

Nukleosynthese: Wie bildeten sich die Elemente?

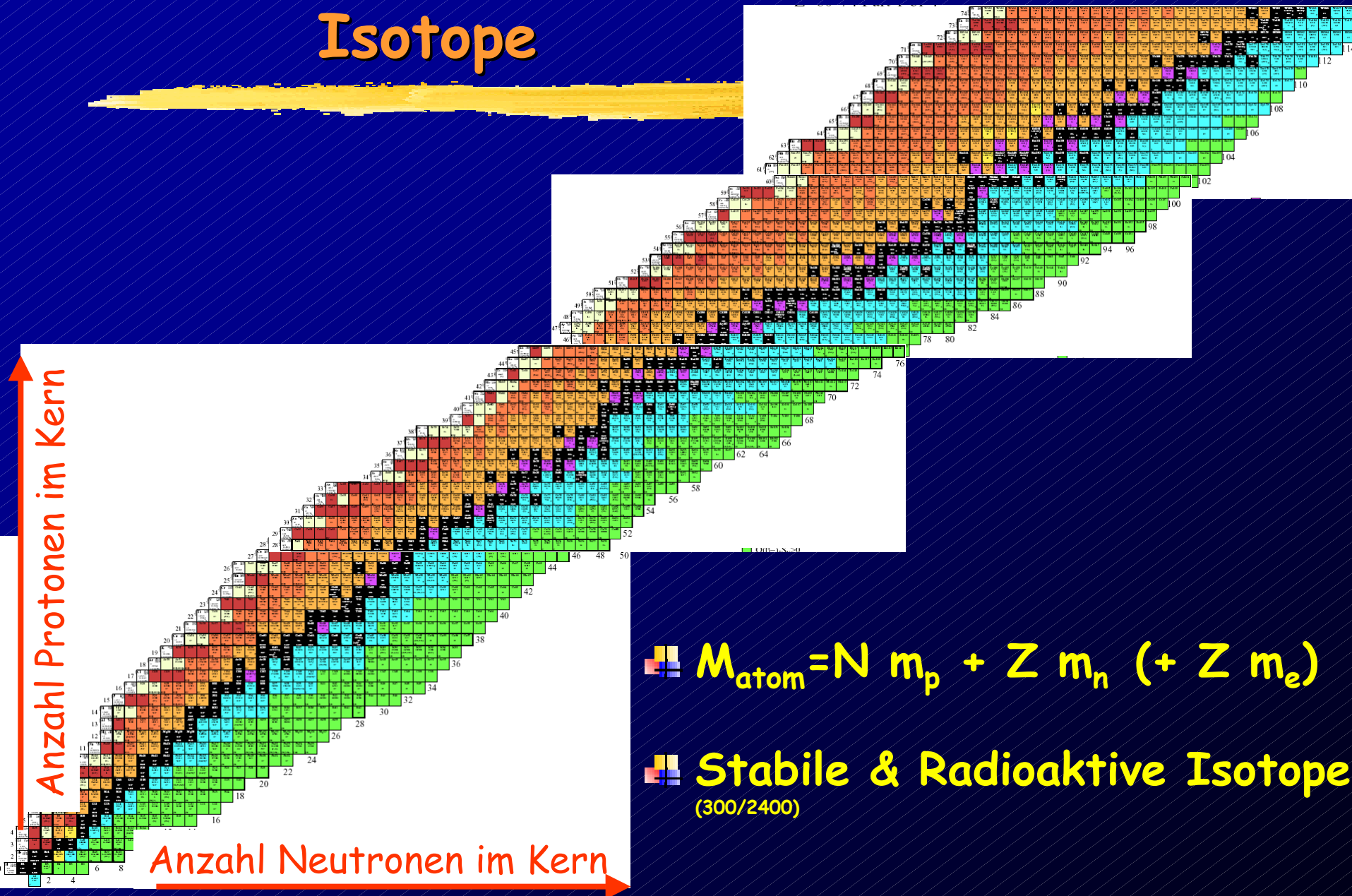
... und was kann man mit INTEGRAL dazu lernen...

Roland Diehl
MPE

"Periodensystem" der Elemente

1 (IA)										18 (VIIIA)									
Hydrogen										Helium									
H_1										He_2									
1.00794										4.002602									
91.09%										8.9%									
2 (IIA)										13 (IIIA) 14 (IVA) 15 (VA) 16 (VIA) 17 (VIIA)									
Lithium										Boron									
Li_3										B_5									
6.941										10.811									
9.012182										12.0107									
1.86x10 ⁻⁶ %										6.96x10 ⁻⁶ %									
Beryllium										Carbon									
Be_4										C_6									
9.012182										12.0107									
2.38x10 ⁻⁶ %										0.033%									
Sodium										Nitrogen									
Na_{11}										N_7									
22.989770										14.00644									
0.000187%										0.0102%									
Magnesium										Oxygen									
Mg_{12}										O_8									
24.3050										15.9994									
0.000509%										0.078%									
Group										Fluorine									
Element										F_9									
E_x										18.9984032									
Oxidation										-1									
At. Weight										20.1797									
Abundance										0.0112%									
Key to Table										Neon									
3 (IIIB)										Ne_{10}									
Potassium										18.9984032									
K_{39}										20.1797									
39.0983										20.1797									
0.0001239%										0.0112%									
Calcium										Argon									
Ca_{40}										Ar_{36}									
40.078										39.948									
0.0001956%										0.000329%									
Scandium										Chlorine									
Sc_{45}										Cl_{35}									
44.955910										35.453									
7.8x10 ⁻⁶ %										0.000329%									
Titanium										Sulfur									
Ti_{48}										S_{32}									
47.867										32.065									
0.000044%										0.000329%									
Vanadium										Phosphorus									
V_{51}										P_{31}									
50.9415										30.973761									
0.000044%										0.000329%									
Chromium										Silicon									
Cr_{52}										Si_{28}									
51.9961										28.0855									
0.000031%										0.000329%									
Manganese										Aluminum									
Mn_{55}										Al_{27}									
54.938040										26.981538									
0.000031%										0.000277%									
Iron										Germanium									
Fe_{56}										Ge_{72}									
55.845										72.61									
0.00294%										3.9x10 ⁻⁶ %									
Cobalt										Arsenic									
Co_{59}										As_{75}									
58.933200										74.9216									
7.8x10 ⁻⁶ %										2.1x10 ⁻⁶ %									
Nickel										Selenium									
Ni_{58}										Se_{78}									
58.6934										78.96									
0.000161%										0.000329%									
Copper										Bromine									
Cu_{63}										Br_{80}									
63.546										79.904									
1.70x10 ⁻⁶ %										1.5x10 ⁻⁶ %									
Zinc										Krypton									
Zn_{65}										Kr_{84}									
65.39										83.80									
4.1x10 ⁻⁶ %										1.5x10 ⁻⁶ %									
Gallium										Xenon									
Ga_{70}										Xe_{131}									
69.723										131.29									
1.23x10 ⁻⁵ %										1.5x10 ⁻⁶ %									
Germanium										Barium									
Ge_{72}										Ba_{137}									
72.61										137.327									
3.9x10 ⁻⁶ %										1.46x10 ⁻⁶ %									
Arsenic										Radium									
As_{75}										Ra_{226}									
74.9216										226									
2.1x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Selenium										Actinium									
Se_{78}										Ac_{227}									
78.96										227									
0.000329%										2.01x10 ⁻⁶ %									
Bromine										Rutherfordium									
Br_{80}										Rf_{261}									
79.904										261									
1.5x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Krypton										Dubnium									
Kr_{84}										Db_{262}									
83.80										262									
1.5x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Xenon										Seaborgium									
Xe_{131}										Sg_{266}									
131.29										266									
1.5x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Barium										Bohrium									
Ba_{137}										Bh_{264}									
137.327										264									
1.46x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Radium										Hassium									
Ra_{226}										Hs_{269}									
226										269									
2.01x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Actinium										Mt									
Ac_{227}										Mt_{268}									
227										268									
2.01x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Rutherfordium										Element-110									
Rf_{261}										110_{271}									
261										271									
2.01x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Dubnium										Element-111									
Db_{262}										111_{272}									
262										272									
2.01x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Seaborgium										Element-112									
Sg_{266}										112_{277}									
266										277									
2.01x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Bohrium										Element-114									
Bh_{264}										114_{289}									
264										289									
2.01x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Hassium										Element-116									
Hs_{269}										116_{289}									
269										289									
2.01x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Mt										Element-118									
Mt_{268}										118_{293}									
268										293									
2.01x10 ⁻⁶ %										2.01x10 ⁻⁶ %									
Element-110										Lanthanides									
110_{271}										Cerium									
271										Ce_{58}									
2.01x10 ⁻⁶ %										140.127									
Element-111										Praseodymium									
111_{272}										Pr_{59}									
272										140.90765									
2.01x10 ⁻⁶ %										5.44x10 ⁻⁶ %									
Element-112										Neodymium									
112_{277}										Nd_{60}									
277										144.24									
2.01x10 ⁻⁶ %										2.70x10 ⁻⁶ %									
Element-114										Promethium									
114_{289}										Pm_{61}									
289										[145]									
2.01x10 ⁻⁶ %										[145]									
Element-116										Samarium									
116_{289}										Sm_{62}									
289										150.36									
2.01x10 ⁻⁶ %										8.42x10 ⁻⁶ %									
Element-118										Europium									
118_{293}										Eu_{63}									
293										151.964									
2.01x10 ⁻⁶ %										3.17x10 ⁻⁶ %									
Lanthanides										Gadolinium									
Cerium										Gd_{64}									
Ce_{58}										157.25									
140.127										1.076x10 ⁻⁶ %									
5.44x10 ⁻⁶ %										1.97x10 ⁻⁶ %									
Neodymium										Terbium									
Nd_{60}										Tb_{63}									
144.24										158.92534									
2.70x10 ⁻⁶ %										1.286x10 ⁻⁶ %									
Promethium										Dysprosium									
Pm_{61}										Dy_{65}									
[145]										162.50									
[145]										2.90x10 ⁻⁶ %									
Samarium										Holmium									
Sm_{62}										Ho_{67}									
150.36										164.93032									
8.42x10 ⁻⁶ %										8.18x10 ⁻⁶ %									
Europium										Erbium									
Eu_{63}										Er_{68}									
151.964										167.26									
3.17x10 ⁻⁶ %										1.28x10 ⁻⁶ %									
Gadolinium										Thulium									
Gd_{64}										Tm_{69}									
157.25										168.93421									
1.076x10 ⁻⁶ %										1.07x10 ⁻⁶ %									
Terbium										Ytterbium									
Tb_{63}										Yb_{70}									
158.92534										173.04									
1.286x10 ⁻⁶ %										1.197x10 ⁻⁶ %									
Dysprosium										Lutetium									
Dy_{65}										Lu_{71}									
162.50										174.967									
2.90x10 ⁻⁶ %										1.197x10 ⁻⁶ %									
Holmium										Actinides									
Ho_{67}										Thorium									
164.93032										Th_{90}									
8.18x10 ⁻⁶ %										232.0381									
Erbium										Protactinium									
Er_{68}										Pa_{91}									
167.26										231.03688									
1.28x10 ⁻⁶ %										1.09x10 ⁻⁶ %									
Thulium										Uranium									
Tm_{69}										U_{92}									
168.93421										238.02891									
1.07x10 ⁻⁶ %										2.84x10 ⁻⁶ %									
Ytterbium										Neptunium									
Yb_{70}										Np_{93}									
173.04										237.04817									
1.197x10 ⁻⁶ %										[237]									
Lutetium										Plutonium									
Lu_{71}										Pu_{94}									
174.967										244									
1.197x10 ⁻⁶ %										[244]									
Actinides										Americium									
Thorium										Am_{95}									
Th_{90}										243									
232.0381										[243]									
1.09x10 ⁻⁶ %										[243]									
Protactinium										Curium									
Pa_{91}										Cm_{96}									
231.03688										247									
1.09x10 ⁻⁶ %										[247]									
Uranium										Berkelium									
U_{92}										Bk_{97}									
238.02891										247									
2.84x10 ⁻⁶ %										[247]									
Neptunium										Californium									
Np_{93}										Cf_{98}									
237.04817										251									
[237]										[251]									
Plutonium										Einsteinium									
Pu_{94}										Es_{99}									
244										252									
[244]										[252]									
Americium										Fermium									
Am_{95}										Fm_{100}									
243										257									
[243]										[257]									
Curium										Mendelevium									
Cm_{96}										Md_{101}									
247										258									
[247]										[258]									
Berkelium										Nobelium									
Bk_{97}										No_{102}									
247										259									
[247]										[259]									
Californium										Lawrencium									
Cf_{98}										Lr_{103}									
251										262									
[251]										[262]									
Einsteinium										Unlabeled									
Es_{99}																			
252																			
[252]																			
Fermium																			
Fm_{100}																			
257																			
[257]																			
Mendelevium																			
Md_{101}																			
258																			
[258]																			
Nobelium																			
No_{102}																			
259																			
[259]																			
Lawrencium																			
Lr_{103}																			
262																			
[262]																			

Atomkern-Vielfalt: Isotope



Anzahl Protonen im Kern

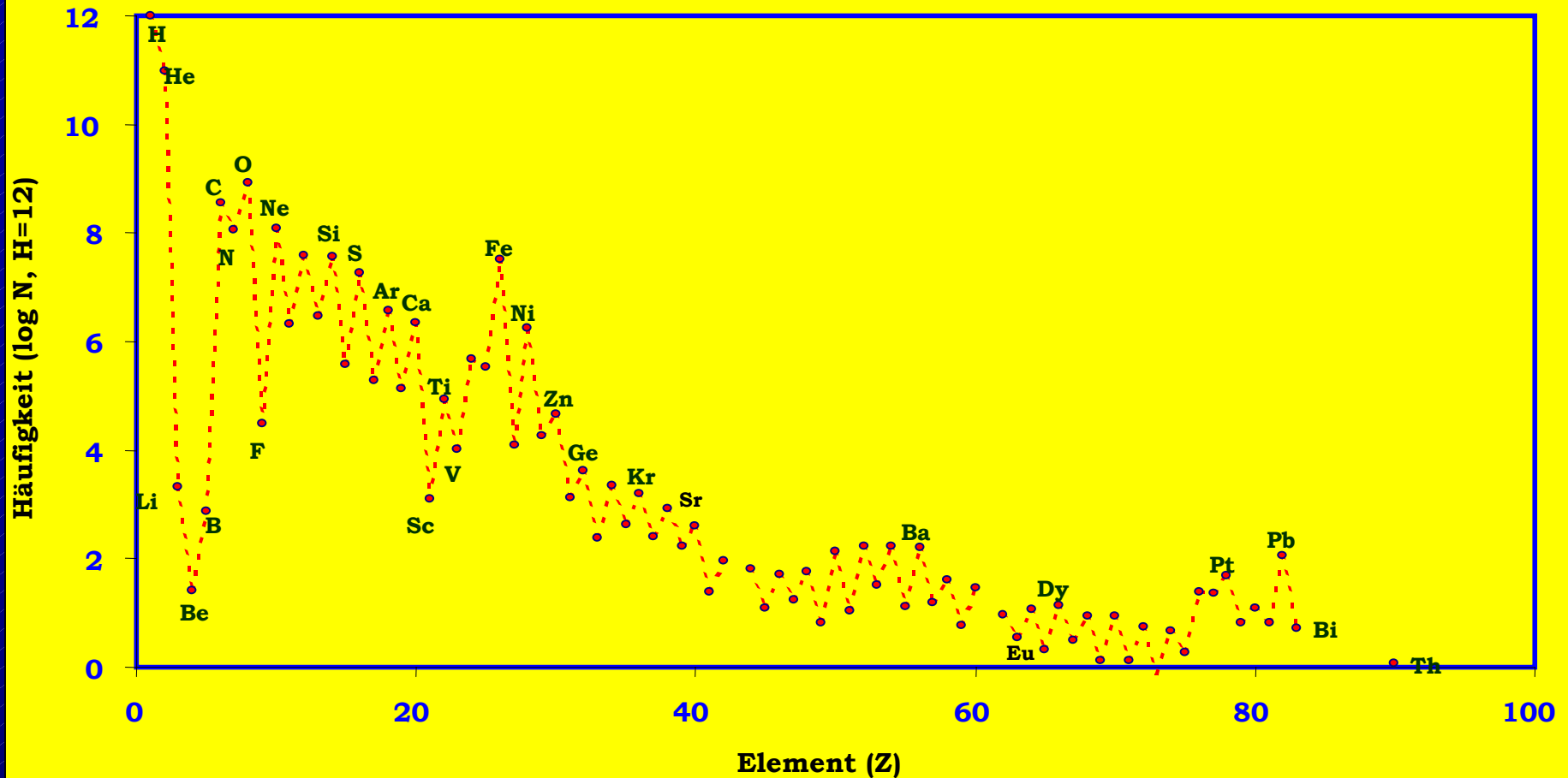
Anzahl Neutronen im Kern

$$M_{\text{atom}} = N m_p + Z m_n (+ Z m_e)$$

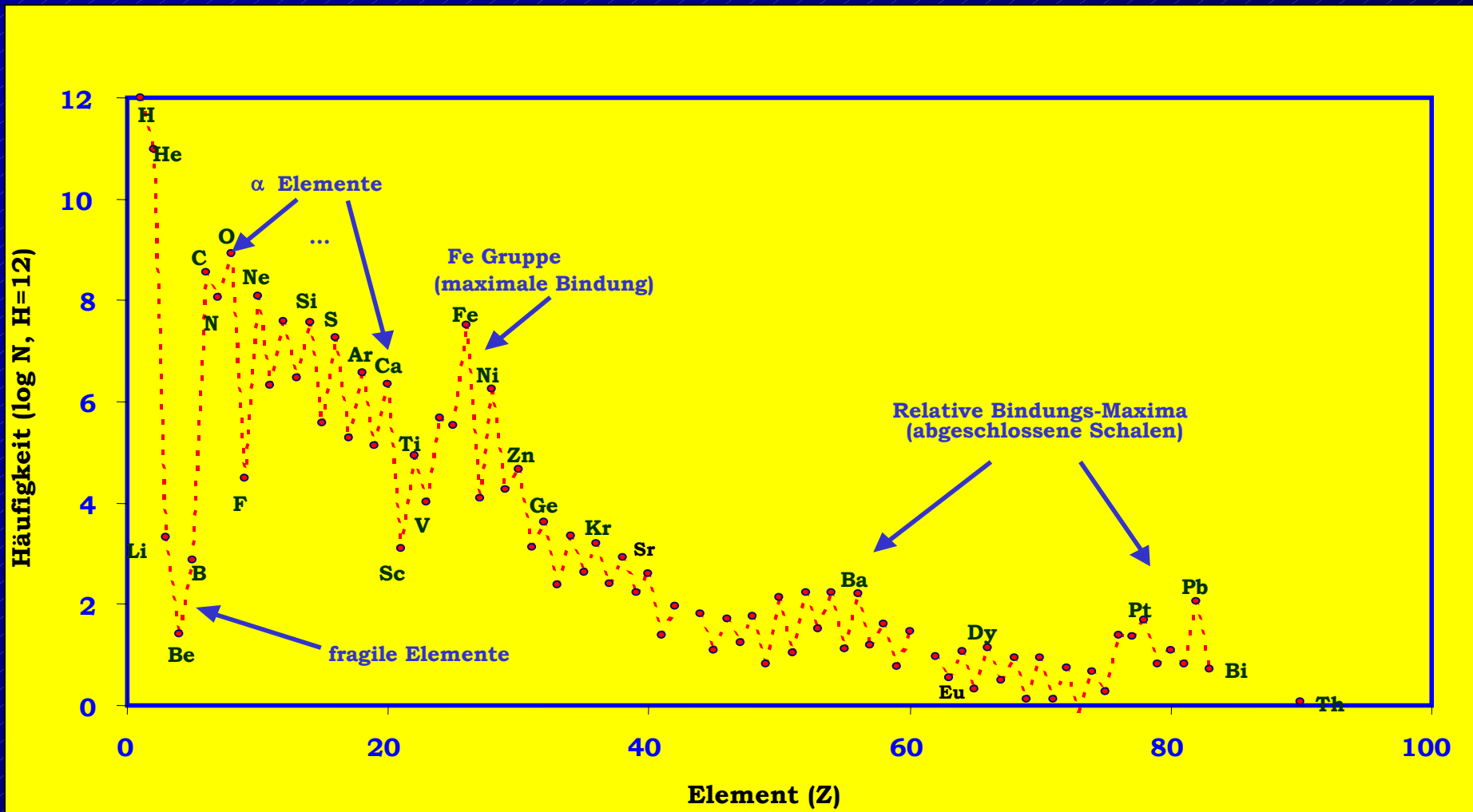
Stabile & Radioaktive Isotope
(300/2400)

Elemente im Universum: Welche, Wieviel?

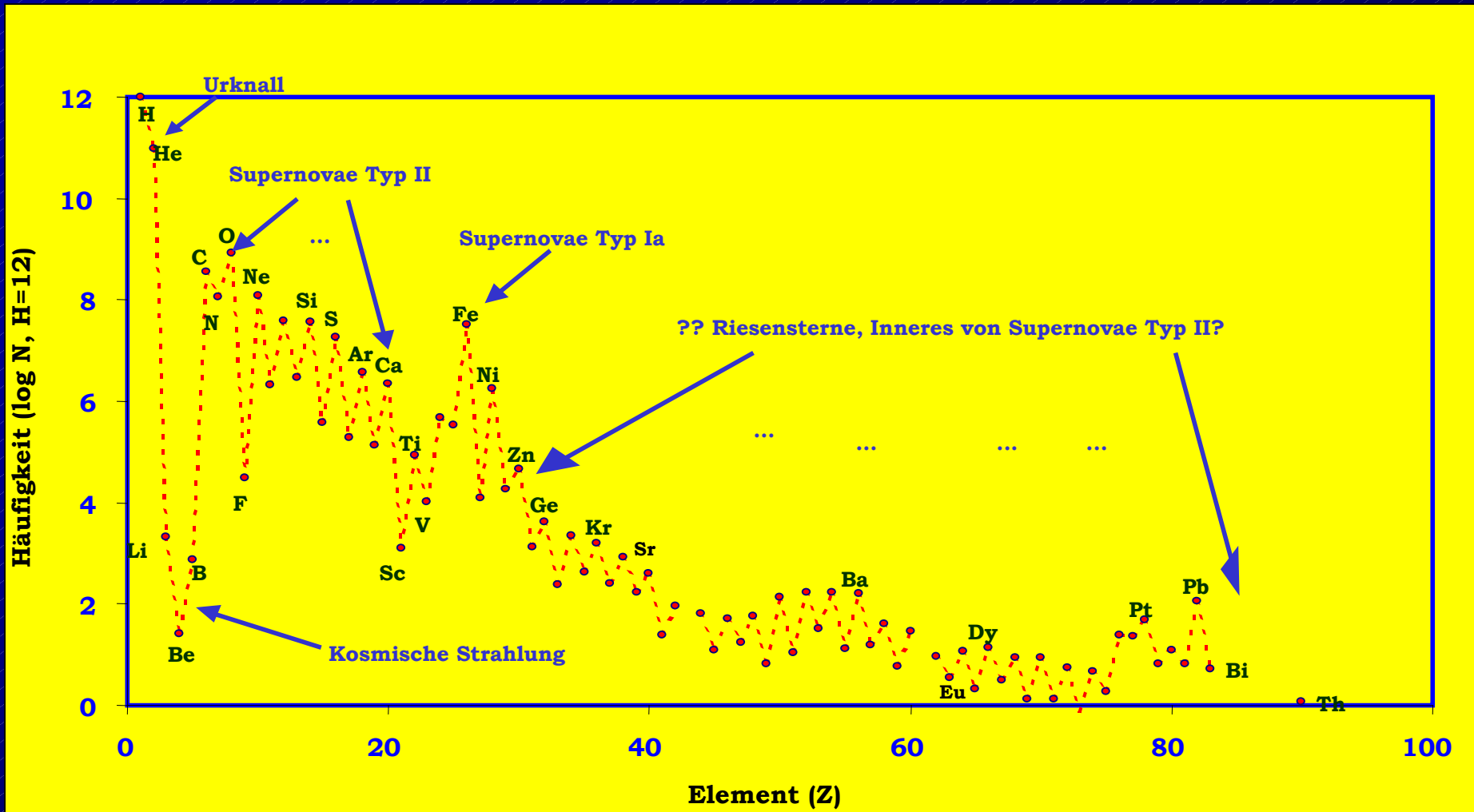
Standard-Häufigkeiten



Element-Häufigkeiten: Kernstruktur

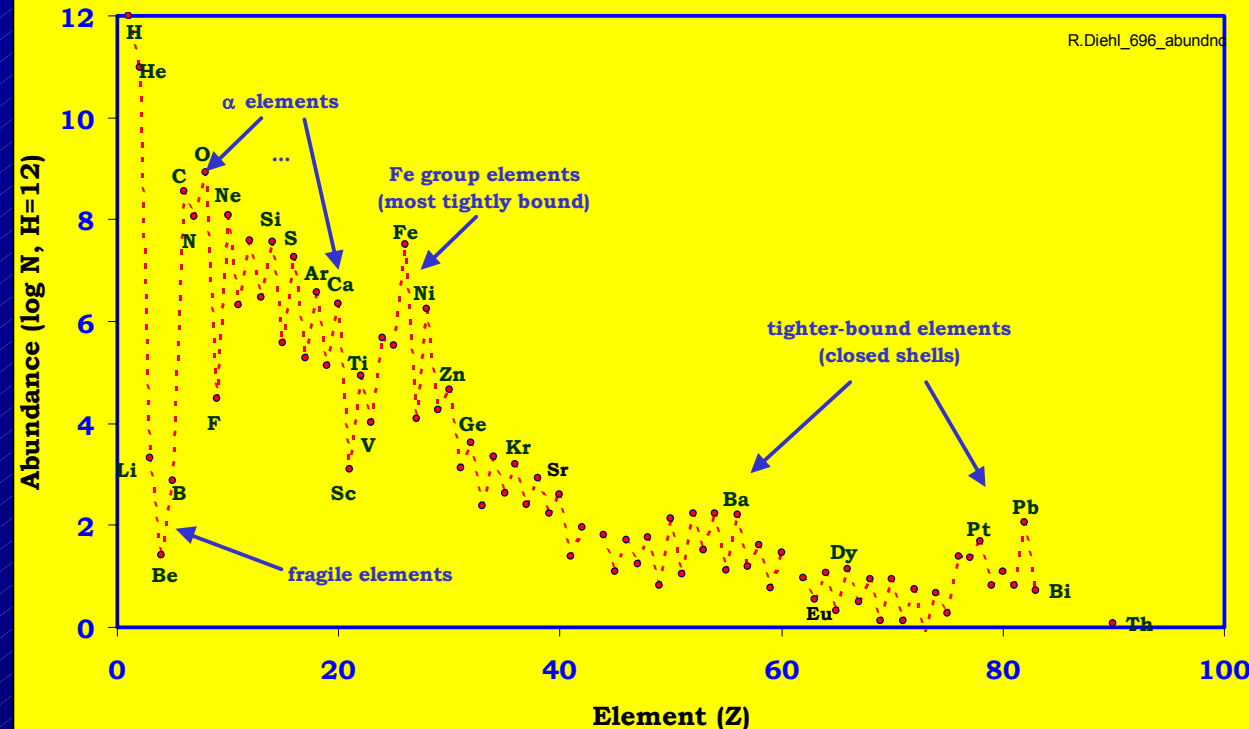


Element-Häufigkeiten: Kosmische Quellen



Studium der Element-Häufigkeiten

Standard Abundances

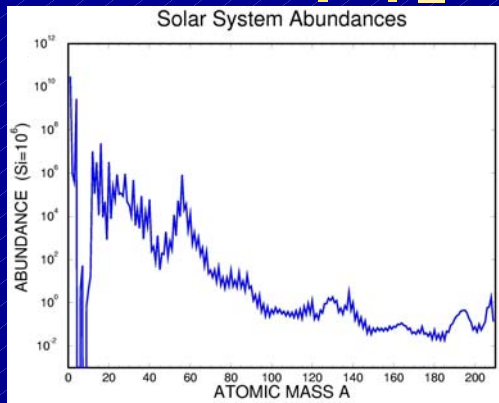


Häufigkeitsunterschiede umfassen 12 Dekaden!

Charakteristische Muster -> spezifische, unterschiedliche Entstehungsprozesse

Welche Prozesse in der Natur sind dafür verantwortlich?

Astro-Physik kosmischer Nukleosynthese

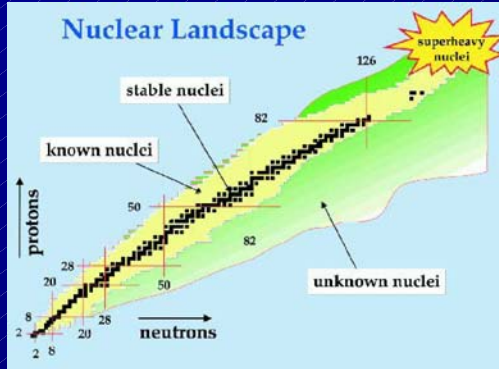


Kern-Struktur, Nukleonen-WW

- ☞ Coulomb-Kraft
- ☞ Starke WW
- ☞ Kollektive WW

Reaktions-Pfade abseits stabiler Elemente

- ☞ Keine Kernphysik-Daten
- ☞ Kernphysikalische Lektionen aus astronomischen Messungen



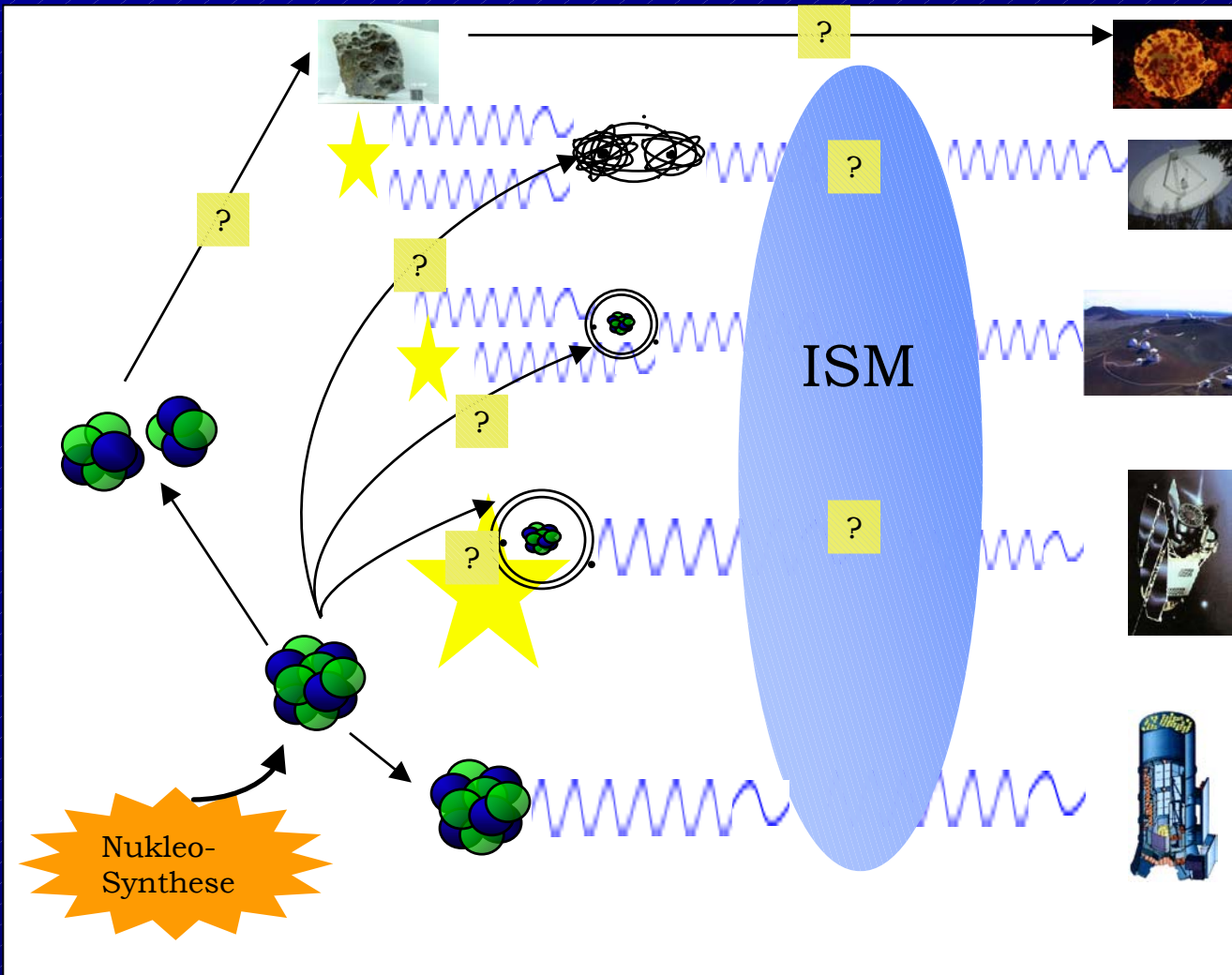
Kosmische Kernreaktoren

- ★ Explosive Heizung, Brennzonen-Verdünnung
- ★ Langzeit-Misch/Entwicklungs-Prozesse



"Nukleare Astrophysik"

Messmöglichkeiten zur Nukleosynthese



Gammastrahlung & Meteoriten-Einschlüsse:
-> Isotope; direkt

Alternativen:
Absorptions- und Emissions-Linien (=Atomhülle)
-> Elemente; indirekt

- ☆ Element-Häufigkeiten aus atomaren Strahlungsprozessen (Opt/UV/X) hilfreich
- ☆ HFS-Effekte in IR...R schwerer zu messen

Elemente & Isotope

☐ Atome:

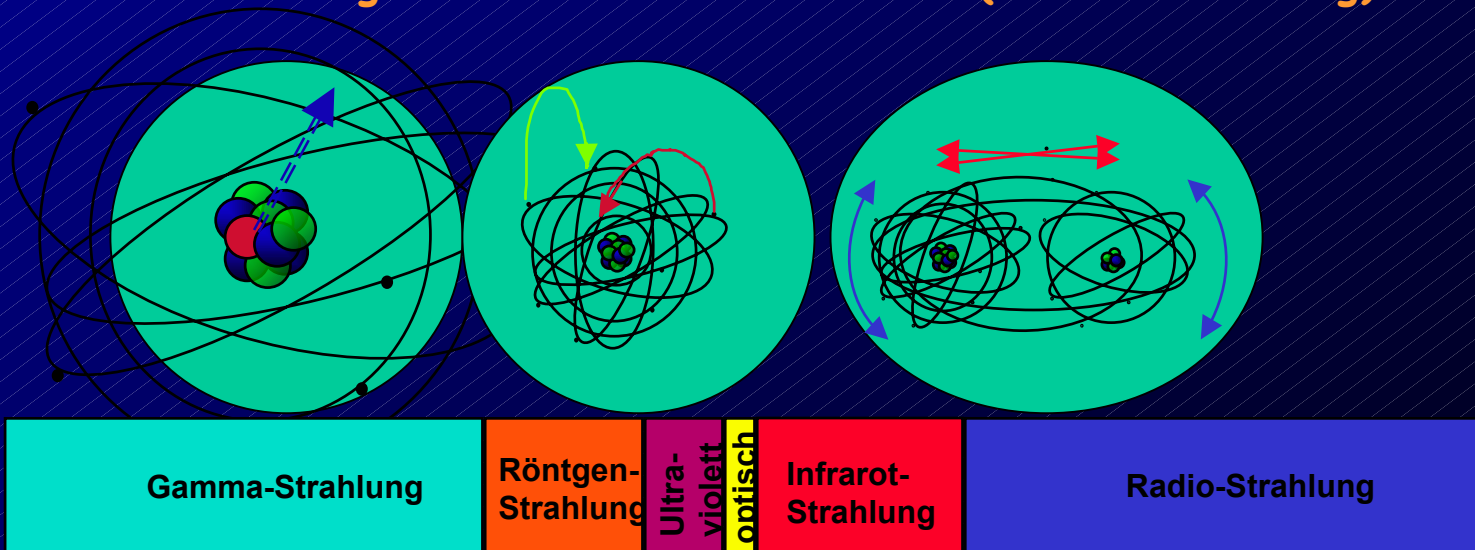
☆ Elektronen-Hülle

- ☞ Chemische Eigenschaften & Bindungsmöglichkeiten
- ☞ e.m. Strahlung / charakteristische Farben (optisch...Röntgen)

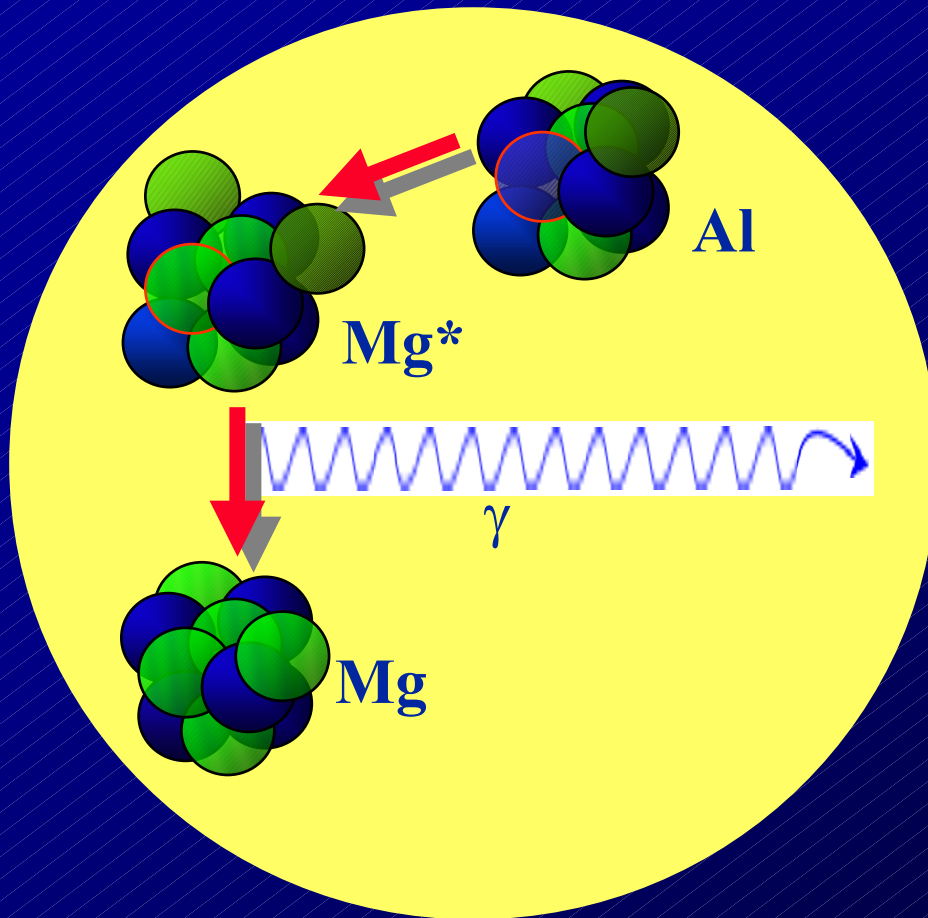
☆ Atomkern

- ☞ Nukleonen: Protonen, Neutronen
- ☞ Radioaktivität, Umwandlungs-Eigenschaften
- ☞ e.m. Strahlung / charakteristische Farben (Gamma-Strahlung)

rod0895 photons



Gammastrahlung kosmischer Isotope



 **Radioaktiver Zerfall**
 -> angeregter Kern
 -> Gamma-Emission

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^7Be	77 d	$^7\text{Be} \rightarrow ^7\text{Li}^*$	478
^{56}Ni	111 d	$^{56}\text{Ni} \rightarrow ^{56}\text{Co}^* \rightarrow ^{56}\text{Fe}^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}\text{Co} \rightarrow ^{57}\text{Fe}^*$	122
^{22}Na	3.8 y	$^{22}\text{Na} \rightarrow ^{22}\text{Ne}^* + e^+$	1275
^{44}Ti	89 y	$^{44}\text{Ti} \rightarrow ^{44}\text{Sc}^* \rightarrow ^{44}\text{Ca}^* + e^+$	78, 68; 1157
^{26}Al	$1.04 \cdot 10^6 \text{y}$	$^{26}\text{Al} \rightarrow ^{26}\text{Mg}^* + e^+$	1809
^{60}Fe	$2.0 \cdot 10^6 \text{y}$	$^{60}\text{Fe} \rightarrow ^{60}\text{Co}^* \rightarrow ^{60}\text{Ni}^*$	59, 1173, 1332
e^+	$\dots \cdot 10^5 \text{y}$	$e^+ + e^- \rightarrow \text{Ps} \rightarrow \gamma\gamma..$	511, <511

Gamma-Astronomie und Nukleosynthese

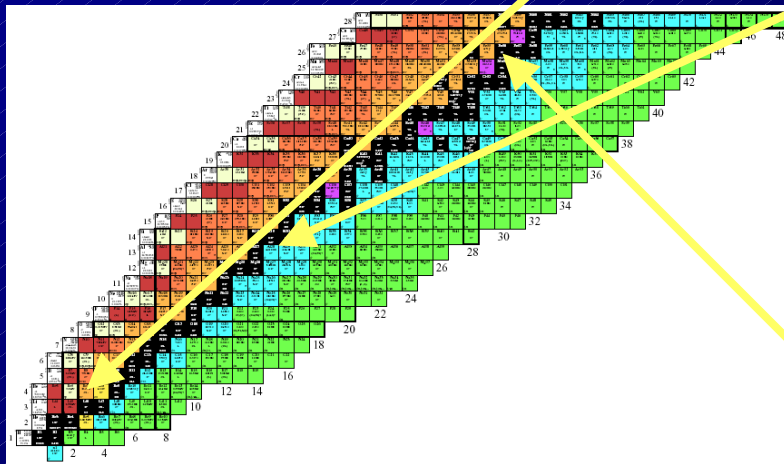


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^{60}Fe	$2.0 \cdot 10^6 \text{y}$	$^{60}\text{Fe} \rightarrow ^{60}\text{Co}^* \rightarrow ^{60}\text{Ni}^*$	59, 1173, 1332
e^+	$\dots 10^5 \text{y}$	$e^+ + e^- \rightarrow \text{Ps} \rightarrow \gamma\gamma$	511, <511

511 keV, ^7Be -> Novae -> p-Anlagerungen, Antimaterie -> Fluor!

^{26}Al -> Reaktionspfad-Details in Sternen/SNe, neutrino-Prozess -> Leichtmetalle (Al, Mg) / Sand am Meer (Si)

^{44}Ti , ^{56}Ni -> stabilste Isotope $^{56}\text{Ni}/^4\text{He}$, Ausfrieren eines Kernfusions-Ofens -> Leichtmetalle/Eisen

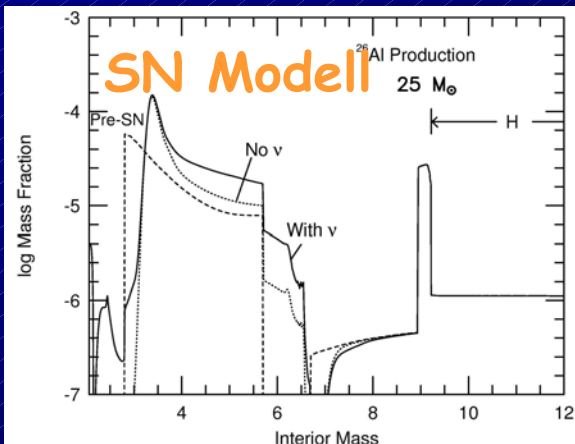
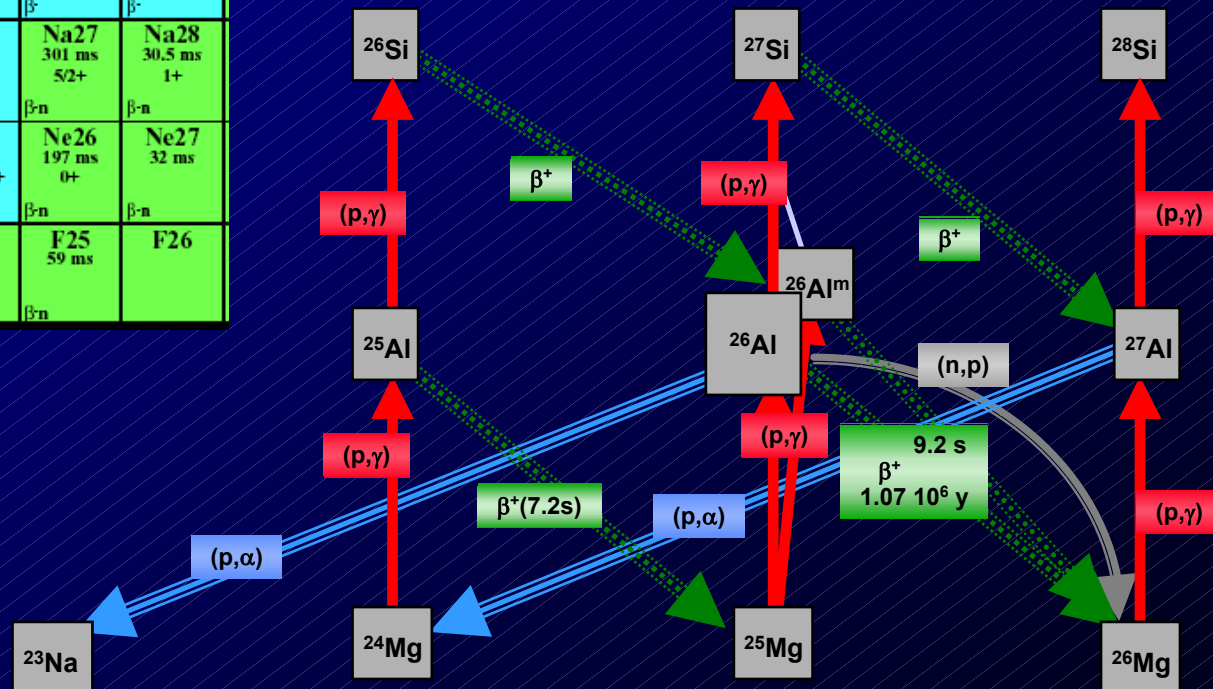


Beispiel: ^{26}Al Synthese

ECp	ECp	ECp	ECp, ECα...	EC	EC	100	β-
Si24 102 ms 0+	Si25 220 ms 5/2+	Si26 2.234 s 0+	Si27 4.16 s 5/2+	Si28 92.23 0+	Si29 4.67 1/2+	Si30 3.10 0+	Si31 157.3 m 3/2+
ECp	ECp	EC	EC	EC	EC	EC	EC
Al23 0.47 s ECp	Al24 2.053 s 4+ ECp	Al25 7.183 s 5/2+ EC	Al26 7.4E+5 y 5+ EC	Al27 5/2+ 100 EC	Al28 2.2414 m 3+ β-	Al29 6.56 m 5/2+ β-	Al30 3.60 s 3+ β-
Mg22 3.857 s 0+ EC	Mg23 11.317 s 3/2+ EC	Mg24 78.99 0+ 100	Mg25 10.00 5/2+ β-	Mg26 11.01 0+ β-	Mg27 9.458 m 1/2+ β-	Mg28 20.91 h 0+ β-	Mg29 1.30 s 3/2+ β-
Na21 22.49 s 3/2+ 100	Na22 2.6019 y 3+ β-	Na23 100 3/2+ β-	Na24 14.9590 h 4+ β-	Na25 59.1 s 5/2+ β-	Na26 1.072 s 3+ β-	Na27 301 ms 5/2+ β-n	Na28 30.5 ms 1+ β-n
Ne20 90.48 0+ 100	Ne21 0.27 3/2+ β-	Ne22 9.25 0+ 100	Ne23 37.24 s 5/2+ β-	Ne24 3.38 m 0+ β-	Ne25 602 ms (1/2, 3/2)+ β-	Ne26 197 ms 0+ β-n	Ne27 32 ms β-n
F19 1/2+ 100	F20 11.00 s 2+ β-	F21 4.158 s 5/2+ β-	F22 4.23 s 4+, (3+) β-	F23 2.23 s (3/2, 5/2)+ β-	F24 0.34 s (1, 2, 3)+ β-	F25 59 ms β-n	F26



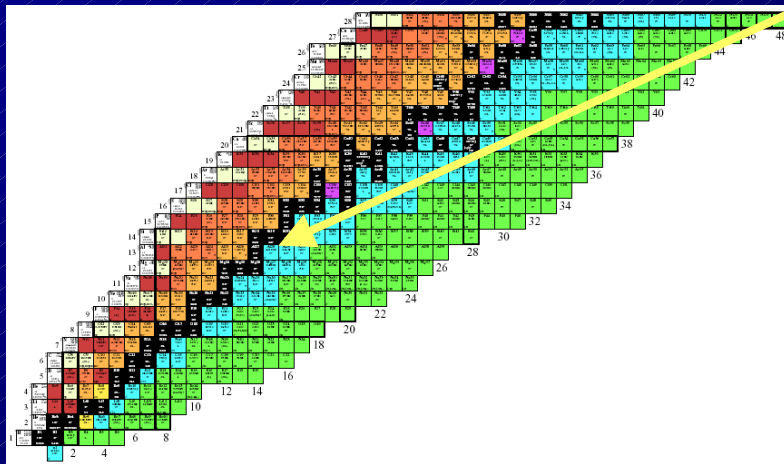
Balance von
p-Einfangs-Produktion und
n/p-Zerstörung



Gamma-Strahlung und Nukleosynthese

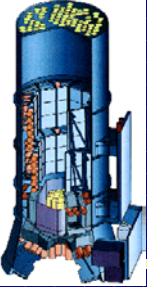
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^{57}Ni	390 d	$^{57}\text{Co} \rightarrow ^{57}\text{Fe}^*$	122
^{22}Na	3.8 y	$^{22}\text{Na} \rightarrow ^{22}\text{Ne}^* + e^+$	1275
^{44}Ti	89 y	$^{44}\text{Ti} \rightarrow ^{44}\text{Sc}^* \rightarrow ^{44}\text{Ca}^* + e^+$	78, 68; 1157
^{26}Al	$1.04 \cdot 10^6 \text{y}$	$^{26}\text{Al} \rightarrow ^{26}\text{Mg}^* + e^+$	1809
^{60}Fe	$2.0 \cdot 10^6 \text{y}$	$^{60}\text{Fe} \rightarrow ^{60}\text{Co}^* \rightarrow ^{60}\text{Ni}^*$	59, 1173, 1332
e^+	$\dots 10^5 \text{y}$	$e^+ + e^- \rightarrow \text{Ps} \rightarrow \gamma\gamma..$	511, <511

511 keV, $^7\text{Be} \rightarrow \text{Novae} \rightarrow p$ -Anlagerungen, Antimaterie $\rightarrow$ Fluor!

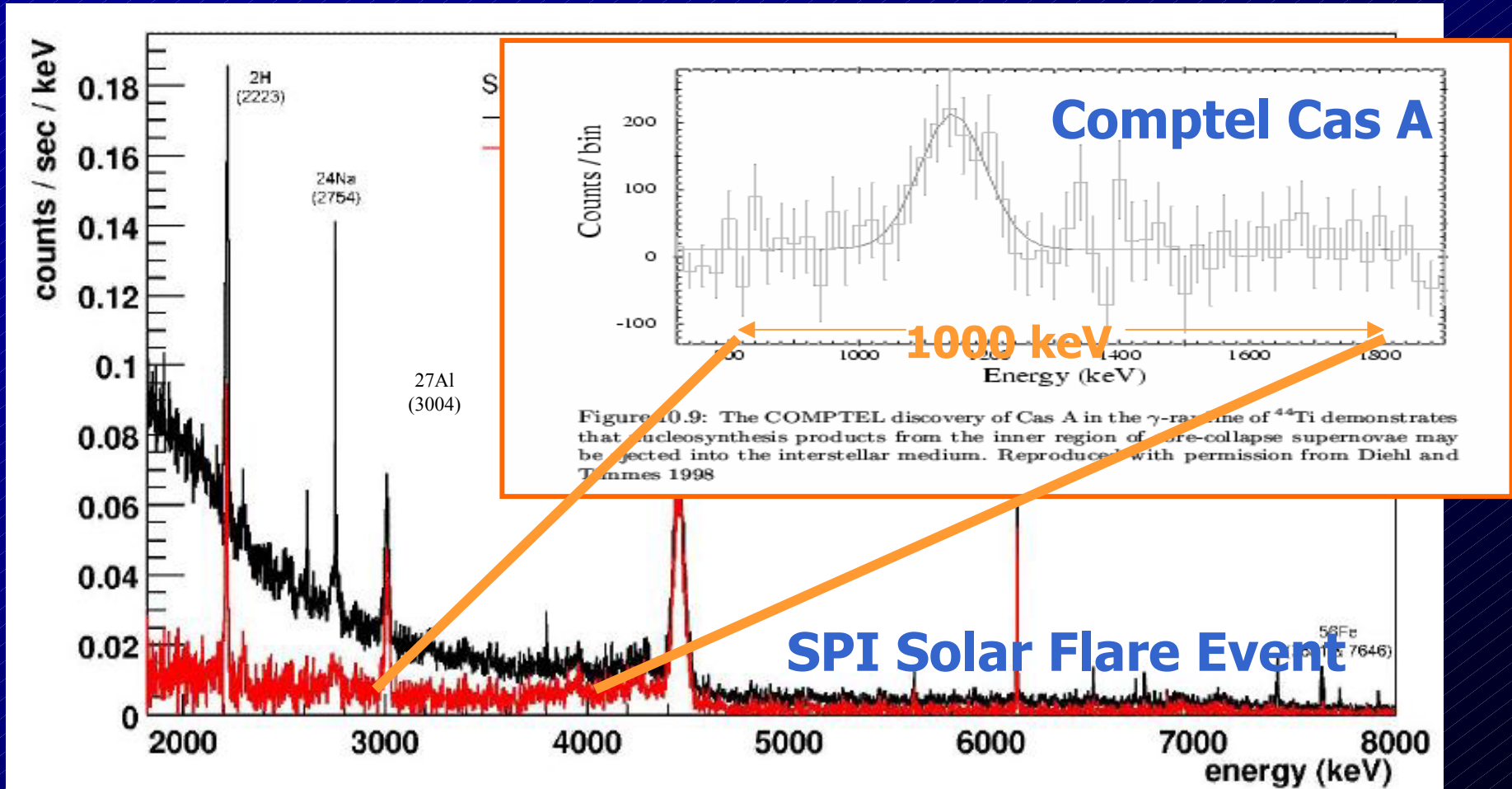


$^{26}\text{Al} \rightarrow$ Reaktionspfad-Details in Sternen/SNe, neutrino-Prozess $\rightarrow$ Leichtmetalle (Al, Mg) / Sand am Meer (Si)

^{44}Ti , $^{56}\text{Ni} \rightarrow$ stabilste Isotope $^{56}\text{Ni}/^4\text{He}$, Ausfrieren eines Kernfusions-Ofens $\rightarrow$ Leichtmetalle/Eisen



INTEGRAL/SPI: Gamma-Linien-Spektroskopie



Spektrale Auflösung nun < Linienbreite! (~2 keV)

INTEGRAL's erste Beiträge

Diffuse Emission aus der inneren Galaxie

- ☆ Antimaterie - Annihilation (e^+)

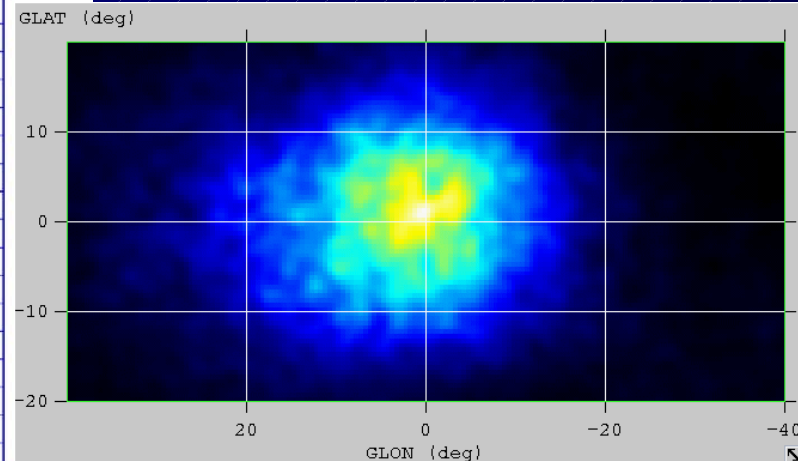
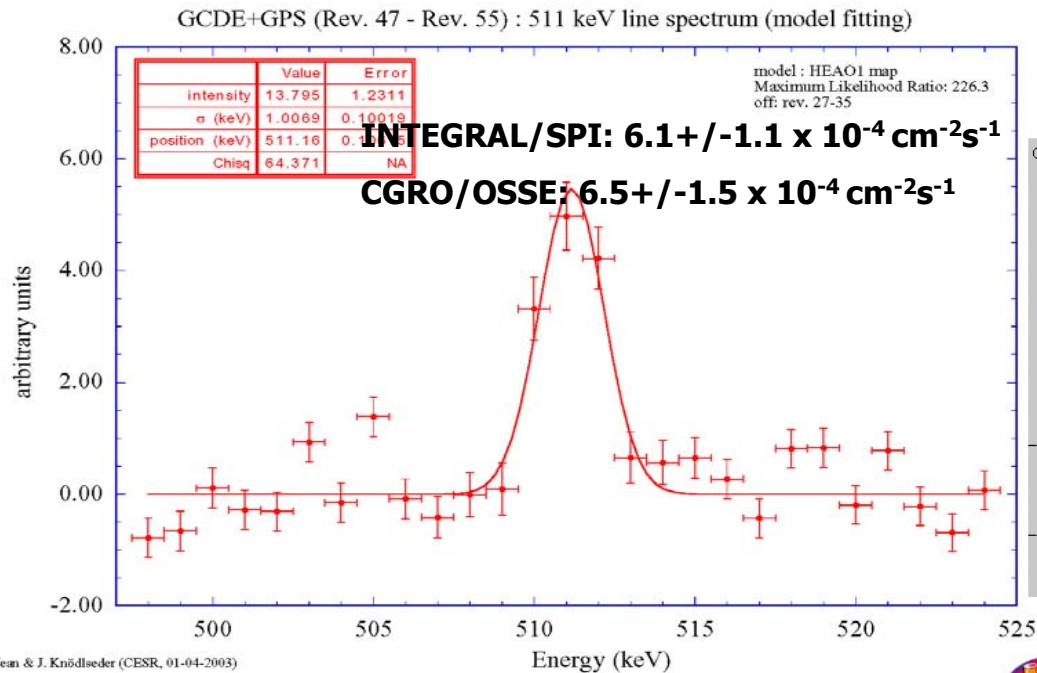
 - ☞ 511 keV Linie

- ☆ ^{26}Al Radioaktivität ($\tau \sim 10^6$ Jahre)

 - ☞ 1809 keV Linie

SPI: e^+ Annihilation aus der Galaxie

07/2003



Antimaterie aus der inneren Galaxie

- ★ Annihilations-Linie bei 511 keV, ~ wie erwartet
- ★ Ausgedehntes aber eher gleichförmiges Quellgebiet



SPI: ^{26}Al Nukleosynthese in der Galaxie

07/2003

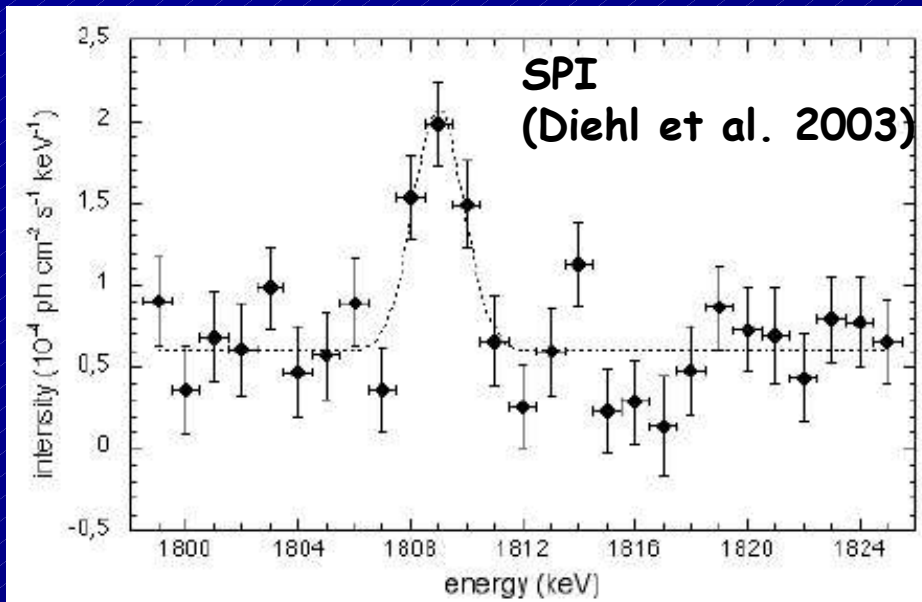
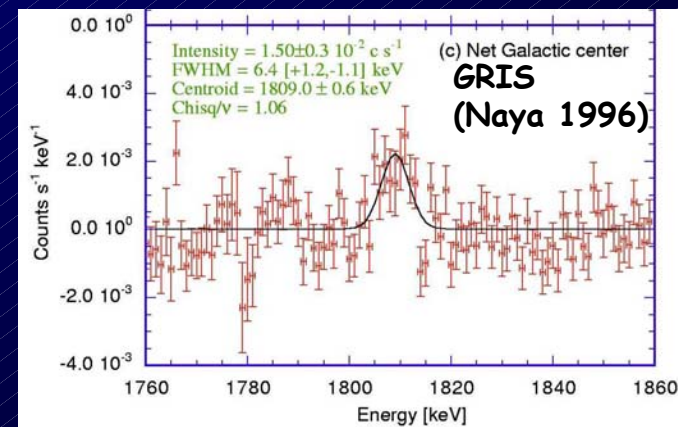
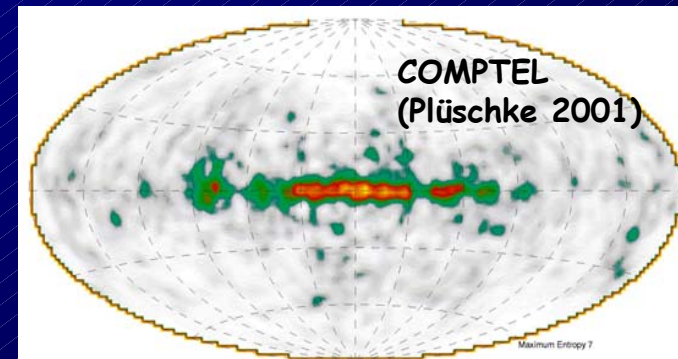


Fig. 6. Imaging analysis result from fitting a sky intensity distribution as modelled from the COMPTEL ^{26}Al skymap to each energy bin. Background was modelled from Crab observation detector ratios, and fitted in intensity to the actual measurement for each pointing, together with the sky signal.



■ ^{26}Al Messung mit SPI:

☆ Entsprechend Erwartungen (COMPTEL etc.)

☆ Keine verbreiterte Linie

INTEGRAL's Beiträge

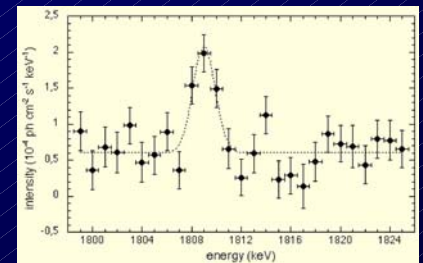
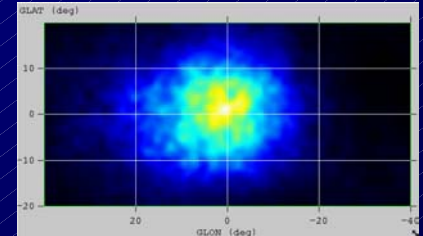
Resultate der ersten Monate:

☆ Antimaterie in der inneren Galaxie

☞ Ausgedehnte, aber eher gleichförmige Annihilation (Nukleosynthese, Pulsare, BH Jets...)

☆ ^{26}Al in der inneren Galaxie

☞ Nukleosynthese-Gebiete massereicher Sterne, Zerfall im ISM ($v < 100$ km/s)



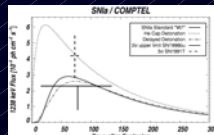
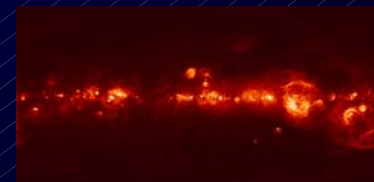
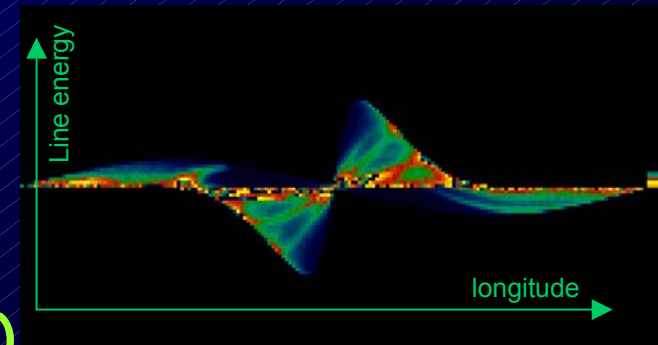
zu erwarten:

☆ Grossräumig-galaktische Verteilung massereicher Sterne

($\rightarrow$ ^{26}Al v/l Profil wie von CO , $\text{H}\alpha$)

☆ Einblicke in dunkle Sternen-Nester (^{44}Ti)

☆ Studien einzelner / prominenter Quell-Objekte (SN, OB Ass., ...)



Nukleosynthese & INTEGRAL

