Nuclear Resonance Fluorescence with monoenergetic photons and fundamental experiments at ELI-NP

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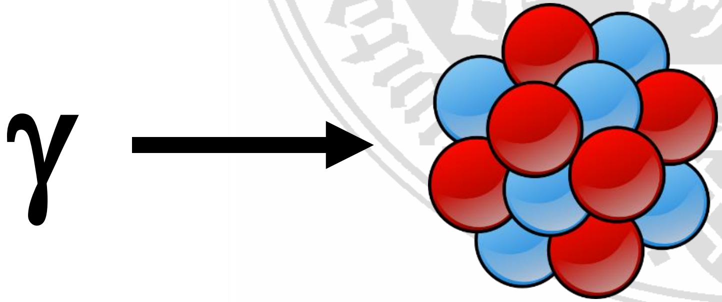

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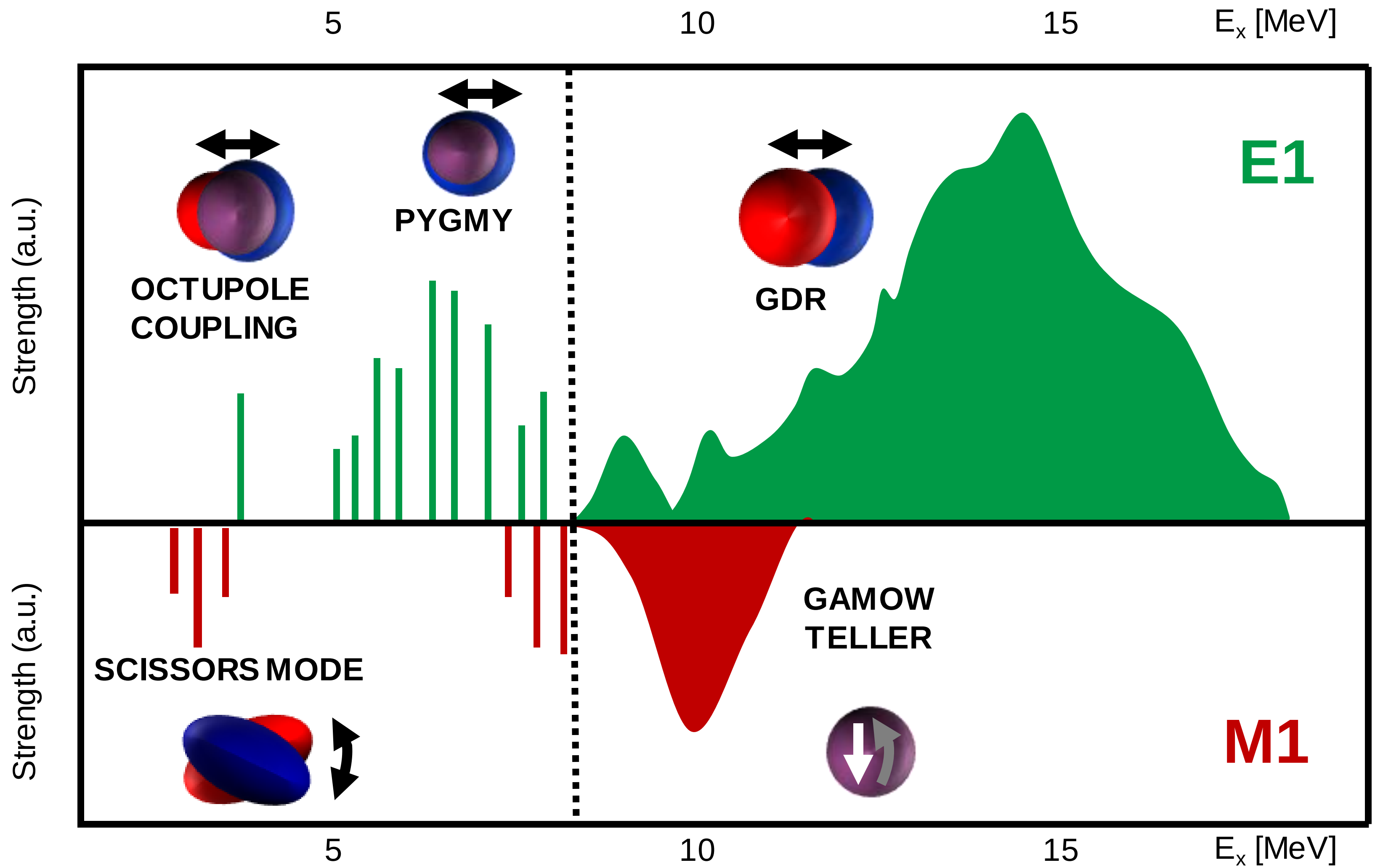
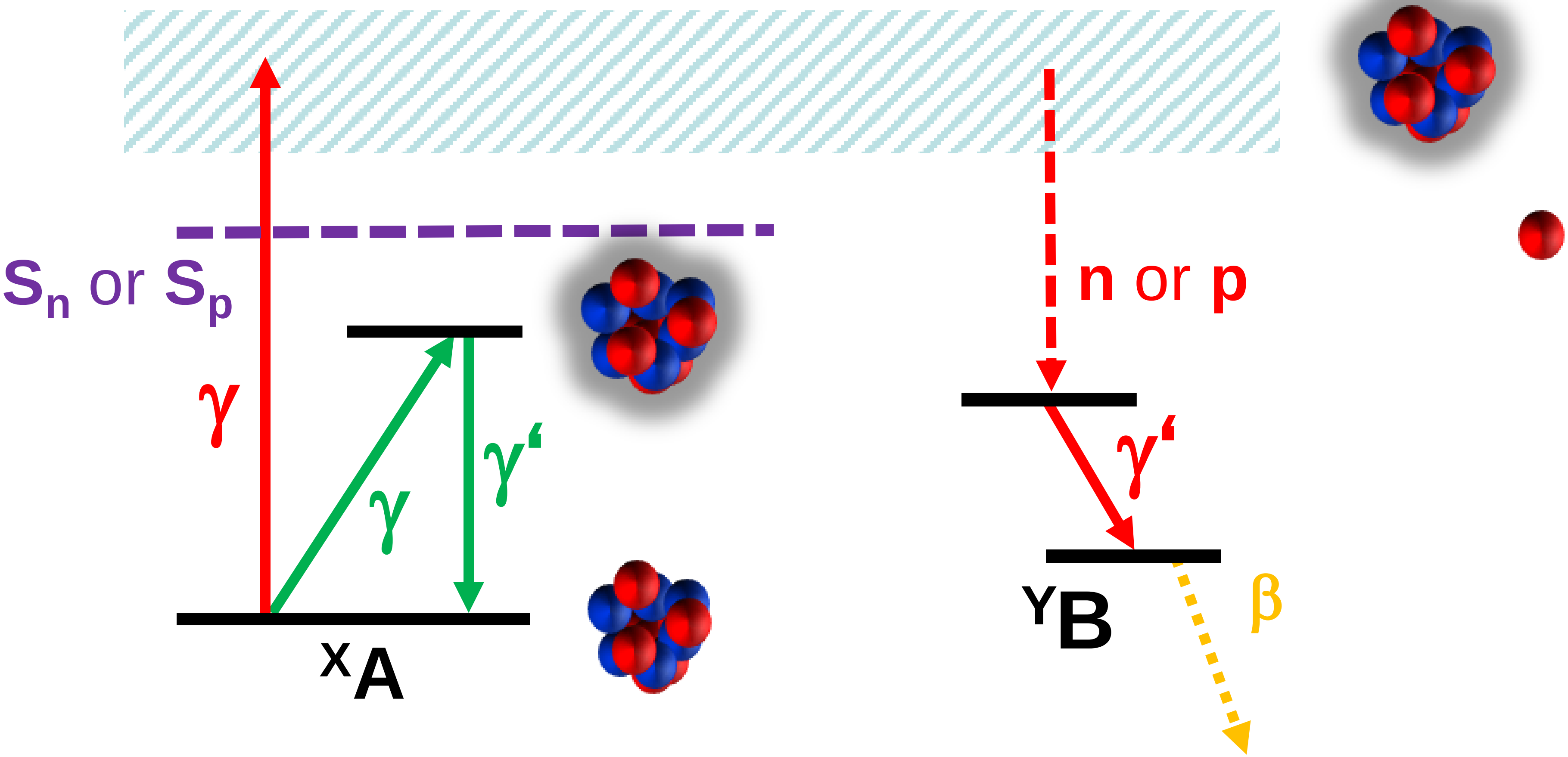
Dipole response in atomic nuclei



Collectivity emerging from complexity

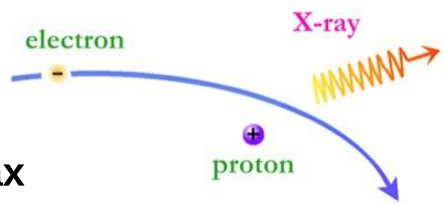
Nuclear Resonance Fluorescence

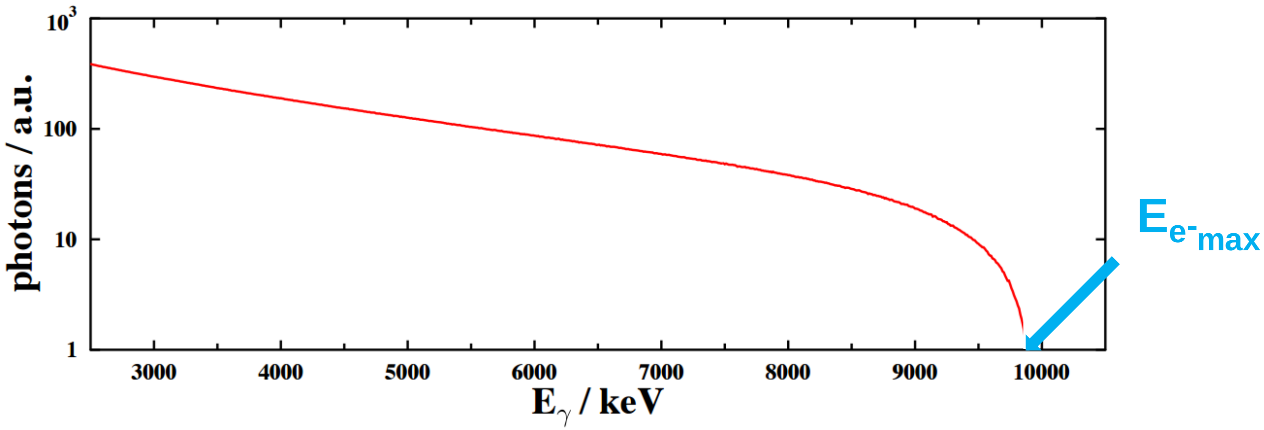


- Nuclear Resonance Fluorescence (NRF)
- Photodisintegration, Photofission

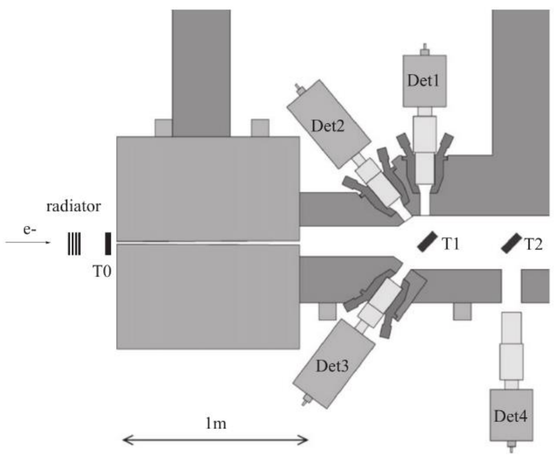
Photon beams production via **bremsstrahlung**:

- **No polarization**
- **High flux**
- **Continuous-energy** photons beams **up to E_{e^-max}**





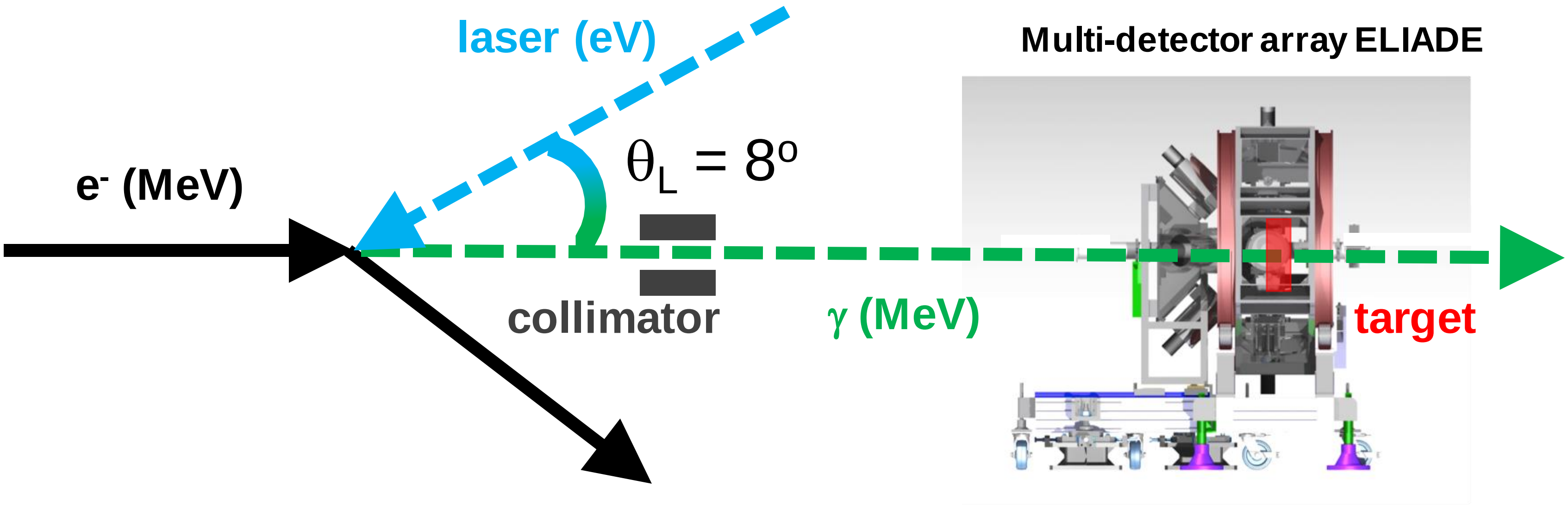
Seminal developments in the last decades by:
TU Darmstadt, University of Cologne,
HZDR, JLU Giessen, University of Stuttgart



Darmstadt **H**igh **I**ntensity **P**hoton **S**etup (**DHIPS**)

TECHNISCHE UNIVERSITÄT DARMSTADT
University of Cologne
HZDR
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
University of Stuttgart

Laser-Compton backscattering

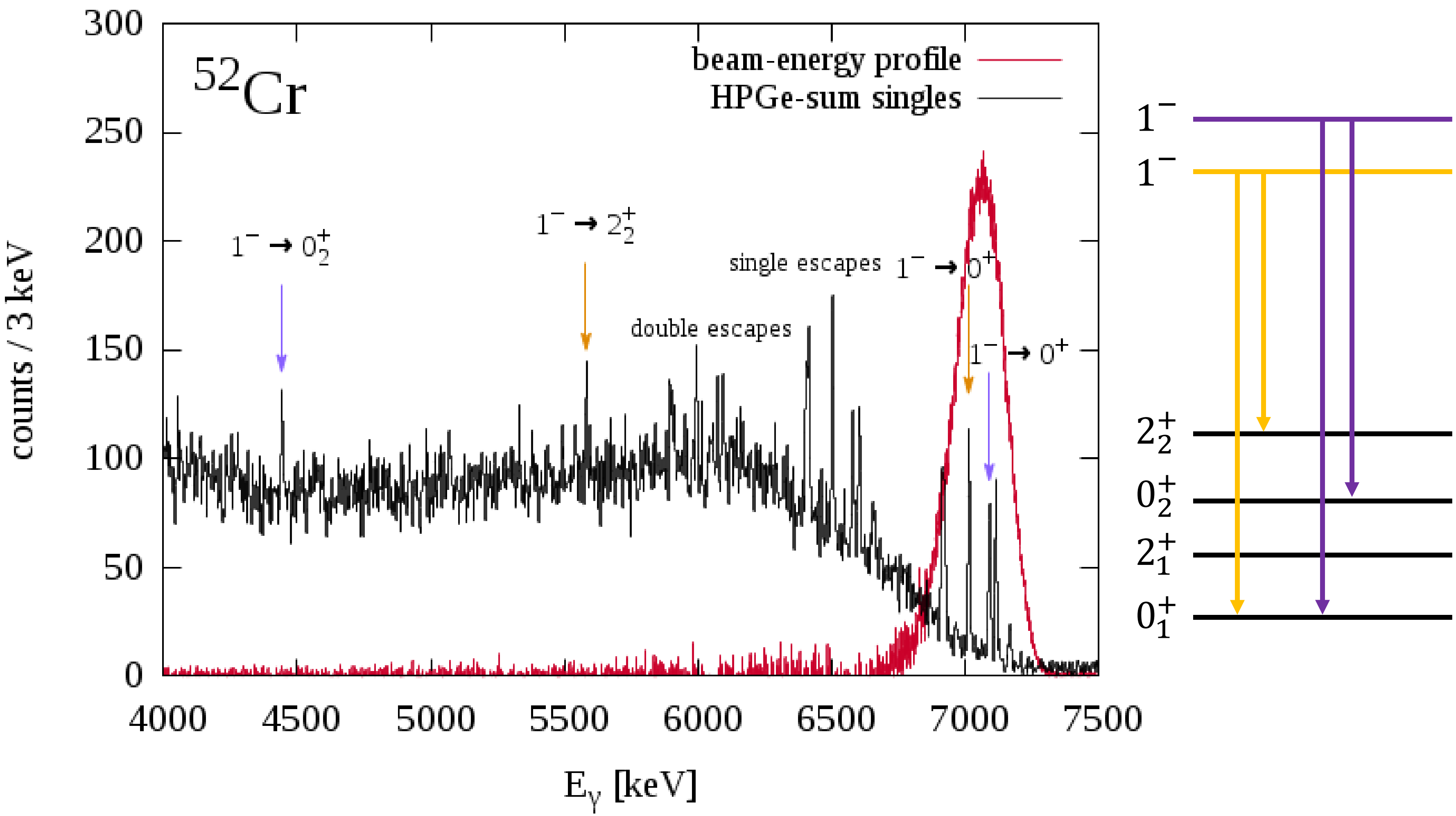


$$E_\gamma = \left(\frac{4E_L\gamma^2/\,(1+R)}{1+\gamma^2\theta^2\;/\;(1+R)}\right) \text{ with } R = \frac{4E_L\gamma}{mc^2} \text{ and } \gamma = \frac{E_e}{mc^2}$$

- Monoenergetic γ-ray beam
- Tunable energies in the MeV-range
- Fully polarized beam

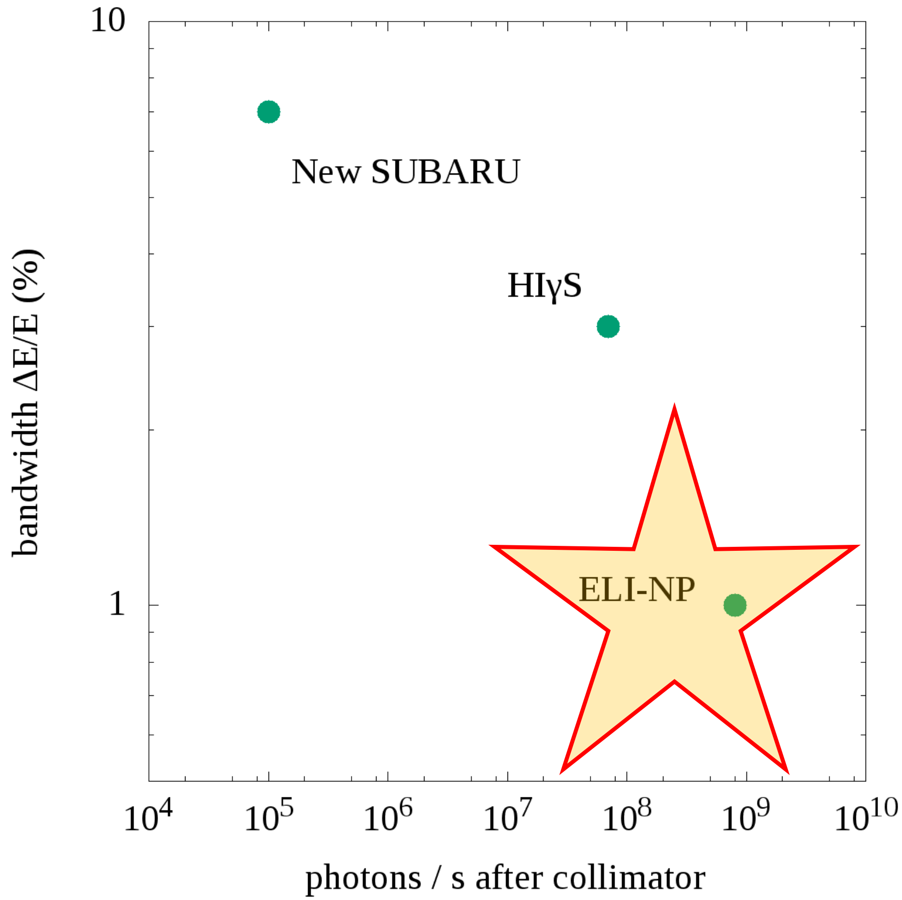
Existing facilities: **H**igh **I**ntensity **G**amma-ray **S**ource (**HIγS**), Duke University, USA
New SUBARU, SPring-8, Japan

Typical γ-ray beam-profile at HIγS



Research groups Pietralla (TUD) / Savran (GSI) / Zilges (UoC)

Typical γ-ray beam-profile at ELI-NP



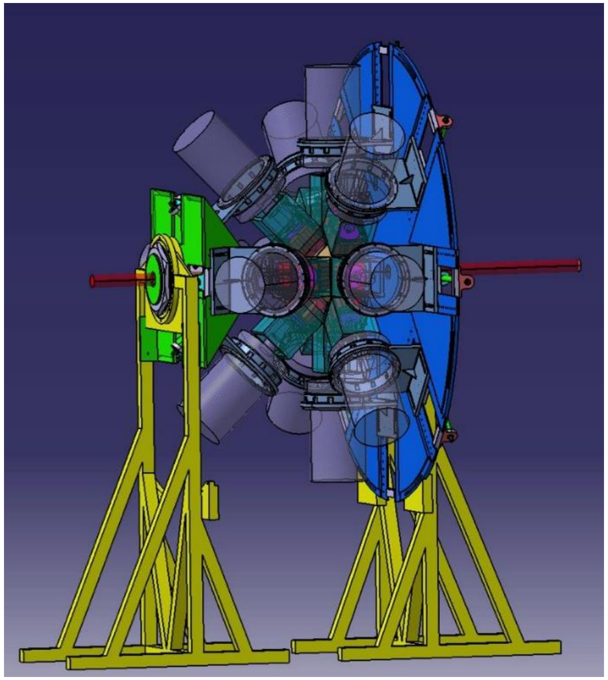
Selection of **energy range** with existing facilities

↓

Selection of **excitations** with ELI-NP!

New physics with ELI-NP!

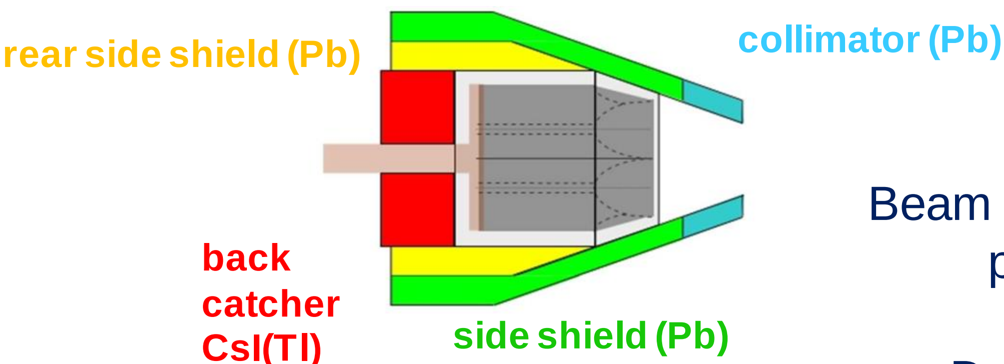
The multi-detector array ELIADE



<u>Detector properties:</u>

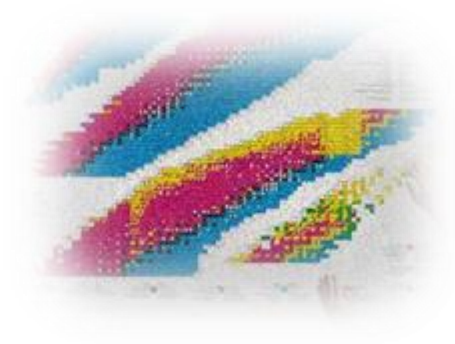
- **8 segmented HPGe Clover semiconductor detectors**
  - **High energy resolution: 2 keV @ 1332 keV**
  - **ε_{total} @ 1.3 MeV ≅ 6%**
  - 4 crystals ('leaves') per Clover
  - 8 segments per crystal
  - Anti-Compton shields

- **4 $LaBr_3$ scintillation detectors**
  - **very fast**

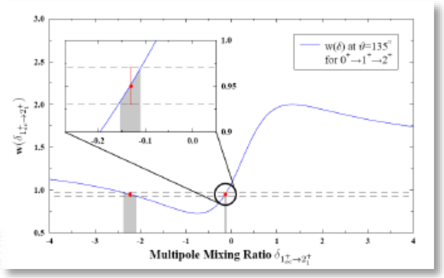


Beam profile monitoring (Pietralla group) and pair-spectrometer (Kröll group) by TU Darmstadt.
Development of signal extraction and detector tests by University of Cologne.

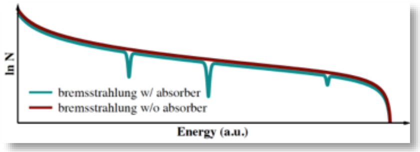
Availability frontier
(access to rare isotopes)

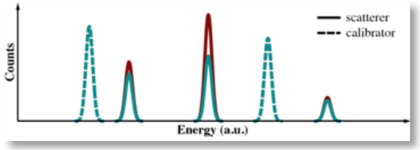


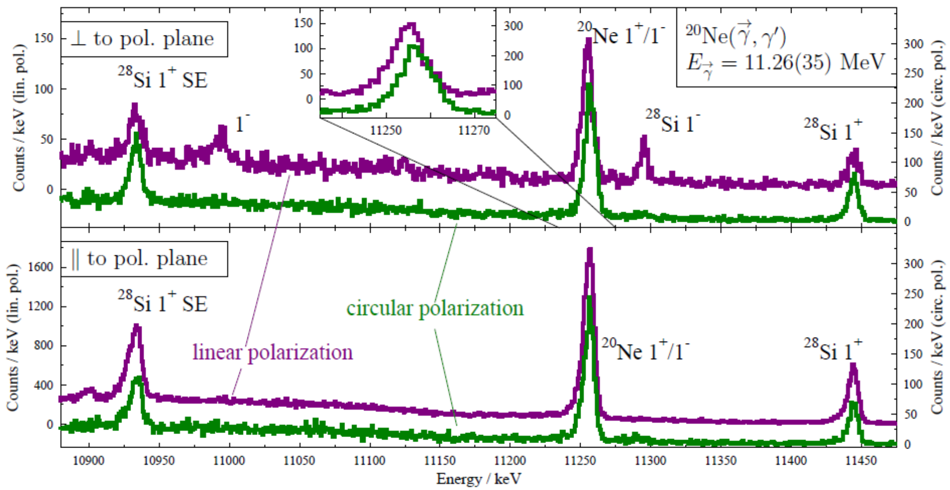
Sensitivity frontier
(weak channels)



Precision frontier
(high statistics)







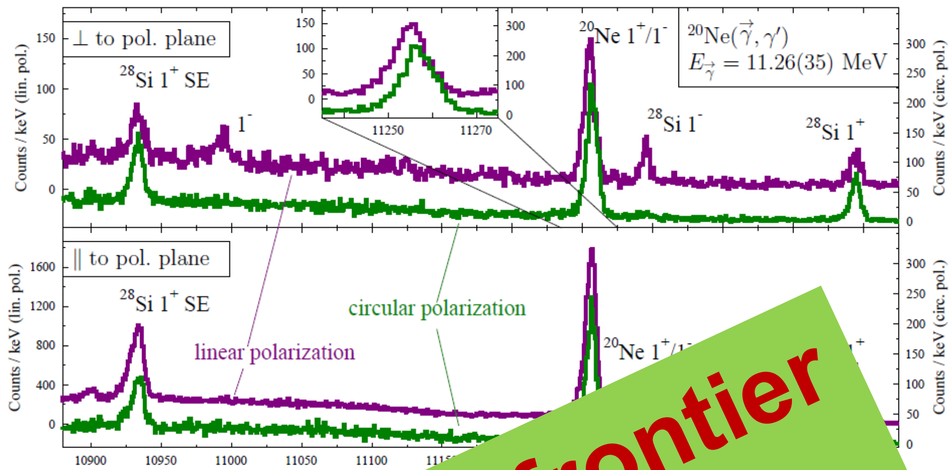
- small contributions of the **weak interaction** to the **effective nucleon–nucleon interaction**
  - ➢ effective nuclear force violates parity
  - ➢ **J^{π} = 1^{+}/ 1^{-} parity doublet** of ^{20}Ne at 11.26 MeV is suited to **observe parity violation**

Only possible with **selective excitation by fully polarized, high-intense γ-ray beams** at ELI-NP!

J. Beller *et. al.*, PLB **741** (2015) 128-133

Pietralla group (TU Darmstadt)

Physics cases – Do nuclear excitations violate parity?



Sensitivity frontier
(weak channels)

- small contributions of t… to the **effective nucleon–nucle…**
  - ➢ effective … es parity
  - ➢ **J$^\pi$ = 1$^+$/ 1** … **ublet** of ^{20}Ne at 11.26 MeV is suited to **observe p… violation**

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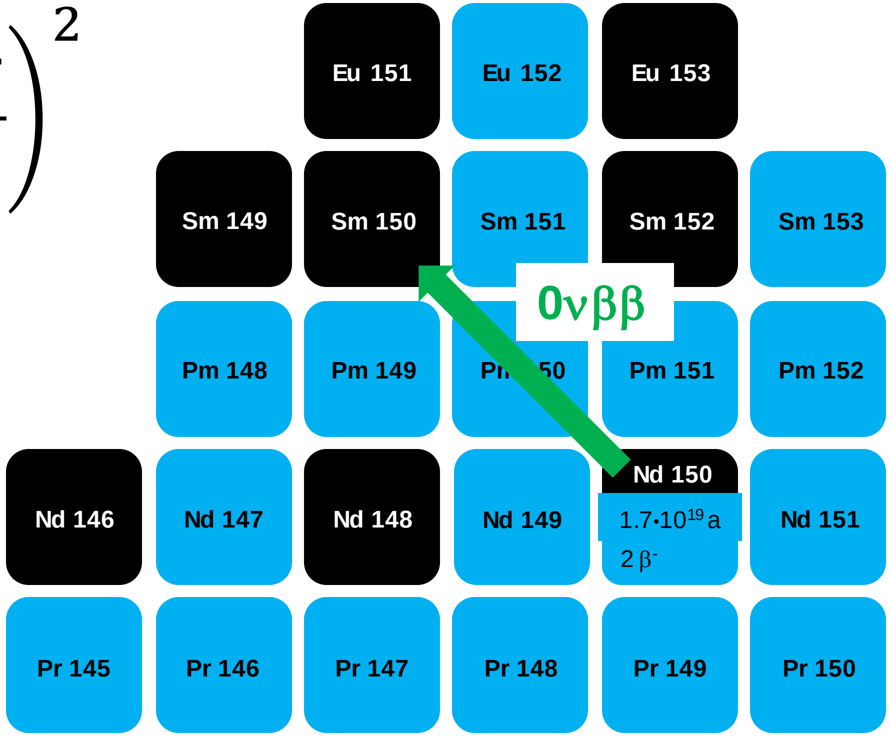
Physics cases – constraints on $0\nu\beta\beta$ decay matrix elements

$$\lambda_{0\nu\beta\beta} = G_{0\nu}\left|M^{(0\nu)}\right|^2 \left(\frac{< m_\nu >}{m_e}\right)^2$$

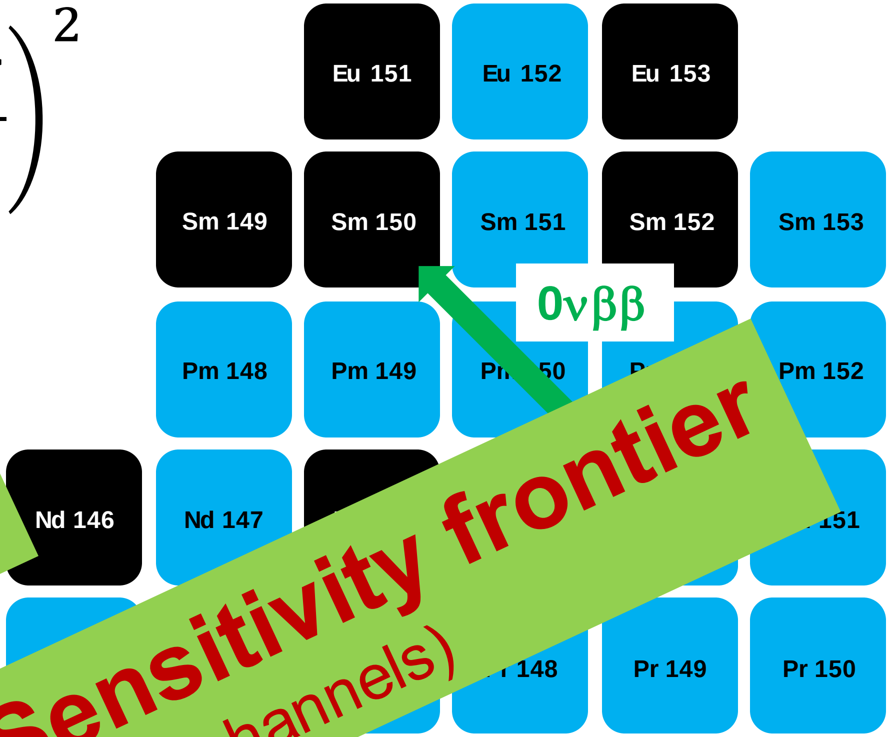


- Precise calculation of **nuclear matrix element** $\boldsymbol{M^{(0\nu)}}$ for determination of **neutrino mass**
- **$J^{\pi} = 1^{+}$ scissors mode sensitive to proton-neutron coupling** in IBM-2

→ Only possible with high-intense γ-ray beams and **high sensitivity to weak decays** at ELI-NP!

Pietralla group (TU Darmstadt)

$$\lambda_{0\nu\beta\beta} = G_{0\nu} \left| M^{(0\nu)} \right|^2 \left(\frac{< m_\nu >}{m_e} \right)^2$$



- Precise calculation of **nuclear matrix elem**... $M^{(0\nu)}$ for deter... **neutrin**...
- **J**$^{\pi}$ ... **ode se**... **proton-neu**... **coupling** in IBM-2

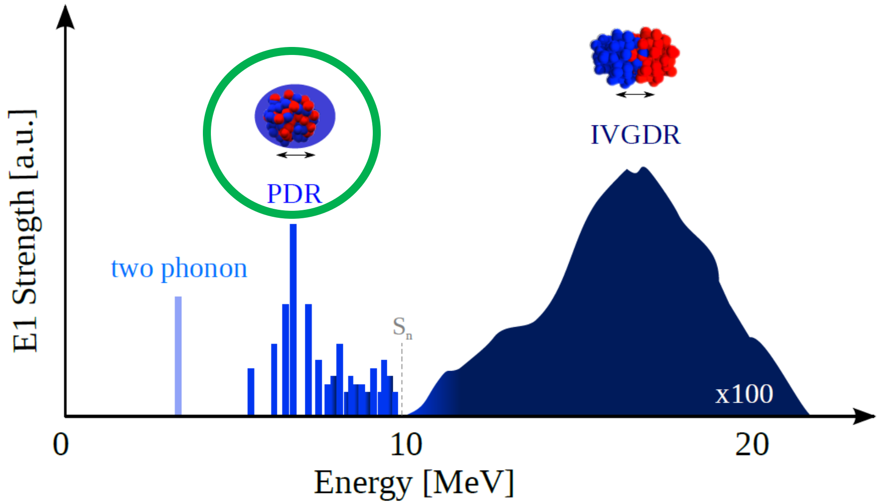
Precision frontier
(high statistics)

Sensitivity frontier
(weak channels)

→ Only possible with high-intense γ-ray beams and **high sensitivity to weak decays** at ELI-NP!

Pietralla group (TU Darmstadt)

Physics cases – Acces to the EOS: Pygmy Dipole Resonance

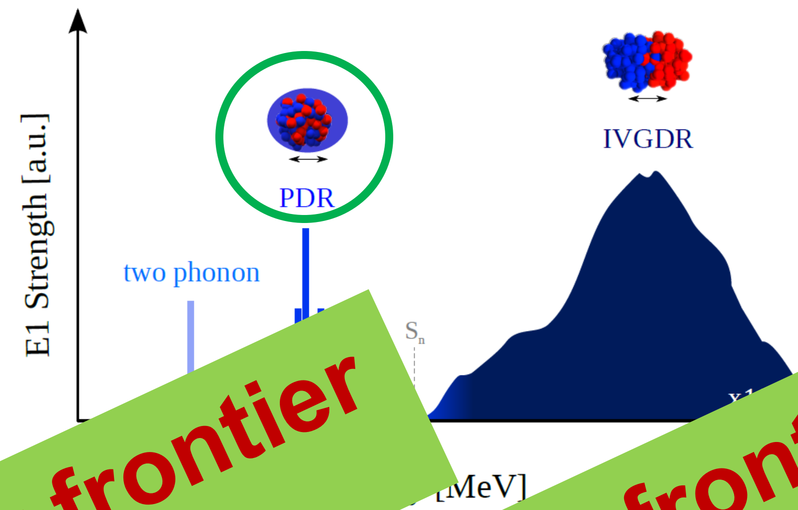


- Energy range of **5-9 MeV**
- Oscillation of **neutron-skin** versus proton-neutron core
  - Determination of **neutron-skin thickness**!
  - Constrain **symmetry energy parameter** in the EOS!
  - Impact on **astrophysical scenarios** like **rapid neutron capture process**!

⇒ Only possible with selective excitation by fully polarized, highly-intense γ-ray beams and high sensitivity to decays at ELI-NP!

Savran group (GSI), Aumann group (TU Darmstadt), Pietralla group (TU Darmstadt), Zilges group (University of Cologne)

Physics cases – Acces to the EOS: Pygmy Dipole Resonance



- E... **...MeV**
- ...**utron** ... utron co...
- ...minati... ...**ckness**!
- Constrain **sy**... **param**...
- Impact on **ast**... **al scenari**... **on capture process**!

Sensitivity frontier
(weak channels)

Availability frontier
(access to rare isotopes)

Precision frontier
(high statistics)

→ Only possible with selective exc... ...on by fully polarized, highly-intense γ-ray beams and high sensitivity to decays at ELI-NP!

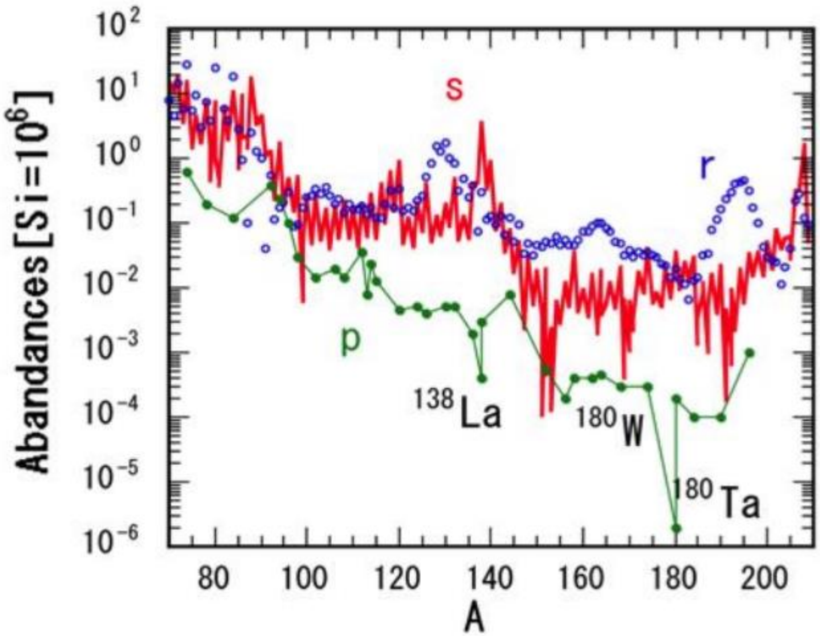
Savran group (GSI), Aumann group (TU Darmstadt), Pietralla group (TU Darmstadt), Zilges group (University of Cologne)

Physics cases – origin of matter: p-process nucleosynthesis

Nucleus	Natural abundence [%]	Abundance (10^6 Si)[97]	
^{74}Se	0.89	0.55	
^{78}Kr	0.35	0.153	*
^{84}Sr	0.56	0.132	
^{92}Mo	14.84	0.378	
^{94}Mo	9.25	0.236	
^{96}Ru	5.54	0.103	
^{98}Ru	1.87	0.035	
^{102}Pd	1.02	0.0142	
^{106}Cd	1.25	0.0201	
^{108}Cd	0.89	0.0143	
^{113}In	4.29	0.0079	
^{112}Sn	0.97	0.0372	
^{114}Sn	0.66	0.0252	
^{115}Sn	0.34	0.0129	*
^{120}Te	0.09	0.0043	
^{124}Xe	0.09	0.00571	
^{126}Xe	0.09	0.00509	*
^{130}Ba	0.106	0.00476	
^{132}Ba	0.101	0.00453	
^{138}La	0.09	0.000409	*
^{136}Ce	0.185	0.00216	*
^{138}Ce	0.251	0.00284	
^{144}Sm	3.07	0.008	
^{152}Gd	0.2	0.00066	
^{156}Dy	0.06	0.000221	
^{158}Dy	0.1	0.000378	*
^{162}Er	0.14	0.000351	*
^{164}Er	1.61	0.00404	*
^{168}Yb	0.13	0.000322	
^{174}Hf	0.16	0.000249	*
^{180}Ta	0.012	2.48E-06	*
^{180}W	0.12	0.000173	
^{184}Os	0.02	0.000122	*
^{190}Pt	0.014	0.00017	
^{196}Hg	0.15	0.00048	

- **γ-process:** highly energetic photons disintegrate stable seed nuclei
- Stable nuclei on neutron deficient side are called **p-nuclei (35 isotopes)**
- **Very low abundances**

Physics cases – origin of matter: p-process nucleosynthesis

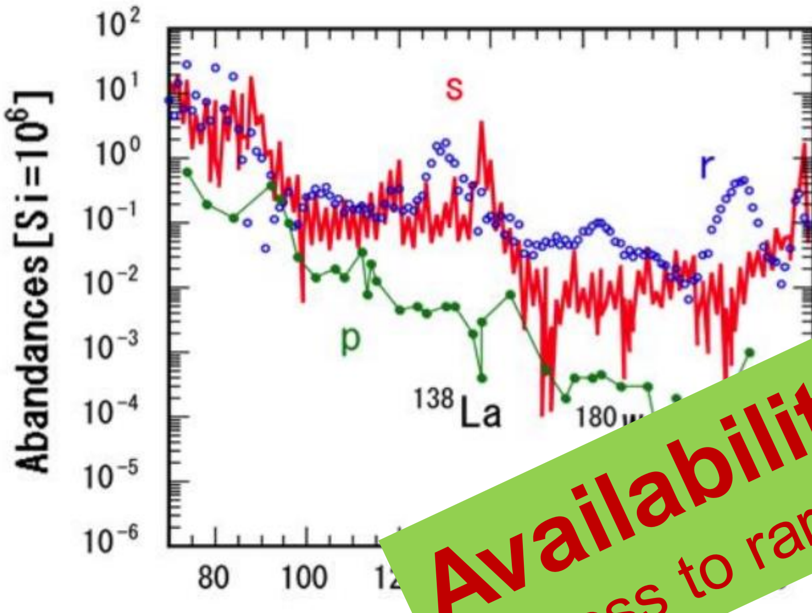


- Typically **1 mg** target samples of p-nuclides

High flux necessary!

Only possible with **high fluxes** and **highly efficient** γ-ray spectrometer ELIADE

Zilges group (University of Cologne), Schwengner group (HZDR)



Availability frontier
(access to rare isotopes)

- Typically **1 mg** target samples of p-nuclides

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Example of ^{240}Pu:

Pu 240
6563 a

- **10 mg target** material
  - **10^{19} nuclei**
  - with $T_{1/2} = 10^{12}$ s one expects **10^7 decays / s,** but **only low-energy gammas (<100 keV)**
  - **Background** can be **almost completely reduced** with lead and copper shielding
- E1 excitation at 500 keV with Γ_0 = 50 meV and M1 excitation at 2000 keV with Γ_0 = 25 meV (values from ^{238}U)
- γ-ray beam with **5000 gammas / (eV•mm²•s)**
  - **50-200 reactions / s**

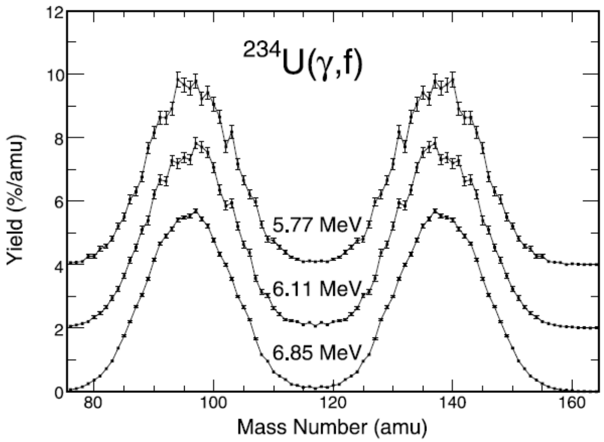
→ **One relevant reaction / s in the HPGe detectors**

Np 237
$2.1 \cdot 10^6$ a

Am 243
7370 a

Pu 240
6563 a

Cm 248
$3.4 \cdot 10^5$ a



- Access to magnetic and electric dipole excitations in **unstable nuclei**!
- Photofission studies

→ Only possible with **selective excitation by fully polarized, high-intense γ-ray beams and high sensitivity** at ELI-NP!

Zilges group (University of Cologne), Schwengner group (HZDR), Enders group (TU Darmstadt)

Physics cases – Dipole response of unstable nuclei

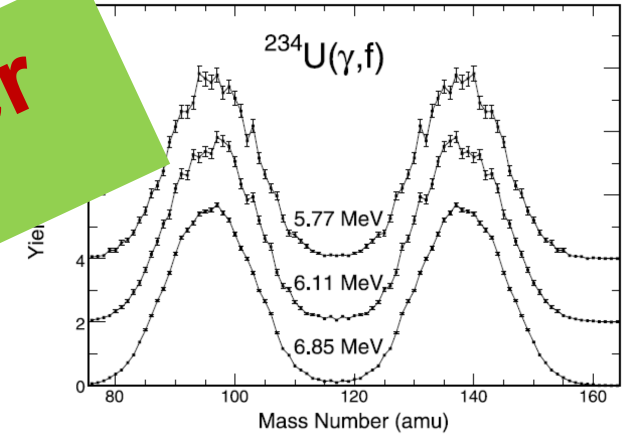
Np 237
$2.1 \cdot 10^6$ a

Am 243
7370 a

Pu 240
6563 a

Cm 248
$3.4 \cdot 10^5$ a

- Access to magnetic a… excitations in u…
- Photofissic…



Availability frontier
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Zilges group (University of Cologne), Schwengner group (HZDR), Enders group (TU Darmstadt)

Involvement of German research groups

More than 20 German research groups

Prof. Dr. Almudena Arcones (TU Darmstadt) Prof. Dr. Thomas Aumann (TU Darmstadt) Prof. Dr. Joachim Enders (TU Darmstadt) Dr. Christoph Fransen (Universität zu Köln) Dr. Jürgen Gerl (GSI Darmstadt) Prof. Dr. Jan Jolie (Universität zu Köln) Prof. Dr. Thorsten Kröll (TU Darmstadt) Prof. Dr. Horst Lenske (Universität Giessen) Dr. Gabriel Martinez-Pinedo (TU Darmstadt) Dr. Oliver Möller (TU Darmstadt) Prof. Dr. Dr. h.c. Norbert Pietralla (TU Darmstadt) Prof. Dr. Peter Reiter (Universität zu Köln) Prof. Dr. Markus Roth (TU Darmstadt) PD Dr. Deniz Savran (GSI) PD Dr. Heiko Scheit (TU Darmstadt) Dr. Ronald Schwengner (HZDR) Prof. Dr. Achim Schwenk (TU Darmstadt) Prof. Dr. Peter von Neumann-Cosel (TU Darmstadt) Dr. Andreas Wagner (HZDR) Dr. Volker Werner (TU Darmstadt) Prof. Dr. Andreas Zilges (Universität zu Köln)