Research opportunities for Nuclear Photonics with an ERL-based hard X-ray source

Norbert Pietralla, TU Darmstadt

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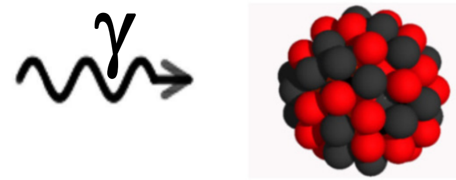
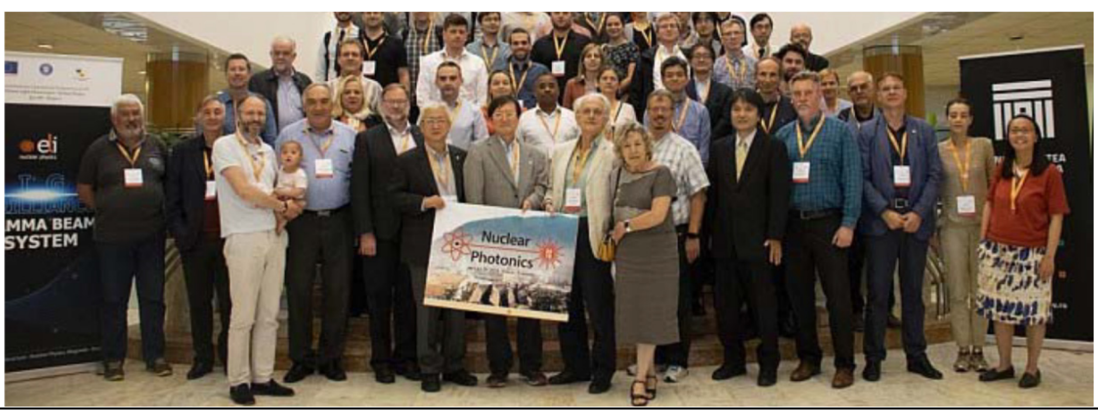
Nuclear Photonics

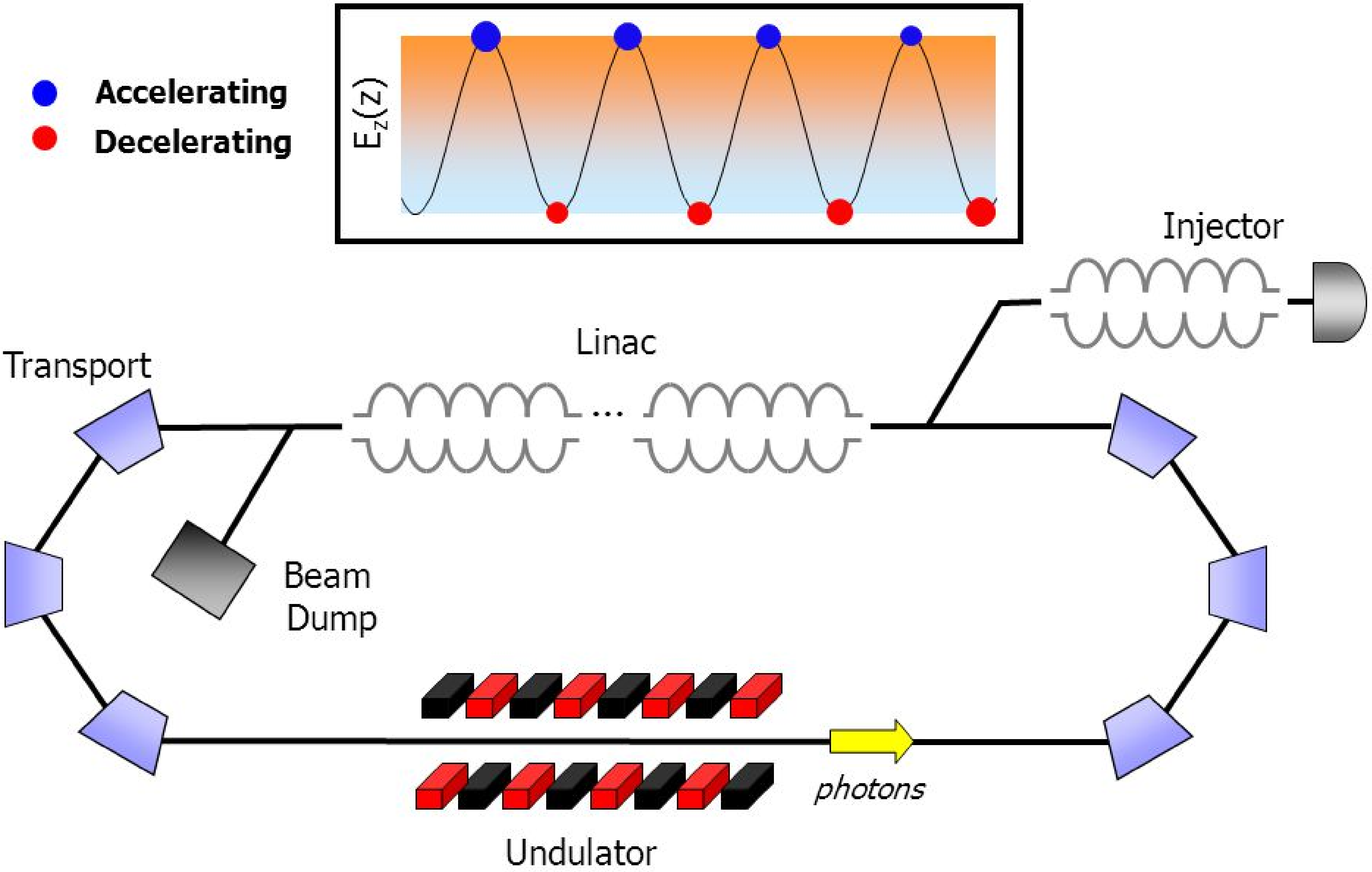


Photonuclear reactions



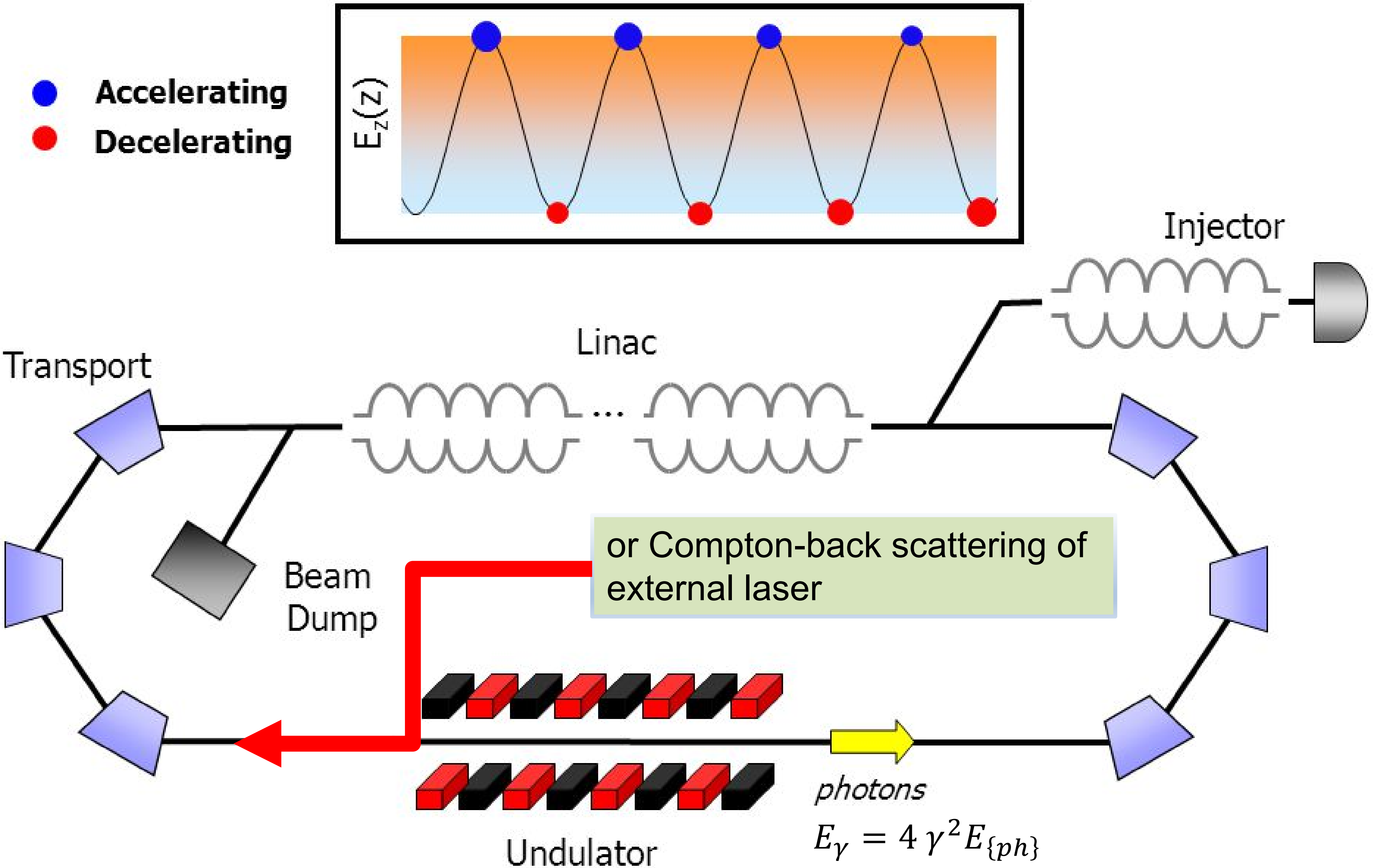
Conference photo
Nuclear Photonics 2018
Brasov, Romania

Generic ERL-based Light Source



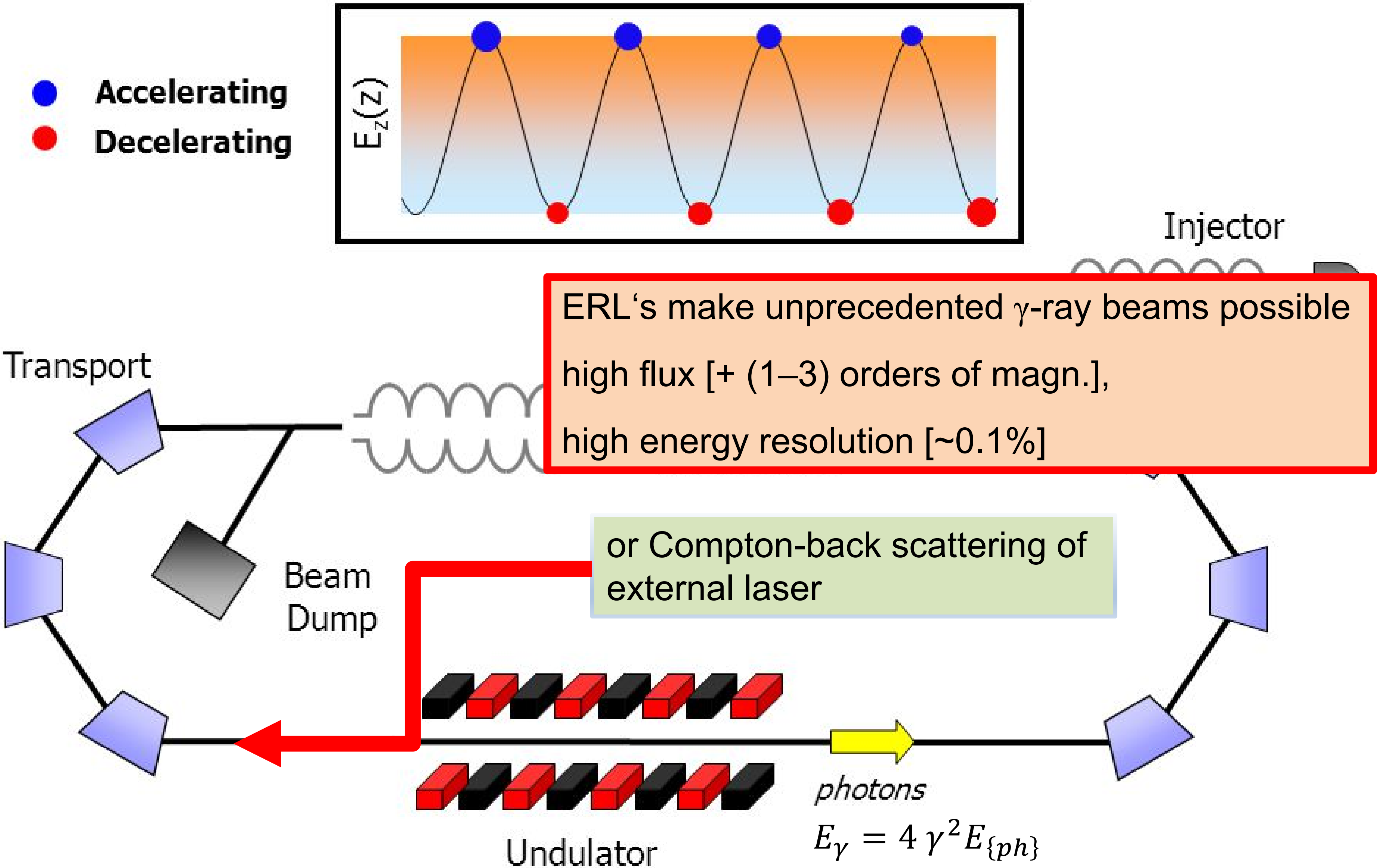
from: Chris Tennant, USPAS 2011 online

Generic ERL-based Light Source



from: Chris Tennant, USPAS 2011 online

Generic ERL-based Light Source



from: Chris Tennant, USPAS 2011 online

Outline

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- Photonuclear reactions with MeV-range γ rays
- Methodological developments for nuclear photonics
- Motivation from astrophysics and particle physics
- Examples for recent achievements
- Concluding remarks

Photonuclear Reactions

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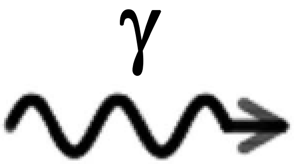
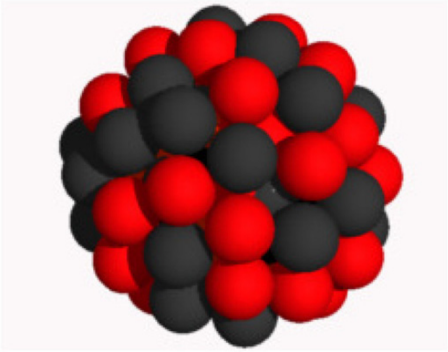


0.1 – 100 MeV



What happens?

Nuclear Physics with photon beams

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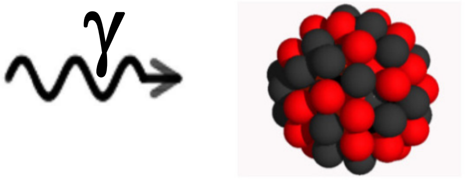
Pure EM-interaction

- (nuclear-)model independent
- “small“ cross sections, intense beams



Minimum projectile mass

- min. angular momentum transfer,
  spin-selective: low-spin modes [E1,M1,E2,(E3?)]

Polarisation

- “Parity Physics“, channel selectivity

Narrow Bandwidth (at 4th generation LCB source)

- Explore specific excitation energy
  “Selective Manipulation of Nuclear States“:

Nuclear Photonics

Photonuclear Reactions

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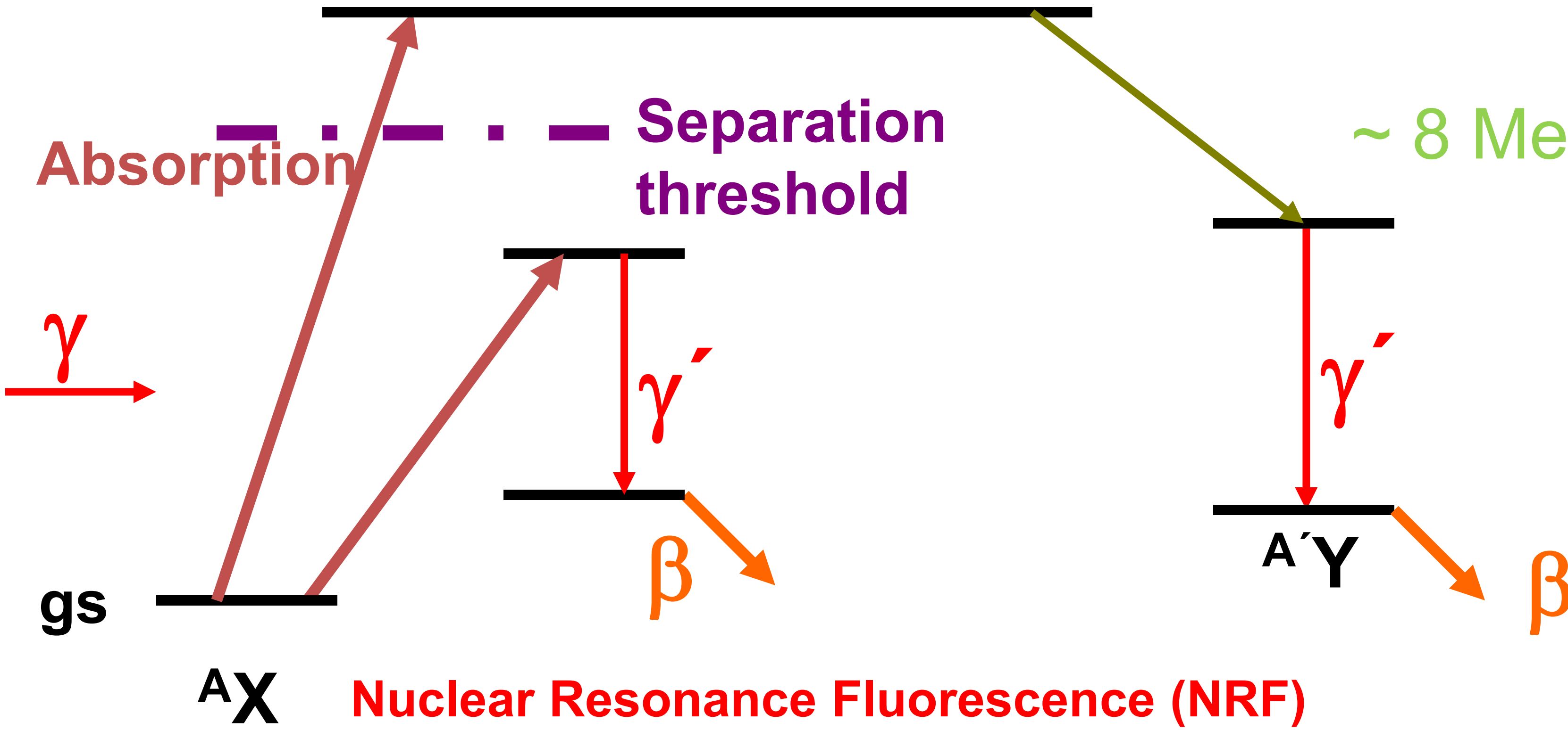


Nuclear Resonance Fluorescence (NRF)

Photoactivation

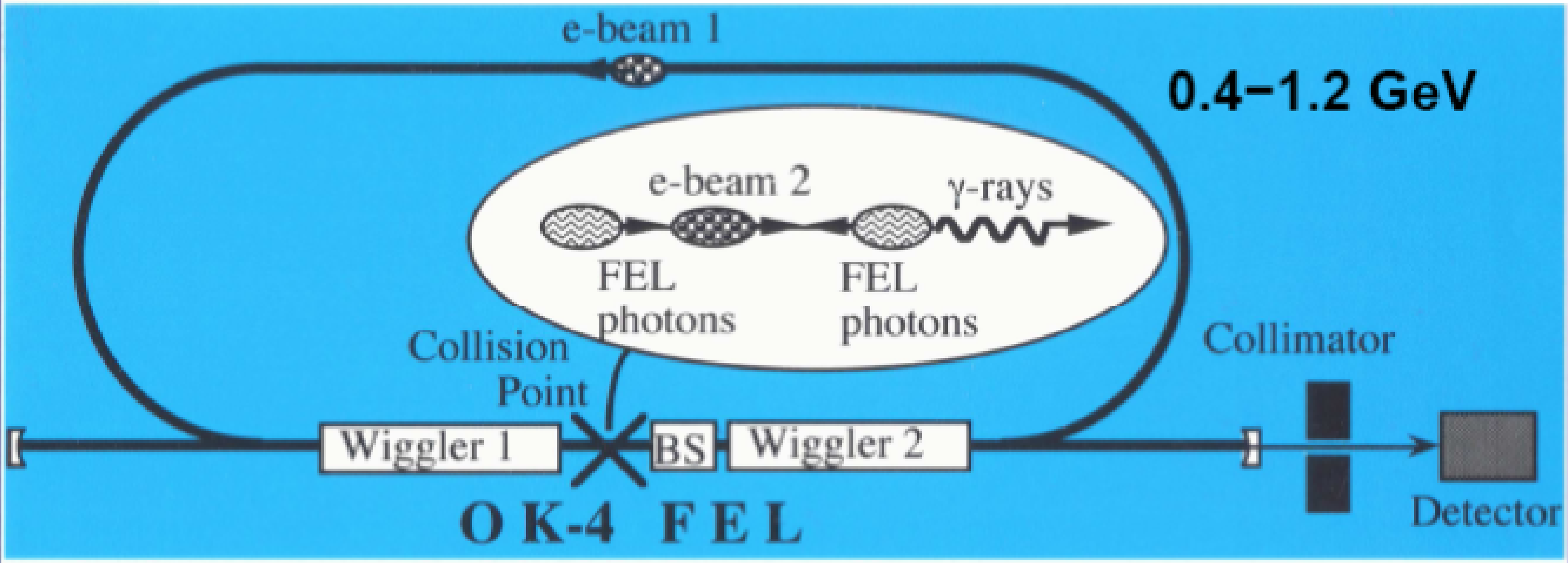
Photodisintegration (-activation)

Photofission

High Intensity γ-Ray Source (HIgS)

H.R.Weller, V.N.Litvinenko
Duke University, Durham, NC, U.S.A.

Compton Backscattering of Intra-cavity Laser Light

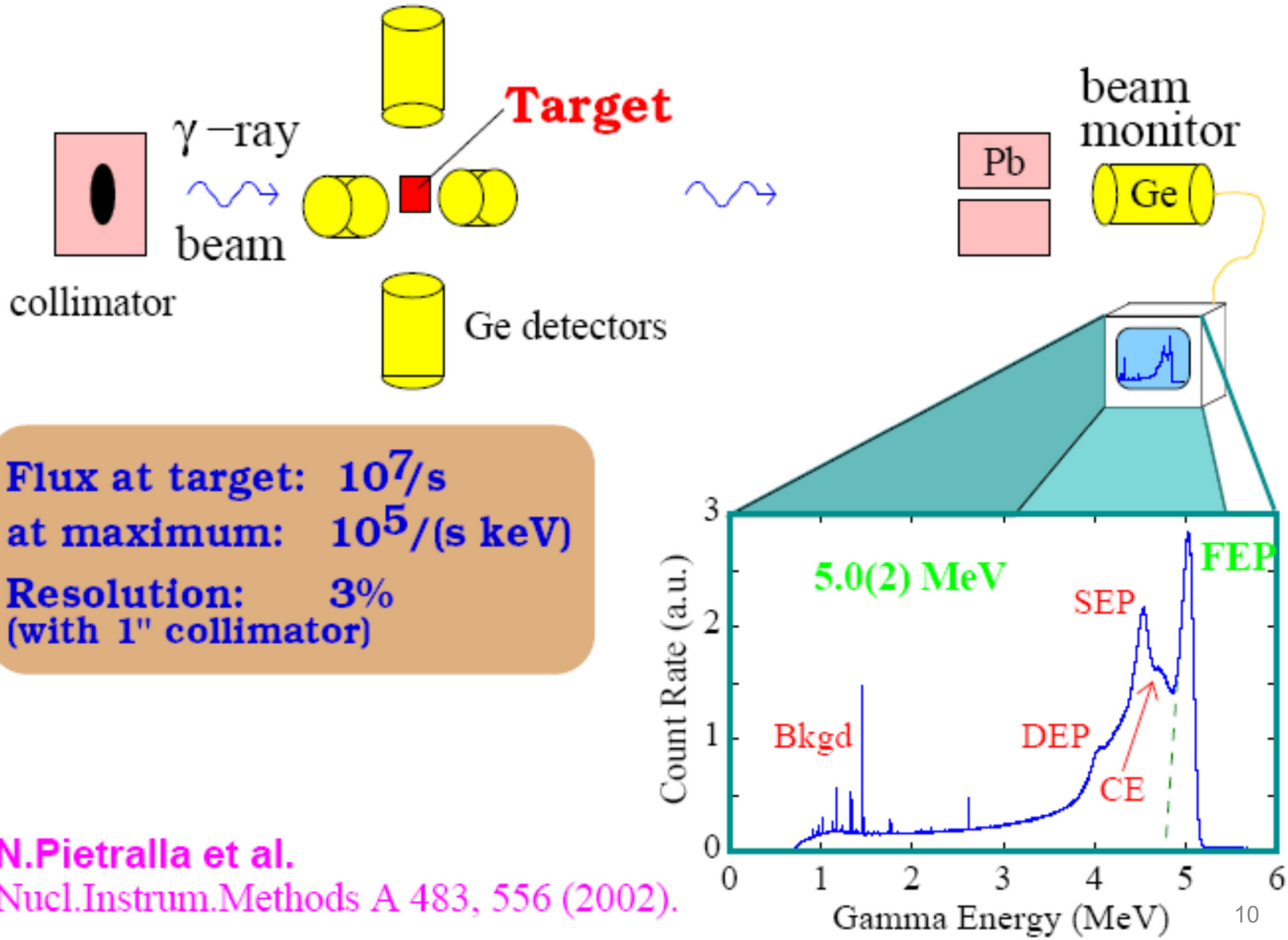


2 − 60 MeV 1.7 − 6.4 eV ~ 1000

$$E_\gamma = \frac{4\gamma^2 E_{ph}}{\left(1 + r + \gamma^2\theta^2\right)}; \quad r = \frac{4\gamma E_{ph}}{mc^2}; \quad E_{ph} = \frac{2\gamma^2 hc}{\lambda_w\left(1 + K_w^{\,2}/2\right)}; \quad \gamma = \frac{E_e}{mc^2};$$

nearly monochromatic, tunable, completely polarized

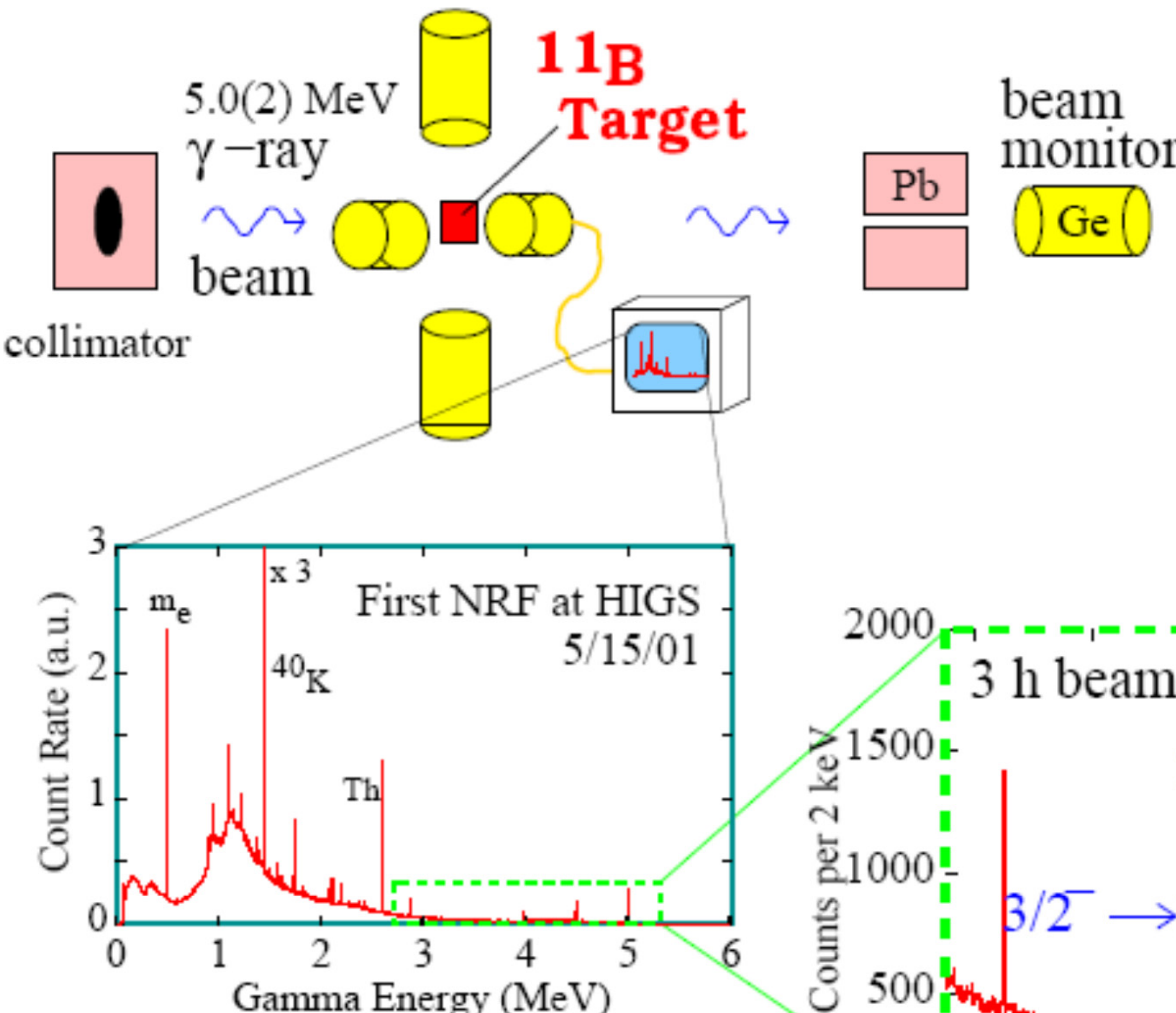
Looking at the HIGS Gamma-Ray Beam

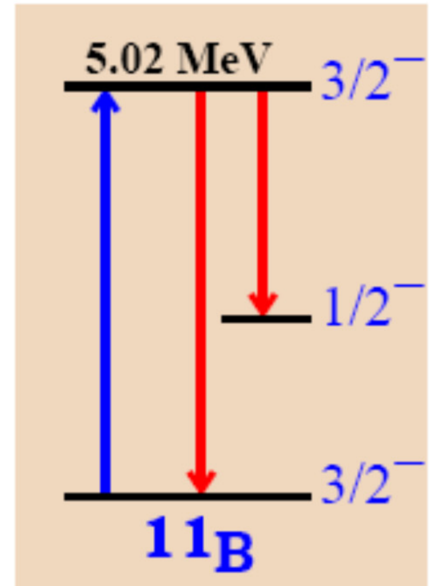


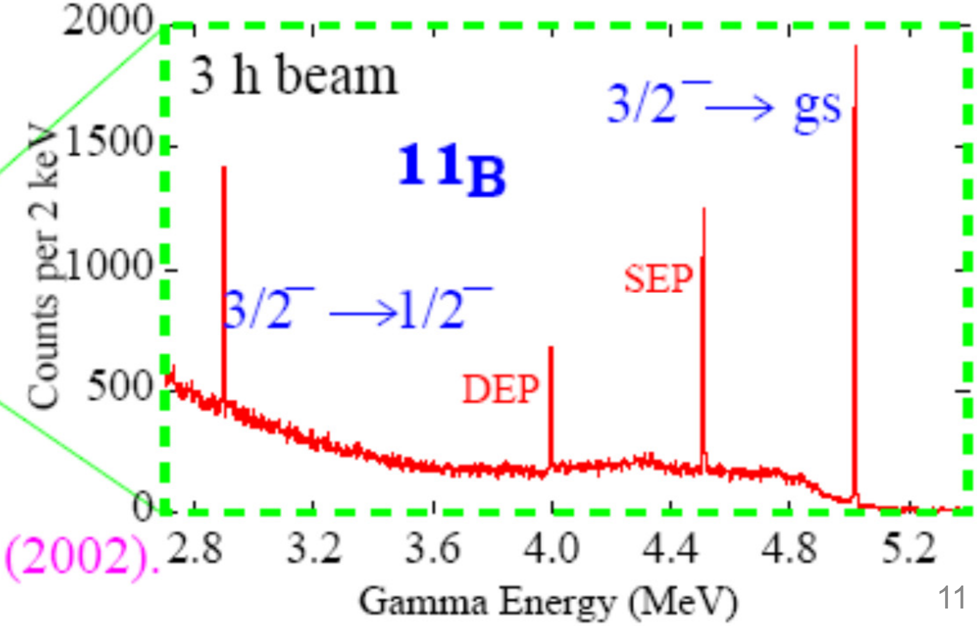
Flux at target: 10^7/s
at maximum: 10^5/(s keV)
Resolution: 3%
(with 1" collimator)

N.Pietralla et al.
Nucl.Instrum.Methods A 483, 556 (2002).

Looking at the Target







N.Pietralla et al.
Nucl.Instrum.Methods A483, 556 (2002).

Polarimetry with linearly polarized γ-ray beams

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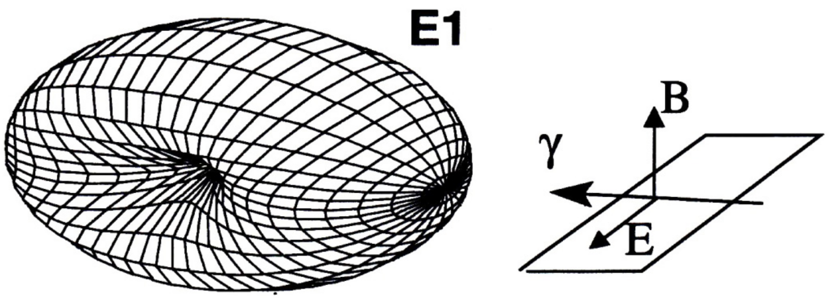
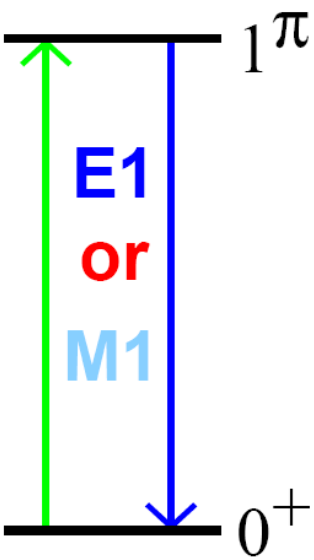
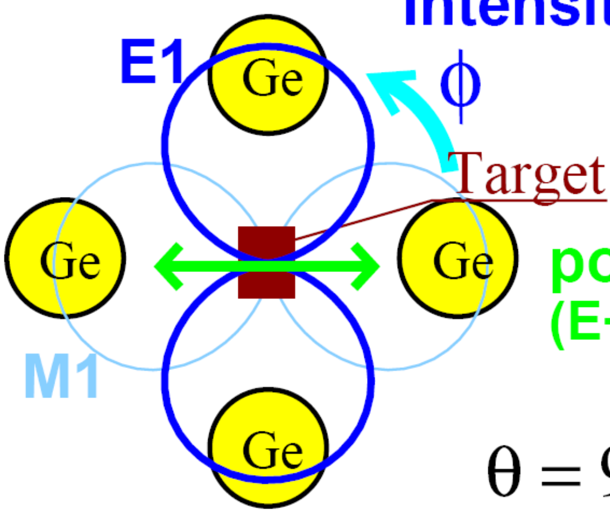
Scattering intensity distribution for linearly polarized photons





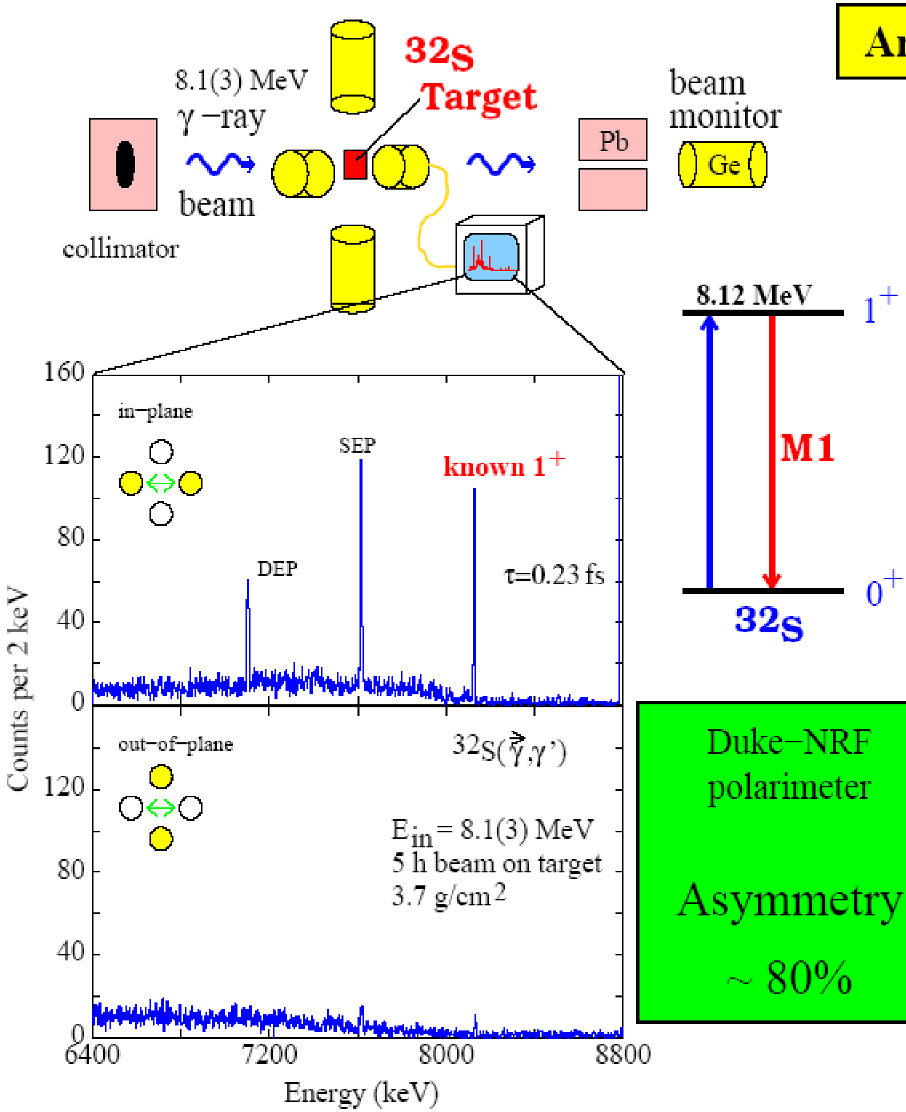
Azimuthal Intensity distribution



polarization plane (E−vector)

$\theta = 90^{o}$

Analyzing Power for the Pygmy Resonance

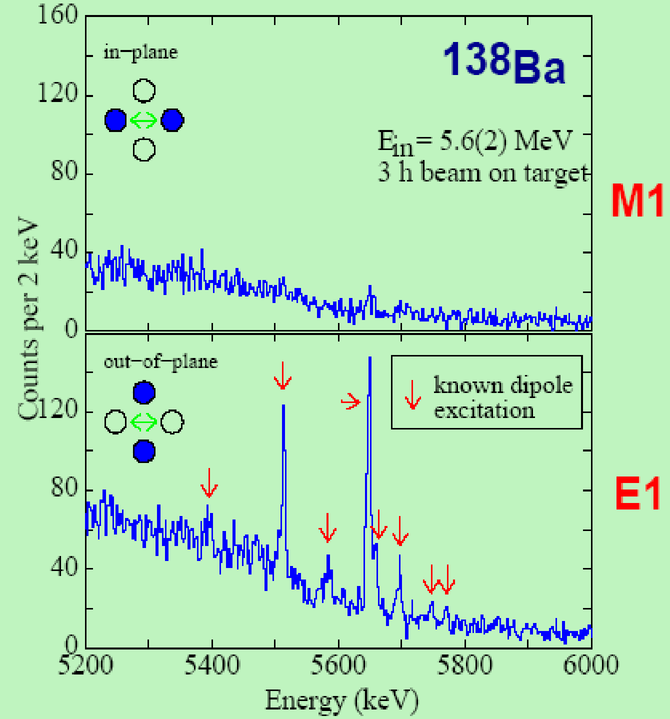


Duke−NRF polarimeter

Asymmetry ~ 80%

N.Pietralla et al., Nucl.Instrum.Methods A483, 556 (2002).

"pygmy resonance": all E1 !



N.Pietralla et al., Phys.Rev.Lett.88, 012502 (2002).

Electromagnetic dipole-response

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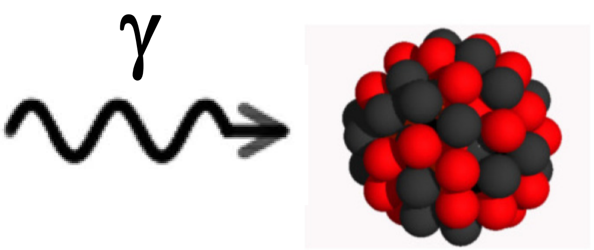
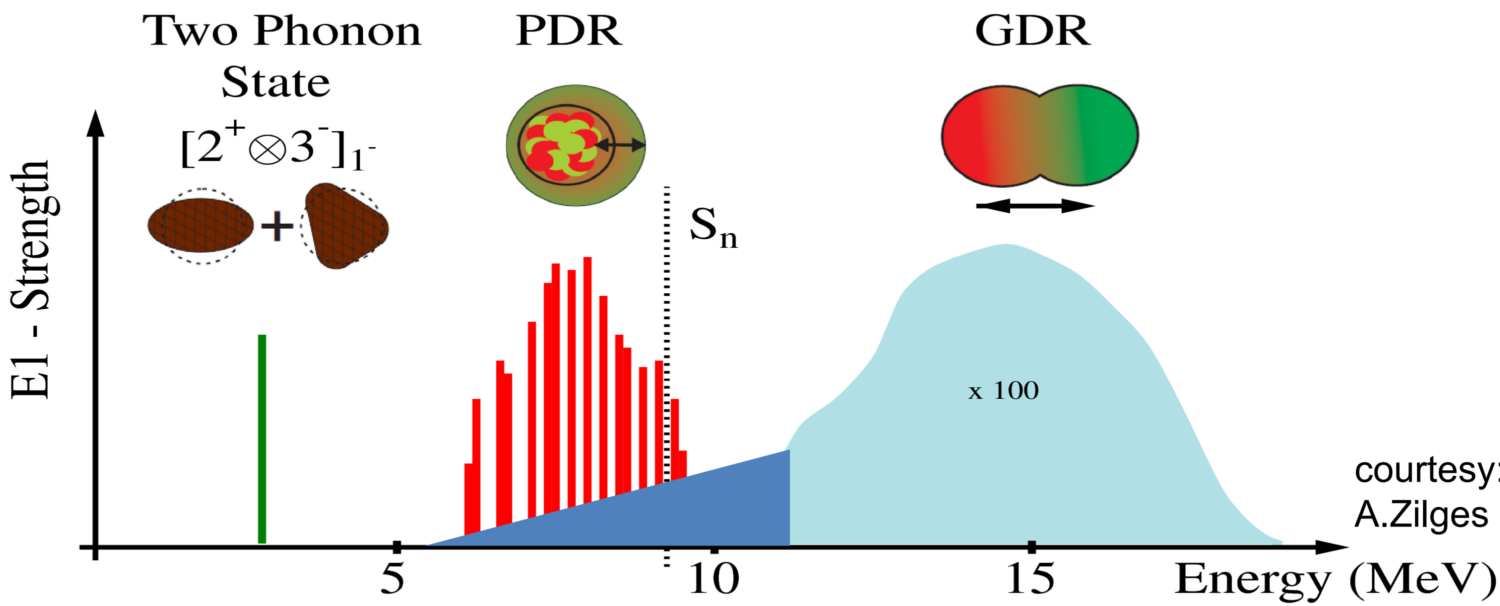
Typical E1 strength distribution in heavy atomic nuclei



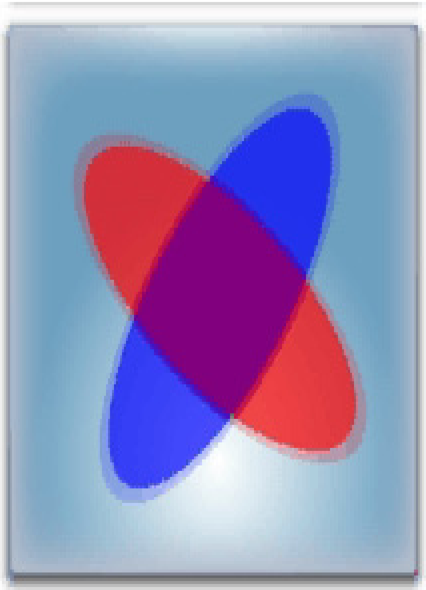


courtesy:
A.Zilges

Discovery of Scissors mode: deformed nuclei

Darmstadt, 1983

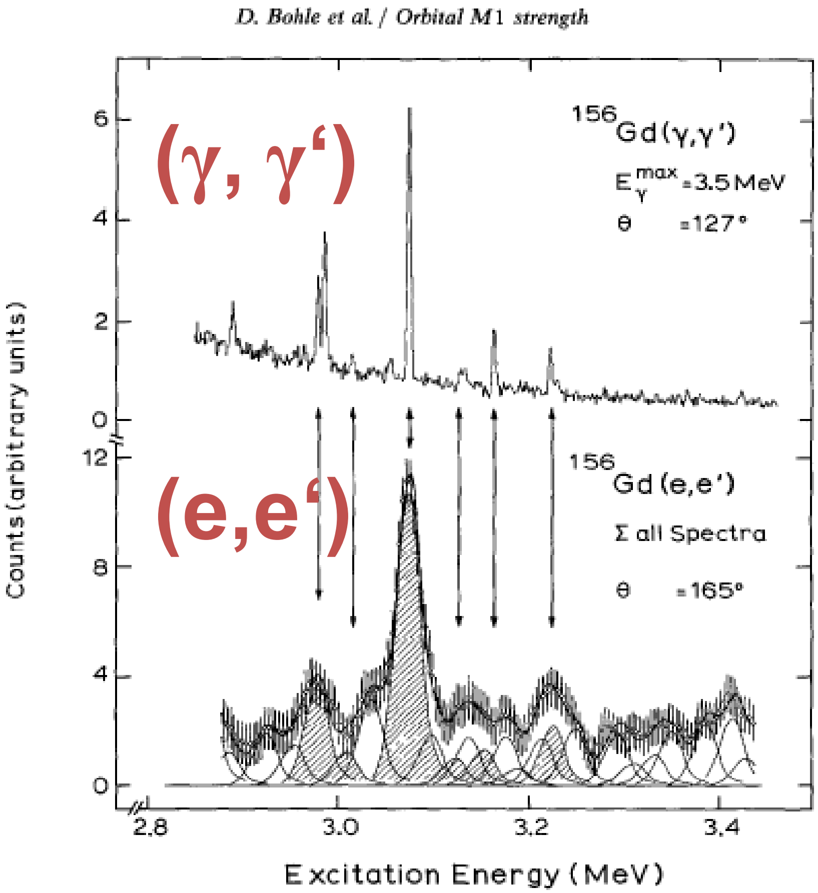
Achim Richter



Predicted by

Lo Iudice & Palumbo, 1978

@ 3 MeV: Iachello, 1981 in IBM-2



Bohle *et al.*, NPA 458, 205 (1986).

DALINAC data

E2 decay strength of the Scissors mode

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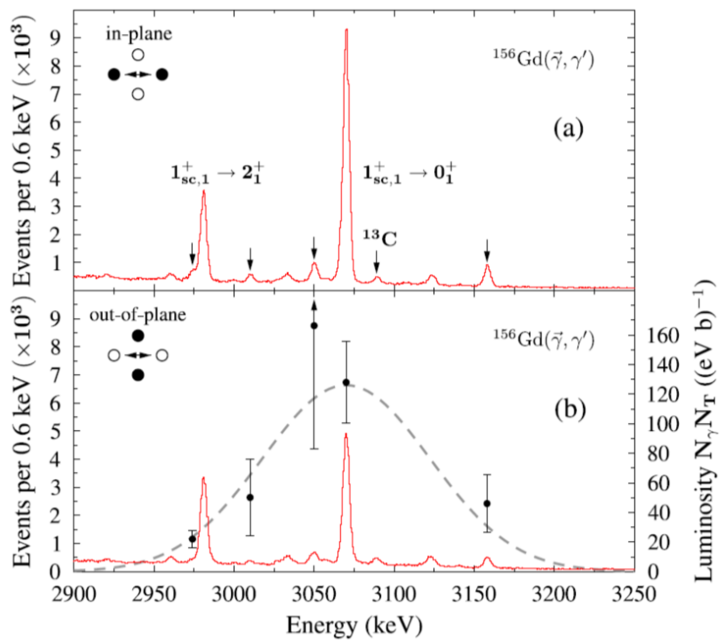
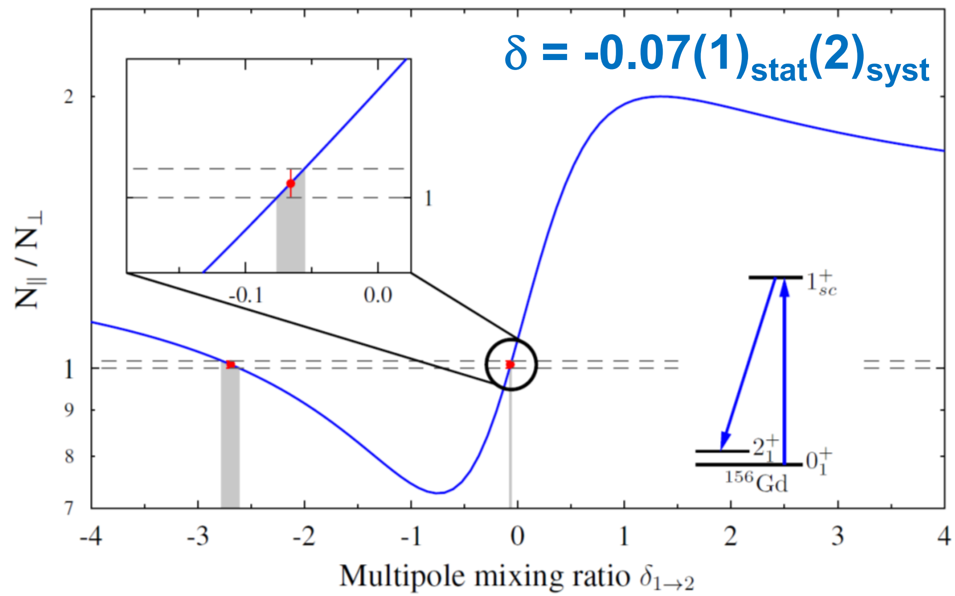
PRL **118**, 212502 (2017) PHYSICAL REVIEW LETTERS week ending 26 MAY 2017

***E*2 decay strength of the *M*1 scissors mode of ^{156}Gd and its first excited rotational state**

T. Beck,[1,*] J. Beller,[1] N. Pietralla,[1] M. Bhike,[2] J. Birkhan,[1] V. Derya,[3] U. Gayer,[1] A. Hennig,[3] J. Isaak,[4,5,†] B. Löher,[4,5] V. Yu. Ponomarev,[1] A. Richter,[1] C. Romig,[1,‡] D. Savran,[4,5] M. Scheck,[1,6,7] W. Tornow,[2] V. Werner,[1] A. Zilges,[3] and M. Zweidinger[1]
[1]*Institut für Kernphysik, TU Darmstadt, Schlossgartenstr. 9, D-64289 Darmstadt, Germany*
[2]*Department of Physics, Duke University and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308, USA*
[3]*Institut für Kernphysik, Universität zu Köln, Zülpicher Str. 77, D-50937 Köln, Germany*

$B(E2;\, 1^+_{ScM} \rightarrow 2^+_1)$
$= 0.037(19)$ W.u.

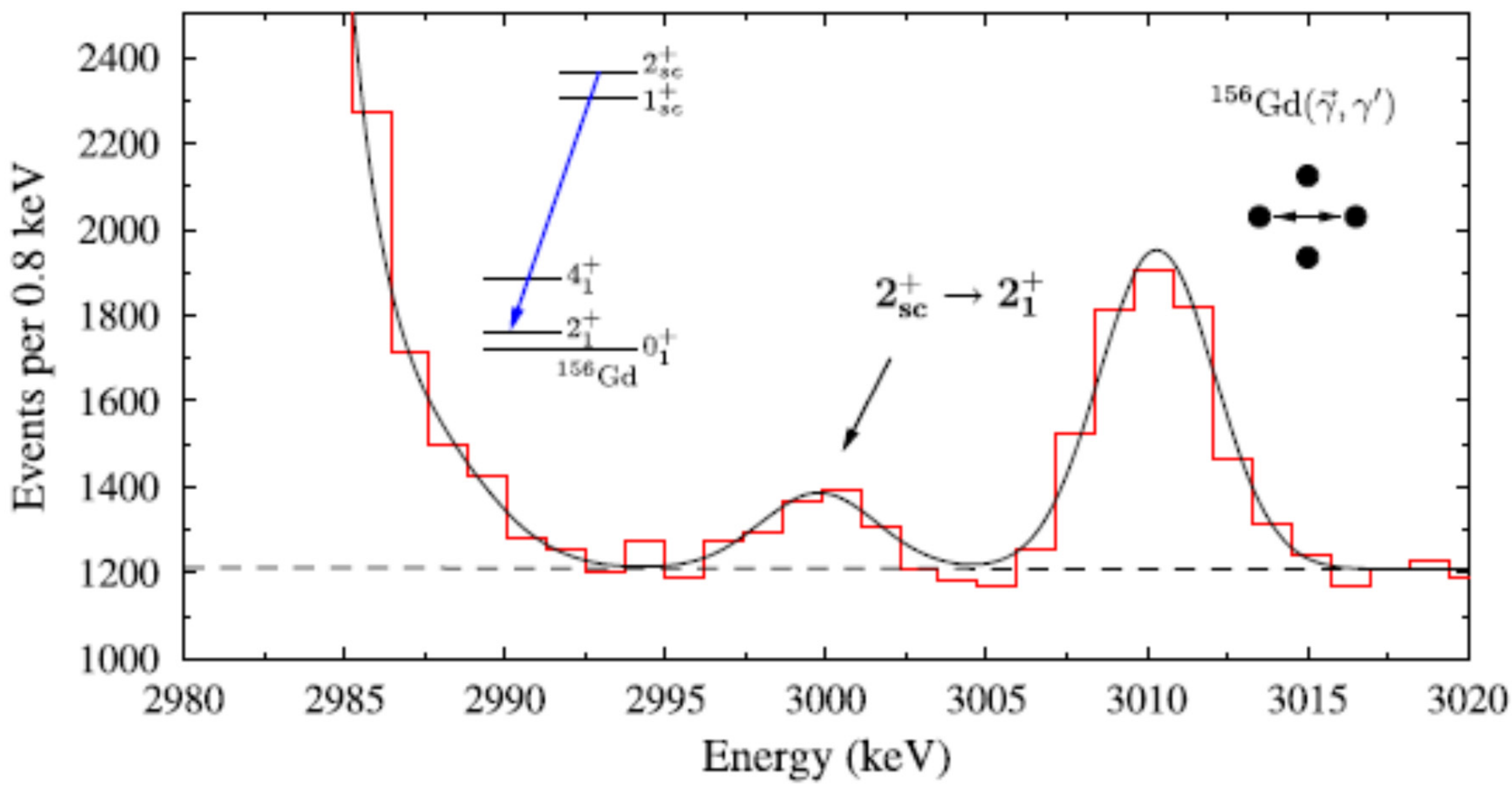




S-DALINAC & HIγS

Evidence for rotational excitation of the Scissors Mode

S-DALINAC & HIγS data

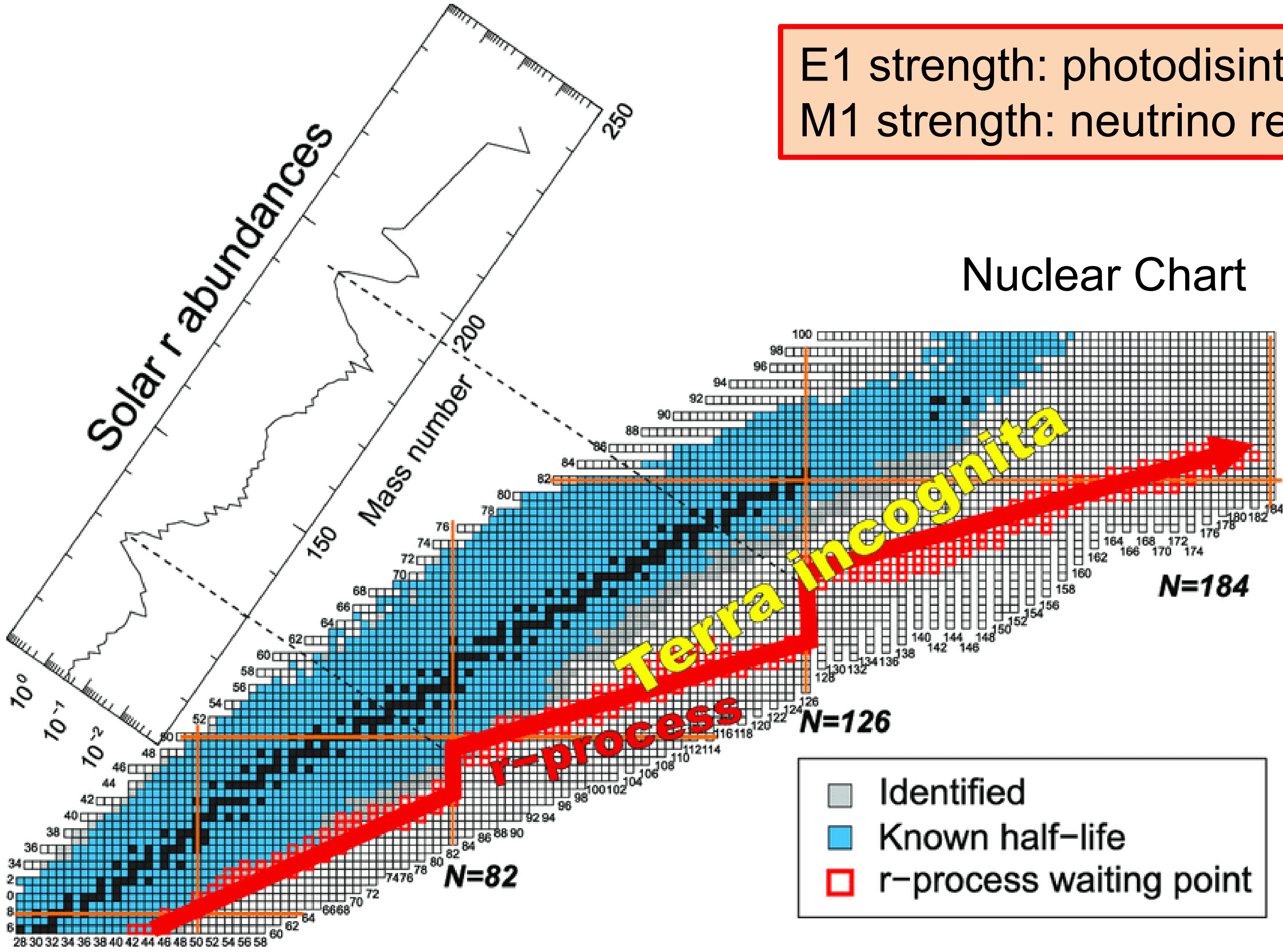


T. Beck et al., Phys. Rev. Lett. 118 212502 (2017).

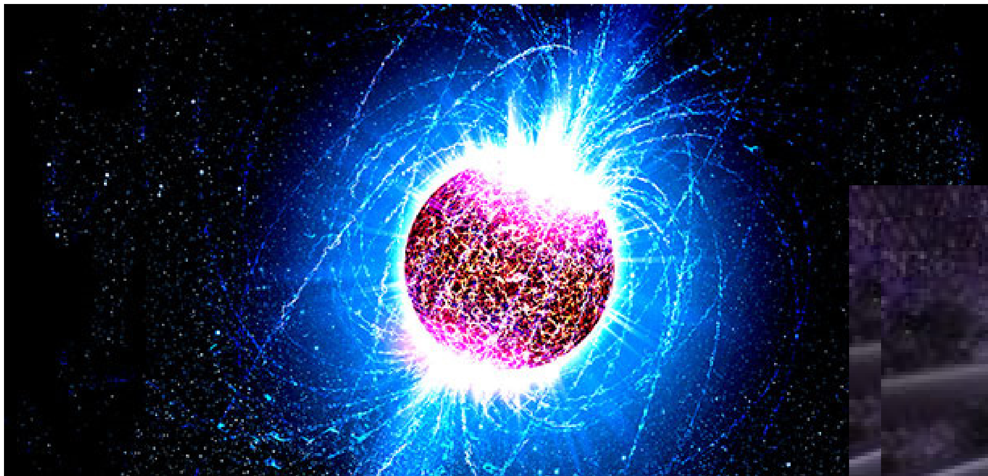
Supernova 1987A

Cosmic Nucleosynthesis

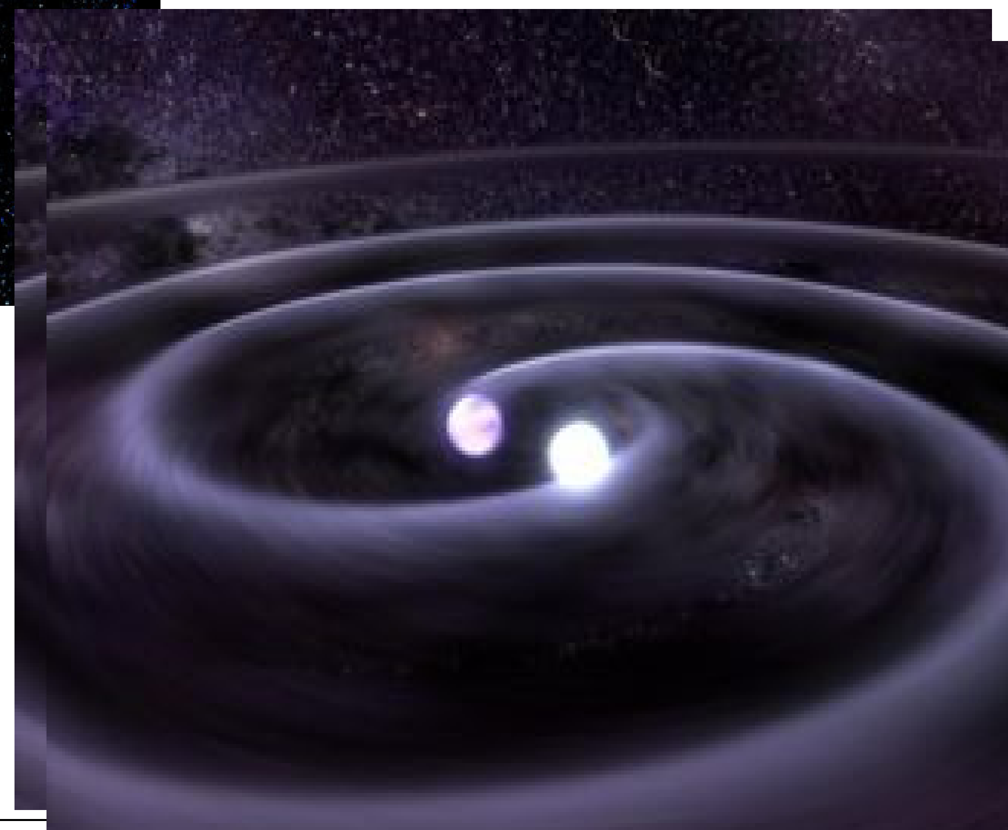
E1 strength: photodisintegration
M1 strength: neutrino reactions



Neutron-Star Mergers



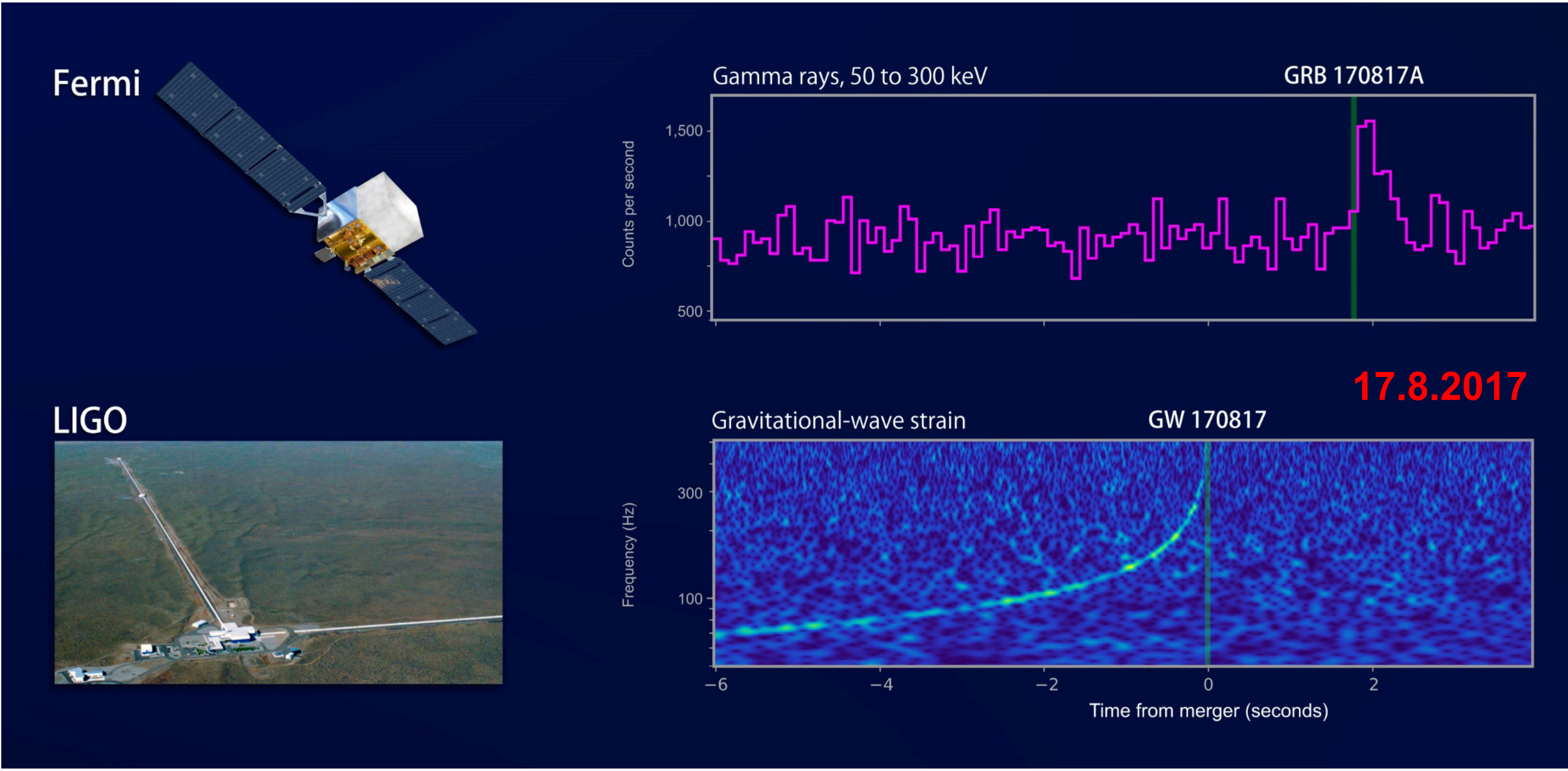
Artist‘s views !



Abundant source of neutrons for nuclesynthesis

Neutron-star merger:
Explosive ejection of neutron-rich matter into space

Multi-Messenger Observation of N-Star Merger



LIGO/VIRGO – collaboration, Fermi Satellite

Neutron-Star Merger in the Visible Spectrum

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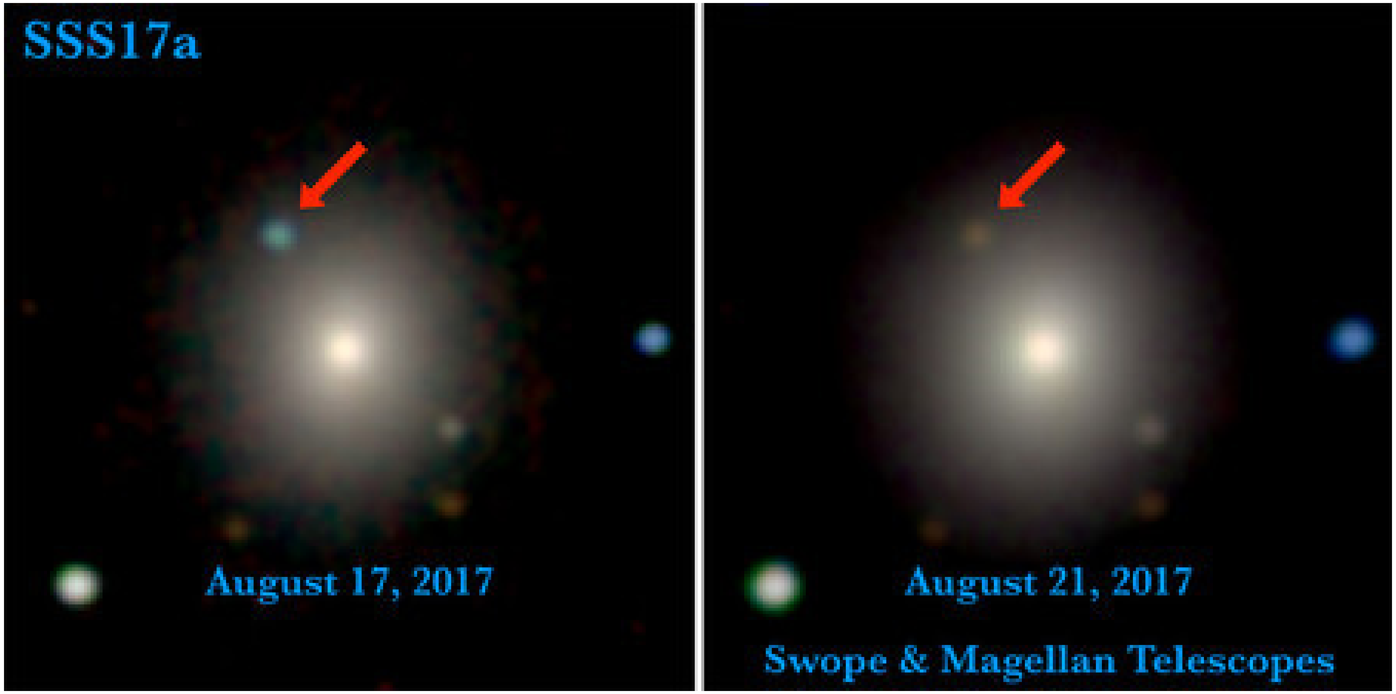
A star changes colour in 4 days !   „Kilonova“



Light curve of neutron-star mergers due to synthesized rare-earth nuclei

B. D. Metzger et al., Mon. Not. Roy. Ast. Soc. 406, 2650 (2010).

Motivation for Nuclear Photonics

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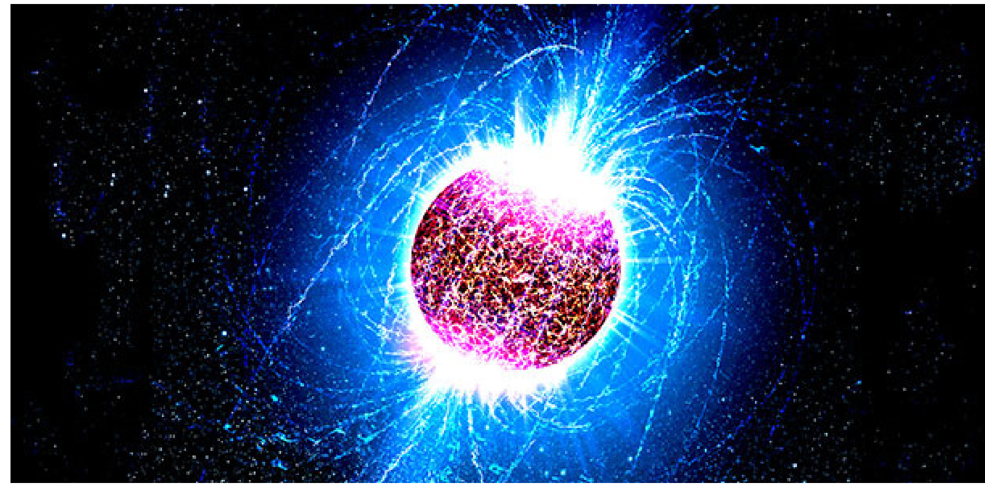
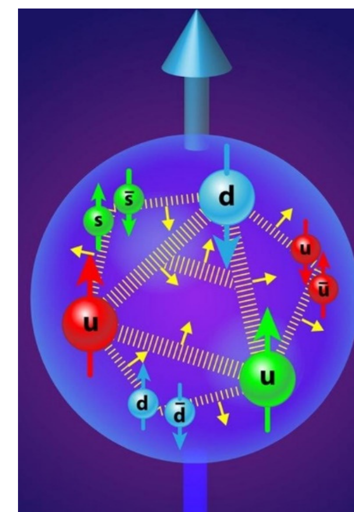
- Photons provide a sensitive probe for nuclear structure
- Properties of nuclear isotopes as a function of mass (neutron number)
- Low-energy frontier of Quantum Chromo-Dynamics
- Photonuclear reactions impact the structure and dynamics of stars
- Formation of chemical elements in the Universe
- Nuclei as detector material for neutrino experiments and searches beyond the Standard Model
- **→ Nuclear photonics**

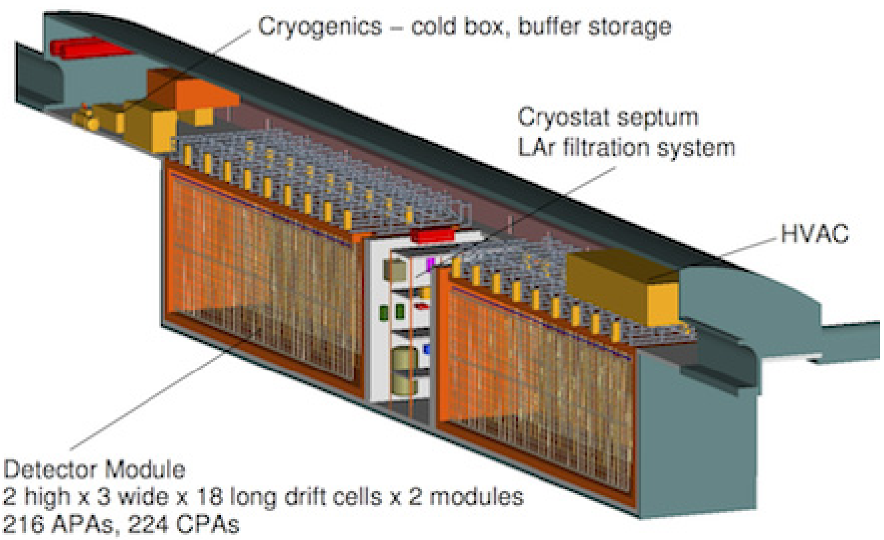




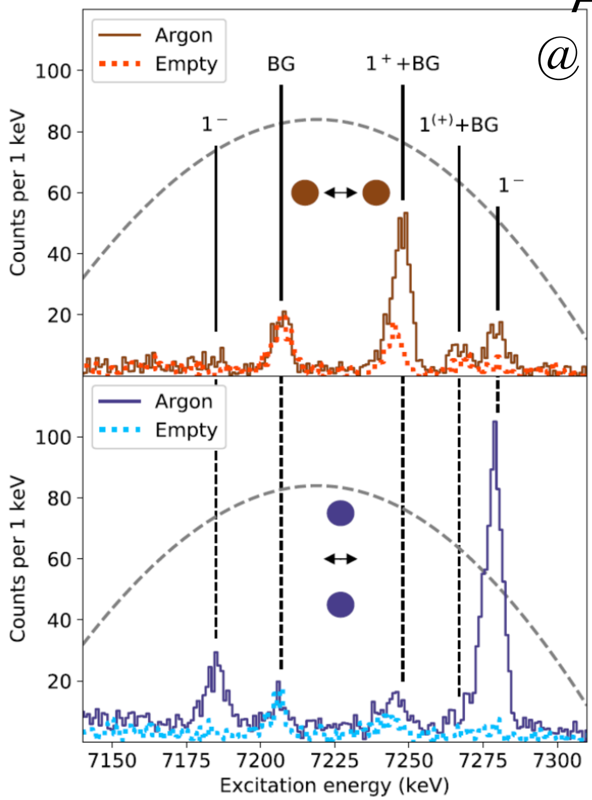
Nuclear Structure for Neutrino Studies

Deep Underground Neutrino Experiment

DUNE LAr – detector for cosmic ν's



^{40}Ar(γ,γ')
@ HIγS



$$\nu + \mathrm{Ar} \rightarrow \nu' + \mathrm{Ar}^*$$

U.Gayer et al., Phys. Rev. C 100, 034305 (2019)

→ total low-energy neutrino cross section

Nuclear Structure for 0νββ searches

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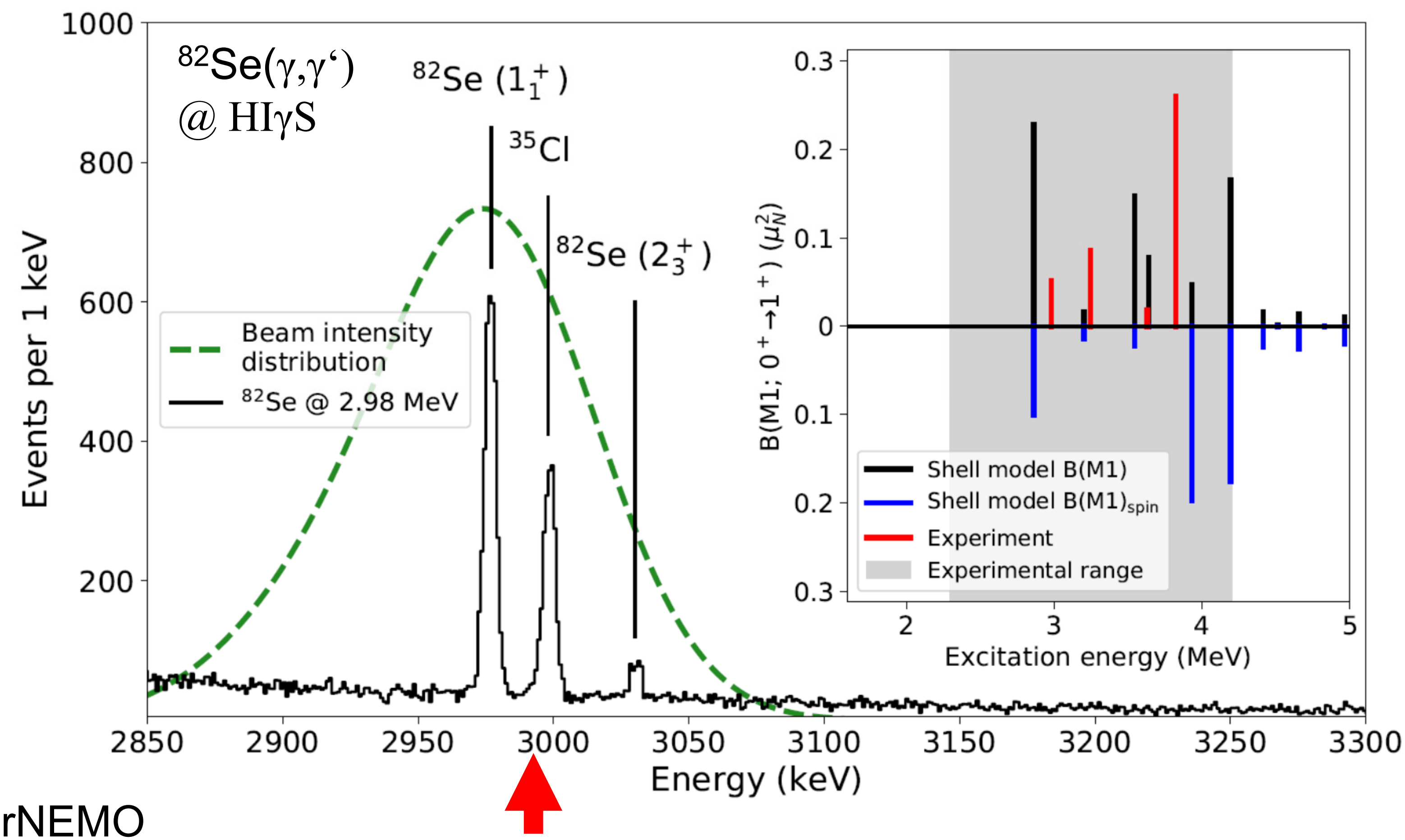

SuperNEMO

$Q_{\{0\nu\beta\beta\}} = 2995\ keV$

V.Werner et al. (TU Darmstadt, 2019)

Physics with Photon Beams

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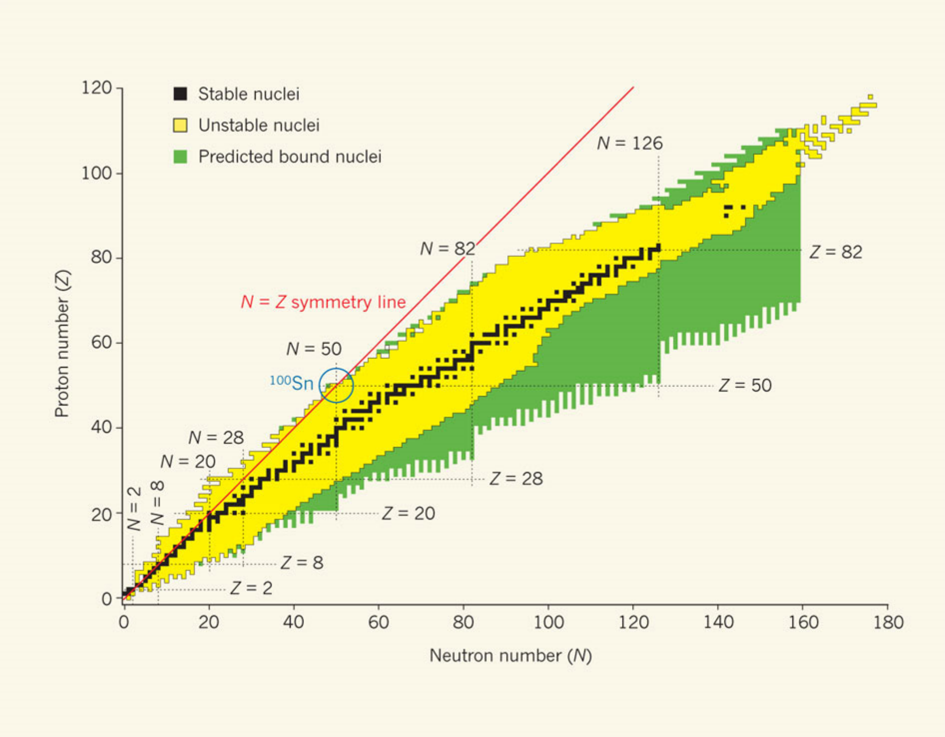
- Nuclear Structure Physics
  - Nuclear single particle structure
  - Collective nuclear structures
  - Photofission
- Particle-Physics Metrology
  - Neutrino detectors
  - Nuclear matrix elements for ββ-decay
- Nuclear Astrophysics
  - Capture / desintegration reactions
  - Nuclear synthesis
- Applications
  - Radiotomography of fuel rods
  - Cultural heritage, etc.



Nuclear Photonics

„Discovery Frontier“ for Nuclear Photonics at 4th Generation γ Source

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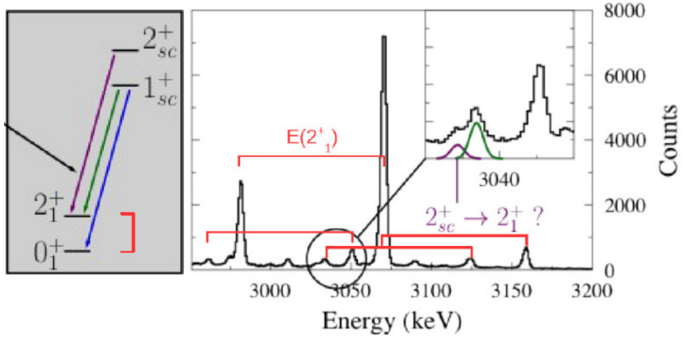
High-Intensity Frontier = „Discovery Frontier“

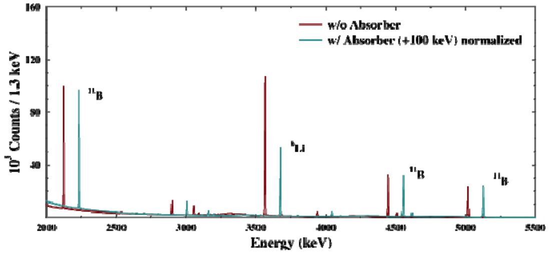
(scientific opportunities)

- **„Availability Frontier“**
  Access to rare isotopes,
  → broader „nuclear gene pool“

- **„Sensitivity Frontier“**
  weak channels: strong physics

- **„Precision Frontier“**
  high count rates, new methods





Thank you very much!