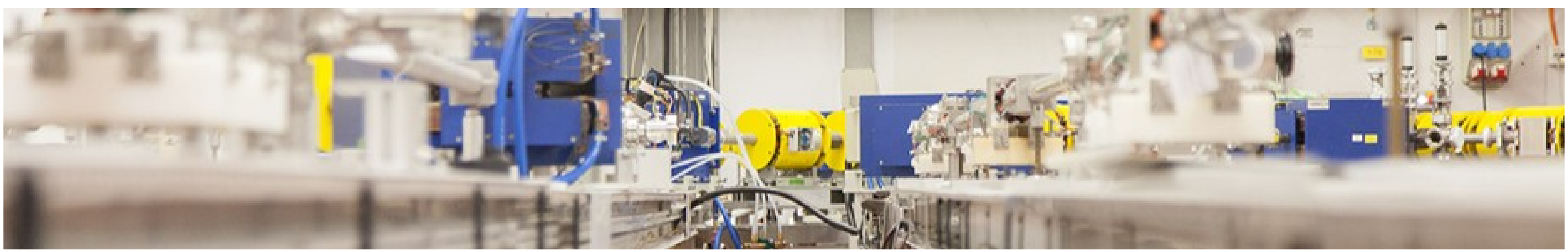
Photon Physics and New ERL Developments at the S-DALINAC

TECHNISCHE UNIVERSITÄT DARMSTADT

Volker Werner

Senior Researcher, Institut für Kernphysik, TU Darmstadt
AG Pietralla



HIC for FAIR Helmholtz International Center

MaRS TEILCHENSTRAHLEN UND MATERIE

ACCELENCE

Deutsche Forschungsgemeinschaft DFG

SFB 1245

Overview

The Nuclear Photo Response:

- **Photo-Excitation**
- **Typical Photon Beams (Bremsstrahlung, CBS)**
- **Overview of Dipole Modes at “Low” Energies (< S_n)**

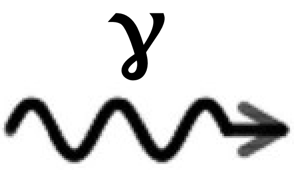
Sample Physics Cases

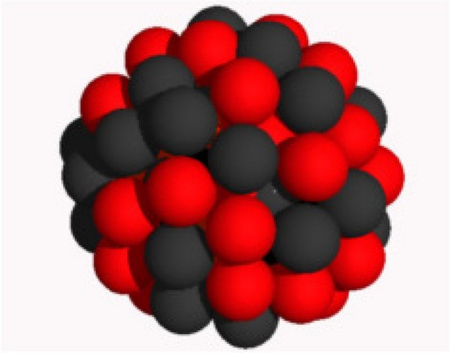
- **The Pygmy Dipole Resonance**
- **The Scissors Mode - Relation to 0υββ**

S-DALINAC Future Plans

- **S-DALINAC now commissioned as ERL**
- **Next Step: FEL → CBS Beams**

Photonuclear Reactions

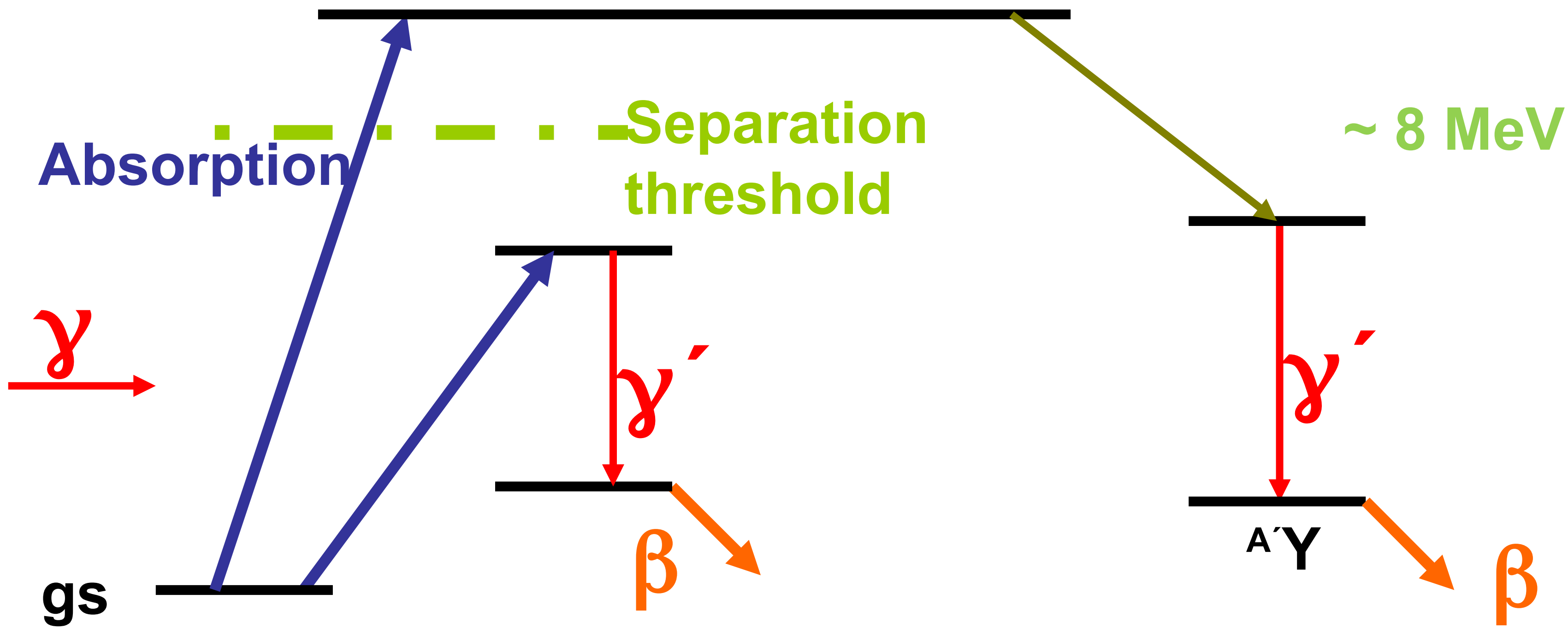




What happens?

Photonuclear Reactions

TECHNISCHE UNIVERSITÄT DARMSTADT



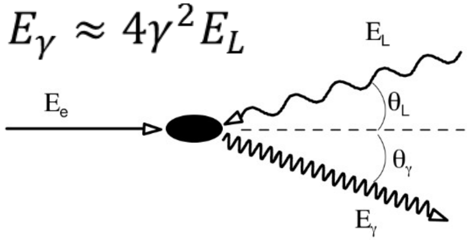
Nuclear Resonance Fluorescence (NRF)

Photoactivation

Photodisintegration (-activation)

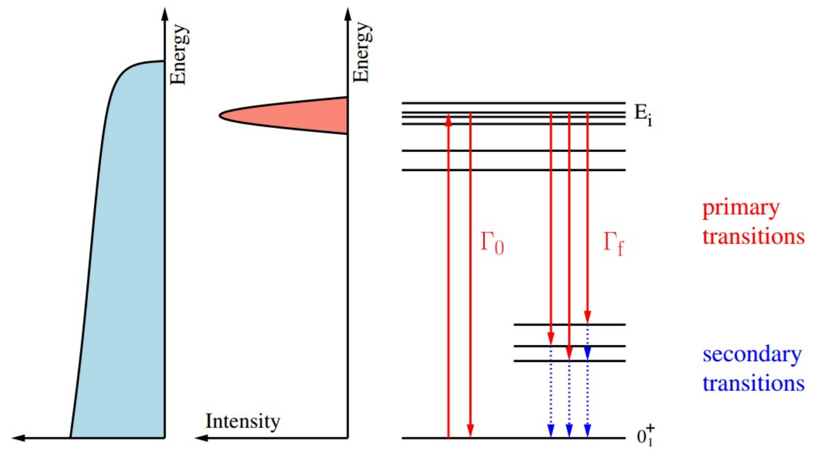
Bremsstrahlung vs. Compton Back Scattering (CBS)

$$E_\gamma \approx 4\gamma^2 E_L$$



Compton back-scattering, FEL

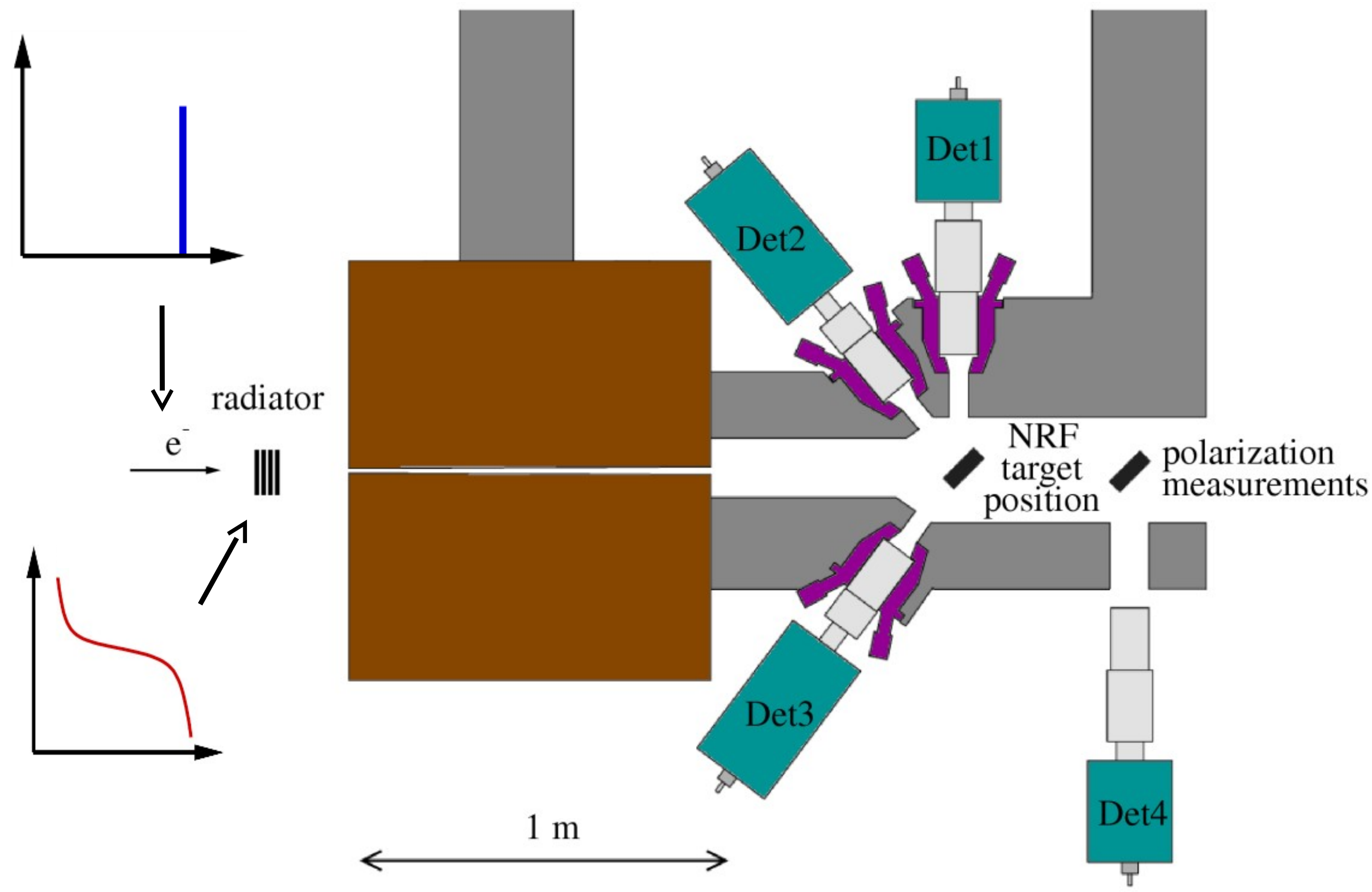
NRF



Savran, Aumann, Zilges, Prog. Part. Nucl. Phys. 70 (2013) 210-245.

Need: γ-beam with high energy resolution and high repetition rate

Darmstadt High-Intensity Photon Setup (DHIPS)

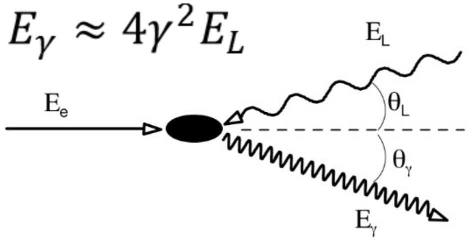


K. Sonnabend et al., NIM A 640, 6 (2011)

Bremsstrahlung vs. Compton Back Scattering (CBS)

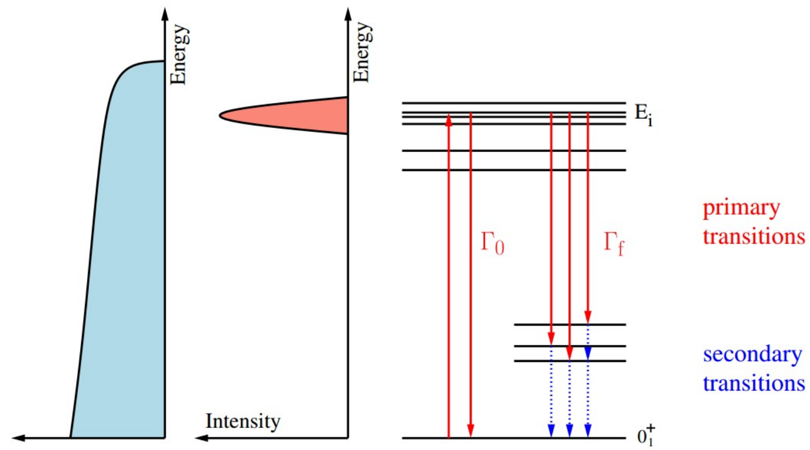
- "mono-energetic"
- ~fully polarized → polarization physics

$$E_\gamma \approx 4\gamma^2 E_L$$



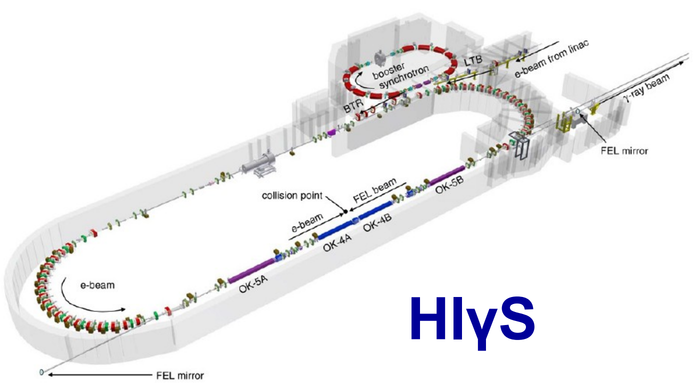
Compton back-scattering, FEL

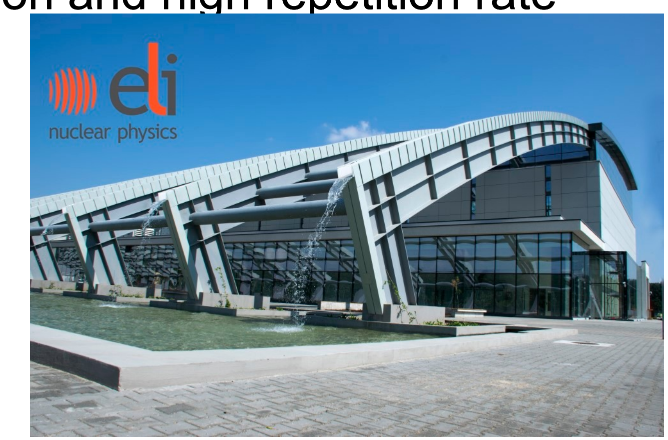
NRF



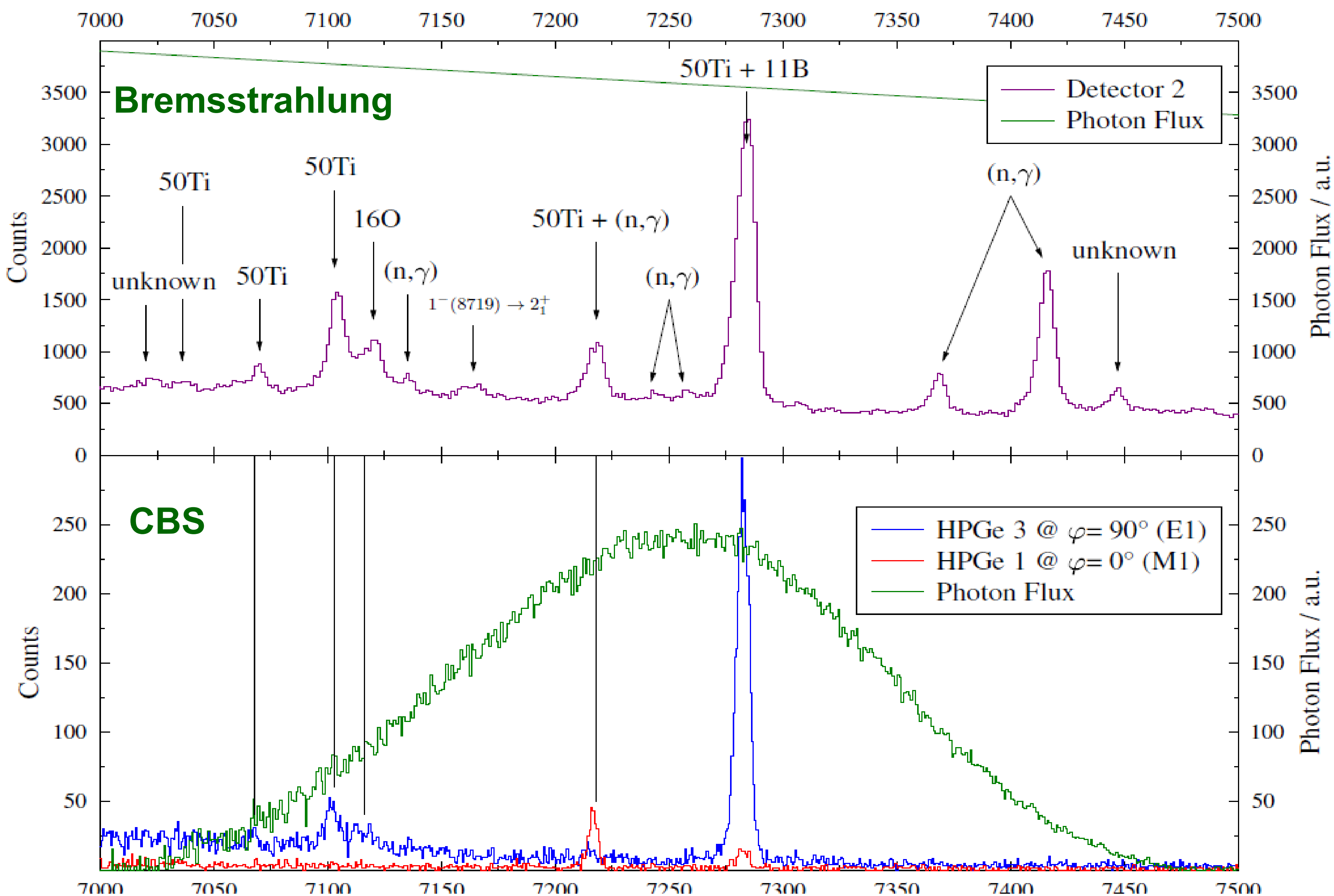
Savran, Aumann, Zilges, Prog. Part. Nucl. Phys. 70 (2013) 210-245.

Need: γ-beam with high energy resolution and high repetition rate

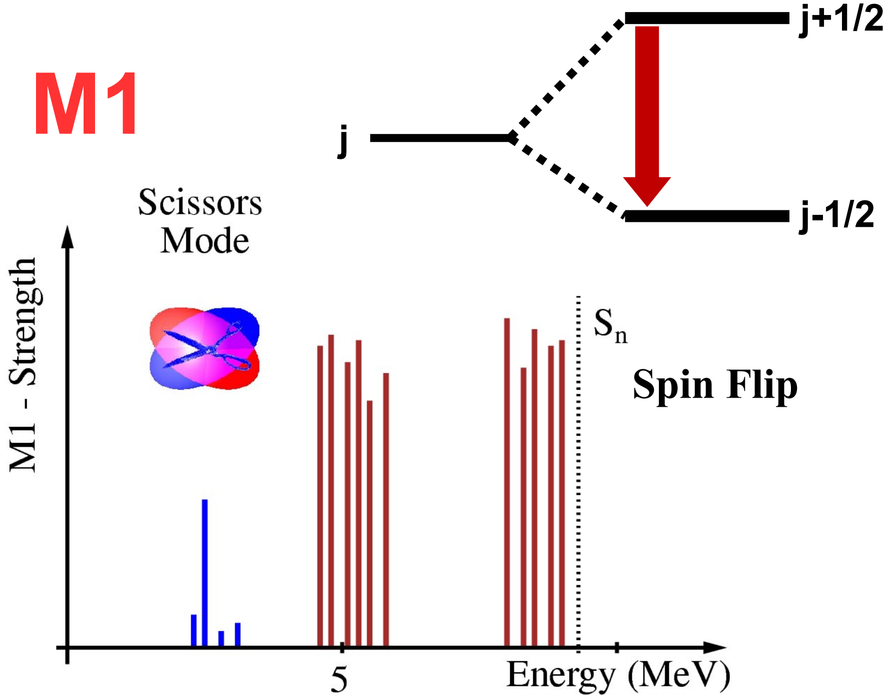


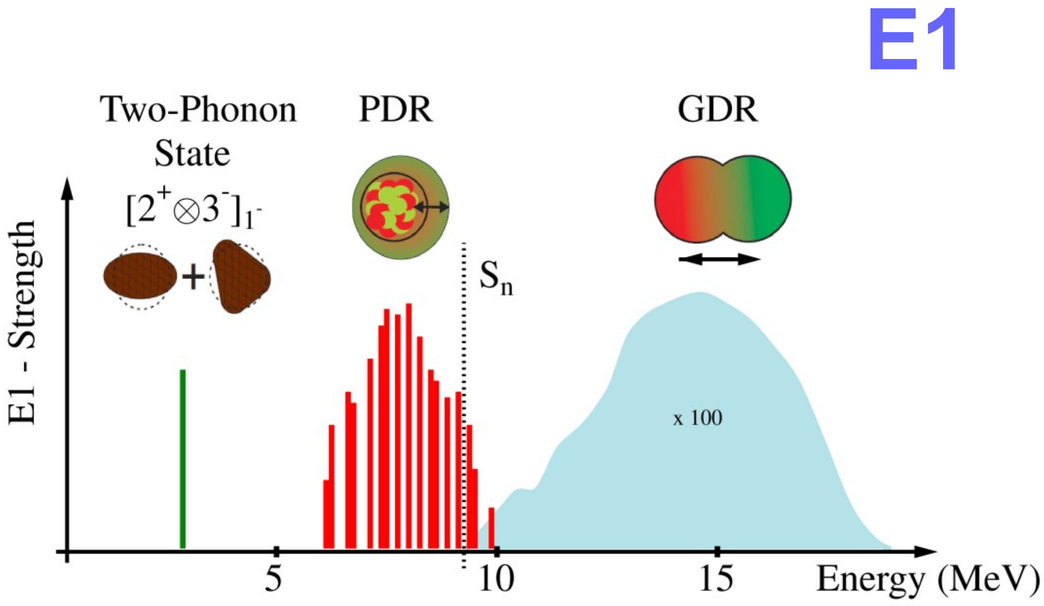


All CBS Beam Advantages in one picture



Dipole Physics





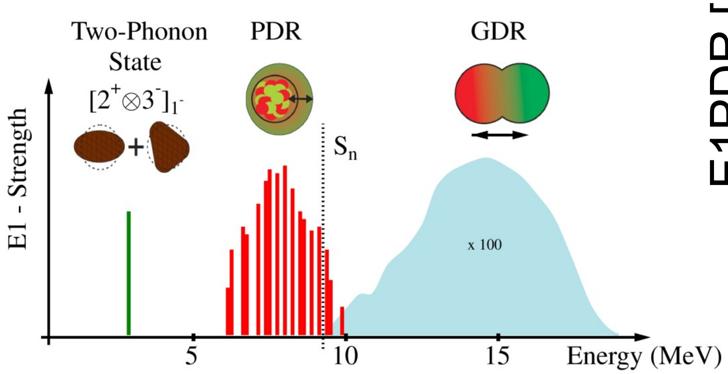
1. Example: nuclear EOS

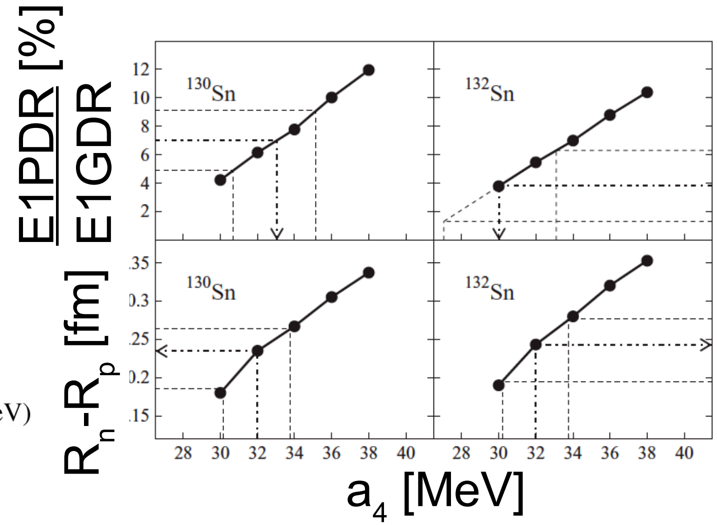
PDR, Neutron Skin, and Asymmetry Parameter

$$\alpha = (N - Z)/A$$

$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + \cdots$$

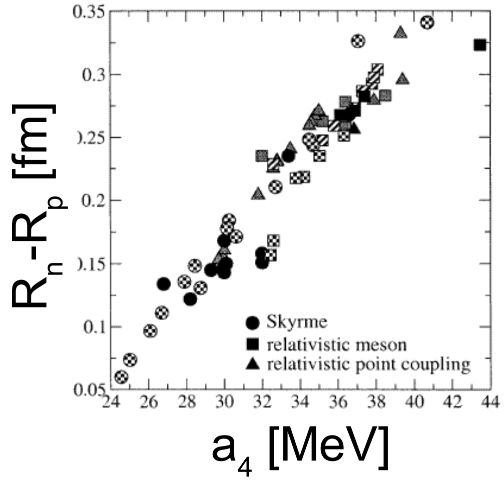
$$S_2(\rho) = \underline{a_4} + \frac{p_o}{\rho_o^2}(\rho - \rho_o) + \cdots$$





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

QRPA



R.J.Furnstahl NPA 706(2002)85-110

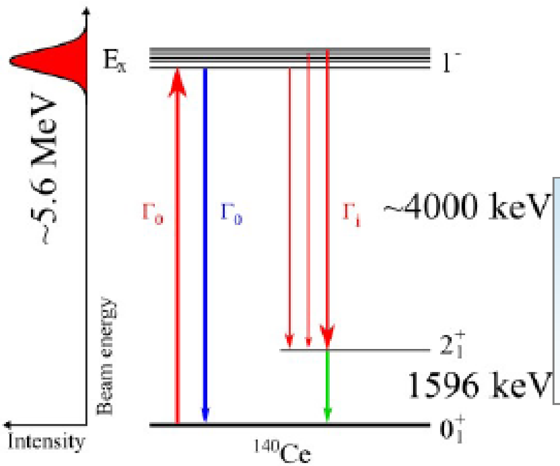
EFT / Mean Field

Models indicate asymmetry parameter dependence on neutron skin !
There seems to be correlation to PDR strength.

(under debate!)

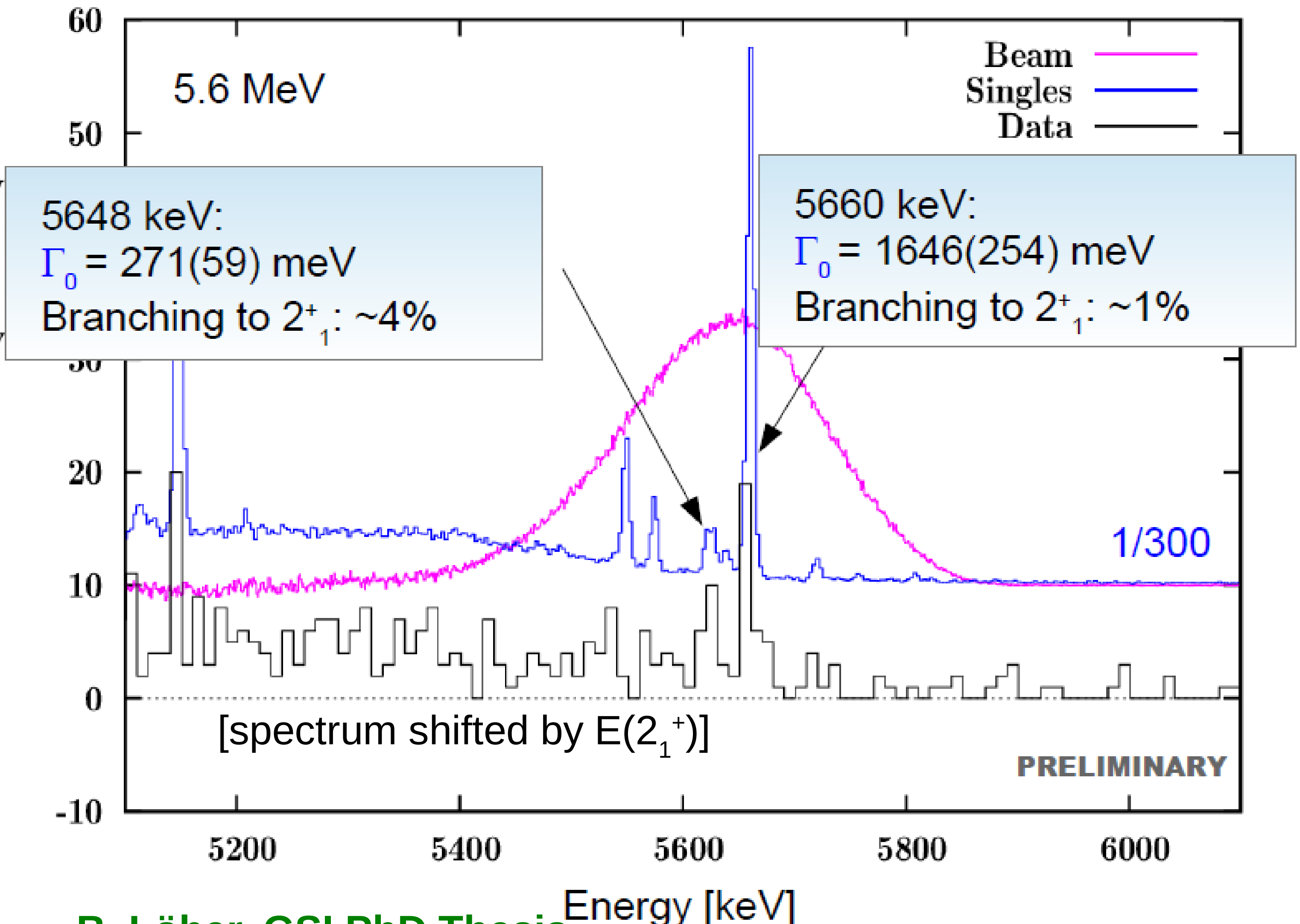
First Coincidence Spectroscopy

Gate on LaBr → HPGe spectra



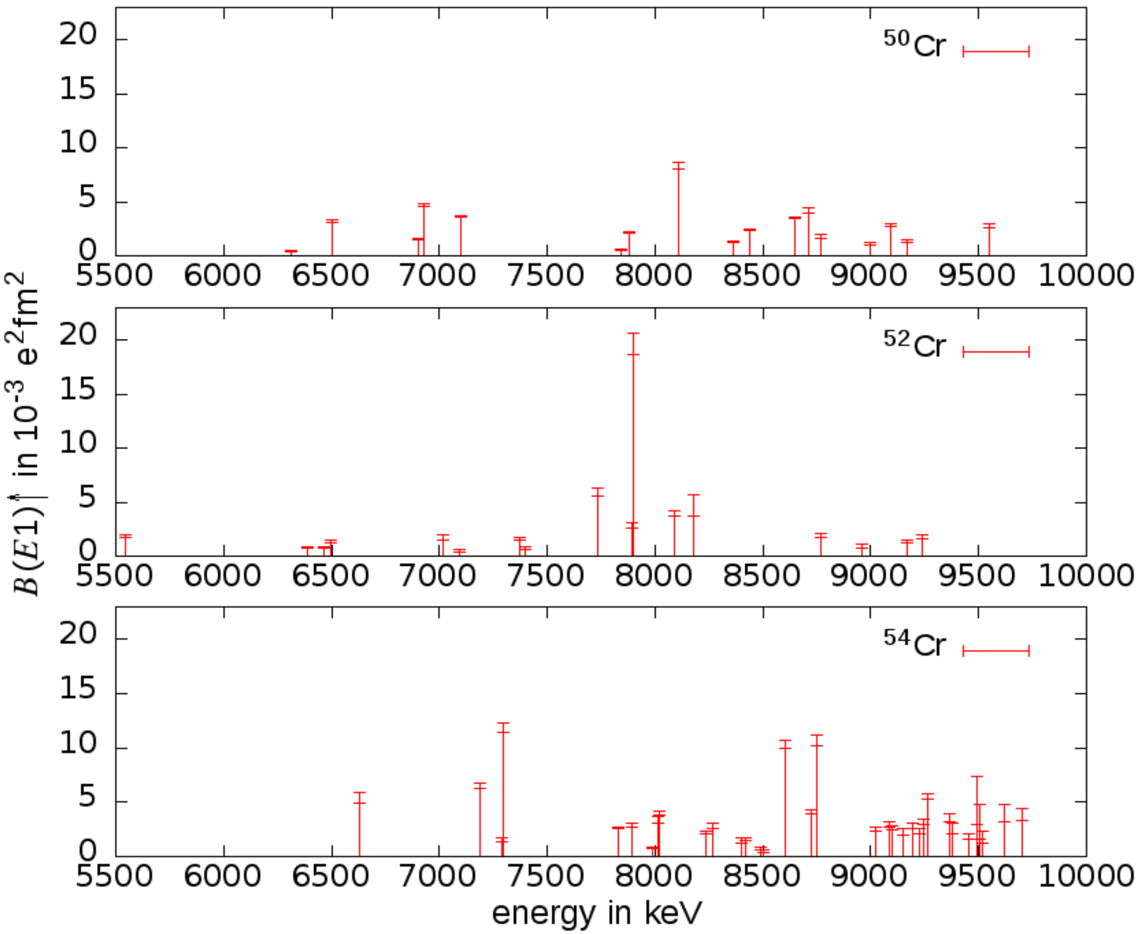
$E(2^+_1) = 1596$ keV

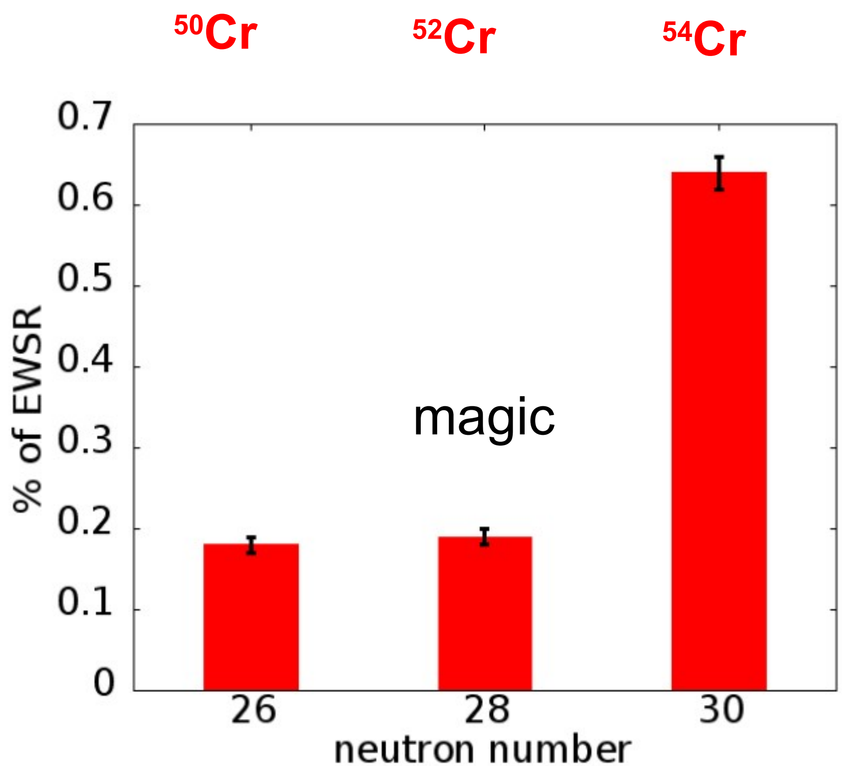
- **Present Experiments at HIγS**
- **First coincidence γ-spectroscopy**



B. Löher, GSI PhD Thesis

Origin of the PDR – Shell Effects





H. Pai et al., Phys. Rev C **88**, 054316 (2013)
P. Ries, MA Thesis, TU Darmstadt (2016)

There clearly seems to be an effect crossing N=28 !

2. Example: 0νββ Decay

0- or 2-Neutrino Double-Beta Decay

TECHNISCHE UNIVERSITÄT DARMSTADT

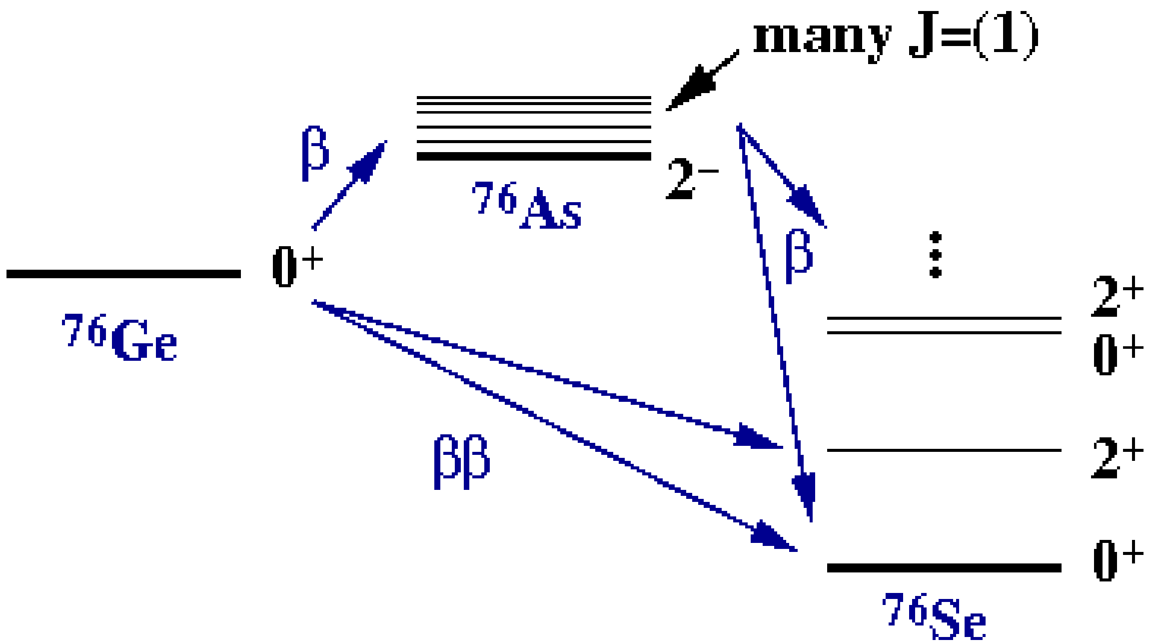
What is the fundamental nature of the neutrino, and what is its mass ?

Heidelberg-Moskow, Gerda, etc...

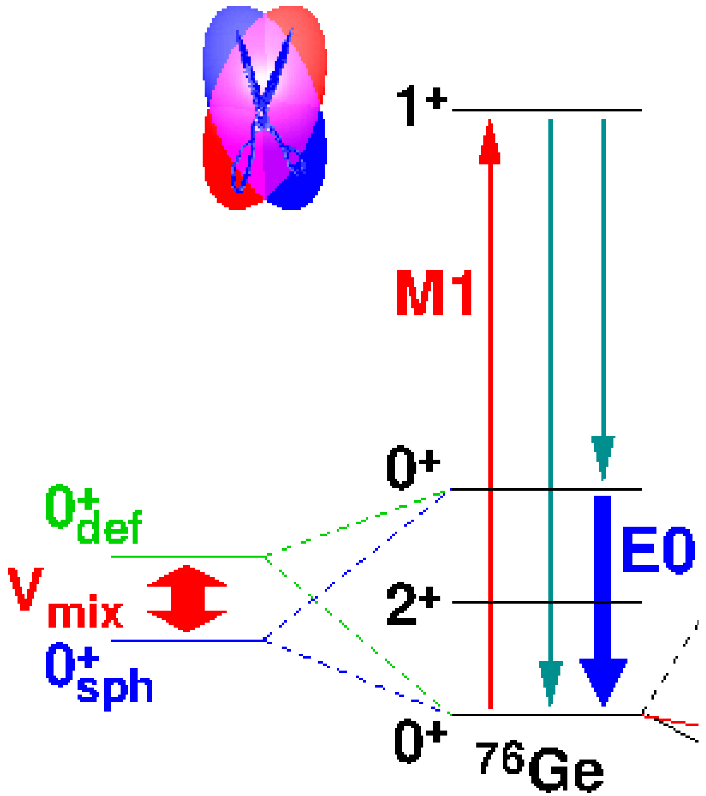
$$\Gamma = G \ |M|^2 \ |m_{\beta\beta}|^2$$

nuclear matrix element

Can only be obtained from theory, e.g. QRPA, shell model, IBM.

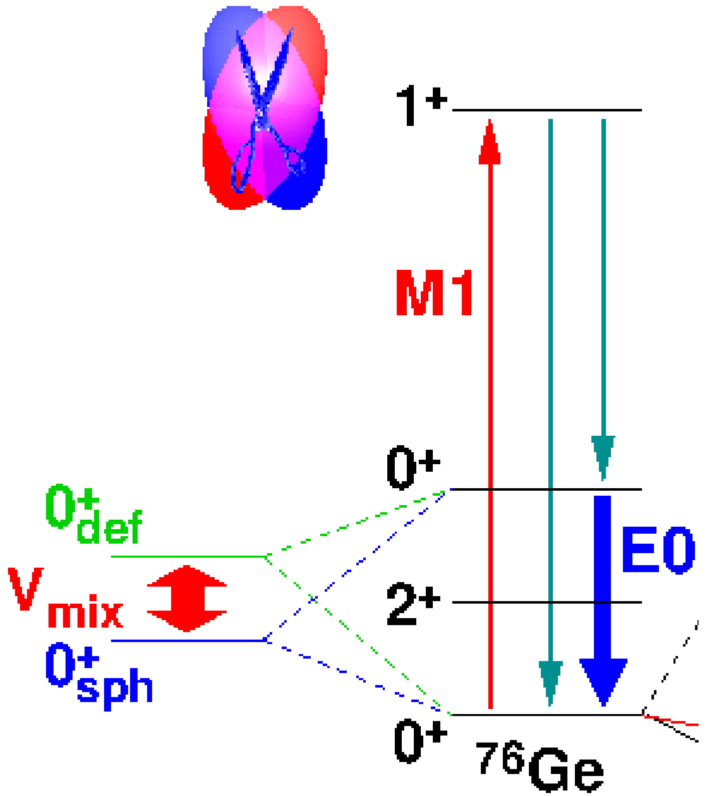


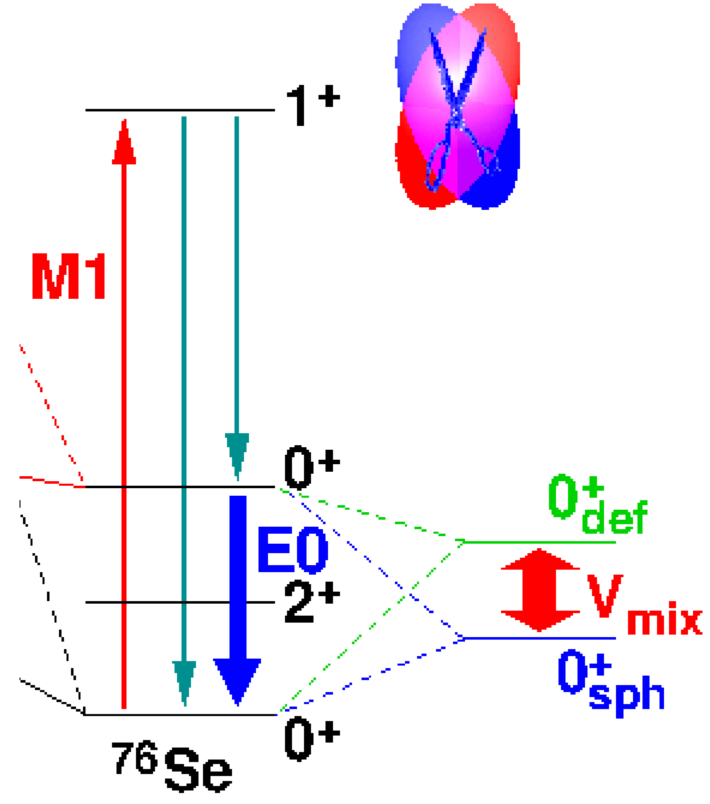
Shape Coexistence has Influence on Decay Behavior of S.M.



- **Scissors Mode excited from sph/def mixed state**
- **Will decay to both 0^+ states, same configurations in both !**
- **Search for Scissors Mode Branching to excited 0^+ state**
- **Complementary observable for shape/configuration mixing: E0-strength**

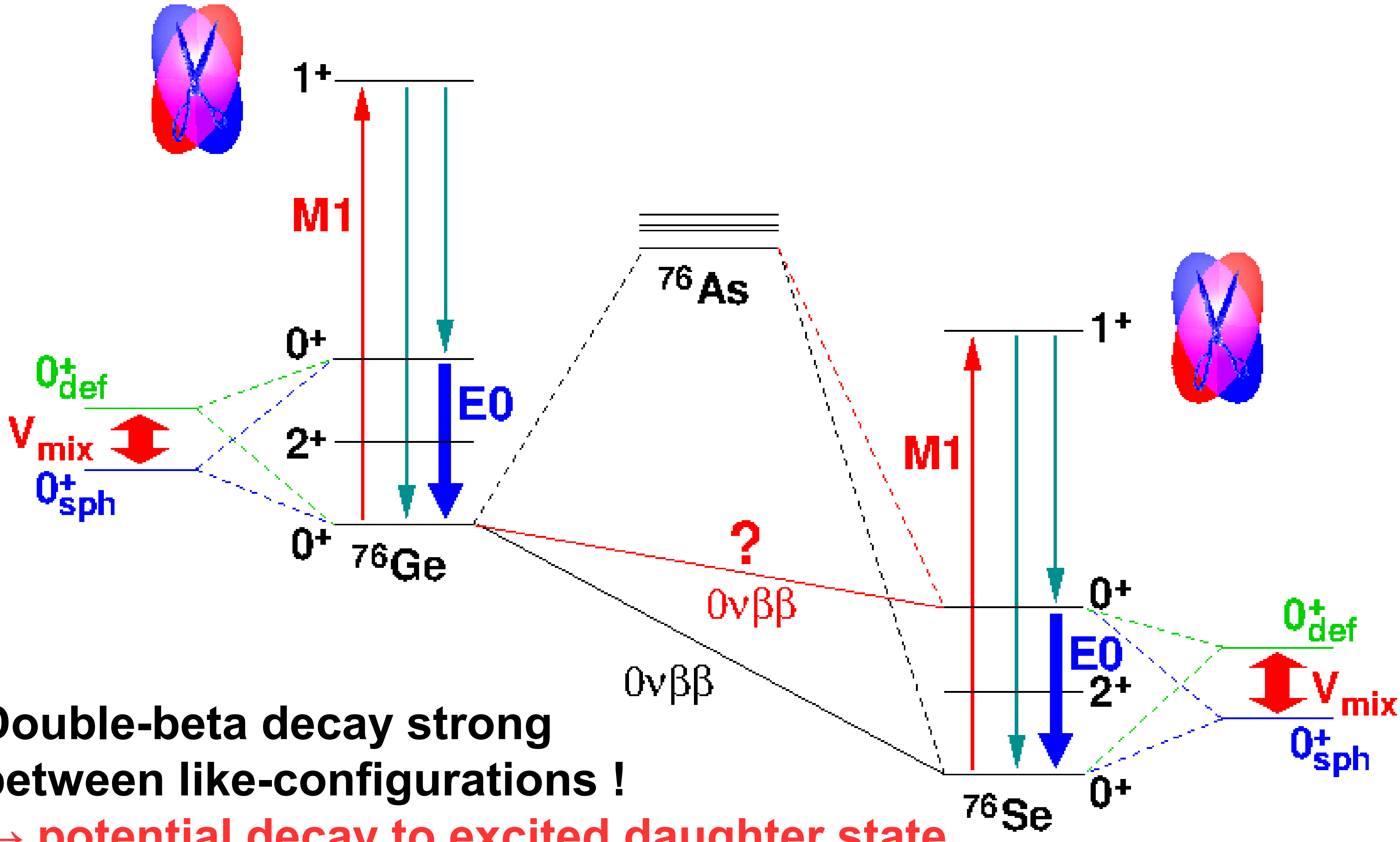
Shape Coexistence has Influence on Decay Behavior of S.M.





Same can (and does) happen for mother and daughter isotopes

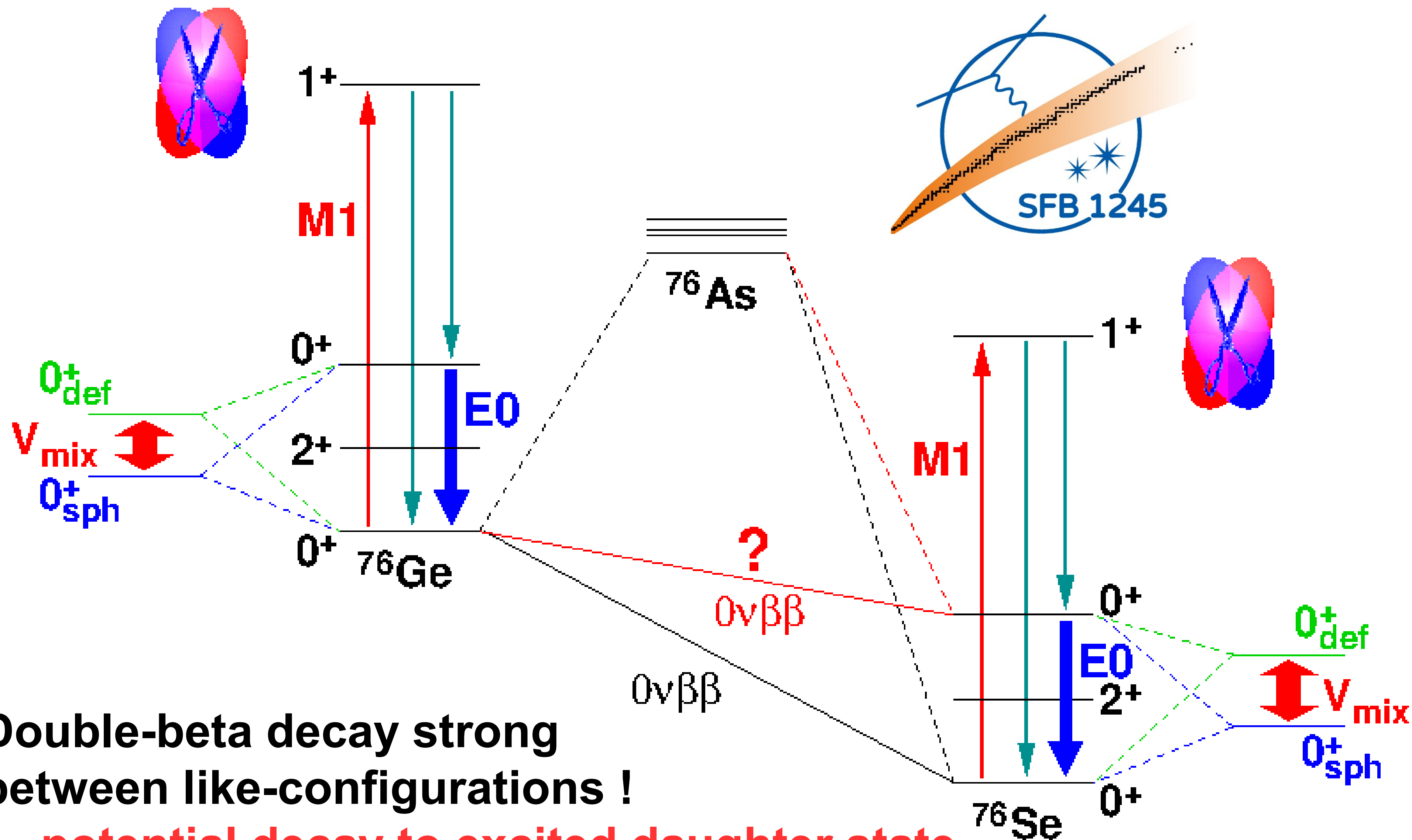
Decay Behavior of S.M. connected to Double-Beta Rates



Double-beta decay strong between like-configurations !

→ potential decay to excited daughter state

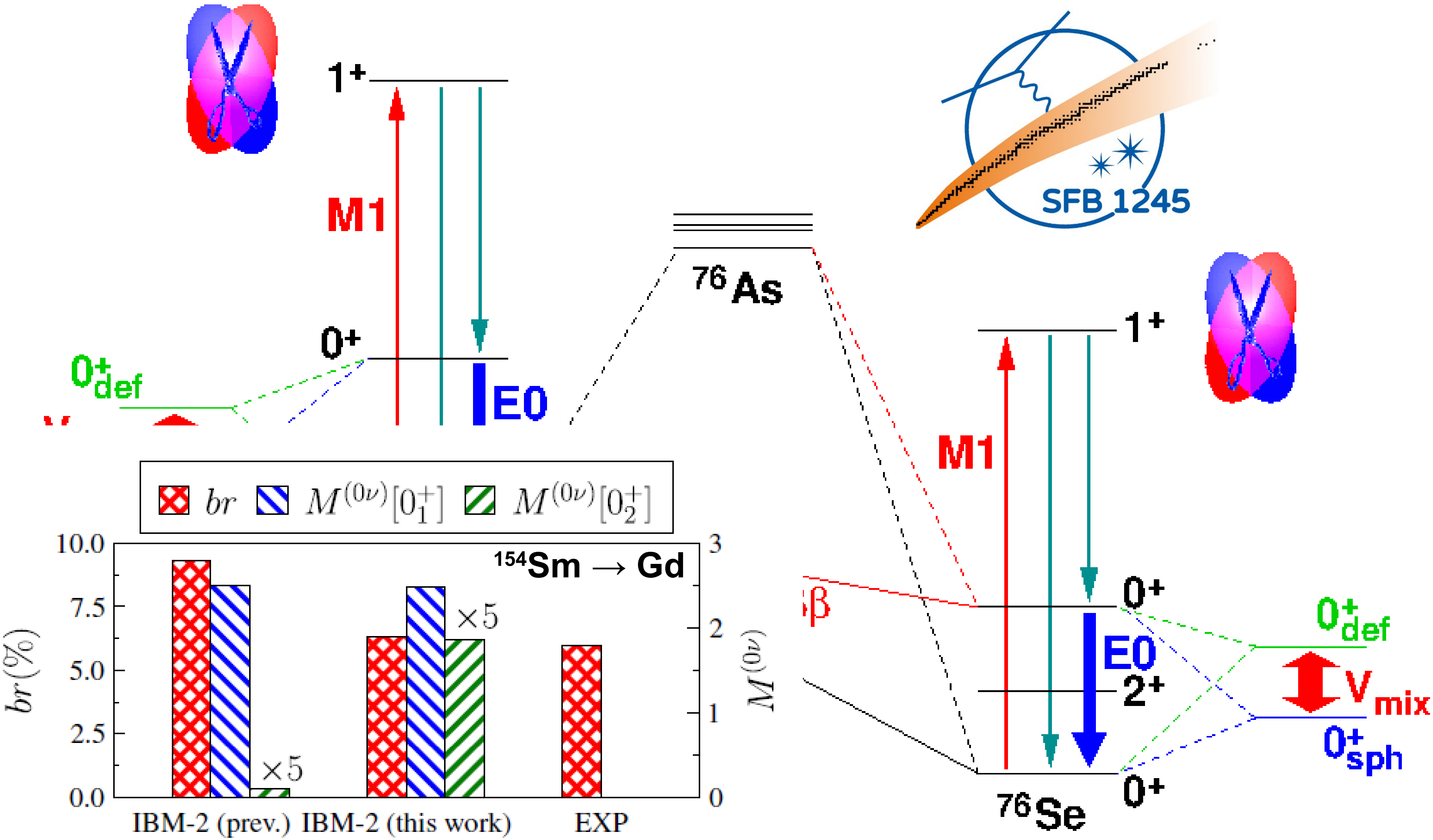
Decay Behavior of S.M. connected to Double-Beta Rates



Double-beta decay strong between like-configurations !

→ potential decay to excited daughter state

Decay Behavior of S.M. connected to Double-Beta Rates



J. Beller, PRL 111, 172501 ('13)

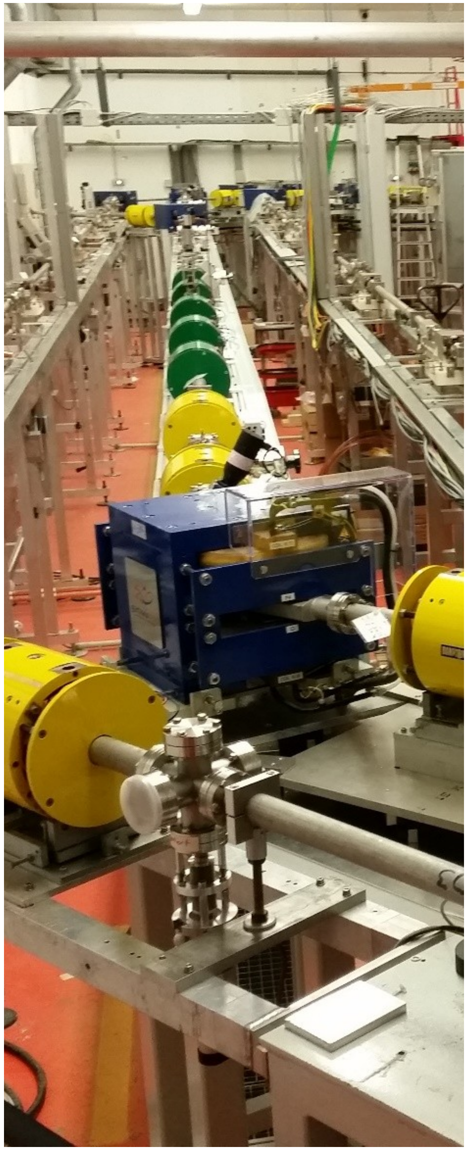
Further applications

TECHNISCHE UNIVERSITÄT DARMSTADT

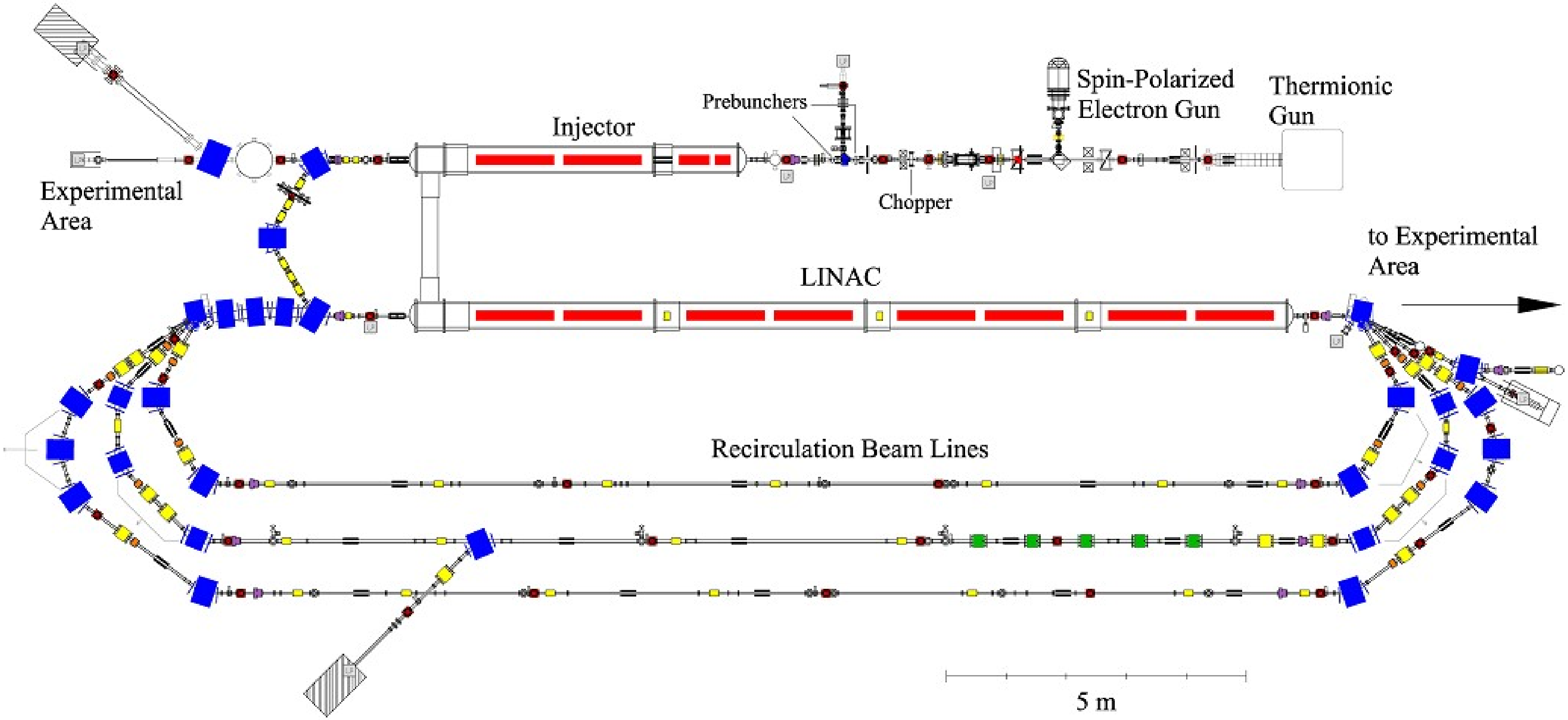
- Nuclear (Multi-)Polarimetry
- Collective Structures
- Multi-Phonon States
- Single-Particle Structures
- Spin-Isospin response
- Photofission.
- M1 Response (→ Neutrino Detection)
- Photo-activation
- (polarized electron source just built)

S-DALINAC

- **Major research instrument for high-resolution nuclear research with electromagnetic probes**
- **Key facility in CRC 634 (2003 - 2015)**
- **Major facility of CRC 1245 (since 2016)**
  - **Off-yrast nuclear spectroscopy (electron-scattering)**
  - **Photonuclear reactions (bremsstrahlung)**
- **Key facility of RTG 2128 (since 2016) - Research on ERL**



S-DALINAC Today



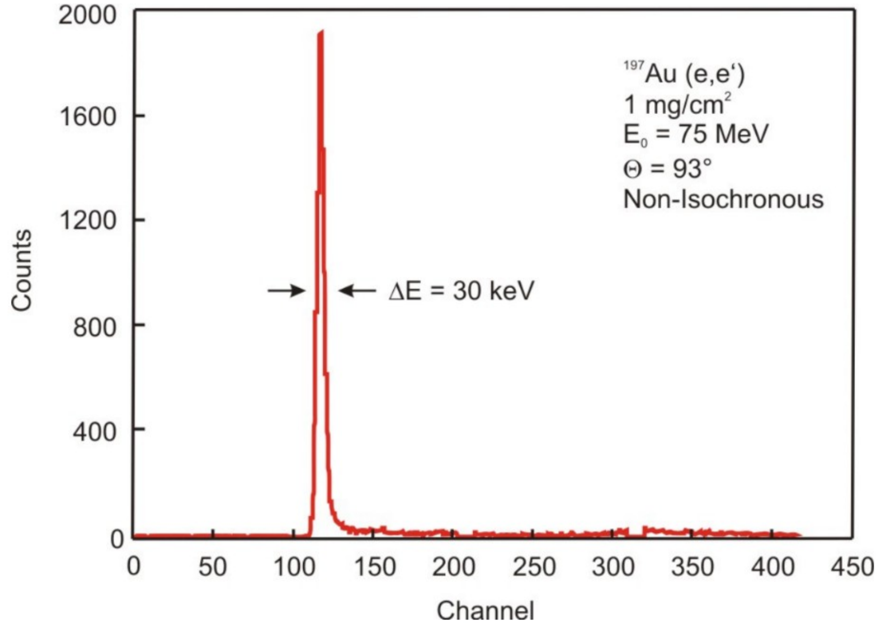
M. Arnold, Dissertation (2016)

S-DALINAC Today

First sc-electron LINAC in Europe (1991)

A. Richter: *Operational Experience at the S-DALINAC*, Proceedings of EPAC 1996, Sitges, Barcelona, (1996) 110.

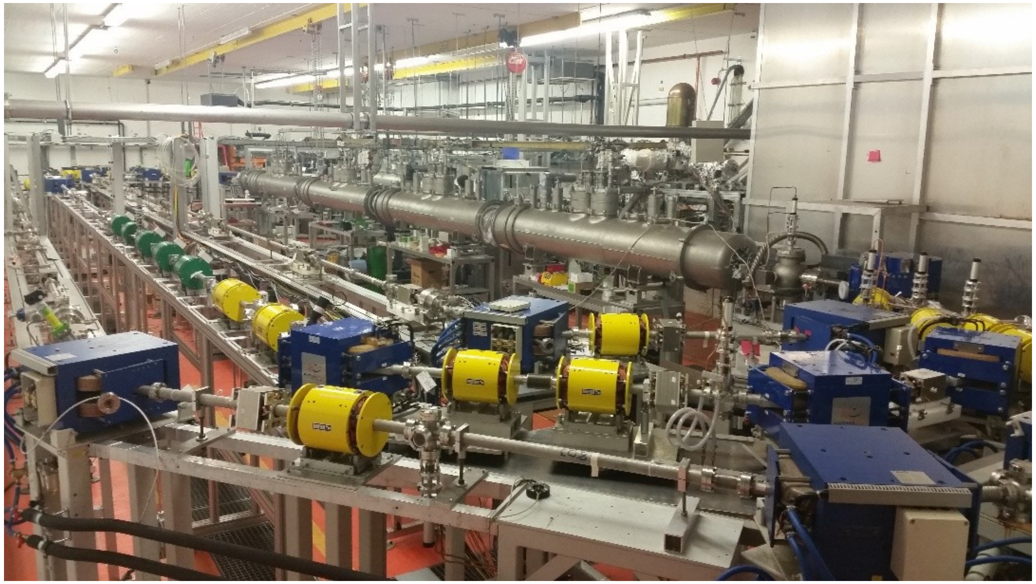
Non-isochronous (Twice recirculating until 2015)



F. Hug, C. Burandt, R. Eichhorn, M. Konrad, N. Pietralla: *Measurements of a Reduced Energy Spread of a Recirculating Linac by Non-Isochronous Beam Dynamics*, Proceedings of LINAC 2012, Tel-Aviv, Israel (2012) 531.

First ERL under commissioning in Germany

M. Arnold, Dissertation, 2016

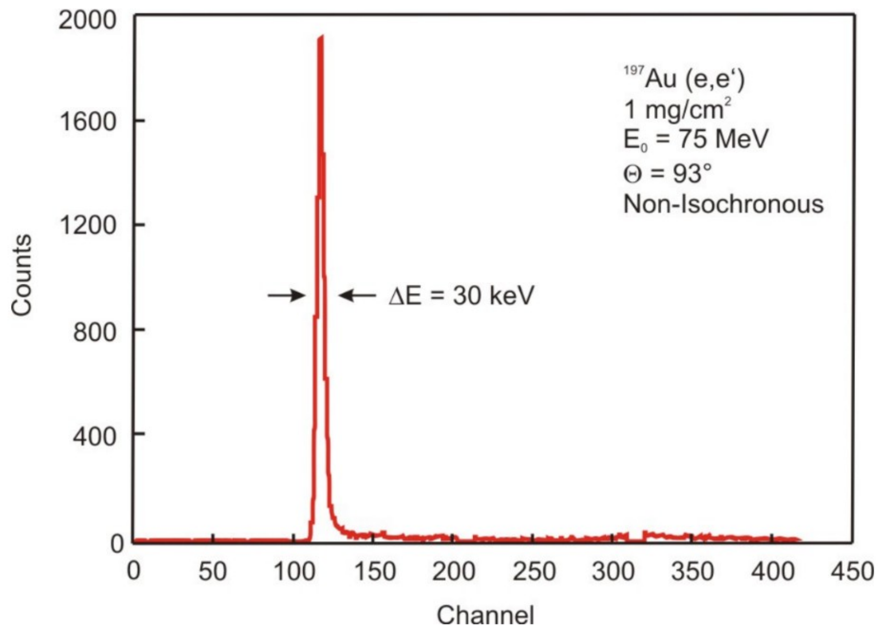


S-DALINAC Today

First sc-electron LINAC in Europe (1991)

A. Richter: *Operational Experience at the S-DALINAC*, Proceedings of EPAC 1996, Sitges, Barcelona, (1996) 110.

Non-isochronous (Twice recirculating until 2015)



F. Hug, C. Burandt, R. Eichhorn, M. Konrad, N. Pietralla: *Measurements of a Reduced Energy Spread of a Recirculating Linac by Non-Isochronous Beam Dynamics*, Proceedings of LINAC 2012, Tel-Aviv, Israel (2012) 531.

First ERL under commissioning in Germany

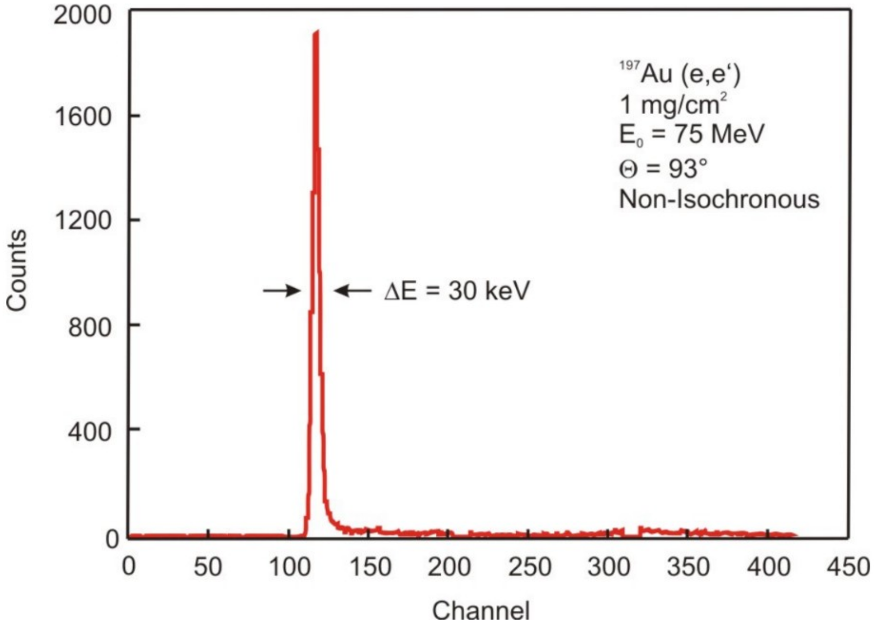
M. Arnold, Dissertation, 2016

S-DALINAC Today

First sc-electron LINAC in Europe (1991)

A. Richter: *Operational Experience at the S-DALINAC*, Proceedings of EPAC 1996, Sitges, Barcelona, (1996) 110.

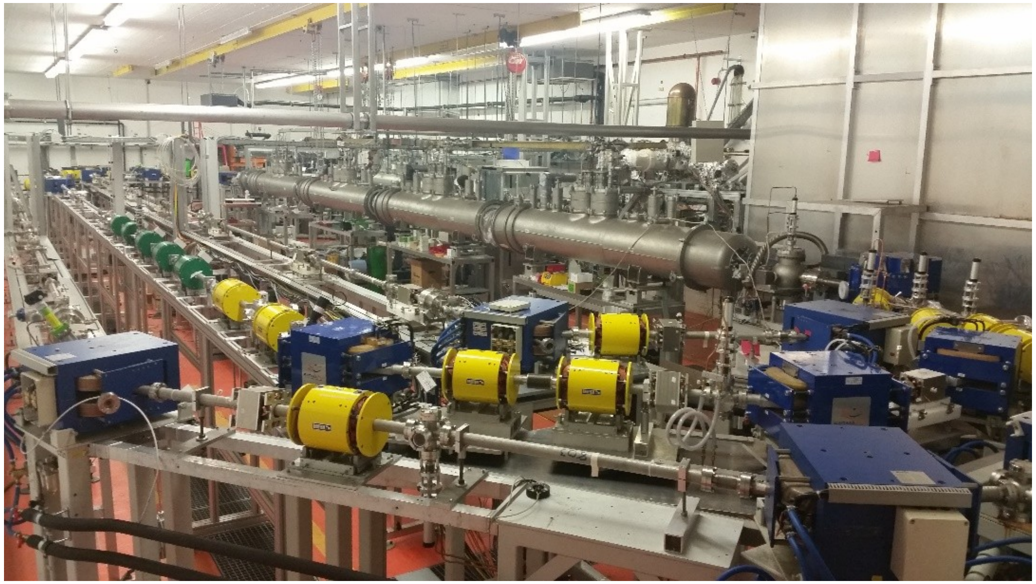
Non-isochronous (Twice recirculating until 2015)



F. Hug, C. Burandt, R. Eichhorn, M. Konrad, N. Pietralla: *Measurements of a Reduced Energy Spread of a Recirculating Linac by Non-Isochronous Beam Dynamics*, Proceedings of LINAC 2012, Tel-Aviv, Israel (2012) 531.

First ERL under commissioning in Germany

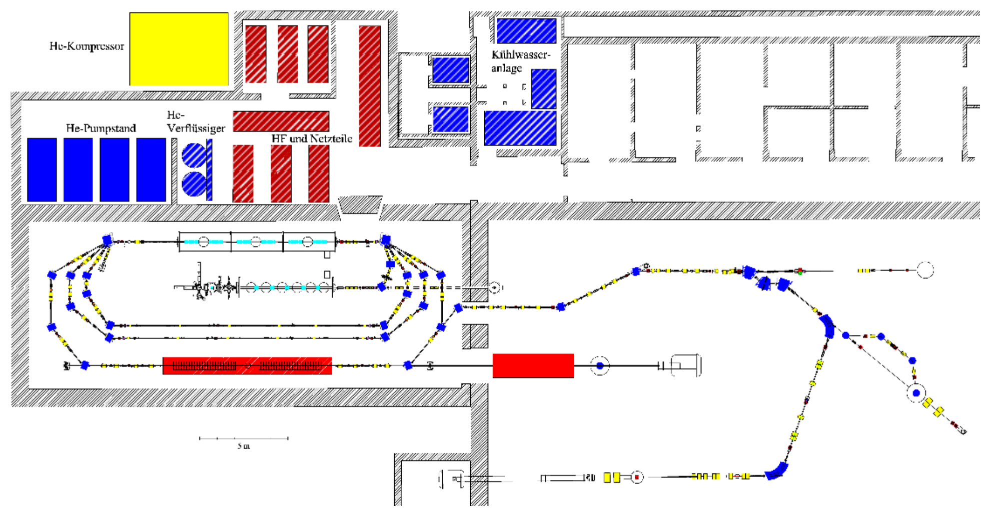
M. Arnold, Dissertation, 2016



Vision: Advanced S-DALINAC

Needs

- Highest energy resolution
  - Low-emittance injector
  - Linear accelerator
  - Non-isochronous mode
- High repetition rates
  - Superconducting RF
  - cw operation
- Quasi-monochromatic gamma-ray beams
  - FEL
  - Compton back-scattering
- Energy saving / intensity increase
  - ERL



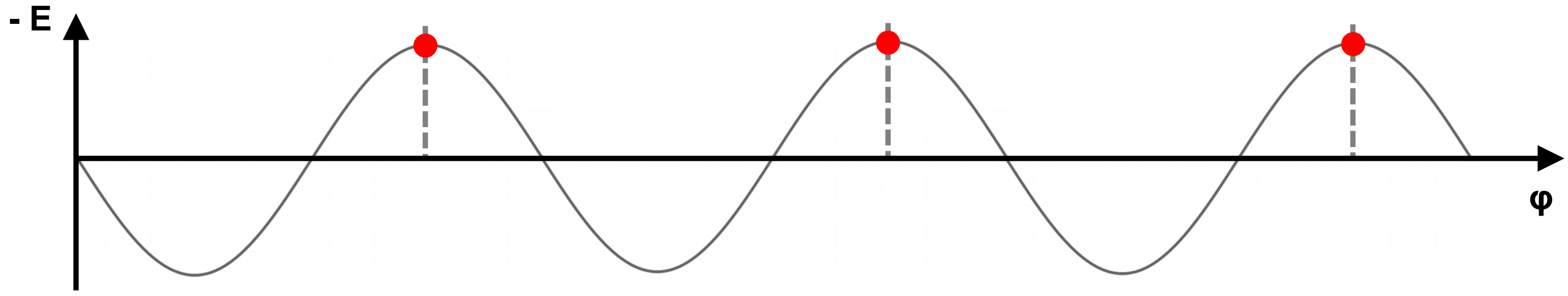
Additional benefit

- High-resolution electron scattering
- Research on ERL and FEL for improved γ-production processes

Isochronous/Non-Isochronous ERL

TECHNISCHE UNIVERSITÄT DARMSTADT

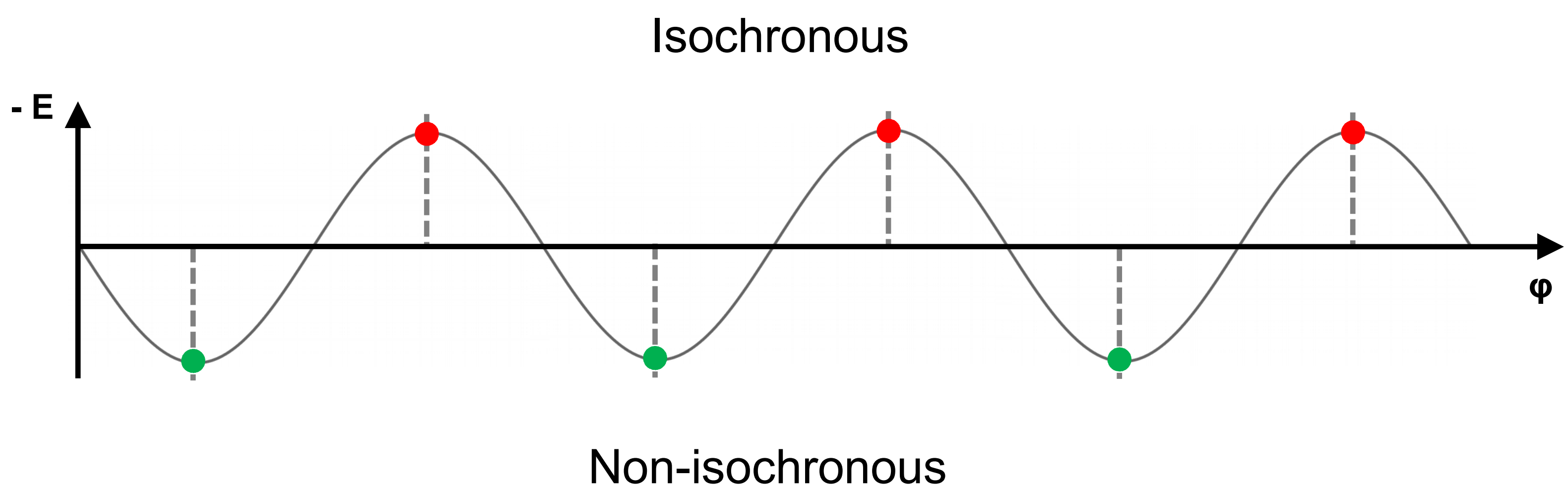
Isochronous



Non-isochronous

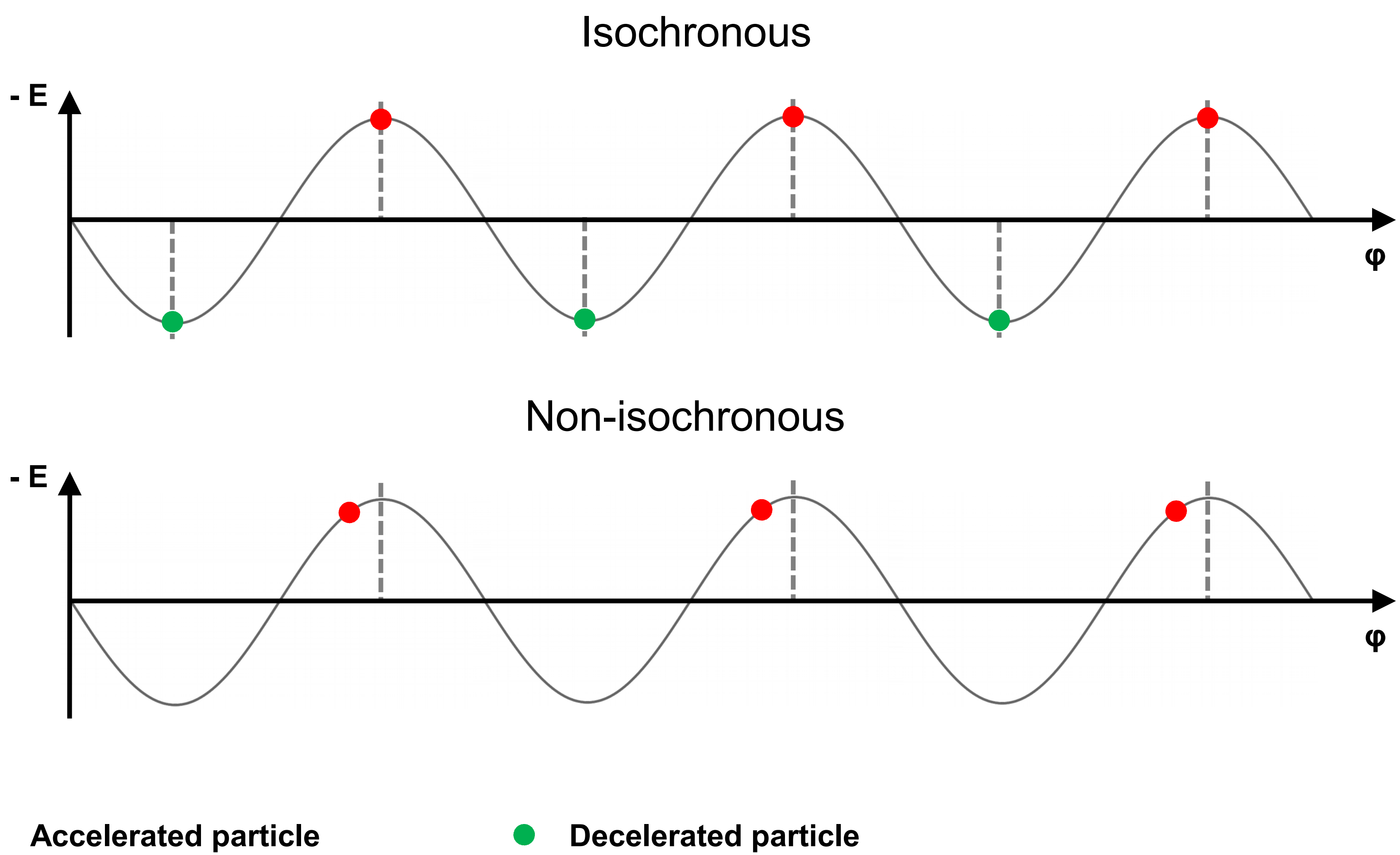
● **Accelerated particle** ● **Decelerated particle**

Isochronous/Non-Isochronous ERL

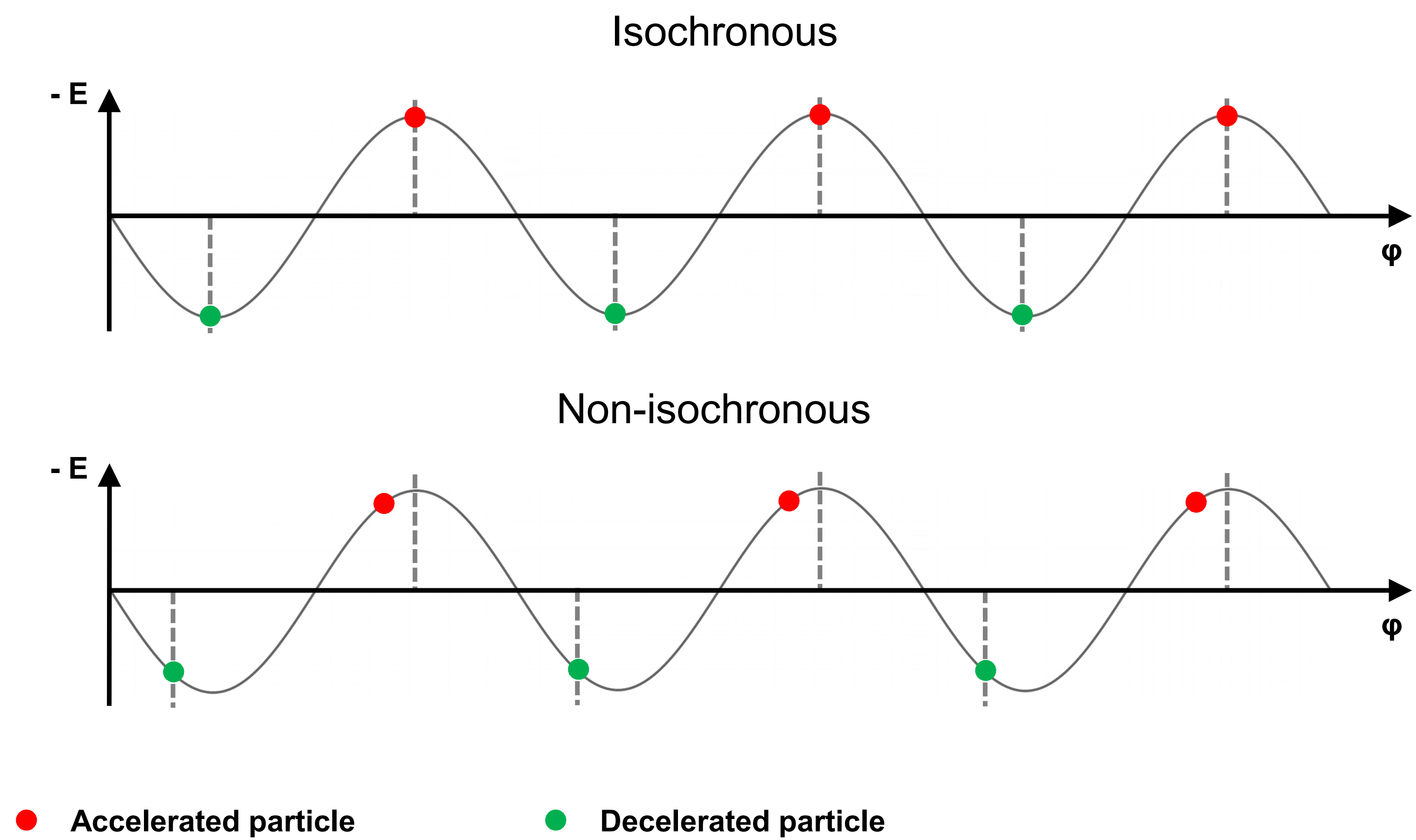


● **Accelerated particle** ● **Decelerated particle**

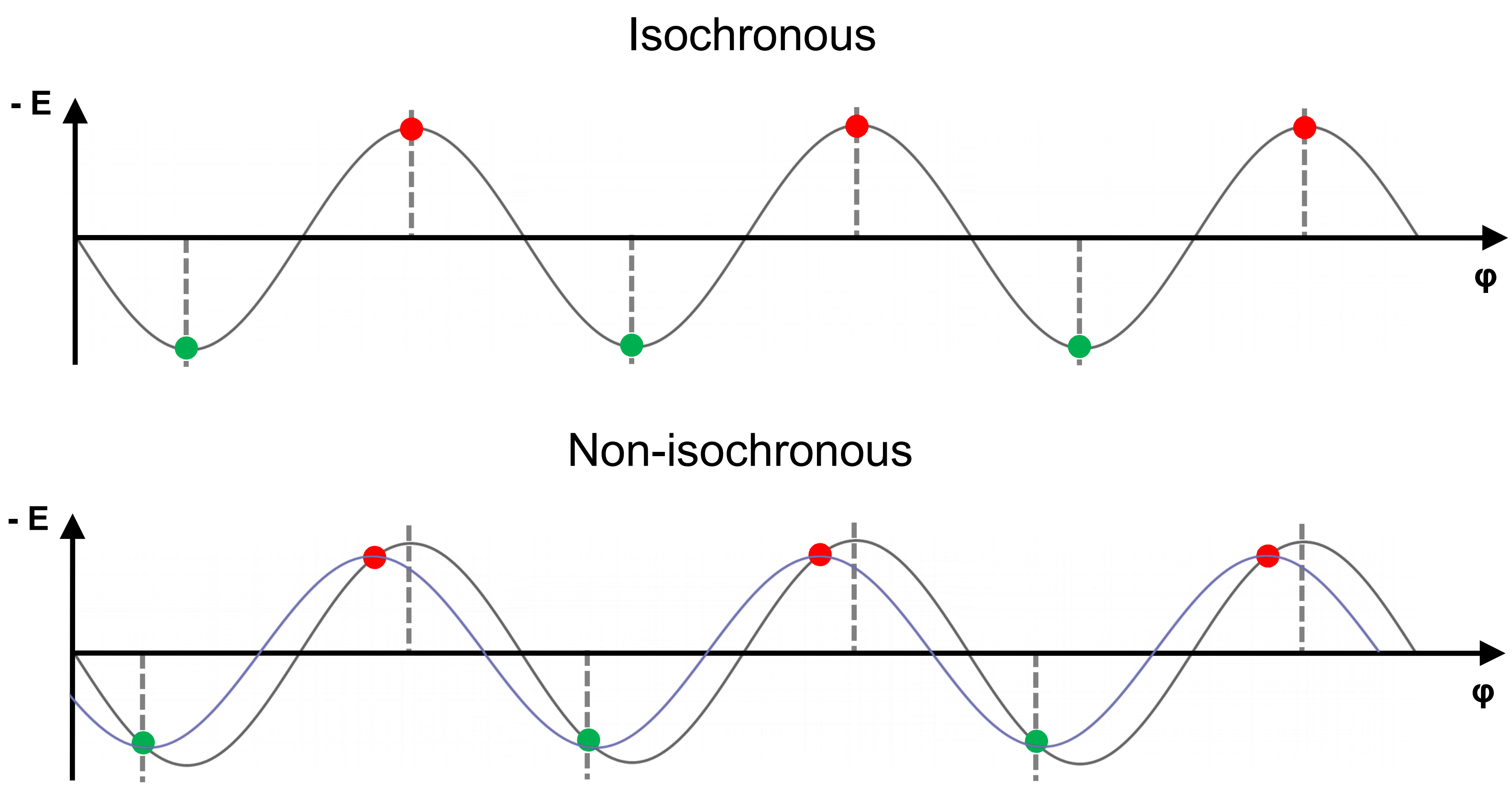
Isochronous/Non-Isochronous ERL



Isochronous/Non-Isochronous ERL



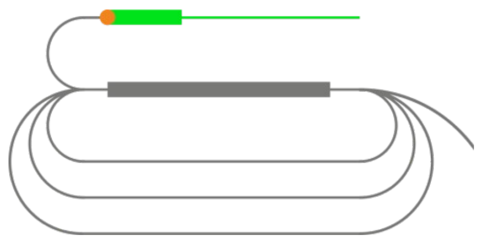
Isochronous/Non-Isochronous ERL



● Accelerated particle ● Decelerated particle

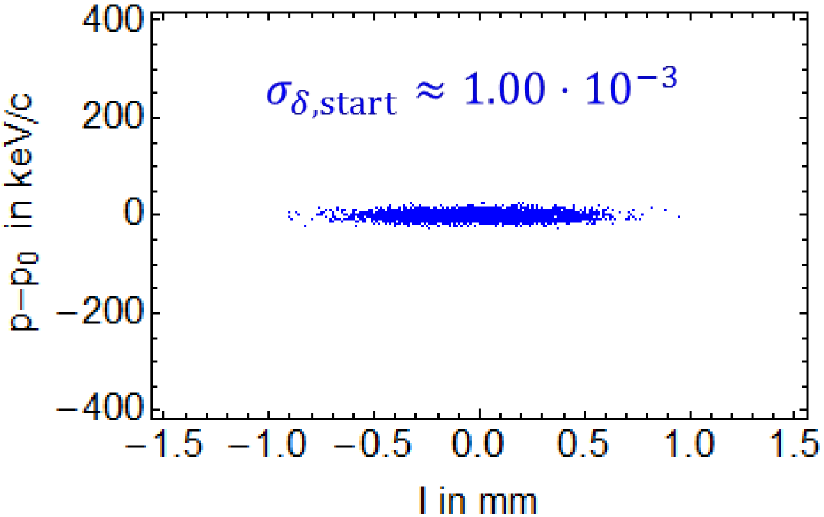
MATLAB / elegant Simulations

S-DALINAC



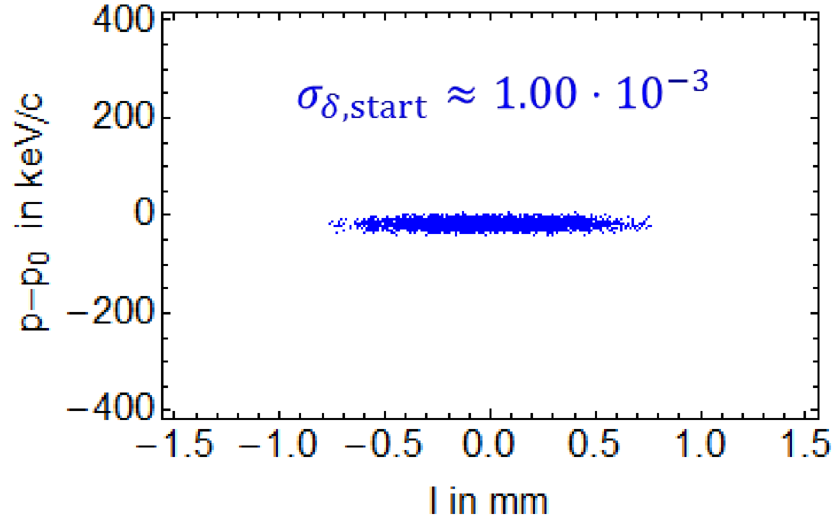
MATLAB
(perfekt entkoppelt)

$\Phi_S = -5.8°$
$R_{56;I} = 0.21$ m
$R_{56;F} = 0.2$ m
$R_{56;S} = 0$ m
$R_{56;T} = 0.54$ m



elegant
(nicht perfekt entkoppelt)

$\Phi_S = -5.8°$
$R_{56;I} \approx 0.210$ m
$R_{56;F} \approx 0.200$ m
$R_{56;S} \approx 0.000$ m
$R_{56;T} \approx 0.540$ m



MATLAB / elegant Simulations

MATLAB
(perfekt entkoppelt)

$\Phi_S = -5.8°$

$R_{56;I} = 0.21$ m

$R_{56;F} = 0.2$ m

$R_{56;S} = 0$ m

$R_{56;T} = 0.54$ m

S-DALINAC

elegant
(nicht perfekt entkoppelt)

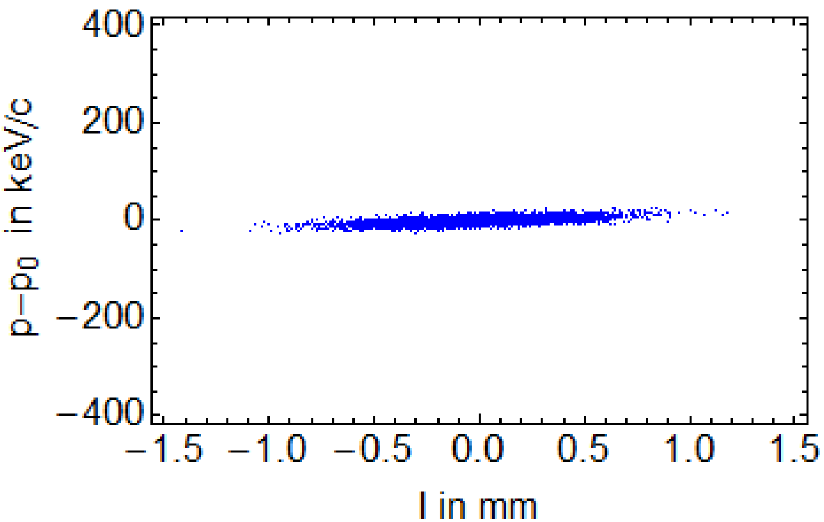
$\Phi_S = -5.8°$

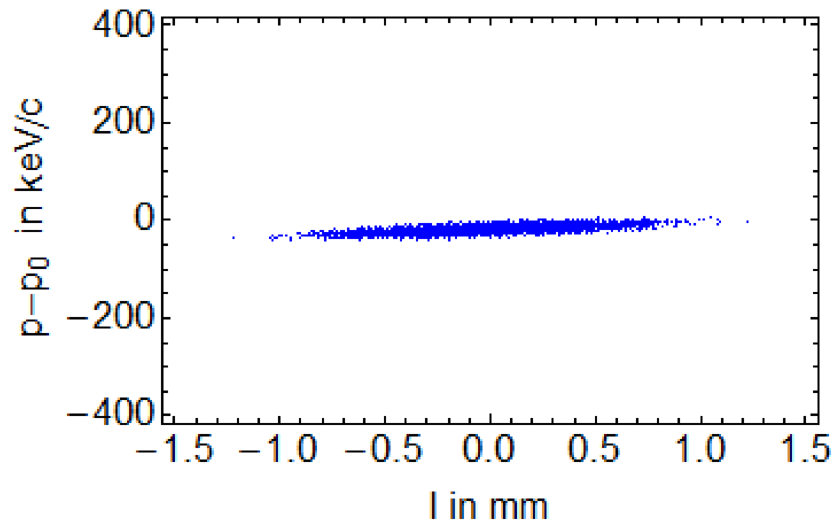
$R_{56;I} \approx 0.210$ m

$R_{56;F} \approx 0.200$ m

$R_{56;S} \approx 0.000$ m

$R_{56;T} \approx 0.540$ m





MATLAB / elegant Simulations

MATLAB
(perfekt entkoppelt)

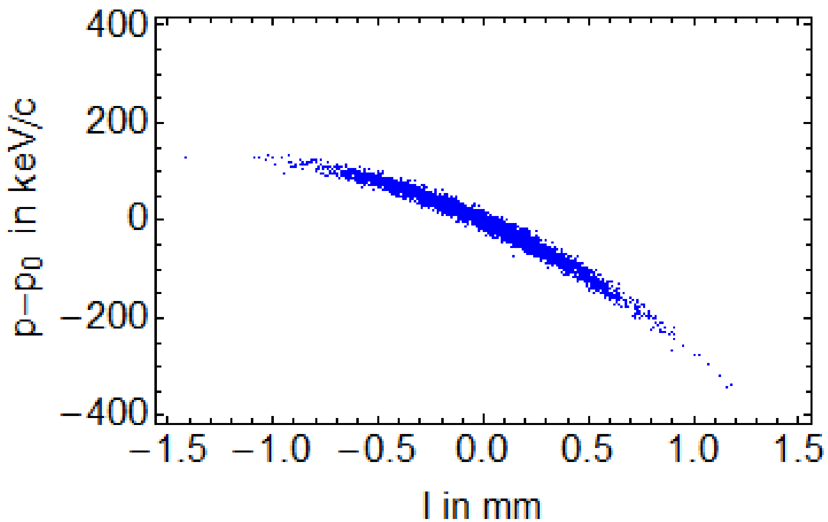
$\Phi_S = -5.8°$

$R_{56;I} = 0.21\ \mathrm{m}$

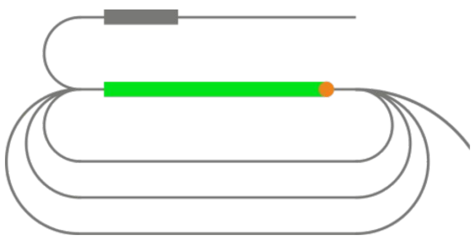
$R_{56;F} = 0.2\ \mathrm{m}$

$R_{56;S} = 0\ \mathrm{m}$

$R_{56;T} = 0.54\ \mathrm{m}$



S-DALINAC



elegant
(nicht perfekt entkoppelt)

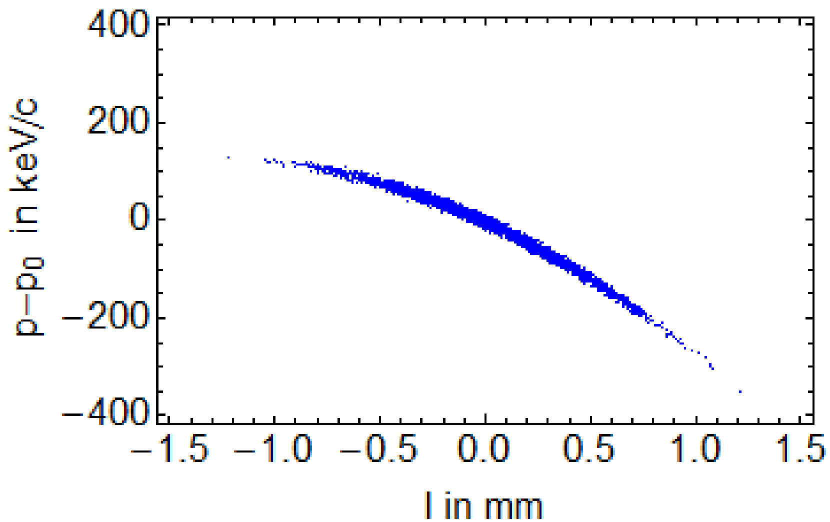
$\Phi_S = -5.8°$

$R_{56;I} \approx 0.210\ \mathrm{m}$

$R_{56;F} \approx 0.200\ \mathrm{m}$

$R_{56;S} \approx 0.000\ \mathrm{m}$

$R_{56;T} \approx 0.540\ \mathrm{m}$

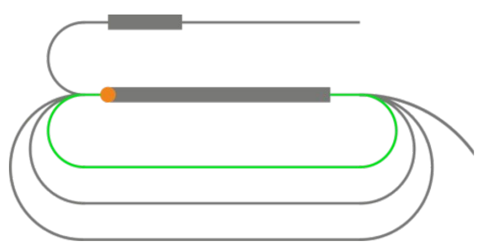


MATLAB / elegant Simulations

MATLAB
(perfekt entkoppelt)

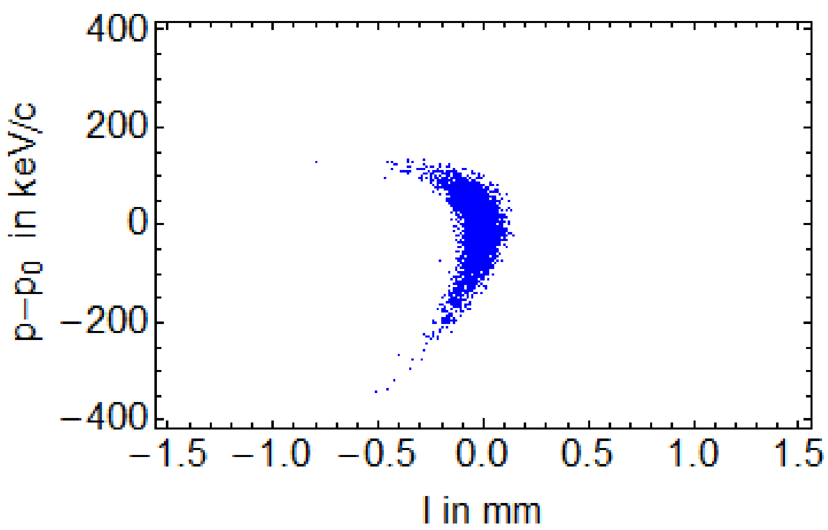
$\Phi_S = -5.8°$
$R_{56;I} = 0.21\ \mathrm{m}$
$R_{56;F} = 0.2\ \mathrm{m}$
$R_{56;S} = 0\ \mathrm{m}$
$R_{56;T} = 0.54\ \mathrm{m}$

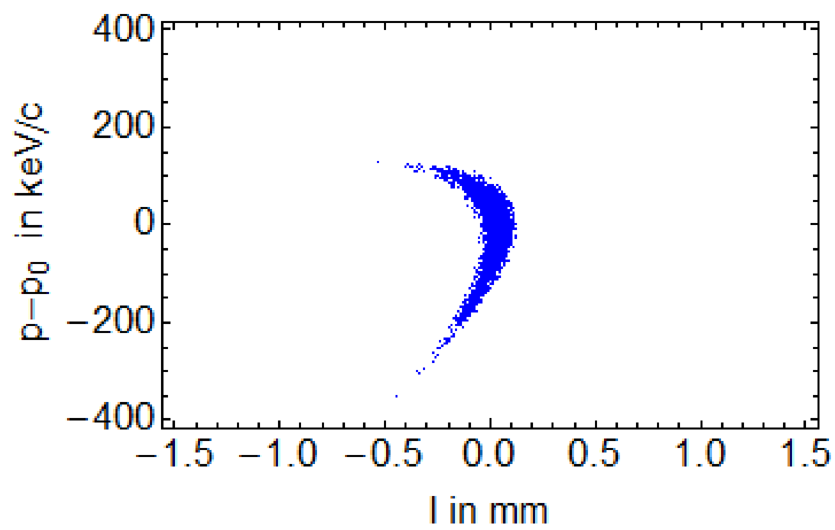
S-DALINAC



elegant
(nicht perfekt entkoppelt)

$\Phi_S = -5.8°$
$R_{56;I} \approx 0.210\ \mathrm{m}$
$R_{56;F} \approx 0.200\ \mathrm{m}$
$R_{56;S} \approx 0.000\ \mathrm{m}$
$R_{56;T} \approx 0.540\ \mathrm{m}$





MATLAB / elegant Simulations

MATLAB
(perfekt entkoppelt)

$\Phi_S = -5.8°$

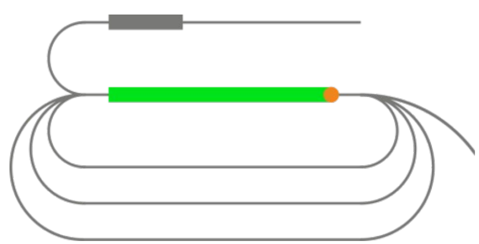
$R_{56;I} = 0.21$ m

$R_{56;F} = 0.2$ m

$R_{56;S} = 0$ m

$R_{56;T} = 0.54$ m

S-DALINAC



elegant
(nicht perfekt entkoppelt)

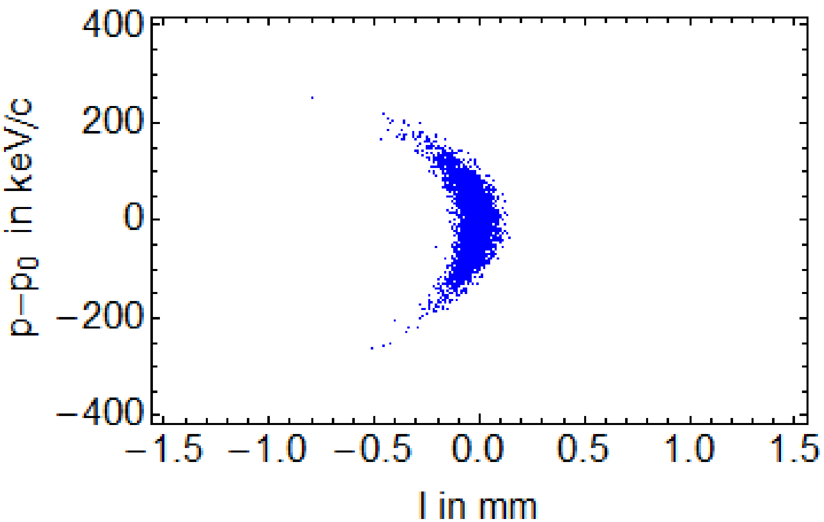
$\Phi_S = -5.8°$

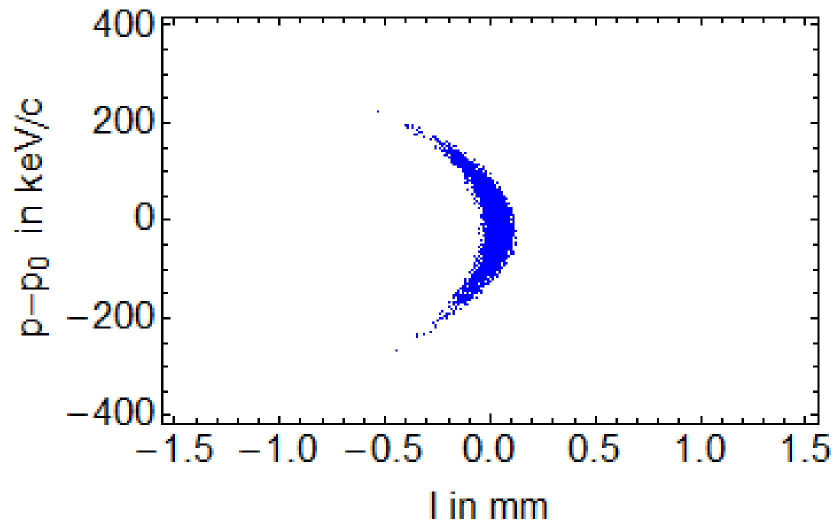
$R_{56;I} \approx 0.210$ m

$R_{56;F} \approx 0.200$ m

$R_{56;S} \approx 0.000$ m

$R_{56;T} \approx 0.540$ m





MATLAB / elegant Simulations

MATLAB
(perfekt entkoppelt)

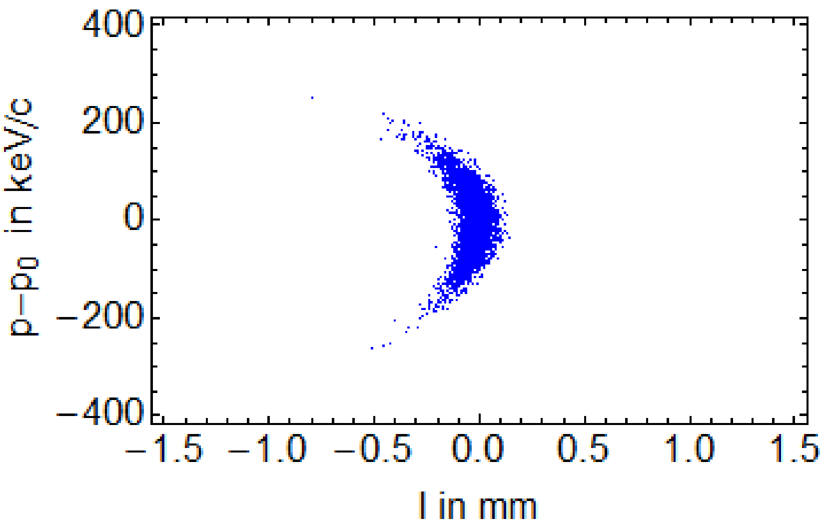
$\Phi_S = -5.8°$

$R_{56;I} = 0.21$ m

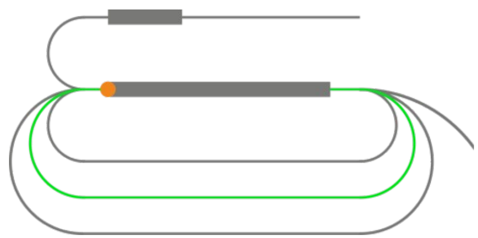
$R_{56;F} = 0.2$ m

$R_{56;S} = 0$ m

$R_{56;T} = 0.54$ m



S-DALINAC



elegant
(nicht perfekt entkoppelt)

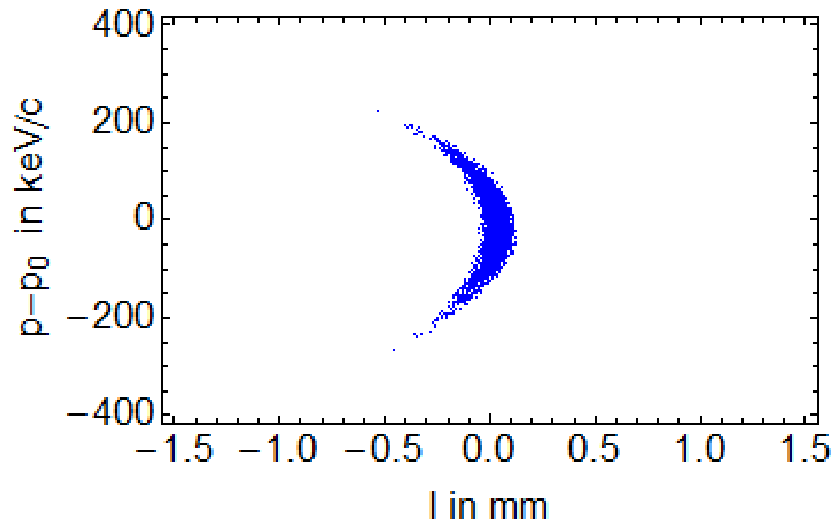
$\Phi_S = -5.8°$

$R_{56;I} \approx 0.210$ m

$R_{56;F} \approx 0.200$ m

$R_{56;S} \approx 0.000$ m

$R_{56;T} \approx 0.540$ m



MATLAB / elegant Simulations

TECHNISCHE UNIVERSITÄT DARMSTADT

MATLAB
(perfekt entkoppelt)

$\Phi_S = -5.8°$

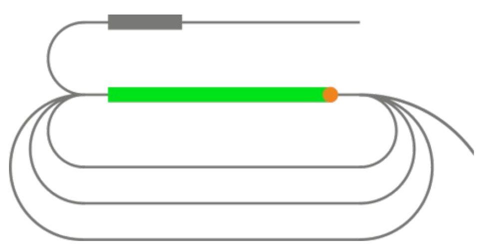
$R_{56;I} = 0.21$ m

$R_{56;F} = 0.2$ m

$R_{56;S} = 0$ m

$R_{56;T} = 0.54$ m

S-DALINAC



elegant
(nicht perfekt entkoppelt)

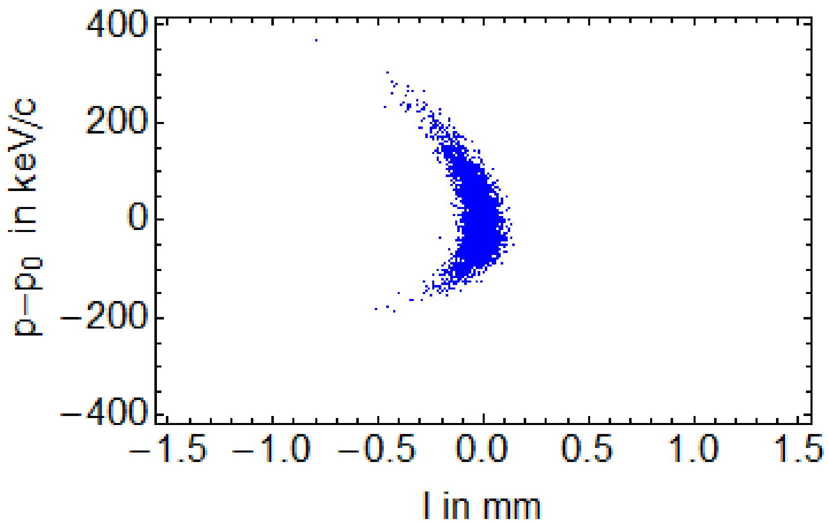
$\Phi_S = -5.8°$

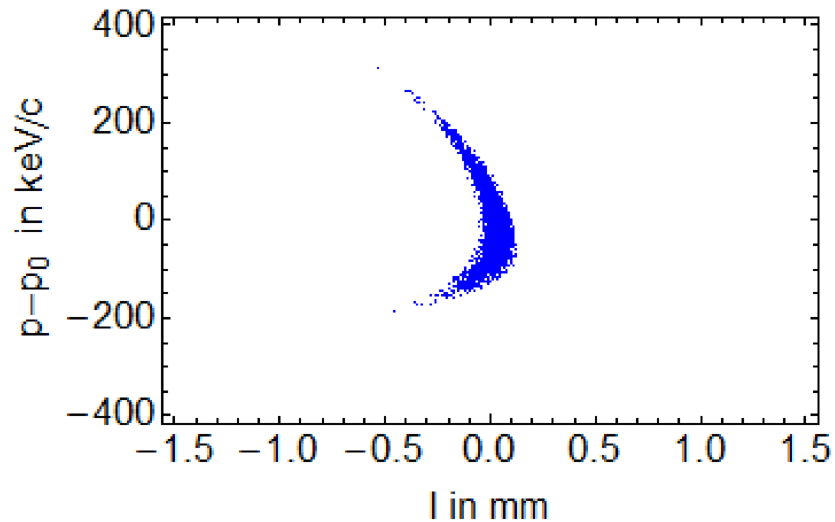
$R_{56;I} \approx 0.210$ m

$R_{56;F} \approx 0.200$ m

$R_{56;S} \approx 0.000$ m

$R_{56;T} \approx 0.540$ m





MATLAB / elegant Simulations

TECHNISCHE UNIVERSITÄT DARMSTADT

MATLAB
(perfekt entkoppelt)

$\Phi_S = -5.8°$

$R_{56;I} = 0.21$ m

$R_{56;F} = 0.2$ m

$R_{56;S} = 0$ m

$R_{56;T} = 0.54$ m

S-DALINAC

elegant
(nicht perfekt entkoppelt)

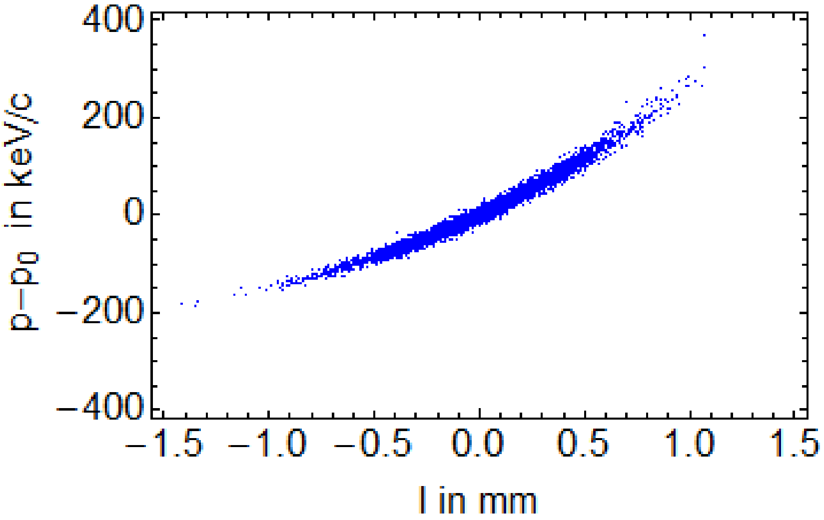
$\Phi_S = -5.8°$

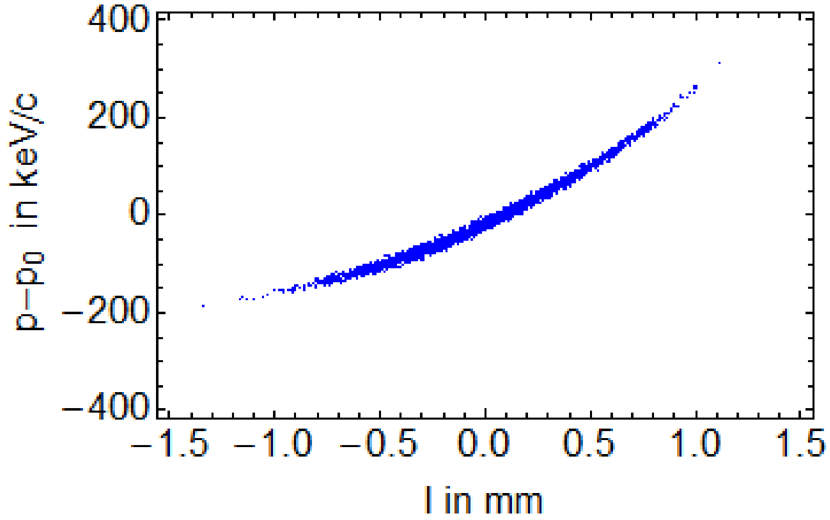
$R_{56;I} \approx 0.210$ m

$R_{56;F} \approx 0.200$ m

$R_{56;S} \approx 0.000$ m

$R_{56;T} \approx 0.540$ m





MATLAB / elegant Simulations

MATLAB
(perfekt entkoppelt)

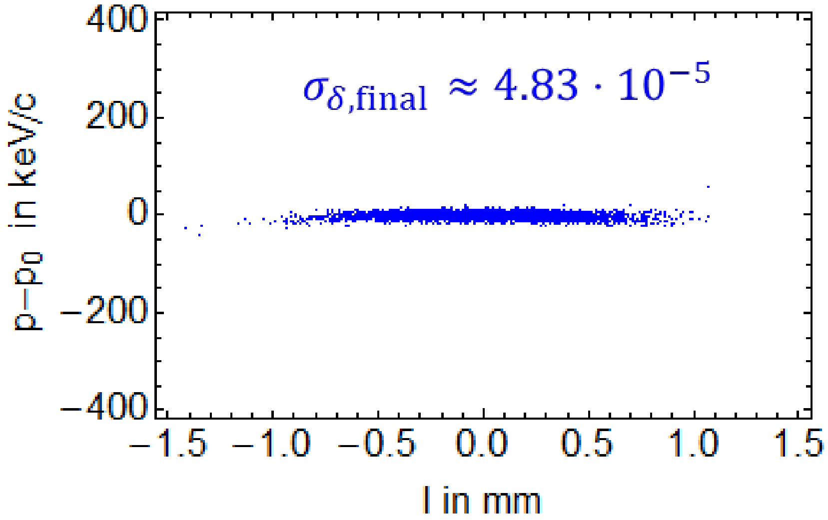
$\Phi_S = -5.8°$

$R_{56;I} = 0.21$ m

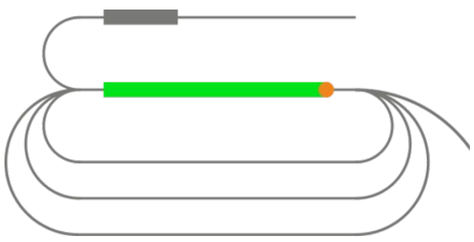
$R_{56;F} = 0.2$ m

$R_{56;S} = 0$ m

$R_{56;T} = 0.54$ m



S-DALINAC



elegant
(nicht perfekt entkoppelt)

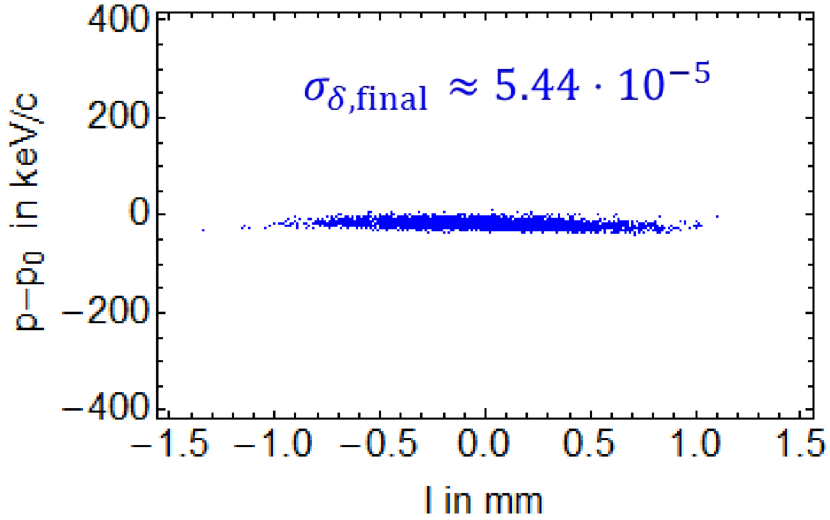
$\Phi_S = -5.8°$

$R_{56;I} \approx 0.210$ m

$R_{56;F} \approx 0.200$ m

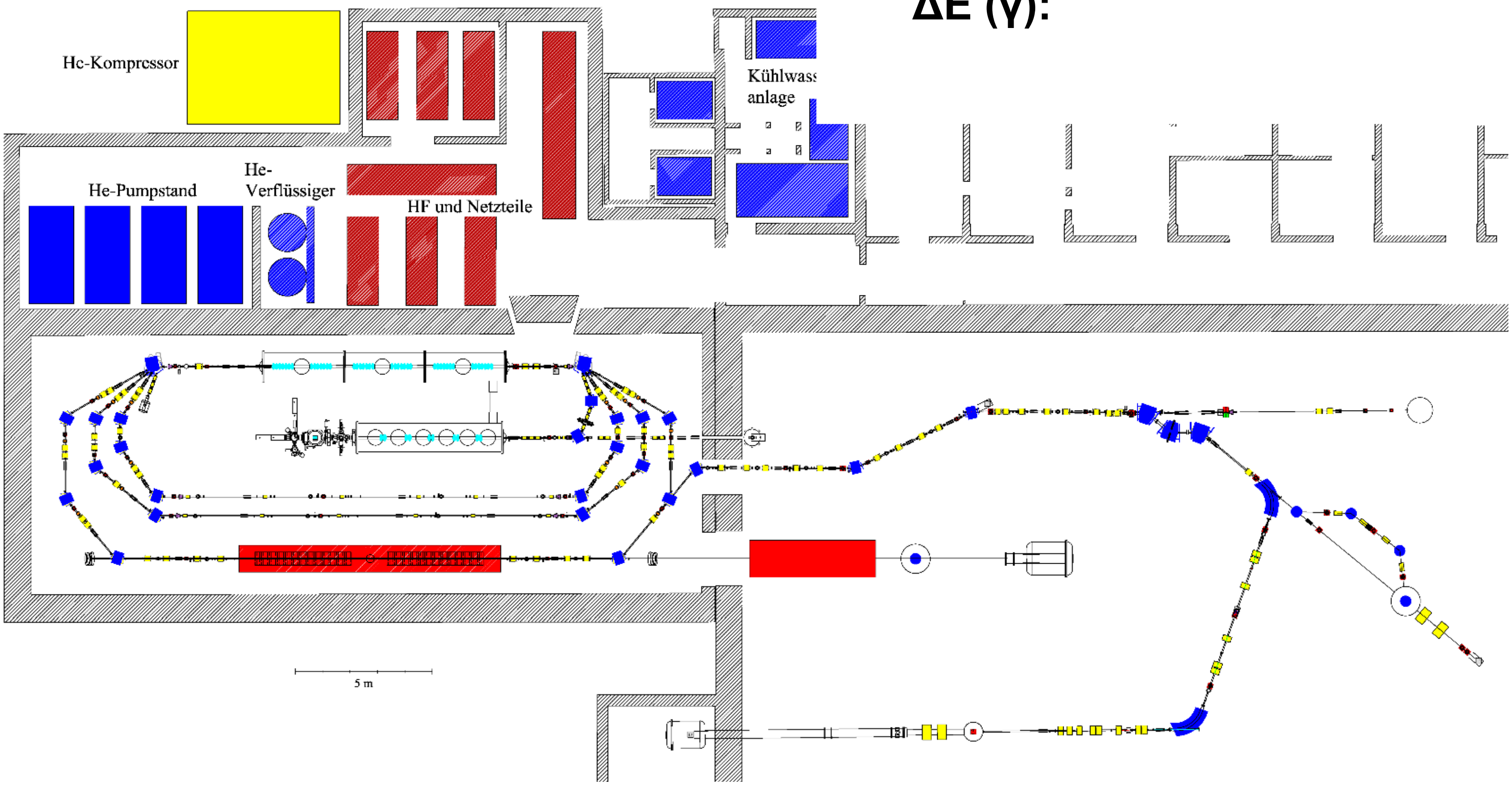
$R_{56;S} \approx 0.000$ m

$R_{56;T} \approx 0.540$ m



Advanced S-DALINAC (3rd Stage)

Electron energy:	**300 MeV**
Beam current:	**100 µA (1 mA ERL)**
Gamma energy:	**≤ 15 MeV**
ΔE (γ):	**10 keV**

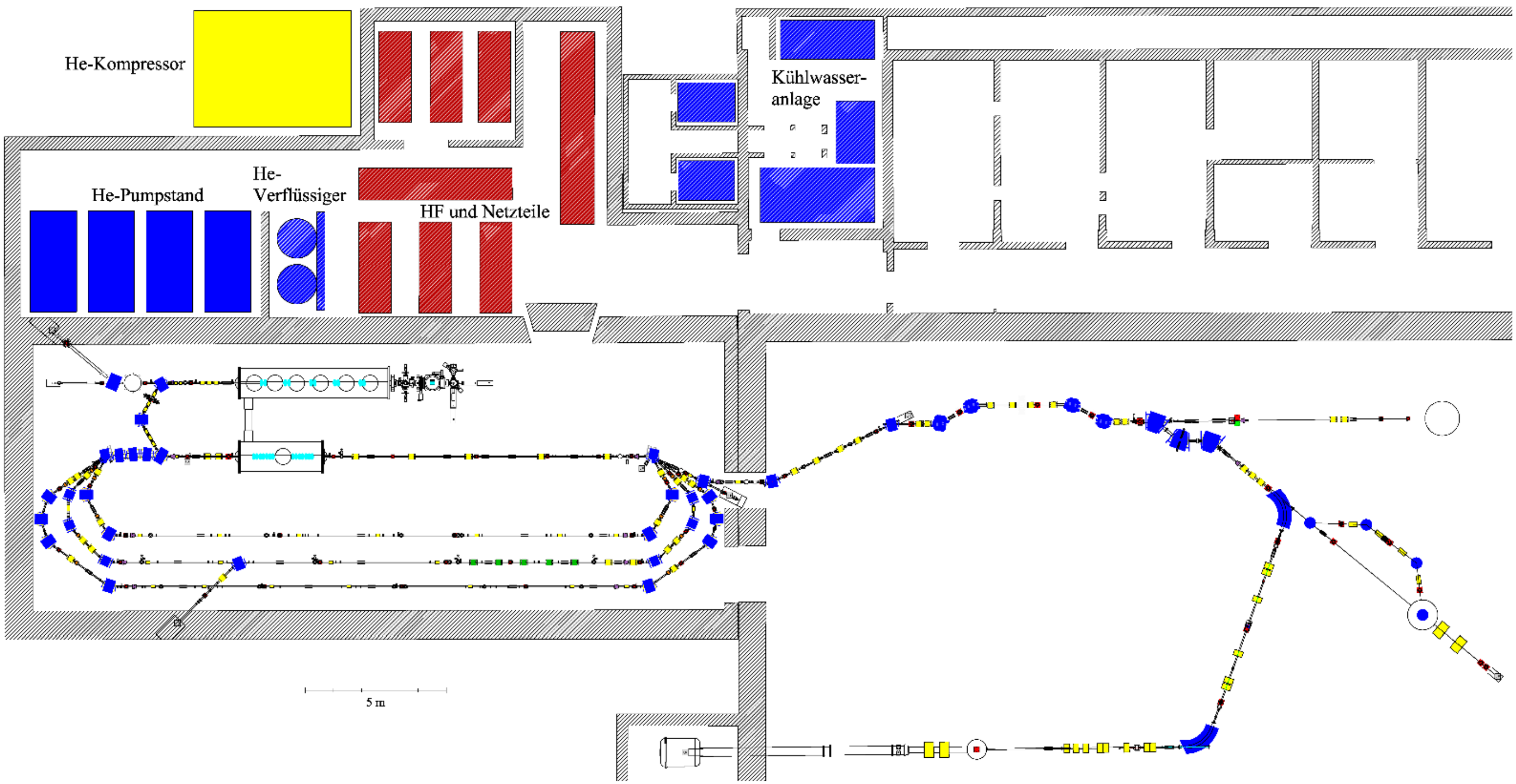


Advanced S-DALINAC (1st Stage)

TECHNISCHE UNIVERSITÄT DARMSTADT

Electron energy: **150 MeV**

Low-emittance injector with 1mA



Summary

- Photo-Nuclear Science:
  - Broad Opportunities for PERLE
  - Good Emittance, CW Beam: crucial for Selective Excitation of Nuclear States
  - Research Applications from Nuclear Structure, over Astrophysics, to Weak-Interaction Physics

- S-DALINAC
  - Operation as ERL commences 2016
  - Stable user operation
  - Vision for Advanced S-DALINAC: ERL + FEL
  - → CBS beams

Potential NRF-based Applications of MEGa-ray Sources are Numerous

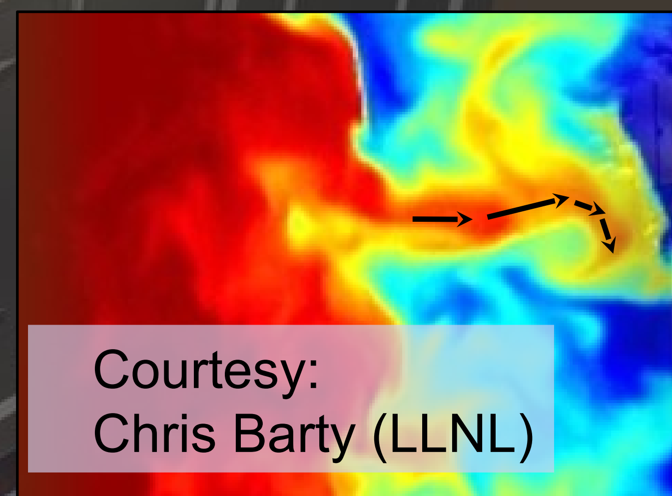
HEU Grand Challenge
detection of shielded material

Nuclear Fuel Assay
100 parts per million per isotope

Waste Imaging & Assay
non-invasive content certification

Stockpile Surveillance
micron-scale & isotope specific

Medical Imaging
low density & isotope specific



Dense Plasma Science
isotope mass, position & velocity

The Early Days ...

TECHNISCHE UNIVERSITÄT DARMSTADT

1937: **Atomumwandlungen durch γ-Strahlen.**

Von **W. Bothe** und **W. Gentner** in Heidelberg.

Z. Phys. ***106*** *(1937) 236*

6. Diskussion.

Die beschriebenen Versuche zeigen, daß bei gewissen Elementen der Prozeß (γ, n) verhältnismäßig leicht beobachtbar ist.

... Vielleicht spielen hierbei Resonanzverhältnisse eine entscheidende Rolle, ...

… and International Recognition

TECHNISCHE UNIVERSITÄT DARMSTADT

1938: **Nuclear Photo-effects**

THE beautiful experiments of Bothe and Gentner[1] on the ejection of neutrons from heavier nuclei by means of γ-rays with energy of about 17 M.v. resulting from impact of protons on lithium, have revealed a remarkable selectivity of these nuclear photo-effects. …

N. BOHR.

Universitetets Institut
for Teoretisk Fysik,
Copenhagen, Ø
Jan. 31.

*nature **141** (1938) 326*

Recent Highlights

TECHNISCHE UNIVERSITÄT DARMSTADT

Photonuclear reactions

- Photoactivation
- Nuclear Resonance Fluorescence
- Nuclear polarimetry
- Photofission
- Photodesintegration

VOLUME 83, NUMBER 25 PHYSICAL REVIEW LETTERS 20 DECEMBER 1999

Photoactivation of $^{180}Ta^{m}$ and Its Implications for the Nucleosynthesis of Nature's Rarest Naturally Occurring Isotope

D. Belic,[1] C. Arlandini,[2] J. Besserer,[3] J. de B
U. Kneissl,[1] M. Loewe,[3] H. J. Maier,[3] H.
A. Richter,[5,6]

Eur. Phys. J. A (2015) 51: 185
DOI 10.1140/epja/i2015-15185-9
THE EUROPEAN PHYSICAL JOURNAL A
Review

Perspectives for photonuclear research at the Extreme Light Infrastructure - Nuclear Physics (ELI-NP) facility*

ognata[2], P. Constantin[1],
. Gheorghe[1,11],
N. Pietralla[13], M. Sin[11],
V.V. Varlamov[12],

VOLUME 88, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 2002

Parity Measurements of Nuclear Levels Using a Free-Electron-Laser Generated γ-Ray Beam

N. Pietralla[1,2] and Z. Berant[1,3]
[1]*A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520*
[3]*Dep*

ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics A 851 (2011) 1–16
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

V.N. I
Free Electron Laser
M. W. Ahmed, J. I
Triangle Uni

Physics Letters B 741 (2015) 128–133
Contents lists available at ScienceDirect
Physics Letters B
ELSEVIER
www.elsevier.com/locate/physletb

Fragment characteristics from fission of ^{238}U and ^{234}U induced by 6.5–9.0 MeV bremsstrahlung

A. Göök[a,b,*], M. Chernykh[a], C. Eckardt[a], J. Enders[a],
P. von Neumann-Cosel[a], A. Oberstedt[b,c], S. Oberstedt[d], A. Richter[a,e]

Separation of the $1^+/1^-$ parity doublet in ^{20}Ne

CrossMark

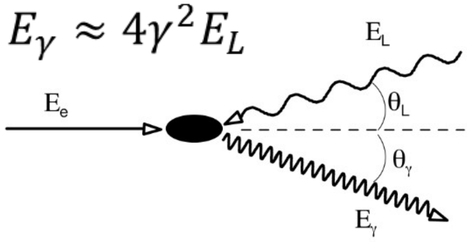
J. Beller[a], C. Stumpf[a], M. Scheck[a,b,c], N. Pietralla[a,*], D. Deleanu[e], D.M. Filipescu[e],
T. Glodariu[e], W. Haxton[f], A. Idini[a], J.H. Kelley[h], E. Kwan[d,1], G. Martinez-Pinedo[a,g],

PRL 110, 152502 (2013) PHYSICAL REVIEW LETTERS week ending 12 APRIL 2013

Unambiguous Identification of the Second 2^+ State in ^{12}C and the Structure of the Hoyle State

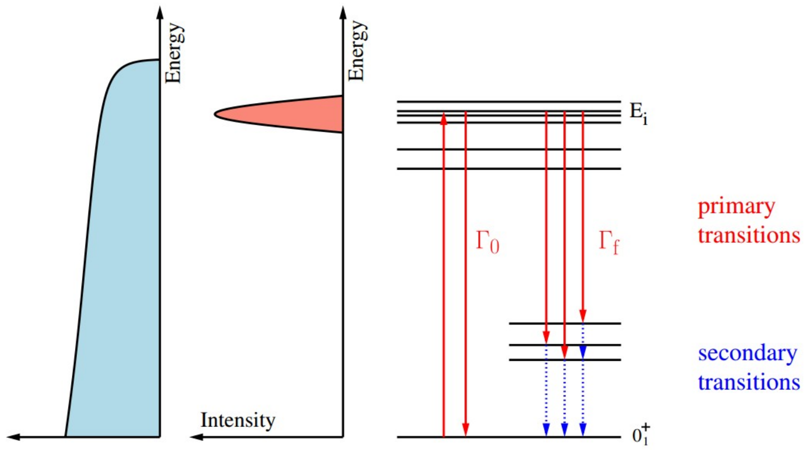
W. R. Zimmerman,[1,2] M. W. Ahmed,[2,3] B. Bromberger,[4] S. C. Stave,[2] A. Breskin,[5] V. Dangendorf,[4] Th. Delbar,[6] M. Gai,[1,7]
S. S. Henshaw,[2] J. M. Mueller,[2] C. Sun,[2] K. Tittelmeier,[4] H. R. Weller,[1,2] and Y. K. Wu[2]

ERL Advantages/Requirements



Compton back-scattering, FEL

NRF



Savran, Aumann, Zilges, Prog. Part. Nucl. Phys. 70 (2013) 210-245.

+ saving energy / intensity increase (ERL)

Need: γ-beam with high energy resolution and high repetition rate

Recirculating LINAC in non-isochronous operation, low-emittance injector

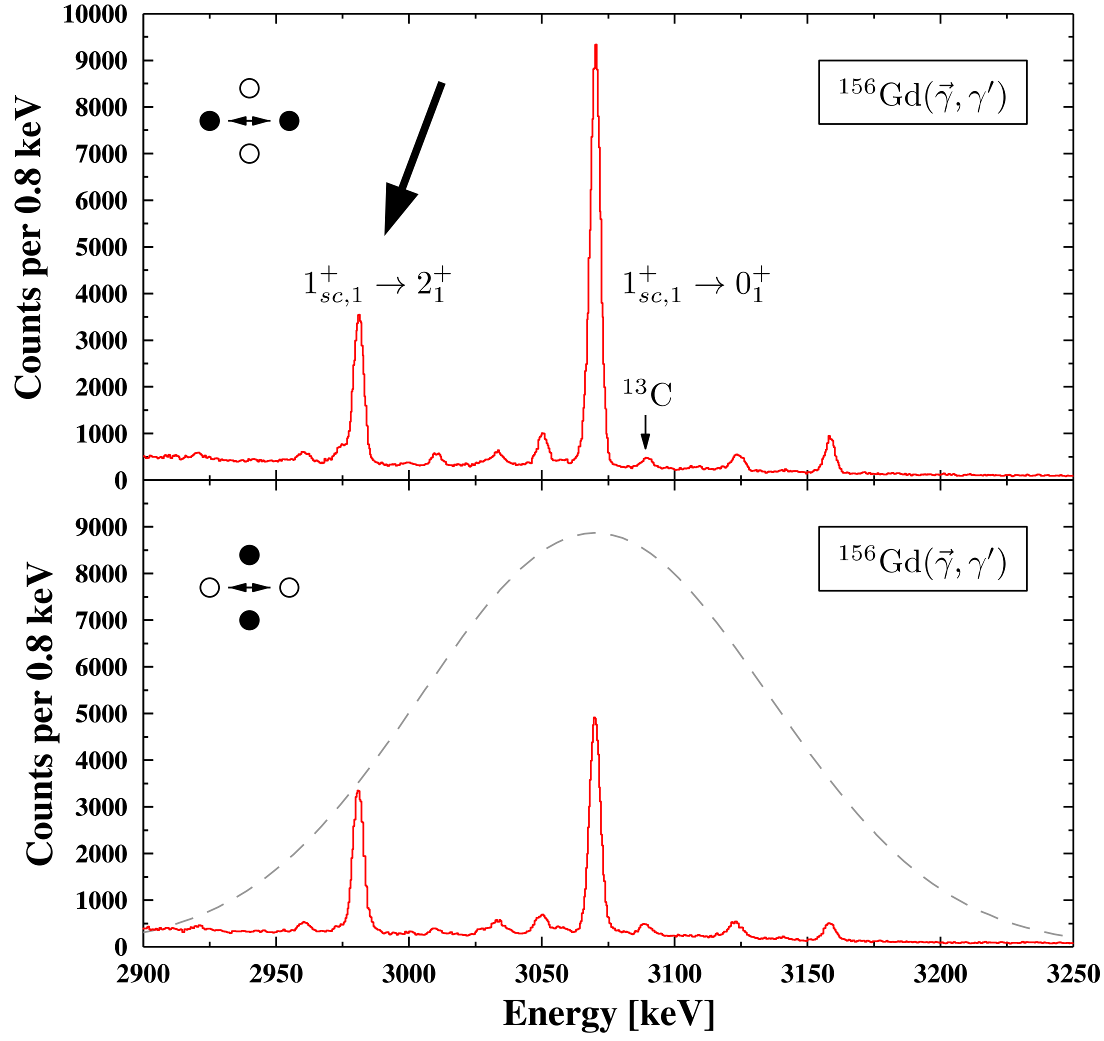
cw, superconducting RF

Example ^{156}Gd: Scissors Mode

from the experiment obtain

$$\frac{A_{\parallel}(1^+_{\rm sc} \rightarrow 2^+_1)/\epsilon_{\parallel}}{A_{\perp}(1^+_{\rm sc} \rightarrow 2^+_1)/\epsilon_{\perp}}$$

Asymmetry at backward angle



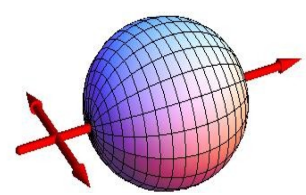
Determination M1/E2 Ratio

<u>Method:</u>

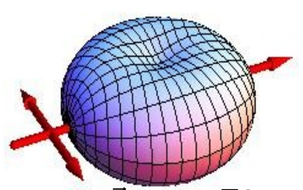
$$w(\delta_{1\to2}) = \frac{W_{\parallel}(\delta_{1\to2})}{W_{\perp}(\delta_{1\to2})}$$

$$\delta_{1\to2} = \frac{\sqrt{3}}{10}\frac{E_\gamma}{\hbar c}\frac{\langle 2_1^+ \| \hat{T}(E2) \| 1_{sc}^+ \rangle}{\langle 2_1^+ \| \hat{T}(M1) \| 1_{sc}^+ \rangle}$$

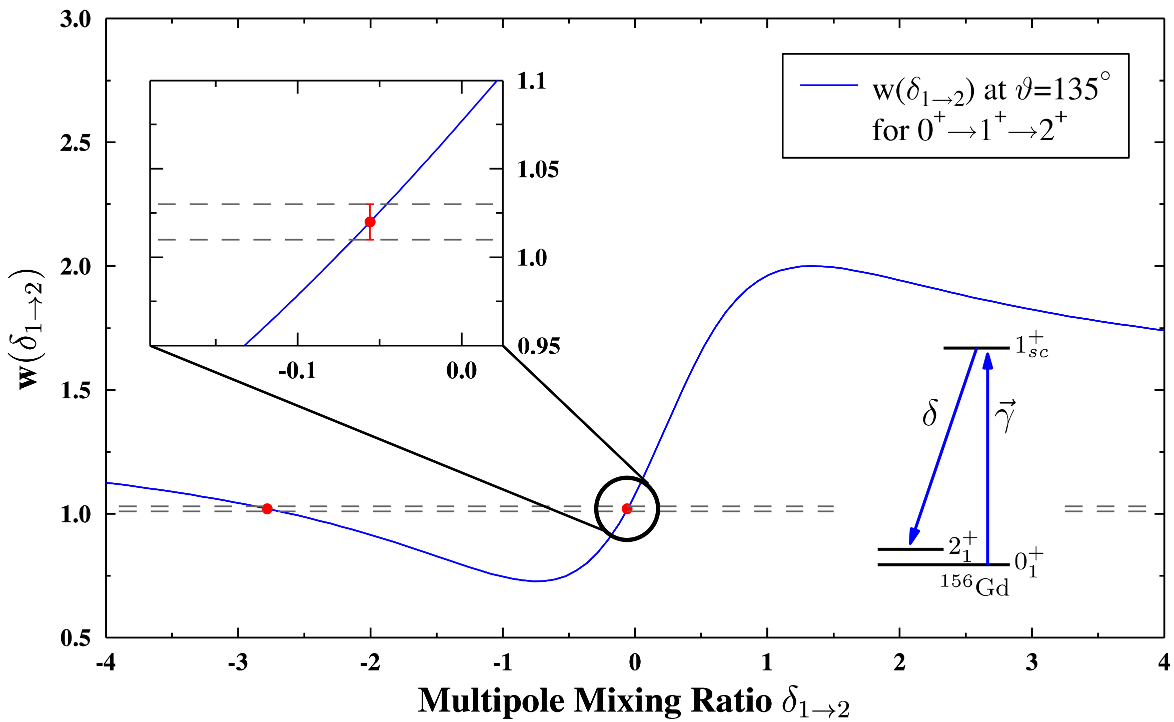
$$\delta_{1\to2} = -0.06(1)$$



$0^+ \xrightarrow{\vec{\gamma}} 1^+_{\mathrm{sc}} \xrightarrow{\mathrm{M1}} 2^+_1$



$0^+ \xrightarrow{\vec{\gamma}} 1^+_{\mathrm{sc}} \xrightarrow{\mathrm{E2}} 2^+_1$



Effective boson charges from *F*-vector *E*2 transitions

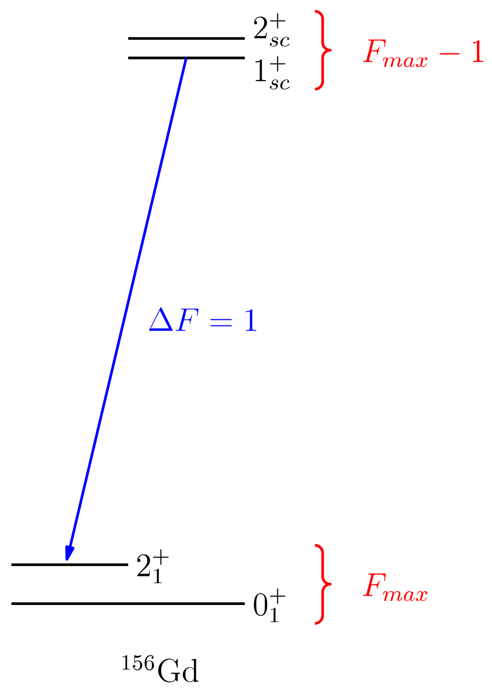
Knowing the multipole mixing ratio allows to determine F-vector E2 transition strength

$$\delta \rightarrow \Gamma_{\mathrm{E2}} = \frac{\delta^2}{1+\delta^2}\Gamma_{\mathrm{ges}} \rightarrow B(E2; 1^+_{\mathrm{sc}} \to 2^+_1)$$

$$\rightarrow B(E2; 1^+_{\mathrm{sc}} \to 2^+_1) = 0.027(11)\ \mathrm{W.u.}$$

First information on an *F*-vector *E*2 transition in an axially-deformed nucleus!

From this obtain local values of the effective boson charges e_π and e_ν for a better description of *E*2 transitions in the IBM-2.



*E*2 transition operator:

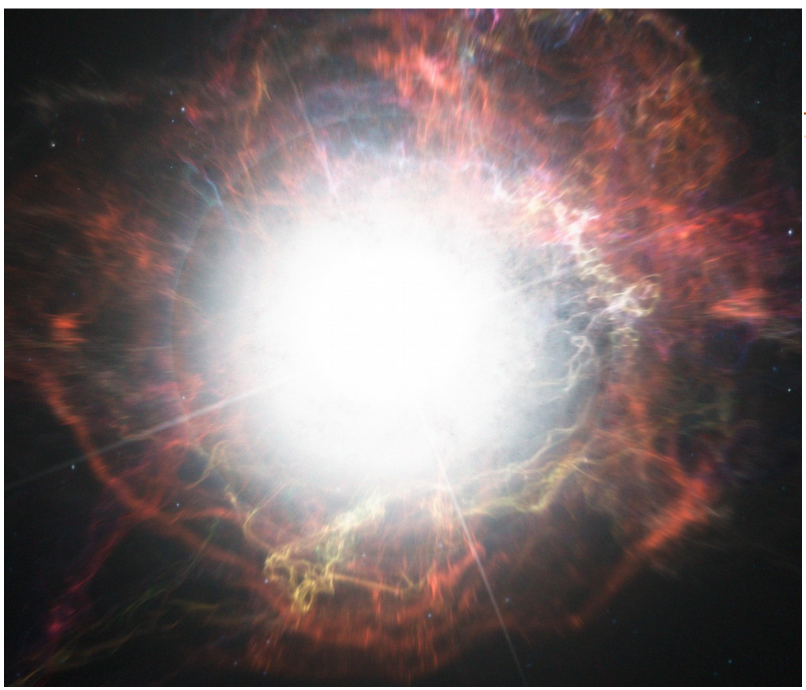
$$T(E2) = e_\pi Q_\pi^{\chi_\pi} + e_\nu Q_\nu^{\chi_\nu}$$

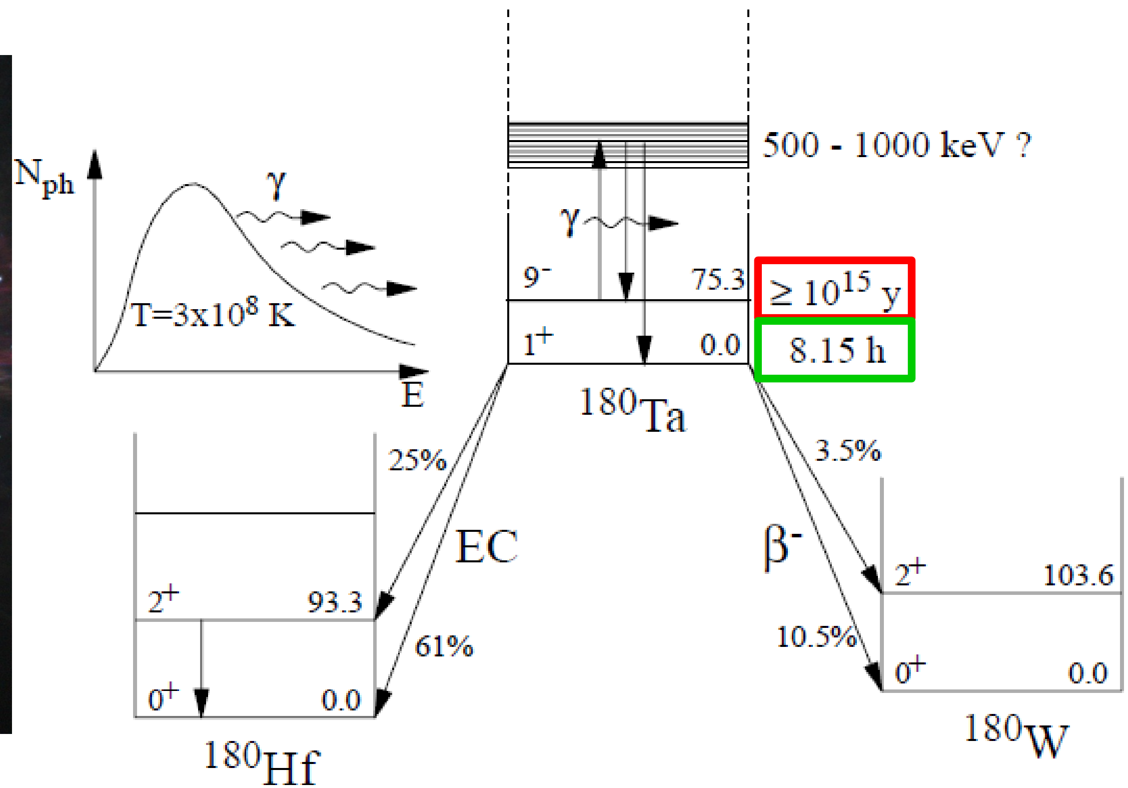
The Stellar Clock: ^{180m}Ta

VOLUME 83, NUMBER 25 PHYSICAL REVIEW LETTERS 20 DECEMBER 1999

Photoactivation of $^{180}Ta^m$ and Its Implications for the Nucleosynthesis of Nature's Rarest Naturally Occurring Isotope

D. Belic,[1] C. Arlandini,[2] J. Besserer,[3] J. de Boer,[3] J. J. Carroll,[4] J. Enders,[5] T. Hartmann,[5] F. Käppeler,[2] H. Kaiser,[5] U. Kneissl,[1] M. Loewe,[3] H. J. Maier,[3] H. Maser,[1] P. Mohr,[5] P. von Neumann-Cosel,[5] A. Nord,[1] H. H. Pitz,[1] A. Richter,[5,6] M. Schumann,[2] S. Volz,[5] and A. Zilges[5]



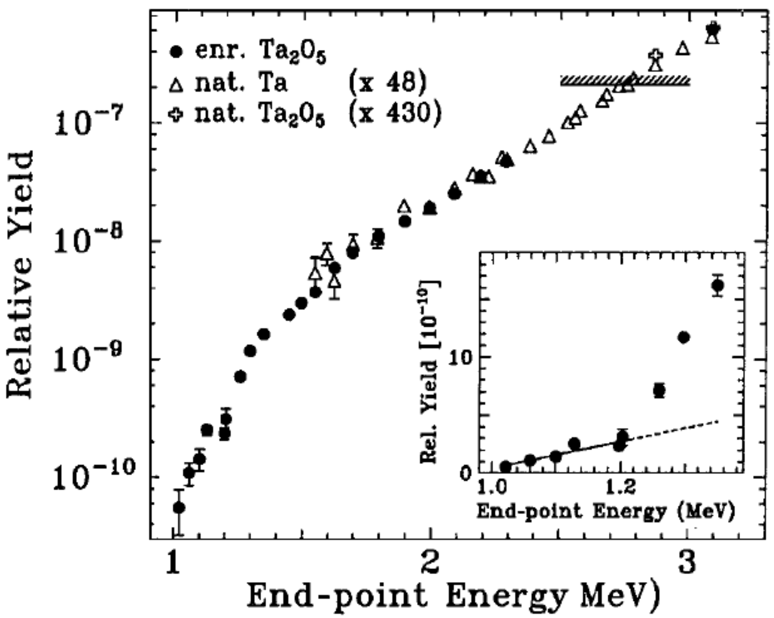


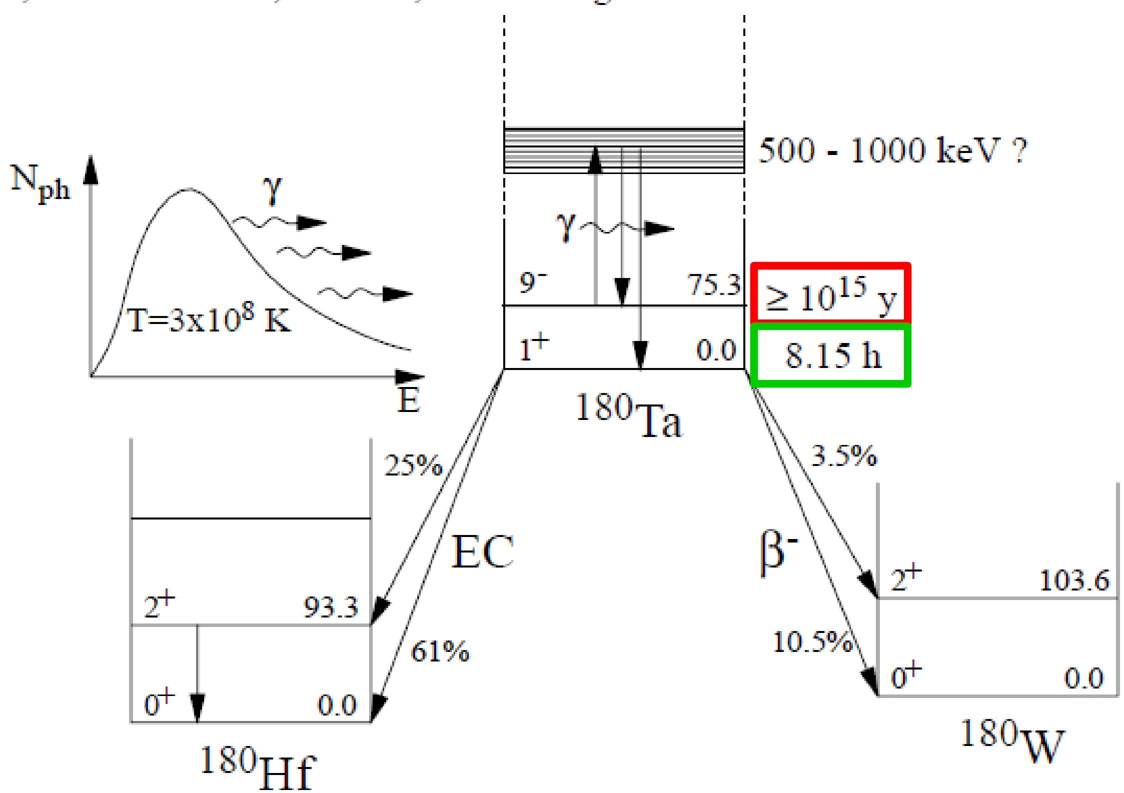
The Stellar Clock: ^{180m}Ta

VOLUME 83, NUMBER 25 PHYSICAL REVIEW LETTERS 20 DECEMBER 1999

Photoactivation of ^{180}Ta^m and Its Implications for the Nucleosynthesis of Nature's Rarest Naturally Occurring Isotope

D. Belic,[1] C. Arlandini,[2] J. Besserer,[3] J. de Boer,[3] J. J. Carroll,[4] J. Enders,[5] T. Hartmann,[5] F. Käppeler,[2] H. Kaiser,[5] U. Kneissl,[1] M. Loewe,[3] H. J. Maier,[3] H. Maser,[1] P. Mohr,[5] P. von Neumann-Cosel,[5] A. Nord,[1] H. H. Pitz,[1] A. Richter,[5,6] M. Schumann,[2] S. Volz,[5] and A. Zilges[5]





The Stellar Clock: ^{180m}Ta

TECHNISCHE UNIVERSITÄT DARMSTADT

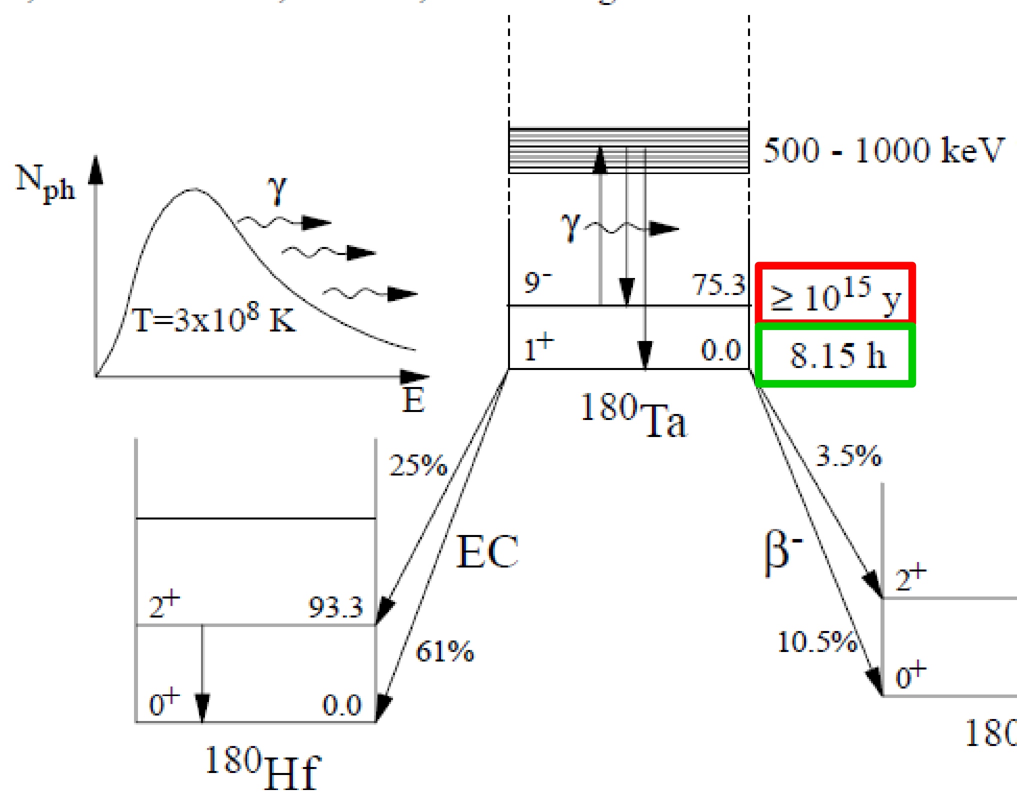
VOLUME 83, NUMBER 25 PHYSICAL REVIEW LETTERS 20 DECEMBER 1999

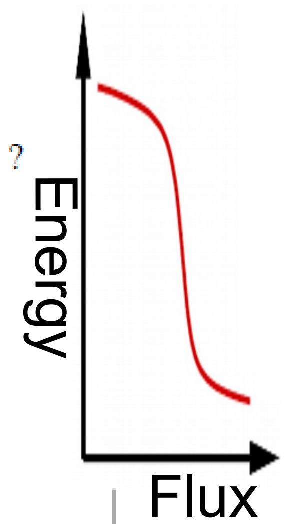
Photoactivation of ^{180}Ta^{m} and Its Implications for the Nucleosynthesis of Nature's Rarest Naturally Occurring Isotope

D. Belic,[1] C. Arlandini,[2] J. Besserer,[3] J. de Boer,[3] J. J. Carroll,[4] J. Enders,[5] T. Hartmann,[5] F. Käppeler,[2] H. Kaiser,[5] U. Kneissl,[1] M. Loewe,[3] H. J. Maier,[3] H. Maser,[1] P. Mohr,[5] P. von Neumann-Cosel,[5] A. Nord,[1] H. H. Pitz,[1] A. Richter,[5,6] M. Schumann,[2] S. Volz,[5] and A. Zilges[5]

Limited resolution and sensitivity due to bremsstrahlung:

Low flux near endpoint, integral cross section





The Stellar Clock: ^{180m}Ta

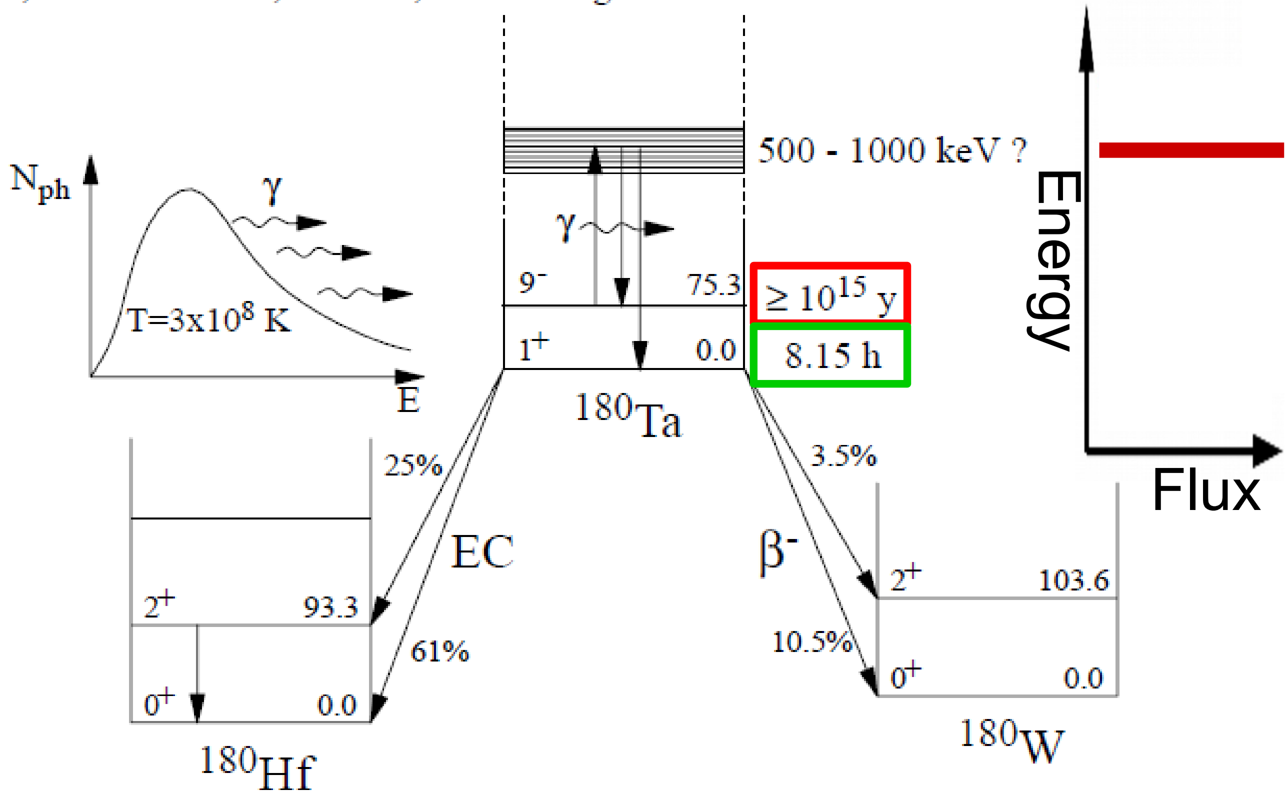
VOLUME 83, NUMBER 25 PHYSICAL REVIEW LETTERS 20 DECEMBER 1999

Photoactivation of $^{180}Ta^{m}$ and Its Implications for the Nucleosynthesis of Nature's Rarest Naturally Occurring Isotope

D. Belic,[1] C. Arlandini,[2] J. Besserer,[3] J. de Boer,[3] J. J. Carroll,[4] J. Enders,[5] T. Hartmann,[5] F. Käppeler,[2] H. Kaiser,[5] U. Kneissl,[1] M. Loewe,[3] H. J. Maier,[3] H. Maser,[1] P. Mohr,[5] P. von Neumann-Cosel,[5] A. Nord,[1] H. H. Pitz,[1] A. Richter,[5,6] M. Schumann,[2] S. Volz,[5] and A. Zilges[5]

Much higher resolution scan at ELI-NP

Allows to search for even lower-lying gateway-states



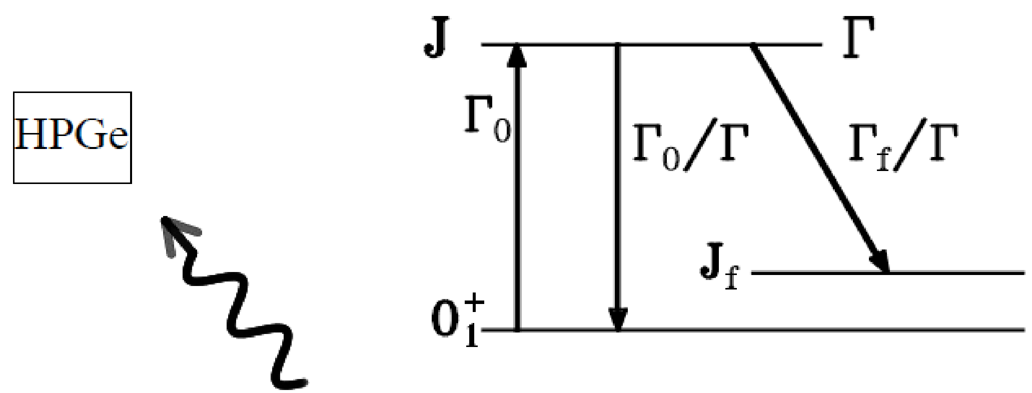
Nuclear Resonance Fluorescence

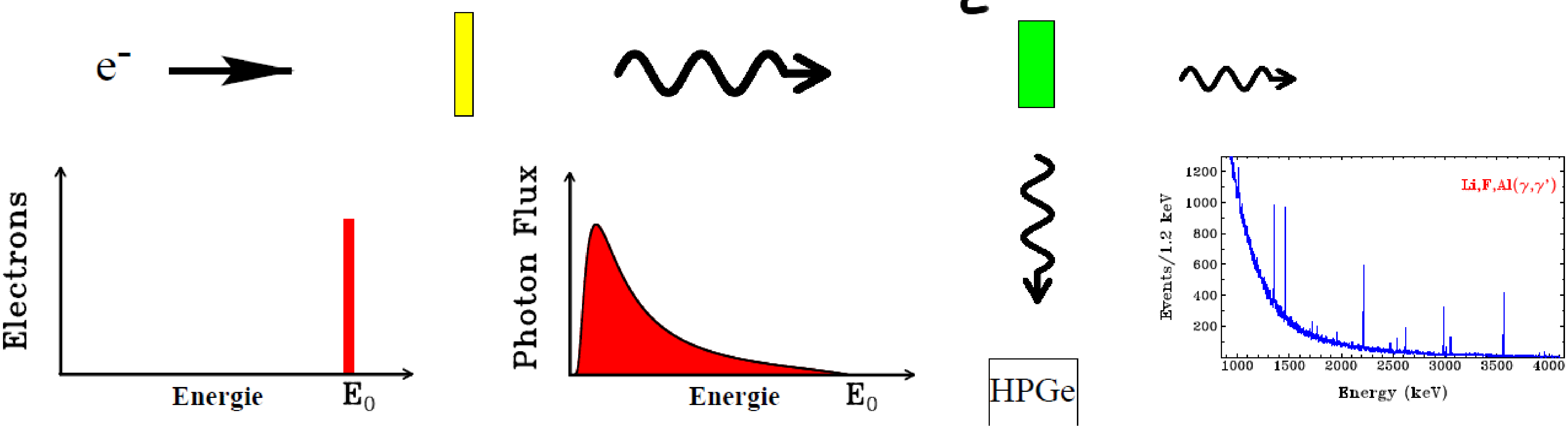
TECHNISCHE UNIVERSITÄT DARMSTADT

$\Pi\lambda$ −strengths

$\Delta J = 1,2$

high energy resolution





Connection to Lifetimes

TECHNISCHE UNIVERSITÄT DARMSTADT

In a nutshell – description of resonance: Breit-Wigner

$$\frac{d^2\sigma_{abs}(E)}{d\Omega dE} = \pi\lambdabar^2 \cdot \frac{2j+1}{2(2j_0+1)} \cdot \frac{\Gamma_0\Gamma_f}{(E-E_r)^2+\frac{1}{4}\Gamma^2} \cdot \frac{W(\theta)}{4\pi}$$

Integrate that over solid angle and the resonance:

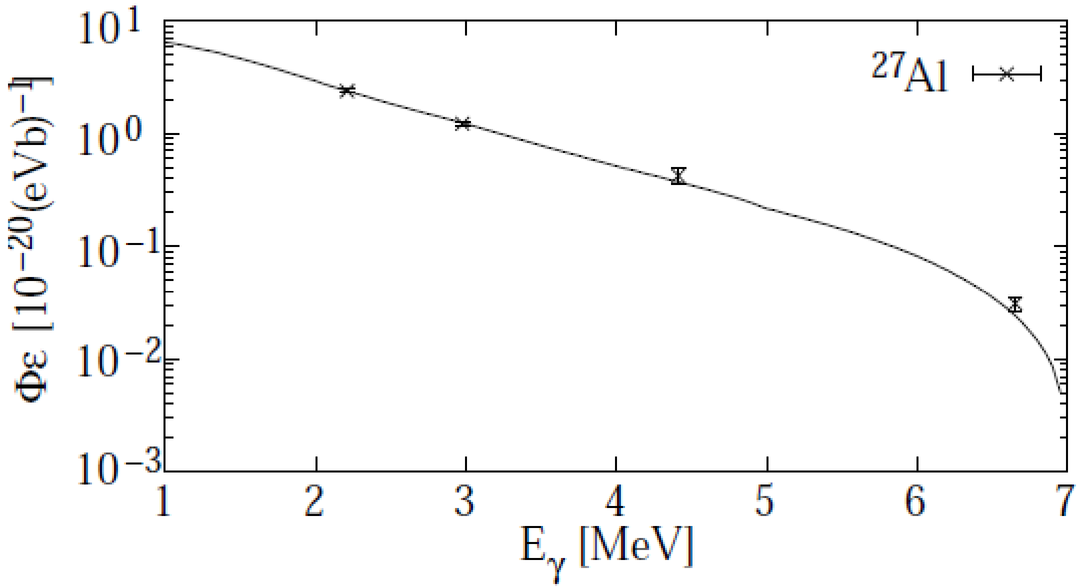
$$I_{s,f} \quad = \quad \pi^2\lambdabar^2 \cdot \frac{2J+1}{2J_0+1} \cdot \frac{\Gamma_0\Gamma_f}{\Gamma}$$

Integrated cross-section from size of the observed peak to „f"inal state.

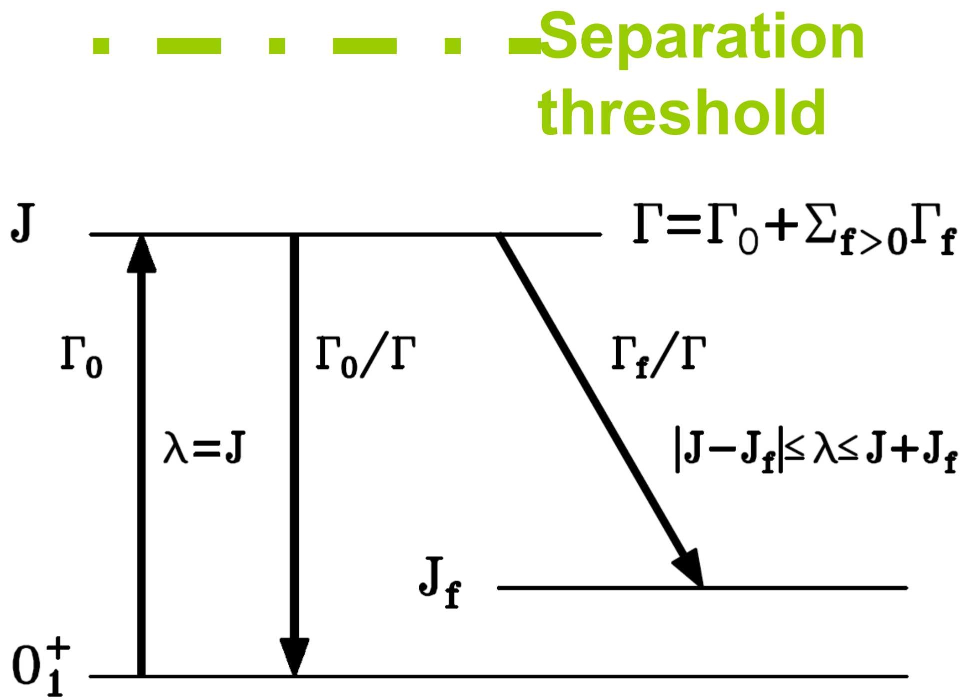
Photon Flux from Standard

Measurement of x-sections always relative to a standard!
For example, ^{27}Al / ^{11}B have well-known cross-sections.

Measure Al/B states, measure / simulate detector efficiency
=> Photon Flux / Cross-section calibration



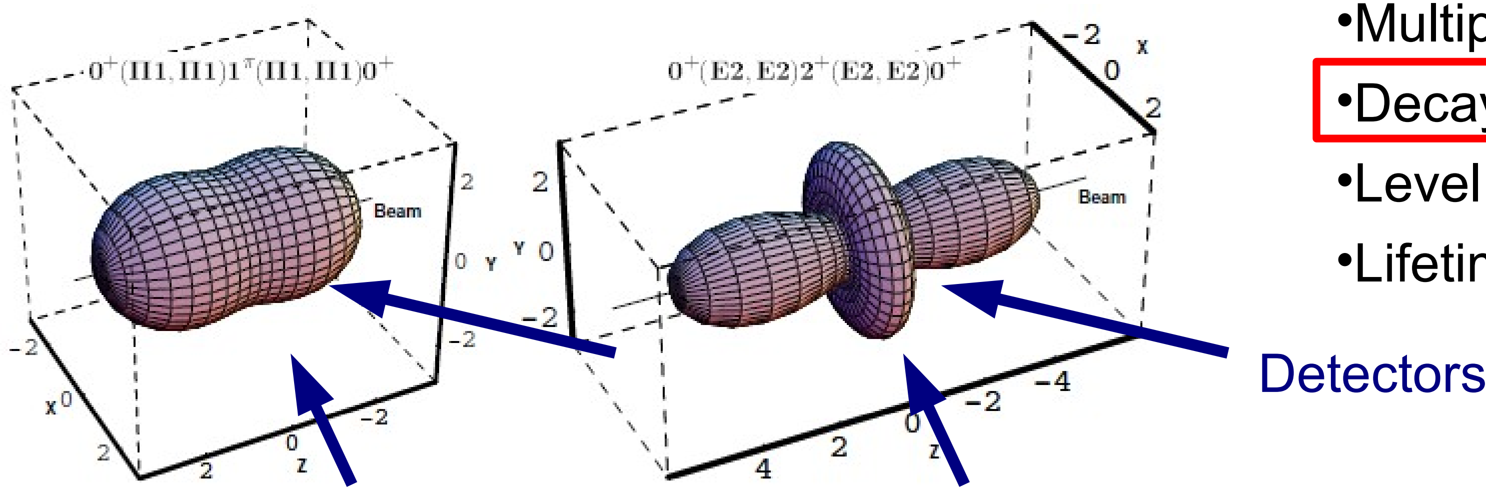
Nuclear Resonance Fluorescence



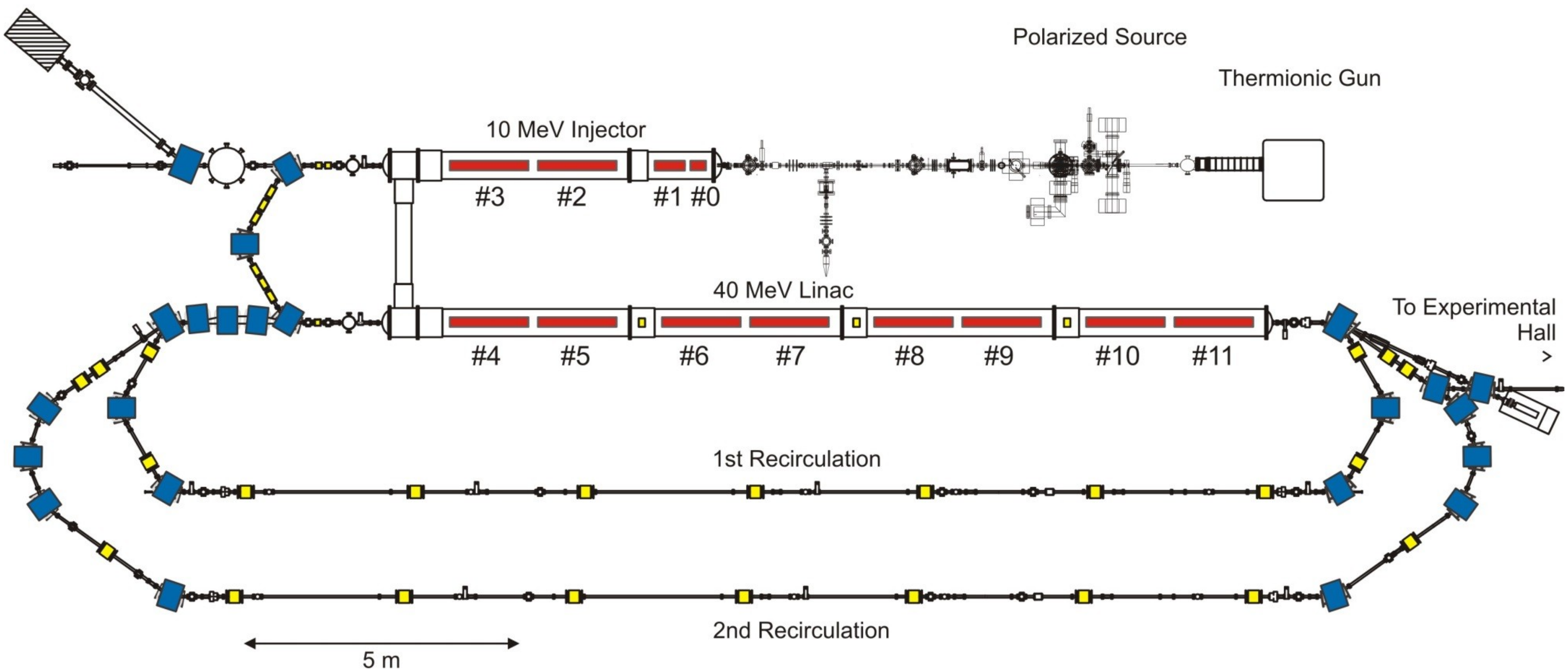
Observables

- •Excitation Energy E_r
- •Spin J
- •Parity π
- •Decay Energies E_γ
- •Partial Widths Γ_i/Γ_0
- •Multipole Mixing δ
- •Decay Strengths $B(\pi\lambda)$
- •Level Width Γ (eV)
- •Lifetime τ (ps – as)

x-sections



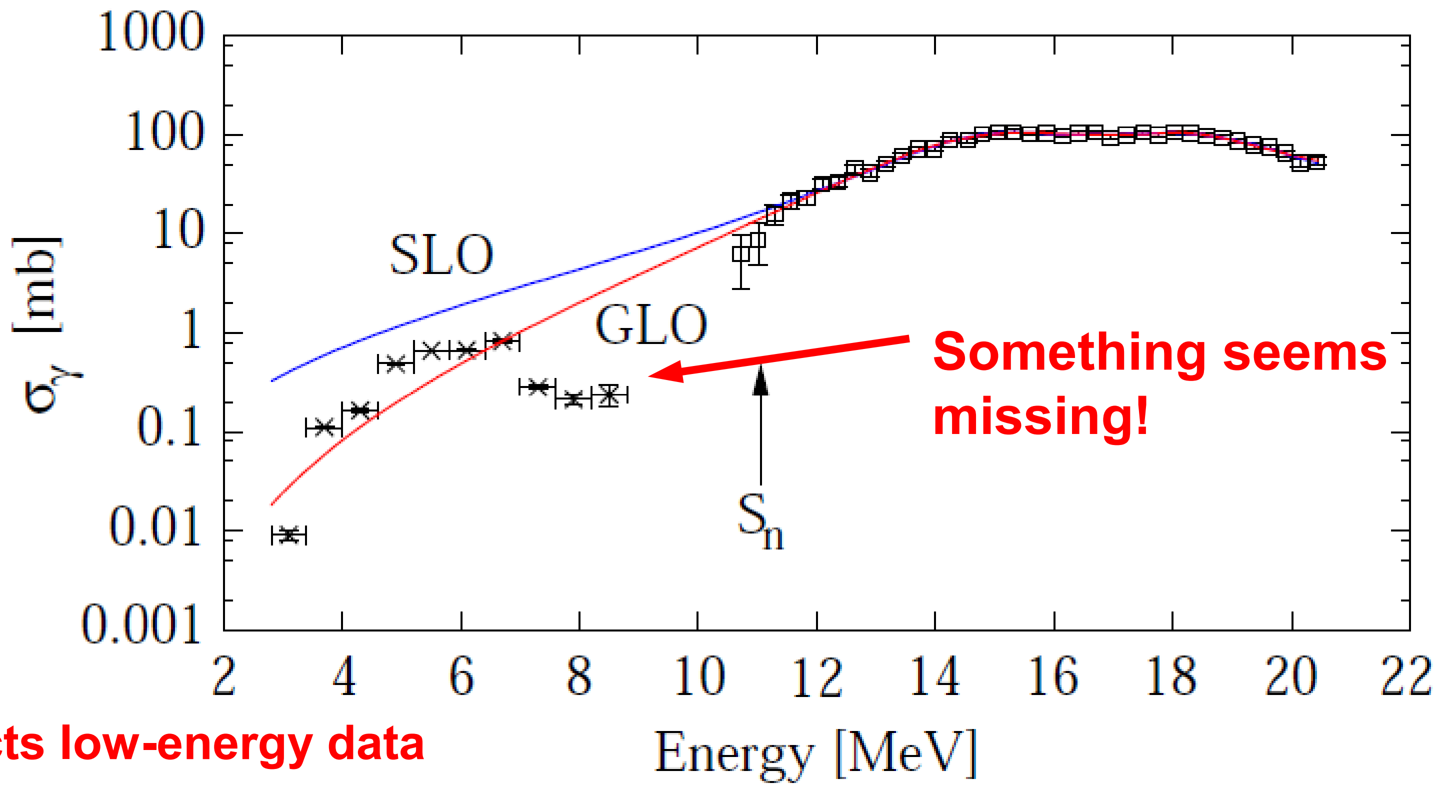
S-DALINAC



F. Hug *et al.*, Proc. of the 2011 Part. Acc. Conf., New York, NY, USA (2011), 1999.

Anything on the GDR Tail ??

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



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

Something seems missing!

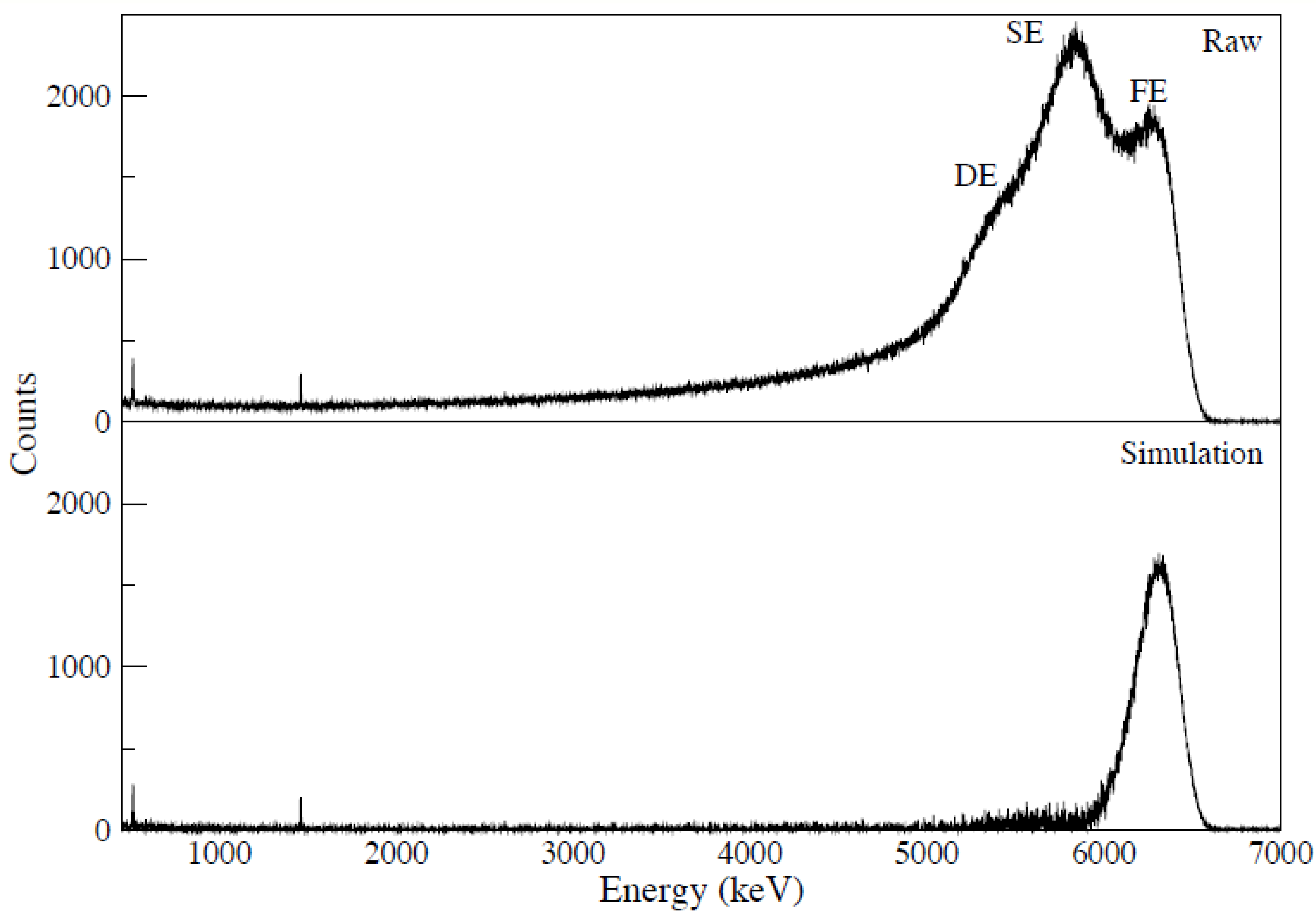
Overpredicts low-energy data

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

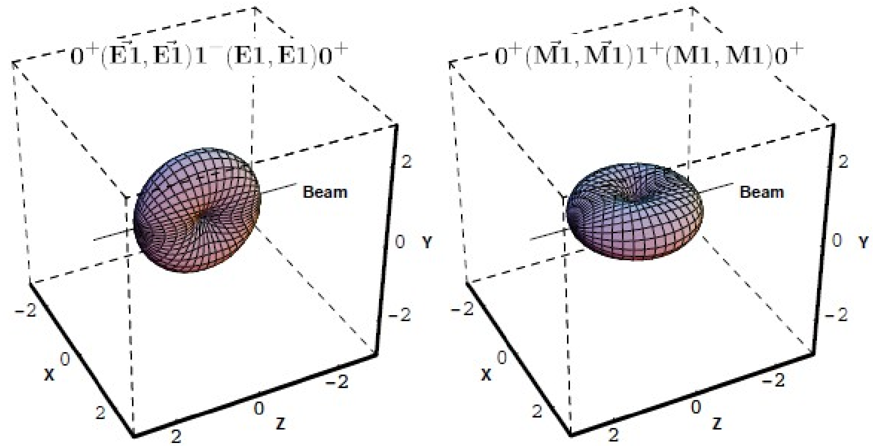
$$\sigma^{GLO} \propto E\Gamma\left[\frac{E\Gamma(E)}{(E^2 - E_0^2)^2 + E^2[\Gamma(E)]^2}\right]$$

HIGS Beam Profile

Actually beam profile derived from 0° HPGe spectrum and GEANT simulation.



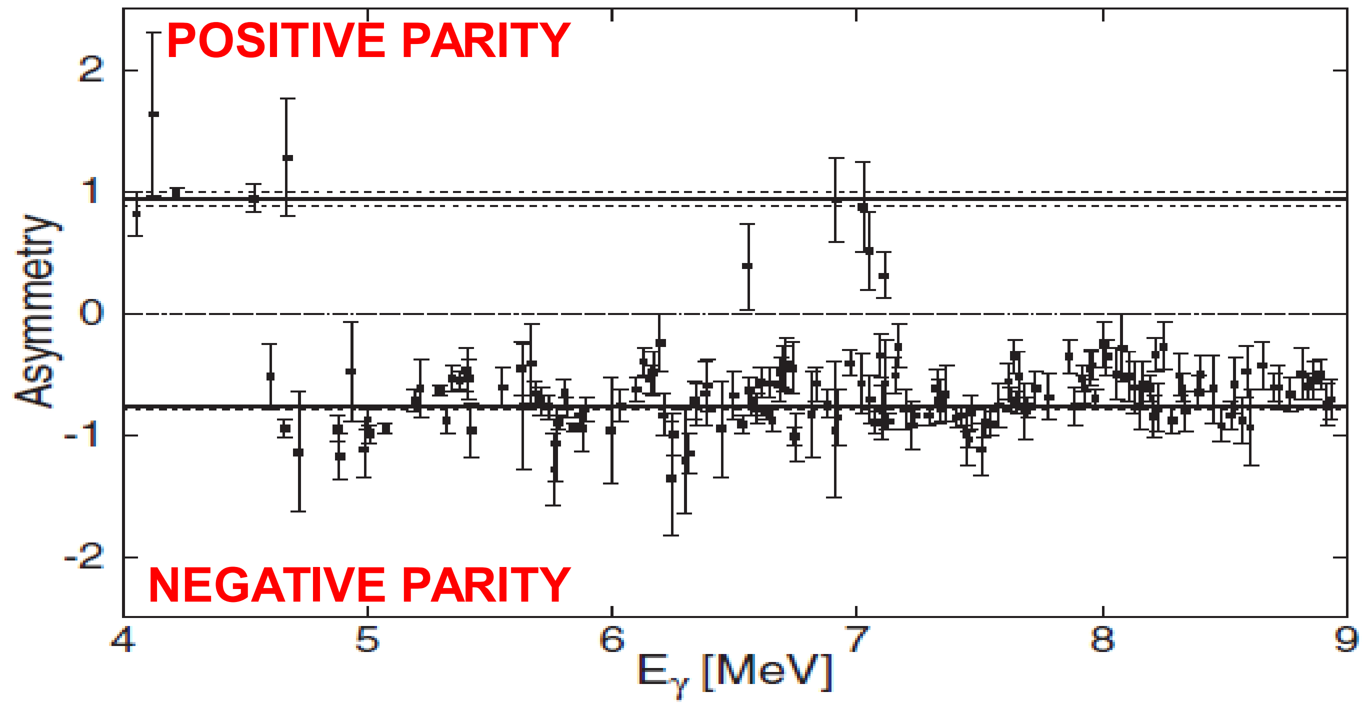
Polarization => Parity



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

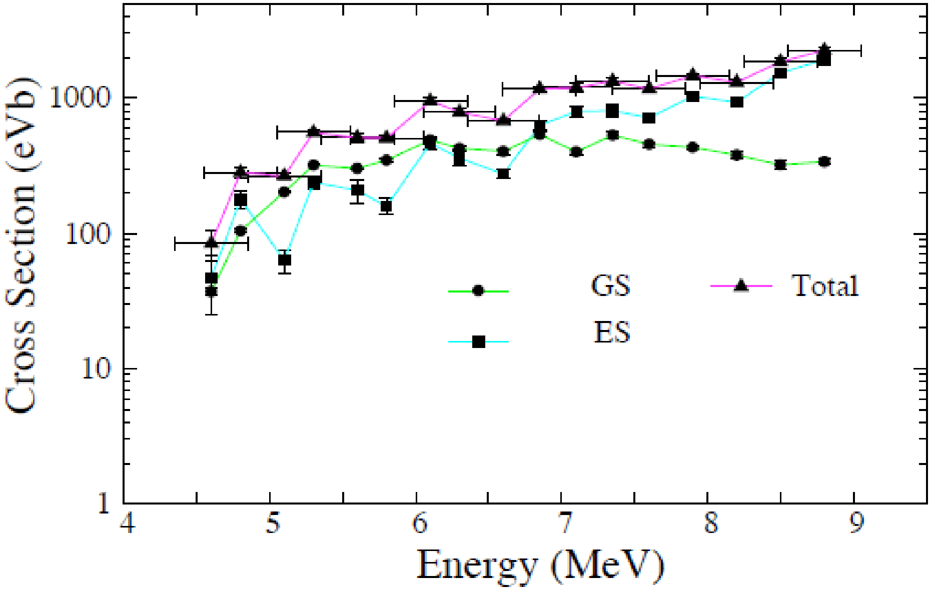
almost all: E1

Much E1 Strength is Hidden

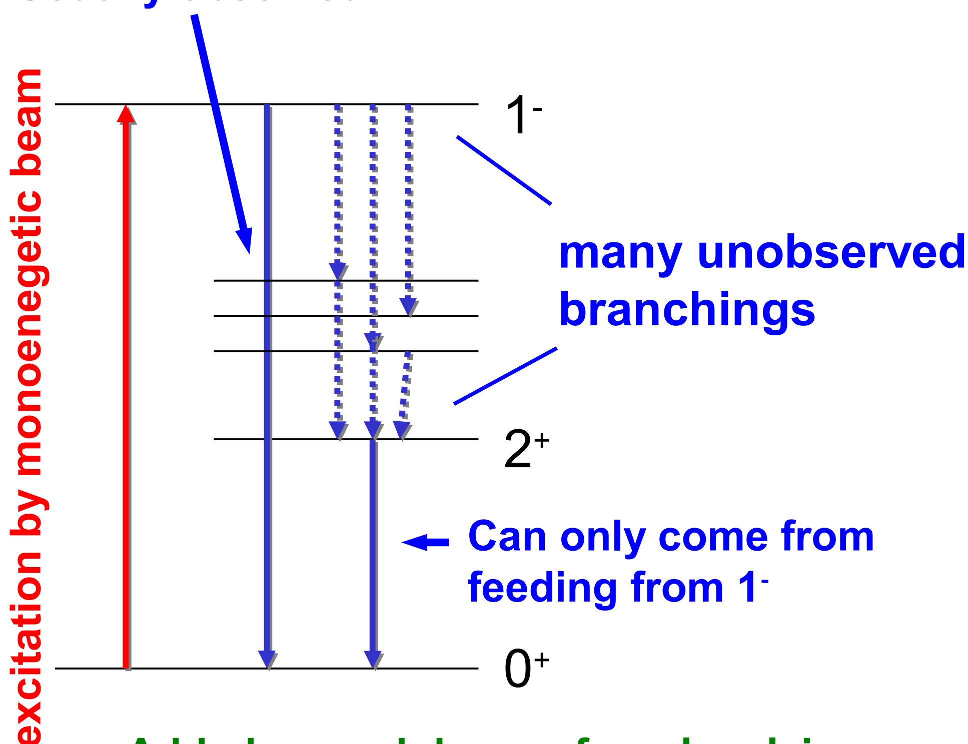
TECHNISCHE UNIVERSITÄT DARMSTADT

Now including HIGS Data:

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



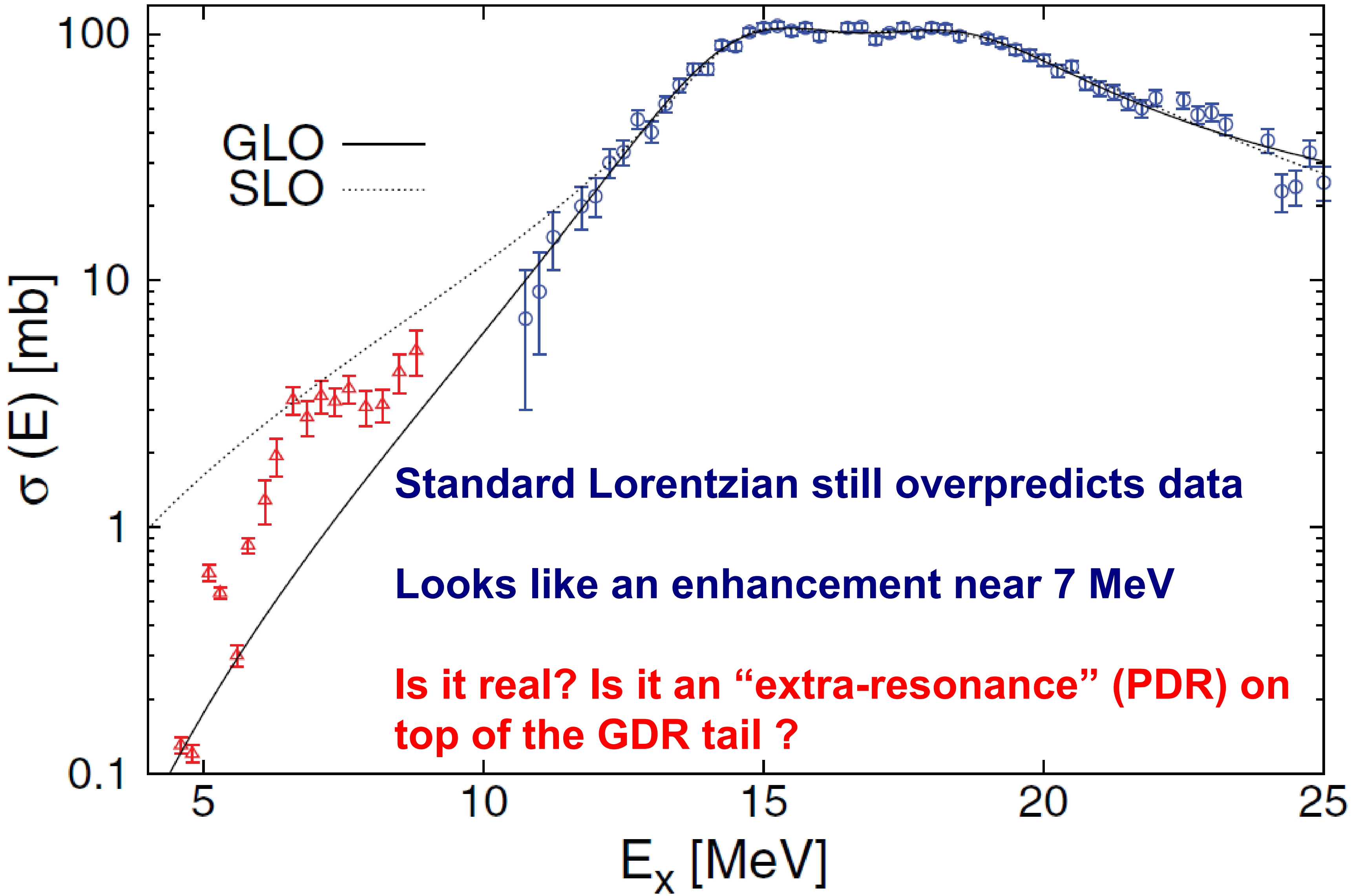
Similar to observation in ^{138}Ba, A. Tonchev, PRL 104, 072501 ('10)



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

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

Branching-corrected x-sections



Standard Lorentzian still overpredicts data

Looks like an enhancement near 7 MeV

Is it real? Is it an "extra-resonance" (PDR) on top of the GDR tail ?

No Enhancement in ^{76}Ge

TECHNISCHE UNIVERSITÄT DARMSTADT

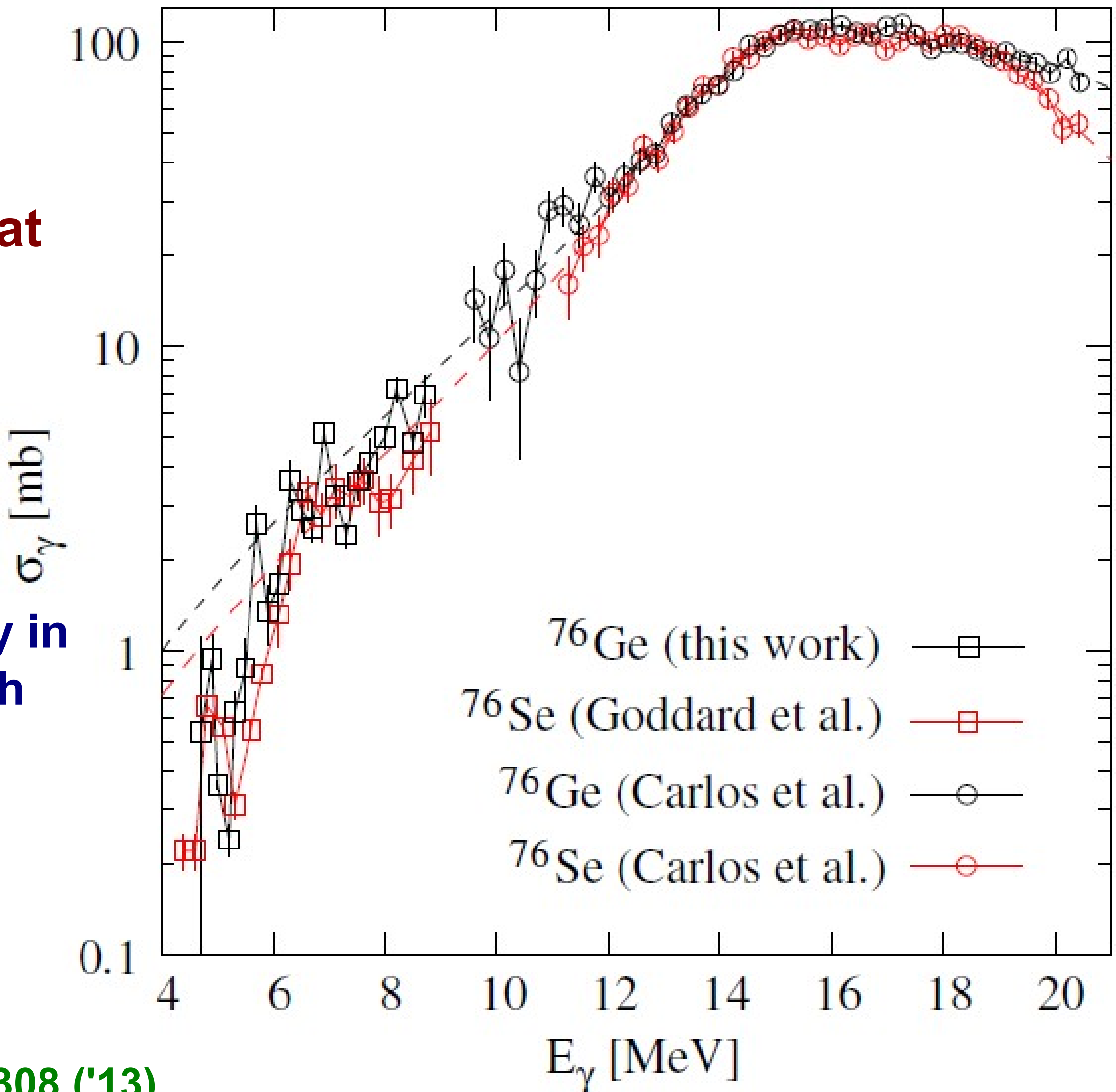
Result from photon-scattering:
(many weeks of beamtime at TUD and HIGS)

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,...



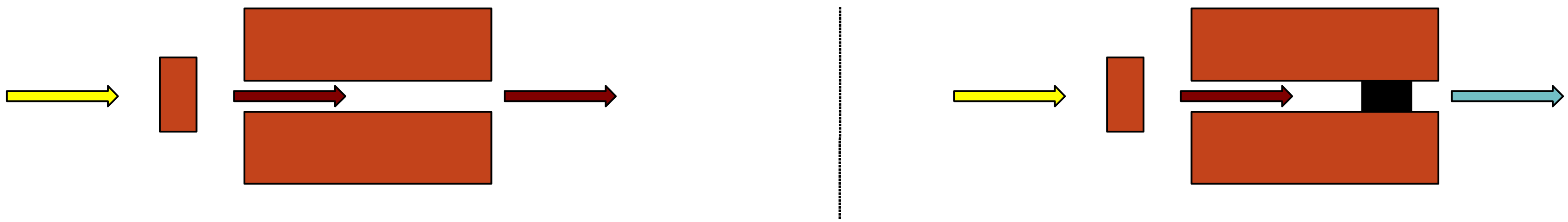
P. Goddard, N. Cooper, VW, ..., PRC 88, 064308 ('13)
R. Ilieva & P. Humby, MA thesis, Yale/Surrey

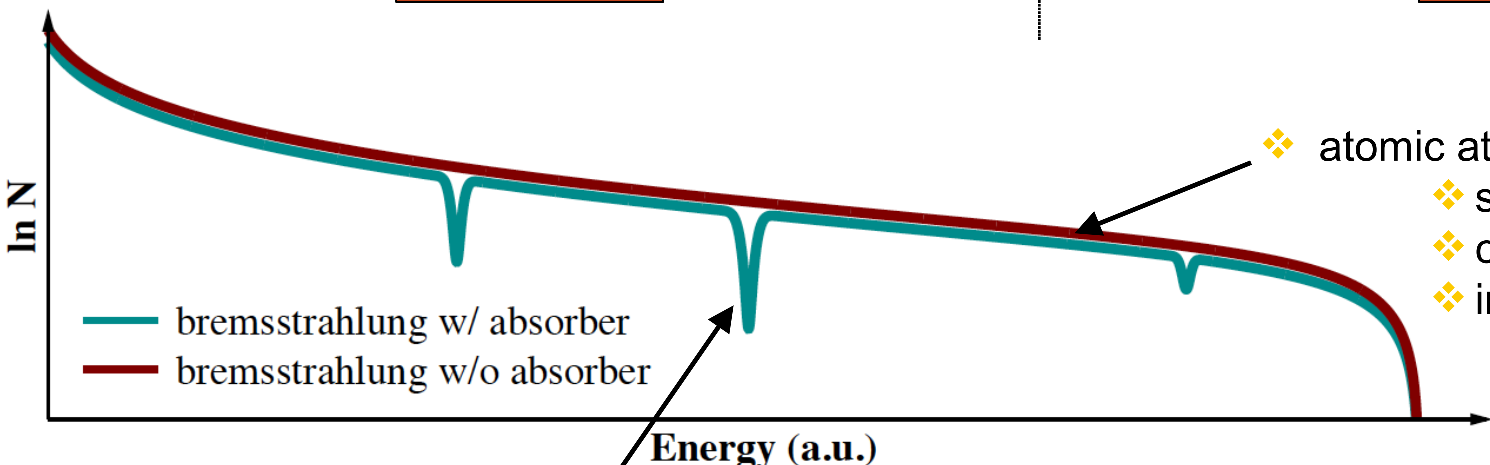
New Prospects

Relative Self-Absorption

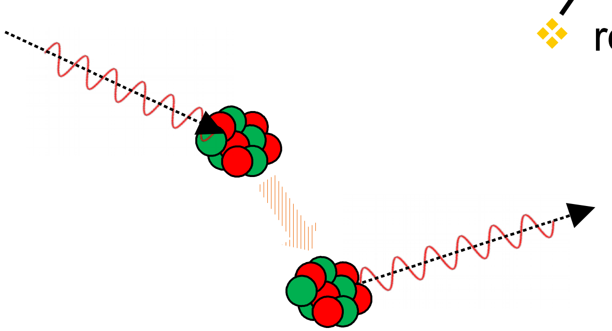
Absorption Processes

Absorption lines only a few eV wide!



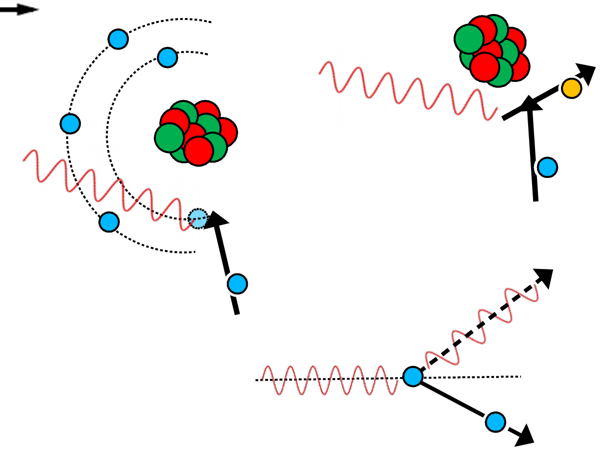


- atomic attenuation
  - several processes
  - contributes at each energy
  - independent of Γ_0



- resonant absorption
  - only at resonance energies
  - depends on Γ_0

$$\sigma_a \propto \Gamma_0 \cdot e^{-\left(\frac{E-E_r}{\Delta}\right)^2}$$

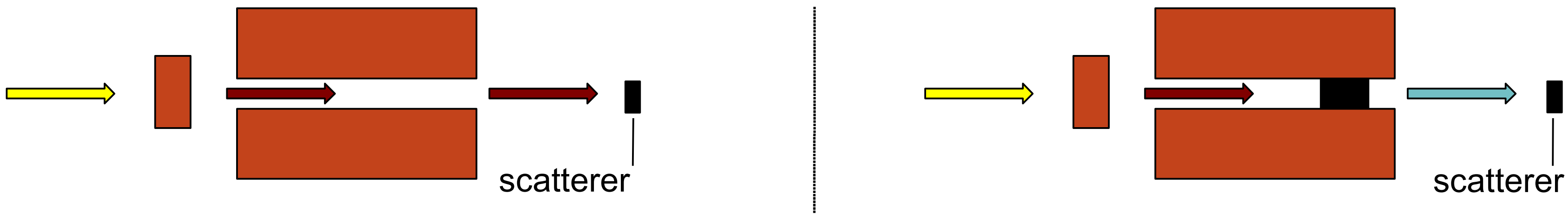


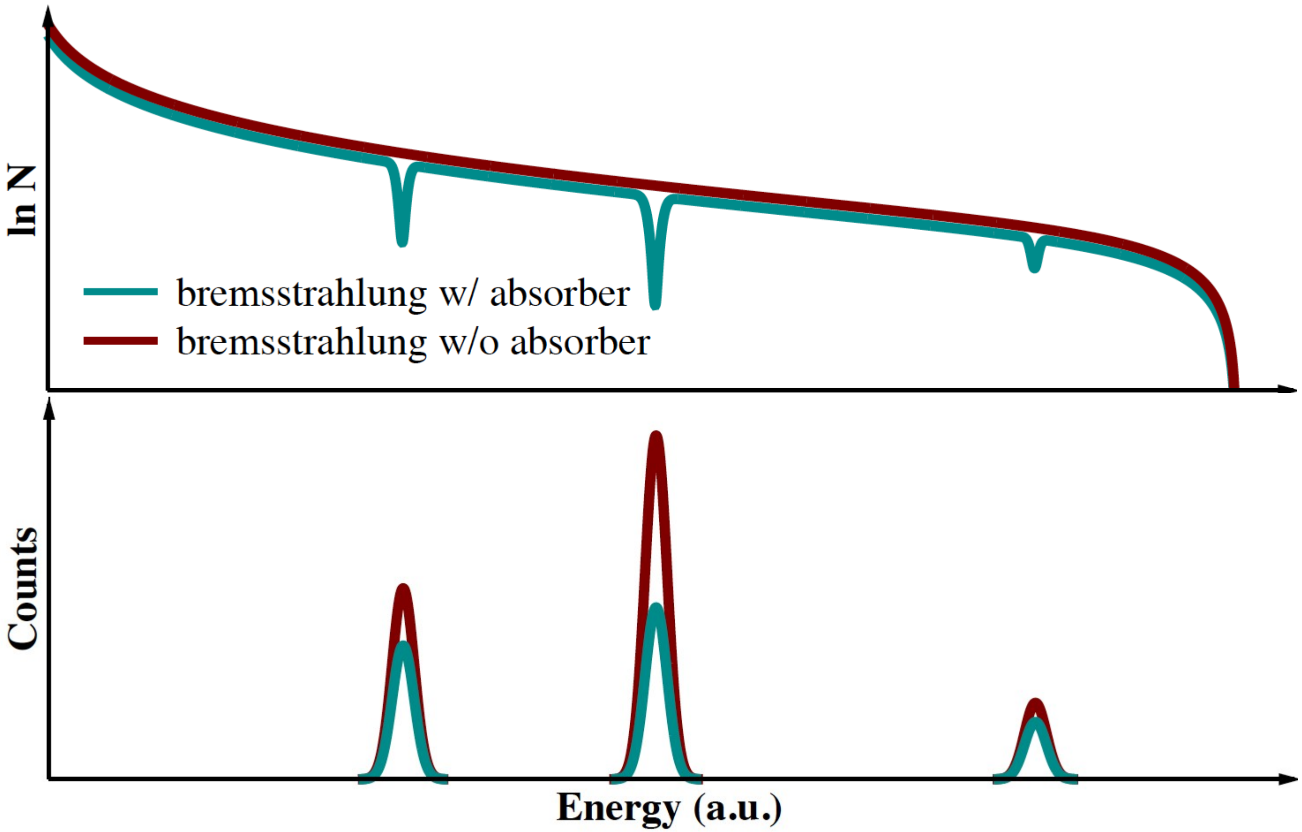
Principle of Measurement and Self Absorption[1]

1 F. R. Metzger, Prog. in Nucl. Phys. **7** (1959) 53

TECHNISCHE UNIVERSITÄT DARMSTADT

Use scatterer made of absorber material as „high-resolution detector".





Self Absorption:
Decrease of Scattered Photons because of Resonant Absorption

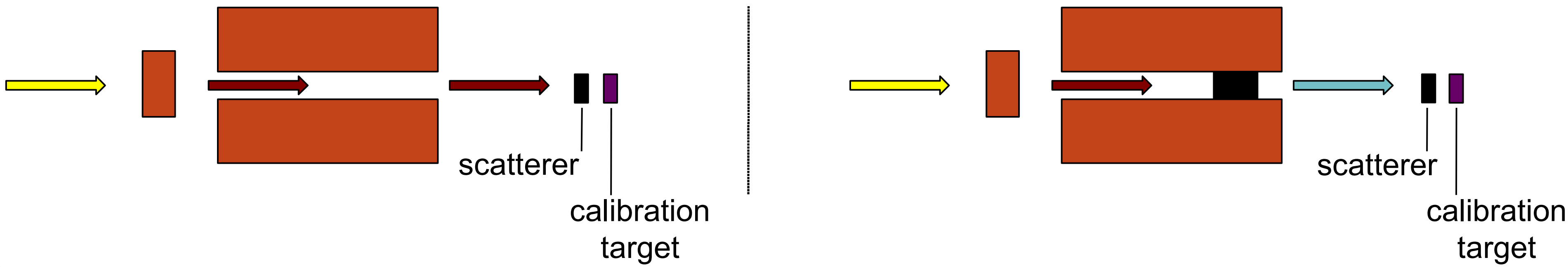
$$R(\Gamma_0) = \frac{N_{\mathrm{woA}} - f \cdot N_{\mathrm{wA}}}{N_{\mathrm{woA}}}$$

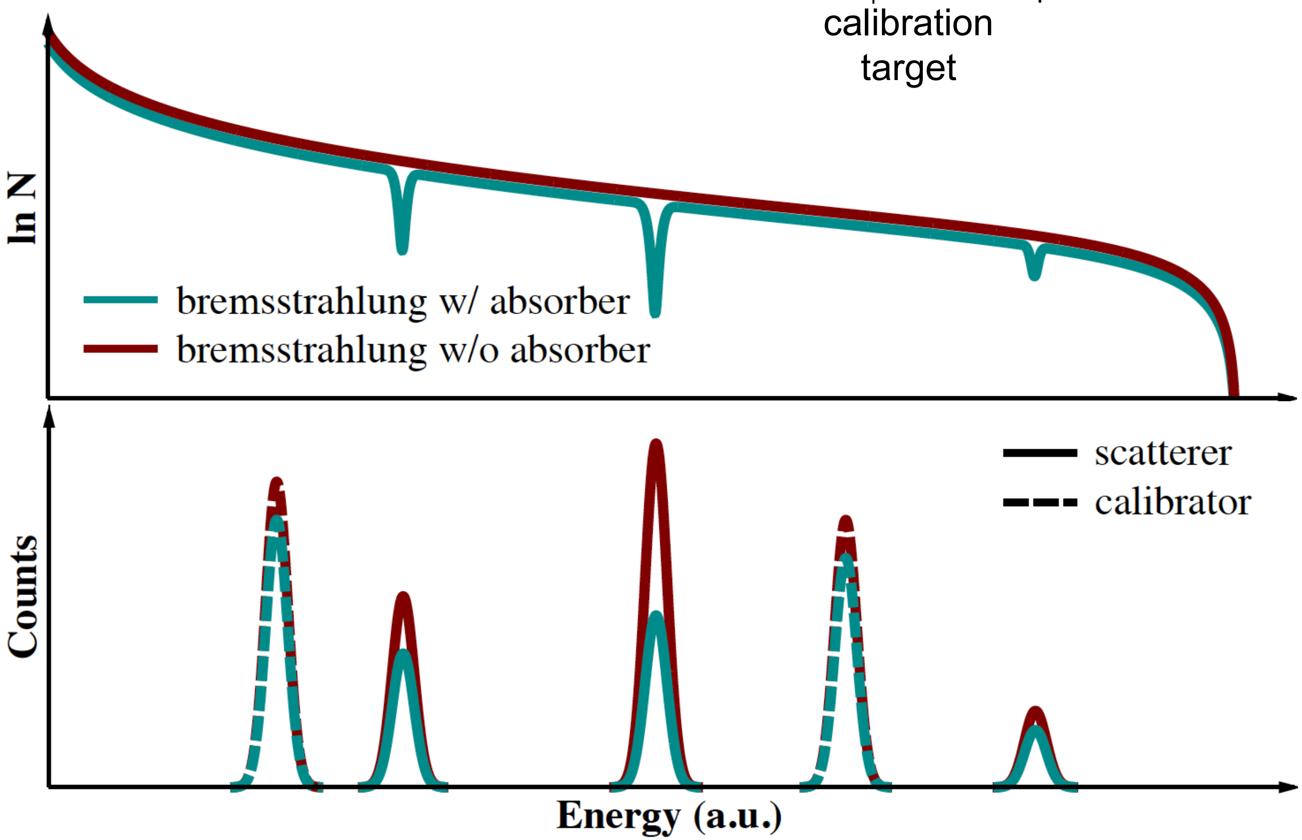
Principle of Measurement and Self Absorption[1]

1 F. R. Metzger, Prog. in Nucl. Phys. **7** (1959) 53

TECHNISCHE UNIVERSITÄT DARMSTADT

Use scatterer made of absorber material as „high-resolution detector".





Self Absorption:
Decrease of Scattered Photons because of Resonant Absorption

$$R(\Gamma_0) = \frac{N_{\mathrm{woA}} - f \cdot N_{\mathrm{wA}}}{N_{\mathrm{woA}}}$$

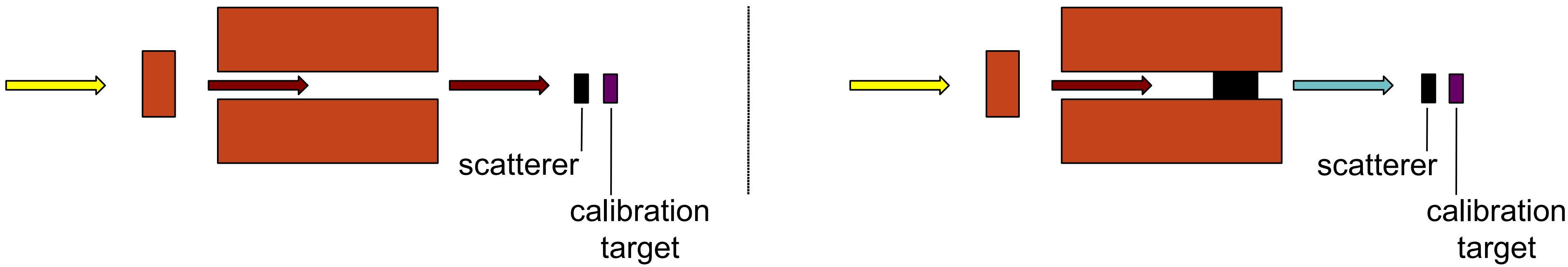
$$f = \frac{N^{\mathrm{std}}_{\mathrm{woA}}}{N^{\mathrm{std}}_{\mathrm{wA}}}$$

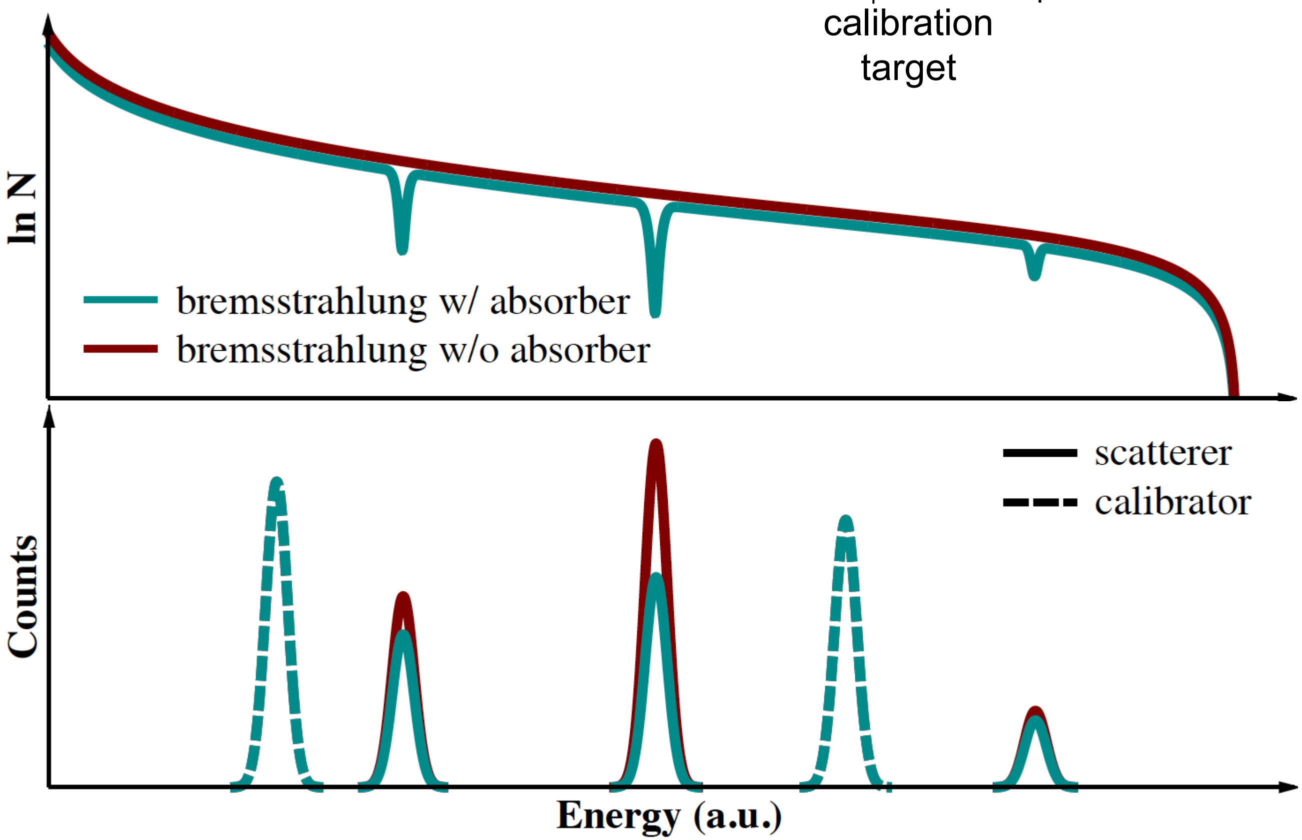
Principle of Measurement and Self Absorption[1]

1 F. R. Metzger, Prog. in Nucl. Phys. **7** (1959) 53

TECHNISCHE UNIVERSITÄT DARMSTADT

Use scatterer made of absorber material as „high-resolution detector“.





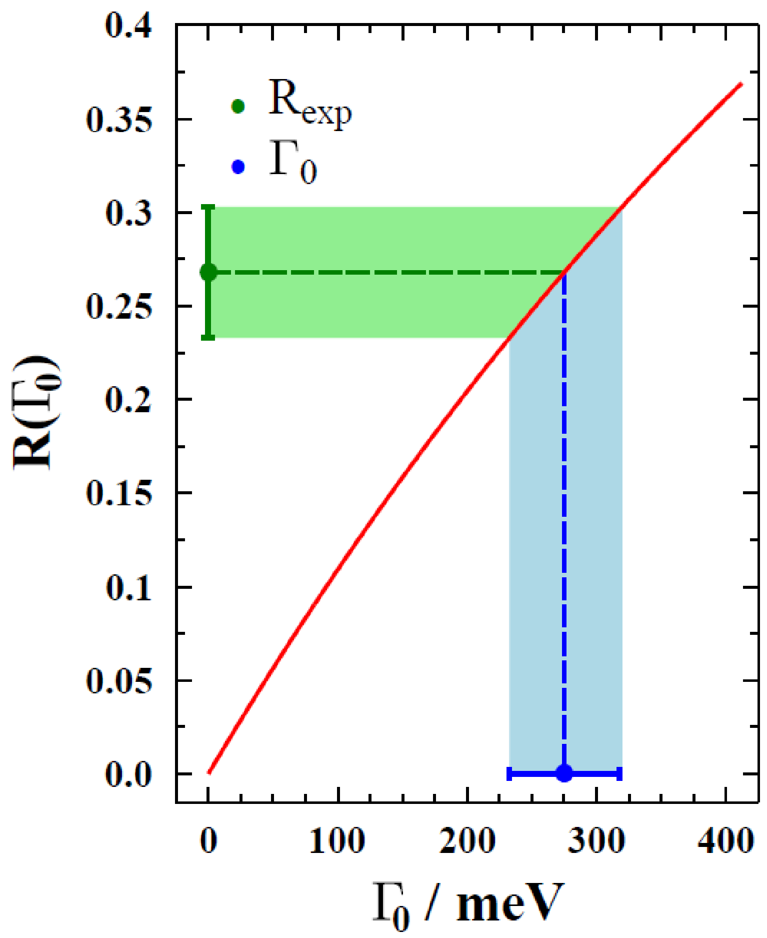
Self Absorption:
Decrease of Scattered Photons because of Resonant Absorption

$$R(\Gamma_0) = \frac{N_{\mathrm{woA}} - f \cdot N_{\mathrm{wA}}}{N_{\mathrm{woA}}}$$

$$f = \frac{N^{\mathrm{std}}_{\mathrm{woA}}}{N^{\mathrm{std}}_{\mathrm{wA}}}$$

Relative Self Absorption (RSA) Technique

- calculate *R* as function of Γ_0
- self absorption R_{exp} determined experimentally
- comparison of experiment and calculation gives ground-state transition width Γ_0
- NRF measurement gives $\Gamma_0 \cdot \frac{\Gamma_0}{\Gamma}$
- thus total transition width Γ and branching ratio Γ_0/Γ to ground state can be determined

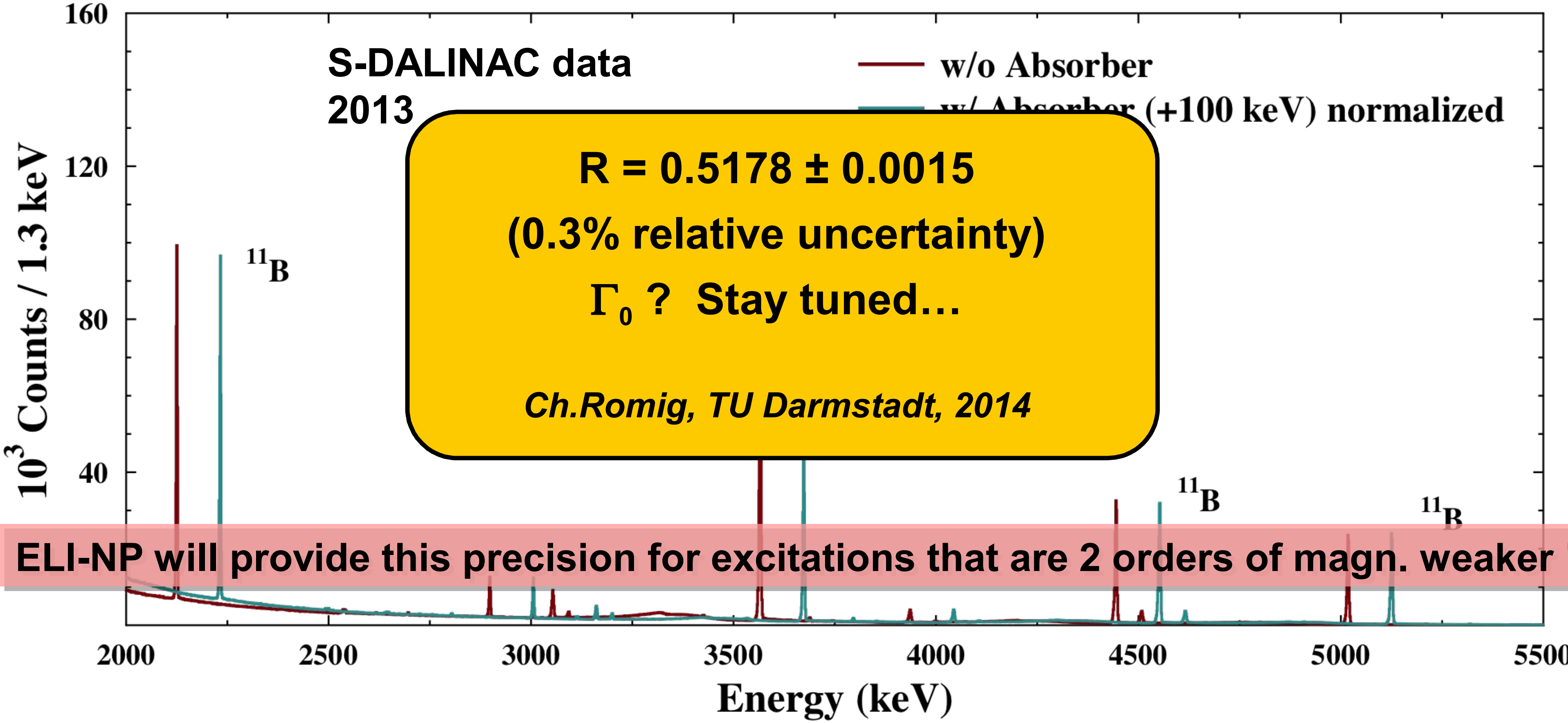


Self Absorption Measurement on ^{6}Li

(Ch.Romig, TU Darmstadt, PhD thesis, 2014 in preparation)

TECHNISCHE UNIVERSITÄT DARMSTADT

- scatterer: 5 g Li_2CO_3 (enriched to 95% in ^{6}Li)
- calibration target: 4.2 g ^{11}B (sandwiched)
- absorber: 10 g Li_2CO_3 (enriched to 95% in ^{6}Li)
- endpoint energy: 7.1 MeV
- 7 days w/o absorber
- 8 days w/ absorber



R = 0.5178 ± 0.0015

(0.3% relative uncertainty)

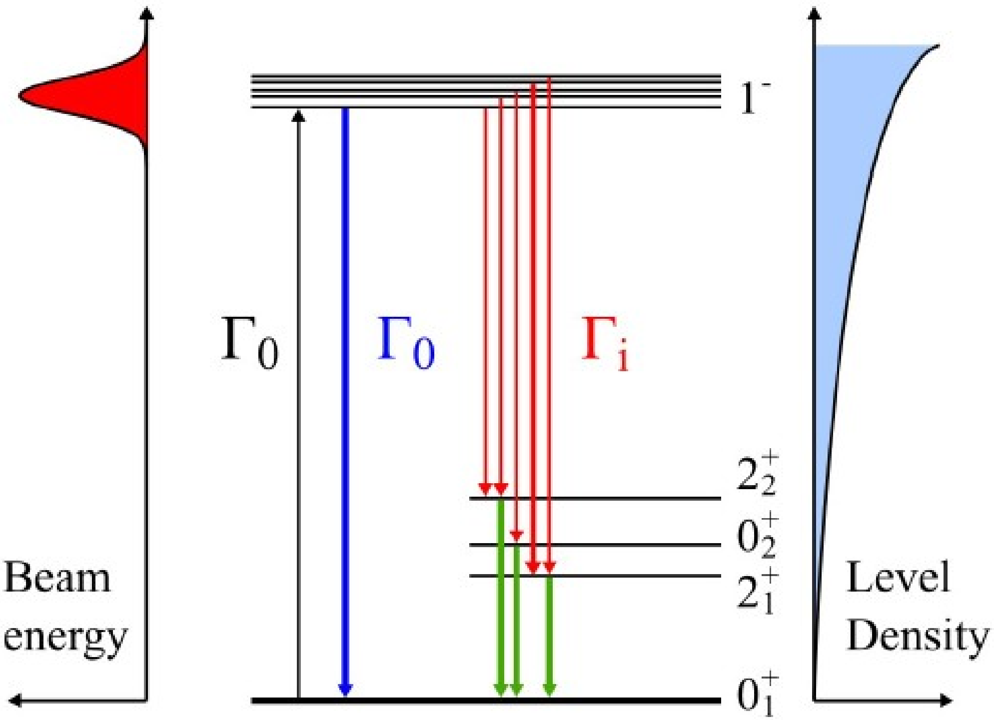
Γ_0 ? Stay tuned…

Ch.Romig, TU Darmstadt, 2014

ELI-NP will provide this precision for excitations that are 2 orders of magn. weaker !

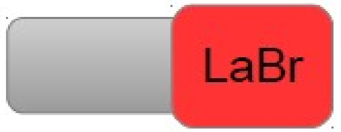
Coincidence Spectroscopy

γ³ Setup



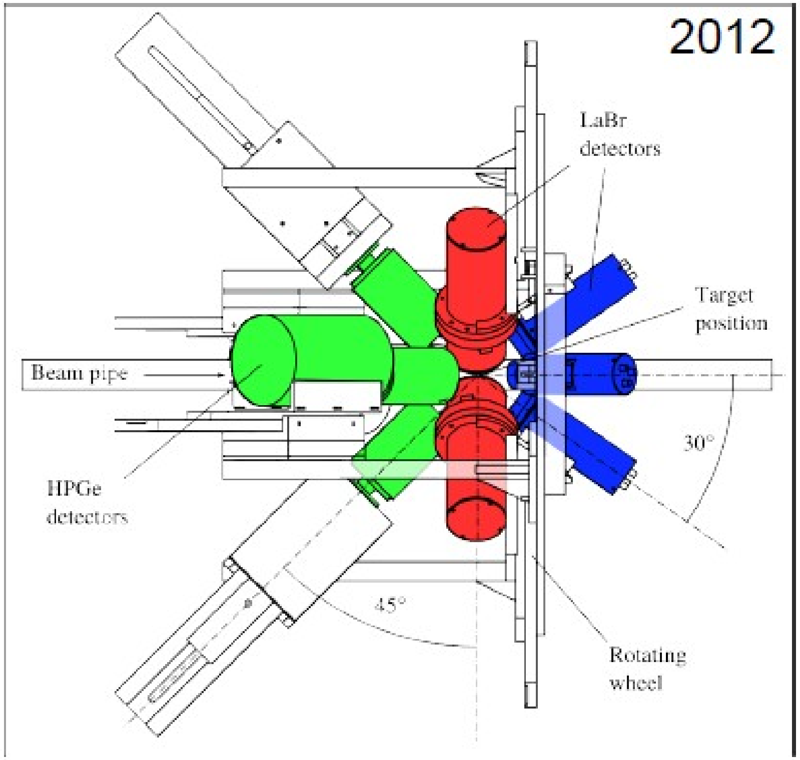
High level density
→ Use high resolution HPGe

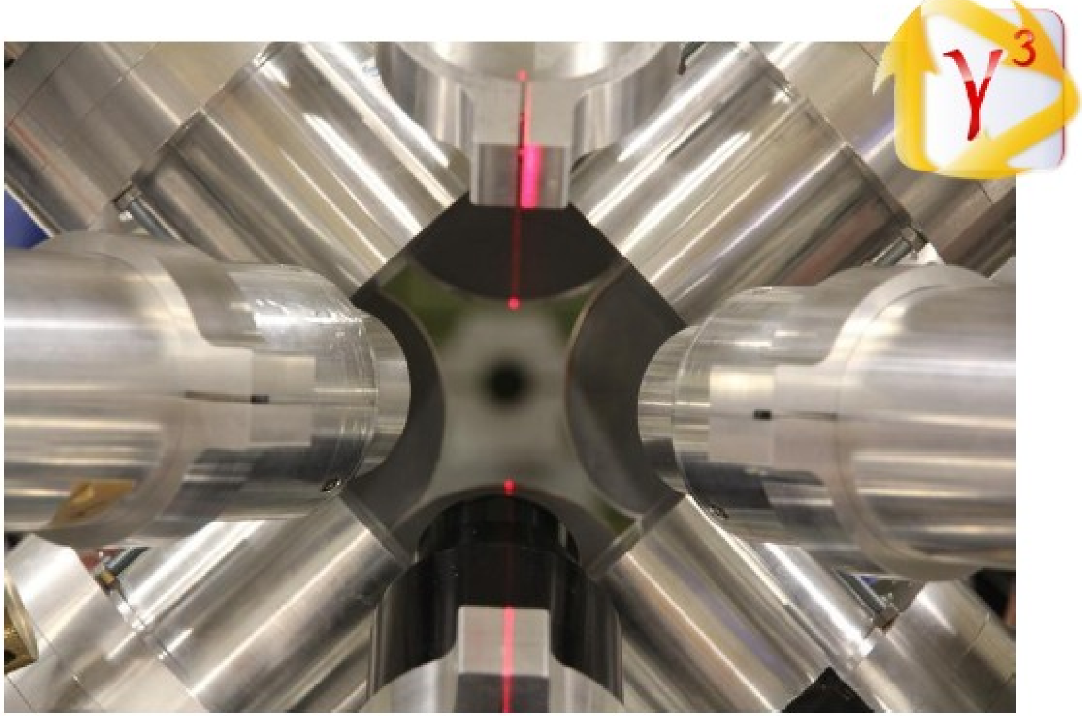
Low level density
→ Use high efficiency LaBr



- Combine HPGe with LaBr detectors

γ³ Setup



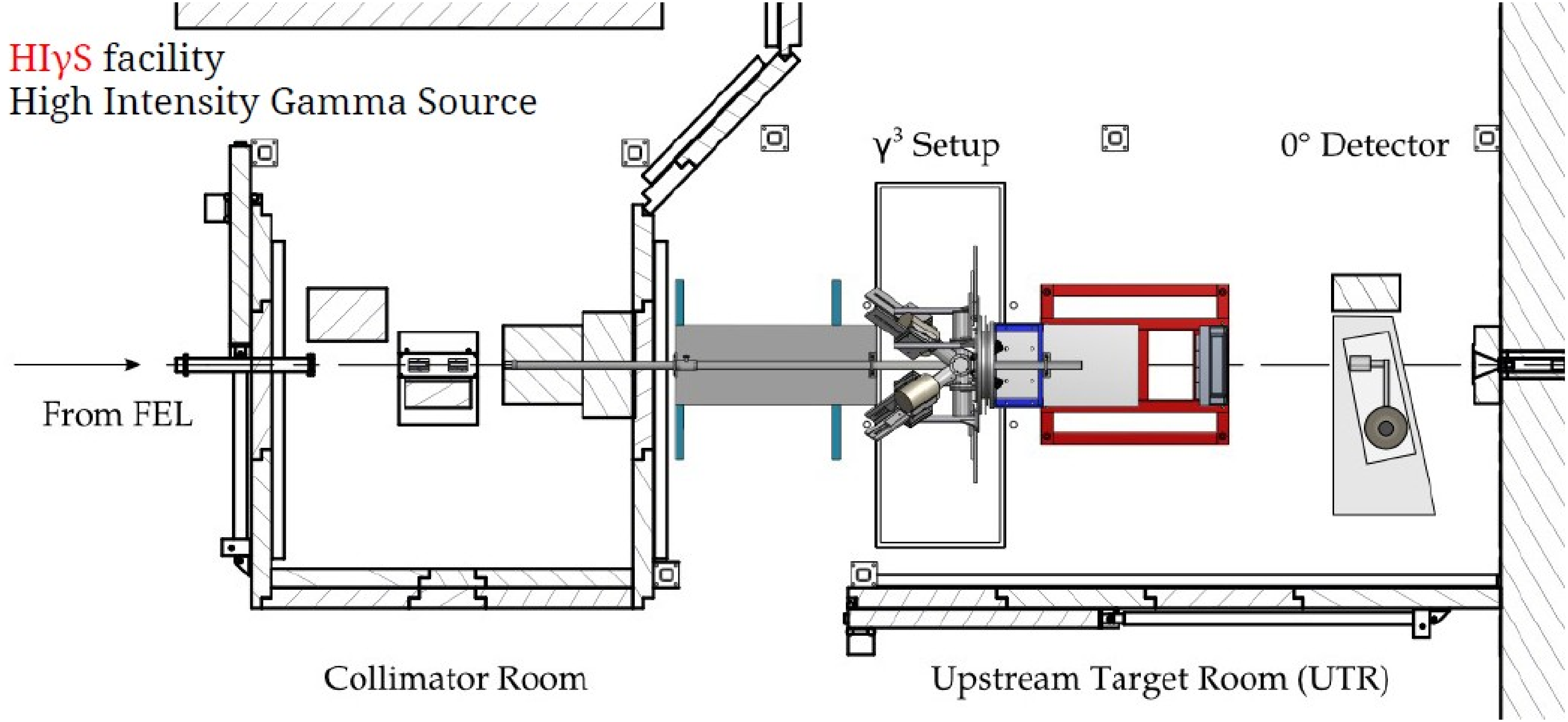


B. Löher et al., Nucl. Instruments Methods Phys. Res. Sect. A **723**, 136–142 (2013).

New detector array at HIγS

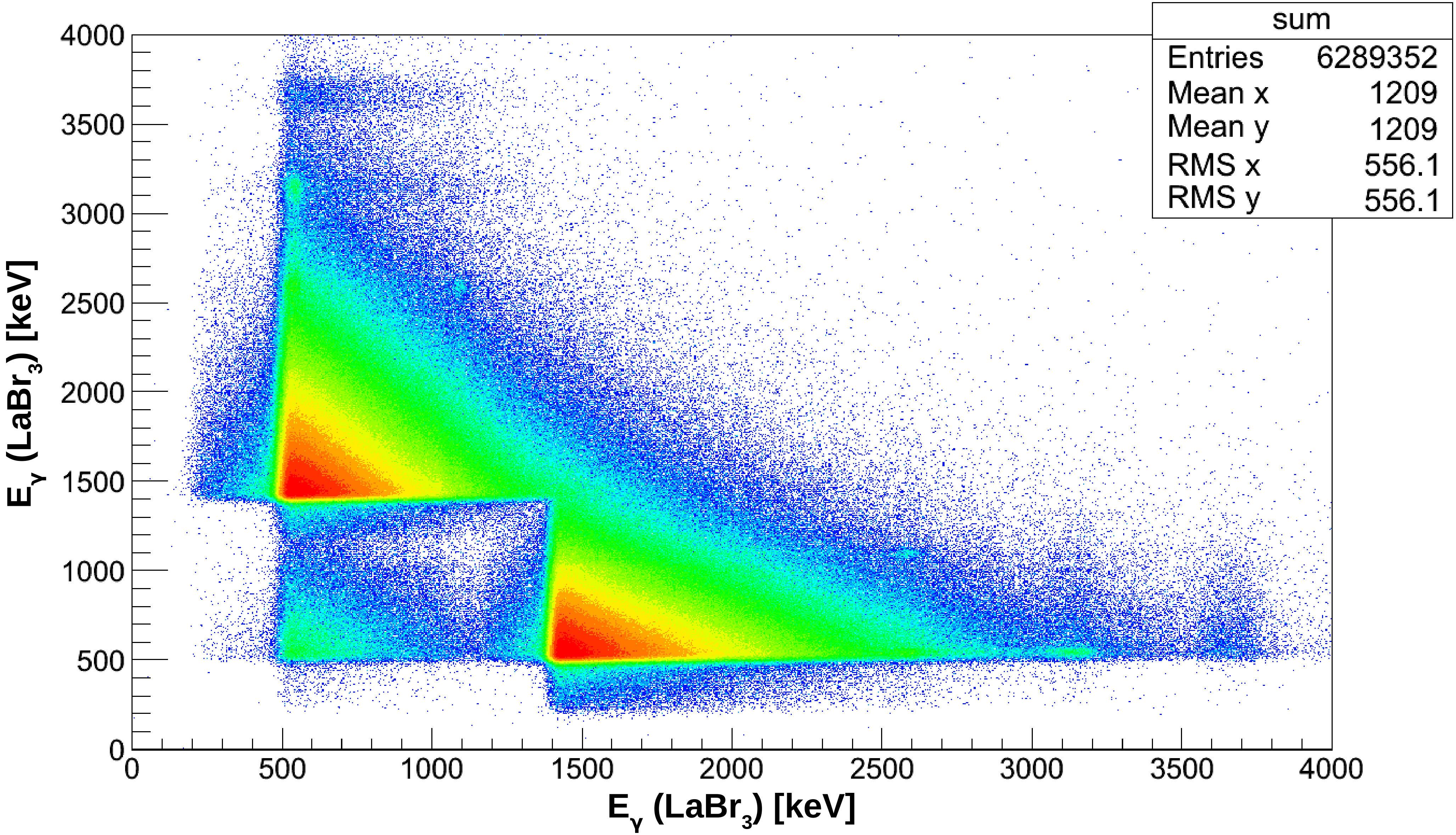
- 4 high resolution HPGe detectors
- 7 high efficiency LaBr detectors
- Total efficiency: 6% + 1.3% @ 1.3 MeV (LaBr+HPGe)

γ³ Setup


HIγS facility
High Intensity Gamma Source
From FEL
γ³ Setup
0° Detector
Collimator Room
Upstream Target Room (UTR)

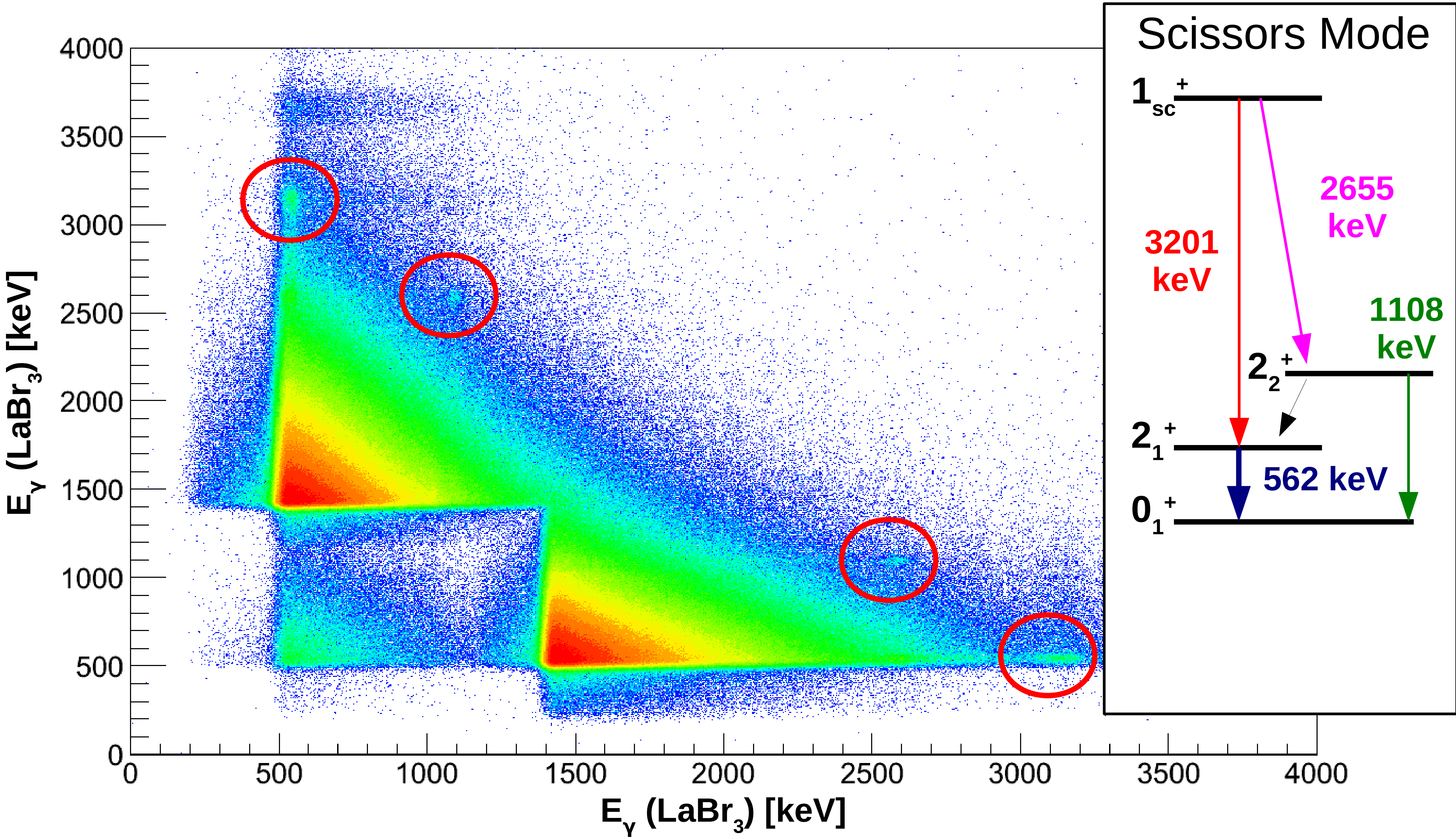
First γ^3 Data ^{76}Ge, low energies!

TECHNISCHE UNIVERSITÄT DARMSTADT

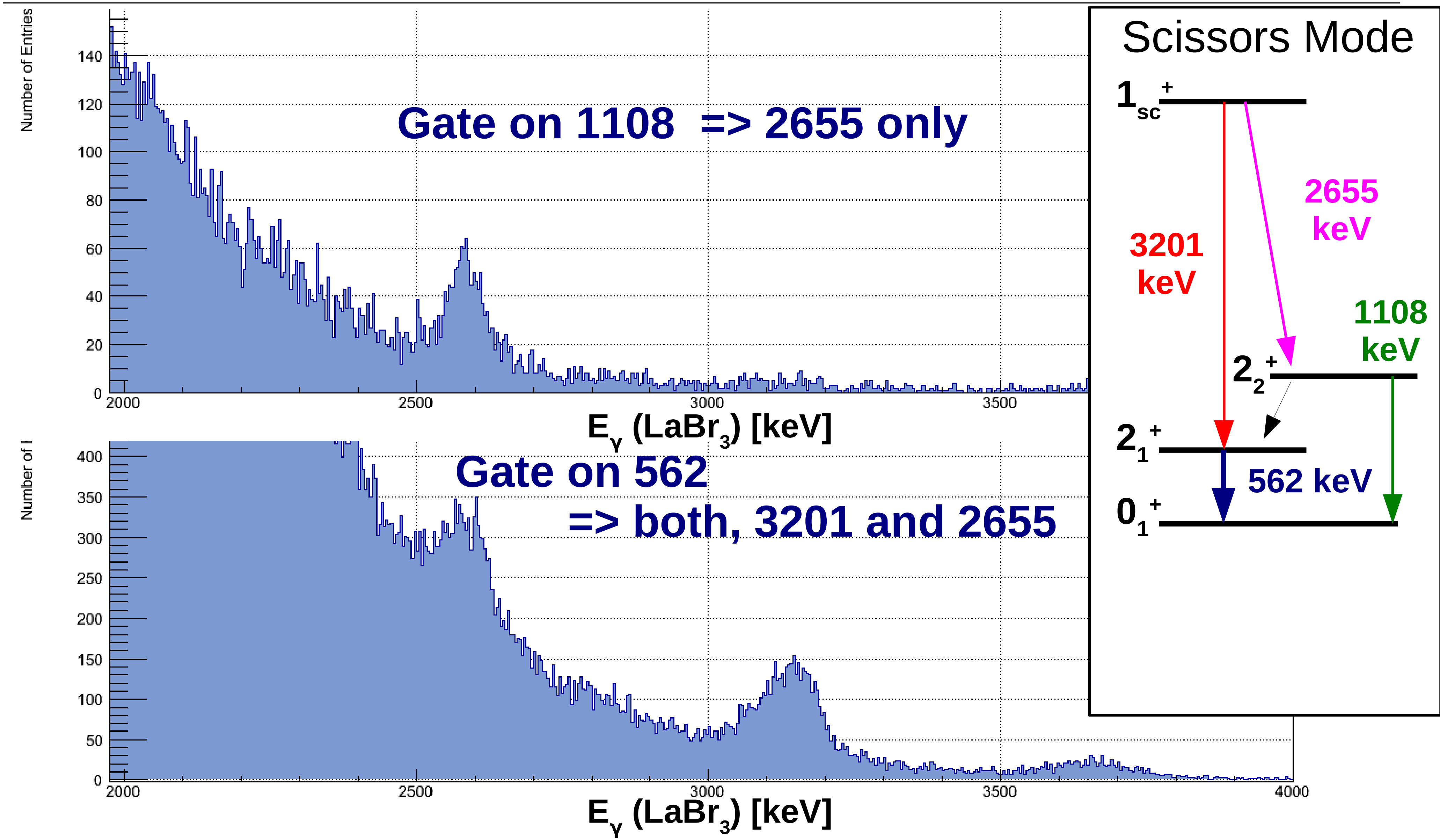


First γ³ Data ^{76}Ge, low energies!

TECHNISCHE UNIVERSITÄT DARMSTADT



First γ³ Data ^{76}Ge, low energies!



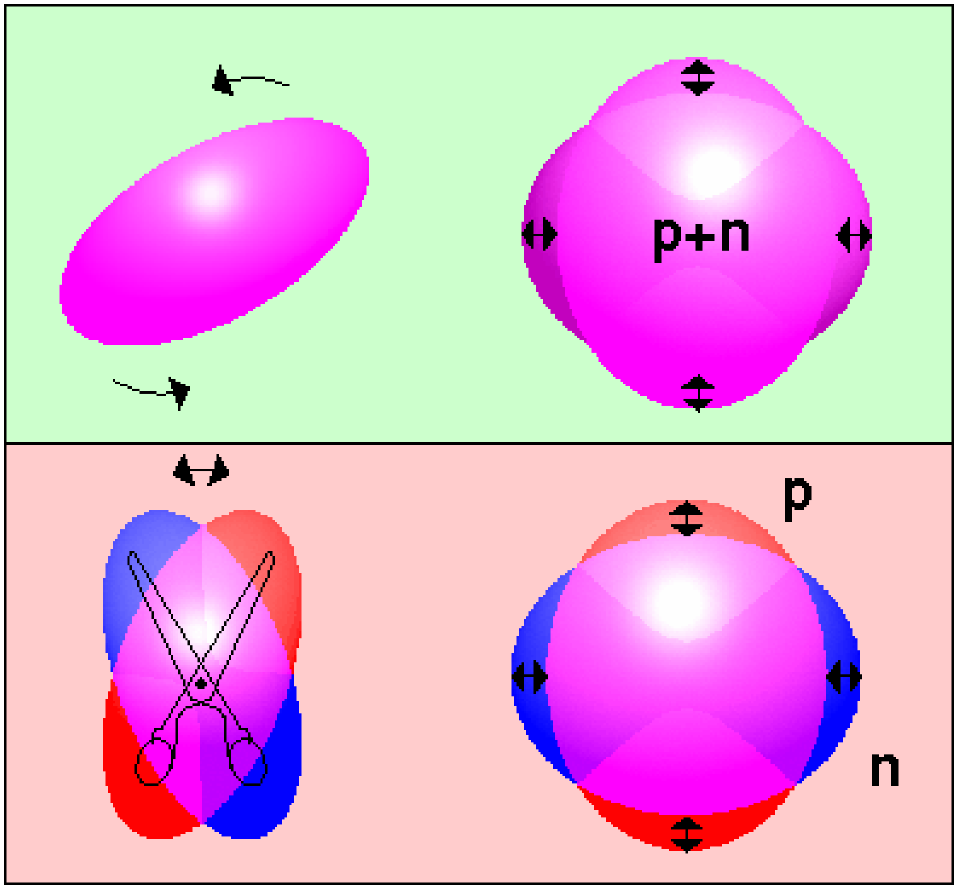
Scissors Mode

So, what is it ?

Quadrupole Collectivity

TECHNISCHE UNIVERSITÄT DARMSTADT

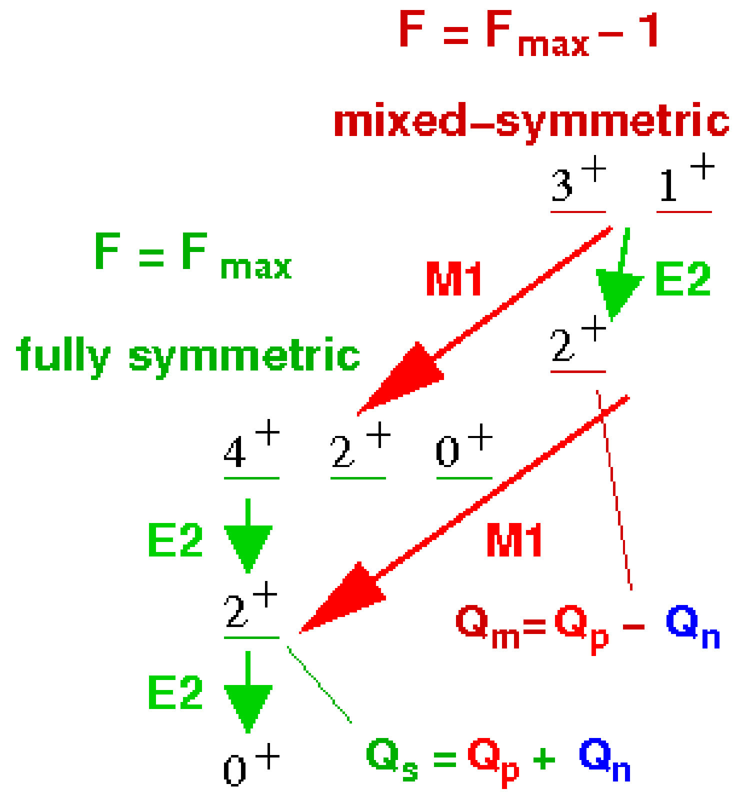
Proton-Neutron symmetric



Rotors Vibrators

Proton-Neutron mixed-symmetric

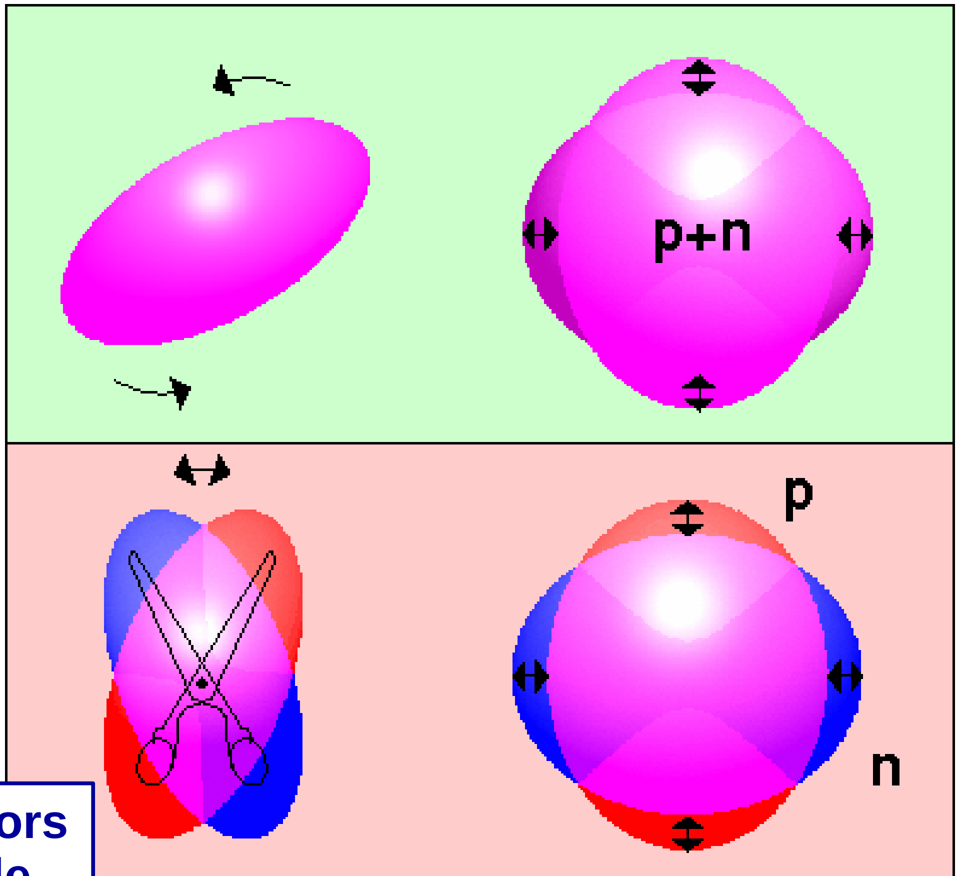
F-Spin is the bosonic analog to isospin



Excitation by the quadrupole operator

Quadrupole Collectivity

Proton-Neutron symmetric

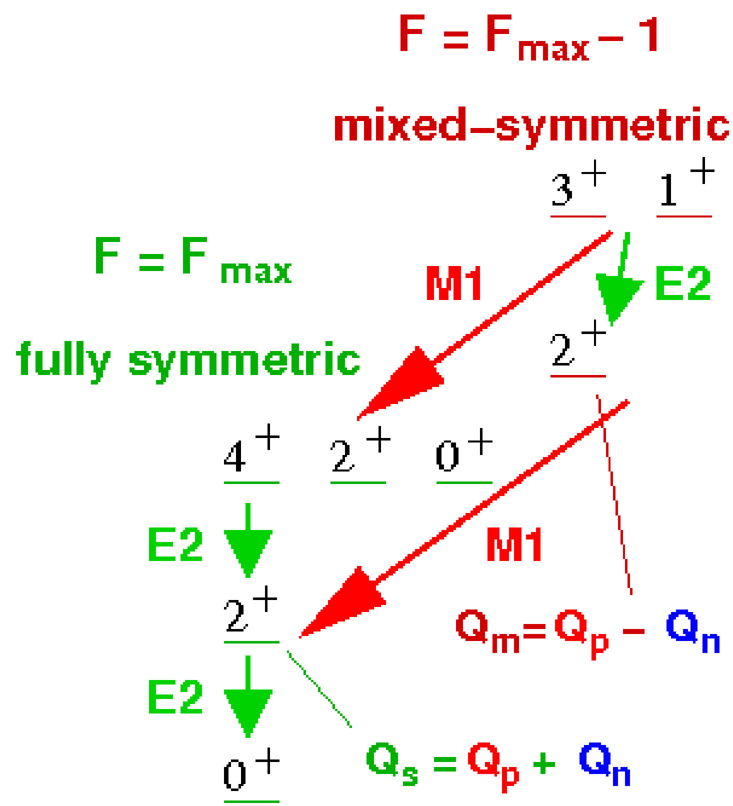


Rotors   Vibrators

Scissors Mode

Proton-Neutron mixed-symmetric

F-Spin is the bosonic analog to isospin

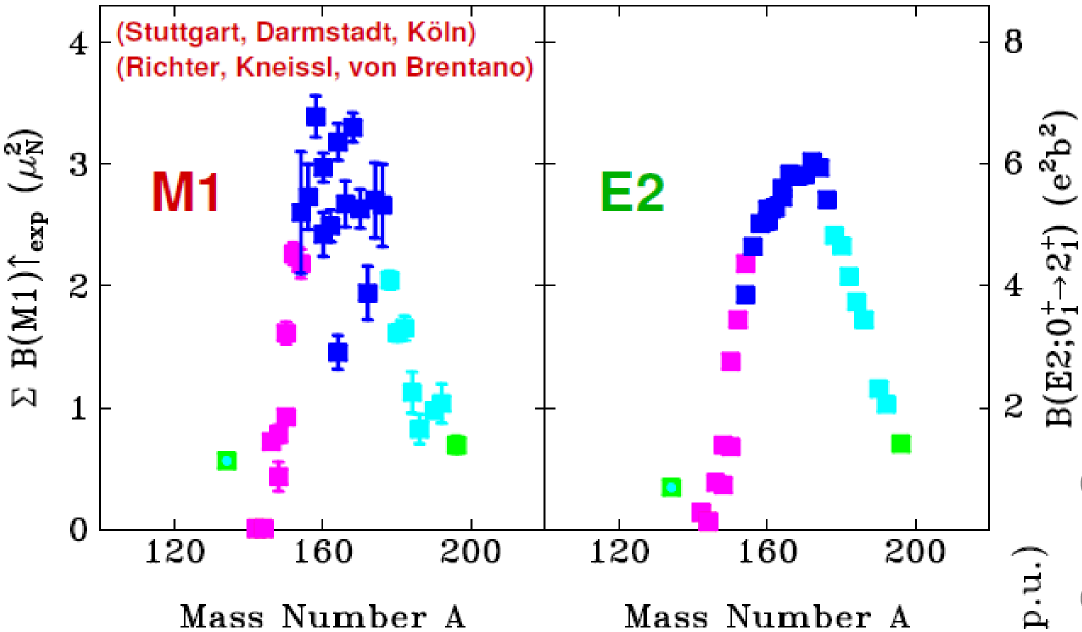


Phonon-Coupling Scheme

Scissors Mode Systematics

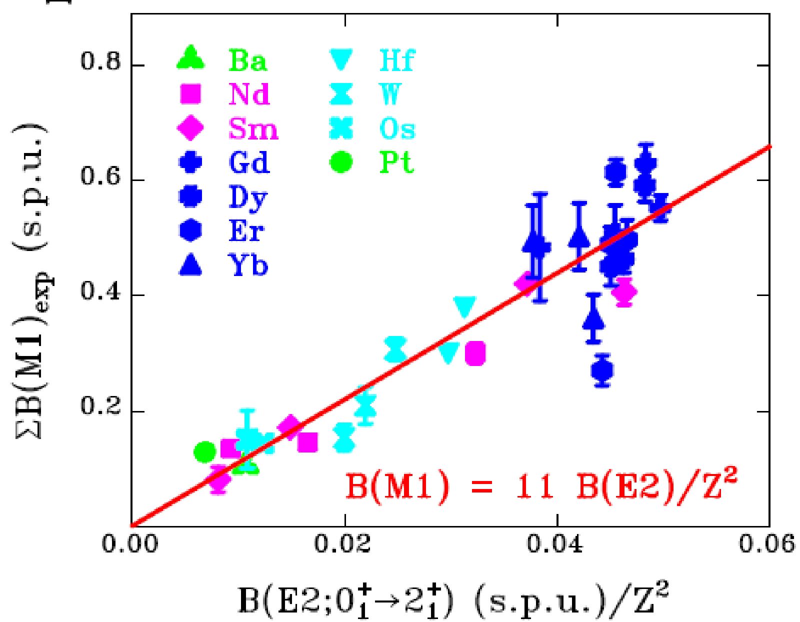
clearly collective, degree of fragmentation depends on deformation

(mixed–symmetric) **(fully–symmetric)**



Systematics:

Quadrupole Collectivity peaks at mid–shell



E2 excitation strength is isoscalar.

(maintain proton–neutron symmetry in the wavefunctions)

M1 excitation strength is isovector.

(wavefunctions not symmetric under proton–neutron exchange)

N. Pietralla et al., PRC 58, 184 (1998)

Scissors Mode

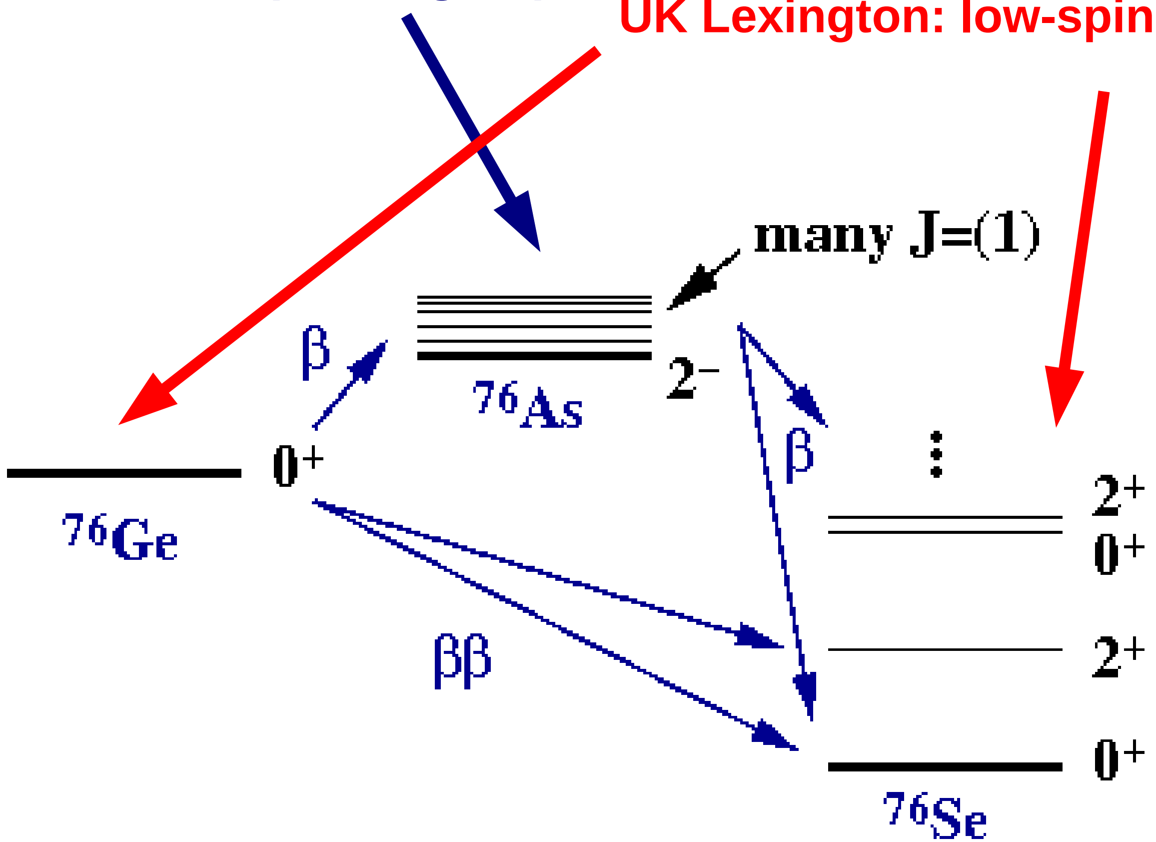
Why do we care in ^{76}Ge?

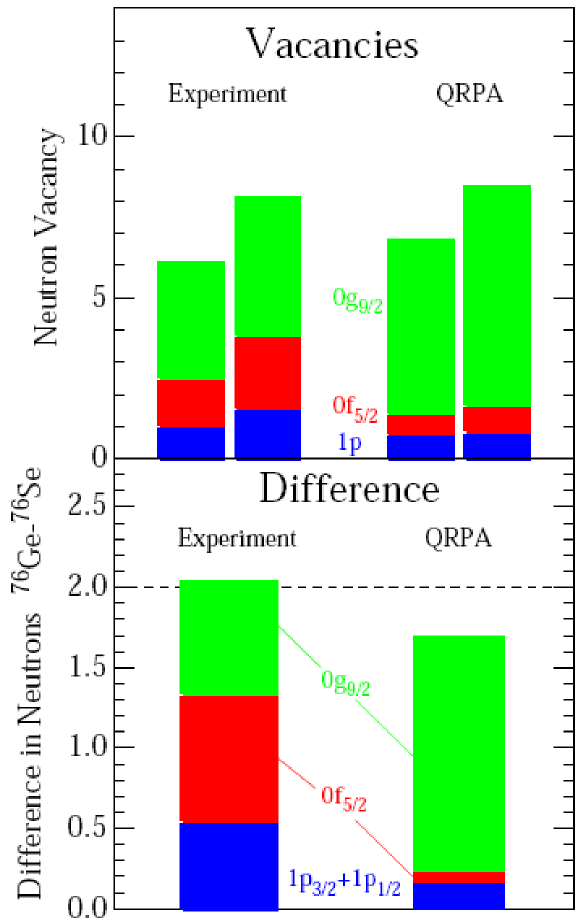
Need to know wave functions of initial + final (+ interm.) states

TECHNISCHE UNIVERSITÄT DARMSTADT

WNSL: γγ-angular correlations and γ-intensities
TRIUMF: test of β-decay ratios within a penning trap

TU Darmstadt: dipole strength distribution (γ,γ')
HIGS: parities ($\vec{\gamma}$,γ')
UK Lexington: low-spin (n,n'γ)



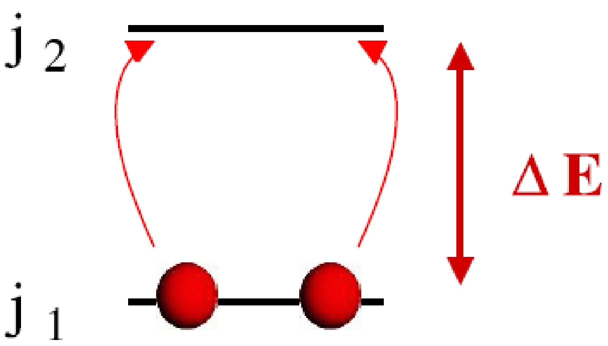


J. Schiffer, S. Freeman et al. @ WNSL

Challenge

The role of shape coexsitence !

E0 Strength and Shape Mixing



$$|0_2^+\rangle = -\beta\ |j_1^2\rangle + \alpha\ |j_2^2\rangle$$

$$|0_1^+\rangle = \alpha\ |j_1^2\rangle + \beta\ |j_2^2\rangle$$

E0 strengths corresponds to different radii (deformations)

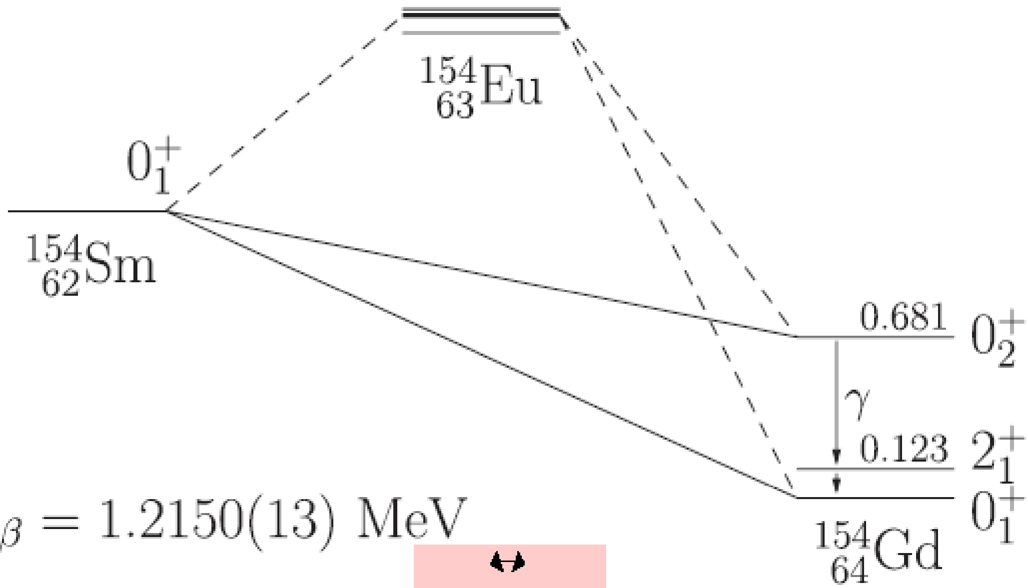
$$\langle 0_1^+|r^2|0_2^+\rangle = (\alpha^2 - \beta^2)\langle j_1^2|r^2|j_2^2\rangle + \alpha\beta\left(\langle j_1^2|r^2|j_1^2\rangle - \langle j_2^2|r^2|j_2^2\rangle\right)$$

E0 is large when

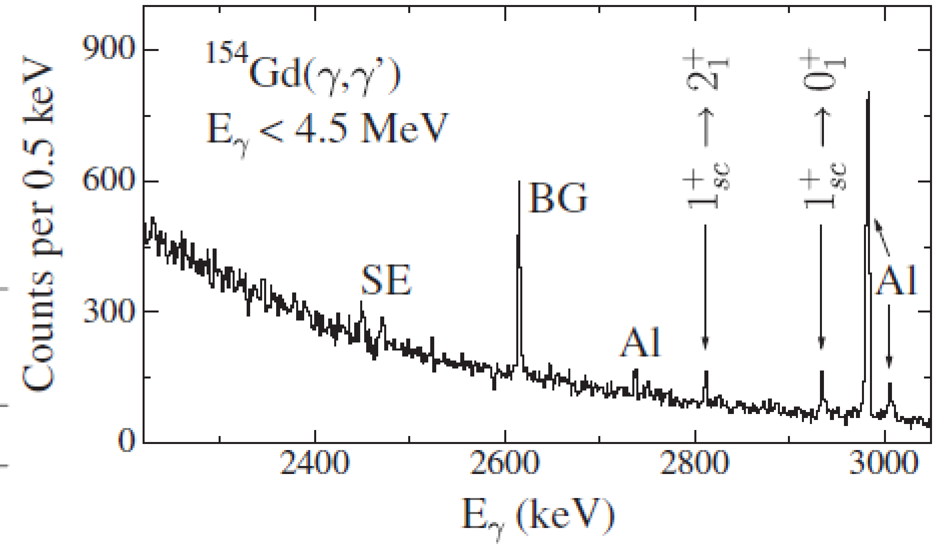
a) the two configurations have different avg. radii (deformations, shapes)

b) the two configurations mix strongly (αβ term)

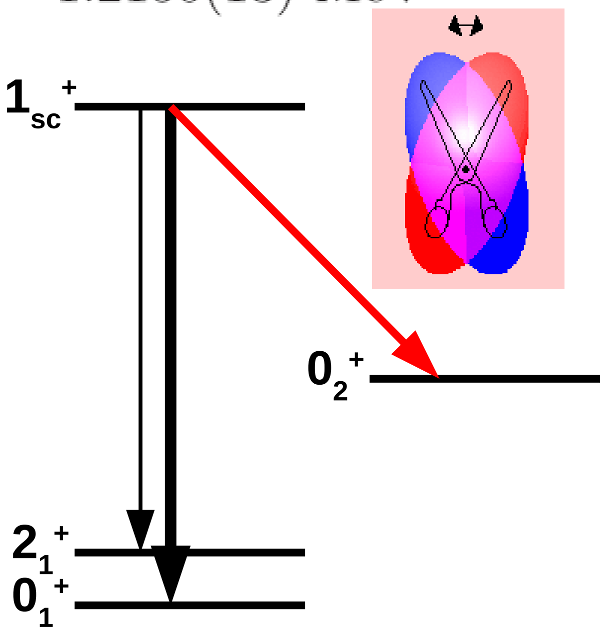
^{154}Sm/Gd – constraints from scissors mode decays



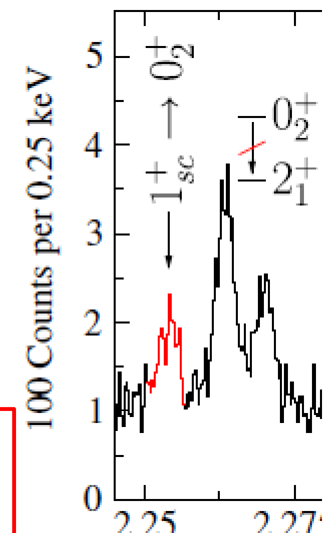
$Q_{\beta\beta} = 1.2150(13)$ MeV



Photon scattering at Darmstadt



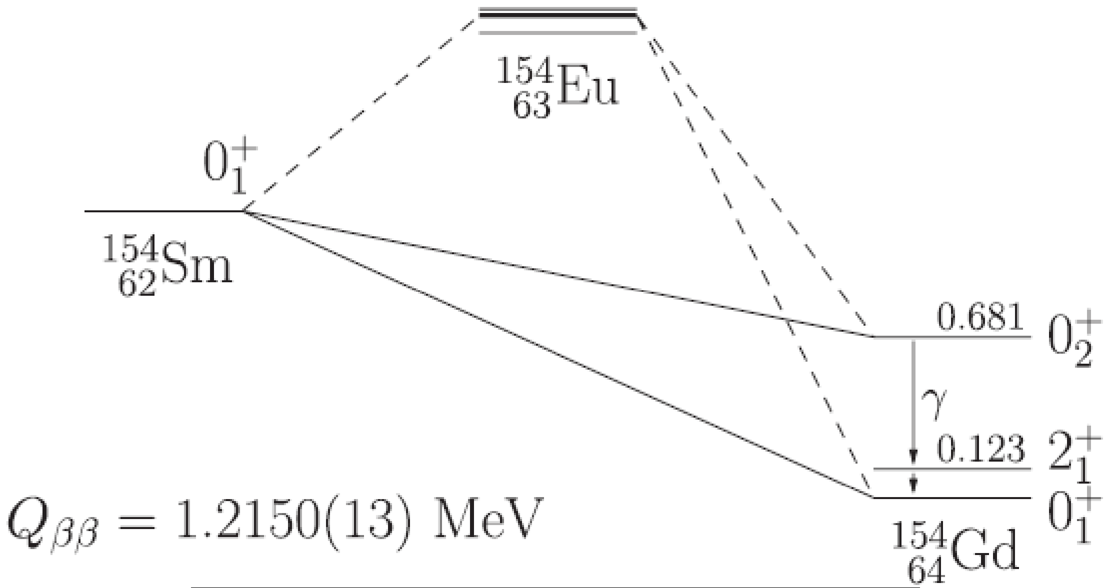
Branching to 0_2^+ observed in β-decay at Cologne Tandem

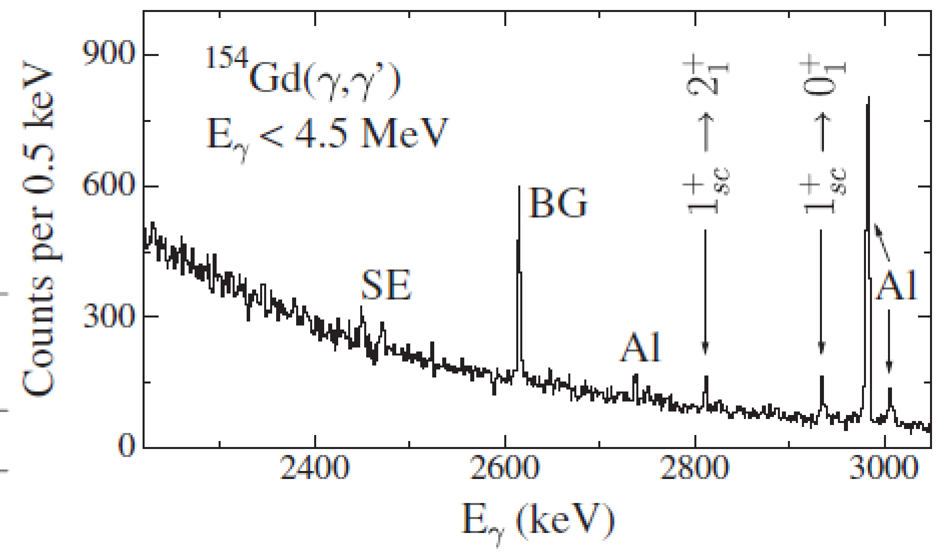


J. Beller, PRL 111, 172501 ('13)

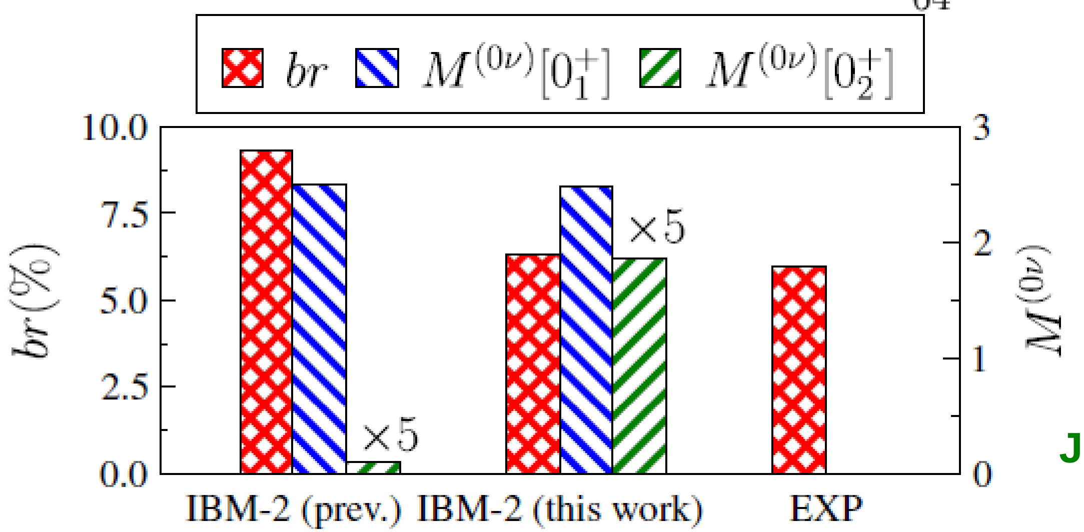
This could be done in one step at ELI-NP using the ~mono-energetic γ-beam !

^{154}Sm/Gd – constraints from scissors mode decays

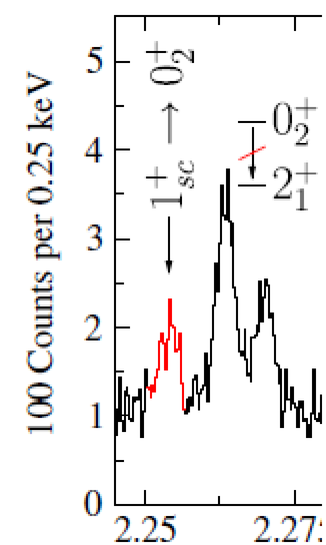




Photon scattering at Darmstadt



Branching to 0_2^+ observed in β-decay at Cologne Tandem



J. Beller, PRL 111, 172501 ('13)

This new structure information leads to corrections of model parameters
IBM-2 -> predicted 0ν2β matrix elements change

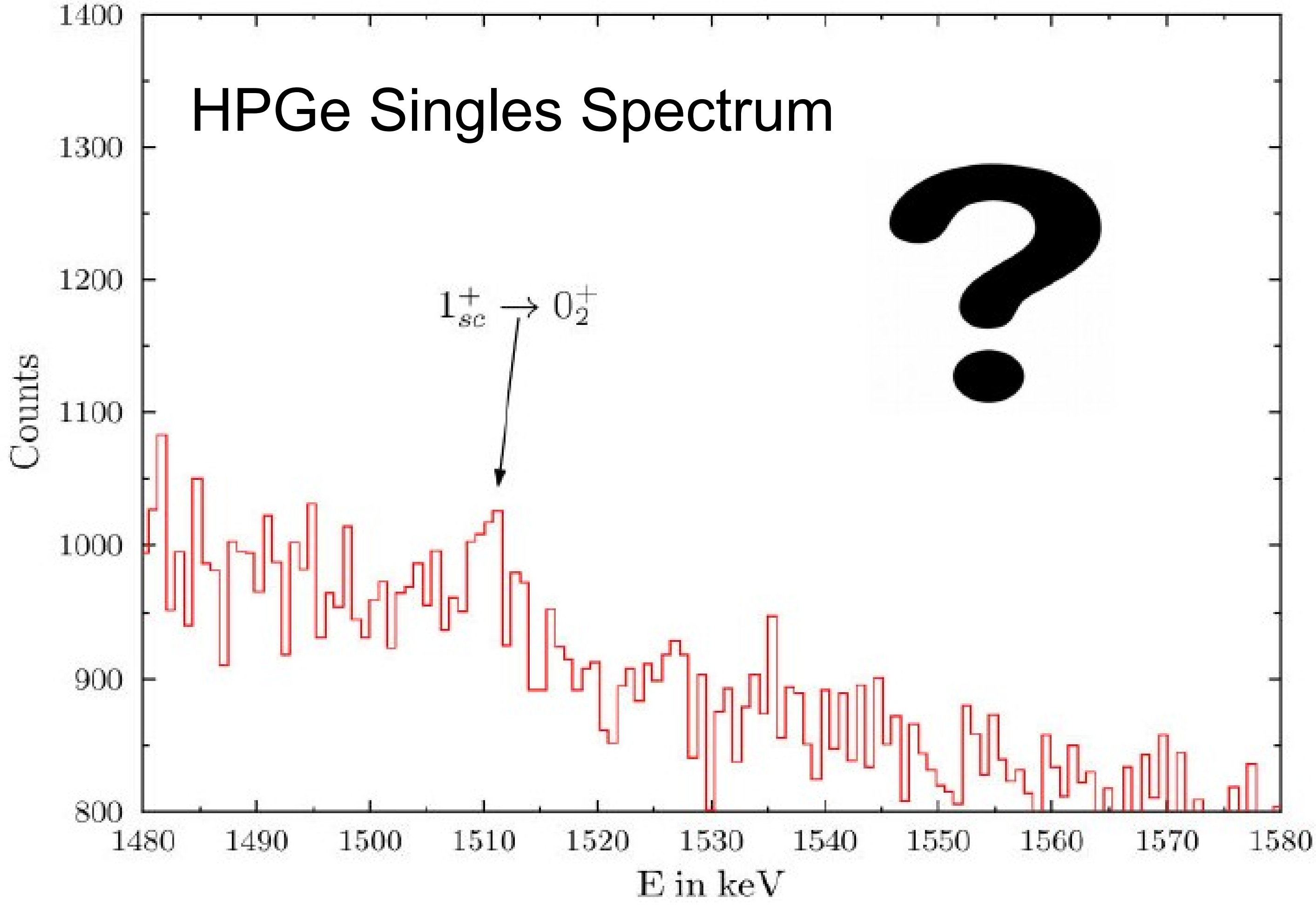
Back to ^{76}Ge

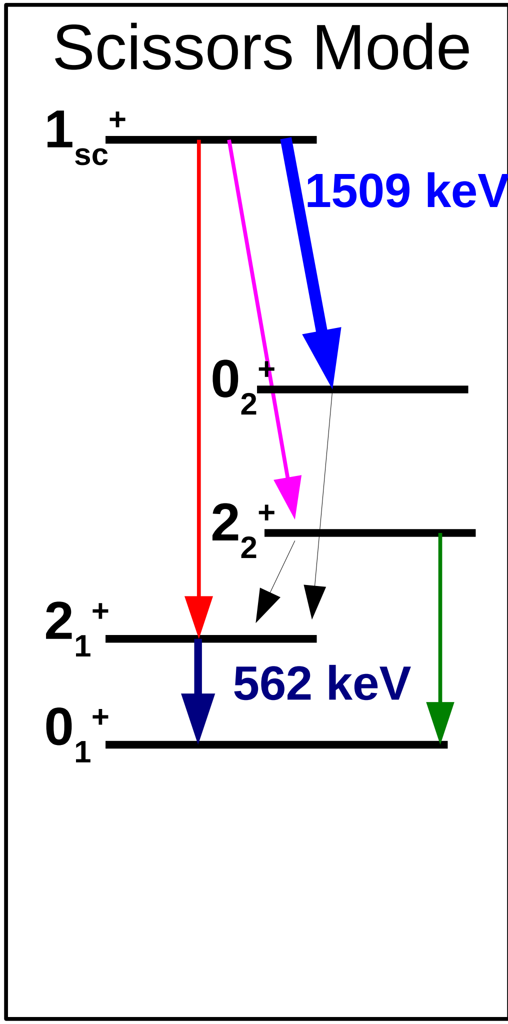
TECHNISCHE UNIVERSITÄT DARMSTADT

How about Scissors Mode decays in ^{76}Ge then ?

We probably observe it

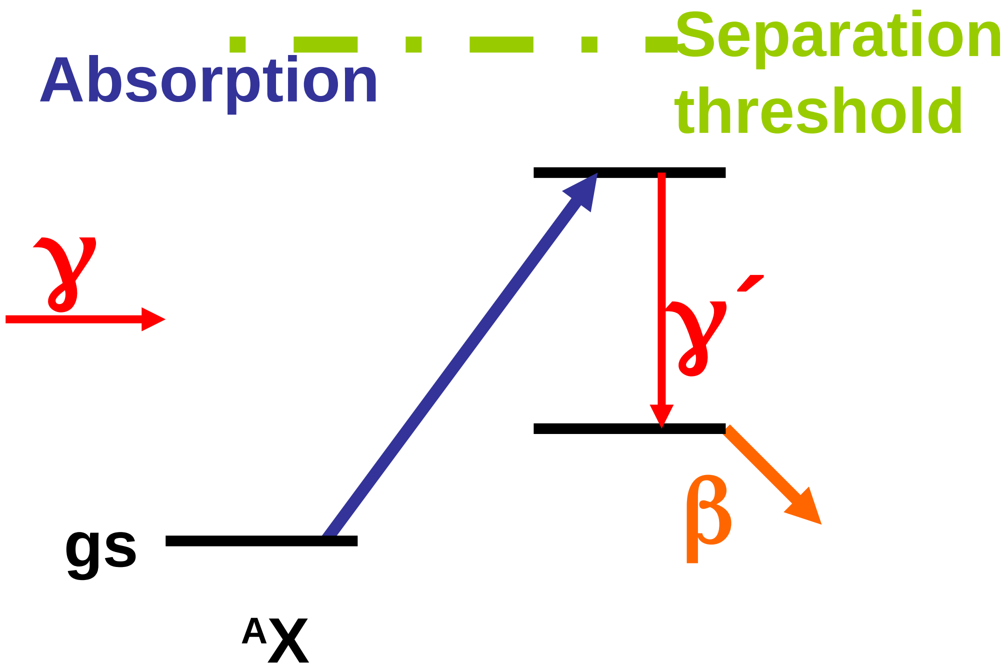
Now: careful analysis of coincidence spectra





Photoactivation Prospects ELI-NP

TECHNISCHE UNIVERSITÄT DARMSTADT



Current / Future Advances

Push the Intensity and Brilliance Frontiers

• Increase in beam intensity needed to be more efficient for example in coincidence experiments

Possibility to narrow the beam profile – know better which state gets excited, access new physics areas

ELI-NP in Romania

HIGS upgrade -> HIGS2

Current / Future Advances

TECHNISCHE UNIVERSITÄT DARMSTADT

Push the Intensity and Brilliance Frontiers

- Increase in beam intensity needed to be more efficient for example in coincidence experiments

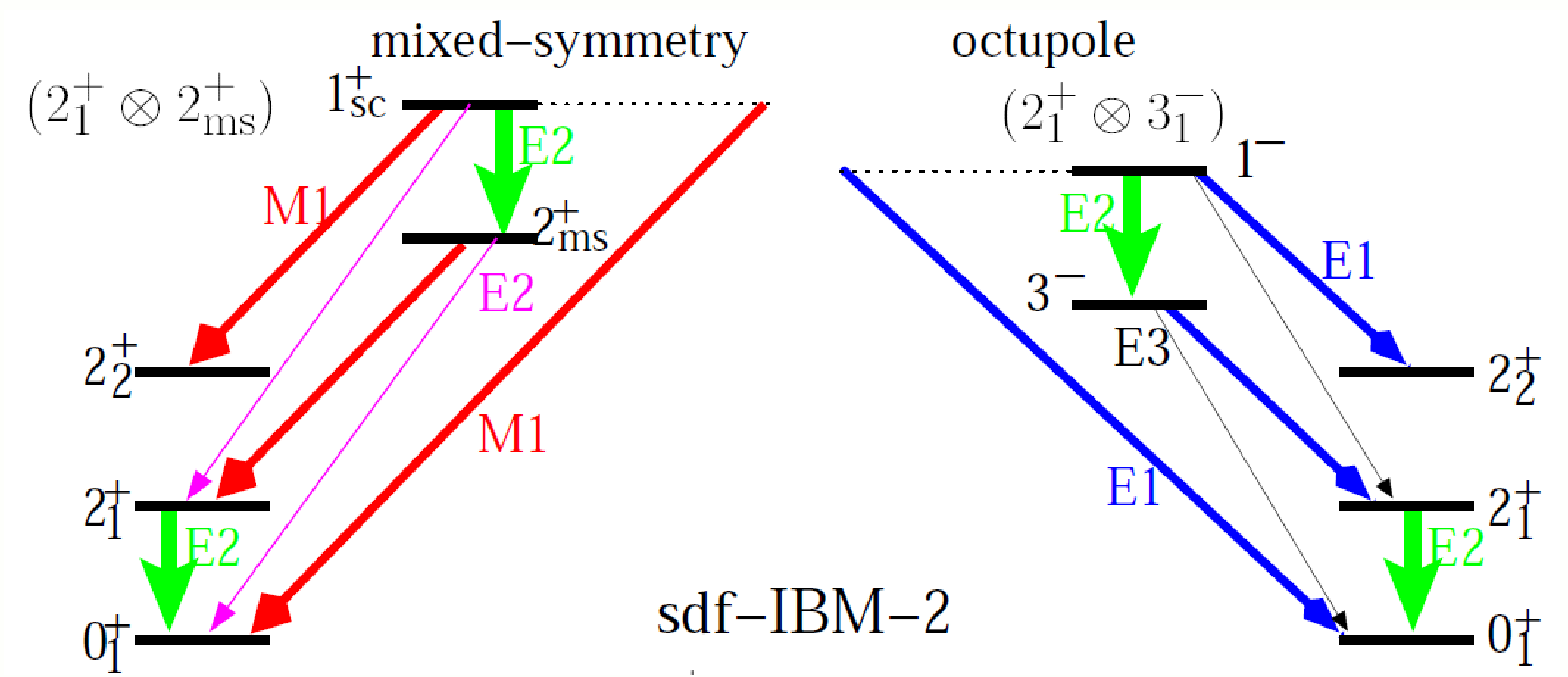
Possibility to narrow the beam profile – know better which state gets excited, access new physics areas

ELI-NP in Romania
HIGS upgrade -> HIGS2

Instrumentation Advances

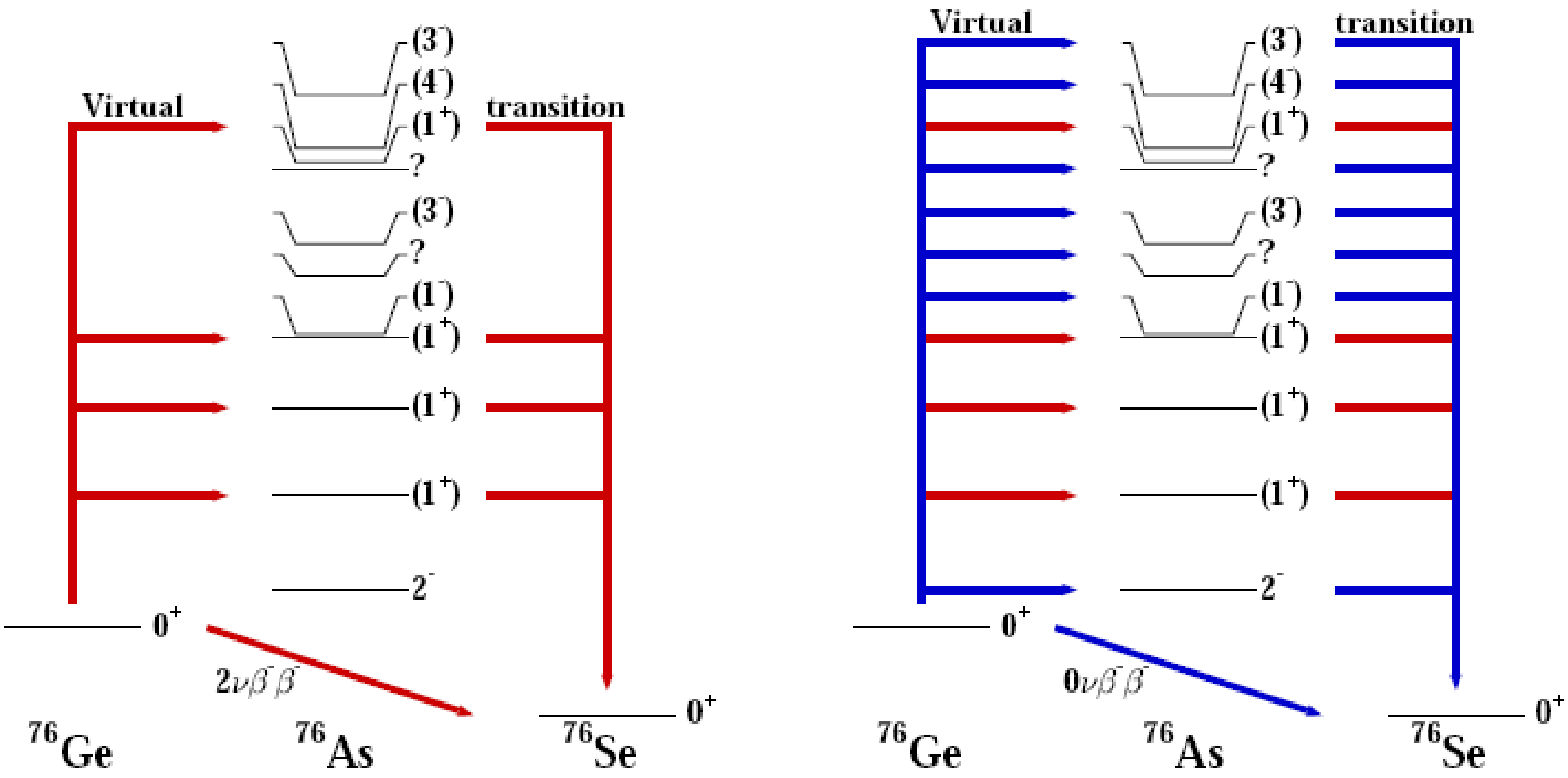
- Use HPGe Clover detectors for higher efficiency
- Close the gap: Simultaneous γ-ray and neutron detection
- Use complementary experiments – e.g., at tandems: γγ-angular correlations, lifetime measurements, (n,n'γ) !!

Q-O Phonon Schemes



Program on ^{76}Ge/As/Se

The intermediate (virtually populated) ^{76}As

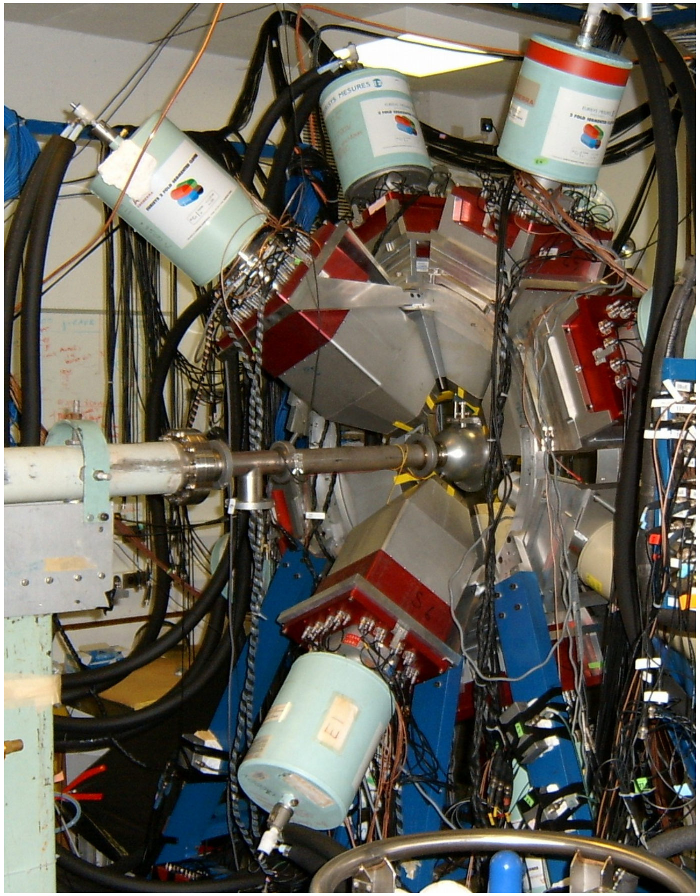


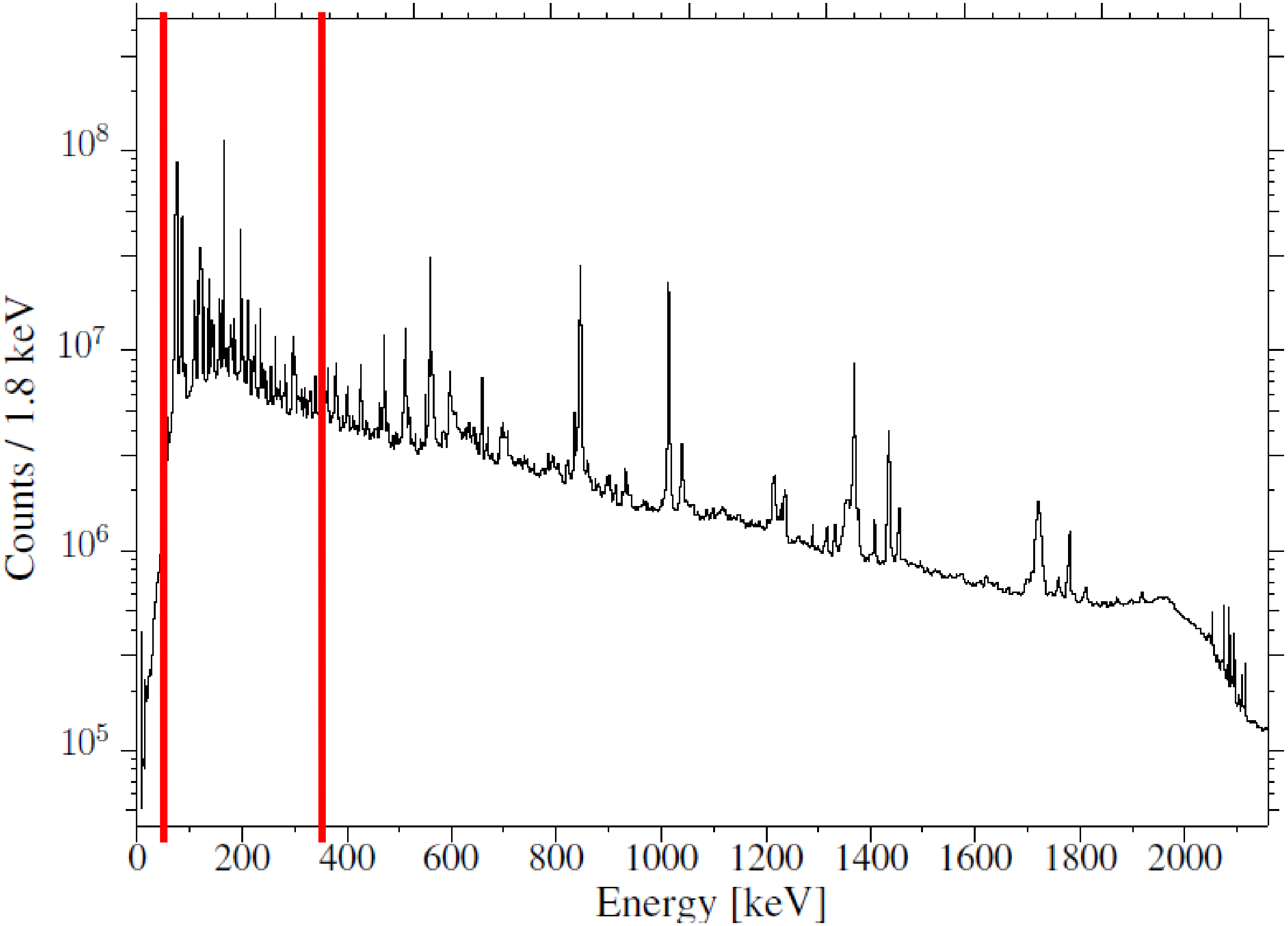
Except for the ground state, no spin is actually known in ^{76}As !

Program on ^{76}Ge/As/Se

TECHNISCHE UNIVERSITÄT DARMSTADT

^{76}Ge(p,n)^{76}As at WNSL Tandem, YRAST-Ball

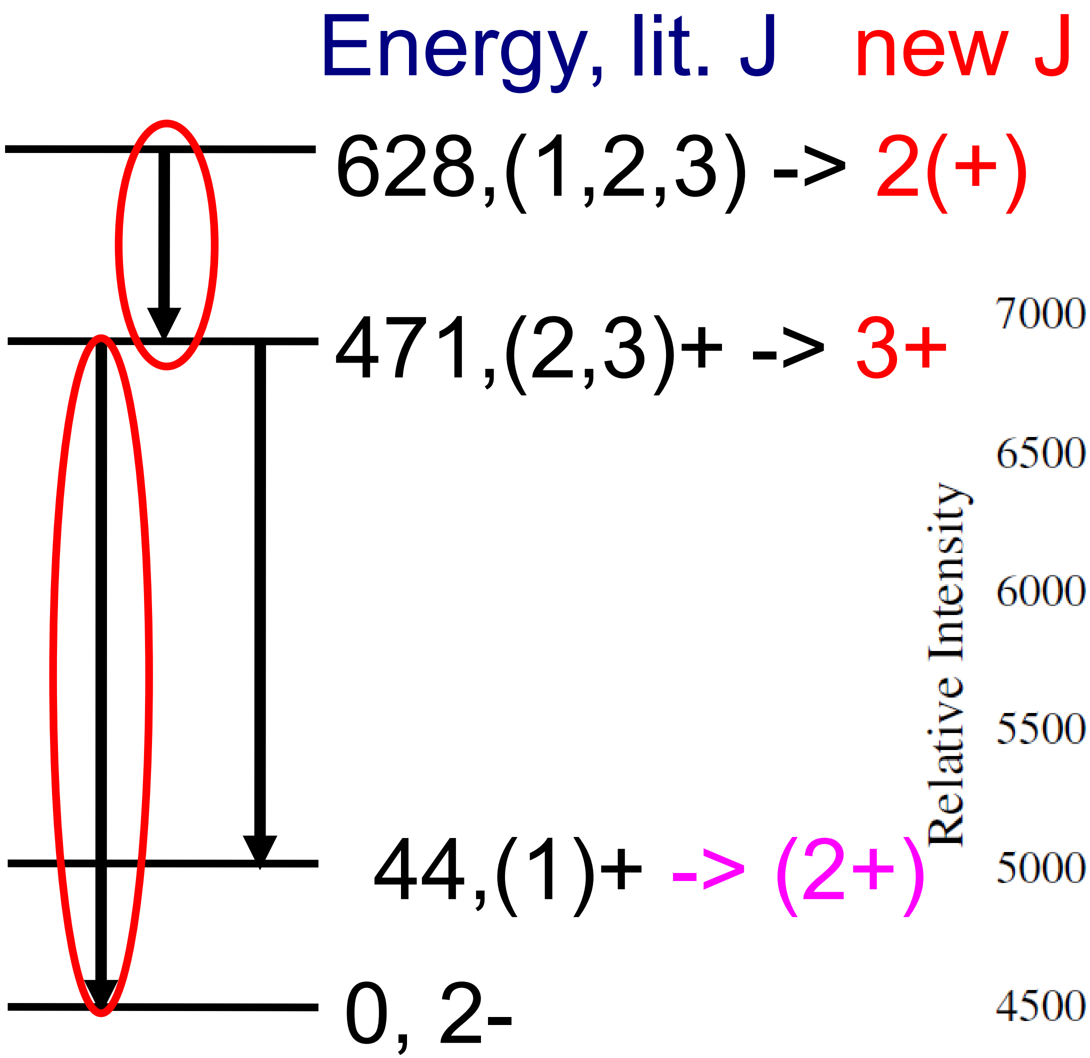




Not an easy spectrum to deal with...

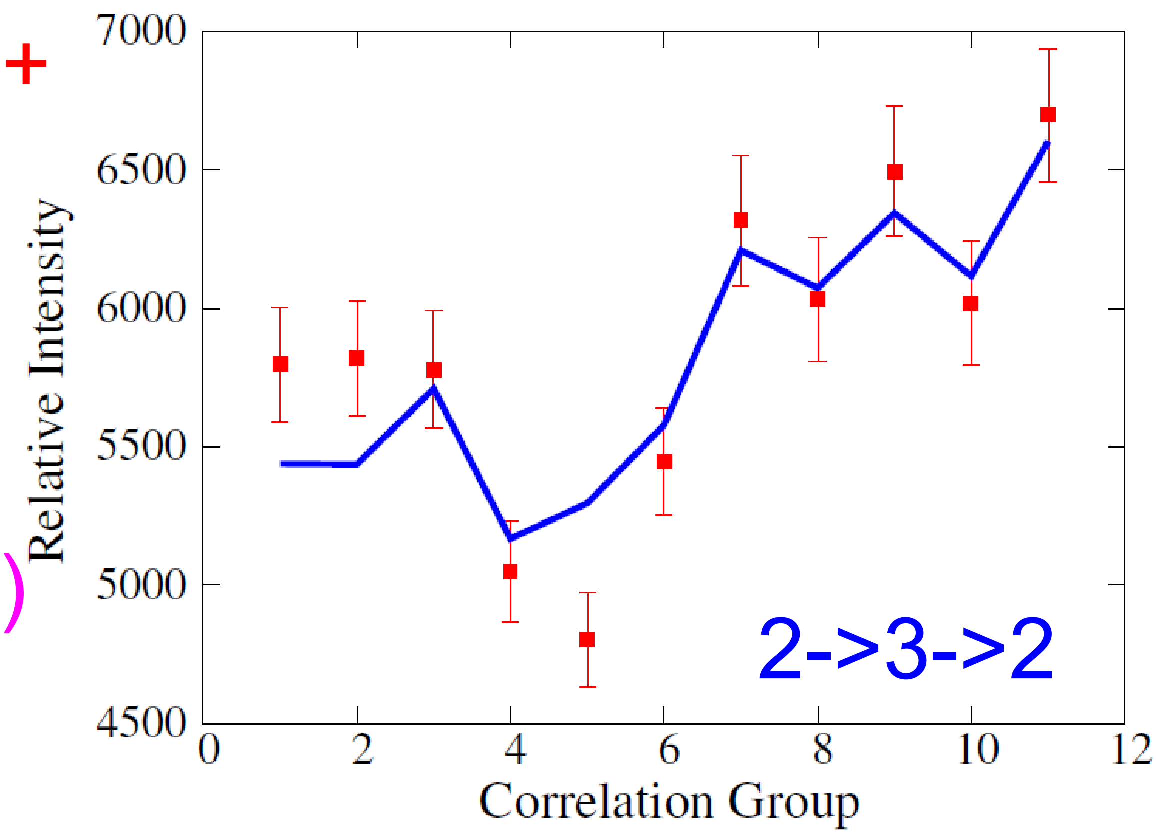
Program on ^{76}Ge/As/Se

TECHNISCHE UNIVERSITÄT DARMSTADT



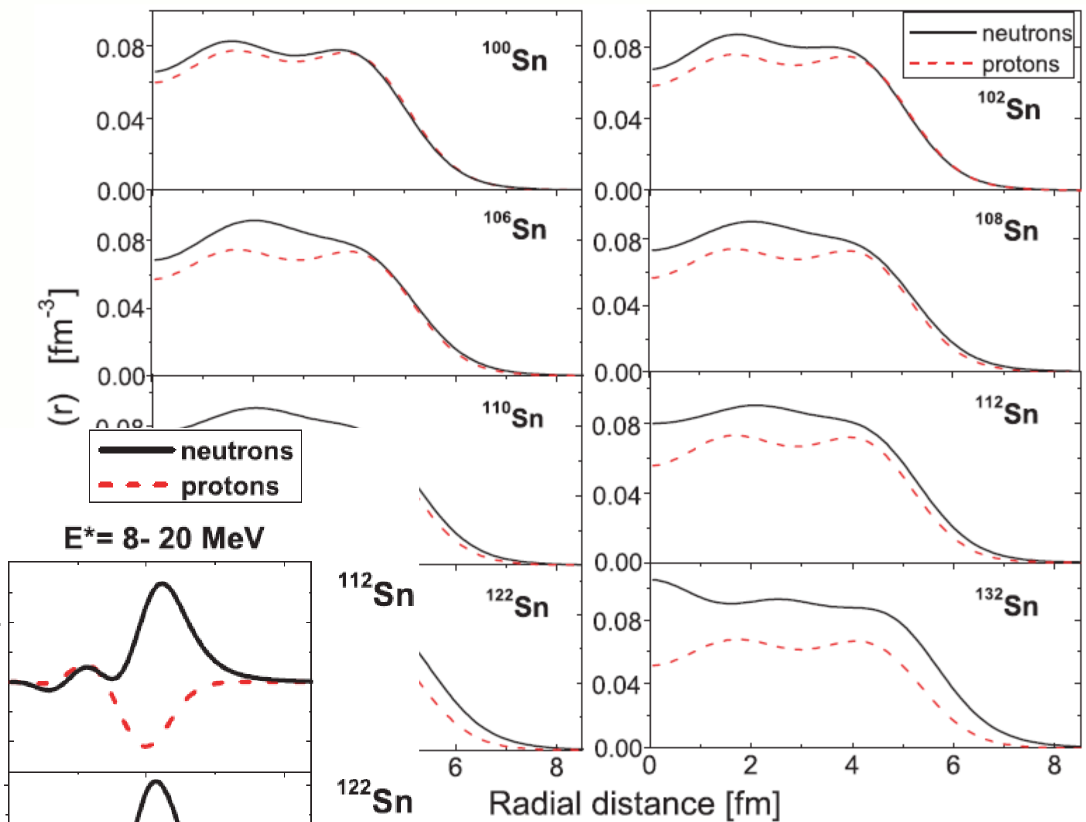
We reshuffle spins in ^{76}As

Can soon be compared to new calculations by Yoshida/Iachello

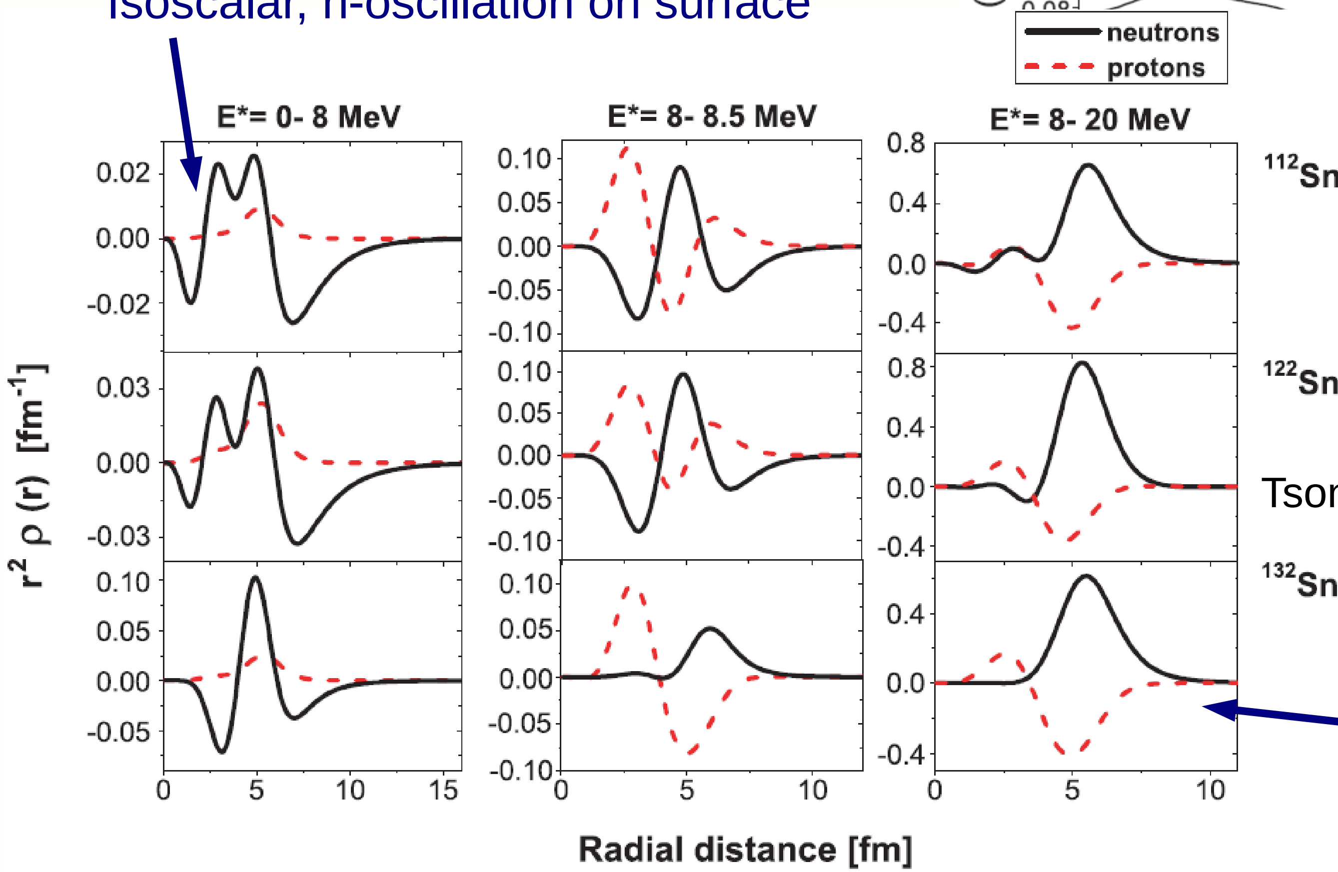


Switch from PDR to GDR ?

Sn isotopes:
Calculated proton / neutron densities
-> neutron skin



Transition densities:
Isoscalar, n-oscillation on surface

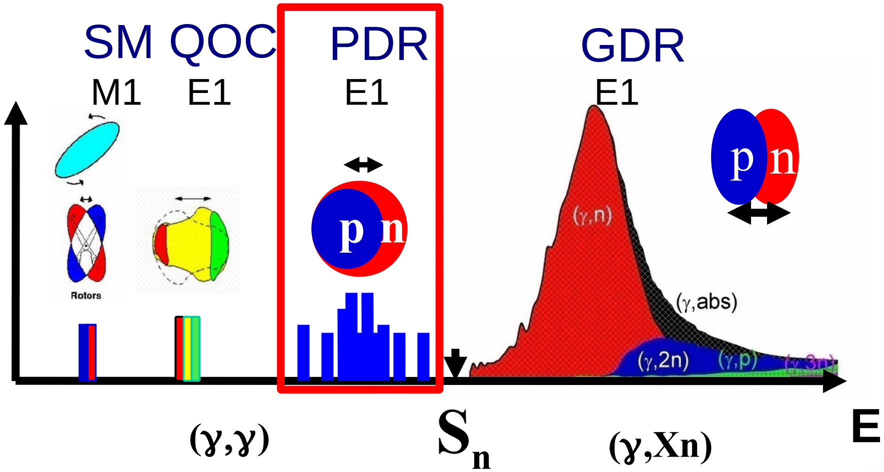


Tsoneva / Lenske, PRC 77, 024321 ('08)
HFB + QPM

isovector -> GDR

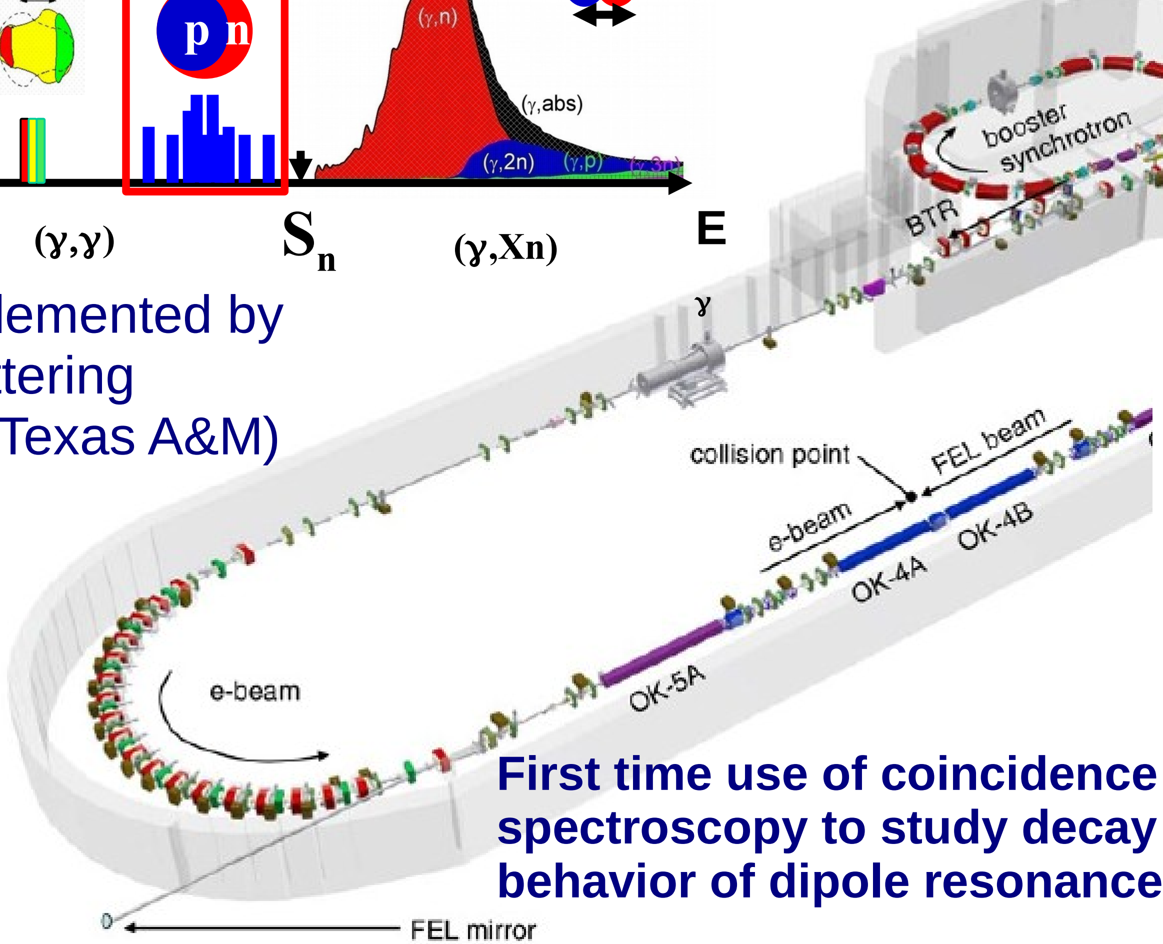
New Advances: Coincidence Spectroscopy

TECHNISCHE UNIVERSITÄT DARMSTADT

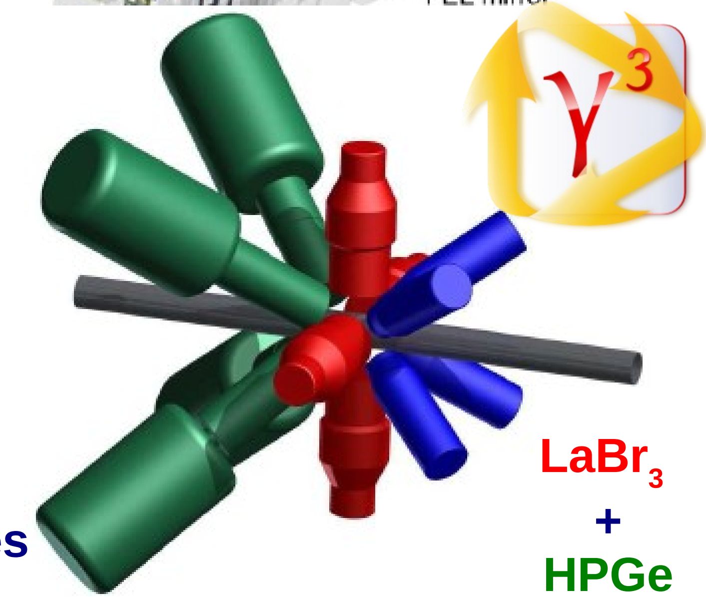


Study of the Pygmy Dipole Resonance
-> Neutron Skins
Study of Multi-Phonon States

Complemented by α-scattering (KVI / Texas A&M)



First time use of coincidence spectroscopy to study decay behavior of dipole resonances



$LaBr_3$ + HPGe

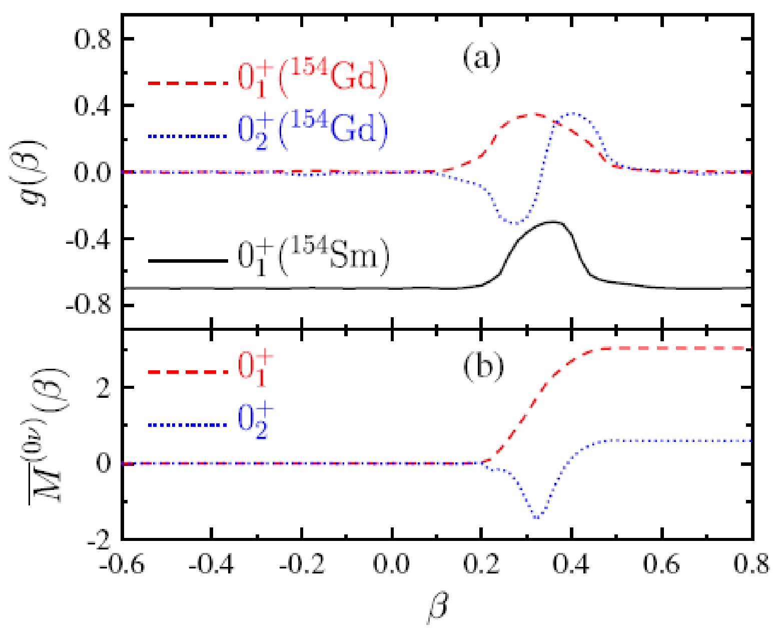
"Application":
Dipole strength and 0νββ-decays

TECHNISCHE UNIVERSITÄT DARMSTADT

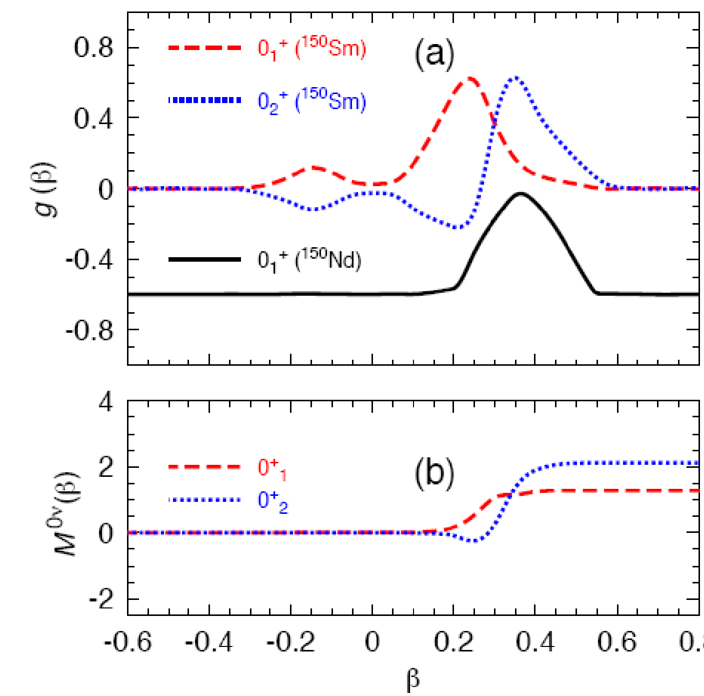
PRL **111**, 172501 (2013) PHYSICAL REVIEW LETTERS week ending 25 OCTOBER 2013

Constraint on $0\nu\beta\beta$ Matrix Elements from a Novel Decay Channel of the Scissors Mode: The Case of ^{154}Gd

J. Beller,[1,*] N. Pietralla,[1] J. Barea,[2] M. Elvers,[3,†] J. Endres,[3,‡] C. Fransen,[3] J. Kotila,[4] O. Möller,[1] A. Richter,[1] T. R. Rodríguez,[1] C. Romig,[1] D. Savran,[5,6] M. Scheck,[1,7] L. Schnorrenberger,[1] K. Sonnabend,[8] V. Werner,[9] A. Zilges,[3] and M. Zweidinger[1]



^{150}Nd:
larger **0νββ-** decay branch **to 0^+_2 state** than to gs due to QSPT at N=90.



SFB 1245

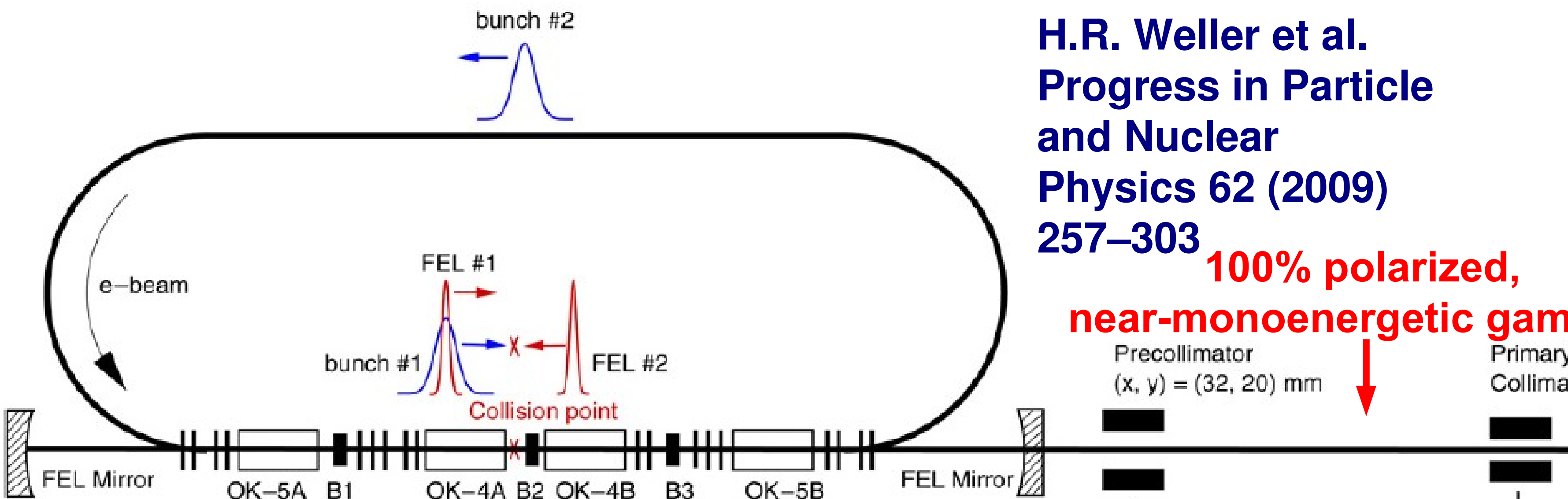
Part of new CRC 1245 "From Fundamental Interactions to Structure and Stars"

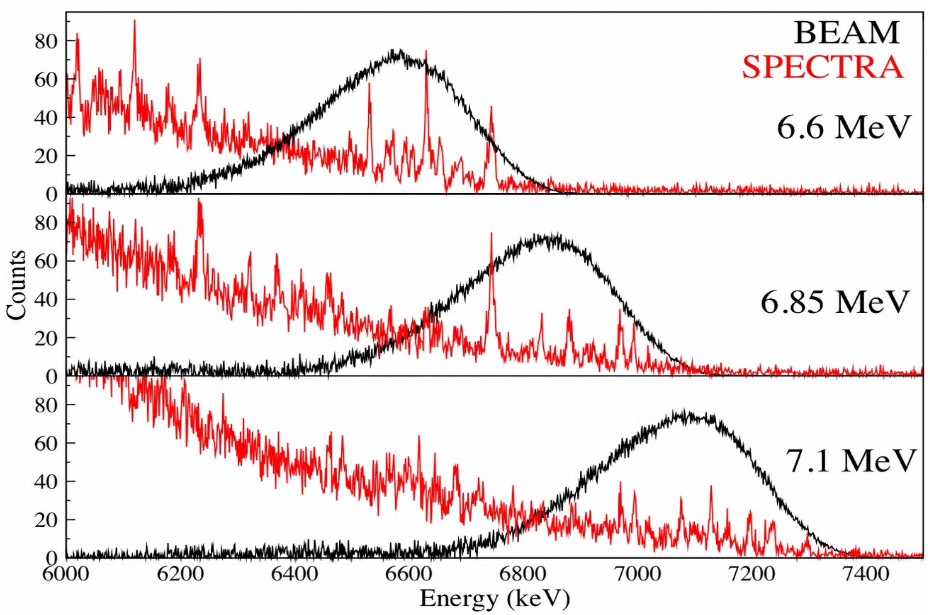
HIGS (Free Electron Laser)

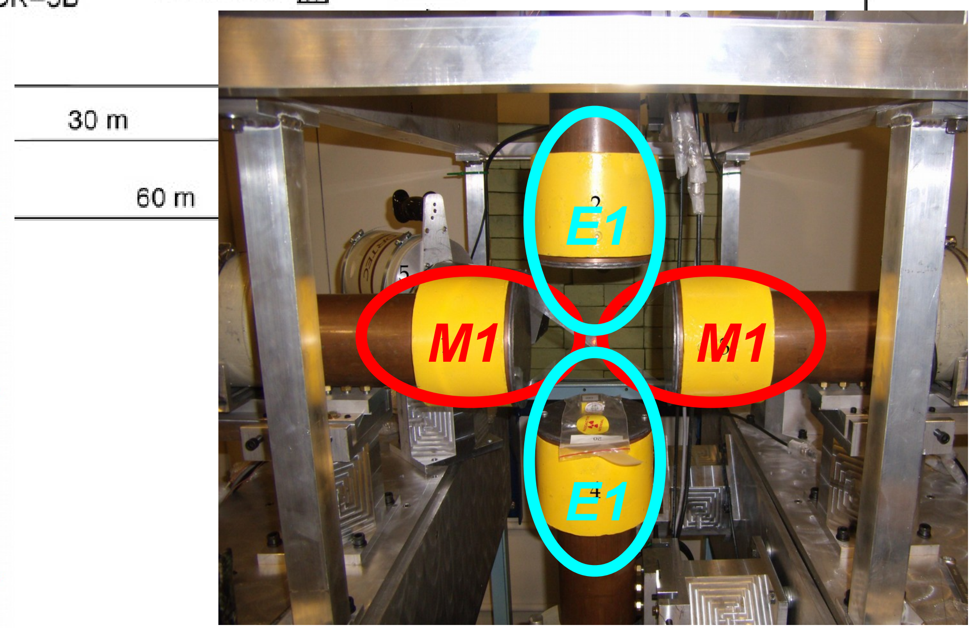
TECHNISCHE UNIVERSITÄT DARMSTADT

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

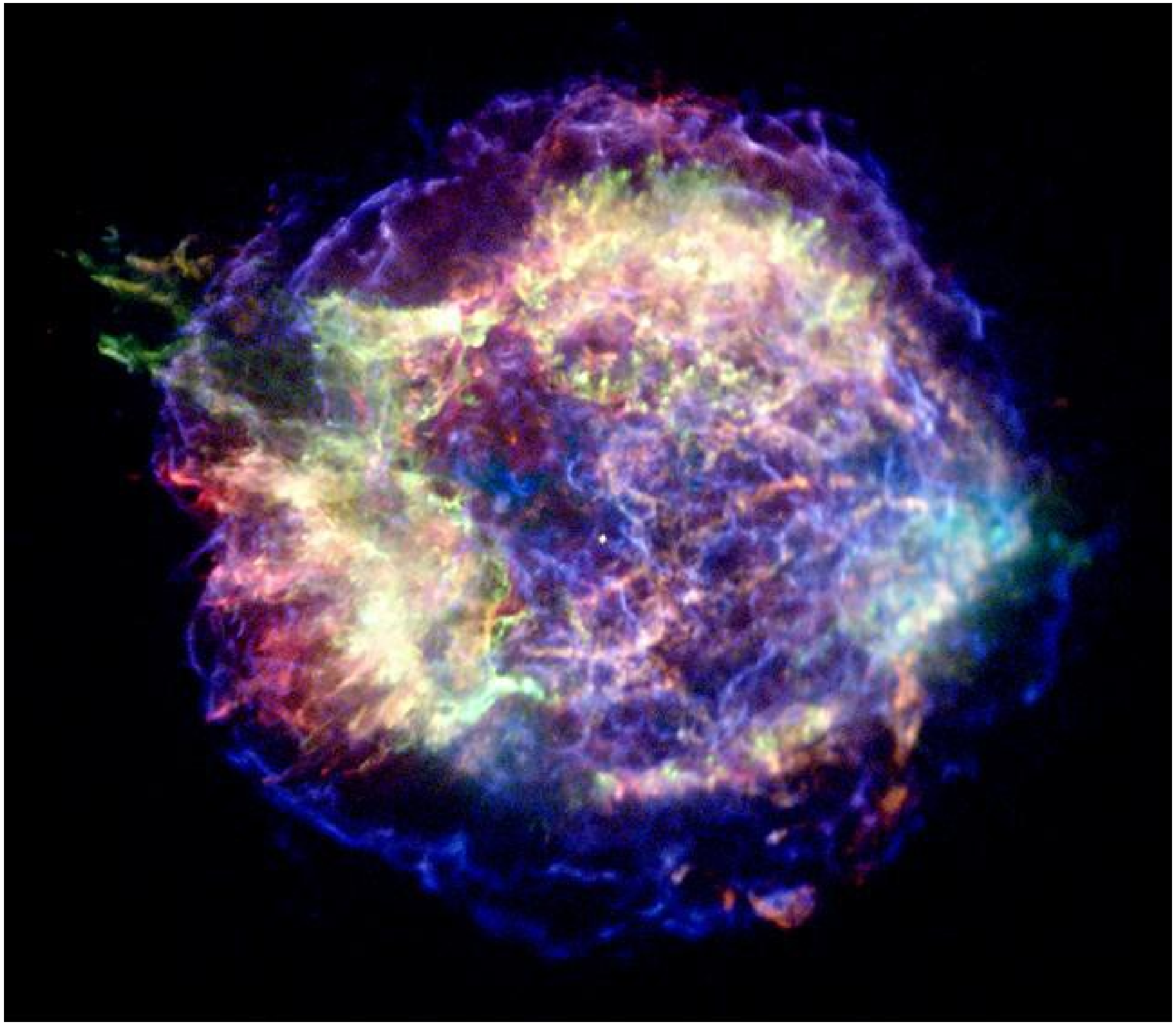
100% polarized, near-monoenergetic gammas







Nucleosynthesis



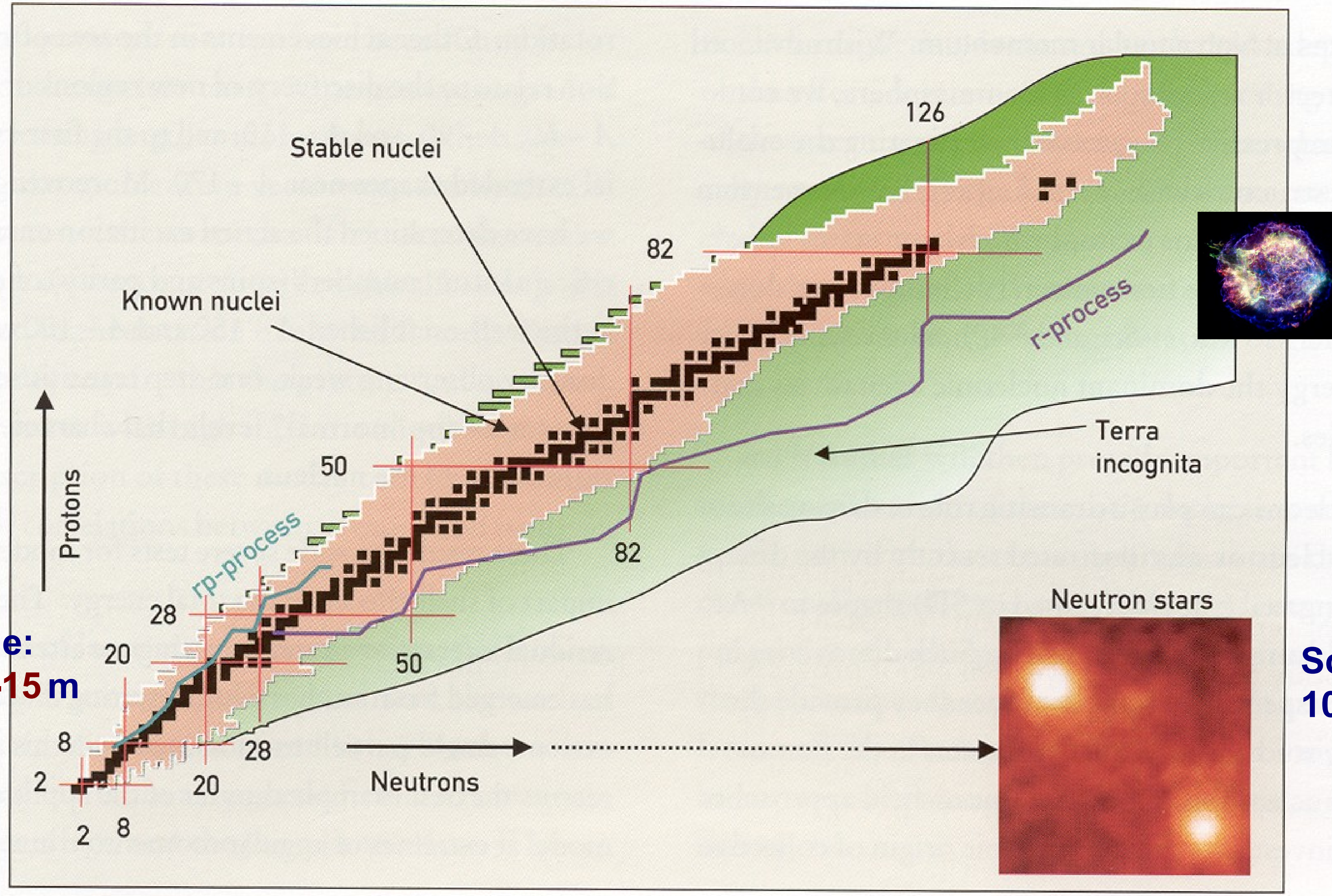
Nuclear Reactions power the sun

... and it takes the death of stars to actually make us!

This death involves lots of photons.

Nucleosynthesis Paths

Scale:
10^-15 m



Scale:
10^5 m