Quasar Cosmology

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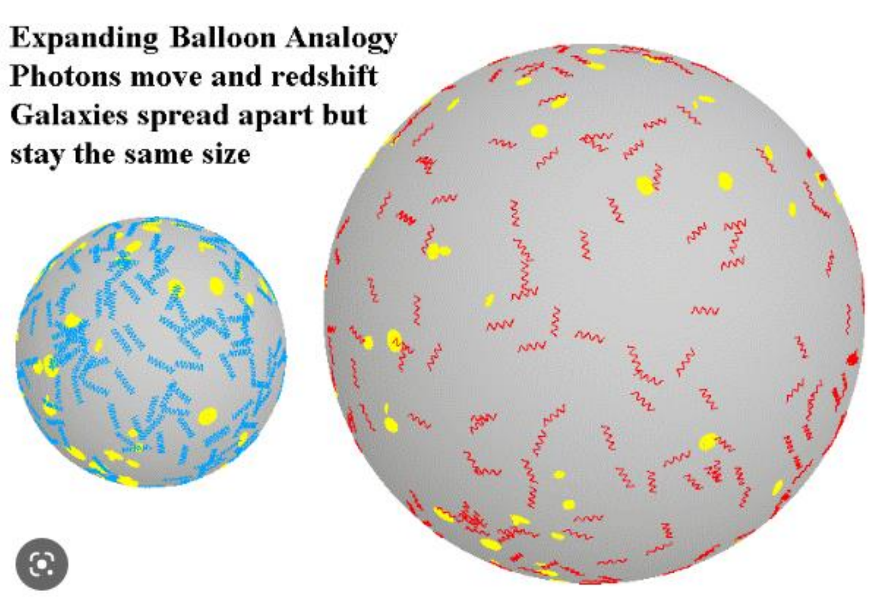
Recap of Cosmology:

- Cosmology is the study of the universe.
- We can think of the analogy of a balloon, when we start inflating the balloon, points on the surface of the balloon are close, but as the balloon is expanded, the points move further away.
- As they move away they redshift as you would expect.
- By using standard candles: ie objects that emit the same frequency of light, we can characterize the redshift, as we know the original frequency of the light.

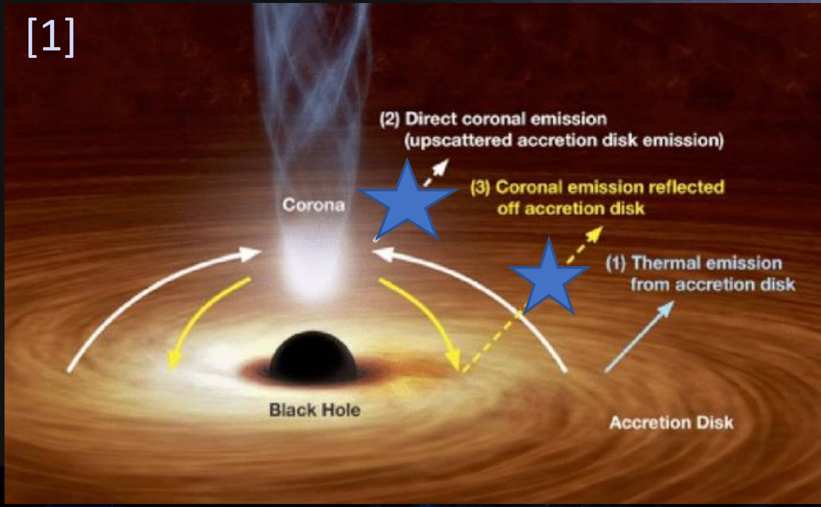


https://astro.ucla.edu/~wright/balloon0.html

What is Quasar Cosmology?

- Why do we need Quasar Cosmology: The hubble crisis in cosmology!
- However, because of the low-red shift constraint of supernovae, we need an alternative that covers a larger red-shift range. Quasars cover large redshift (0-7z)
- Quasars work as so called "standard candles" because the relationship of their UV and X-ray flux from reflection and thermal emission is constant

$$\log L_{x-ray} = b + m_{avg} \times \log L_{UV}$$

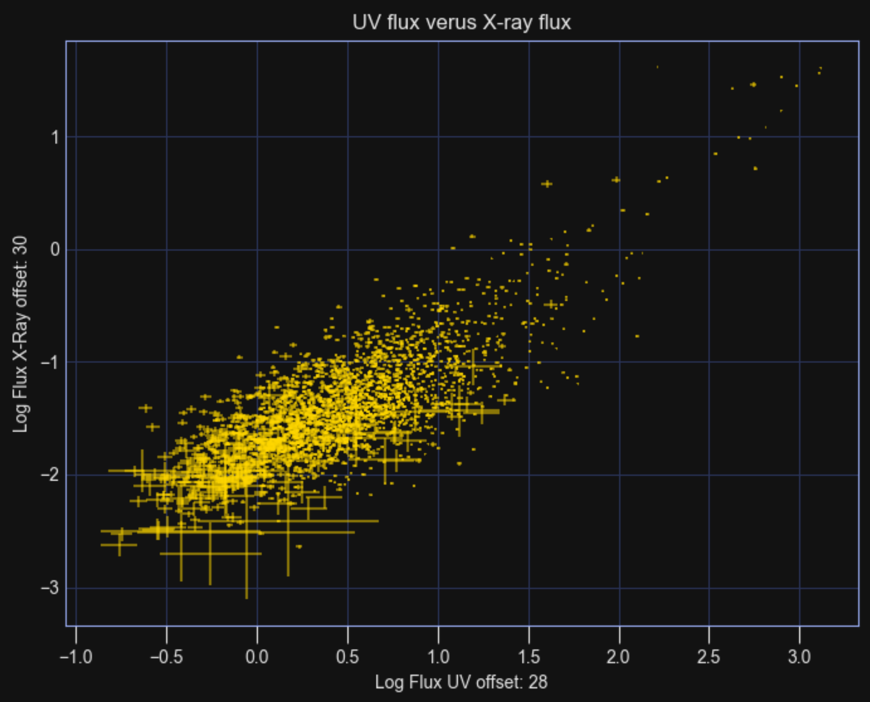


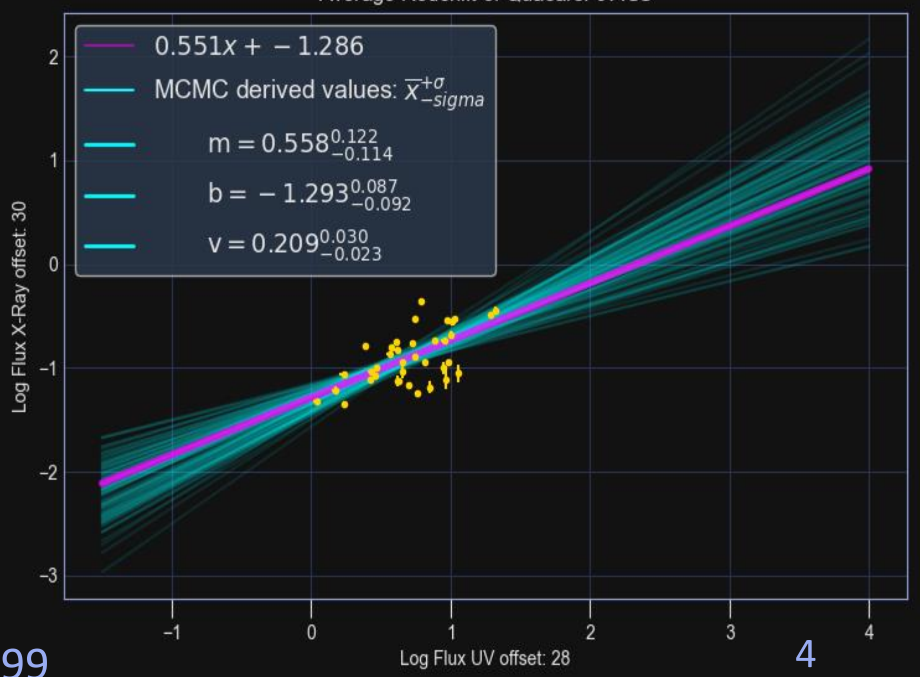
[1] Krawczynski, Henric. (2018). Difficulties of quantitative tests of the Kerr-hypothesis with X-ray observations of mass accreting black holes. General Relativity and Gravitation. 50. 10.1007/s10714-018-2419-8.
[2] A. C. Fabian. The Innermost Extremes of Black Hole Accretion. DOI: 10.1002/asna.201612316
[3] https://www.wallpaperflare.com/supernova-black-background-digital-art-blue-minimalism-wallpaper-uakmj

What has been done already?

Work from Lusso et al. 2020:

- In order to the do our cosmology latter down the line, we need to obtain an average fit values for our fluxes.
- Can't just use the average fit as there is just more quasars near low redshift which will affect the fit drastically (not good for cosmology)
- How Lusso et al. got around this by:
  - By dividing quasars into red-shift bins, then you can find a slope for each red-shift range.
  - Using Markov Chain Monte Carlo (MCMC) simulations for each red-shift bin, you can find the error from the variance of the MCMC.





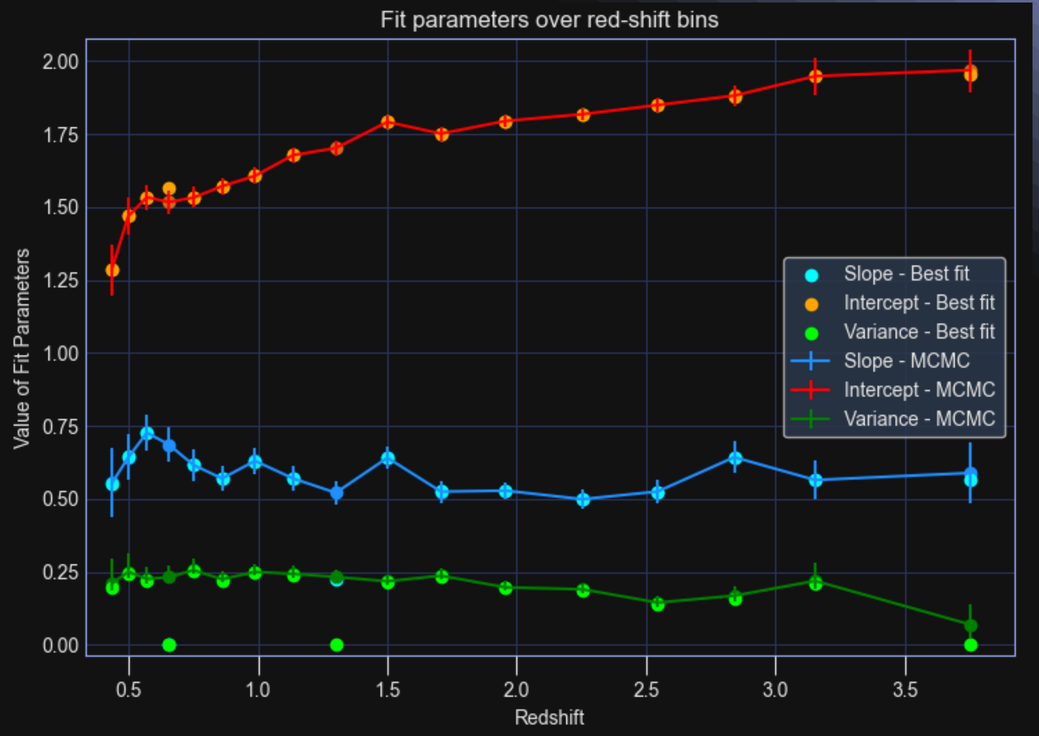
Quasars as standard candles - III. Validation of a new sample for cosmological studies E. Lusso, et al. A & A 642 A150(2020) DOI: 10.1051/0004-6361/202038899

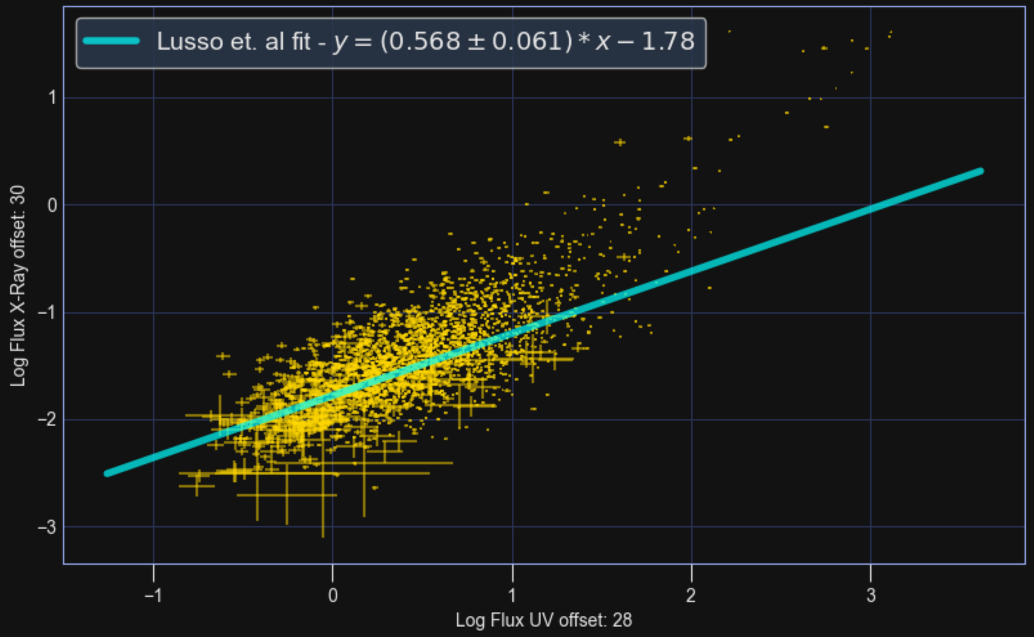
Lusso Et Al. Results:

- We derived this equation to replicate Lusso et al. fits. It is a chi^2 with a term for the intrinsic variance.

$$\ln \ell = -\sum \ln\left(\sigma_{y,i}^2 + V^2\right) - \sum \frac{y_i - f(x)}{\left(\sigma_{y,i}^2 + V^2\right)}$$

- This replicated Lusso et al's fit parameters as seen in the top figure.
- Then using the assuming there is not any variation in slope through red-shift a weighted average is taken.



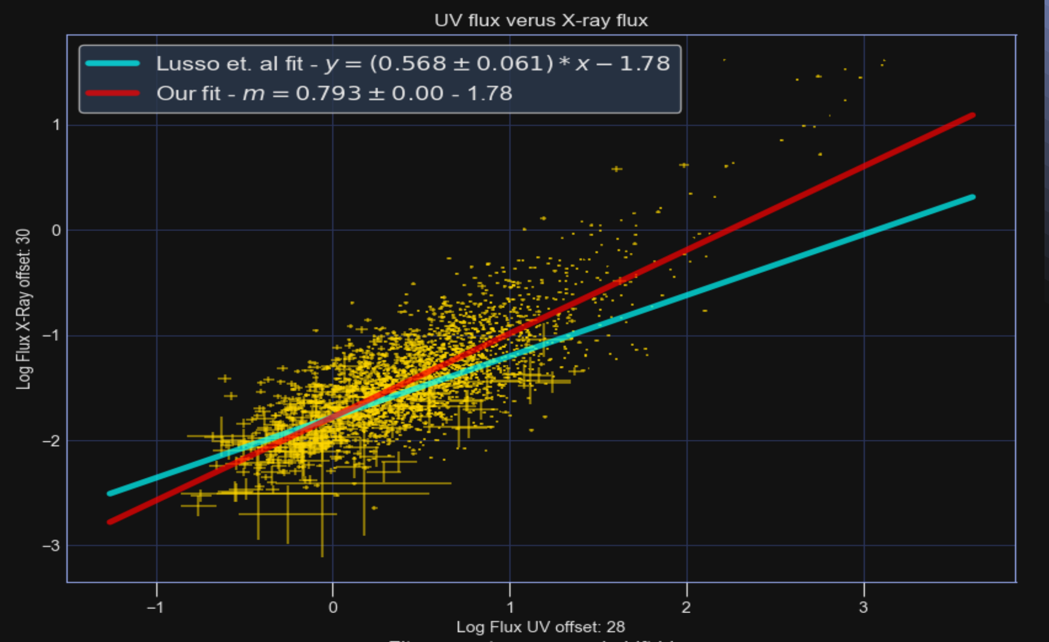


Improvements:

- Although pretty good at low UV and X-ray fluxes, the fit does not accurately convey what it happening at high UV and X-ray.
- To remedy this, we used a more sophisticated fitting function which accounts for x and y errors from Hogg et. al as seen below:

$$\ln \ell = \kappa - \sum \ln \frac{(\Sigma^2 + V^2)}{2} - \sum \frac{\Delta_i^2}{2 \times (\Sigma^2 + V^2)}$$

- The new fits, accurately describe high X-ray and UV flux!



[2] = Hogg, David & Bovy, Jo & Lang, Dustin. (2010). Data analysis recipes: Fitting a model to data. ArXiv e-prints.

Pragmatics of cosmology:

- For now we will assume there is a flat universe (which makes calculations easier)
- With a flat universe with **ΛCDM** there are two real parameters: The Hubble constant (expansion of the universe) and the amount of matter in the universe.
- Then we find the luminosity distance which is defined as the distance that satisfies the luminosity of the object equaling the flux of the object.

$$F = \frac{L}{4\pi D_L^2(z, H_0, \Omega_M)} \qquad D_L(z, H_0, \Omega_M) = \int_0^z \frac{dz}{H_0\sqrt{\Omega_M\,(1+z)^3 + (1+\Omega_M)}}$$

Gong-Bo Zhao et al. https://doi.org/10.1016/j.physletb.2007.02.070

Translating the Pragmatics with the fits:

- Since we have supernovae (well-studied) and quasars at the same red-shifts, we can normalize quasar cosmology to supernovae cosmology

- Lusso et. Al 2020 normalizes by optimizing the measured y-axis (x-ray flux) with the cosmological model predictions where the cosmology parameters from Scolnic. et al 2018 (69.192 ± 2.815 km s^-1 Mpc^-1, 0.299 ± 0.024)

$$\log\left(F_{x-ray}\right) = b_{free} + m_{avg} \times \log\left(F_{UV}\right) + 2\left(m_{avg} - 1\right) \times \left(\log\left(D_L(z, H_0, \Omega_M)\right)\right)$$

- Once we obtain b, we obtain the "offset" for our high red-shift supernovae with respect to the low-redshift. From there we can optimize for the cosmological parameters (pink) instead of the offset (yellow)

The Complete Light-curve Sample of Spectroscopically Confirmed Type Ia Supernovae from Pan-STARRS1 and Cosmological Constraints from The Combined Pantheon Sample - D. M. Scolnic et al. ApJ 859 101 DOI: 10.3847/1538-4357/aab9bb

Hubble Diagram:

- Using the cosmological constants from the high red-shift quasars, we use the luminosity distance we found earlier.

$$D_L(z, H_0, \Omega_M) = \int_0^z \frac{dz}{H_0\sqrt{\Omega_M\,(1+z)^3 + (1+\Omega_M)}}$$

- We then convert the luminosity distance to the distance modulus (relationship between the apparently and actual magnitude of an object)

$$D_M = 5\,(\log D_L - \log 10pc)$$

- Now plotting the distance modulus as a function of red-shift, we find this Hubble plot for our high red-shift quasars.

Conclusions From The Hubble Diagram:

- From this we can determine that the values we get are fit dependent, which means a better fitting algorithm means a better value.
- However, there are large errors but do cover with realistic values

Quasar: $H_0 = 0.550^{0.393}_{0.085}$, $\Omega_M = 0.273^{0.114}_{0.254}$ Supernovae: $H_0 = 0.692 \pm 0.03$, $\Omega_M = 0.299 \pm 0.024$