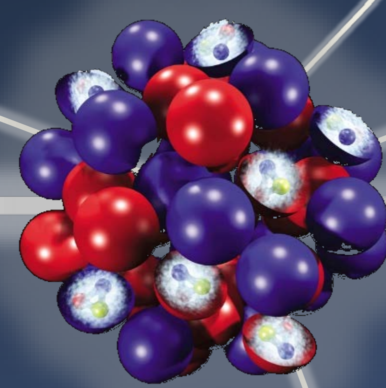
PHOTONS AND THE ATOMIC NUCLEUS: FROM FUNDAMENTAL RESEARCH TO APPLICATIONS

- Introduction
- Photon sources
- Some research highlights
- Outlook



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Review article:
A.Z., D. Balabanski, J. Isaak, and N. Pietralla
submitted to Prog. Part. Nucl. Phys.

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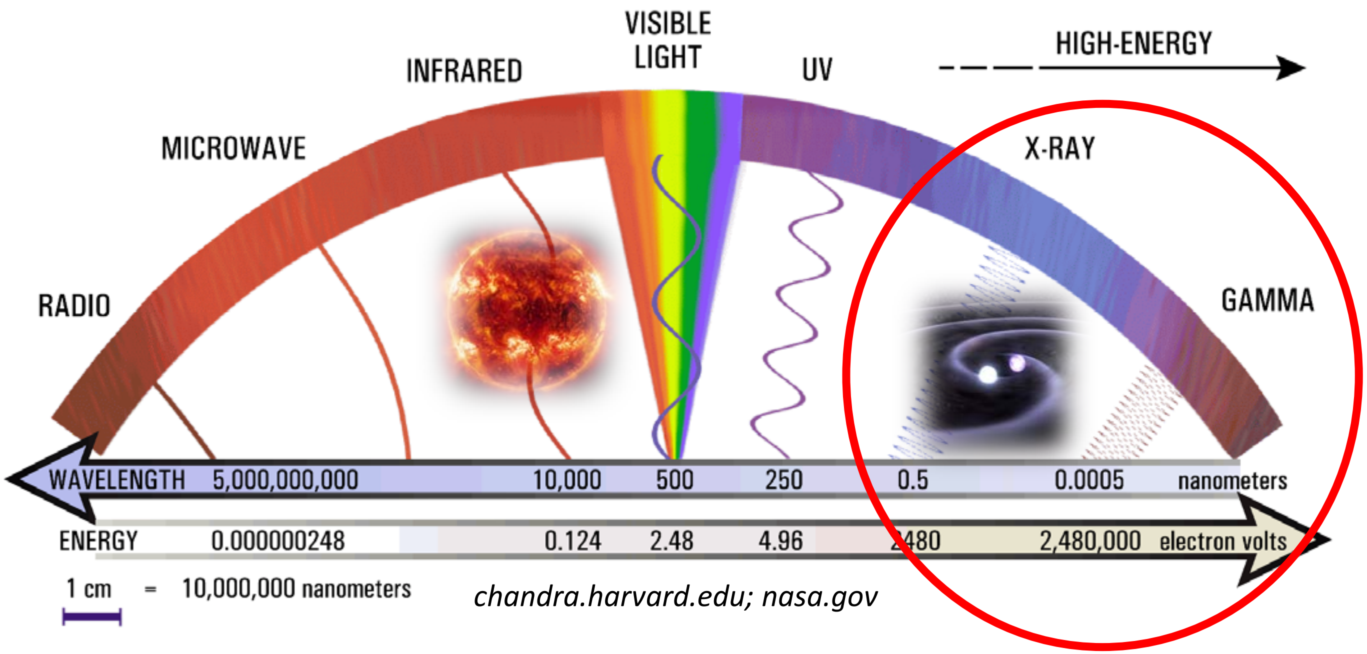
Photons in the MeV range



chandra.harvard.edu; nasa.gov

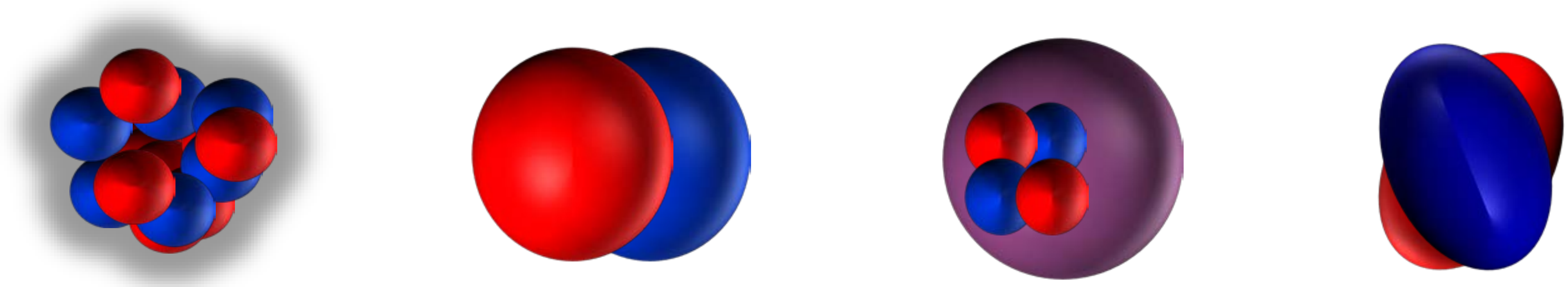
- MeV-photons are abundant in the universe
  (Planck photon bath, e.g., from supernovae, neutron star mergers)

  → photon-nucleus interaction important, e.g.,
  for the synthesis of elements - „Nuclear Astrophysics“

Photons in the MeV range

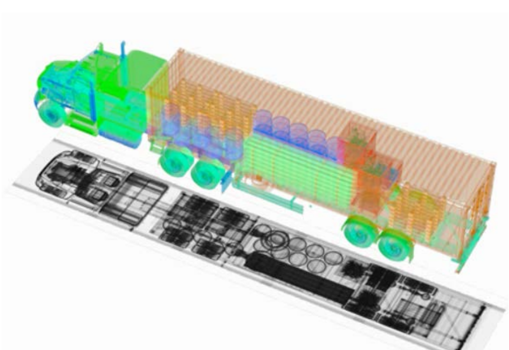
- MeV-photons are complementary to „standard“ probes in nuclear physics and excite nuclei very selectively

  → precision study of excitation modes in nuclei for Nuclear Structure and fundamental physics



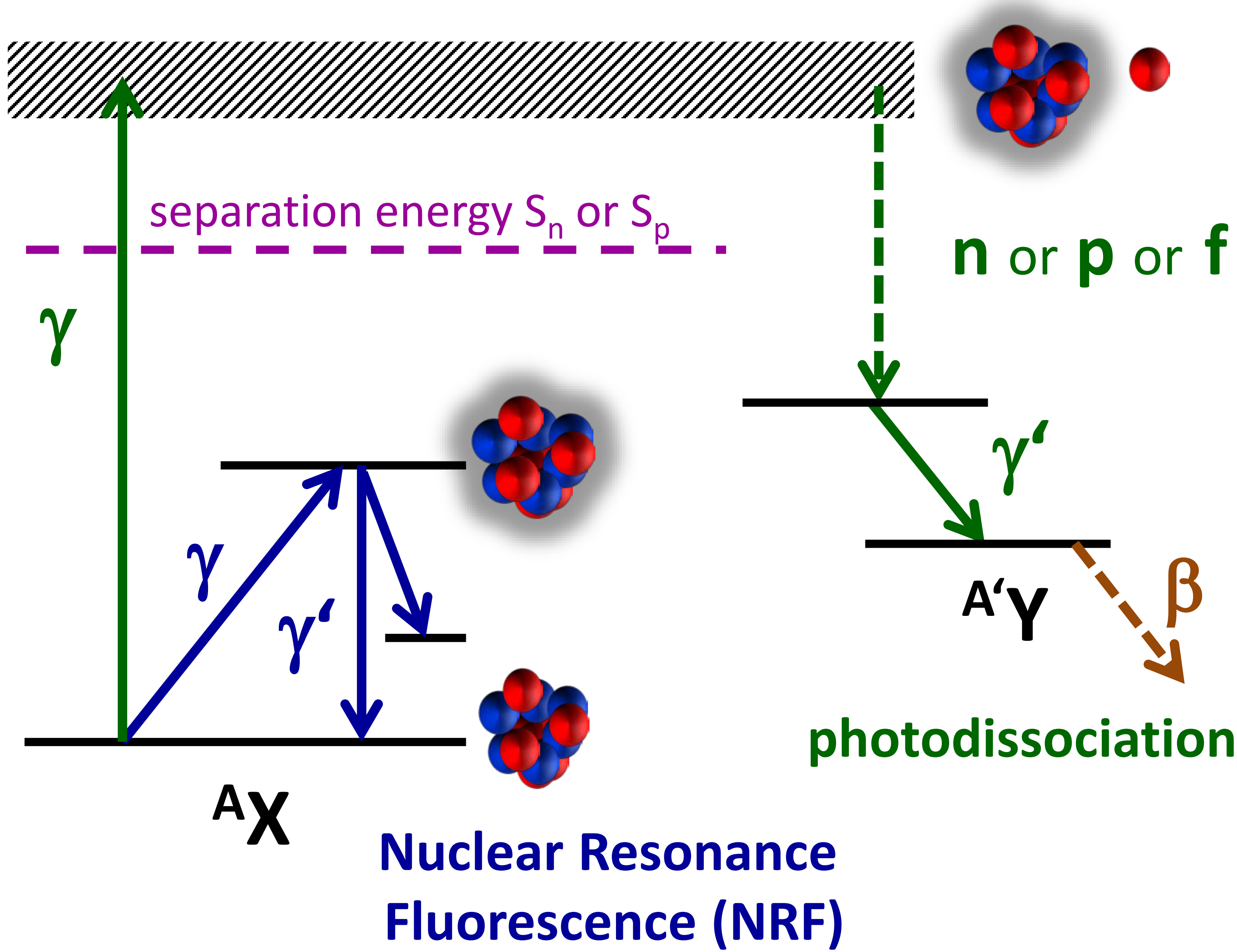
- MeV-photons are very penetrative

  → various applications (e.g. cargo inspection)



www.passportsystems.com

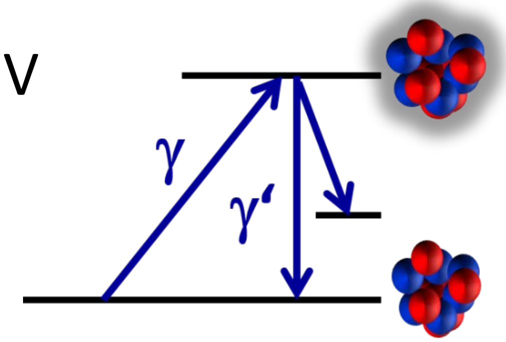
Photonuclear reactions



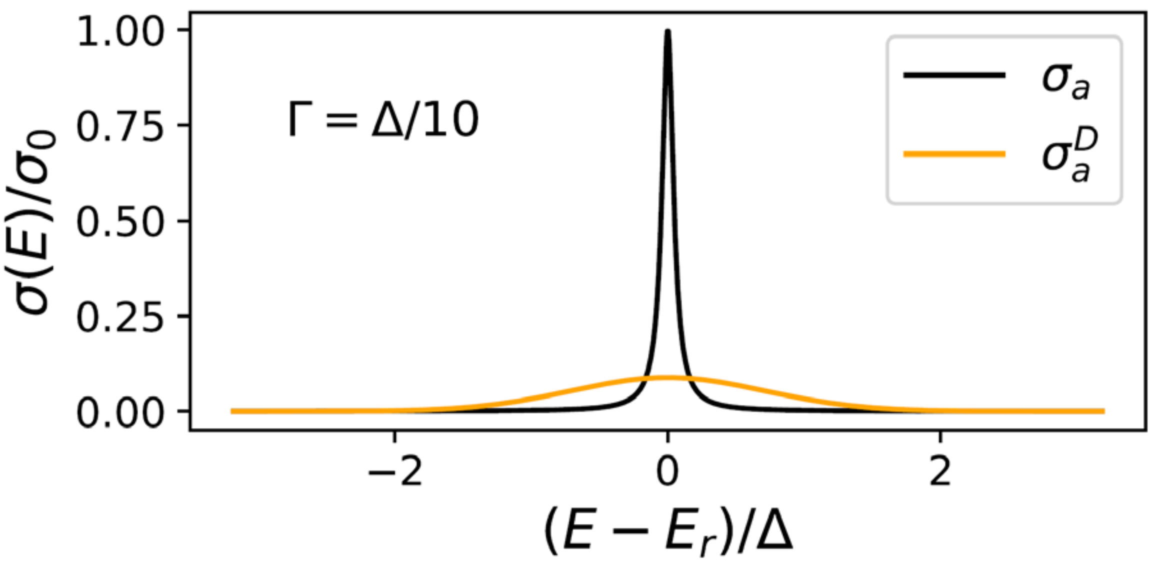
Some facts on Nuclear Resonance Fluorescence

- typical γ decay width Γ of bound levels: ≈ 0.1 eV

$$\Gamma = \frac{\hbar}{\tau} \approx \frac{658}{\tau / \mathrm{fs}} \mathrm{meV}$$



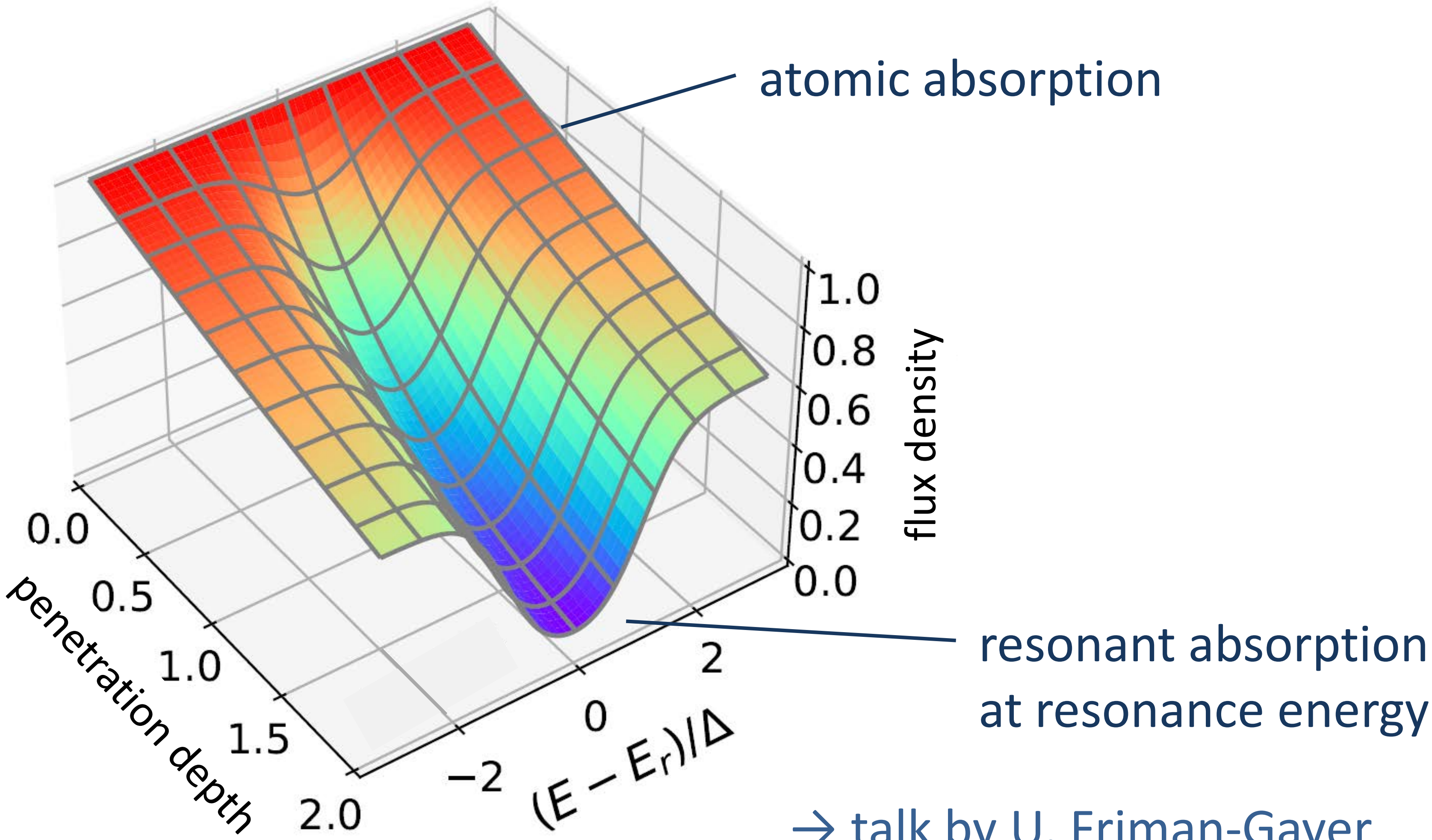
- thermal Doppler broadening Δ of line width ≈ eV



courtesy: U. Friman-Gayer

Some facts on Nuclear Resonance Fluorescence

- resonant „self absorption“ in the target material reduces the on-resonance photon flux density
- effect depends on penetration depth and resonance strength



→ talk by U. Friman-Gayer

Photonuclear reactions with real photons

- pure EM interaction
- spin selectivity (mainly E1, M1, E2 transitions)
- strength selectivity
- many model-independent observables, e.g.:
  - excitation energies ▪ spin quantum numbers
  - parity quantum numbers ▪ level widths
  - lifetimes ▪ decay branchings
  - multipole mixing ratios ▪ transition strengths

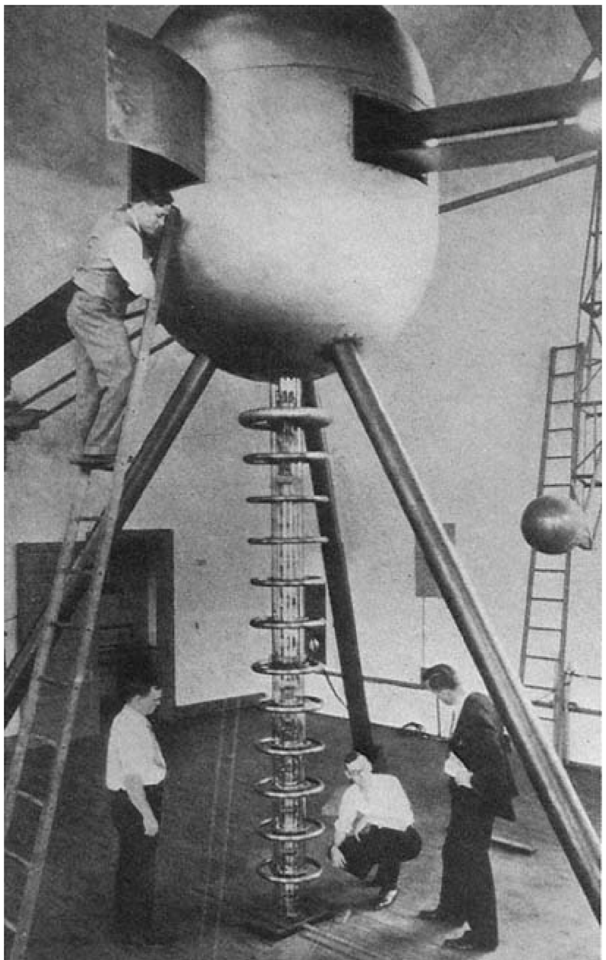
The first photonuclear experiment

1937:

Atomumwandlungen durch γ-Strahlen.

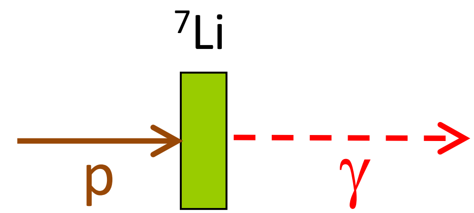
Von **W. Bothe** und **W. Gentner** in Heidelberg.

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



http://ark.cdlib.org/ark:/13030/ft5s200764/

<u>photon source:</u>



^{7}Li(p,γ)^{8}Be @ 600 kV van de Graaff generator

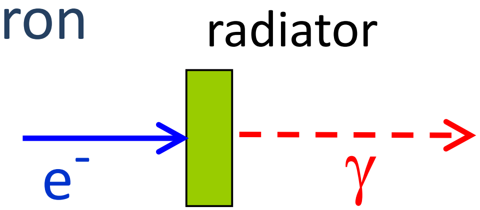
Subsequent (γ,n) reactions produced radioactive isotopes.

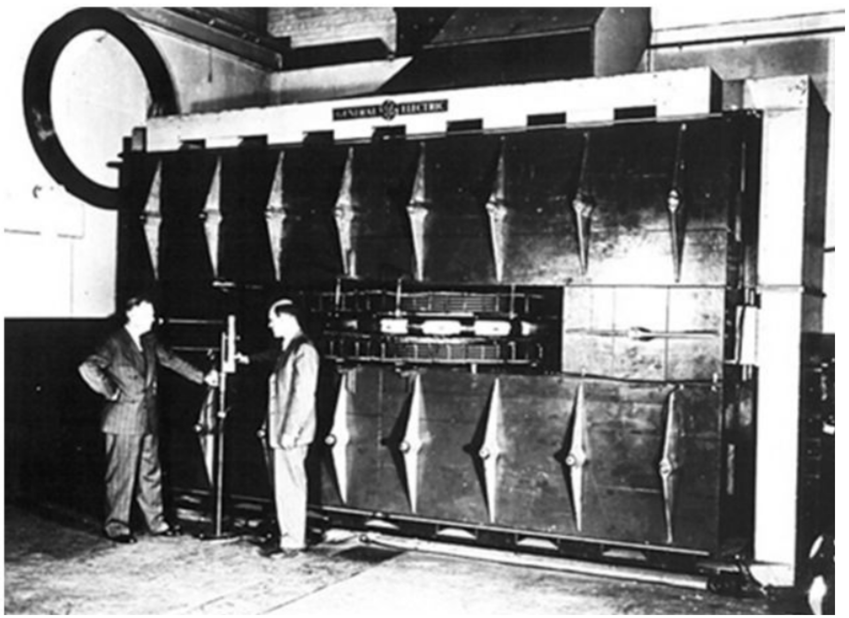
→ „giant resonance“

Photons from bremsstrahlung

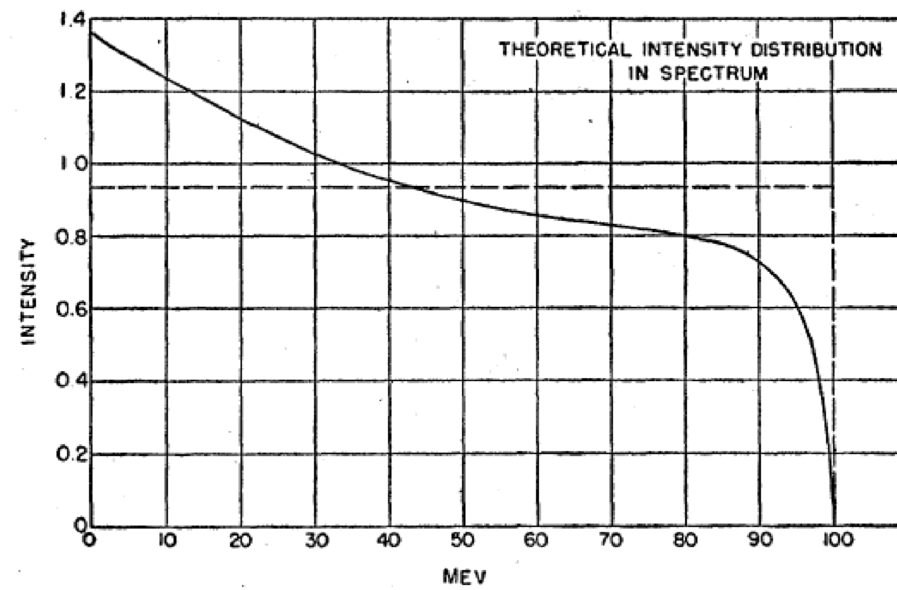
1947: G.C. Baldwin and G.S. Klaiber

bremsstrahlung from 100 MeV betatron





From: A.M. Sessler, LBNL



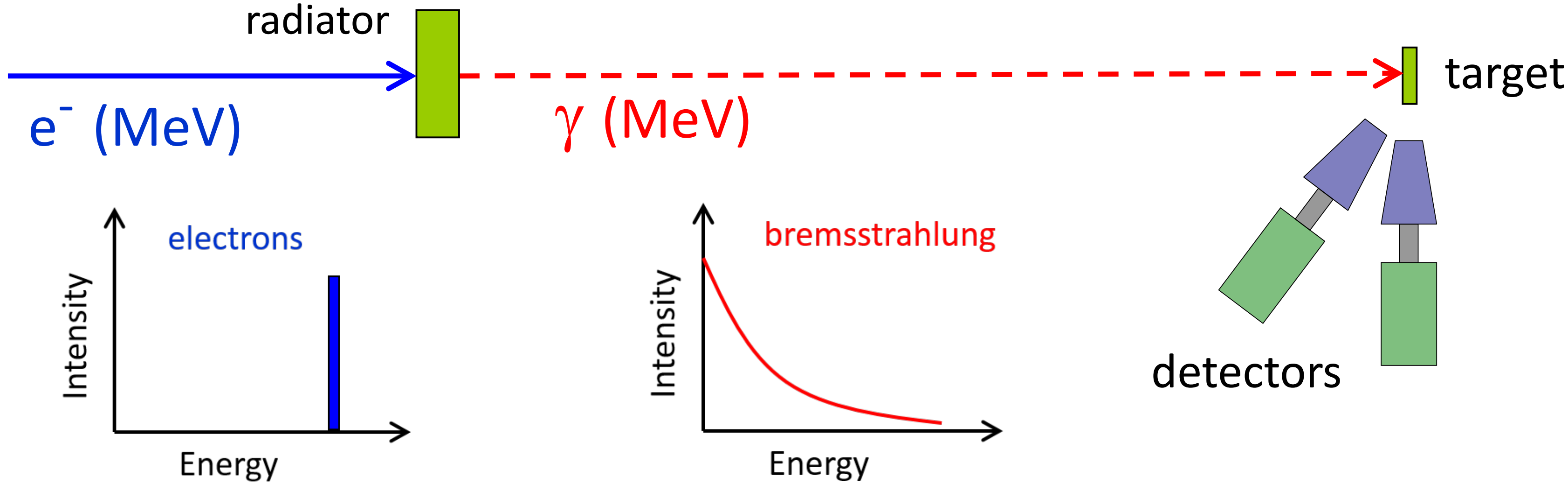
G.C. Baldwin and G.S. Klaiber, Phys. Rev. ***71*** *(1947) 3*

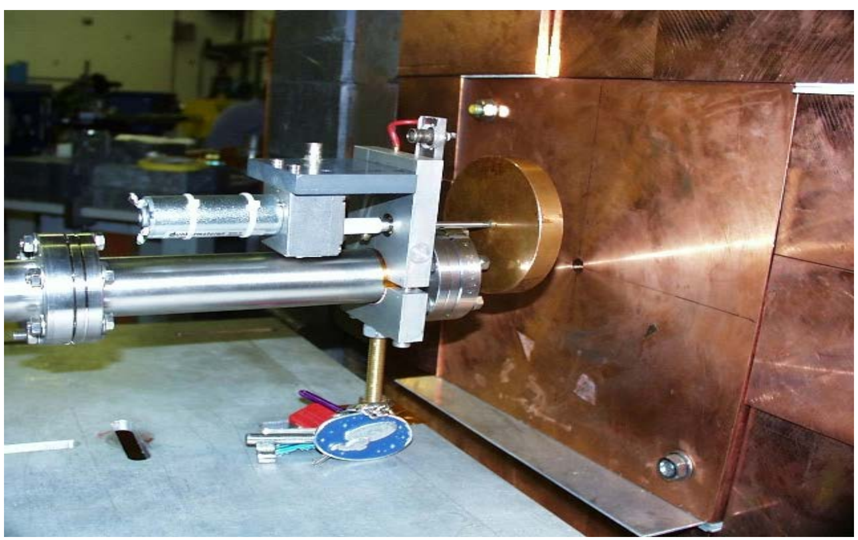
1969: F.R. Metzger et al.

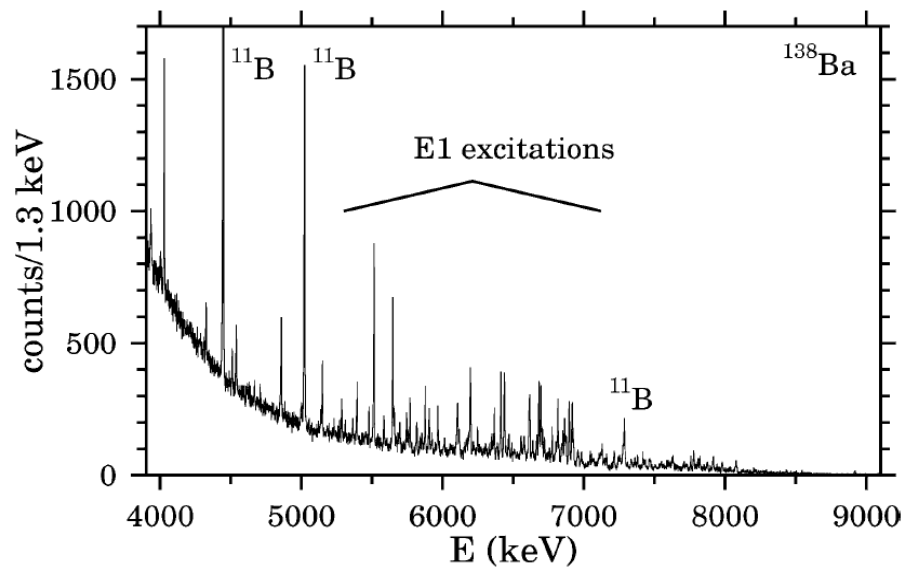
bremsstrahlung from van de Graaff accelerator for electrons

High resolution Nuclear Resonance Fluorescence (NRF)

1980s, 1990s: U. Kneissl et al., A. Richter et al.







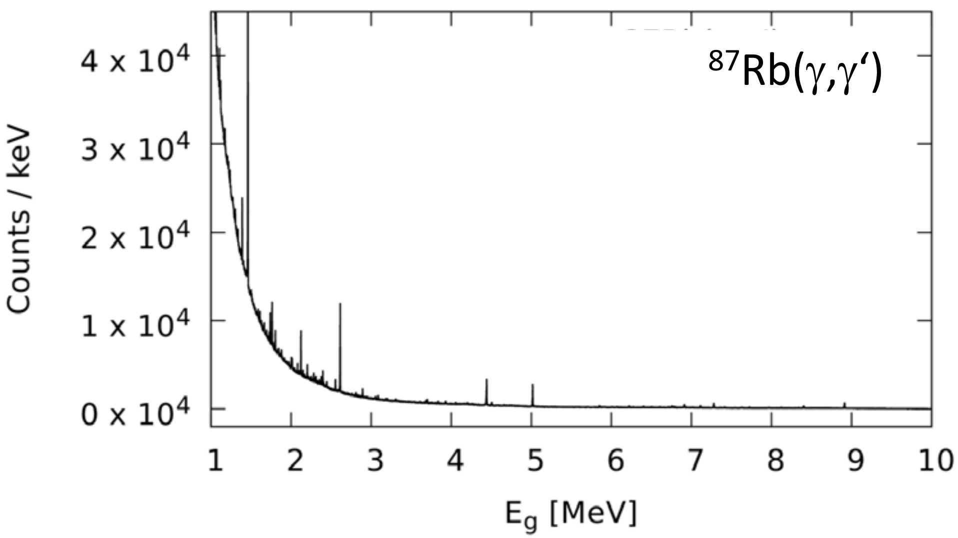
*Review: U. Kneissl, H.H. Pitz, and A.Z., PPNP **37** (1996) 349*

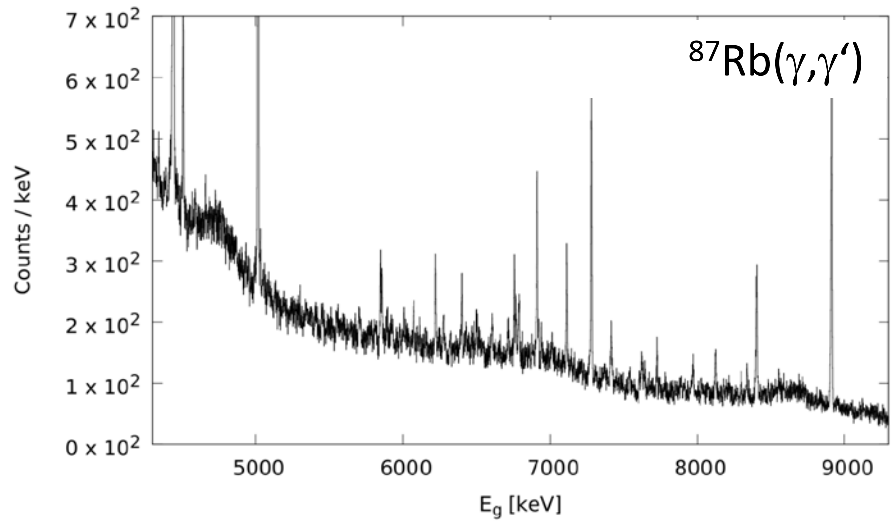
Some bremsstrahlung facilities

- **HVRL@MIT:** $E(e^-) < 3.5$ MeV, $I_{max} \approx 100$ μA
- **DHIPS@TU Darmstadt**: $E(e^-) < 10$ MeV, $I_{max} \approx 60$ μA
- **γELBE@HZDR**: $E(e^-) < 13$ MeV, $I_{max} \approx 1$ mA
- **MT-25@JINR**: $E(e^-) < 25$ MeV, $I_{max} \approx 20$ μA
- **PRISM@LLNL**: $E(e^-) < 25$ MeV, $I_{max} \approx 30$ μA
- **MT-25@CAS**: $E(e^-) < 25$ MeV, $I_{max} \approx 20$ μA
- **IAC@Idaho State University**: $E(e^-) < 40$ MeV, $I_{max} \approx 240$ μA
- **TARLA@Ankara**: $E(e^-) < 40$ MeV, $I_{max} \approx 1.5$ mA (from 2022 on)
- **NSC KIPT@Kharkov**: $E(e^-) < 95$ MeV, $I_{max} \approx 70$ mA (pulsed)

Limitations using bremsstrahlung

- no selectivity of excitation energy („white“ photon spectrum)
- strongly increasing continuous background at low energies
- background from γ decays of higher lying states
- beam only very weakly polarized (and only using a thin radiator)
- large amount (100s of mg) of target material needed

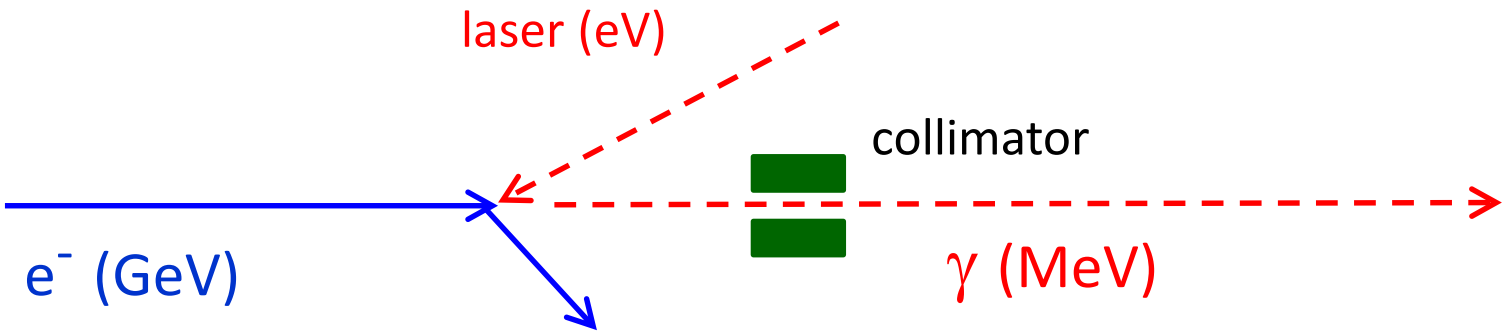




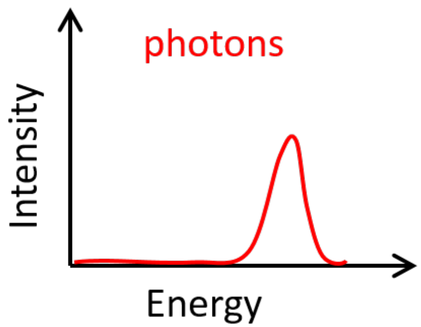
*J. Wilhelmy et al., PRC **102** (2020) 044327*

Photons from Laser Compton Backscattering (LCB)

1963: R. H. Milburn; F.R. Arutyunian and V.A. Tumanian



- polarized beam
- quasi-monoenergetic
- tunable energy



$$E_\gamma \approx 4 \cdot \gamma_{e^-}^2 \cdot E_{laser}$$

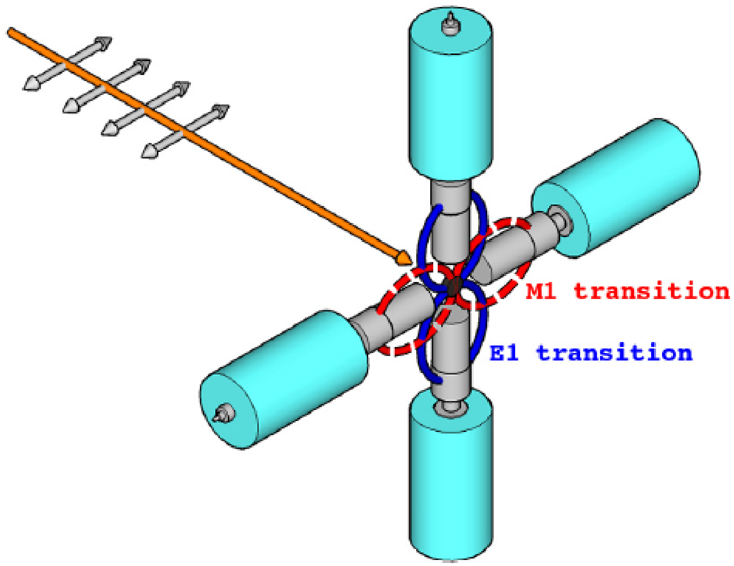
$$\left(\gamma_{e^-} = \frac{E_{e^-}^{kin}}{m_{e^-} c^2} + 1 \right)$$

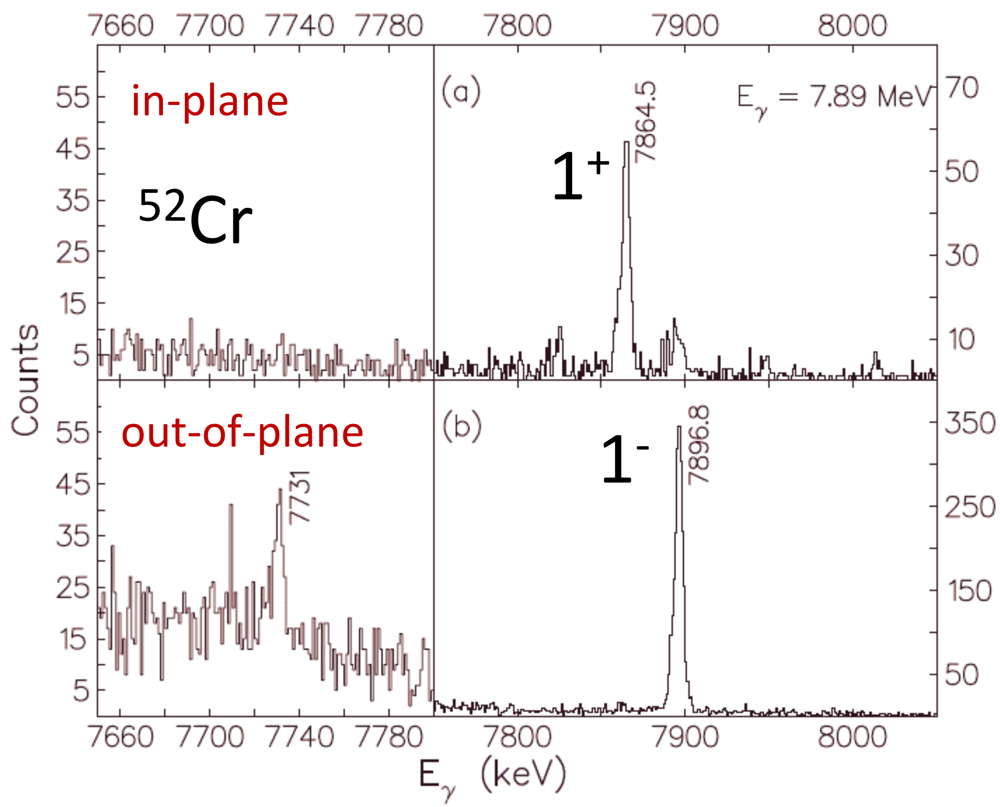
→ talks by C. Barty, C. Howell, Y. K. Wu, B. Hornberger

*R.H. Milburn, PRL **10** (1963) 75*
*F.R. Arutyunian and V.A. Tumanian, PL **4** (1963) 176*

Polarization of LCB beam

parity determination by measuring asymmetries

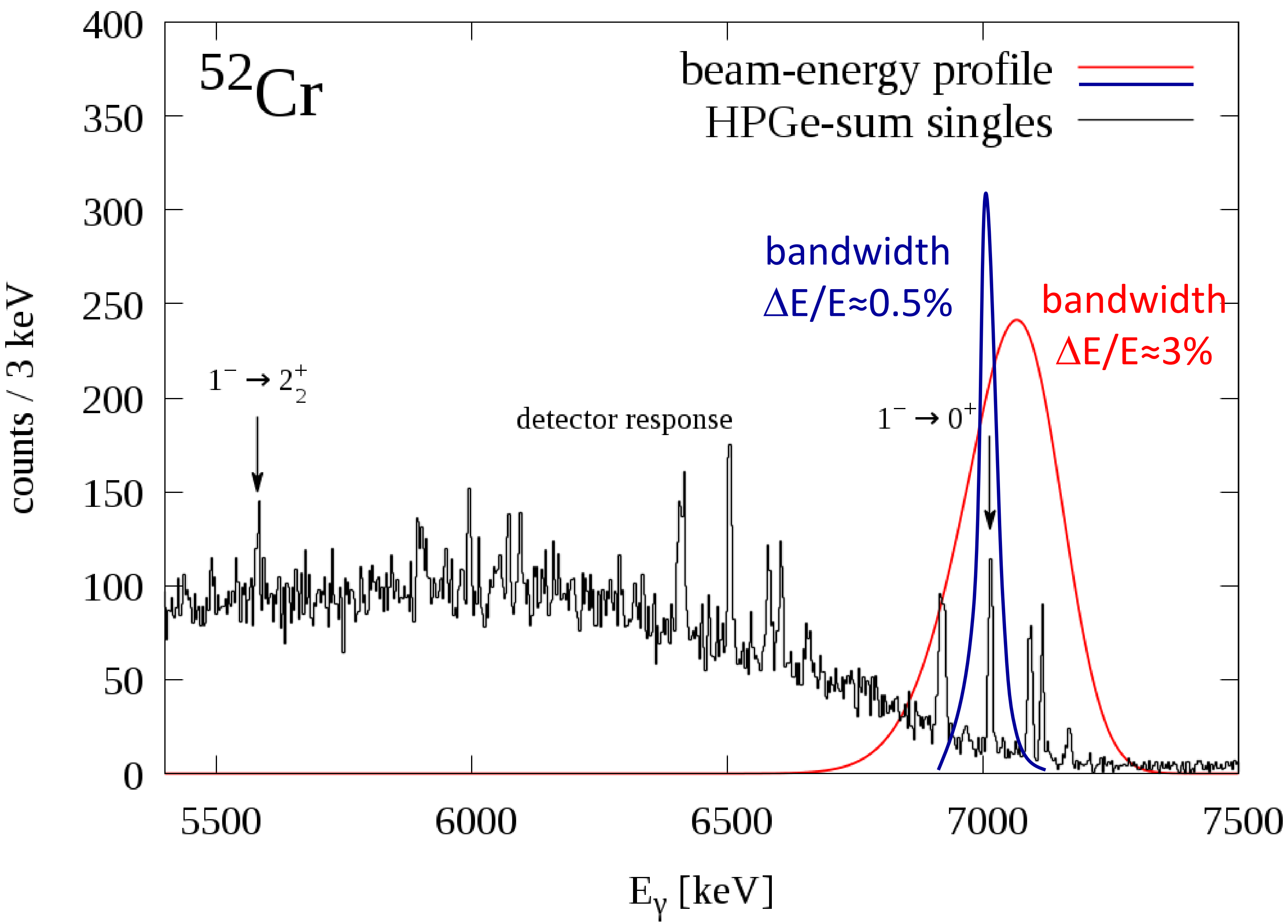




*J. Beller et al., PLB **741** (2015) 128*

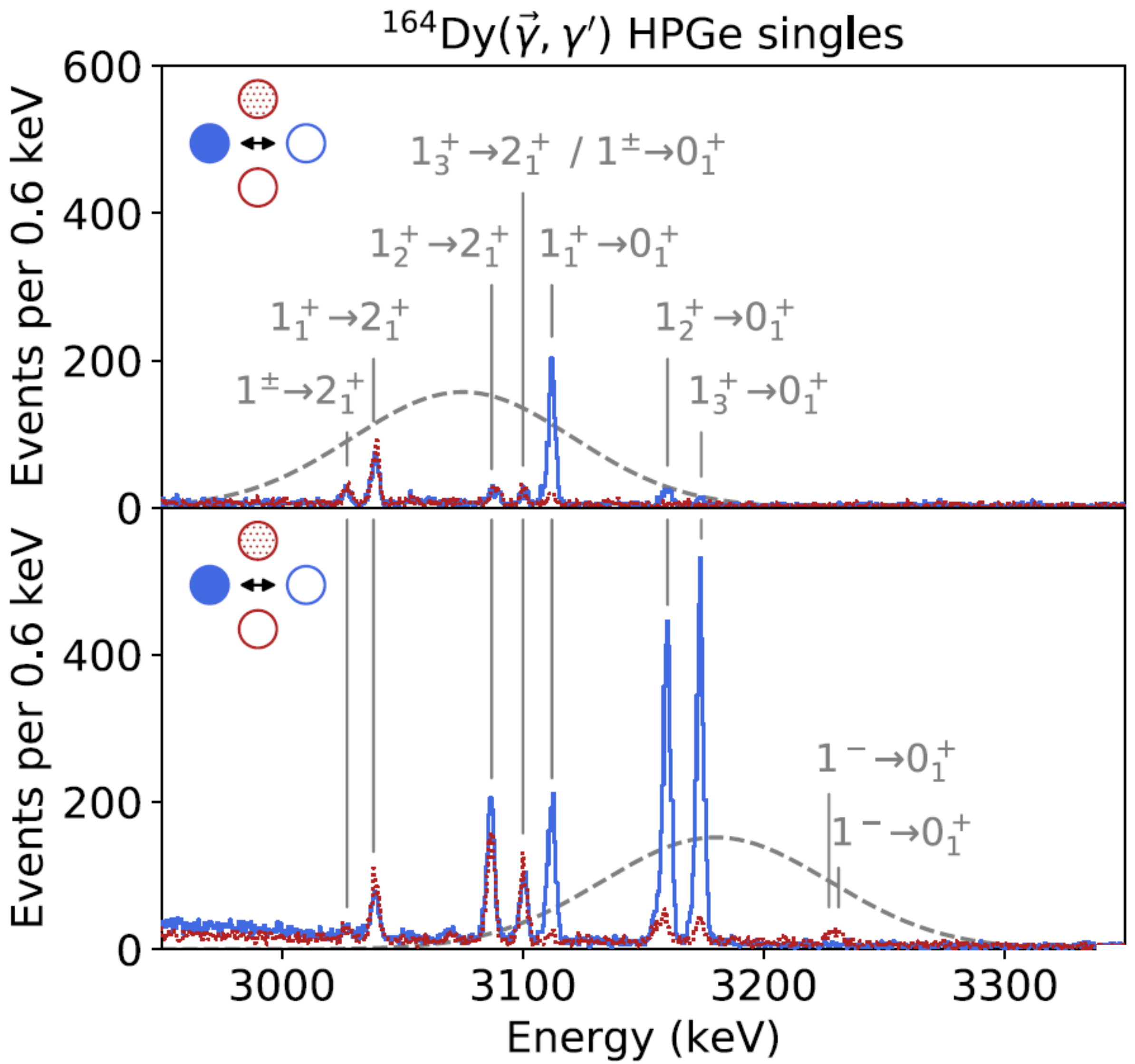
*Krishichayan et al., PRC **91** (2015) 044328*

Energy profile of LCB beams



*J. Wilhelmy et al., PRC **98** (2018) 034315*

Tunable energy of LCB beams



*T. Beck et al., PRL **125** (2020) 092501*

Some low-energy LCB facilities

XGLS@CAS, Xi`an: $E_{max}(\gamma) < 3$ MeV,
N_γ on target $< 10^8$/s , $\Delta E/E \approx$ 1-10%

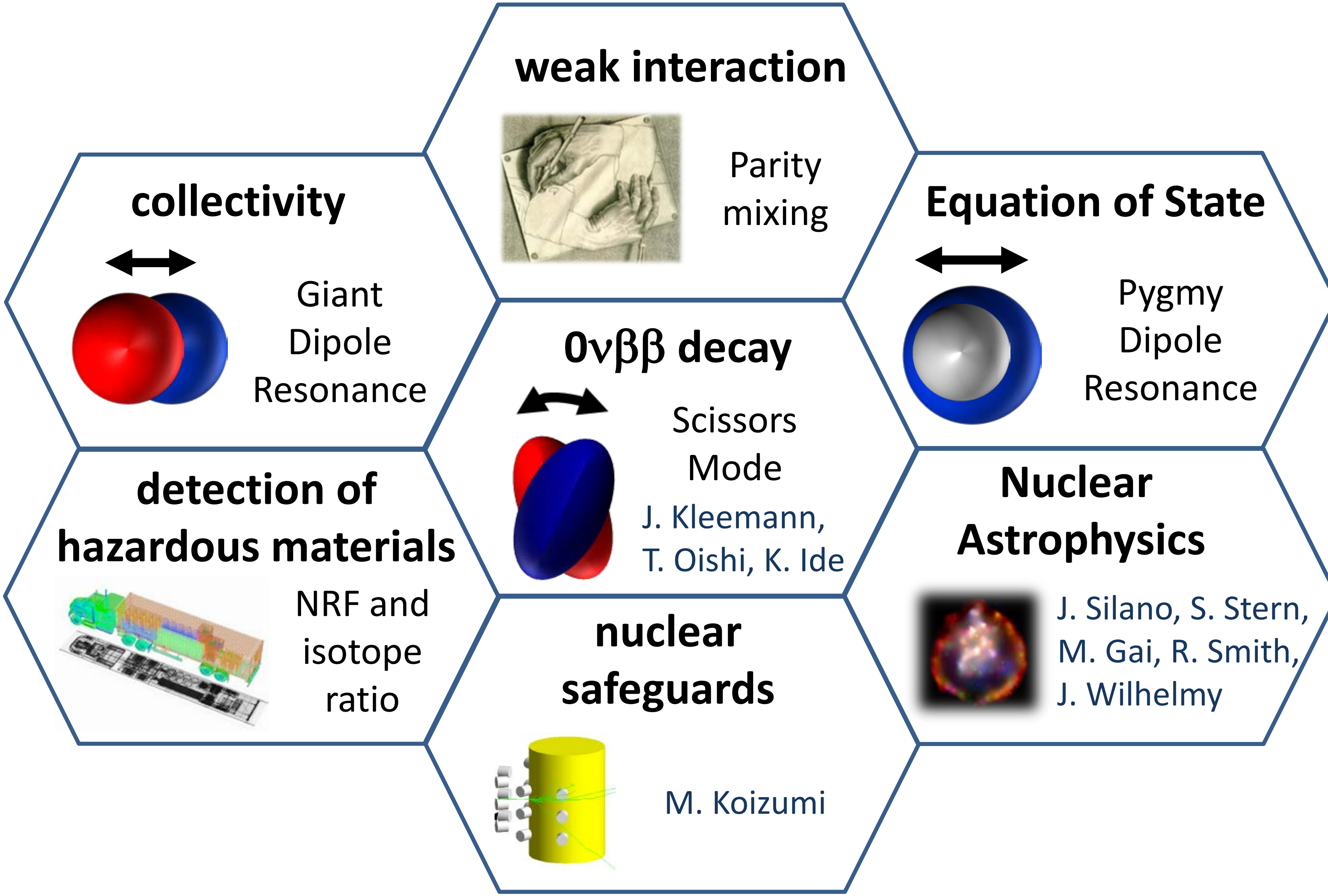
UVSOR-III@NINS, Okazaki: $E_{max}(\gamma) < 5.4$ MeV,
N_γ on target $< 10^5$/s , $\Delta E/E \approx$ 2.9%

VEGA@ELI-NP: $E_{max}(\gamma) < 19.5$ MeV,
N_γ on target $\approx 10^8$/s , $\Delta E/E <$ 0.5% (from 2023)

SLEGS@CAS, Shanghai: $E_{max}(\gamma) < 20$ MeV,
N_γ on target $< 10^7$/s , $\Delta E/E <$ 5% (from 2022)

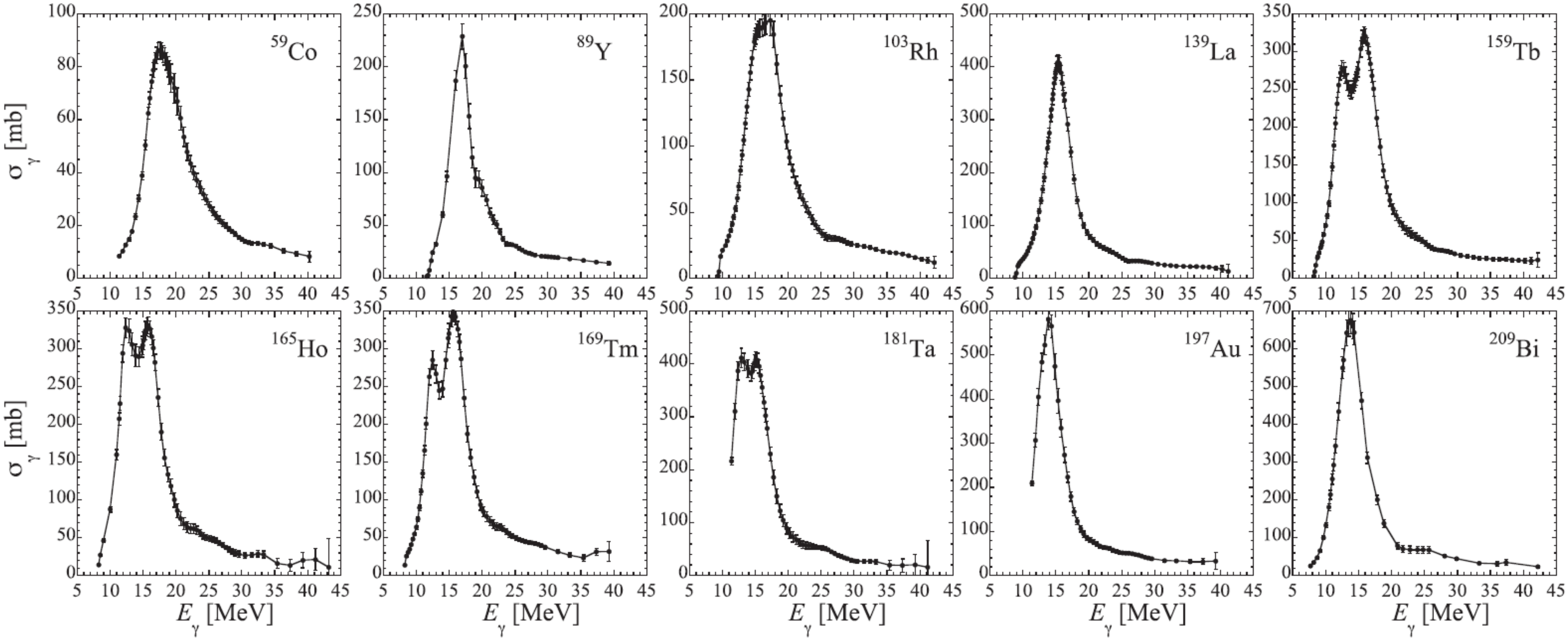
HIγS@TUNL: $E_{max}(\gamma) < 100$ MeV,
N_γ on target $< 10^9$/s , $\Delta E/E \approx$ 0.8-10%

Selection of research highlights



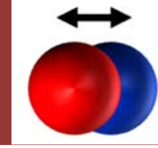
Giant Dipole Resonance (GDR)

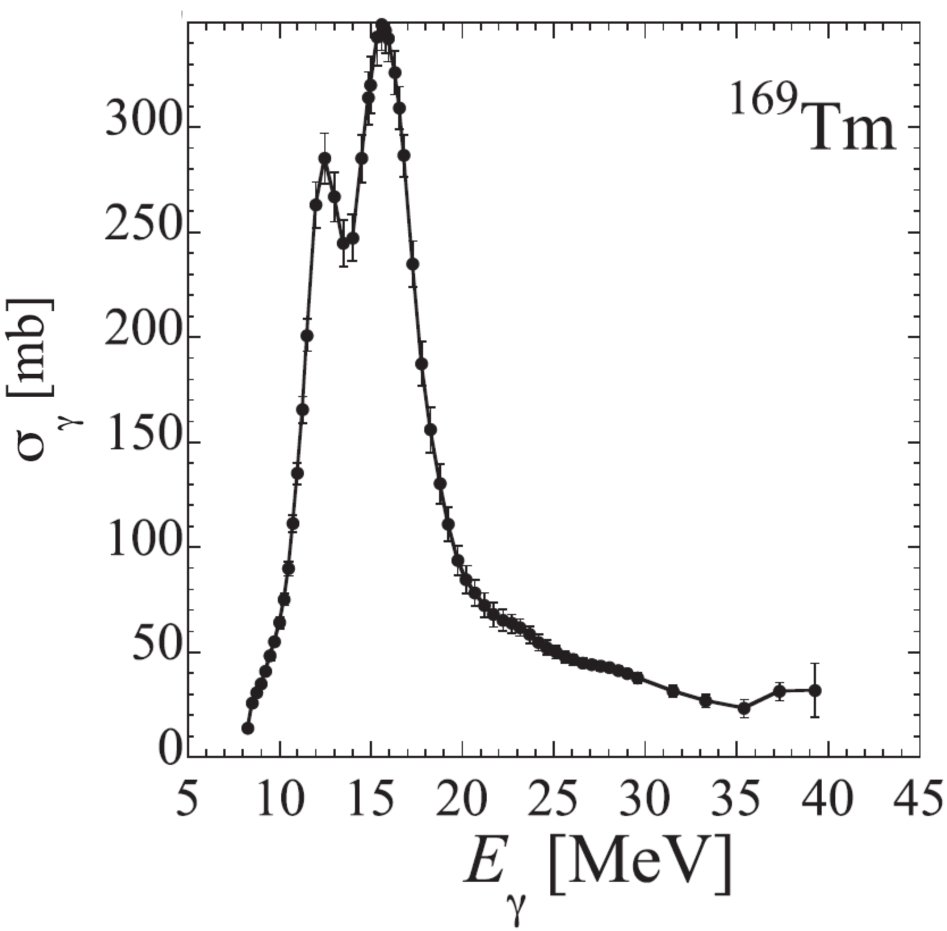
- GDR exhausts about 100% of the isovector E1 sum rule
- 1970's: Saclay and Livermore studies with photons from positron annihilation in flight
- fine structure in low energy tail → LCB beam at TERAS/ETL and at NewSUBARU (H. Utsunomiya et al., T. Kondo et al.)



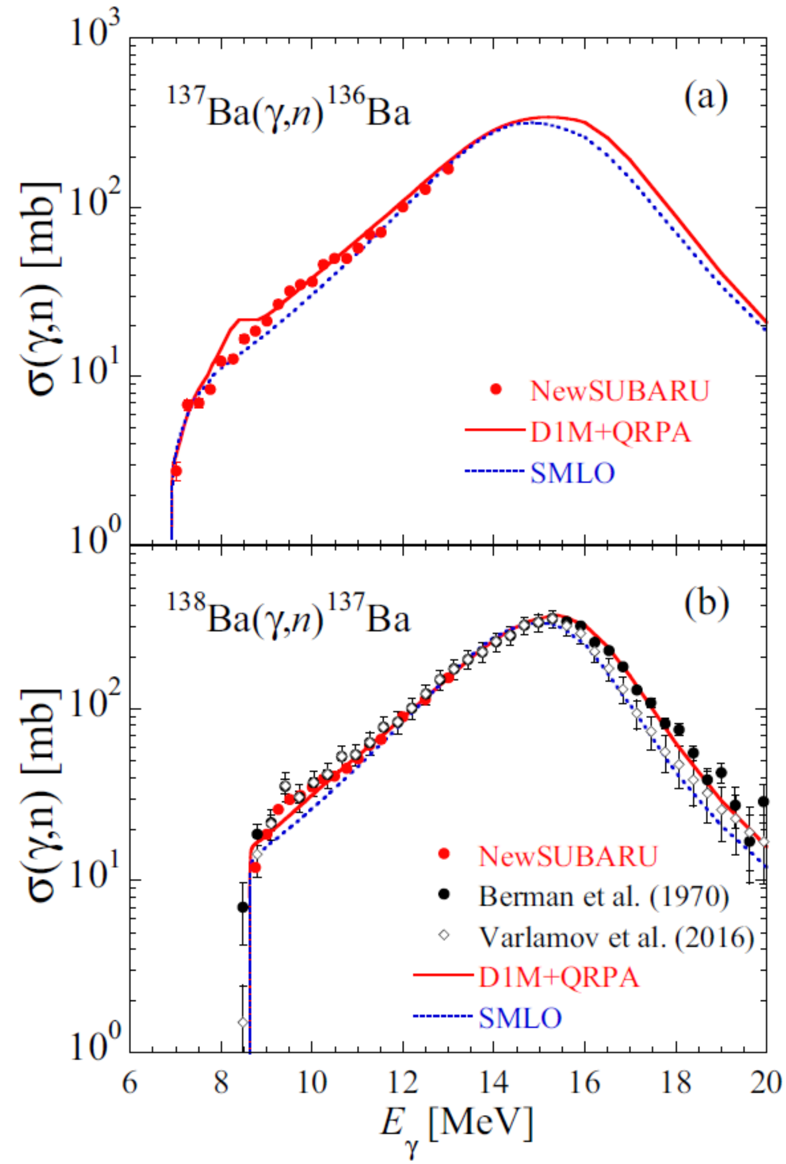
S. Goriely et al., Phys. Rev. C ***102*** *(2020) 064309*

Giant Dipole Resonance (GDR)





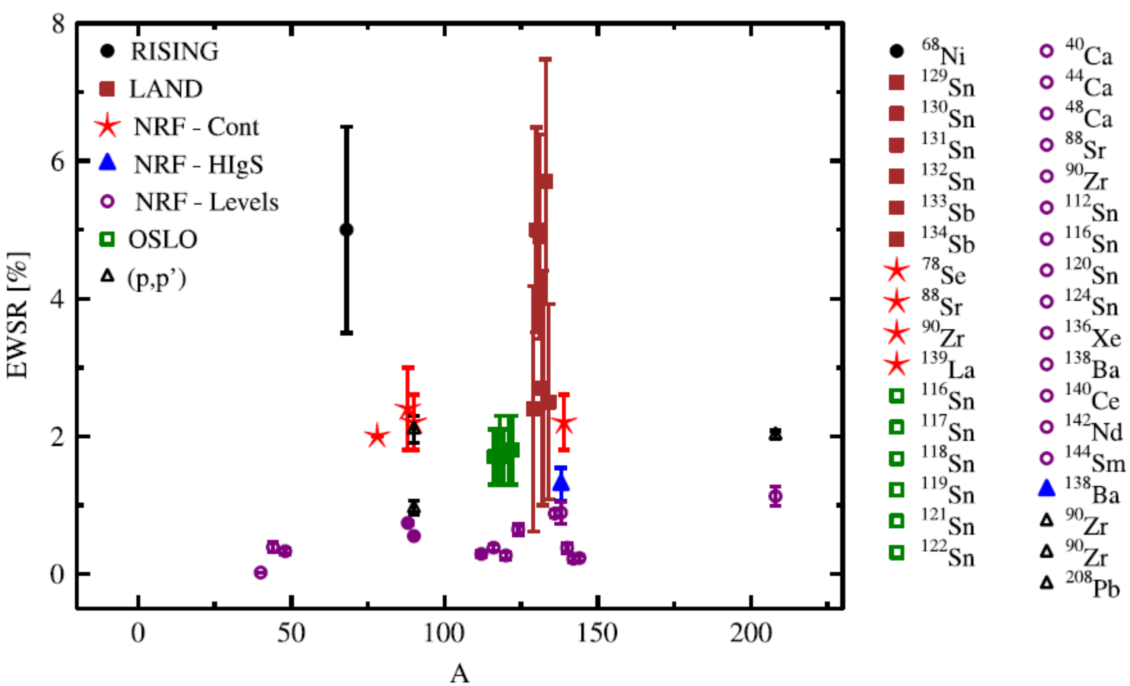
S. Goriely et al., PRC **102** (2020) 064309



H. Utsunomiya et al., PRC **100** (2019) 034605

Pygmy Dipole Resonance (PDR)

- first detected by Bartholemew in the 1950‘s (neutron capture)
- PDR exhausts about 1% of the isovector E1 sum rule
- scaling with neutron excess (exotic n-rich nuclei!)
- important for symmetry parameter in Equation of State (EoS)

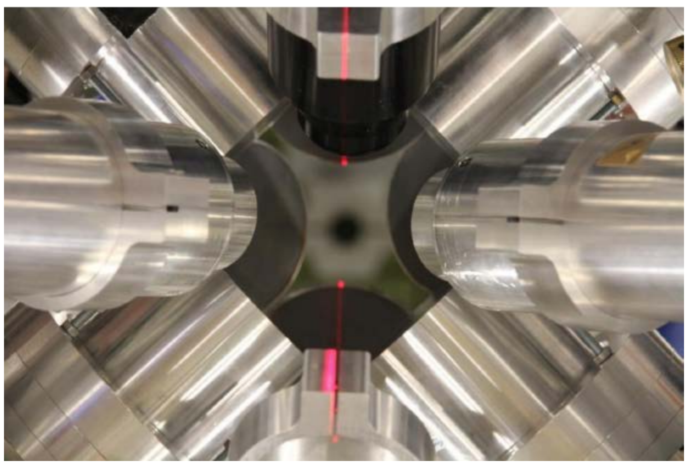


D. Savran, T. Aumann, and A. Zilges, Prog. Part. Nucl. Phys. ***70*** *(2013) 210*

Pygmy Dipole Resonance (PDR)

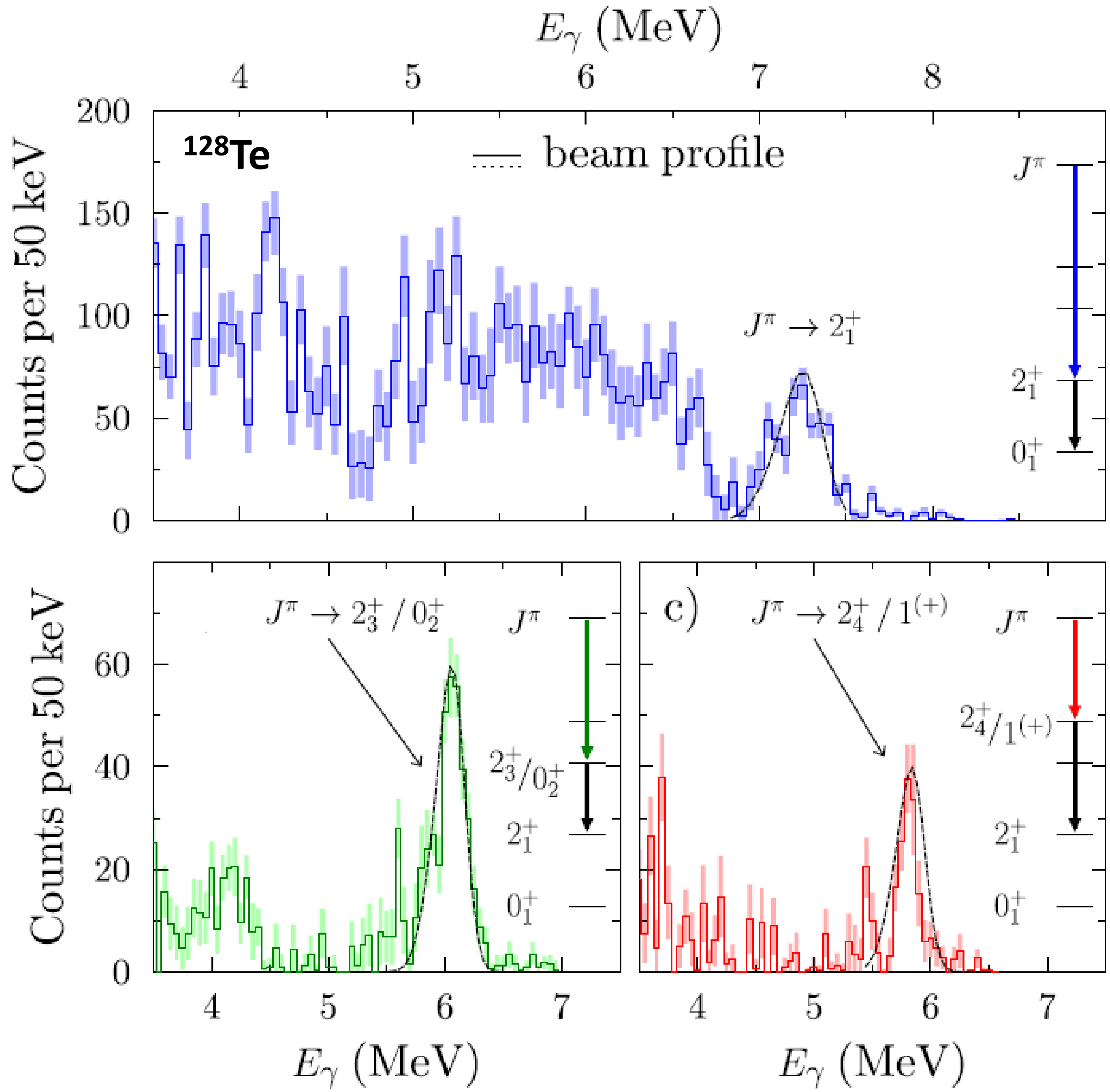
$(\vec{\gamma}, \gamma'\gamma'')$ coincidence experiments:

γ^3 setup @HIγS



*B. Löher et al., NIM A **723** (2013) 136*

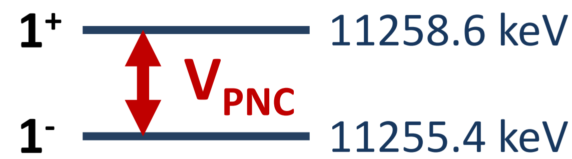
→ talks by J. Isaak, M. Müscher

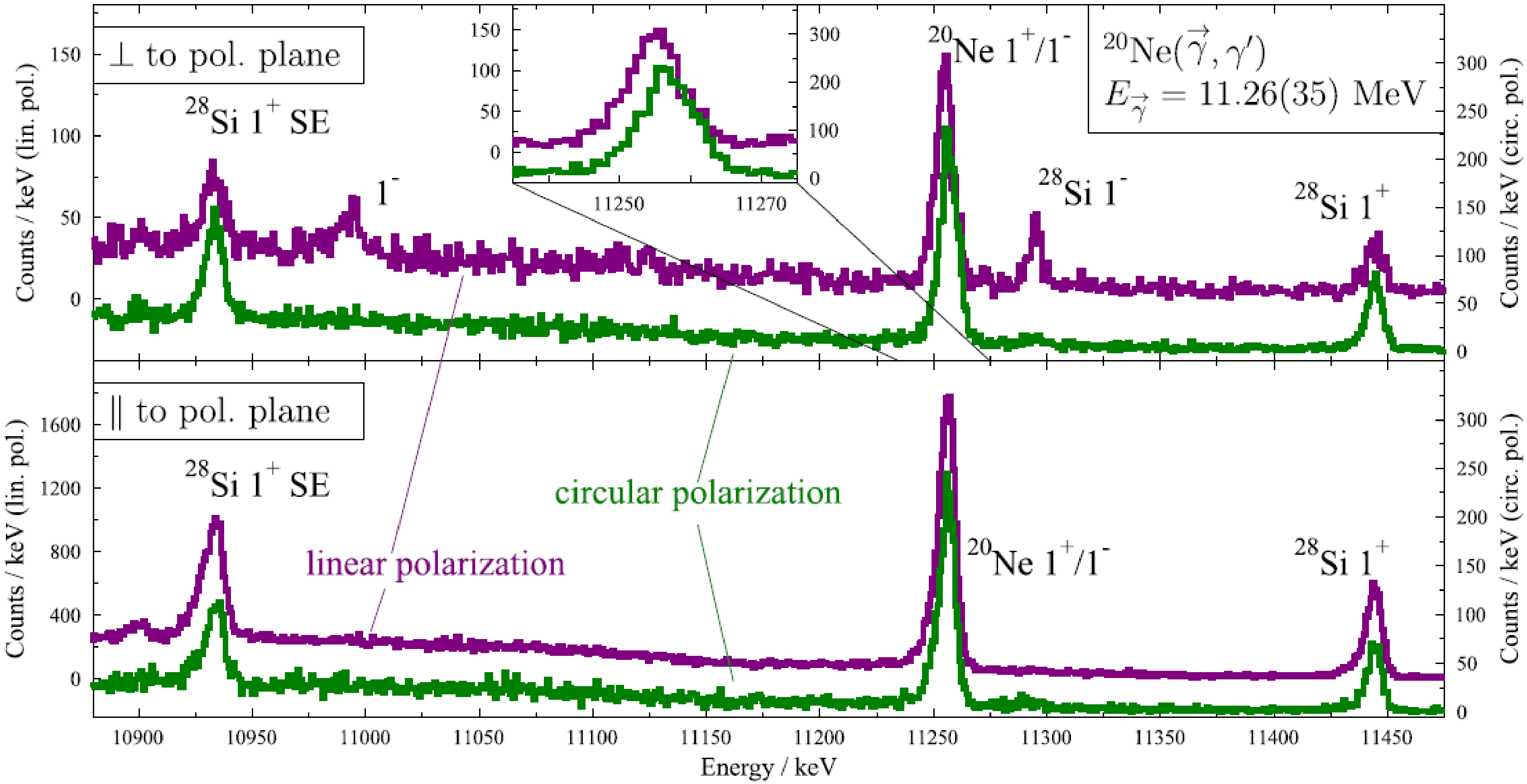


*J. Isaak et al., Phys. Lett. B **788** (2019) 225 and PRC **103** (2021) 044317*

Weak meson-nucleon coupling

- parity doublet in ^{20}Ne at 11.26 MeV
- use polarization of LCB photon beam (linear vs. circular) → level order, ΔE, I_{S+}/I_{S-}

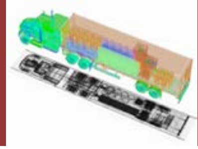




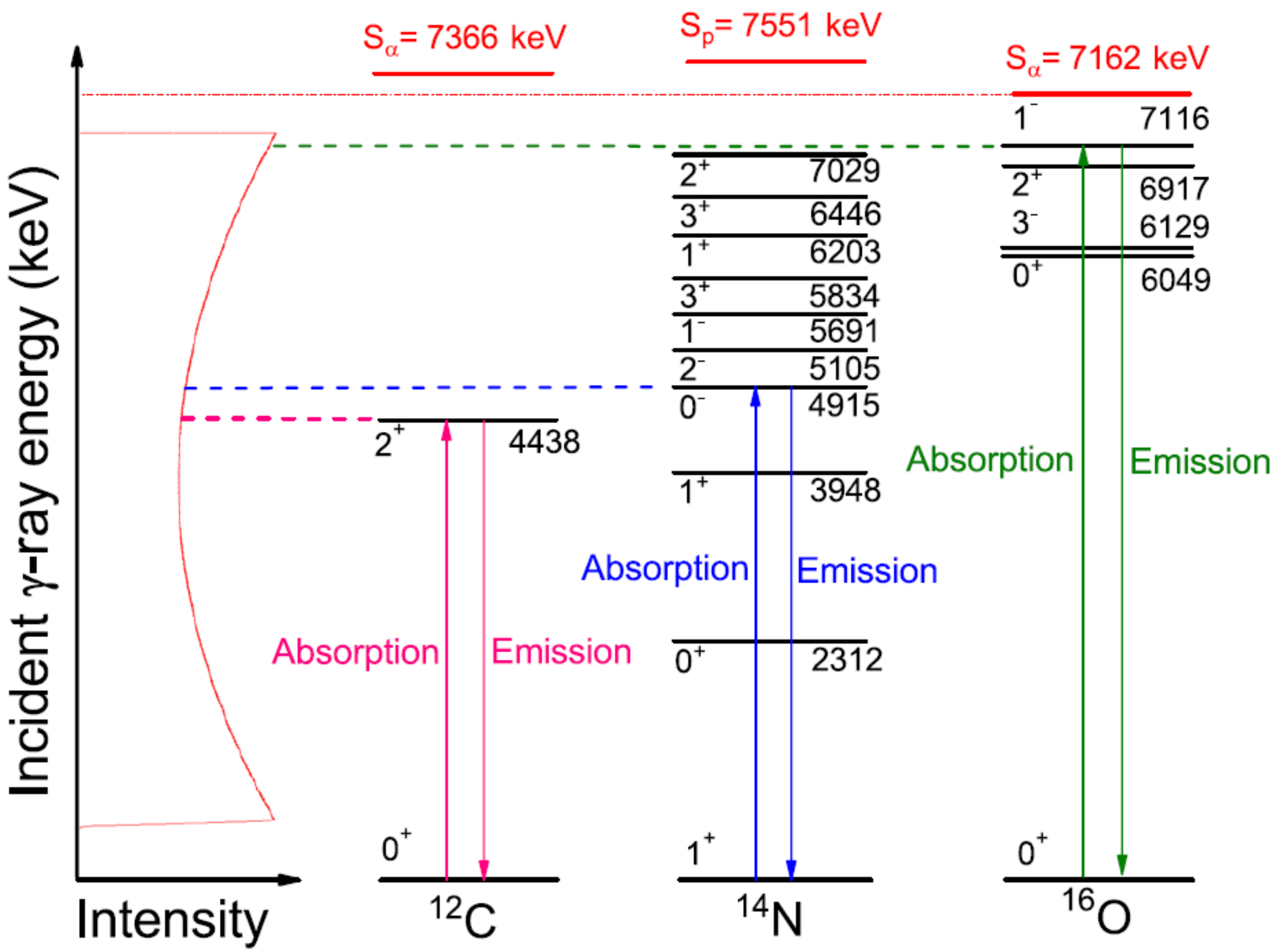
→ talk by V. Werner

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

Drug inspection by photon scattering



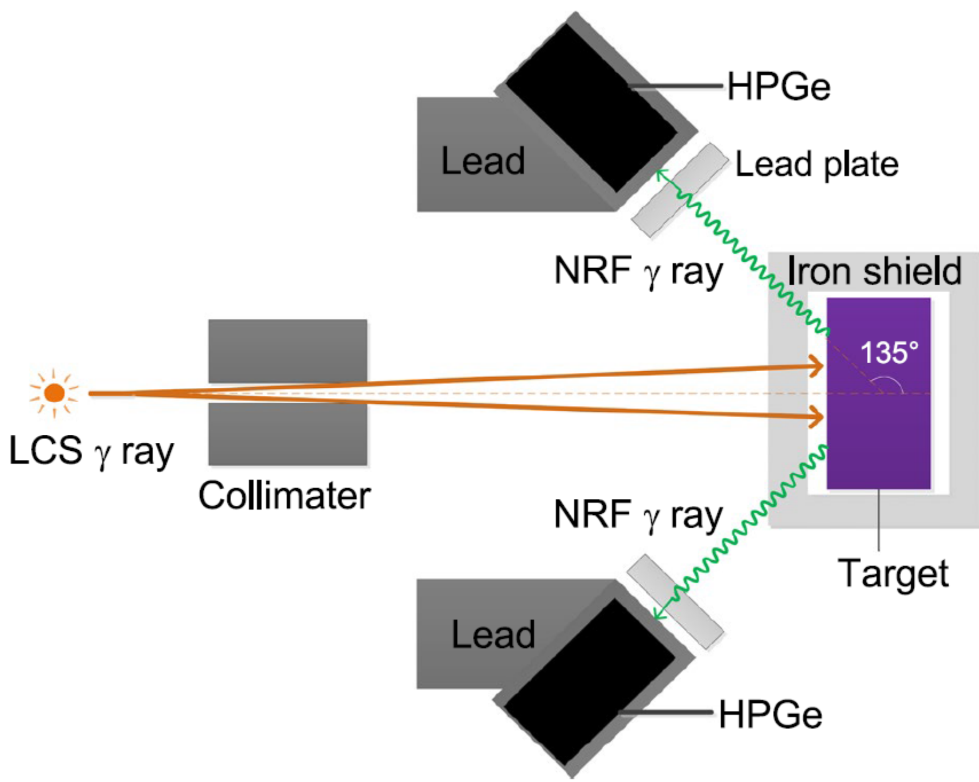
- identification of isotopes by their nuclear fingerprint

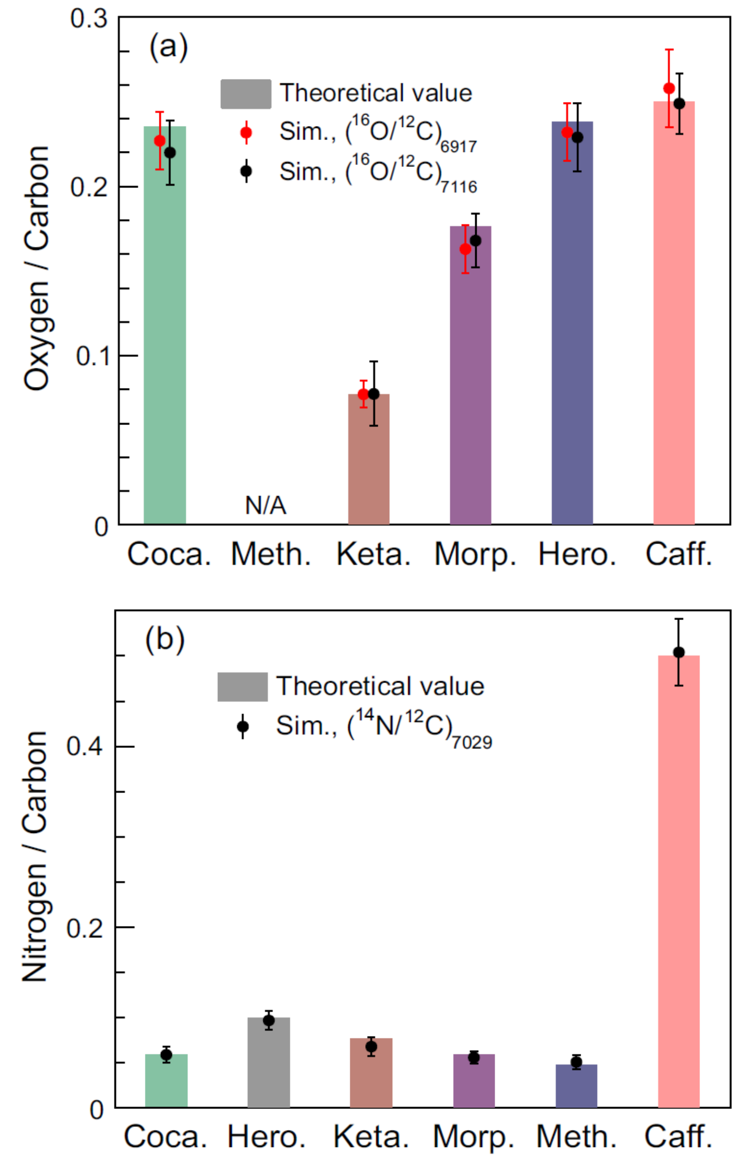


H. Lan et al., nature Sci. Rep. ***11*** *(2021) 1306*

Drug inspection by photon scattering

- ratios identify different compounds
- Monte Carlo simulation





→ talk by K. Olshanoski

H. Lan et al., nature Sci. Rep. ***11*** *(2021) 1306*

MeV photons as an invaluable tool for basic research and applications

ingredient I:

different photon sources
(intensity, bandwidth, beam spot size, polarization, dimension)

1^{st} generation: radioactive atoms, (x,γ) reactions

2^{nd} generation: bremsstrahlung, e^+ annihilation

3^{rd} generation: Laser Compton Backscattering

4^{th} generation: LCB with superconducting ERL, multi-bunch

5^{th} generation: Gamma Factory (partially stripped ions)

MeV photons as an invaluable tool for basic research and applications

ingredient II:

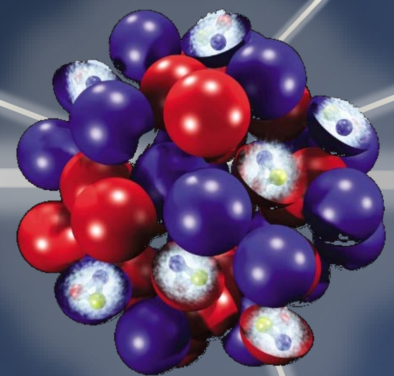
optimized detection capabilities

gamma detection (γ^3@HIγS, Clover-Share, ELIADE@ELI-NP, …)
neutron detection (BLOWFISH, ELIGANT, …)
charged particle detection (SIDAR, ELISSA, O-TPC, ELITPC, …)

ingredient III:

smart researchers with good ideas

Photons and the atomic nucleus:
From fundamental research to applications



D. Balabanski, J. Isaak,
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