X-Rays from the Dawn of Time

A Science Talk for the Benefit of Learning About Studying Faint Point Sources with Chandra

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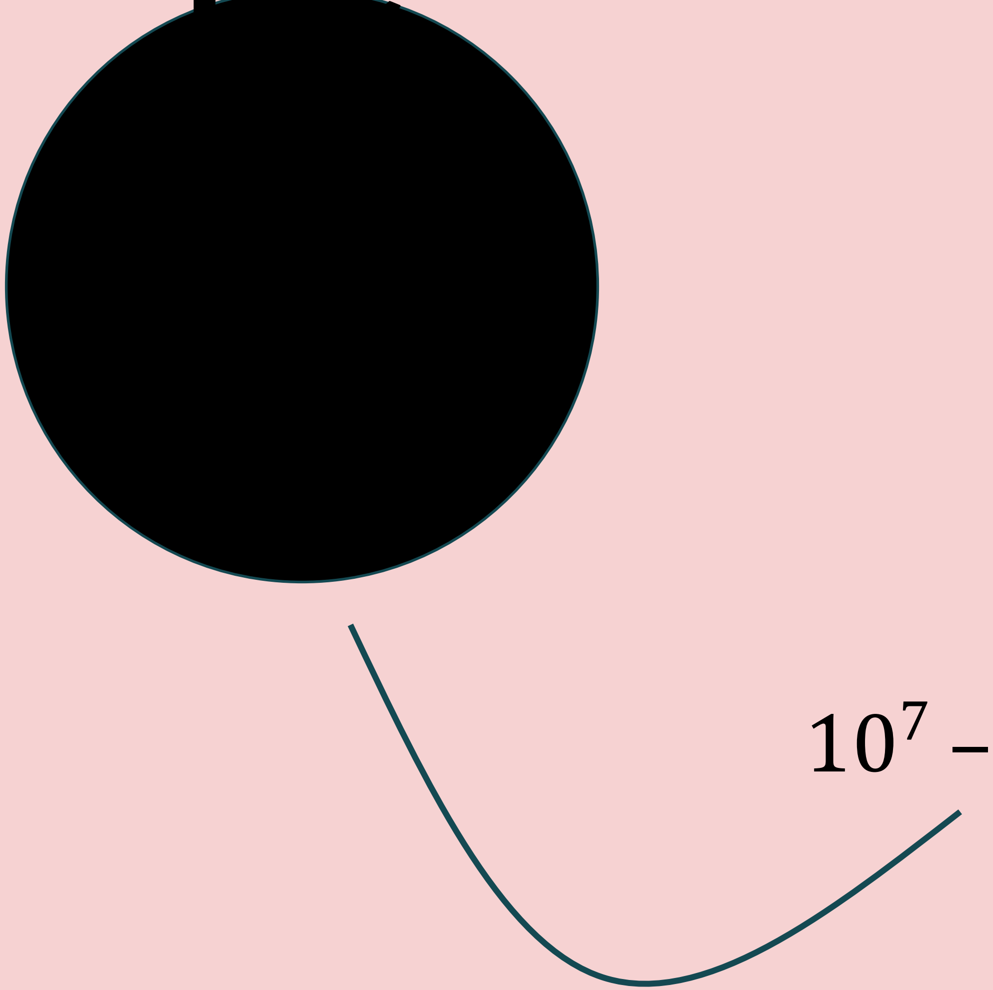
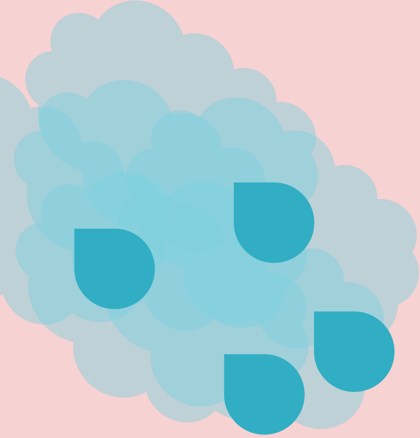
Chandra X-Ray Center

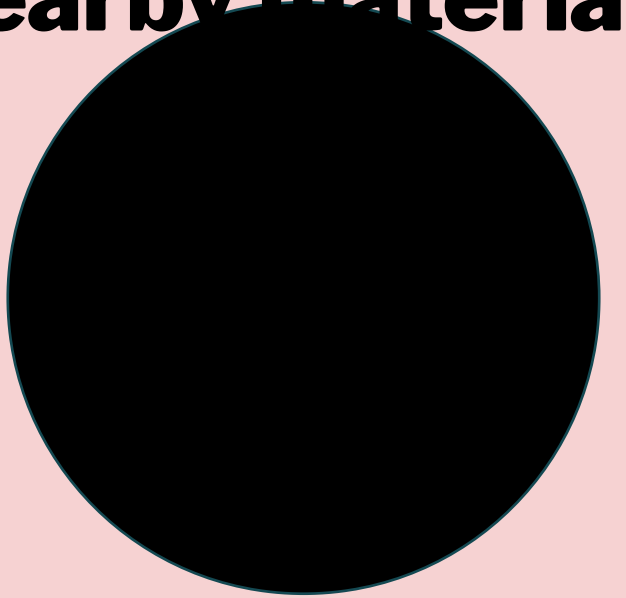
Consider the humble Supermassive Black Hole



$10^7 – 10^9\ M_{Sun}$

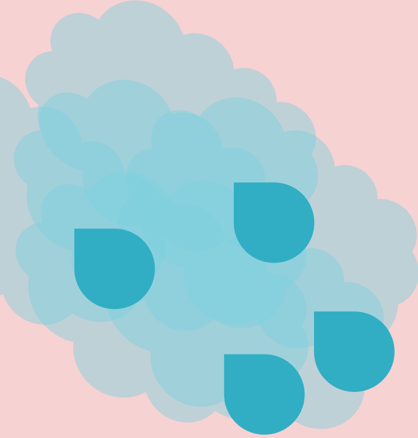
It is known for eating nearby material

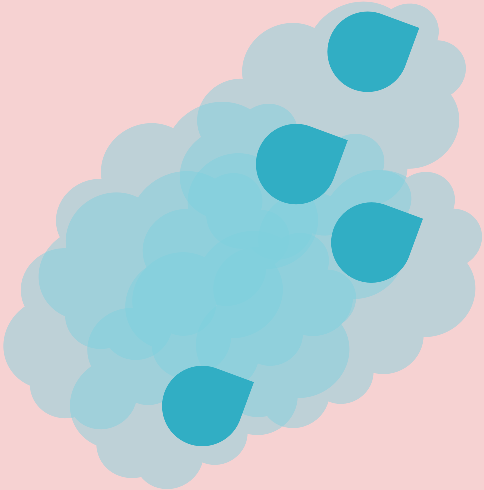




The more there is to eat

The more it eats





All of the infalling material builds up an accretion

Angular momentum must be conserved

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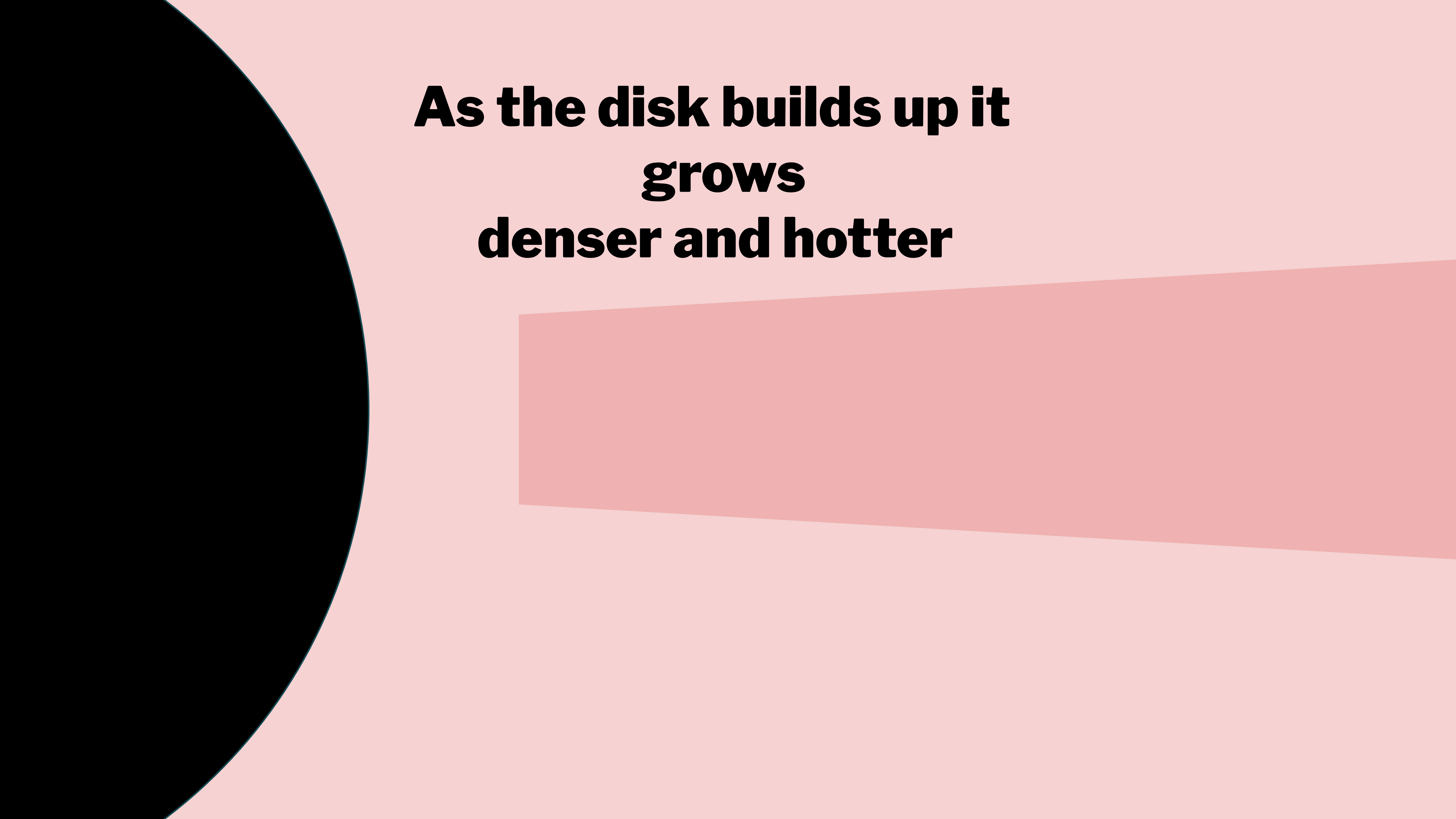
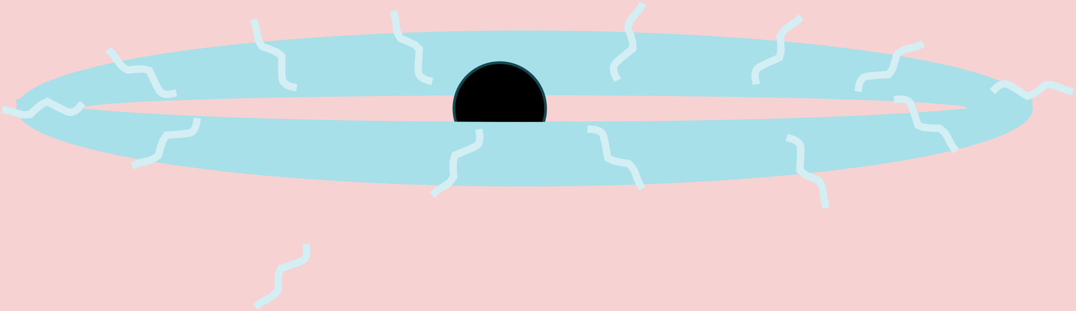
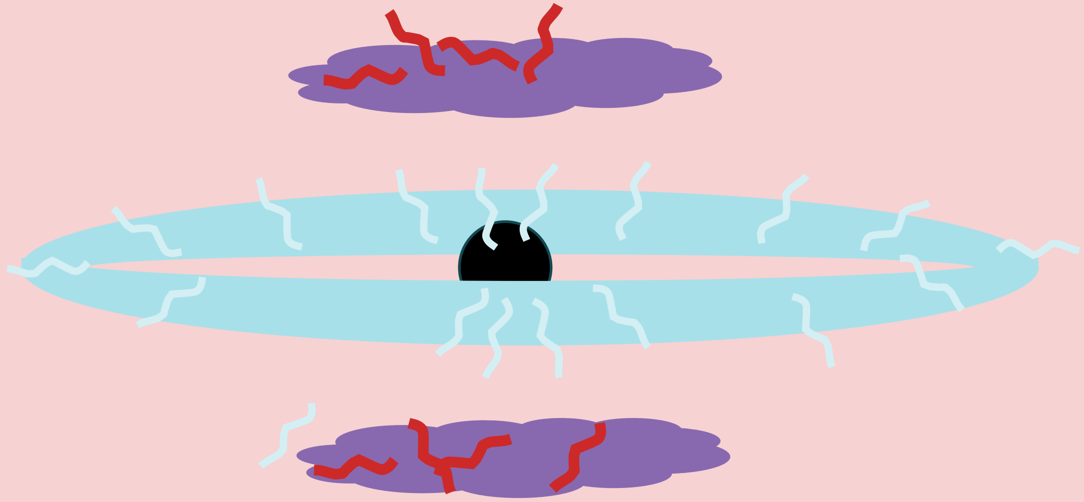
Angular momentum must be conserved


As the disk builds up it grows
denser and hotter

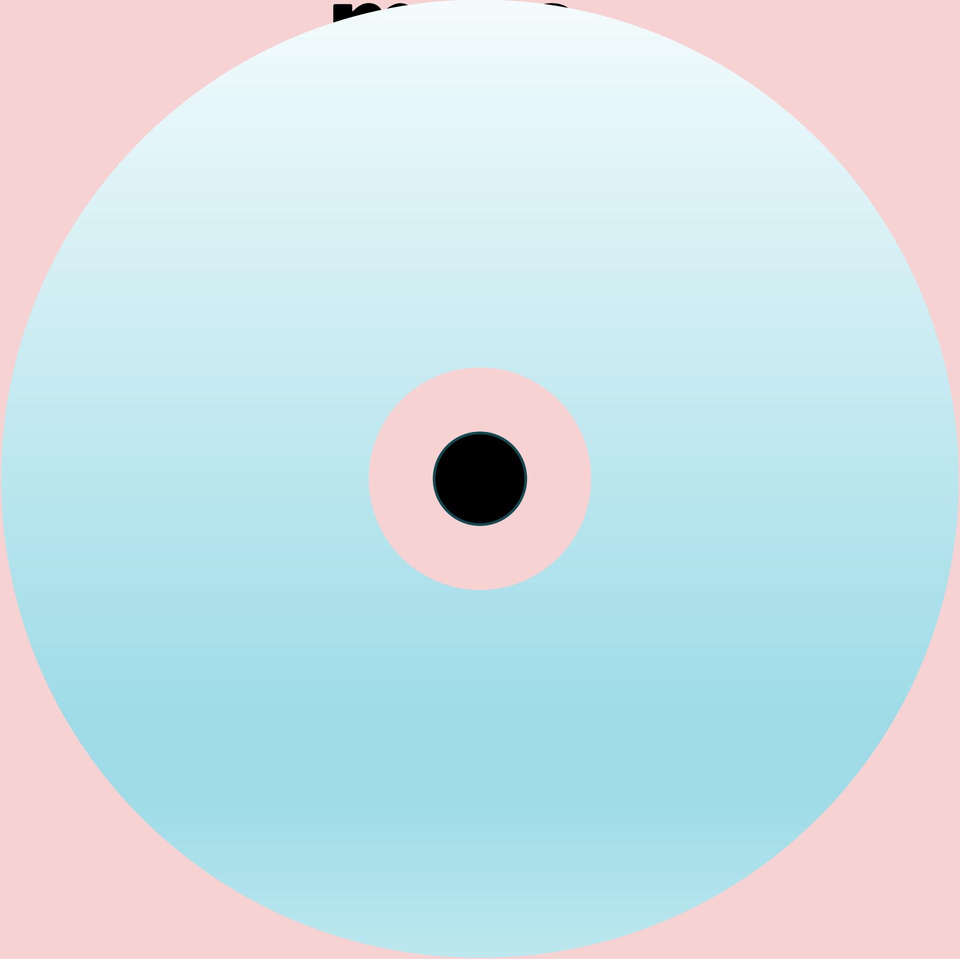
Turning a black hole into a luminous AGN



Disk emission is scattered to X-Ray energies in a corona



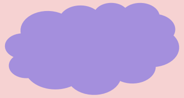
The spin rate of this disk gives us the black hole

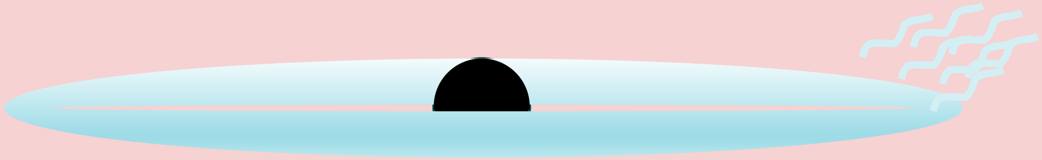


$$\text{Mass} \propto \frac{\text{Orbital Distance}^3}{\text{Period}^2}$$

I'm glossing over a lot of physics here that isn't important to this talk

If the disk gets too bright it will start preventing further infall

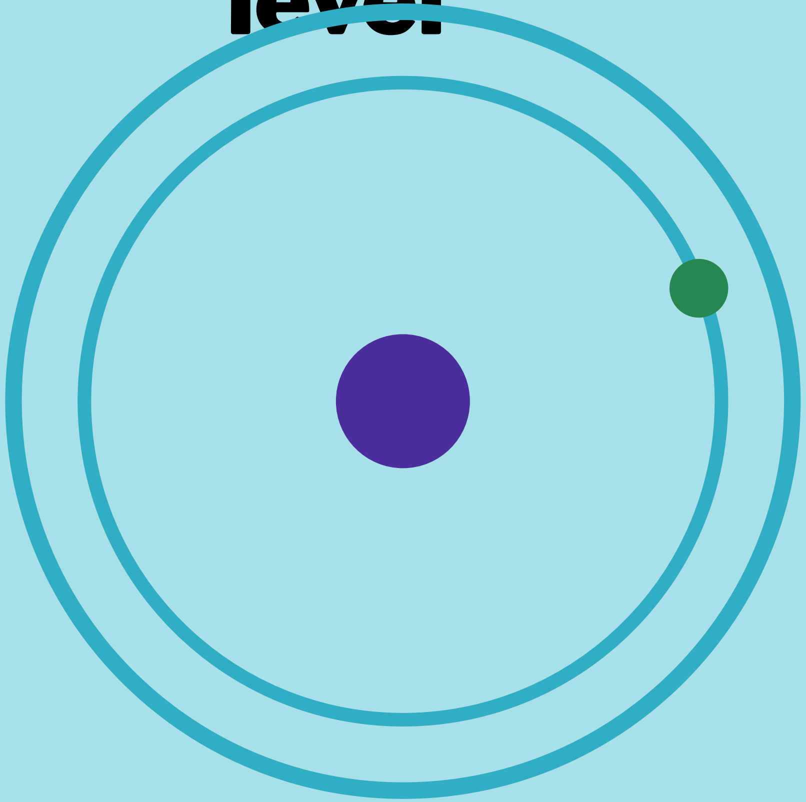




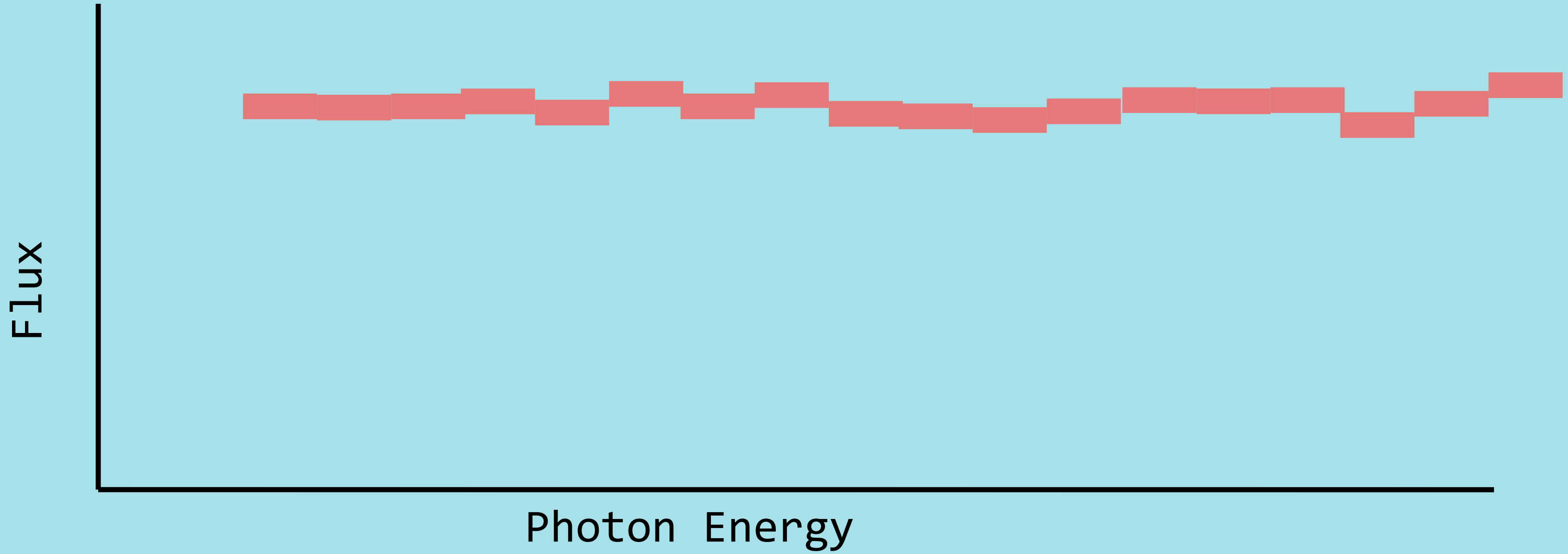
Eddington Limit

Consider the humble photon
from
our AGN accretion disk

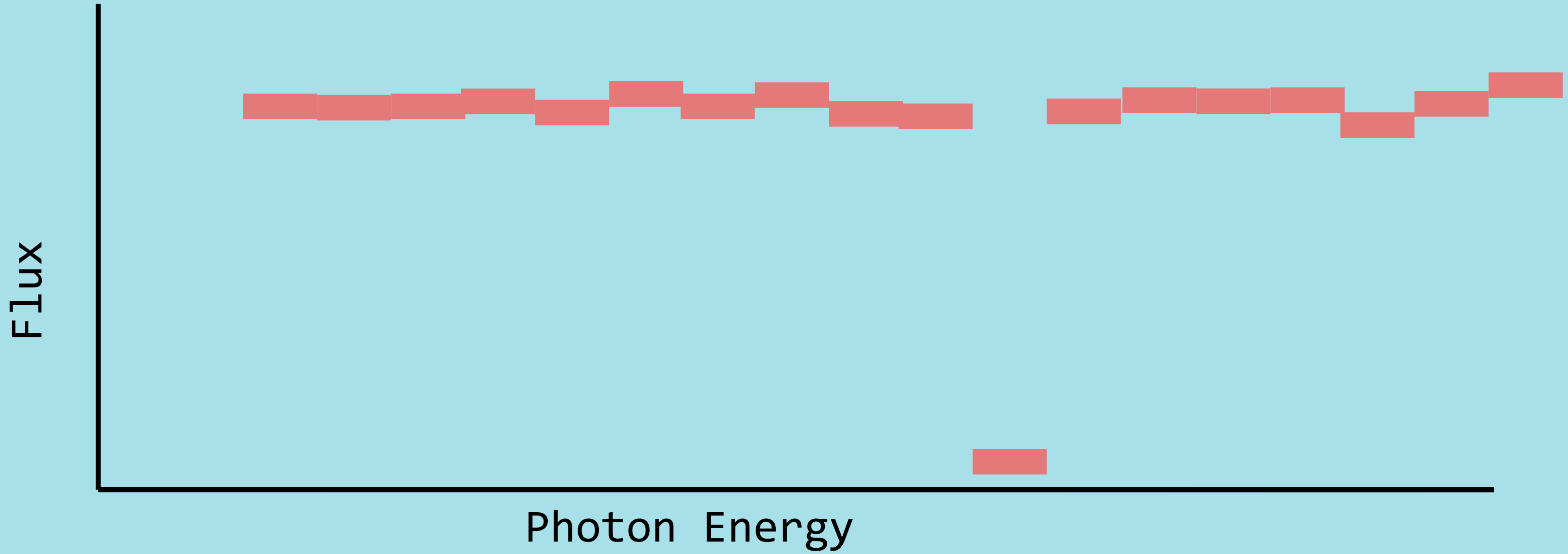
If that photon strikes neutral Hydrogen
it can raise the electron energy level



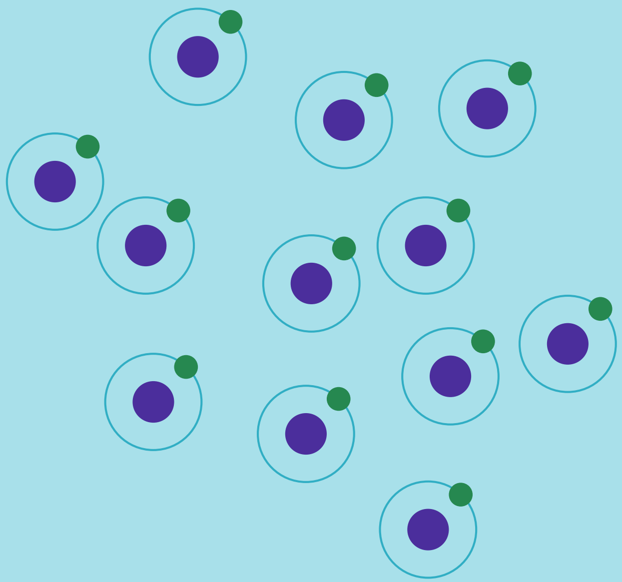
The flux of photons at that energy goes to 0 as all photons are absorbed

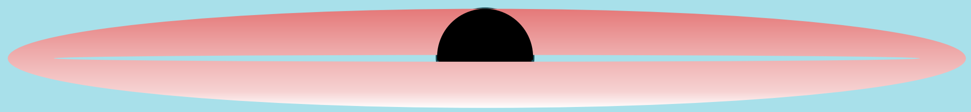


The spectrum is then redshifted and a new batch of photons is ready to be absorbed



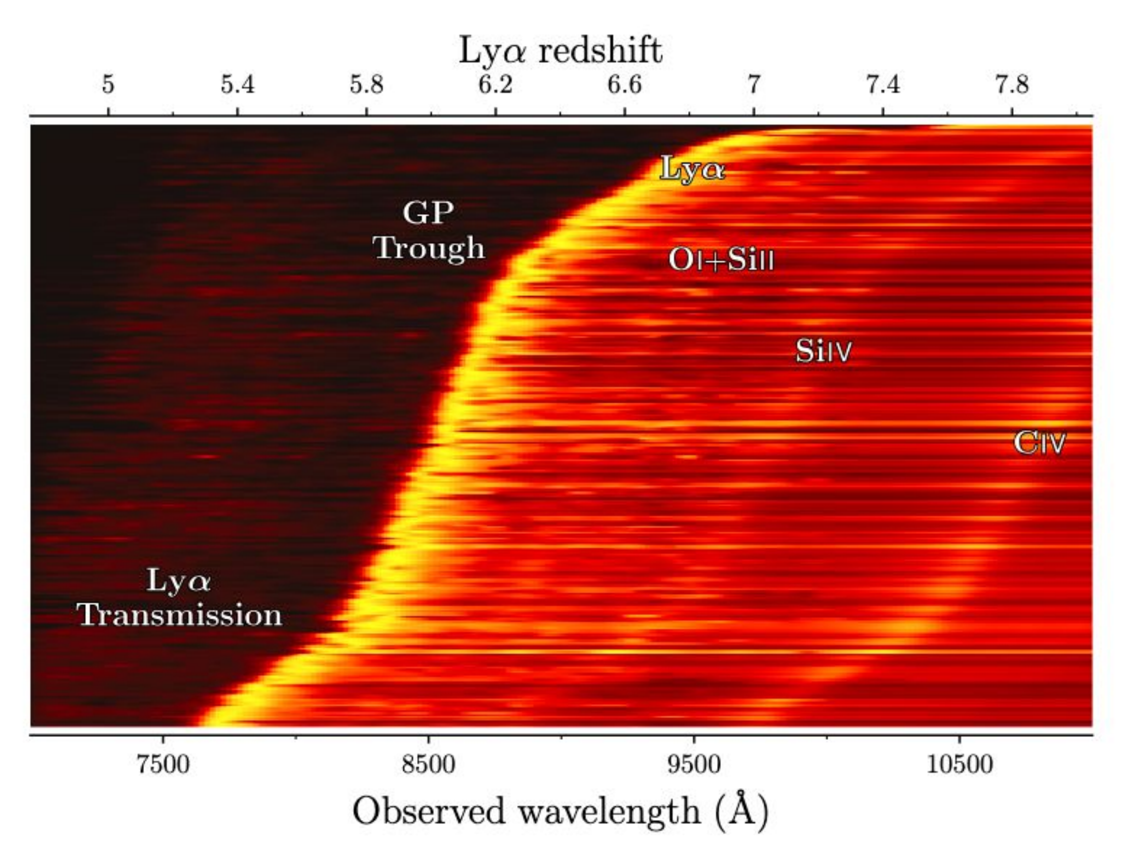
Early black holes are surrounded by a neutral hydrogen universe



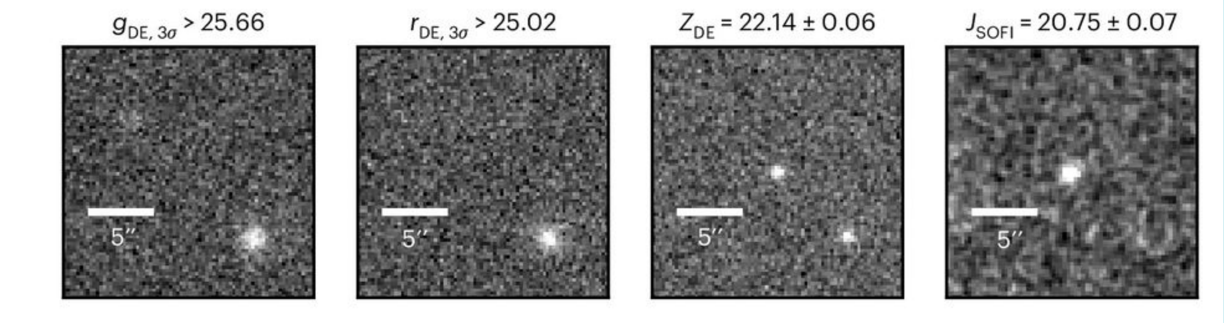


This is the Epoch of Reionization

So we find them and redshift them using this absorption trough

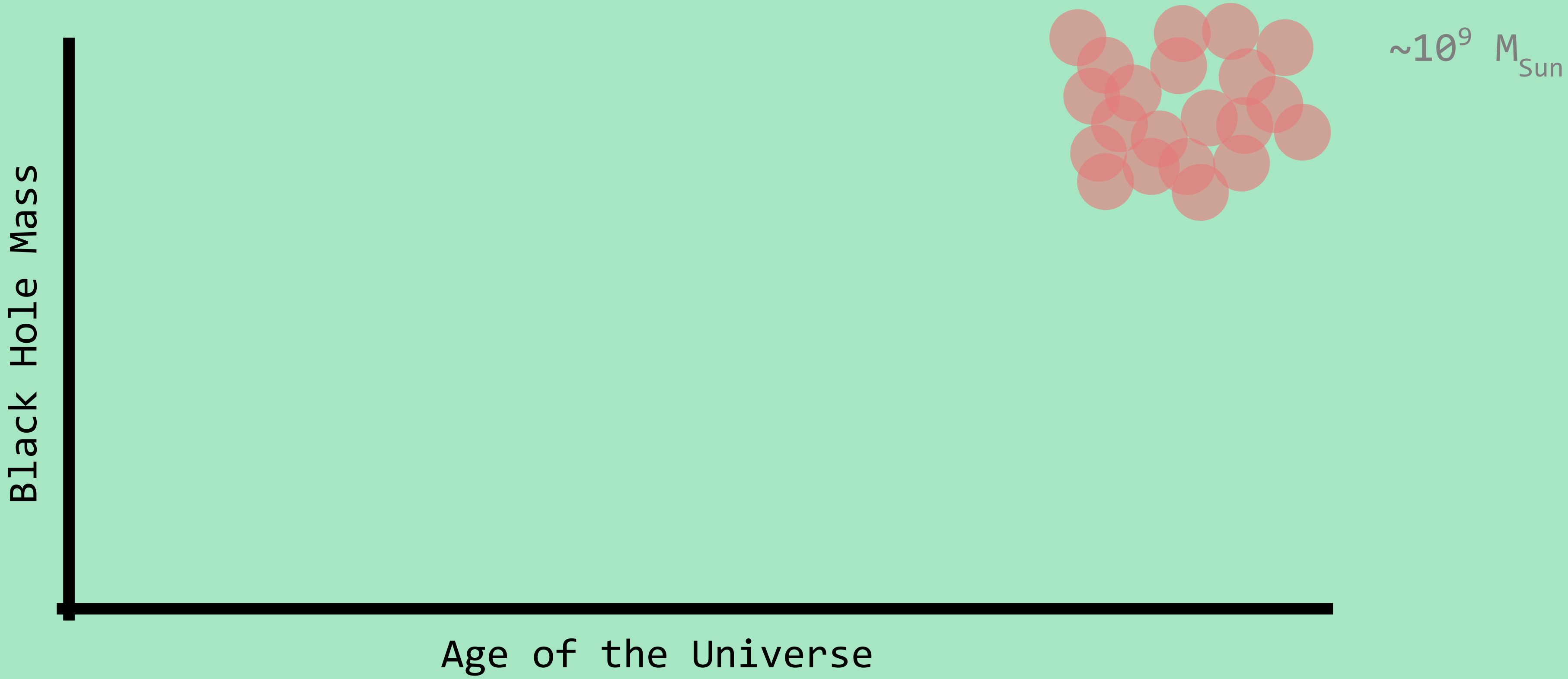


Fan, Bañados, & Simcoe 2023

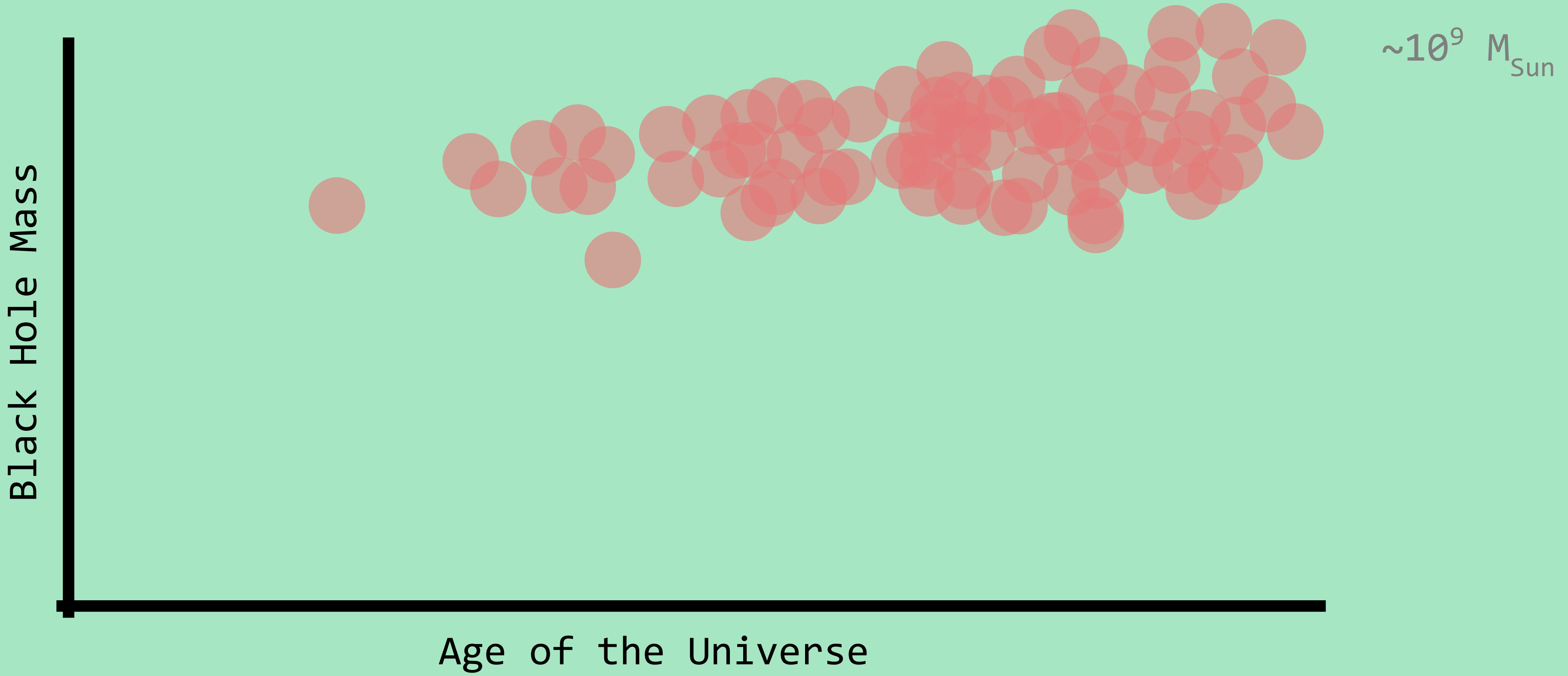


Bañados et al. 2025

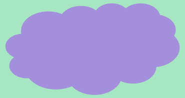
We have been finding SMBHs into the first billion years

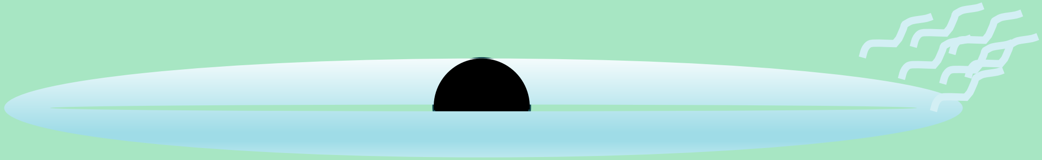


But now we're finding them even further, and they're still supermassive

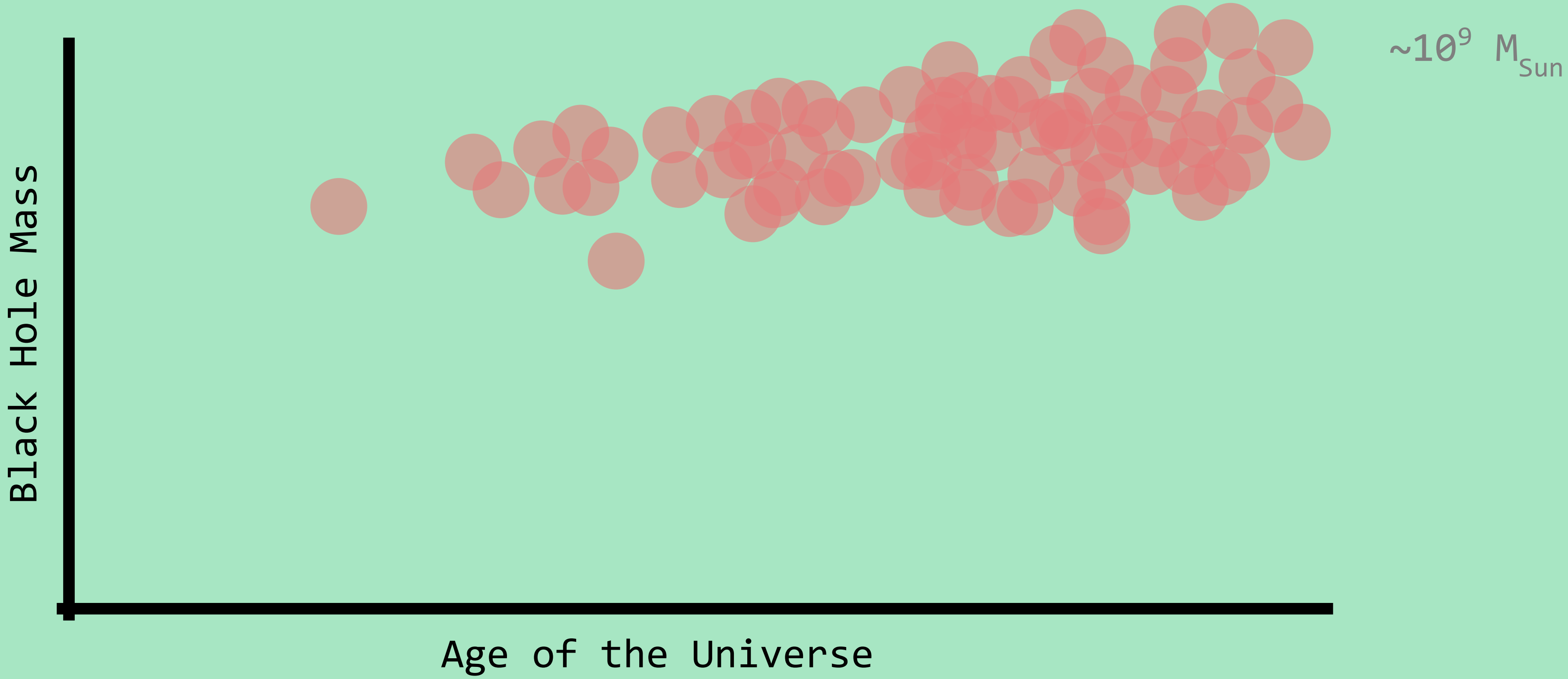


The Eddington Limit says it takes 116 Myr
to grow a factor of 10x





And so the observed SMBHs require early, massive seeds.



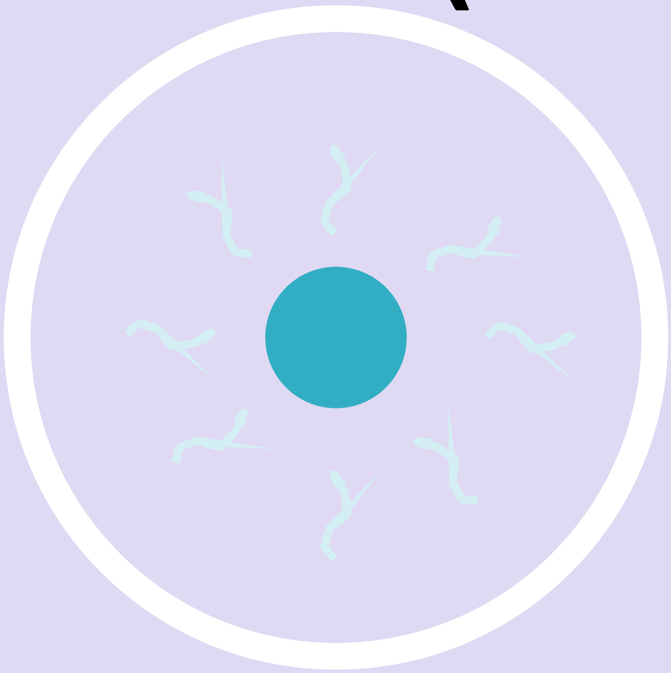
How did the first SMBHs form?

Question 1: Are they at the Eddington luminosity?

That is, are they growing as fast as they can?

Note: These questions aren't going to have conclusive answers

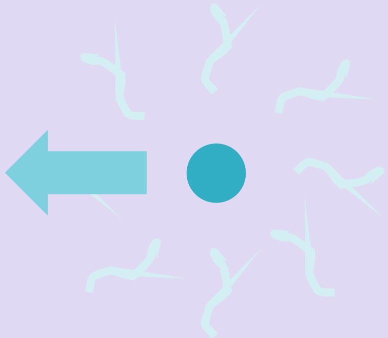
Luminosity is the energy flux per second from the entire AGN (all directions)



We can’t directly measure this

erg / s

Flux is that luminosity divided onto the
surface area of a sphere with radius equal to your distance from the source

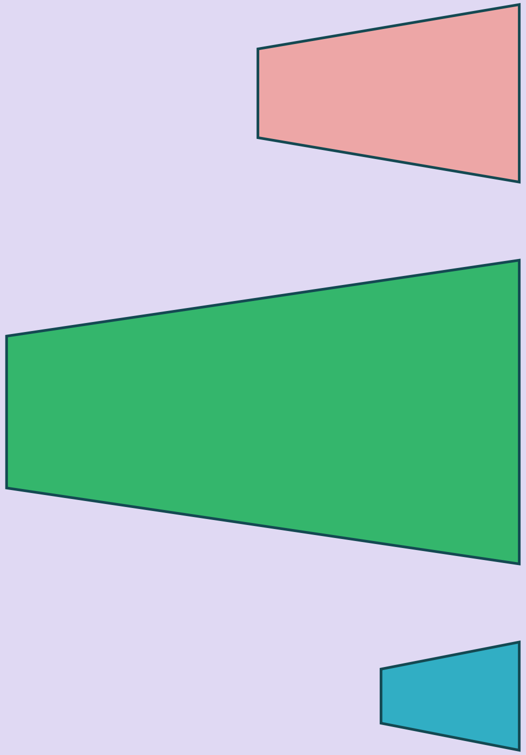


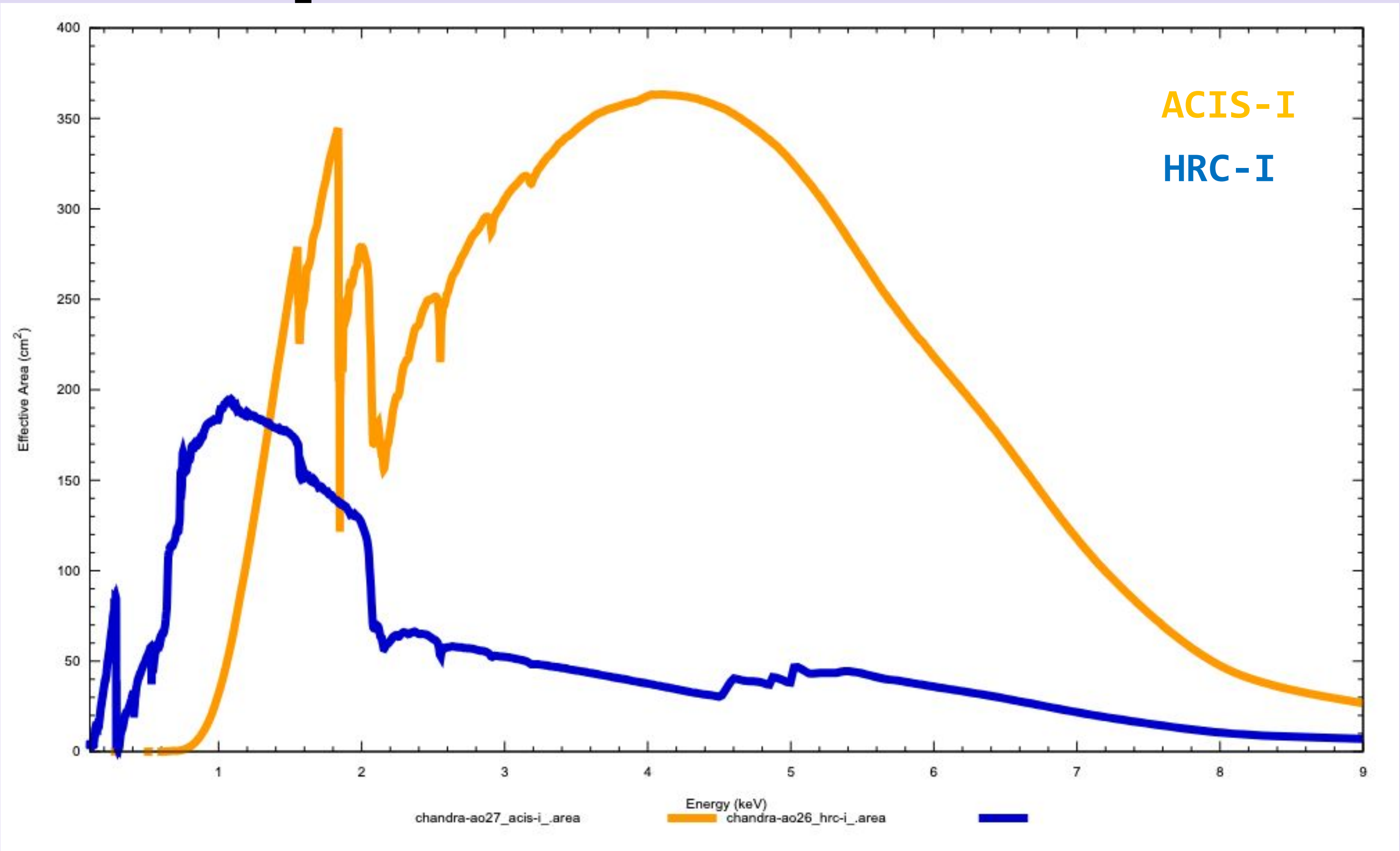
Luminosity distance, to be cosmologically accurate

$erg / s / cm^2$

Or, more eloquently, if your bucket can collect 1% of the light, the flux is 1/100th of the Luminosity

Chandra's "bucket" size is energy dependent



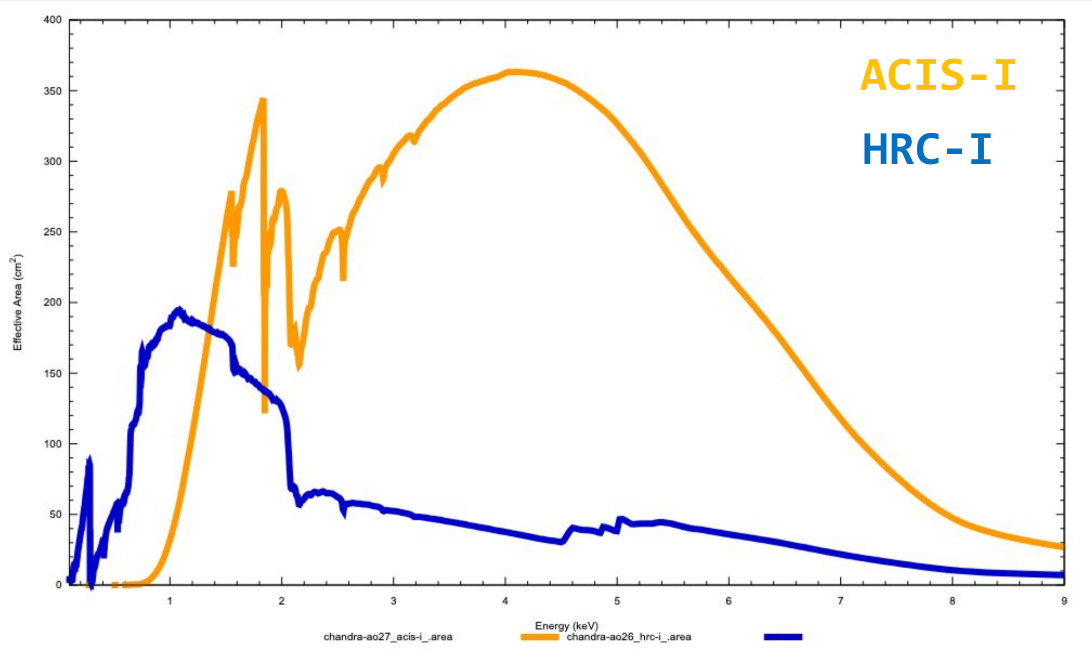


Luminosity

=

Observed photons

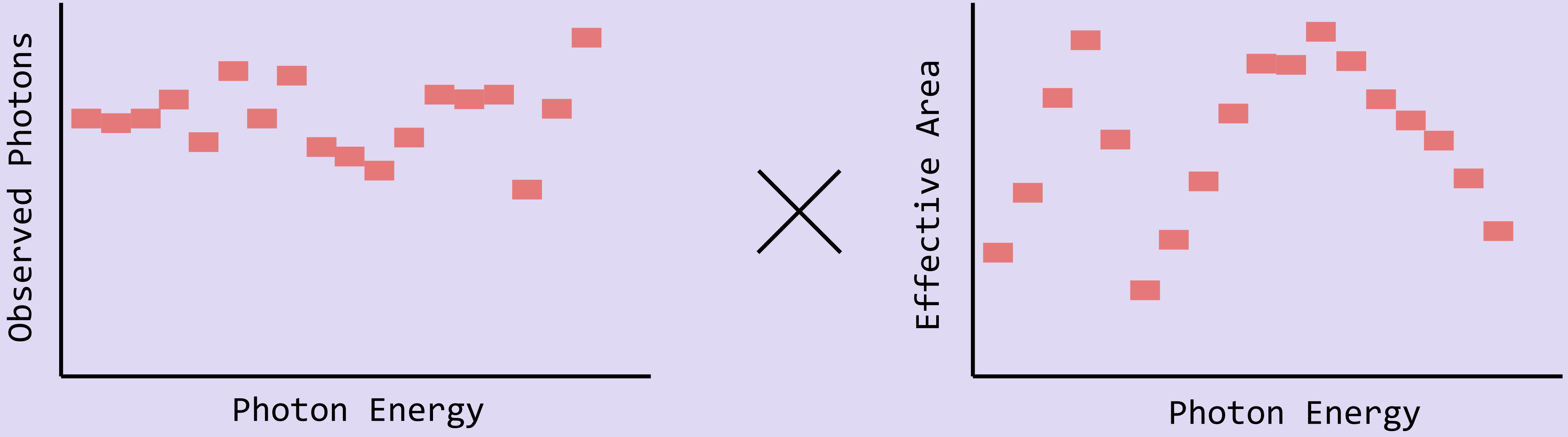
x



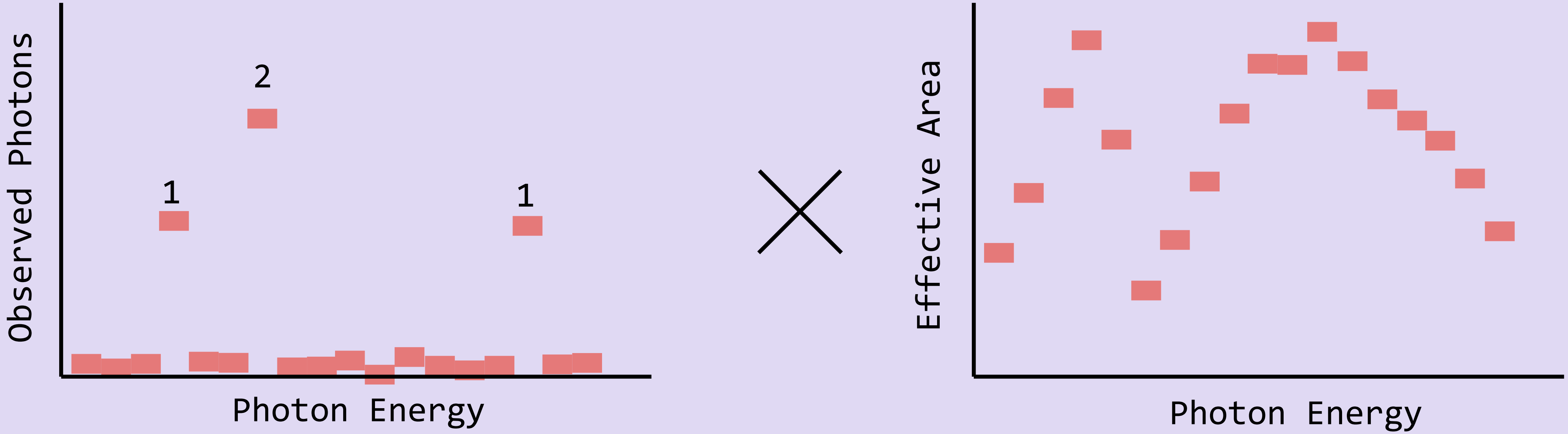
x 4 pi

r^2

If you have infinite (or at least a lot of) photons

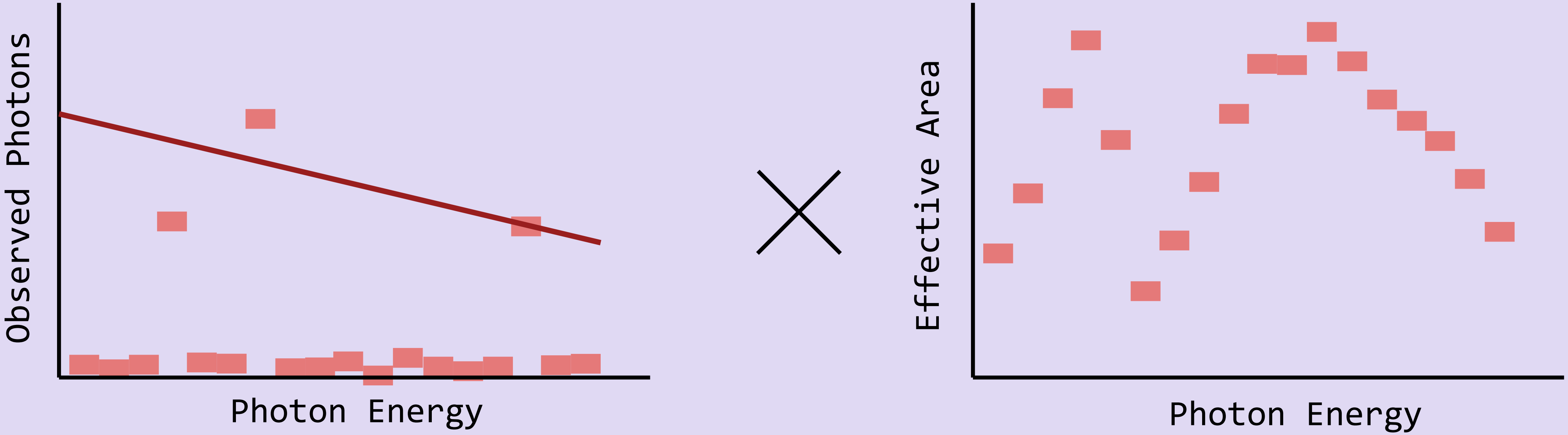


But in the low photon regime



that just doesn't work

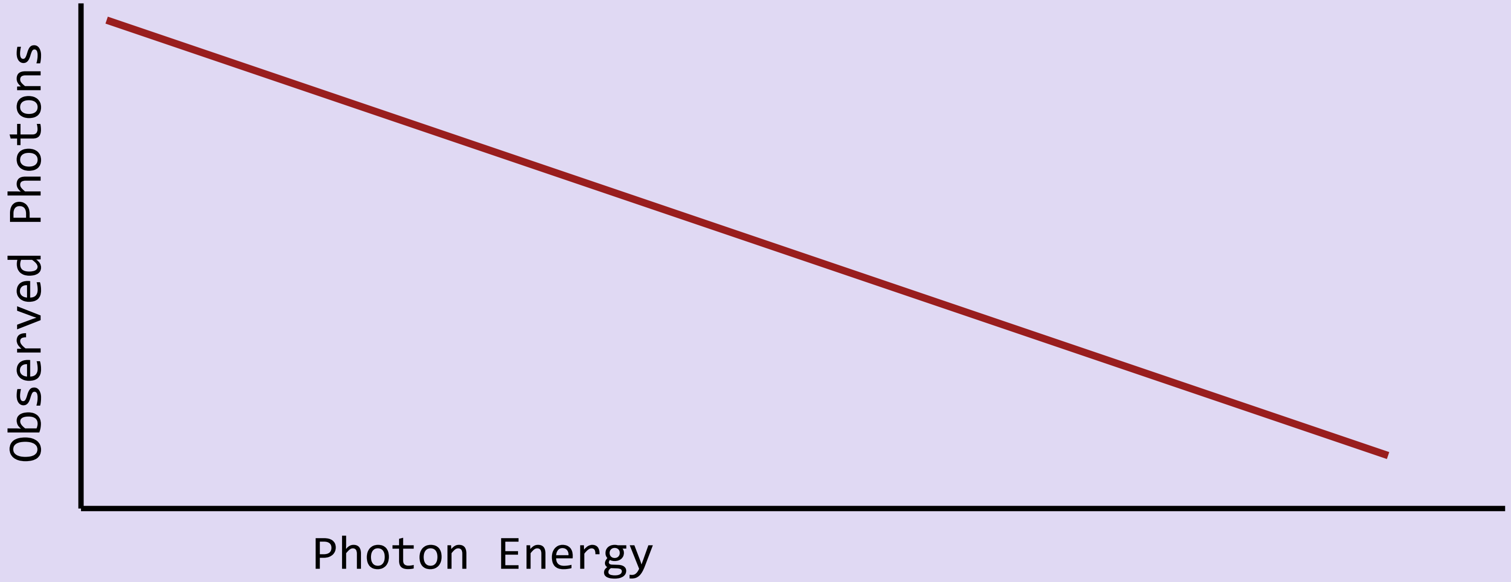
But in the low photon regime



that just doesn't work

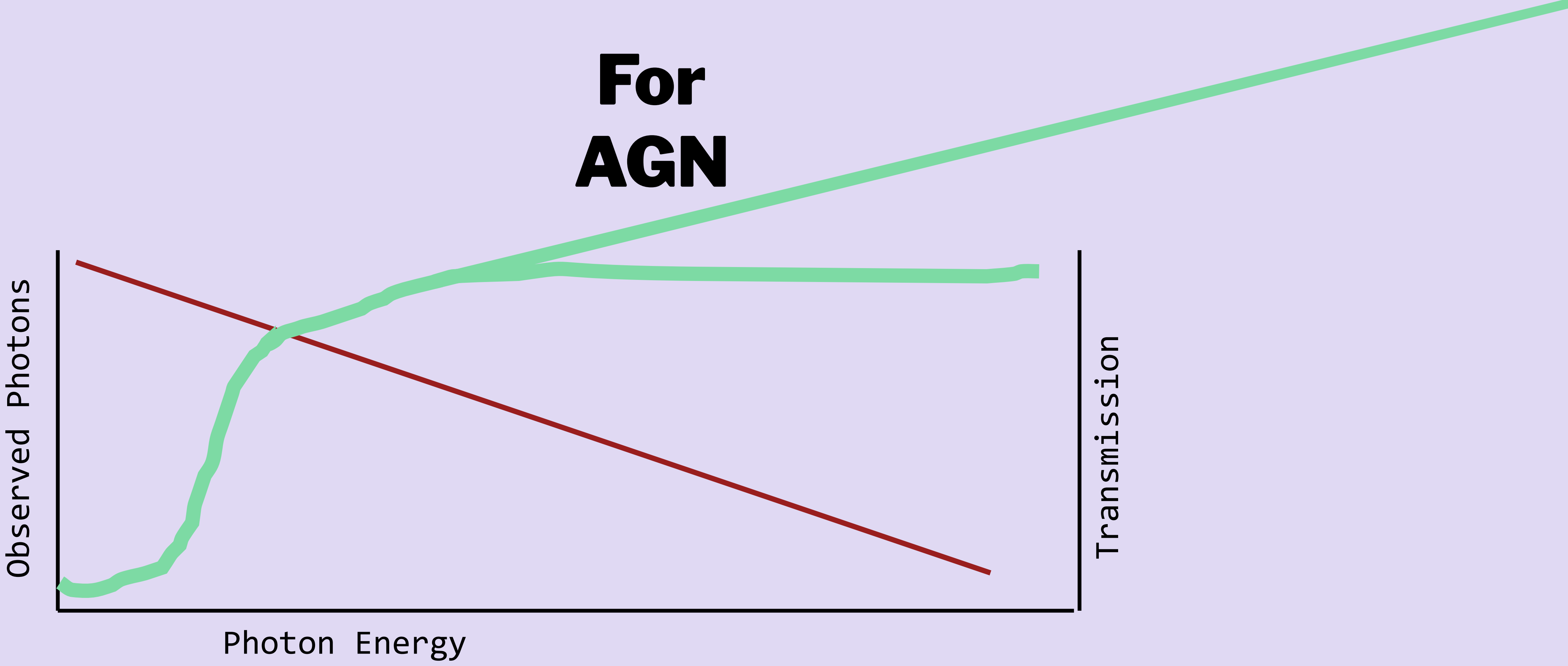
so we fit the flux of the best model

For AGN



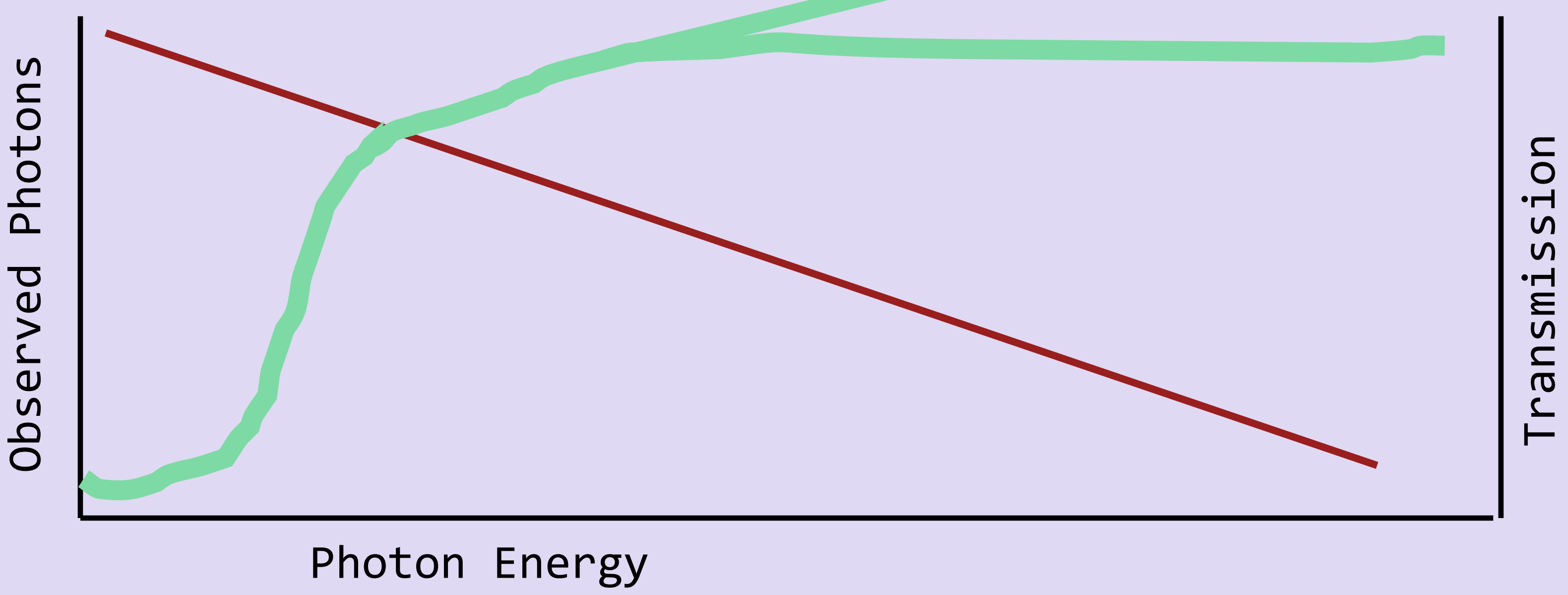
Intrinsic spectrum: power law

For AGN



Observed spectrum: Absorbed power law

For AGN

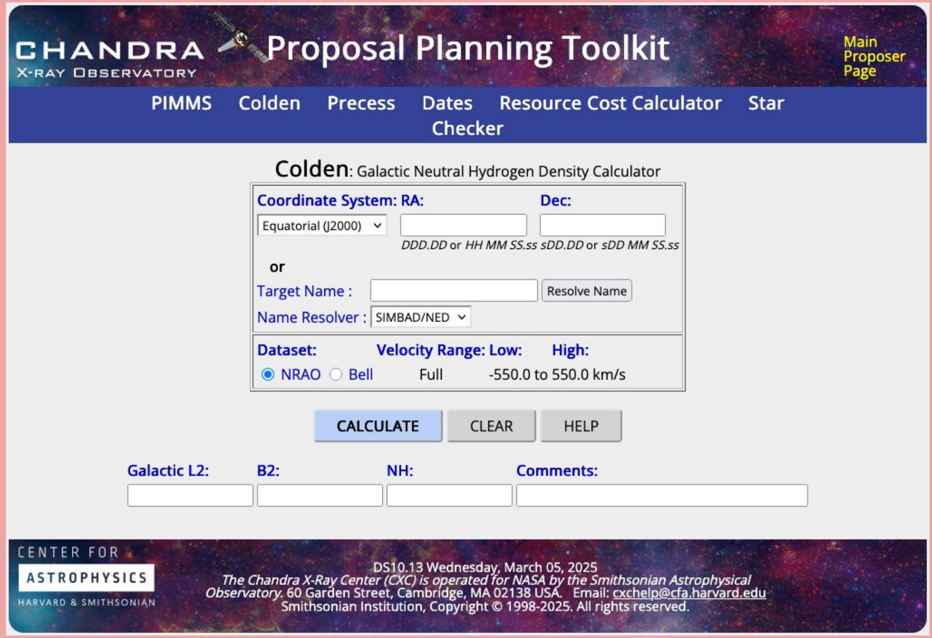


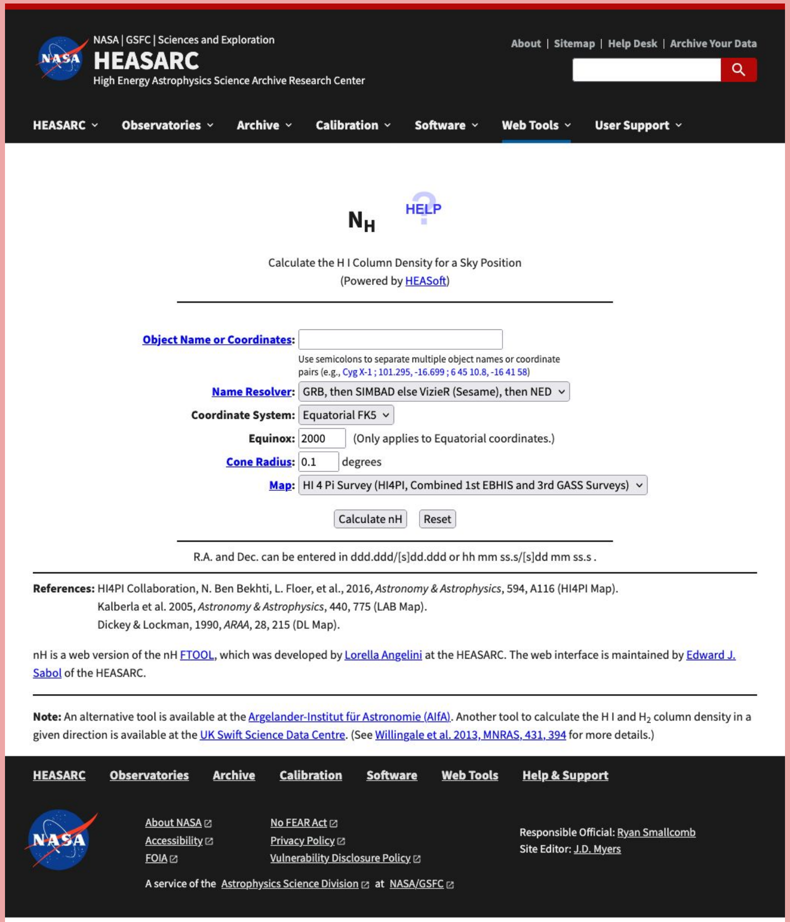
phabs x pow

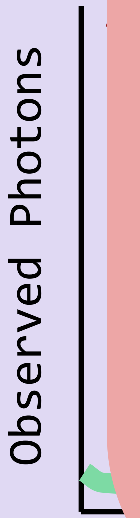
NH: Column Density
Gamma: Power Law Slope
norm: Power Law Normalization

Observed spectrum: Absorbed power law

Colden (Chandra)
NH (HEASARC)







phabs x pow

NH: Column Density
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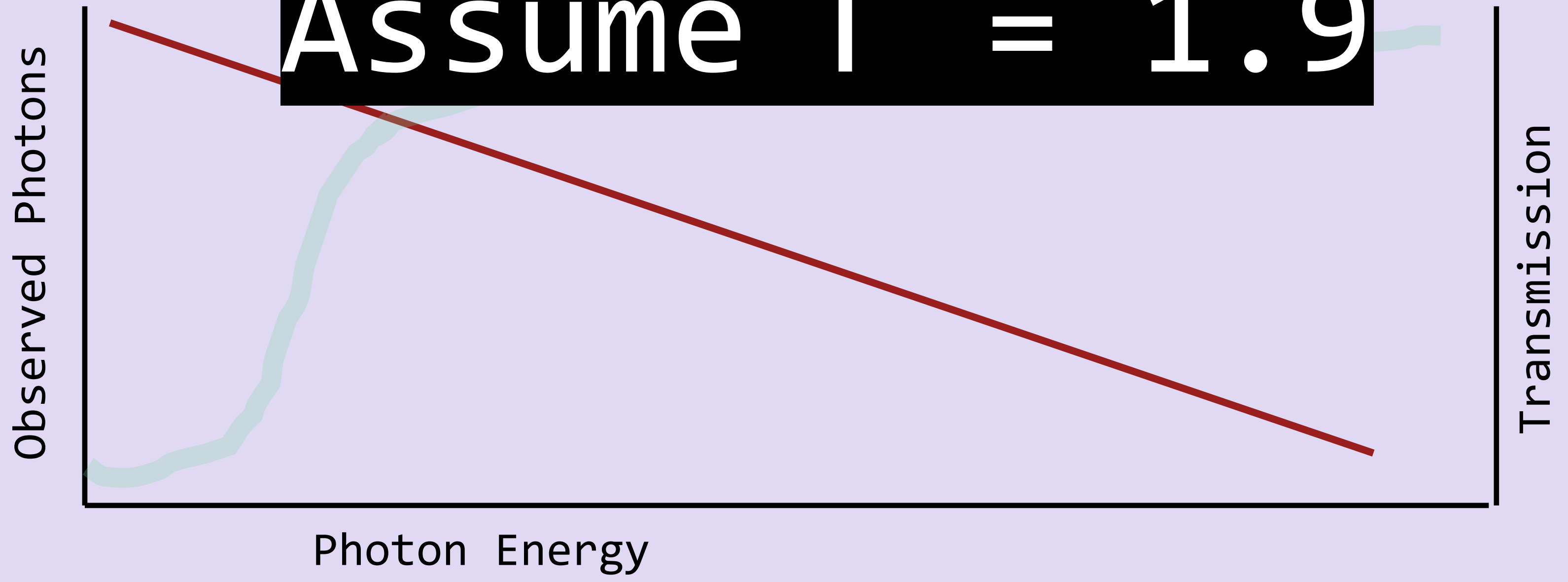
Observed spectrum: Absorbed power law

For AGN

Assume Γ = 1.9



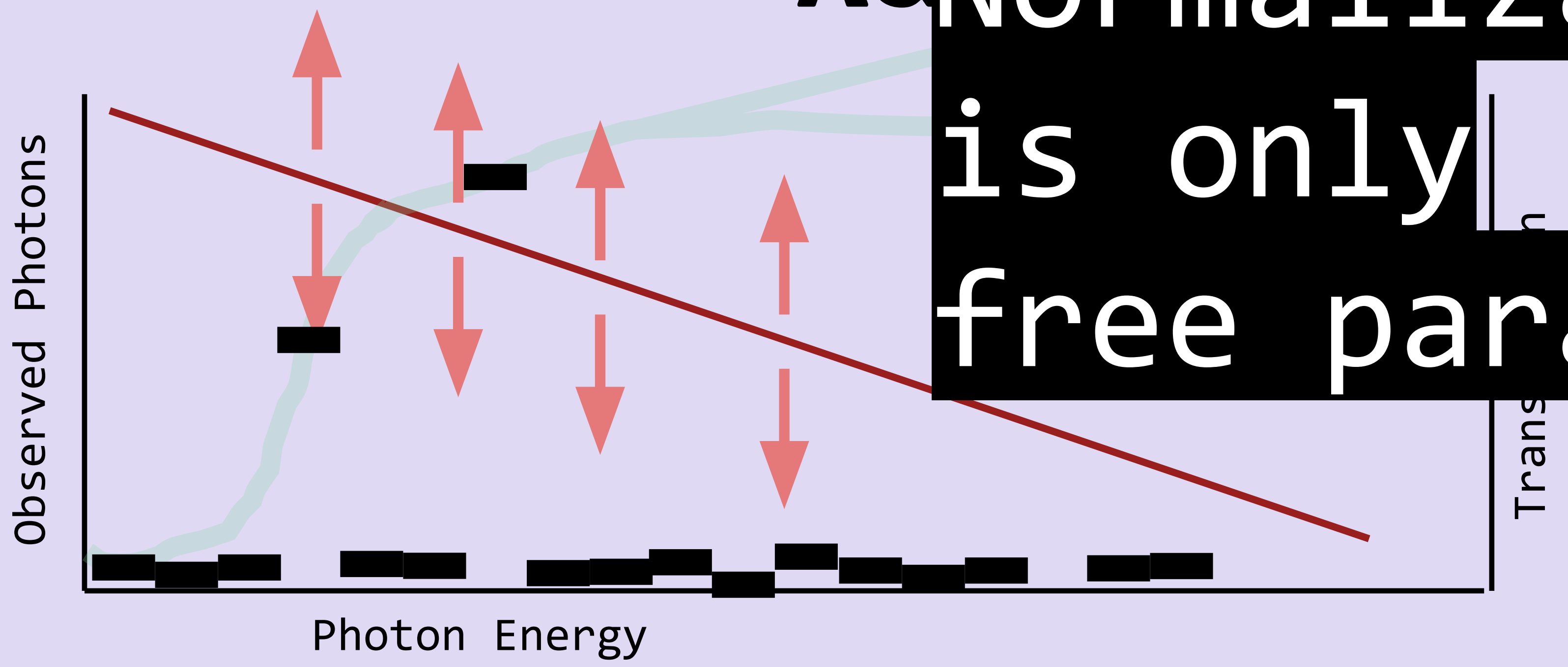
Observed spectrum: Absorbed power law

phabs x pow

NH: Column Density
Gamma: Power Law Slope
norm: Power Law Normalization

For AG

Normalization is only free parameter



Observed spectrum: Absorbed power law

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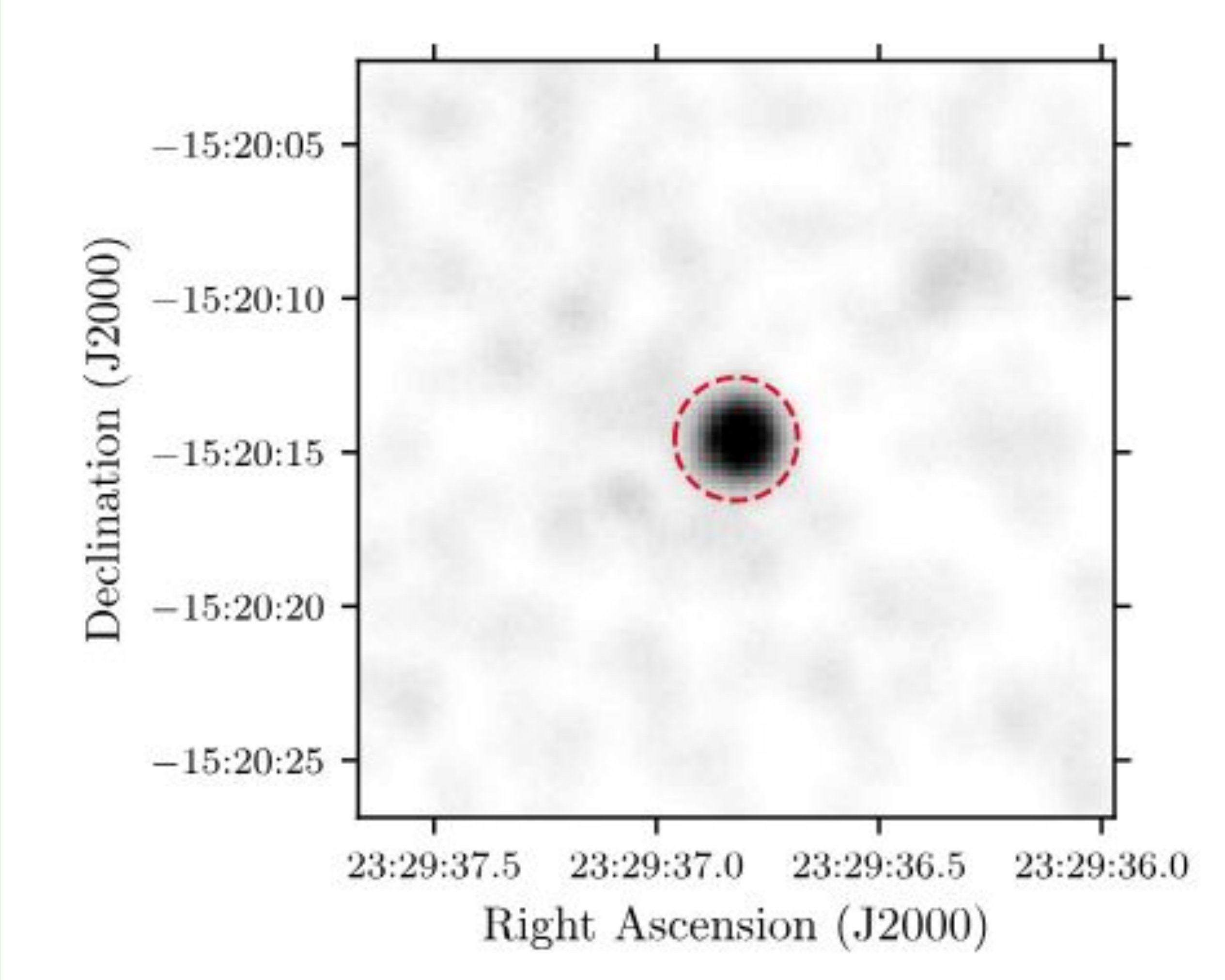
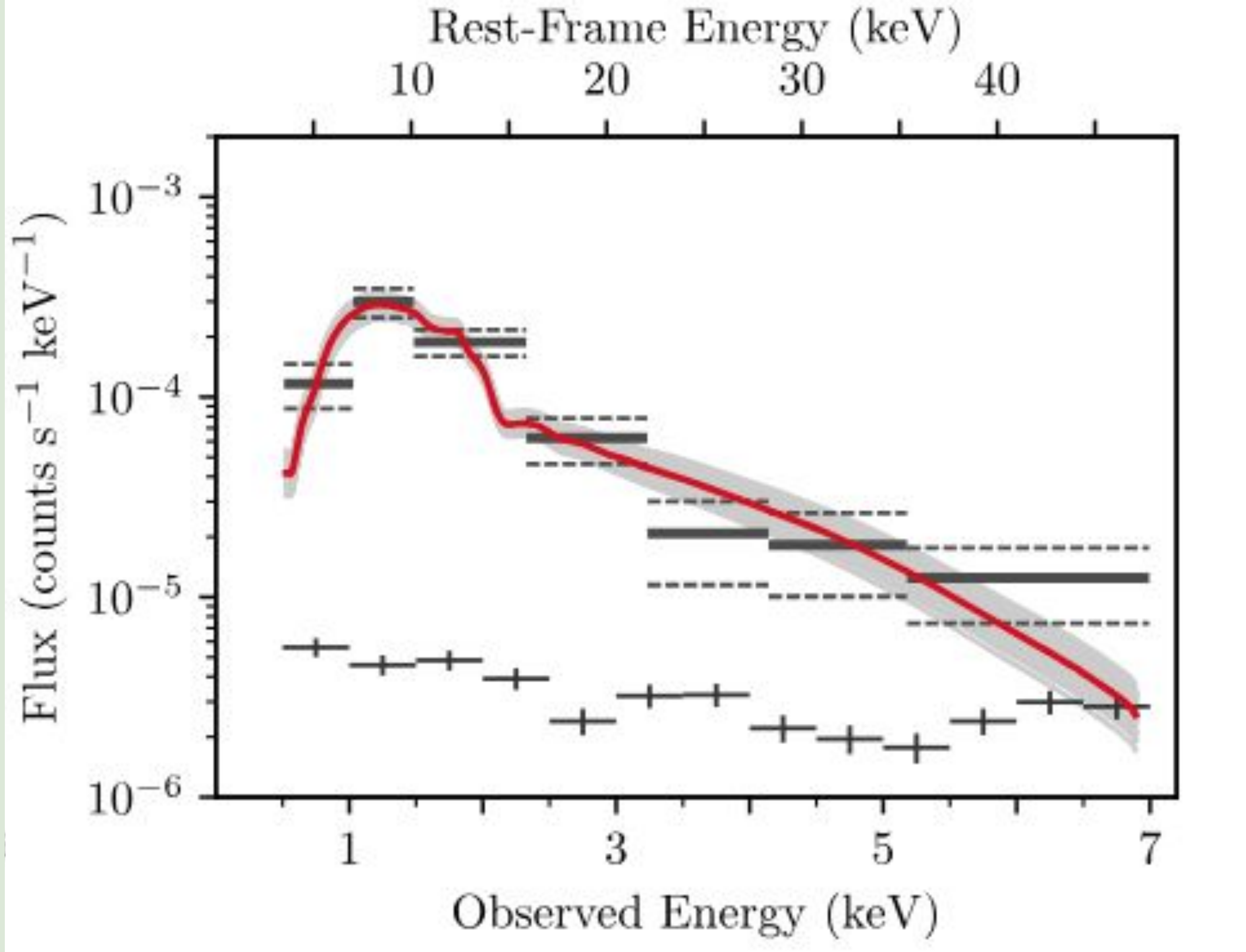


Connor et al. 2021

Using CIAO

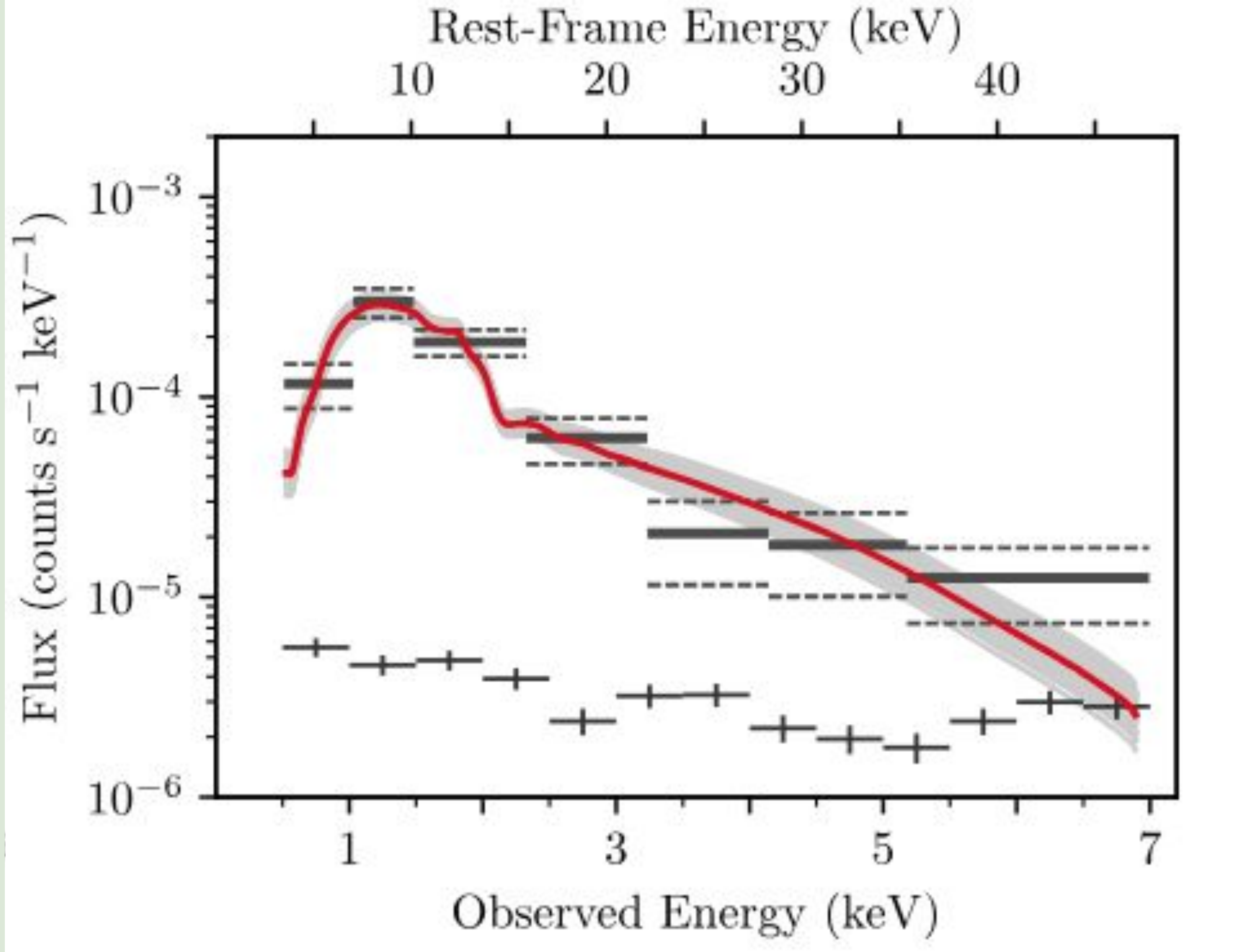
- Process Data
- Extract Source Spectrum
- Extract Bkg Spectrum
- Extract ARF
- Extract RMF

Using Sherpa/XSpec



Connor et al. 2021

- Load Spectra
- Set Statistic
- Load model
- Freeze parameters
- Fit
- Find errors on fit



Connor et al. 2021

Using Sherpa/XSpec

- Load Spectra
- Set Statistic
- Load model
- Freeze parameters
- Fit
- Find errors on fit

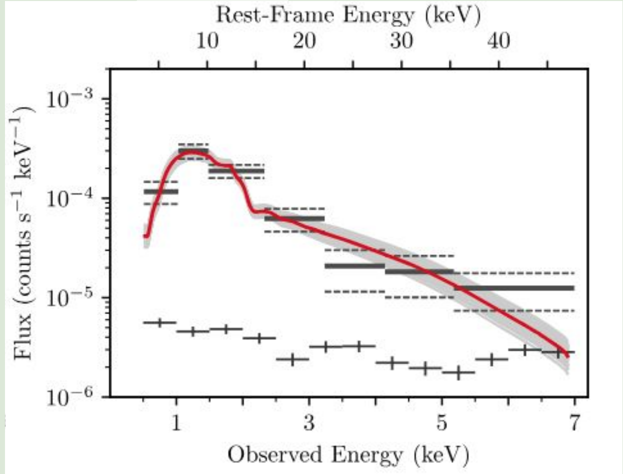
Modified C-Stat

(Cash 1979, Wachter 1979)

Too few photons for
Gaussian errors in bins

Flux is observed
Entire model

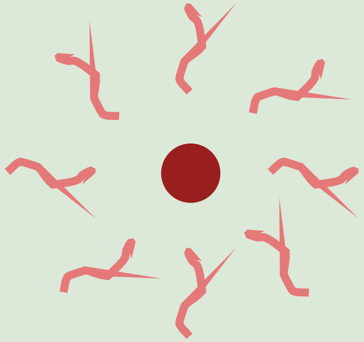
phabs x pow

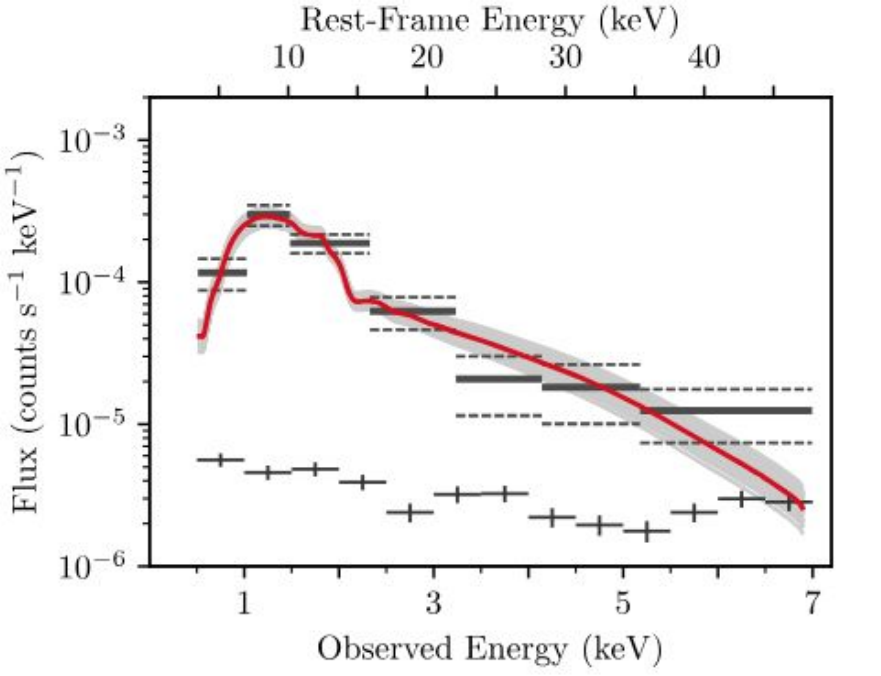


phabs

Luminosity is
intrinsic
Source Model

pow





Sherpa or XSpec

Establish source model parameters

Flux

phabs x pow

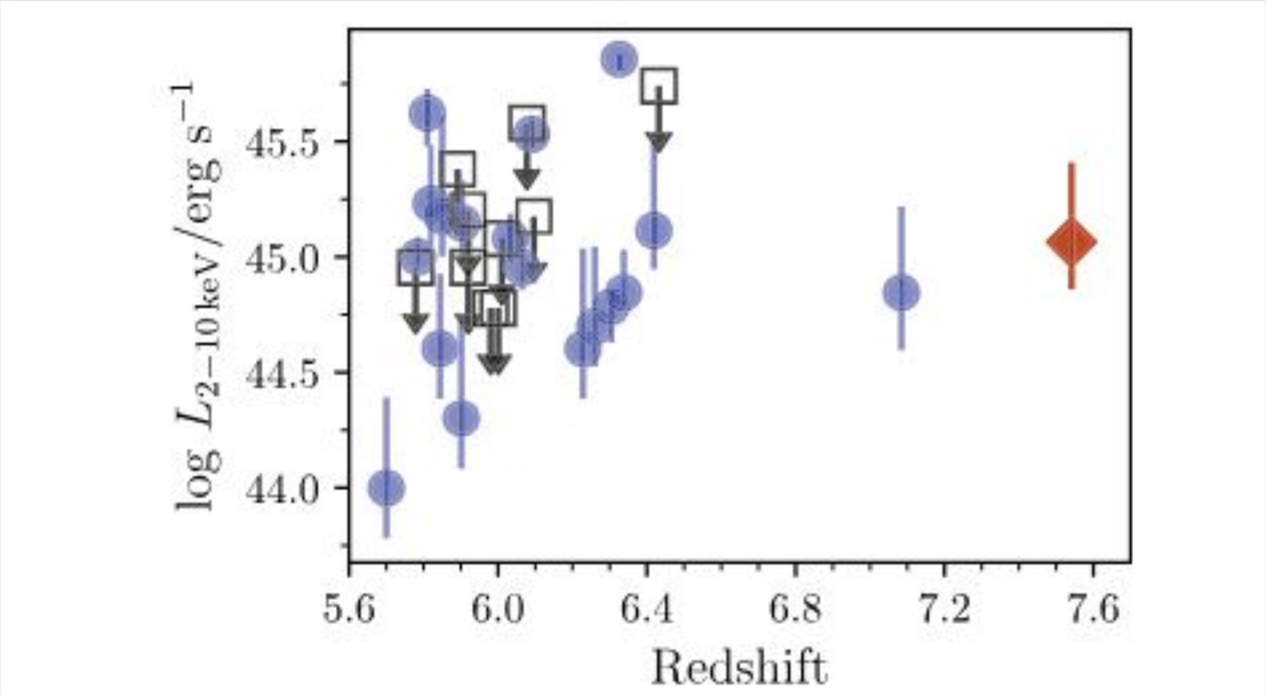
Energy range 0.5 – 7 keV

Luminosity

pow

Energy range 2 – 10 keV

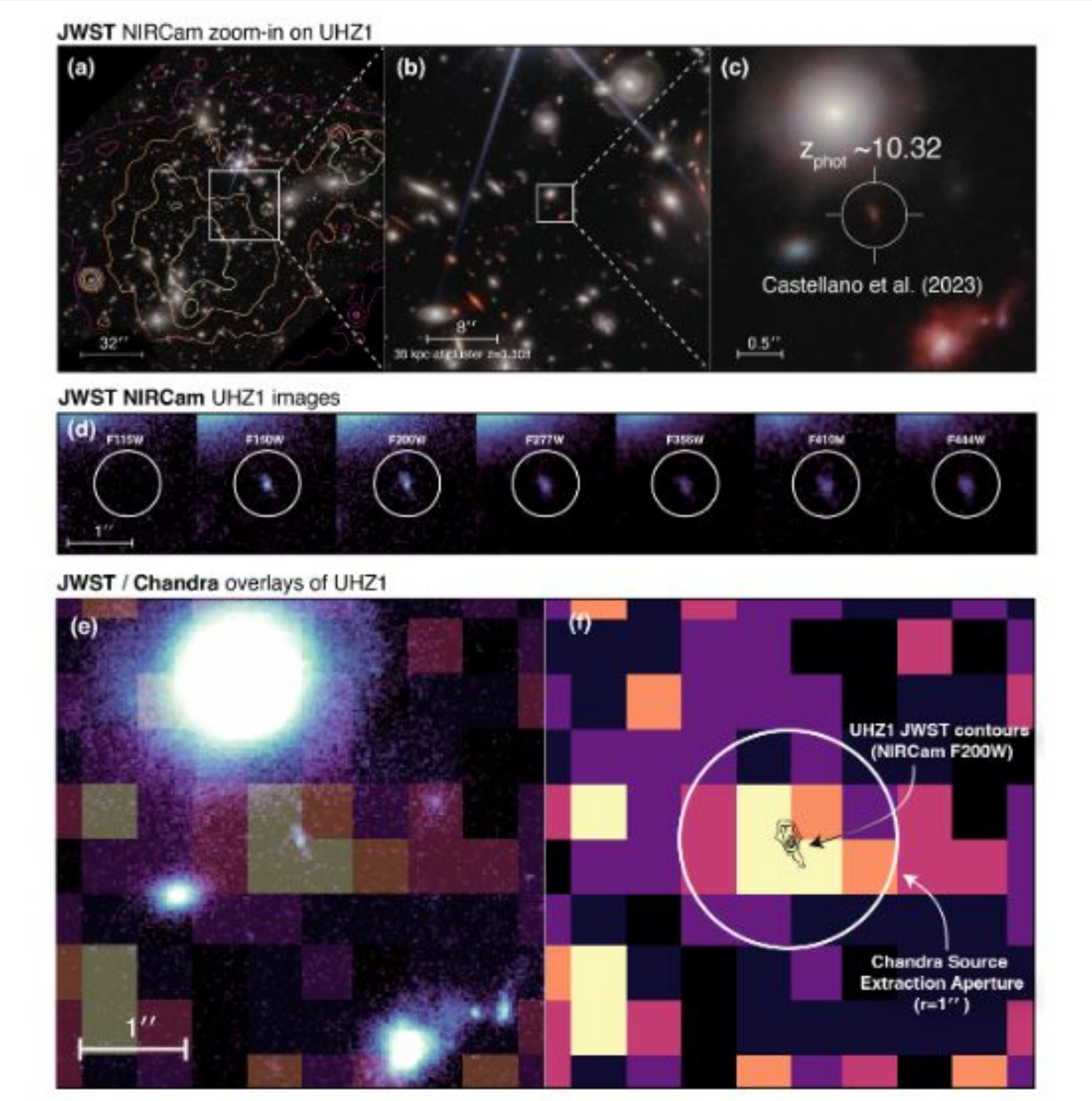
Redshift needed (and cosmology)



Bañados, Connor, et al. 2019

Do X-rays show Eddington luminosity?

Far too many uncertainties, including the fraction of bolometric luminosity produced as X-rays



Bogdan et al. 2024

Assuming Eddington luminosity

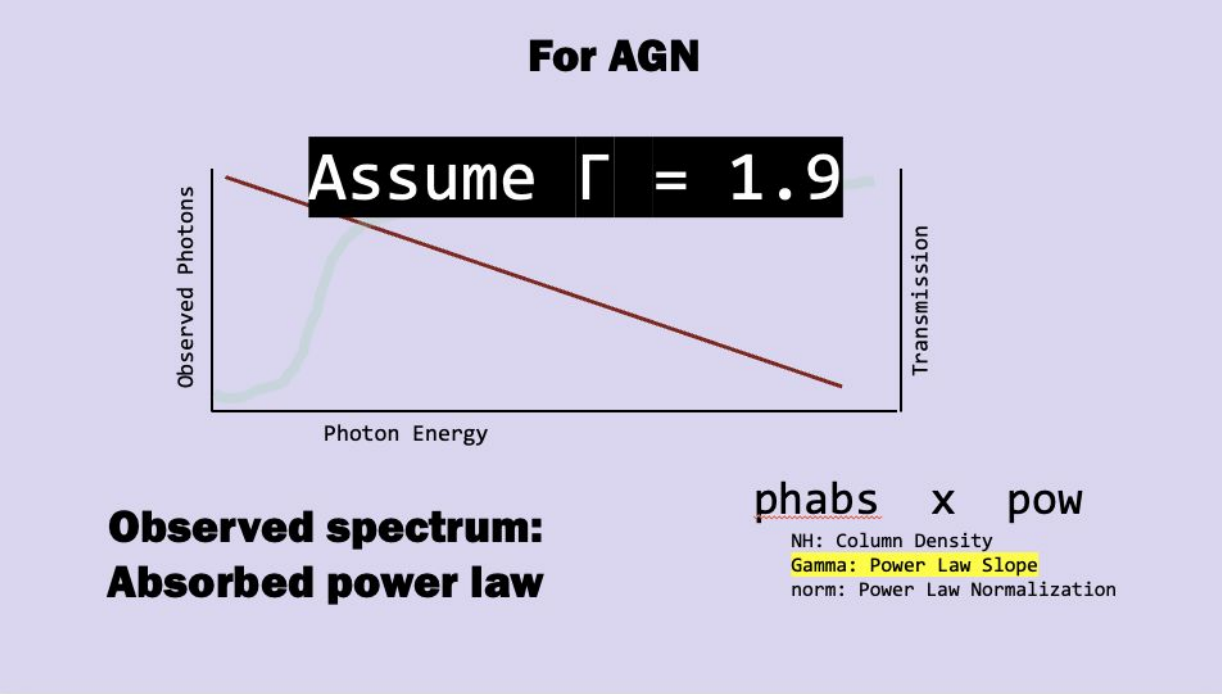
X-Ray source at z~10 is 10^{7-8} M_{Sun}

How did the first SMBHs form?

Question 2: So what can we say about their ongoing accretion?

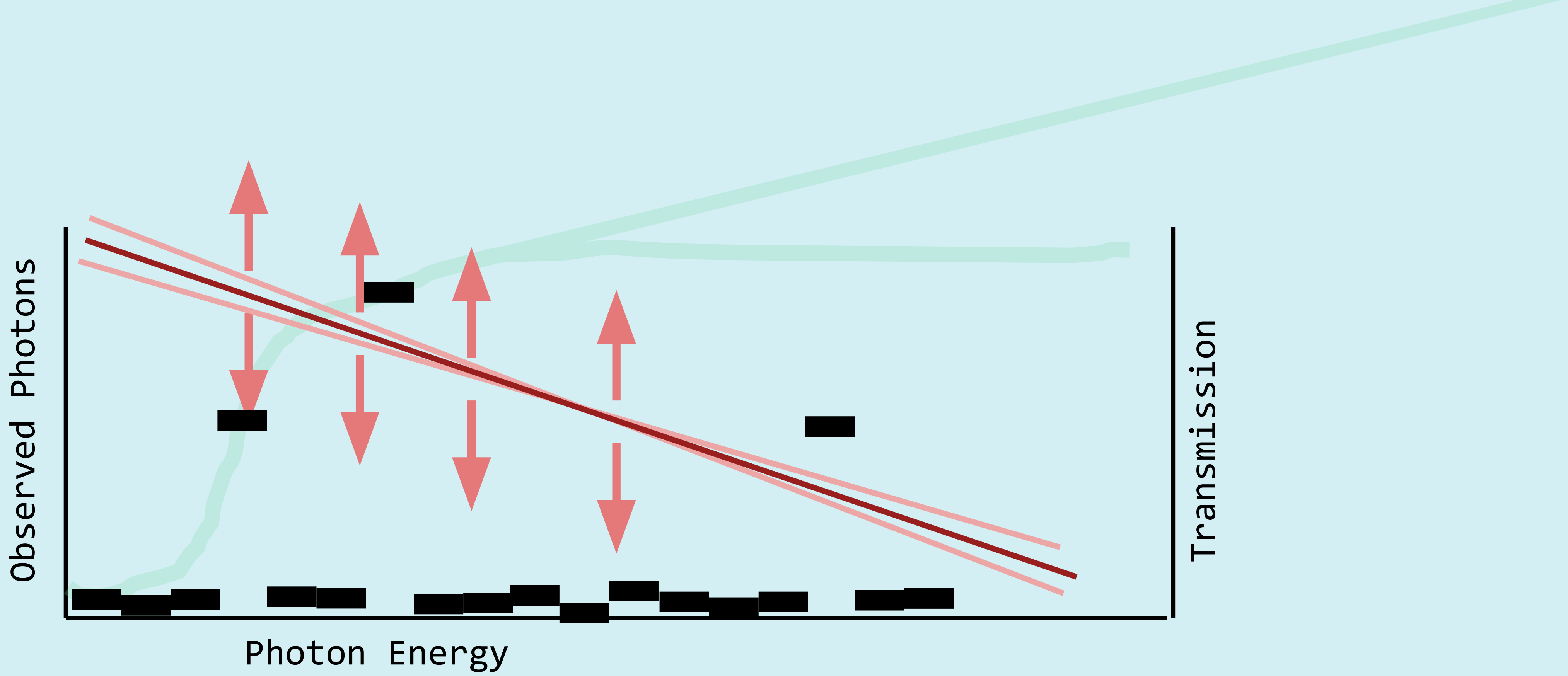
Is there other evidence for rapid growth?

Note: These questions aren’t going to have conclusive answers

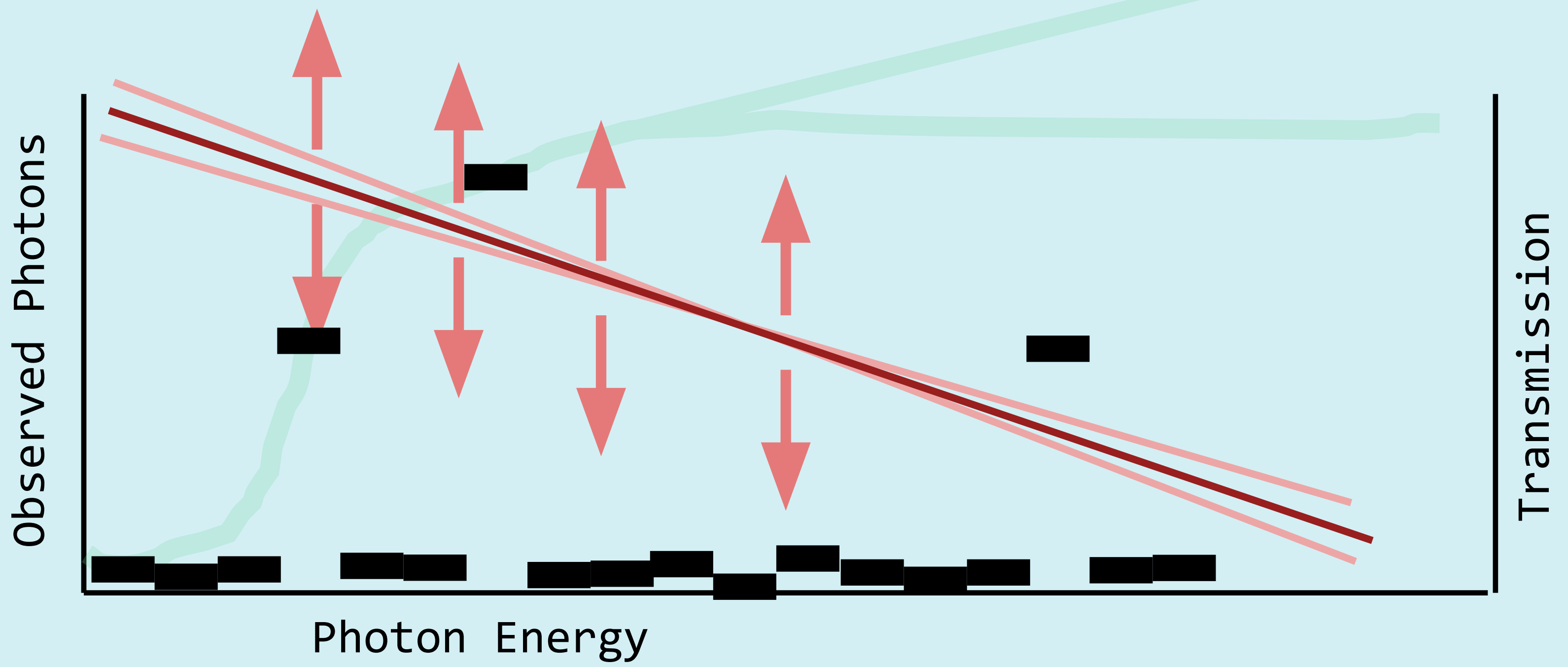


For simplicity, we fixed the power law slope

Let’s let it vary

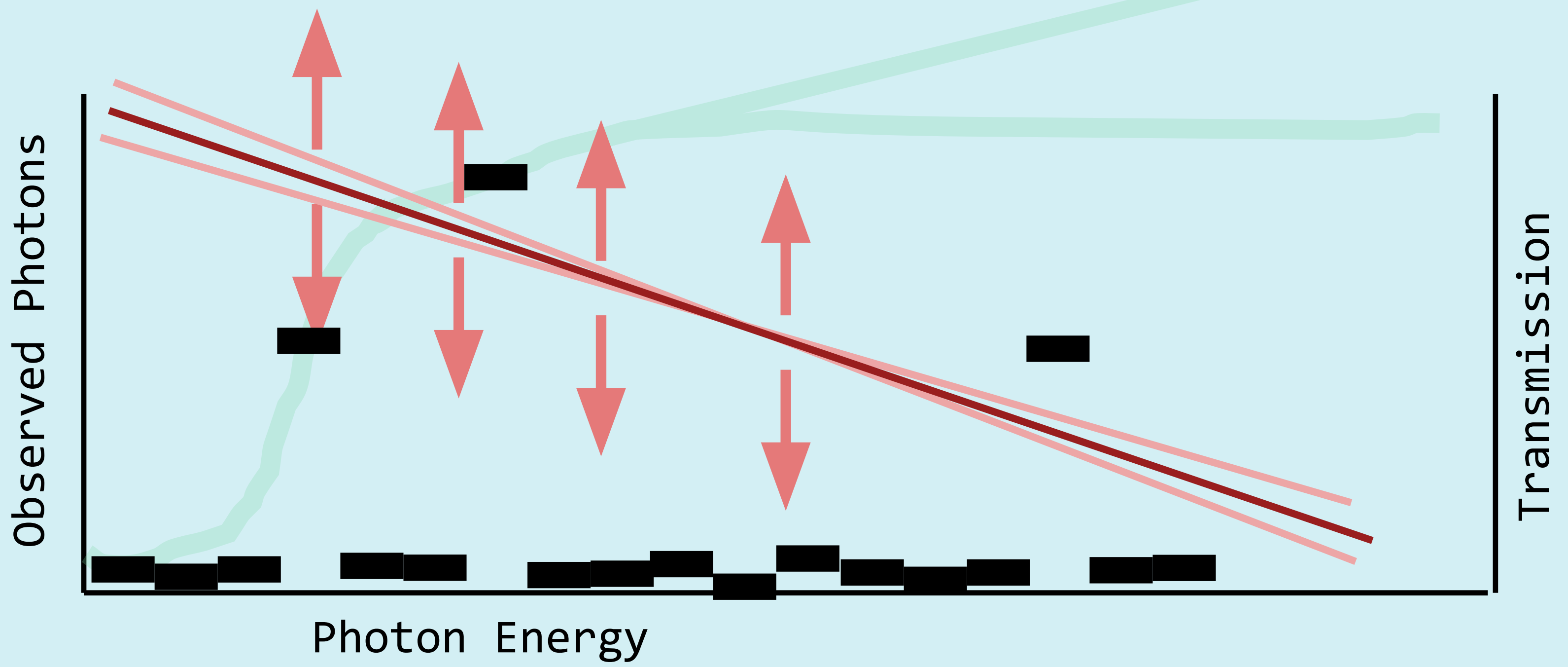


When fitting parameters, you can freeze them or thaw them



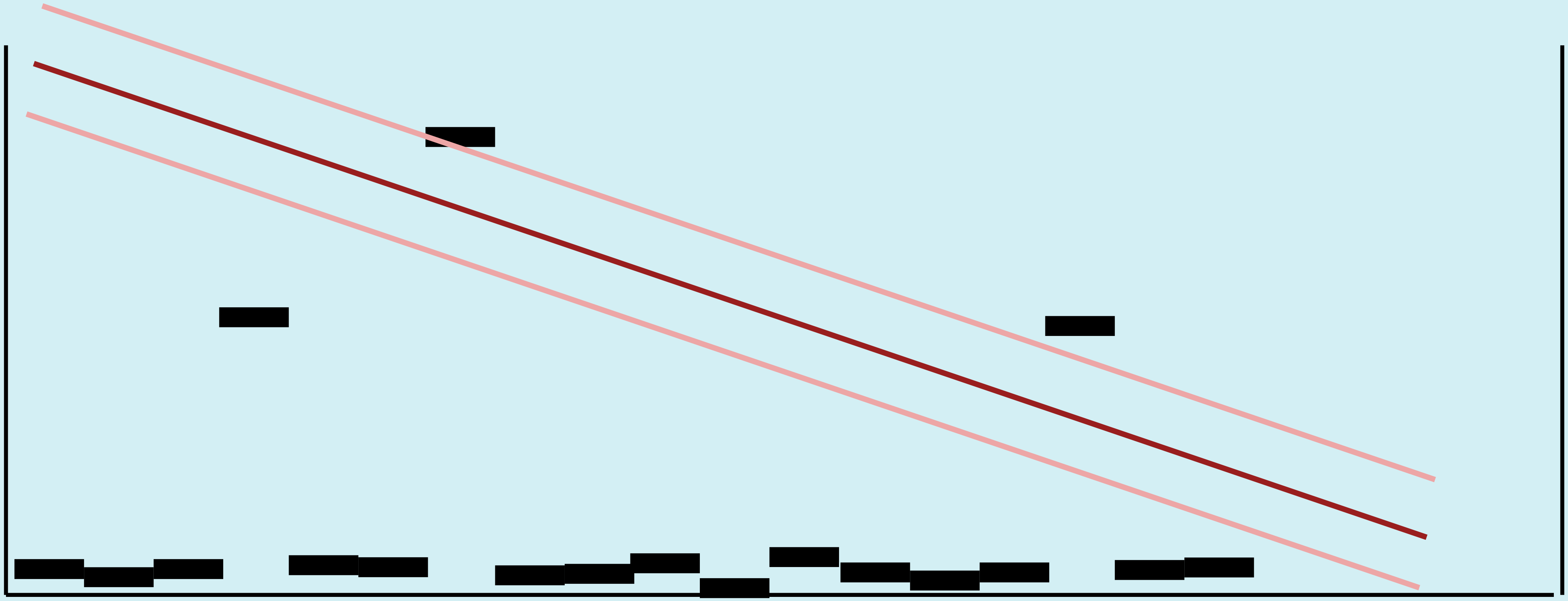
When fitting parameters, you can freeze them or thaw them

More parameters is better: you capture the nuances of the model

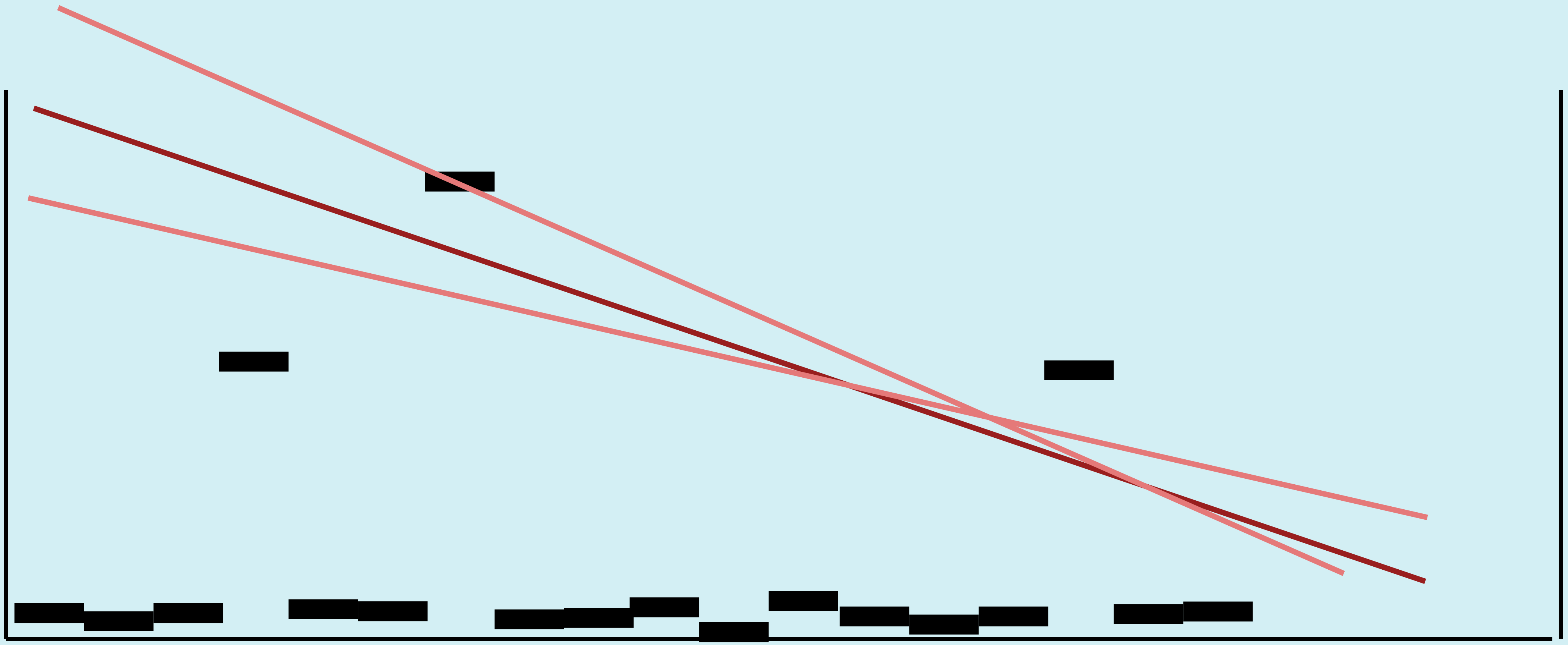


When fitting parameters, you can freeze them or thaw them

But every new parameter gives you more room to vary from the truth



Normalization is constrained by best fit



Not so when slope can vary

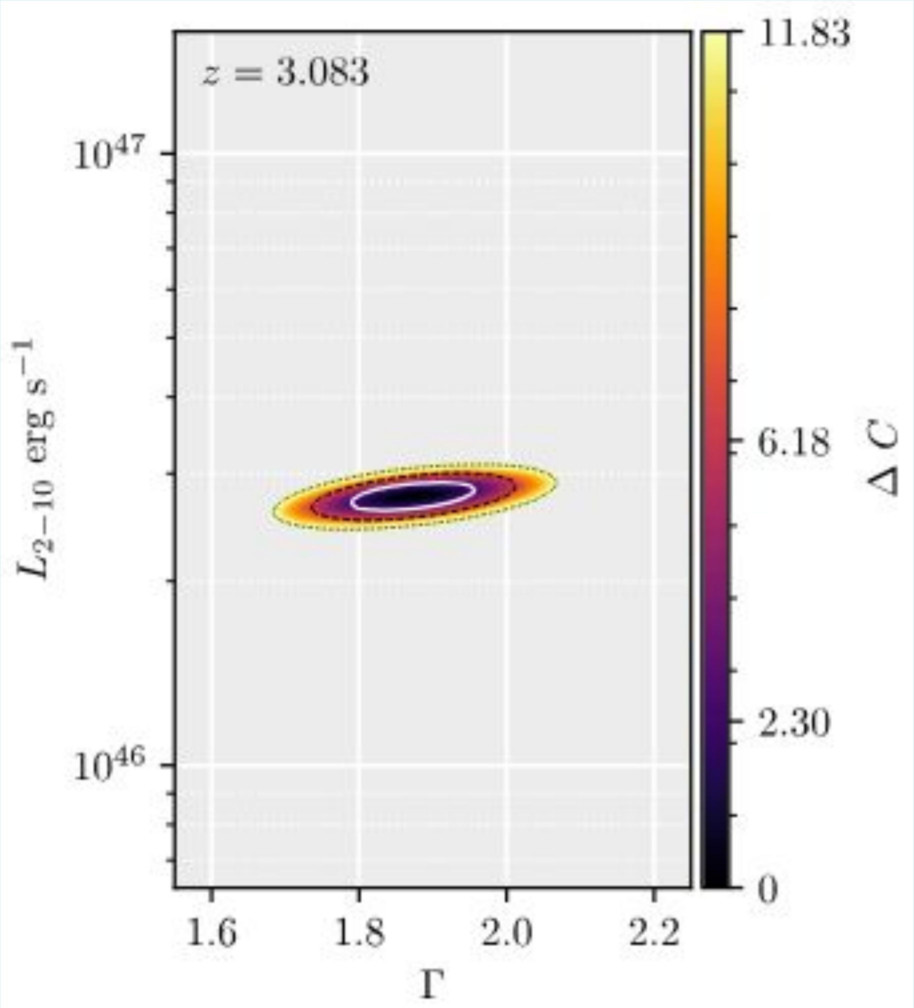
For faint sources

Make your model as simple as you can
while still being physically meaningful

For faint sources

Make your mode… you can
while sti… ically meaningful

Reduced Chi-squared of 1 indicates a fit is good
C Stat has no comparable metric –
it can only evaluate if a fit is better



Connor et al. 2022

Spectral fitting

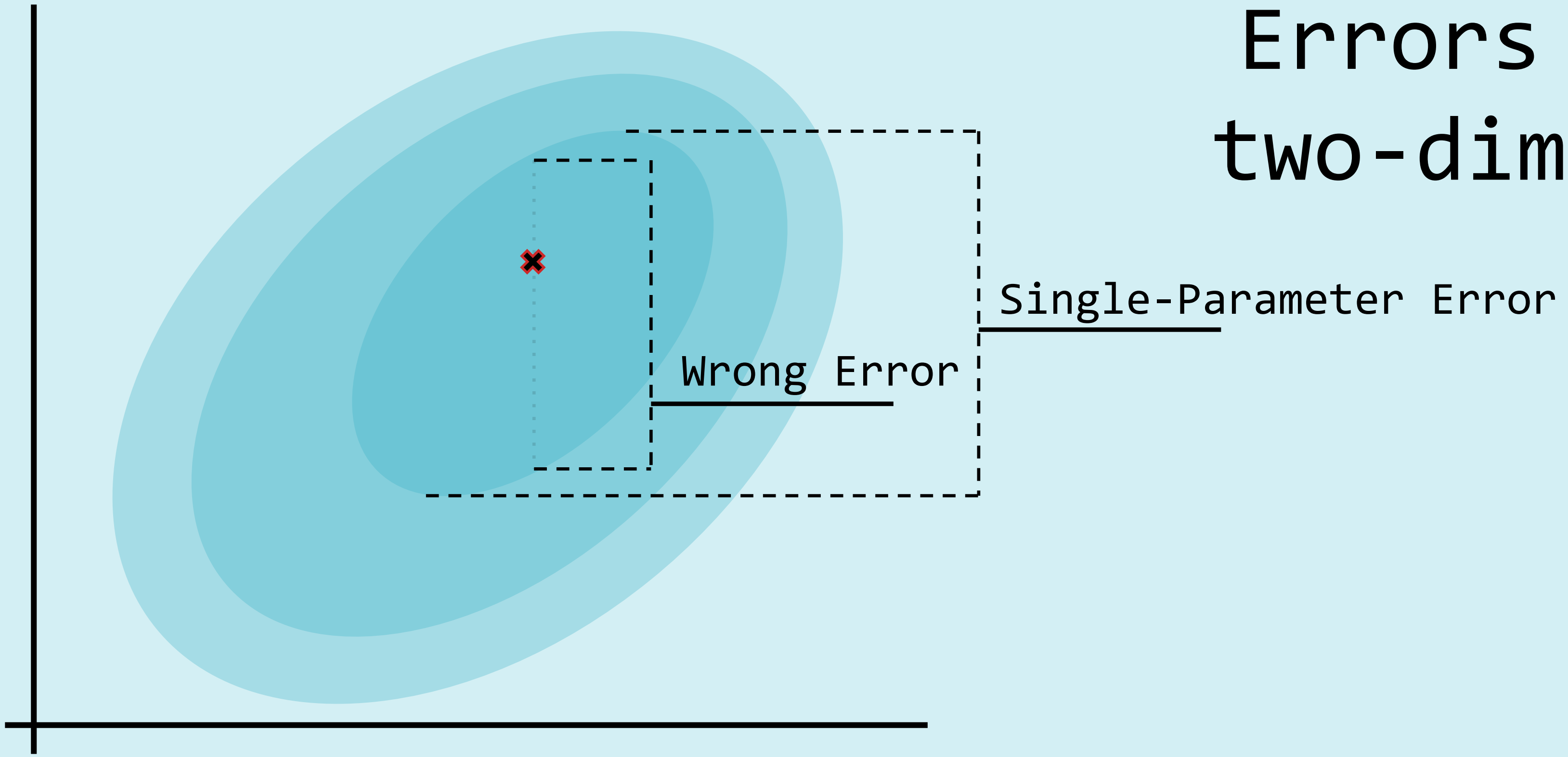
Errors are now two-dimensional

phabs x pow

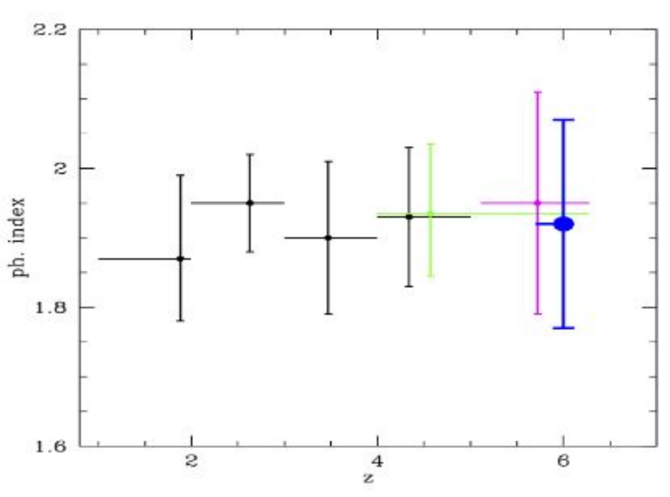
NH: Column Density
Gamma: Power Law Slope
norm: Power Law Normalization

Spectral fitting

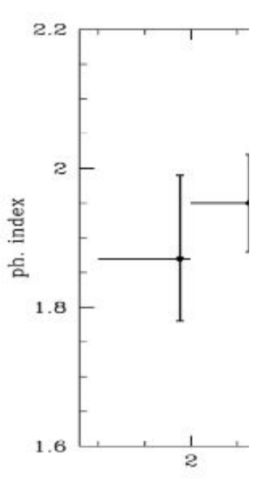
Errors are now two-dimensional



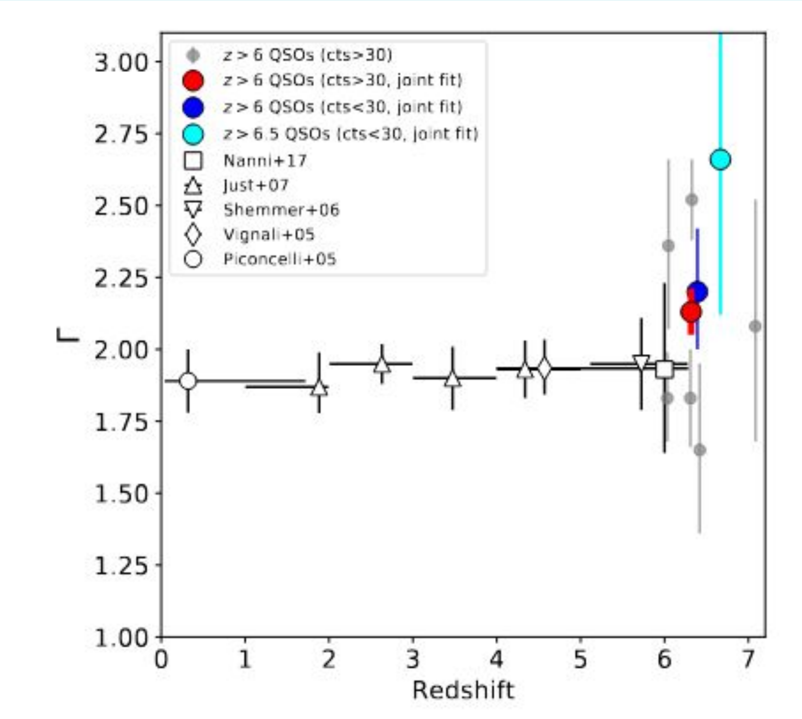
Average Spectral Index with redshift



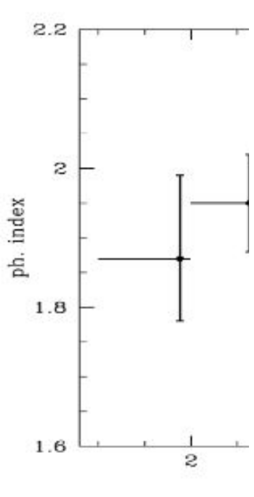
Nanni et al. 2017



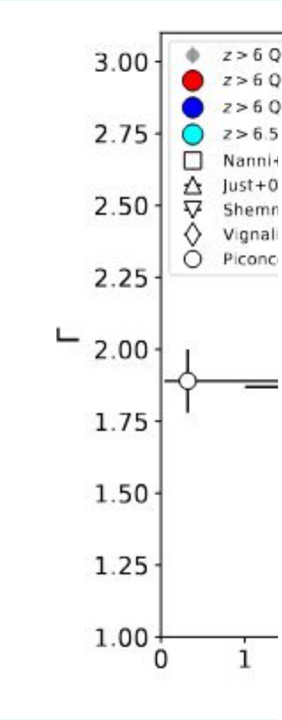
Nanni et a



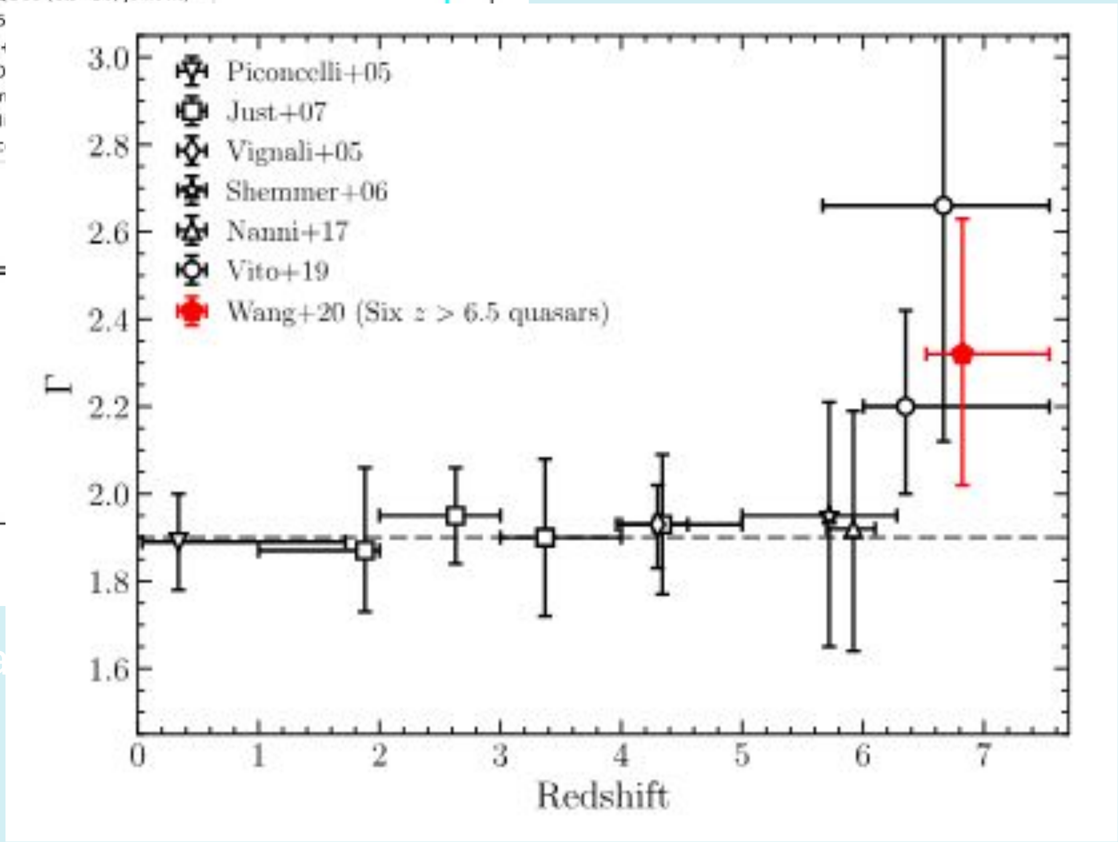
Vito et al. 2019



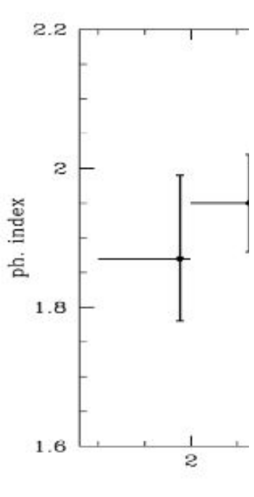
Nanni et a



Vito et a



Wang et al. 2021



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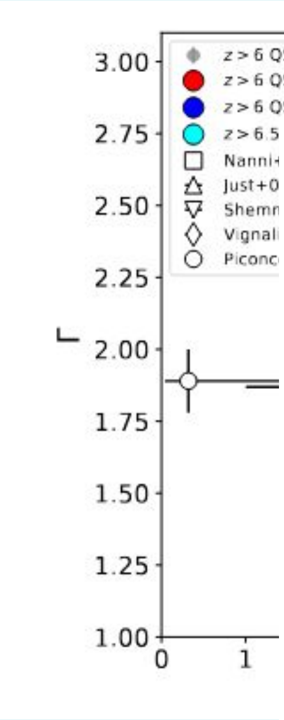
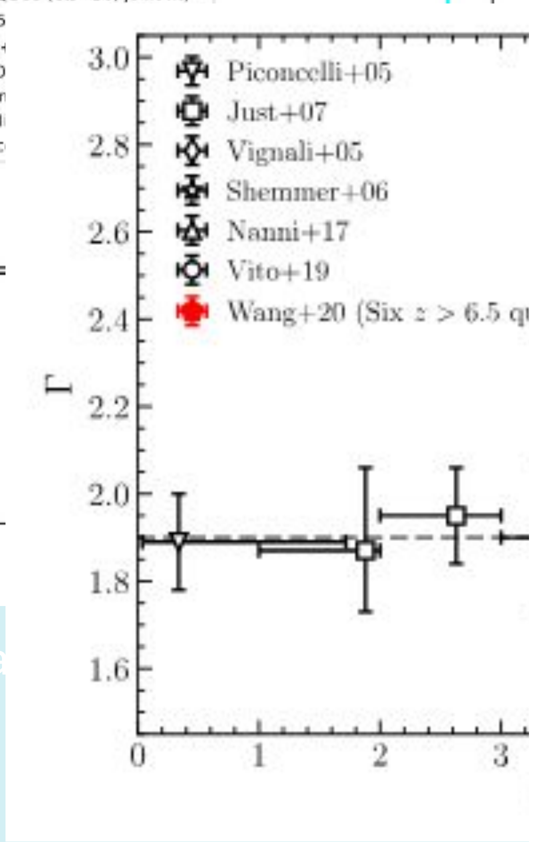
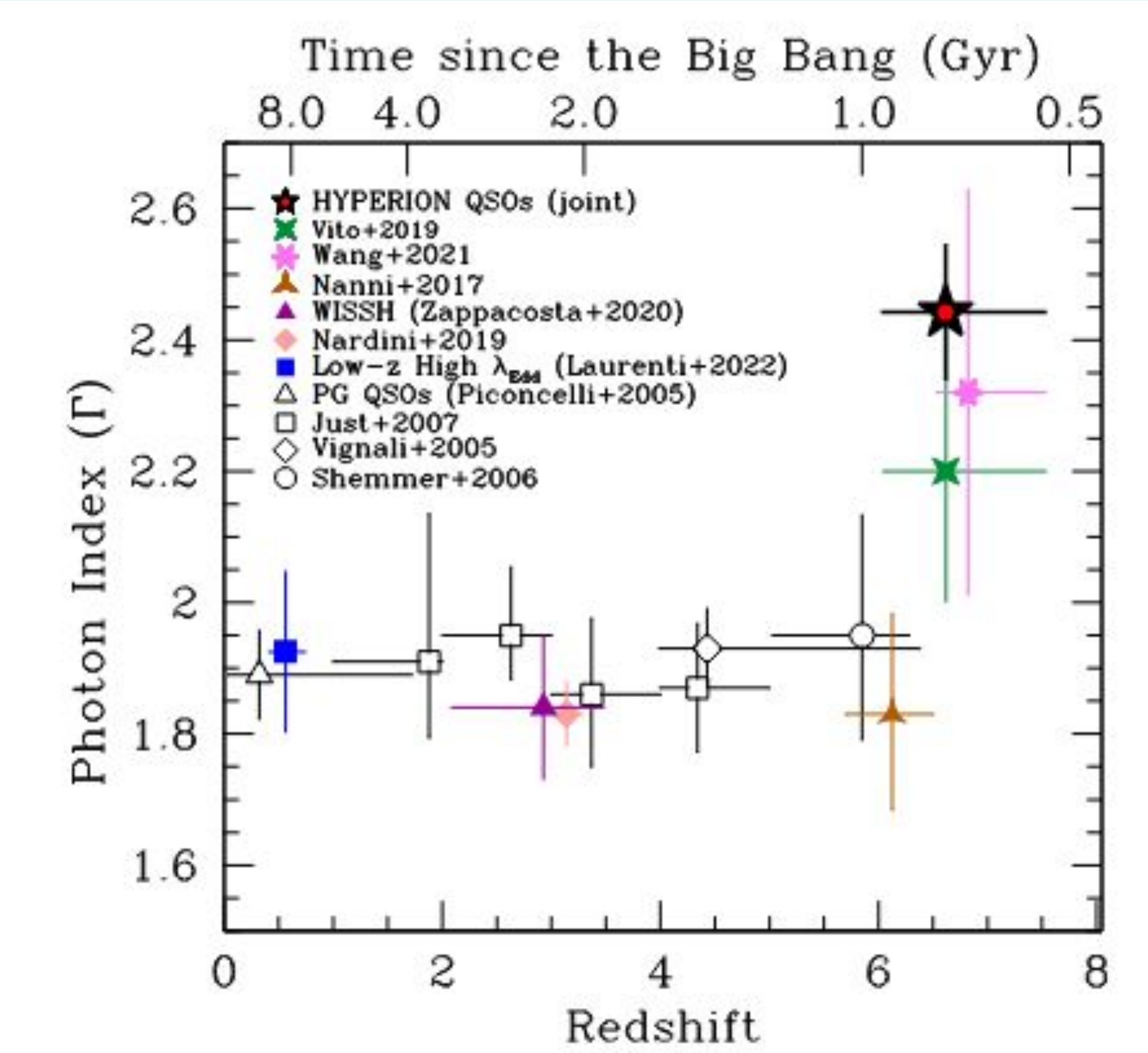


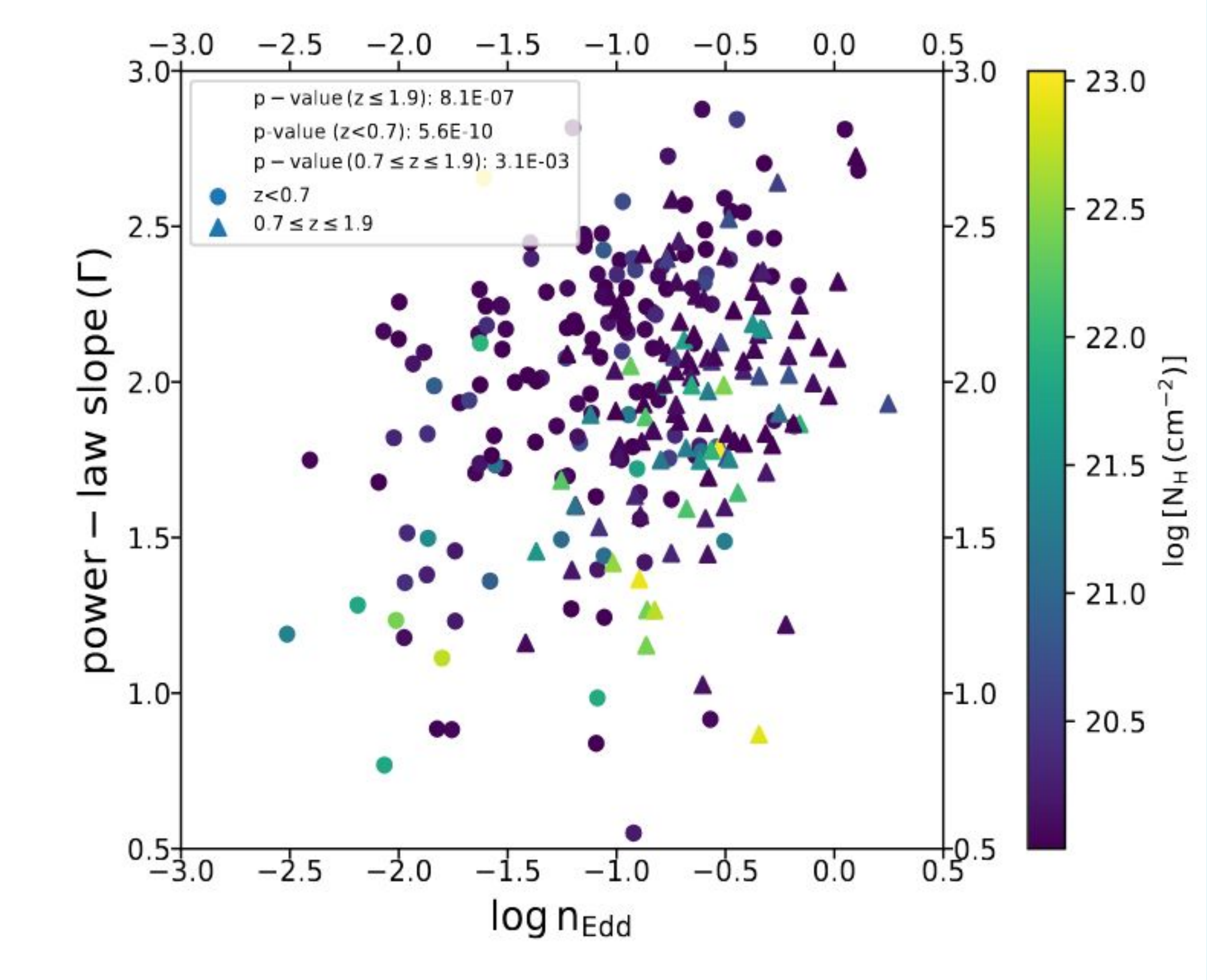
Vito et a



Wang et al. 2021



Zappacosta et al. 2023



Mountrichas et al. 2024

Γ correlates with Eddington rate

Tentative X-ray evidence for rapid ongoing accretion

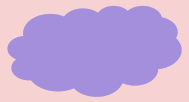
How did the first SMBHs form?

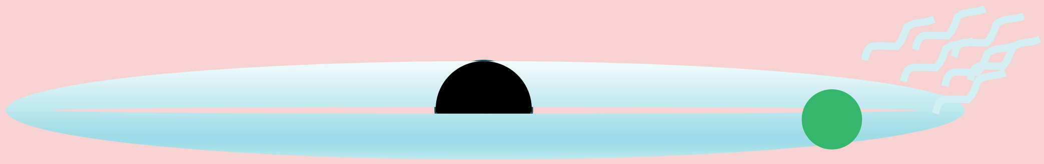
Question 3: What about just ignoring the Eddington Limit?

Is there other evidence for rapid growth?

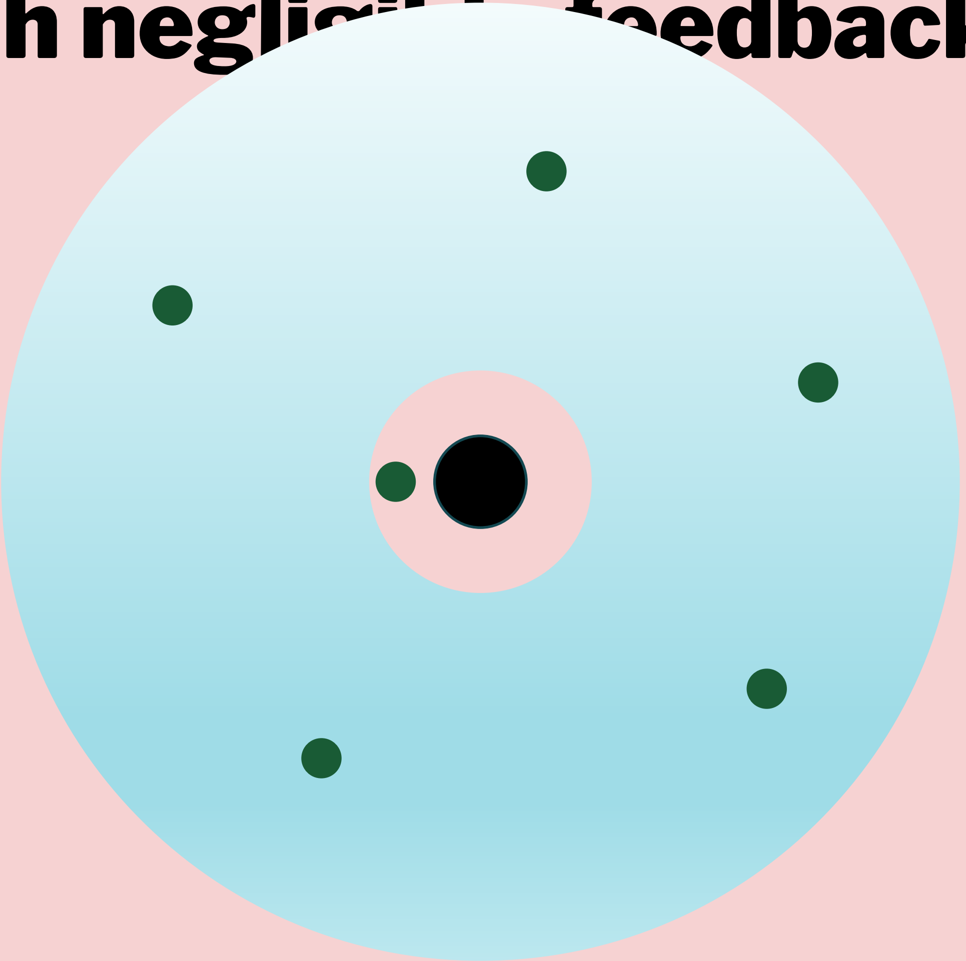
Note: These questions aren't going to have conclusive answers

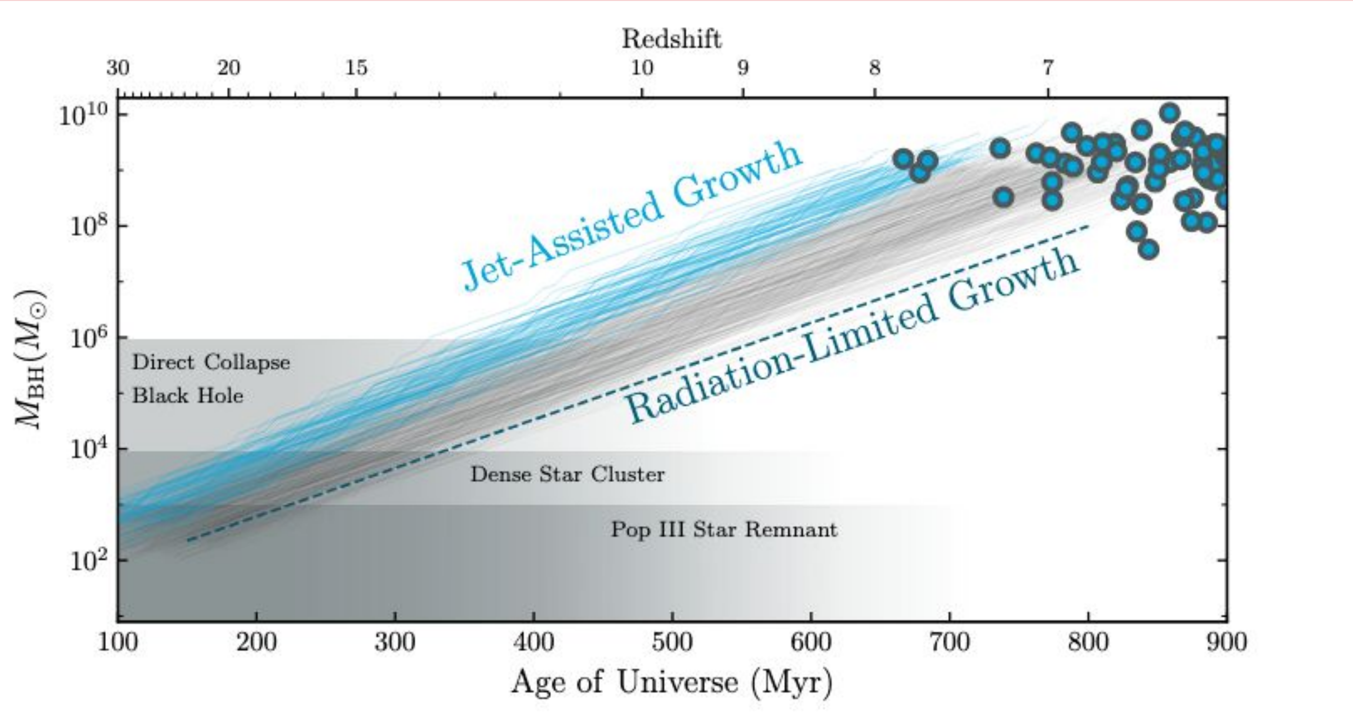
Disk radiation is how gravitational infall proceeds





Jets allow momentum/energy loss with negligible feedback

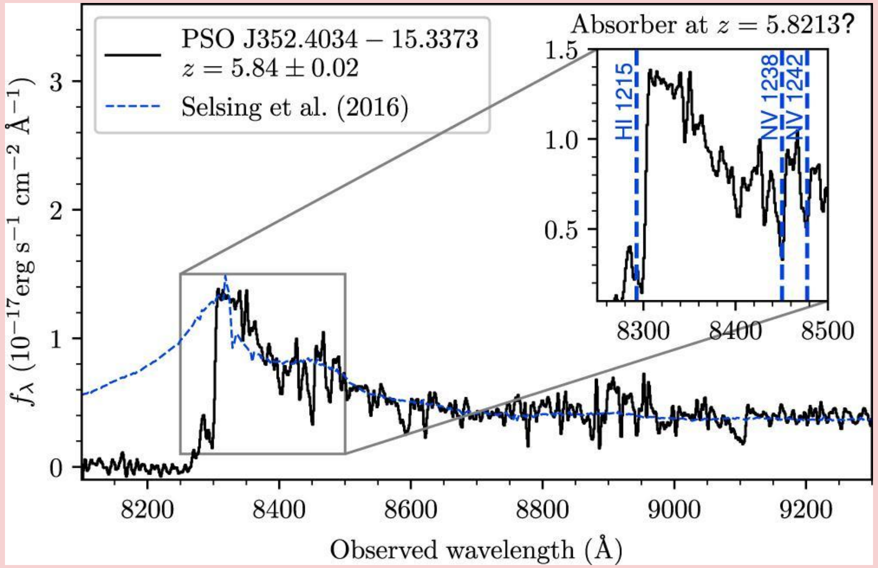




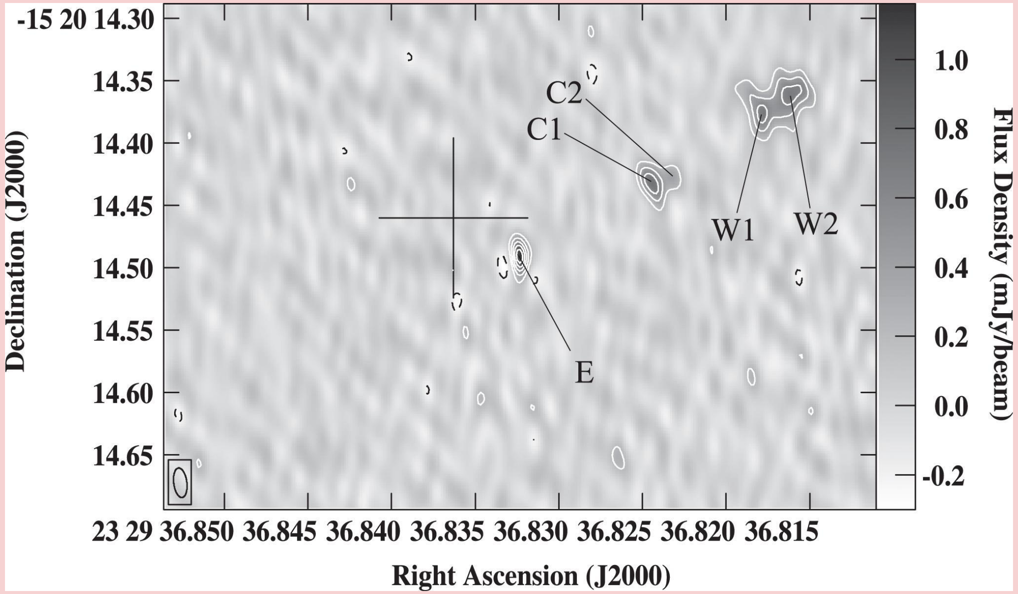
Connor et al. 2024

Jet-Assisted growth

If seen, would enable faster growth (and thus less massive seeds)



Bañados et al. 2018



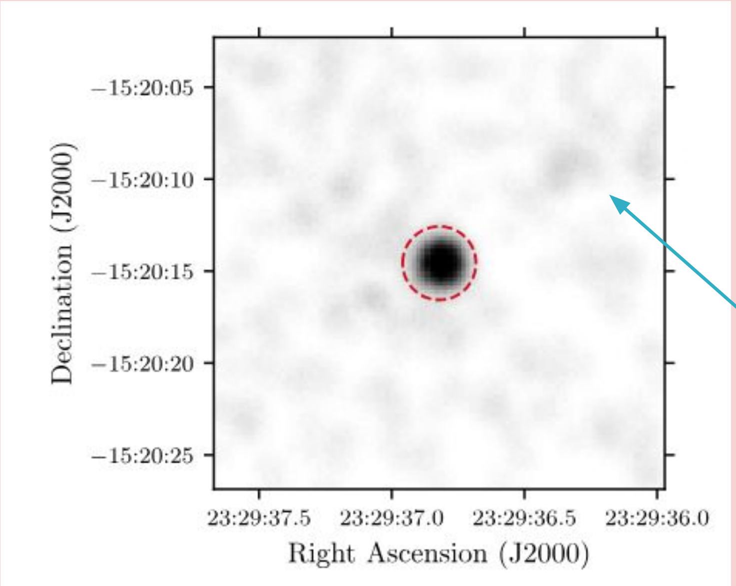
Momjian et al. 2018

A High-Redshift AGN

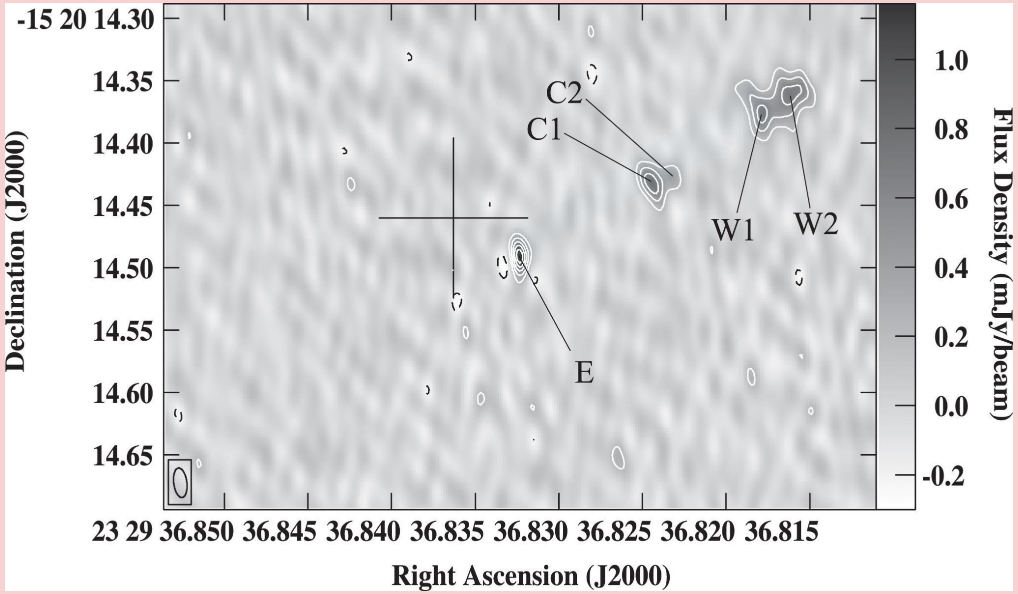
Jets seen at kpc scales by VLBA (radio) observations

Chandra Observations

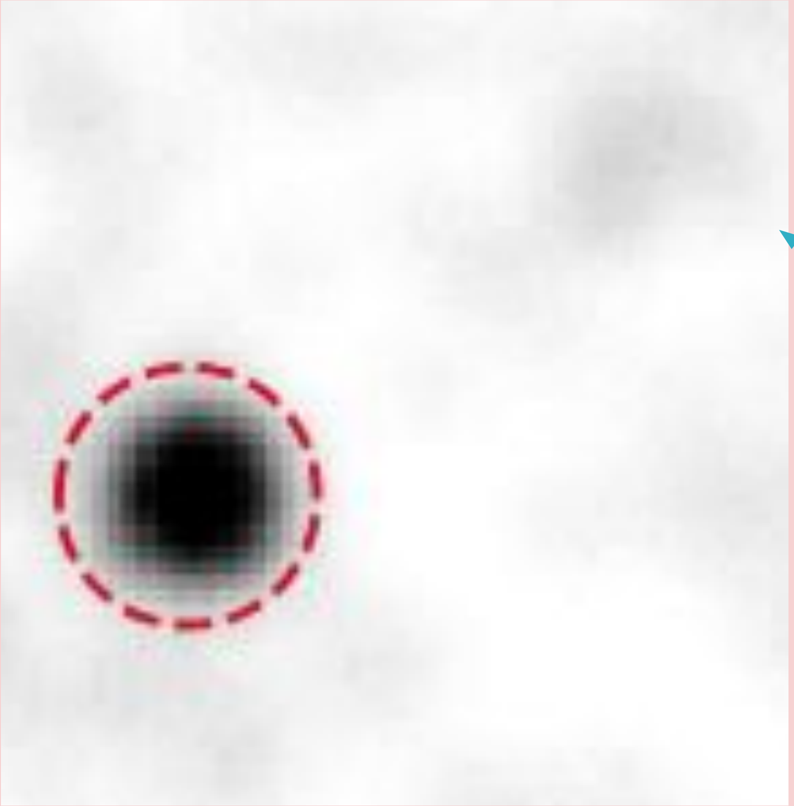
Flux enhancement at same angle – but much further away (~25 kpc)



Connor et al. 2021

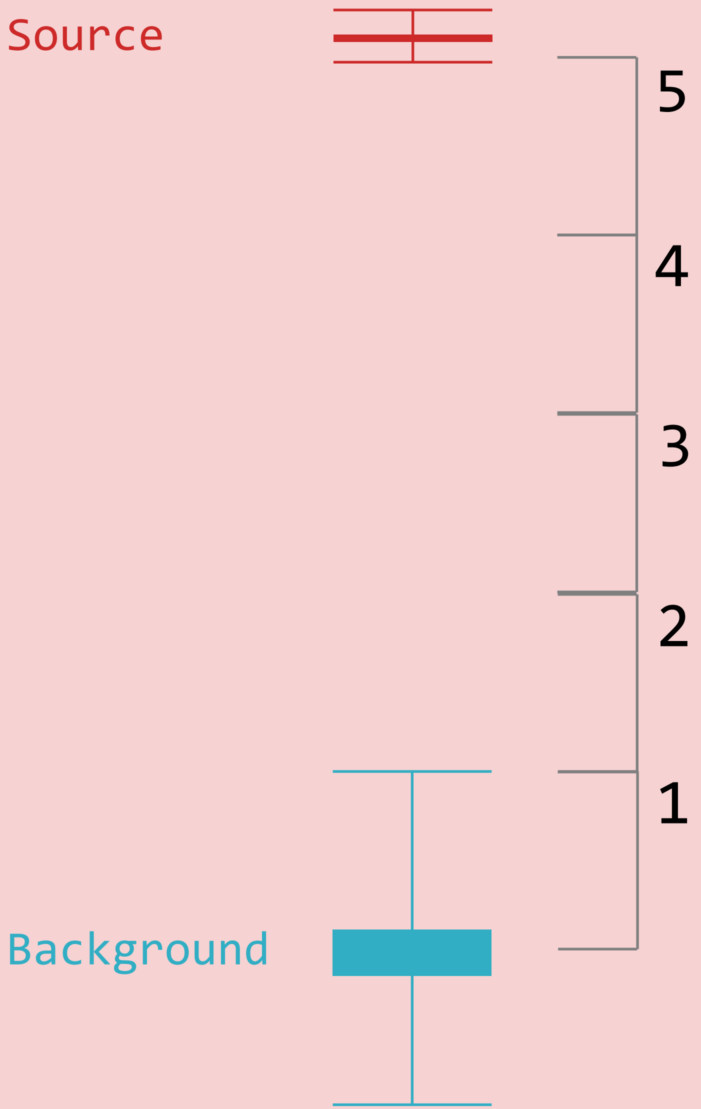


Momjian et al. 2018

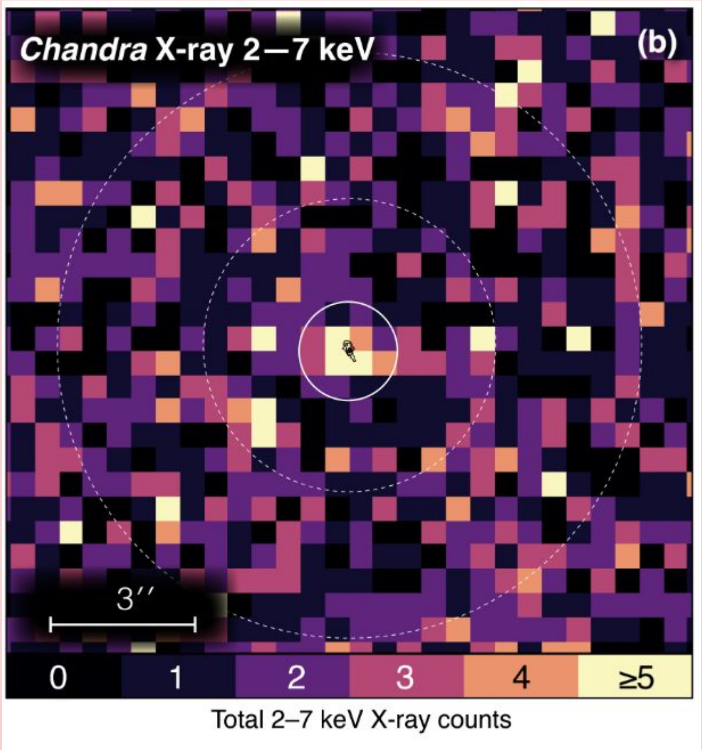


Significance

When background is Gaussian, significance can be measured in sigmas.



Significance

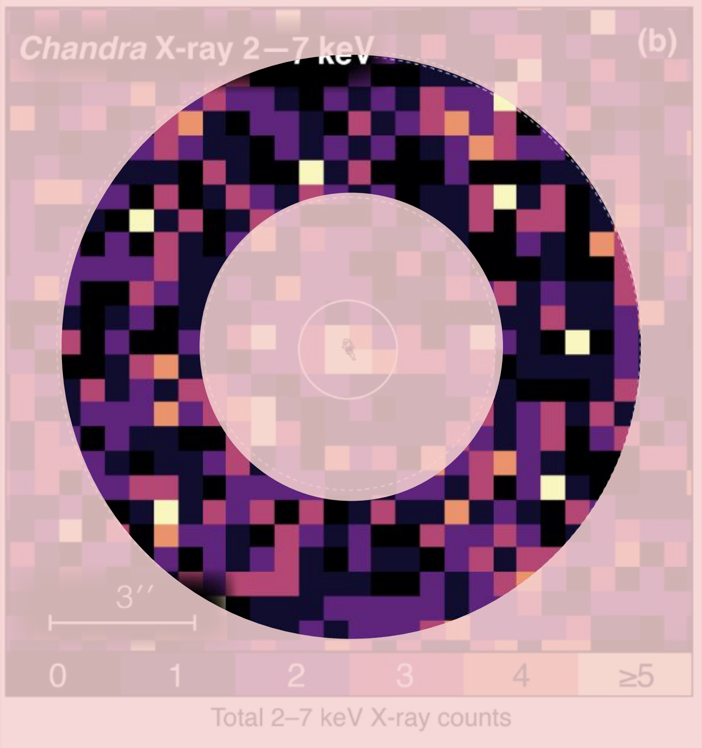


Bogdan et al. 2024

Our backgrounds aren't Gaussian.

Can 2 photons be significant?

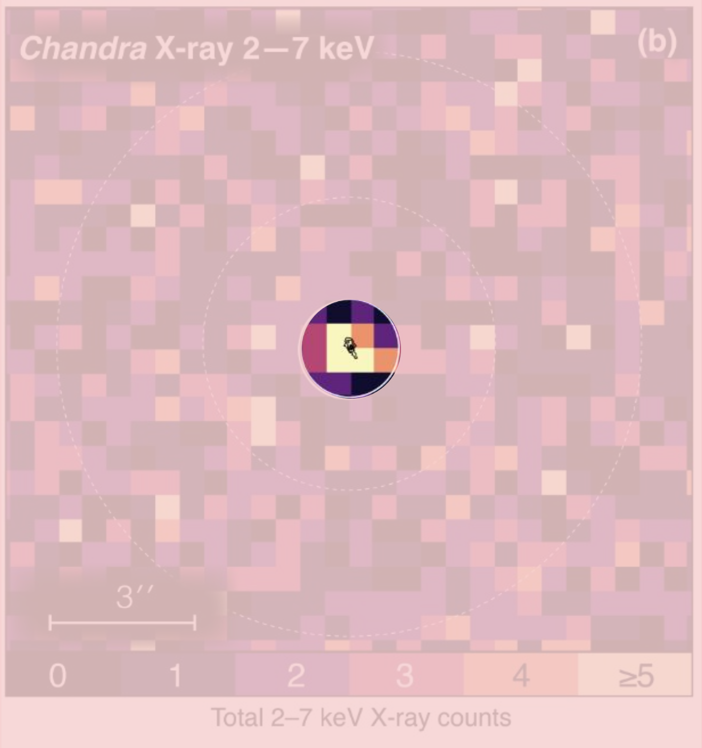
Significance



Bogdan et al. 2024

The backgrounds says you should expect 0.1 photons in a 1’’ radius aperture

Significance



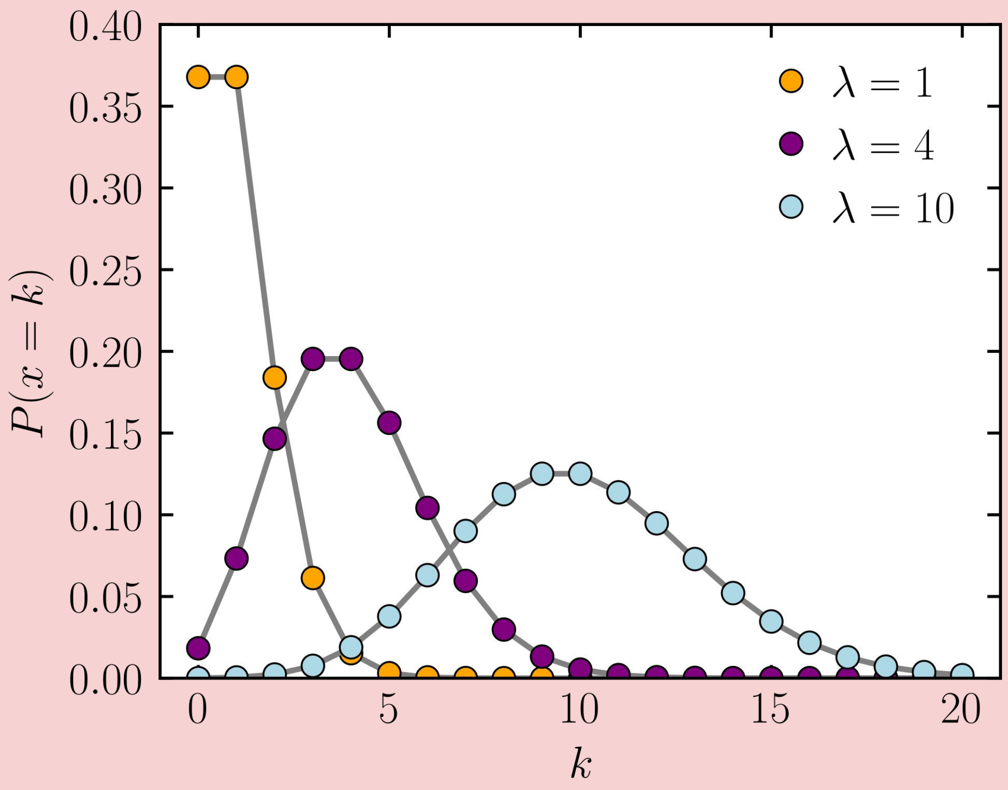
Bogdan et al. 2024

The backgrounds says you should expect 0.1 photons in a 1’’ radius aperture

And you detect two photons in that aperture…

Significance

I can tell when I'm not wanted...

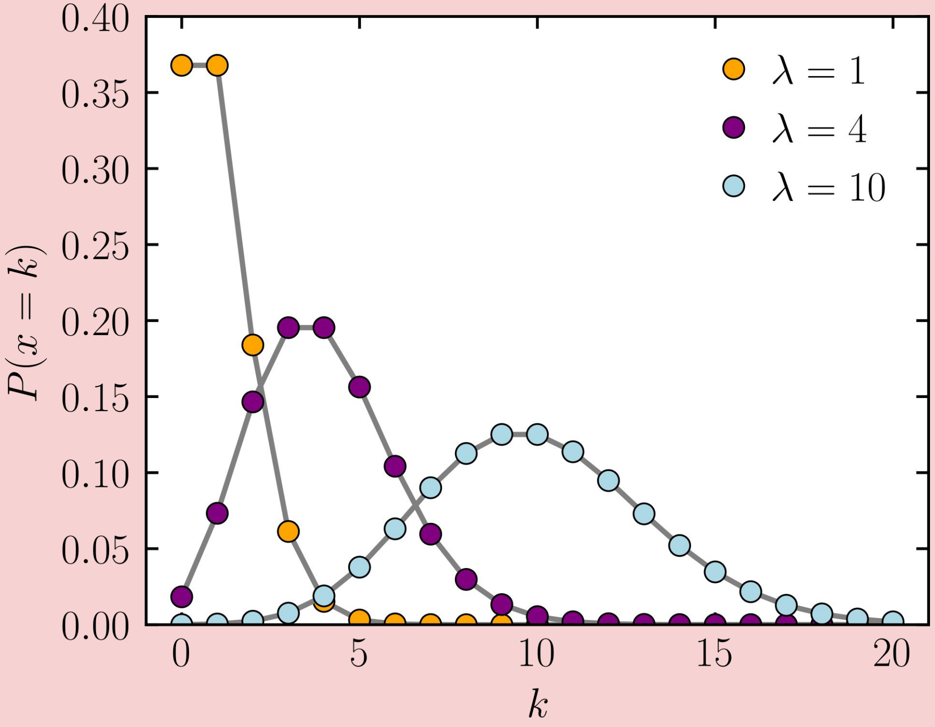


Poisson distribution:

Integer, >= 0

Significance

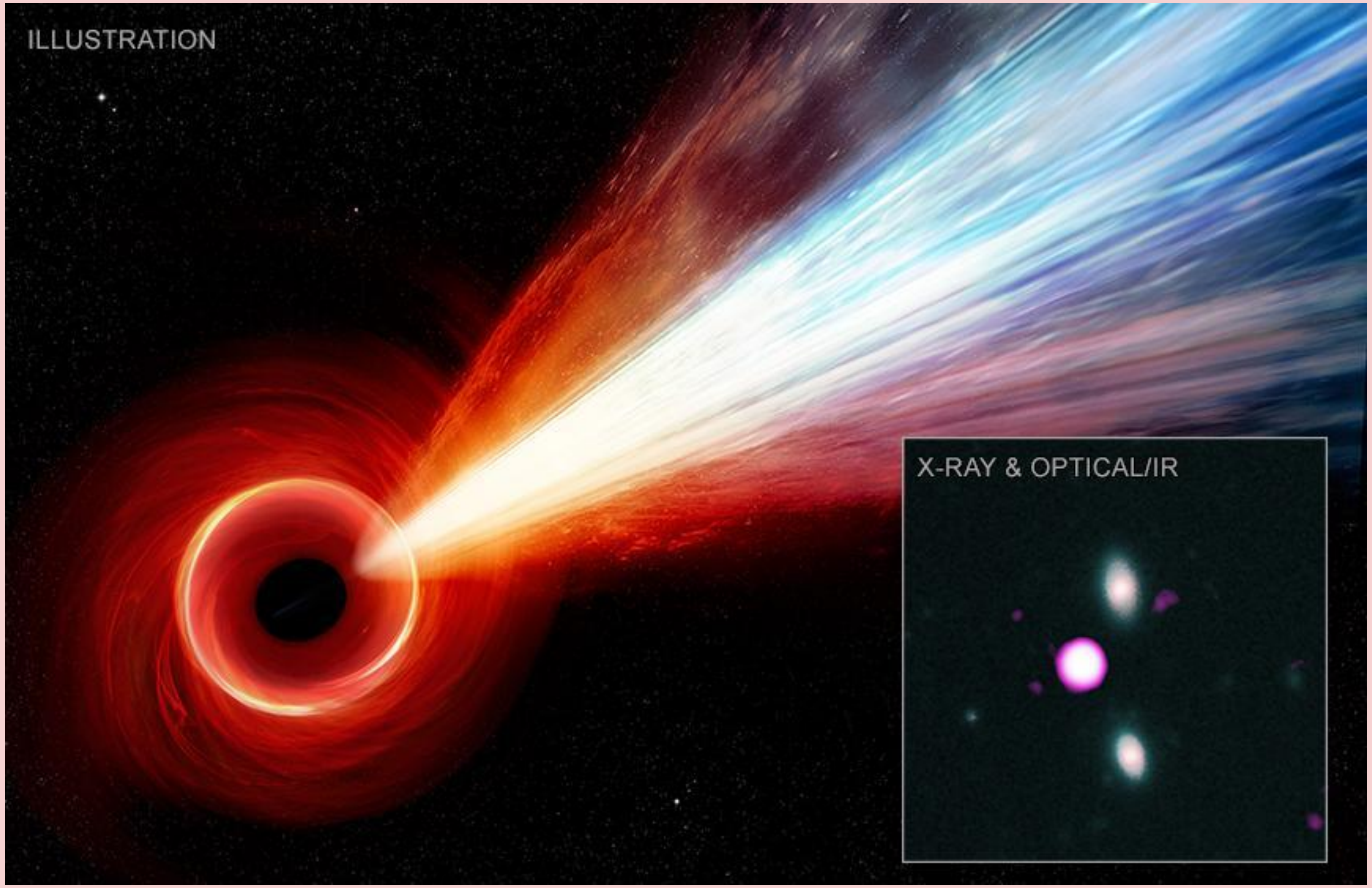
$$\Pr(X{=}k) = \frac{\lambda^k e^{-\lambda}}{k!},$$



If expectation is 0.1
And seen is 2

P(>=2) = 0.00468

It is *highly unlikely* the background could generate that many counts



X-ray jets ARE out there

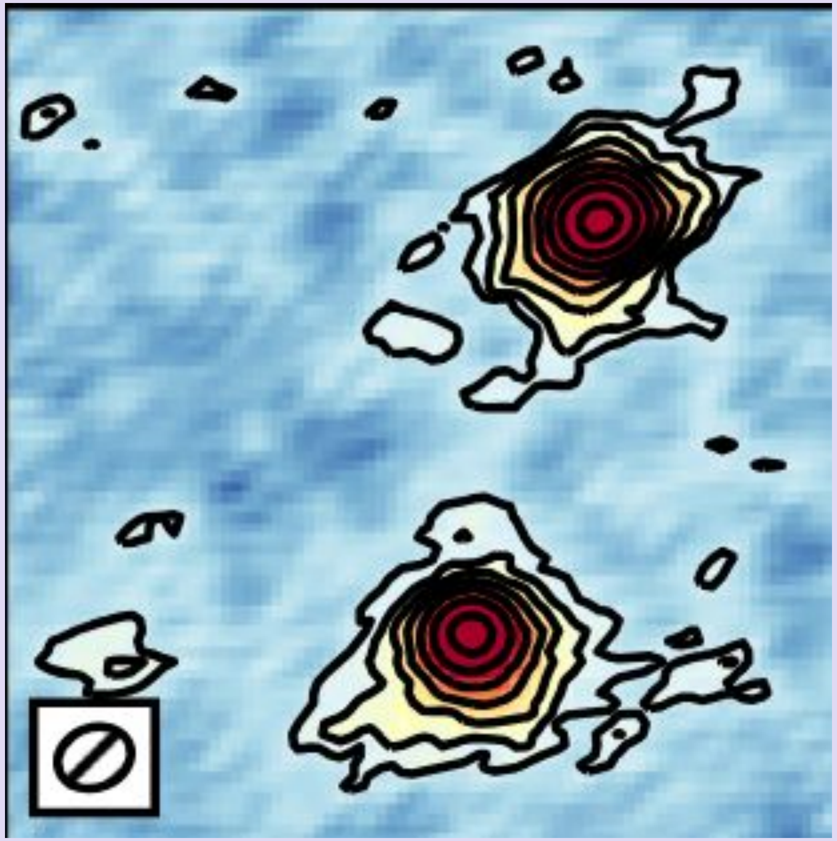
They’re just faint

How did the first SMBHs form?

Question 4: Do all massive galaxies at high redshift host AGN?

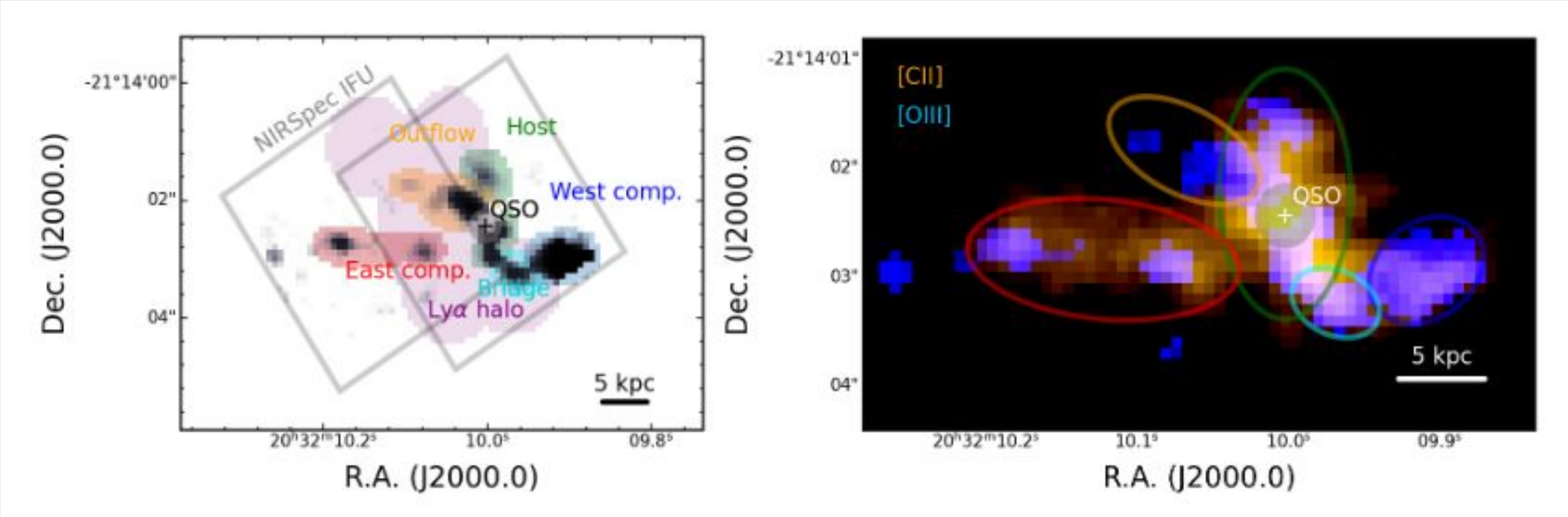
Or are we looking at special snowflakes?

Note: These questions aren’t going to have conclusive answers



Neeleman et al. 2019

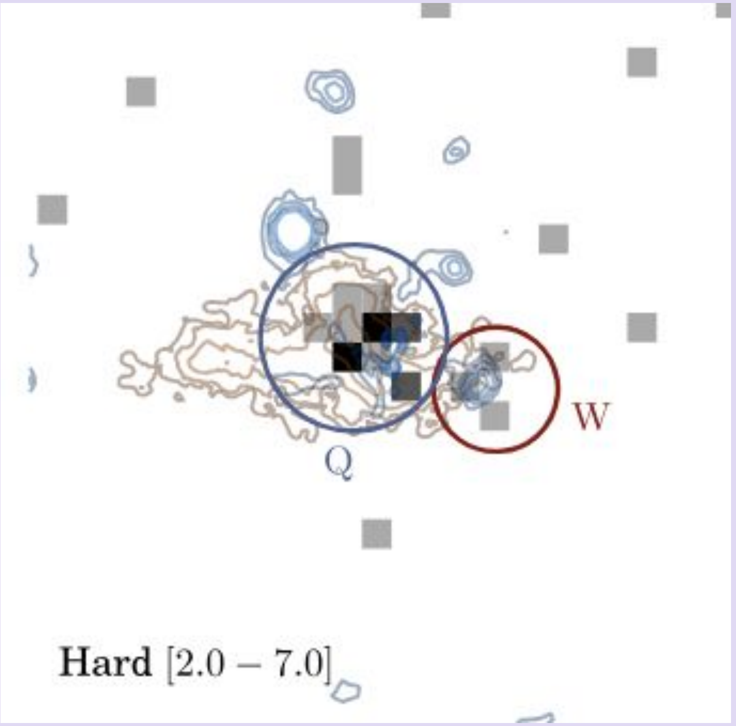
Sub-mm observations of high-z quasars show equally massive companion galaxies



Decarli et al. 2024

One of particular note is undergoing a merger

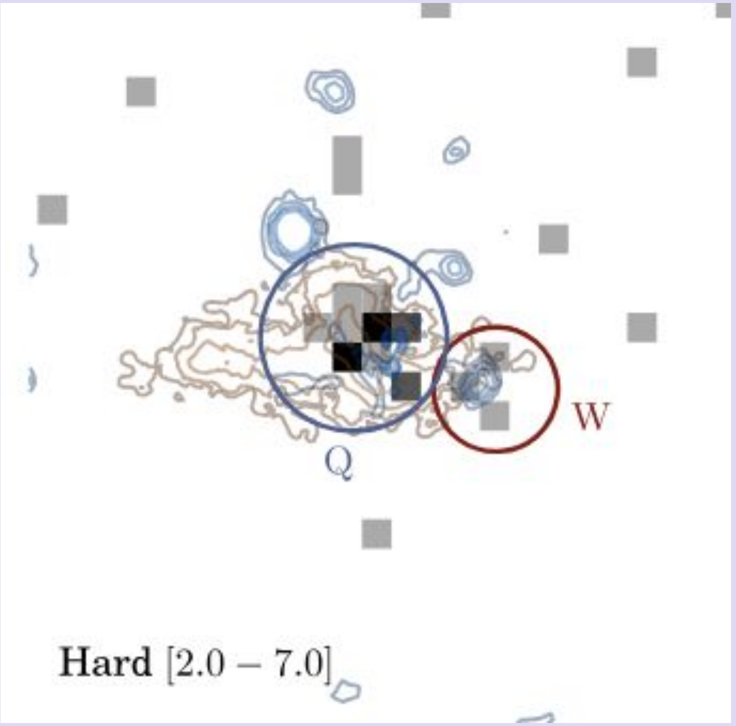
Does the companion galaxy ALSO host a massive AGN?



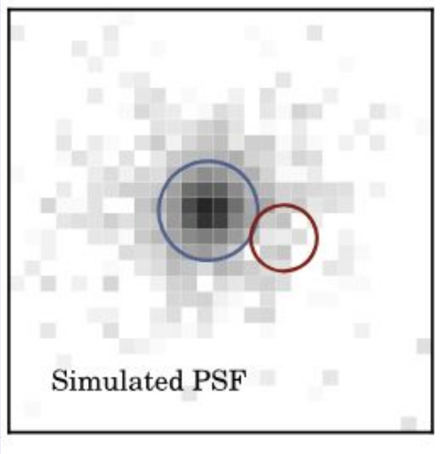
Connor et al. 2019

Three counts in Chandra hard-band image

Clear detection over background (P=0.013)



Connor et al. 2019



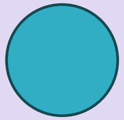
Three counts in Chandra hard-band image

Clear detection over background (P=0.013)

But what about the contribution from the quasar?

Simulating a PSF

Source Properties

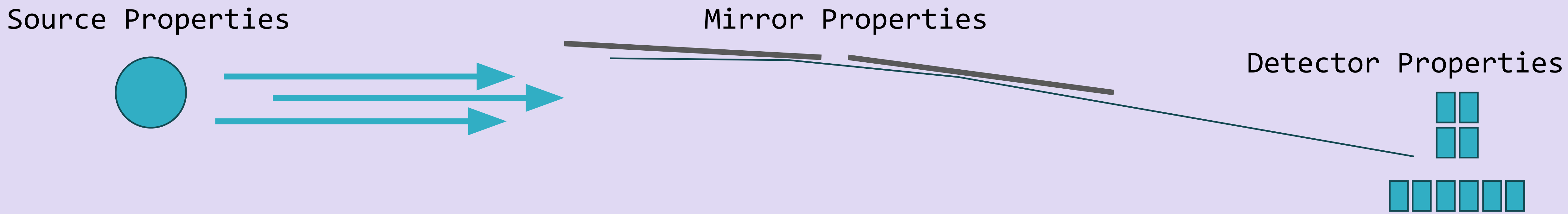


Simulating a PSF

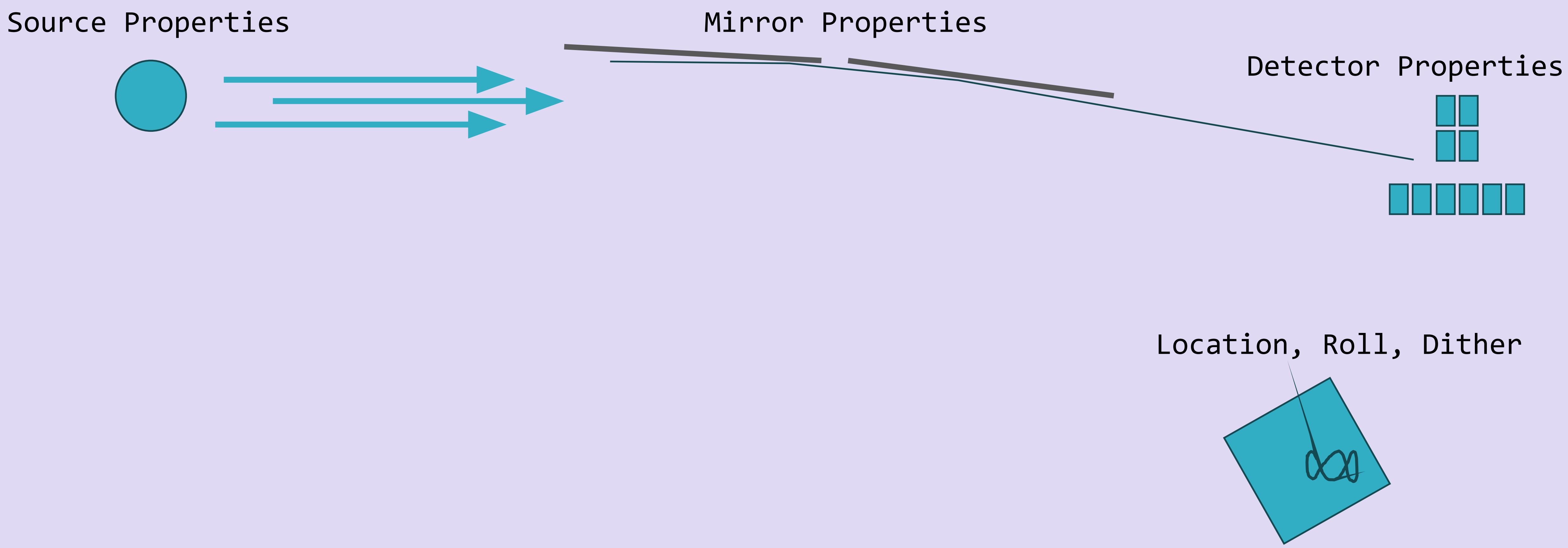
Source Properties

Mirror Properties

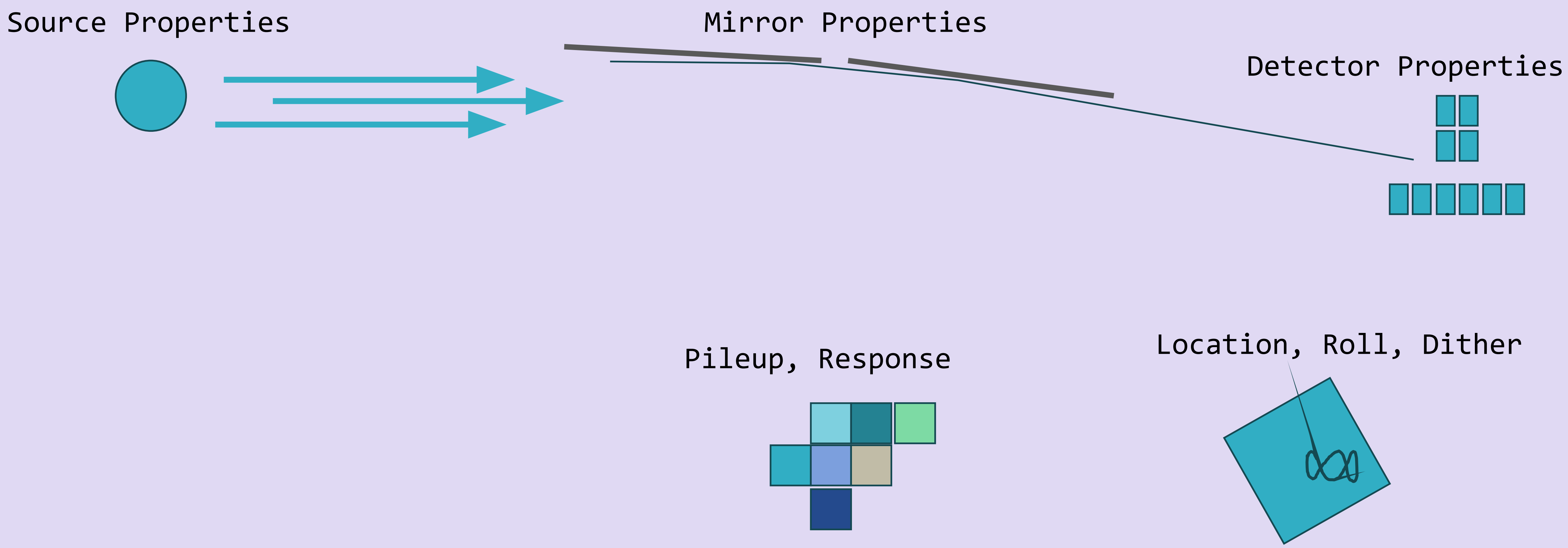
Simulating a PSF



Simulating a PSF



Simulating a PSF

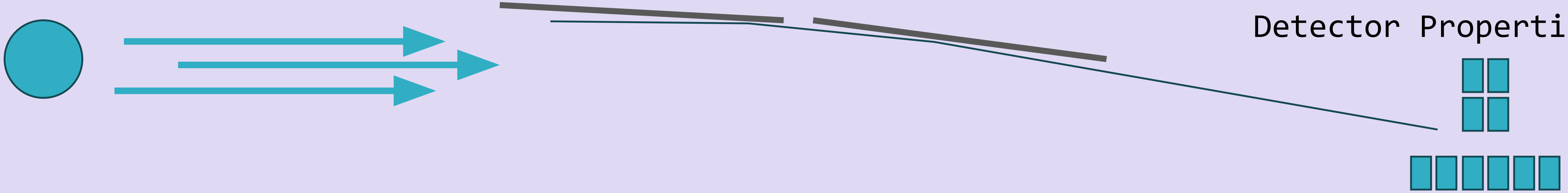


Simulating a PSF

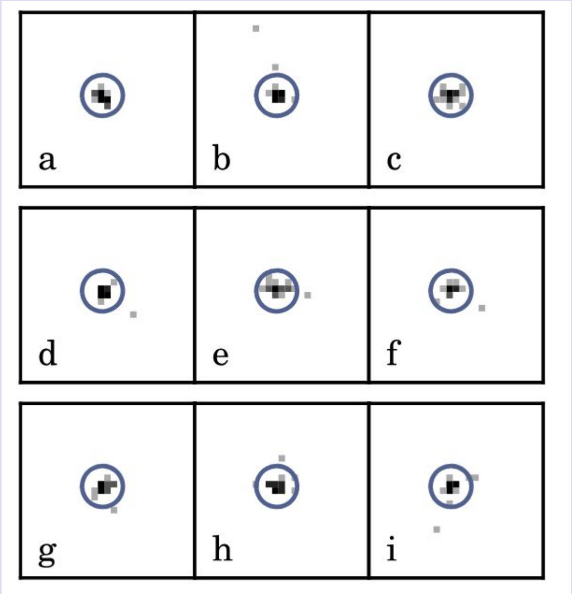
Source Properties

Mirror Properties

Detector Properties

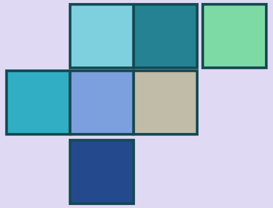


Simulated Events Files

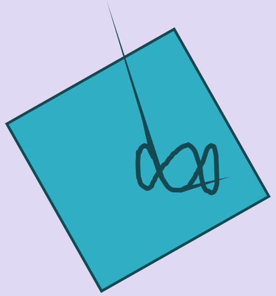


Connor et al. 2019

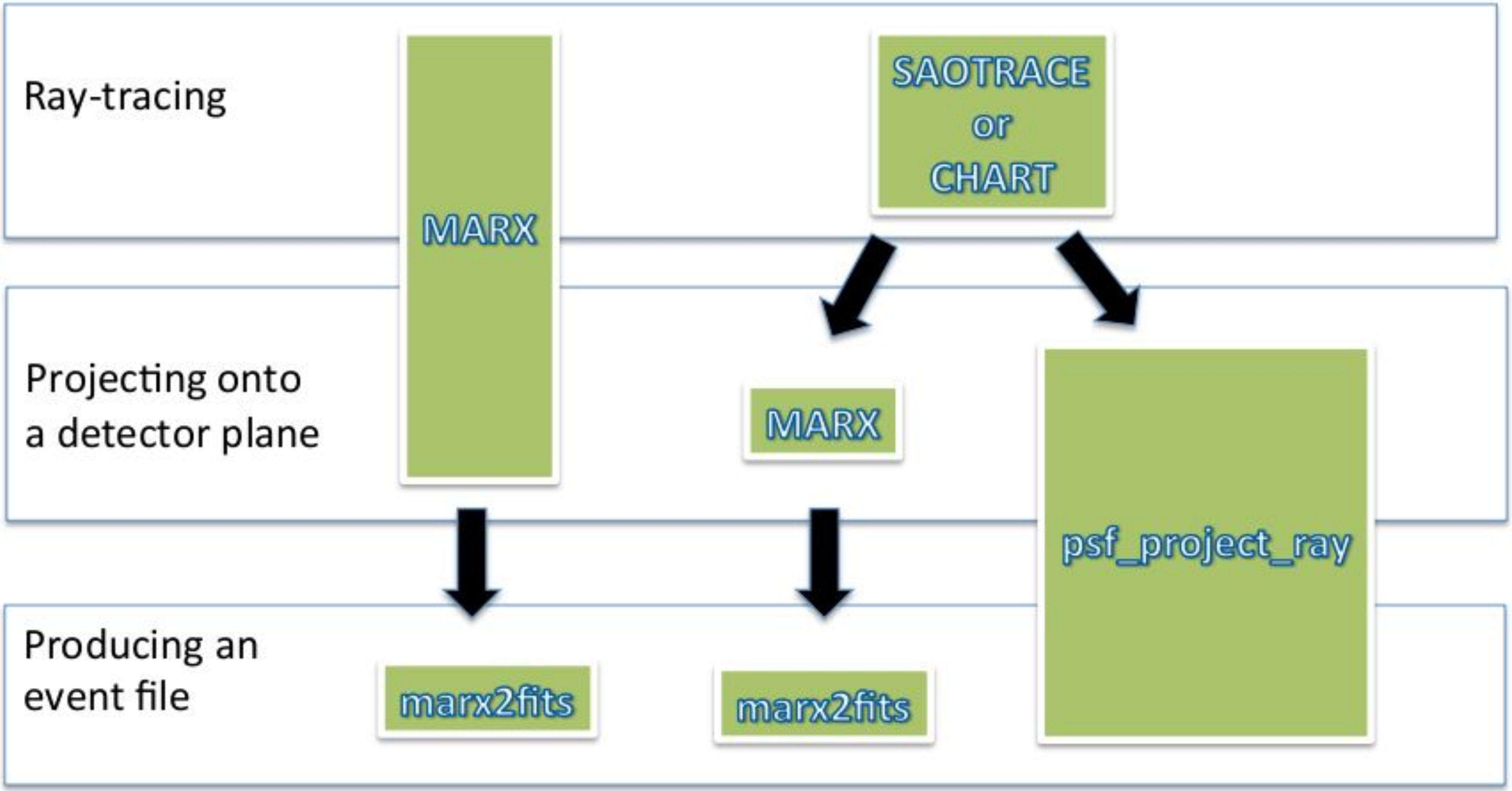
Pileup, Response

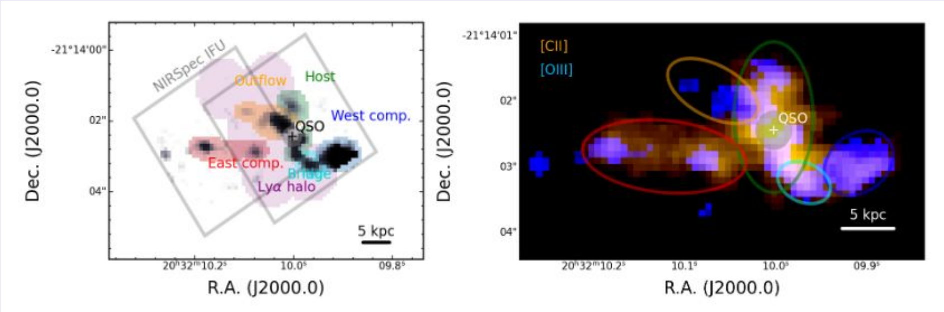


Location, Roll, Dither



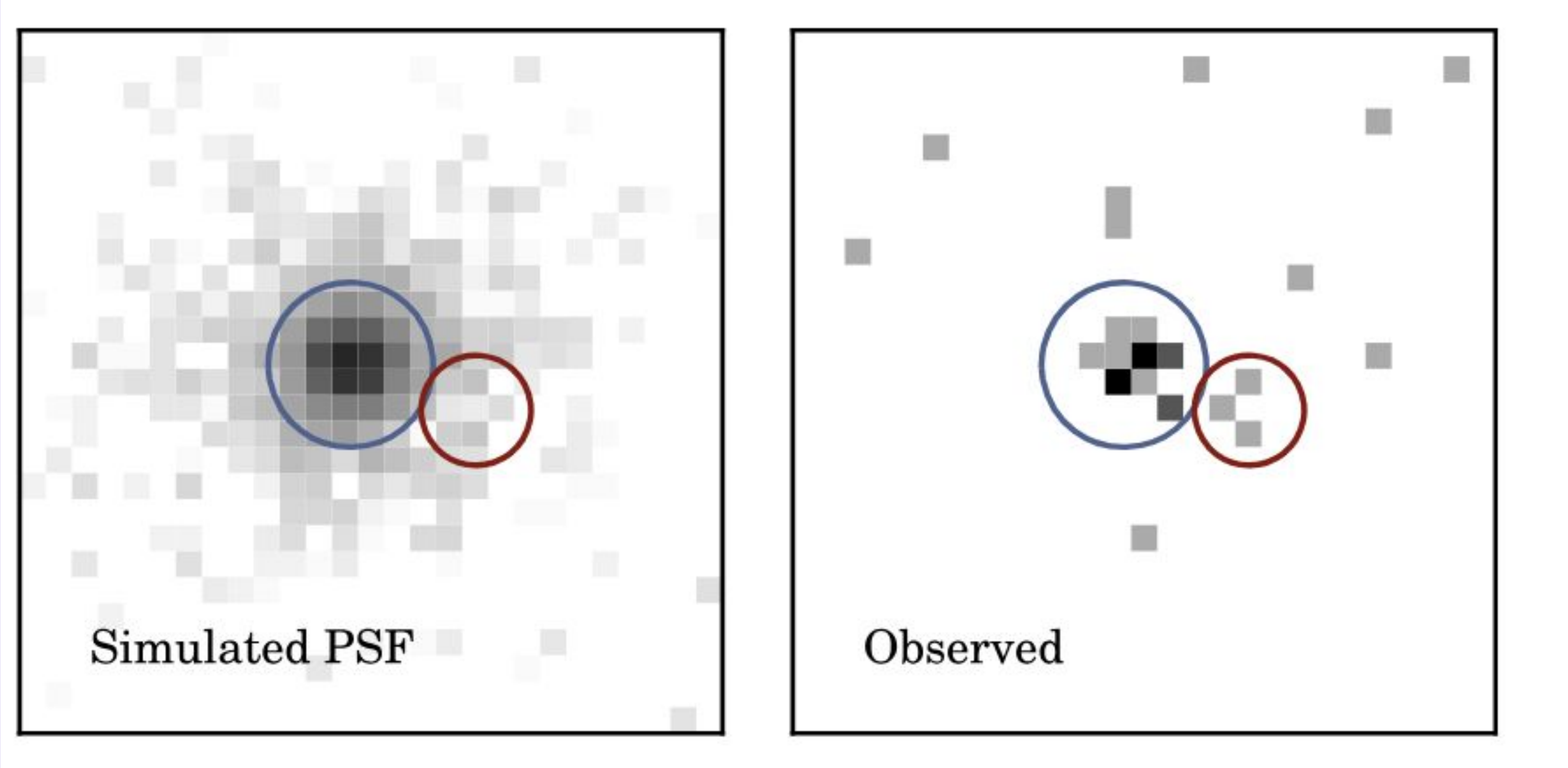
From PSF model to event file



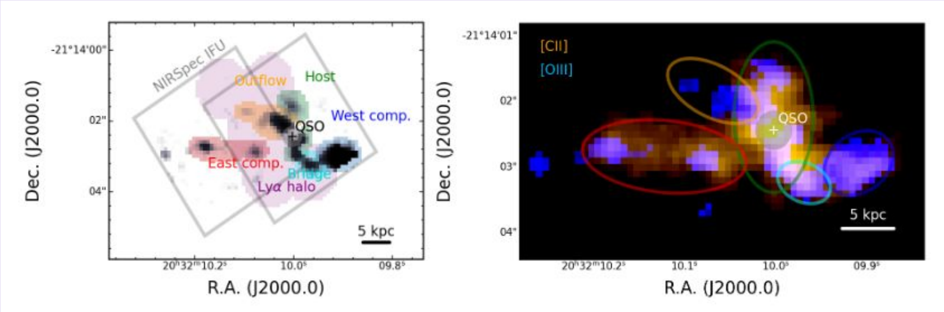


Decarli et al. 2024

Background: P=0.013
+PSF: P=0.021



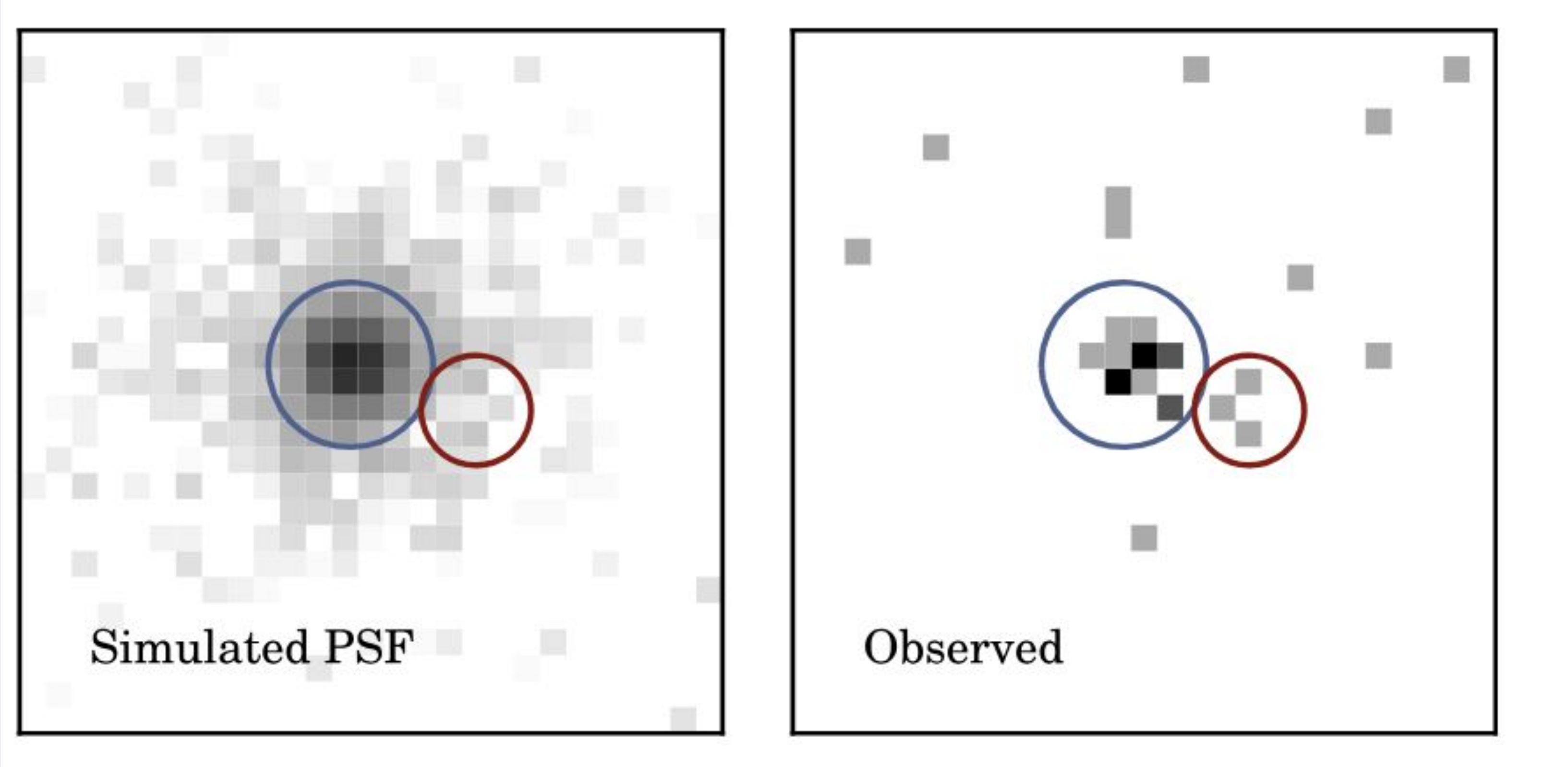
Connor et al. 2019



Decarli et al. 2024

Background: P=0.013

+PSF: P=0.021



Connor et al. 2019

Deeper exposure needed!

Summary (Scientific)

- Building the first SMBHs requires rapid growth from massive seeds
- There seems to be evidence from X-rays for Eddington growth
- Growing evidence for jets, which could rachet growth up even further
- Detection of companion AGN still beyond current observations

Summary (Technical)

- In low counts regime, keep models simple
- Gaussianity is almost never applicable
- Fluxes are observed, luminosities are intrinsic, but when you lack photons they need to come from the model
- Backgrounds are Poisson
- Source modeling is non-trivial, but well documented

And the HelpDesk and Documentation are there to help!