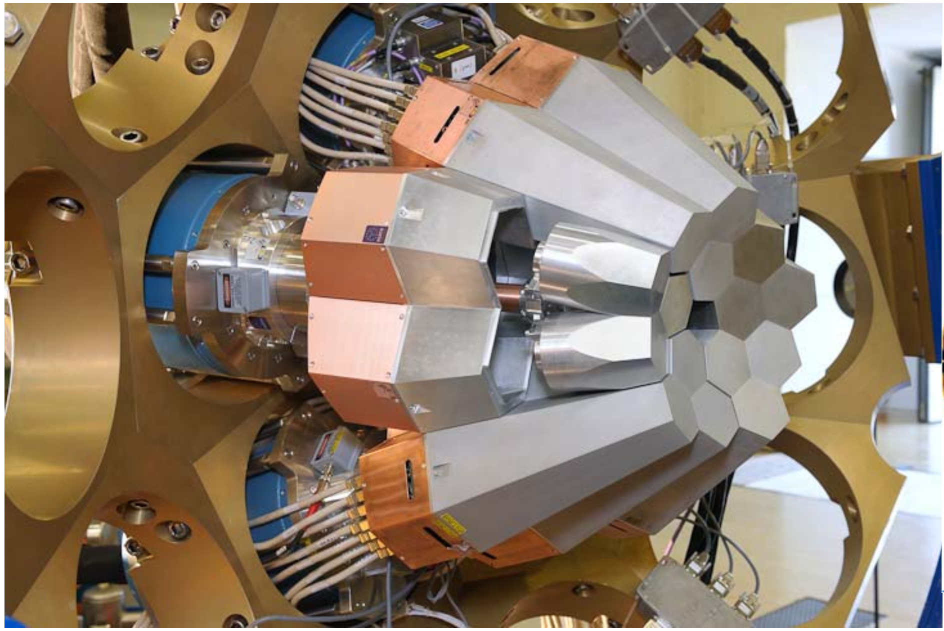
Gamma-Ray Spectroscopy for Nuclear Astrophysics: a few Examples

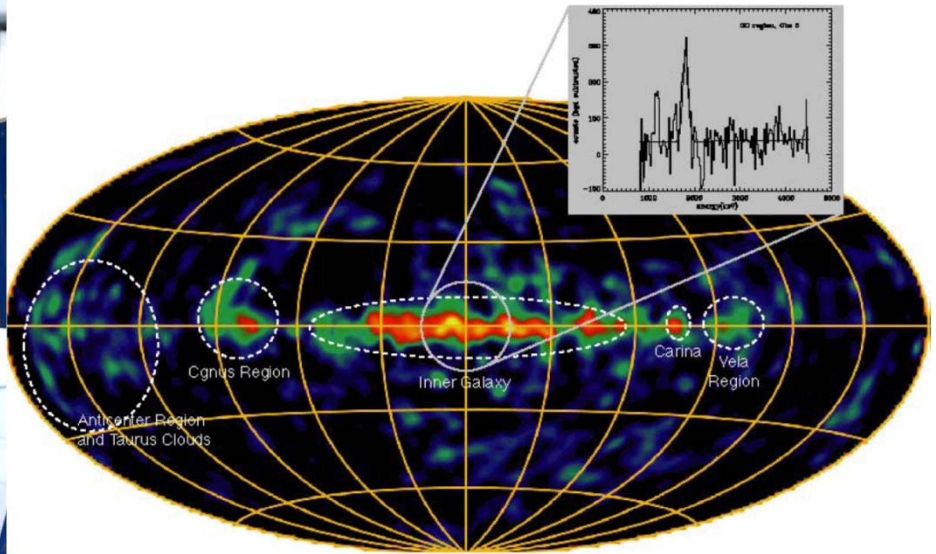
TECHNISCHE UNIVERSITÄT DARMSTADT

Norbert Pietralla

Institut für Kernphysik, TU Darmstadt

GSI Helmholtzzentrum für Schwerionenforschung GmbH





HIC for FAIR
Helmholtz International Center

NAVI

SFB 634

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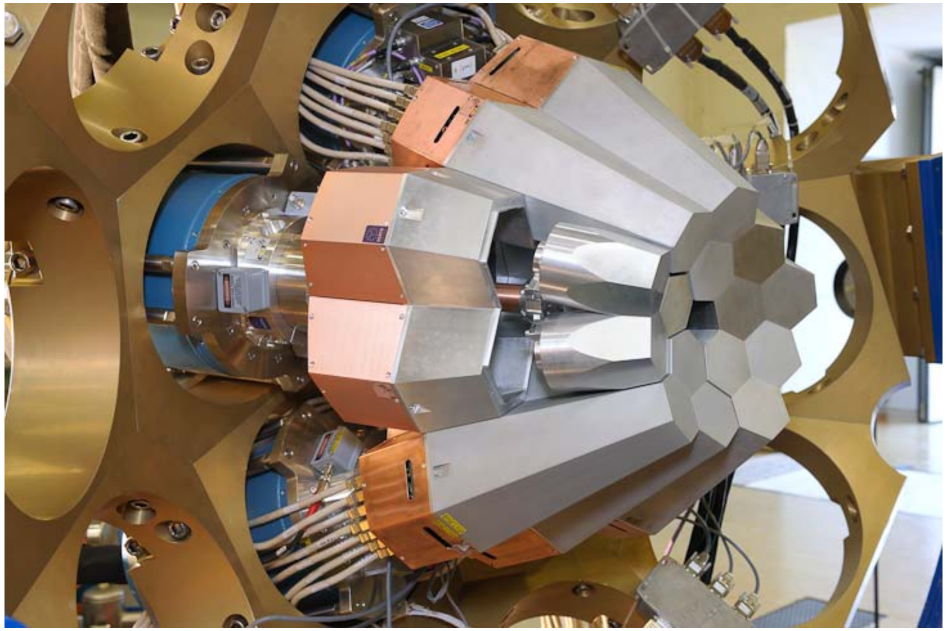

Instrumentation → J.Gerl

Approach to Nuclear Synthesis

- **Photonuclear reactions**
- **Opportunities with exotic ion beams at FAIR**
- **Let‘s discuss!**

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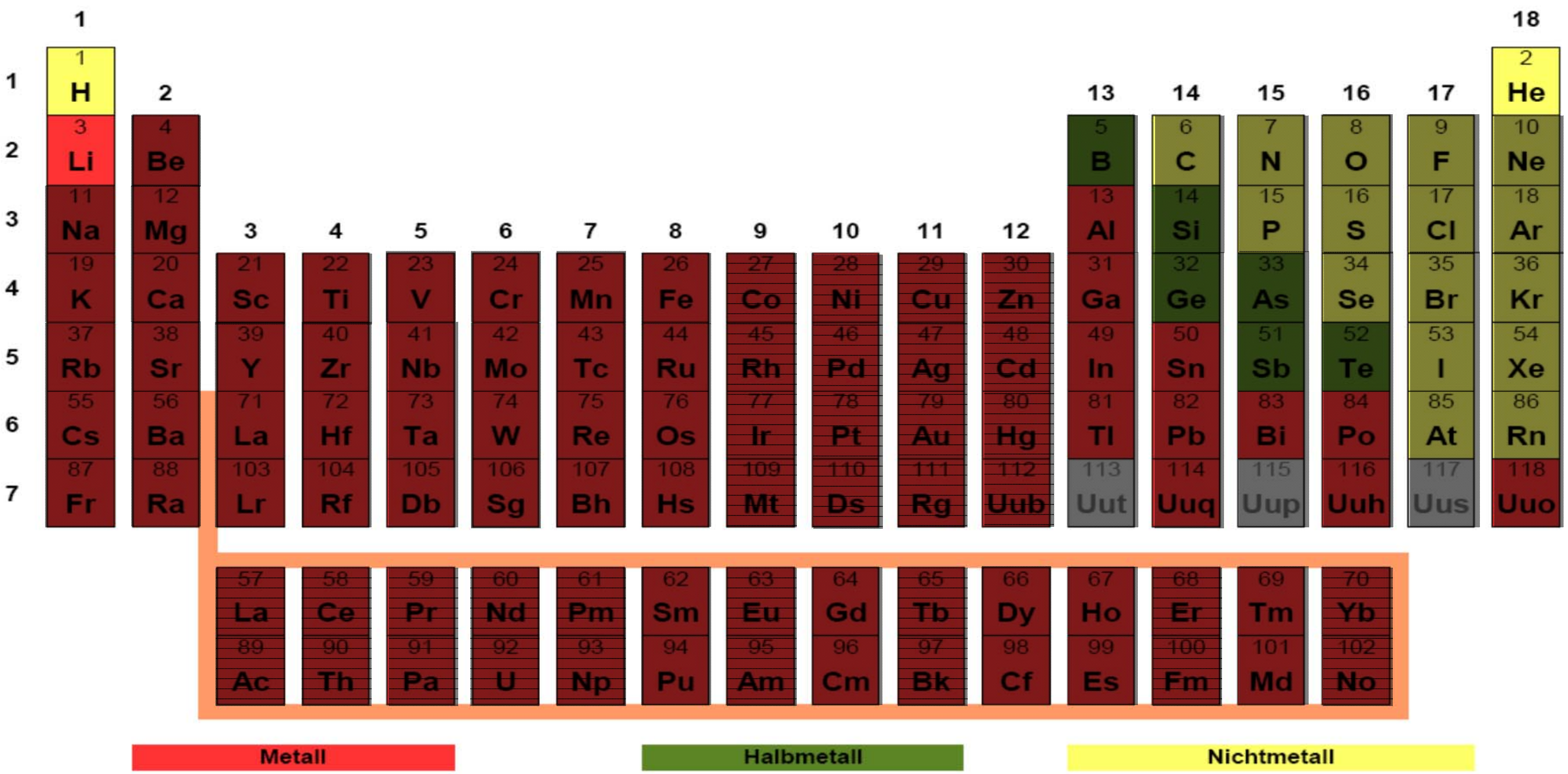
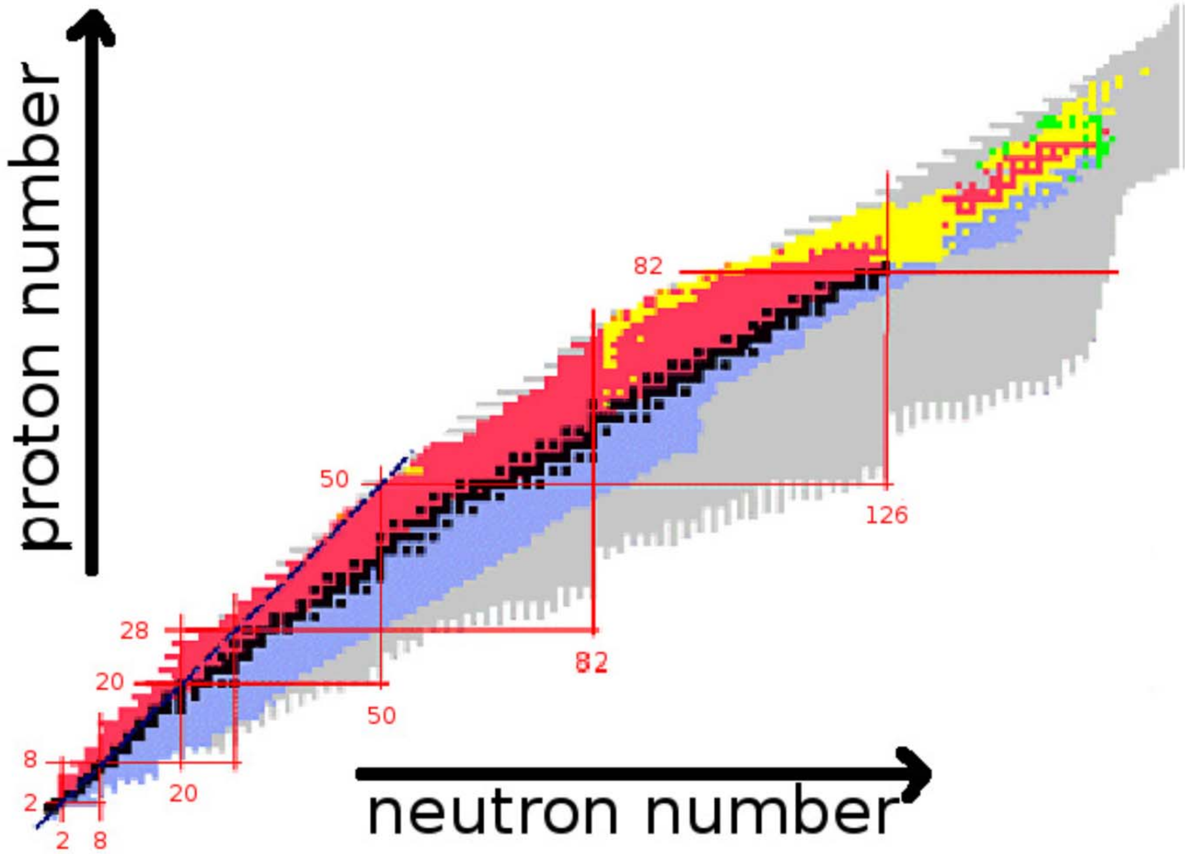
Synthesis of the Chemical Elements

Fusion synthesizes the elements until iron.



The Nuclear Chart



s - Process

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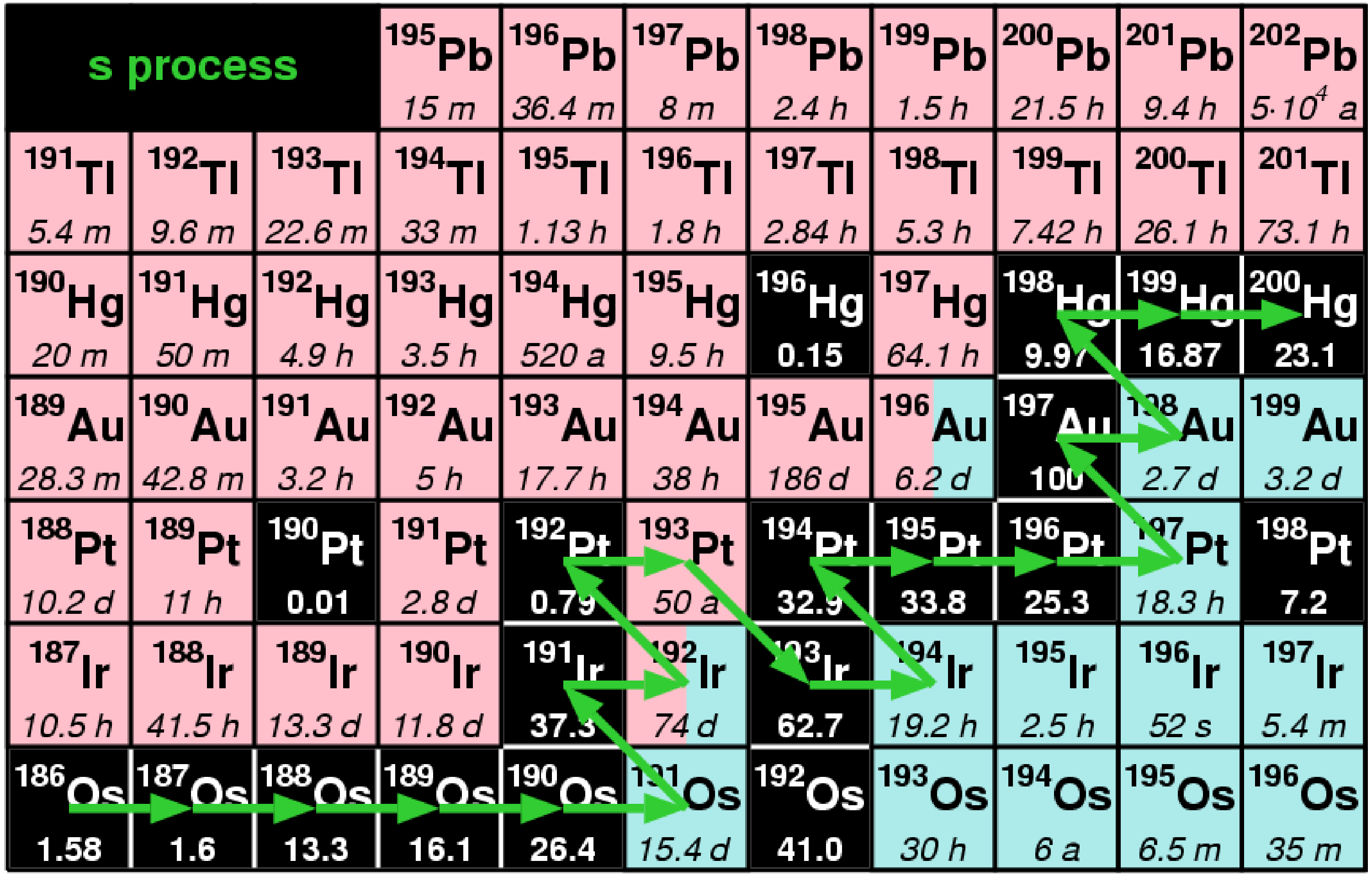
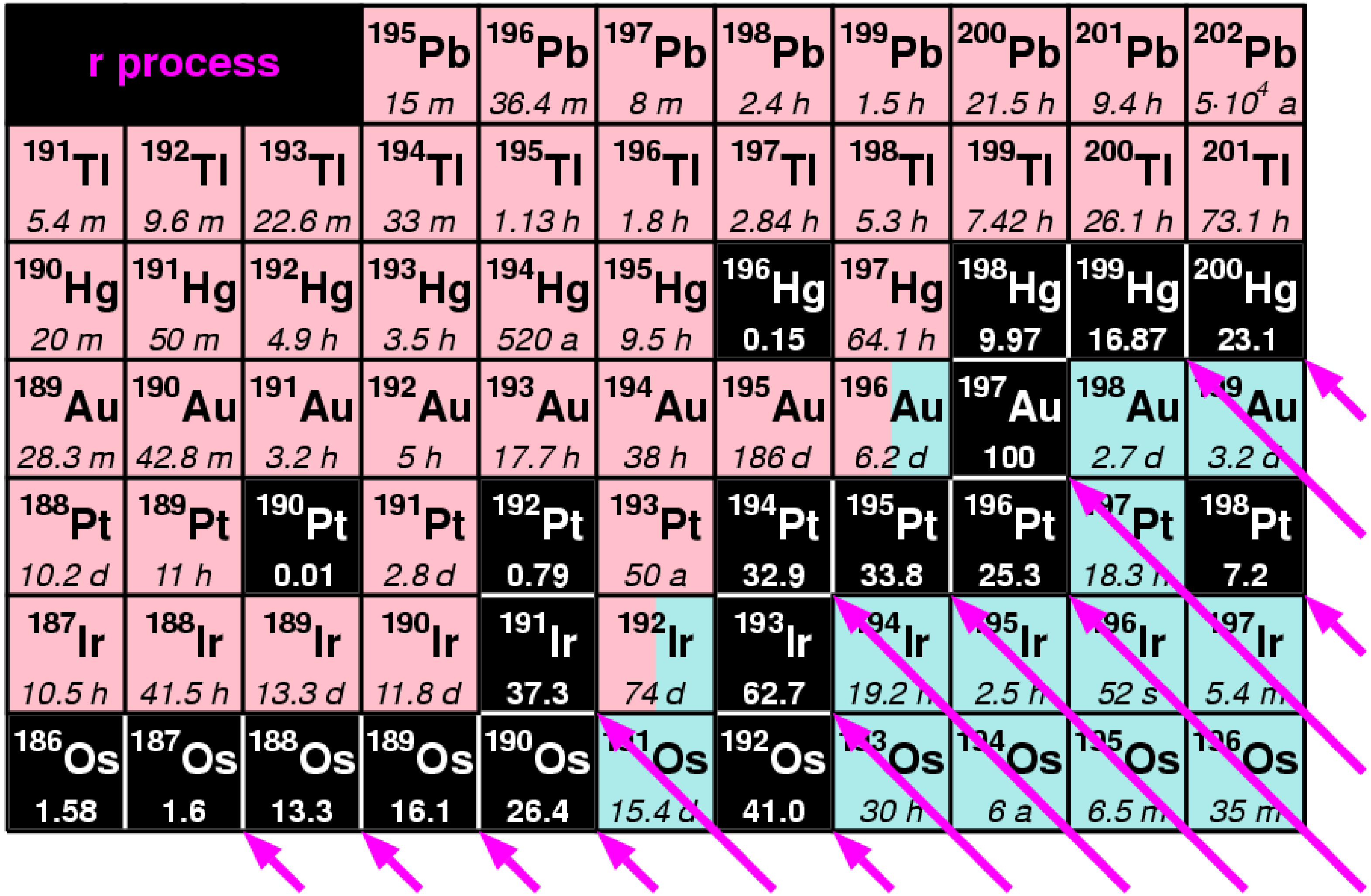


low neutron density → decay before capture → close to stability

Synthesis of Heavy Nuclei



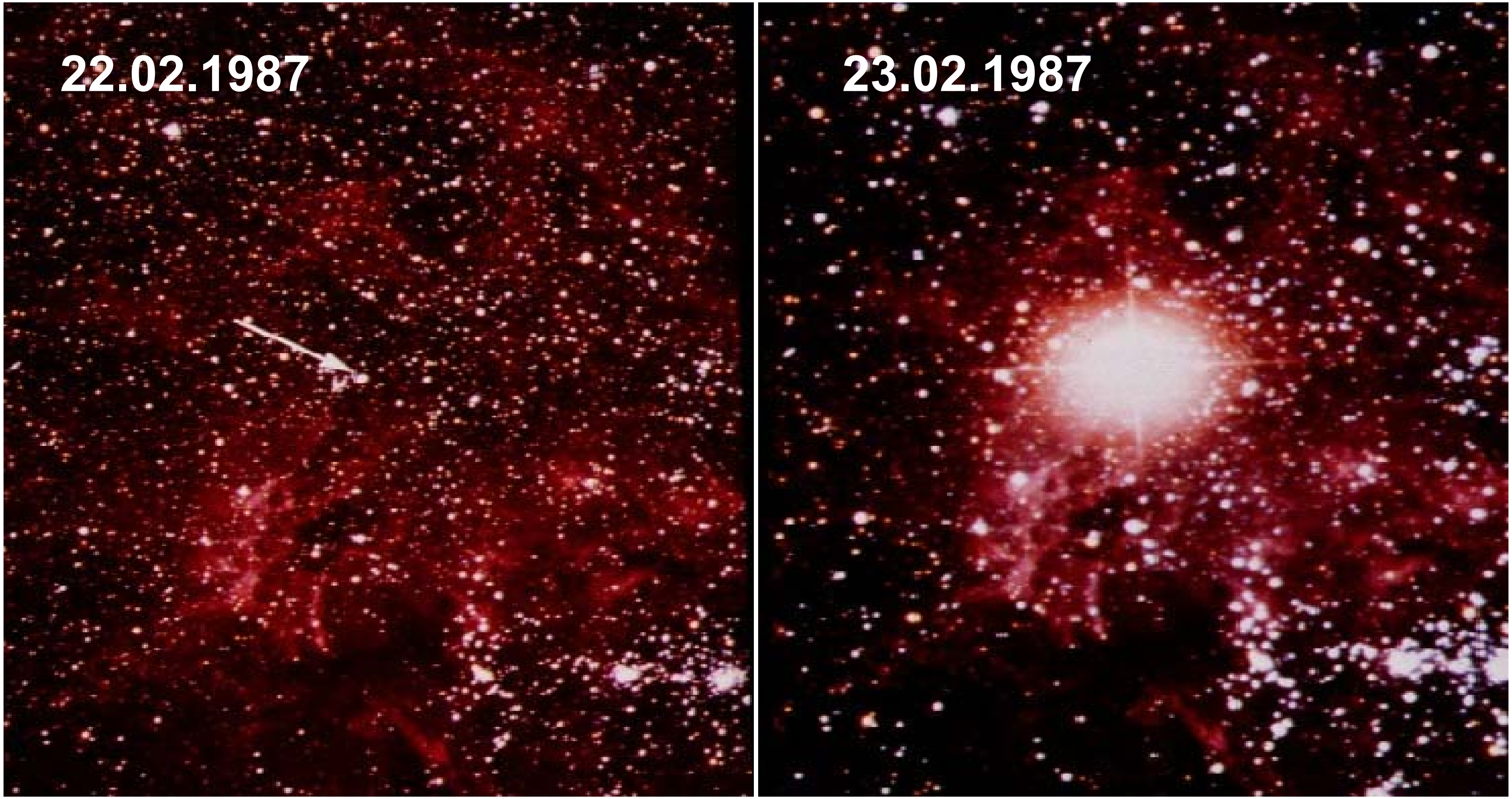
high neutron density→neutron-rich nuclei→decay after flux stops

Synthesis of Heavy Nuclei

r-/s-nucleus s-only nucleus			^{195}Pb 15 m	^{196}Pb 36.4 m	^{197}Pb 8 m	^{198}Pb 2.4 h	^{199}Pb 1.5 h	^{200}Pb 21.5 h	^{201}Pb 9.4 h	^{202}Pb $5\cdot10^4$ a
r-only nucleus p-only nucleus			^{194}Tl 33 m	^{195}Tl 1.13 h	^{196}Tl 1.8 h	^{197}Tl 2.84 h	^{198}Tl 5.3 h	^{199}Tl 7.42 h	^{200}Tl 26.1 h	^{201}Tl 73.1 h
^{190}Hg 20 m	^{191}Hg 50 m	^{192}Hg 4.9 h	^{193}Hg 3.5 h	^{194}Hg 520 a	^{195}Hg 9.5 h	^{196}Hg 0.15	^{197}Hg 64.1 h	^{198}Hg 9.97	^{199}Hg 16.87	^{200}Hg 23.1
^{189}Au 28.3 m	^{190}Au 42.8 m	^{191}Au 3.2 h	^{192}Au 5 h	^{193}Au 17.7 h	^{194}Au 38 h	^{195}Au 186 d	^{196}Au 6.2 d	^{197}Au 100	^{198}Au 2.7 d	^{199}Au 3.2 d
^{188}Pt 10.2 d	^{189}Pt 11 h	^{190}Pt 0.01	^{191}Pt 2.8 d	^{192}Pt 0.79	^{193}Pt 50 a	^{194}Pt 32.9	^{195}Pt 33.8	^{196}Pt 25.3	^{197}Pt 18.3 h	^{198}Pt 7.2
^{187}Ir 10.5 h	^{188}Ir 41.5 h	^{189}Ir 13.3 d	^{190}Ir 11.8 d	^{191}Ir 37.3	^{192}Ir 74 d	^{193}Ir 62.7	^{194}Ir 19.2 h	^{195}Ir 2.5 h	^{196}Ir 52 s	^{197}Ir 5.4 m
^{186}Os 1.58	^{187}Os 1.6	^{188}Os 13.3	^{189}Os 16.1	^{190}Os 26.4	^{191}Os 15.4 d	^{192}Os 41.0	^{193}Os 30 h	^{194}Os 6 a	^{195}Os 6.5 m	^{196}Os 35 m

A ≥ 100: photodisintegration reactions

Supernova 1987A



Journey to the „known Unknown“

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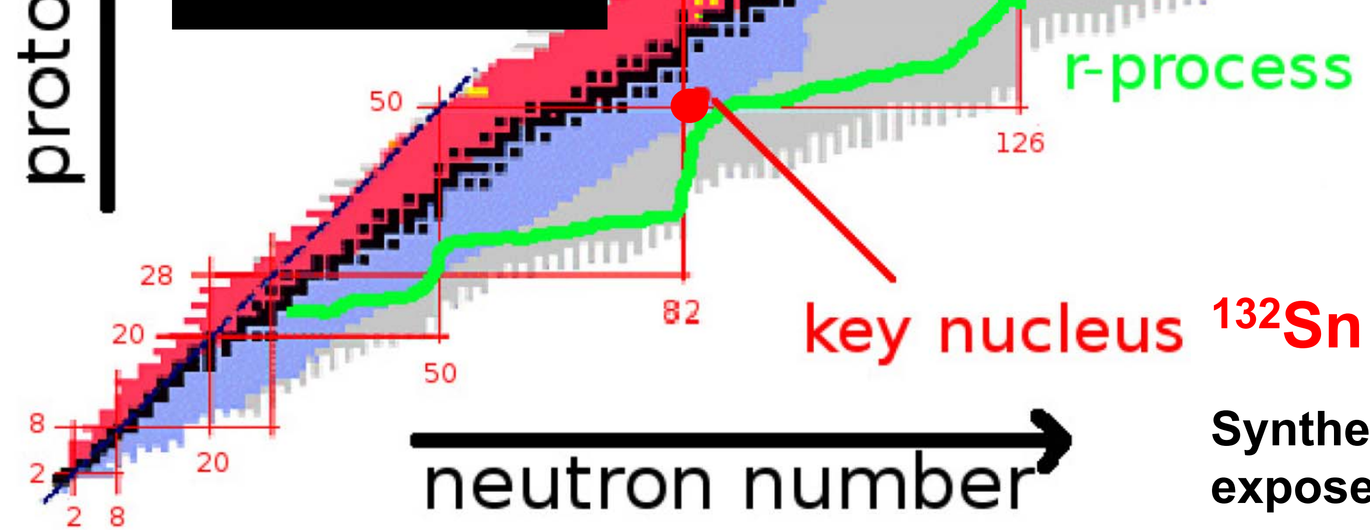
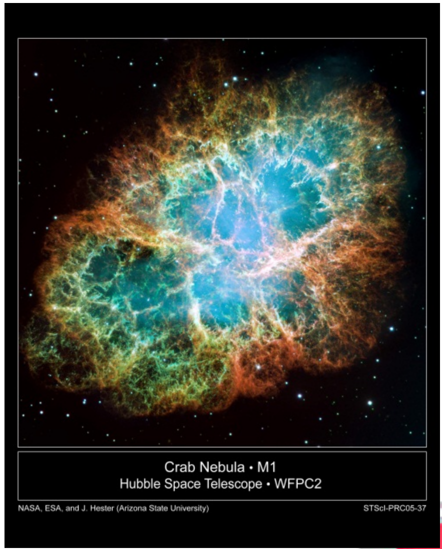
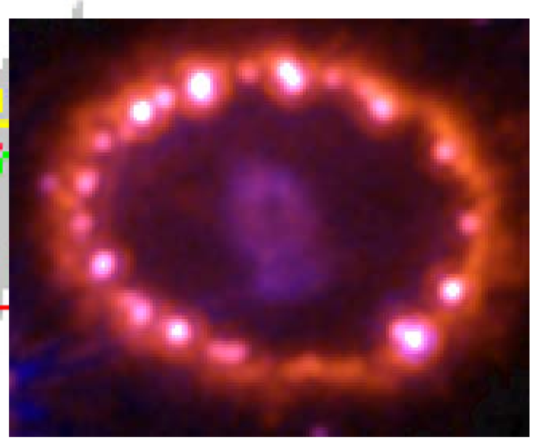




Crab Nebula
Hubble ST



SN 1987A
Hubble ST

Synthesized nuclei are exposed to neutrino and gamma-radiation

„Photon bath“ at 1000° Celsius

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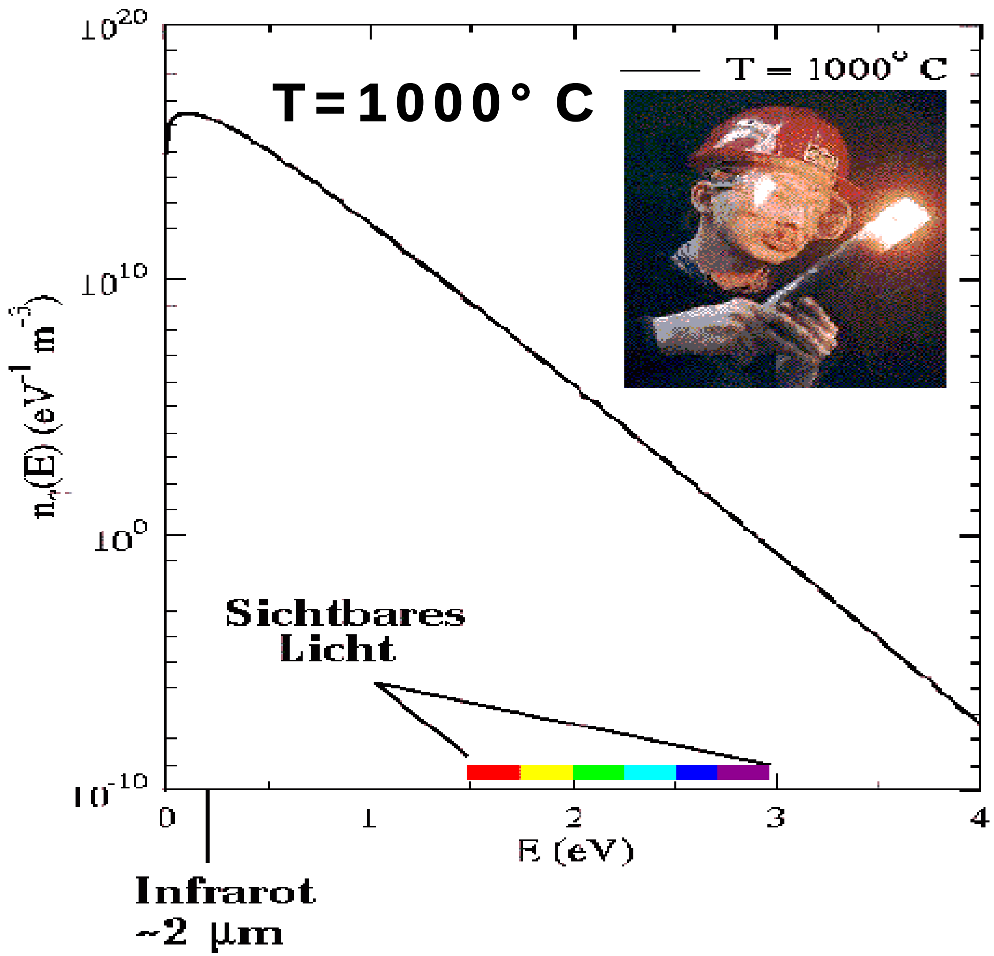
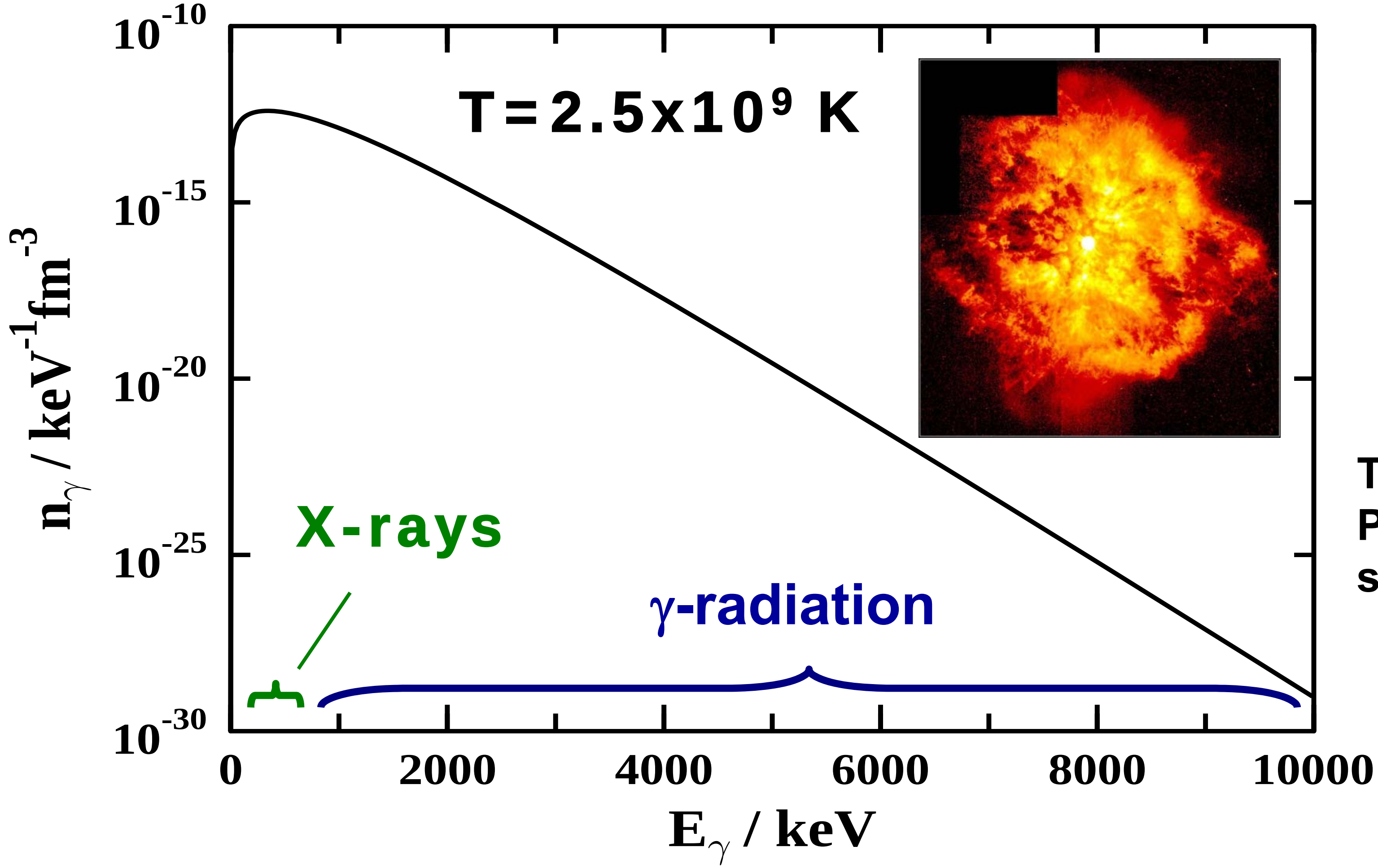


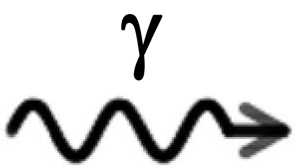
Thermal Planck-spectrum

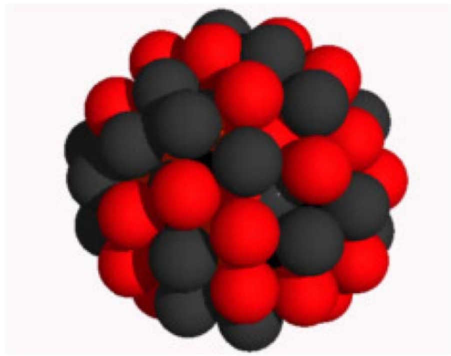
Photon bath at 2.5 billion degrees



Thermal Planck-spectrum

Photonuclear Reactions





What happens?

Photonuclear Reactions

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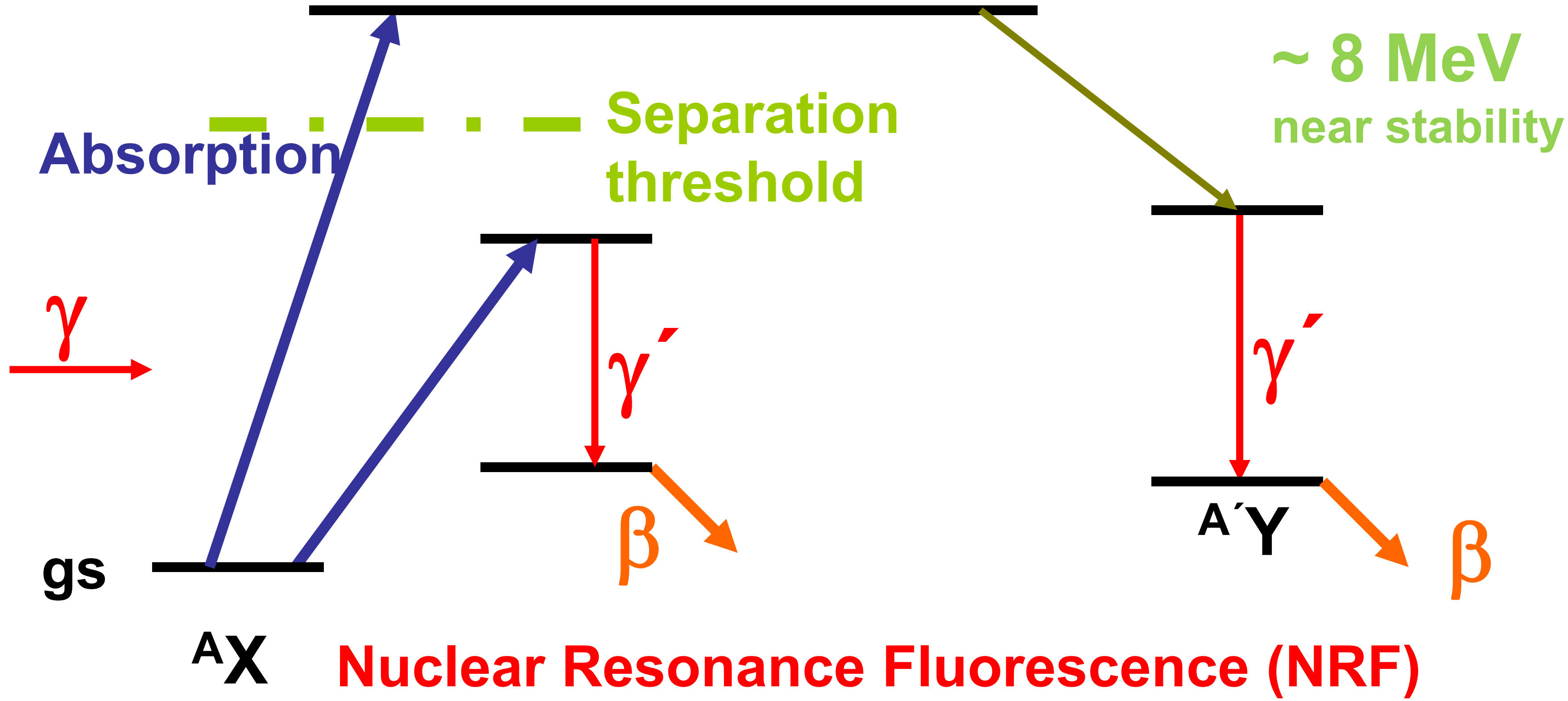
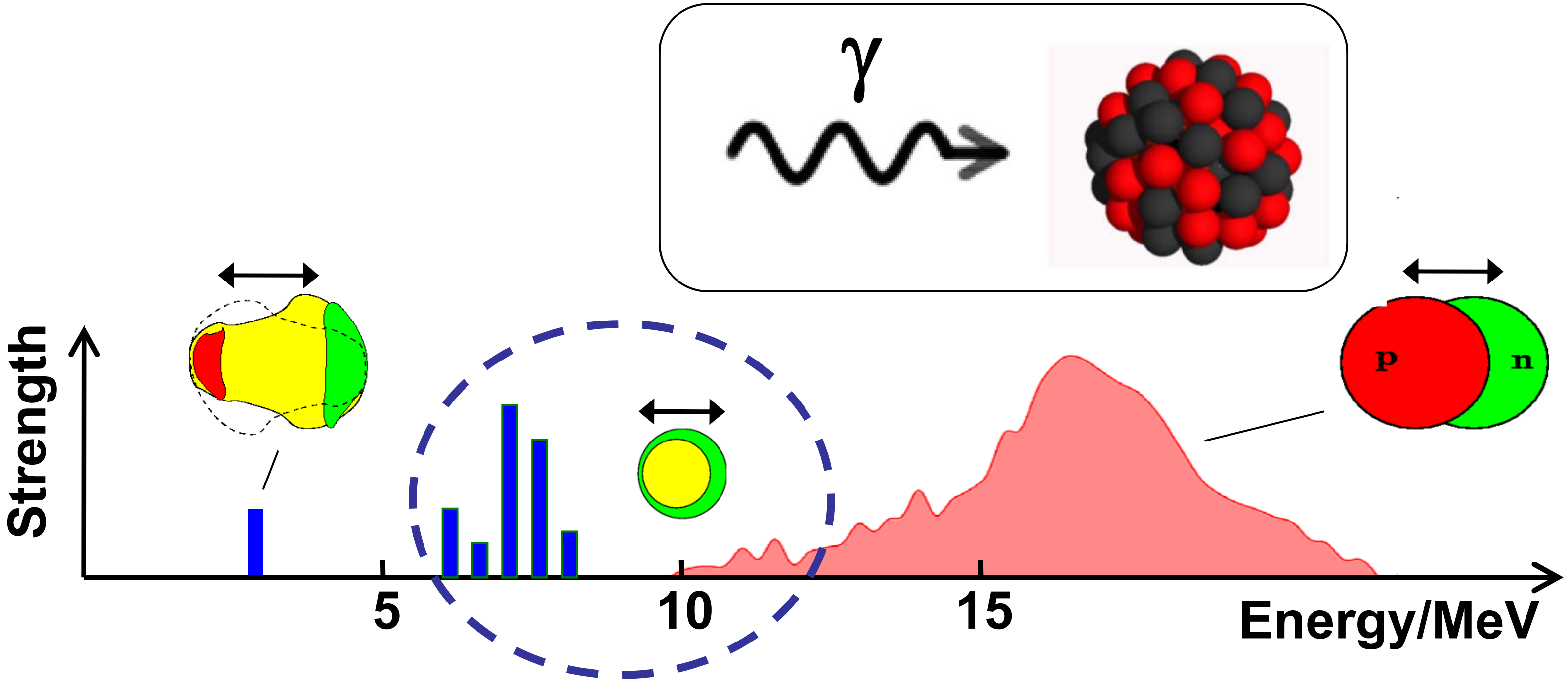


Nuclear Resonance Fluorescence (NRF)

Photoactivation

Photodesintegration (-activation)

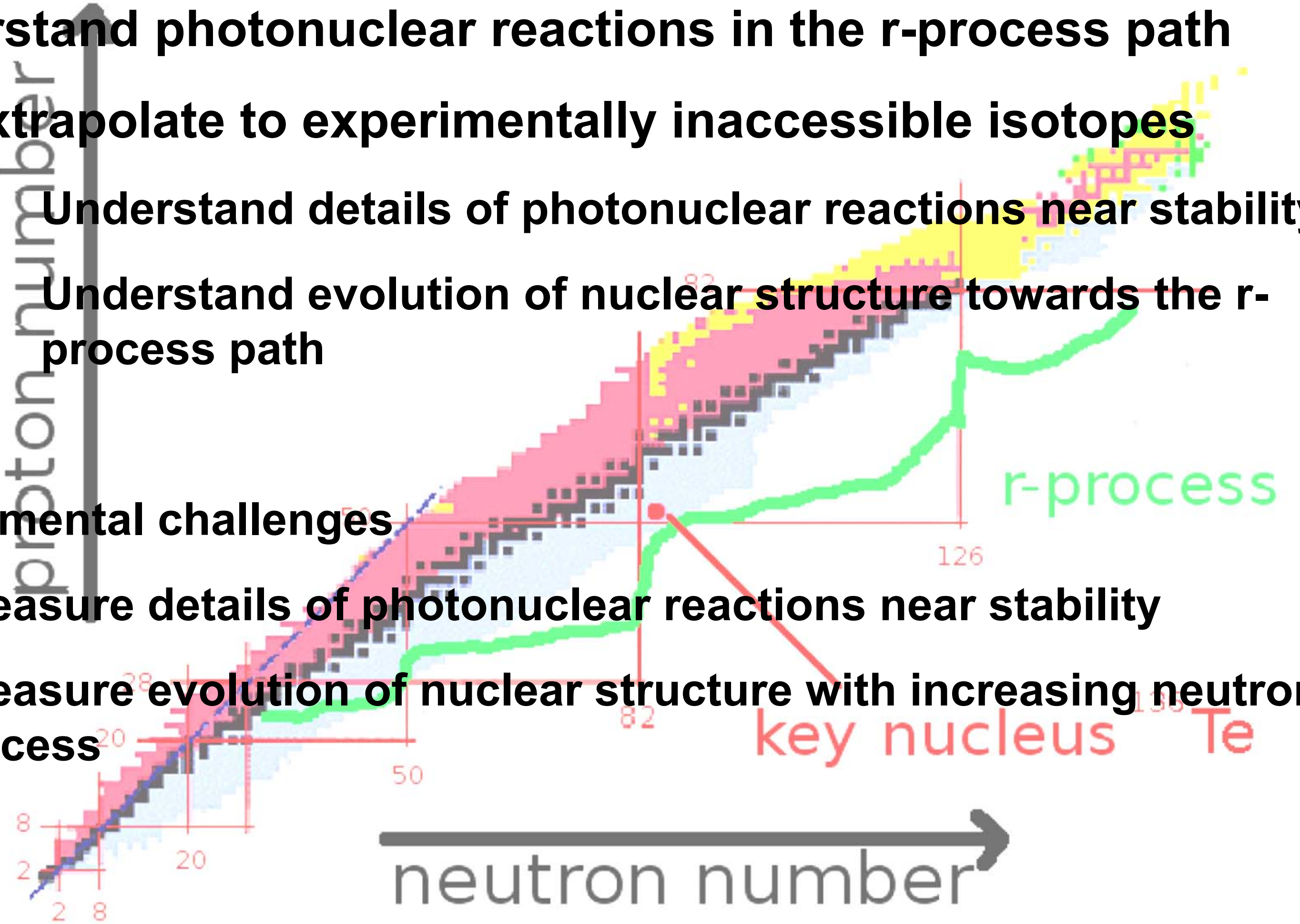
Nuclear Electromagnetic Excitation Strength Distribution (E1)



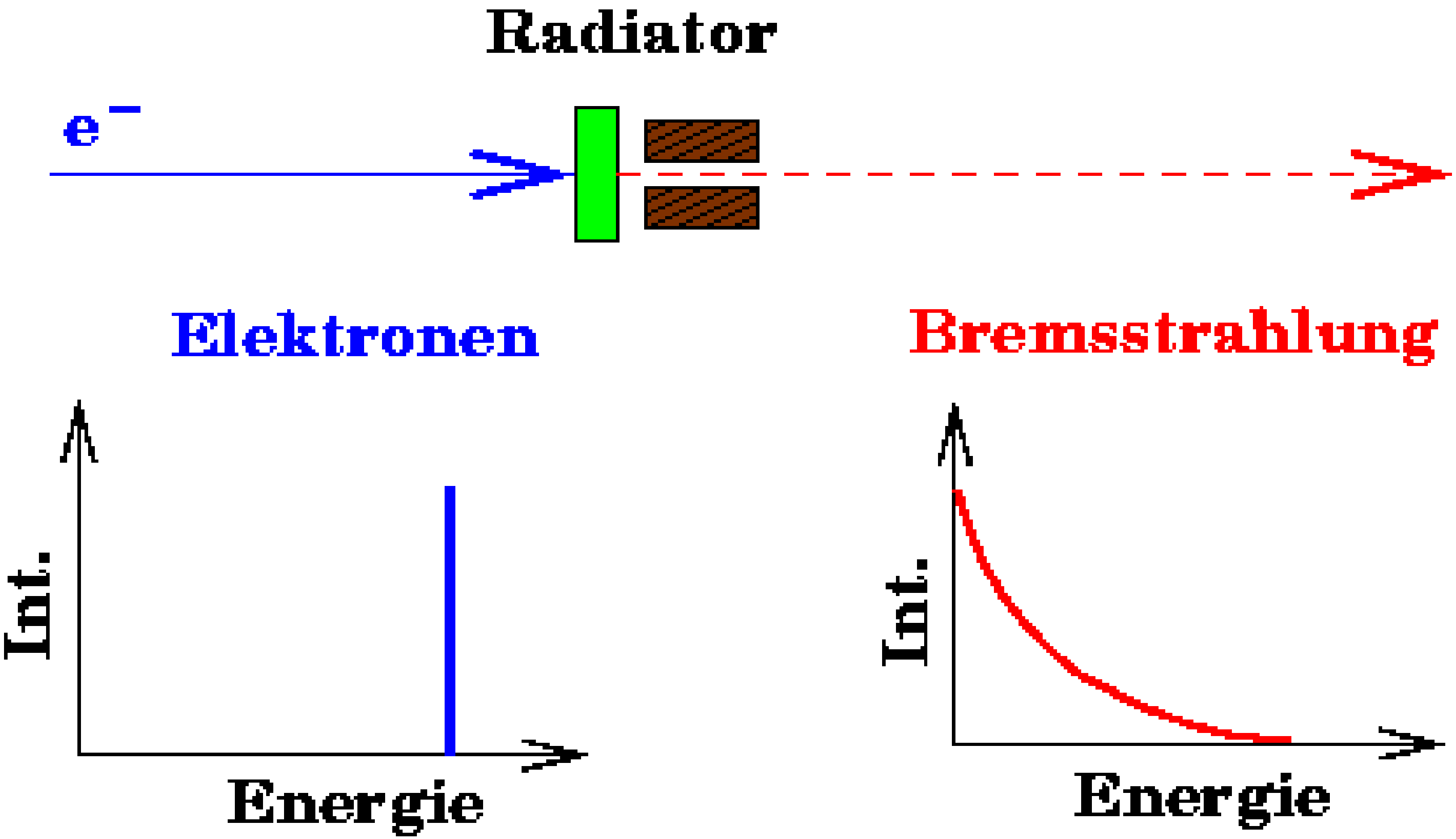
- Various structures determine the photonuclear reaction rate
- Neutron separation energy drops with neutron excess
- Low-energy structures contribute to desintegration
- Contribution enhanced due to exponential Planck-spectrum

Scientific Needs

- **Understand photonuclear reactions in the r-process path**
  - **Extrapolate to experimentally inaccessible isotopes**
    - **Understand details of photonuclear reactions near stability**
    - **Understand evolution of nuclear structure towards the r-process path**
- **Experimental challenges**
  - **Measure details of photonuclear reactions near stability**
  - **Measure evolution of nuclear structure with increasing neutron excess**



Energetic gamma-rays in the lab



Superconducting electron accelerator S-DALINAC @ TU Darmstadt

S-DALINAC and Experimental Areas

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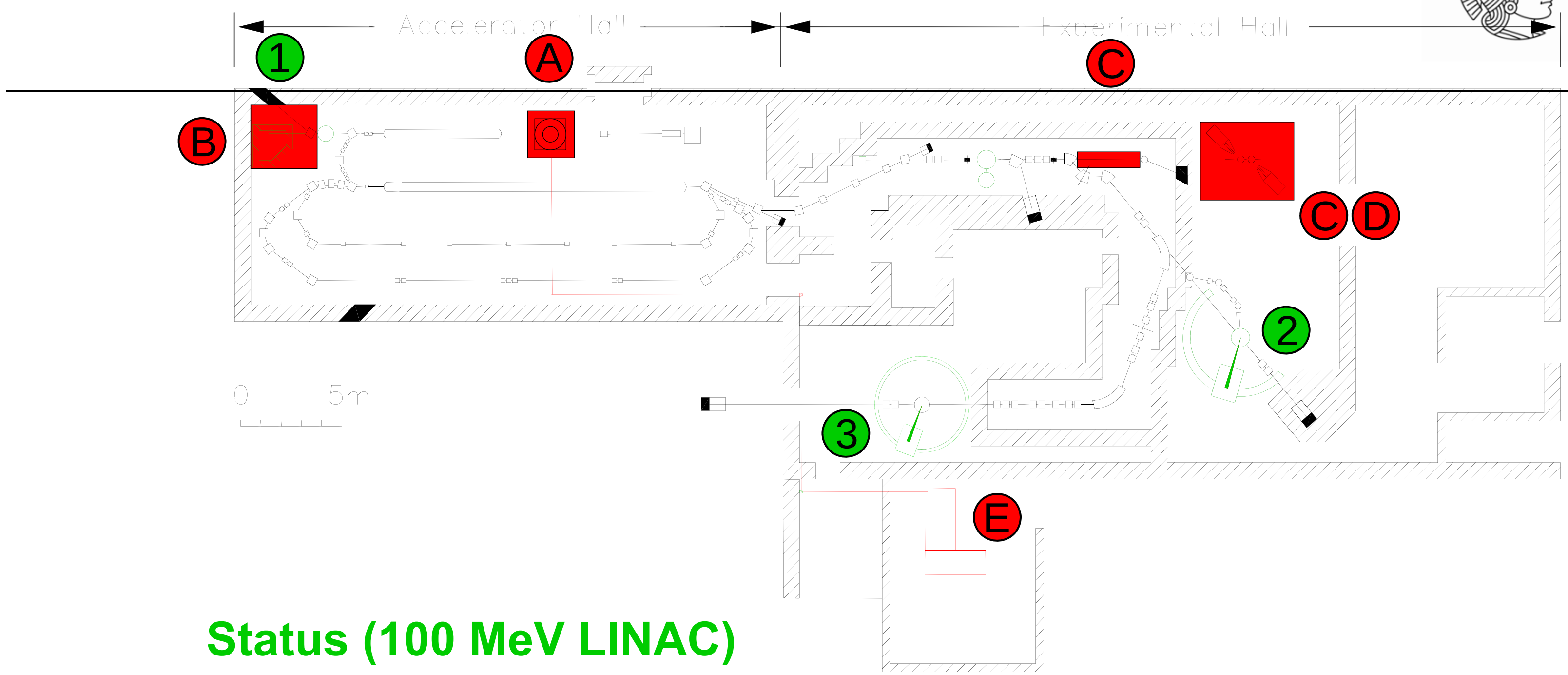
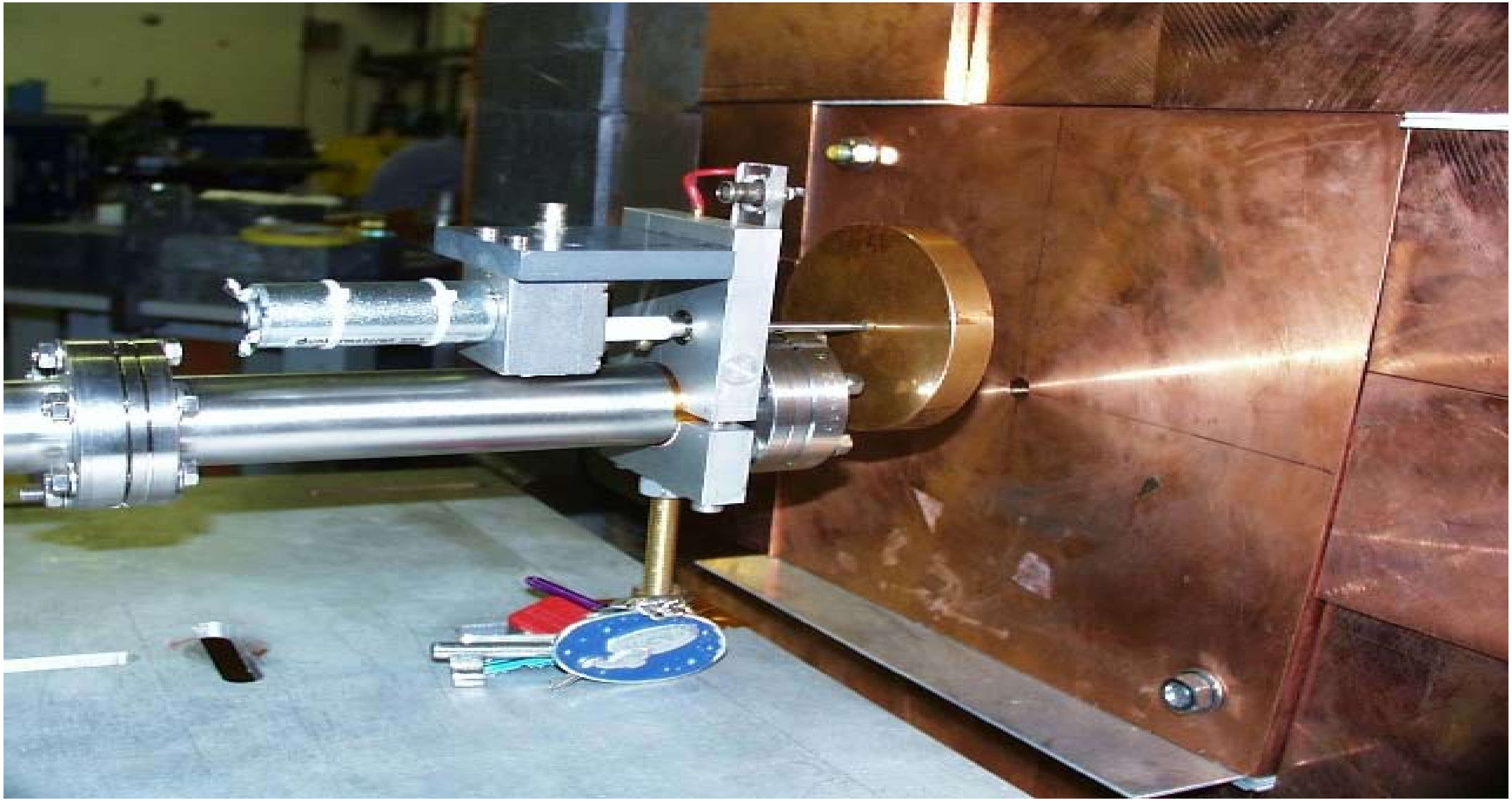


Status (100 MeV LINAC)

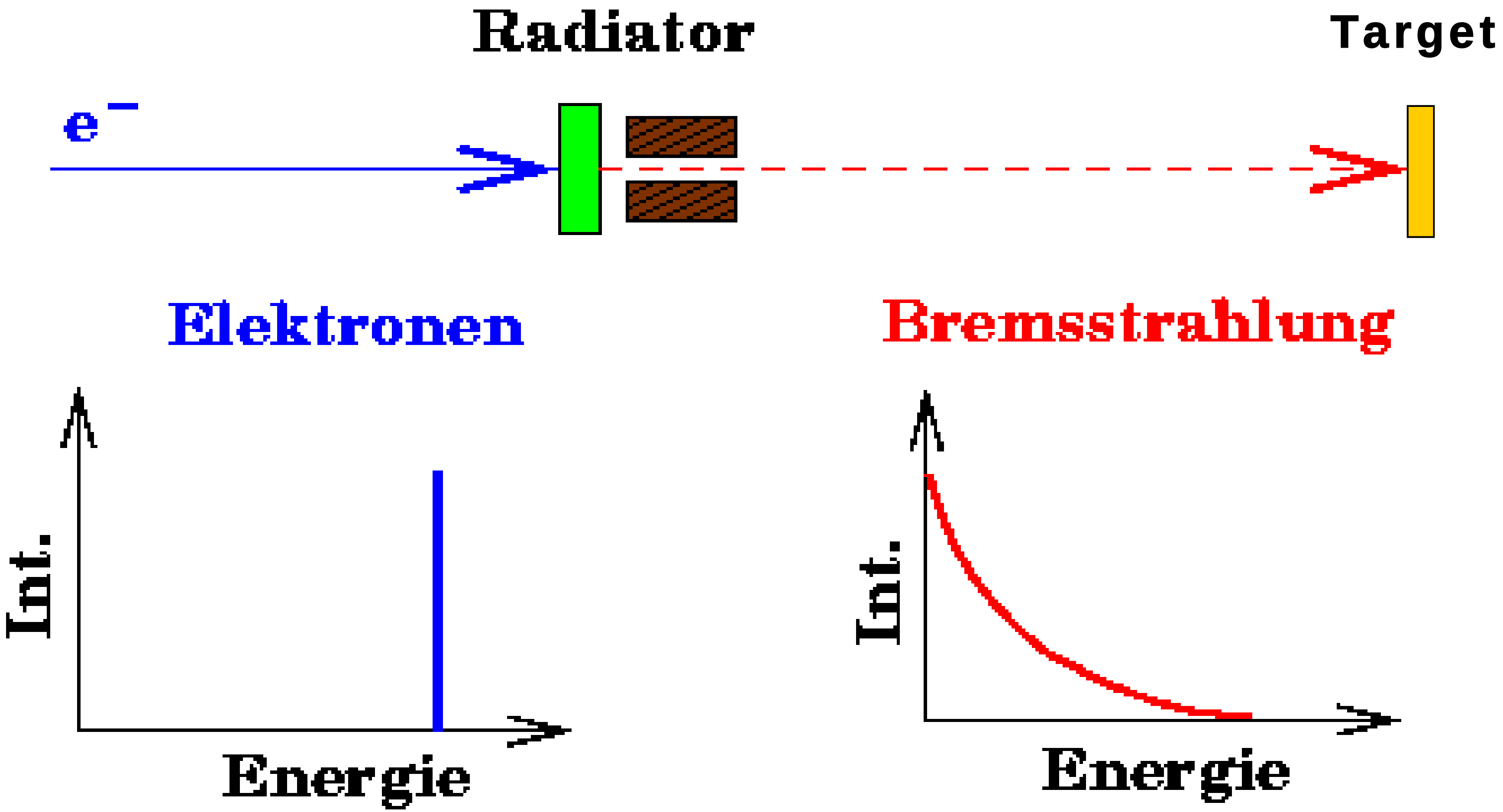
- (1) Gamma-ray beam at low energy (< 10 MeV)
- (2) (e,e´x) experiments & 180°-spectrometer
- (3) (e,e´) experiments at high resolution

- (A) Polarized source
- (B) 14 MeV bremsstrahlung
- (C) Photon tagger
- (D) High-energy bremsstrahlung beam
- (E) Laser for polarized source

Gamma-ray production



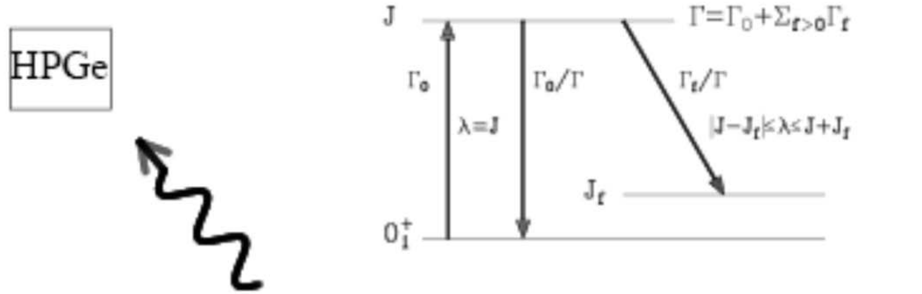
Irradiation of Target

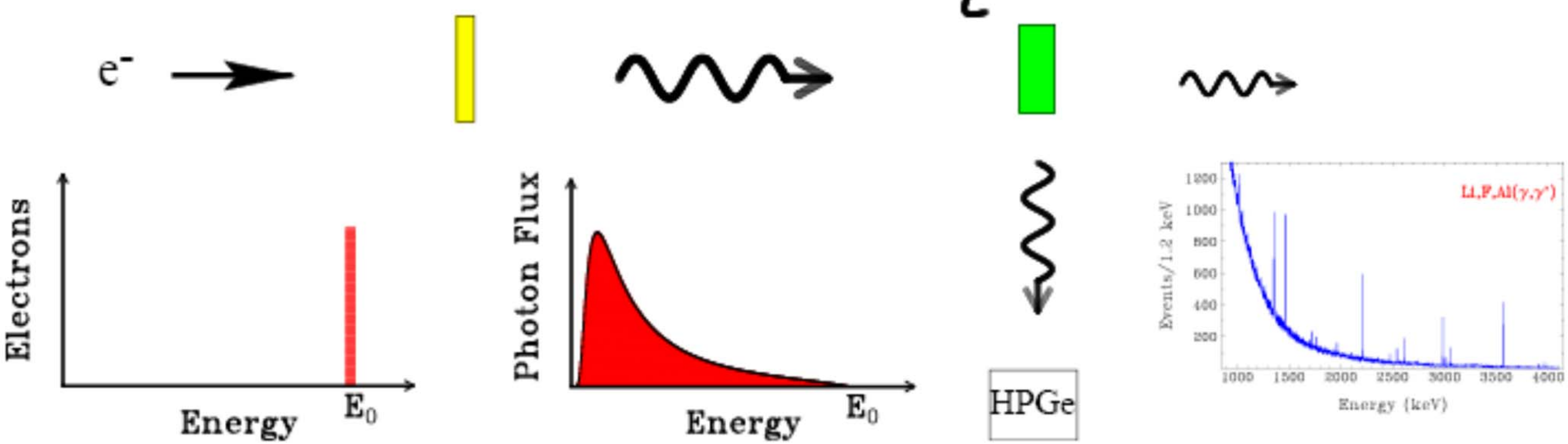


Photon Scattering
(Nuclear Resonance Fluorescence)

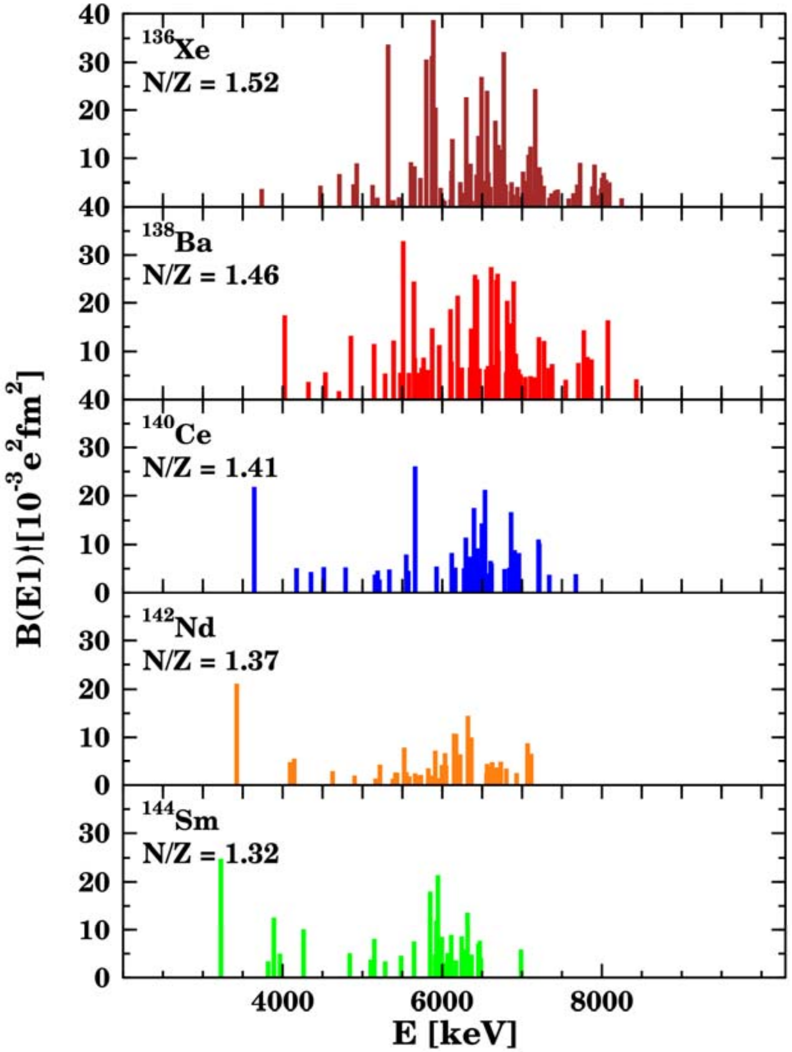
Traditionally Bremsstrahlung: Kneissl,Pietralla,Zilges, J.Phys.G 32, R217 (2006).

high energy resolution
spin selective: ΔJ=1,2
strength selective

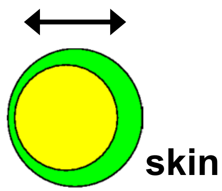




Systematics of the Pygmy Dipole Resonance



- Concentration around 5-7 MeV
- Strong fragmentation
- Summed strength: Scaling with N/Z ?



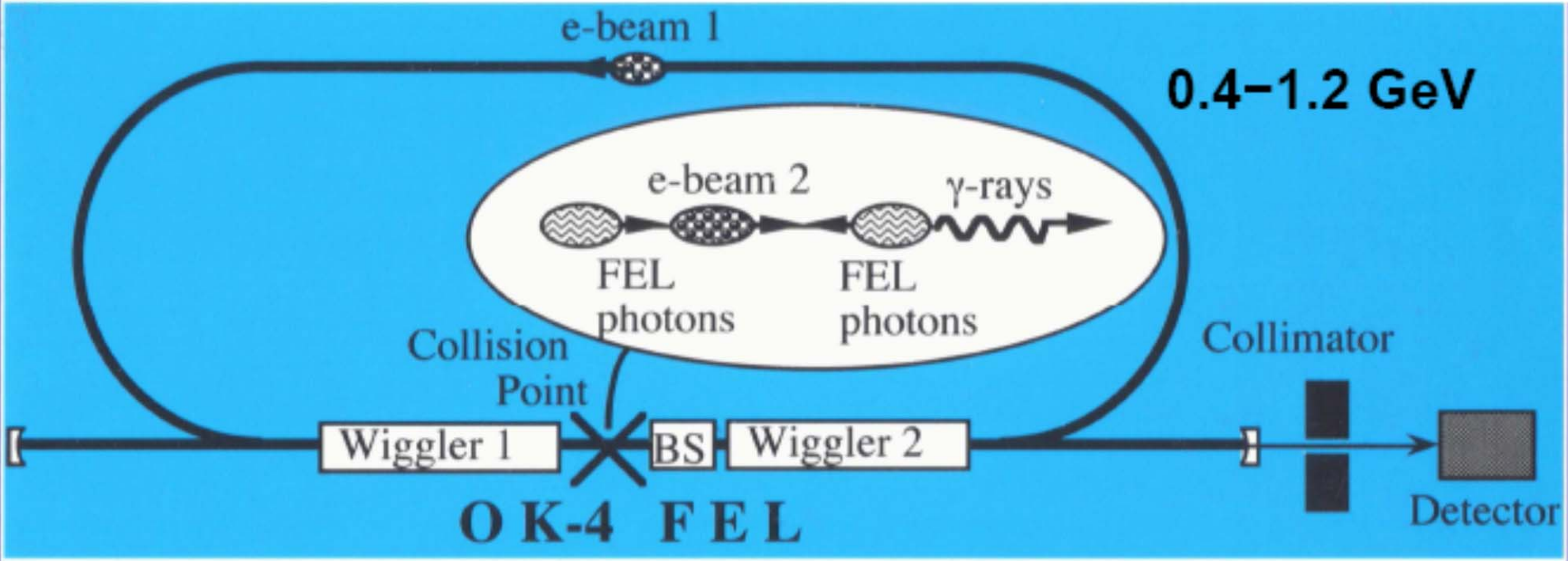
A. Zilges et al., PLB 542, 43 (2002).
D. Savran et al., PRC 84, 024326 (2011).

U. Kneissl et al., J.Phys.G 32, R217 (2006).

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

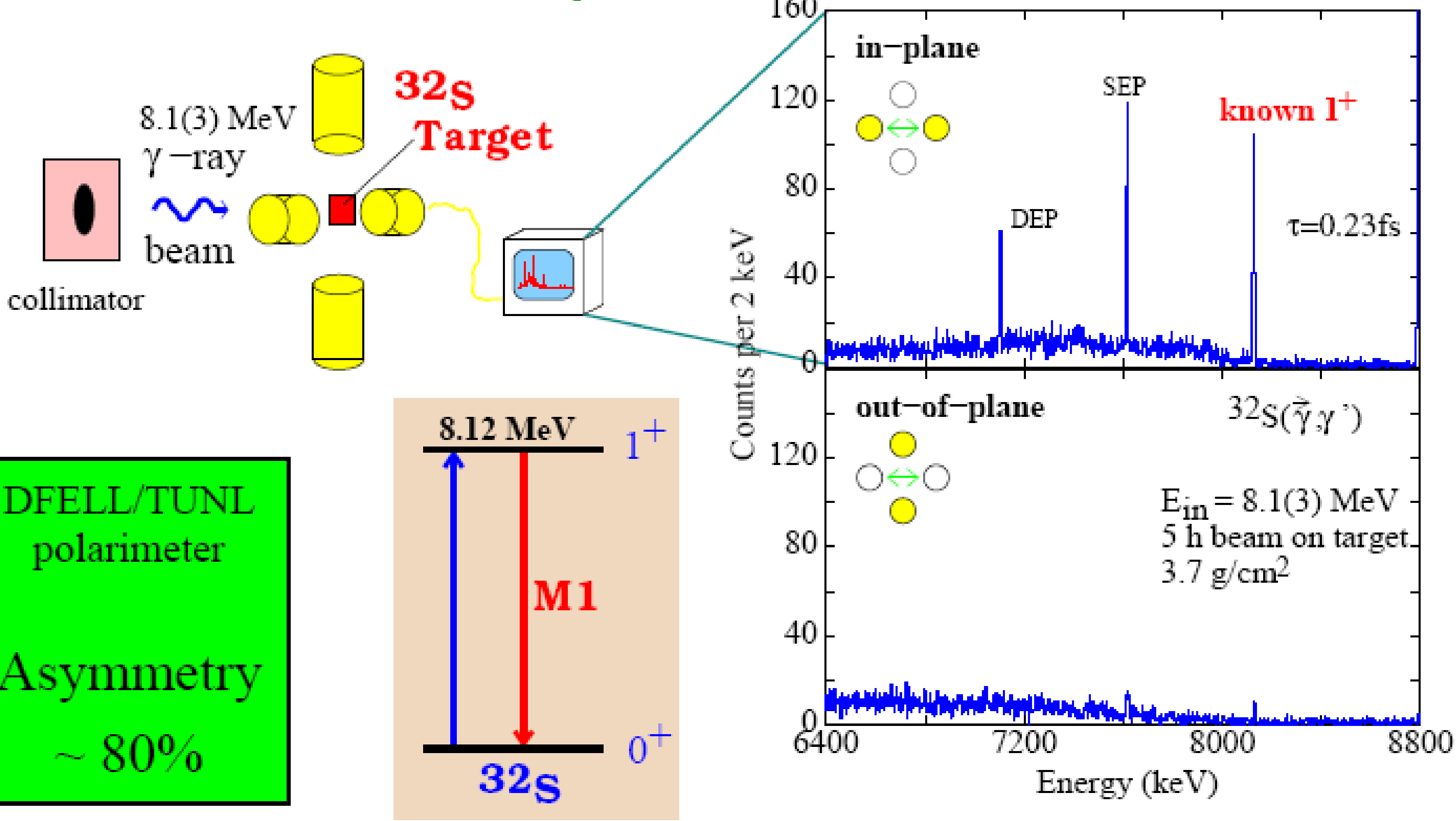


2 − 60 MeV 1.7 − 6.4 eV ~ 1000

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

nearly monochromatic, tunable, completely polarized

Proof of Principle



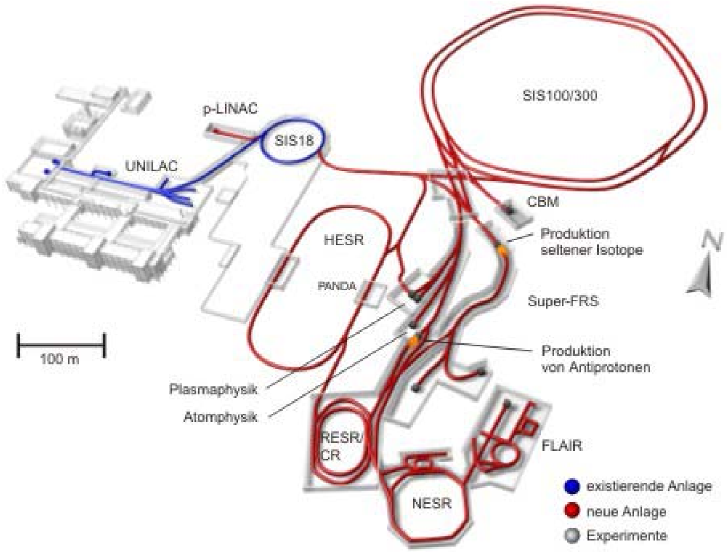
DFELL/TUNL polarimeter

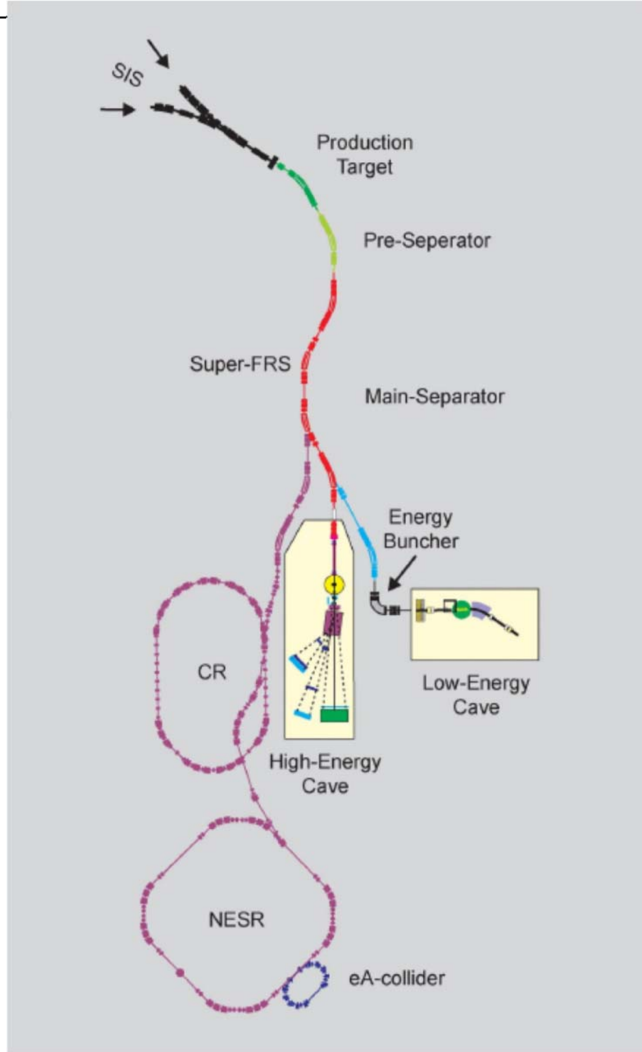
Asymmetry

~ 80%

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

Nuclear STructure Astrophysics and Reactions (NuSTAR)





- Largest Collaboration at FAIR (~ 800 scientists)
- 10 Subcollaborations (numerous working groups)
- Experiments with intense Radioactive Ion Beams from fragmentation and in-flight fission
- Smooth phasing-in from current GSI programme

Produktion radioaktiver Strahlen am Super-FRS

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Projectile:
- Elements p - U
- Energy up to 1.5 GeV/u
- Intensity up to 10^{12} /s (depending on element)
- DC or pulsed operation

Design Parameters:

$\varepsilon_x = \varepsilon_y =$ 40 π mm mrad

$\Phi_x = \pm 40$ mrad

$\Phi_y = \pm 20$ mrad

$\Delta P/P = \pm 2.5$ %

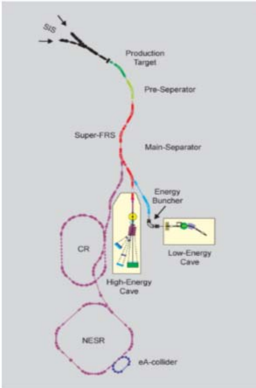
$B\rho$ = 2 - 20 Tm

R_{ion} = 750 / 1500 (first / second stage)

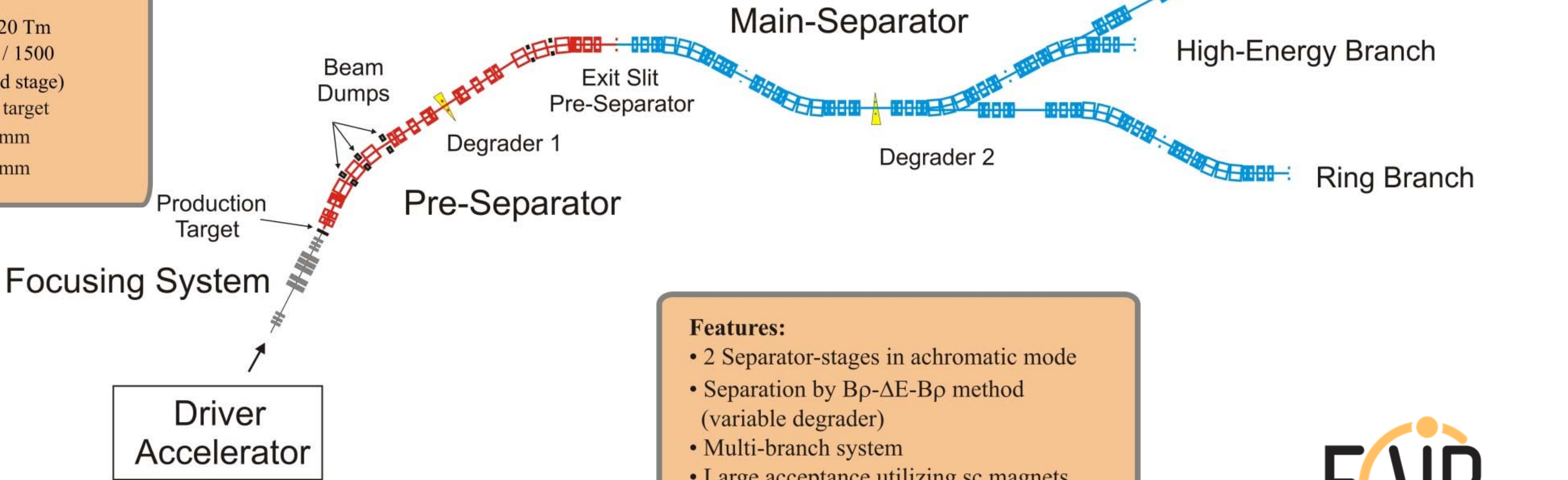
Spot size on target

σ_x = 1.0 mm

σ_y = 2.0 mm



NuSTAR-Anlage
Vollausbau



Features:
- 2 Separator-stages in achromatic mode
- Separation by Bρ-ΔE-Bρ method (variable degrader)
- Multi-branch system
- Large acceptance utilizing sc magnets
- Handling concept for high- radiation area

FAIR

HISPEC – High-resolution Gamma-ray spectroscopy

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Purpose:

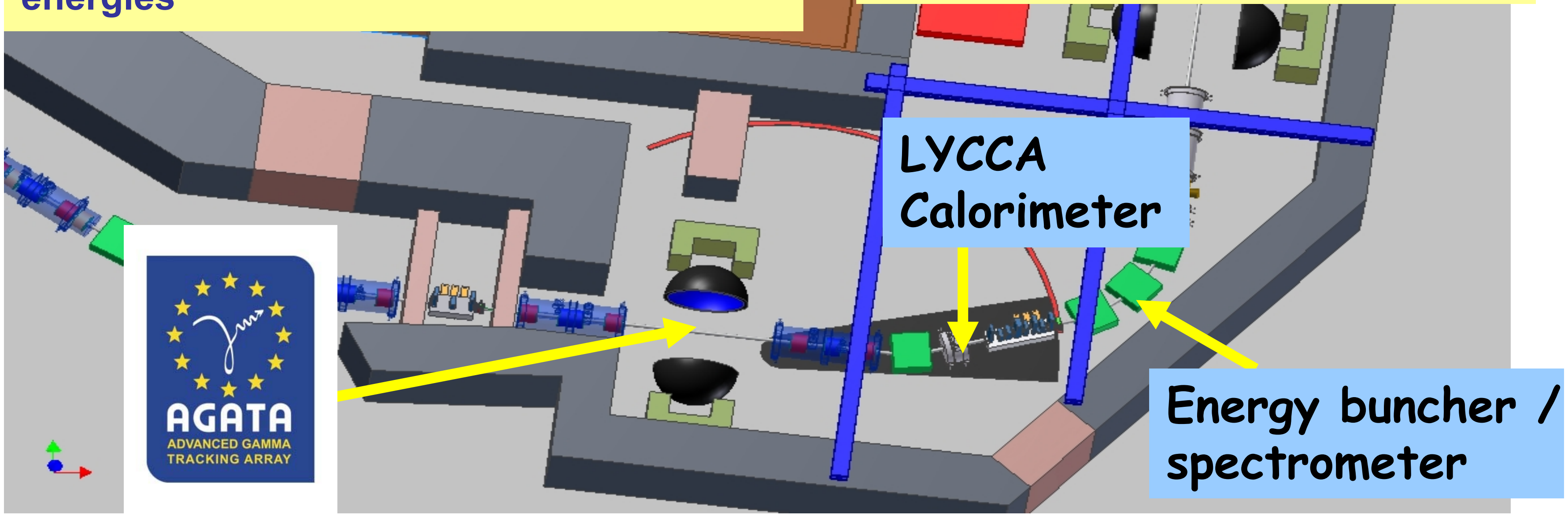
High-resolution in-flight spectroscopy of exotic nuclei using Super-FRS RIB beams at 3 – 400 A·MeV

Methods:

- Coulex, knock-out, fragmentation at relativistic energies
- Coulex, direct reactions, fusion at barrier energies

Set-up:

- Beam tracking and identification (LYCCA)
- Active target
- AGATA
- Fast timing
- HYDE particle array
- Magnetic spectrometer



AGATA – the Gamma-ray spectrometer for HISPEC

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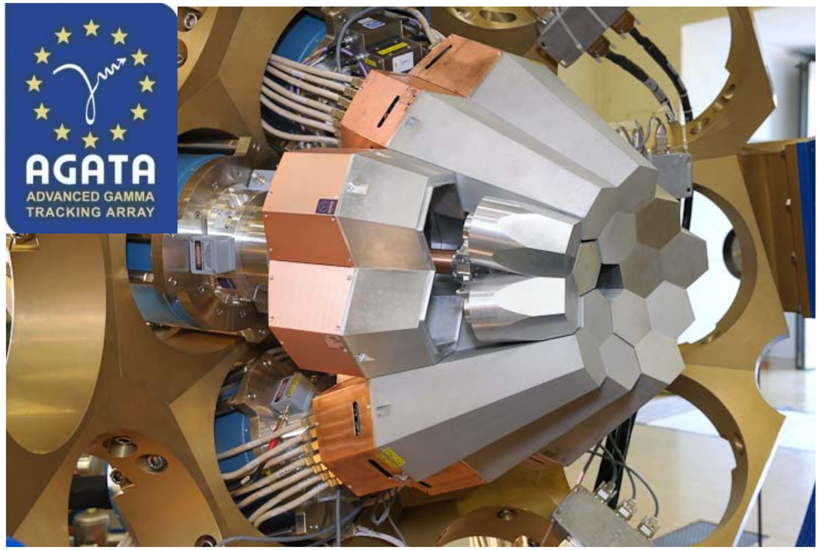
- **AGATA demonstrator commissioning:**
  - ✓ highly segmented HPGe detectors
  - ✓ digitizer & front-end electronics
  - ✓ pulse shape analysis & γ-ray tracking
- **position sensitive γ-detection: Δx~3-4 mm**
- **AGATA@GSI starts 2012**



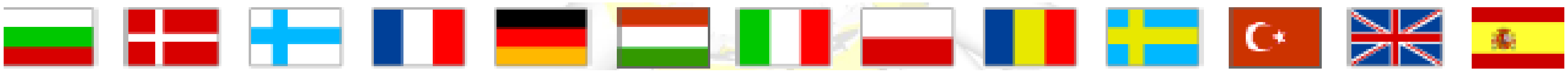
TU Darmstadt
- triple cluster, tracking, tagged photons

GSI Darmstadt
- imaging, infra structure & FRS

Univ. Köln
- triple cluster detector & preamplifier

TU München
- pulse shape analysis

AGATA MoU
- Complete 1/3 of full AGATA
- 15 new AGATA modules & 5 demonstrator modules



From RISING to HISPEC / AGATA

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2010 | 2011 | 2012 | 2013 | 2014 | 2015

RISING

PRESPEC In-beam
LYCCA-0 Commis.

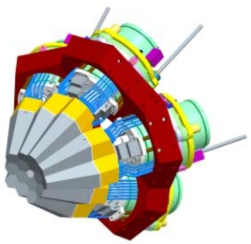
PRESPEC in-beam
with AGATA

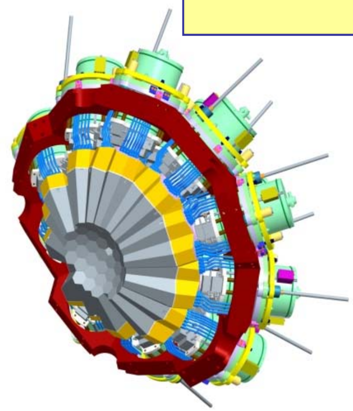
active stopper
g-factors

Min. 25% at
FAIR, GANIL,
Legnaro

AGATA Demonst.
Legnaro

AGATA at GANIL

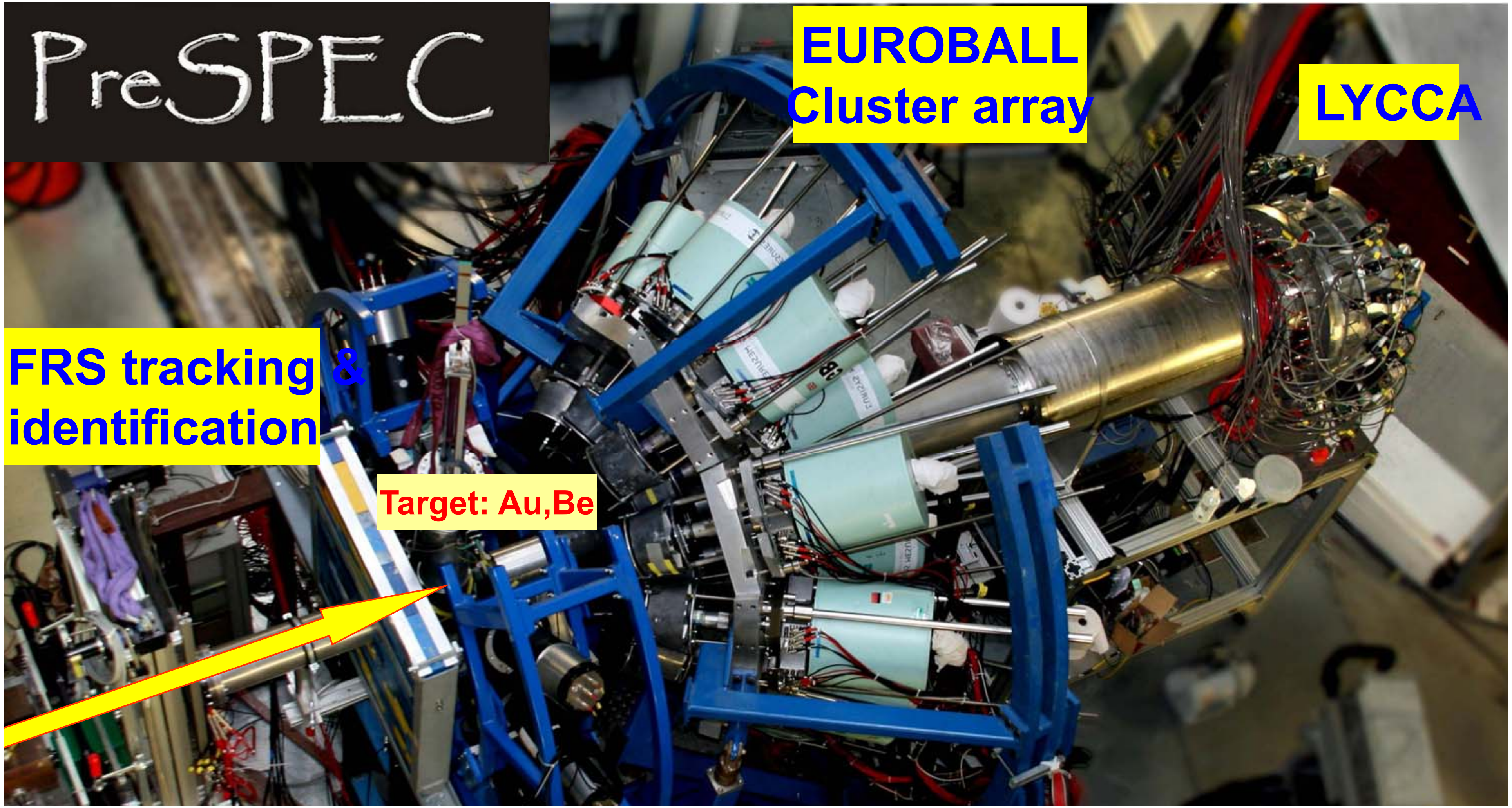


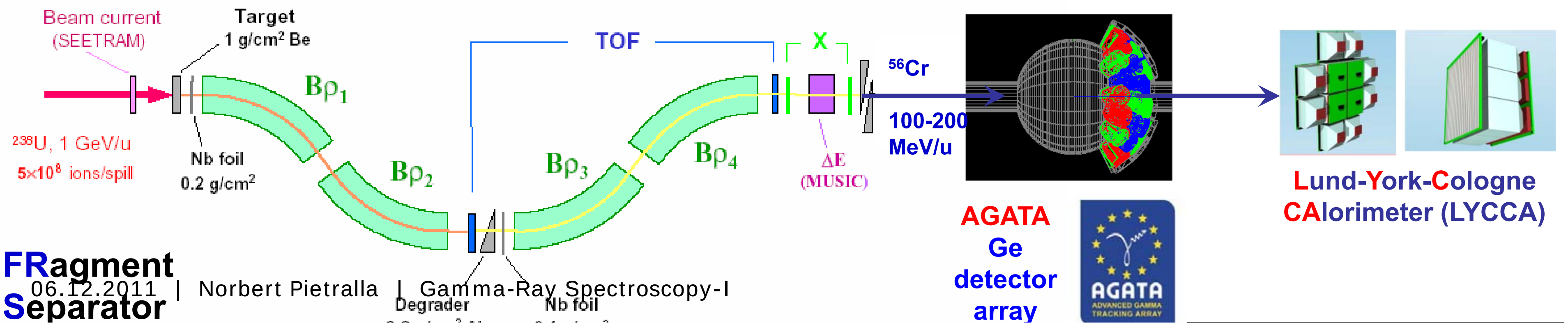


AGATA
ADVANCED GAMMA TRACKING ARRAY

Experimental program 2010-2015: running!

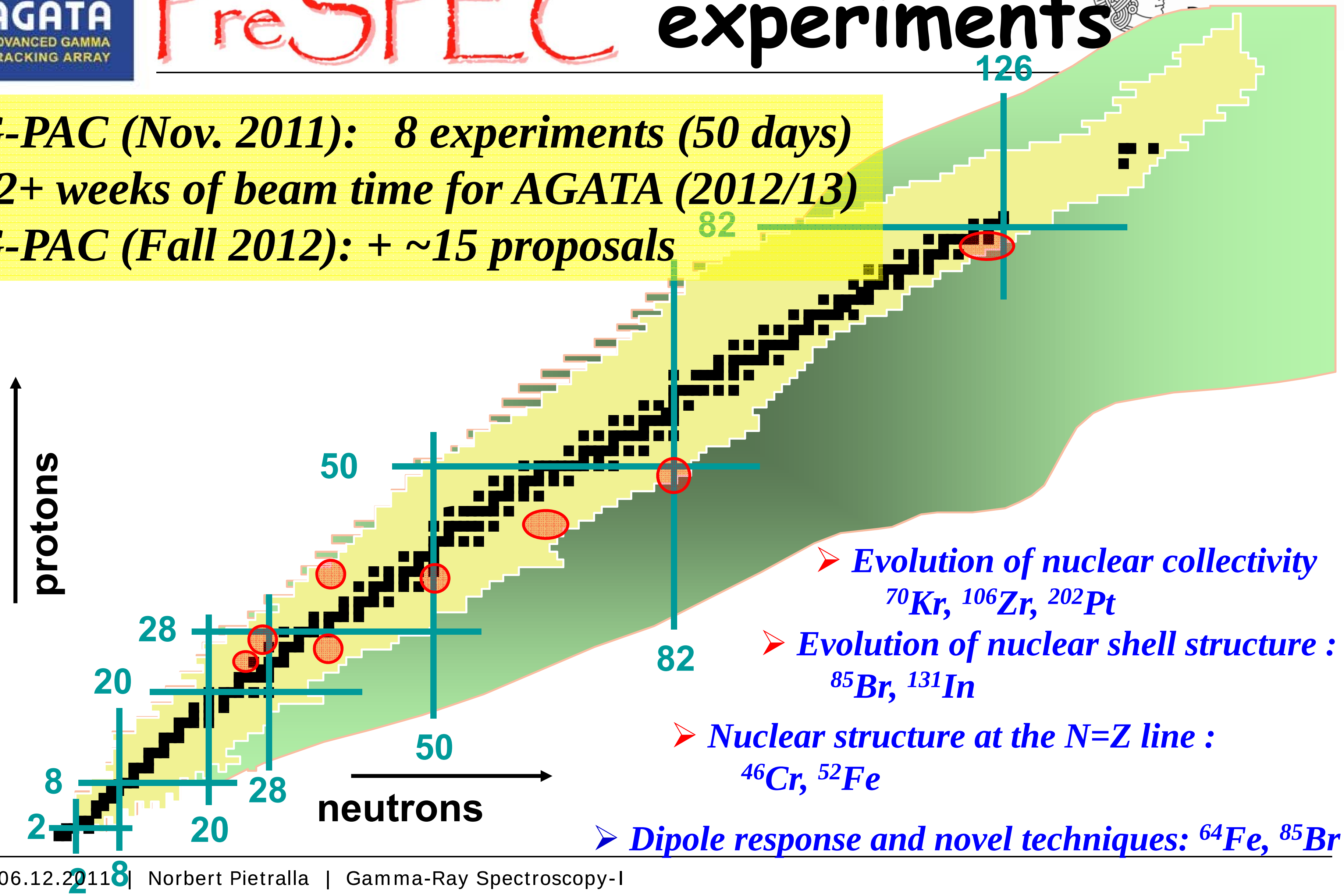
- First Experiments w. AGATA Demonstr. at Legnaro (2010 – now)
- PRESPEC Experiments at GSI (from summer 2012 - 2014 w. AGATA)


PreSPEC
EUROBALL Cluster array
LYCCA
FRS tracking & identification
Target: Au,Be


Beam current (SEETRAM)
Target 1 g/cm² Be
238U, 1 GeV/u
5×10⁸ ions/spill
Nb foil 0.2 g/cm²
Bρ1
Bρ2
Bρ3
Bρ4
TOF
X
ΔE (MUSIC)
56Cr
100-200 MeV/u
Degrader
Nb foil
FRagment Separator
AGATA Ge detector array
AGATA ADVANCED GAMMA TRACKING ARRAY
Lund-York-Cologne CAlorimeter (LYCCA)

PreSPEC experiments

G-PAC (Nov. 2011): 8 experiments (50 days)
12+ weeks of beam time for AGATA (2012/13)
G-PAC (Fall 2012): + ~15 proposals



- ***Evolution of nuclear collectivity***
  ^{70}*Kr*, ^{106}*Zr*, ^{202}*Pt*
- ***Evolution of nuclear shell structure :***
  ^{85}*Br*, ^{131}*In*
- ***Nuclear structure at the N=Z line :***
  ^{46}*Cr*, ^{52}*Fe*
- ***Dipole response and novel techniques:*** ^{64}*Fe*, ^{85}*Br*

Summary

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Nuclear Gamma-ray spectroscopy and nuclear astrophysics

- Address nuclear-physics input to astrophysical problems
- Example: photonuclear reactions in r-process path
  - For quantifying photodesintegration rates of freshly synthesized nuclei
  - Study details of photonuclear reactions where accessible
  - Study evolution of nuclear structure with increasing neutron excess
- What I didn't talk about:
  - Synthesis of p-process isotopes
  - Neutrino-nuclear reactions (related by electroweak force)
  - Access to neutron matter and nuclear equation of state
  - And much more...

Cross-disciplinary discussion highly welcome!

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