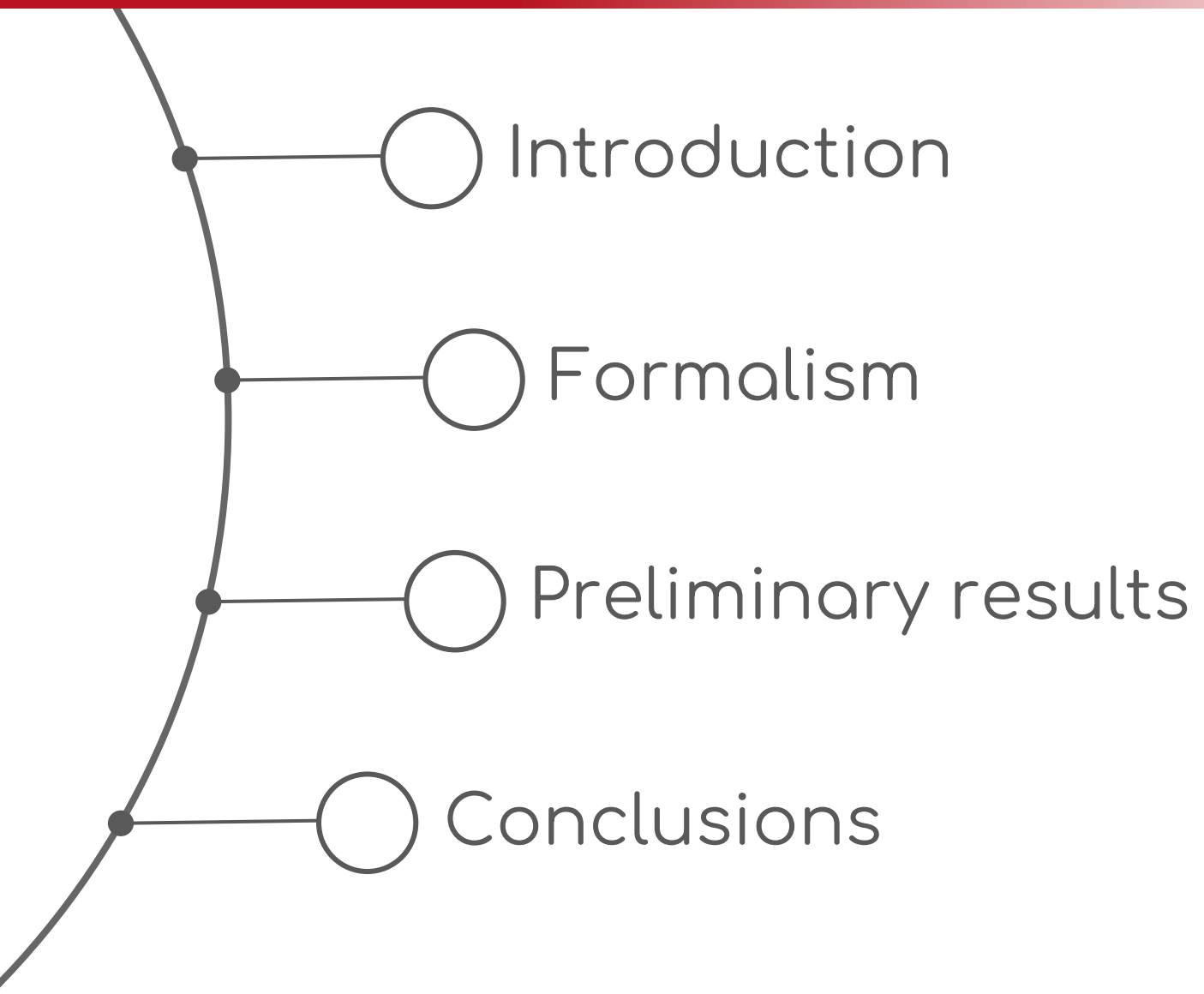
Ab-initio description of monopole resonances in light- and medium-mass nuclei

Preliminary results

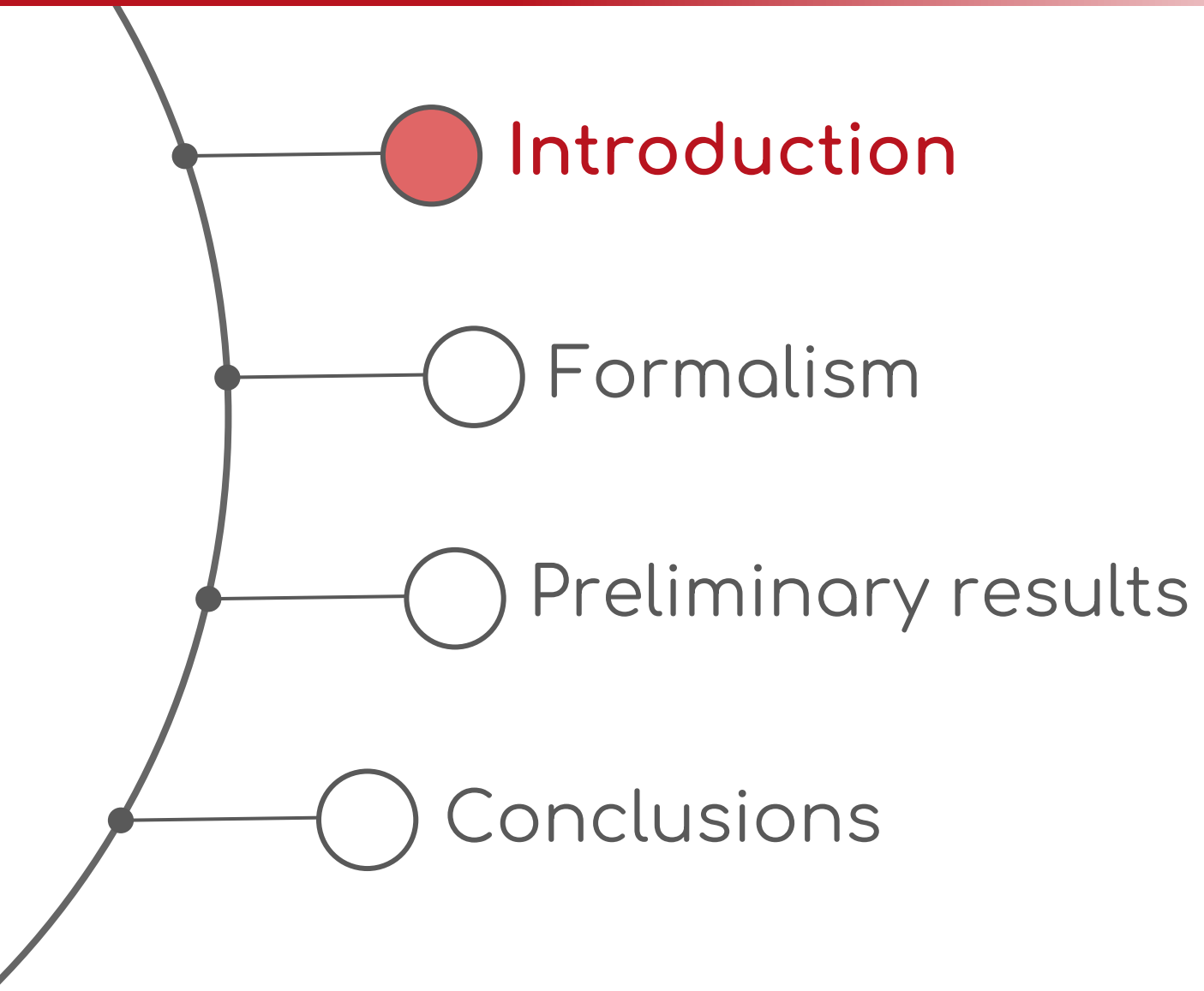
Andrea Porro, PhD Student
IRFU, CEA, Université Paris-Saclay

May 20, 2022
International Spring Seminar on Nuclear Physics
Sant'Angelo d'Ischia

Outline


Introduction
Formalism
Preliminary results
Conclusions

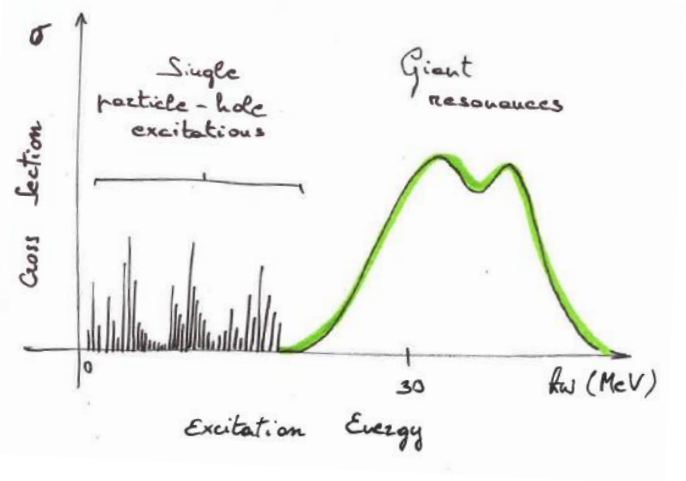
Outline


Introduction
Formalism
Preliminary results
Conclusions

Introduction and Motivation

Dual nature of nucleus

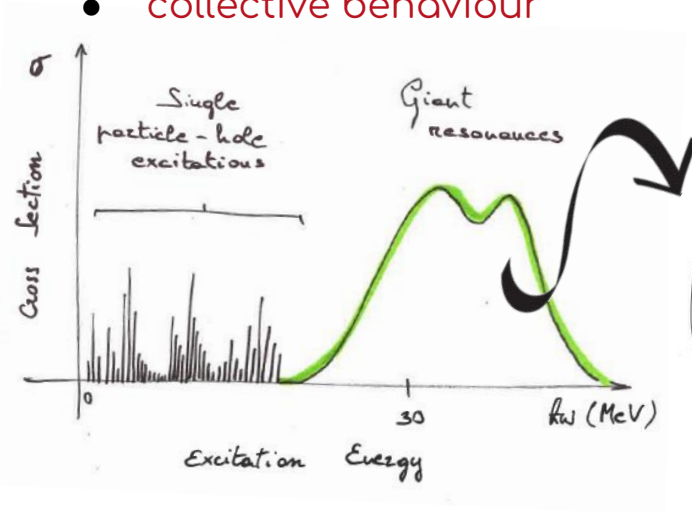
- single-particle features
- collective behaviour



Introduction and Motivation

Dual nature of nucleus

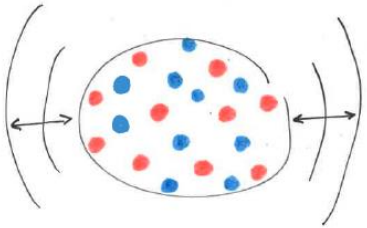
- single-particle features
- collective behaviour



Giant Resonances (GRs)

clearest manifestation of collective motion

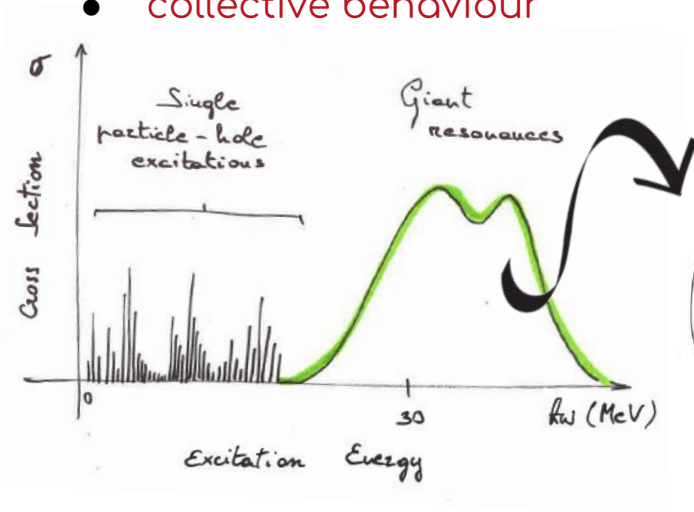
Liquid drop picture
vibrations, oscillations



Introduction and Motivation

Dual nature of nucleus

- single-particle features
- collective behaviour

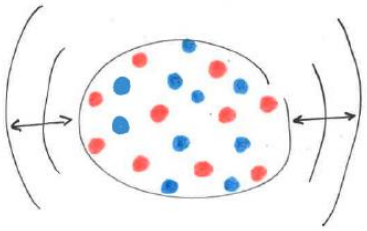


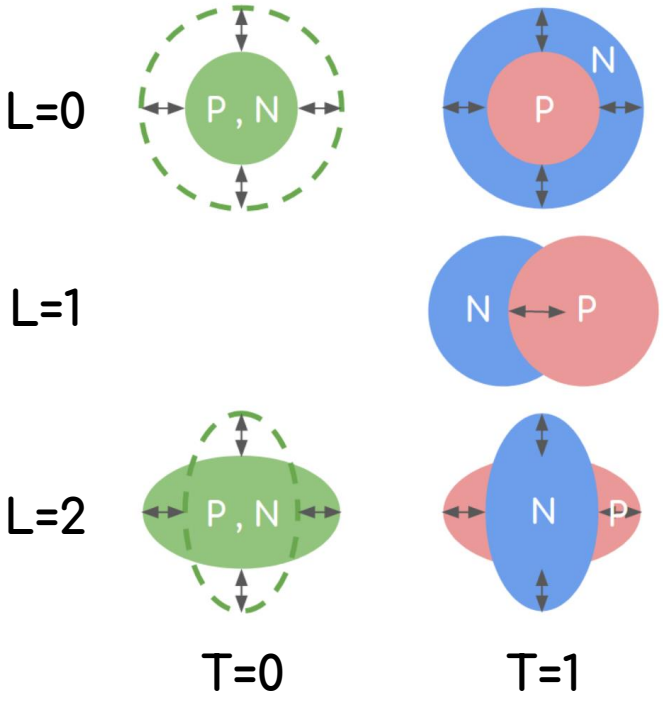
Giant Resonances (GRs)

clearest manifestation of collective motion

decomposed in terms of angular momentum L

Liquid drop picture
vibrations, oscillations

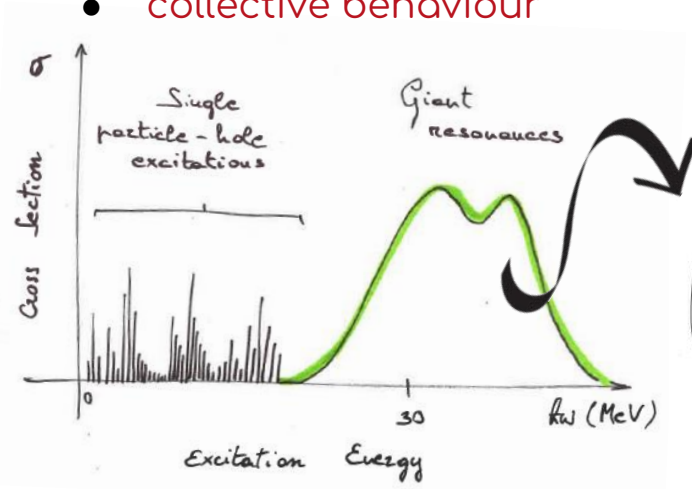




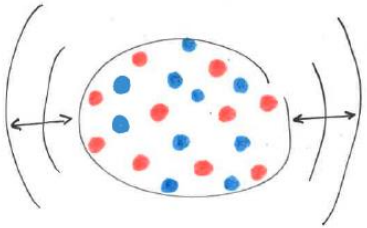
Introduction and Motivation

Dual nature of nucleus

- single-particle features
- collective behaviour



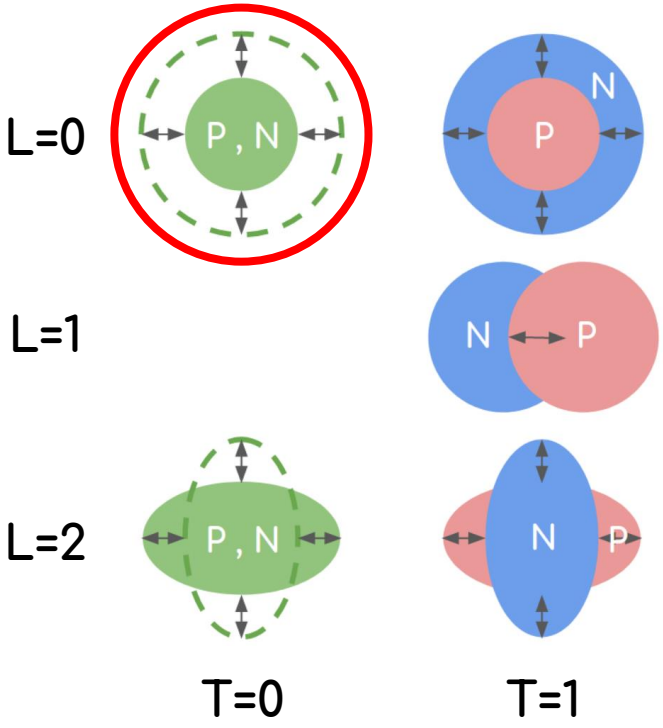
Liquid drop picture
vibrations, oscillations

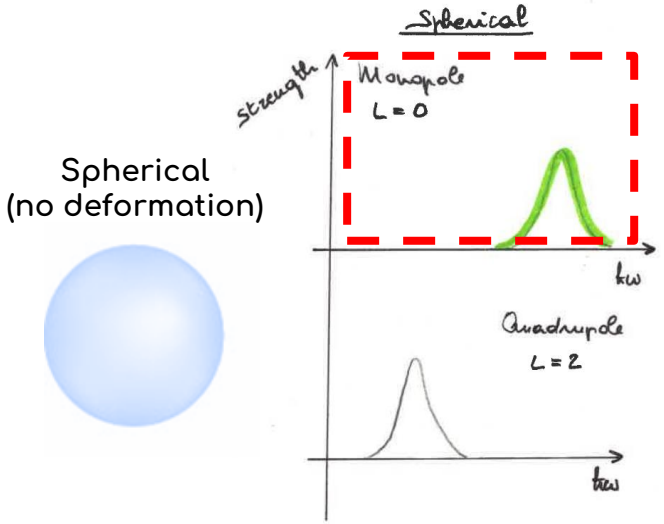


Giant Resonances (GRs)

clearest manifestation of collective motion

decomposed in terms of angular momentum L

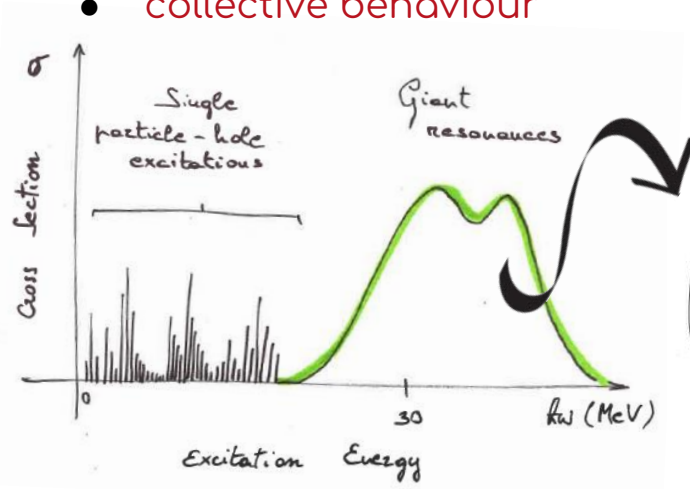




Introduction and Motivation

Dual nature of nucleus

- single-particle features
- collective behaviour

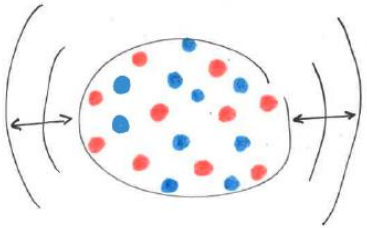


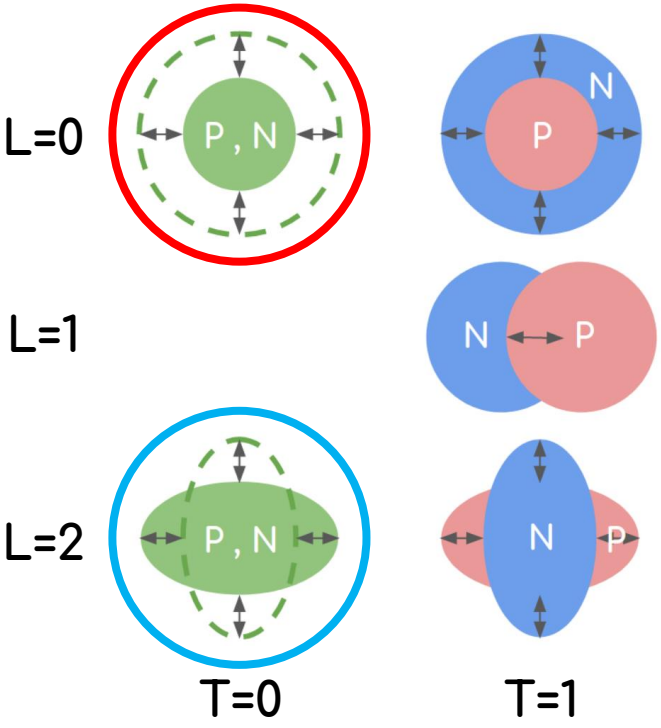
Giant Resonances (GRs)

clearest manifestation of collective motion

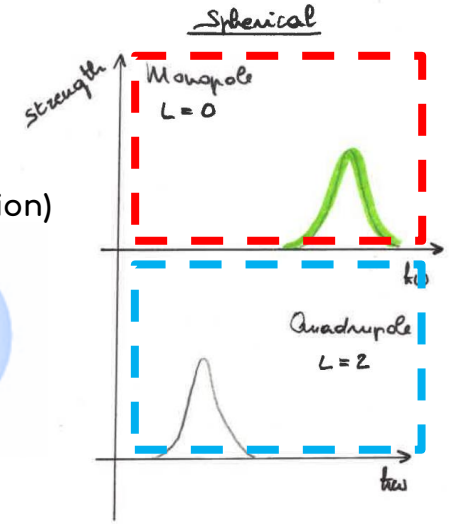
decomposed in terms of angular momentum L

Liquid drop picture
vibrations, oscillations





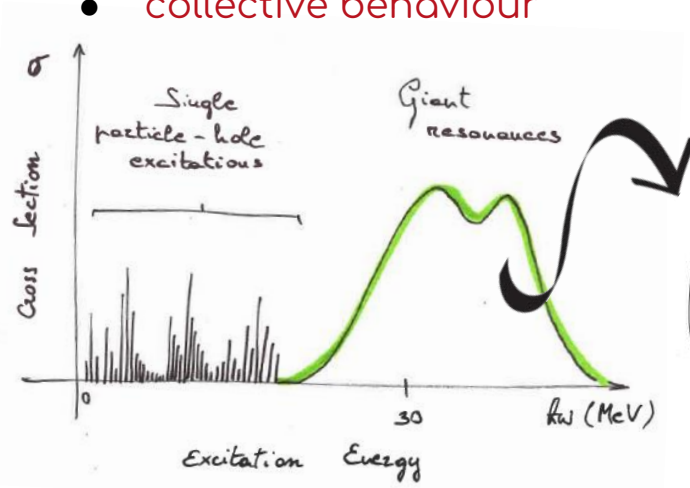
Spherical
(no deformation)



Introduction and Motivation

Dual nature of nucleus

- single-particle features
- collective behaviour

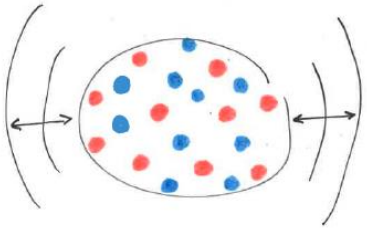


Giant Resonances (GRs)

clearest manifestation of collective motion

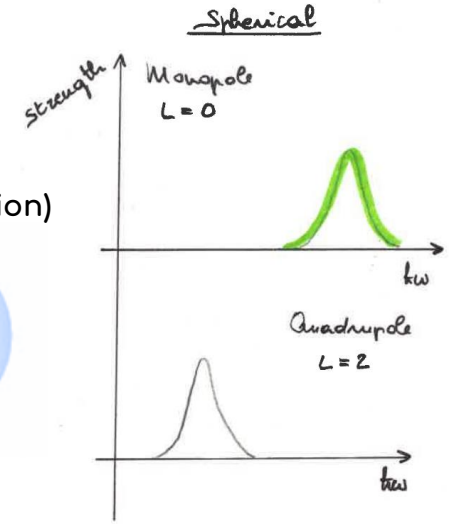
decomposed in terms of angular momentum L

Liquid drop picture
vibrations, oscillations



Deformation
↓
Coupling between different L

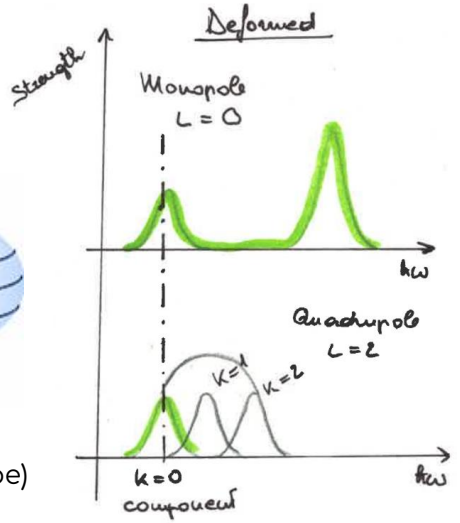
Spherical
(no deformation)



Spheroidal
(deformed)

Prolate
(cigar type)

Oblate
(pancake type)



Introduction and Motivation

Isoscalar Giant Monopole Resonance (ISGMR)

What is it ?

- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Introduction and Motivation

Isoscalar Giant Monopole Resonance (ISGMR)

What is it ?

- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Why studying again GMR ?

- Renewed experimental interest
- Investigate new physics

Introduction and Motivation

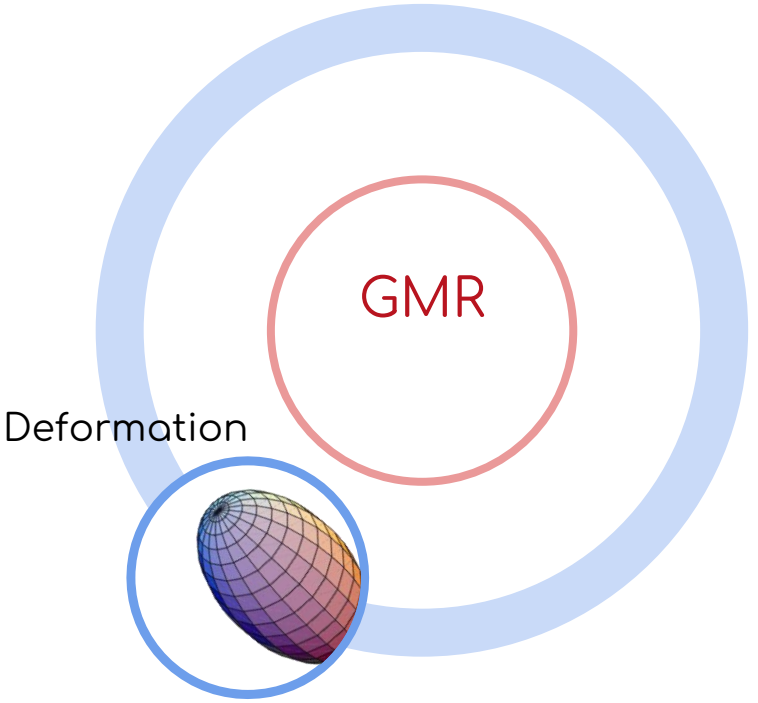
Isoscalar Giant Monopole Resonance (ISGMR)

What is it ?

- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Why studying again GMR ?

- Renewed experimental interest
- Investigate new physics



Introduction and Motivation

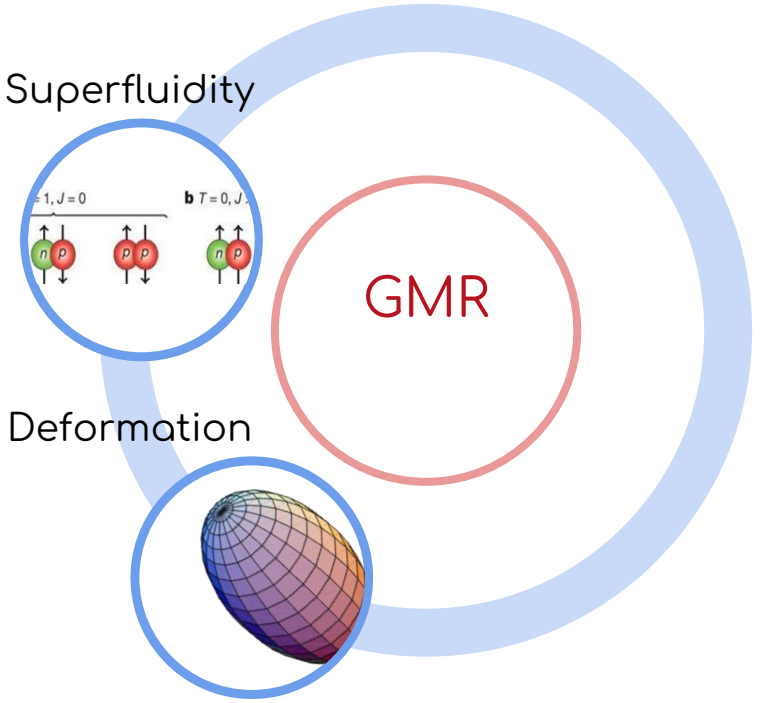
Isoscalar Giant Monopole Resonance (ISGMR)

What is it ?

- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Why studying again GMR ?

- Renewed experimental interest
- Investigate new physics



Introduction and Motivation

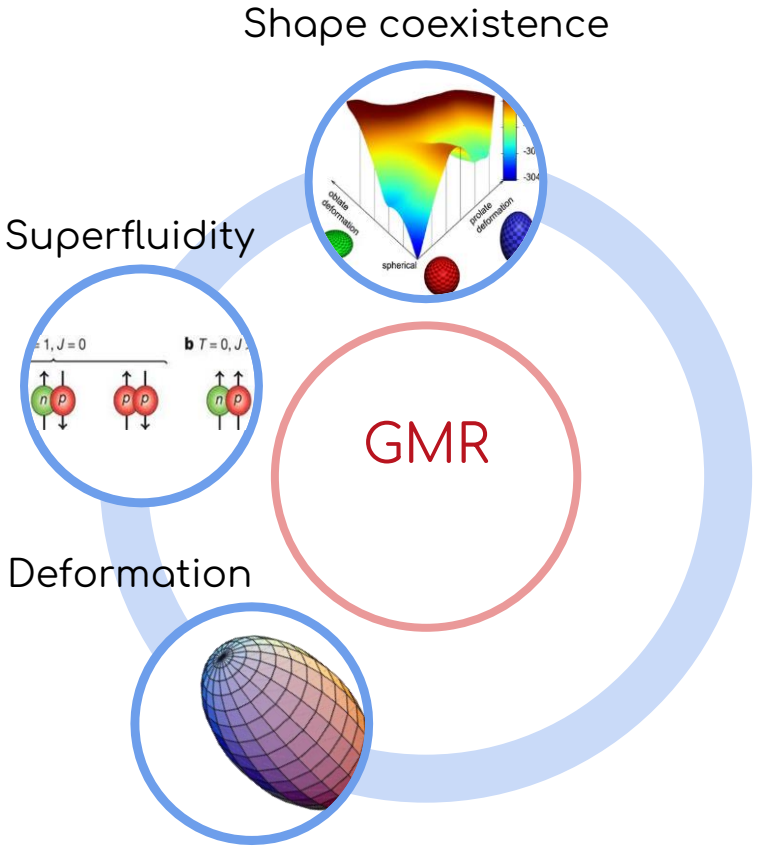
Isoscalar Giant Monopole Resonance (ISGMR)

What is it ?

- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Why studying again GMR ?

- Renewed experimental interest
- Investigate new physics



Introduction and Motivation

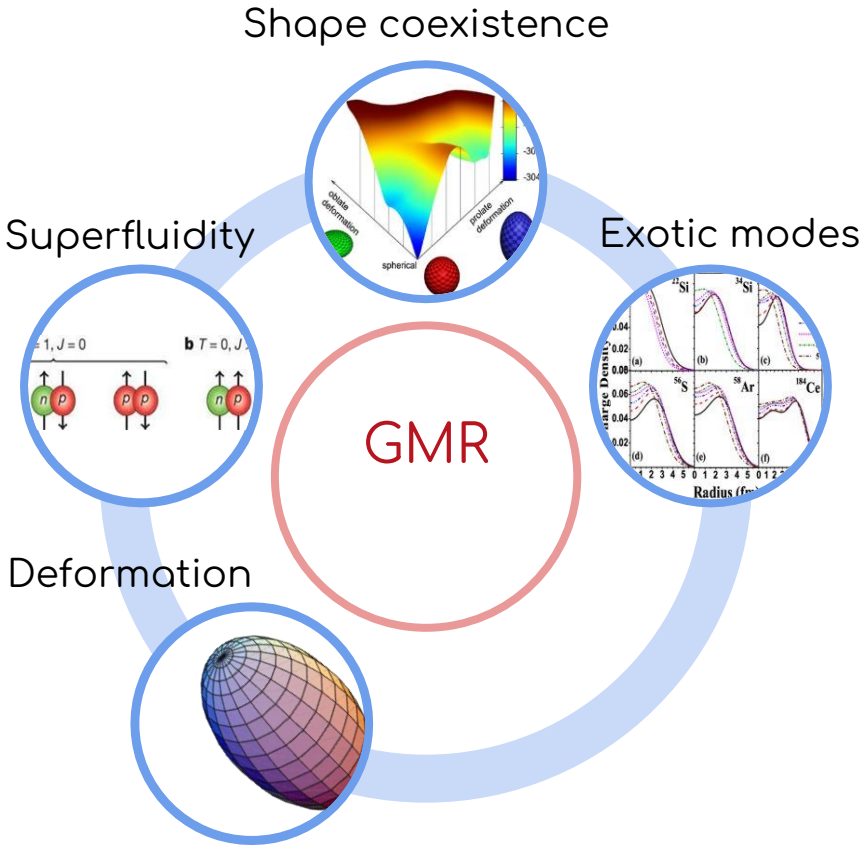
Isoscalar Giant Monopole Resonance (ISGMR)

What is it ?

- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Why studying again GMR ?

- Renewed experimental interest
- Investigate new physics



Introduction and Motivation

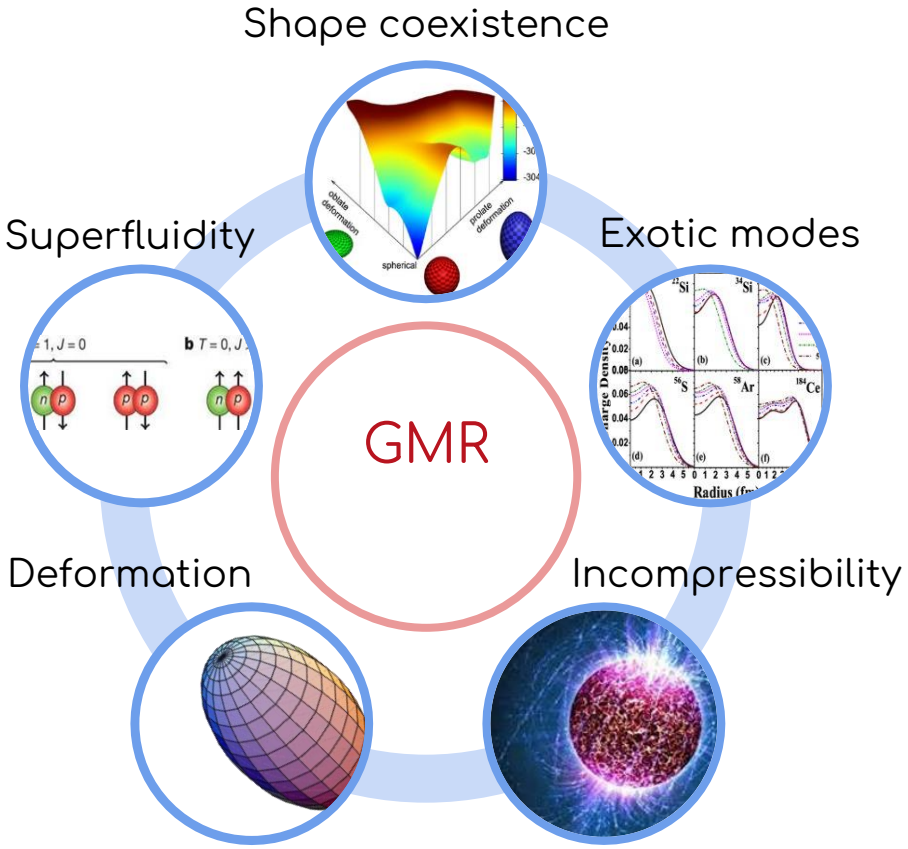
Isoscalar Giant Monopole Resonance (ISGMR)

What is it ?

- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Why studying again GMR ?

- Renewed experimental interest
- Investigate new physics



Introduction and Motivation

Isoscalar Giant Monopole Resonance (ISGMR)

What is it ?

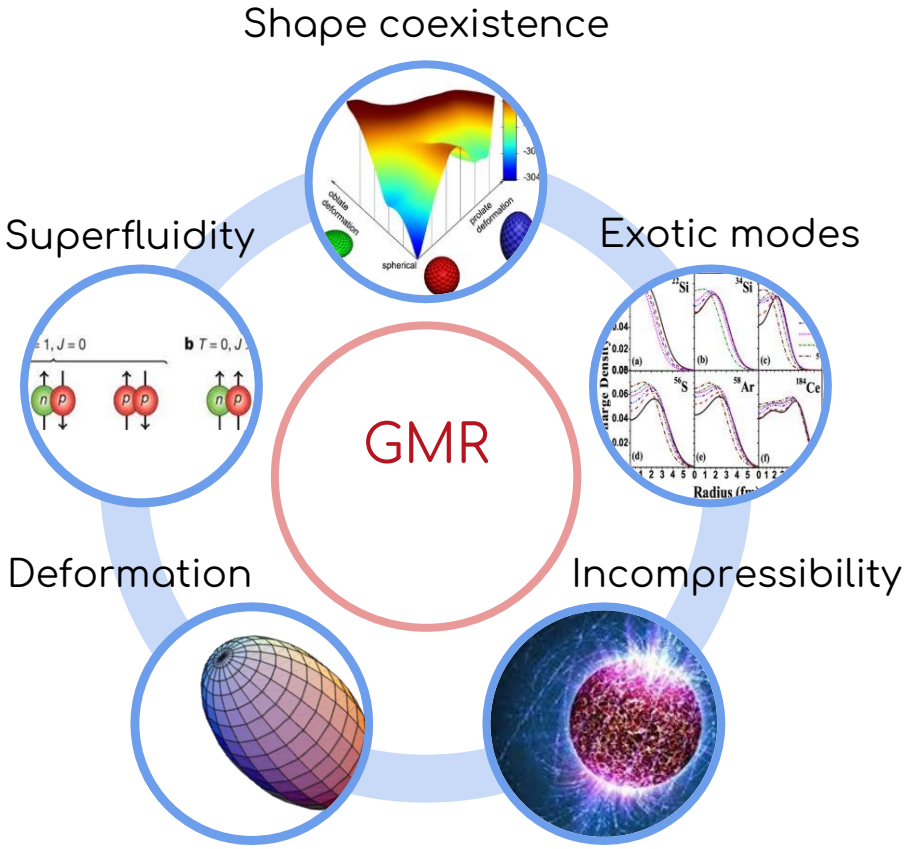
- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Why studying again GMR ?

- Renewed experimental interest
- Investigate new physics

Much is still to be understood !

- No systematic studies (even within EDF)
  - Very generic numerical codes needed
- **Ab-initio description still seminal**



Introduction and Motivation

Isoscalar Giant Monopole Resonance (ISGMR)

What is it ?

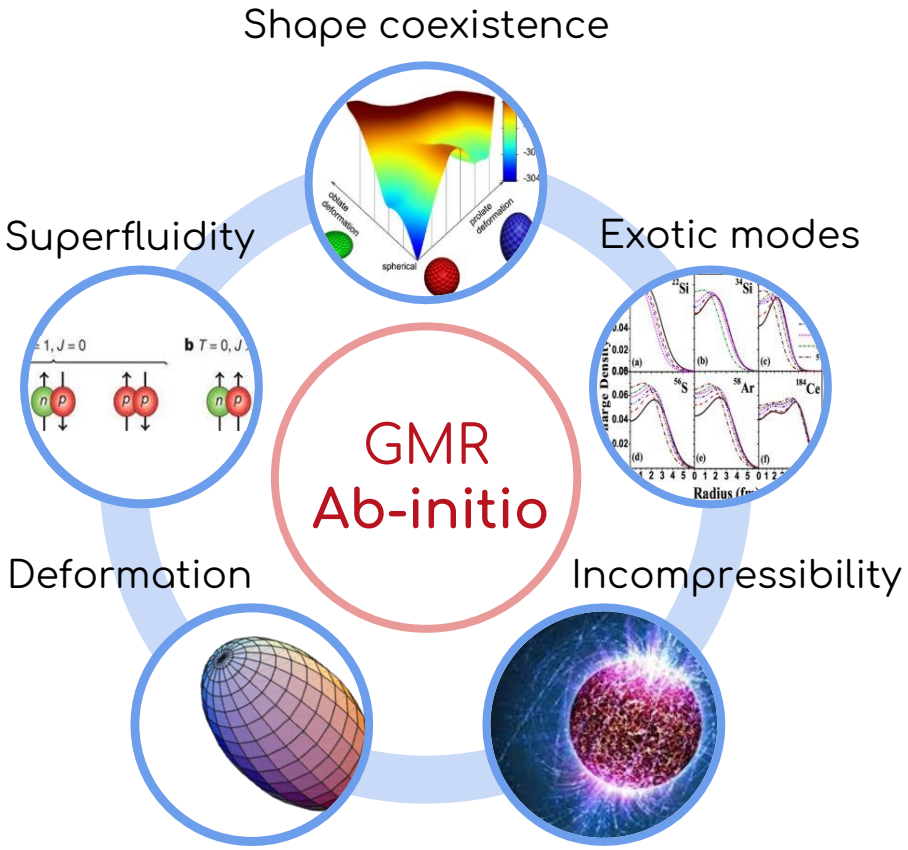
- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Why studying again GMR ?

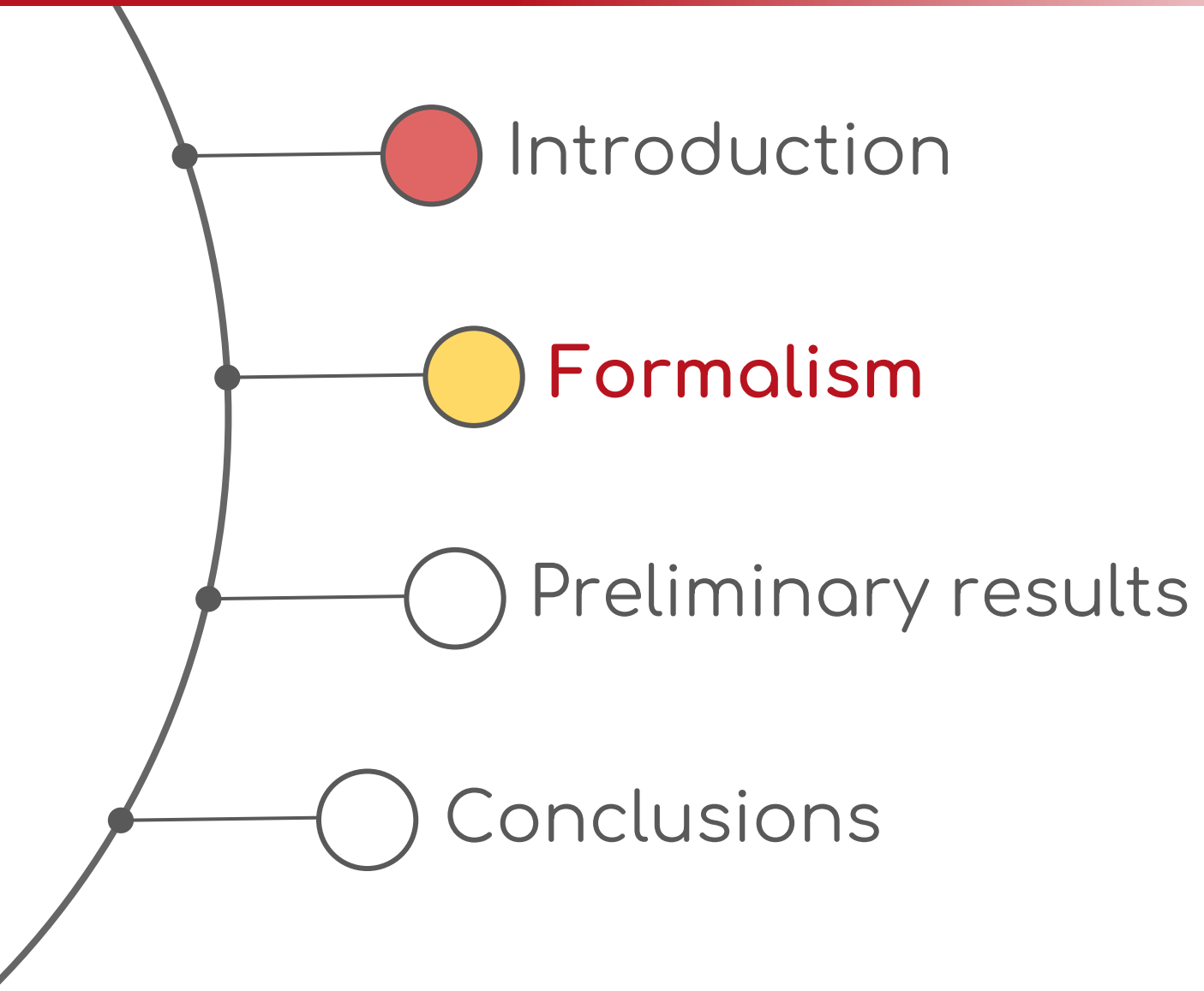
- Renewed experimental interest
- Investigate new physics

Much is still to be understood !

- No systematic studies (even within EDF)
  - Very generic numerical codes needed
- **Ab-initio description still seminal**



Outline


Introduction
Formalism
Preliminary results
Conclusions

Theoretical Frame

Ab-initio methods

Ab-initio methods : EFT Hamiltonian, QCD link

$$H|\Psi_\nu\rangle = E_\nu\,|\Psi_\nu\rangle$$

Theoretical Frame

Ab-initio methods

Ab-initio methods : EFT Hamiltonian, QCD link

$$H|\Psi_\nu\rangle = E_\nu |\Psi_\nu\rangle$$

GMR has historically been studied within **EDF** theory [Garg, Colò, 2018]

Ab-initio unicum: (Q)RPA for spherical systems [Papakonstantinou et al., 2007] ... [Roth et al., 2021]

Theoretical Frame

Ab-initio methods

Ab-initio methods : EFT Hamiltonian, QCD link

$$H|\Psi_\nu\rangle = E_\nu |\Psi_\nu\rangle$$

GMR has historically been studied within EDF theory [Garg, Colò, 2018]

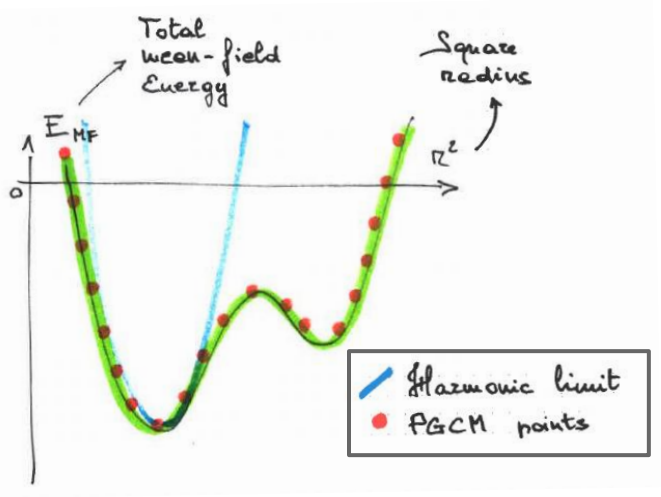
Ab-initio unicum: (Q)RPA for spherical systems [Papakonstantinou et al., 2007] ... [Roth et al., 2021]

Present goal: First systematic ab-initio study of the GMR

- PGCM Projected Generator Coordinate Method
- QRPA Superfluid version of RPA

PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$



PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$

PGCM

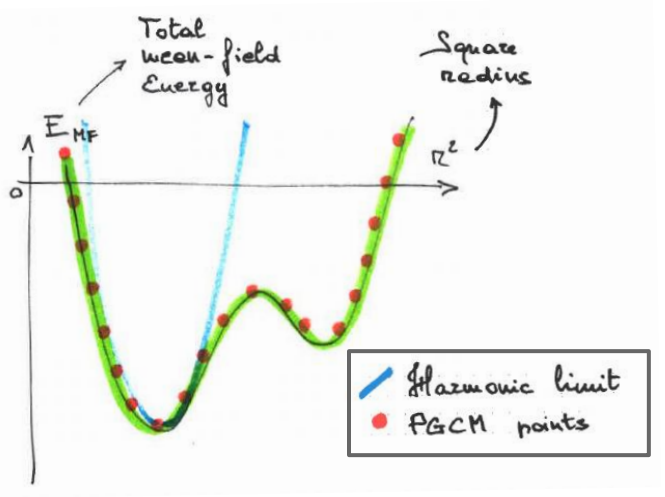
$$|\Psi_\nu\rangle \equiv \sum_{r^2,q} f_\nu(r^2,q)|\Phi(r^2,q)\rangle$$

r^2 to study GMR

q to couple to other modes

Symmetry breaking and restoration

Variational method



PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$

PGCM

$$|\Psi_\nu\rangle \equiv \sum_{r^2,q} f_\nu(r^2,q)|\Phi(r^2,q)\rangle$$

r^2 to study GMR

q to couple to other modes

Symmetry breaking and restoration

Variational method

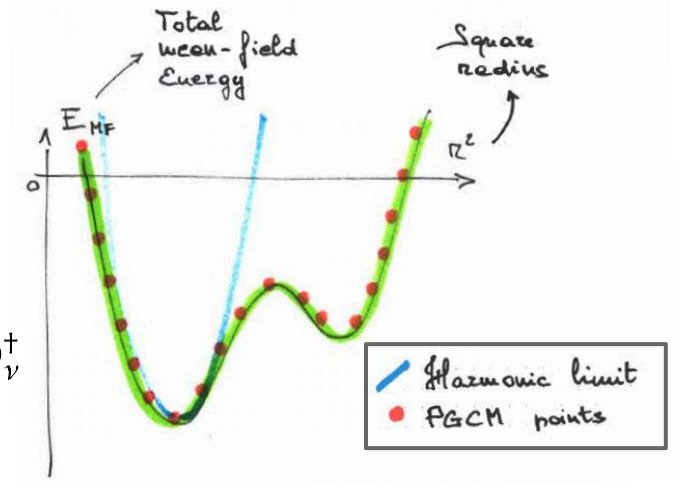
QRPA

$$|\Psi_\nu\rangle \equiv Q_\nu^\dagger|\Psi_0\rangle$$

Boson-like excitation operators $Q_\nu^\dagger$

QRPA matrix diagonalization

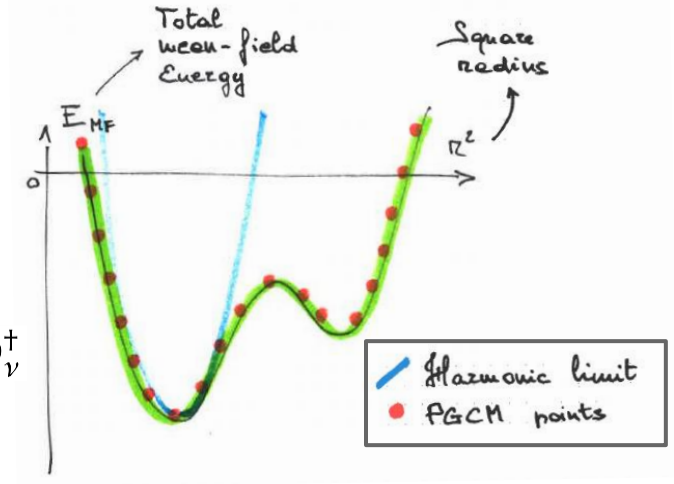
QFAM formulation frequencies $\mathbb{C}$



PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$

PGCM	QRPA
$\|\Psi_\nu\rangle \equiv \sum_{r^2,q} f_\nu(r^2,q)\|\Phi(r^2,q)\rangle$	$\|\Psi_\nu\rangle \equiv Q^\dagger_\nu\|\Psi_0\rangle$
r^2 to study GMR	Boson-like excitation operators $Q^\dagger_\nu$
q to couple to other modes	QRPA matrix diagonalization
Symmetry breaking and restoration	QFAM formulation frequencies $\mathbb{C}$
Variational method	



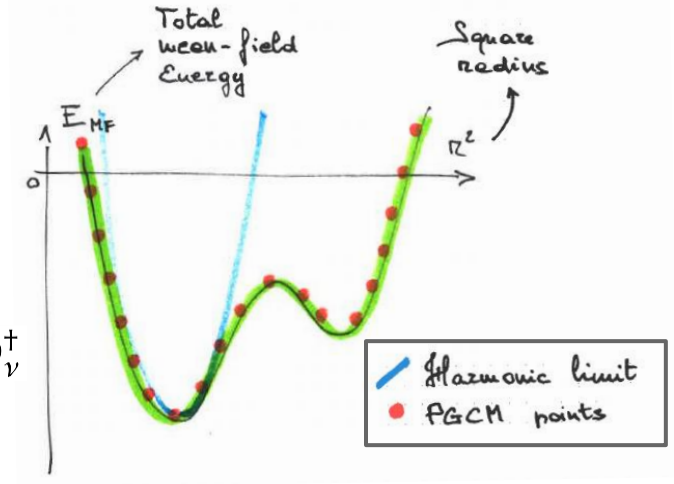
Pros and Cons

Handle anharmonicities and shape coexistence	Harmonic limit of GCM [Brink, Weiguny, 1968]
Select few collective coordinates	All coordinates are explored
Symmetries are restored	Symmetries are not restored
Computationally expensive	Low computational cost

PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$

PGCM	QRPA
$\|\Psi_\nu\rangle \equiv \sum_{r^2,q} f_\nu(r^2,q)\|\Phi(r^2,q)\rangle$	$\|\Psi_\nu\rangle \equiv Q^\dagger_\nu\|\Psi_0\rangle$
r^2 to study GMR	Boson-like excitation operators $Q^\dagger_\nu$
q to couple to other modes	QRPA matrix diagonalization
Symmetry breaking and restoration	QFAM formulation frequencies $\mathbb{C}$
Variational method	



Pros and Cons

Handle anharmonicities and shape coexistence	⊕ ⊖	Harmonic limit of GCM [Brink, Weiguny, 1968]
Select few collective coordinates		All coordinates are explored
Symmetries are restored		Symmetries are not restored
Computationally expensive		Low computational cost

PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$

PGCM

$$|\Psi_\nu\rangle \equiv \sum_{r^2,q} f_\nu(r^2,q)|\Phi(r^2,q)\rangle$$

r^2 to study GMR

q to couple to other modes

Symmetry breaking and restoration

Variational method

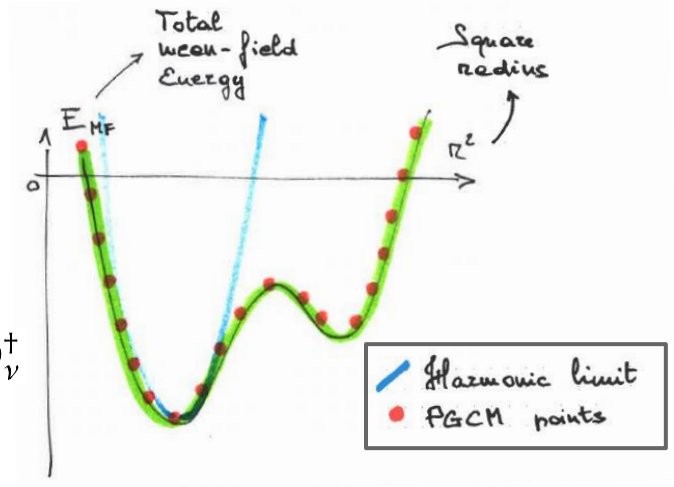
QRPA

$$|\Psi_\nu\rangle \equiv Q^\dagger_\nu|\Psi_0\rangle$$

Boson-like excitation operators $Q^\dagger_\nu$

QRPA matrix diagonalization

QFAM formulation frequencies $\mathbb{C}$



Pros and Cons

Handle anharmonicities and shape coexistence	⊕ ⊖	Harmonic limit of GCM
Select few collective coordinates	⊖ ⊕	All coordinates are explored
Symmetries are restored		Symmetries are not restored
Computationally expensive		Low computational cost

[Brink, Weiguny, 1968]

PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$

PGCM

$$|\Psi_\nu\rangle \equiv \sum_{r^2,q} f_\nu(r^2,q)|\Phi(r^2,q)\rangle$$

r^2 to study GMR

q to couple to other modes

Symmetry breaking and restoration

Variational method

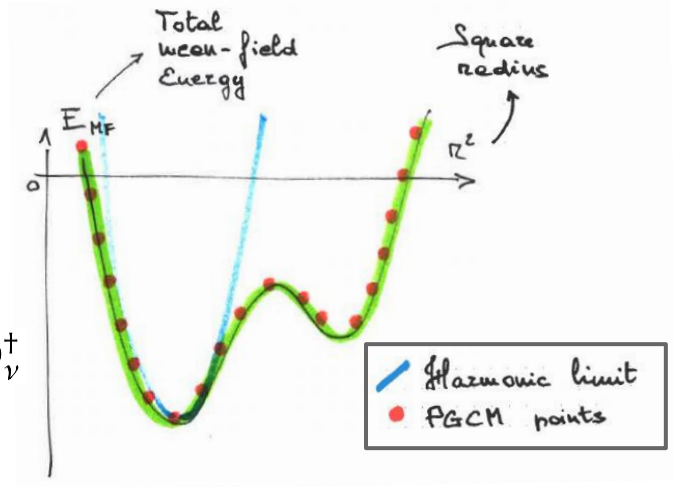
QRPA

$$|\Psi_\nu\rangle \equiv Q_\nu^\dagger|\Psi_0\rangle$$

Boson-like excitation operators $Q_\nu^\dagger$

QRPA matrix diagonalization

QFAM formulation frequencies $\mathbb{C}$



Pros and Cons

Handle anharmonicities and shape coexistence	⊕ ⊖	Harmonic limit of GCM
Select few collective coordinates	⊖ ⊕	All coordinates are explored
Symmetries are restored	⊕ ⊖	Symmetries are not restored (yet !)
Computationally expensive		Low computational cost

[Brink, Weiguny, 1968]

PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$

PGCM

$$|\Psi_\nu\rangle \equiv \sum_{r^2,q} f_\nu(r^2,q)|\Phi(r^2,q)\rangle$$

r^2 to study GMR

q to couple to other modes

Symmetry breaking and restoration

Variational method

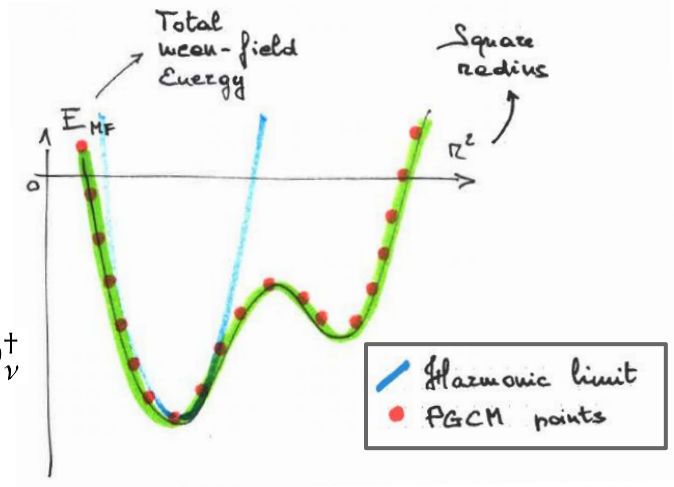
QRPA

$$|\Psi_\nu\rangle \equiv Q_\nu^\dagger|\Psi_0\rangle$$

Boson-like excitation operators $Q_\nu^\dagger$

QRPA matrix diagonalization

QFAM formulation frequencies $\mathbb{C}$



Pros and Cons

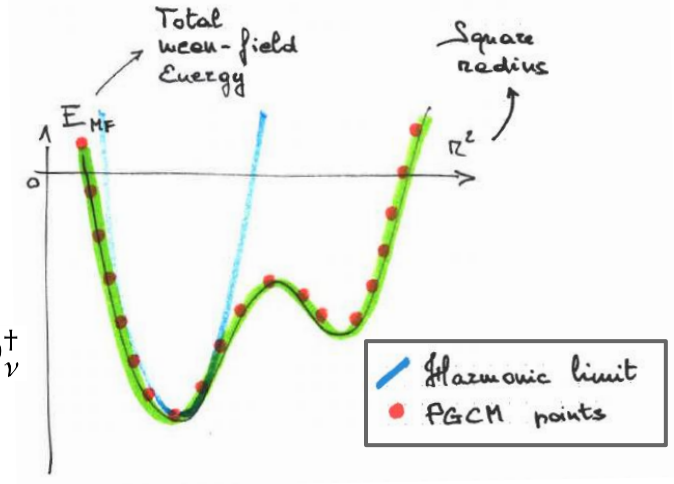
Handle anharmonicities and shape coexistence	⊕ ⊖	Harmonic limit of GCM
Select few collective coordinates	⊖ ⊕	All coordinates are explored
Symmetries are restored	⊕ ⊖	Symmetries are not restored
Computationally expensive	⊖ ⊕	Low computational cost

[Brink, Weiguny, 1968]

PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$

PGCM	QRPA
$\|\Psi_\nu\rangle \equiv \sum_{r^2,q} f_\nu(r^2,q)\|\Phi(r^2,q)\rangle$	$\|\Psi_\nu\rangle \equiv Q^\dagger_\nu\|\Psi_0\rangle$
r^2 to study GMR	Boson-like excitation operators $Q^\dagger_\nu$
q to couple to other modes	QRPA matrix diagonalization
Symmetry breaking and restoration	QFAM formulation frequencies $\mathbb{C}$
Variational method	



Pros and Cons

Handle anharmonicities and shape coexistence	⊕ ⊖	Harmonic limit of GCM
Select few collective coordinates	⊖ ⊕	All coordinates are explored
Symmetries are restored	⊕ ⊖	Symmetries are not restored
Computationally expensive	⊖ ⊕	Low computational cost

[Brink, Weiguny, 1968]

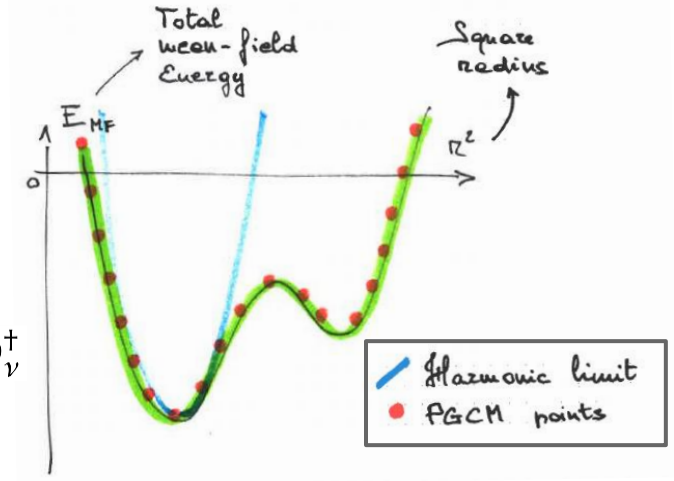
First ab-initio realization very recently developed

1) PGCM (M. Frosini, CEA Saclay)
2) QFAM (Y. Beaujeault-Taudière, CEA DAM)

PGCM vs QRPA

Schrödinger equation $H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$

PGCM	QRPA
$\|\Psi_\nu\rangle \equiv \sum_{r^2,q} f_\nu(r^2,q)\|\Phi(r^2,q)\rangle$	$\|\Psi_\nu\rangle \equiv Q^\dagger_\nu\|\Psi_0\rangle$
r^2 to study GMR	Boson-like excitation operators $Q^\dagger_\nu$
q to couple to other modes	QRPA matrix diagonalization
Symmetry breaking and restoration	QFAM formulation frequencies $\mathbb{C}$
Variational method	



Pros and Cons

Handle anharmonicities and shape coexistence	⊕ ⊖	Harmonic limit of GCM
Select few collective coordinates	⊖ ⊕	All coordinates are explored
Symmetries are restored	⊕ ⊖	Symmetries are not restored
Computationally expensive	⊖ ⊕	Low computational cost

[Brink, Weiguny, 1968]

First ab-initio realization very recently developed

1) PGCM (M. Frosini, CEA Saclay)
2) QFAM (Y. Beaujeault-Taudière, CEA DAM)

General implementation, can access

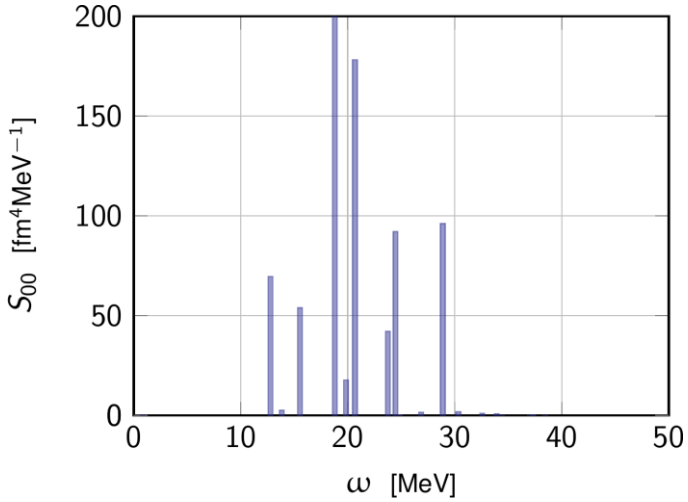
1. Doubly-closed-shell nuclei
2. Singly-open-shell nuclei
3. Doubly-open-shell nuclei

Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks



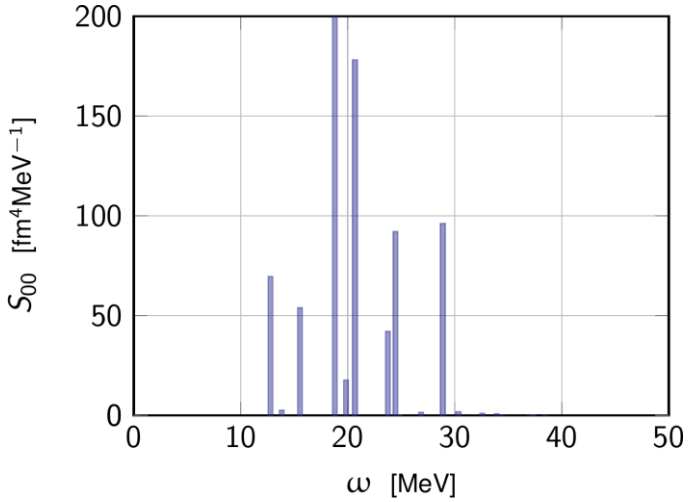
Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

JM=00

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks

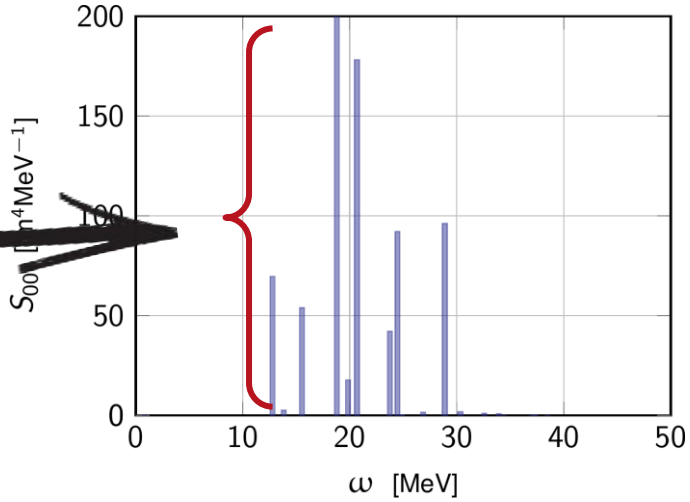


Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks

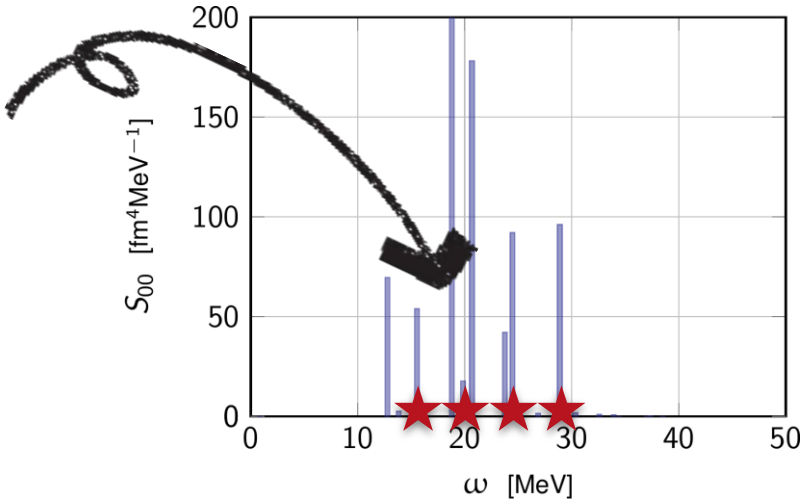


Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks

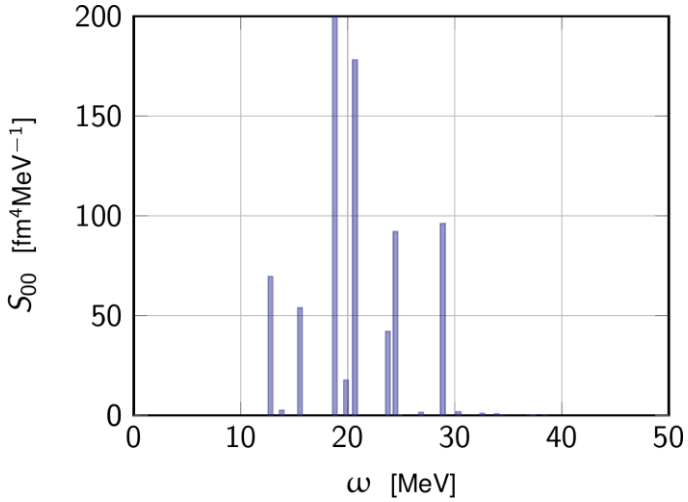


Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks

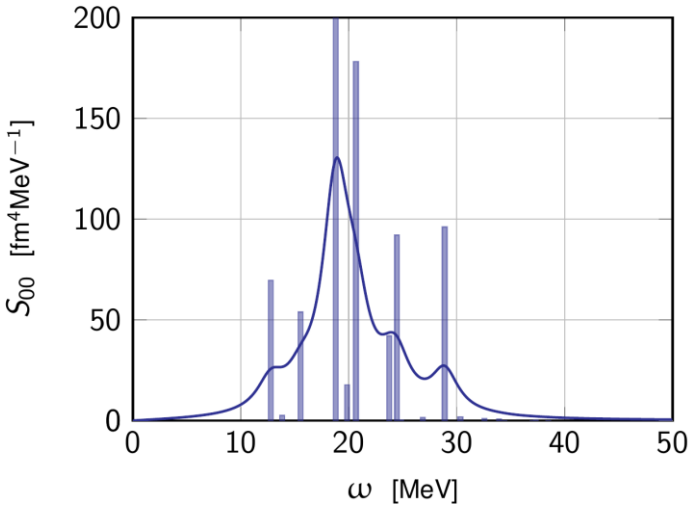


Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks



Moments and Strength

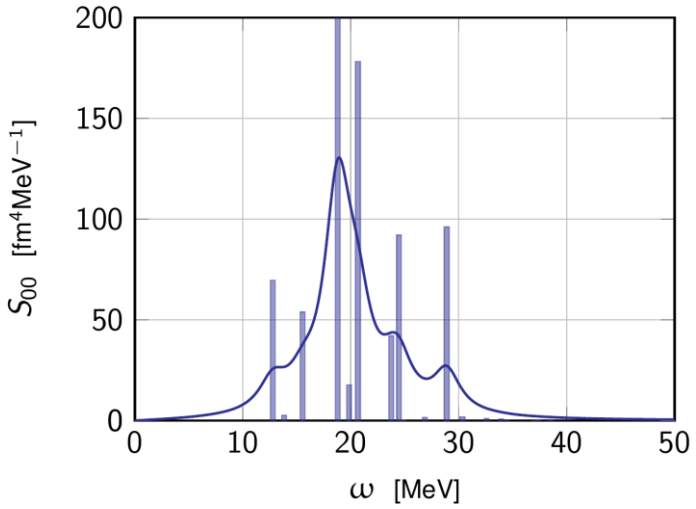
- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks

- Related moments

$$\begin{aligned} m_k &\equiv \int_0^\infty S_{00}(\omega)\, \omega^k \, d\omega \\ &= \sum_{\nu} (E_\nu - E_0)^k |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \\ &\equiv \langle \Psi_0 | \check{M}_k(i,j) | \Psi_0 \rangle \end{aligned}$$



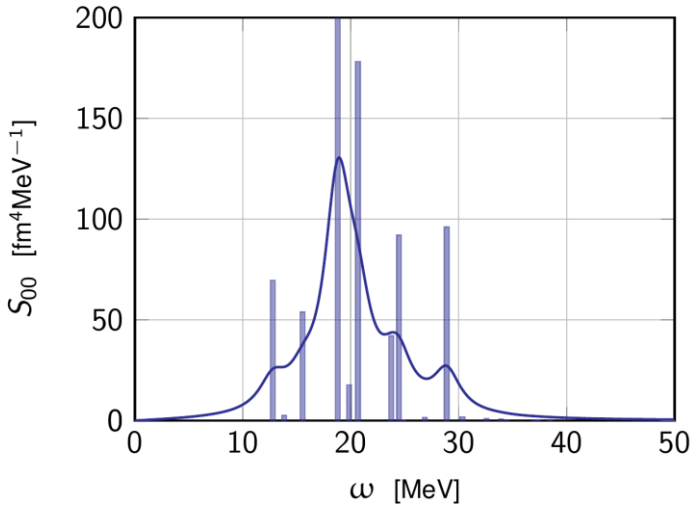
[Bohigas et al., 1979]

Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks



- Related moments

$$m_k \equiv \int_0^\infty S_{00}(\omega)\, \omega^k \, d\omega$$
$$= \sum_{\nu} (E_\nu - E_0)^k |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2$$
$$\equiv \langle \Psi_0 | \check{M}_k(i,j) | \Psi_0 \rangle$$

→ Must know excited states

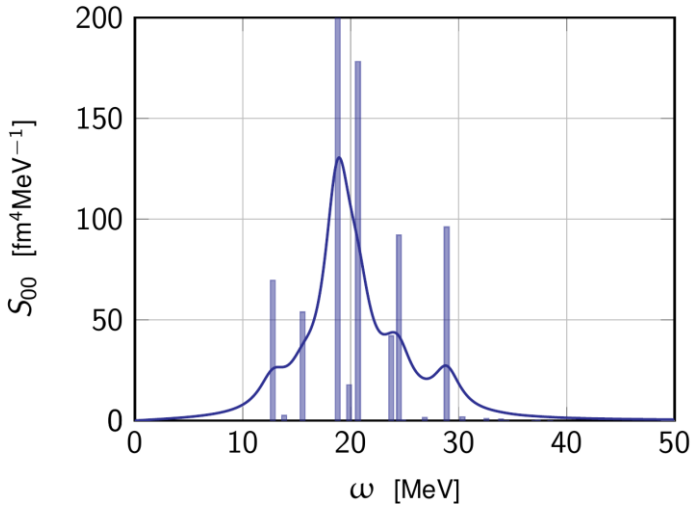
[Bohigas et al., 1979]

Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks



- Related moments

$$m_k \equiv \int_0^\infty S_{00}(\omega)\, \omega^k \, d\omega$$

$$= \sum_{\nu} (E_\nu - E_0)^k |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \longrightarrow \text{Must know excited states}$$

$$\equiv \langle \Psi_0 | \check{M}_k(i,j) | \Psi_0 \rangle \longrightarrow \text{Ground state only}$$

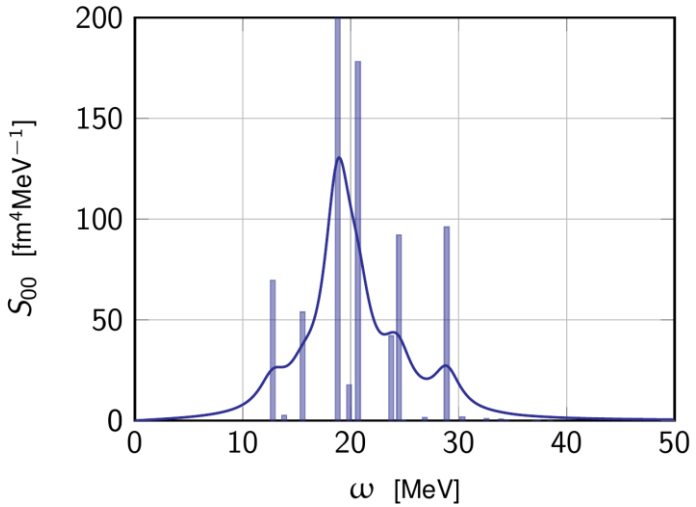
[Bohigas et al., 1979]

Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks



- Related moments $m_k \equiv \int_0^\infty S_{00}(\omega)\, \omega^k \, d\omega$

$$= \sum_{\nu} (E_\nu - E_0)^k |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \longrightarrow \text{Must know excited states}$$

$$\equiv \langle \Psi_0 | \check{M}_k(i,j) | \Psi_0 \rangle \longrightarrow \text{Ground state only}$$

[Bohigas et al., 1979]

Complexity is shifted to the operator structure

$$\check{M}_k(i,j) \equiv (-1)^i C_i C_j \qquad \forall \;\; k \geq 0$$

$$M_k(i,j) \equiv \frac{1}{2}(-1)^i [C_i, C_j] \;\; \text{if} \;\; k = 2n+1, \;\; n \in \mathbb{N}$$

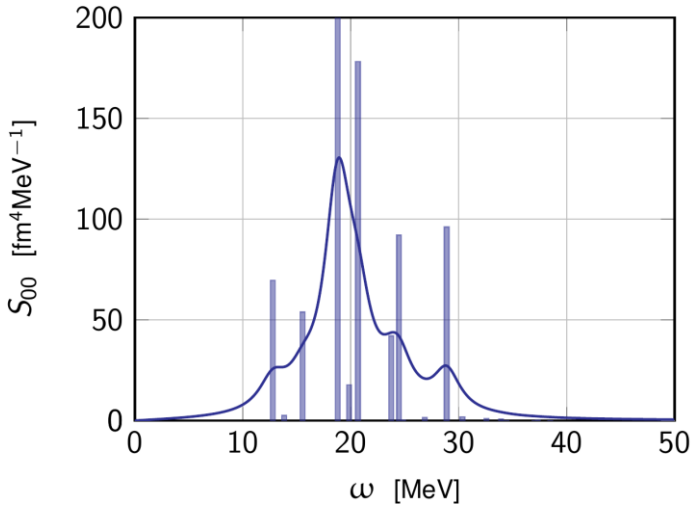
$$C_l \equiv [\underbrace{H,[H,\ldots[H,[H}_{l \text{ times}}, r^2]]\ldots]]$$

Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks



- Related moments $m_k \equiv \int_0^\infty S_{00}(\omega)\, \omega^k \, d\omega$

$$= \sum_{\nu} (E_\nu - E_0)^k |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \longrightarrow \text{Must know excited states}$$

$$\equiv \langle \Psi_0 | \check{M}_k(i,j) | \Psi_0 \rangle \longrightarrow \text{Ground state only}$$

[Bohigas et al., 1979]

Complexity is shifted to the operator structure

$$\check{M}_k(i,j) \equiv (-1)^i C_i C_j \qquad \forall \; k \geq 0$$

$$M_k(i,j) \equiv \frac{1}{2}(-1)^i [C_i, C_j] \quad \text{if } k = 2n+1, \; n \in \mathbb{N}$$

$$C_l \equiv [\underbrace{H,[H,\ldots[H,[H}_{l \text{ times}}, r^2]]\ldots]]$$

Encode the main physical features of the strength

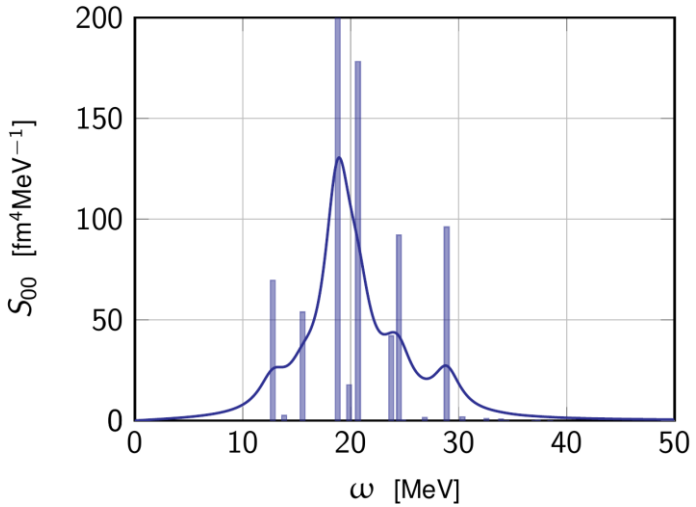
$$\bar{E}_1 = \frac{m_1}{m_0} \qquad \sigma^2 = \frac{m_2}{m_0} - \left(\frac{m_1}{m_0}\right)^2 \geq 0$$

Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks



- Related moments $m_k \equiv \int_0^\infty S_{00}(\omega)\,\omega^k\,d\omega$

$$= \sum_{\nu} (E_\nu - E_0)^k |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \longrightarrow \text{Must know excited states}$$

$$\equiv \langle \Psi_0 | \check{M}_k(i,j) | \Psi_0 \rangle \longrightarrow \text{Ground state only}$$

[Bohigas et al., 1979]

Complexity is shifted to the operator structure

$$\check{M}_k(i,j) \equiv (-1)^i C_i C_j \qquad \forall\ k \geq 0$$

$$M_k(i,j) \equiv \frac{1}{2}(-1)^i [C_i, C_j] \quad \text{if } k = 2n+1,\ n \in \mathbb{N}$$

$$C_l \equiv [\underbrace{H,[H,\ldots[H,[H}_{l \text{ times}},r^2]]\ldots]]$$

Encode the main physical features of the strength

$$\bar{E}_1 = \frac{m_1}{m_0} \qquad \sigma^2 = \frac{m_2}{m_0} - \left(\frac{m_1}{m_0}\right)^2 \geq 0$$

First comparison ever of the two approaches !

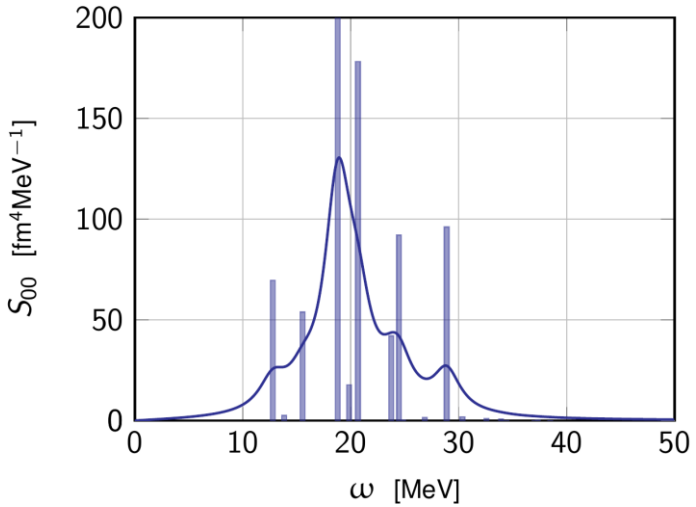
Derived and **implemented** in an ab-initio PGCM code

Moments and Strength

- Studied quantity: monopole strength

$$S_{00}(\omega) \equiv \sum_{\nu} |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \delta(E_\nu - E_0 - \omega)$$

  - Transition amplitudes: height of peaks
  - Energy difference: position of peaks



- Related moments $m_k \equiv \int_0^\infty S_{00}(\omega)\,\omega^k\,d\omega$

$$= \sum_{\nu} (E_\nu - E_0)^k |\langle \Psi_\nu | r^2 | \Psi_0 \rangle|^2 \longrightarrow \text{Must know excited states}$$

$$\equiv \langle \Psi_0 | \check{M}_k(i,j) | \Psi_0 \rangle \longrightarrow \text{Ground state only}$$

[Bohigas et al., 1979]

Complexity is shifted to the operator structure

$$\check{M}_k(i,j) \equiv (-1)^i C_i C_j \qquad \forall\ k \geq 0$$

$$M_k(i,j) \equiv \frac{1}{2}(-1)^i [C_i, C_j] \quad \text{if } k = 2n+1,\ n \in \mathbb{N}$$

$$C_l \equiv [\underbrace{H,[H,\ldots[H,[H}_{l \text{ times}},r^2]]\ldots]]$$

Encode the main physical features of the strength

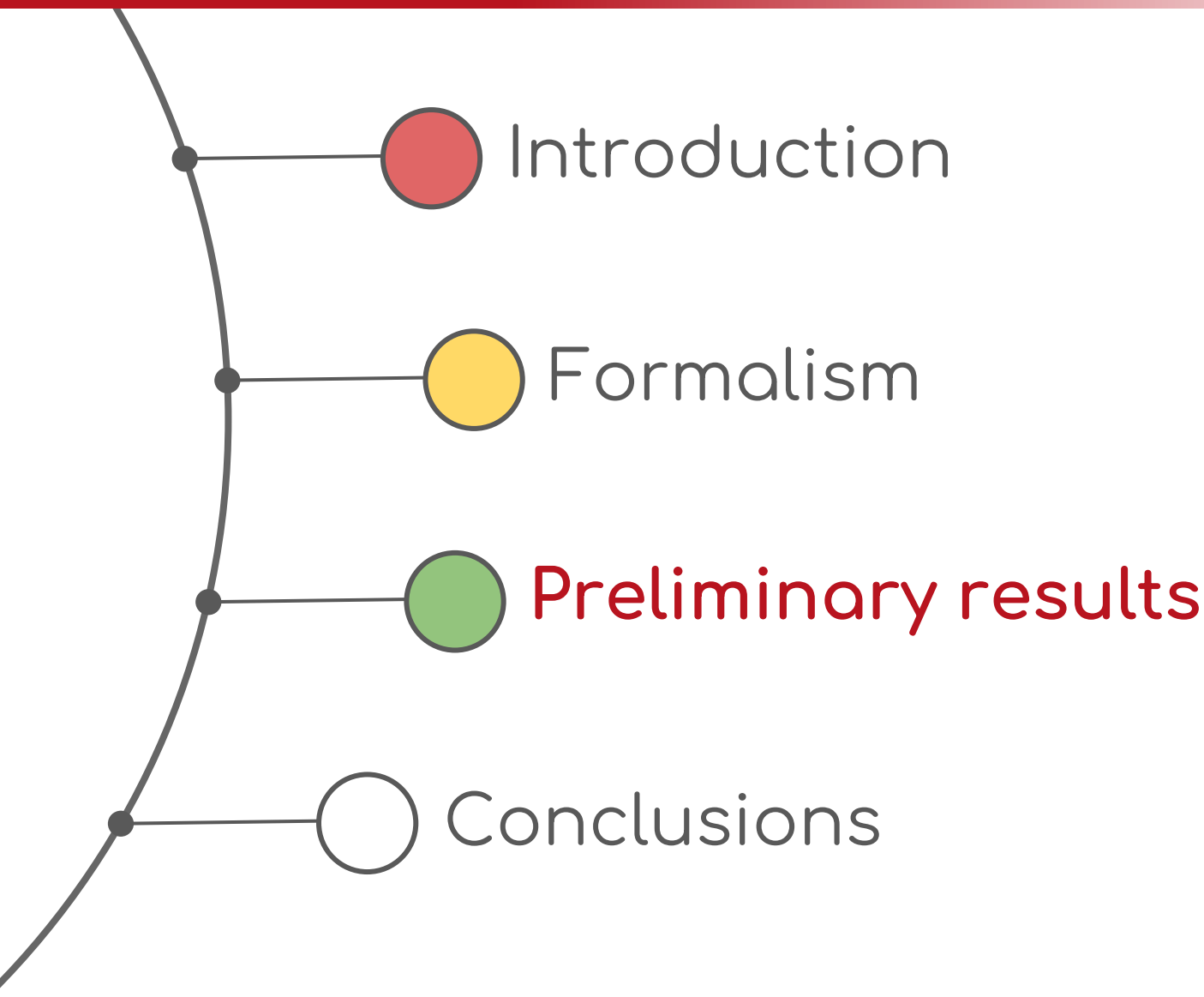
$$\bar{E}_1 = \frac{m_1}{m_0} \qquad \sigma^2 = \frac{m_2}{m_0} - \left(\frac{m_1}{m_0}\right)^2 \geq 0$$

First comparison ever of the two approaches !

Derived and **implemented** in an ab-initio PGCM code

Not discussed in the present talk

Outline

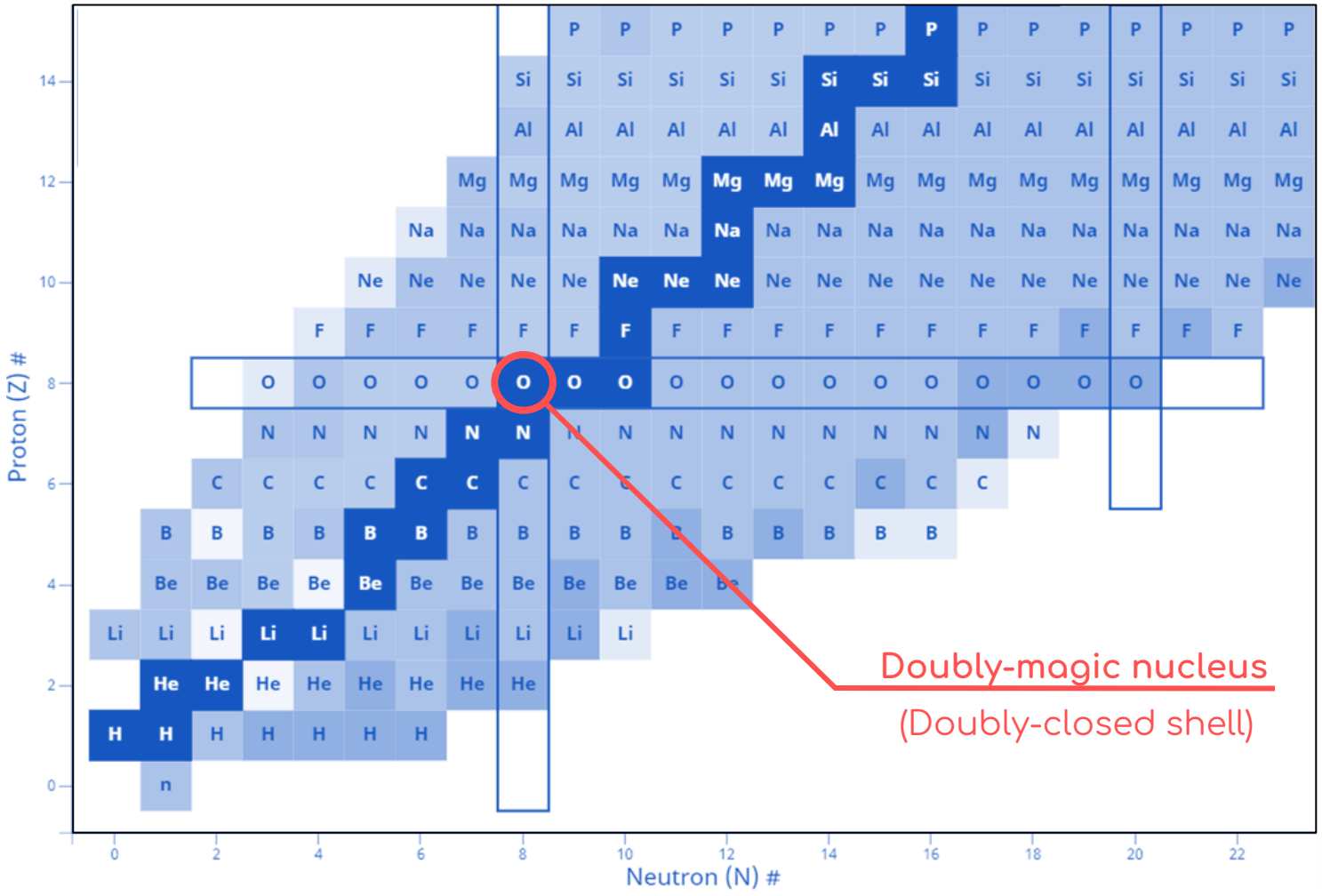

Introduction
Formalism
Preliminary results
Conclusions

Common features

PGCM and QFAM have consistent numerical settings

- One-body spherical harmonic oscillator basis
  - e_{max} = 10
  - $\hbar\omega$ = 20 MeV
- Chiral two-plus-three-nucleon in-medium interaction
  - T. Hüther, K. Vobig, K. Hebeler, R. Machleidt and R. Roth, "Family of chiral two- plus three-nucleon interactions for accurate nuclear structure studies", *Phys. Lett. B,* 808, 2020
  - M. Frosini, T. Duguet, B. Bally, Y. Beaujeault-Taudière, J.-P. Ebran and V. Somà, "In-medium k-body reduction of n-body operators", *The European Physical Journal A*, *57*(4), 2021
- Only monopole strength is addressed
- The PGCM wavefunction explores the β_2 and r^2 collective coordinates (quadrupolar coupling)

Benchmarking ^{16}O

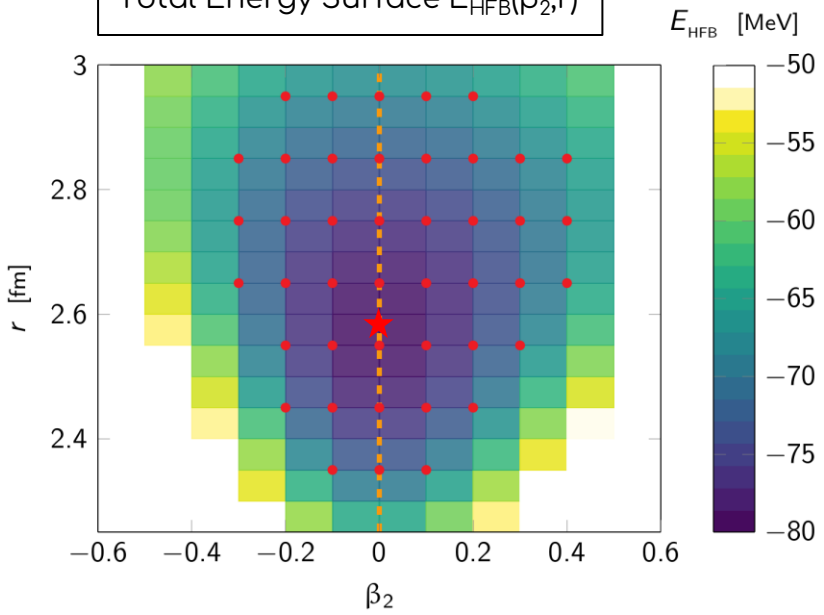


Benchmarking ^{16}O

Difficulty

☐ Benchmark on existing spherical QRPA code

Total Energy Surface $E_{HFB}(\beta_2,r)$



Results

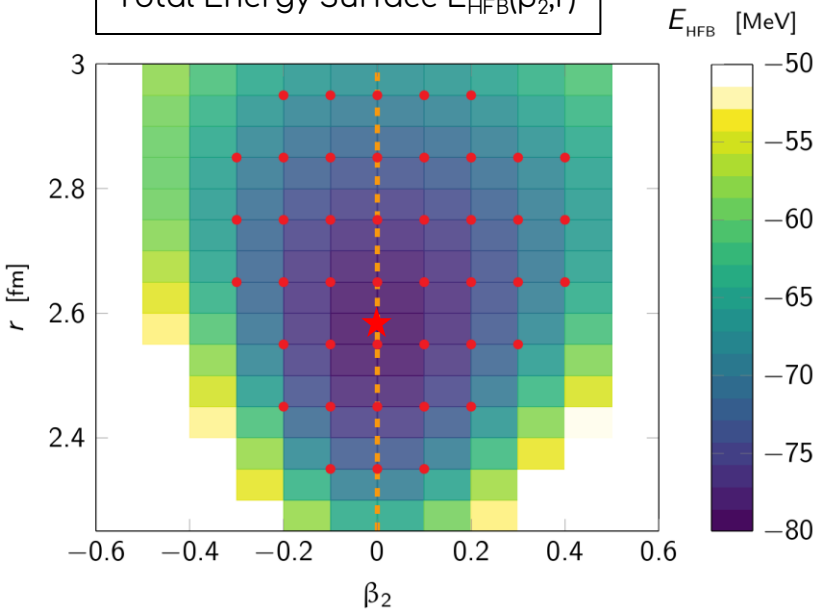
- Single spherical harmonic energy minimum

Benchmarking ^{16}O

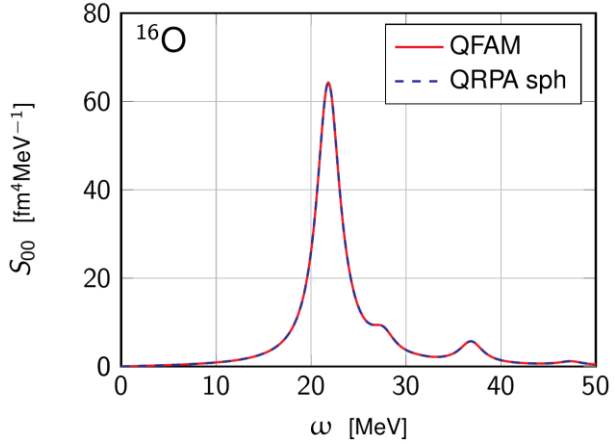
Difficulty

☐ Benchmark on existing spherical QRPA code

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



Results

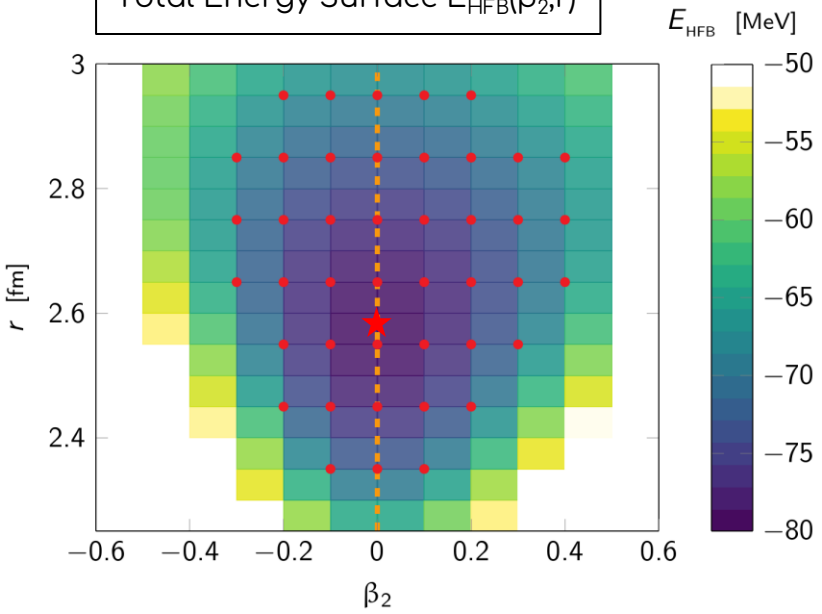
- Single spherical harmonic energy minimum
- Exact QRPA/QFAM superposition

Benchmarking ^{16}O

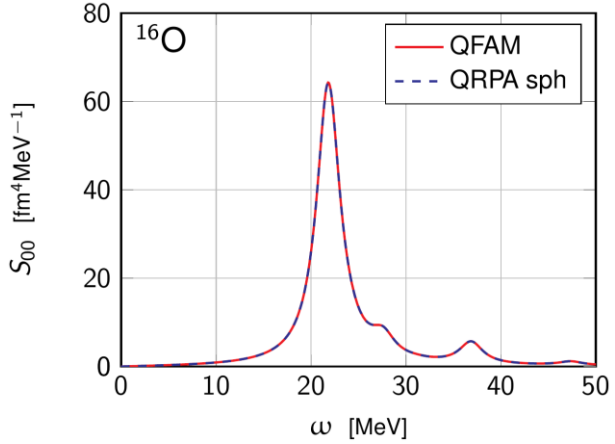
Difficulty

☑ Benchmark on existing spherical QRPA code

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



Results

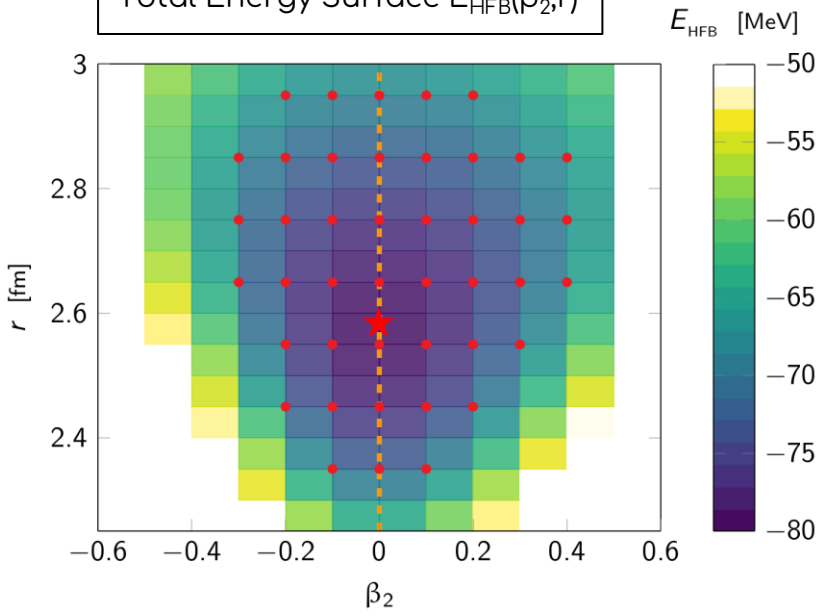
- Single spherical harmonic energy minimum
- Exact QRPA/QFAM superposition

Benchmarking ^{16}O

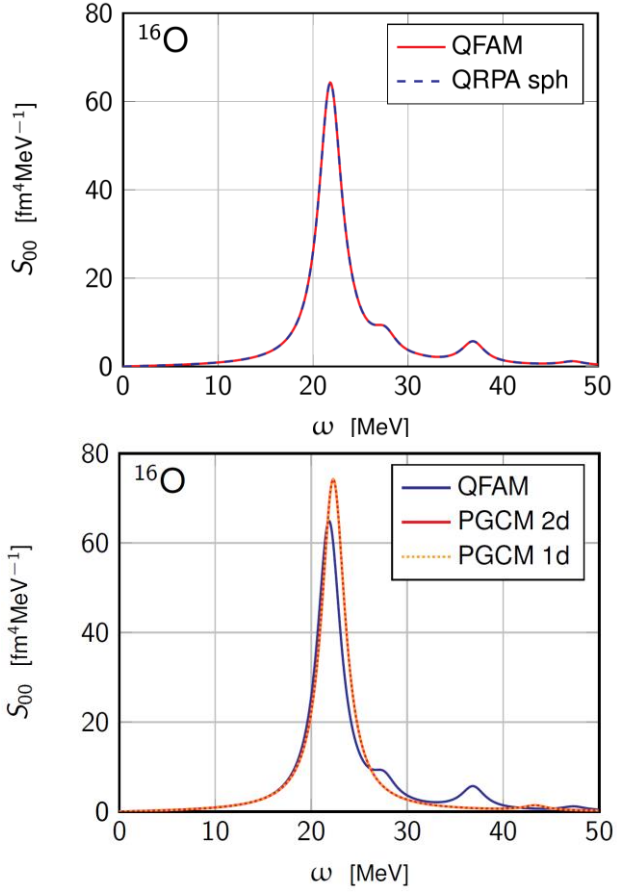
Difficulty

☑ Benchmark on existing spherical QRPA code

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



Results

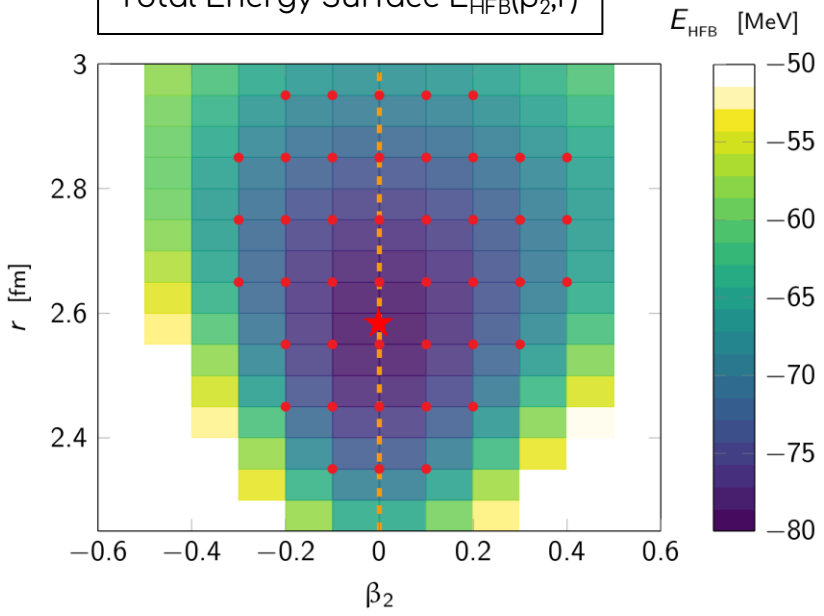
- Single spherical harmonic energy minimum
- Exact QRPA/QFAM superposition
- Excellent QFAM/PGCM agreement

Benchmarking ^{16}O

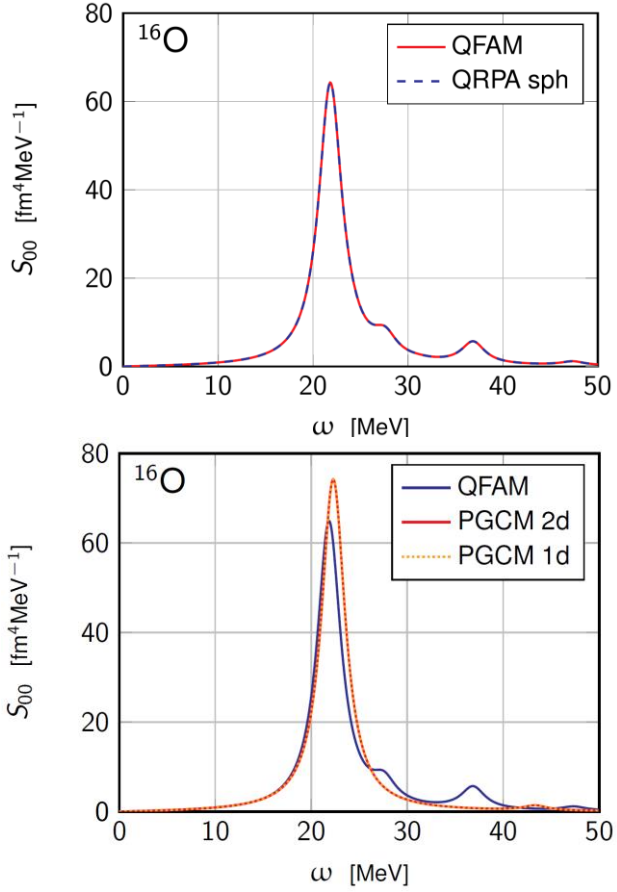
Difficulty

☑ Benchmark on existing spherical QRPA code

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



Results

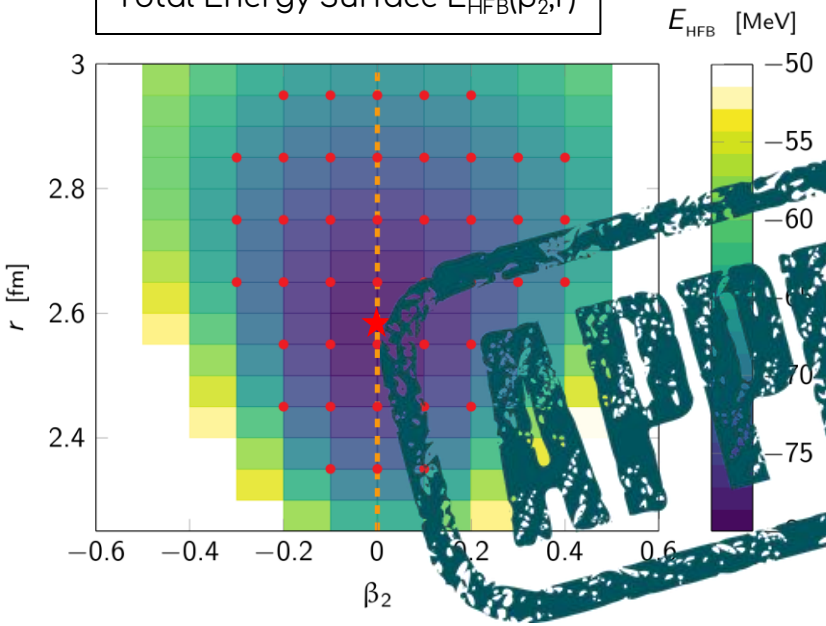
- Single spherical harmonic energy minimum
- Exact QRPA/QFAM superposition
- Excellent QFAM/PGCM agreement
- No coupling with quadrupolar vibrations

Benchmarking ^{16}O

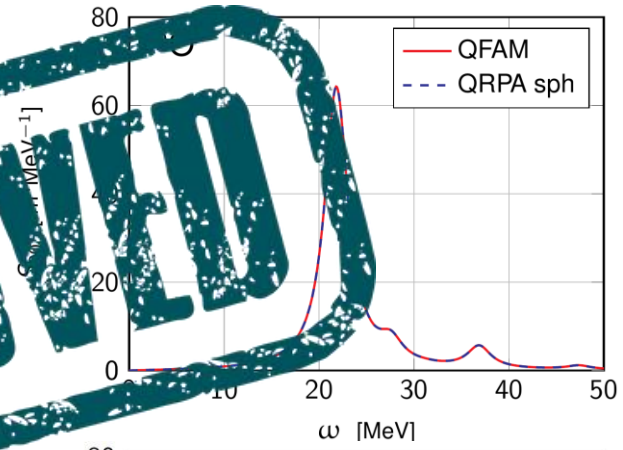
Difficulty

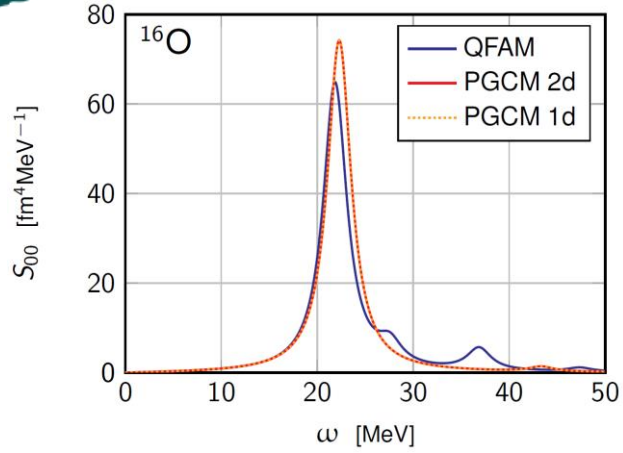
☑ Benchmark on existing spherical QRPA code

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



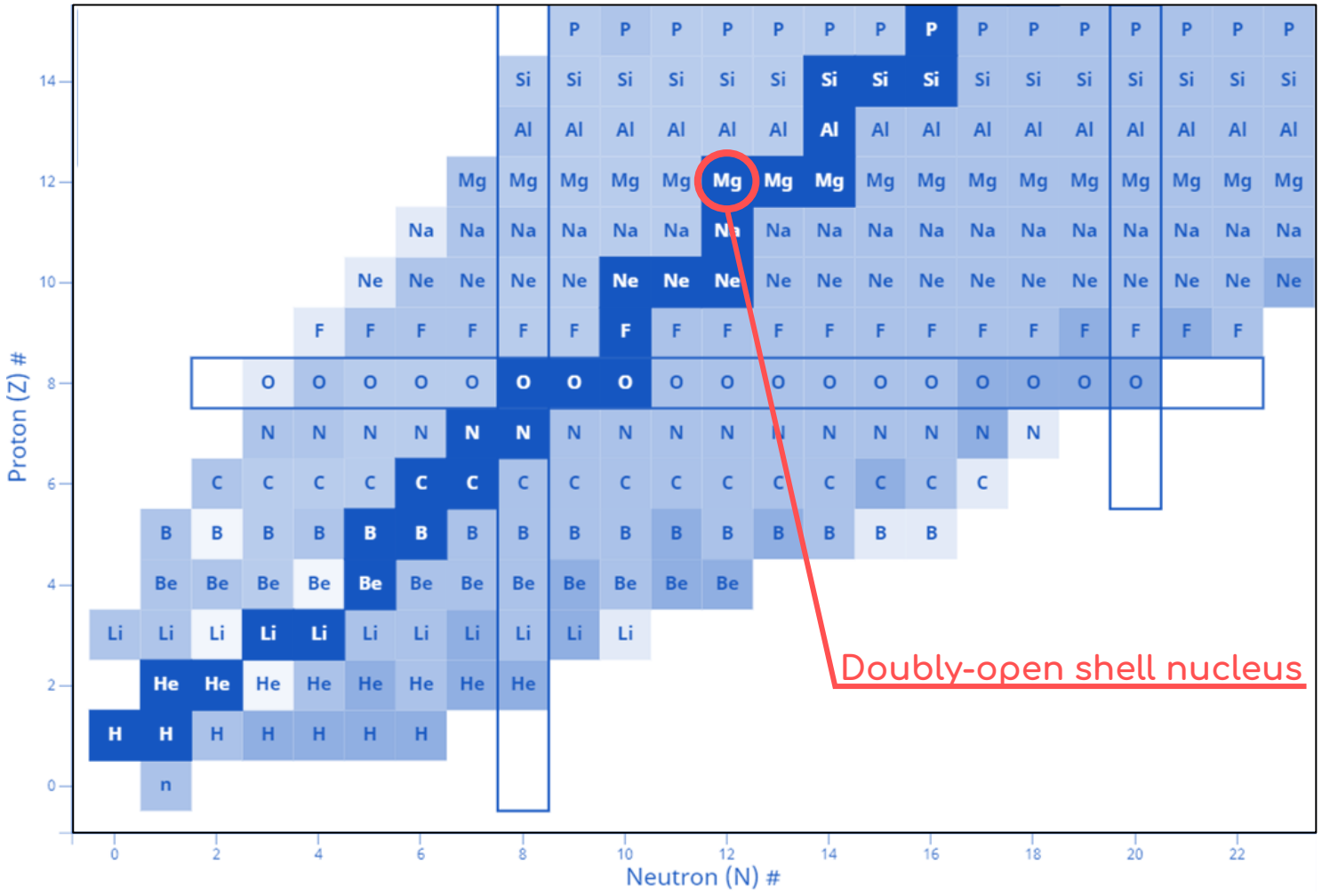


APPROVED

Results

- Single spherical harmonic energy minimum
- Exact QRPA/QFAM superposition
- Excellent QFAM/PGCM agreement
- No coupling with quadrupolar vibrations

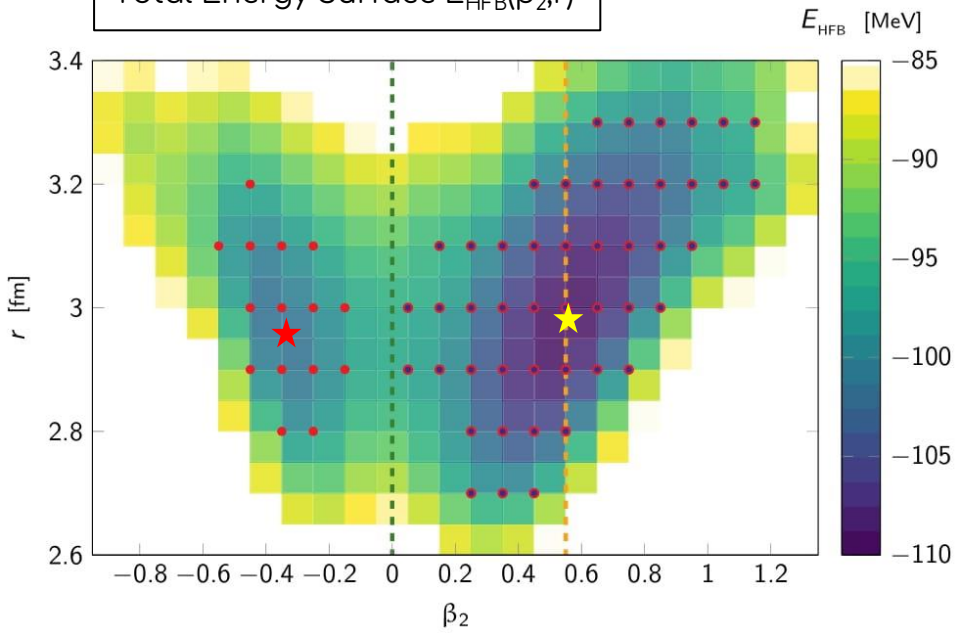
Deformation effects in ^{24}Mg



Deformation effects in ^{24}Mg

Difficulty

Total Energy Surface $E_{HFB}(\beta_2,r)$



Results

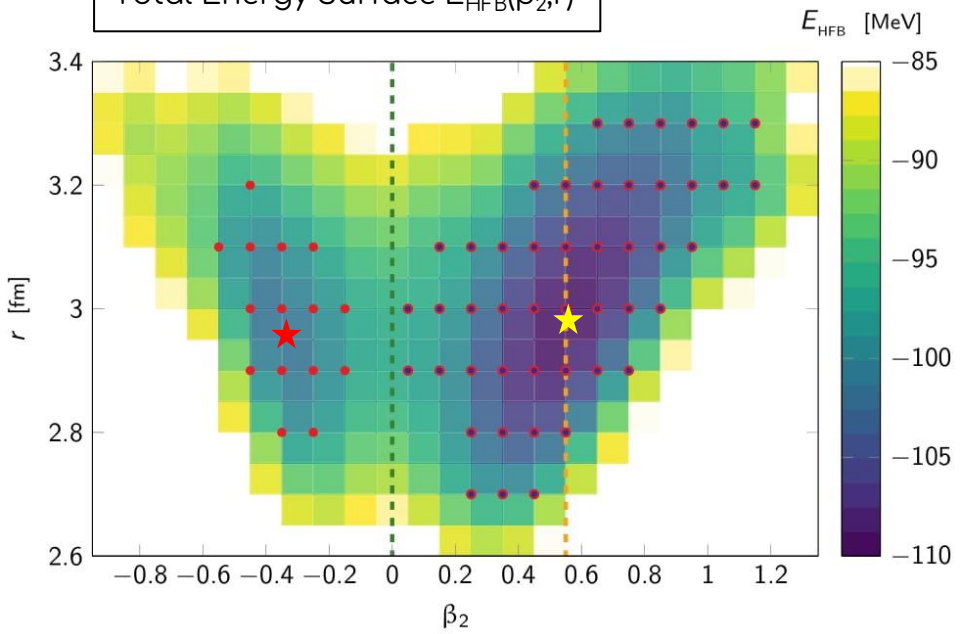
- Dominant prolate minimum

Deformation effects in ^{24}Mg

Difficulty

Deformation

Total Energy Surface $E_{HFB}(\beta_2,r)$

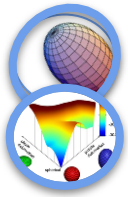


Results

- Dominant prolate minimum

Deformation effects in ^{24}Mg

Difficulty

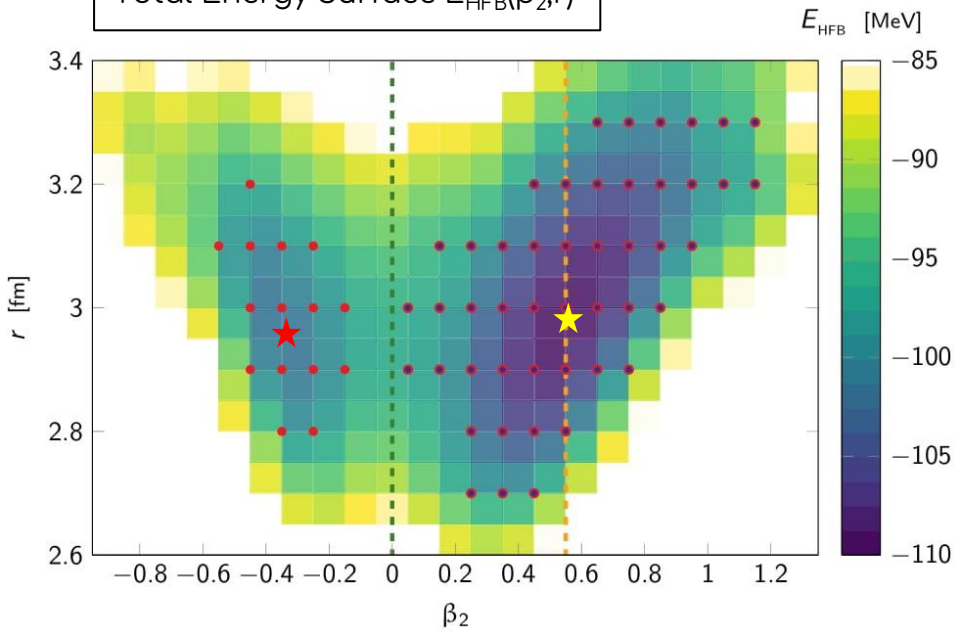


Deformation

Shape coexistence ? (1)

(1) [Dowie et al., 2020]

Total Energy Surface $E_{HFB}(\beta_2,r)$

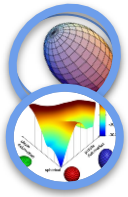


Results

- Dominant prolate minimum

Deformation effects in ^{24}Mg

Difficulty

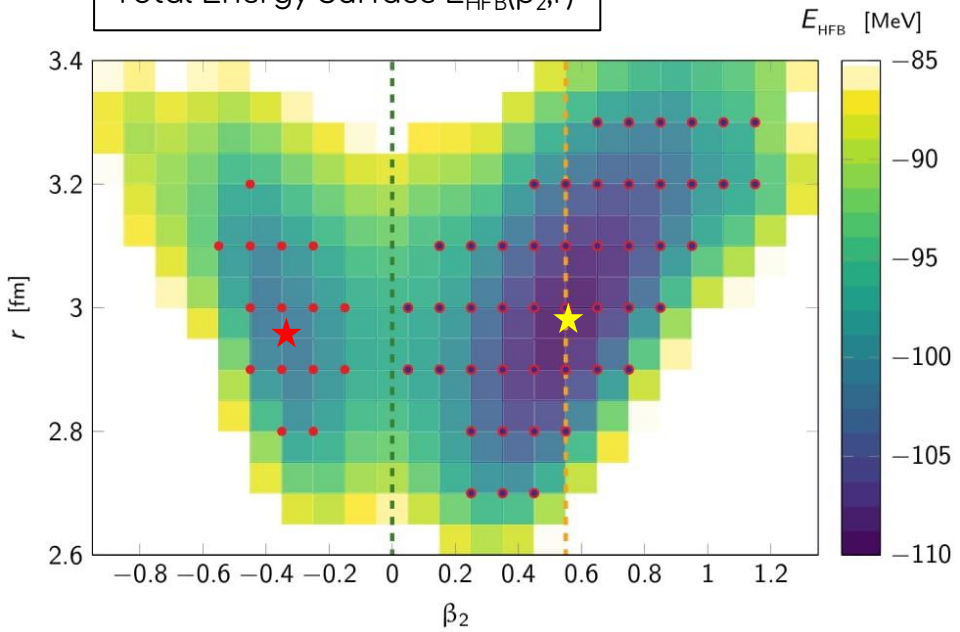


Deformation

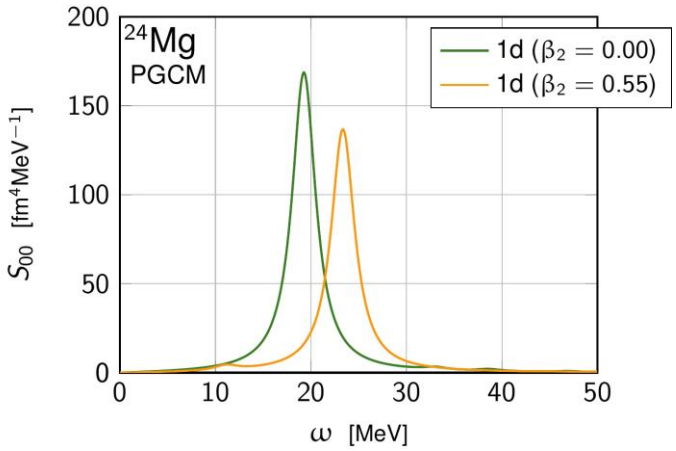
Shape coexistence ? (1)

(1) [Dowie et al., 2020]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength

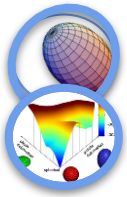


Results

- Dominant prolate minimum
- Important static quadrupole deformation

Deformation effects in ^{24}Mg

Difficulty

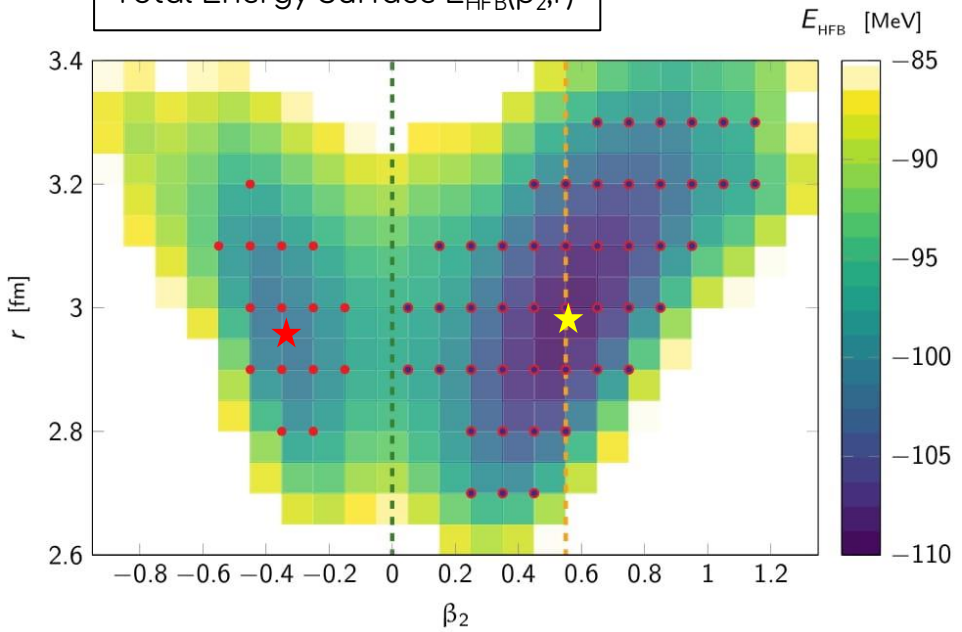


Deformation

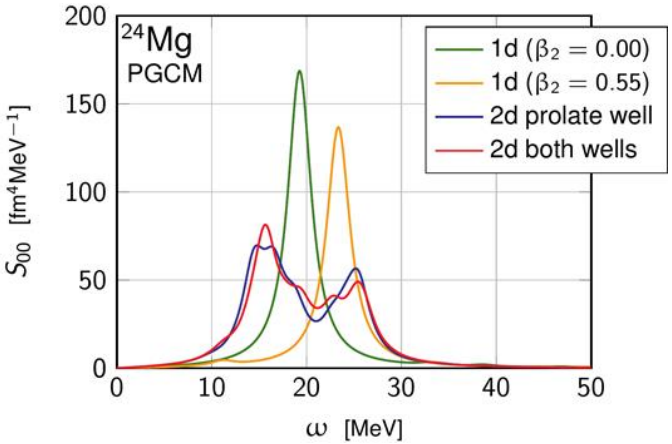
Shape coexistence ? (1)

(1) [Dowie et al., 2020]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength

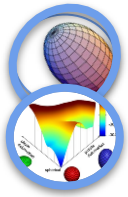


Results

- Dominant prolate minimum
- Important static quadrupole deformation
- No coupling between different wells

Deformation effects in ^{24}Mg

Difficulty

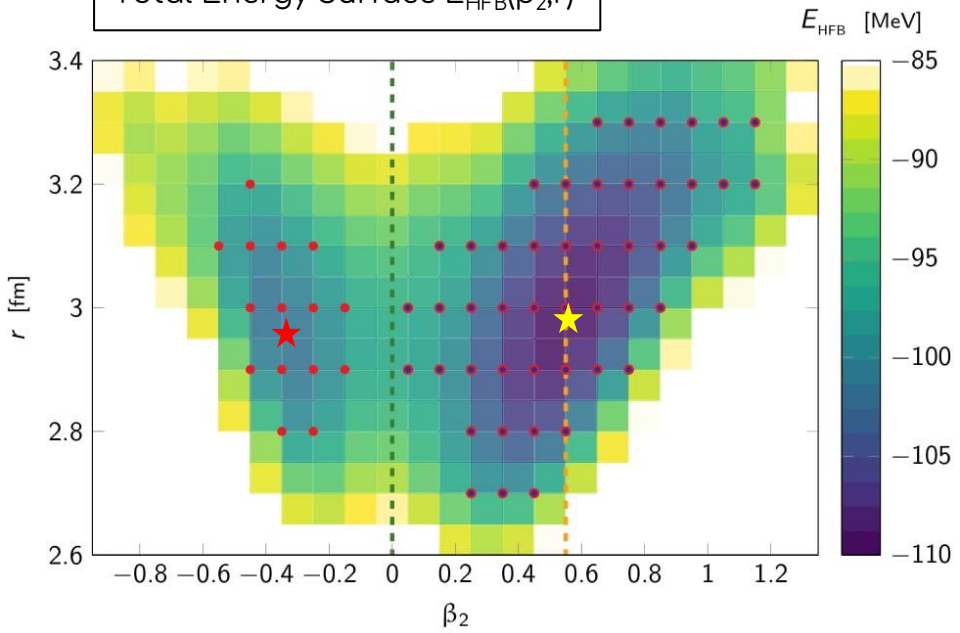


Deformation

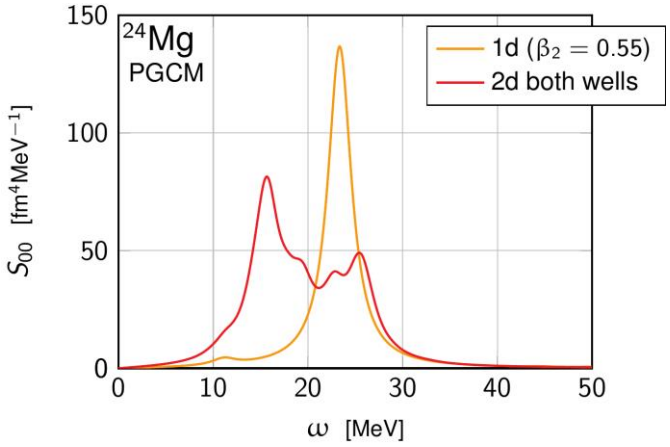
Shape coexistence ? (1)

(1) [Dowie et al., 2020]

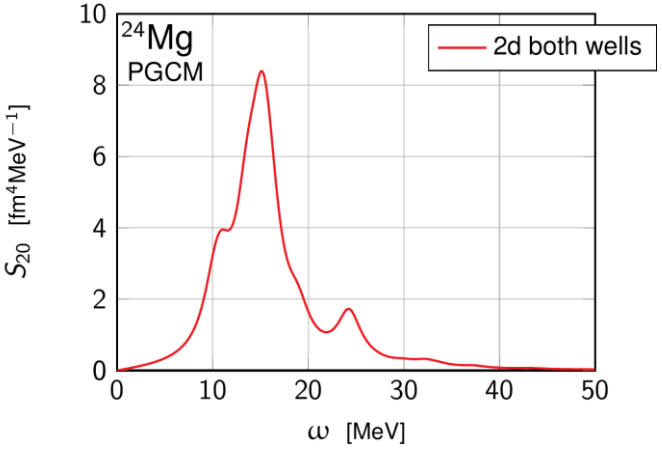
Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



Quadrupole Strength

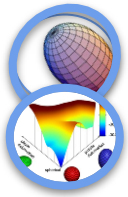


Results

- Dominant prolate minimum
- Important static quadrupole deformation
- No coupling between different wells
- Coupling to quadrupole fluctuation

Deformation effects in ^{24}Mg

Difficulty

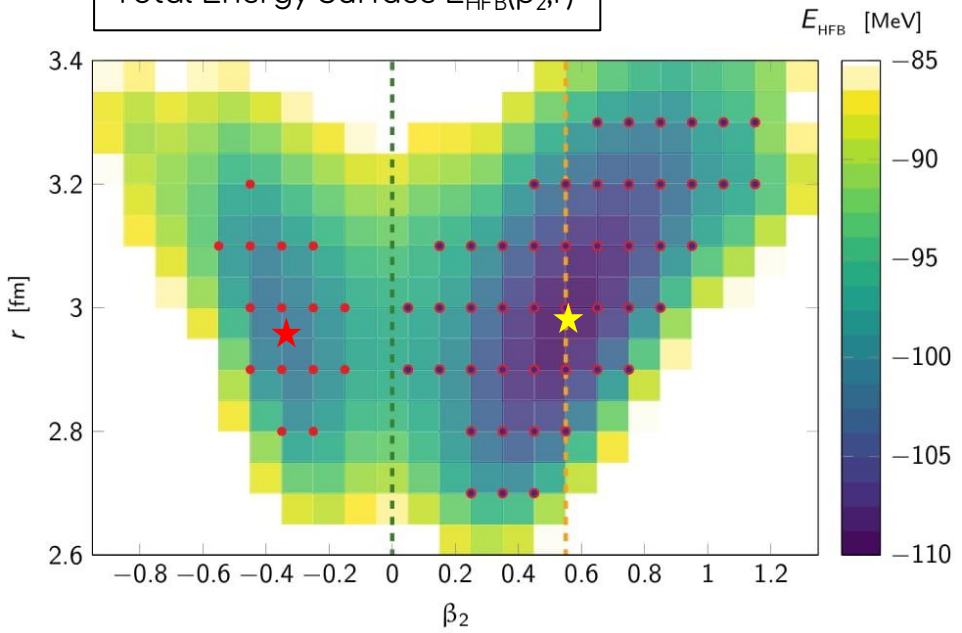


Deformation

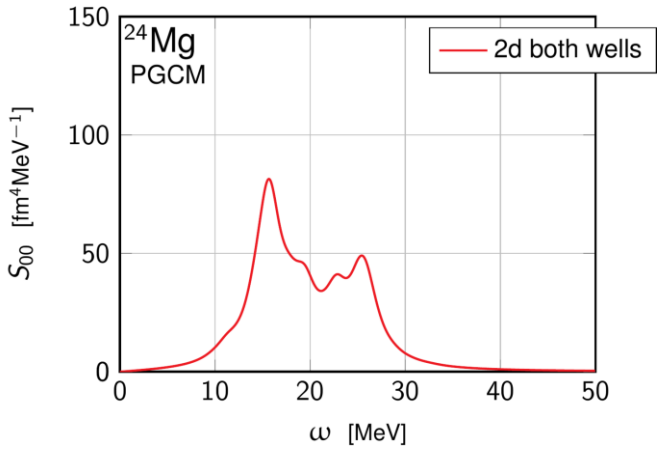
Shape coexistence ? (1)

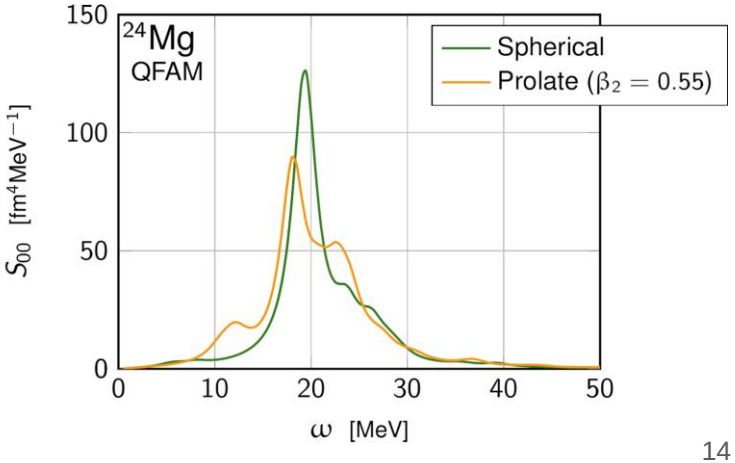
(1) [Dowie et al., 2020]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



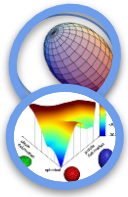


Results

- Dominant prolate minimum
- Important static quadrupole deformation
- No coupling between different wells
- Coupling to quadrupole fluctuation
- Important anharmonic effects QRPA unreliable

Deformation effects in ^{24}Mg

Difficulty

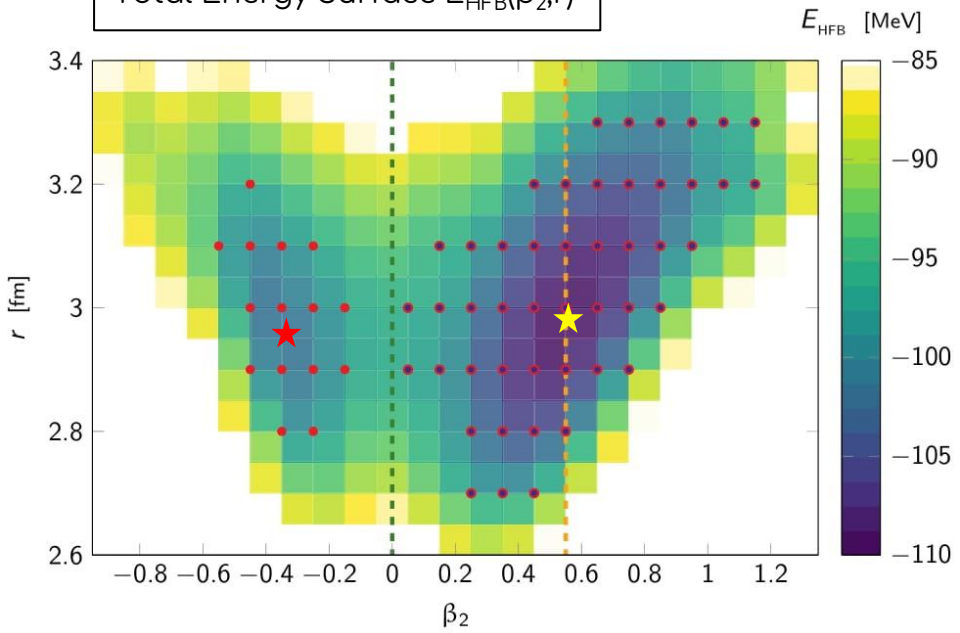


Deformation

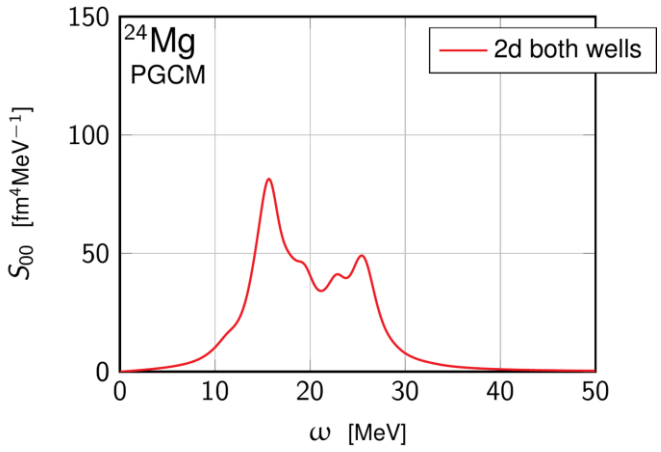
Shape coexistence ? (1)

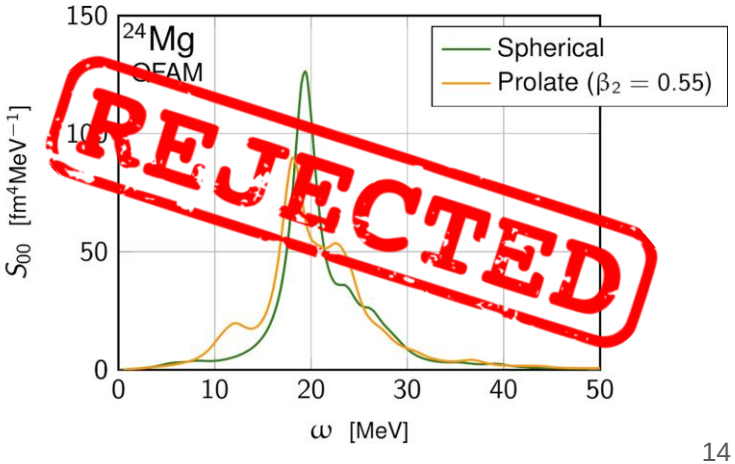
(1) [Dowie et al., 2020]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength





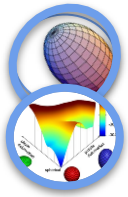
REJECTED

Results

- Dominant prolate minimum
- Important static quadrupole deformation
- No coupling between different wells
- Coupling to quadrupole fluctuation
- Important anharmonic effects QRPA unreliable

Deformation effects in ^{24}Mg

Difficulty

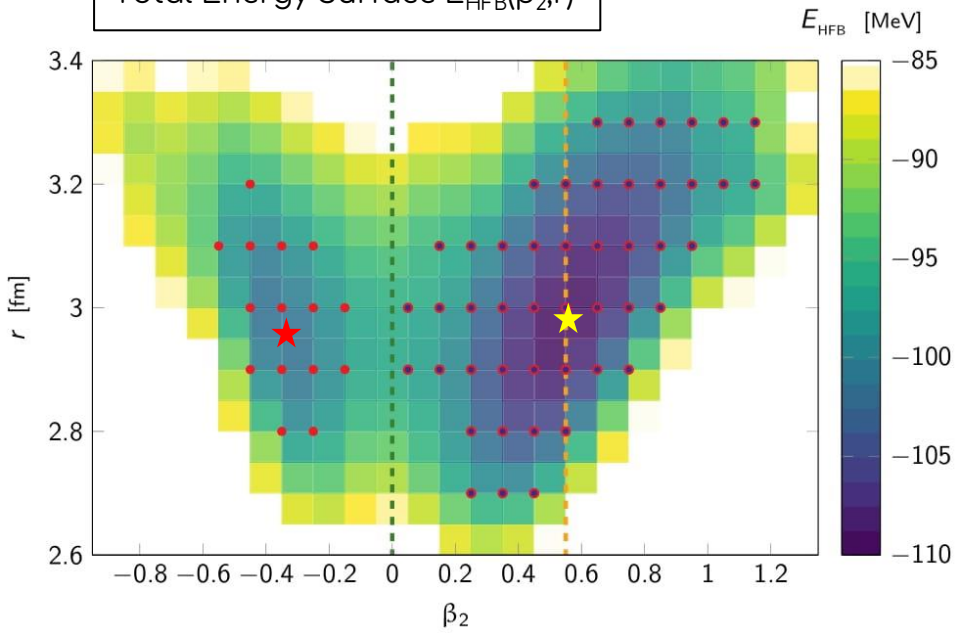


Deformation

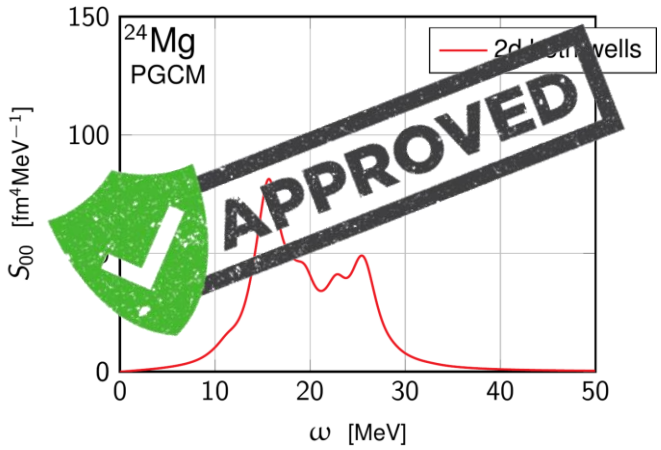
Shape coexistence ? (1)

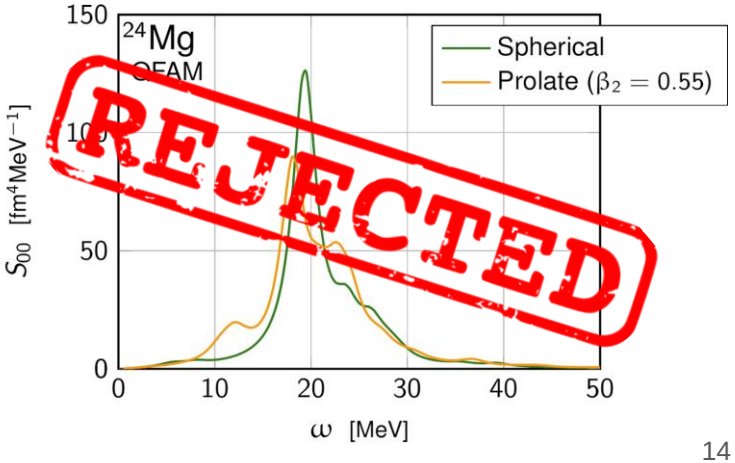
(1) [Dowie et al., 2020]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



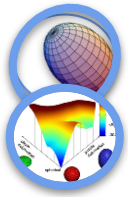


Results

- Dominant prolate minimum
- Important static quadrupole deformation
- No coupling between different wells
- Coupling to quadrupole fluctuation
- Important anharmonic effects QRPA unreliable

Deformation effects in ^{24}Mg

Difficulty

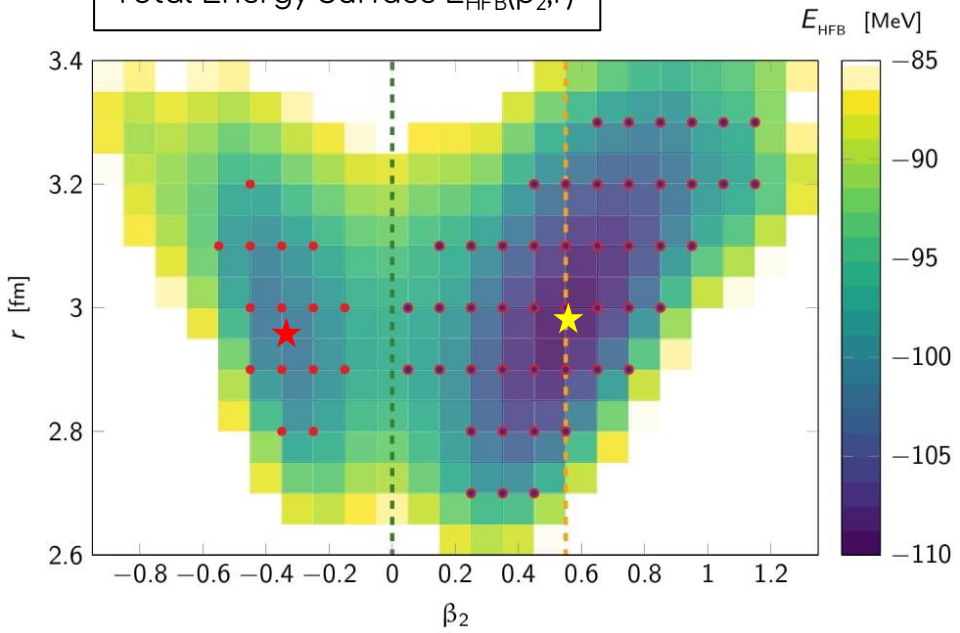


Deformation

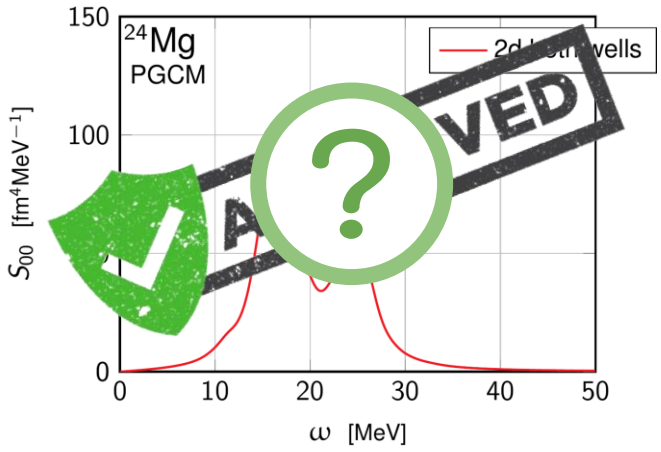
Shape coexistence ? (1)

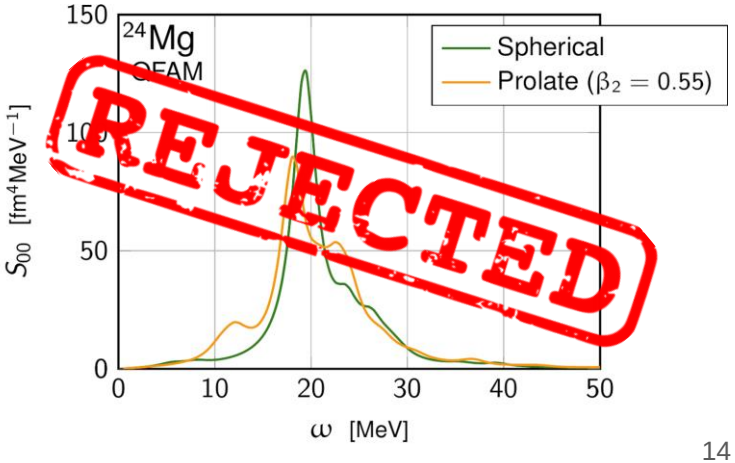
(1) [Dowie et al., 2020]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



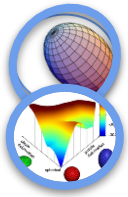


Results

- Dominant prolate minimum
- Important static quadrupole deformation
- No coupling between different wells
- Coupling to quadrupole fluctuation
- Important anharmonic effects QRPA unreliable

Deformation effects in ^{24}Mg

Difficulty

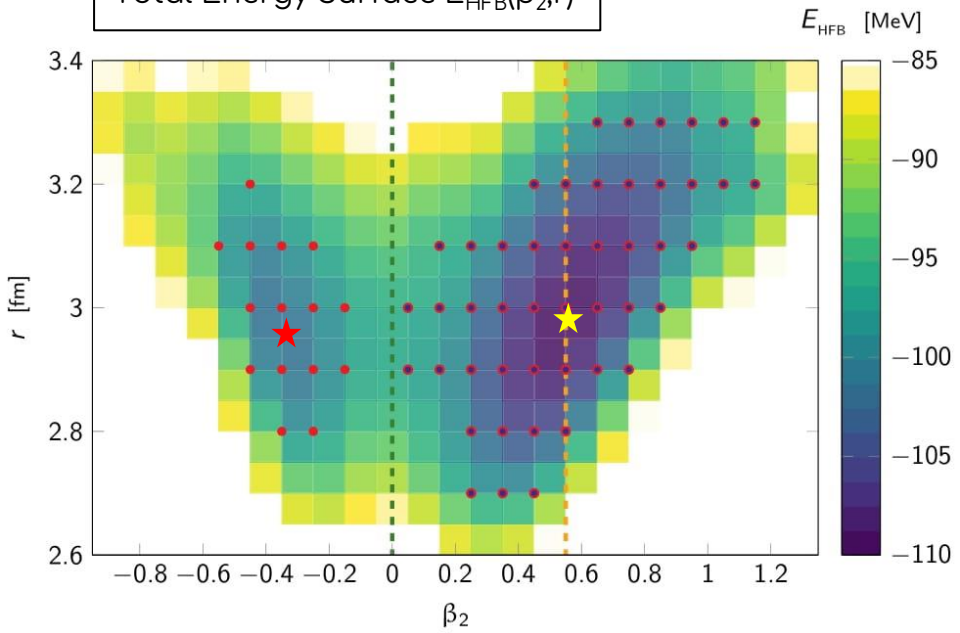


Deformation

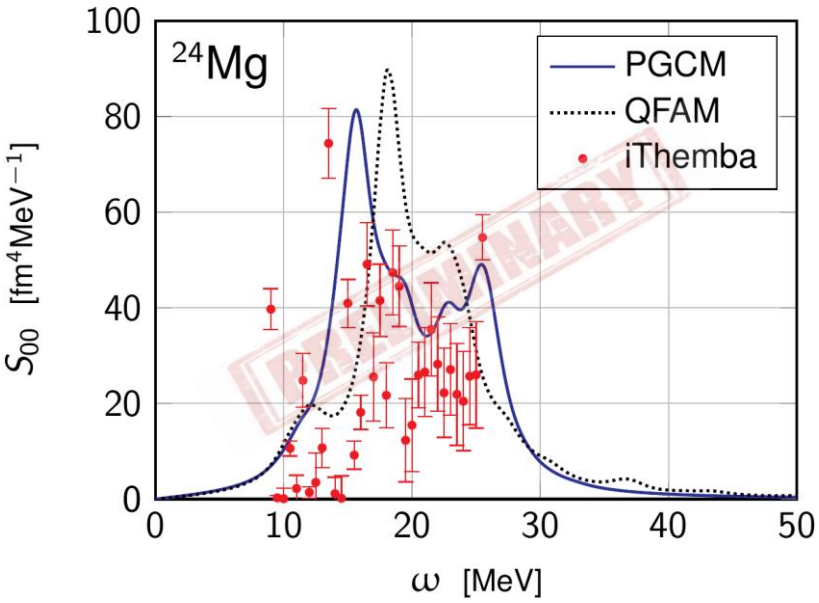
Shape coexistence ? (1)

(1) [Dowie et al., 2020]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength



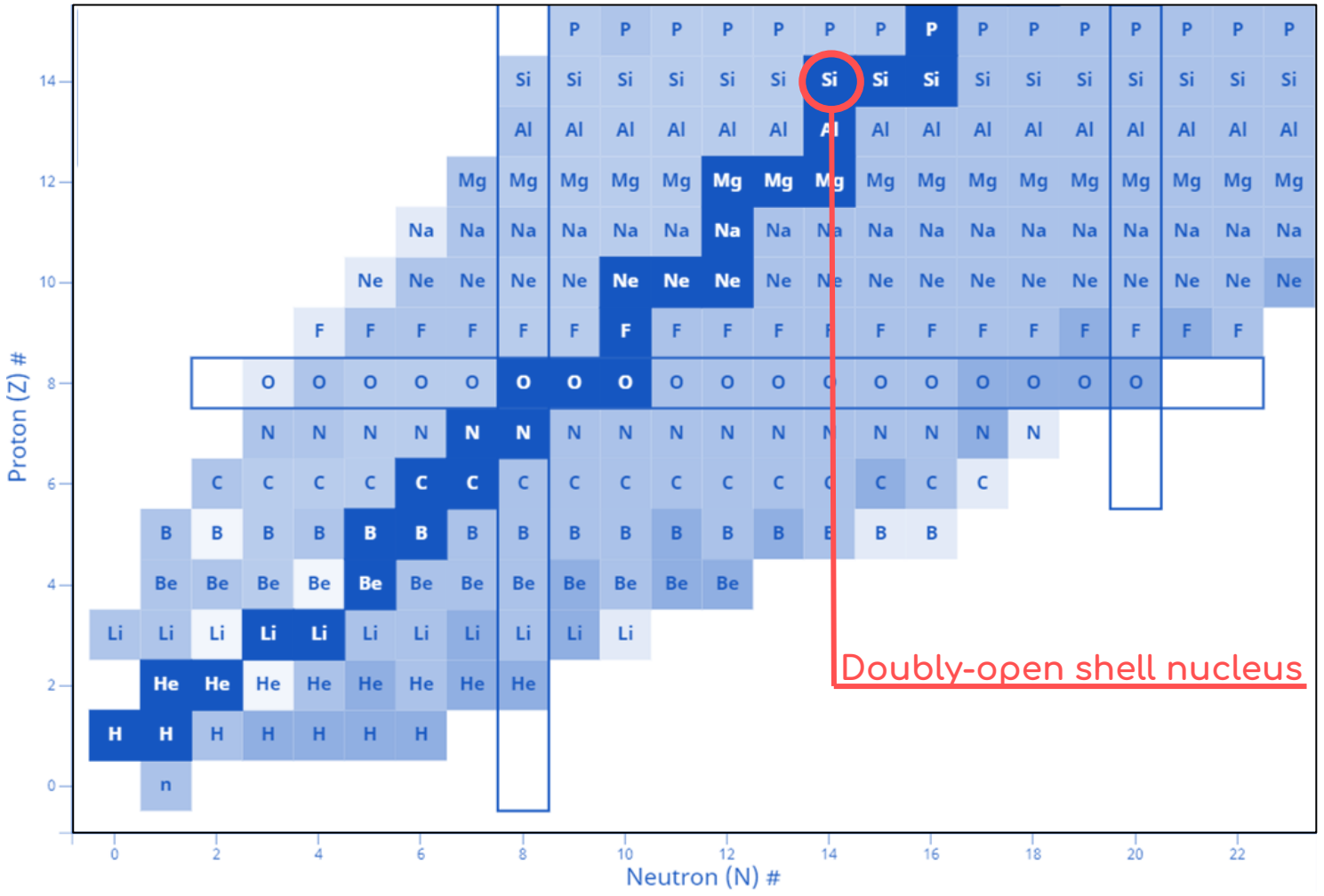
iThemba, Bahini 2021

Results

- Dominant prolate minimum
- Important static quadrupole deformation
- No coupling between different wells
- Coupling to quadrupole fluctuation
- Important anharmonic effects QRPA unreliable

1. PGCM superior to QRPA
2. Experiments **useful** and **promising**
3. Data are **not unambiguous**

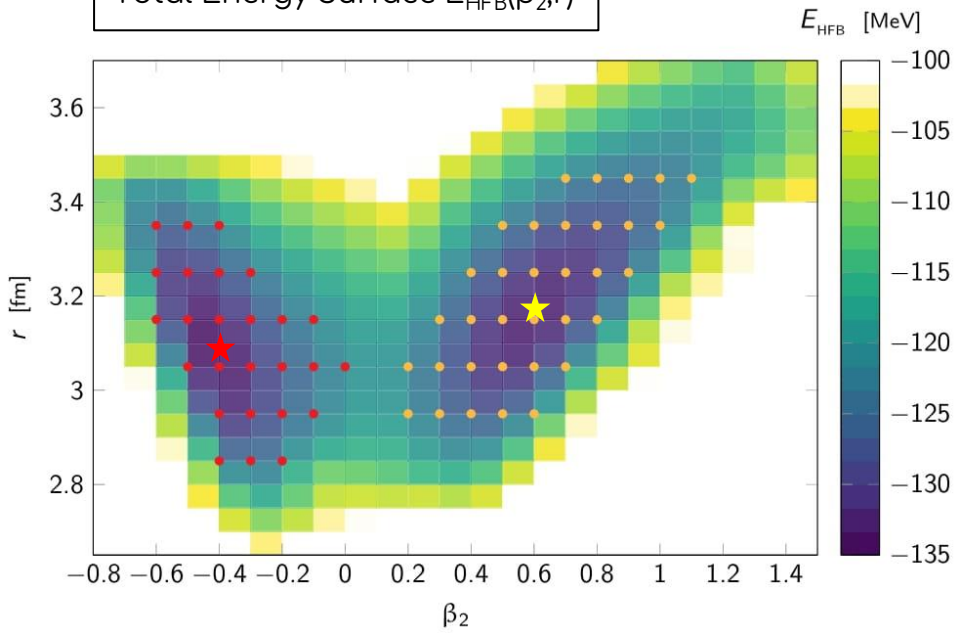
Deformation effects in ^{28}Si



Deformation effects in ^{28}Si

Difficulty

Total Energy Surface $E_{HFB}(\beta_2,r)$



Results

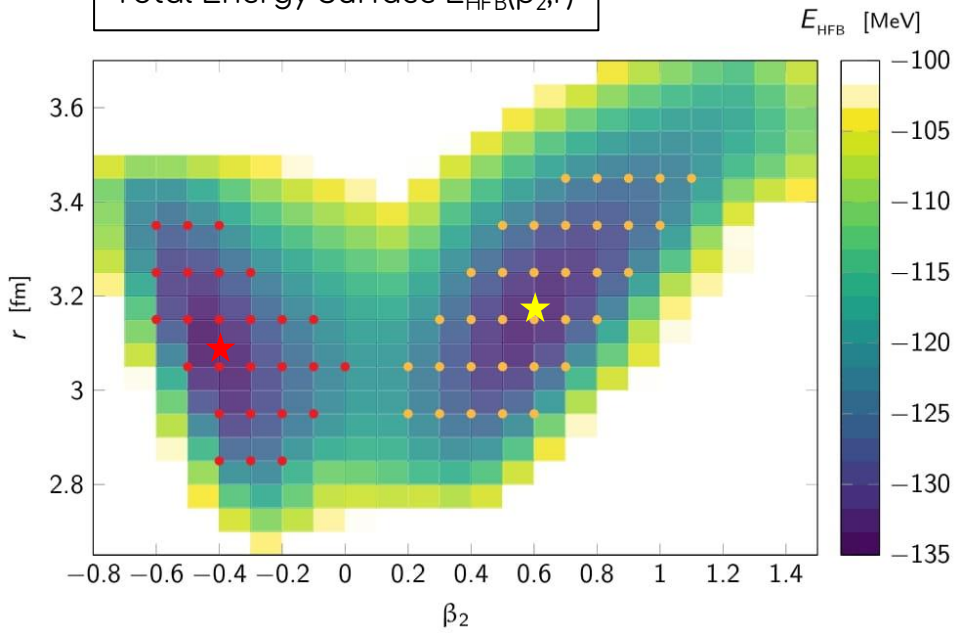
- Two wells clearly separated, oblate dominant

Deformation effects in ^{28}Si

Difficulty

Deformation

Total Energy Surface $E_{HFB}(\beta_2,r)$

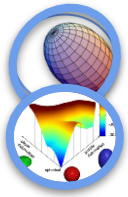


Results

- Two wells clearly separated, oblate dominant

Deformation effects in ^{28}Si

Difficulty

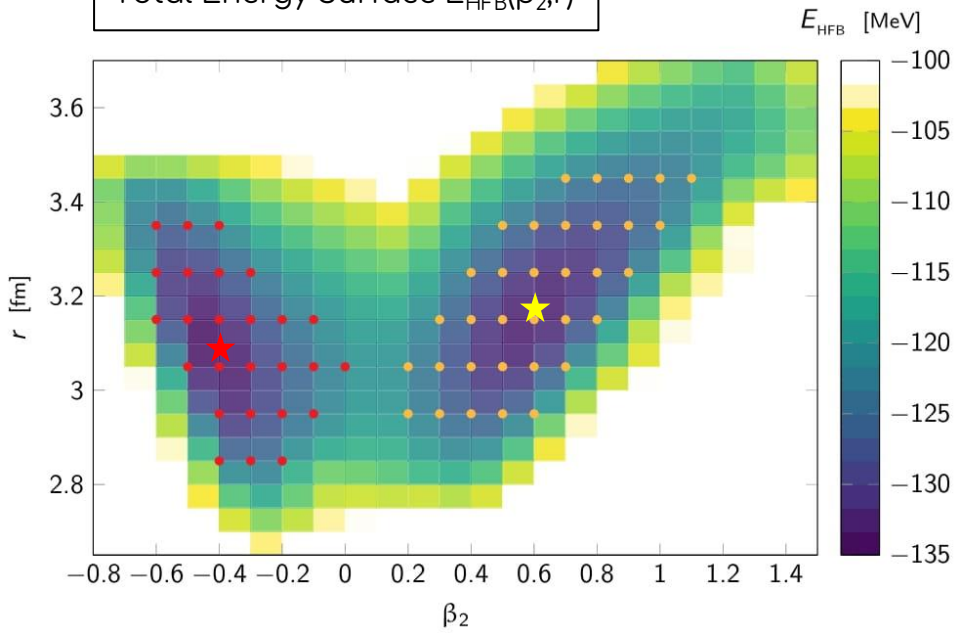


Deformation

Shape coexistence ? (1)

(1) [Jenkins et al., 2012]

Total Energy Surface $E_{HFB}(\beta_2,r)$

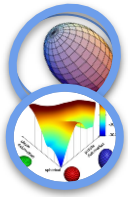


Results

- Two wells clearly separated, oblate dominant

Deformation effects in ^{28}Si

Difficulty

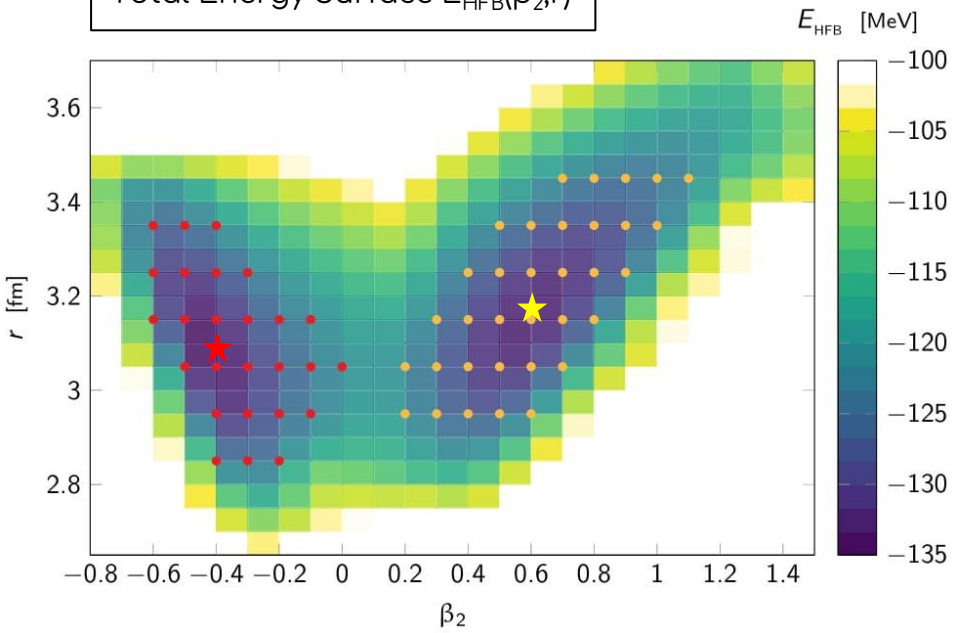


Deformation

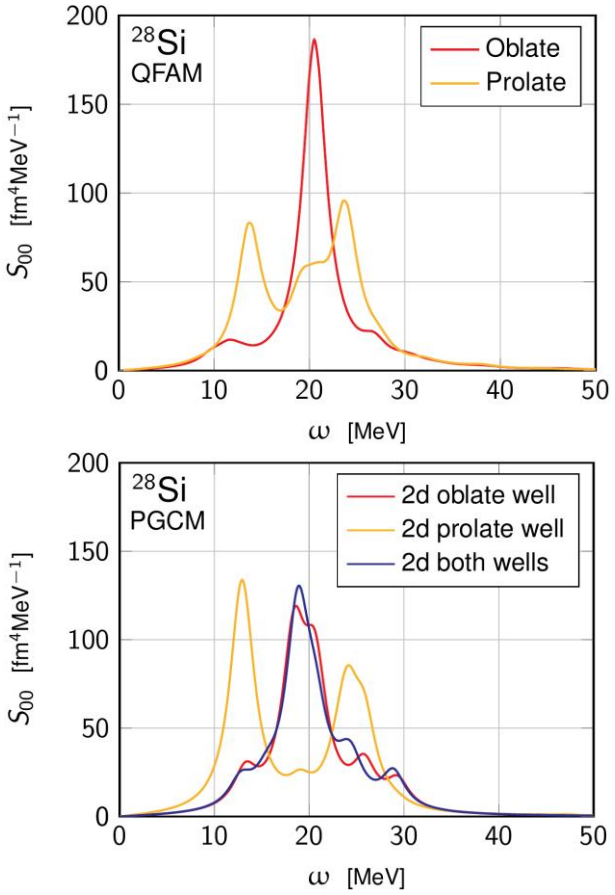
Shape coexistence ? (1)

(1) [Jenkins et al., 2012]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength

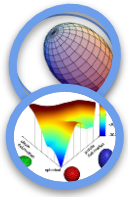


Results

- Two wells clearly separated, oblate dominant
- Qualitatively similar results QFAM/PGCM

Deformation effects in ^{28}Si

Difficulty

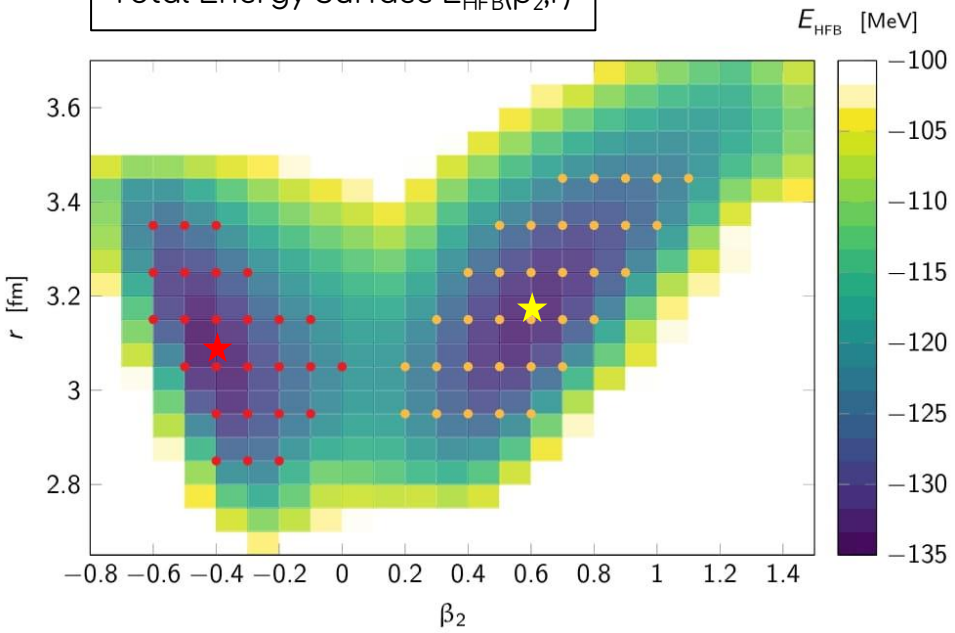


Deformation

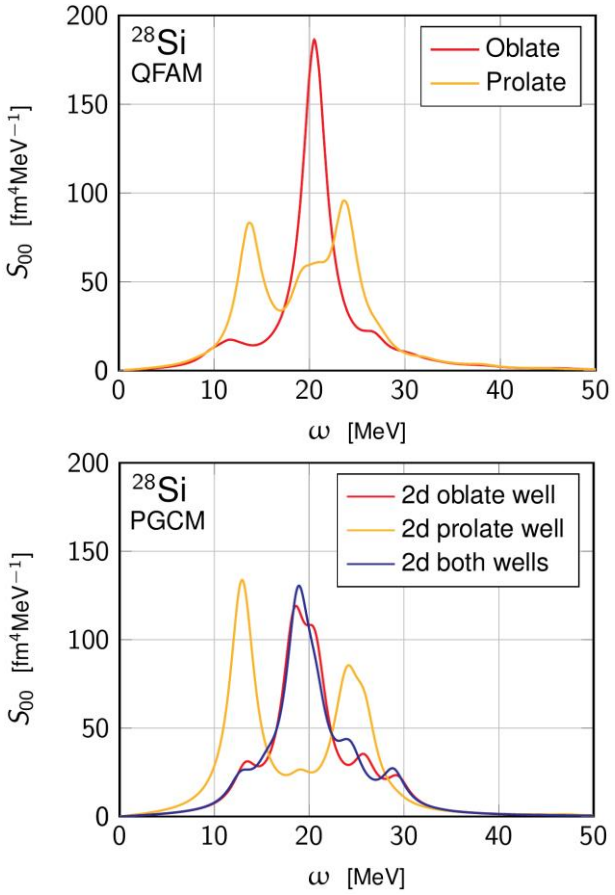
Shape coexistence ? (1)

(1) [Jenkins et al., 2012]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength

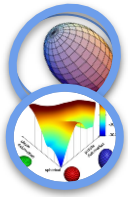


Results

- Two wells clearly separated, oblate dominant
- Qualitatively similar results QFAM/PGCM
- No shape mixing

Deformation effects in ^{28}Si

Difficulty

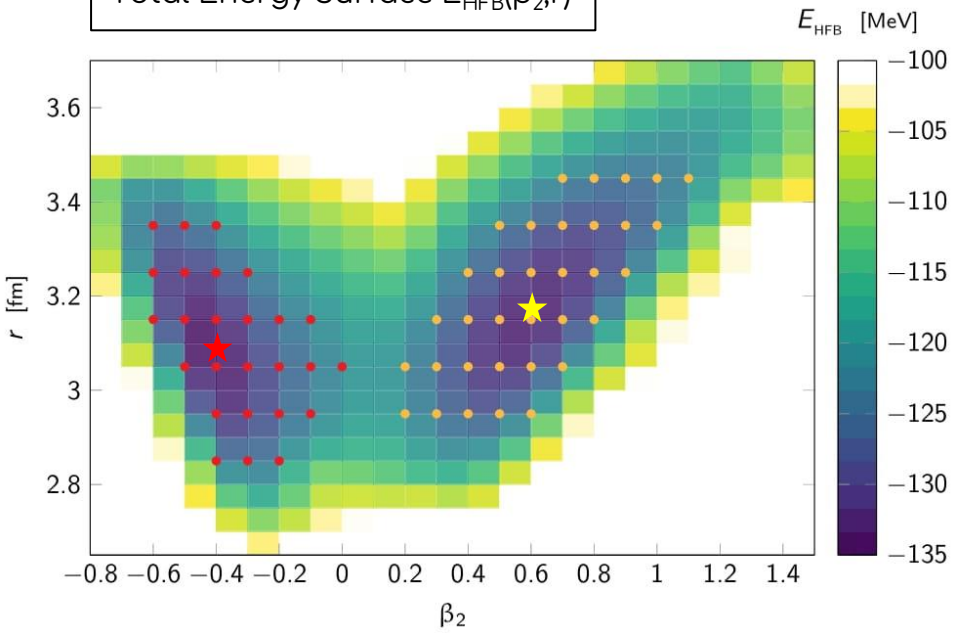


Deformation

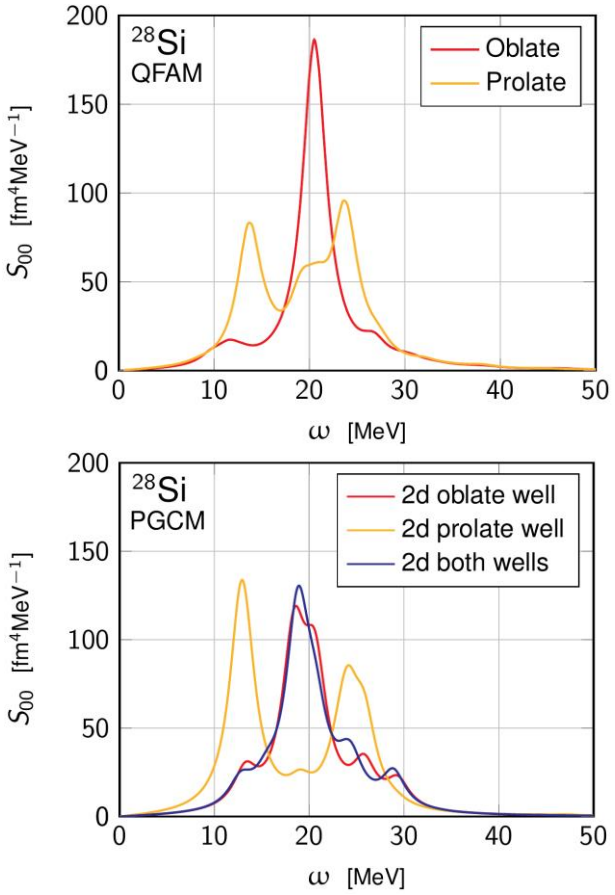
Shape coexistence ? (1)

(1) [Jenkins et al., 2012]

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength

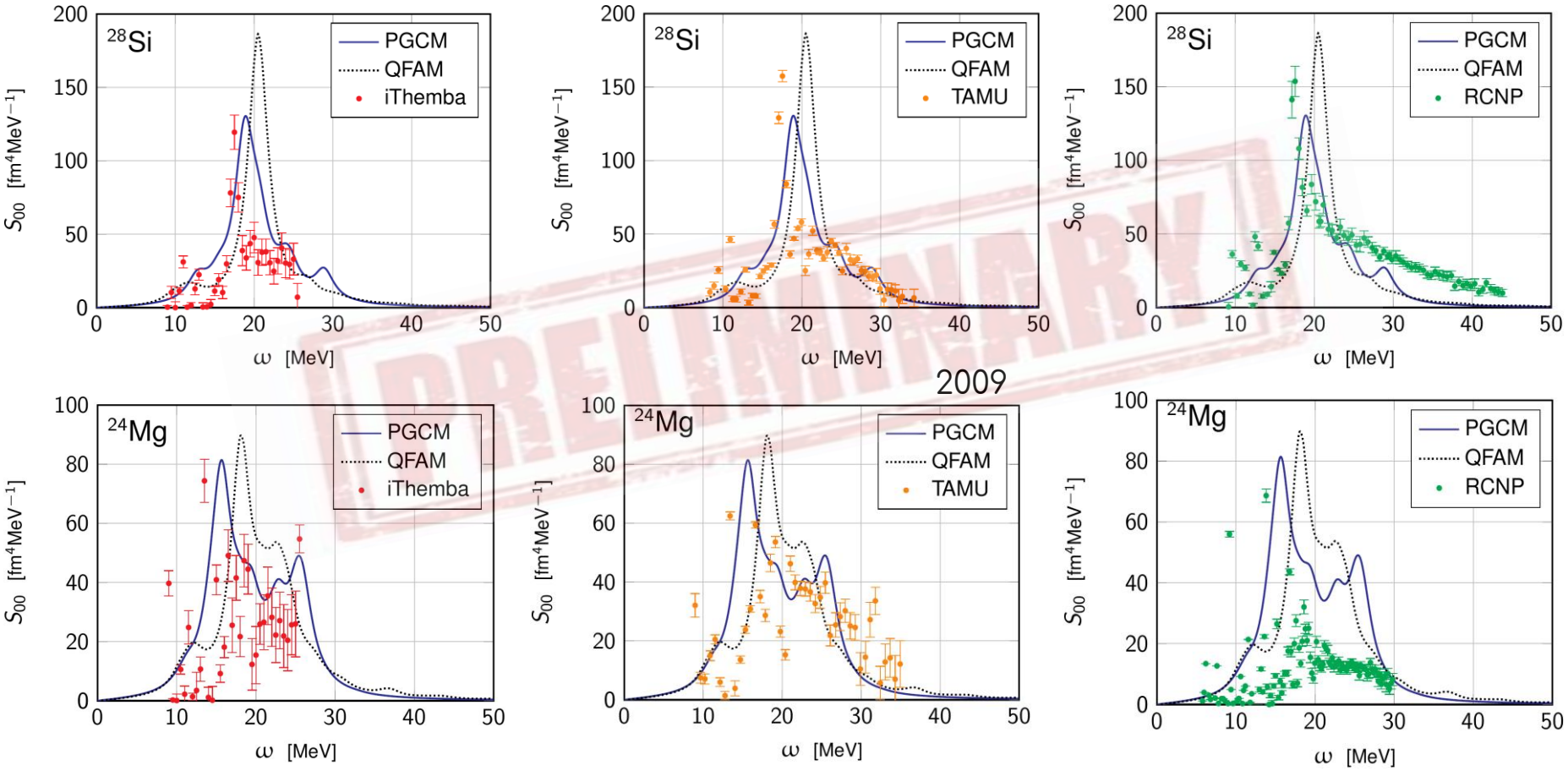


Results

- Two wells clearly separated, oblate dominant
- Qualitatively similar results QFAM/PGCM
- No shape mixing
- Two-peak GMR on the prolate shape isomer ?

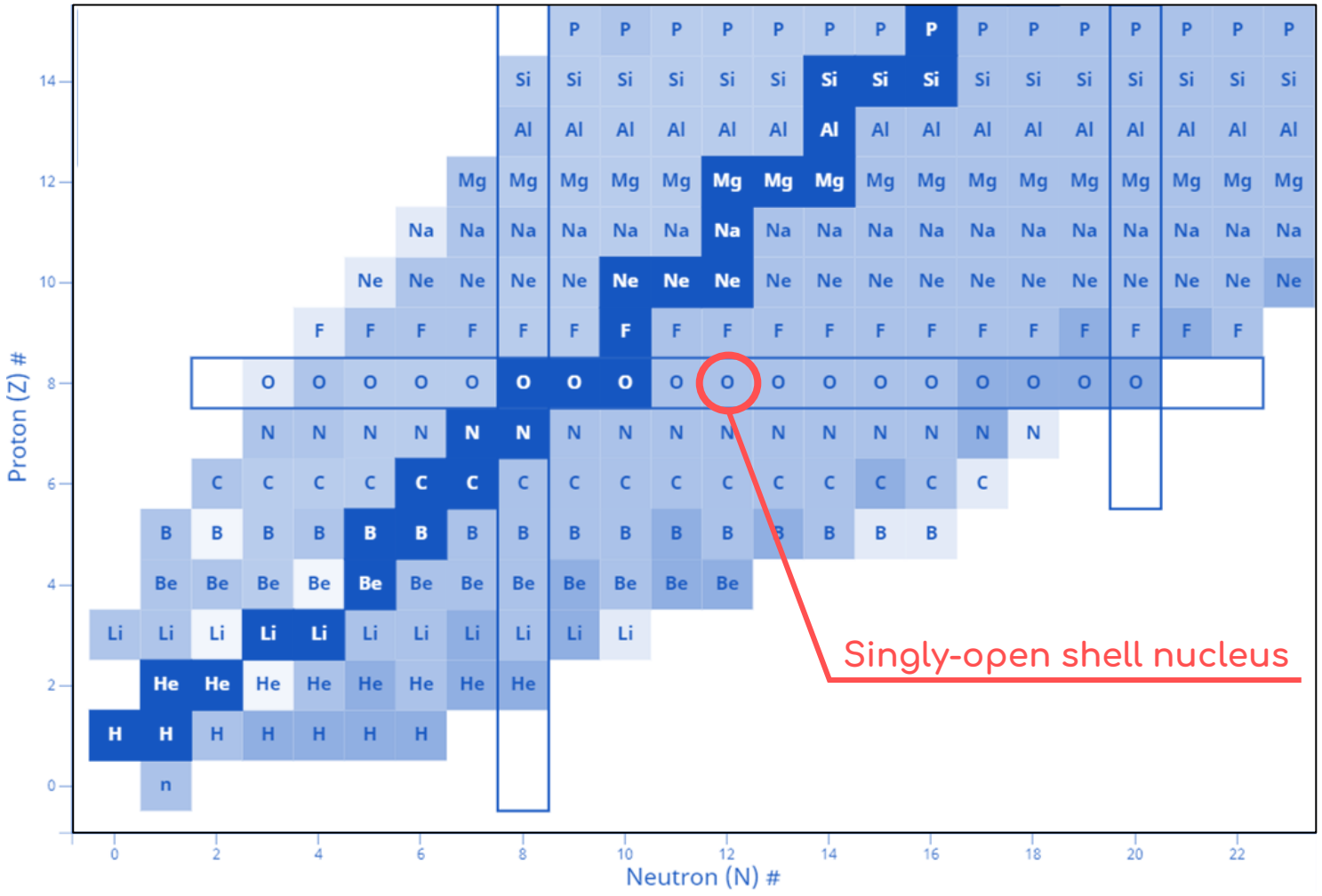
Comparison to experiment

iThemba, Bahini 2021 | TAMU, Youngblood 2007 | RCNP, Kawabata 2013



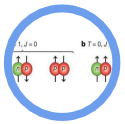
1. **PGCM superior to QRPA**, i.e. coupling to quadrupole deformation/fluctuations captured
2. Experimental data in doubly open-shell nuclei very useful and promising
3. Data are **not unambiguous**, i.e. better data would be beneficial

Superfluidity effects in ^{20}O



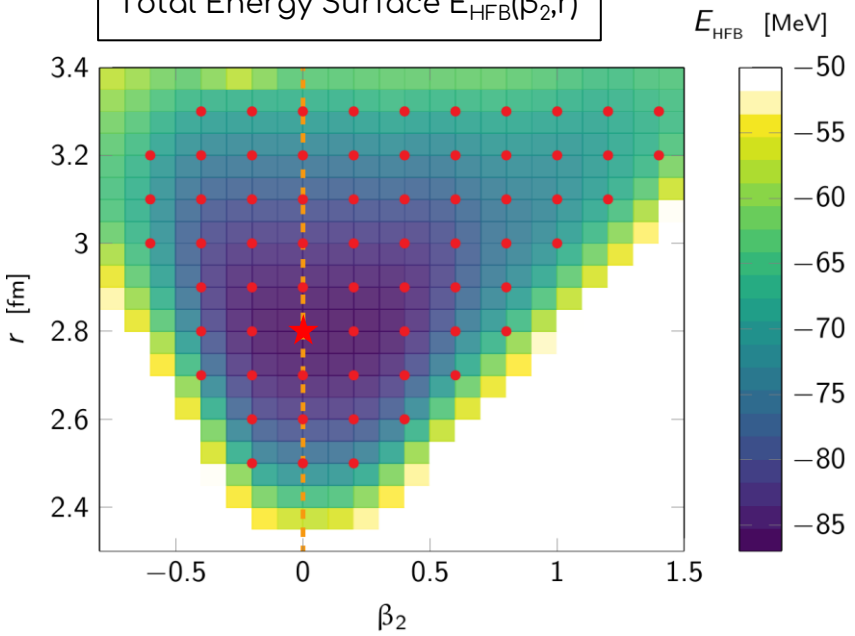
Superfluidity effects in ^{20}O

Difficulty



Superfluidity

Total Energy Surface $E_{HFB}(\beta_2,r)$

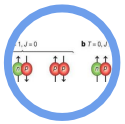


Results

- Single spherical minimum

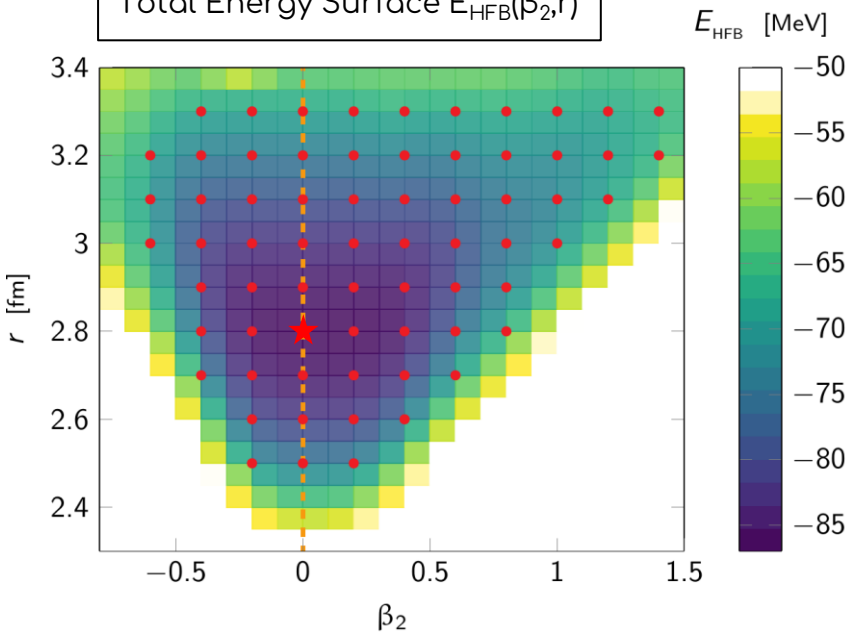
Superfluidity effects in ^{20}O

Difficulty

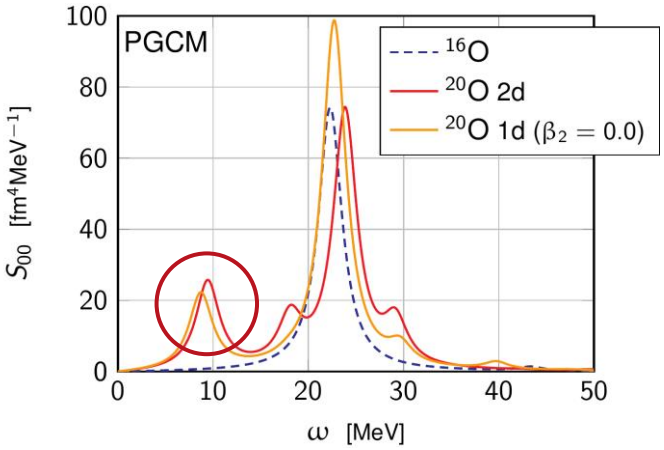


Superfluidity

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength

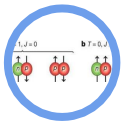


Results

- Single spherical minimum
- In PGCM low energy strength appears

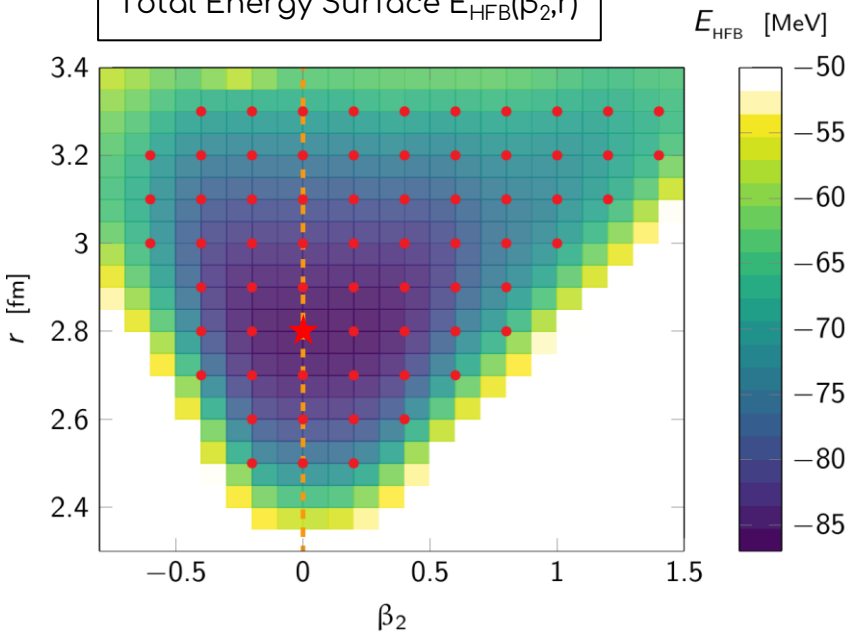
Superfluidity effects in ^{20}O

Difficulty

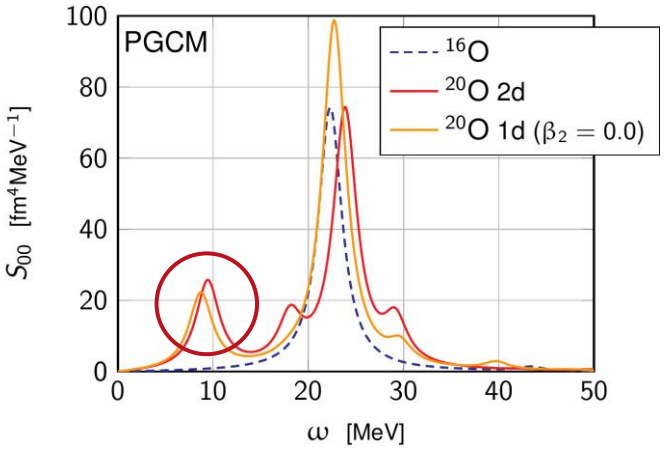


Superfluidity

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength

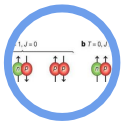


Results

- Single spherical minimum
- In PGCM low energy strength appears
- Weak coupling with quadrupolar vibrations

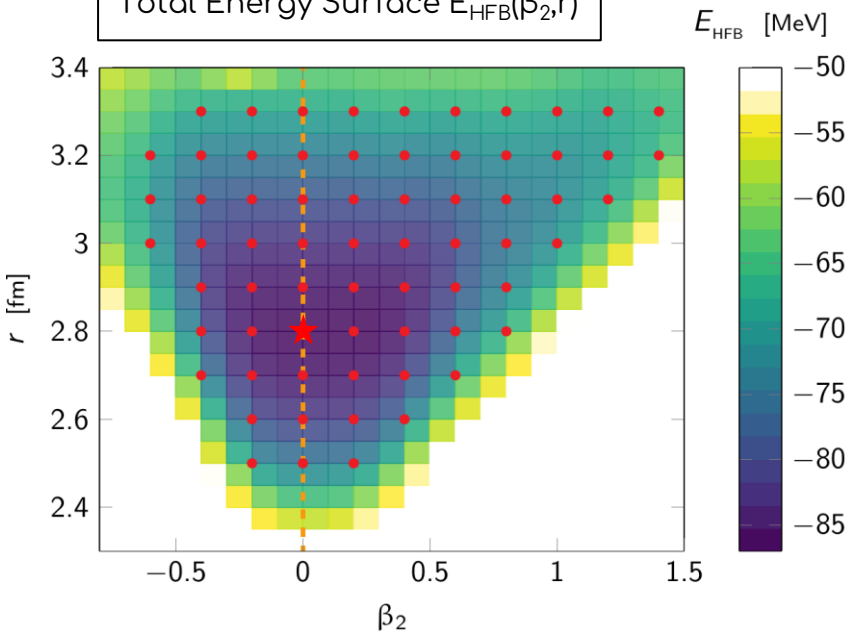
Superfluidity effects in ^{20}O

Difficulty

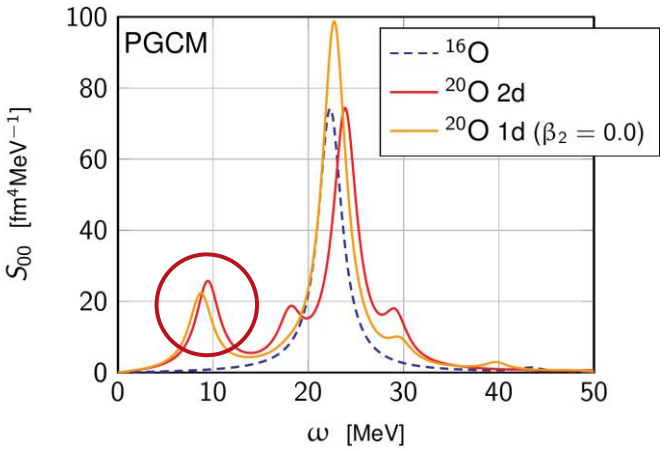


Superfluidity

Total Energy Surface $E_{HFB}(\beta_2,r)$



Monopole Strength

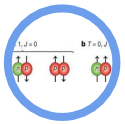


Results

- Single spherical minimum
- In PGCM low energy strength appears
- Weak coupling with quadrupolar vibrations
- Further investigations coupling pairing (Δ , r)

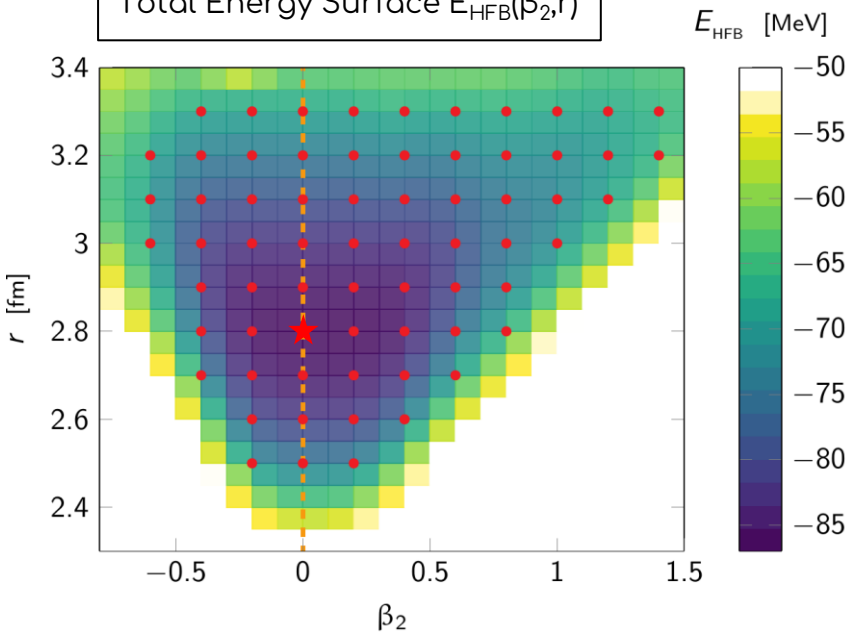
Superfluidity effects in ^{20}O

Difficulty

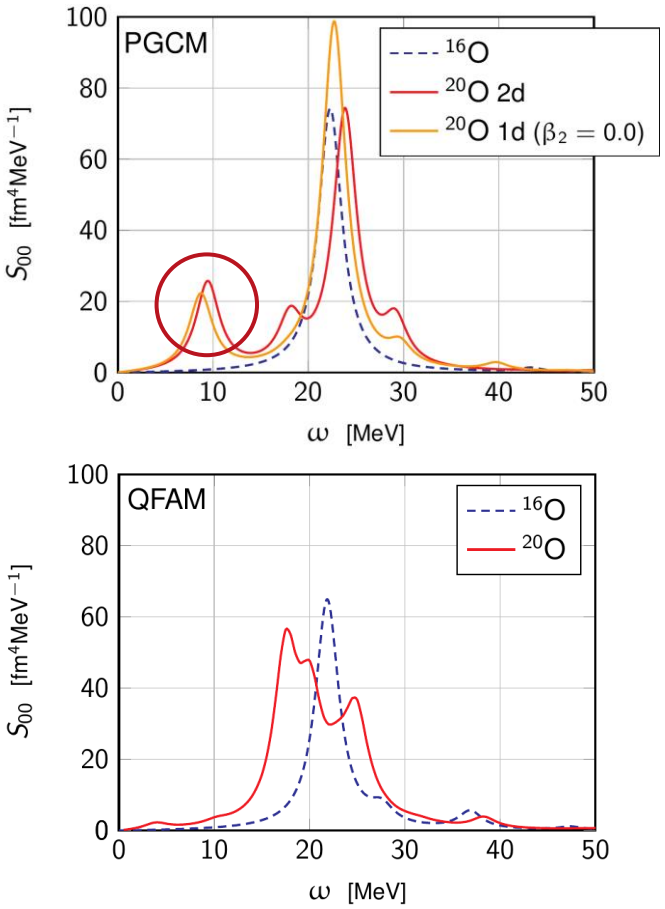


Superfluidity

Total Energy Surface $E_{HFB}(\beta_2,r)$



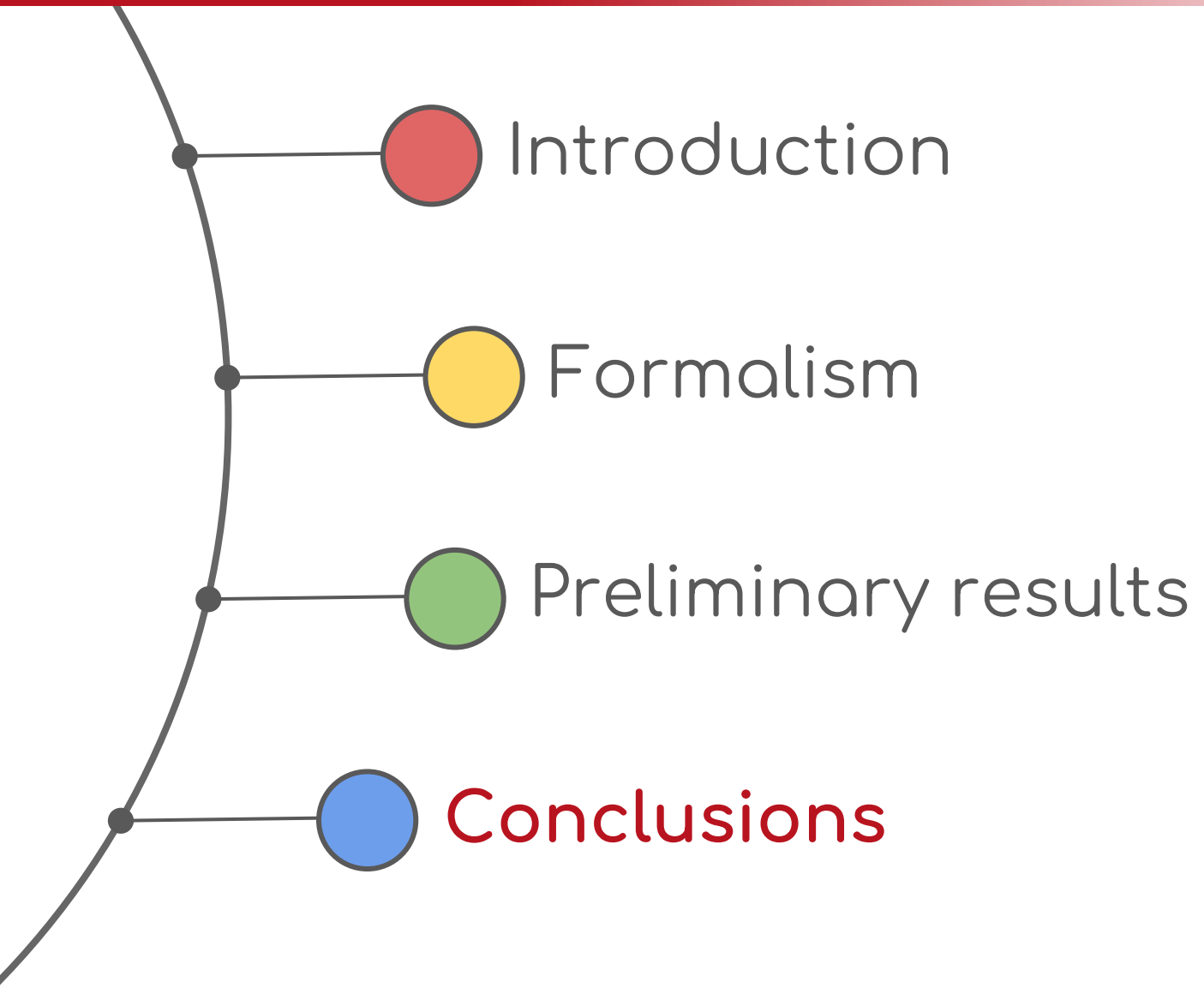
Monopole Strength



Results

- Single spherical minimum
- In PGCM low energy strength appears
- Weak coupling with quadrupolar vibrations
- Further investigations coupling pairing (Δ , r)
- Inconsistency between QFAM and PGCM

Outline


Introduction
Formalism
Preliminary results
Conclusions

Conclusions and Perspectives

First ab-initio systematic description of GMR

Choose physics according to selected coordinates

No limitation on the nucleus choice

Conclusions and Perspectives

First ab-initio systematic description of GMR

Choose physics according to selected coordinates

No limitation on the nucleus choice

Plan of the complete study

- ☐ Static quadrupolar deformation
- ☐ Coupling to quadrupolar vibrations
- ☐ Shape isomers
- ☐ Theoretical comparison of moment computation
- ☐ Hamiltonian uncertainty through different chiral EFT orders
- ☐ Superfluidity (Oxygen isotopic chains, pairing variations)
- ☐ Bubble structure (^{34}Si and ^{36}S)
- ☐ Nuclei of current experimental interest (^{68}Ni and ^{70}Ni) [ACTAR TPC]

Conclusions and Perspectives

First ab-initio systematic description of GMR

Choose physics according to selected coordinates

No limitation on the nucleus choice

Plan of the complete study

- [x] Static quadrupolar deformation
- [ ] Coupling to quadrupolar vibrations
- [ ] Shape isomers
- [ ] Theoretical comparison of moment computation
- [ ] Hamiltonian uncertainty through different chiral EFT orders
- [ ] Superfluidity (Oxygen isotopic chains, pairing variations)
- [ ] Bubble structure (^{34}Si and ^{36}S)
- [ ] Nuclei of current experimental interest (^{68}Ni and ^{70}Ni) [ACTAR TPC]

Conclusions and Perspectives

First ab-initio systematic description of GMR

Choose physics according to selected coordinates

No limitation on the nucleus choice

Plan of the complete study

- [x] Static quadrupolar deformation
- [x] Coupling to quadrupolar vibrations
- [ ] Shape isomers
- [ ] Theoretical comparison of moment computation
- [ ] Hamiltonian uncertainty through different chiral EFT orders
- [ ] Superfluidity (Oxygen isotopic chains, pairing variations)
- [ ] Bubble structure (^{34}Si and ^{36}S)
- [ ] Nuclei of current experimental interest (^{68}Ni and ^{70}Ni) [ACTAR TPC]

Conclusions and Perspectives

First ab-initio systematic description of GMR

Choose physics according to selected coordinates

No limitation on the nucleus choice

Plan of the complete study

- [x] Static quadrupolar deformation
- [x] Coupling to quadrupolar vibrations
- [x] Shape isomers
- [ ] Theoretical comparison of moment computation
- [ ] Hamiltonian uncertainty through different chiral EFT orders
- [ ] Superfluidity (Oxygen isotopic chains, pairing variations)
- [ ] Bubble structure (^{34}Si and ^{36}S)
- [ ] Nuclei of current experimental interest (^{68}Ni and ^{70}Ni) [ACTAR TPC]

Thanks for the attention

CEA DRF

Thomas Duguet
Vittorio Somà
Benjamin Bally
Alberto Scalesi

CEA DES

Mikael Frosini

CEA DAM

Jean-Paul Ebran
Yann Beaujeault-Taudière
Antoine Roux

Gianluca Colò
Danilo Gambacurta

Technische Universität Darmstadt

Alexander Tichai

KU Leuven

Pepijn Demol