TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

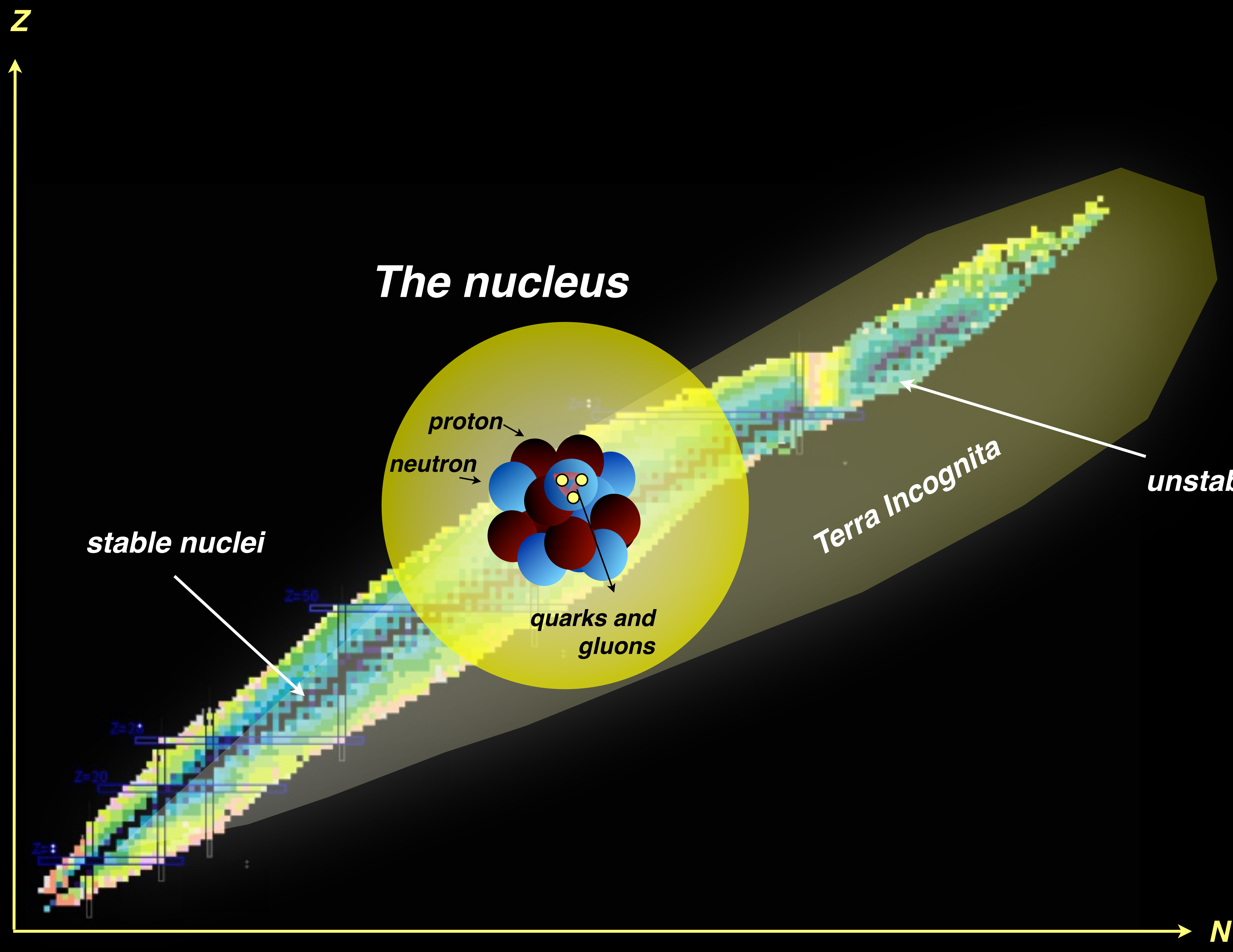
Recent Developments in Nuclear Structure Theory

Sonia Bacca | Scientist

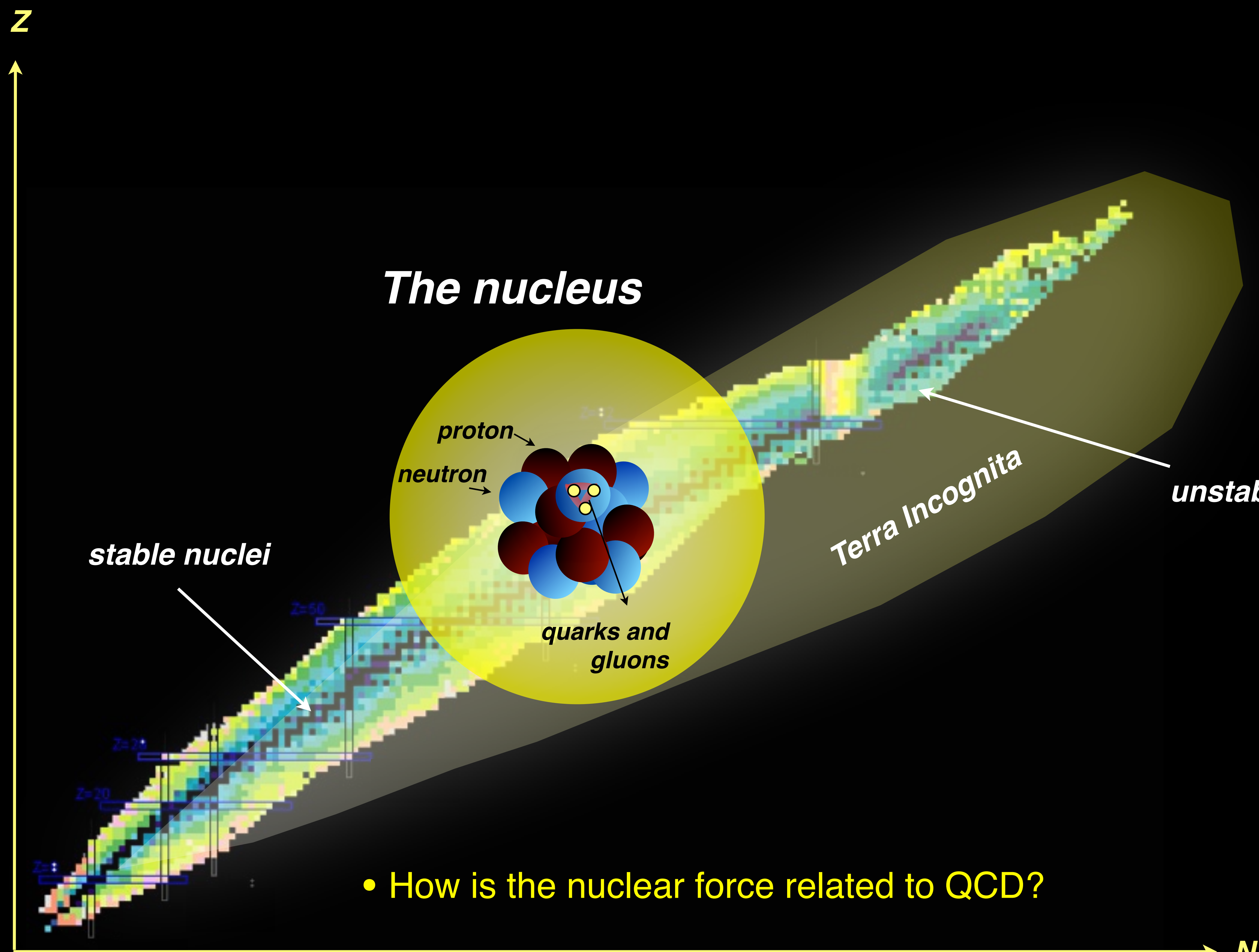
Jan. 26th 2017

Bormio
55th International Winter Meeting on Nuclear Physics

Nuclear Structure

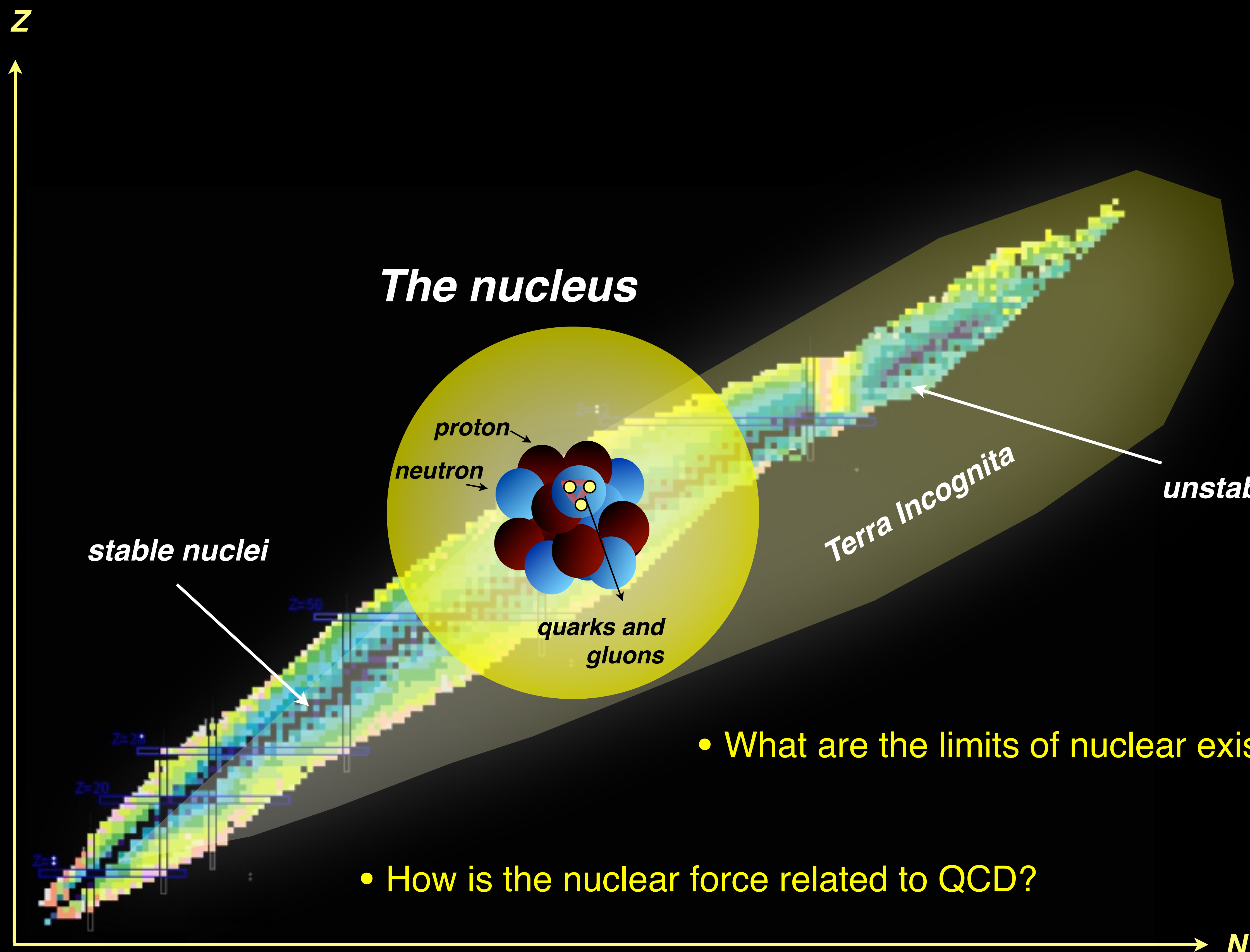


Nuclear Structure



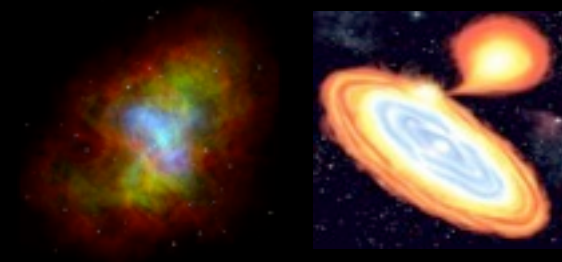
- How is the nuclear force related to QCD?

Nuclear Structure

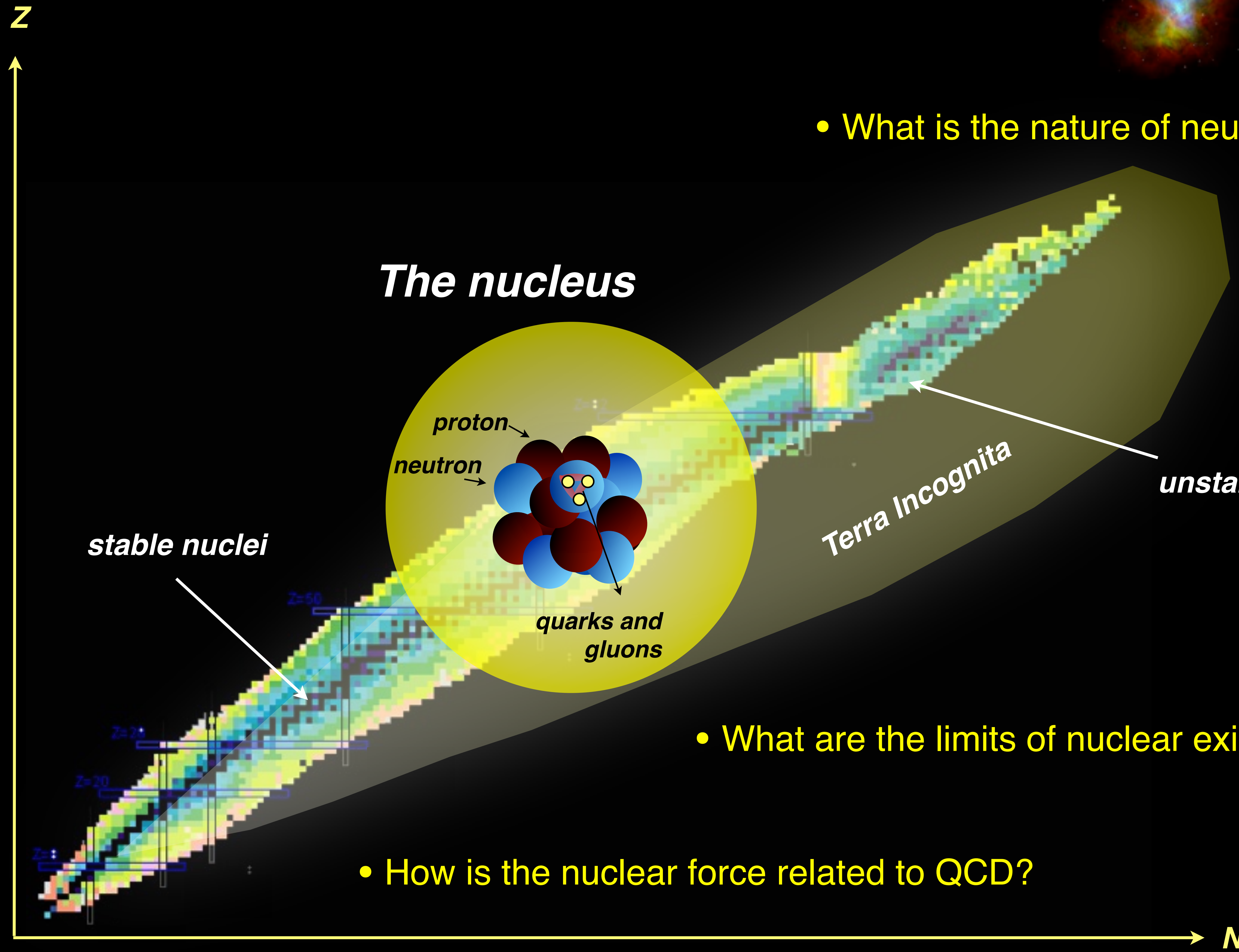


- What are the limits of nuclear existence?
- How is the nuclear force related to QCD?

Nuclear Structure

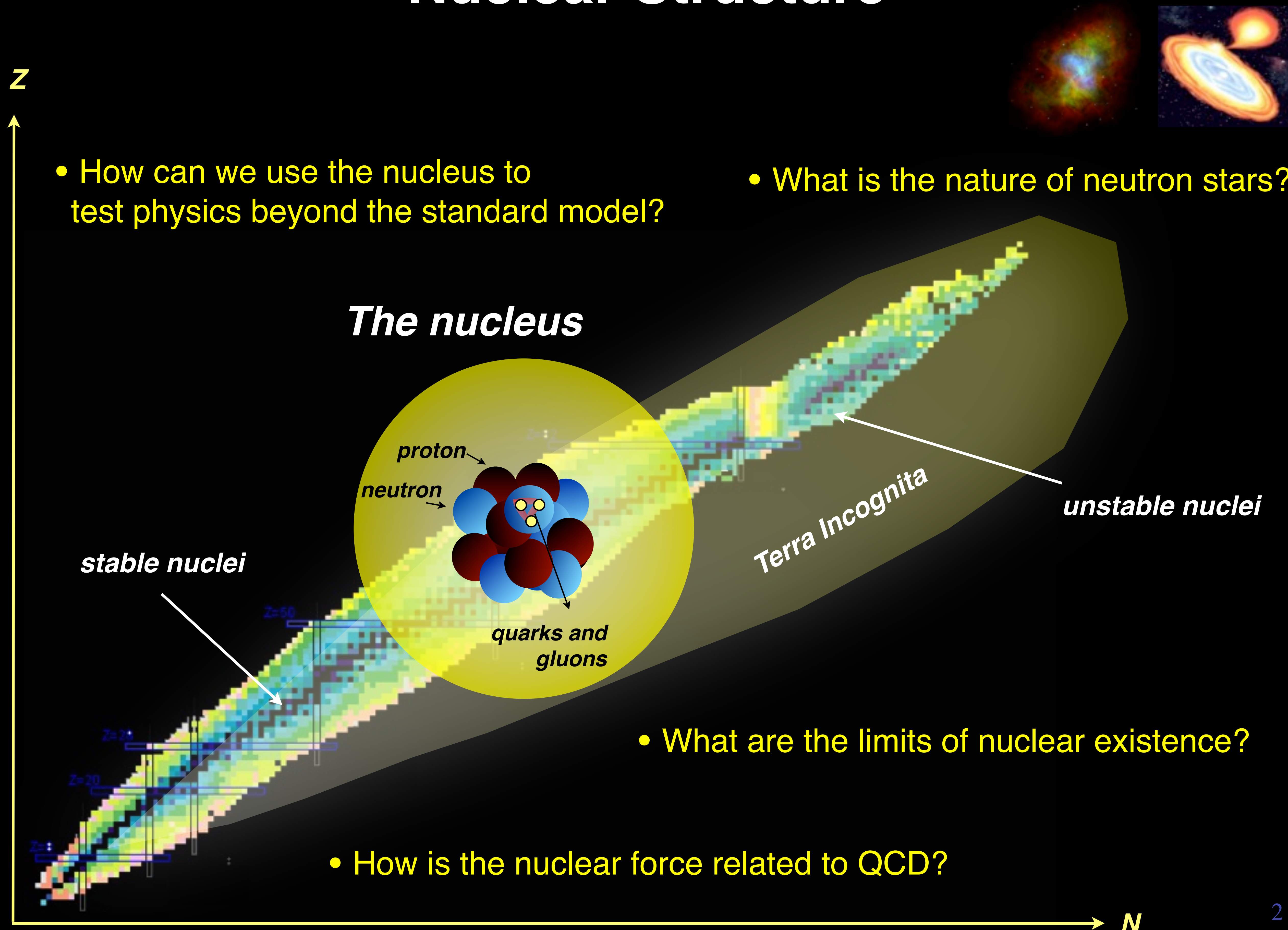


- What is the nature of neutron stars?



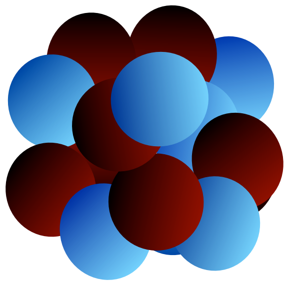
- What are the limits of nuclear existence?
- How is the nuclear force related to QCD?

Nuclear Structure

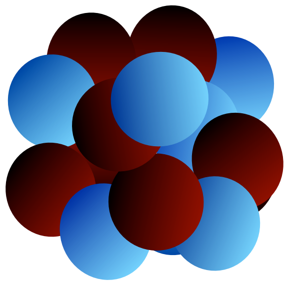


"Ab initio" theory

- Start from neutrons and protons as building blocks
  (centre of mass coordinates, spins, isospins)



"Ab initio" theory



- Start from neutrons and protons as building blocks (centre of mass coordinates, spins, isospins)

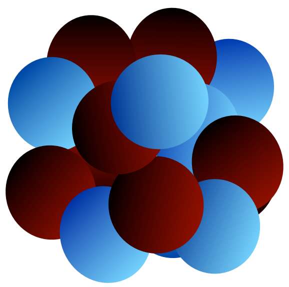
- Solve the non-relativistic quantum mechanical problem of A-interacting nucleons

$$H|\psi_i\rangle = E_i|\psi_i\rangle$$

$$H = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \ldots$$

“Ab initio” theory

- Start from neutrons and protons as building blocks (centre of mass coordinates, spins, isospins)



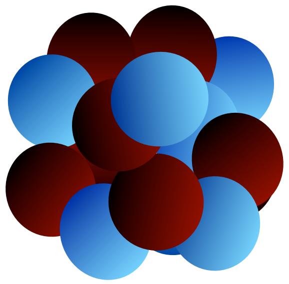
- Solve the non-relativistic quantum mechanical problem of A-interacting nucleons

$$H|\psi_i\rangle = E_i|\psi_i\rangle$$

$$H = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \ldots$$

- Find numerical solutions with no approximations or controllable approximations

"Ab initio" theory



- Start from neutrons and protons as building blocks (centre of mass coordinates, spins, isospins)

- Solve the non-relativistic quantum mechanical problem of A-interacting nucleons

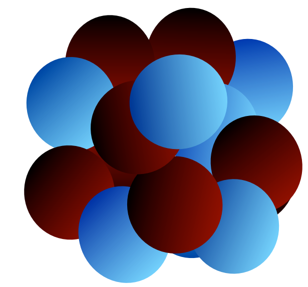
$$H|\psi_i\rangle = E_i|\psi_i\rangle$$

$$H = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \dots$$

- Find numerical solutions with no approximations or controllable approximations

- Calibrate the force and then calculate A-body nuclei to compare with experiment or to provide predictions for observables which are hard or impossible to measure

“Ab initio” theory



- Start from neutrons and protons as building blocks (centre of mass coordinates, spins, isospins)

- Solve the non-relativistic quantum mechanical problem of A-interacting nucleons

$$H|\psi_i\rangle = E_i|\psi_i\rangle$$

$$H = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \dots$$

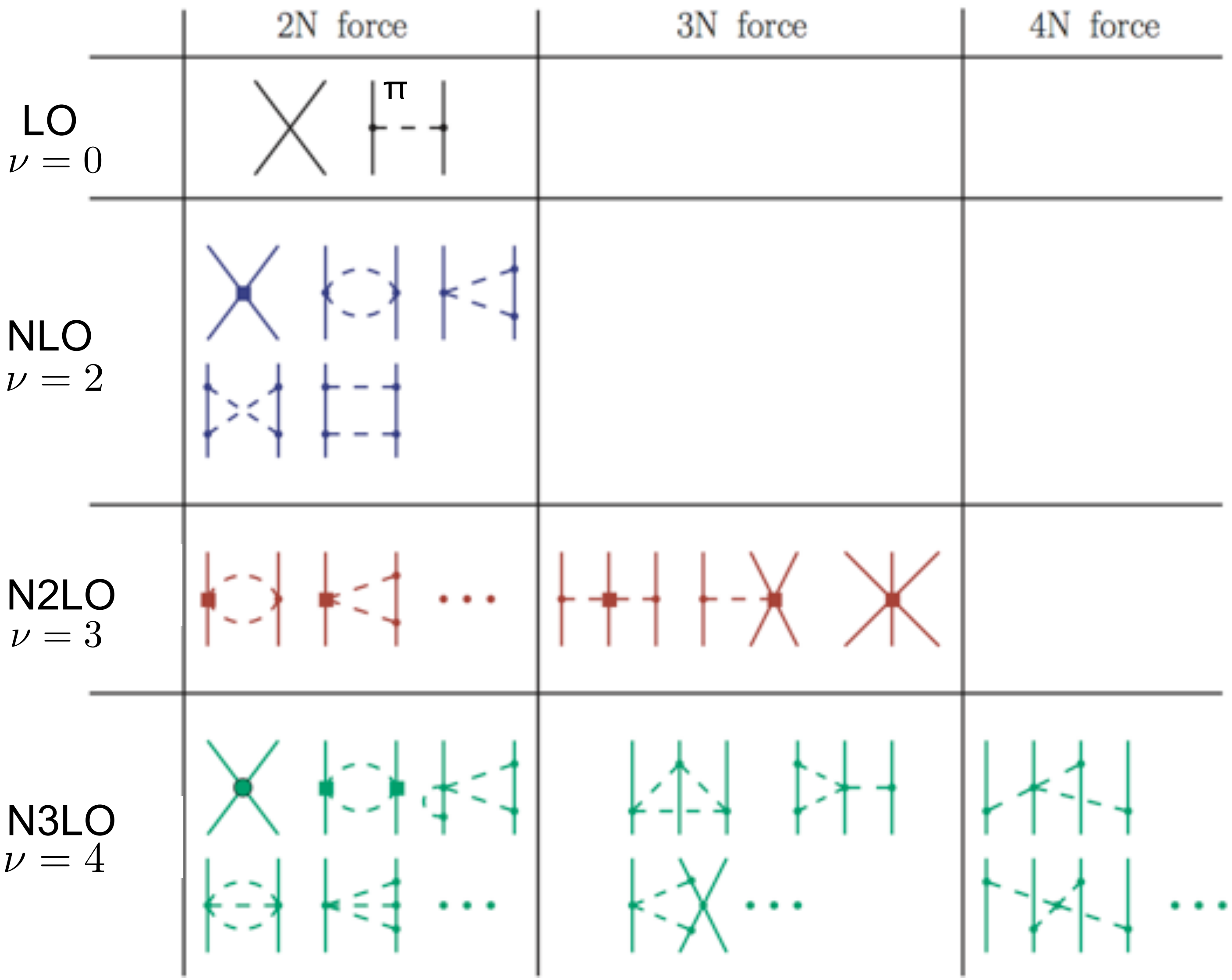
- Find numerical solutions with no approximations or controllable approximations

- Calibrate the force and then calculate A-body nuclei to compare with experiment or to provide predictions for observables which are hard or impossible to measure

Chiral Effective Field Theory

Weinberg, van Kolck, Epelbaum, Meissner, Machleidt, Phillips, ...

Talk on Tue by Epelbaum

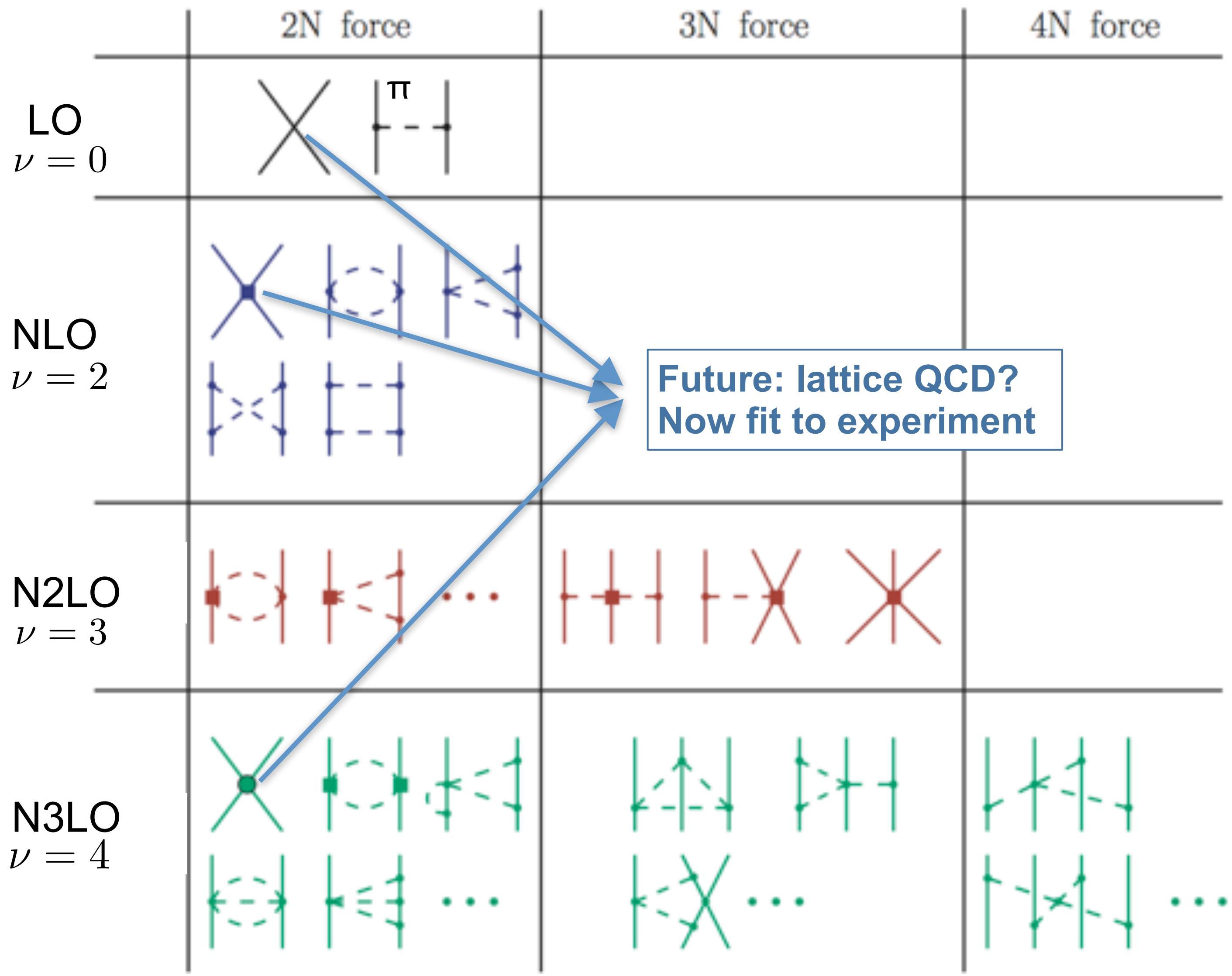


Systematic expansion $$\mathcal{L} = \sum_{\nu} c_{\nu} \left(\frac{Q}{\Lambda_b} \right)^{\nu}$$

Chiral Effective Field Theory

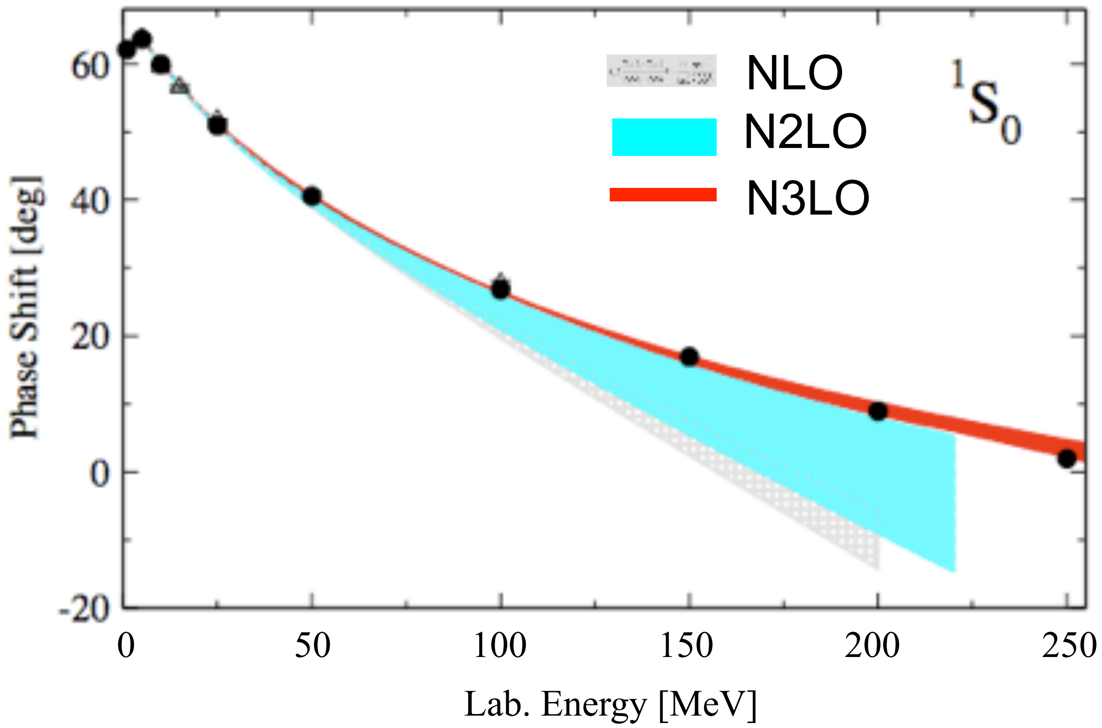
Weinberg, van Kolck, Epelbaum, Meissner, Machleidt, Phillips, ...

Talk on Tue by Epelbaum



Details of short distance physics not resolved, but captured in low energy constants (LEC)

LEC fit to experiment - NN sector -



Epelbaum *et al.* (2009)

Systematic expansion

$$\mathcal{L} = \sum_{\nu} c_\nu \left(\frac{Q}{\Lambda_b}\right)^\nu$$

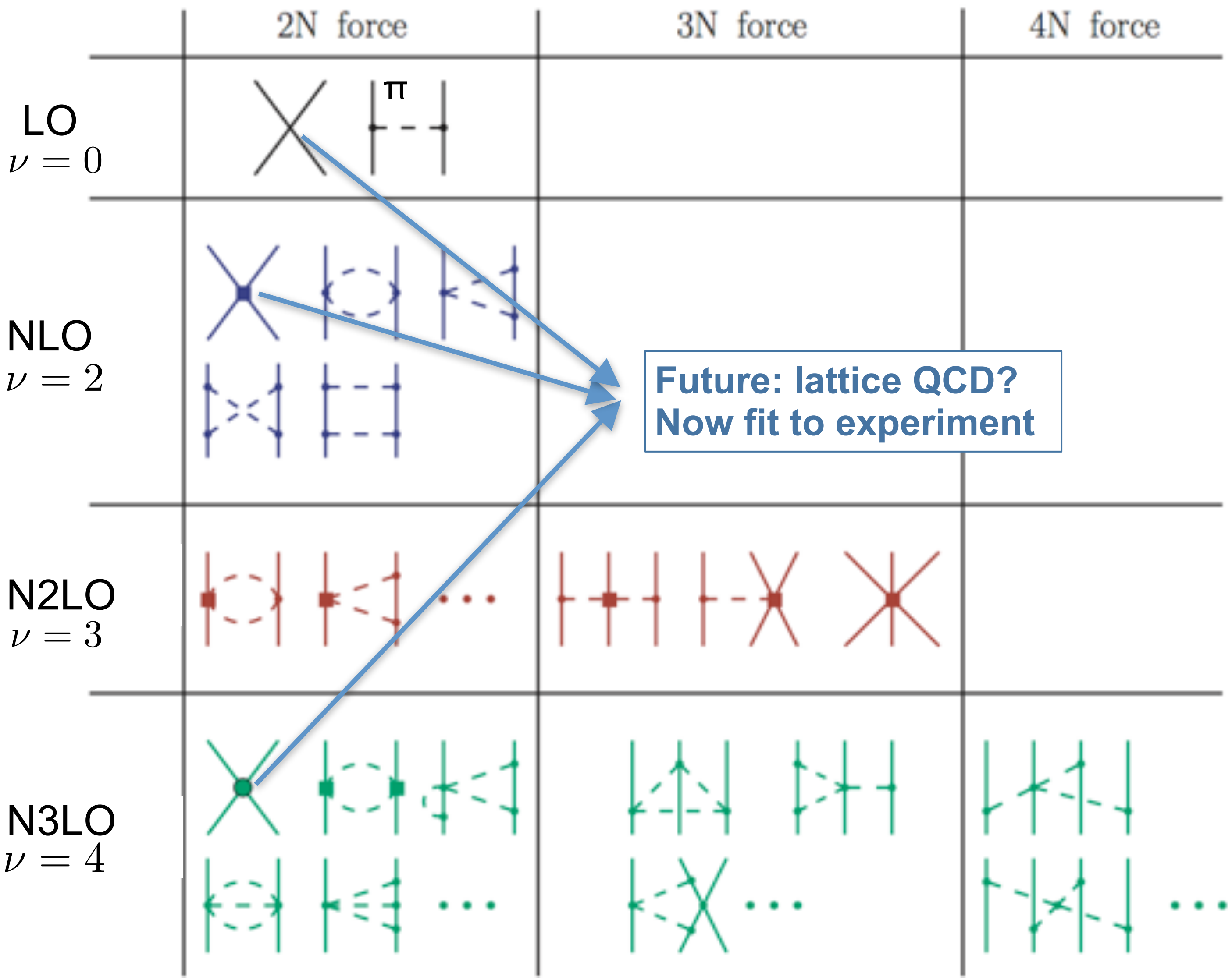
LEC fit to NN experimental data
- 3N sector using A=3 data

TRIUMF

Chiral Effective Field Theory

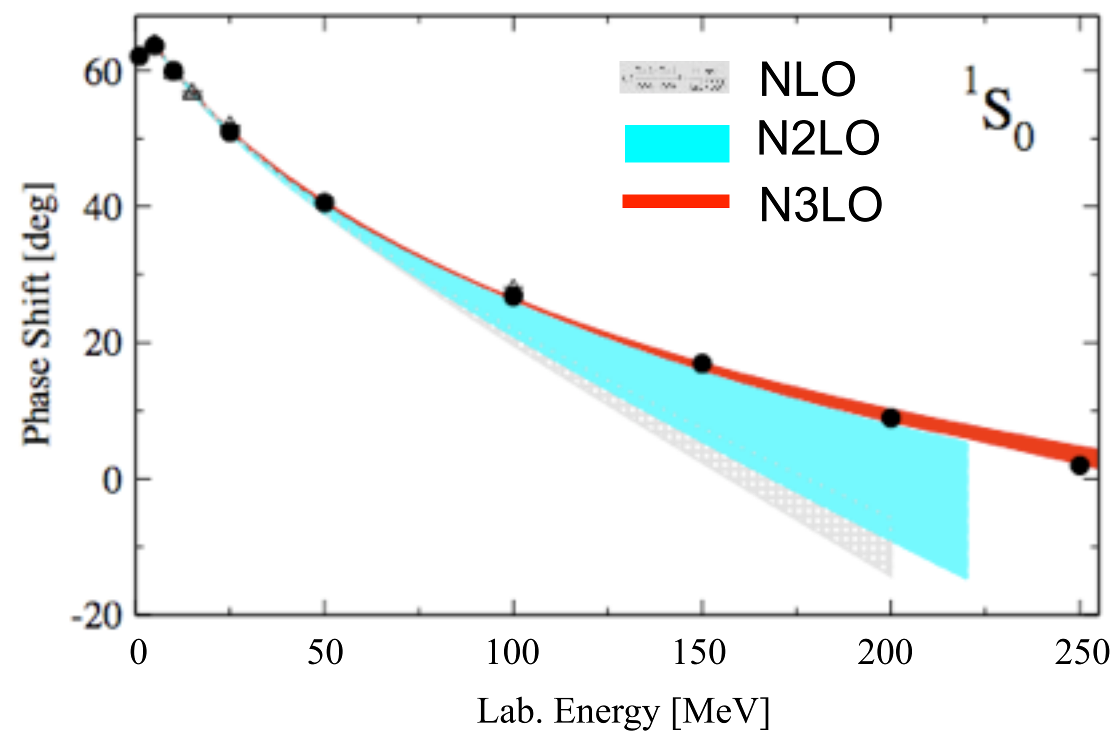
Weinberg, van Kolck, Epelbaum, Meissner, Machleidt, Phillips, ...

Talk on Tue by Epelbaum



Details of short distance physics not resolved, but captured in low energy constants (LEC)

LEC fit to experiment - NN sector -



Epelbaum *et al.* (2009)

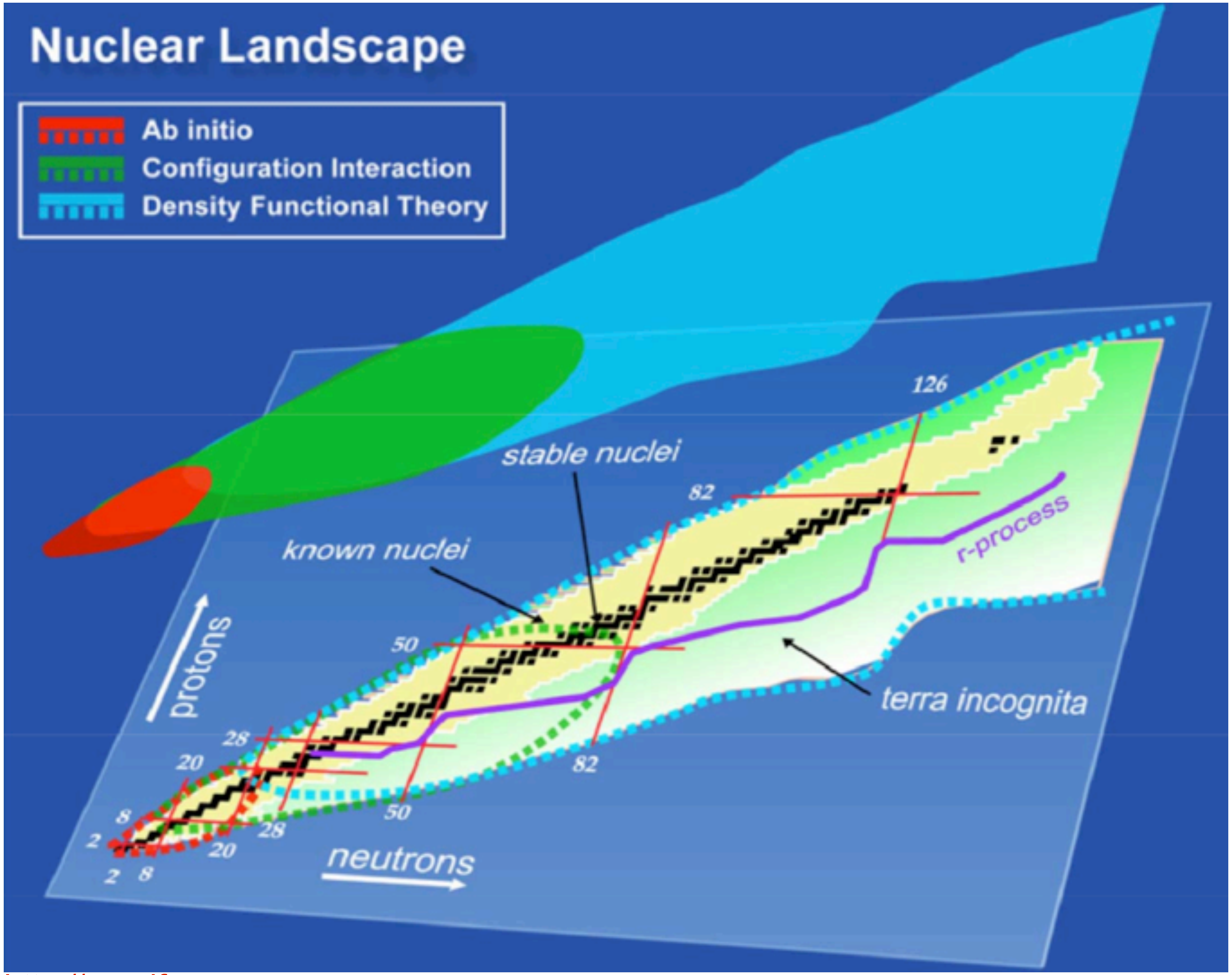
Systematic expansion $$\mathcal{L} = \sum_{\nu} c_\nu \left(\frac{Q}{\Lambda_b}\right)^\nu$$

LEC fit to NN experimental data
- 3N sector using A=3 data

Goal: Calibrate Hamiltonian and then predict other observables

Nuclear Structure Theory

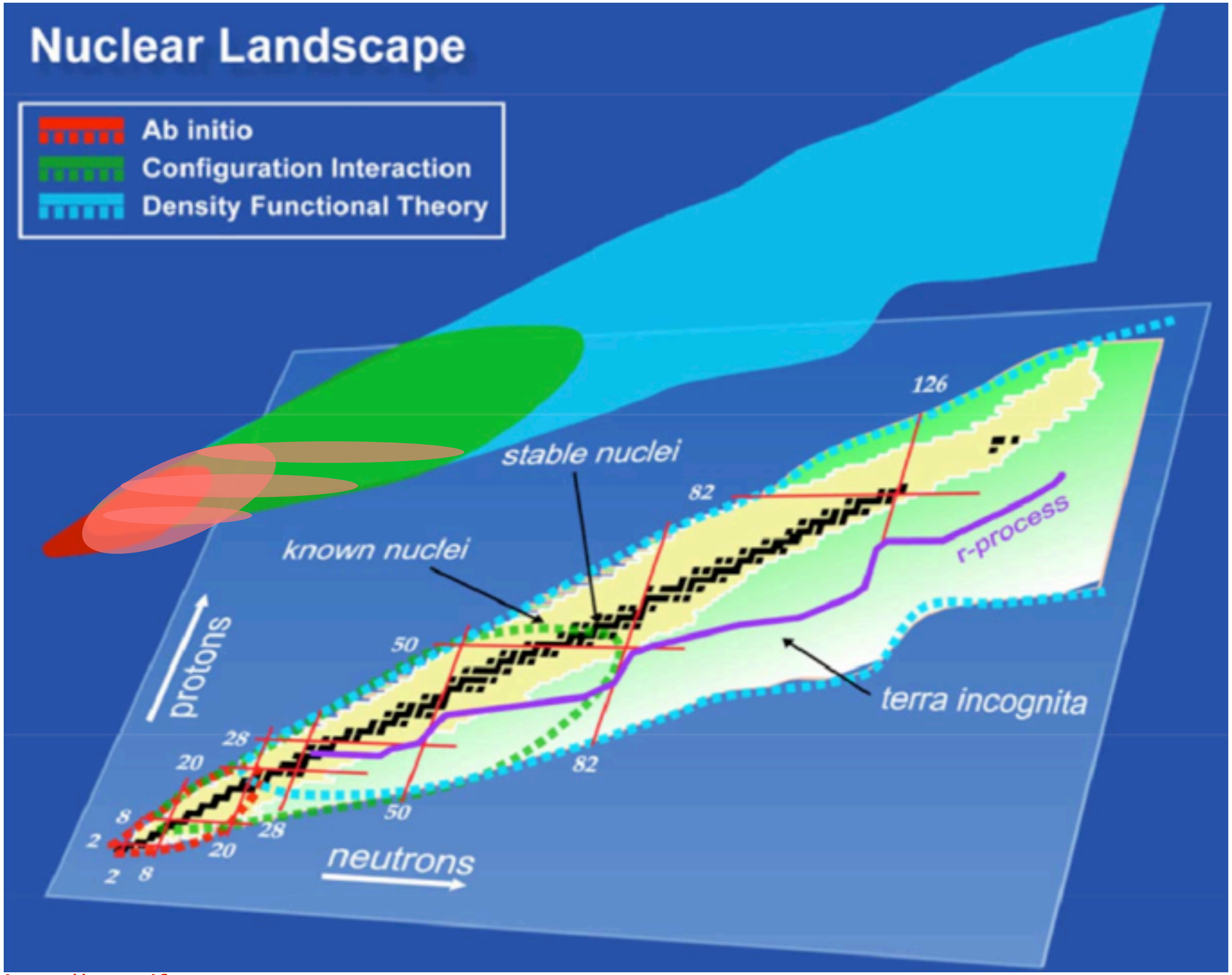
Goal: develop a theory of nuclei with predictive power



http://unedf.org

Nuclear Structure Theory

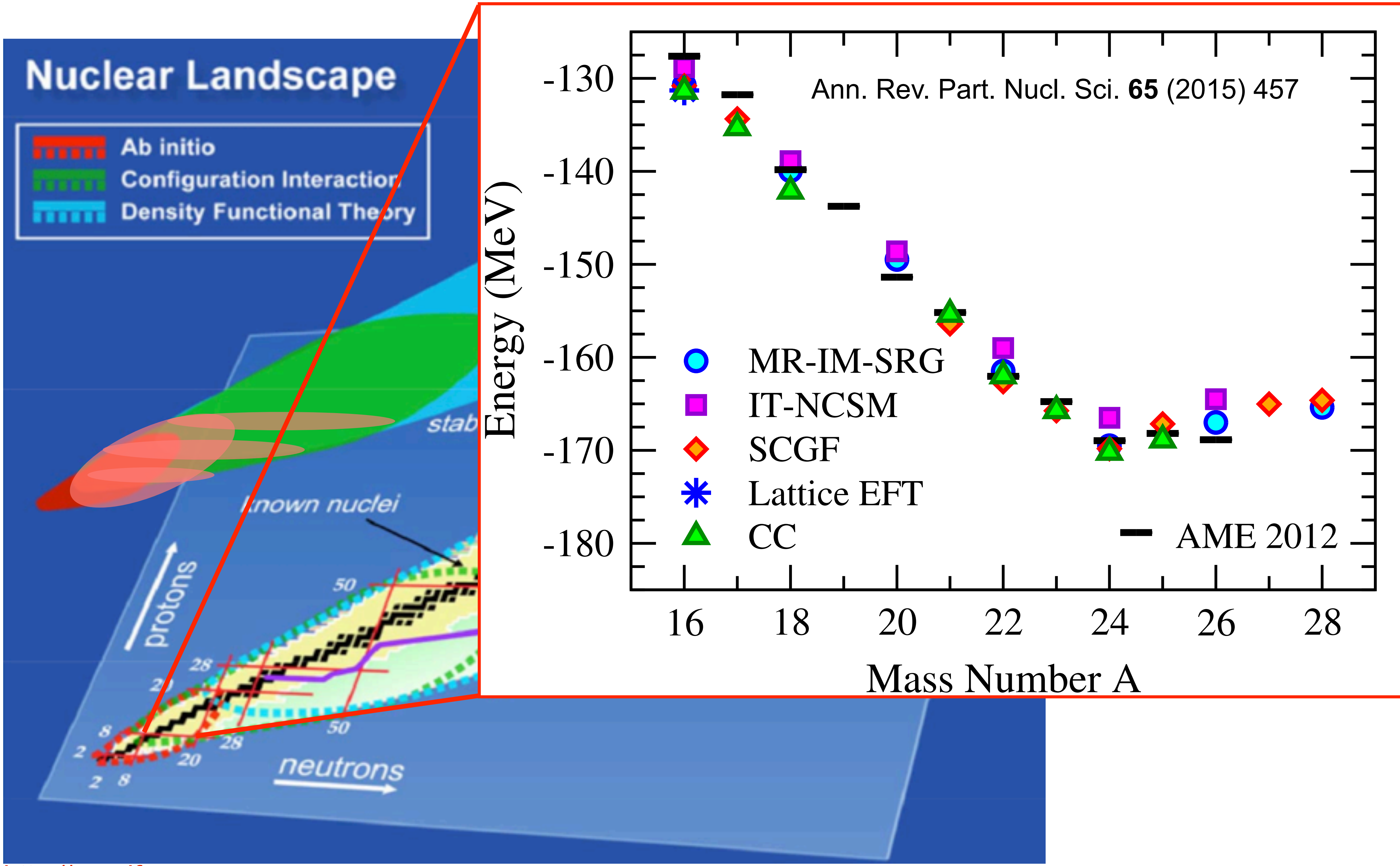
Goal: develop a theory of nuclei with predictive power



http://unedf.org

Nuclear Structure Theory

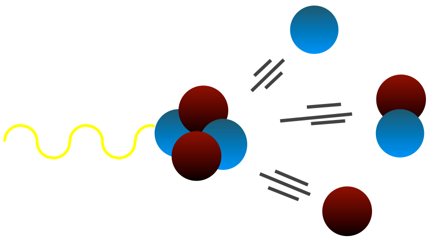
Goal: develop a theory of nuclei with predictive power



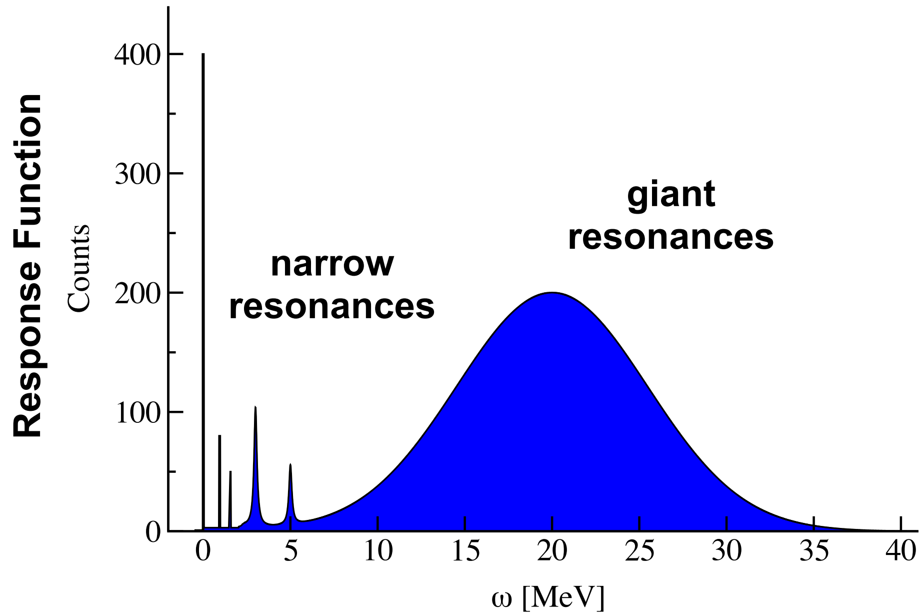
http://unedf.org

Electroweak probes

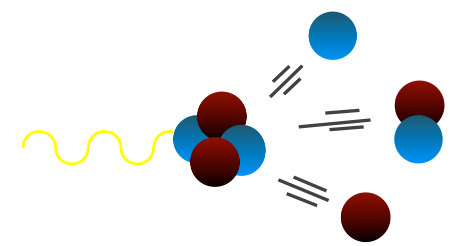
- How does the nucleus respond to external electroweak excitations?



$$R(\omega, q) = \sum\!\!\!\!\!\!\int_f |\langle \Psi_f | \mathcal{O}(q) | \Psi_0 \rangle|^2 \delta(\omega - E_f + E_0)$$

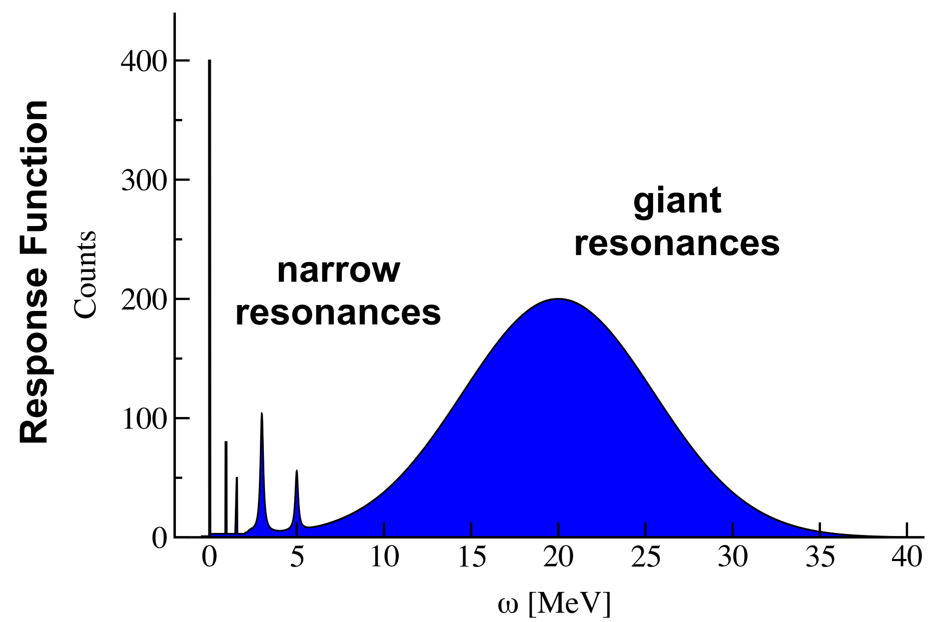


Electroweak probes

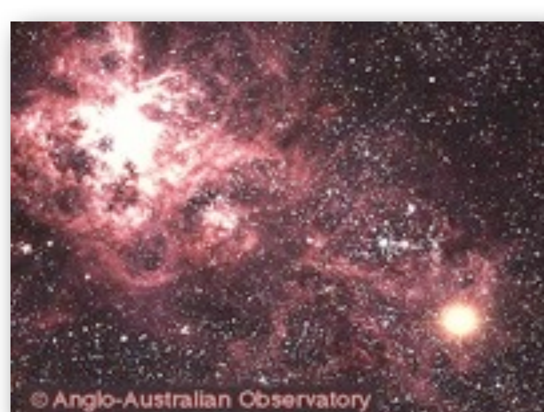


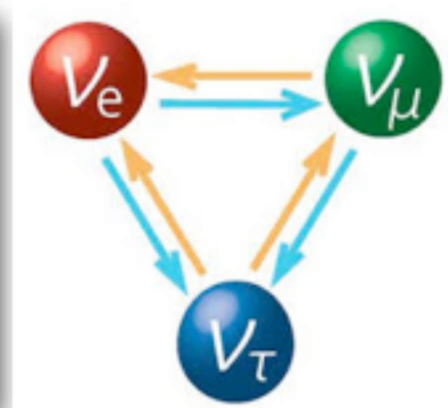
- How does the nucleus respond to external electroweak excitations?

$$R(\omega, q) = \sum_f |\langle \Psi_f | \mathcal{O}(q) | \Psi_0 \rangle|^2 \delta(\omega - E_f + E_0)$$

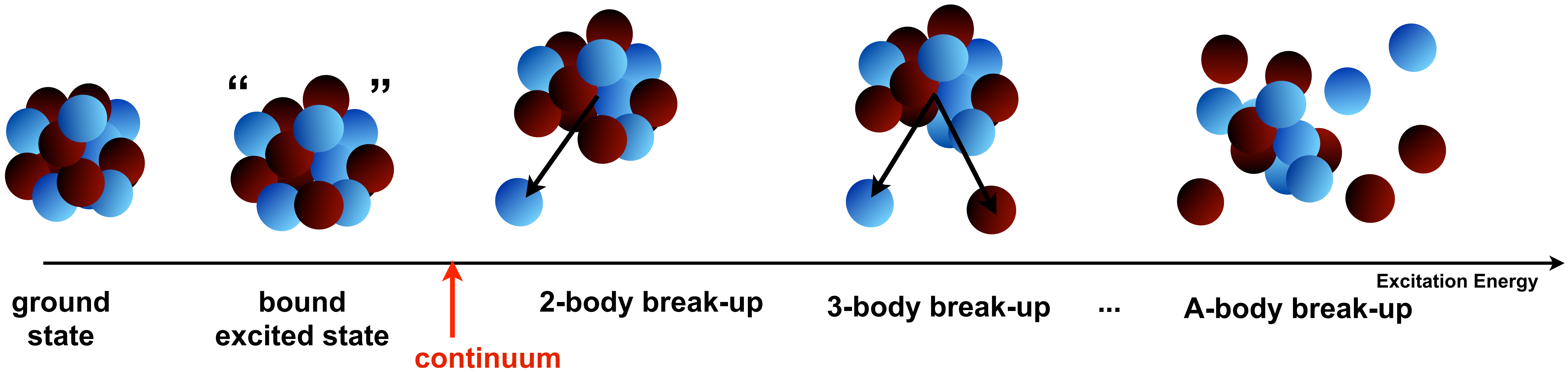


- Provide important informations in other fields of physics, where nuclear physics plays a crucial role:
  - Astrophysics:
  - Atomic physics
  - Particle physics





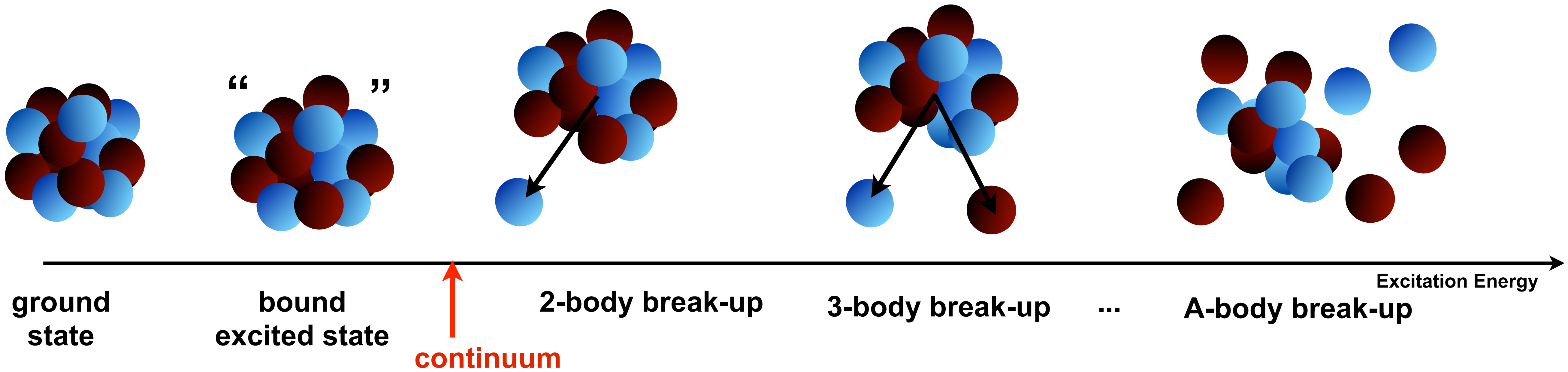
The Continuum Problem



$$R(\omega, q) \quad \propto \left| \langle \Psi_f | J^\mu | \Psi_0 \rangle \right|^2$$

Exact knowledge limited in
energy and mass number

The Continuum Problem



$$R(\omega, q) \quad \propto \left| \langle \Psi_f | J^\mu | \Psi_0 \rangle \right|^2$$

Exact knowledge limited in
energy and mass number

Lorentz Integral Transform ⇨ Reduce the continuum problem to a bound-state-like equation

Efros, *et al.*, JPG.: Nucl.Part.Phys. **34** (2007) R459

$$(H - z)|\tilde{\Psi}\rangle = J^\mu |\Psi_0\rangle$$

Similar to Laplace Transform discussed on Wed by S.Gandolfi

Selected Highlights

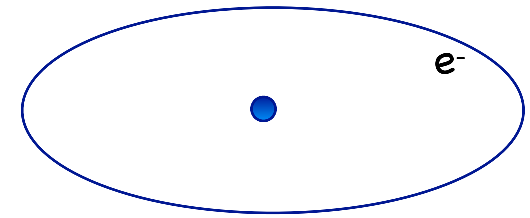
Interfacing with precision atomic physics to search for beyond standard model physics

The proton-radius puzzle

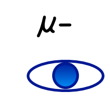
Merkel Talk on Tue & Vanderhaeghen Talk on Fri.

The proton charge radius is measured from:

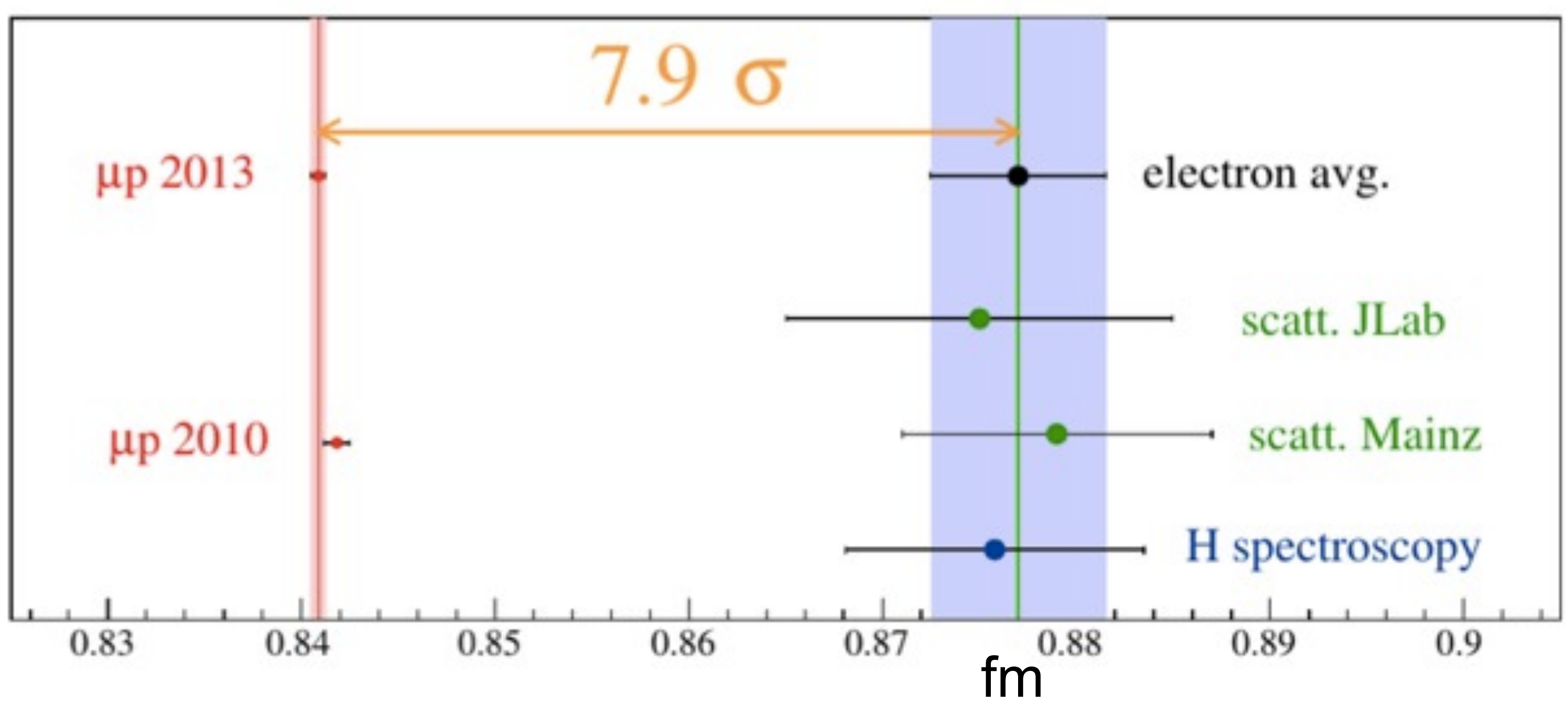
- electron-proton interactions: 0.8770 ± 0.0045 fm
  - eH spectroscopy
  - e-p scattering



- muonic -proton interactions: 0.8409 ± 0.0004 fm
  - μH Lamb-shift



Pohl *et al.*, Nature (2010)
Antognini *et al.*, Science (2013)

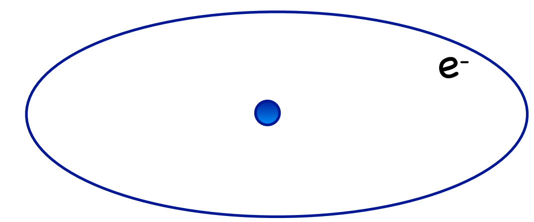


The proton-radius puzzle

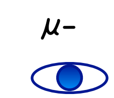
Merkel Talk on Tue & Vanderhaeghen Talk on Fri.

The proton charge radius is measured from:

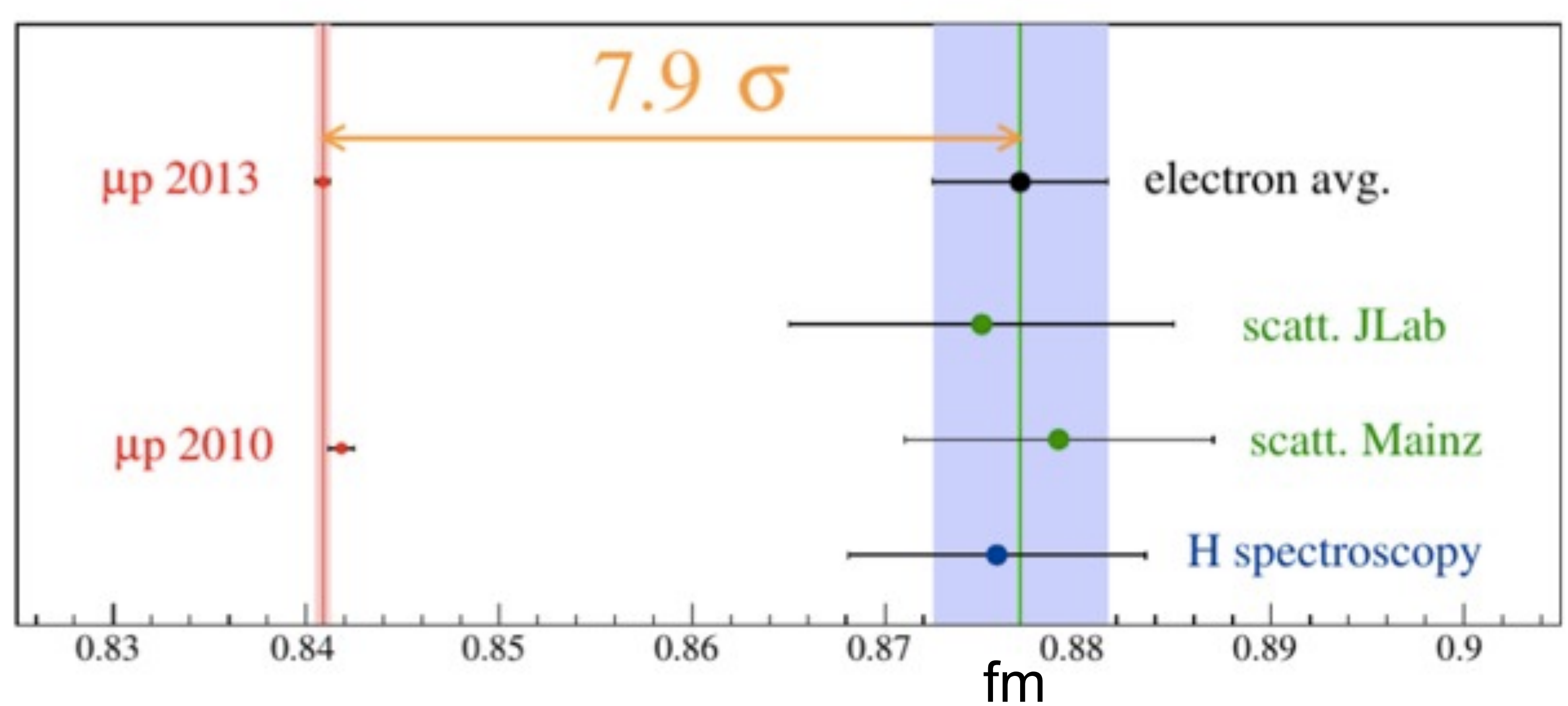
- electron-proton interactions: 0.8770 ± 0.0045 fm
  - eH spectroscopy
  - e-p scattering



- muonic -proton interactions: 0.8409 ± 0.0004 fm
  - μH Lamb-shift



Pohl *et al.*, Nature (2010)
Antognini *et al.*, Science (2013)

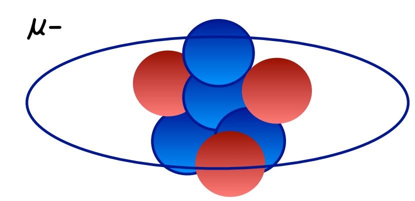


Is lepton universality violated?

Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

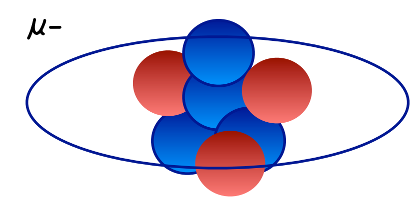
- μD
- μ^4He^+
- μ^3He^+
- μ^3H
- μ^6Li^{2+}, μ^7Li^{2+}



Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD
- μ^4He$^+$
- μ^3He$^+$
- μ^3H
- μ^6Li^{2+}, μ^7Li^{2+}

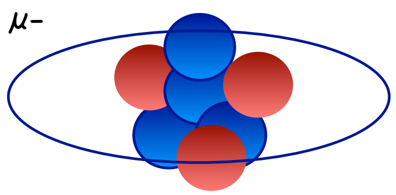


$$\Delta E_{2S-2P} = \delta_{\rm QED} + \mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \delta_{\rm TPE}$$

Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD
- μ^4He$^+$
- μ^3He$^+$
- μ^3H
- μ^6Li^{2+}, μ^7Li^{2+}



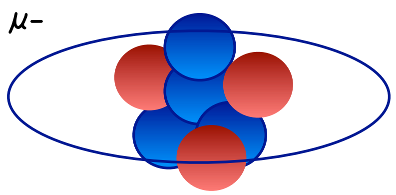
$$\Delta E_{2S-2P} = \delta_{\rm QED} + \mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \delta_{\rm TPE}$$

well known

Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD
- μ^4He$^+$
- μ^3He$^+$
- μ^3H
- μ^6Li^{2+}, μ^7Li^{2+}



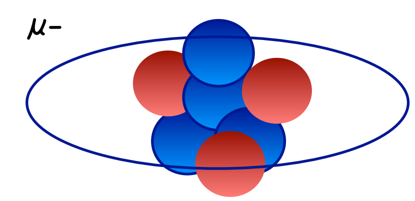
$$\Delta E_{2S-2P} = \delta_{\rm QED} + \boxed{\mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \delta_{\rm TPE}}$$

well known

Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD
- μ^4He$^+$
- μ^3He$^+$
- μ^3H
- μ^6Li^{2+}, μ^7Li^{2+}

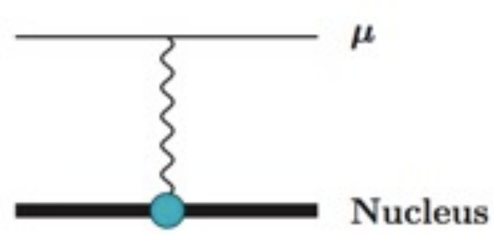


$$\Delta E_{2S-2P} = \delta_{\rm QED} + \boxed{\mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \delta_{\rm TPE}}$$

well known

$$\wr|$$

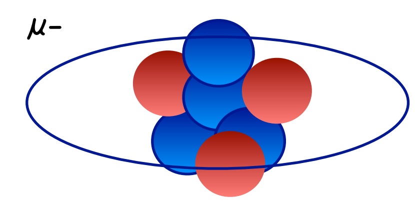
$$\frac{m_r^4 (Z\alpha)^4}{12}$$



Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD
- μ^4He$^+$
- μ^3He$^+$
- μ^3H
- μ^6Li^{2+}, μ^7Li^{2+}



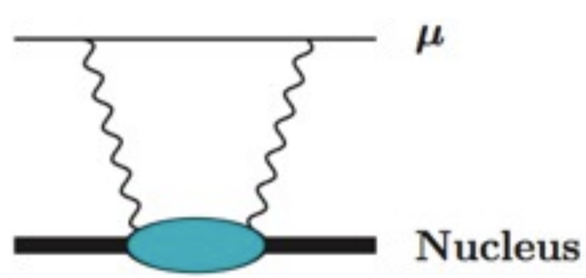
$$\Delta E_{2S-2P} = \delta_{\rm QED} + \boxed{\mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \delta_{\rm TPE}}$$

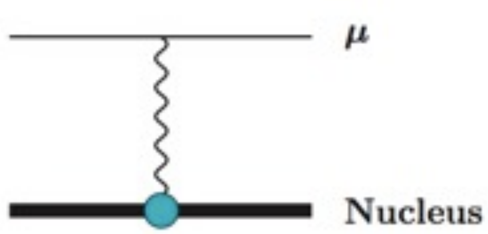
well known

$\wr|$

$$\frac{m_r^4(Z\alpha)^4}{12}$$

unknown



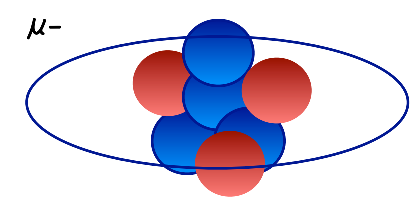


$$\delta_{TPE} \rightarrow \int d\omega\ R(\omega,q)\ g(\omega)$$

Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD (results just released)
- μ^4He^+ (analyzing data)
- μ^3He^+ (analyzing data)
- μ^3H (impossible/possible?)
- μ^6Li^{2+}, μ^7Li^{2+} (future)



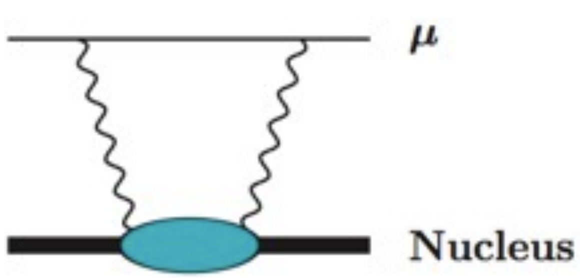
$$\Delta E_{2S-2P} = \delta_{\rm QED} + \boxed{\mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \delta_{\rm TPE}}$$

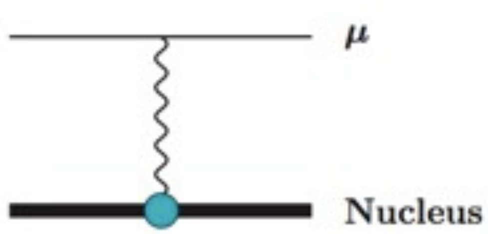
well known

$\wr|$

$$\frac{m_r^4 (Z\alpha\ )^4}{12}$$

unknown





$$\delta_{TPE} \to \int d\omega\ R(\omega, q)\ g(\omega)$$

Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

μD (results just released)	-1.727(20) meV	$\Rightarrow$	PLB **736**, 334 (2014)
μ^4He$^+$ (analyzing data)	-9.58(38) meV	$\Rightarrow$	PRL **111**, 143402 (2013)
μ^3He$^+$ (analyzing data)	-15.46(39) meV	$\Rightarrow$	PLB **755**, 380 (2016)
μ^3H (impossible/possible?)	-0.767(25) meV	$\Rightarrow$	PLB **755**, 380 (2016)
μ^6Li^{2+}, μ^7Li^{2+} (future)			

$$\Delta E_{2S-2P} = \delta_{\rm QED} + \mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \boxed{\delta_{\rm TPE}}$$

Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

μD (results just released)	-1.727(20) meV	$\Rightarrow$	PLB **736**, 334 (2014)	1%
μ^4He$^+$ (analyzing data)	-9.58(38) meV	$\Rightarrow$	PRL **111**, 143402 (2013)	6%
μ^3He$^+$ (analyzing data)	-15.46(39) meV	$\Rightarrow$	PLB **755**, 380 (2016)	3%
μ^3H (impossible/possible?)	-0.767(25) meV	$\Rightarrow$	PLB **755**, 380 (2016)	
μ^6Li^{2+}, μ^7Li^{2+} (future)				

$$\Delta E_{2S-2P} = \delta_{\text{QED}} + \mathcal{A}_{\text{OPE}} \langle r_c^2 \rangle + \boxed{\delta_{\text{TPE}}}$$

Understanding the proton-radius puzzle

Theory provides crucial information for precision experiments

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

μD (results just released)	-1.727(20) meV	⇒ PLB **736**, 334 (2014)	1%
μ^4He^+ (analyzing data)	-9.58(38) meV	⇒ PRL **111**, 143402 (2013)	6%
μ^3He^+ (analyzing data)	-15.46(39) meV	⇒ PLB **755**, 380 (2016)	3%
μ^3H (impossible/possible?)	-0.767(25) meV	⇒ PLB **755**, 380 (2016)	
μ^6Li^{2+}, μ^7Li^{2+} (future)			

$$\Delta E_{2S-2P} = \delta_{\mathrm{QED}} + \mathcal{A}_{\mathrm{OPE}}\langle r_c^2\rangle + \boxed{\delta_{\mathrm{TPE}}}$$

Understanding the proton-radius puzzle

Theory provides crucial information for precision experiments

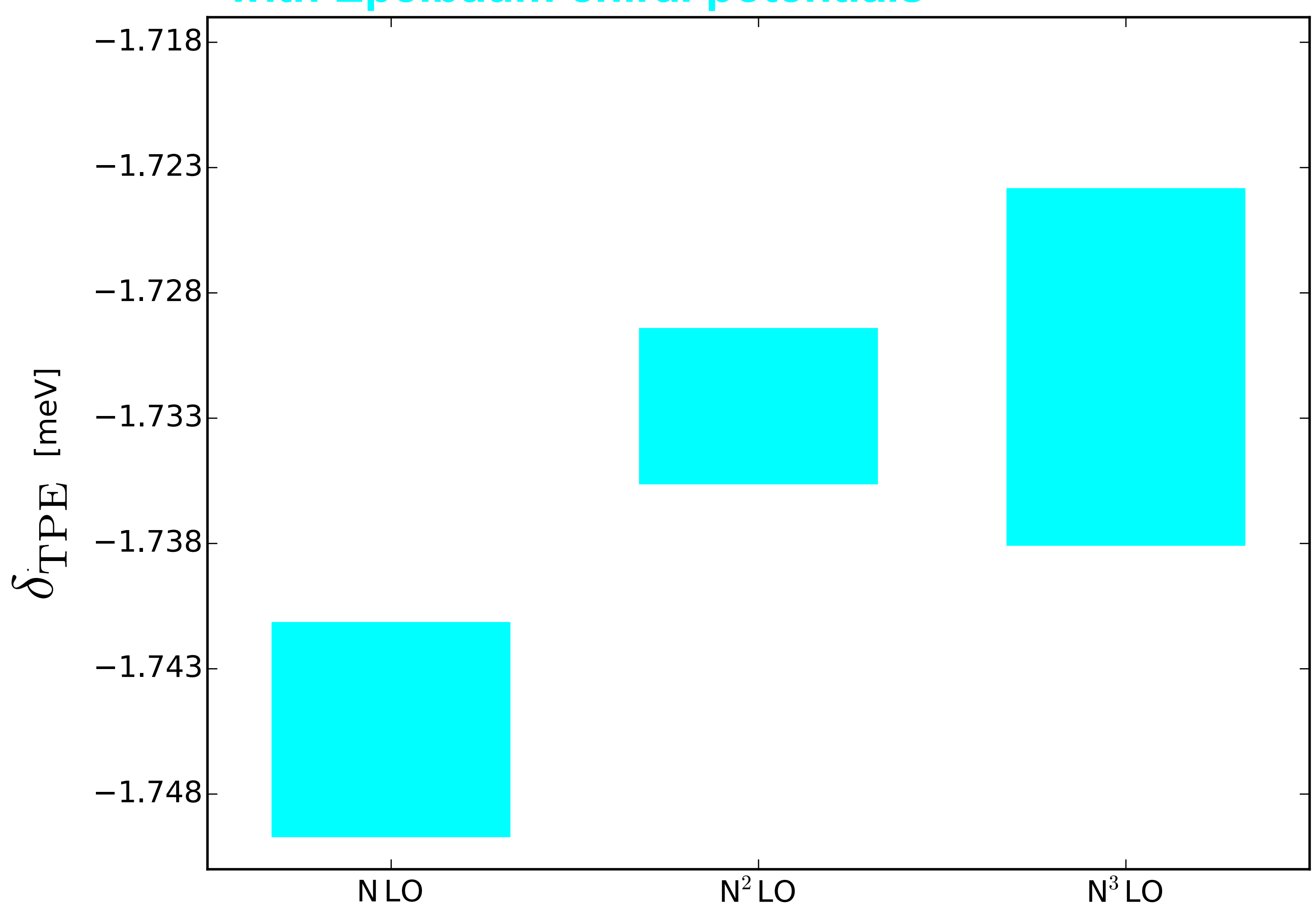
Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD (results just released) -1.727(20) meV $\Rightarrow$ PLB **736**, 334 (2014) 1%

  R.Pohl *et al.*, Science 2016 $\delta_{\rm TPE}$ $\Rightarrow$ work led by J. Hernandez

  7.5σ deviations from μD and CODATA

with Epelbaum chiral potentials



Understanding the proton-radius puzzle

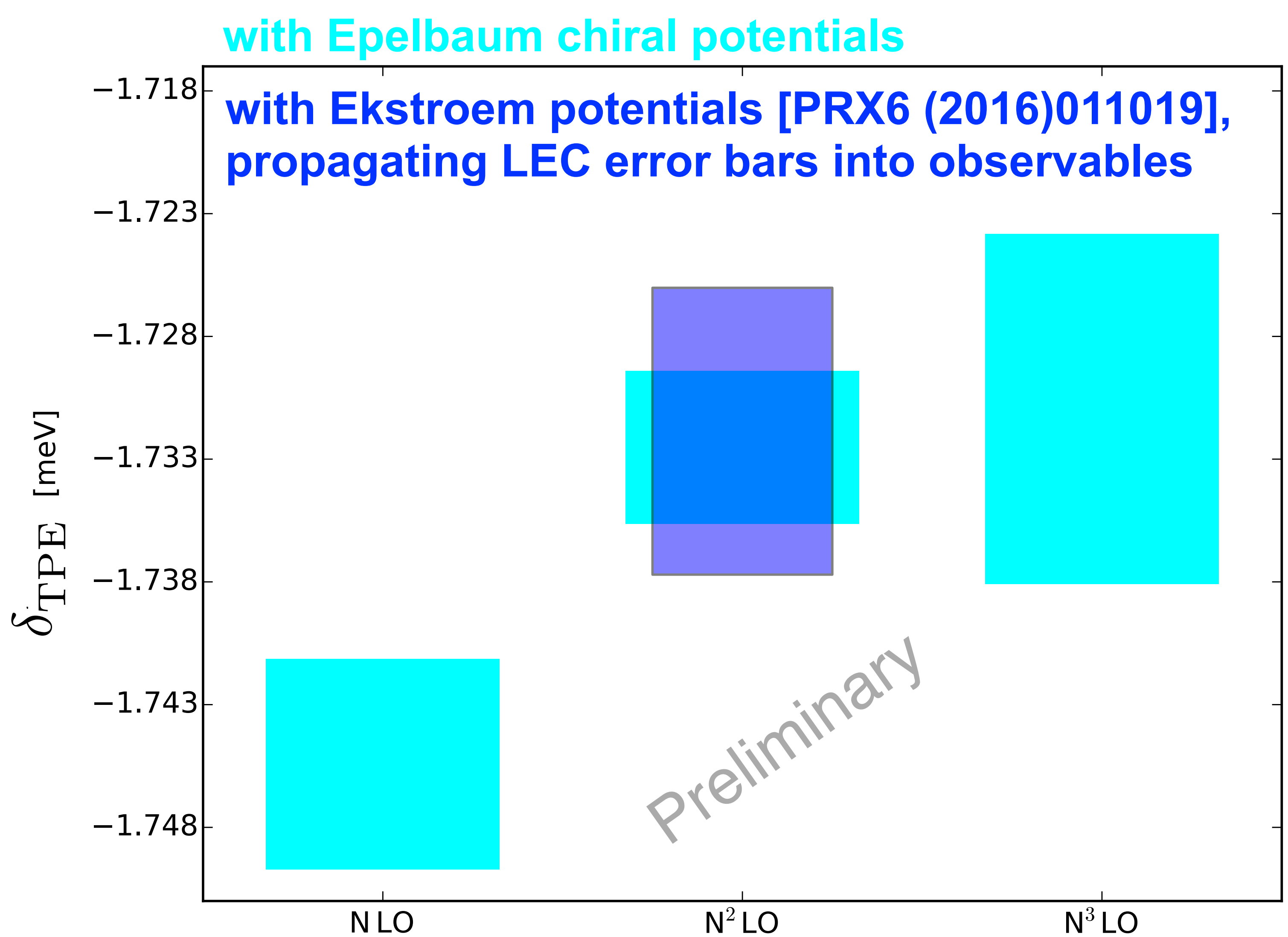
Theory provides crucial information for precision experiments

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD (results just released) -1.727(20) meV $\Rightarrow$ PLB **736**, 334 (2014) 1%

  R.Pohl *et al.*, Science 2016 δ_{TPE} $\Rightarrow$ work led by J. Hernandez

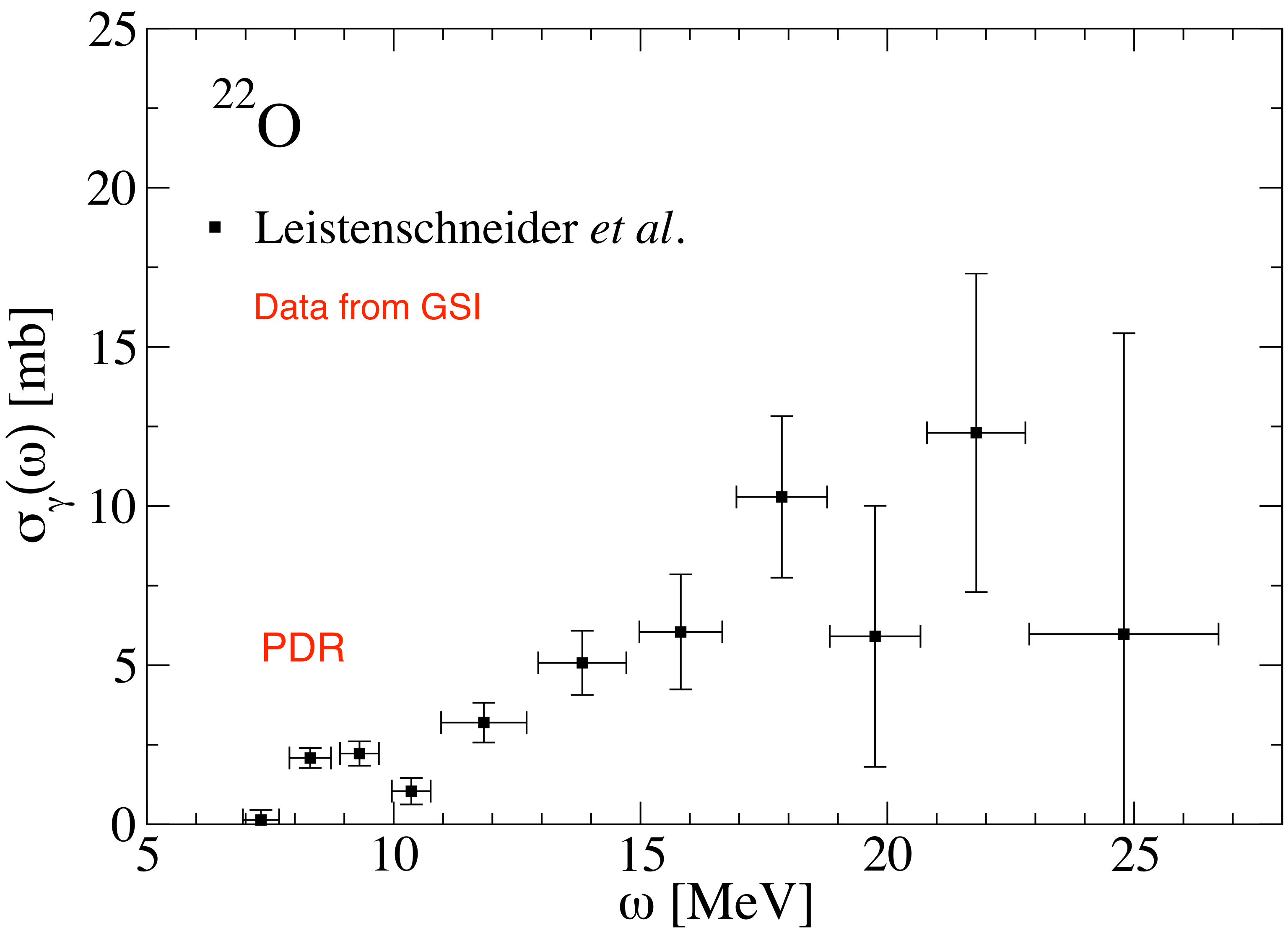
  7.5σ deviations from μD and CODATA

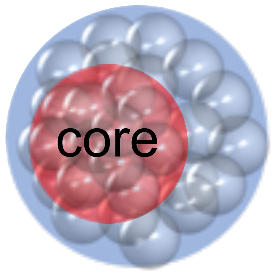


Selected Highlights

Pushing the limits in mass number to challenge our understanding of neutron-rich nuclei

Photoexcitation of neutron-rich nuclei

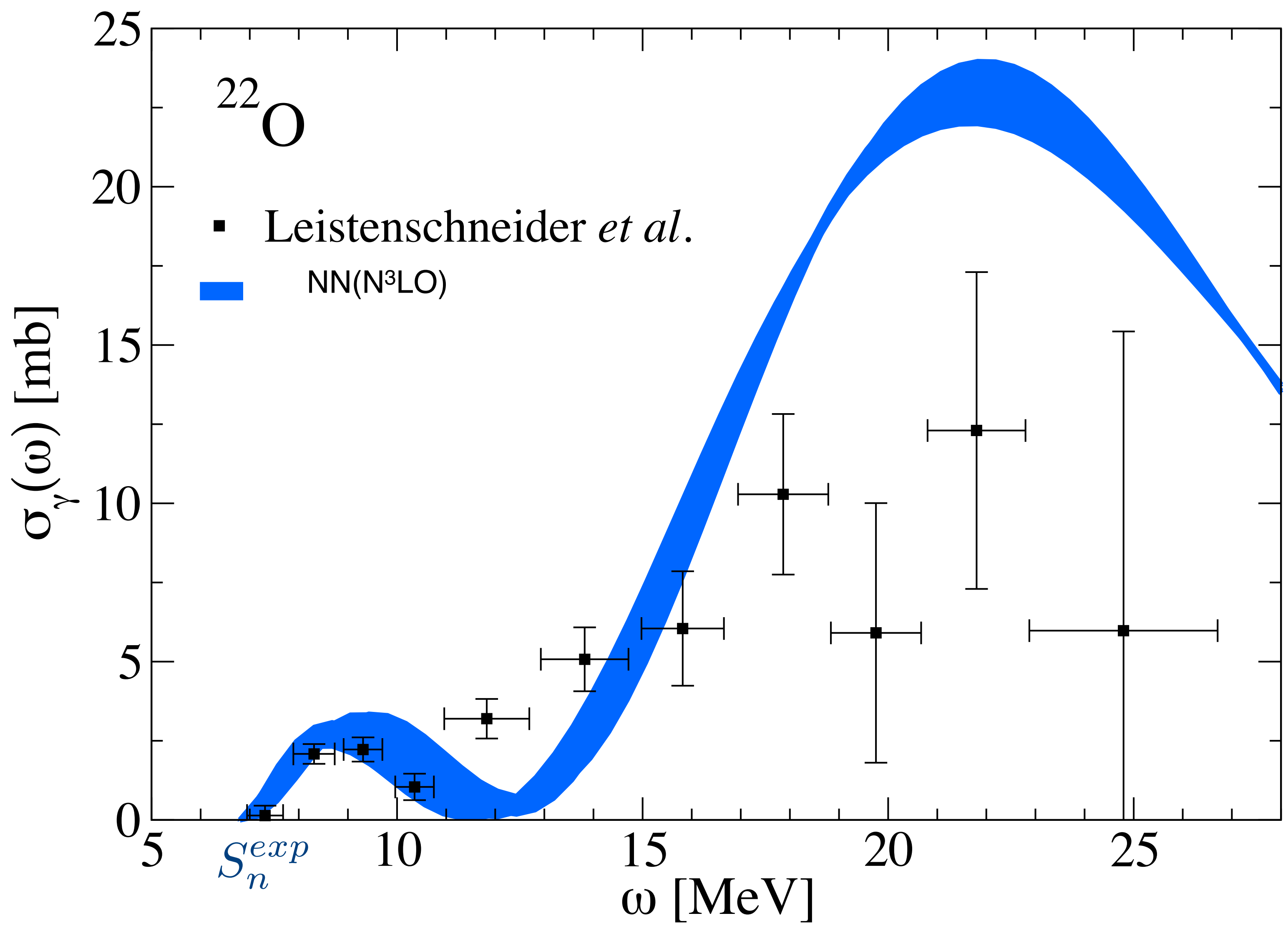


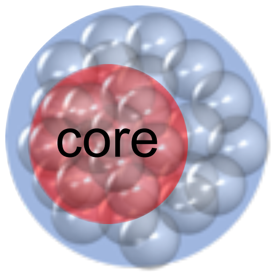


Pigmy Dipole Resonance (PDR)

Photoexcitation of neutron-rich nuclei

S.B. *et al.*, PRC **90**, 064619 (2014)



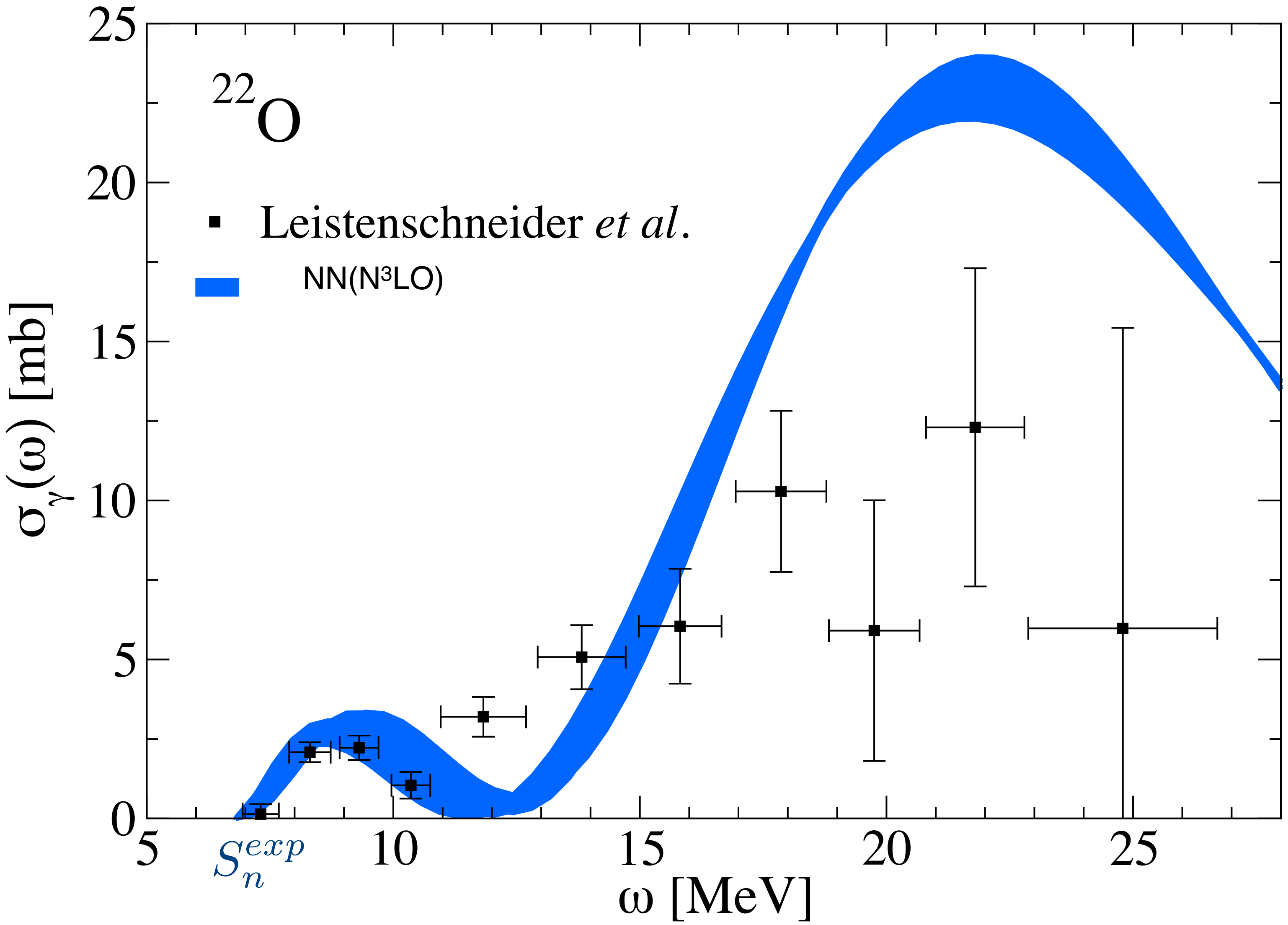


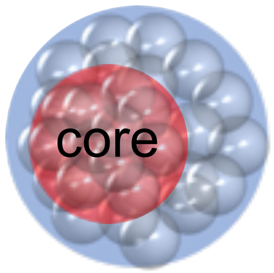
Pigmy Dipole Resonance (PDR)

Well described by ab initio theory

Photoexcitation of neutron-rich nuclei

S.B. *et al.*, PRC **90**, 064619 (2014)





Pigmy Dipole Resonance (PDR)

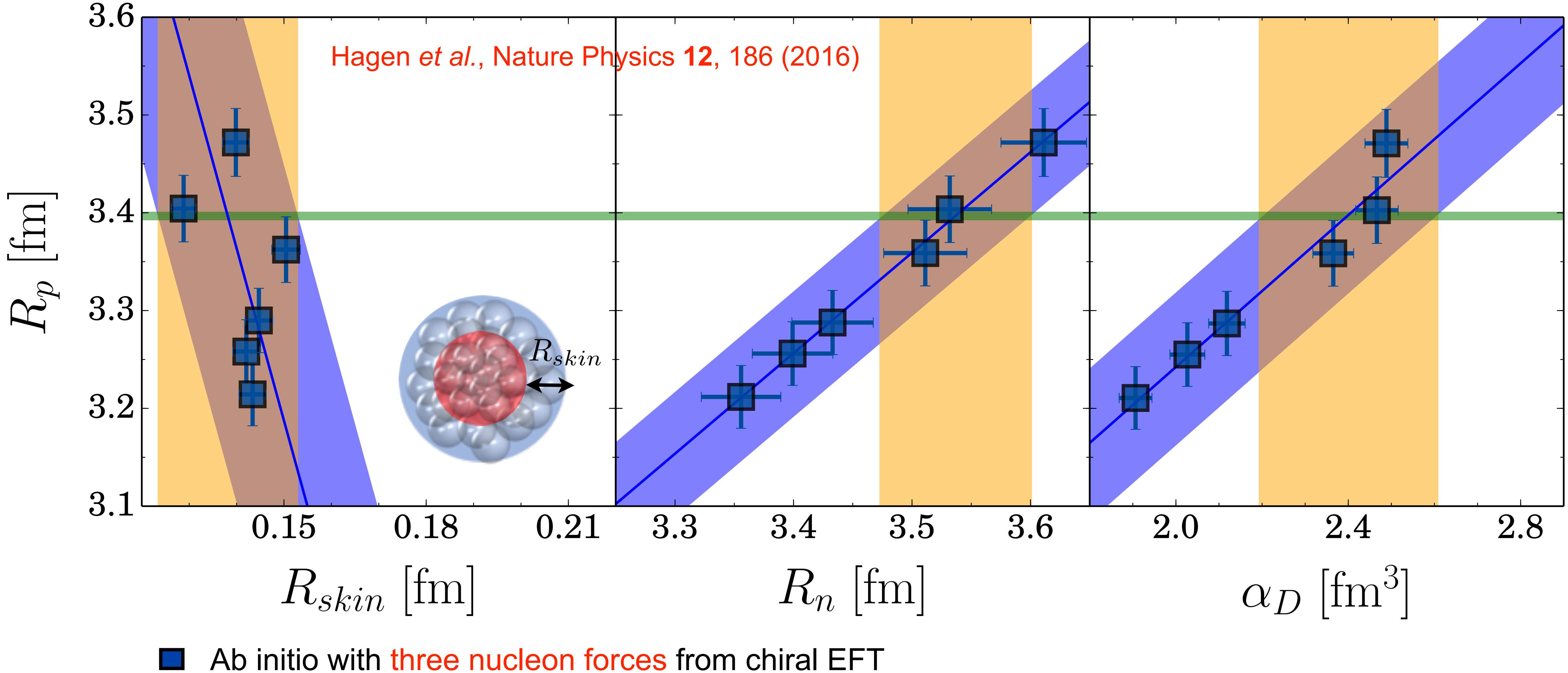
Well described by ab initio theory

Theory provides a deeper understanding: microscopic interpretation of collective phenomena

Theory motivates new experiments: e.g. ^{8}He will be measured in RIKEN by T. Aumann

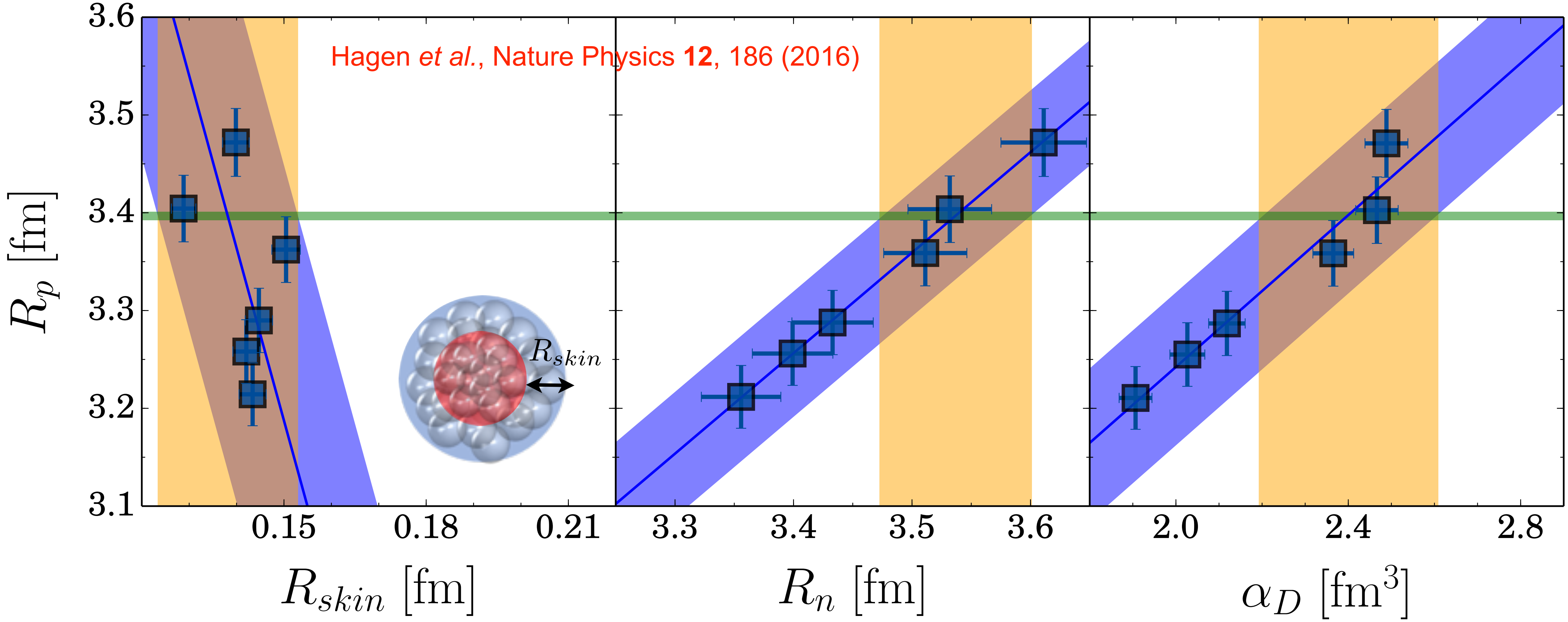
^{48}Ca from first principles

International collaboration (USA/Canada/Europe/Israel) using coupled-cluster theory



^{48}Ca from first principles

International collaboration (USA/Canada/Europe/Israel) using coupled-cluster theory



■ Ab initio with three nucleon forces from chiral EFT

Strong correlations with R_p allow to put narrow constraints to R_{skin} and α_D

Ab-initio predictions:

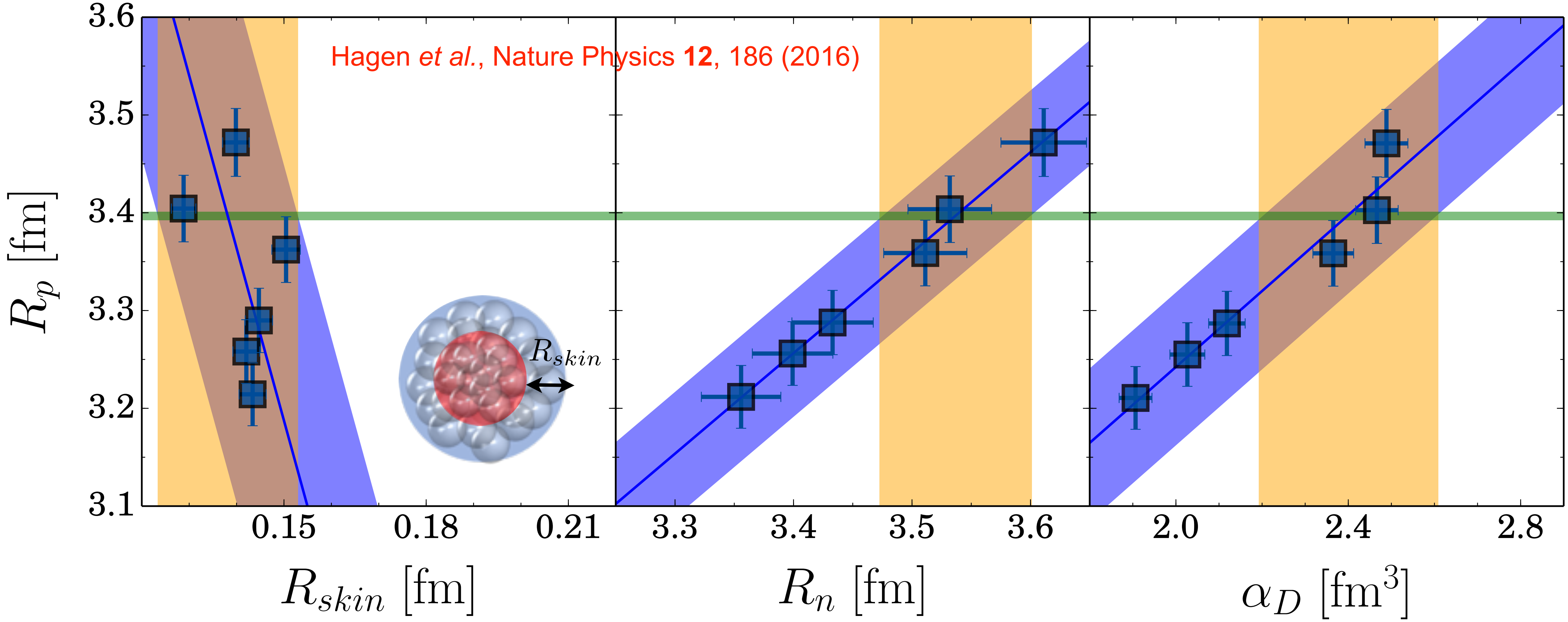
$$0.12 \leq R_{\text{skin}} \leq 0.15 \text{ fm}$$

$$2.19 \leq \alpha_D \leq 2.60 \text{ fm}^3$$

^{48}Ca from first principles

Theory provides predictions for modern experiments

International collaboration (USA/Canada/Europe/Israel) using coupled-cluster theory



■ Ab initio with three nucleon forces from chiral EFT

Strong correlations with R_p allow to put narrow constraints to R_{skin} and α_D

Ab-initio predictions:

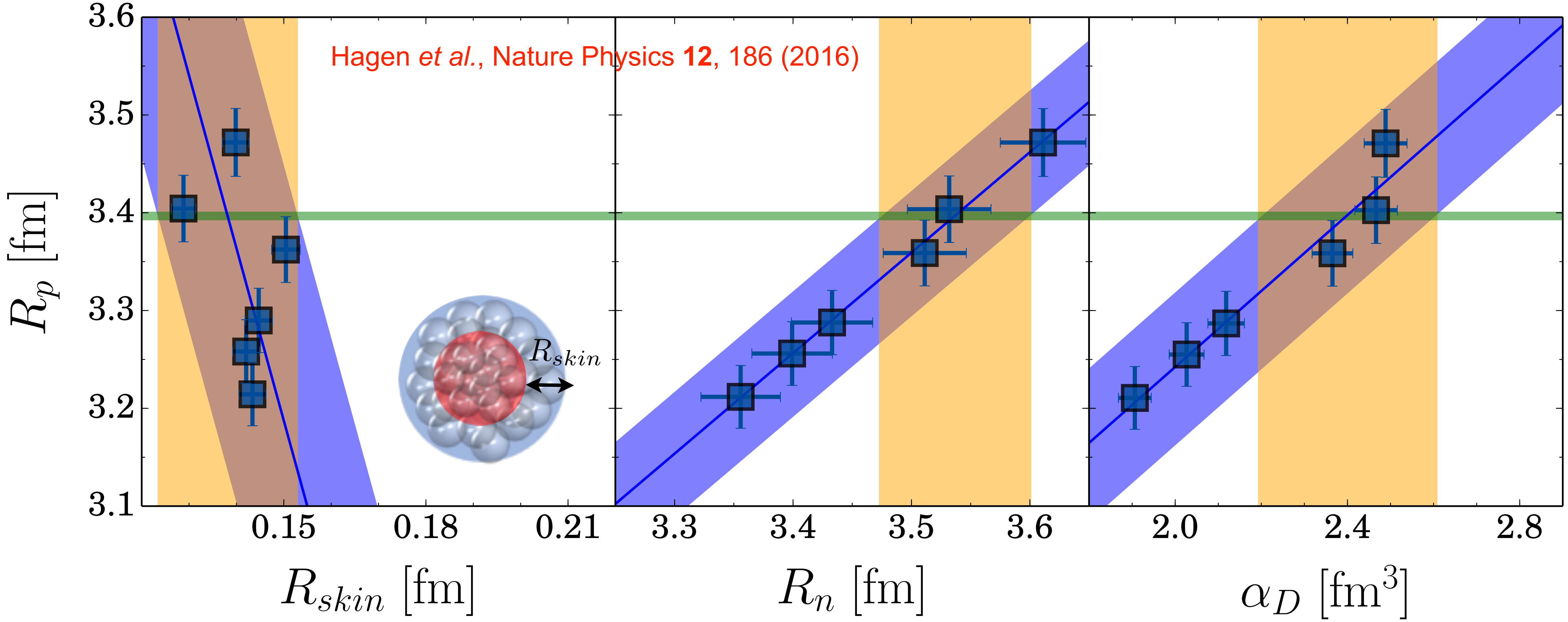
$$0.12 \leq R_{\text{skin}} \leq 0.15 \text{ fm}$$

$$2.19 \leq \alpha_D \leq 2.60 \text{ fm}^3$$

^{48}Ca from first principles

Theory provides predictions for modern experiments

International collaboration (USA/Canada/Europe/Israel) using coupled-cluster theory



■ Ab initio with three nucleon forces from chiral EFT

Strong correlations with R_p allow to put narrow constraints to R_{skin} and α_D

Ab-initio predictions:

$$0.12 \leq R_{\rm skin} \leq 0.15 \text{ fm}$$

$$2.19 \leq \alpha_D \leq 2.60 \text{ fm}^3$$

R_{skin} will be measured with Parity violation electron scattering CREX MREX

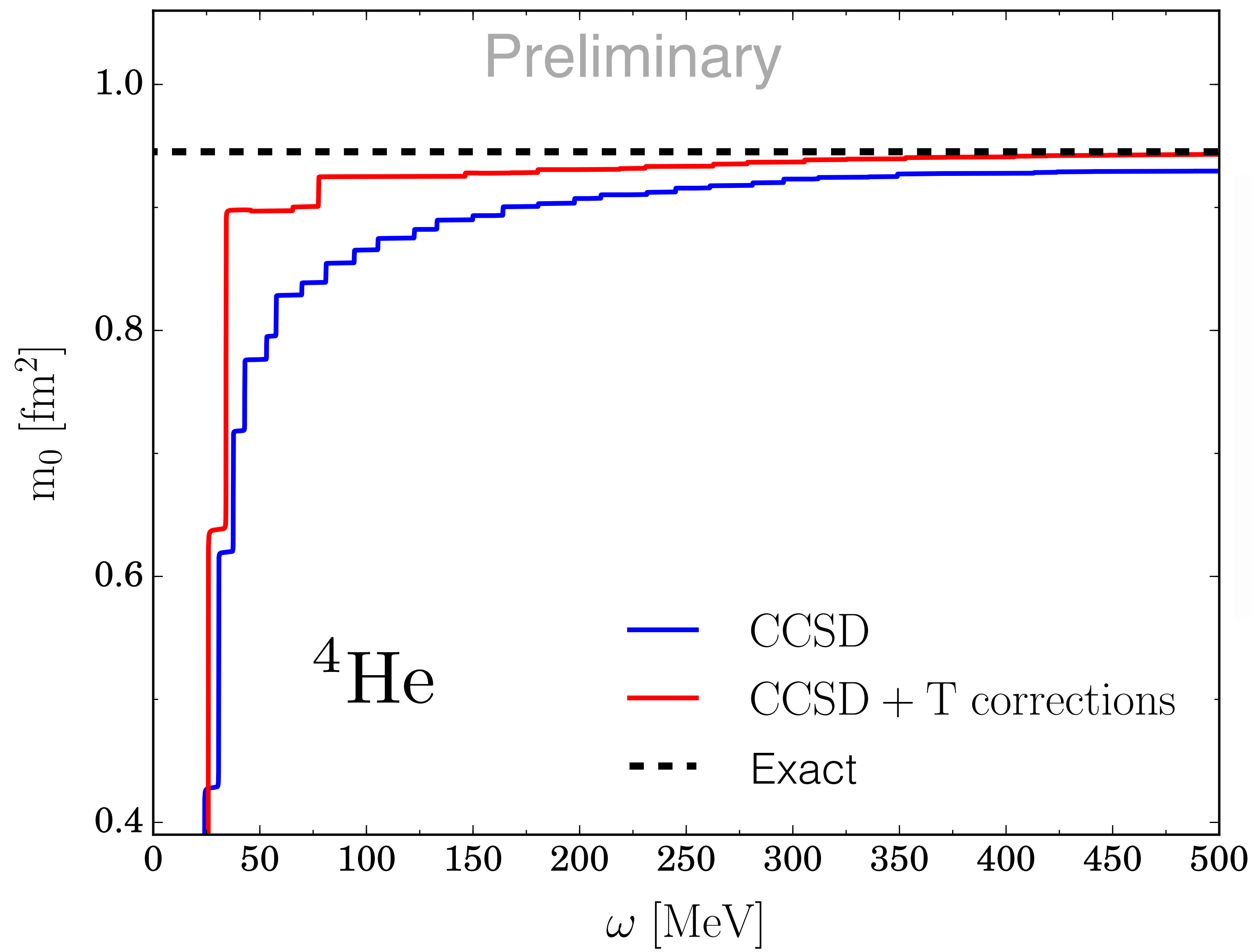
α_D measured at Osaka with (p,p')

J.Birkhan, *et al.*, arXiv:1611.07072

Future Developments

Adding triple corrections to coupled cluster theory

M.Miorelli. *et al.*, (2017)



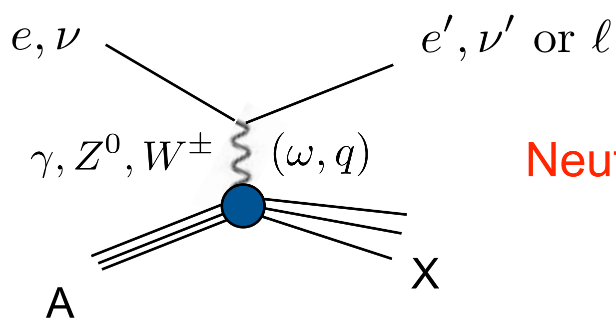
Frontiers at higher energies

How nuclear theory can help particle physics searches of fundamental neutrino properties

Neutrino-Nucleus Cross Section

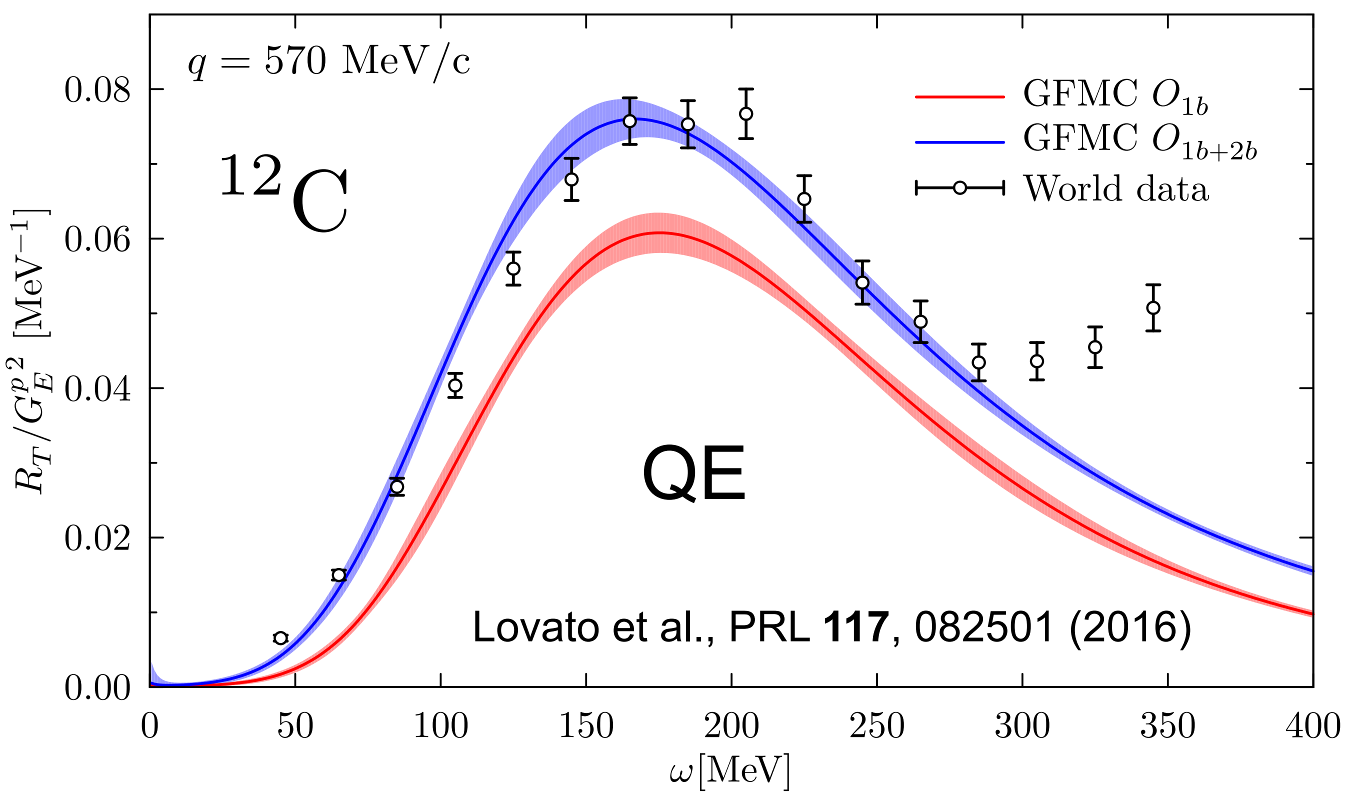
Neutrino long baseline experiments require understanding of interactions of neutrinos with the detector material (^{12}C, ^{16}O, ^{40}Ar, ...). So far very simple models are used.

How well do we understand neutrino nucleus cross sections?



Neutrino scattering ⇔ electron scattering

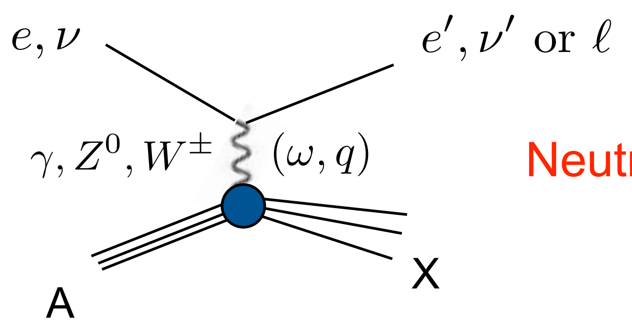
Monte Carlo Calculations - Talk by S.Gandolfi



Neutrino-Nucleus Cross Section

Neutrino long baseline experiments require understanding of interactions of neutrinos with the detector material (^{12}C, ^{16}O, ^{40}Ar, ...). So far very simple models are used.

How well do we understand neutrino nucleus cross sections?

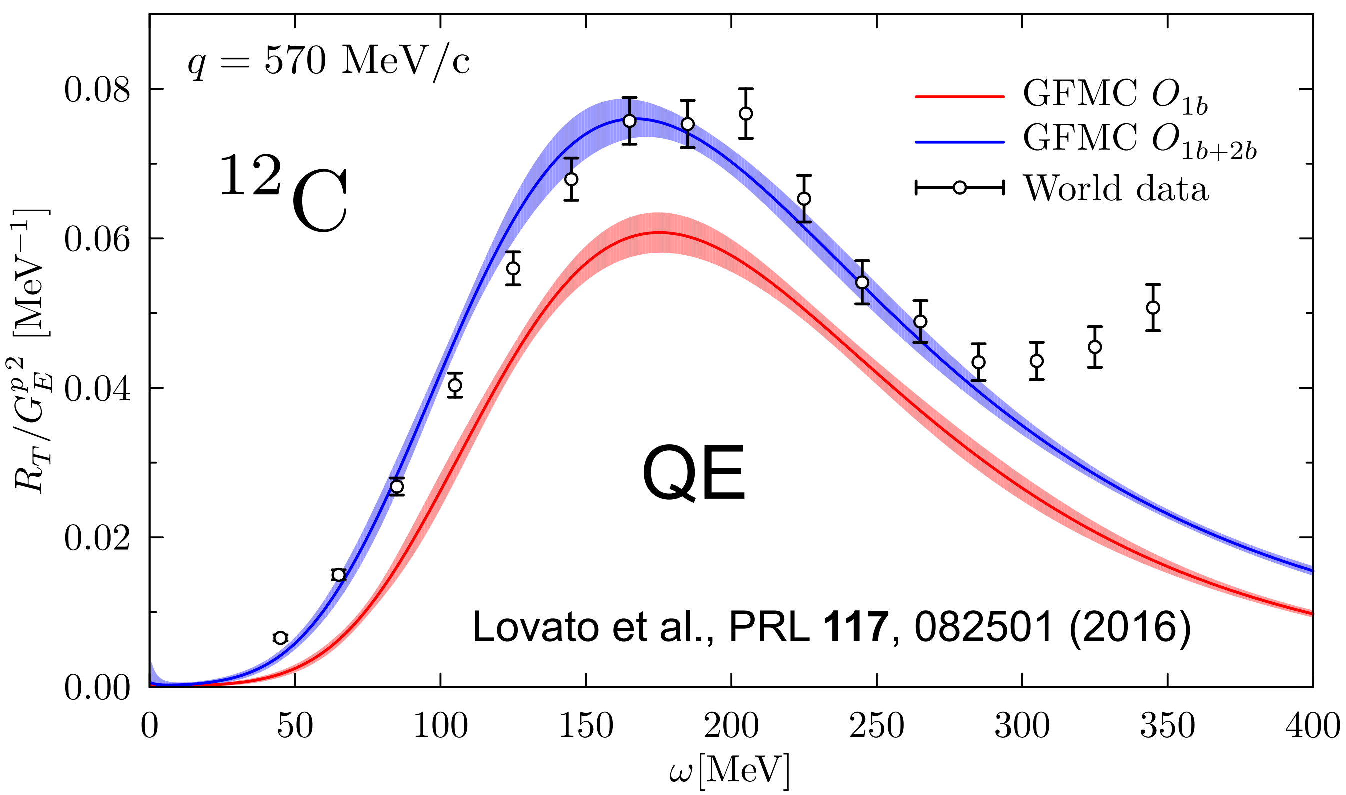


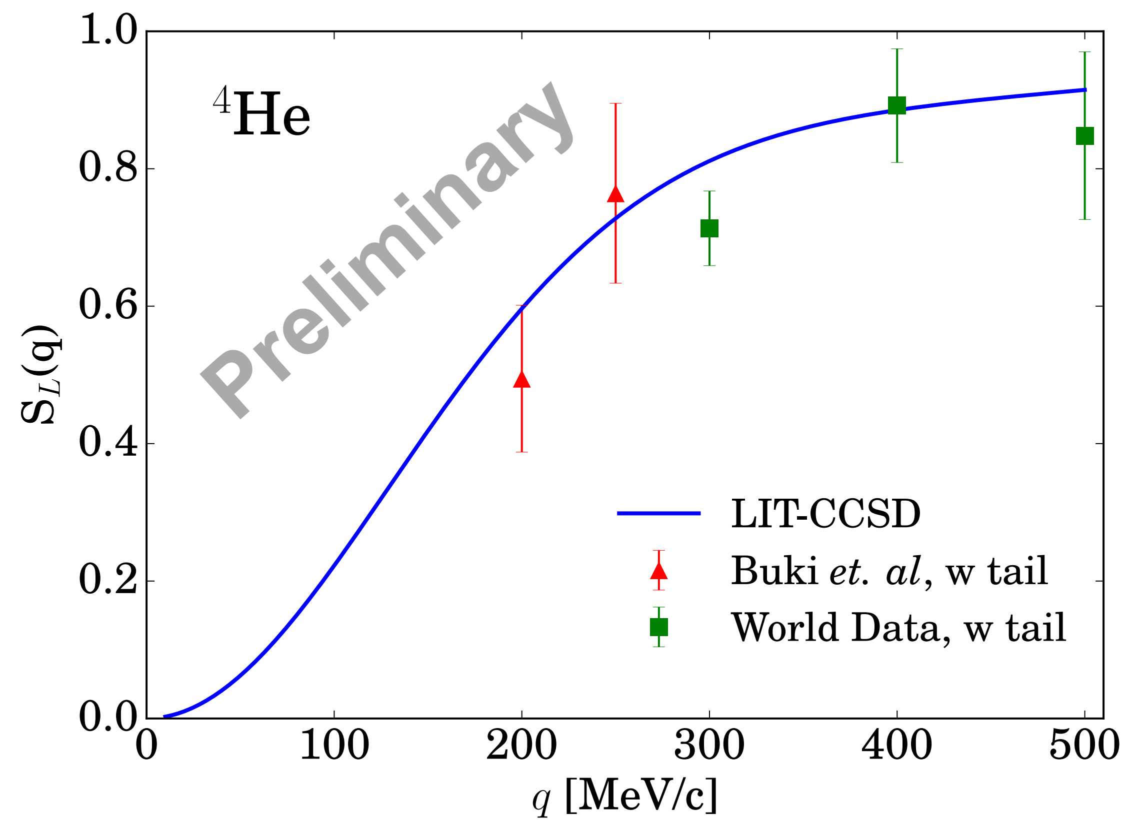
Neutrino scattering ⇔ electron scattering

Coupled-Cluster Calculations of the Coulomb Sum Rule

Monte Carlo Calculations - Talk by S.Gandolfi

T.Xu *et al.*, EPJ Web of Conferences **113**, 04016 (2016)





Outlook

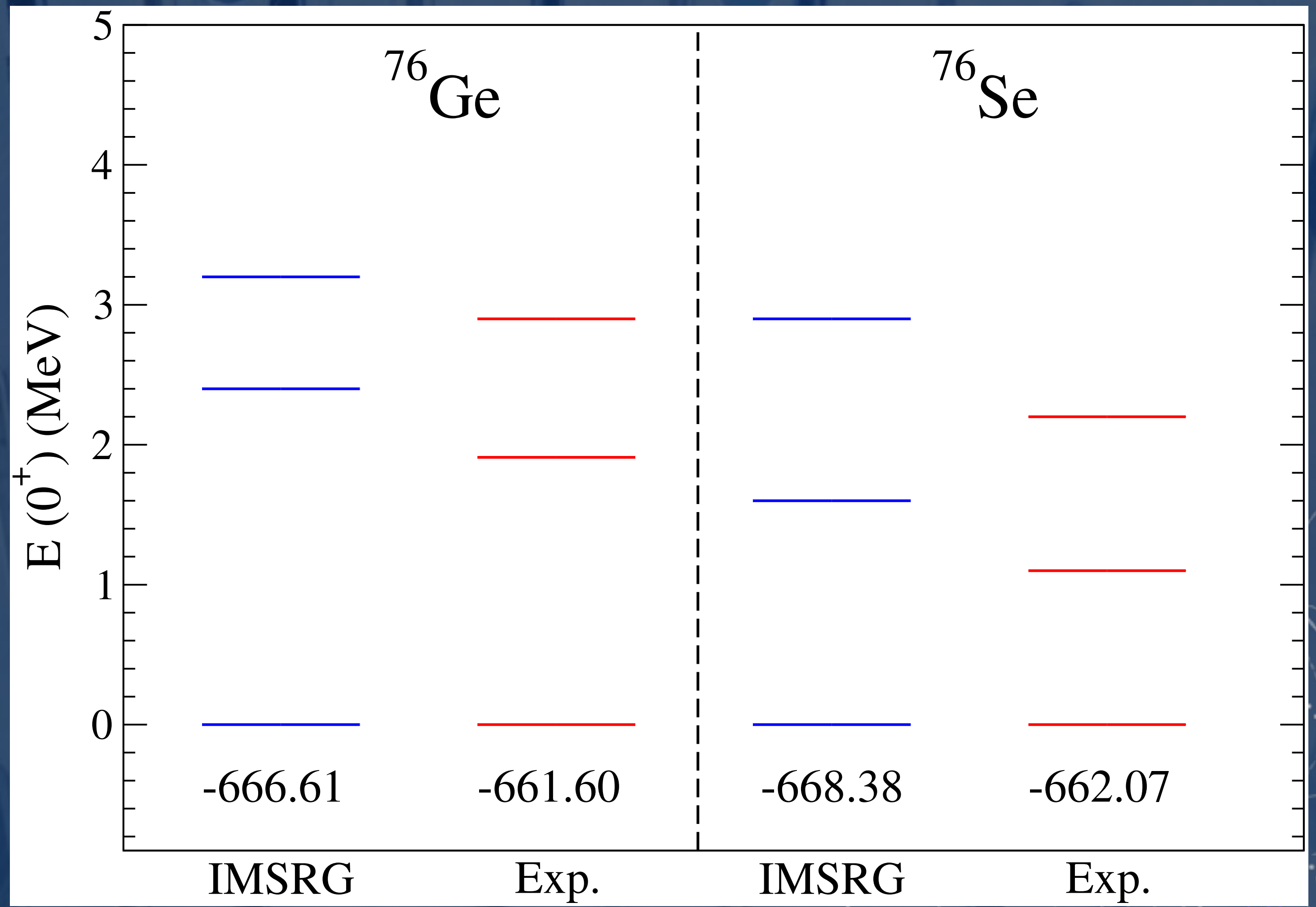
- Remarkable progress has been done in ab initio calculations of nuclear structure

- Electroweak probes are very reach tools to investigate nuclear dynamics which allow an interplay with atomic, particle and astrophysics

Future long term goals:

⋆ Neutrinoless double beta decay

Fig from J.D. Holt



Outlook

- Remarkable progress has been done in ab initio calculations of nuclear structure

- Electroweak probes are very reach tools to investigate nuclear dynamics which allow an interplay with atomic, particle and astrophysics

Thanks to my collaborators:

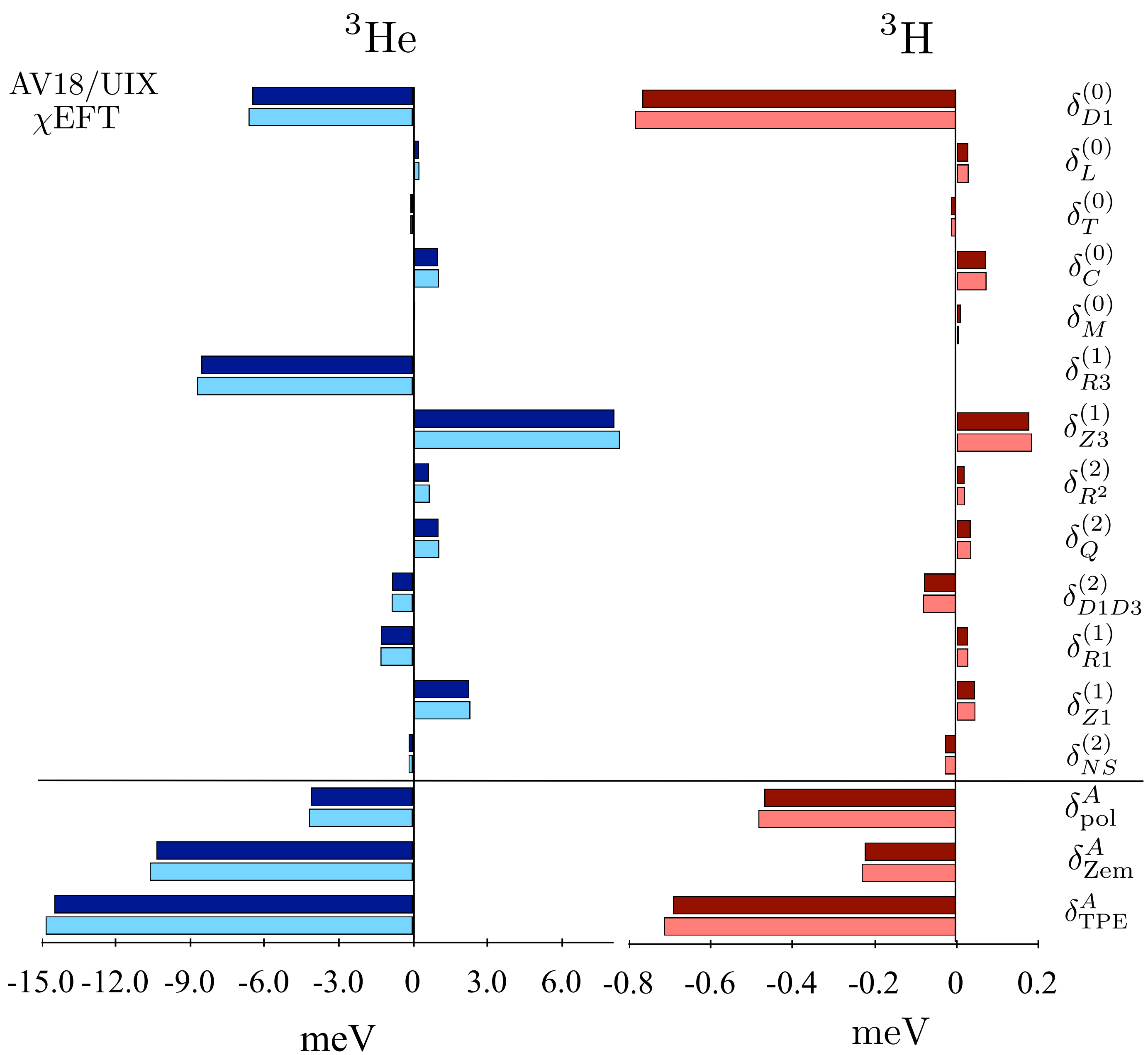
N.Barnea, B.Carlsson, C. Drischler,
A. Ekstrom, C.Forssen, G. Hagen,
O.H. Hernandez, J.D.Holt, K.Hebeler,
M. Hjorth-Jensen, G.R. Jansen, **C.Ji**,
M.Miorelli, W. Nazarewicz, **N.Nevo Dinur**,
G.Orlandini, T.Papenbrock, J. Simonis,
A.Schwenk, S.R. Stroberg, K.Wendt, **T. Xu**

Thank you!
Merci!

Backup Slides

Calculating TPE with HH

N.Nevo-Dinur *et al.*, PLB **755**, 380 (2016)

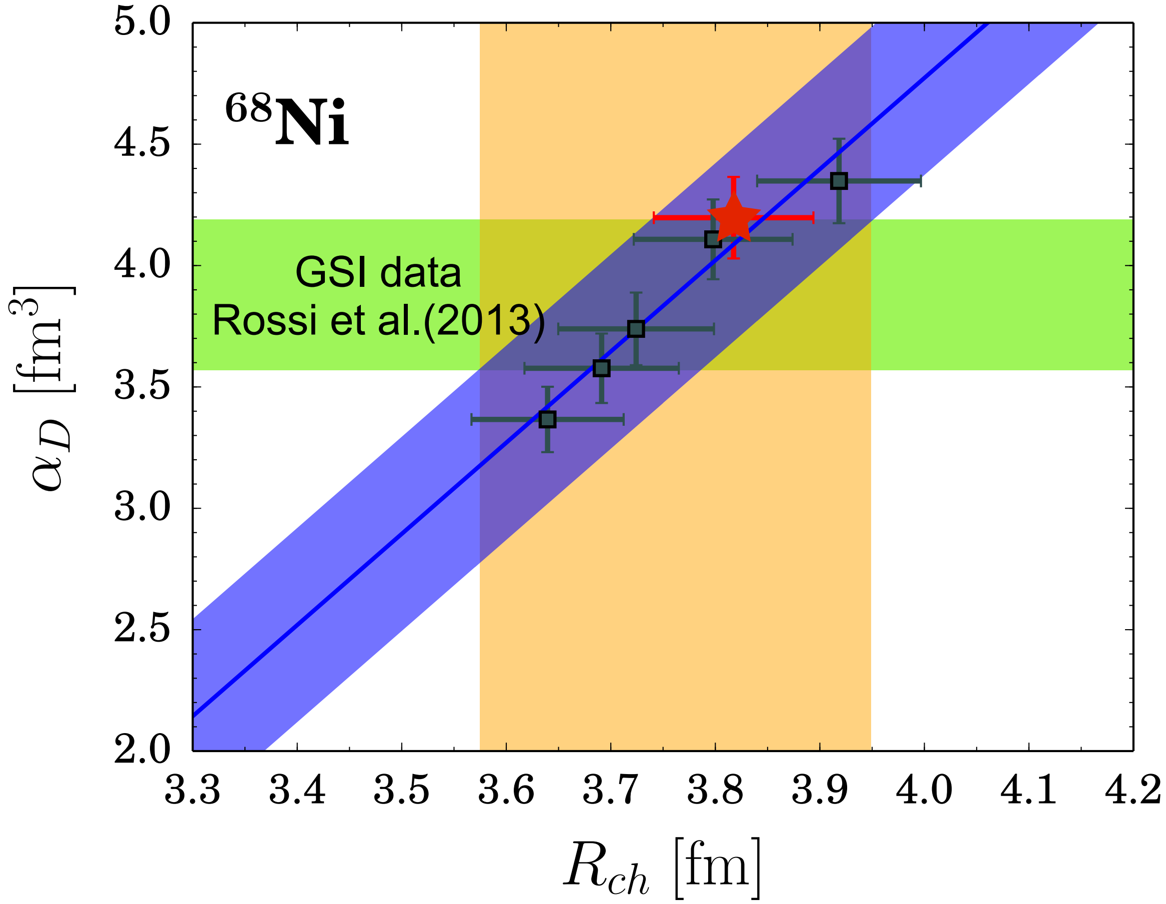


Total error budget: numerical error, atomic physics error, nuclear physics error (in quadrature)

Pushing the mass limits...

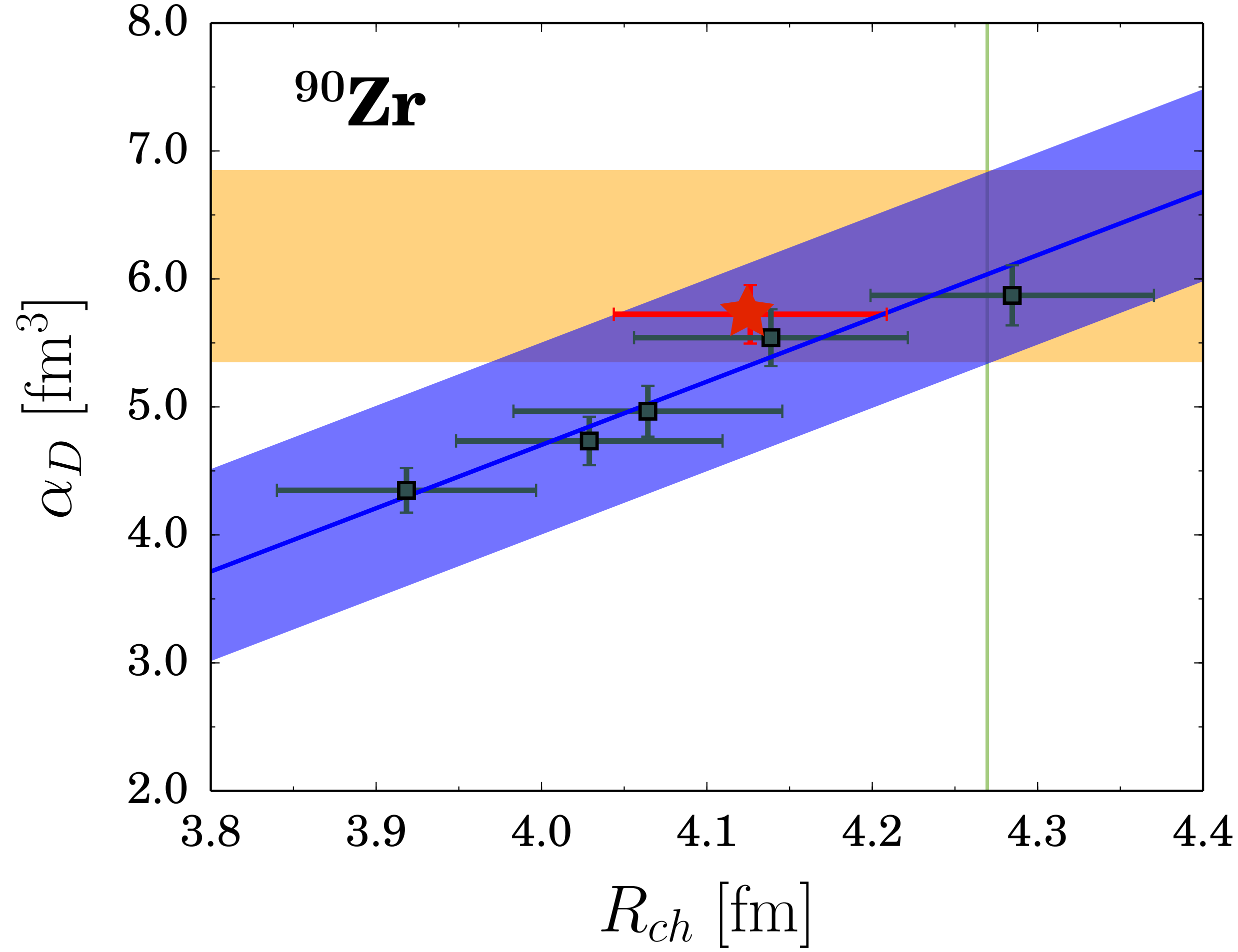
With M. Miorelli

Very preliminary



$^{64}\mathrm{Ni}\quad R_{ch} = 3.8572\ \mathrm{fm}$

Very preliminary



Consistent with DFT calculations, Roca-Maza (2015)

$\alpha_D \approx 5.65\ \mathrm{fm}^3$

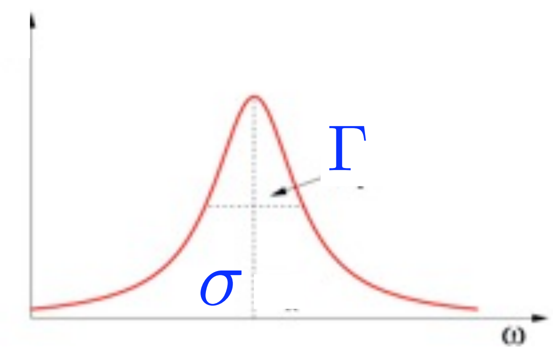
Lorentz Integral Transform Method

Equation can be solved with any bound-state method

Reduces the continuum problem to a bound-state problem

$$L(\sigma,\Gamma) = \int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2} = \left\langle \tilde{\psi} | \tilde{\psi} \right\rangle < \infty$$

Efros, *et al.*, JPG.: Nucl.Part.Phys. **34** (2007) R459



$$\boxed{(H - E_0 - \sigma + i\Gamma)|\tilde{\psi}\rangle = \Theta|\Psi_0\rangle}$$

We solved this equation with HH, NCSM and Coupled-cluster Theory

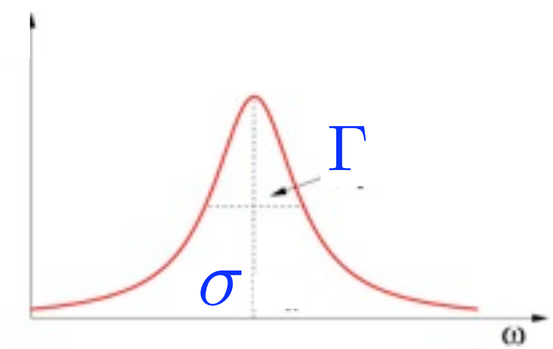
Lorentz Integral Transform Method

Equation can be solved with any bound-state method

Reduces the continuum problem to a bound-state problem

$$L(\sigma,\Gamma) = \int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2} = \left\langle \tilde{\psi} | \tilde{\psi} \right\rangle < \infty$$

Efros, *et al.*, JPG.: Nucl.Part.Phys. **34** (2007) R459



$$\boxed{(H - E_0 - \sigma + i\Gamma)|\tilde{\psi}\rangle = \Theta|\Psi_0\rangle}$$

We solved this equation with HH, NCSM and Coupled-cluster Theory

$$\langle\tilde{\psi}|\tilde{\psi}\rangle \xrightarrow{\text{inversion}} R(\omega)$$

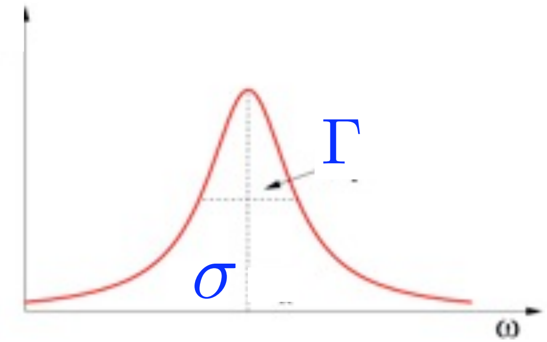
Lorentz Integral Transform Method

Equation can be solved with any bound-state method

Reduces the continuum problem to a bound-state problem

$$L(\sigma,\Gamma) = \int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2} = \left\langle \tilde{\psi} | \tilde{\psi} \right\rangle < \infty$$

Efros, *et al.*, JPG.: Nucl.Part.Phys. **34** (2007) R459

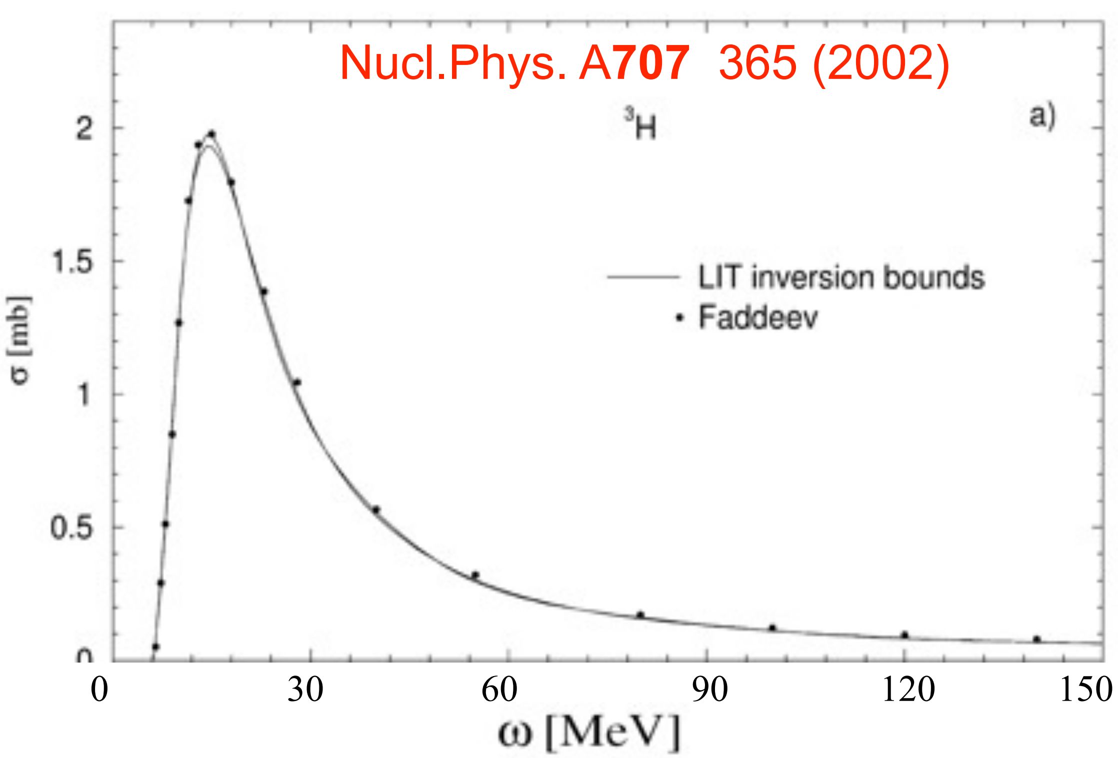


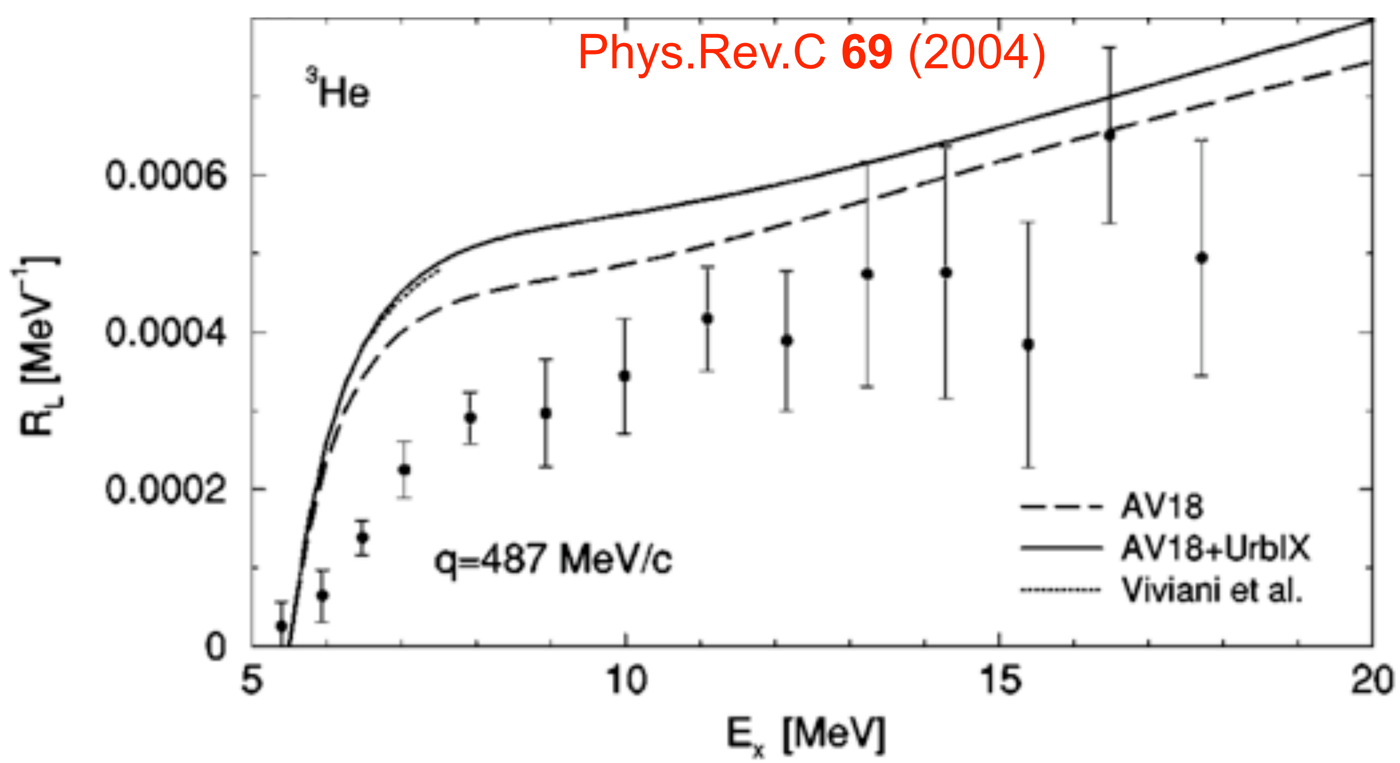
$$\boxed{(H - E_0 - \sigma + i\Gamma)|\tilde{\psi}\rangle = \Theta|\Psi_0\rangle}$$

We solved this equation with HH, NCSM and Coupled-cluster Theory

$$\langle\tilde{\psi}|\tilde{\psi}\rangle \xrightarrow{\text{inversion}} R(\omega)$$

Benchmarks with methods that calculate the final states





Coulomb Sum Rule

With Tianrui Xu, undergrad at UBC

Following Lovato *et al.* PRL **111** 092501 (2013), we starting from the Coulomb sum rule

$$S_L(q) = \frac{1}{Z}\int_{\omega_{th}}^{\infty} d\omega \frac{R_L(\omega, q)}{{G_E^p}^2(Q^2)}$$

Total inelastic strength

$$R_L(\omega, \mathbf{q}) = \sum_f |\langle\Psi_f| \rho(\mathbf{q}) |\Psi_0\rangle|^2 \, \delta\left(E_f - E_0 - \omega + \frac{\mathbf{q}^2}{2M}\right)$$

Coulomb Sum Rule

With Tianrui Xu, undergrad at UBC

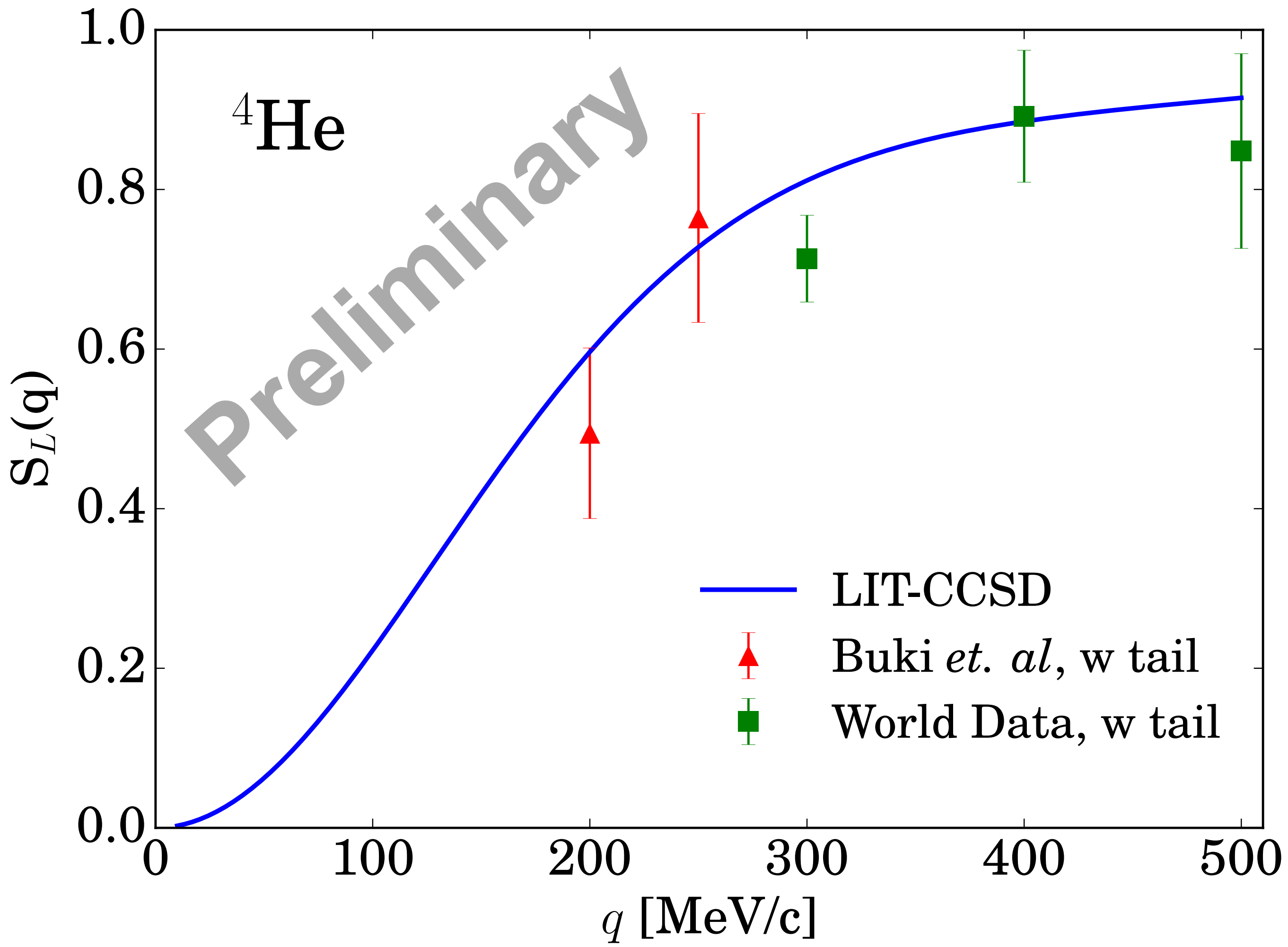
Following Lovato *et al.* PRL **111** 092501 (2013), we starting from the Coulomb sum rule

$$S_L(q) = \frac{1}{Z}\int_{\omega_{th}}^{\infty} d\omega \frac{R_L(\omega,q)}{{G_E^p}^2(Q^2)}$$

Total inelastic strength

$$R_L(\omega,\mathbf{q}) = \sum\!\!\!\!\!\!\int_f |\langle\Psi_f|\,\rho(\mathbf{q})\,|\Psi_0\rangle|^2\,\delta\left(E_f - E_0 - \omega + \frac{\mathbf{q}^2}{2M}\right)$$

T.Xu *et al.*, EPJ Web of Conferences **113**, 04016 (2016)



Coulomb Sum Rule

With Tianrui Xu, undergrad at UBC

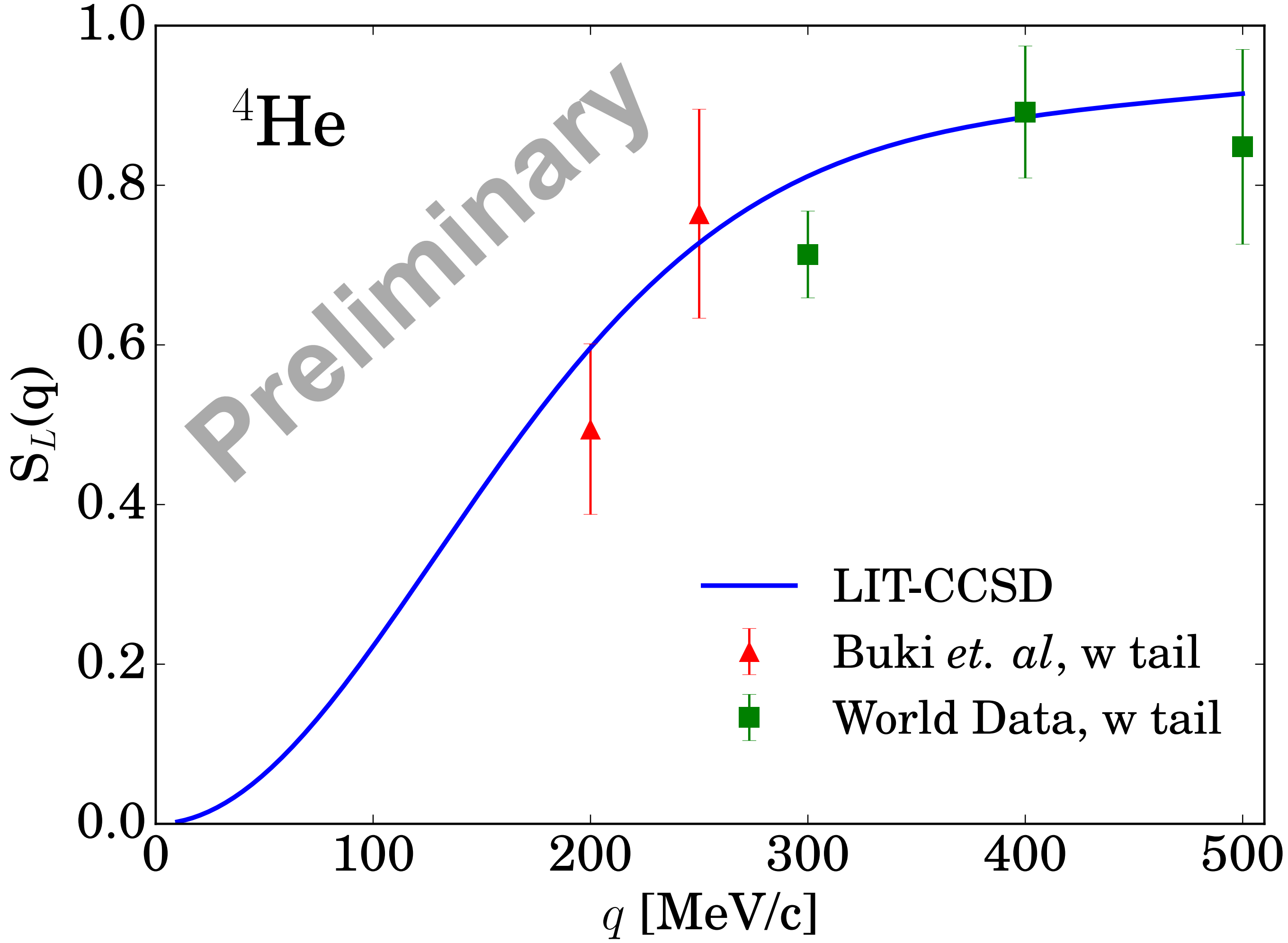
Following Lovato *et al.* PRL **111** 092501 (2013), we starting from the Coulomb sum rule

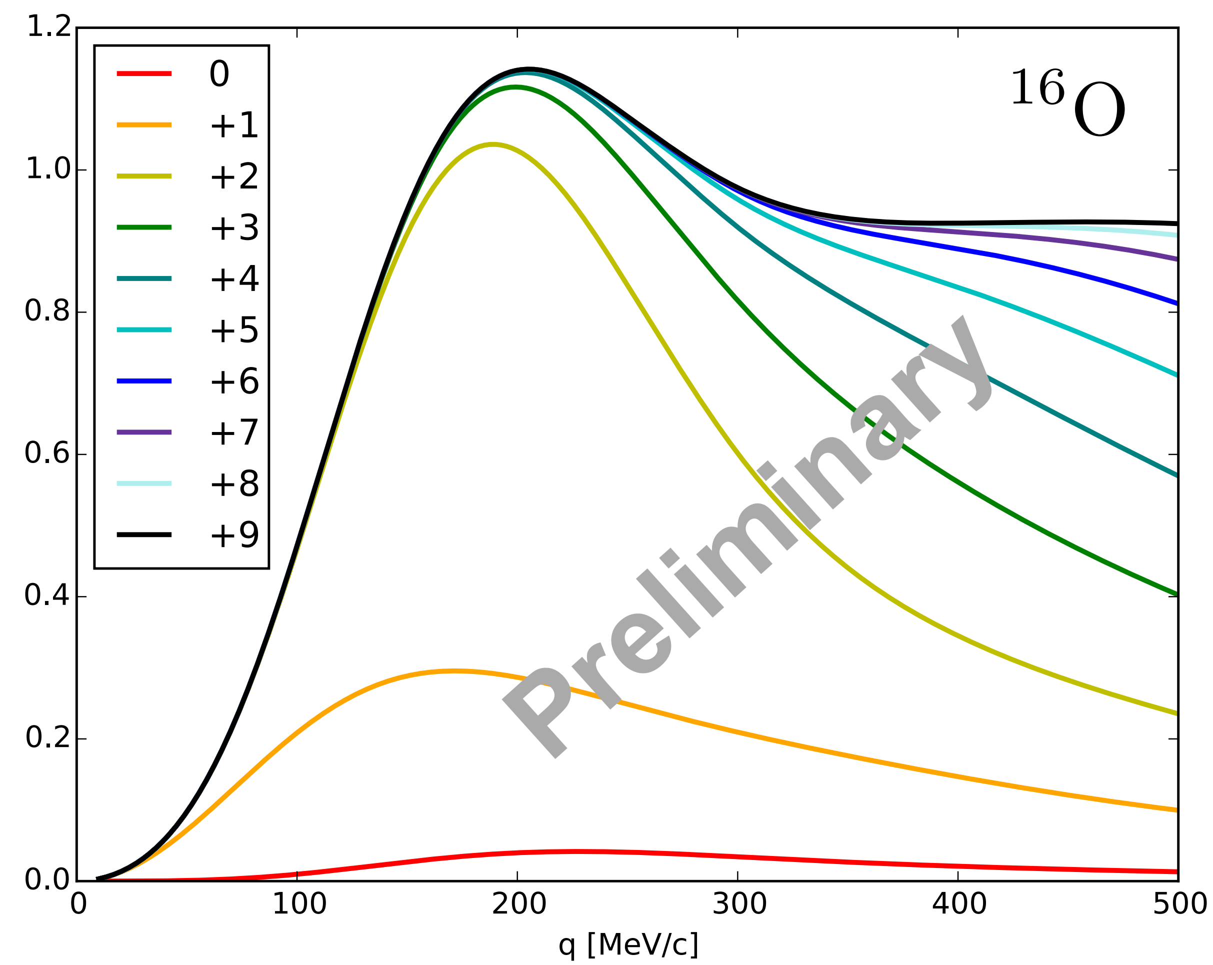
$$S_L(q) = \frac{1}{Z}\int_{\omega_{th}}^{\infty} d\omega \frac{R_L(\omega,q)}{{G_E^p}^2(Q^2)}$$

Total inelastic strength

$$R_L(\omega,\mathbf{q}) = \sum_f |\langle\Psi_f|\,\rho(\mathbf{q})\,|\Psi_0\rangle|^2\,\delta\left(E_f - E_0 - \omega + \frac{\mathbf{q}^2}{2M}\right)$$

T.Xu *et al.*, EPJ Web of Conferences **113**, 04016 (2016)





Coulomb Sum Rule

With Tianrui Xu, undergrad at UBC

Following Lovato *et al.* PRL **111** 092501 (2013), we starting from the Coulomb sum rule

$$S_L(q) = \frac{1}{Z}\int_{\omega_{th}}^{\infty} d\omega \frac{R_L(\omega,q)}{G_E^{p\,2}(Q^2)}$$

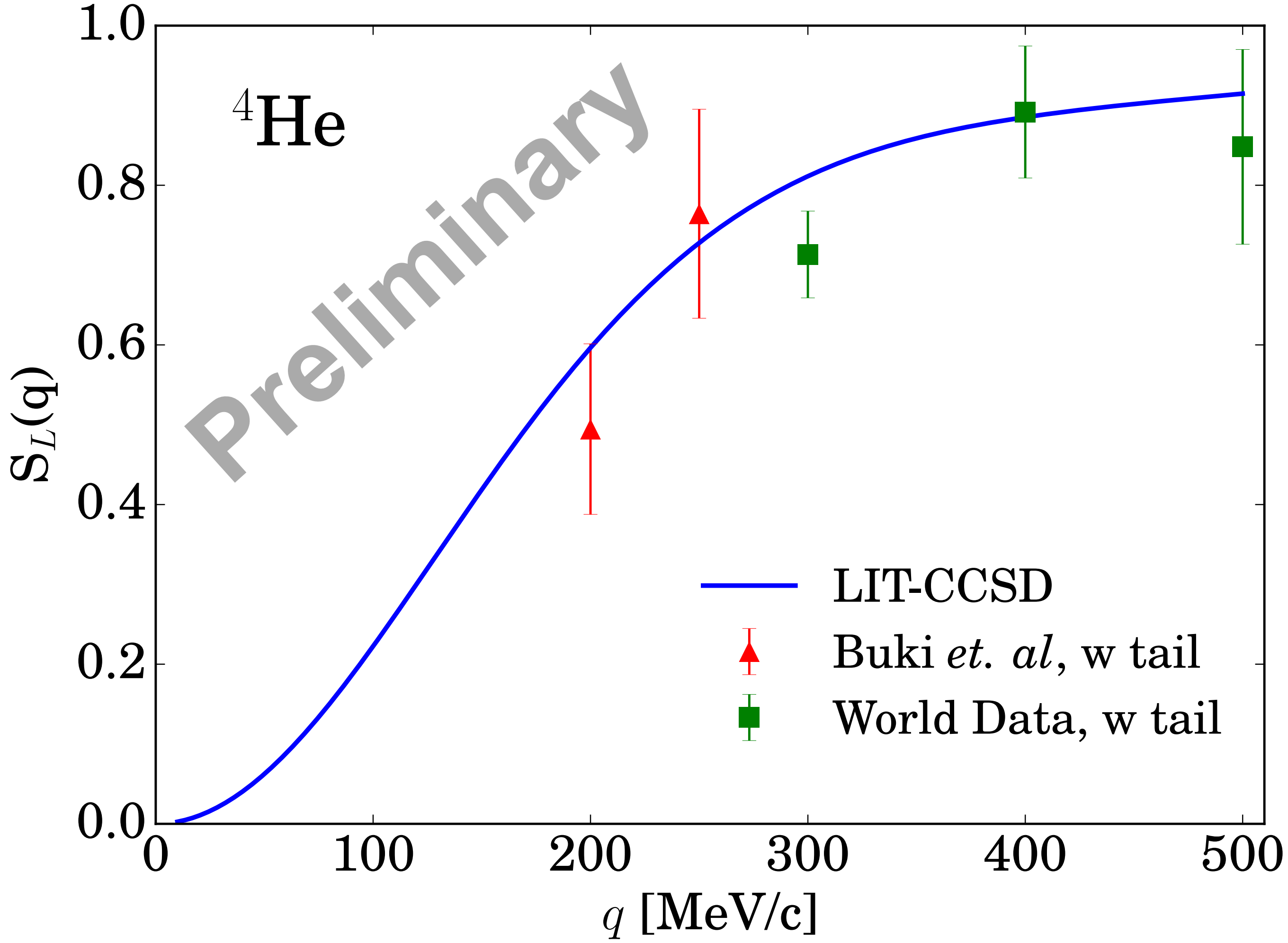
Total inelastic strength

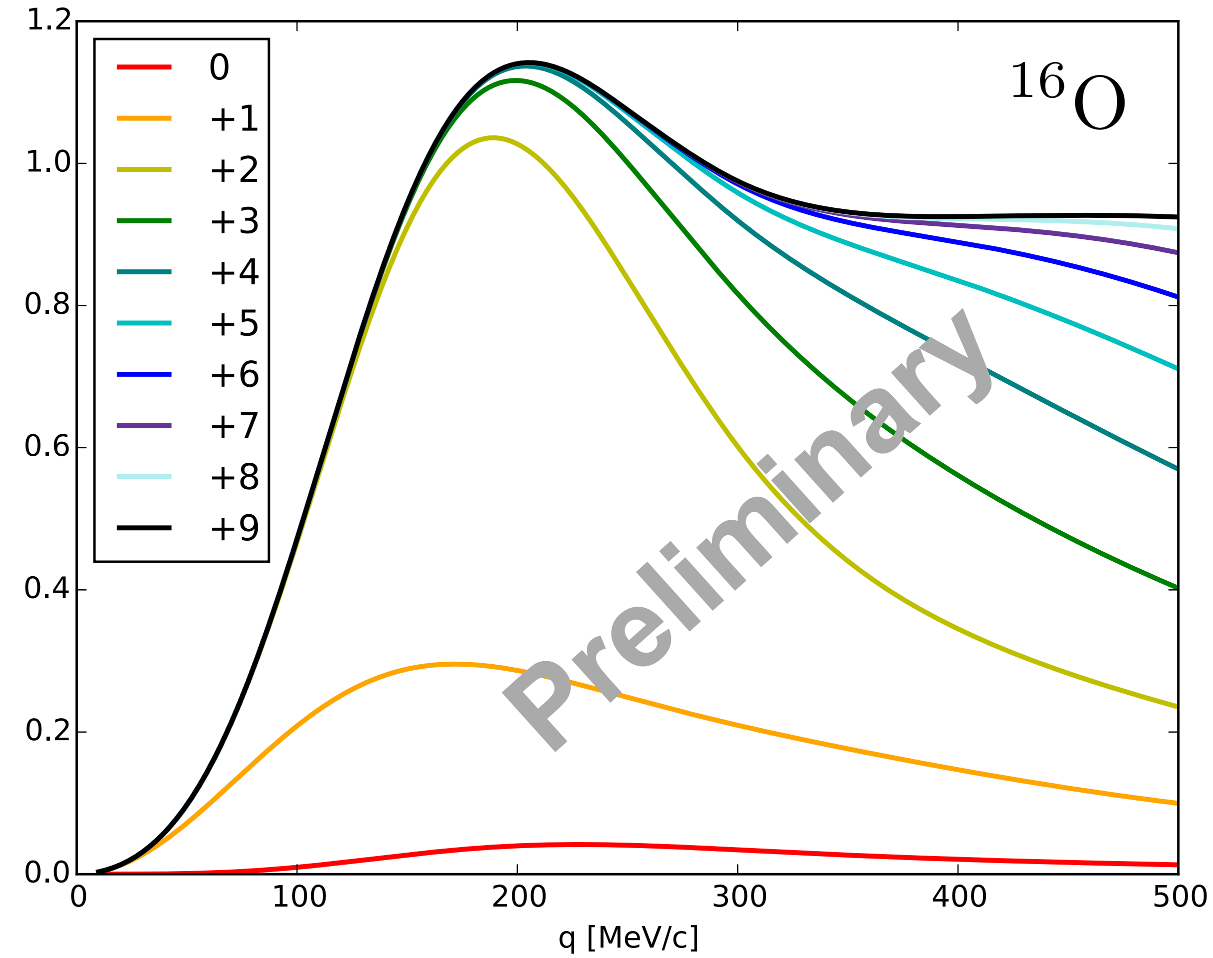
$$R_L(\omega,\mathbf{q}) = \sum_f |\langle\Psi_f|\,\rho(\mathbf{q})\,|\Psi_0\rangle|^2\,\delta\left(E_f - E_0 - \omega + \frac{\mathbf{q}^2}{2M}\right)$$

Future:

Addressing transverse and weak response in ^{16}O with two-body currents

T.Xu *et al.*, EPJ Web of Conferences **113**, 04016 (2016)





Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD (results just released) -1.727(20) meV ⇒ PLB **736**, 334 (2014)
- μ^4He$^+$ (analyzing data) -9.58(38) meV ⇒ PRL **111**, 143402 (2013)
- μ^3He$^+$ (analyzing data) -15.46(39) meV ⇒ PLB **755**, 380 (2016)
- μ^3H (impossible/possible?) -0.767(25) meV ⇒ PLB **755**, 380 (2016)
- μ^6Li^{2+}, μ^7Li^{2+} (future)

$$\Delta E_{2S-2P} = \delta_{\mathrm{QED}} + \mathcal{A}_{\mathrm{OPE}} \langle r_c^2 \rangle + \boxed{\delta_{\mathrm{TPE}}}$$

Understanding the proton-radius puzzle

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

μD (results just released)	-1.727(20) meV	$\Rightarrow$	PLB **736**, 334 (2014)	1%
μ^4He$^+$ (analyzing data)	-9.58(38) meV	$\Rightarrow$	PRL **111**, 143402 (2013)	6%
μ^3He$^+$ (analyzing data)	-15.46(39) meV	$\Rightarrow$	PLB **755**, 380 (2016)	3%
μ^3H (impossible/possible?)	-0.767(25) meV	$\Rightarrow$	PLB **755**, 380 (2016)	
μ^6Li^{2+}, μ^7Li^{2+} (future)				

$$\Delta E_{2S-2P} = \delta_{\mathrm{QED}} + \mathcal{A}_{\mathrm{OPE}}\langle r_c^2 \rangle + \boxed{\delta_{\mathrm{TPE}}}$$

Understanding the proton-radius puzzle

Theory provides crucial information for precision experiments

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

μD (results just released)	-1.727(20) meV	⇒	PLB **736**, 334 (2014)	1%
μ^4He$^+$ (analyzing data)	-9.58(38) meV	⇒	PRL **111**, 143402 (2013)	6%
μ^3He$^+$ (analyzing data)	-15.46(39) meV	⇒	PLB **755**, 380 (2016)	3%
μ^3H (impossible/possible?)	-0.767(25) meV	⇒	PLB **755**, 380 (2016)	
μ^6Li^{2+}, μ^7Li^{2+} (future)				

$$\Delta E_{2S-2P} = \delta_{\rm QED} + \mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \boxed{\delta_{\rm TPE}}$$

Understanding the proton-radius puzzle

Theory provides crucial information for precision experiments

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

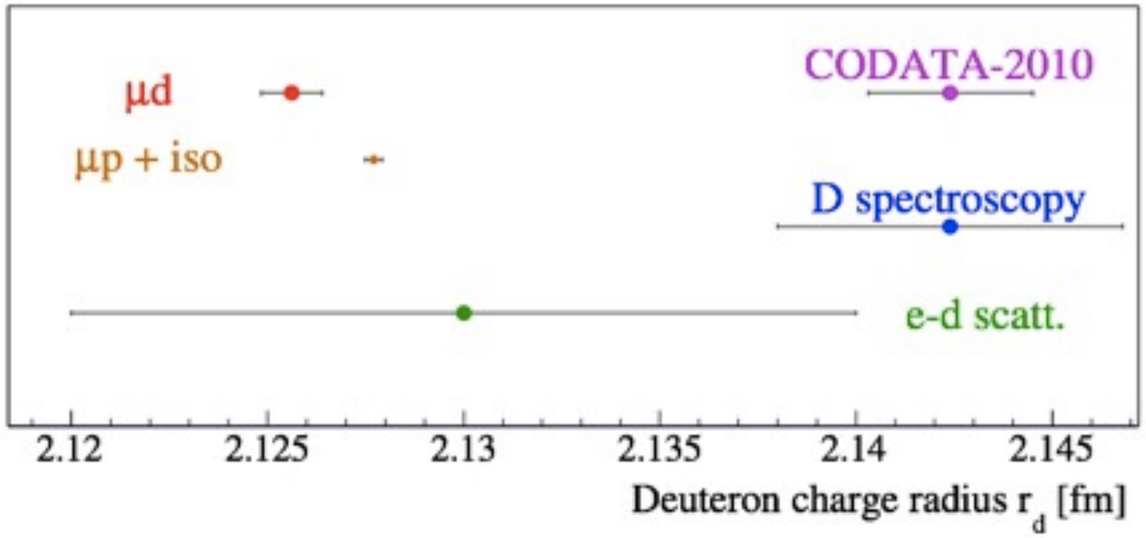
- μD (results just released) -1.727(20) meV ⇒ PLB **736**, 334 (2014) 1%
- μ^4He$^+$ (analyzing data) -9.58(38) meV ⇒ PRL **111**, 143402 (2013) 6%
- μ^3He$^+$ (analyzing data) -15.46(39) meV ⇒ PLB **755**, 380 (2016)
- μ^3H (impossible/possible?) -0.767(25) meV ⇒ PLB **755**, 380 (2016) 3%
- μ^6Li^{2+}, μ^7Li^{2+} (future)

$$\Delta E_{2S-2P} = \delta_{\rm QED} + \mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \boxed{\delta_{\rm TPE}}$$

Recent experimental news - R.Pohl *et al.*, Science 2016

- μD: There is a puzzle!

  7.5σ deviations from μD and CODATA



Understanding the proton-radius puzzle

Theory provides crucial information for precision experiments

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD (results just released) -1.727(20) meV $\Rightarrow$ PLB **736**, 334 (2014) 1%
- μ^4He$^+$ (analyzing data) -9.58(38) meV $\Rightarrow$ PRL **111**, 143402 (2013) 6%
- μ^3He$^+$ (analyzing data) -15.46(39) meV $\Rightarrow$ PLB **755**, 380 (2016) 3%
- μ^3H (impossible/possible?) -0.767(25) meV $\Rightarrow$ PLB **755**, 380 (2016)
- μ^6Li^{2+}, μ^7Li^{2+} (future)

$$\Delta E_{2S-2P} = \delta_{\rm QED} + \mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \boxed{\delta_{\rm TPE}}$$

Recent experimental news - R.Pohl *et al.*, Science 2016

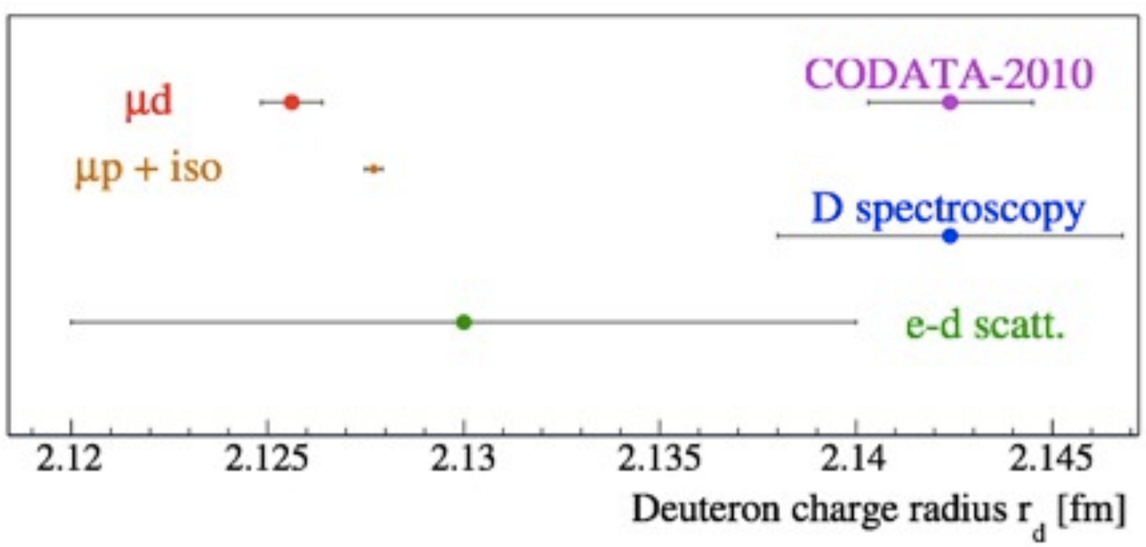
- μD: There is a puzzle!

  7.5σ deviations from μD and CODATA

- μ^4He$^+$: No puzzle!

  muonic atom: 1.679XX(20)$_{\rm exp}$(52)$_{\rm theo}$ fm

  e-scattering: 1.6810(40)



Understanding the proton-radius puzzle

Theory provides crucial information for precision experiments

Strong experimental program at PSI (Switzerland) from the CREMA collaboration to unravel the mystery by studying other muonic atoms:

- μD (results just released) -1.727(20) meV ⇒ PLB **736**, 334 (2014) 1%
- μ^4He^+ (analyzing data) -9.58(38) meV ⇒ PRL **111**, 143402 (2013) 6%
- μ^3He^+ (analyzing data) -15.46(39) meV ⇒ PLB **755**, 380 (2016)
- μ^3H (impossible/possible?) -0.767(25) meV ⇒ PLB **755**, 380 (2016) 3%
- μ^6Li^{2+}, μ^7Li^{2+} (future)

$$\Delta E_{2S-2P} = \delta_{\rm QED} + \mathcal{A}_{\rm OPE}\langle r_c^2\rangle + \boxed{\delta_{\rm TPE}}$$

Stay tuned!

Vanderhaeghen talk on Fri.

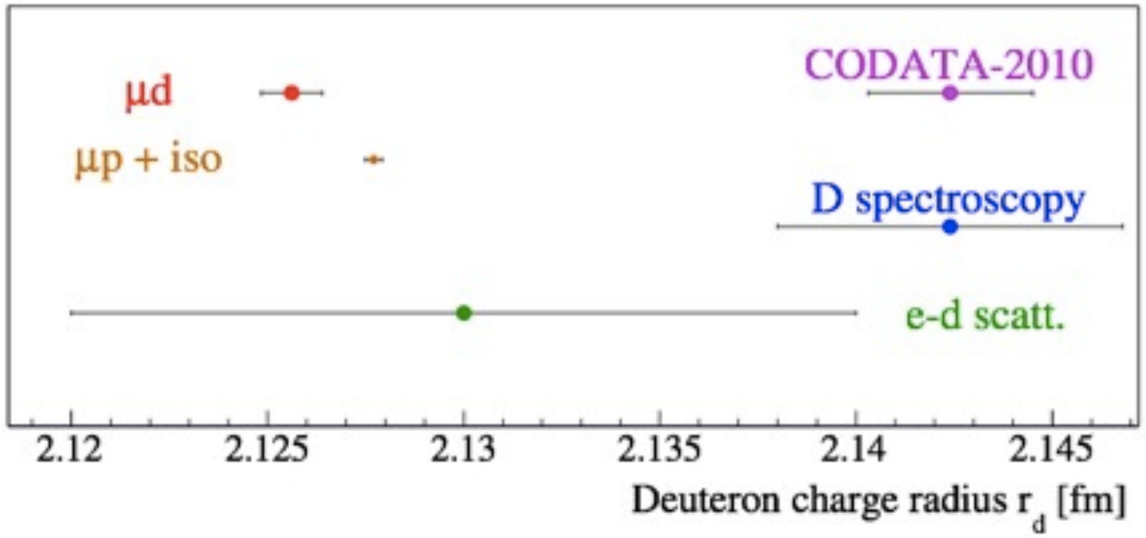
Recent experimental news - R.Pohl *et al.*, Science 2016

- μD: There is a puzzle!

  7.5σ deviations from μD and CODATA

- μ^4He^+ : No puzzle!

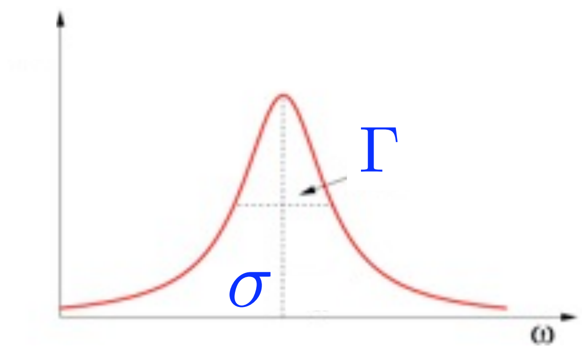
  muonic atom: 1.679XX(20)$_{\rm exp}$(52)$_{\rm theo}$ fm
  e-scattering: 1.6810(40)



LIT with Coupled-cluster method

Merging the Lorentz integral transform method with coupled-cluster theory :
New many-body method to extend *ab initio* calculations of em reactions to medium-mass-nuclei

S.B. *et al.*, Phys. Rev. Lett. **111**, 122502 (2013)



$$L(\sigma,\Gamma) = \int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2} = \left\langle \tilde{\psi} | \tilde{\psi} \right\rangle < \infty$$

$$\boxed{(\bar{H} - E_0 - \sigma + i\Gamma)|\tilde{\Psi}_R\rangle = \bar{\Theta}|\Phi_0\rangle}$$

$$\bar{H} = e^{-T} H e^{T}$$

$$\bar{\Theta} = e^{-T} \Theta e^{T}$$

$$|\tilde{\Psi}_R\rangle = \hat{R}|\Phi_0\rangle$$

$$\hat{R} = \hat{R}_0 + \hat{R}_1 + \hat{R}_2$$

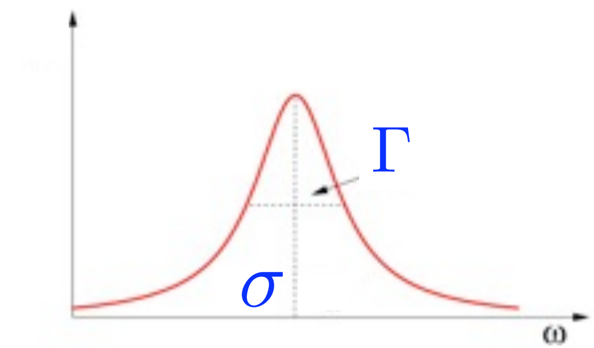
Presenting results in the CCSD scheme

LIT with Coupled-cluster method

Merging the Lorentz integral transform method with coupled-cluster theory :
New many-body method to extend *ab initio* calculations of em reactions to medium-mass-nuclei

S.B. *et al.*, Phys. Rev. Lett. **111**, 122502 (2013)

$$L(\sigma,\Gamma)=\int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2}=\left\langle\tilde{\psi}|\tilde{\psi}\right\rangle<\infty$$



$$\boxed{(\bar{H}-E_0-\sigma+i\Gamma)|\tilde{\Psi}_R\rangle=\bar{\Theta}|\Phi_0\rangle}$$

$$\bar{H}=e^{-T}He^{T}$$

$$\bar{\Theta}=e^{-T}\Theta e^{T}$$

$$|\tilde{\Psi}_R\rangle=\hat{R}|\Phi_0\rangle$$

$$\hat{R}=\hat{R}_0+\hat{R}_1+\hat{R}_2$$

Presenting results in the CCSD scheme

Successful benchmark for ^{4}He at CCSD

M.Miorelli *et al.*, Phys. Rev. C **94**, 034317 (2016)