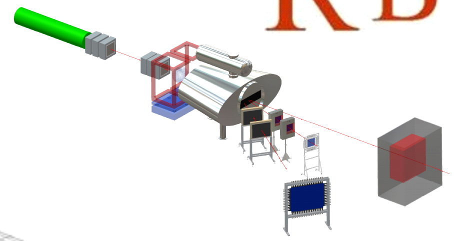
Quasi-free knockout reactions with radioactive beams at R^3B



Thomas Aumann

TECHNISCHE UNIVERSITÄT DARMSTADT

HIC for FAIR
Helmholtz International Center

GSI

EMMI

20th January 2012

Facets of Strong-Interaction Physics

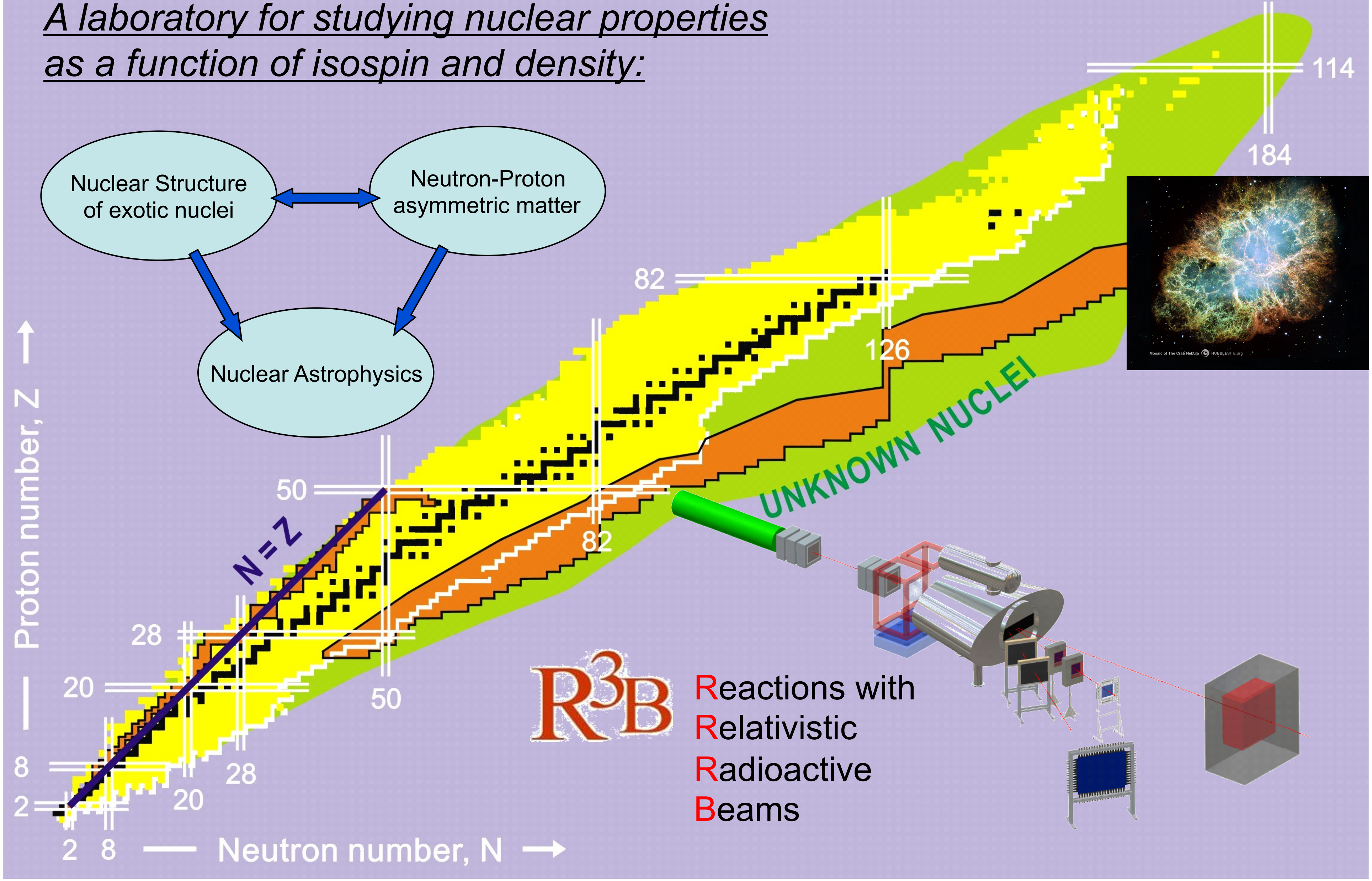
International Workshop XL on Gross Properties of Nuclei and Nuclear Excitations

Hirschegg 2012

- Introduction
- Quasi-free scattering with radioactive beams
  single-particle structure, nucleon-nucleon correlations
- (Future perspectives at FAIR)

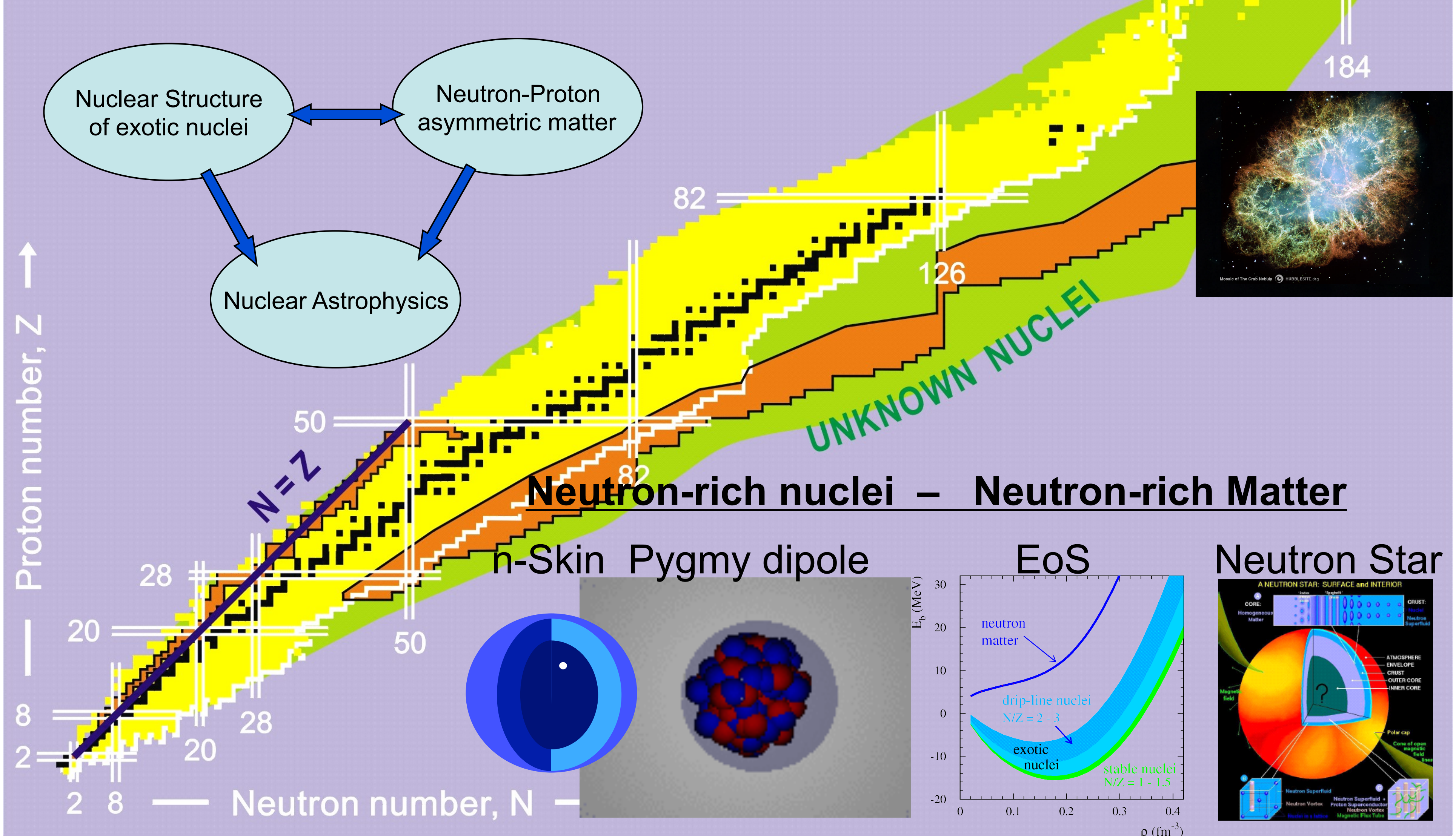
Reactions with neutron-proton asymmetric nuclei

A laboratory for studying nuclear properties as a function of isospin and density:



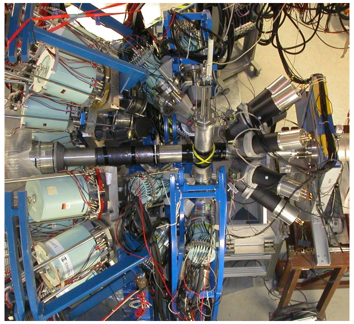
Reactions with neutron-proton asymmetric nuclei

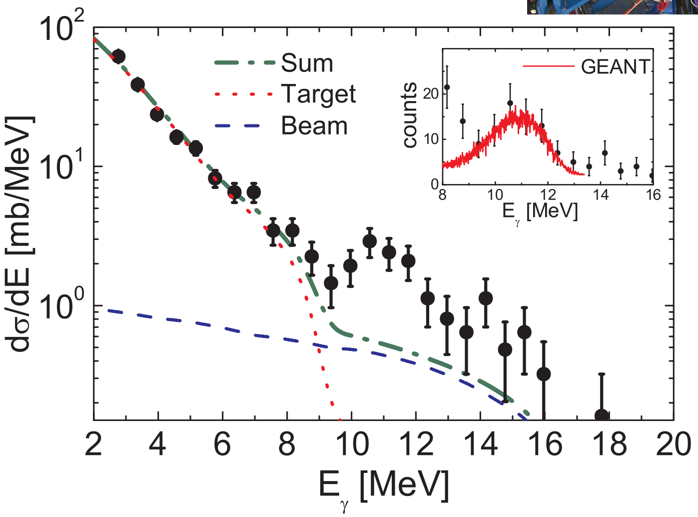
A laboratory for studying nuclear properties as a function of isospin and density:



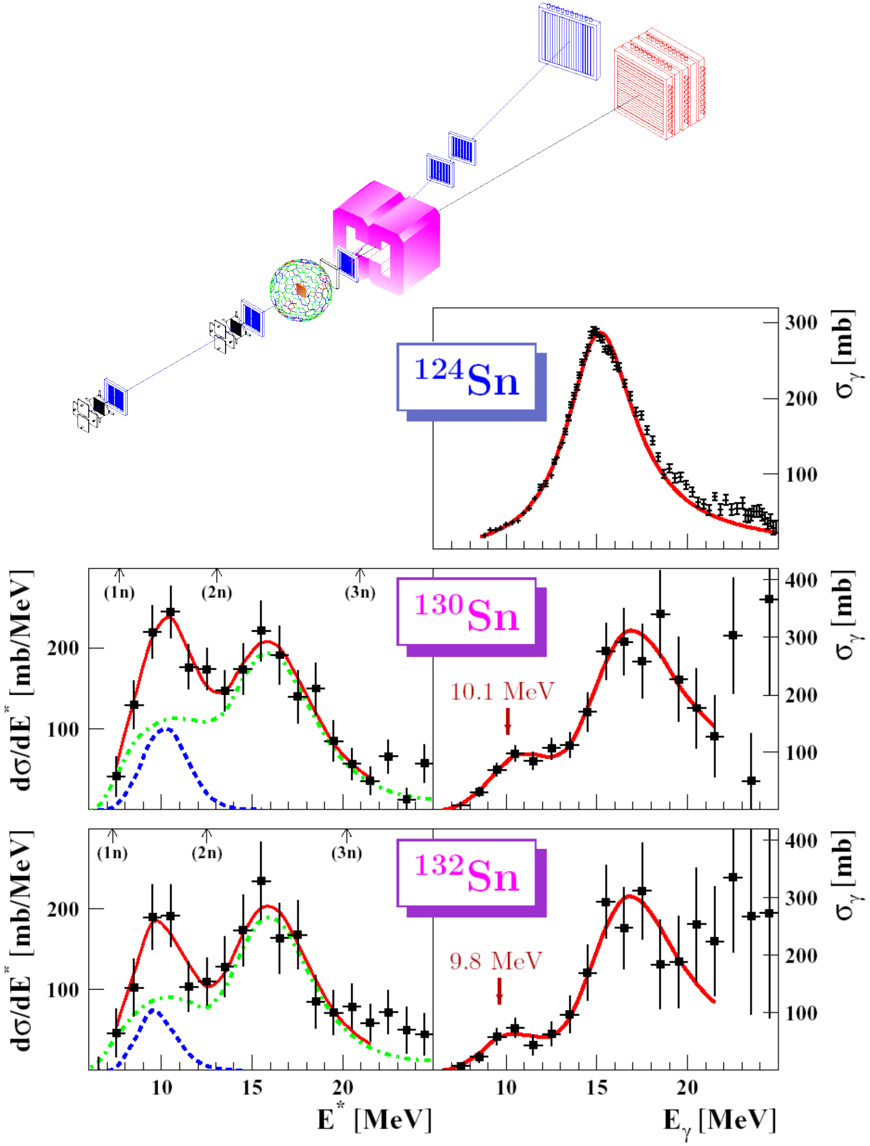
PDR – Electromagnetic excitation of neutron-rich nuclei

- PDR strength observed in neutron-rich Sn nuclei below the GDR at energies above particle threshold (around 10 MeV excitation energy exhausting about 5% EWSR)
- Virtual photon scattering on ^{68}Ni identifies PDR above threshold





O. Wieland et al., PRL 102 (2009) 092502



P. Adrich et al., PRL 95 (2005) 132501

Symmetry energy and dipole response

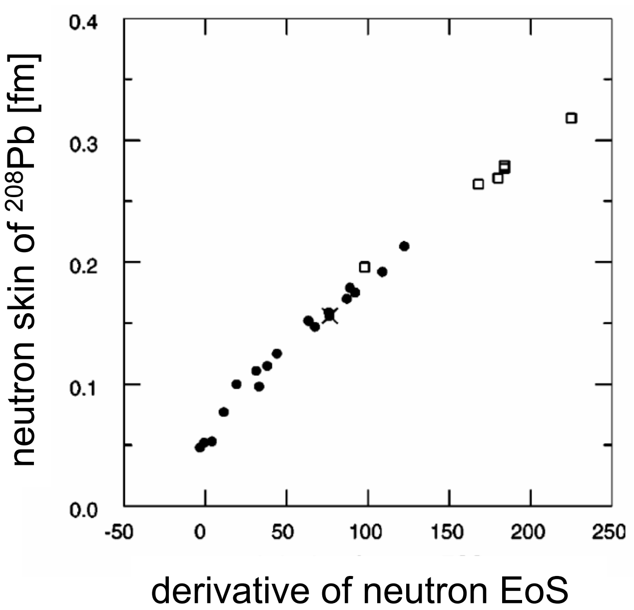
neutron-skin thickness
low-lying Pygmy mode

⟺

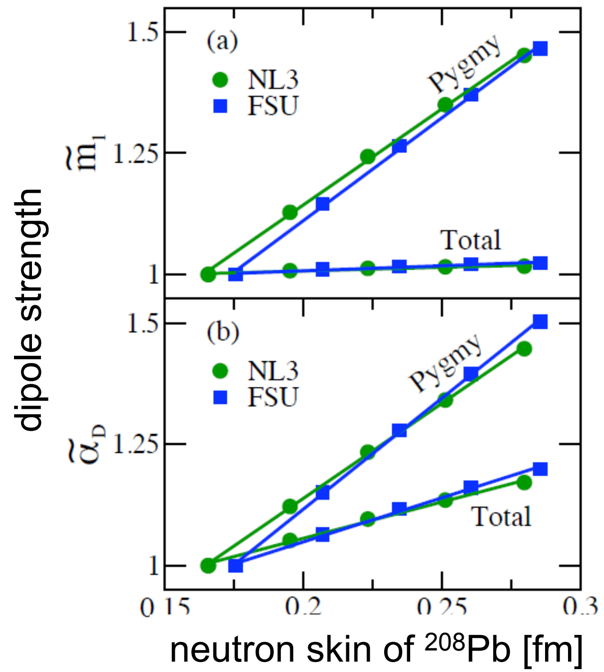
density dependence
of symmetry energy

⟺

properties of
neutron-rich matter



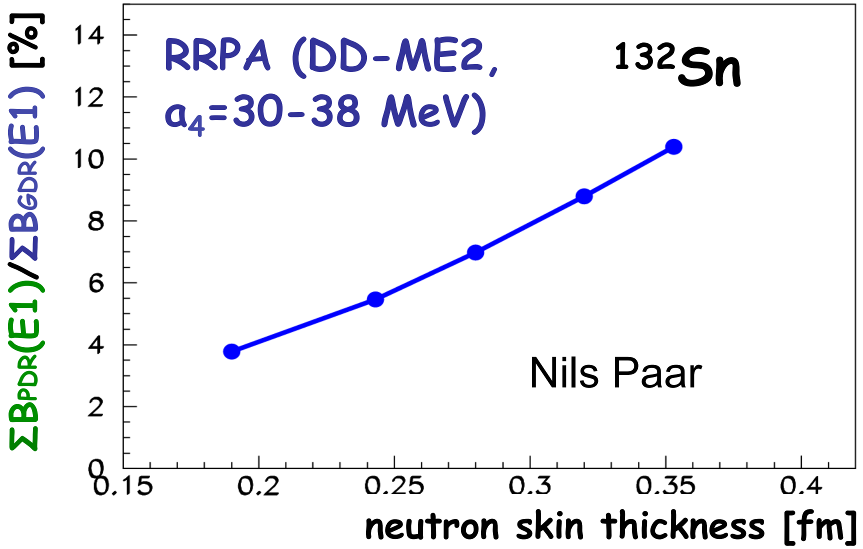
*S. Typel and B.A. Brown, Phys. Rev. C **64** (2001) 027302*



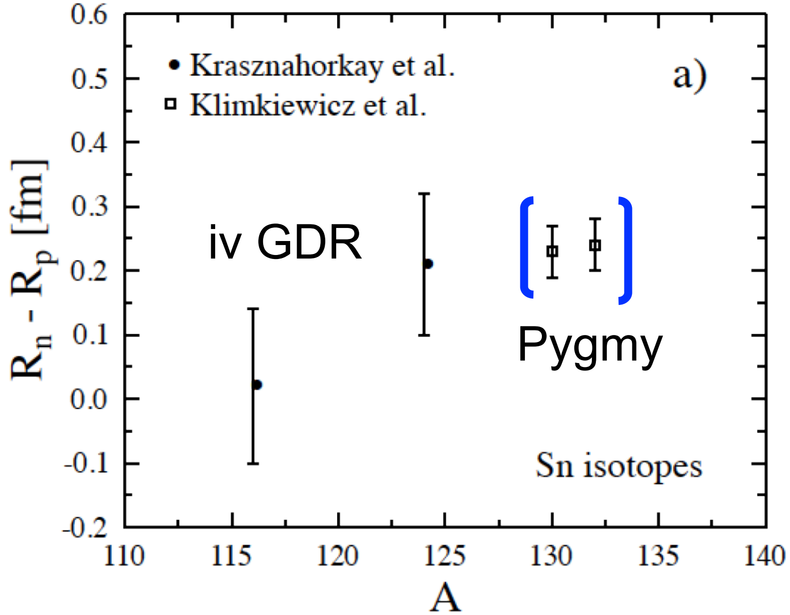
J. Piekarewicz, arXiv:1012.1803 (2010)

Pygmy dipole strength, neutron skin, and the equation of state of neutron-rich matter

Relation between dipole strength and n-skin thickness



n-skin thickness derived from dipole strength



"...,*the pygmy dipole resonance may place important constraints on the neutron skin of heavy nuclei and, as a result, on the equation of state of neutron-rich matter*."

J. Piekarewicz, PRC 73 (2006) 044325

Constraints on EoS of neutron-rich matter derived from dipole strength of n-rich Sn isotopes

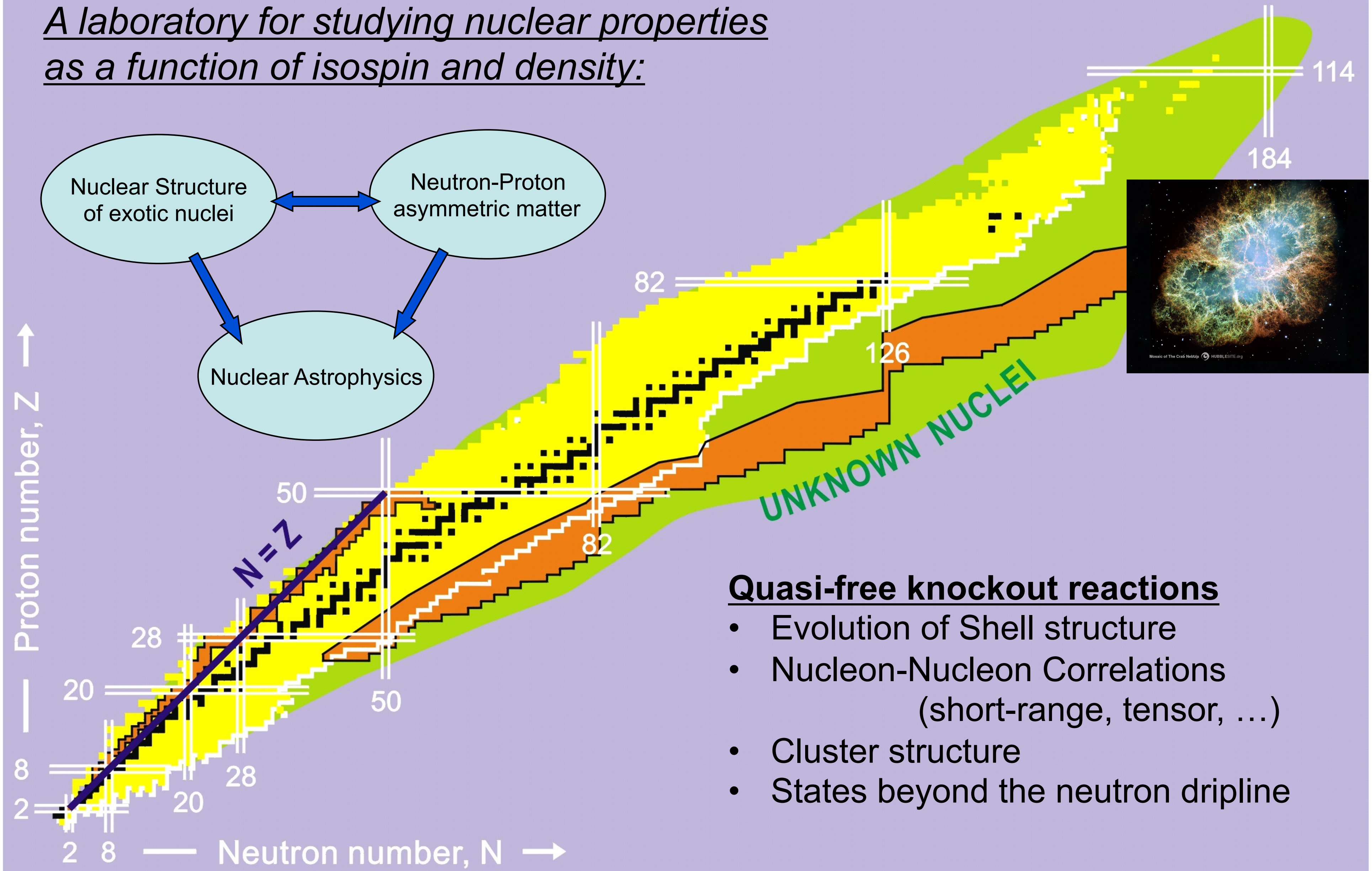
symmetry energy a_4 = 32.0 ± 1.8 MeV

pressure p_o = 2.3 ± 0.8 MeV/fm^3

A. Klimkiewicz et al., PRC 76 (2007) 051603(R)

Reactions with neutron-proton asymmetric nuclei

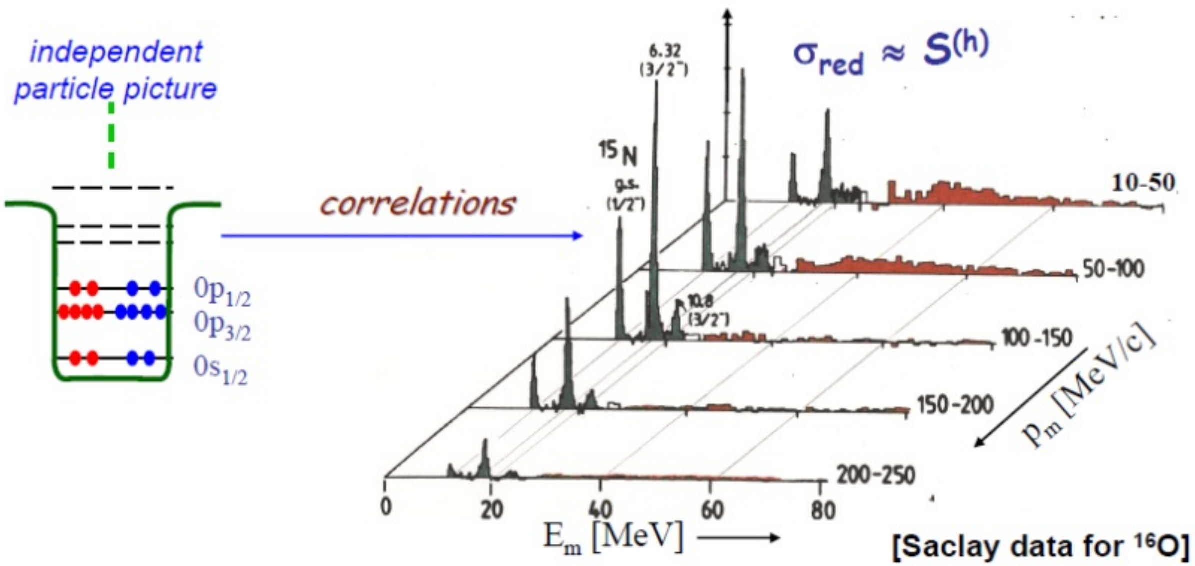
A laboratory for studying nuclear properties as a function of isospin and density:



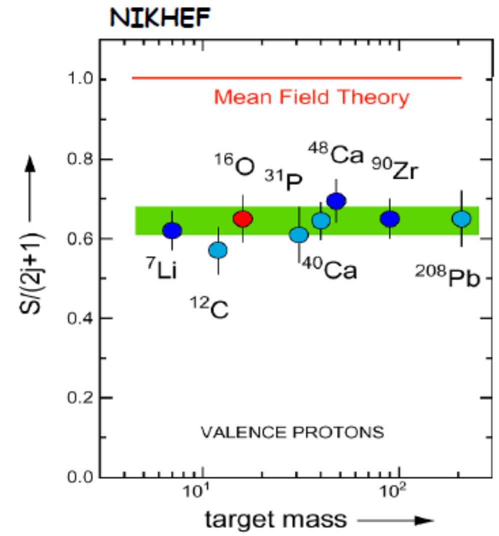
Quasi-free knockout reactions

- Evolution of Shell structure
- Nucleon-Nucleon Correlations (short-range, tensor, …)
- Cluster structure
- States beyond the neutron dripline

Single-particle structure and correlations



[Saclay data for ^{16}O]



Nucl. Phys. A553 (1993) 297c

Deviation from the independent-particle picture:

Correlations: Configuration mixing,

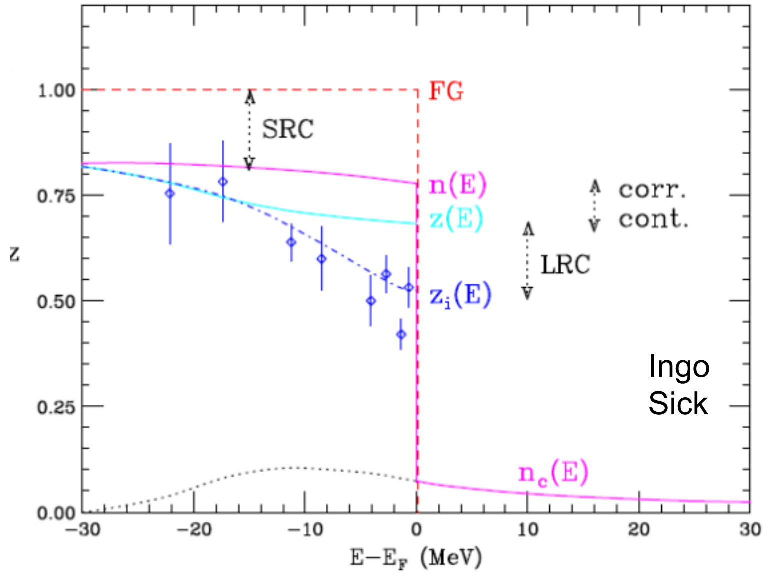
Coupling to collective phonons

Short-range and tensor correlations

→ high momenta

→ reduced single-particle strength

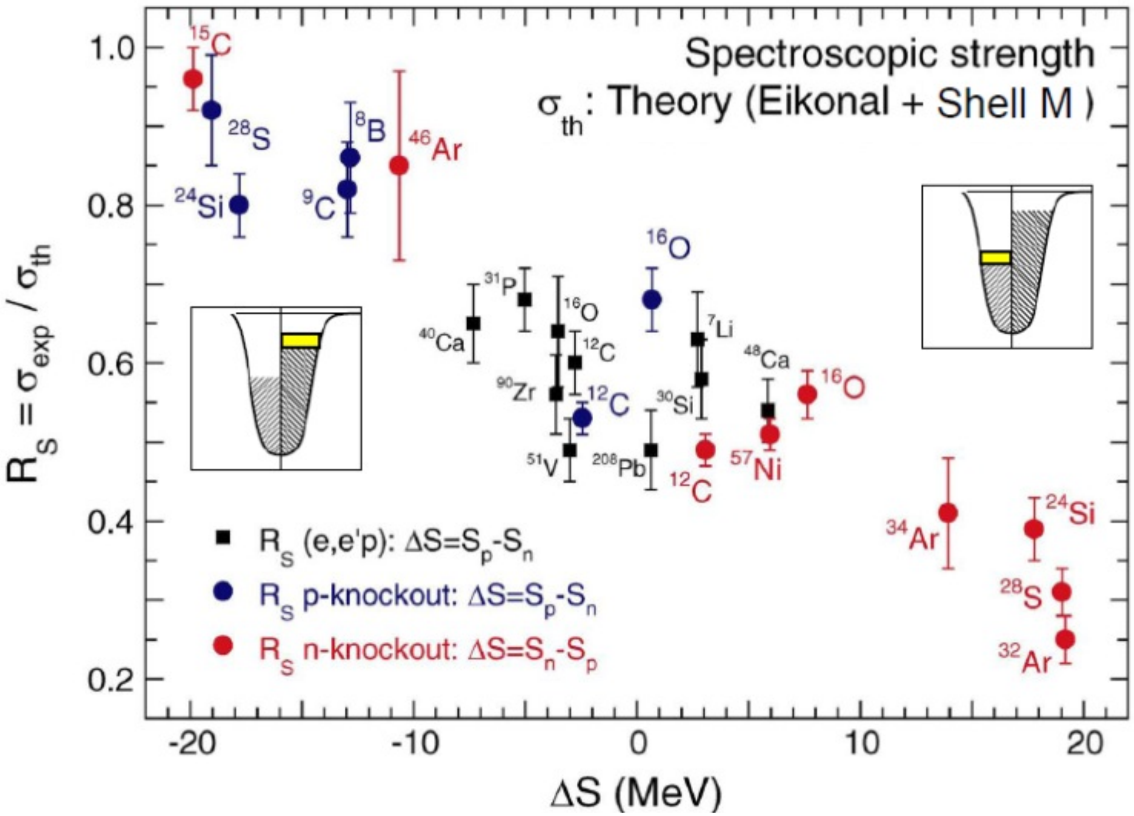
(occupations, spectroscopic factors)



Single-particle cross sections
Quenching for neutron-proton asymmetric nuclei

weakly bound nucleons

strongly bound nucleons



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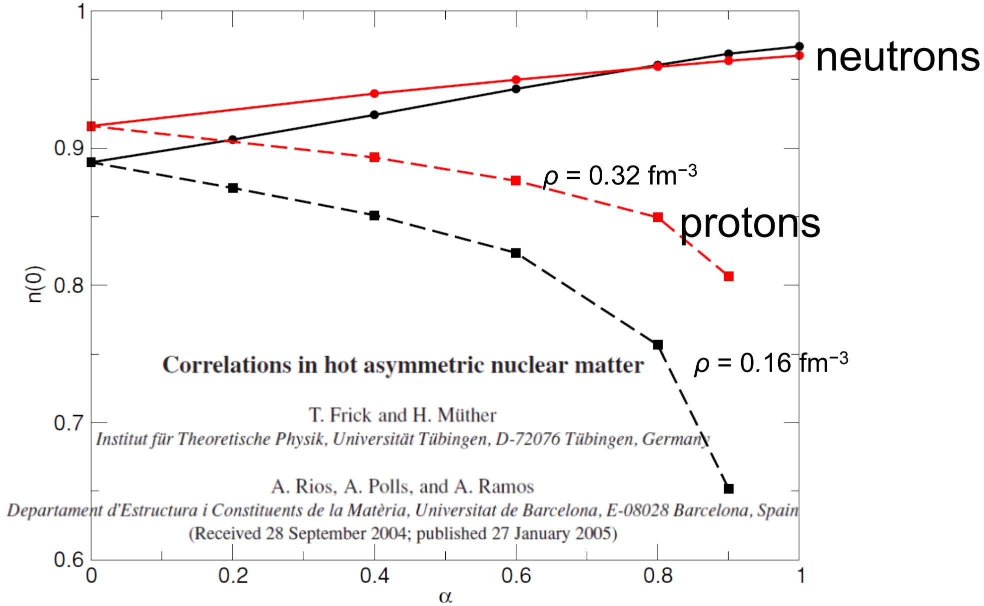
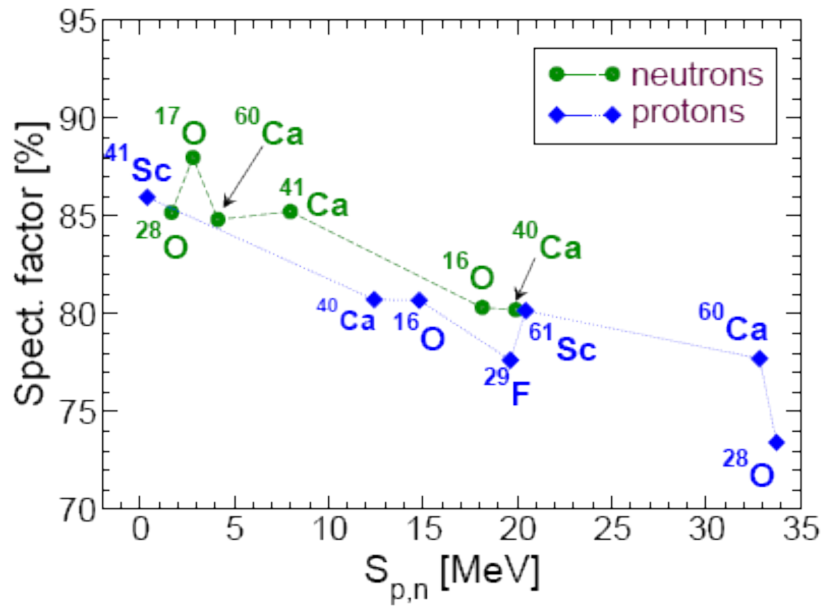
Origin unclear

?

Figure from Alexandra Gade, Phys. Rev. C 77, 044306 (2008)

Correlations in asymmetric nuclei and nuclear matter





Probing Cold Dense Nuclear Matter

Subedi et al. 13 JUNE 2008 VOL 320 **SCIENCE**

SPECTROSCOPIC FACTORS IN ^{16}O AND NUCLEON ASYMMETRY

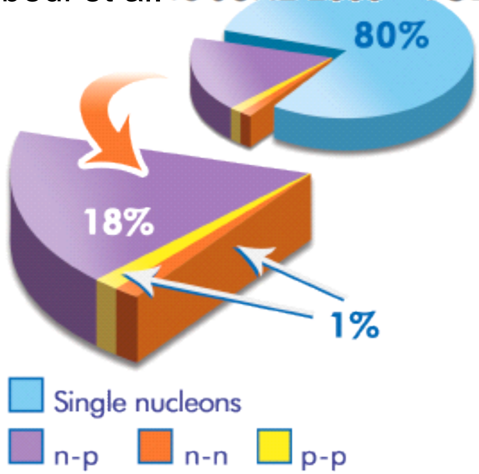
arXiv:0901.1920v1 [nucl-th] 14 Jan 2009

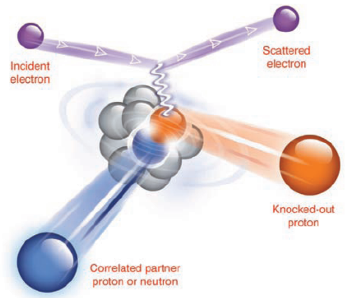
C. Barbieri

Theoretical Nuclear Physics Laboratory, RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198 Japan

W. H. Dickhoff

Department of Physics, Washington University, St.Louis, Missouri 63130, USA

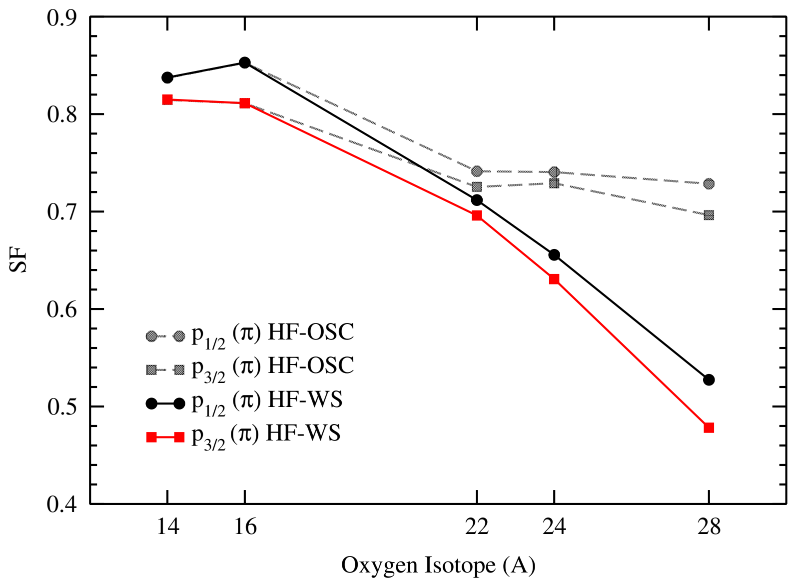


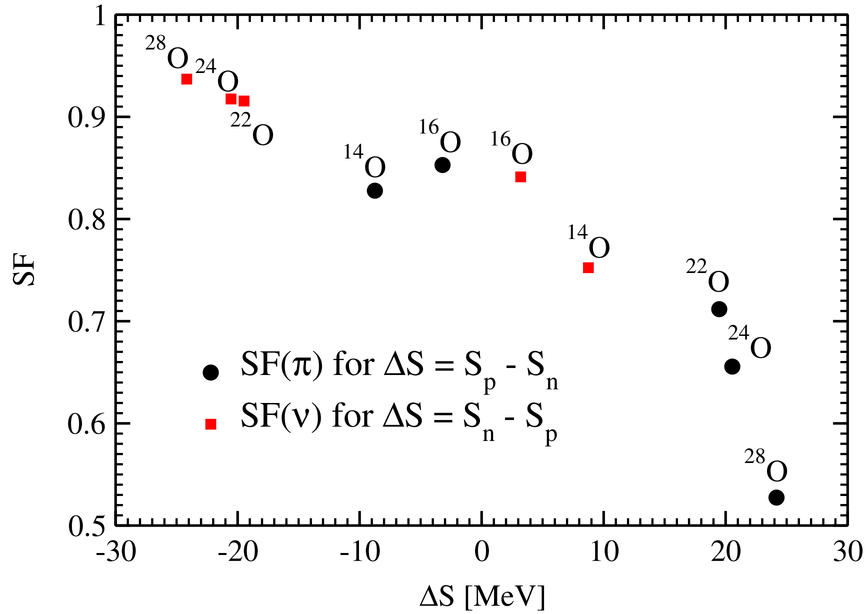


Electron-induced knockout (JLab)

Quenching of Spectroscopic Factors for Proton Removal in Oxygen Isotopes

Ø. Jensen,[1] G. Hagen,[2,3] M. Hjorth-Jensen,[1] B. Alex Brown,[4,5] and A. Gade[4,5]

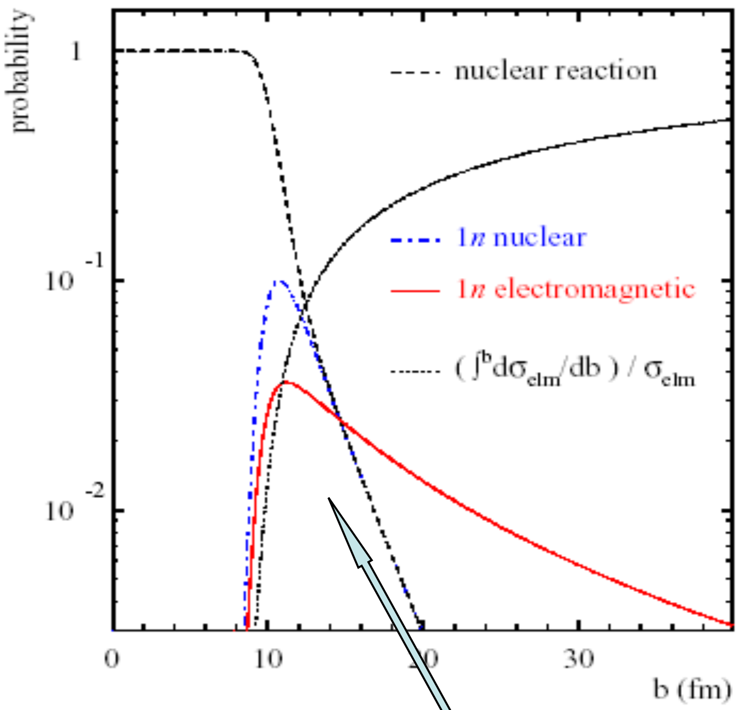




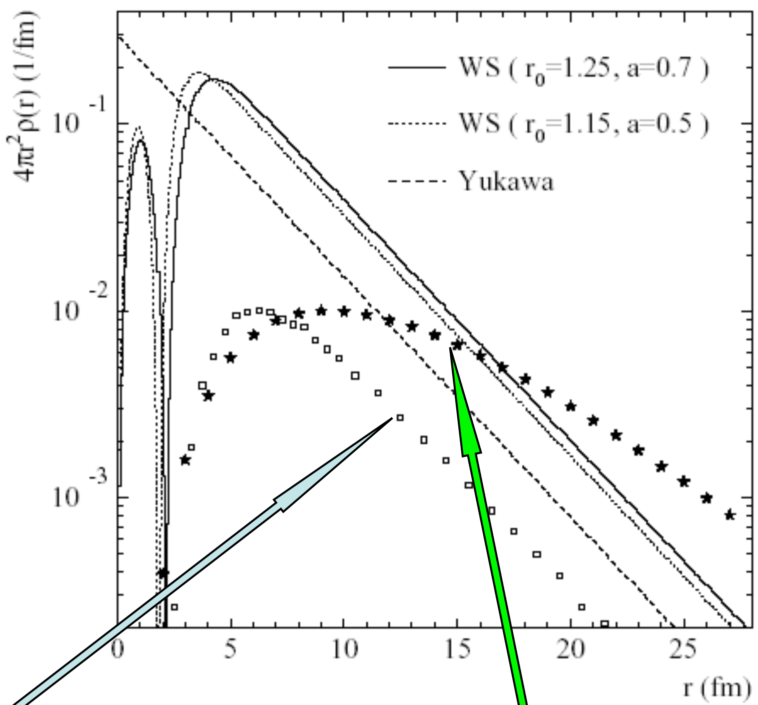
Coupled-cluster calculation N^3LO
including coupling to scattering states above the neutron separation threshold

Sensitivity of Coulomb and nuclear breakup

Reaction probabilities



Halo-Neutron Densities



Nuclear breakup

Coulomb breakup

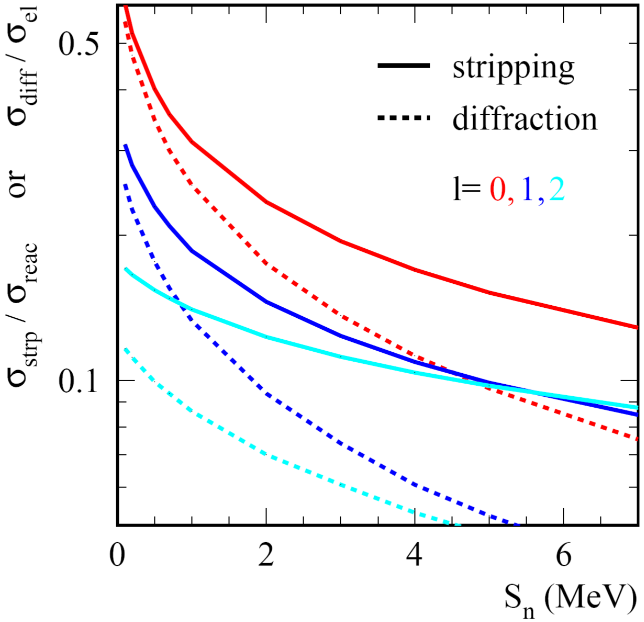
Overlap with continuum wave function

Sensitivity to the tail of the wave function only

Alternative approach: quasi-free scattering: (p,2p), (p,pn) etc. at LAND and R3B

or (e,e'p) at the e-A collider at FAIR

One-neutron removal reaction (nuclear breakup)



Reaction mechanisms:

- knockout (stripping)
- inelastic scattering (diffraction)

cross section dominated by knockout for

- high beam energies
- non-halo states

$$p_{stripping} = < S_c^2(\mathbf{b_c})[1 - S_n^2(\mathbf{b_n})] >$$

$$p_{inelastic} = < [1 - S_c(\mathbf{b_c})S_n(\mathbf{b_n})]^2 > - < 1 - S_c(\mathbf{b_c})S_n(\mathbf{b_n}) >^2$$

<u>no-recoil limit:</u> $A_c >> 1, \mathbf{b_c} = \mathbf{b}$

$$p_{diffraction} = S_c^2 < [1 - S_n(\mathbf{b_n})]^2 > - S_c^2 < 1 - S_n(\mathbf{b_n}) >^2$$

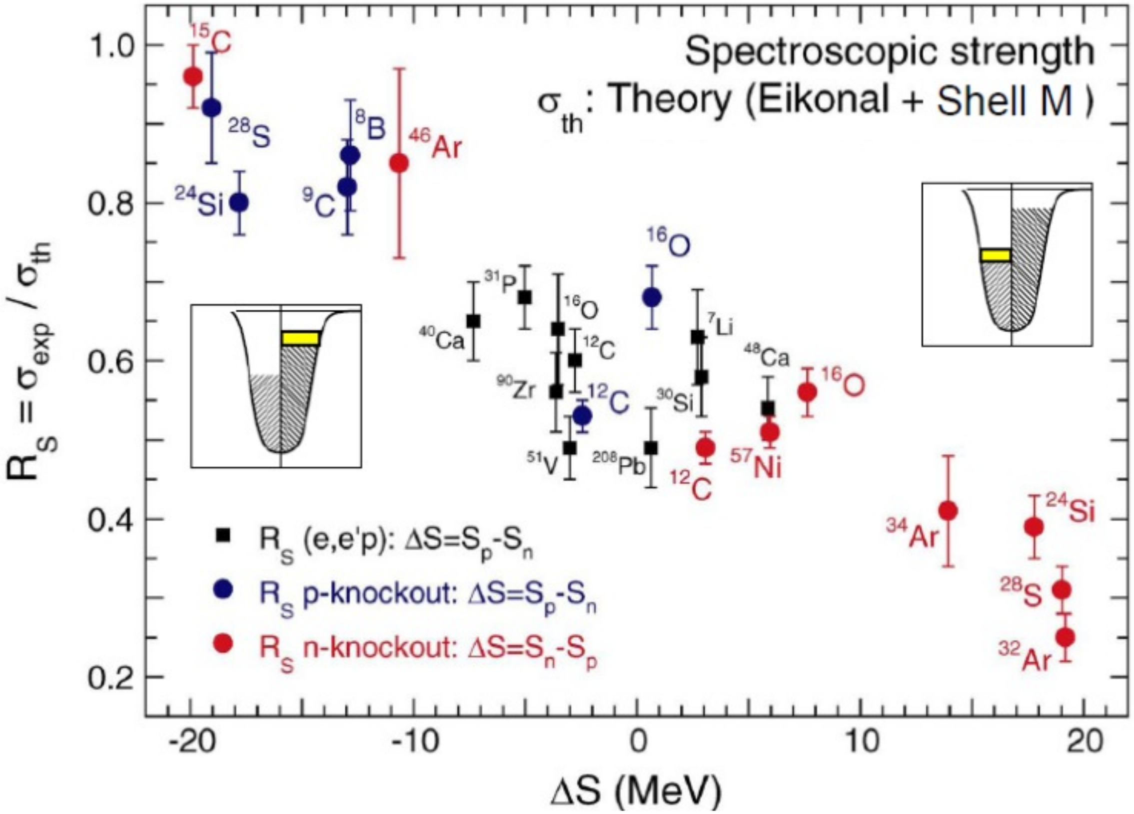
elastic scattering of neutron

elastic scattering of projectile

Single-particle cross sections
Quenching for neutron-proton asymmetric nuclei

weakly bound nucleons

strongly bound nucleons



?

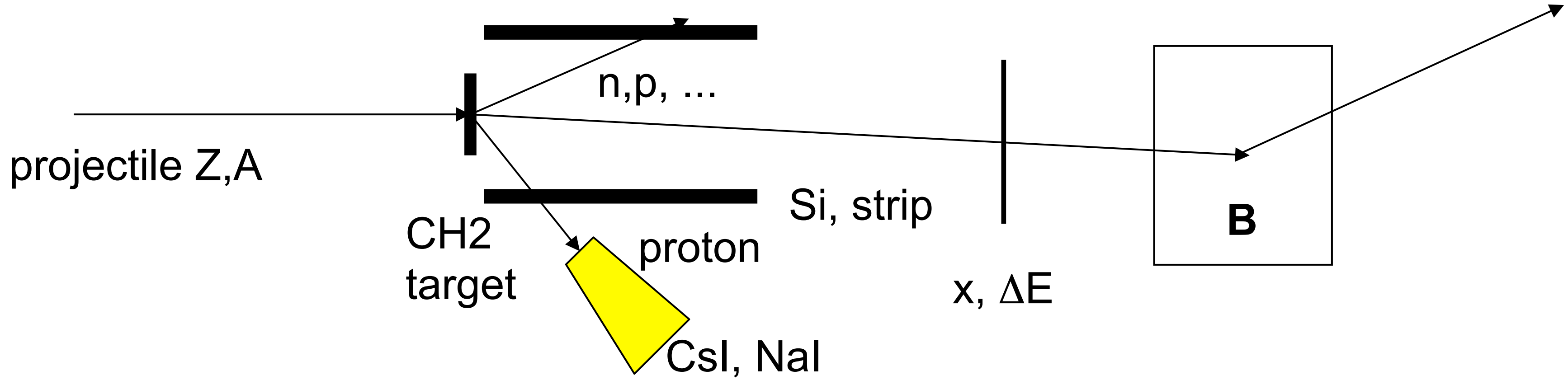
Origin unclear

?

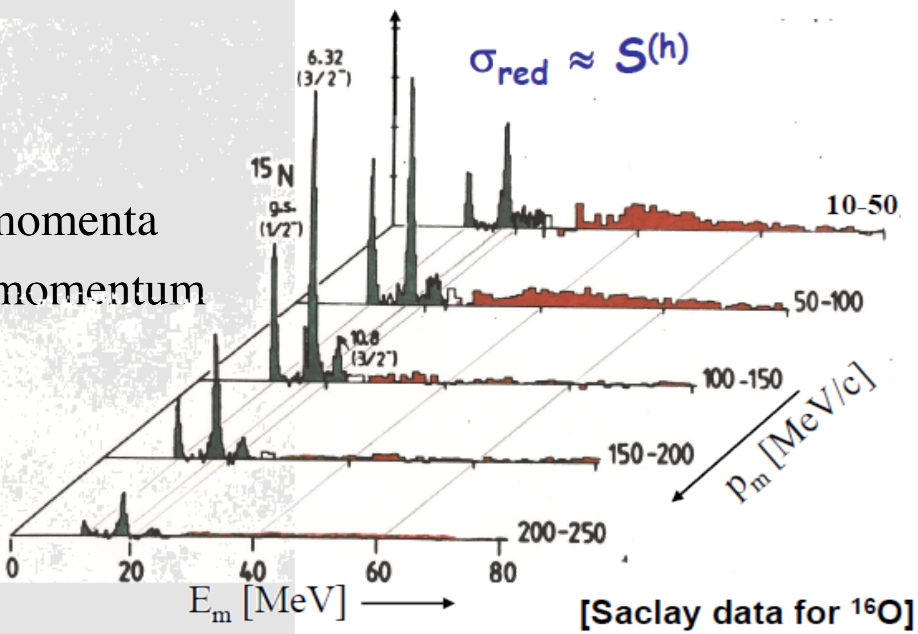
Figure from Alexandra Gade, Phys. Rev. C 77, 044306 (2008)

Quasi-free scattering in inverse kinematics

Measurement of proton recoils after knockout reactions with a CH_2 target

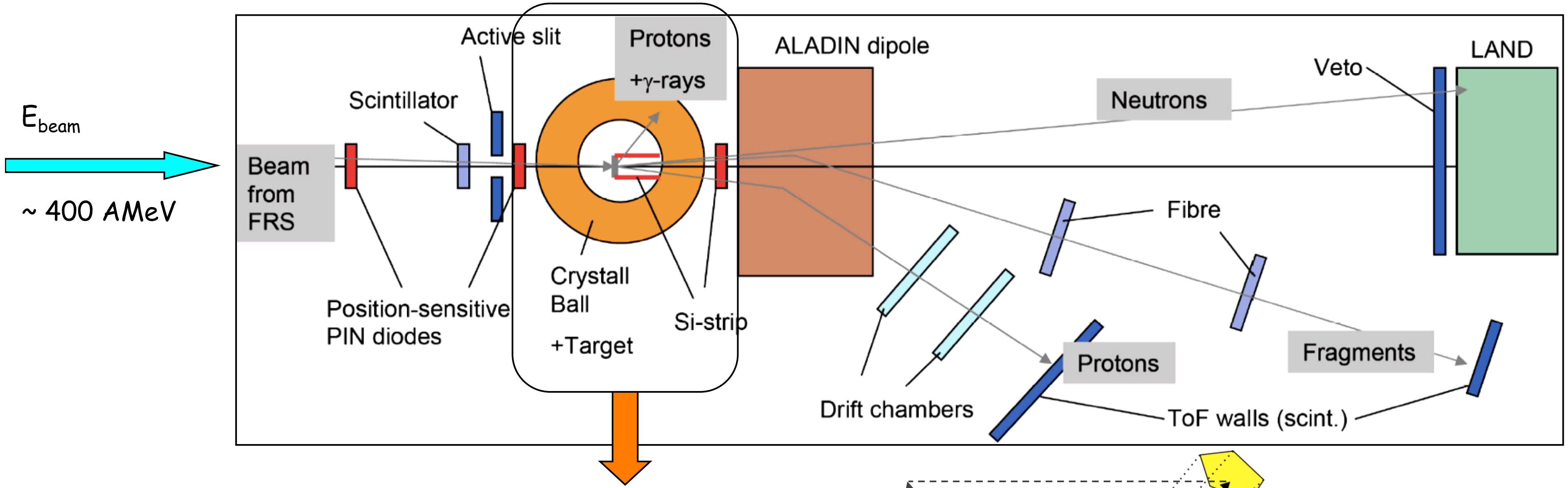


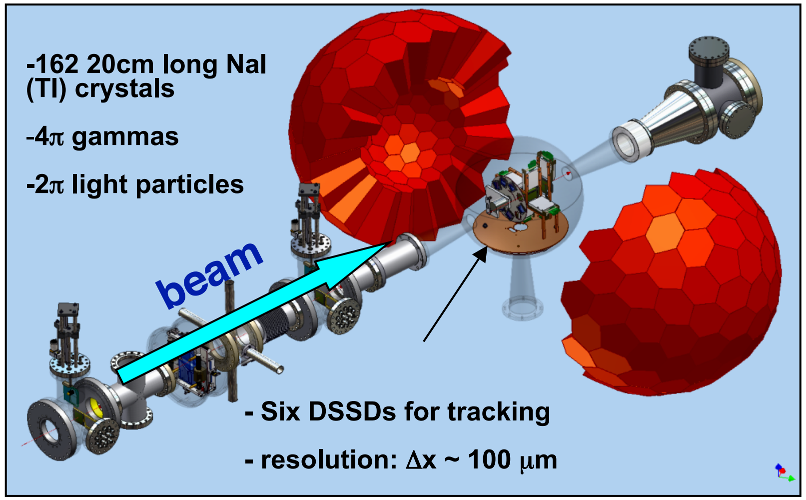
- kinematical complete measurement of
  (p,pn), (p,2p), (p,pd), (p,α), ... reactions
- redundant experimental information:
  kinematical reconstruction from proton momenta
  plus gamma rays, invariant mass, recoil momentum
- sensitivity not limited to surface
  → spectral functions
  → knockout from deeply bound states
- cluster knockout reactions

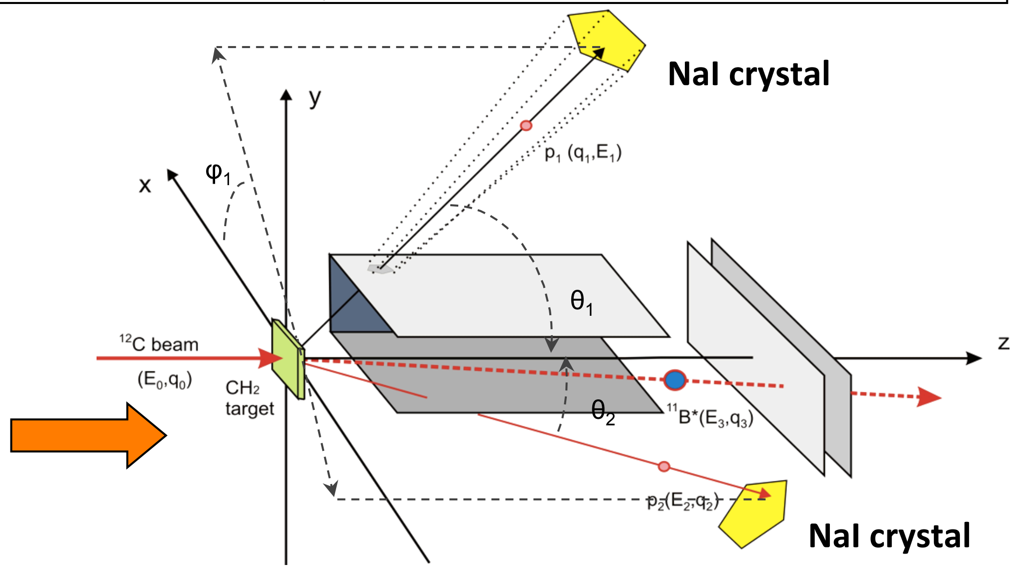


[Saclay data for ^{16}O]

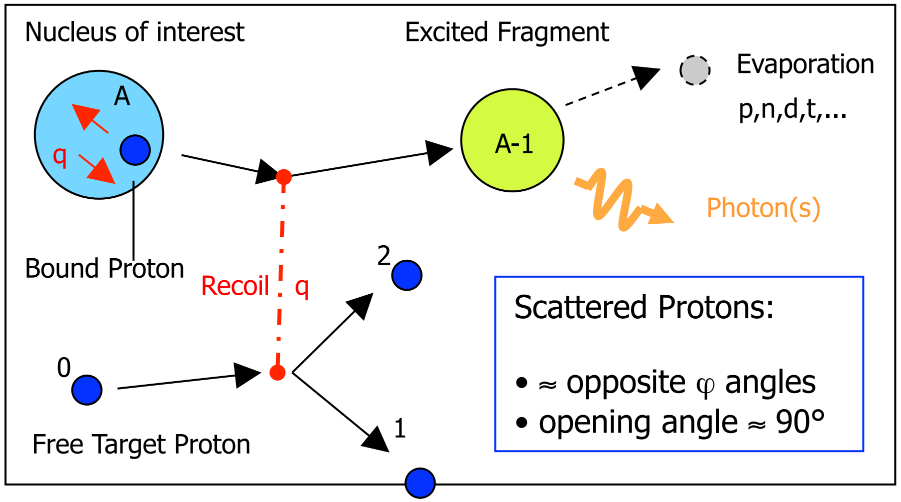
Experimental setup: LAND/R3B@GSI







Quasi-free scattering with exotic nuclei: $^{17}Ne(p,2p)^{15}O+p$
The two-proton Halo (?) nucleus ^{17}Ne



Internal Momentum | Separation Energy

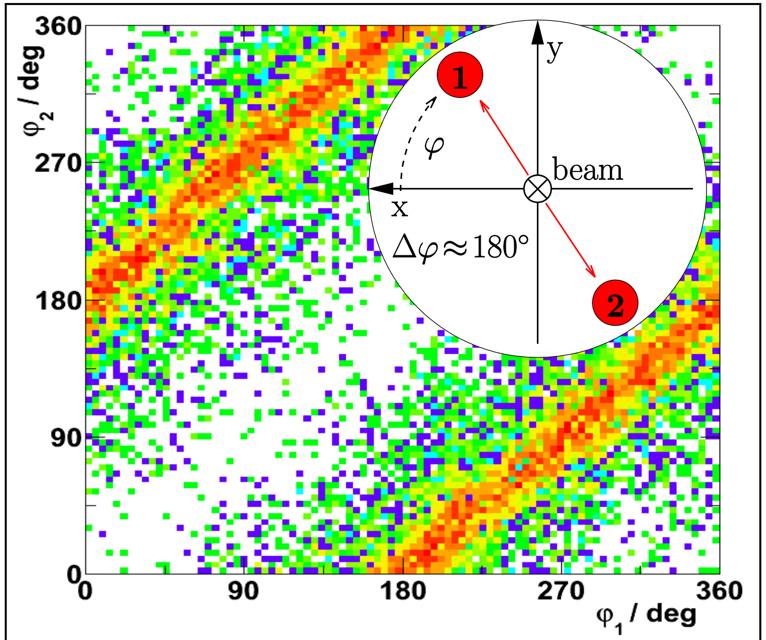
$$q = -p_{A-1} = p_1 + p_2 - p_0 \qquad E_S = T_1 + T_2 + T_{A-1} - T_0$$

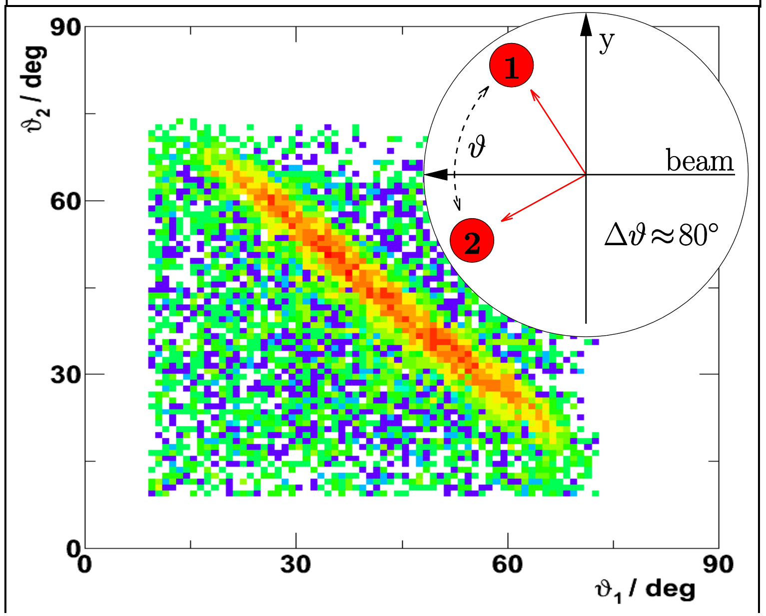
Pilot experiments with ^{12}C, ^{17}Ne and Ni isotopes already performed at the LAND-R3B setup are under analysis …

Angular Correlations measured with Si-strip detectors for $^{17}Ne(p,2p)^{15}O+p$

Δθ~180°, Δϕ~83° (sim. as for free pp scattering)

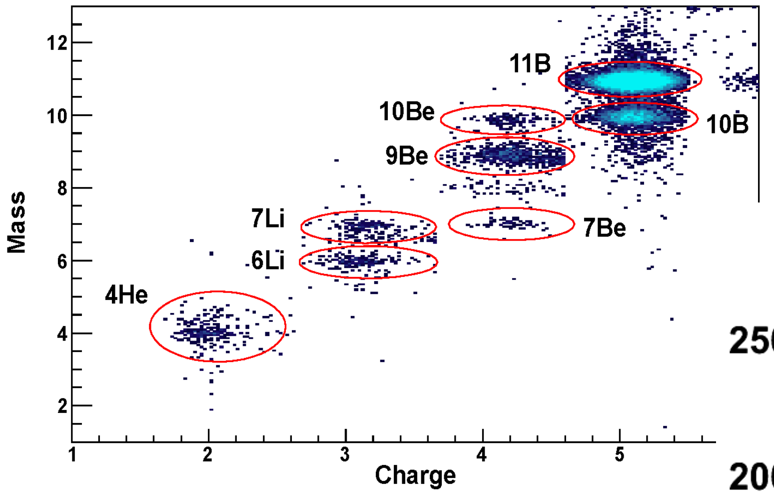
^{17}Ne, Felix Wamers, PhD thesis





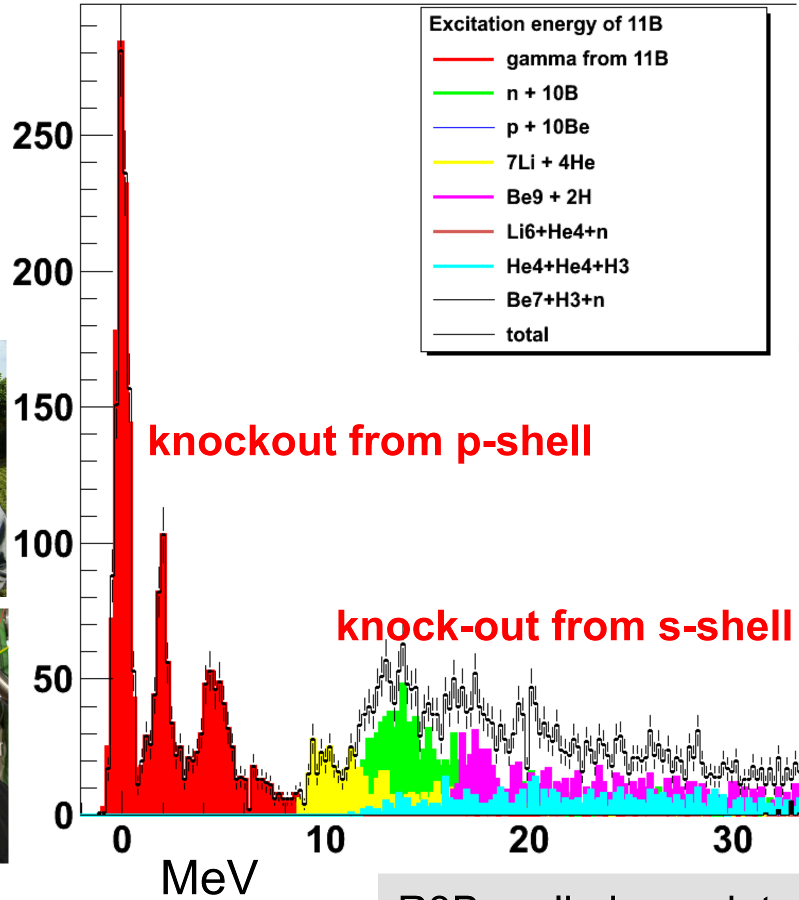
Benchmark experiment: $^{12}C(p,2p)$ in inverse kinematics

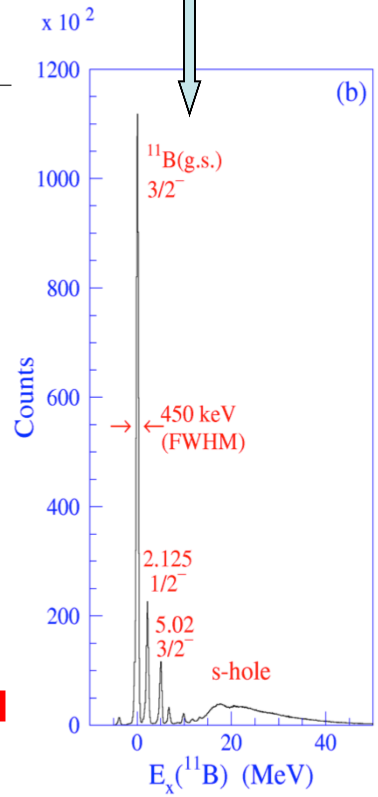
Fragments produced in $^{12}C(p,2p)$



M. Yosoi, PhD Thesis, 2003,
Kyoto University

Reconstructed excitation energy of ^{11}B





Jon Taylor, PhD thesis,

Univ. of Liverpool

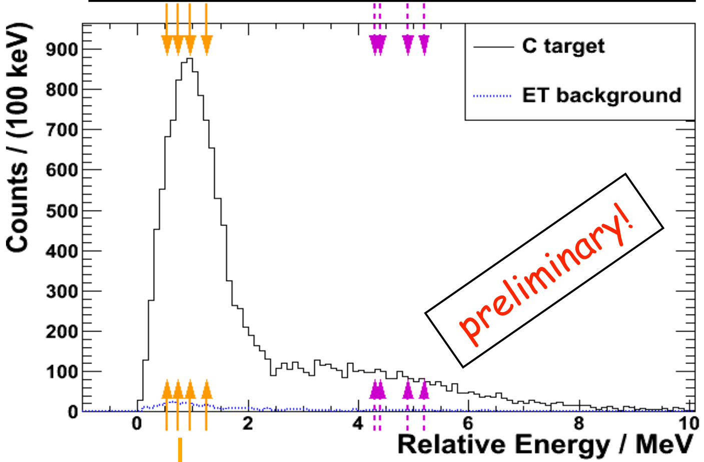
Valeri Panin, PhD thesis,

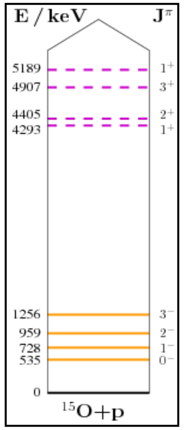
TU Darmstadt

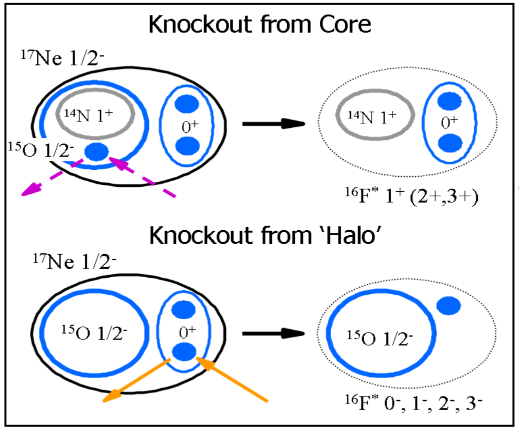
R3B preliminary data 2011, unpublished

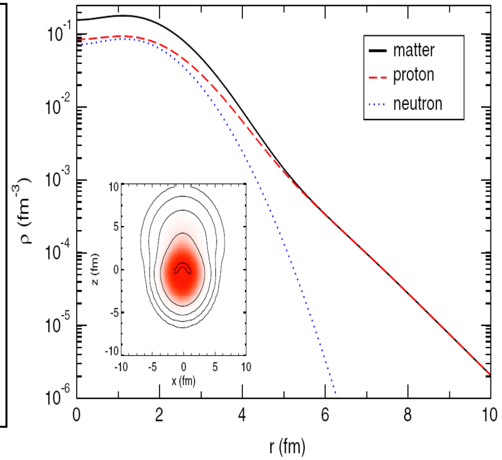
Selective one-proton knockout from core- and 'Halo'- states in ^{17}Ne

^{16}F (=^{15}O+p) relative energy

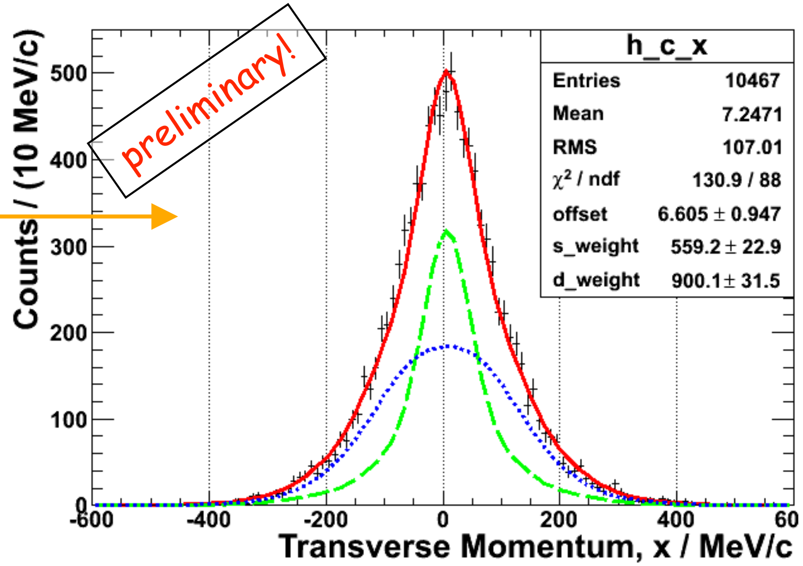








Exclusive selection of knockout from 'halo'-states for the first time possible!

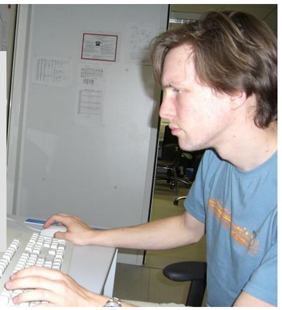


s-wave content of ~40%
moderate halo character

Good agreement with charge-radius measurement and FMD prediction of Geithner and Neff et al. *PRL 101 (2008) 252502.* and from 3b-model of Grigorenko, *PRC 71 (2005) 051604(R).*

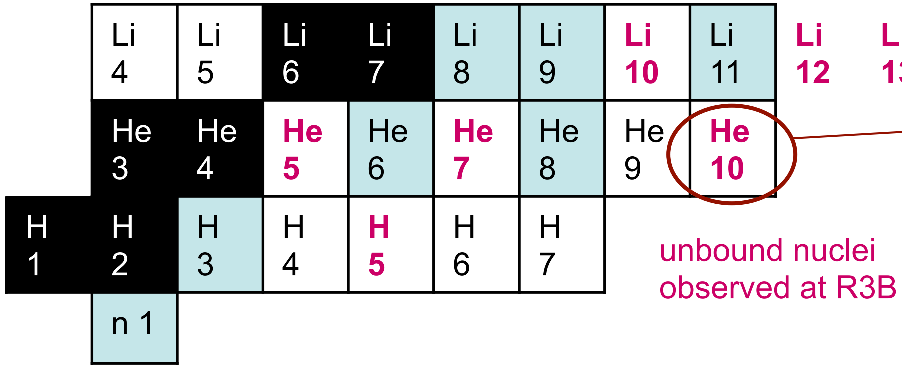
Felix Wamers,
PhD thesis,

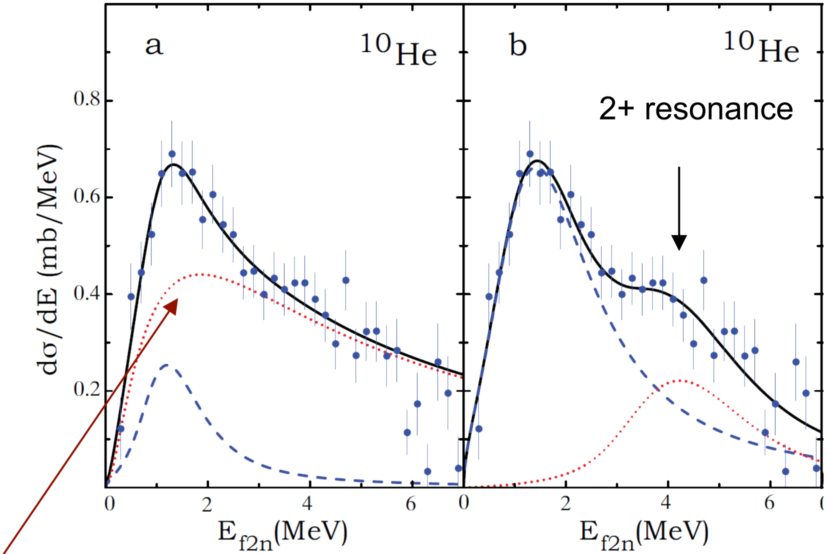
TU Darmstadt



R3B preliminary data 2011, unpublished

Beyond the dripline: Ground and first excited state of ^{10}He
- three-body correlations in the decay of unbound nuclei -





<u>Unbound nuclear systems</u>

problem of overlapping resonances

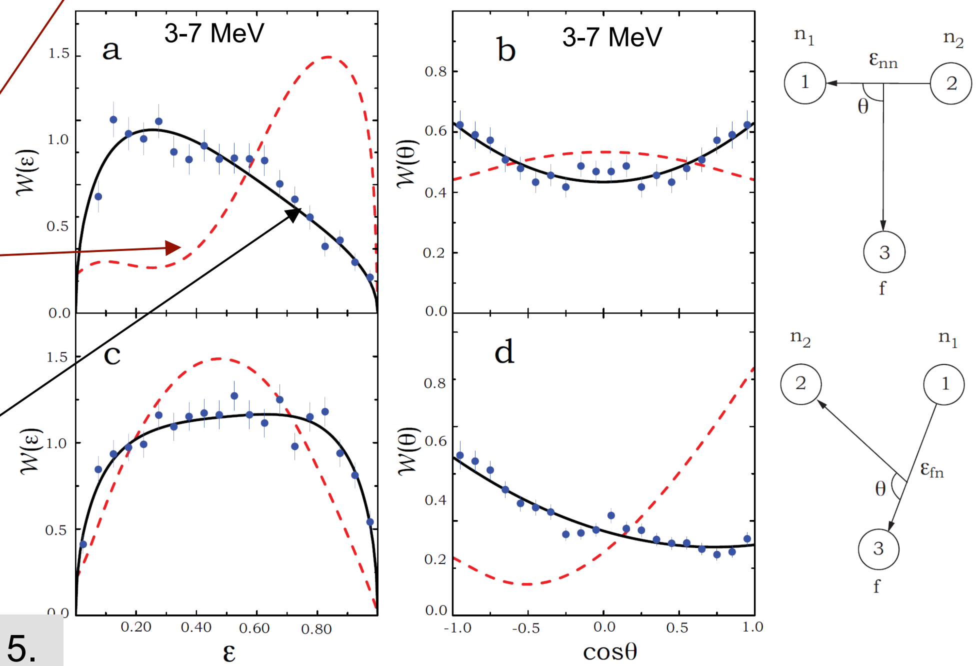
ambiguity: resonances or correlated background?

solution demonstrated for ^{10}He:

observation of characteristic 3-body correlations in the decay

correlated background (initial-state correlations, ^{11}Li wave function)

2+ resonance



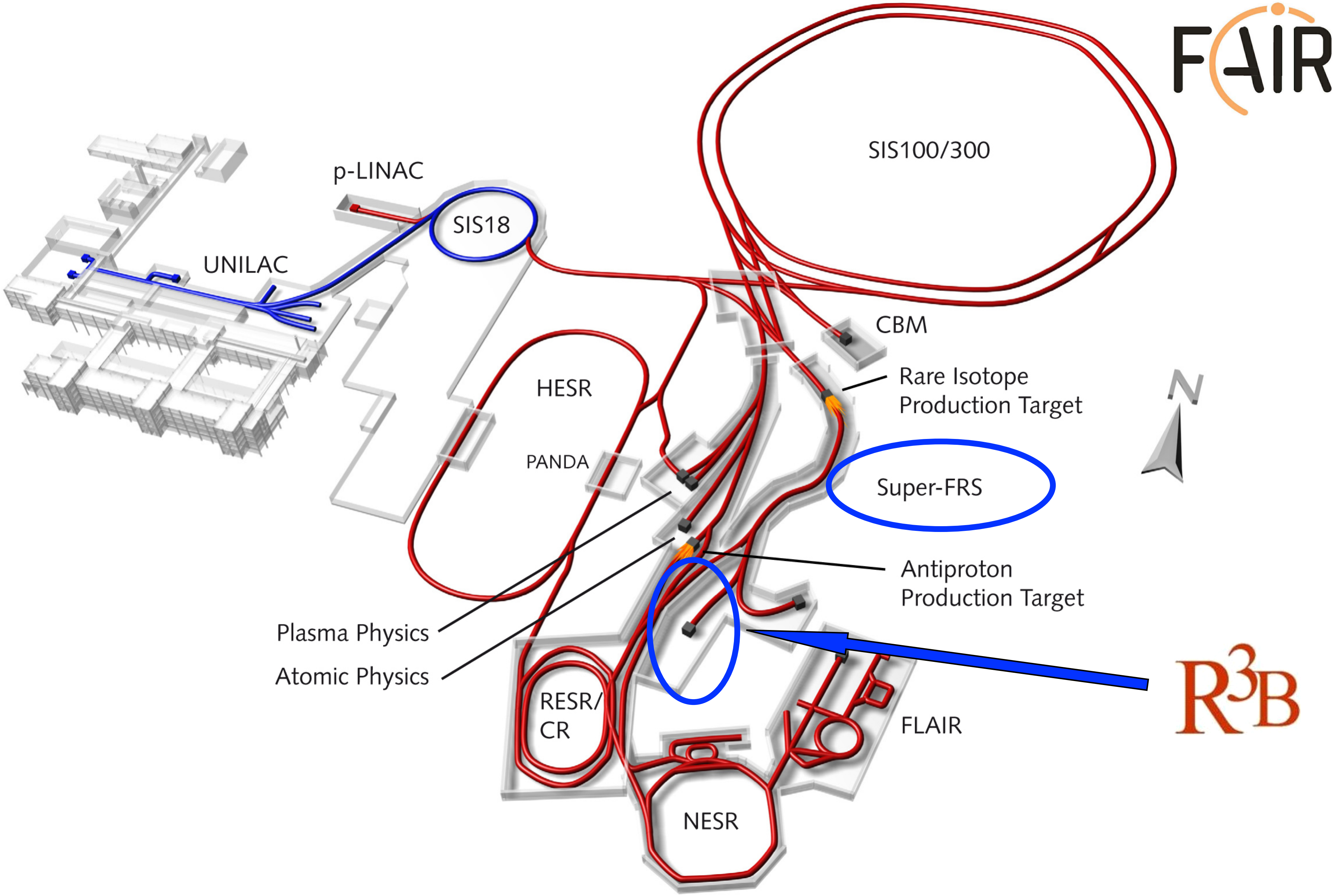
identification of ^{10}He resonances produced in ^{11}Li(p,2p) reactions:

0^+ ground state

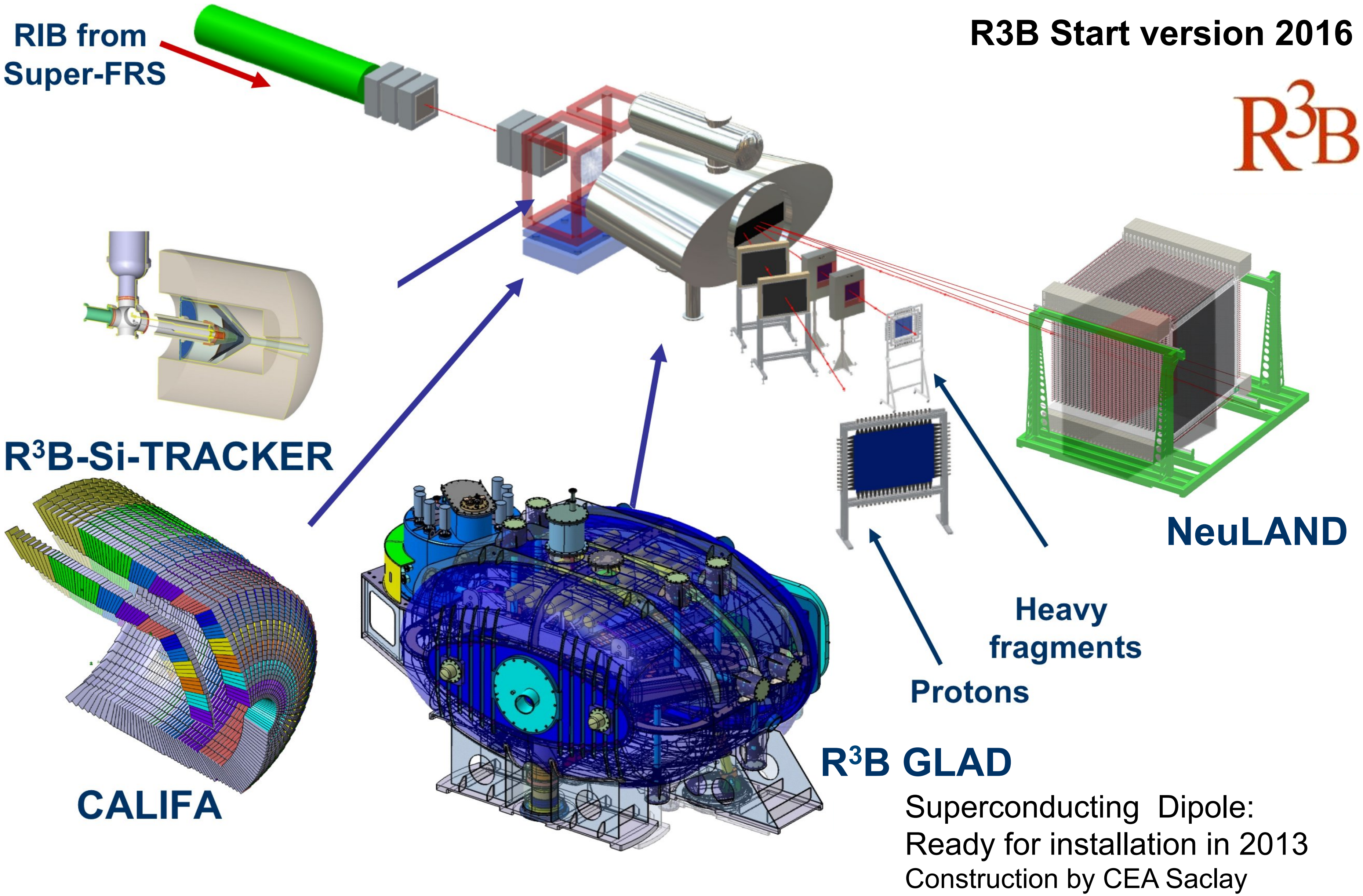
2^+ excited state

H.T. Johansson, Yu. Aksyutina et al., NPA 842 (2010) 15.

High-energy radioactive beams at FAIR



Reactions with Relativistic Radioactive Beams



The R3B Collaboration

T. Adachi[1], Y. Aksyutina[2,15], J. Alcantara[3], S. Altstadt[4], H. Alvarez-Pol[3], N. Ashwood[5], T. Aumann[6,2], M. Borri[5], S. Beceiro, D. Bemmerer[7], J. Benlliure[3], K. Boretzky[2], G. Burgunder[8], M. Caamano[3], C. Caesar[6], E. Casarejos[3], W. Catford[9], S. Chakraborty[10], M. Chartier[11], D. Cortina-Gil[3], U. Datta Pramanik, P. Diaz[3], I. Dillmann[2], J. Enders[6], O. Ershova[4], A. Estrade[2], F. Farinon[2], L.M. Fraile[12], M. Freer[5], M. Freudenberger[6], D. Galaviz Redondo[13], D. Gonzalez Diaz[6], J. Hagdahl[8], T. Heftrich[4], M. Heil[2], M. Heine[6], A. Henriques[13], M. Holl[6], A. Ignatov, H. Johansson[8], B. Jonson[8], N. Kalantar[1], R. Knöbel[2], T. Kroell[6], R. Krücken[14], J. Kurcewicz, M. Labiche[7], C. Langer[4], T. LeBleis[14], R. Lemmon[7], J. Machado[13], J. Marganiec[15], A. Movsesyan[6], A. Najafi[1], T. Nilsson[8], C. Nociforo, V. Panin[6], S. Pietri[2], R. Plag[4], A. Prochazka[2], A. Rahaman[10], G. Rastrepina[2], R. Reifarth[4], G. Ribeiro, M.V. Ricciardi[2], C. Rigollet[1], K. Riisager[1], M. Röder[16], D. Rossi[2], J. Sanchez del Rio[12], D. Savran[15,17], H. Scheit[18], H. Simon[2], O. Sorlin[8], B. Streicher, J. Taylor[11], O. Tengblad[12], S. Terashima[2], R. Thies[8], T. Yasuhiro[18], E. Uberseder[19], J. Van de Walle, P. Velho[13], V. Volkov[6], A. Wagner, F. Wamers[6], J. Weick[2], M. Weigand[4], C. Wheldon[5], G. Wilson[9], C. Wimmer[4], J. Winfield[2], P. Woods[20], D. Yakorev[7], M. Zoric[2], and K. Zuber[16]

[1]KVI Groningen, Netherlands; [2]GSI Darmstadt, Germany; [3]University of Santiago de Compostela, Spain; [4] University of Frankfurt, Germany; [5]Birmingham University, United Kingdom; [6] TU Darmstadt, Germany; [7] HZDR Dresden-Rossendorf, Germany; [8]GANIL, Caen, France; [9] University of Surrey, United Kingdom; [10] SINP Kolkata, India; [11] University of Liverpool, United Kingdom; [12] Universidad Complutense of Madrid, Spain; [13]University of Lisbon, Portugal; [14] TU Munich, Germany; [15]ExtreMe Matter Institute EMMI and Research Division, GSI Darmstadt, Germany; [16]TU Dresden, Germany; [17]Frankfurt Institut for Advanced Studies FIAS, Frankfurt, Germany; [18] RIKEN, Japan; [19]University of Notre Dame, United States; [20]University of Edinburgh, United Kingdom

Summary

- Quasi-free scattering
  - QFS successfully applied in inverse kinematics
  - Rich physics program: N-N correlations, shell structure, cluster structure, unbound nuclei
- R3B development
  - Technical Design Report for neutron detector NeuLAND and calorimeter CALIFA ready
  - Start construction in 2012, physics run with new dipole GLAD and 20% NeuLAND and CALIFA in 2014
  - **Full R3B detection system operational in Cave C for physics runs 2016**
- FAIR
  - R3B hall ready for installation in 2017
  - **R3B @ FAIR with Super FRS will start in 2018**