The Chandra and XMM-Newton views of the Einstein Cross

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Chandra data

Thirty-five public observations of the gravitationally lensed radio quiet quasar Q2237+030 ($z_{QSO}\sim 1.695$, $z_{lens}\sim 0.0395$, Hucra et al., 1985, Falco et al., 1996) are available in the Chandra Data Archive, spanning over years (**2000 - 2017**) with exposures from few to over 30 ks. Given the unprecented angular resolution that Chandra offers (on-axis PSF FWHM = 0.5''), it is possibile to **distinguish** the **four images** (**Fig. 1**) and analyse their spectra separately through all the epochs, hence a **time and spatially resolved spectral analysis**.

Previous works mainly focused on the investigation of its microlensing variability (Dai et al., 2003, Chen et al., 2011, Guerrs et al. 2017); what I intend to investigate is the variation of the quasar's spectral features.

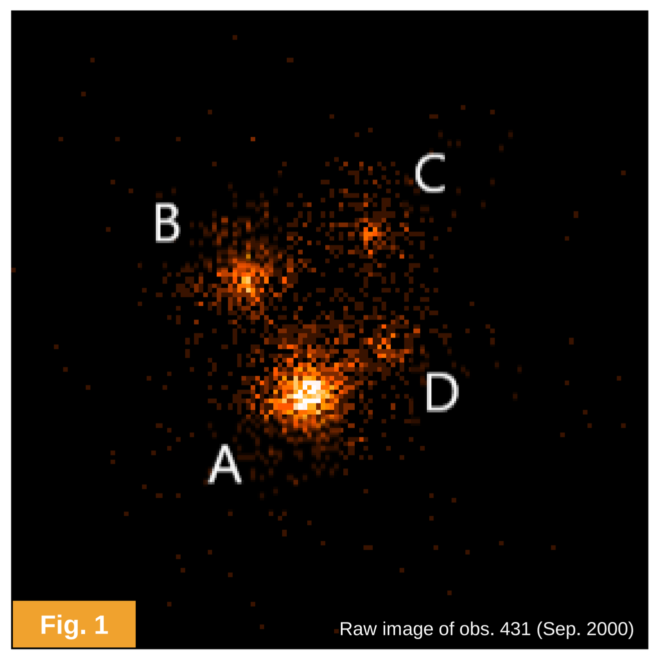

Fig. 1 Raw image of obs. 431 (Sep. 2000)

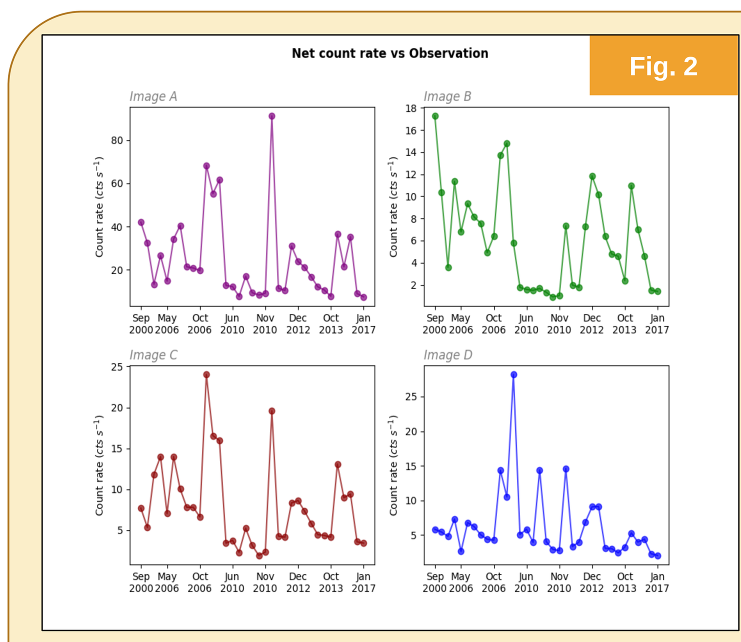

Fig. 2

As can be seen from the light curves (**Fig. 2**), the source shows **significant variability**. Since the source is lensed, the variability pattern changes among the images due to **microlensing effects** (Wambsganss 2006; Kochanek et al. 2007) and the lens **time delay** (Schmidt et al. 1998). Image A is always the brightest one, showing a mean relative weight with respect to the quasar's total count rate of 0.54, while the other three images show a very similar mean relative weight:

Single images mean contribute to the total count rate:

- **Image A**: 54%
- **Image B**: 13%
- **Image C**: 18%
- **Image D**: 15%

$\Delta t_{AB}\approx 2\text{hr}$ $\Delta t_{AC}\approx 16\text{hr}$ $\Delta t_{AD}\approx 5\text{hr}$

From a **preliminary analysis** (simple power law and Galactic absorption model, 0.4 – 7.0 keV observed energy range, > 1 cnt/bin, C stat - Cash, 1979), the **Photon index varies both** (**Fig. 3**)

→ **among** the four **images** at **fixed epoch**

→ through the **different epochs** for the **same image**

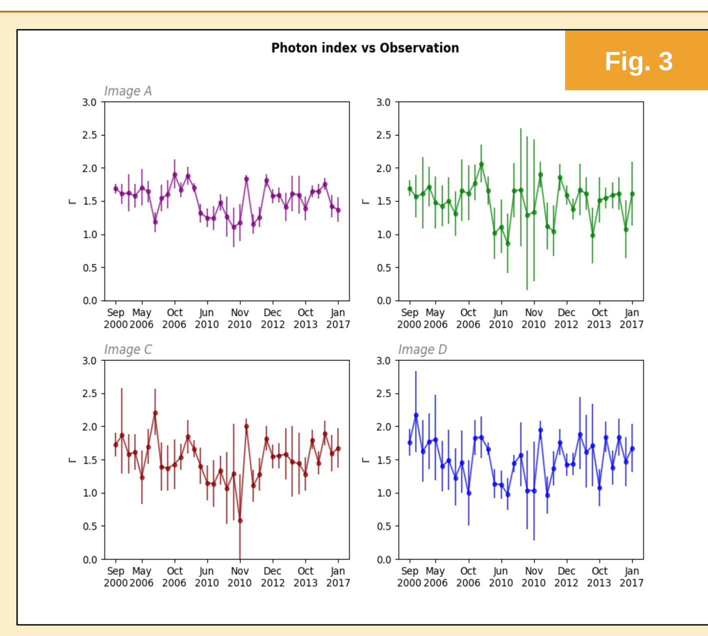

Fig. 3

→ Thirteen spectra out of 140 have more than 500 counts in the 4.0 – 8.0 keV obs. energy band

- 20 cts/bin binning and χ^2 statistics

→ **Obs. ID 12831, image A** → brightest image of all sample

- **Hint** of emission and absorption **lines** from power law residuals (**Fig. 4**)
- Only **emission line detected** ($\Delta\chi^2/\Delta\nu = 9.2$) – $E_{obs}\sim 2.4$ keV ($E_{rest}\sim 6.4$ keV - **Fig. 5**)
- **Hint** of **absorption features** at $E_{obs}\sim 4$ keV ($E_{rest}\sim 11$ keV - **Fig. 5**), similar to what found in XMM 2002 (see right panel).

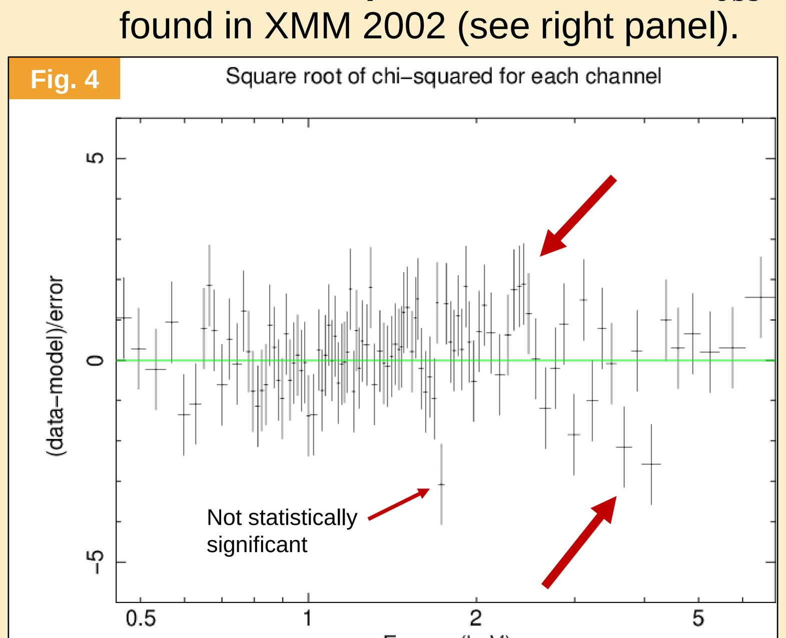

Fig. 4

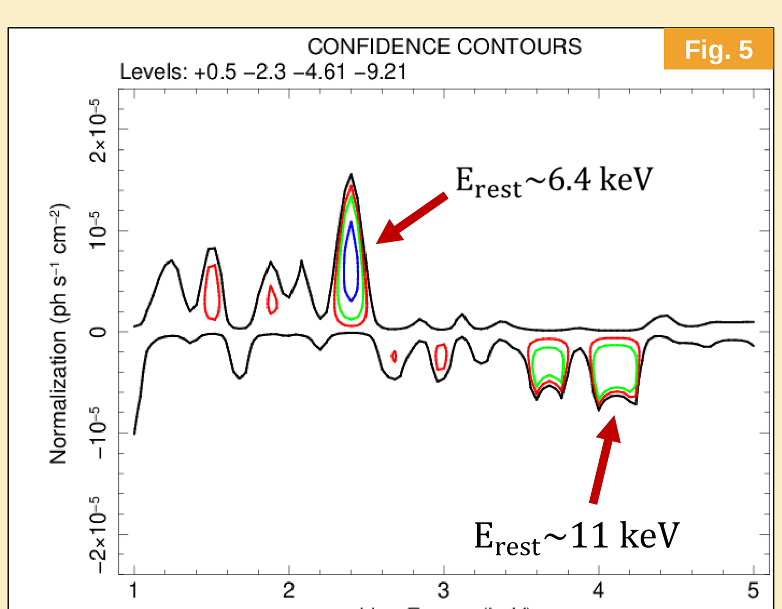

Fig. 5

Obs. ID 12831 (May 2011)

XMM-Newton data

XMM-Newton has observed the Einstein Cross three times so far:

1. May **2002**, exp. 42.87 ks (Fedorova et al., 2008)
2. November **2016**, exp. 24.90 ks
3. May **2018**, exp. 141.69 ks

The first two observations (2002, 2016) are highly affected by soft-p⁺ flares, which made the latter useless in terms of spectral analysis. Hence, I **focus on** analysing the **data** from **2002** and **2018**.

While with Chandra we can resolve the four images and study the variation among them, with XMM-Newton we can carry out a more solid spectral analysis thanks to the **better statistics** it can provide. Not resolving the images means though that their signal is being averaged-out. Based on the mean relative weights that I was able to evaluate from the Chandra observations, **image A** is the **dominant** contributor in the Einstein Cross' XMM **spectra**.

2002 data

Using a simple Galactic absorption and power law model for the 2002 data leads to the residuals in **Fig. 6**. Here we can clearly see some **complex structures** at lower energies and **hints** of **narrow** emission/absorption **lines**:

- **emission** line at $\mathbf{E_{rest}\sim 5.8\ keV}$, might be a **microlensed FeKα** as found for other lensed quasars in Chartas et al. (2017) - $\Delta\chi^2/\Delta\nu = 10.5$
- one narrow **absorption** line at $\mathbf{E_{rest}\sim 7.4\ keV}$ ($\Delta\chi^2/\Delta\nu = 11.7$)
- one narrow **absorption** line $\mathbf{E_{rest}\sim 11.8\ keV}$ ($\Delta\chi^2/\Delta\nu = 13.4$)

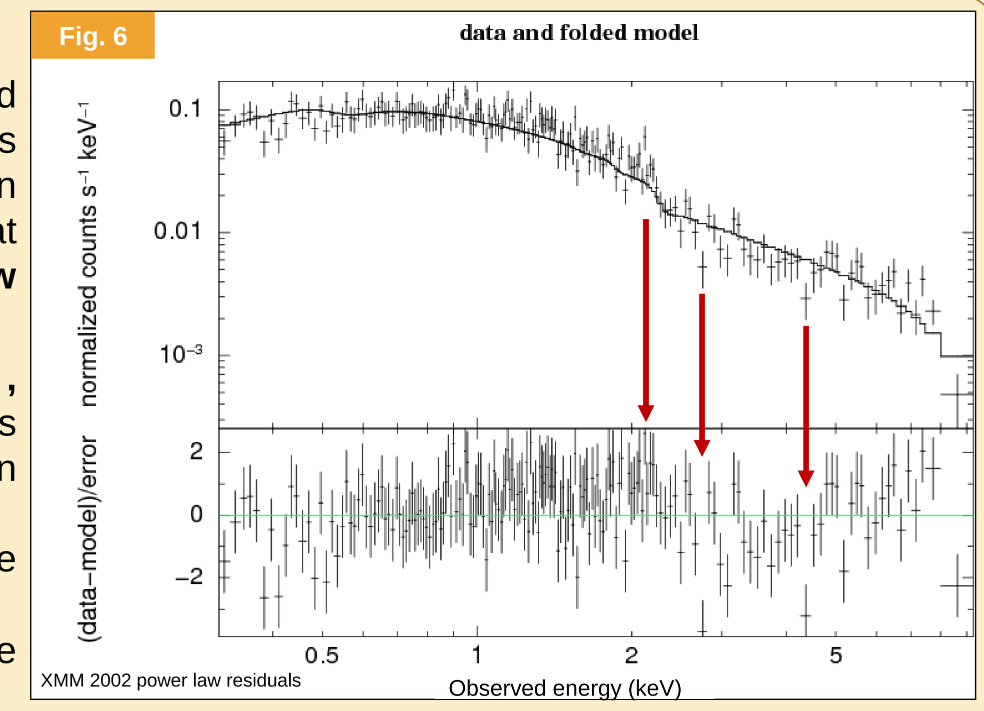

Fig. 6

The absorption at 7.4 keV could be a **blueshifted Fe XXVI** (H-like) component which leads to an **outflow** velocity of $\mathbf{v\approx 0.06\ c}$. **Fig. 7 – 9** show those lines' confidence contours.

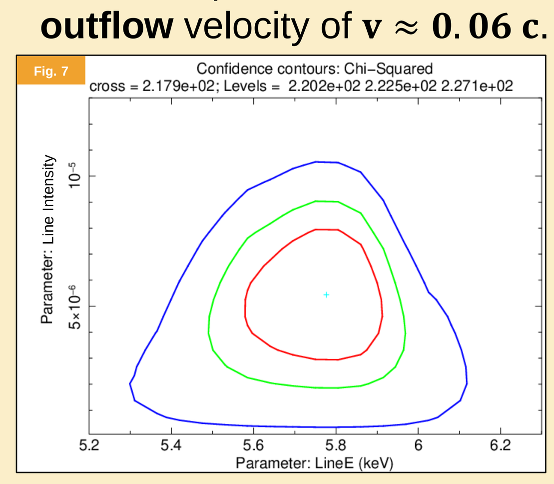

Fig. 7

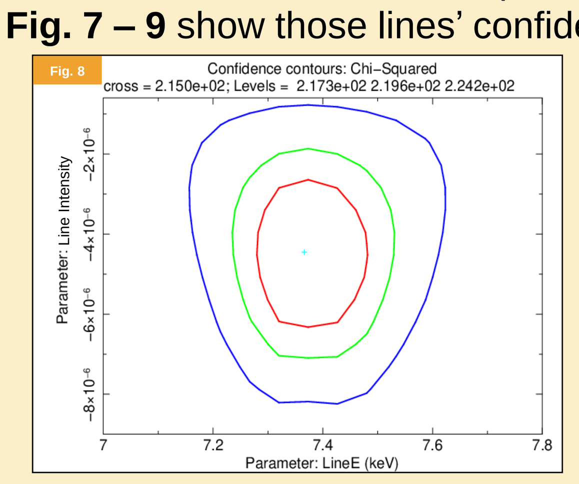

Fig. 8

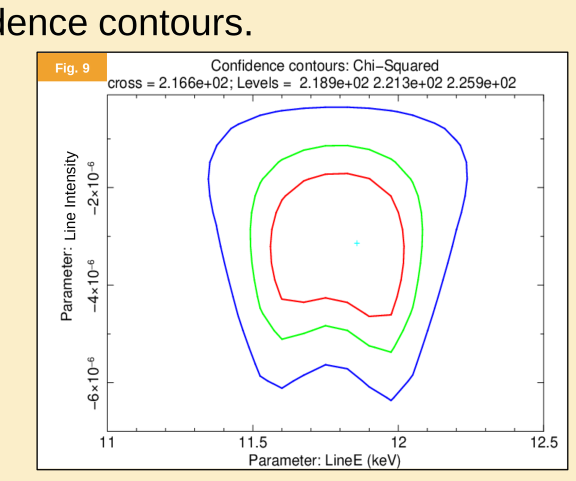

Fig. 9

To assess the actual significance of these structures and to provide a better characterization of the continuum beneath 2 keV (observed frame), a **more complex modelling** is **required**, considering absorption and/or reflection components, along with Monte Carlo simulations (Protassov et al., 2002). According to my preliminary analysis so far, the absorption line at $E_{rest}\sim 7.4$ keV seems to be actually required by the data, reguardless of the specific modelling.

2018 data

In **Fig. 10** the residuals of a simple Galactic absorption and power law model are displayed. Here we find again very structured residuals below 3 keV (obs. frame), but there seems to be no sign of absorption components as significant as the ones present in the 2002 data at high energies. Furthermore, we also find a hint of emission line at $\mathbf{E_{obs}\sim 2.5\ keV}$ ($\mathbf{E_{rest}\sim 6.8\ keV}$); adding a narrow line component to the model leads to contours in **Fig. 11**. Once again, a more complex modelling is required to better understand the underlying physical phenomena.

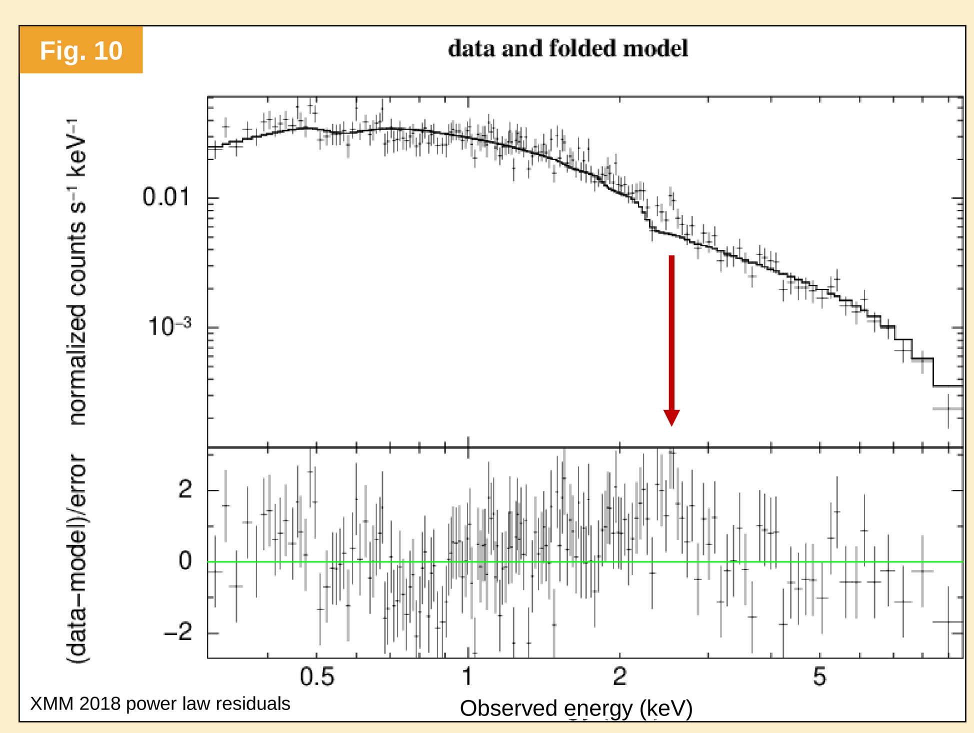

Fig. 10

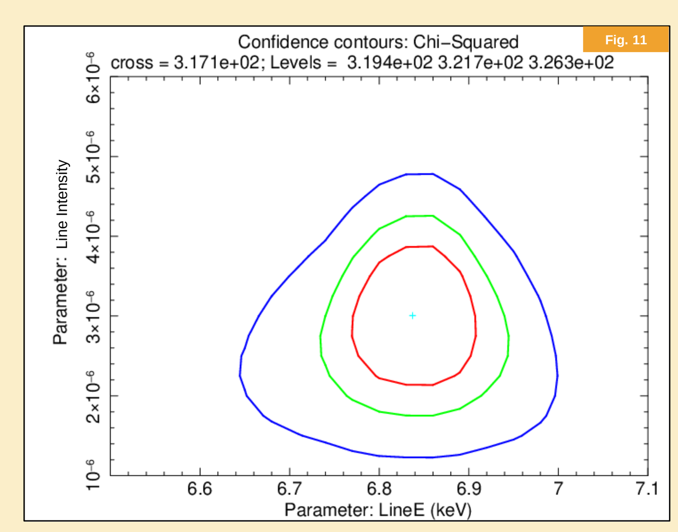

Fig. 11

Summary and results

I analysed thirty-five Chandra and two XMM-Newton observations of the Einstein Cross. Spanning over eighteen years and given that Chandra's PSF allows to resolve the quasar in its four images, I managed to carry out a time and spatially resolved spectral analysis.

Chandra:

- Spectral variability detected between images and through years
- Obs. 12831 shows an emission line at $E_{rest}\sim 6.4$ keV and some absorptions similar to what found in XMM's observation from 2002

XMM-Newton 2002:

- Complex features in the soft band
- Two significant absorption narrow lines ($E_{rest}\sim 7.4$ keV and $E_{rest}\sim 11.8$ keV) - possible outflow at $v\approx 0.06$ c
- One narrow emission line whose energy, if confirmed by more accurate modelling, could be compatible to that detected by Dai et al. (2003)

XMM-Newton 2018:

- Complex features in the soft band
- One emission narrow line at $E_{rest}\sim 6.8$ keV

Future work

- **Better modelling** of the **Chandra data**, for instance, adding an absorber at the lens's redshift ($z_{lens}\sim 0.0395$)
- **Extend** the **analysis** of the Chandra spectra with **more than 500 counts**
- **Better characterization** of the **XMM** spectral **continuum**
- **More thorough analysis** of the **emission** and **absorption features**, characterization of a possible outflow component

References: •Chen B., Dai X., Kochanek C. S. et al 2011 ApJL 740 L34; •Guerras, E., Dai, X., Steele, S., et al. 2017, ApJ, 836, 206; •Chartas, G., Krawczynski, H., Zalesky, L., et al. 2017, ApJ, 837, 26; •Protassov, R., van Dyk, D. A., Connors, A., Kashyap, V. L., & Siemiginowska, A. 2002, ApJ, 571, 545; •Kochanek, C. S., Dai, X., Morgan, C., et al. 2007, Statistical Challenges in Modern Astronomy IV, 371, 43; •Wambsganss, J. 2006, Saas-Fee Advanced Course 33: Gravitational Lensing: Strong, Weak and Micro, 453; •Dai X., Agol E., Bautz M.W., and Garmire G.P. 2003, in ApJ, 589, 100; •Huchra J., Gorenstein M., Kent S. et al. 1985, in AJ, 90, 691; •Schmidt R., Webster R.L. & Lewis F.G. 1998, in MNRAS, 295, 488; •Falco, E. E., Leha´r, J., Perley, R. A.,Wambsganss, J., & Gorenstein, M. V.1996, AJ, 112, 897; •Fedorova, E. V., Zhdanov, V. I., Vignali, C., & Palumbo, G. G. C. 2008, A&A, 490, 989