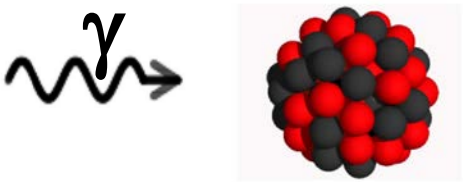
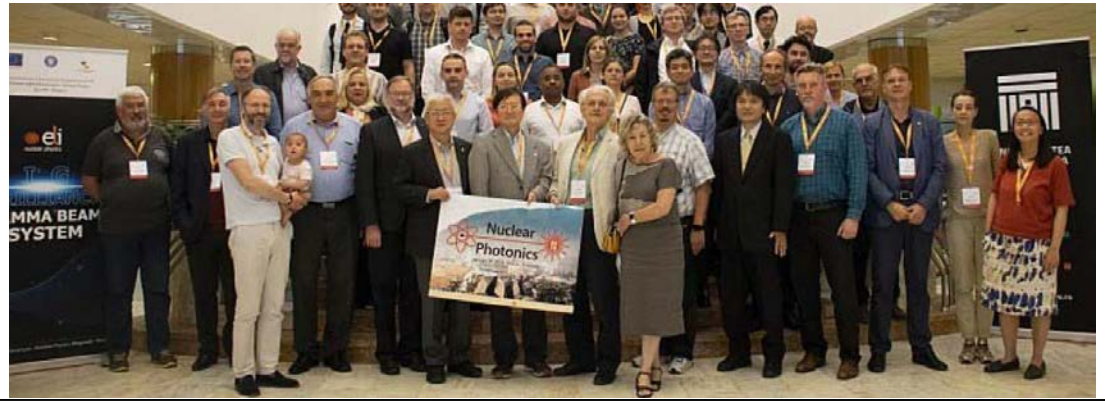
Photo-Nuclear Physics with PERLe

Norbert Pietralla, TU Darmstadt

Nuclear Photonics

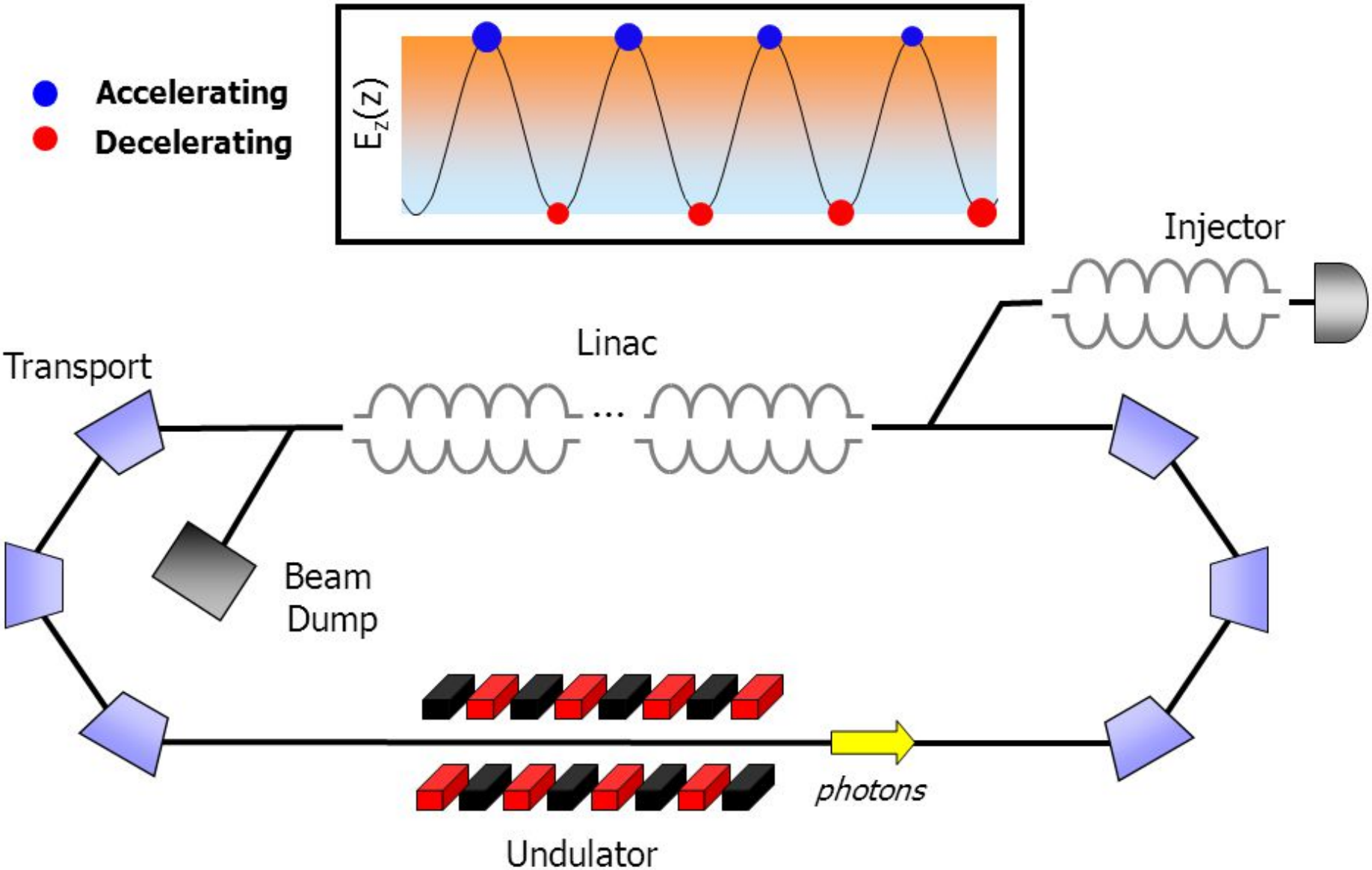


Photonuclear reactions



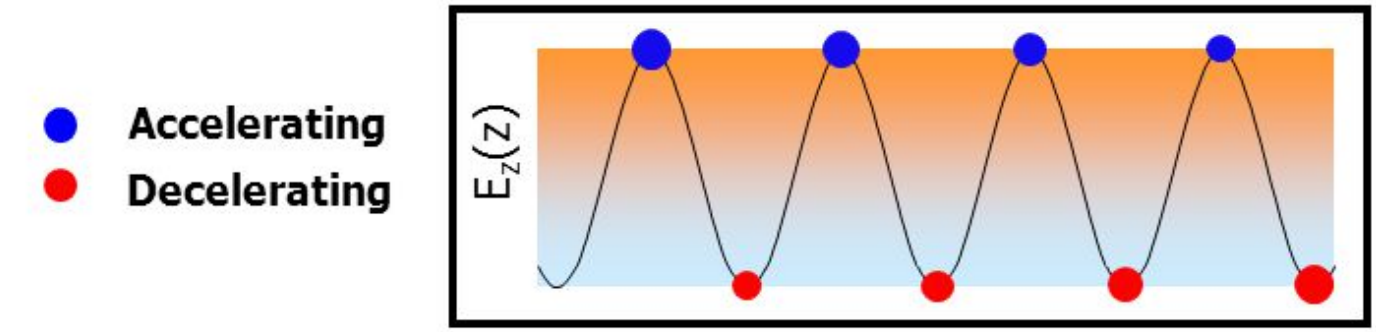
Conference photo
Nuclear Photonics 2018
Brasov, Romania

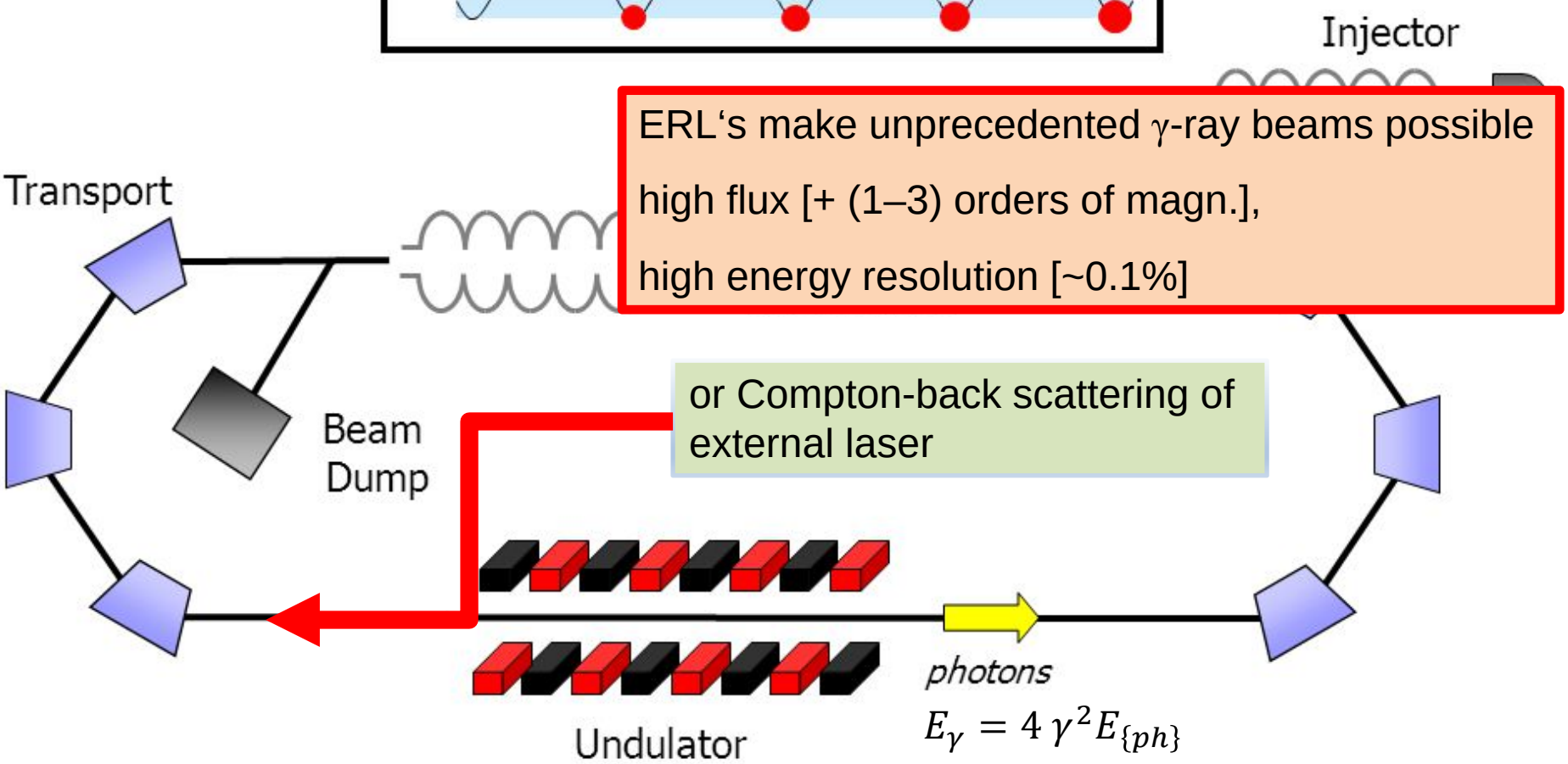
Generic ERL-based Light Source



from: Chris Tennant, USPAS 2011 online

Generic ERL-based Light Source





ERL's make unprecedented γ-ray beams possible

high flux [+ (1–3) orders of magn.],

high energy resolution [~0.1%]

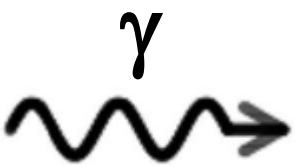
or Compton-back scattering of external laser

from: Chris Tennant, USPAS 2011 online

Outline

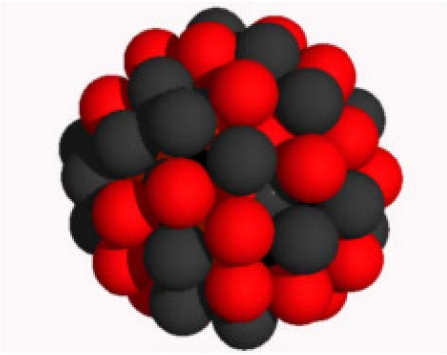
- Photonuclear reactions with MeV-range γ rays
- Motivation from astrophysics and particle physics
- Examples for recent achievements
- Concluding remarks

Photonuclear Reactions



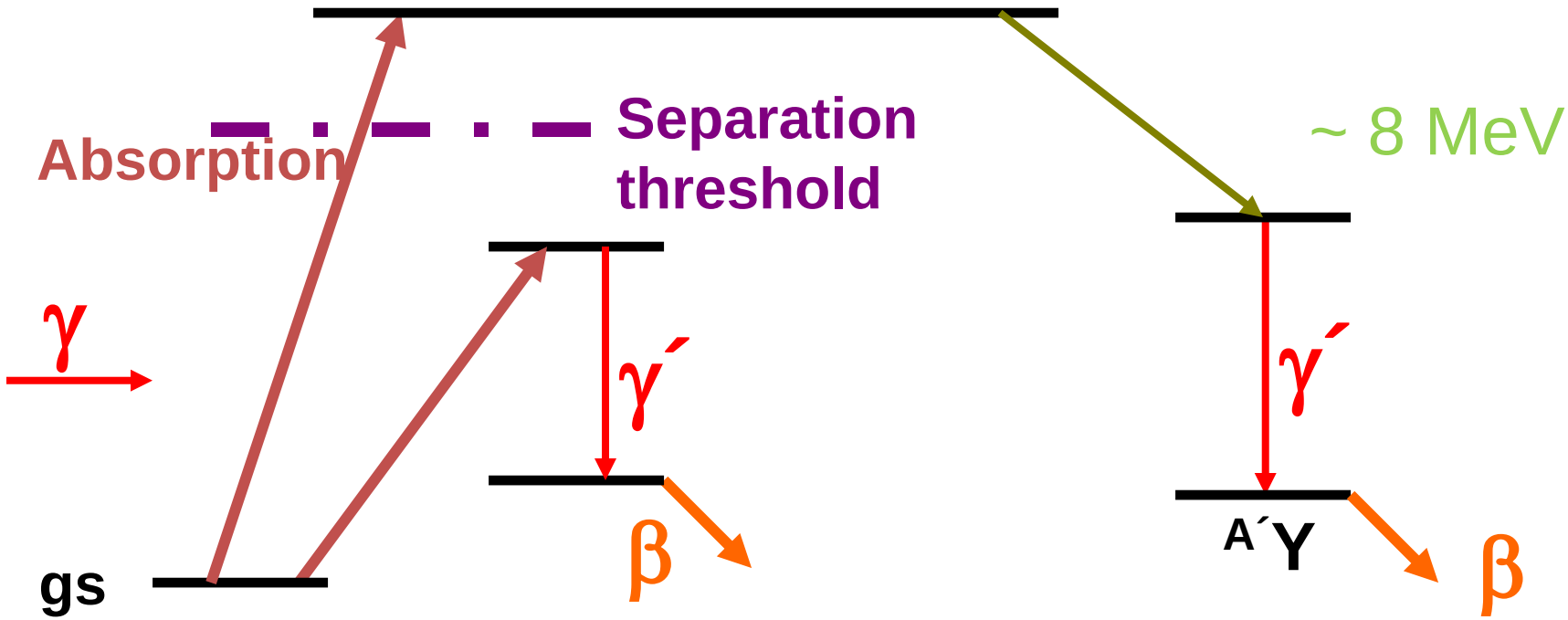
0.1 – 100 MeV

PERLe: $4\gamma^2 E_{ph}$
~ 0.2 – 5 MeV



What happens?

Photonuclear Reactions



Nuclear Resonance Fluorescence (NRF)

Photoactivation

Photodisintegration (-activation)

Photofission

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

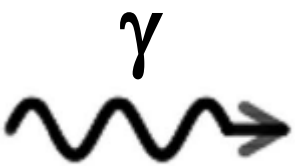
- **“Parity Physics“, channel selectivity**

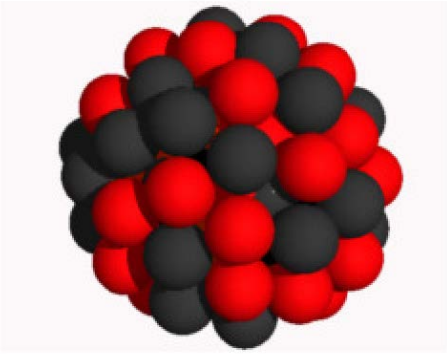
Narrow Bandwidth (at 4th generation LCB source)

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

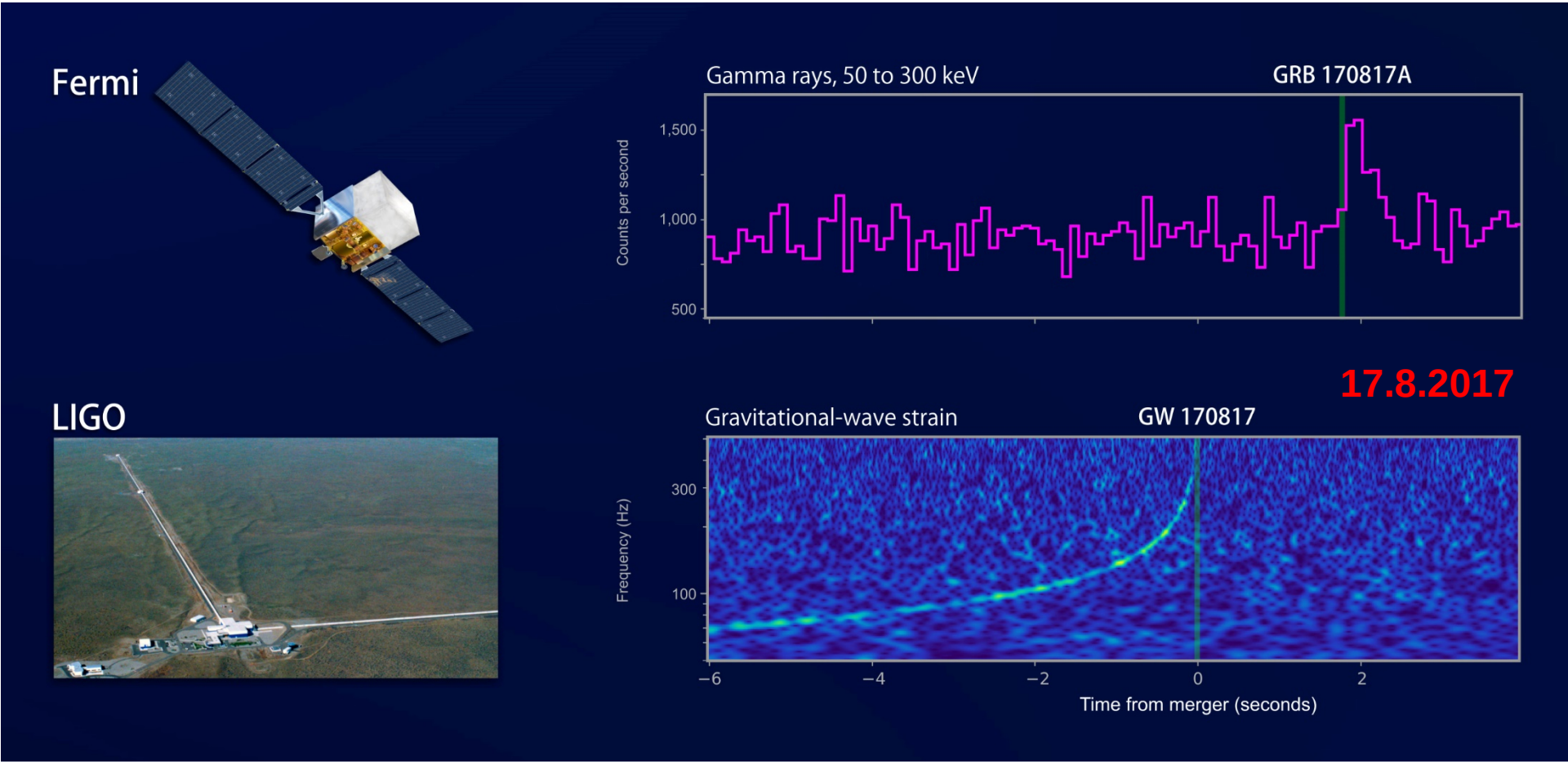
Nuclear Photonics

Astrophysical Motivation





Multi-Messenger Observation of N-Star Merger



LIGO/VIRGO – collaboration, Fermi Satellite

Neutron-Star Merger in the Visible Spectrum

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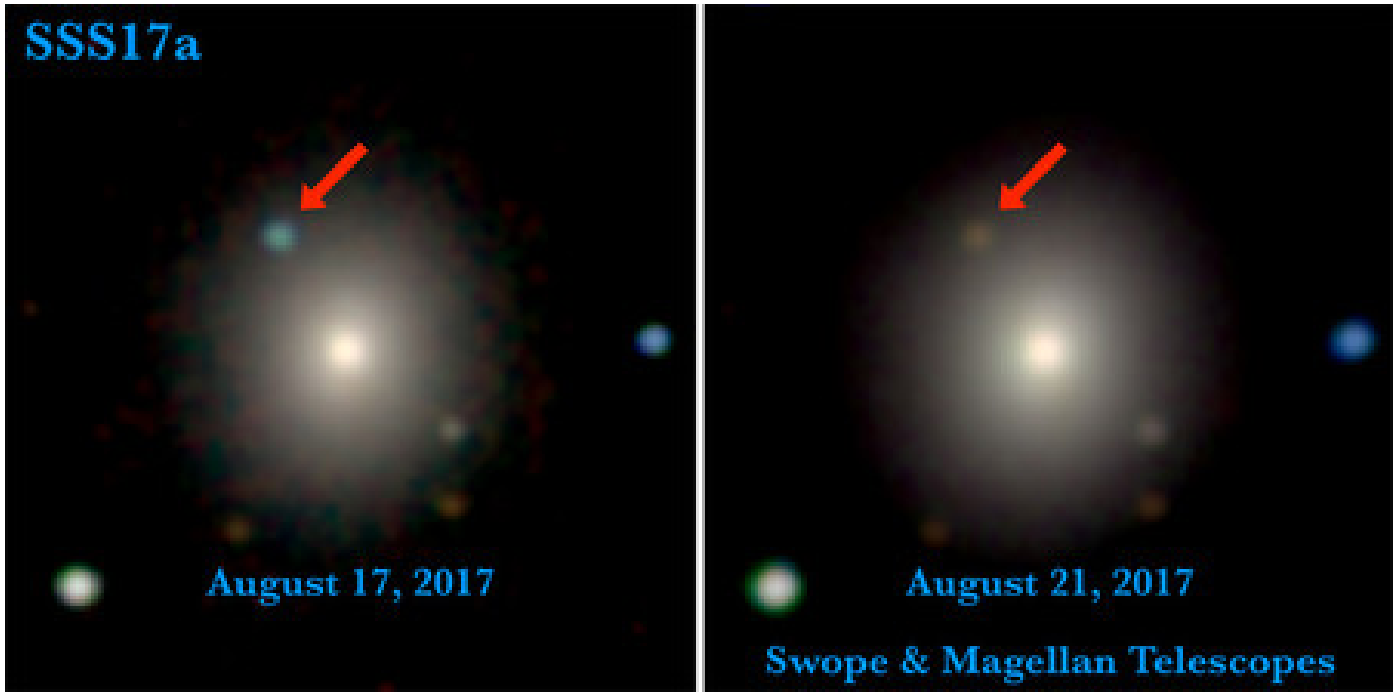
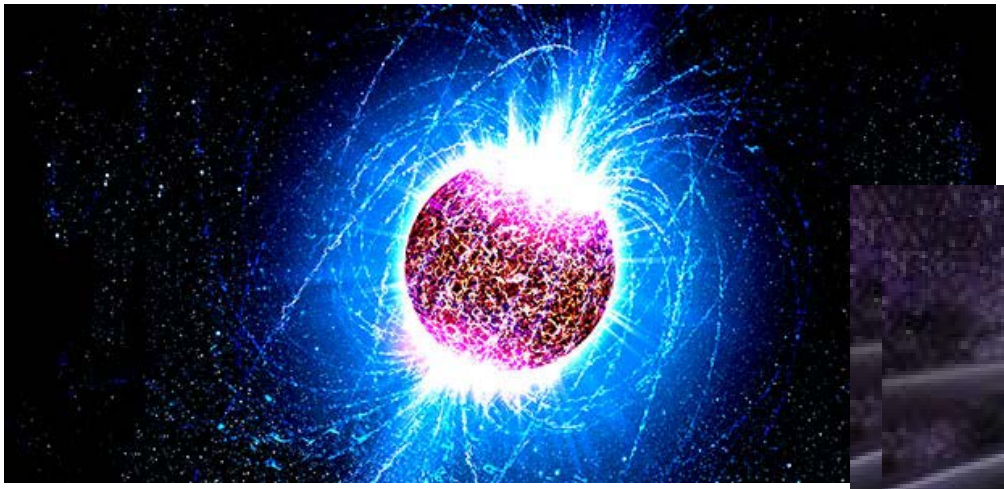
A star changes colour in 4 days ! „Kilonova“



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).

Neutron-Star Mergers



Artist‘s views !

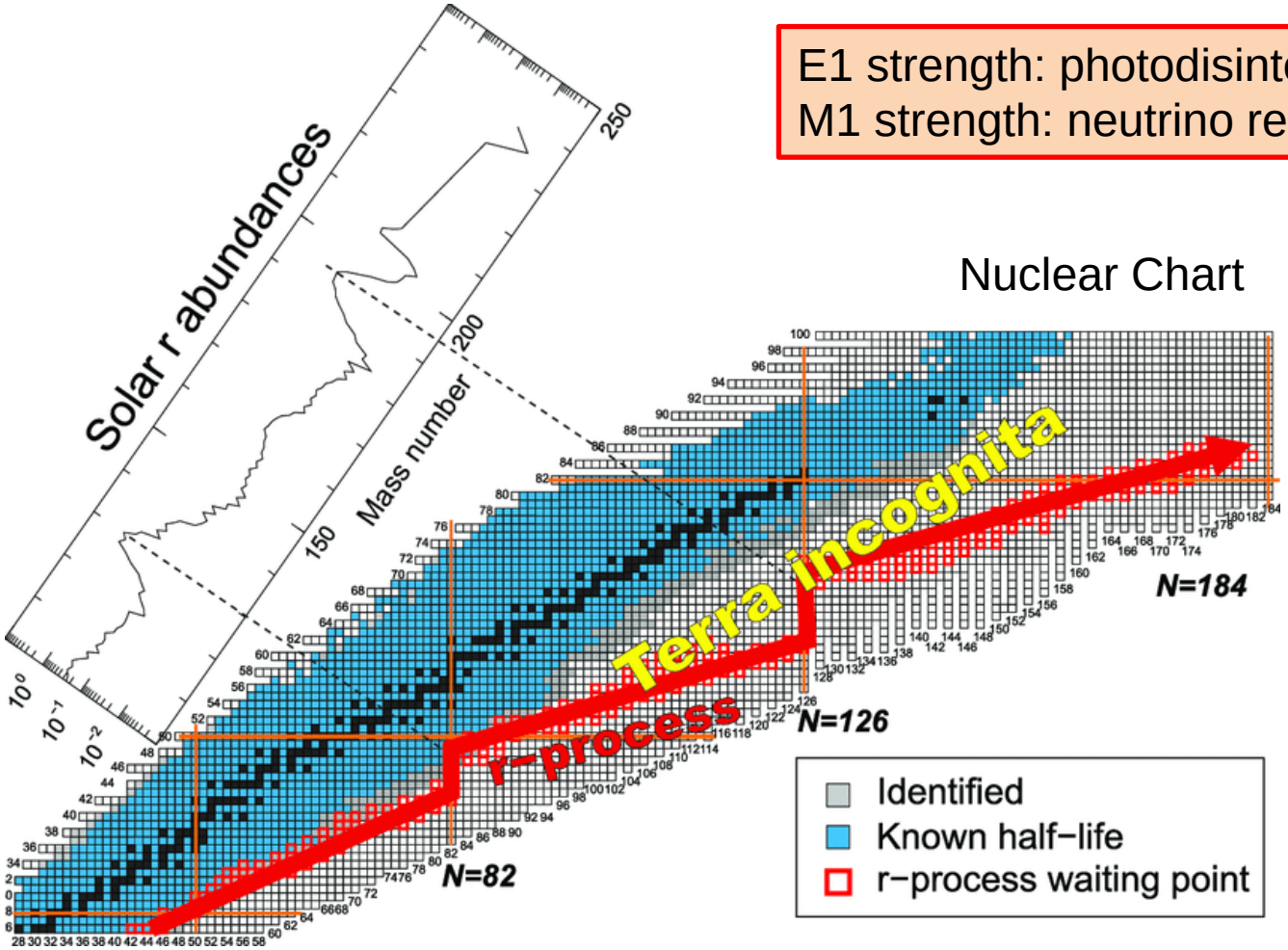
Neutron-star merger:
Cosmic heavy-element nucleosynthesis

Rapid neutron-capture process and fission cycling

Nuclear dynamics govern GW signal

Cosmic Nucleosynthesis

E1 strength: photodisintegration
M1 strength: neutrino reactions



Motivation from Astrophysics and Particle Physics

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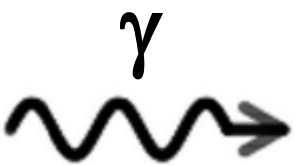
- Nuclear Equation of State (EoS) determines properties of neutron stars (e.g. radius) and dynamics of n-star mergers incl. GW signal.
- Constrains on density-dependence of symmetry-energy of EoS from nuclear dipole-polarizability, i.e., inversely energy-weighted E1 excitation strength from photonuclear reactions

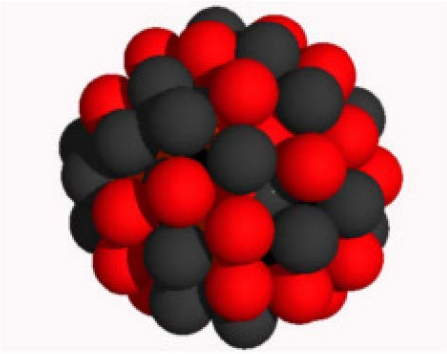
- Fission-cycling in n-star mergers determines resulting abundance distribution
- Energy-resolved studies of photo-induced fission resonances of long-lived trans-uranium actinides

- Calibration of spin-response of neutrino-detectors and detectors for Dark-Matter searches from photonuclear reactions

- etc.

Examples of Recent Achievements

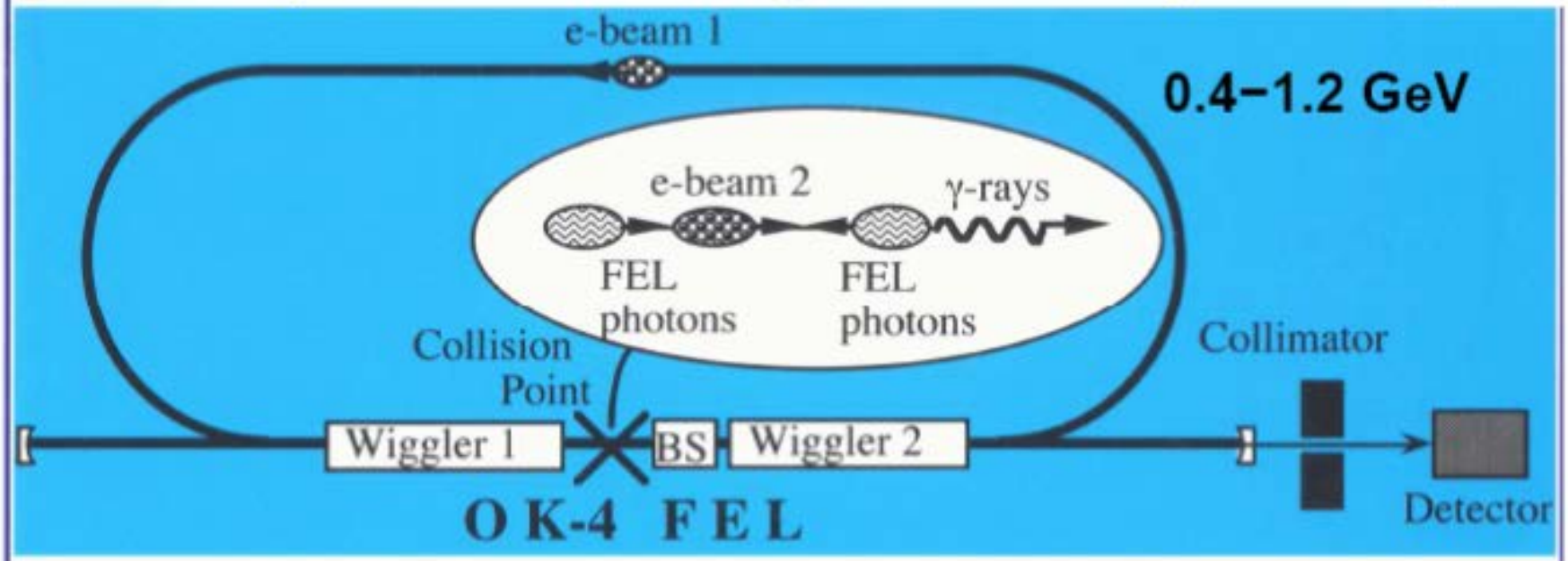




High Intensity γ−Ray Source (HIgS)

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

Compton Backscattering of Intra−cavity Laser Light

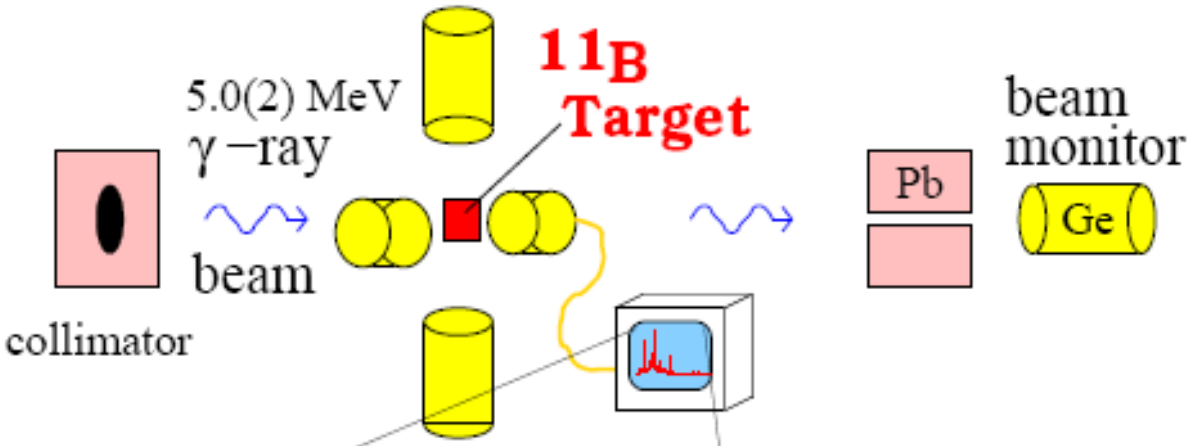


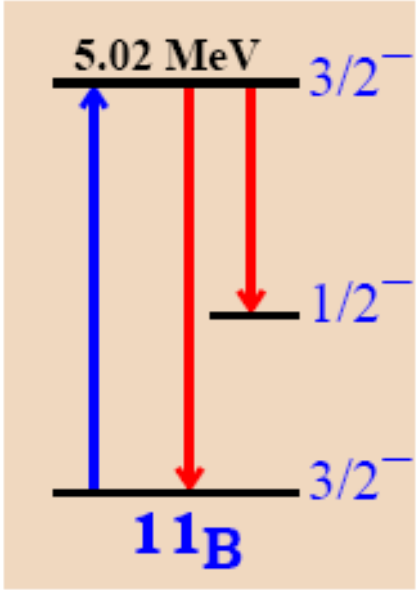
2 − 60 MeV 1.7 − 6.4 eV ~ 1000

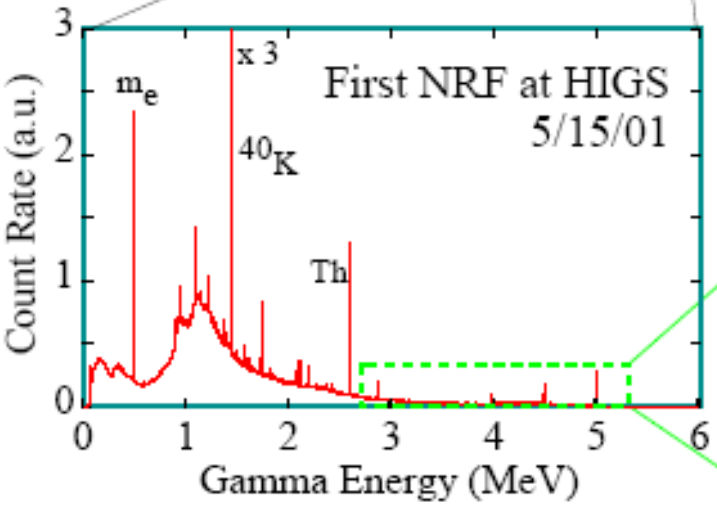
$$E_\gamma = \frac{4\gamma^2 E_{ph}}{\left(1 + r + \gamma^2\theta^2\right)}; \quad r = \frac{4\gamma E_{ph}}{mc^2}; \quad E_{ph} = \frac{2\gamma^2 hc}{\lambda_w\left(1 + K_w^2/2\right)}; \quad \gamma = \frac{E_e}{mc^2};$$

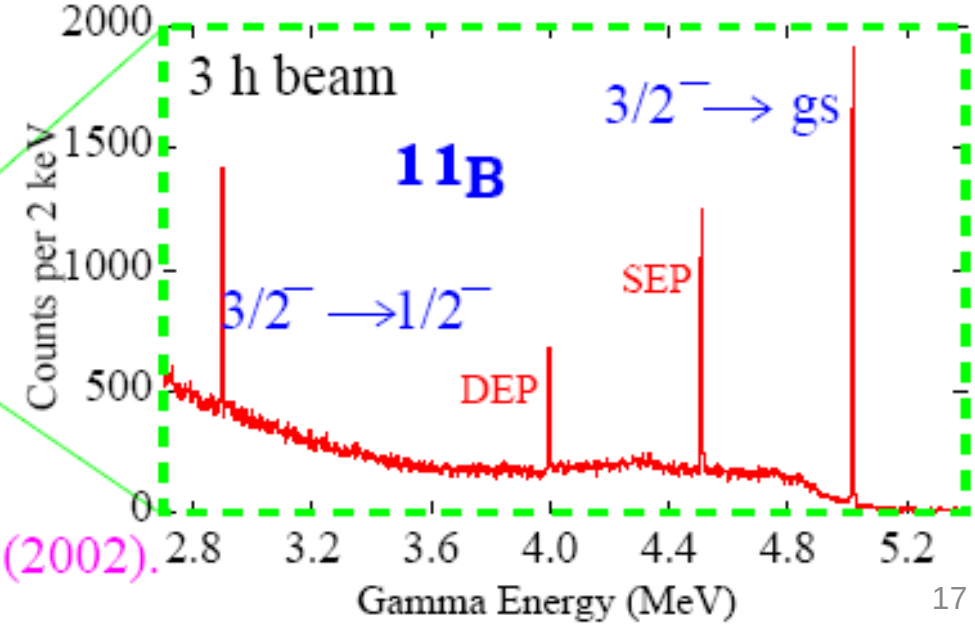
nearly monochromatic, tunable, completely polarized

Looking at the Target









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

Photonuclear Reactions for EoS

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PHYSICAL REVIEW C **100**, 021301(R) (2019)

Rapid Communications

Valence-shell dependence of the pygmy dipole resonance: $E1$ strength difference in ^{50,54}Cr

P. C. Ries,[1,*] H. Pai,[1,2] T. Beck,[1] J. Beller,[1] M. Bhike,[3] V. Derya,[4] U. Gayer,[1] J. Isaak,[1,5] B. Löher,[1] Krishichayan,[3] L. Mertes,[1] N. Pietralla,[1] C. Romig,[1] D. Savran,[5] M. Schilling,[1] W. Tornow,[3] S. Typel,[1,5] V. Werner,[1] J. Wilhelmy,[4] A. Zilges,[4] and M. Zweidinger[1]

[1]*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[2]*Saha Institute of Nuclear Physics, Kolkata 700064, India*
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[4]*University of Cologne, Institute for Nuclear Physics, 50937 Köln, Germany*
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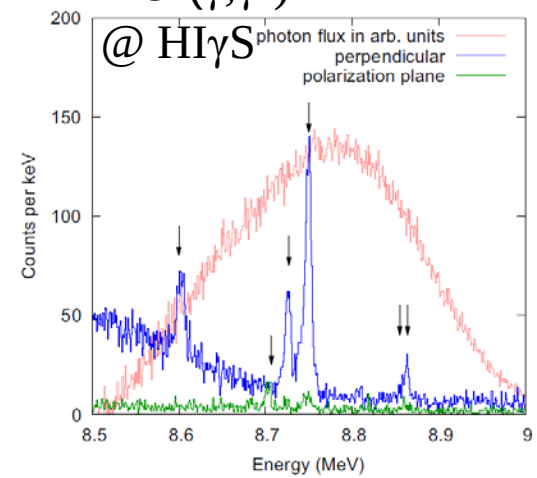
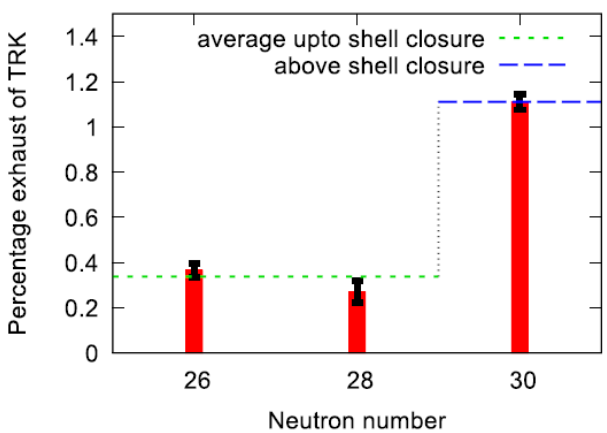
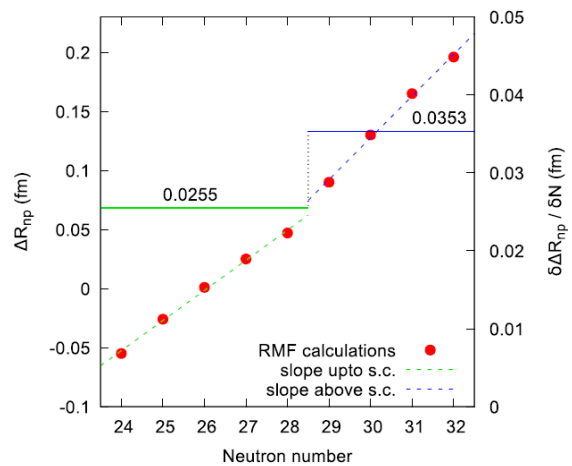
P. C. RIES *et al.*

^{54}Cr(γ,γ‘)







Evidence for shell-dependence of nuclear neutron skin

Nuclear Structure for Neutrino Studies

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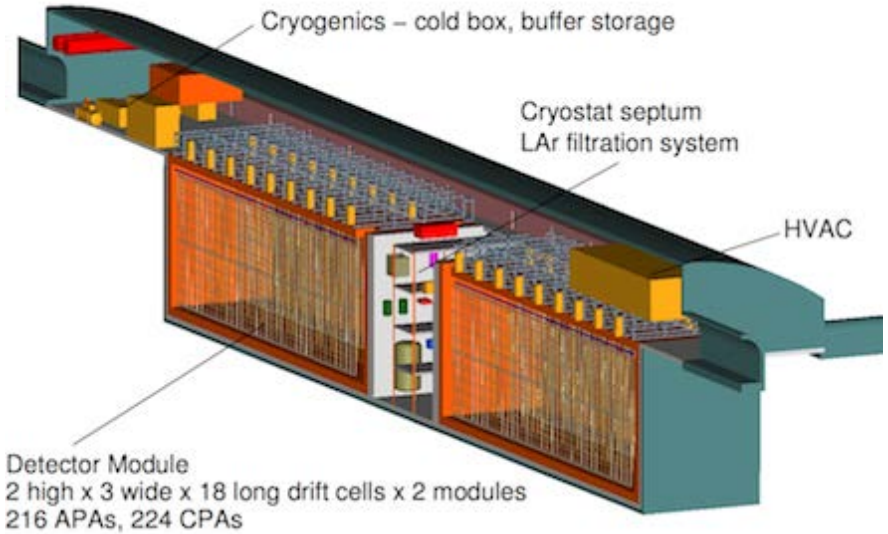
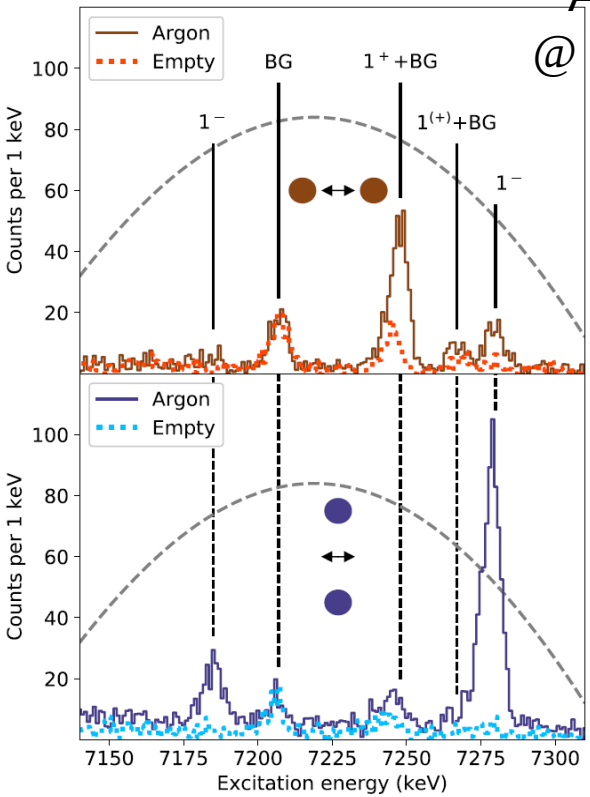
Deep Underground Neutrino Experiment

DUNE LAr – detector for cosmic ν's



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

^{40}Ar(γ,γ') @ HIγS



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

→ total low-energy neutrino cross section

E2 decay strength of the Scissors mode

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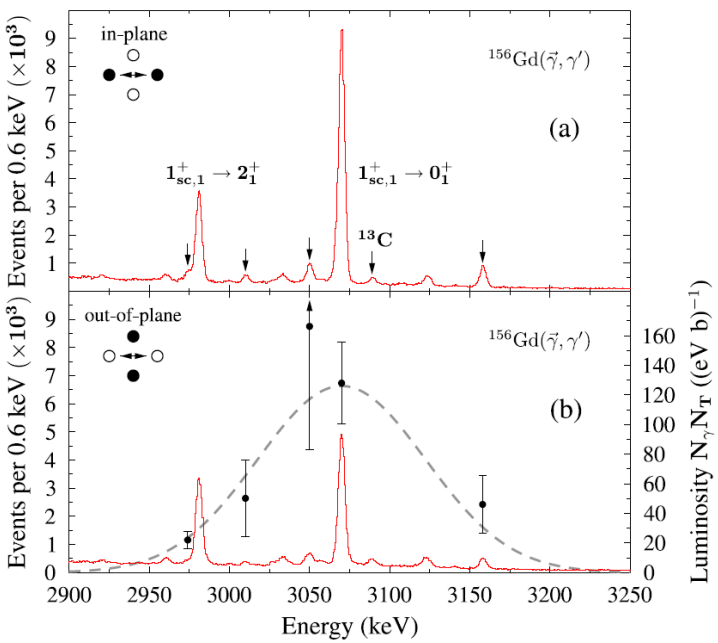
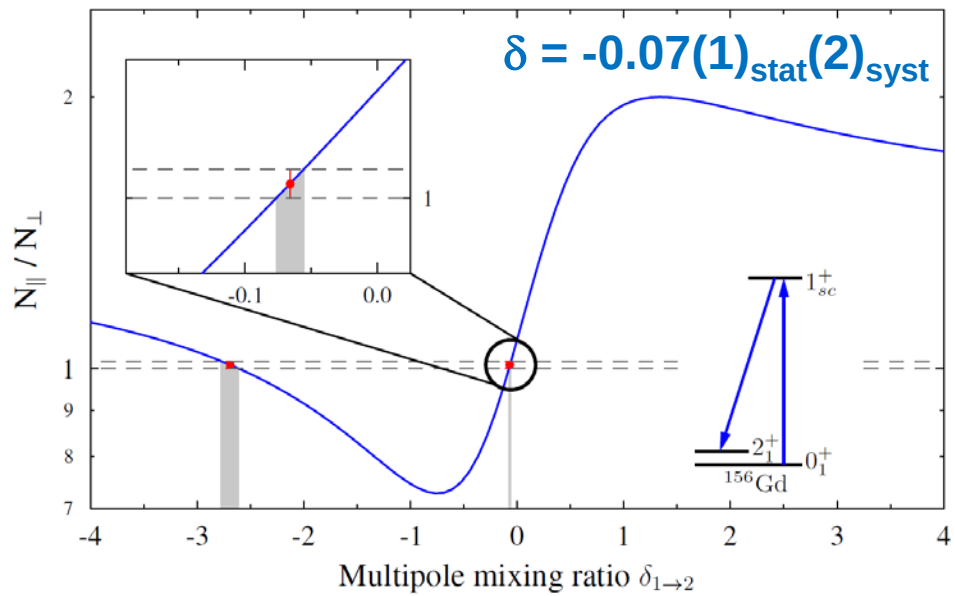
PRL **118,** 212502 (2017) PHYSICAL REVIEW LETTERS week ending 26 MAY 2017

$E2$ decay strength of the $M1$ 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

Motivation for Nuclear Photonics @ PERLe

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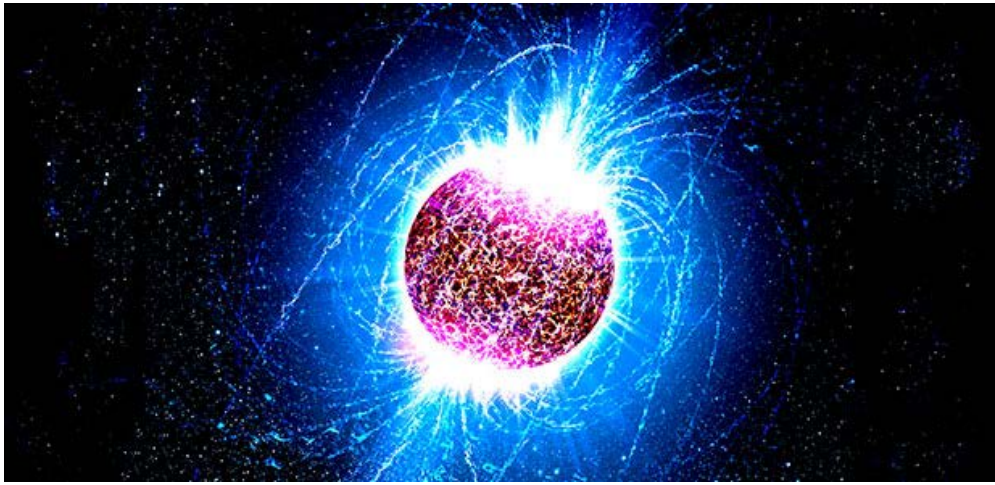
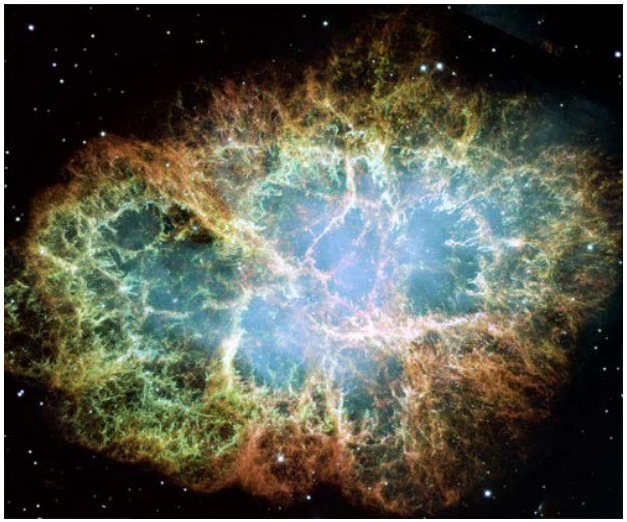
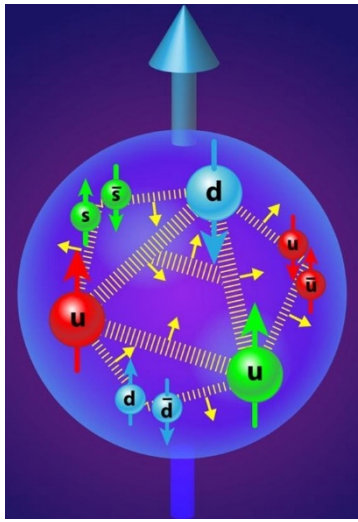
- Photons provide a sensitive probe for nuclear structure
- Properties of nuclear isotopes as a function of mass (neutron number)
- Low-energy frontier of Quantum Chromo-Dynamics
- Photonuclear reactions impact the structure and dynamics of stars
- Formation of chemical elements in the Universe
- Nuclei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

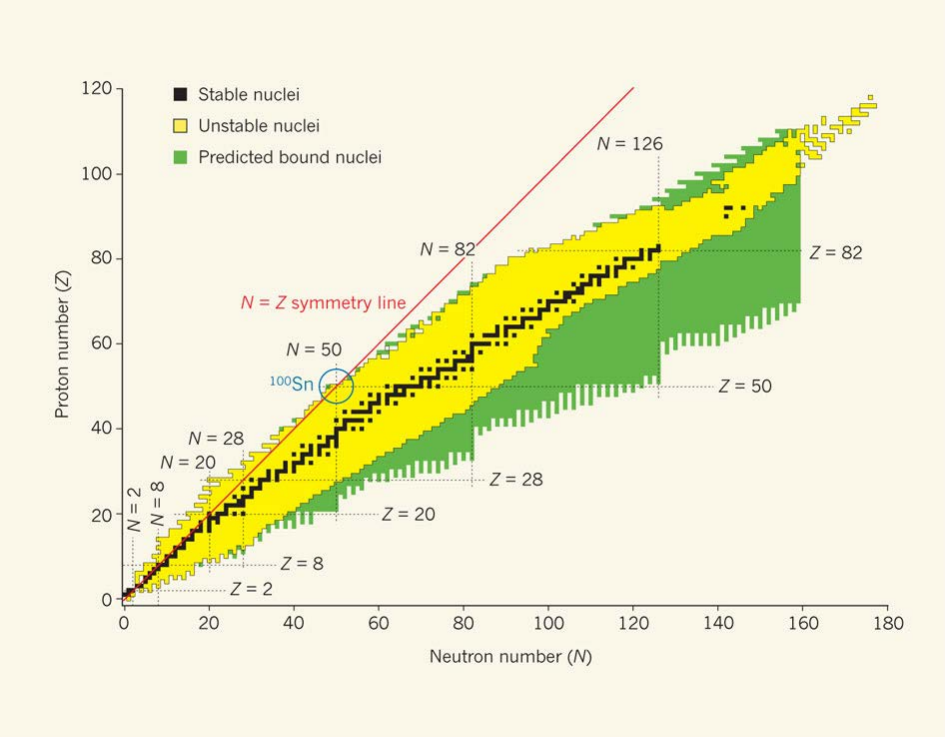






Physics with Photon Beams

- 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.



Thank you very much!