THE PUZZLING DETECTION OF PLUTO IN THE X-RAY BY *CHANDRA*

- Or -

We've Just Invented the Field of KBO X-ray Astronomy, Now What?

Scott J.Wolk

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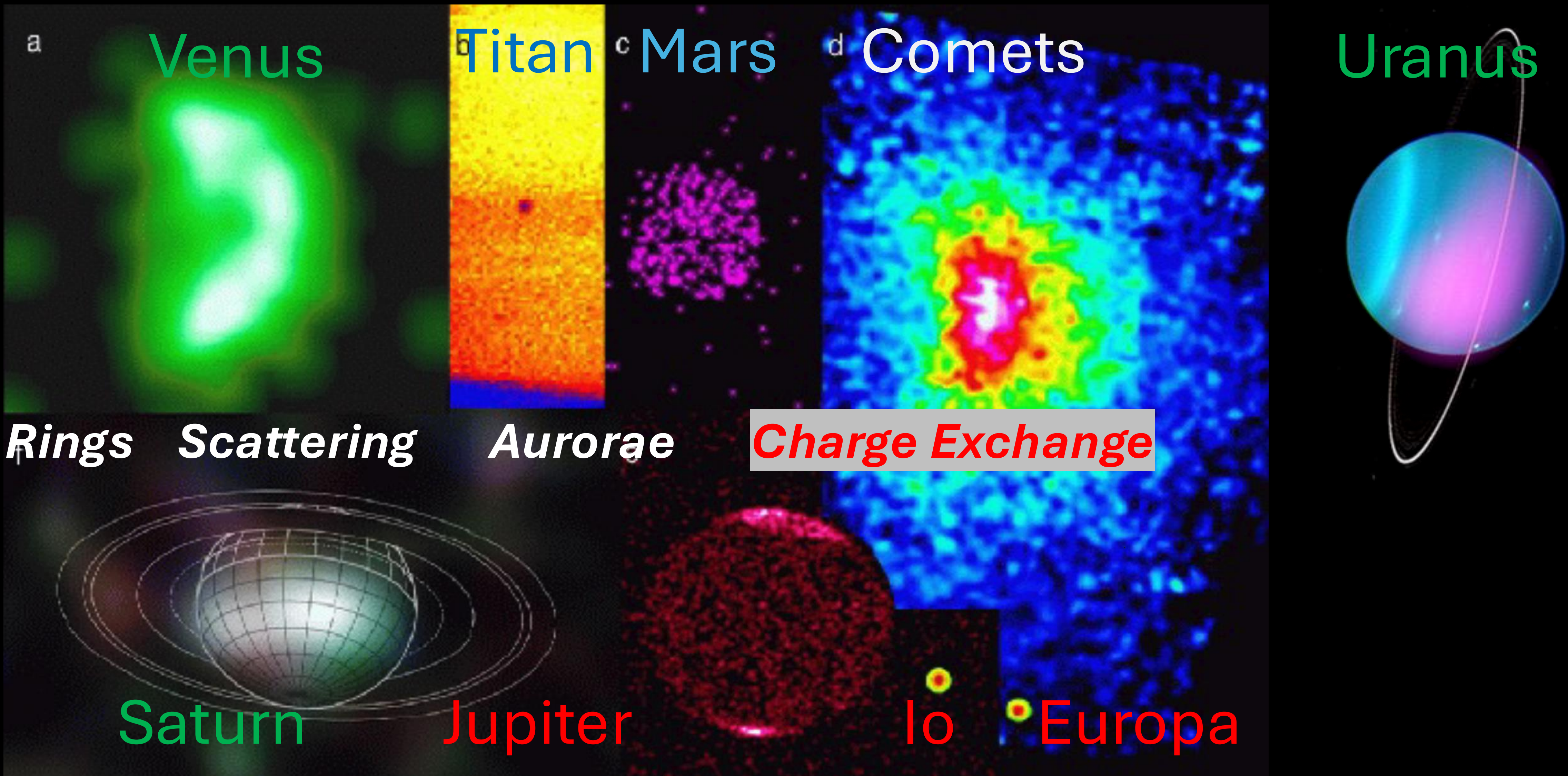
25 years of The Study of Solar System X-rays is a Very Rich Field, Still Developing. Low Lx but important physical processes.

This is the Universe Chandra Opened up to us.



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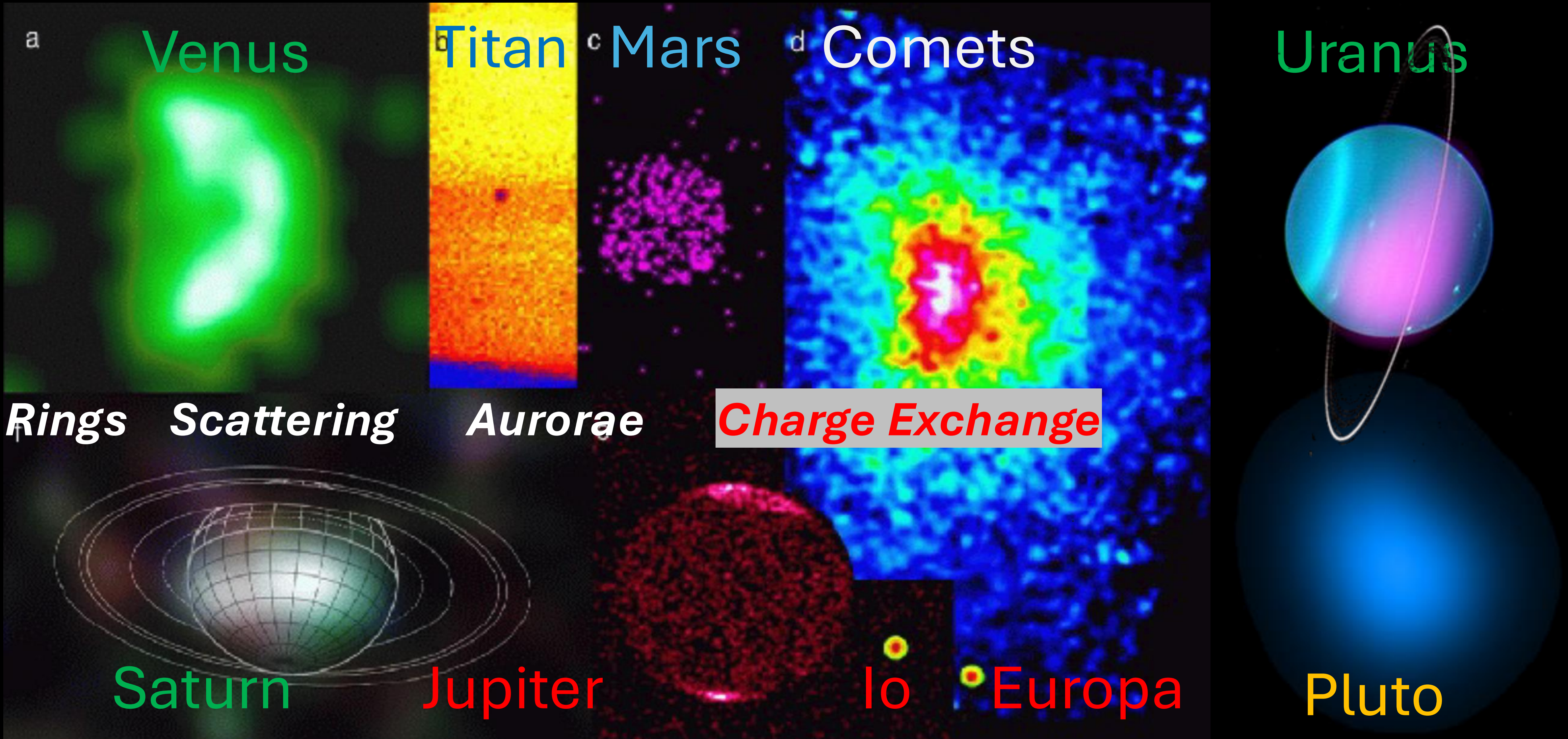
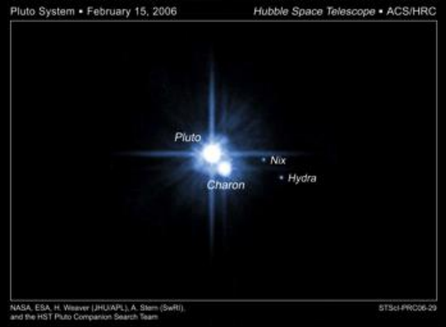
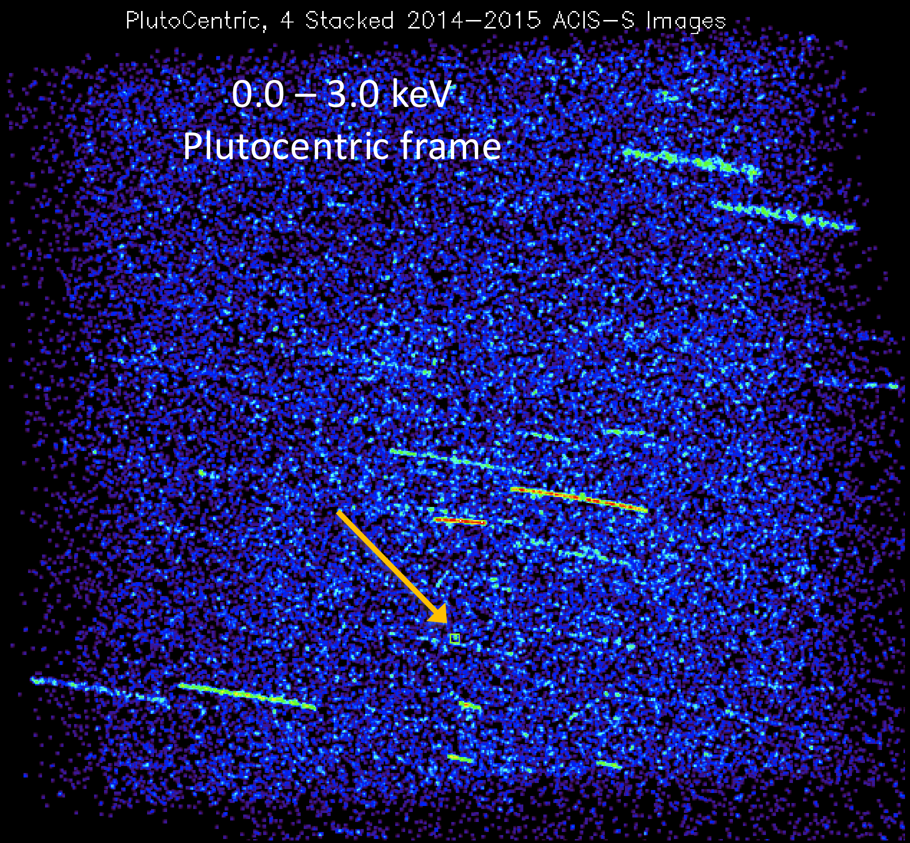
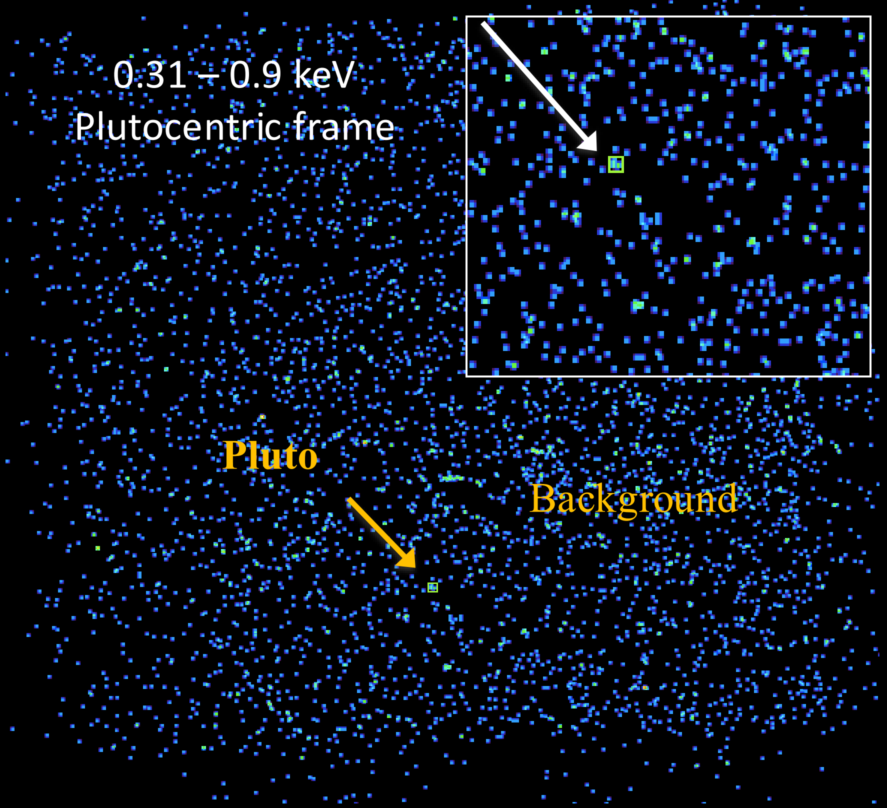




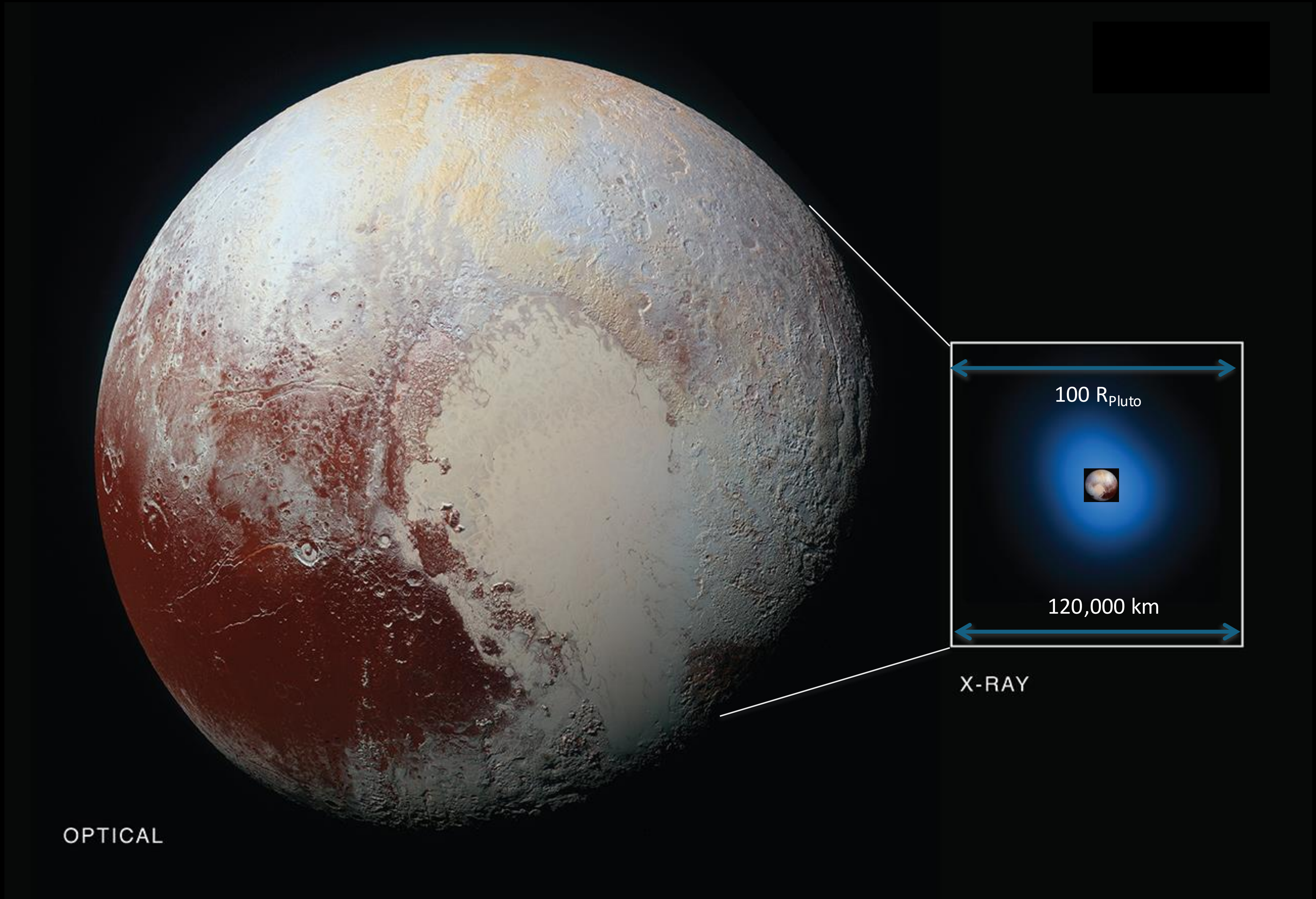
Chandra Pluto ACIS-S Results from the 175 ksec (2 days) of pointings on 24 Feb 2014, 26- 30 Jul 2015 and 01 - 03 Aug 2015

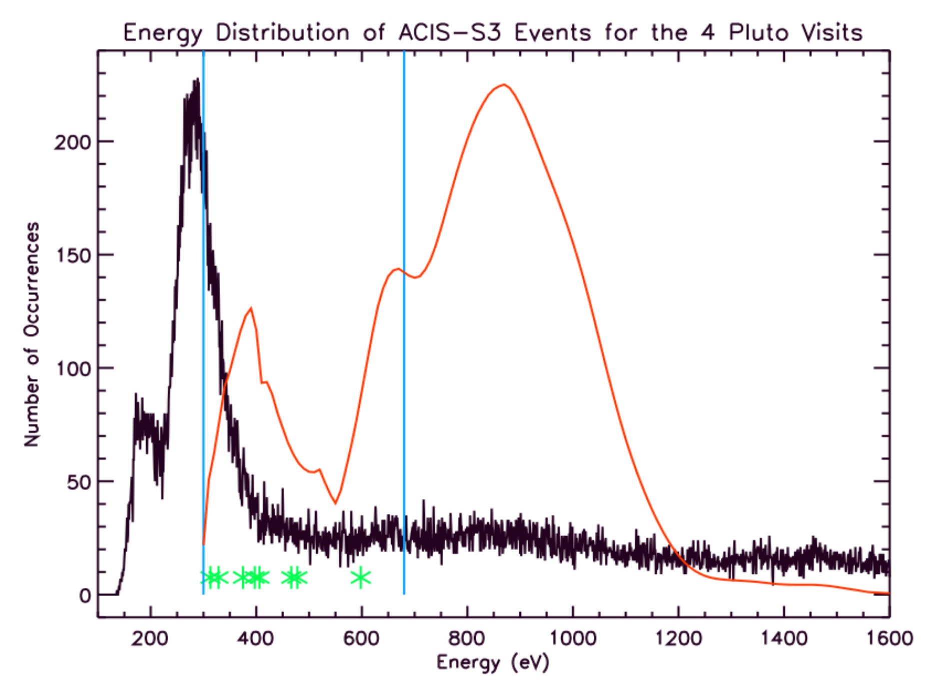




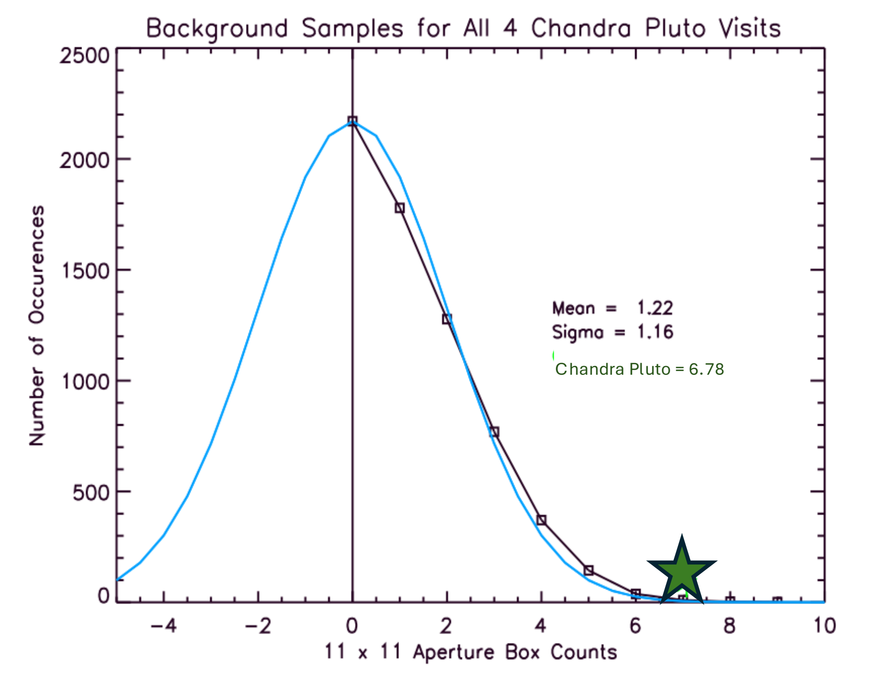
1st Solar System X-rays detected outside Saturn's orbit!*

Pluto is Surrounded by X-ray Emission

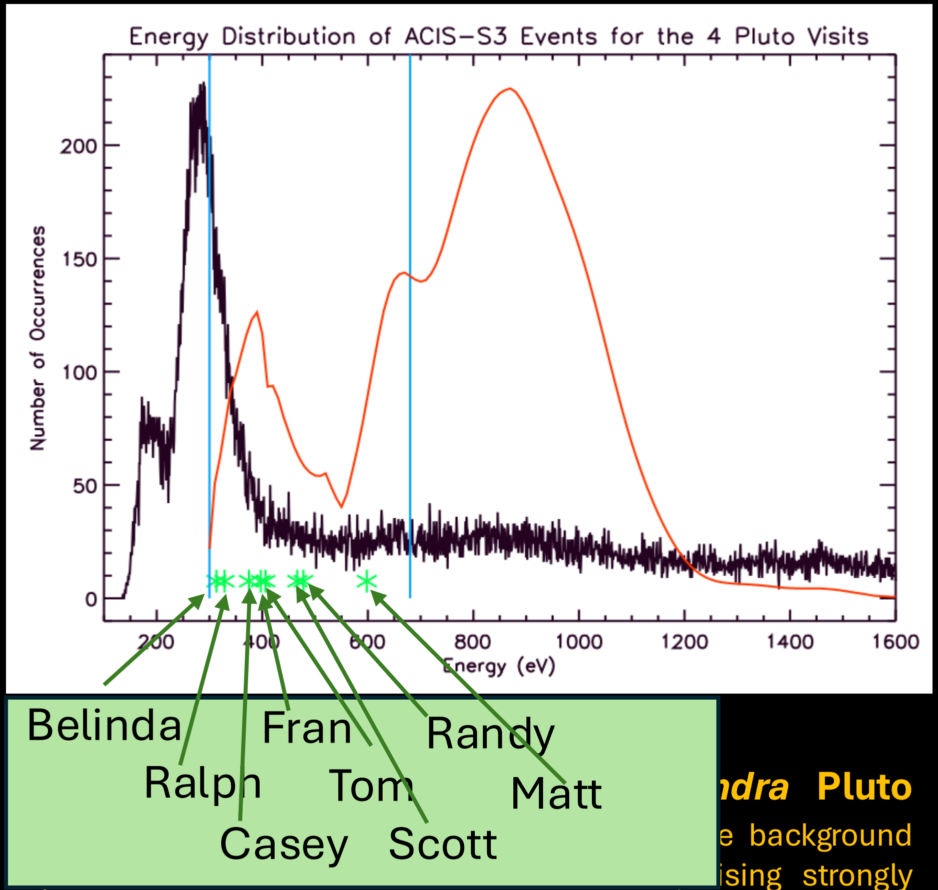




Total event spectrum for the *Chandra* Pluto observations. The spectrum is typical of the background spectra measured for the ACIS-S detector, rising strongly shortwards of 0.35 keV and relatively flat from 0.4 to 1.0 keV. It is unlike the measured 8 count Pluto spectrum (green crosses), which are all clustered in the 0.3 - 0.6 keV region typical of SW CNO minor ion charge exchange (dashed blue line region), with none seen at 0.6 - 1.2 keV especially not near the expected maximum emission created by coherent and incoherent X-ray scattering (dashed red line).



Frequency distribution plot of the number of events in a 11 pixel x 11 pixel box (90% flux footprint) for 1000 footprints placed randomly across the *Chandra* Pluto-frame combined image. The green star denotes the 6.8 cts found for Pluto after removal of average background value of 1.2 counts. The statistical significance of the detection (using Poisson statistics) is evident **> 99.95%**.



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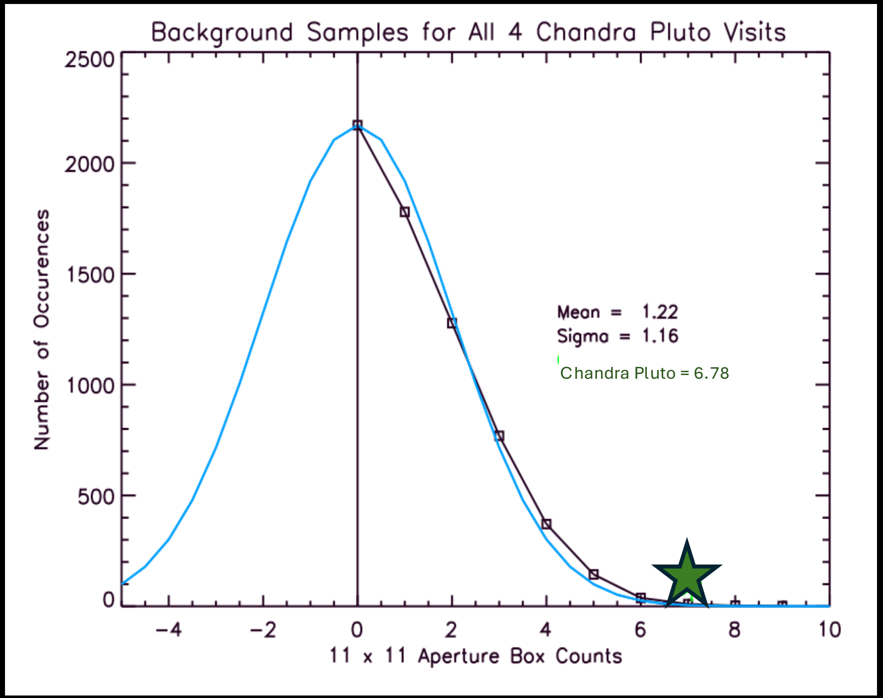

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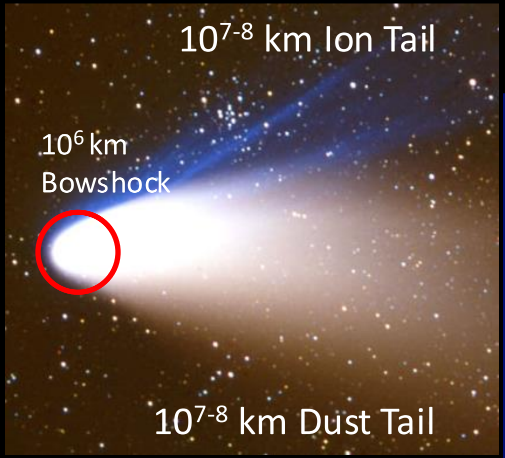
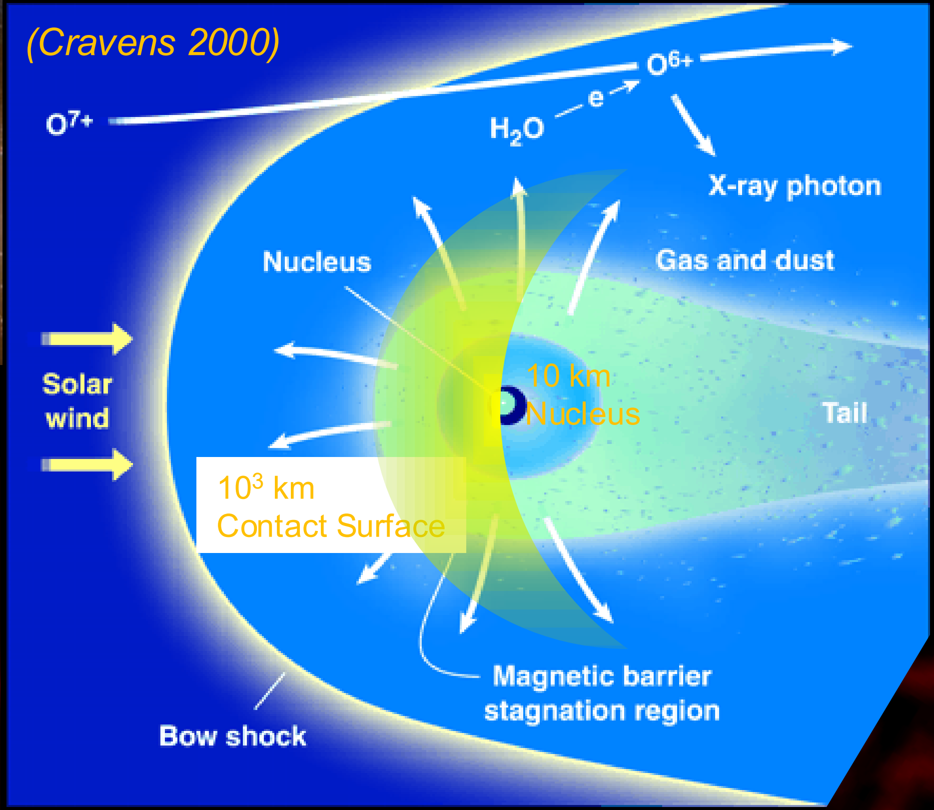
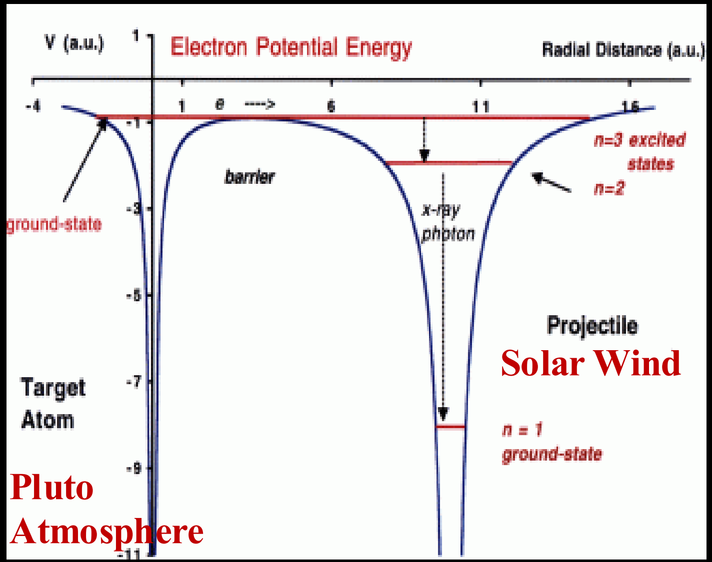
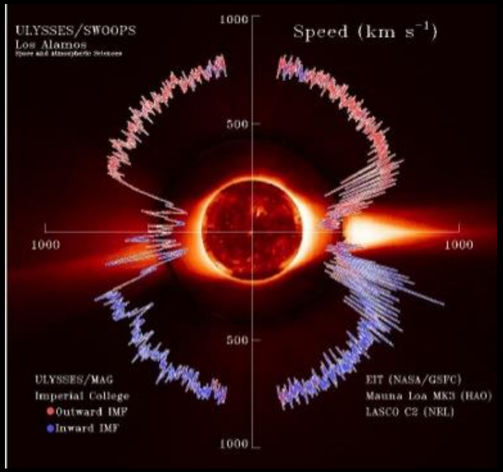
Example of Solar System Plasma Process Producing X-rays:
Charge Exchange Interaction between the Gravitationally Unbound Neutral Atmospheres of Comets and the Solar Wind

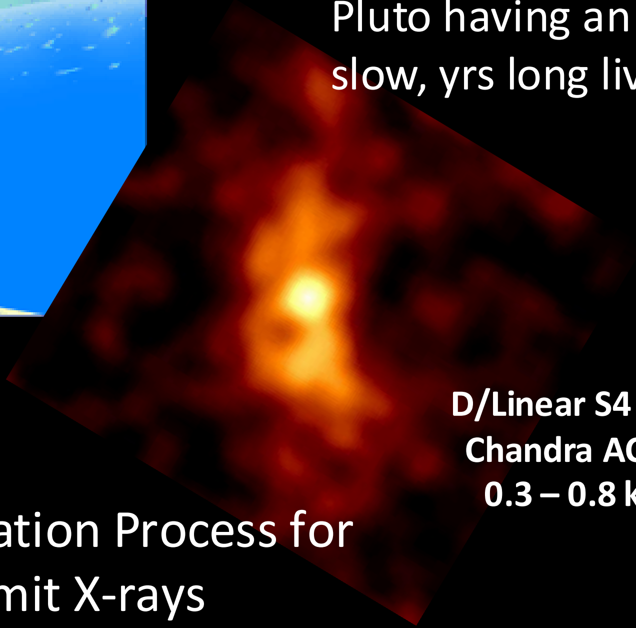






Pluto Case: Need to allow for Pluto having an exobase + very slow, yrs long lived neutrals

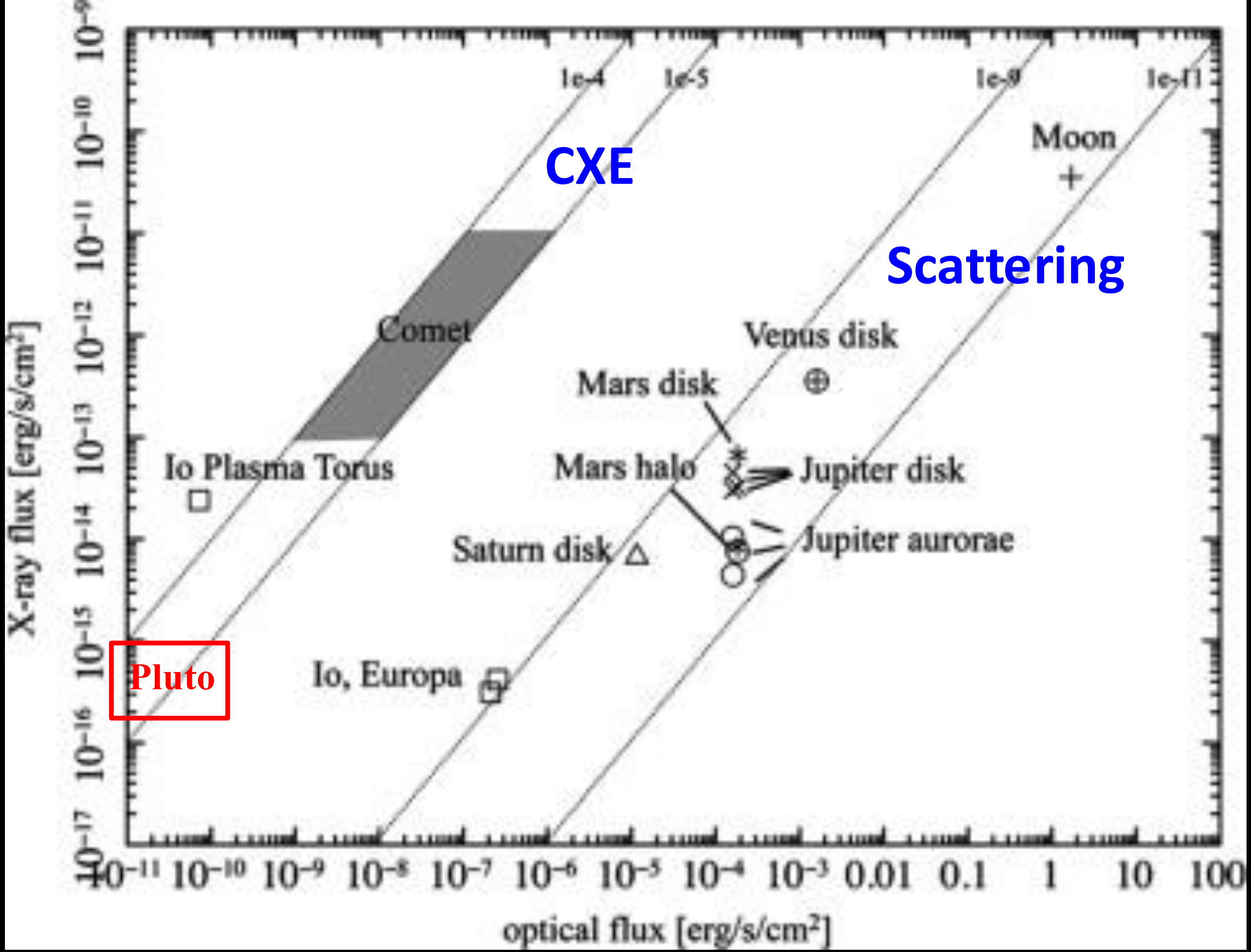




D/Linear S4 2000
Chandra ACIS-S
0.3 – 0.8 keV

Solar Wind Charge Exchange (CXE) is the Dominant Ionization Process for Outflowing Cometary Gases. ALL Active Comets Emit X-rays

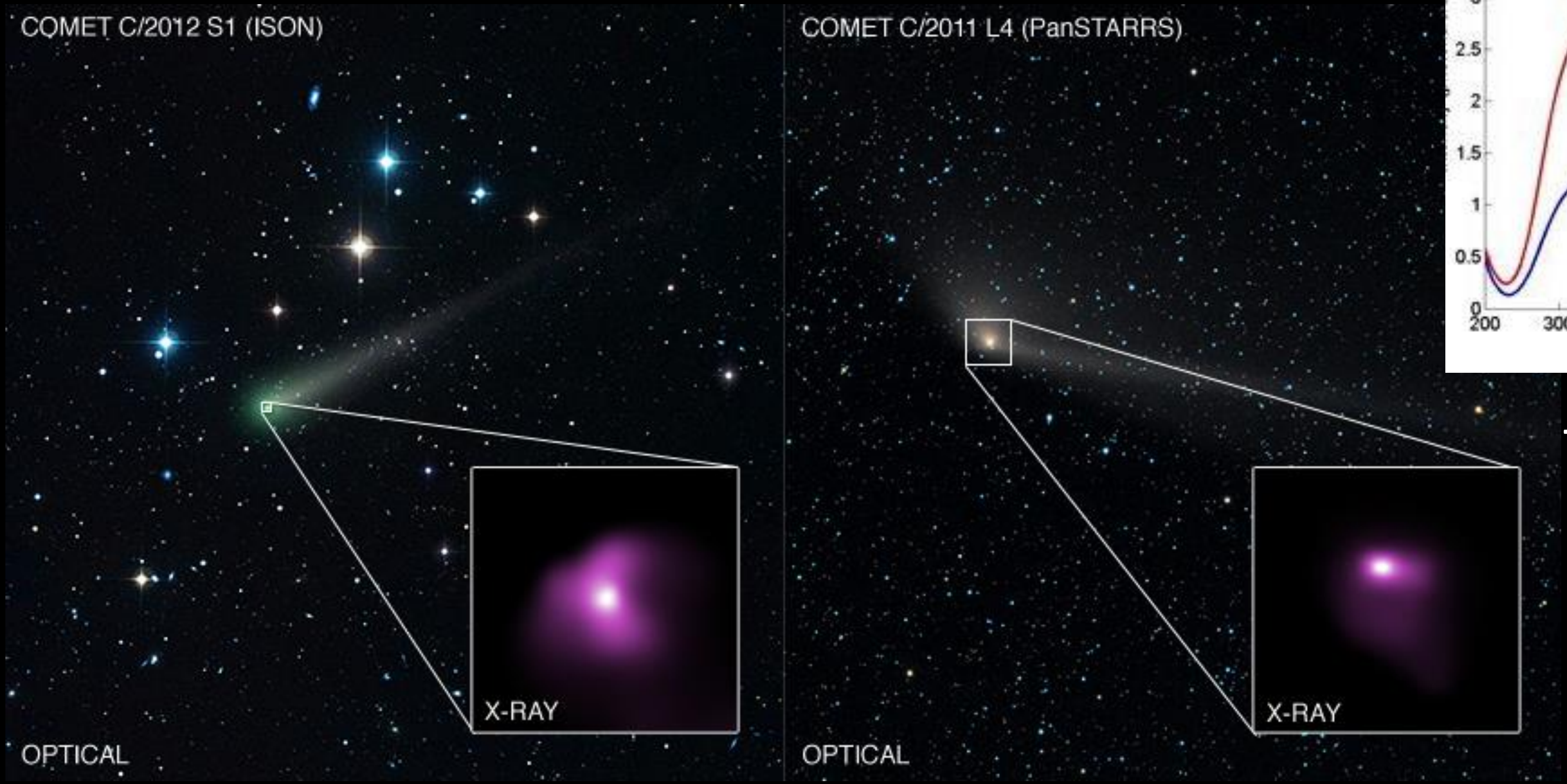
$F_{pluto, X\text{-}ray}$ vs. $F_{Optical}$ Suggests a Charge Exchange (CXE) Source

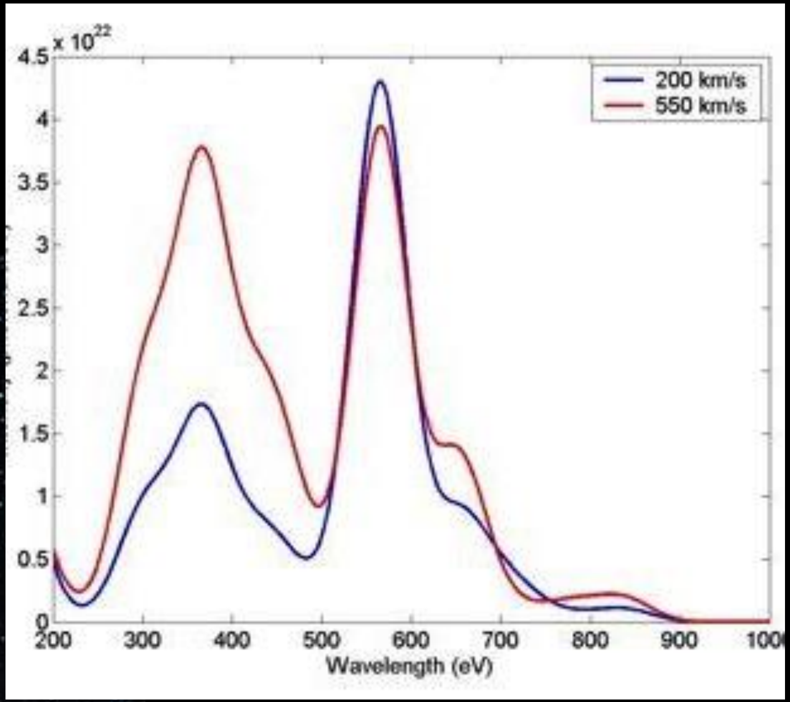


- $F_{solar\_at\_Pluto}$ = 3.85e26/(4π*(33 AU*1.496e11 m/AU)^2) = **1.26 J/m^2**
- $F_{x\_off\_Pluto}$ = (20e7 J/sec)/(4π*(1190e3 m)^2) = **1.1e-05 J/m^2** [6.7e-16 erg/sec/cm^2]

  L_x = 4π*(33.*1.496e11)^2*(3.9e-5*0.425e3*1.609e-19/0.004m^2) = **2.x10^8 J/s ~ 200 MW**

We've Seen Similar X-ray Behavior Before: Cometary X-ray Emission





The emitting regions are huge!
~ 1,000,000 km in diameter.
They are spectrally dominated by CNO from the Sun de-exciting in the cometary atmosphere.

The Total X-ray Power Emitted by Pluto is Consistent With Other Sources of X-rays in the Solar System

Summary of the characteristics of soft X-ray emission from solar system bodies

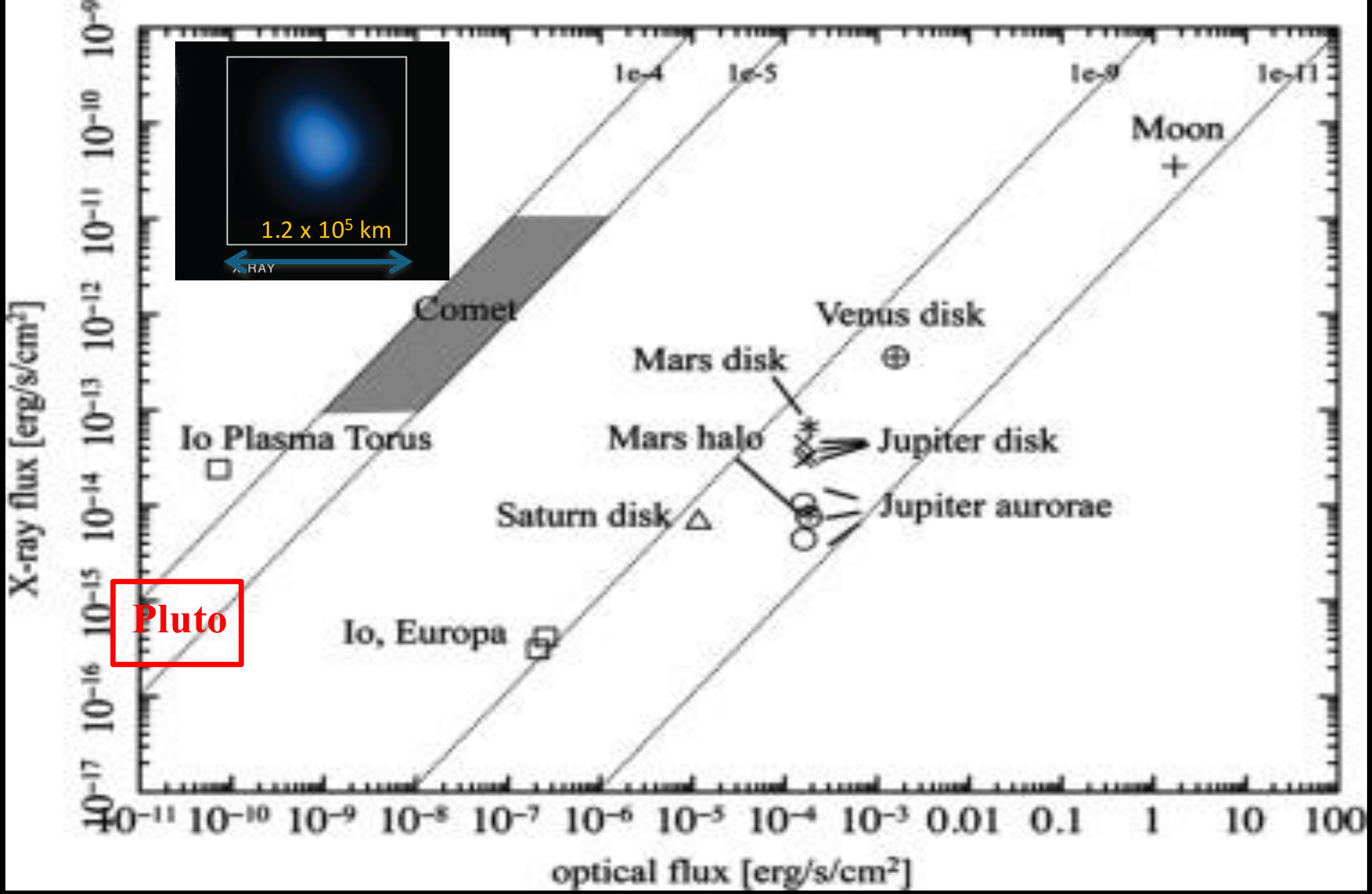
Bhardwaj, Lisse, et al. 2007 & Encyclopedia of the Solar System II, 2008

Object	Emitting region	Power emitted[a]	Special characteristics	Production mechanism
Earth	Auroral atmosphere	10–30 MW	Correlated with magnetic storm and substorm activity	Bremsstrahlung from precipitating electrons, and characteristic line X-rays from atmospheric neutrals due to precipitating electron impact, + (see note[b])
Earth	Non-auroral atmosphere	40 MW	Correlated with solar X-ray flux	Scattering of solar X-rays by atmosphere
Moon	Dayside	0.07 MW	Correlated with solar X-ray flux	Scattering and fluorescence due to solar X-rays by the surface elements on dayside.
	Geocoronal (Nightside)		Nightside emissions are ~1% of the dayside emissions	SWCX with geocorona
Venus	Sunlit atmosphere	50 MW	Emissions from ~120–140 km above the surface	Fluorescent scattering of solar X-rays by C and O atoms in the atmosphere
Mars	Sunlit atmosphere	1–4 MW	Emissions from ~110–130 km above the surface	Fluorescent scattering of solar X-rays by C and O atoms in the upper atmosphere
	Exosphere	1–10 MW	Emissions extend out to ~8 Mars radii	SWCX with Martian corona
Jupiter	Auroral atmosphere	0.4–1 GW	Pulsating (~20–60 min) X-ray hot spot in north polar region	Energetic ion precipitation from magnetosphere and/or solar wind + electron bremsstrahlung
Jupiter	Non-auroral atmosphere	0.5–2 GW	Relatively uniform over disk	Scattering of solar X-rays + possible ion precipitation from radiation belts
Saturn	Sunlit disk	0.1–0.4 GW	Correlated with solar X-ray flux	scattering of solar X-rays + Electron bremsstrahlung ?
Comets	Sunward-side coma	0.2–1 GW	Intensity peaks in sunward direction ~10^5–10^6 km ahead of cometary nucleus	SWCX with cometary neutrals
Io Plasma Torus	Plasma torus	0.1 GW	Dawn-dusk asymmetry observed	Electron bremsstrahlung + ?
Io	Surface	2 MW	Emissions from upper few microns of the surface	Energetic Jovian magnetospheric ions impact on the surface
Europa	Surface	1.5 MW	Emissions from upper few microns of the surface	Energetic Jovian magnetospheric ions impact on the surface
Rings of Saturn	Surface	80 MW	Emissions confined to a narrow energy band around at 0.53 keV.	Fluorescent X-ray emission from atomic oxygen in H_2O ice excited by incident solar X-rays + ?
Asteroid	Sunlit surface		Correlated with solar X-ray flux	Fluorescent X-ray emission from elements in the surface excited by incident solar X-rays
Pluto	Exosphere	200 MW	Charge Exchange?	
Heliosphere	Entire heliosphere	10^{16} W	Emissions vary with solar wind variation	SWCX with heliospheric neutrals

[a]The values quoted are those at the time of observation. X-rays from all bodies are expected to vary with time. For comparison the total X-ray luminosity from the Sun is 10^{20} W. SWCX = solar wind charge exchange = charge exchange of heavy highly ionized solar wind ions with neutrals.

[b]X-rays can also result from accelerated electrons over thunderstorm regions, i.e., related to the atmospheric electric circuit. However, there is no clear detection of such soft X-rays so far.

Problem: We Need More Solar Wind CNO Ions Than a Simple Plane Wave Flow Into a 1.2e5 x 1.2e5 km^2 (10^2 x 10^2 R_{Pluto}^2) Box Provides



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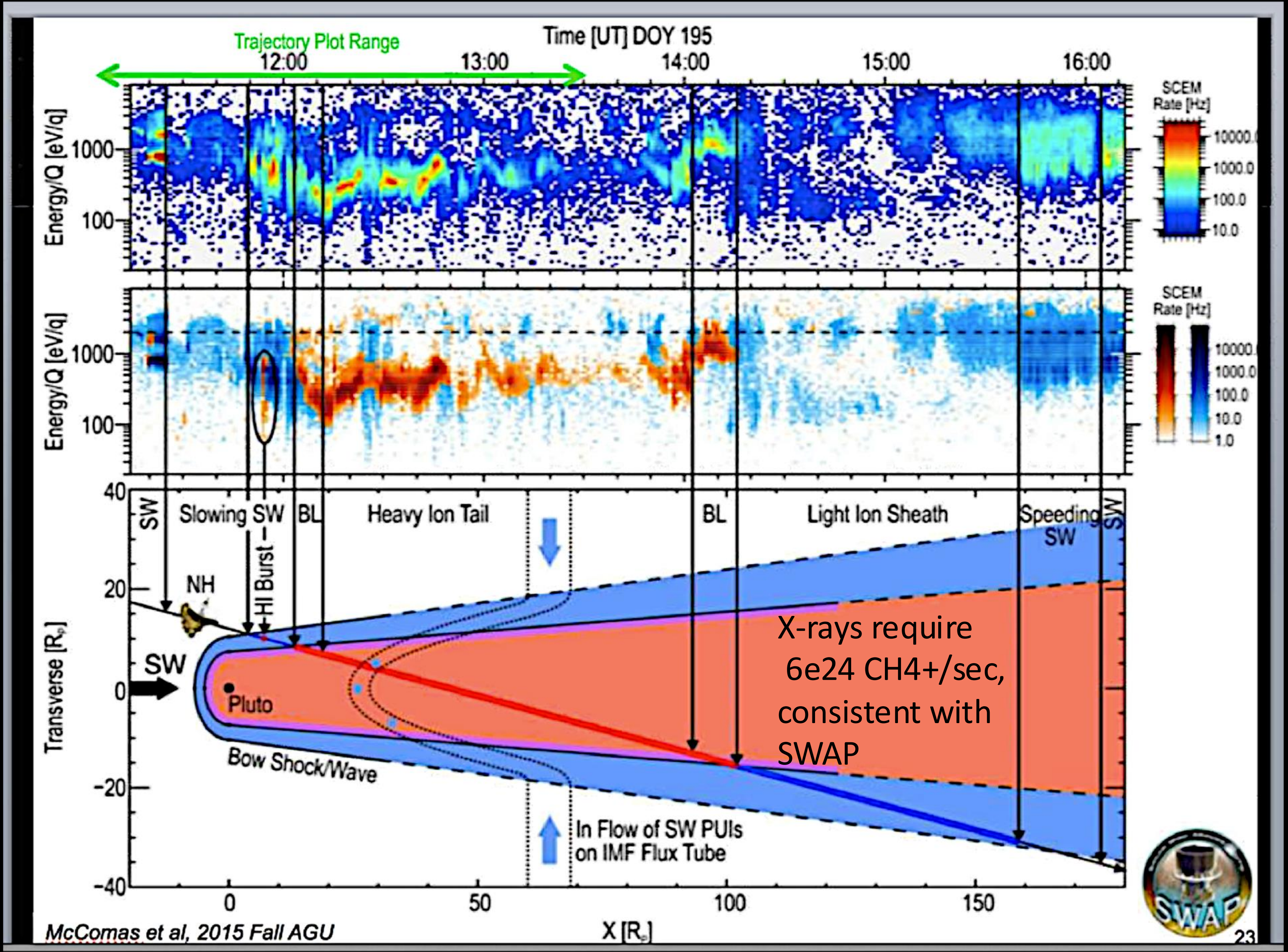
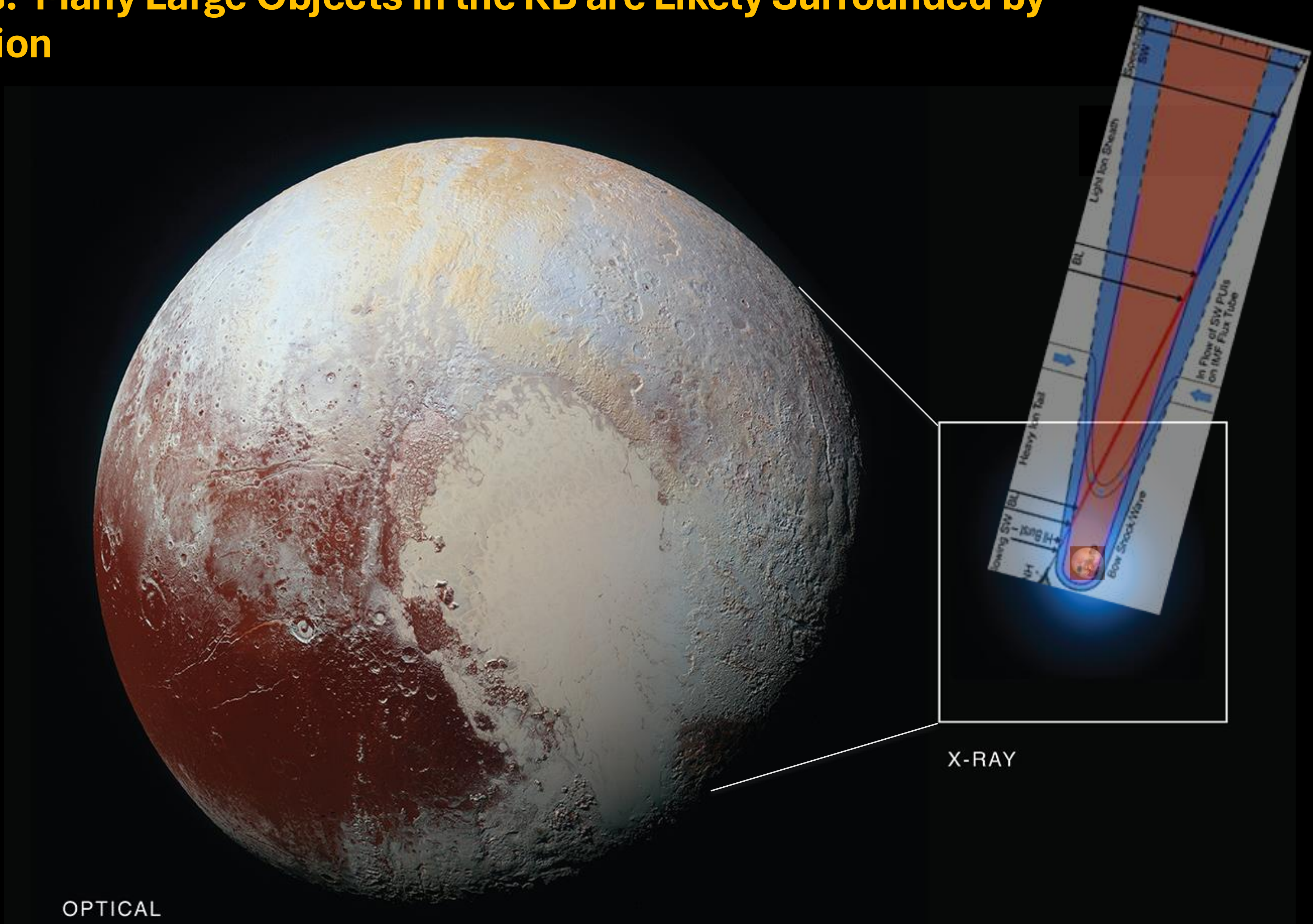
  L_x = 4p*(33.*1.496e11)^2*(3.9e-5*0.425e3*1.609e-19/0.004m^2) = **2.0e+08 J/s ~ 200 MW**
- $N_{xray\_from\_Pluto}$ = 4p*(33.*1.496e11)^2 *(3.9e-5/0.004m^2)= **3.0e+24/sec** = **5% of 6e25 mol/sec**
- $N_{SW\_minor\_ions}$ = (11x11 Chandra pixel box) = (11*0.5''*4.85e-6 rad/''*33AU*1.5e13cm/AU)^2 *(3.8e7 cm/sec)***(0.0115cm^{-3} from SWAP)*1e-3 minor ions/H$^+$ = 7.6e22 sec^{-1}**

=> Need ~40x more SW wind minor ions than are naively in a 120,000 x 120,000 km box!

Chandra Agrees w/ SWAP – Only Much Bigger



Implications: Many Large Objects in the KB are Likely Surrounded by X-ray Emission

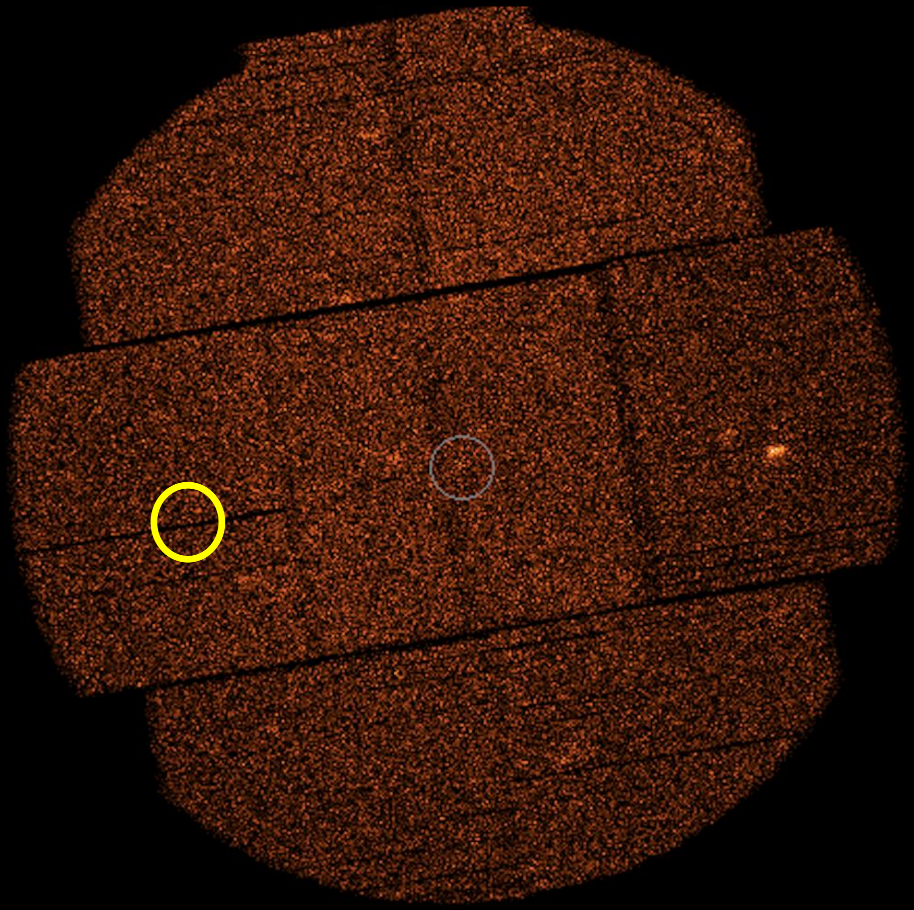


Eris, Haumea, Makemake, Orcus, may all have detectable x-ray emission

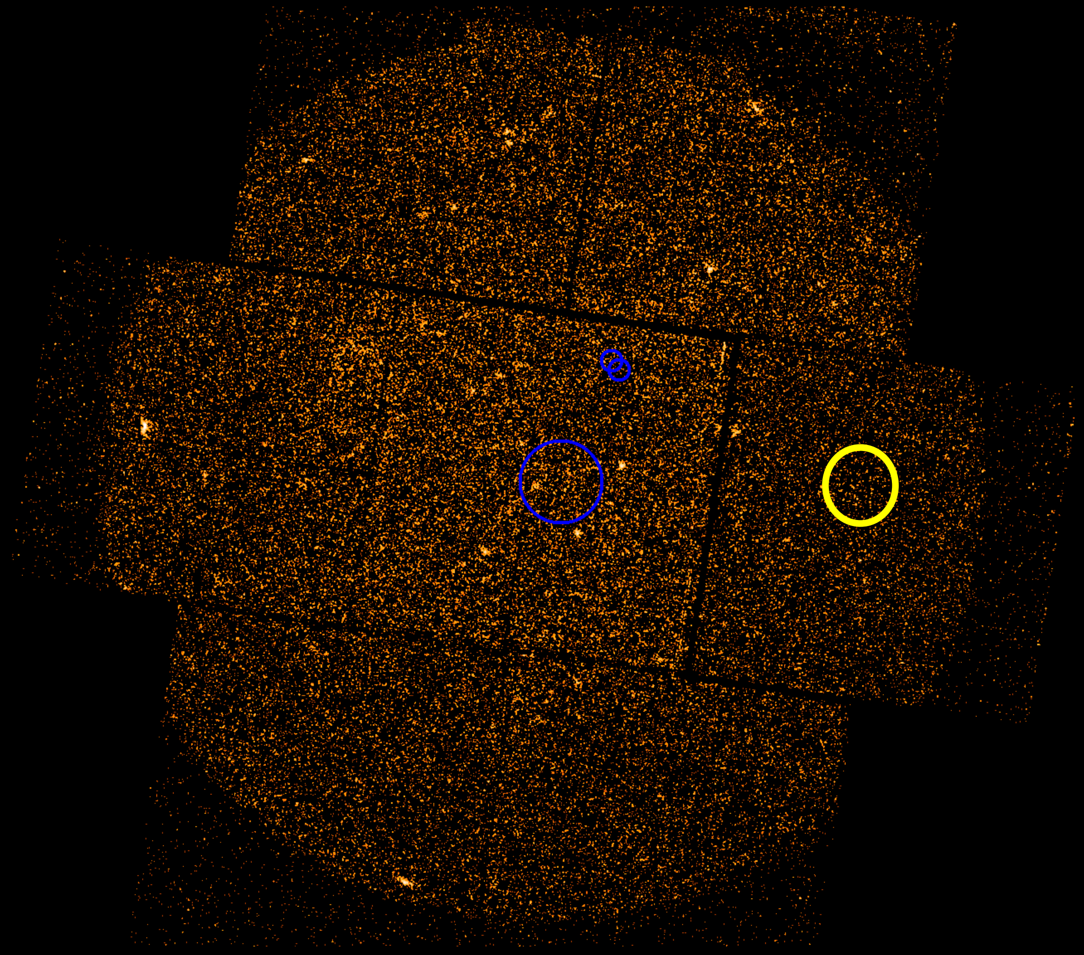
XMM Observations of Pluto: 27 - 28 Mar 2017

- XMM provides an independent detection platform observing 1.5 yrs after Chandra
- Will observe Pluto in a new, quiet part of the x-ray sky
- XMM has 20x the soft x-ray collecting area of Chandra, but 2-10x the instrument noise
- Observations performed simultaneously in 3 different x-ray cameras (EPIC) + RGS x-ray spectrometer using thin optical blocking window
- 200 – 800 nm Optical Monitor (OM) measurements obtained simultaneously
- Energy distribution of the ~50 photons + (non) correlation of x-ray/UVIS lightcurves will help determine CSE vs Scattering source
- Pathfinder for other “gassy” KBO measurements [assuming CXE source, high SNR detection of Pluto]

XMM Observations

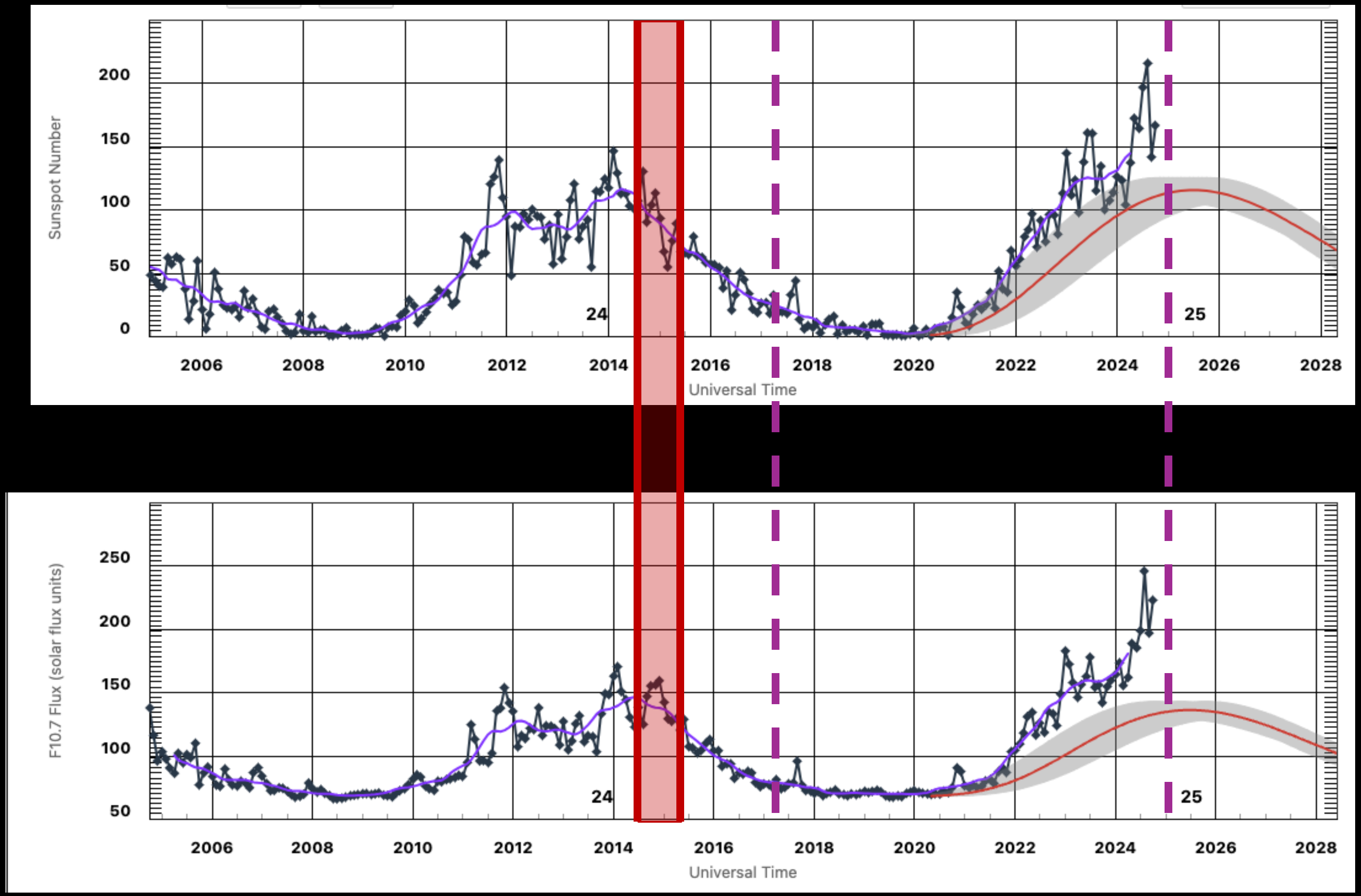


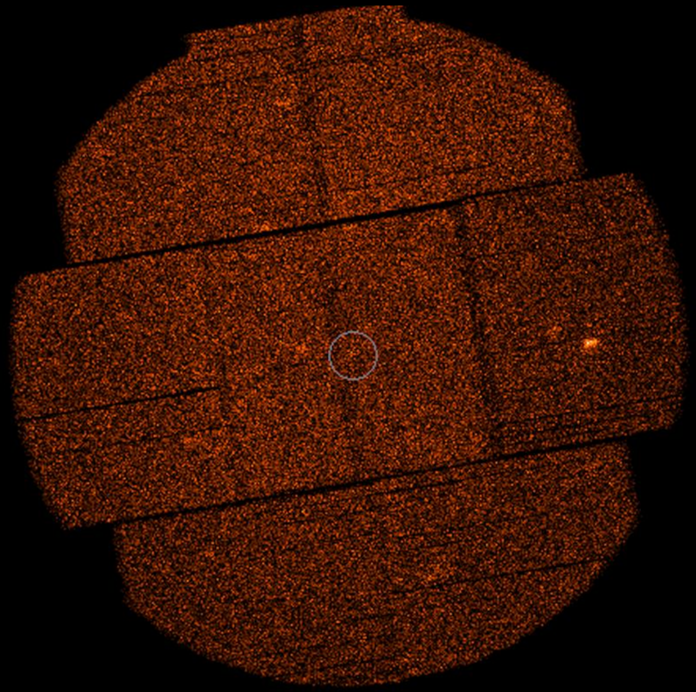
March 2017



April 2017

Why was Pluto so faint with XMM-Newton?





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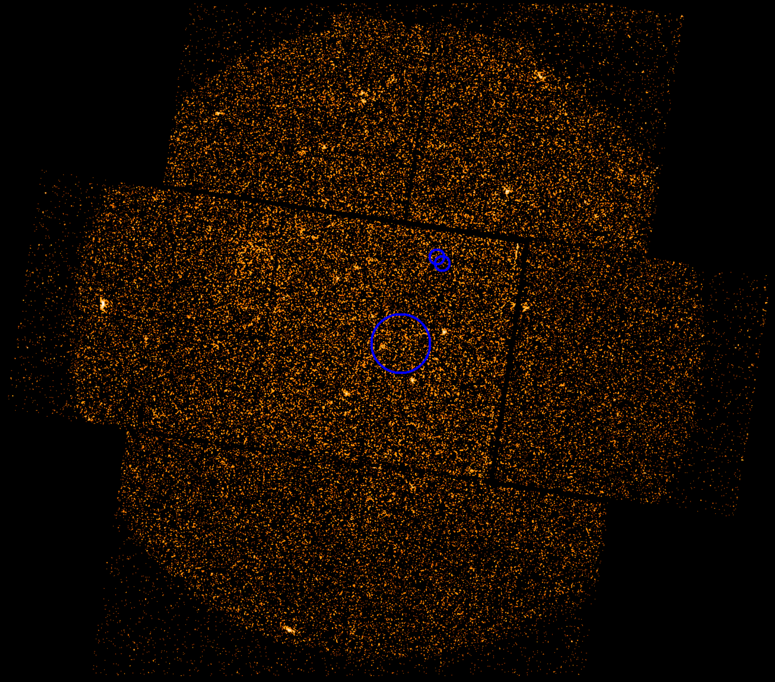

April 2017

Timing matters

Summary : X-rays from Pluto

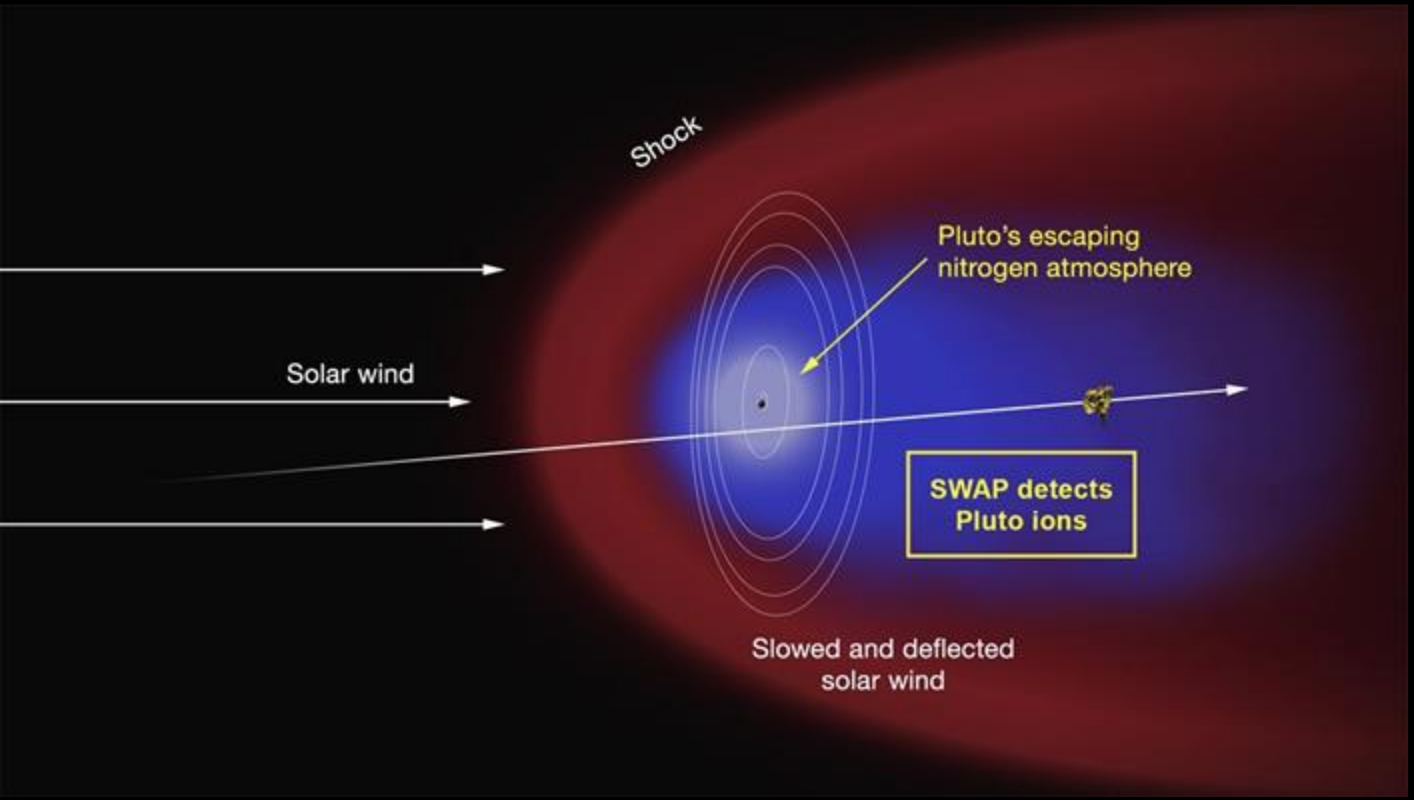

Image credit: Dunn/Wolk/NASA (Dunn+ 2021)

Chandra observed Pluto in July 2015, shortly after the close approach by the New Horizons (NH) spacecraft and made the first ever detection of x-rays from the Kuiper Belt.

Combining New Horizons (NH) and Chandra data provides a more complete description of the interaction between the solar wind (SW) and Pluto's escaping atmosphere.

NH found that Pluto's atmospheric nitrogen escape rate was >10,000x smaller than predicted, yet Chandra still detected 7 low energy X-rays, likely produced by charge exchange between escaping $6x10^{24}$ mol/sec CH_4 from Pluto and SW ions in a long trailing tail that was also detected by the NH SWAP instrument.

Thank You