Charge-Exchange Measurements and Astrophysical Applications

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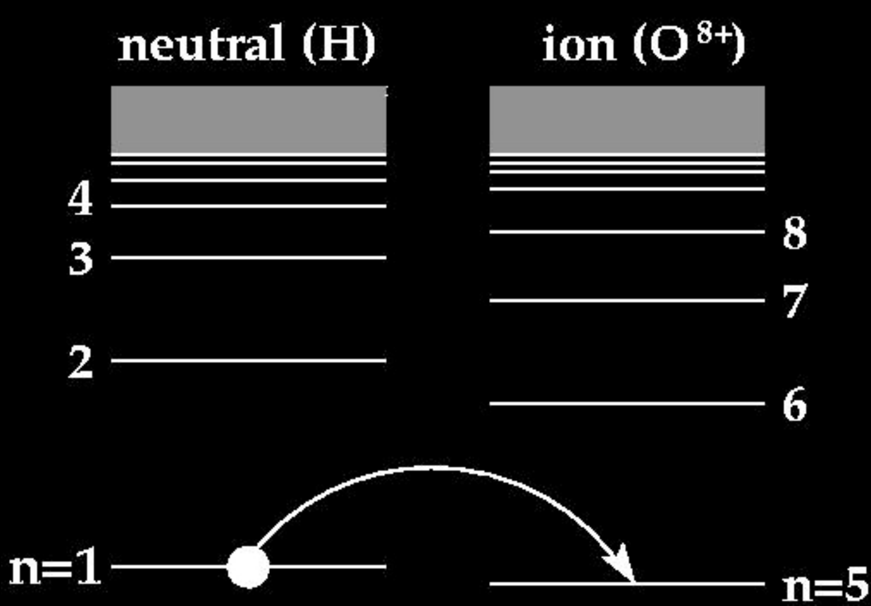
Outline

- Charge exchange (CX) basics
- Astrophysical examples--solar wind CX
- Key features and examples of CX spectra
- Future work

What is Charge Exchange?

$A^{q+} + X \text{ --> } {}^{*}A^{(q-1)+} + X^{+}$



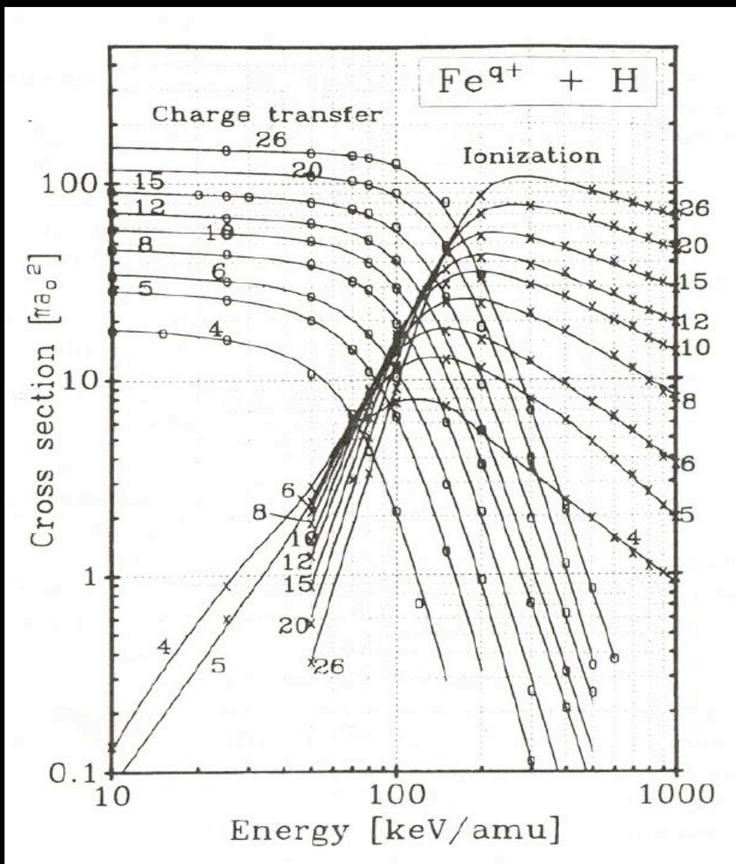
Semi-resonant collisional electron transfer

"Projectile" + "Target"

⇔ Ion + Atom/Molecule

Large q → high n → X-ray

$n_{max} \sim q^{3/4}$



Katsonis, Maynard, Janev
Physica Scripta (1991)

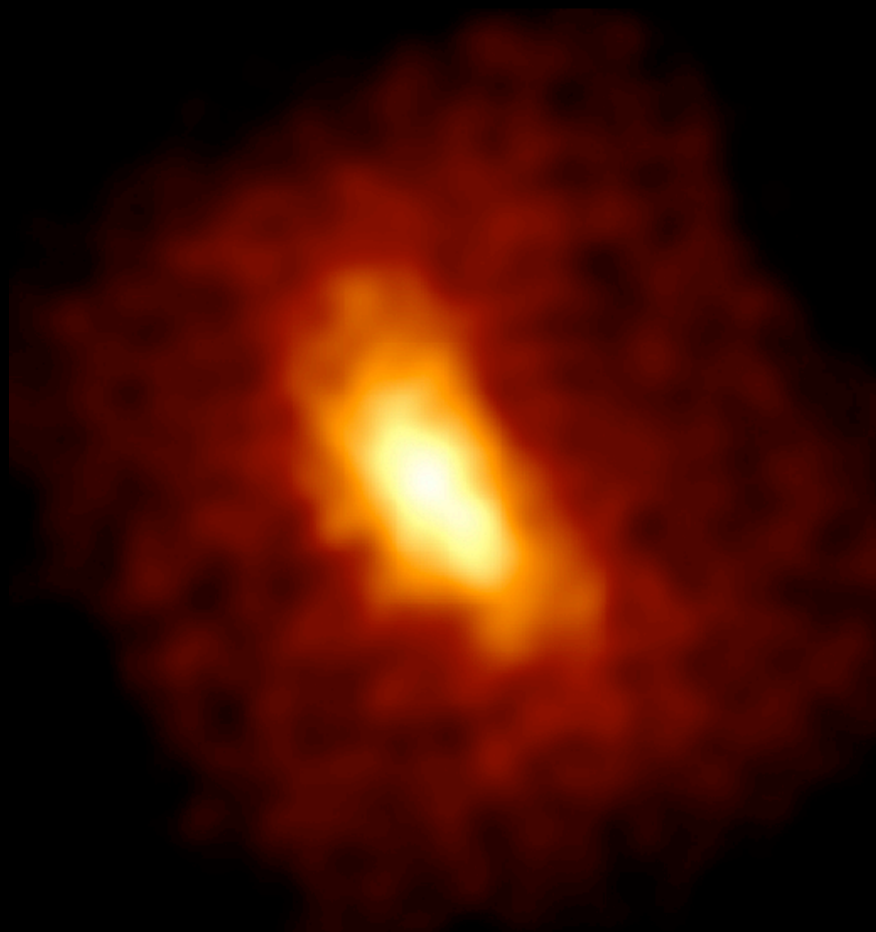
General behavior ≠ f(target):

- $E_{crit} \approx 25\sqrt{q}$ keV/amu
- $\sigma_{CX} \approx q \times 10^{-15}$ cm^2
- $n_{max} \approx q^{3/4} \sqrt{(I_H/I_n)}$

Collision energy regimes:

- EBIT -- 1-10 eV/amu
- 10^7 K ⇔ 46 eV/amu (Fe)
  162 eV/amu (O)
- Solar wind
  - 300 km/s ⇔ 0.5 keV/amu
  - 800 km/s ⇔ 3.3 keV/amu
- Cosmic rays -- ≥1 GeV/amu

Solar Wind Charge Exchange (SWCX)



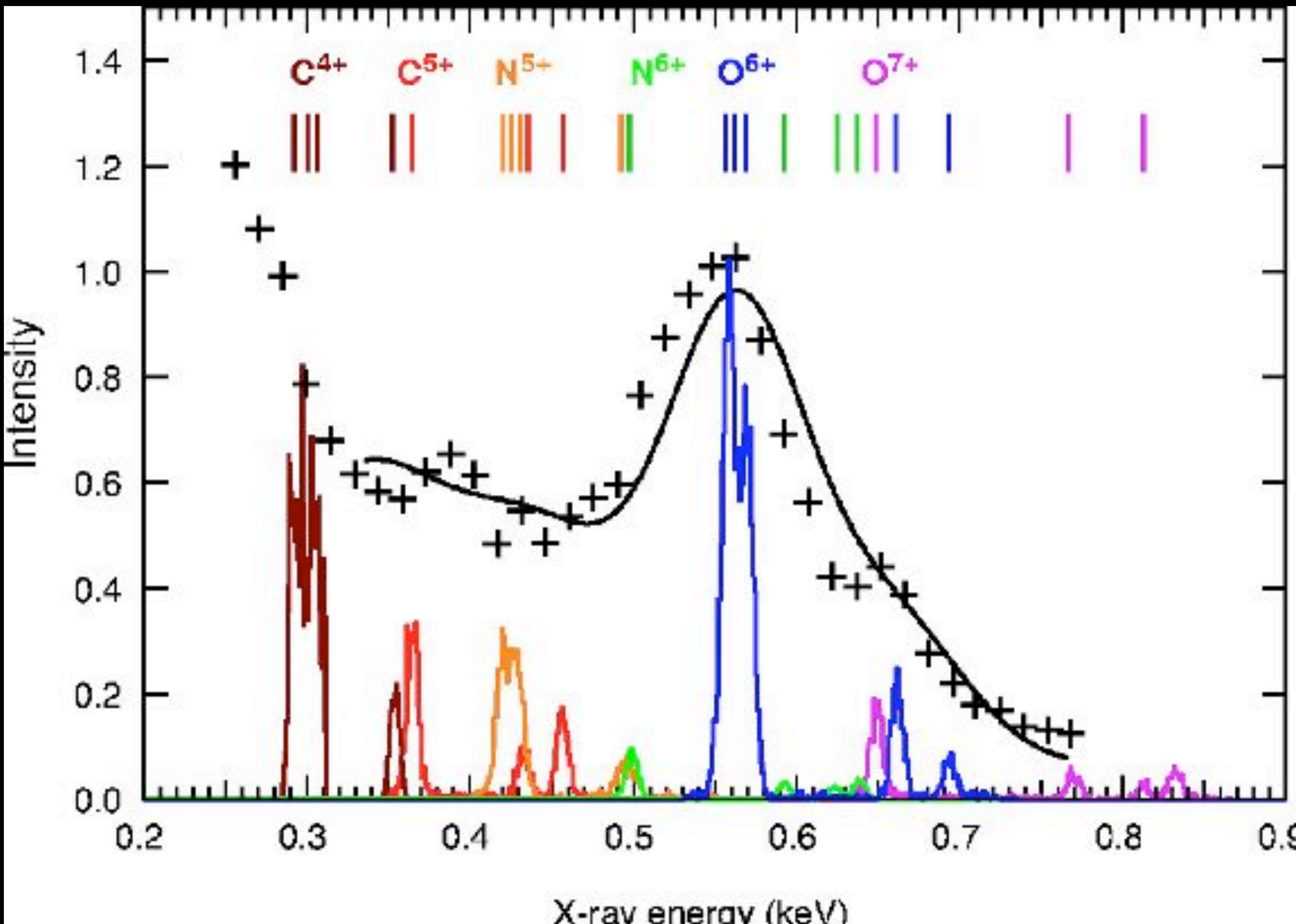
C/1999 S4 (LINEAR), *Chandra*/Lisse 2000

Observed from:
- Comets
- Planets (including Earth)
- Heliosphere

HCIs from solar corona
- 300-800 km/s (~1 keV/amu)
- C, N, O + Ne, Mg, Fe… (higher charge states during CMEs)

Neutral gas:
- Comets--H_2O, CO_2
- Planetary exospheres--H
- Heliosphere (H, He)

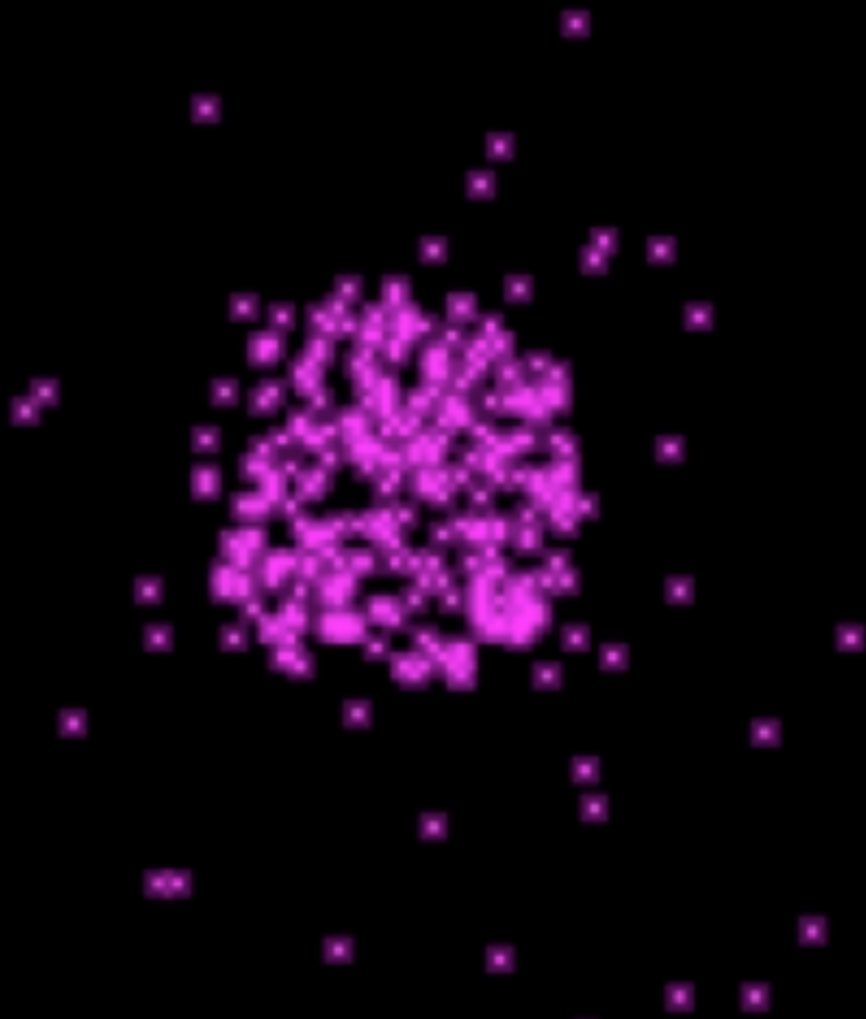
Comets



Over 20 observed in X-ray/uv since 1996.

LINEAR S4, Beiersdorfer et al, Science (2003)

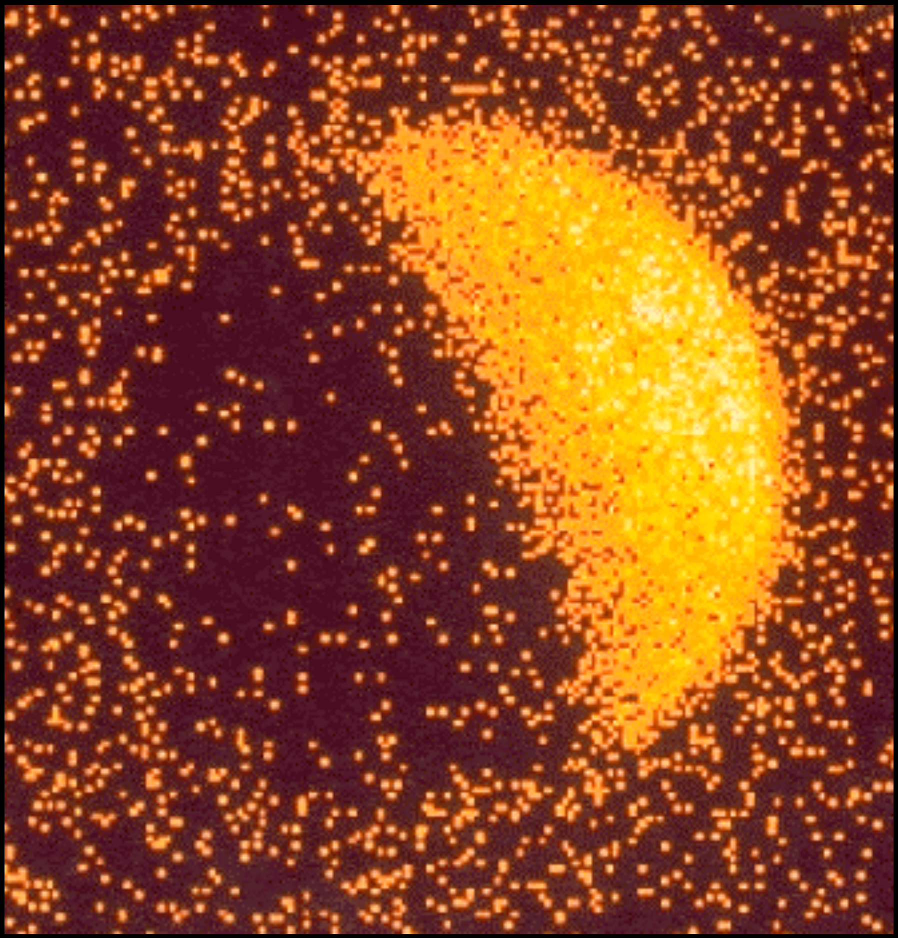
Planets



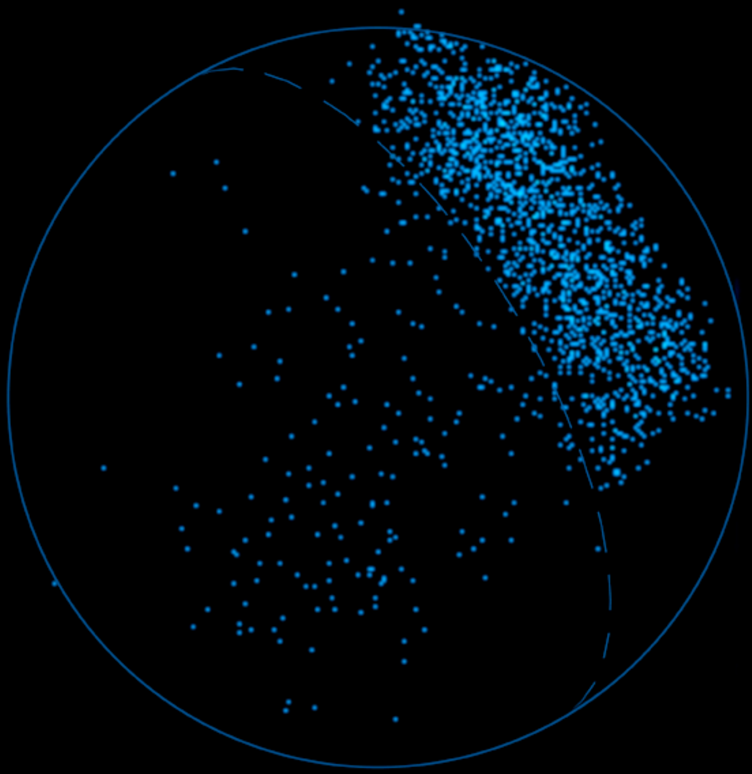
- Mars (*Chandra*, *XMM*, including grating spectra)
- Venus? (Fluor » CX)
- Jupiter/Io Plasma Torus?

Mars, *Chandra* Dennerl 2001. First detection of planetary CX.

Earth--Geocoronal CX

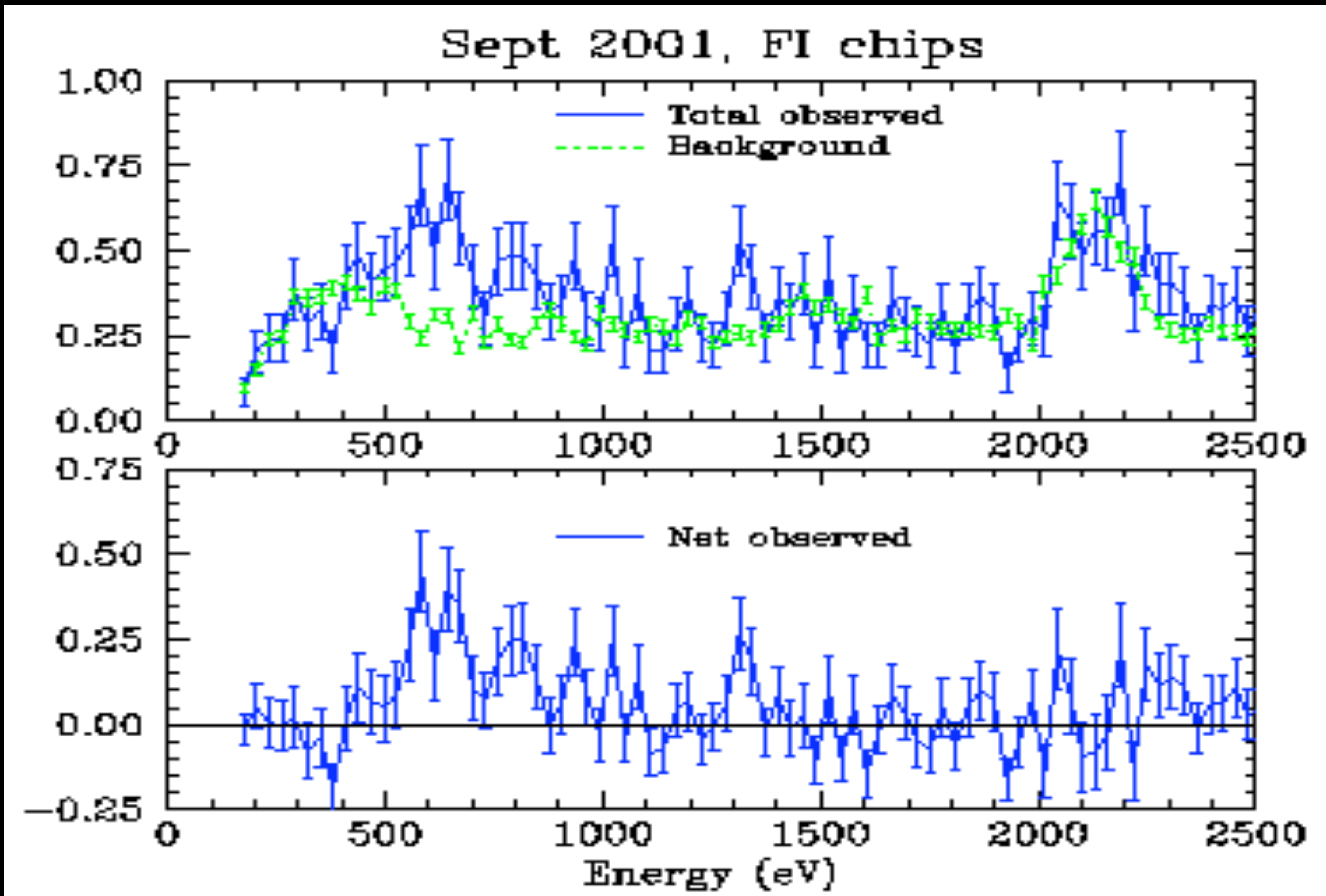


Moon, *ROSAT* Schmitt 1990



Chandra 2001

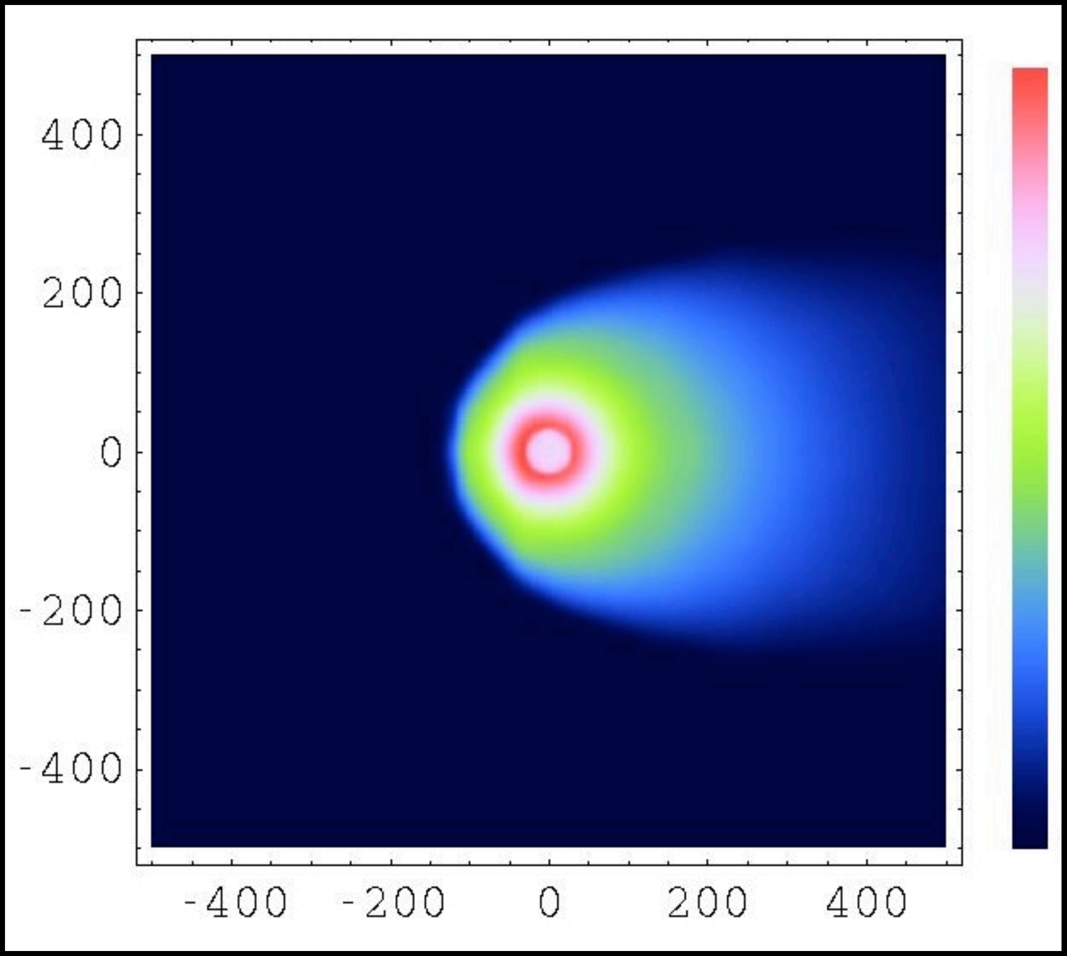
Chandra Geocoronal/Moon Observation



Wargelin et al, ApJ (2004)

Predicted CX emission, based on measured SW params (*n*, *v*, O/H, ‹ *q* ›), matches observation.

Heliospheric Charge Exchange

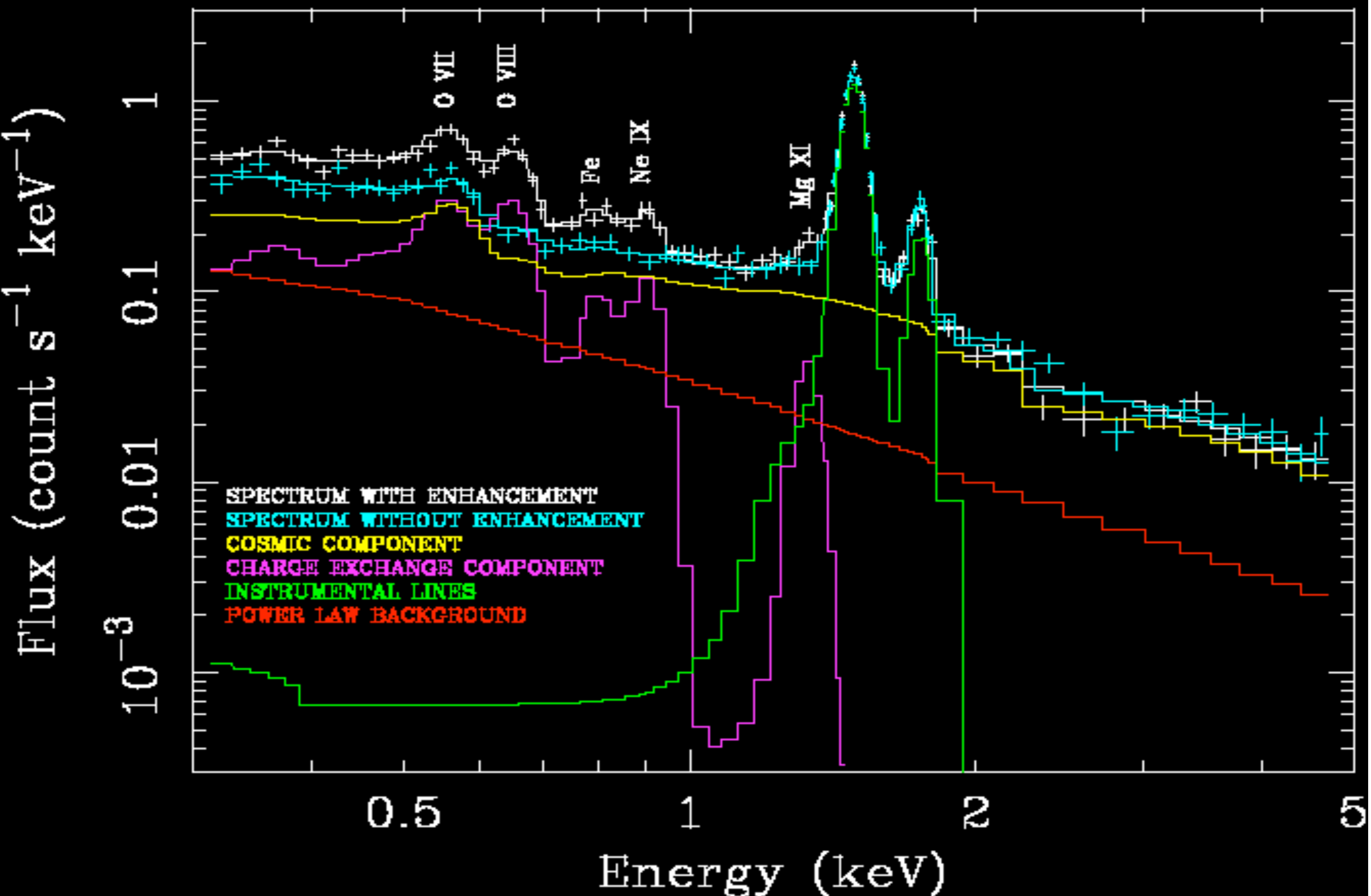


- Solar wind + H/He from ISM → 100-AU halo.
- Intensity varies with look direction and solar activity.
- Heliospheric CX ~ 10x geocoronal CX

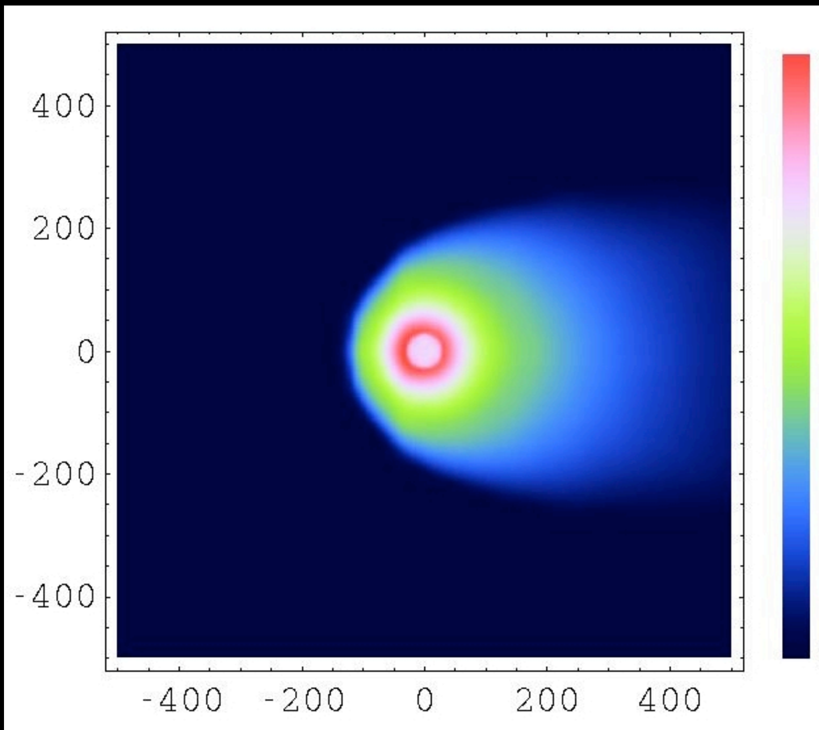
Geo+Helio CX contributes 5-50^{+}% of SXRB, with major implications for models of LISM/Local Bubble.

Model heliospheric CX emission. Axis units in AU. LIC is moving to the right. Robertson et al. AIP Proc. 719 (2004).

XMM HDF-N. Snowden et al, ApJ (2004)



Astrospheric Charge Exchange



CX must also occur around other stars with highly ionized winds (G,K,M) residing inside clouds with neutral gas (LIC, G).

Imaging + spectra yields:

- Mass-loss rate
- Local $n_{neutral}$
- Wind velocity and composition
- Astrosphere geometry

CX emission weak, coronal emission ~10^4x brighter.

Need very large collecting area, good spatial and spectra res---not quite doable yet…

Non-EBIT Experiments

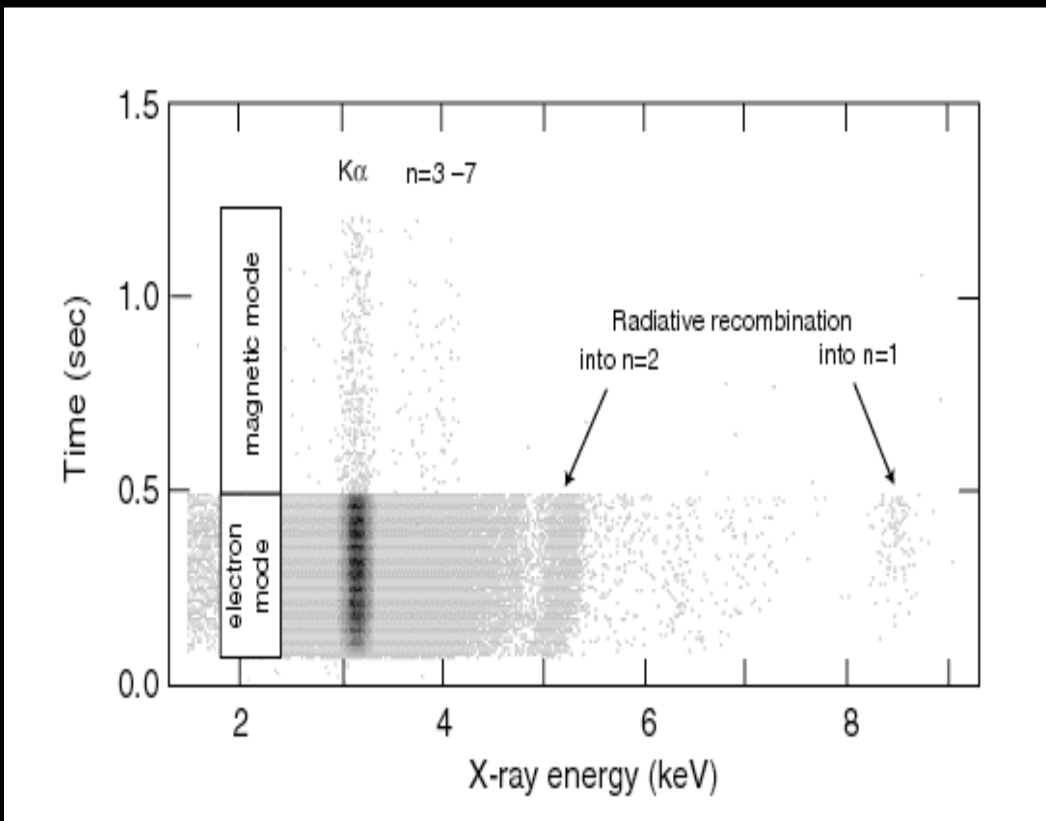
Tokamaks with neutral beam injection (10’s keV/amu)

Penning traps

Merged beams = ion beam + gas jet (storage ring, ECR, EBIS/T)

- Measure σ (total, state-selective) and charges (SEC vs DEC)
- Usually ≥ 1 keV/amu
- Often no photon spectra (metastables always a complication)

EBIT Measurements



Beiersdorfer et al, PRL (2000)

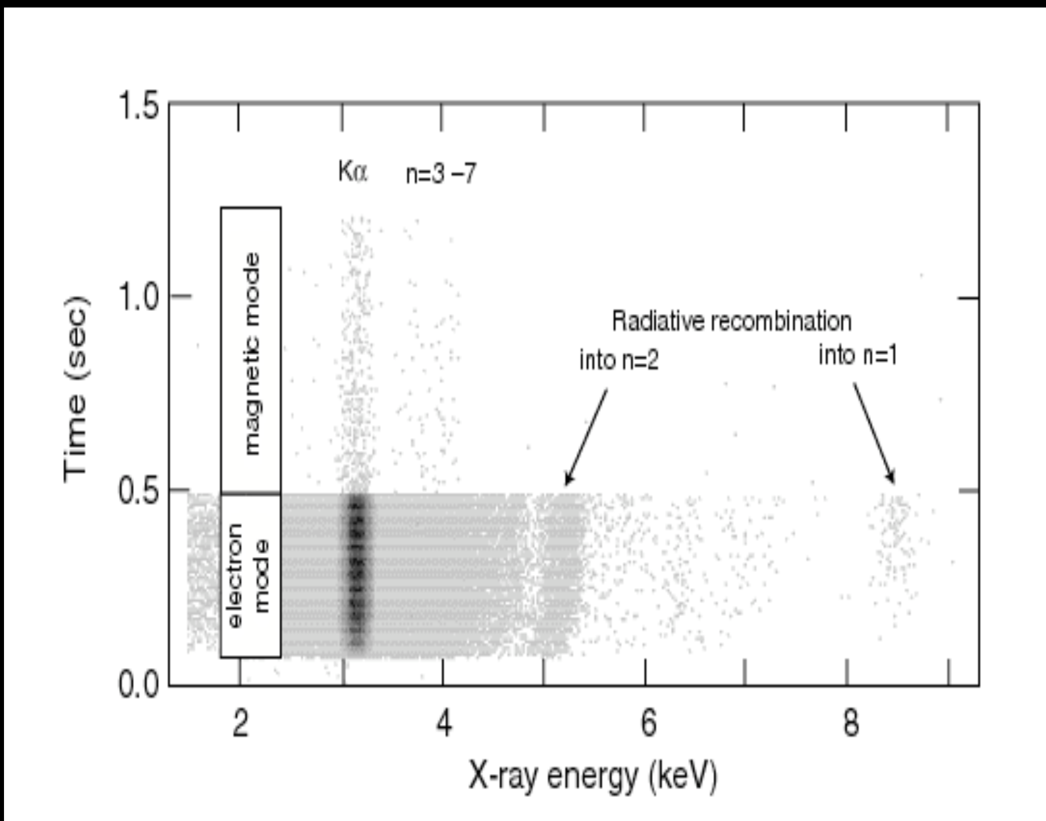
Key features:

- Magnetic trapping mode
- Unpolarized emission
- from ion cloud (⇒ non-dispersive detector)

$$R_{DE} = V_e n_i \, n_e \, \sigma_{DE} \, v_e$$

$$R_{CX} = V_i \, n_i \, n_n \, \sigma_{CX} \, v_i$$

EBIT Measurements



Beiersdorfer et al, PRL (2000)

Key features:

- Magnetic trapping mode
- Unpolarized emission
- from ion cloud (⇒ non-dispersive detector)

$$10^{12}\ 10^{-20}\ 10^{10}$$

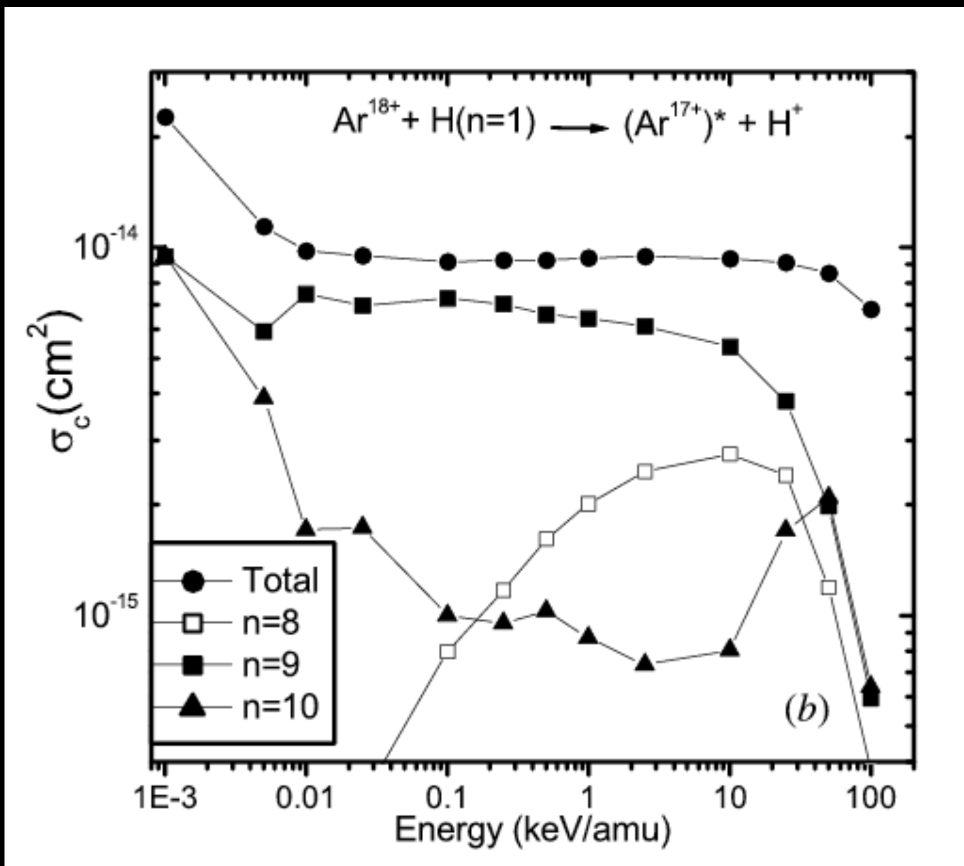
$$R_{DE} = V_e n_i\, n_e\, \sigma_{DE}\, v_e$$

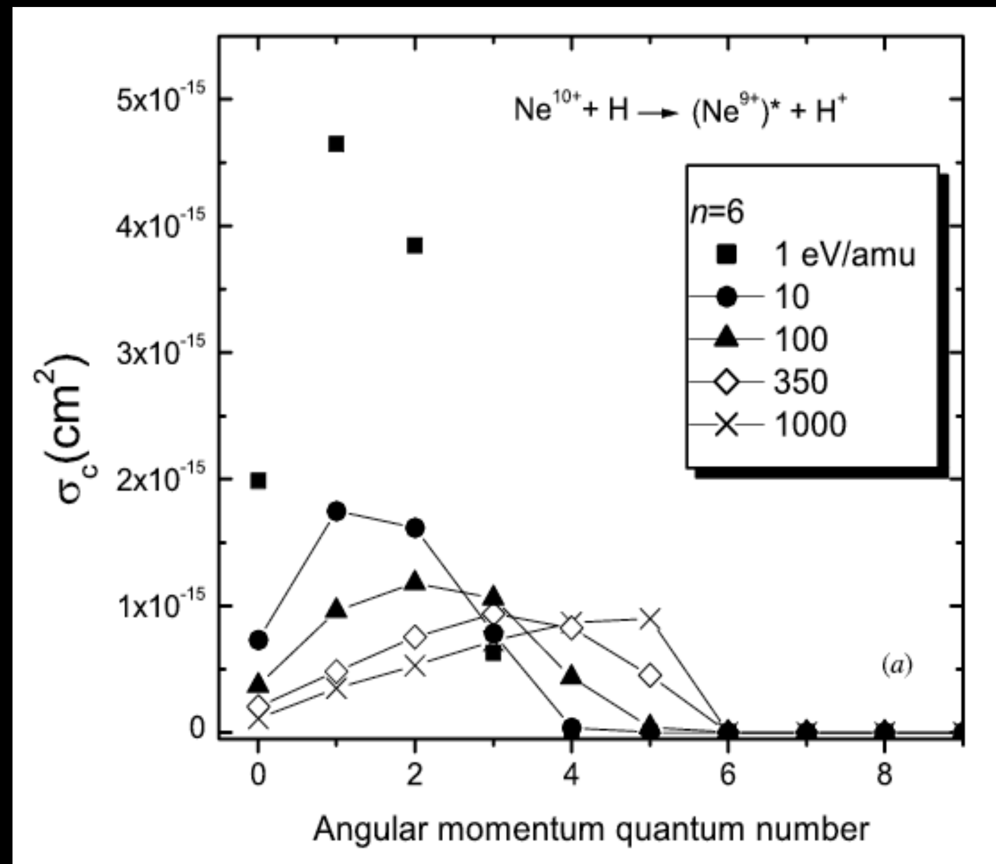
$$R_{CX} = V_i\, n_i\, n_n\, \sigma_{CX}\, v_i$$

$$10^{6}\ 10^{-14}\ 10^{6}$$

$$\Rightarrow R_{DE}/R_{CX} \approx 10^4$$

n and *l* Distributions





Perez, Olson, Beiersdorfer , J Phys B (2001)

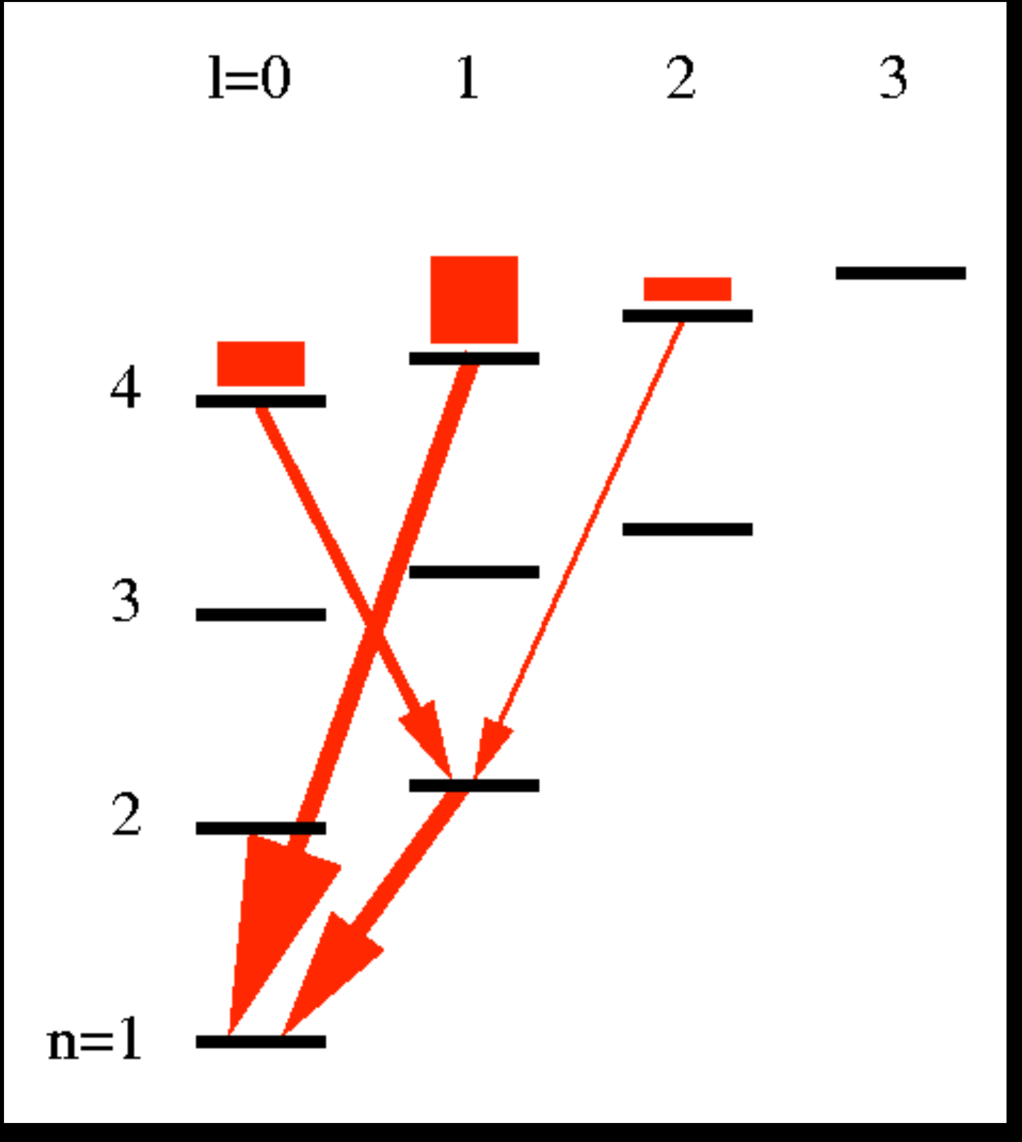
σ_{total} ~constant as *f(E)*

n_{max} ~constant as *f(E)*

l_{max} small (~1) at low energy

Statistical distrib for *E* ≥1 keV/amu

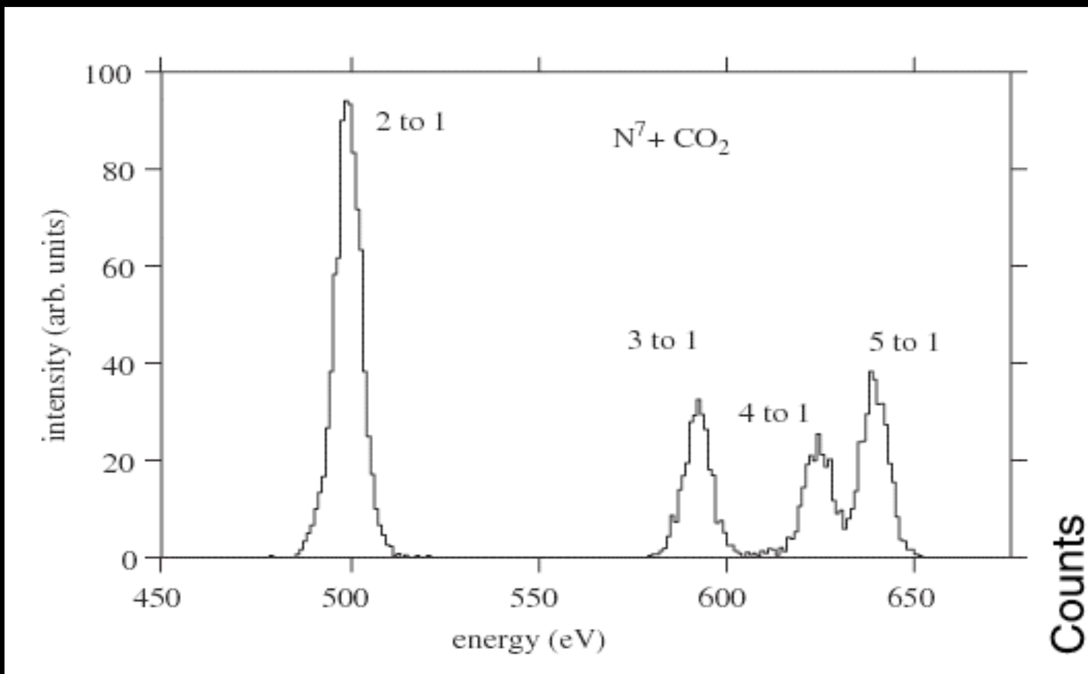
H-like Spectra (Low E_{coll})



$\Delta l = \pm 1$, Δn=max

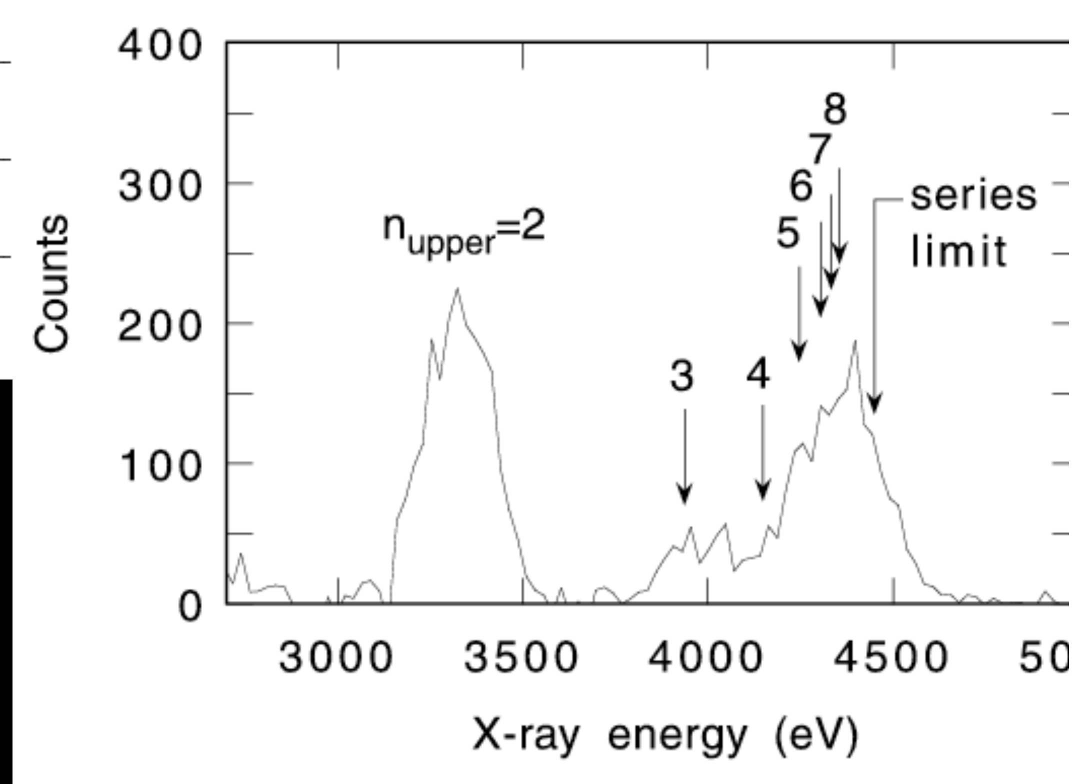
Large population of l =1
⇒ strong high-n emission

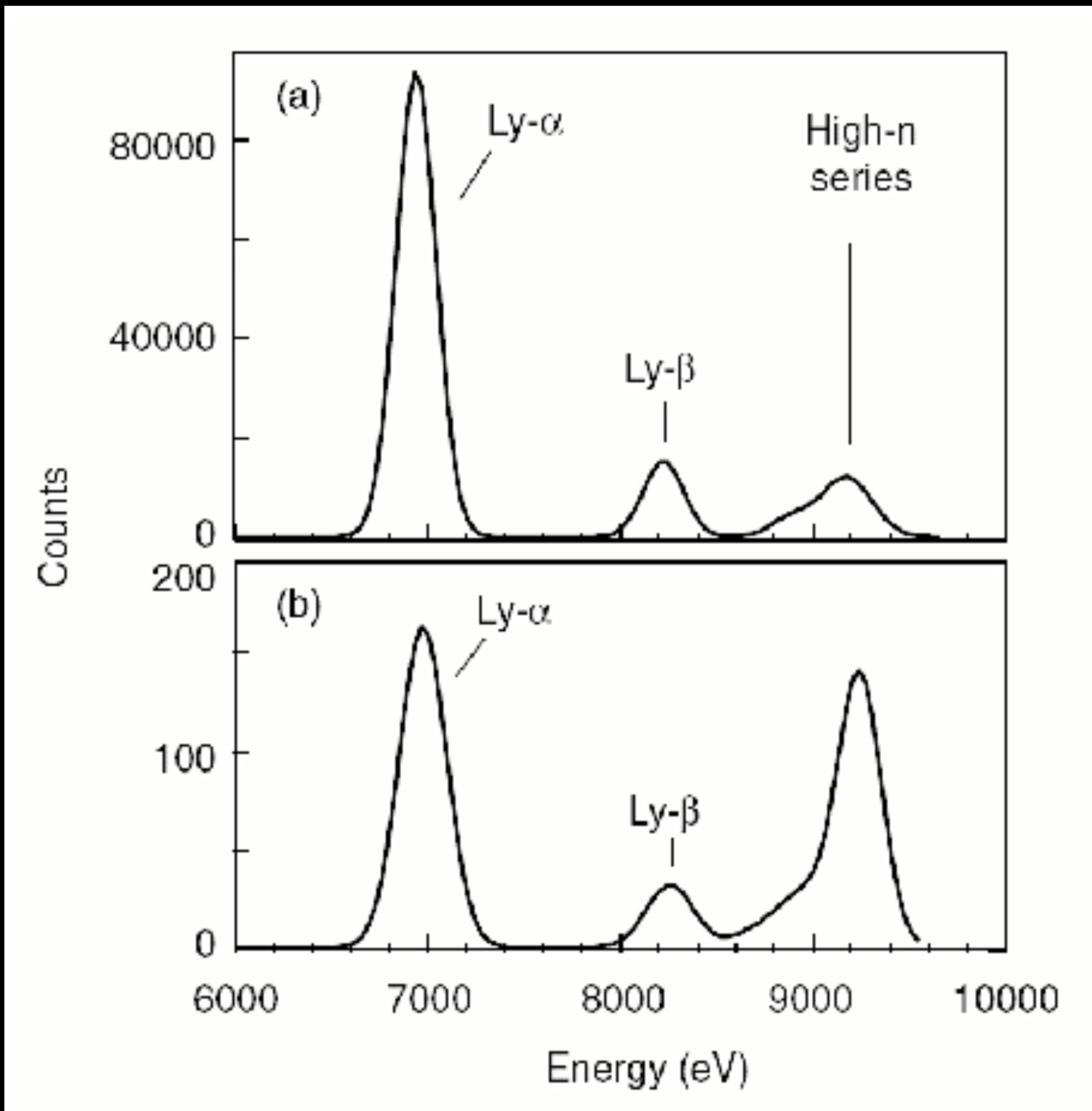
H-like Spectra (Low E_{coll})



Brown et al, NIMPRA (2006)

Ar^{18+} + Ar. Perez et al, J Phys B (2001)



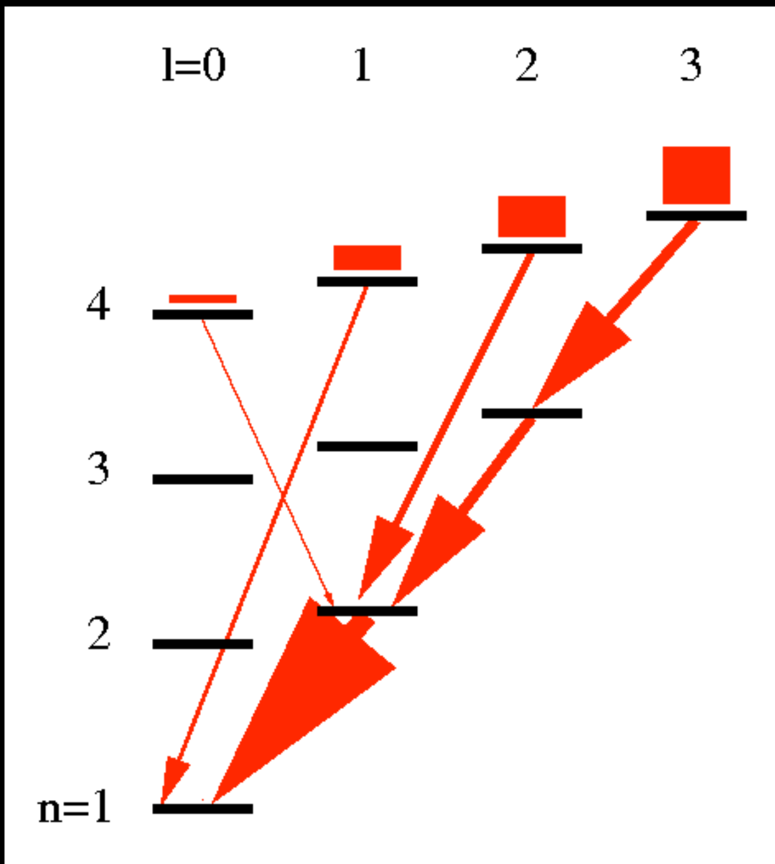


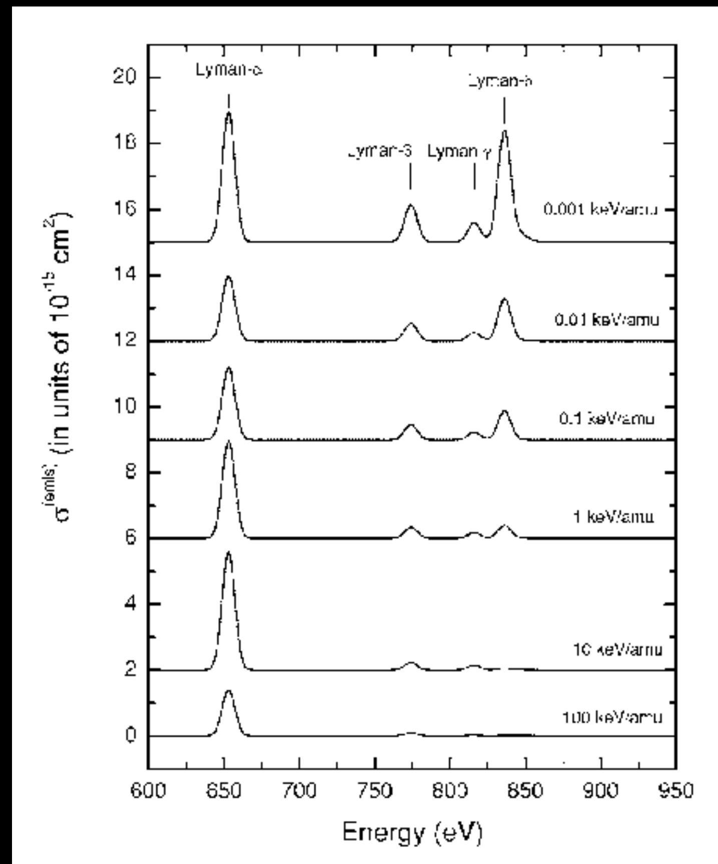
H-like Fe:

← Direct Excitation

← Fe^{26+} + N_2 CX

H-like Spectra (Higher E_{coll})





1 eV/amu

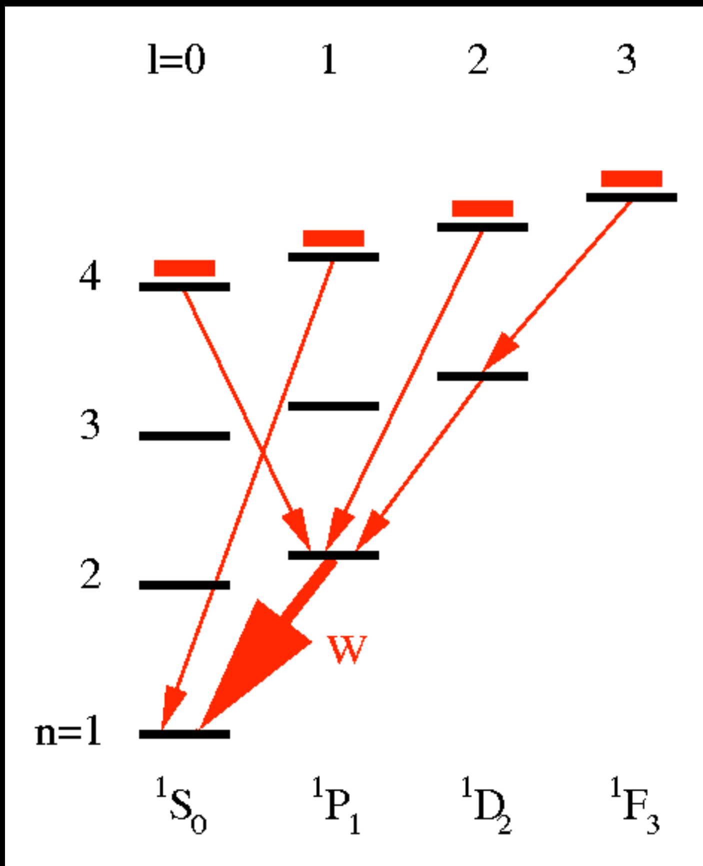
100 keV/amu

Statistical l population and $\Delta l = \pm 1$
⇒ yrast cascades and little high-n emission

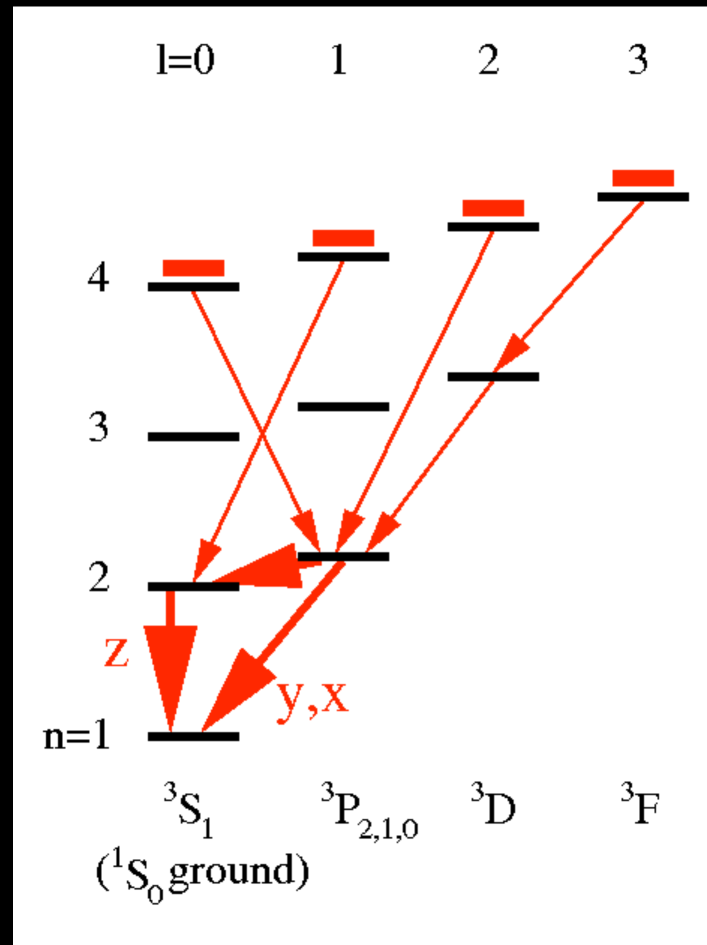
CTMC model predictions for O^{8+} CX.
Otranto, Olson, Beiersdorfer PRA (2006).

He-like Spectra

S=0 (singlets)



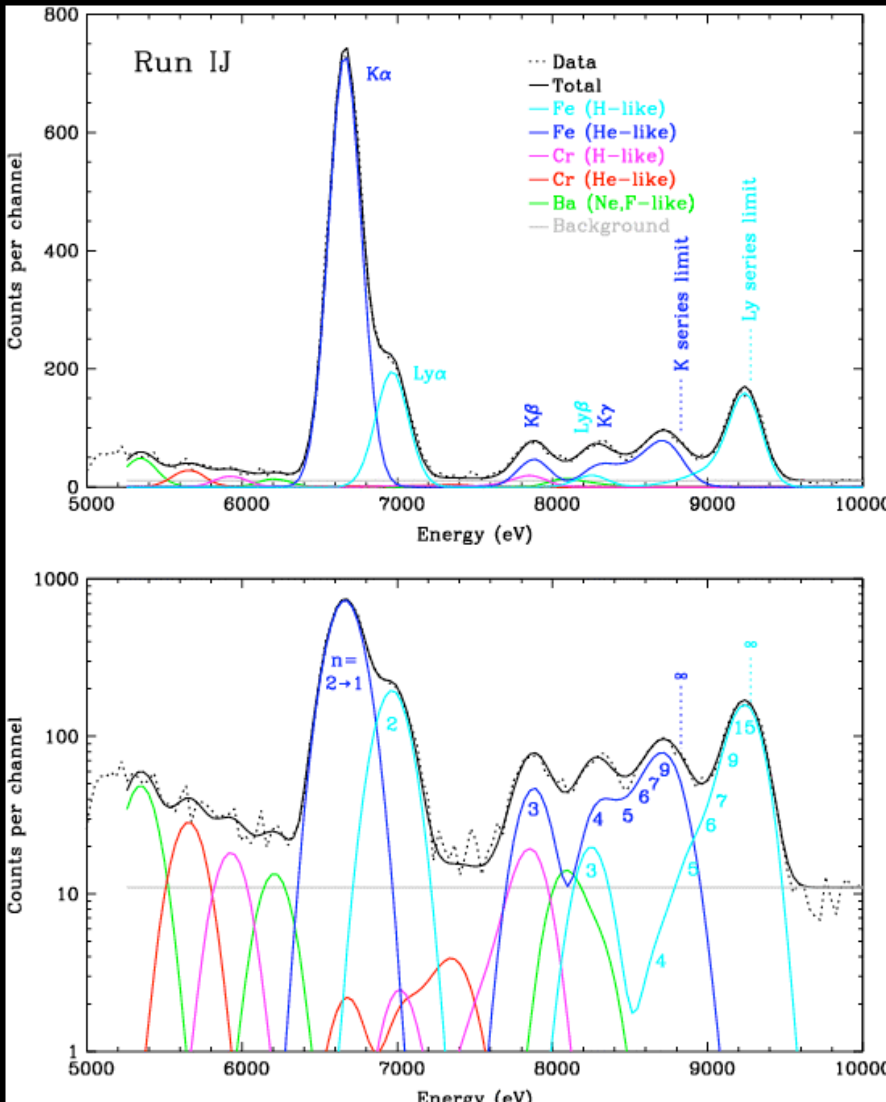
S=1 (triplets)



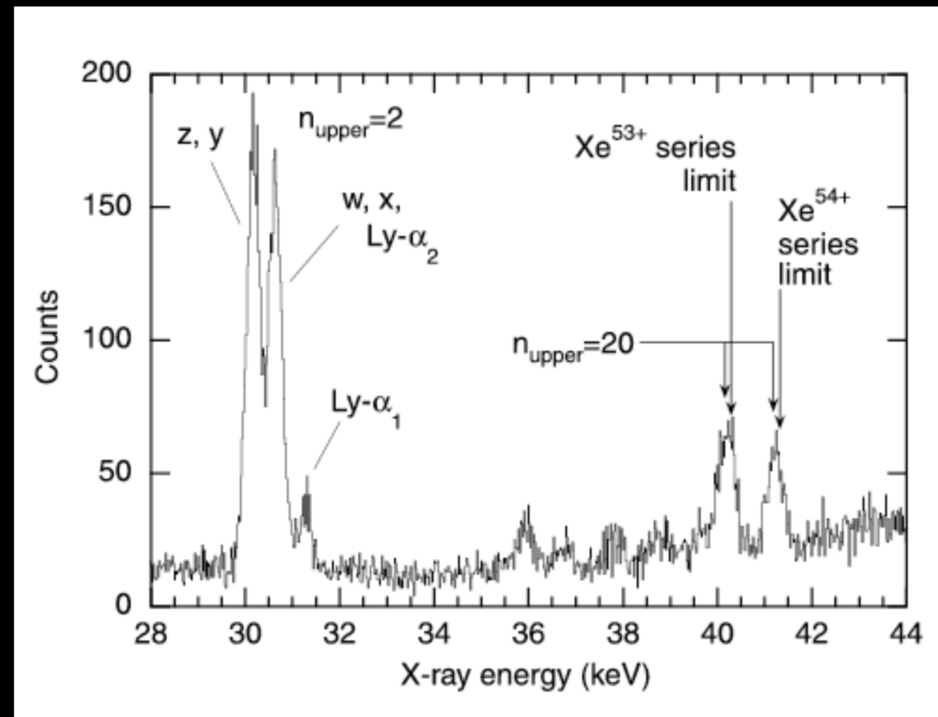
$\Delta S=0$

Singlet emission is similar to that for H-like, but …

No E-dipole decay to ground so everything funnels into Kα.

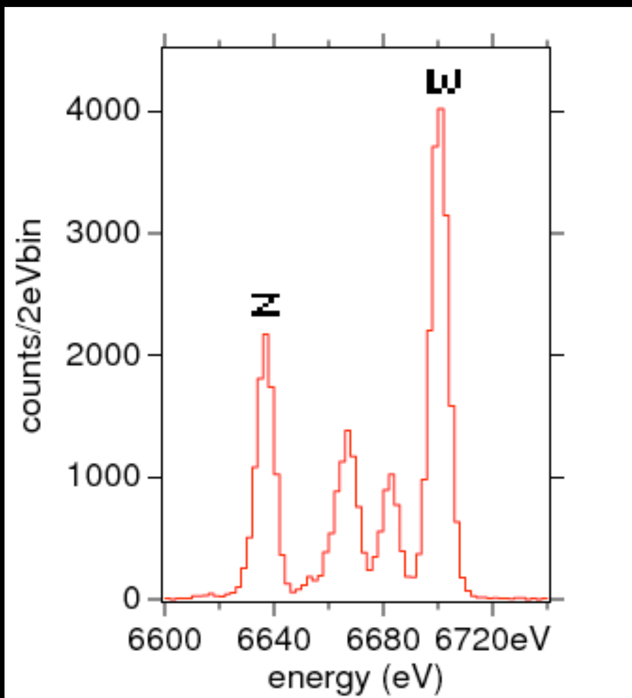


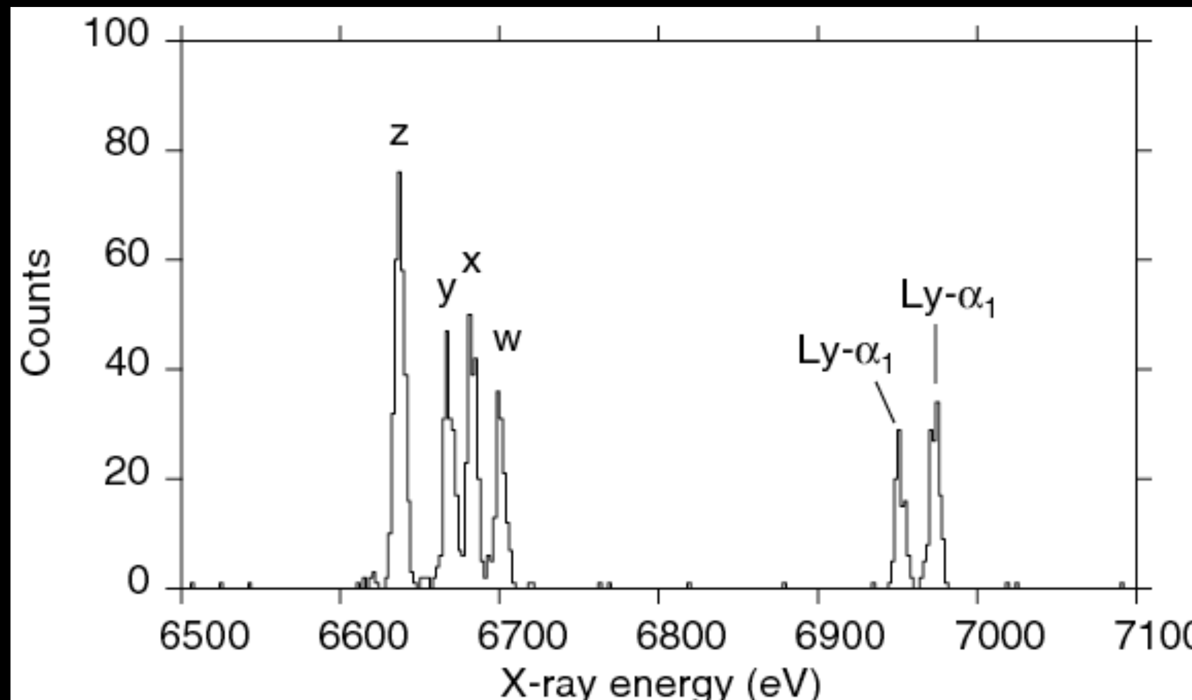
Fe CX with N_2. Wargelin et al, ApJ (2005).



$Xe^{53,54+}$ + Xe. Perez et al , J Phys B (2001)

Enhancement of He-like Triplets

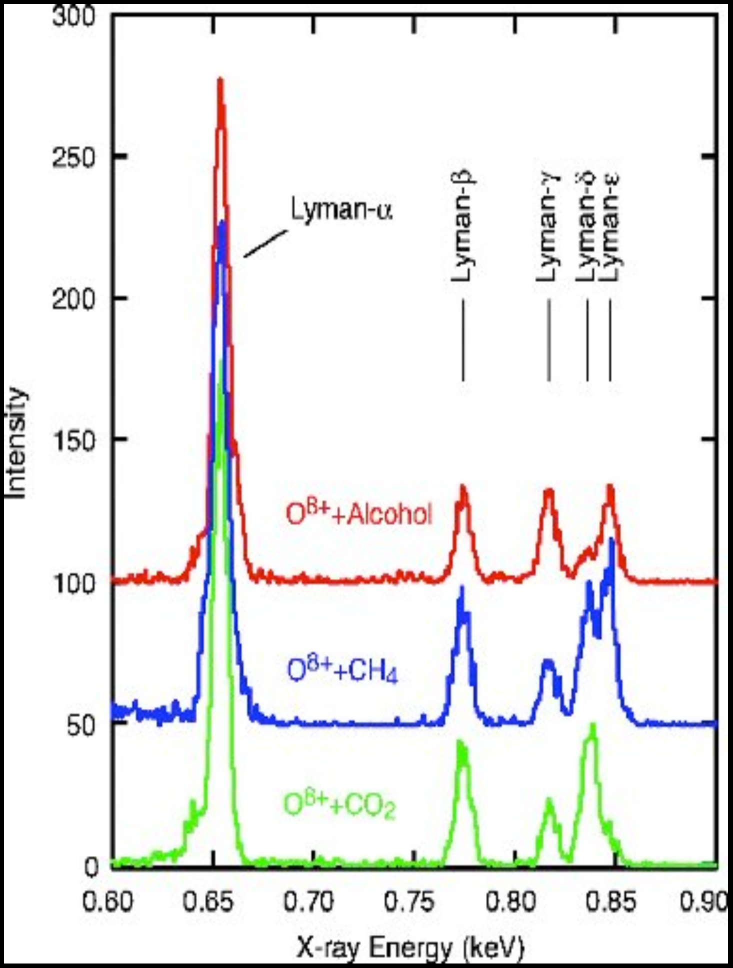




Direct excitation (G. Brown)

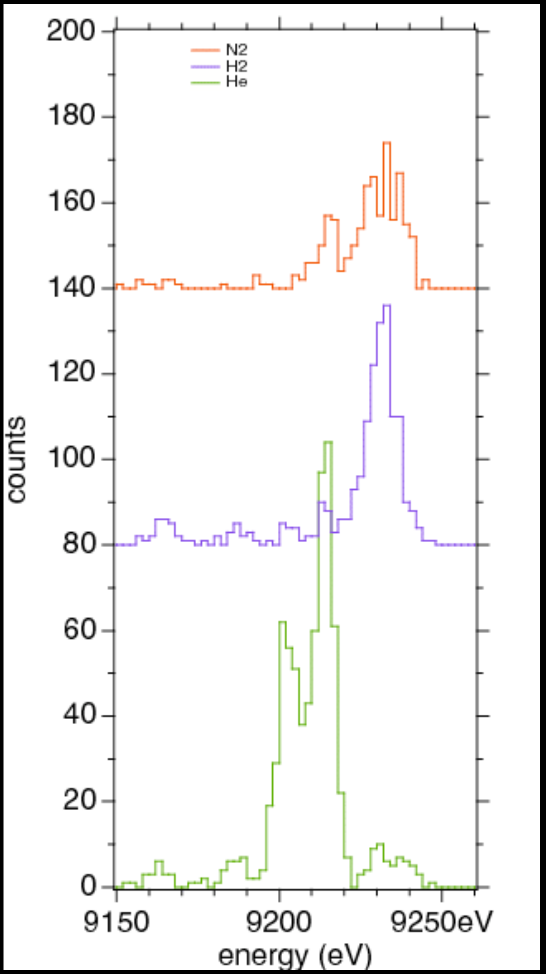
CX with N_2 (P. Beiersdorfer)

Target Dependence



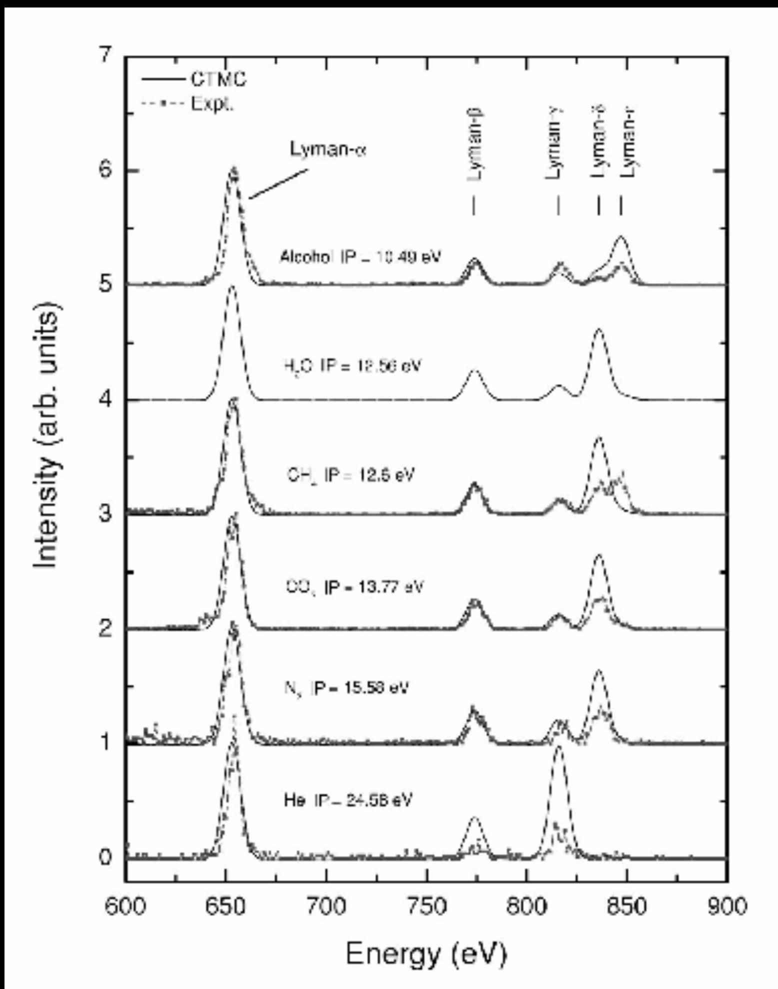
Beiersdorfer et al, Science (2003)

$n_{max} \propto \sqrt{(I_H/I_n)}$



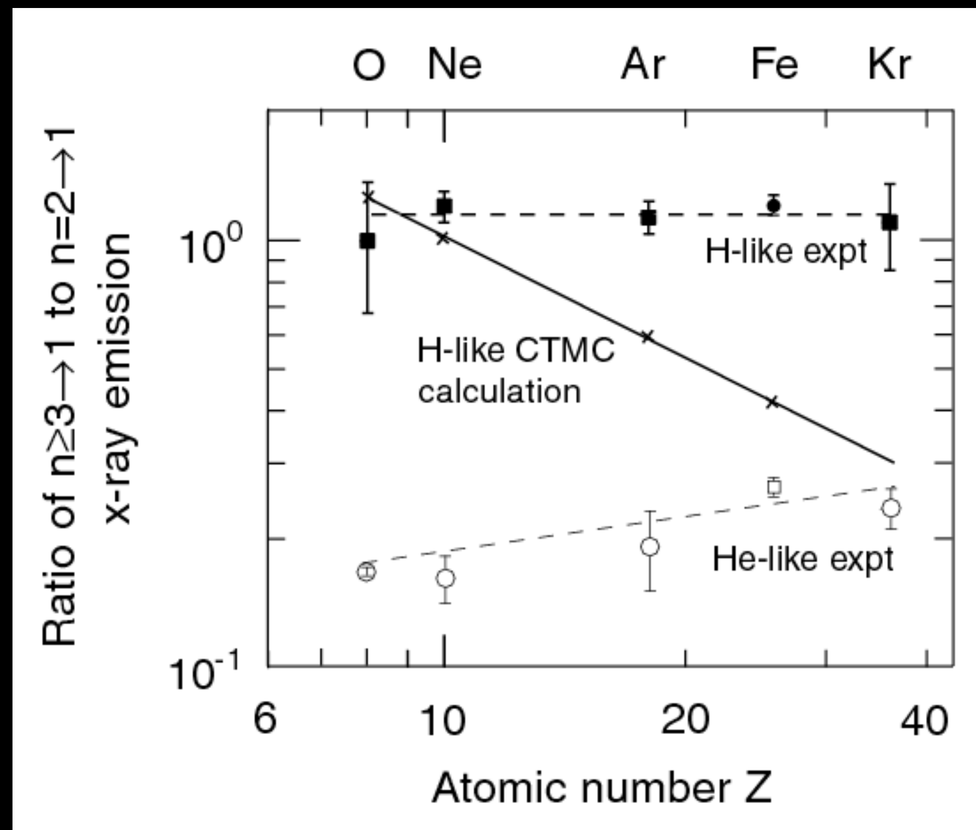
High-*n* Fe Lyman (G. Brown)

Multi-*e* Targets



Otranto et al, PRA (2006)

Theory using H OK for σ_{total} and n_{max}, but not *l* distrib.

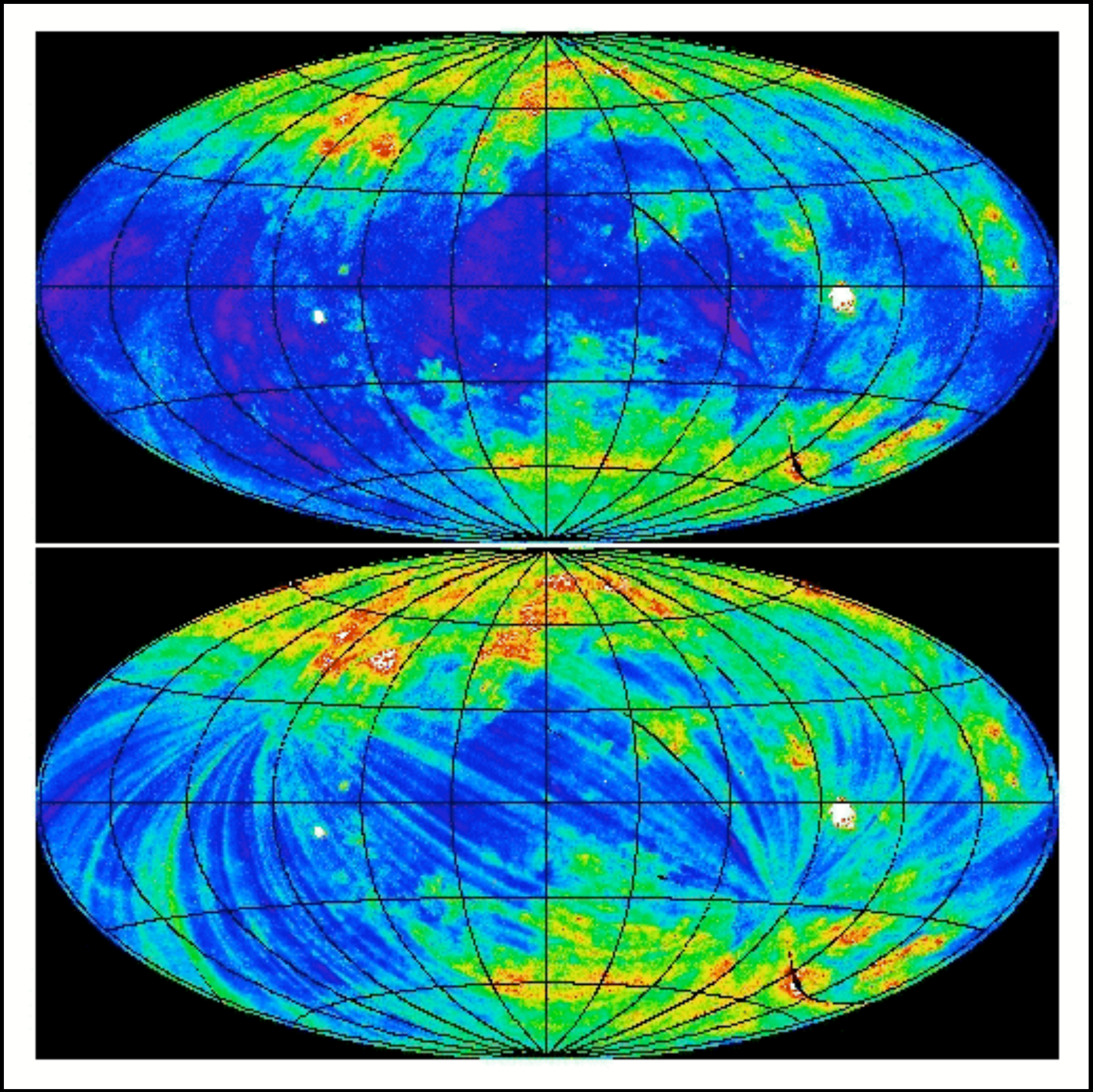


HR for $O+CO_2$, Ne+Ne, Ar+Ar, $Fe+N_2$, Kr+Kr, all with ~several eV/amu. Wargelin et al, ApJ (2005)

Future Work

- Measurements with H (and He) most important astrophysically
- Push theory to model *l*-distributions for CX with multi-*e* targets
- Extend to L-shell, especially in C band
  - Geo/helio CX strongest in *ROSAT* C band (R12)

ROSAT All-Sky Survey Map (R12) and LTEs



Long Term Enhancements from geo/helio CX fluctuations.

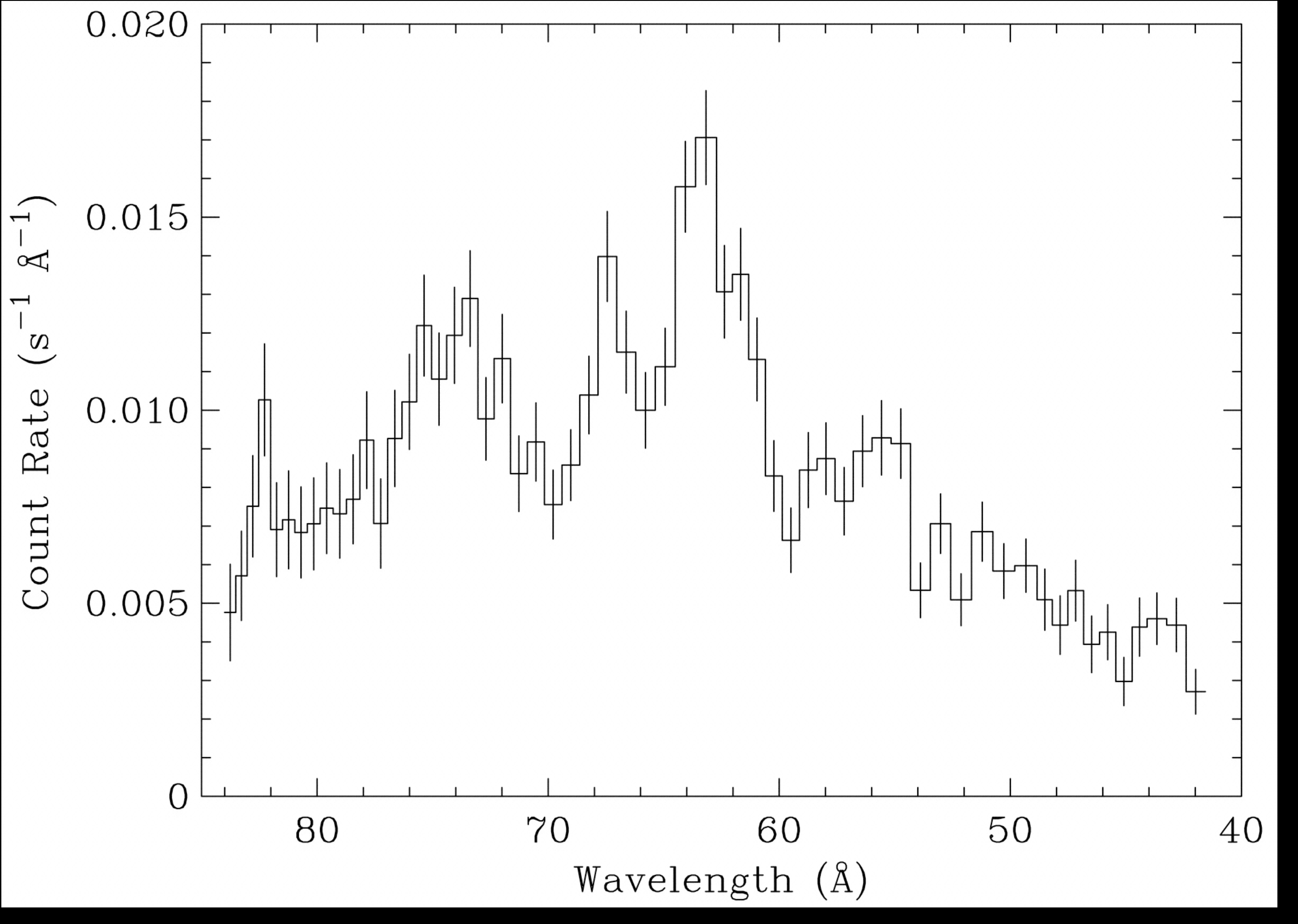
Strongest in R12 band.

Current CX models known to be incomplete (no L-shell Mg, Si, S, Fe).

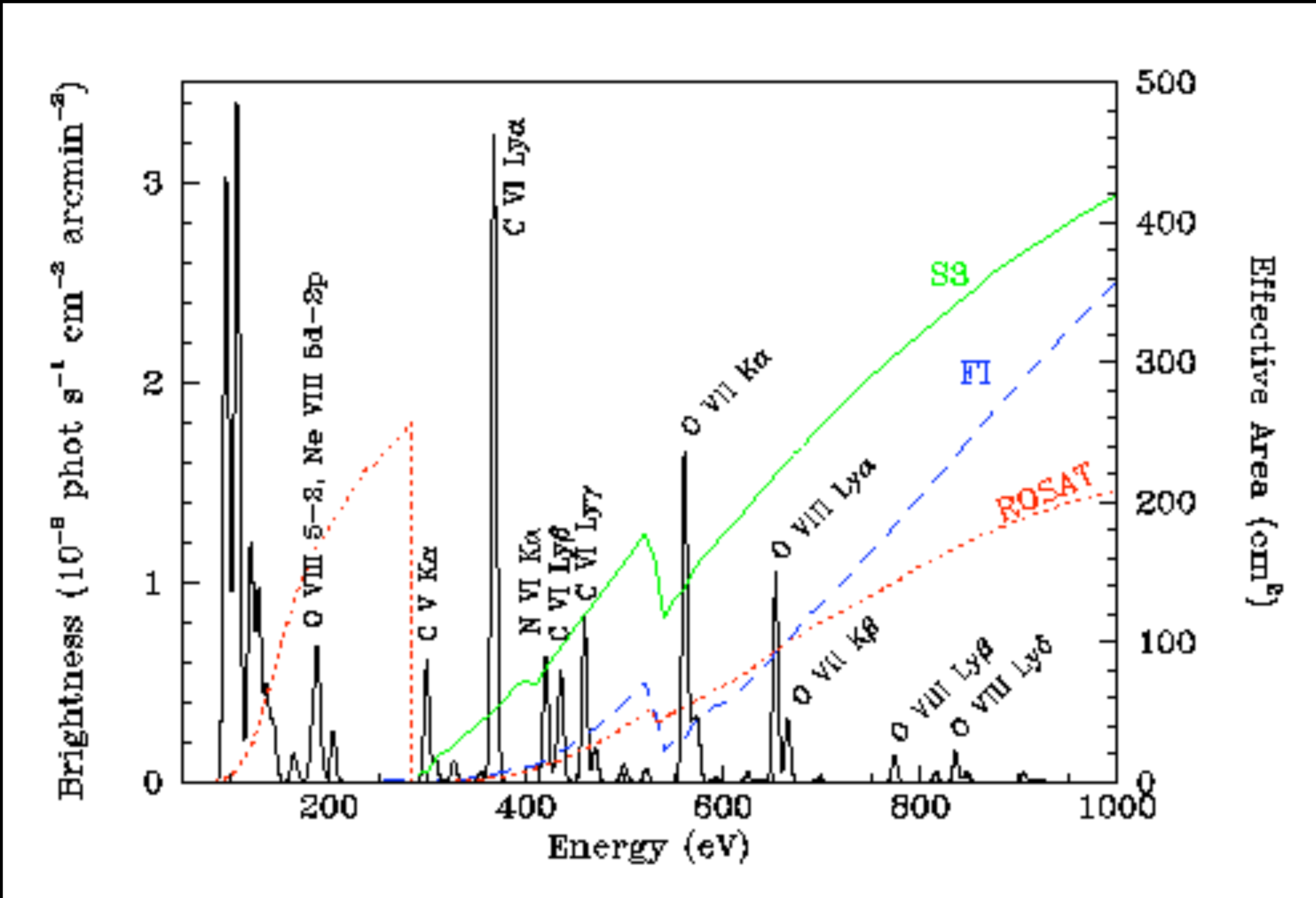
Some hints in current data.

S. Snowden

Diffuse X-Ray Spectrometer (DXS)

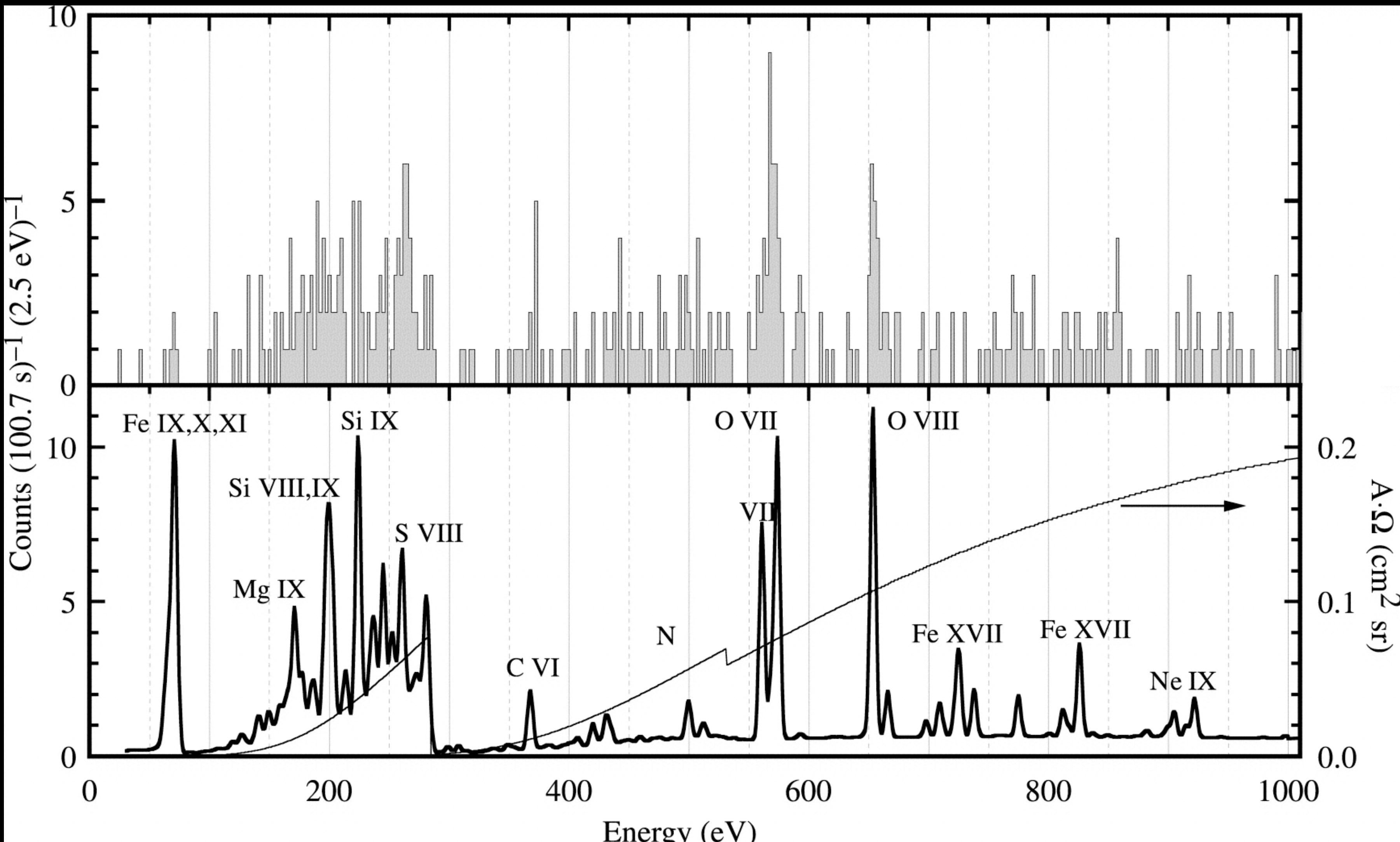


SXRB 150-300 eV. Sanders et al. (2004?)



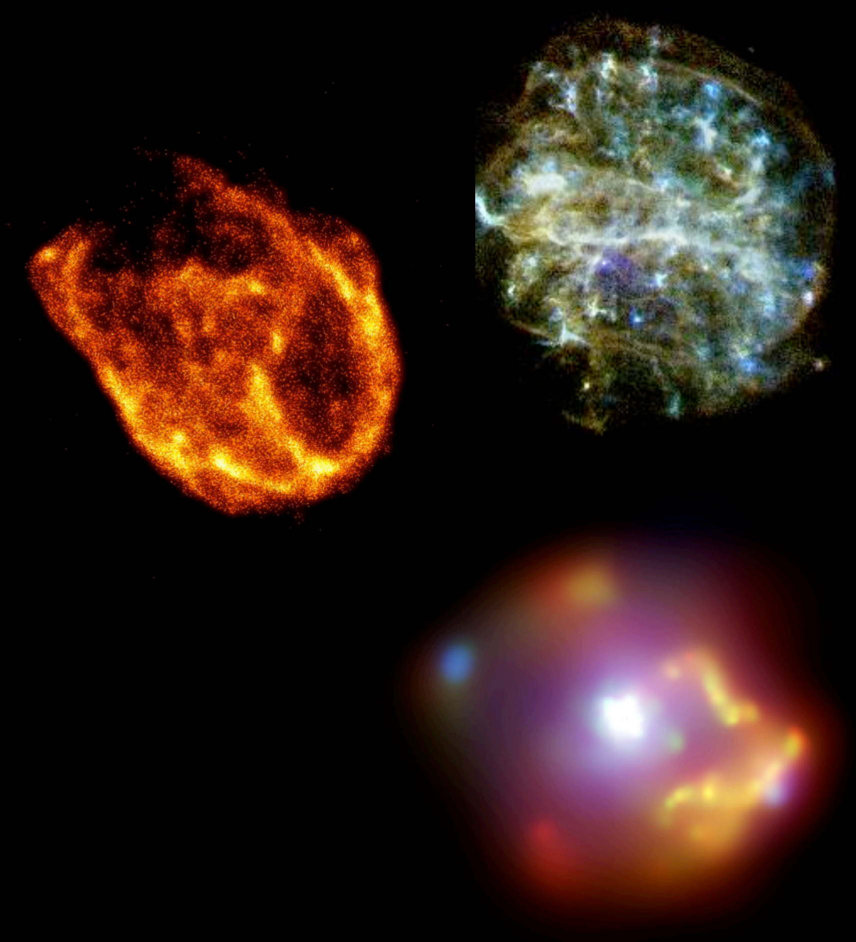
Model SWCX spectrum. Wargelin et al (2004).

X-Ray Quantum Calorimeter (XQC)



100s of SXRB from rocket flight. McCammon et al (2004?)

Astrophysical Examples: Supernova Remnants

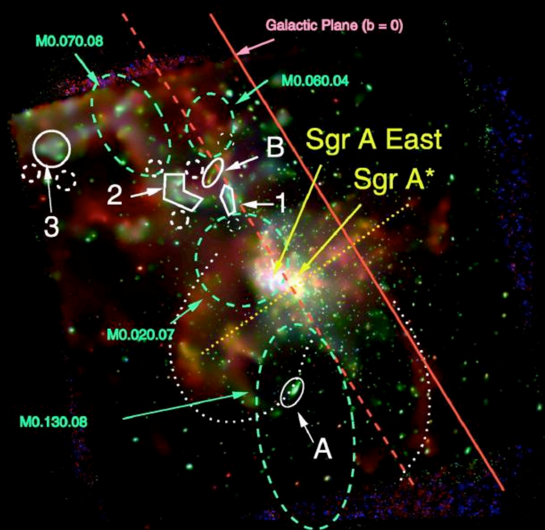


CX from SNR in inhomogeneous ISM as shocked ionized gas interacts with neutral clouds?

Wise & Sarazin (ApJ 1989) concluded that <10% of He-like N and C X-rays from CX based on *Einstein* OGS observations of old SNRs.

No solid evidence yet. Need high-res non-dispersive detectors to see CX spectral signatures.

Galactic Center



High-*T* gas + molecular clouds --> CX ??
Probably only at low level.

Low-E cosmic rays and Galactic Ridge???

Galactic Center Positronium

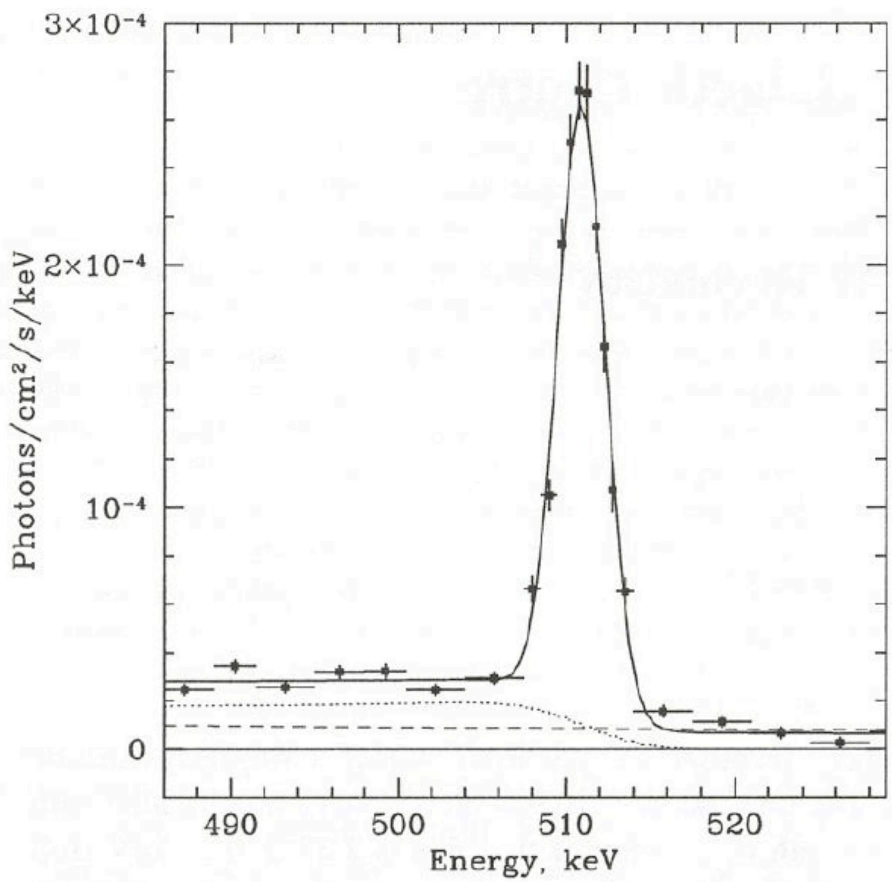


Figure 1. Spectrum of the e^+e^- annihilation radiation (fixed background model) detected by SPI from the GC region and the best-fitting model (thick solid line, see Table 1 for parameters). The dotted line shows the ortho-positronium radiation and the dashed line shows the underlying power-law continuum.

Roughly 30% of positronium is formed by CX of positron+gas.

Para-positronium (opposite spins) annihilates in 2-photon emission.

Ortho-positronium (spin 1) requires 3-photon decay.

INTEGRAL/SPI observation. Churazov et al. MNRAS (2005)