# Dipole Strength Distributions from HIGS Experiments

TECHNISCHE UNIVERSITÄT DARMSTADT


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U.S. DEPARTMENT OF ENERGY
Office of Science

HIC for FAIR
Helmholtz International Center

Deutsche Forschungsgemeinschaft DFG

SFB634

# Outlook

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**Nuclear Resonance Fluorescence:**

**DHIPS at the S-DALINAC – Bremsstrahlung Photon Beams**

**HIGS at TUNL – Compton-Backscattering Photon Beams**

**Example of Recent Structure Program:**

**Investigation of the potential 0ν2β Pair $^{76}$Ge/Se**

**The Pygmy Dipole Resonance Region**

**Do we see enhanced E1 strength at low energies?**

# Dipole Physics

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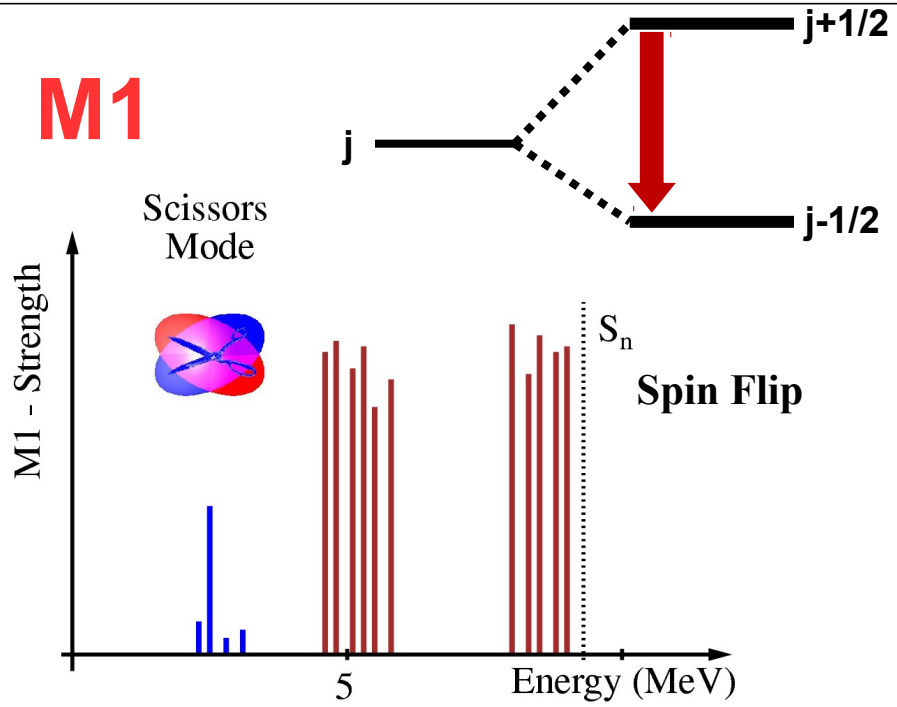
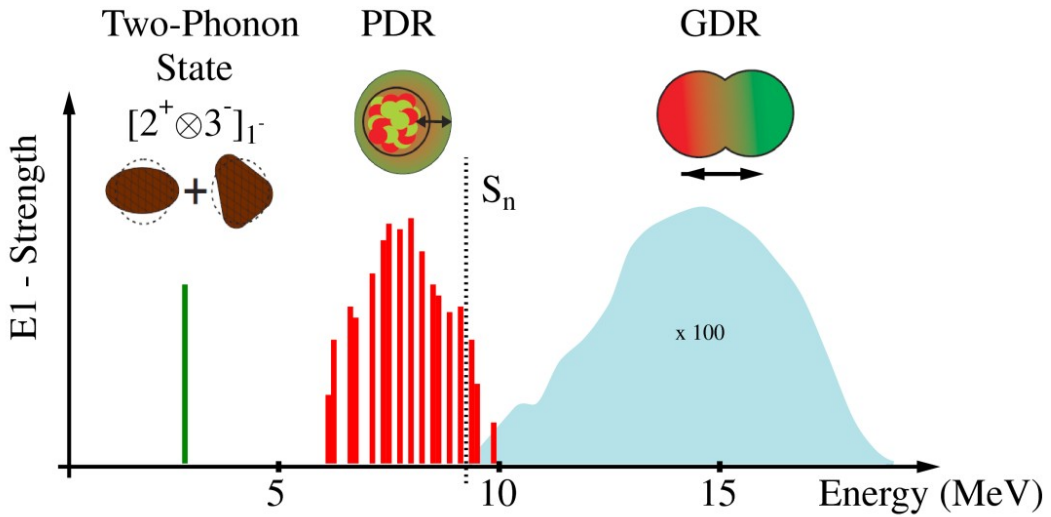
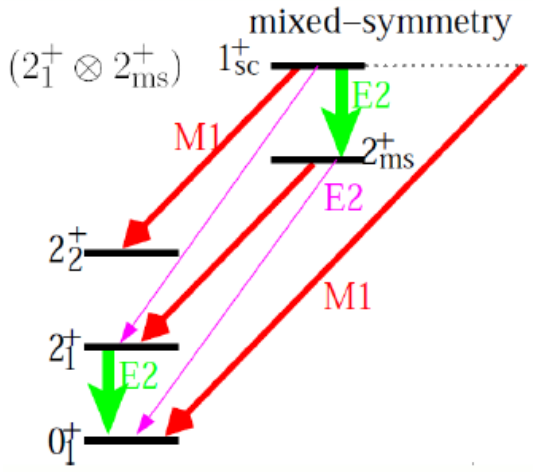
**M1**

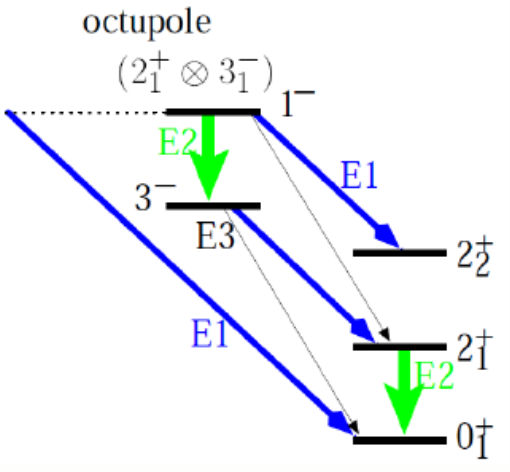



**E1**

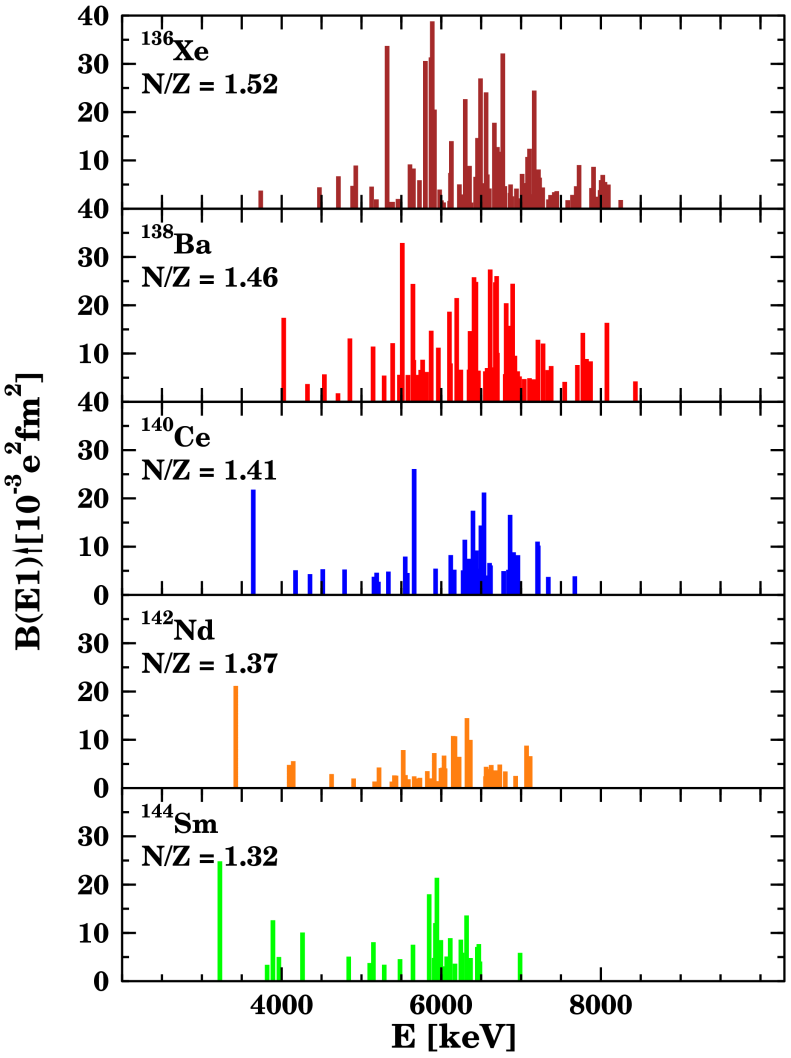



2-Phonon
J=1 States

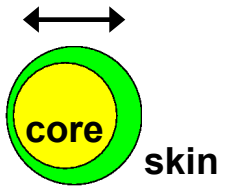


# Systematics of the PDR




- **Concentration around 5-7 MeV**
- **Strong fragmentation**
- **Summed strength: Scaling with N/Z ?**

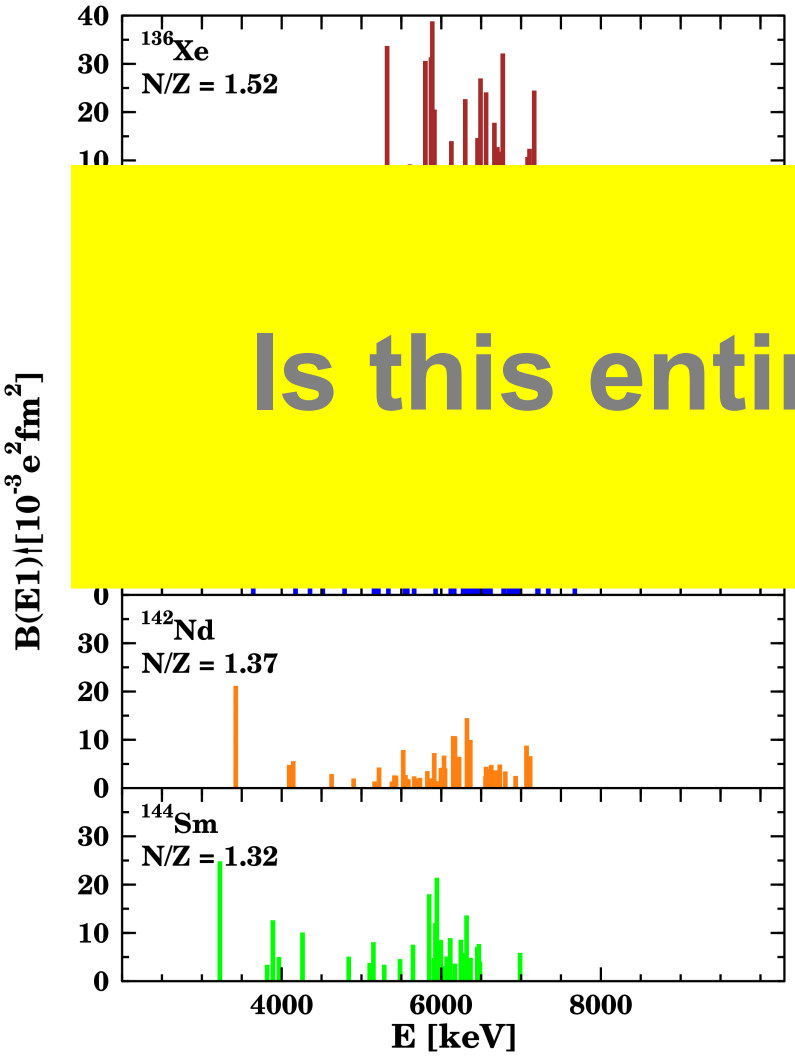




*A. Zilges et al., PLB **542**, 43 (2002).*
*D. Savran et al., PRC **84**, 024326 (2011).*
*U. Kneissl et al., J.Phys.G **32**, R217 (2006).*


**And what about deformation?**
**Most systematics in semi-magic isotopes.**

# Systematics of the PDR




- **Concentration around 5-7 MeV**

**Is this entirely E1 strength ?**



*A. Zilges et al., PLB **542**, 43 (2002).*
*D. Savran et al., PRC **84**, 024326 (2011).*
*U. Kneissl et al., J.Phys.G **32**, R217 (2006).*


**And what about deformation?**
**Most systematics in semi-magic isotopes.**

# Investigation of $^{76}$Ge/Se

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- Isobars with quite different deformation values:
  $\beta(^{76}Ge) = 0.26$ ; $\beta(^{76}Se) = 0.31$
- Until this work only *one* J=1 state known in $^{76}$Se
- Previous experiment on $^{76}$Ge (Jung et al., 1995) had low sensitivity
- 0ν2β partners: could E1/M1 dipole strength constrain theory?

(For PDR: don't know yet, theory (QRPA/QPM) is needed, has to handle deformation)

Lower-lying states: yes, recent example shows potential impact on 0ν2β nuclear matrix elements

J. Beller et al., PRL 111, 172501 (2013)

# Nuclear Resonance Fluorescence

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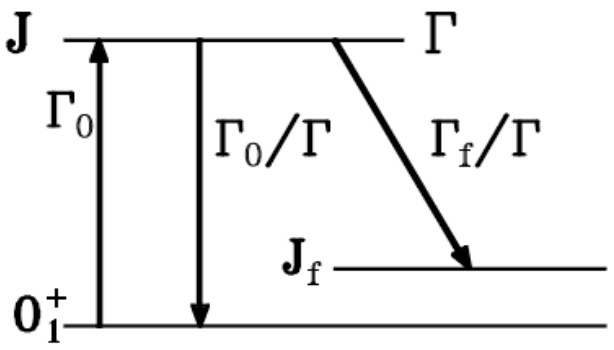
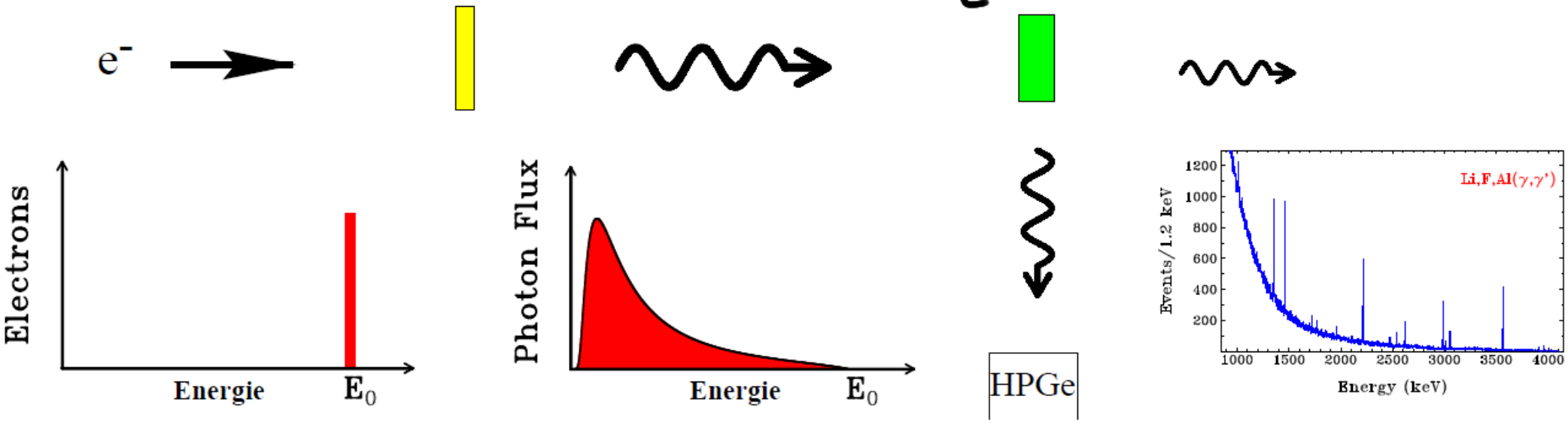
$\Pi\lambda$ −strengths

$\Delta J = 1,2$

high energy resolution



# Nuclear Resonance Fluorescence

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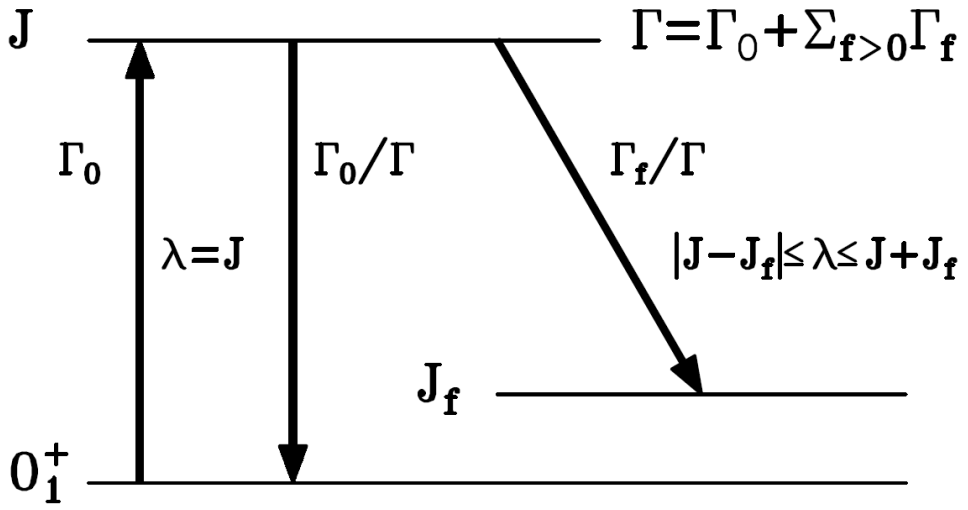
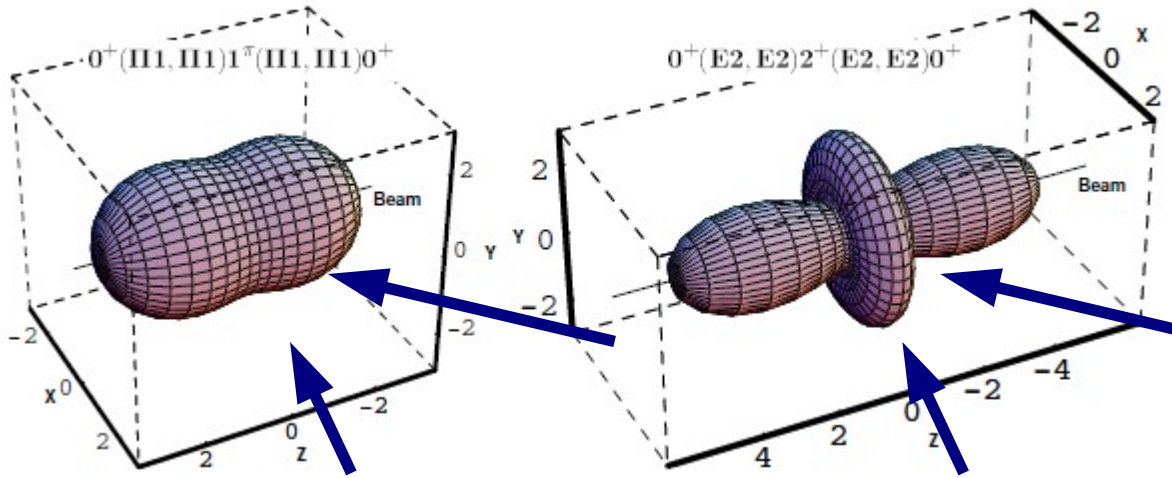
Separation threshold




Detectors

Observables

- Excitation Energy $E_r$
- Spin $J$
- Parity $\pi$
- Decay Energies $E_\gamma$
- Partial Widths $\Gamma_i/\Gamma_0$
- Multipole Mixing $\delta$
- Decay Strengths $B(\pi\lambda)$
- Level Width $\Gamma$ (eV)
- Lifetime $\tau$ (ps – as)

x-sections

# S-DALINAC

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# Darmstadt High-Intensity Photon Setup (DHIPS)

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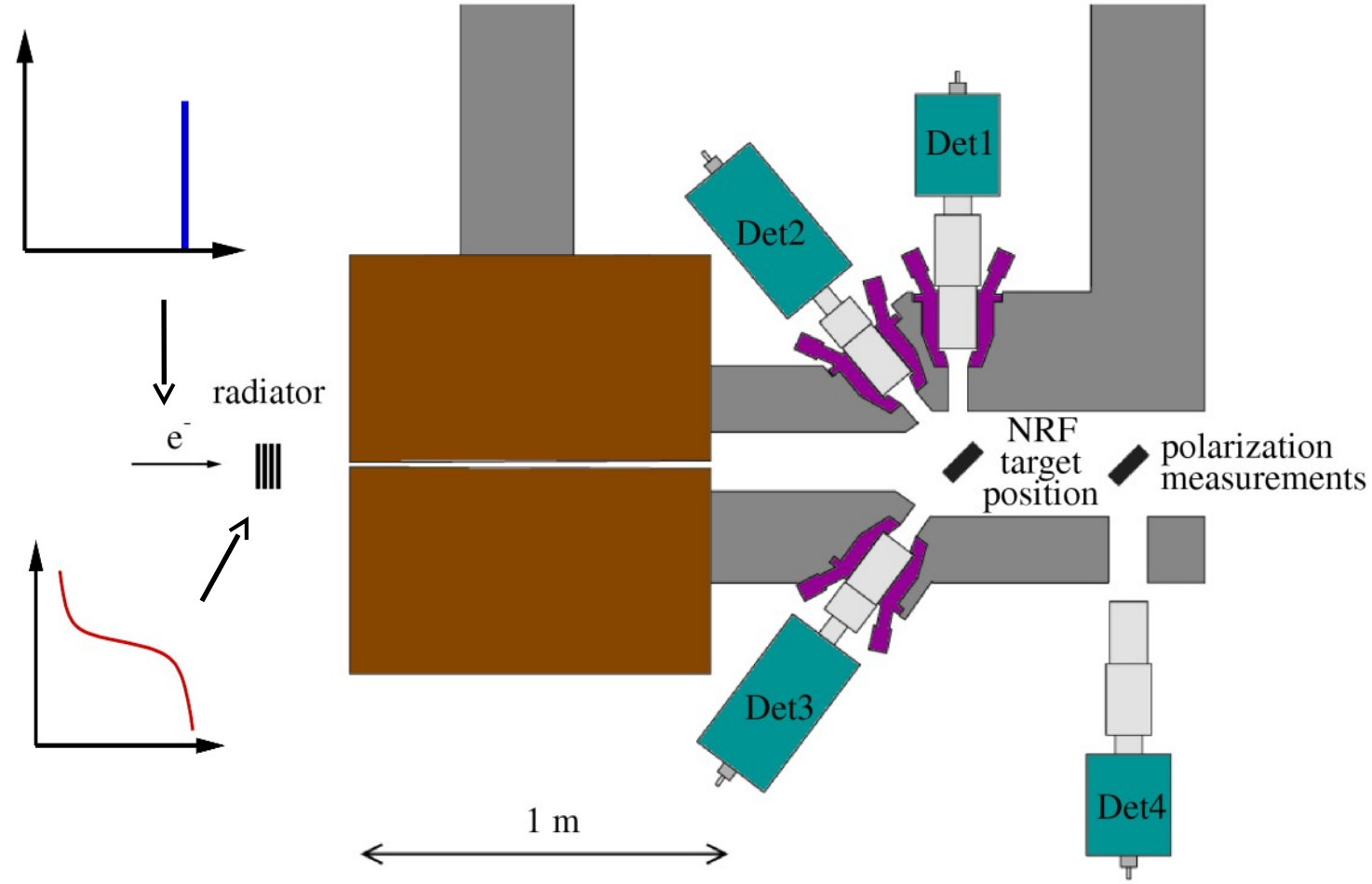


Adapted from K. Son

**K. Sonnabend et al., NIM A 640, 6 (2011)**

# Darmstadt High-Intensity Photon Setup (DHIPS)

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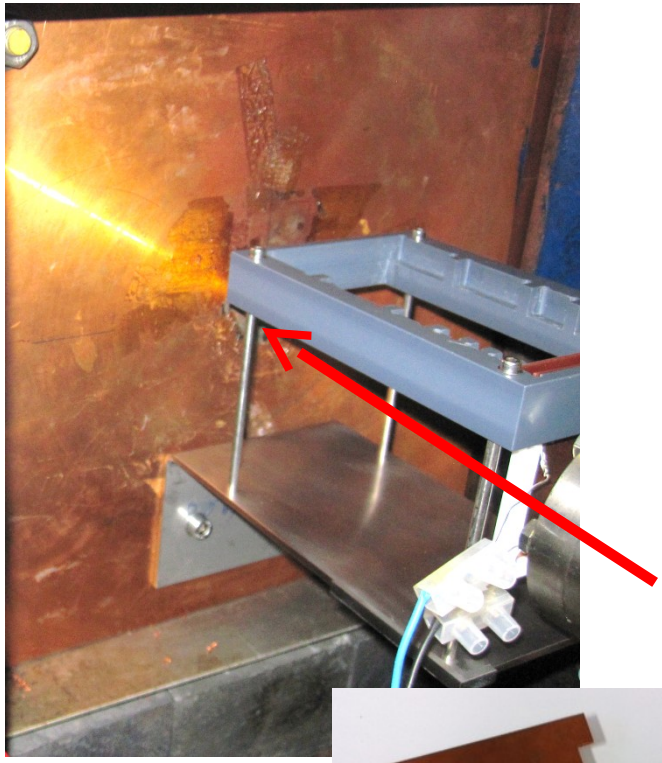
Radiator targets:

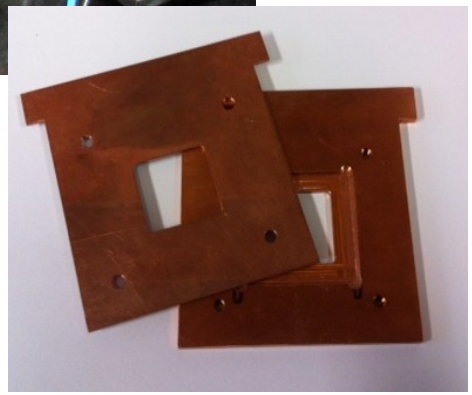
E < 8 MeV → Au

8 MeV < E < 9.2 MeV → Ag

9.2 MeV < E < 9.9 MeV → Cu

E > 9.9 MeV → Al





Suppress low energy background:
Al beam hardener

# Darmstadt Data lacks Parities ...

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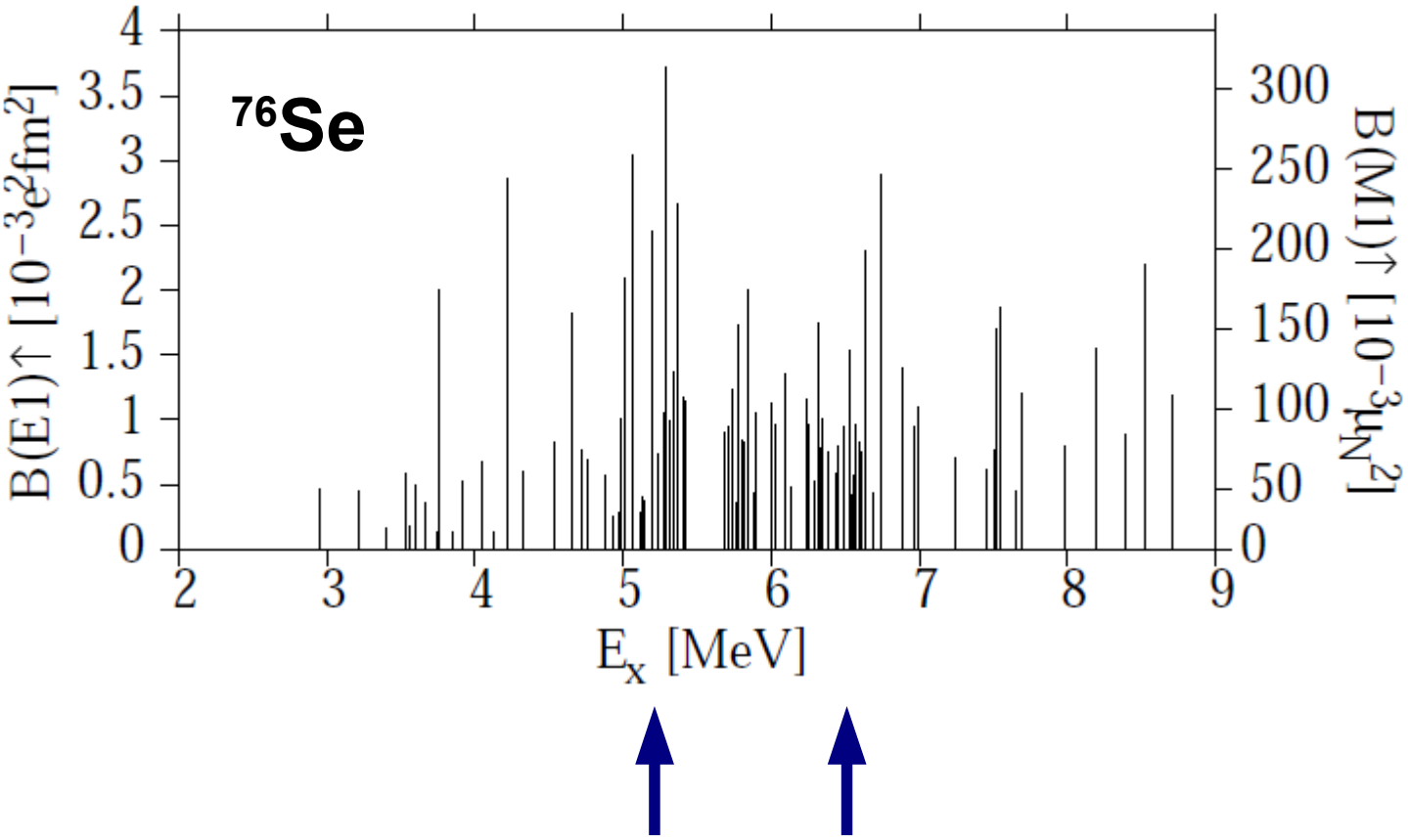
## ... but gives absolute x-sections / B(E1) or B(M1) strengths




**Strength concentrations – E1?**

# Anything on the GDR Tail ??

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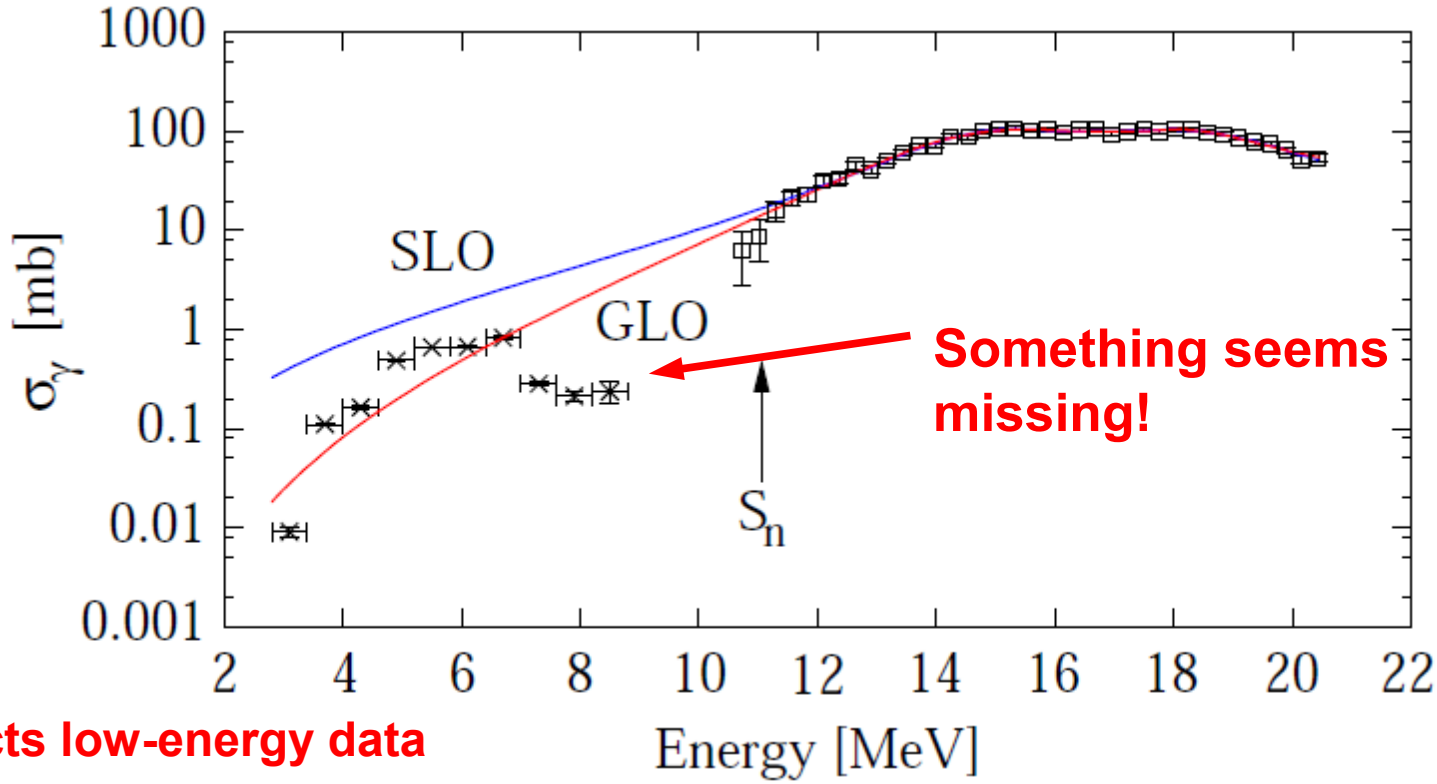
**Data from Bremsstrahlung only!**
**Two Lorentzians fitted because $^{76}$Se is deformed (β~0.31)**




**Something seems missing!**

**(n,γ) data from Carlos et al., NPA 258, 365 (1976)**

**Overpredicts low-energy data**

$$\sigma^{SLO} \propto \frac{E^2\Gamma^2}{(E^2 - E_0^2)^2 + E^2\Gamma^2}$$

$$\sigma^{GLO} \propto E\Gamma\left[\frac{E\Gamma(E)}{(E^2 - E_0^2)^2 + E^2[\Gamma(E)]^2}\right]$$

# HIGS (Free Electron Laser)

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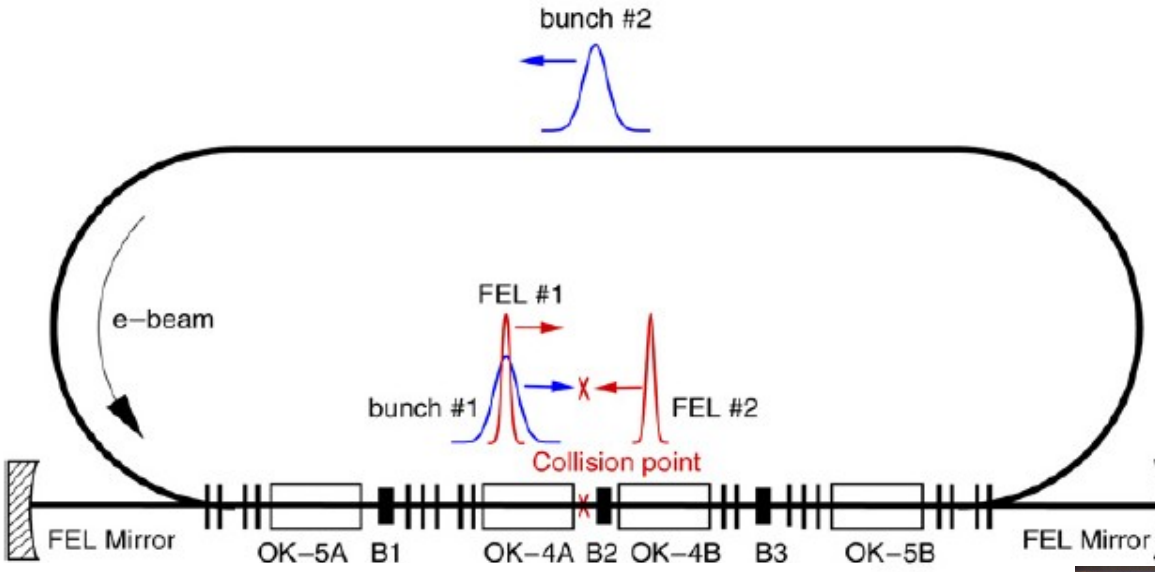
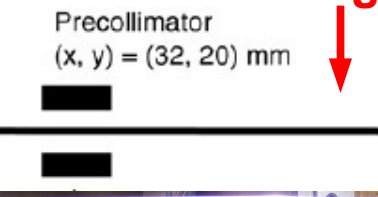
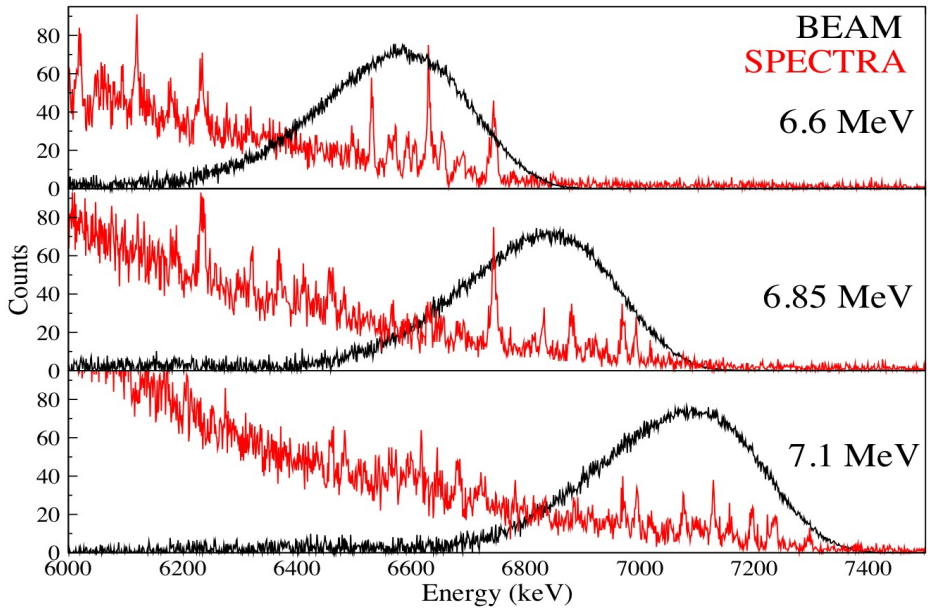
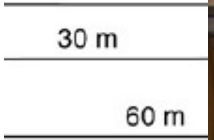


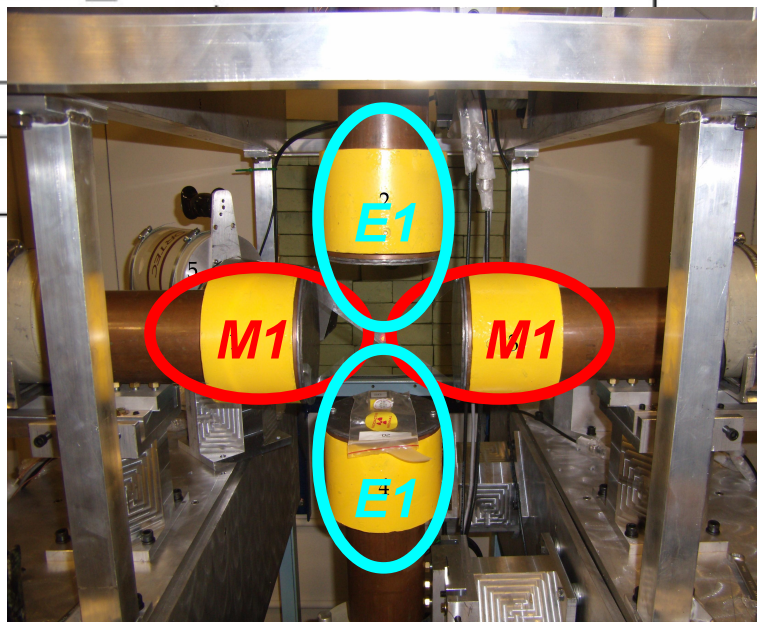

**H.R. Weller et al. Progress in Particle and Nuclear Physics 62 (2009) 257–303**

**100% polarized, near-monoenergetic gammas**

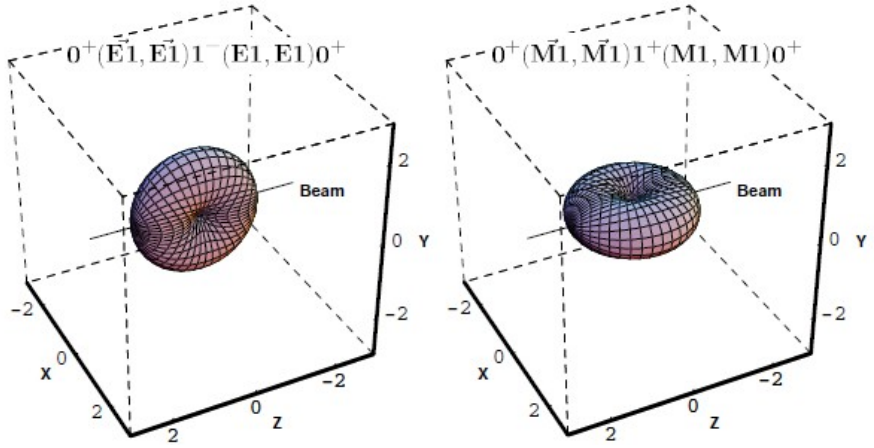


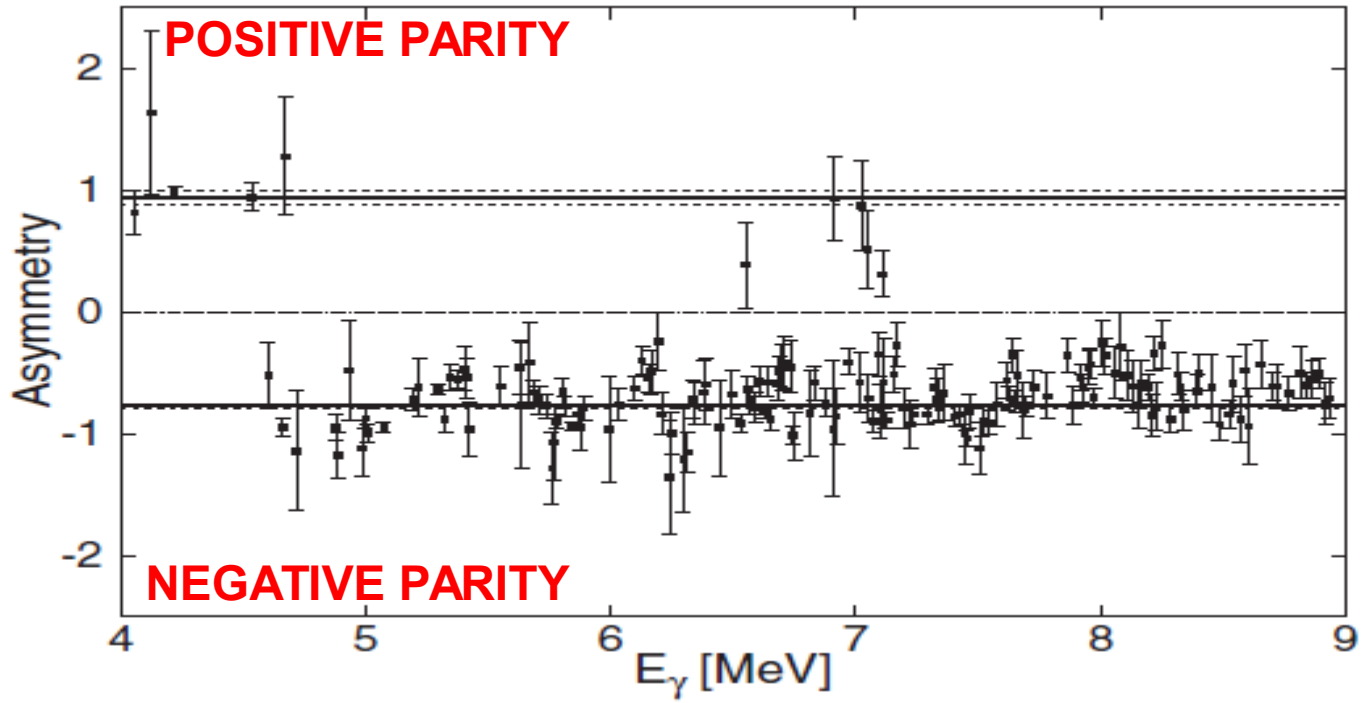
# Polarization => Parity




**Clear (and easy) identification Of E1 excited states through asymmetry horizontal/vertical**

$$P_{ana} = \frac{W^{hor} - W^{ver}}{W^{hor} + W^{ver}}$$

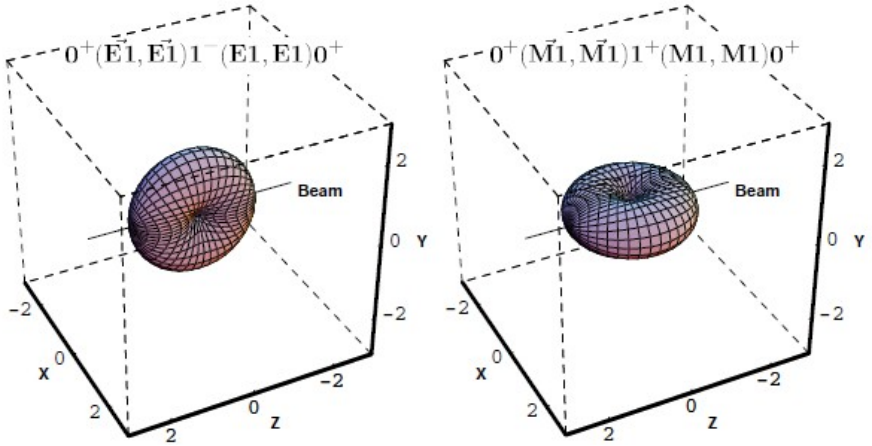
**$^{76}$Se**




**M1**

**almost all: E1**

# Polarization => Parity

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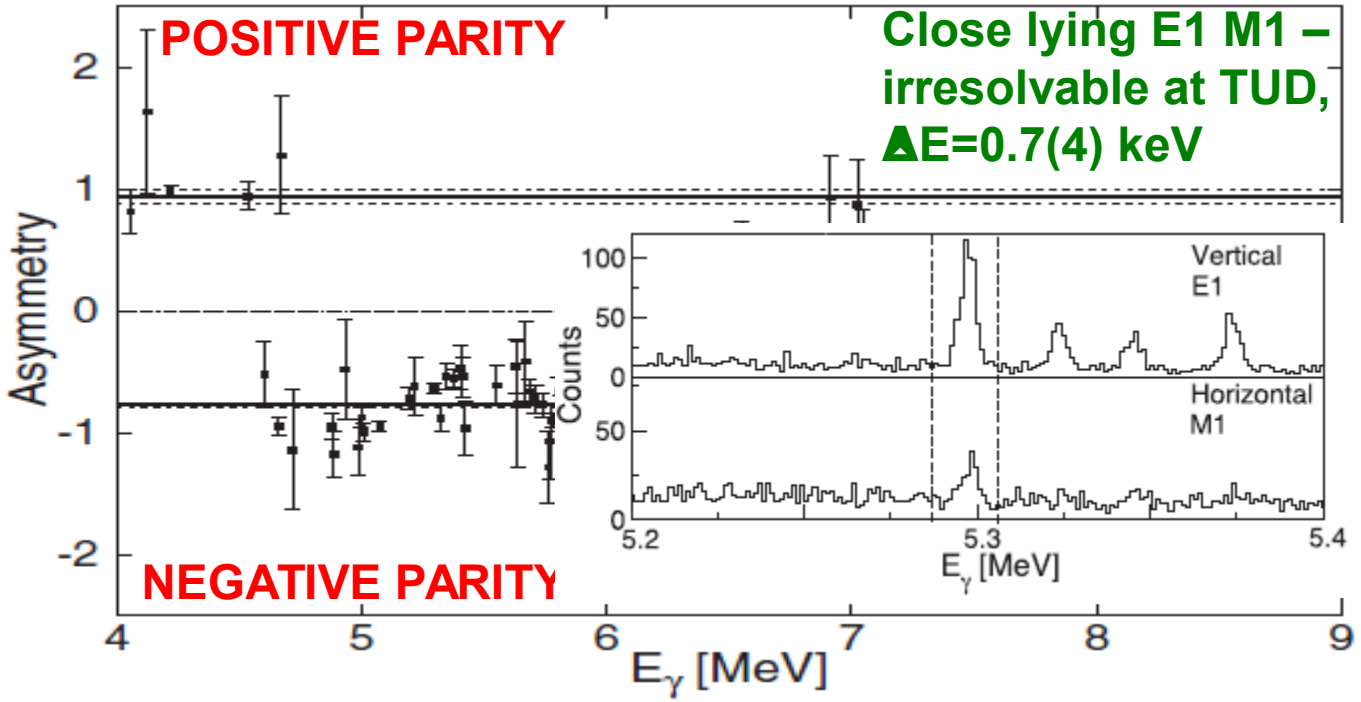


**M1**

**almost all: E1**

# Much E1 Strength is Hidden

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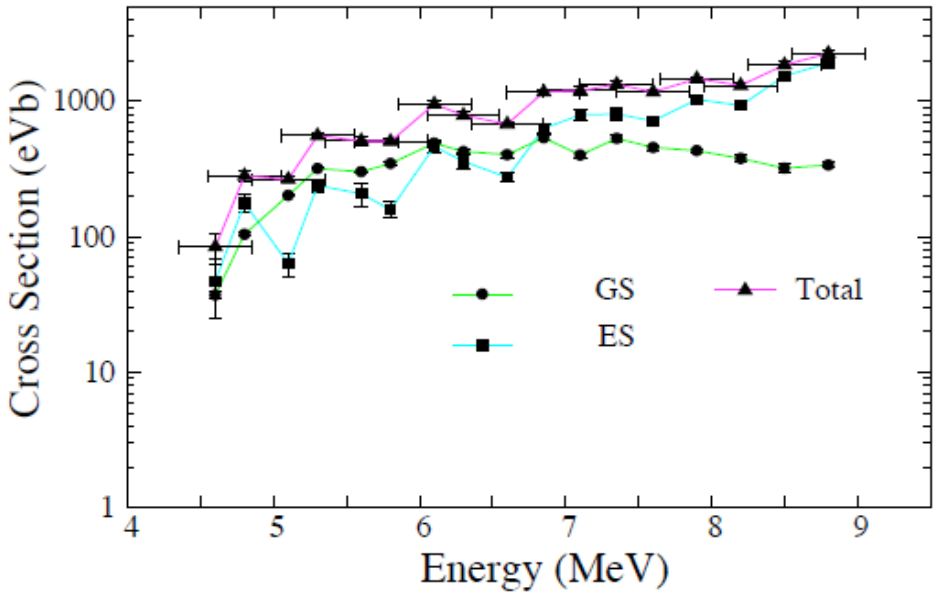
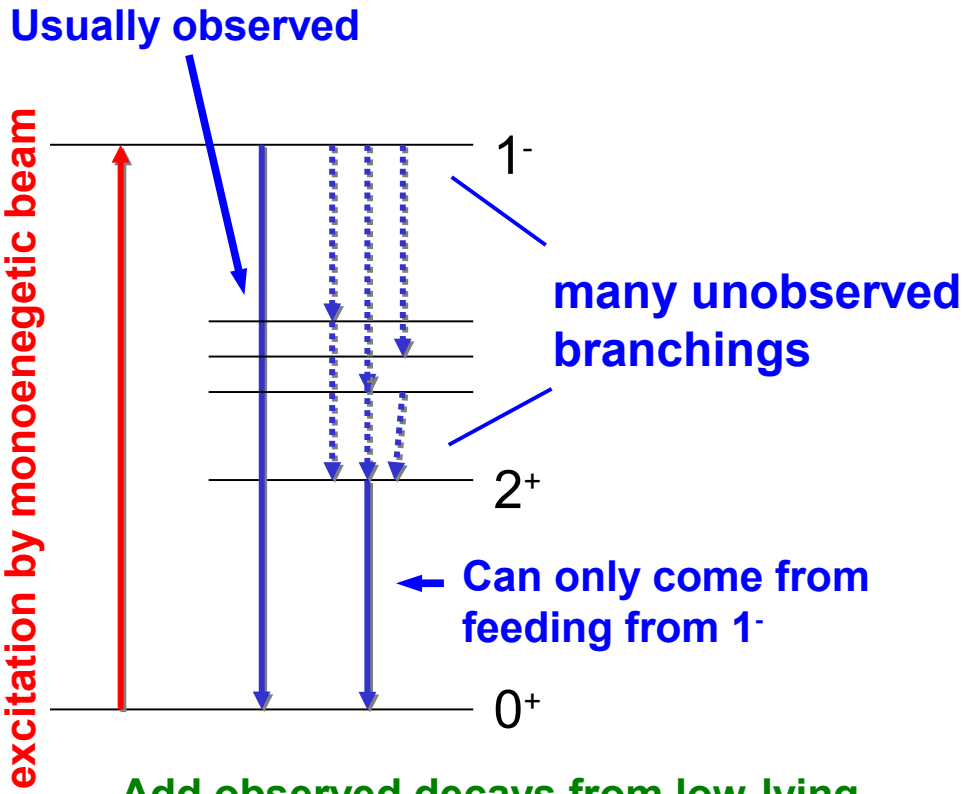
## Now including HIGS Data:

**Higher-lying states decay stronger to excited states – corrections to total E1 excitation strength!**




Add observed decays from low-lying states into excitation cross section

Similar to observation in $^{138}$Ba,
A. Tonchev, PRL 104, 072501 ('10)

**In Pygmy region: affects sum strength by a factor of 2 or more**

# Branching-corrected x-sections

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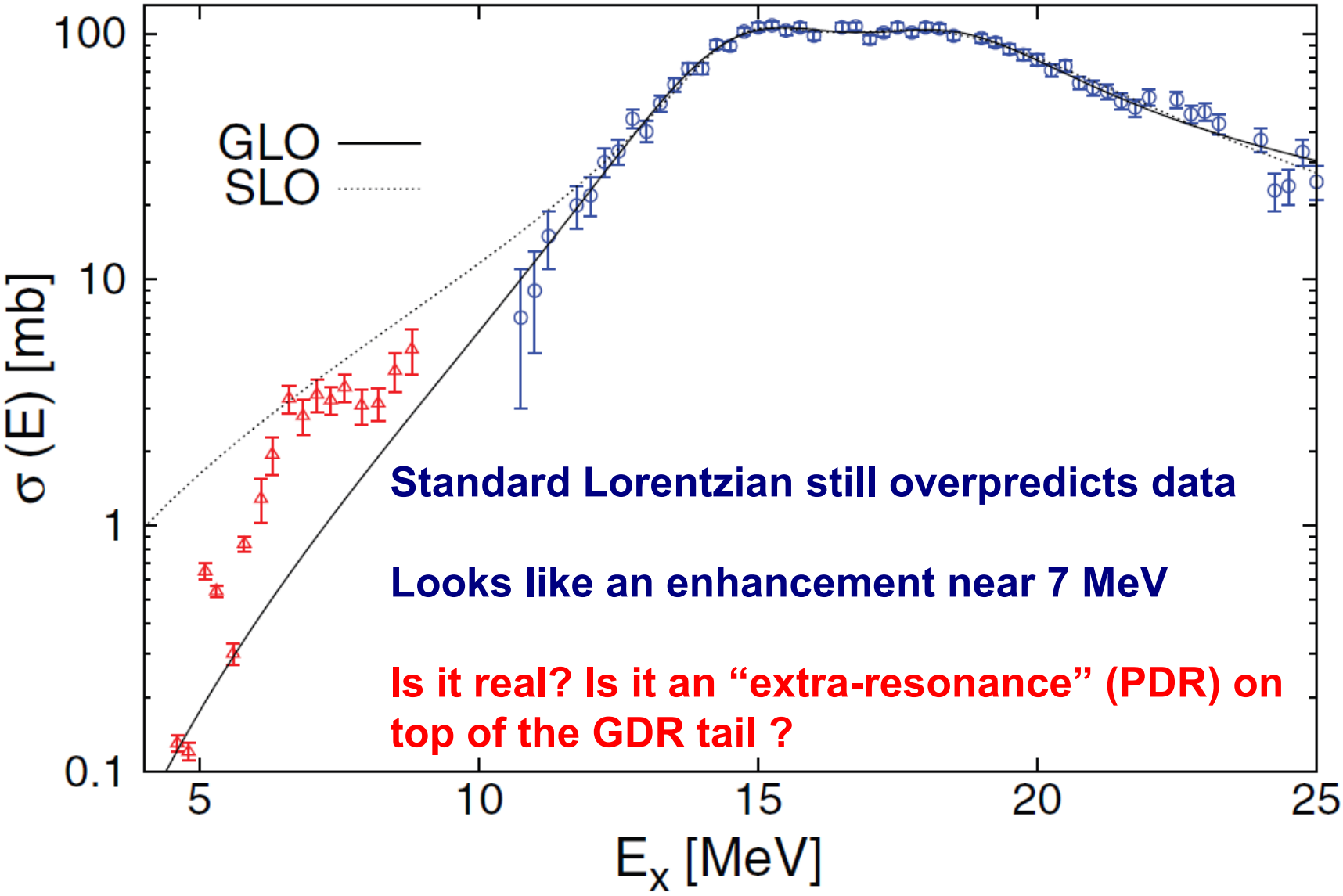

# No Enhancement in $^{76}$Ge

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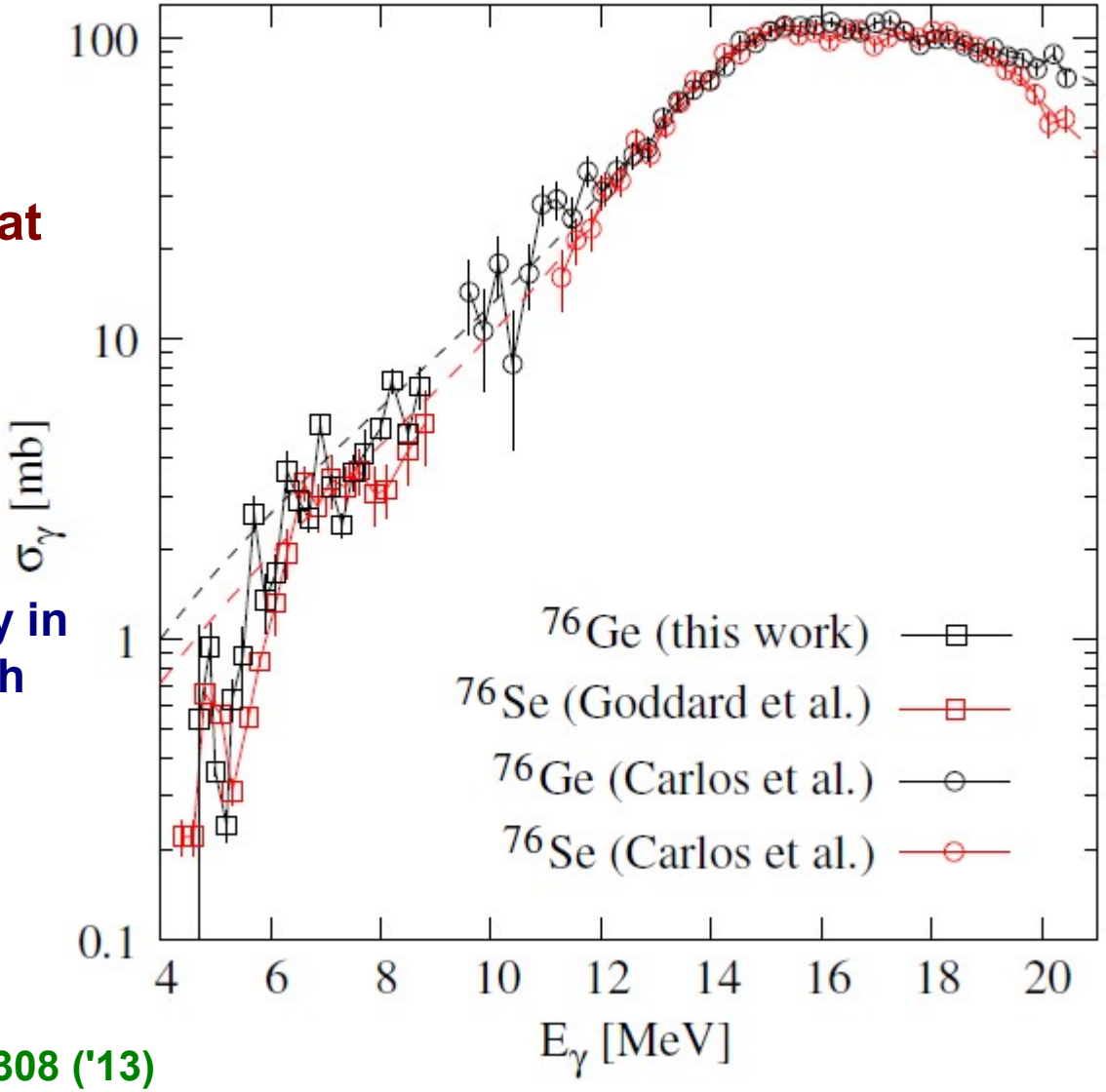
**Result from photon-scattering:**
***(many weeks of beamtime at TUD and HIGS)***

**There appears to be a structure at ~7 MeV in $^{76}$Se**

**Analog experiments on $^{76}$Ge give a puzzling result: no enhancement !**

**Maybe because of higher level density in $^{76}$Se due to deformation => E1 strength more fragmented, unobserved.**

**PSFs may be tested from such data!**
**Important for astro, reactions,...**




**P. Goddard, N. Cooper, VW, ..., PRC 88, 064308 ('13)**
**R. Ilieva & P. Humby, MA thesis, Yale/Surrey**

# PDR or not ??

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**Do we know there is E1 strength *in addition* to GDR tail ?**

# Isovector / Isoscalar Components

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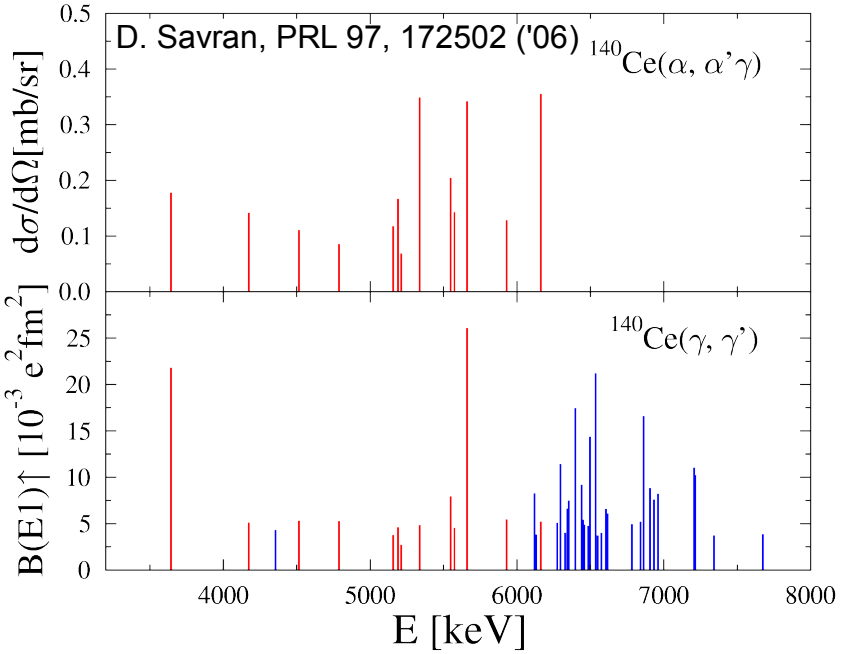
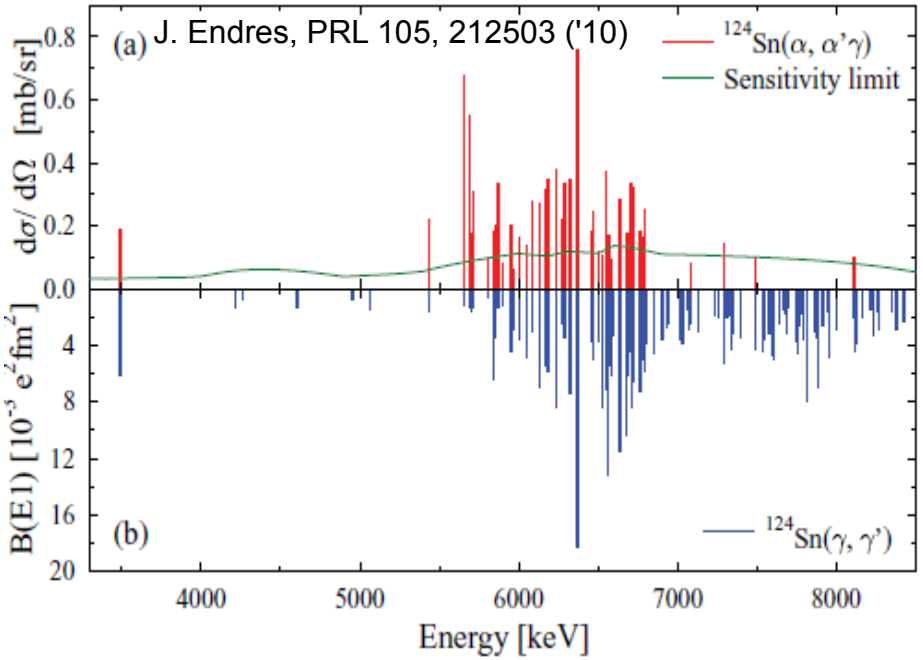
**Yes, there is a *structural* change in the wave functions !**




**Higher lying states <u>not</u> excited in α-scattering**

**⇒ Different underlying structure**

**(isoscalar / isovector part)**

# Strong states, little branching, a PDR Signature ?

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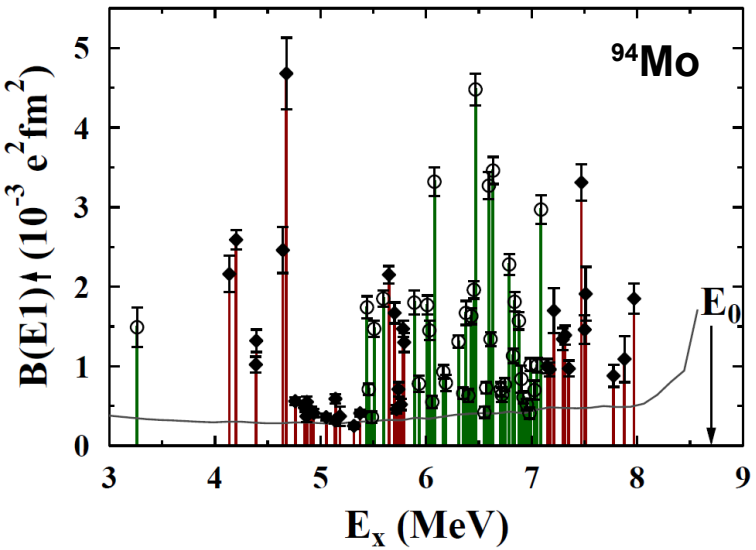
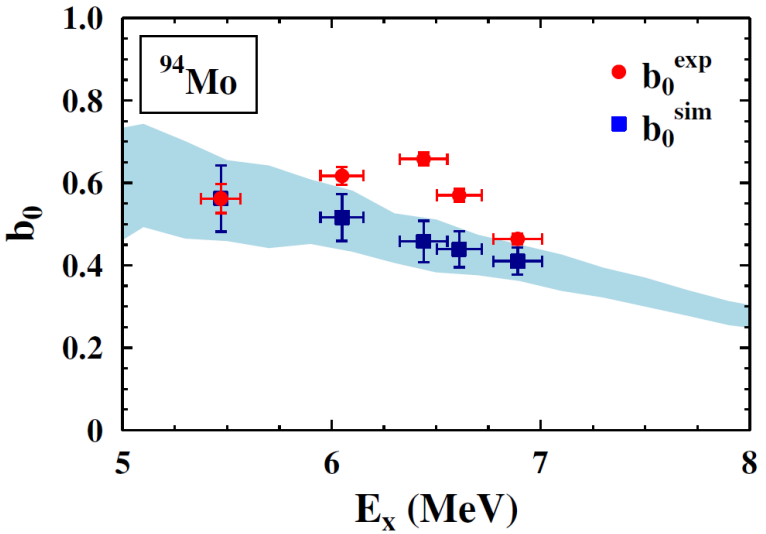
C. Romig et al., PRC 88, 044331 (2013) *(-> Thursday afternoon session)*



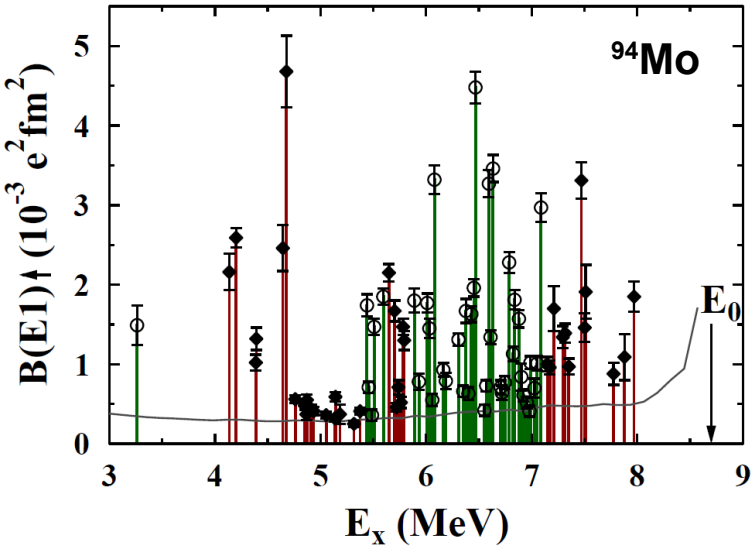

$b_0$ = I (decays -> g.s.) / I (decays -> excited states)

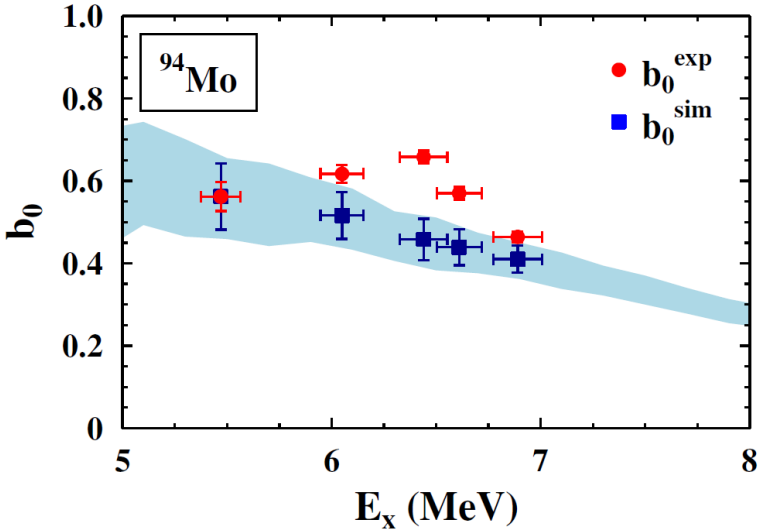
**In the PDR region: enhancement of strong states**
**predominant decay to ground state**

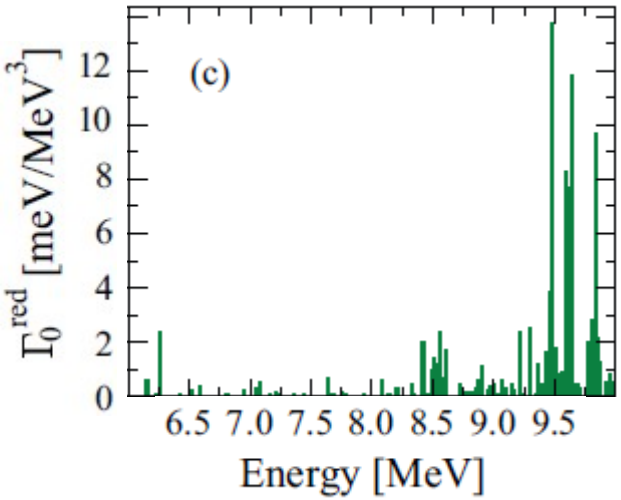
# Strong states, little branching, a PDR Signature ?

TECHNISCHE UNIVERSITÄT DARMSTADT

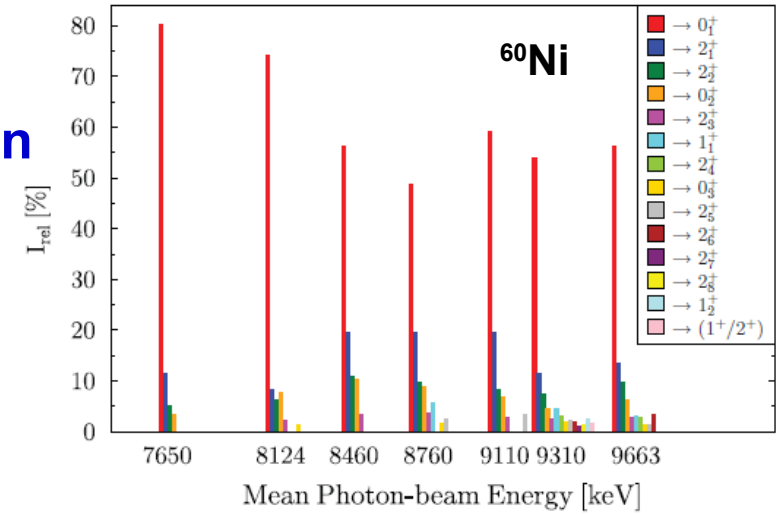
C. Romig et al., PRC 88, 044331 (2013) *(-> Thursday afternoon session)*




**Similar in $^{60}$Ni**



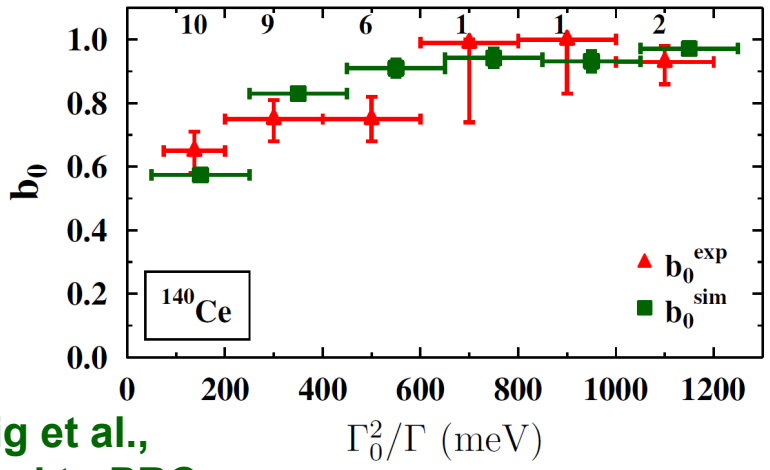

M. Scheck et al., PRC 87, 051304(R) (2013)

# Strong states, little branching, a PDR Signature ?

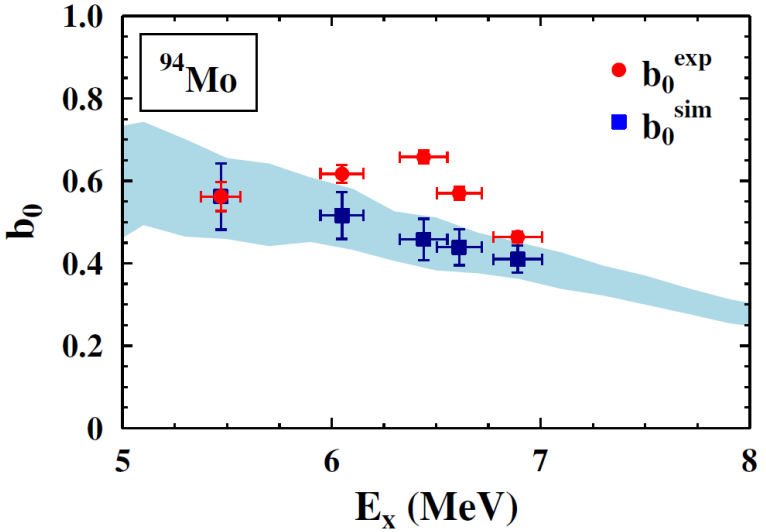
TECHNISCHE UNIVERSITÄT DARMSTADT

C. Romig et al., PRC 88, 044331 (2013) *(-> Thursday afternoon session)*

$^{140}$Ce




C. Romig et al., submitted to PRC




**In self-absorption we measure that strong states decay ~100% to g.s.**

**In agreement with statistical model calculation -> general feature**

**In the PDR region: enhancement of strong states**
**predominant decay to ground state**

# Statistical Model Approaches

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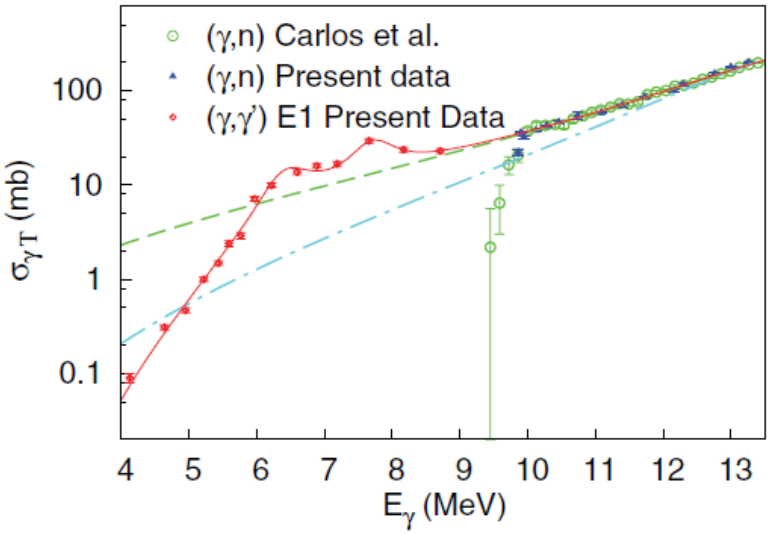
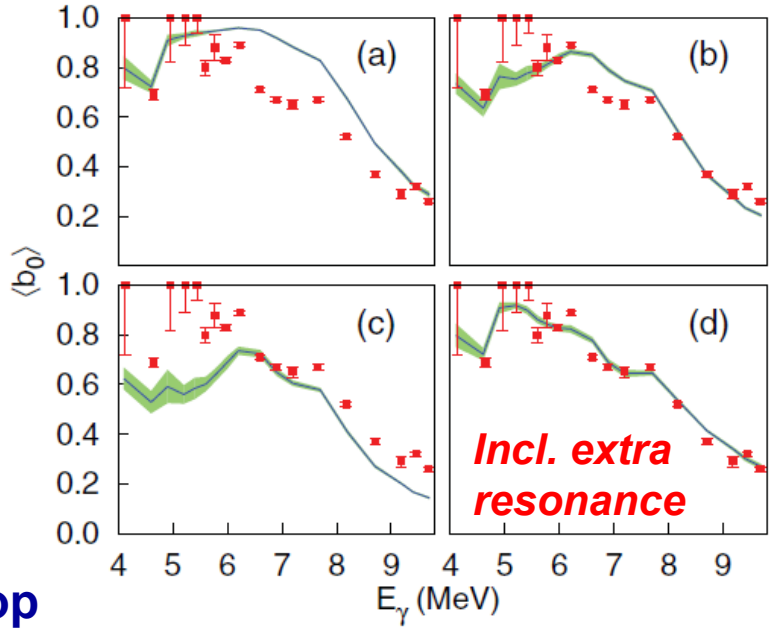
- Generally, need to know photon strength function (PSF)
- How much strength is there in addition to low-energy GDR tail ?
- Data quality starts allowing test of different PSFs
- Few recent examples: $^{142}$Nd

C. Angell et al., PRC 86, 051302(R) (2012)




**Brink Hypothesis broken at low energies**




**Lorentzian + *Extra Resonance on GDR Tail* + exp. drop**

# Statistical Model Approaches

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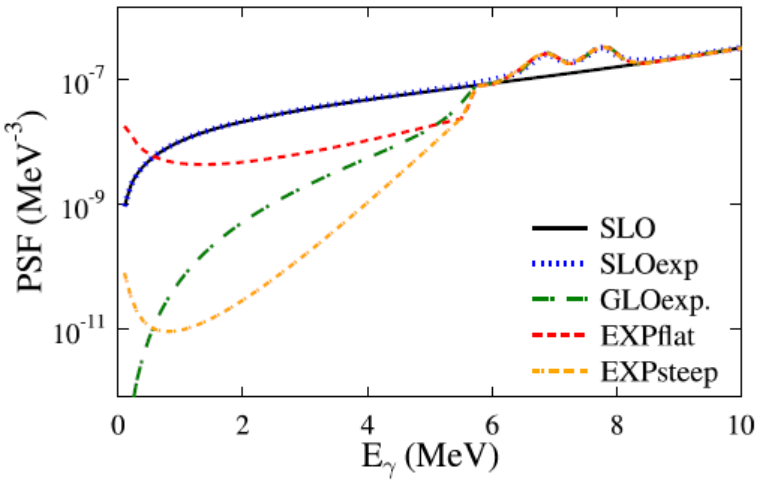
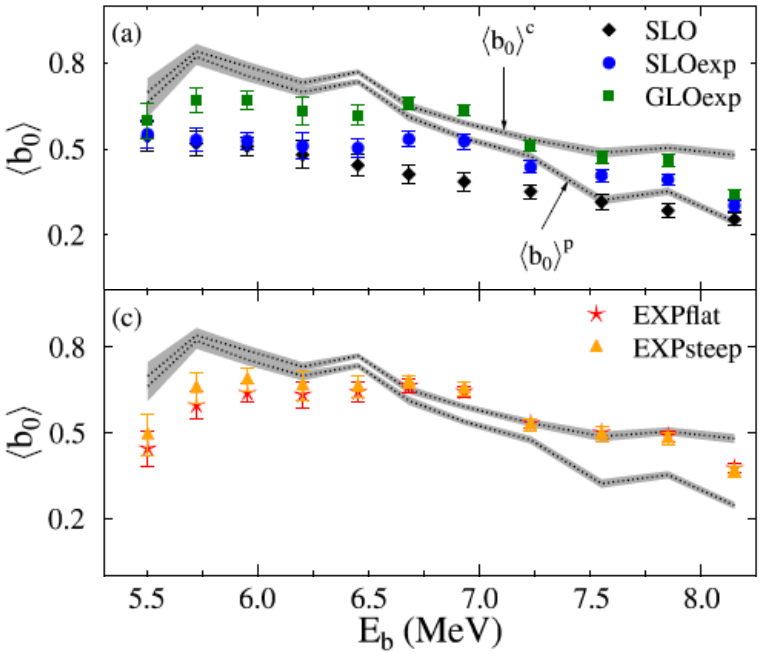
- Generally, need to know photon strength function (PSF)
- How much strength is there in addition to low-energy GDR tail ?
- Data quality starts allowing test of different PSFs
- Few recent examples: $^{130}$Te

**Trial PSFs**




**None describes branching consistently**

J. Isaak et al., PLB 727, 361 (2013)




**Lorentzians / fitted to data / exp. decrease at low-E**

# Statistical Model Approaches

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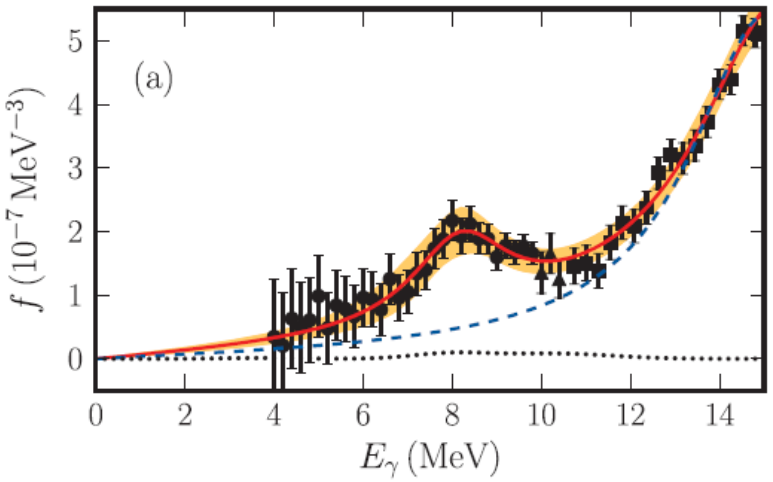
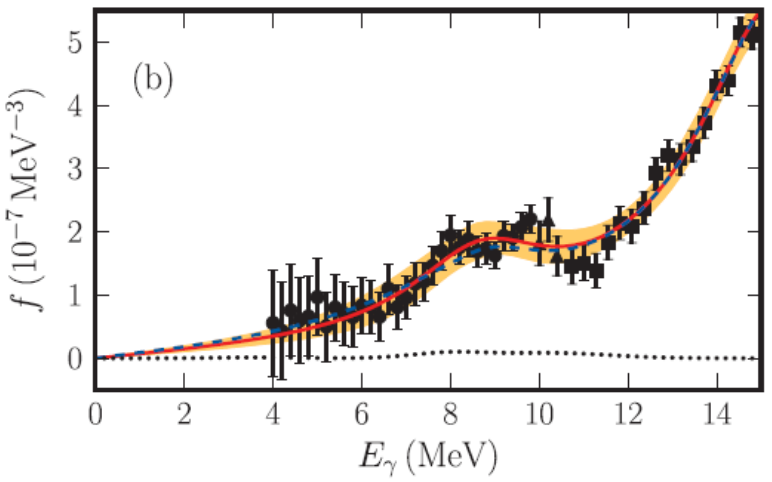
- Generally, need to know photon strength function (PSF)
- How much strength is there in addition to low-energy GDR tail ?
- Data quality starts allowing test of different PSFs
- Few recent examples: $^{78}$Se G. Schramm et al., PRC 85, 014311 (2012)



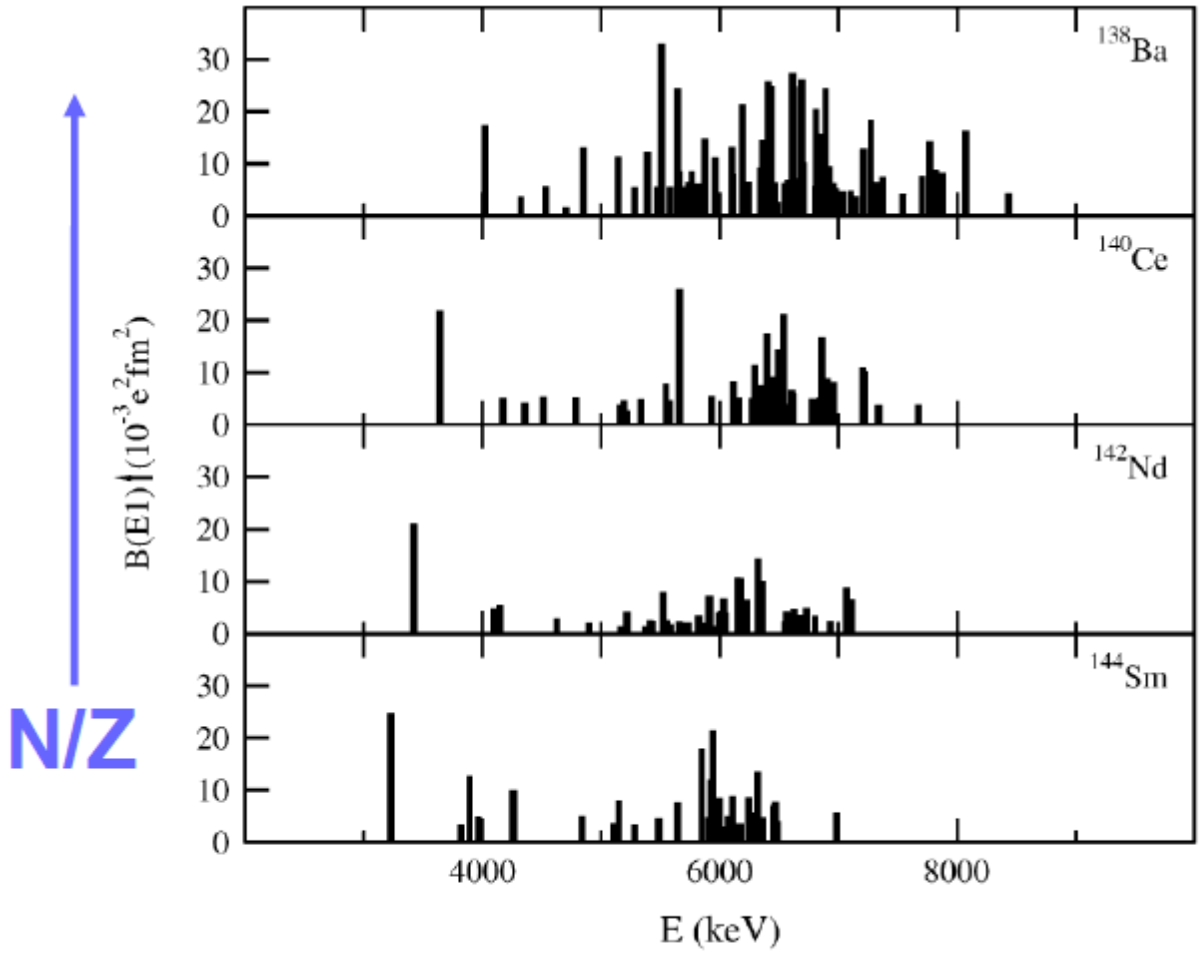

Iterations until input / output PSFs match




Start PSF Lorentzian, M1 PSF included !

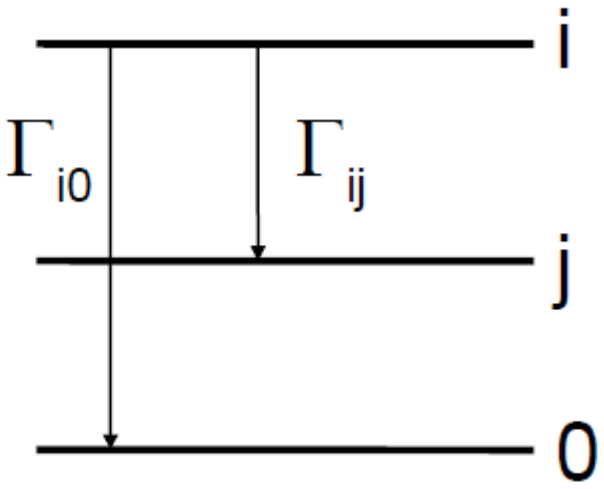
Note: typically (g,n) data by Carlos et al. scaled to 85%

# Our Approach for $^{76}$Se




S. Volz et al, NPA 779 1 (2006)

**Deduced from resolved depopulating transitions only!**



# Statistical Properties

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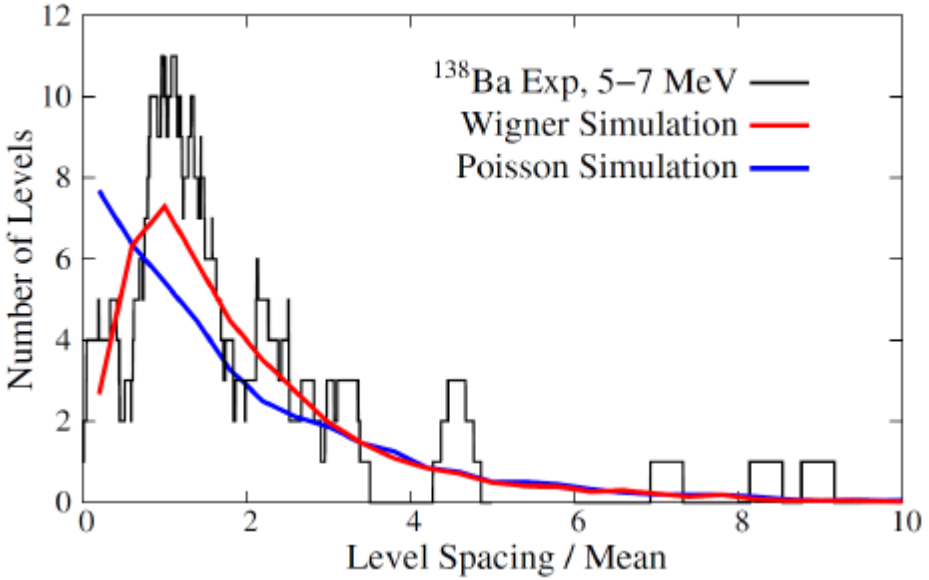
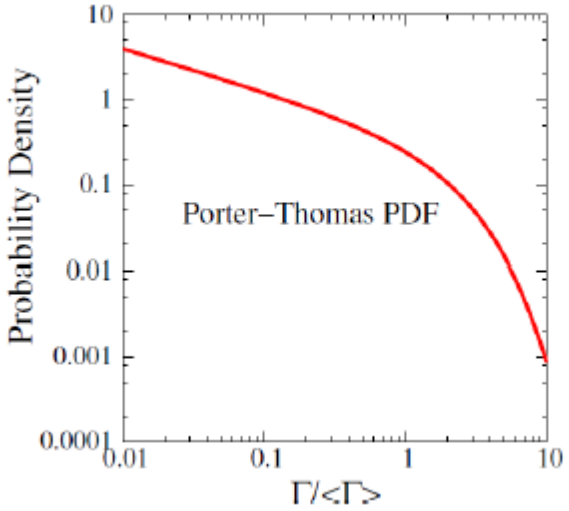
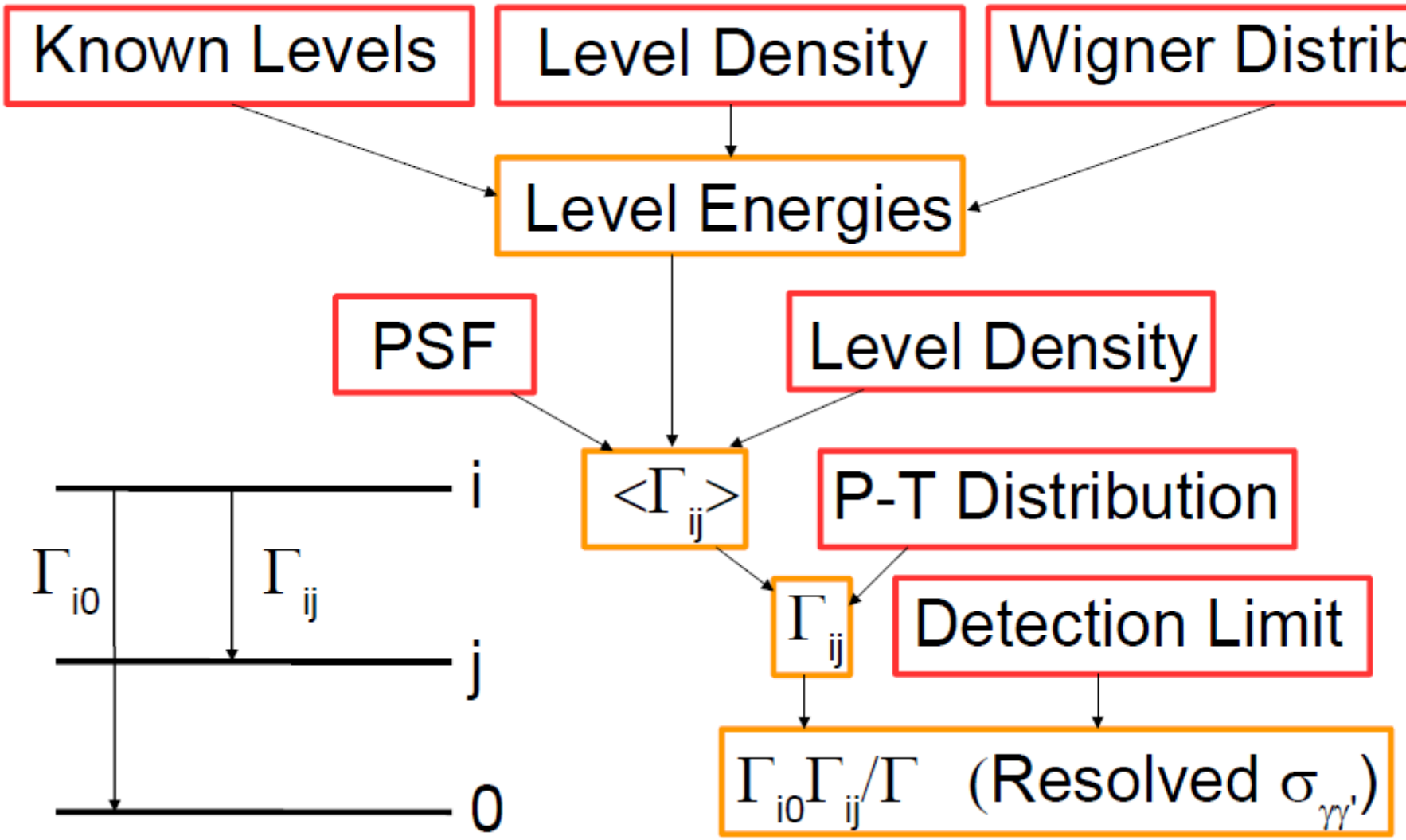
- **Level Spacings : Wigner Distribution**




- **Partial Radiative Widths: Porter-Thomas Distribution**

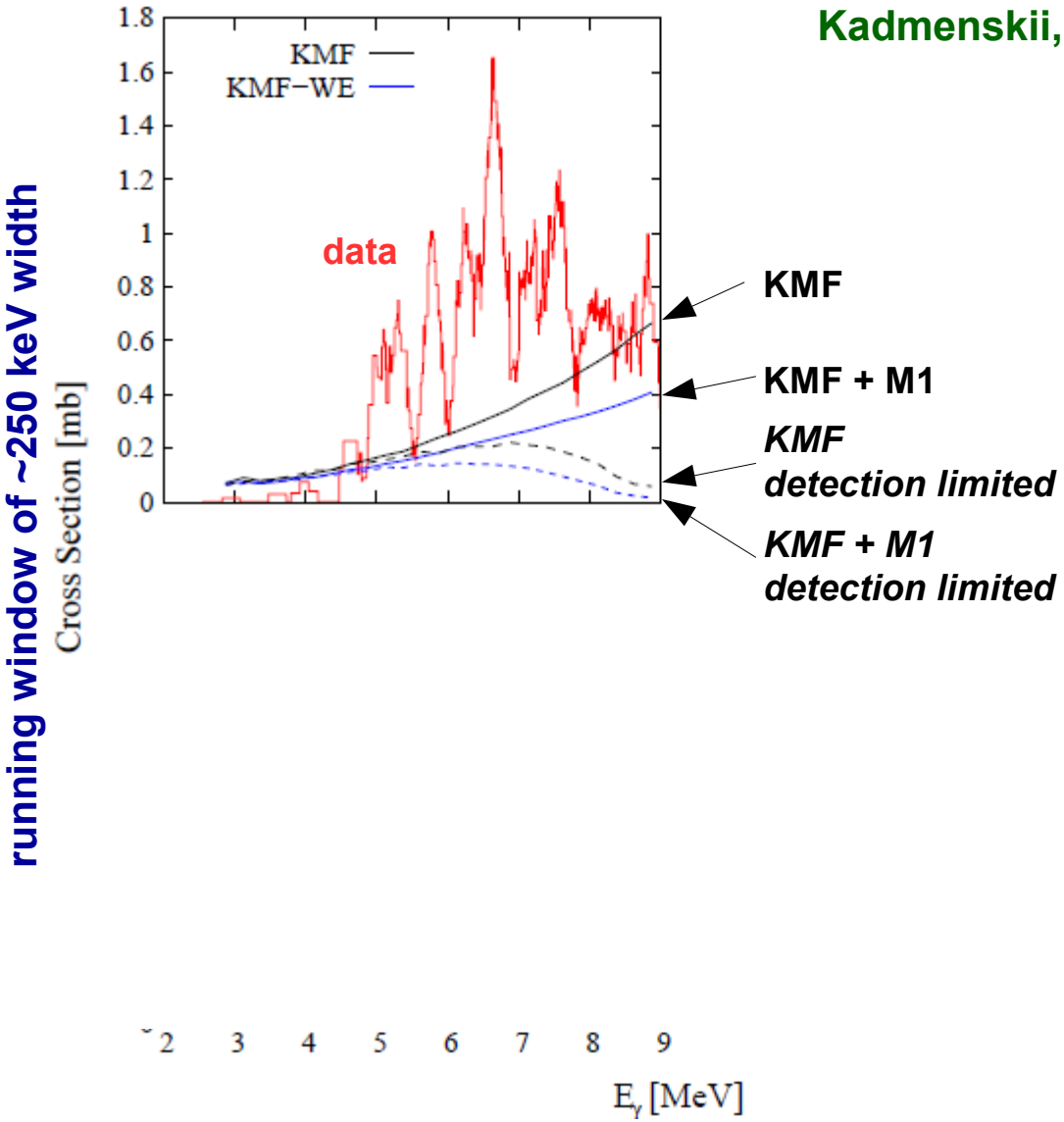


# Run MC Cascade Simulations




**N. Cooper, PhD student, Yale**

# $^{76}$Se for trial PSFs




Kadmenskii, Markushev, Furman, Yad. Fiz. 37, 277 (1983)

$$f_{E1}^{KMF}(E_\gamma) = \frac{1}{3}\frac{1}{(\pi\hbar c)^2} 0.7\sigma_0 \frac{\Gamma_0^2(E_\gamma^2 + 4\pi T^2)}{E_0(E_\gamma^2 - E_0^2)^2}$$

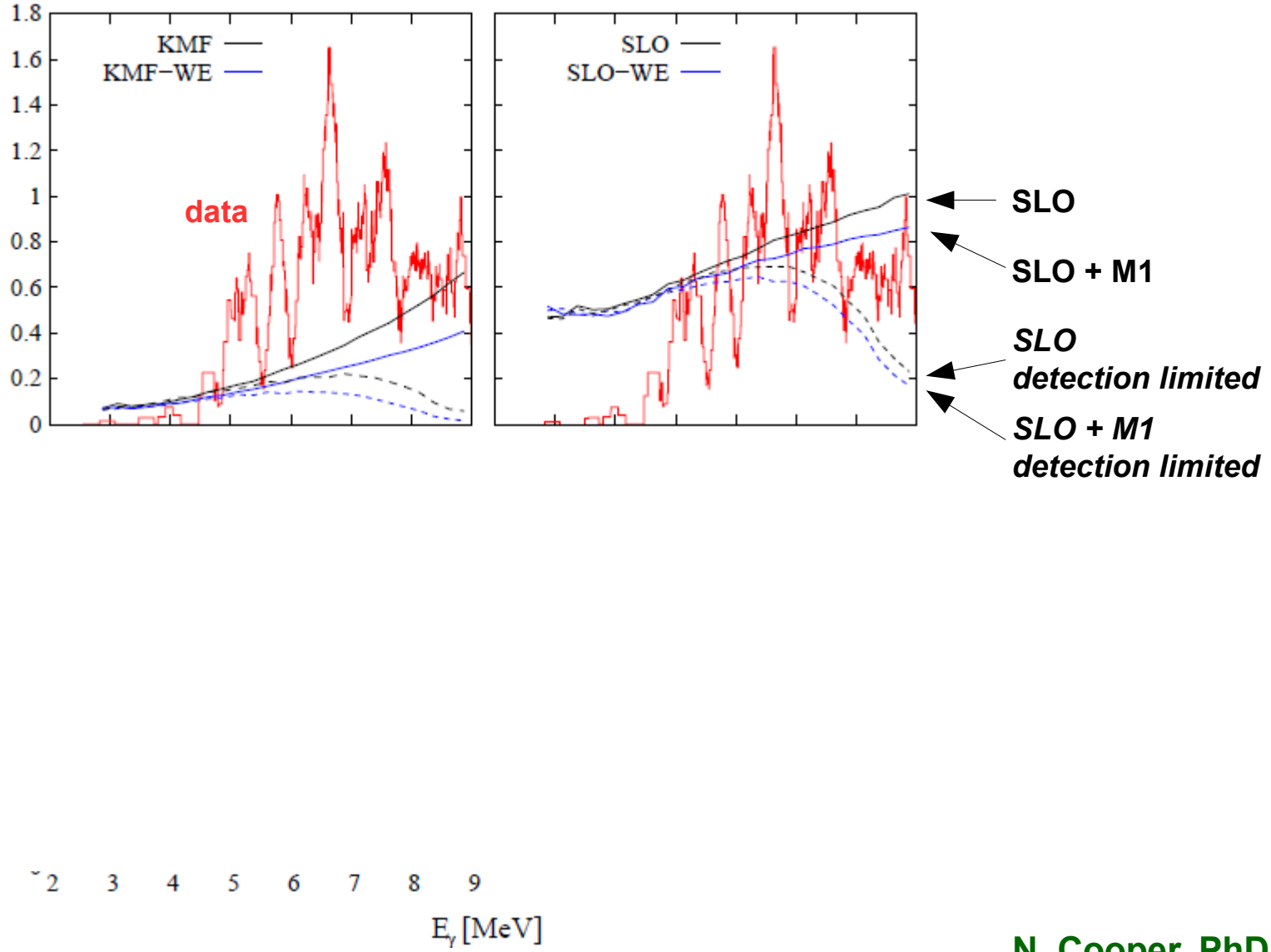
**tailored to match low-energy data**

**used here: T=0**

**M1 from Weisskopf estimate**

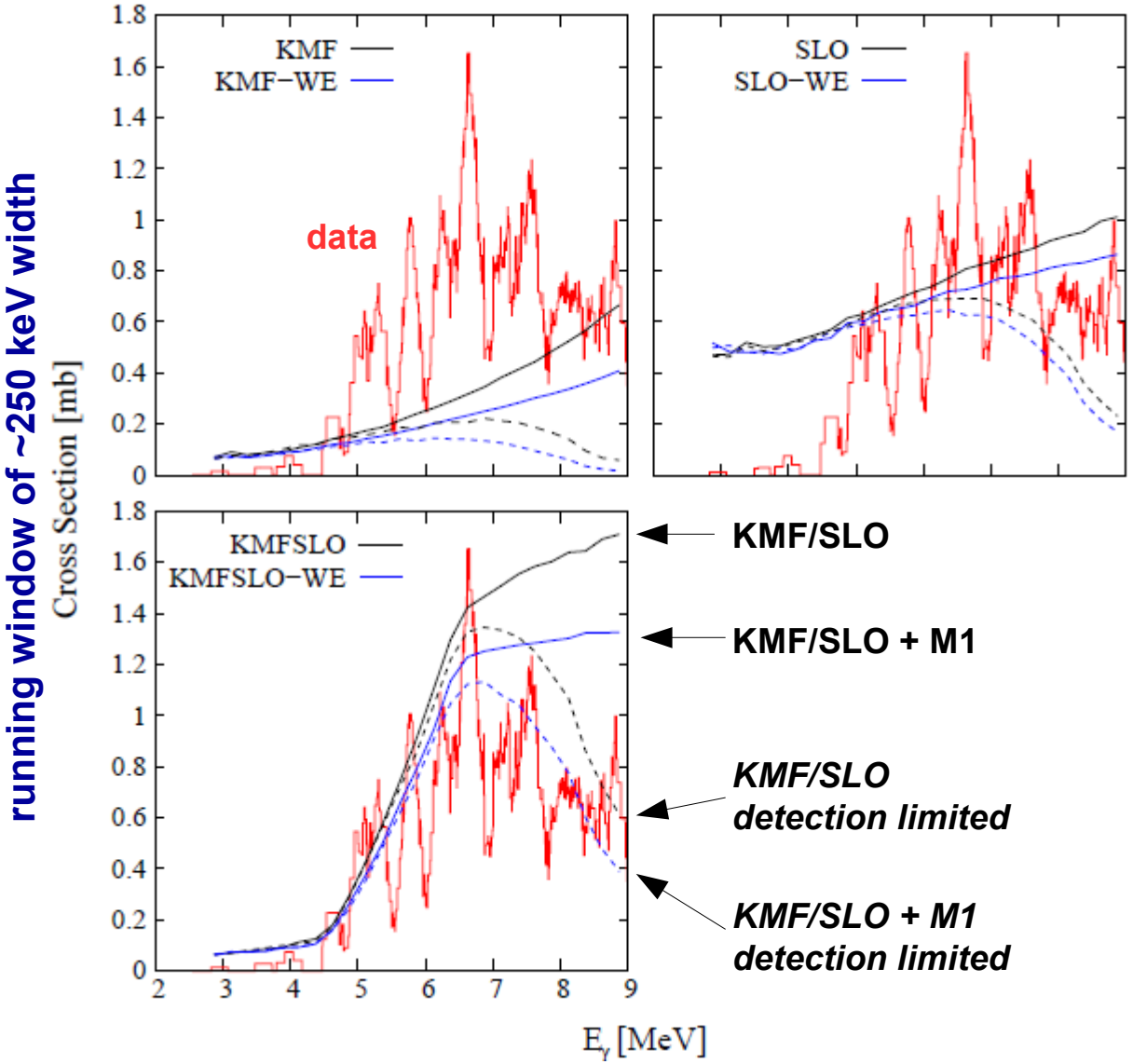
N. Cooper, PhD project (Yale)

# $^{76}$Se for trial PSFs




N. Cooper, PhD project (Yale)

# $^{76}$Se for trial PSFs

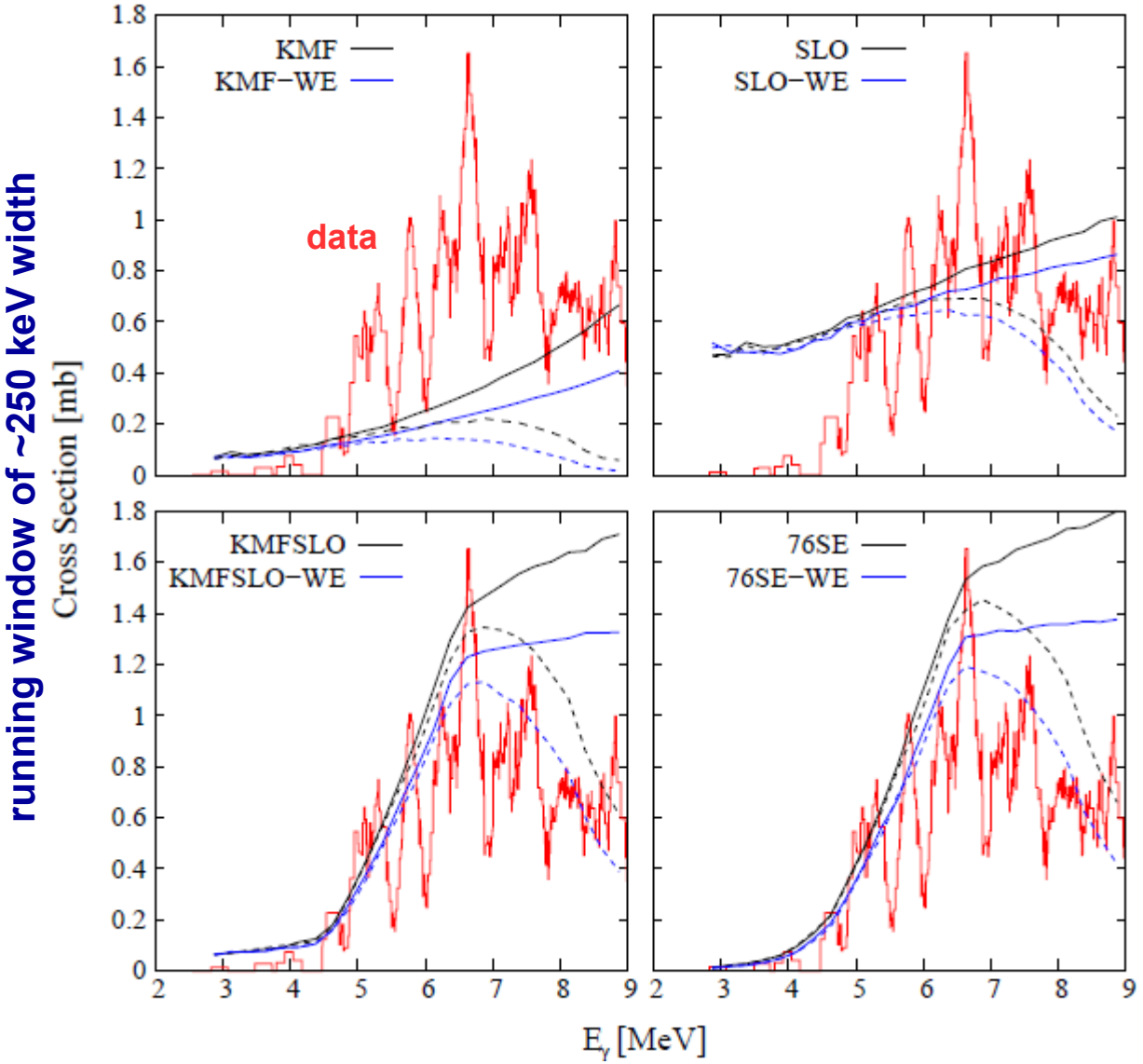



**Suggested by M. Krticka**
**(PhD thesis)**
**use KMF at low energy**
**SLO at high energy**

**Linear transition betwen KMF/SLO chosen between 4-6 MeV**

**N. Cooper, PhD project (Yale)**

# $^{76}$Se for trial PSFs




**Suggested by M. Krticka**
**(PhD thesis)**
**use KMF at low energy**
**SLO at high energy**

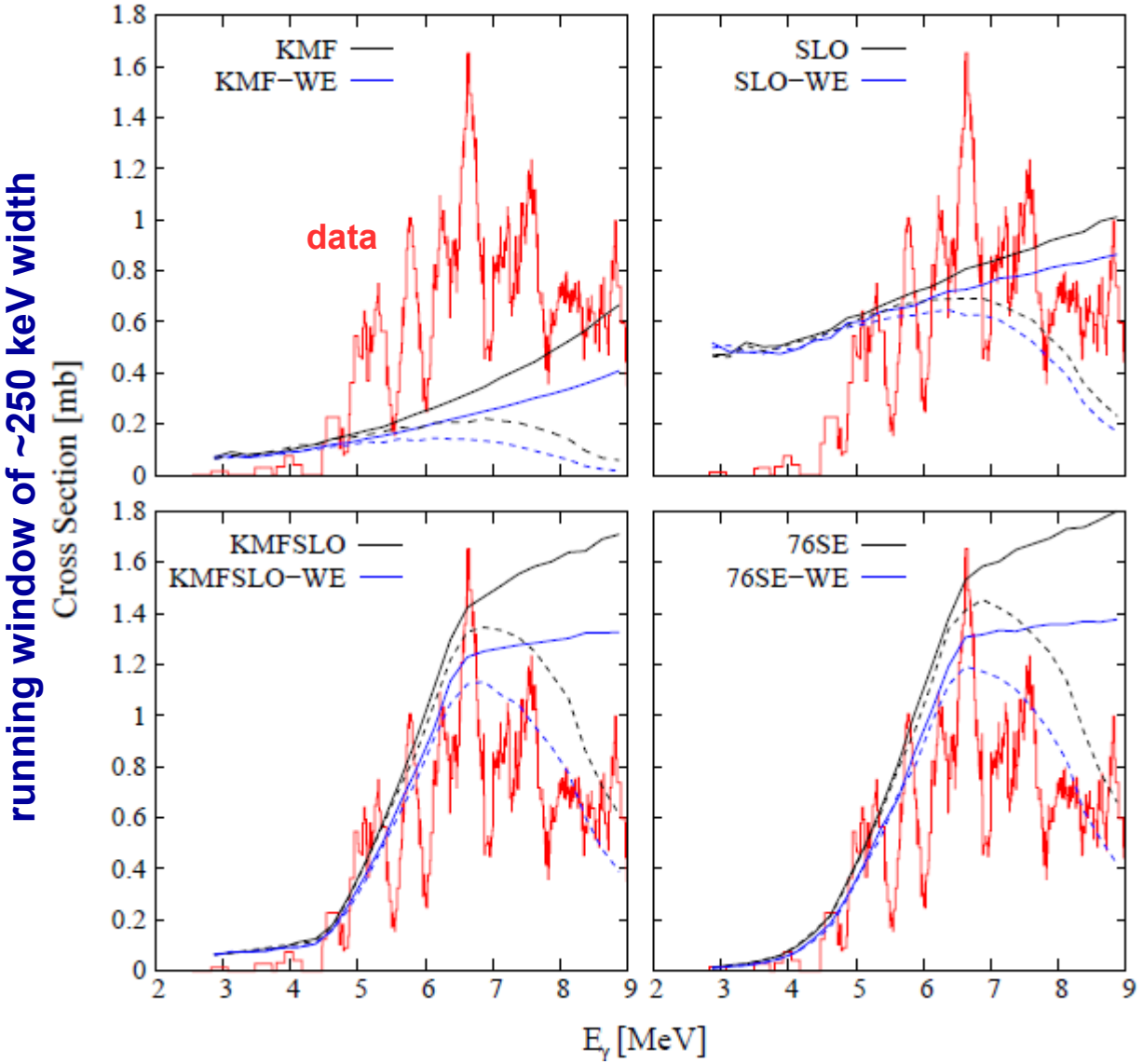
**Linear transition betwen KMF/SLO chosen between 4-6 MeV**

**Same, but with exponential low-energy tail instead of KMF**

**Similar to previous findings of exponential drop-off**

**N. Cooper, PhD project (Yale)**

# $^{76}$Se for trial PSFs

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**(PhD thesis)**
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**SLO at high energy**

**Linear transition betwen KMF/SLO chosen between 4-6 MeV**

**Good description of data**

**No extra-resonance**

**Knowing M1 is *important***

**N. Cooper, PhD project (Yale)**

# Summed Strength Reproduced without extra-PDR (on top of GDR)

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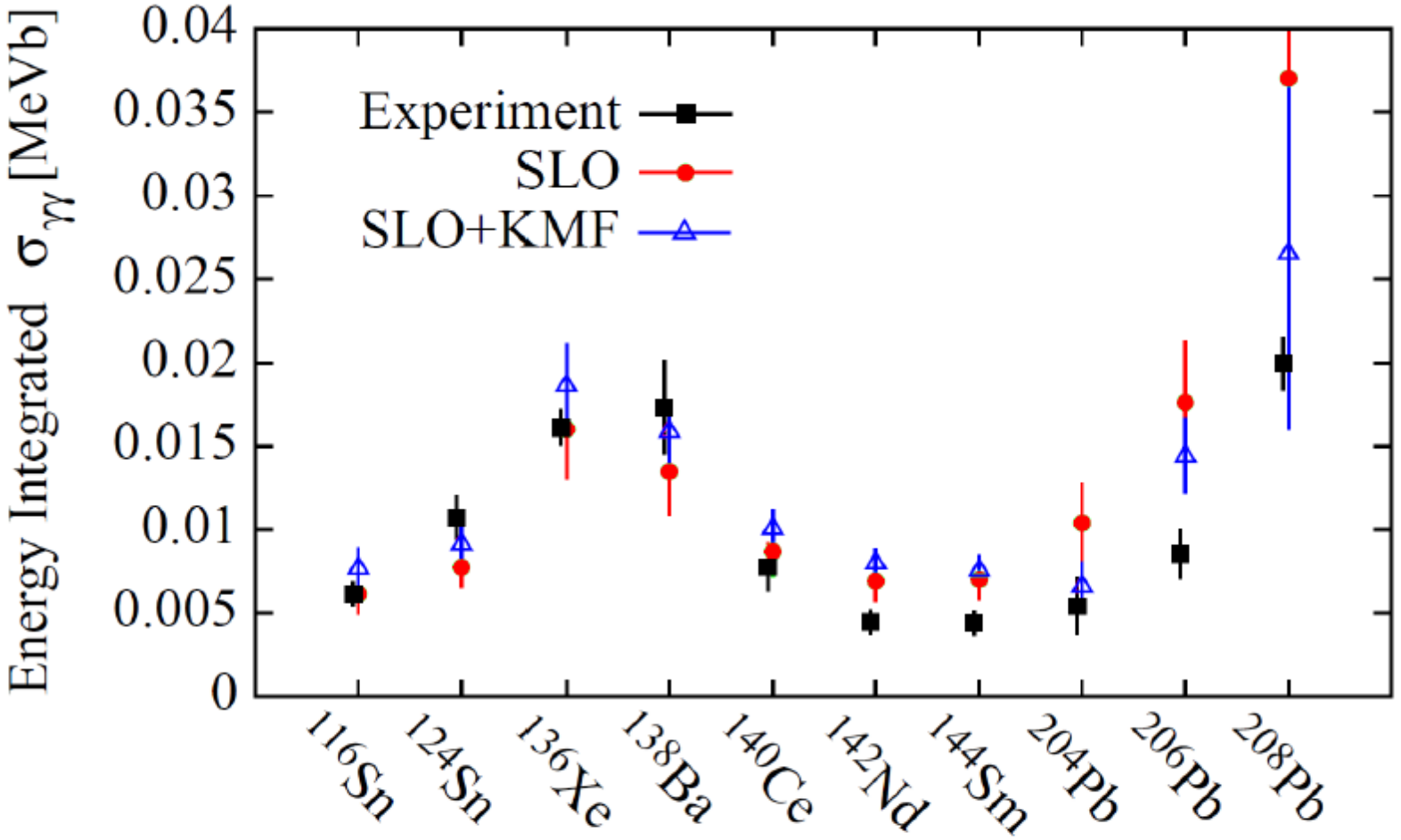


Experimental data from : S. Volz et al, NPA 779 1 (2006), D. Savran et al, PRC 84, 024326 (2011), K. Govaert et al, PRC 57 2229 (1998), J. Enders et al, NPA 724 243 (2003)

# Conclusions

TECHNISCHE UNIVERSITÄT DARMSTADT

- Experiment series NRF at TUD and HIGS $^{76}$Se/$^{76}$Ge completed
- High-Energy data: no evidence for extra (PDR) strength
- Statistical calculations show:
  - Quantifying "extra-strength" depends strongly on PSF
  - PSFs can be tested from NRF (HIGS!) data
  - Observation of branching transitions important
    -> new approach within $\gamma^3$ collaboration at HIGS
  - Need more information on M1 resonances as well
- Did not talk about low-energy 2-phonon structures, but:
  - Analysis E < 4 MeV being finalized, preliminary:
    - $^{76}$Se: scissors mode ~3.8 MeV,
      quad.-oct. $1^-$ candidate ~2.9 MeV
    - $^{76}$Ge: scissors mode ~3.5 MeV
      quad.-oct. $1^-$ candidates ~2.9-3.1 MeV

# $^{140}$Ce Decay Branches

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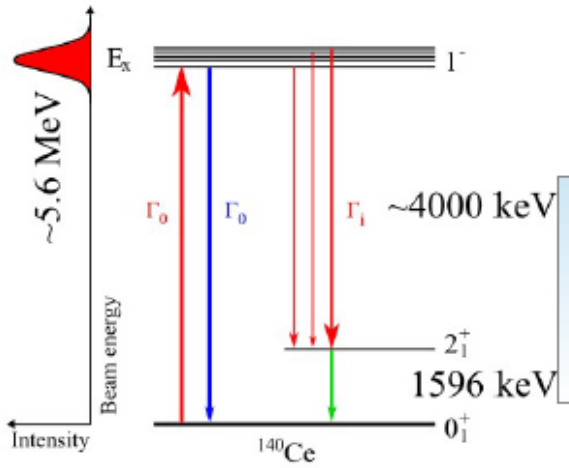
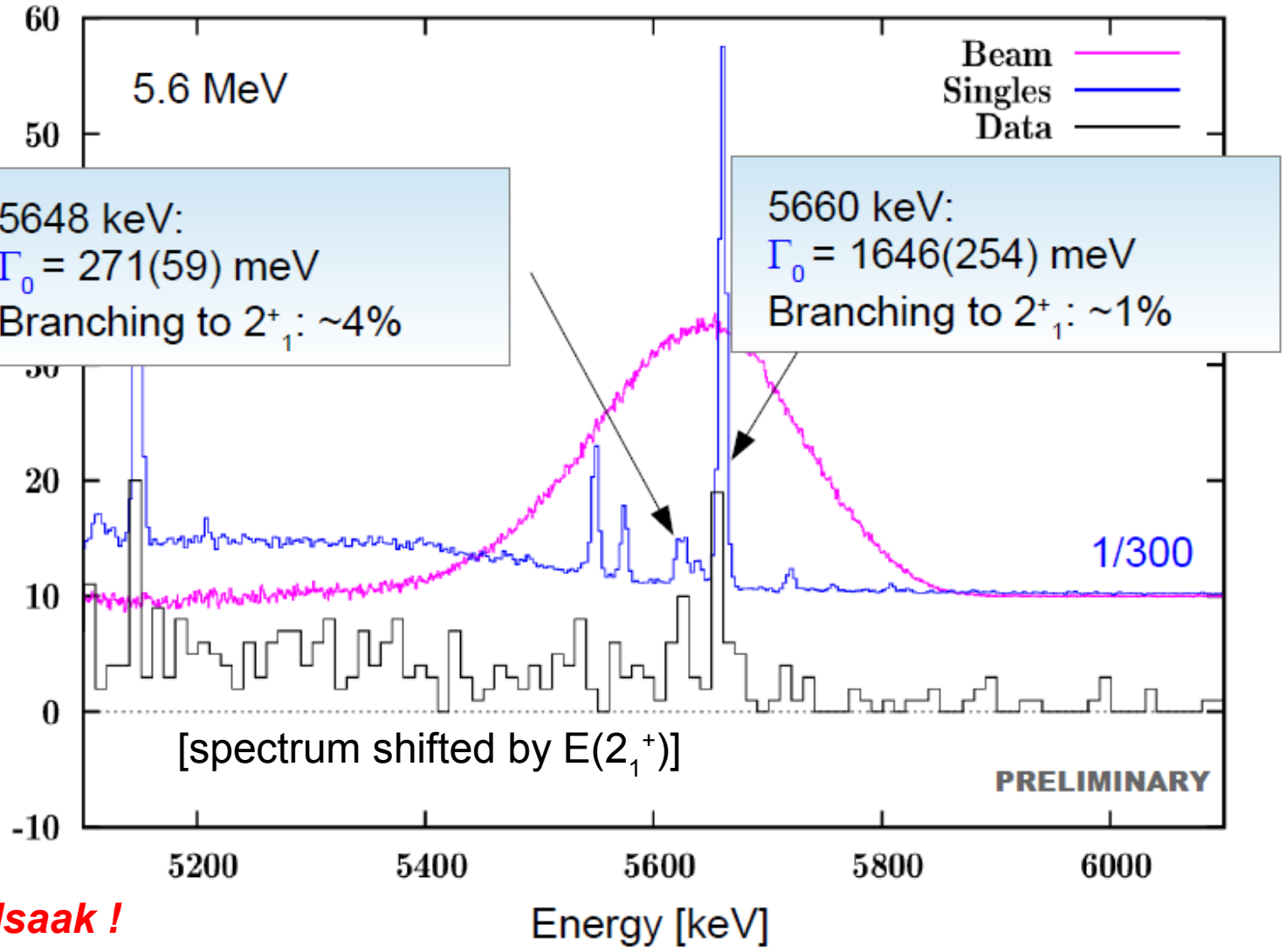
Gate on LaBr → HPGe spectra




$E(2^+_1)$ = 1596 keV




**B. Löher, *see Poster J. Isaak !***

# Conclusions

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# Summary

TECHNISCHE UNIVERSITÄT DARMSTADT

*Thank you !*

**And thanks to my postdocs and (visiting) students at Yale working on what I showed during the past ~5 years:**

**N. Cooper, F. Naqvi, Ch. Bernards, L. Bettermann, P. Goddard, P. Humby, R. Ilieva**

**And the groups from TU Darmstadt, GSI, HIGS, Lexington, Los Alamos, Livermore, and Cologne:**
**G. Rusev, J. Beller, M. Bhike, B.P. Crider, V. Derya, J. Isaak, J.H. Kelley, E. Kwan, B. Löher, E.E. Peters, N. Pietralla, R. Raut, C. Romig, D. Savran, M. Scheck, A.P. Tonchev, W. Tornow, S.W. Yates, M. Zweidinger, A. Zilges**

**... and for support:**

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Yale

Bundesministerium für Bildung und Forschung
BMBF

HIC for FAIR
Helmholtz International Center

Deutsche Forschungsgemeinschaft
DFG

SFB634

DAAD

# The present crew...

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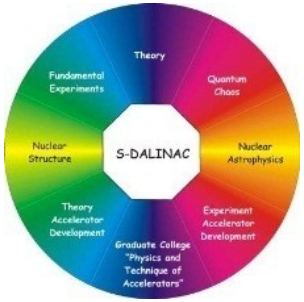
## Our group

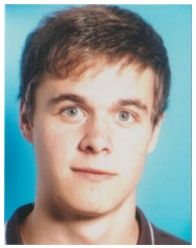

N. Pietralla, V. Werner

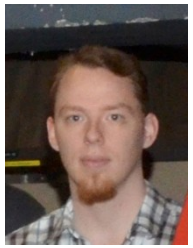






J. Beller, H. Pai, C. Romig, M. Zweidinger



T. Beck, U. Gayer, L. Mertes, P. Ries