n-n correlations in the decay of ^{13}Li
-
Perspectives on neutron detection and multi-neutron correlations measurements at FRIB

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WPCF 2023, Catania

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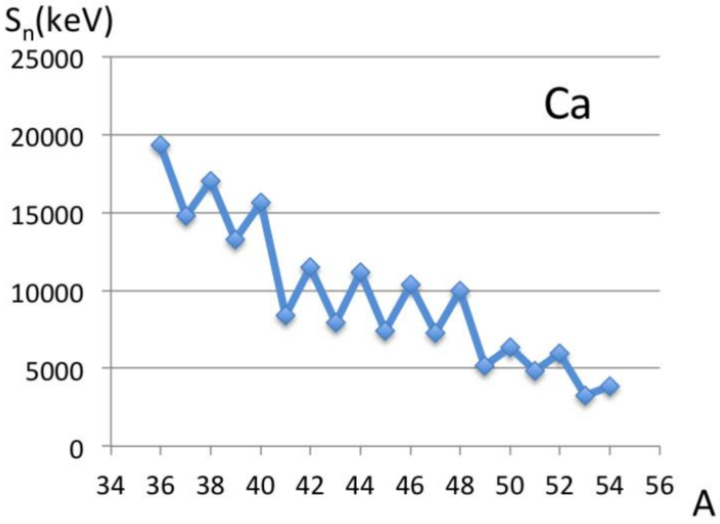
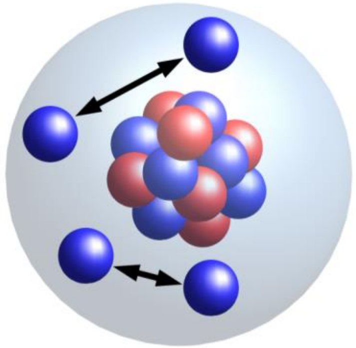
Motivations

- Pairing correlations play an essential role in atomic nuclei and in neutron stars
  - Oscillations of Sn values
  - Enhanced pair transfer

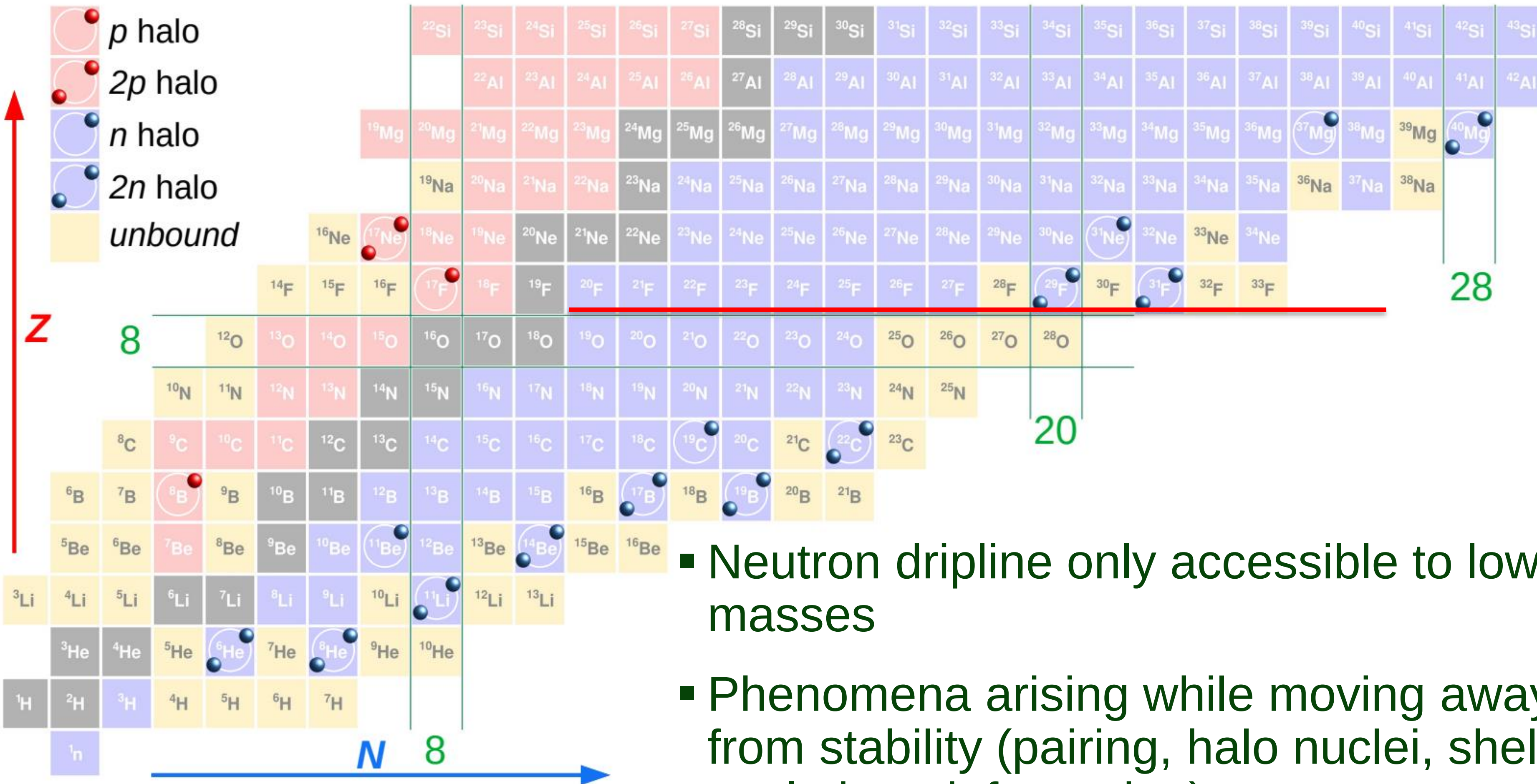


- n-n correlations evolution toward the dripline ?
  - Scarce experimental studies
  - Different systems needed in order to understand pairing



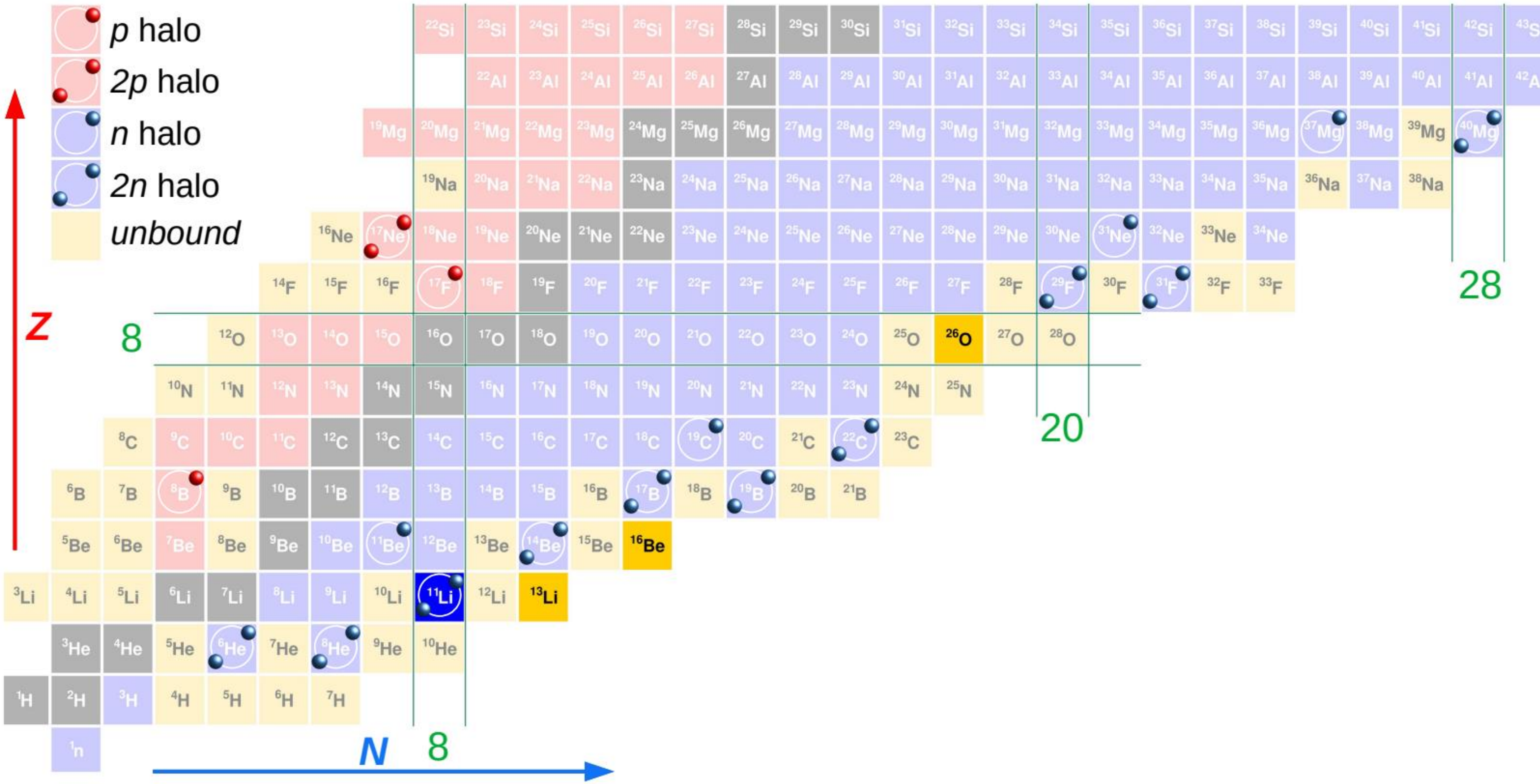
- Multi-neutron correlations
  - Tetra neutron (Stefanos' talk)
  - More than 4 neutrons ?

Motivations



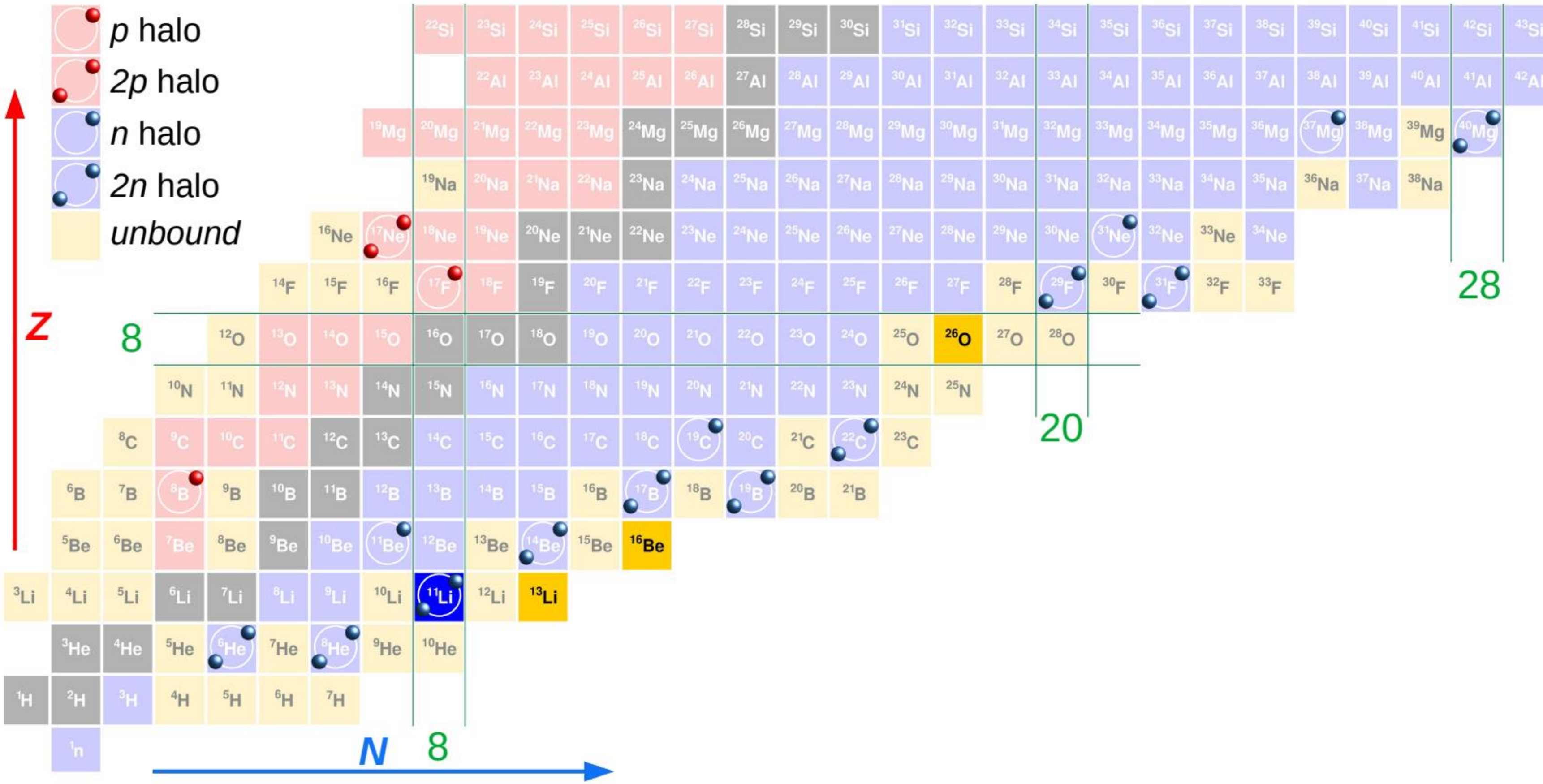
- Neutron dripline only accessible to low masses
- Phenomena arising while moving away from stability (pairing, halo nuclei, shell evolution, deformation)

Motivations



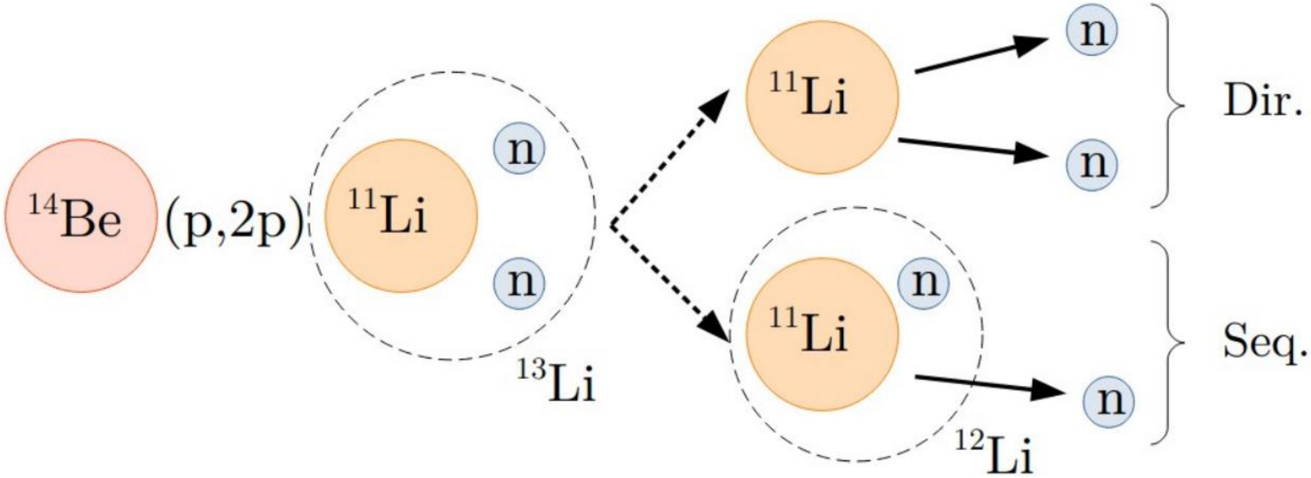
- ^{11}Li is famous 2n-halo Borromean nucleus
- n-n correlations beyond dripline ? ^{13}Li

Concept to study n-n correlations



- $^{14}Be(p,2p)^{13}Li \longrightarrow {}^{11}Li + n + n$
- Information on initial configuration from the kinematic of the decay ?

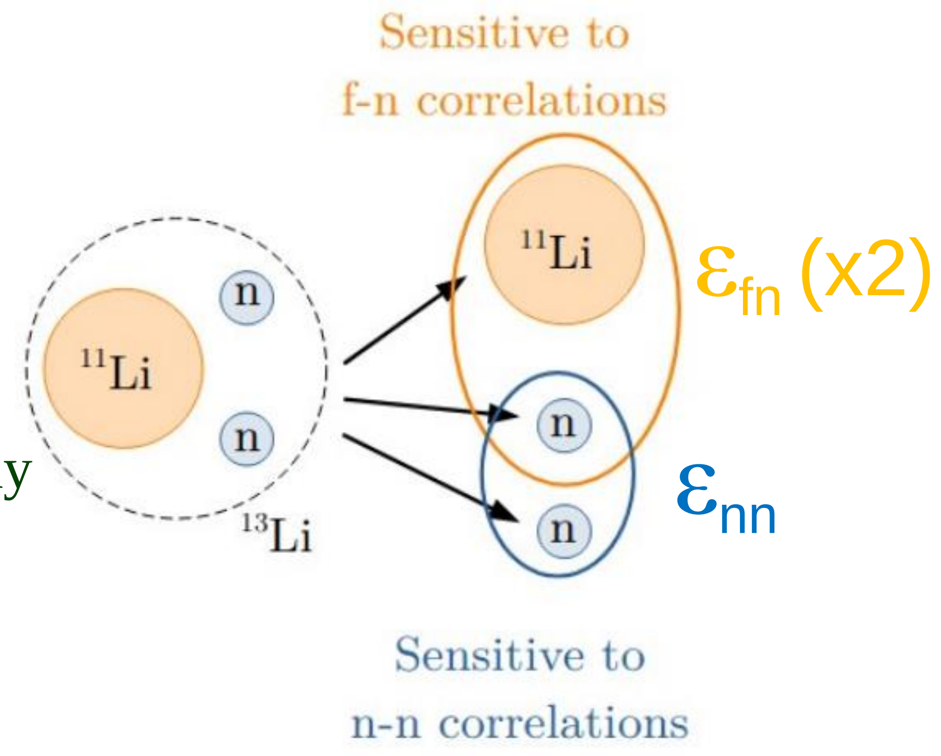
Method to study n-n correlations



- Measure momenta of all the decay products
- Kinematically complete measurement
- Invariant-mass method to reconstruct relative energy of ^{13}Li and sub-systems
- Need to measure ^{11}Li + n + n in coincidence
- Investigate the decay mechanism

Method to study n-n correlations

- Erel : 3-body relative energy (^{13}Li)
- ε_{nn} = Erel,nn/Erel
- ε_{fn} = Erel,fn/Erel
- Reduced relative energy for the 2-body sub-systems (^{11}Li+n / n+n)
- Construct Dalitz plots



Dalitz plots and correlations

Direct decay

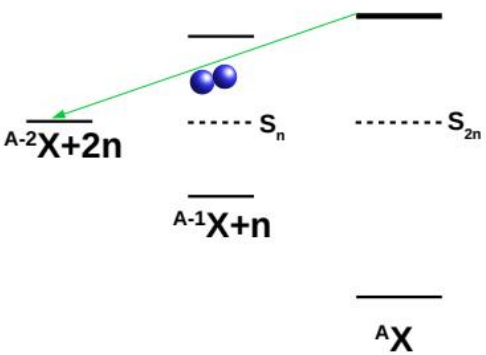
- Phase-Space modified by *n*-*n* correlations

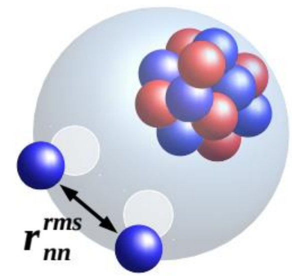
Lednicky Model

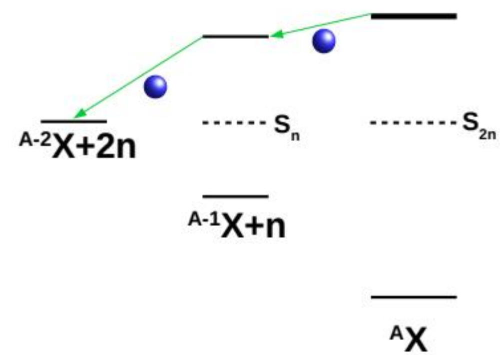
- Simple model to describe FSI in exp. data

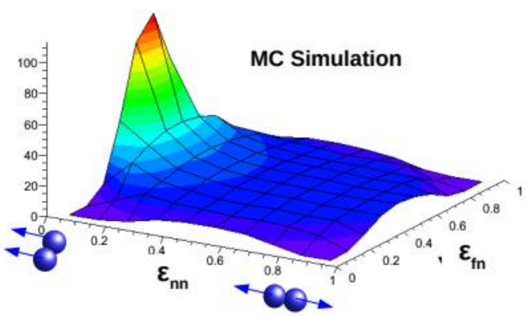
Sequential decay

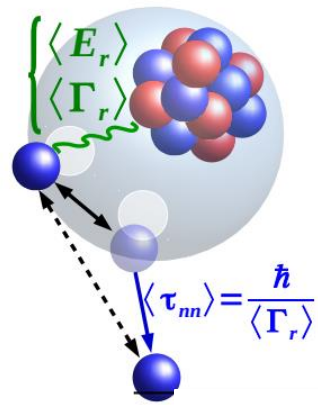
- core+*n* correlations

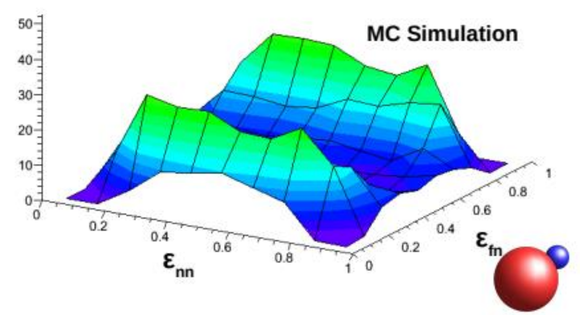






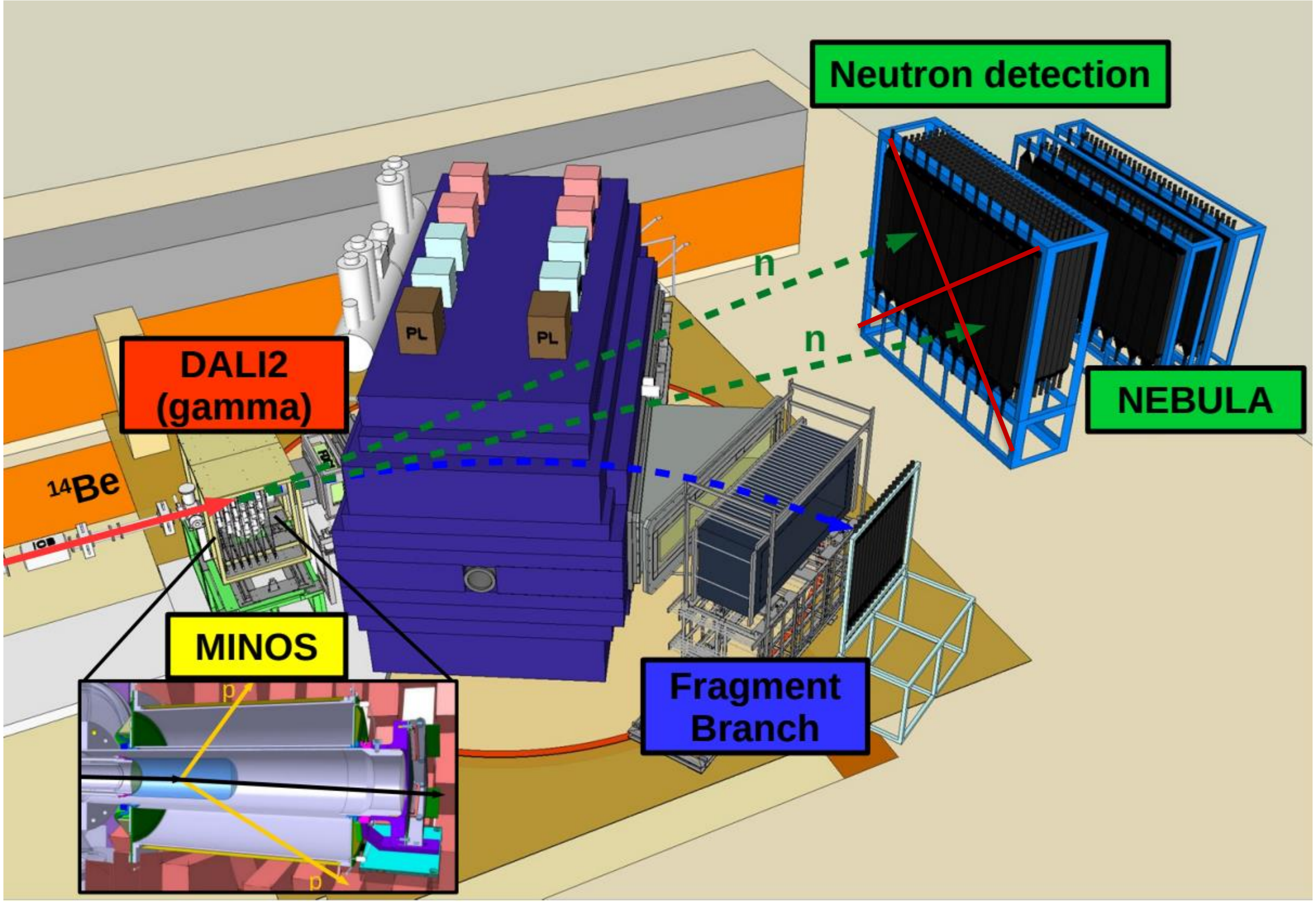






R. Lednicky and V. Lyuboshits, SJNP 35 (1982) 770

Samurai experimental setup at RIKEN

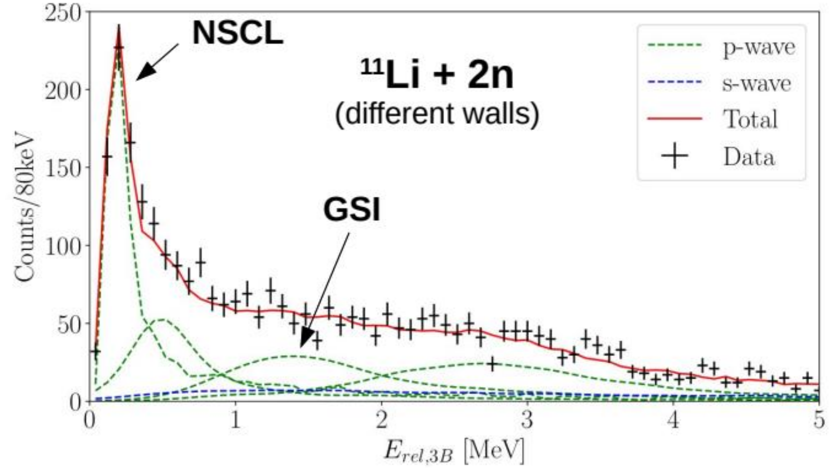


^{13}Li relative energy

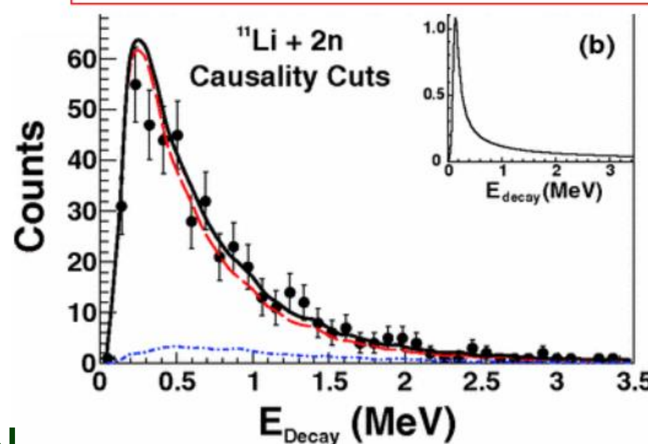
p-wave	E_{res} [MeV]	Γ_{res} [MeV]
1 [1]	0.16(1)	0.16(4)
2	0.45(6)	0.26(11)
3 [2]	1.47(31)	1.7(7)
4	2.8(2)	1.7(7)

[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

[2] Yu. Aksyutina *et al.*, Phys. Lett. B **666** (2008)



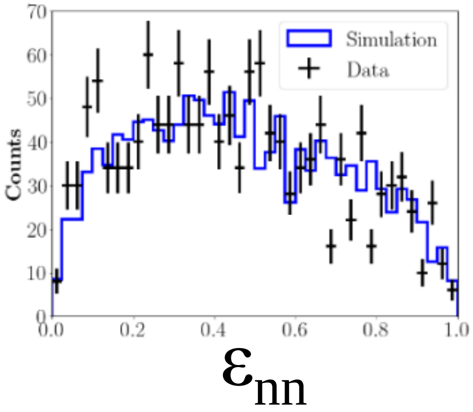
Z. Kohley *et al.*, Phys. Rev. C **87**, 011304 (2013)

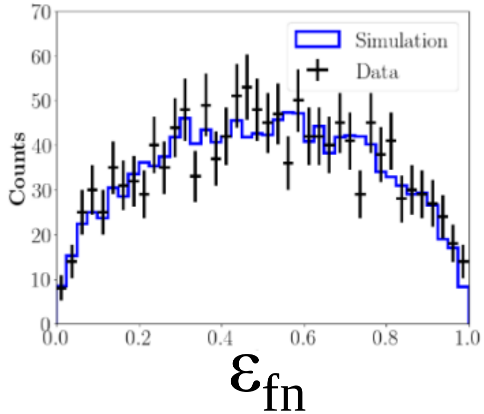


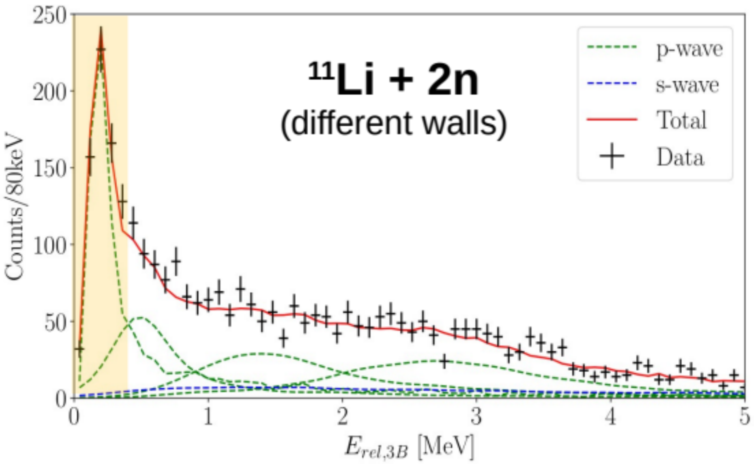
- Improved resolution
- Resonances compatible with previous results
- Tentative 2 new resonances observed
- n-n correlations evolution with Erel

^{13}Li n-n correlations

$0<E_{rel,3B}<0.4\text{MeV}$

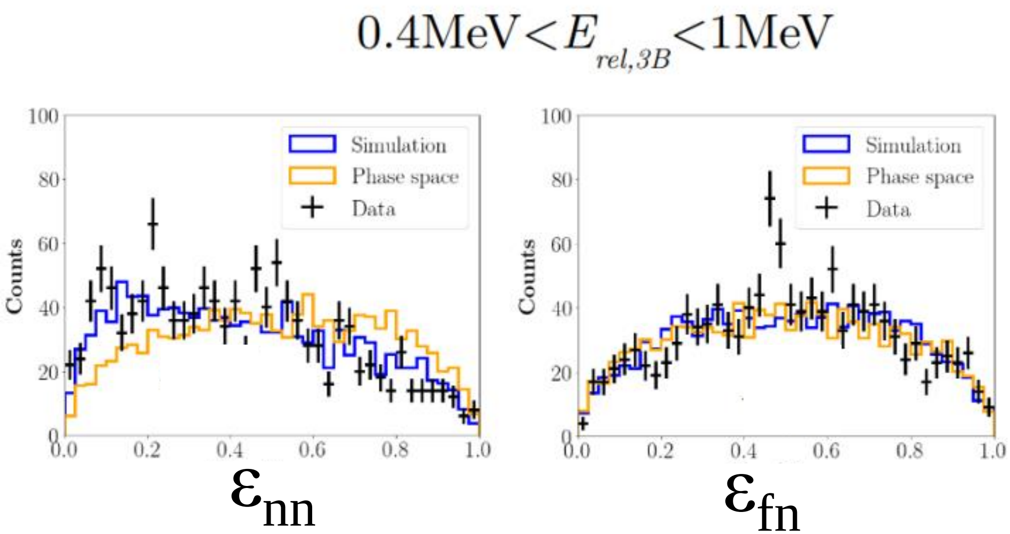


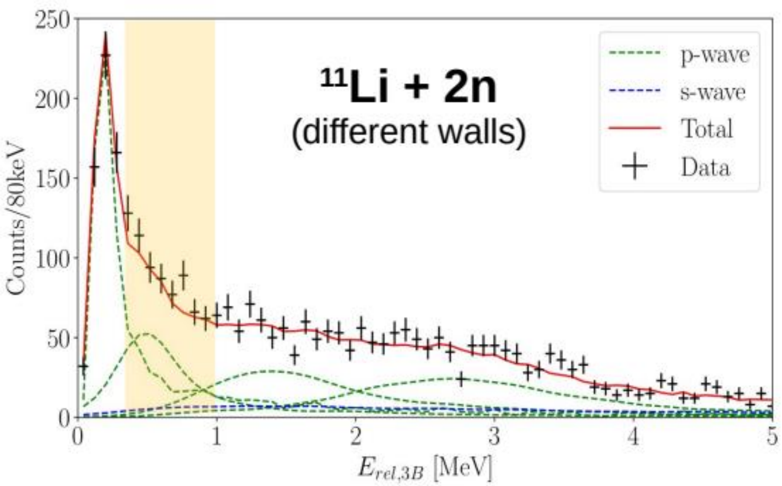




- Gate corresponding to the ground state of ^{13}Li
- 100% Direct decay
- n-n rms distance = 12.7fm

^{13}Li n-n correlations

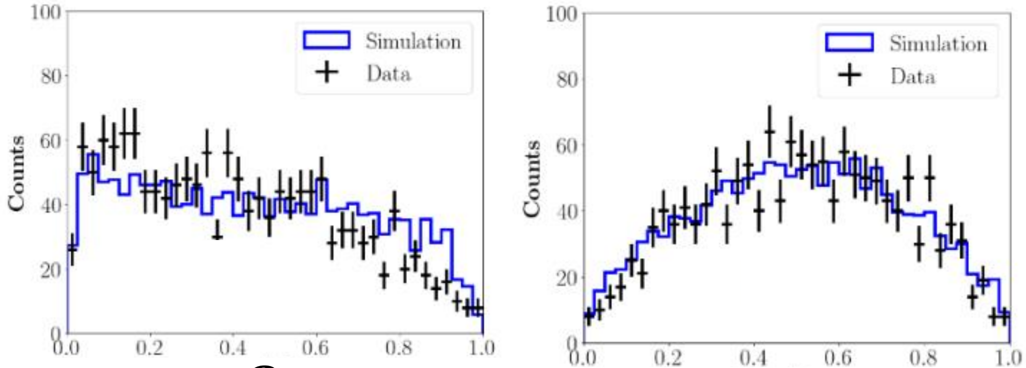




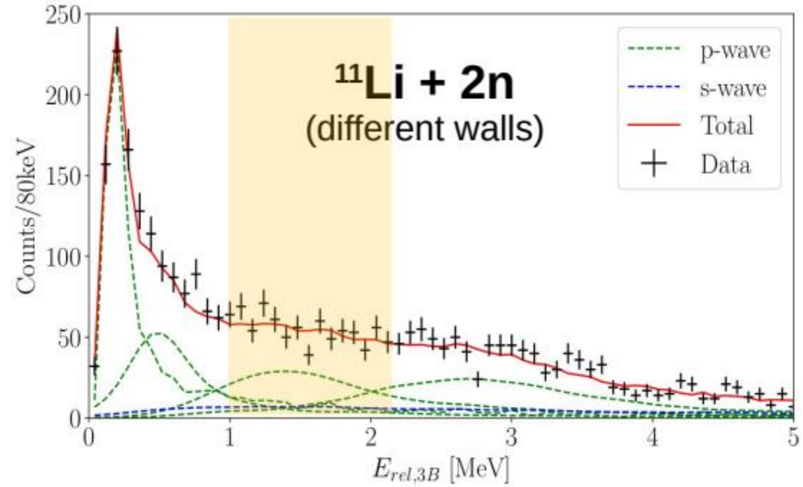
- 100% Direct decay
- n-n rms distance = 12.7fm

^{13}Li n-n correlations

$$1<E_{rel,3B}<2.1\text{MeV}$$

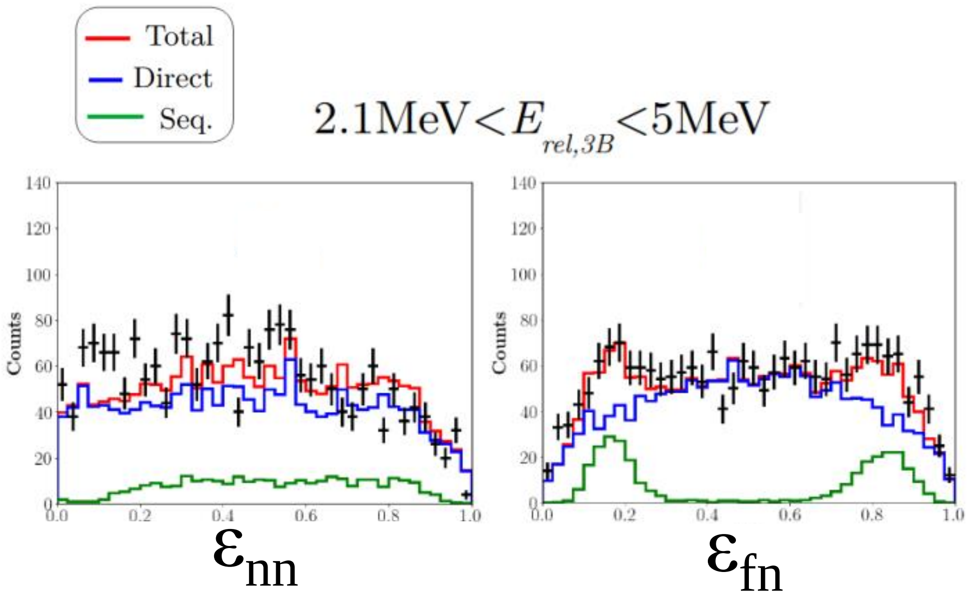


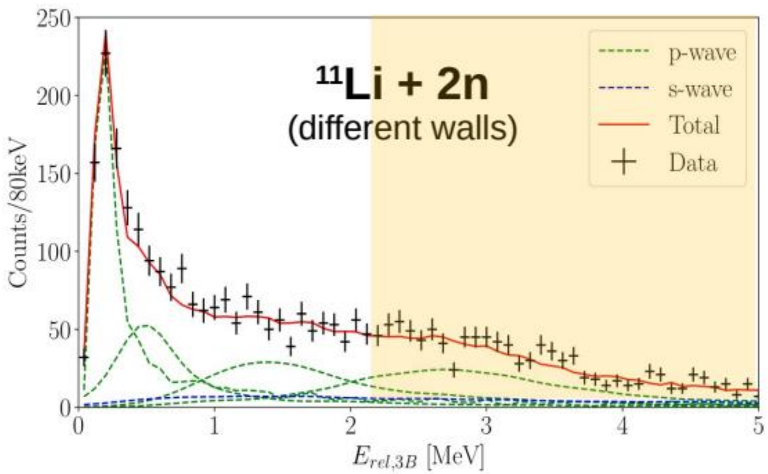
ε_{nn} ε_{fn}

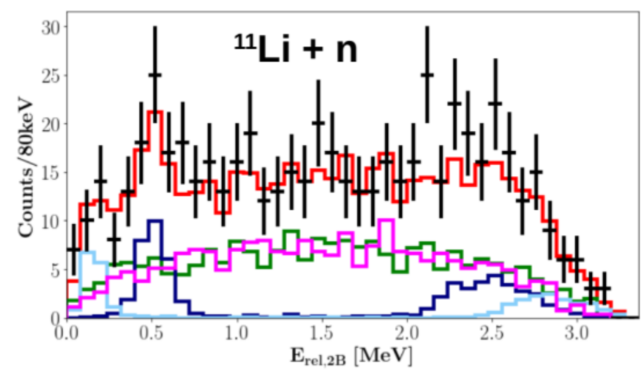


- 100% Direct decay
- n-n rms distance = 12.7fm

^{13}Li n-n correlations





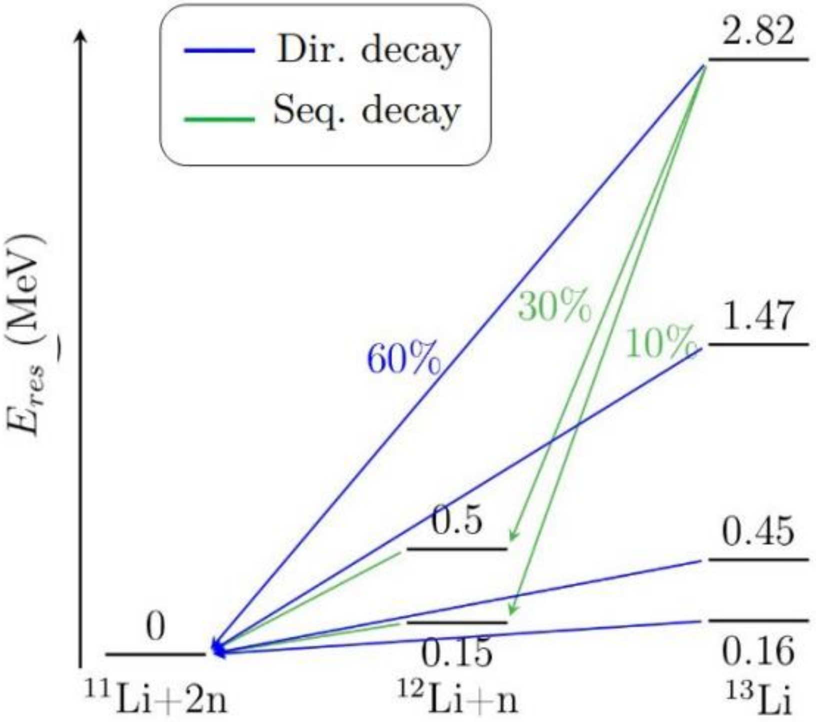


2 resonances in ^{12}Li
Direct decay of high energy resonance in ^{13}Li
Direct decay of other states in ^{13}Li

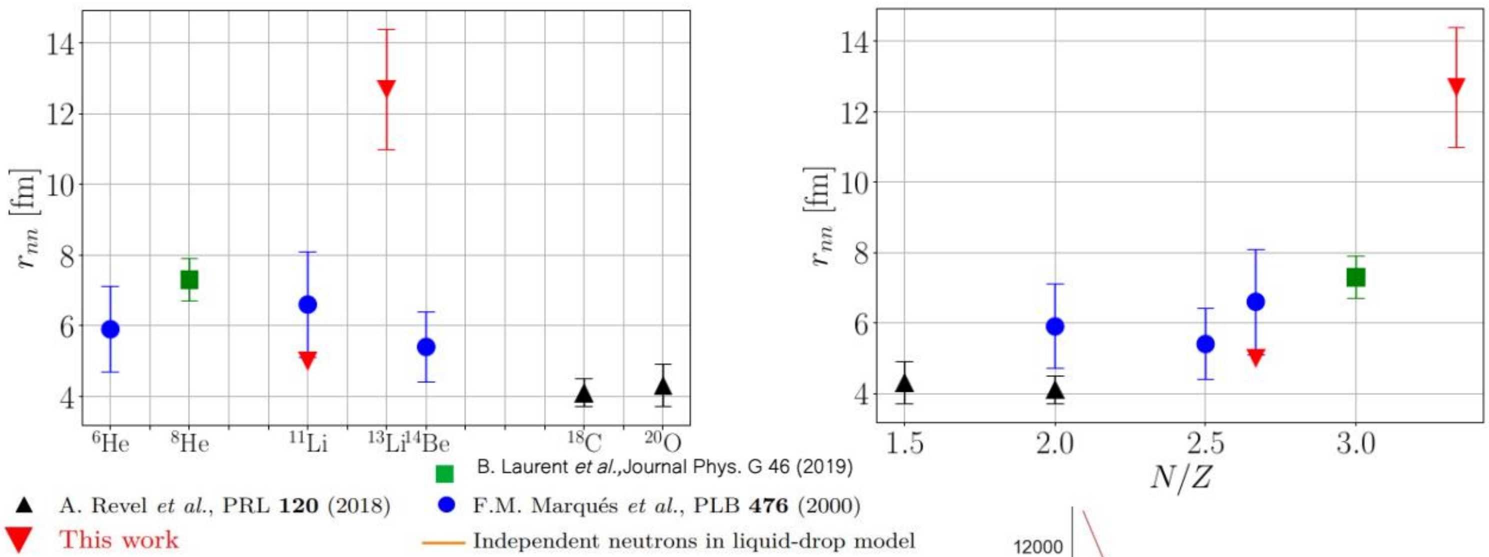
- Clear signature of sequential decay (~40%)
- 100% Direct decay
- n-n rms distance = 12.7fm

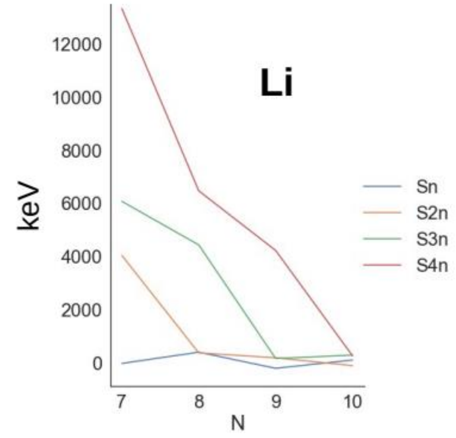
Summarized decay scheme

- Direct decay dominates below 2MeV
- Sequential decay plays a role at higher excitation energies
- n-n rms distance of 12.7fm obtained using our simple "Lednicky model" reproduces the data
- How does it compare to other systems studied within the same framework ?



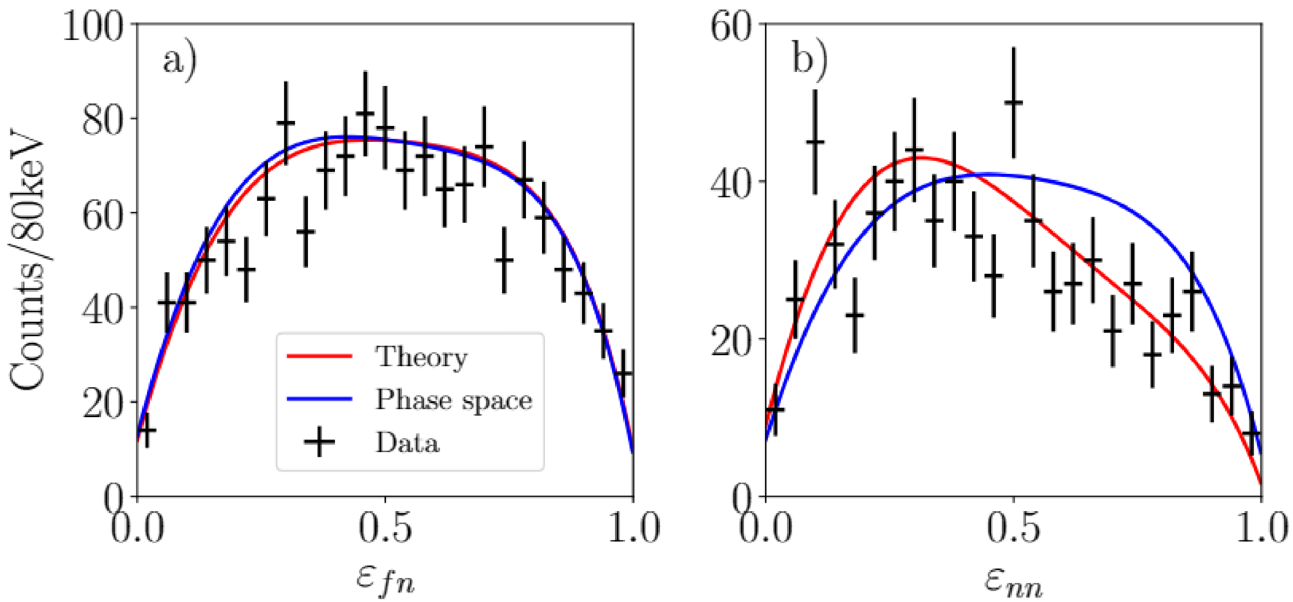
Systematic of results using “Lednicky Model”





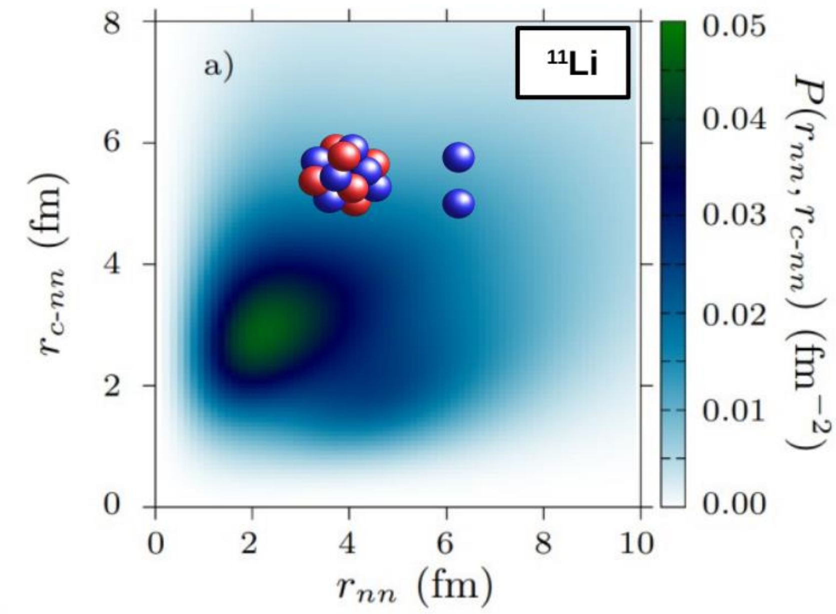
- Comparison with results obtained within the same framework (“Lednicky model”)
- ^{13}Li unbound
- ^{13}Li as ^{9}Li + 4n
- Call for microscopic calculations

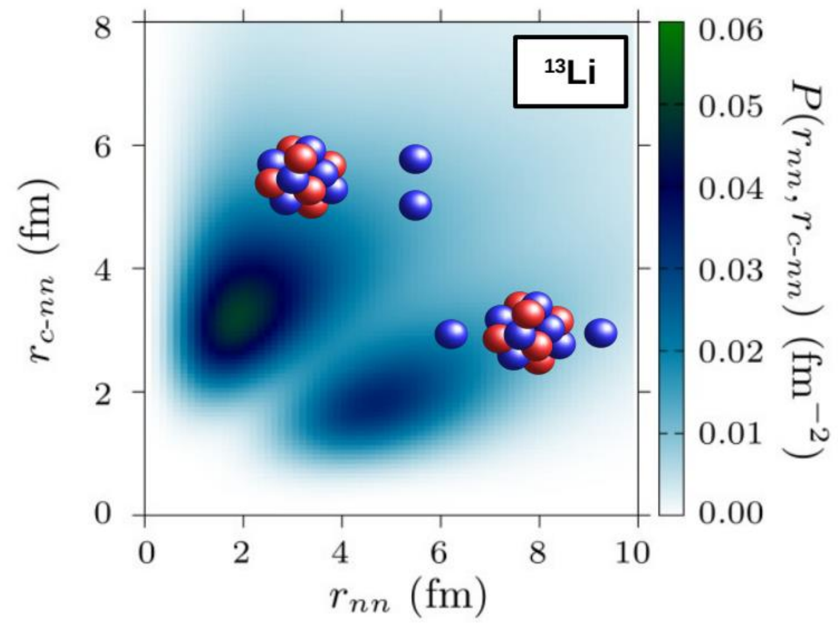
Comparison of three-body calculation ^{13}Li gs



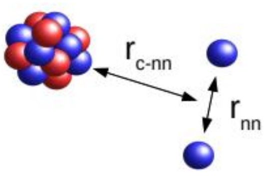
- Time evolution of three-body wave-functions
- Partial relative energies for the ground-state
- Good reproduction of the experimental data
- See Jesus’ talk tomorrow for more details

Comparison of three-body calculation



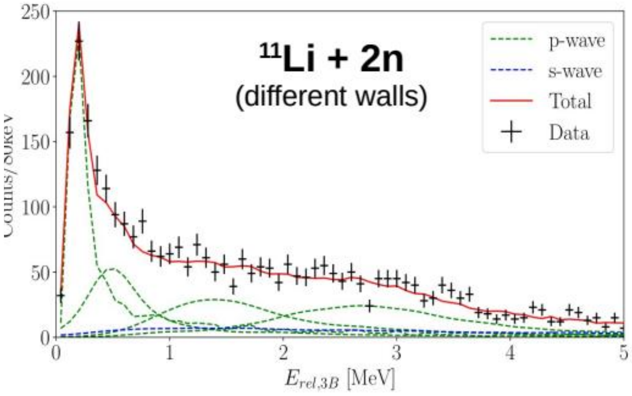


- Time evolution of three-body wave-functions
- Partial relative energies for the ground-state
- Good reproduction of the experimental data
- Correlations more diffused in ^{13}Li



Conclusion on ^{13}Li study

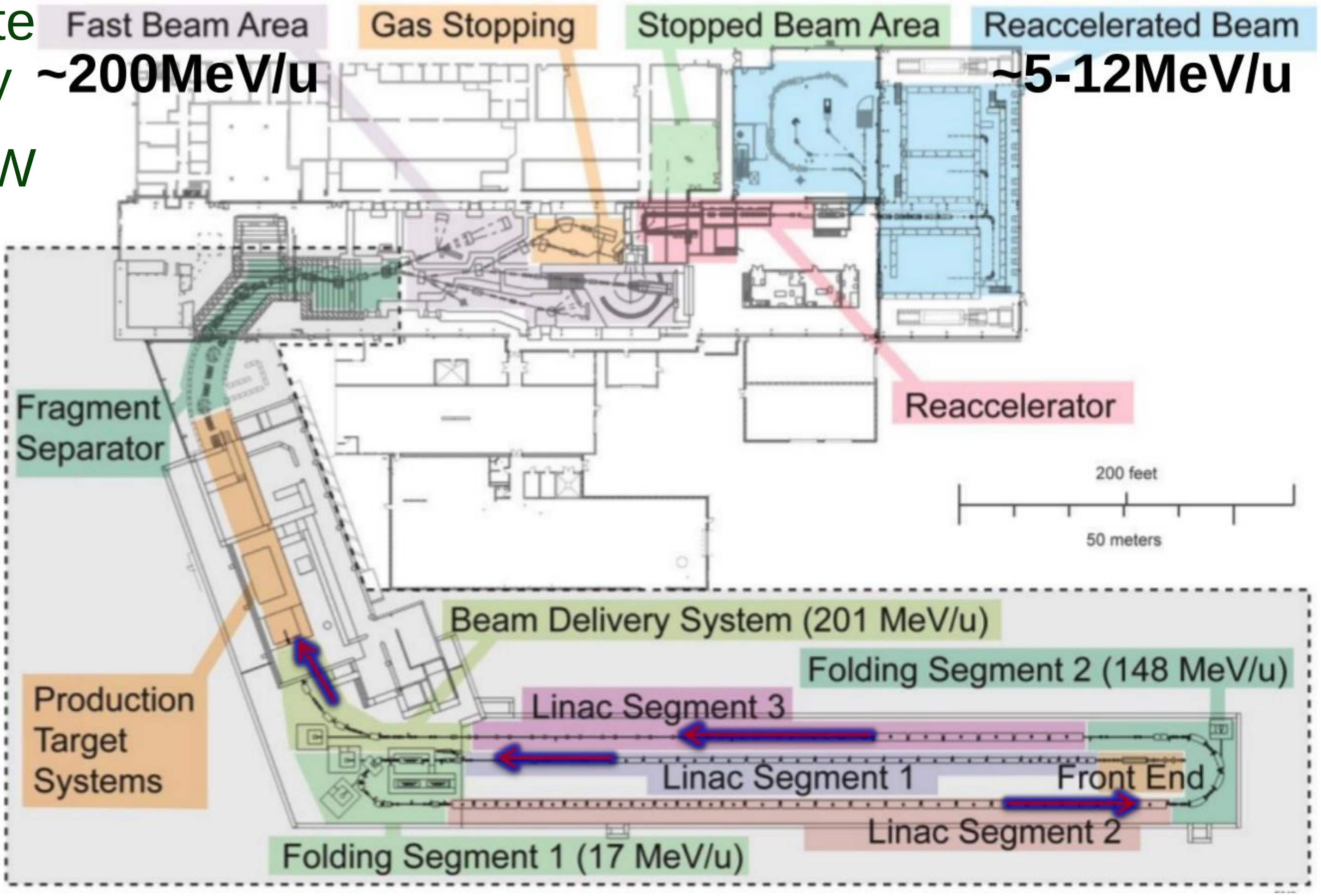
- n-n correlations in the decay of ^{13}Li
- Improved resolution compared to previous results
- Evolution of 3-body correlation with Erel
- Decrease of n-n correlation strength between ^{11}Li and ^{13}Li
- Reflected by steep growth of $s_{1/2}$ orbital occupancy predicted by G-DMRG calc.
- ^{11}Li also analyzed (dominated by seq. decay)



Paul André, CEA PhD

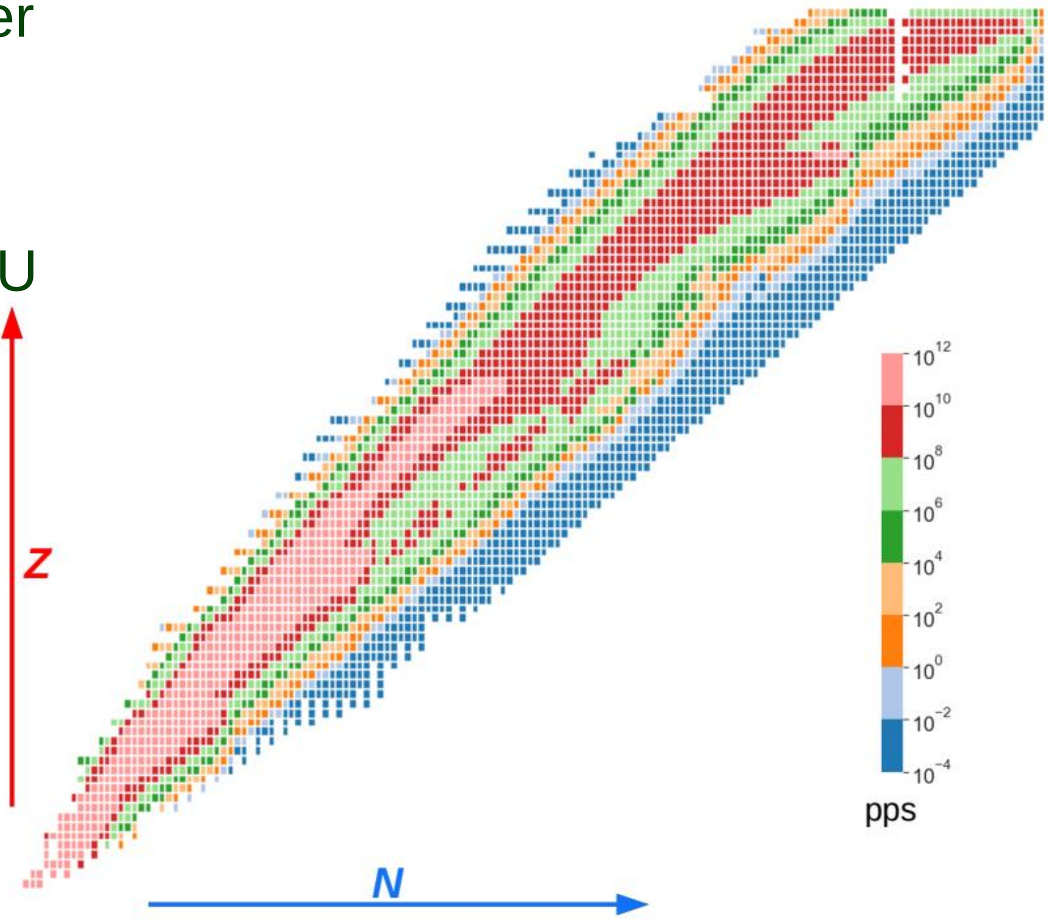
Future opportunities at FRIB ?

- 400kW ultimate beam intensity
- Currently 10kW



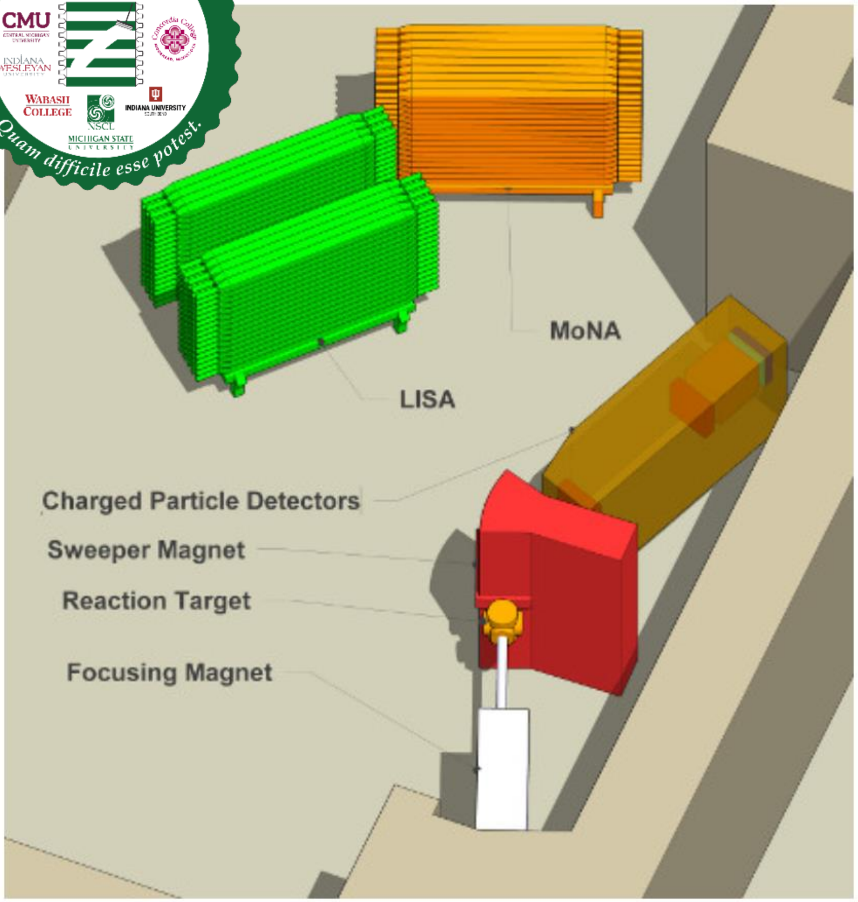
FRIB capabilities

- Extends reach compare to other facilities
- 80% of predicted nuclei below U
- Push toward neutron-rich side
- 150/250 MeV/u
- New opportunities for n-n correlations studies



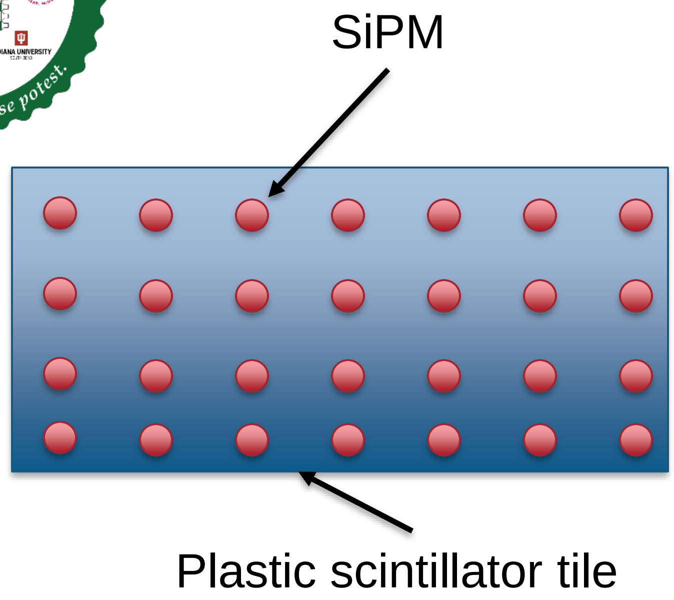
FRIB setup for neutron mass-invariant

- Current setup from the MoNA collaboration (previously used at NSCL)
- FRIB roughly double beam energy
- Flight distance neutrons fixed
  - Better acceptance
  - Worse resolution
- Bρ magnet limited
  - Cannot use full energy (intensity) of FRIB beam for neutron-rich systems

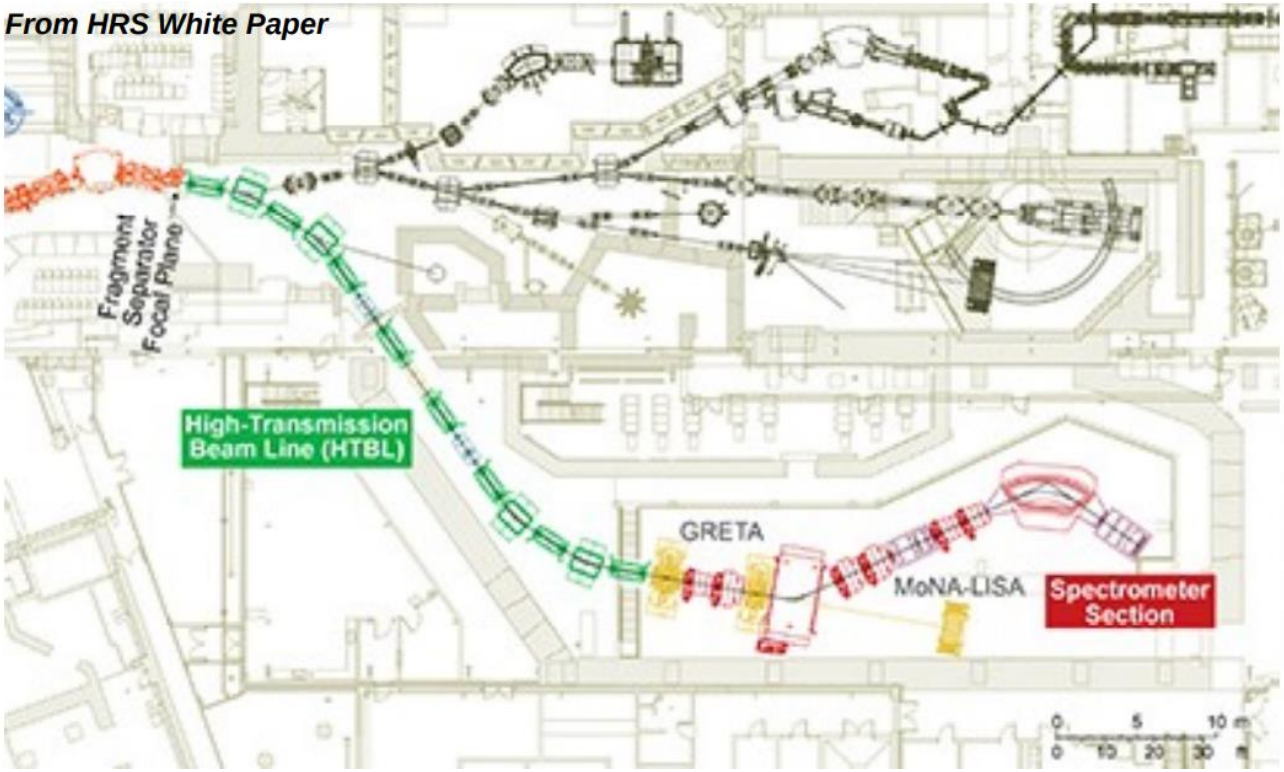


Next Generation Neutron Detector

- Development of a new neutron detector by the MoNA collaboration
- Plastic scintillator tiles with SiPM “grid”
- Position resolution improved by roughly factor 5
- Prototype tested at TUNL and results are promising
- Can be coupled to MoNA detector to enhance efficiency

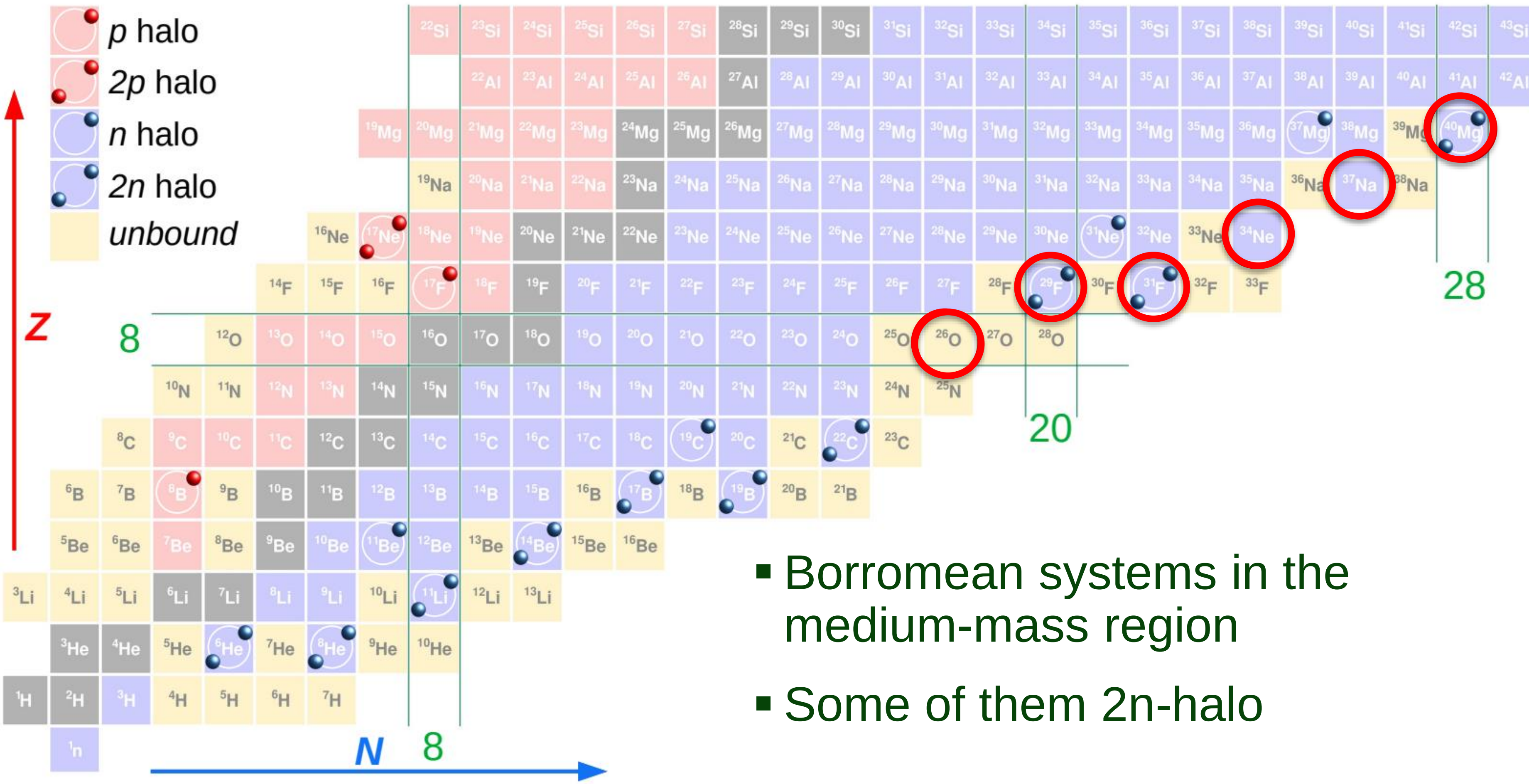


HRS : High Rigidity Spectrometer



- 8Tm magnetic rigidity
- Longer neutron flight path (~15m)

Cases of interests for n-n correlations studies



- Borromean systems in the medium-mass region
- Some of them 2n-halo

More than two neutrons ?

- Experimentally challenging (very low efficiency)

- Combination of high-efficiency neutron arrays, high-intensity beams and high-luminosity target allow to perform such study

- ^{28}O results from SAMURAI Y. Kondo et al., Nature 620, 965 (2023)
  - Detection of ^{24}O+n+n+n+n in coincidence
  - Sequential decay through gs of ^{26}O

- Possibility to study 6 neutrons decay: ^{30}O ?

- WPCF 2013: M. Marques mentioned plans to study ^{28}O, ^{7}H, ^{4,6}n

Thank you !

PHYSICAL REVIEW LETTERS **131,** 172501 (2023)

Editors' Suggestion | Featured in Physics

Strong Evidence for ^{9}N and the Limits of Existence of Atomic Nuclei

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The boundaries of the chart of nuclides contain exotic isotopes that possess extreme proton-to-neutron asymmetries. Here we report on strong evidence of ^{9}N, one of the most exotic proton-rich isotopes where more than one half of its constitute nucleons are unbound. With seven protons and two neutrons, this extremely proton-rich system would represent the first-known example of a ground-state five-proton emitter. The invariant-mass spectrum of its decay products can be fit with two peaks whose energies are consistent with the theoretical predictions of an open-quantum-system approach; however, we cannot rule out the possibility that only a single resonancelike peak is present in the spectrum.

DOI: 10.1103/PhysRevLett.131.172501

Evidence of 5p emitter