Precision γ-ray spectroscopy of neutron-rich C, N and O isotopes as a test-bench of nuclear structure theory

Silvia Leoni (University of Milan and INFN)
on behalf of the collaboration …

26 SEP > 1 OCT 2021 Autrans-Méaudre en Vercors, FRANCE

XXIInd COLLOQUE GANIL

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AGATA
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VAMOS
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T. Suzuki *(Nihon University, Japan)*, T. Otsuka *(University of Tokyo, Japan)*

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M. Ploszajczak *(GANIL, France)*, J. Okolowicz *(IFJ-PAN, Poland)*

Light Nuclei: Li, Be, B, C, N, O, F, …

- Test Bench for most advanced THEORY predictions:
  ab-initio and Shell Model, including also coupling with the Continuum …

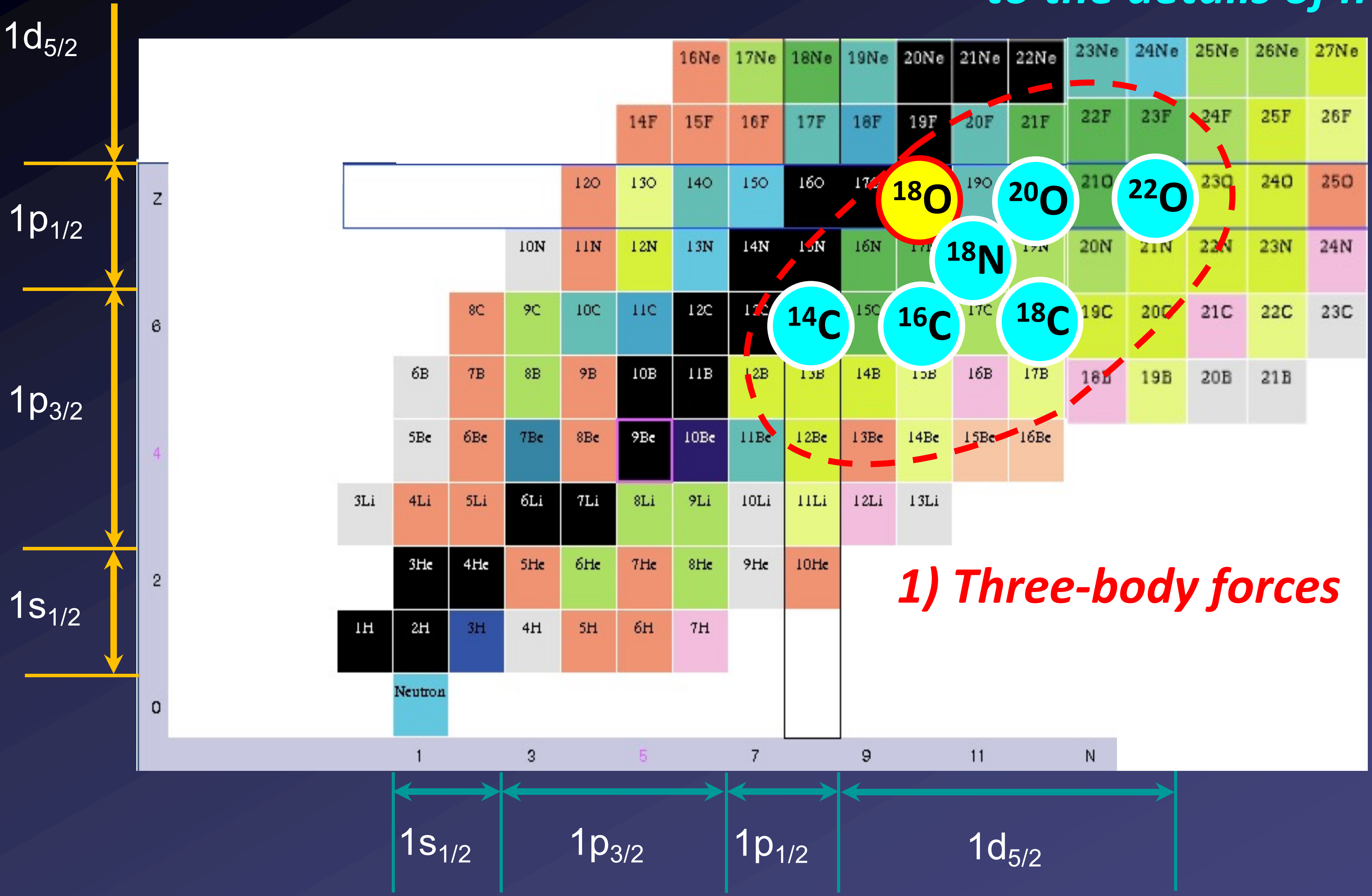
- Importance in ASTROPHYSICS (nucleosynthesis, …)

Results from experiment E656@GANIL - AGATA+PARIS+VAMOS (July 2017)

1. *M. Ciemała , S. Ziliani, F.C.L. Crespi, S. Leoni, B. Fornal, A. Maj, et al., Phys. Rev. C 101, 021303(R), 2020 (lifetimes in: **^{16}C, ^{17}O, ^{19}O, ^{20}O**)*
2. *M. Ciemała, S. Ziliani, F.C.L. Crespi, S. Leoni, B. Fornal, A. Maj, et al., Eur Phys. J A, 57, 156, 2021 (New DSAM technique)*
3. *S. Ziliani, M. Cimała, F.C.L. Crespi, S. Leoni, B. Fornal, et al. (in print in Phys. Rev. C Letter) (Spectroscopy of: **^{18}N**)*
4. *S. Ziliani, M. Cimała, F.C.L. Crespi, S. Leoni, B. Fornal, et al. (in preparation) (**^{14}C**)….*

Nuclei of Interest

sensitivity of some observables to the details of n-n force

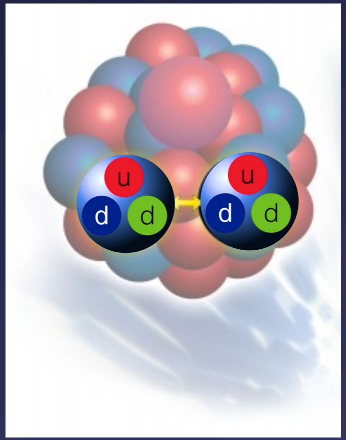


Nuclear force is the „heart” of nuclear physics and has been studied from ~1930.

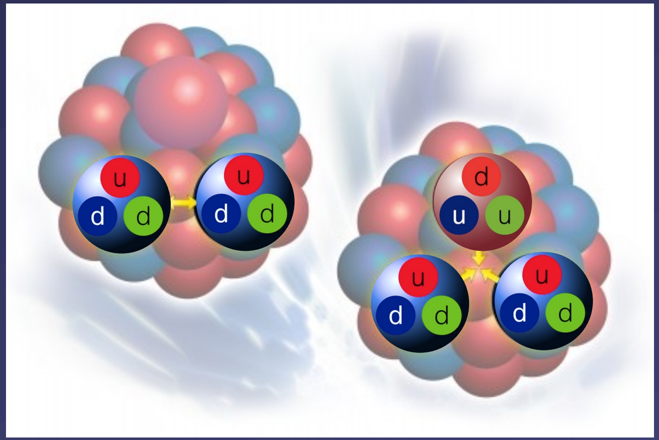
THEORY effort in the last decades:

description of nucleon-nucleon (NN) interaction in the framework of chiral Effective Field Theory (EFT).

Main idea: exploit symmetries of QCD to obtain an effective theory for low energy nuclear systems.



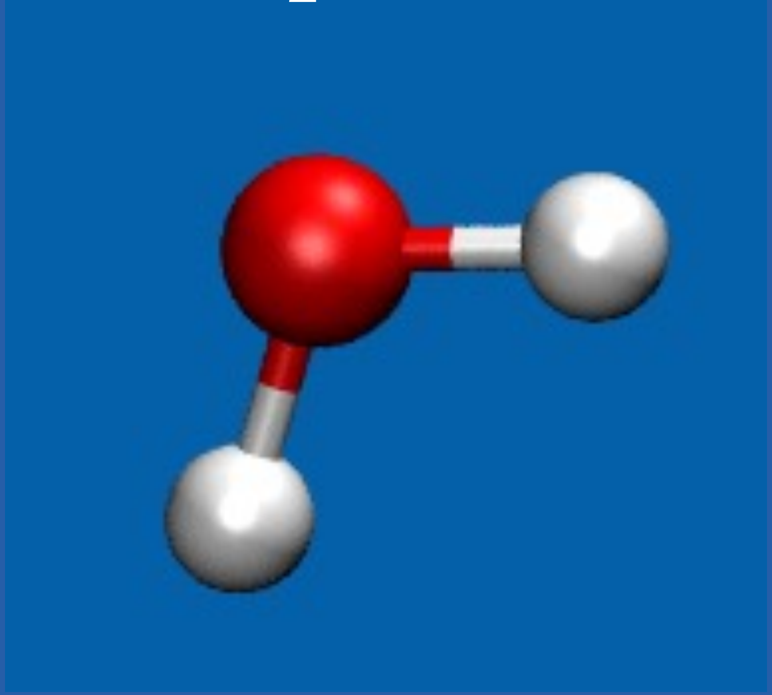
NN



NN+NNN

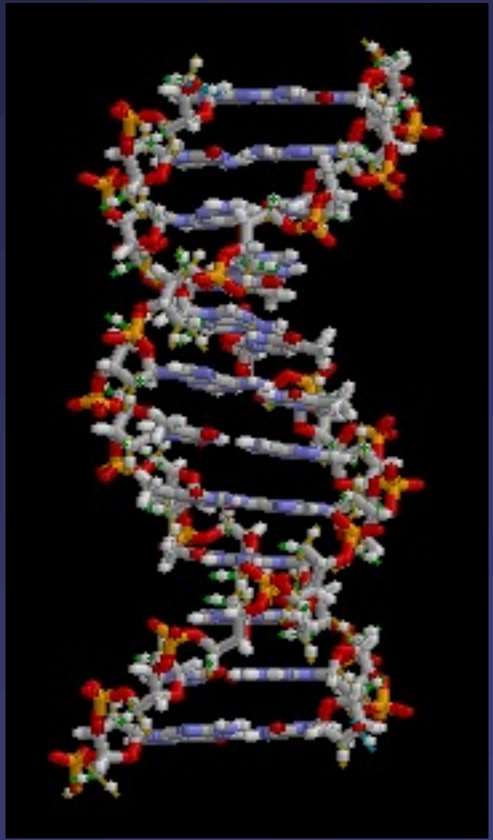
3 body interactions are common in many fields of complex systems

water molecule H_2O



three body interaction contribution **14.5%**

DNA molecule

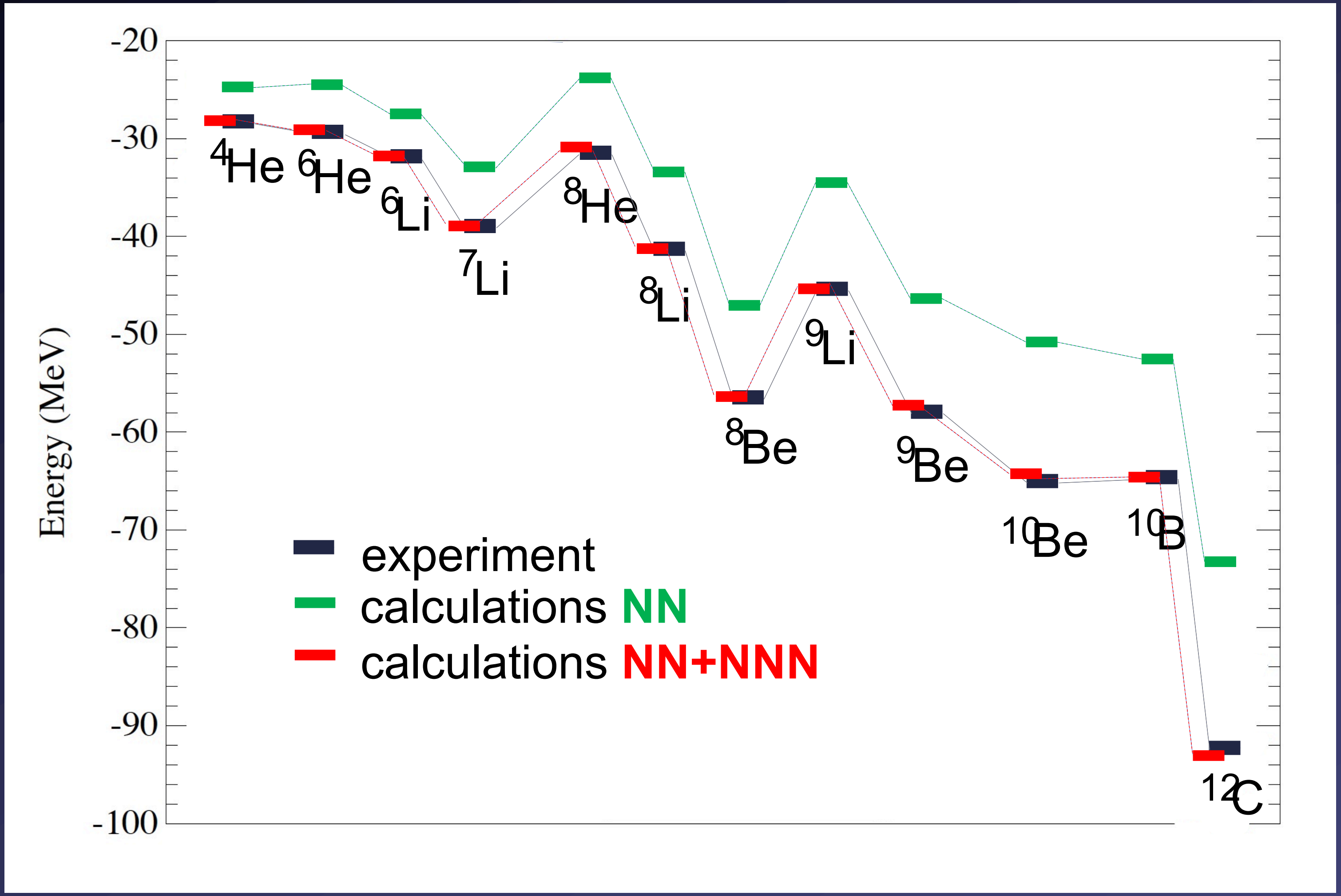


three body interaction contribution **24%**

Source: wikipedia

Importance of THREE-BODY term of Nucleon-Nucleon interaction

Binding energy of selected light nuclei



three-nucleon forces:
10-30% effect on binding energy and excited state energy

Argonne V_{18} potential and Green's function Monte Carlo (GFMC) method; Pieper & Wiringa, Ann. Rev. Nucl. Part. Sci. 51, 53 (2001)

Importance of THREE-BODY term of Nucleon-Nucleon interaction

Binding energy of light-heavy nuclei

PRL **105**, 032501 (2010) PHYSICAL REVIEW LETTERS week ending 16 JULY 2010

Three-Body Forces and the Limit of Oxygen Isotopes

Takaharu Otsuka,[1,2,3] Toshio Suzuki,[4] Jason D. Holt,[5] Achim Schwenk,[5] and Yoshinori Akaishi[6]
[1]*Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan*
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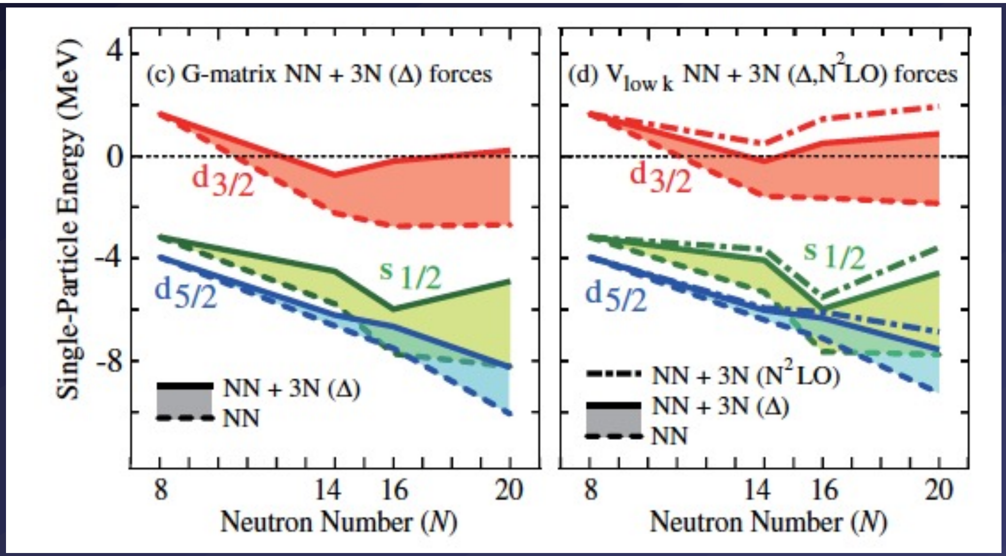
(Received 17 August 2009; published 13 July 2010)



Scattering Cross Sections

Selected for a Viewpoint in *Physics*
PRL **118**, 262502 (2017) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with ^{10}C

A. Kumar,[1] R. Kanungo,[1*] A. Calci,[2] P. Navrátil,[2†] A. Sanetullaev,[1,2] M. Alcorta,[2] V. Bildstein,[3] G. Christian,[2] B. Davids,[2] J. Dohet-Eraly,[2,4] J. Fallis,[2] A. T. Gallant,[2] G. Hackman,[2] B. Hadinia,[3] G. Hupin,[5,6] S. Ishimoto,[7] R. Krücken,[2,8] A. T. Laffoley,[3] J. Lighthall,[2] D. Miller,[2] S. Quaglioni,[9] J. S. Randhawa,[1] E. T. Rand,[3] A. Rojas,[2] R. Roth,[10] A. Shotter,[11] J. Tanaka,[12] I. Tanihata,[12,13] and C. Unsworth[2]
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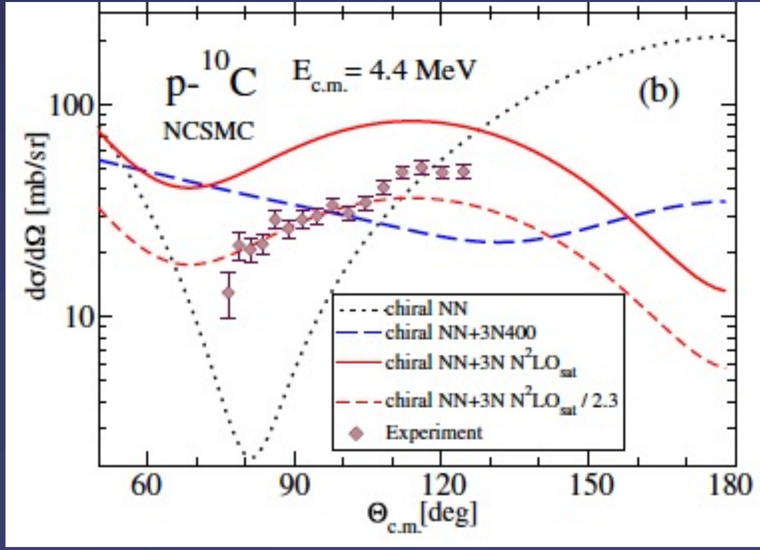
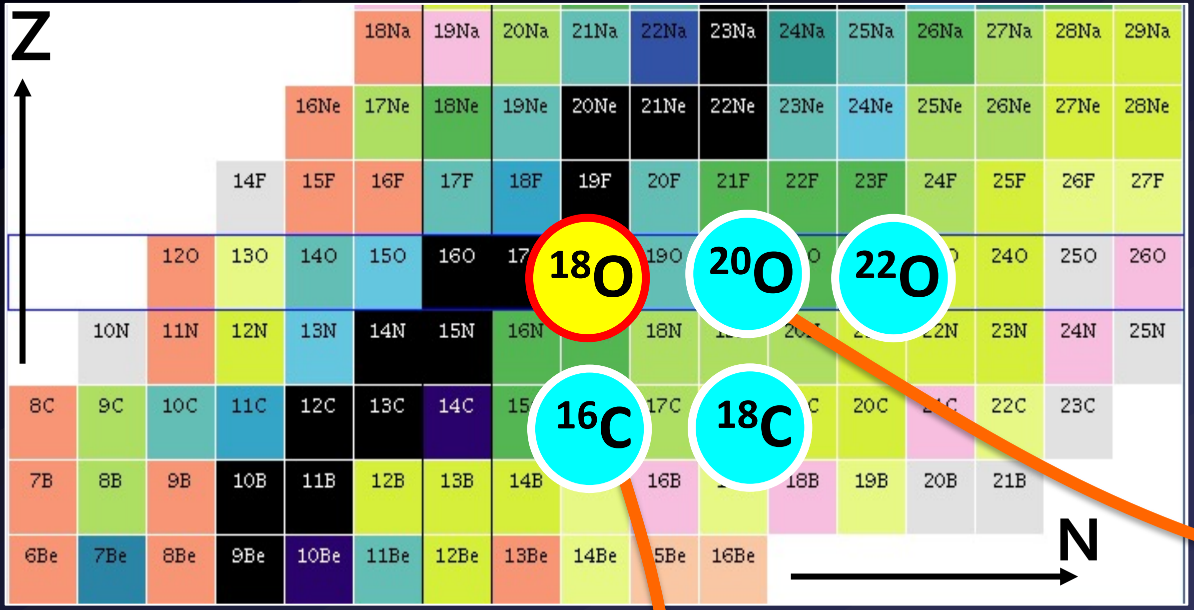


Can we use *ELECTROMAGNETIC observables*
to pin down in greater details the state wave functions?

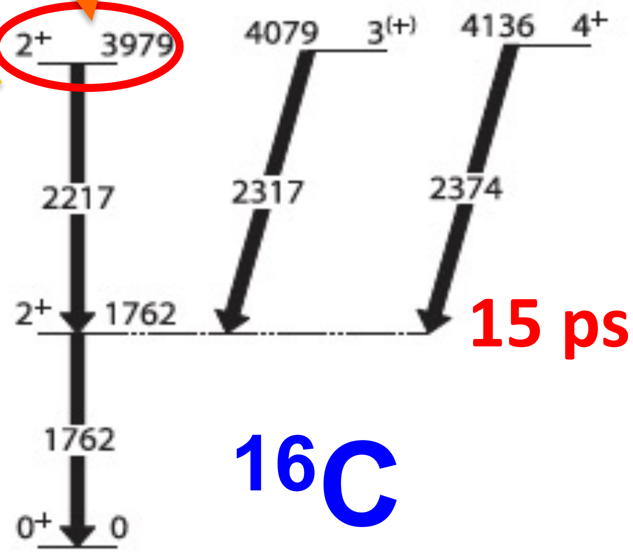
Predicted sensitivity of 2^+_2 state lifetimes from *ab initio* calculations



NN 0.34 ps

NNN 0.08 ps

No-Core Shell Model (2013)



15 ps

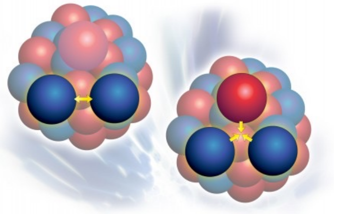
16C

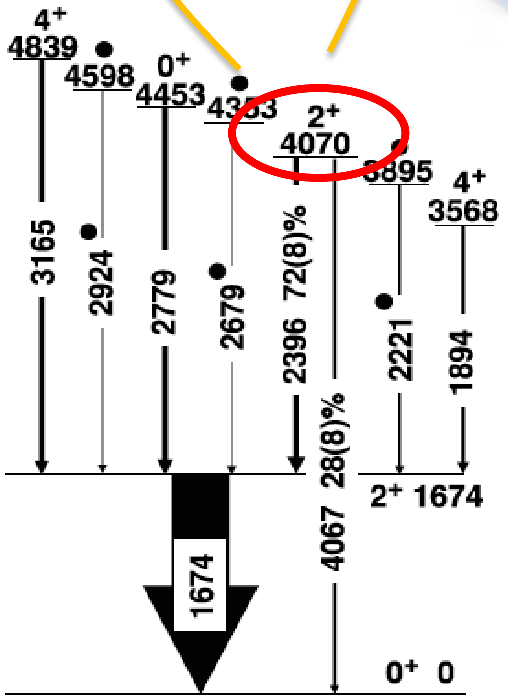
C. Forssen, R. Roth, P Navratil

MANY BODY Pert. THEORY (2014)

A. Schwenk
J. Menendez

$\tau(2^+_2)=$ NN 0.32 ps NNN 0.20 ps





11 ps

20O

Lifetime range of interest

τ = 50 femtoseconds – 1 picosecond

→ **Low Velocity/Energy reactions**

1) ~~FUSION~~ - *we are interested in exotic neutron rich products*

2) TRANSFER/DEEP Inelastic with Heavy Ions

→ **Experimental technique**

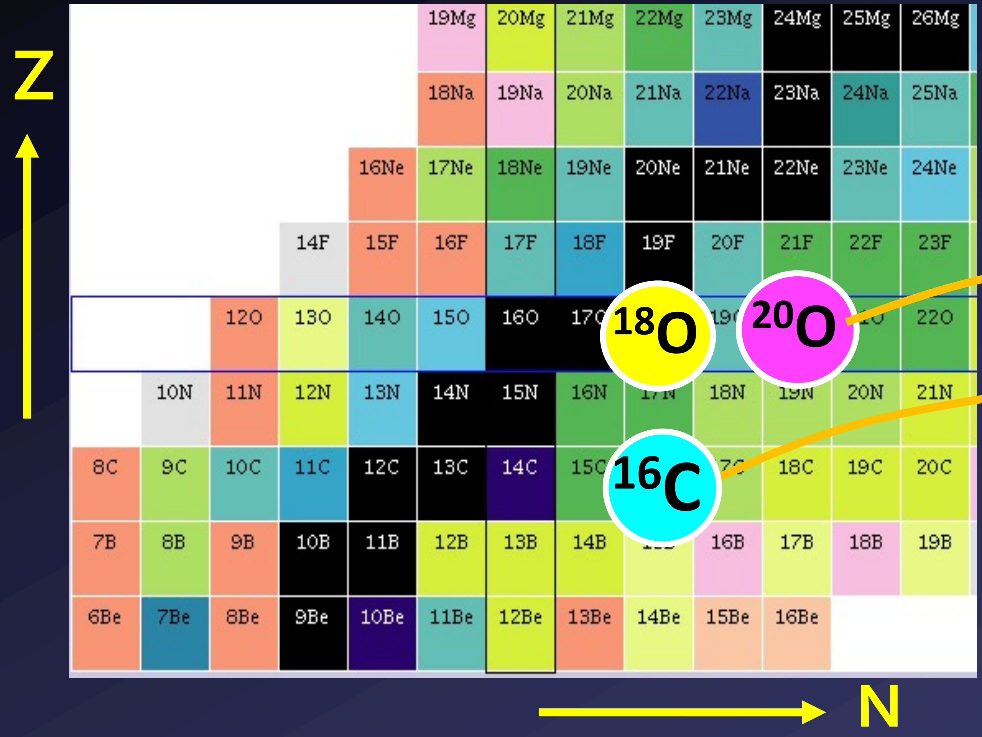
Doppler Shift Attenuation Method

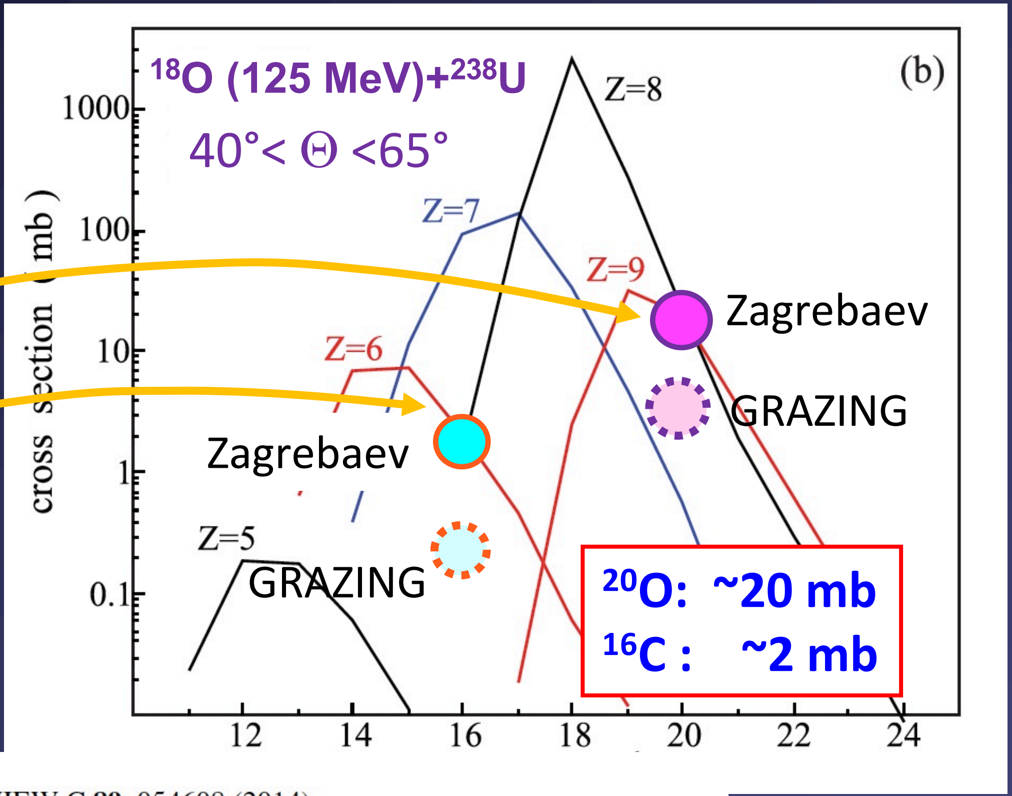
very precise measurement of the γ line shape

perfect case for AGATA tracking array

Production of neutron-rich nuclei “south-east” of ^{18}O for gamma-ray spectroscopy studies

ZAGREBAEV and GREINER Model of Deep-Inelastic Processes





PHYSICAL REVIEW C **89**, 054608 (2014)

Formation of light exotic nuclei in low-energy multinucleon transfer reactions

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[3]*Dipartimento di Fisica, University of Milano, Milano, Italy*

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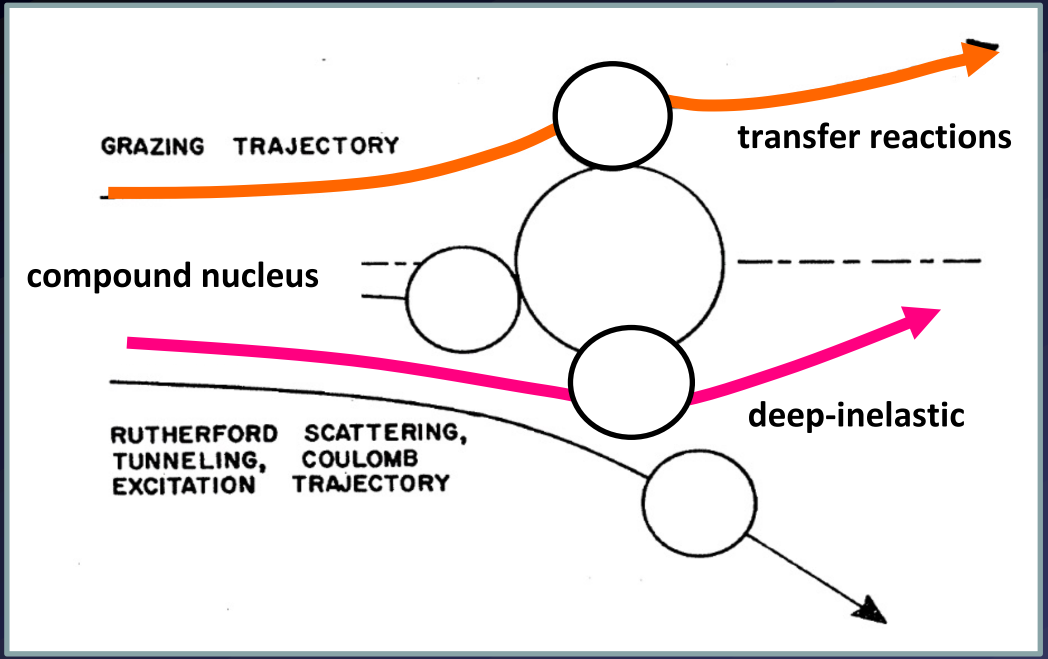
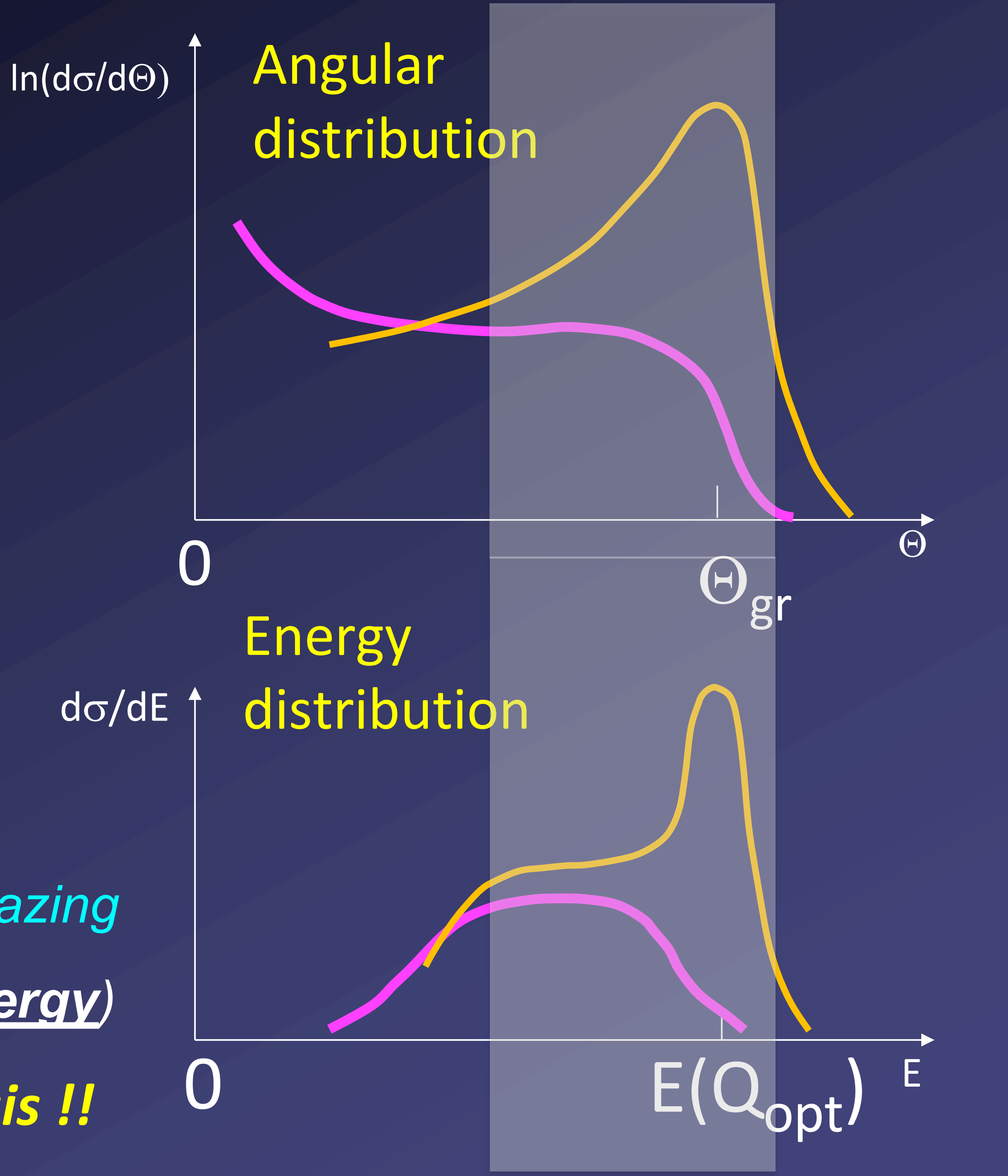
(Received 13 March 2014; published 9 May 2014)

How to best profit of deep inelastic reactions





*Slightly **Forward angles** with respect to grazing*

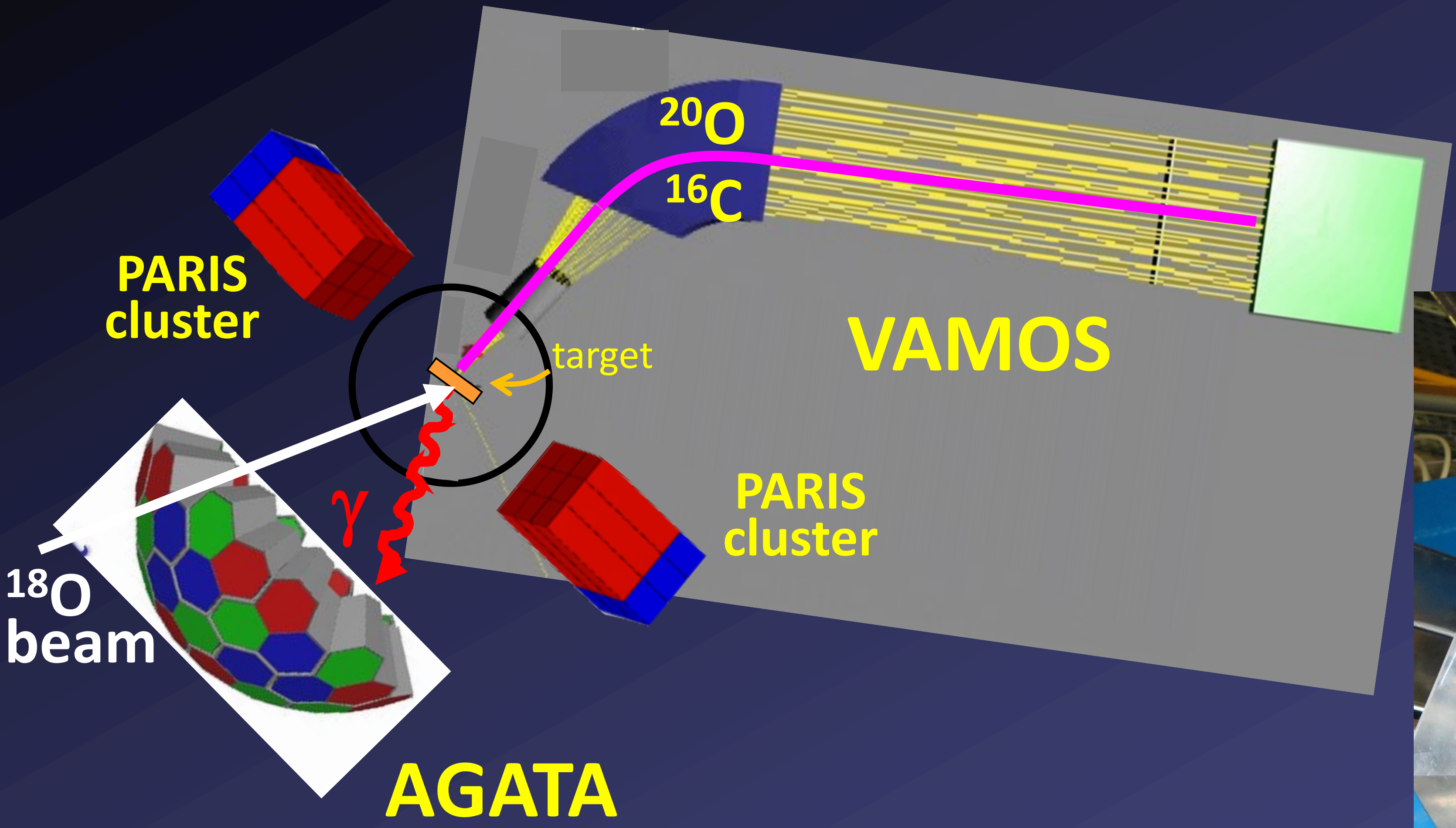
*Very dissipative process (**less defined energy**)*

Gain in cross section BUT Complex analysis !!

Experiment E656@GANIL - AGATA+PARIS+VAMOS (July 2017)

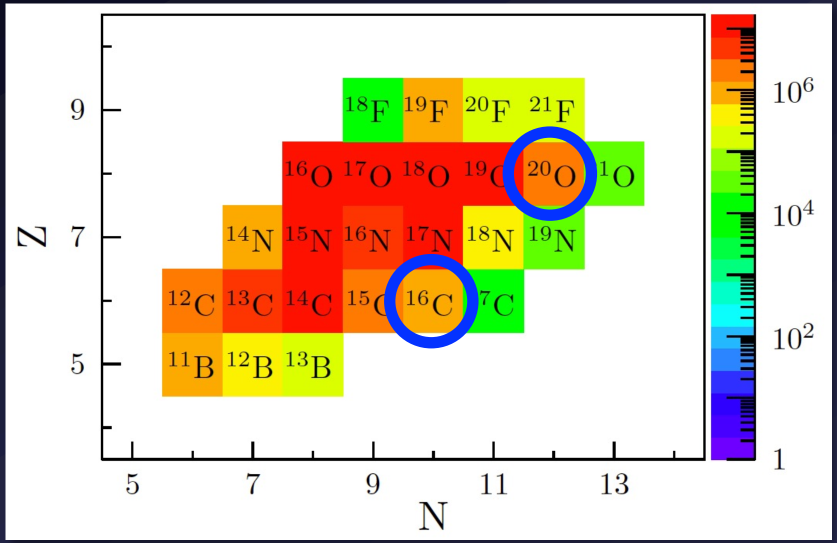
$^{18}O + ^{181}Ta \rightarrow$ $^{20}O + ^{181-xn}Ta$
$^{16}C + ^{183-xn}Re$

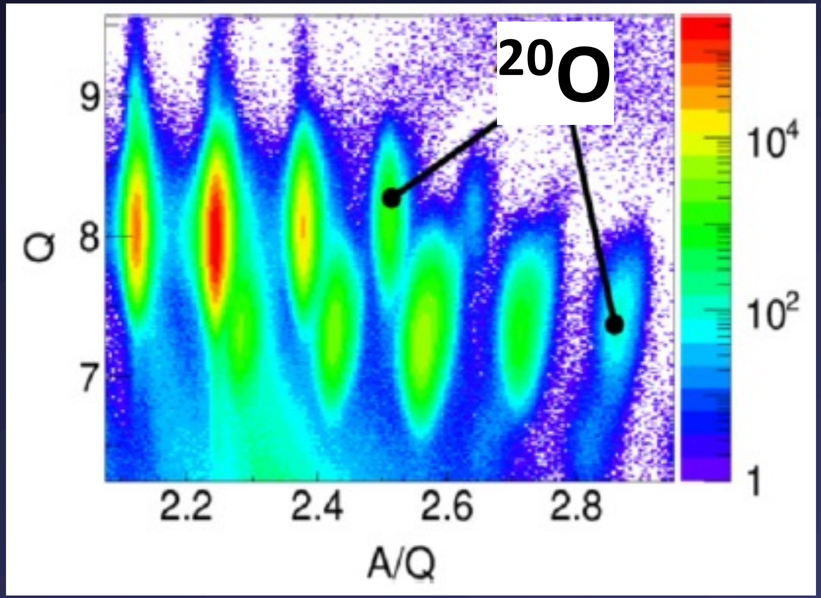
Spokespersons:
S. Leoni, B. Fornal, M. Ciemala

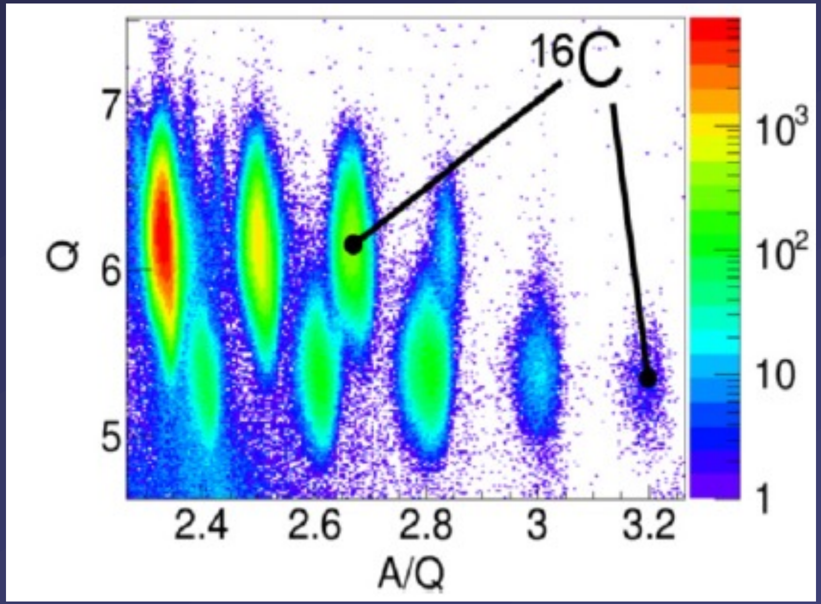


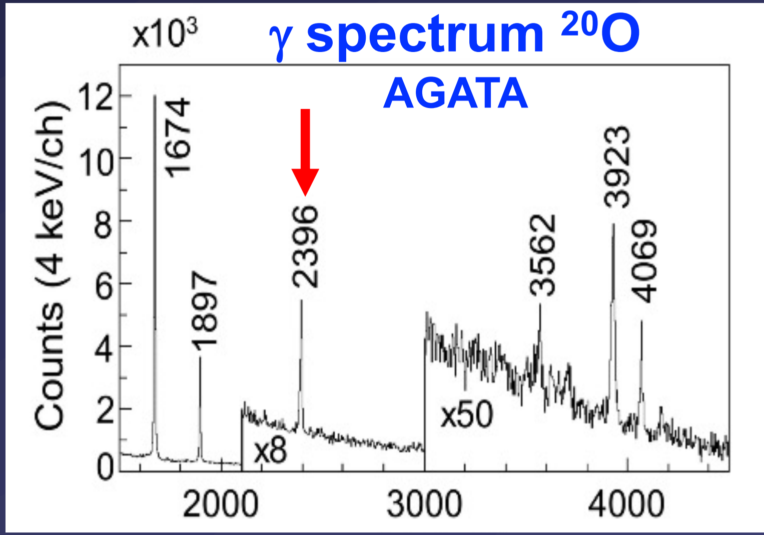
VAMOS magnetic spectrometer - ion selection

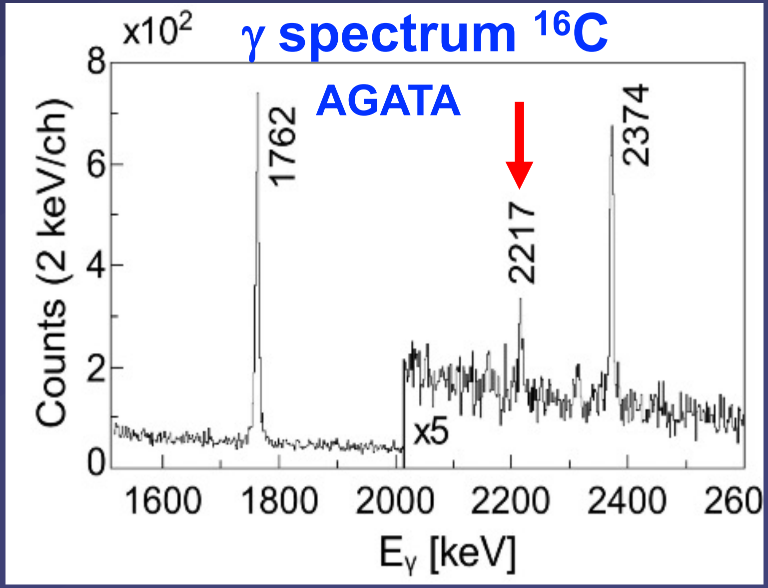
Population







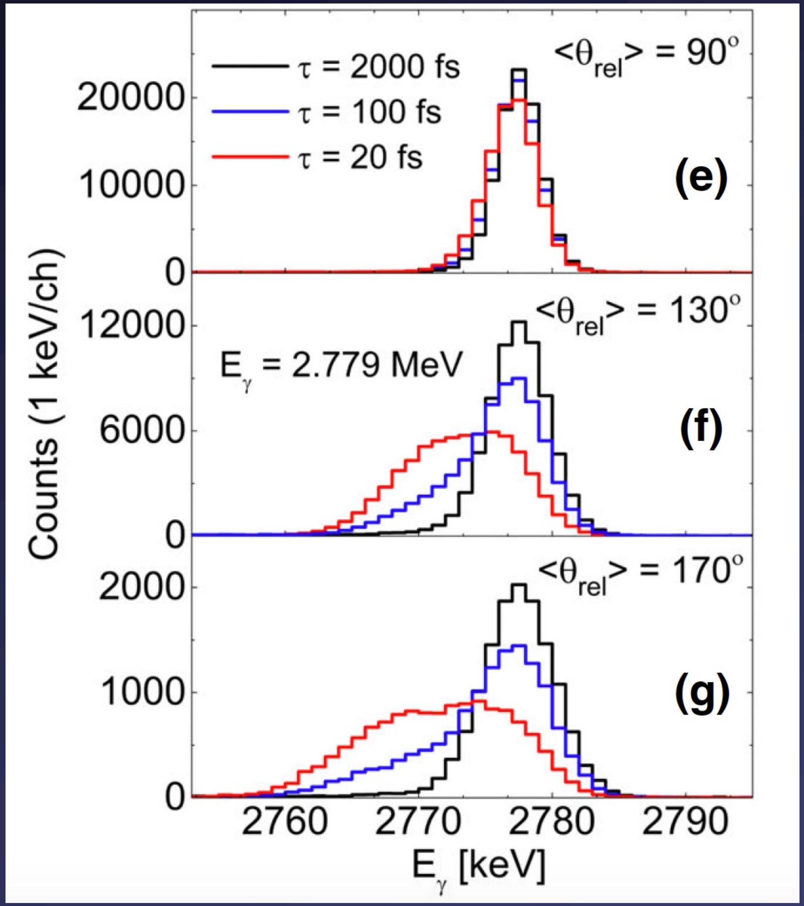


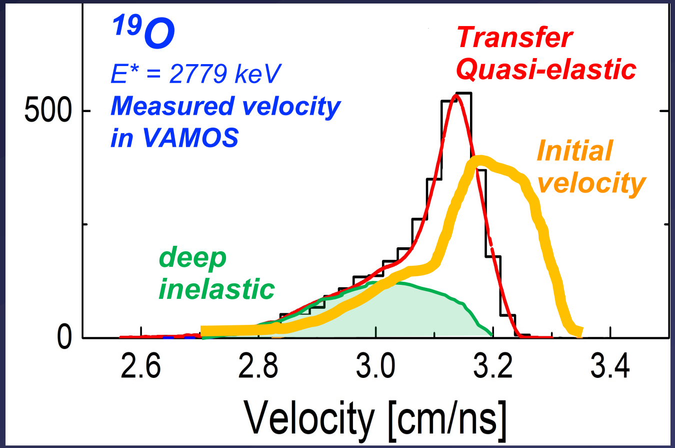


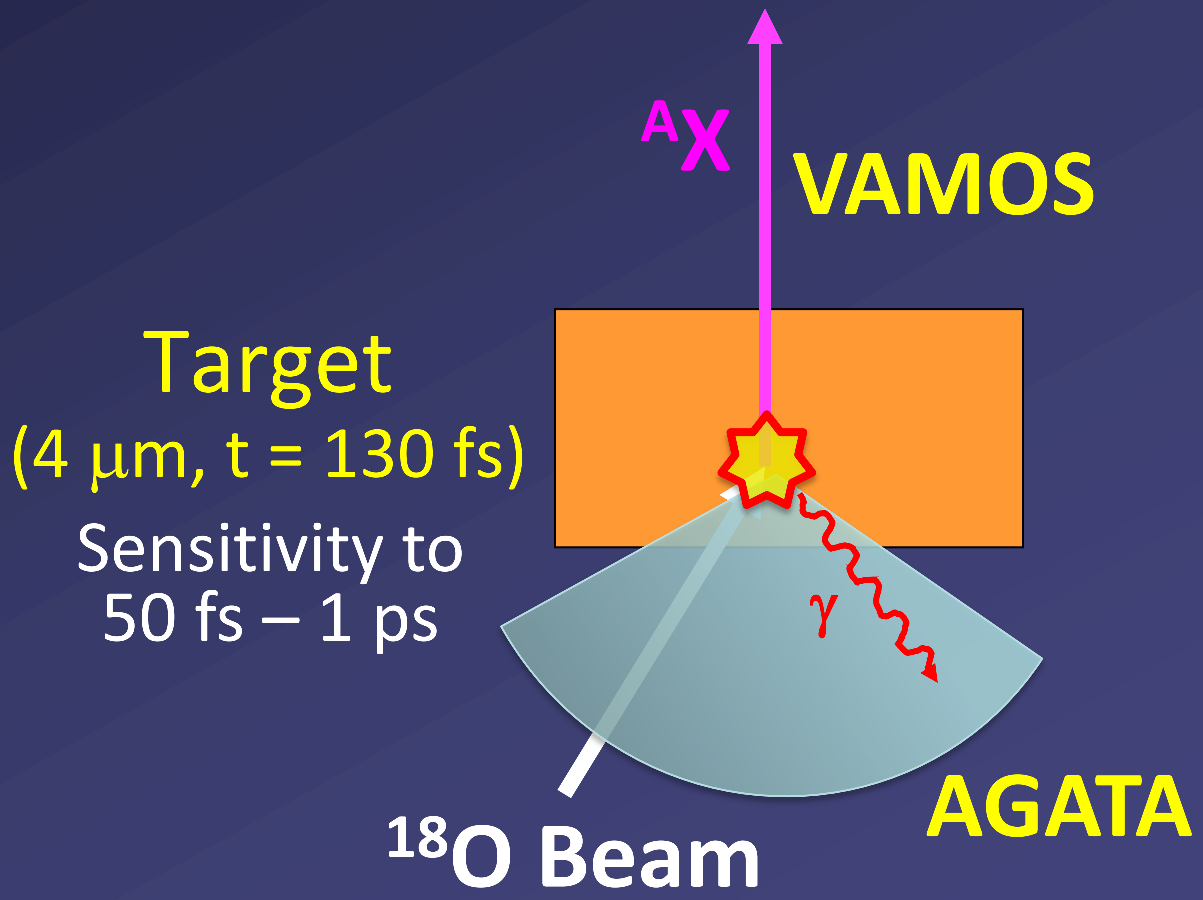
METHOD: Doppler shift dependence on the point of gamma emission

^{18}O (7 MeV/A) + ^{181}Ta target (6 mg/cm^2)

$$E = \frac{E_0}{\gamma(1 - v/c \cos\Theta)}$$

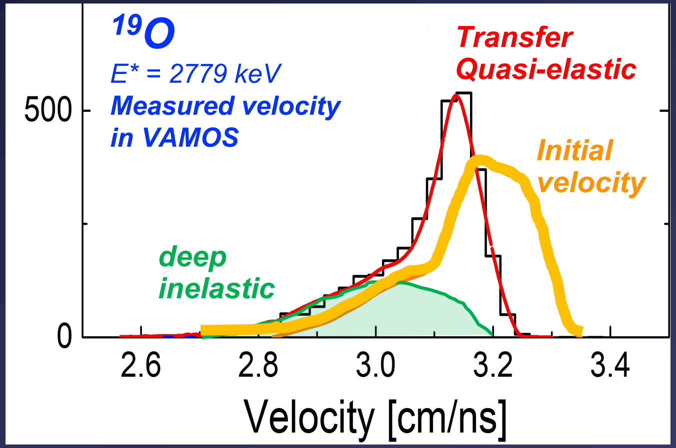




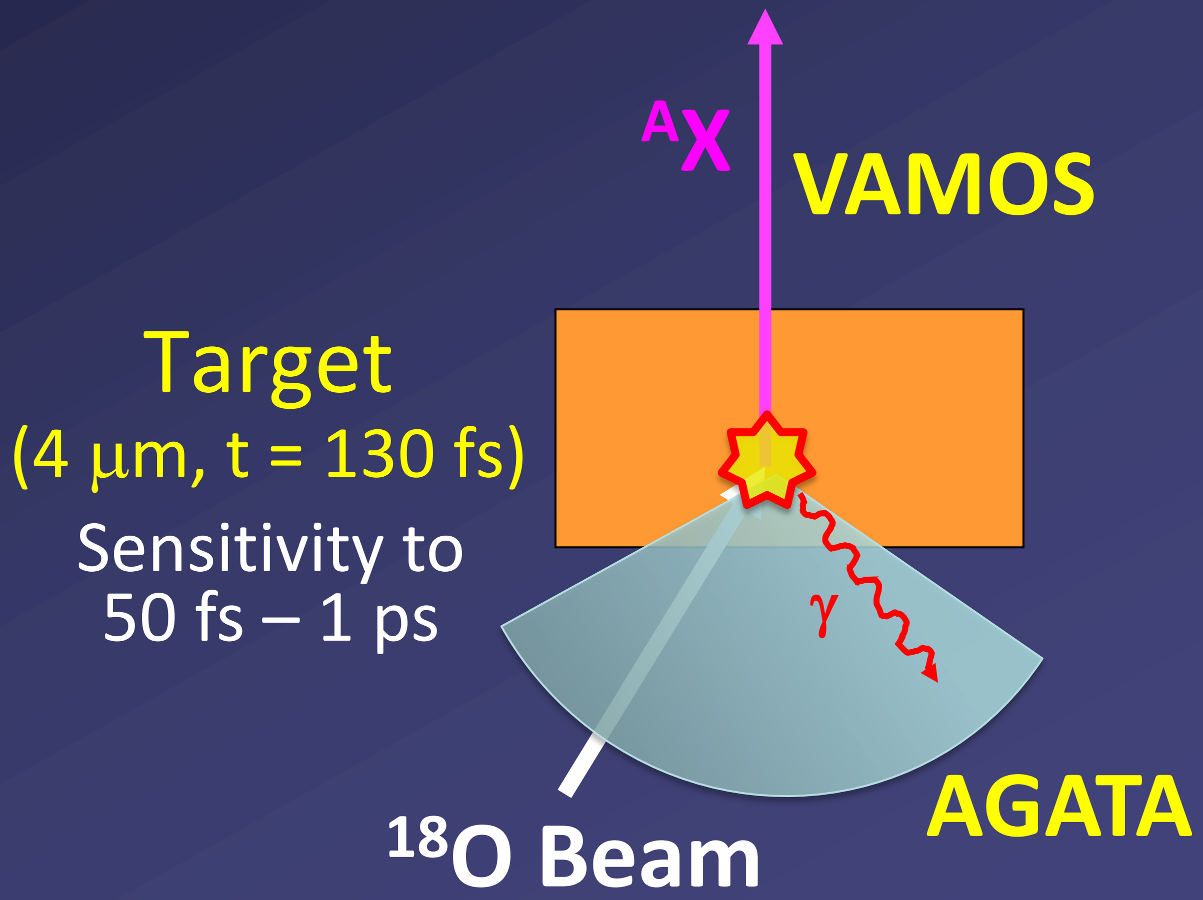


Monte Carlo SIMULATION Method of Doppler Shifted Lineshape Passing through a THICK target

M. Ciemala et al., Eur Phys. J. A57, 156, 2021



- Reconstruction of ion velocity at the reaction point from measured velocity in VAMOS
- Simulation of Doppler Shifted γ energy – ***1.5° precision***
- **minimization of likelihood surface in E_γ, τ coordinates**



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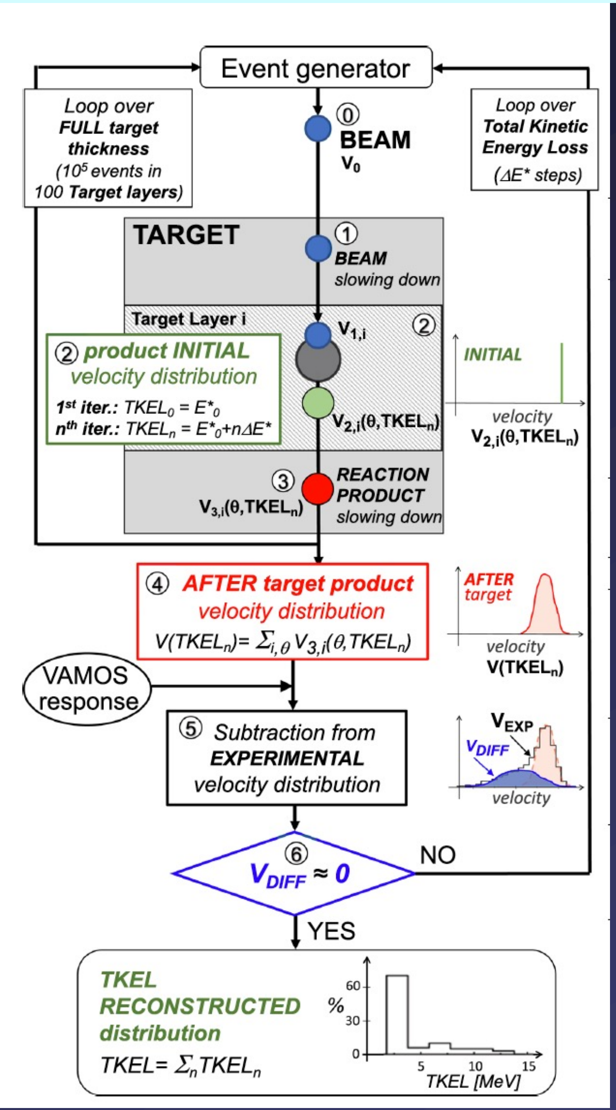
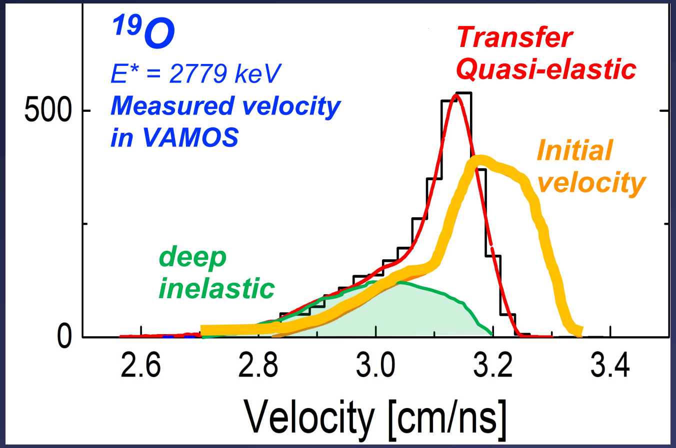
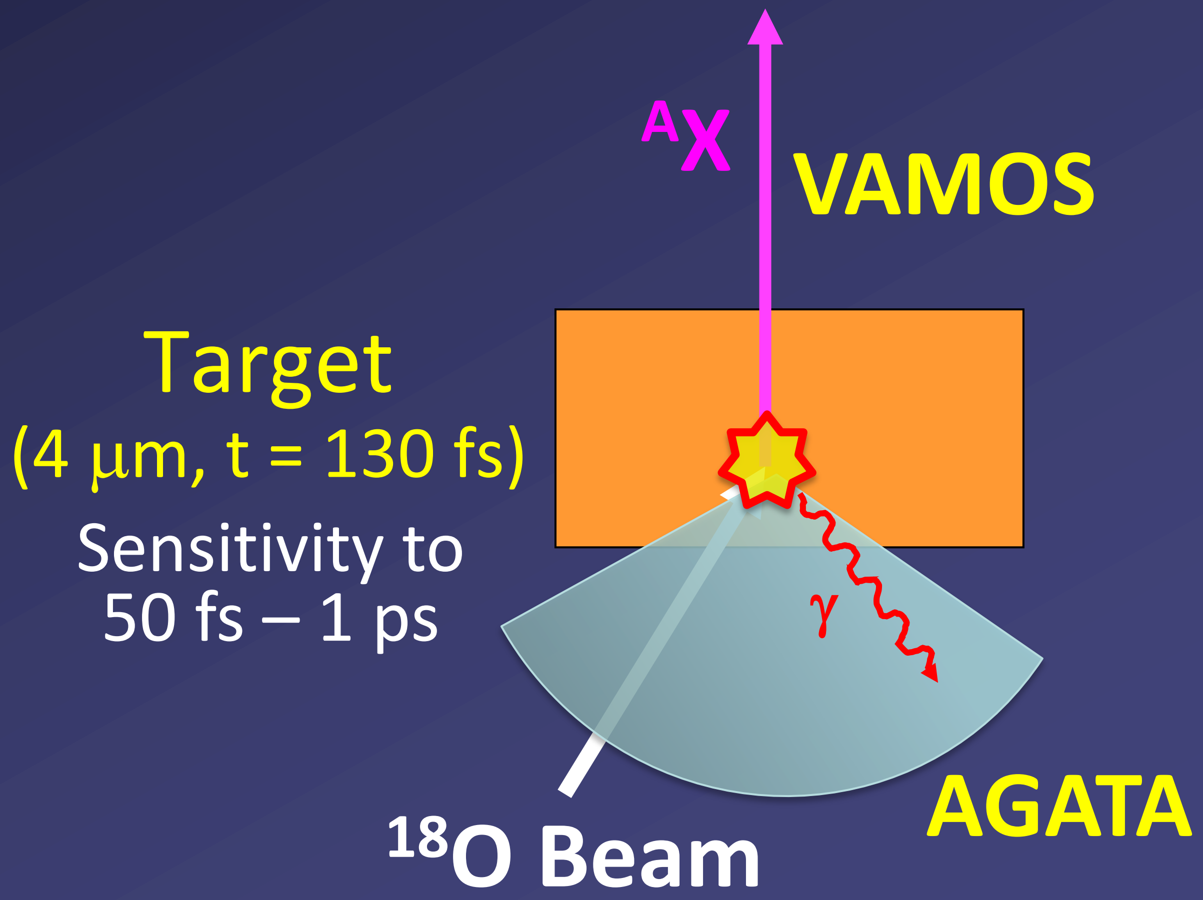
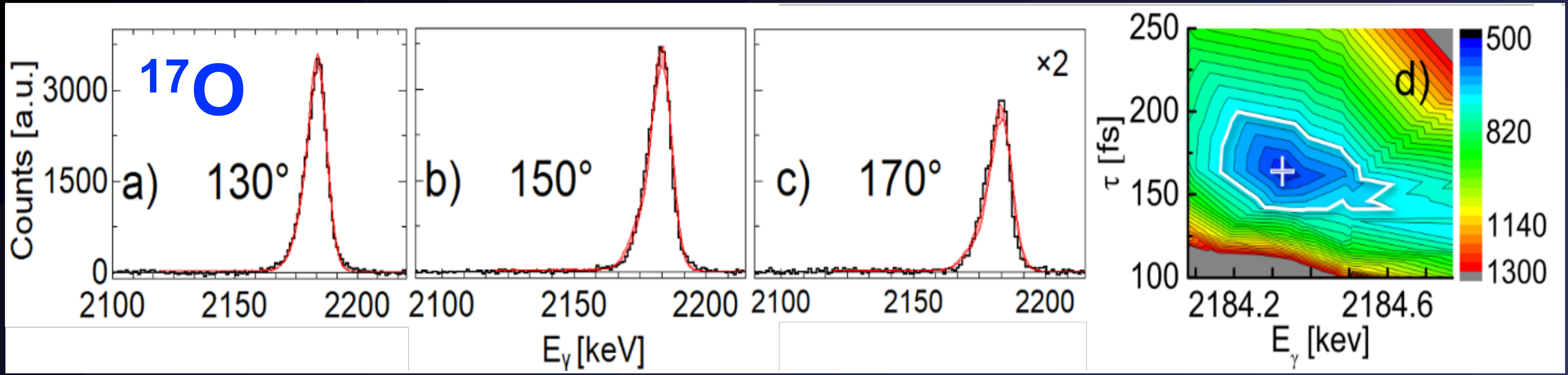
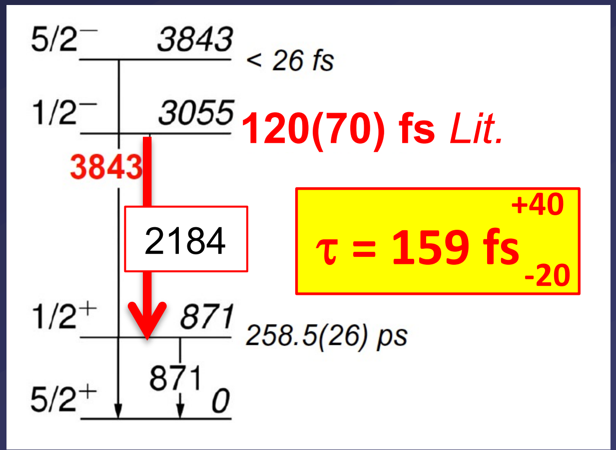


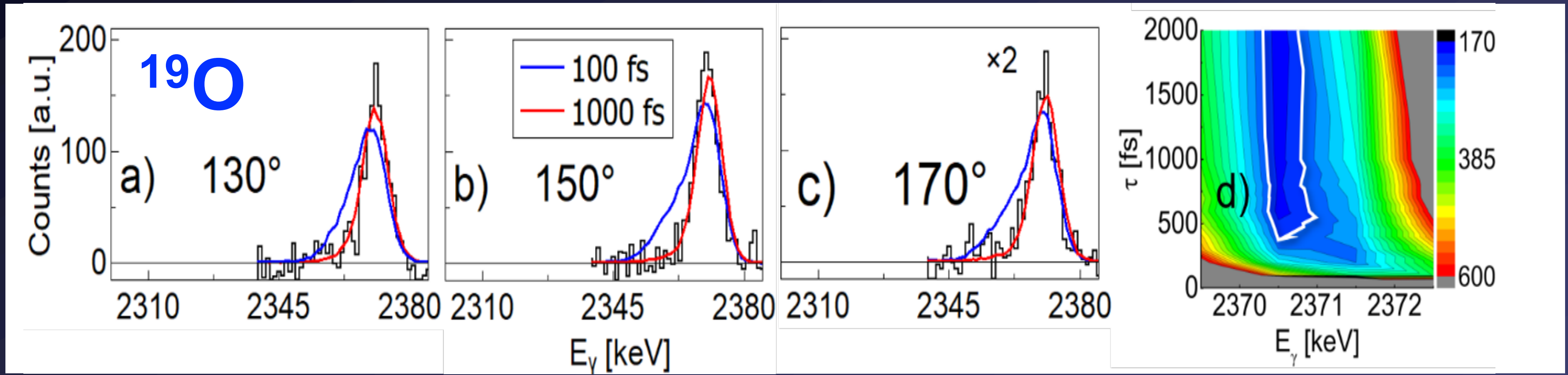


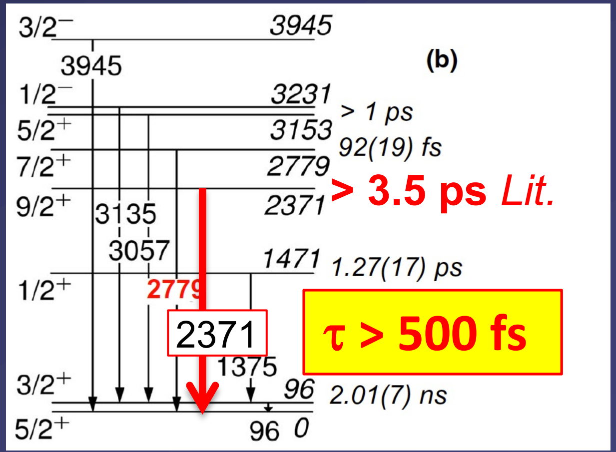


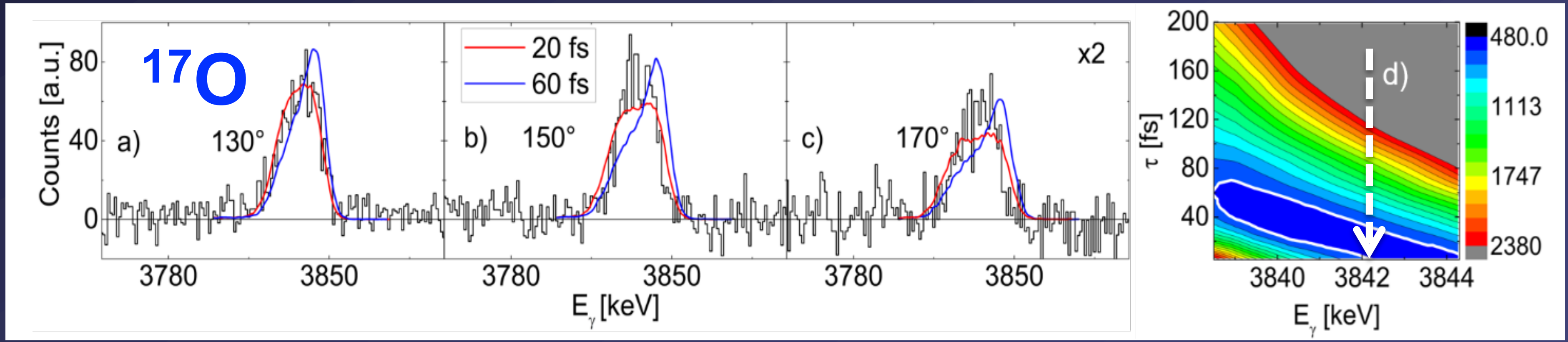
TEST of the Method on known cases *(M. Ciemala et al., Eur Phys. J A, 57, 156, 2021)*

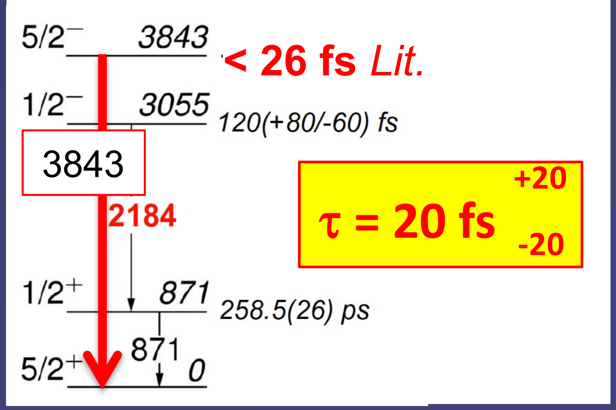






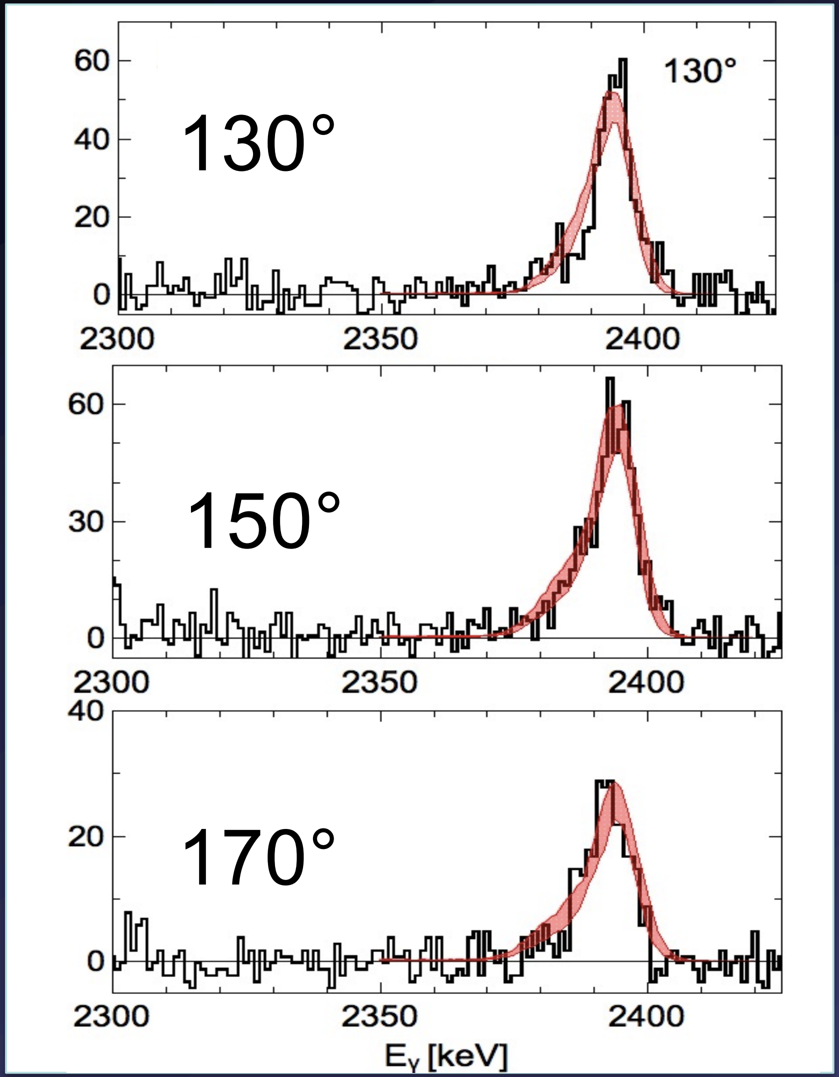




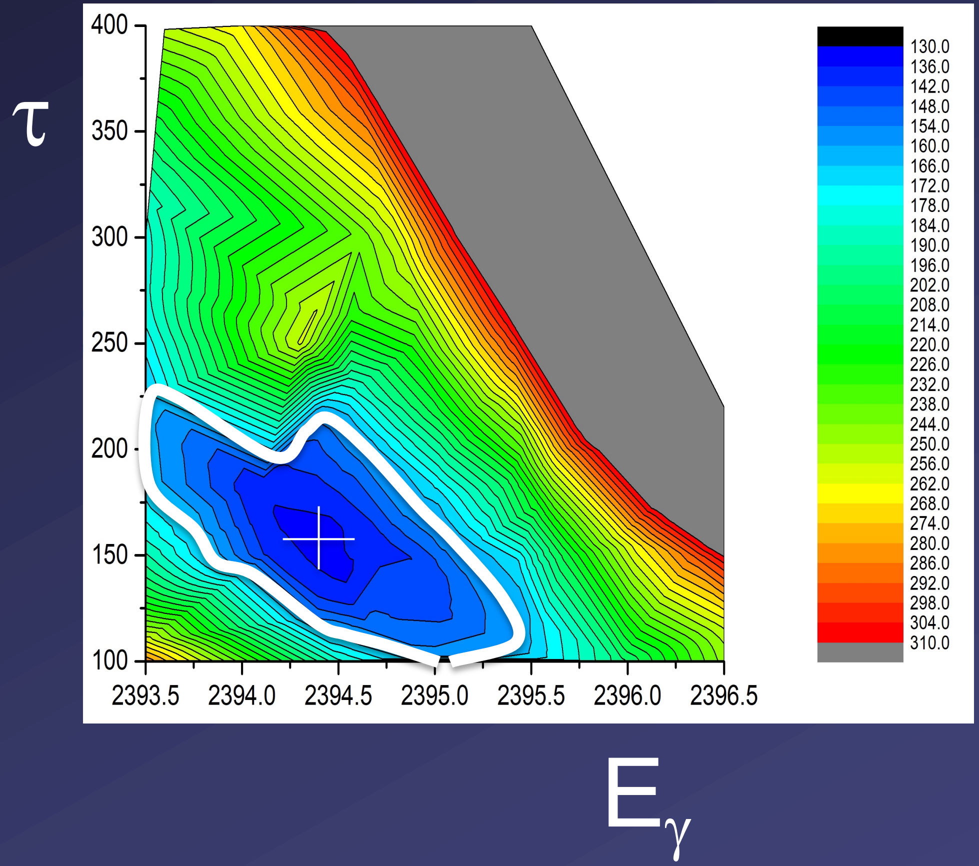


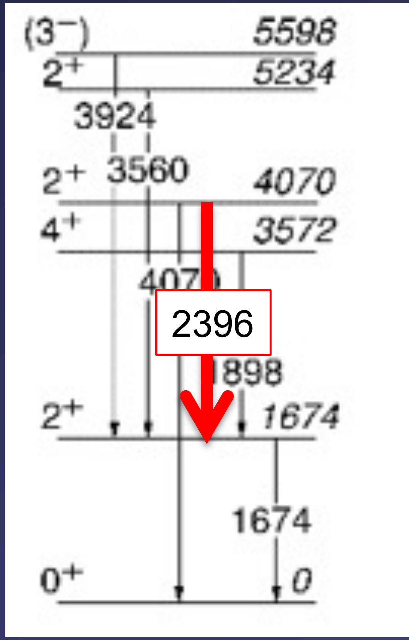
OUR Case - ^{20}O

$2^+_2 \rightarrow 2^+_1$ (2396 keV)



Likelihood surface

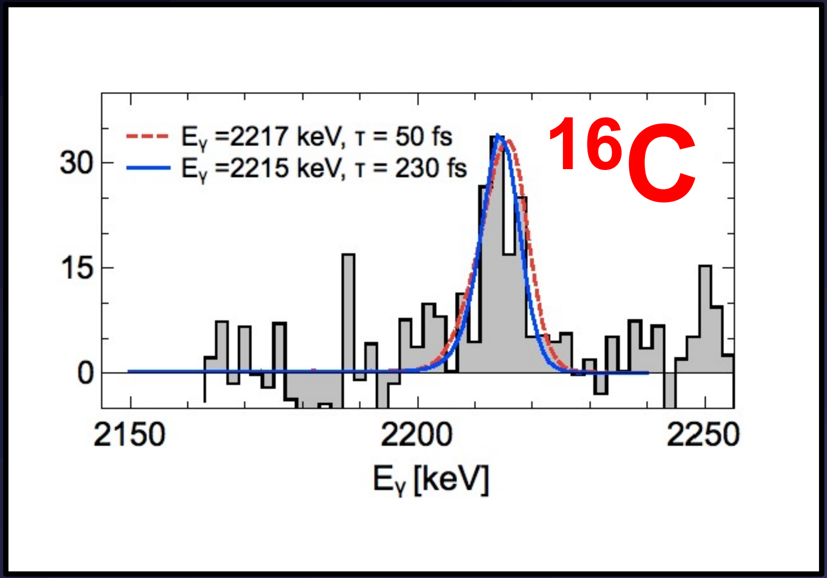




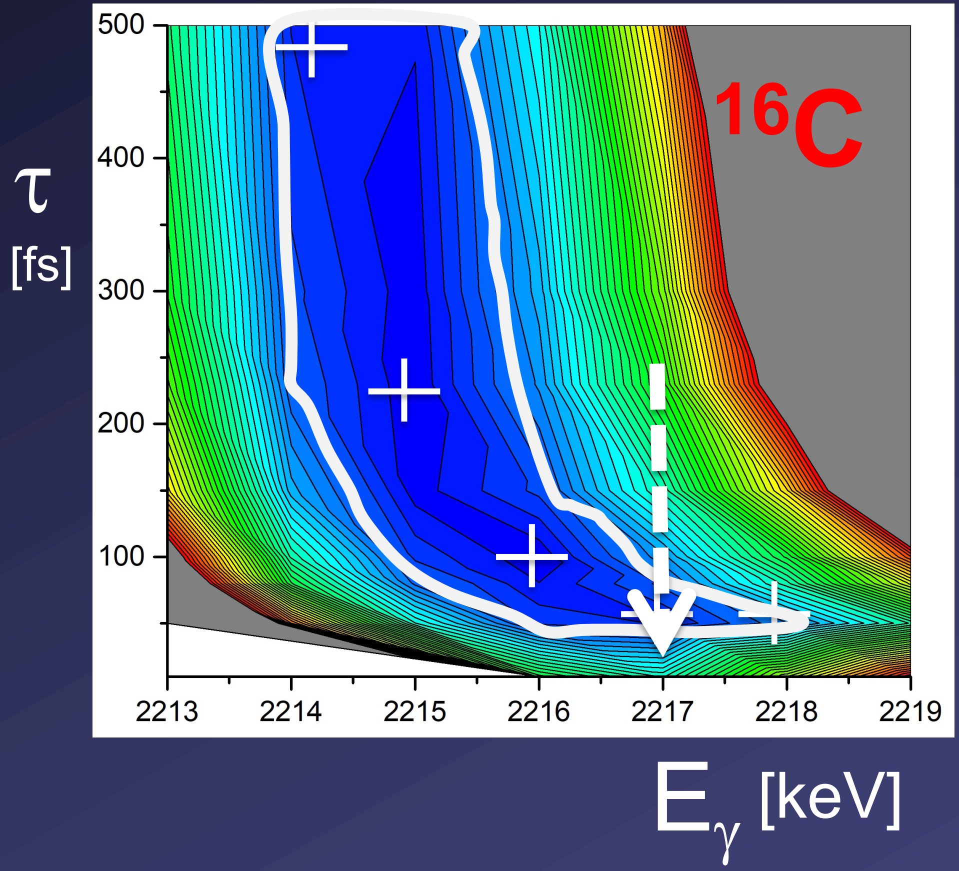
$\tau = 150^{+80}_{-30}$ fs

Only Possible with AGATA !!!

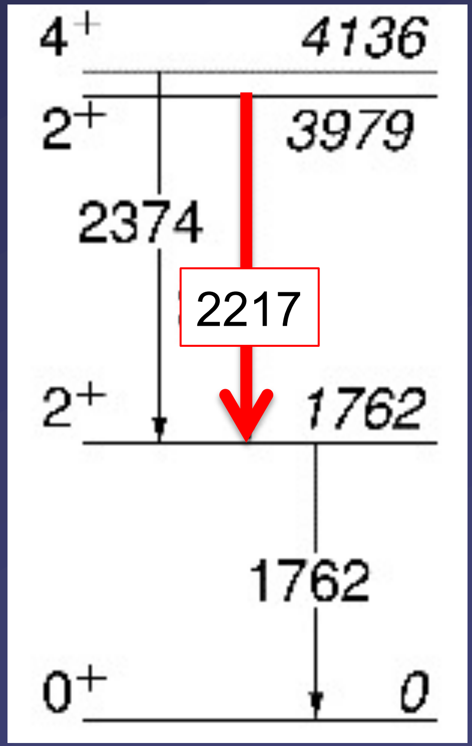
OUR Case – ^{16}C



Likelihood surface



^{16}C



Literature Eγ = 2217(2) keV

Comparison with *ab initio* predictions

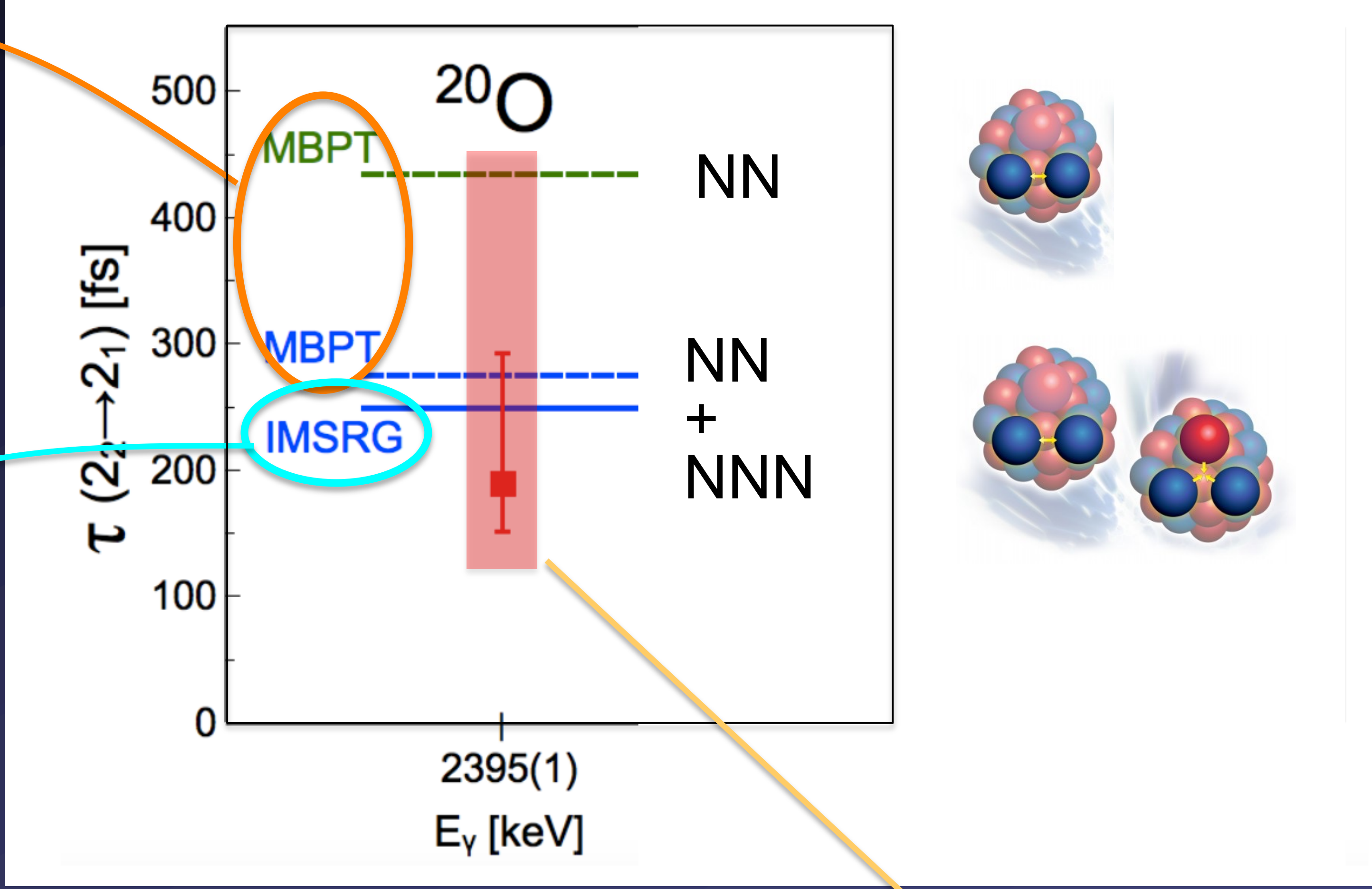
Partial Lifetimes

MANY BODY Pert. THEORY

Clear need for Three body term

In-Medium Similarity Renormalization Group (IMSRG)

One of most advanced approaches (with meson-exchange currents)



NO sensitivity would be obtained with conventional HPGe detectors
MUCH broader line shapes

Comparison with *ab initio* predictions

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

Partial Lifetimes

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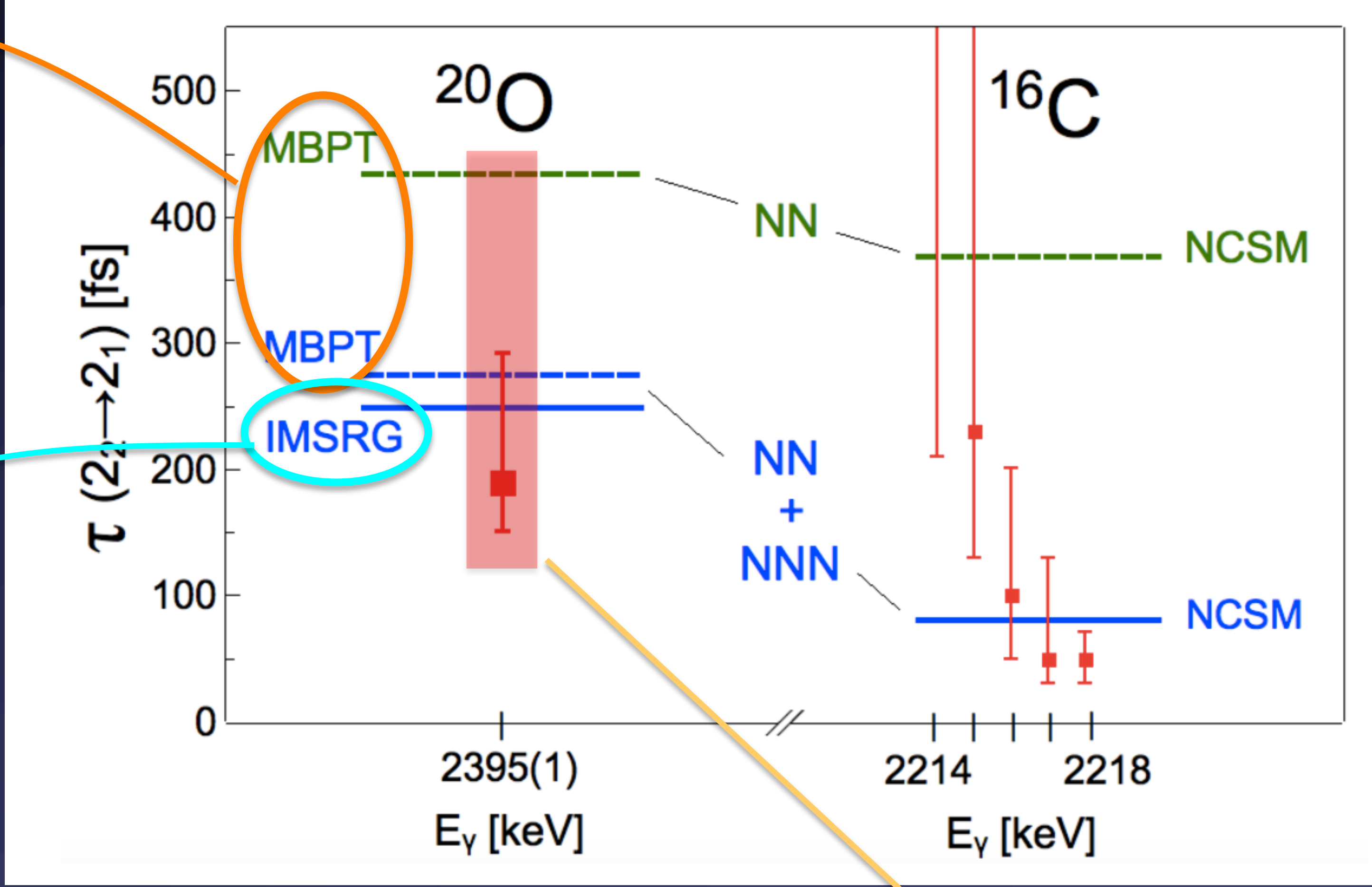
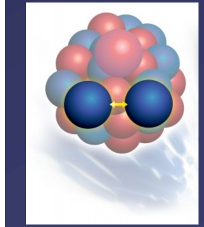
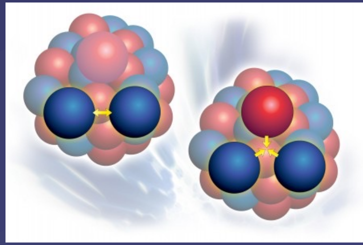


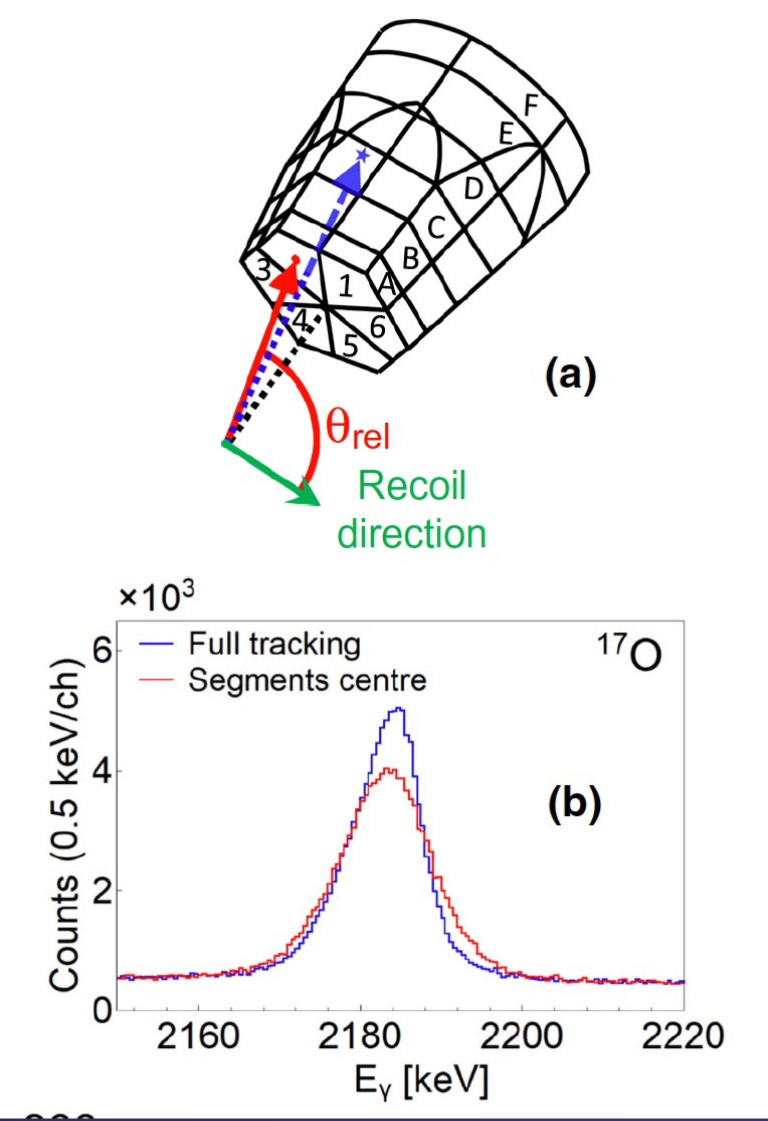


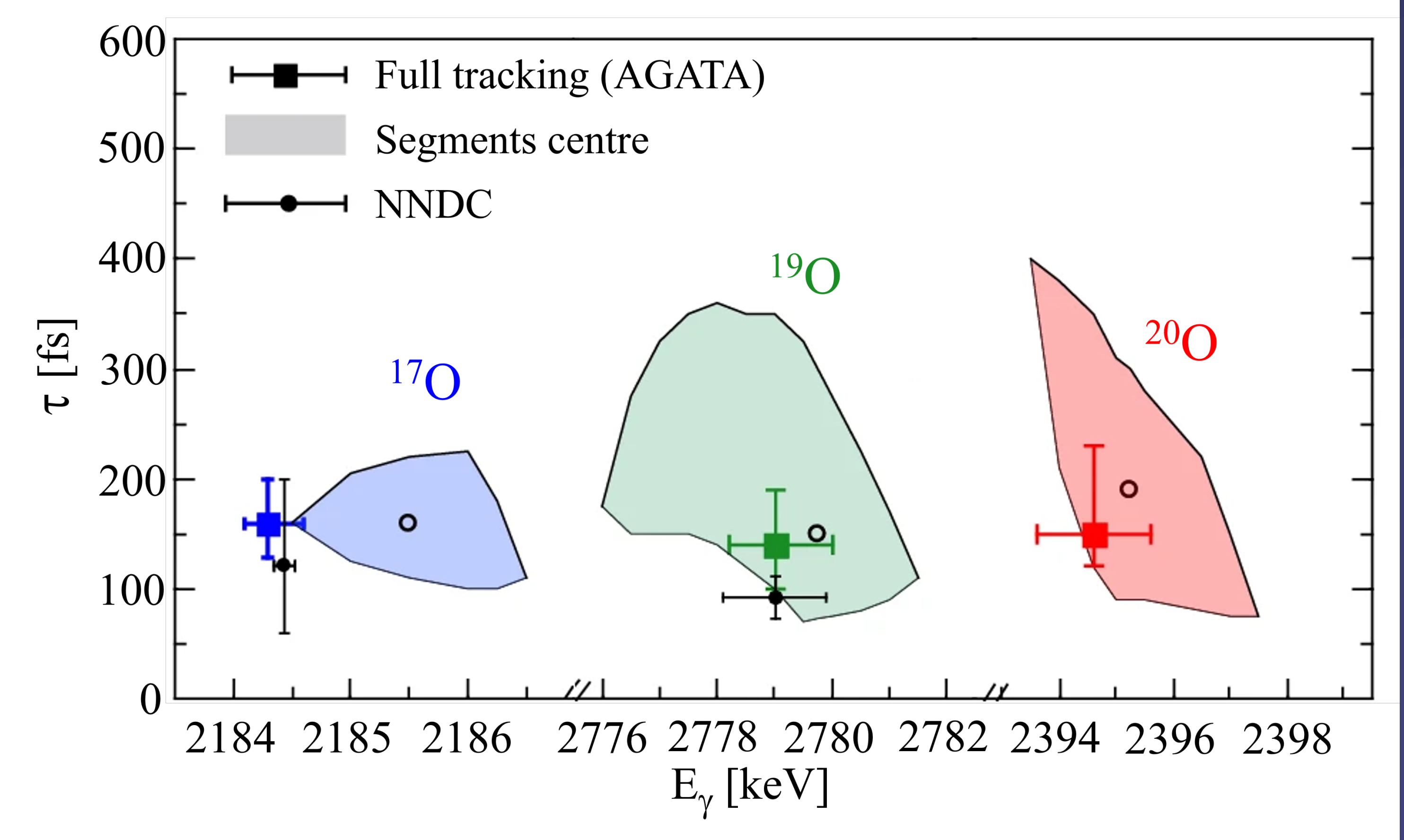


NO sensitivity would be obtained with conventional HPGe detectors
<u>MUCH broader line shapes</u>

TAKE-HOME message:

Tracking array essential for detailed analysis of the γ–ray line shapes **both at low and relativistic energies!**

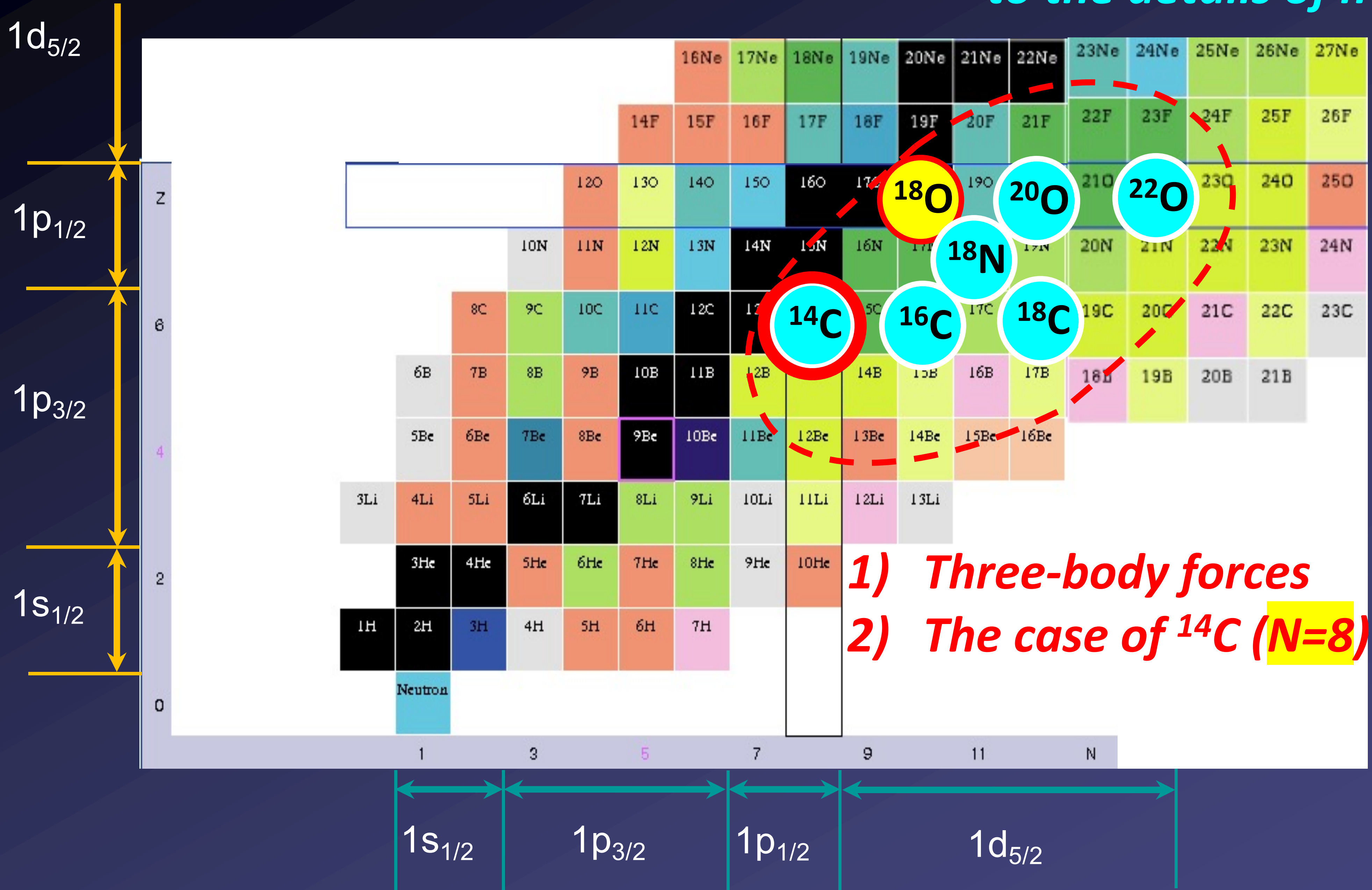




M. Ciemała, S. Ziliani, F.C.L. Crespi, S. Leoni, B. Fornal, A. Maj, et al., Eur Phys. J A, 57, 156, 2021

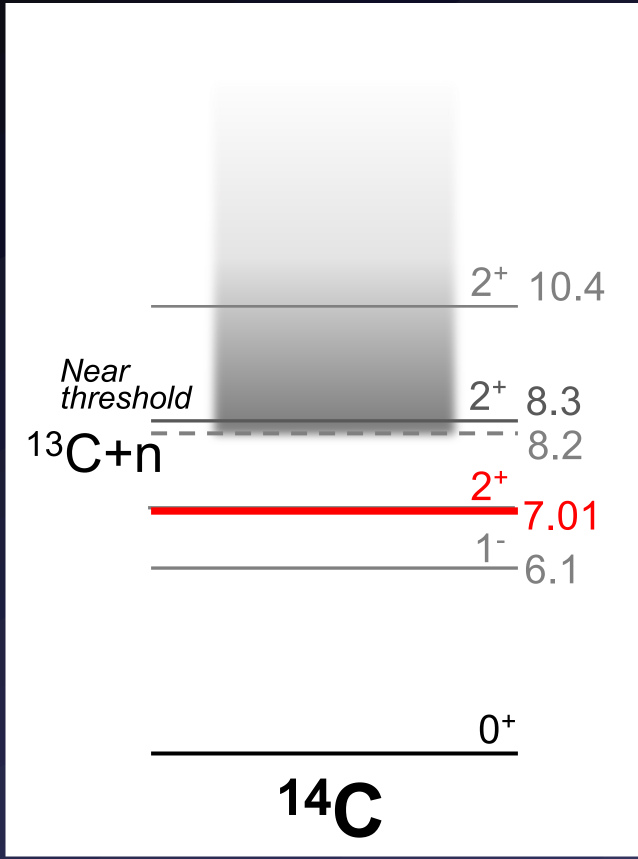
Nuclei of Interest

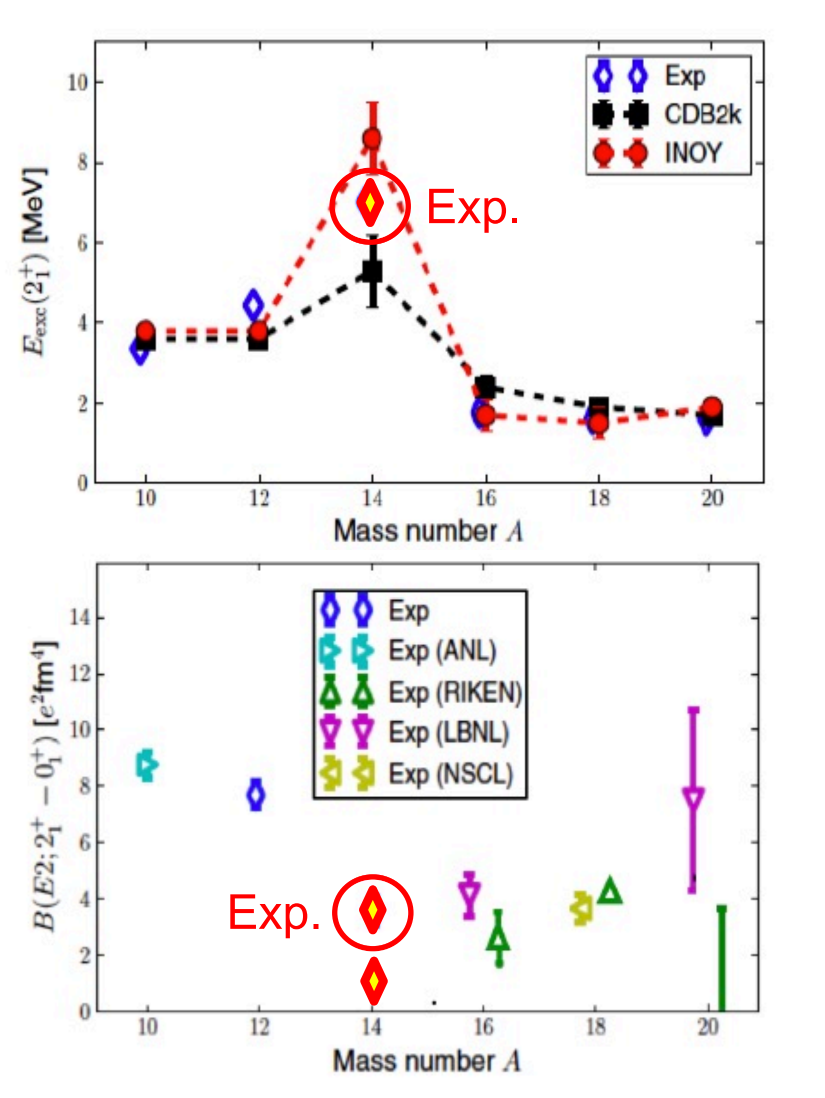
sensitivity of some observables to the details of n-n force

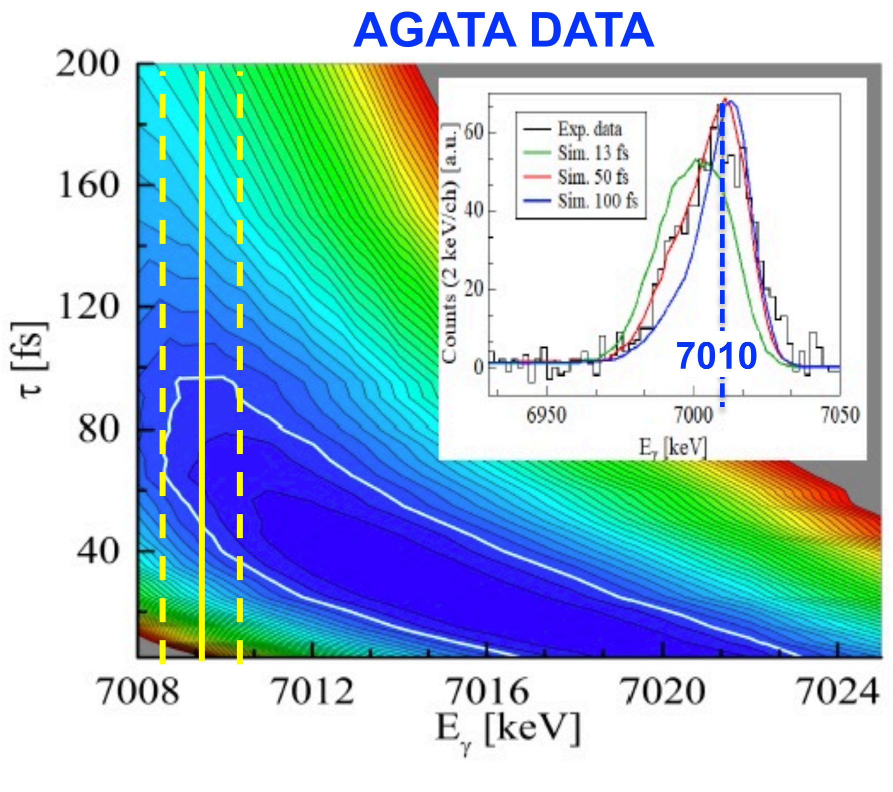


1) *Three-body forces*
2) *The case of ^{14}C (N=8)*

The case of ^{14}C – B(E2) of 2^+_1







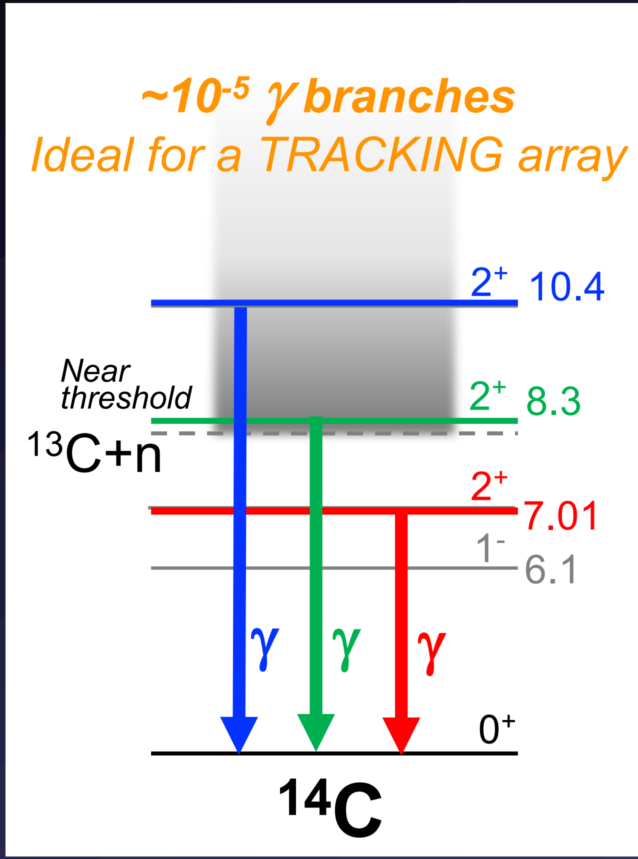
- E_γ = 7010(4) keV (NUDAT)
- **E_γ = 7009.5(8) keV**
  (extrapolated value from Q3D exp.)

$\tau = 65^{+32}_{-29}$ fs → B(E2) ~ 1 e^2fm^4

IN LINE with difficulties reported by **Coulex experiments** at iThemba and Florida State Univ.

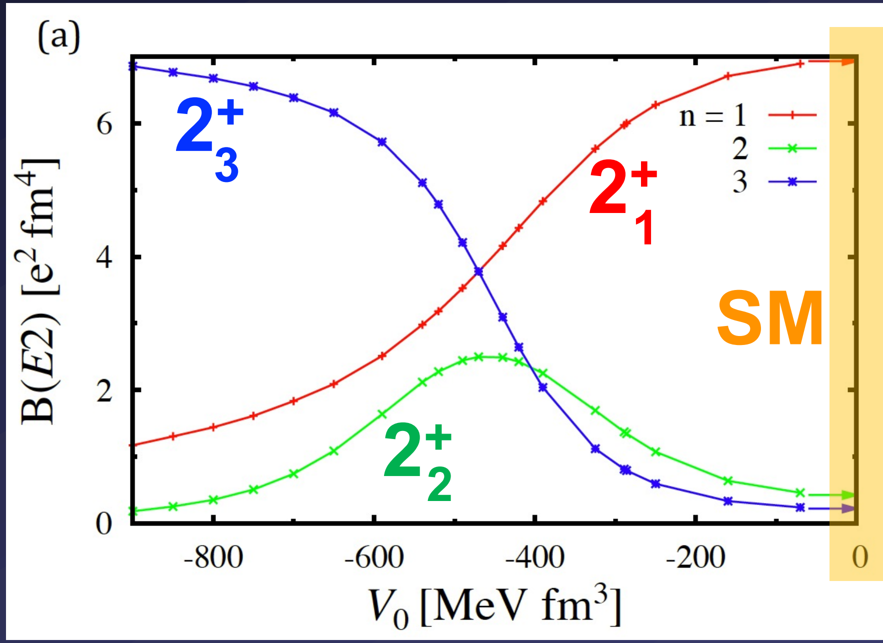
for 14C: B(E2) from <u>electron scattering</u> measurement reported in Conf. Proc. (1972)

The case of ^{14}C – B(E2) of $2^+_{1,2,3}$



SHELL MODEL Embedded in the Continuum (SMEC)

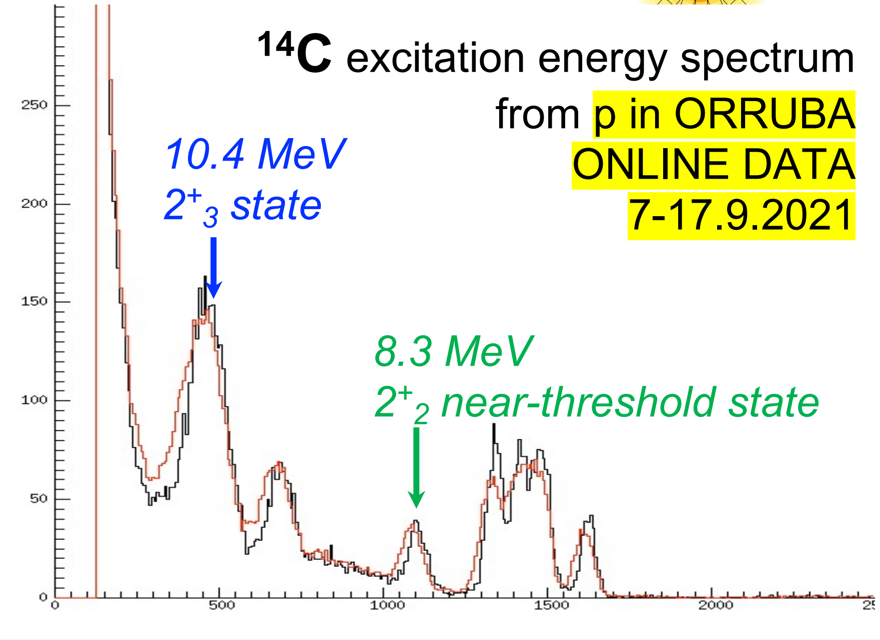
J. Okolowicz, M. Ploszajczak, W. Nazarewicz, Fortschr. Phys. 61, 66 (2013)



B(E2)'s from 2+ states give access to V_0
Continuum Coupling constant

- ***2016: Exp. Approved high-p. AGATA@GANIL** → Never Run*
- ***2019: Exp. Approved high-p. GRETINA@Argonne** → Run in 2021*

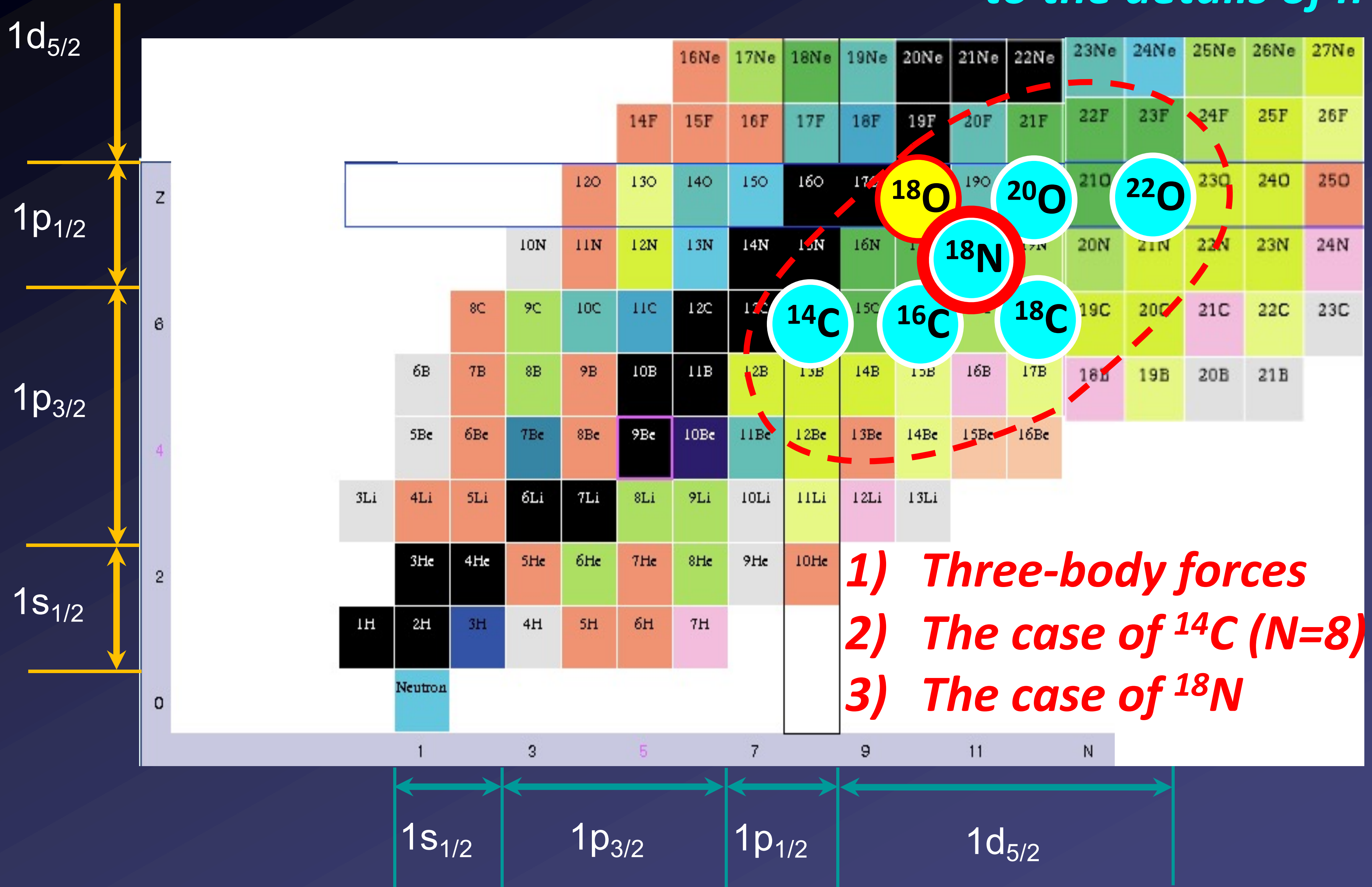
GODDESS



***Our sensitivity limit is 10^{-5}** … We will answer the question about the expected γ branch !*

Nuclei of Interest

sensitivity of some observables to the details of n-n force

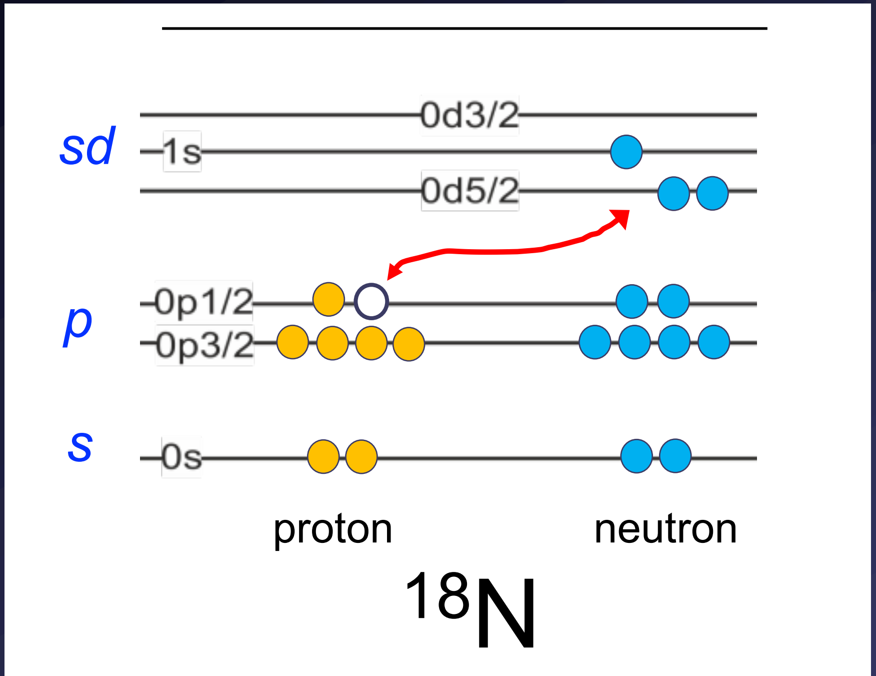


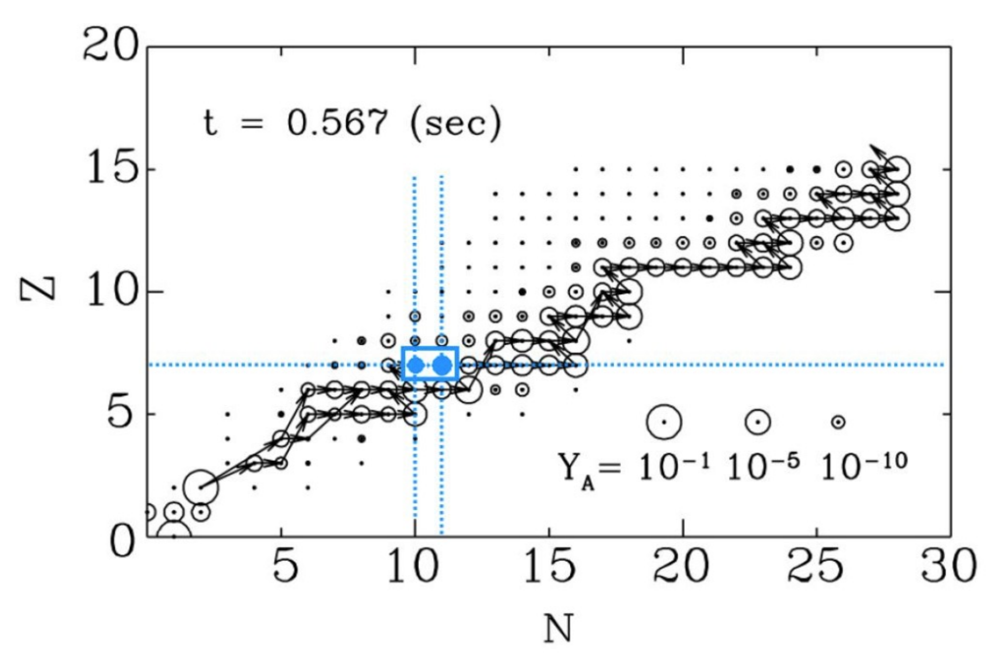
1) *Three-body forces*
2) *The case of ^{14}C (N=8)*
3) *The case of ^{18}N*

The case of ^{18}N:

a challenge for Shell Model approaches (and *ab initio*)

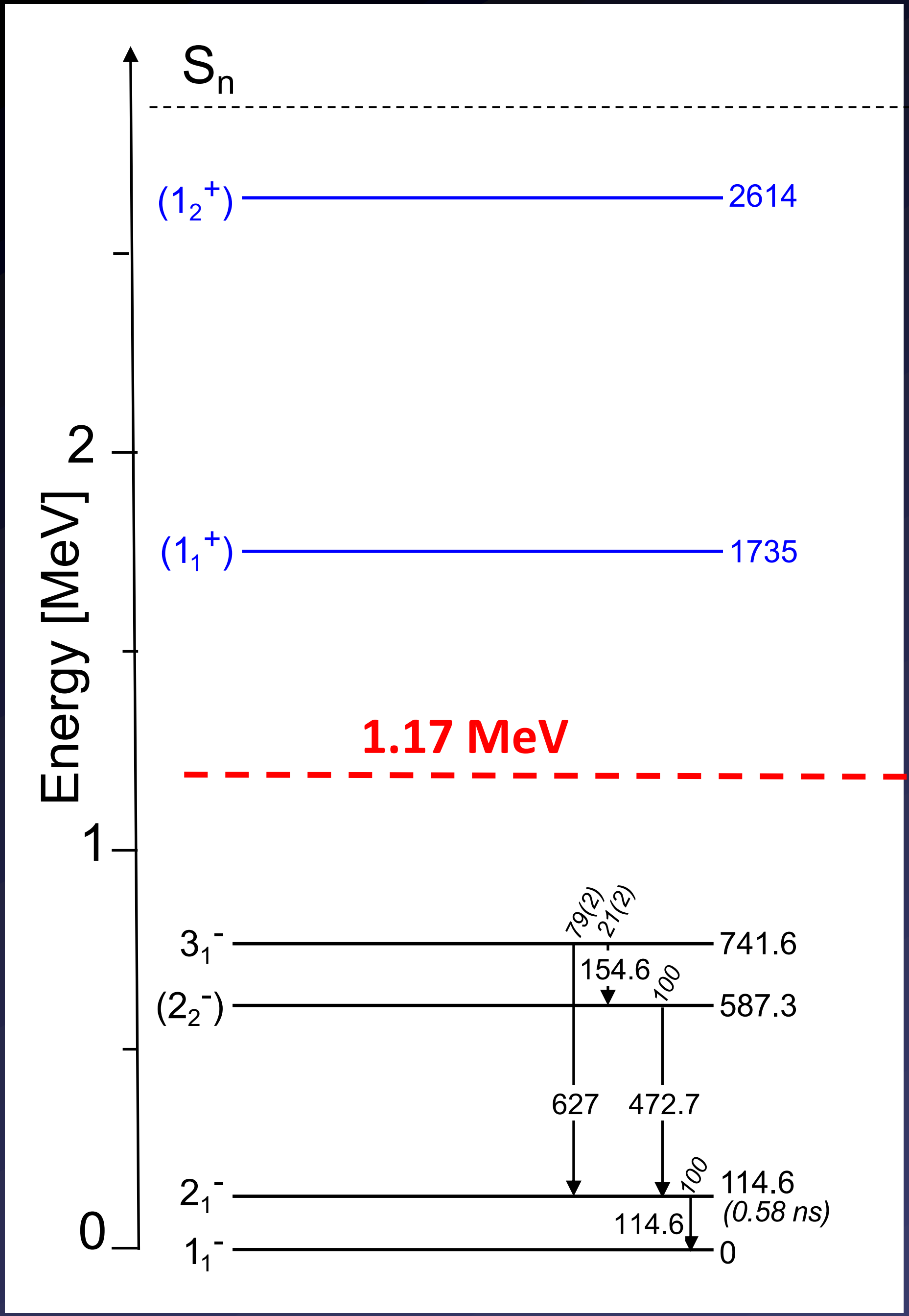
M. Terasawa et al., Astrophys. J. 562, 470 (2001).

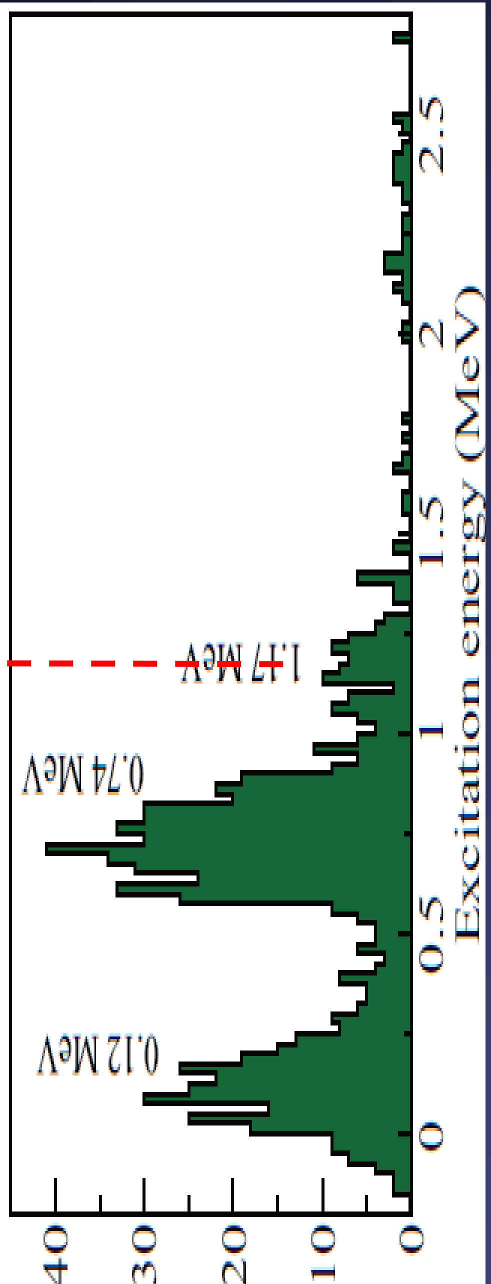




a good testing ground
for multishell *p-sd* interactions

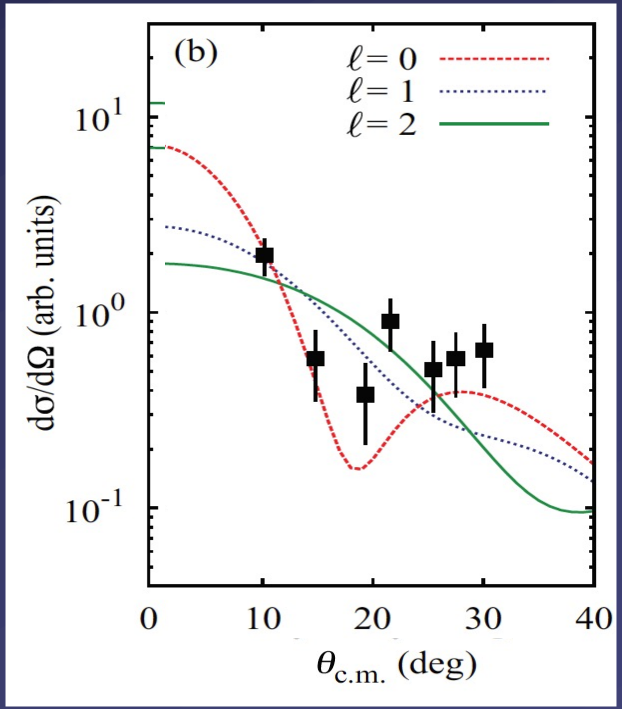
^{18}N structure has strong influence
on (n,γ) cross sections
entering network calculations for
r-process nucleosynthesis in supernovae





HELIOS DATA

(d,p) with ^{17}N beam



(1^-_2)

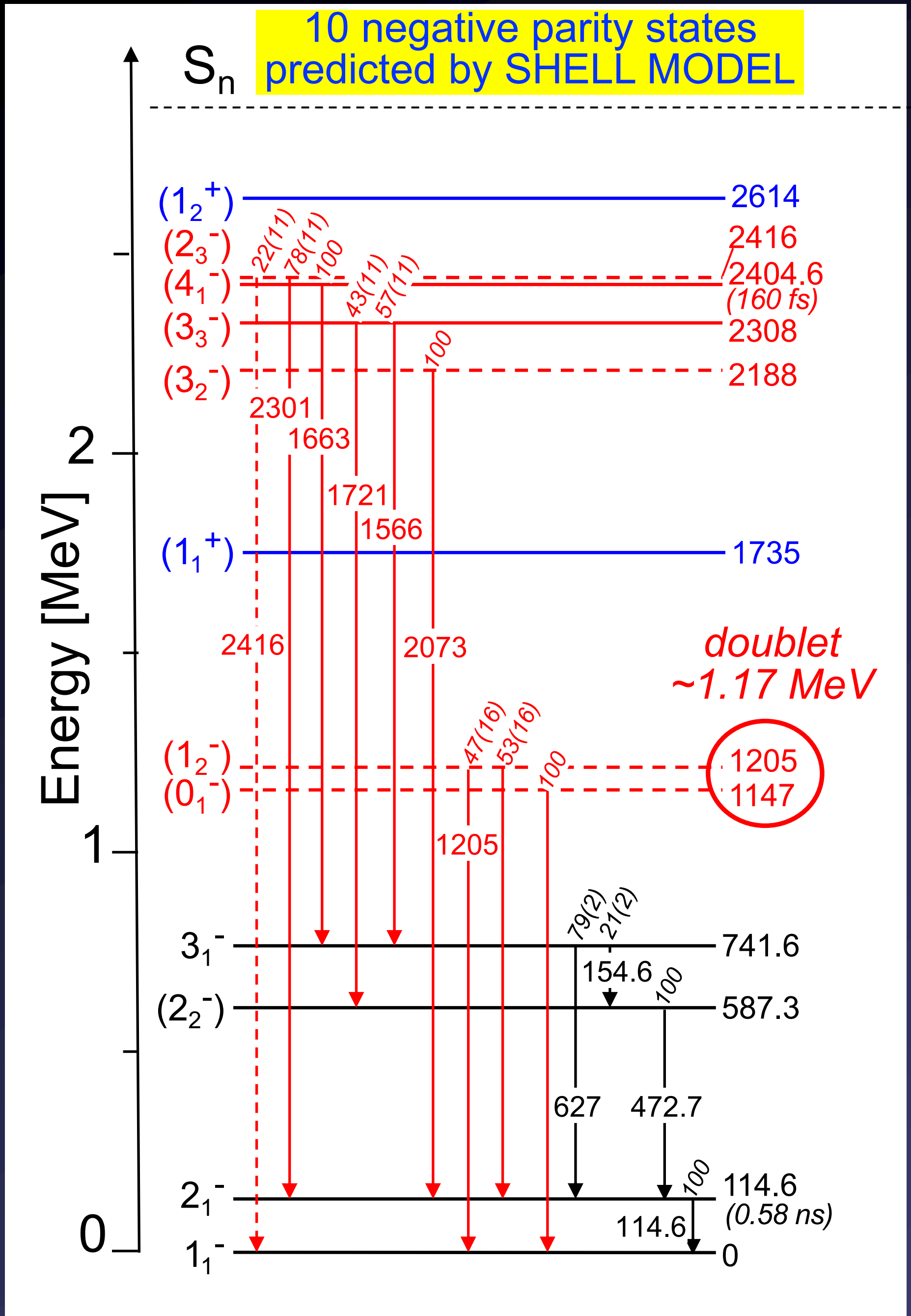
or

(0^-_1) & (1^-_2)

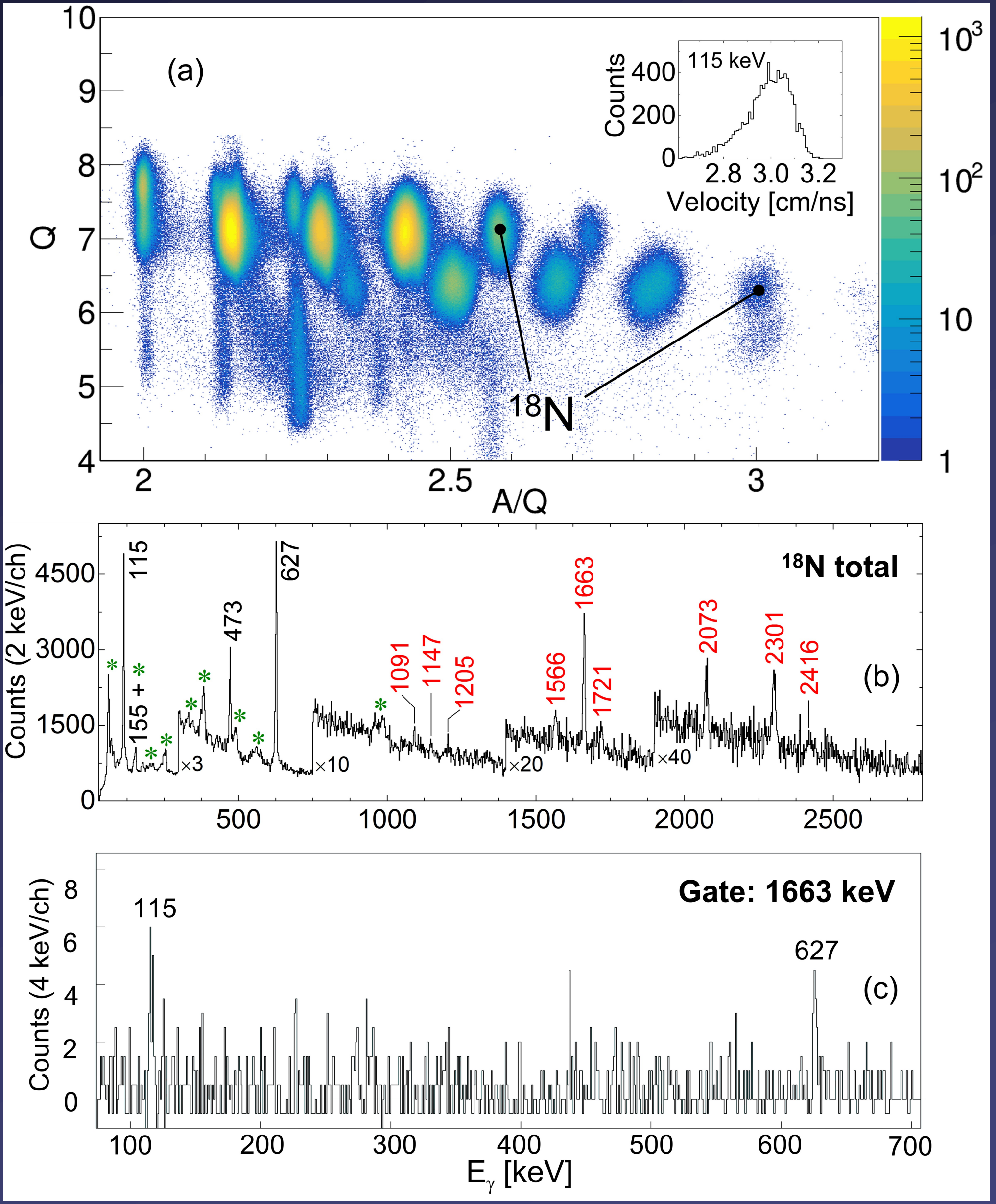
state of interest for (n,γ) cross section for astrophysics

C.R. Hoffman et al., PRC88, 0443317 (2013)

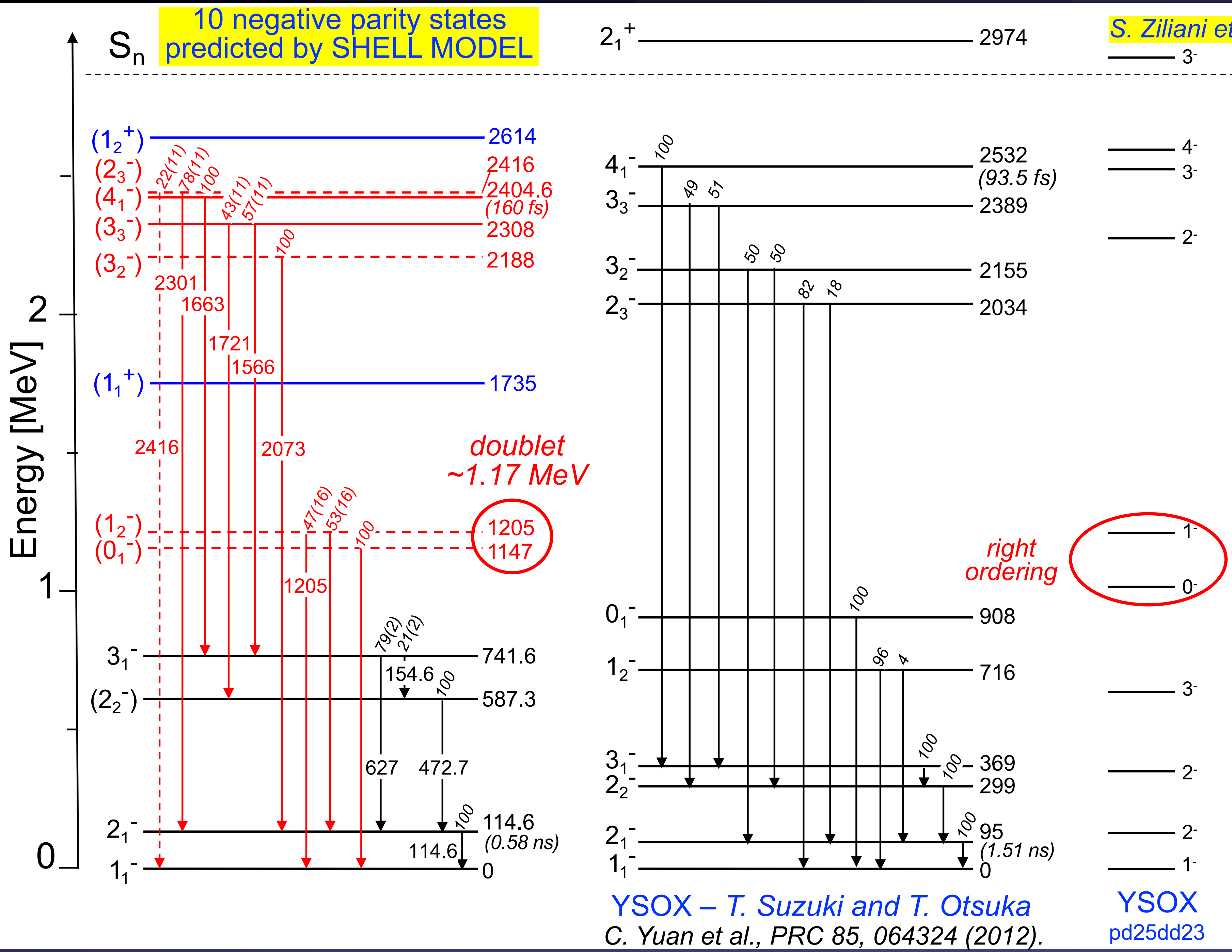
AGATA+ VAMOS DATA



in agreement with HELIOS data

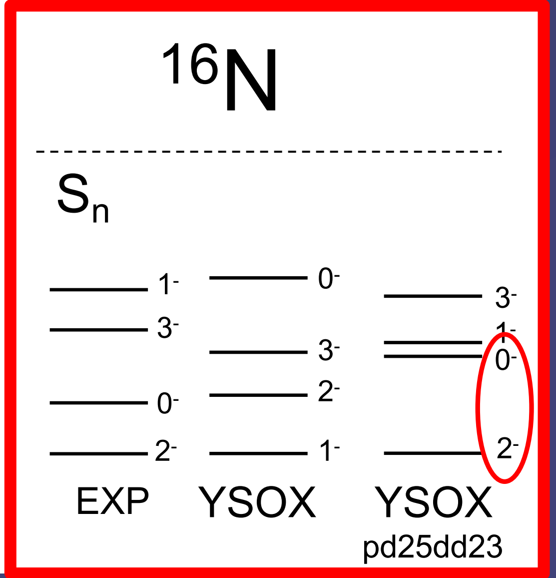


S. Ziliani et al., in print in Phys. Rev. C Letter



20-30% adjustments of selected **cross-shell** ***p-sd*** two-body matrix elements

simultaneous reproduction of ^{16}N
(g.s. state and first exc. state correct!)
long standing issue



CONCLUSIONS

exp. E656@GANIL - AGATA+PARIS+VAMOS

Light Nuclei

Test Bench for most advanced THEORY predictions:
ab-initio and Shell Model, including also coupling with the Continuum …

- **^{16}C, ^{20}O: impact of three-body forces on electromagnetic observables**
  → development of DSAM technique for deep-inelastic reactions
  tested on known litterature cases

- **^{14}C: need for precision measurements of B(E2)'s of 2^+_1 (and 2^+_2 and 2^+_3)**
  → impact of continuum on states properties

- **^{18}N: complete set of bound negative parity states**
  → impact on cross shell p-sd matrix elements of Shell Model

key importance of tracking arrays in low-energy reactions experiments

Thank you for the attention

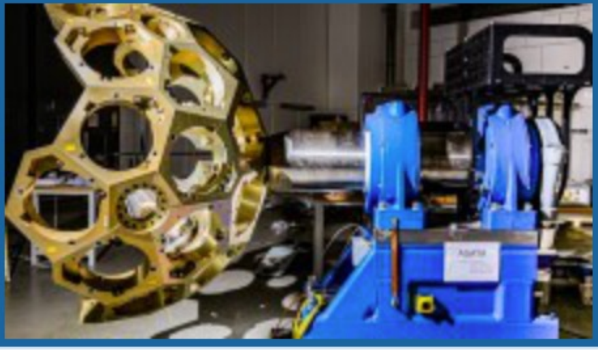
Thank to the AGATA+PARIS+VAMOS Collaborations

Results from experiment E656@GANIL - AGATA+PARIS+VAMOS (July 2017)

*M. Ciemała , S. Ziliani, F.C.L. Crespi, S. Leoni, B. Fornal, A. Maj, et al., Phys. Rev. C 101, 021303(R), 2020 (3N-forces in: ^{16}**C**, ^{20}**O**)*
M. Ciemała, S. Ziliani, F.C.L. Crespi, S. Leoni, B. Fornal, A. Maj, et al., Eur Phys. J A, 57, 156, 2021 (New DSAM technique)
*S. Ziliani, M. Cimała, F.C.L. Crespi, S. Leoni, B. Fornal, et al. (in print in Phys. Rev. C Letter) (Spectroscopy of: ^{18}**N**)*
*S. Ziliani, M. Cimała, F.C.L. Crespi, S. Leoni, B. Fornal, et al. (in preparation) (^{14}**C**)….*

REMINDER for the AGATA Community

LEGNARO (Italy) – 8-12 November 2021



pre-PAC Workshop of AGATA@LNL

Discussion of proposal preparation (PAC in Feb. 2022)

8-10 November 2021
INFN-LNL
Europe/Rome timezone

https://agenda.infn.it/event/26966/

AGATA Collaboration Meeting 2021

STATUS Report of AGATA experiments (GANIL Campain)
Requested from AGATA Collaboration

AGATA
ADVANCED GAMMA TRACKING ARRAY

10-12 November 2021
Legnaro National Laboratory
Europe/Rome timezone

https://agenda.infn.it/event/27358/

PLEASE REGISTER TO BOTH EVENTS !!!