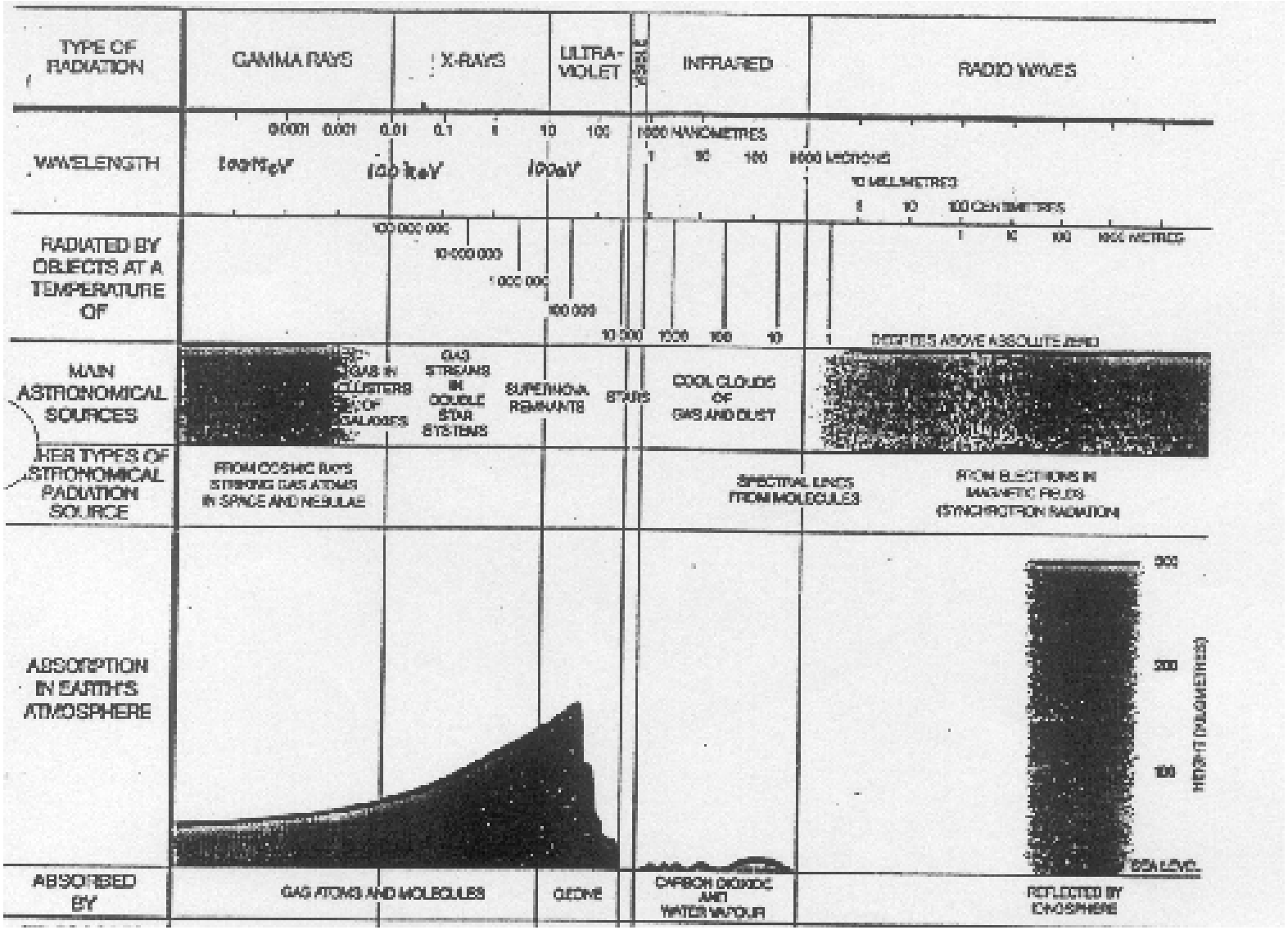
Procesos cósmicos de producción de rayos X y γ

Juan Fabregat

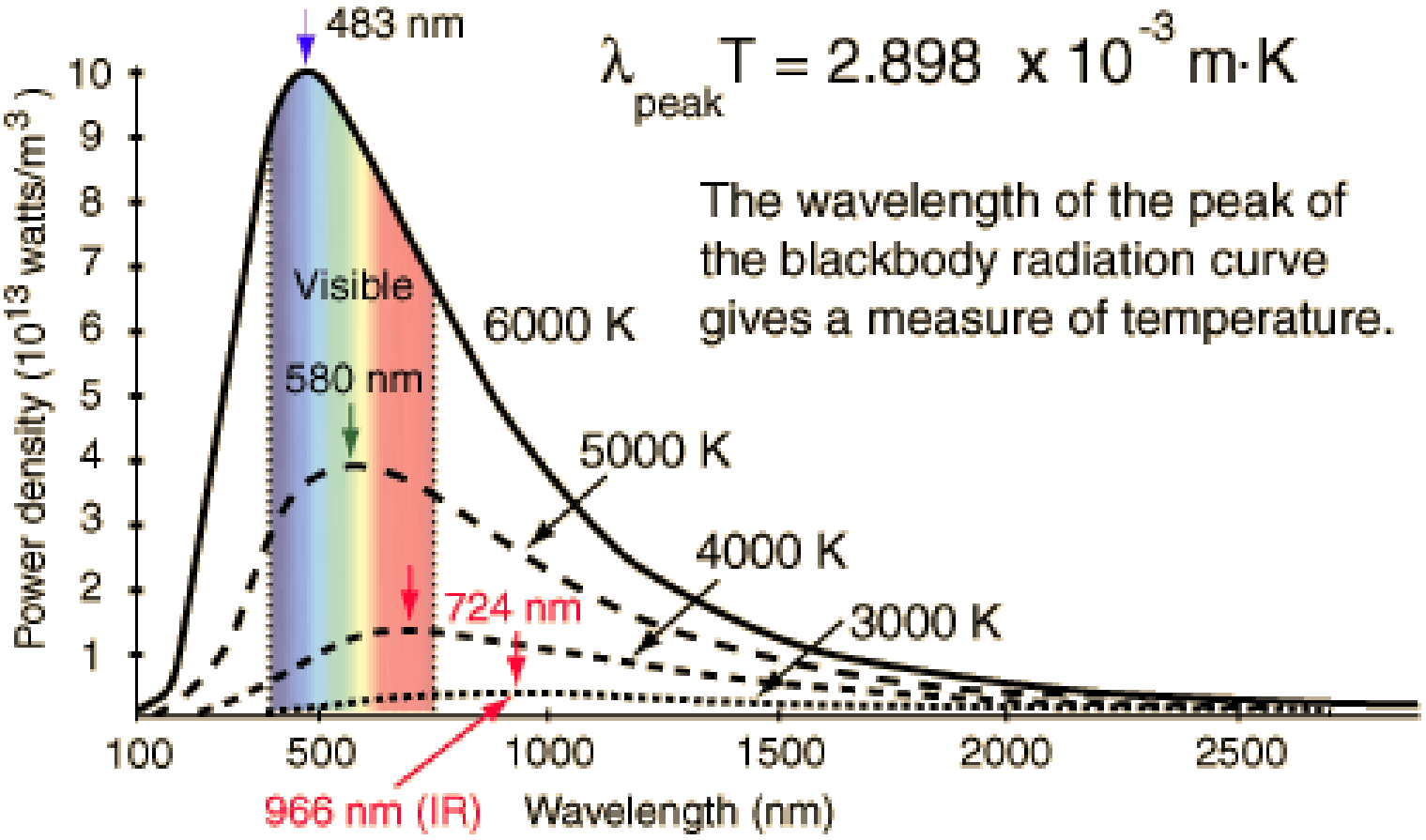
Observatorio Astronómico de la Universidad de Valencia


TYPE OF RADIATION
GAMMA RAYS
X-RAYS
ULTRA-VIOLET
VISIBLE
INFRARED
RADIO WAVES
WAVELENGTH
0.0001 0.001 0.01 0.1 1 10 100 1000 NANOMETRES
1 10 100 1000 MICRONS
10 MILLIMETRES
1 10 100 CENTIMETRES
1 10 100 1000 METRES
100 MeV
100 keV
100 eV
RADIATED BY OBJECTS AT A TEMPERATURE OF
100 000 000
10 000 000
1 000 000
100 000
10 000 1000 100 10 1
DEGREES ABOVE ABSOLUTE ZERO
MAIN ASTRONOMICAL SOURCES
GAS IN CLUSTERS OF GALAXIES
GAS STREAMS IN DOUBLE STAR SYSTEMS
SUPERNOVA REMNANTS
STARS
COOL CLOUDS OF GAS AND DUST
OTHER TYPES OF ASTRONOMICAL RADIATION SOURCE
FROM COSMIC RAYS STRIKING GAS ATOMS IN SPACE AND NEBULAE
SPECTRAL LINES FROM MOLECULES
FROM ELECTRONS IN MAGNETIC FIELDS (SYNCHROTRON RADIATION)
ABSORPTION IN EARTH'S ATMOSPHERE
300
200
100
HEIGHT (KILOMETRES)
SEA LEVEL
ABSORBED BY
GAS ATOMS AND MOLECULES
OZONE
CARBON DIOXIDE AND WATER VAPOUR
REFLECTED BY IONOSPHERE

Emisión térmica

- Radiación del cuerpo negro:
  $I(\lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{h\nu/kT} - 1}$

Radiación del cuerpo negro



Emisión térmica

- Radiación del cuerpo negro:
  $I(\lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{h\nu/kT}-1}$

- Ley de deplazamiento de Wien:
  $\lambda_{max} T = 2.898 \times 10^{-3}$

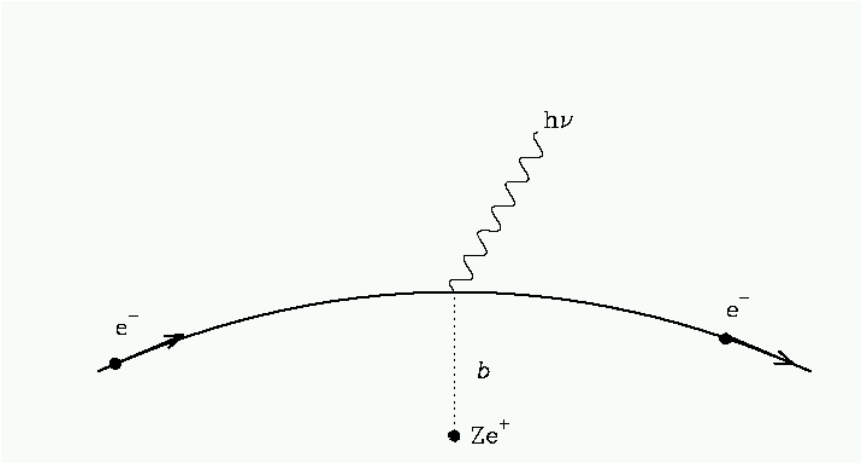
- Emisión en rayos X:
  $\lambda_{max} < 10nm \rightarrow K > 289\,800K$

Ejemplos:

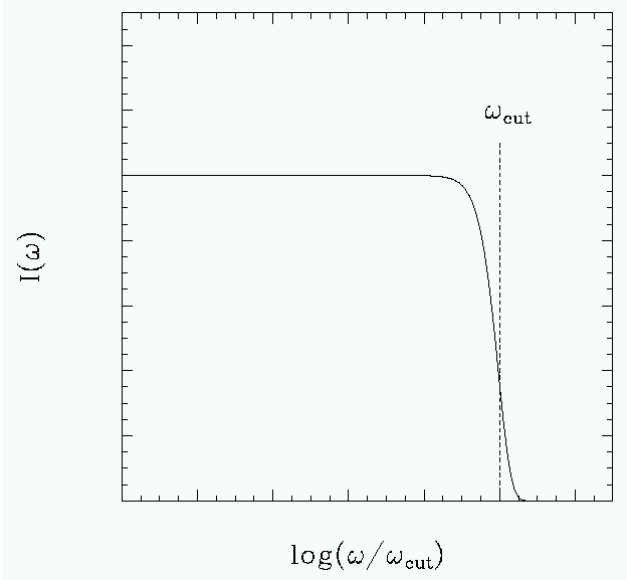
- Estrellas de neutrones jóvenes: Cangrejo, Geminga
- Estrellas calientes:
  $L_X \sim 10^{-7} L_B$
  para tipos anteriores a B5

Bremsstrahlung

- Fórmula de Larmor:
  $P = \frac{2q^2a^2}{3c^3}$



- $I(\omega) = \frac{8Z^2e^6}{3\pi c^3 m_e^2 v^2 b^2} e^{(-\frac{2\omega b}{v})}$

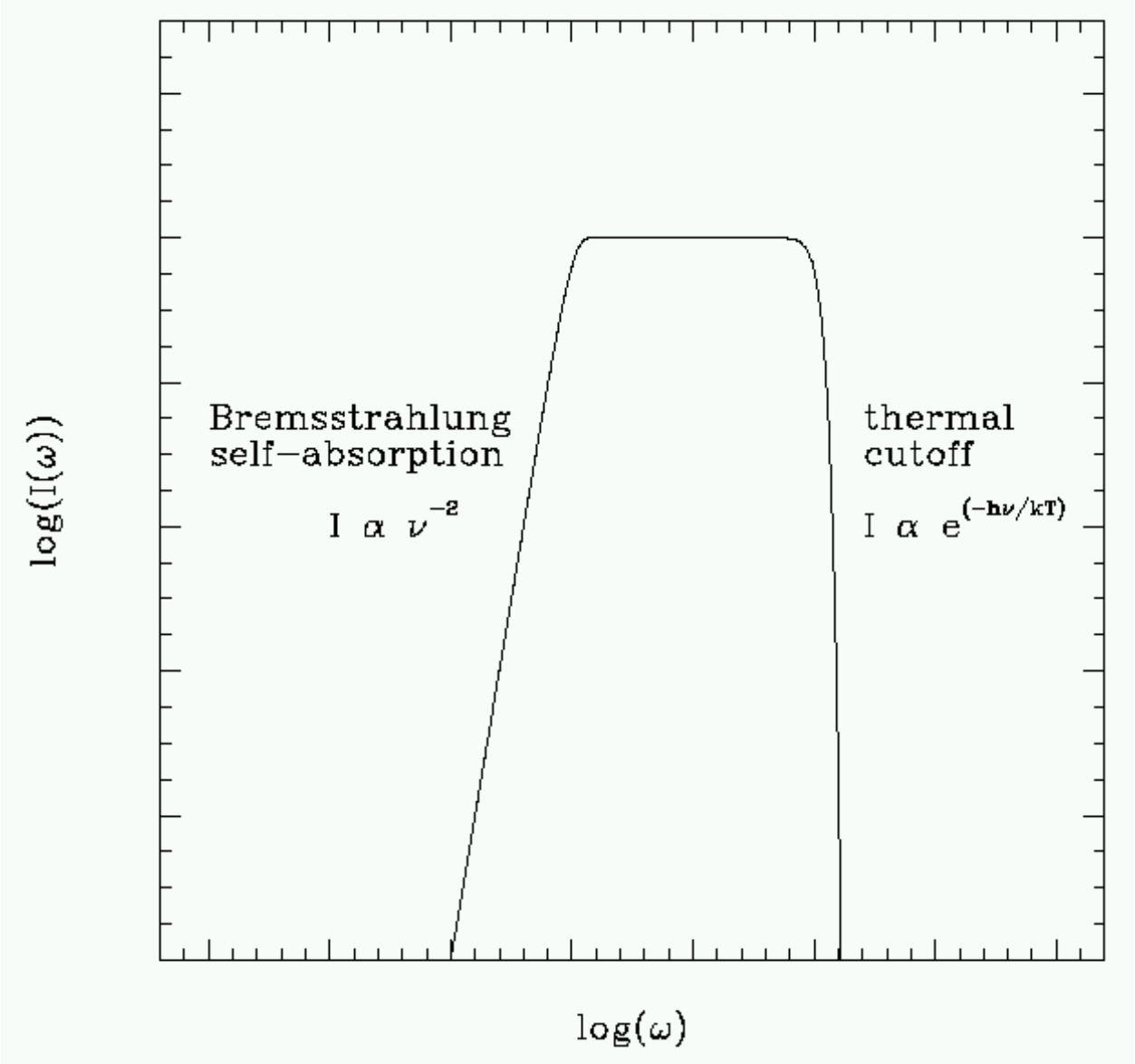


Bremsstrahlung térmico

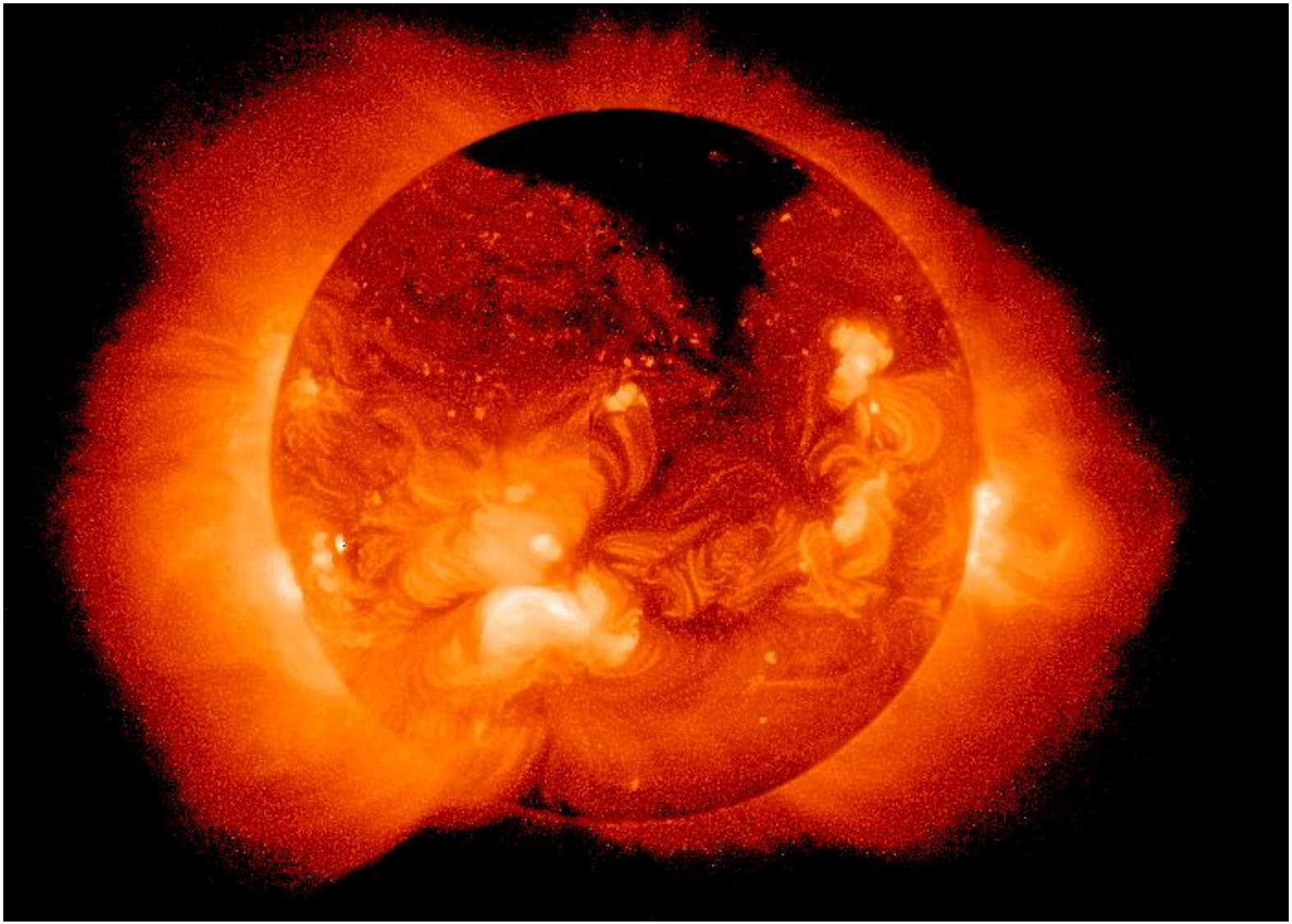
- Distribución de Maxwell:
  $f(v) = 4\pi(\frac{m_e}{2\pi kT})^{\frac{3}{2}} v^2 e^{-(\frac{m_e v^2}{2kT})}$

- Potencia por unidad de volumen:
  $e_{ff} = g_{ff} \frac{2^5 \pi e^6}{2 m_e c^3} (\frac{2\pi}{2 m_e k})^{\frac{1}{2}} T^{-\frac{1}{2}} Z^2 n_e n_i e^{-(\frac{h\nu}{kT})}$

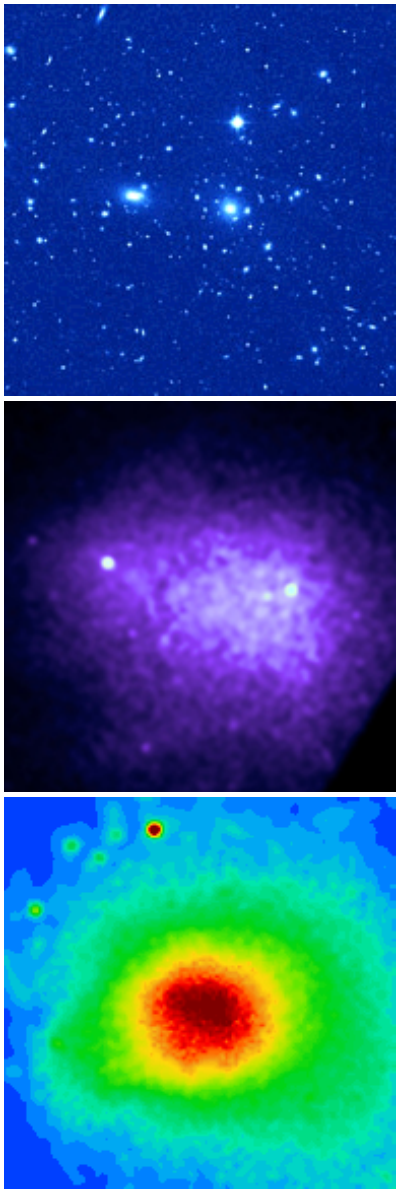
Autoabsorción

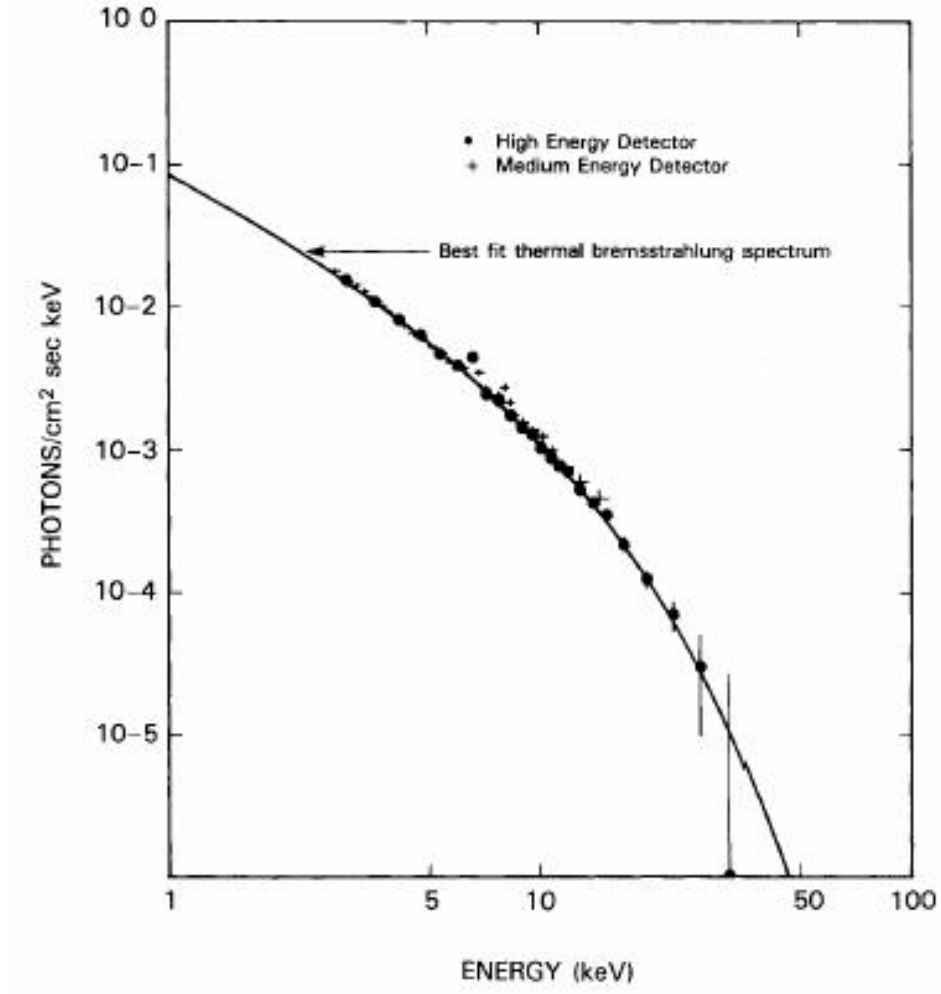


La corona solar en rayos X



El cúmulo de Coma



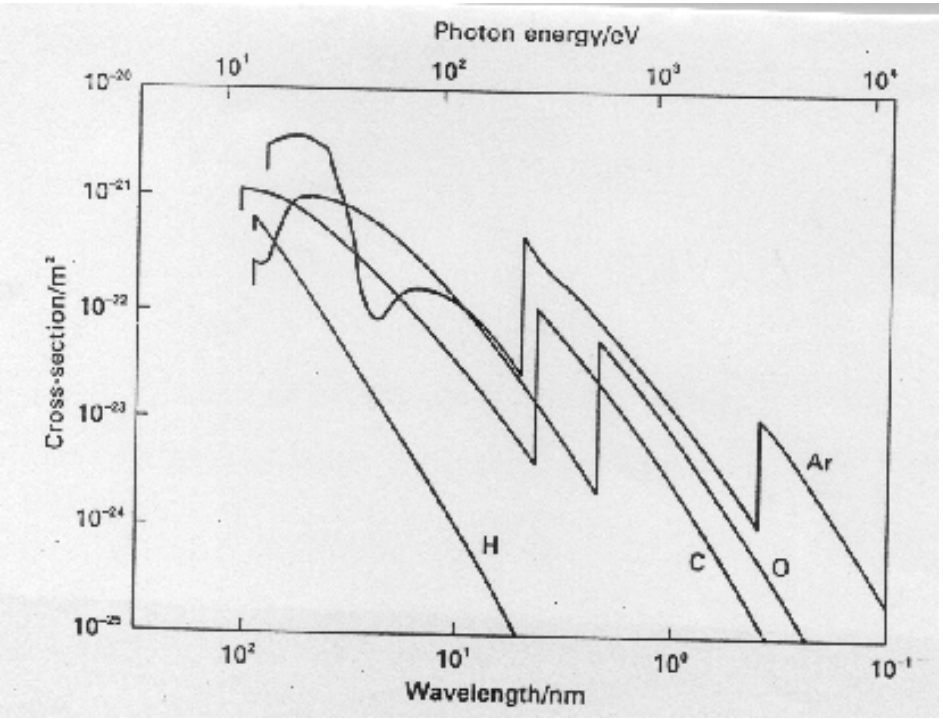


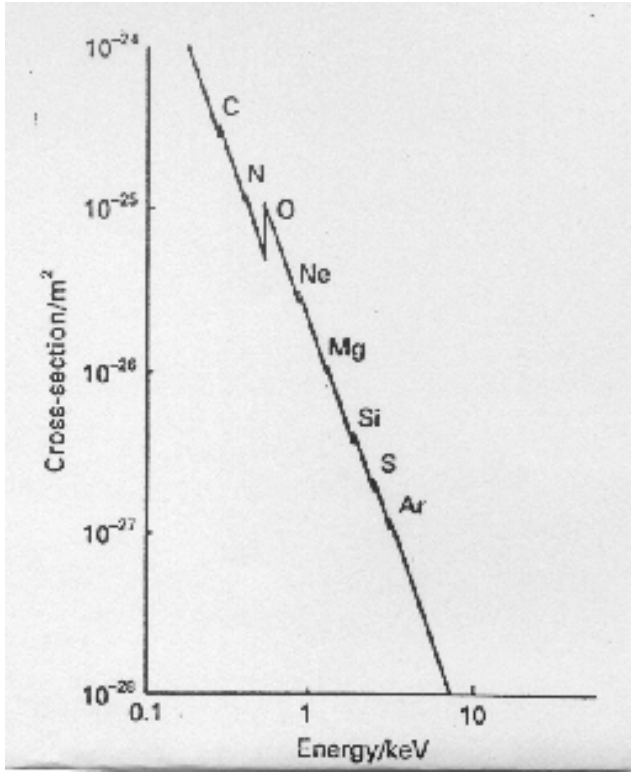
Absorción fotoeléctrica

- Para fotones de baja energía
  $h\nu << m_e c^2 = 511$ KeV
  - El fotón puede arrancar un electrón con energía de ligadura $E_I < h\nu$
  - El electrón quedará libre con energía cinética $E_c = h\nu - E_I$

- La sección eficaz de la fotoabsorción es:
  $\sigma_K = \frac{e^{12} m_e^{3/2} Z^5}{192\sqrt{2}\pi^5 \epsilon_0^6 h^4 c} \left(\frac{1}{h\nu}\right)^{\frac{7}{2}}$

Absorción fotoeléctrica





Absorción fotoeléctrica

- Sección eficaz fotoeléctrica:
  $\sigma_{PE} = 10^{-22} E^{-8/3} cm^2$ (E en KeV)

- $\frac{I}{I_0} = e^{-\sigma_{PE} N_H} = e^{-(10^{-22} E^{-8/3} N_H)}$

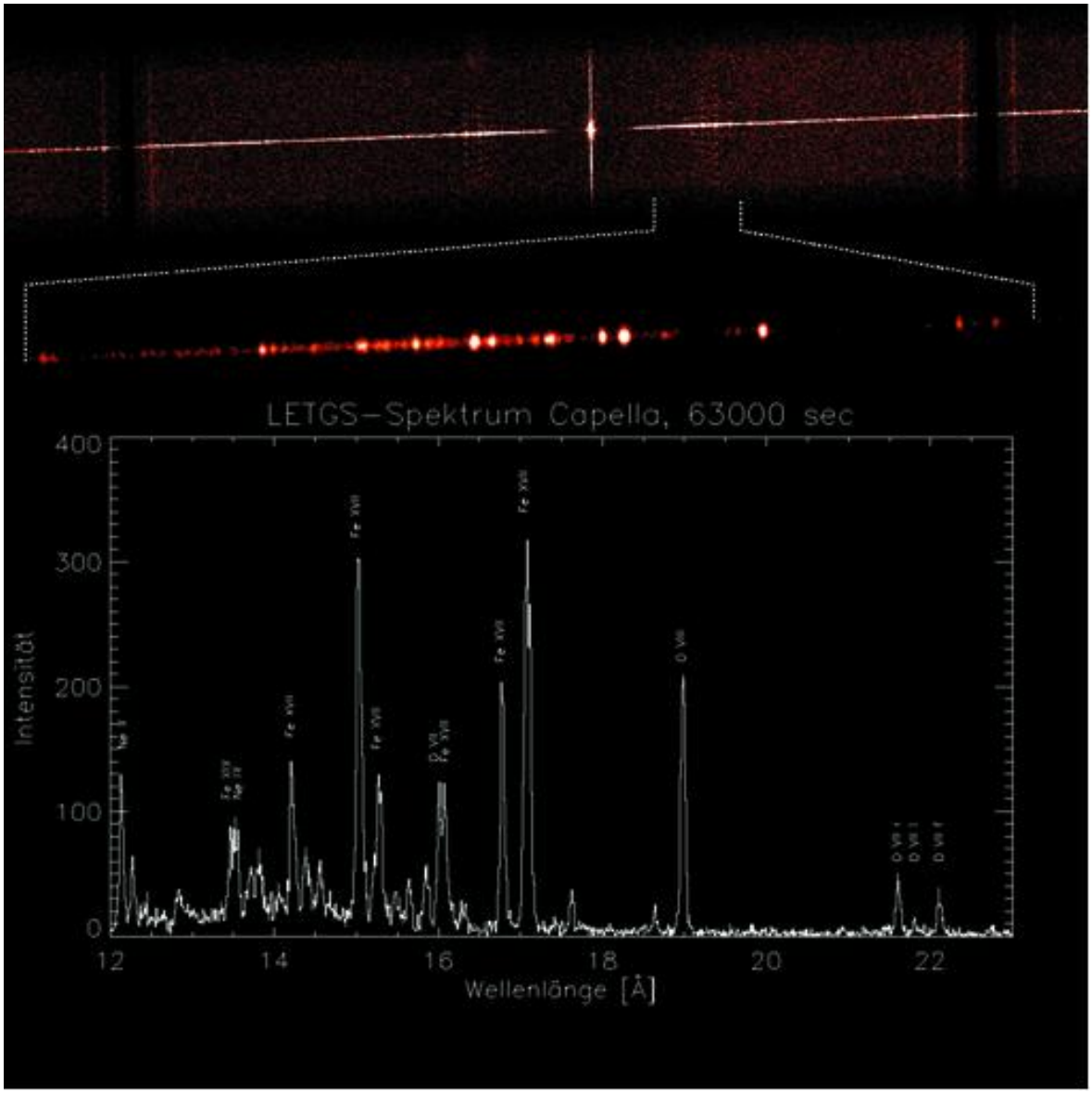
- Ejemplo: $N_H = 7 \times 10^{21}$ cm^{-2}
  - 10 Kev $\rightarrow I = 0.998 I_0$
  - 1 Kev $\rightarrow I = 0.497 I_0$
  - 100 ev $\rightarrow I = 0$

Líneas X

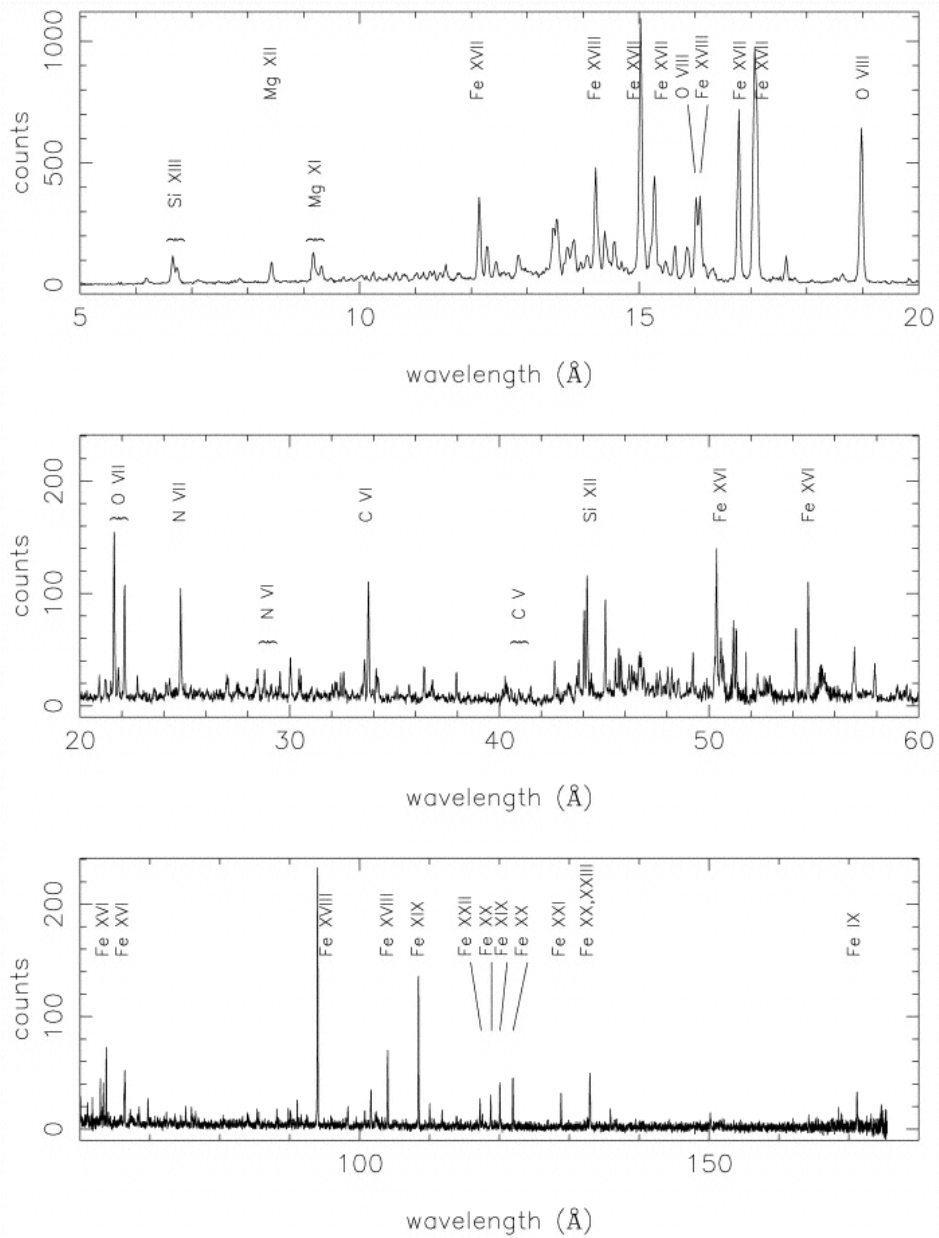
Identification	Energy (keV)†	Identification	Energy (keV)†
Fe I LIII edge	0.707	Si XIII	1.86
Fe I LII edge	0.721	S I K edge	2.472
Fe XVII	0.826	Ar I K edge	3.203
Ne I K edge	0.867	Fe I $K\alpha_2$	6.391
Ne IX	0.915	Fe I $K\alpha_1$	6.404
Ne IX	0.922	Fe XXV	6.64
Fe XX	0.996	Fe XXV	6.68
Ne X	1.022	Fe XXV	6.70
Mg I K edge	1.305	Fe XXVI	6.93
Mg XI	1.340	Fe I $K\beta$	7.058
Mg XI	1.352	Fe I K edge	7.111
Si K edge	1.839		

† λ (Å) = 12.399/E (keV).

Espectro X de Capella



Espectro X de Capella



Radiación ciclotrón y sincrotrón

- Emisión de partículas aceleradas por campos magnéticos:
  - Si $v << c \rightarrow$ radiación ciclotrón
  - Si $v \sim c \rightarrow$ radiación sincrotrón

- Fuerza de Lorentz:
  $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$

- En Astrofísica:
  $\vec{F} = e(\vec{v} \times \vec{B})$

Radiación ciclotrón y sincrotrón

- Llamamos v a la componente de $\vec{v}$ perpendicular a $\vec{B}$:
  $|\vec{F}| = m_e|\vec{a}| = ev|\vec{B}|$
  $|\vec{a}| = \frac{ev|\vec{B}|}{m_e}$

- La potencia de la emisión viene dada por la fórmula de Larmor:
  $P = \frac{2q^2a^2}{3c^3} = \frac{2e^4v^2|\vec{B}|^2}{3c^3m_e^2}$

- En términos de la energía cinética:
  $E_c = \frac{1}{2}m_ev^2 \rightarrow v^2 = 2E_cm_e$
  $P = \frac{e^4E_c|\vec{B}|^2}{3c^3m_e}$

Radiación ciclotrón y sincrotrón

- En situaciones astrofísicas:
  $N_e(E) = Cte \times E^{-\alpha}$

- La intensidad de la radiación es:
  $I(E, |\vec{B}|) = Cte' \times E^{-\alpha}|\vec{B}|$

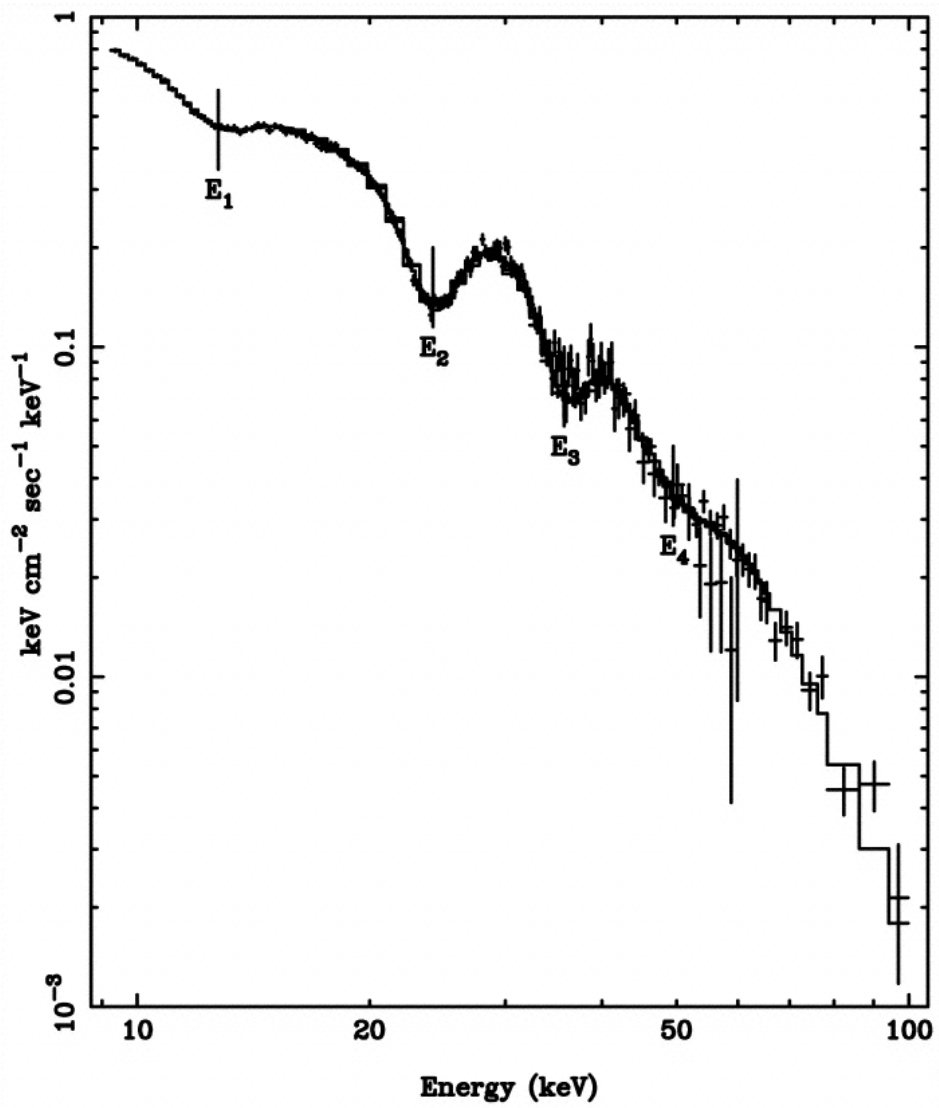
Radiación ciclotrón y sincrotrón

- Niveles de Landau:

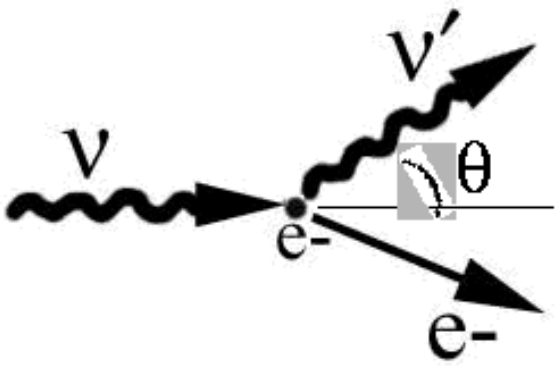
$$E_{j,s} = m_e c^2 \left\{ \left[1 + \left(\frac{P_z}{m_e c^2} \right)^2 + (2j + s + 1) \frac{|\vec{B}|}{|\vec{B_{cr}}|} \right]^{1/2} - 1 \right\}$$

- Donde:
  - $|\vec{B_{cr}}| = \frac{m_e^2 c^3}{eh} = 44.14 \times 10^{12}$ Gauss
  - P_z es el momento del e^- sobre la línea
  - j = 0, 1, 2.... es el momento angular
  - s = ± 1 es el spin

Líneas ciclotrón



Dispersión de Compton



	Estado inicial	Estado final
$P_\gamma =$	$h\nu/c$	$h\nu'/c$
$E_\gamma =$	$h\nu$	$h\nu'$
$P_e =$	0	$\gamma m_e v$
$E_e =$	$m_e c^2$	$\gamma m_e c^2 = (m_e^2 c^4 + P_e^2 c^2)^{1/2}$

Dispersión de Compton

- Imponiendo conservación de la energía :
$$h\nu + m_e c^2 = h\nu' + (m_e^2 c^4 + P_e^2 c^2)^{1/2} \tag{1}$$

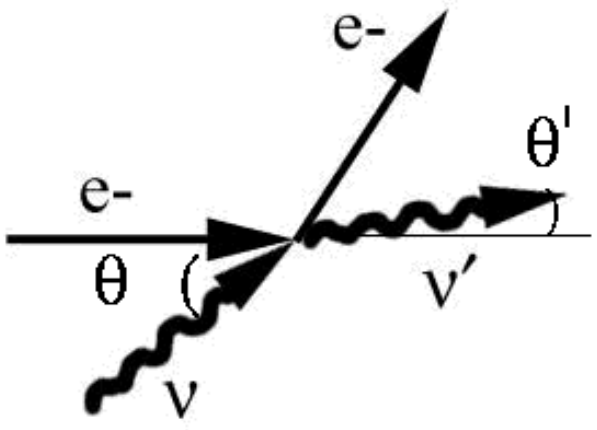
- Imponiendo conservación de momento (vectorial) :
$$\frac{h\nu}{c} = \frac{h\nu'}{c} + P_e \rightarrow$$
$$P_e = \frac{h\nu}{c} - \frac{h\nu'}{c} \rightarrow$$
$$P_e^2 = \frac{h^2\nu^2}{c^2} + \frac{h^2\nu'^2}{c^2} - \frac{2h\nu h\nu' \cos\theta}{c^2} \tag{2}$$

- $(1)^2 \rightarrow P_e$ en (2) :
$$\frac{\nu'}{\nu} = \frac{1}{1+(h\nu/m_e c^2)(1-\cos\theta)}$$

Dispersión de Compton

- $\frac{\nu'}{\nu} = \frac{1}{1+(h\nu/m_e c^2)(1-\cos\theta)}$
- Si $h\nu << m_e c^2 \rightarrow$
  $\nu = \nu'$
- Si $h\nu >> m_e c^2 \rightarrow$
  $\nu' = \frac{\nu}{(h\nu/m_e c^2)(1-\cos\theta)} = \frac{m_e c^2}{h}(1-\cos\theta)^{-1} \rightarrow h\nu' \sim m_e c^2$

Dispersión de Compton inversa



- Sistema inercial del e^- en reposo ($\sim$)
  - Para el fotón incidente:
    $\tilde{E} = E\gamma(1 - \beta\cos\theta)$
  - Para el fotón saliente:
    $E' = \tilde{E}\gamma(1 + \beta\cos\theta)$

Dispersión de Compton inversa

- En el sistema ($\sim$) consideramos $h\nu << m_e c^2$:
  $\tilde{\nu} = \tilde{\nu'}$

- Sustituyendo las relaciones anteriores:
  $\nu\gamma(1 - \beta\cos\theta) = \frac{\nu'}{\gamma(1+\beta\cos\tilde{\theta'})} \rightarrow$
  $\nu' = \nu\gamma^2(1 - \beta\cos\theta)(1 + \beta\cos\tilde{\theta})$

- Las energías producidas son del orden de:
  $\nu' \sim \gamma^2\nu$
  Con un máximo de
  $\nu'_{max} = 4\gamma^2\nu$

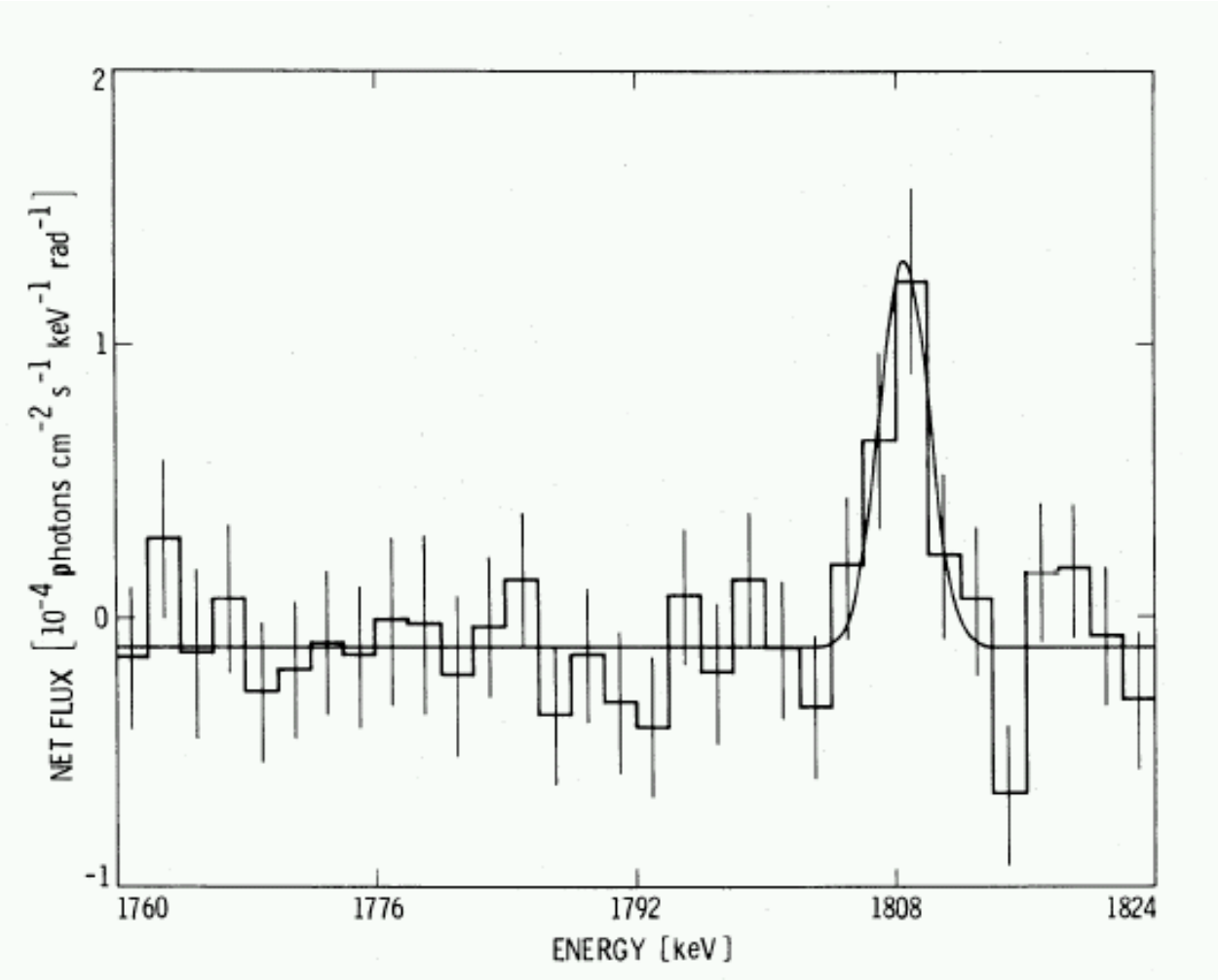
Dispersión de Compton inversa. Ejemplo:

- e^- en rayos cósmicos: $\gamma \sim 10^3 \rightarrow \beta \sim 0.9999995$
  - Dispersión de un fotón del fondo de microondas:
    $\nu' \sim (10^3)^2 \times (3 \times 10^{11}\text{Hz}) = 3 \times 10^{17}\text{Hz} \sim 1.2\text{keV} \rightarrow$ rayos X
  - Dispersión de un fotón óptico:
    $\nu' \sim (10^3)^2 \times 10^{15}\text{Hz} = 10^{21}\text{Hz} \sim 4.1\text{MeV} \rightarrow$ rayos γ

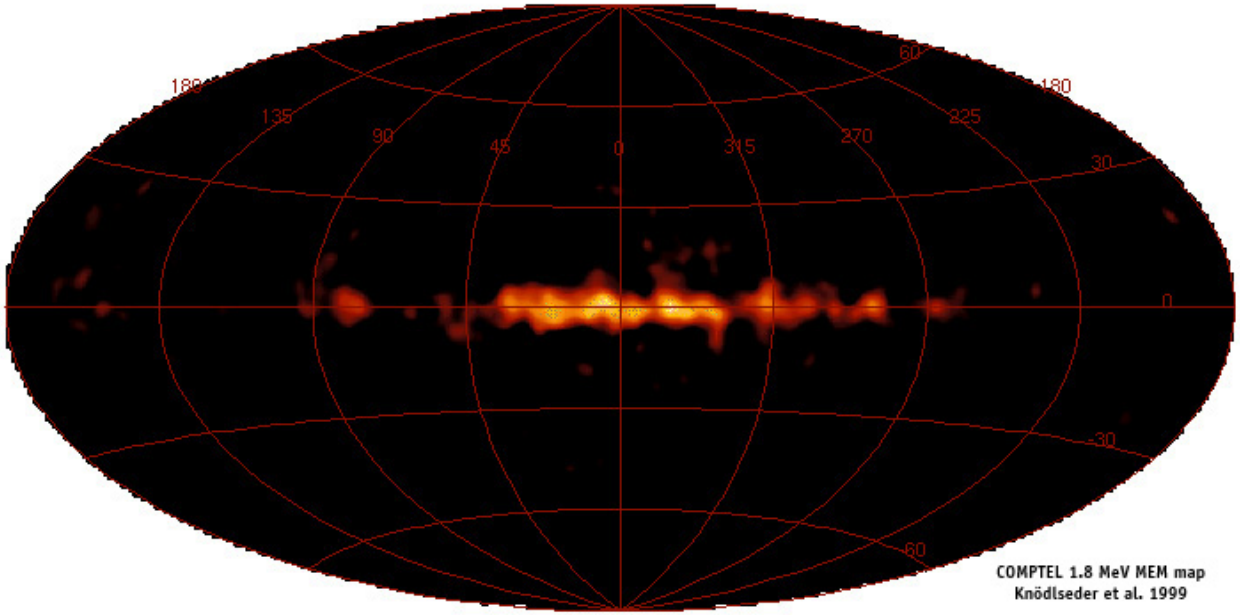
Emisión nuclear

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

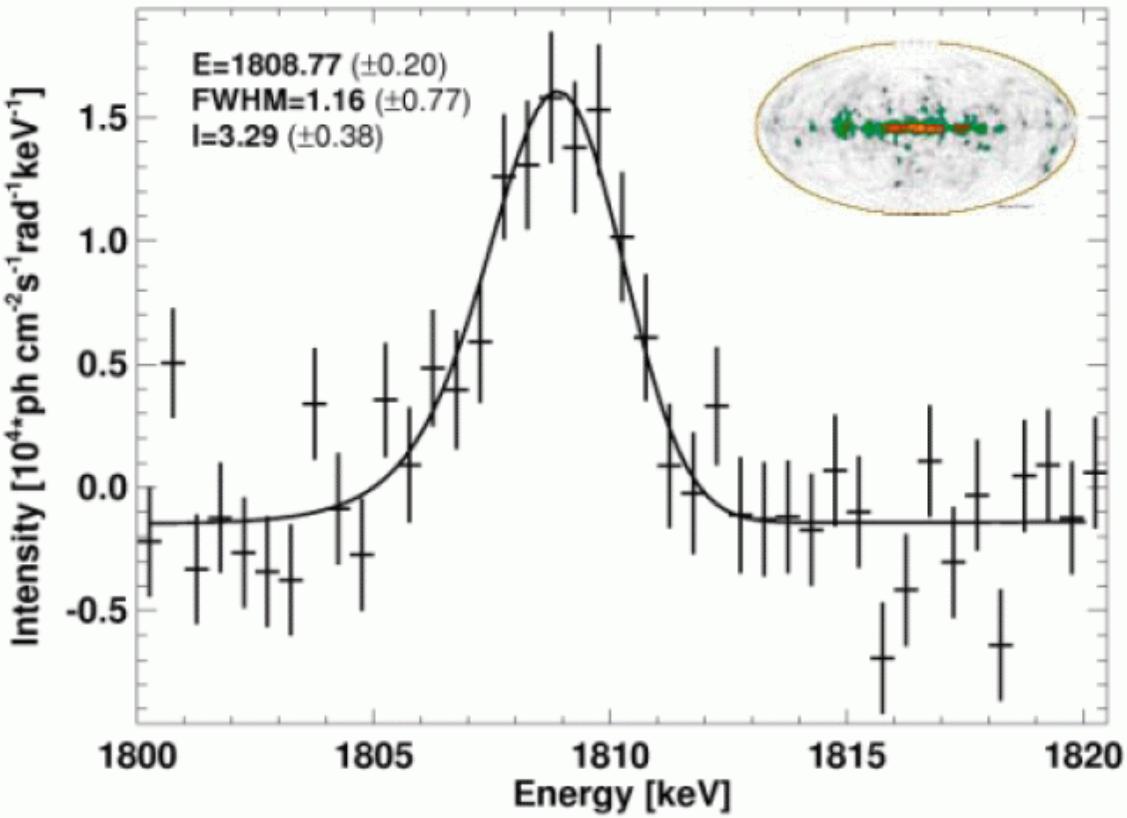
Emisión nuclear (^{26}Al, HEAO-3)



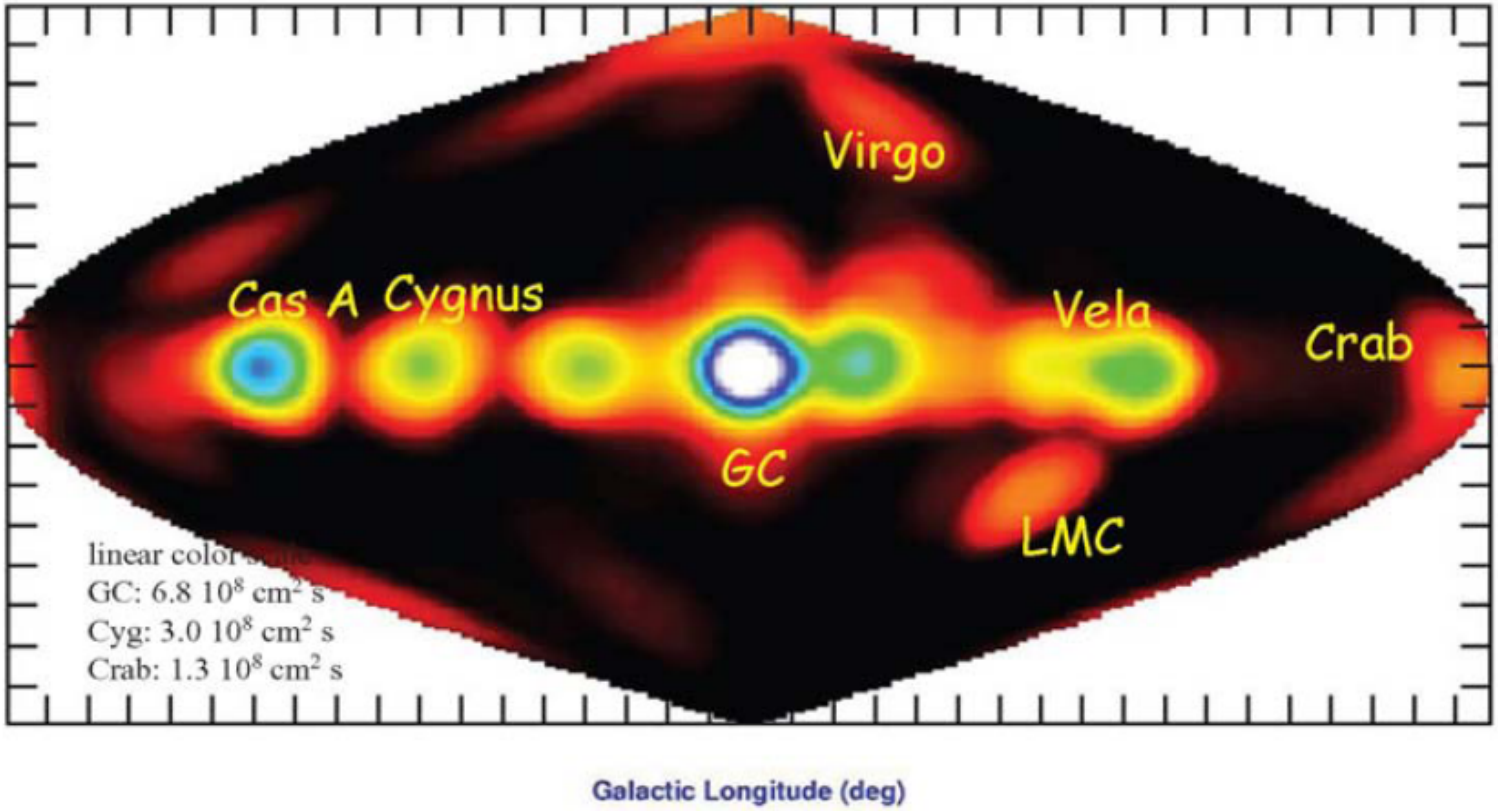
Emisión nuclear (COMPTEL-CGRO)



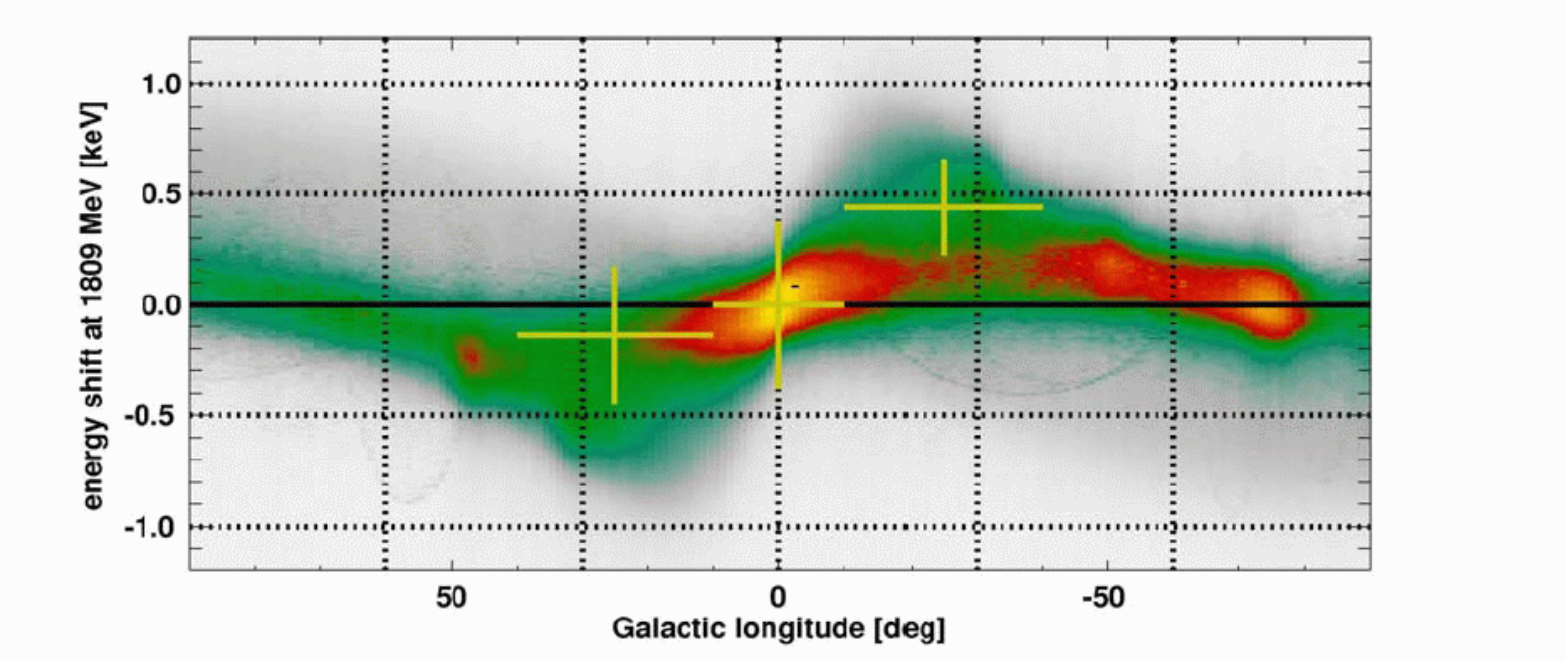
Emisión nuclear (SPI-INTEGRAL)



Emisión nuclear (SPI-INTEGRAL)

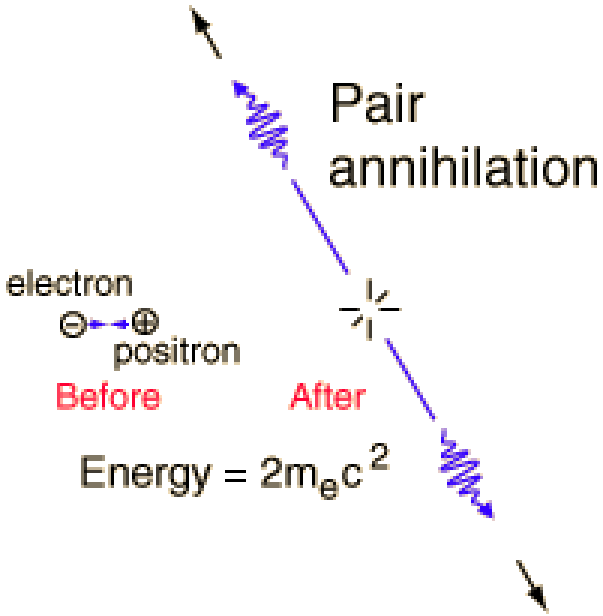


Emisión nuclear (SPI-INTEGRAL)

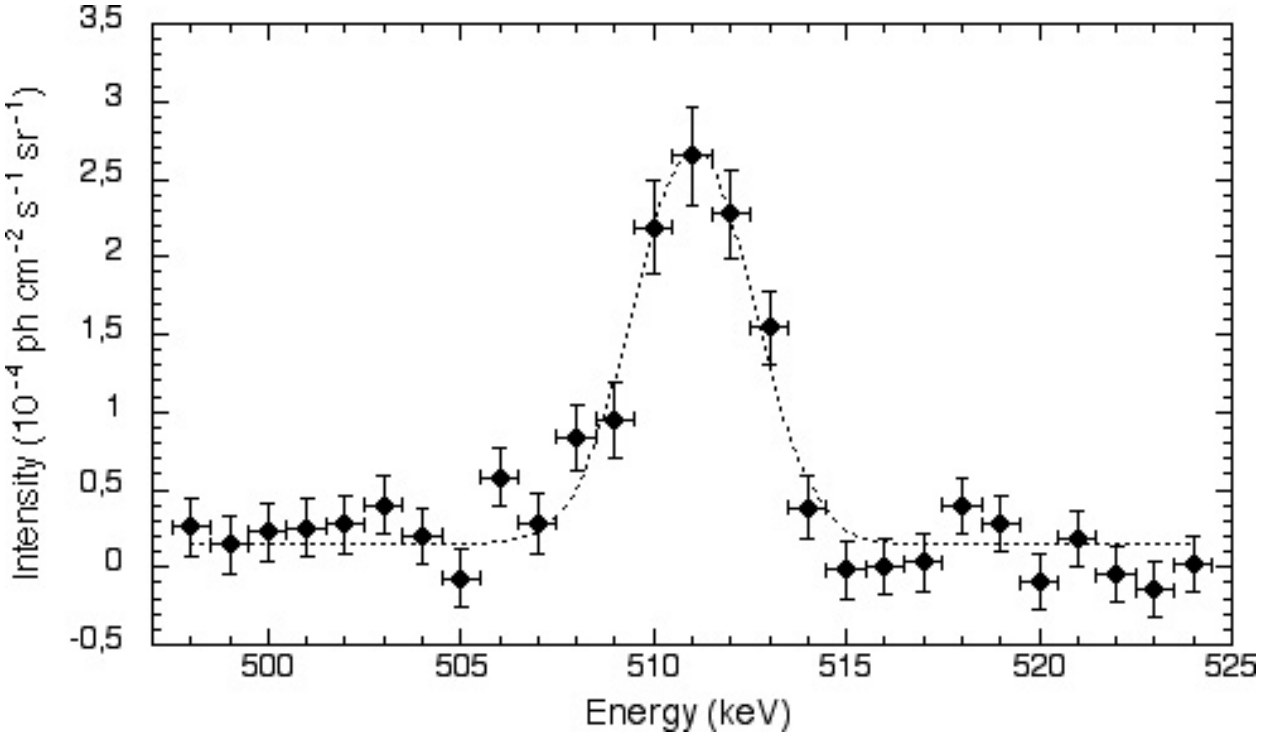


Aniquilación e^- e^+

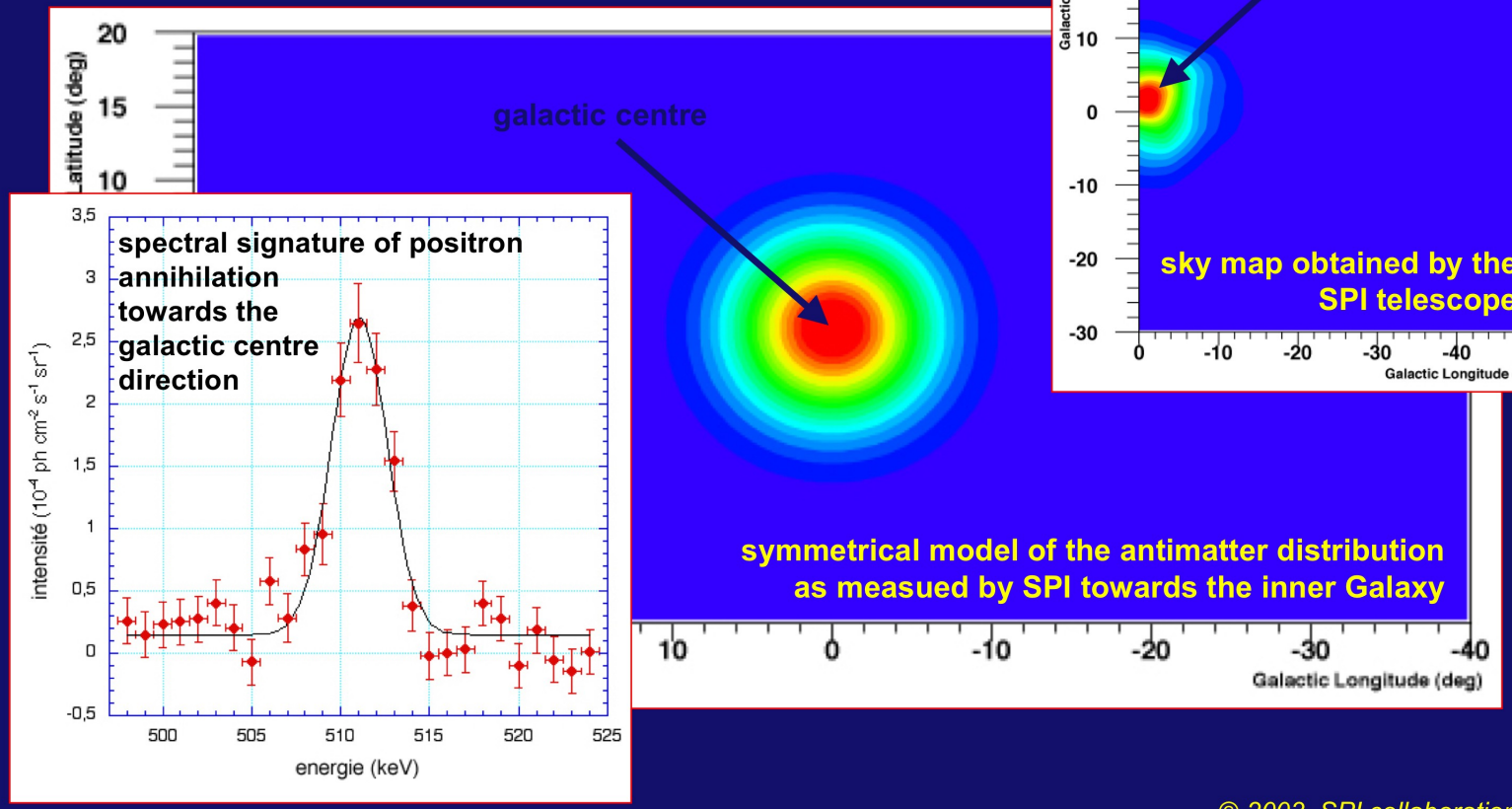
- $e^- + e^+ \rightarrow 2\gamma$
- $h\nu = m_e c^2 = 511$ keV



Línea de aniquilación (SPI-INTEGRAL)

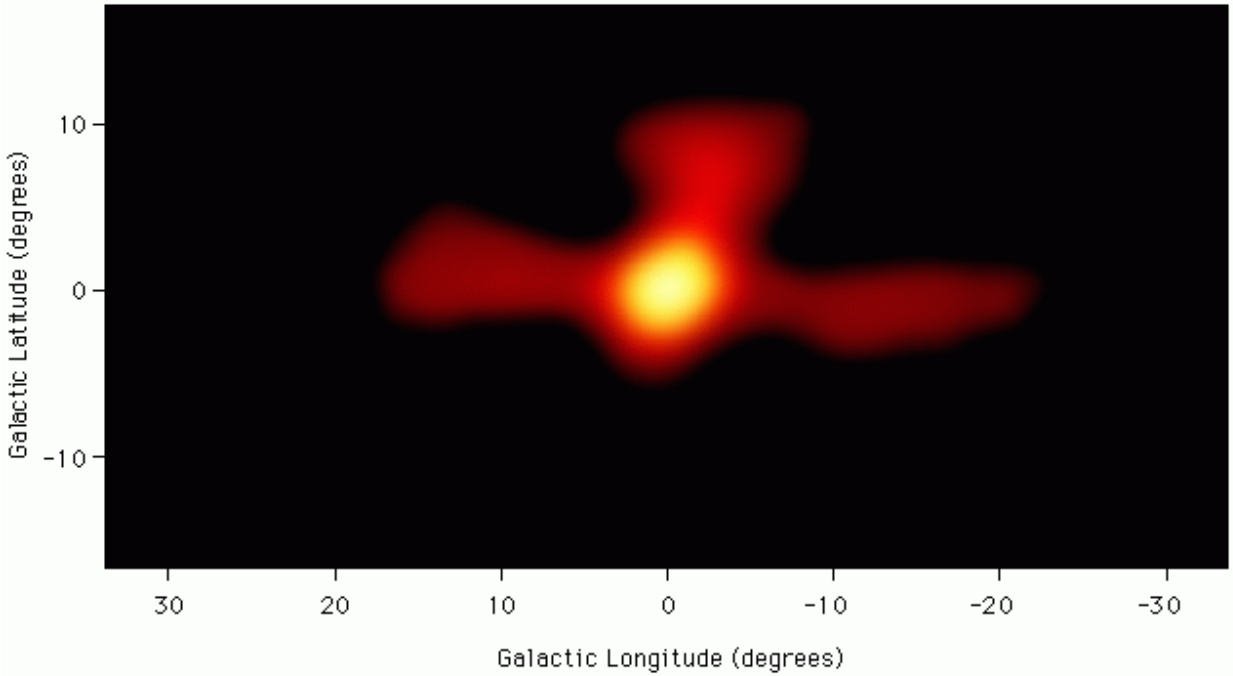


Antimatter in the centre of our Galaxy



© 2003, SPI collaboration

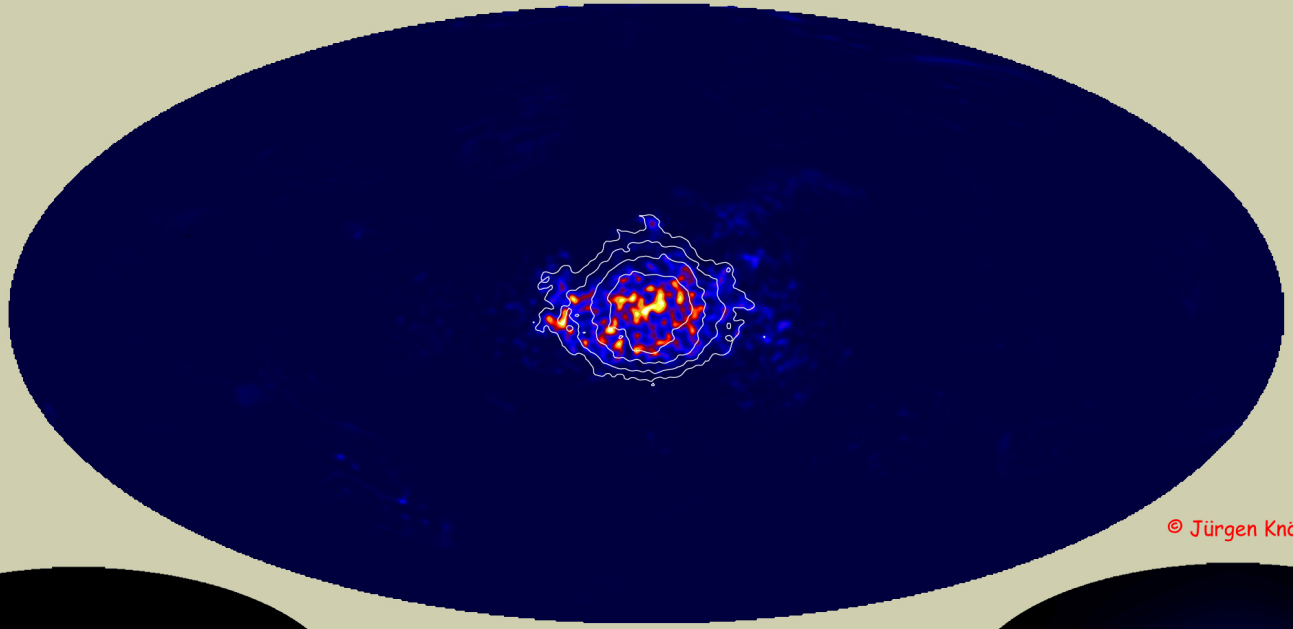
Línea de aniquilación (OSSE-CGRO)



Caption: Map of the distribution of positrons towards the center of the Milky Way Galaxy, including the newly discovered antimatter "cloud". The brightest feature corresponds to the nucleus of the Galaxy. The horizontal structure lies along the plane of the Galaxy. The antimatter "cloud" is located above the Galactic center.

Courtesy of D. D. Dixon (University of California, Riverside) and W. R. Purcell (Northwestern University)

The first all-sky map of 511 keV positron-electron annihilation radiation



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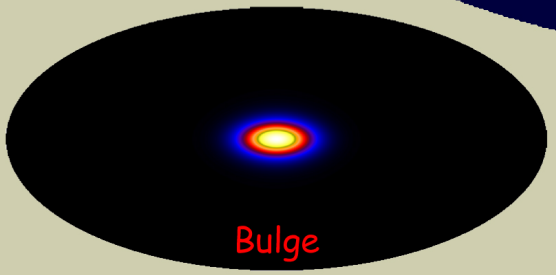
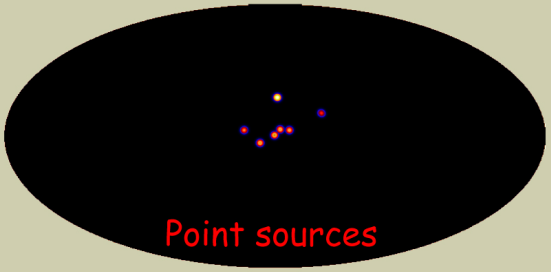
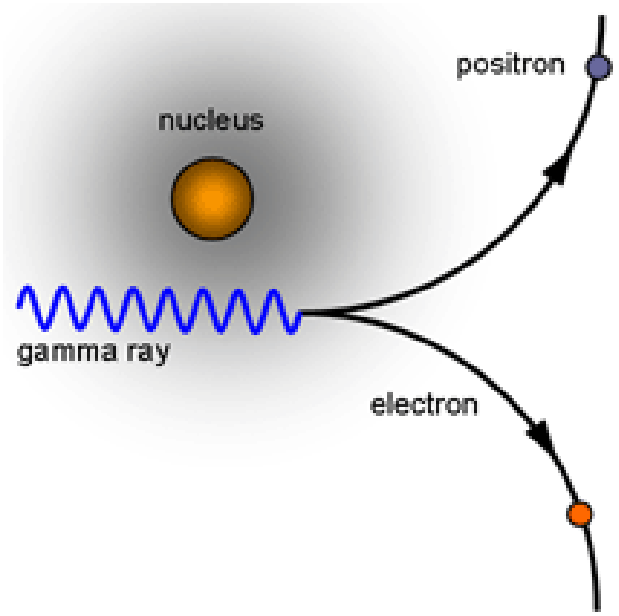


SPI/INTEGRAL has searched for the 511 keV line signature of positron-electron annihilation all over the sky. The above image presents the result of this search : 511 keV line emission is only seen towards the centre of our Galaxy. So far, the origin of the positrons that annihilate is unknown. The SPI/INTEGRAL data are equally compatible with galactic bulge or halo distributions, the combination of a bulge and a disk component, or a combination of at least 7 point sources (illustrated by the four small images). Such distributions are expected if positrons originate either from low-mass X-ray binaries, novae, Type Ia supernovae, or possibly light dark matter.

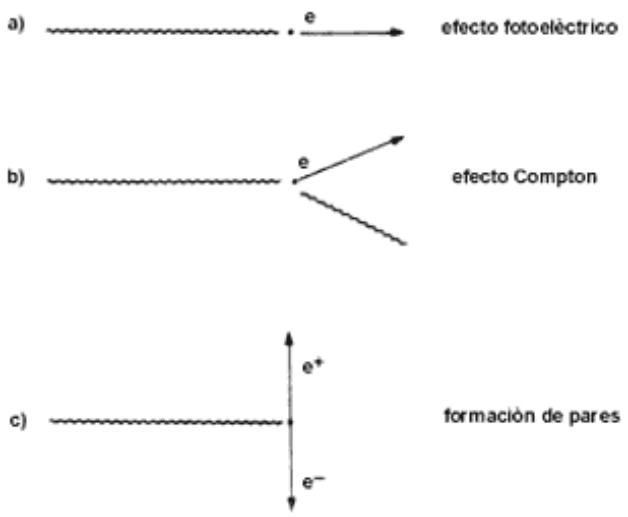


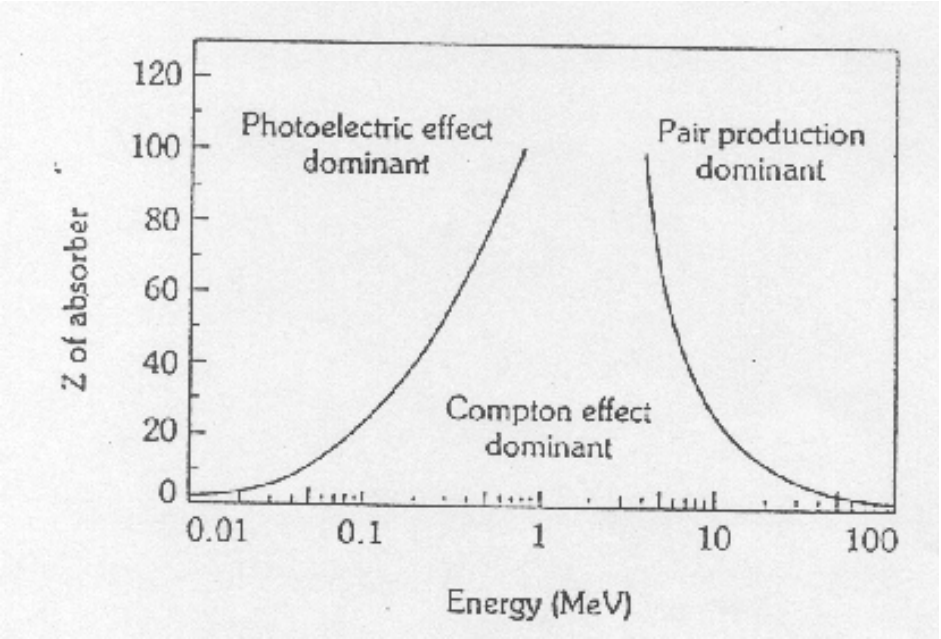
Creación de pares e^- e^+

- $\gamma \rightarrow e^- + e^+$
- $h\nu > 2m_e c^2 = 1.022$ MeV



Atenuación de fotones





La potencia del acrecimiento

- Energía generada:
  $\Delta E_{ac} = \frac{GMm}{R}$
  - En el caso de una estrella de neutrones:
  - $R \sim 10Km$
  - $M \sim M_{\odot}$
  - $\Delta E_{ac} = 10^{20}\ erg\ g^{-1}$

- Energía de fusión nuclear:
  $\Delta E_{fusion} \sim 0.007mc^2 \sim 6 \times 10^{18} erg\ g^{-1}$

El límite de Eddington

- Fuerza gravitatoria sobre las partículas:
  $F = GM(m_p + m_e)/r^2 \sim GMm_p/r^2$

- Fuerza repulsiva sobre los electrones ($\sigma_p << \sigma_e$):
  $F = \sigma_T S/c \sim \sigma_T L/4\pi r^2 c$

- Fuerza total:
  $F = (GMm_p - \sigma_T L/4\pi c)/r^2$

- Límite de Eddington:
  $L_{Edd} = 4\pi GMm_p c/\sigma_T \sim 1.3 \times 10^{38}(M/M_\odot)$ erg s^{-1}