Study of multi-neutron configurations towards the neutron drip-line

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+ the R3B collaboration

How is superfluidity evolving towards the drip line (seq / direct / BCS-BEC/ quasi molecular) ?

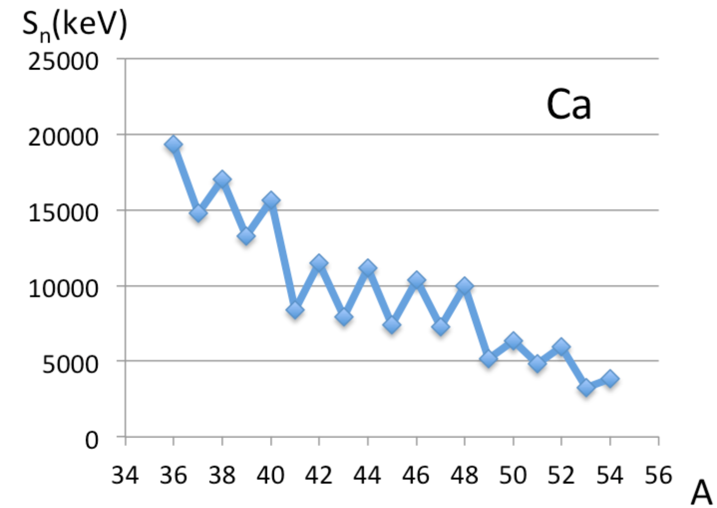
Does a generalized Ikeda conjecture hold for di- and tetra-neutron configurations ?

Which reaction mechanism can be used to study these pheneomena ?

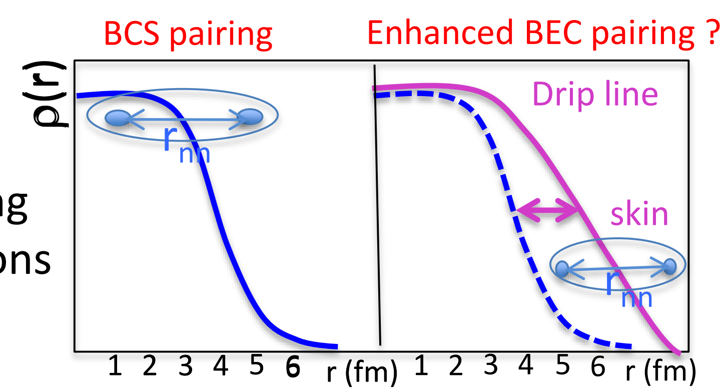
Signs of superfluidity, evolution towards the drip line

Pairing correlations play essential role in atomic nuclei and in neutron stars (NS)

- oscillations in S_n values
- g.s. spin 0^+ of even-even nuclei
- Moment of inertia << rigid value
- Enhanced pair transfer
- cooling of NS, glitches



Pairing scheme towards drip-line: from BCS to BEC ? *(e.g. Hagino et al. PRL99 (2007))*



- Few information available
- Evolution with binding energy ?

-> Different systems needed to underestand pairing

-> Determine average distance r_{nn} between neutrons

Possible existence of a narrow 4n resonance (e.g. Marquès, Shimura)

-> Tetra neutron correlations could play a role in describing the superfluidity in nuclei

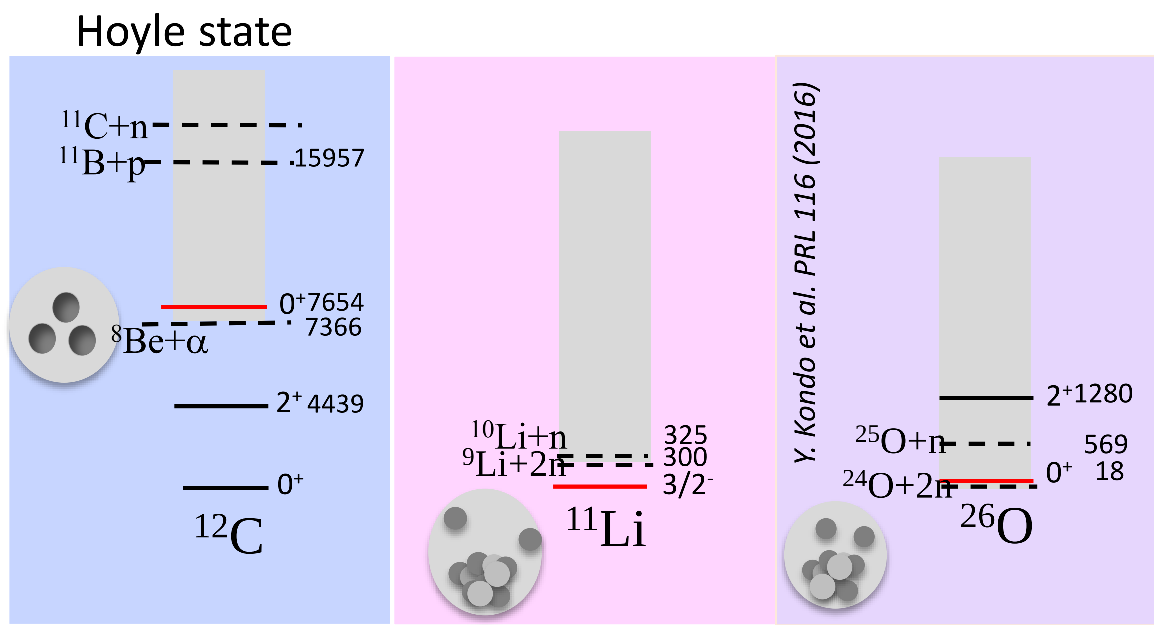
-> Role not yet revealed or studied in atomic nuclei

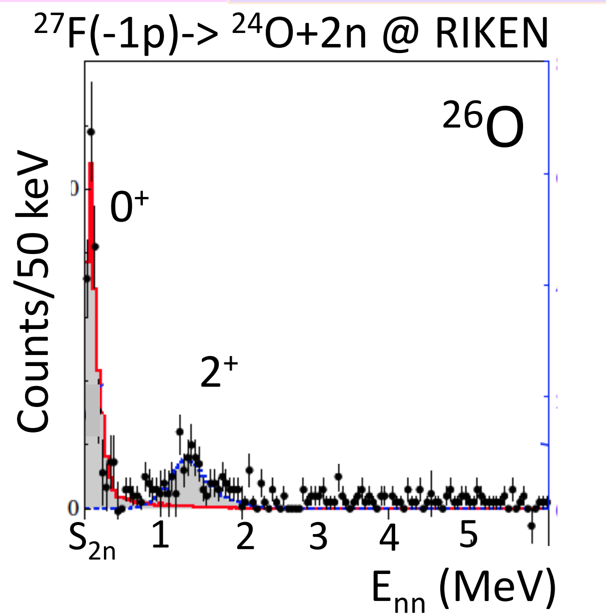
How to study these correlations ?

-> Suddenly promote neutrons in the continuum and observe their decay -> GSI/NEULAND/GLAD

Ikeda's conjecture applied to neutron cluster configurations?

α,2p,2n clustering (*adapted from J. Okolowicz, et al. Prog. Th. Phys. Supp. 196 (2012)*)

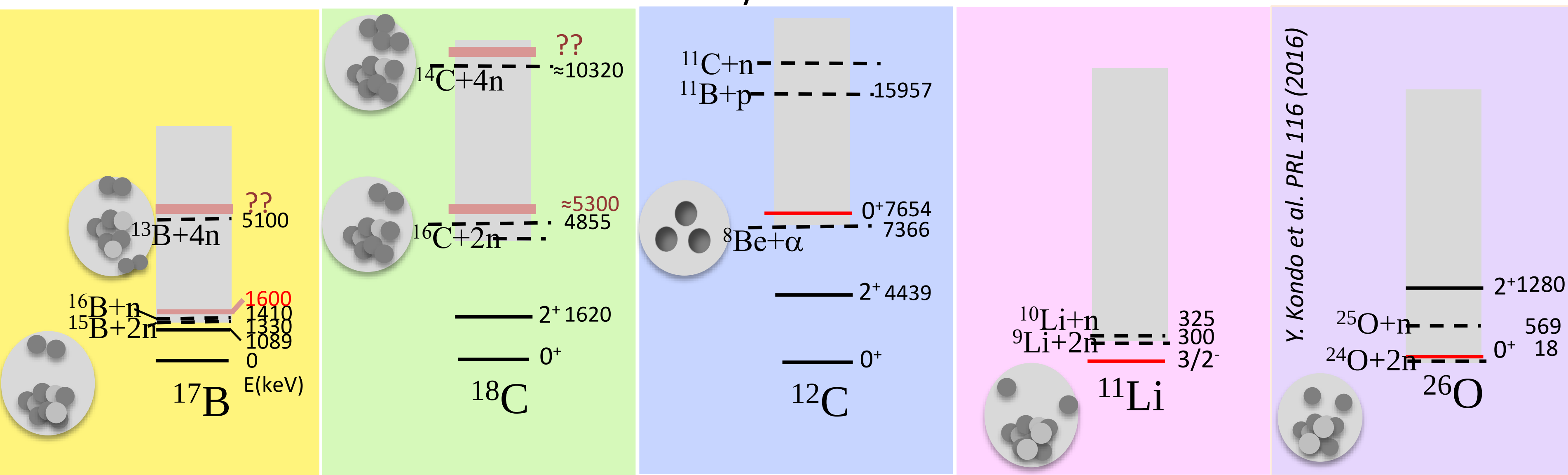




Ikeda's conjecture applied to neutron cluster configurations?

α,2p,2n clustering (*adapted from J. Okolowicz, et al. Prog. Th. Phys. Supp. 196 (2012)*)

Hoyle state



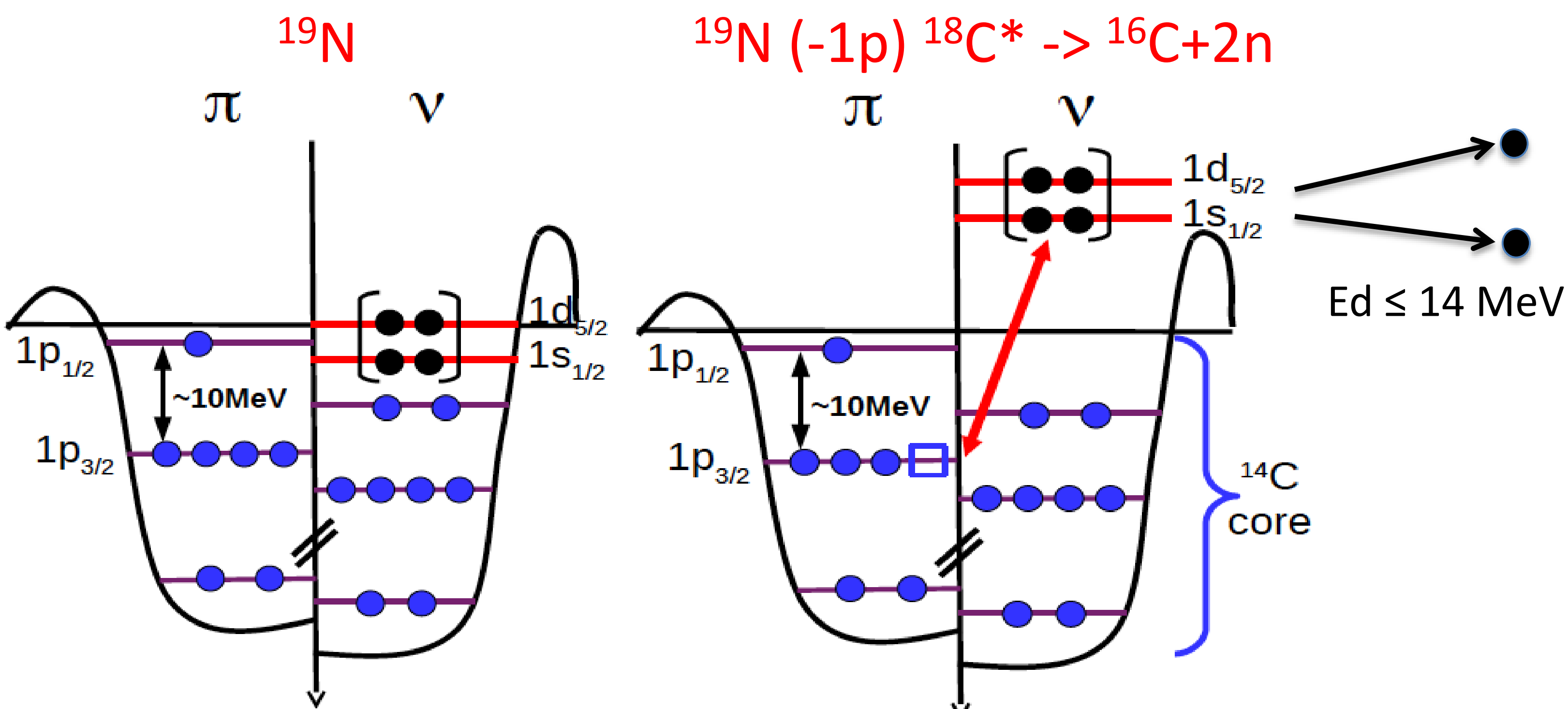
Future work

Present study

- Are there narrow resonances systematically present around $S_{2n,4n}$ thresholds?
- If present, are their production influenced by the reaction mechanism?
  - -> use different probes, i.e. (-1n) and (-1p) knockout.
- How 2n correlations look like above S_{2n}?
  - -> Direct or Sequential decays / gamma-decay ?

Neutron correlations in the neutron-rich ^{18}C nucleus

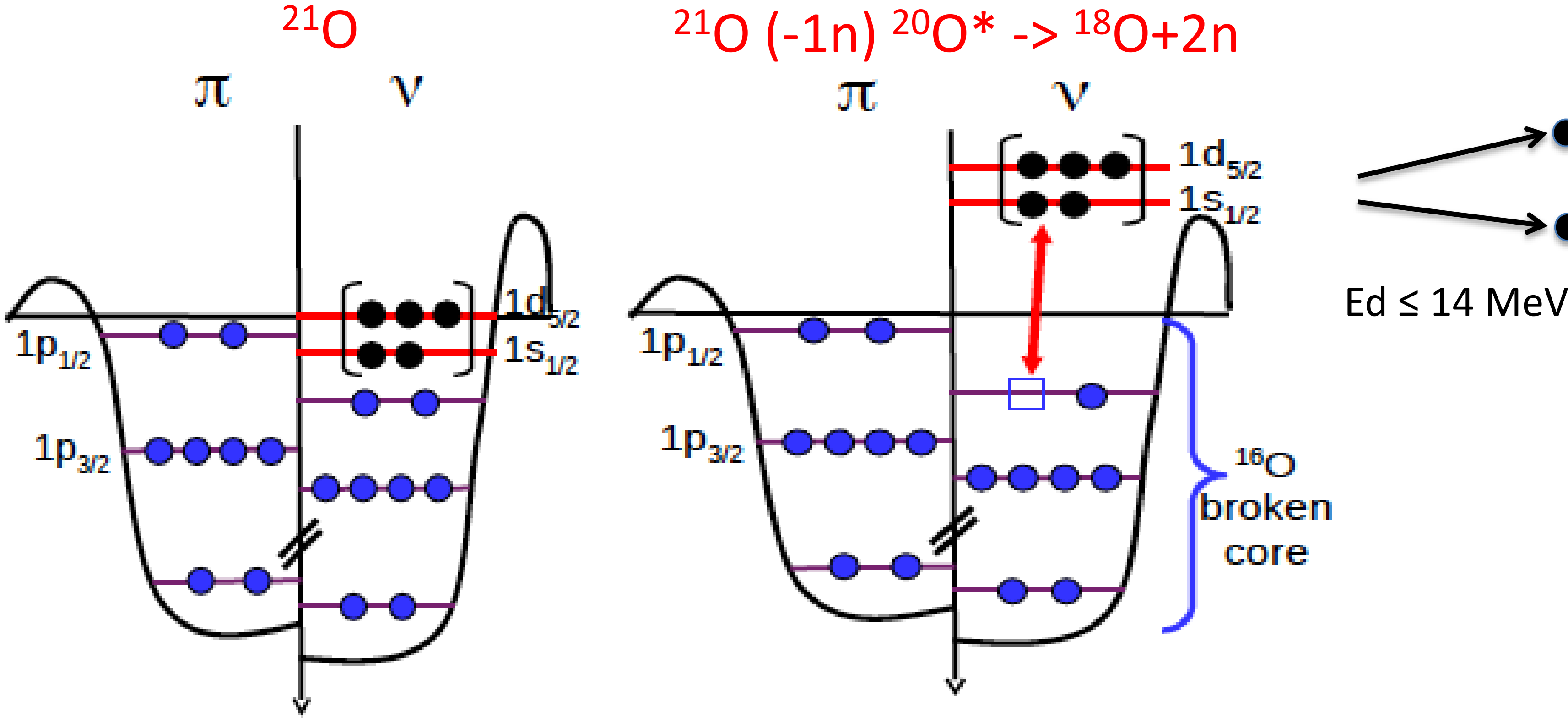
$^{18}C \approx {}^{14}C$ core +4n valence neutrons



- High energy *proton* knock-out reaction (p,2p) at GSI (400A.MeV) *-> quasi-free mechanism*
- Deeply bound *proton* orbitals *-> energy piston to promote neutrons into the continuum*
- Sudden approximation *-> neutron correlations weakly affected by proton knock-out*
- Deduce information on their correlations from their observed decay patterns

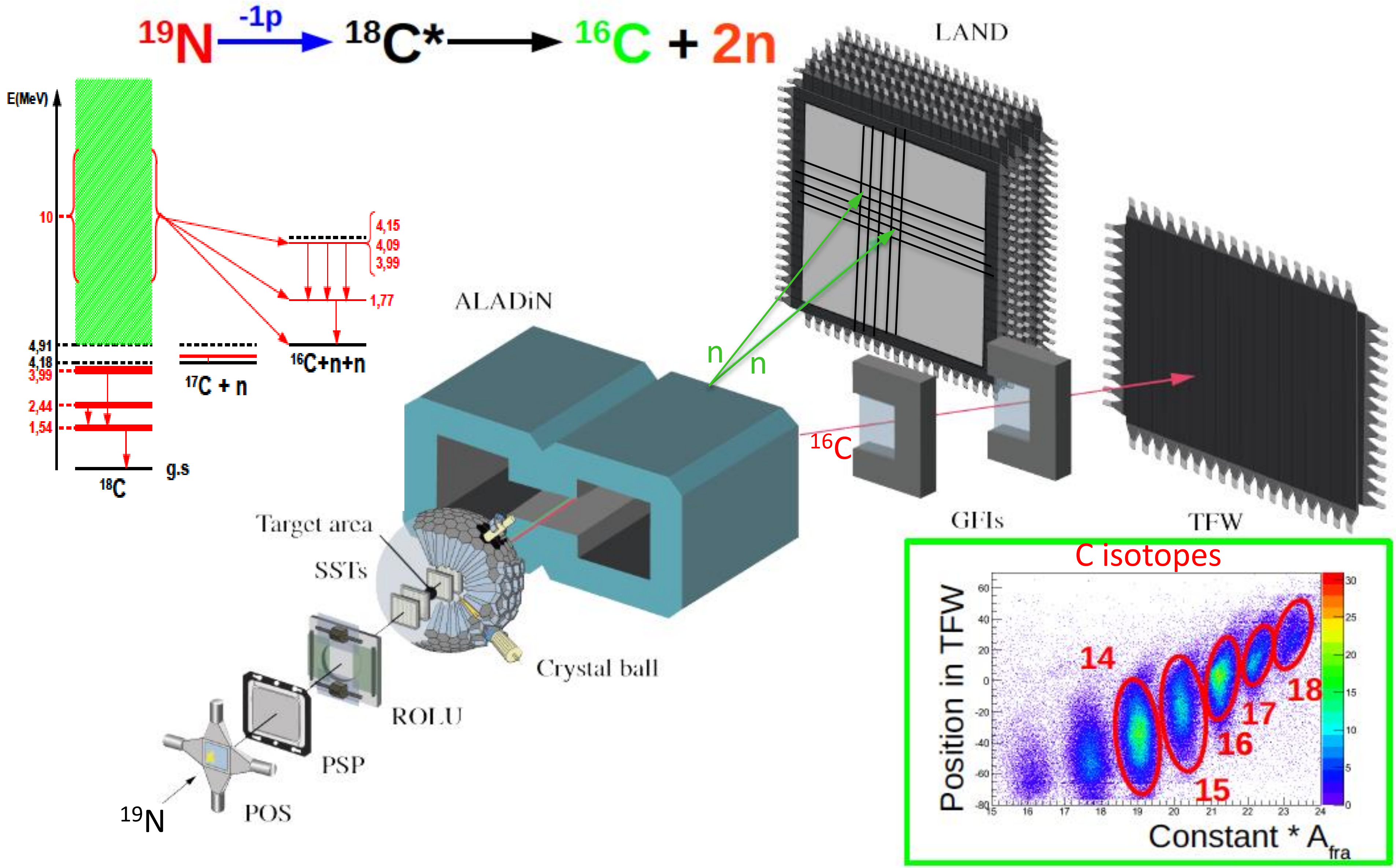
Neutron correlations in the neutron-rich ^{20}O nucleus

$^{20}O \approx {}^{16}O$ core +4n valence neutrons



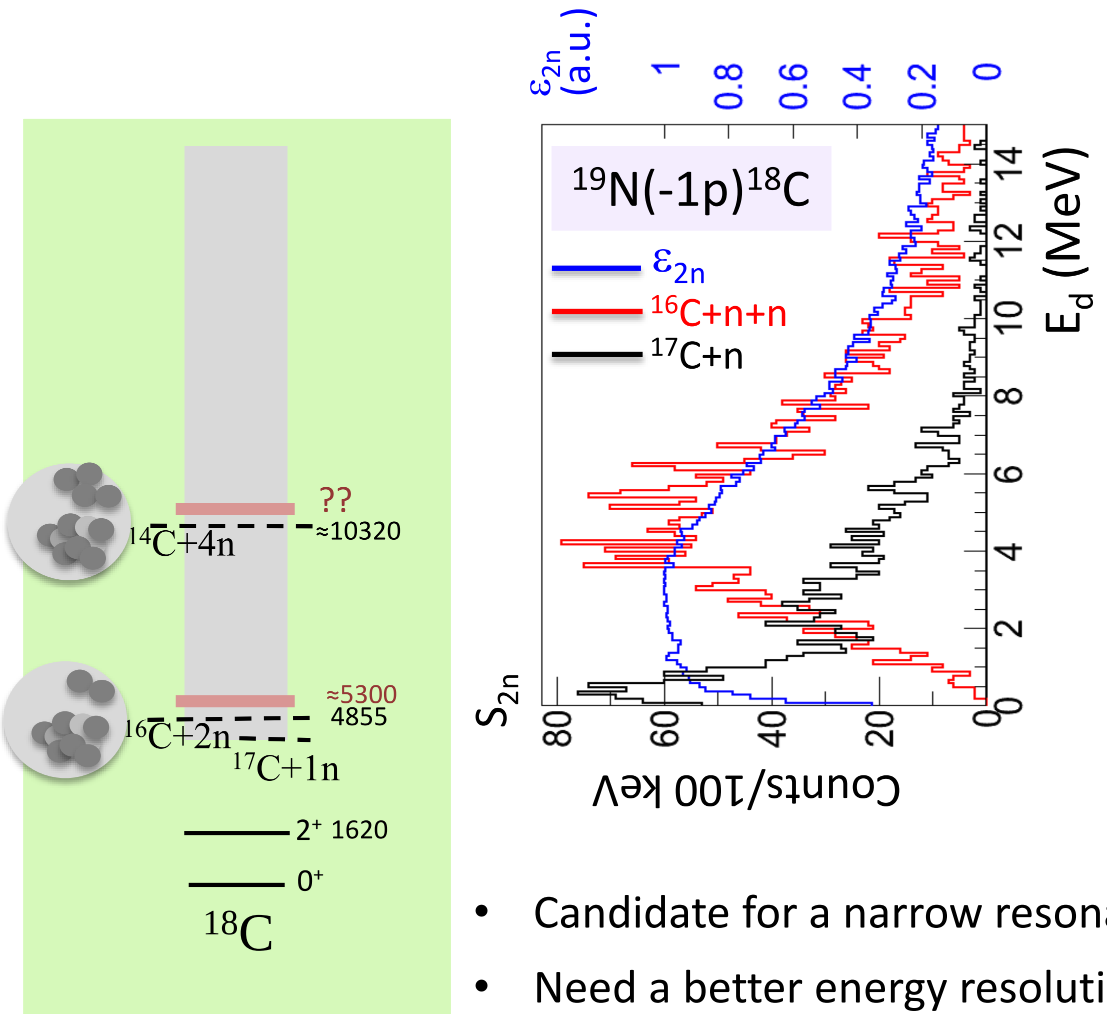
- High energy *neutron* knock-out reaction (p,pn) at GSI (400A.MeV)
- Deeply bound *neutron* orbitals *-> energy piston to promote neutrons into the continuum*
- Neutron *correlations likely affected by neutron knock-out*
- How their correlations in ^{20}O deviate from the ^{18}C isotone ?

Proton knockout reaction to study unbound states in ^{18}C at GSI



90% of the decays proceeds without γ-decay

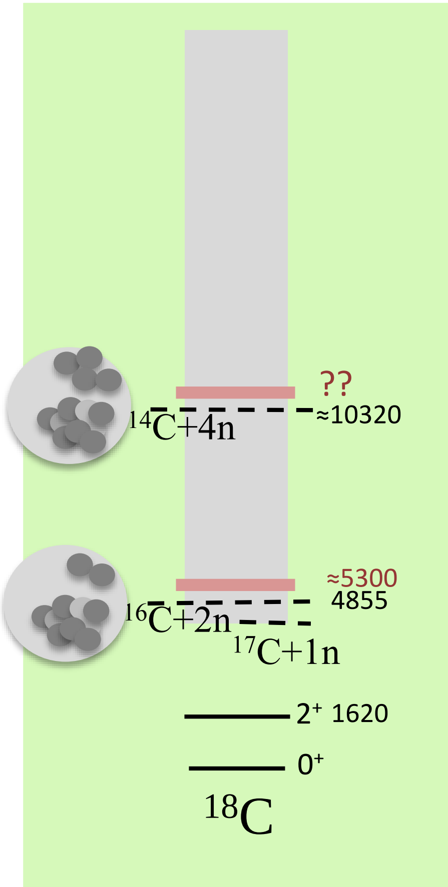
Energy spectra of ^{18}C derived from detecting 1n or 2n

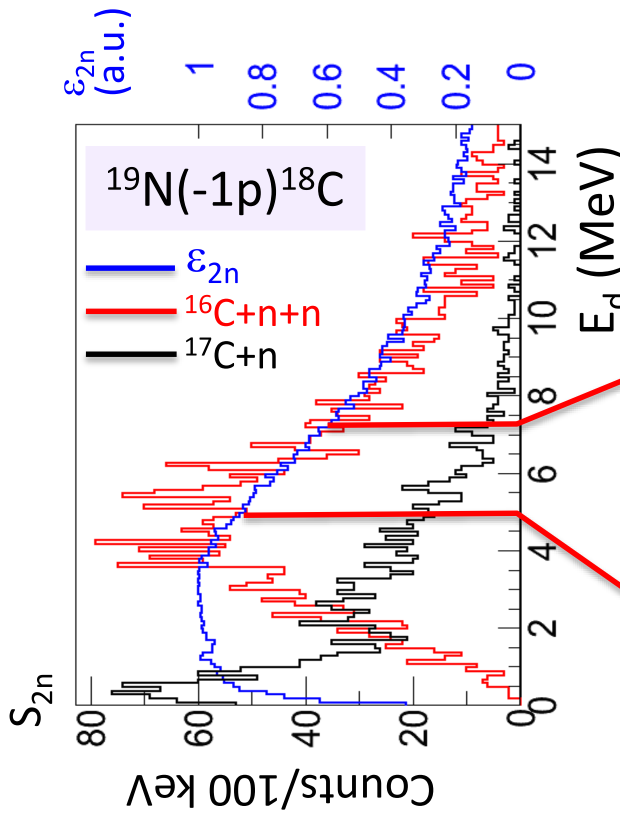


- Candidate for a narrow resonance around S_{2n}
- Need a better energy resolution to confirm its narrow width
- Need a better efficiency at low energy to see its possible 2n branch
- Need a better granularity to identify 4n decays

A. Revel (GANIL) preliminary

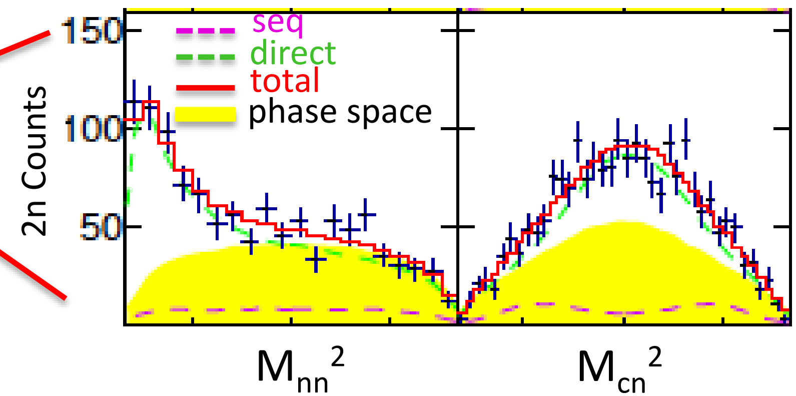
Neutron-neutron and core-neutron correlations in ^{18}C

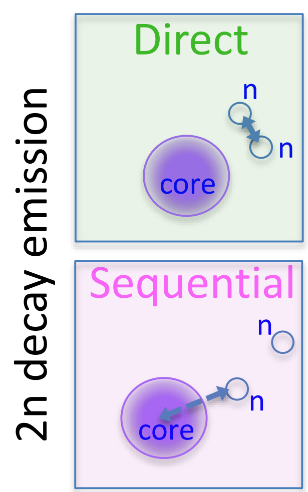




Direct decay strongly dominating

$\langle r_{nn} \rangle \approx 3.7$ fm





Small relative n-n energies

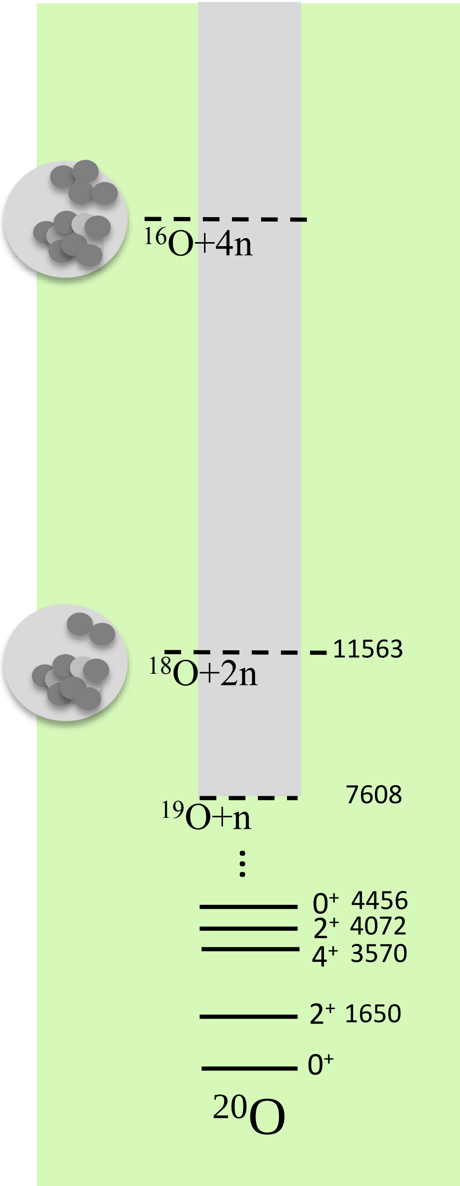
Rise of invariant mass M_{nn}^2 curve at ≈ 0

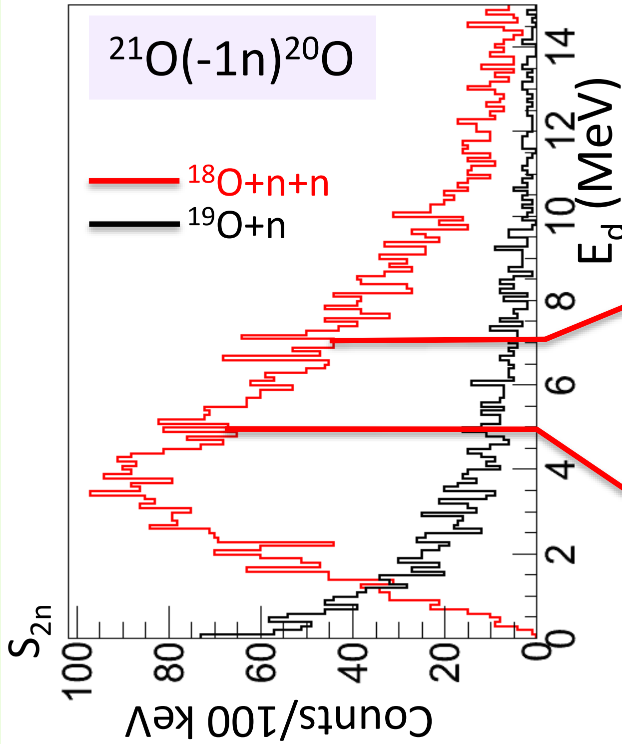
Sharp rise when short mean distance $\langle r_{nn} \rangle$

Resonant state in the core-n system

-> Peak in invariant mass M_{cn}^2

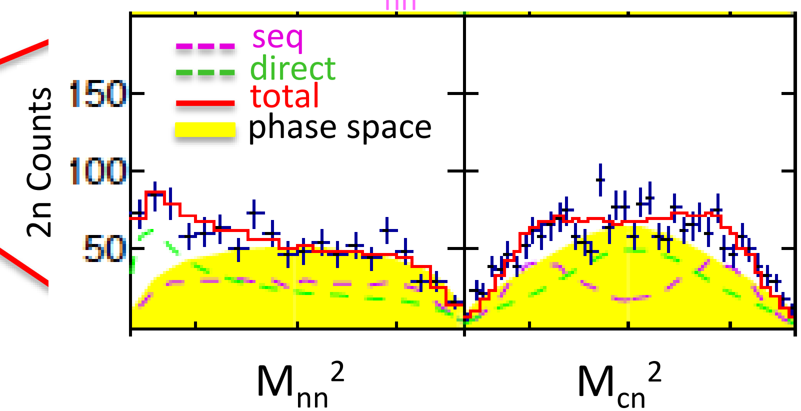
Neutron-neutron and core-neutron correlations in ^{20}O

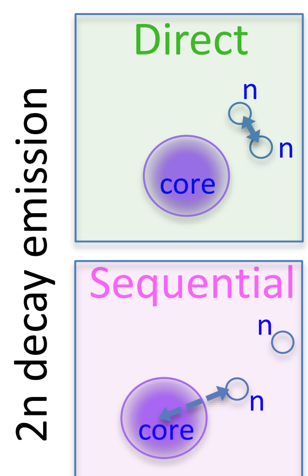




Strong evidence of sequential decay

$\langle r_{nn} \rangle \approx 4$ fm





Small relative n-n energies

Short mean distance between neutrons $\langle r_{nn} \rangle$

-> Rise of invariant mass M_{nn}^2 curve at ≈ 0

Resonant state in the core-n system

-> Peak in invariant mass M_{cn}^2

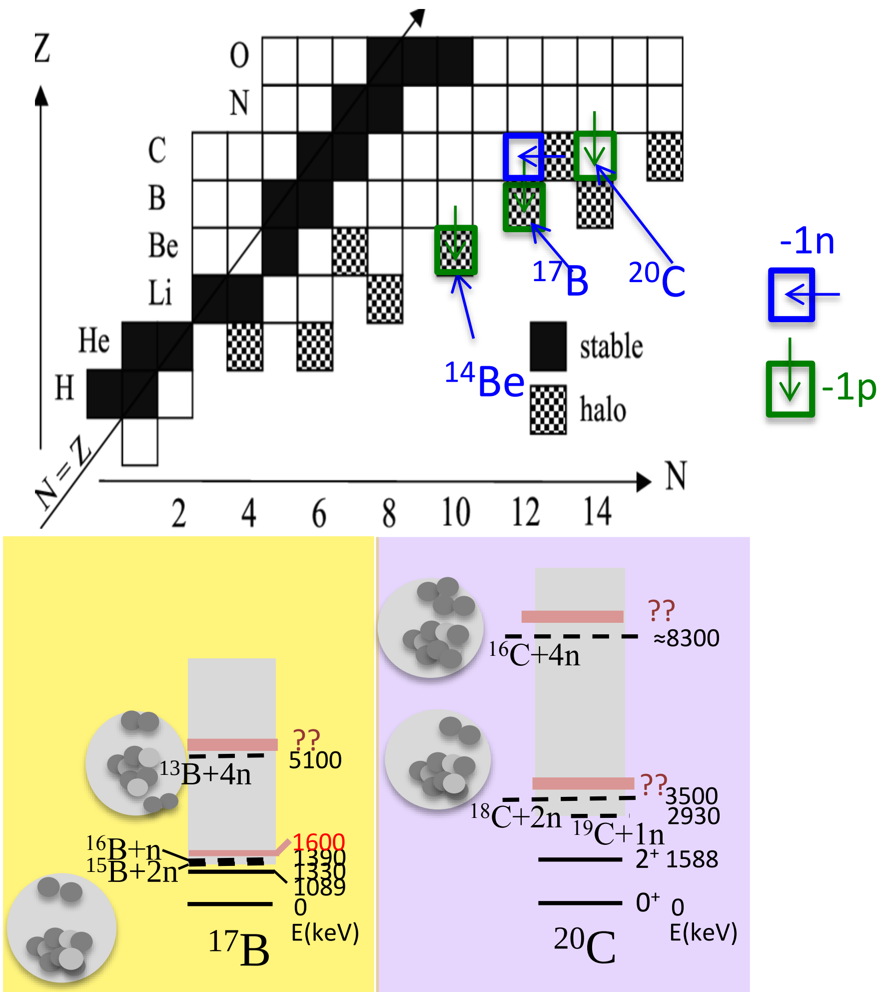
Proposal at the next PAC (to be run in 2019)

- Benefit from the increased granularity of NEULAND -> better energy resolution, multi neutron
- Increased primary beam intensity (factor 3), use of a LH_2 target (factor 5.5)

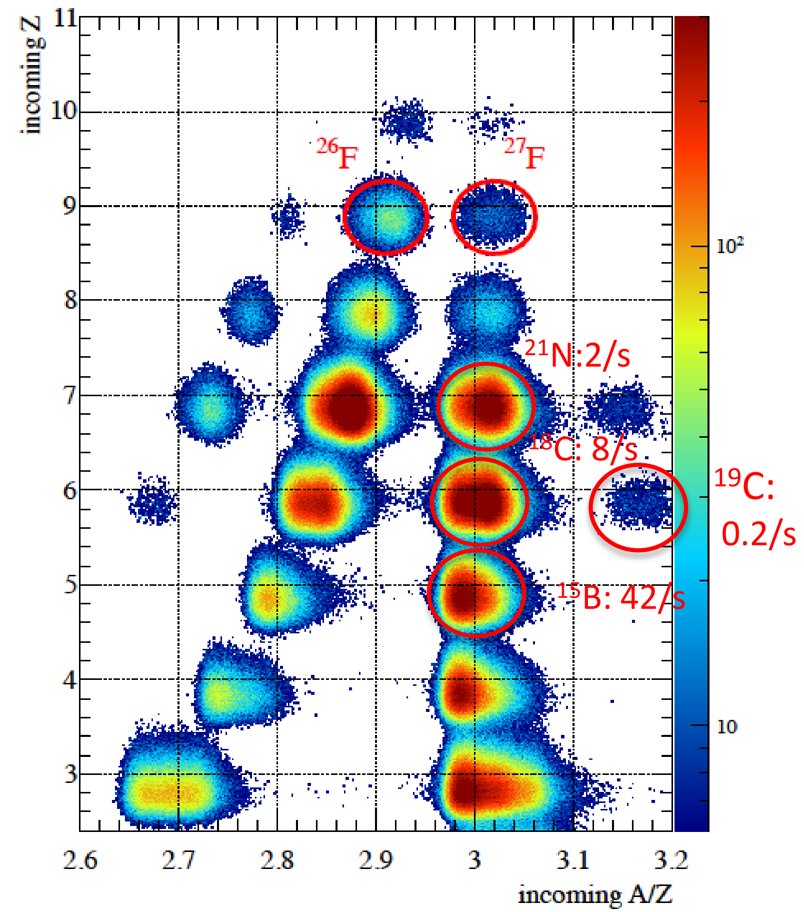
-> Search for 2n (and 4n) resonances at thresholds in ^{20}C and ^{17}B / competition with γ decay

-> see if neutron correlations observed in ^{18}C vanish when studied through ^{19}C(-1n)^{18}C

^{18}C and ^{17}B & ^{20}C studies



Set up for ^{26}O study (C. Caesar et al.)



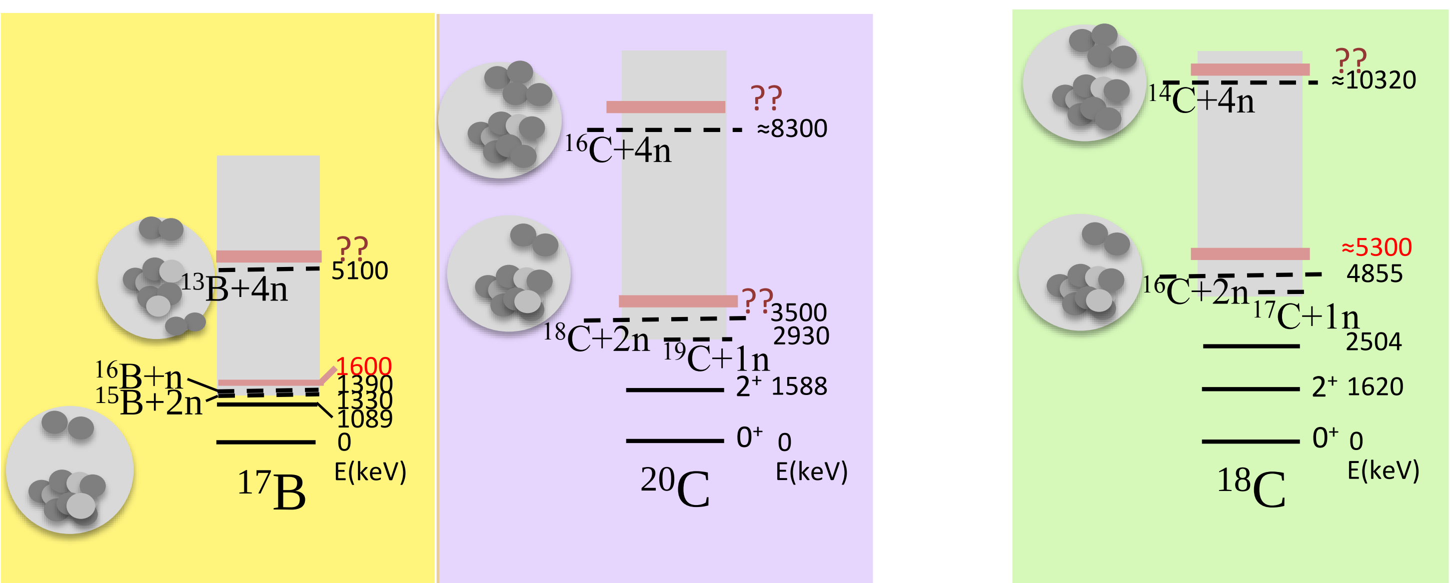
Proposal at the next PAC (to be run in 2019)

- Benefit from the increased granularity of NEULAND

  -> better energy resolution, possibility to disentengle multi neutron events
- Increased primary beam intensity (factor 3)
- Use of a LH_2 target (factor 5.5)

-> Search for 2n (and 4n) resonances at thresholds in ^{20}C and ^{17}B / competition with γ decay

-> see if neutron correlations observed in ^{18}C vanish when sudied through the $^{19}C(-1n)^{18}C$ reaction

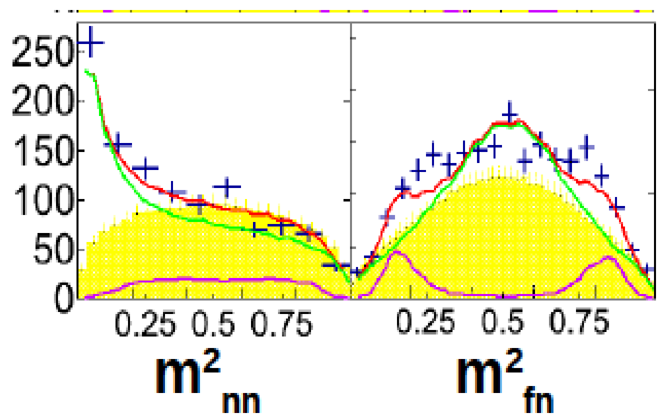


Study of correlations and mean distance between neutrons

Observables:

E_d,

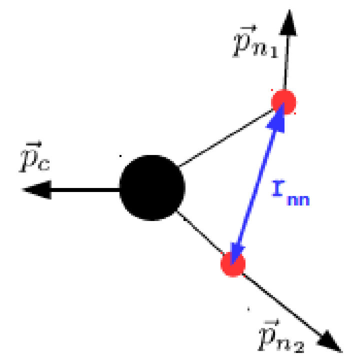
M^2_{nn} and M^2_{fn},



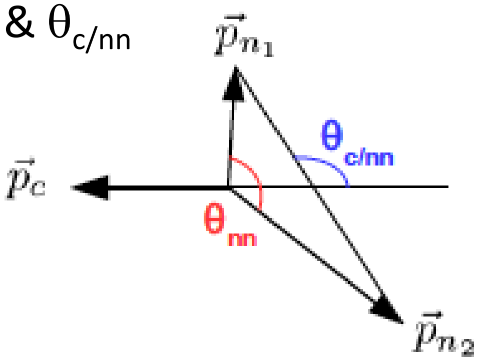
Fit data using ≠ r_{nn} & (E_r, Γ_r)

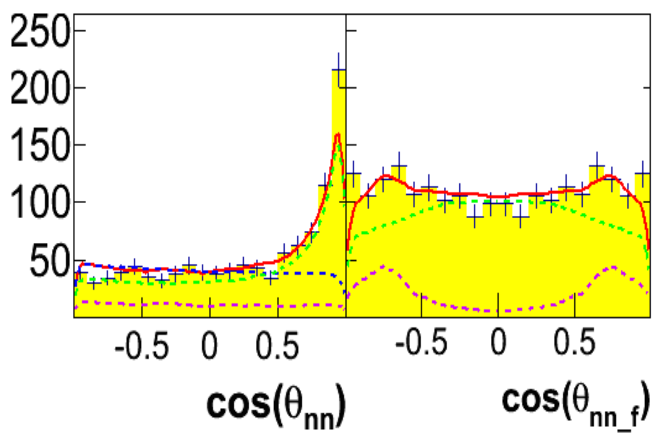
Treat FSI

Direct /Sequential decay



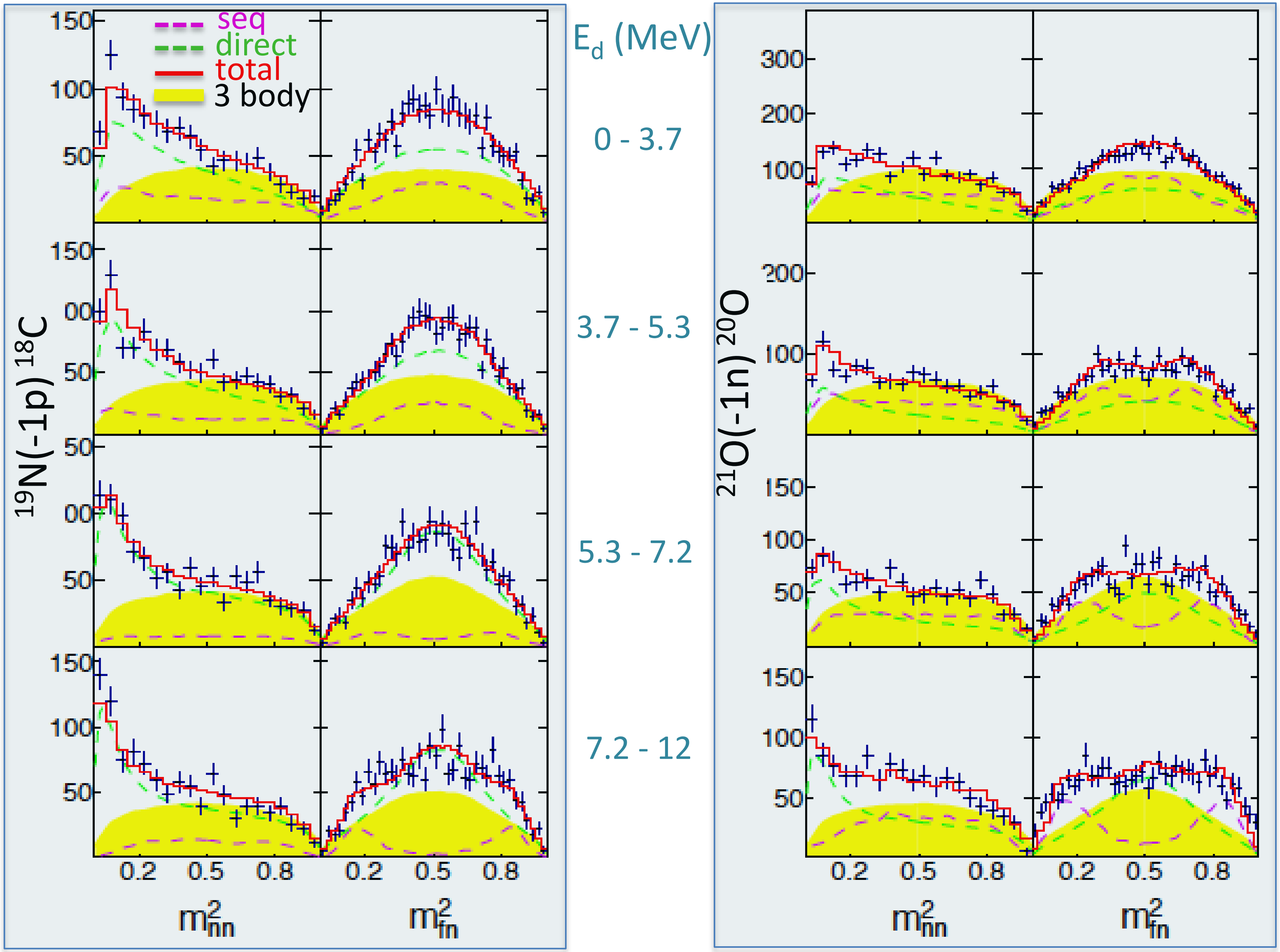
θ_{nn} & $\theta_{c/nn}$





A. Revel, M. Marquès

Invariant mass spectra between nn and core-n as a function of E_d

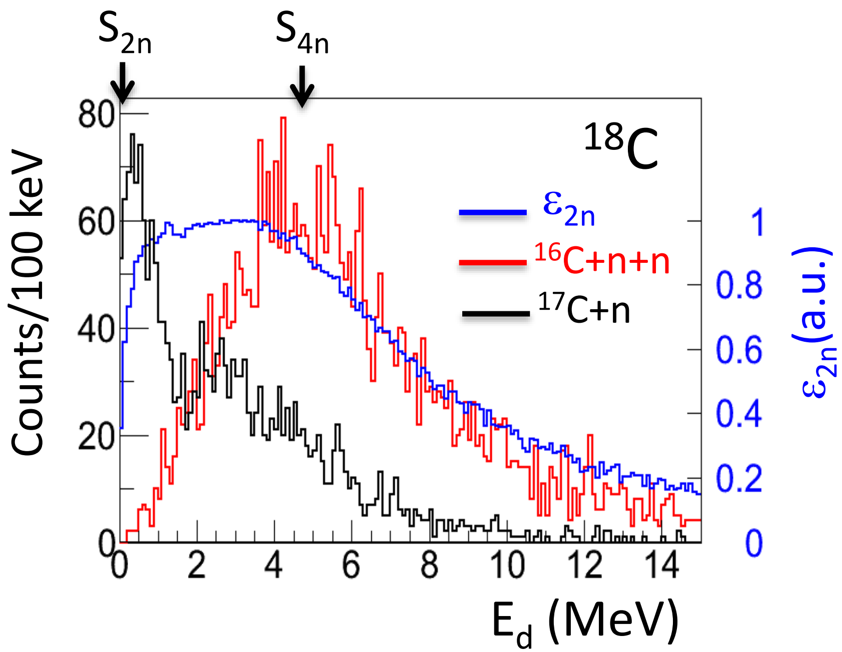


Very different behavior between the (-1p) and (-1n) decays -> less correlations in ^{20}O

Strong nn correlations in ^{18}C -> Predominance of direct decay

Much weaker correlations in ^{20}O -> 50% of sequential decay

Energy spectrum of ^{18}C derived from detecting 1n or 2n



Relative energies between core and neutrons *A. Revel (GANIL)*

Short range strategy:

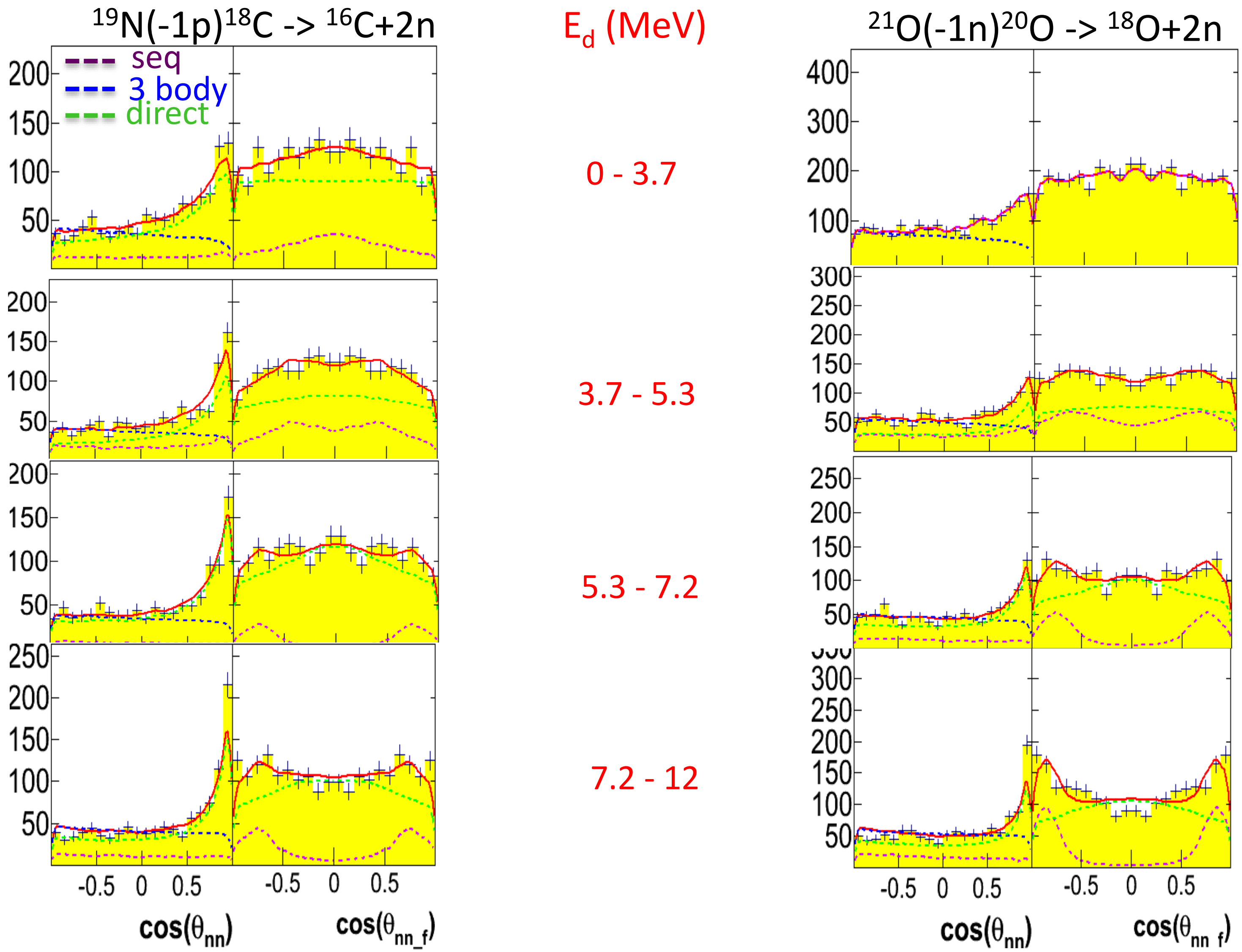
- Finish the present analysis
- Select sequential events for spectroscopy of intermediate states (in progress)

- E*xploit already existing data in other systems studied at R3B*
- Look at the evolution of neutron correlations in isotopic & isotonic chains
- Study correlations in systems produced from different reactions

From existing data of the last campaign

Anyone Interested ?

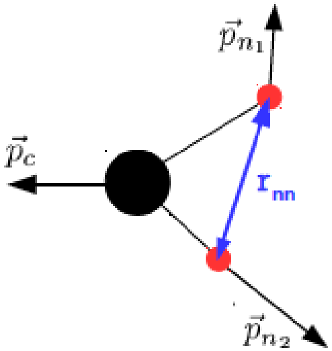
Angular spectra of ^{18}C and ^{20}O

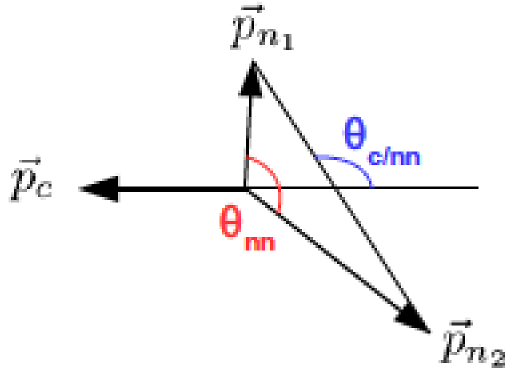


Strongly peaked signal as small $\cos(\theta_{nn})$
Direct decay dominates + very short r_{nn}
Indication of di-neutron component ?

Modest increase at small $\cos(\theta_{nn})$
Depletion at $\cos(\theta_{c/nn}) = 0$ at large E_d
Sequential decay strongly dominating

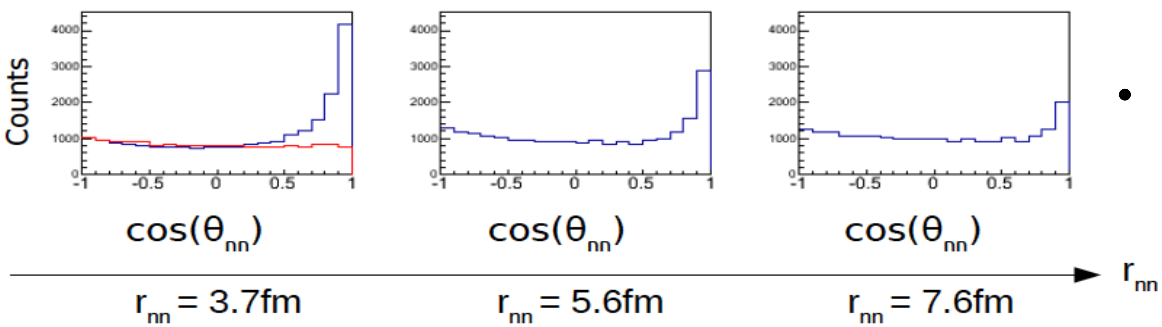
Angular spectra between the neutrons





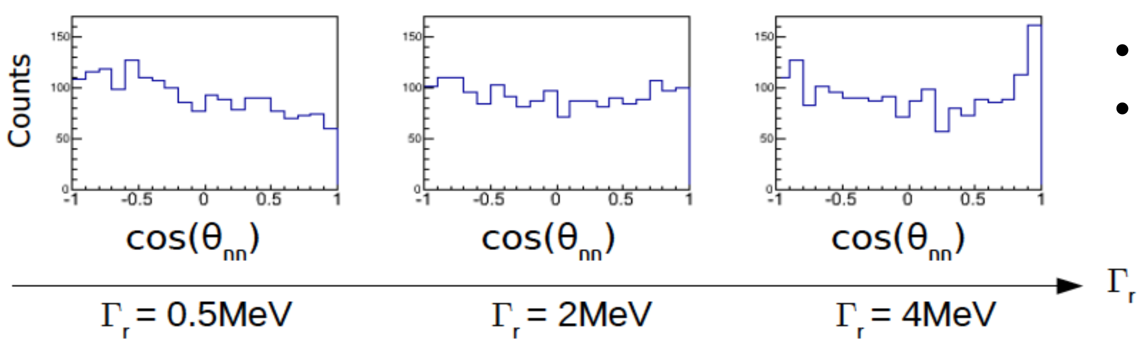
- Relative energies as observables
- Two angles θ_{nn} & $\theta_{c/nn}$ as observables
- Fit the data using ≠ r_{nn} & E_r , Γ_r values
- Treat FSI with each set of parameters
- Derive fraction of sequential and direct decay

n-n FSI simulation



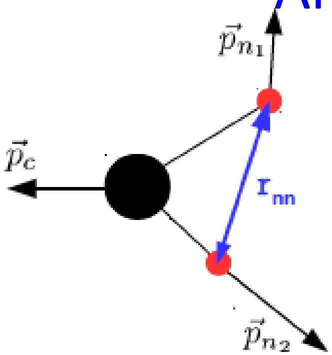
- Increase at low $\cos(\theta_{nn})$ for short r_{nn}

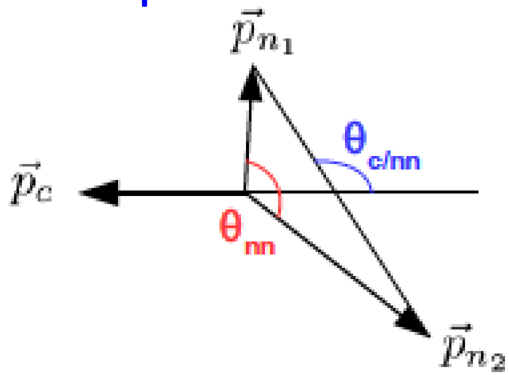
Sequential decay + n-n FSI simulation



- Basically flat
- Increase at low $\cos(\theta_{nn})$ for broad Γ_r
  -> mimic direct decay

Angular spectra between the neutrons and the core





- Two angles as observables: θ_{nn} & $\theta_{c/nn}$
- Relative energies as observables
- Fit the data using ≠ r_{nn} & E_r , Γ_r values
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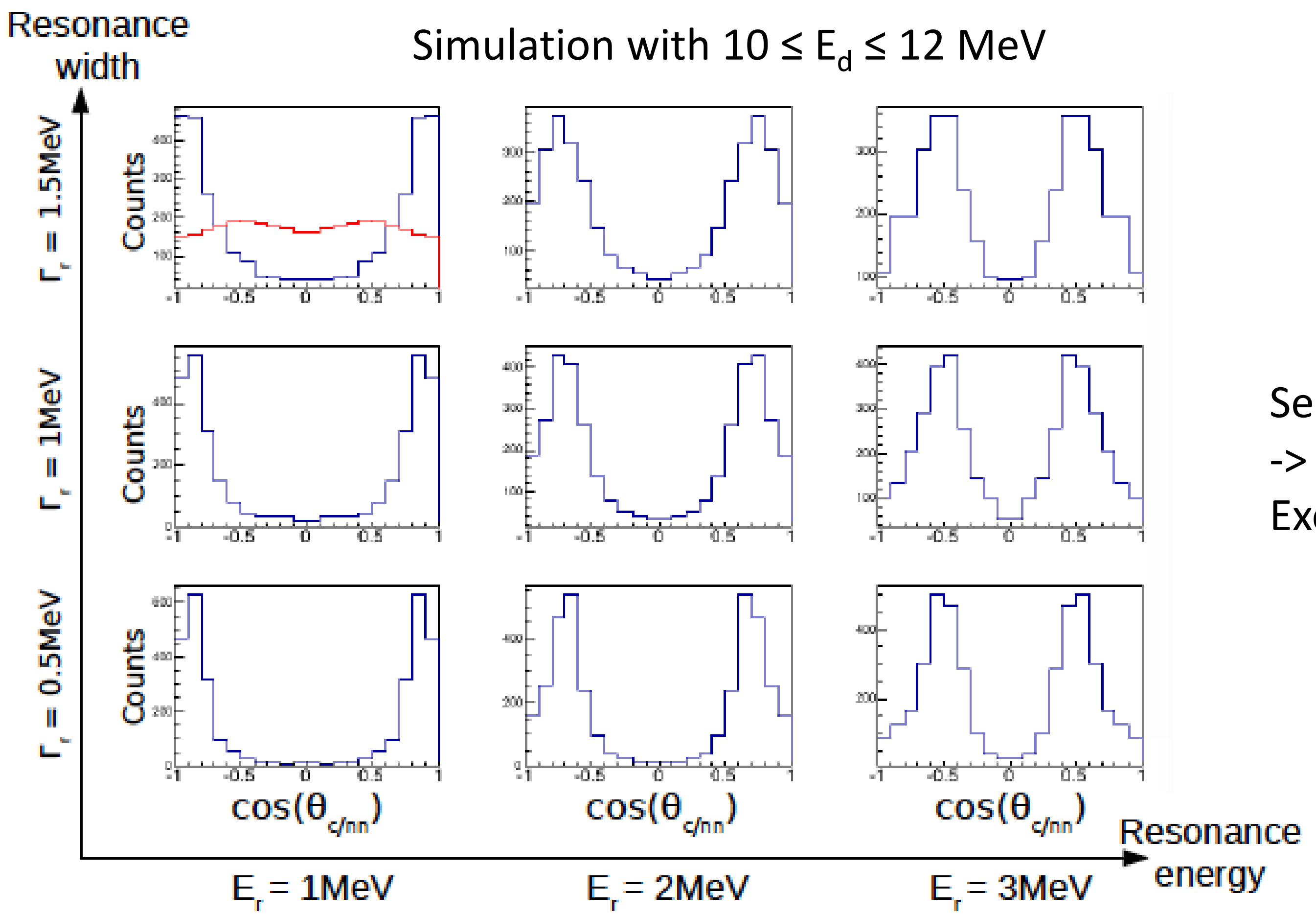
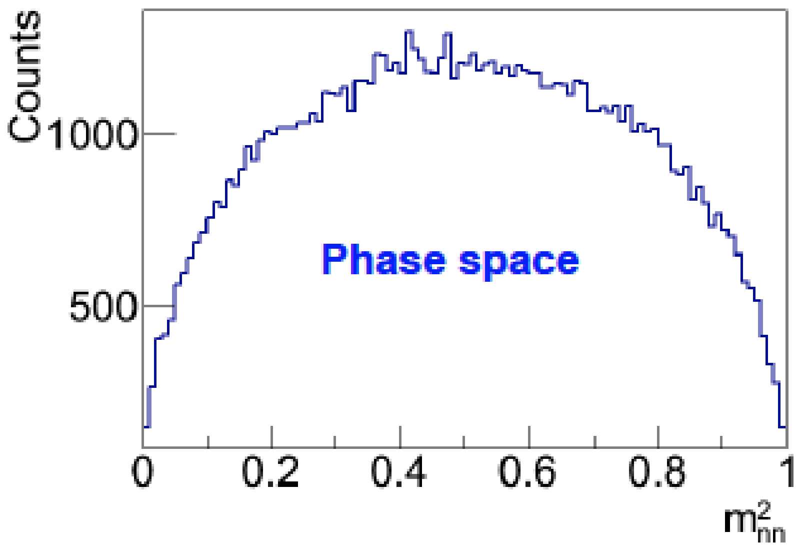
Simulation with $10 \leq E_d \leq 12$ MeV

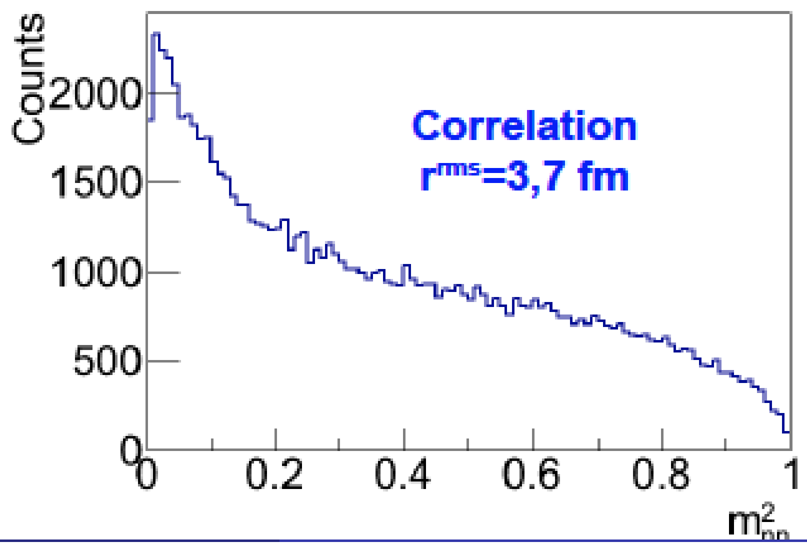


Sequential decay
-> Dip at $\cos(\theta_{nn})=0$
Except if $E_r=1/2\ E_d$

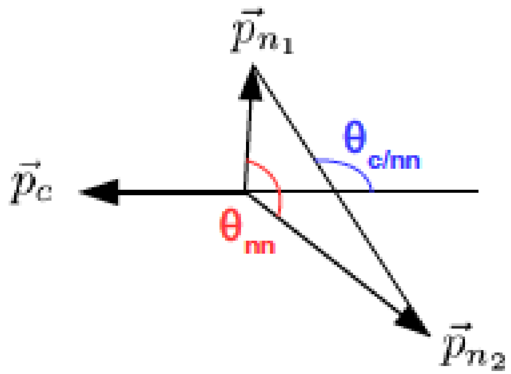
Simulation program

- Geometry of the setup
  - Dead paddles
  - Interaction with the detector
    - Deepness
    - Discrimination between 1n and 2n events
- Event generator
  - 2-body simulation (fragment + neutron)
    - Phase space
  - **3-body simulation (fragment + neutron + neutron)**
    - **Phase space**
    - **Correlation between neutrons**
    - Sequential emission of neutrons





Angular spectra between the core and neutrons



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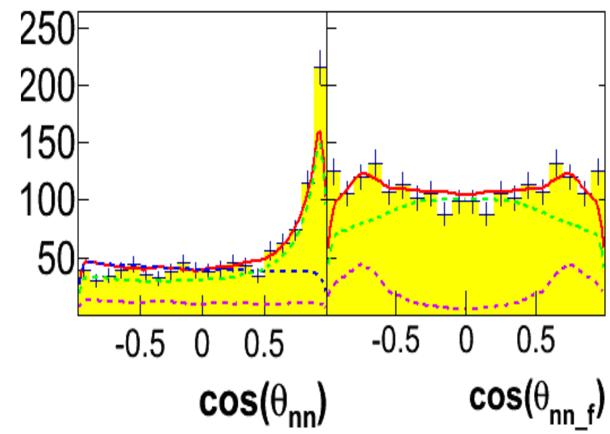
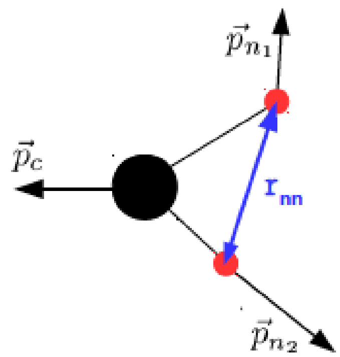
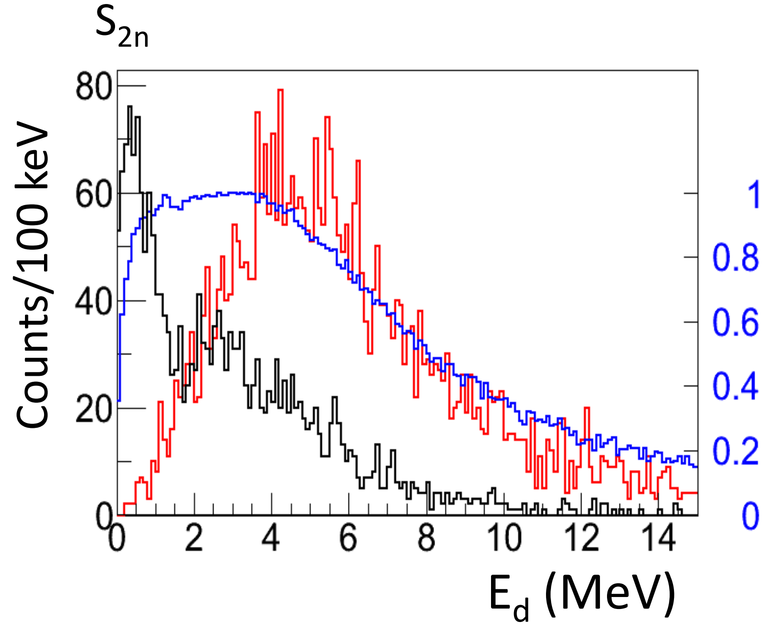




- Fit the data using ≠ r_{nn} & (E_r , Γ_r) values
- Treat FSI with each set of parameters
- Derive fraction of sequential and direct decay

Simulations A. Revel, M. Marquès



S_{2n}
Counts/100 keV
E_d (MeV)
0
20
40
60
80
2
4
6
8
10
12
14
0.2
0.4
0.6
0.8
1