

Start
Liverpool, June 2007

Monoenergetic photons from 4GLS and Nuclear Astrophysics

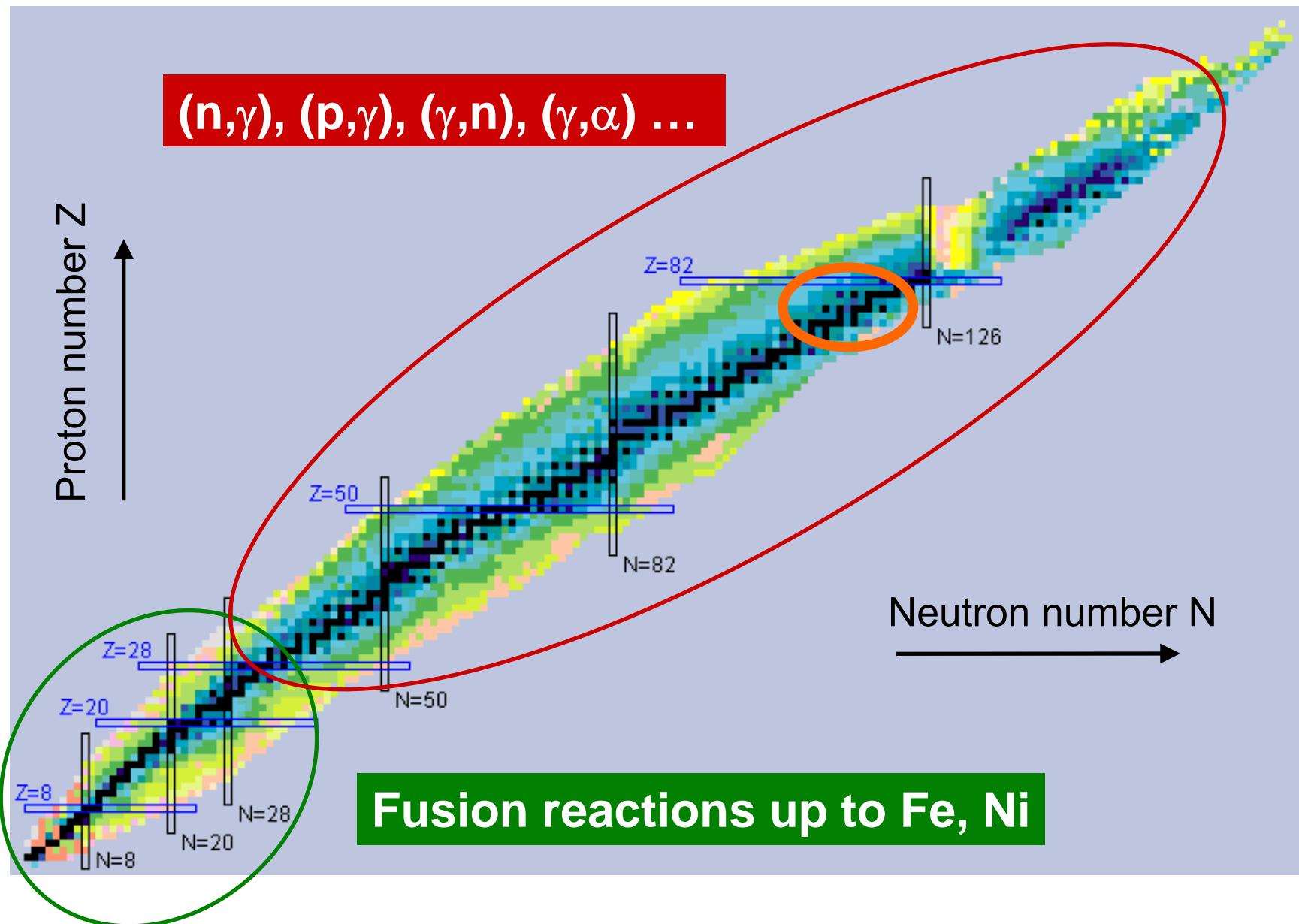
- **Synthesis of heavy nuclei**
- **Photon induced reaction rates**
- **New opportunities with 4GLS**



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Synthesis of heavy nuclei



Synthesis of heavy nuclei

The figure displays a periodic table of elements with various decay chains highlighted by colored arrows:

- p-process**: Indicated by red arrows pointing upwards from the bottom of the table towards the upper right.
- s-process**: Indicated by green arrows pointing upwards from the middle of the table towards the upper right.
- r-process**: Indicated by blue arrows pointing upwards from the bottom left towards the upper right.

Key decay chains shown include:

- p-process** paths: Hg-186 → Hg-187 → Hg-188 → Hg-189; Pt-184 → Pt-185 → Pt-186 → Pt-187 → Pt-188 → Pt-189 → Pt-190 → Pt-191 → Pt-192 → Pt-193 → Pt-194 → Pt-195 → Pt-196 → Pt-197 → Pt-198; Ir-183 → Ir-184 → Ir-185 → Ir-186 → Ir-187 → Ir-188 → Ir-189 → Ir-190 → Ir-191 → Ir-192 → Ir-193 → Ir-194 → Ir-195 → Ir-196 → Ir-197; Os-182 → Os-183 → Os-184 → Os-185 → Os-186 → Os-187 → Os-188 → Os-189 → Os-190 → Os-191 → Os-192 → Os-193 → Os-194 → Os-195 → Os-196; Re-181 → Re-182 → Re-183 → Re-184 → Re-185 → Re-186 → Re-187 → Re-188 → Re-189 → Re-190 → Re-191 → Re-192.
- s-process** paths: Hg-186 → Hg-187 → Hg-188 → Hg-189; Au-185 → Au-186 → Au-187 → Au-188 → Au-189 → Au-190 → Au-191 → Au-192 → Au-193 → Au-194 → Au-195 → Au-196 → Au-197 → Au-198 → Au-199 → Au-200.
- r-process** paths: W-180 → W-181 → W-182 → W-183 → W-184 → W-185 → W-186 → W-187 → W-188 → W-189 → W-190.

p-process

s-process

(γ ,n), (γ ,p) and (γ , α) reactions

(γ ,n) reactions

r-process

(n, γ) / (γ ,n) equilibrium

Reactions and decays in the p-process

Pb 188 25,5 s	Pb 189 51 s	Pb 190 1,2 m	Pb 191 2,2 m	Pb 192 3,5 m	Pb 193 5,6 m	Pb 194 12,0 m	Pb 195 16,0 m	Pb 196 36,4 m	Pb 197 49 m	Pb 198 2,40 h	Pb 199 122 d	Pb 200 21,5 h	Pb 201 61 s	Pb 202 8,4 h	Pb 203 6,2 s	Pb 204 67,2 m			
c, β^+ , - 5,890; γ 185; 758... 0	*	c, β^+ , - 5,72; γ 271; 107... 0	*	c, β^+ , - 5,577; γ 942; 142; 151... 0	*	c, β^+ , - 5,112; γ 1195; 908; 108... 0	*	c, β^+ , - 4,64; γ 592; 1619; 204... 0	*	c, β^+ , - 2,92; 502; γ 125; 132... 0	*	c, β^+ , - 1,56; 385; γ 173... 0	*	c, β^+ , - 1,35; 257; γ 238; 280... 0	*	c, β^+ , - 1,25; 120; 142; 151... 0	*	c, β^+ , - 1,14; 91; 122; 131... 0	
Tl 187 18 d	Tl 188 45 s	Tl 189 1,2 m	Tl 190 2,3 m	Tl 191 3,7 m	Tl 192 7,4 m	Tl 193 10,8 m	Tl 194 13 m	Tl 195 35 s	Tl 196 1,13 h	Tl 197 1,41	Tl 198 1,41	Tl 199 1,87	Tl 200 26,1 h	Tl 201 81 s	Tl 202 8,4 h	Tl 203 6,2 s	Tl 204 31,3 h		
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
Hg 186 1,4 m	Hg 187 24 m	Hg 188 2,2 m	Hg 189 3,7 m	Hg 190 6,7 m	Hg 191 7,7 m	Hg 192 20,0 m	Hg 193 60,8 m	Hg 194 50 m	Hg 195 520 a	Hg 196 40 h	Hg 197 0,15	Hg 198 0,15	Hg 199 42,5 m	Hg 200 23,10	Hg 201 13,18	Hg 202 29,86	Hg 203 29,524		
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
Au 18 4,2 m	Au 187 3,1 m	Au 188 3,4 m	Au 189 4,6 m	Au 190 28,3 m	Au 191 42,8 m	Au 192 1 a	Au 193 3,18 h	Au 194 5,0 h	Au 195 10,4	Au 196 17,65 h	Au 197 36,0 h	Au 198 32,4	Au 199 103	Au 200 3,139 d	Au 201 18,7	Au 202 48,4 m	Au 203 26,4 m		
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
Pt 184 17,3 m	Pt 185 33 m	Pt 186 1,2 h	Pt 187 2,3	Pt 188 11 h	Pt 189 0,01	Pt 190 0,01	Pt 191 2,8 d	Pt 192 0,79	Pt 193 4,33 d	Pt 194 - 30 s	Pt 195 32,9	Pt 196 4,02 d	Pt 197 33,8	Pt 198 25,3	Pt 199 94,4 m	Pt 200 13,8 a	Pt 201 50,8 m	Pt 202 12,5 h	
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
Ir 183 55 m	Ir 184 3,0 h	Ir 185 3,1	Ir 186 16,64 h	Ir 187 10,5 h	Ir 188 41,5 h	Ir 189 13,3 d	Ir 190 3,1 h	Ir 191 13,8	Ir 192 11,6 d	Ir 193 10,63 d	Ir 194 12,7	Ir 195 171 d	Ir 196 19,15 h	Ir 197 2,8 h	Ir 198 52 s	Ir 199 8,9 m	Ir 200 5,8 m	Ir 201 8 s	
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
Os 182 22,1 h	Os 183 0,9 h	Os 184 10,0 h	Os 185 0,02	Os 186 94 d	Os 187 0,58	Os 188 2,0 - 10 ¹⁰ a	Os 189 1,6	Os 190 8 h	Os 191 14,1	Os 192 8,9 m	Os 193 13,10 h	Os 194 15,4 d	Os 195 6,1 s	Os 196 41,0	Os 197 30,11 h	Os 198 6,0 a	Os 199 6,5 m	Os 200 34,9 m	122
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Re 181 20 h	Re 182 13 h	Re 183 84 h	Re 184 71 d	Re 185 169 d	Re 186 38,0 d	Re 187 2 - 10 ⁵ a	Re 188 62,60	Re 189 5 - 10 ¹⁰ a	Re 190 24,3 h	Re 191 3,0 h	Re 192 3,1 m	Re 193 16 s	Re 194 16	Re 195 11 s	Re 196 11 s	Re 197 11 s	Re 198 11 s	Re 199 11 s	
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
W 180 0,13	W 181 121,2 d	W 182 26,3	W 183 53,6	W 184 14,3	W 185 30,67	W 186 1,87 m	W 187 76,1 d	W 188 28,6	W 189 23,72 h	W 190 69 d	W 191 11 m	W 192 30,0 m	118	120					
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		

(γ, n)

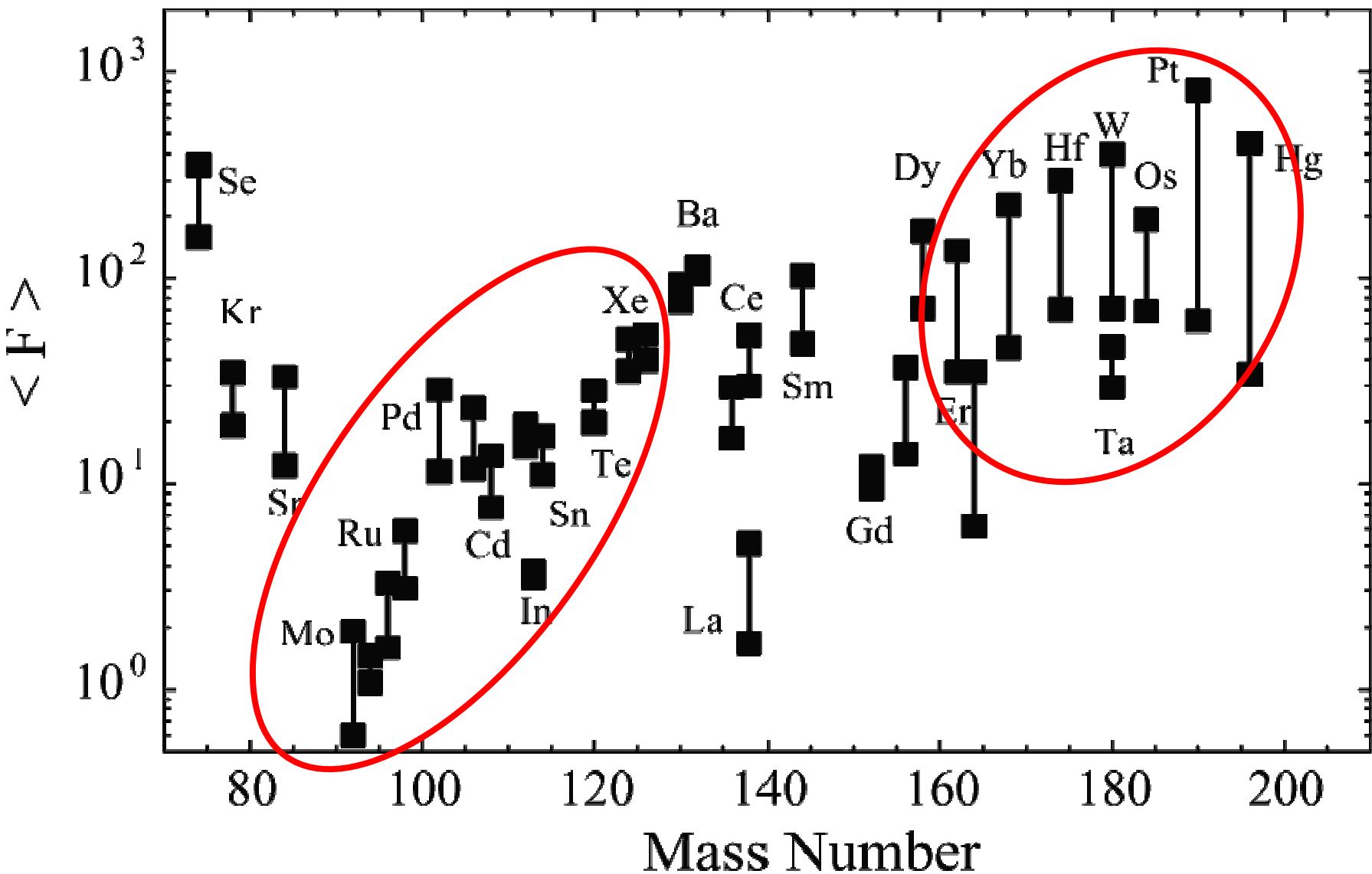
(γ, p)

(γ, α)

β^+

Especially for lighter nuclei:
Competing (n, γ), (p, γ), (α, γ)-reactions, νp -process

Abundance of p-nuclei: model vs. experiment

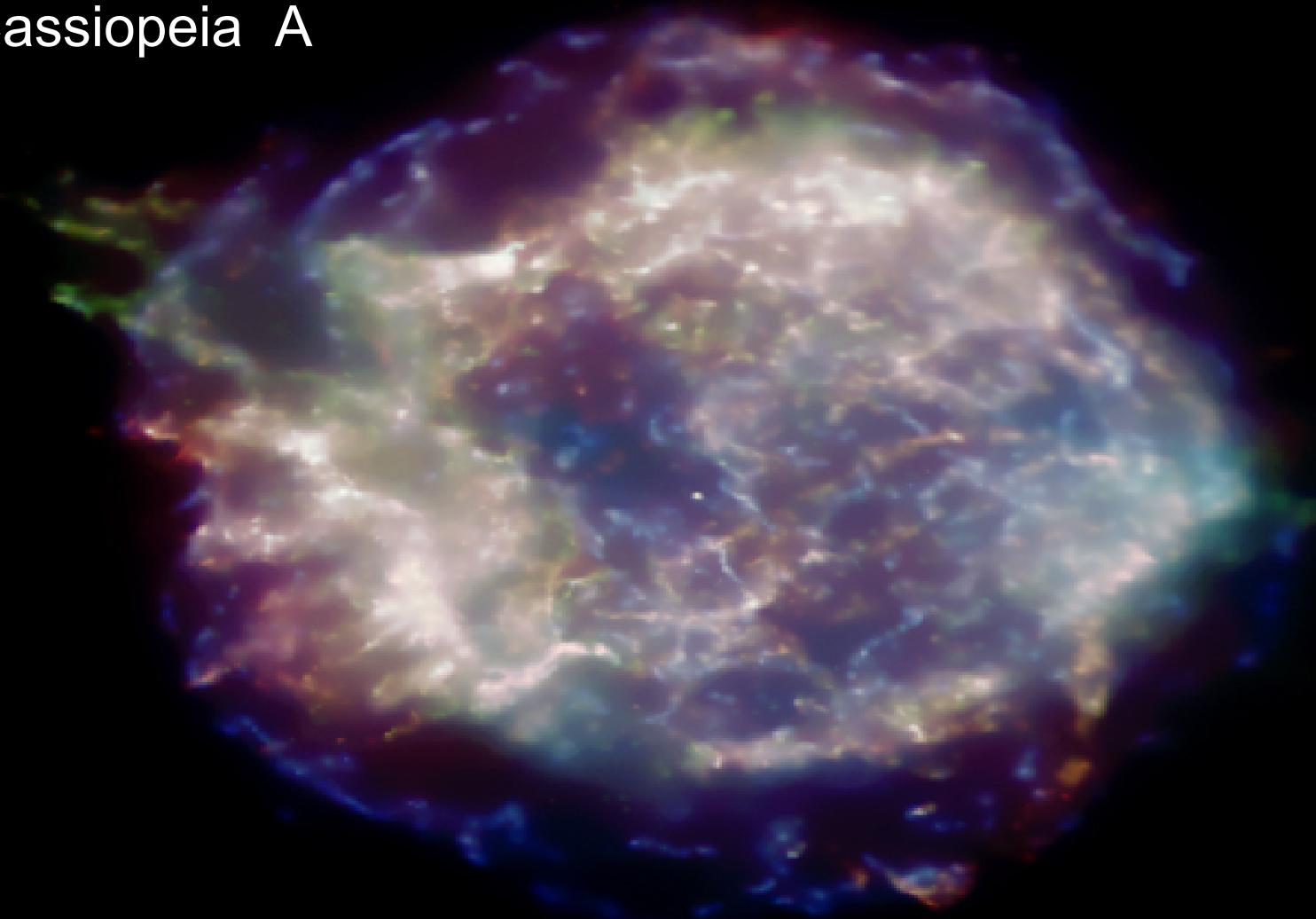


Nuclear Physics input for the p-process

- Groundstate masses
- Properties of excited states
- Level densities
- Photoresponse (γ, γ'), (γ, n), (γ, α), (γ, p)
- Optical potentials

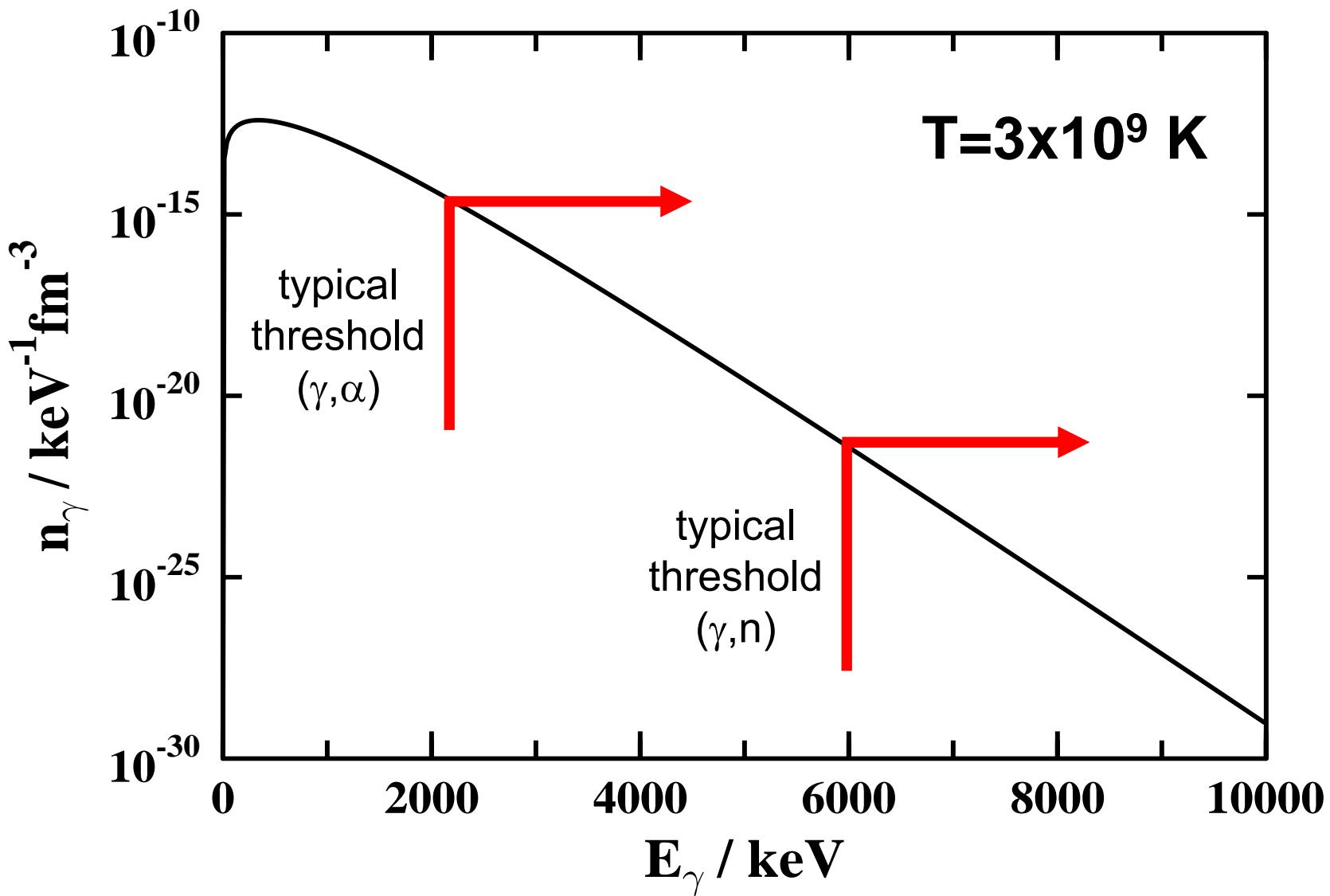
Origin of the photons

Cassiopeia A



Temperatures up to 3×10^9 K ~ 200 keV

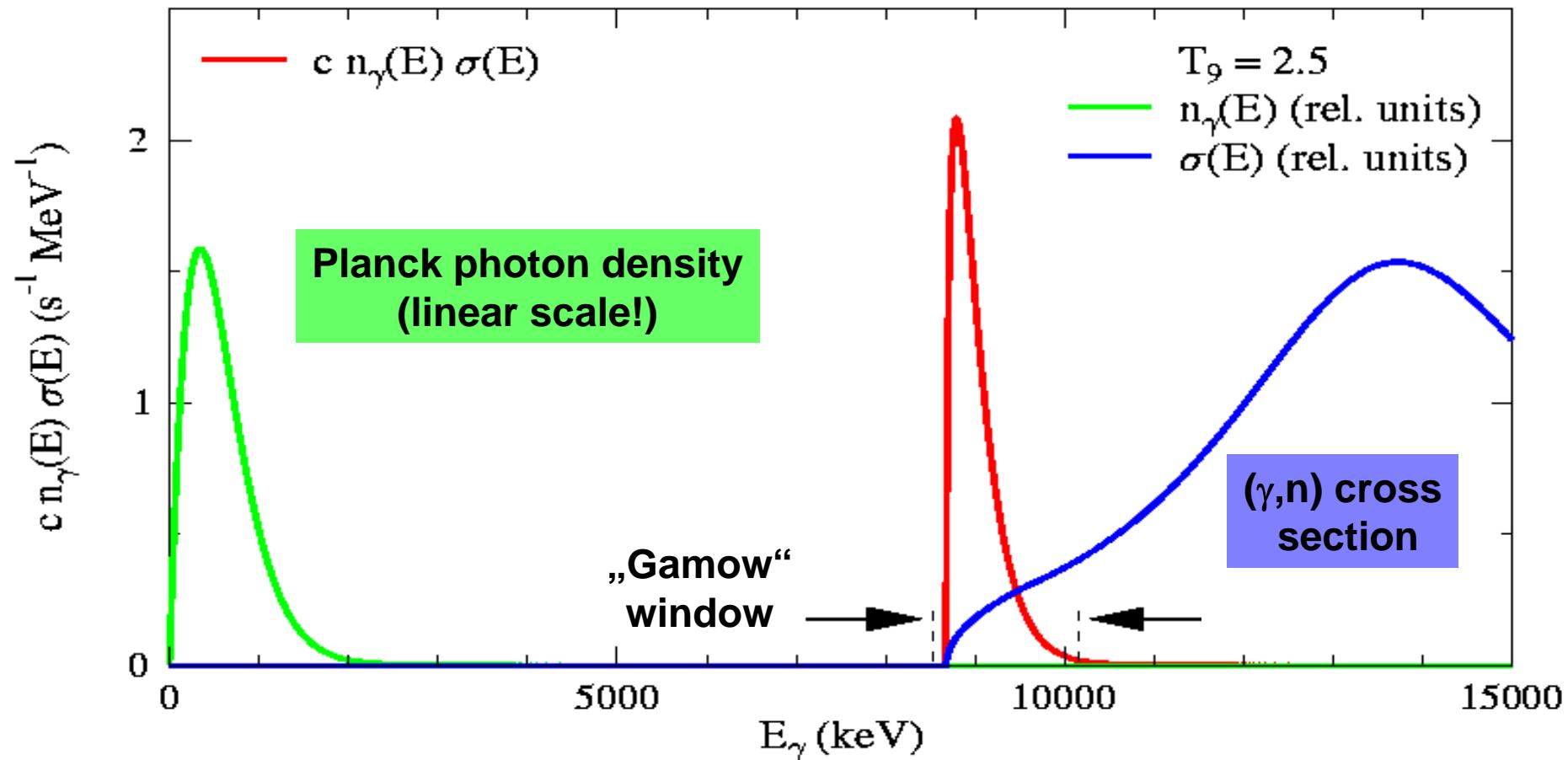
The photon density – a Planck distribution



What is the relevant energy range ?

Reaction Rate:

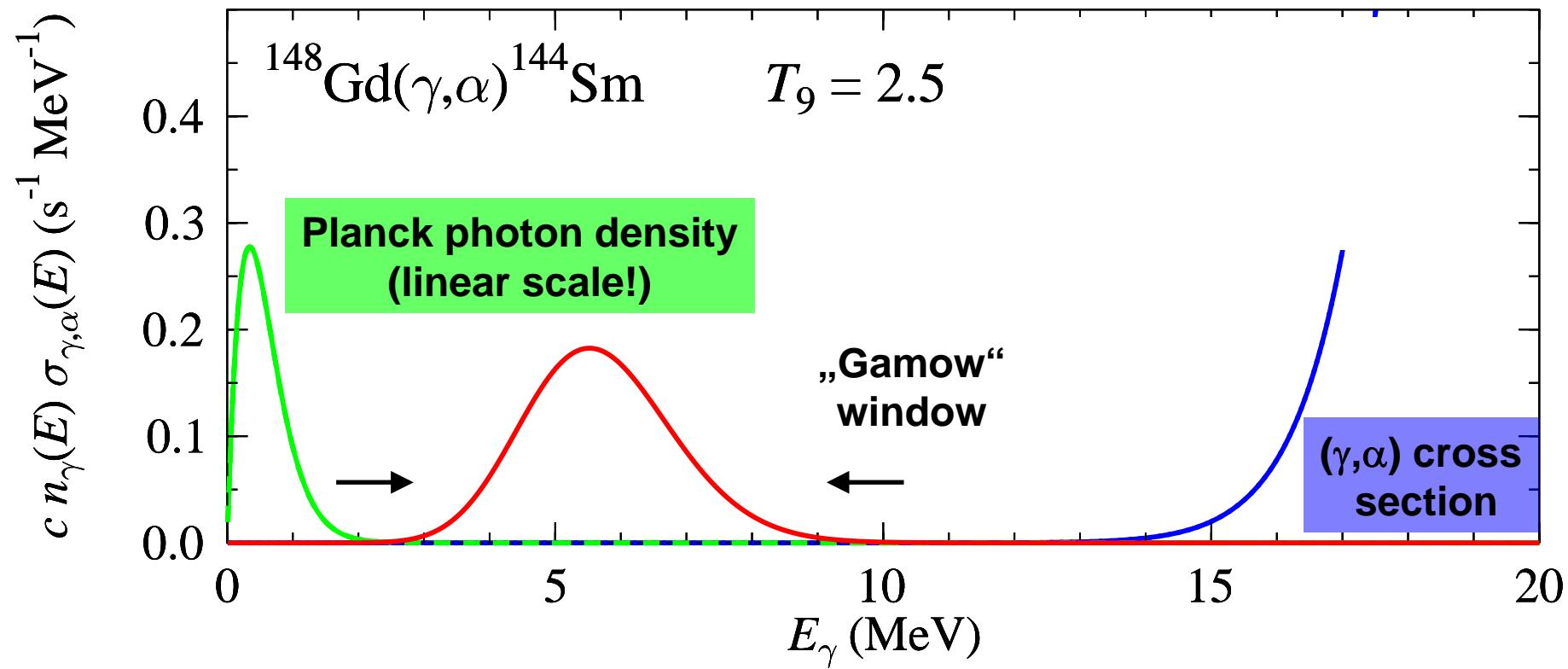
$$\lambda(T) = c \int n_\gamma(E) \sigma(E) dE$$



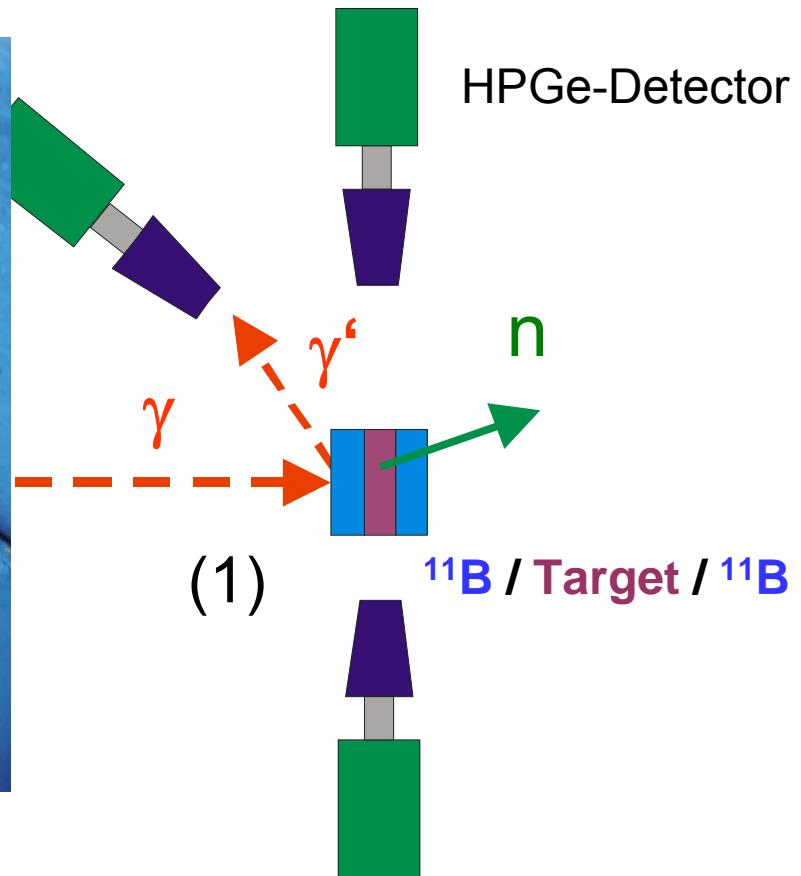
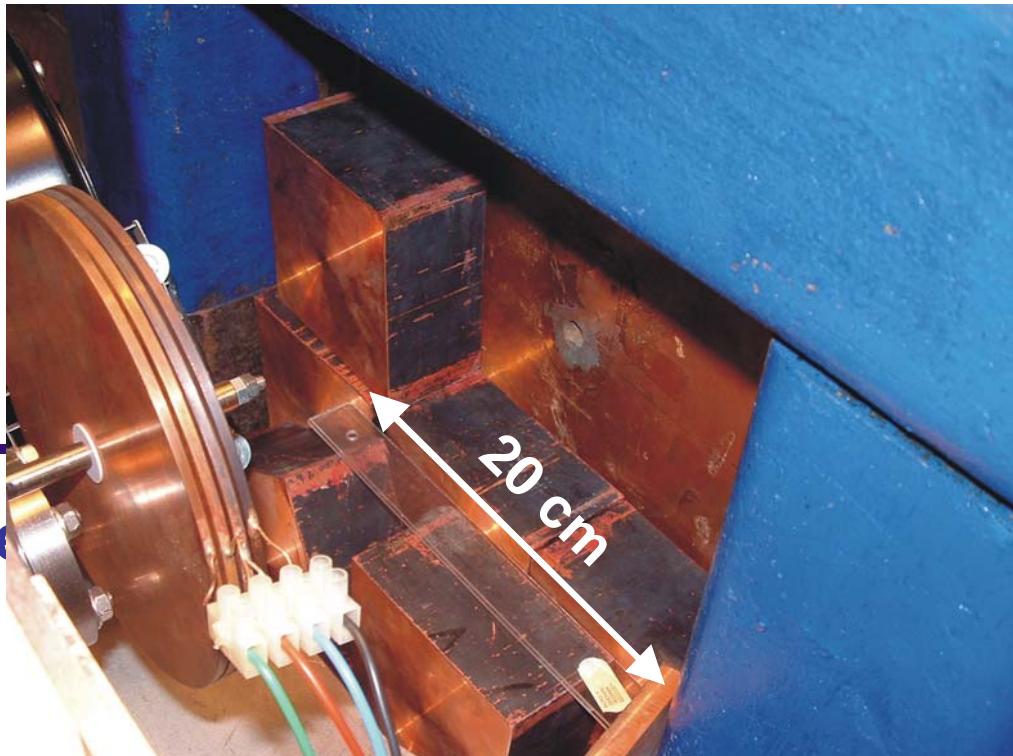
What is the relevant energy range ?

Reaction Rate: $\lambda(T) = c \int n_\gamma(E) \sigma(E) dE$

Now: $\sigma(E) = \sigma(\gamma, \alpha)$



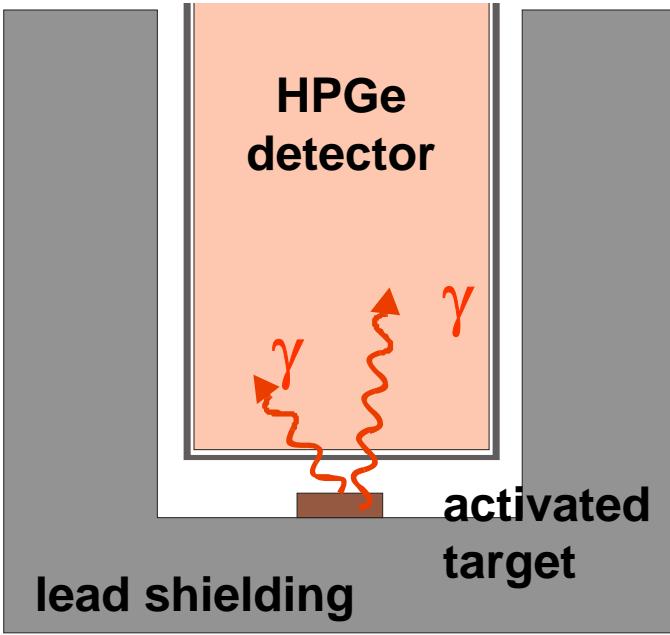
The photoactivation setup at S-DALINAC



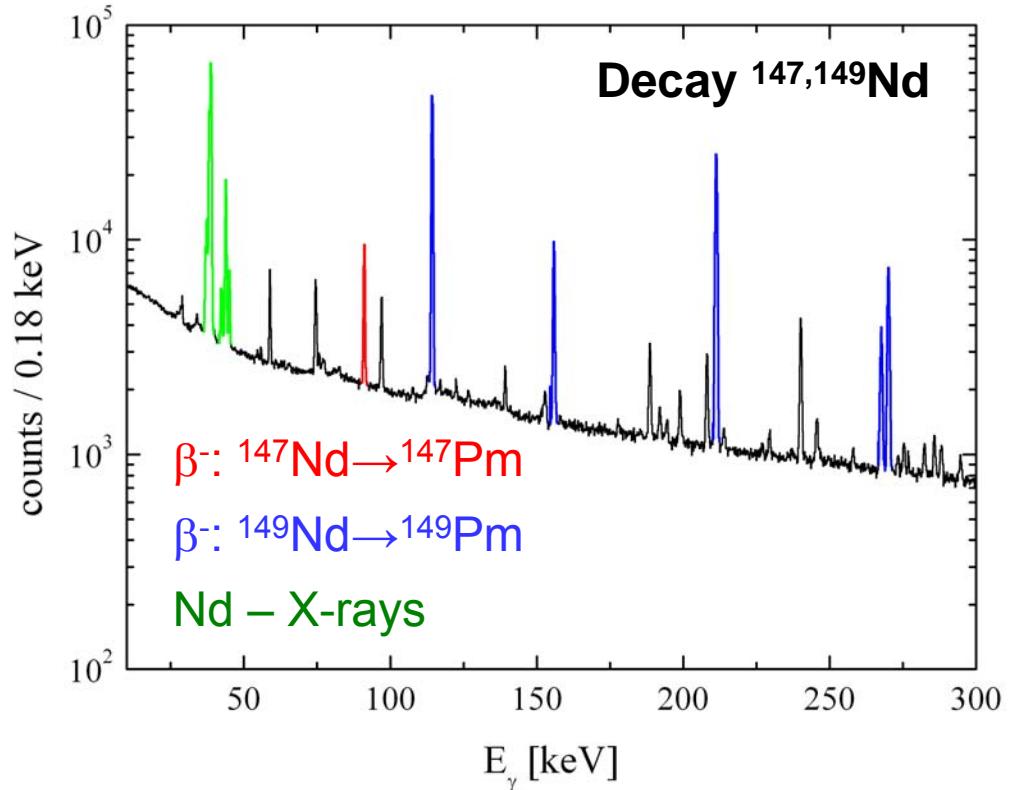
(1) Photon flux $\sim 10^5 \text{ } \gamma / (\text{keV s cm}^2)$
Calibration of the photon flux via $^{11}\text{B}(\gamma, \gamma')$

(2) Photon flux $\sim 10^7 \text{ } \gamma / (\text{keV s cm}^2)$
Calibration of the photon flux via $^{197}\text{Au}(\gamma, n)$ and $^{187}\text{Re}(\gamma, n)$

Determination of reaction yield



(or sample analysis
with AMS)



Reaction yield: $Y \propto \int \sigma(E) n_\gamma(E) dE$

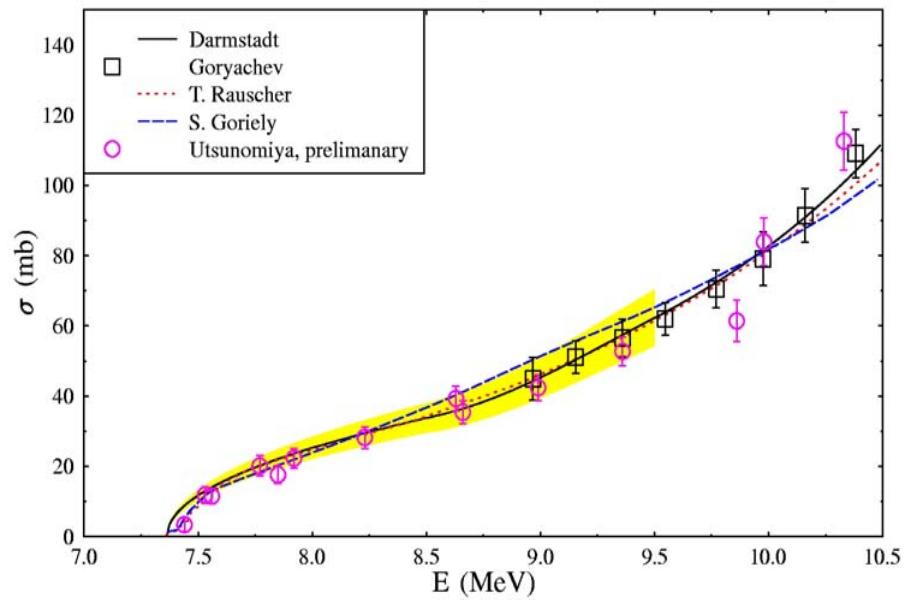
$n_\gamma(E)$ is a continuous bremsstrahlung spectrum

Challenges for cross section measurements

Only integrated cross sections can be determined in conventional **bremsstrahlung** experiments:

$$Y \propto \int \sigma(E) n_{\gamma}(E) dE$$

Many informations
are hidden in the
energy dependence



→ Direct measurement of $\sigma(E)$!

Challenges of (γ, p) and (γ, α) measurements

Coulomb barrier for protons and α -particles:

Mass A	$E_{\text{coul}}(\alpha)$ [MeV]	$E_{\text{coul}}(p)$ [MeV]
50	12	7
100	18	11
150	27	15

Charged particles reactions are strongly suppressed in the relevant energy range

→ Very small cross sections !

4GLS for Nuclear Astrophysics

- How to determine $\sigma(E)$ directly ?
 - How to increase laboratory reaction rate ?
- A tunable γ ray source
with highest intensities
- Laser Compton Back-scattering at 4GLS



4GLS for Nuclear Astrophysics

- Determination of small cross sections of photon induced reactions
- Versatile research program feasible including reaction rates of elements with $A < 60$
- Complementary and/or superior to existing or planned other facilities
(HIGS, AIST, ELBE, S-DALINAC, NEPTUN, SPRING 8)
- Broad interest from Nuclear Astrophysicists world wide



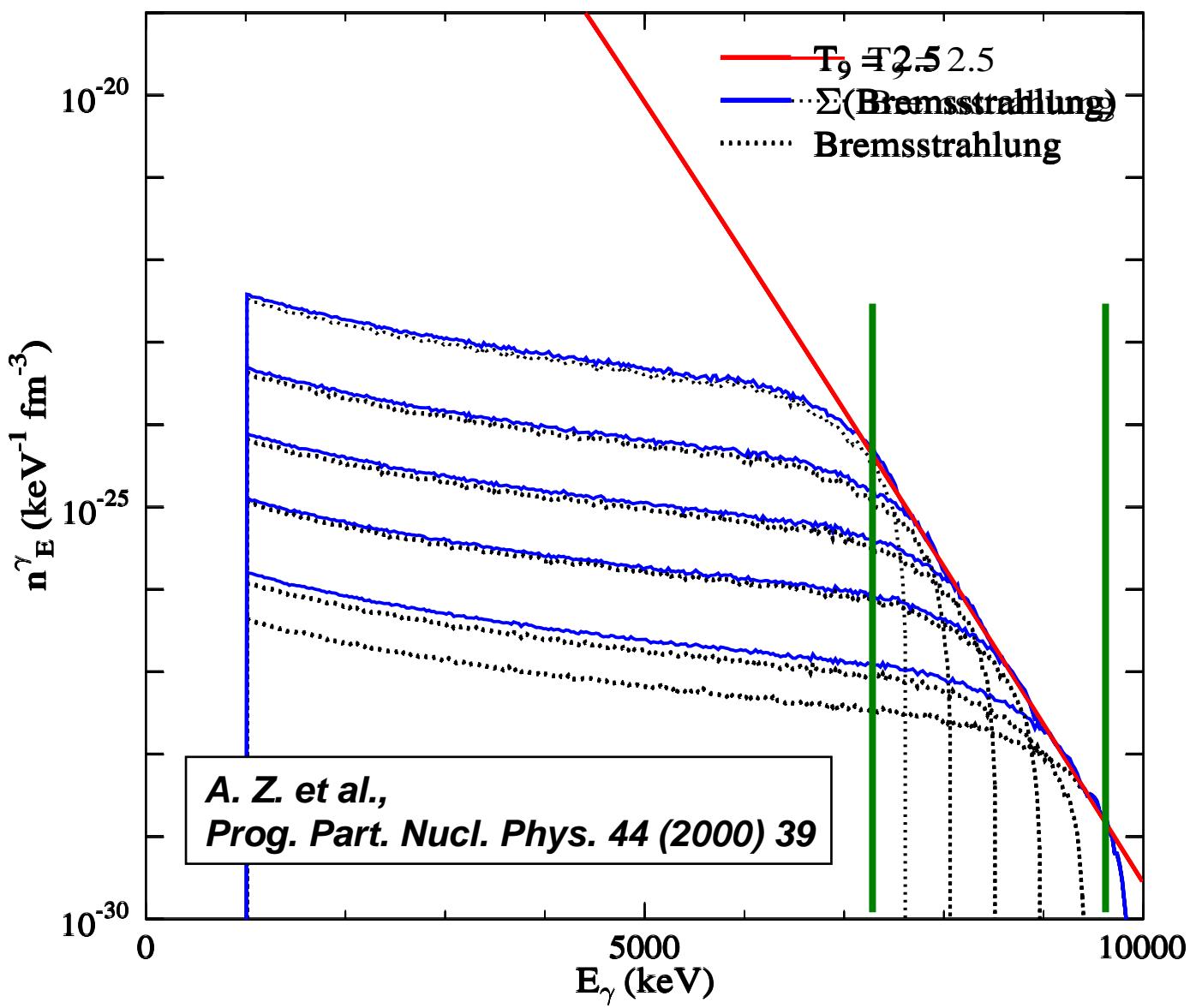
End

Groundstate (γ ,n) reaction rates

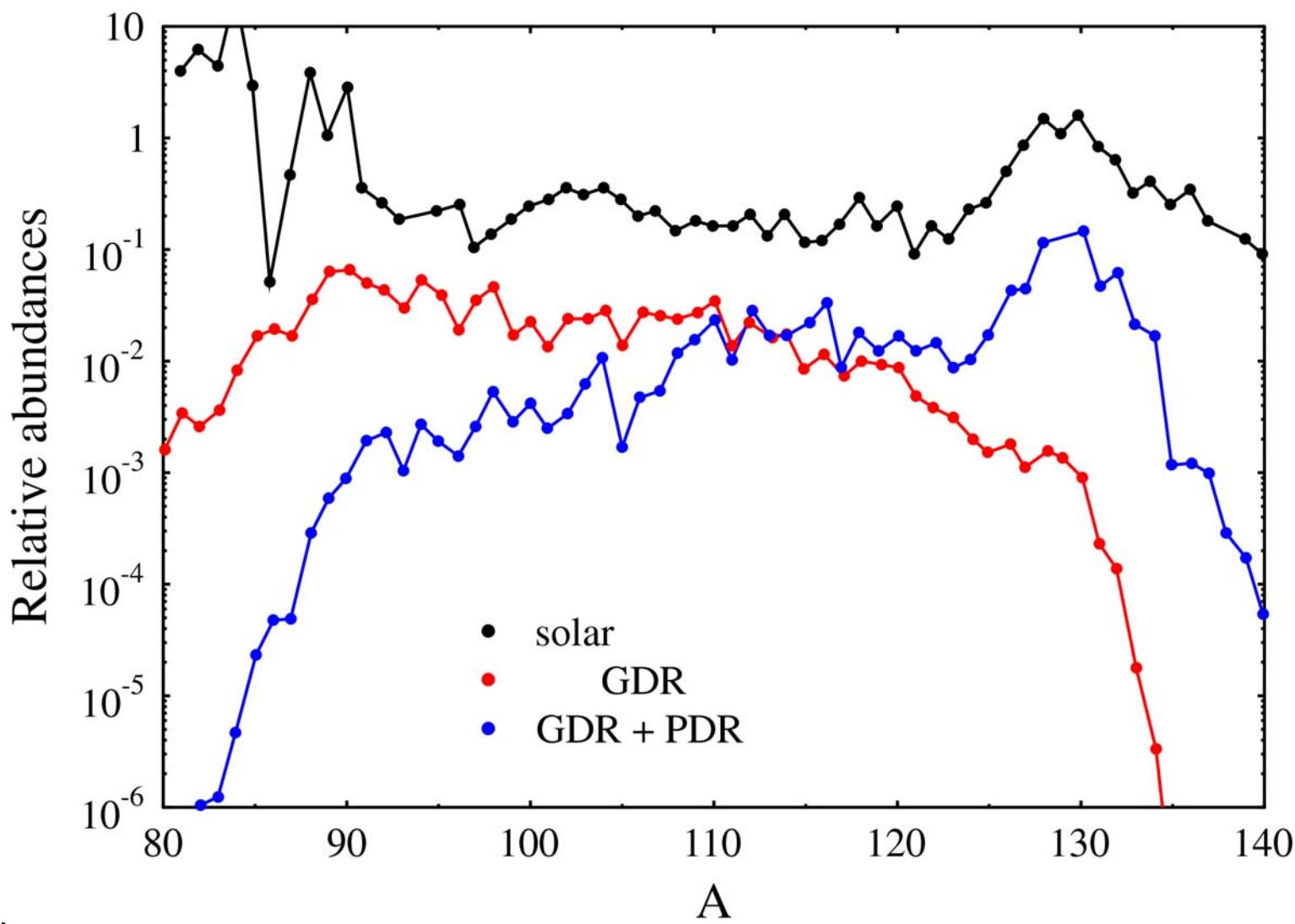
Kern	S_n (MeV)	λ_{exp} (s ⁻¹)
^{190}Pt	8911	0.4(2)*
^{192}Pt	8676	0.5(2)
^{198}Pt	7557	87(21)
^{197}Au	8071	6.2(8)
^{196}Hg	8840	0.42(7)*
^{198}Hg	7103	2.0(3)
^{204}Hg	7495	57(21)
^{204}Pb	8394	1.9(3)

Temperature: T=2.5x10⁹ K

Simulation of a Planck spectrum



Abundance of r-nuclei: Influence of photoresponse



Modelling the s-process nucleosynthesis

Stellar Evolution

- **Evolutionary models**
(O.Straniero and R. Gallino,
NPA 777 (2006) 311)
- **Spectral observations**
(M. Busso et al., Annu.
Rev. Astron. Astrophys. 37
(1999) 239)

Elemental Abundances

- High-resolution spectroscopy and investigation of meteorites
(E. Anders and N. Grevesse, Geochim. Cosmochim. Acta 53 (1989) 197)

Galactic Evolution

- Averaging over stars with various metallicity and mass
(C. Travaglio et al., ApJ 521 (1999) 691)

s-process nucleosynthesis

Nuclear Physics Input

- Neutron capture cross sections
(KADONIS online database)
- Beta-decay rates at branching points
(K. Takahashi and K. Yokoi, ADNDT 36 (1987) 375)
- Rates of neutron sources
(F. Käppeler et al., ApJ 437 (1994) 396)

Investigation of branching points

Branching	(n,γ) (MACS@30 keV) [mb]	(ν,n) (Normalization)	Code	Reference
$^{147}\text{Nd} / ^{148}\text{Nd}$	382	1.03 (20)	NON-SMOKER (2003)	J. Hasper, to be published
	453	0.86 (17)	NON-SMOKER-Web	
$^{185}\text{W} / ^{186}\text{W}$	599	1.22 (17)	NON-SMOKER	K. Sonnabend et al., ApJ 583 (2003) 506
	654	0.97 (13)	Mengoni	
$^{95}\text{Zr} / ^{96}\text{Zr}$	126	1.22	NON-SMOKER	K. Sonnabend, to be published
	23	1.54	MOST	
$^{186}\text{Re} / ^{187}\text{Re}$	1546	1.15 (31)	NON-SMOKER	S. Müller et al., PRC 73 (2006)
	623	1.07 (28)	MOST	