Microscopic Structure of the Low-Energy Electric Dipole Response of ^{120}Sn

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in **Nuclear Structure** and Astrophysics
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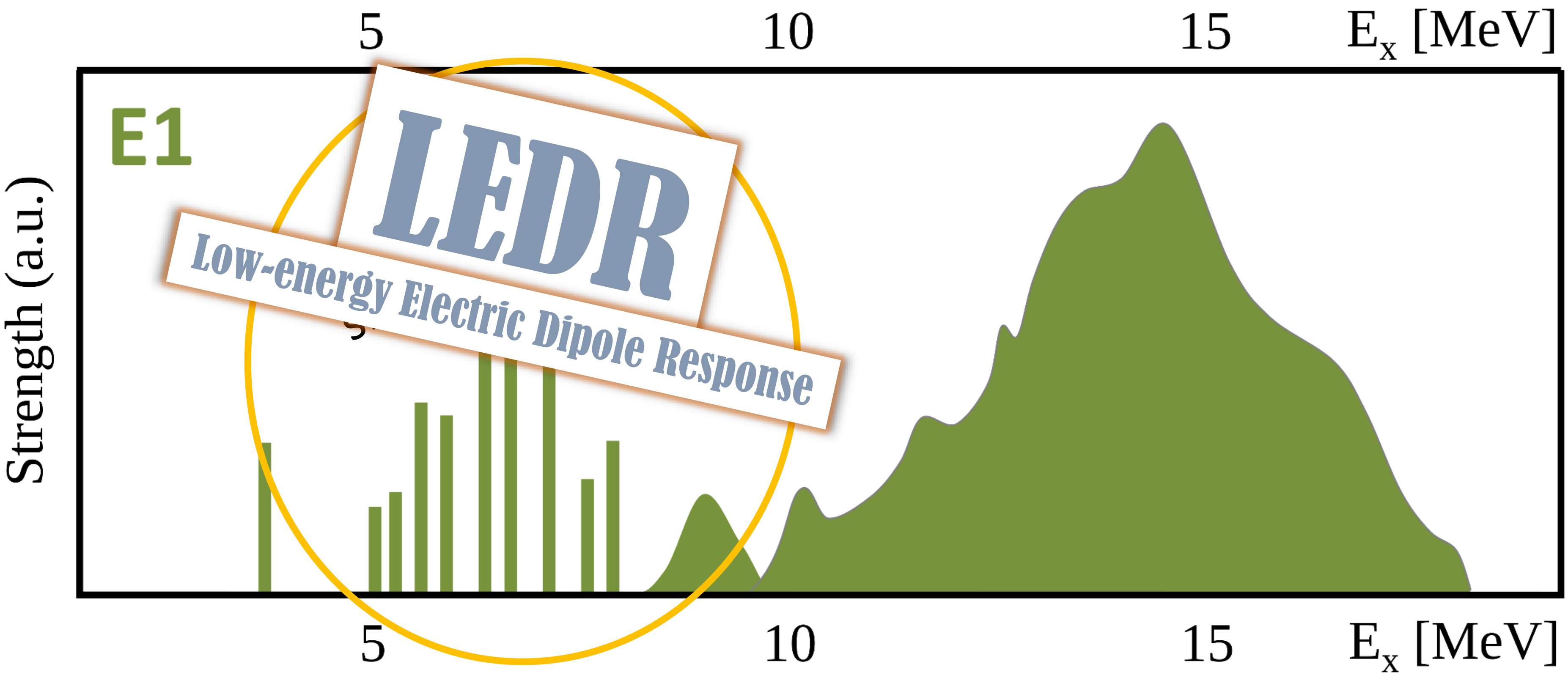
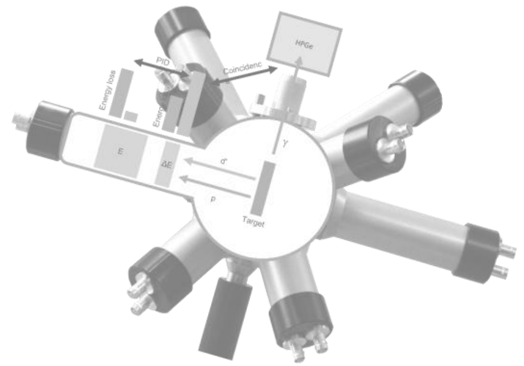
Typical Dipole-Strength Distribution in Atomic Nuclei



- Part of the photon strength function
  - Used to model $(\gamma,n)/(n,\gamma)$ reactions during late *r* process
- General nuclear structure phenomena
  - How are specific features generated?

Overview

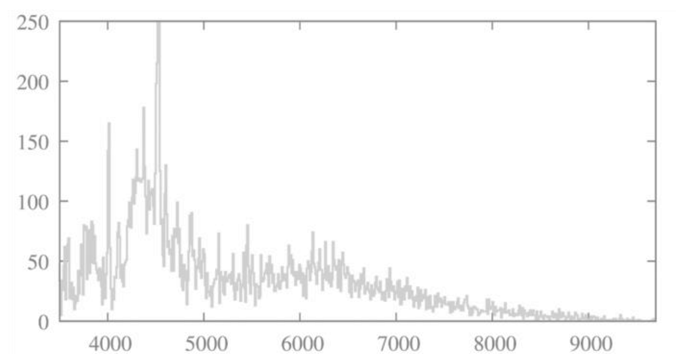
- A short history of complementary experiments on the LEDR



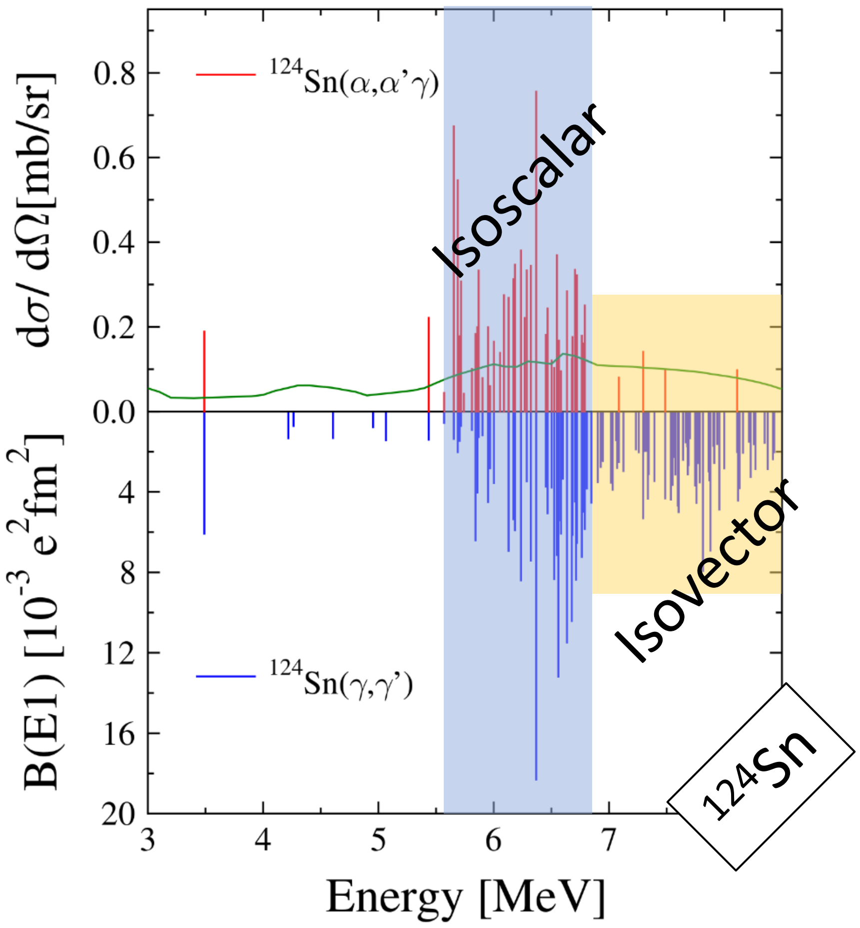
- Microscopic structure:
  - ^{119}Sn(d,pγ) and ^{120}Sn(γ,γ')
  - Quasiparticle-Phonon-Model
  - Comparing apples to apples

$$\Psi_\nu = \Big\{ \sum_i R_i(\nu)\, Q^+_{1Mi} + \sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(\nu) \big[Q^+_{\lambda_1\mu_1 i_1} \times Q^+_{\lambda_2\mu_2 i_2}\big]_{1M} + \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2\\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(\nu) \Big[\big[Q^+_{\lambda_1\mu_1 i_1} \times Q^+_{\lambda_2\mu_2 i_2}\big]_{IK} \times Q^+_{\lambda_3\mu_3 i_3}\Big]_{1M} \Big\} \Psi_0$$

- Isoscalar response:
  - ^{120}Sn(α,α'γ) at E_α= 130 MeV



The Low-Energy Electric Dipole Response

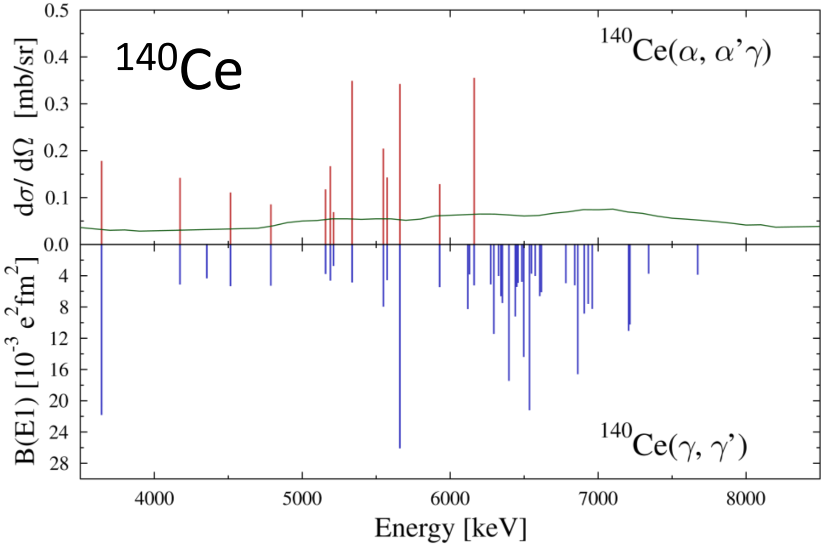


- Photon scattering used to *chart* the LEDR
- Study of total strength and decay behavior
- Comparison to other probes yields deeper insight!
- For example: (α,α'γ), (p,p'γ), (^{17}O,^{17}O'γ)

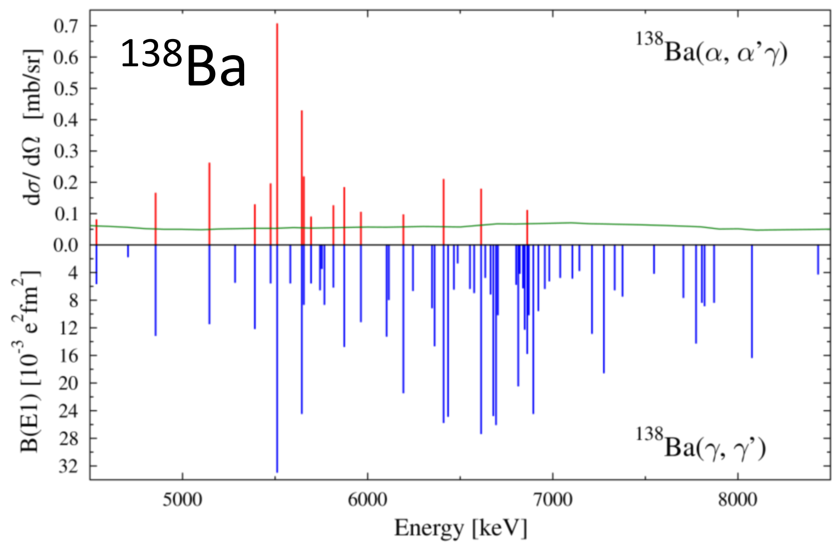
J. Endres *et al.*, Phys. Rev. Lett. **105** (2010) 212503

Isoscalar E1 response – Isospin *Splitting*

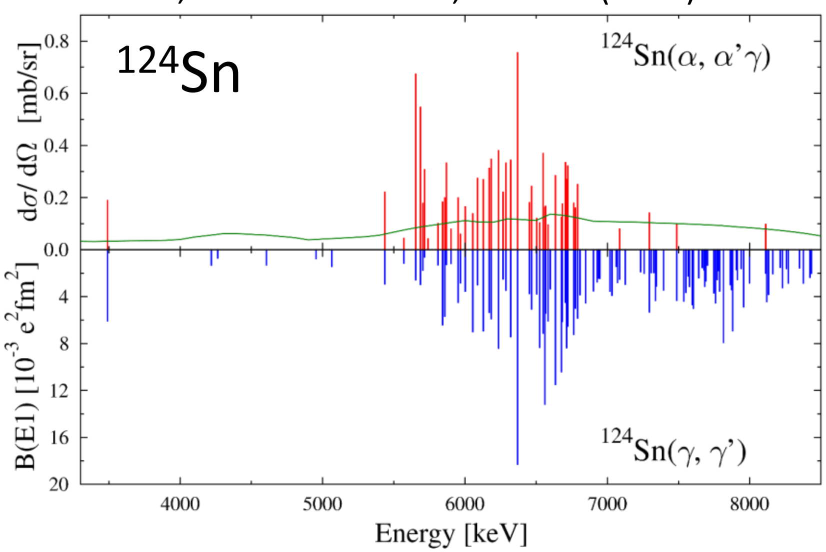
D. Savran *et al.*, PLB **786** (2018) 16



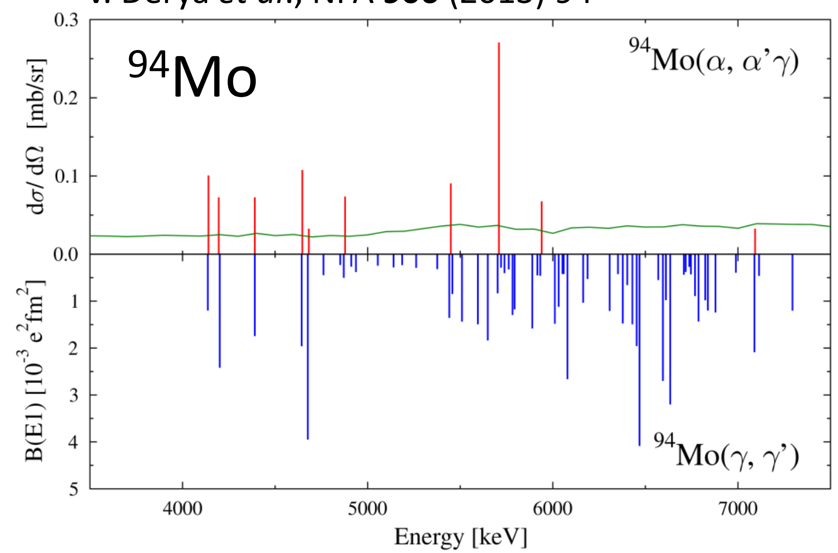
J. Endres *et al.*, PRC **80** (2009) 034302



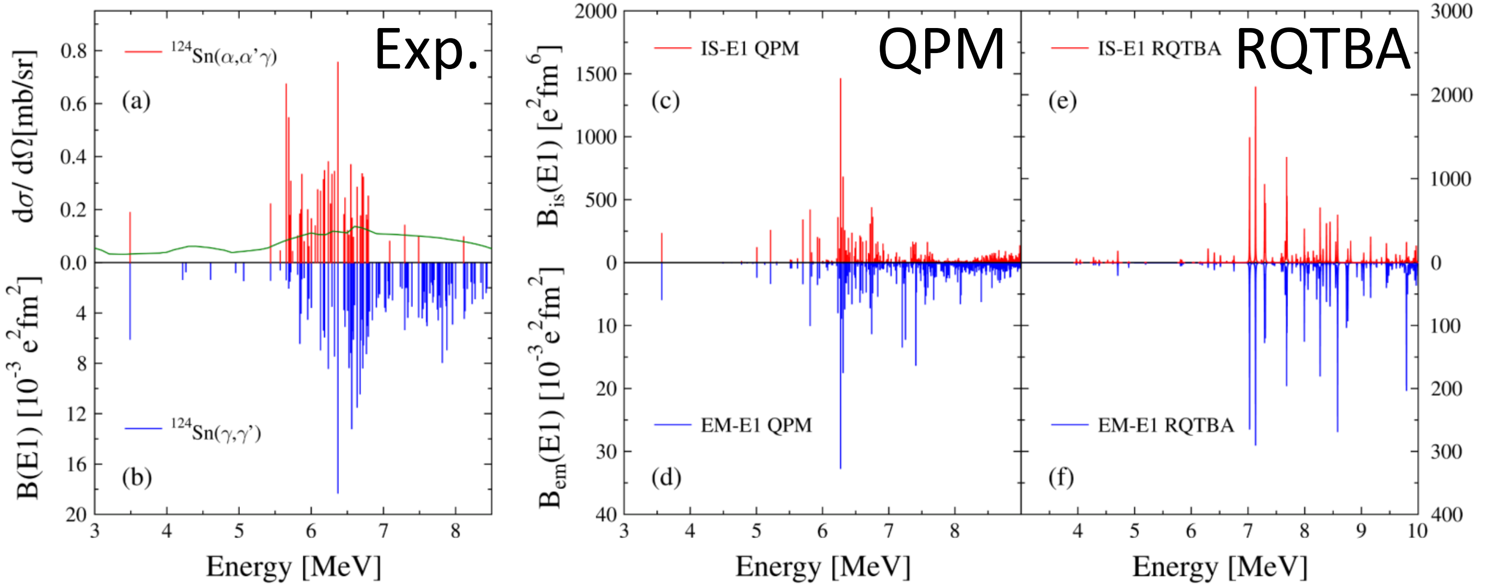
J. Endres, E. Litvinova *et al.*, PRL **105** (2010) 212503



V. Derya *et al.*, NPA **906** (2013) 94

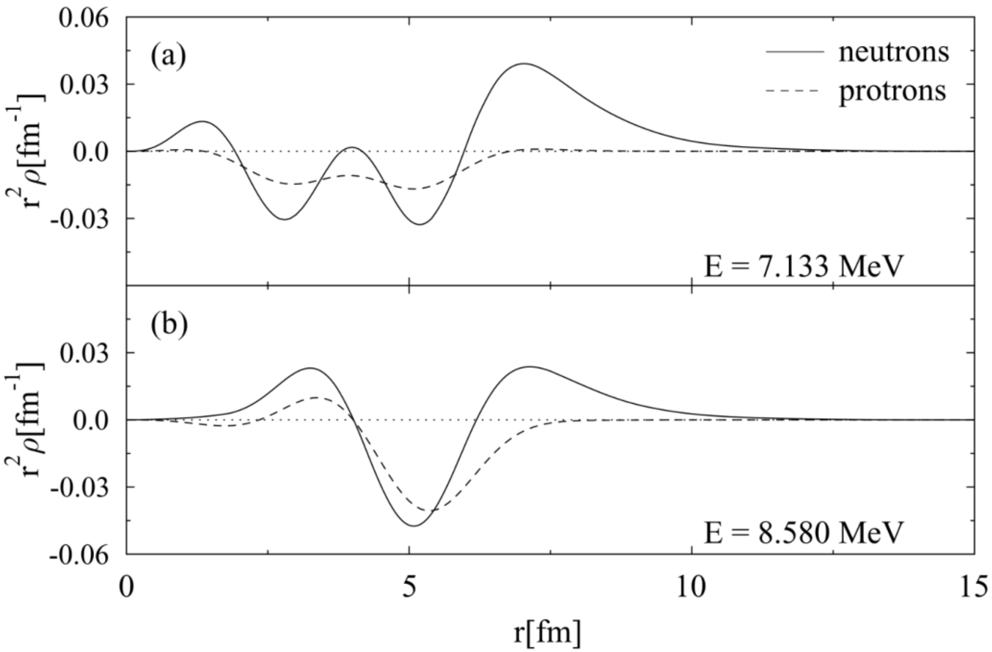


^{124}Sn – Experiment and Theory



^{124}Sn!

RQTBA



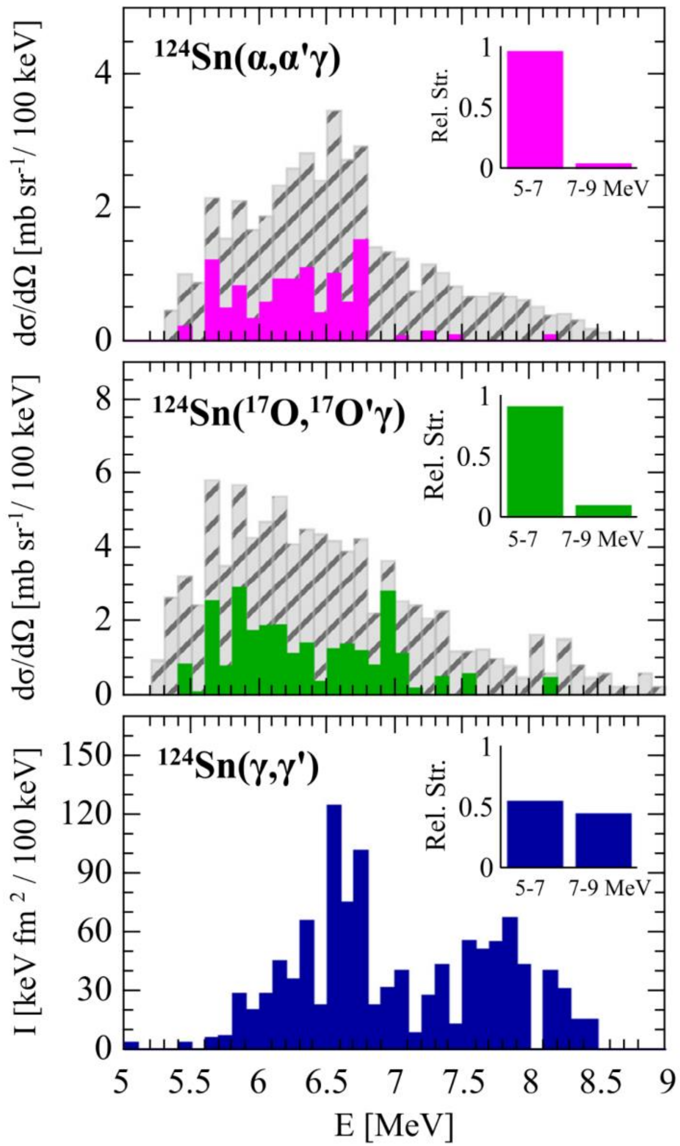
Splitting of cross sections reproduced by QPM and RQTBA

Transition densities (TRDs) show *neutron-skin* character in isoscalar part

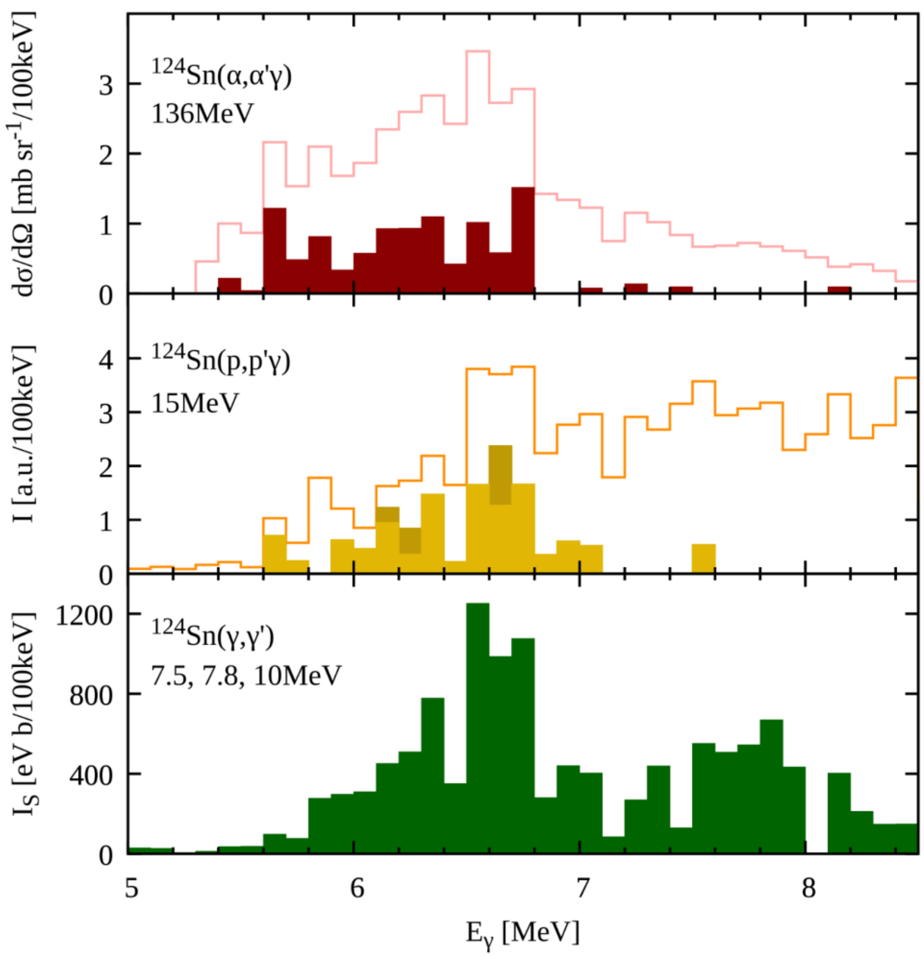
J. Endres, E. Litvinova *et al.*, PRL **105** (2010) 212503

J. Endres, D. Savran *et al.*, PRC **85** (2012) 064331

^{124}Sn – Other Experiments

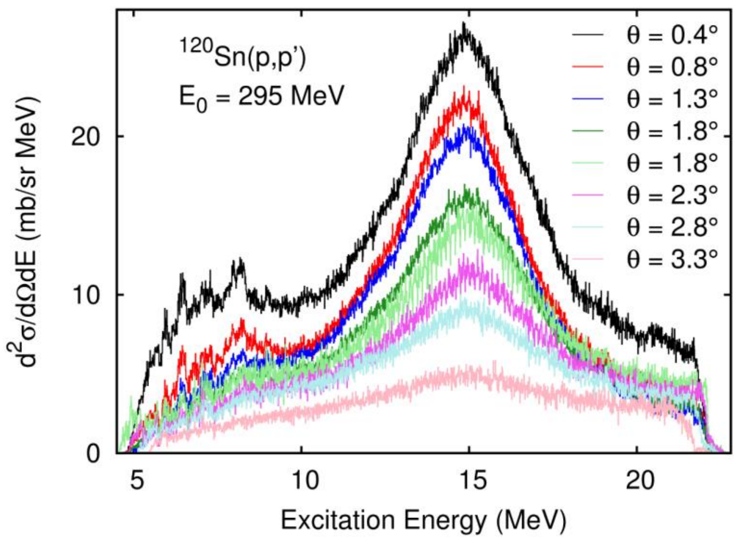


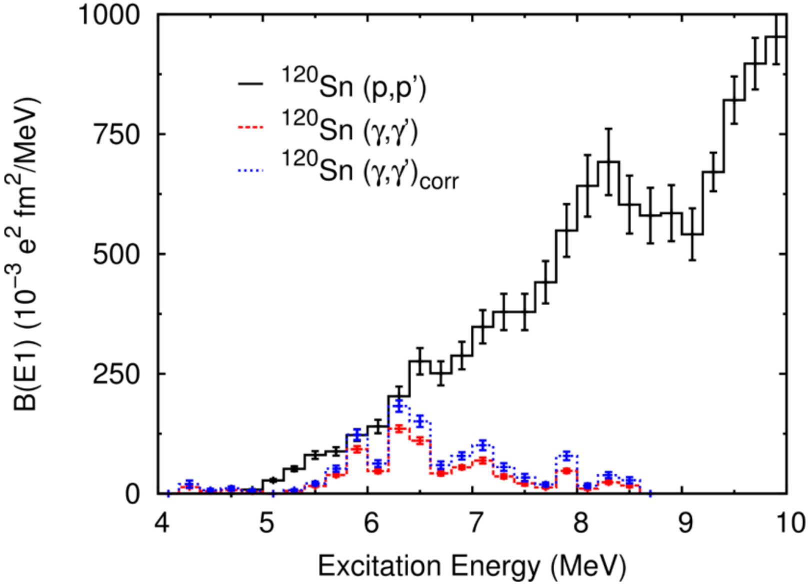
L. Pellegri *et al.*, PLB **738** (2014) 519



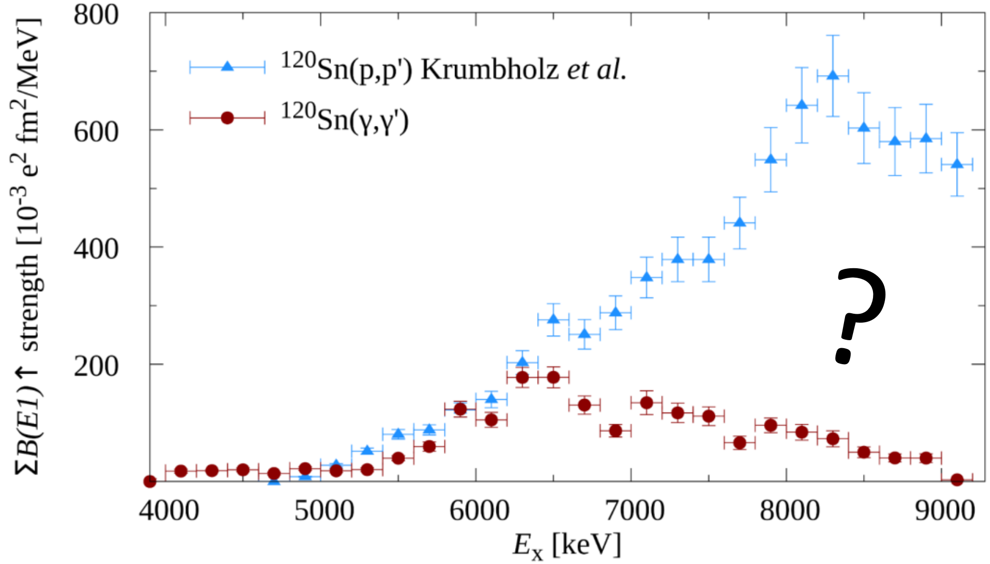
M. Färber, M. Weinert *et al.*, EPJ A **57** (2021) 191

^{120}Sn – NRF and CoulEx





A.M. Krumbholz *et al.*, PLB **744** (2015) 7



Recent confirmation of CoulEx data and high sensitivity remeasurement of NRF

→ Discrepancy remains!

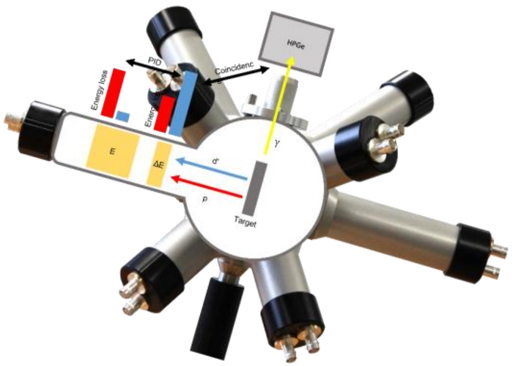
→ Caused by nuclear structure?

S. Bassauer *et al.*, PRC **102** (2020) 034327

M. Müscher *et al.*, PRC **102** (2020) 014317

Overview

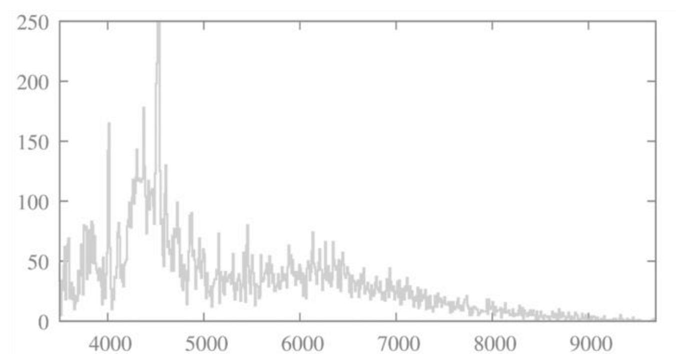
- A short history of complementary experiments on the LEDR



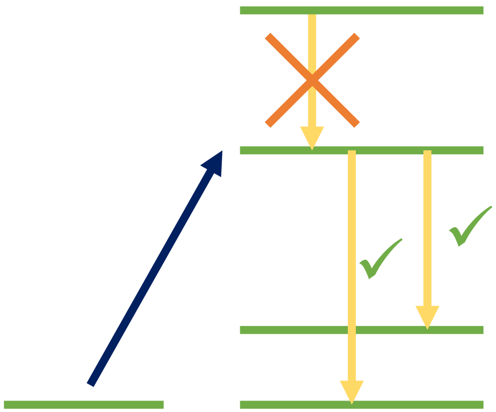
- Microscopic structure:
  - $^{119}Sn(d,p\gamma)$ and $^{120}Sn(\gamma,\gamma')$
  - Quasiparticle-Phonon-Model
  - Comparing apples to apples

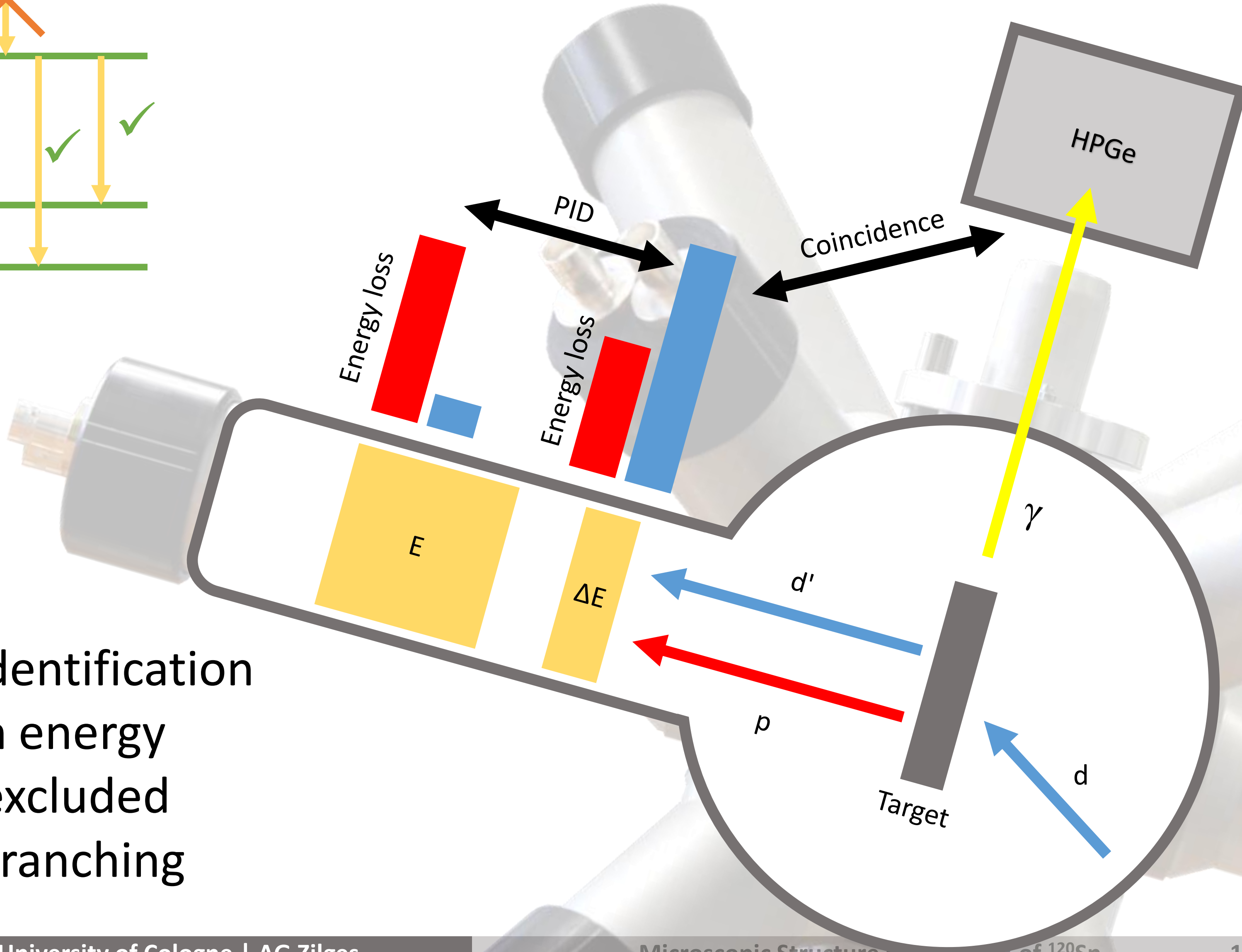
$$\Psi_\nu = \Big\{ \sum_i R_i(\nu)\, Q^+_{1Mi} + \sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(\nu)\Big[Q^+_{\lambda_1\mu_1 i_1} \times Q^+_{\lambda_2\mu_2 i_2}\Big]_{1M} + \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2\\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(\nu)\Big[\Big[Q^+_{\lambda_1\mu_1 i_1} \times Q^+_{\lambda_2\mu_2 i_2}\Big]_{IK} \times Q^+_{\lambda_3\mu_3 i_3}\Big]_{1M} \Big\}\Psi_0$$

- Isoscalar response:
  - $^{120}Sn(\alpha,\alpha'\gamma)$ at E_α= 130 MeV



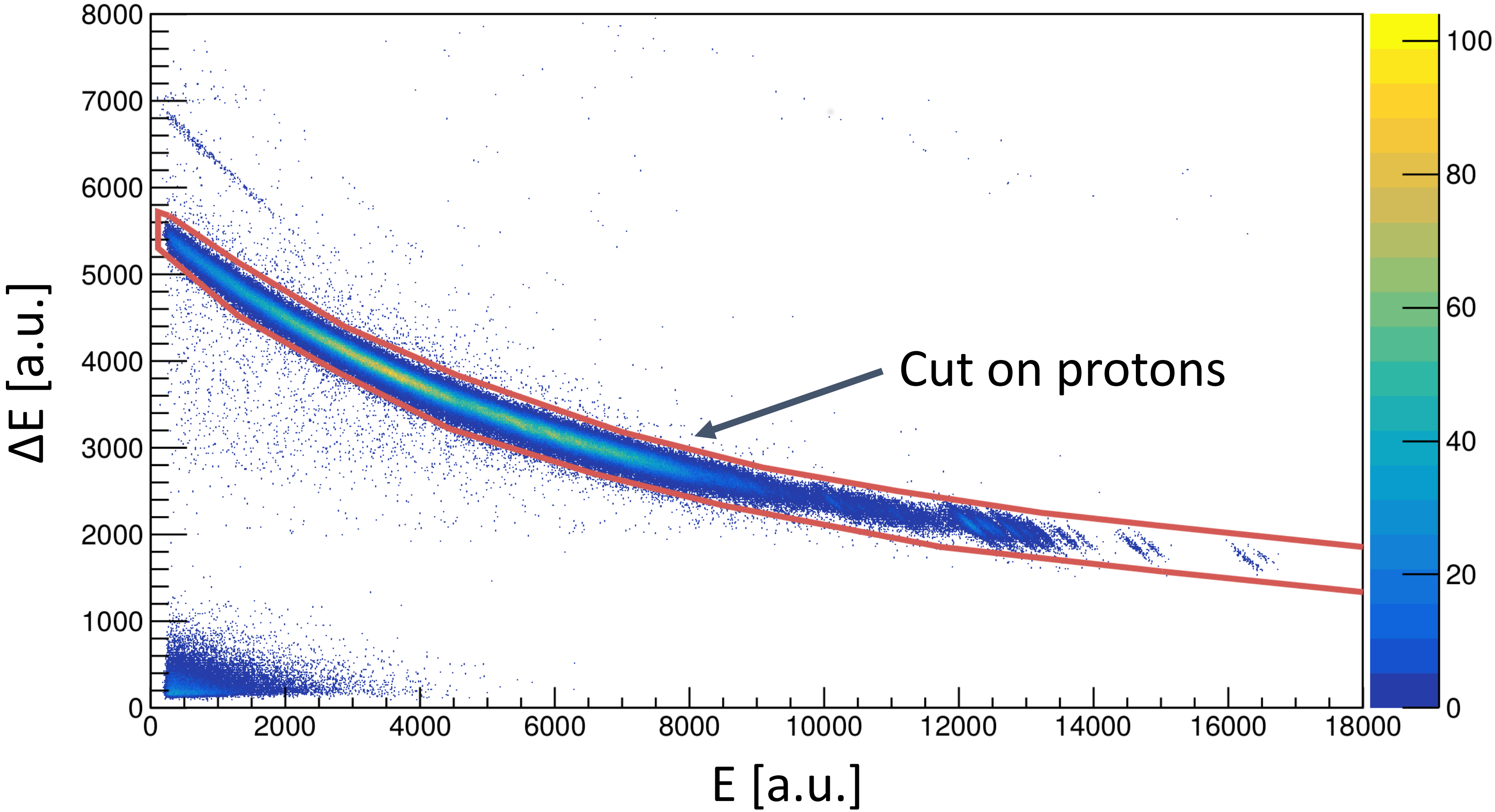
$^{119}Sn(d,p\gamma)$@8.5MeV – SONIC@HORUS





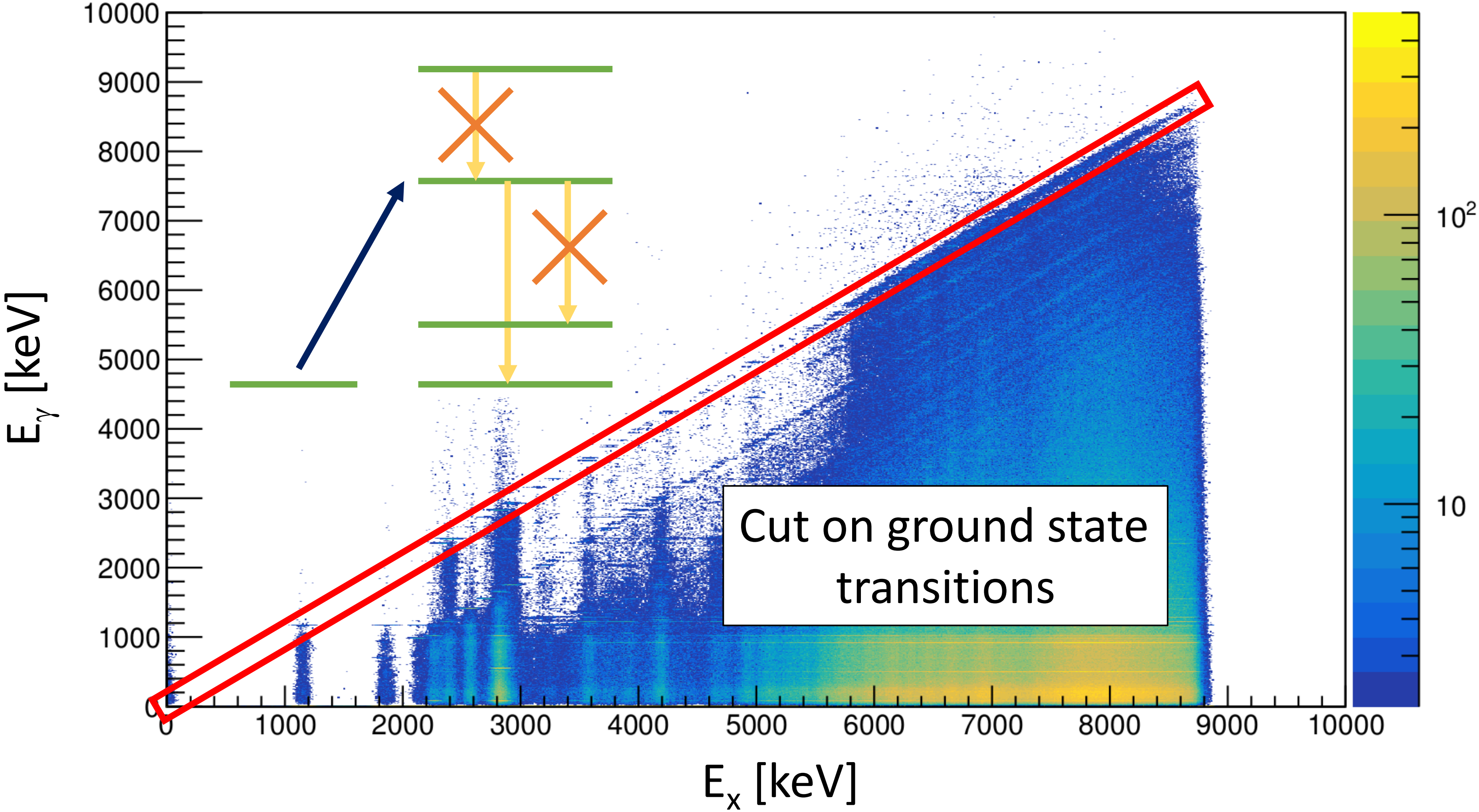
- ✓ Particle identification
- ✓ Excitation energy
- ✓ Feeding excluded
- ✓ γ-decay branching

$^{119}Sn(d,p\gamma)$@8.5MeV – SONIC@HORUS



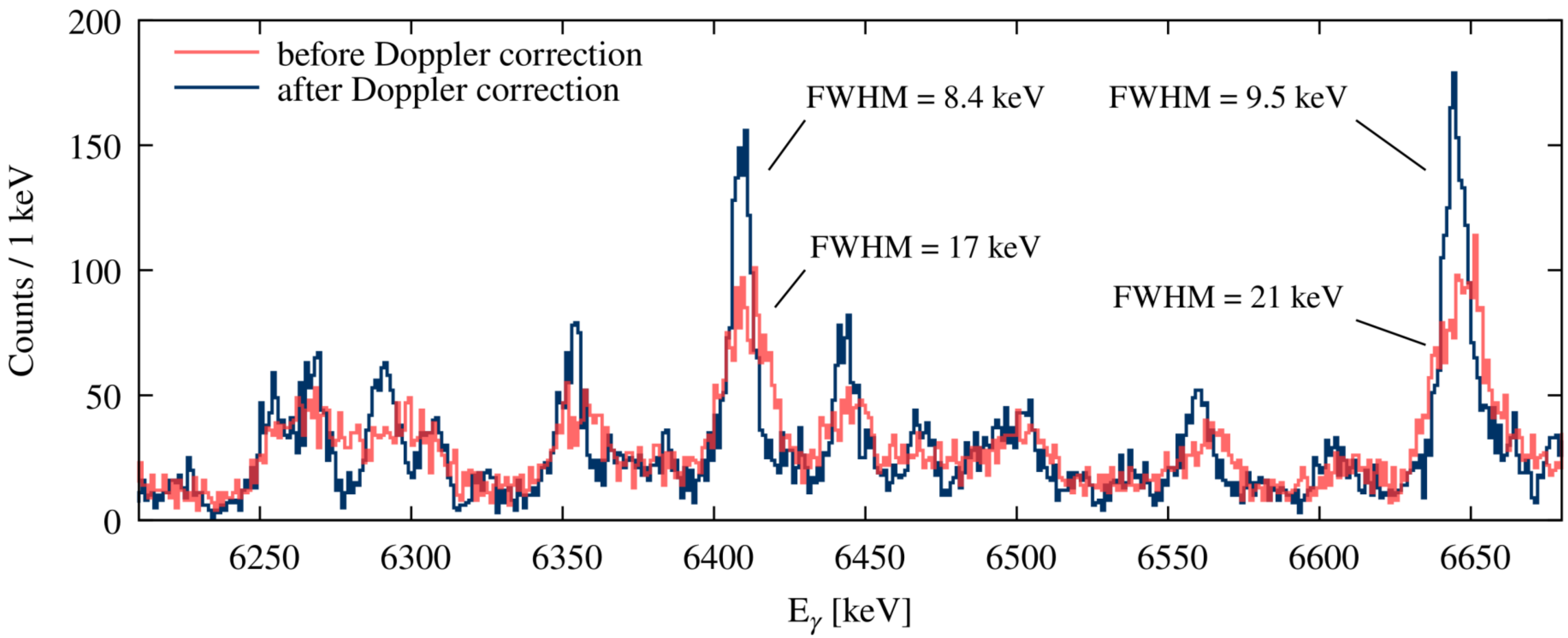
Select protons in ΔE-E to distinguish (d,p) from (d,d')

$^{119}Sn(d,p\gamma)$@8.5MeV – SONIC@HORUS



Select direct excitation and decay into specific state in ^{120}Sn

^{119}Sn(d,pγ)@8.5MeV – SONIC@HORUS

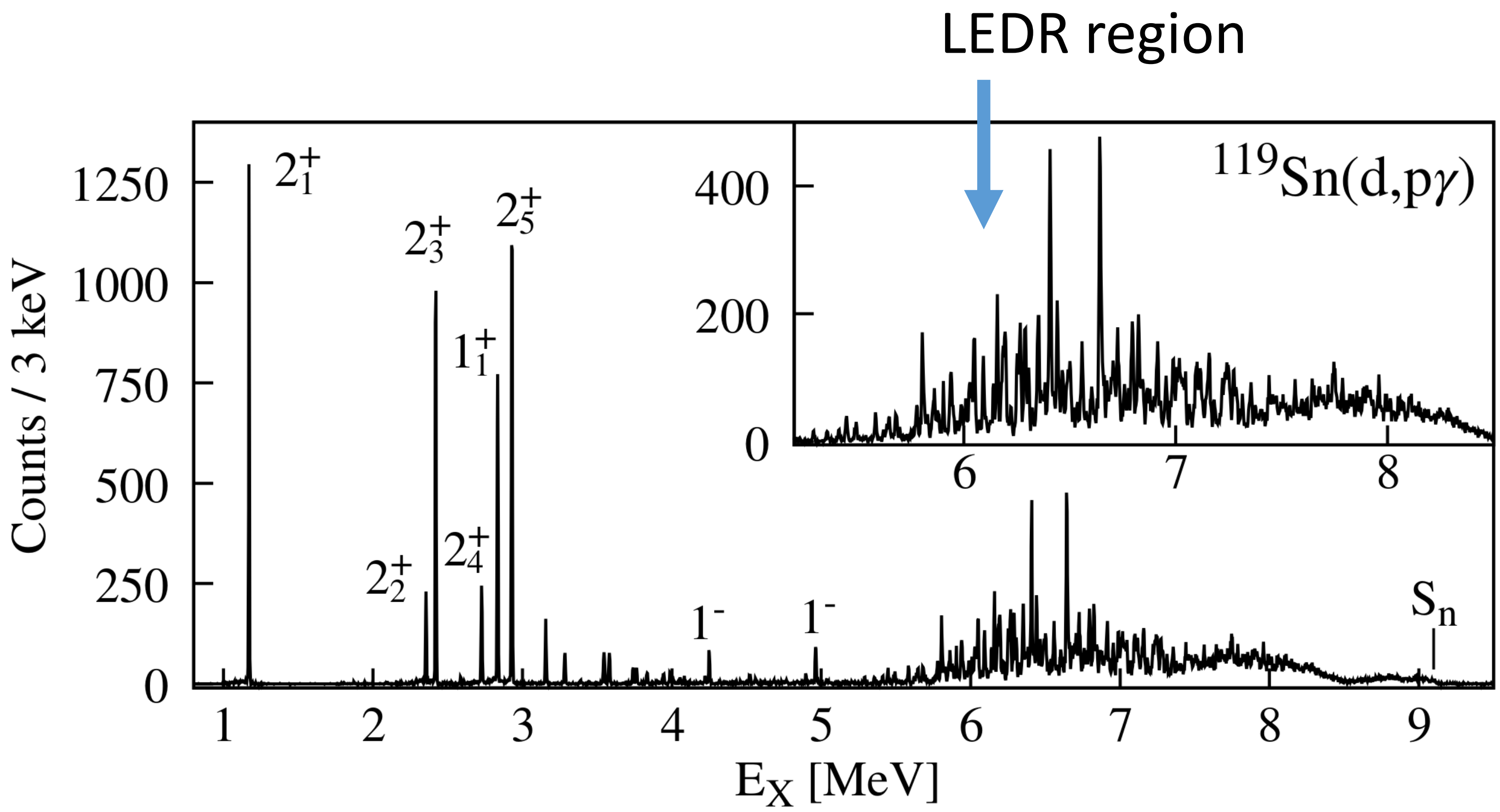


Doppler shift due to recoiling target nuclei (β=0.0025)

Correction assuming very short lifetime and in-flight decay

Nominal HPGe resolution restored in summed spectrum!

$^{119}Sn(d,p\gamma)$@8.5MeV – SONIC@HORUS



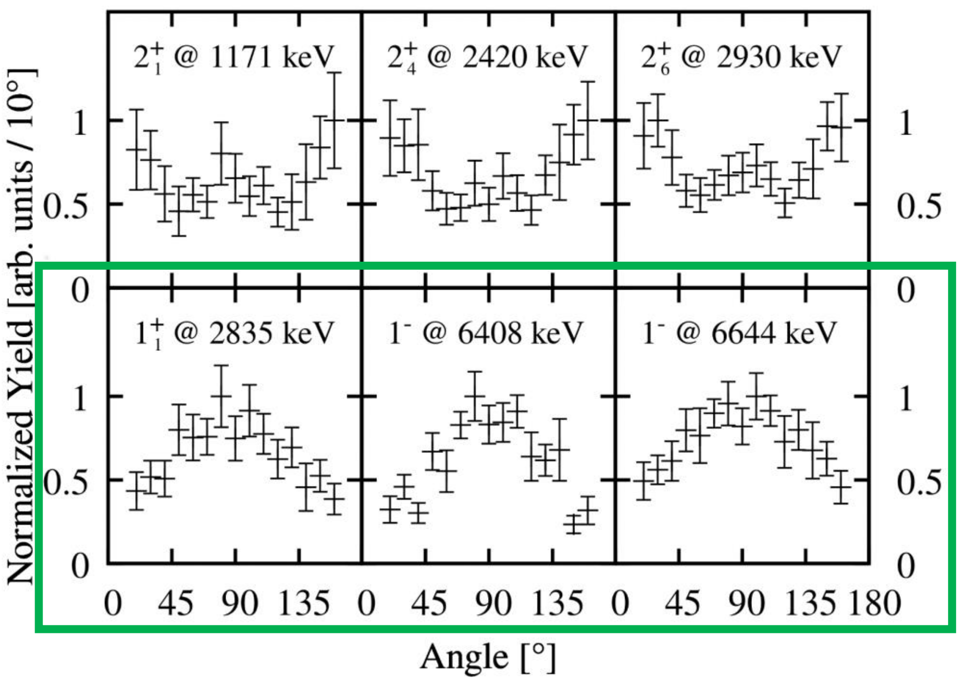
Ground state γ-decay spectrum after Doppler correction and gating on $E_X = E_\gamma$ shows only J=1,2 states

M. Weinert *et al.*, Phys. Rev. Lett. **127** (2021) 242501

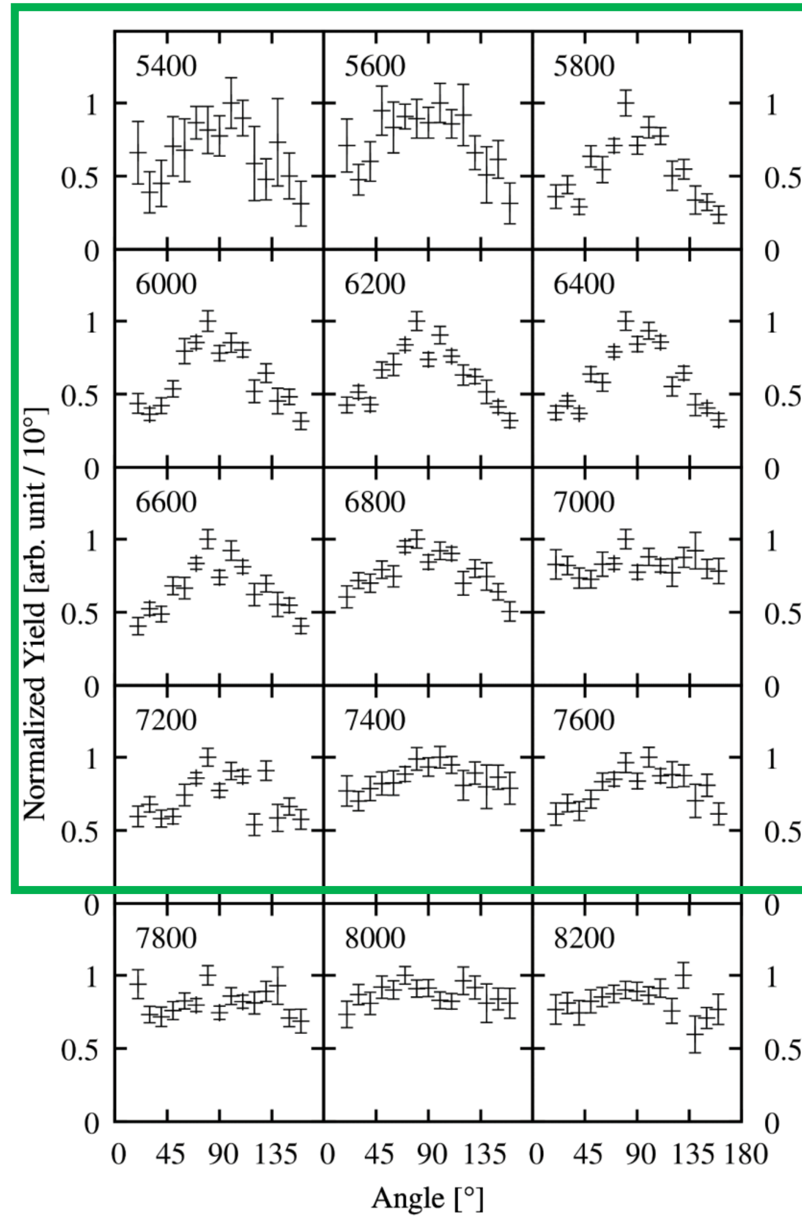
^{119}Sn(d,pγ)@8.5MeV – SONIC@HORUS

γ-ray angular distributions relative to recoil nucleus, a.k.a. the Doppler-angle

Discrete transitions

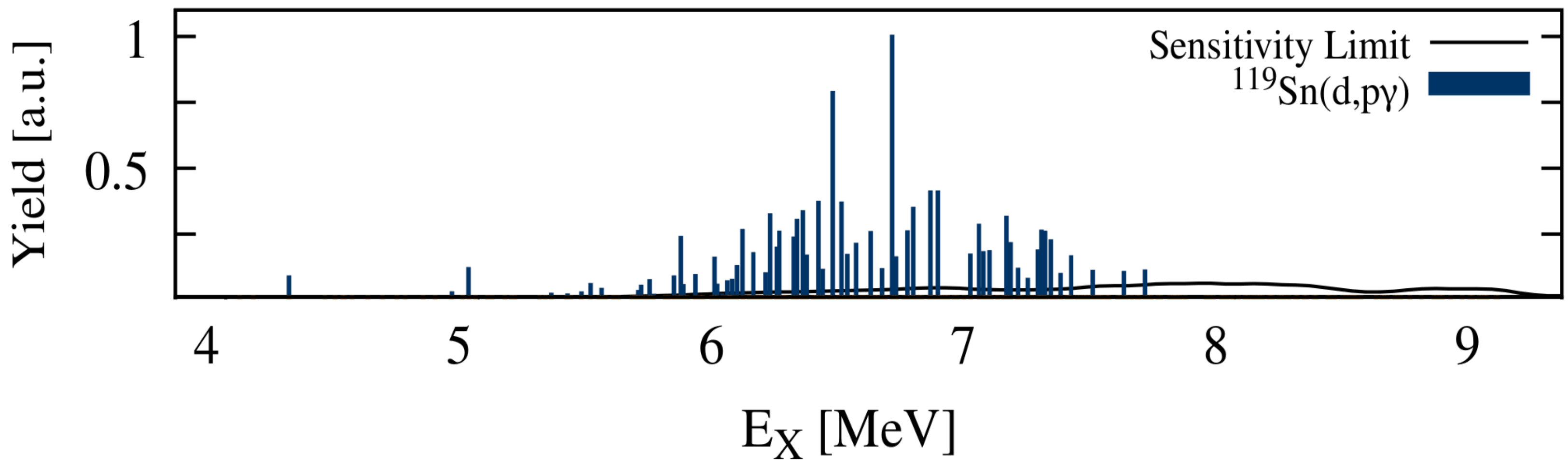


Continuous



M. Weinert *et al.*, Phys. Rev. Lett. **127** (2021) 242501

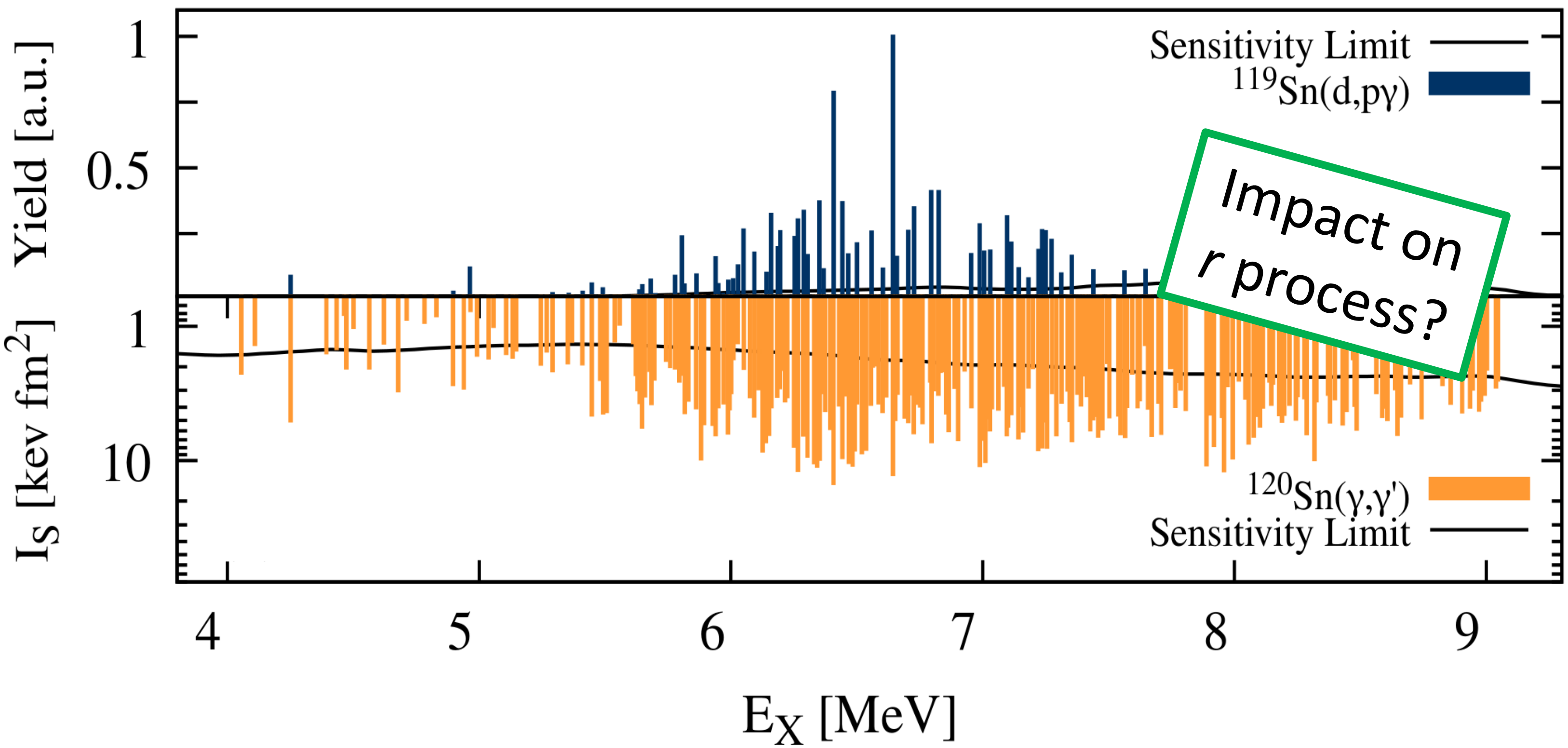
$^{119}Sn(d,p\gamma)$



- 64 of 80 observed lines have matching energy to (γ,γ')
- Angular distributions confirm $\Delta L=1$ dominant up to 7.5 MeV
- From CoulEx: M1 contribution likely negligible

→ All discretely observed lines are $J^{\pi} = 1^{-}$ states !

^{119}Sn(d,pγ) vs ^{120}Sn(γ,γ')



- Strong state-to-state difference between (d,pγ) and (γ,γ')
- Missing strength above 7.5 MeV intriguing…

→ Structure reasons?

NRF data from: M. Müscher *et al.*, PRC **102**, 014317 (2020)

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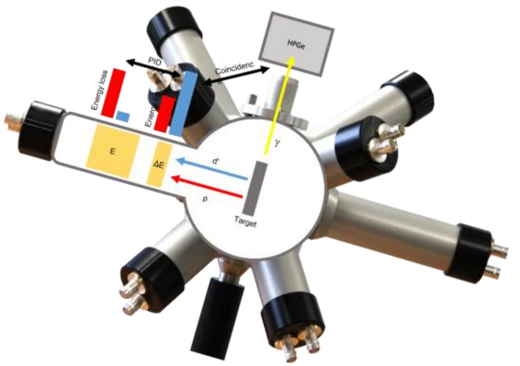

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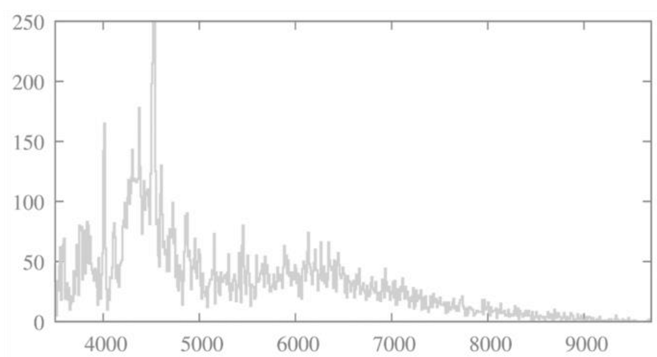
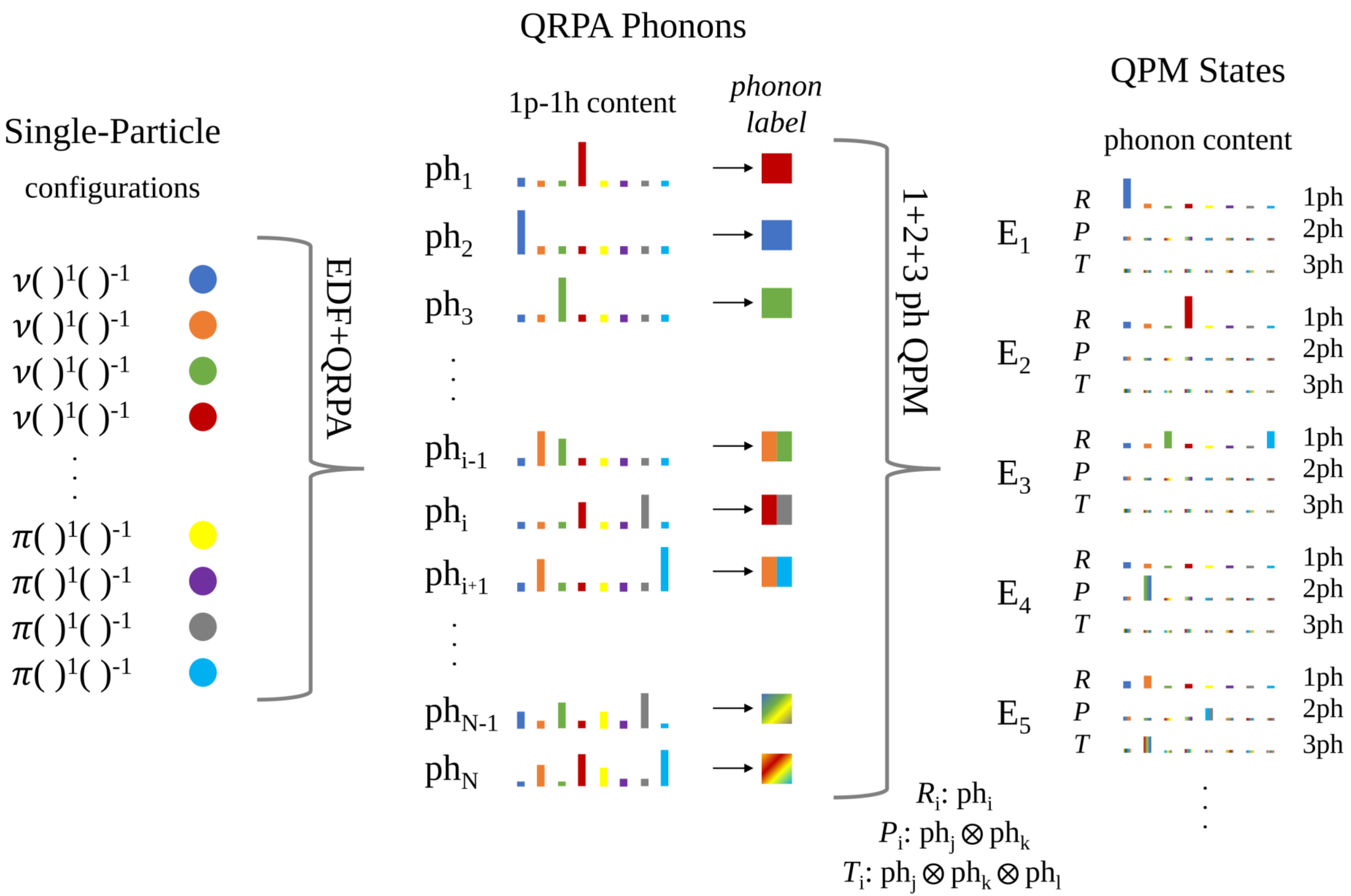


^{119}Sn(d,pγ) – Quasiparticle-Phonon-Model



^{119}Sn(d,pγ) – Quasiparticle-Phonon-Model

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Each QPM state is built from contributions that represent

one phonon

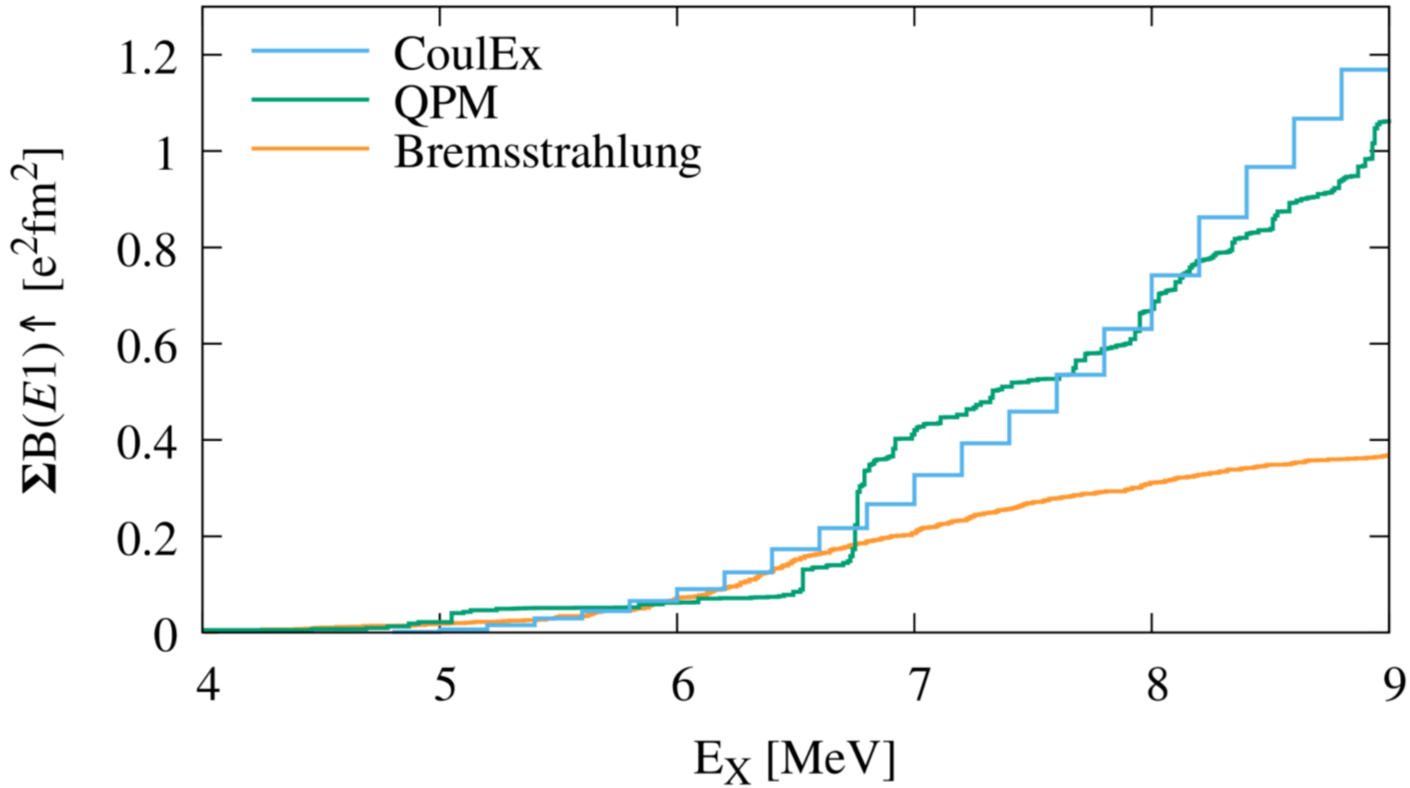
two phonons

three phonons

Theory provided by N. Tsoneva

^{120}Sn QPM – Electromagnetic Response

B(E1)↑ running sums from (γ,γ‘) and (p,p’)-CoulEx



1.169(12) e^2fm^2

1.066 e^2fm^2

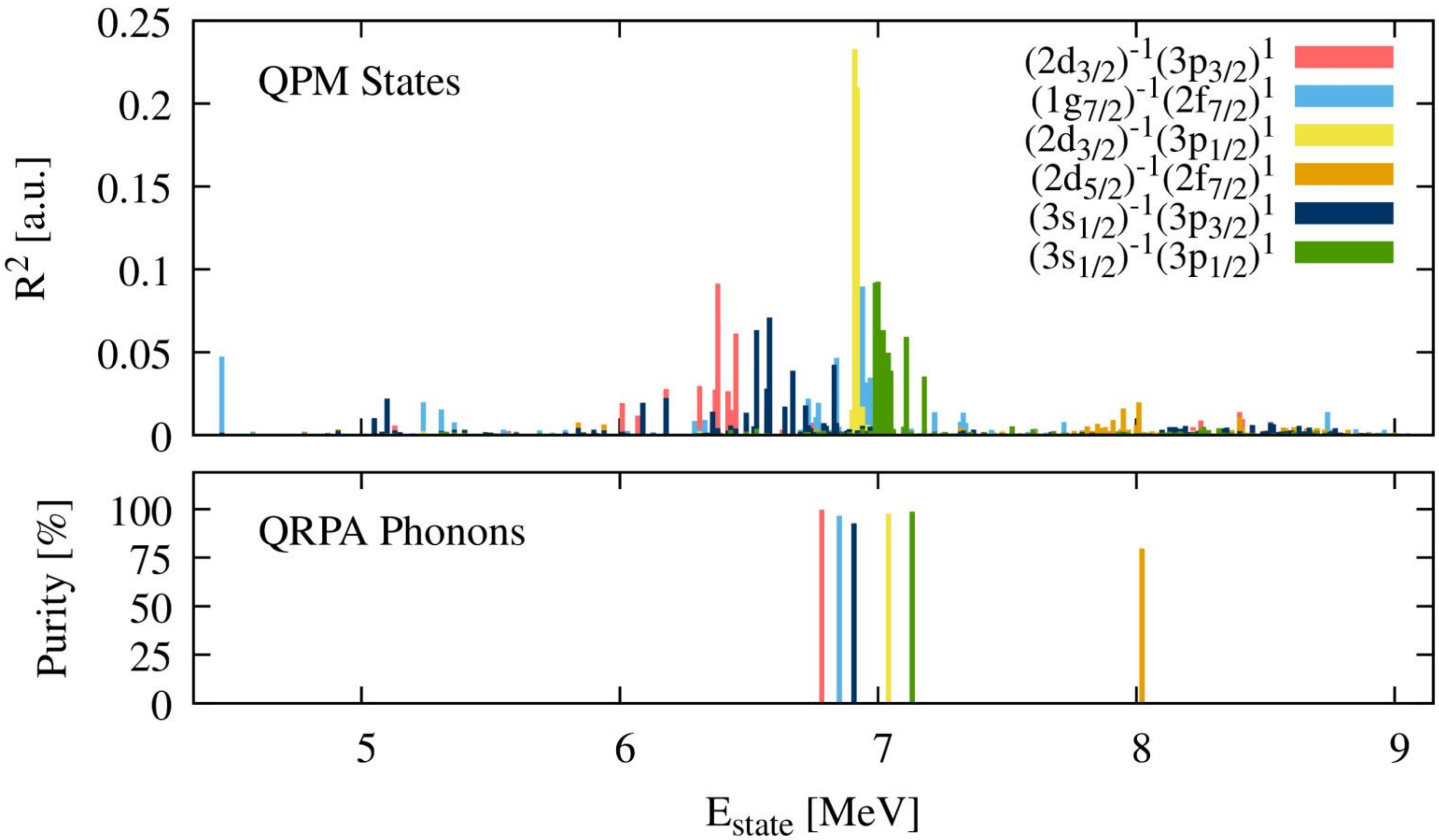
0.369(49) e^2fm^2

QPM reproduces CoulEx data nicely!

CoulEx: A.M. Krumbholz *et al.*, PLB **744** (2015) 7

Bremsstrahlung: M. Müscher *et al.*, PRC **102**, 014317 (2020)

^{120}Sn – QPM One-Phonon Distribution



Distribution of <u>only</u> the <u>dominant</u> 1ph contributions to QPM states

Concentrated around 6-7 MeV

Theory provided by N. Tsoneva

^{119}Sn(d,pγ) – QPM+Reaction Theory

$$\Psi_\nu = \Bigg\{ \sum_i R_i(\nu)\, Q^+_{1Mi}$$

$$+ \sum_{\substack{\lambda_1 i_1 \\ \lambda_2 i_2}} P^{\lambda_q i_1}_{\lambda_2 i_2}(\nu) \left[Q^+_{\lambda_1 \mu_1 i_1} \times Q^+_{\lambda_2 \mu_2 i_2} \right]_{1M}$$

$$+ \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2 \\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(\nu) \Big[\left[Q^+_{\lambda_1 \mu_1 i_1} \times Q^+_{\lambda_2 \mu_2 i_2} \right]_{IK}$$

$$\times Q^+_{\lambda_3 \mu_3 i_3} \Big]_{1M} \Bigg\} \Psi_0$$

Each QPM state is built from contributions that represent

one phonon

two phonons

three phonons

(d,p) reaction selects only one phonon contributions that are accessible from the ground state of ^{119}Sn!

$$\frac{d\sigma_\nu}{d\Omega}(\theta) = \frac{\mu_i \mu_f}{(2\pi\hbar^2)^2} \frac{k_f}{k_i} \times$$

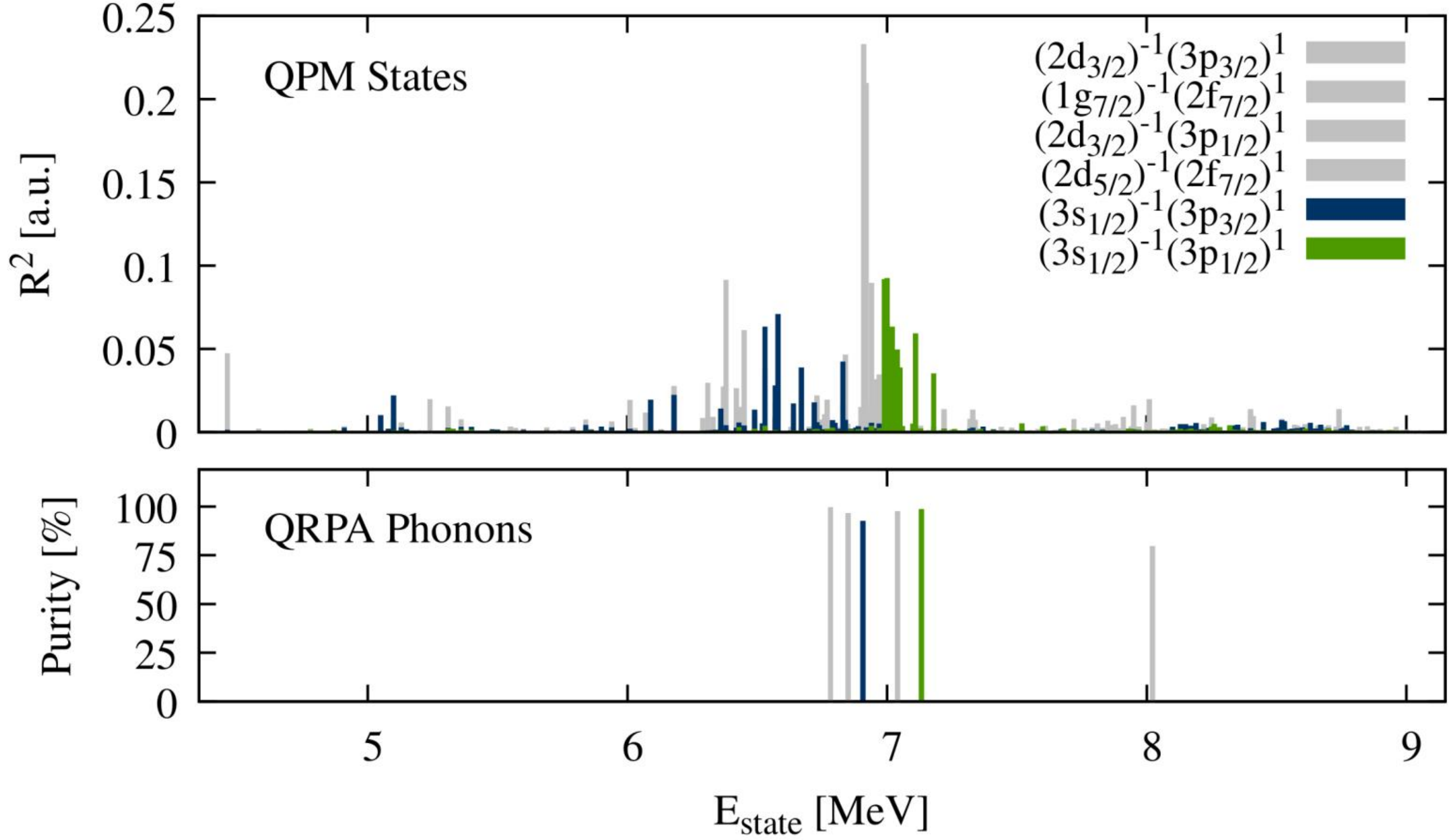
$$\Big| u_{3p_{1/2}} R_{3p_{1/2}}(\nu)\, \psi^{3\,p_{1/2}}_{\frac{1}{2}\,\frac{1}{2}}\, \mathcal{T}_{p_{1/2}}(\theta)$$

$$+ u_{3p_{3/2}} R_{3p_{3/2}}(\nu)\, \psi^{3\,p_{3/2}}_{\frac{1}{2}\,\frac{3}{2}}\, \mathcal{T}_{p_{3/2}}(\theta) \Big|^2$$

Theory provided by N. Tsoneva and G. Potel

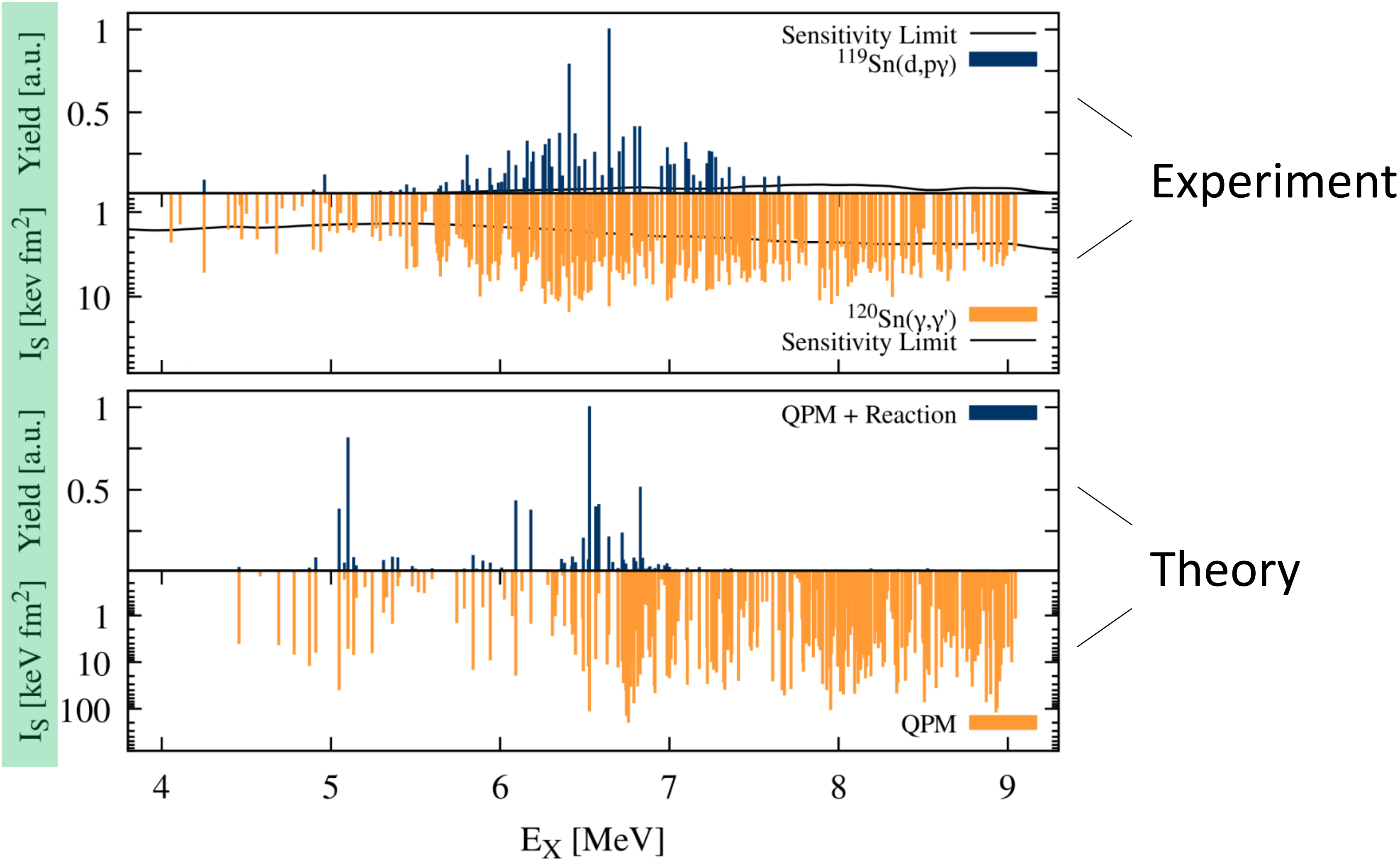
^{120}Sn – QPM One-Phonon Distribution

QPM 1ph contributions relevant for ^{119}Sn(d,p)



Theory provided by N. Tsoneva

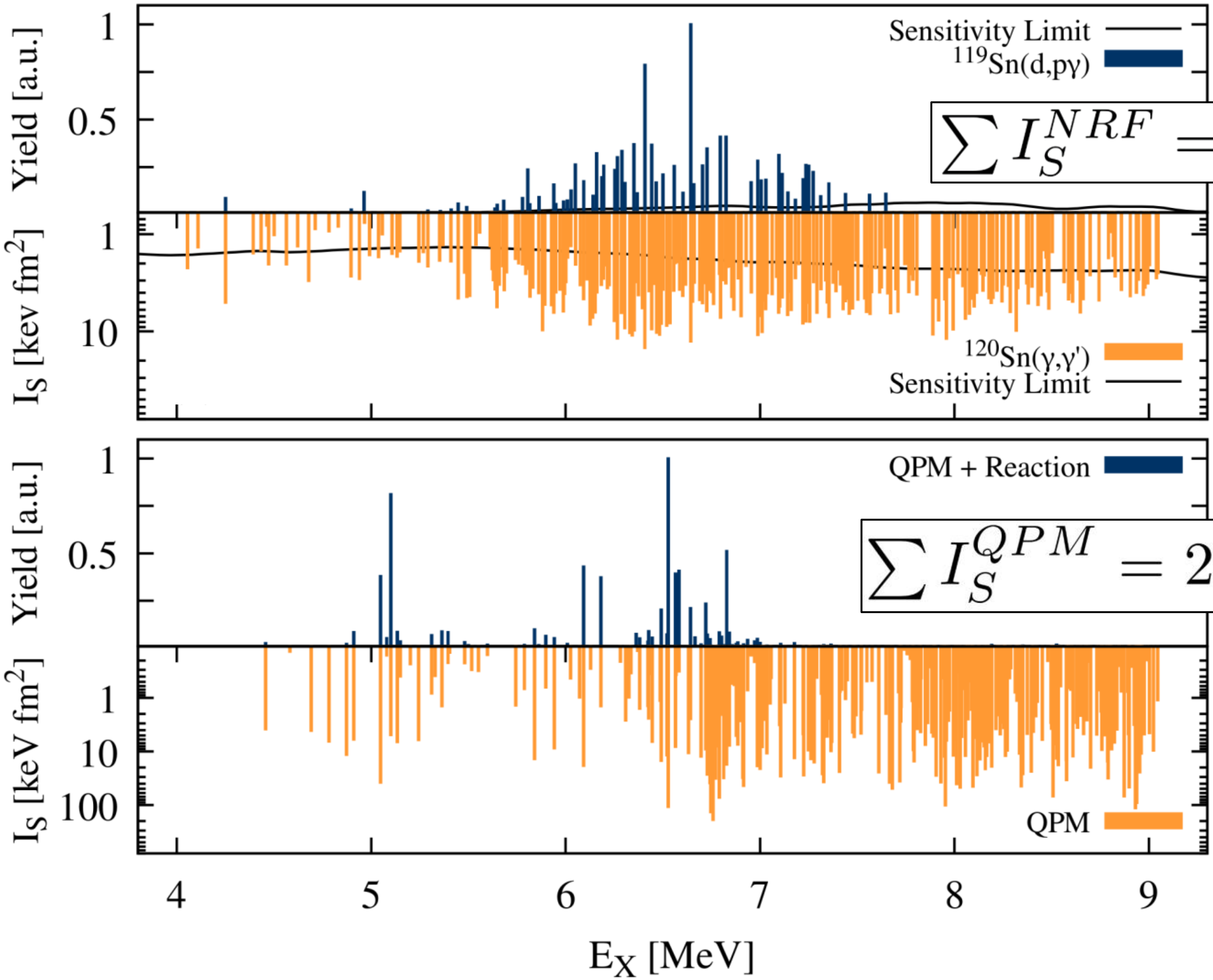
Experiment and Theory – Apples and Apples



Theory provided by N. Tsoneva and G. Potel

M. Weinert *et al.*, Phys. Rev. Lett. **127** (2021) 242501

Experiment and Theory – Apples and Apples



$$\sum I_S^{NRF} = 337(21)\,\mathrm{keV\,fm}^2$$

for states seen in both experiments

$$\sum I_S^{QPM} = 243 \text{ - } 360\,\mathrm{keV\,fm}^2$$

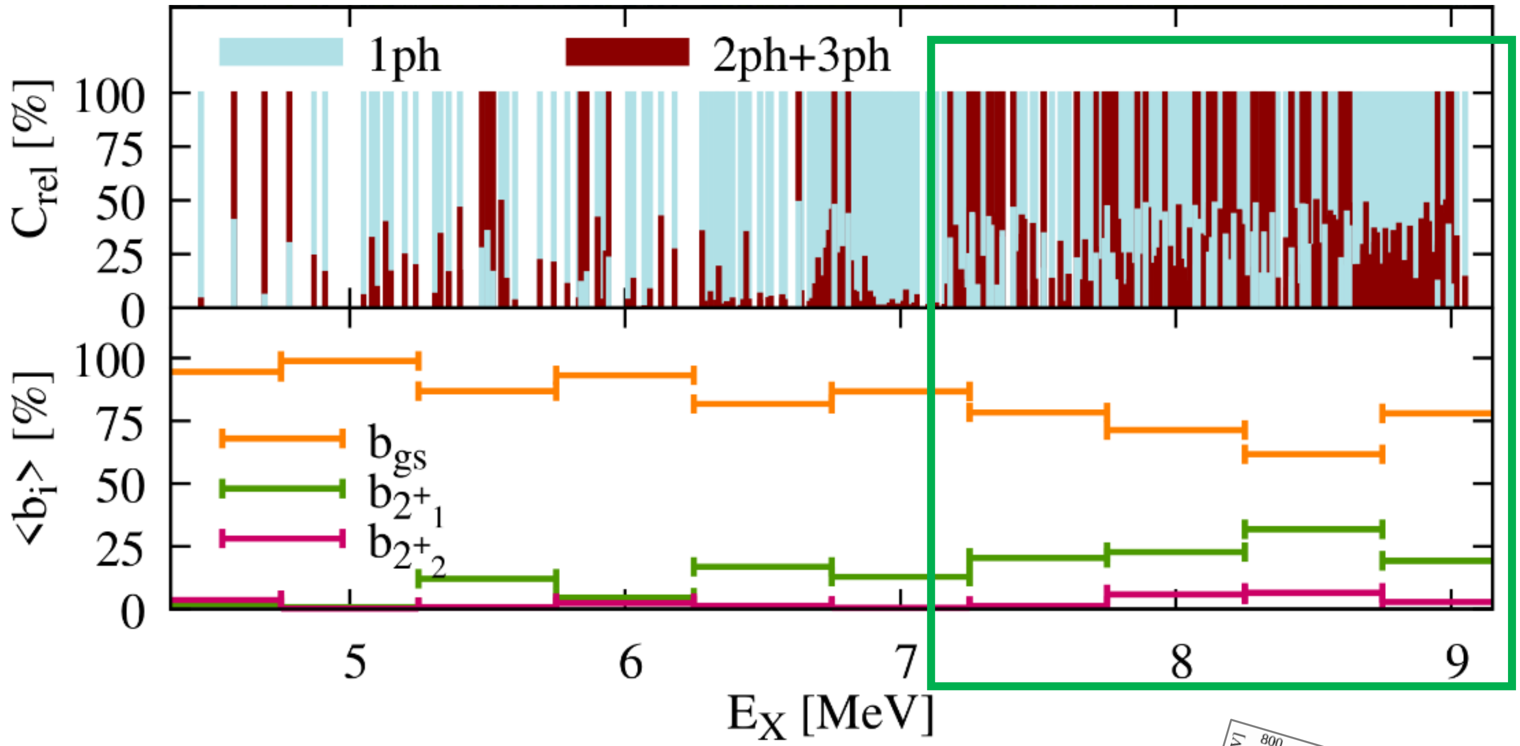
for states above experimental sensitivity limit of 1.0 - 0.5 %

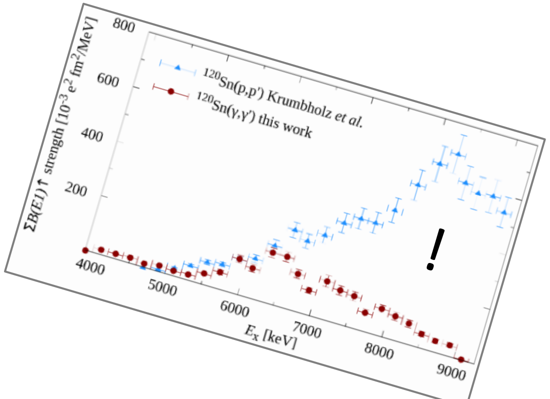
Theory provided by N. Tsoneva and G. Potel

M. Weinert *et al.*, Phys. Rev. Lett. **127** (2021) 242501

QPM – Detailed Access to Wave Functions

$C_{rel}^{1ph} = \sum R^2 / \sum (R^2 + P^2 + T^2)$ $C_{rel}^{2ph+3ph} = \sum (P^2 + T^2) / \sum (R^2 + P^2 + T^2)$



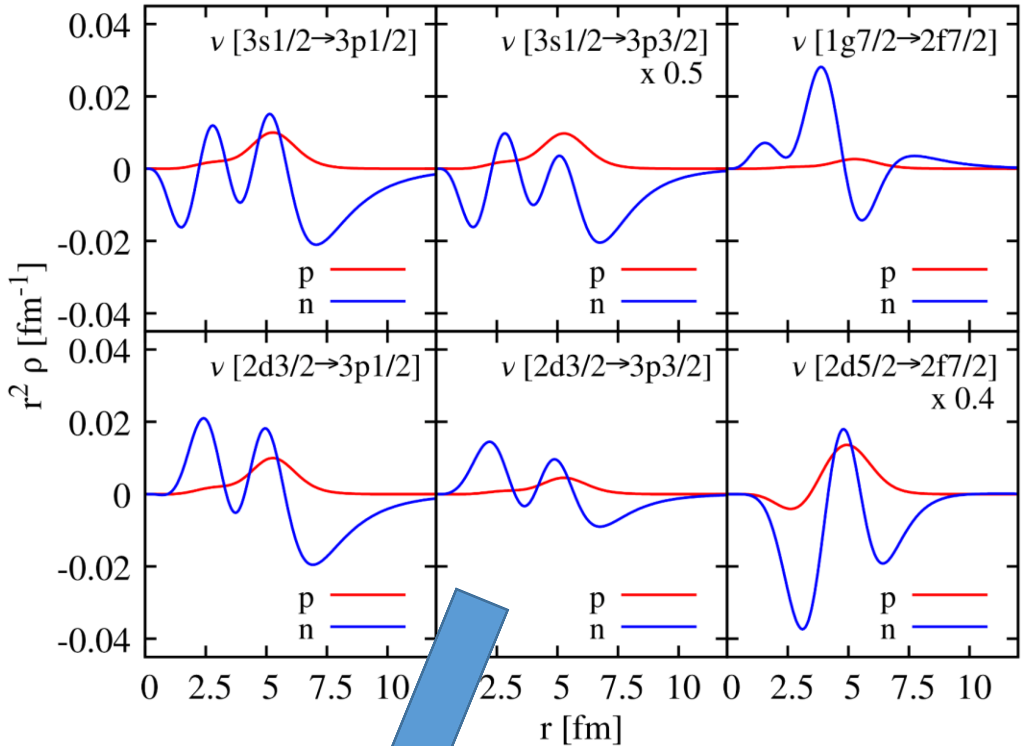


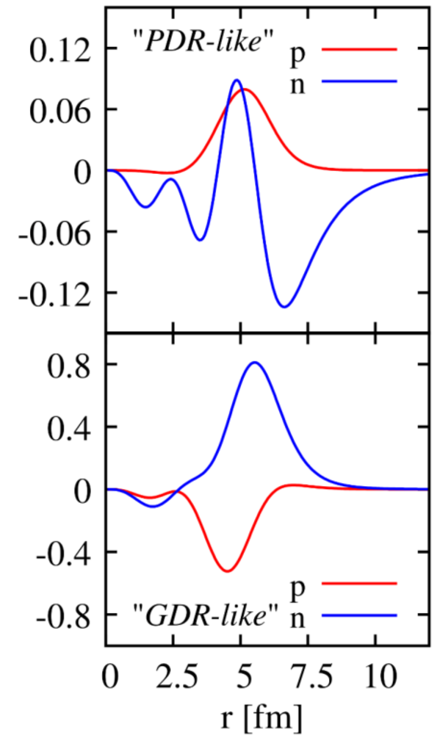
Single-particle character and increasing complexity at the right excitation energies predicted by the QPM!

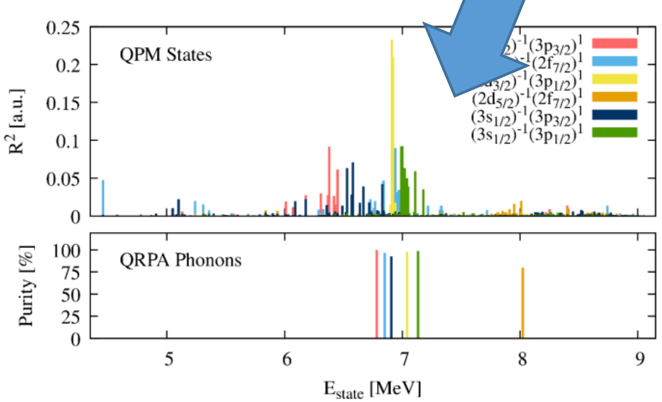
Theory provided by N. Tsoneva

M. Weinert *et al.*, Phys. Rev. Lett. **127** (2021) 242501

QPM Transition Densities





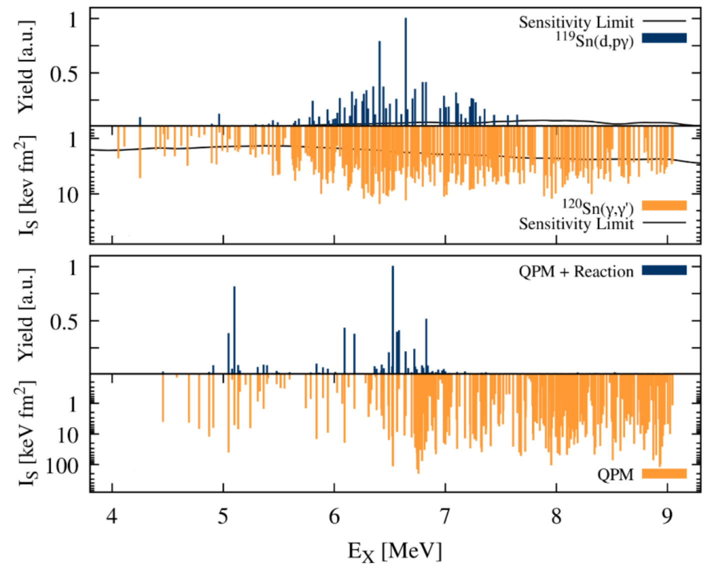


1ph TRD show characteristic behavior

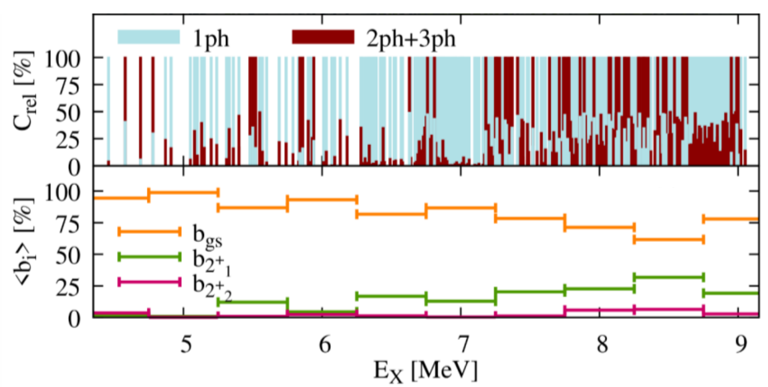
Connection between 1p-1h structure and *neutron skin* oscillation?

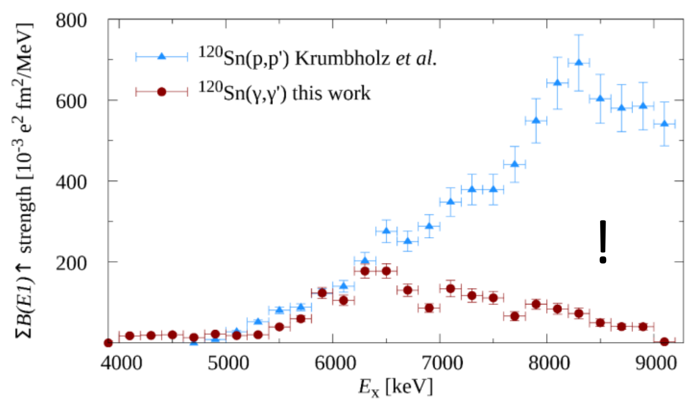
What have we learned so far?

$$\Psi_\nu = \Big\{ \sum_i R_i(\nu)\, Q^+_{1Mi} + \sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} P^{\lambda_q i_1}_{\lambda_2 i_2}(\nu) \left[Q^+_{\lambda_1\mu_1 i_1} \times Q^+_{\lambda_2\mu_2 i_2}\right]_{1M} + \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2\\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(\nu) \Big[\left[Q^+_{\lambda_1\mu_1 i_1} \times Q^+_{\lambda_2\mu_2 i_2}\right]_{IK} \times Q^+_{\lambda_3\mu_3 i_3}\Big]_{1M} \Big\} \Psi_0$$



SONIC@HORUS

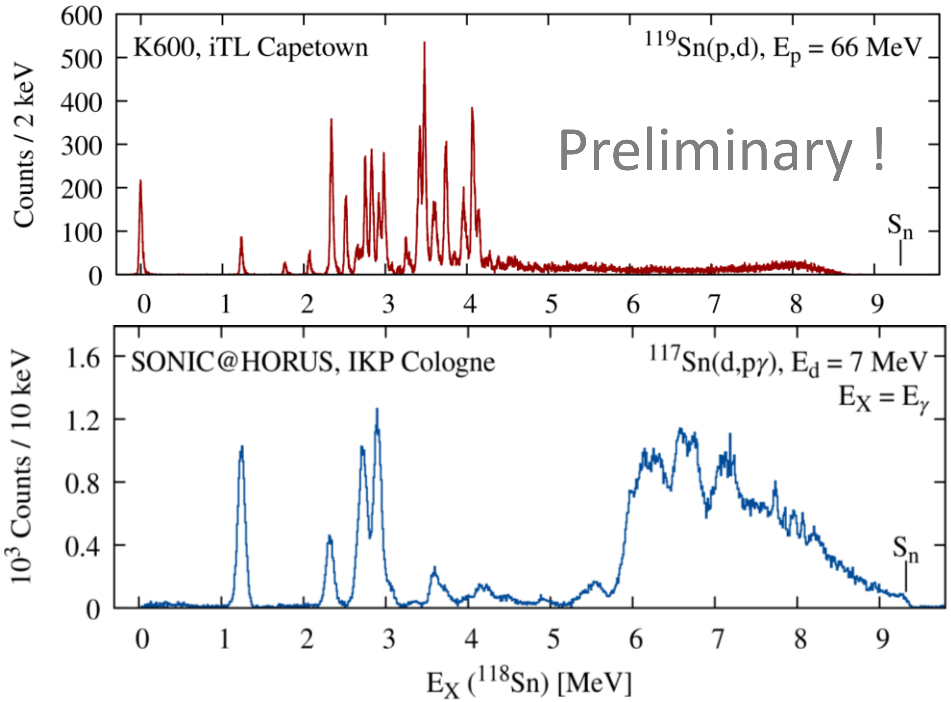




What's next?

Further (d,pγ) studies:

- ^{115,117}Sn(d,pγ) SONIC@HORUS
- ^{118}Sn(γ,γ') NRF at γ-ELBE
- ^{61}Ni(d,pγ) at ROSPHERE, IFIN-HH

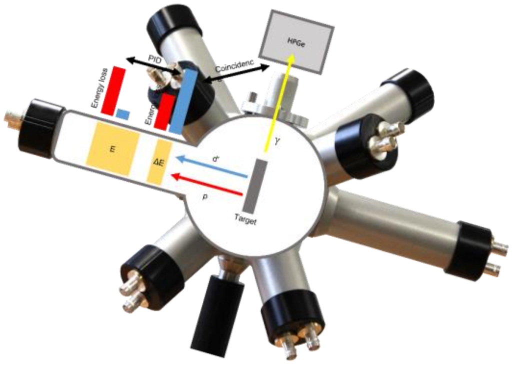


Let's try this:

^{119}Sn(p,dγ)^{118}Sn with BaGeL+K600 at iThemba Labs, Capetown

Overview

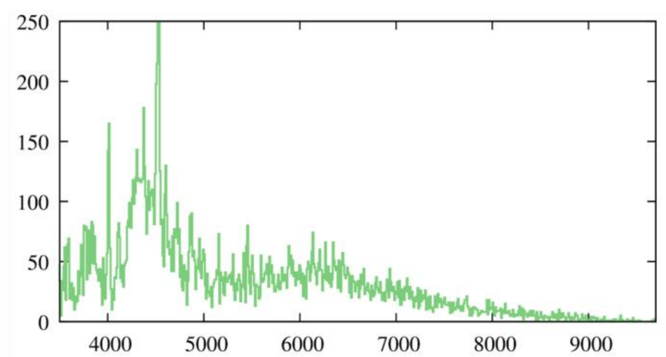
- A short history of complementary experiments on the LEDR



- Microscopic structure:
  - ^{119}Sn(d,pγ) and ^{120}Sn(γ,γ‘)
  - Quasiparticle-Phonon-Model
  - Comparing apples to apples

$$\Psi_\nu = \Big\{ \sum_i R_i(\nu)\, Q^+_{1Mi} + \sum_{\substack{\lambda_1 i_1\\ \lambda_2 i_2}} P^{\lambda_1 i_1}_{\lambda_2 i_2}(\nu)\left[Q^+_{\lambda_1\mu_1 i_1}\times Q^+_{\lambda_2\mu_2 i_2}\right]_{1M} + \sum_{\substack{\lambda_1 i_1 \lambda_2 i_2\\ \lambda_3 i_3 I}} T^{\lambda_1 i_1 \lambda_2 i_2 I}_{\lambda_3 i_3}(\nu)\Big[\left[Q^+_{\lambda_1\mu_1 i_1}\times Q^+_{\lambda_2\mu_2 i_2}\right]_{IK} \times Q^+_{\lambda_3\mu_3 i_3}\Big]_{1M} \Big\}\Psi_0$$

- **Isoscalar response:**
  - ^{120}Sn(α,α’γ) at E_α= 130 MeV



CAGRA+GR Campaign @ RCNP, Osaka

GrandRaiden Spectrometer

- High energy resolution under **forward angles** incl. 0°

CAGRA Clover array

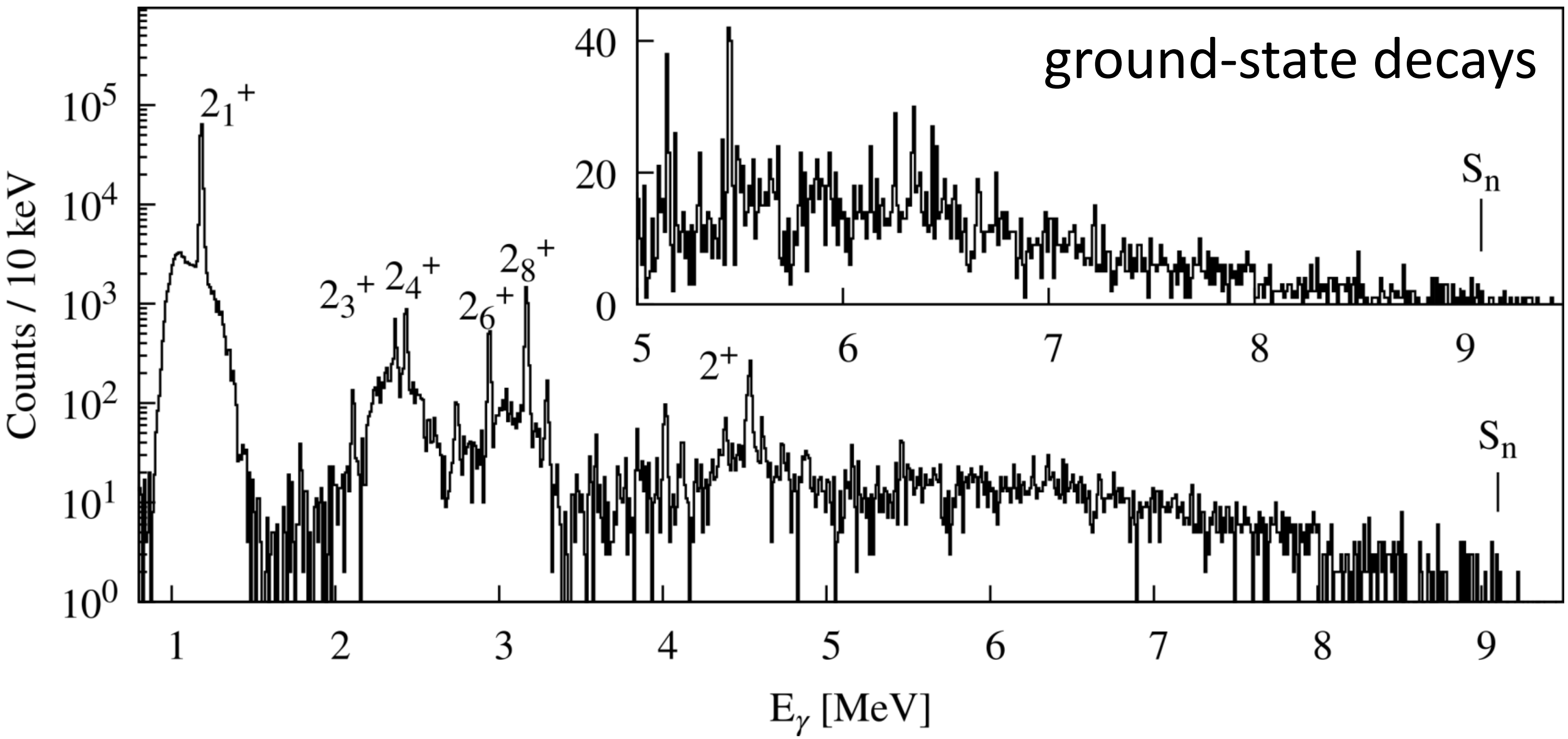
- 12 clover type detectors + BGO shields
- 4 large volume $LaBr_3$ detectors

$^{120}Sn(\alpha,\alpha'\gamma)$
E_α = 130 MeV
θ_α = 4.5°

Over **1100 hours** of beam time!

$^{120}Sn(\alpha,\alpha'\gamma)$ – Ground-State Decay Spectrum

$^{120}Sn(\alpha,\alpha'\gamma)$ at E_α = 130 MeV, θ_α = 4.5°

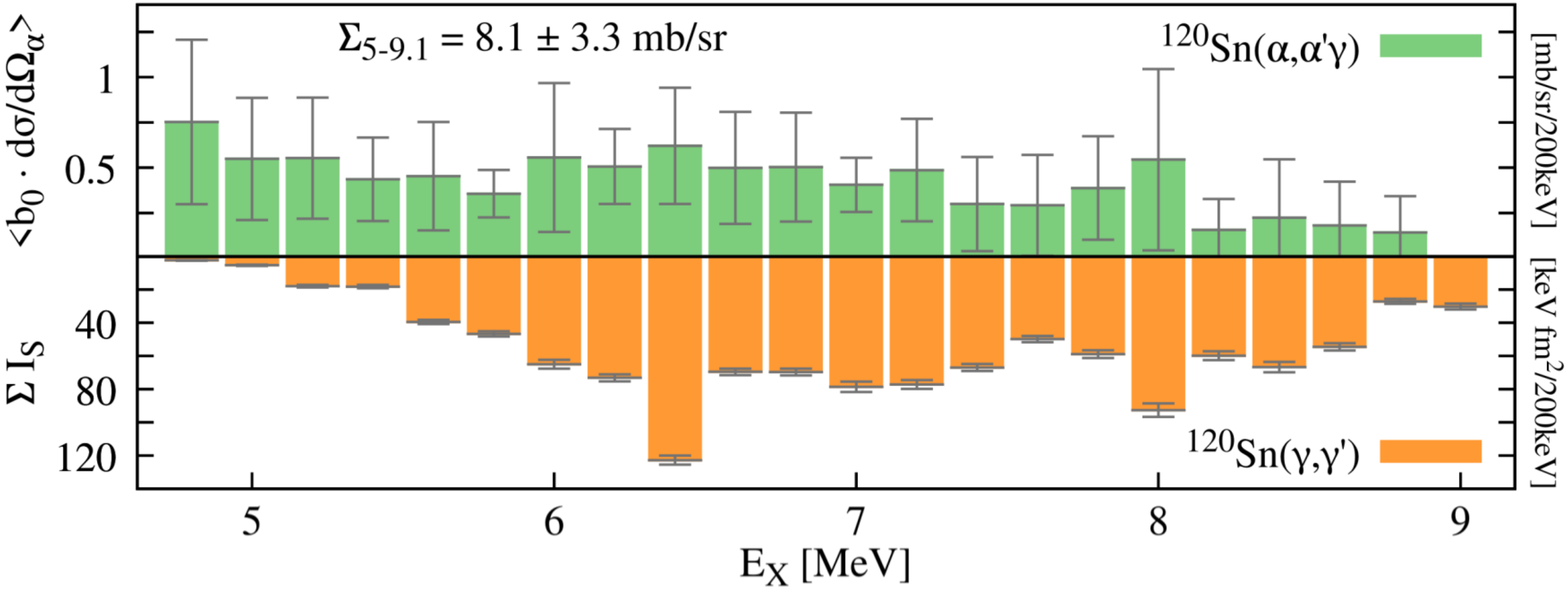


Low statistics above 5 MeV, but above background

Isoscalar response evident!

^{120}Sn(α,α'γ) vs ^{120}Sn(γ,γ')

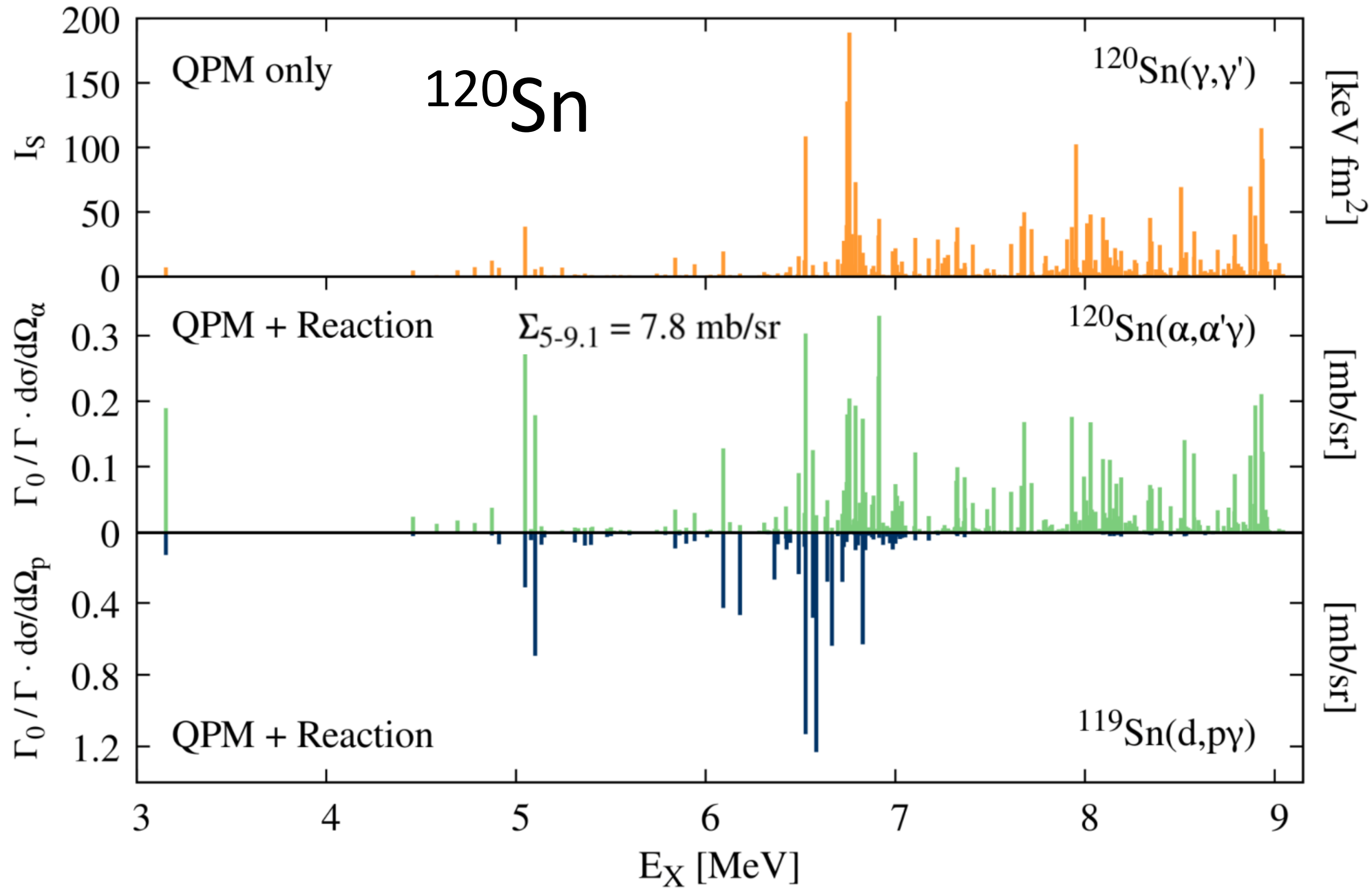
Integrated cross sections for excitation and ground-state decay



Mostly flat isoscalar response, large uncertainties

Summed cross section approx. 5 times lower than ^{124}Sn(α,α'γ)!

State-to-State QPM+Reaction Predictions



N. Tsoneva

E. Lanza

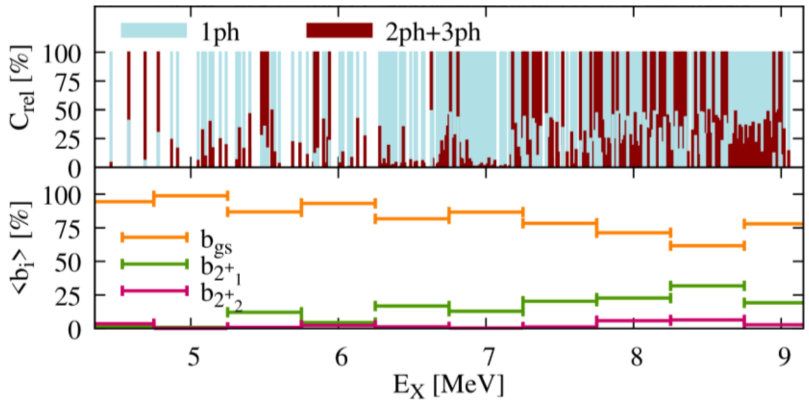
G. Potel

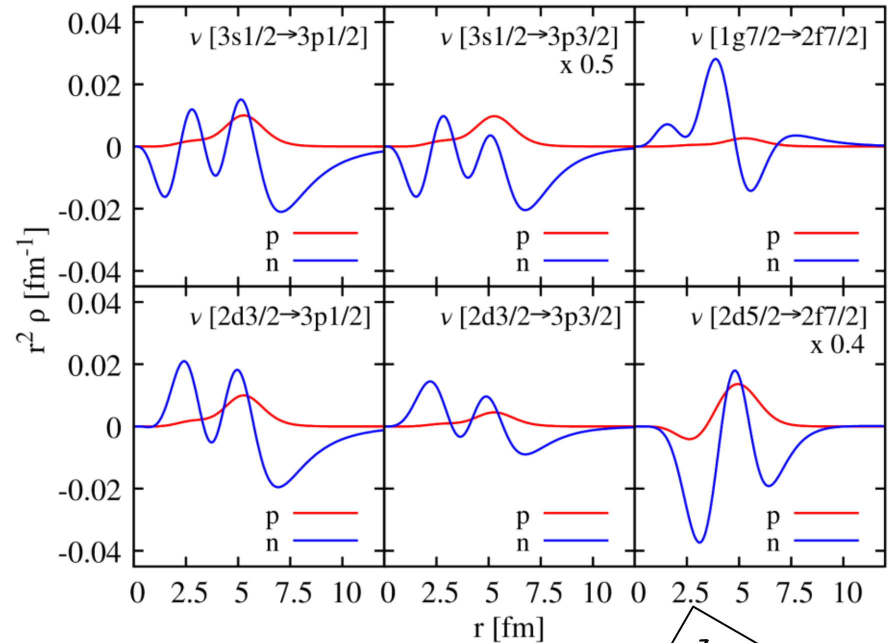
No pronounced difference between (α,α'γ) and (γ,γ') suggested

Total isoscalar response reproduced from only the 1ph TRDs!

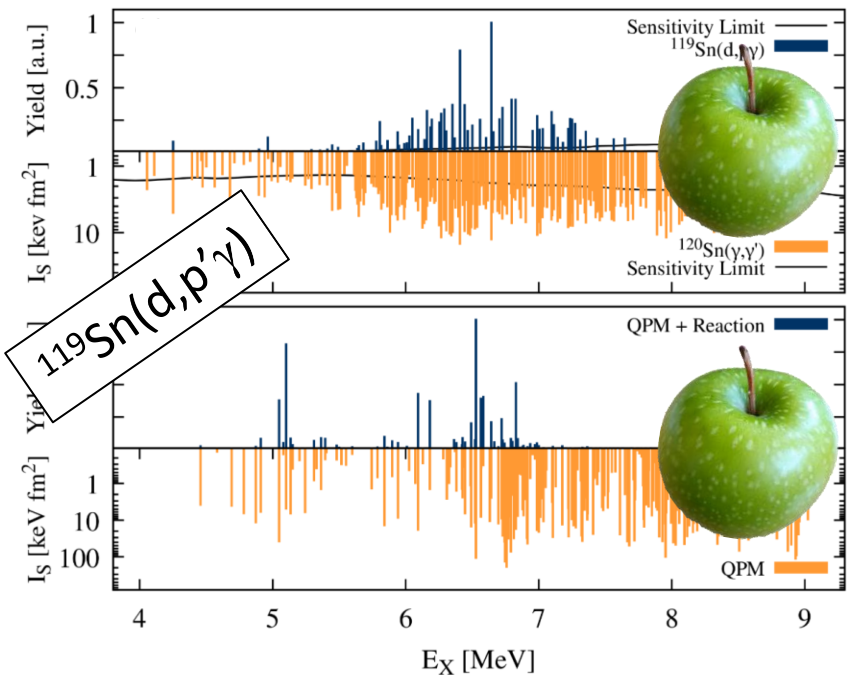
→ How does the (this) QPM render ^{124}Sn(α,α'γ)?

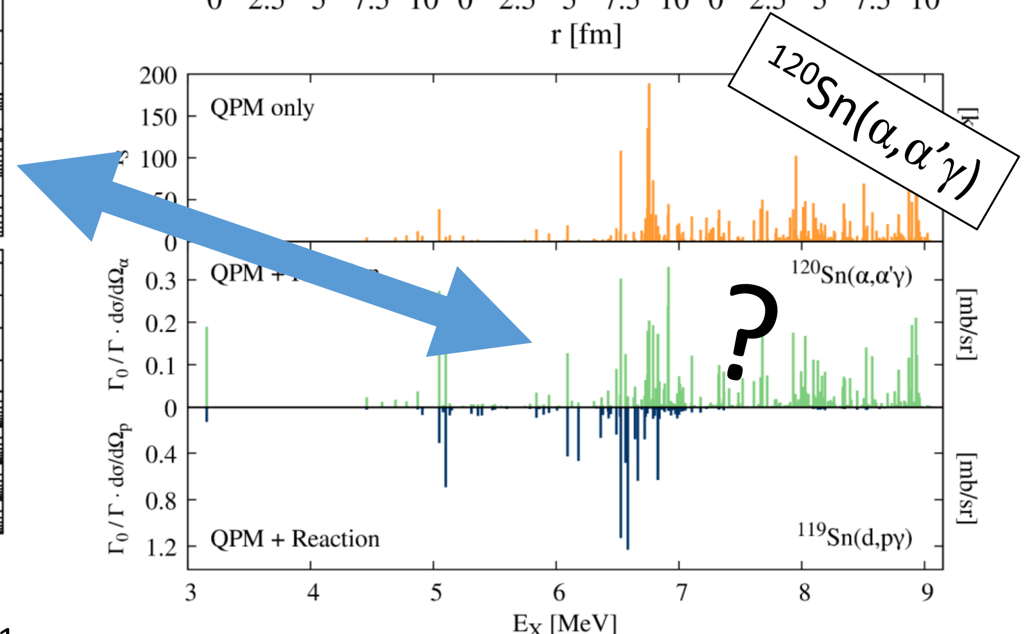
Summary





SONIC@HORUS





M. Weinert *et al.*, Phys. Rev. Lett. **127** (2021) 242501