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

Methods, uses and recent results

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

SUPERVISORS
Thomas Duguet
Vittorio Somà

July 21st, 2023

XVII International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics – CGS17

ILL Grenoble

Outline

- Introduction
- Formalism
- Results
- Conclusions

Outline

- Introduction
  - Ab-initio methods and Giant Resonances
- Formalism
- Results
- Conclusions

Ab initio nuclear structure

Global philosophy

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

Ab initio nuclear structure

Global philosophy

$$\textcircled{H} |\Psi_\nu\rangle = E_\nu |\Psi_\nu\rangle$$

INPUT HAMILTONIAN

Ab initio nuclear structure

Global philosophy

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

INPUT HAMILTONIAN

MANY-BODY SOLUTION

Ab initio nuclear structure

Global philosophy

The approximate solution must be systematically improvable and approach the exact solution in a well-defined limit.

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

INPUT HAMILTONIAN

MANY-BODY SOLUTION

Ab initio nuclear structure

Global philosophy

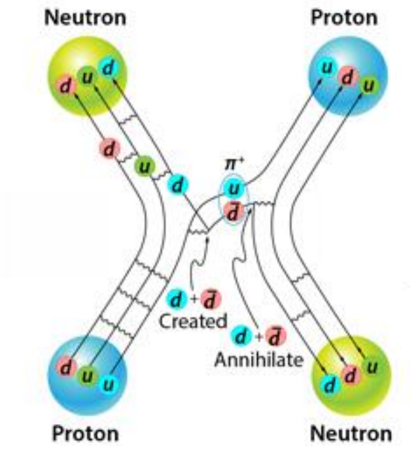
The approximate solution must be systematically improvable and approach the exact solution in a well-defined limit.

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

INPUT HAMILTONIAN

MANY-BODY SOLUTION

QCD



Ab initio nuclear structure

Global philosophy

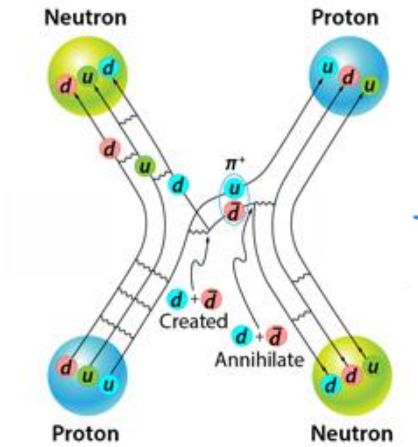
The approximate solution must be systematically improvable and approach the exact solution in a well-defined limit.

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

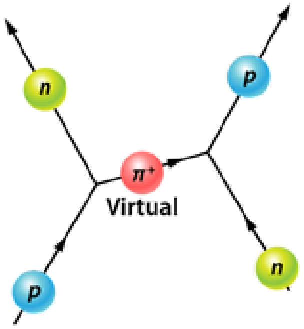
INPUT HAMILTONIAN

MANY-BODY SOLUTION

QCD



Nuclear forces



Ab initio nuclear structure

Global philosophy

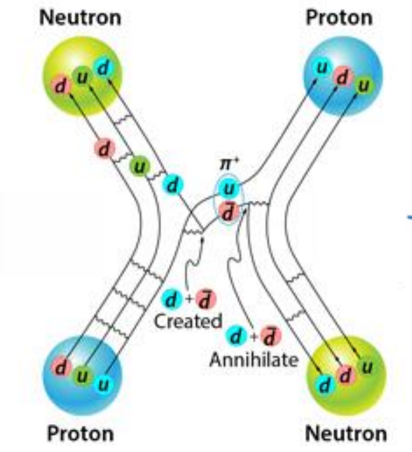
The approximate solution must be systematically improvable and approach the exact solution in a well-defined limit.

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

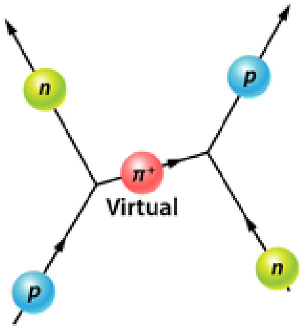
INPUT HAMILTONIAN

MANY-BODY SOLUTION

QCD



Nuclear forces



Ab initio nuclear structure

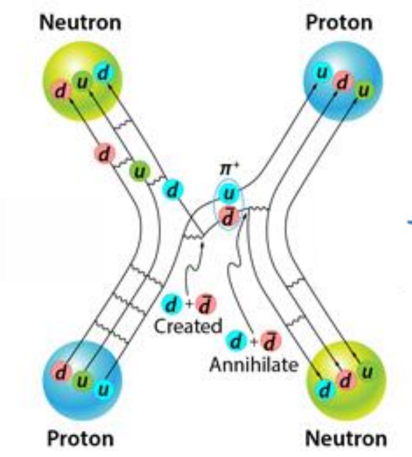
Global philosophy

The approximate solution must be systematically improvable and approach the exact solution in a well-defined limit.

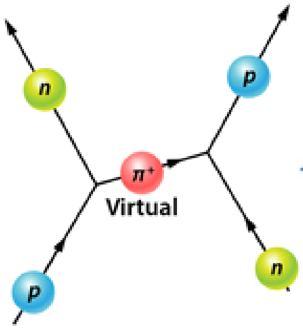
$$H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$$

INPUT HAMILTONIAN **MANY-BODY SOLUTION**

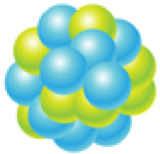
QCD



Nuclear forces



Nuclear structure



Ab initio nuclear structure

Global philosophy

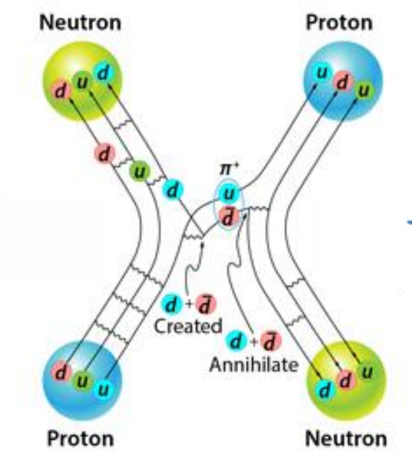
The approximate solution must be systematically improvable and approach the exact solution in a well-defined limit.

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

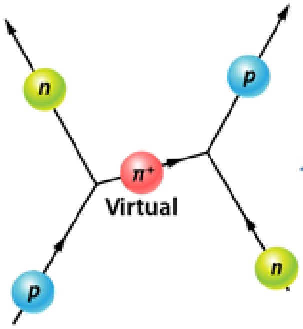
INPUT HAMILTONIAN

MANY-BODY SOLUTION

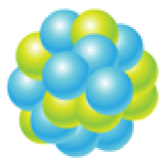
QCD



Nuclear forces



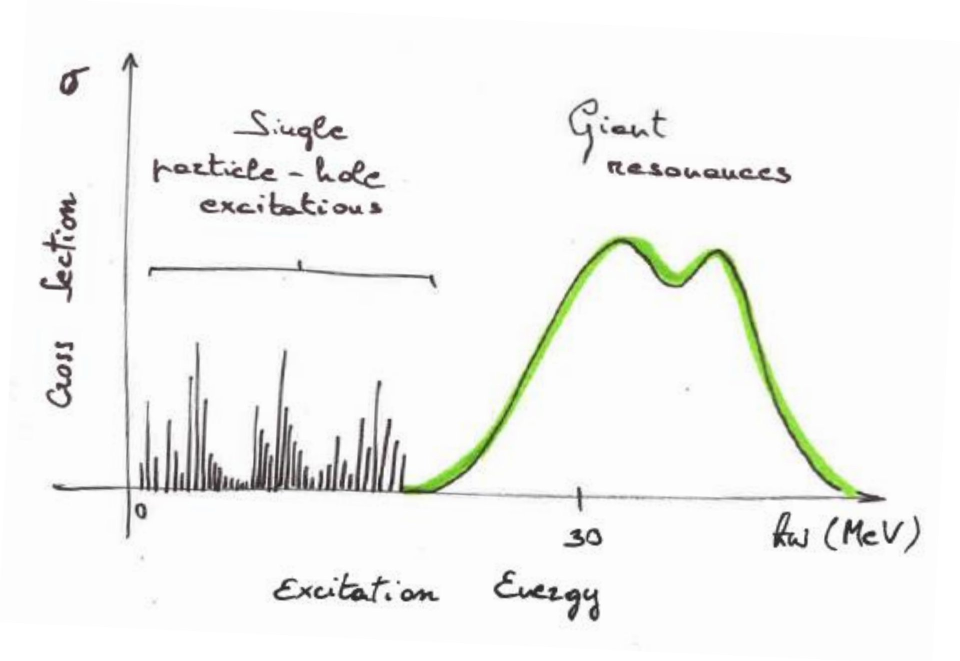
Nuclear structure



Giant Resonances

Dual nature of nucleus

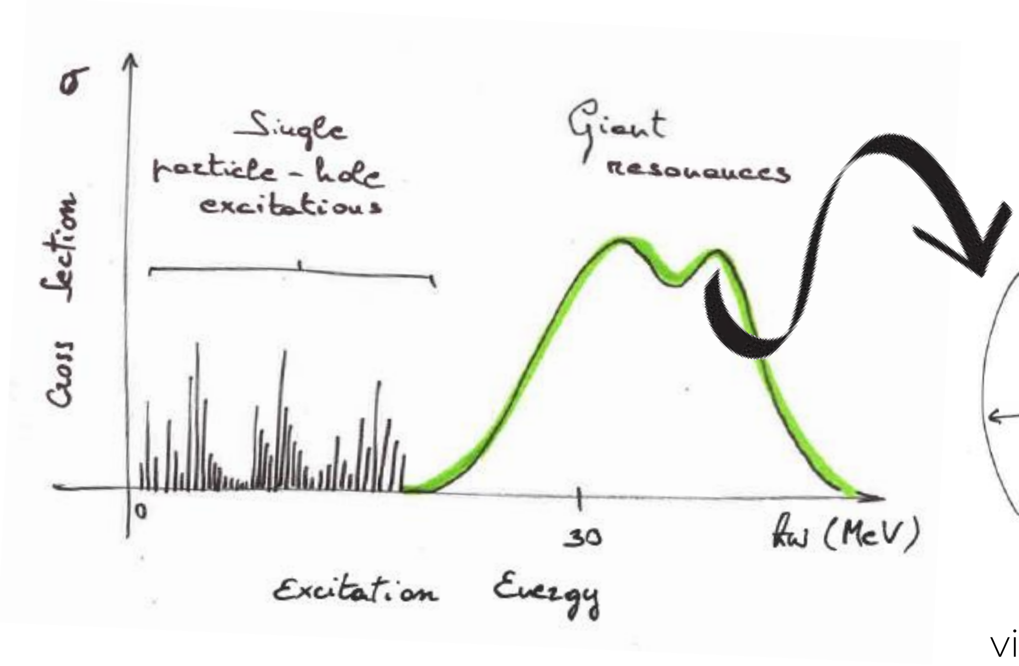
- single-particle features
- collective behaviour

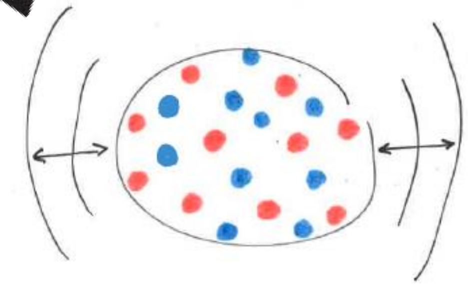


Giant Resonances

Dual nature of nucleus

- single-particle features
- collective behaviour





Liquid drop picture
vibrations, oscillations

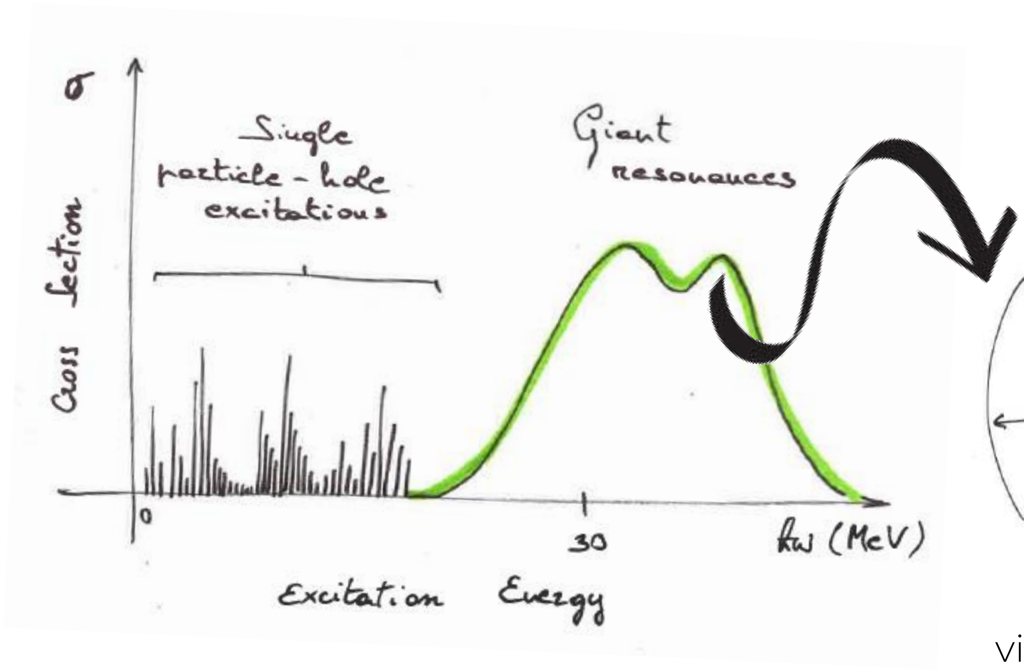
Giant Resonances (GRs)

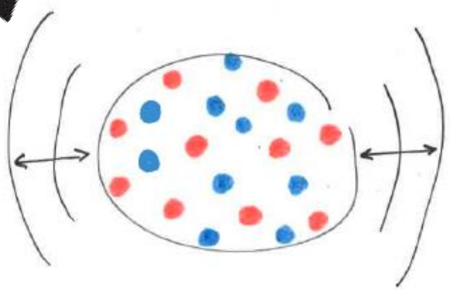
clearest manifestation of collective motion

Giant Resonances

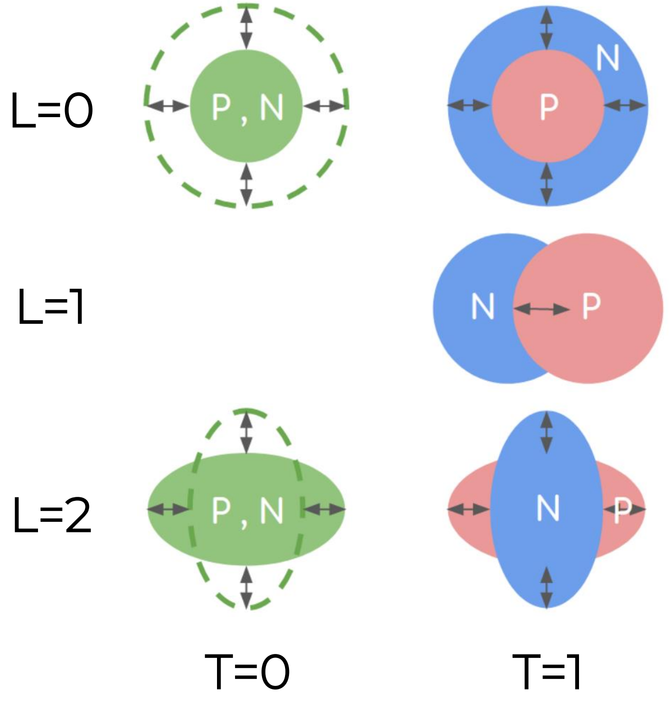
Dual nature of nucleus

- single-particle features
- collective behaviour





Liquid drop picture
vibrations, oscillations



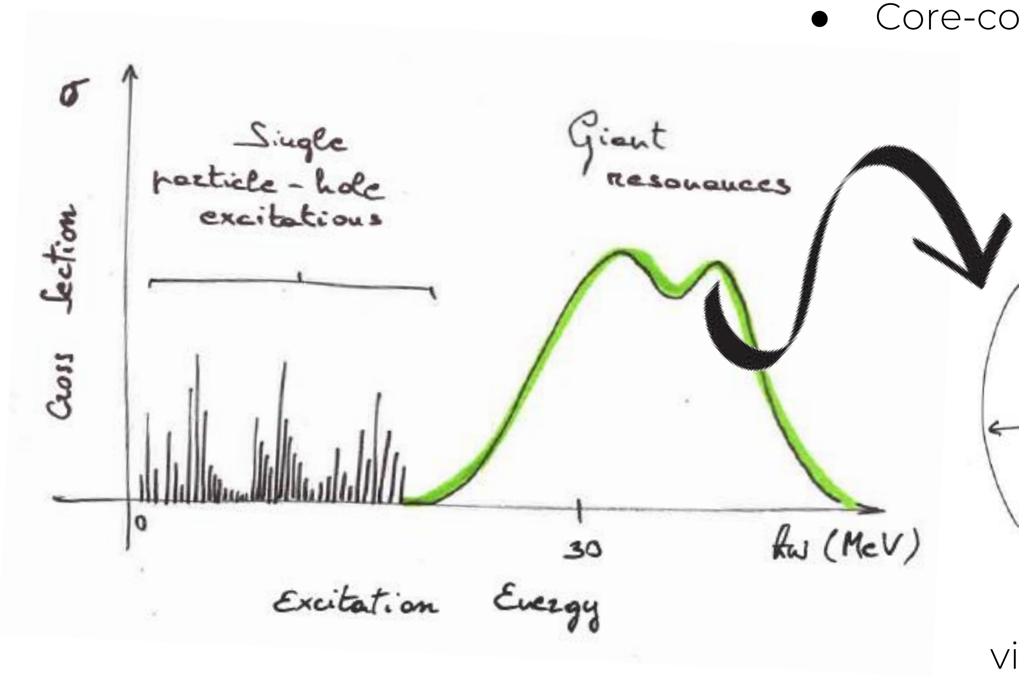
Giant Resonances (GRs)

clearest manifestation of collective motion

Giant Resonances

Dual nature of nucleus

- single-particle features
- collective behaviour

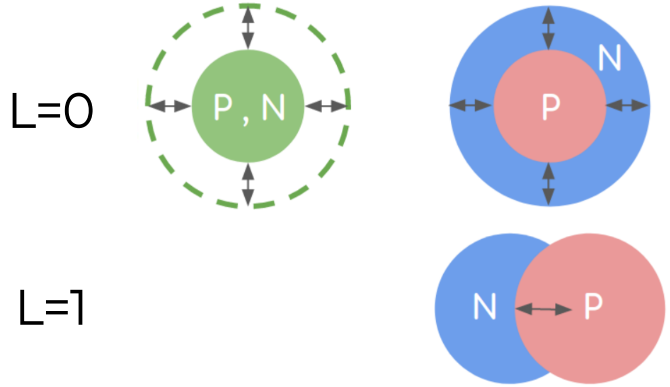


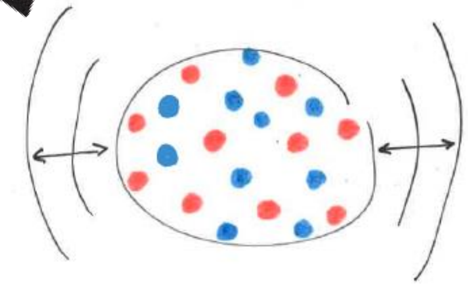
Giant Resonances (GRs)

clearest manifestation of collective motion

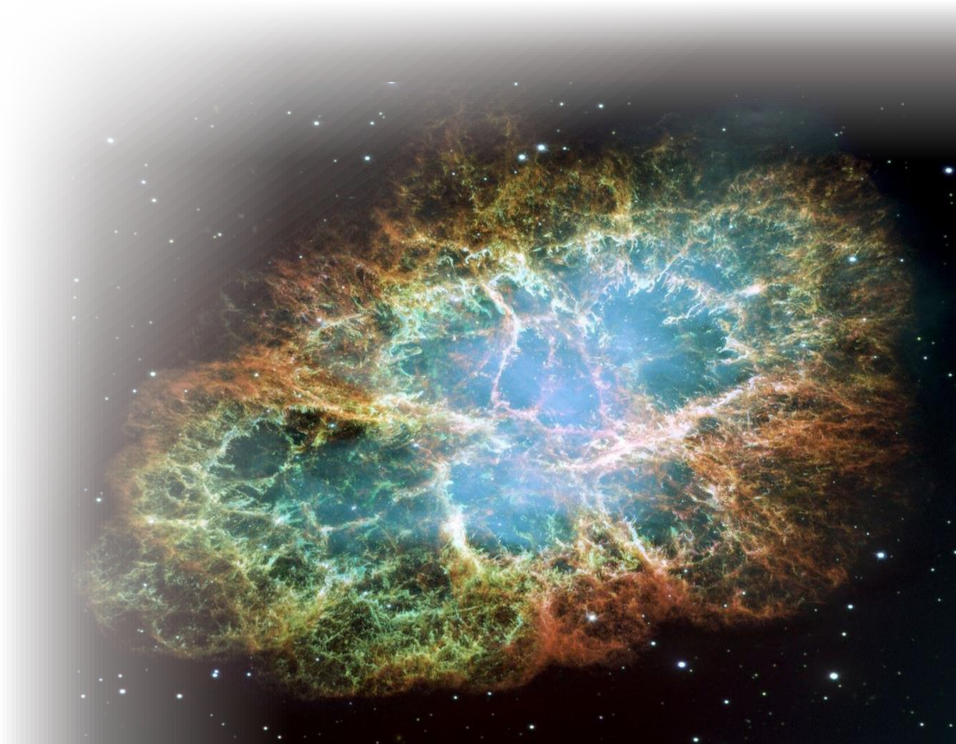
Compression-mode resonances

- Incompressibility of nuclear matter K_∞
- Nuclear Equation of State
- Core-collapse supernova explosion





Liquid drop picture
vibrations, oscillations



Giant Monopole Resonance

Giant Monopole Resonance

What is it ?

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

Giant Monopole Resonance

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

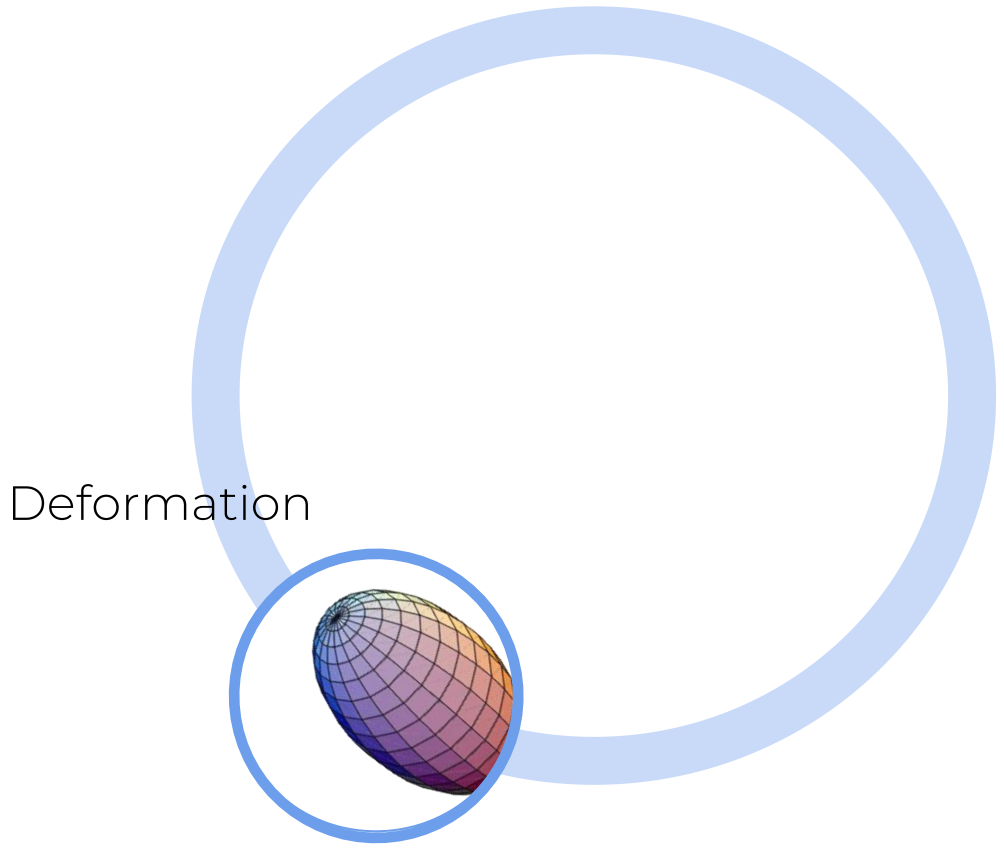
Giant Monopole Resonance

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



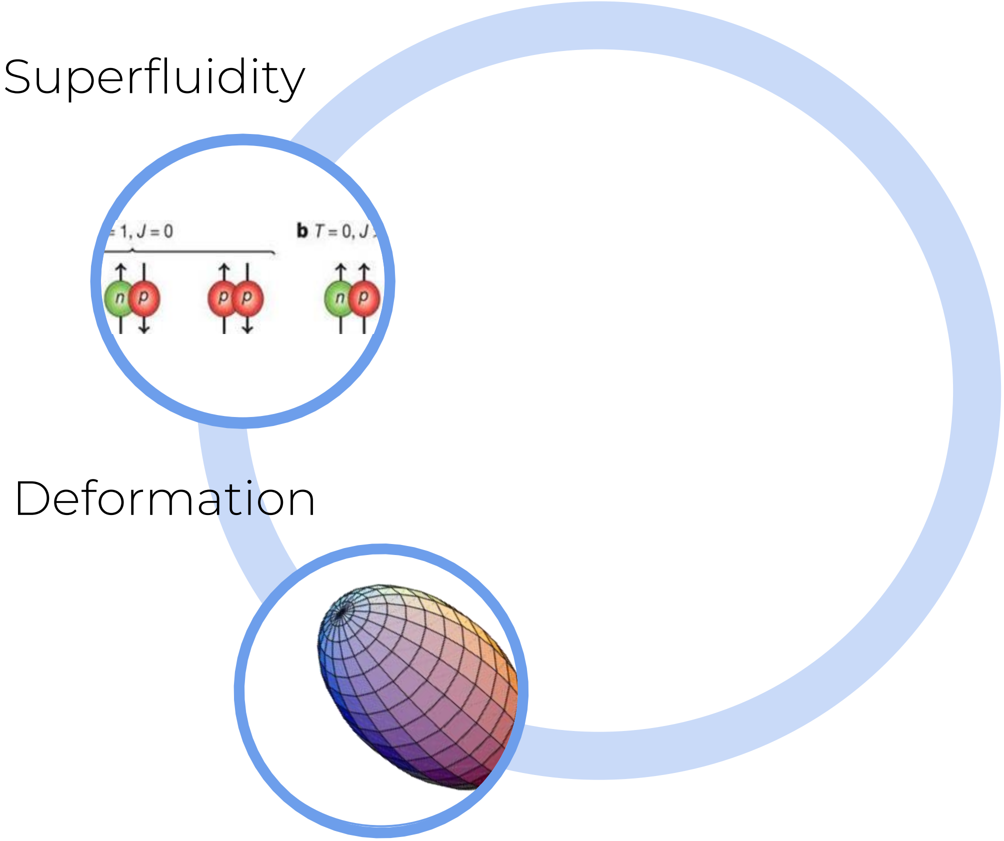
Giant Monopole Resonance

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



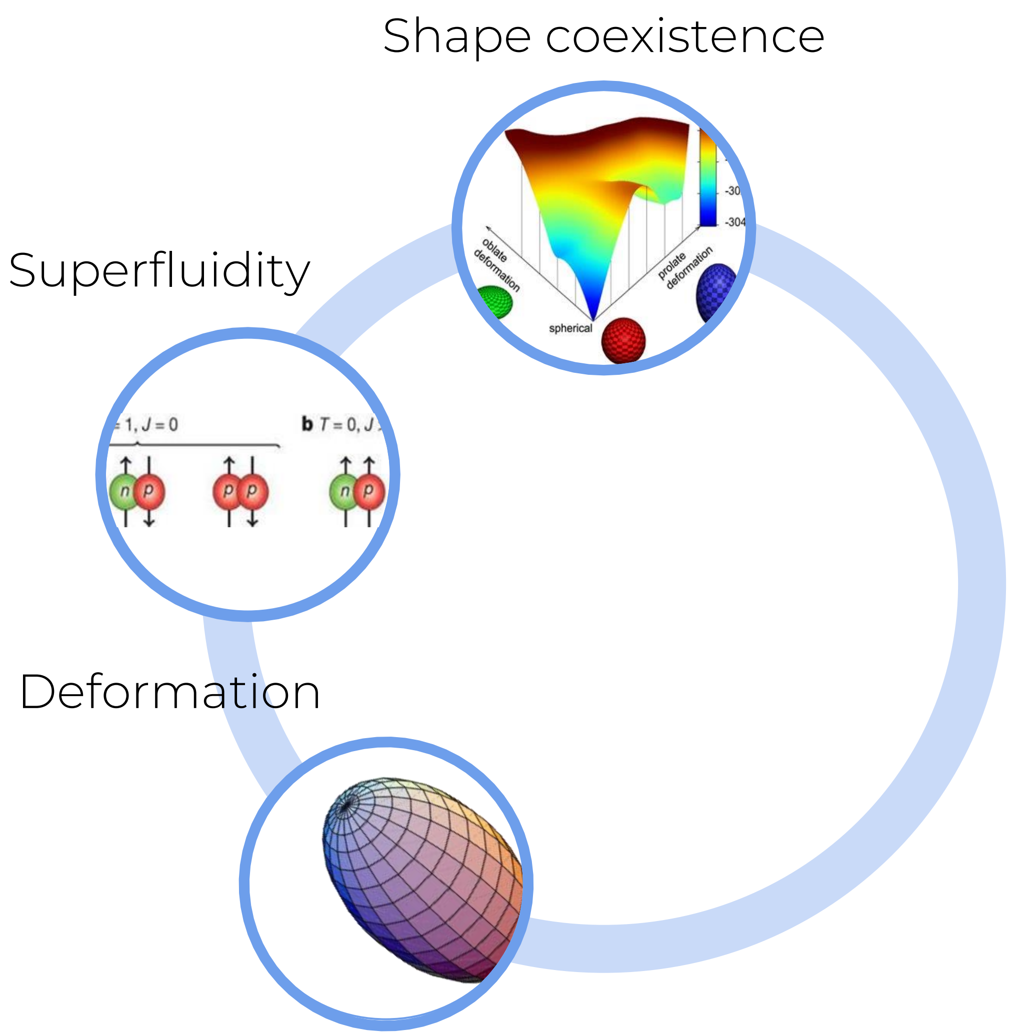
Giant Monopole Resonance

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



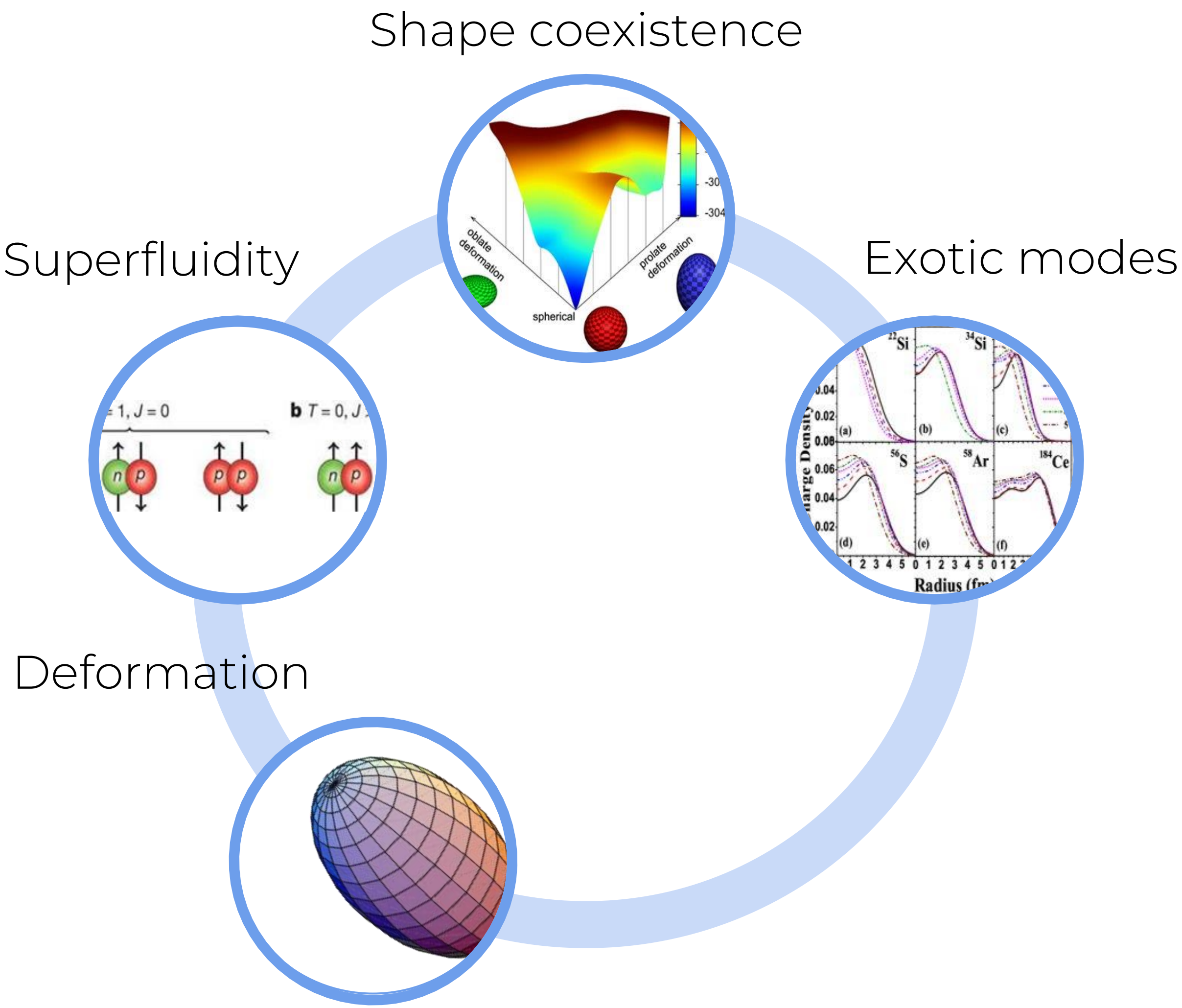
Giant Monopole Resonance

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



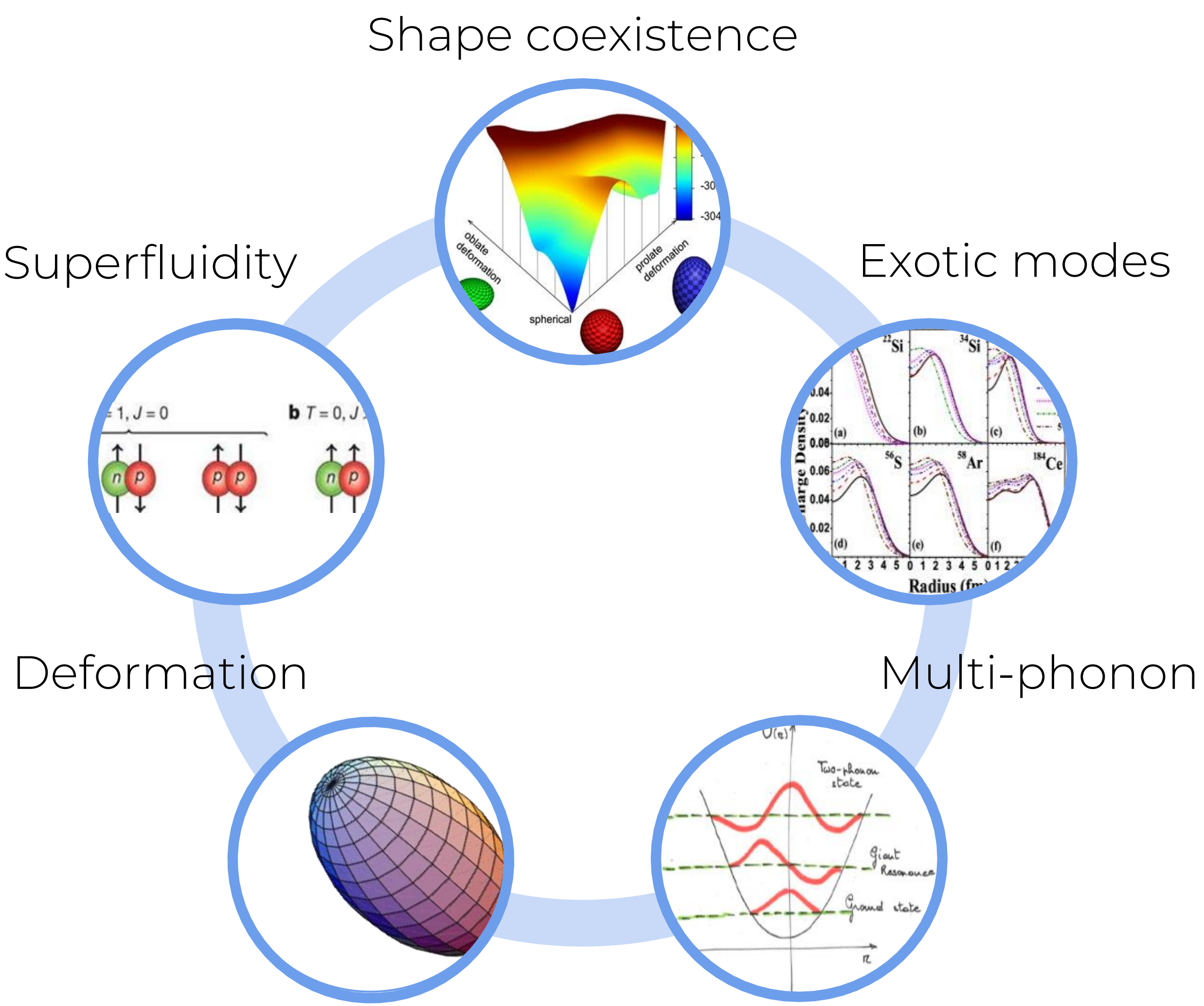
Giant Monopole Resonance

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



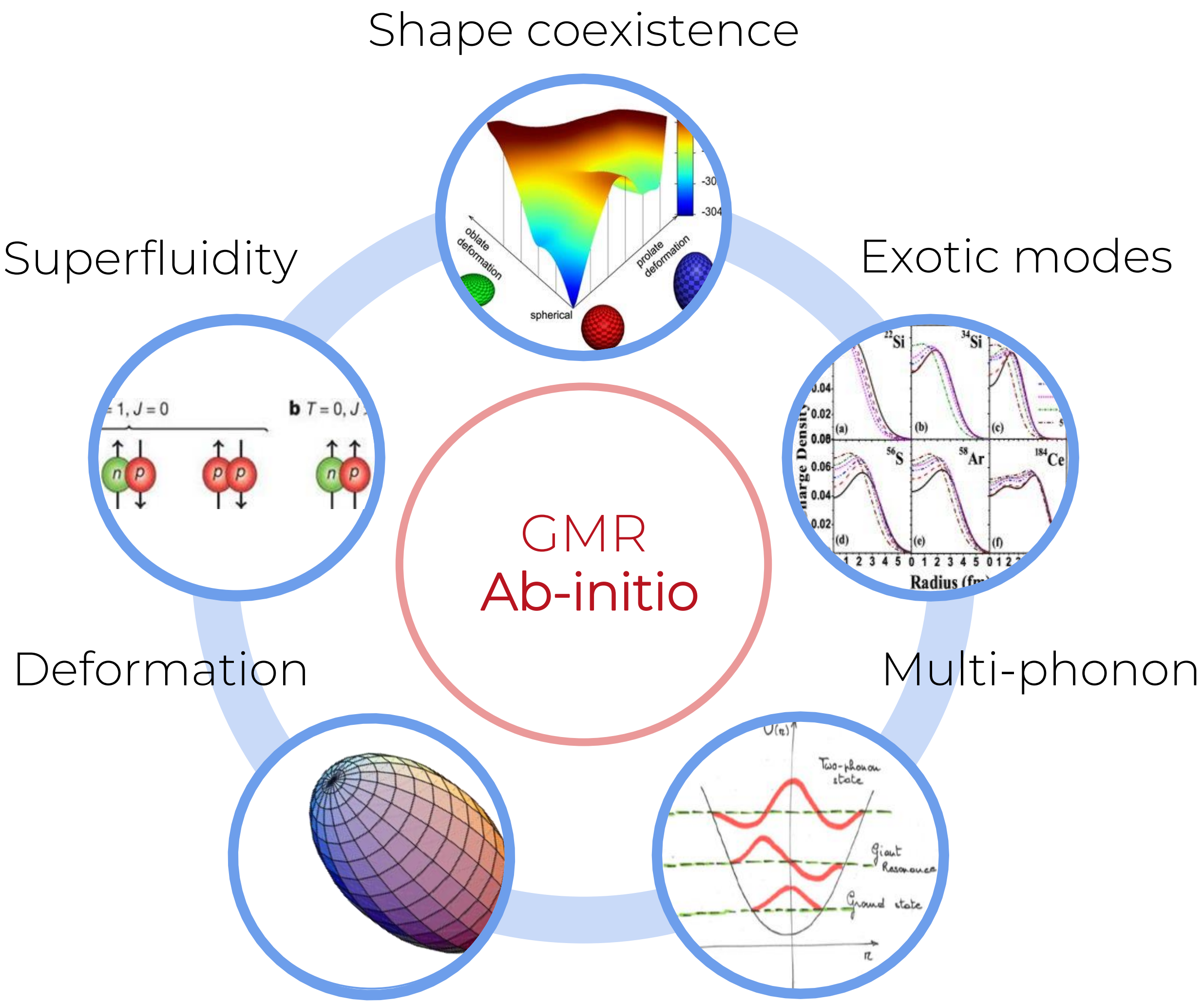
Giant Monopole Resonance

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



Giant Monopole Resonance

What is it ?

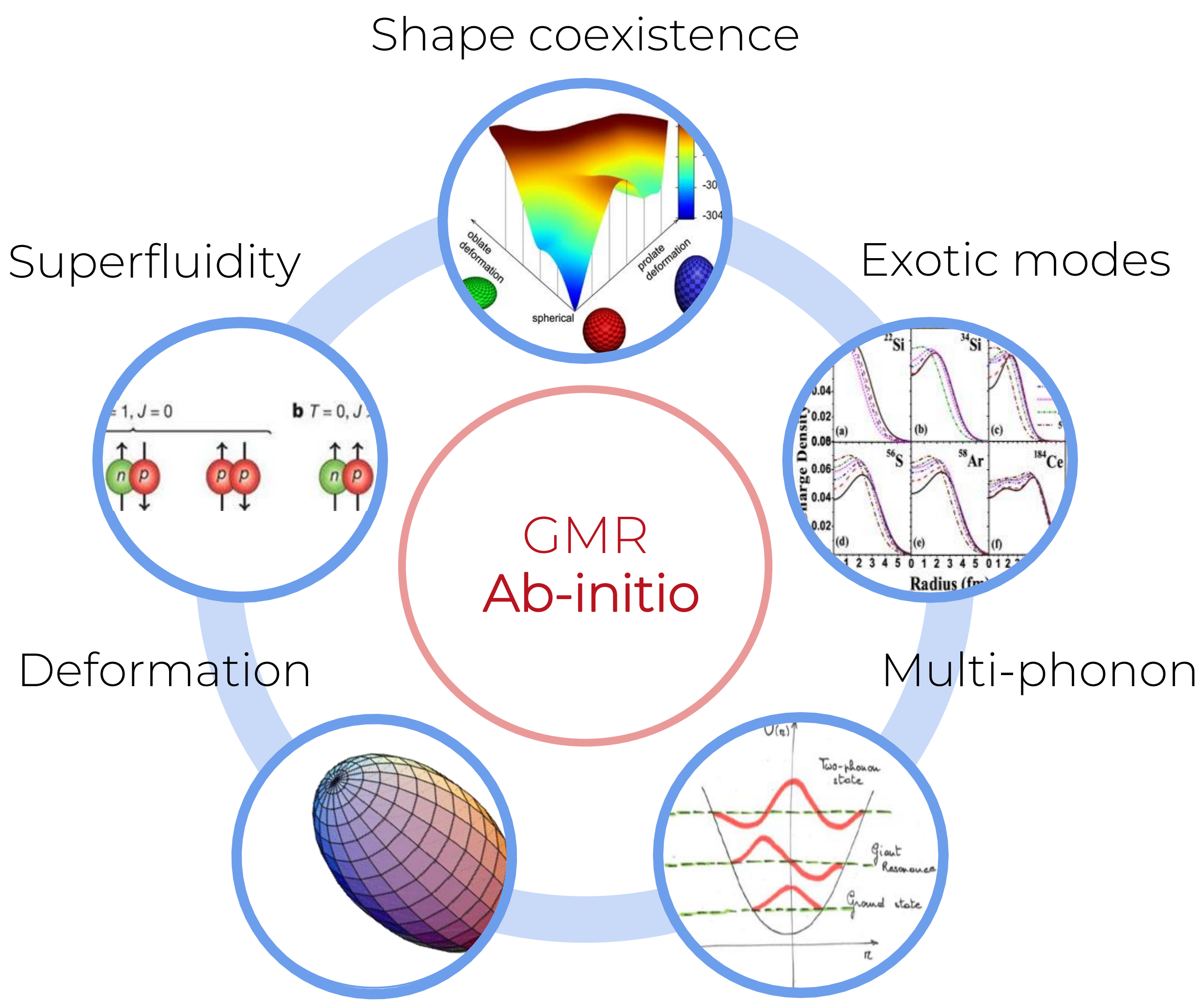
- Collective excitation (breathing mode)
- Involving most if not all the nucleons
- Coherent particle-hole excitations

Why studying again GMR ?

- Renewed experimental interest
- Investigate new physics

Much is still to be understood !

- No systematic studies (EDF as well)
  - Very generic numerical codes needed
- Ab-initio description still seminal



Outline

Introduction

Formalism

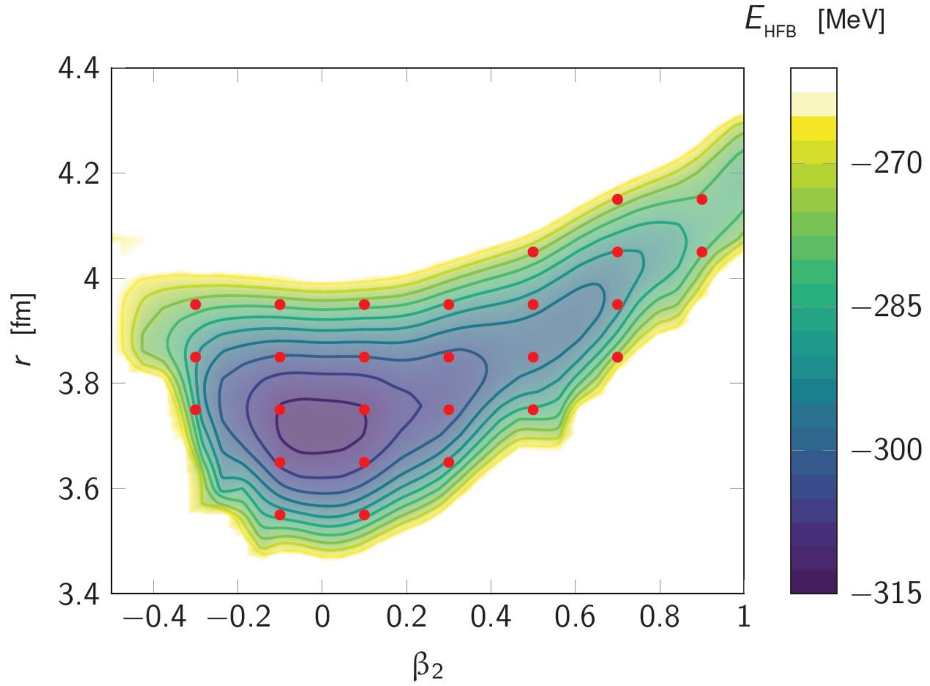
Ab-initio PGCM and QRPA for GMR

Results

Conclusions

Projected Generator Coordinate Method

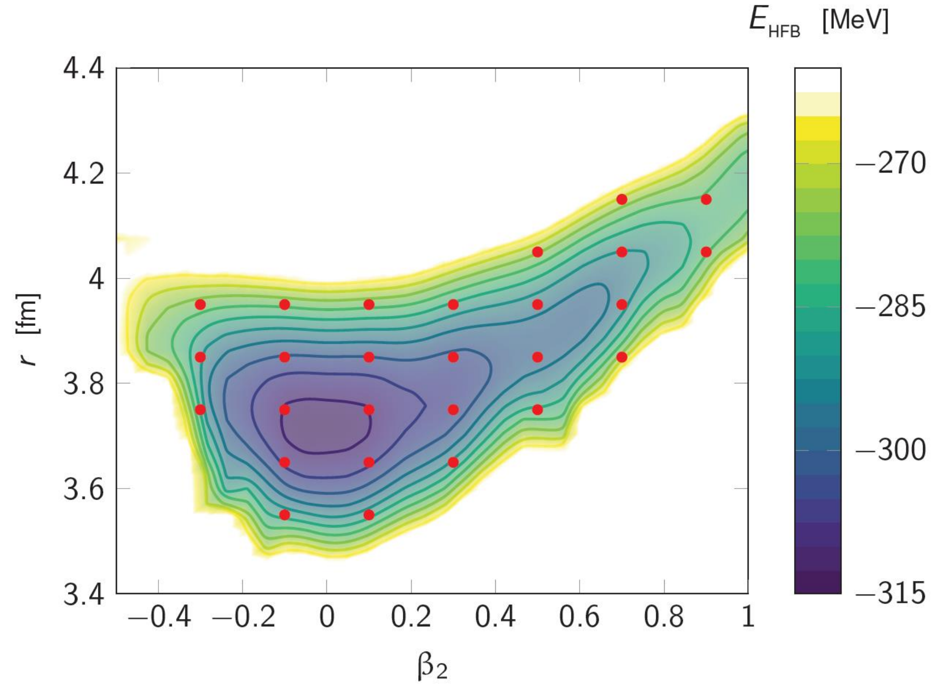
Schrödinger equation $H\,|\Psi_\nu\rangle = E_\nu\,|\Psi_\nu\rangle$



Projected Generator Coordinate Method

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

Open-shell systems

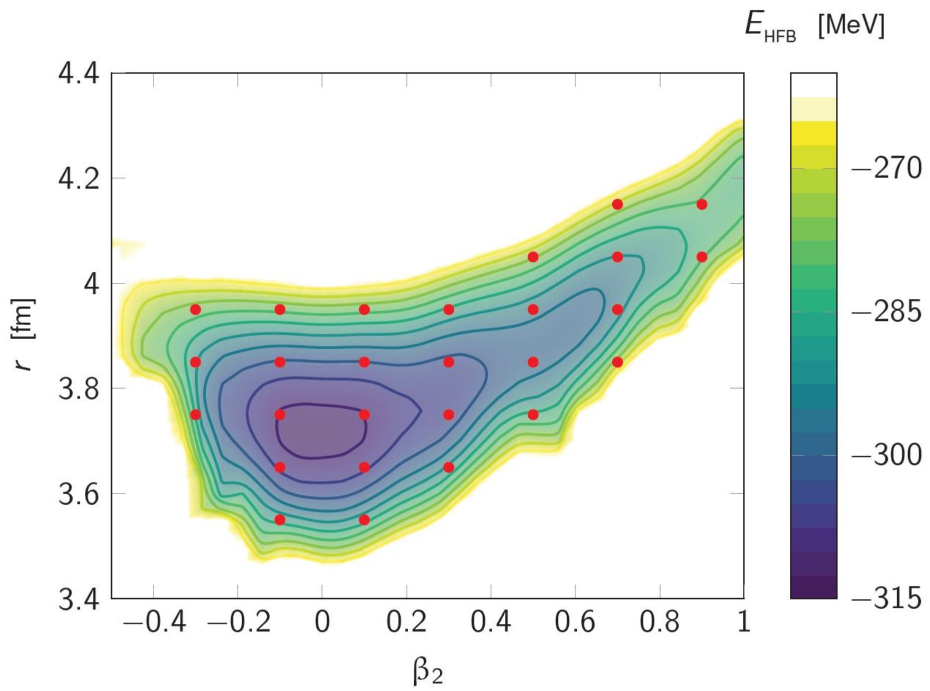


Projected Generator Coordinate Method

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

Open-shell systems

→ Strong static correlations



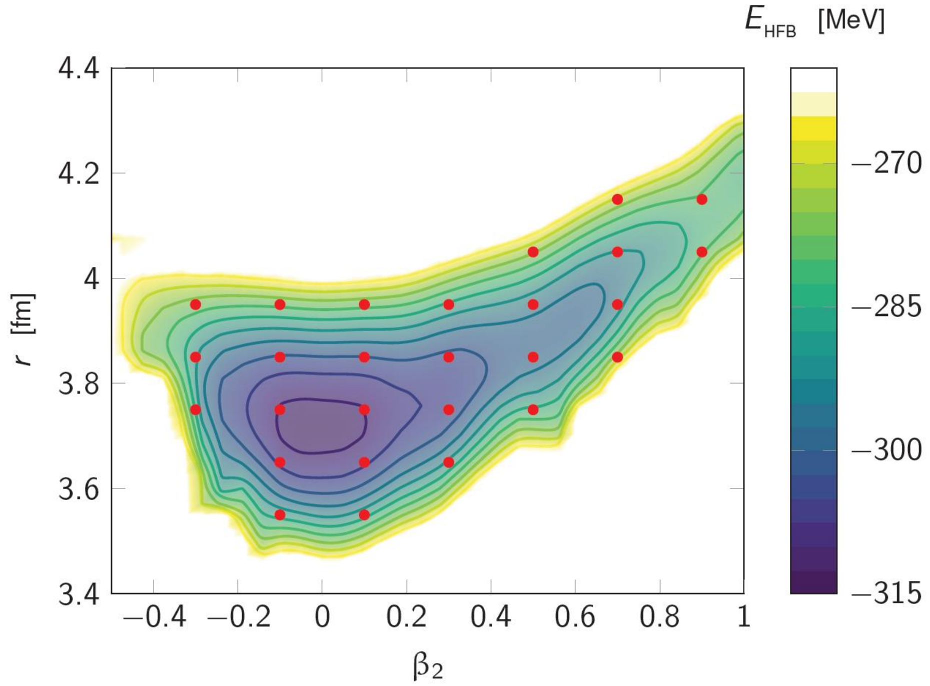
Projected Generator Coordinate Method

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

Open-shell systems

Strong static correlations

Symmetry-breaking reference states



Projected Generator Coordinate Method

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

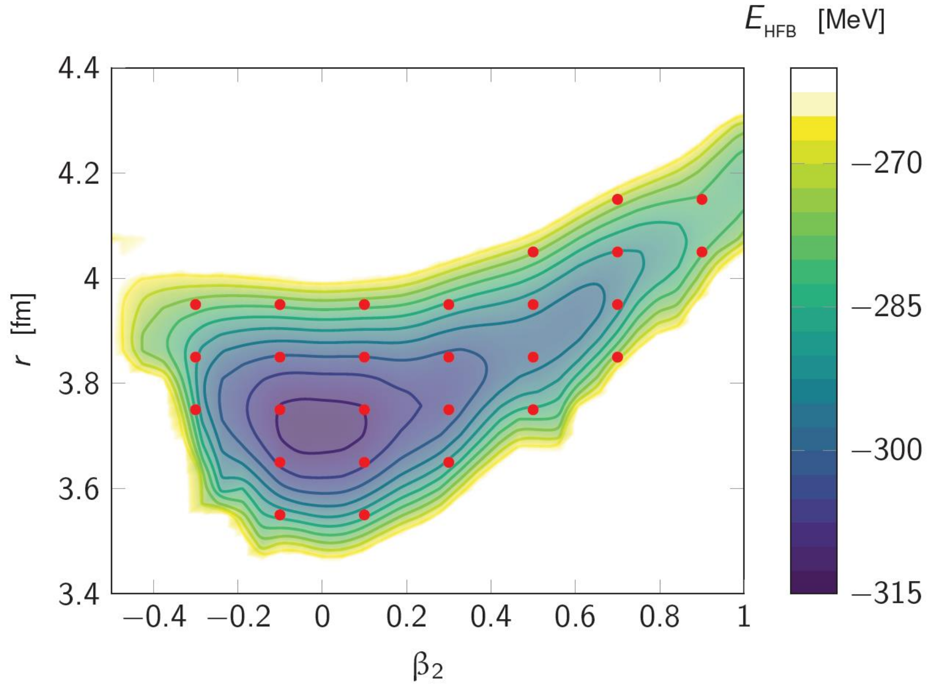
Open-shell systems

Symmetry-breaking reference states

Strong static correlations

1 Constrained HFB solutions

$|\Phi(r^2,\beta_2)\rangle$



Projected Generator Coordinate Method

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

Open-shell systems

Strong static correlations

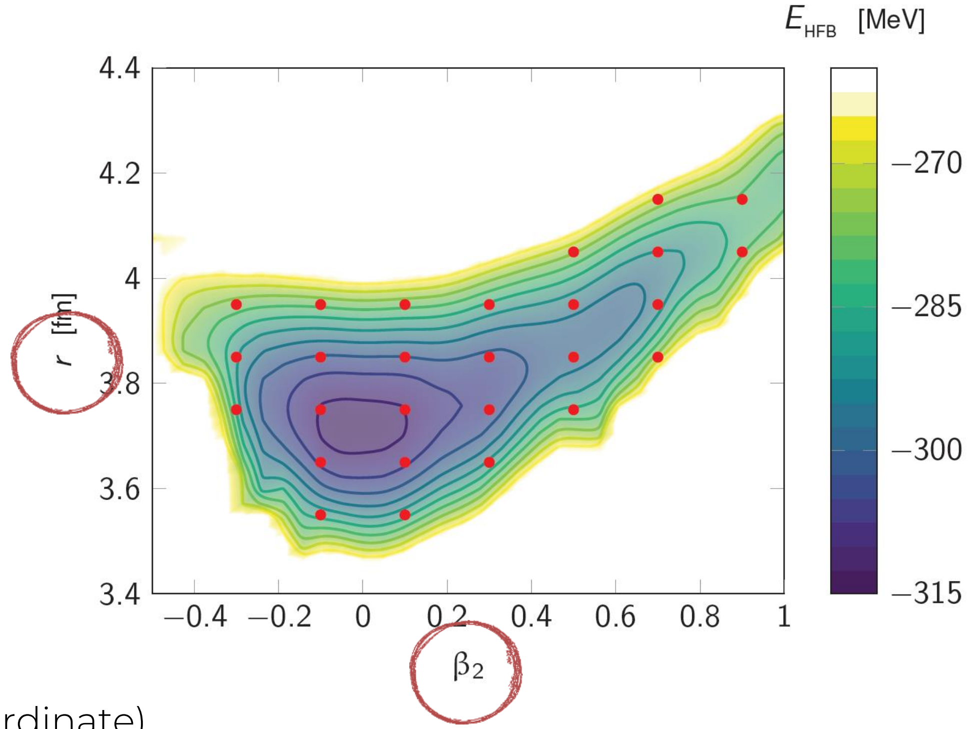
Symmetry-breaking reference states

1 Constrained HFB solutions

$|\Phi(r^2, \beta_2)\rangle$

Generator coordinates

(can be in principle whatever coordinate)



Projected Generator Coordinate Method

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

Open-shell systems

Symmetry-breaking reference states

Strong static correlations

1 Constrained HFB solutions

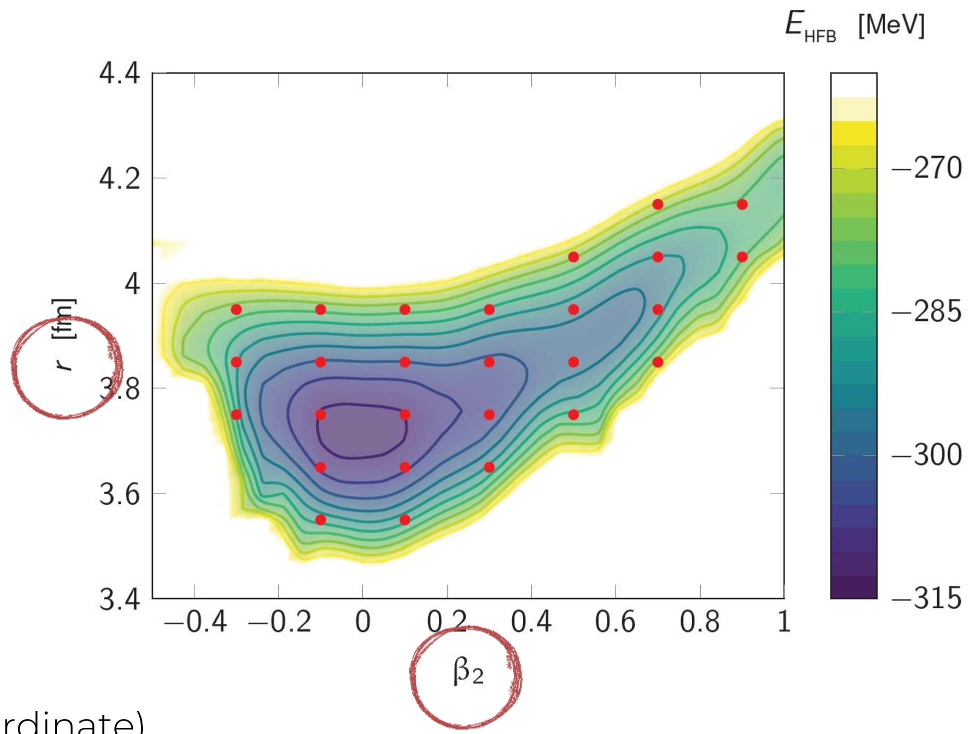
$|\Phi(r^2, \beta_2)\rangle$

Generator coordinates

(can be in principle whatever coordinate)

2 PGCM Ansatz

$$|\Psi_\nu\rangle = \sum_{r^2,\beta_2} f_\nu(r^2,\beta_2)\,|\Phi(r^2,\beta_2)\rangle$$



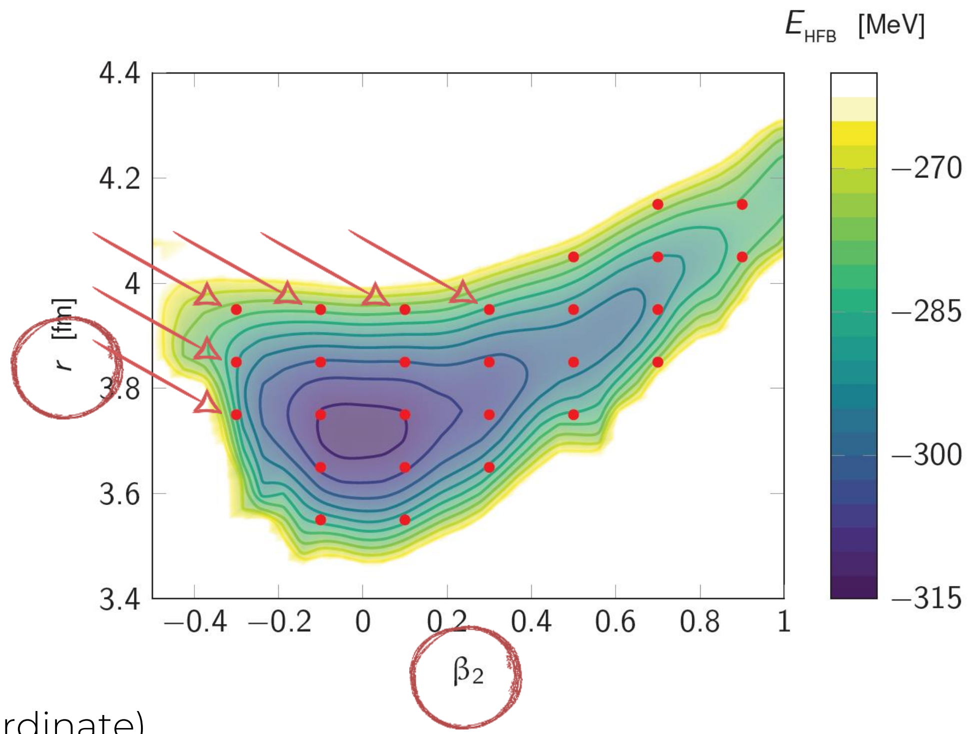
Projected Generator Coordinate Method

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

Open-shell systems

Strong static correlations

Symmetry-breaking reference states



1 Constrained HFB solutions

$$|\Phi(r^2, \beta_2)\rangle$$

Generator coordinates

(can be in principle whatever coordinate)

2 PGCM Ansatz

$$|\Psi_\nu\rangle = \sum_{r^2,\beta_2} f_\nu(r^2, \beta_2)\,|\Phi(r^2, \beta_2)\rangle$$

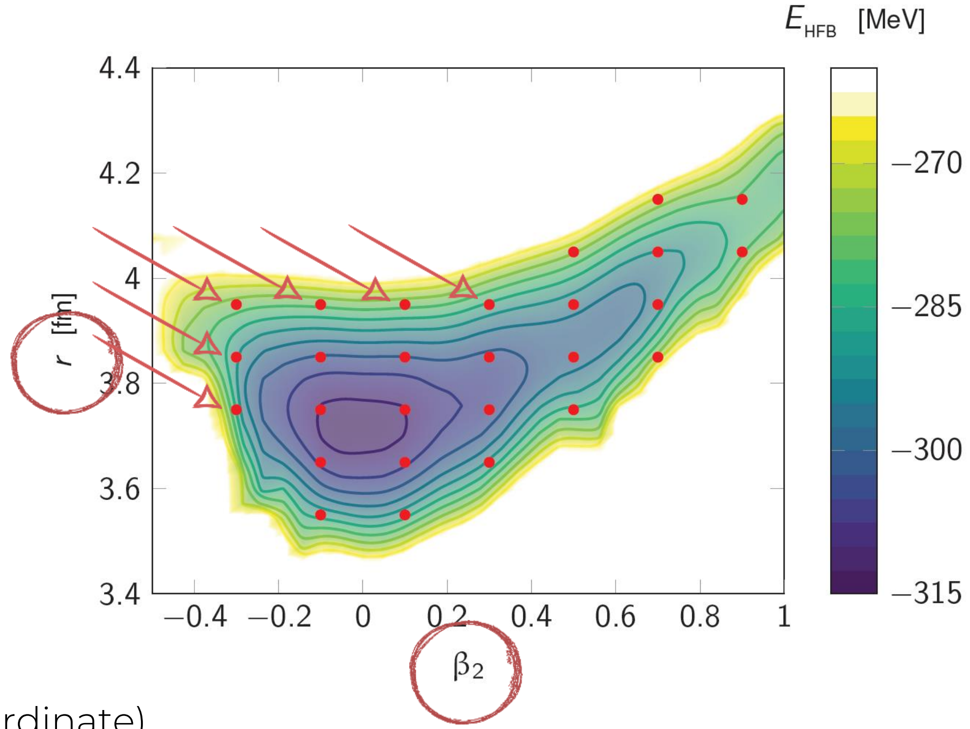
Projected Generator Coordinate Method

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

Open-shell systems

Strong static correlations

Symmetry-breaking reference states



1 Constrained HFB solutions

$|\Phi(r^2, \beta_2)\rangle$

Generator coordinates

(can be in principle whatever coordinate)

2 PGCM Ansatz

$$|\Psi_\nu\rangle = \sum_{r^2,\beta_2} f_\nu(r^2, \beta_2)\,|\Phi(r^2, \beta_2)\rangle$$

Linear coefficients

Projected Generator Coordinate Method

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

Open-shell systems

Strong static correlations

Symmetry-breaking reference states

1 Constrained HFB solutions

$|\Phi(r^2, \beta_2)\rangle$

Generator coordinates

(can be in principle whatever coordinate)

2 PGCM Ansatz

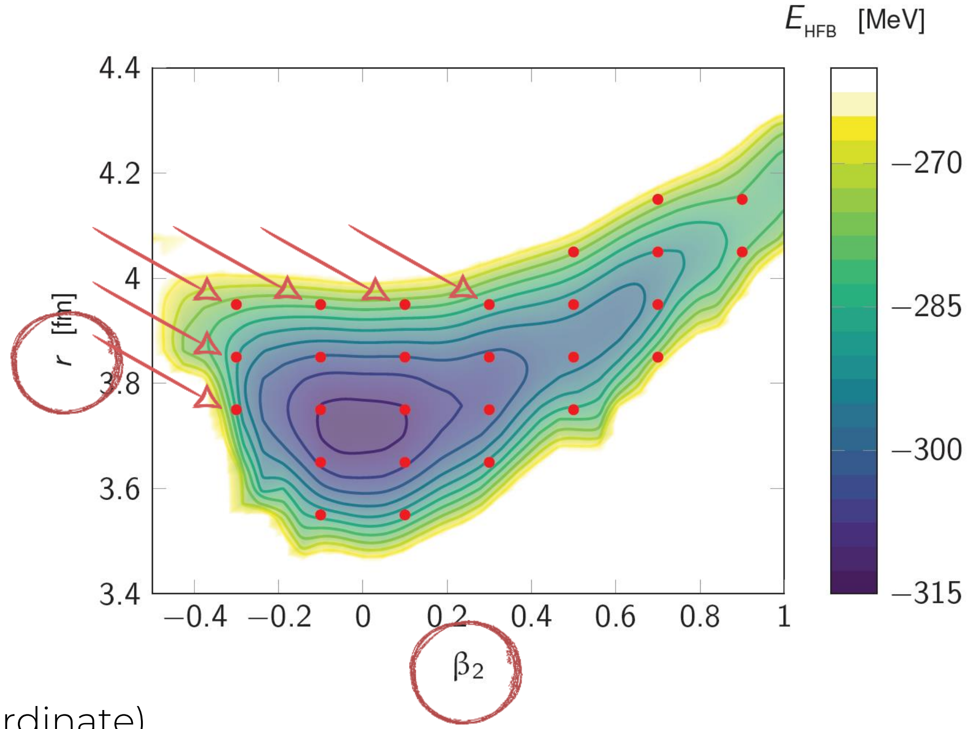
$$|\Psi_\nu\rangle = \sum_{r^2,\beta_2} f_\nu(r^2,\beta_2)\,|\Phi(r^2,\beta_2)\rangle$$

Linear coefficients

3 HWG Equation

Variational method

$$\delta \frac{\langle \Psi_\nu | H | \Psi_\nu \rangle}{\langle \Psi_\nu | \Psi_\nu \rangle} = 0$$



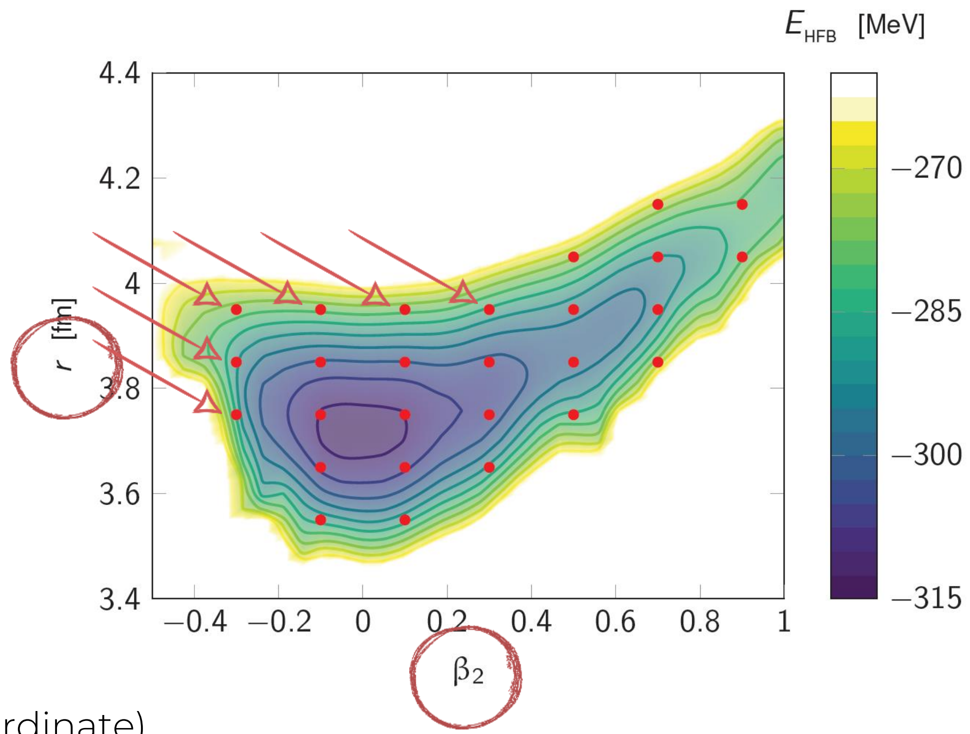
Projected Generator Coordinate Method

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

Open-shell systems

Strong static correlations

Symmetry-breaking reference states



1 Constrained HFB solutions

$|\Phi(r^2,\beta_2)\rangle$

Generator coordinates

(can be in principle whatever coordinate)

2 PGCM Ansatz

$$|\Psi_\nu\rangle = \sum_{r^2,\beta_2} f_\nu(r^2,\beta_2)\,|\Phi(r^2,\beta_2)\rangle$$

Linear coefficients

3 HWG Equation

Variational method

$$\delta\frac{\langle\Psi_\nu|H|\Psi_\nu\rangle}{\langle\Psi_\nu|\Psi_\nu\rangle} = 0$$

Schrödinger-like equation

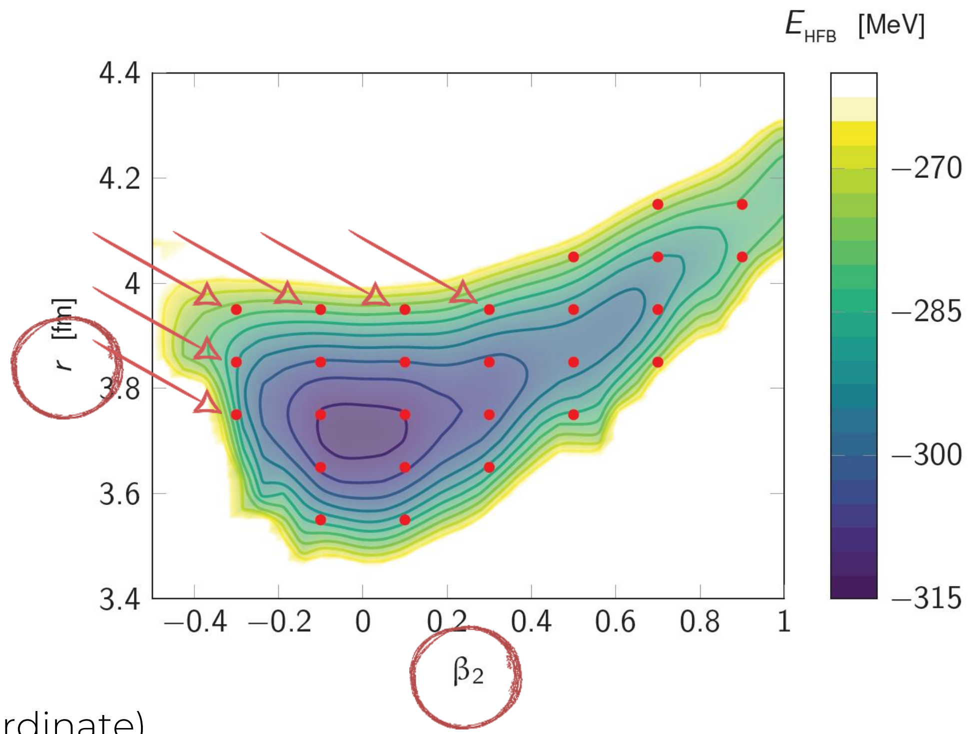
$$\sum_q \Big[\mathcal{H}(p,q) - E_\nu \mathcal{N}(p,q)\Big] f_\nu(q) = 0$$

Kernels evaluation

$$\mathcal{H}(p,q) \equiv \langle\Phi(p)|H|\Phi(q)\rangle$$
$$\mathcal{N}(p,q) \equiv \langle\Phi(p)|\Phi(q)\rangle$$

Projected Generator Coordinate Method

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



Diagonalization in a physically-informed reduced Hilbert space

1 Constrained HFB solutions

$|\Phi(r^2,\beta_2)\rangle$

Generator coordinates

(can be in principle whatever coordinate)

2 PGCM Ansatz

$$|\Psi_\nu\rangle = \sum_{r^2,\beta_2} f_\nu(r^2,\beta_2)\,|\Phi(r^2,\beta_2)\rangle$$

Linear coefficients

3 HWG Equation

Variational method

$$\delta\frac{\langle\Psi_\nu|H|\Psi_\nu\rangle}{\langle\Psi_\nu|\Psi_\nu\rangle} = 0$$

Schrödinger-like equation

$$\sum_q \left[\mathcal{H}(p,q) - E_\nu \mathcal{N}(p,q)\right] f_\nu(q) = 0$$

Kernels evaluation

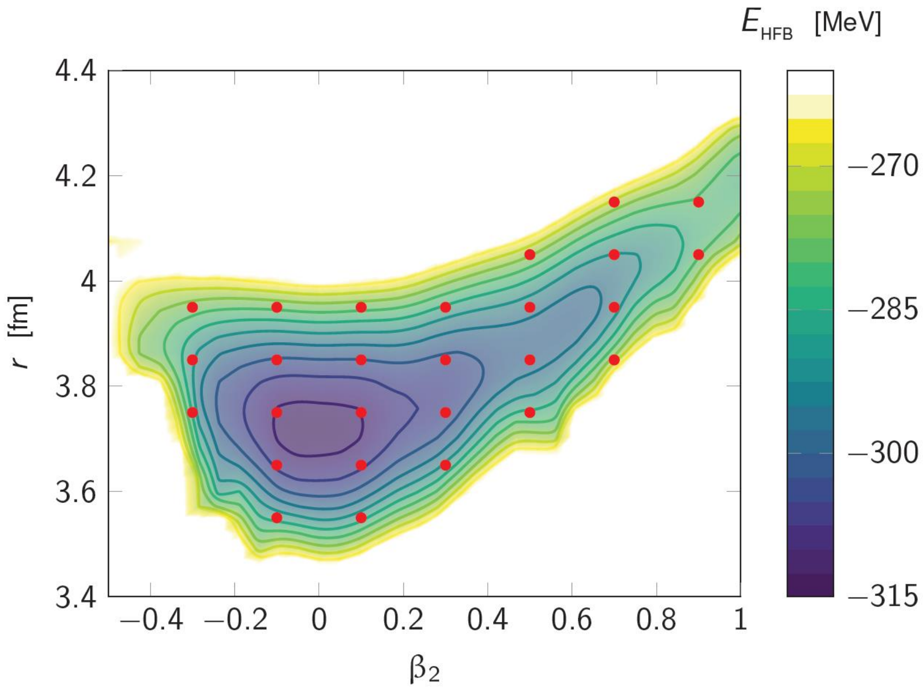
$$\mathcal{H}(p,q) \equiv \langle\Phi(p)|H|\Phi(q)\rangle$$
$$\mathcal{N}(p,q) \equiv \langle\Phi(p)|\Phi(q)\rangle$$

(Q)RPA from GCM

Thouless theorem

(q can be whatever coordinate)

$$|\Phi(q)\rangle = \langle\Phi(q_{min})|\Phi(q)\rangle\, e^{\mathbf{Z}(q,q_{min})}\, |\Phi(q_{min})\rangle$$



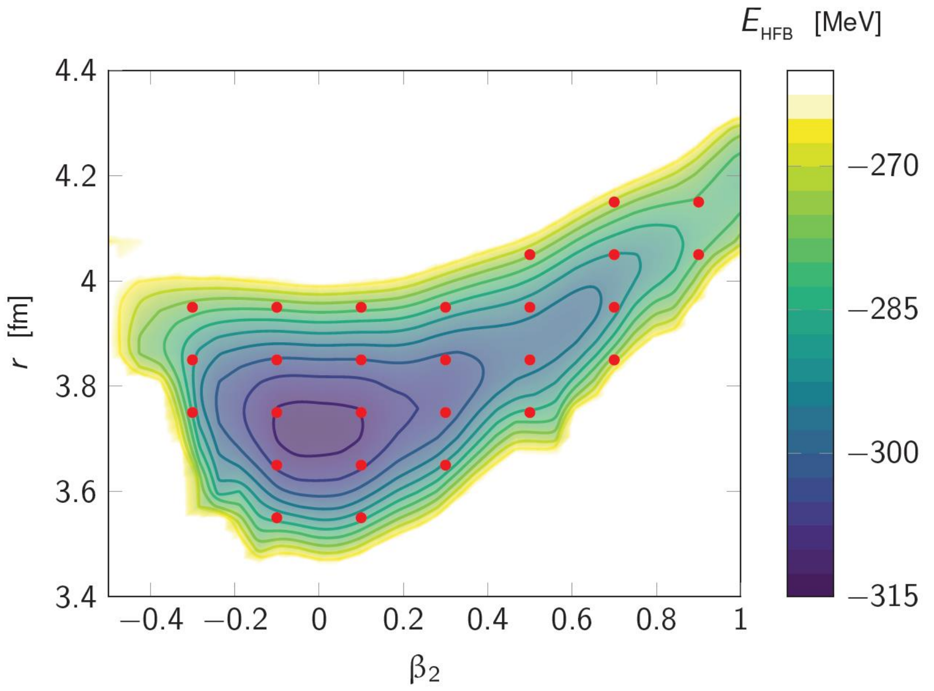
(Q)RPA from GCM

Thouless theorem

(q can be whatever coordinate)

$$|\Phi(q)\rangle = \langle\Phi(q_{min})|\Phi(q)\rangle e^{\mathbf{Z}(q,q_{min})}|\Phi(q_{min})\rangle$$

Non-unitary transformation



(Q)RPA from GCM

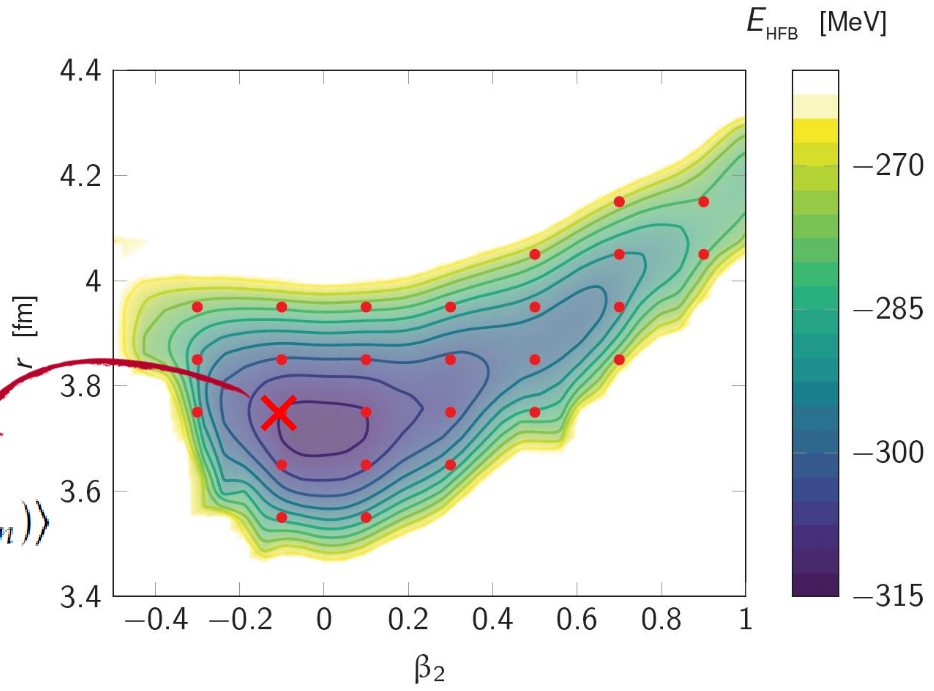
Thouless theorem

(q can be whatever coordinate)

$$|\Phi(q)\rangle = \langle\Phi(q_{min})|\Phi(q)\rangle e^{\mathbf{Z}(q,q_{min})}|\Phi(q_{min})\rangle$$

Non-unitary transformation

$|\Phi(q_{min})\rangle$



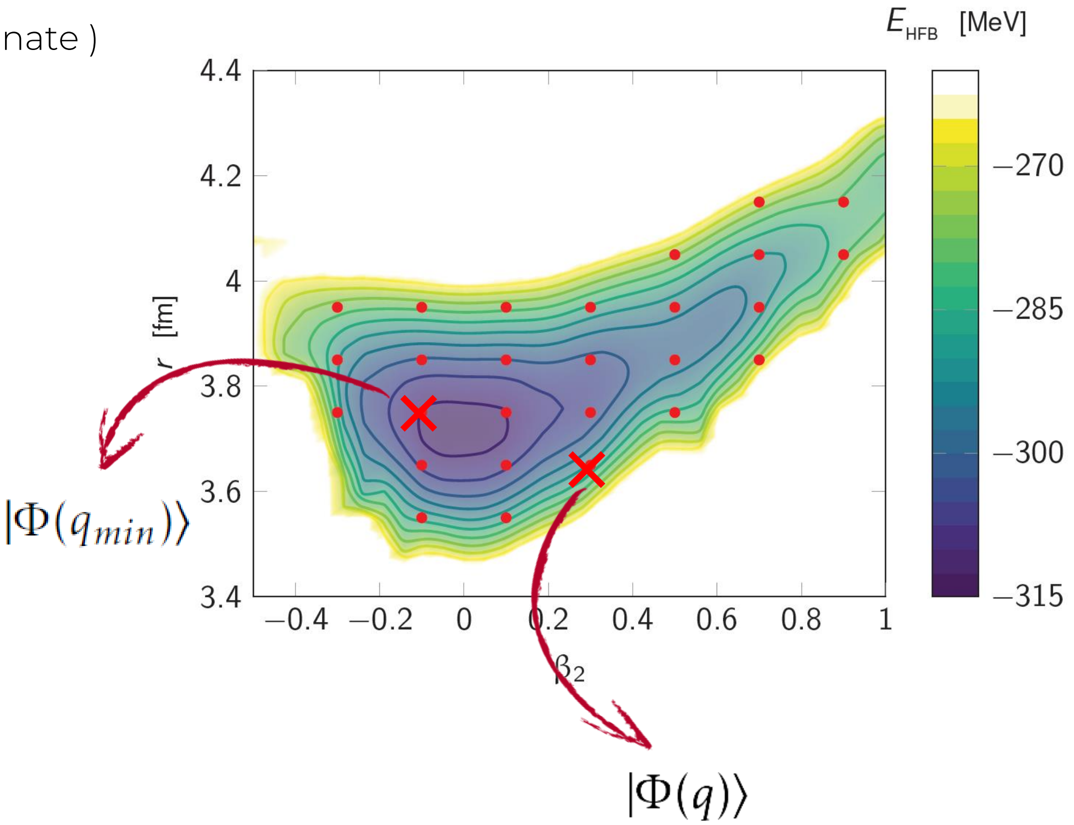
(Q)RPA from GCM

Thouless theorem

(q can be whatever coordinate)

$$|\Phi(q)\rangle = \langle\Phi(q_{min})|\Phi(q)\rangle e^{\mathbf{Z}(q,q_{min})}|\Phi(q_{min})\rangle$$

Non-unitary transformation



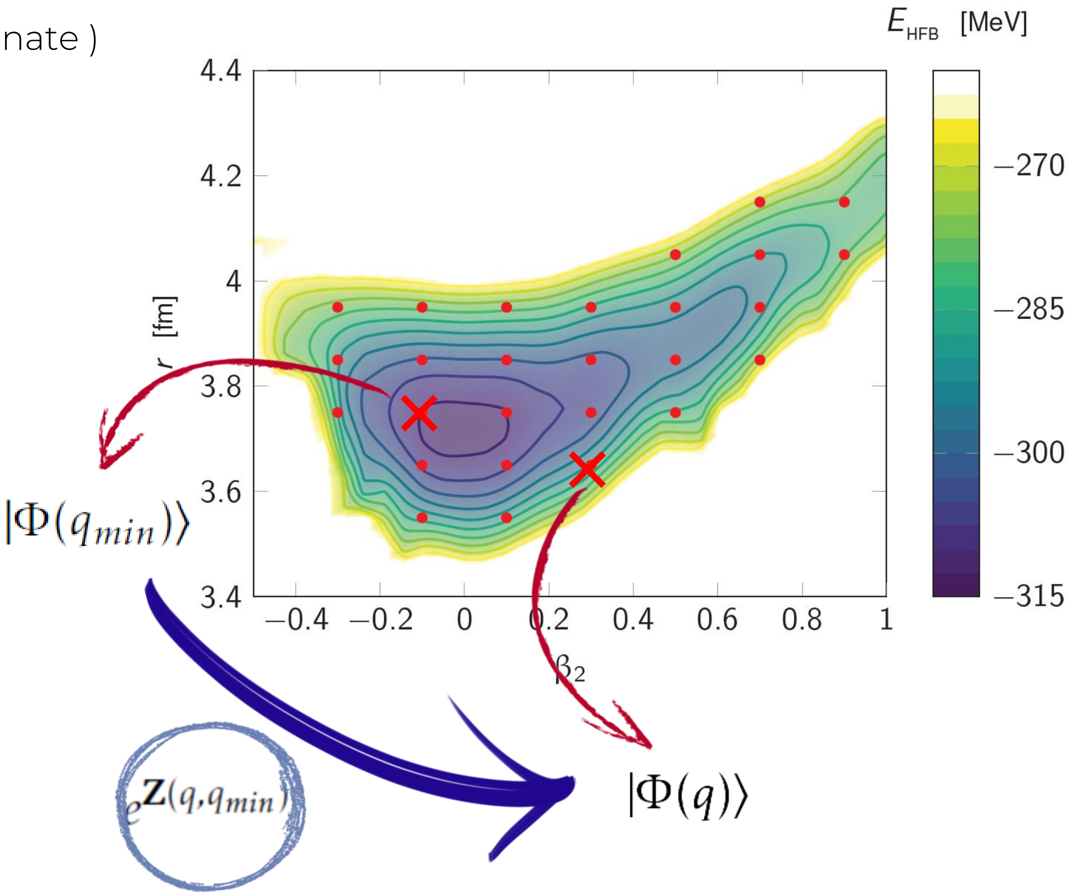
(Q)RPA from GCM

Thouless theorem

(q can be whatever coordinate)

$$|\Phi(q)\rangle = \langle\Phi(q_{min})|\Phi(q)\rangle e^{\mathbf{Z}(q,q_{min})}|\Phi(q_{min})\rangle$$

Non-unitary transformation



(Q)RPA from GCM

Thouless theorem

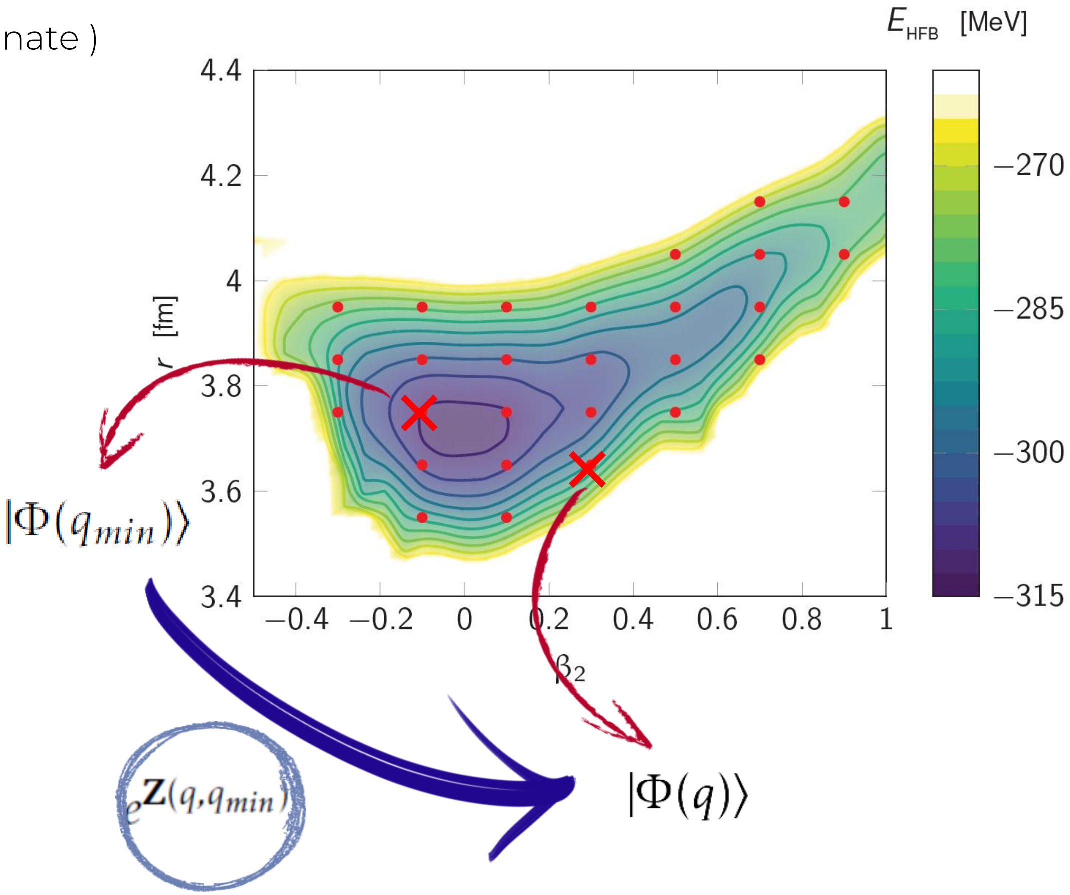
(q can be whatever coordinate)

$$|\Phi(q)\rangle = \langle\Phi(q_{min})|\Phi(q)\rangle e^{\mathbf{Z}(q,q_{min})}|\Phi(q_{min})\rangle$$

Non-unitary transformation

HWG Equation

$$\delta\frac{\langle\Psi_\nu|H|\Psi_\nu\rangle}{\langle\Psi_\nu|\Psi_\nu\rangle} = 0$$



(Q)RPA from GCM

Thouless theorem

(q can be whatever coordinate)

$$|\Phi(q)\rangle = \langle\Phi(q_{min})|\Phi(q)\rangle e^{\mathbf{Z}(q,q_{min})}|\Phi(q_{min})\rangle$$

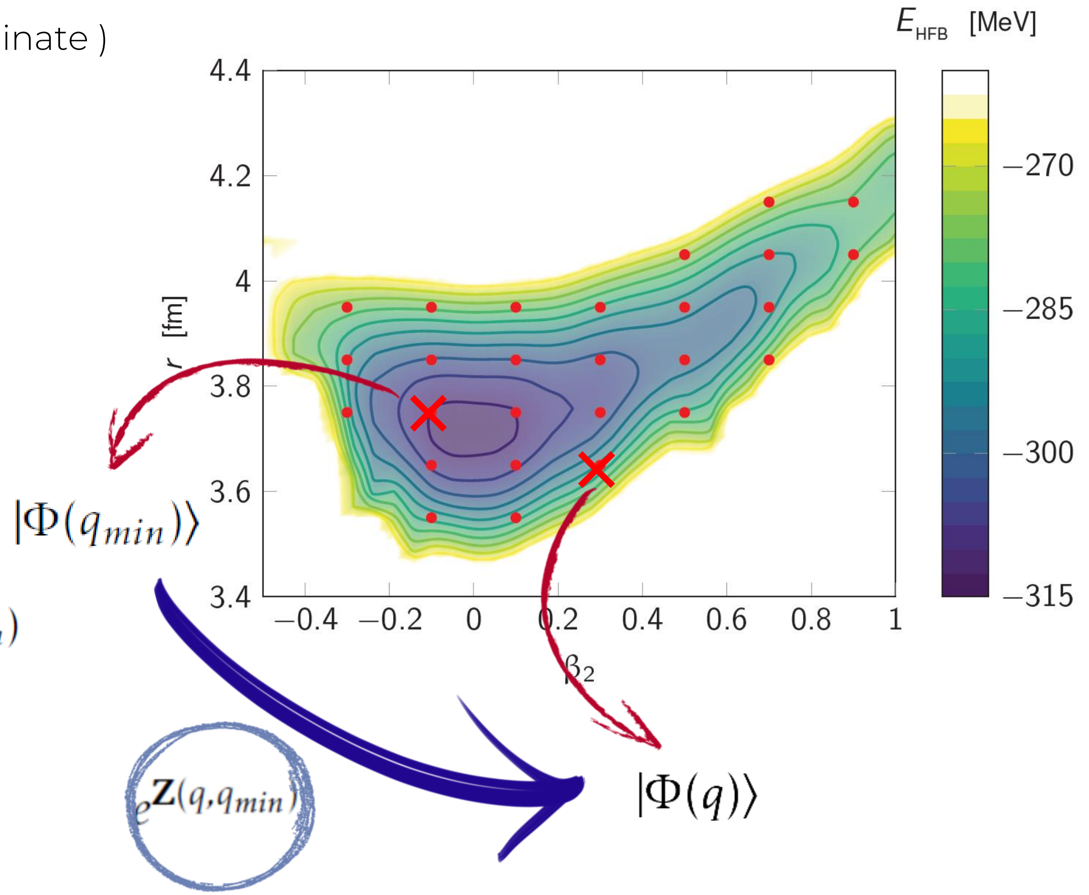
Non-unitary transformation

HWG Equation

$$\delta\frac{\langle\Psi_\nu|H|\Psi_\nu\rangle}{\langle\Psi_\nu|\Psi_\nu\rangle} = 0$$

Solve with **two approximations**:

- Quasi-Boson approximation (QBA)
- Expand to the quadratic level in $\mathbf{Z}(q, q_{min})$
  - → Harmonic approximation



(Q)RPA from GCM

Thouless theorem

(q can be whatever coordinate)

$$|\Phi(q)\rangle = \langle\Phi(q_{min})|\Phi(q)\rangle e^{\mathbf{Z}(q,q_{min})}|\Phi(q_{min})\rangle$$

Non-unitary transformation

HWG Equation

$$\delta\frac{\langle\Psi_\nu|H|\Psi_\nu\rangle}{\langle\Psi_\nu|\Psi_\nu\rangle} = 0$$

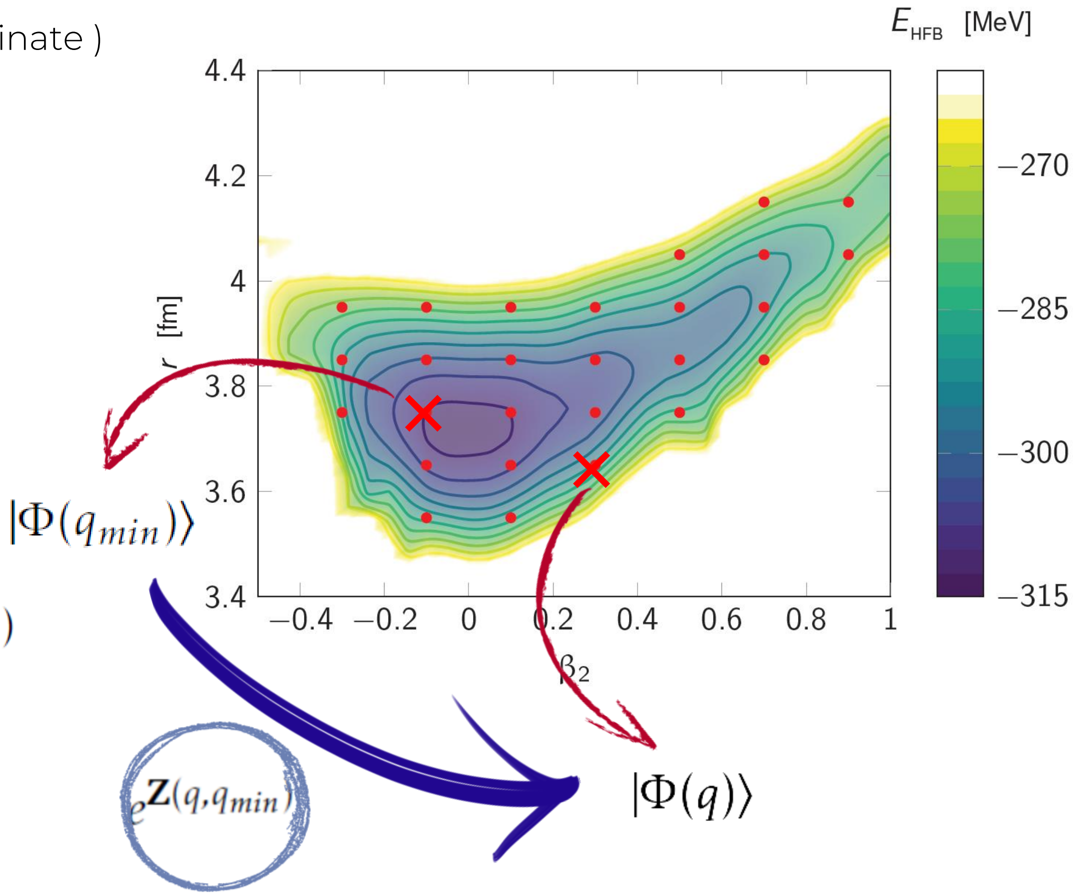
Solve with **two approximations**:

- Quasi-Boson approximation (QBA)
- Expand to the quadratic level in $\mathbf{Z}(q, q_{min})$
  - → Harmonic approximation

No coordinates dependency !

All coordinates are explored

(differently from PGCM)



(Q)RPA from GCM

Thouless theorem

(q can be whatever coordinate)

$$|\Phi(q)\rangle = \langle\Phi(q_{min})|\Phi(q)\rangle e^{\mathbf{Z}(q,q_{min})}|\Phi(q_{min})\rangle$$

Non-unitary transformation

HWG Equation

$$\delta \frac{\langle\Psi_\nu|H|\Psi_\nu\rangle}{\langle\Psi_\nu|\Psi_\nu\rangle} = 0$$

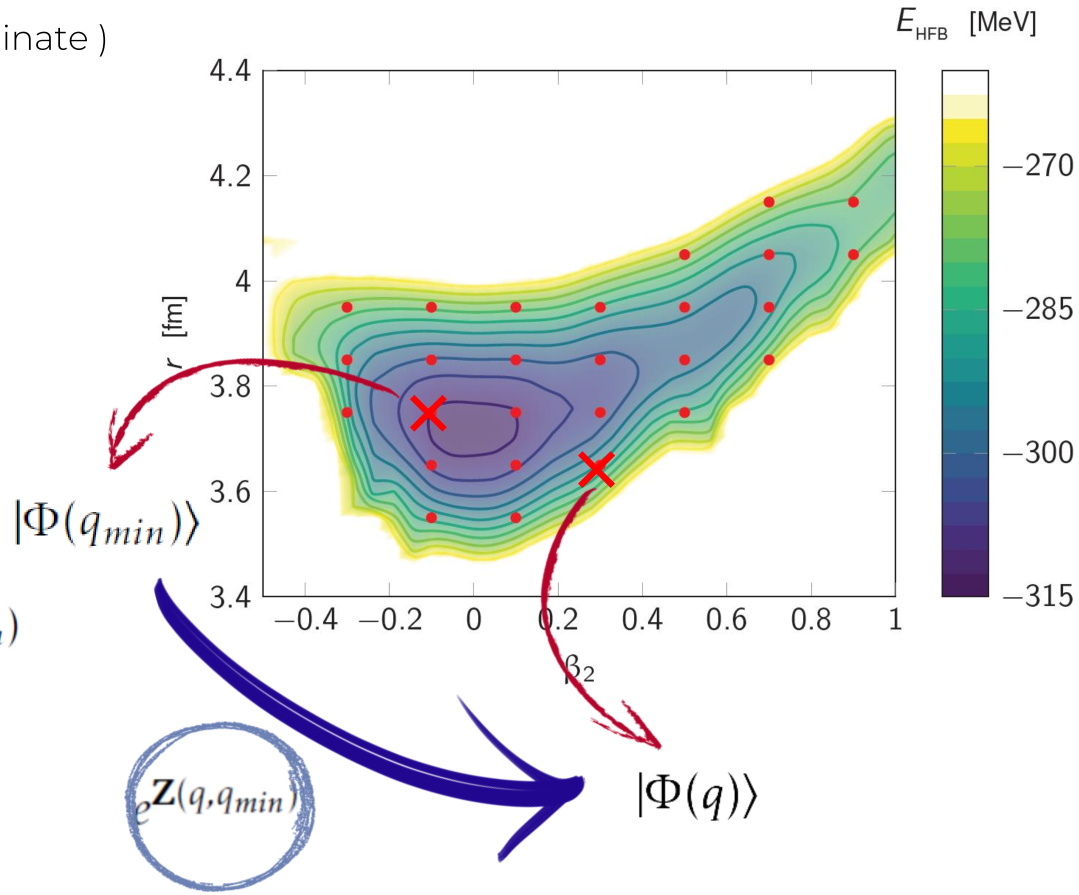
Solve with **two approximations**:

- Quasi-Boson approximation (QBA)
- Expand to the quadratic level in $\mathbf{Z}(q, q_{min})$
  - → Harmonic approximation

No coordinates dependency !

All coordinates are explored

(differently from PGCM)



Eventually rewrites as QRPA

$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix}^k \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix} = E^k_\nu \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix}$$

[Jancovici, Schiff, 1964]

Outline

Introduction

Formalism

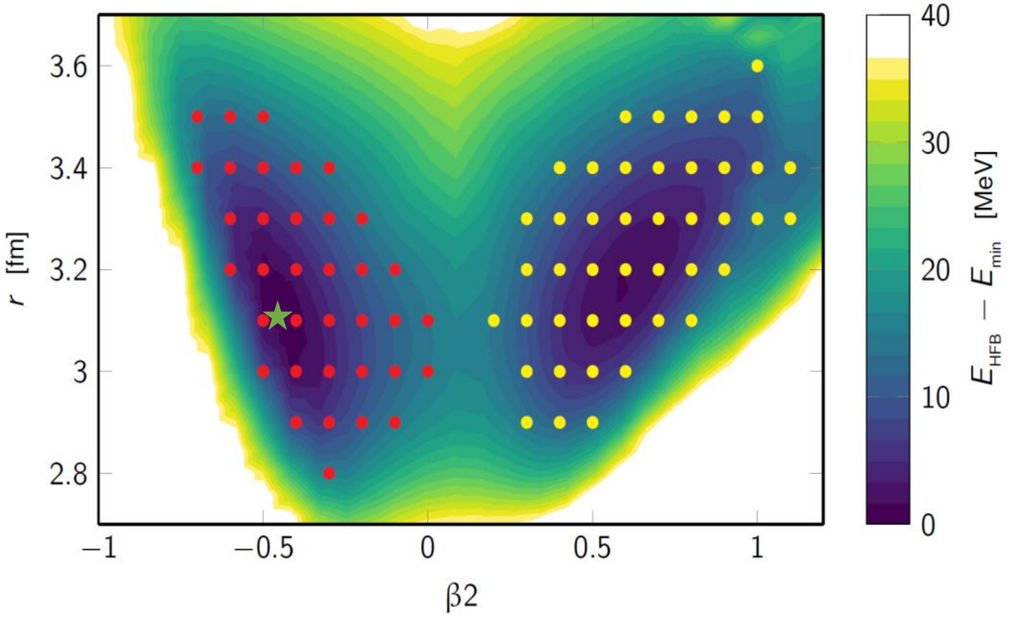
Results

Shape coexistence and deformation in ^{28}Si

Conclusions

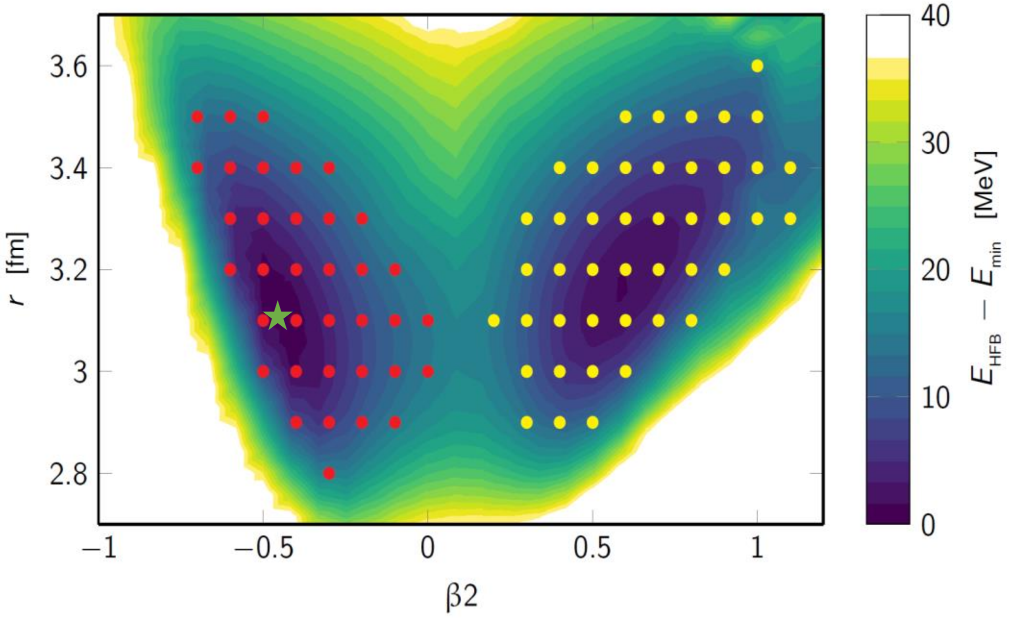
Shape coexistence effects in ^{28}Si

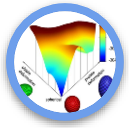
Total Energy Surface $E_{HFB}(\beta_2, r)$



Shape coexistence effects in ^{28}Si

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

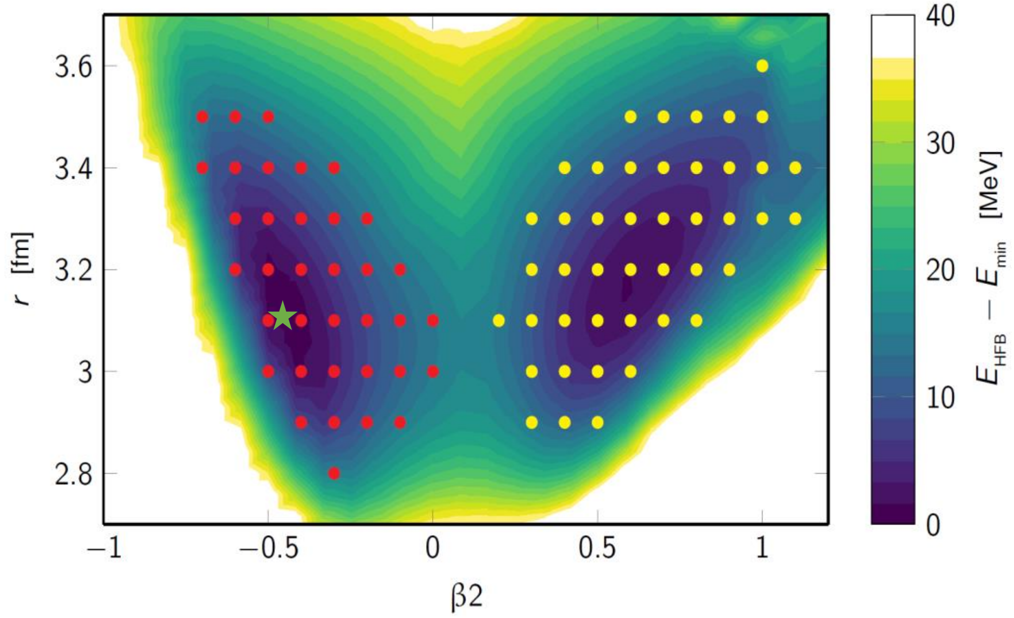


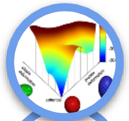


Shape coexistence [Jenkins et al., 2012]

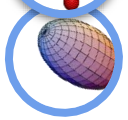
Shape coexistence effects in ^{28}Si

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



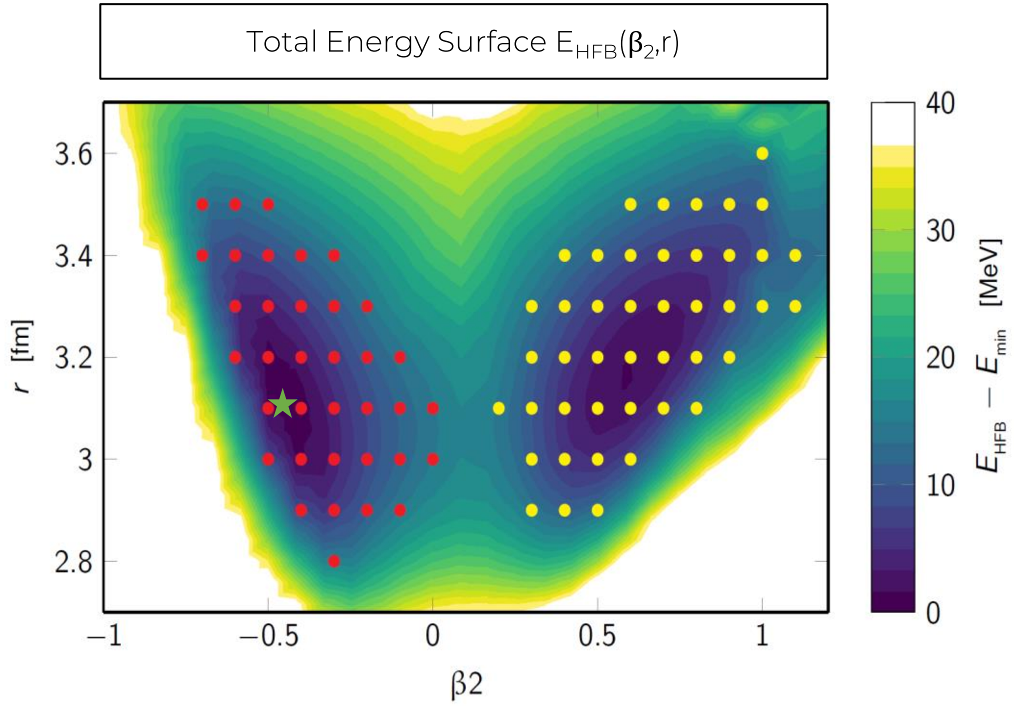


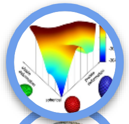
Shape coexistence [Jenkins et al., 2012]



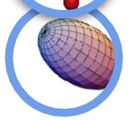
Deformation

Shape coexistence effects in ^{28}Si





Shape coexistence [Jenkins et al., 2012]

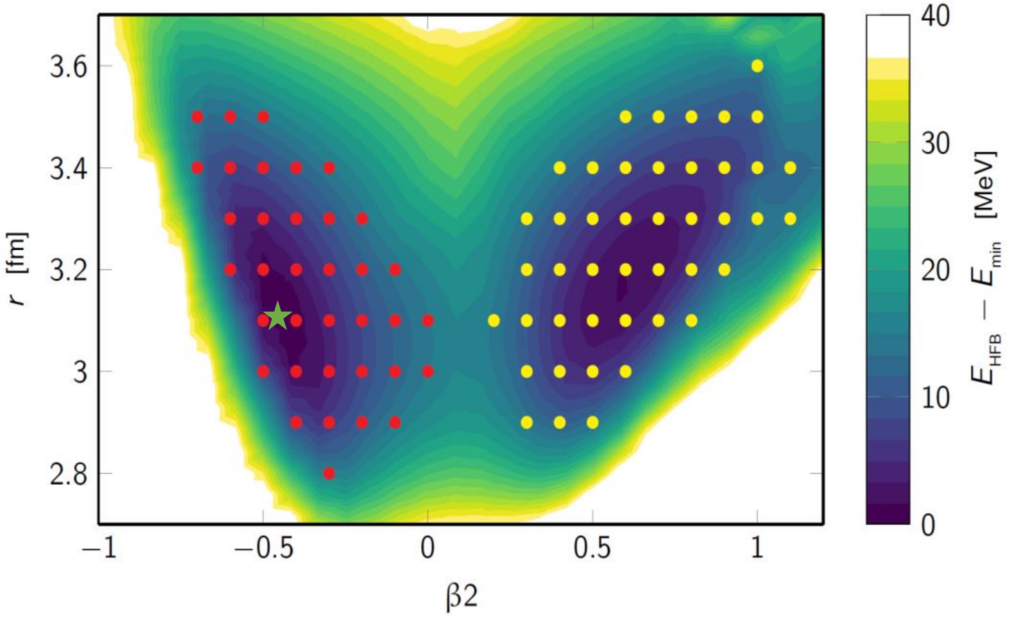


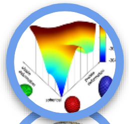
Deformation

- Oblate minimum and prolate-shape isomer

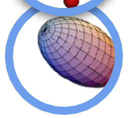
Shape coexistence effects in ^{28}Si

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

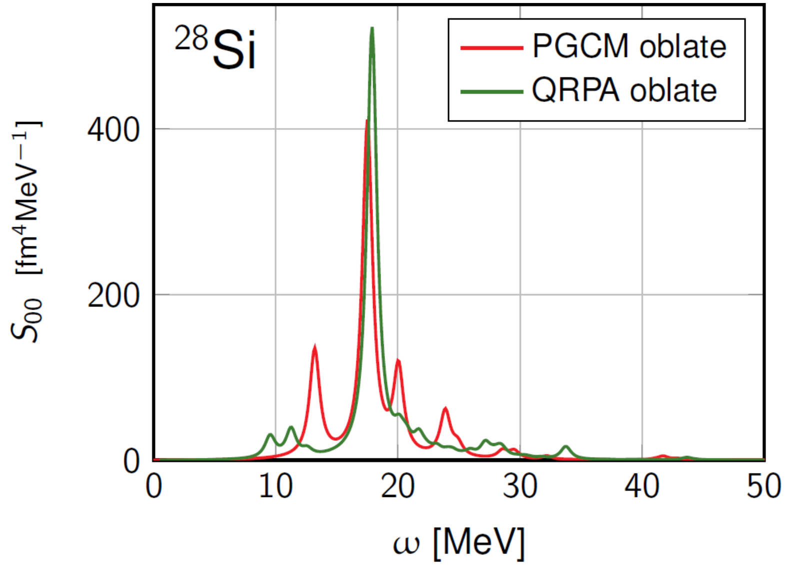




Shape coexistence [Jenkins et al., 2012]



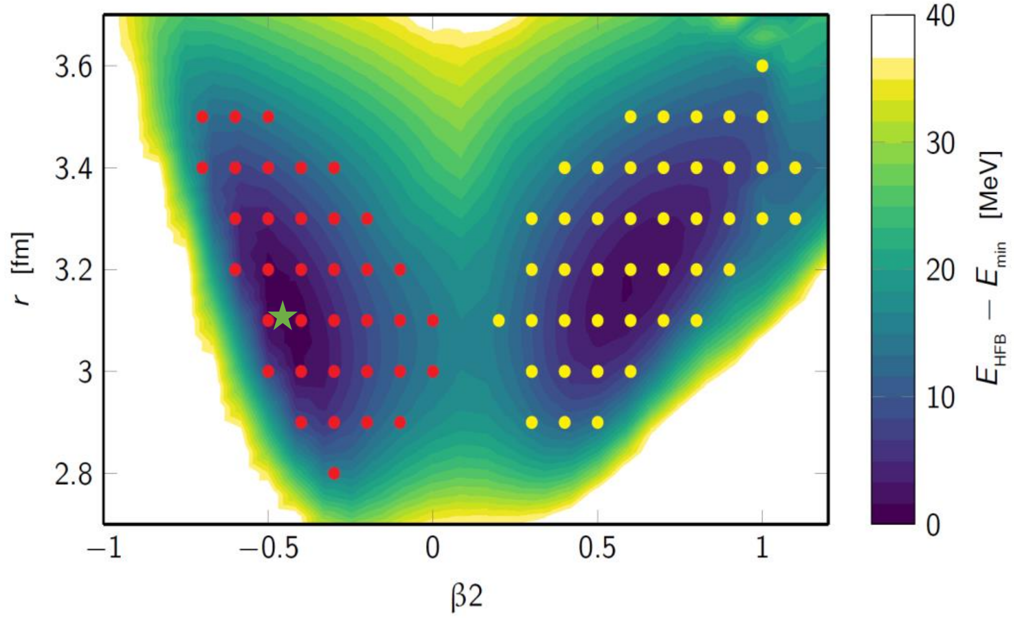
Deformation

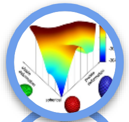


- Oblate minimum and prolate-shape isomer
- Qualitatively similar results QRPA/PGCM
    - QRPA response less fragmented

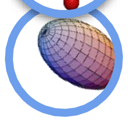
Shape coexistence effects in ^{28}Si

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

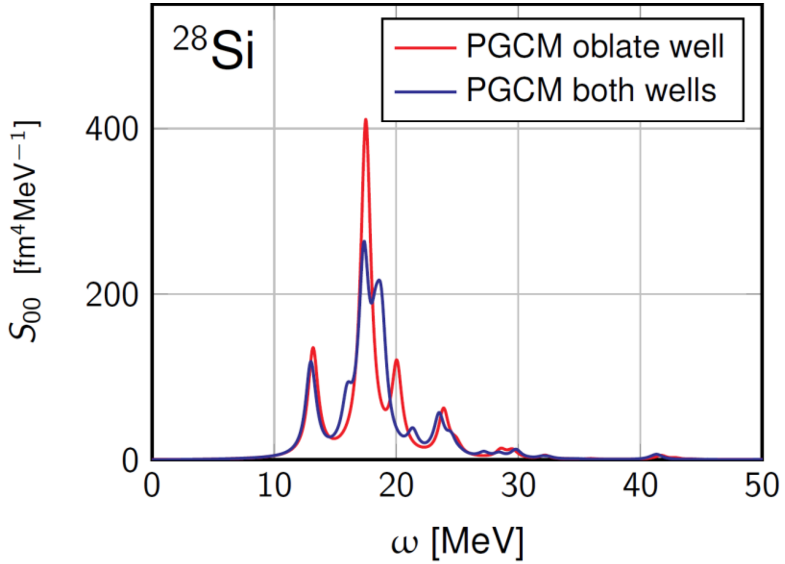




Shape coexistence [Jenkins et al., 2012]



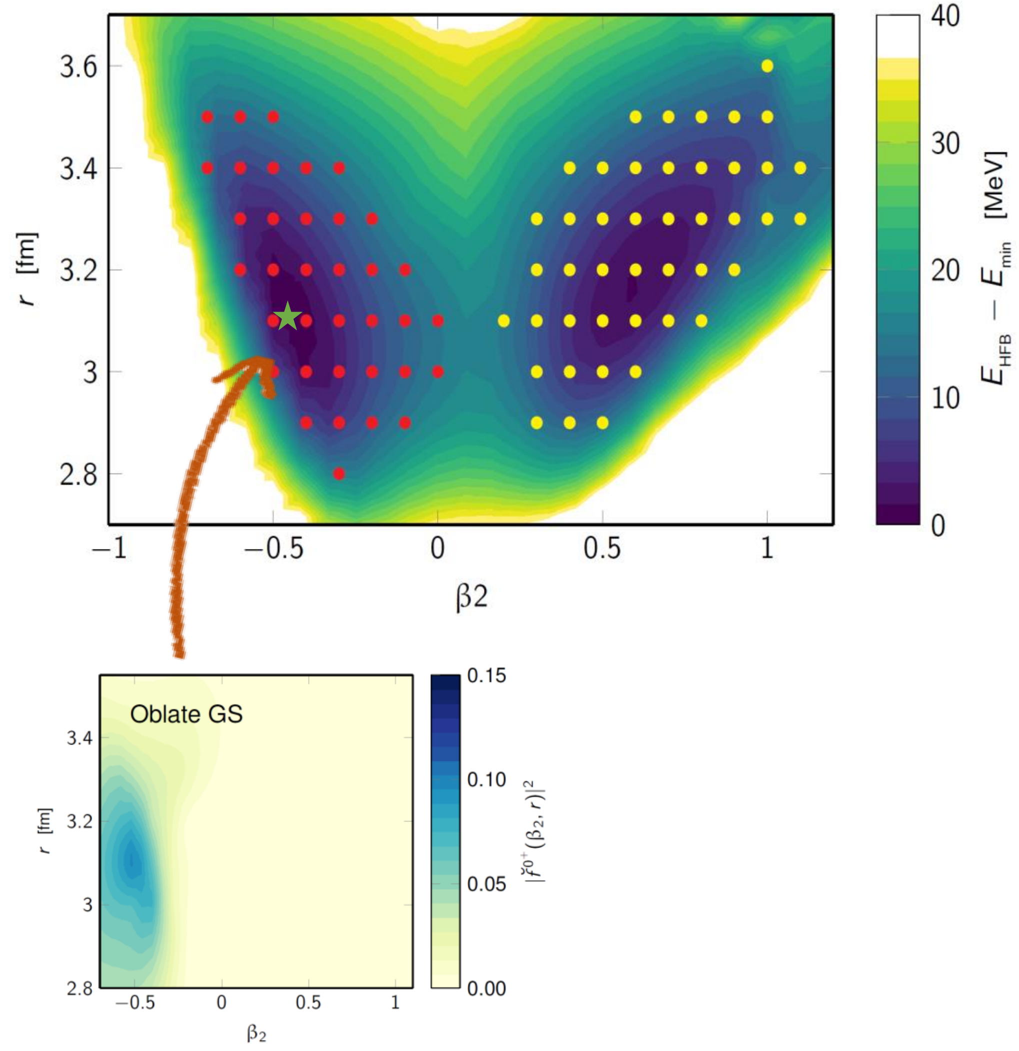
Deformation

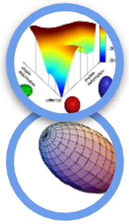


- Oblate minimum and prolate-shape isomer
- Qualitatively similar results QRPA/PGCM
  - QRPA response less fragmented
- Proper study of shape coexistence in PGCM
  - Shape coexistence but no shape mixing

Shape coexistence effects in ^{28}Si

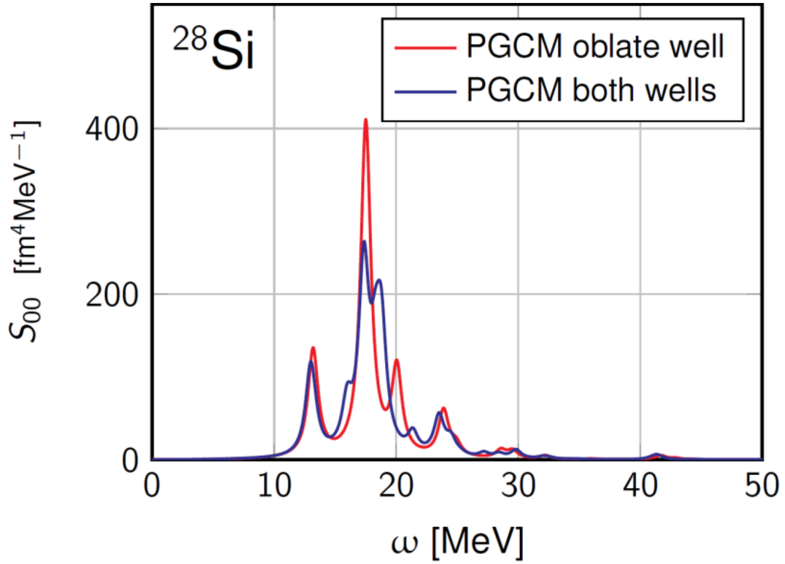
Total Energy Surface $E_{HFB}(\beta_2,r)$





Shape coexistence [Jenkins et al., 2012]

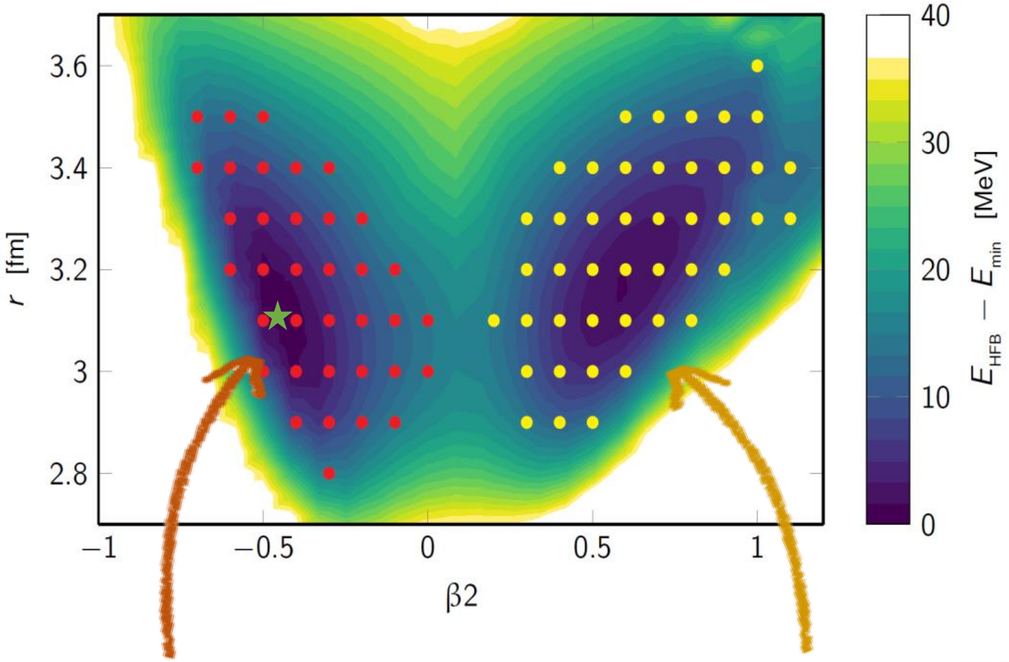
Deformation

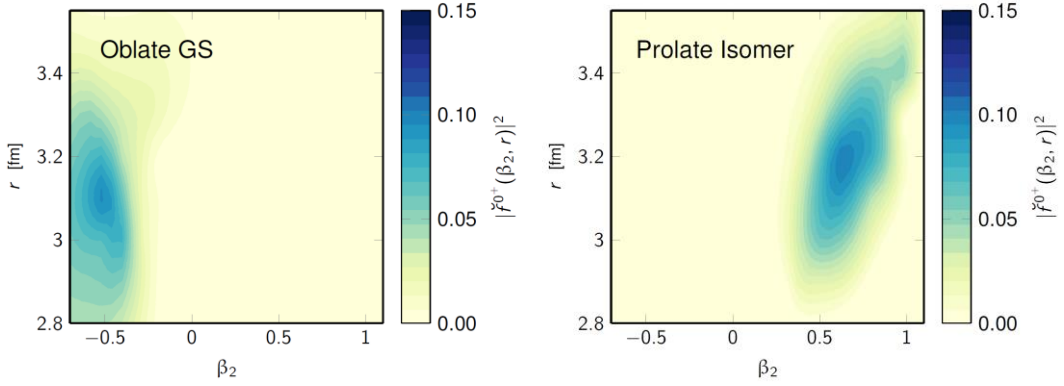


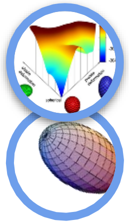
- Oblate minimum and prolate-shape isomer
- Qualitatively similar results QRPA/PGCM
  - QRPA response less fragmented
- Proper study of shape coexistence in PGCM
  - Shape coexistence but no shape mixing

Shape coexistence effects in ^{28}Si

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

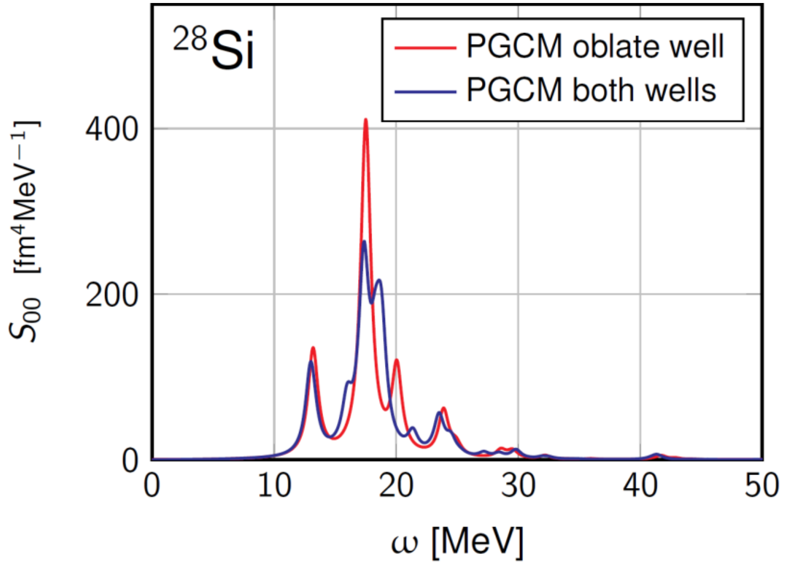






Shape coexistence [Jenkins et al., 2012]

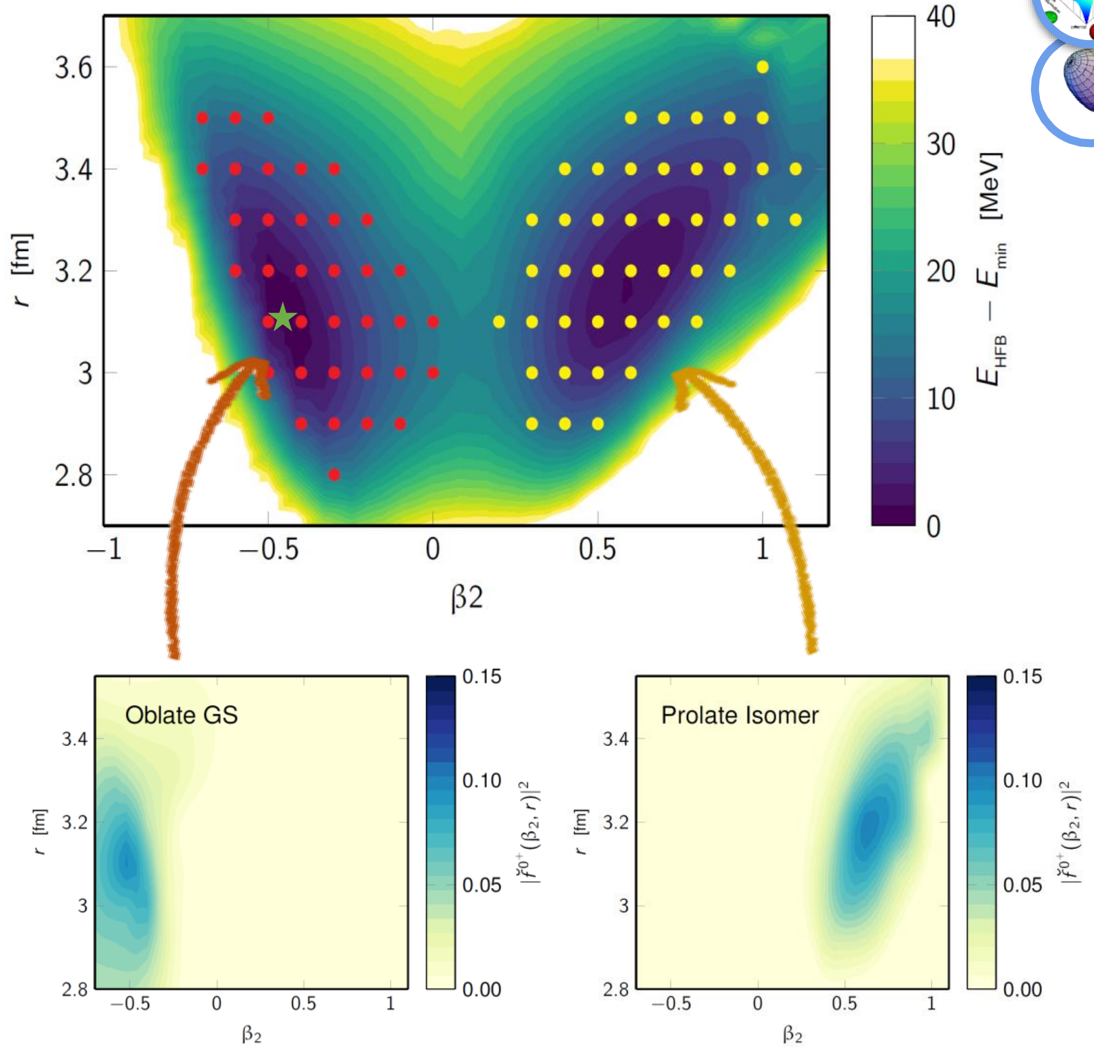
Deformation

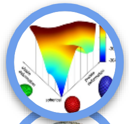


- Oblate minimum and prolate-shape isomer
- Qualitatively similar results QRPA/PGCM
  - QRPA response less fragmented
- Proper study of shape coexistence in PGCM
  - Shape coexistence but no shape mixing

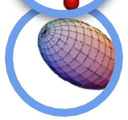
Shape coexistence effects in ^{28}Si

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

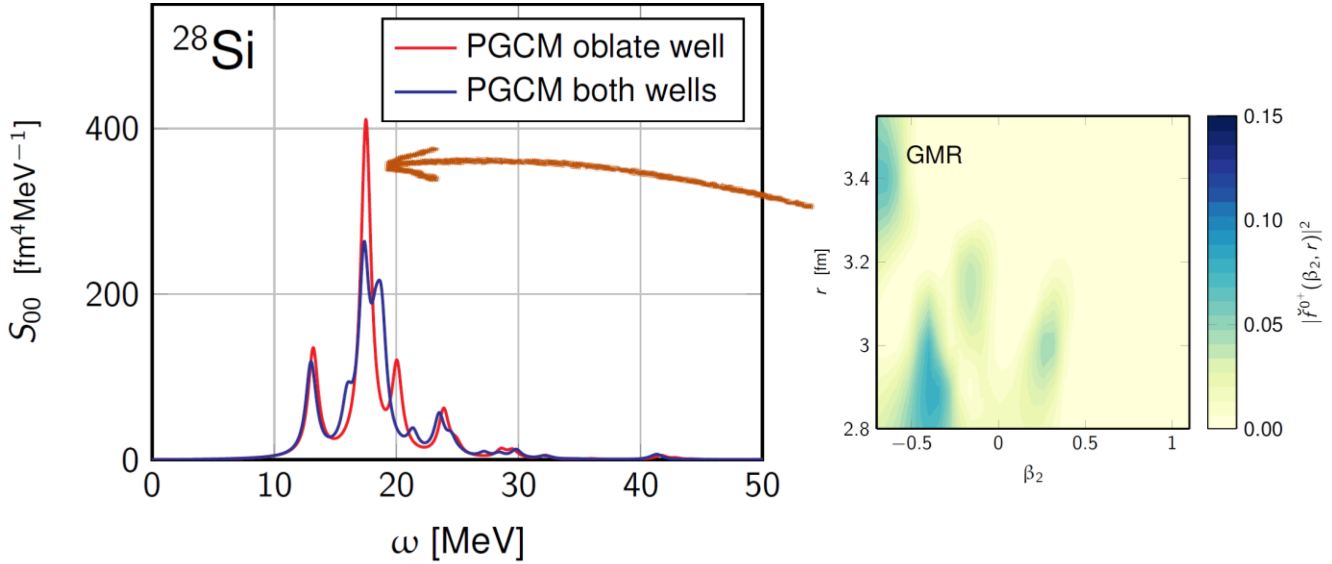




Shape coexistence [Jenkins et al., 2012]

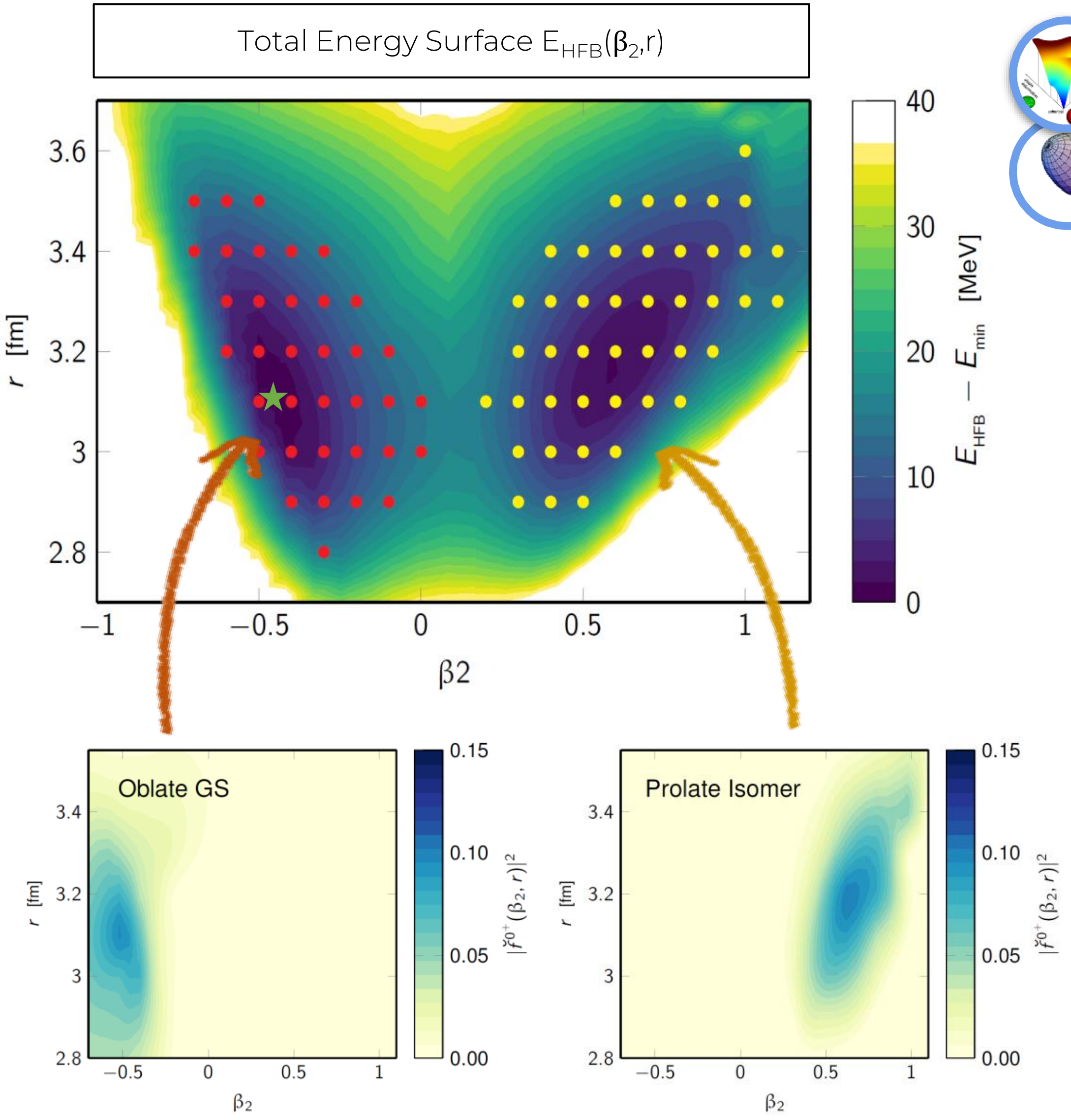


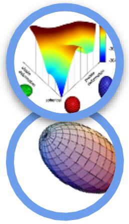
Deformation



- Oblate minimum and prolate-shape isomer
- Qualitatively similar results QRPA/PGCM
  - QRPA response less fragmented
- Proper study of shape coexistence in PGCM
  - Shape coexistence but no shape mixing

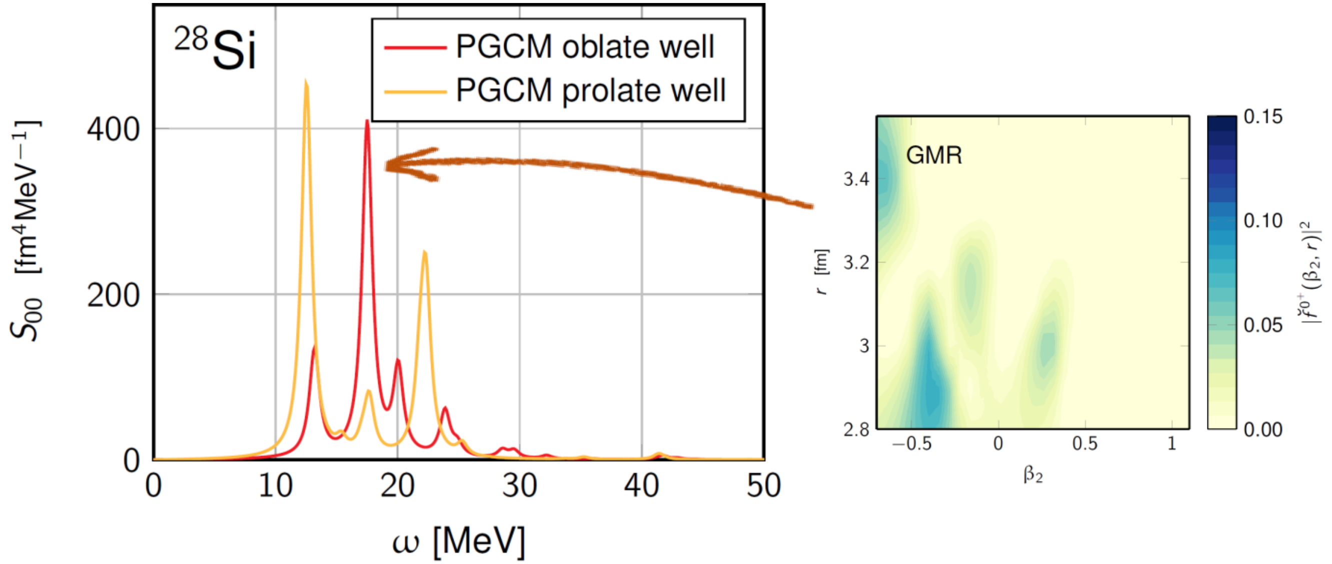
Shape coexistence effects in ^{28}Si





Shape coexistence [Jenkins et al., 2012]

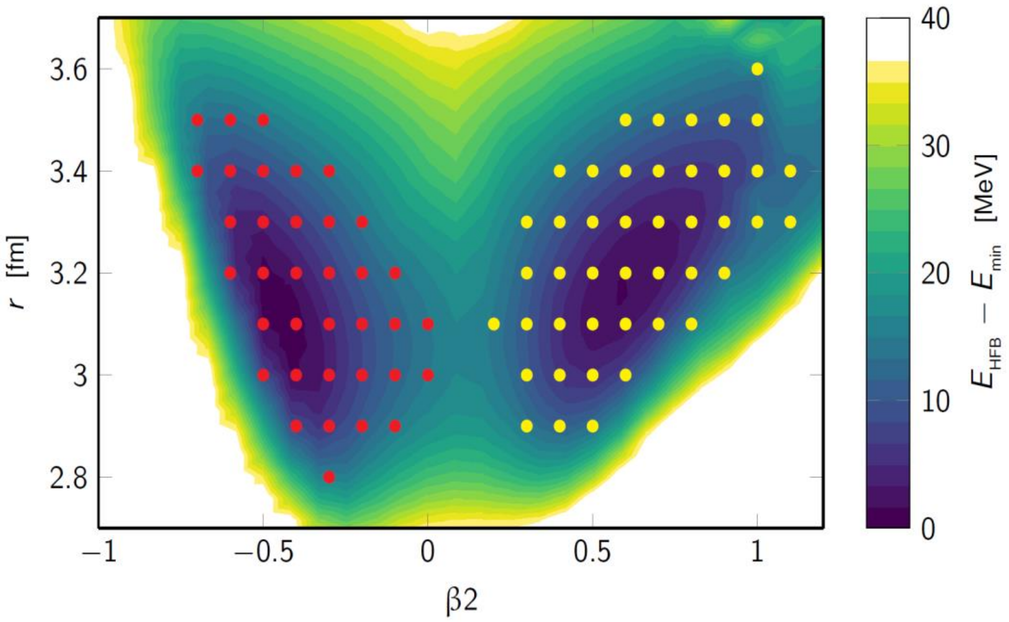
Deformation



- Oblate minimum and prolate-shape isomer
- Qualitatively similar results QRPA/PGCM
  - QRPA response less fragmented
- Proper study of shape coexistence in PGCM
  - Shape coexistence but no shape mixing

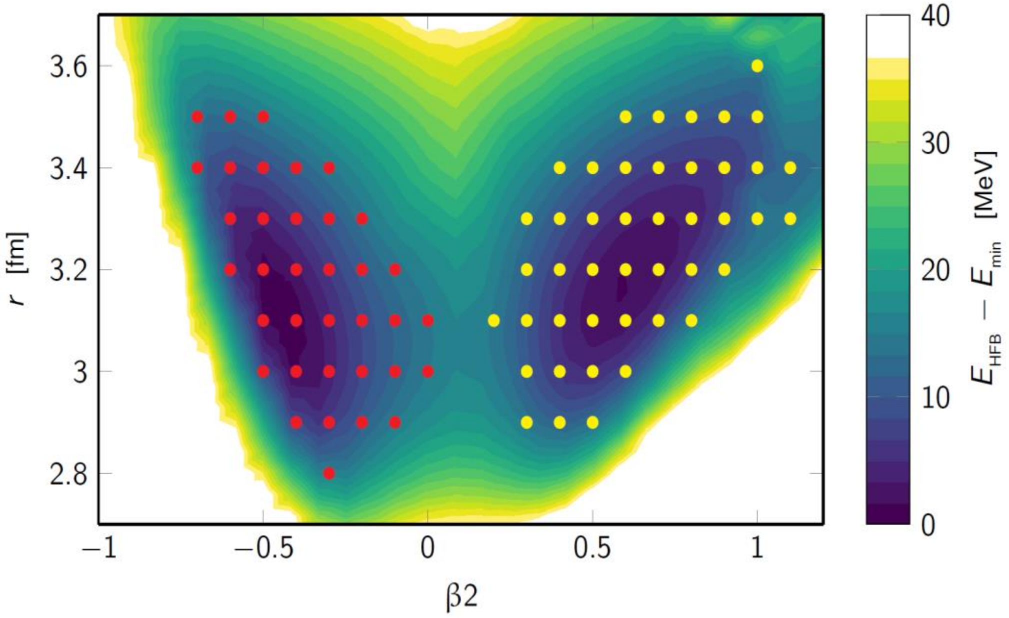
Deformation effects in prolate ^{28}Si

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



Deformation effects in prolate ^{28}Si

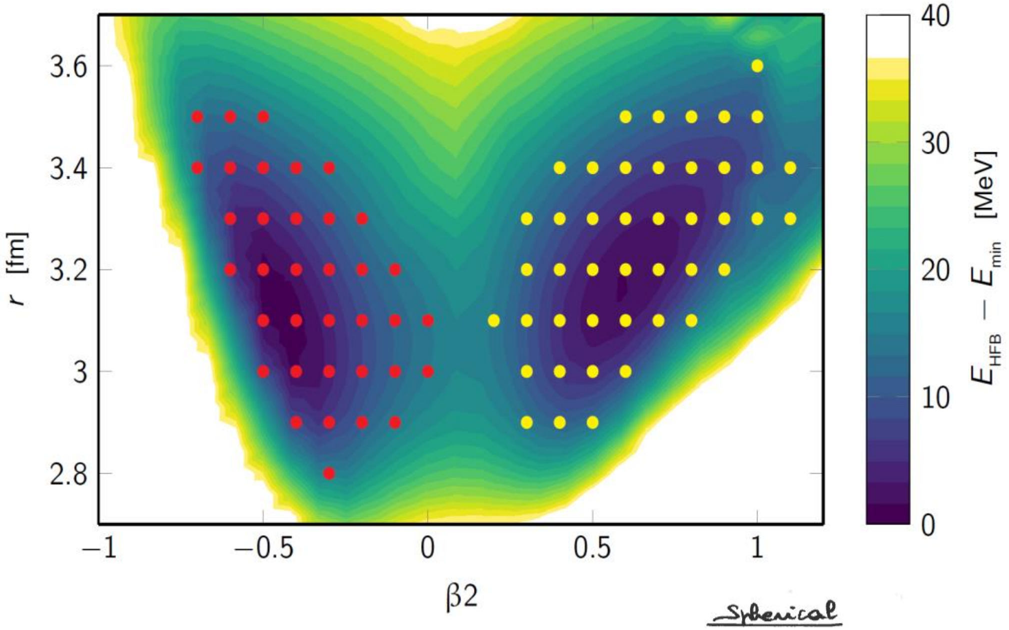
Total Energy Surface $E_{HFB}(\beta_2,r)$



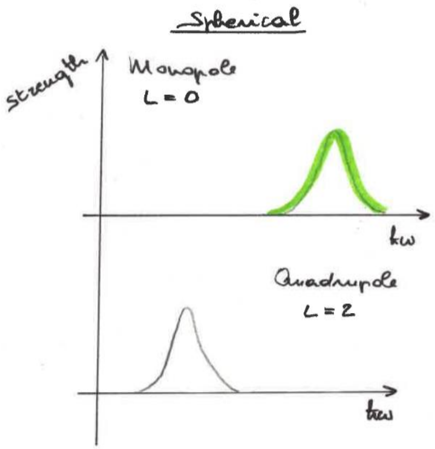
- Focus on the prolate-shape isomer

Deformation effects in prolate ^{28}Si

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



Spherical
(no deformation)

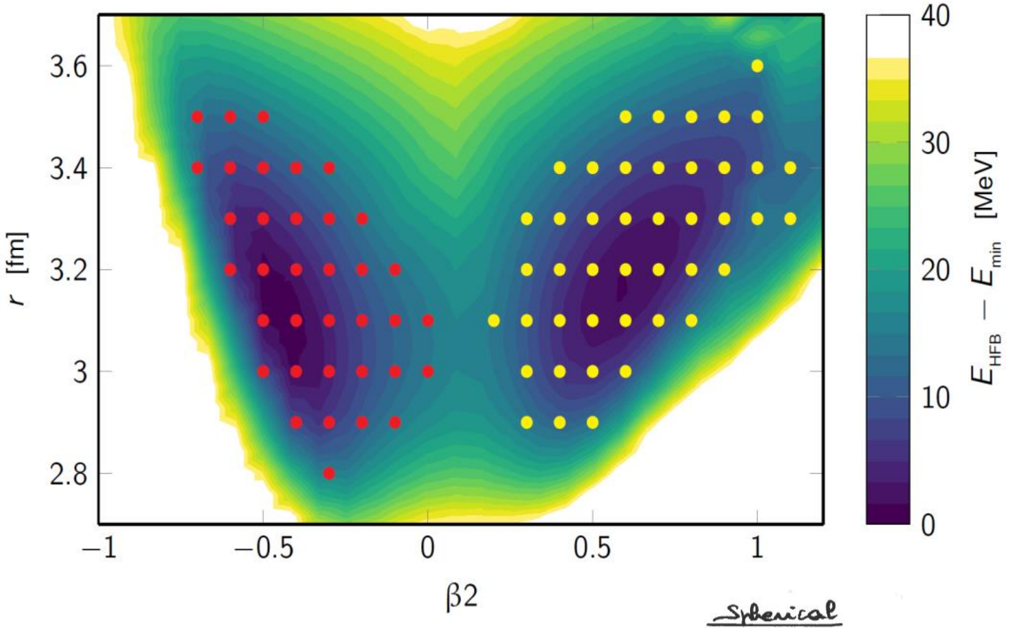


- Focus on the prolate-shape isomer

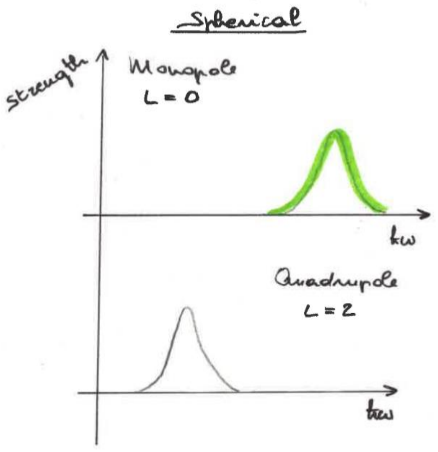
Deformation effects in prolate ^{28}Si

- Focus on the prolate-shape isomer
- Coupling to GQR generates splitting
  - x High peak = shifted “spherical” breathing mode
  - x Low peak = induced by coupling to GQR (K=0)

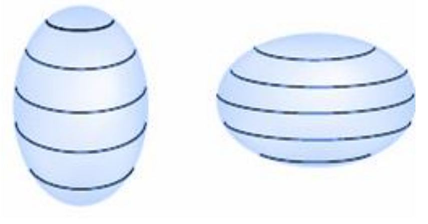
Total Energy Surface $E_{HFB}(\beta_2, r)$



Spherical
(no deformation)

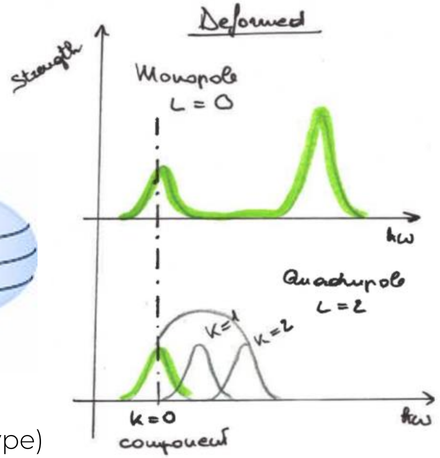


Spheroidal
(deformed)



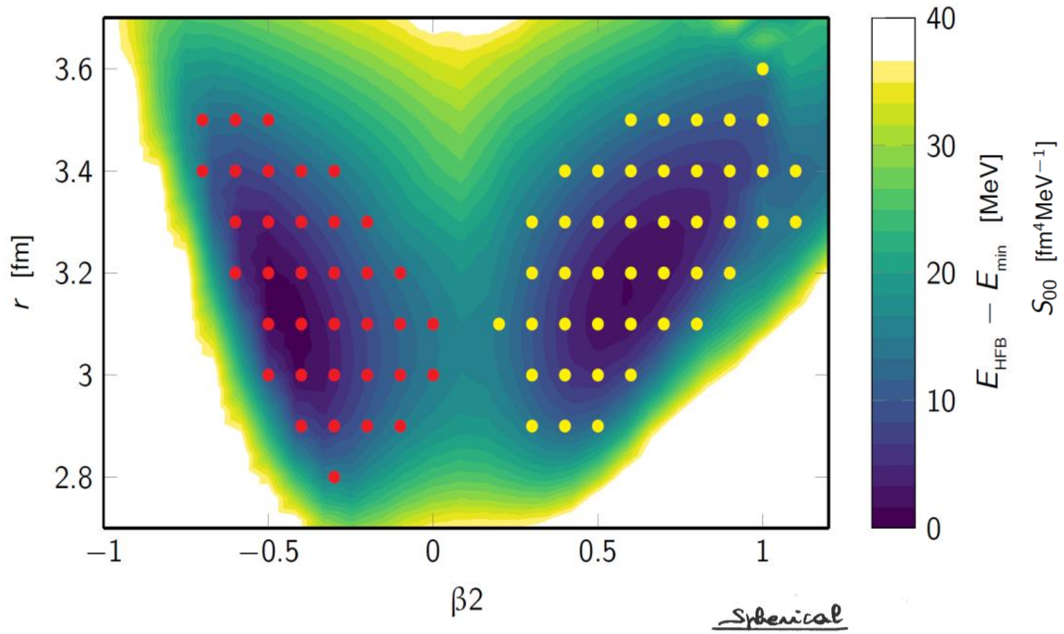
Prolate
(cigar type)

Oblate
(pancake type)

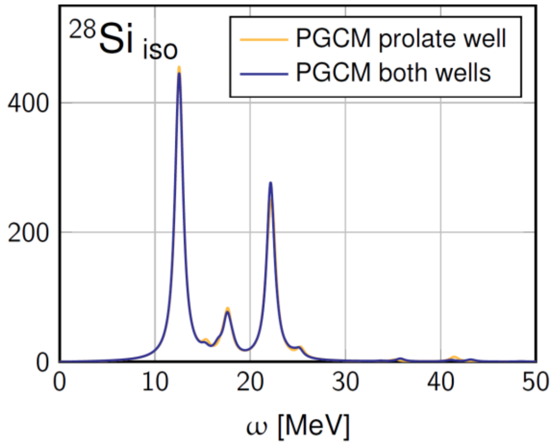


Deformation effects in prolate ^{28}Si

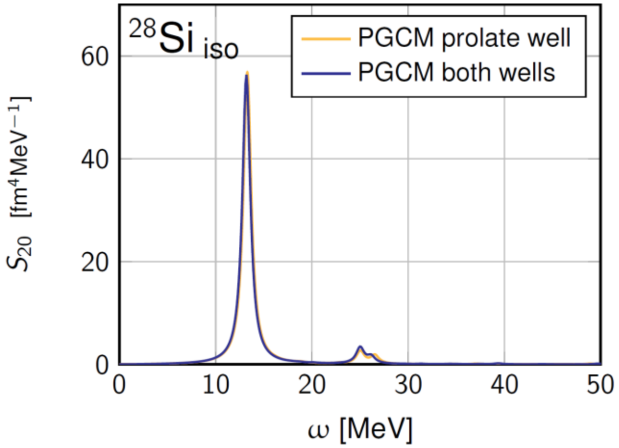
Total Energy Surface $E_{HFB}(\beta_2, r)$



Monopole Strength

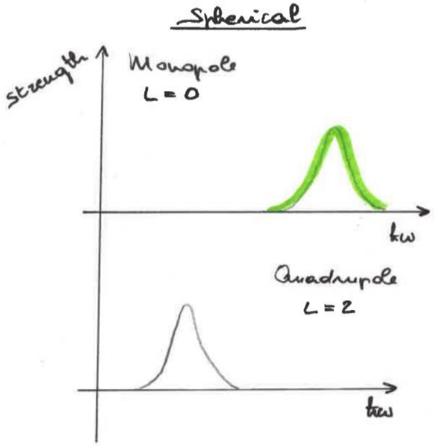


K=0 Quadrupole Strength



- Focus on the prolate-shape isomer
- Coupling to GQR generates splitting
  - x High peak = shifted "spherical" breathing mode
  - x Low peak = induced by coupling to GQR (K=0)
- Two-peak GMR on the prolate shape isomer

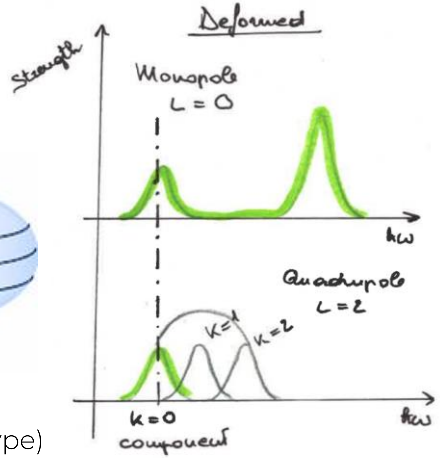
Spherical (no deformation)



Spheroidal (deformed)

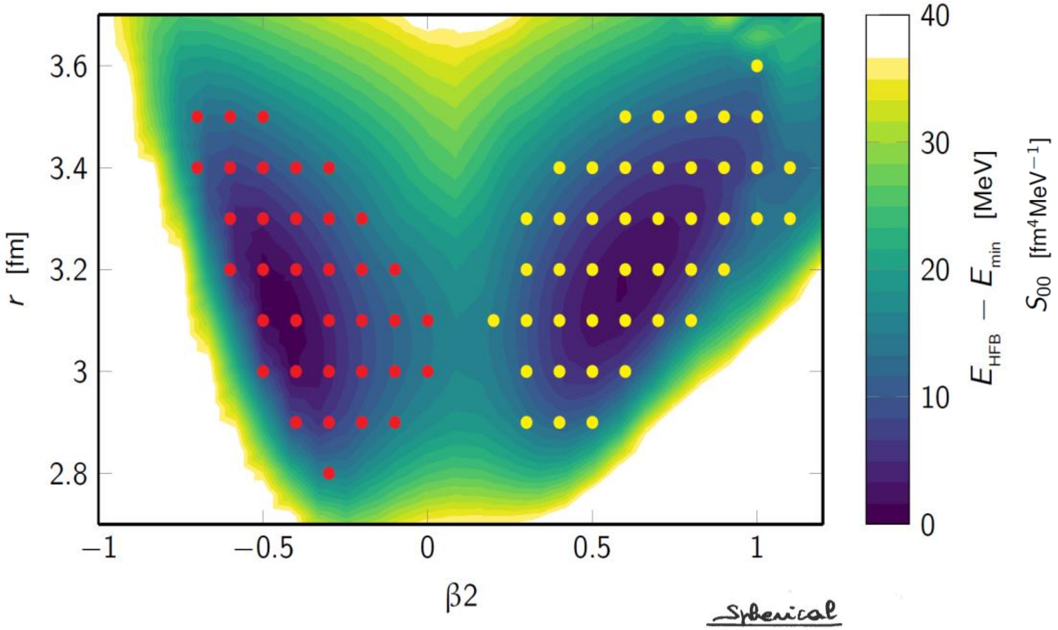
Prolate (cigar type)

Oblate (pancake type)

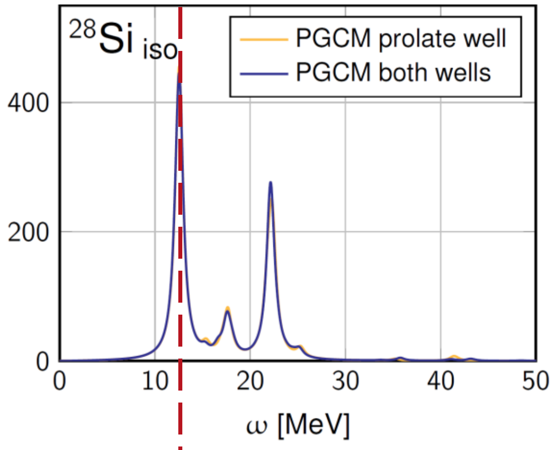


Deformation effects in prolate ^{28}Si

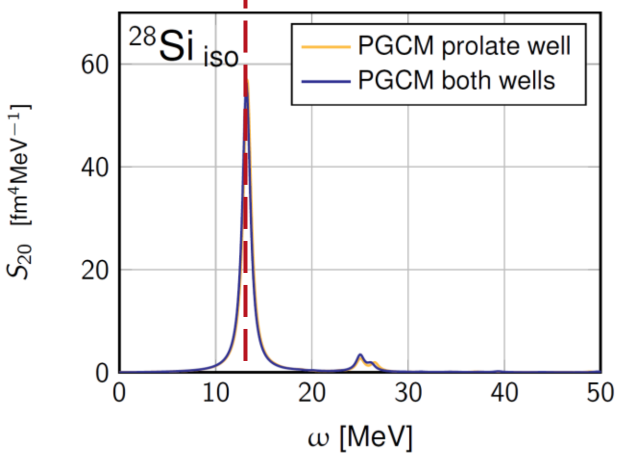
Total Energy Surface $E_{HFB}(\beta_2, r)$



Monopole Strength

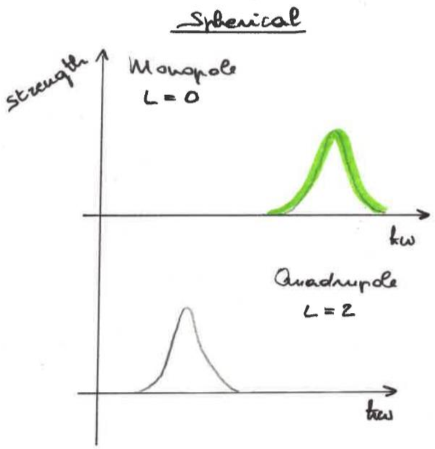


K=0 Quadrupole Strength



- Focus on the prolate-shape isomer
- Coupling to GQR generates splitting
  - x High peak = shifted "spherical" breathing mode
  - x Low peak = induced by coupling to GQR (K=0)
- Two-peak GMR on the prolate shape isomer

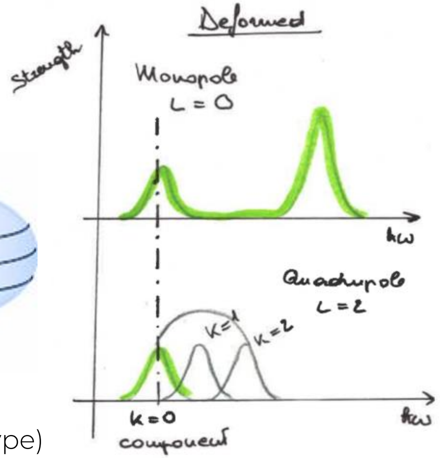
Spherical
(no deformation)



Spheroidal
(deformed)

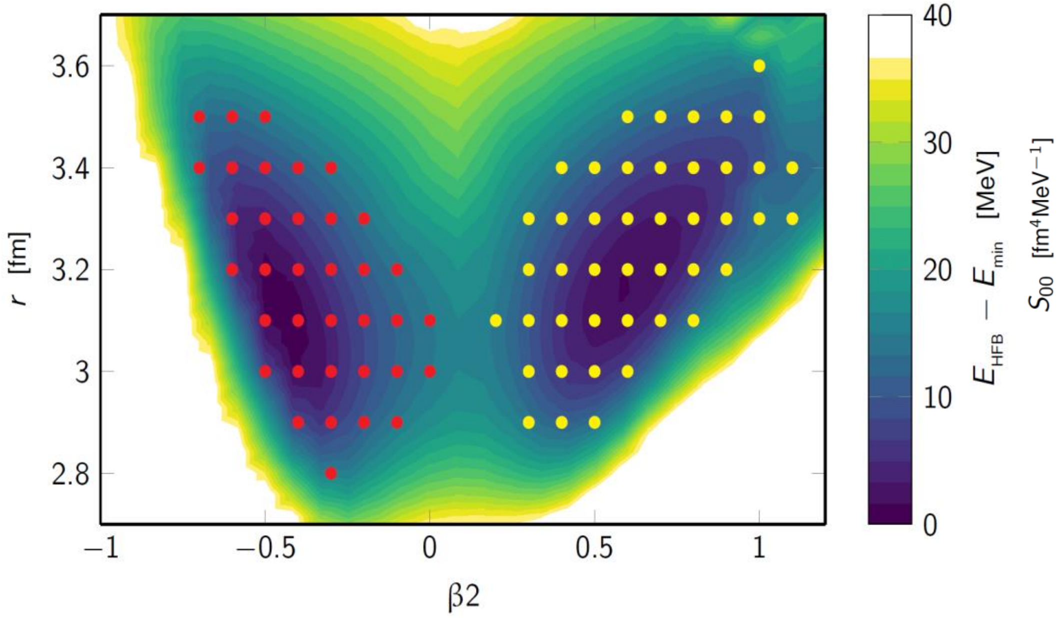
Prolate
(cigar type)

Oblate
(pancake type)

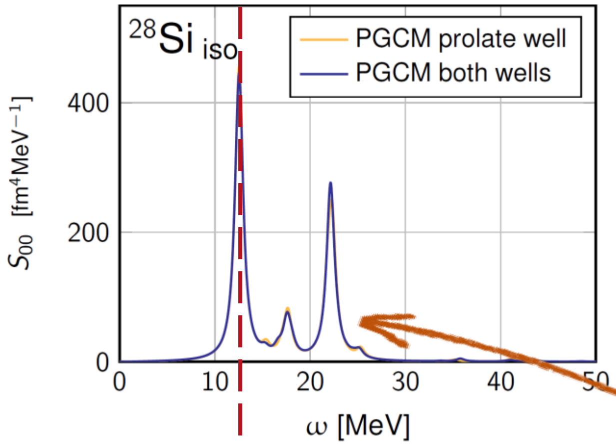


Deformation effects in prolate ^{28}Si

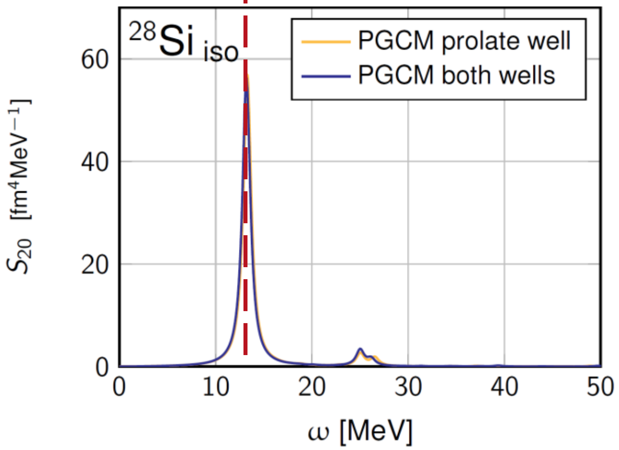
Total Energy Surface $E_{HFB}(\beta_2, r)$



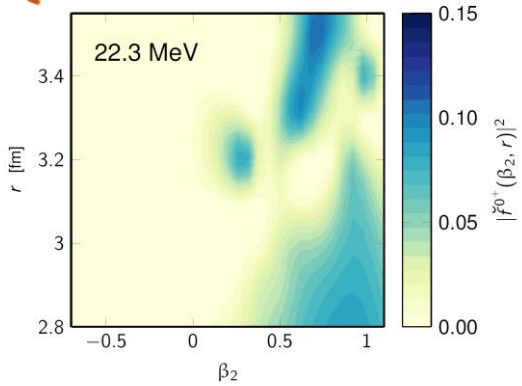
Monopole Strength



K=0 Quadrupole Strength

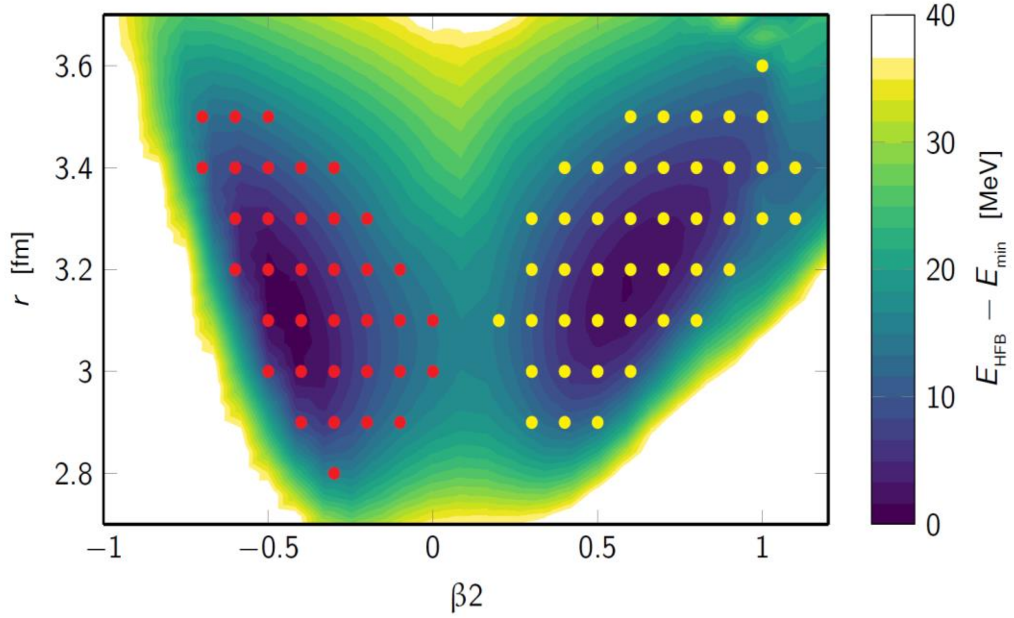


- Focus on the prolate-shape isomer
- Coupling to GQR generates splitting
  - x High peak = shifted "spherical" breathing mode
  - x Low peak = induced by coupling to GQR (K=0)
- Two-peak GMR on the prolate shape isomer

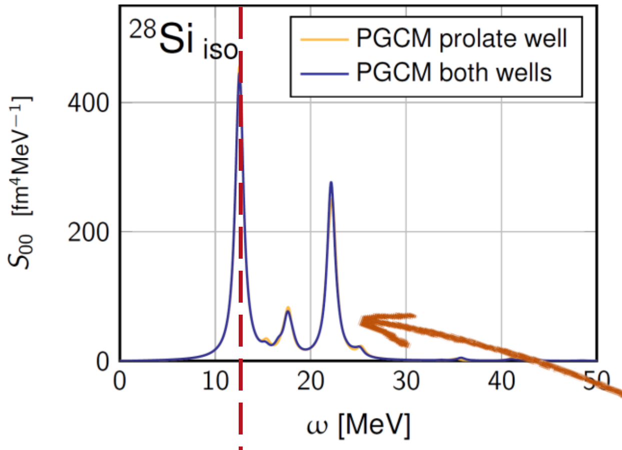


Deformation effects in prolate ^{28}Si

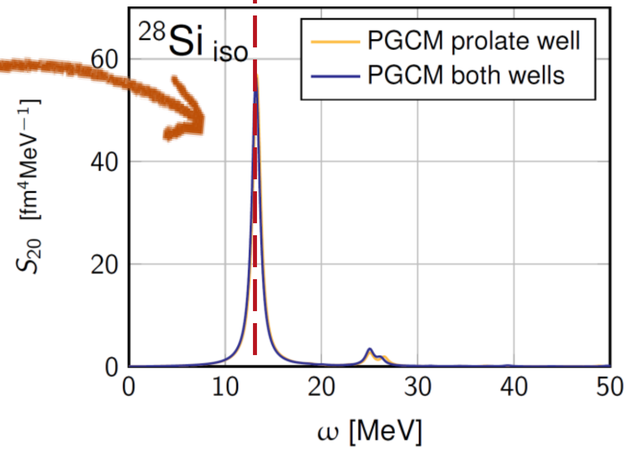
Total Energy Surface $E_{HFB}(\beta_2, r)$

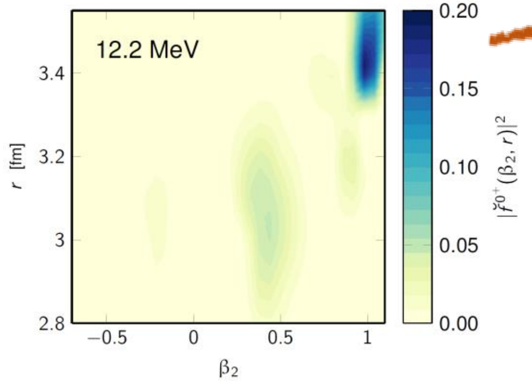


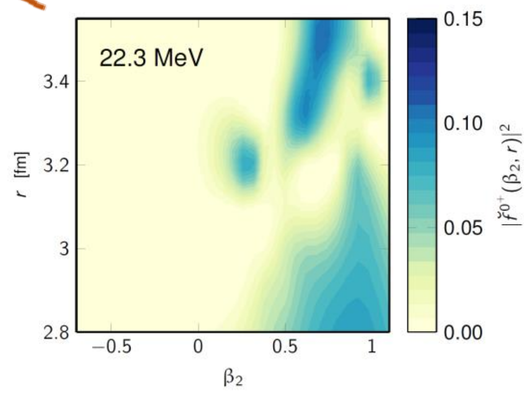
Monopole Strength



K=0 Quadrupole Strength



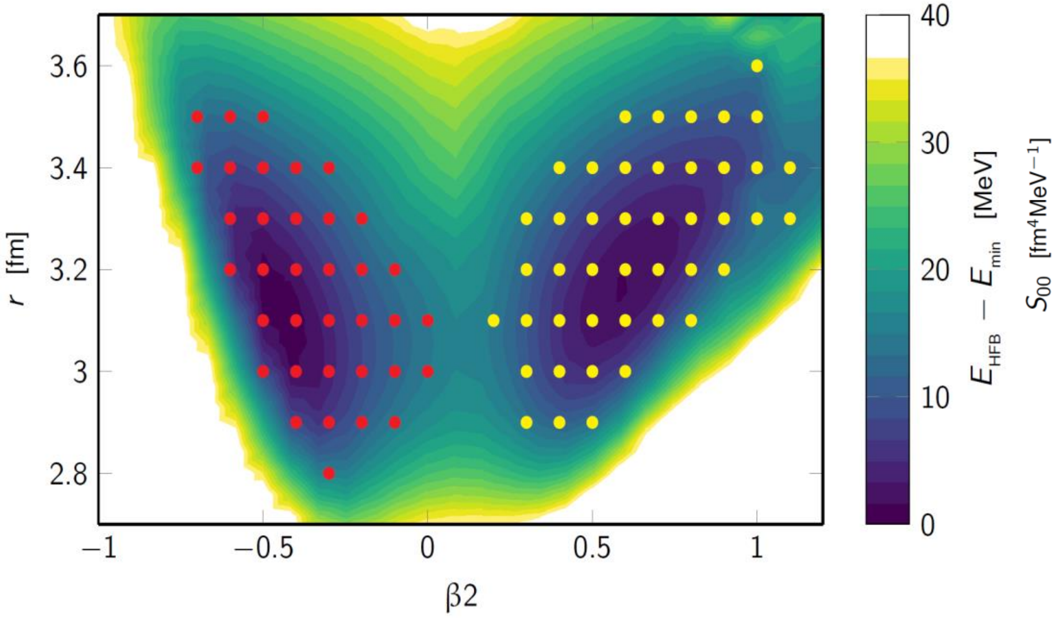


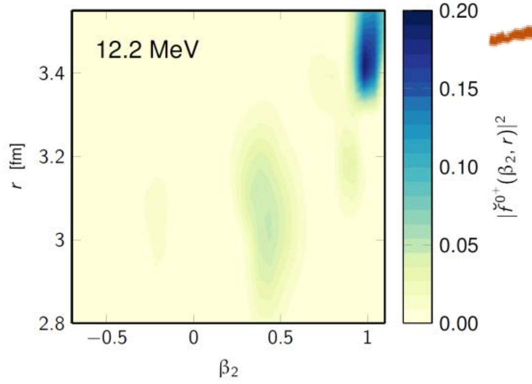


- Focus on the prolate-shape isomer
- Coupling to GQR generates splitting
  - x High peak = shifted "spherical" breathing mode
  - x Low peak = induced by coupling to GQR (K=0)
- Two-peak GMR on the prolate shape isomer

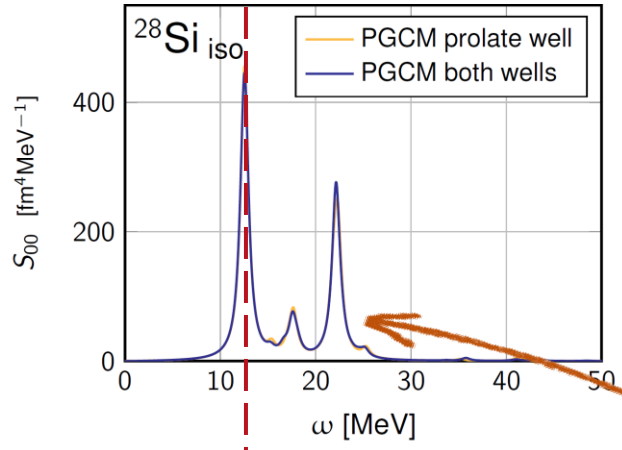
Deformation effects in prolate ^{28}Si

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

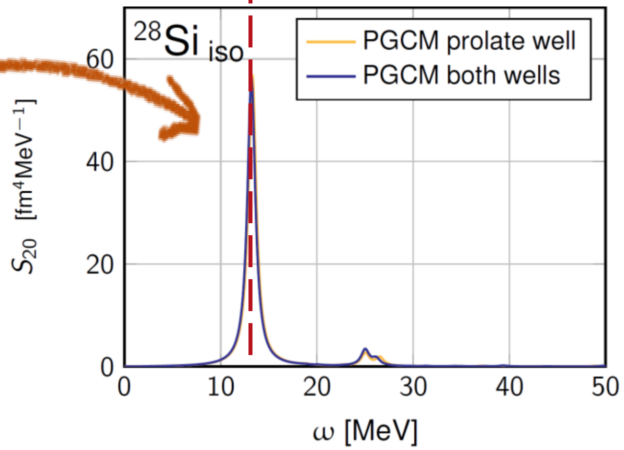




Monopole Strength

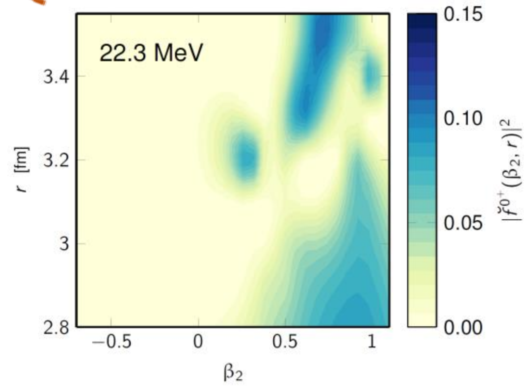


K=0 Quadrupole Strength

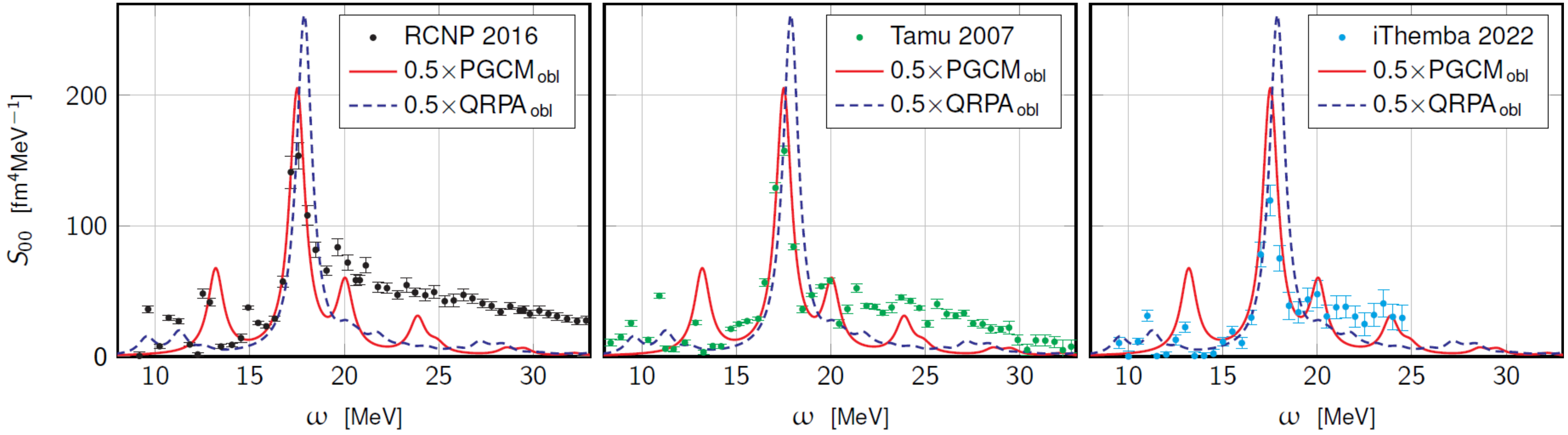


- Focus on the prolate-shape isomer
- Coupling to GQR generates splitting
  - x High peak = shifted "spherical" breathing mode
  - x Low peak = induced by coupling to GQR (K=0)
- Two-peak GMR on the prolate shape isomer

Experimentally accessible ?



Comparison to experiment ^{28}Si



PGCM better reproduces the experimental data

- Better description of the main resonance
- Fragmentation effects are better captured than in QRPA

Experimental data are useful and promising to test different many-body methods

Data are not unambiguous, i.e. better resolution would be beneficial

Outline

Introduction

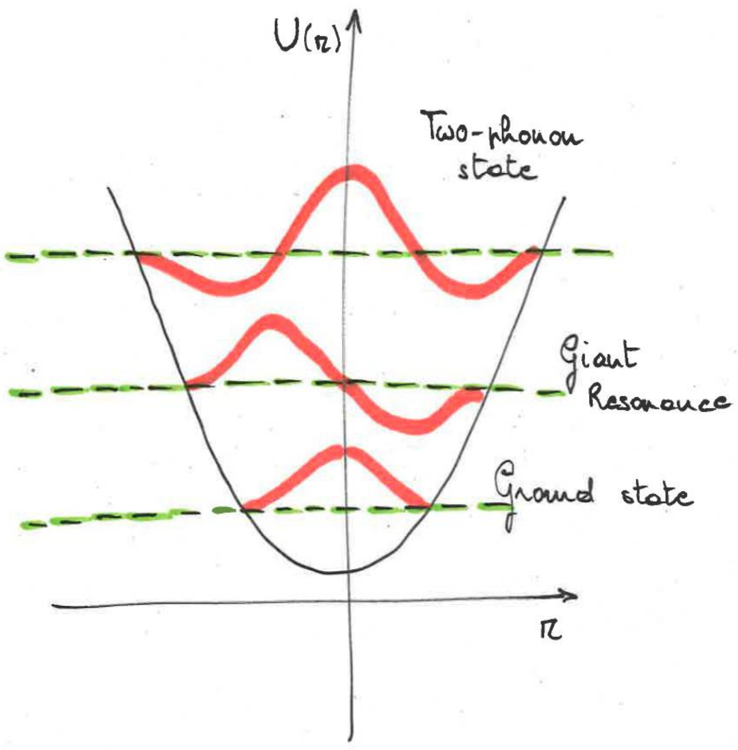
Formalism

Results

Multi-phonon states in ^{46}Ti

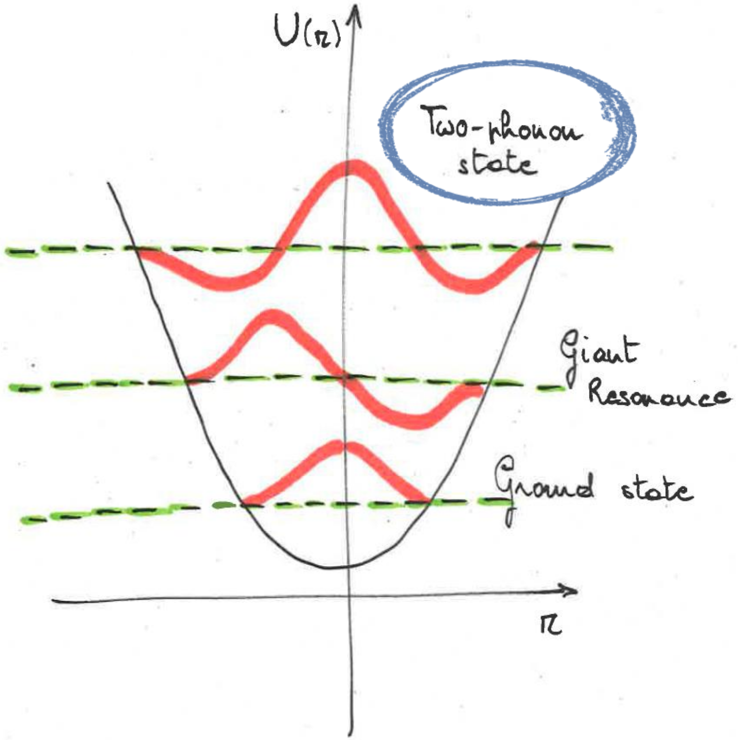
Conclusions

Multi-phonon states in ^{46}Ti



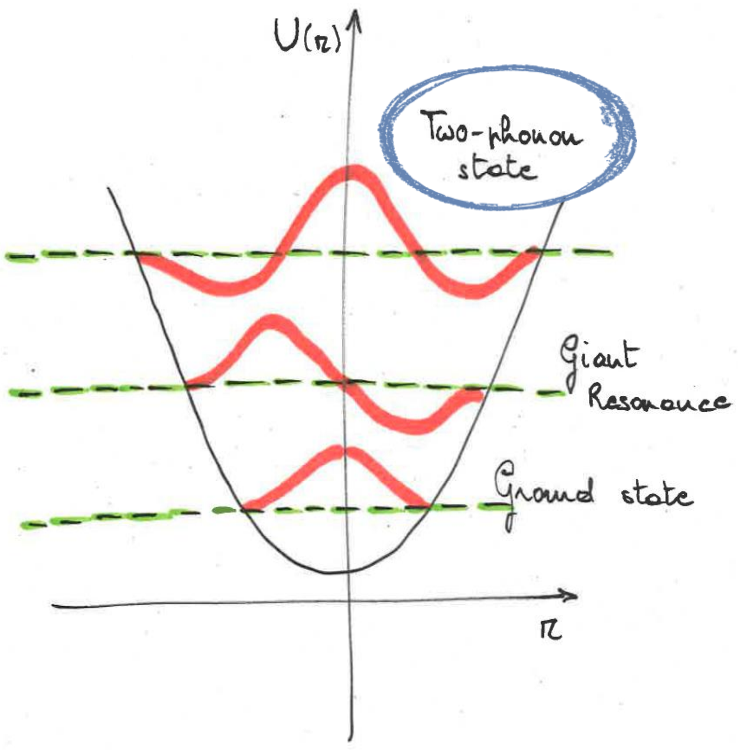
- GRs are the first phonon of a collective excitation

Multi-phonon states in ^{46}Ti



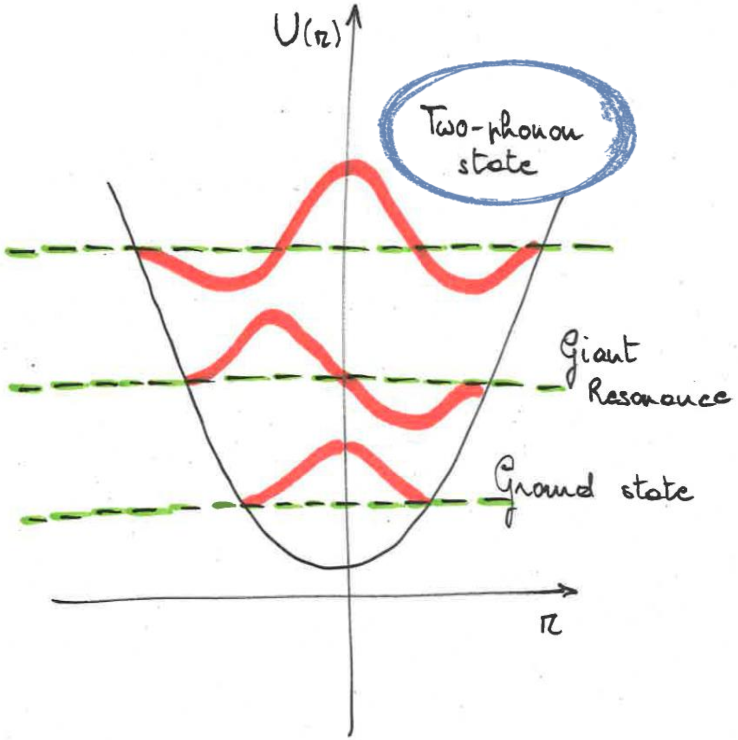
- GRs are the first phonon of a collective excitation
- Higher phonons also exist ! Multi-phonon states

Multi-phonon states in ^{46}Ti



- GRs are the first phonon of a collective excitation
- Higher phonons also exist ! Multi-phonon states
- Not accessible to QRPA

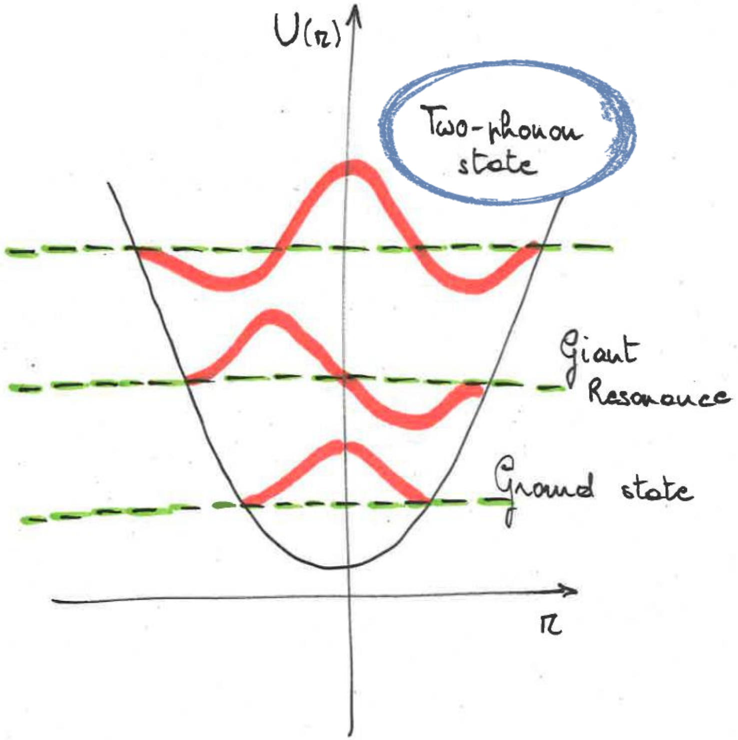
Multi-phonon states in ^{46}Ti



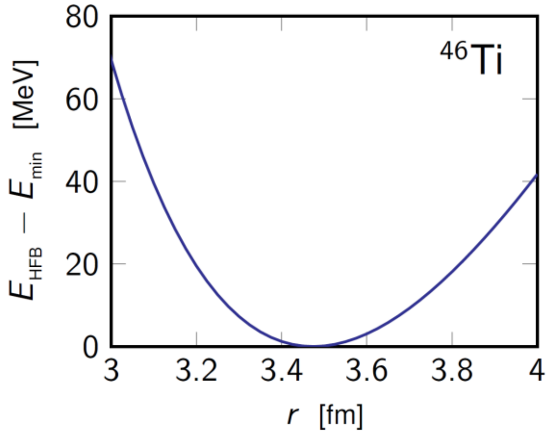
- GRs are the first phonon of a collective excitation
- Higher phonons also exist ! Multi-phonon states
- Not accessible to QRPA
- Equally spaced in the harmonic limit

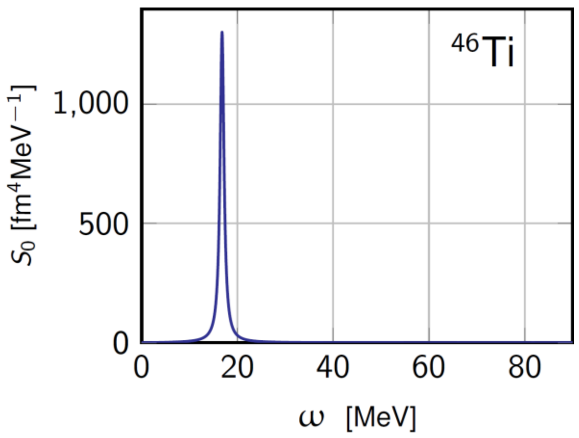
Multi-phonon states in ^{46}Ti

- GRs are the first phonon of a collective excitation
- Higher phonons also exist ! Multi-phonon states
- Not accessible to QRPA
- Equally spaced in the harmonic limit

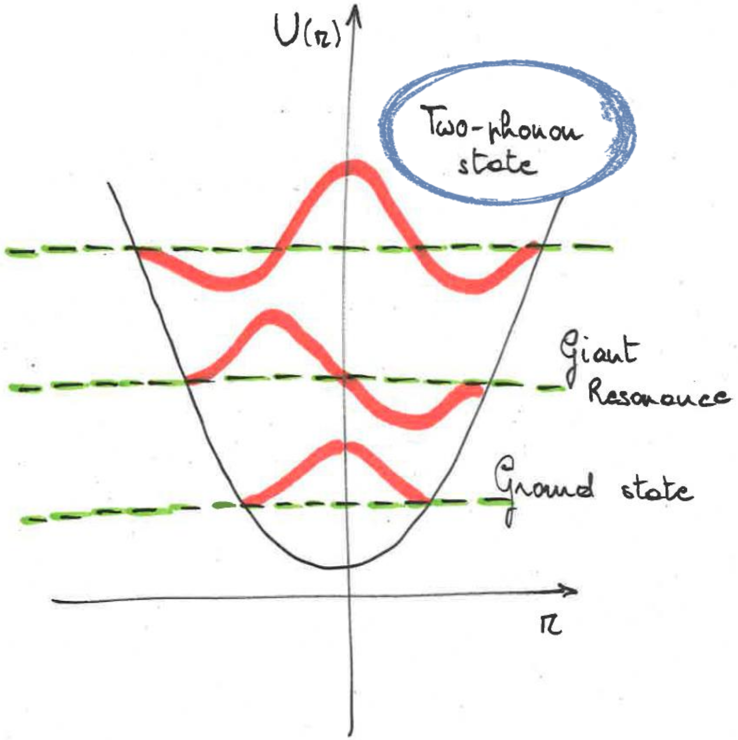


One-dimensional PGCM calculation



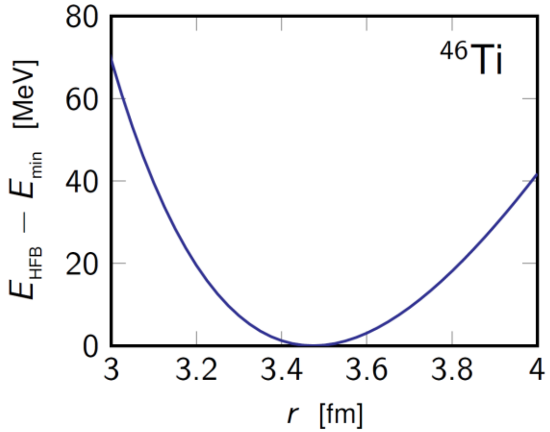


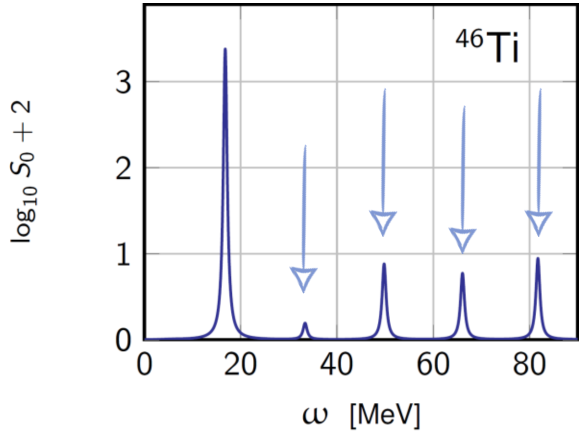
Multi-phonon states in ^{46}Ti



- GRs are the first phonon of a collective excitation
- Higher phonons also exist ! Multi-phonon states
- Not accessible to QRPA
- Equally spaced in the harmonic limit

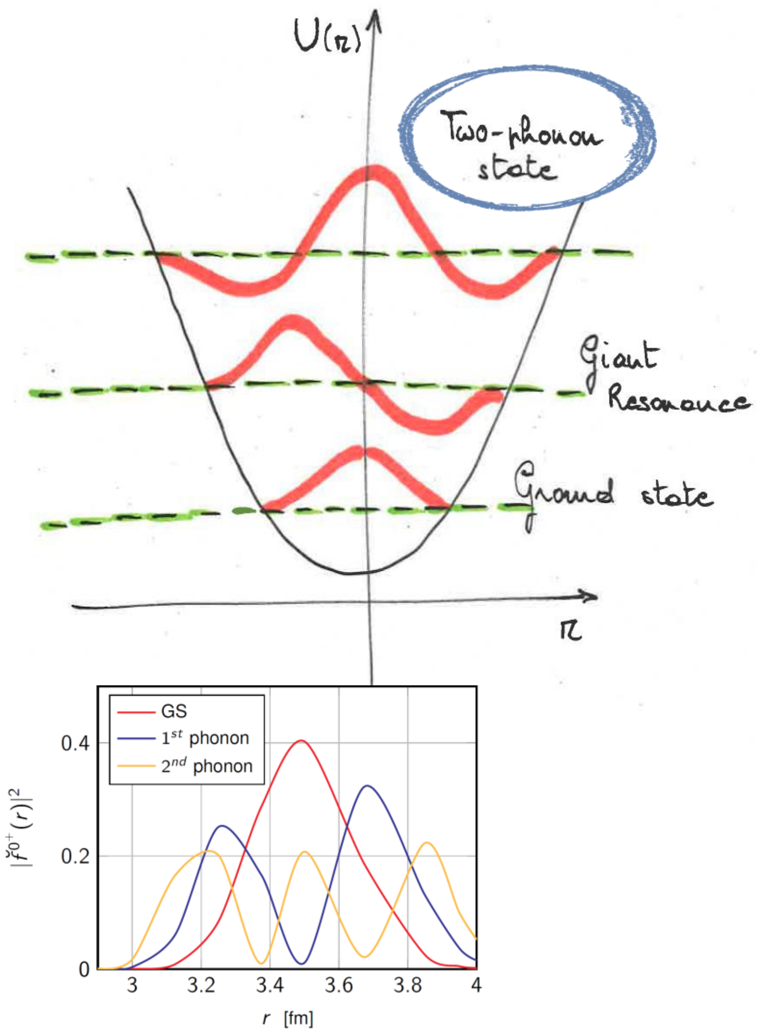
One-dimensional PGCM calculation





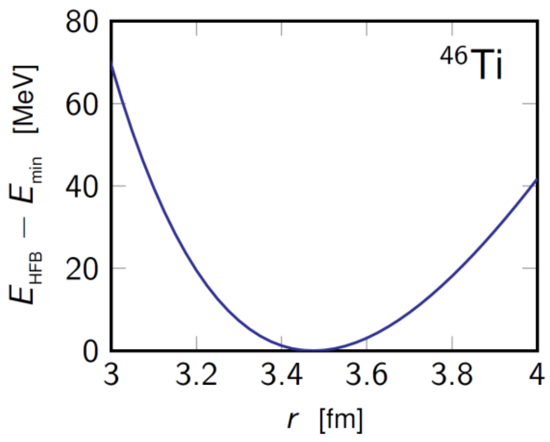
- PGCM predicts high-lying states

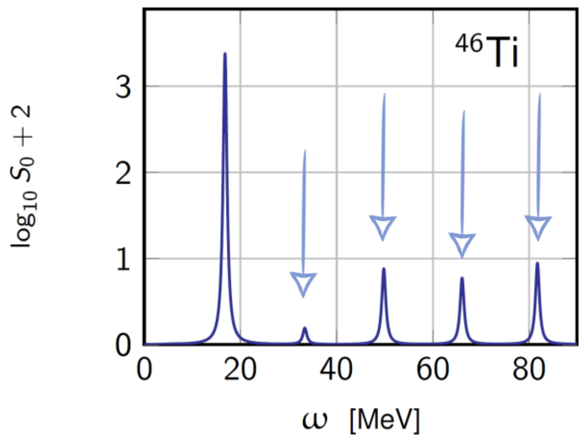
Multi-phonon states in ^{46}Ti



- GRs are the first phonon of a collective excitation
- Higher phonons also exist ! Multi-phonon states
- Not accessible to QRPA
- Equally spaced in the harmonic limit

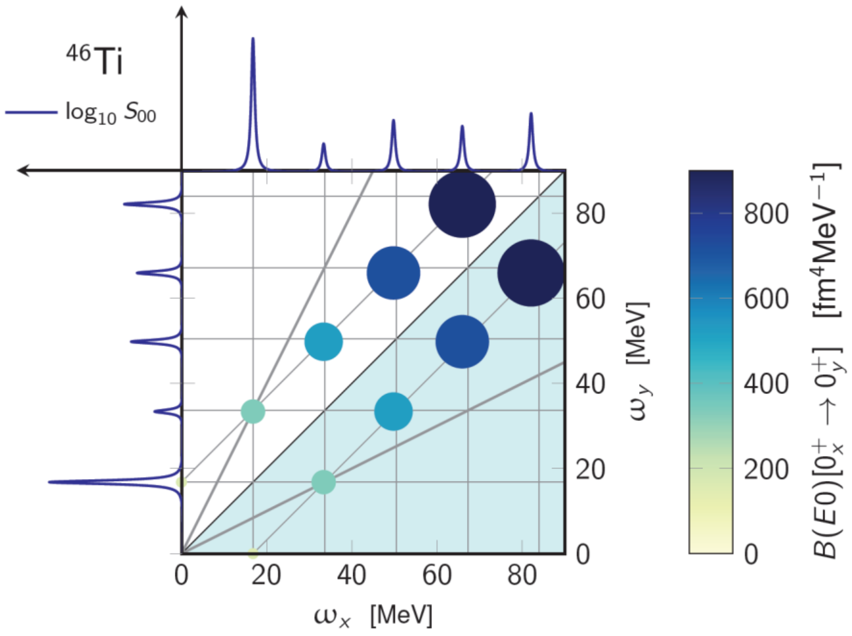
One-dimensional PGCM calculation

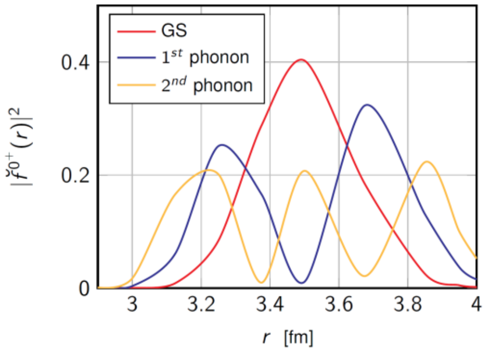




- PGCM predicts high-lying states
- Close to the harmonic oscillator eigen-solutions

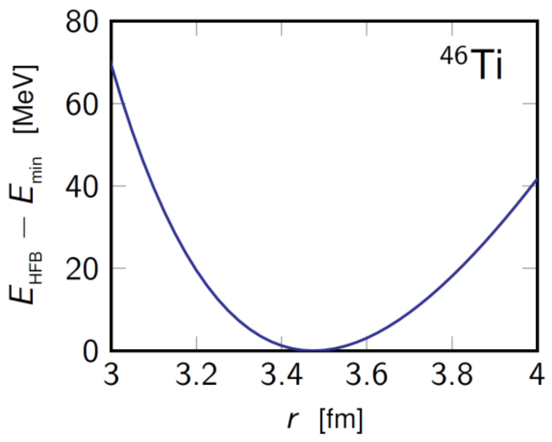
Multi-phonon states in ^{46}Ti

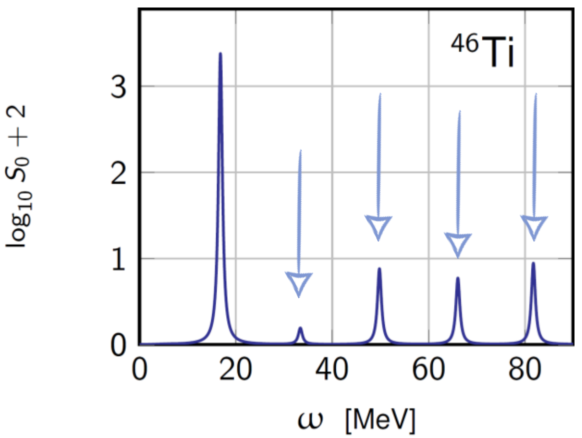




- GRs are the first phonon of a collective excitation
- Higher phonons also exist ! Multi-phonon states
- Not accessible to QRPA
- Equally spaced in the harmonic limit

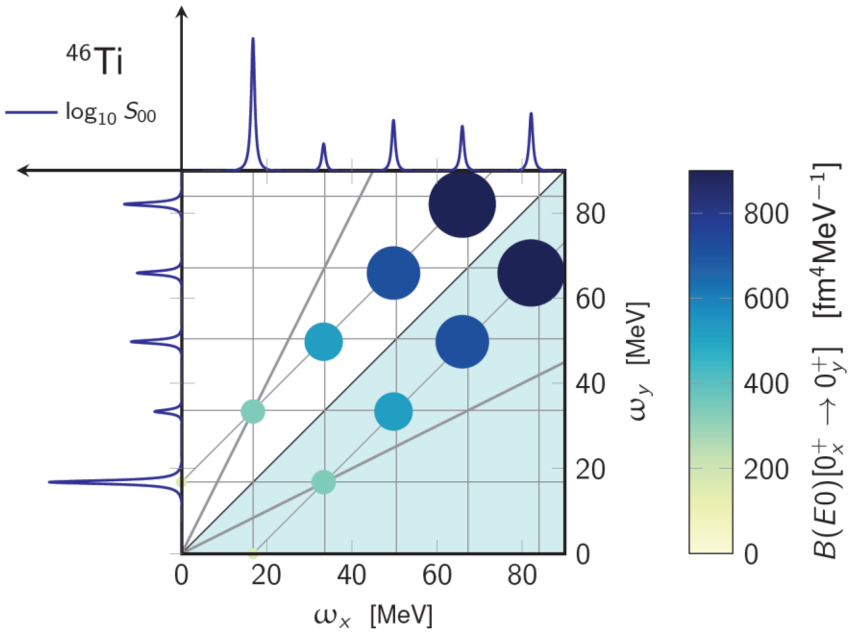
One-dimensional PGCM calculation

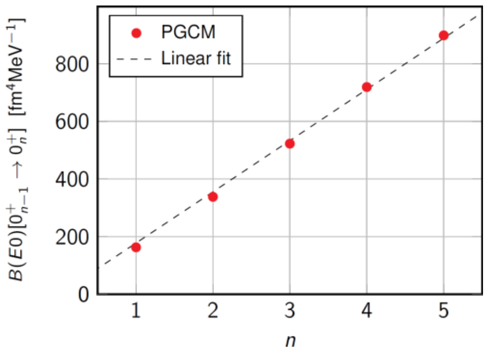




- PGCM predicts high-lying states
- Close to the harmonic oscillator eigen-solutions
- Transitions maximised between neighbouring phonons

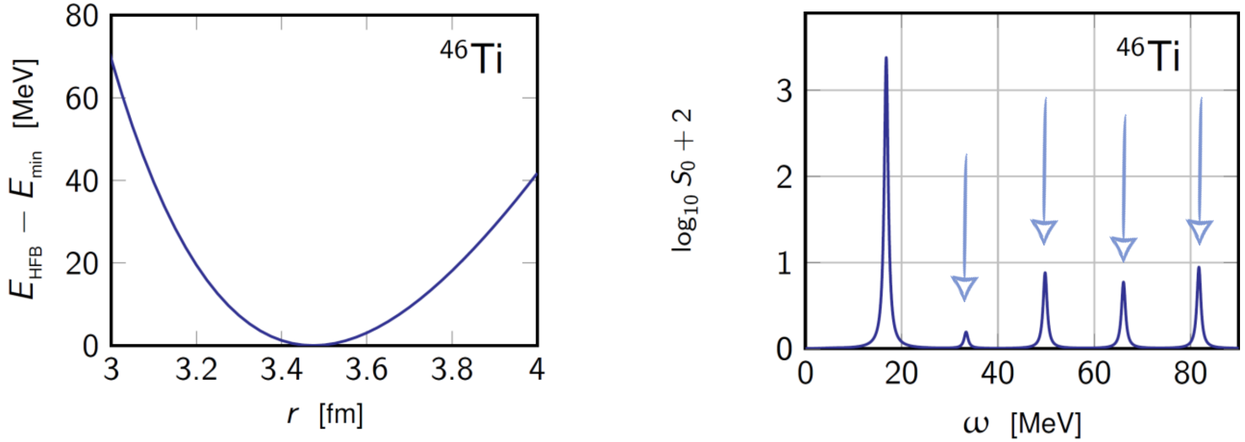
Multi-phonon states in ^{46}Ti





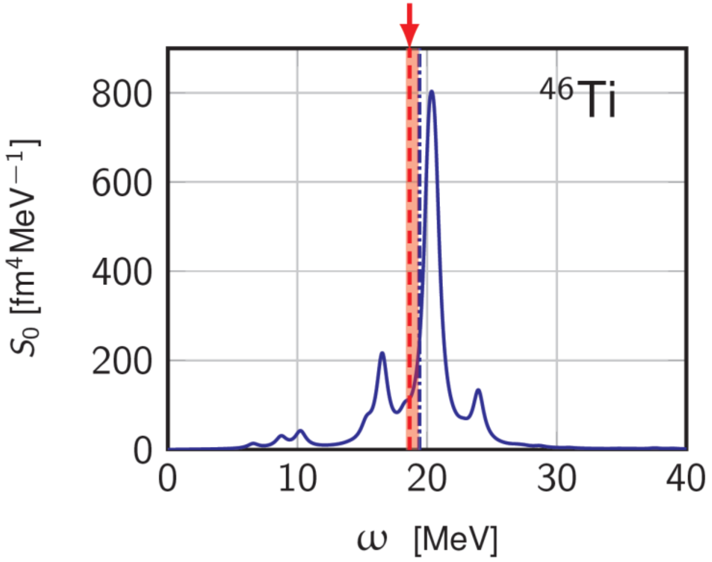
- GRs are the first phonon of a collective excitation
- Higher phonons also exist ! Multi-phonon states
- Not accessible to QRPA
- Equally spaced in the harmonic limit

One-dimensional PGCM calculation



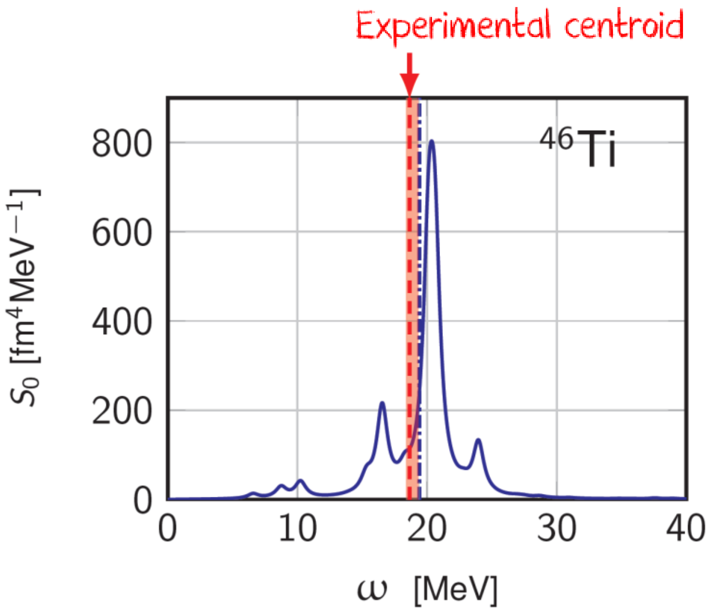
- PGCM predicts high-lying states
- Close to the harmonic oscillator eigen-solutions
- Transitions maximised between neighbouring phonons
  - x Linear trend in the transition strength

Realistic calculations



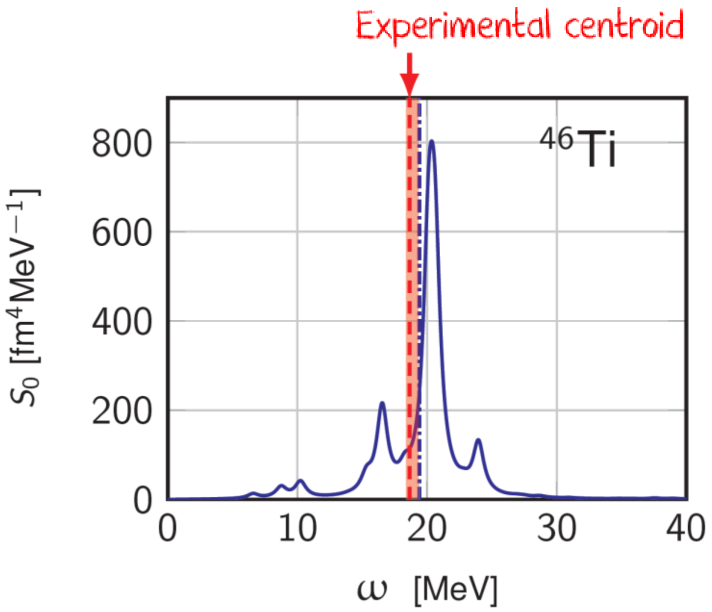
- Realistic PGCM in the (r, β_2) plane

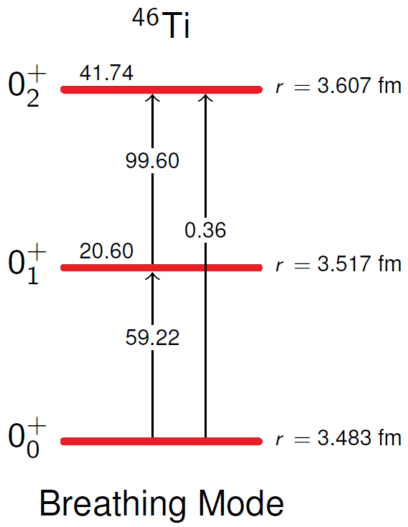
Realistic calculations



- Realistic PGCM in the (r, β_2) plane
- Good agreement with experiment

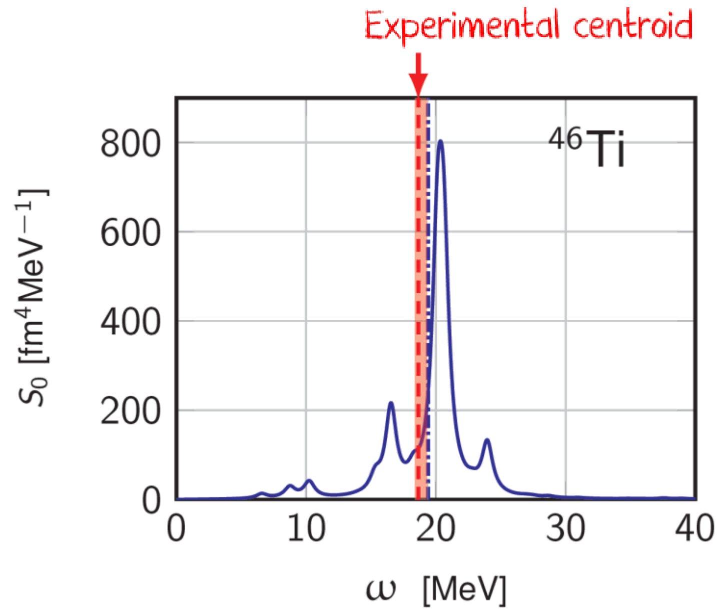
Realistic calculations

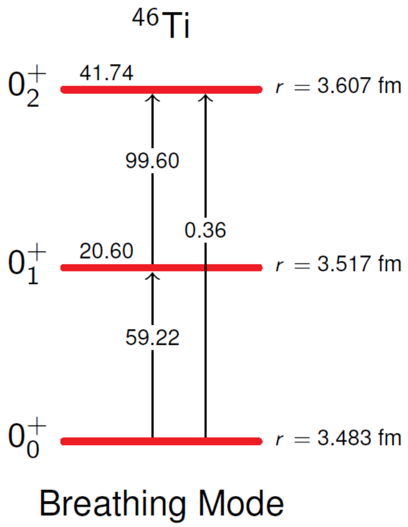




- Realistic PGCM in the (r, β_2) plane
- Good agreement with experiment
- Multi-phonon states observed

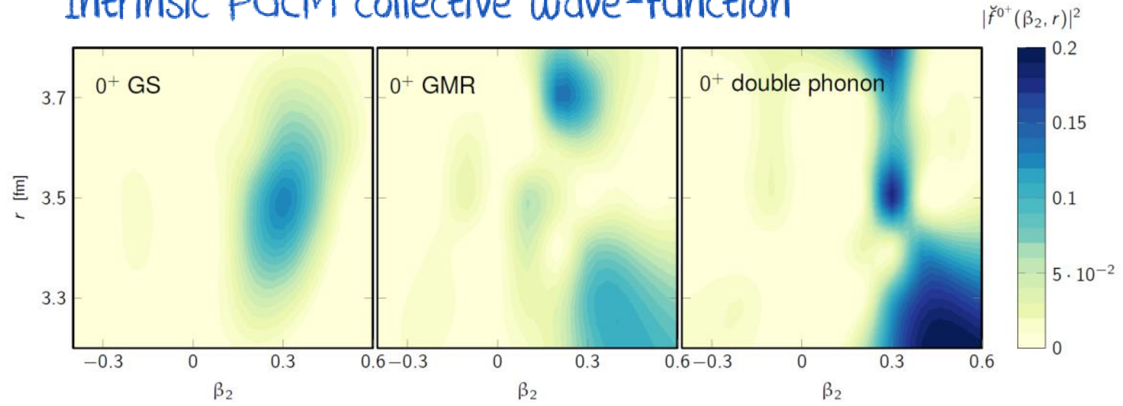
Realistic calculations



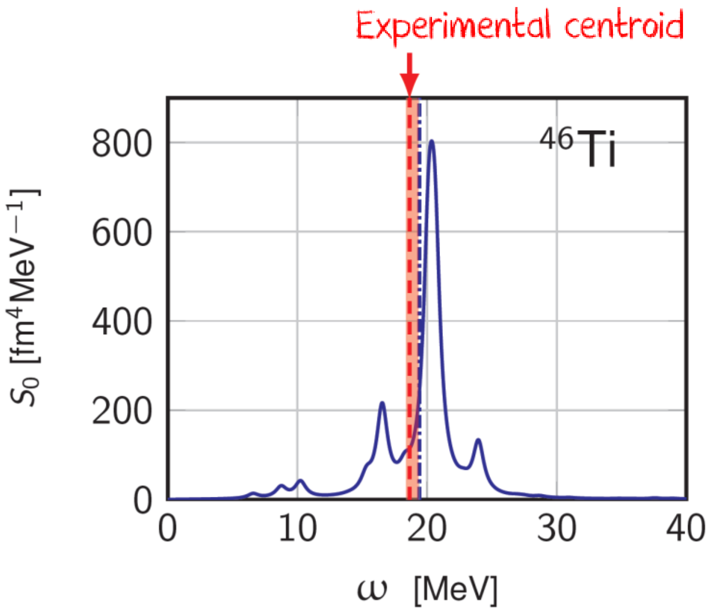


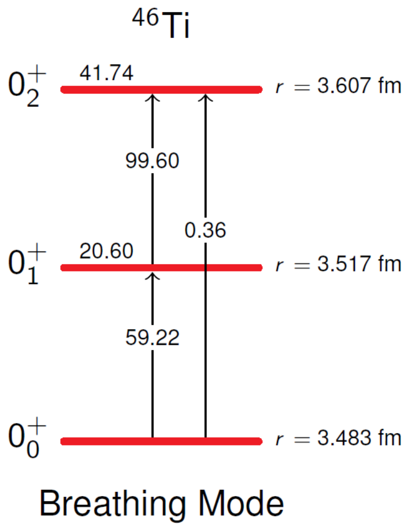
- Realistic PGCM in the (r, β_2) plane
- Good agreement with experiment
- Multi-phonon states observed

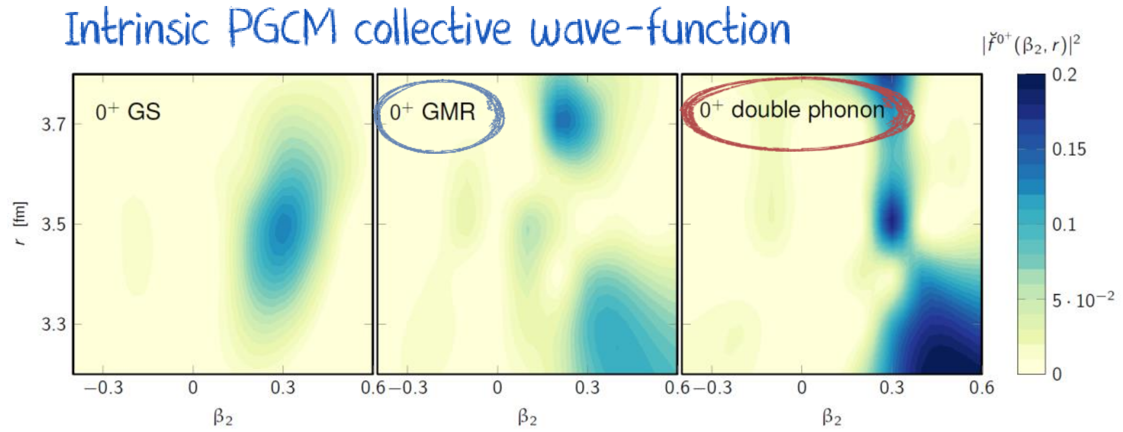
Intrinsic PGCM collective wave-function



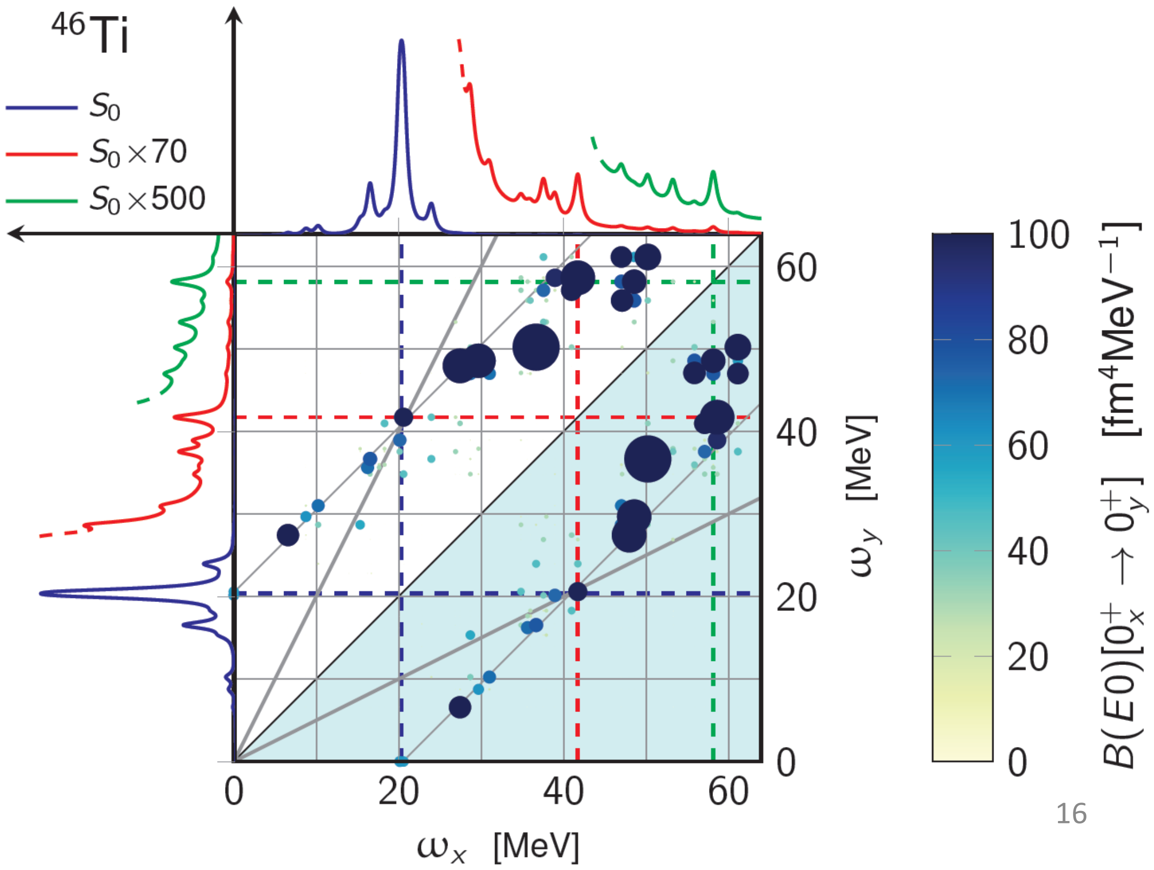
Realistic calculations





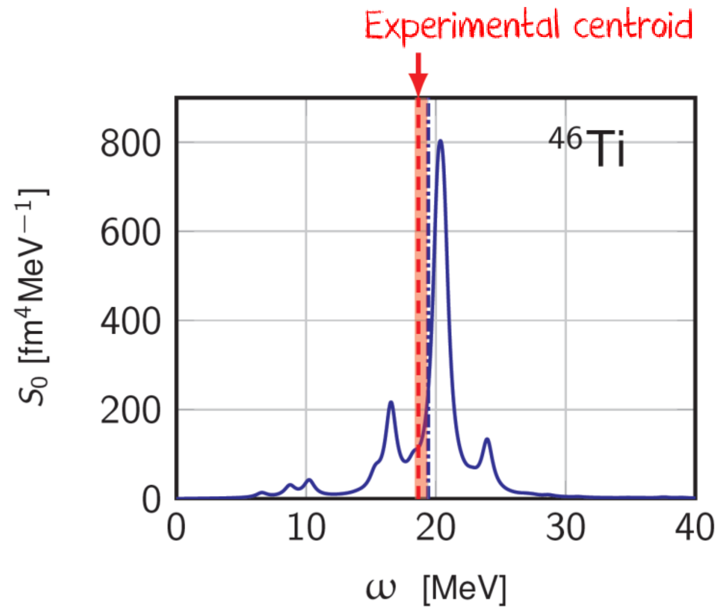


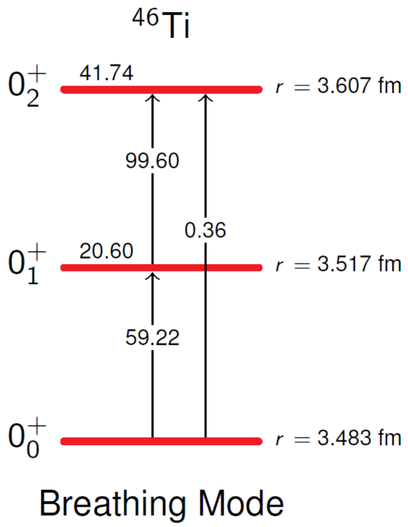
- Realistic PGCM in the (r, β_2) plane
- Good agreement with experiment
- Multi-phonon states observed

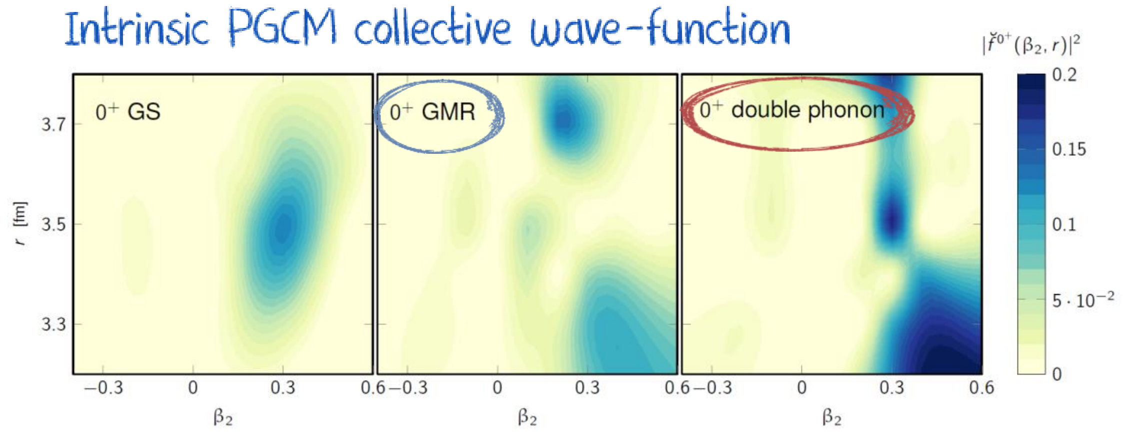


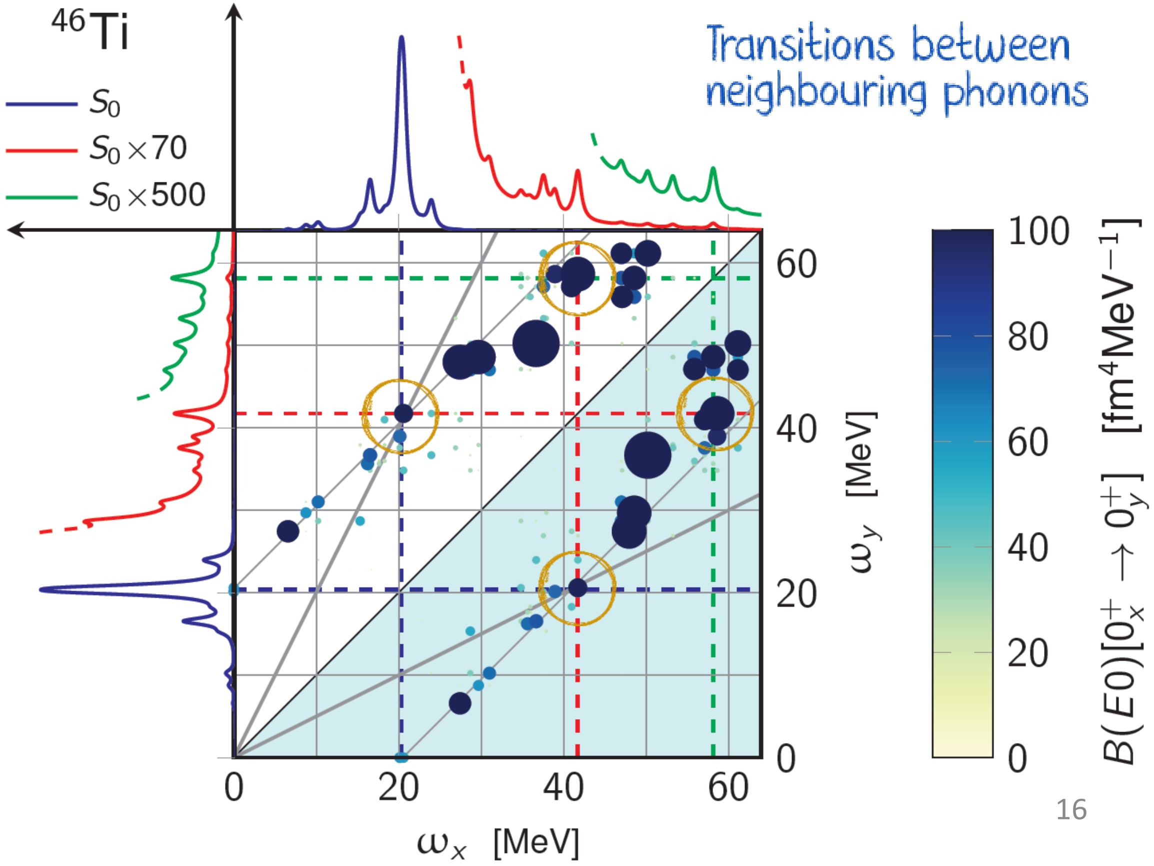
Realistic calculations

- Realistic PGCM in the (r, β_2) plane
- Good agreement with experiment
- Multi-phonon states observed



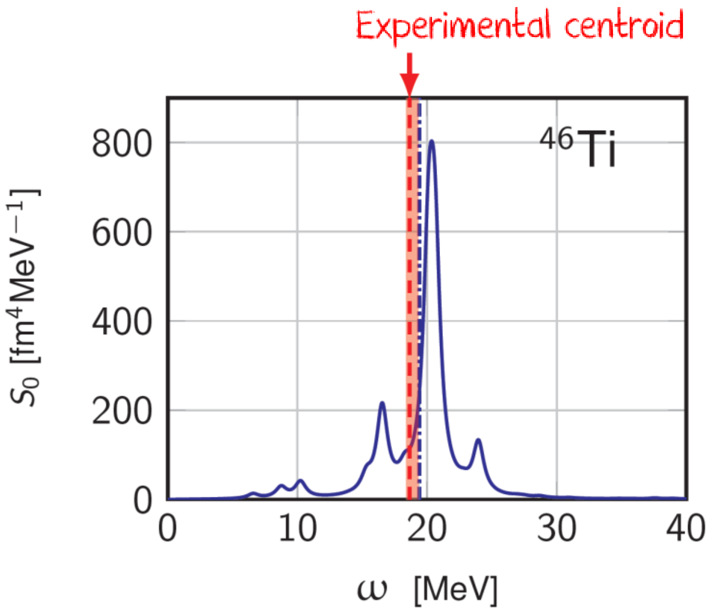


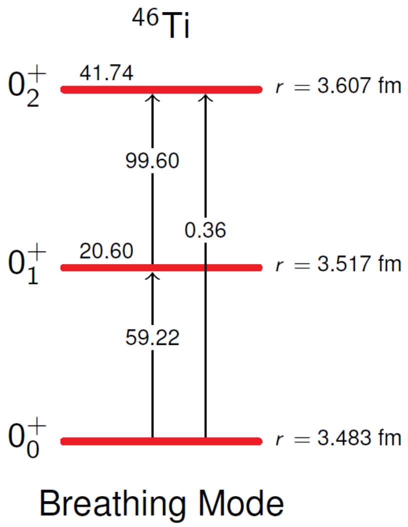


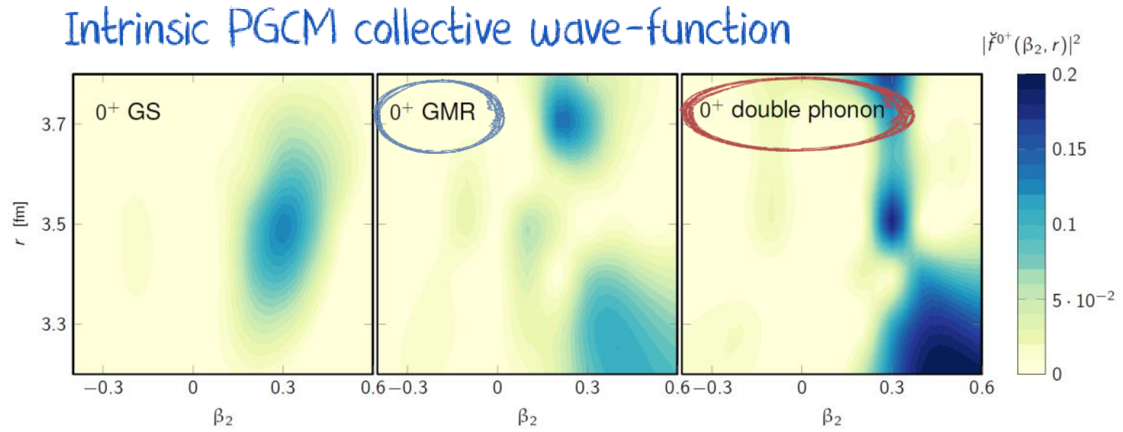


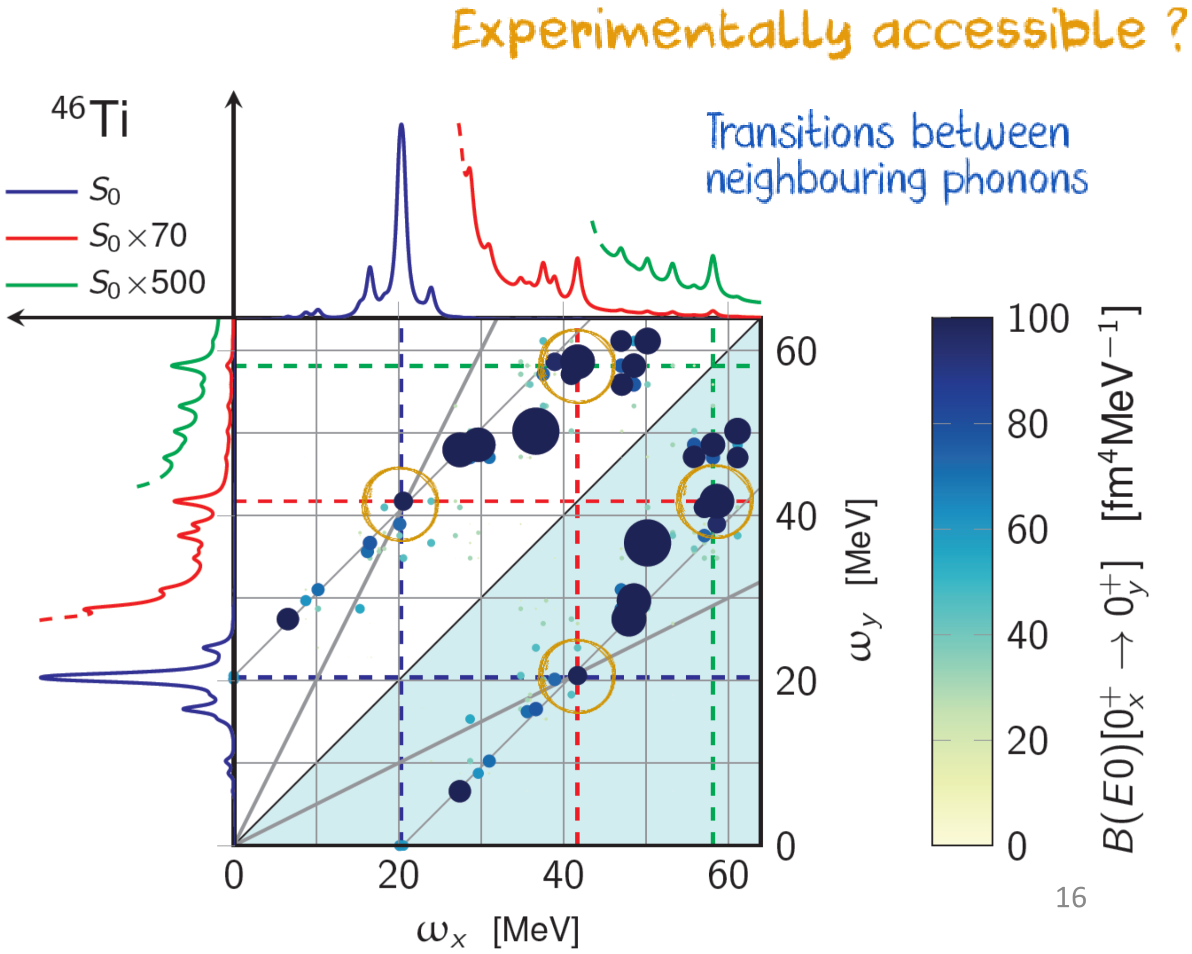
Realistic calculations

- Realistic PGCM in the (r, β_2) plane
- Good agreement with experiment
- Multi-phonon states observed









Outline

- Introduction
- Formalism
- Results
- Conclusions

Conclusions and Perspectives

Conclusions and Perspectives

- PGCM is a valuable and reliable tool for *ab-initio* spectroscopy

Conclusions and Perspectives

PGCM is a valuable and reliable tool for *ab-initio* spectroscopy

Different levels of symmetry breaking and restoration can reveal new physical and/or theoretical insights

Conclusions and Perspectives

- PGCM is a valuable and reliable tool for *ab-initio* spectroscopy

- Different levels of symmetry breaking and restoration can reveal new physical and/or theoretical insights

- Access to observables and phenomena scarcely investigated previously in *ab-initio*

Conclusions and Perspectives

- PGCM is a valuable and reliable tool for *ab-initio* spectroscopy

- Different levels of symmetry breaking and restoration can reveal new physical and/or theoretical insights

- Access to observables and phenomena scarcely investigated previously in *ab-initio*

What's next ?

Conclusions and Perspectives

PGCM is a valuable and reliable tool for *ab-initio* spectroscopy

Different levels of symmetry breaking and restoration can reveal new physical and/or theoretical insights

Access to observables and phenomena scarcely investigated previously in *ab-initio*

What's next ?

Many upgrade concerning PGCM

- Explore further generator coordinates
- Deeper convergence sudy
- Uncertainty quantification
- Nuclear incompressibility

Conclusions and Perspectives

PGCM is a valuable and reliable tool for *ab-initio* spectroscopy

Different levels of symmetry breaking and restoration can reveal new physical and/or theoretical insights

Access to observables and phenomena scarcely investigated previously in *ab-initio*

What's next ?

Many upgrade concerning PGCM

- Explore further generator coordinates
- Deeper convergence sudy
- Uncertainty quantification
- Nuclear incompressibility

Eigenvector Continuation

Conclusions and Perspectives

PGCM is a valuable and reliable tool for *ab-initio* spectroscopy

Different levels of symmetry breaking and restoration can reveal new physical and/or theoretical insights

Access to observables and phenomena scarcely investigated previously in *ab-initio*

What's next ?

Many upgrade concerning PGCM

- Explore further generator coordinates
- Deeper convergence sudy
- Uncertainty quantification
- Nuclear incompressibility

Eigenvector Continuation

Develop full symmetry-conserving QRPA

[Federschmidt and Ring, NucPhysA, 1985]

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

INFN

Gianluca Colò
Danilo Gambacurta

Technische Universität Darmstadt

Alexander Tichai

KU Leuven

Pepijn Demol