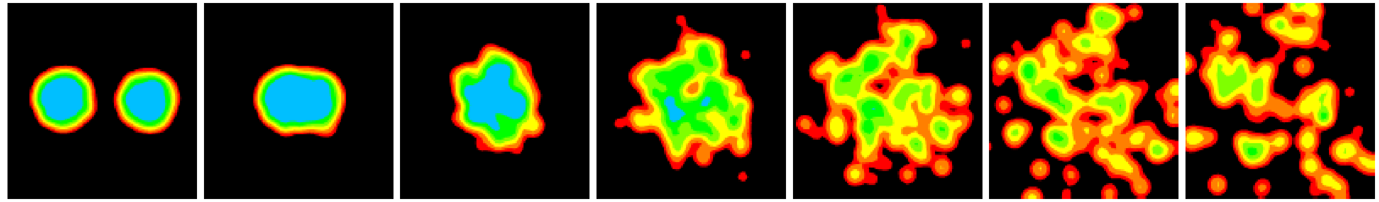
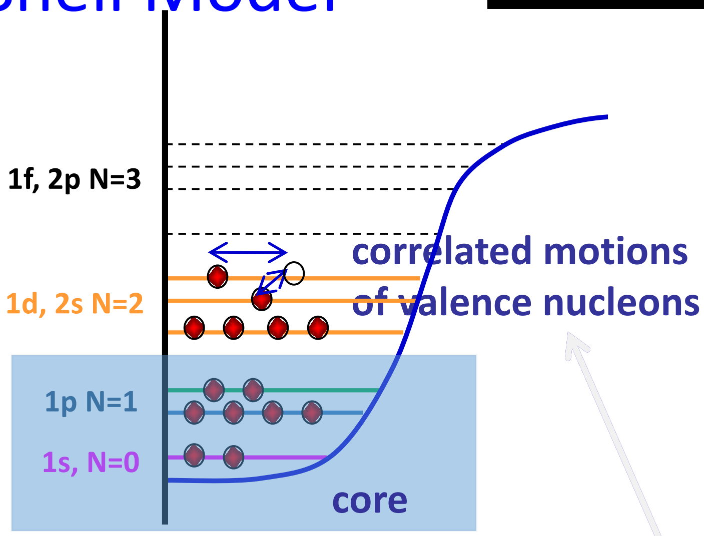
NN correlations in shell structure and nuclear dynamics



Femto-nova explosion created by Heavy Ion collisions

Shell Model



Large Basis Shell Model (LB-SM)

$$H = \sum_i \left(\frac{p_i^2}{2m} + U(r_i) \right) + \sum_{i<j} V_{NN}(\vec{r}_i - \vec{r}_j) - \sum_i U(r_i)$$

Mean field **Residual interactions**

Propagates single particle wave functions subject to the mean field and NN collisions

- Density dependence of symmetry energy
- Effective nucleon mass splitting
- Sn+Sn reactions

- Short range correlations: σ_{nn}; σ_{pp}; σ_{pn}
- propagation of nucleons in the interacting medium
- Ca+Sn reactions

Deep hole-states in N=27 isotopes

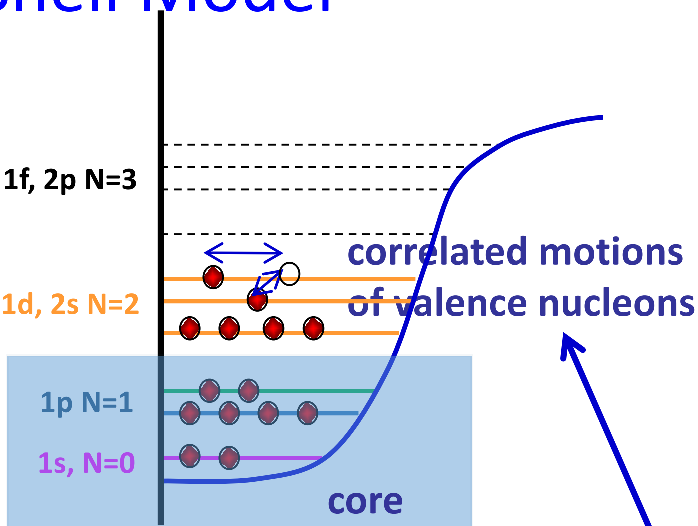
Outline

1. Introduction
2. (p,d) experiments to study the hole states in ^{45}Ar and ^{55}Ni, with N=27.
3. Limitations of current SM.
4. Systematics of the energy and SF's in N=27 isotones and new SD$\otimes$PF interactions
5. Summary

NN correlations in shell structure and nuclear dynamics

Deep hole-states in N=27 isotopes: to probe Interactions in sd+pf orbits

Shell Model



Large Basis Shell Model (LB-SM)

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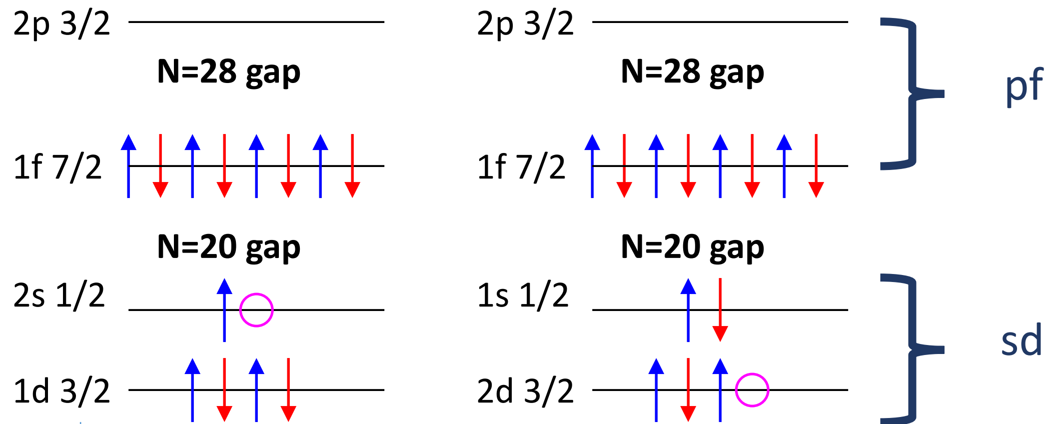
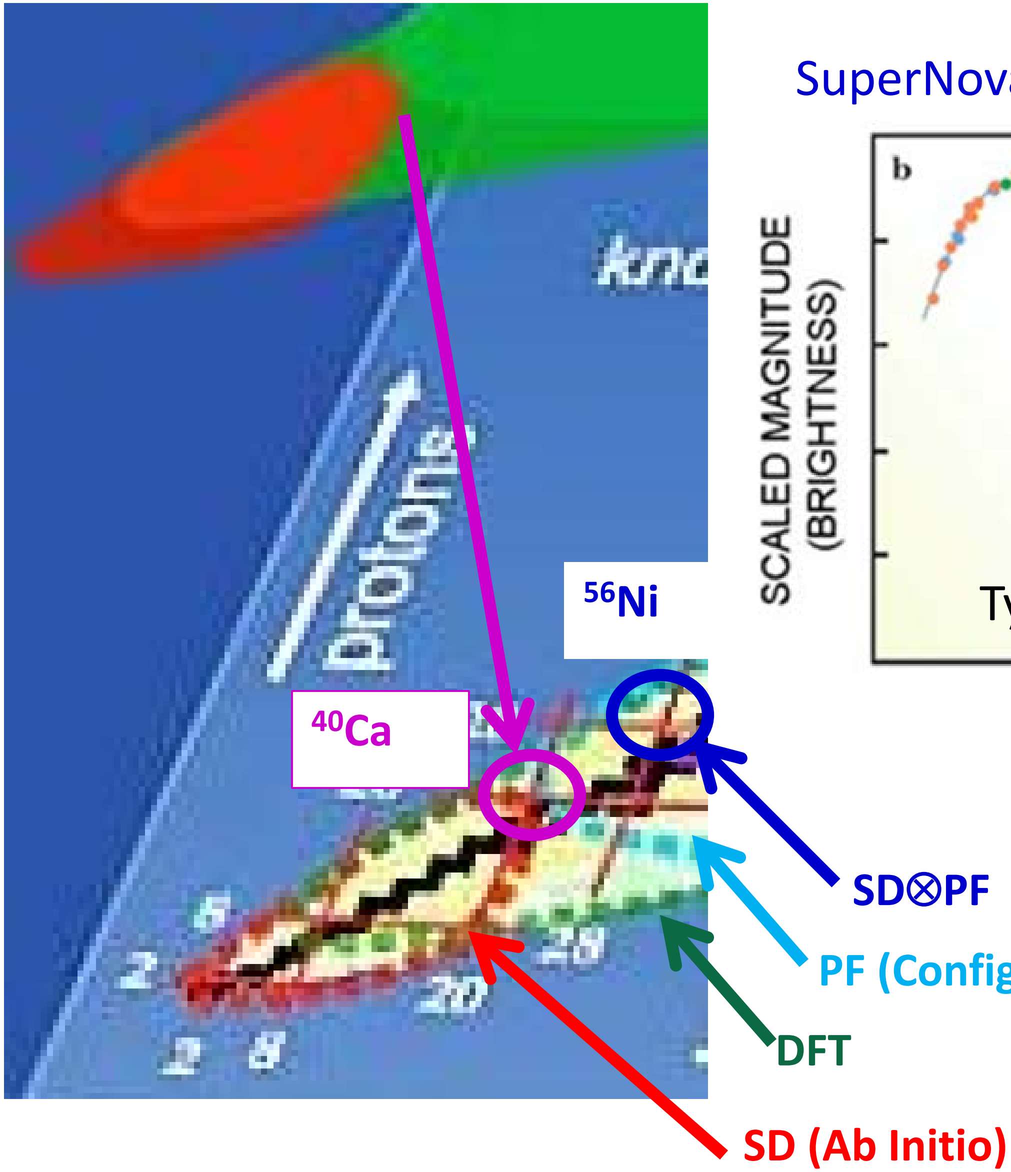
Mean field **Residual interactions**



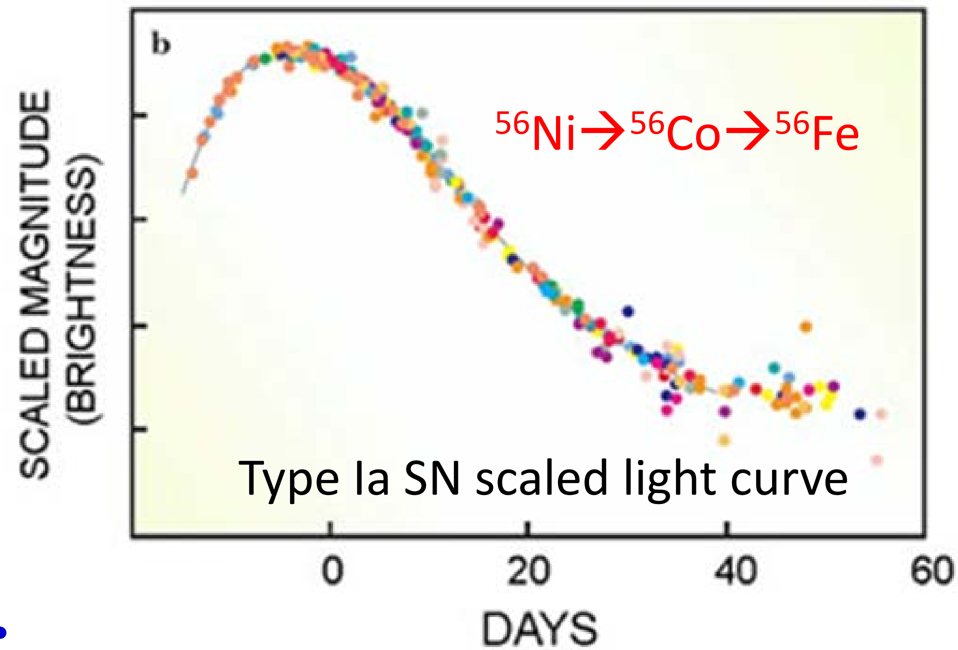
What does a “hole” do in the nucleus?

From SD to PF shell nuclei

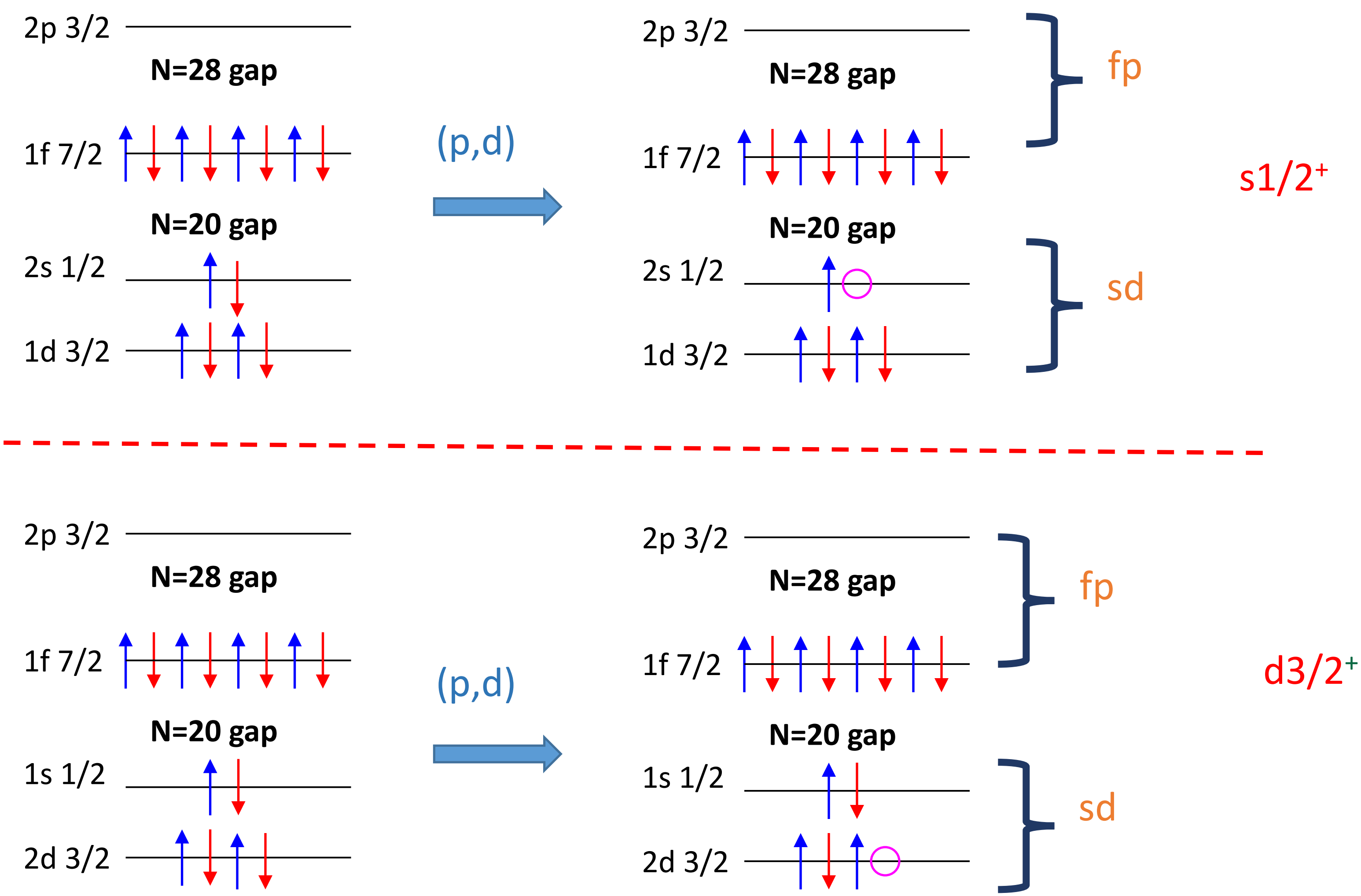
Overlap between Ab Initio, Microscopic and DFT



SuperNova powered by decay of A=56 nuclei



^{46}Ar,^{48}Ca,^{50}Ti,^{52}Cr,^{54}Fe,^{56}Ni (p,d) ^{45}Ar,^{47}Ca,^{49}Ti,^{51}Cr,^{53}Fe,^{55}Ni

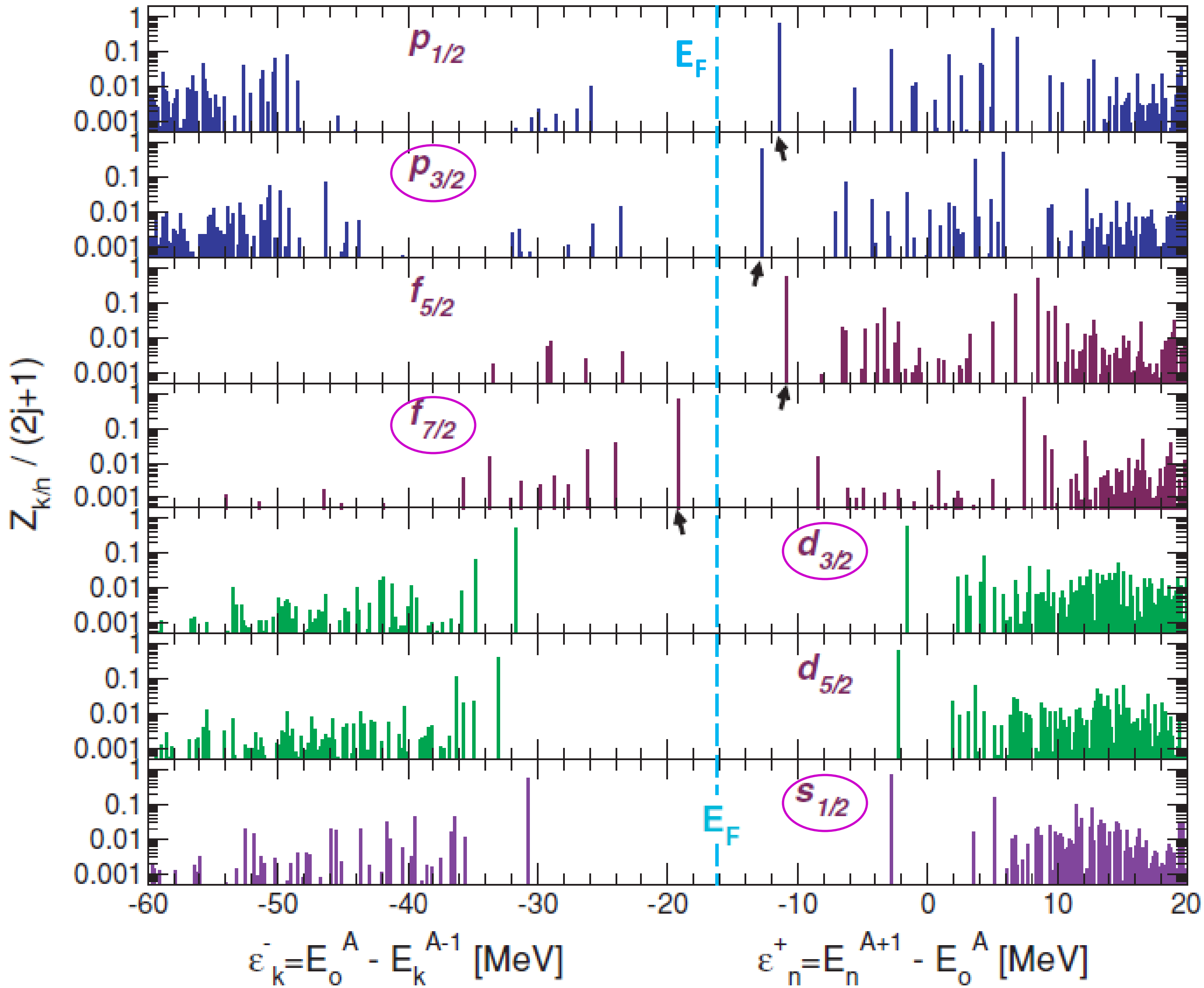


Predictions from SCGF

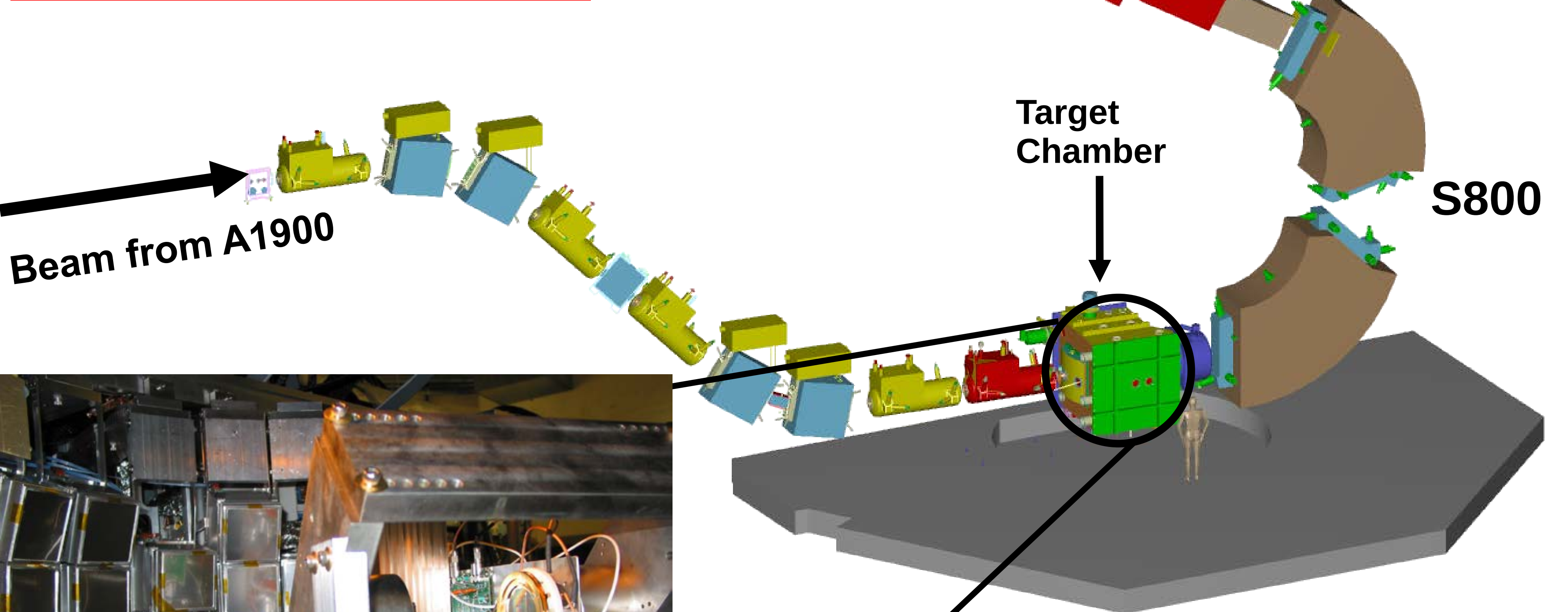
^{55}Ni hole states

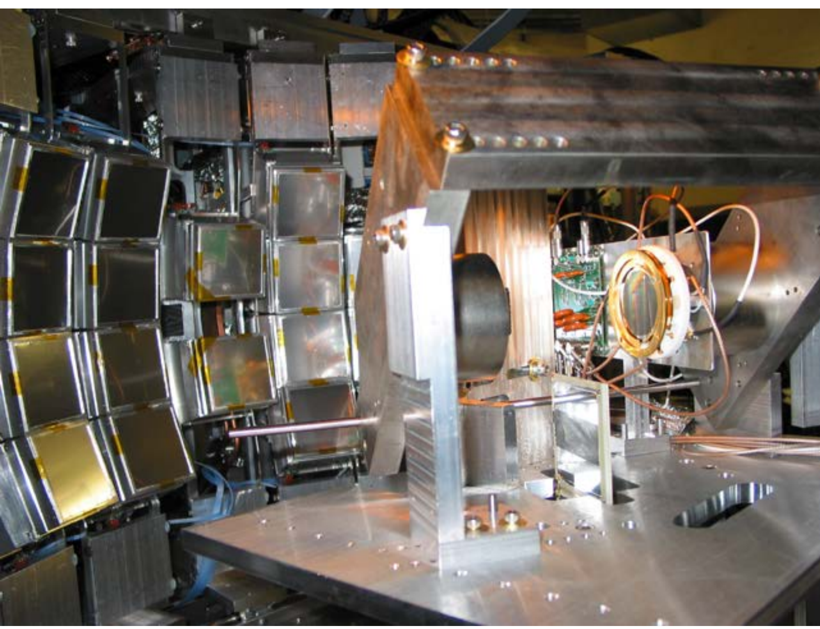
^{57}Ni particle states

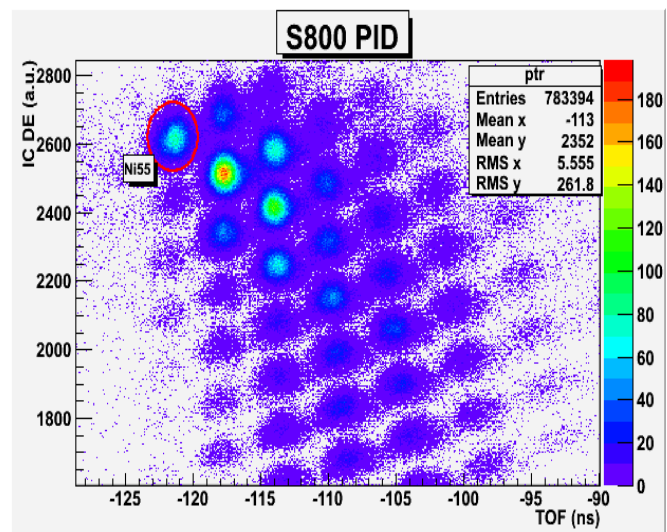
PRC 79, 064313 (2009)



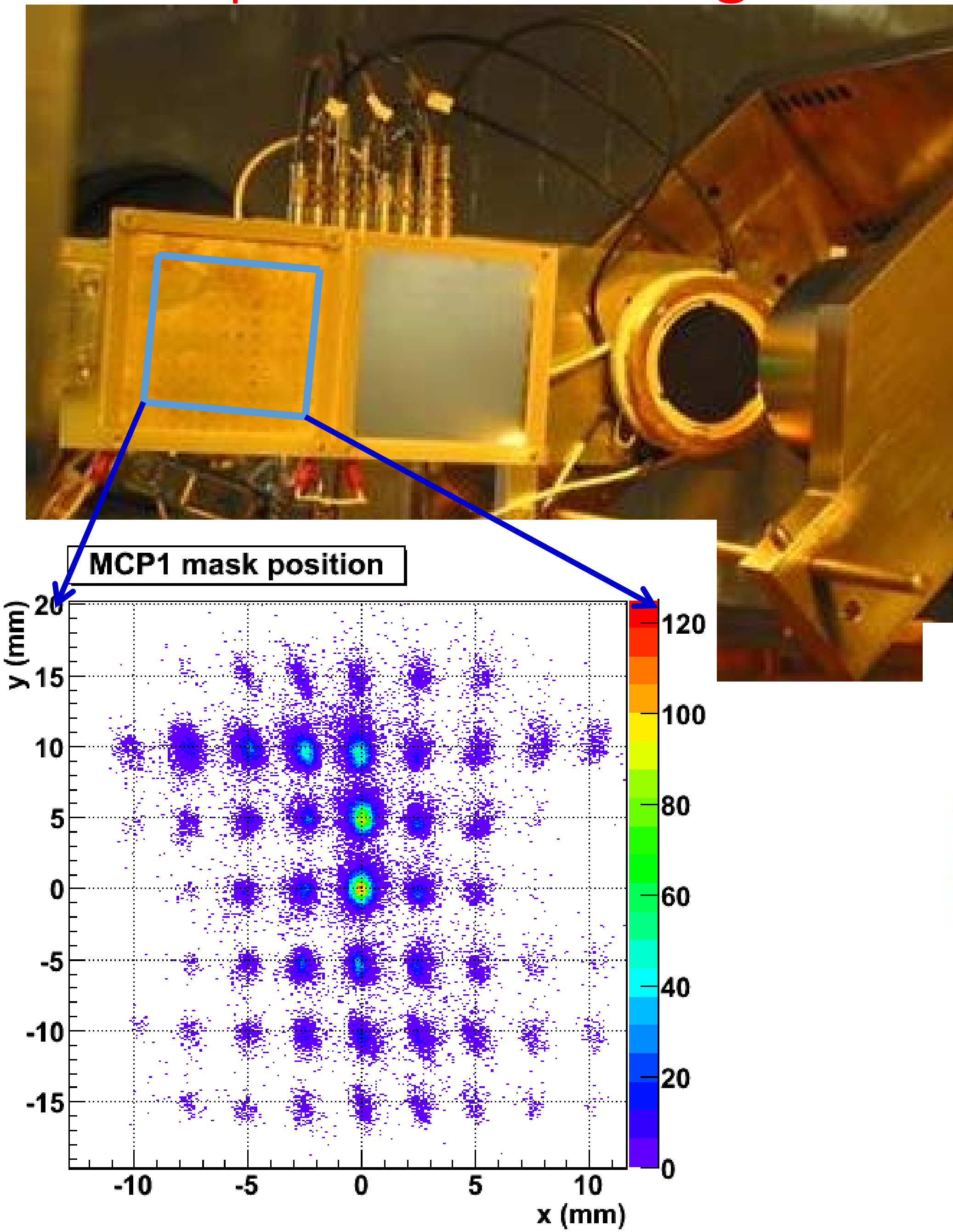
$^{56}Ni + p \rightarrow d + ^{55}Ni$

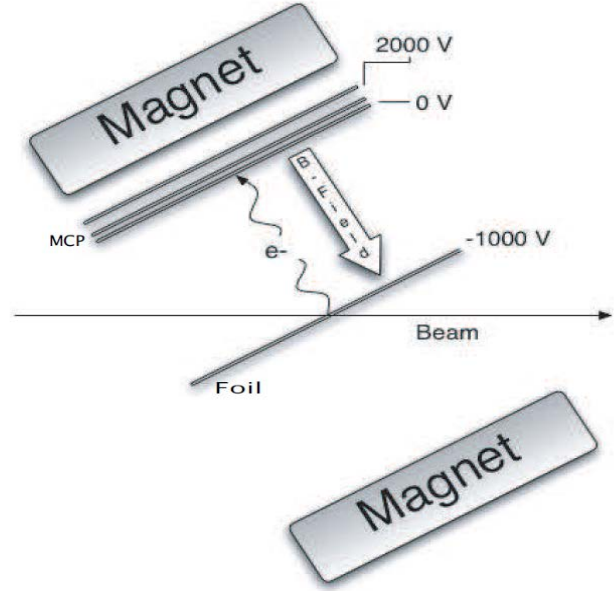


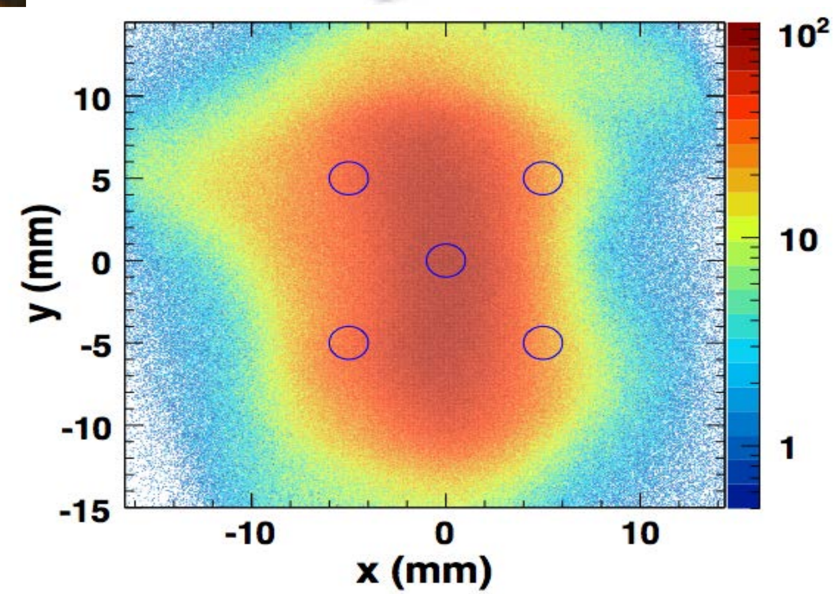




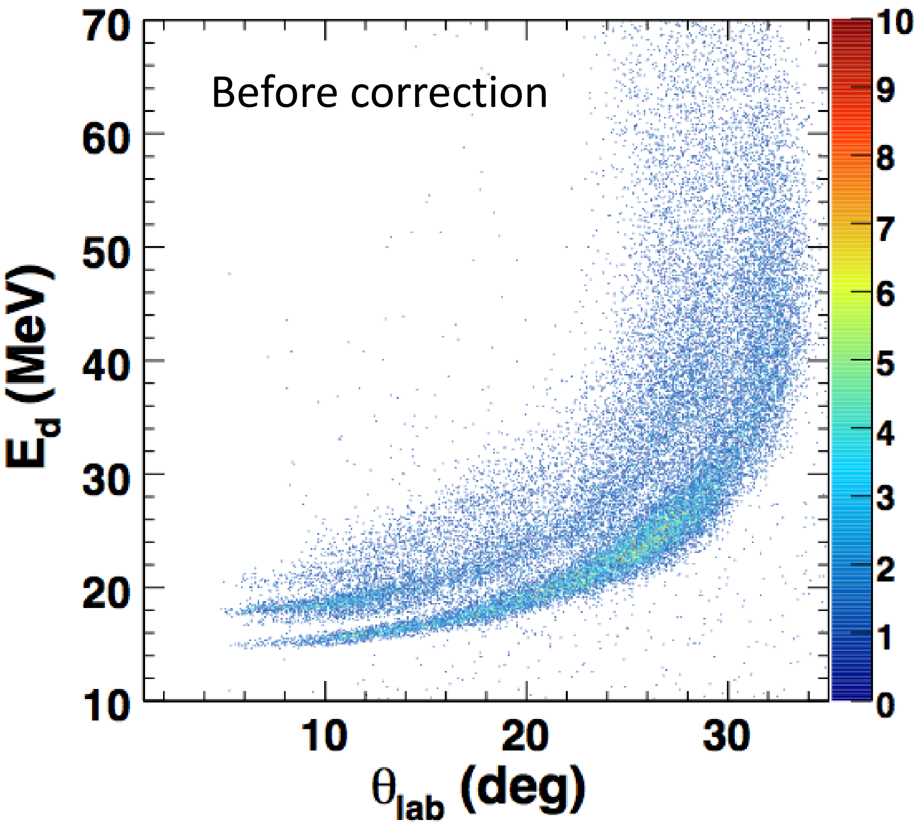
Beam position and angle determination with MCP

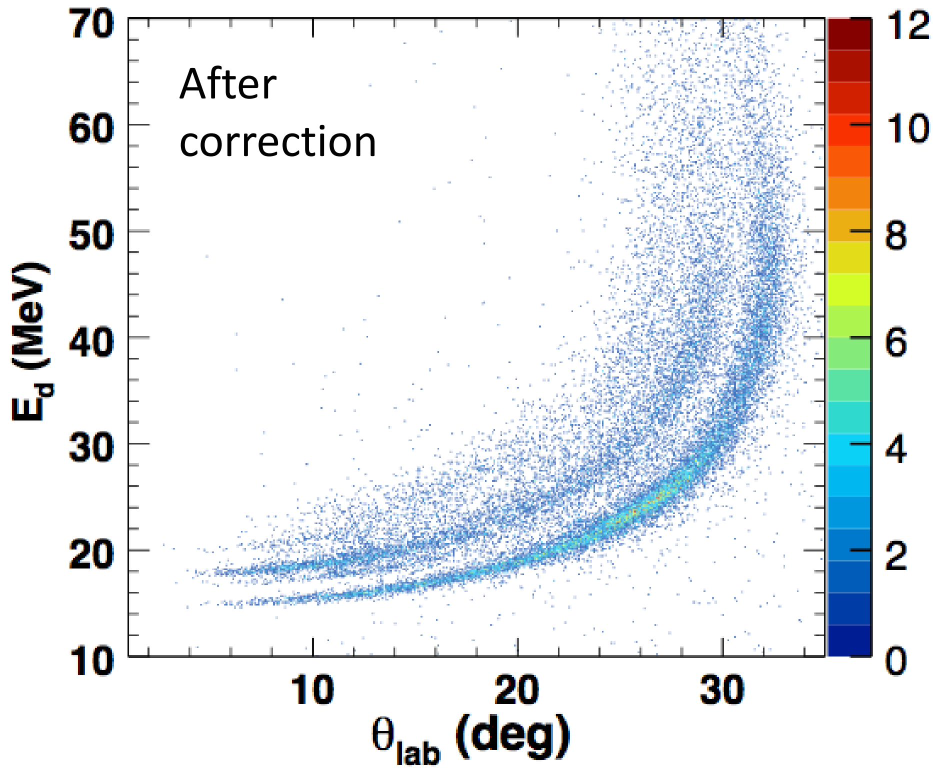




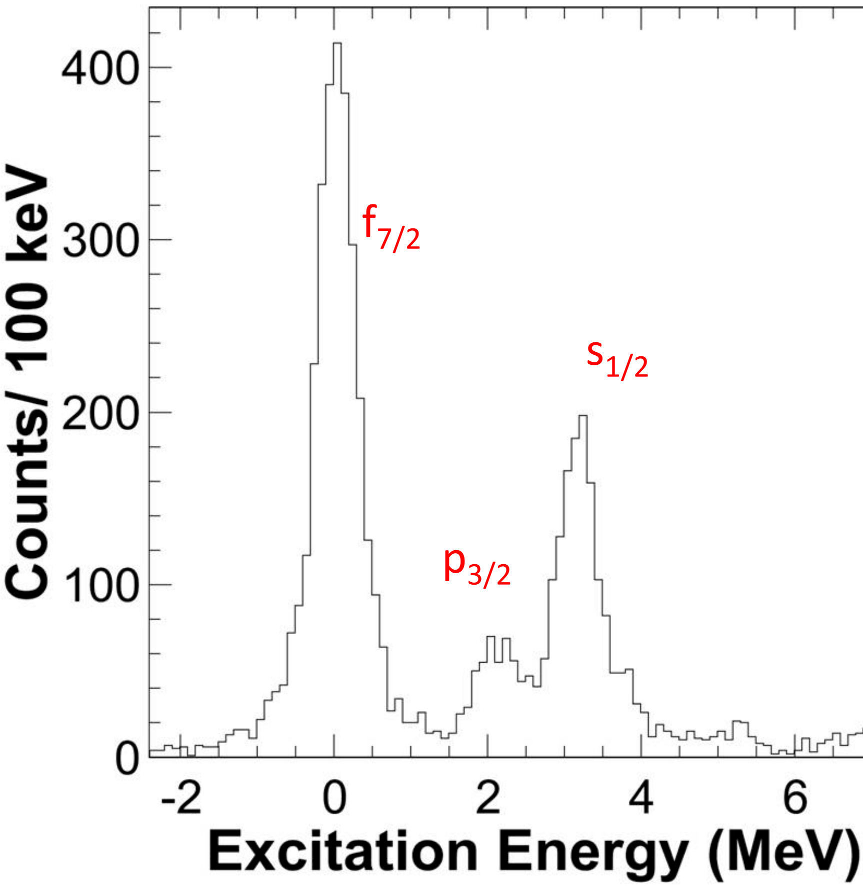


Beam position and angle corrections with MCP





$^{56}Ni + p \rightarrow d + ^{55}Ni$

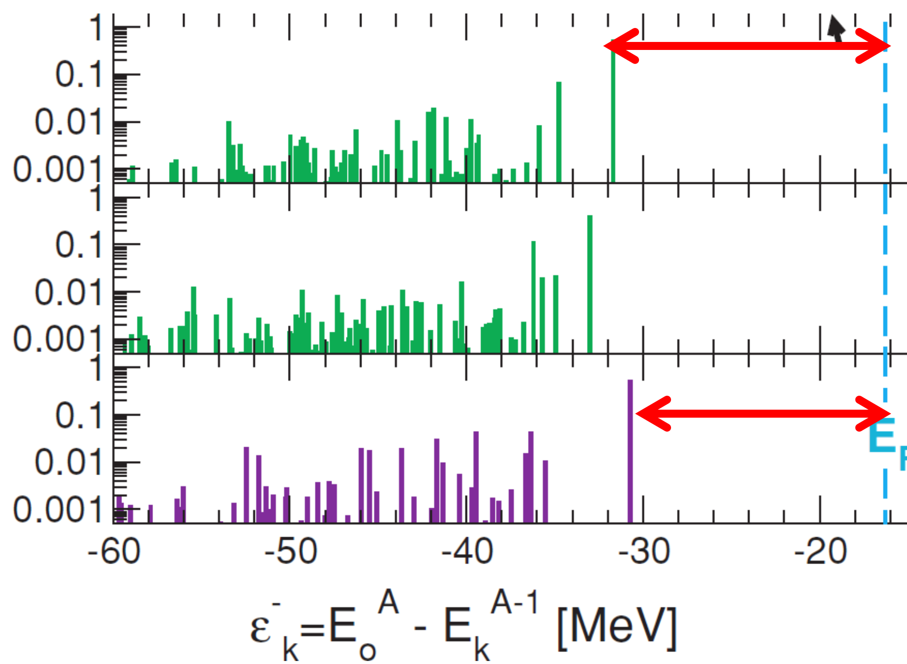


Data:

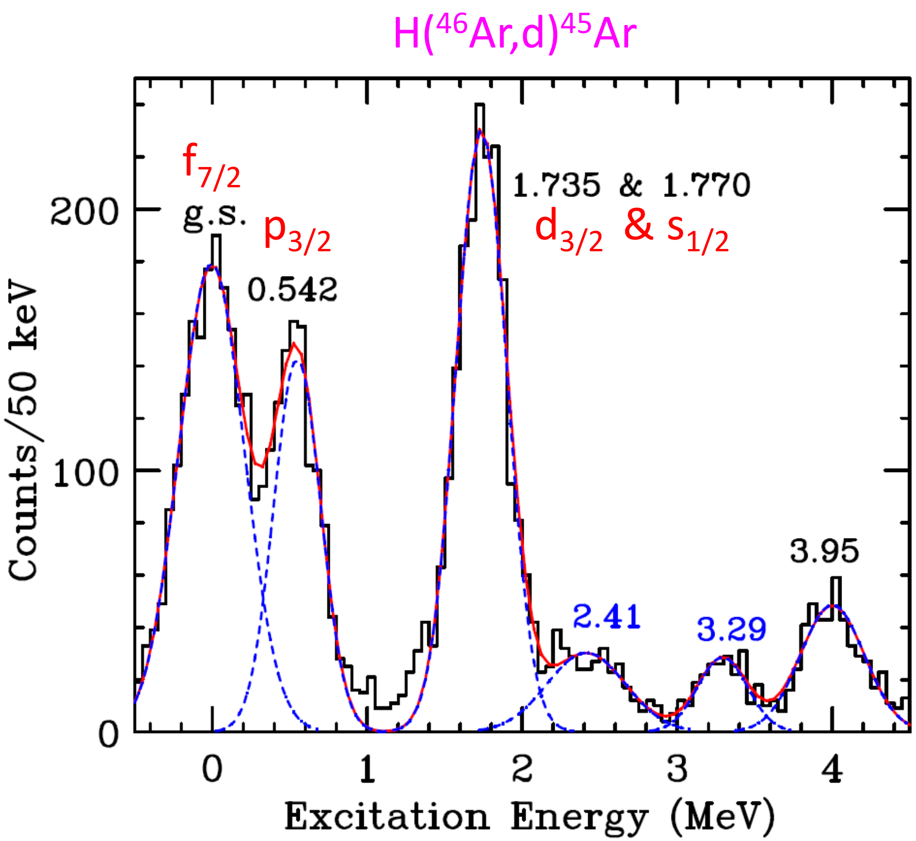
- $s_{1/2}$ and $d_{3/2}$ hole states occur around 2-4 MeV
- Regular shell models cannot describe these states.

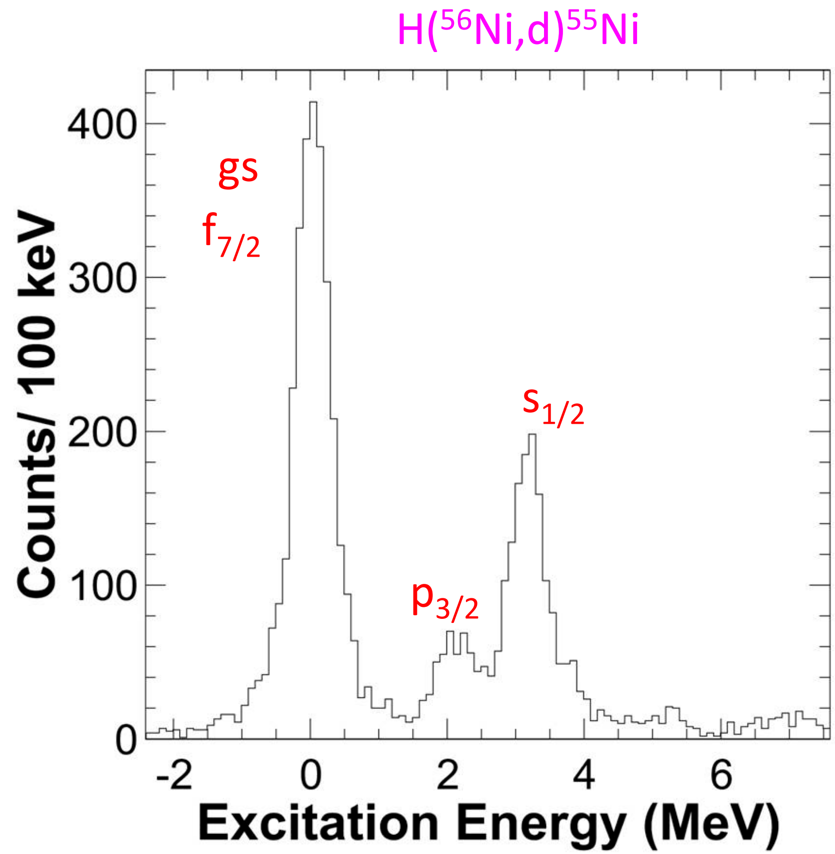
Theory (SCGF)

- $s_{1/2}$ and $d_{3/2}$ hole states occur around ~15 MeV.



Comparisons of excited hole states in ^{45}Ar & ^{55}Ni

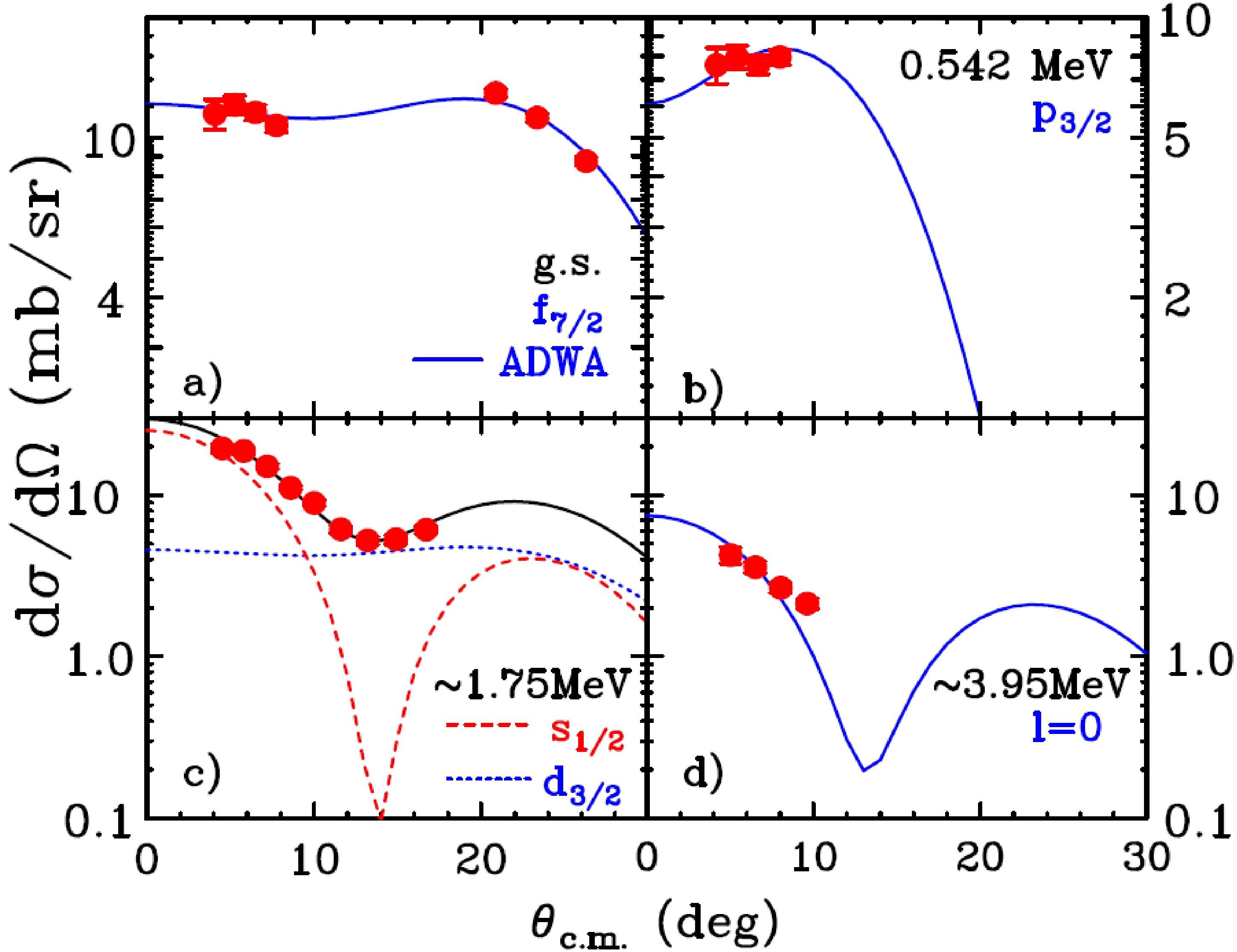




States that have substantial cross-sections from (p,d) transfer reactions are g.s. ($7/2^-$), 1st excited states ($p3/2^-$) state (very small c.s.), $s_{1/2}^+$, and $d_{3/2}^+$ (often come as doublets).

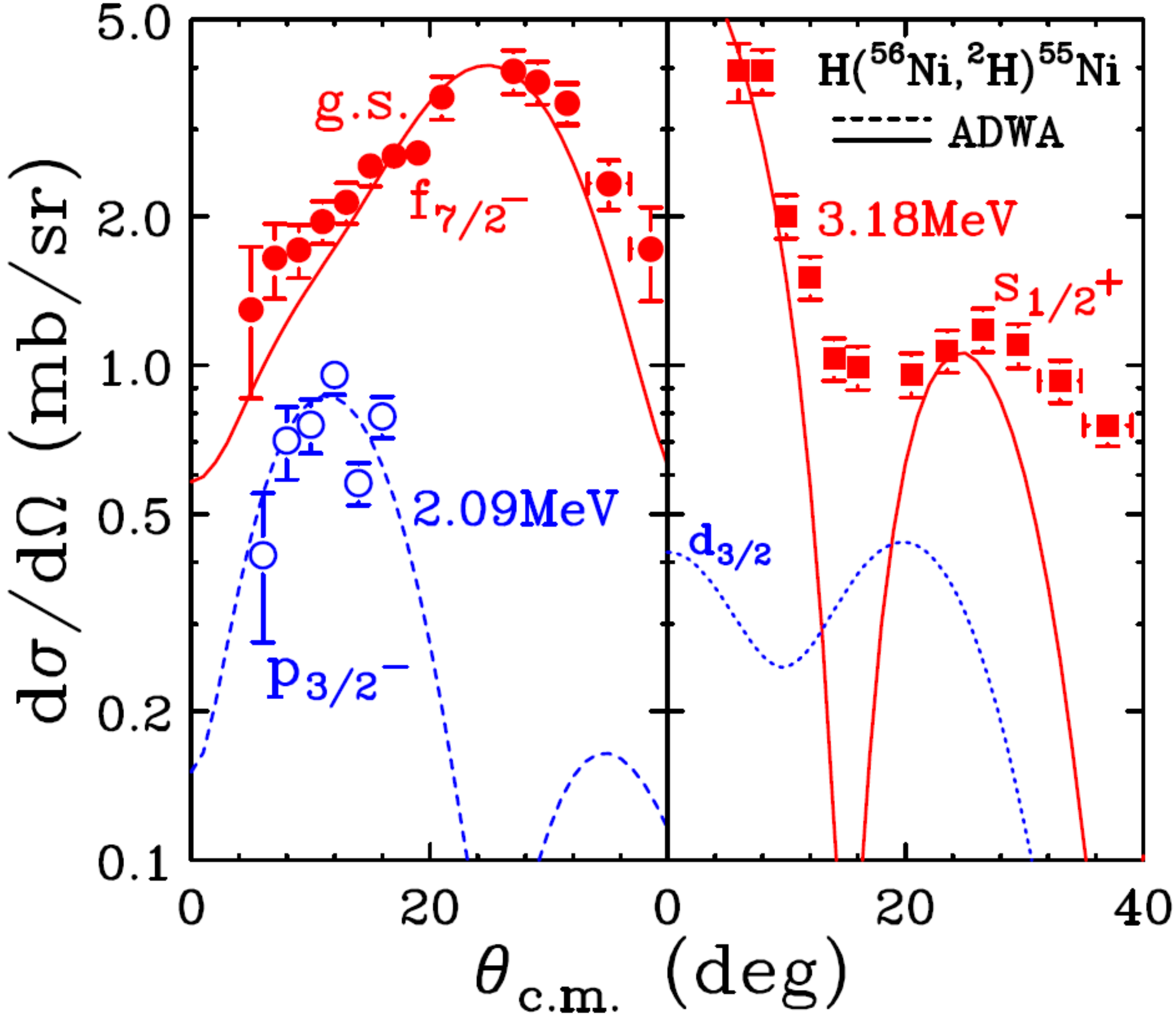
Angular Distributions: spin & parity assignments

$^{46}Ar + p \rightarrow d + ^{45}Ar$

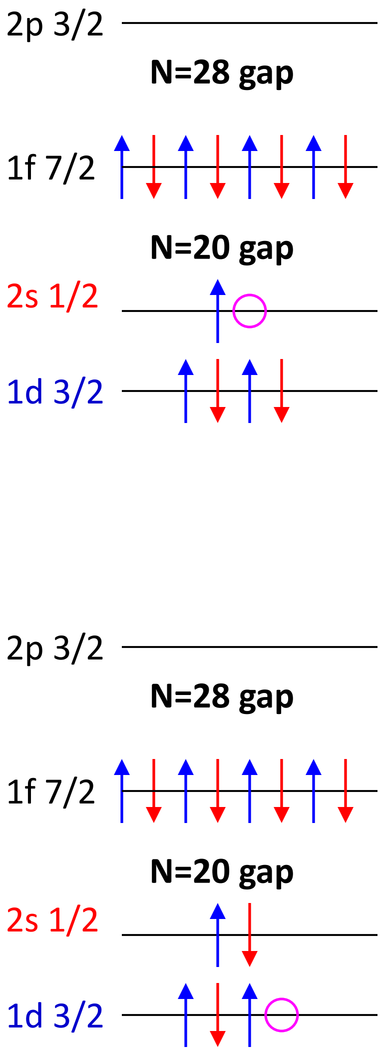


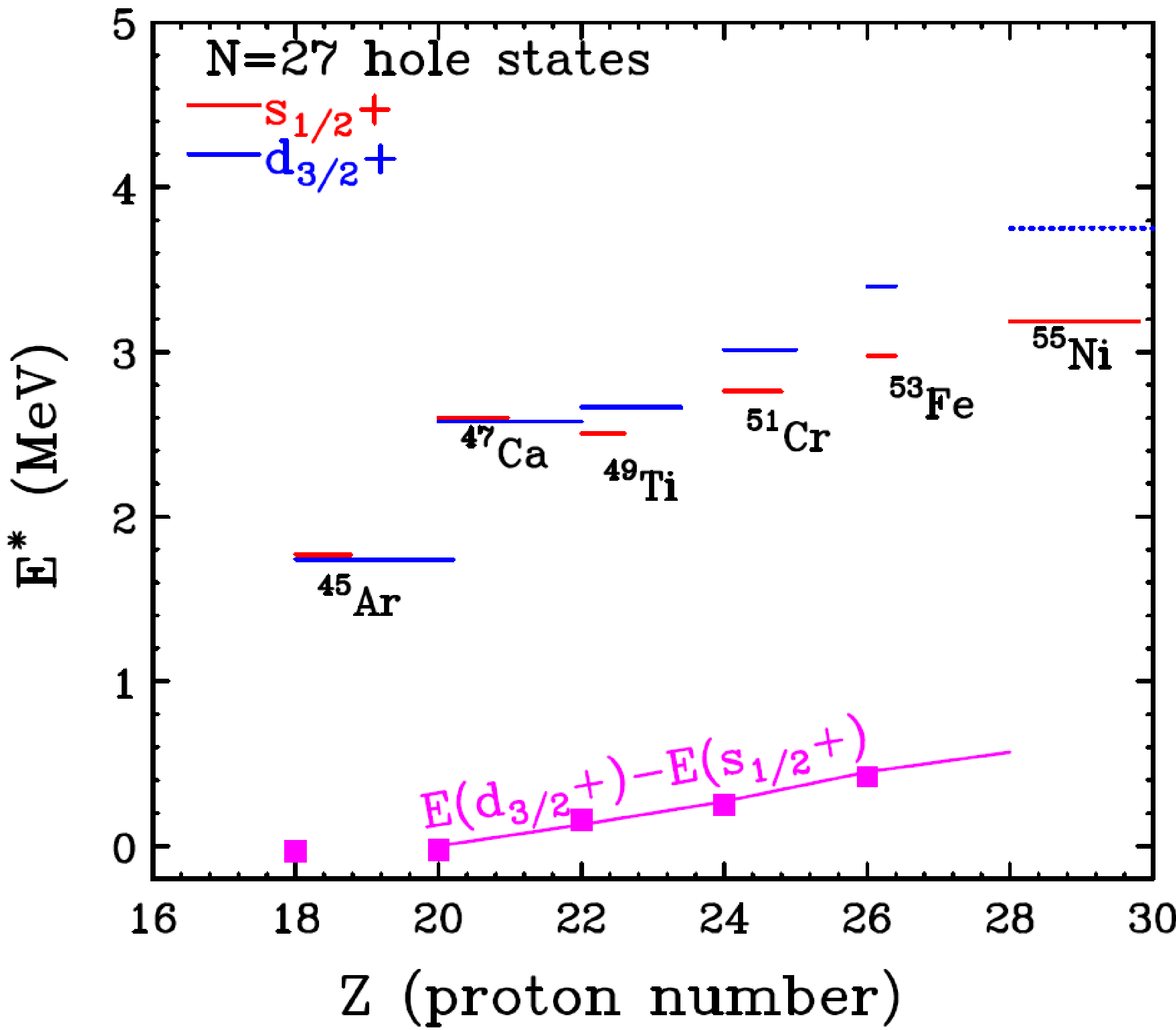
Angular Distributions: spin & parity assignments

$^{56}Ni + p \rightarrow d + ^{55}Ni$



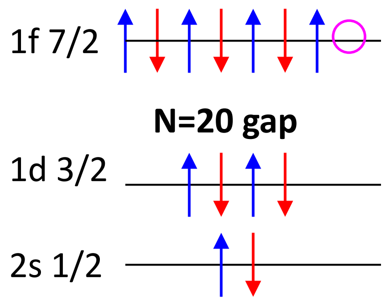
Regular Shell Models cannot describe energy systematics of deep-hole states

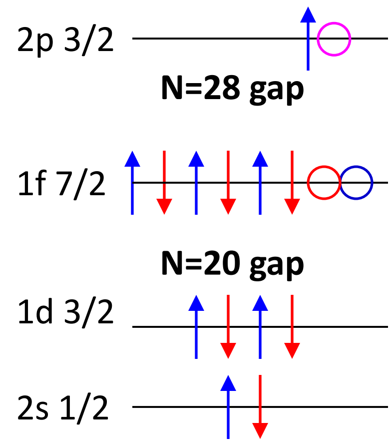


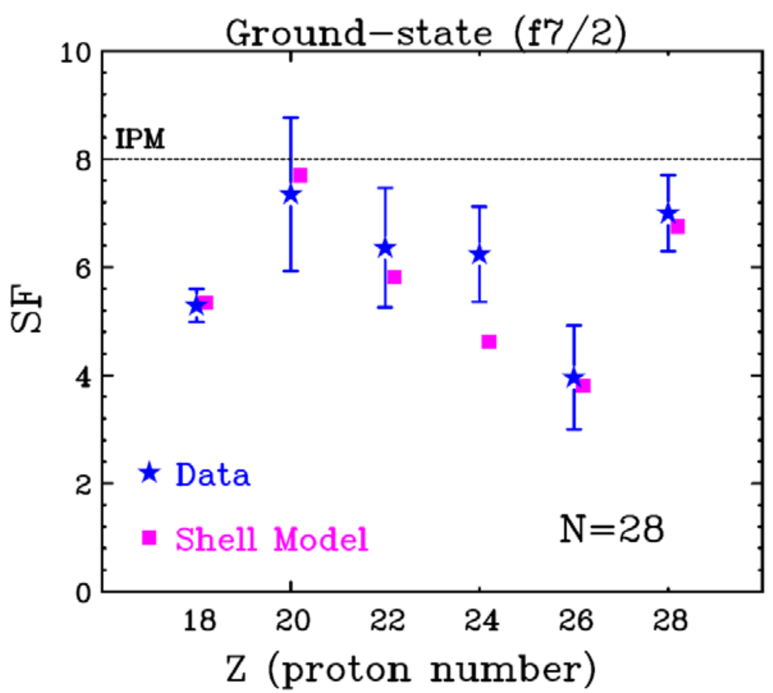


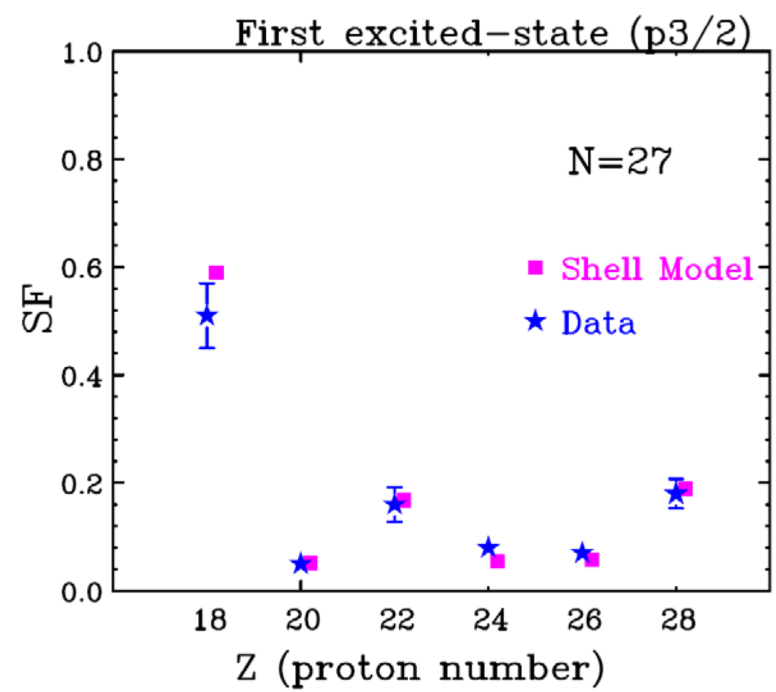
States with substantial cross-sections from (p,d) transfer

$7/2^-$ (g.s.) & ($p3/2^-$): well described by standard shell models

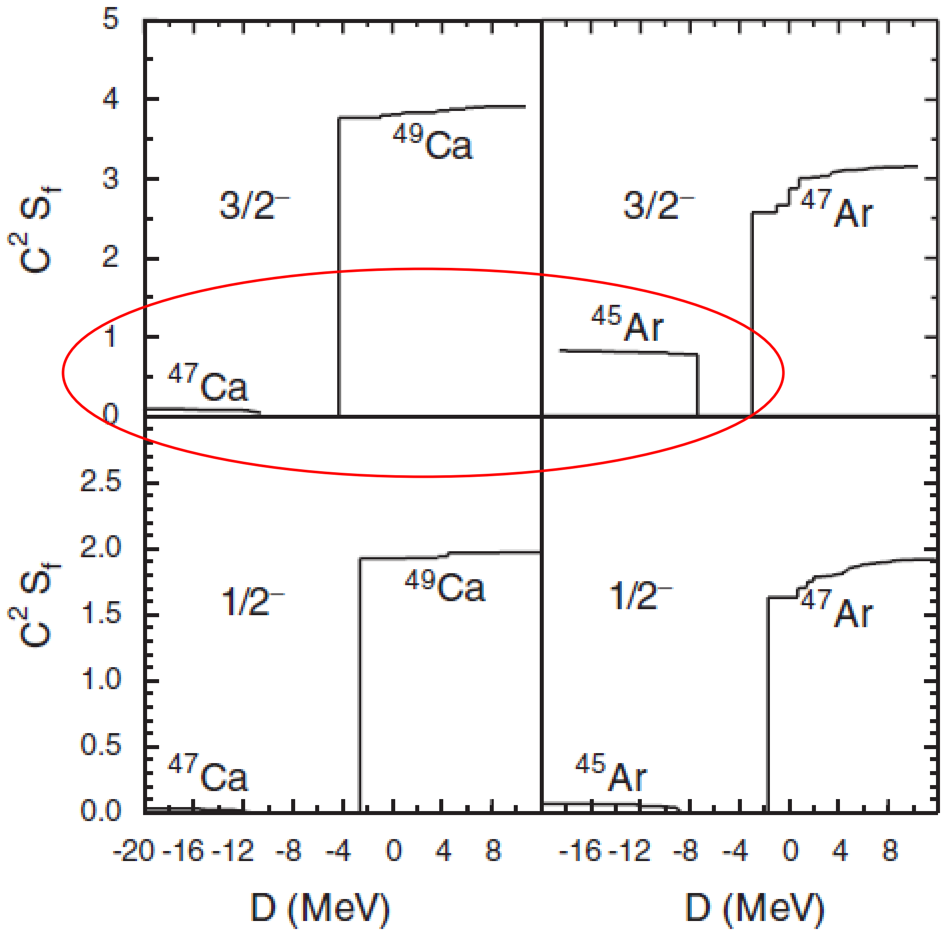


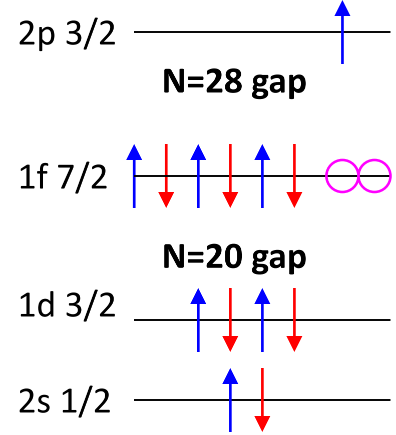


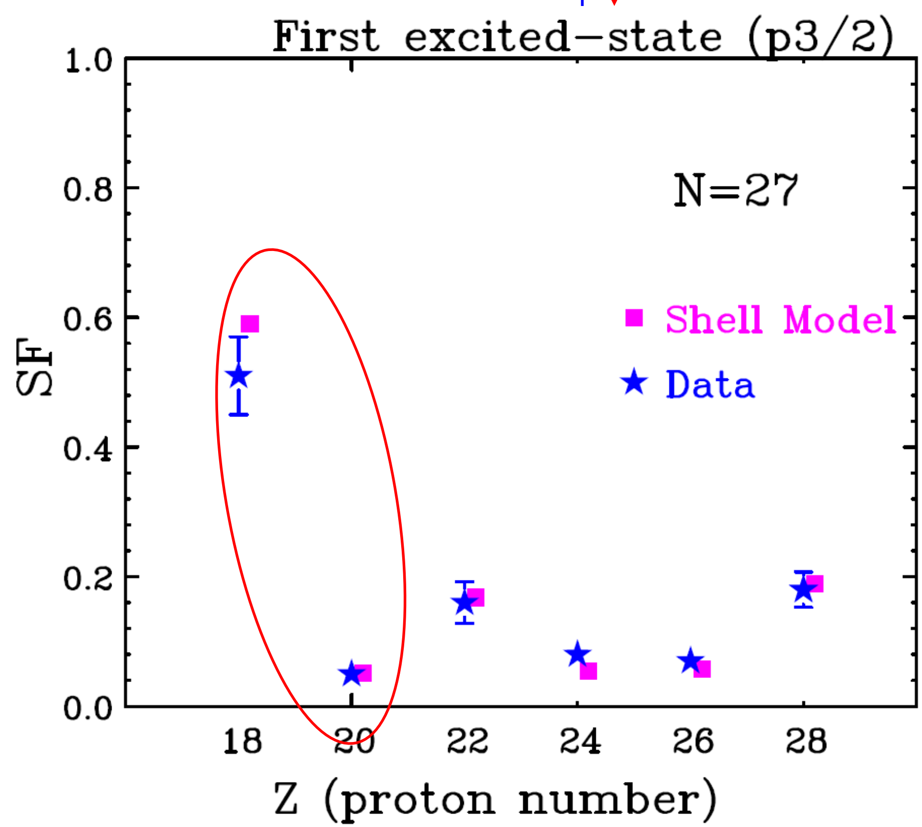




Angelo Signoracci and B. Alex Brown, PRL 99, 099201 (2007)



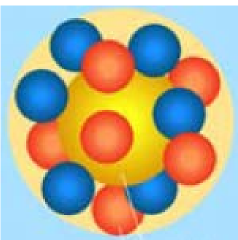




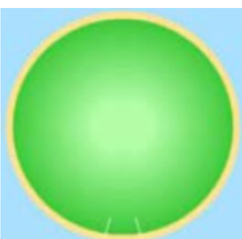
Predictions before measurements

States with substantial cross-sections from (p,d) transfer

Residual interactions:
sd-shell region -- USDA/USDB
pf shell interactions



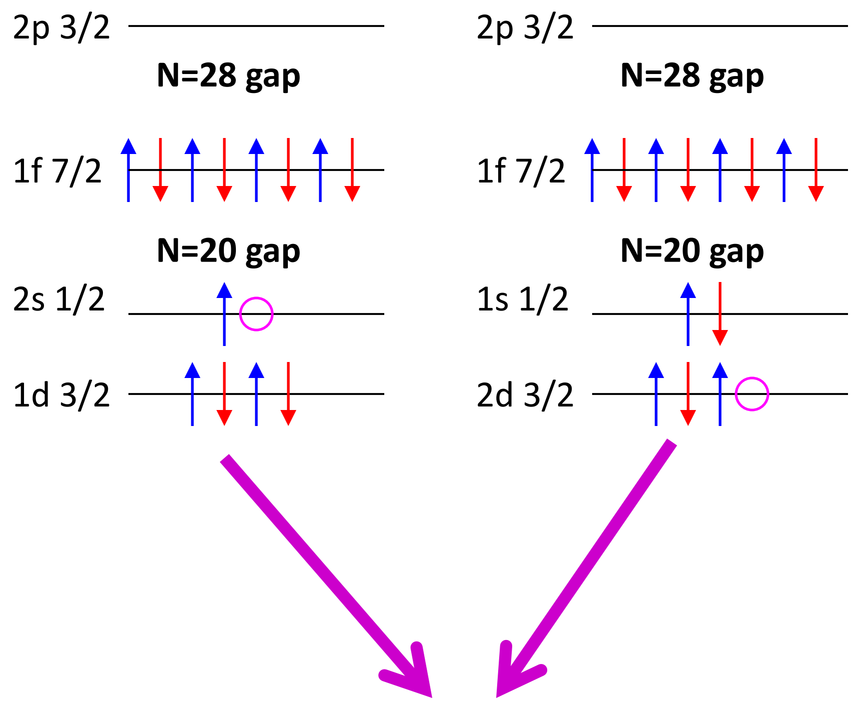
^{40}Ca core, in fp space
- GXPF1A, GXPF1B
- KB3G
- …



^{56}Ni core
- IPM
- Auerbach interaction ('60)
- XT

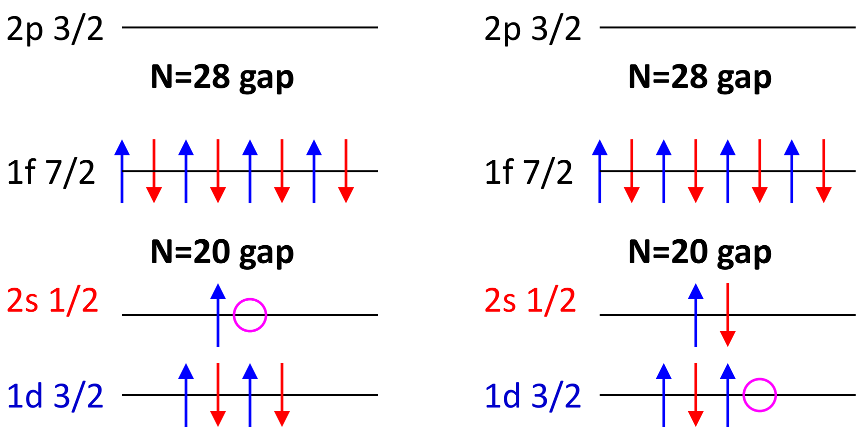
New state of the art SP-PF Interactions
SDPFM : Honma et al., *PRC60, 054315 (1999)*
SDPFMH : Horoi et al., new calc
SDPFMU : Utsuno, *PRC **86**, 051301(R) (2012)*
SDPFMU': Utsuno et al. new calc
SCGF: Barbieri, Hjorth-Jensen, PRC **79** 064313
??

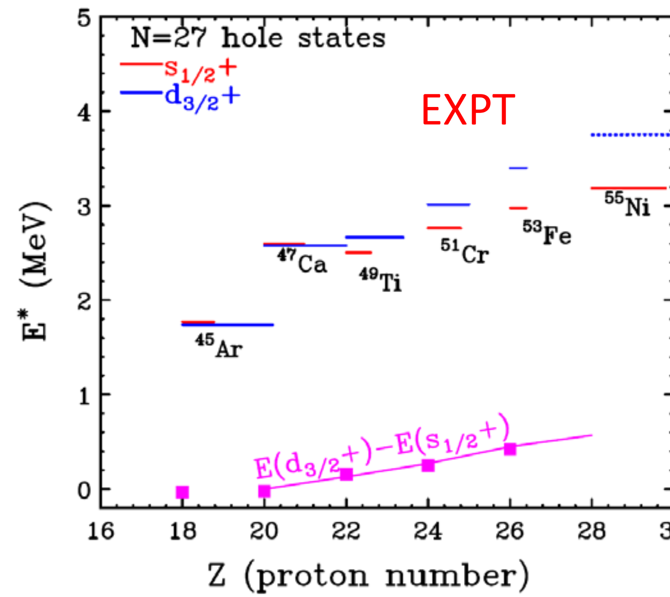
s1/2$^+$, d3/2$^+$
(often come as doublets)

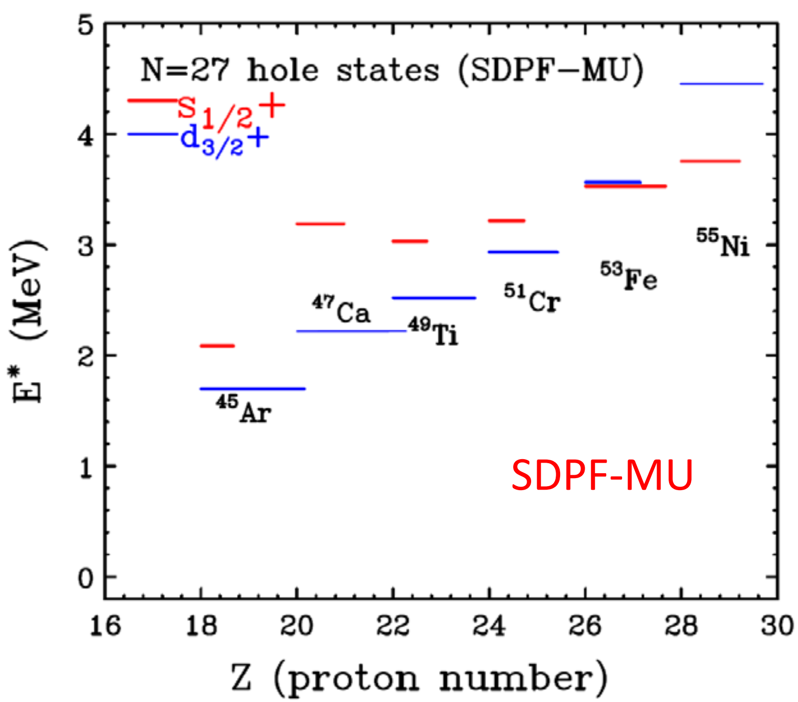


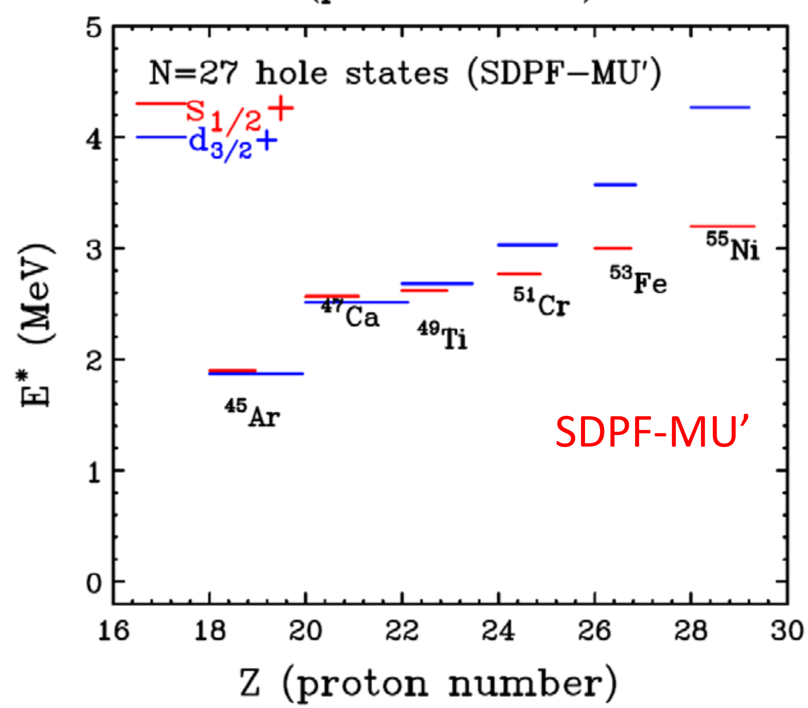
SM non-predictions reflect the importance of SD⊗PF

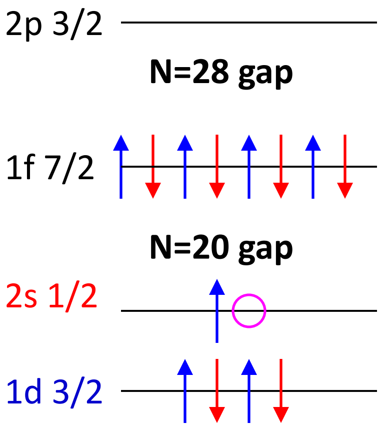
Regular Shell Models cannot describe energy systematics of deep-hole states



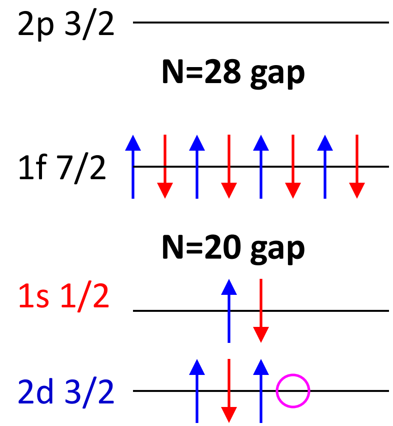


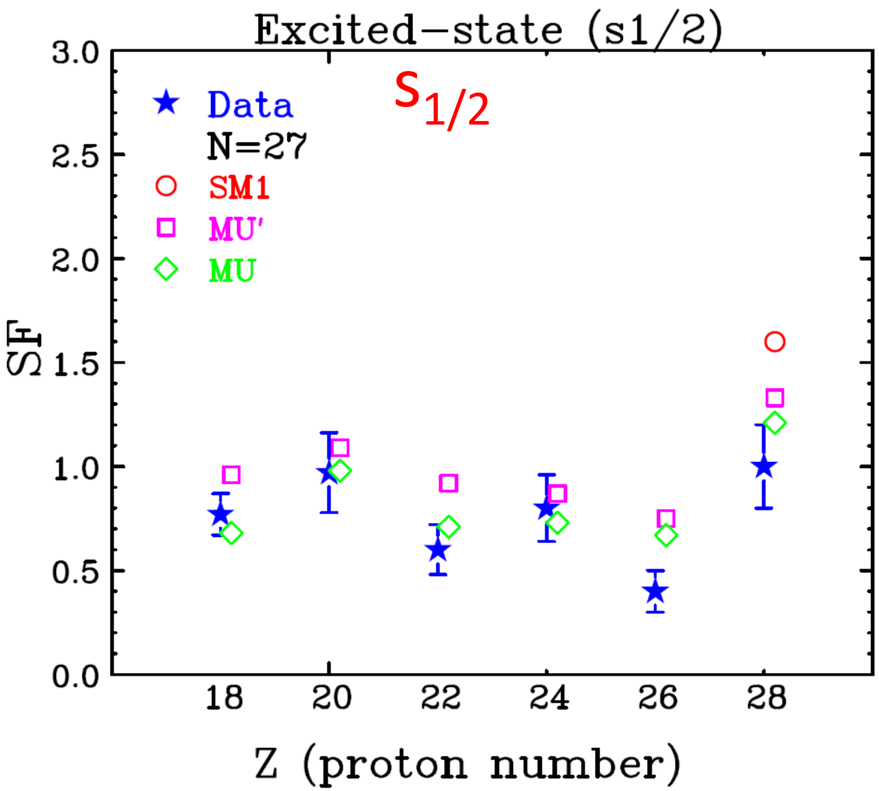


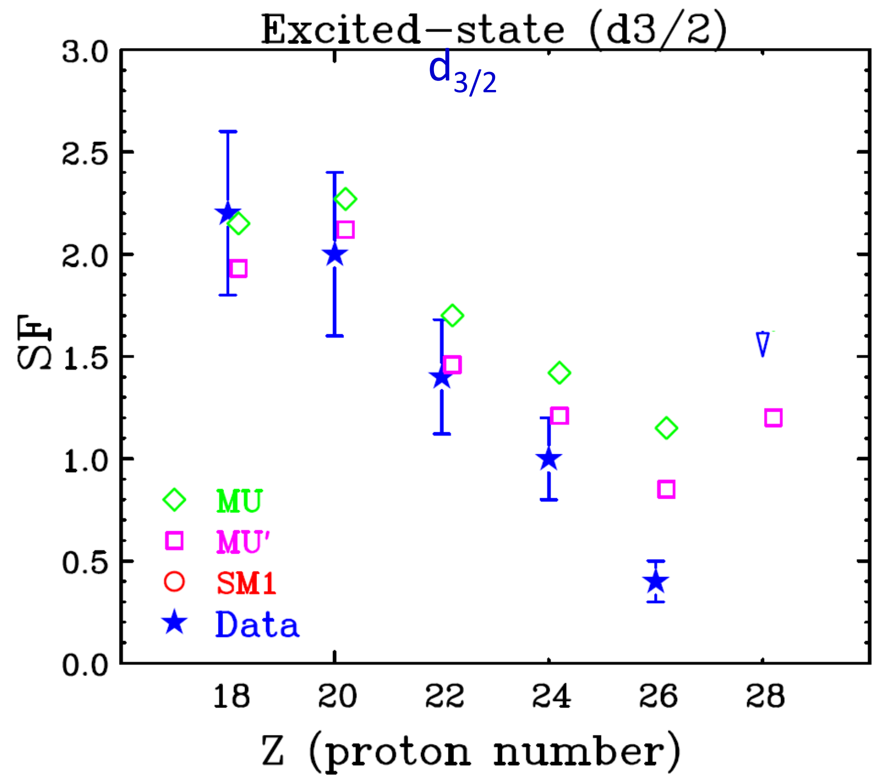




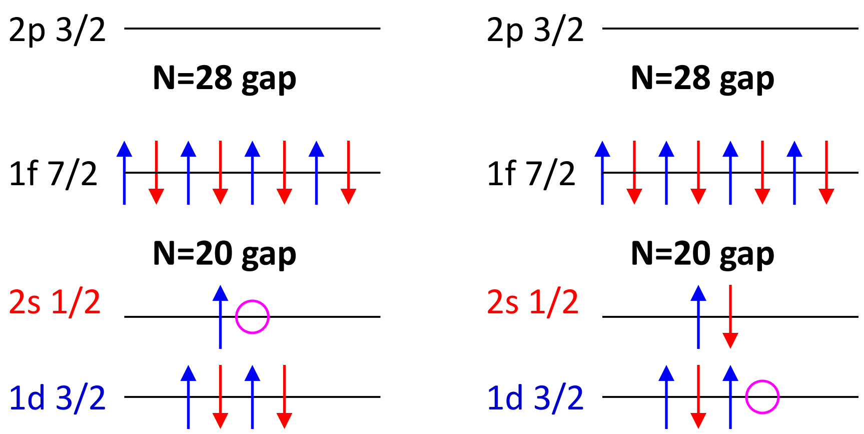
SF values of $s_{1/2}$ correspond to 50% occupation.
SDPFMU reproduces the experimental trend





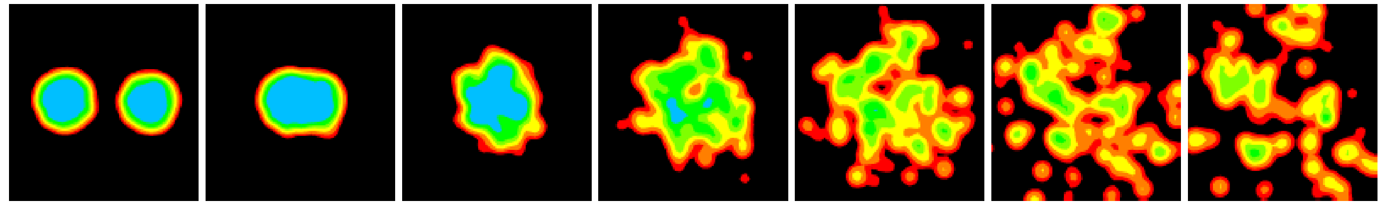


Summary



1. The s1/2 and d3/2 deep hole states in N=27 isotones allow us to explore the couplings of the SD and PF shells and provide data to test the development of SM interactions to describe the emergence of the SD shell interaction to PF shell.
2. State of the art SDPF(MU') interactions describe SF data, but still lacking in reproducing the energy levels.
3. We need models to describe the systematic trends, not just individual nucleus.

Transport model



Femto-nova explosion created by Heavy Ion collisions

Outline

- Introduction
- Symmetry energy constraints at subsaturation density
- Importance of symmetry energy at twice saturation density
- Effective mass splitting & σ_{NN} from HIC data
- LRP on nuclear symmetry research.

Propagates single particle wave functions subject to the mean field and NN collisions

- mean field:
  - •Density dependence of symmetry energy
  - •Effective nucleon mass splitting
  - •Sn+Sn reactions
- NN collisions:
  - •Short range correlations: σ_{nn}; σ_{pp}; σ_{pn}
  - •propagation of nucleons in the interacting medium
  - •Ca+Sn reactions

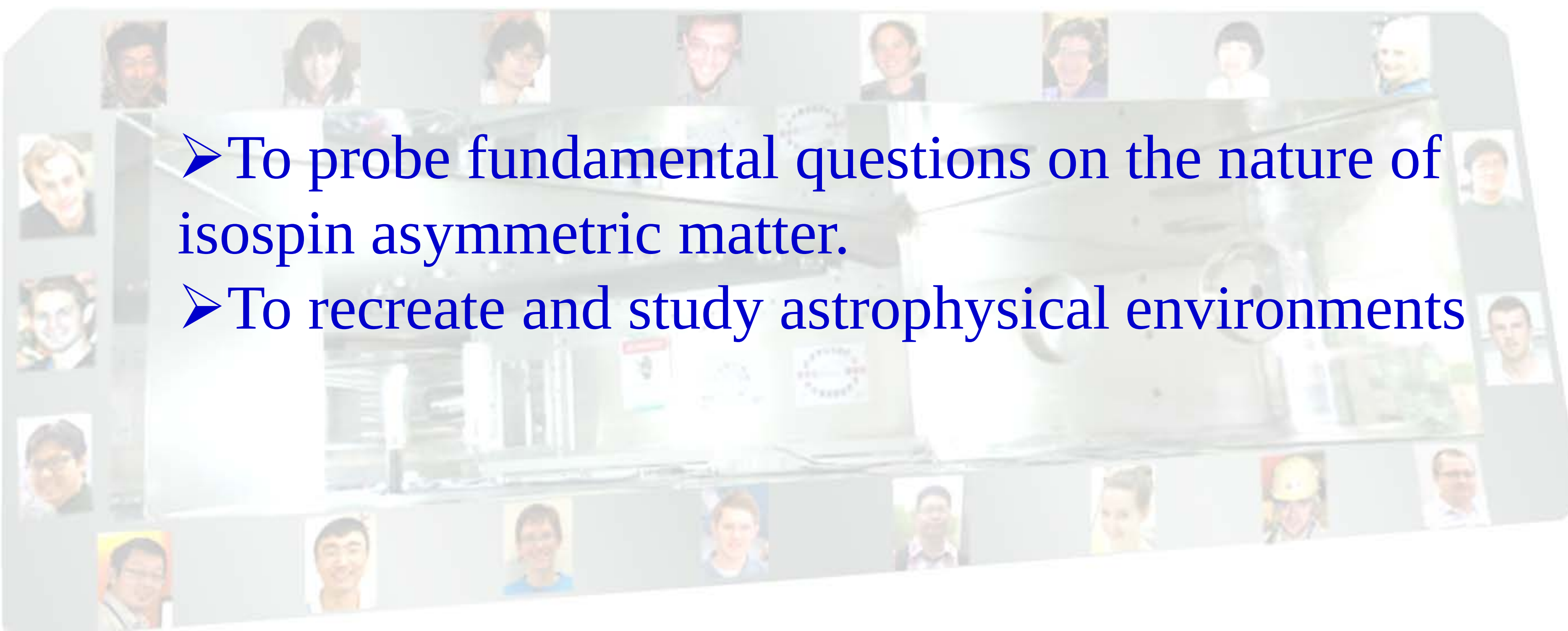
From Earth to Heavens: Femto-scale nuclei to Astrophysical objects

Equation of State of nuclear matter

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

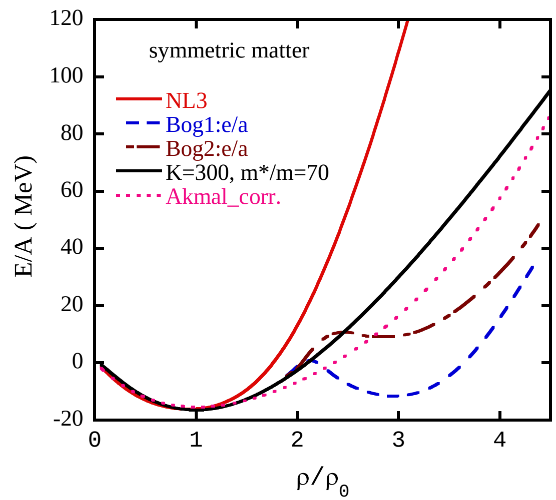
Symmetry Energy of asymmetric matter

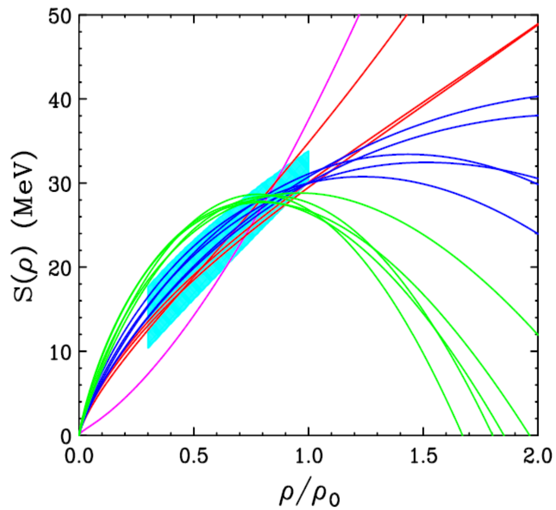


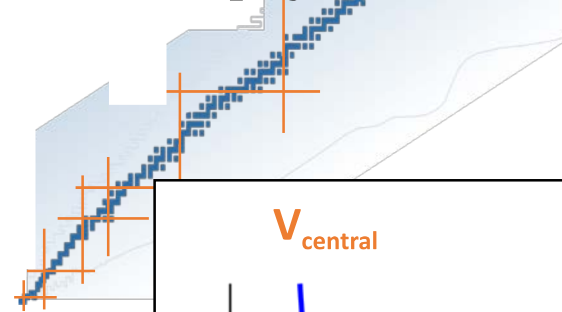
- To probe fundamental questions on the nature of isospin asymmetric matter.
- To recreate and study astrophysical environments

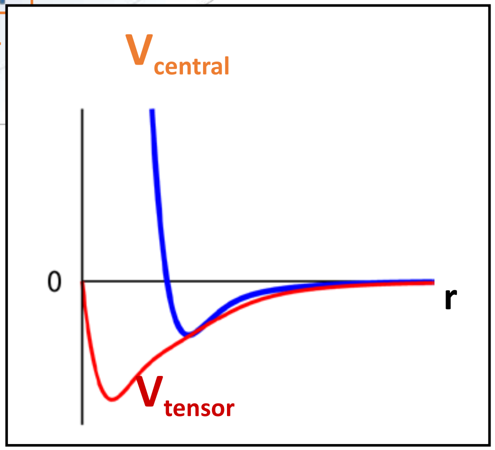
Equation of State of nuclear matter

EOS is a fundamental property of nuclear matter. The asymmetric terms has wide implications to nuclear physics and astrophysics.









- **Nuclear Structure**

  Radii, masses, saturation density, nature of nuclear force.

- **Nuclear Reactions**

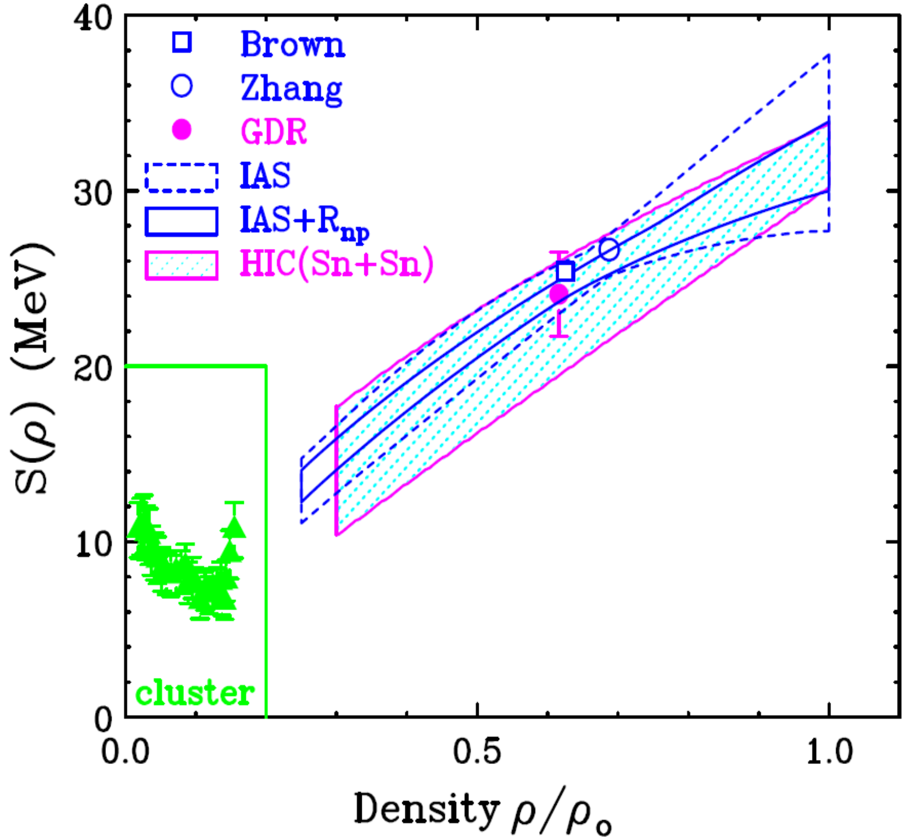
  Fusion, Fission, Fragment productions, nucleon transport, phase transitions.

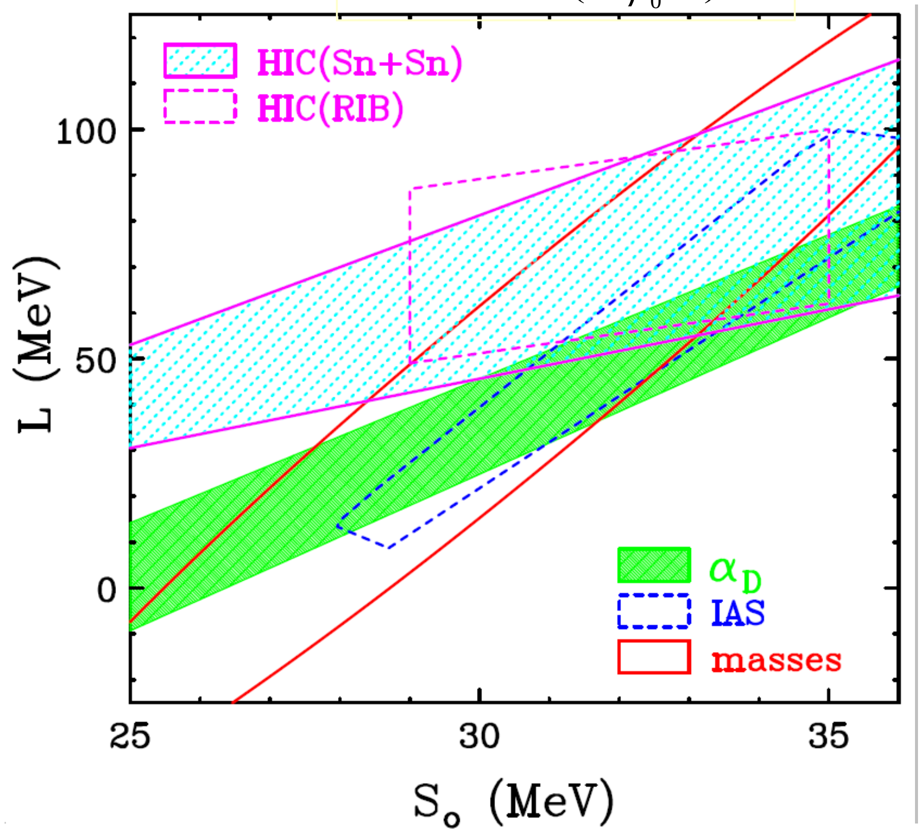
- **Nuclear Astrophysics**

  Core collapse supernova, Neutron Star, Nucleosynthesis.

Consistent Constraints from nuclear structure and reactions with credible uncertainties NuSYM13 & ICNT2013

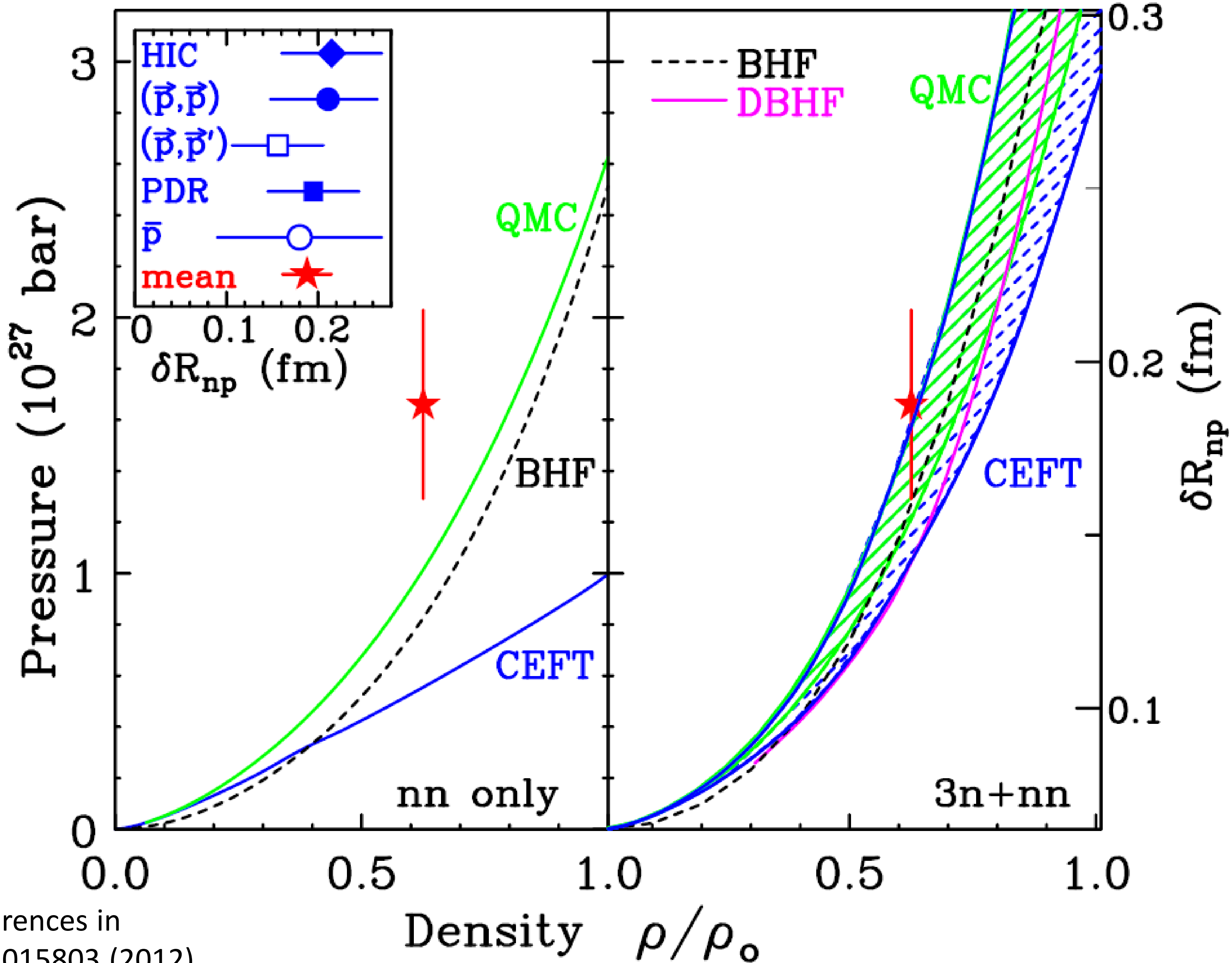
$$S(\rho) = S_o + \frac{L}{3}\left(\frac{\rho_B - \rho_0}{\rho_0}\right) + \ldots$$





"A Way Forward" from ICNT2013 & NuSYM13; J. of Phys G 41(2014) 093001

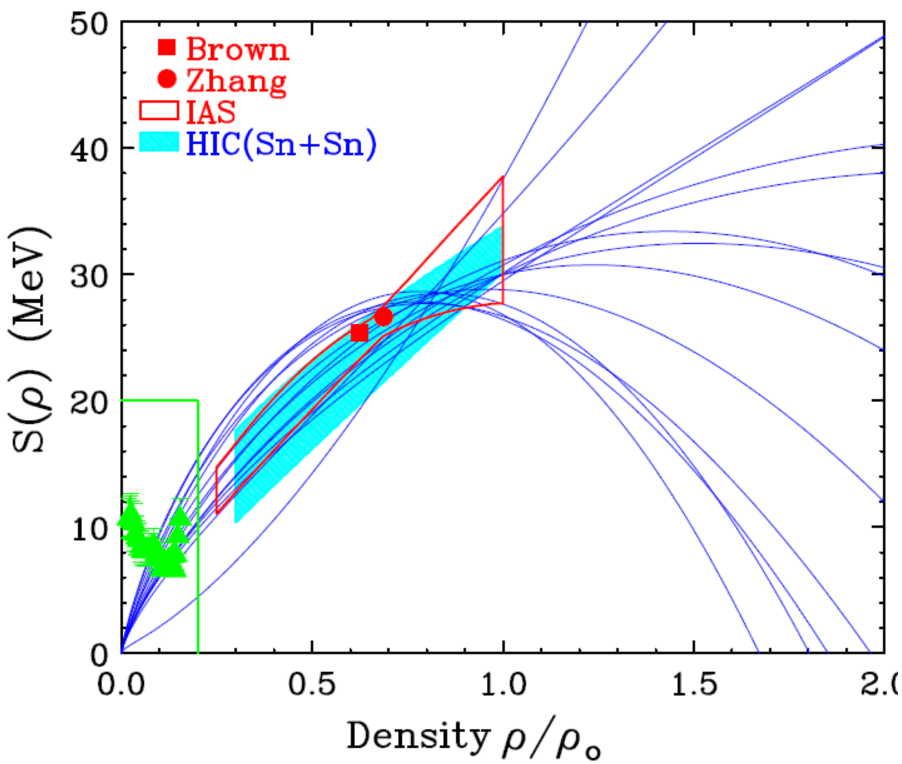
Importance of 3-body neutron-neutron force in the Equation of State of pure neutron matter

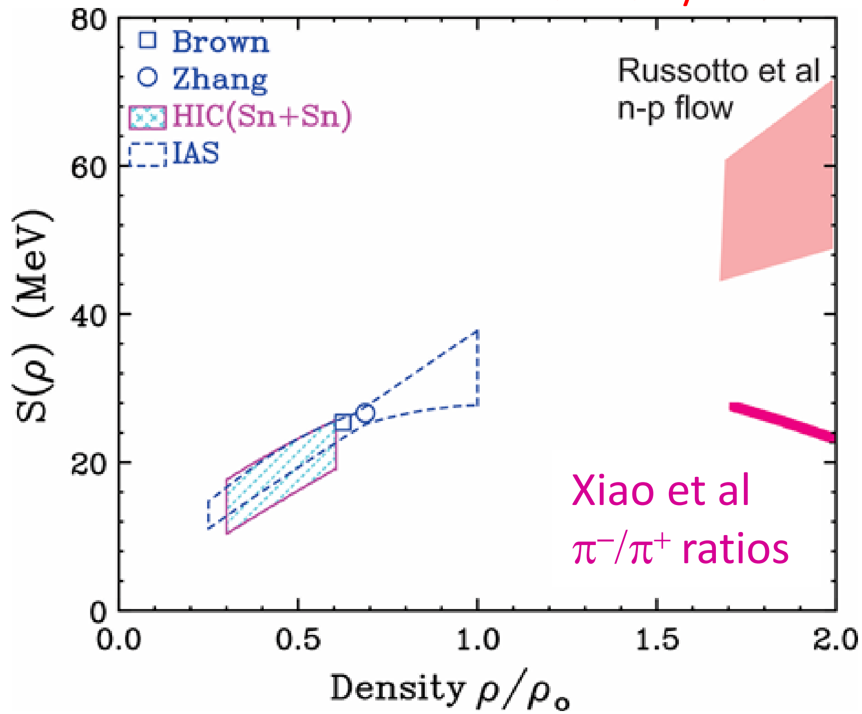


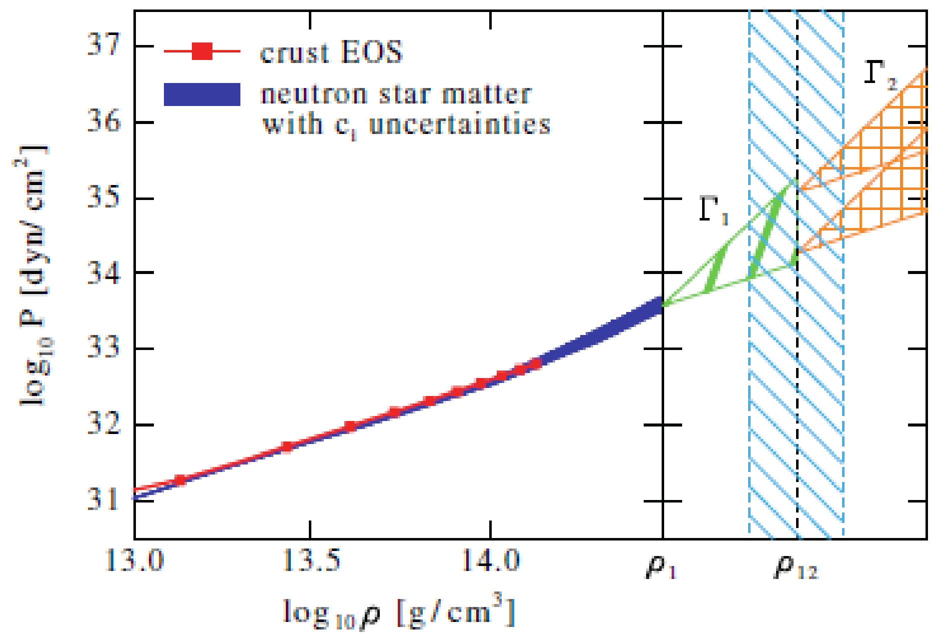
See references in
PRC 86, 015803 (2012)

Challenges at High Densities

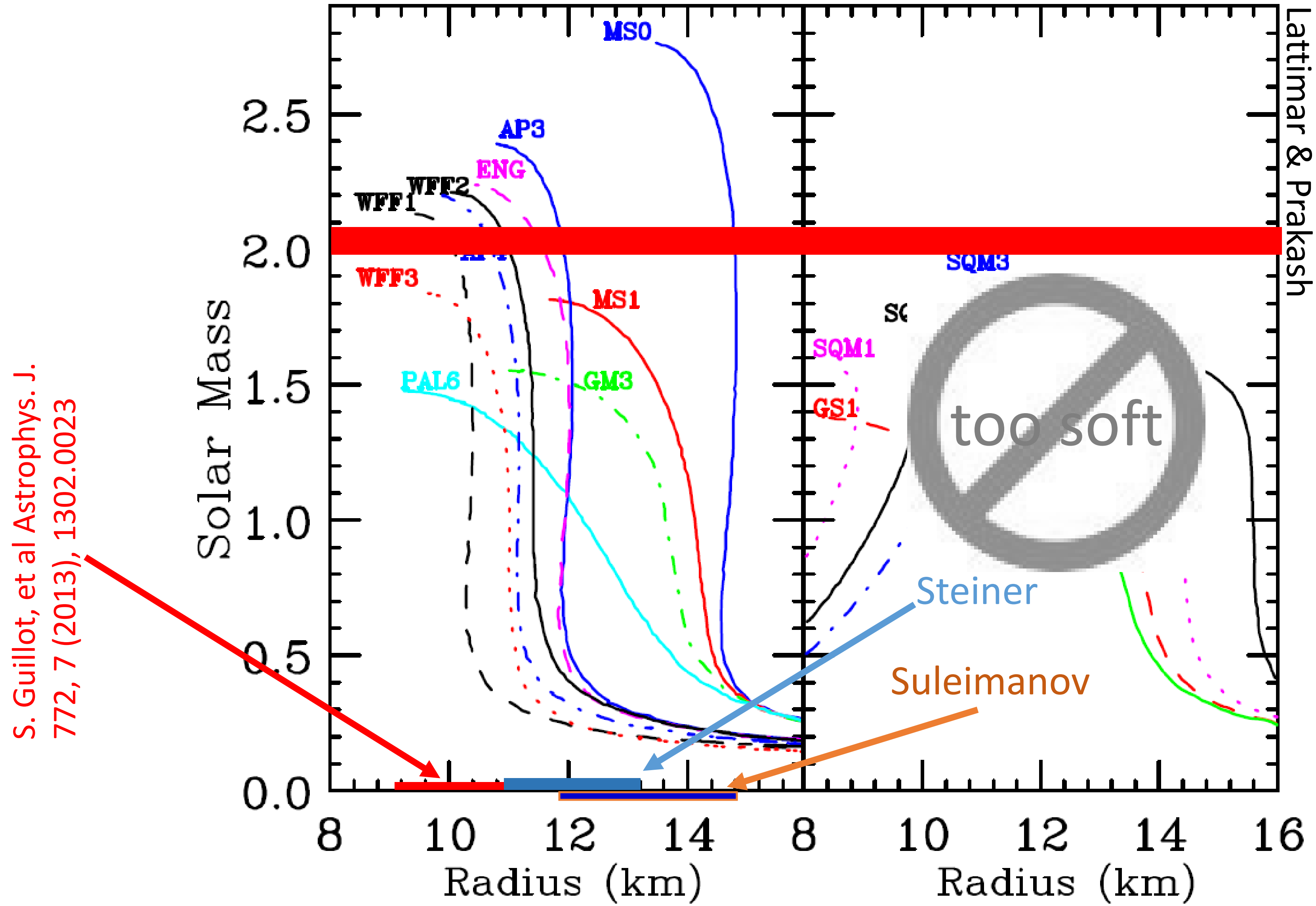
Au+Au E/A=0.4-1 GeV





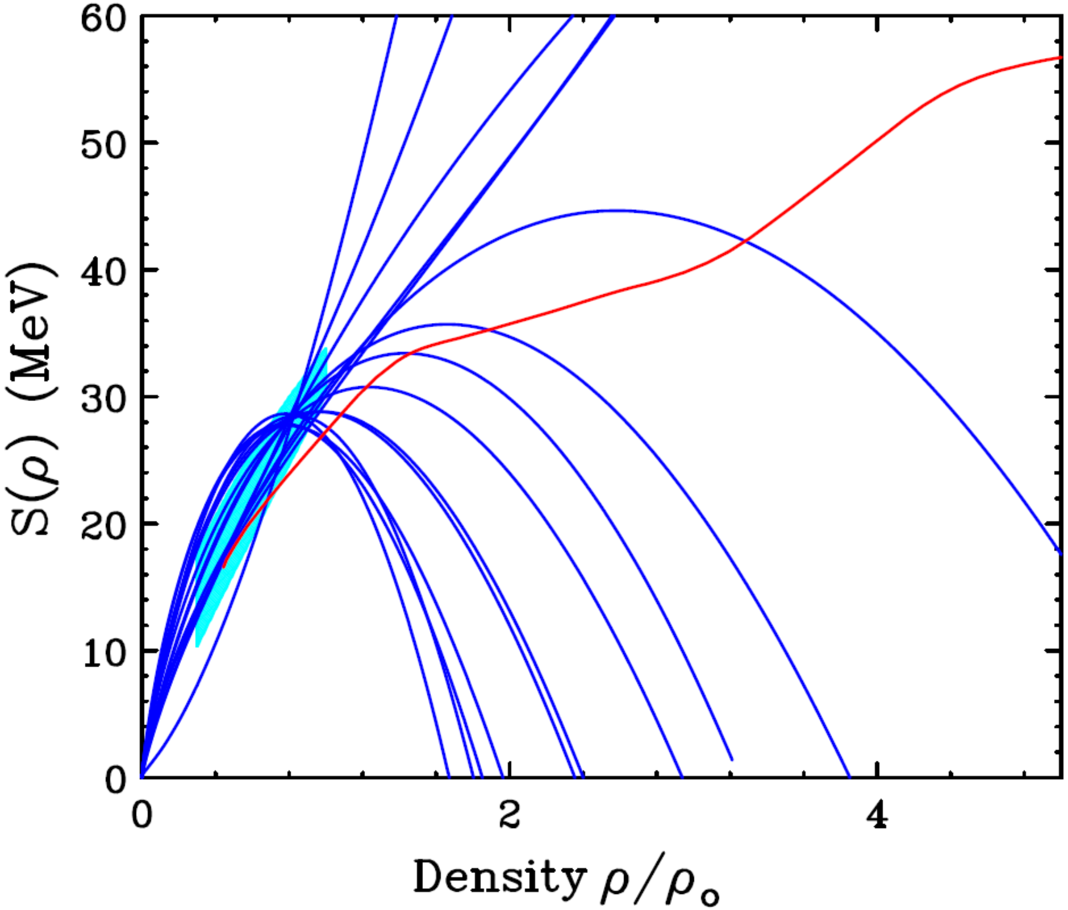


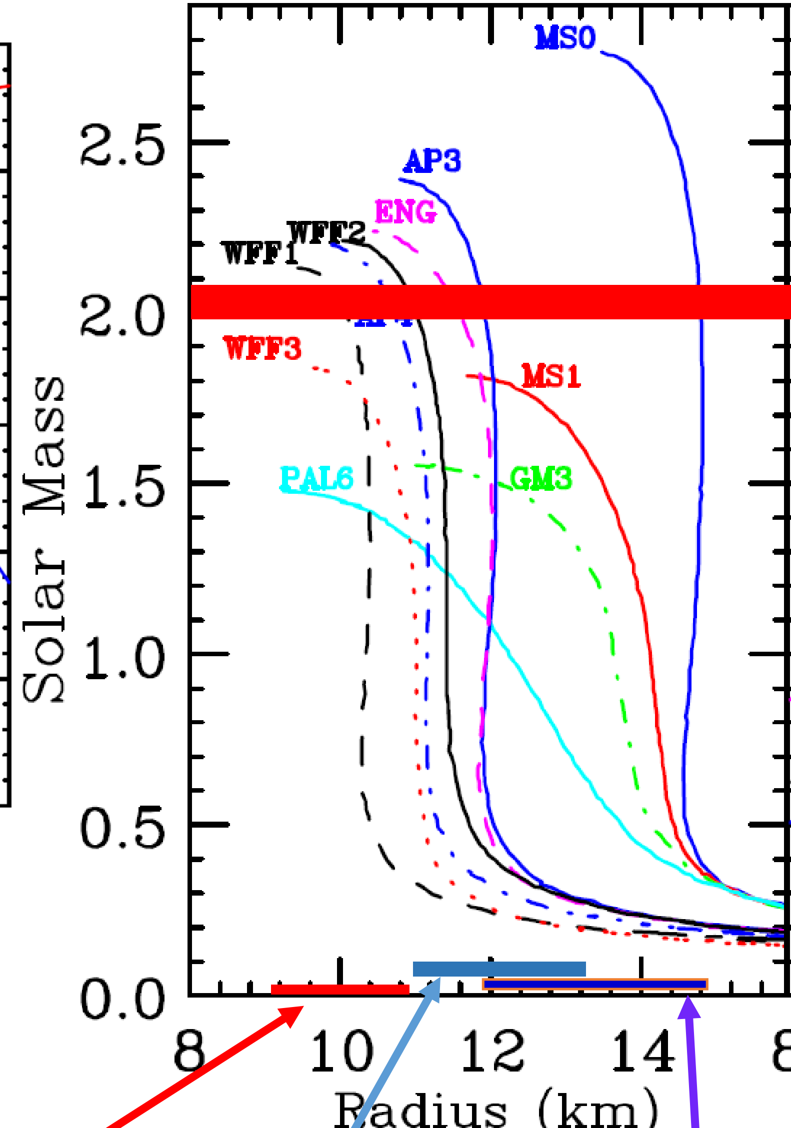
New observations of Neutron Stars (radius/Radii)



Very small Neutron Star radius rules out nearly all EOS

New observations of Neutron Stars (radius/Radii)





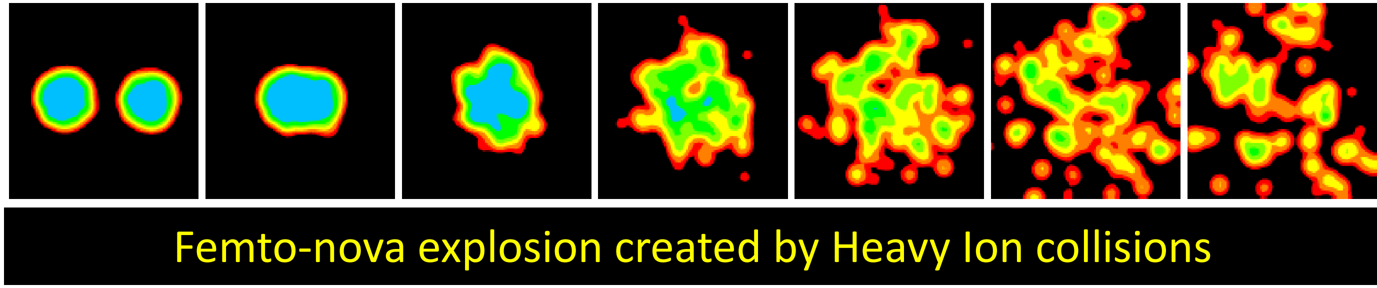
S. Guillot, et al Astrophys. J. 772, 7 (2013), 1302.0023

Steiner

Suleimanov

Challenges at High Densities

Transport models



Propagates single particle wave functions subject to the mean field and NN collisions

- Density dependence of symmetry energy
- Effective nucleon mass splitting
- Sn+Sn reactions

- Short range correlations: σ_{nn}; σ_{pp}; σ_{pn}
- propagation of nucleons in the interacting medium
- Ca+Sn reactions

Above Saturation Density
- Effective mass splitting
- Isospin dependence of σ_{NN}

Experimental Layout

PhD thesis: Daniel Coupland, Michael Youngs, Rachel Hodges

LASSA – charged particles

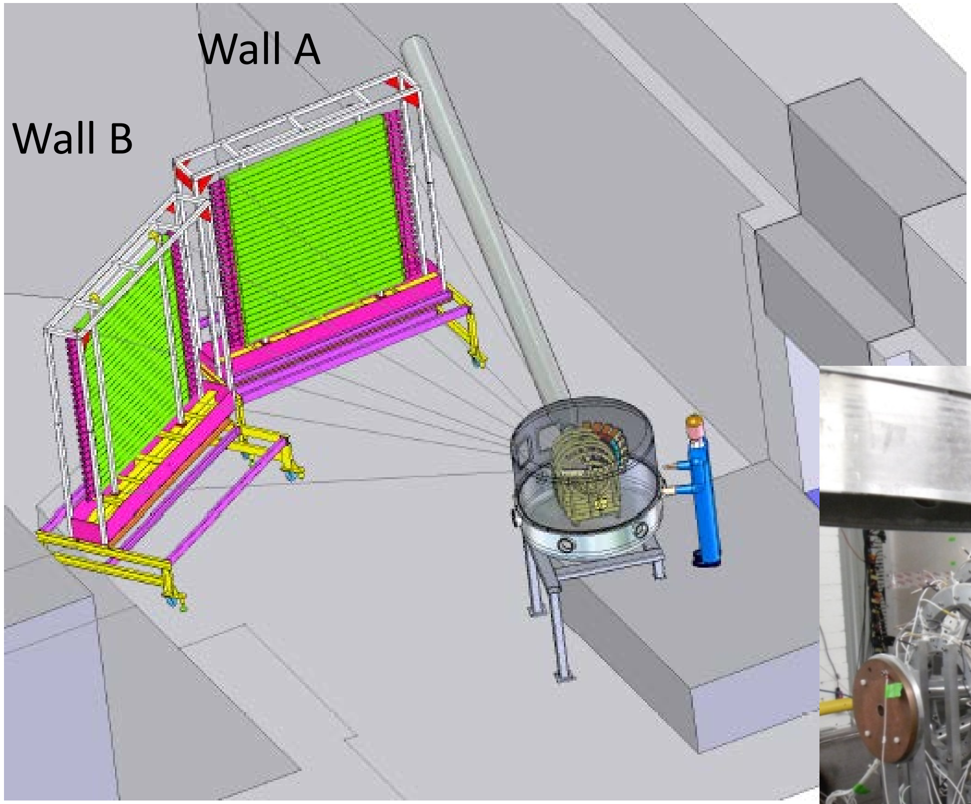
Miniball – impact parameter

$^{124}Sn+^{124}Sn$; $^{112}Sn+^{112}Sn$

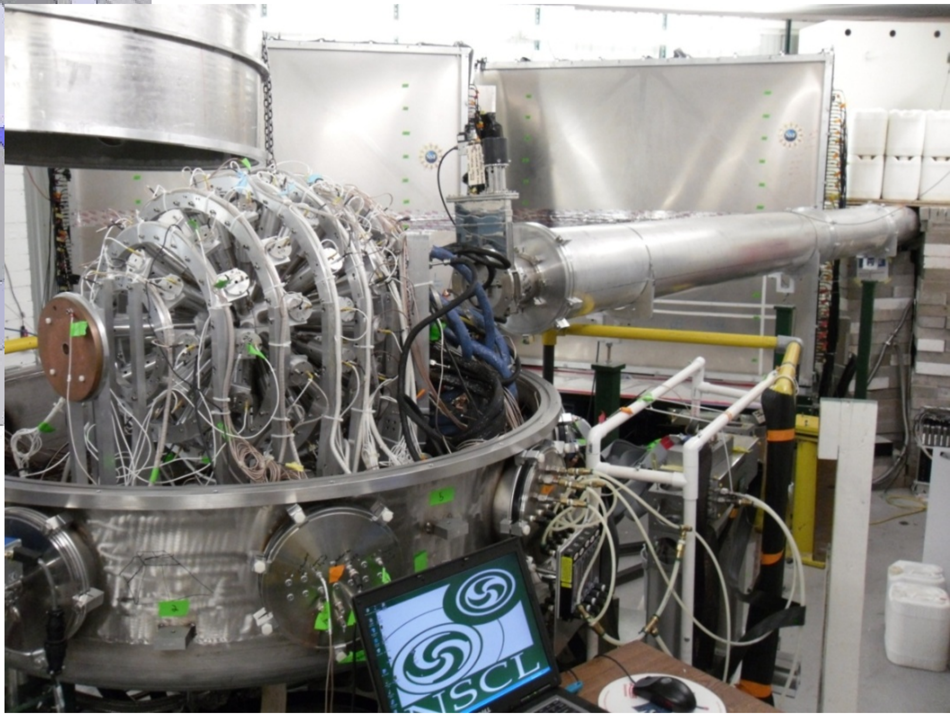
E/A=50 & 120 MeV

$^{48}Ca+^{124}Sn$; $^{48}Ca+^{112}Sn$

E/A=140 MeV



Courtesy Mike Famiano

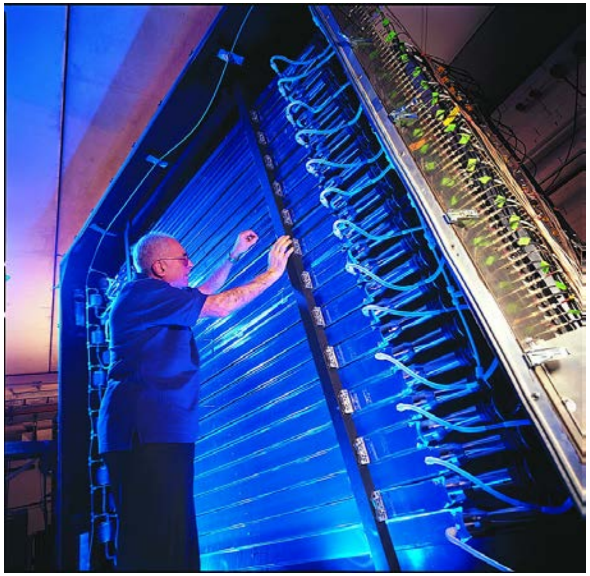


Neutron walls – neutrons

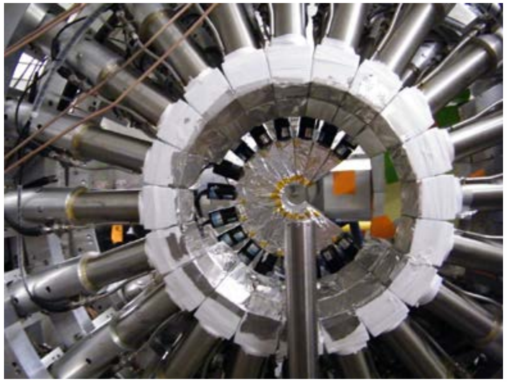
Forward Array – time start

Proton Veto scintillators

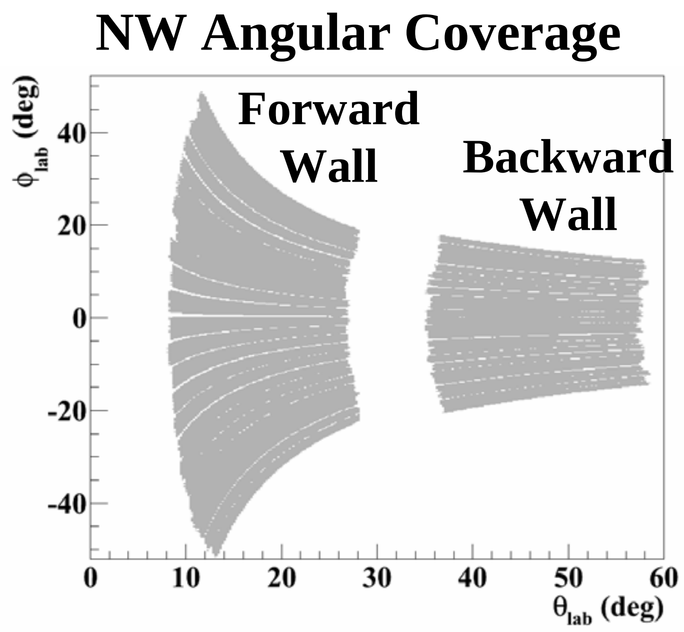
Neutron Wall Basics


Inside the Neutron Walls

Forward Array



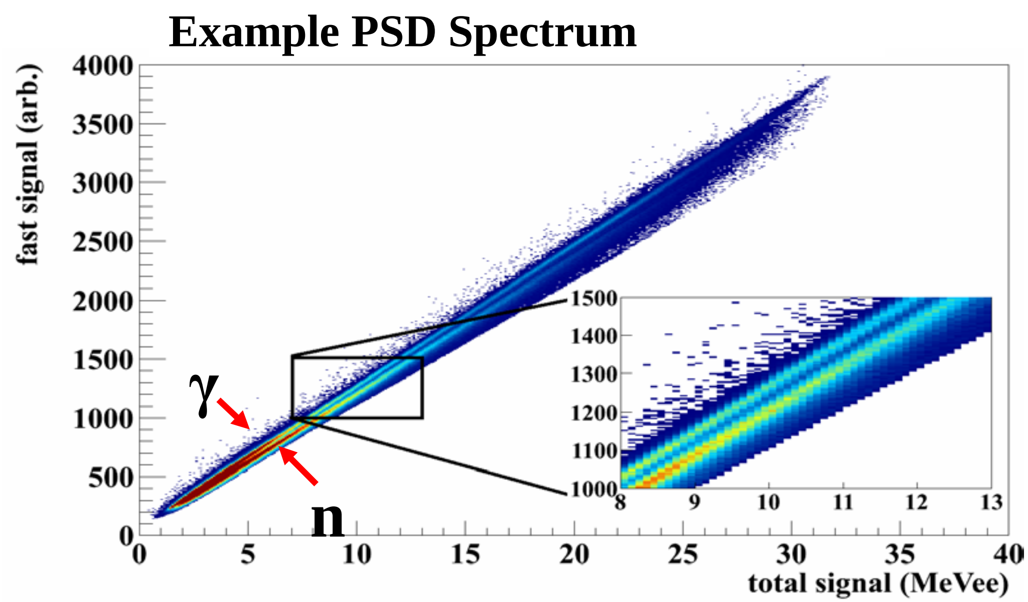
- 16 scintillators 10 cm in front of target
- Provide start time for NW

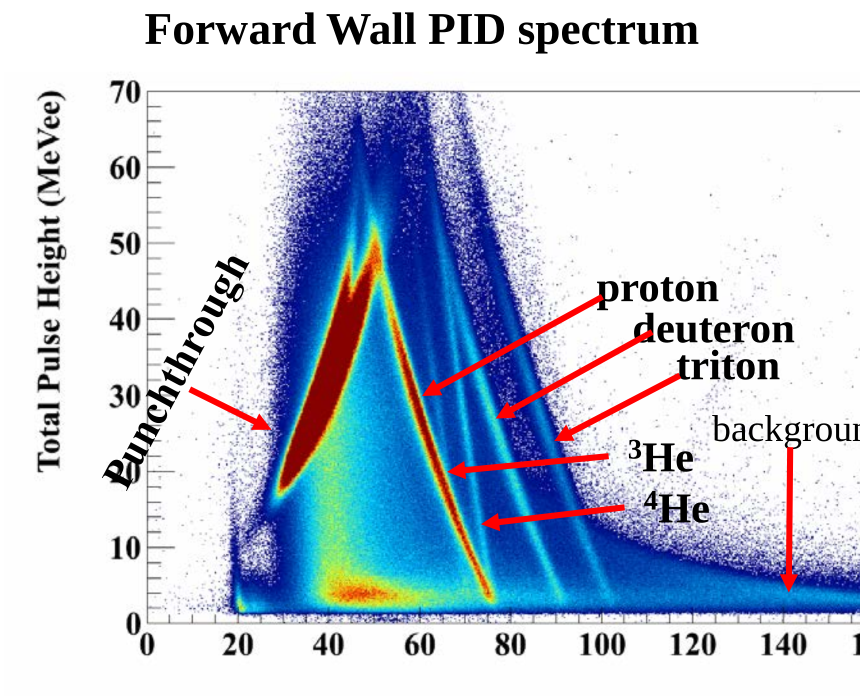


- Designed for high-energy neutrons
- ~ 2m x 2m
- 24 liquid plastic scintillator bars with PMT on each end
- Collect information: time, position, pulse height
  - 1 ns time resolution
  - 7 cm position resolution (5-6 m away from target: <1° resolution)
- 10% neutron detection efficiency
- Calculate E_{kin} from time-of-flight (TOF)

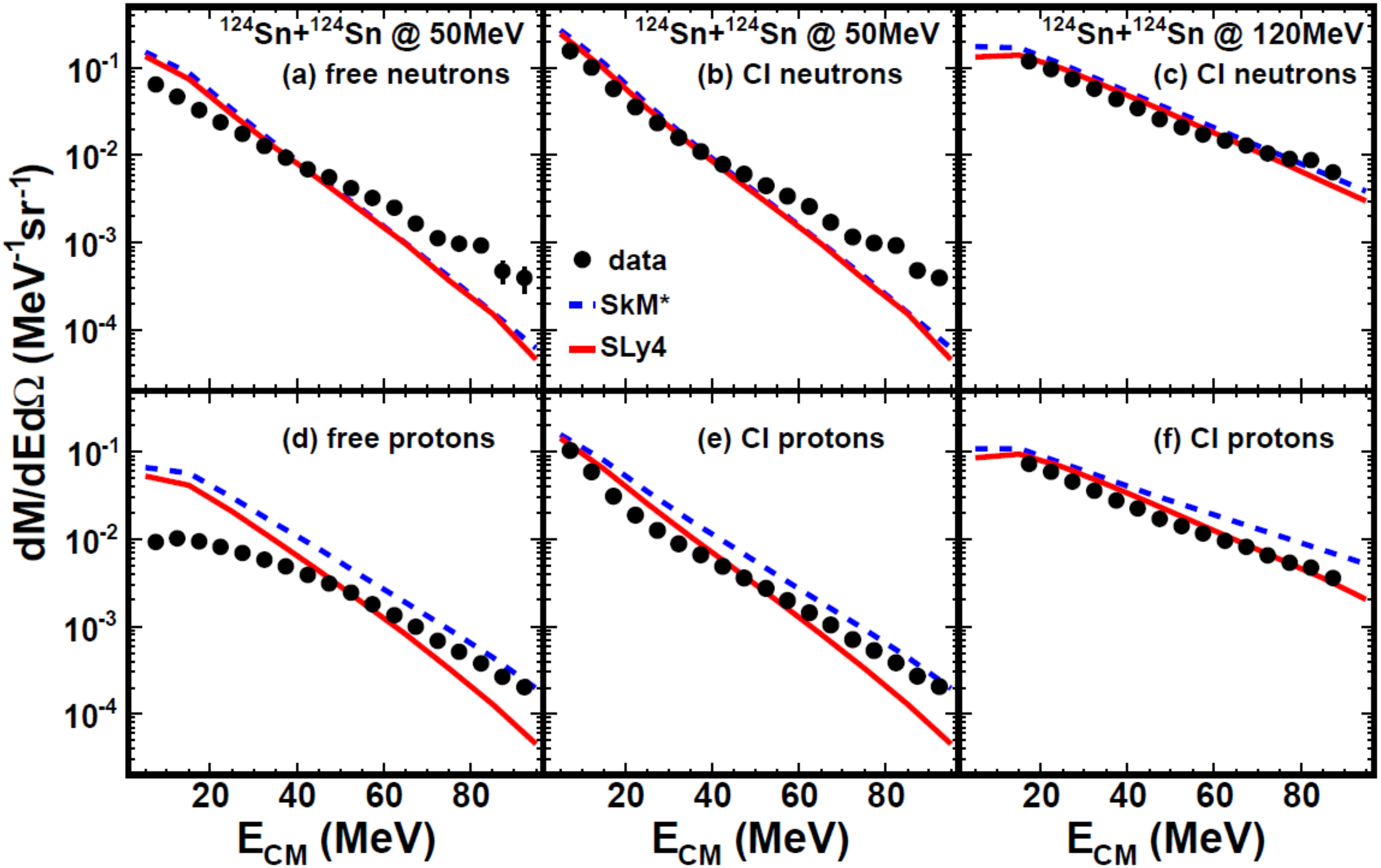
Measurements of Neutrons

- Protons was discovered in 1911
- neutrons was discovered in 1932





Nucleon energy spectra
Data vs. ImQMD calculations



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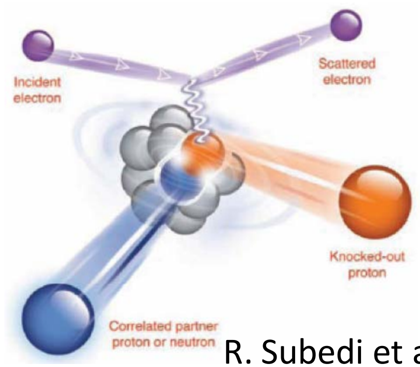
Isospin-Independent σ_{NN}^*

$^{12}C(e,e'pN)$ @ 4.627 GeV



18 times

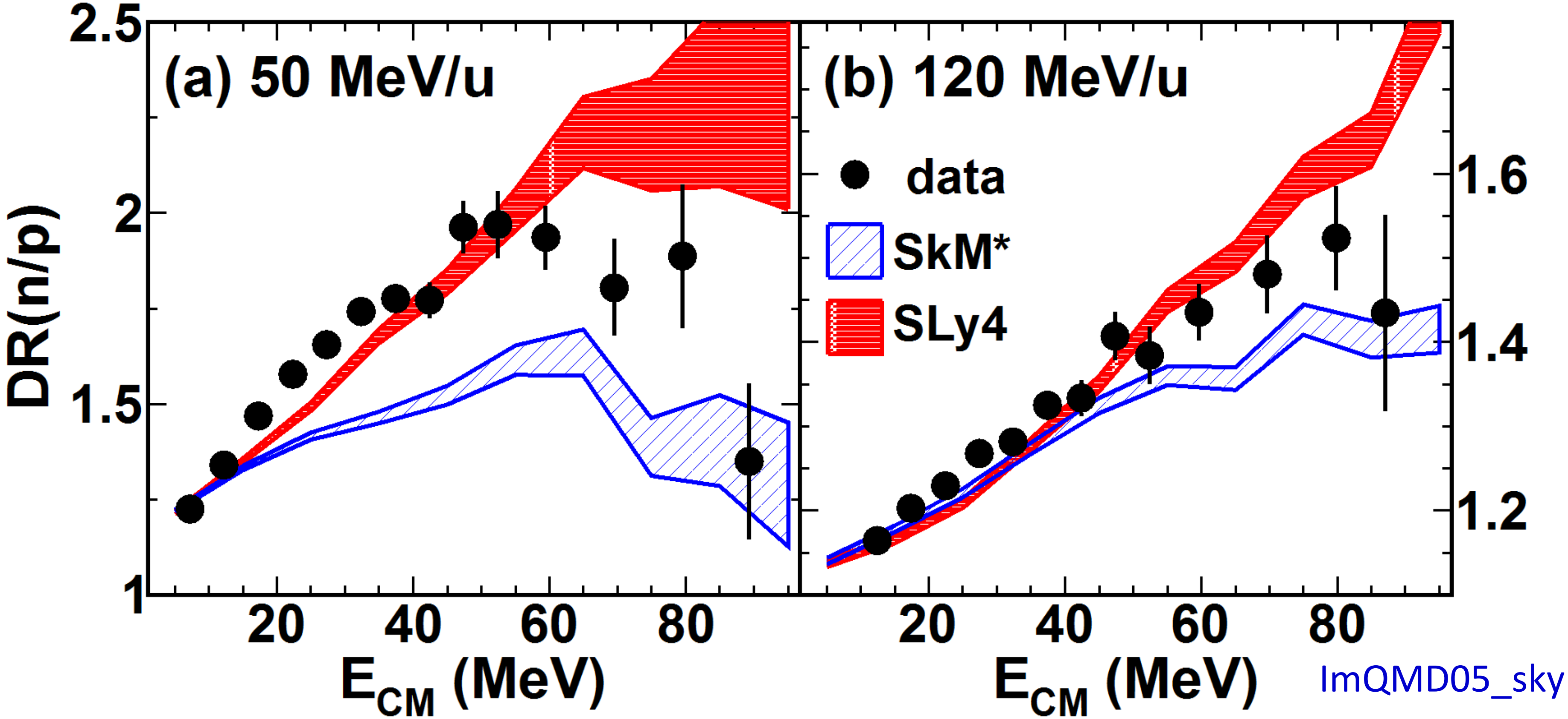
Jefferson Lab. (US)

R. Subedi et al.,Science 320 (2008) 1476.

In Transport model ~100 AMeV:
Effect is not very big ~10%
Mainly manifested in asymmetric reactions

Effective nucleon mass splitting

$^{124}Sn+^{124}Sn/^{112}Sn+^{112}Sn$



Thesis data : Daniel Coupland & Michael Youngs

Skyrme	S_0(MeV)	L (MeV)	m_n^*/m_n	m_p^*/m_p
SLy4	32	46	0.68	0.71
SkM*	30	46	0.82	0.76

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