Nuclear Physics Mid Term Plan in Italy

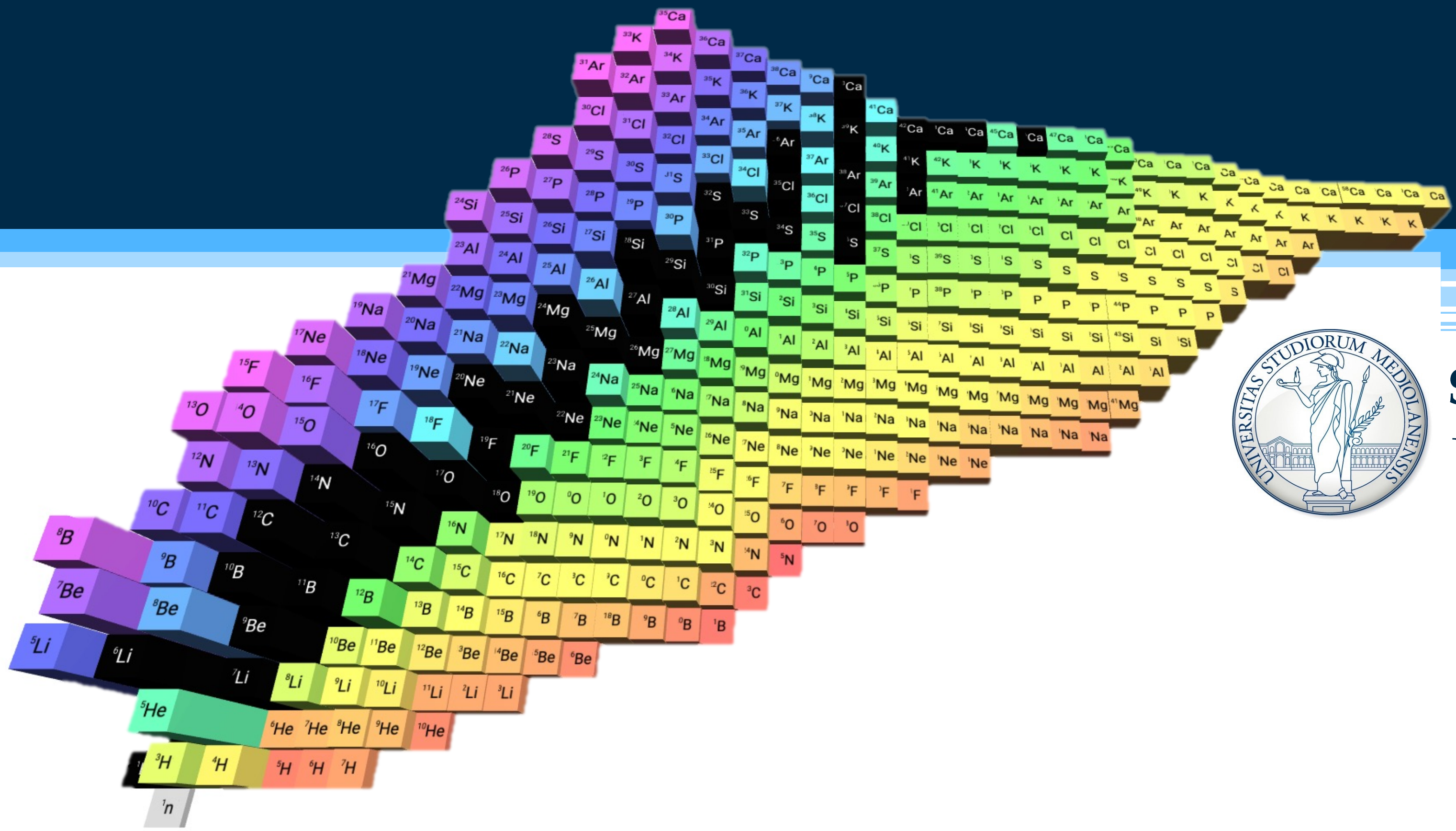
LNL – Session

Legnaro, April 11th-12th 2022

Nuclear Physics Mid Term Plan in Italy

1951 2021 infn

Light to medium-mass exotic nuclei



Simone Bottoni

Università degli Studi di Milano and INFN

INFN Istituto Nazionale di Fisica Nucleare

The working group and contributions

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IJC Lab, Orsay, France

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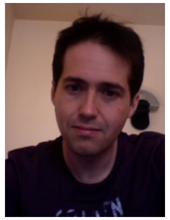

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Bogdan **Fornal**
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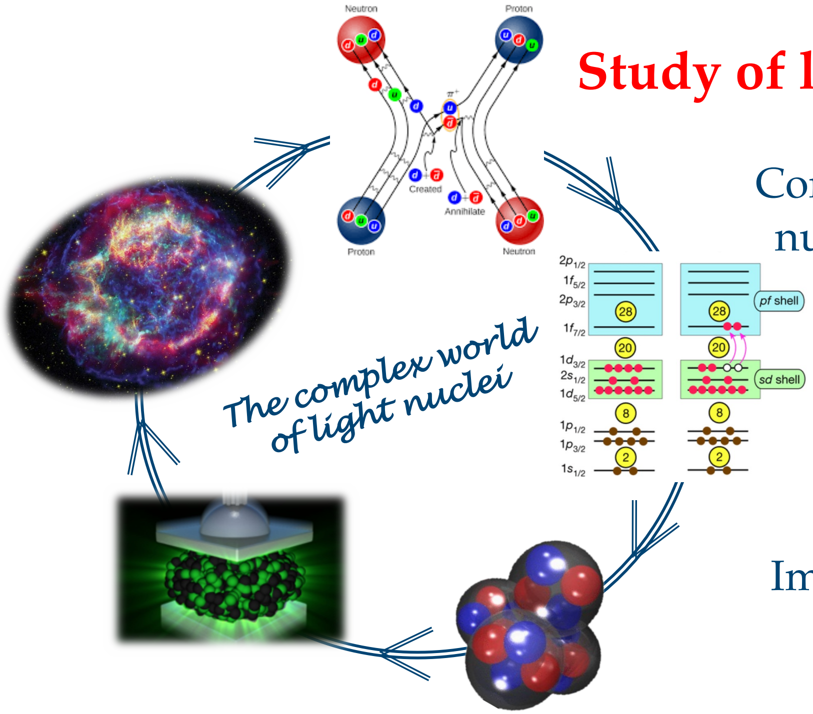


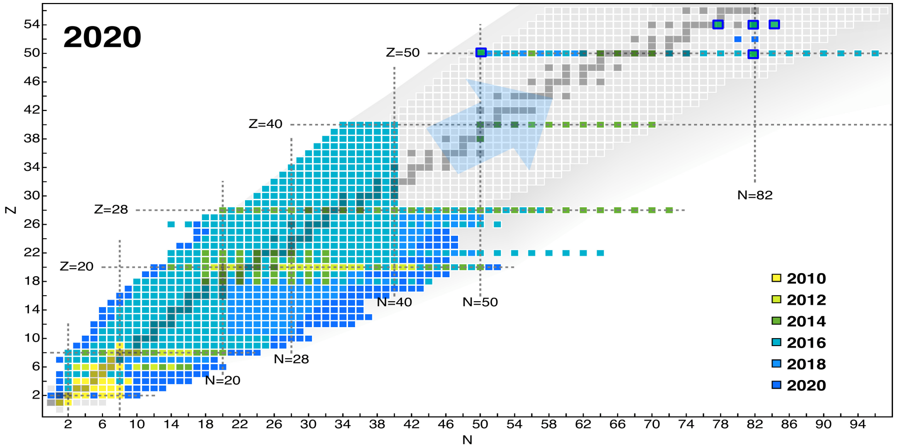
Study of light and medium mass nuclei

Comprehensive understanding of nuclear structure and dynamics from first principles

Nature of the nuclear forces and nuclear interactions

Implications for stellar nucleosynthesis

H. Hergert, Frontiers in Phys. **8**, 379 (2020)



A Guided Tour of *ab initio* nuclear Many-Body Theory

Synergy between experiments and theory

Different nuclear models

with different predictive powers

Shell Model calculations

E. Caurier *et al*, Rev. Mod. Phys. **77**, 427 (2005)

Density functional theories

G. Colò, Adv. Phys.-X **5**, 1740061 (2020)

Ab initio methods

V. Somà, Frontiers in Phys. 8, 340 (2020)

Light and medium-mass nuclei: benchmark for heavier systems

Two pillars for *ab initio* nuclear theory

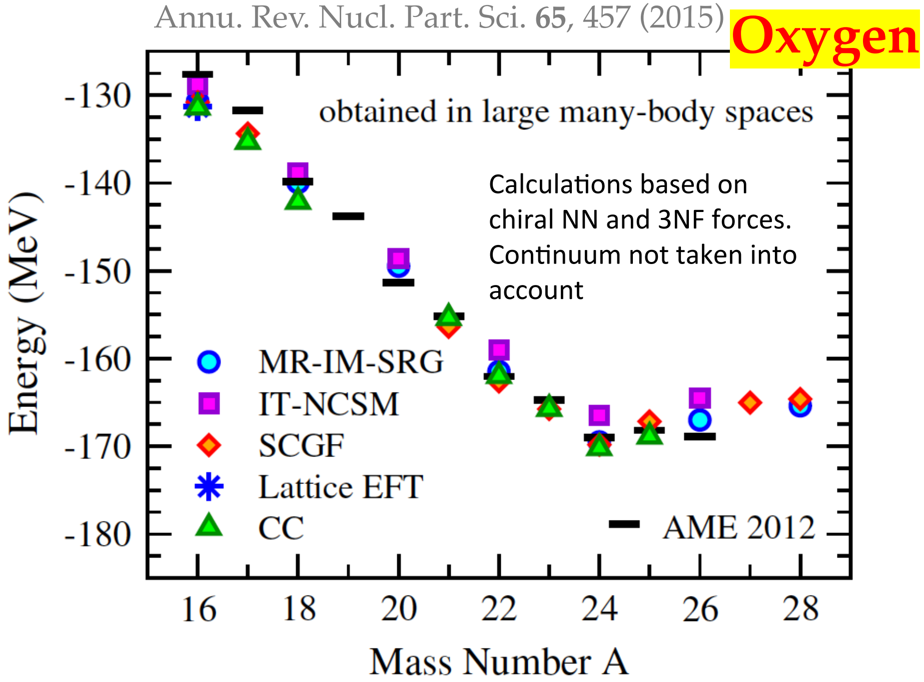
Learning Nuclar Forces from QCD

p, **n**, **π** are the dominant d.o.f. ➔ **chial EFT** forces

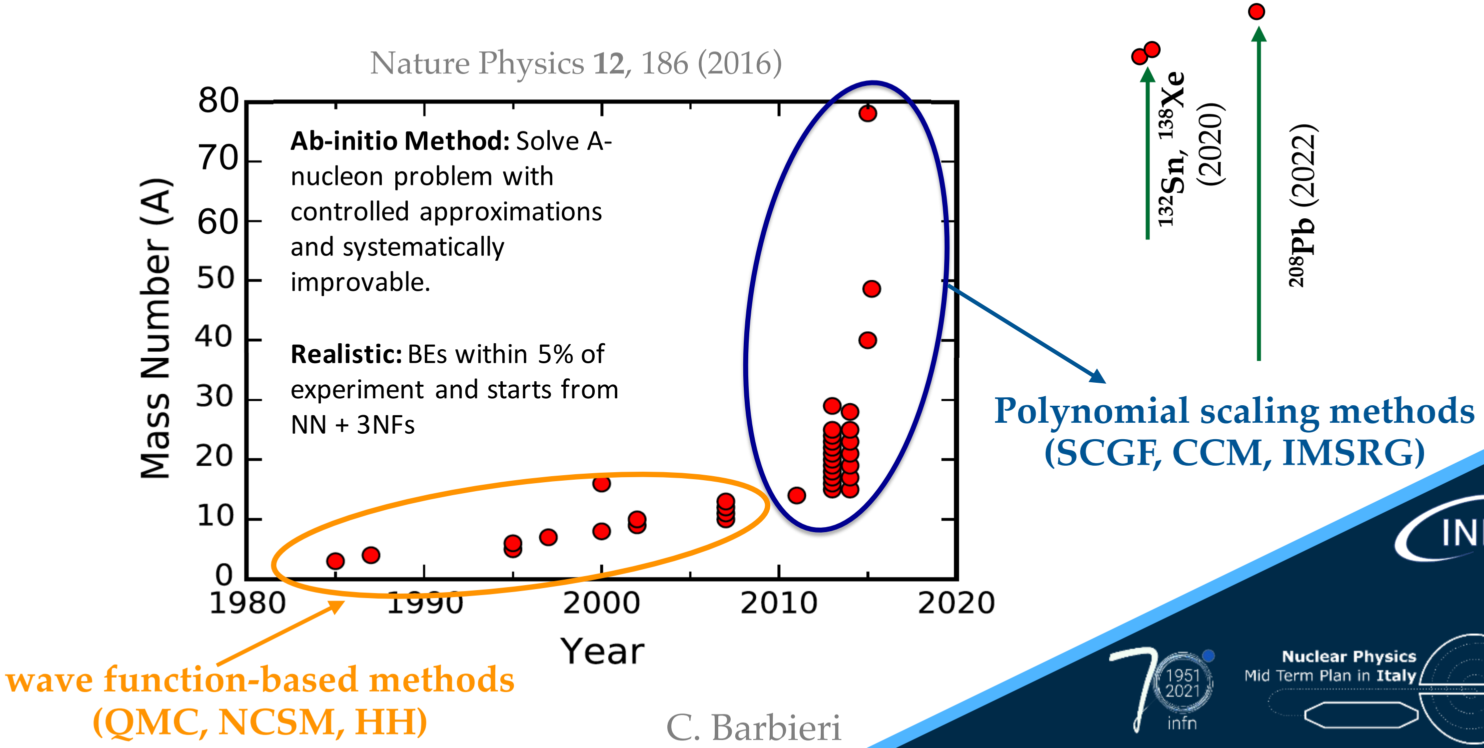
Predictive and learning nuclear properties

Solve the (hard) **few-** and **many-body problem**

Annu. Rev. Nucl. Part. Sci. **65**, 457 (2015)

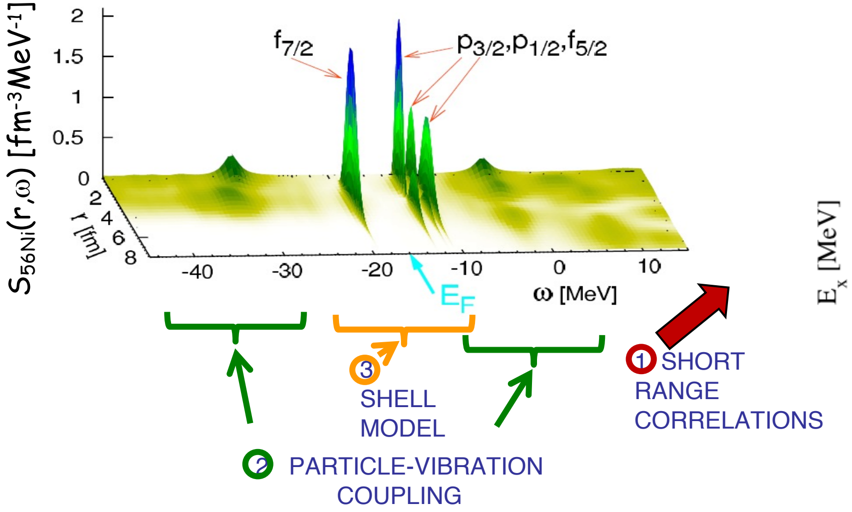


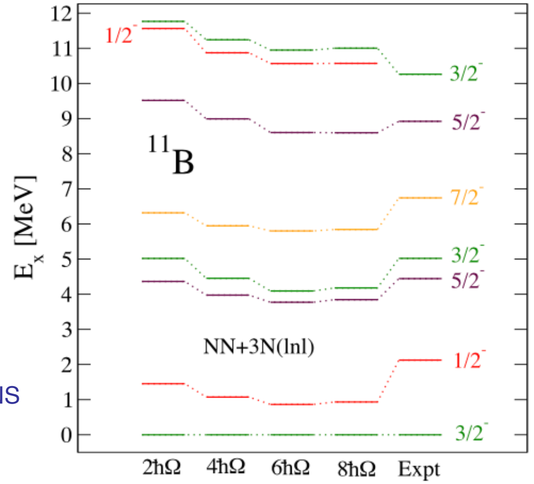
Nature Physics **12**, 186 (2016)



C. Barbieri

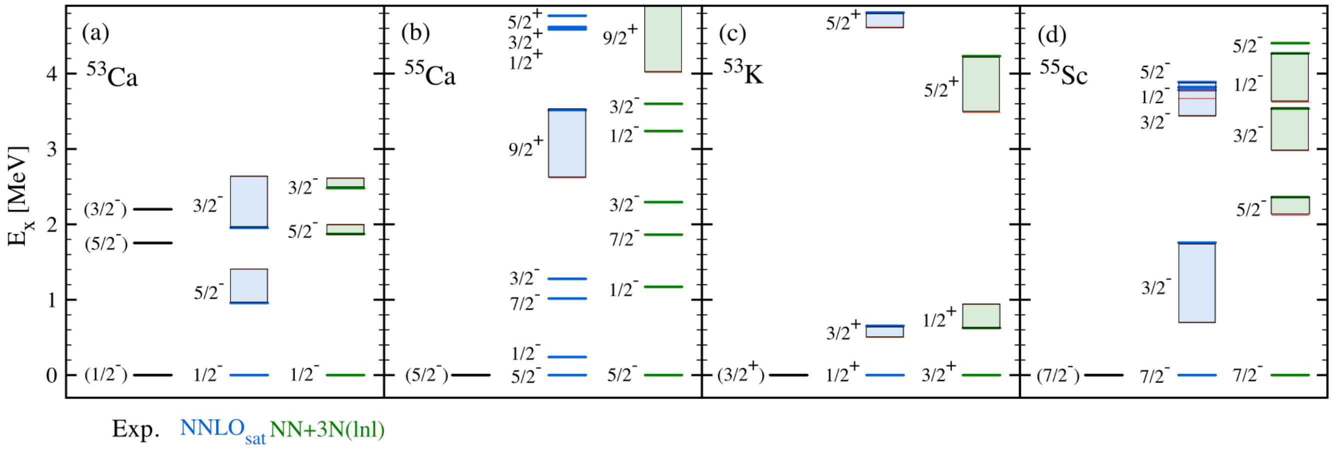
Nuclear spectroscopy





C. Barbieri, Phys. Rev. Lett. **103**, 202502 (2009)

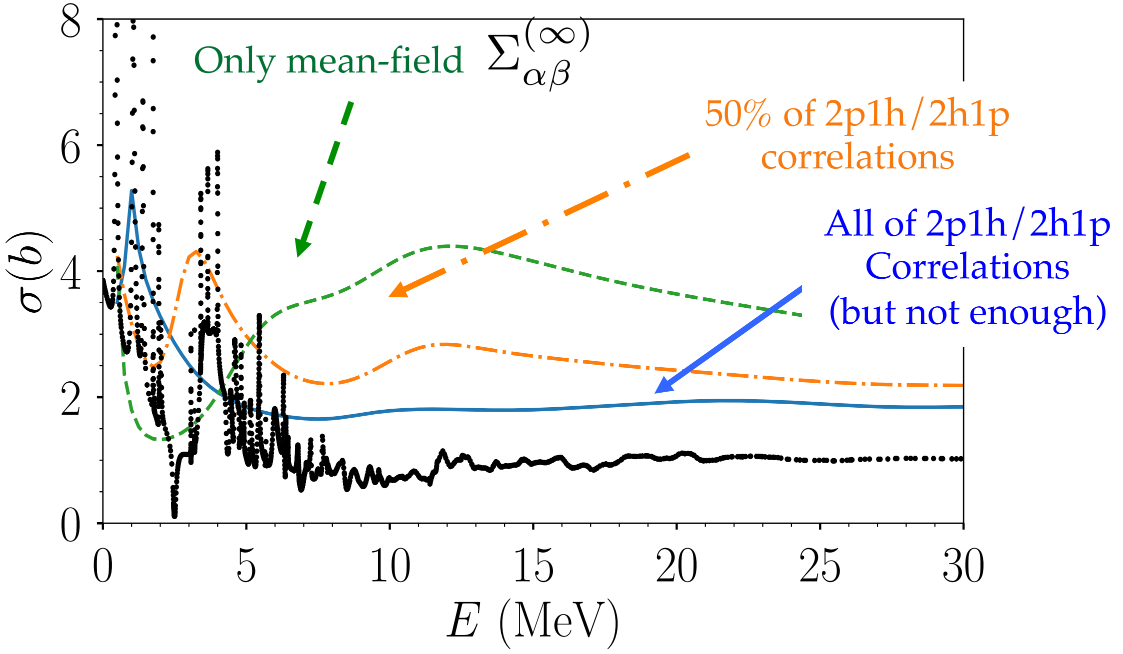
V. Somà *et al.*, Phys. Rev. C **101**, 014318 (2020)



Tight connection with LNL experimental programs

Microscopic optical potentials

n-^{16}O, total elastic cross section

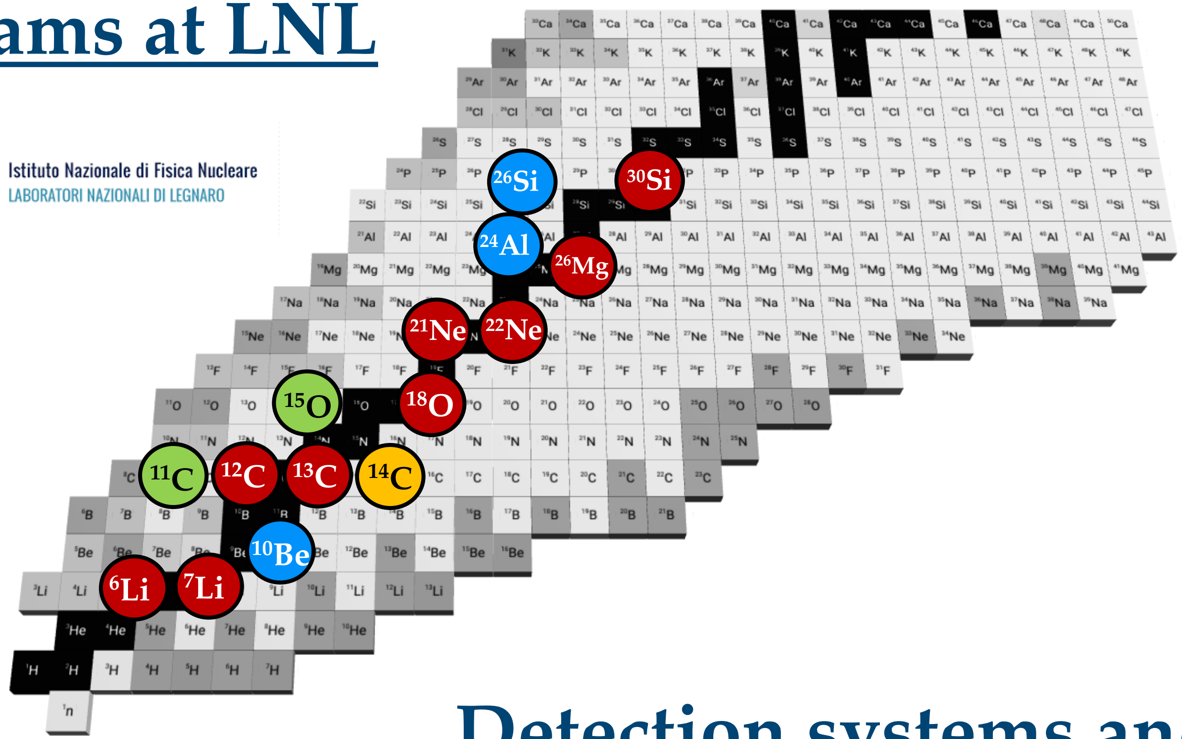


A. Idini, C. Barbieri, P. Navratil, Phys. Rev. Lett. **123**, 092501 (2019)

A great opportunity and a current challenge for low-energy nuclear physics!

Light beams at LNL

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI LEGNARO

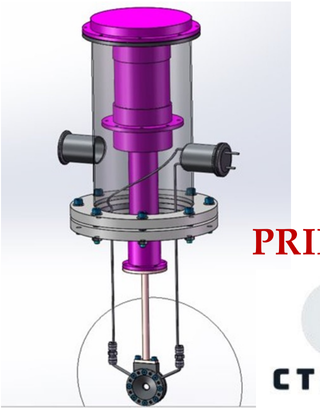


STABLE

EXOTIC

SPES (phase 2-3)

^{14}C

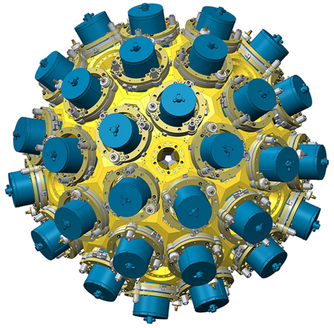


PRIN2017

CTADIR

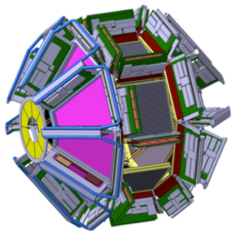
CRYOGENIC TARGET

Detection systems and targets

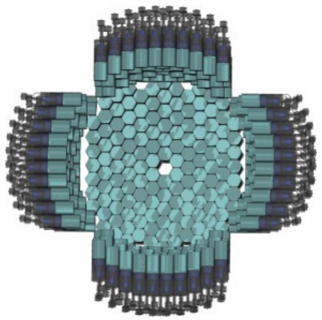


AGATA
γ rays

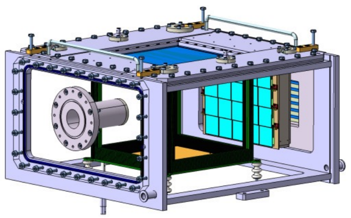
PRISMA
heavy ions



GRIT
charged particles

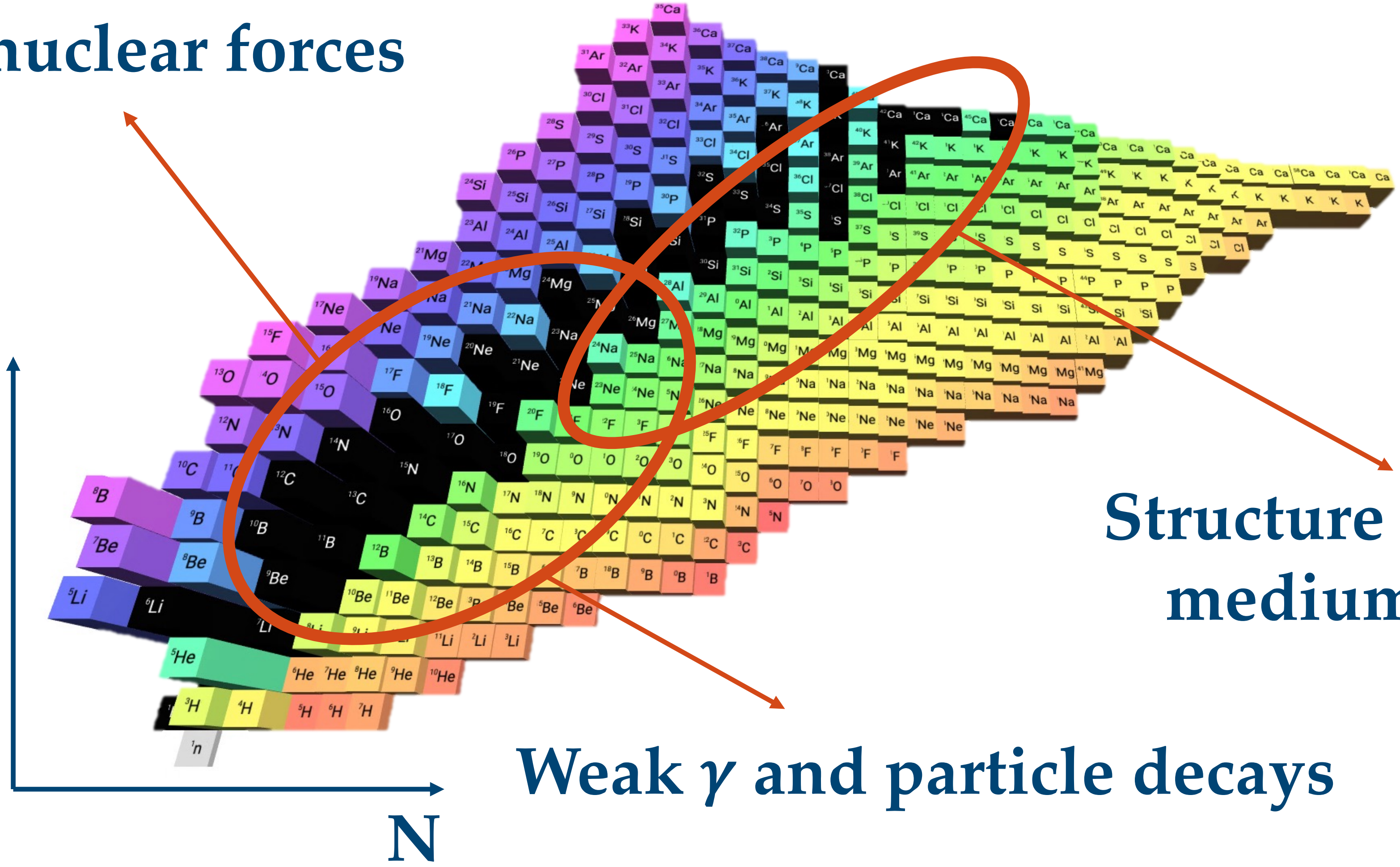


NEDA
neutrons



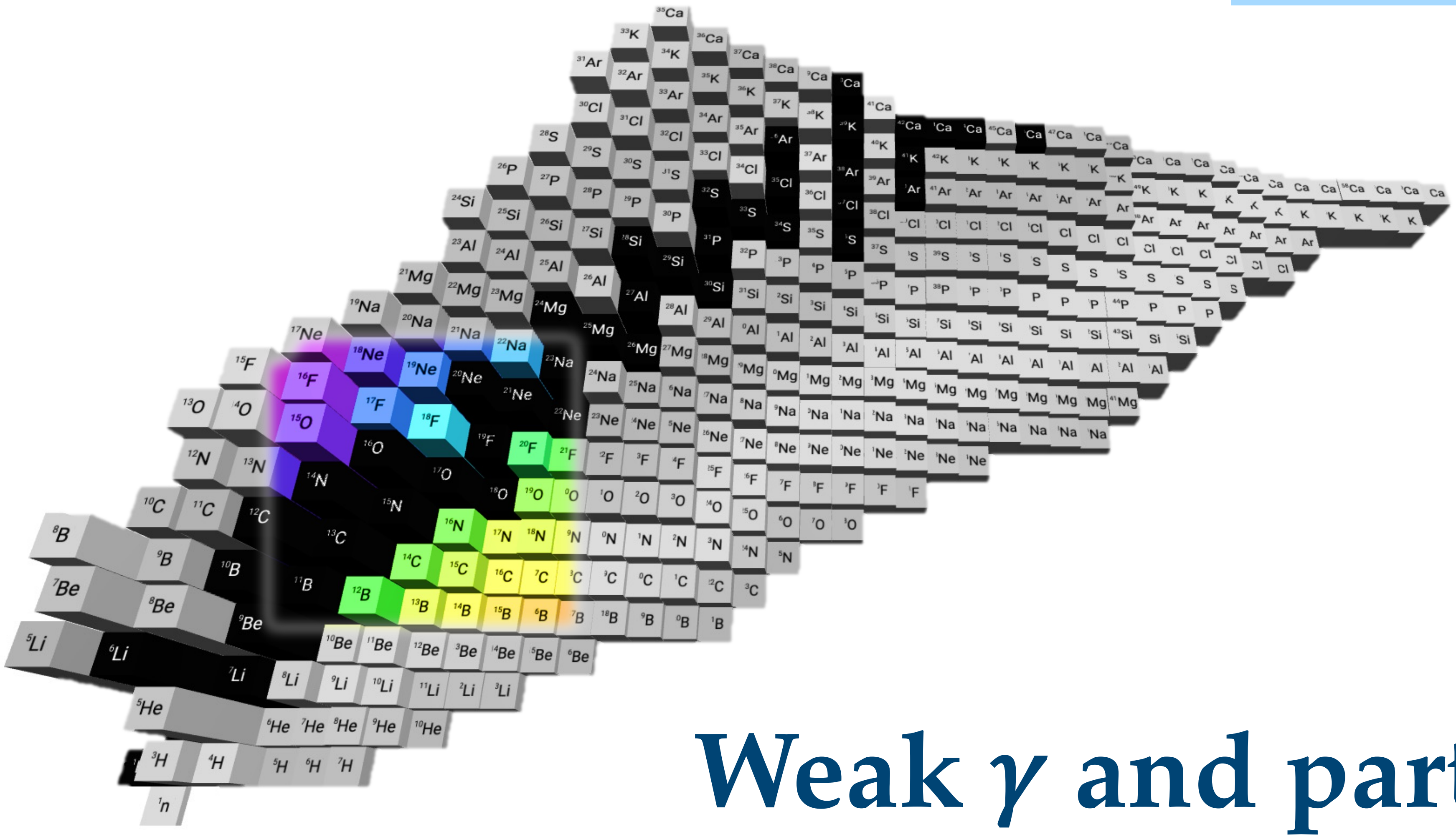
ACTIVE TARGETS

Nuclear correlations and nuclear forces

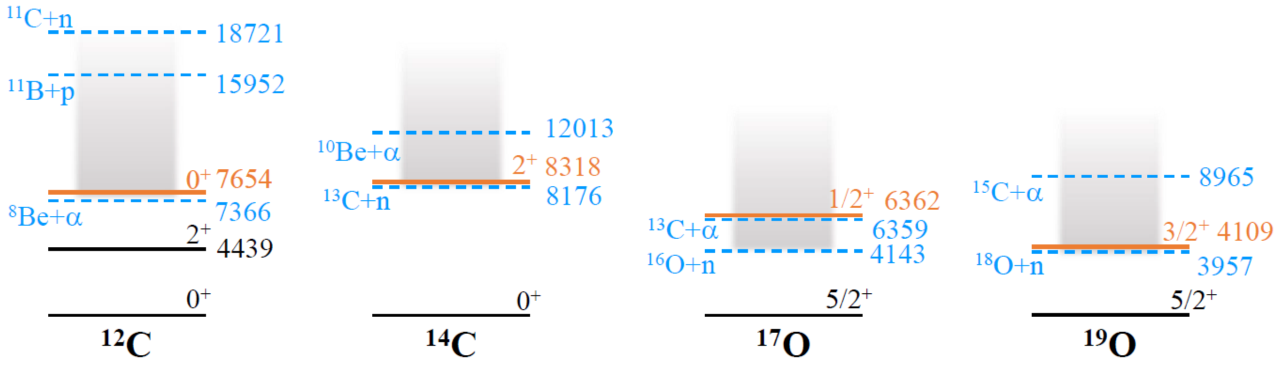


Structure of neutron-rich medium-mass nuclei

Weak γ and particle decays



Weak γ and particle decays



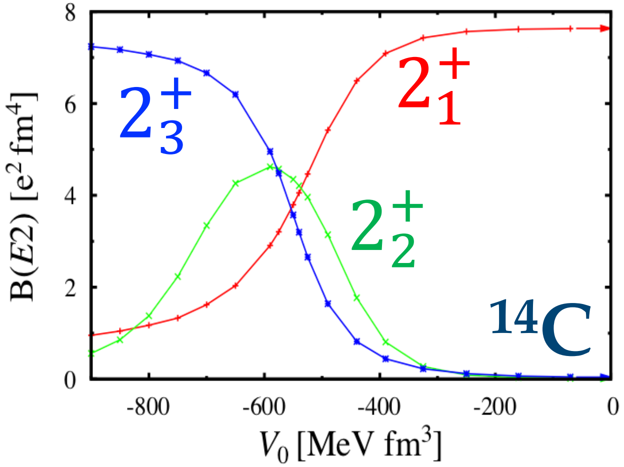
Onset of collectivization and clusterization

Strong impact in nuclear astrophysics

Limited information from γ spectroscopy:
very weak γ branchings < 10^{-3}

Shell Model Embedded in the Continuum (SMEC)

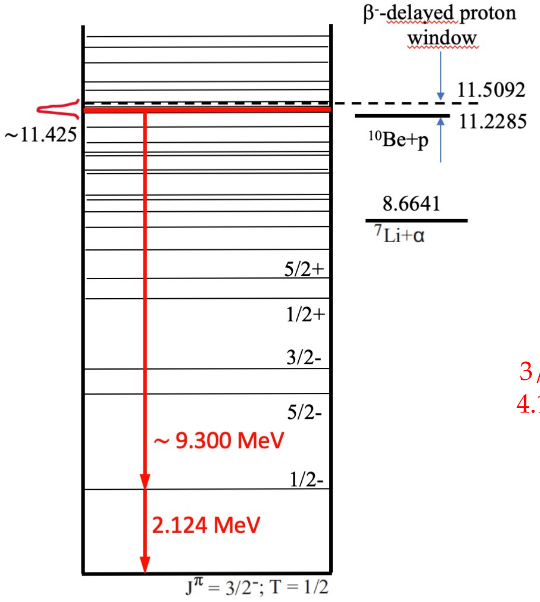
J. Okołowicz, M. Płoszajczak, W. Nazarewicz, Fortschr. Phys. 61, 66 (2013)



- **Open quantum systems**
- Prediction of narrow resonances
- Enhanced E/M transition probabilities
- Couplings with the continuum

Possible measurements

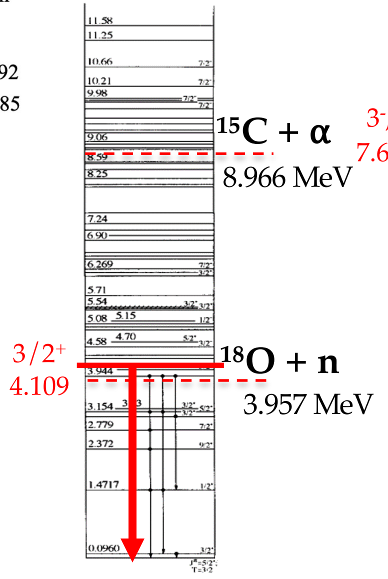
^{6}Li(^{6}Li,p)^{11}B



11B

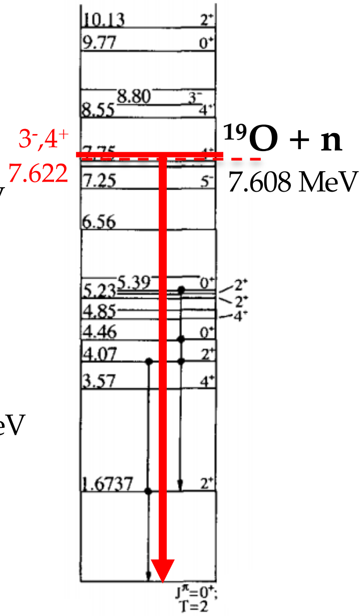
experiment with GALILEO (2021)
→ upper limit < 3 10^{-3}

^{13}C(^{7}Li,p)^{19}O



19O

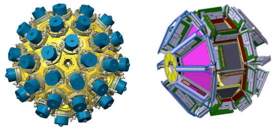
^{7}Li(^{14}C,p)^{20}O



20O

Fusion reactions with stable beams + ^{14}C

AGATA + TRACE/GRIT



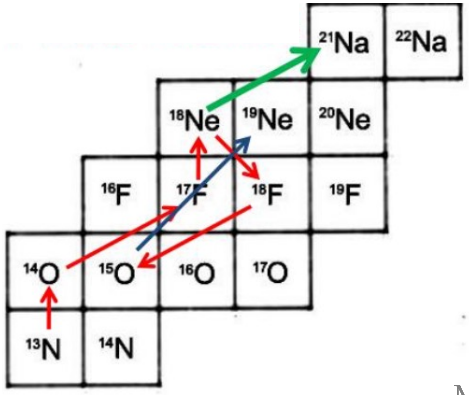
B. Fornal, S. Leoni

α-cluster structures relevant for nuclear astrophysics

Break -out from the CNO cycle

Nuclear states close to α-emission thresholds

weak decay branchings ~ 10^{-3}



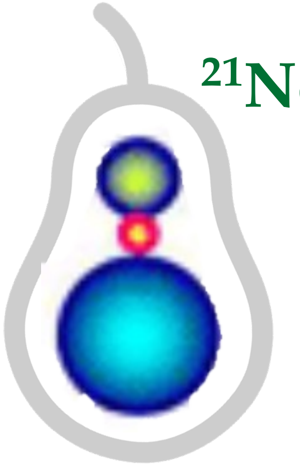
^{19}Ne Three states close to the alpha-decay threshold

M. Wiescher, *et al.*, Prog. in Part. & Nucl. Phys. **59**, 51 (2007)

^{15}O Tentative α structures

M. Wiescher, *et al.*, Annual Rev. Nucl. Part. Sci. **60**, 381 (2010)

Clusterization in medium-light nuclei



^{21}Ne

Molecular octupole deformations

Identification of octupole bands

weak and fast γ branchings < 10^{-3}

C. Wheldon, *et al.*, Eur. Phys. J. A **26**, 321 (2015)

Cluster shell model

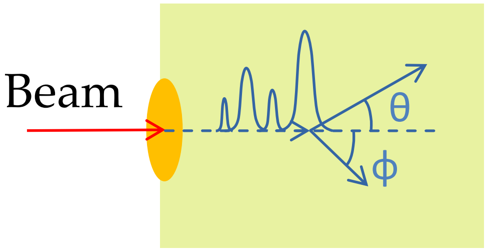
Octupole structure doesn't emerge easily from calculations

R. Bijker and F. Iachello, Nucl. Phys. A **1010**, 122193 (2021)

Possible measurements

Resonant scattering with EXOTIC and stable beams

Reaction kinematics event-by-event (TPC)



^{15}O(α,α′)

^{11}C(α,α′)

No angular uncertainty at 0°

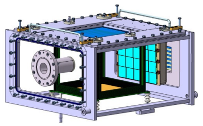
Solid ^{3}He and ^{4}He thin targets

Next developments: ^{20}Ne and ^{21}Ne

A. Fernández *et al.*, Materials and Design **186**, 108337 (2020).

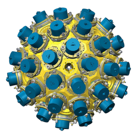
^{21}Ne inelastic scattering

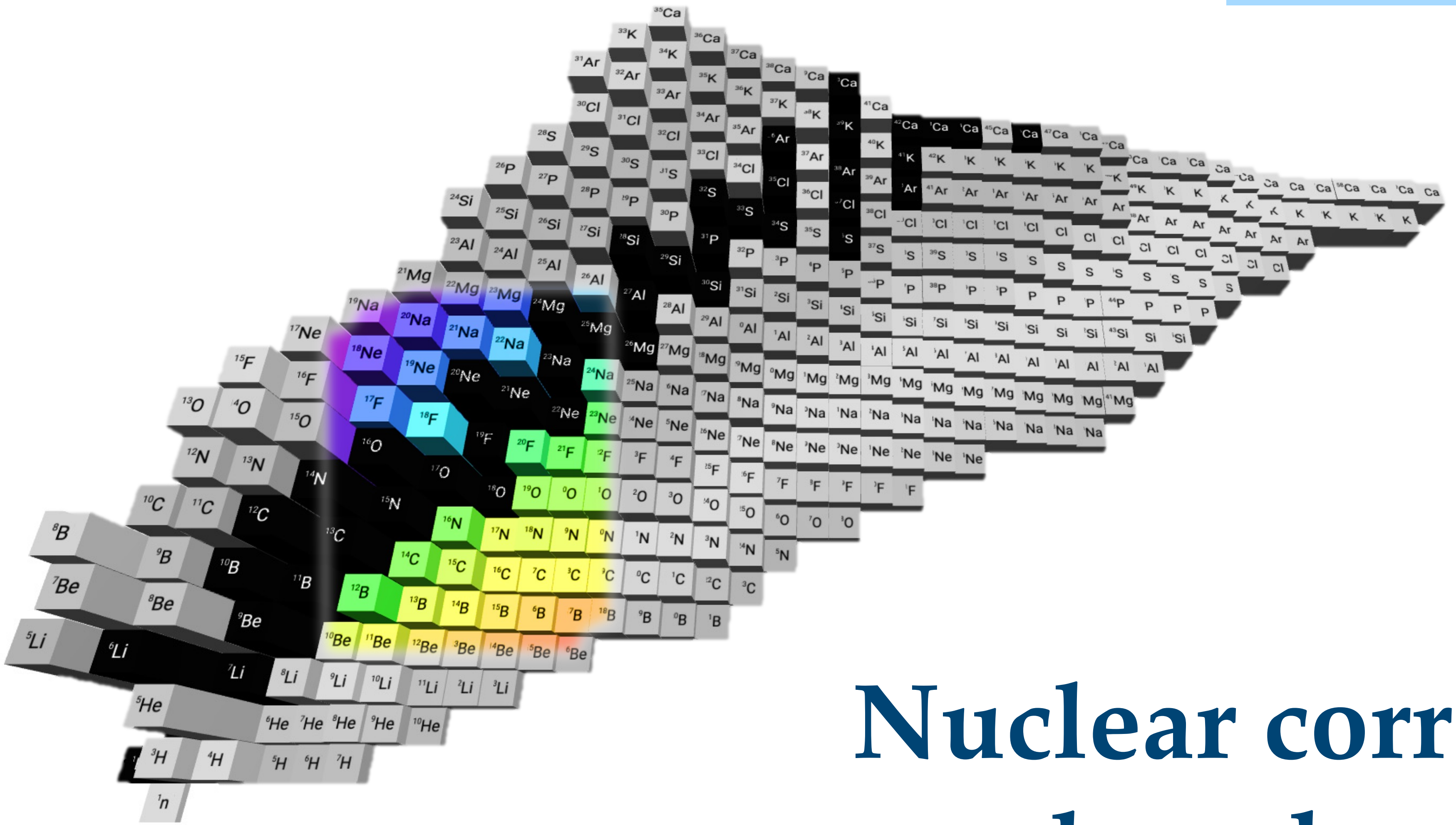
ACTIVE TARGET



C. Wheldon

AGATA



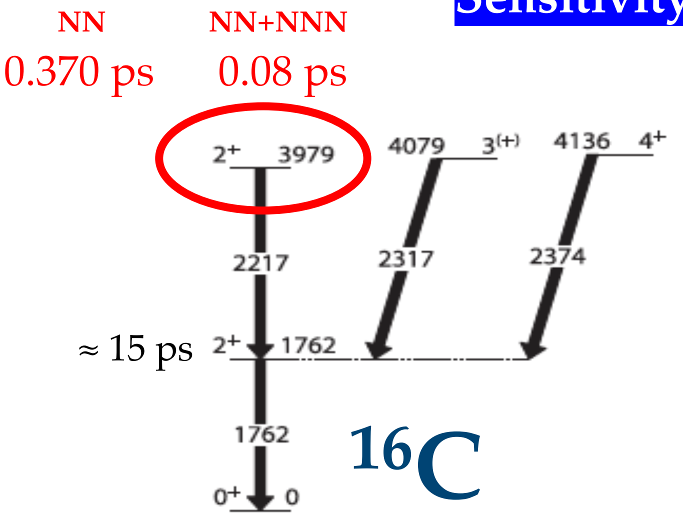


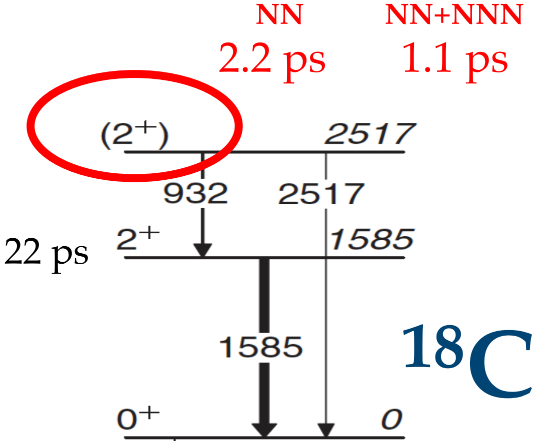
Nuclear correlations and nuclear forces

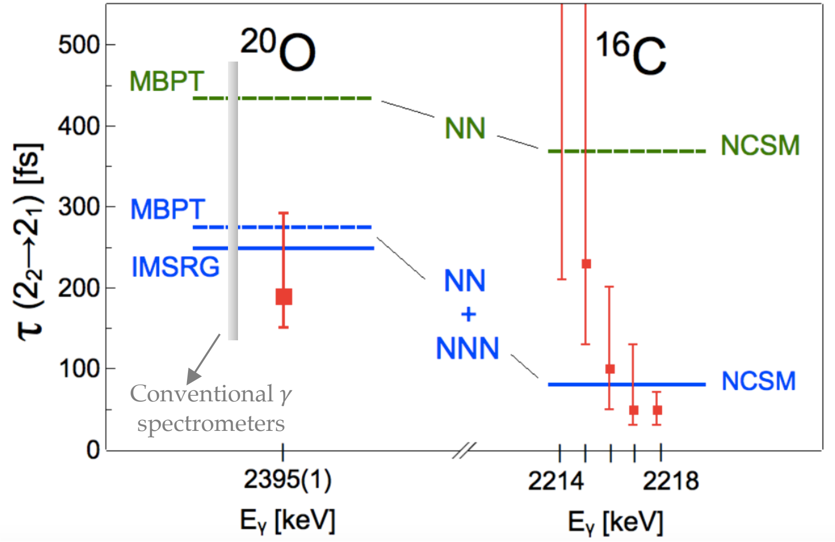
ab initio No-Core-Shell-Model Calculations

C. Forssen et al., J. Phys. G: Nucl. Part. Phys. 40, 055105 (2013).

Sensitivity to 3-body forces







AGATA+VAMOS deep-inelastic experiment

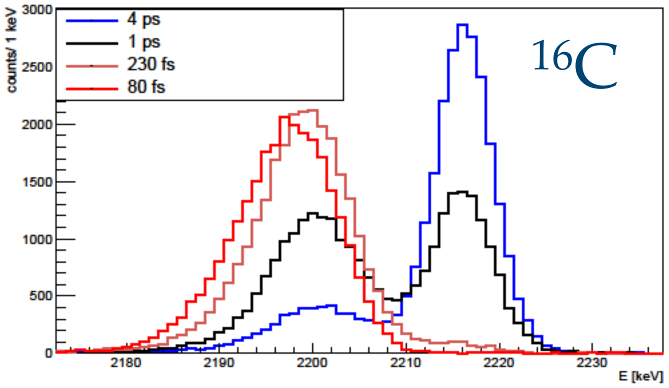
M. Ciemała , S. Ziliani, F.C.L. Crespi, S. Leoni, B. Fornal, A. Maj, *et al.*, Phys. Rev. C **101**, 021303(R) (2020)

development of lifetime measurement techniques for deep-inelastic reactions

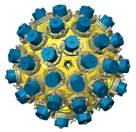
Possible measurements

Deep-inelastic reactions with ^{18}O

- ^{198}Pt thick target and degrader
- AGATA to achieve enough sensitivity
- Advantages from PRISMA upgrade

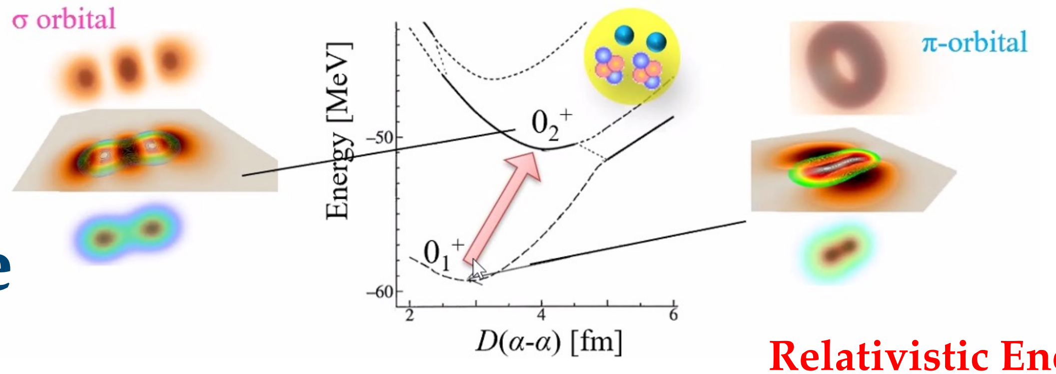


AGATA + PRISMA



B. Fornal, S. Leoni

^{10}Be



Molecular bonding

Relativistic Energy Density Functional theory

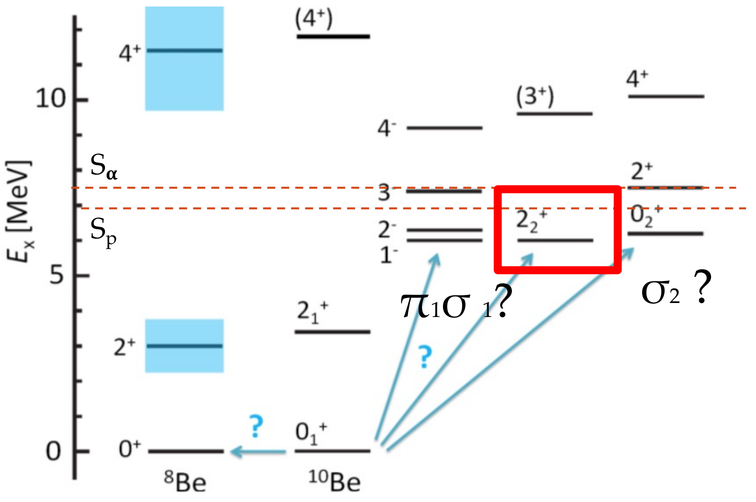
J. -P. Ebran, E. Khan et al., Phys. Rev. C **90**, 054329 (2014)

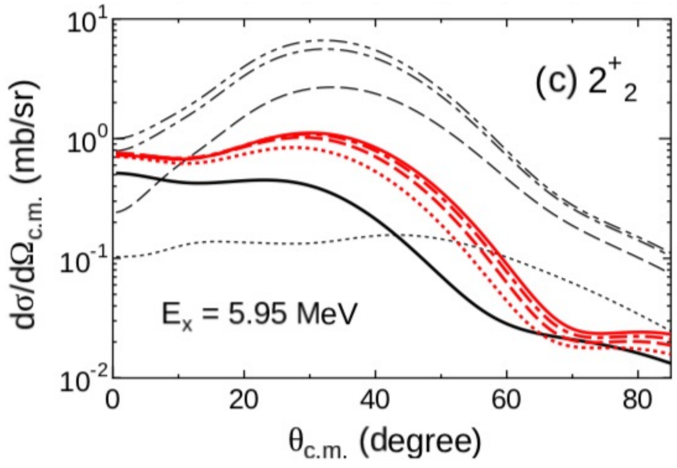
Sensitivity to inelastic cross sections

- Transition strength from π- to σ-type molecular states
- Di-neutron configuration

2 alphas +2n $(\pi_{3/2})^2$

2 alphas + 2n$(\pi_{1/2})$ $(\pi_{3/2})$





Furumoto et al, PRC104 (2021).

Possible measurements

Inelastic excitation of ^{10}Be SPES beam

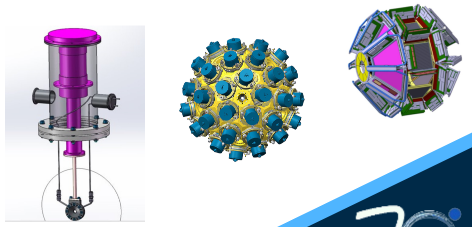
- ^{10}Be(α,α′) or ^{10}Be(d,d′)
  probing molecular states
  γ detection needed

- ^{10}Be(p,p′)
  probing di-neutron correlations
  γ detection needed

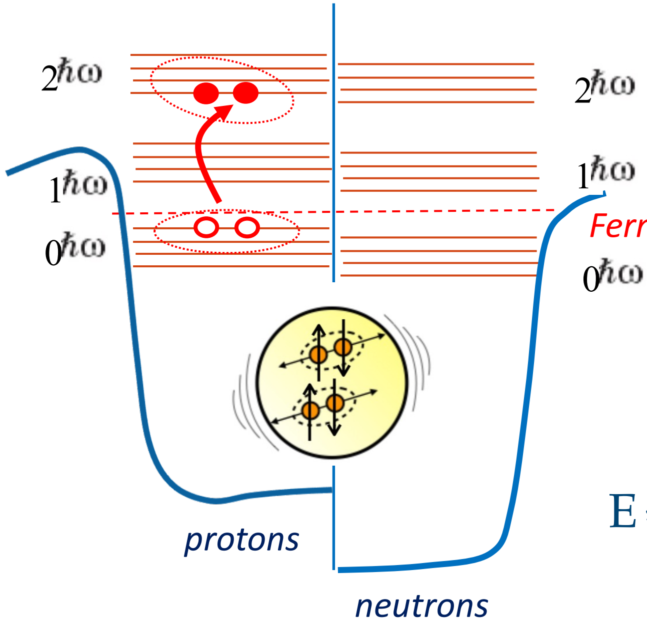
Same technique with ^{14}C

AGATA + GRIT

CRYOGENIC TARGET



M. Assié



Superconductive phase

Collective mode 0^+
coherent superposition of 2p-2h

Predicted Energy
$E \approx 10\text{-}20$ MeV / Width: $\Gamma = 1\text{-}2$ MeV
in heavy systems

R. Broglia, Phys. Lett. B. 69(1977) 129
M.W. Herzog Phys. Rev. C 31, (1985) 259.

M. Assié et al Eur. PJA 55 (2019) 245

nn GPV not observed in heavy nuclei with (p,t) reactions
continuum effect (low l state dominant with low centrifugal barrier): too wide to be observed

Possible signature of nn GPV identified in light C isotopes

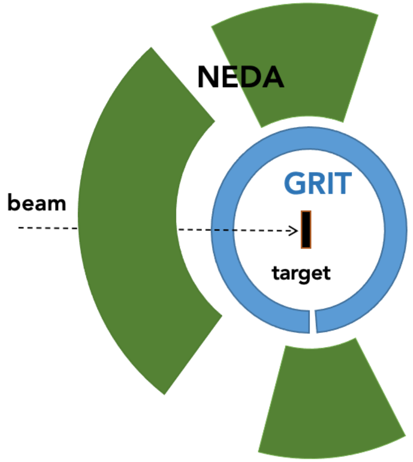
F. Capuzzello et al., Nat. Commun. 6, 6743 (2015)

Possible measurements

(^{3}He,n) reactions with stable C beams + ^{14}C

Two-proton Giant Pairing vibration

- Narrower due to the Coulomb Barrier
- L=0 angular distribution from scattered n
- Trigger on the 2p decay



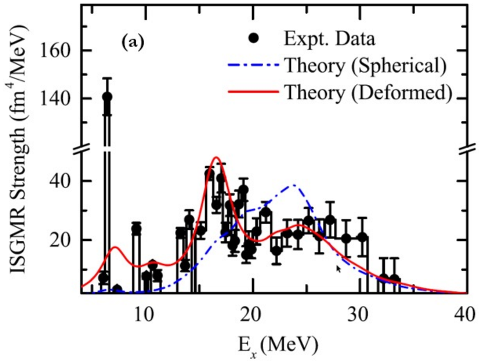
NEDA + GRIT

CRYOGENIC TARGET

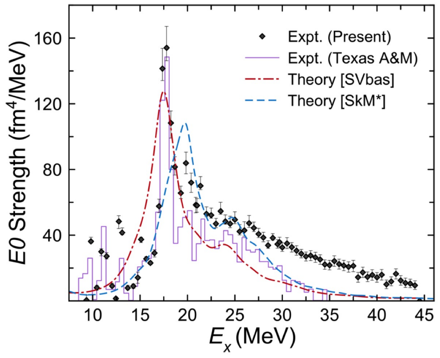
M. Assié

Giant monopole resonances in light deformed nuclei

^{24}Mg



^{28}Si



Y.K. Gupta *et al.*, Phys. Lett. B **748**, 343 (2015)   T. Peach *et al.*, Phys. Rev. C **93** 064325 (2016)

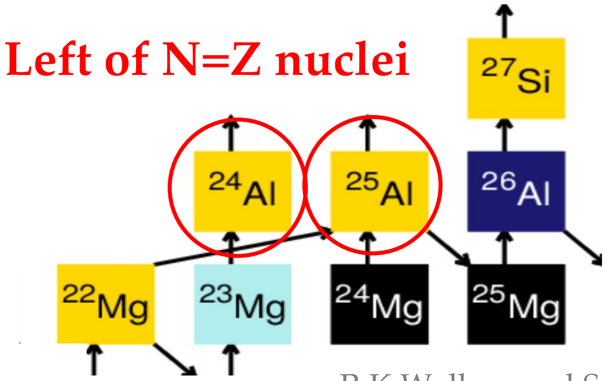
Nuclear incompressibility

Energy Density Functional theory

U. Garg and G. Colò, Prog. Part. Nucl. Phys. 101 (2018)

- Effects of deformations
- Fragmentation of ISGMR
- K=0 couplings with L=2

Left of N=Z nuclei



Astrophysical interest

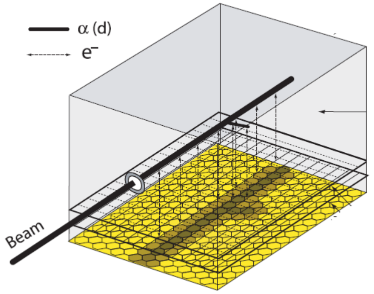
Path of the rp-process

- Resonant excited states
- Impact on capture rates

R.K.Wallace and S.E.Woosley, Astr. J. **45**, 389 (1981)

Possible measurements

Elastic and inelastic scattering in inverse kinematics with SPES

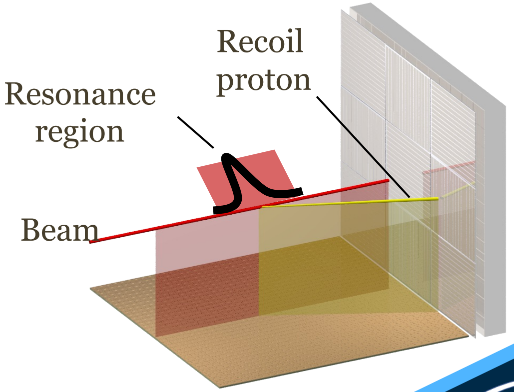


^{26}Si(α,α′)

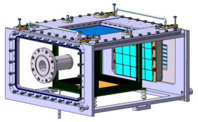
- Inelastic scattering
- Low momentum transfer

^{24,25}Al(p,p′)

- Resonant scattering
- Large CM angles

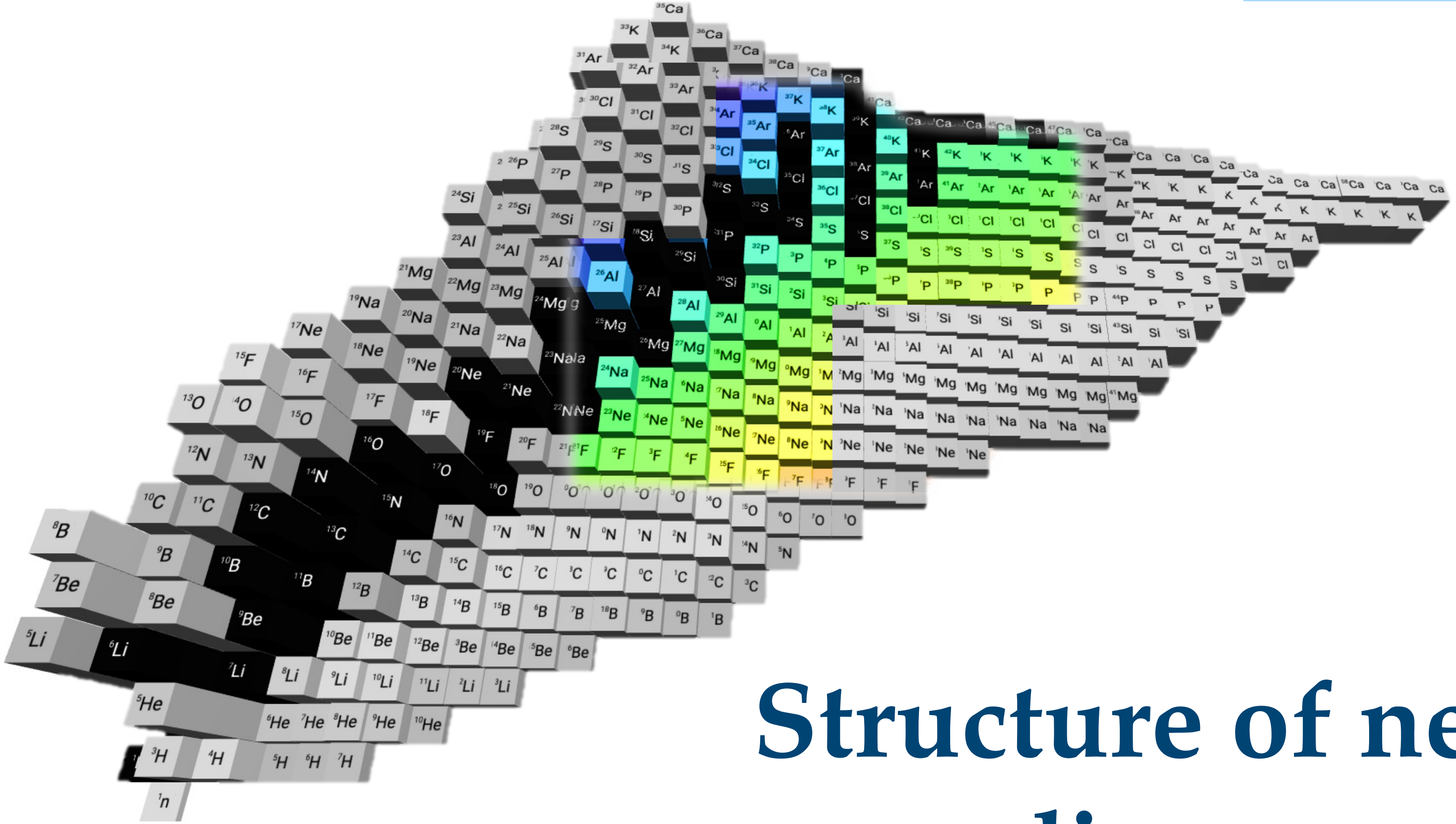


ACTIVE TARGET

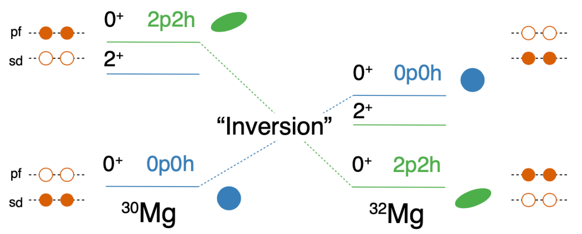


Possible coupling with γ detections

R. Raabe



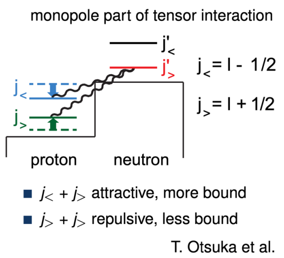
Structure of neutron-rich medium-mass nuclei

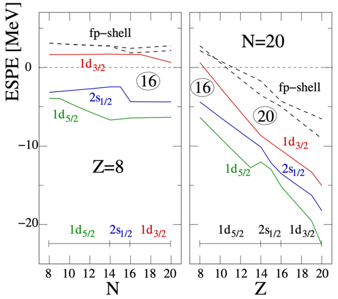


K. Wimmer et al., Phys. Rev. Lett. **105**, 252501 (2010)

Anomalies towards N=20

- Non-standard ordering of orbitals
- Inversion of spherical and deformed structures



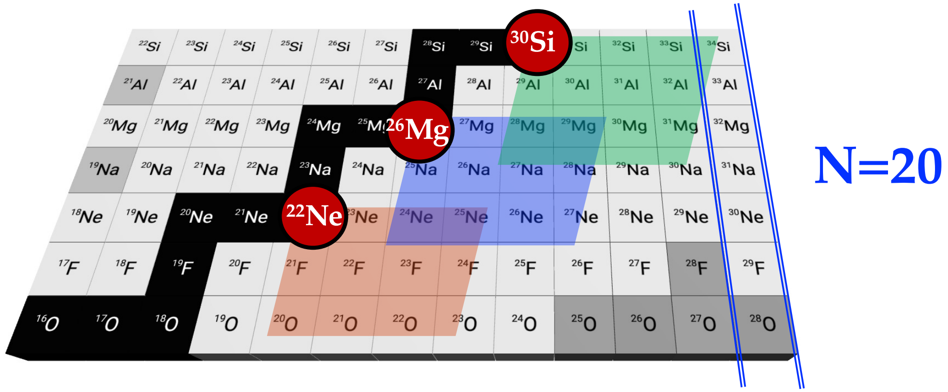


Tracking shape changes

Monte-Carlo Shell Model

Possible measurements

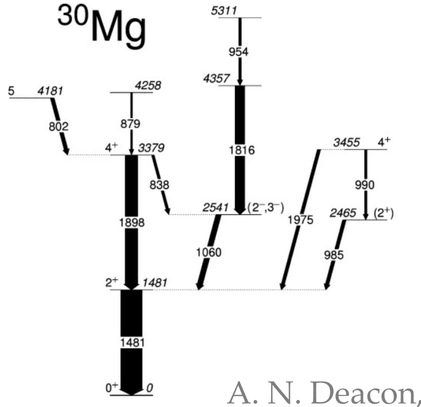
Multi-nucleon transfer reactions

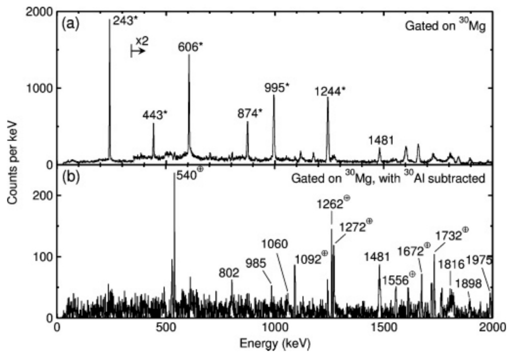


Island of Inversion at higher spin

Origin of collectivity

Mixing of multi-particle-multi hole configurations



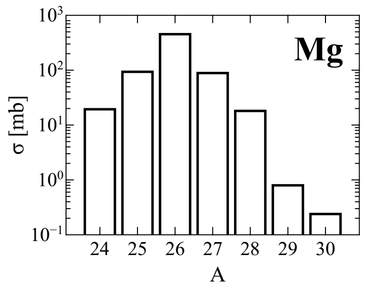


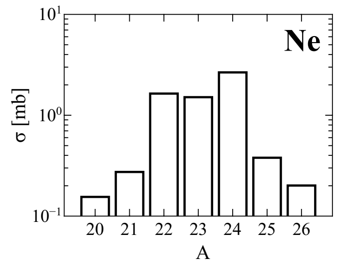
A. N. Deacon, et al., Phys. Rev. C 82 (2010) 034305.c

Approaching N=20

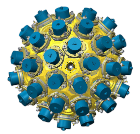
- γ spectroscopy
- Lifetimes
- Advantages from PRISMA upgrade

^{26}Mg+^{238}U @ 7 MeV A





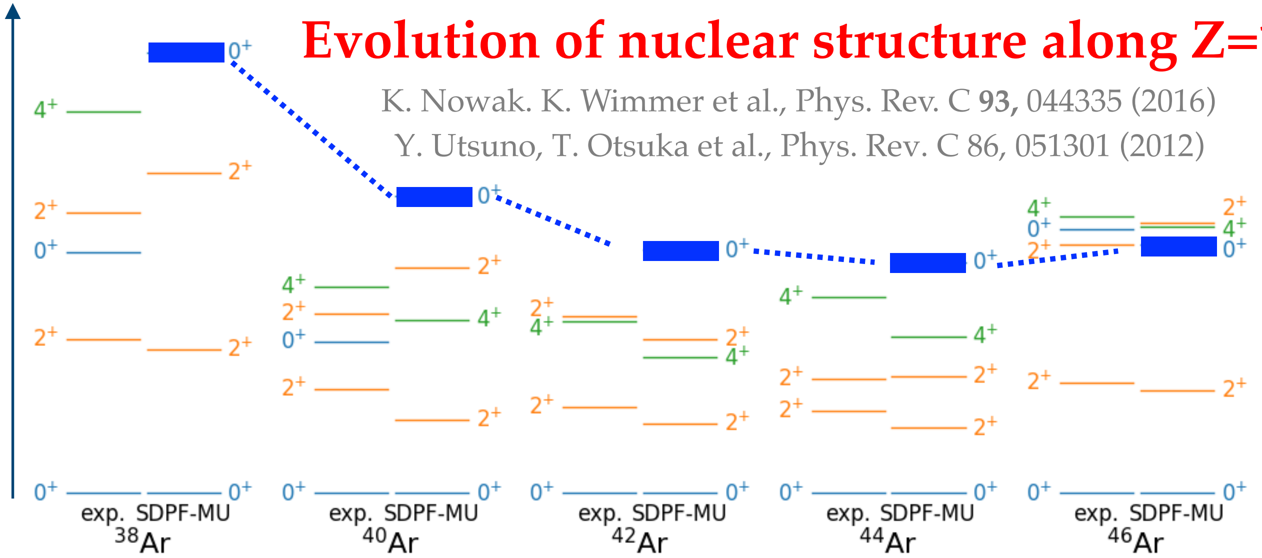
AGATA + PRISMA



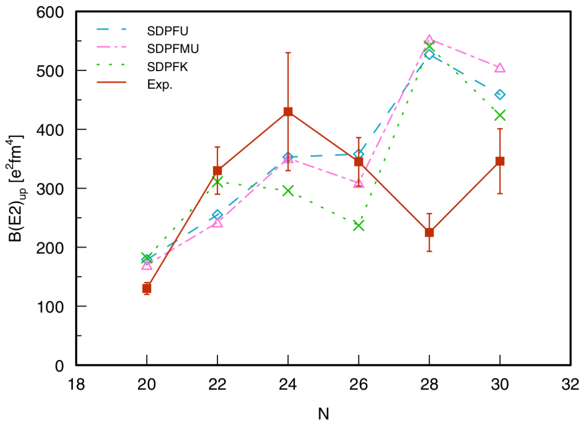
K. Wimmer

Evolution of nuclear structure along Z=18

K. Nowak. K. Wimmer et al., Phys. Rev. C **93**, 044335 (2016)
Y. Utsuno, T. Otsuka et al., Phys. Rev. C 86, 051301 (2012)

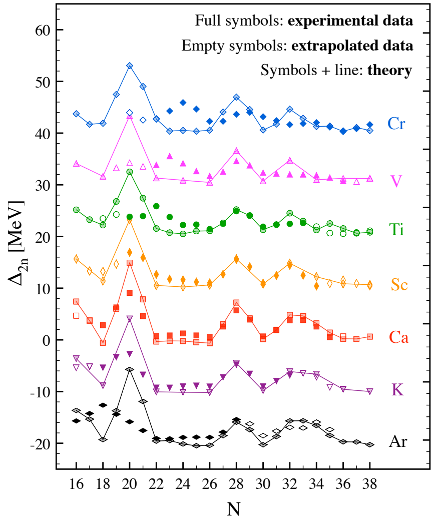


Emergence of shape coexistence



Discrepancies with standard shell-model interactions

S. Calinescu et al., Phys. Rev. C **93,** 044333 (2016)

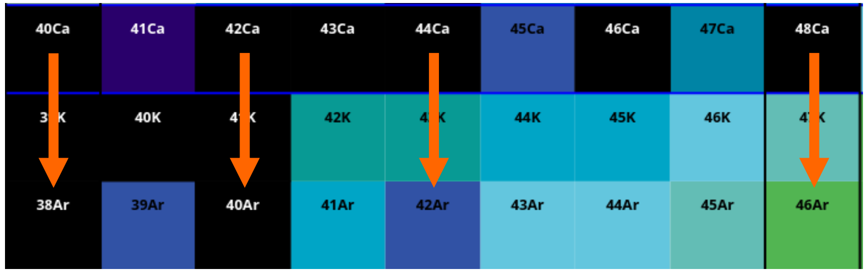


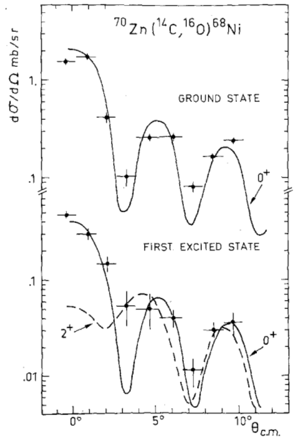
Two-particle overlaps possible with *ab-initio*

V. Somà, C. Barbieri et al., Eur. Phys. J. A **57,** 135 (2019)

Possible measurements

(^{14}C,^{16}O) two-proton transfer reactions





M. Bernas et al., Phys. Lett. B, **113** 279 (1982)

Sensitivity to transferred angular momentum

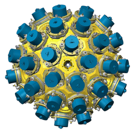
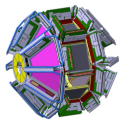
Study of 2p-2h proton strength

Study of 0+ states

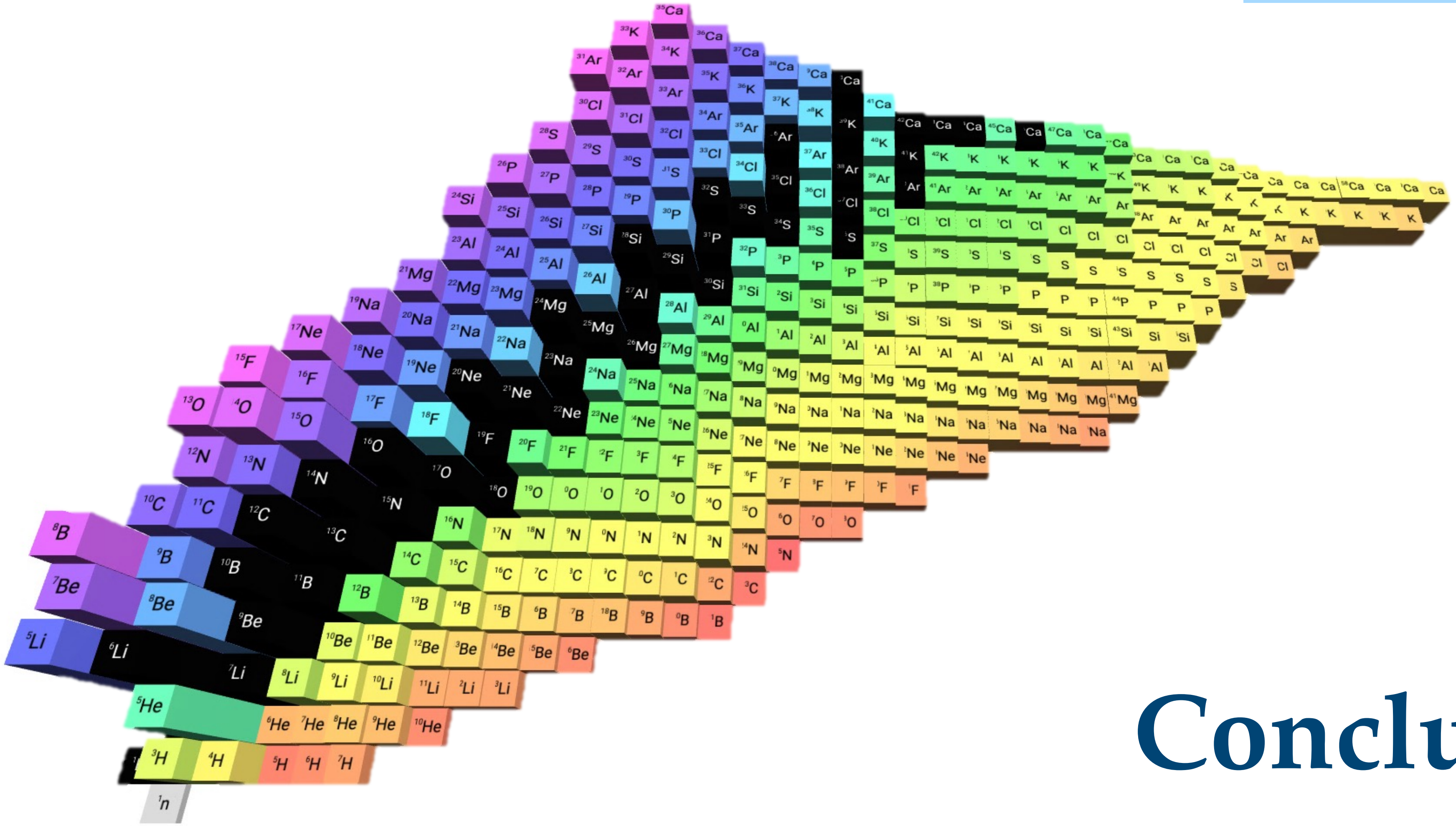
Search for shape coexistence

- γ decays + lifetimes
- E0 decays

AGATA + GRIT

K. Wimmer



Conclusions

Title	Topics	Beams	Reactions	Setup	Phase
γ decay from near-threshold states	• Onset of collectivization and clusterization	STABLE	• ^{6}Li(^{6}Li,p)^{11}**B** • ^{13}C(^{7}Li,p)^{19}**O** • ^{7}Li(^{14}C,p)^{20}**O***	AGATA + GRIT	**A/C**
Particle and γ decays from α-cluster states	• Breakout of CNO cycle • Molecular octupole deformations	EXOTIC and STABLE	• ^{11}C(α,α′) • ^{15}O(α,α′) • ^{21}Ne inelastic	ACTIVE TARGET and AGATA	**B**
Role of 3-body forces in C and O nuclei	• Sensitivity to 3-body forces	STABLE	• ^{18}O deep inelastic	AGATA+PRISMA	**A**
Molecular orbitals and di-neutron correlations	• Molecular bonding	SPES	• ^{10}Be(α,α′) • ^{10}Be(p,p′)	AGATA + GRIT+ CTADIR	**C**
Two-proton giant pairing vibrations	• Superconductive phases	STABLE + ^{14}C	• ^{A}C(^{3}He,n)	NEDA+ GRIT	**B/C**
Resonance in proton-rich nuclei	• Nuclear incompressibility • Path of rp-process	SPES	• ^{26}Si(α,α′) • $^{24\text{-}25}$Al(p,p′)	ACTIVE TARGET	**C**
Approaching the Island of Inversion at higher spins	• Origin of collectivity	STABLE	• Multi-nucleon transfer ^{22}Ne,^{26}Mg,^{30}Si	AGATA+PRISMA	**A**
Proton excitations and 0+ states in Ar isotopes	• Emergence of shape coexistance	^{14}C	• Two-proton transfer ^{A}Ca(^{14}C,^{16}O)	AGATA + GRIT	**C**

Thank you!