Chiral Effective Field Theory and Nuclear Forces: overview and applications

Kai Hebeler

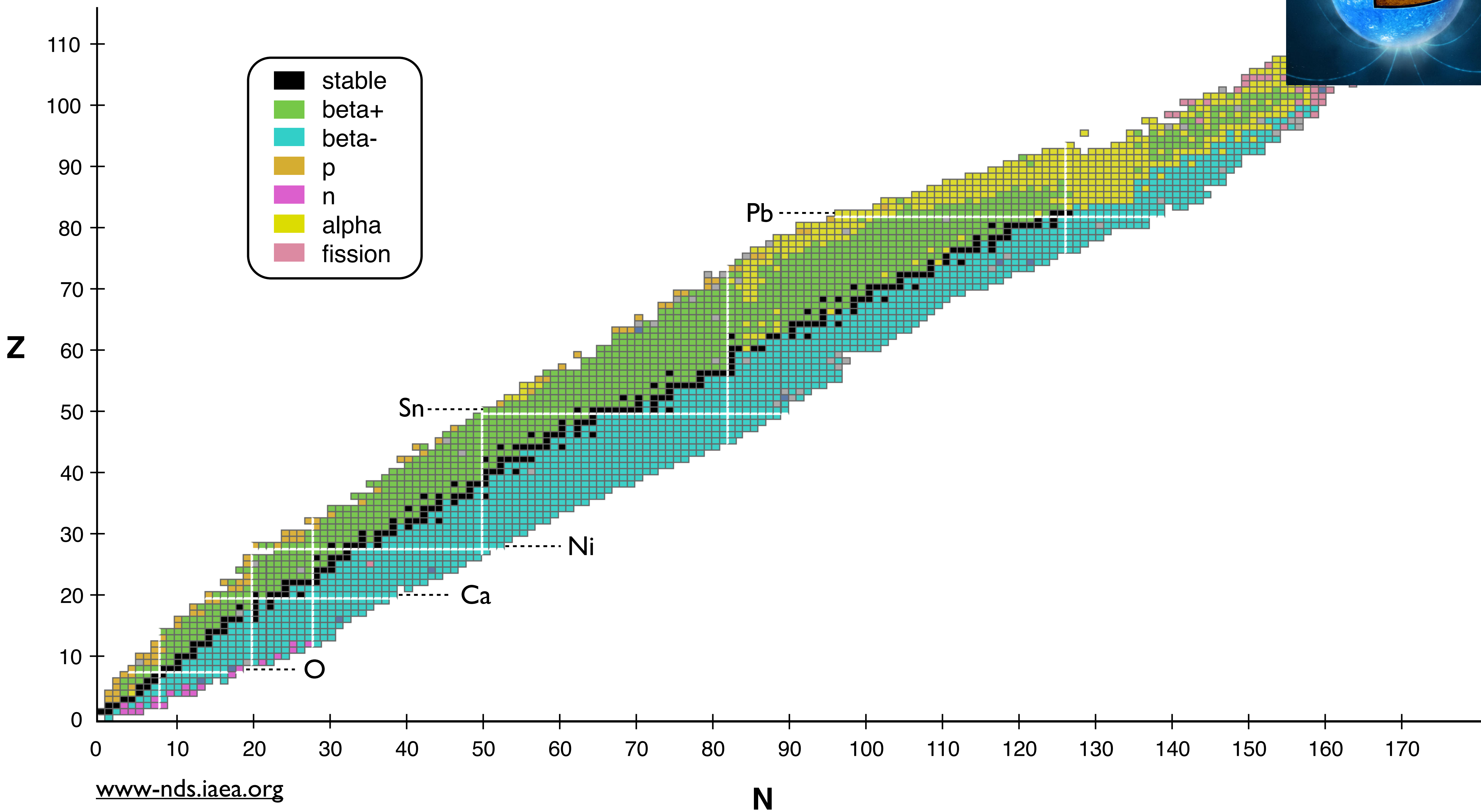
Mainz, July 27, 2022

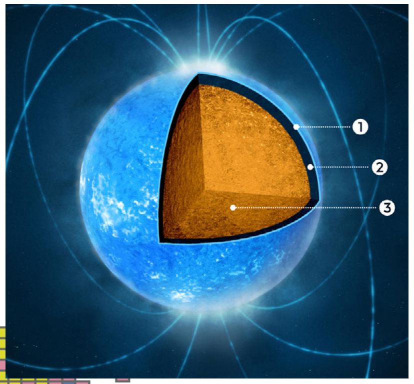
TALENT school @MITP:
Effective field theories in light nuclei

SFB 1245

TECHNISCHE UNIVERSITÄT DARMSTADT

The nuclear landscape:
New frontiers from rare isotope facilities





www-nds.iaea.org

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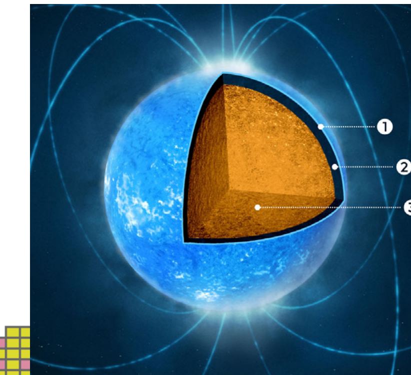

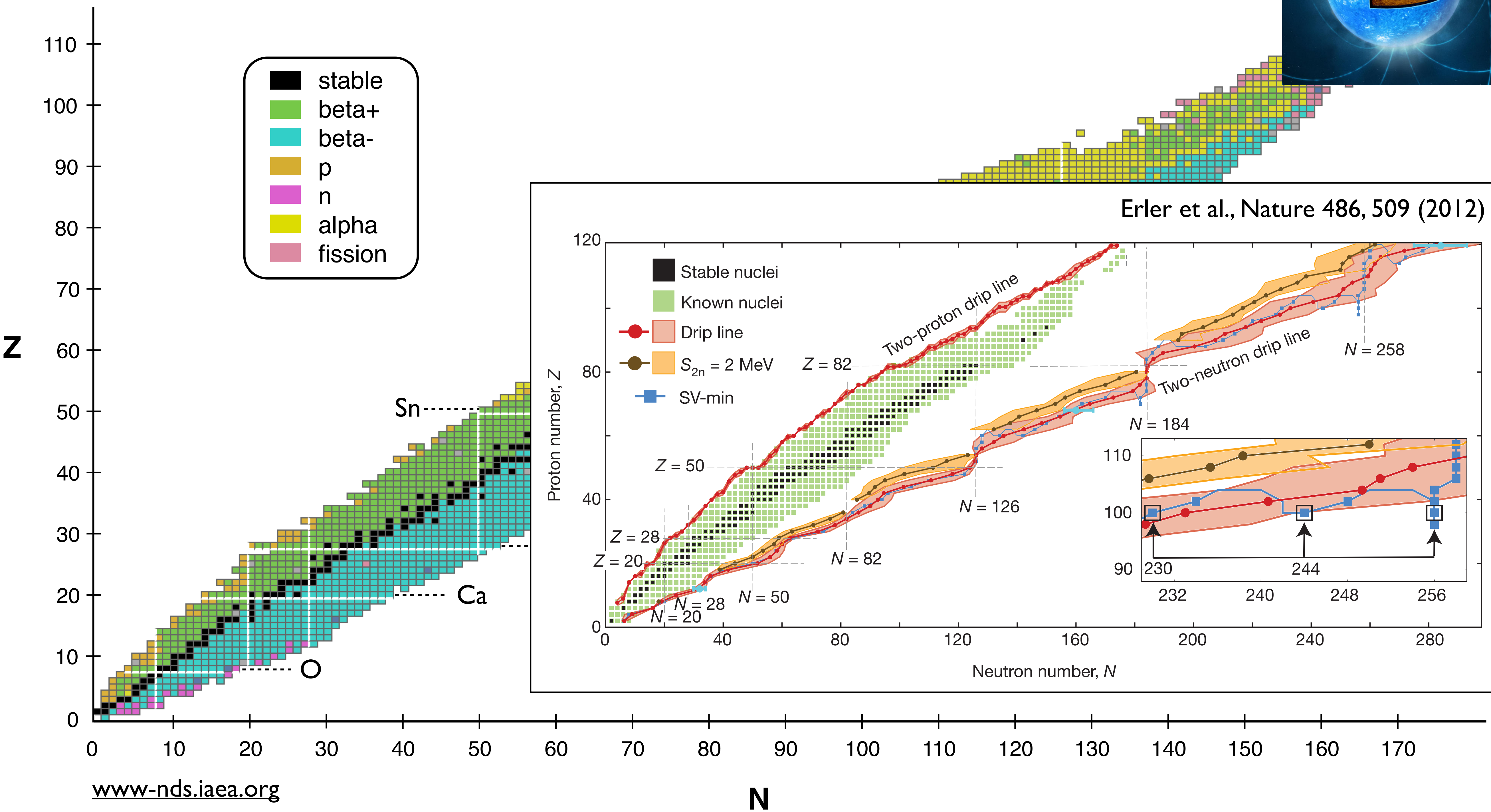

Erler et al., Nature 486, 509 (2012)

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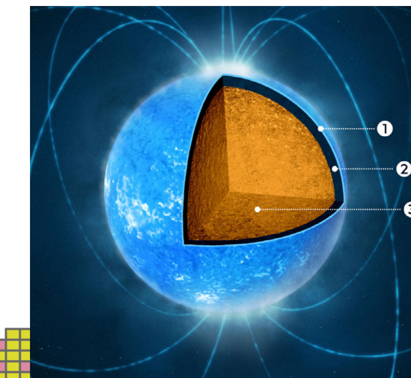

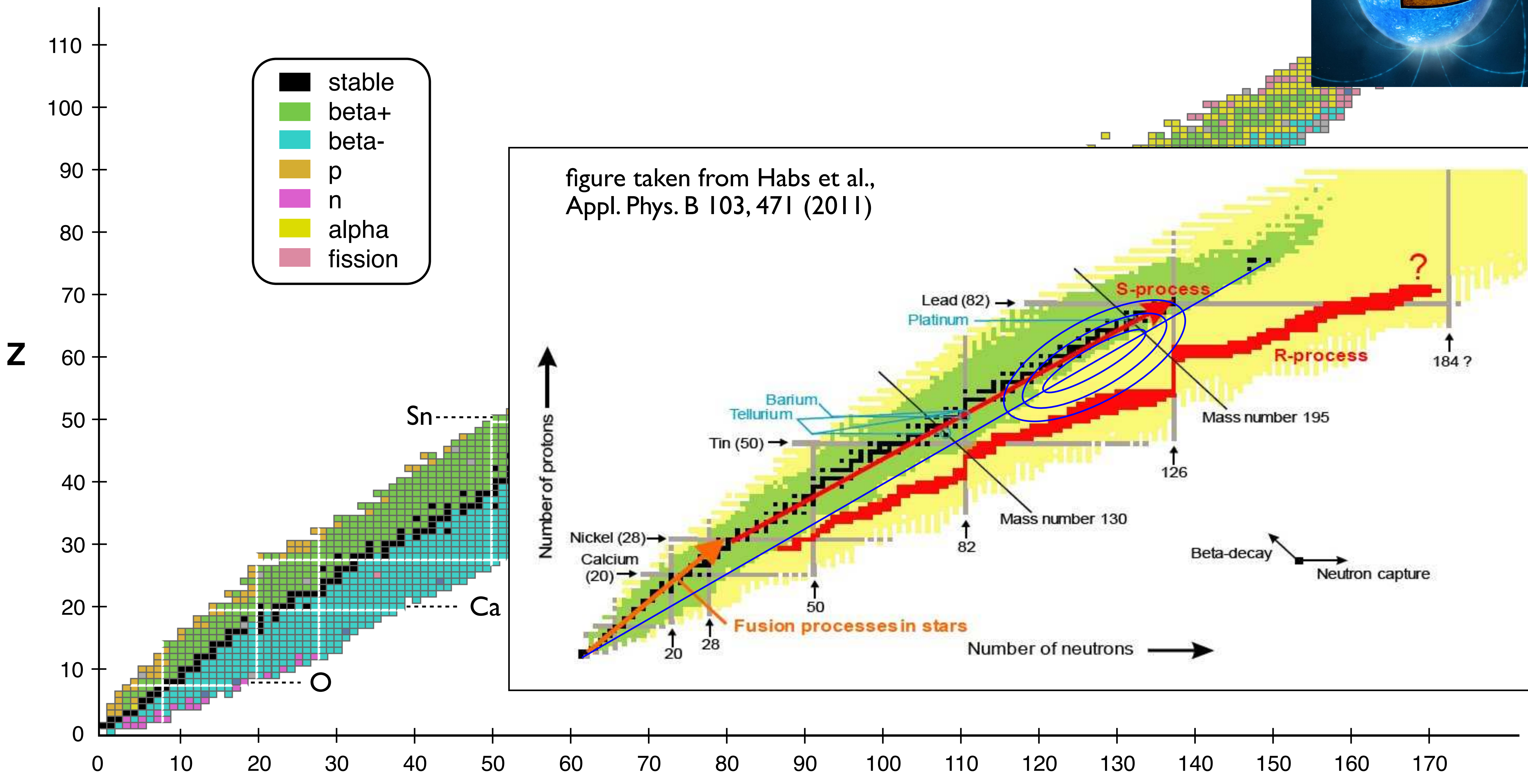

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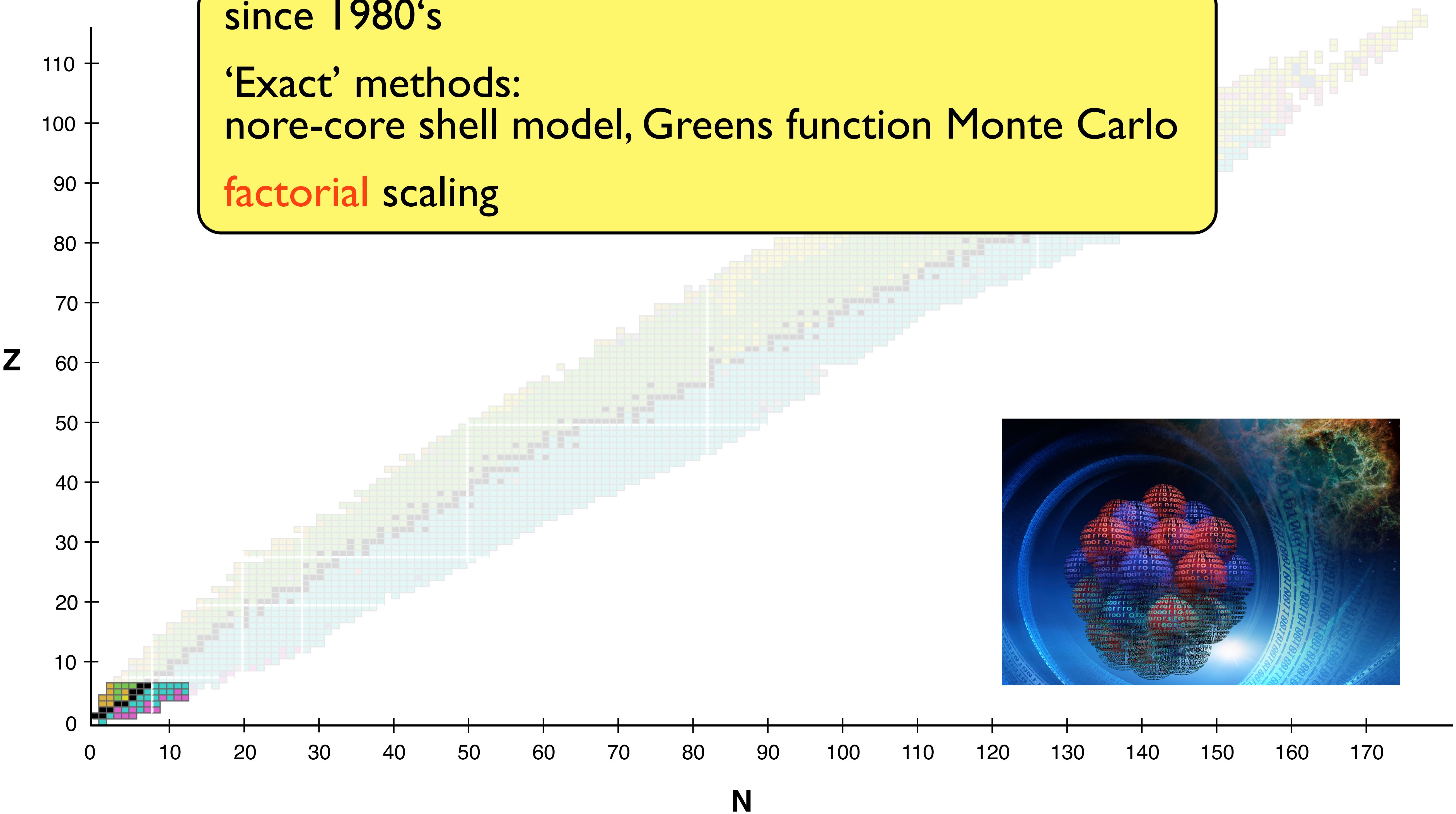
The theoretical nuclear landscape: Scope of ab initio methods for atomic nuclei

since 1980‘s

‘Exact’ methods:
nore-core shell model, Greens function Monte Carlo

factorial scaling



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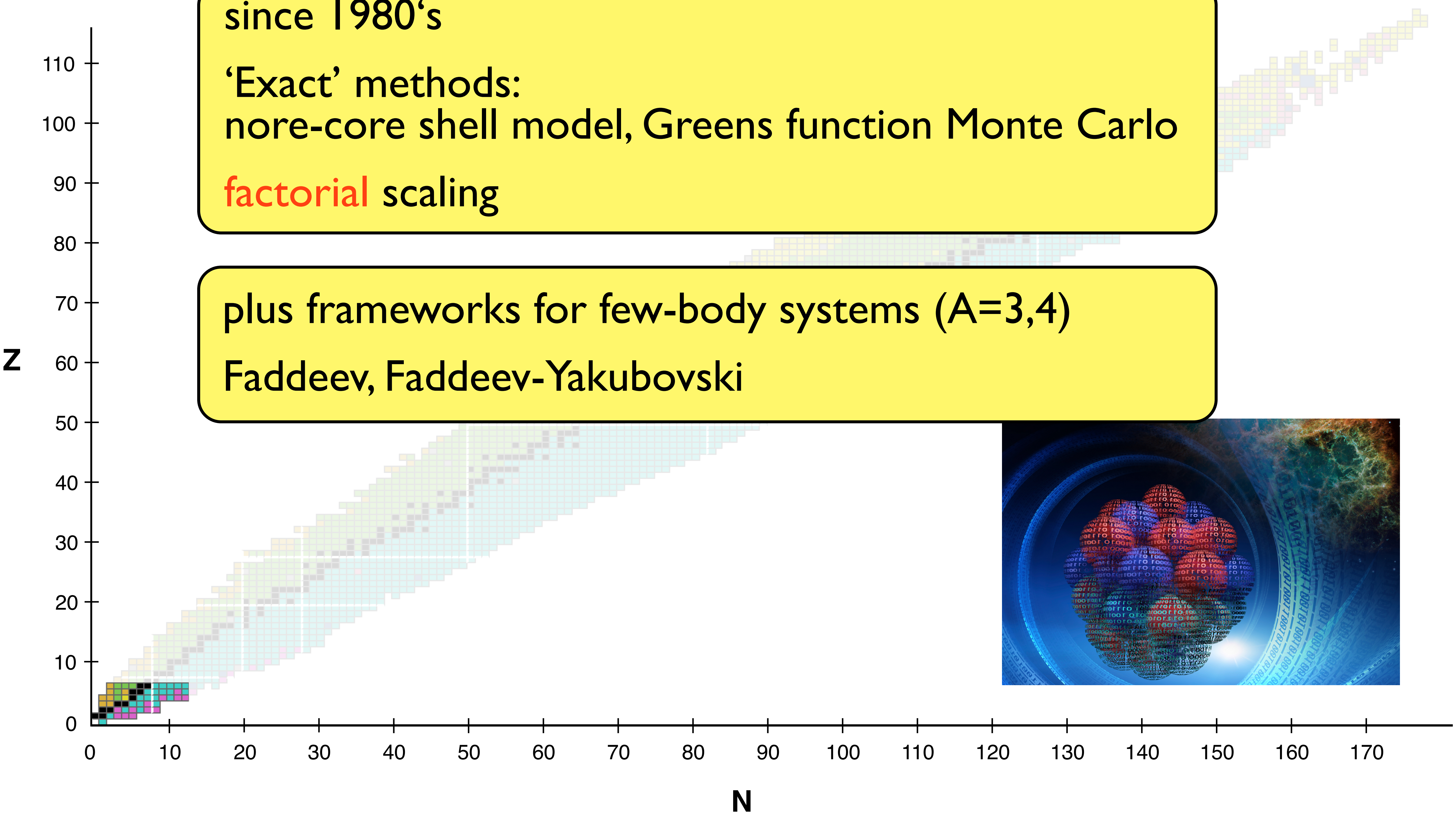
plus frameworks for few-body systems (A=3,4)

Faddeev, Faddeev-Yakubovski

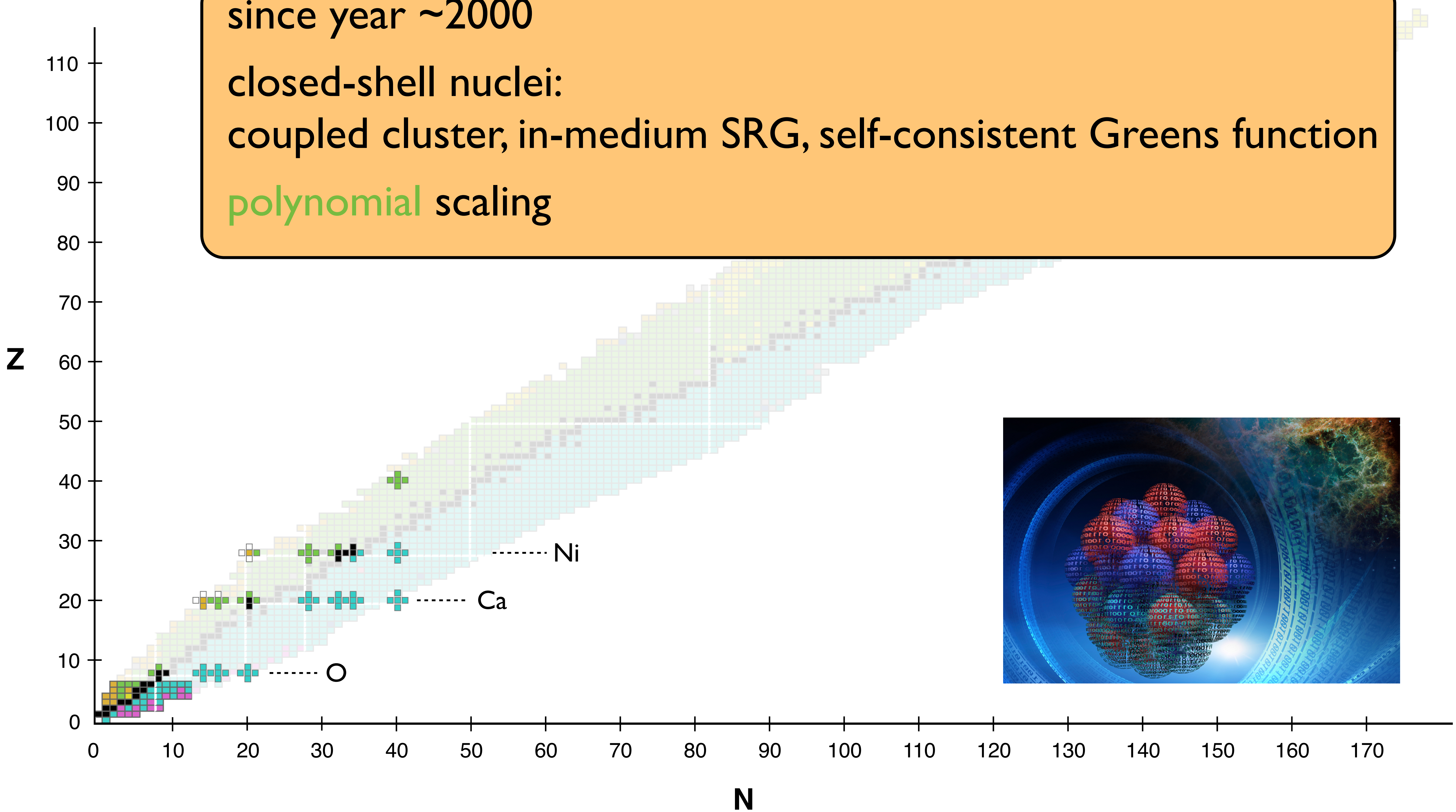


The theoretical nuclear landscape: Scope of ab initio methods for atomic nuclei

since year ~2000

closed-shell nuclei:
coupled cluster, in-medium SRG, self-consistent Greens function

polynomial scaling

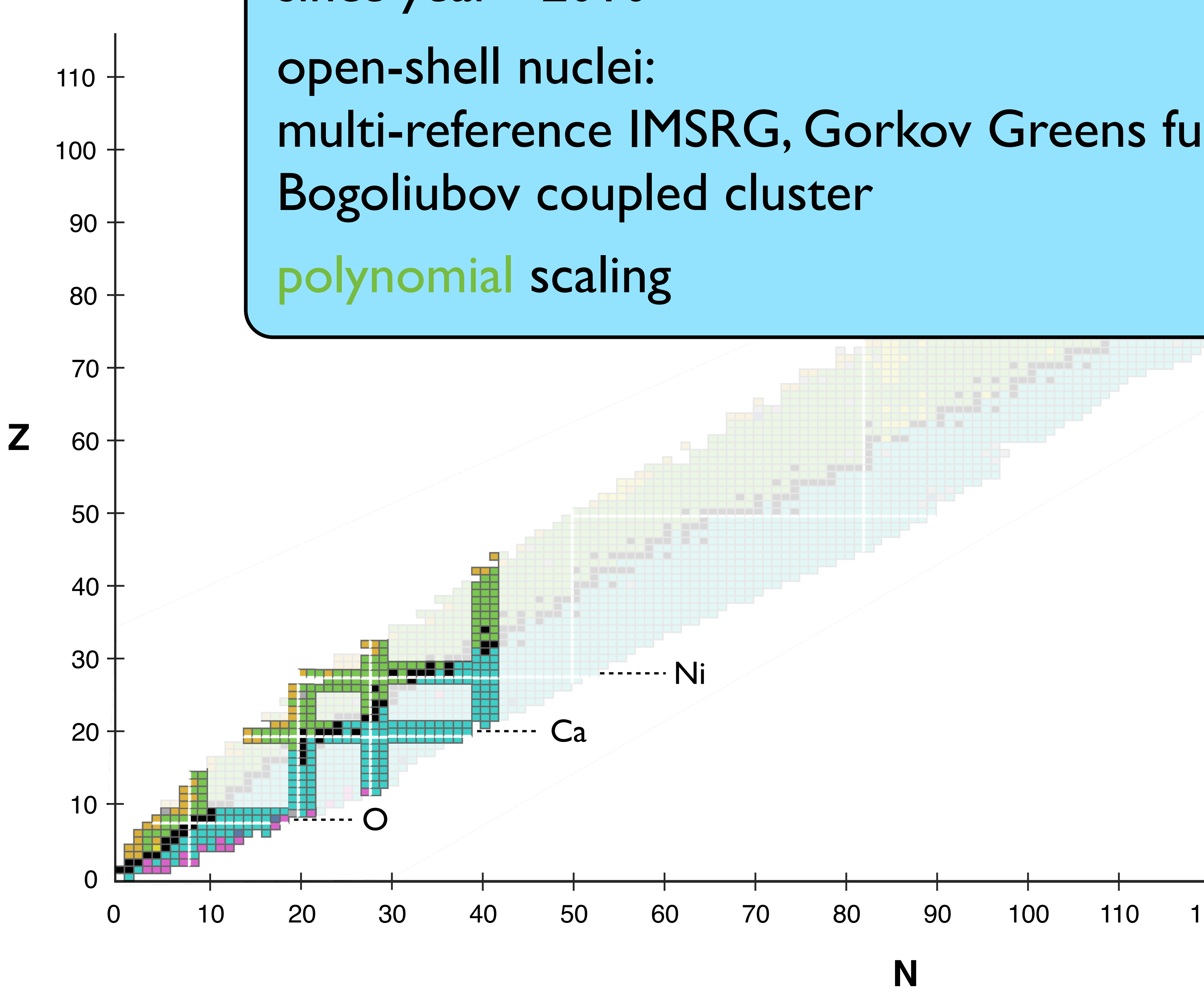


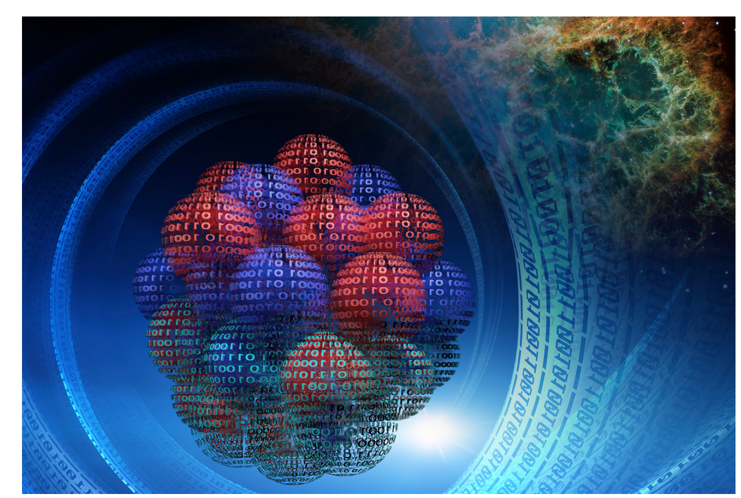
The theoretical nuclear landscape: Scope of ab initio methods for atomic nuclei

since year ~2010

open-shell nuclei:
multi-reference IMSRG, Gorkov Greens function, Bogoliubov coupled cluster

polynomial scaling



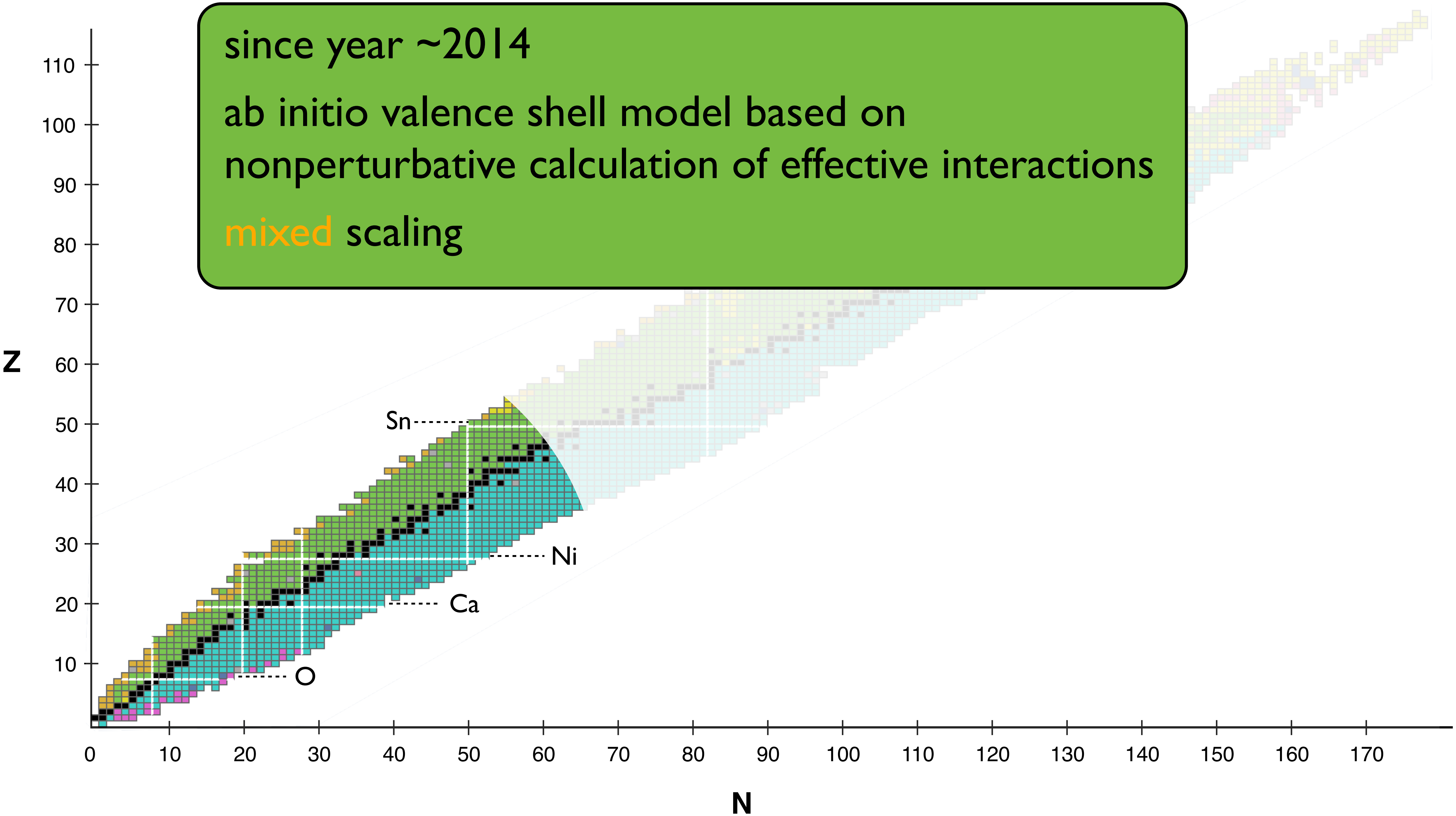


The theoretical nuclear landscape:
Scope of ab initio methods for atomic nuclei

since year ~2014

ab initio valence shell model based on nonperturbative calculation of effective interactions

mixed scaling



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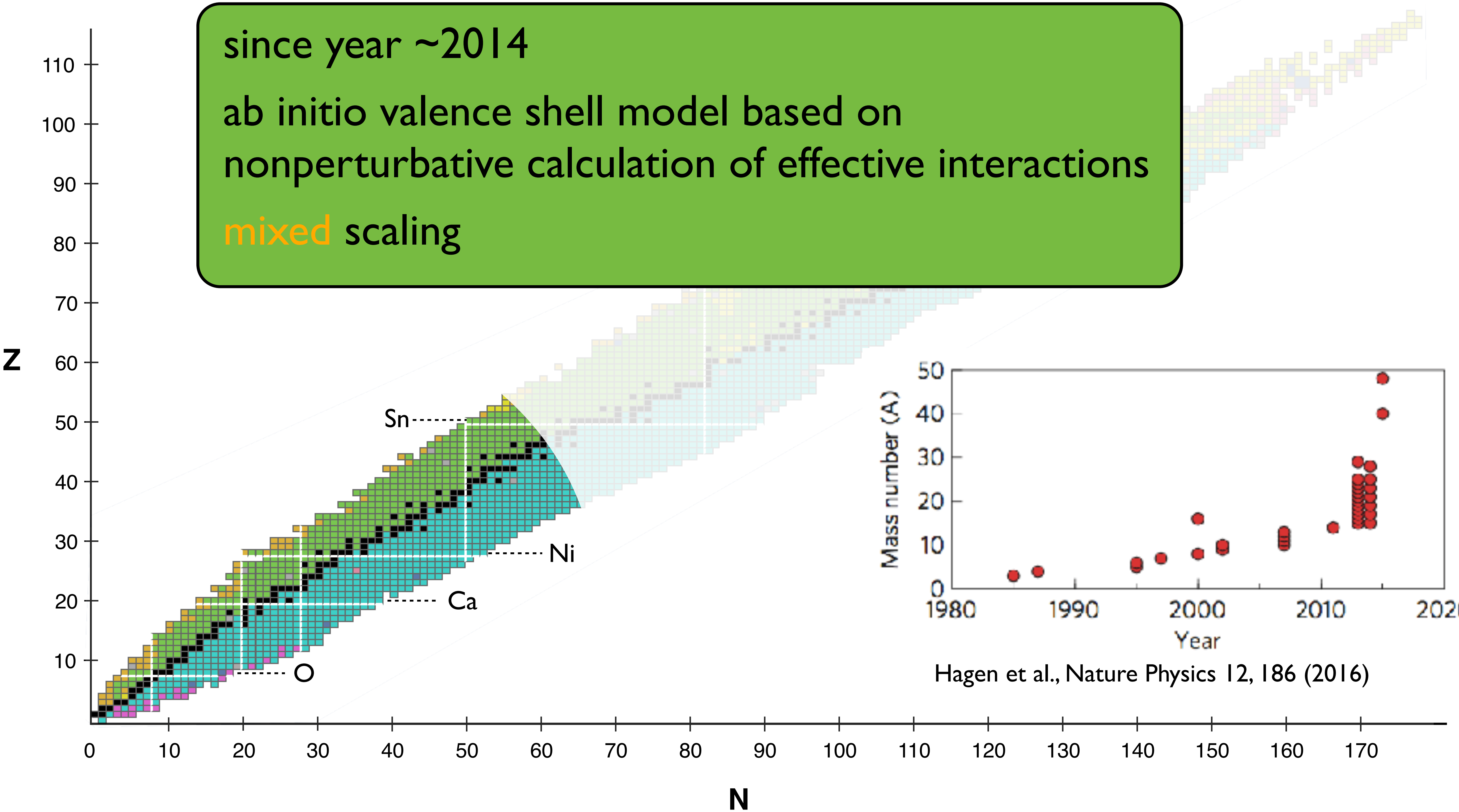
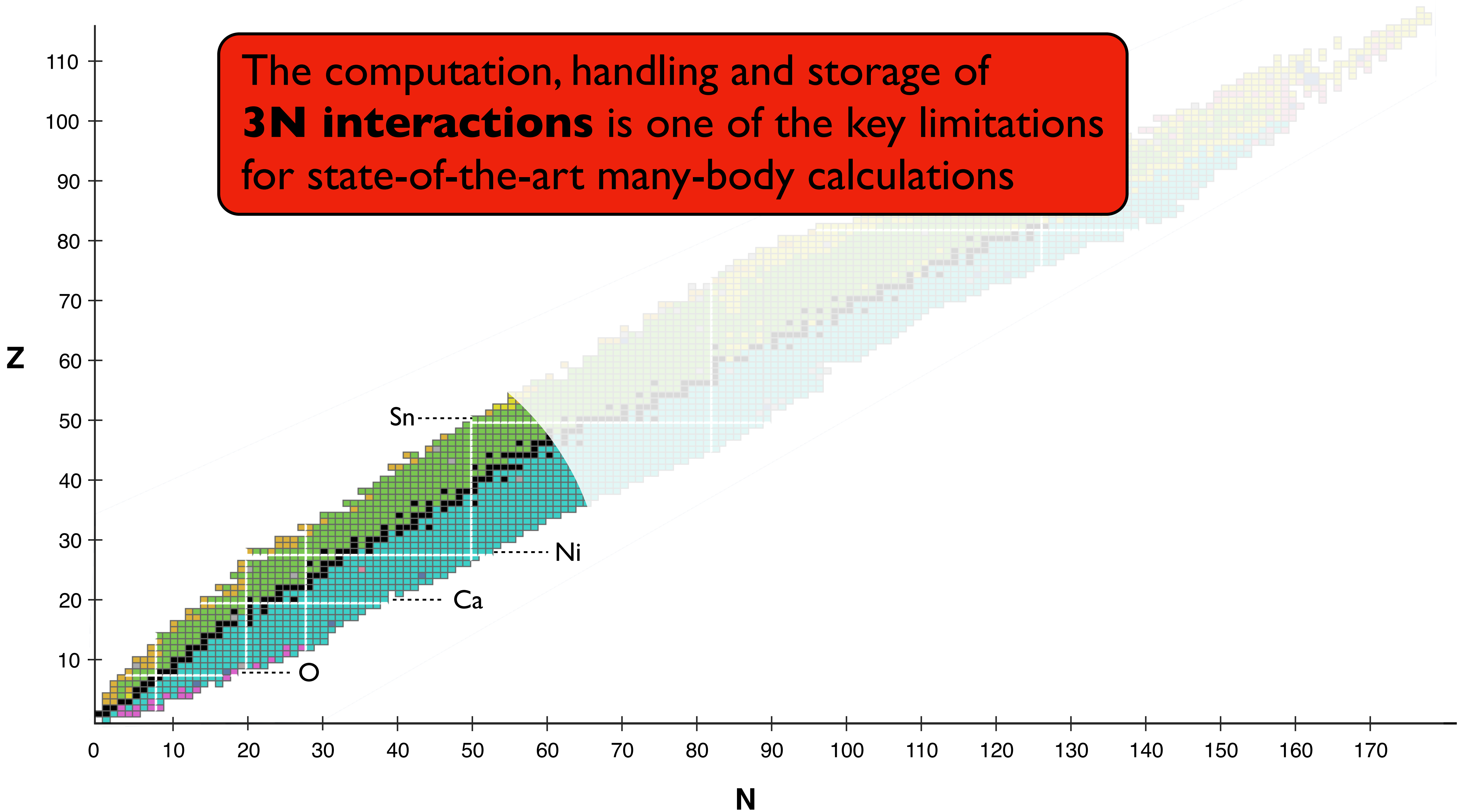


Hagen et al., Nature Physics 12, 186 (2016)

The theoretical nuclear landscape: Scope of ab initio methods for atomic nuclei

The computation, handling and storage of **3N interactions** is one of the key limitations for state-of-the-art many-body calculations



The theoretical nuclear landscape: Scope of ab initio methods for atomic nuclei

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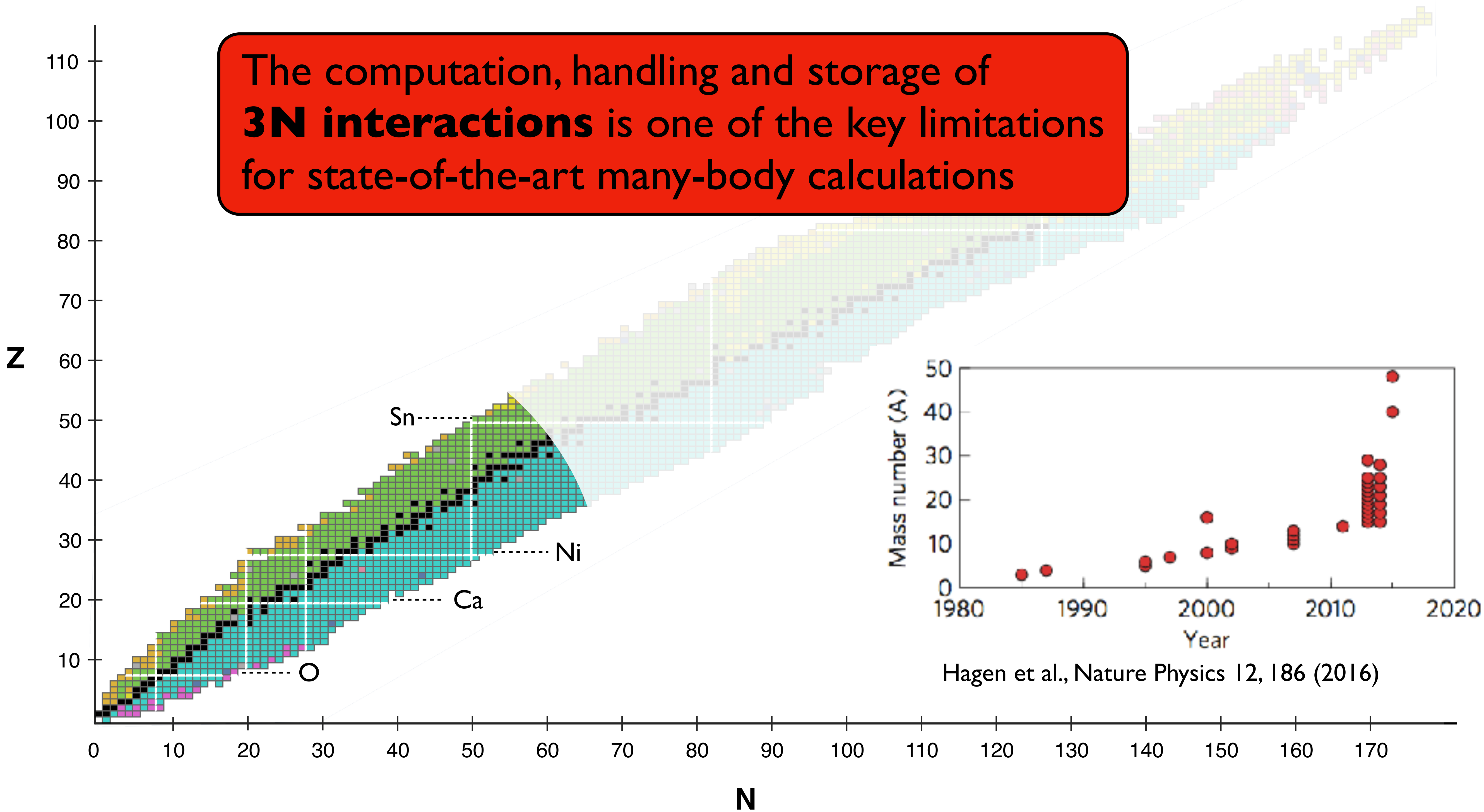

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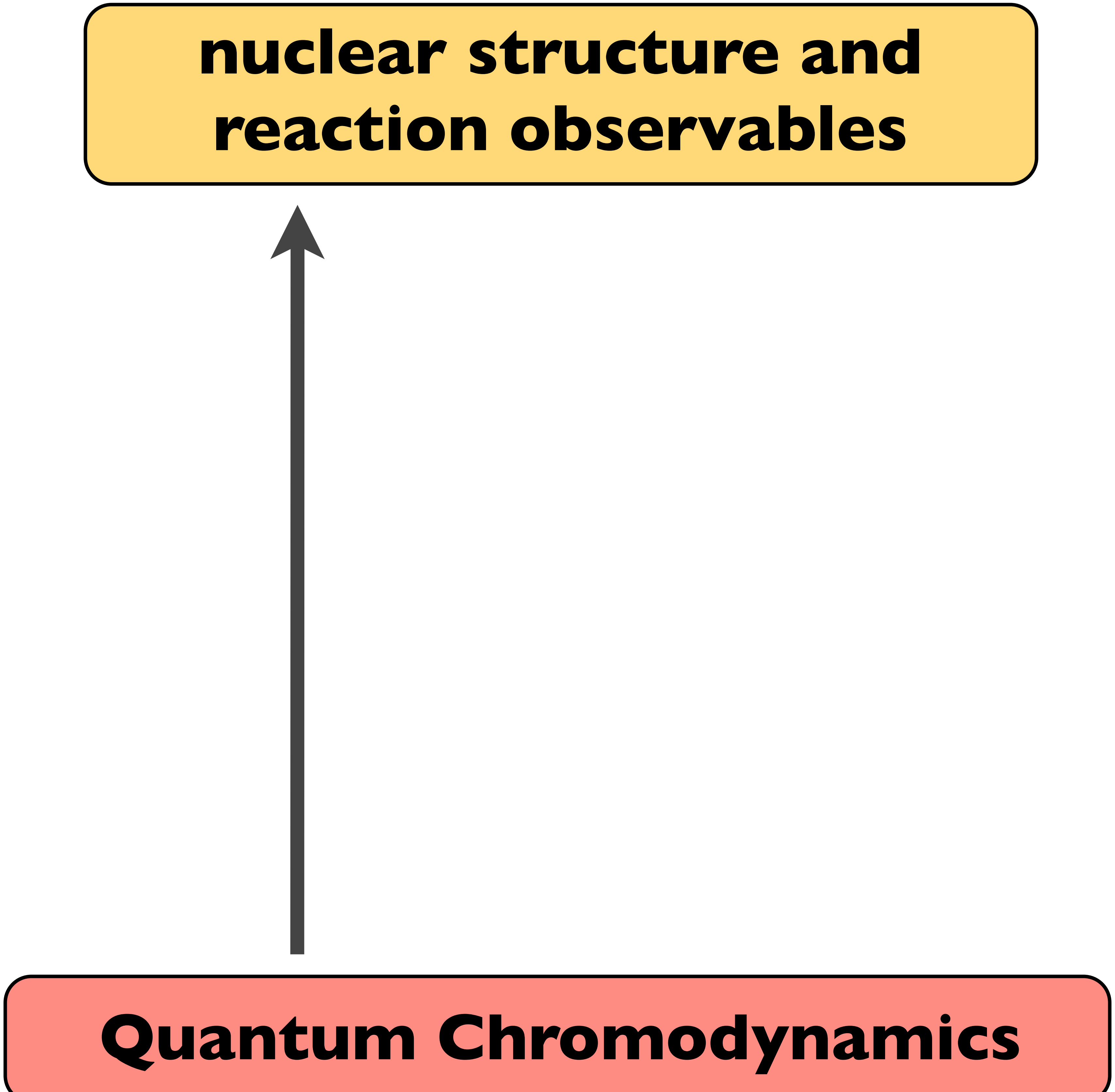
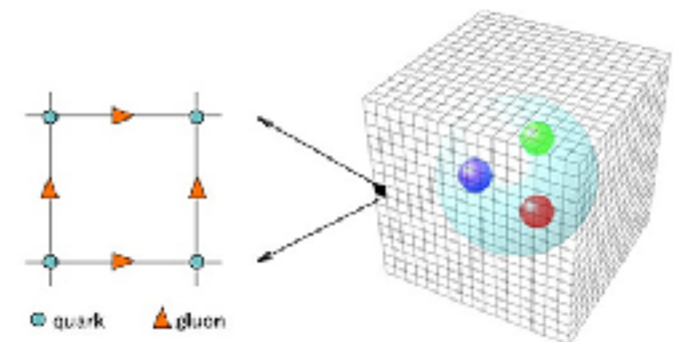
Ab initio nuclear structure and reaction theory



Ab initio nuclear structure and reaction theory

nuclear structure and reaction observables

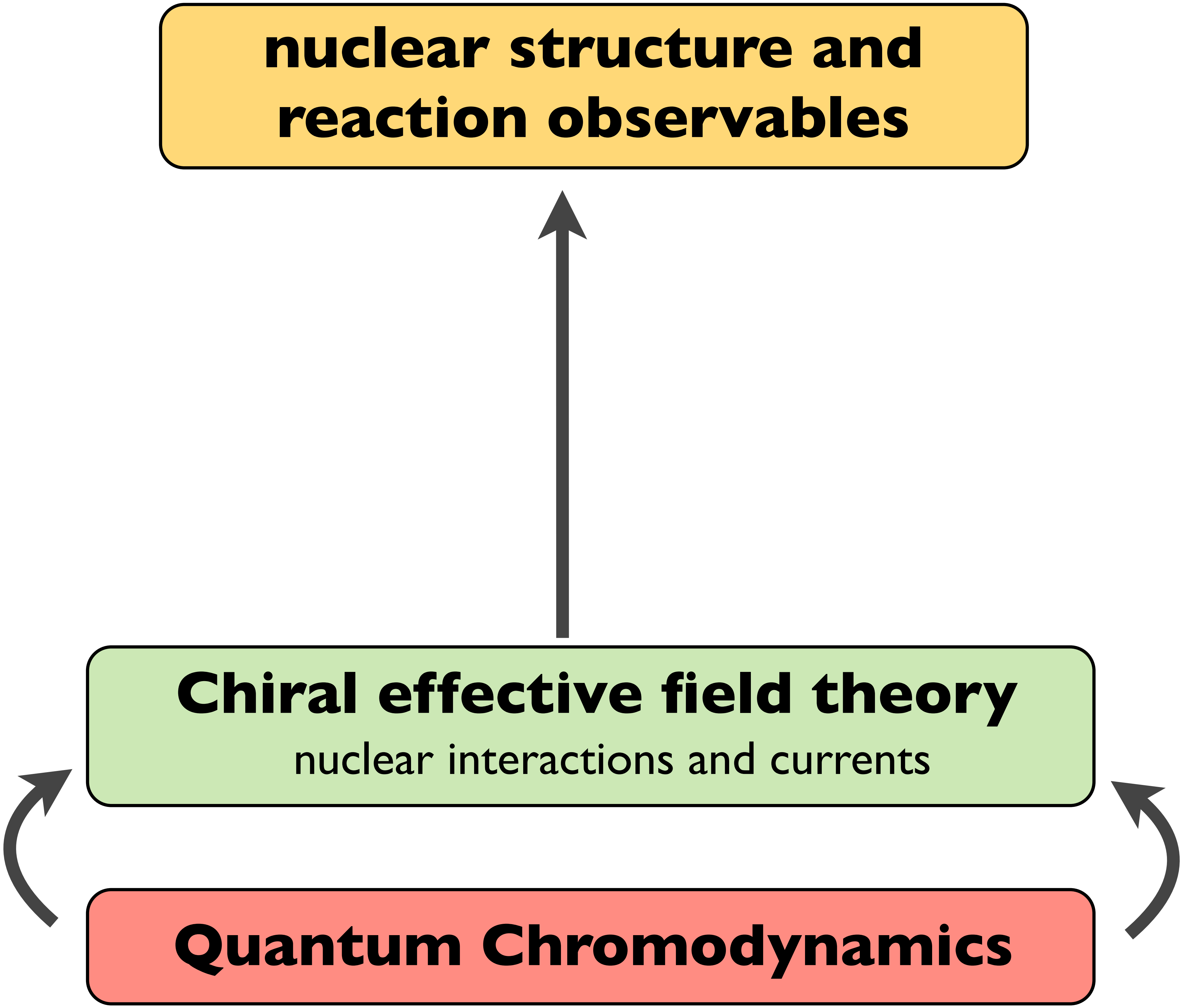
Lattice QCD



- requires extreme amounts of computational resources
- currently limited to 1- or 2-nucleon systems
- current accuracy insufficient for precision nuclear structure

Quantum Chromodynamics

Ab initio nuclear structure and reaction theory



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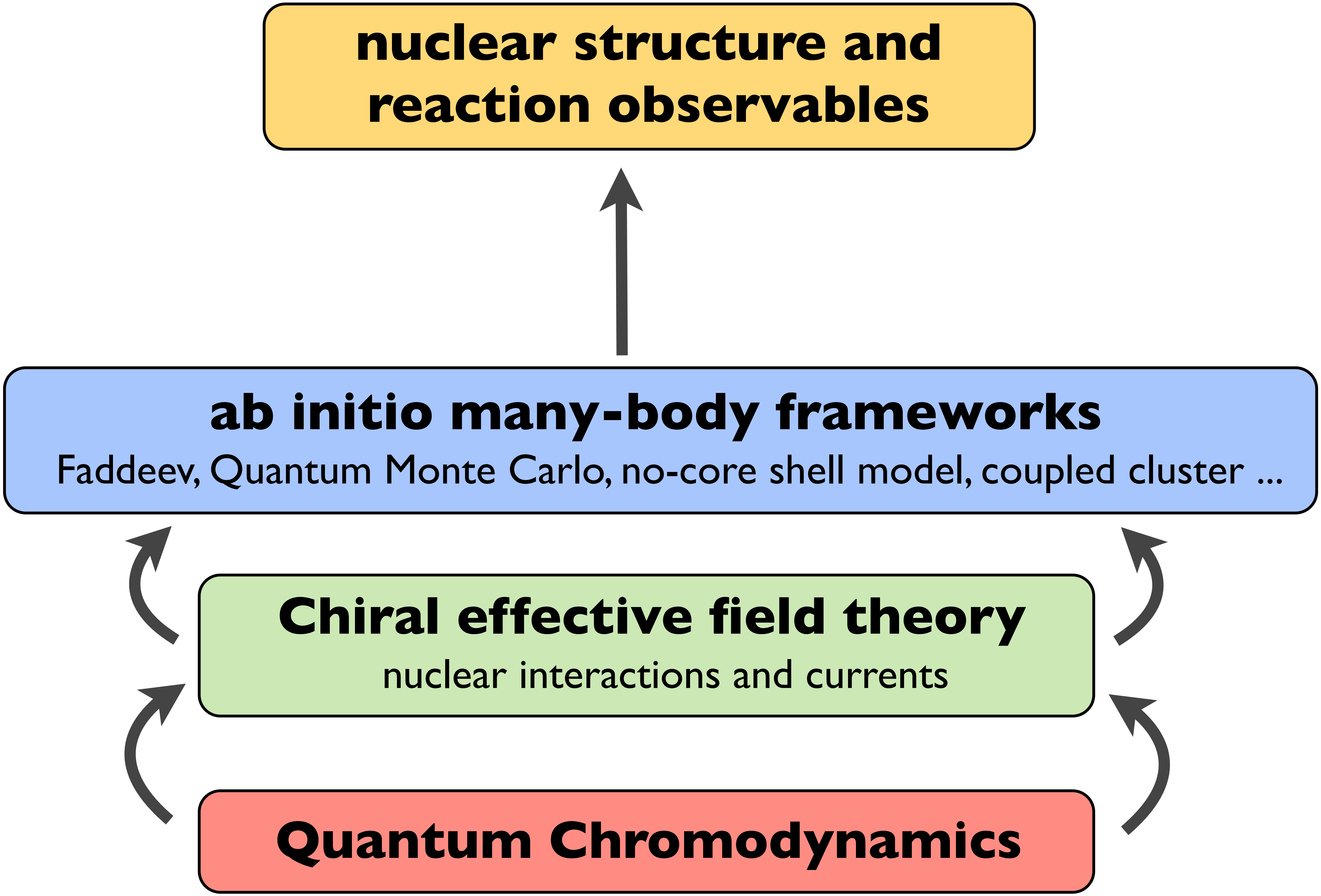

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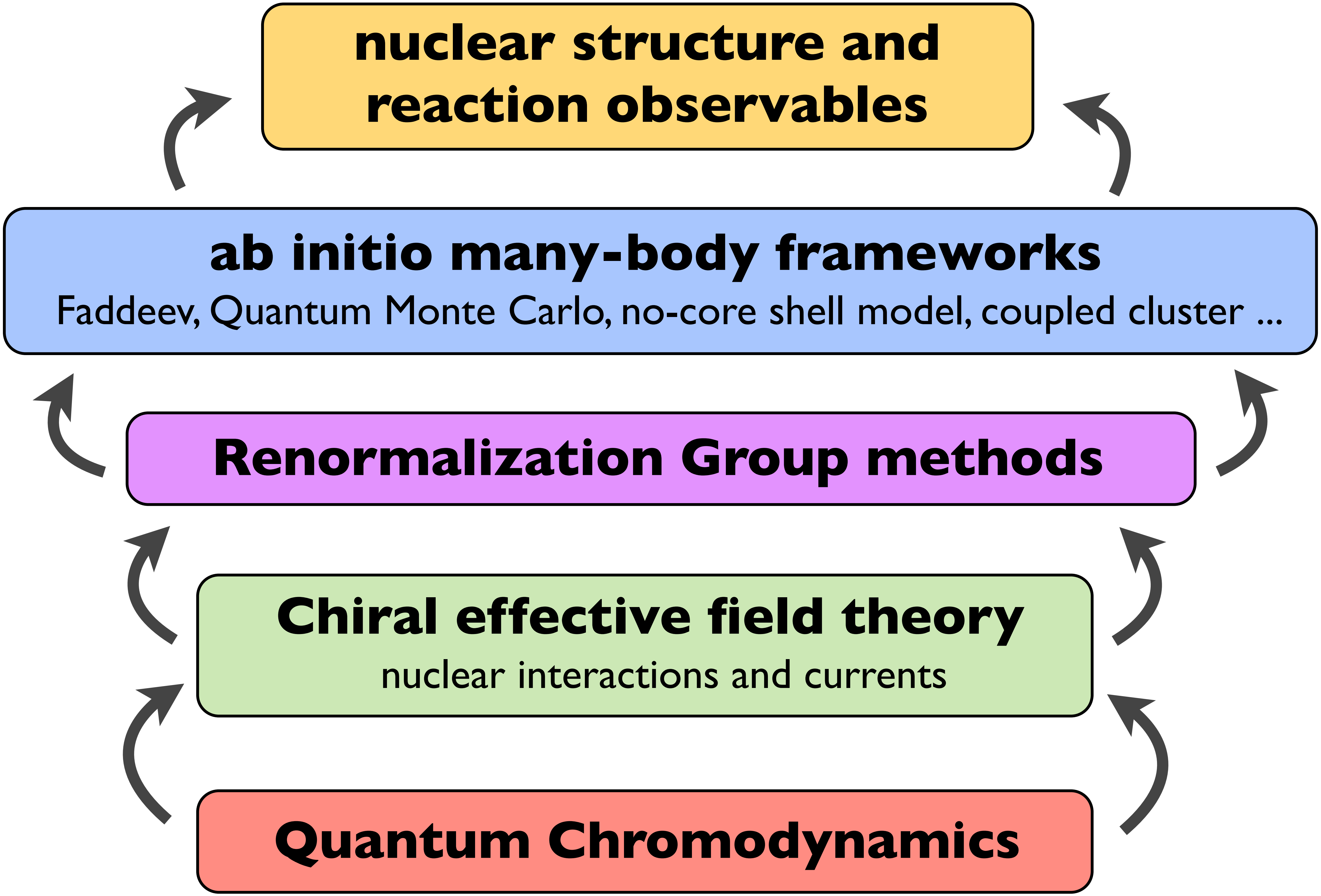
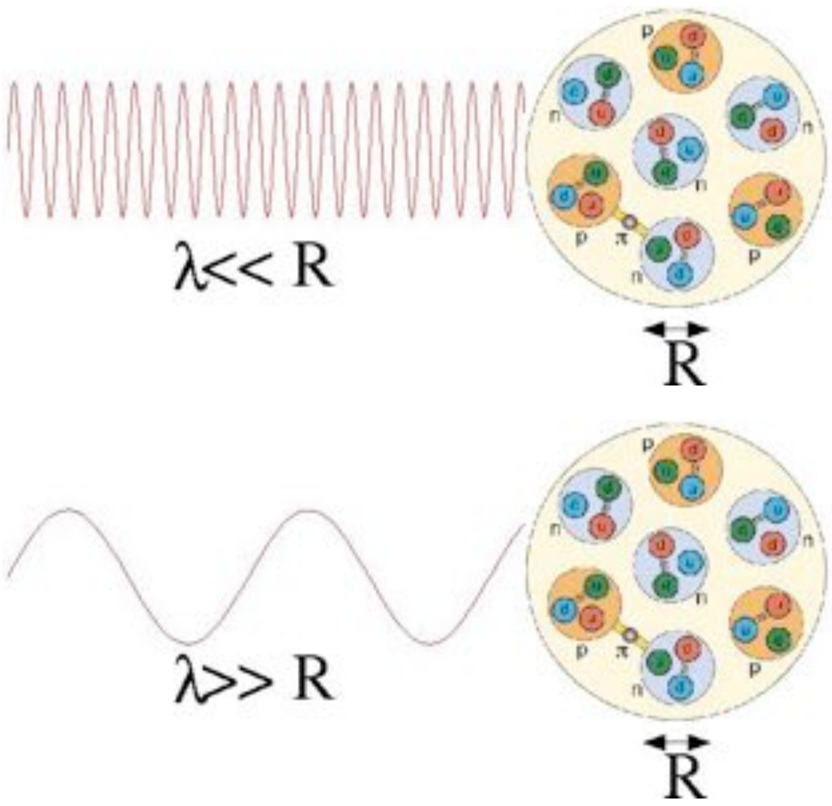


Nuclear effective degrees of freedom



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- at low energies, details are not resolved

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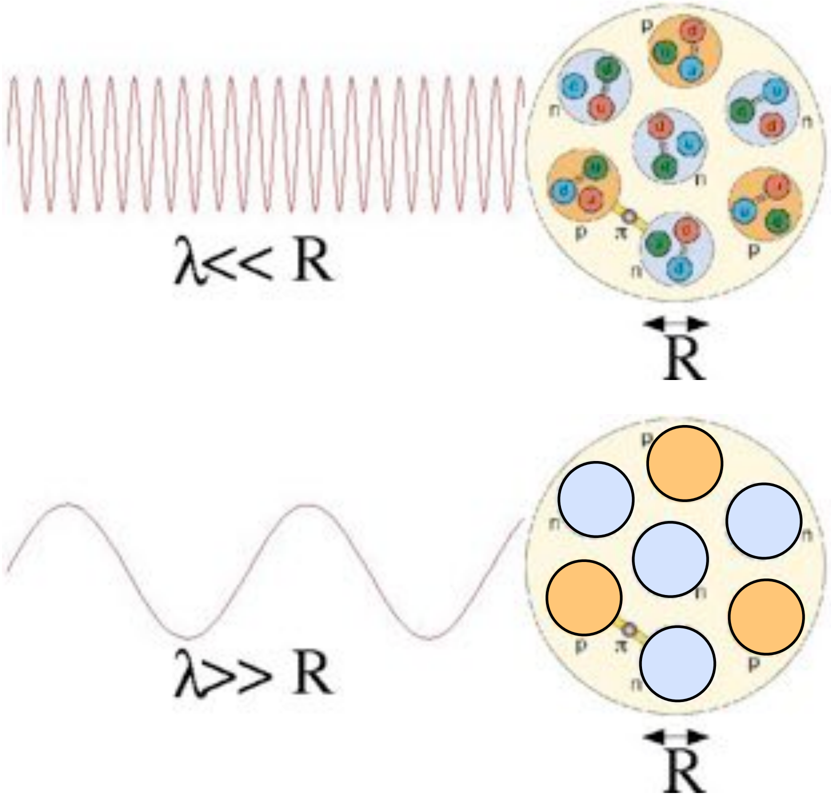
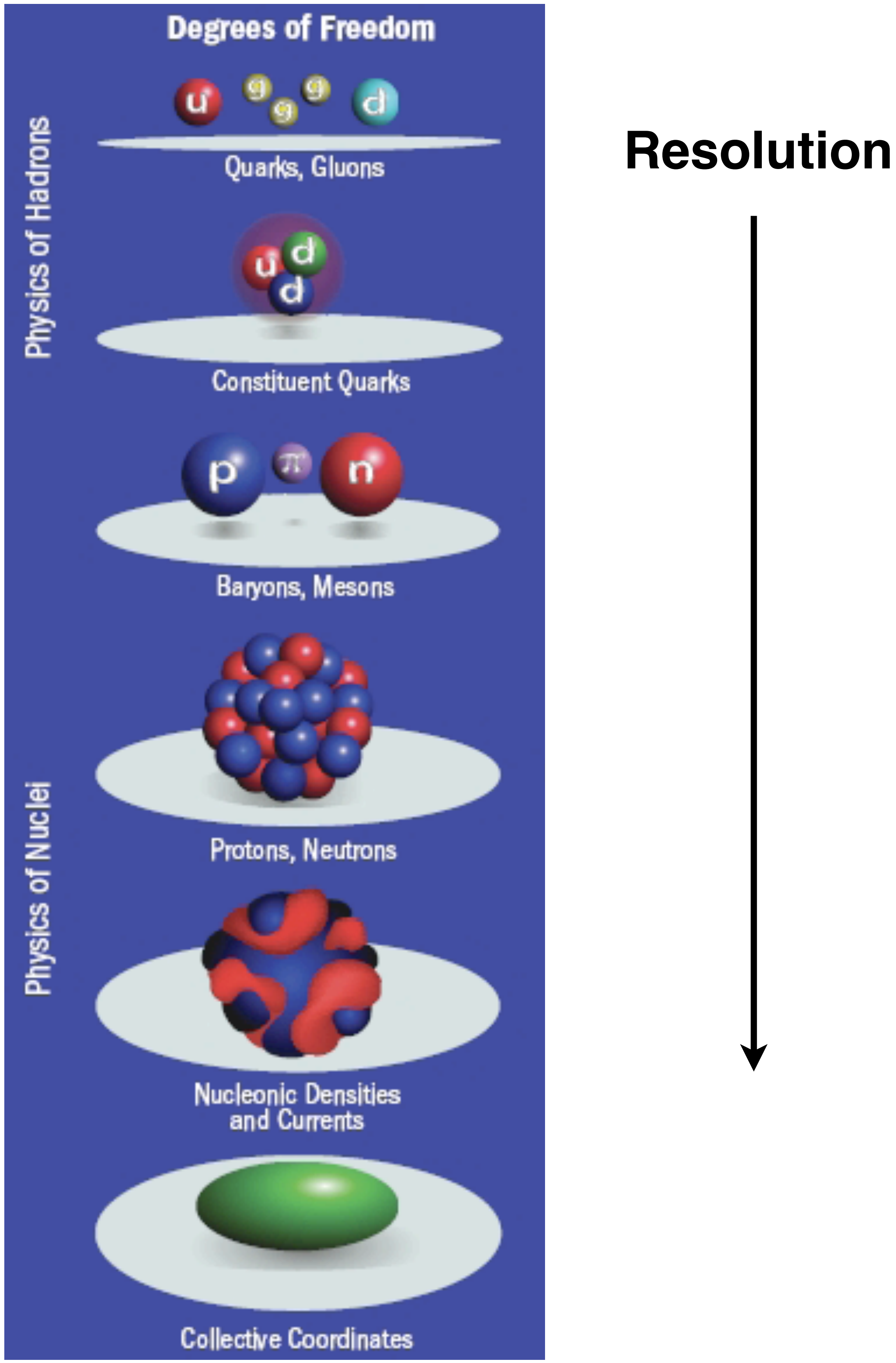
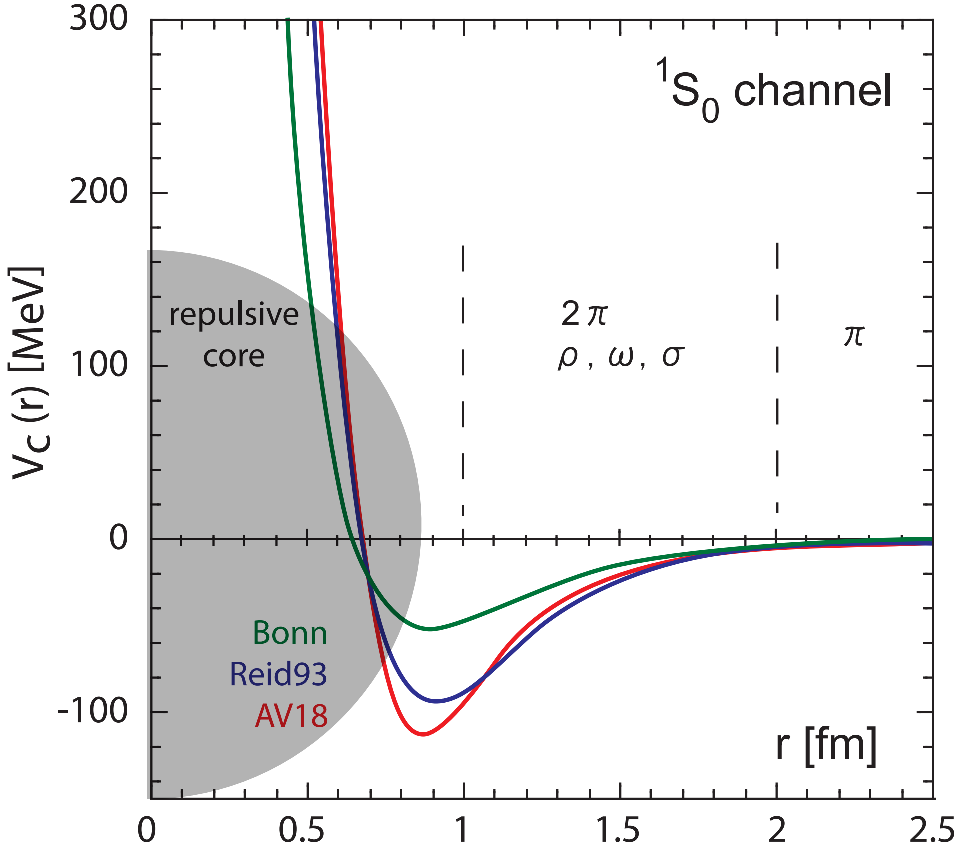


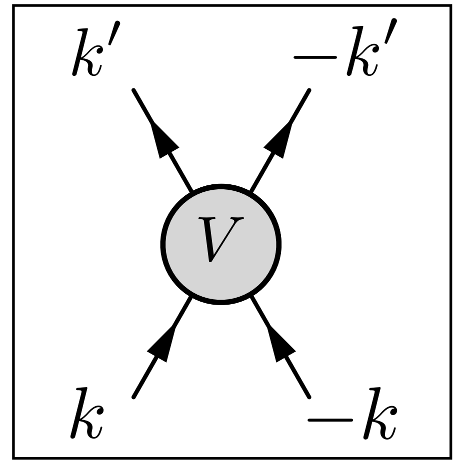


- if a nucleus is probed at high energies, nucleon substructure is resolved
- at low energies, details are not resolved
- replace fine structure by something simpler (compare multipole expansion)

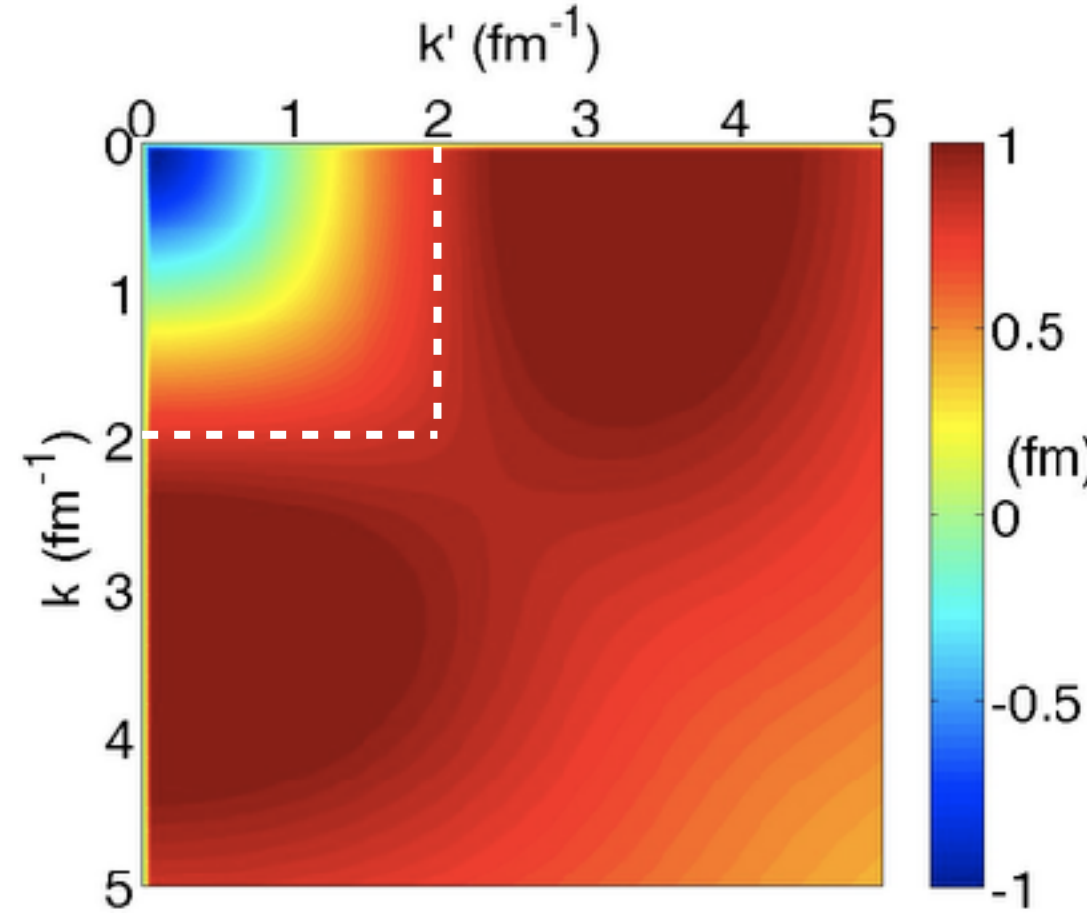
→ effective field theory

Problem: Traditional "hard" NN interactions





$\langle k' | V | k \rangle$

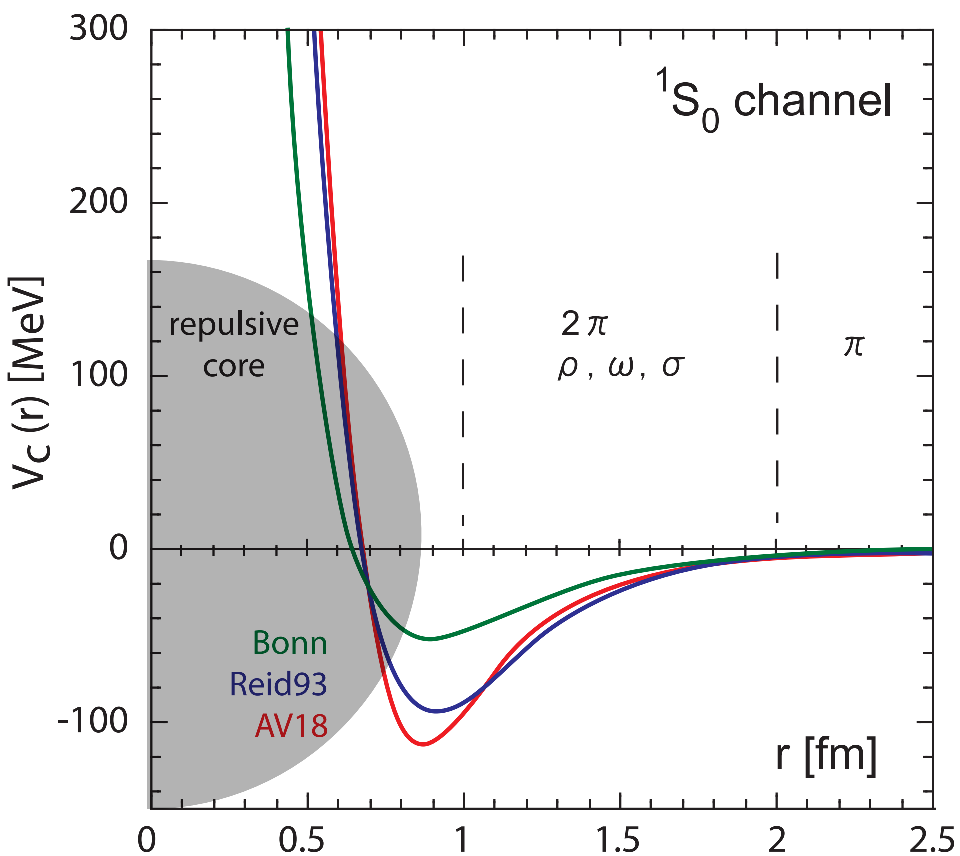


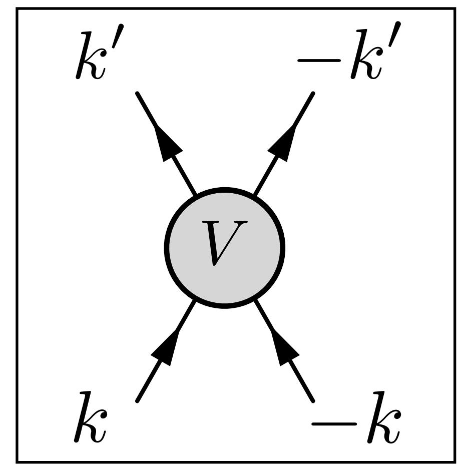
- constructed to fit low-energy scattering data
- "hard" NN interactions contain repulsive core at small relative distance
- strong coupling between low and high-momentum components

  $\Rightarrow$ nuclear many-body problem non-perturbative, hard to solve!

Claim:
Problems due to high resolution from interaction!

Problem: Traditional "hard" NN interactions





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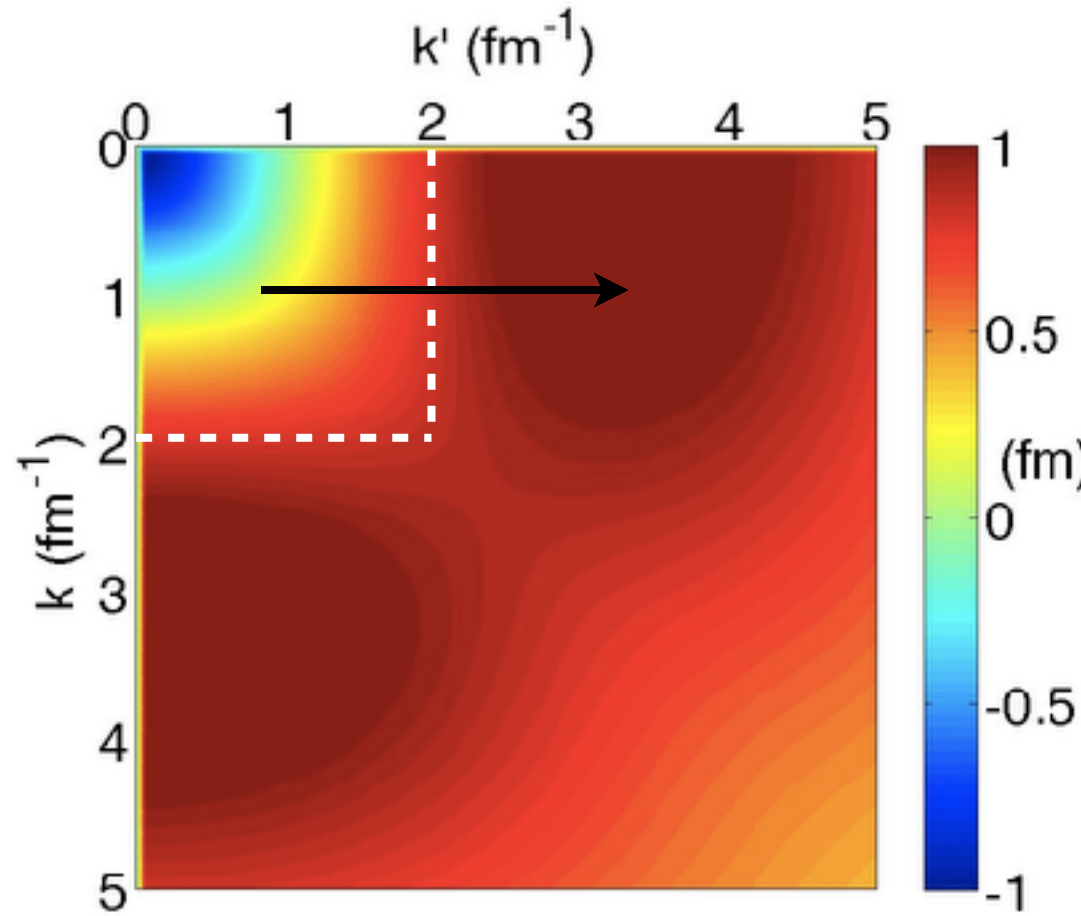

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Resolution: the higher the better?

in nuclear structure we are interested in low-energy observables

(long-wavelength information!)

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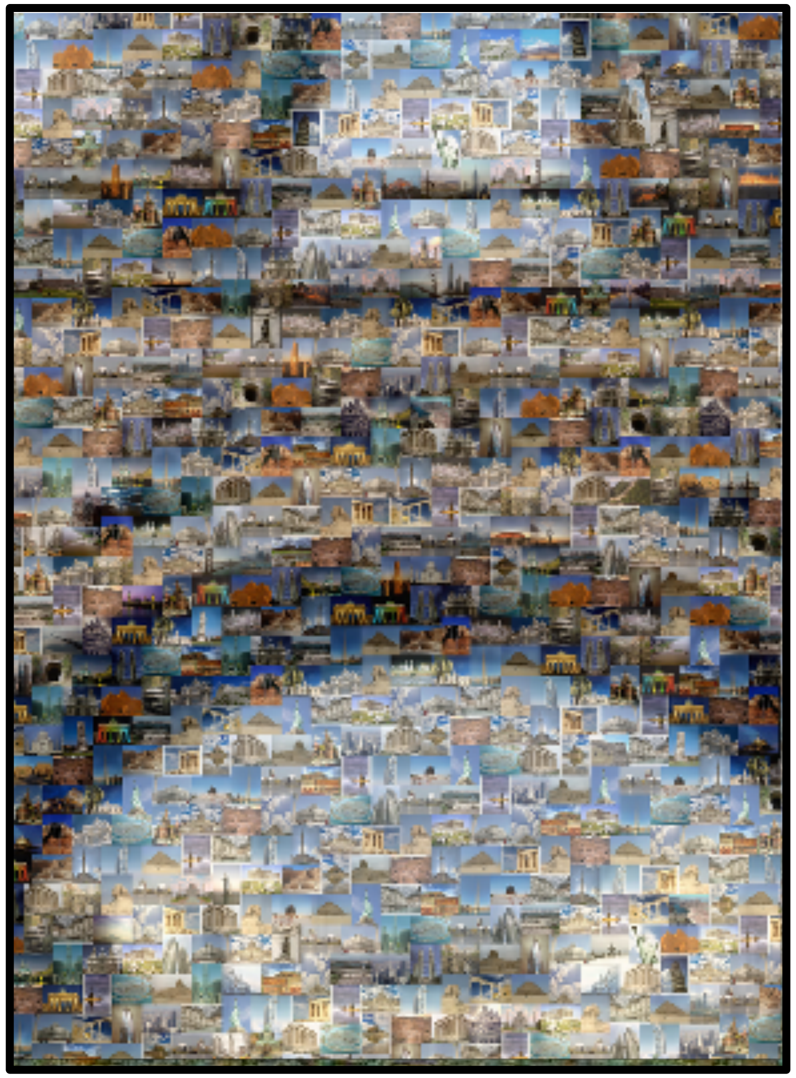

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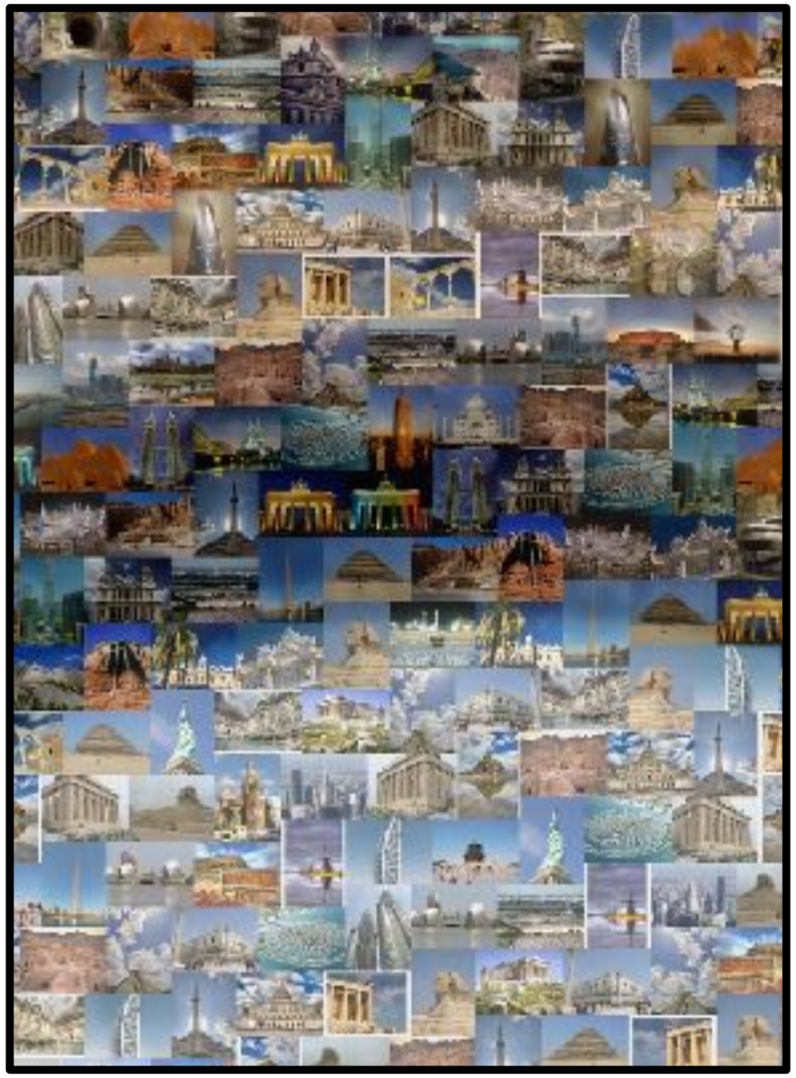


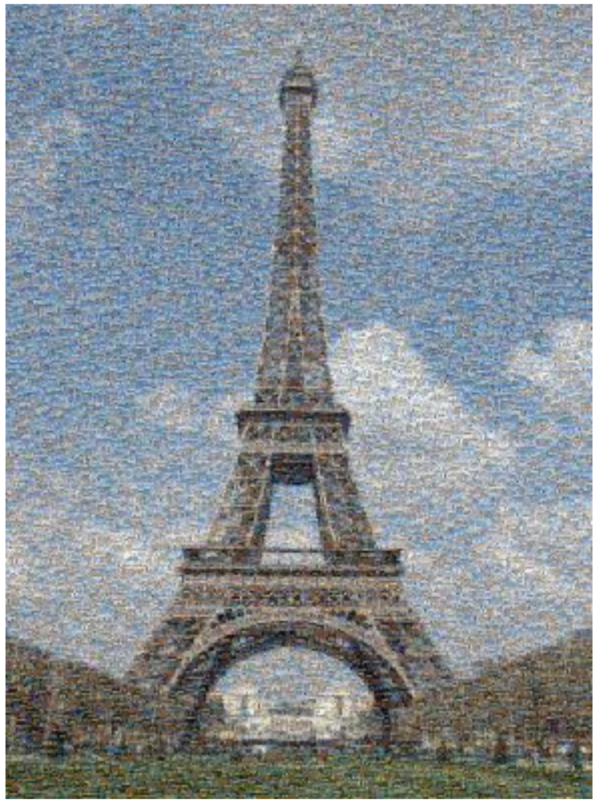
Resolution: the higher the better?

in nuclear structure we are interested in low-energy observables

(long-wavelength information!)

- resolution of short-distance structures can obscure this information
- small details have nothing to do with long-wavelength information!

Strategy: use a lower-resolution version



low-pass filter

- long-wavelength information is preserved
- much less information necessary

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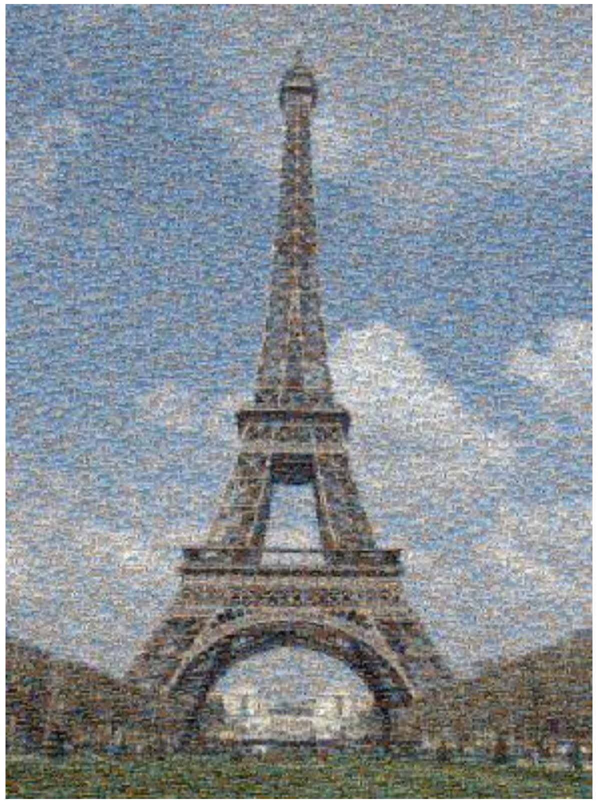

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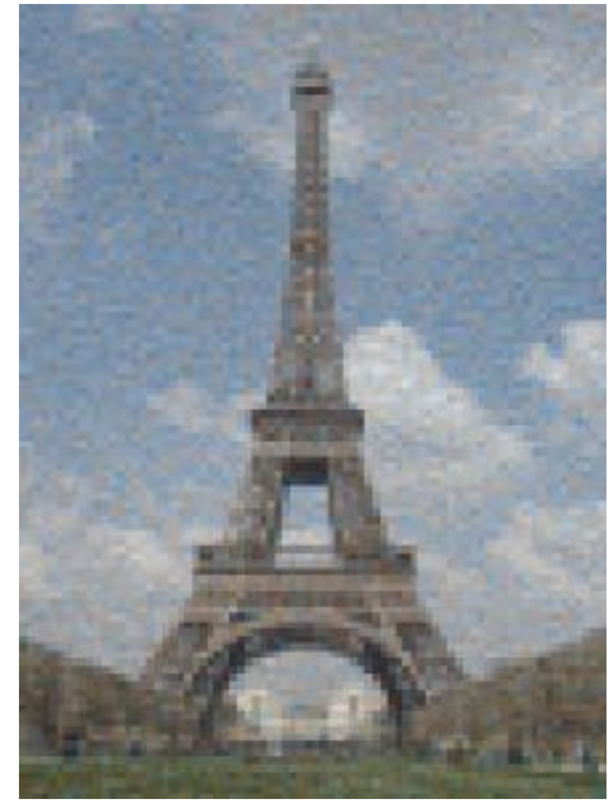

- long-wavelength information is preserved
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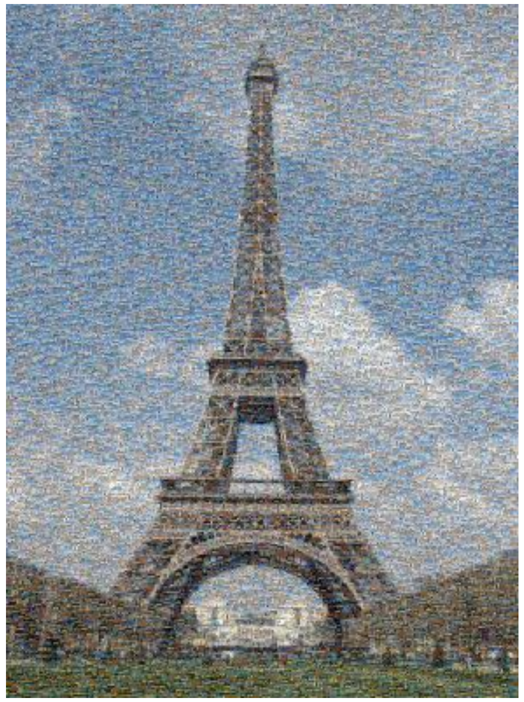
... however, it's not that easy in nuclear physics.

Strategy: use a lower-resolution version



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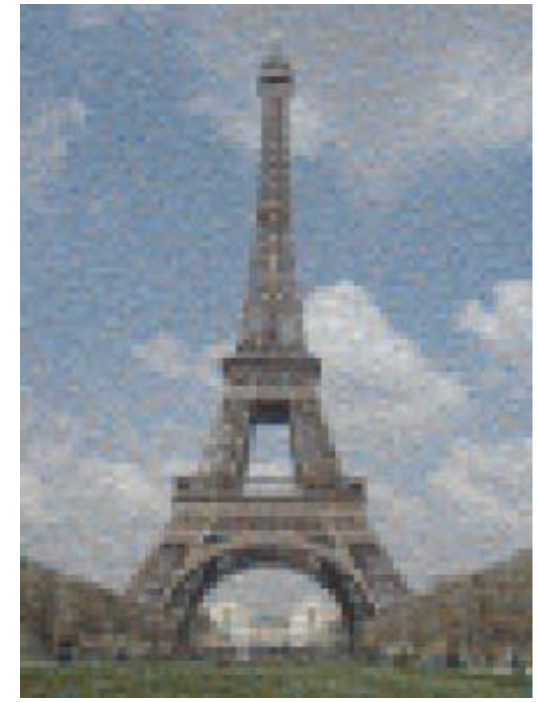

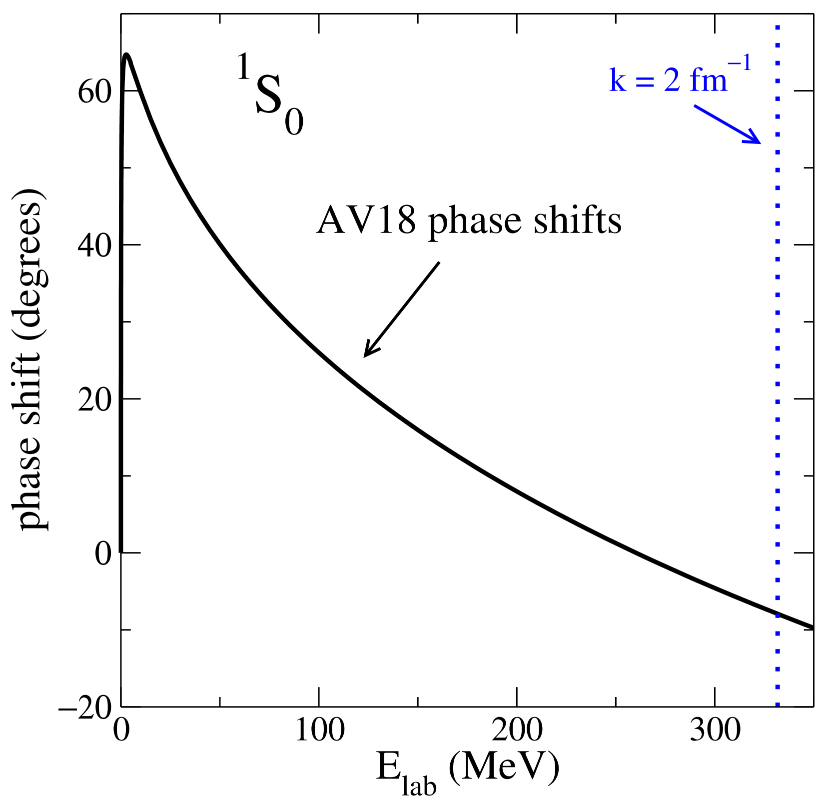

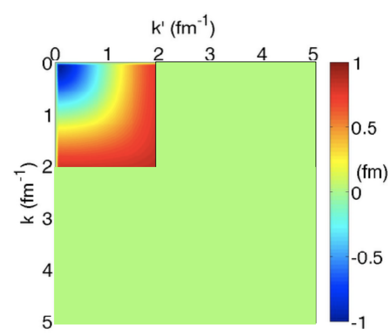

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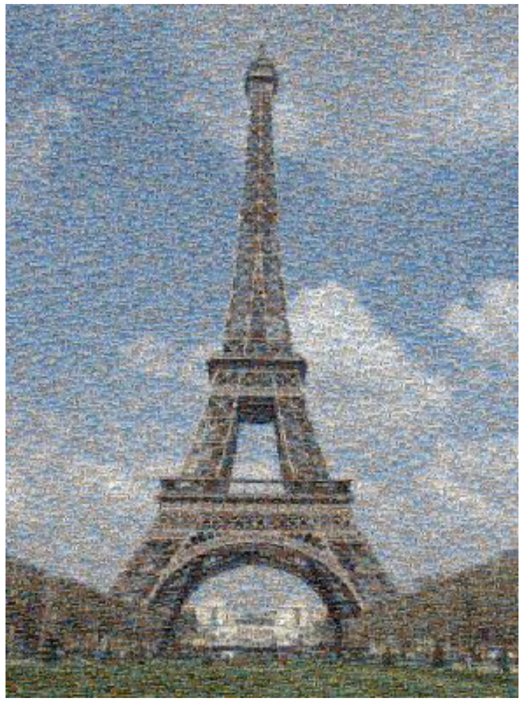

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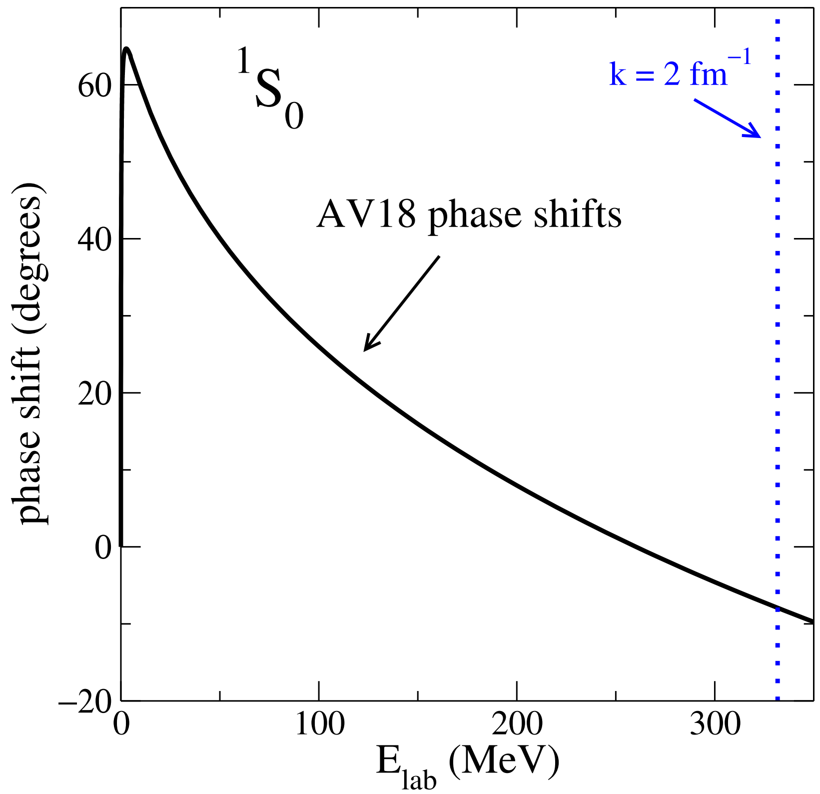

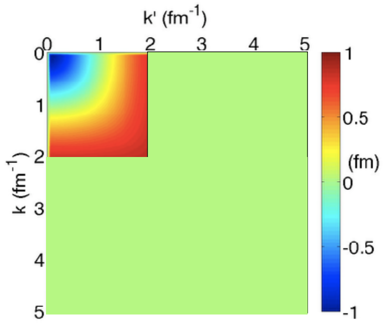

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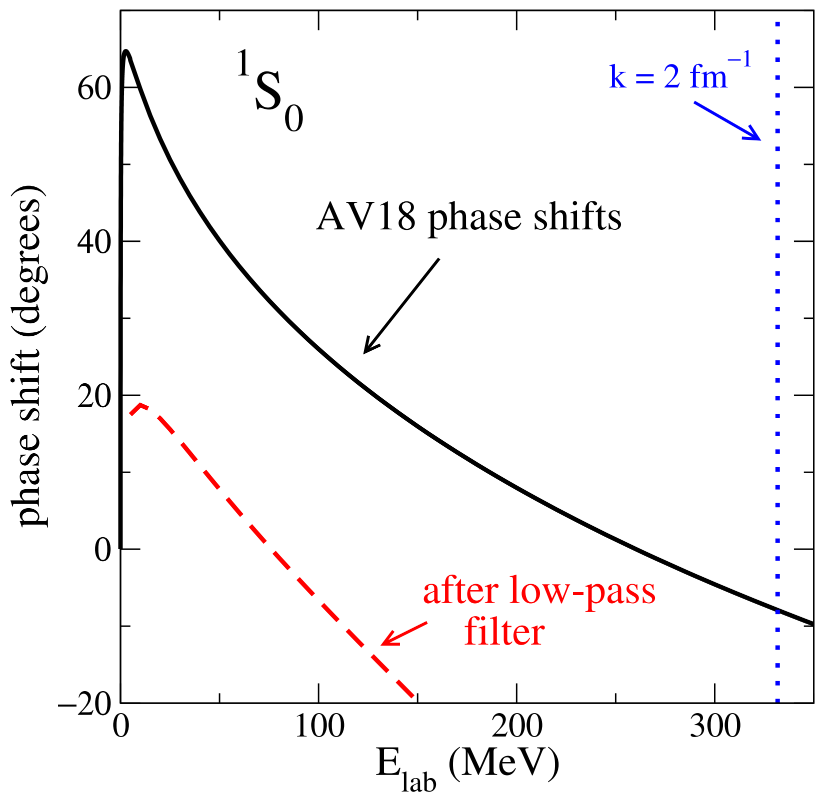
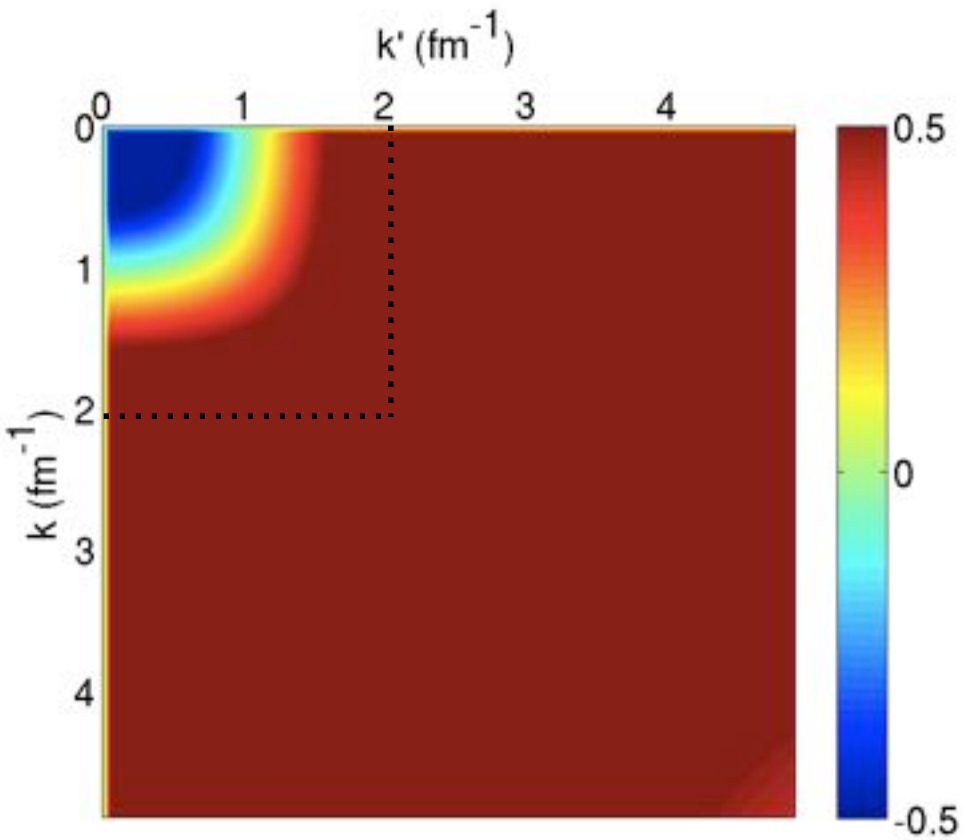
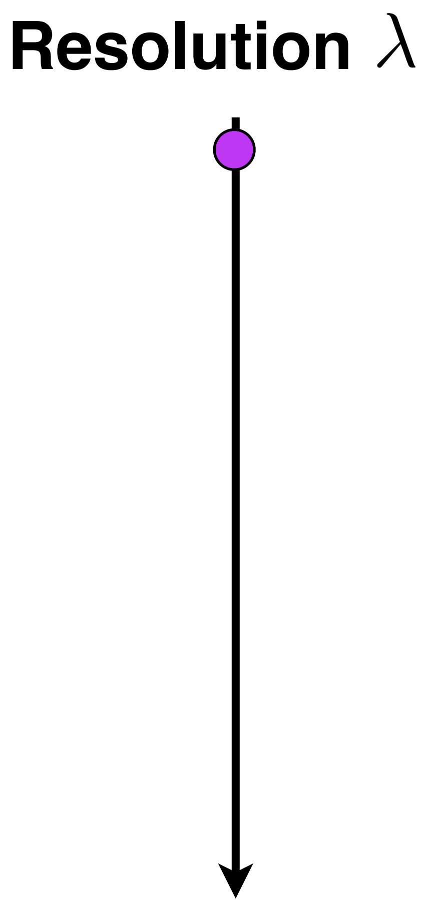


- truncated interaction fails completely to reproduce original phase shifts
- problem: low- and high momentum states are coupled by interaction!

Systematically changing the resolution: the Similarity Renormalization Group





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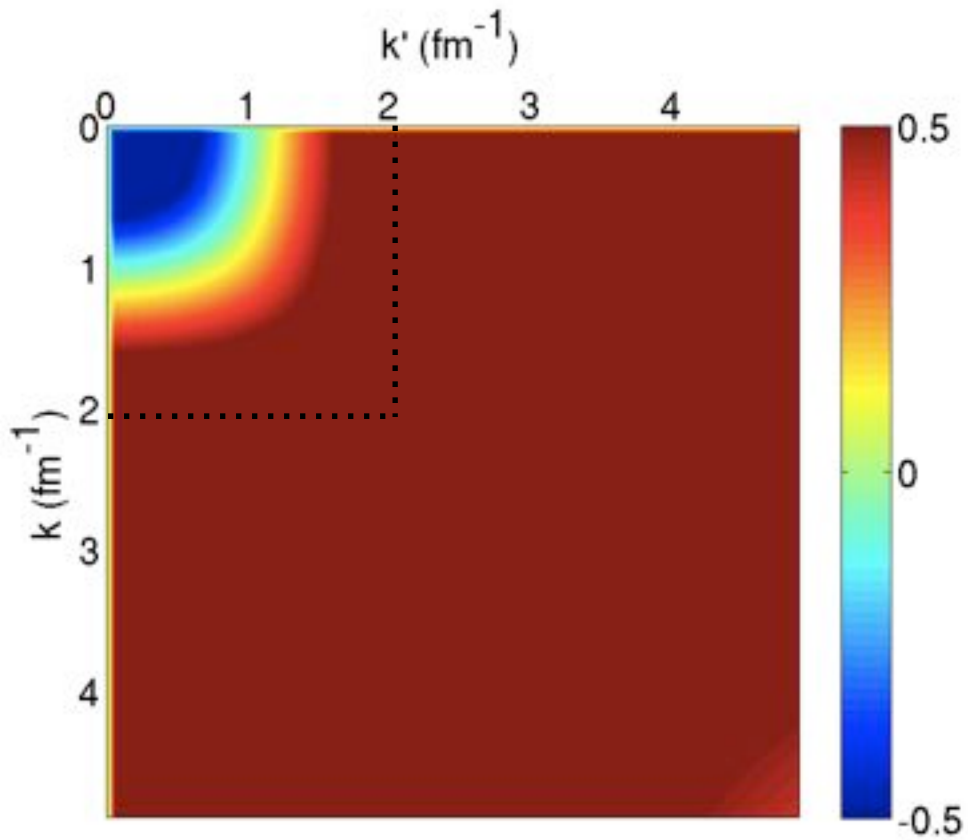

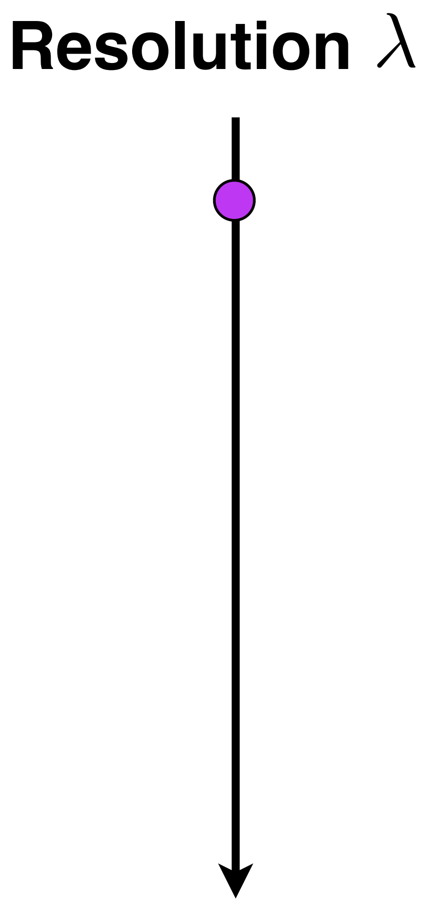

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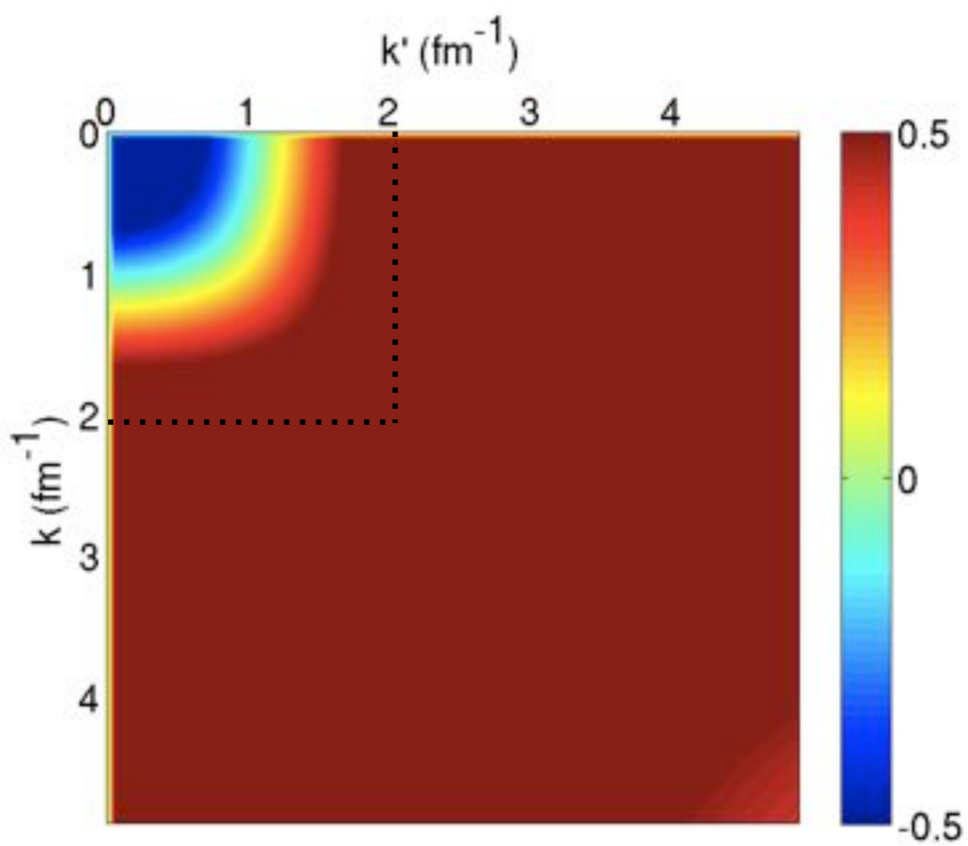

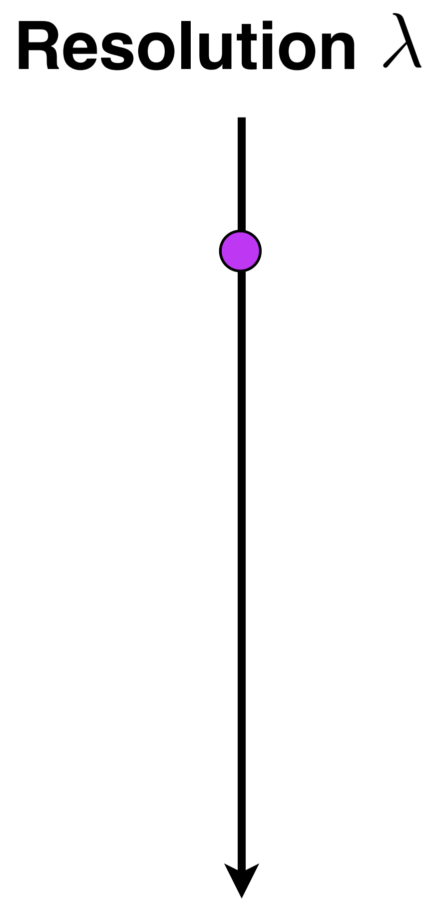

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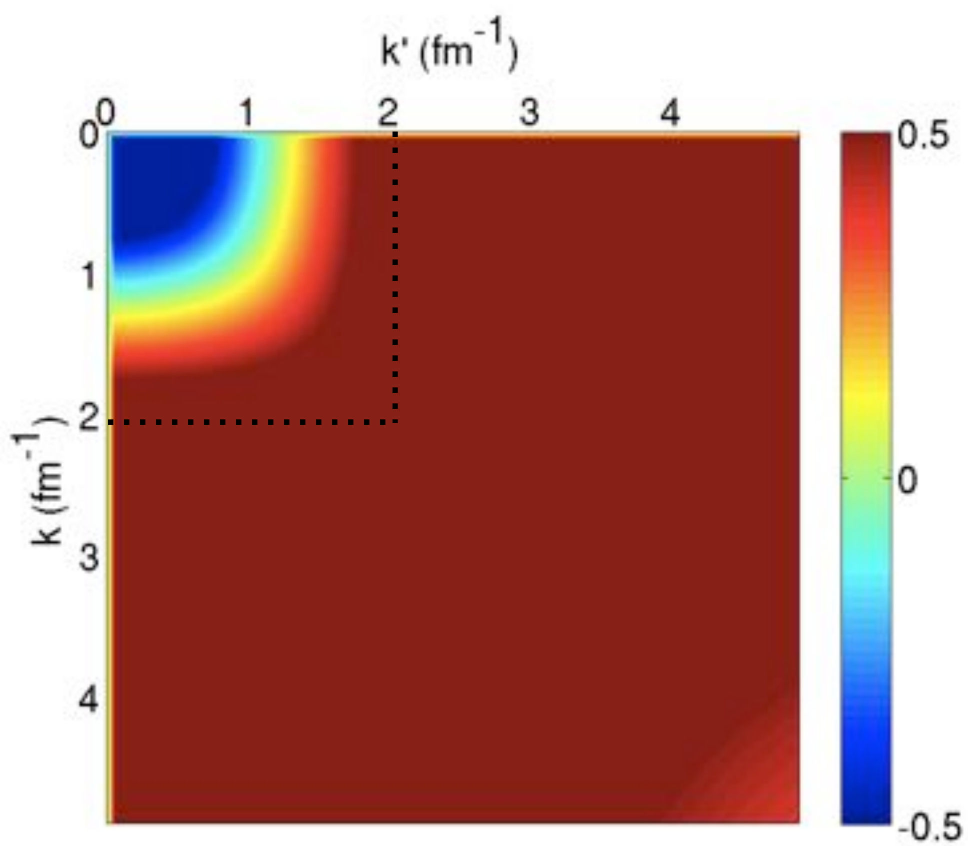

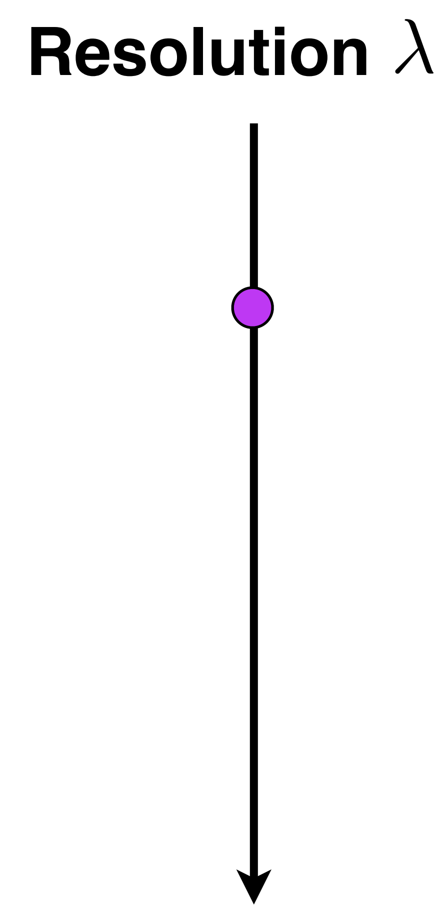

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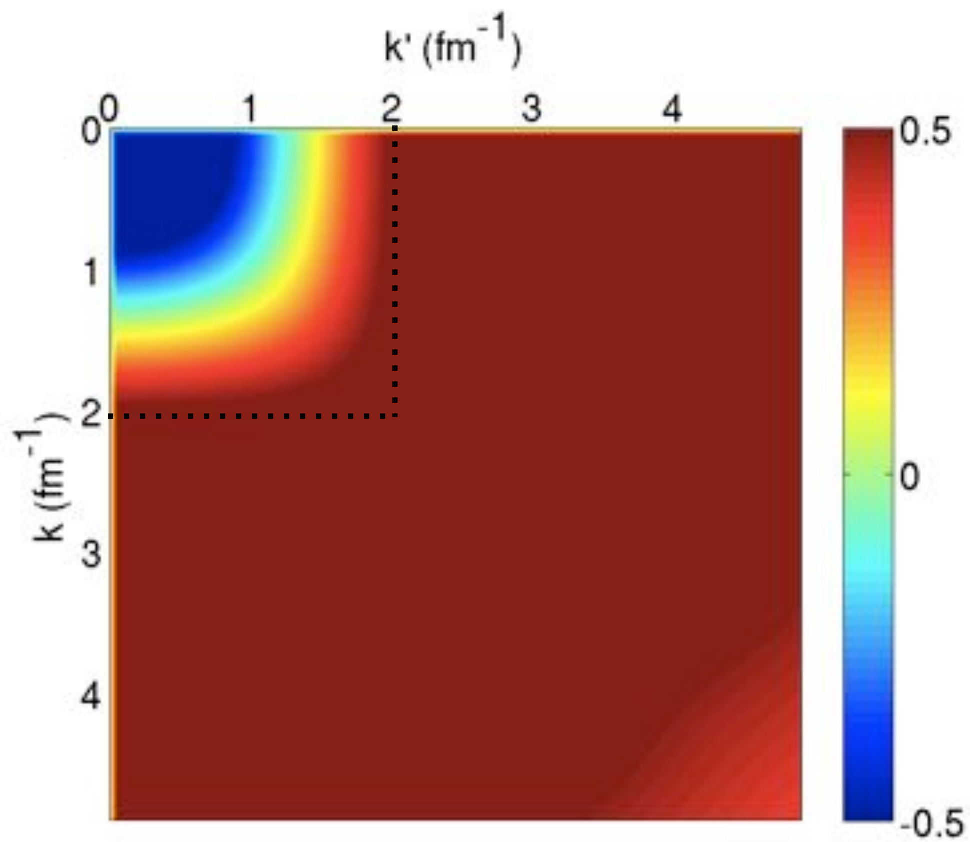

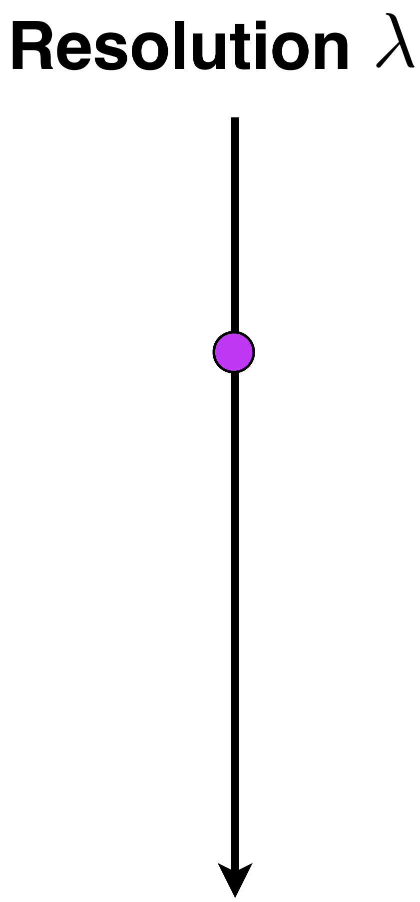

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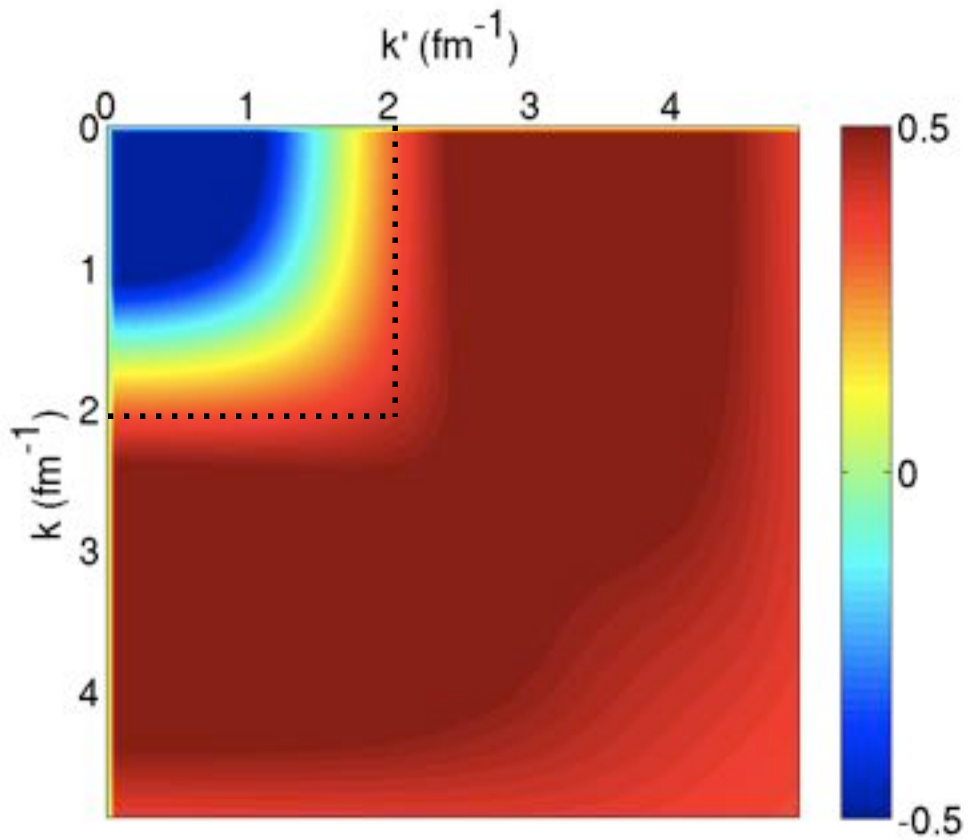

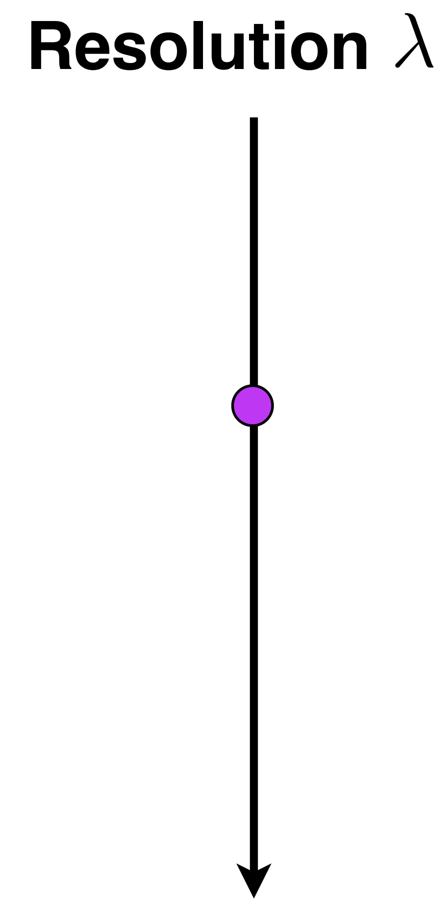

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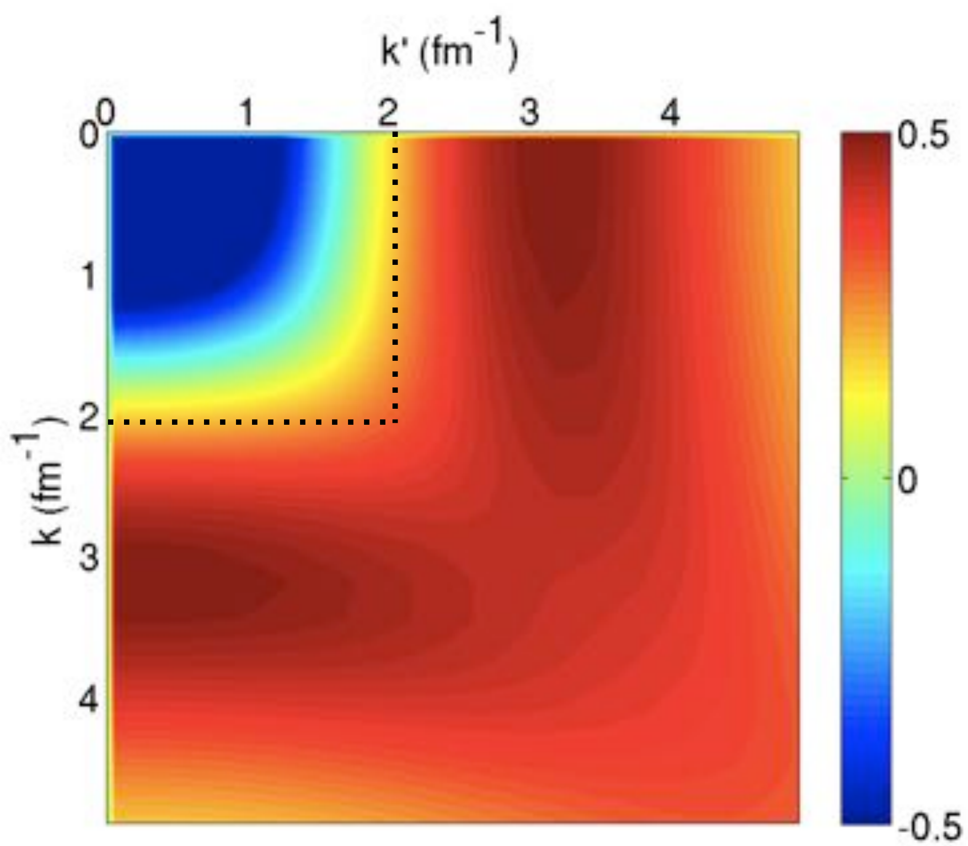

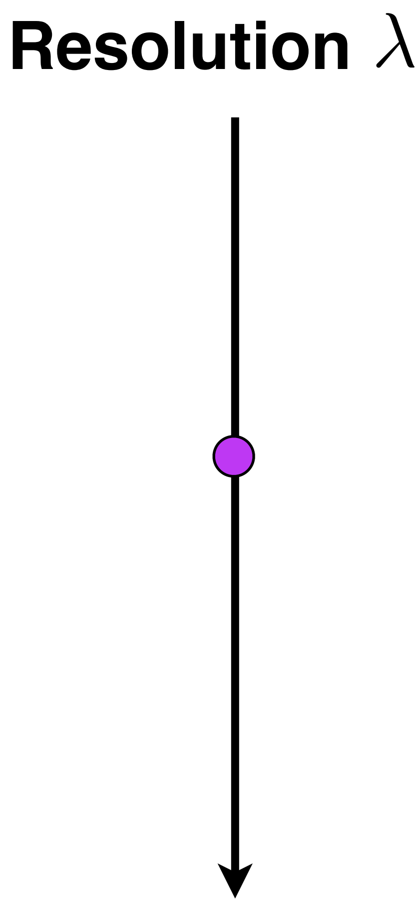

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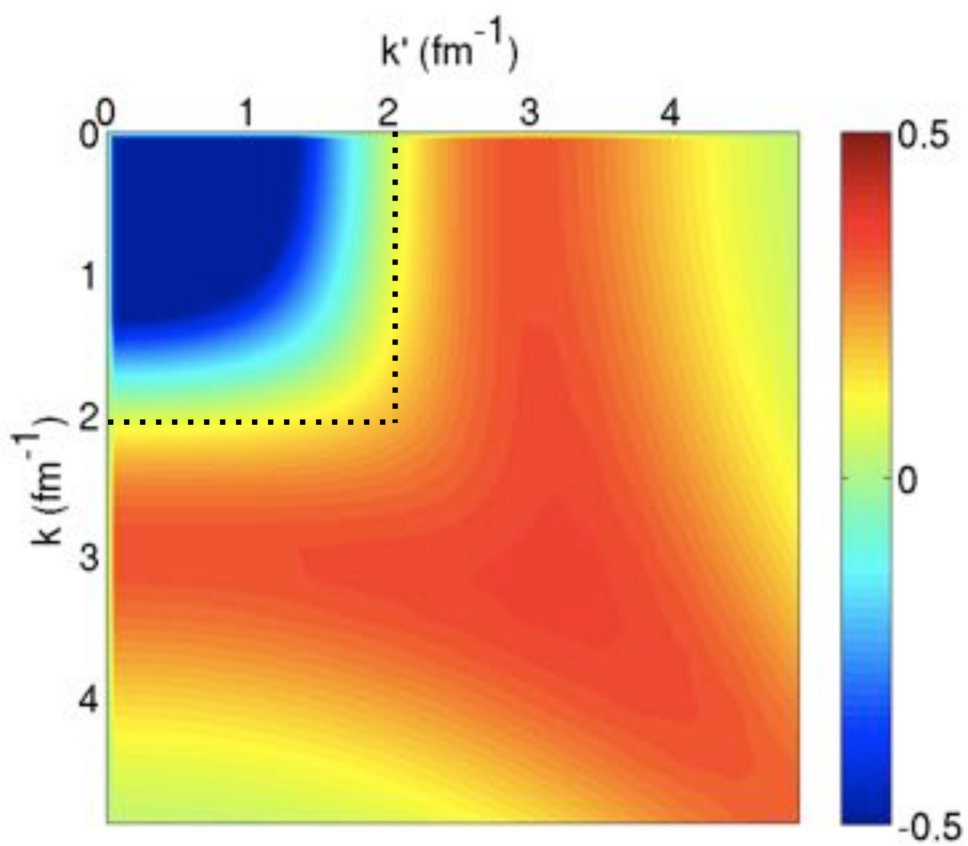

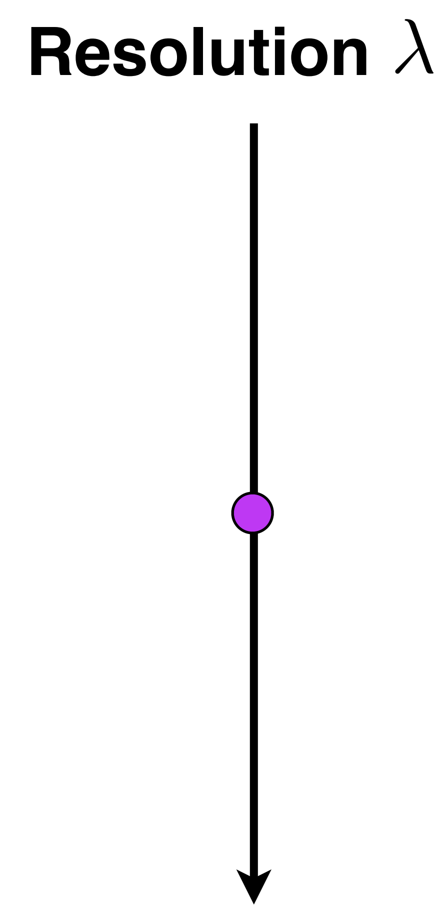

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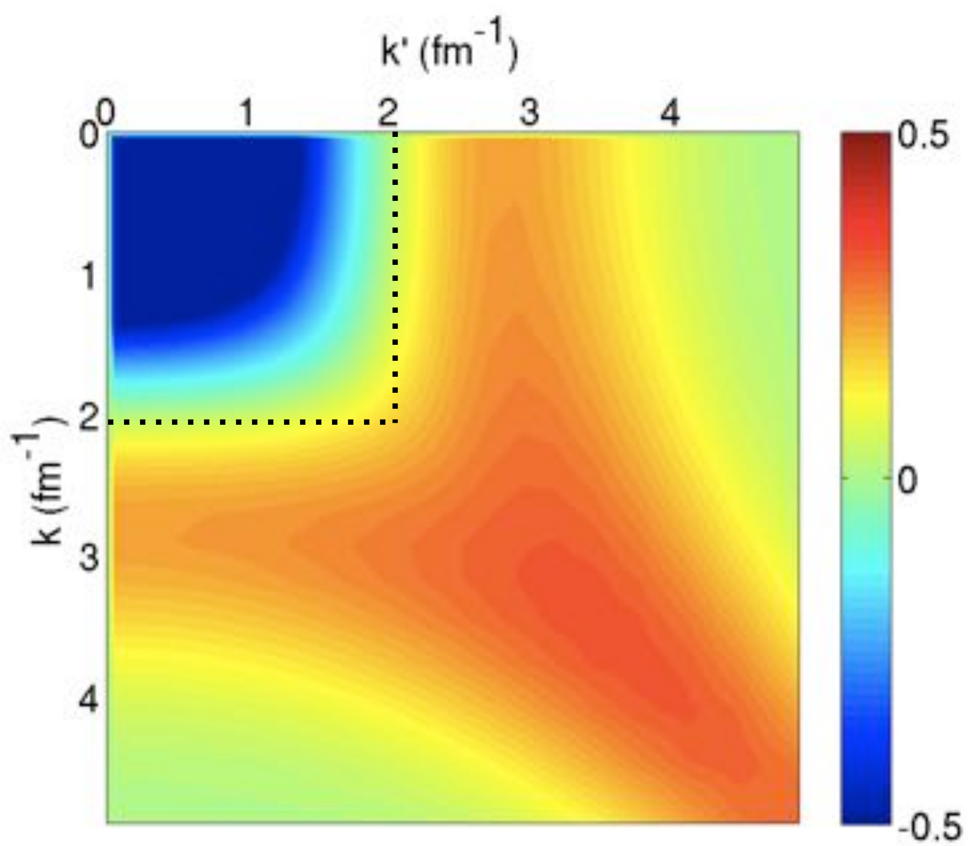

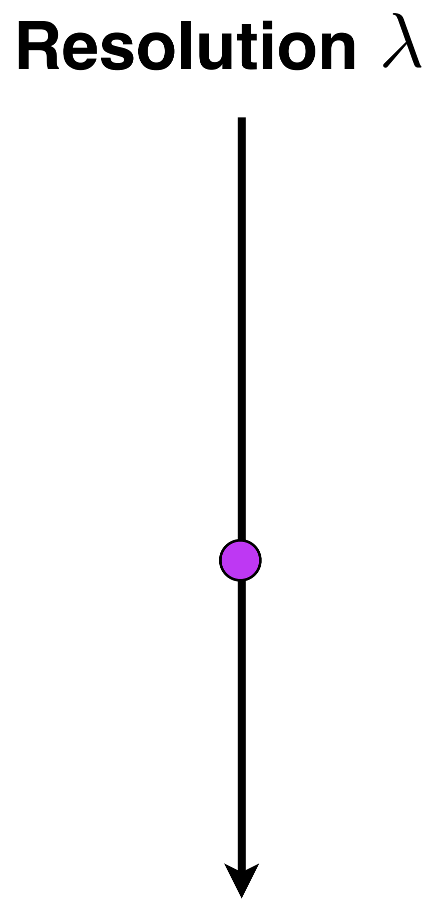

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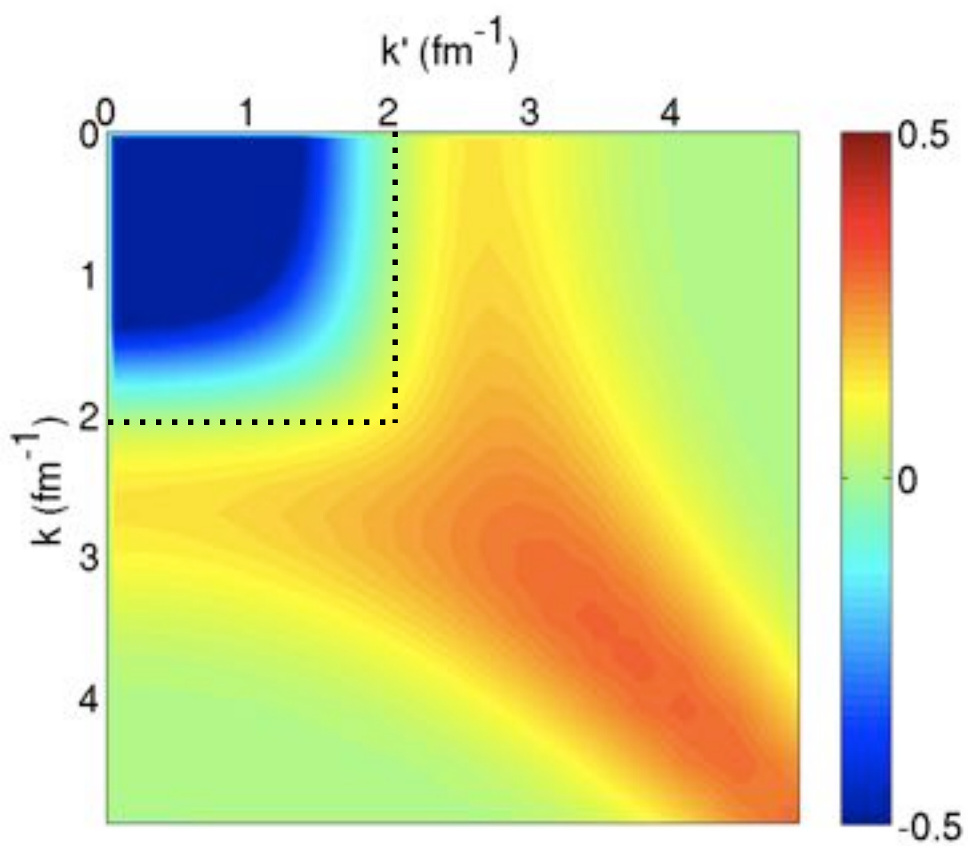

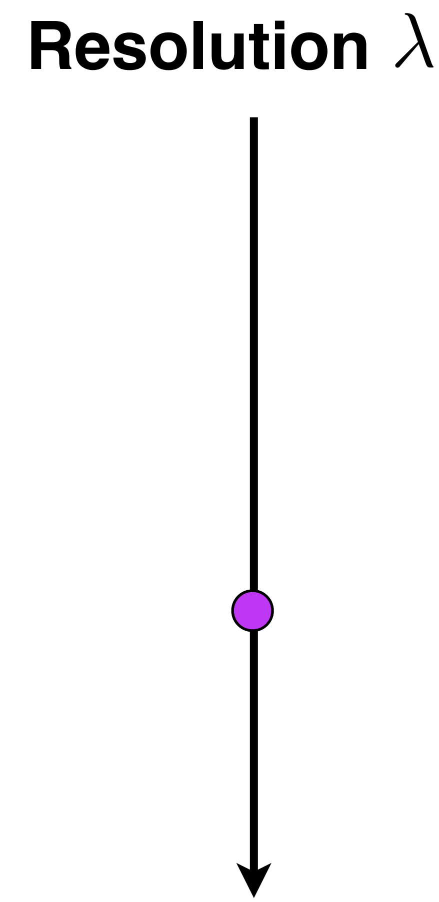

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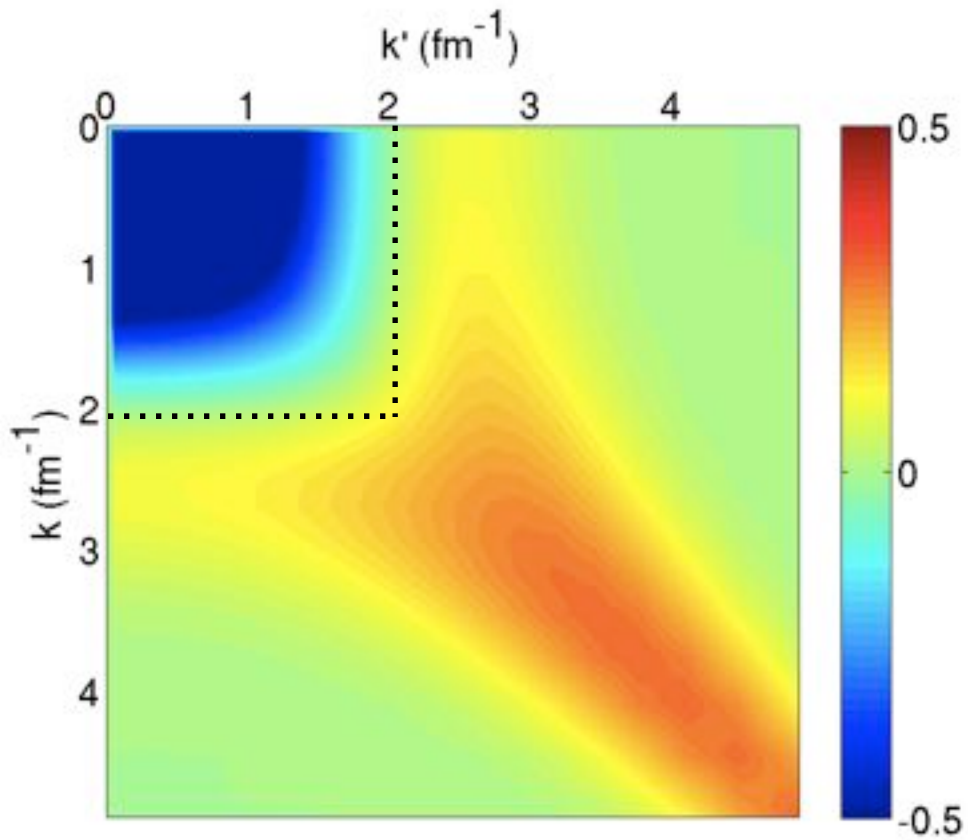

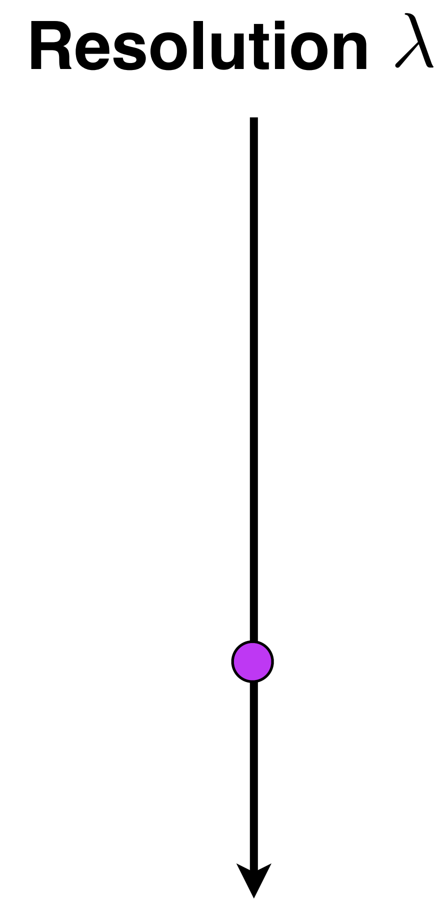

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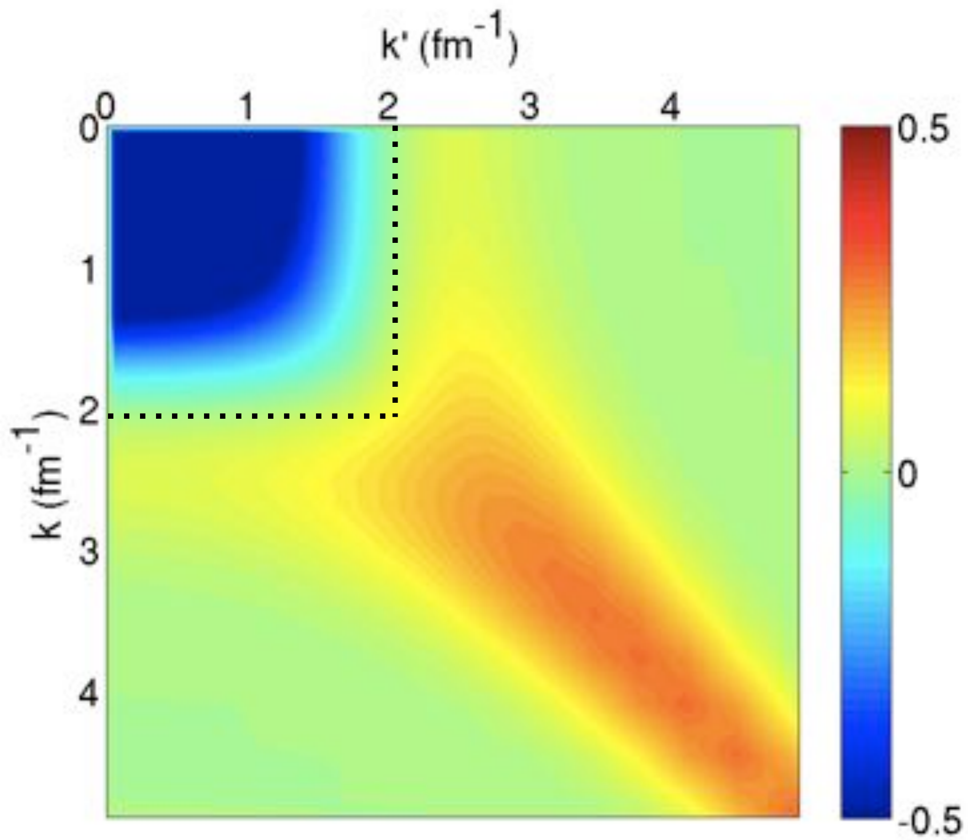
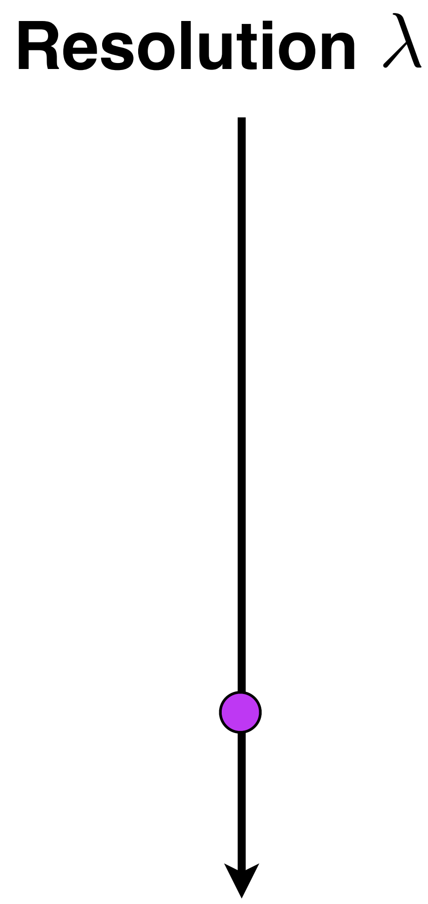
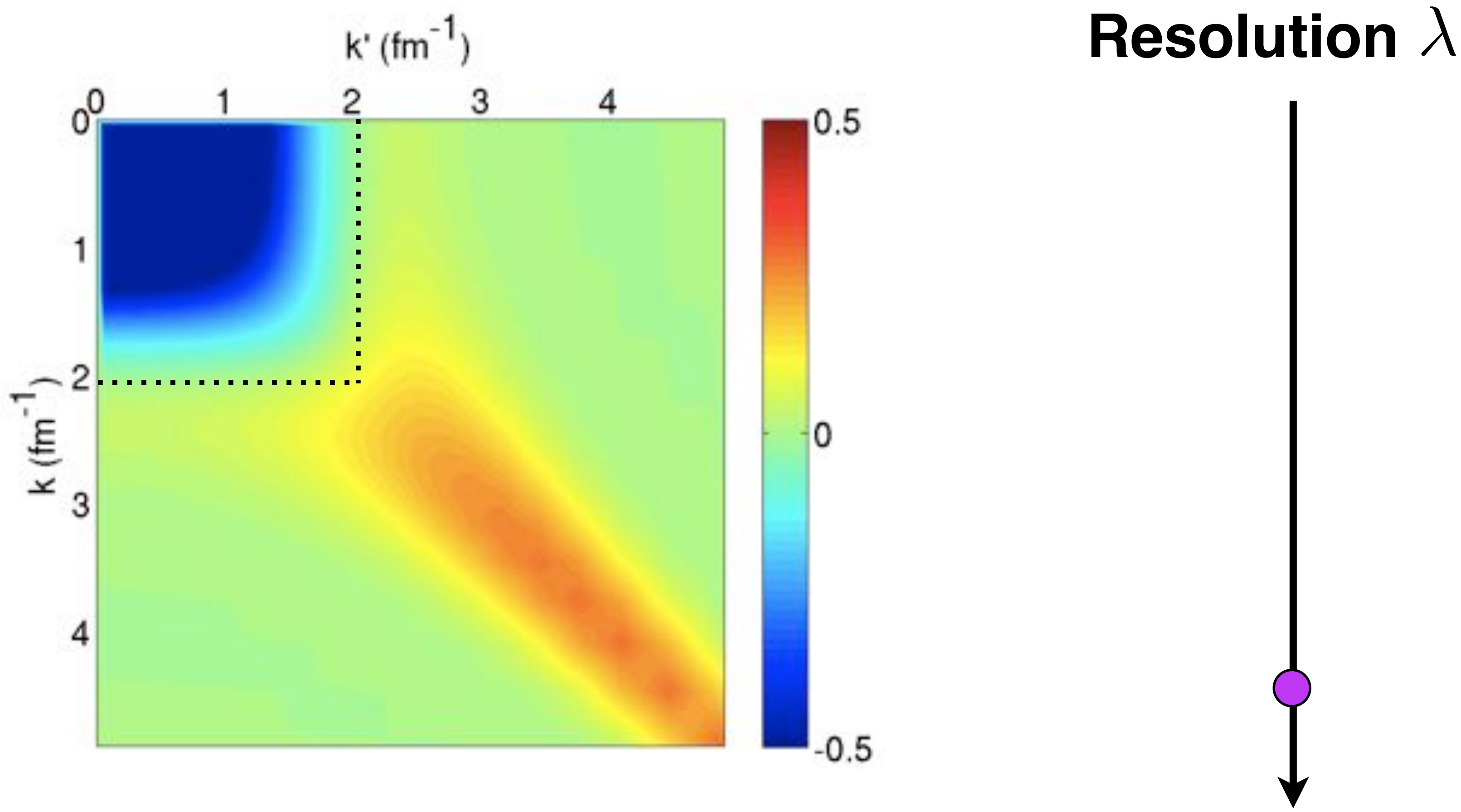
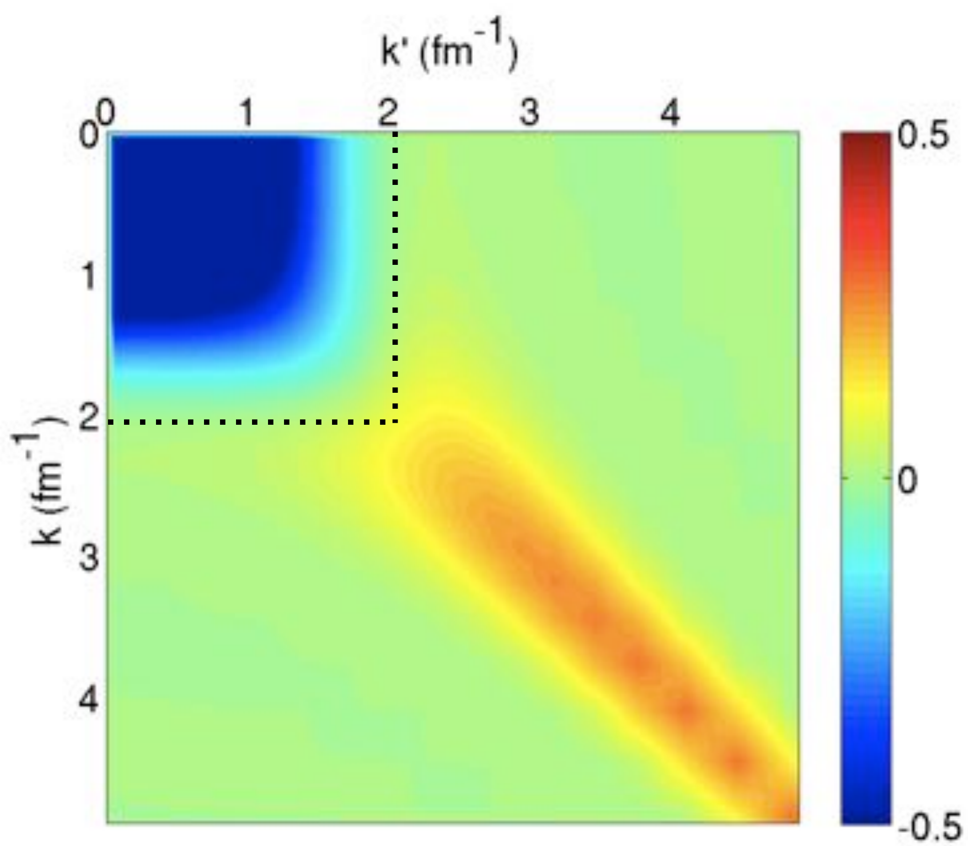




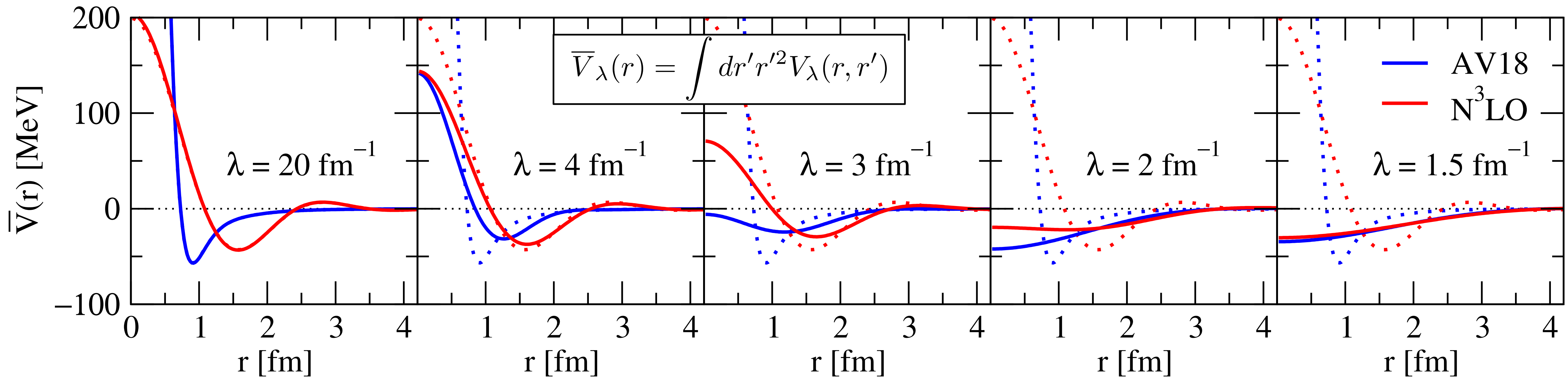
Systematically changing the resolution: the Similarity Renormalization Group



Systematically changing the resolution: the Similarity Renormalization Group

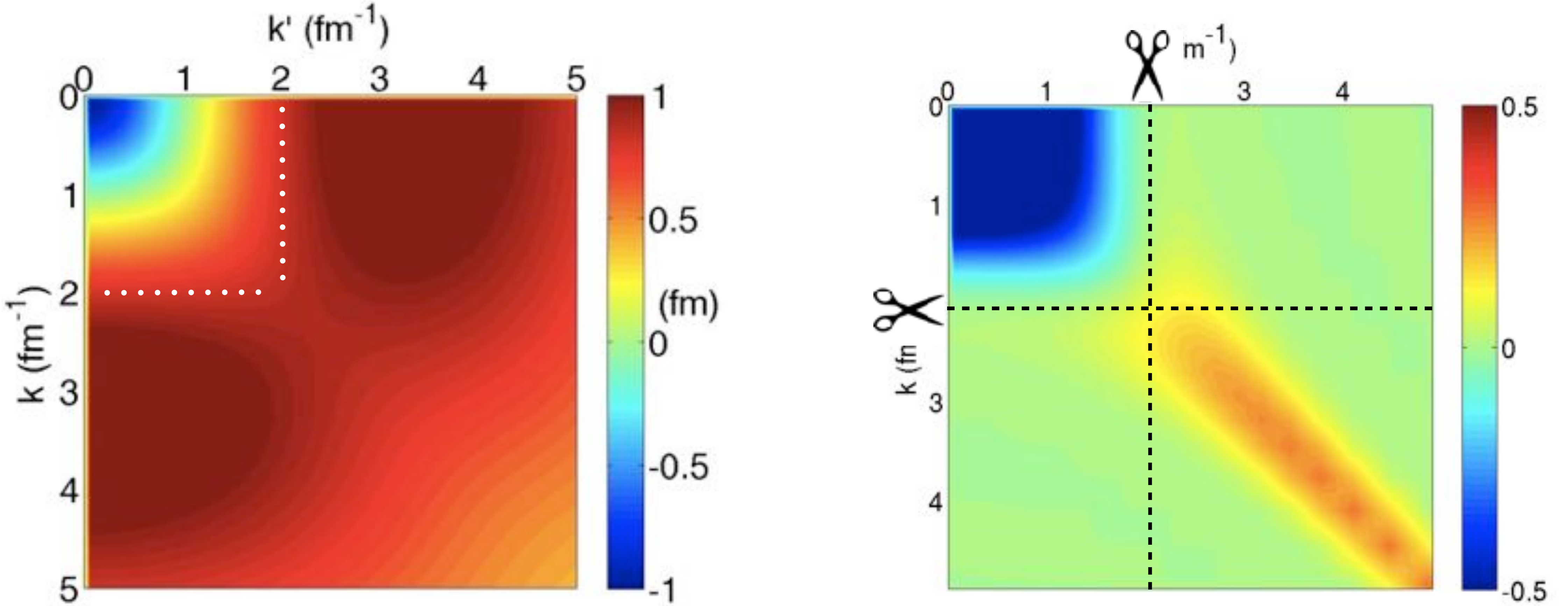


Resolution λ



Wendt et al., PRC 86, 014003 (2012)

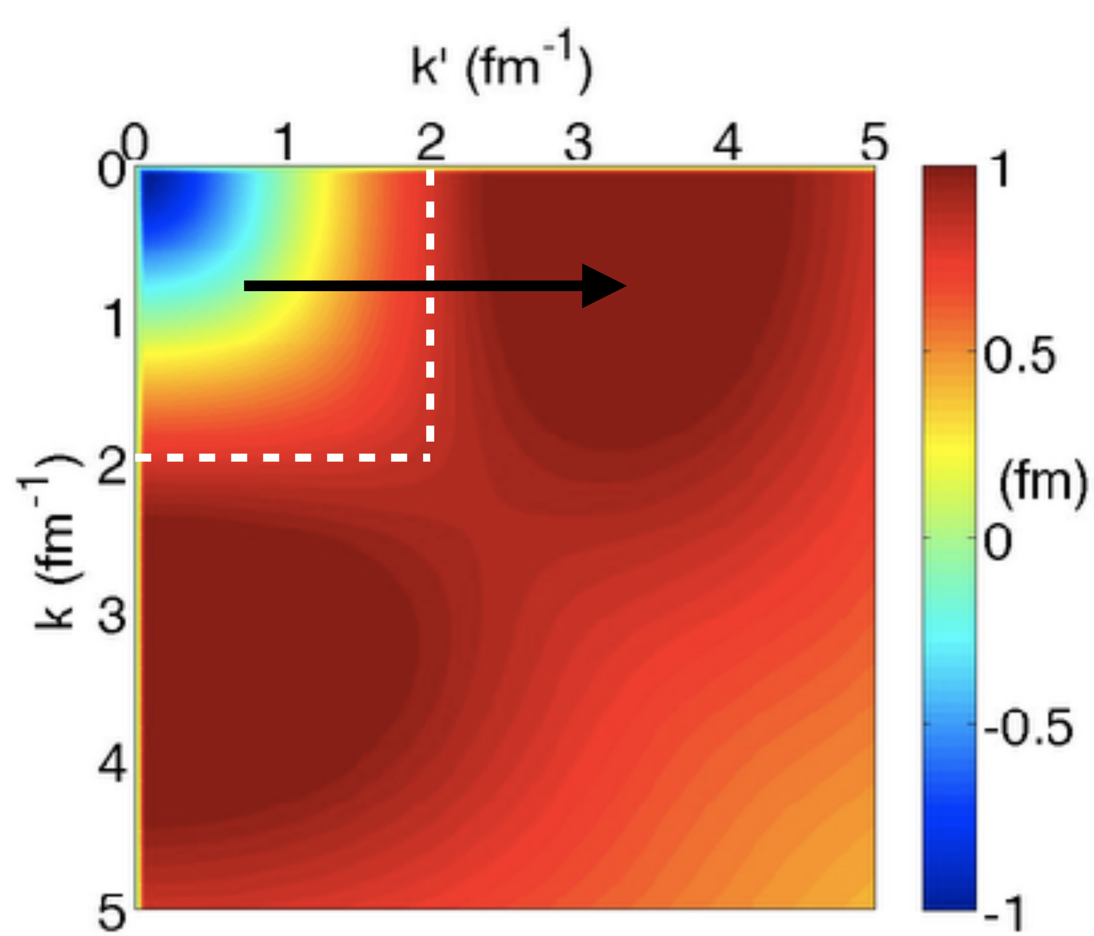
Systematic decoupling of high-momentum physics: the Similarity Renormalization Group



- elimination of coupling between low- and high momentum components,
  $\longrightarrow$ simplified many-body calculations!
- observables unaffected by resolution change (for exact calculations)
- residual resolution dependences can be used as tool to test calculations

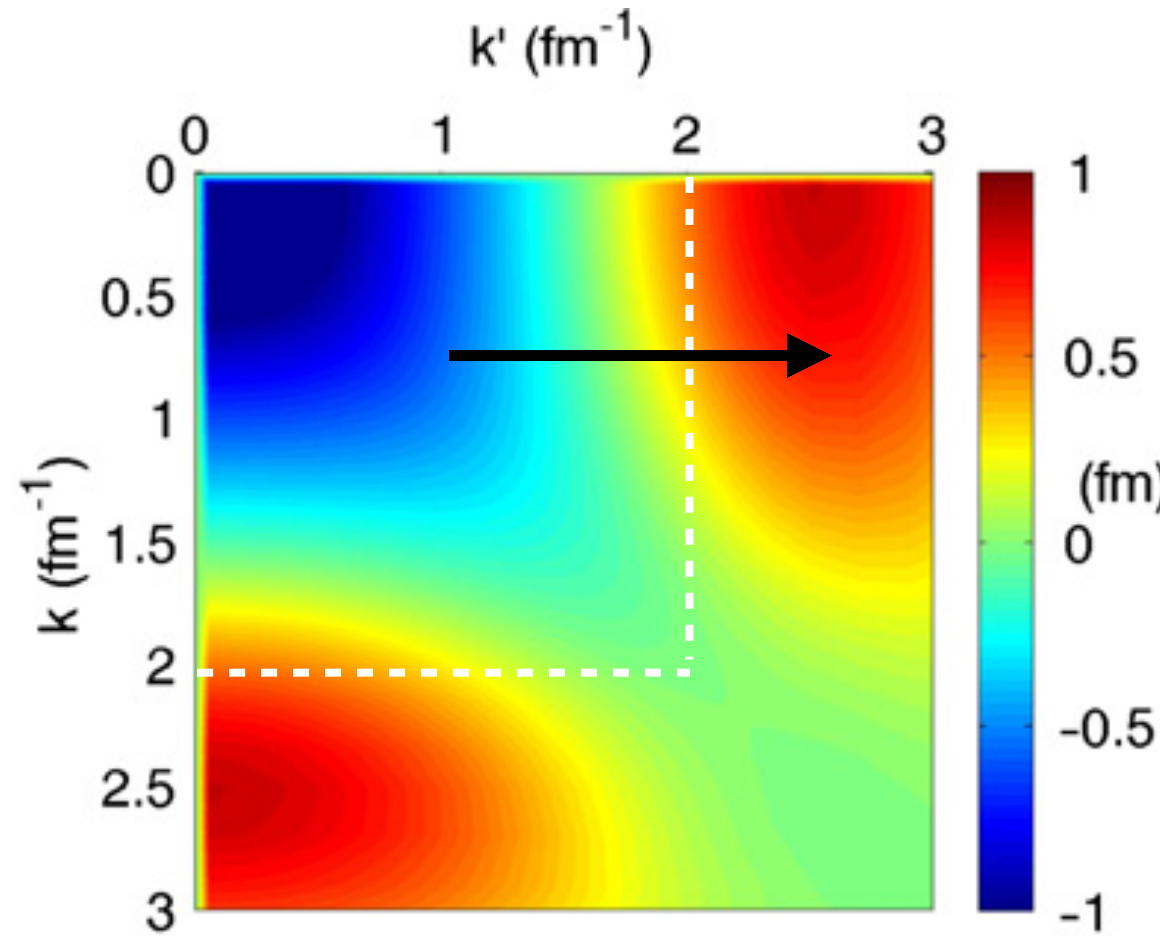
Not the full story:
RG transformations also change three-body (and higher-body) interactions!

Low- and high momentum couplings in interactions



AV18

($^1S_0$ channel)



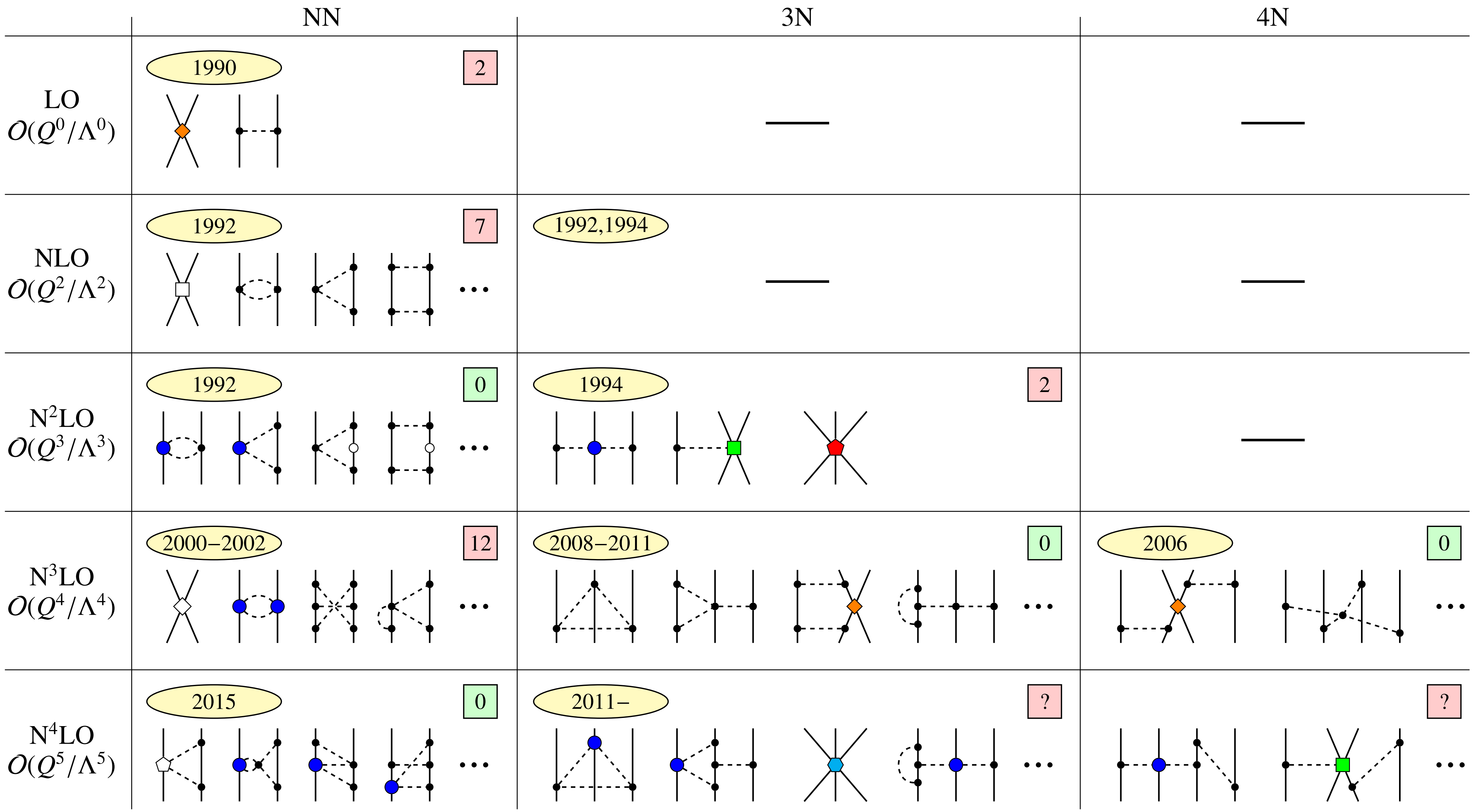
EM 500 MeV N3LO

($^3S_1$ channel)

- strong couplings of low- and high-momenta in interactions complicates convergence ab initio many-body calculations
- these couplings are reduced in chiral potentials compared to 'traditional' interactions, but still present!

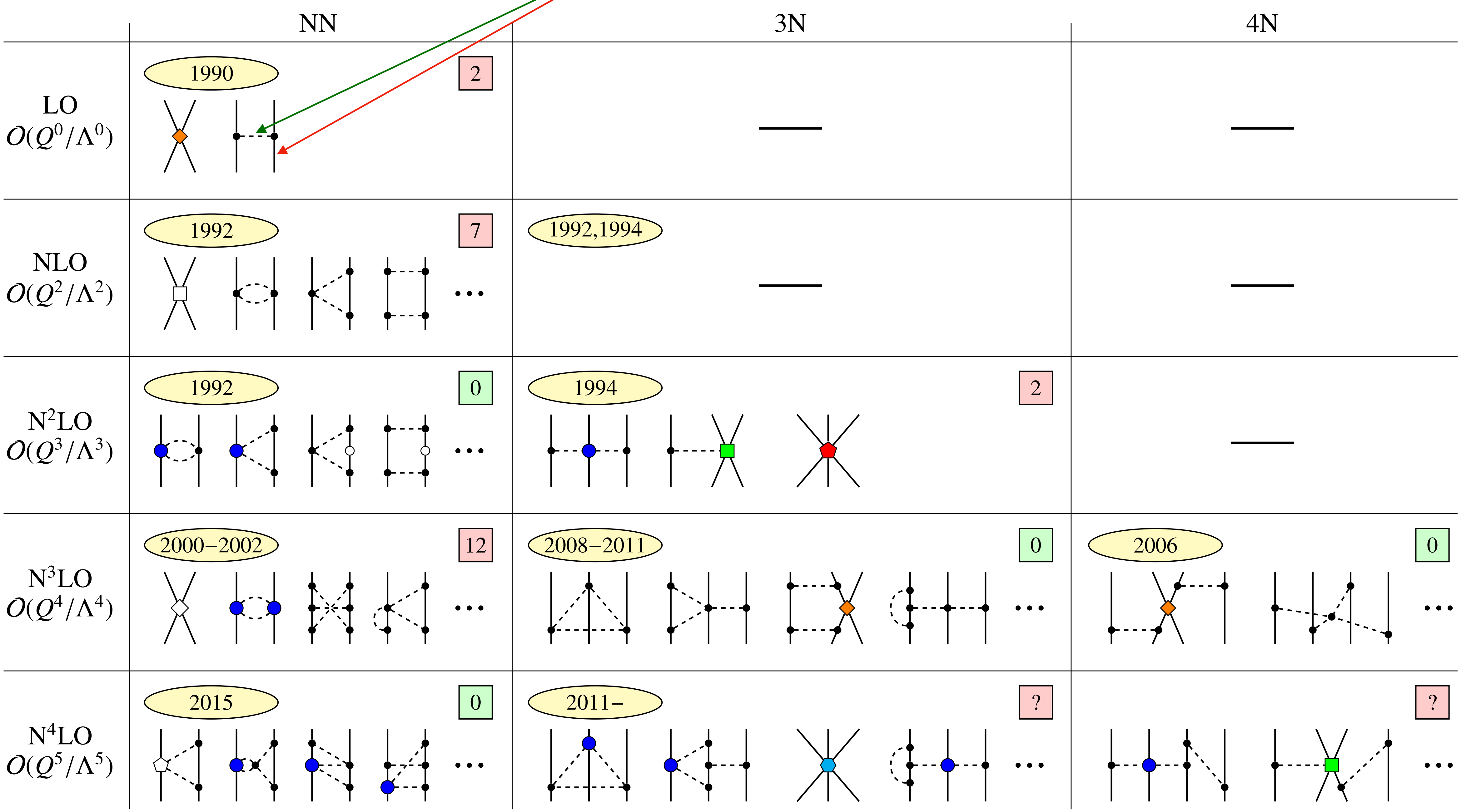
More on this in the SRG exercise session!

Chiral effective field theory for nuclear forces

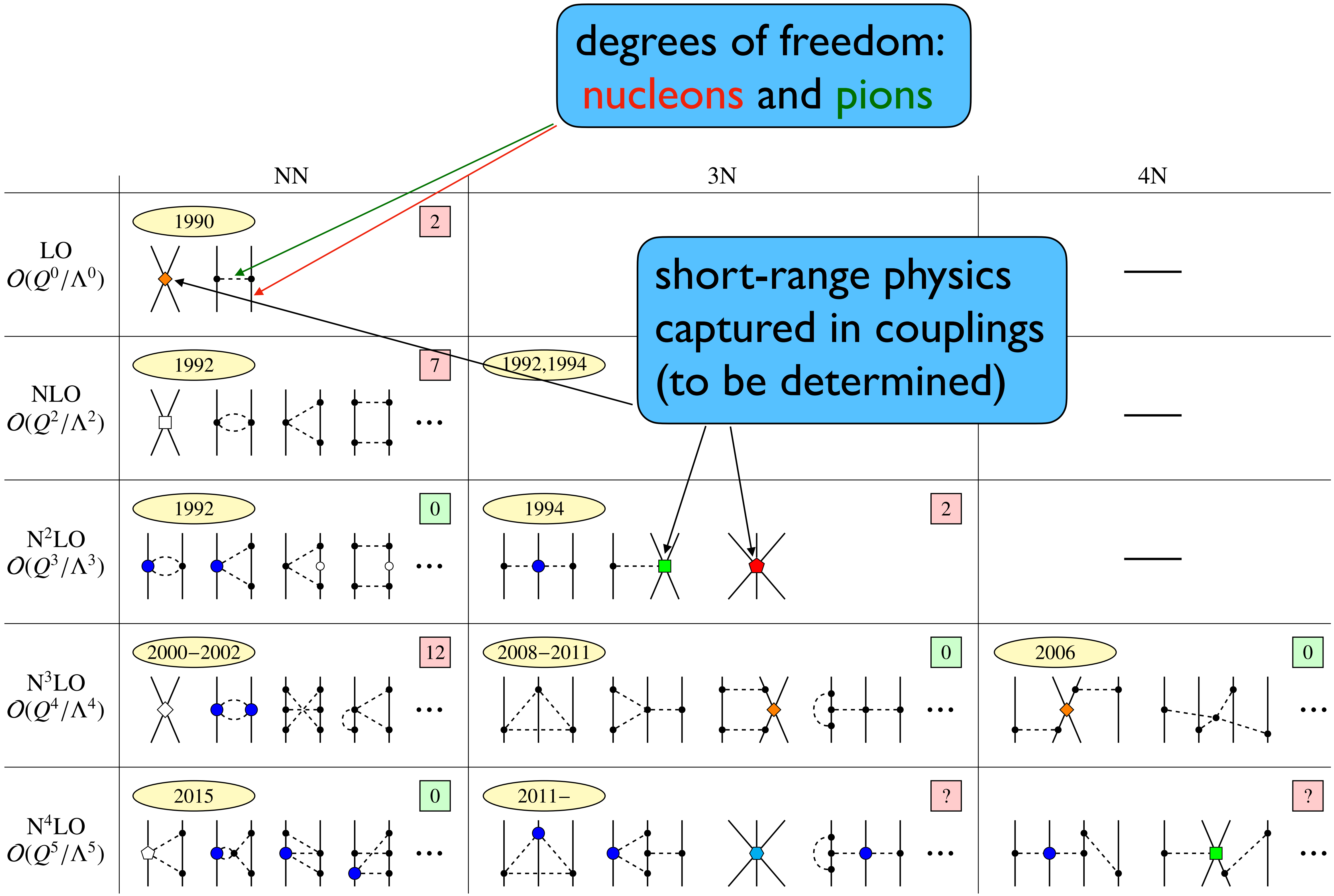


Chiral effective field theory for nuclear forces

degrees of freedom:
nucleons and pions



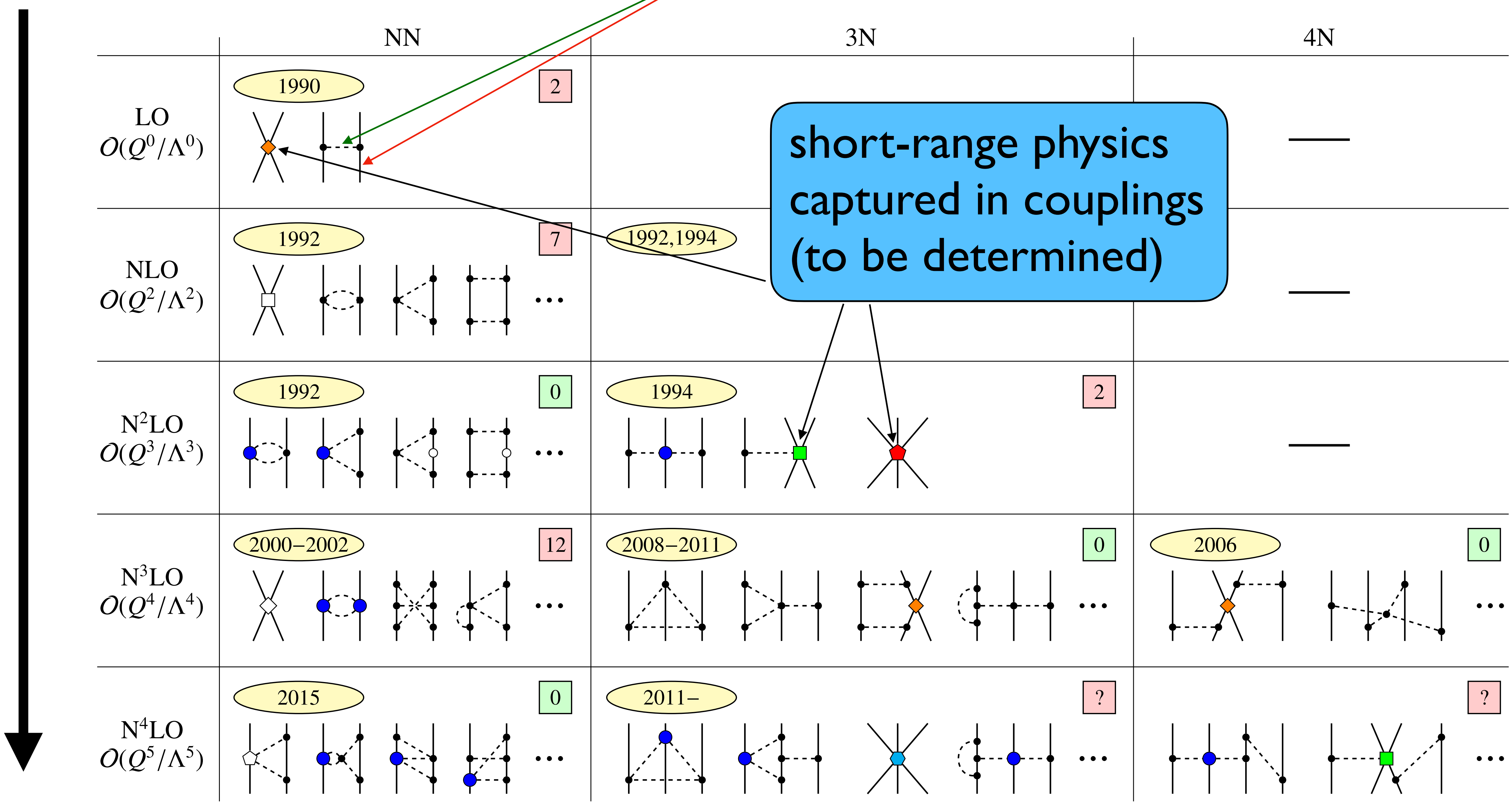
Chiral effective field theory for nuclear forces



Chiral effective field theory for nuclear forces

power-counting:
expand in Q/Λ, error estimates!

degrees of freedom:
nucleons and pions



Chiral effective field theory for nuclear forces

power-counting:
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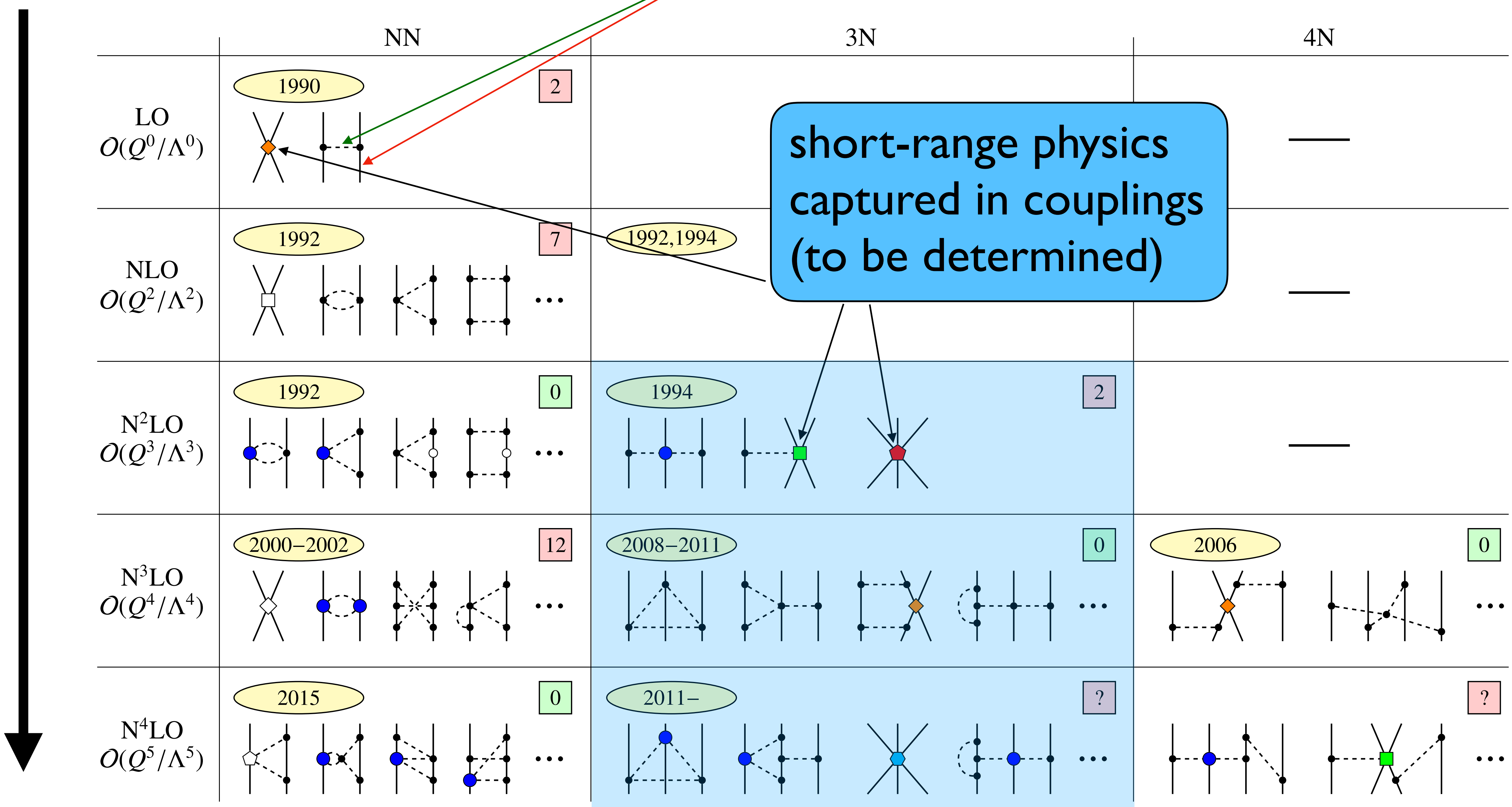
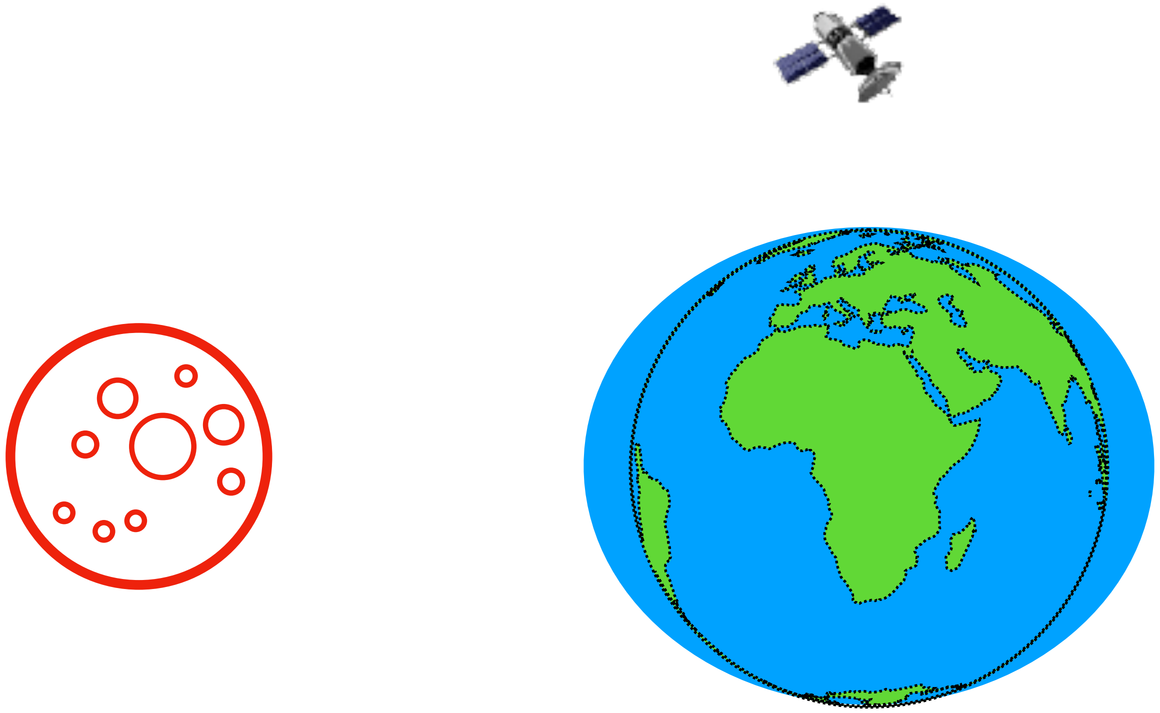


3N forces appear naturally

Aren’t 3N forces unnatural? Do we really need them?



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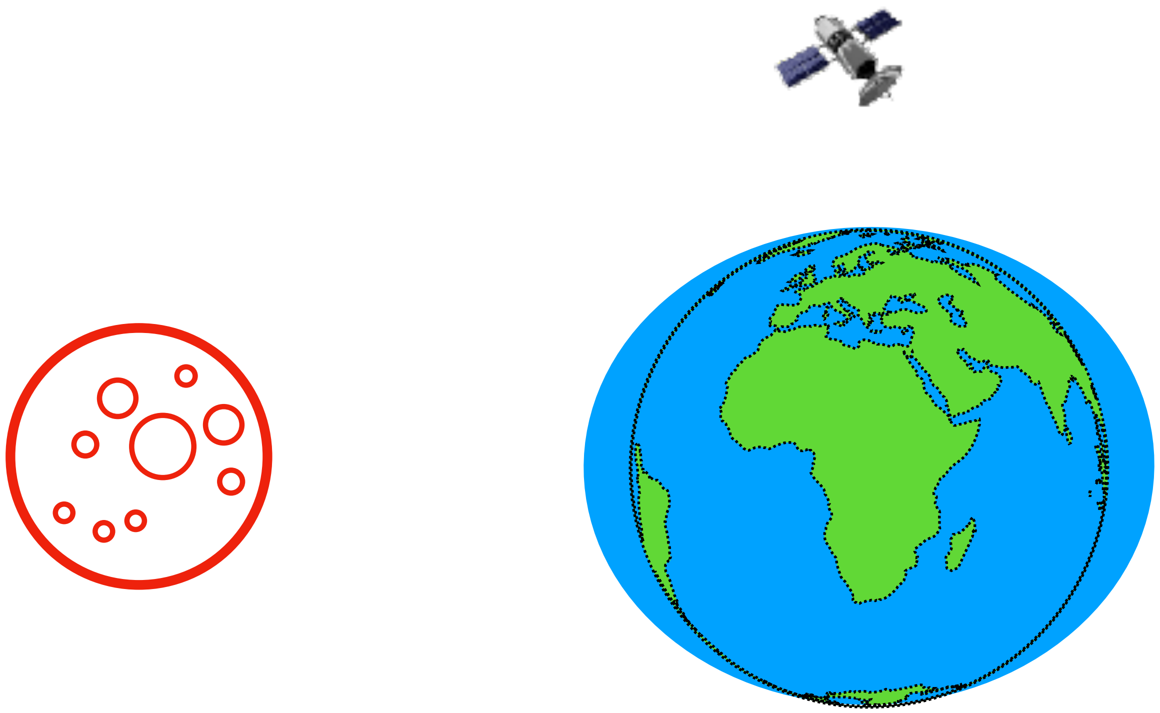

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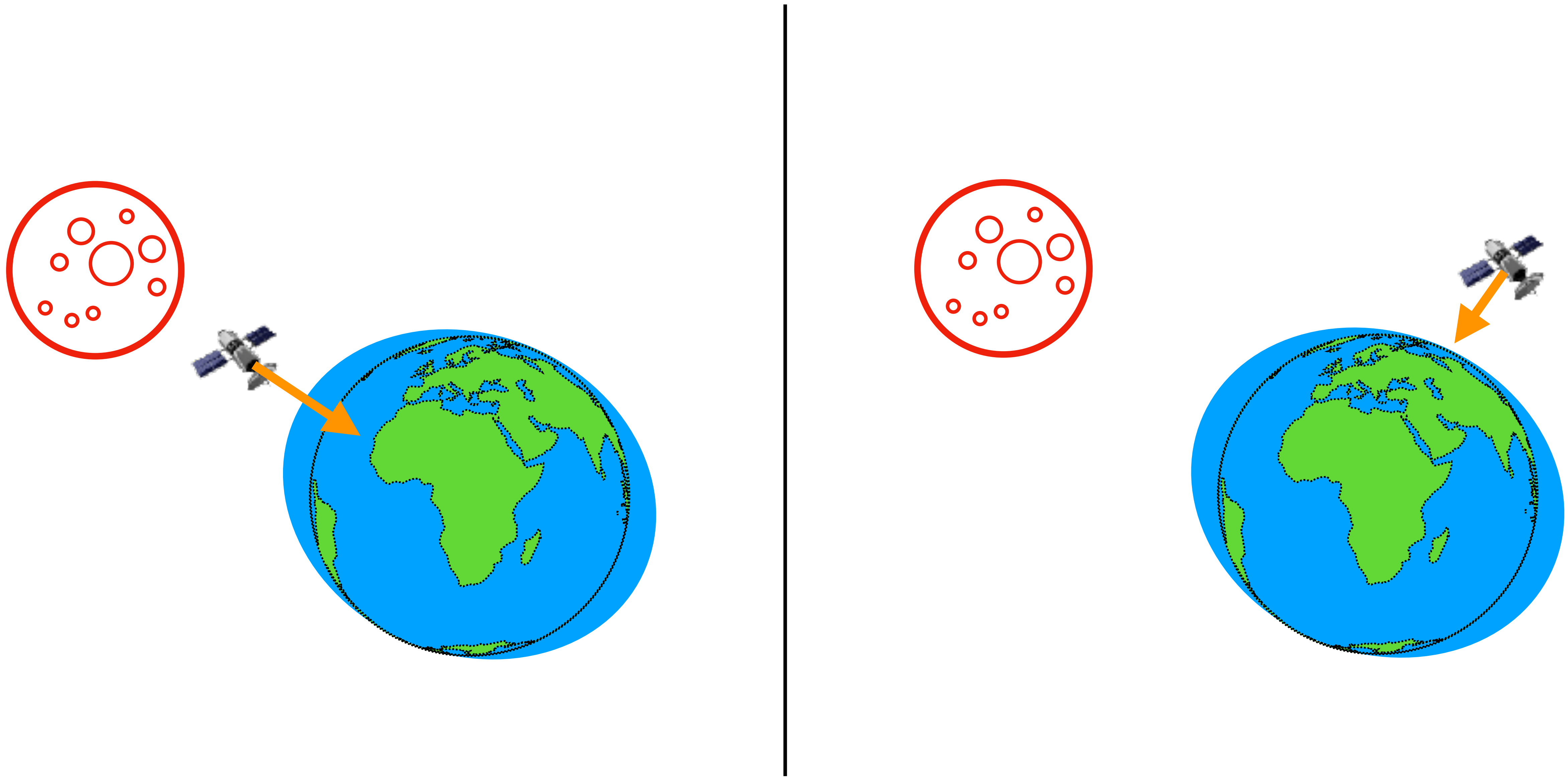
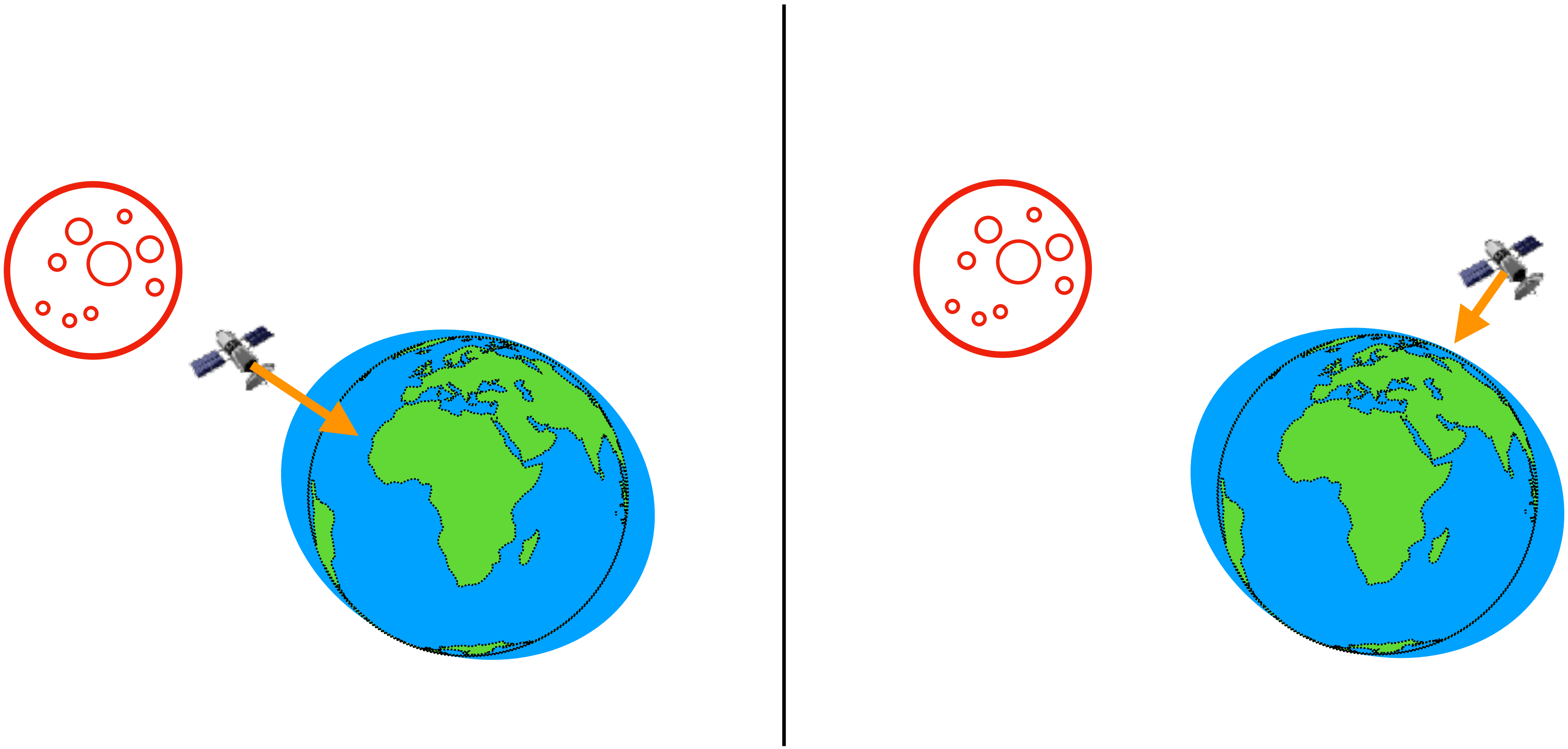


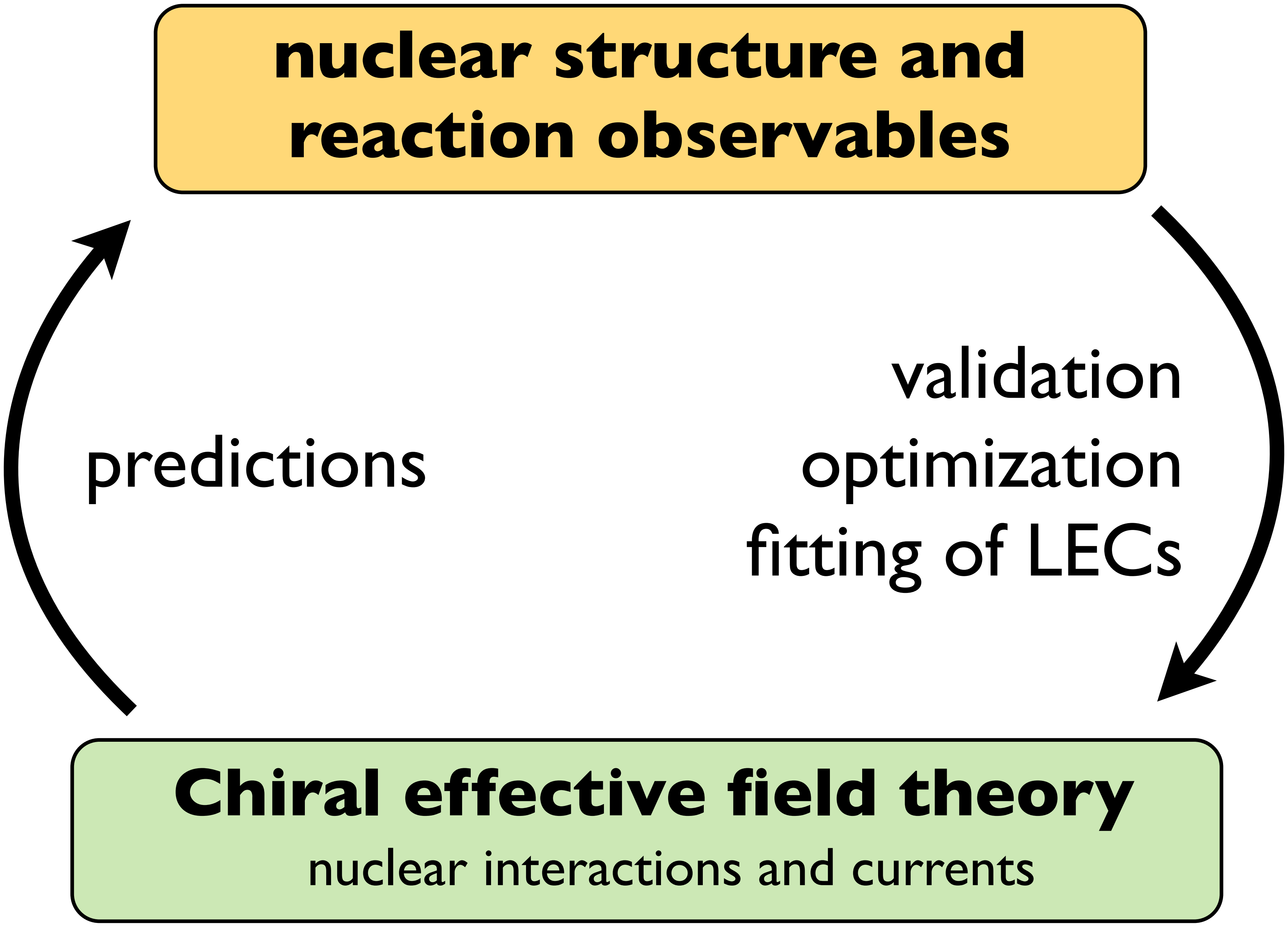
- force between earth and satellite depends on the position of moon
- tidal deformations represent internal excitations
- when all objects are described as point particles 3N forces inevitable!
- effects for the present classical problem rather small

Aren't 3N forces unnatural? Do we really need them?

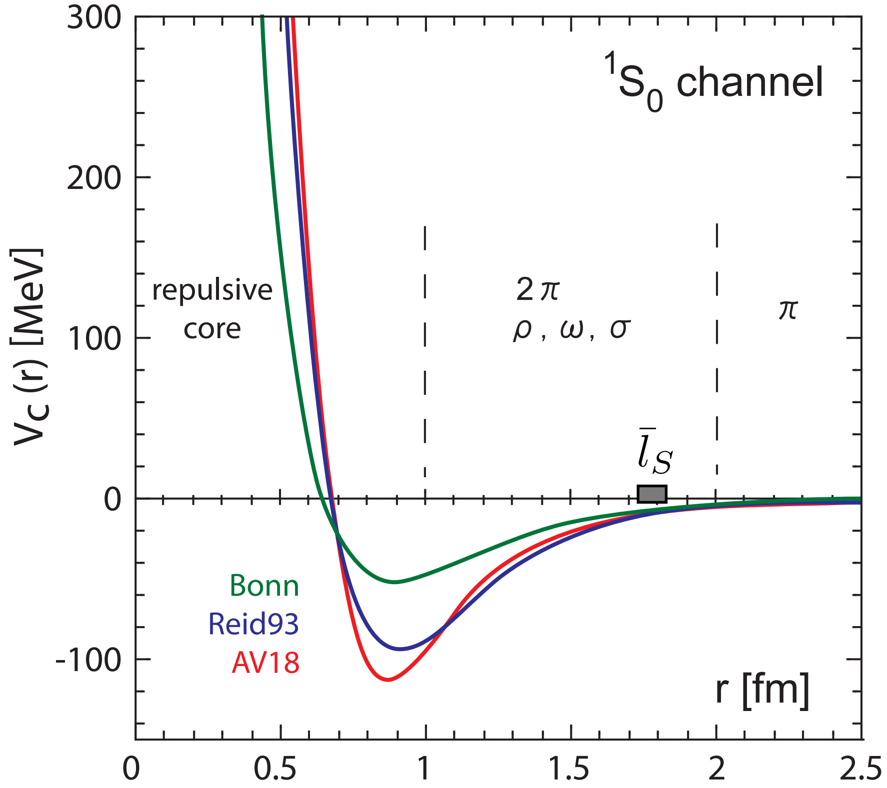


- nucleons are composite particles, they can also be internally excited
- existence of three-nucleon forces natural
- key questions:
  - » how big are their contributions?
  - » how do they depend on the resolution

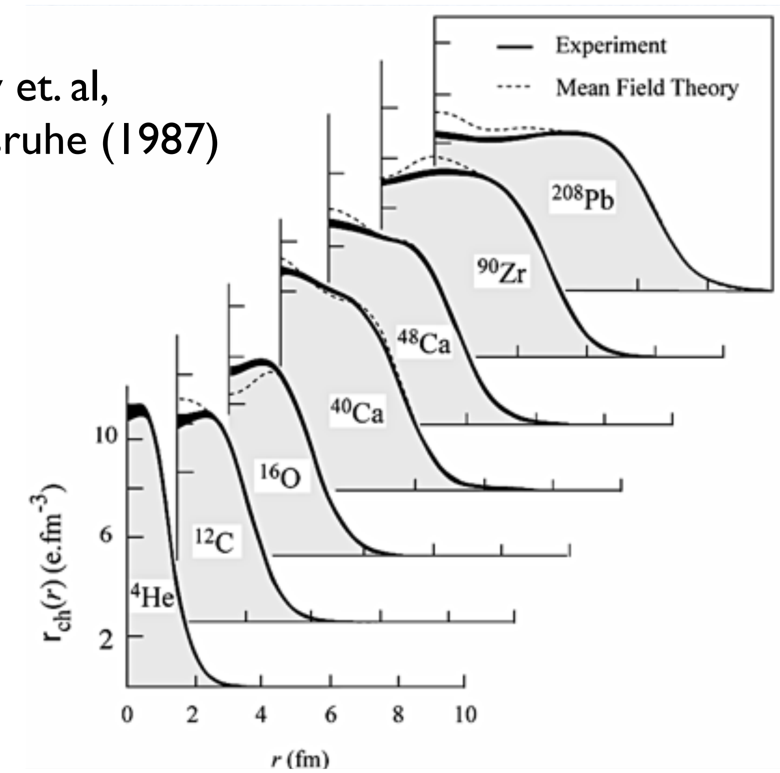
Development of nuclear interactions

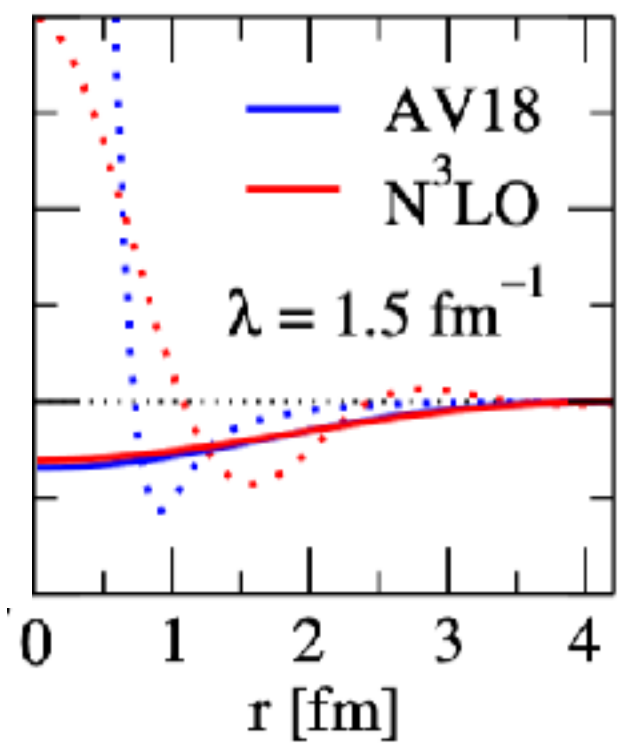


Equation of state of symmetric nuclear matter: nuclear saturation



Batty et. al, Karlsruhe (1987)





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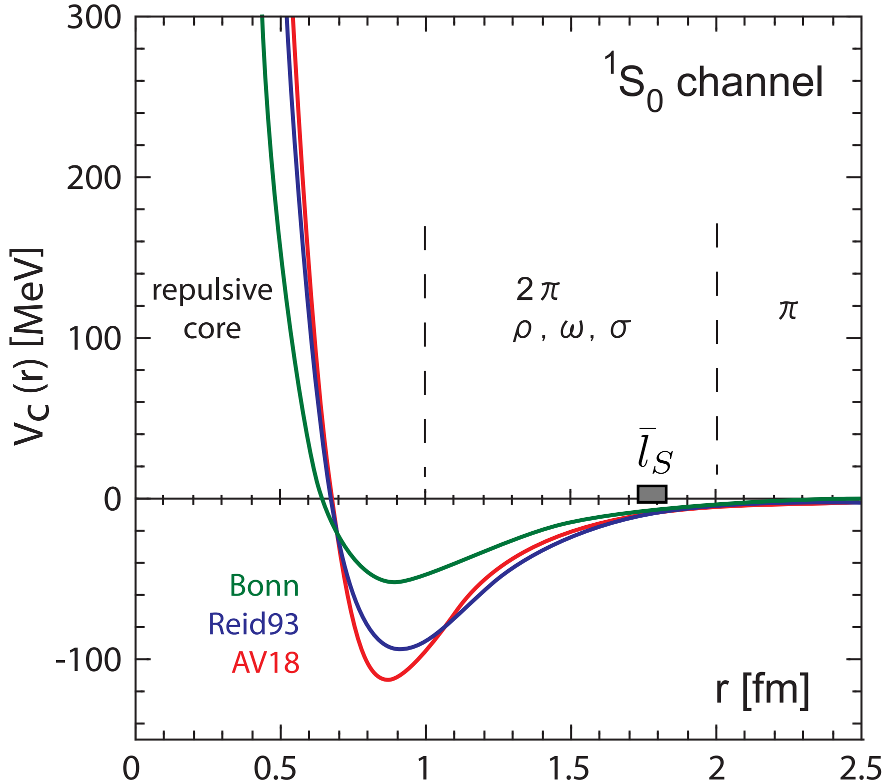
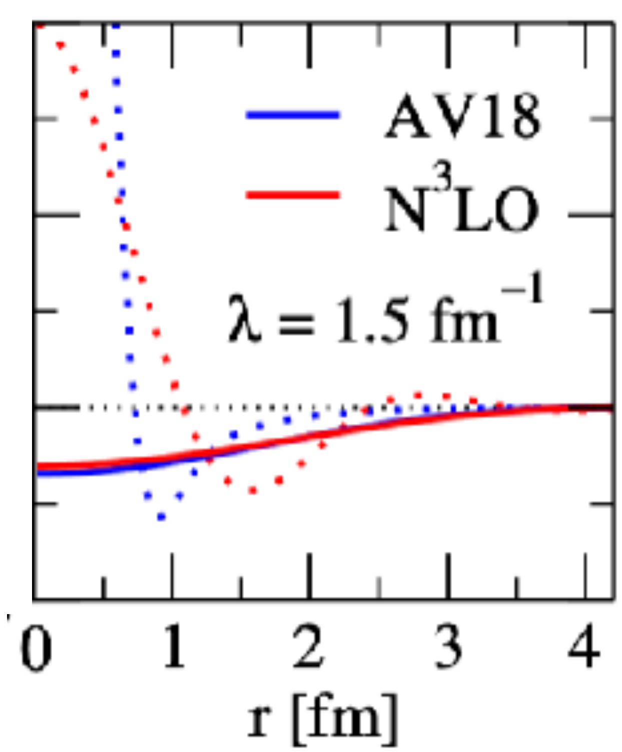
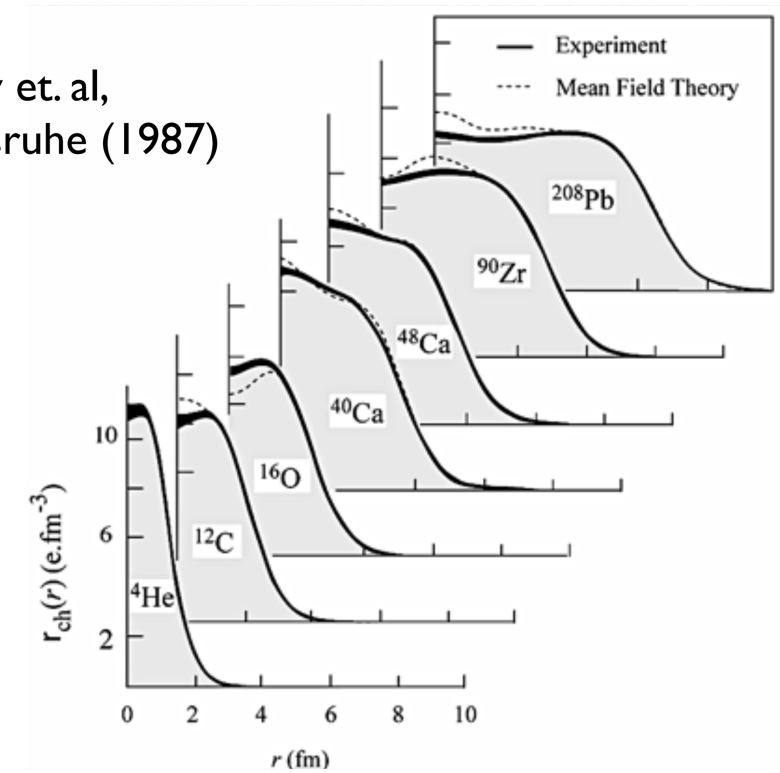
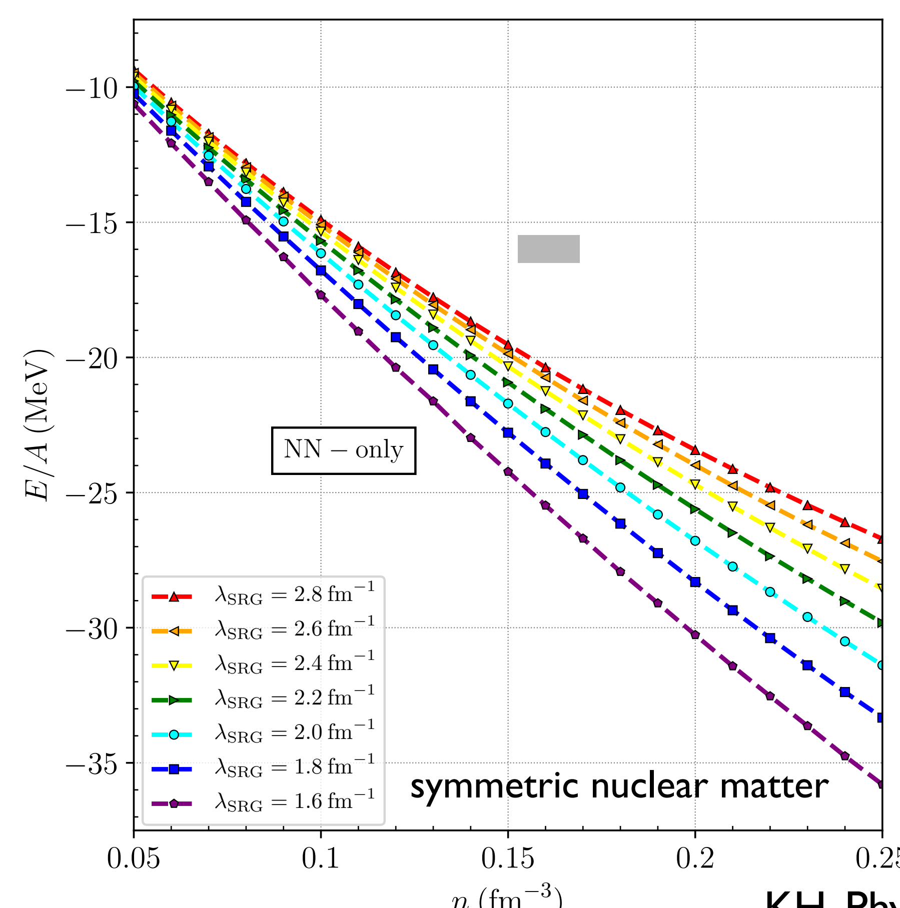




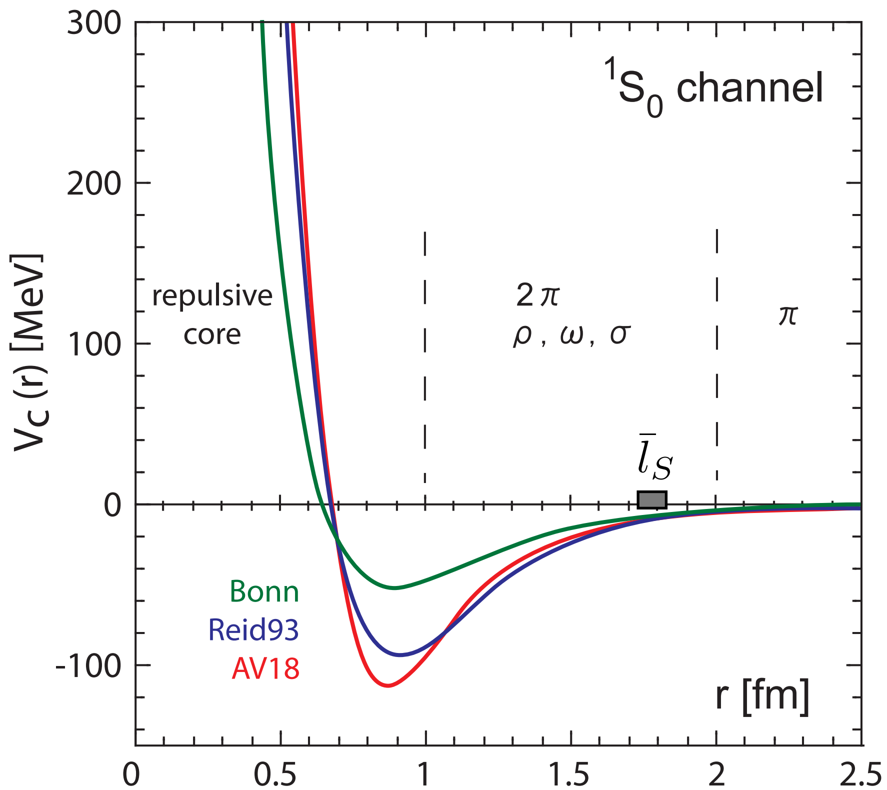
Batty et. al,
Karlsruhe (1987)



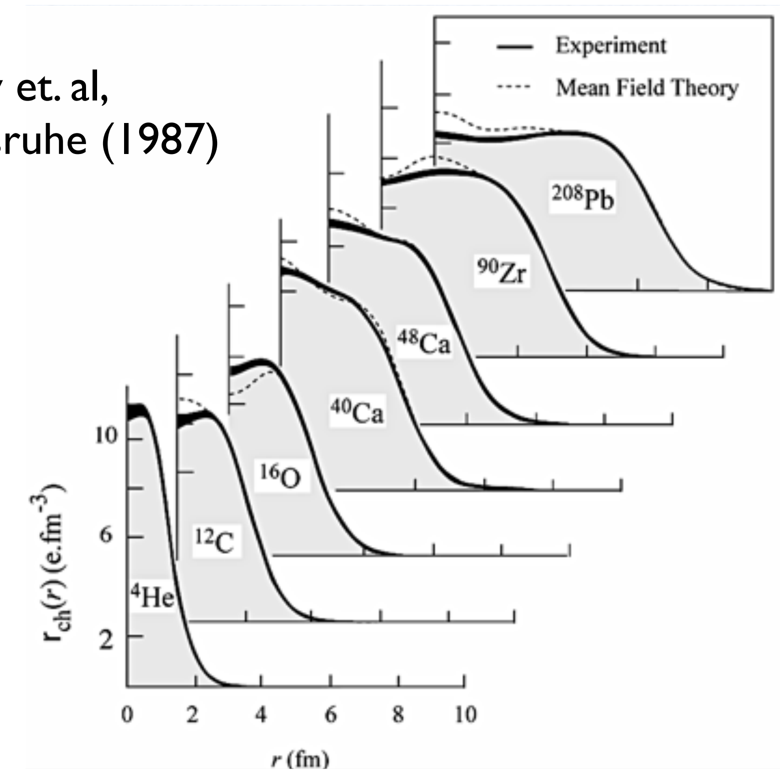


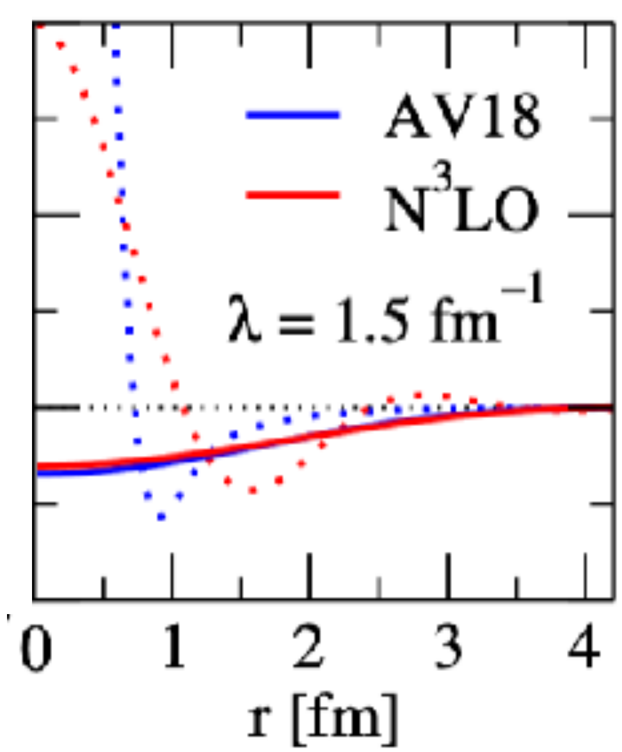
KH, Phys. Rept. 890, 1 (2021)

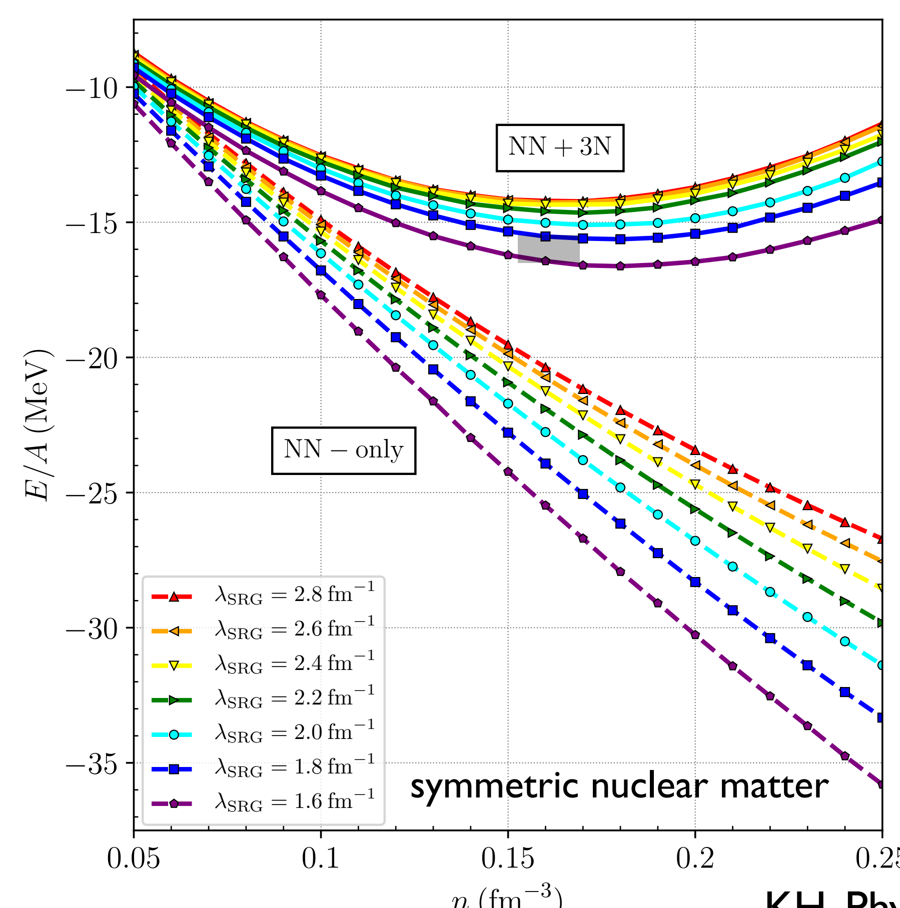
Equation of state of symmetric nuclear matter: nuclear saturation



Batty et. al, Karlsruhe (1987)







KH, Phys. Rept. 890, 1 (2021)

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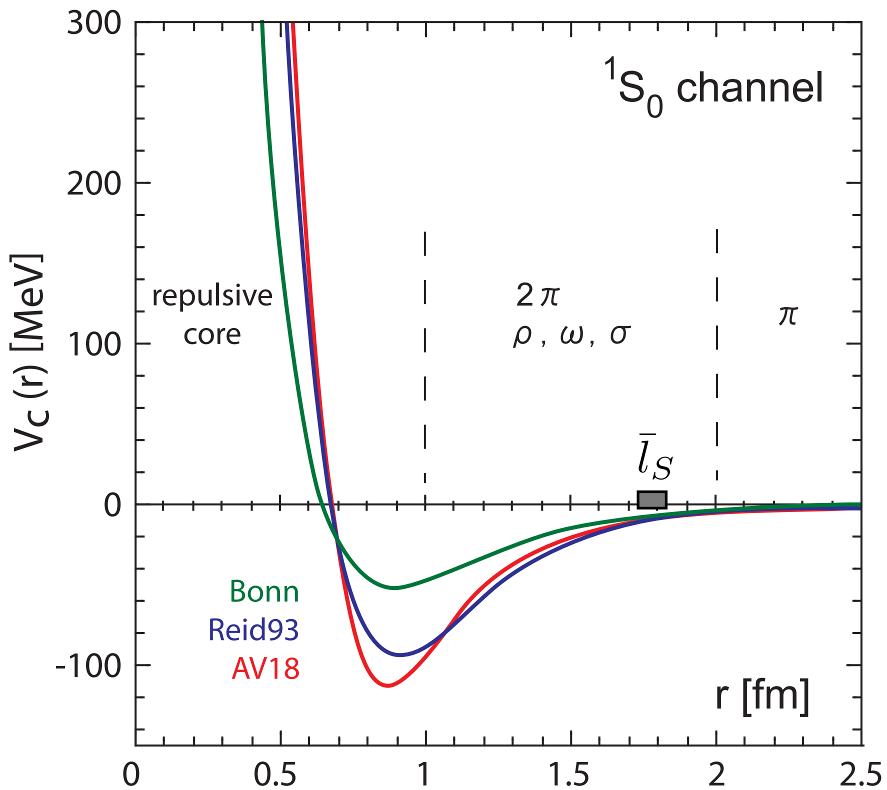
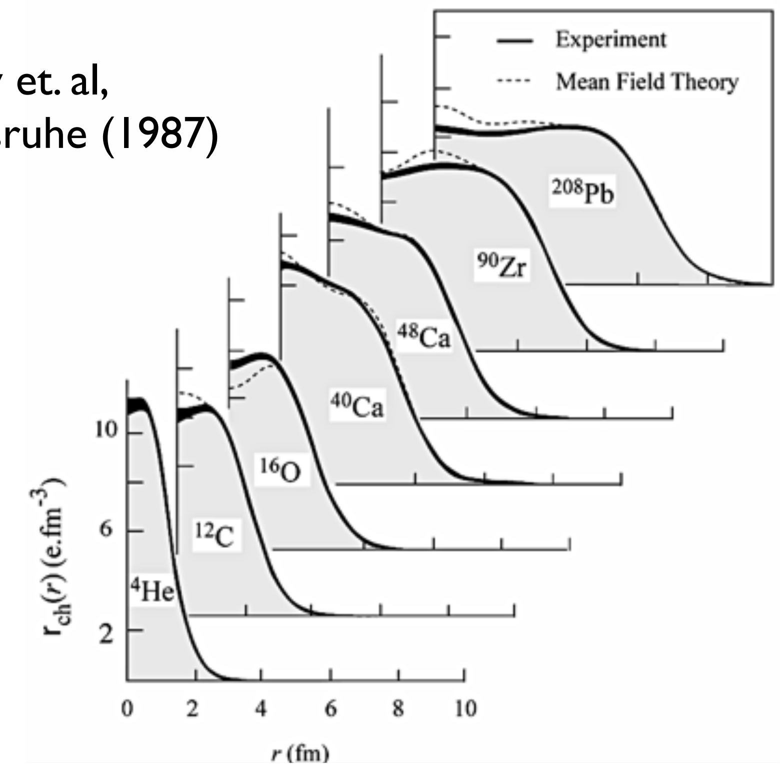
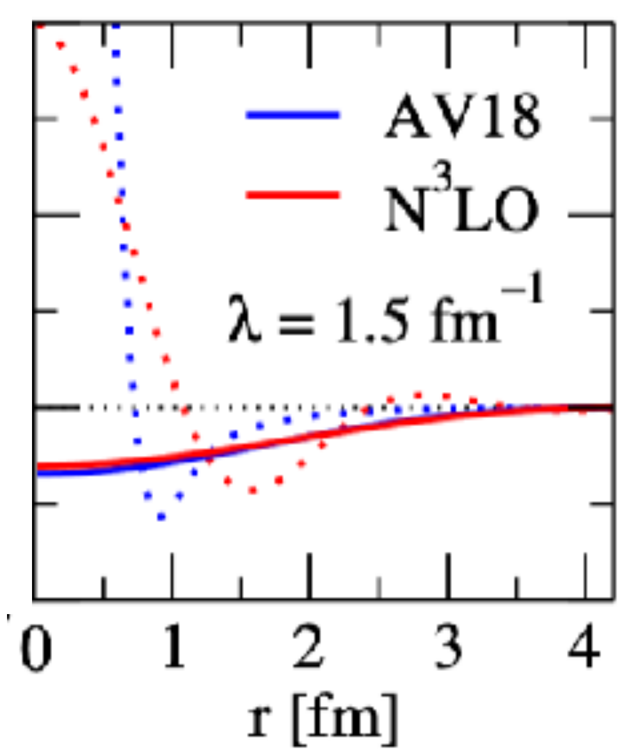
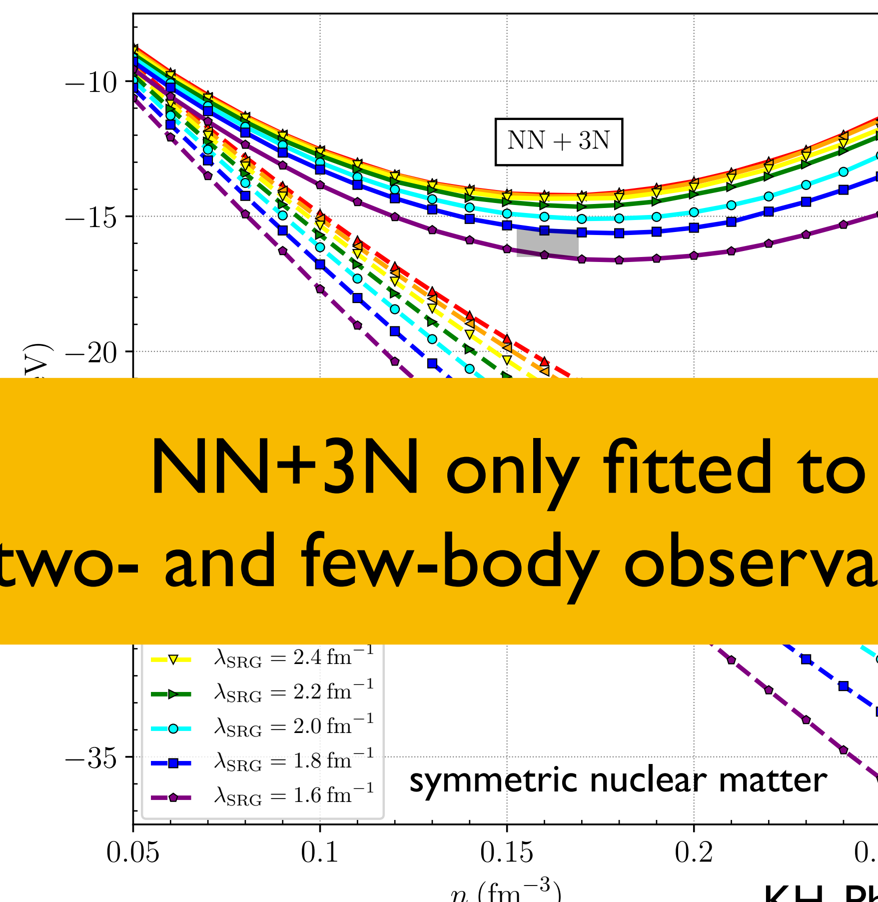


Batty et. al, Karlsruhe (1987)



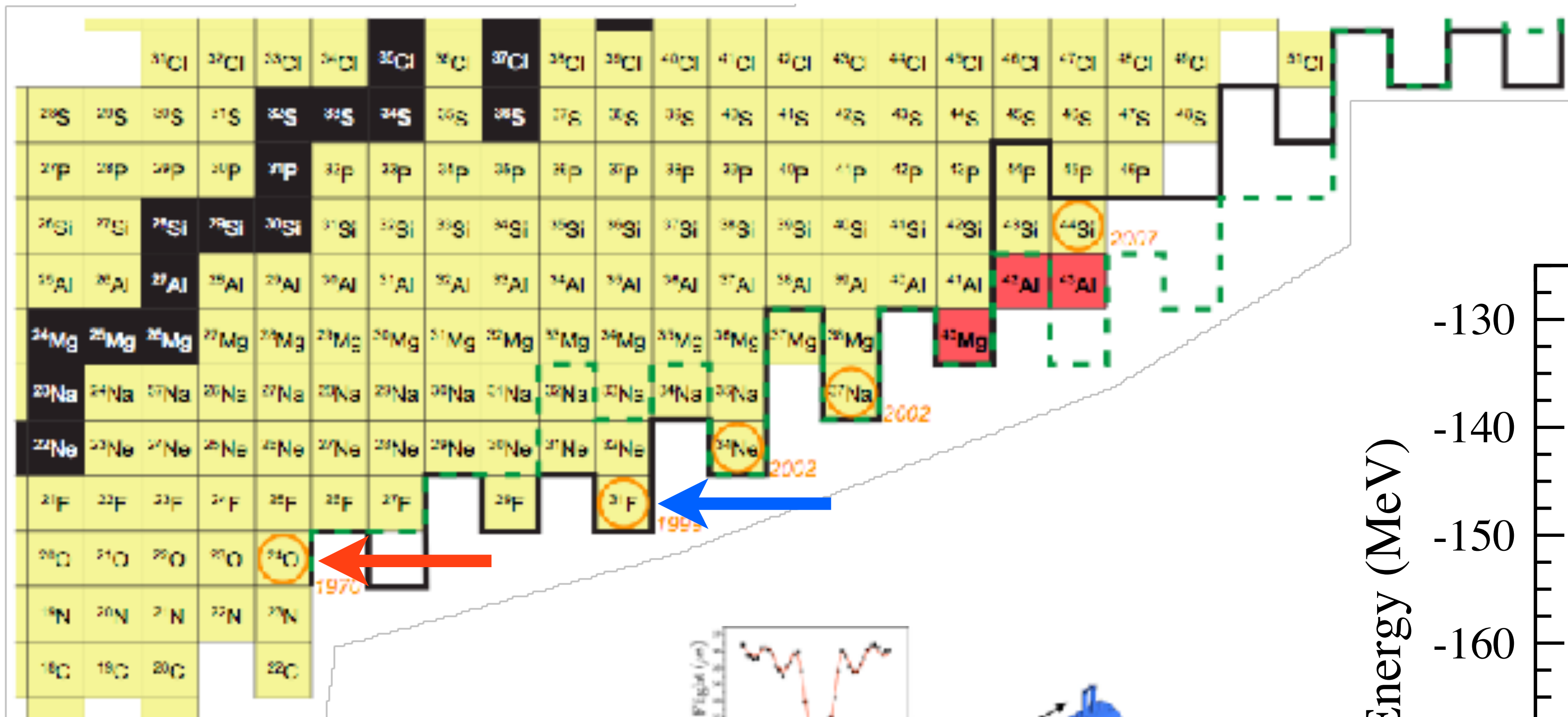




NN+3N only fitted to two- and few-body observables!

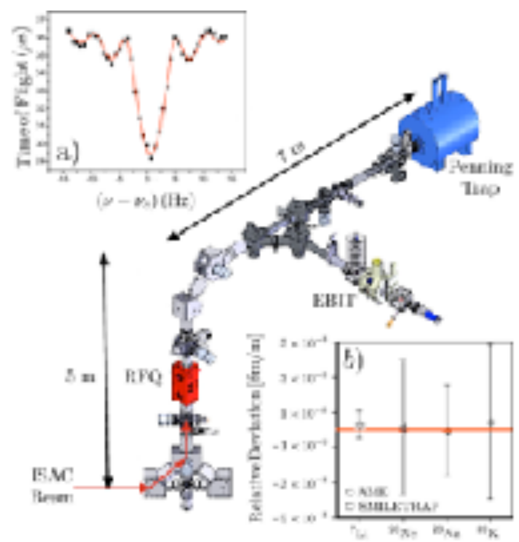
KH, Phys. Rept. 890, 1 (2021)

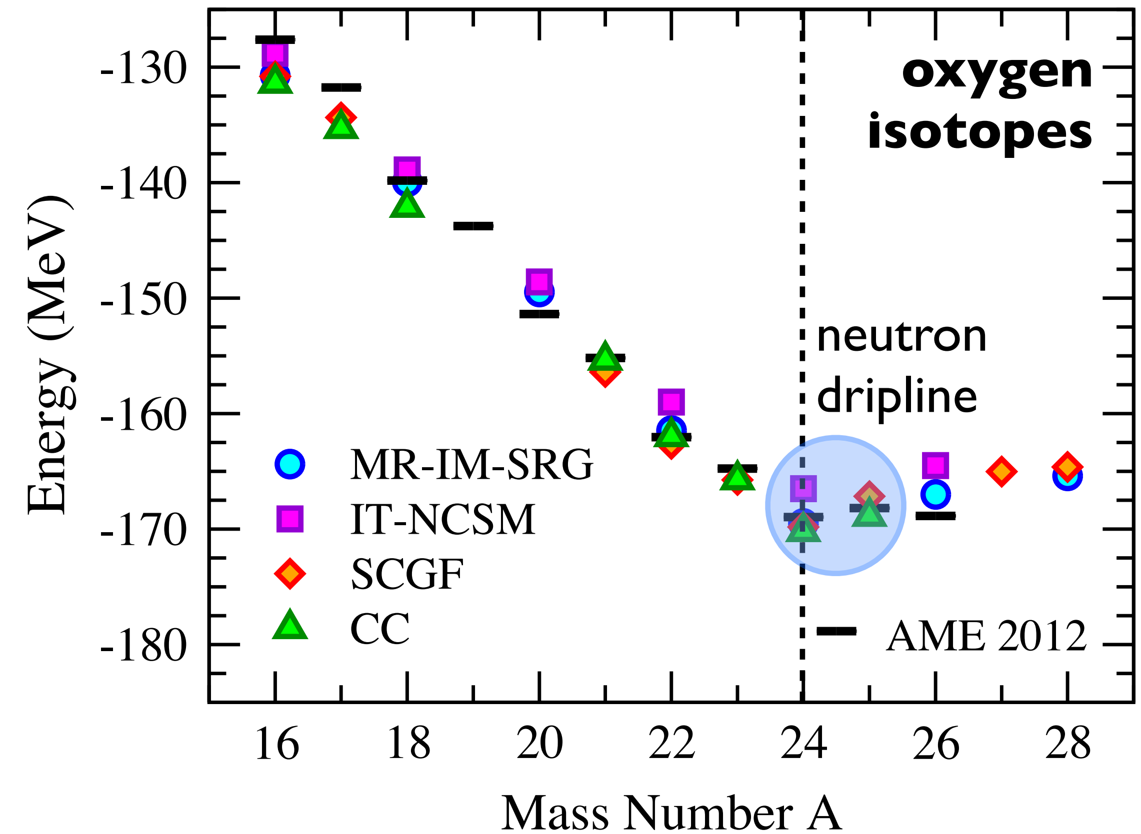
Studies of neutron-rich nuclei: Neutron dripline and the oxygen anomaly



Gallant et al.
PRL 109, 032506 (2012)

Wienholtz et al.
Nature 498, 346 (2013)



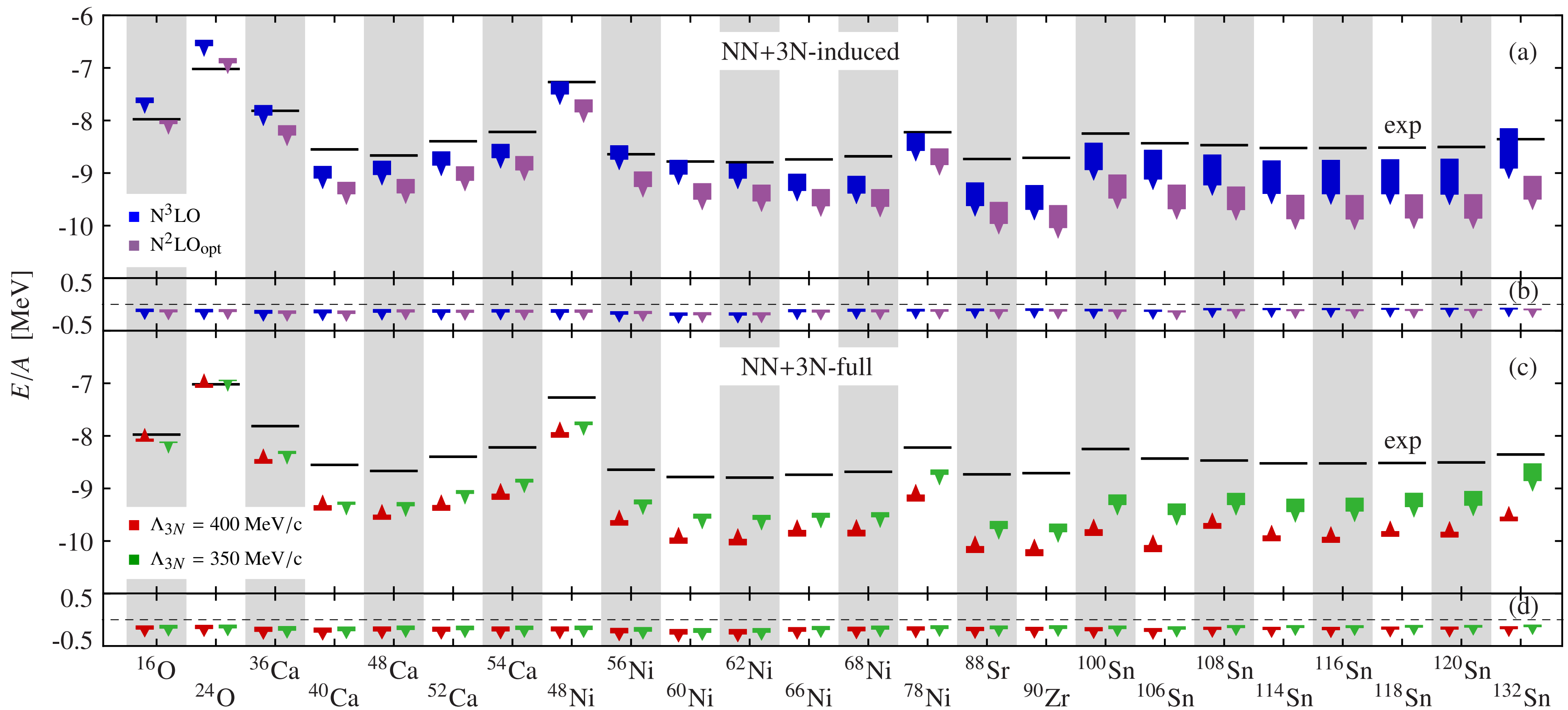


adapted from
KH et al. , Ann. Rev. Nucl. Part. Sci.165, 457 (2015)

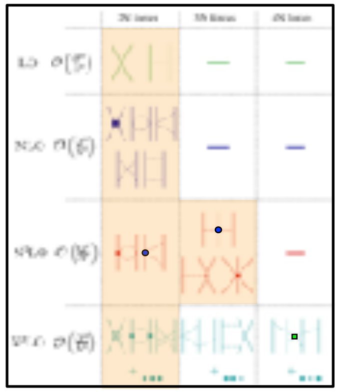
- remarkable agreement between different many-body frameworks
- very good agreement between theory and experiment for masses of oxygen and calcium isotopes based on specific chiral interactions
- contributions from 3N force play important role for drip line

Ab initio calculations of heavier nuclei

coupled cluster (CC) framework



Binder et al., Phys. Lett B 736, 119 (2014)



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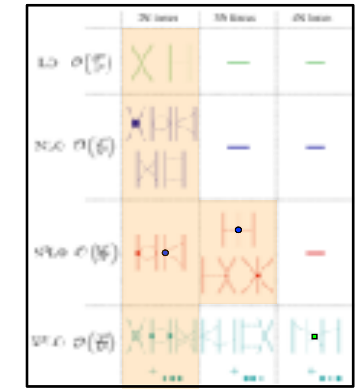
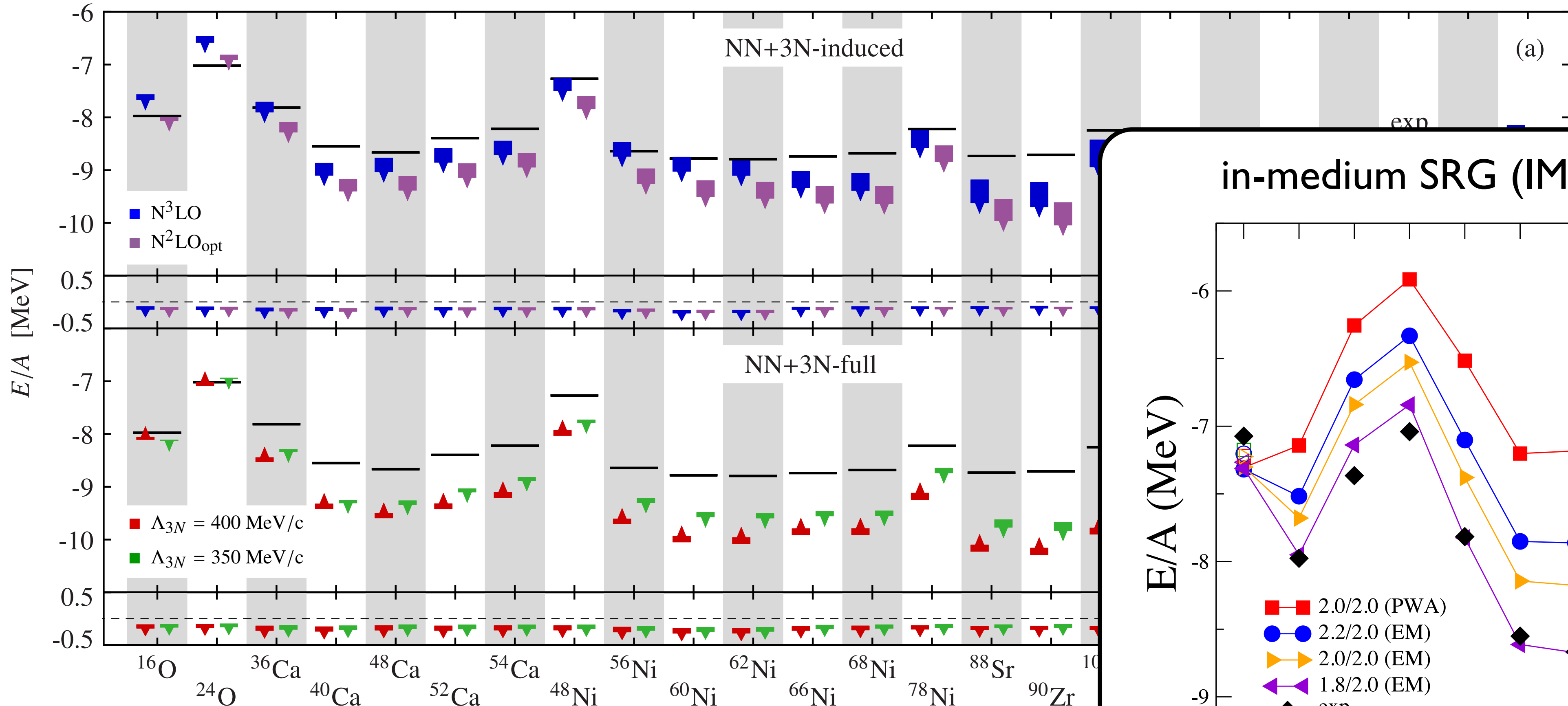
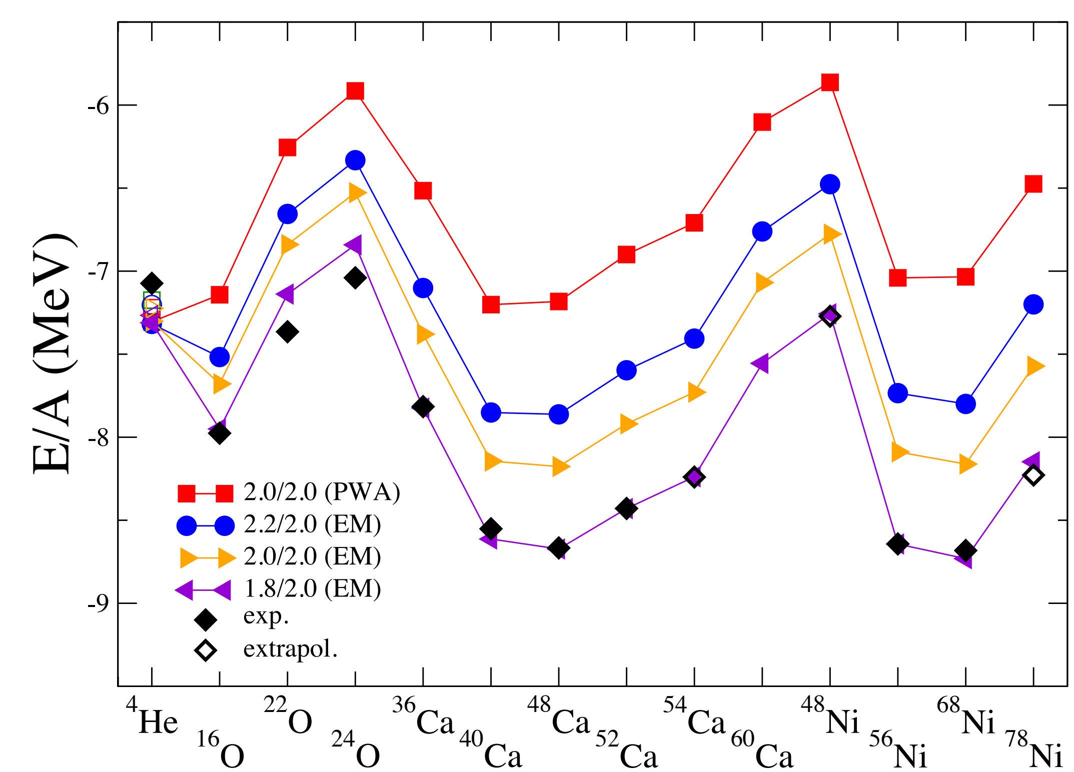


coupled cluster (CC) framework



Binder et al., Phys. Lett B 736, 119 (2014)

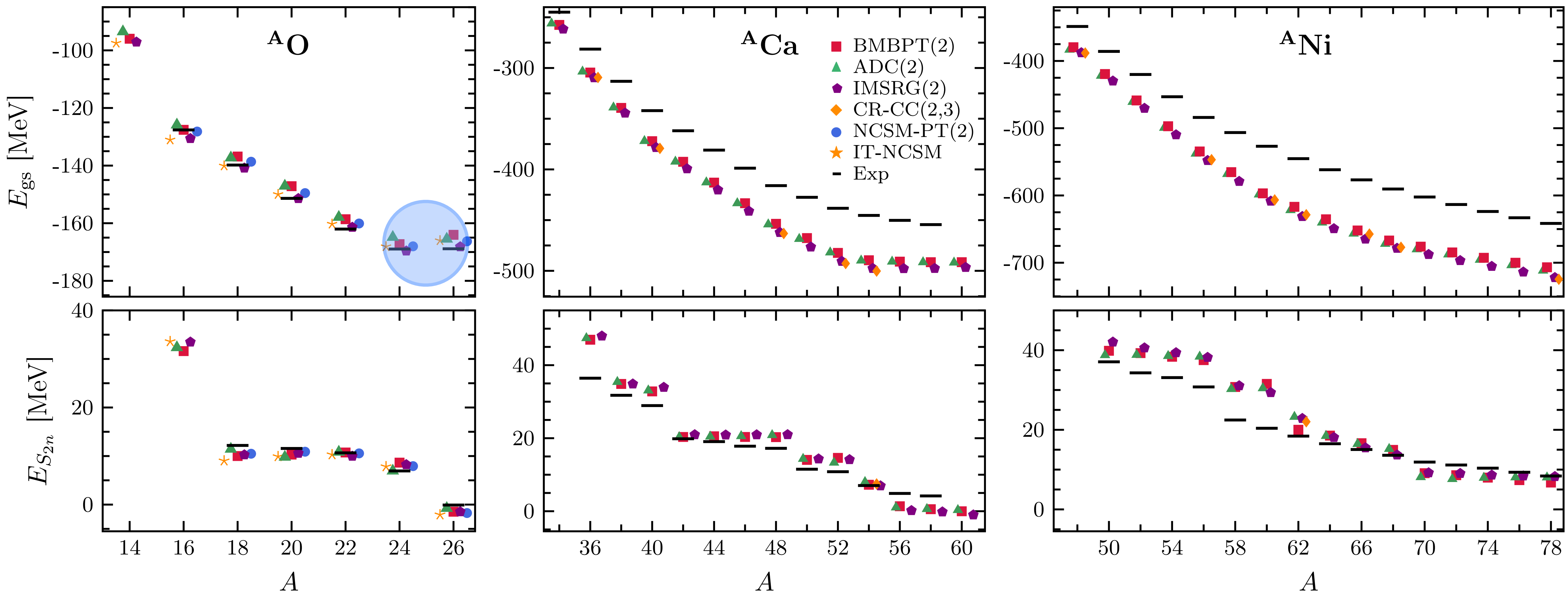
in-medium SRG (IMSRG) framework



Simonis, Stroberg et al., in preparation

- spectacular increase in range of applicability of ab initio many body frameworks
- significant discrepancies to experimental data for heavy nuclei for (most of) presently used nuclear interactions
- need to quantify theoretical uncertainties

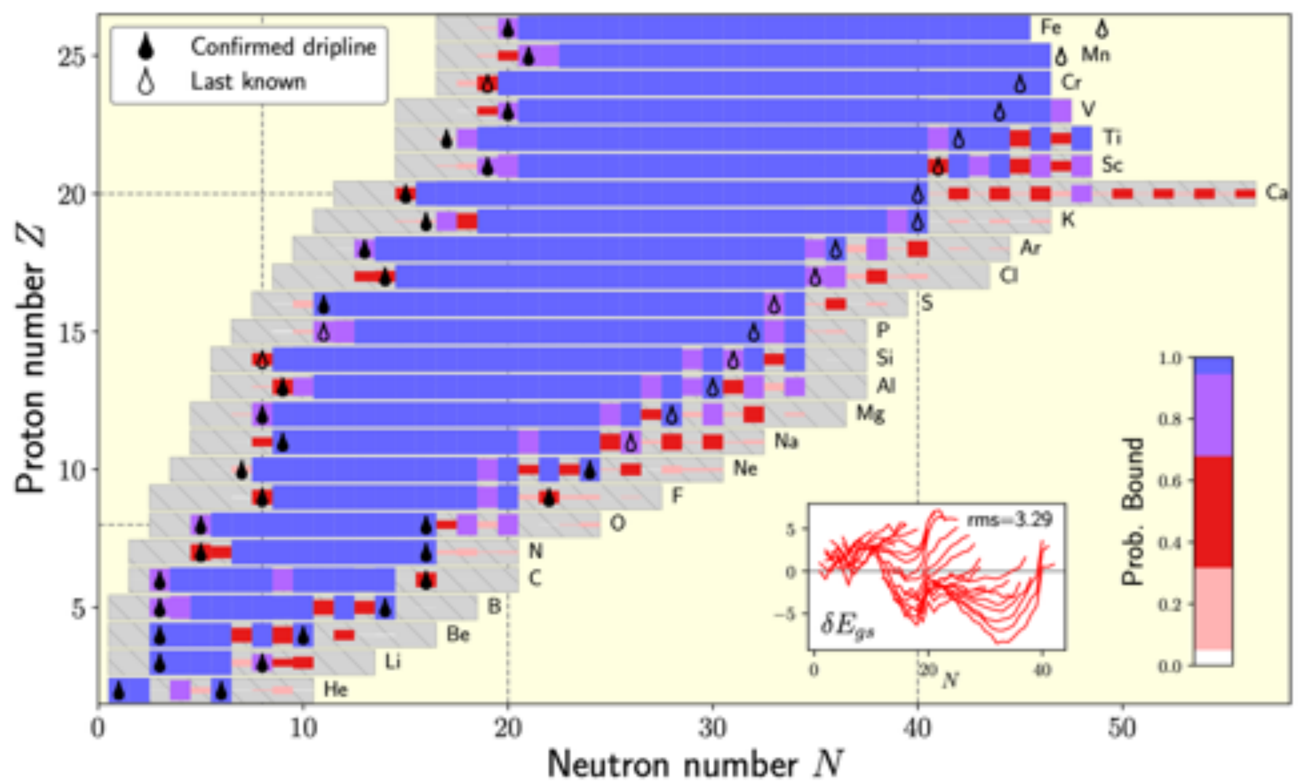
Applications of NN plus 3N forces to atomic nuclei



Tichai et al., Phys. Lett. B 786, 195 (2018)

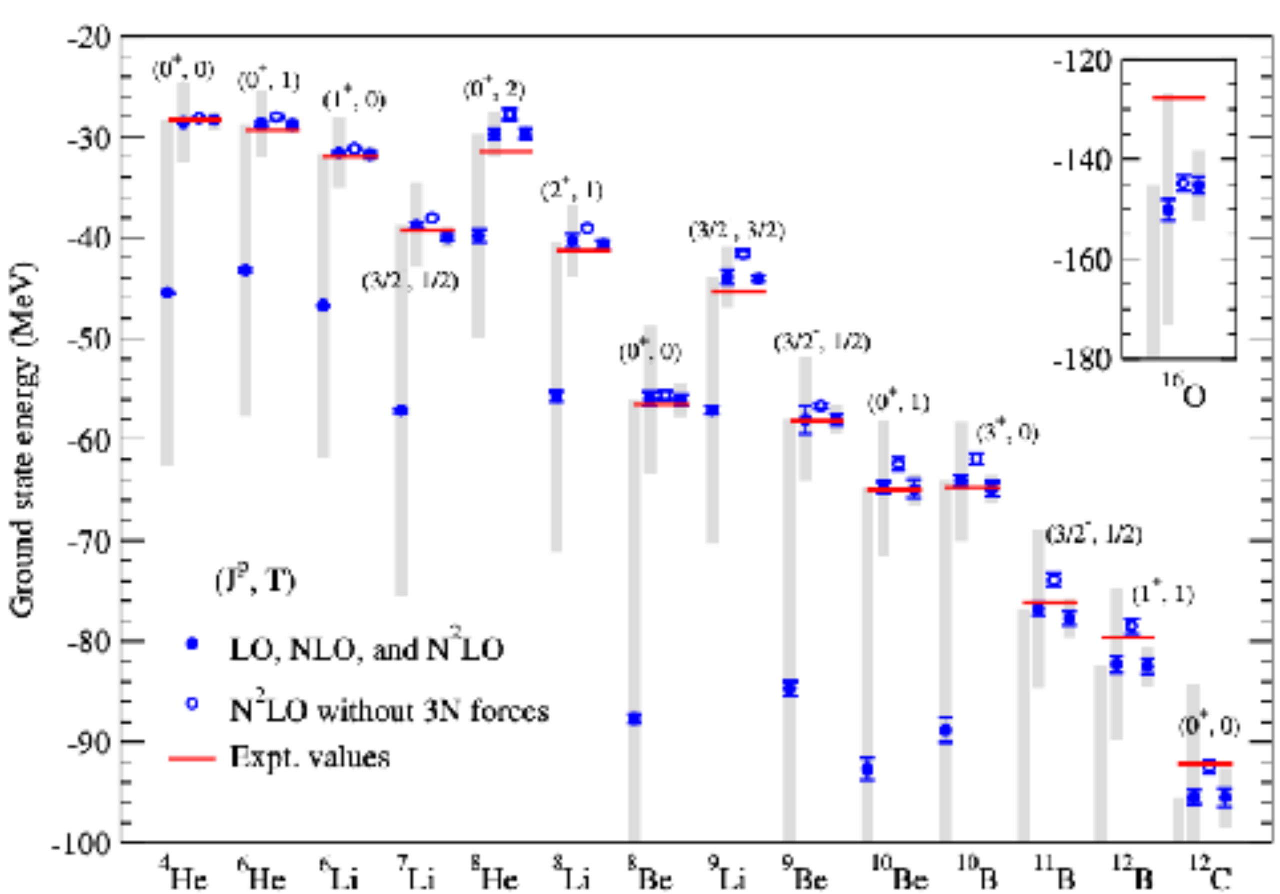
- contributions from 3N force play important role for location of drip lines
- remarkable agreement between different many-body frameworks
- excellent agreement between theory and experiment for energies of oxygen isotopes based on specific chiral interactions
- challenge: correct description of different observables over wide range of the nuclear chart

Applications of NN plus 3N forces to atomic nuclei



remarkable reproduction of energies over wide range of the nuclear chart based on a single NN+3N interaction

KH et al., PRC 83, 031301 (2011)
Stroberg et al., PRL 126, 022501 (2021)



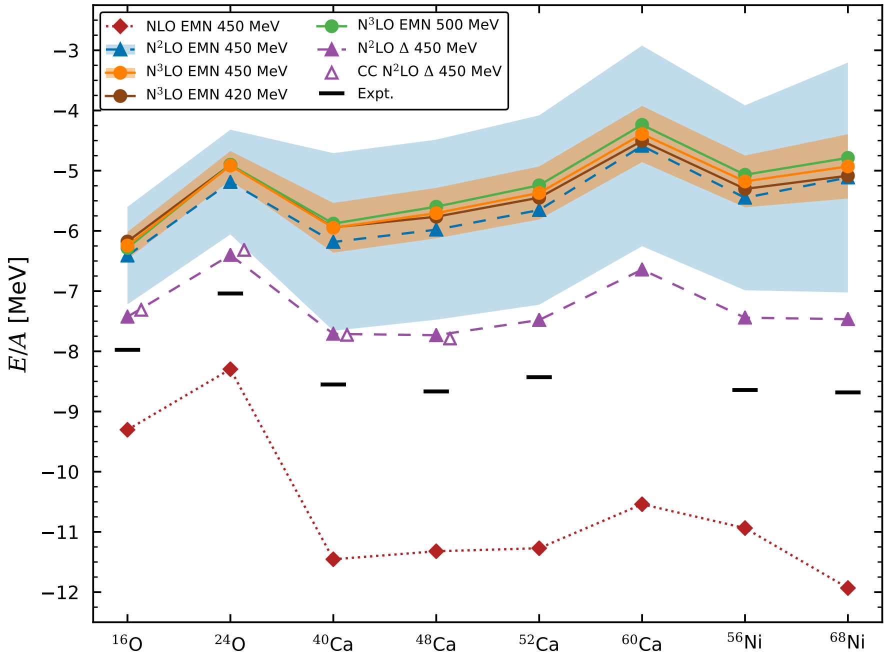
order-by-order calculations of light nuclei based on semilocal NN+3N interactions

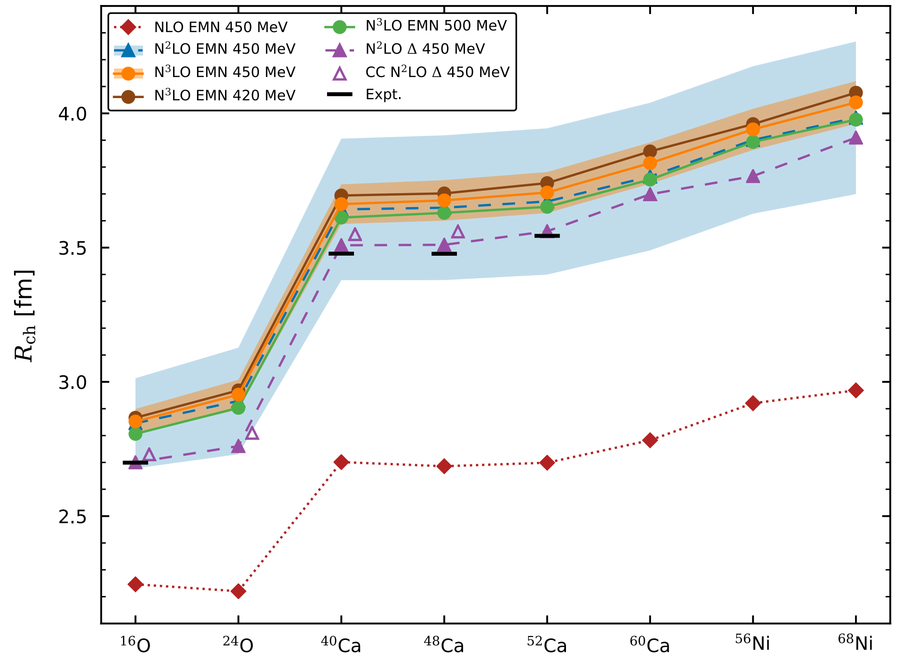
LENPIC

E. Epelbaum, PRC 99, 024313 (2019)

First inclusions of subleading 3N contributions

3N forces fitted to empirical saturation properties of nuclear matter:





Hoppe et al.
PRC 100, 024318 (2019)

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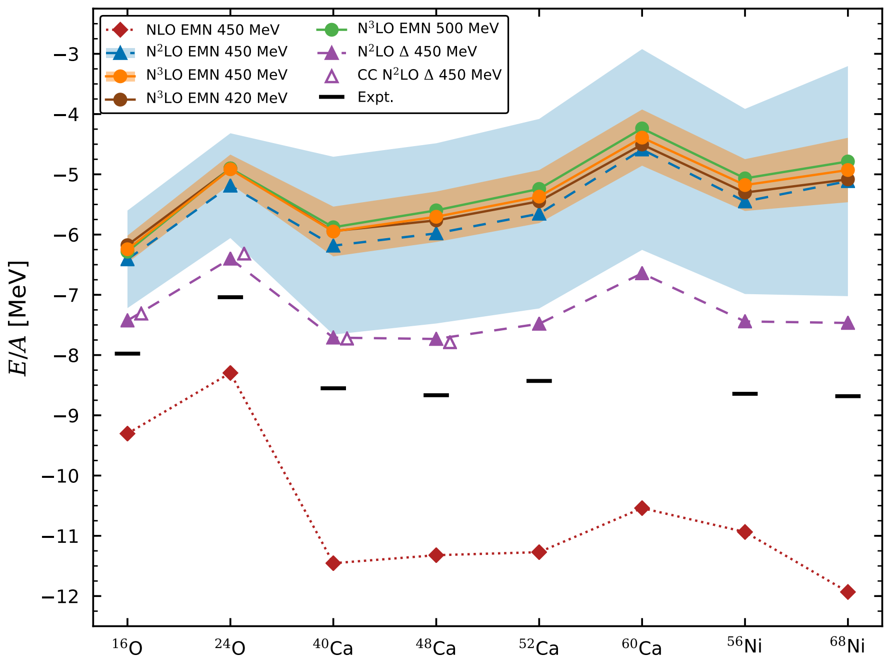
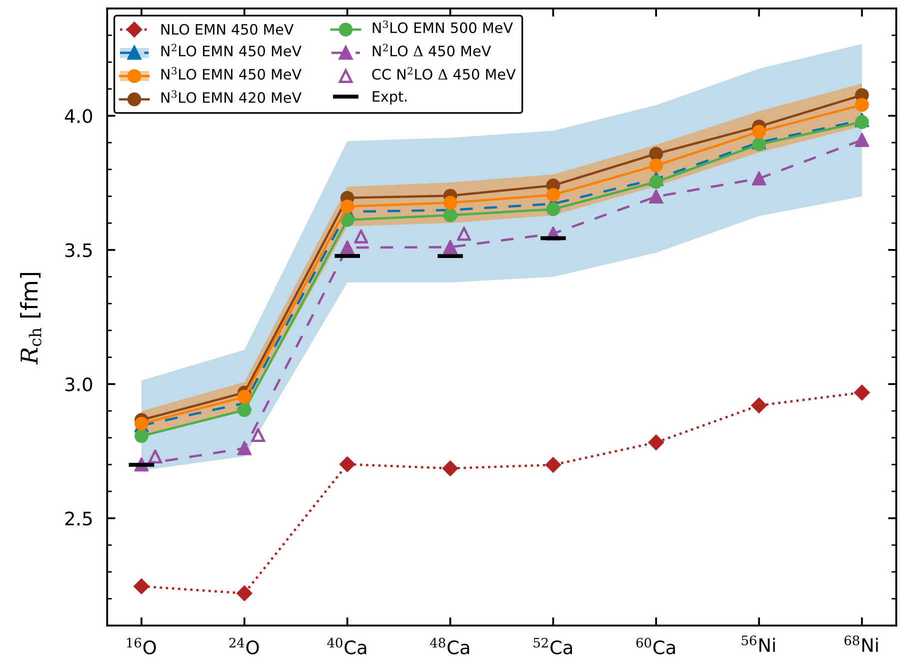
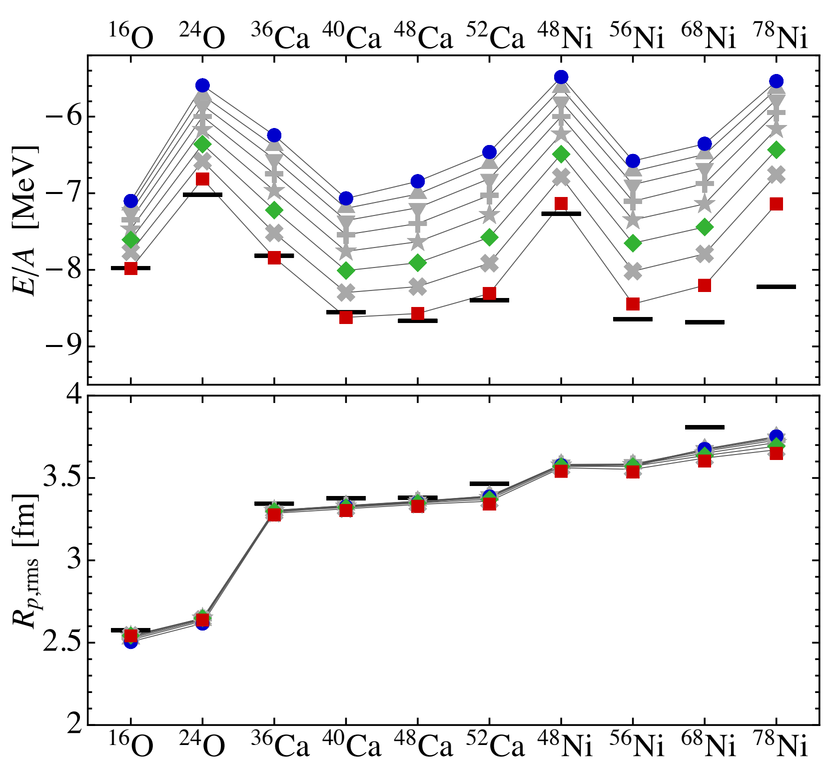
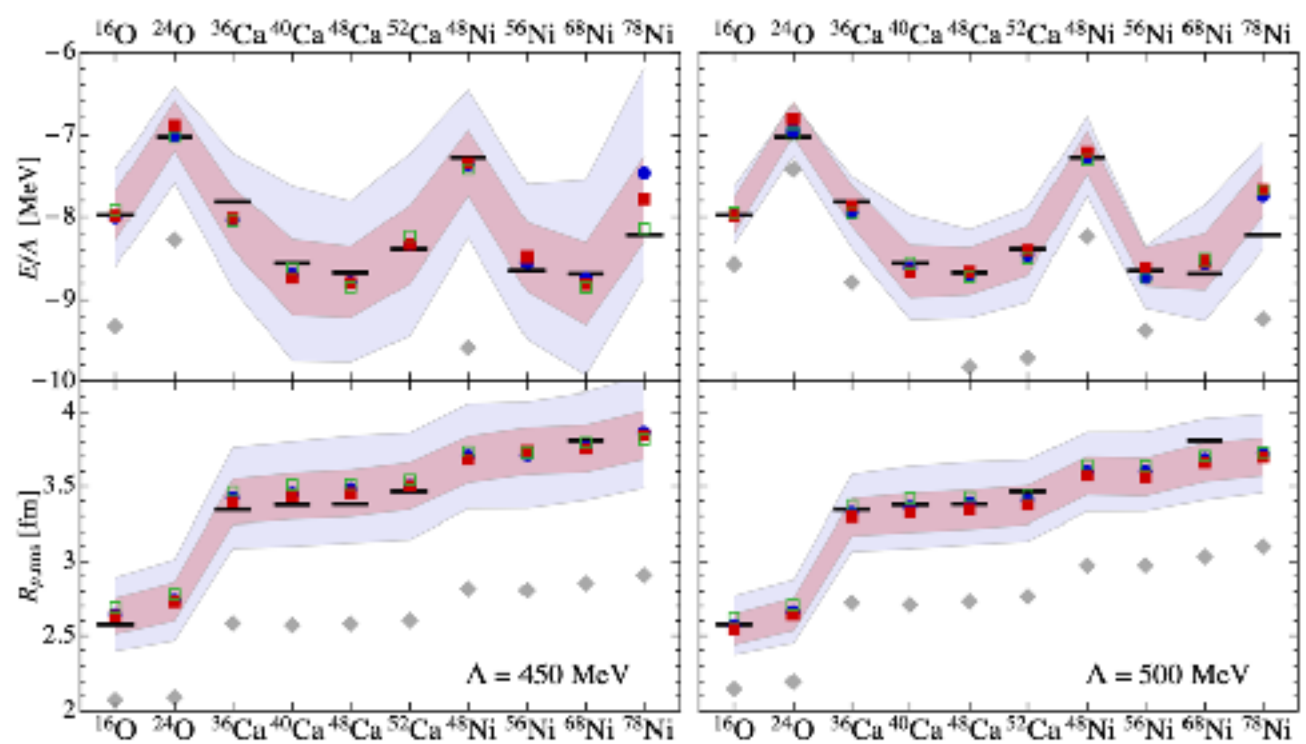




Hoppe et al.
PRC 100, 024318 (2019)

3N forces fitted few-body systems and medium-mass nuclei:





Hüther et al.
PLB 808, 135651 (2020)

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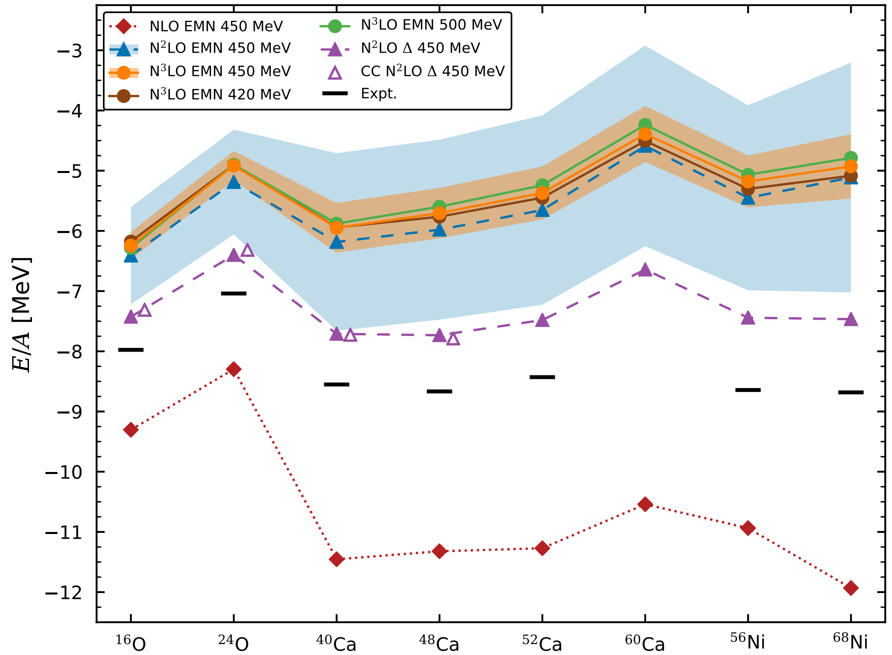

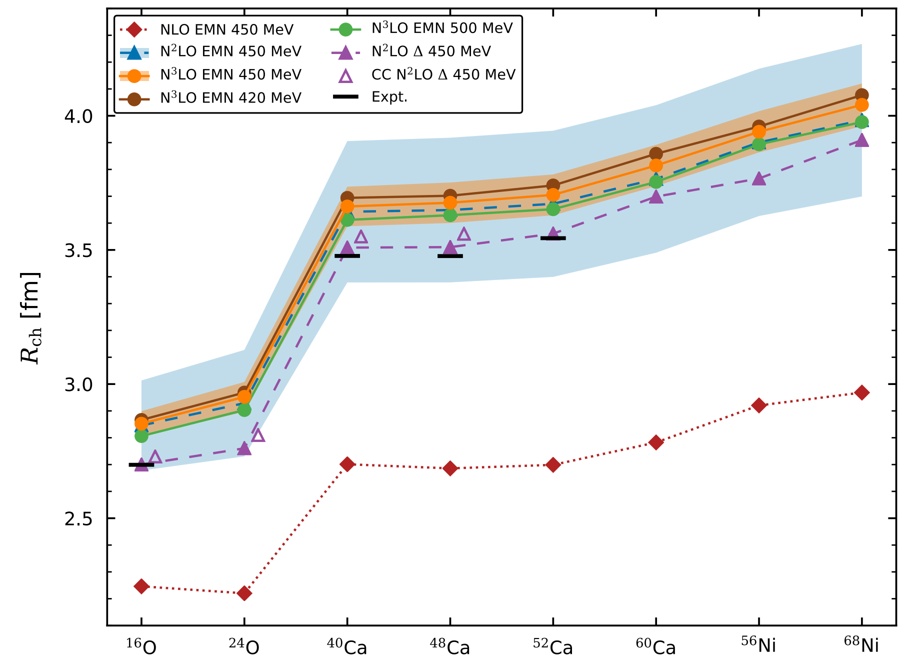

Hoppe et al.
PRC 100, 024318 (2019)

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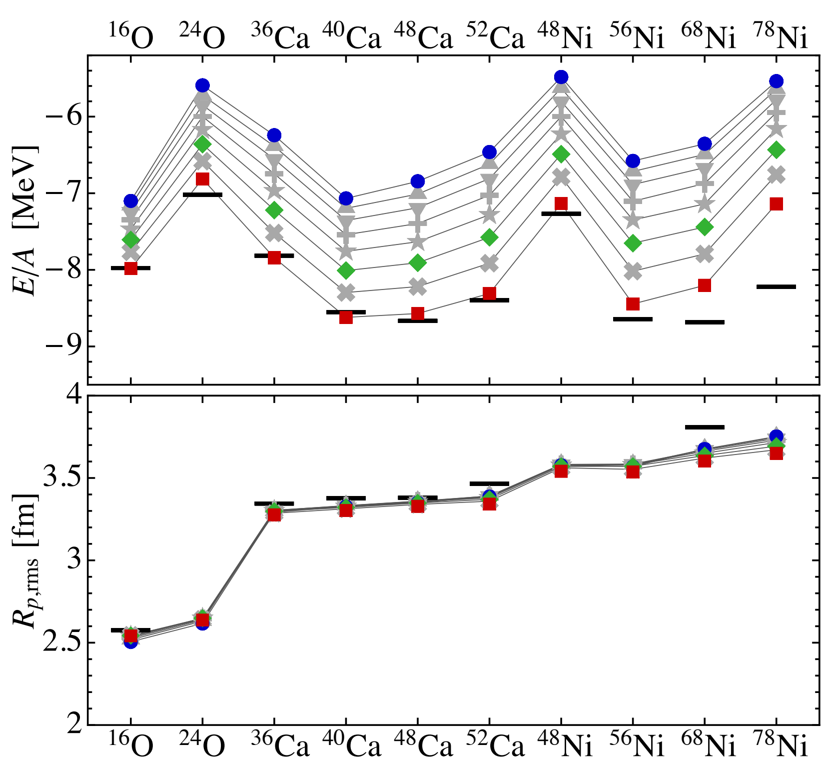
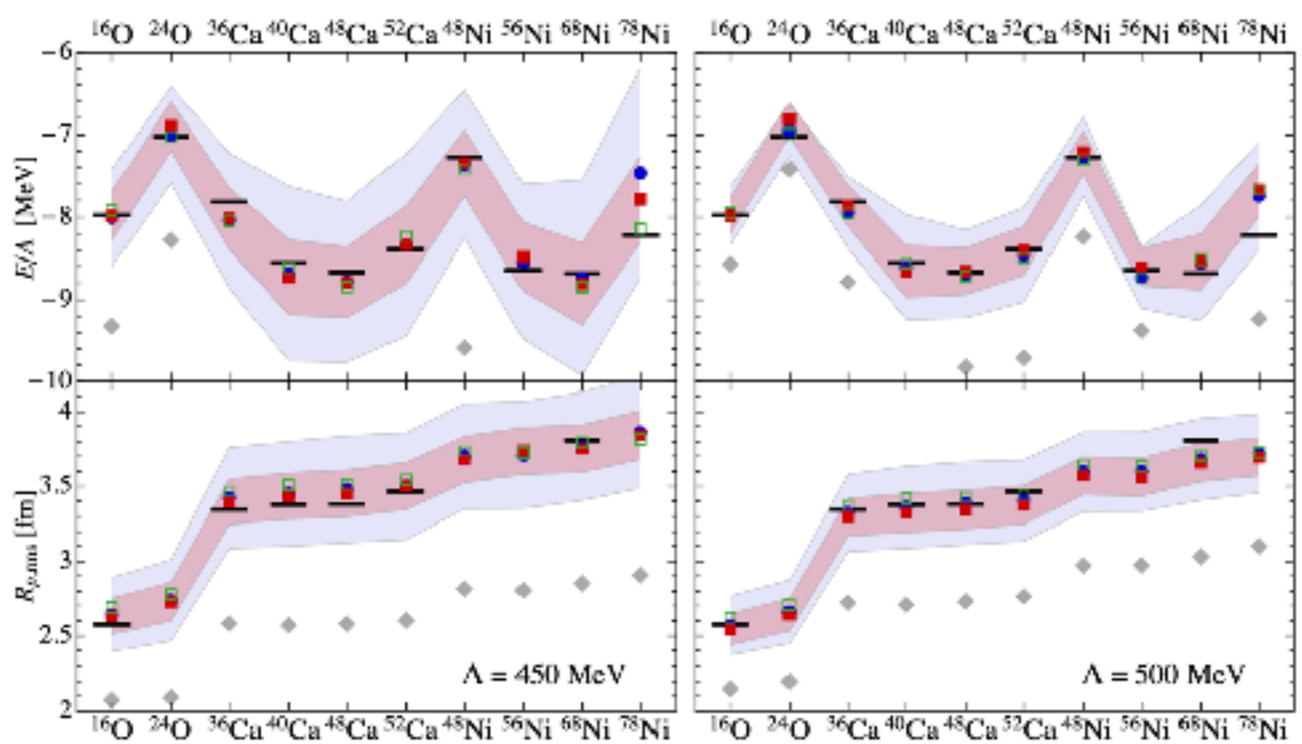


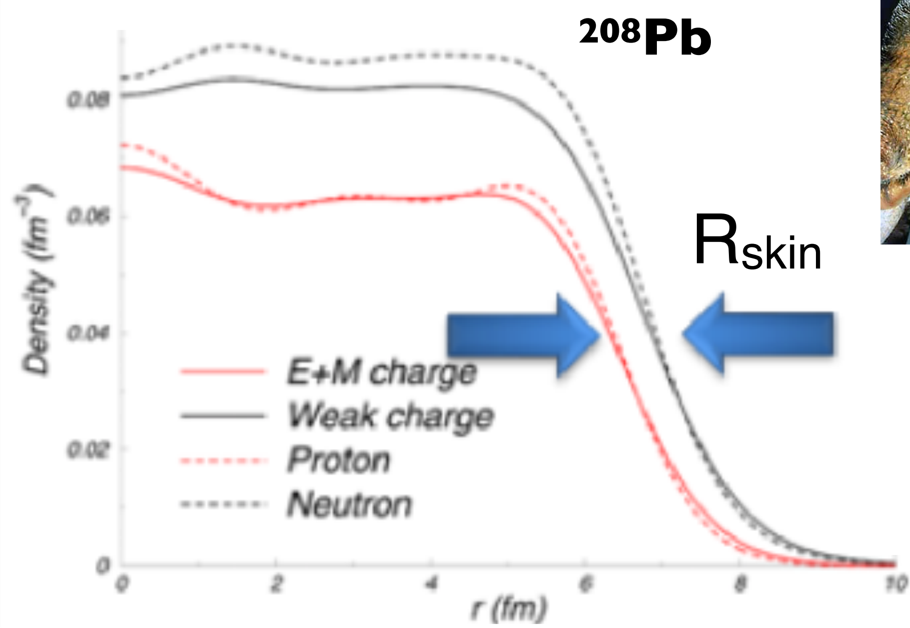


Hüther et al.
PLB 808, 135651 (2020)

no simultaneous description of matter and nuclei possible for these NN forces

The size of the atomic nucleus: challenges from novel high-precision measurements

Horowitz

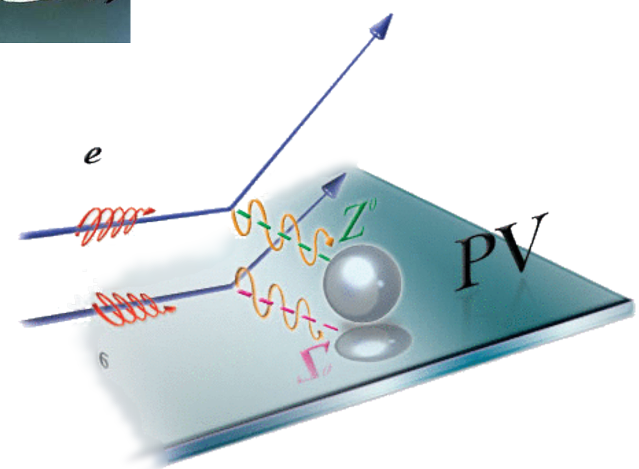


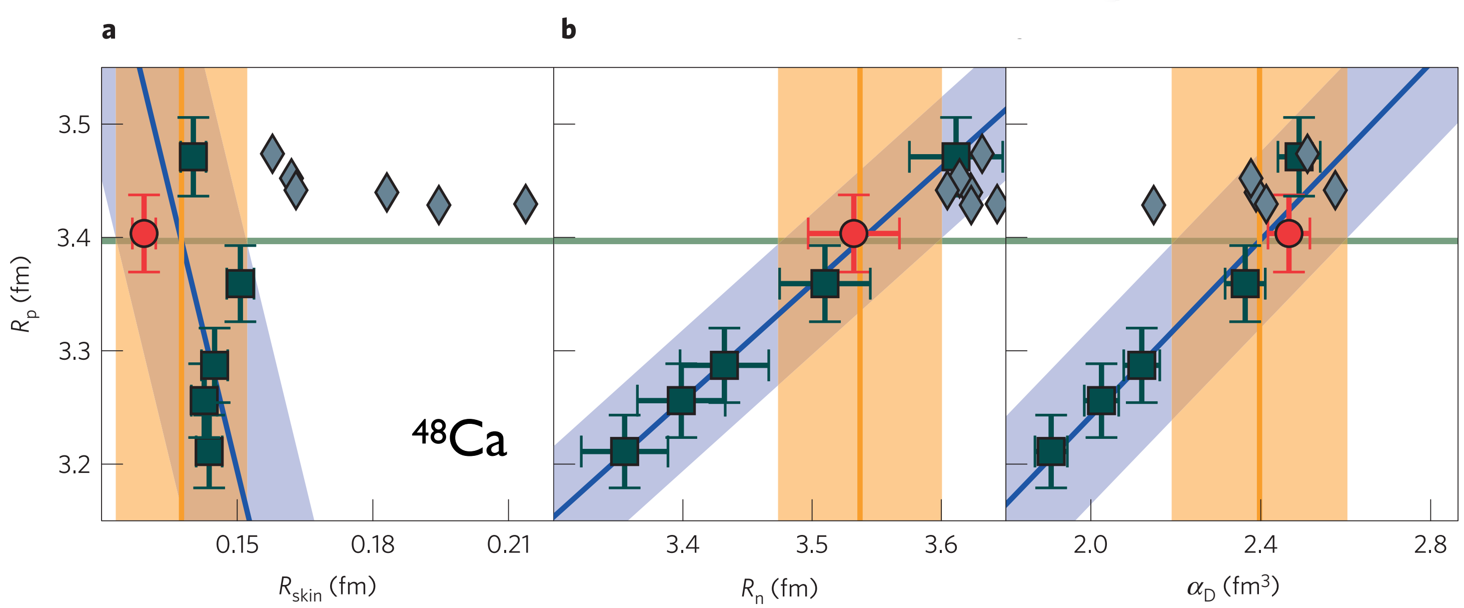
PREX

Pb Radius Experiment

CREX

Ca Radius Experiment

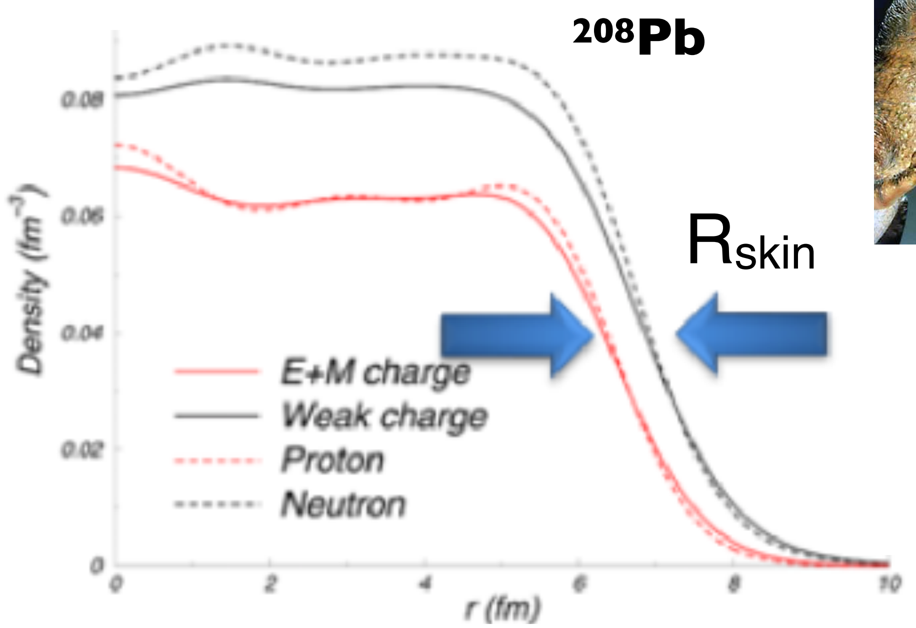




Hagen. et al.. Nature Phys. 12, 186 (2015)

The size of the atomic nucleus: challenges from novel high-precision measurements

Horowitz

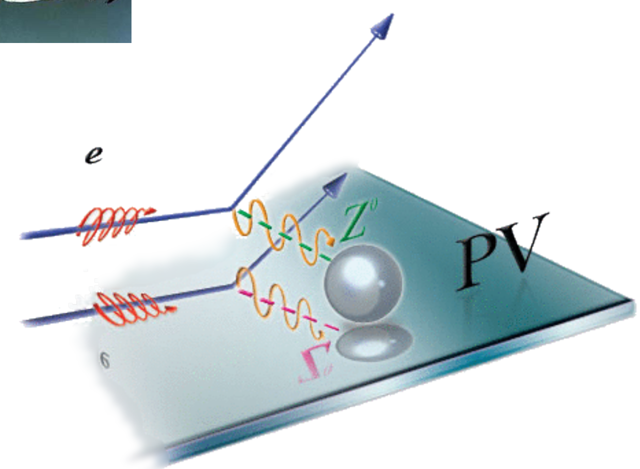


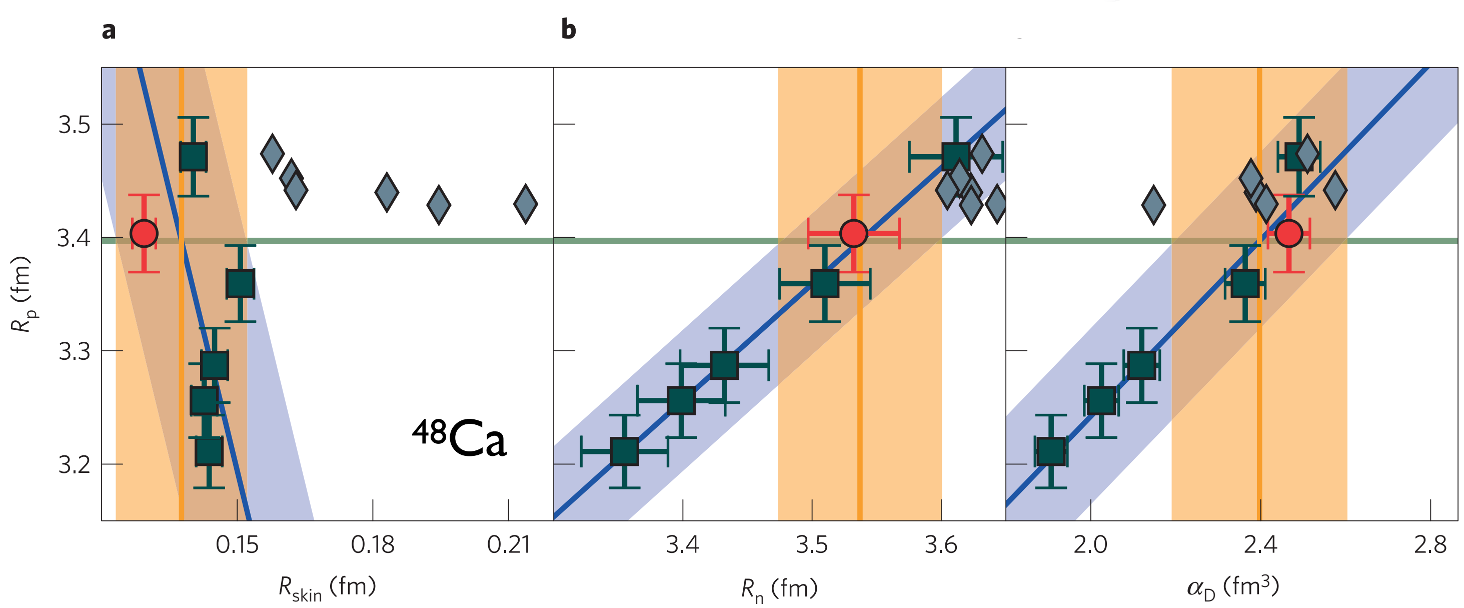
PREX

Pb Radius Experiment

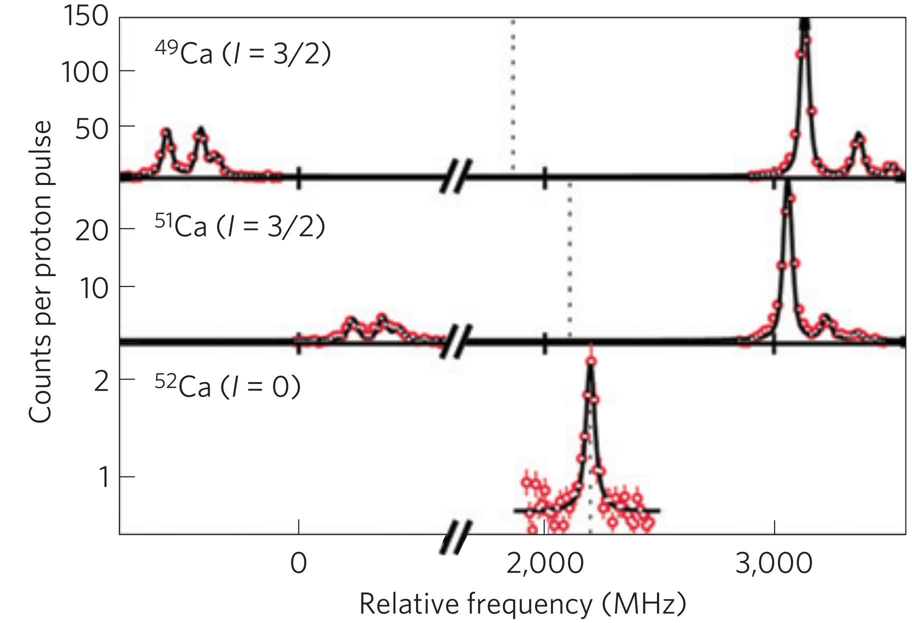
CREX

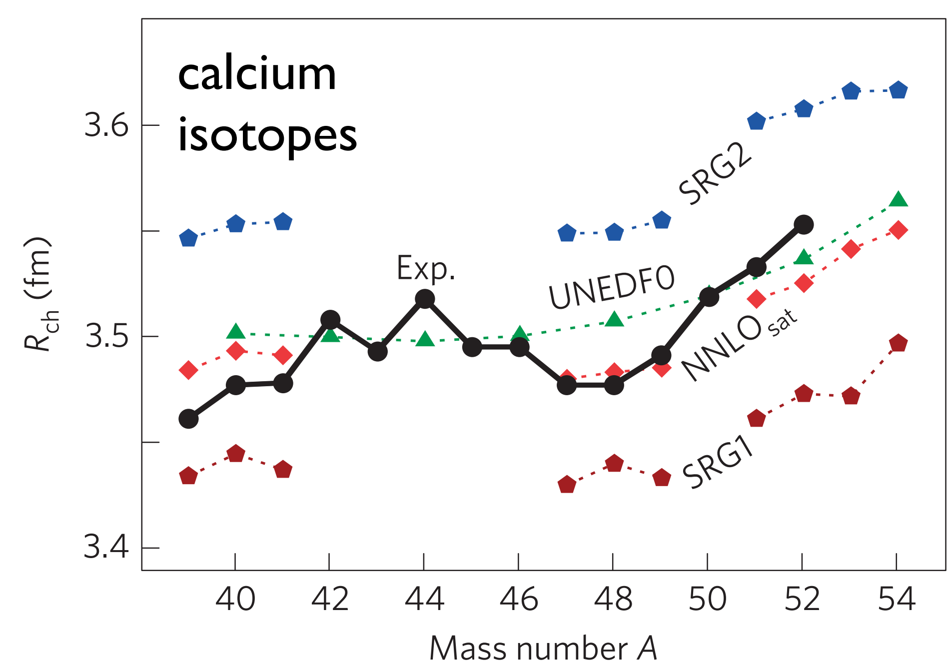
Ca Radius Experiment





Hagen. et al.. Nature Phys. 12, 186 (2015)

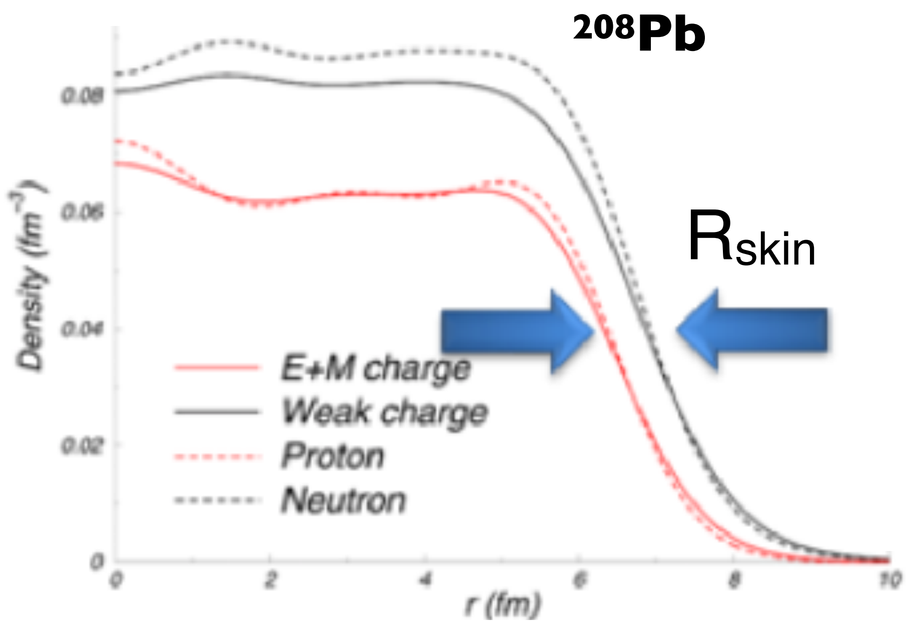


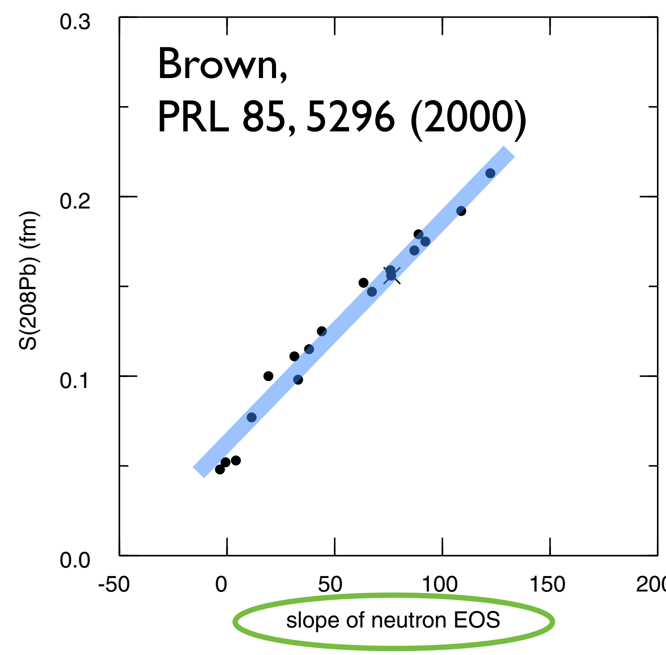


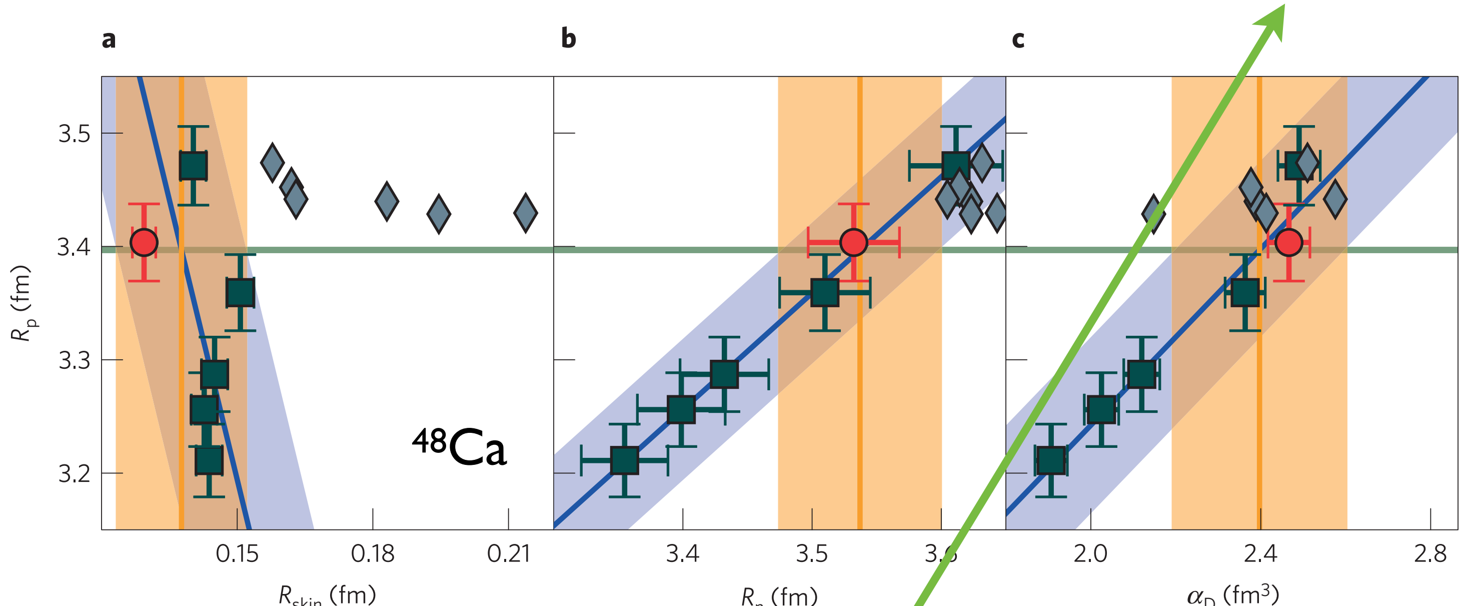
Garcia Ruiz. et al.,
Nature Phys. 12, 594 (2016)

The size of the atomic nucleus: challenges from novel high-precision measurements

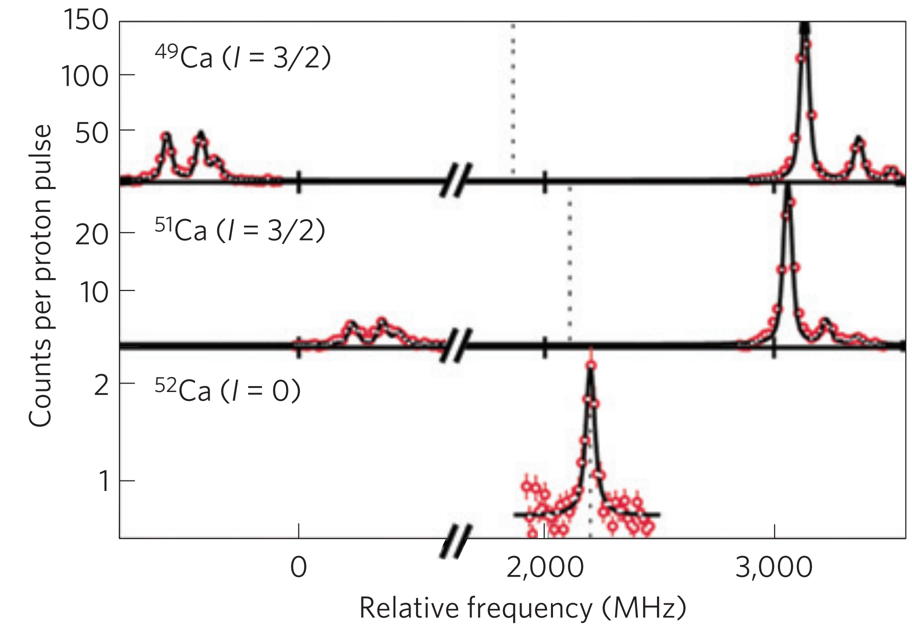
Horowitz

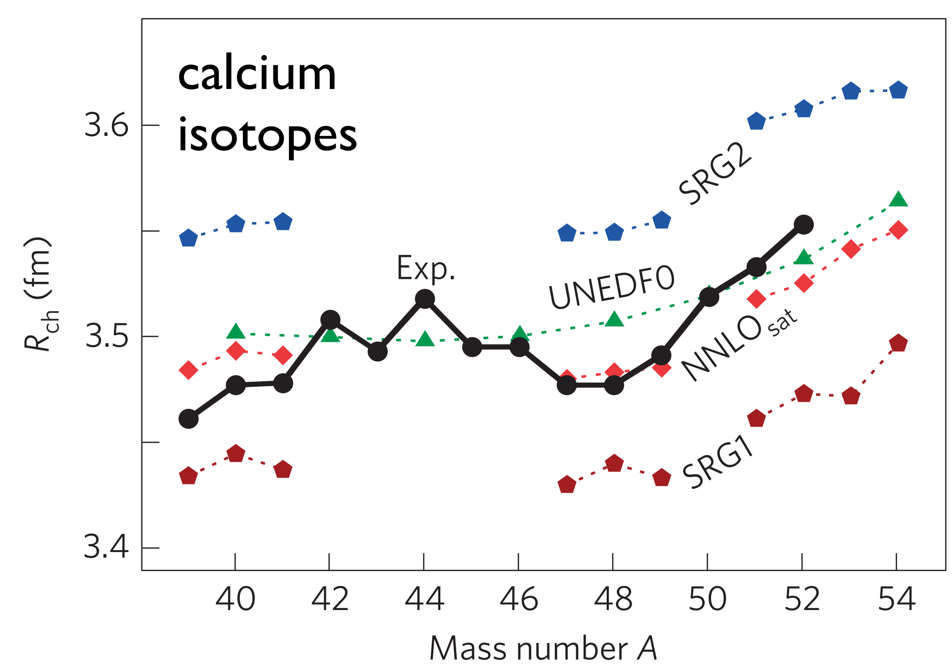






Hagen. et al.. Nature Phys. 12, 186 (2015)

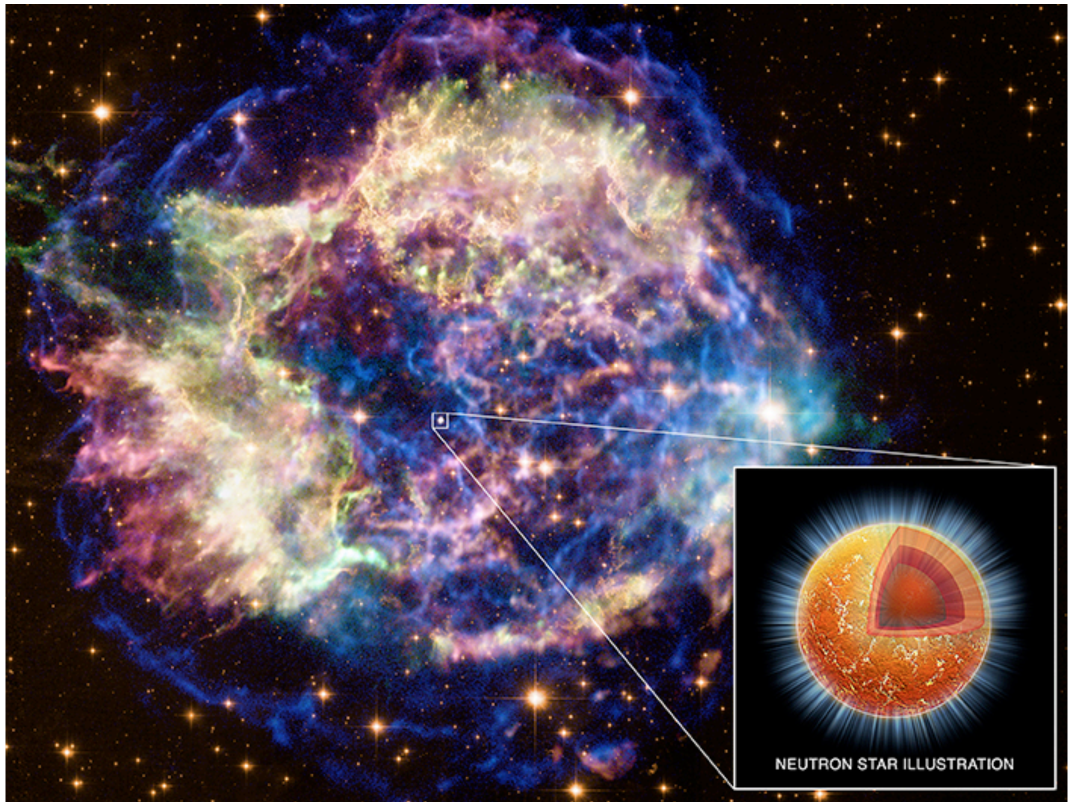


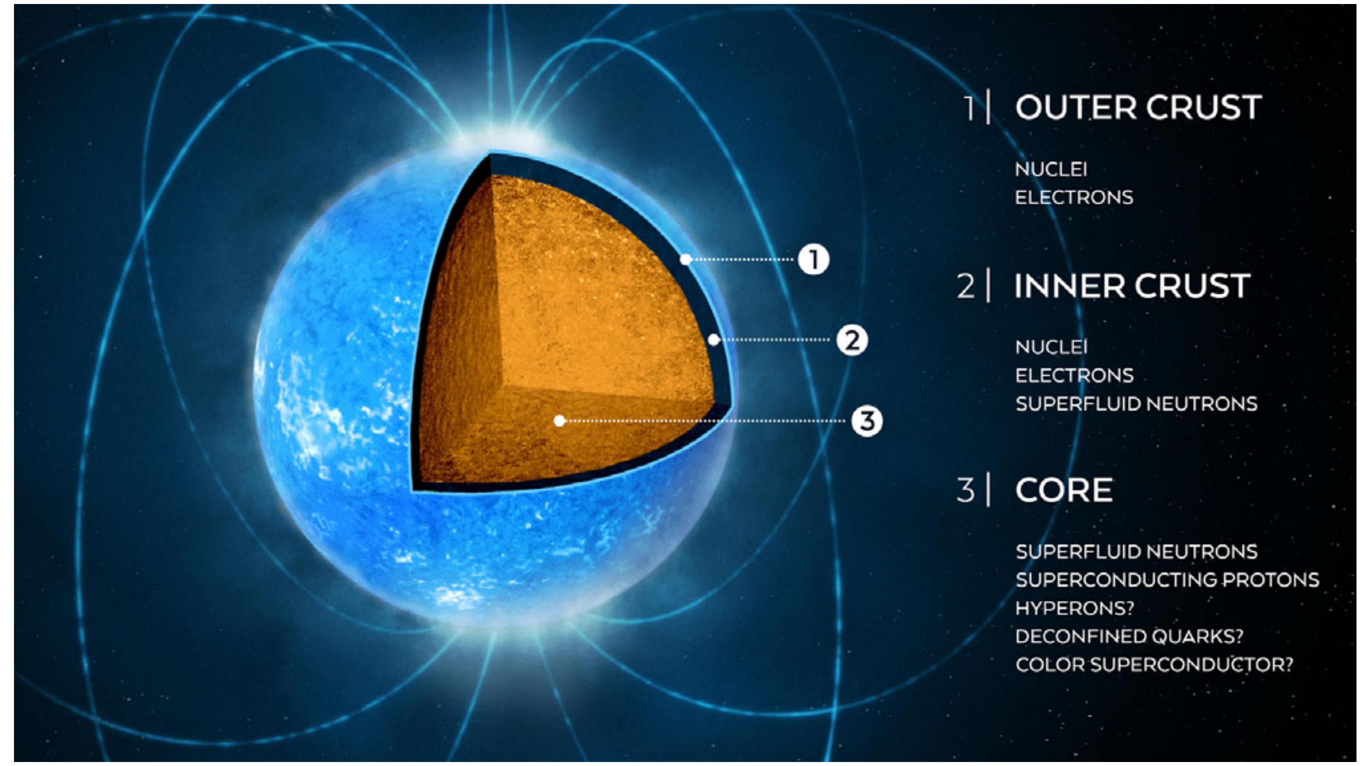


Garcia Ruiz. et al.,
Nature Phys. 12, 594 (2016)

direct connections to astrophysics!

The equation of state of high-density matter: constraints for neutron stars from nuclear physics





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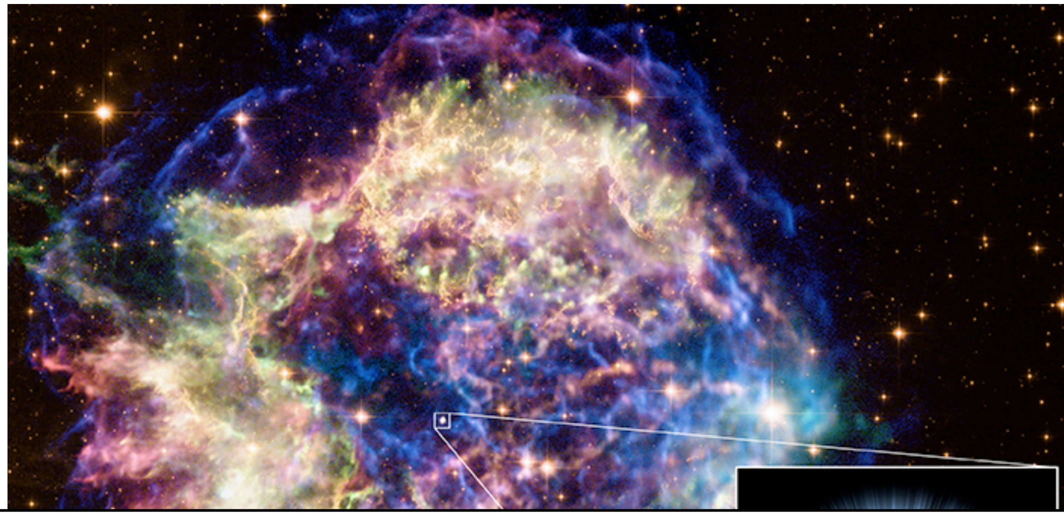

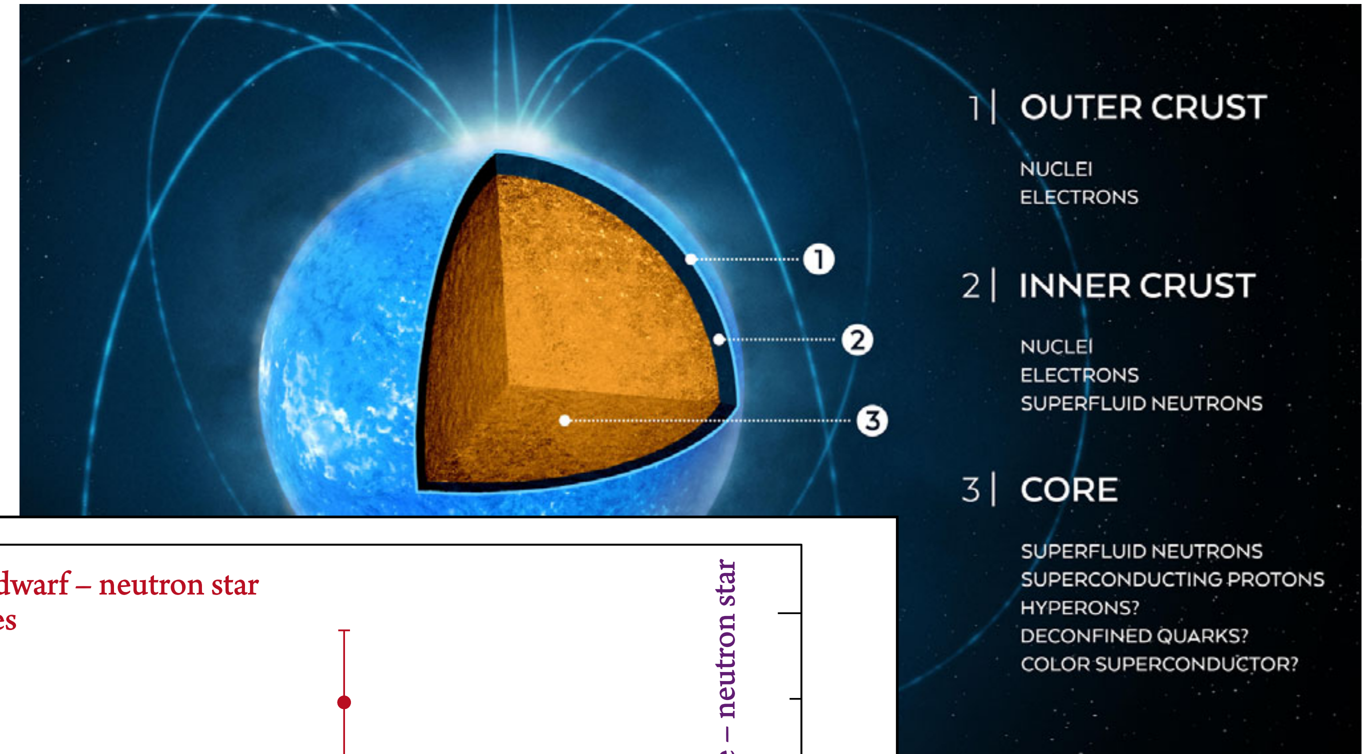

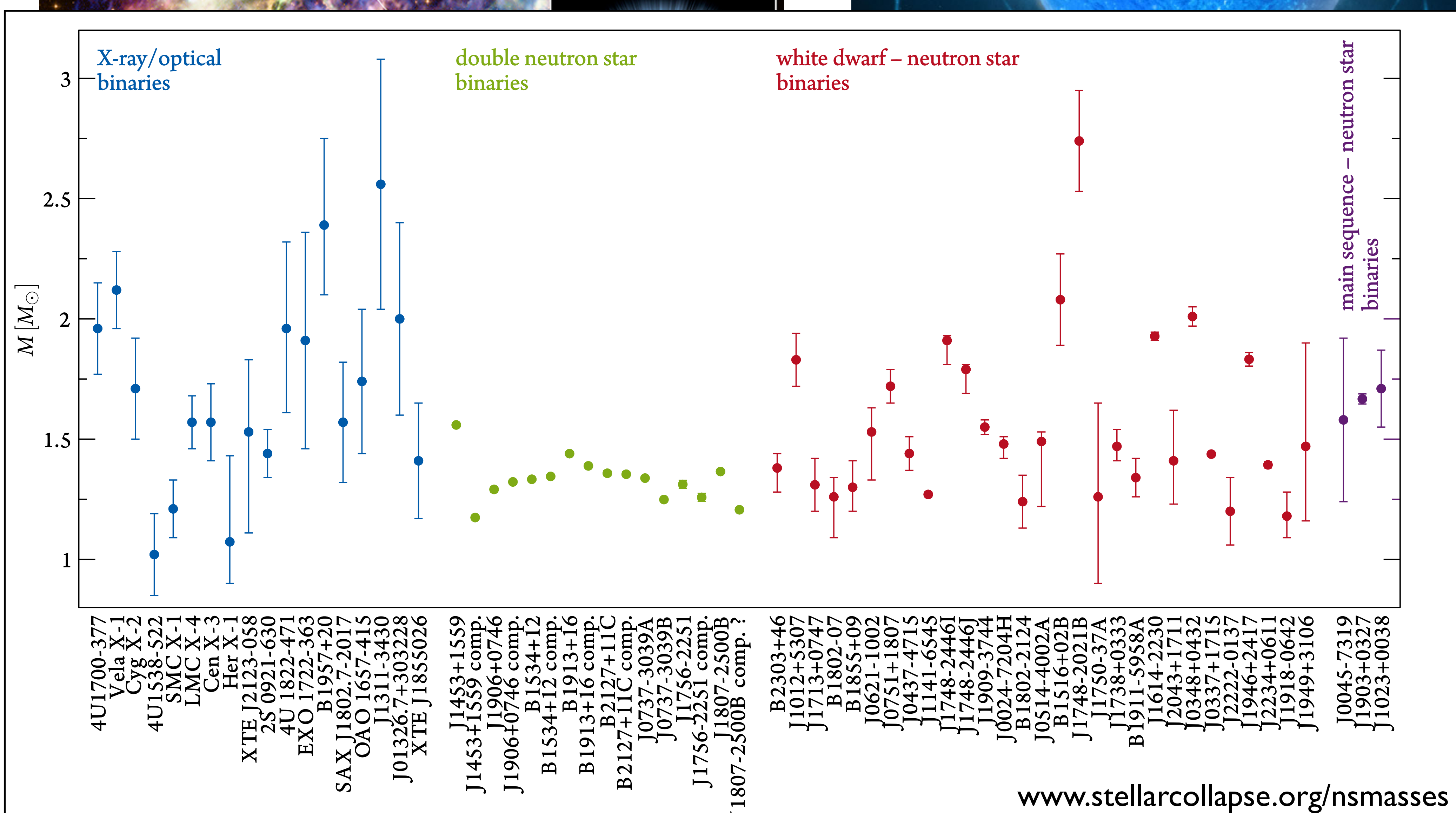

figure taken from Krüger, doctoral thesis (2016)

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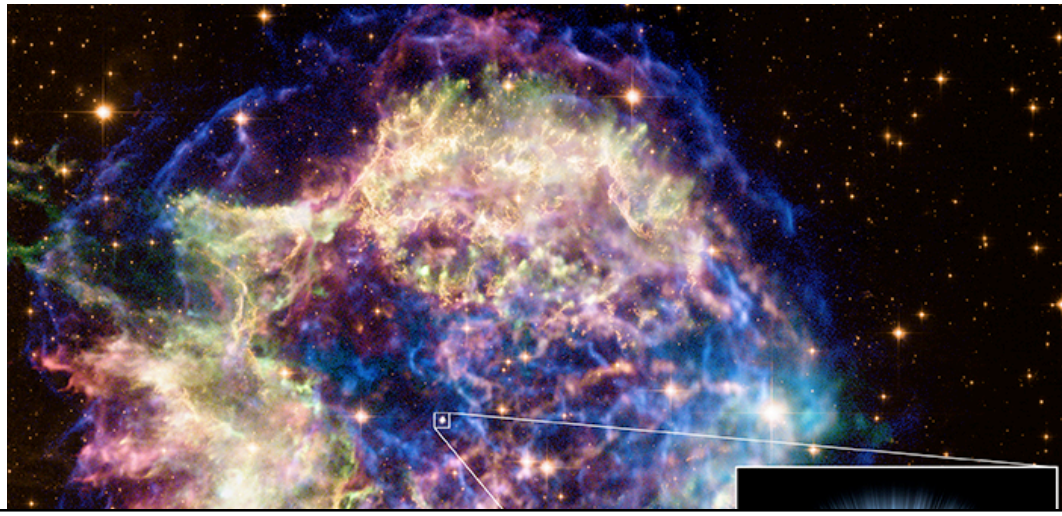

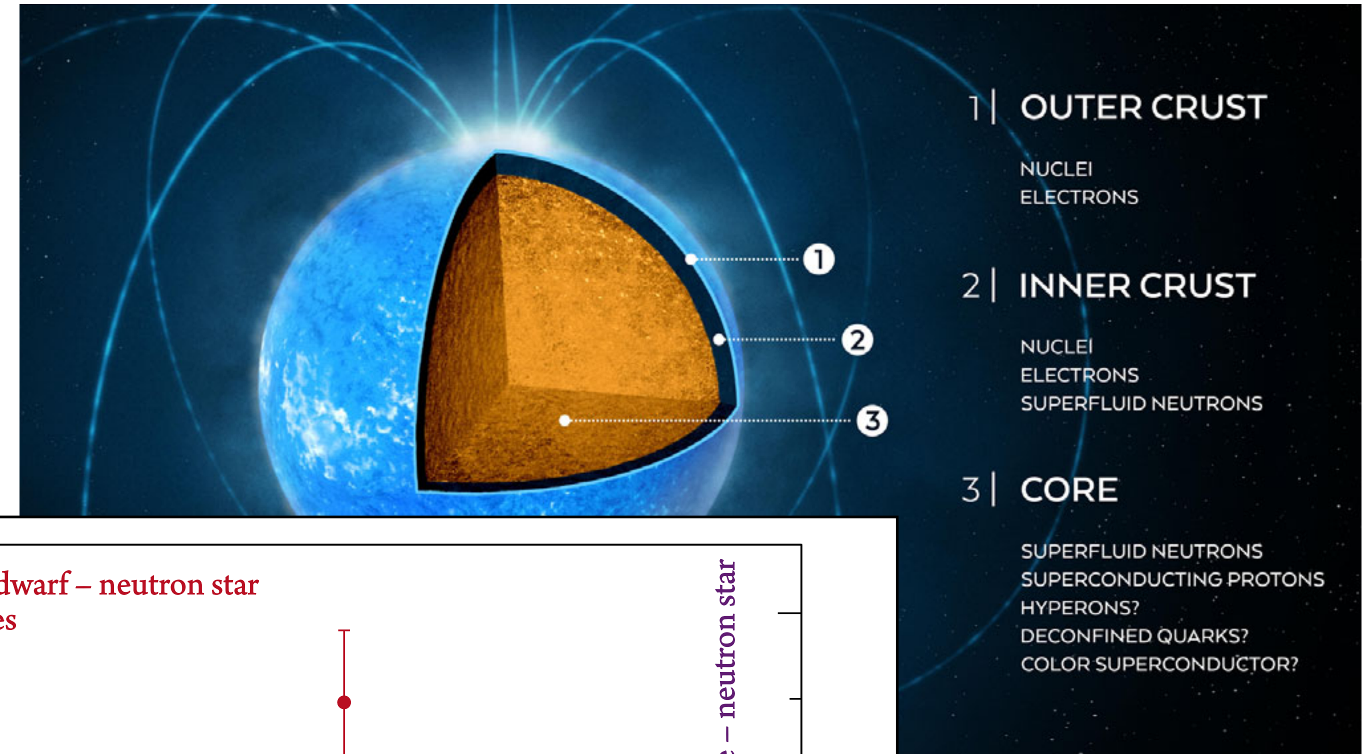

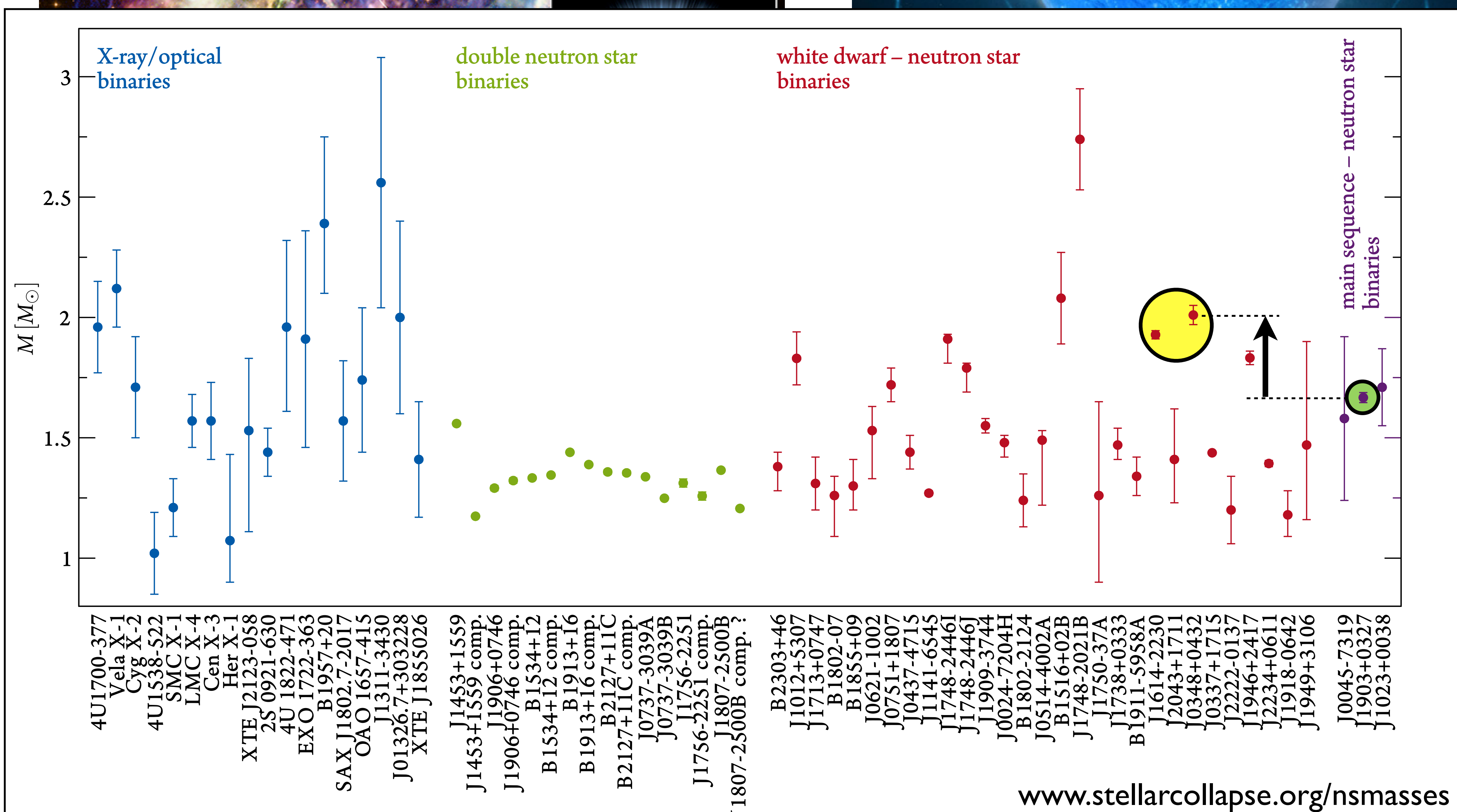

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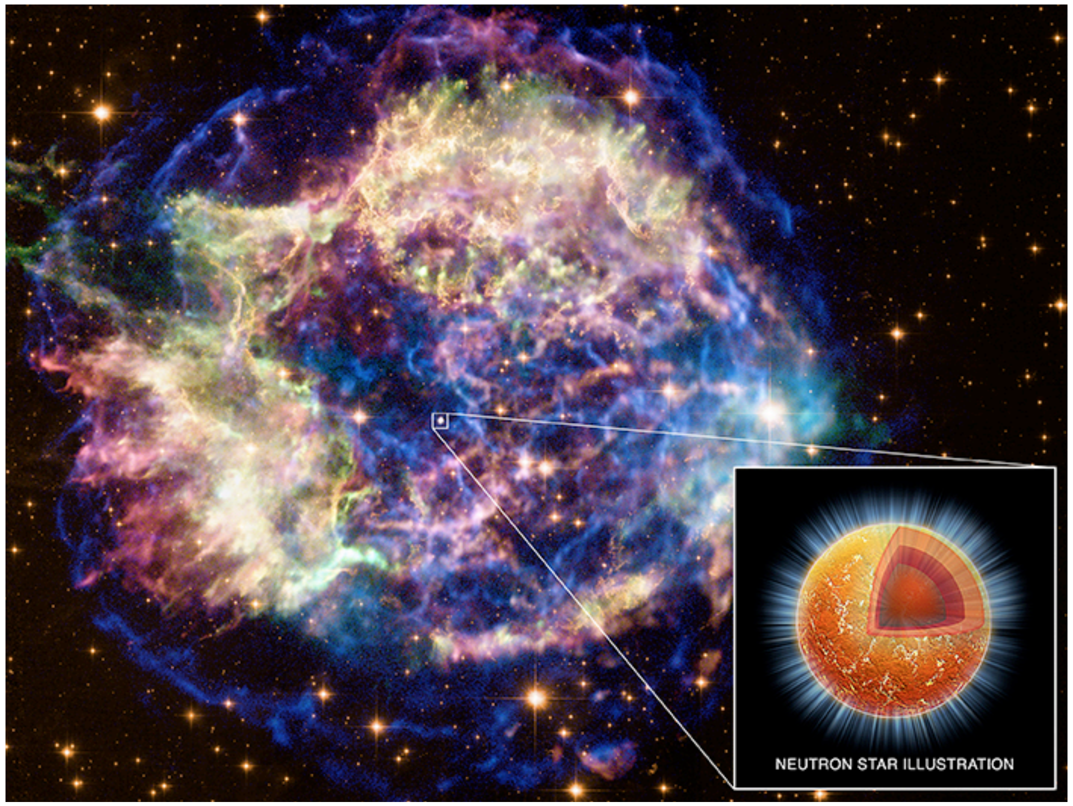
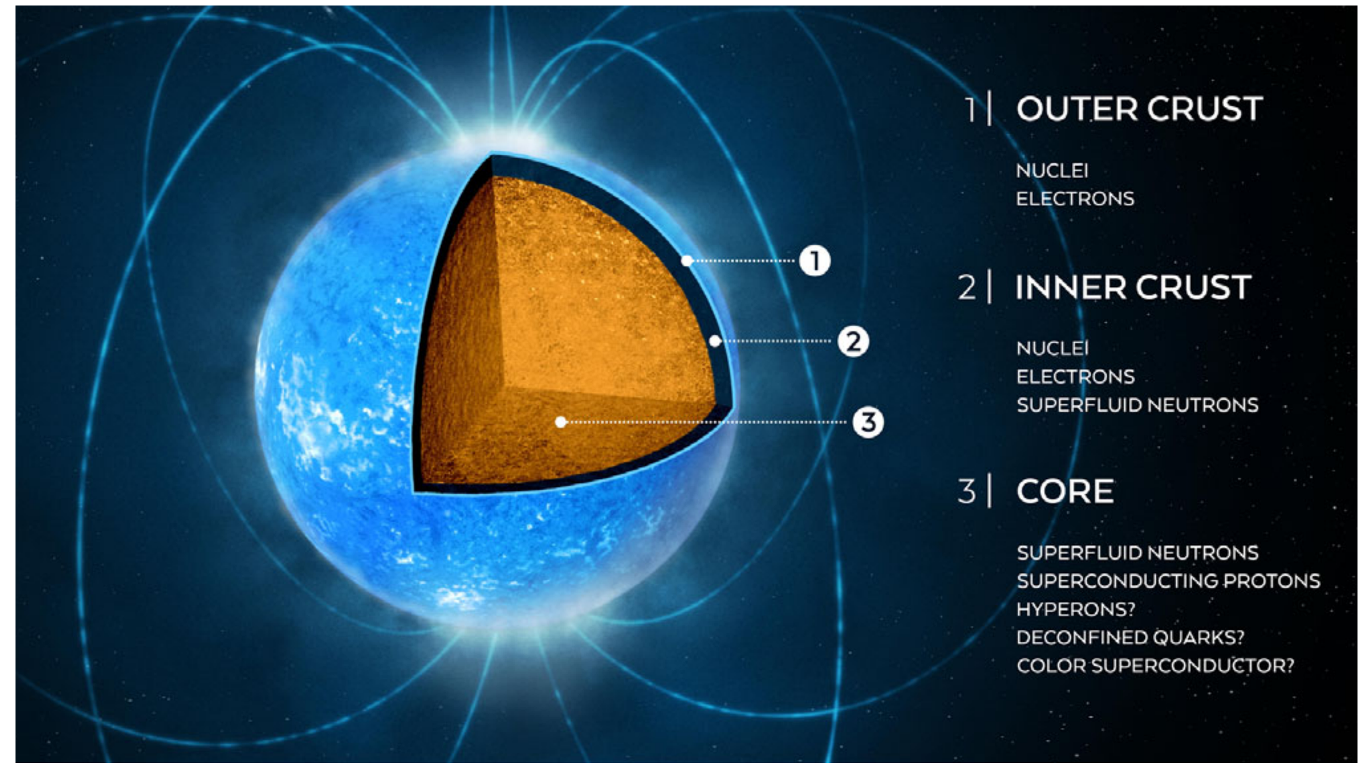
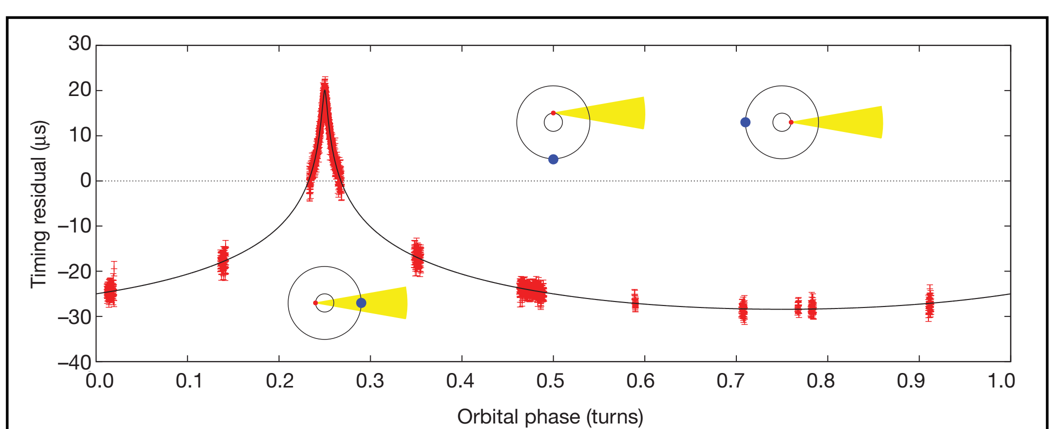


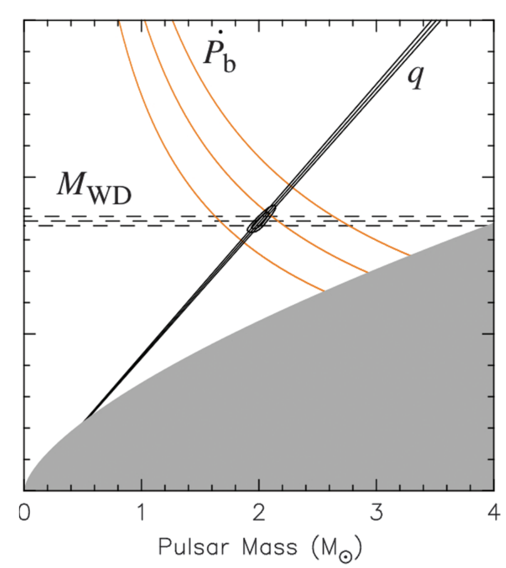


nature **A two-solar-mass neutron star measured using Shapiro delay**

Science **A Massive Pulsar in a Compact Relativistic Binary**

Demorest et al., Nature 467, 1081 (2010)
Antoniadis et al., Science 340, 448 (2013)

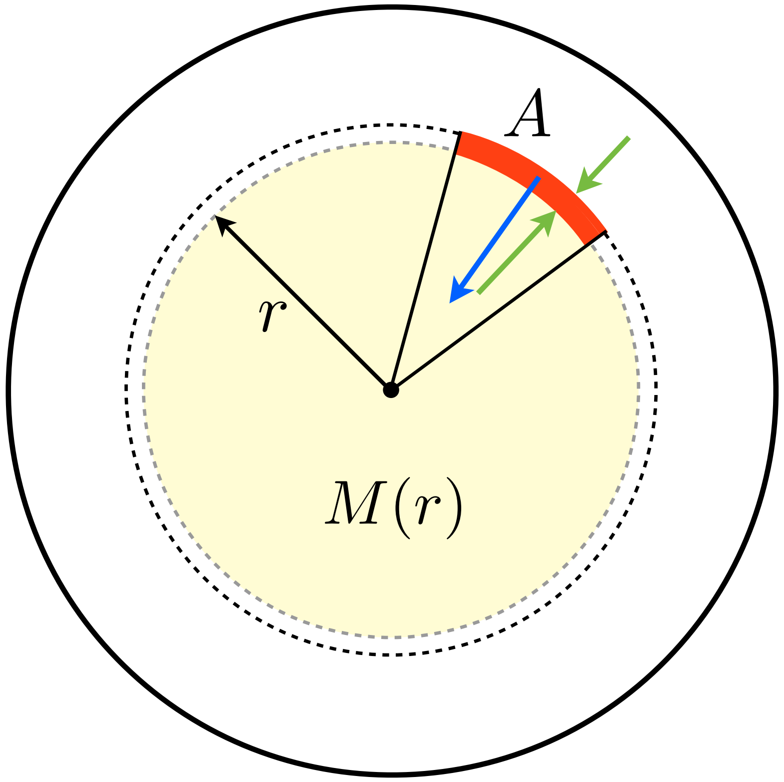




$$M_{\max} = 2.0 \pm 0.04\, M_\odot$$

$$R \sim 10 \text{ km}$$

The equation of state of high-density matter: constraints for neutron stars from nuclear physics

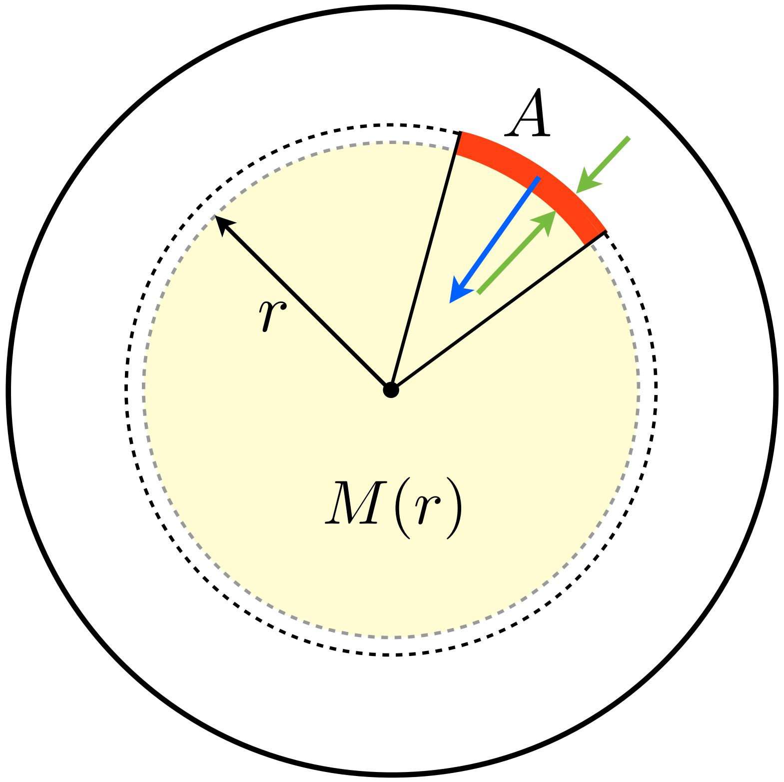


- consider forces on a mass element:

gravity: $$F_g = -\frac{GM(r)\rho(r)A\,dr}{r^2}$$

pressure difference: $$F_p = A\,(p_{\text{out}} - p_{\text{in}}) = A\,dp$$

The equation of state of high-density matter: constraints for neutron stars from nuclear physics



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$$F_g = F_p \Rightarrow \frac{dp}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$

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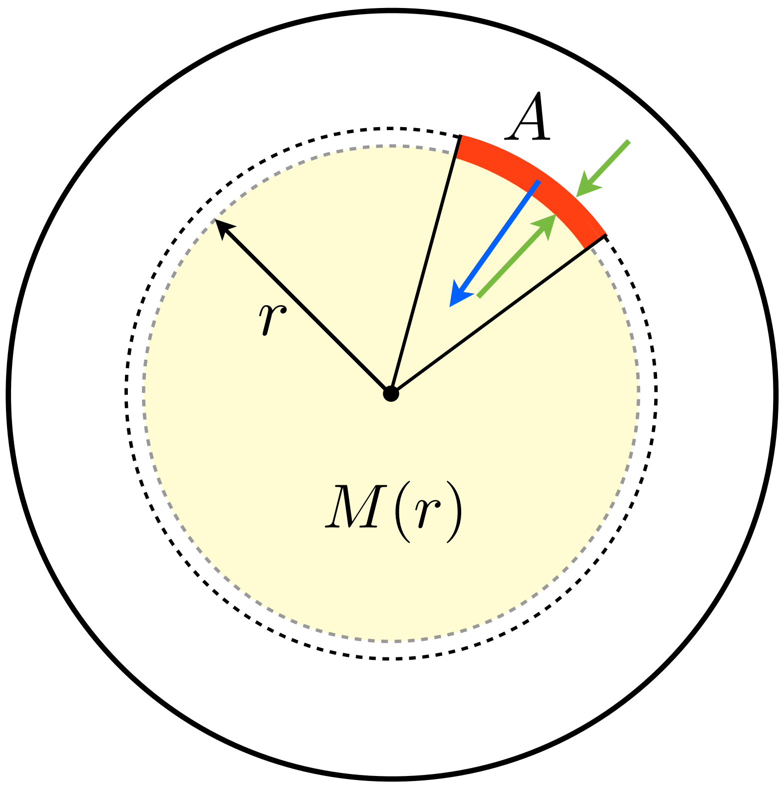

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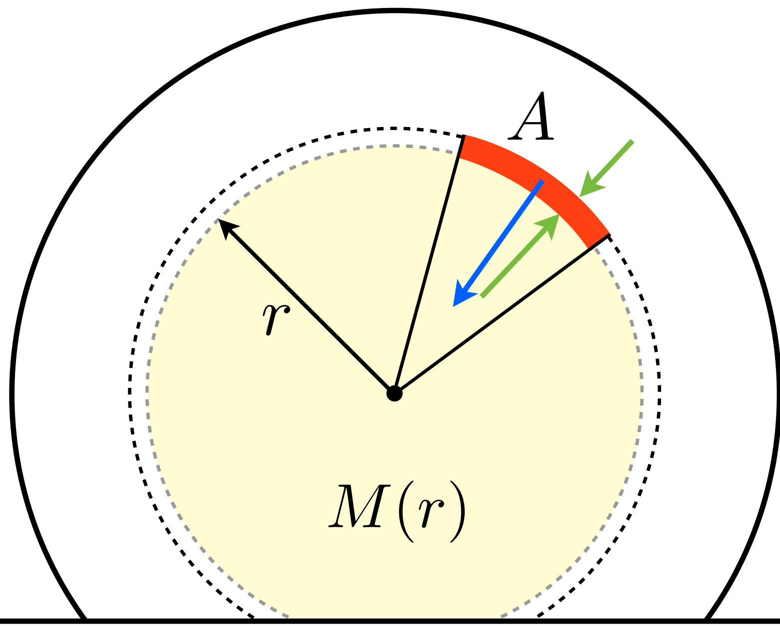
$$\frac{dp}{dr} = -\frac{GM(r)\varepsilon(r)}{r^2}\left[1+\frac{p(r)}{\varepsilon(r)c^2}\right]\left[1+\frac{4\pi r^3 p(r)}{M(r)c^2}\right]\left[1-\frac{2GM(r)}{c^2 r}\right]$$

'Tolman-Oppenheimer-Volkov' equation

The equation of state of high-density matter: constraints for neutron stars from nuclear physics



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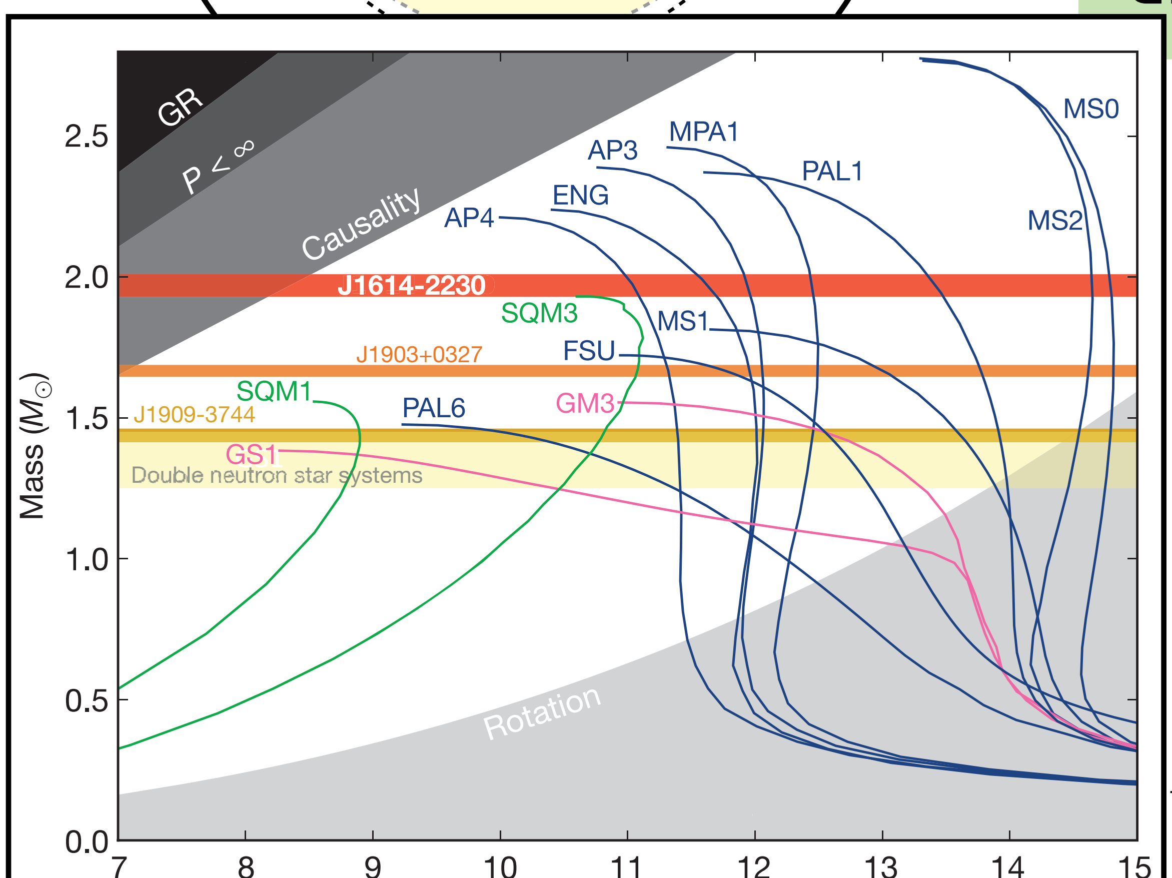
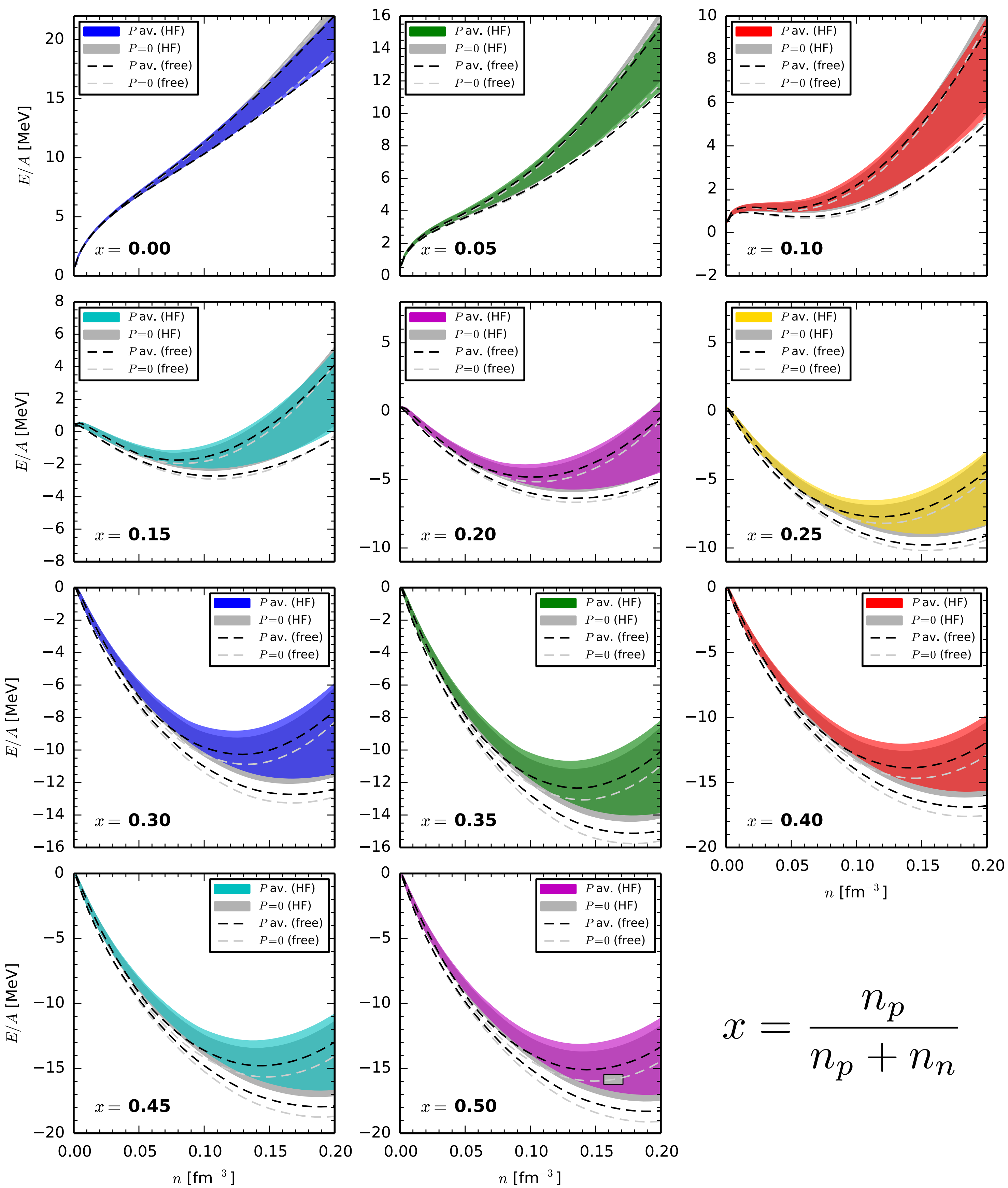


Demorest et al., Nature 467, 1081 (2010)

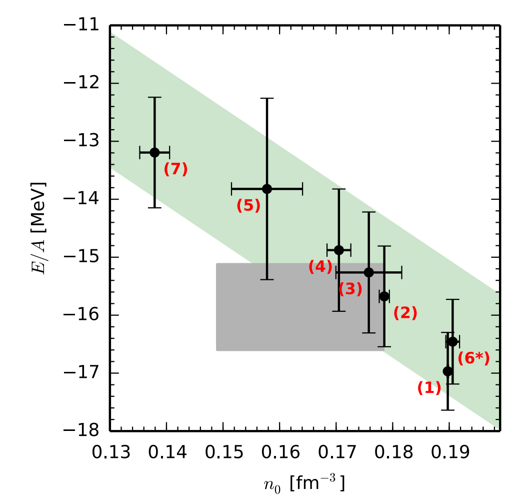
Microscopic calculations of the equation of state



$$x = \frac{n_p}{n_p + n_n}$$

- microscopic framework to calculate equation of state for general proton fractions

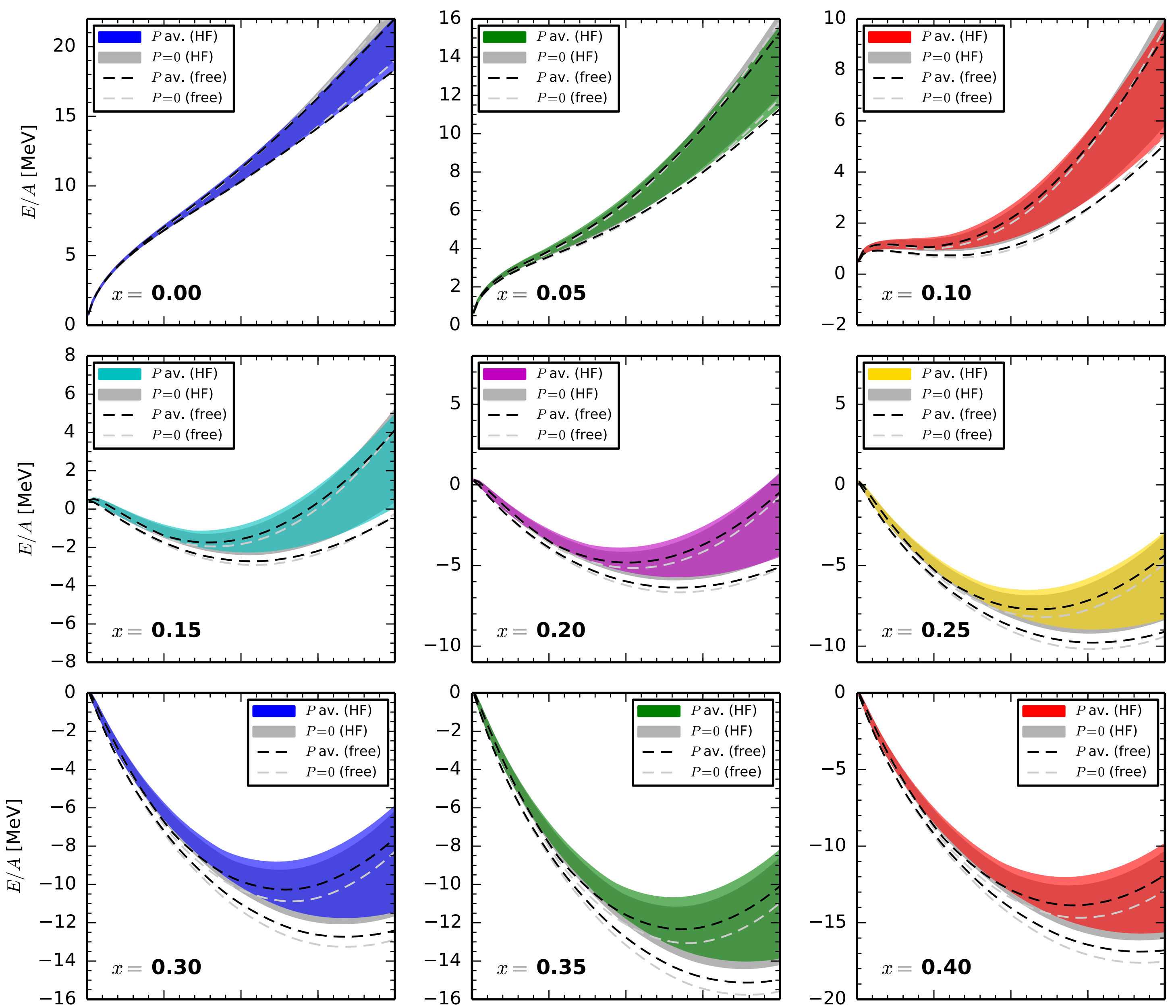
- uncertainty bands determined by set of 7 Hamiltonians



- many-body framework allows treatment of general 3N interaction

Drischler, KH, Schwenk, PRC 054314 (2016)

Microscopic calculations of the equation of state



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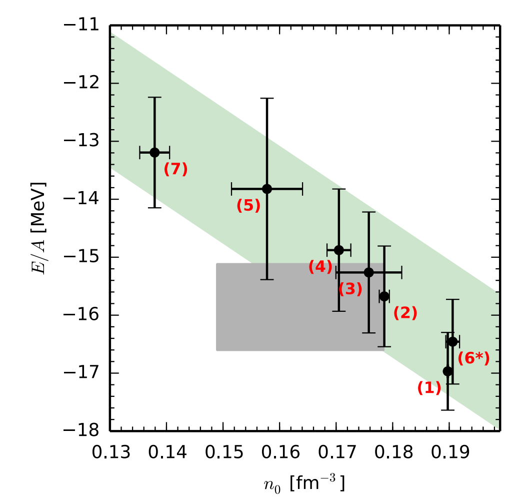


- many-body framework allows

Problem:

Calculation of neutron star properties require EOS up to high densities.

Strategy:

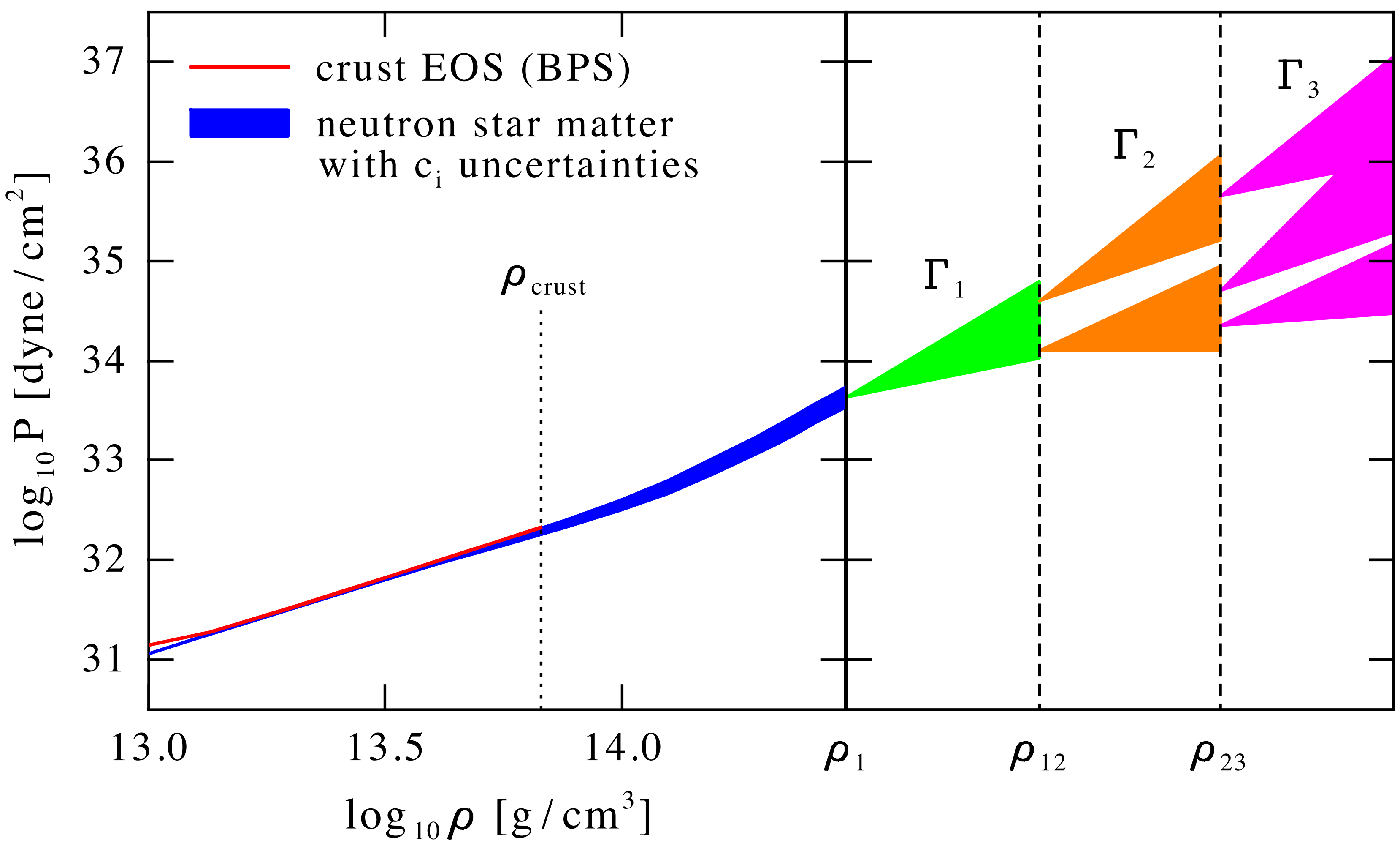
Use observations to constrain the high-density part of the nuclear EOS.

Neutron star radius constraints

incorporation of beta-equilibrium: neutron matter $\longrightarrow$ neutron star matter

parametrize our ignorance via piecewise high-density extensions of EOS:

- use polytropic ansatz $p \sim \rho^{\Gamma}$ (results insensitive to particular form)
- range of parameters $\Gamma_1, \rho_{12}, \Gamma_2, \rho_{23}, \Gamma_3$ limited by physics



KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)
KH, Lattimer, Pethick, Schwenk, PRL 105, 161102 (2010)

The equation of state of high-density matter: constraints from neutron star observations

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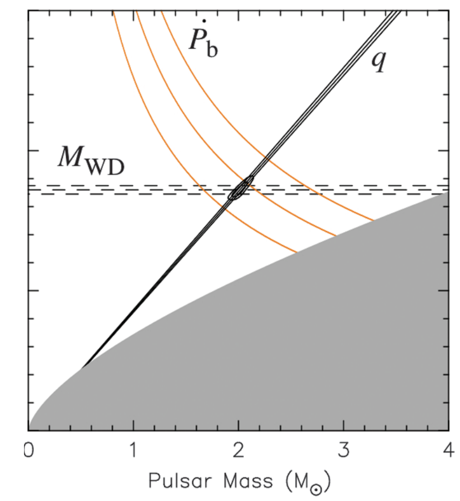

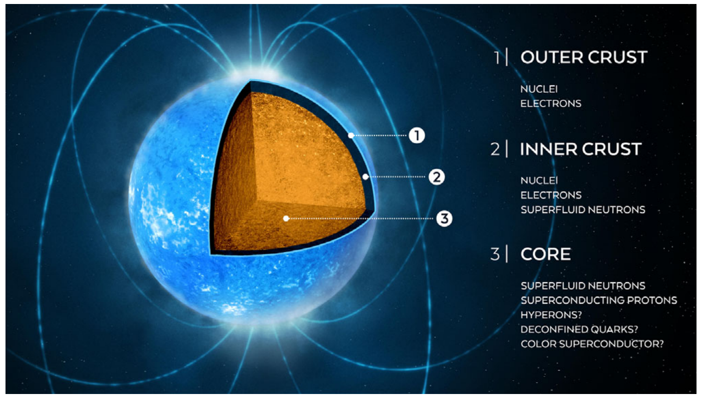

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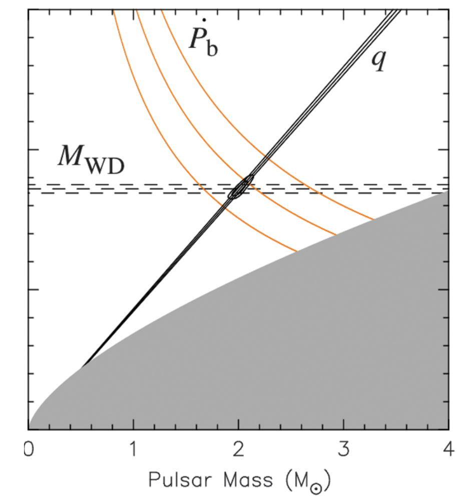
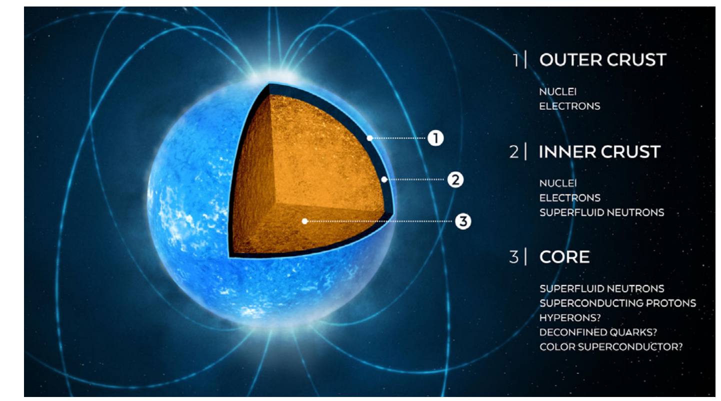
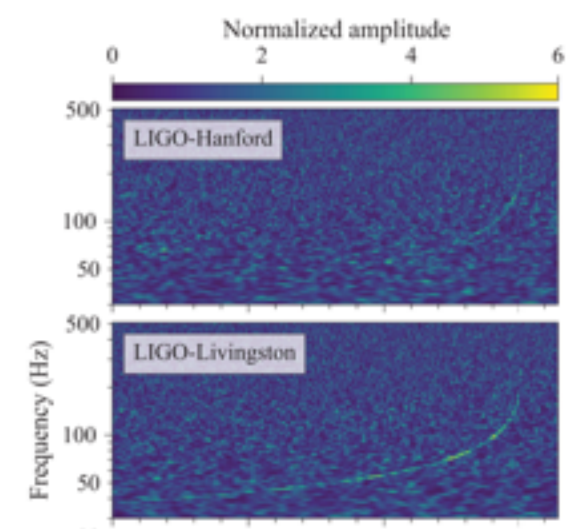




- detection of gravitational waves from neutron star merger event

  Abbott et al., PRL 119, 161101 (2017)

LIGO Laser Interferometer Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT



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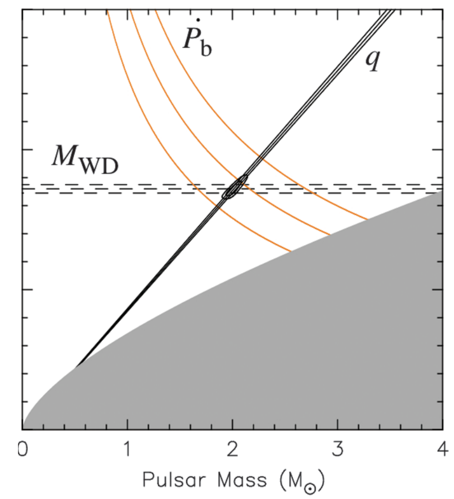

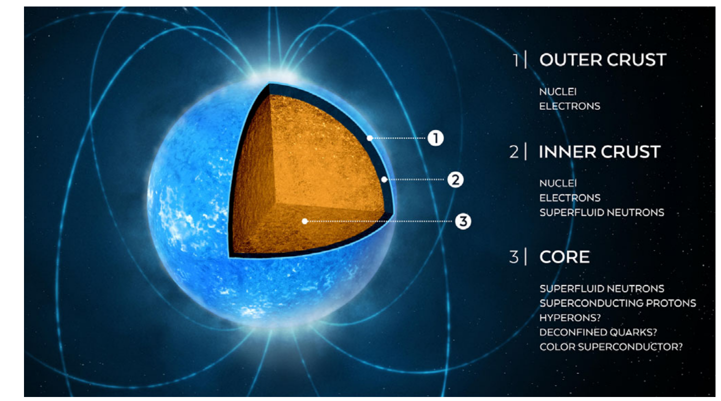

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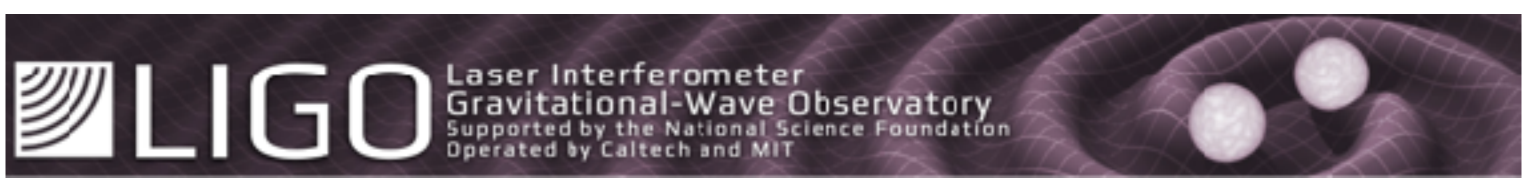
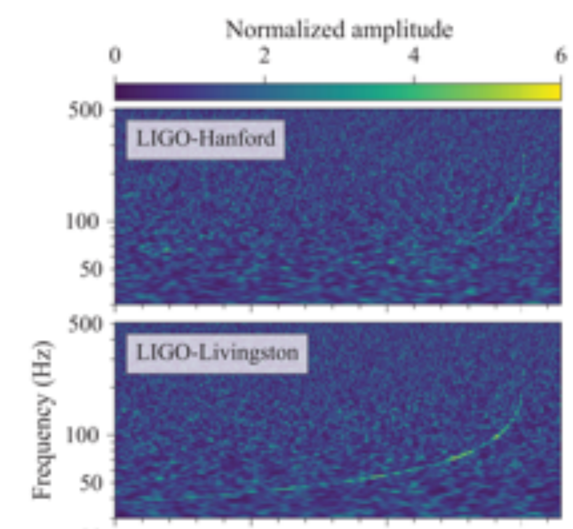
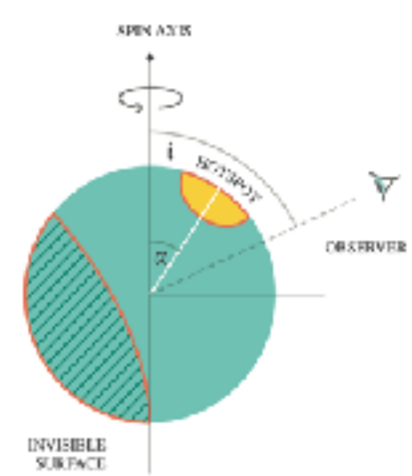
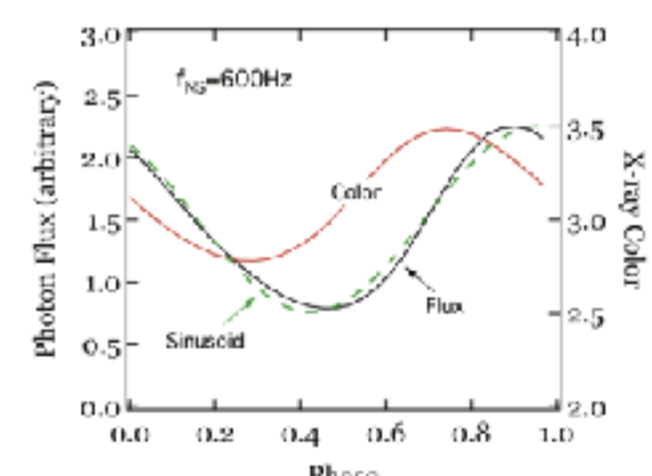




- radius measurements from pulsar x-ray timing

  Watts et al., RMP 88, 021001 (2016)
  Riley at al., APJL 887, 21 (2019)
  Raaijmakers et al., APJL 887, 22 (2019)





Constraints on the nuclear equation of state

use the constraints:

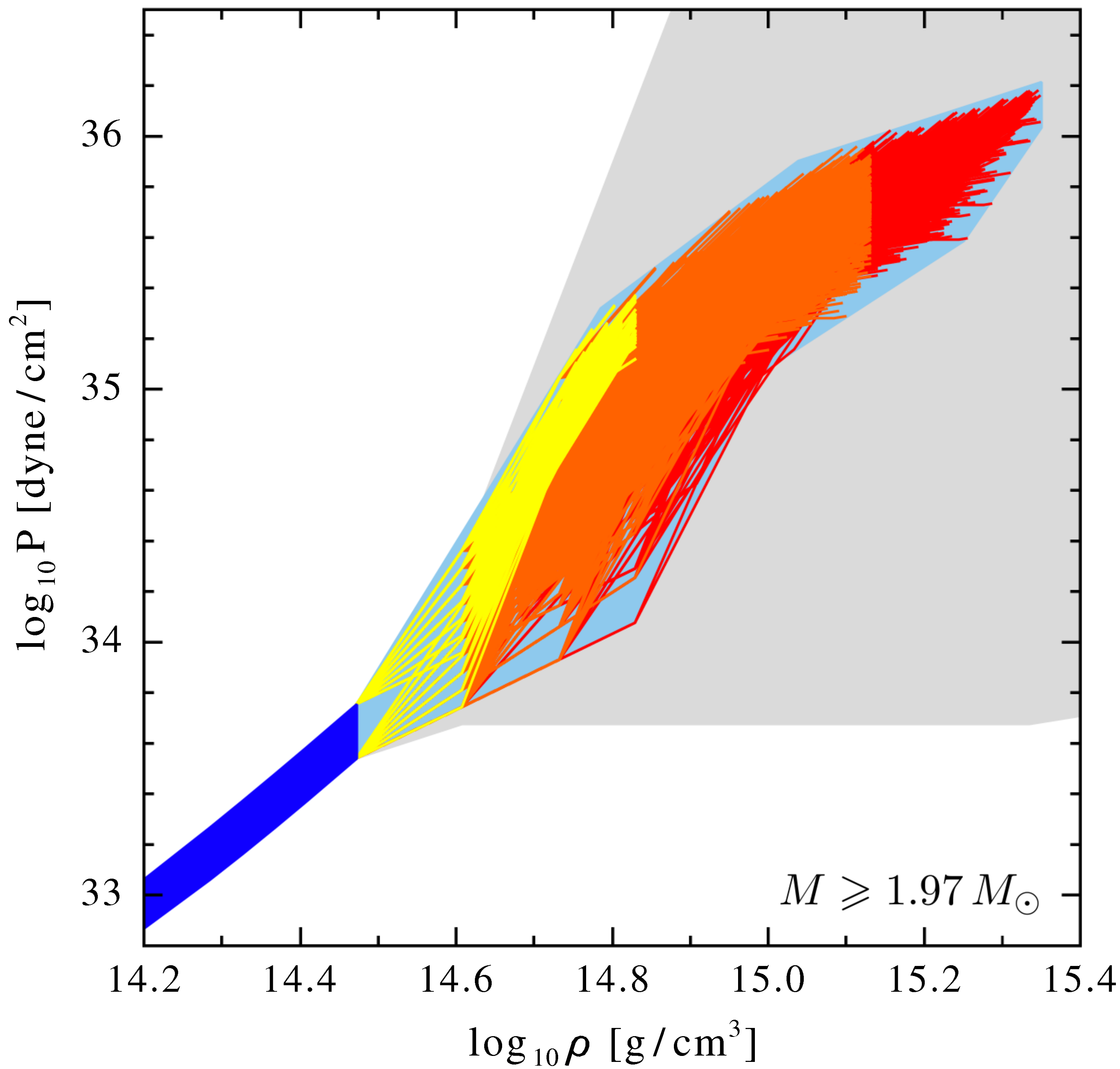
recent NS observations

$$M_{\rm max} > 1.97\, M_\odot$$

causality

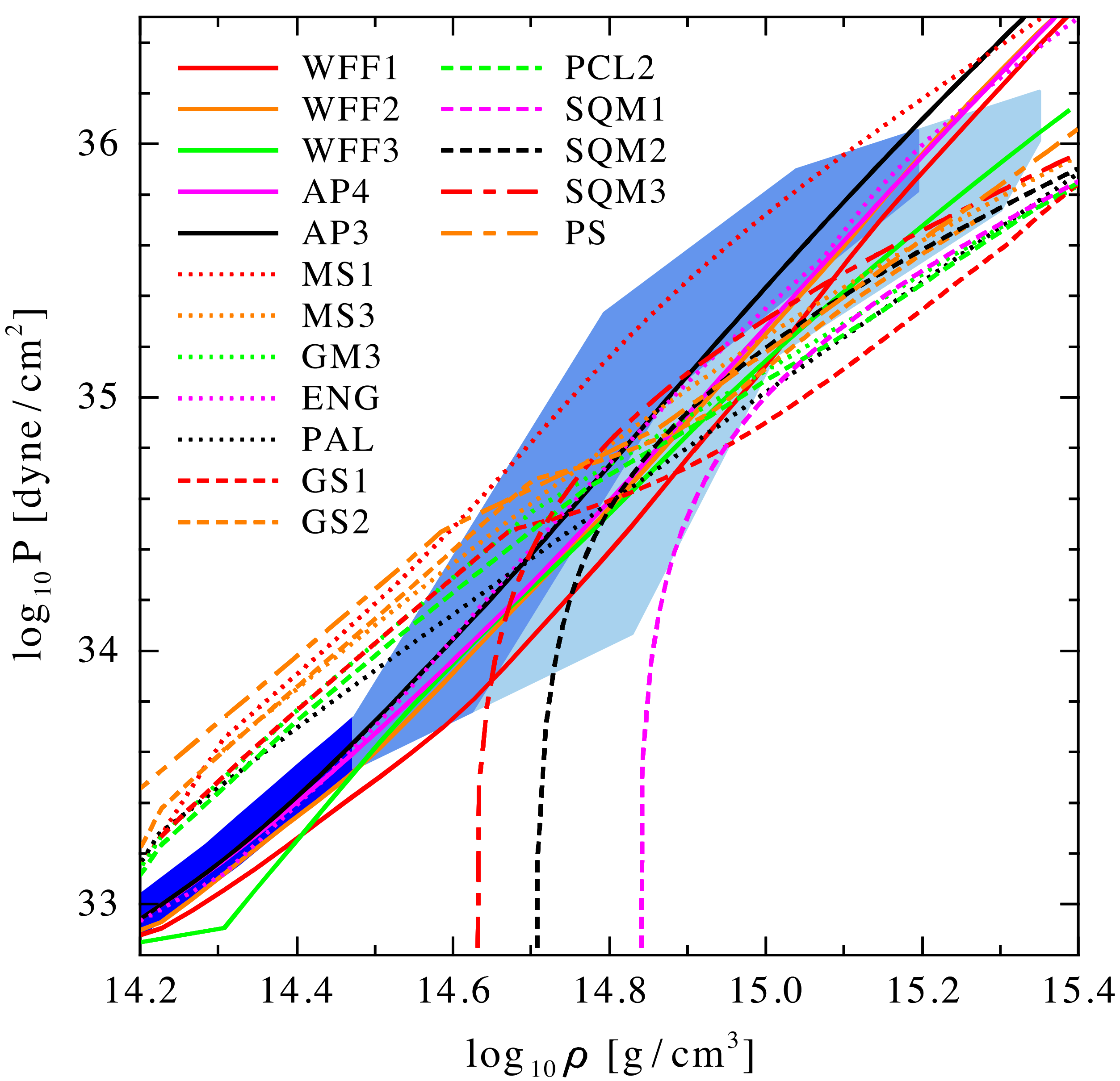
$$v_s(\rho) = \sqrt{dP/d\varepsilon} < c$$

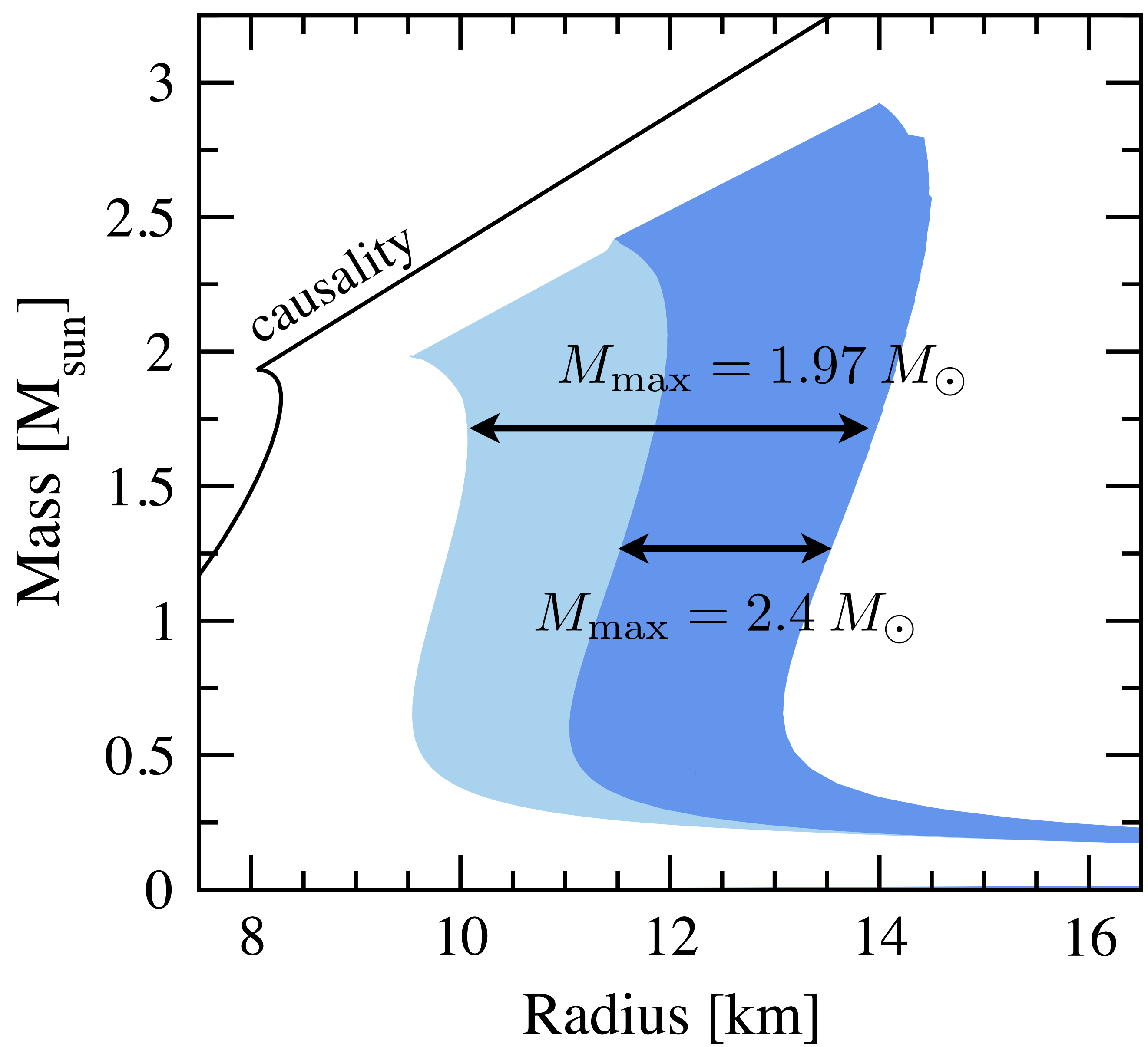
KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)



constraints lead to significant reduction of EOS uncertainty band

Constraints on neutron star radii





KH, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)
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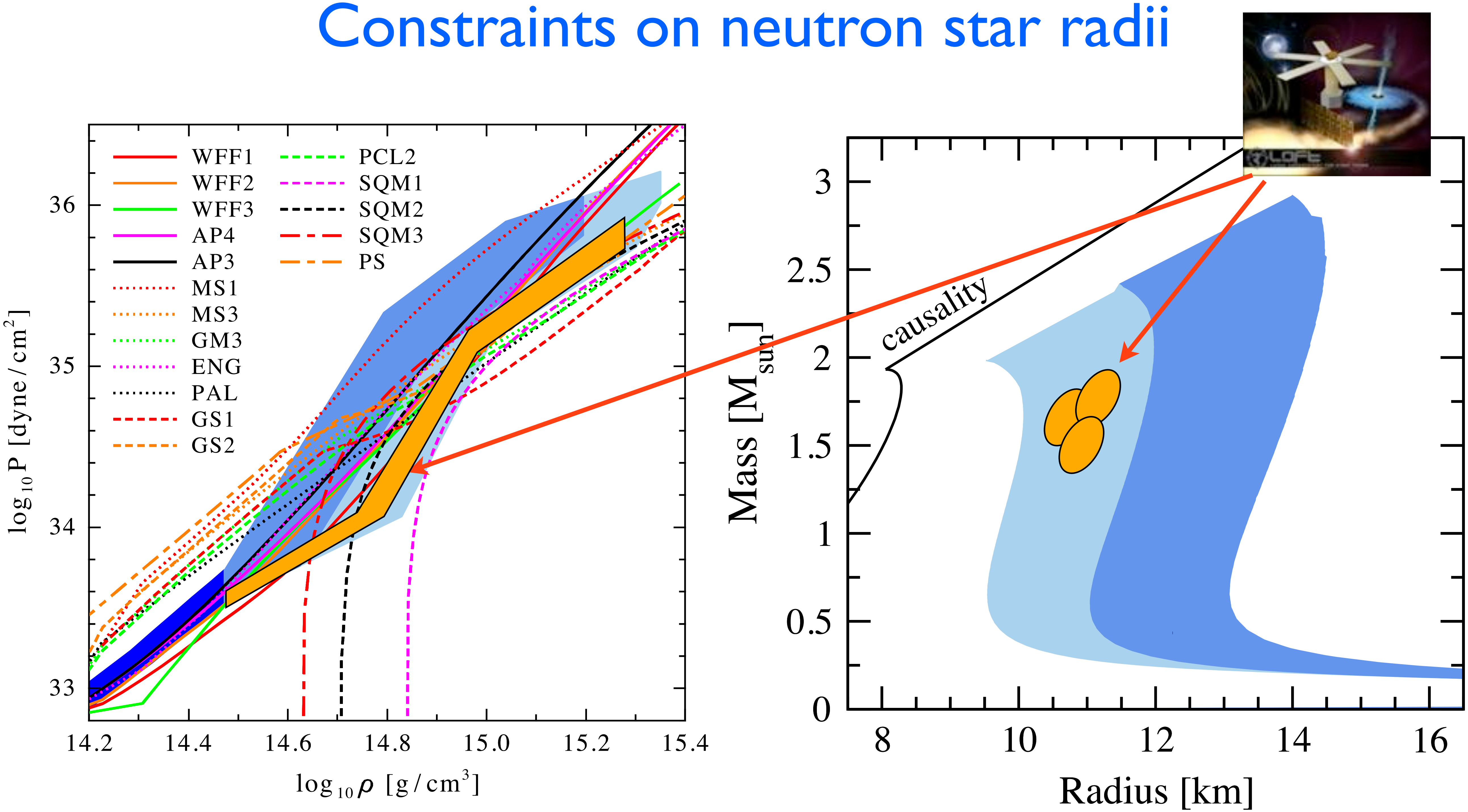
- current radius prediction for typical $1.4\, M_\odot$ neutron star: $9.7 - 13.9\,\mathrm{km}$

Constraints on neutron star radii



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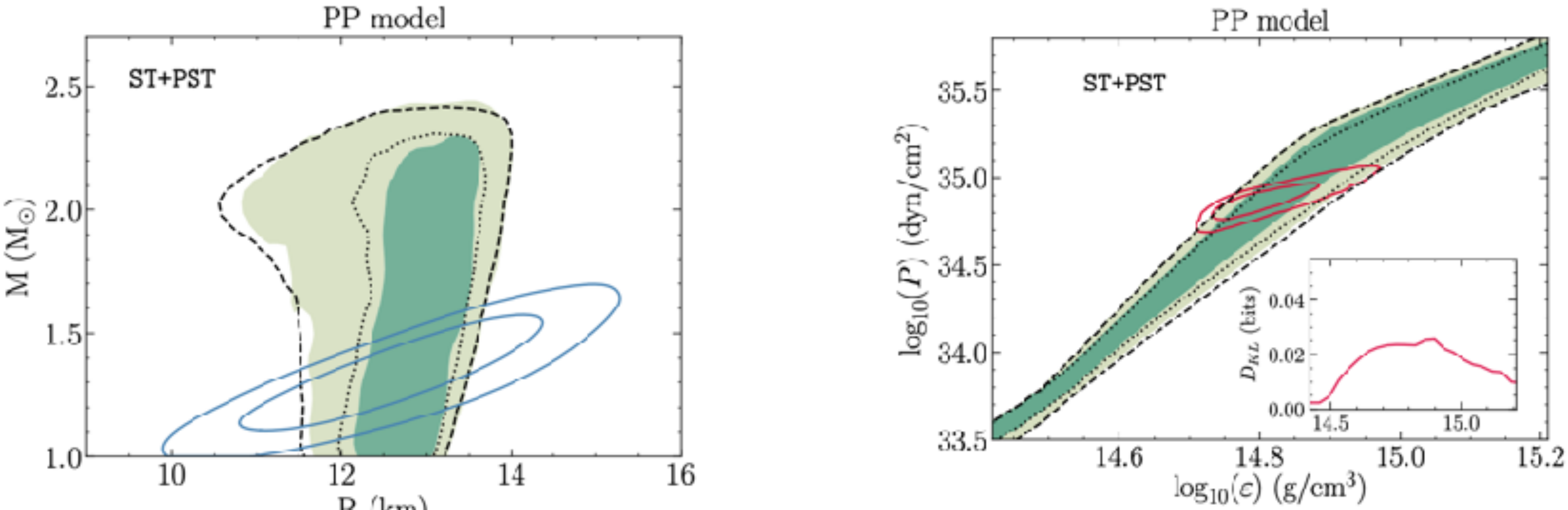
- low-density part of EOS sets scale for allowed high-density extensions
- current radius prediction for typical $1.4\,M_\odot$ neutron star: $9.7 - 13.9\,\mathrm{km}$
- proposed missions (LOFT,NICER...) could significantly improve constraints

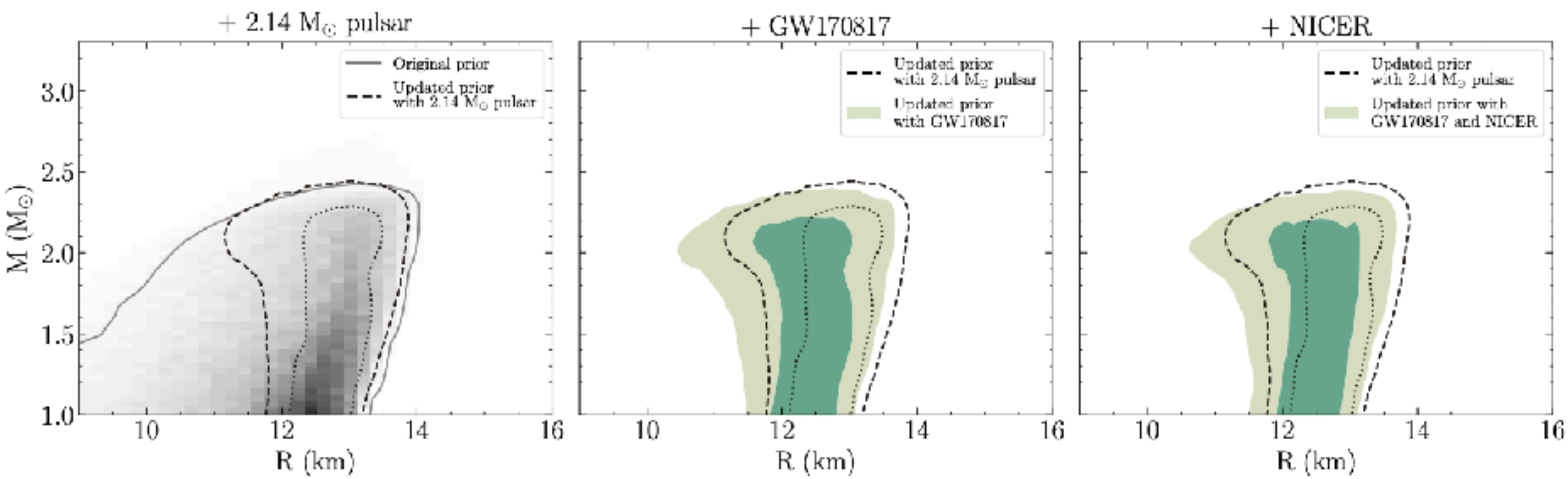
Constraints on neutron star radii

constraints on EOS and NS radii from first NICER observations:



Raaijmakers et al., APJL 887, 22 (2019)

additionally incorporating constraints from LIGO and mass measurements:



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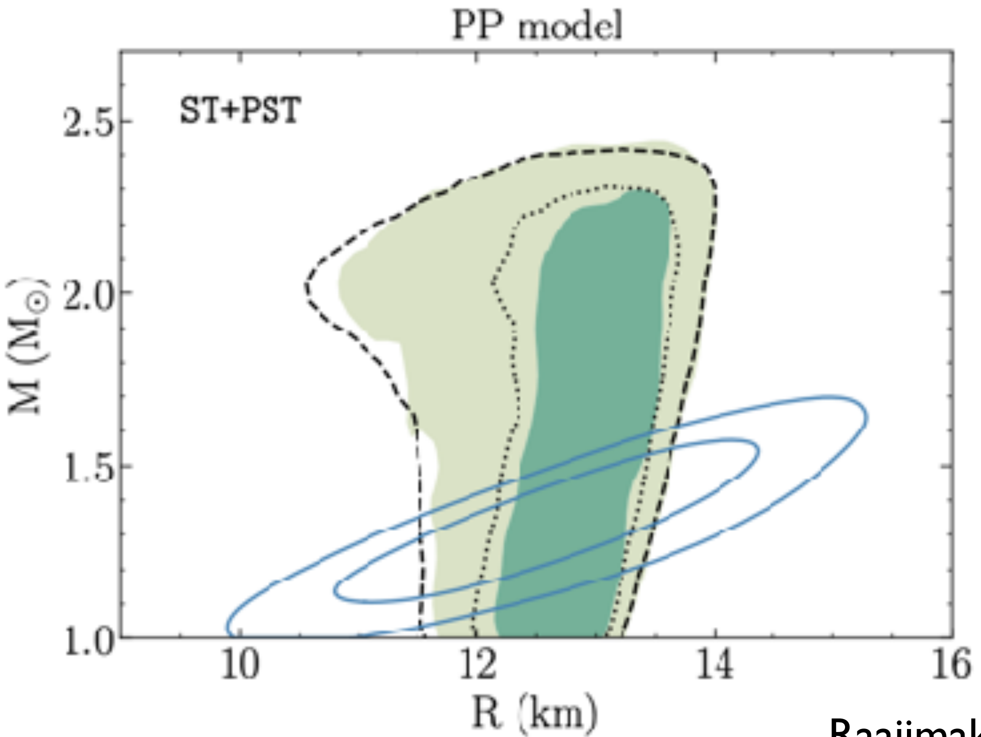

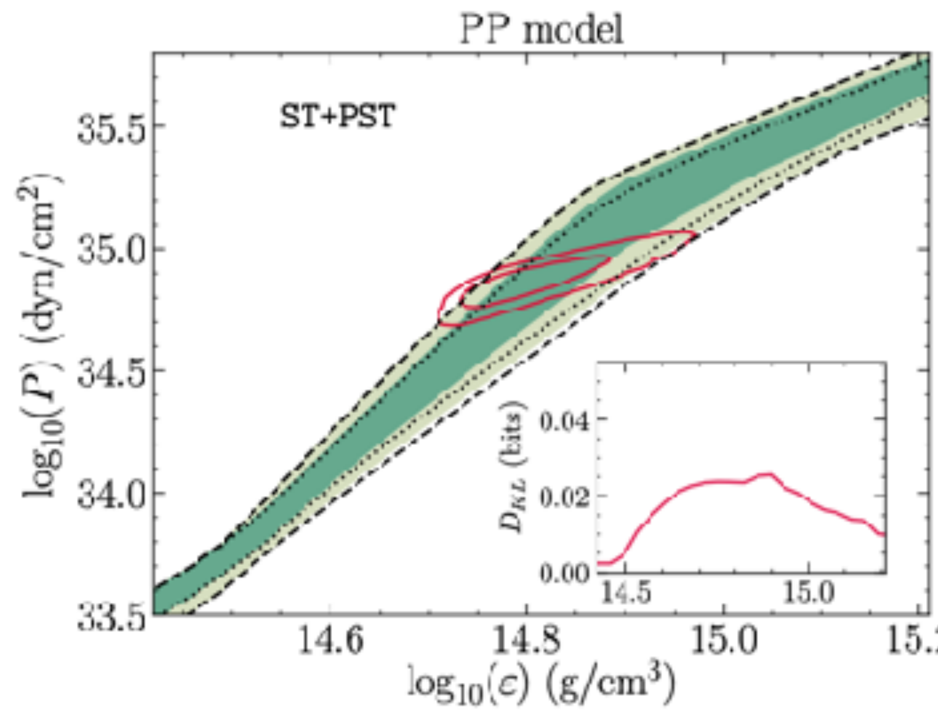

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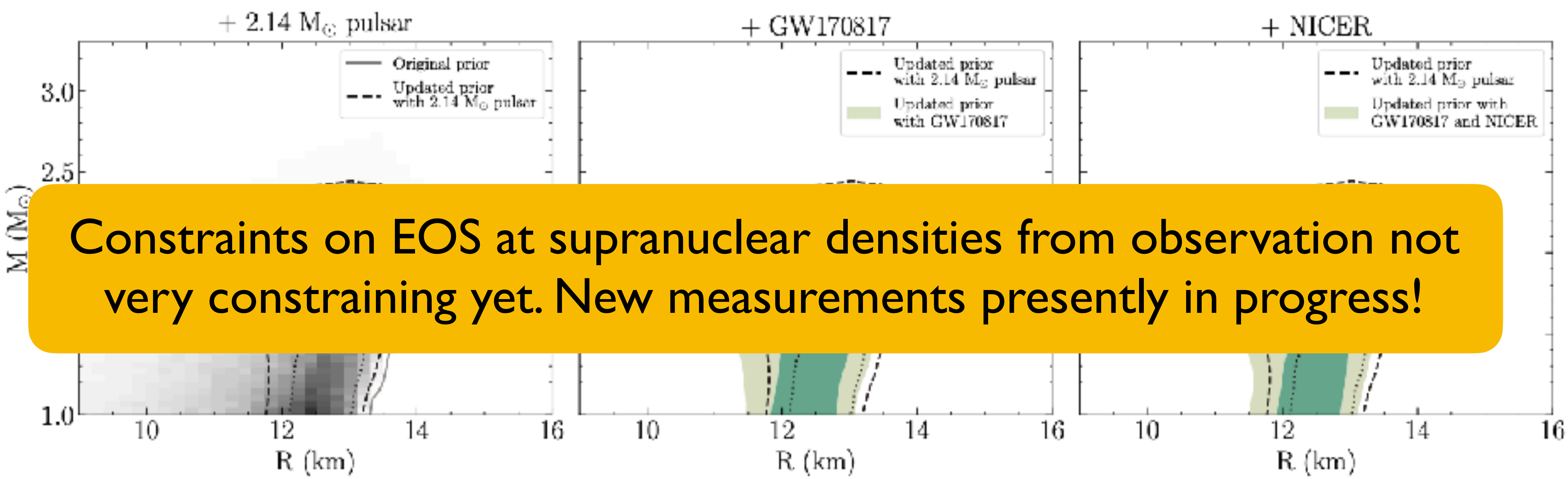

Constraints on EOS at supranuclear densities from observation not very constraining yet. New measurements presently in progress!

Status and achievements

significant increase in scope of ab initio many-body frameworks

remarkable agreement between different ab intio many-body methods

discrepancies to experiment dominated by deficiencies of present nuclear interactions

Current developments and open questions

presently active efforts to develop improved NN and 3N interactions (improved fits of LECs, power counting, regularization...)

Key goals

unified study of atomic nuclei, nuclear matter and reactions based on novel interactions

systematic estimates of theoretical uncertainties