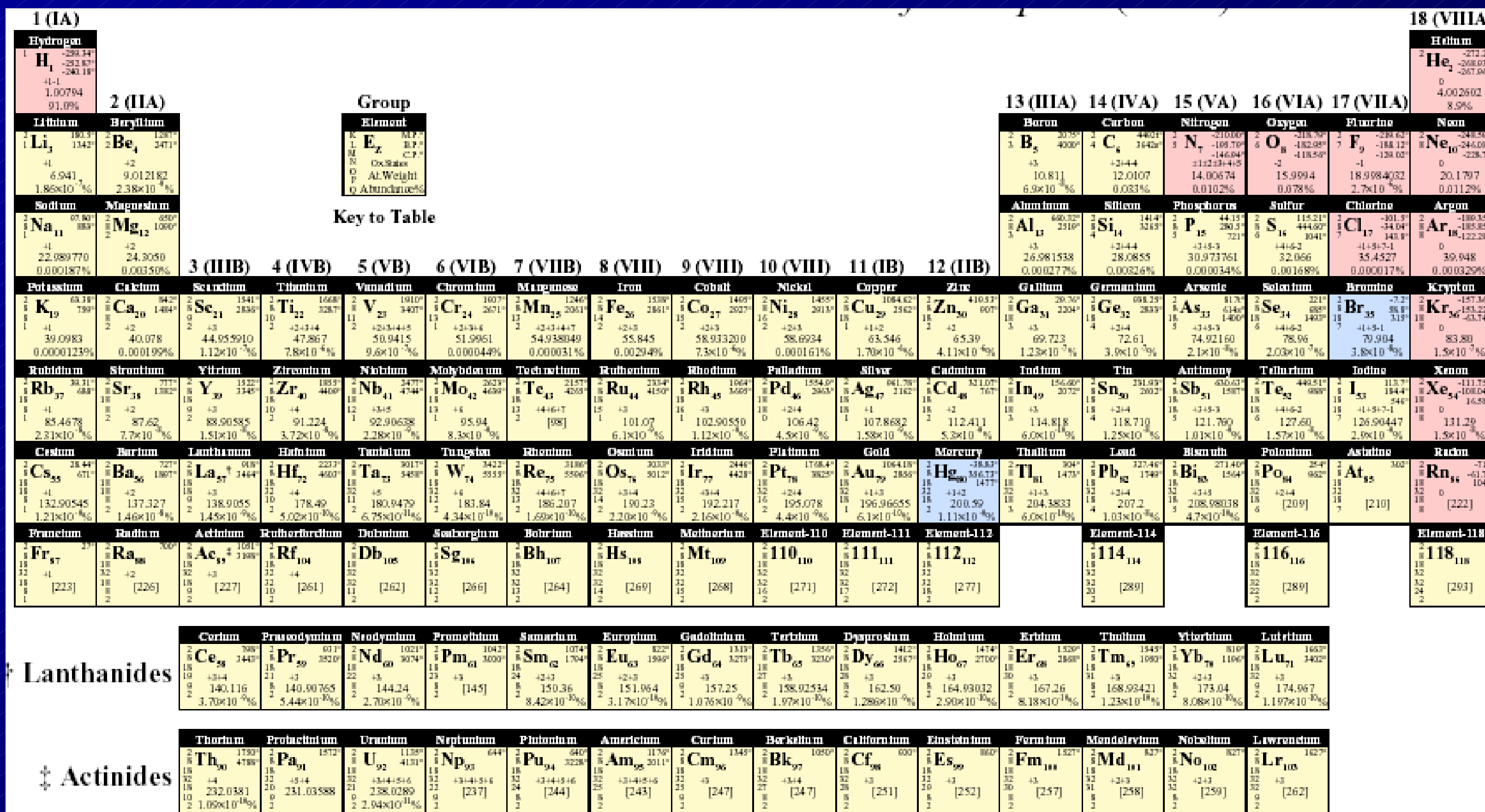
Nukleosynthese: Wie bildeten sich die Elemente?

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

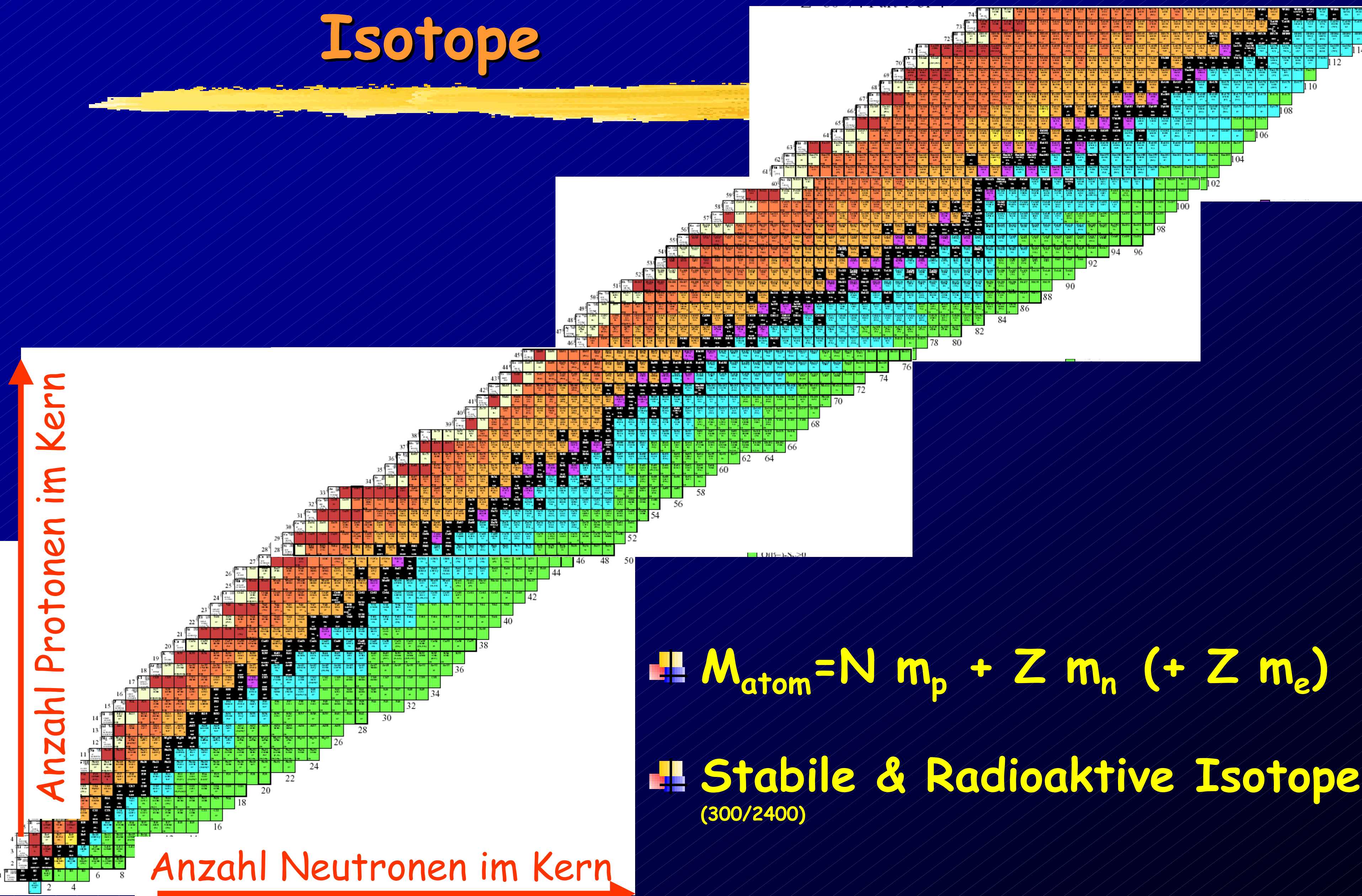
Roland Diehl
MPE

"Periodensystem" der Elemente



- "Periodensystem": Chemische "Elemente",
  Anordnung nach Eigenschaften der Elektronenhülle (1869, Mendelejew/Meyer)

Atomkern-Vielfalt:
Isotope



- $M_{atom} = N\ m_p + Z\ m_n\ (+\ Z\ m_e)$
- Stabile & Radioaktive Isotope
  (300/2400)

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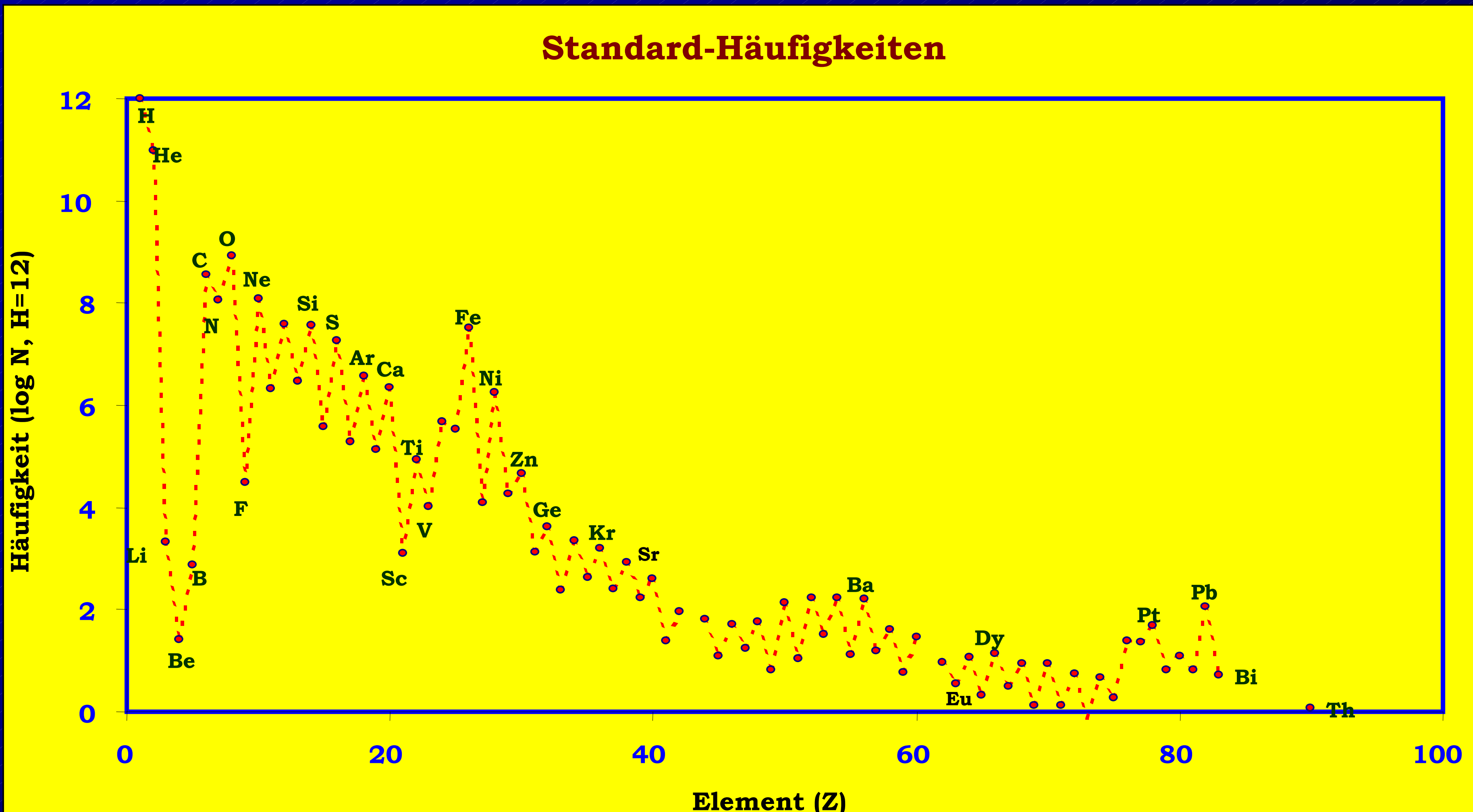
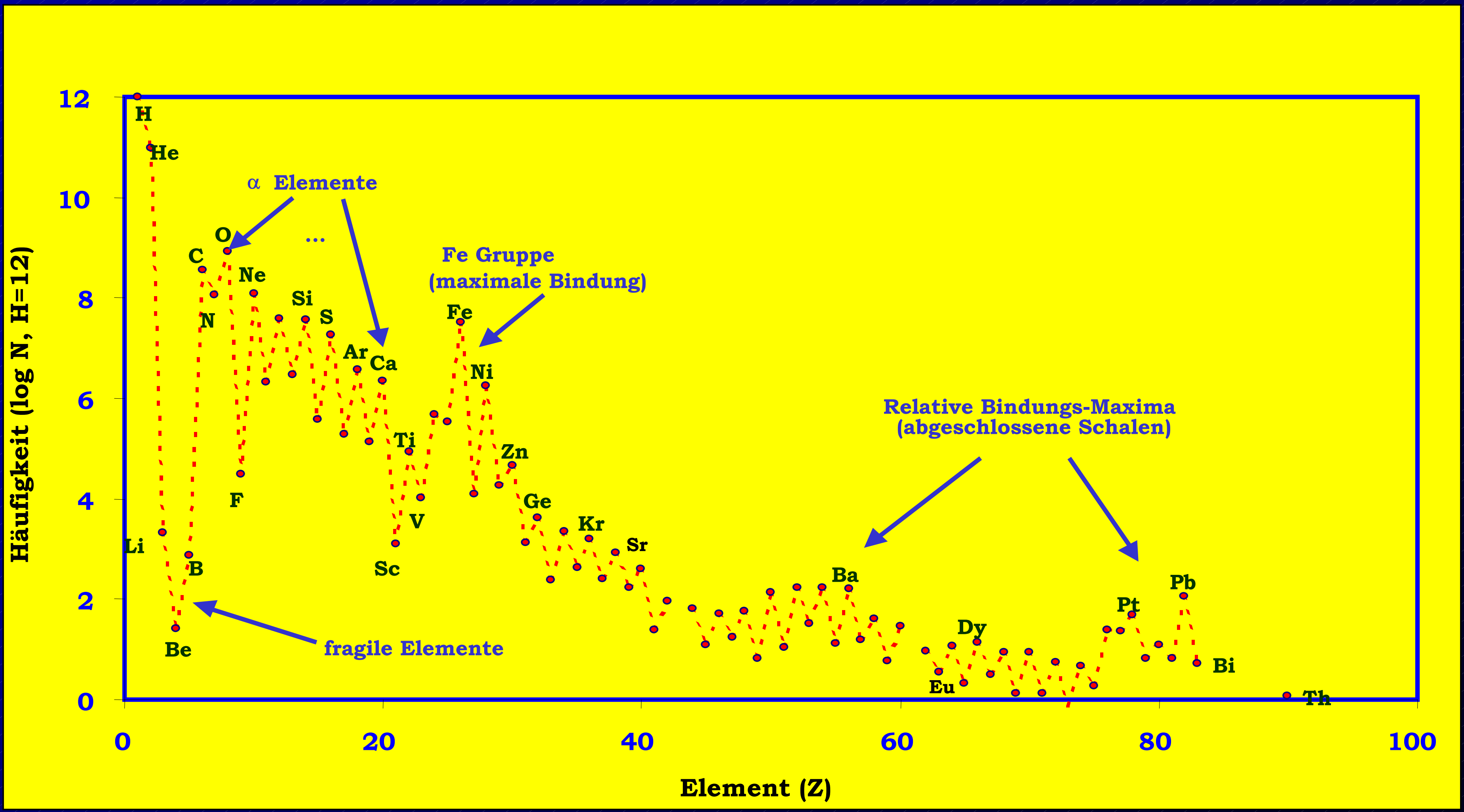
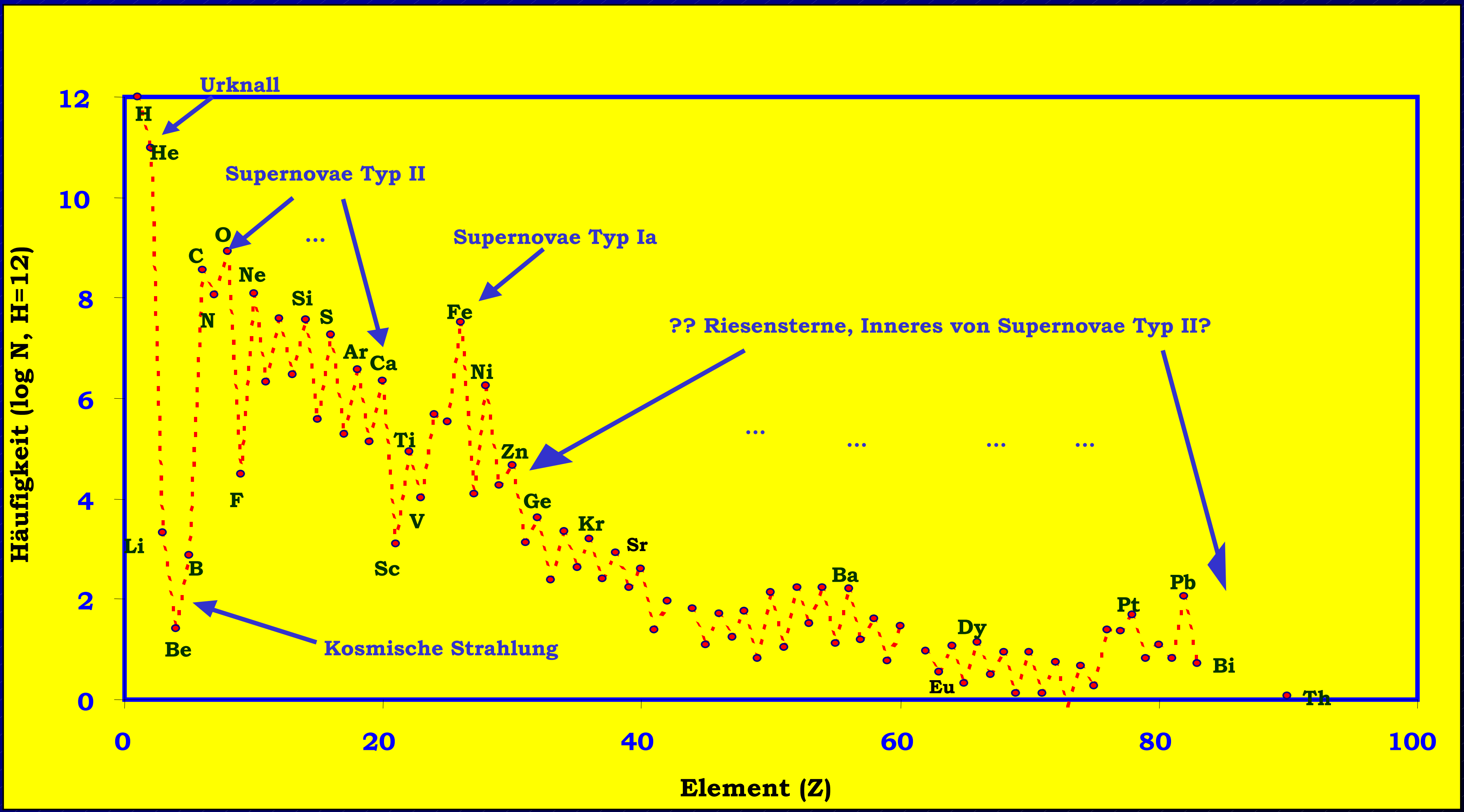
Elemente im Universum: Welche, Wieviel?



Element-Häufigkeiten: Kernstruktur



Element-Häufigkeiten: Kosmische Quellen



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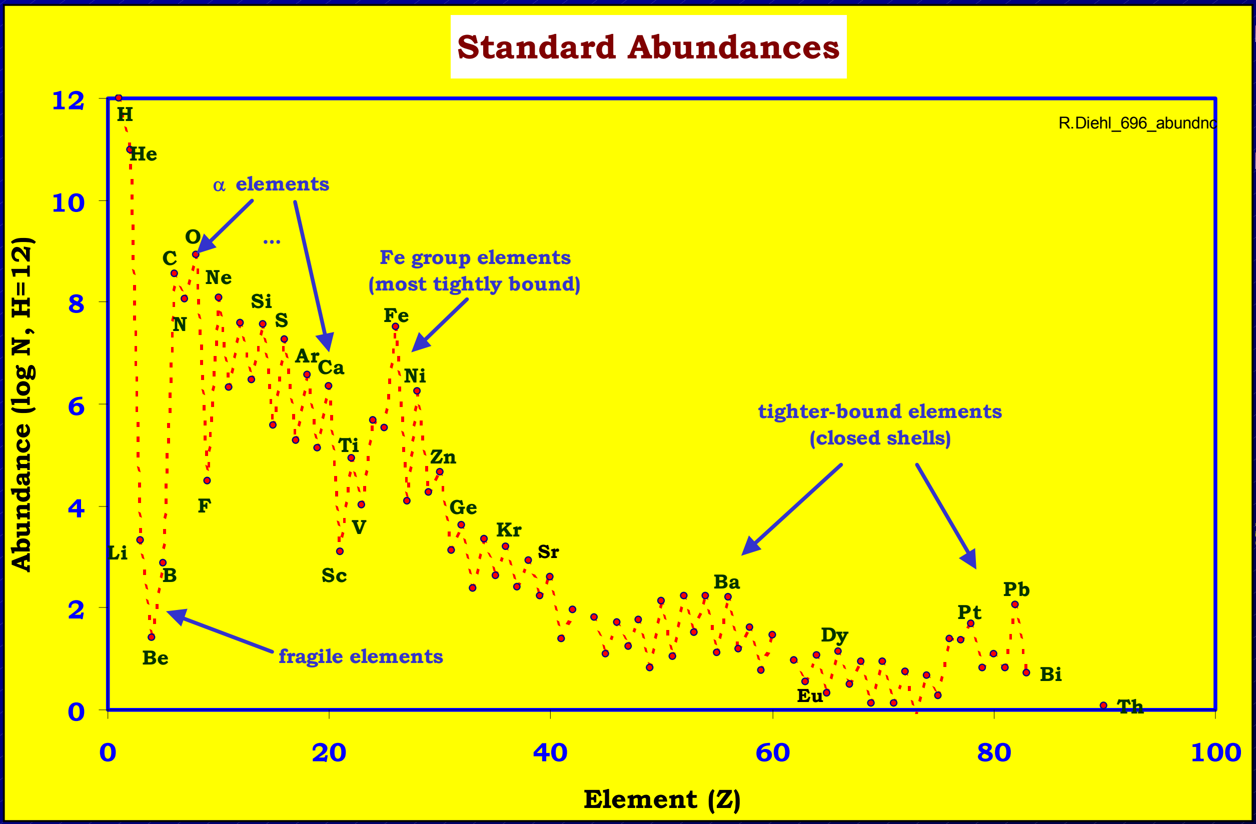
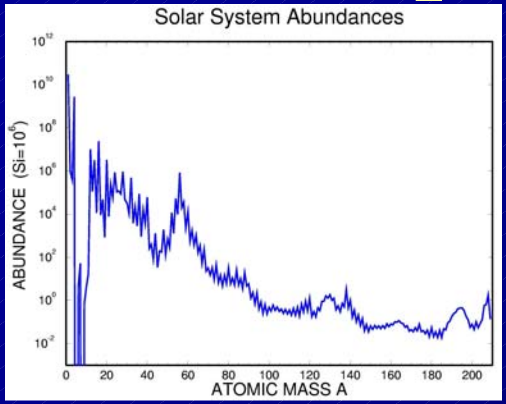
Studium der Element-Häufigkeiten

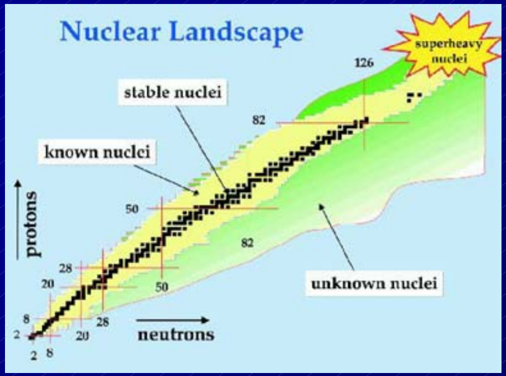


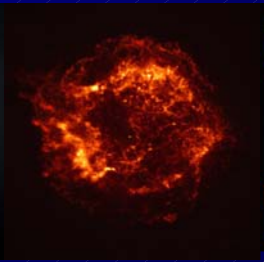
- Häufigkeitsunterschiede umfassen 12 Dekaden!
- Charakteristische Muster -> spezifische, unterschiedliche Entstehungsprozesse

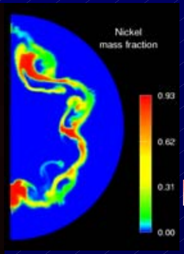
- Welche Prozesse in der Natur sind dafür verantwortlich?

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"

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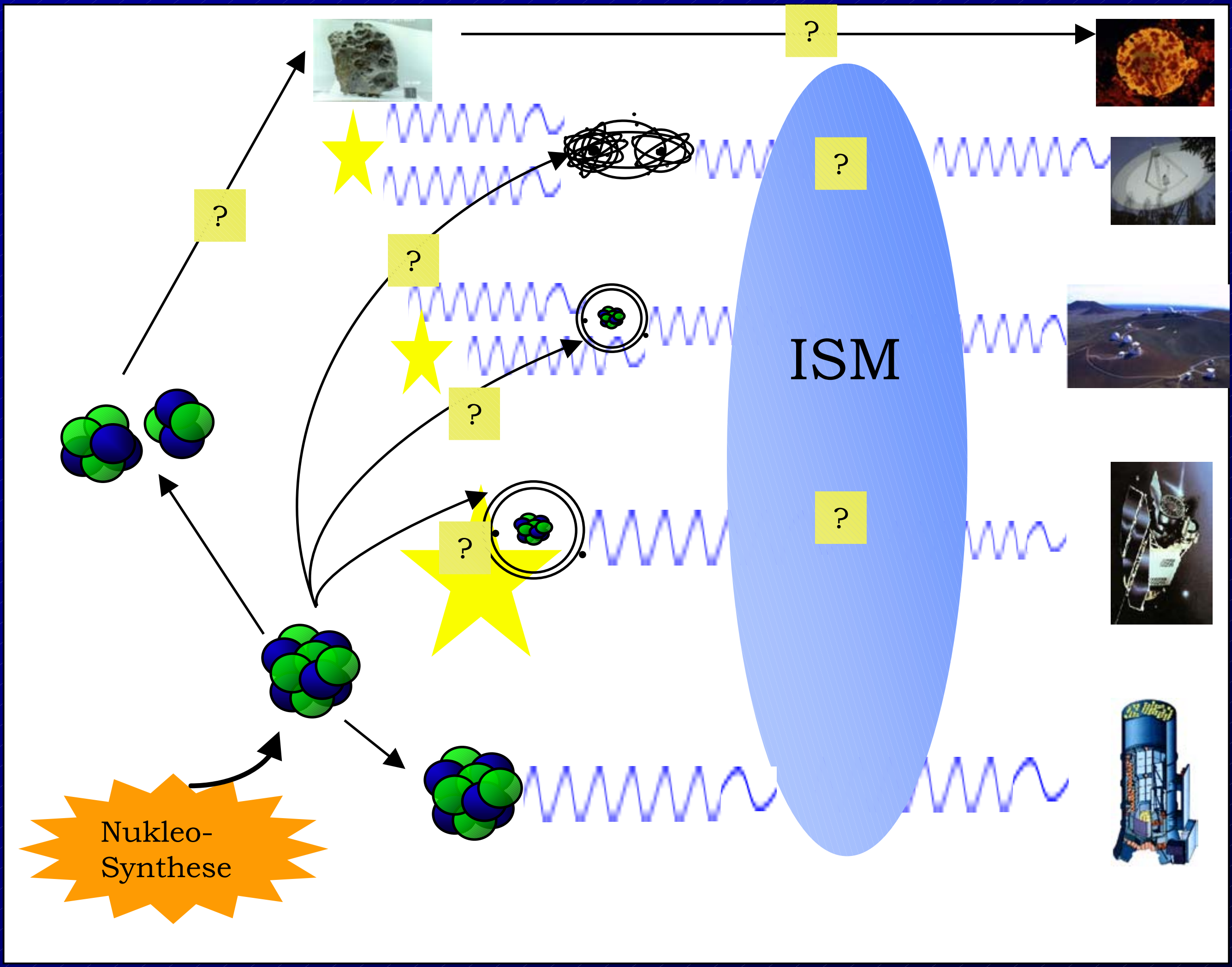
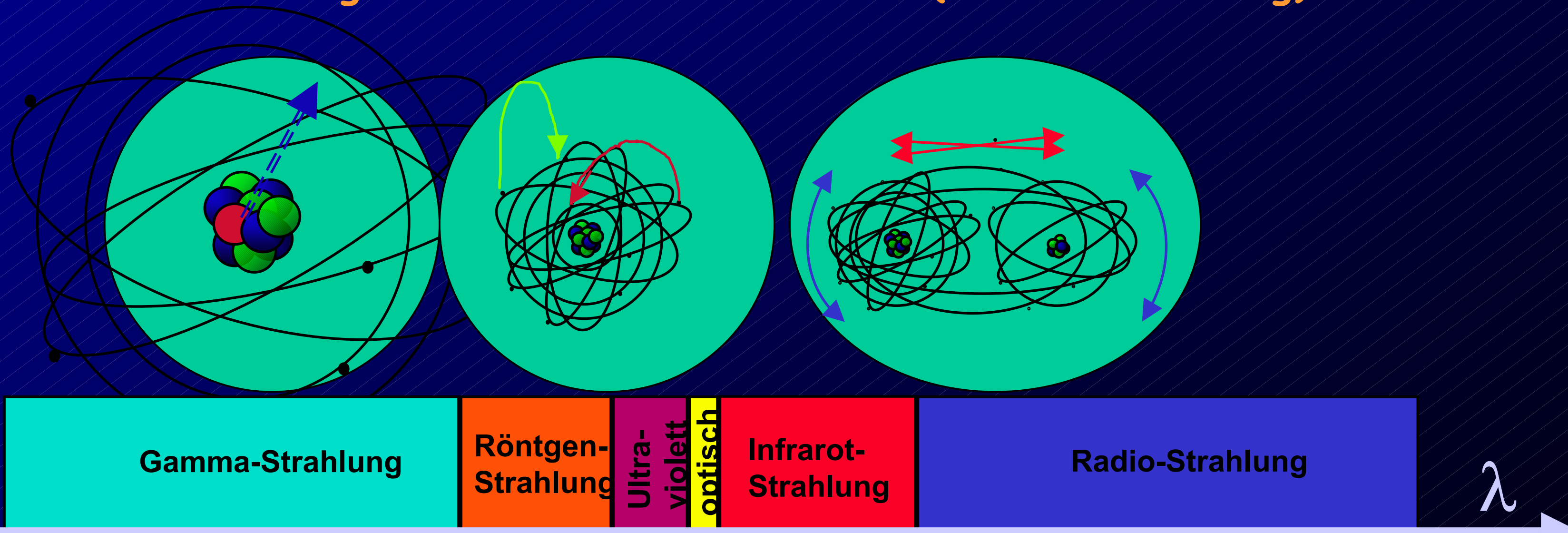
Messmöglichkeiten zur Nukleosynthese



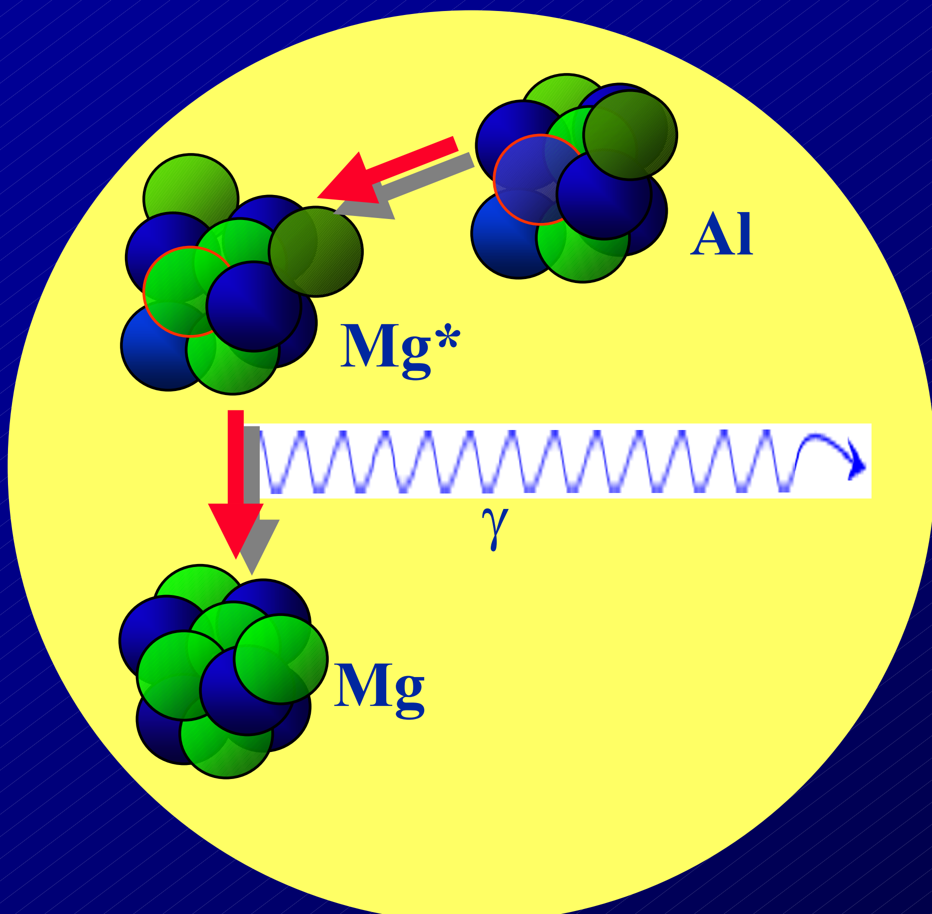
- Gammastrahllung & Meteoriten-Einschlüsse:
  -> Isotope; direkt
- Alternativen: Absorptions- und Emissions-Linien (=Atomhülle)
  -> Elemente; indirekt
  - ☆ Element-Häufigkeiten aus atomaren Strahlungsprozessen (Opt/UV/X) hilfreich
  - ☆ HFS-Effekte in IR…R schwerer zu messen

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)



Gammastrahlung kosmischer Isotope



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

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

Gamma-Astronomie und Nukleosynthese

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
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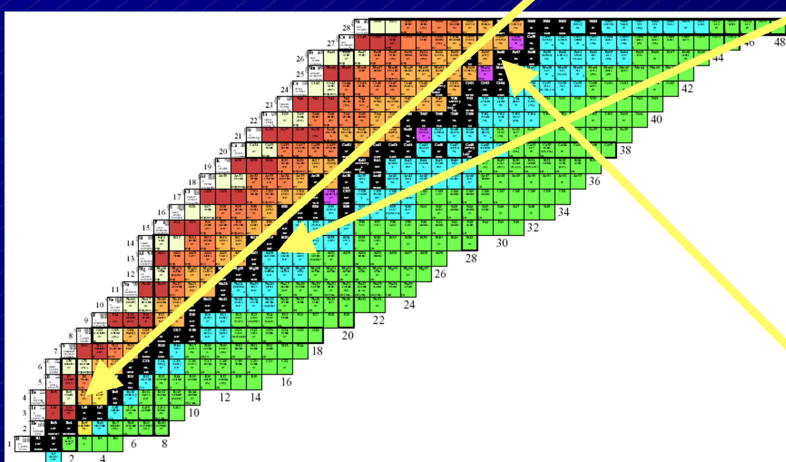
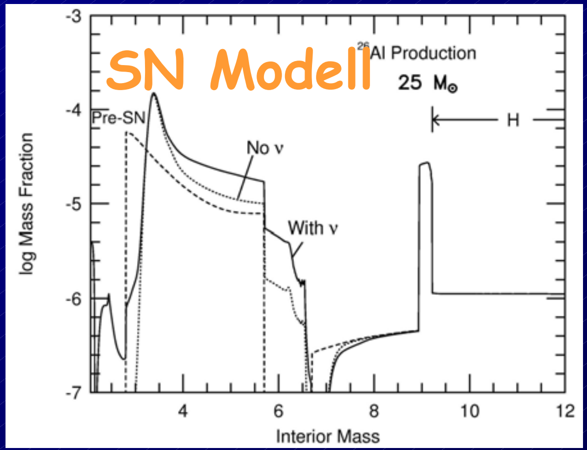


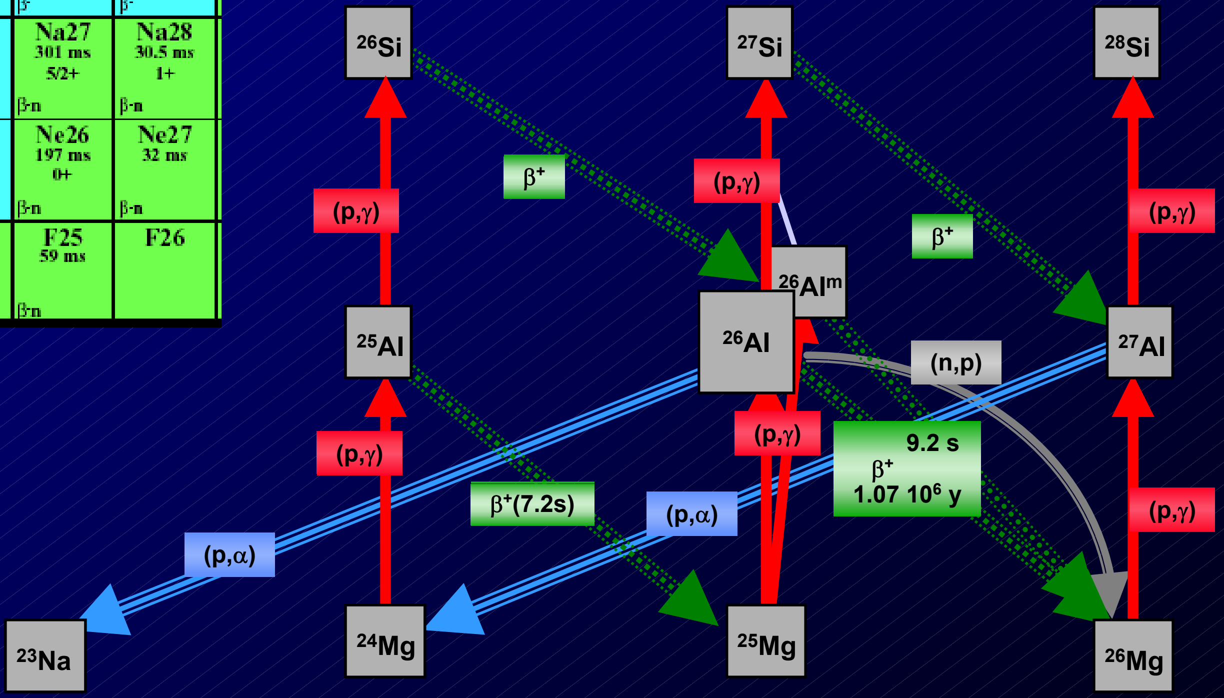
- 511 keV, ^{7}Be -> Novae -> p-Anlagerungen, Antimaterie -> Fluor!
- ^{26}Al -> Reaktionspfad-Details in Sternen/SNe, neutrino-Prozess -> Leichtmetalle (Al, Mg) / Sand am Meer (Si)
- ^{44}Ti, ^{56}Ni -> stabilste Isotope ^{56}Ni/^{4}He, Ausfrieren eines Kernfusions-Ofens -> Leichtmetalle/Eisen

Beispiel: ^{26}Al Synthese

	ECp	ECp	ECp,ECα,...	EC	EC	100	β-
Si24 102 ms 0+ ECp	Si25 220 ms 5/2+ ECp	Si26 2.234 s 0+ EC	Si27 4.16 s 5/2+ EC	Si28 0+ 92.23	Si29 1/2+ 4.67	Si30 0+ 3.10	Si31 157.3 m 3/2+ β-
Al23 0.47 s ECp	Al24 2.053 s 4+ * ECα	Al25 7.183 s 5/2+ EC	Al26 7.4E+5 y 5+ * EC	Al27 5/2+ 100	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 0+ 78.99	Mg25 5/2+ 10.00	Mg26 0+ 11.01	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+	Na22 2.6019 y 3+	Na23 3/2+ 100	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 0+ 90.48	Ne21 3/2+ 0.27	Ne22 0+ 9.25	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





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Gamma-Strahlung und Nukleosynthese

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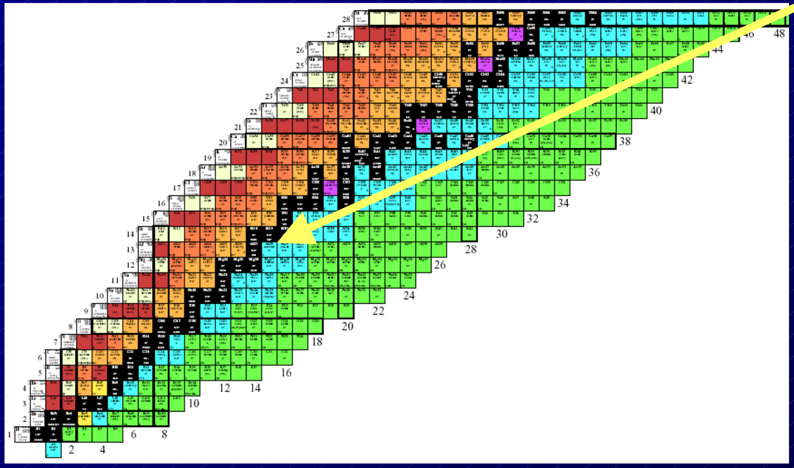
- 511 keV, ^{7}Be -> Novae -> p-Anlagerungen, Antimaterie -> Fluor!



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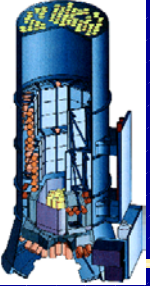
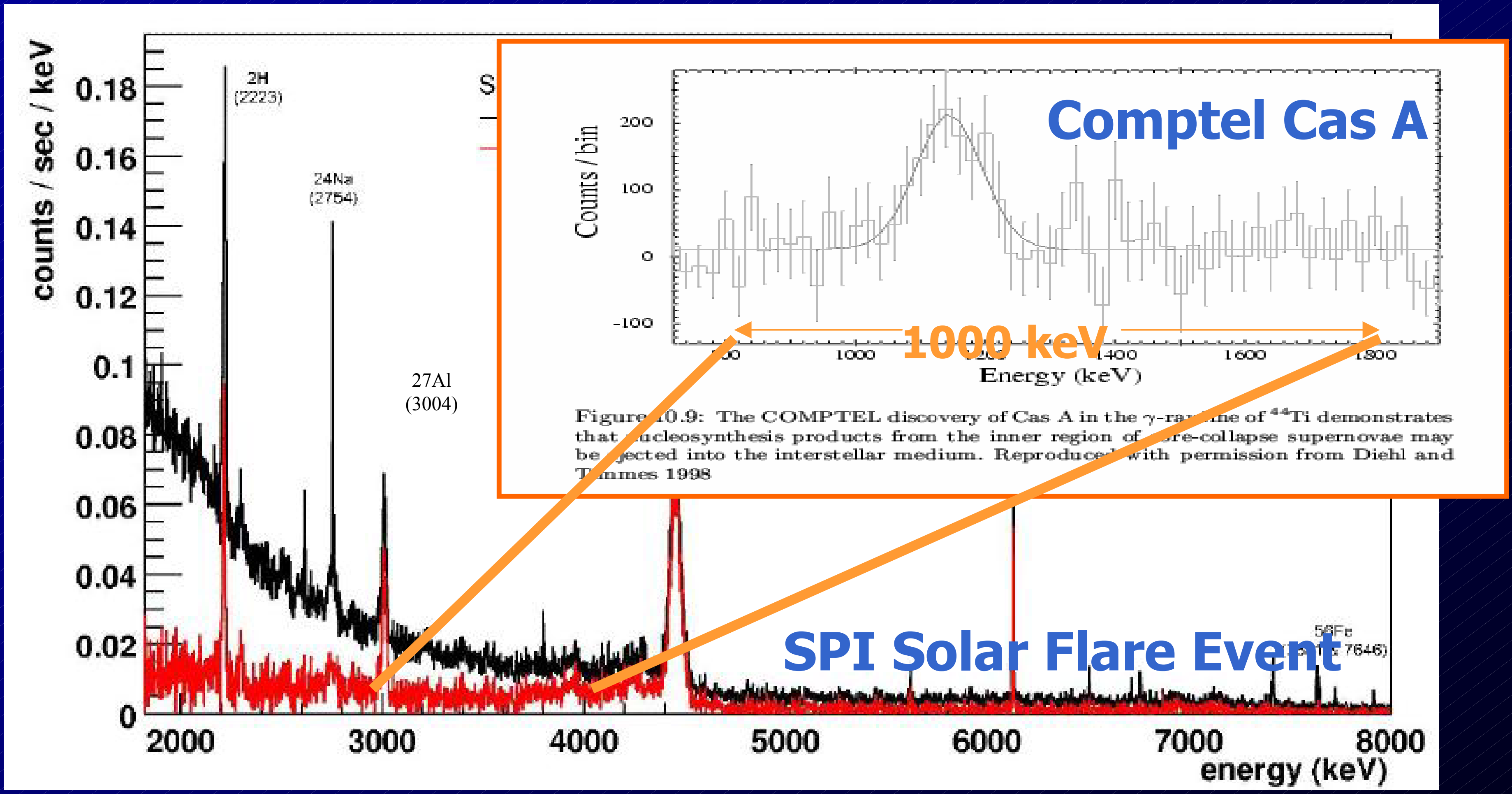


INTEGRAL/SPI: Gamma-Linien-Spektroskopie



- 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

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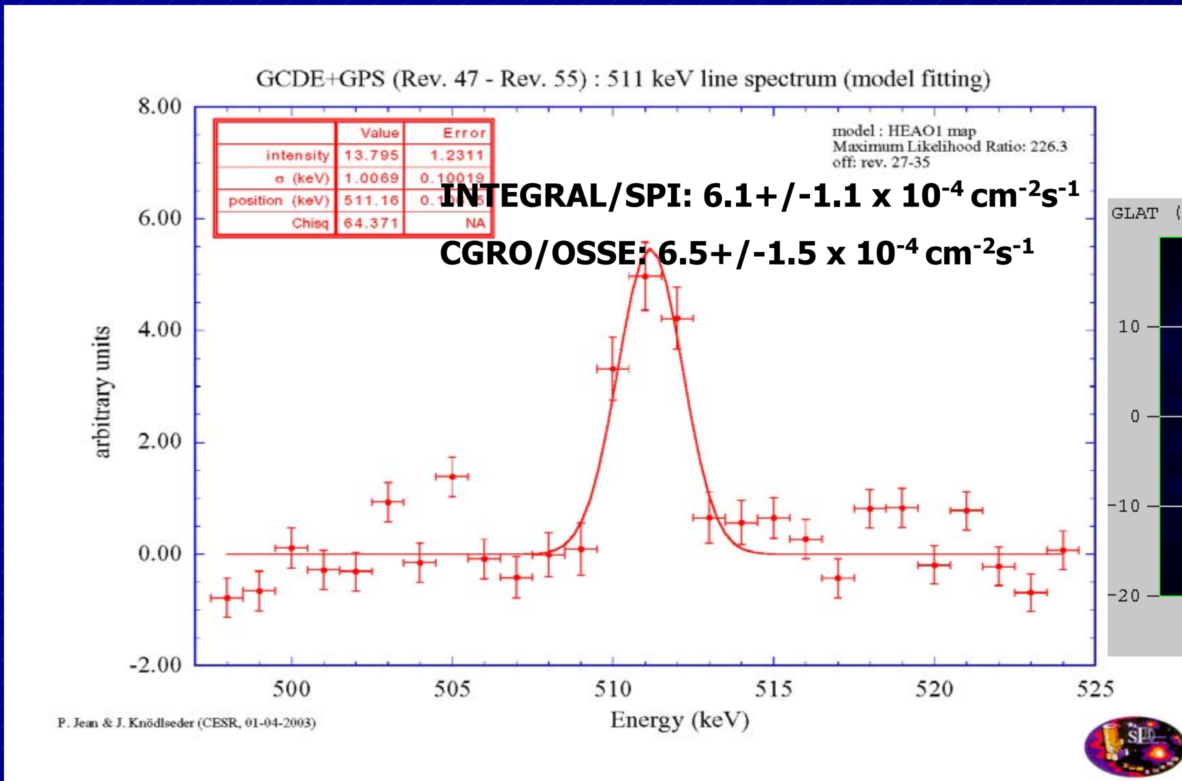
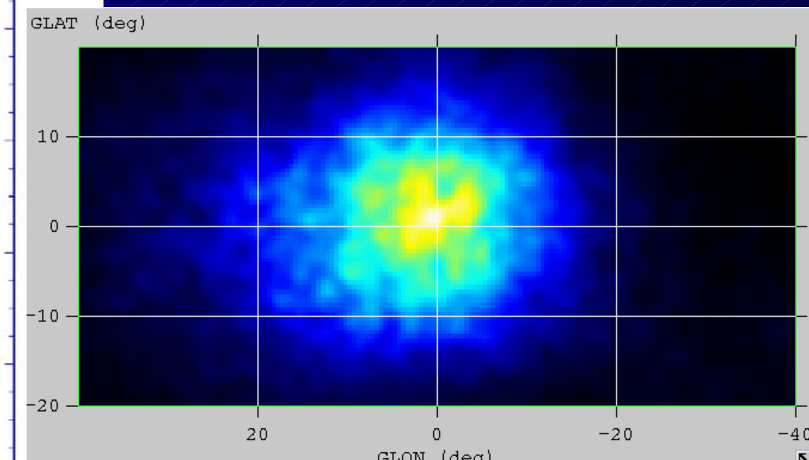
SPI: e^+ Annihilation aus der Galaxie

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

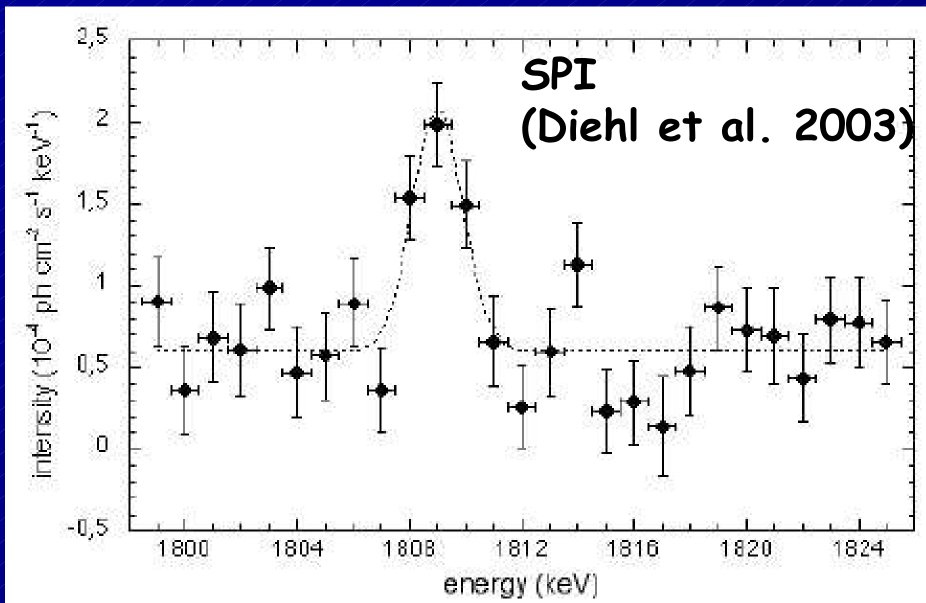
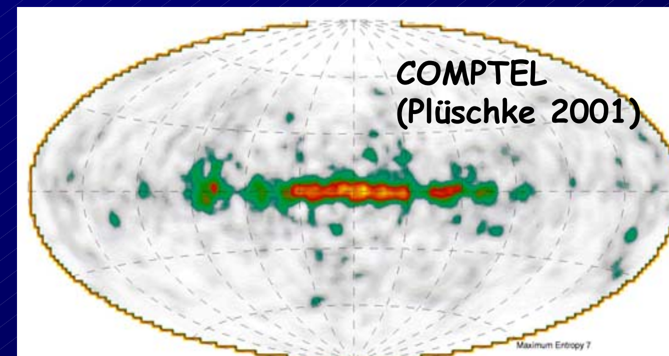
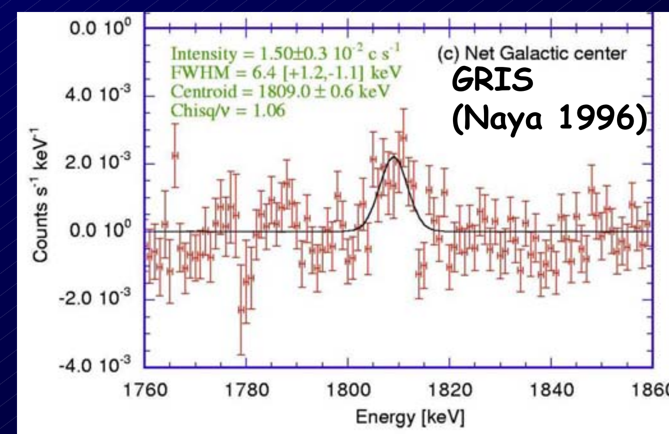


Fig. 6. Imaging analysis result from fitting a sky intensity distribution as modelled from the COMPTEL ^{26}Al skymap to each energy bin. Background was modelled from Crab observation detector ratios, and fitted in intensity to the actual measurement for each pointing, together with the sky signal.



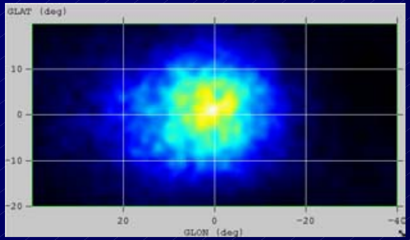


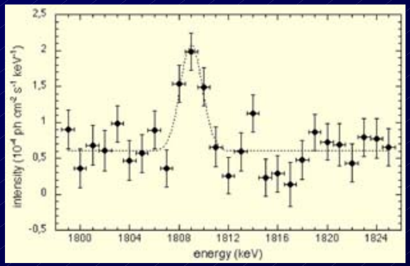
- ^{26}Al Messung mit SPI:
  - ☆ Entsprechend Erwartungen (COMPTEL etc.)
  - ☆ Keine verbreiterte Linie

INTEGRAL's Beiträge

Resultate der ersten Monate:

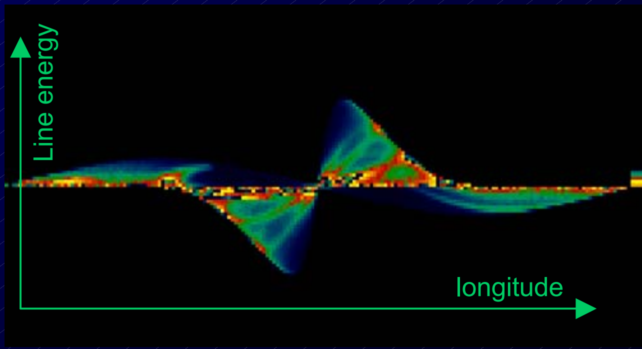
- Antimaterie in der inneren Galaxie
  - Ausgedehnte, aber eher gleichförmige Annihilation (Nukleosynthese, Pulsare, BH Jets…)
- ^{26}Al in der inneren Galaxie
  - Nukleosynthese-Gebiete massereicher Sterne, Zerfall im ISM (v<100 km/s)

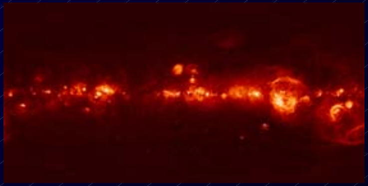


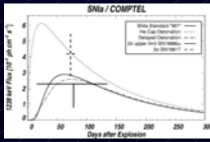


zu erwarten:

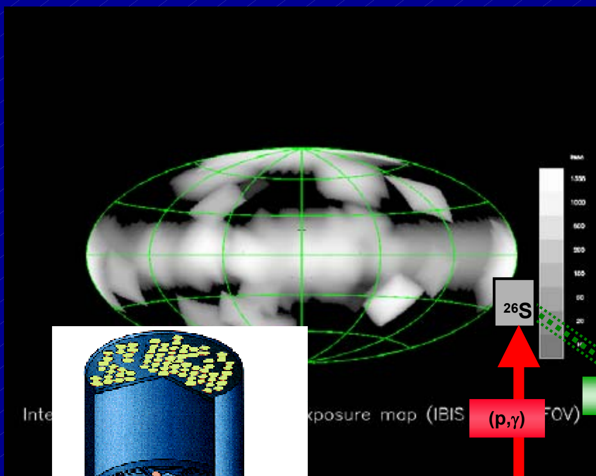
- Grossräumig-galaktische Verteilung massereicher Sterne (-> ^{26}Al v/l Profil wie von CO, Hα)
- Einblicke in dunkle Sternen-Nester (^{44}Ti)
- Studien einzelner / prominenter Quell-Objekte (SN, OB Ass.,…)

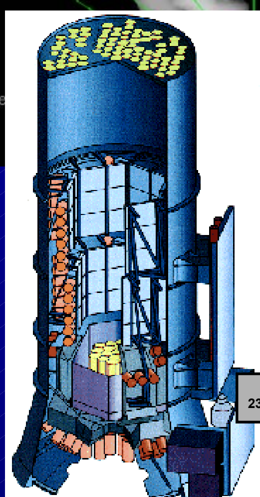


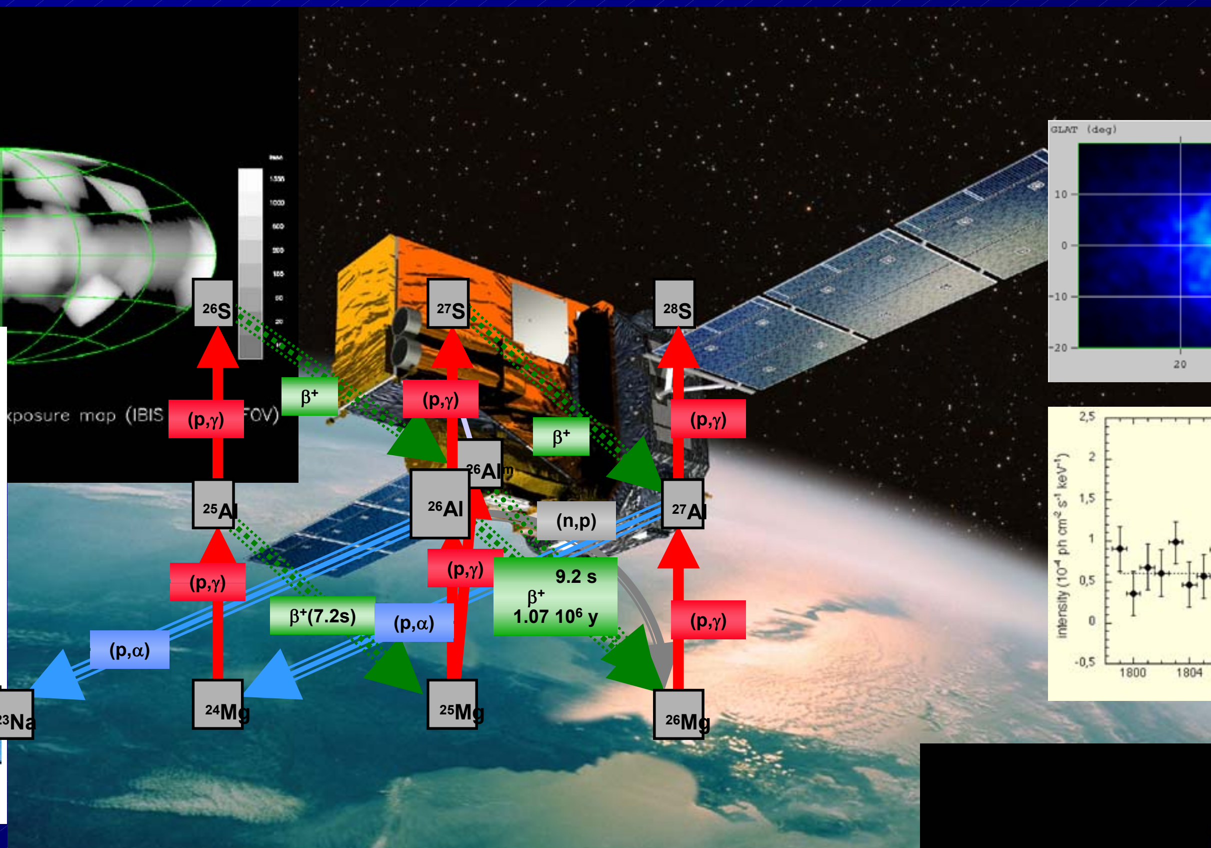


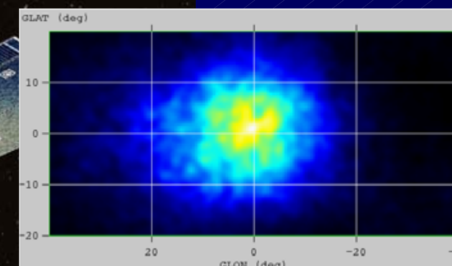


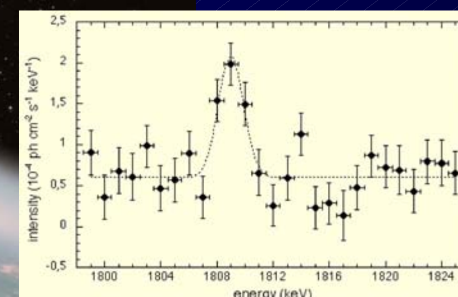
Nukleosynthese & INTEGRAL

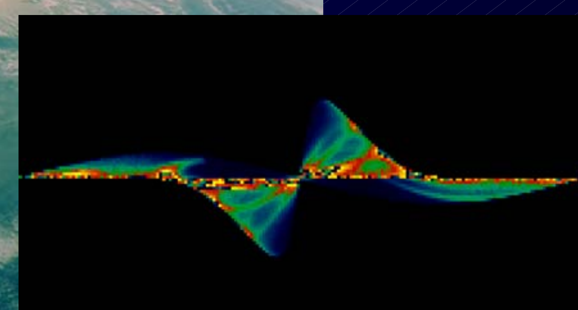












- Hohe spektrale Auflösung
  -> neue Messpunkte für
  kosmische Nukleosynthesemodelle