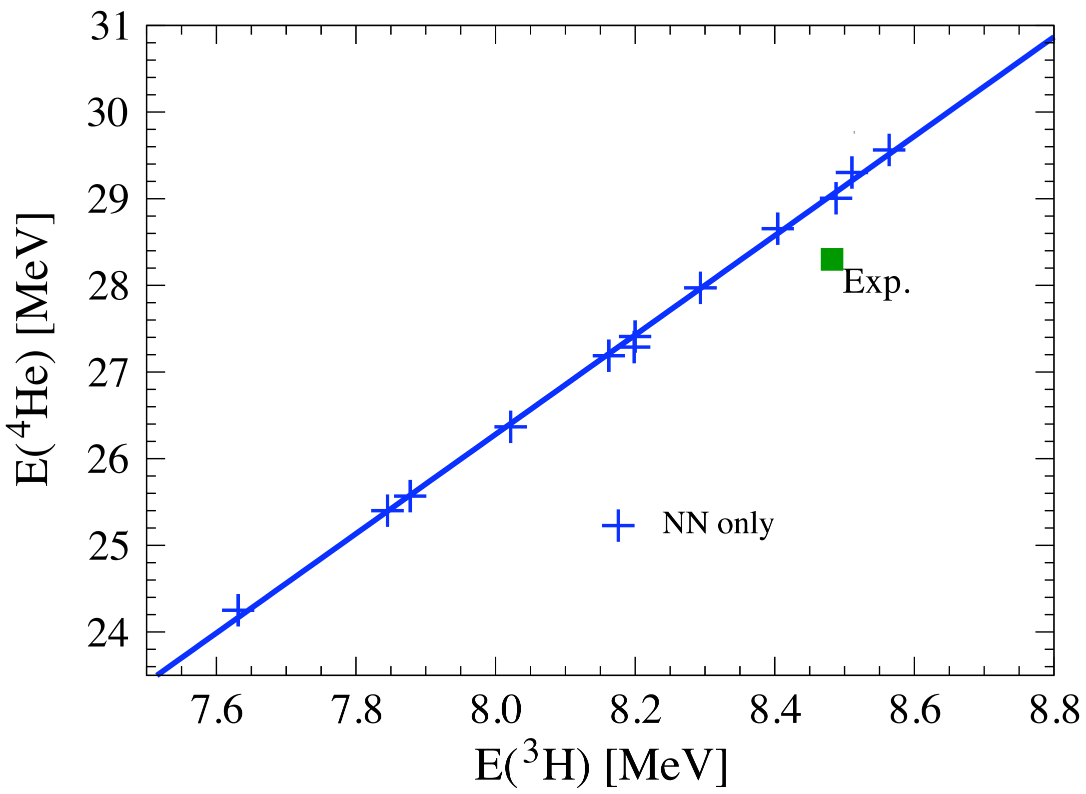
- How to constrain it?

  By fitting the coupling constants to data for an observable which is sensitive to 3NF



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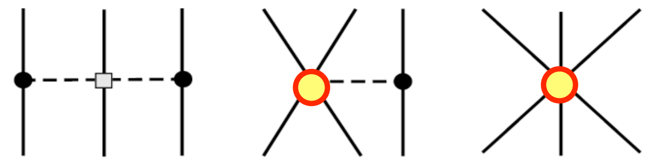

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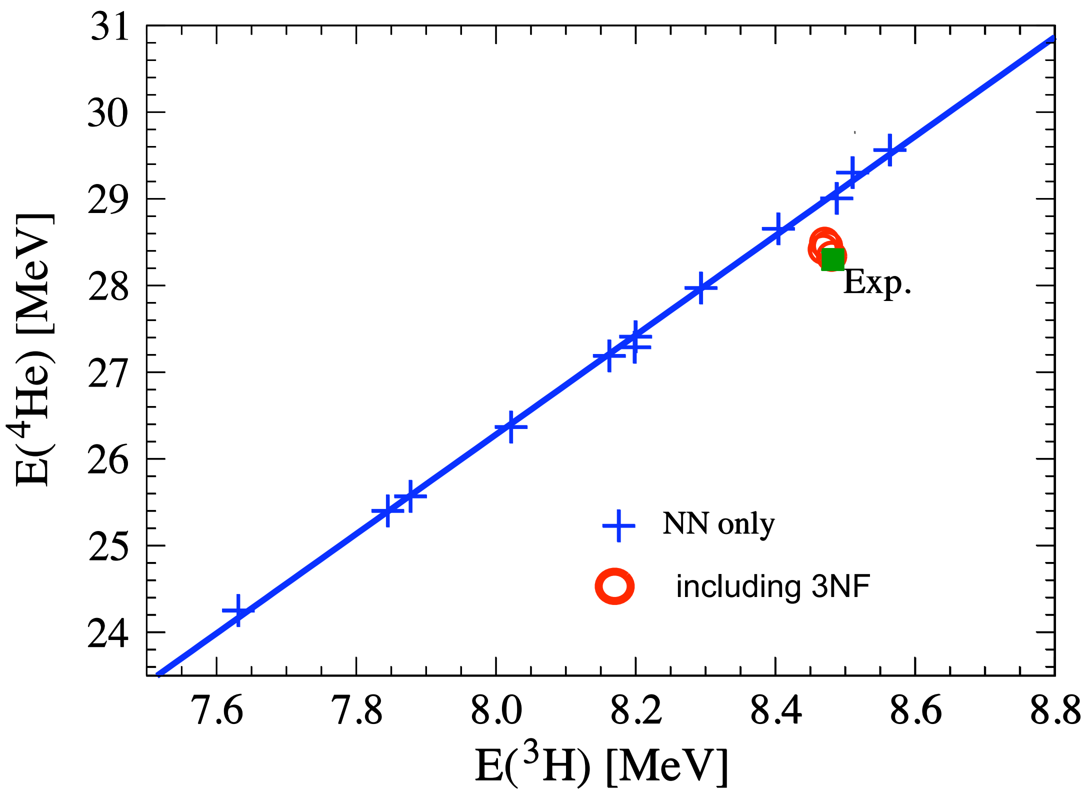

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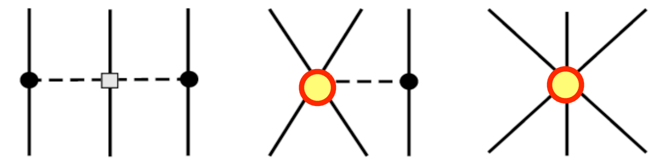
N^{2}LO  $A \geq 3$

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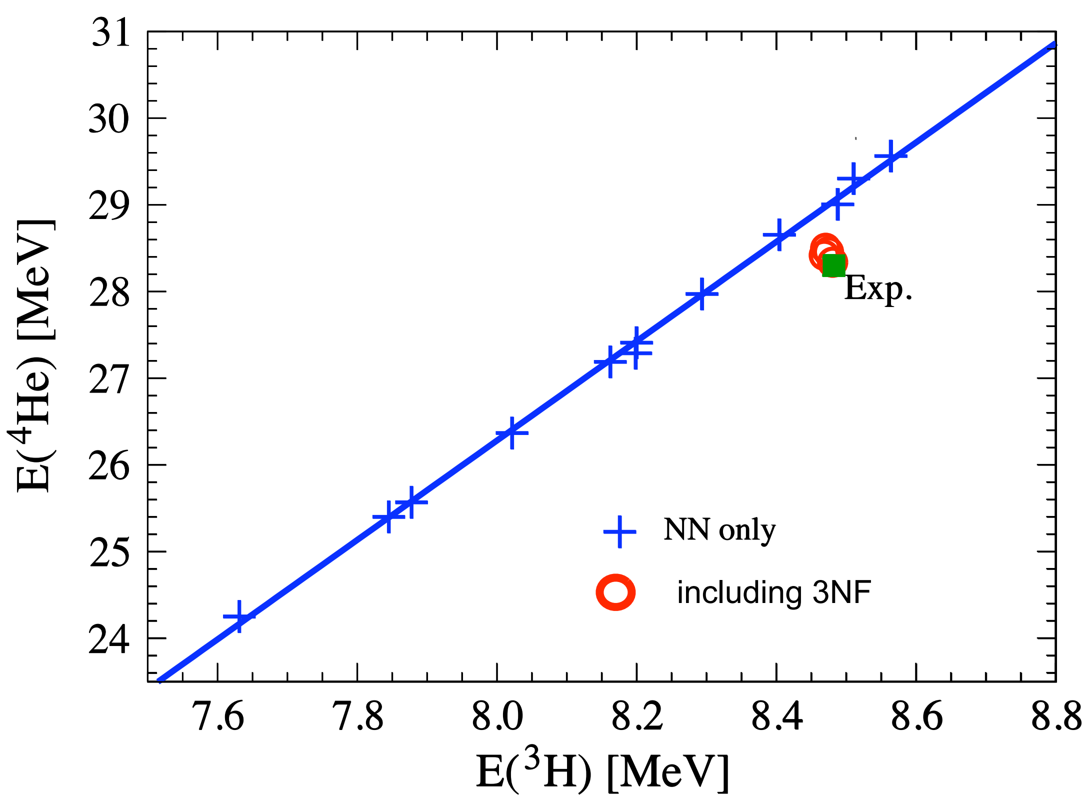

- **Predict new observables!**

Few- and many-body challenges

In the sector of few-body nuclei (A<5) we have reached an incredible level of accuracy.

Challenge: develop new many-body methods that can extend the frontiers to heavier nuclei

Coupled Cluster Theory

Nucleus	E/A [MeV]	V/A [MeV]	$\Delta E/A$ [MeV]
^{4}He	−5.99	−22.75	1.08
^{16}O	−6.72	−30.69	1.25
^{40}Ca	−7.72	−36.40	0.84
^{48}Ca	−7.40	−37.97	1.27
^{48}Ni	−6.02	−36.04	1.21

Hagen et al., PRL 101 (2008)

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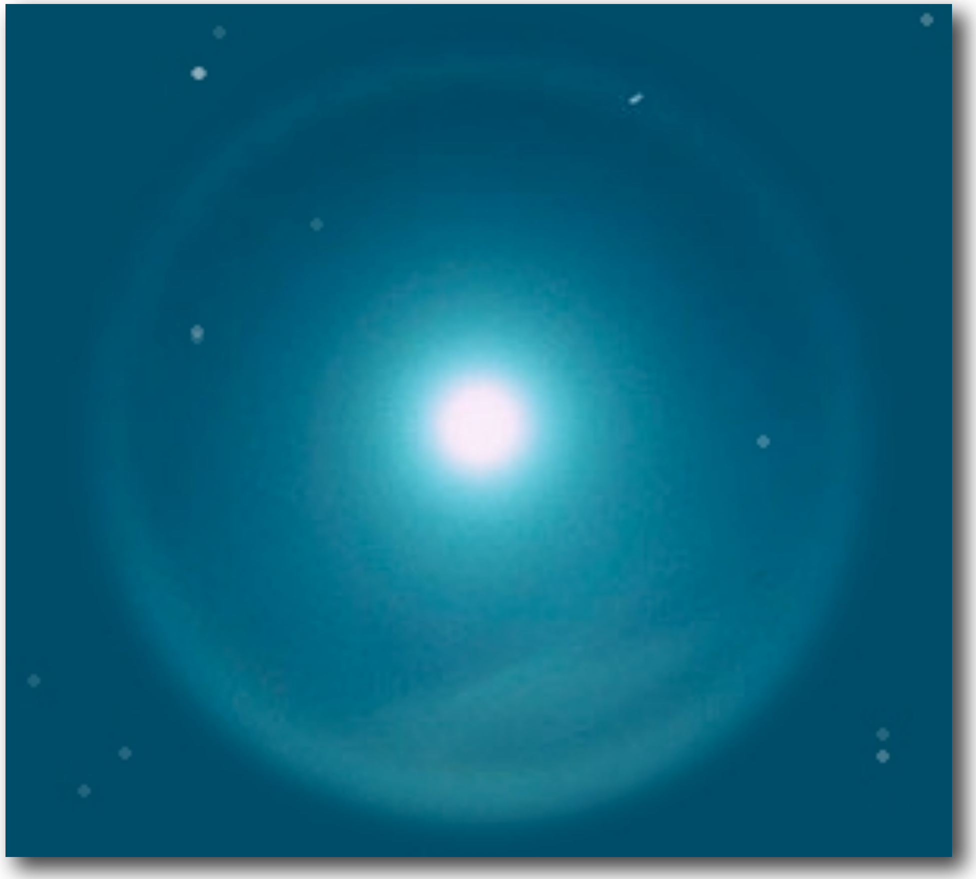
^{40}Ca	-7.72	-36.40	0.84
^{48}Ca	-7.40	-37.97	1.27
^{48}Ni	-6.02	-36.04	1.21

Hagen et al., PRL 101 (2008)

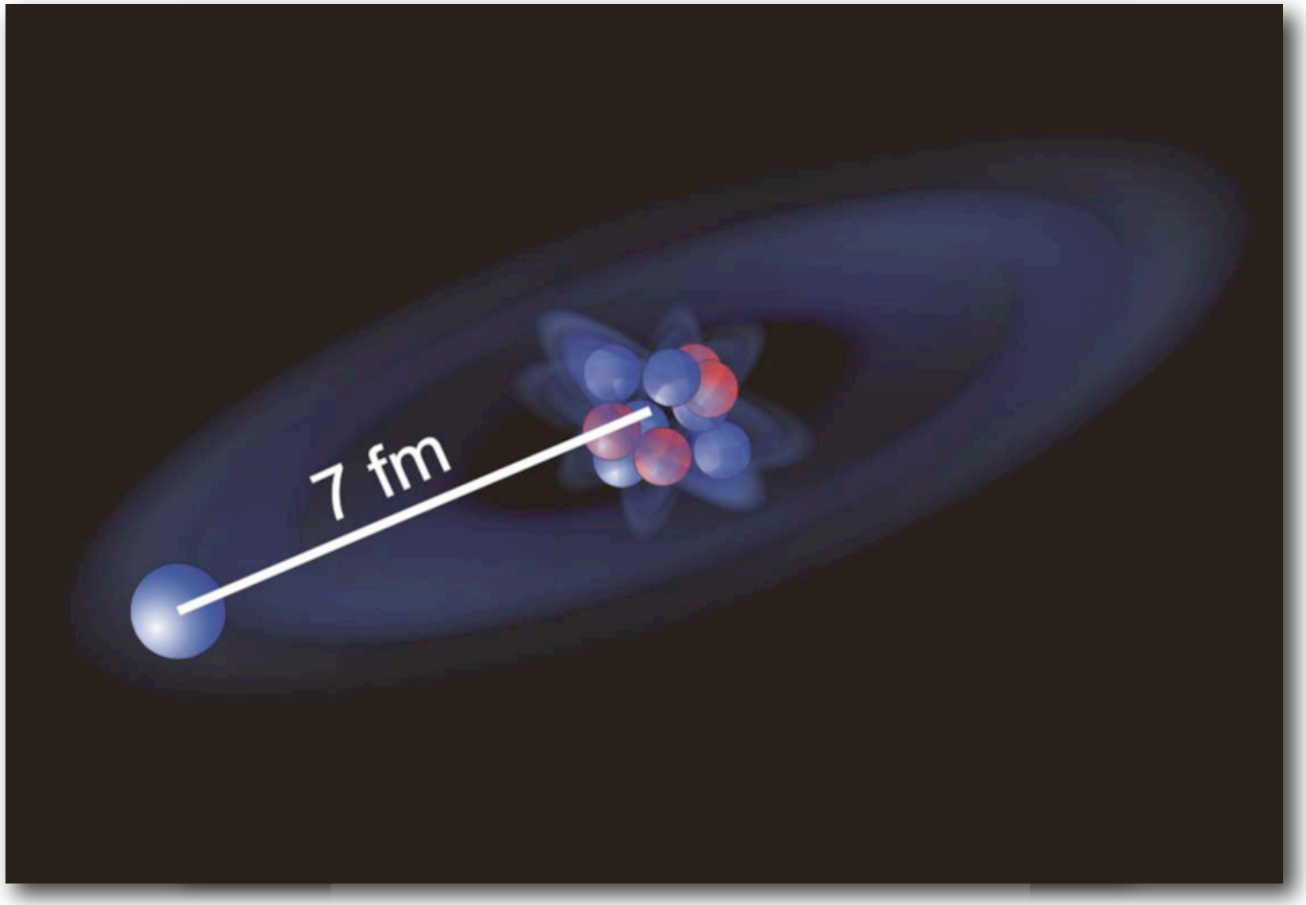
Future: advance ab-initio methods to heavier and neutron rich nuclei

The physics of Halo Systems

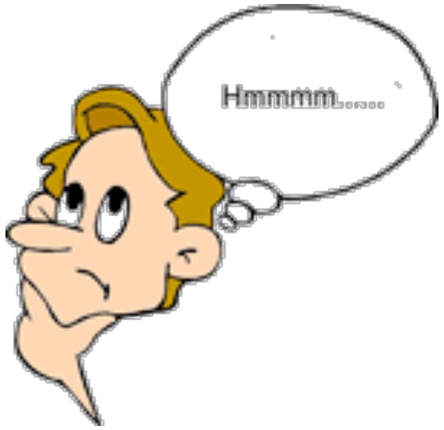


Moon Halo

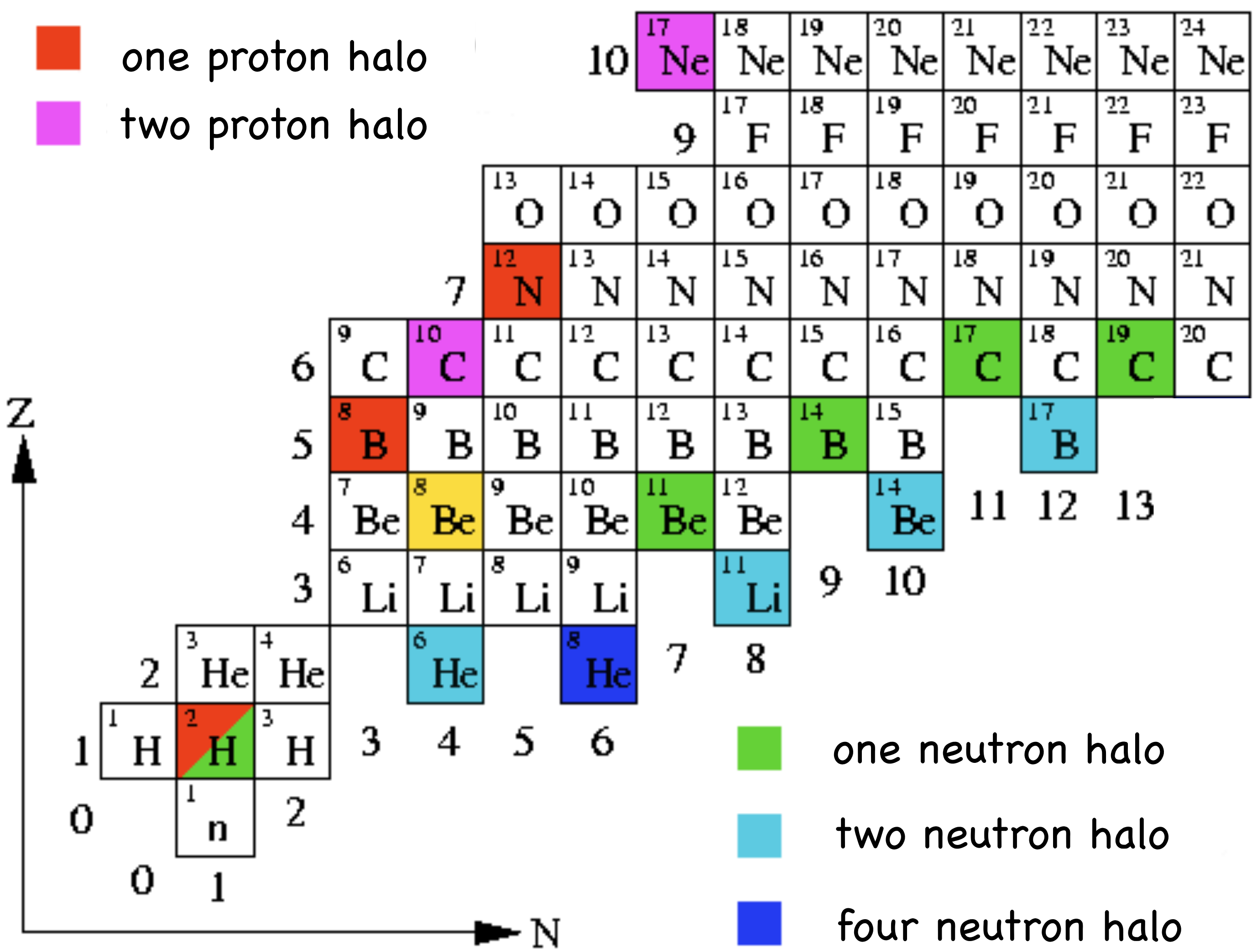
The physics of Halo Systems

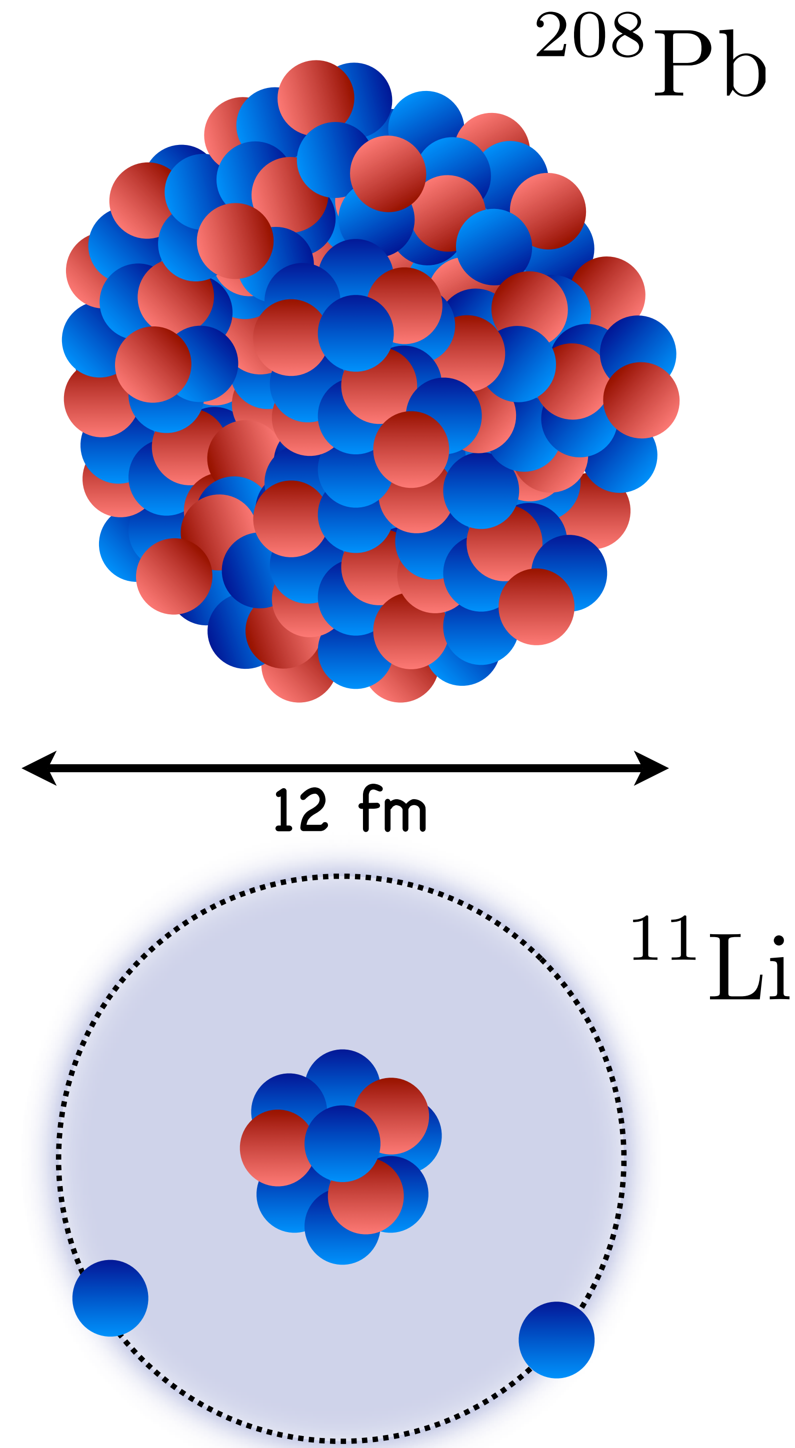


Nuclear Halo



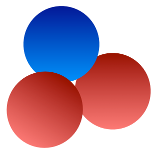
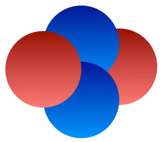
Halo nuclei


one proton halo
two proton halo
one neutron halo
two neutron halo
four neutron halo
Z
N


^{208}Pb
12 fm
^{11}Li

The helium isotope chain

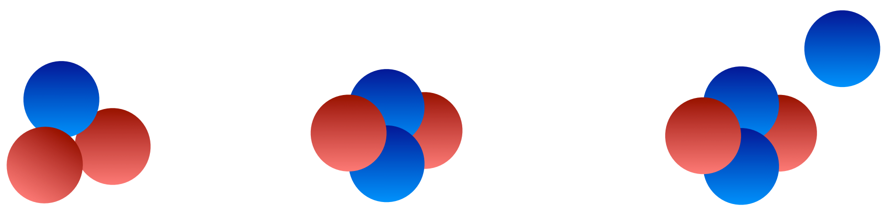
Shows many interesting features:

^{3}He	^{4}He
	
bound	bound

The helium isotope chain

Shows many interesting features:

$^{3}\mathrm{He}$ $^{4}\mathrm{He}$ $^{5}\mathrm{He}$

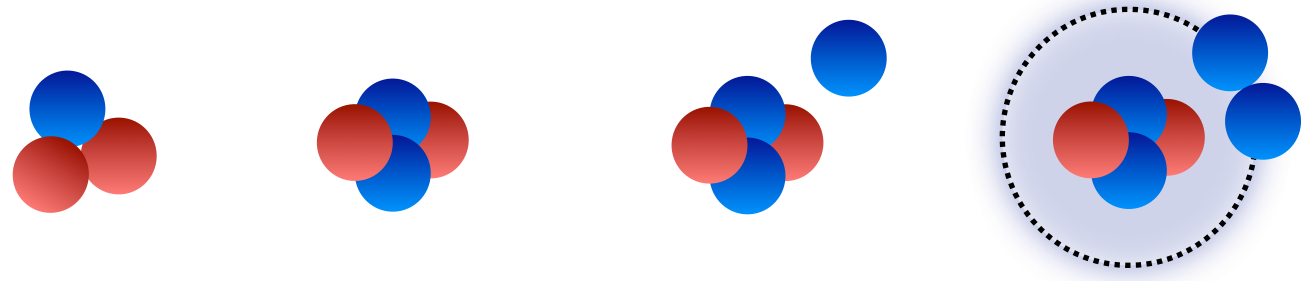


bound bound unbound

The helium isotope chain

Shows many interesting features:

$^{3}\mathrm{He}$ $^{4}\mathrm{He}$ $^{5}\mathrm{He}$ $^{6}\mathrm{He}$

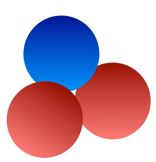


bound | bound | unbound | bound halo

The helium isotope chain

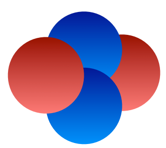
Shows many interesting features:

$^{3}\mathrm{He}$



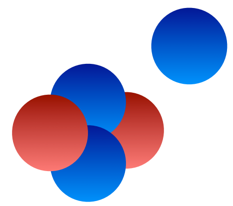
bound

$^{4}\mathrm{He}$



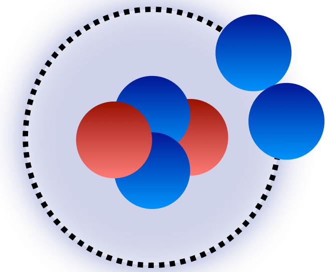
bound

$^{5}\mathrm{He}$



unbound

$^{6}\mathrm{He}$



bound

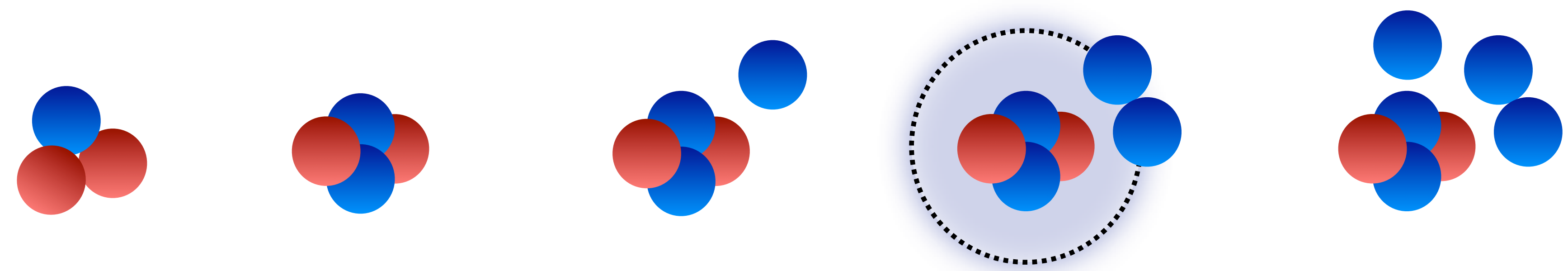
halo

Borromean system

The helium isotope chain

Shows many interesting features:

^{3}He ^{4}He ^{5}He ^{6}He ^{7}He



bound bound unbound bound unbound

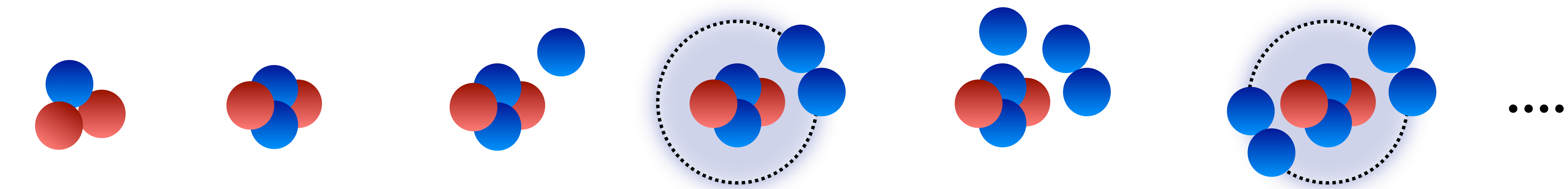
halo

Borromean system

The helium isotope chain

Shows many interesting features:

^{3}He	^{4}He	^{5}He	^{6}He	^{7}He	^{8}He	



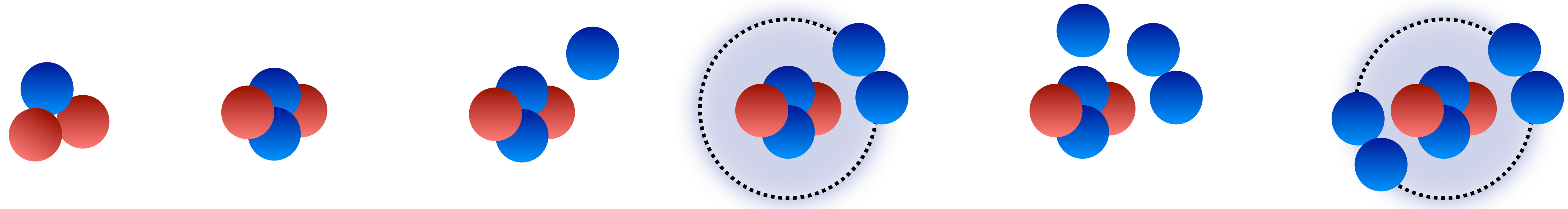
bound	bound	unbound	bound	unbound	bound
			halo		halo

Borromean system

The helium isotope chain

Shows many interesting features:

^{3}He	^{4}He	^{5}He	^{6}He	^{7}He	^{8}He	



bound	bound	unbound	bound halo	unbound	bound halo	....

Borromean system

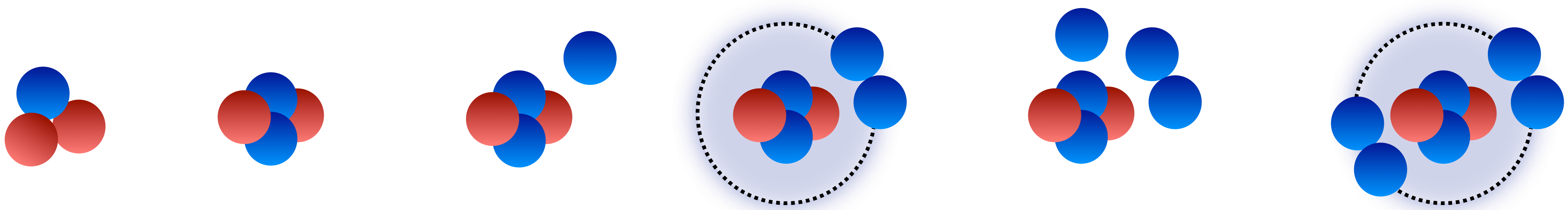
Most exotic nucleus "on earth"

$$\frac{N}{Z} = 3$$

The helium isotope chain

Shows many interesting features:

$^3\mathrm{He}$	$^4\mathrm{He}$	$^5\mathrm{He}$	$^6\mathrm{He}$	$^7\mathrm{He}$	$^8\mathrm{He}$	
bound	bound	unbound	bound	unbound	bound	....
			halo		halo	



Borromean system

lives 806 ms

Most exotic nucleus "on earth"

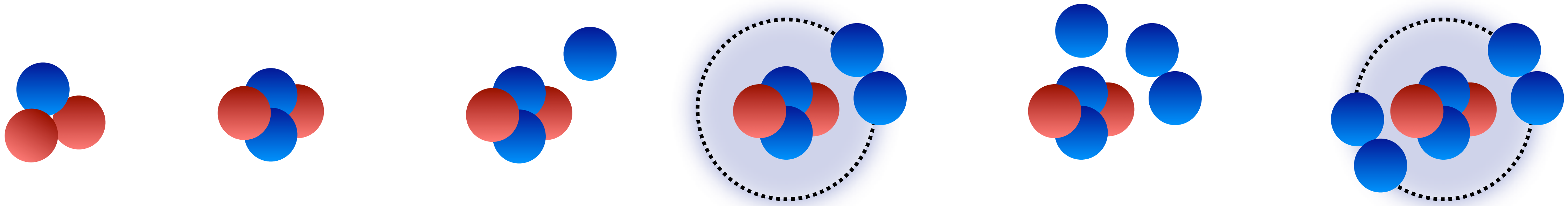
$$\frac{N}{Z} = 3$$

lives 108 ms

The helium isotope chain

Shows many interesting features:

$^3\mathrm{He}$	$^4\mathrm{He}$	$^5\mathrm{He}$	$^6\mathrm{He}$	$^7\mathrm{He}$	$^8\mathrm{He}$	
bound	bound	unbound	bound halo	unbound	bound halo	....



Borromean system

lives 806 ms

Most exotic nucleus "on earth"

$$\frac{N}{Z} = 3$$

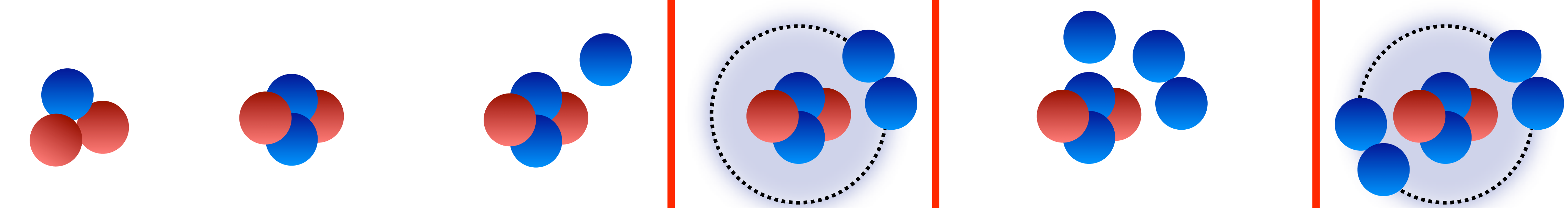
lives 108 ms

Synthesized in the laboratory

TRIUMF

The helium isotope chain

Shows many interesting features:



$^{3}\mathrm{He}$	$^{4}\mathrm{He}$	$^{5}\mathrm{He}$	$^{6}\mathrm{He}$	$^{7}\mathrm{He}$	$^{8}\mathrm{He}$	....
bound	bound	unbound	bound	unbound	bound	
			halo		halo	

Borromean system

lives 806 ms

Most exotic nucleus "on earth"

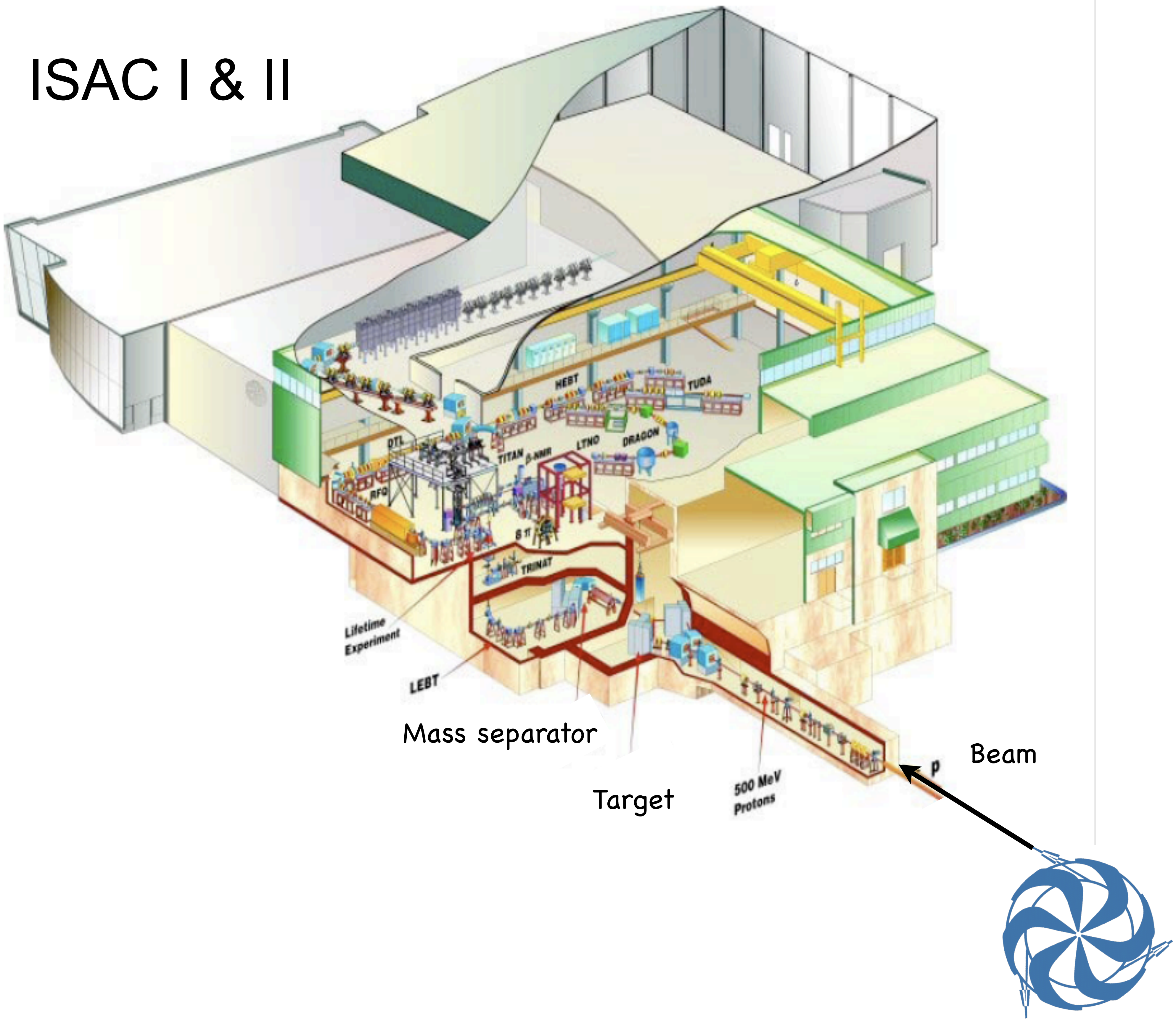
$$\frac{N}{Z} = 3$$

lives 108 ms

Synthesized in the laboratory

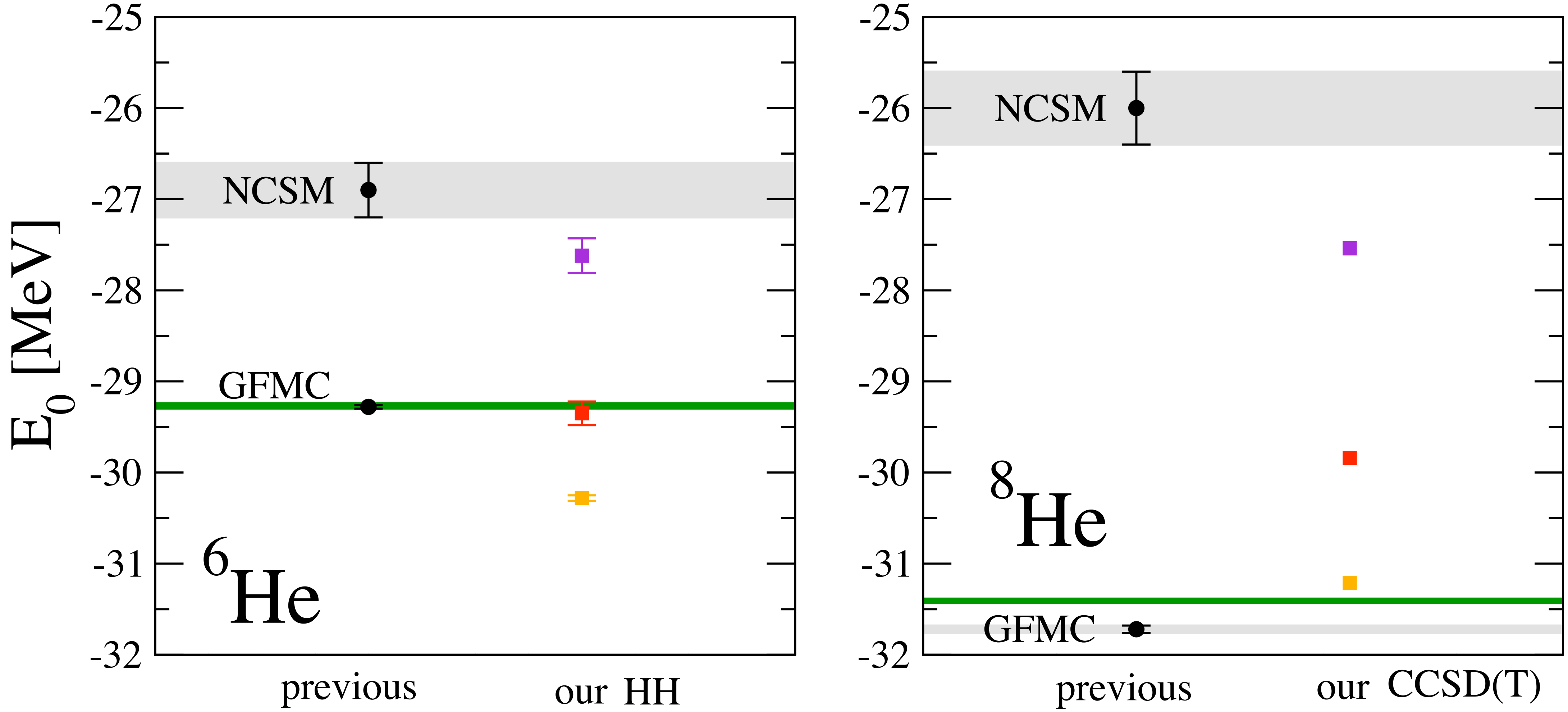
Production of rare isotopes at TRIUMF

ISAC I & II



Ab initio calculations for halo nuclei

S.Bacca et al., arXiv:0902.1696



Experimental data

TITAN ISAC-TRIUMF

Our calculations:

low-momentum EFT NN force

- $\Lambda = 1.8\ \mathrm{fm}^{-1}$
- $\Lambda = 2.0\ \mathrm{fm}^{-1}$
- $\Lambda = 2.4\ \mathrm{fm}^{-1}$

Previous calculations:

NCSM NN only

GFMC NN+3NF

Ab initio calculations for halo nuclei

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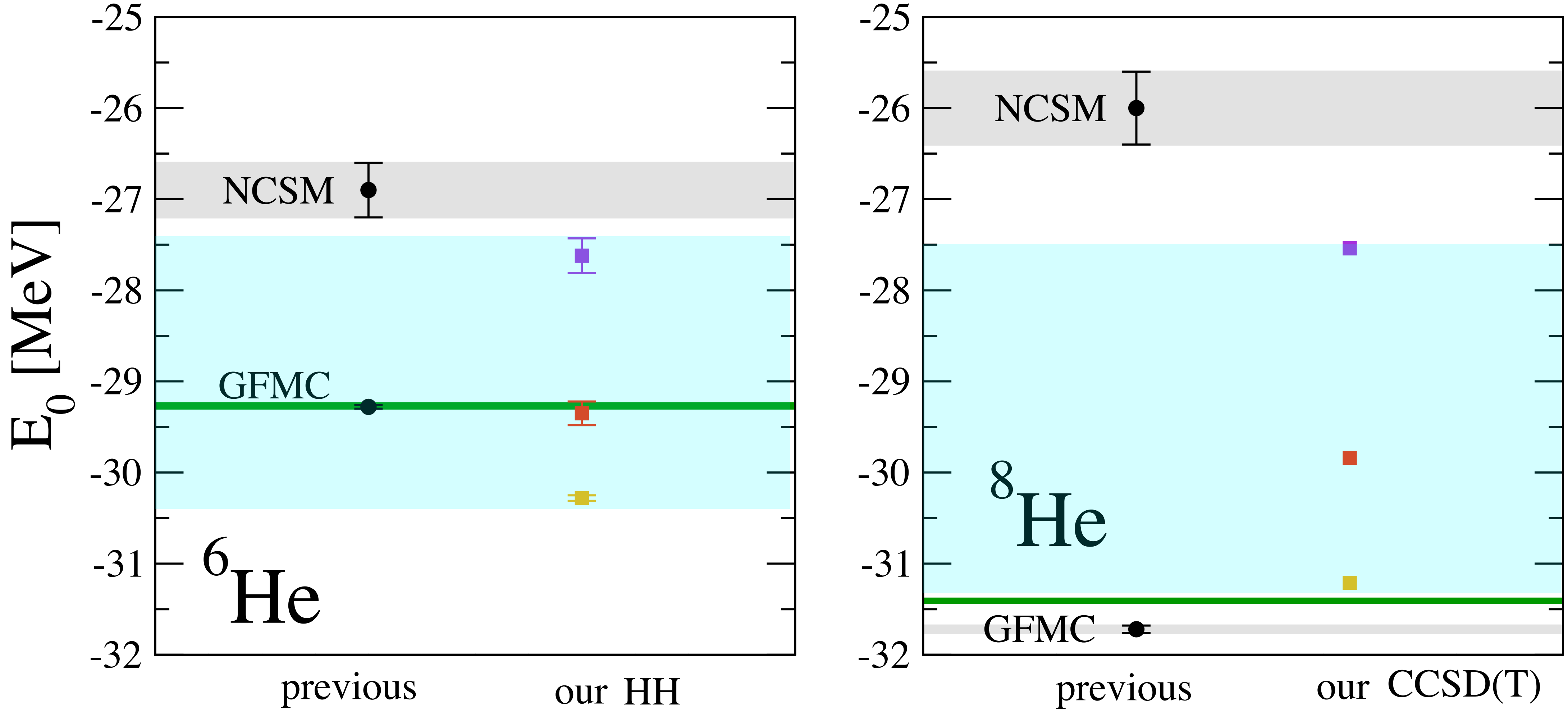

Experimental data

— TITAN ISAC-TRIUMF

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Previous calculations:

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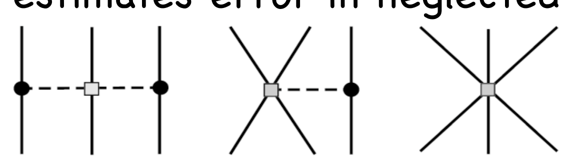
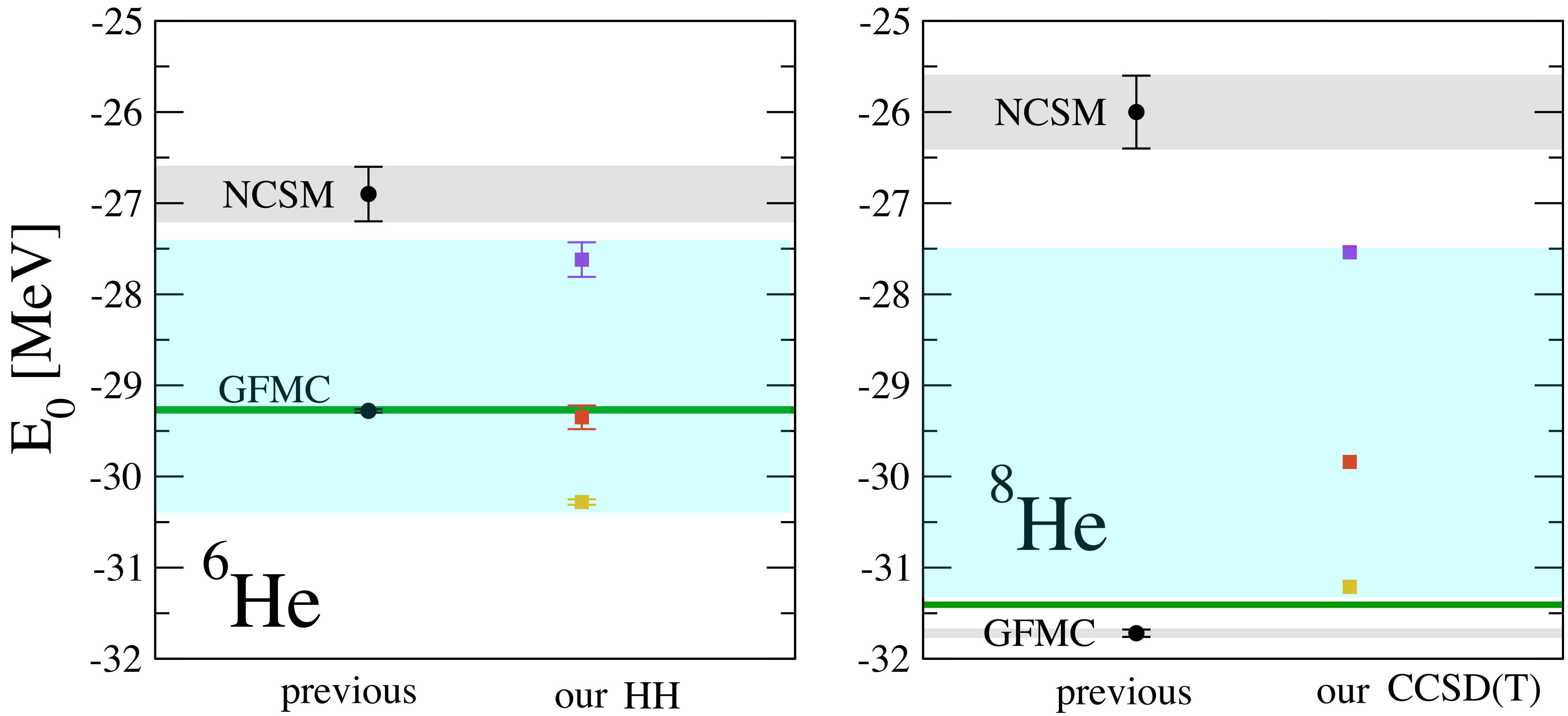
estimates error in neglected



Ab initio calculations for halo nuclei

S.Bacca et al., arXiv:0902.1696



Experimental data

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Our calculations:

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- $\Lambda = 2.4\ \mathrm{fm}^{-1}$

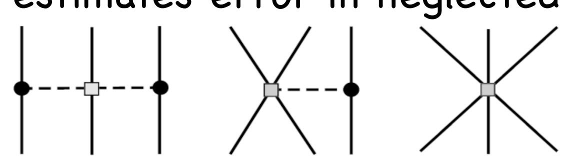
Future

Previous calculations:

NCSM NN only

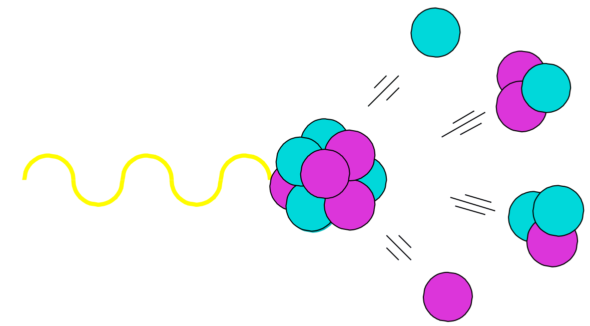
GFMC NN+3NF

estimates error in neglected

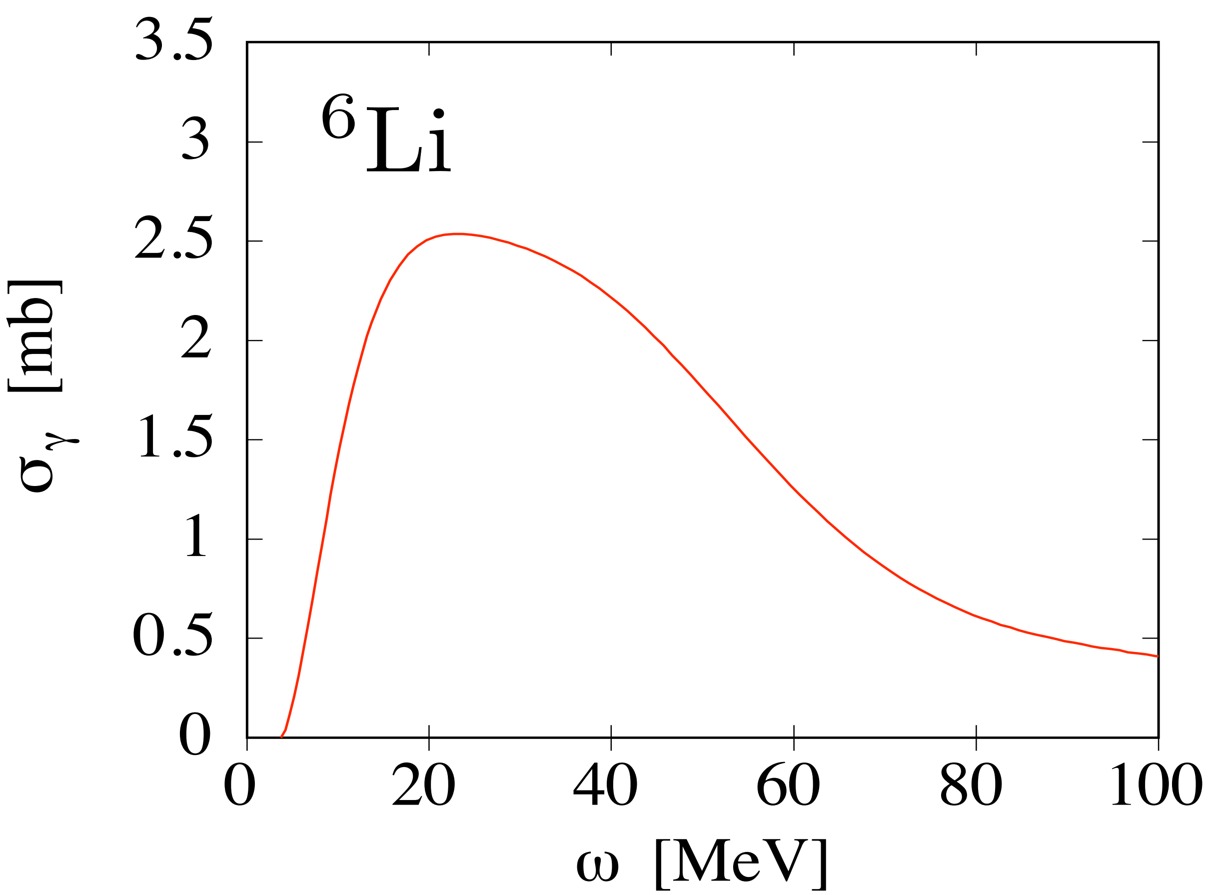


- Include 3NF
- Apply to other isotope chains with halo features

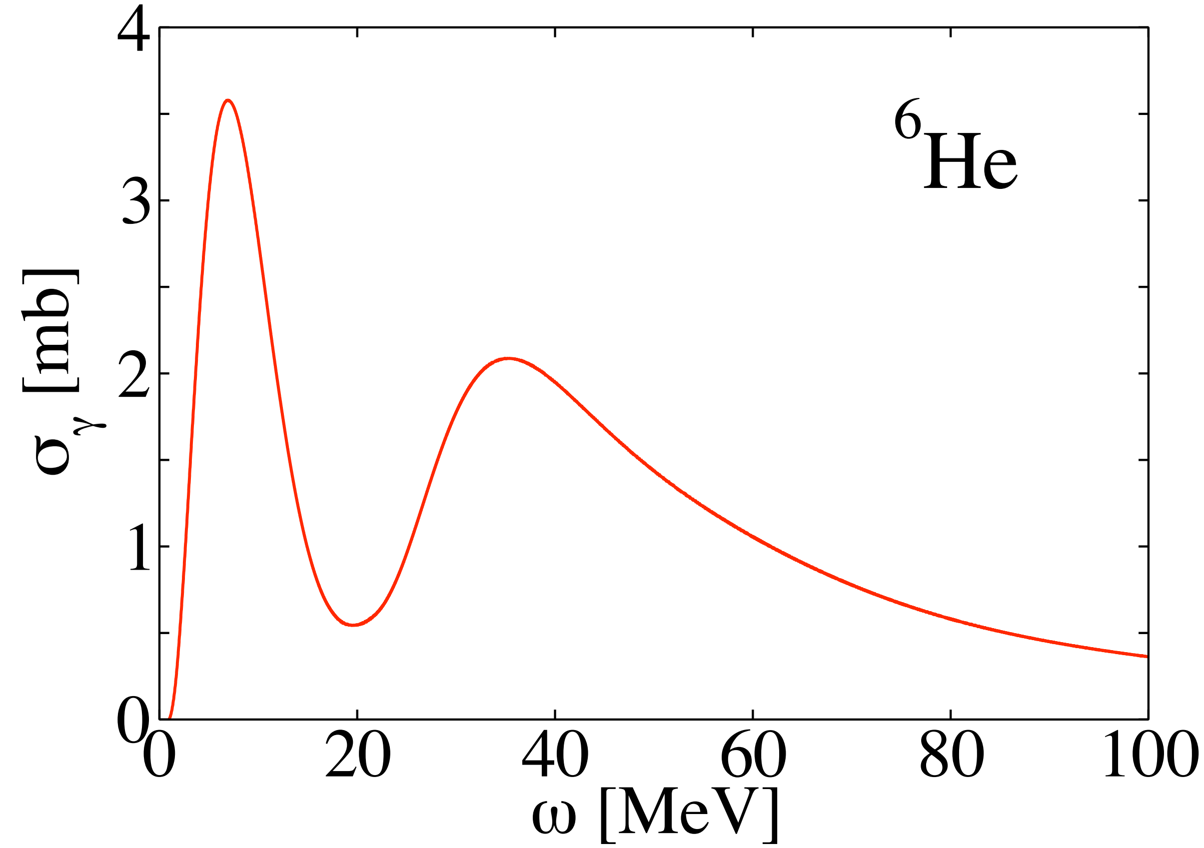
Nuclear Reactions: photo-absorption



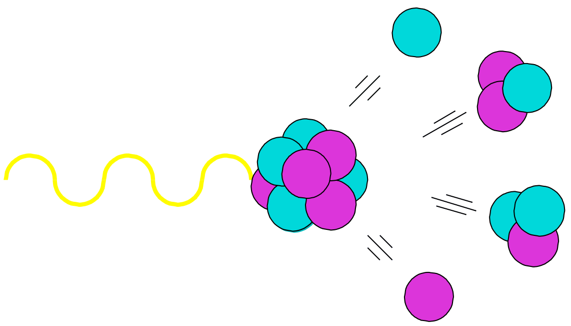
Semi-realistic NN force



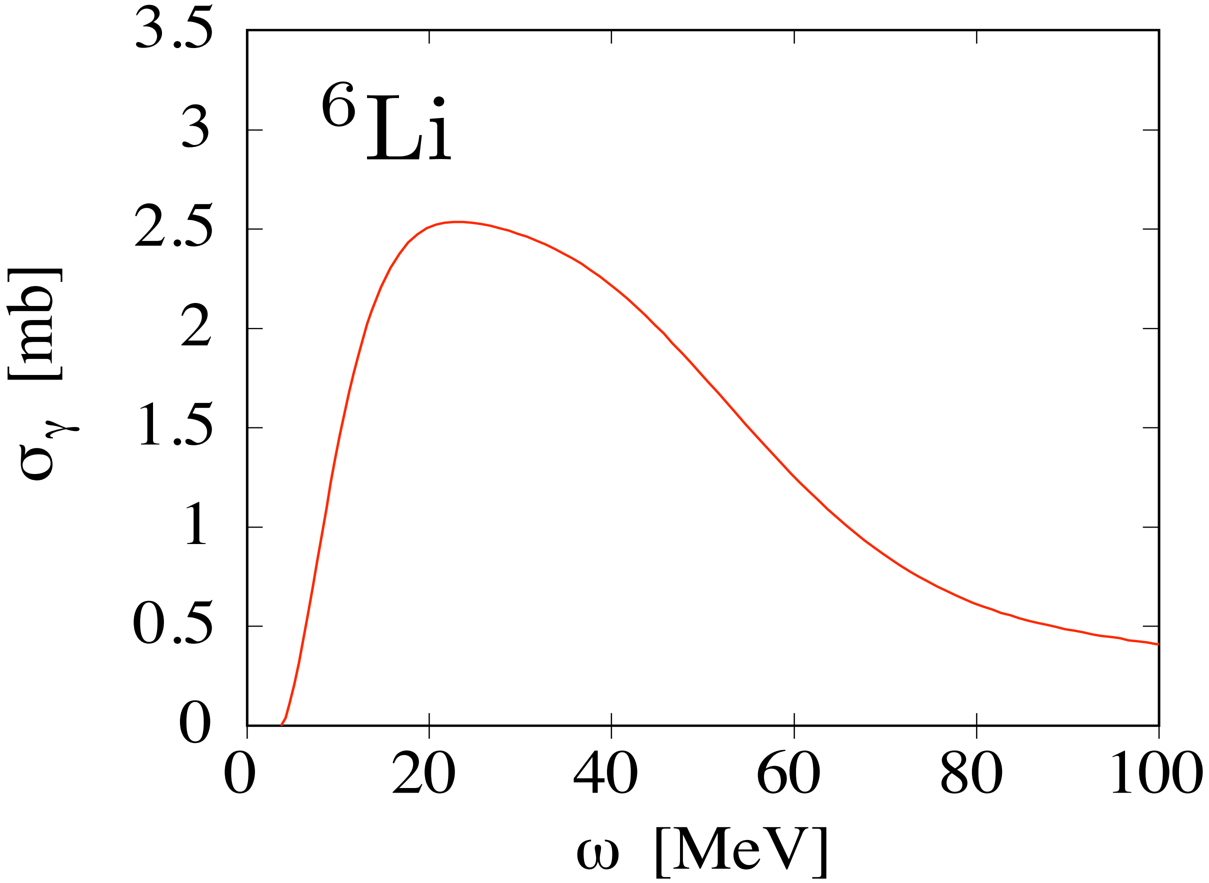
S.B. et al., PRL 89 ('02), PLB 603 and PRC 69 ('04)



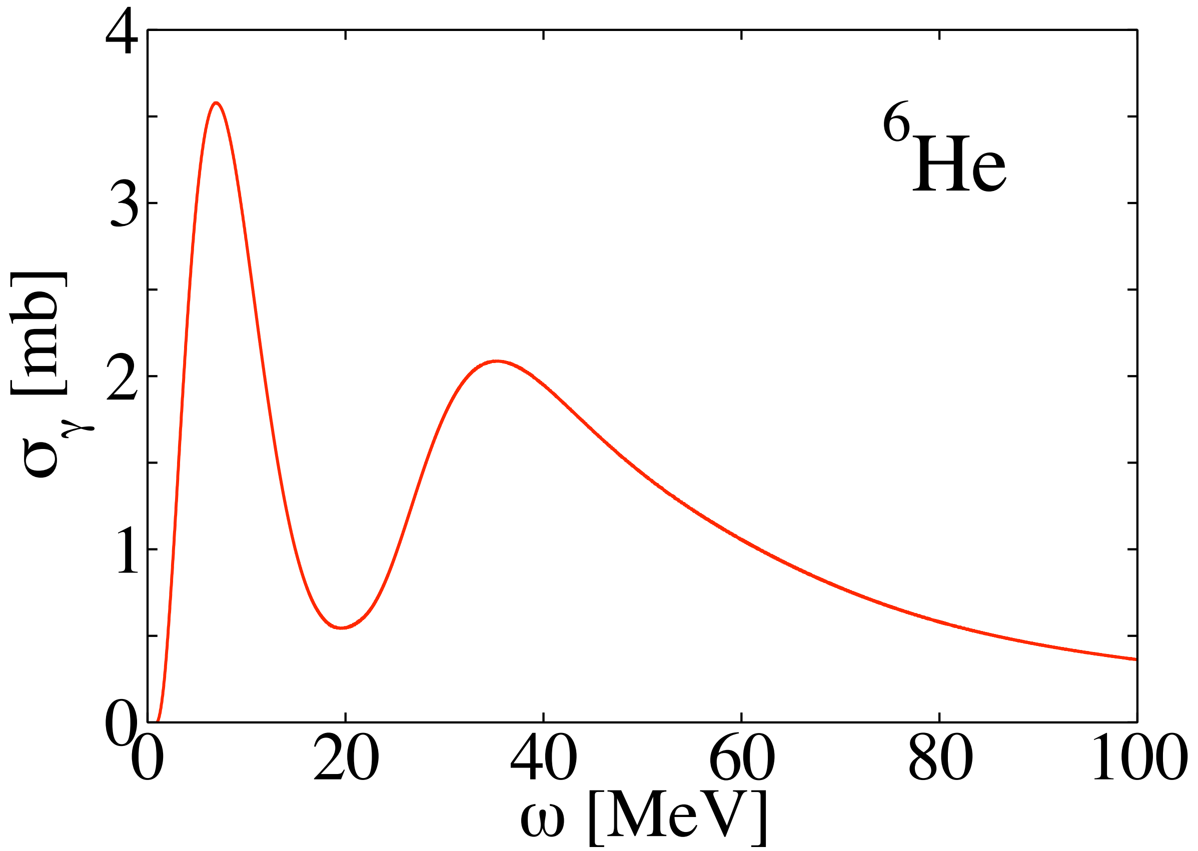
Nuclear Reactions: photo-absorption



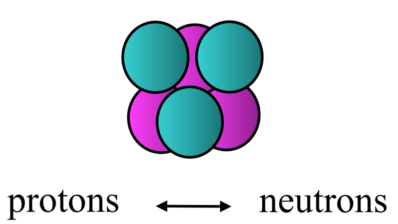
Semi-realistic NN force



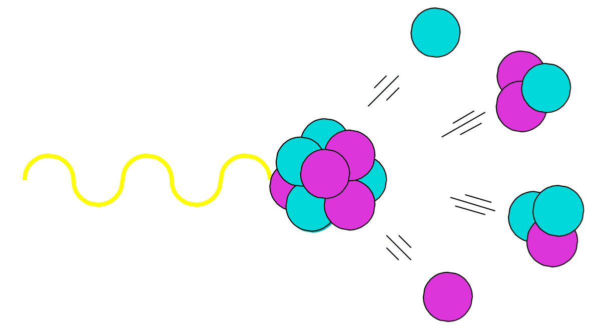
S.B. et al., PRL 89 ('02), PLB 603 and PRC 69 ('04)



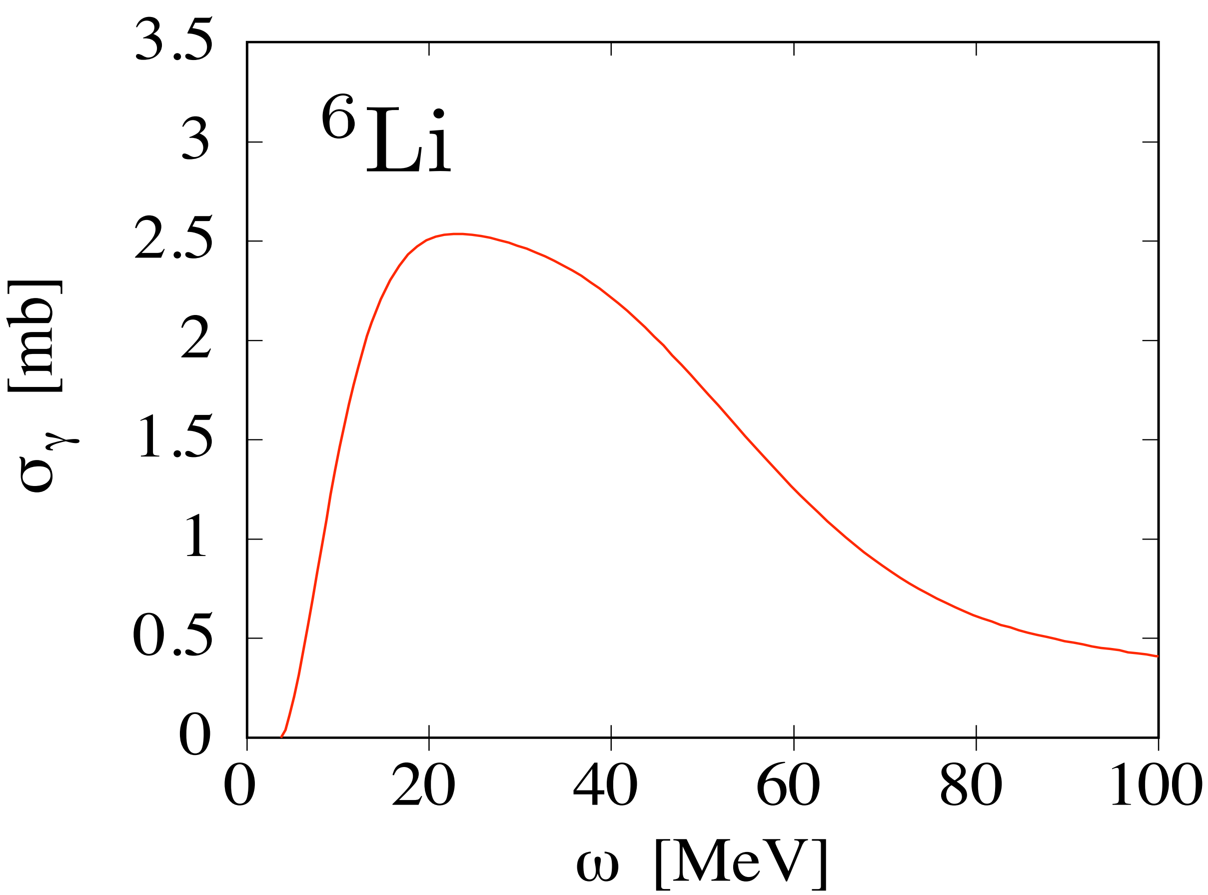
Giant Dipole Resonance



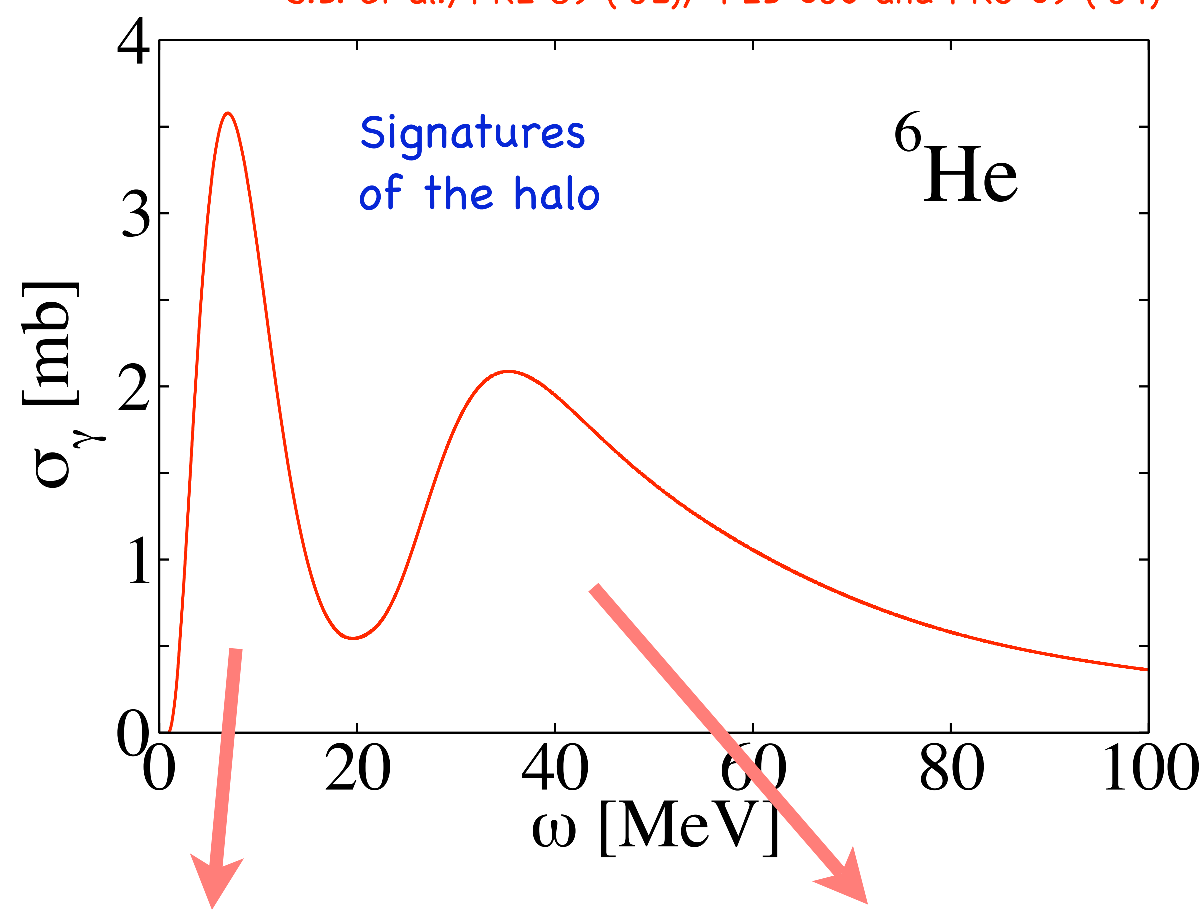
Nuclear Reactions: photo-absorption



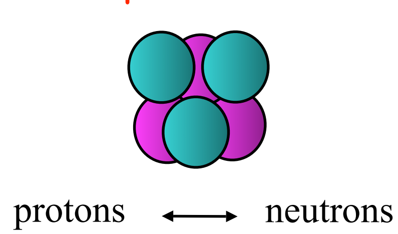
Semi-realistic NN force



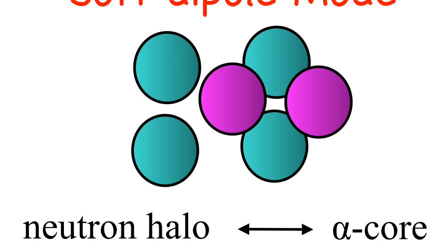
S.B. et al., PRL 89 ('02), PLB 603 and PRC 69 ('04)



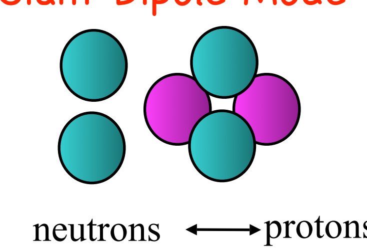
Giant Dipole Resonance



Soft-dipole Mode

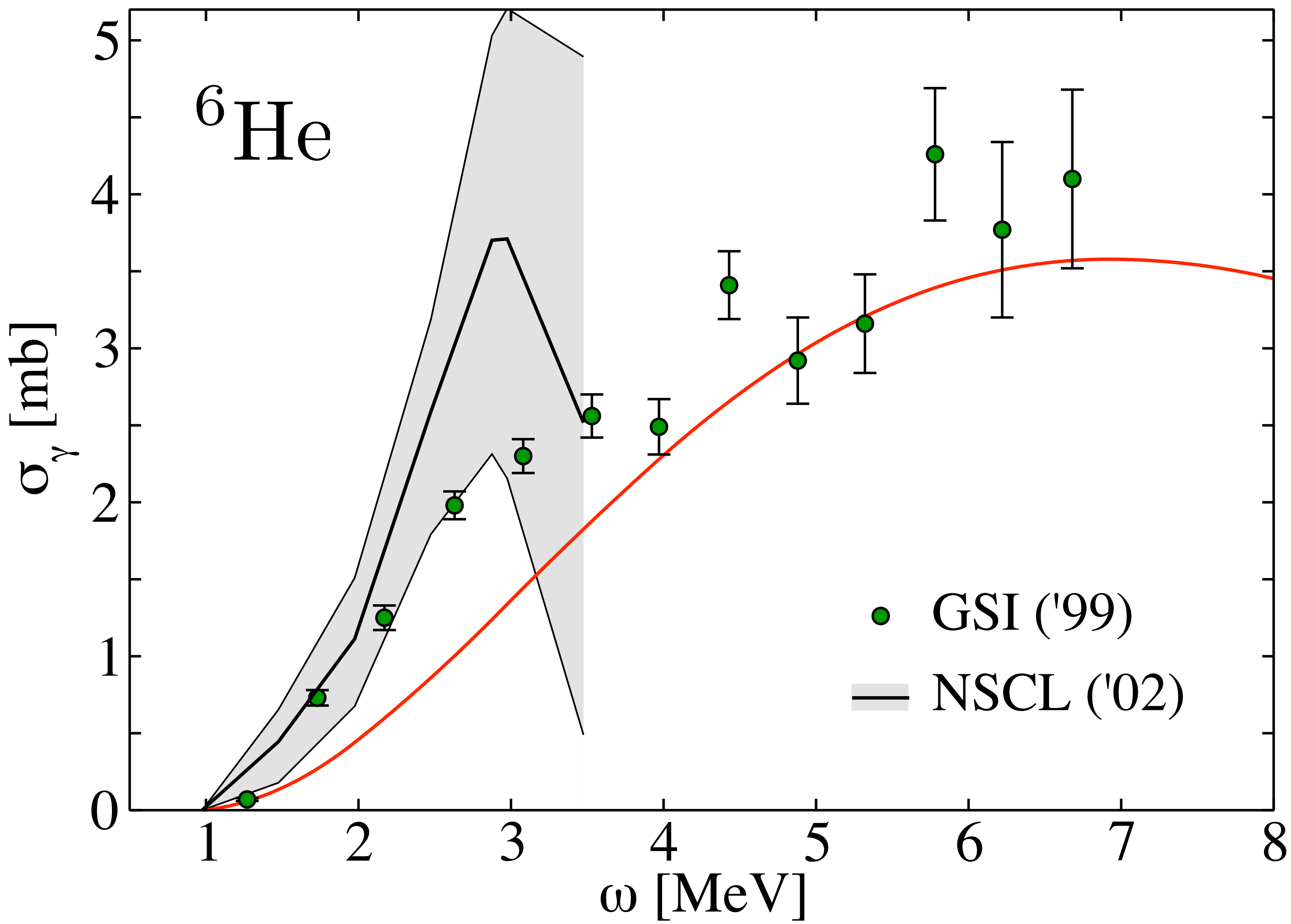


Giant Dipole Mode



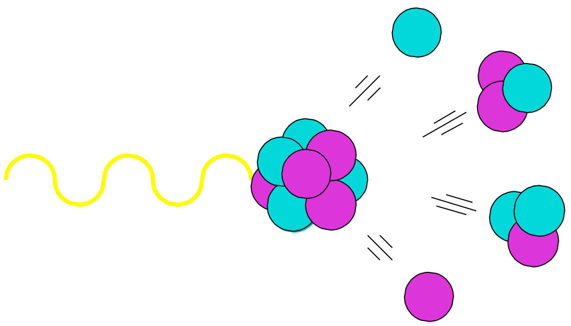
Nuclear Reactions: photo-absorption

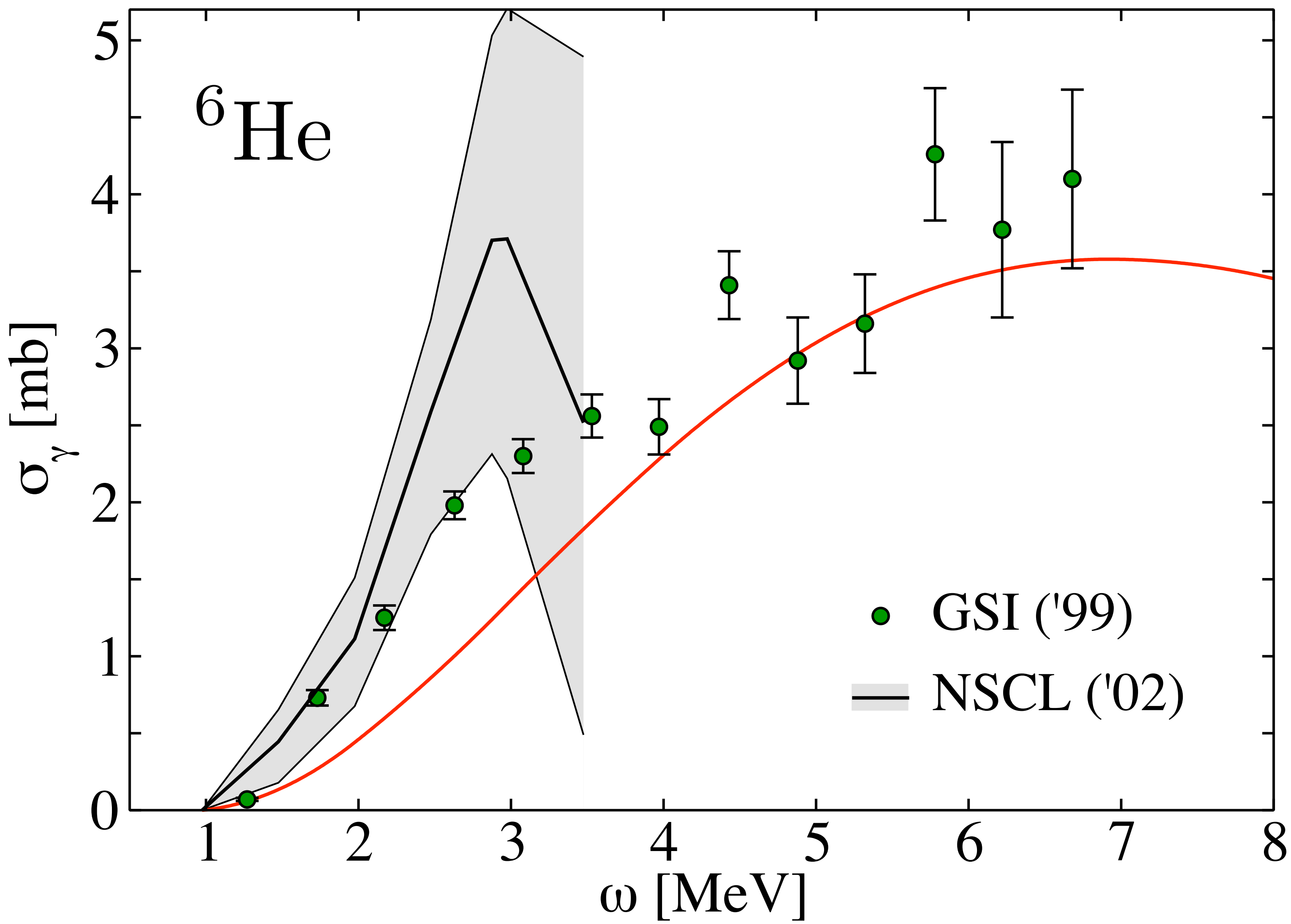
Semi-realistic NN force



Nuclear Reactions: photo-absorption

Semi-realistic NN force



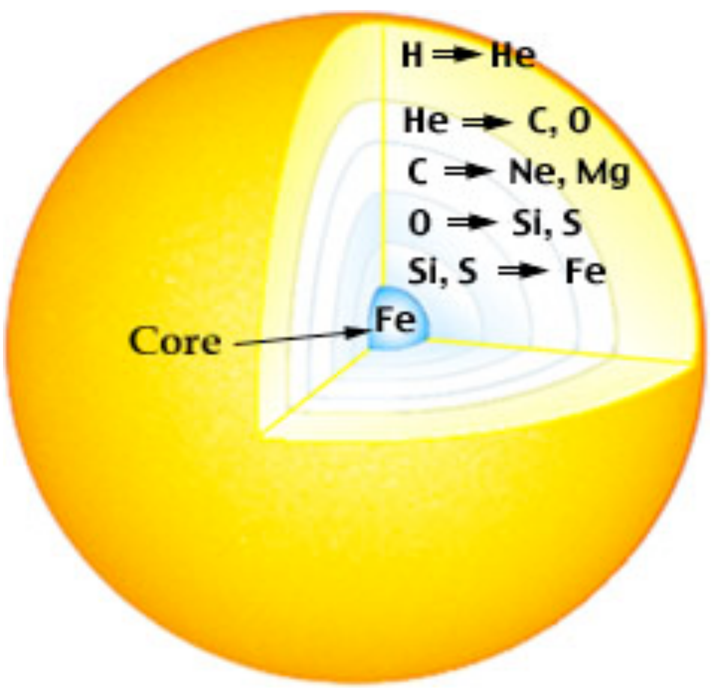


- Photo-absorption can be also related to neutron capture reactions for astrophysics

Astrophysics: Neutrino Reactions in Supernovae

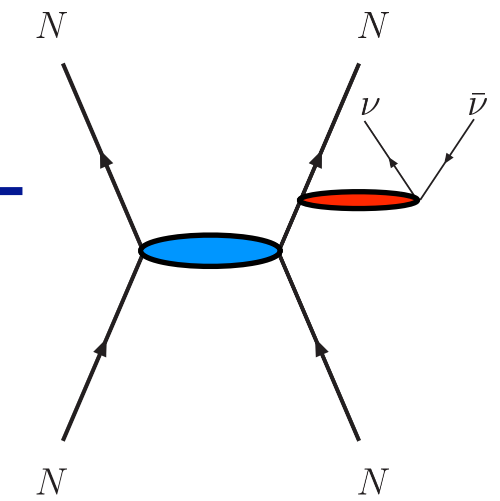
- Core collapse supernovae are gigantic explosions of massive stars
- 99% of the released energy is carried by neutrinos in all flavors, therefore

  neutrino interactions with matter are crucial

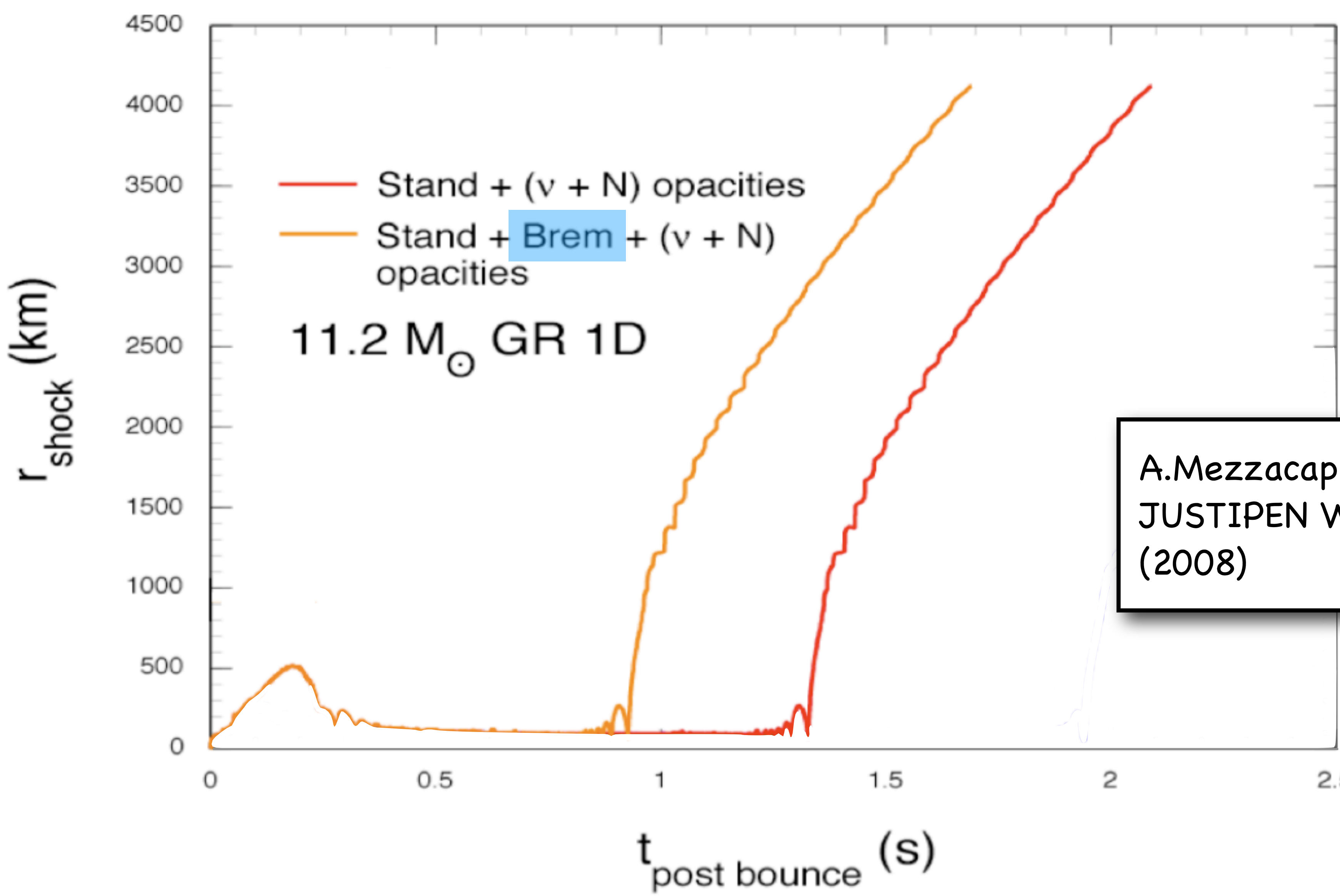


- In the iron core the burning process stops and it becomes gravitationally unstable ⟶ the core collapses
- Nuclear forces halt the collapse, and drive an outgoing shock, which loses energy due to dissociation, neutrino radiation.
- The shock stalls ... possibly revived by neutrino heating

Neutrino bremsstrahlung reaction $NN \rightarrow NN\nu\bar{\nu}$



Neutrino bremsstrahlung affects the time scale of the delayed explosion

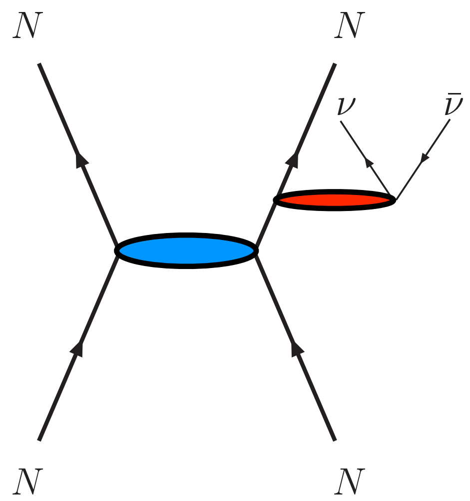


A.Mezzacappa (ORNL), JUSTIPEN Workshop (2008)

but standard neutrino rates are based on one-pion-exchange for NN

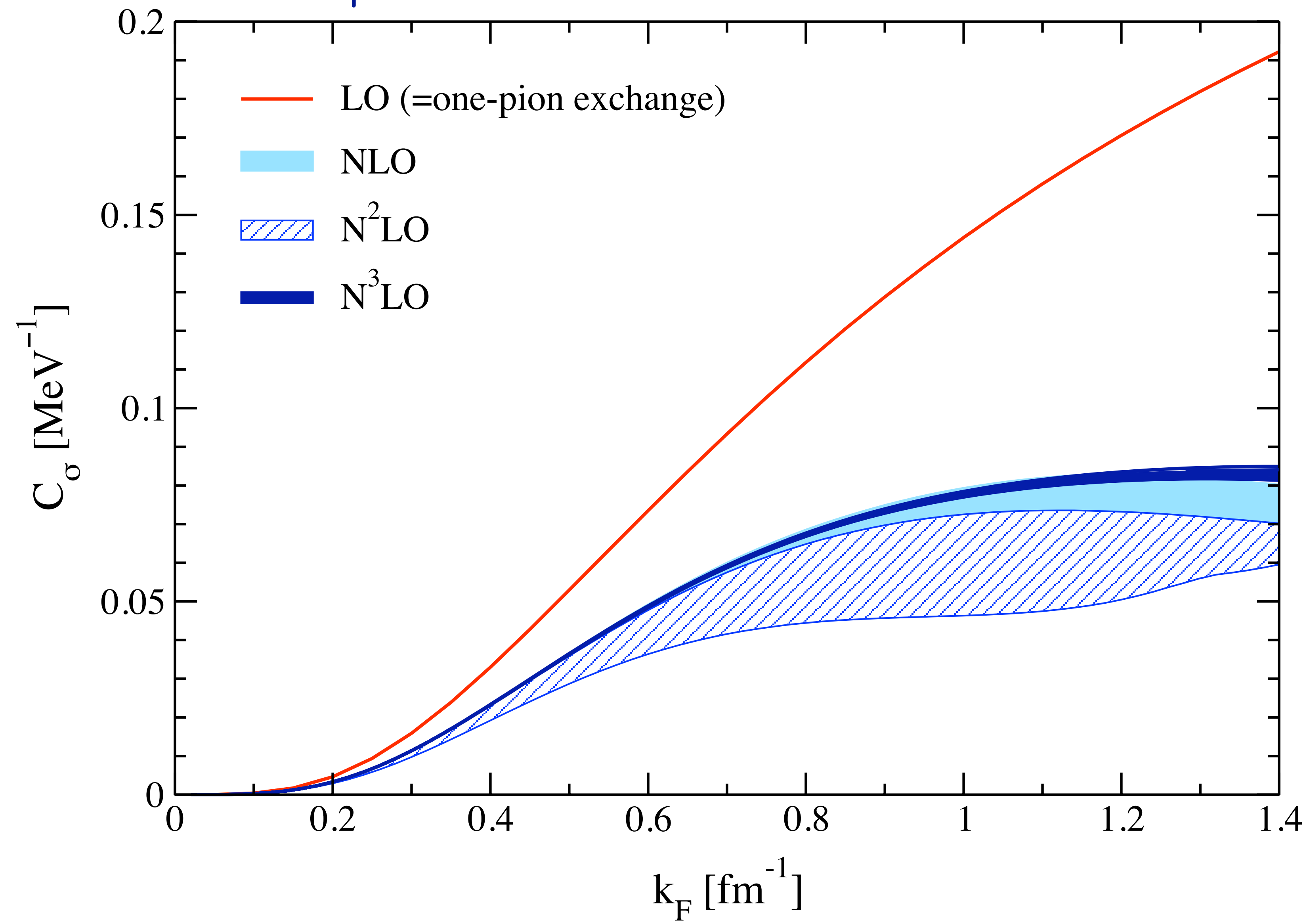
Neutrino bremsstrahlung from EFT

Pure neutron matter $NN \rightarrow NN\nu\bar{\nu}$

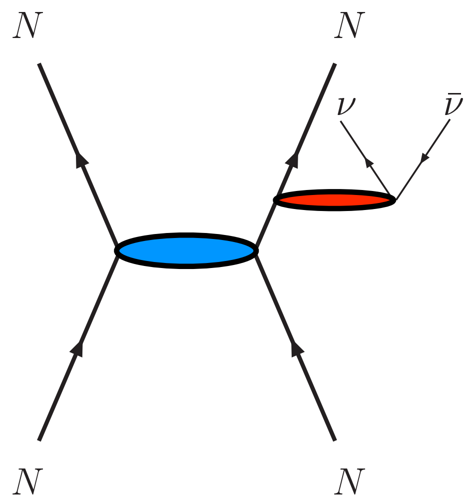


Chiral expansion

S.B. et al. arXiv:0812.0102

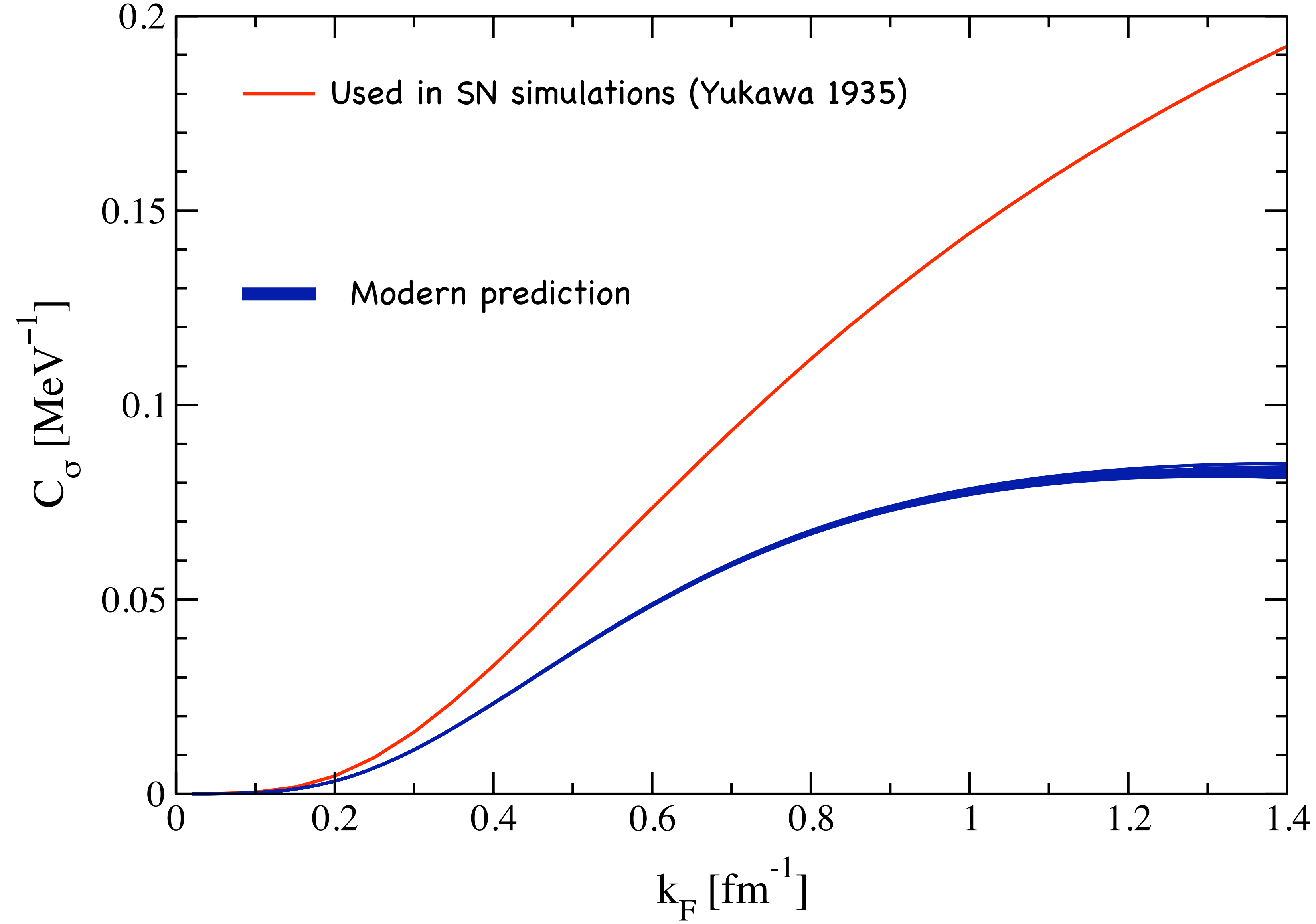


Neutrino bremsstrahlung from EFT



Pure neutron matter $NN \to NN\nu\bar{\nu}$

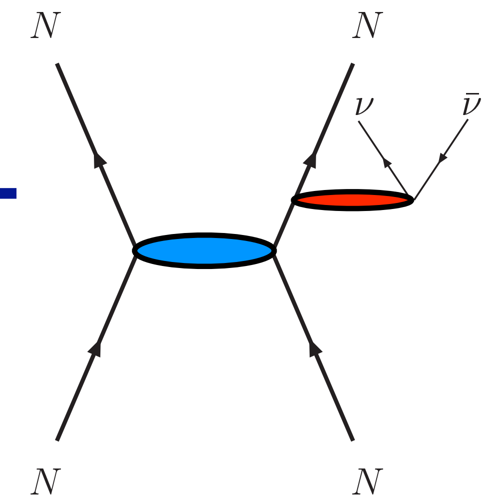
S.B. et al. arXiv:0812.0102

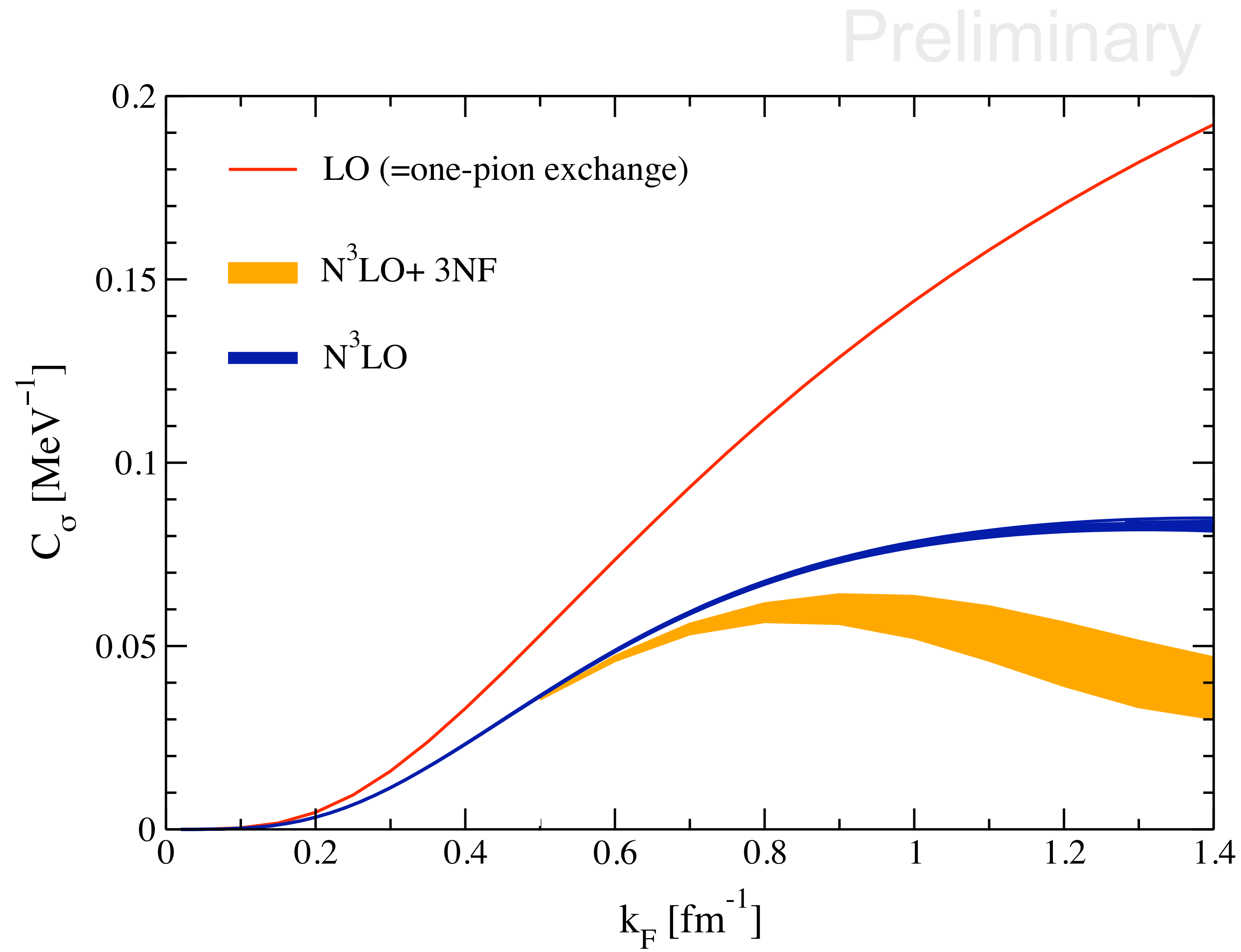


Modern Hamiltonians give a very different result!

Neutrino bremsstrahlung from EFT

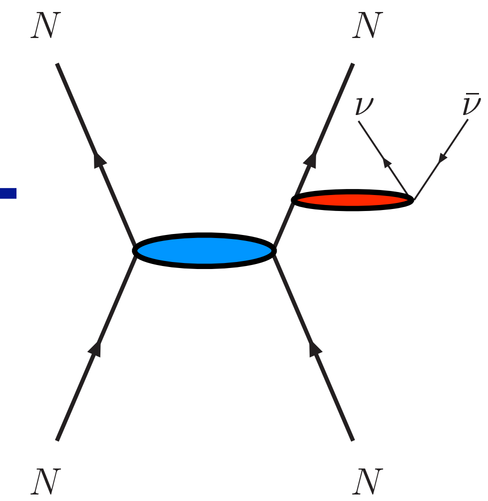
Pure neutron matter $NN \rightarrow NN\nu\bar{\nu}$





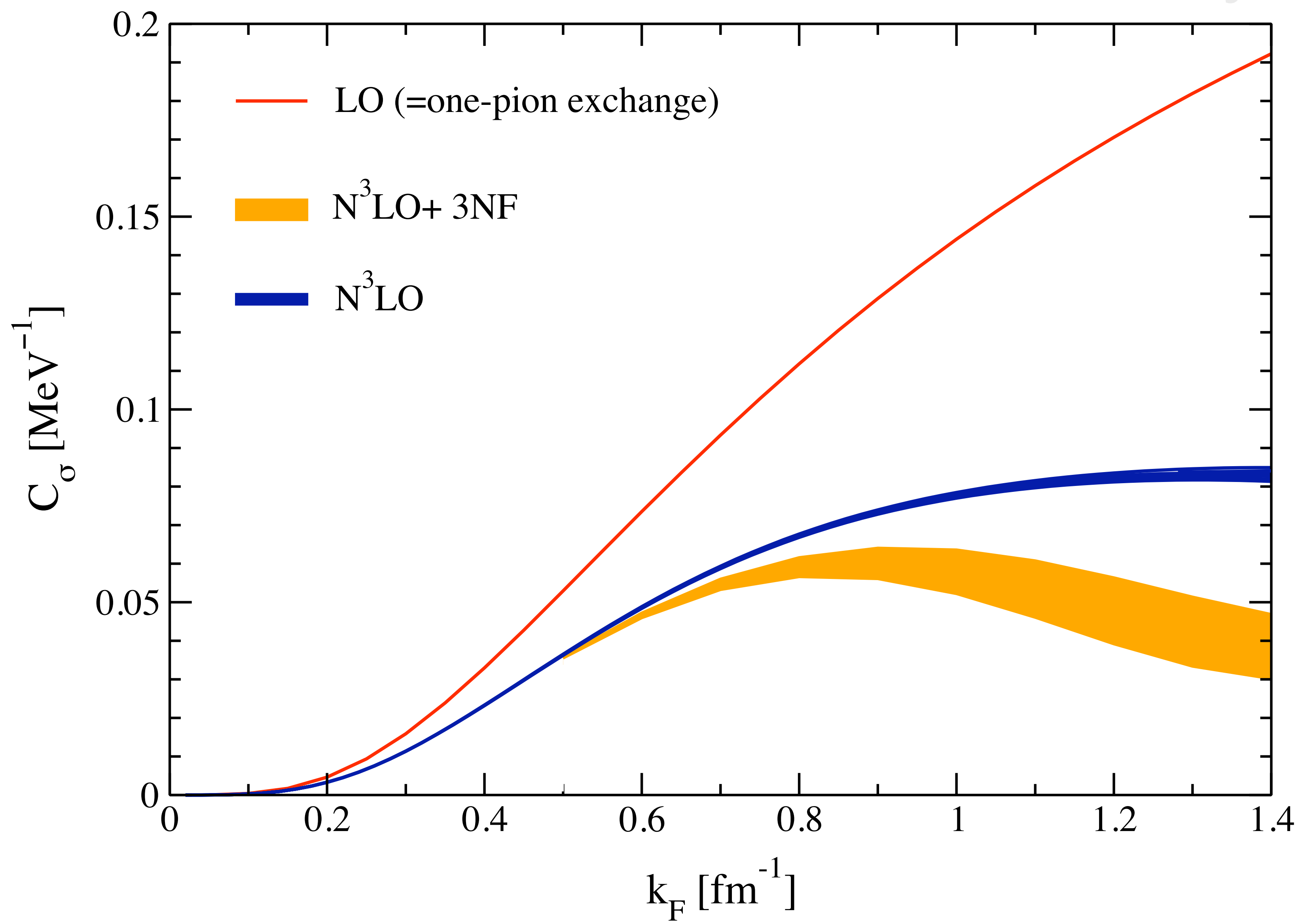
Visible effect of 3NF at higher density

Neutrino bremsstrahlung from EFT



Pure neutron matter $NN \to NN\nu\bar{\nu}$

Preliminary



Visible effect of 3NF at higher density

Aim: the new standard rates in SN simulation!

Summary

Exciting era in nuclear physics with advances on many fronts!

Nuclear physics is build upon a strong connection theory-experiment: fundamental for testing our knowledge of nuclear forces

- Enormous progress done in ab-initio approaches to nuclear structure
  - ★ Description of helium halo isotopes from evolved Effective Field Theory forces
- Advances in the accurate calculation of nuclear reactions
  - ★ Different dipole strength distribution in stable-unstable light nuclei
- Nuclear physics provides fundamental microscopic input for astrophysics
  - ★ First neutrino rates based on Effective Field Theory

Future: the study of the role of 3NF is key in all areas from light nuclei to astrophysics

Thanks to my collaborators:

האוניברסיטה העברית בירושלים The Hebrew University of Jerusalem — Nir Barnea

Oak Ridge National Laboratory, UT — Gaute Hagen, Thomas Papenbrock

Acadia University — Katy Hally

TRIUMF — Kai Hebeler, Achim Schwenk

Universitas Studiorum Athesina — Winfried Leidemann, Giuseppina Orlandini

NORDITA — Chris Pethick

I acknowledge useful discussions with the TITAN ISAC-TRIUMF group members

Thank you!

Merci!