Quasars and Gravitational Lensing:
A case study in X-ray analysis

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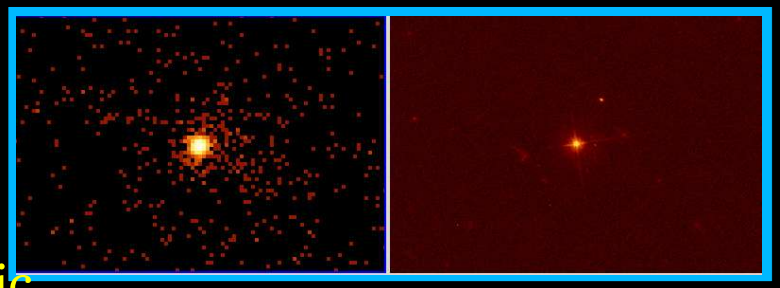
OVERVIEW

- Structure and absorption in AGN
- Broad Absorption Line (BAL) QSOs
- UM425: Characteristics and motivation for Chandra observation
- Gravitational Lensing
- UM425 data: first look
- Spectral analysis
  - UM425A (high counts)
  - UM425B (low counts)
- Image analysis
- Lensing and microlensing in AGN

Structure of AGN

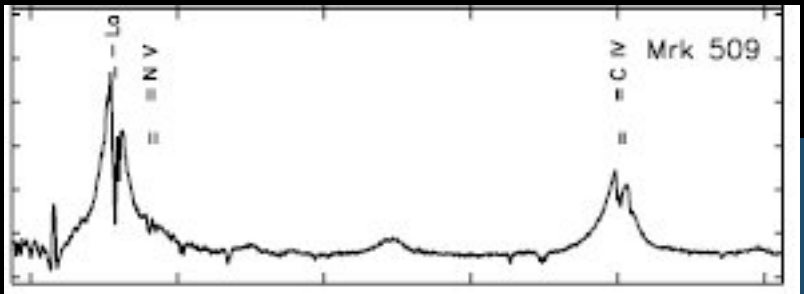


- What does a QSO look like?
- Jets, bi-conical outflows, dusty torus
- Quasars are not spherically symmetric
- Direct imaging of central engine of AGN including accretion disk and BELR will require significant technological advances

BELR has variability on ~month timescale => ~0.1 pc size
Direct imaging requires 10 micro-arcsec resolution
=> 100 km ground-based IR interferometer
=> 10 km space-based UV interferometer
Optical/X-ray continuum regions even smaller (by factors of 10 - 100)

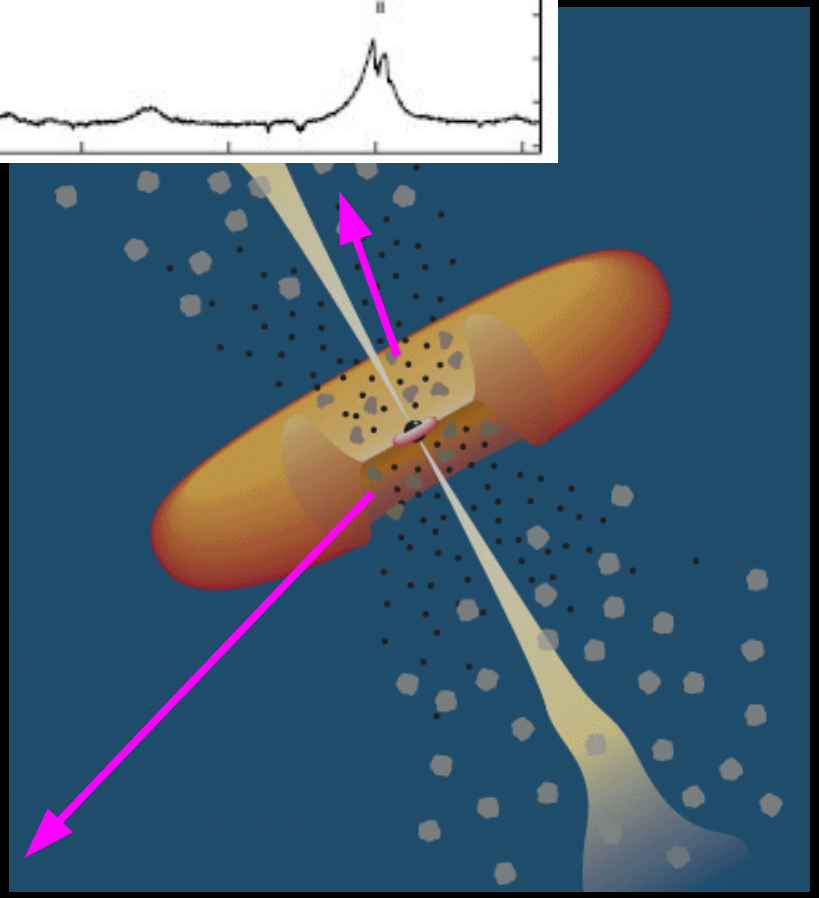
- Most of what we know about AGN central engine depends on photometry, spectroscopy and people with good imaginations

Structure of AGN

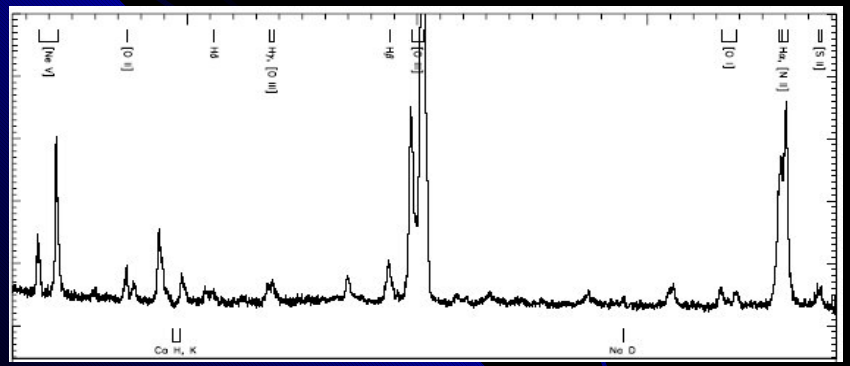


Scales for $M=10^8\ M_\odot$

Black hole	3×10^{13} cm
Accretion disk	$1\text{-}30\times10^{14}$ cm
BLR	$2\text{-}20\times10^{16}$ cm
Torus	10^{17} cm ??
NLR	$10^{18}\text{-}10^{20}$ cm
Jets	$10^{17}\text{-}10^{24}$ cm



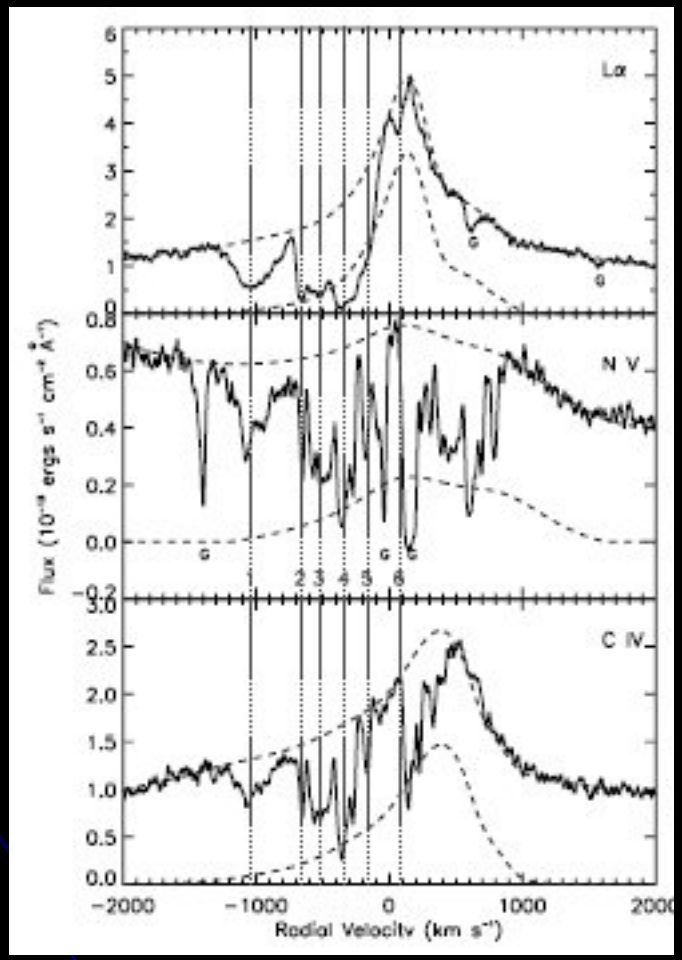
- This picture based on integrated emission is only part of the story!



Urry C.M. & Padovani P. 1995 PASP, 107, 803. [727 ADS citations]

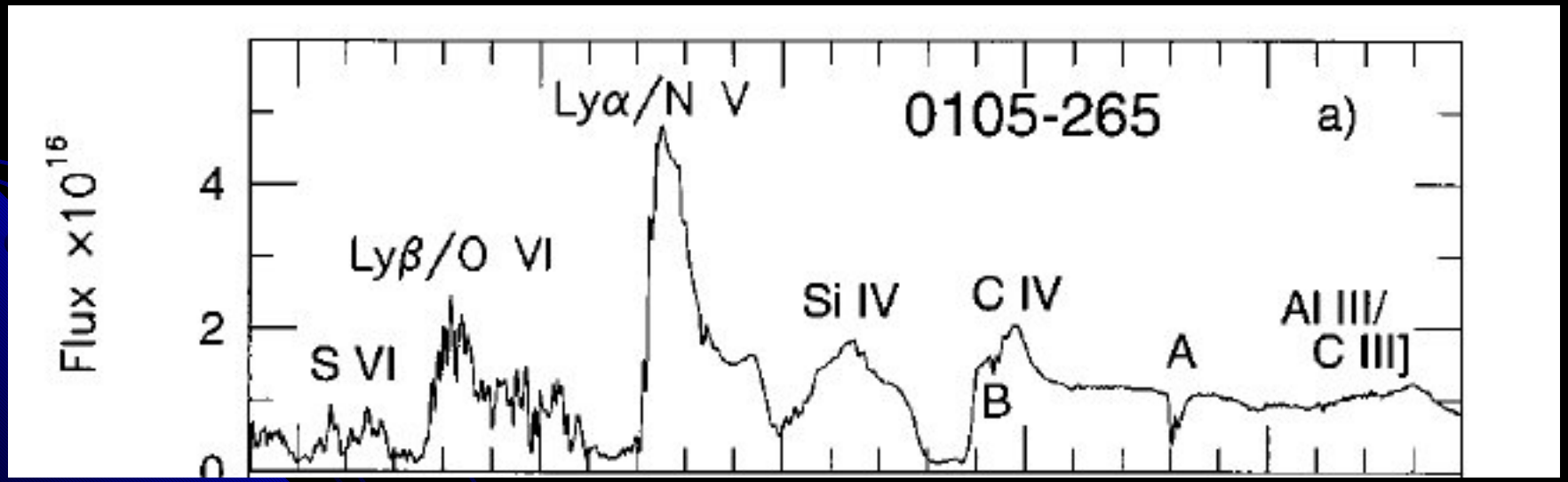
Absorbing outflows in AGN

- AGN of all stripes show absorption in optical through X-ray

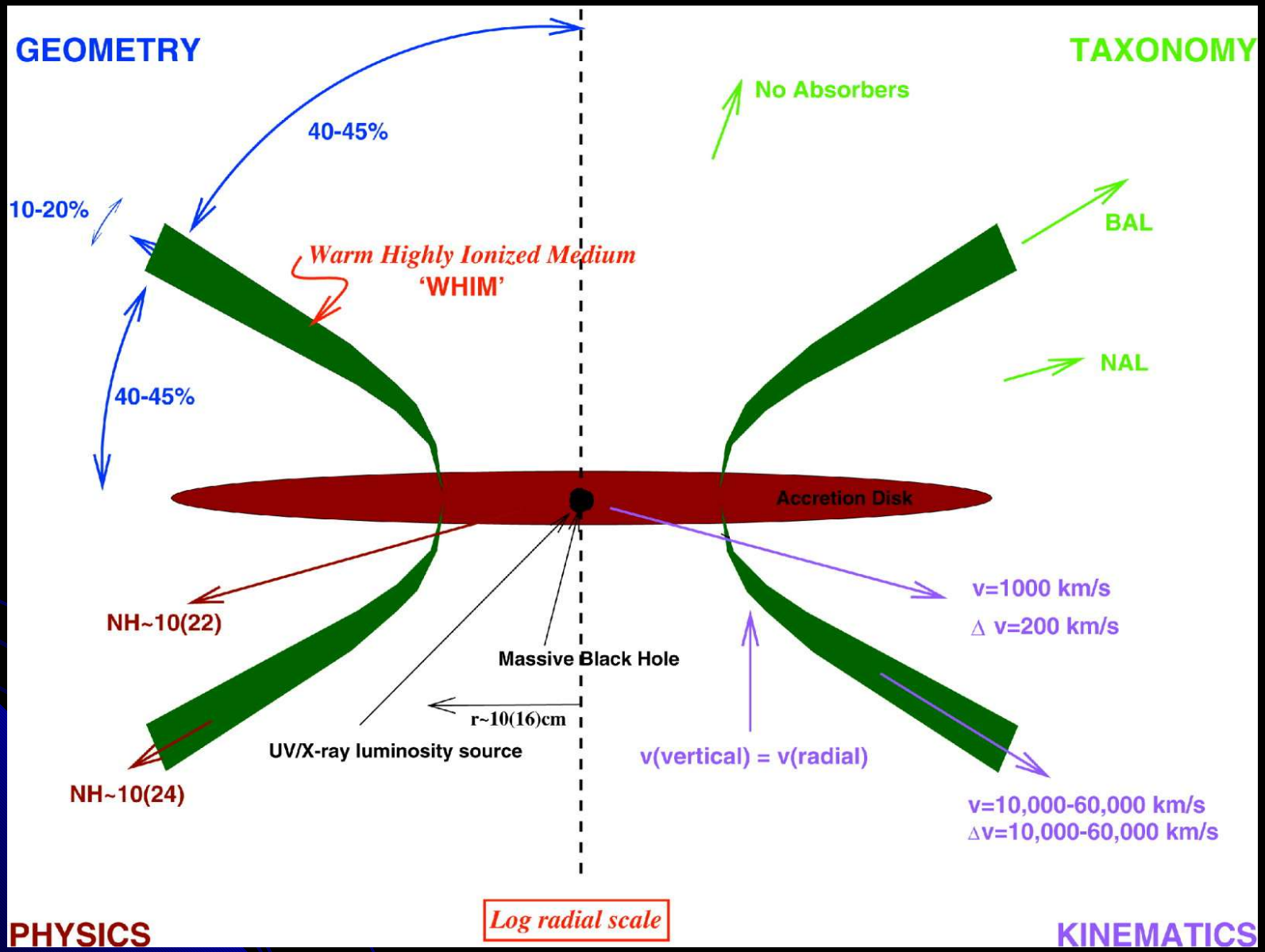


Absorbing outflows in AGN

- AGN of all stripes show absorption in optical through X-ray
- Outflowing material with ejection velocities up to ~0.2*c* in extreme BALQSOs, but typically narrow with v_{out} ~few 1000 km/s in Seyferts
- Absorption presents opportunity for detailed physical analysis along a single sightline (vs. integrated emission)

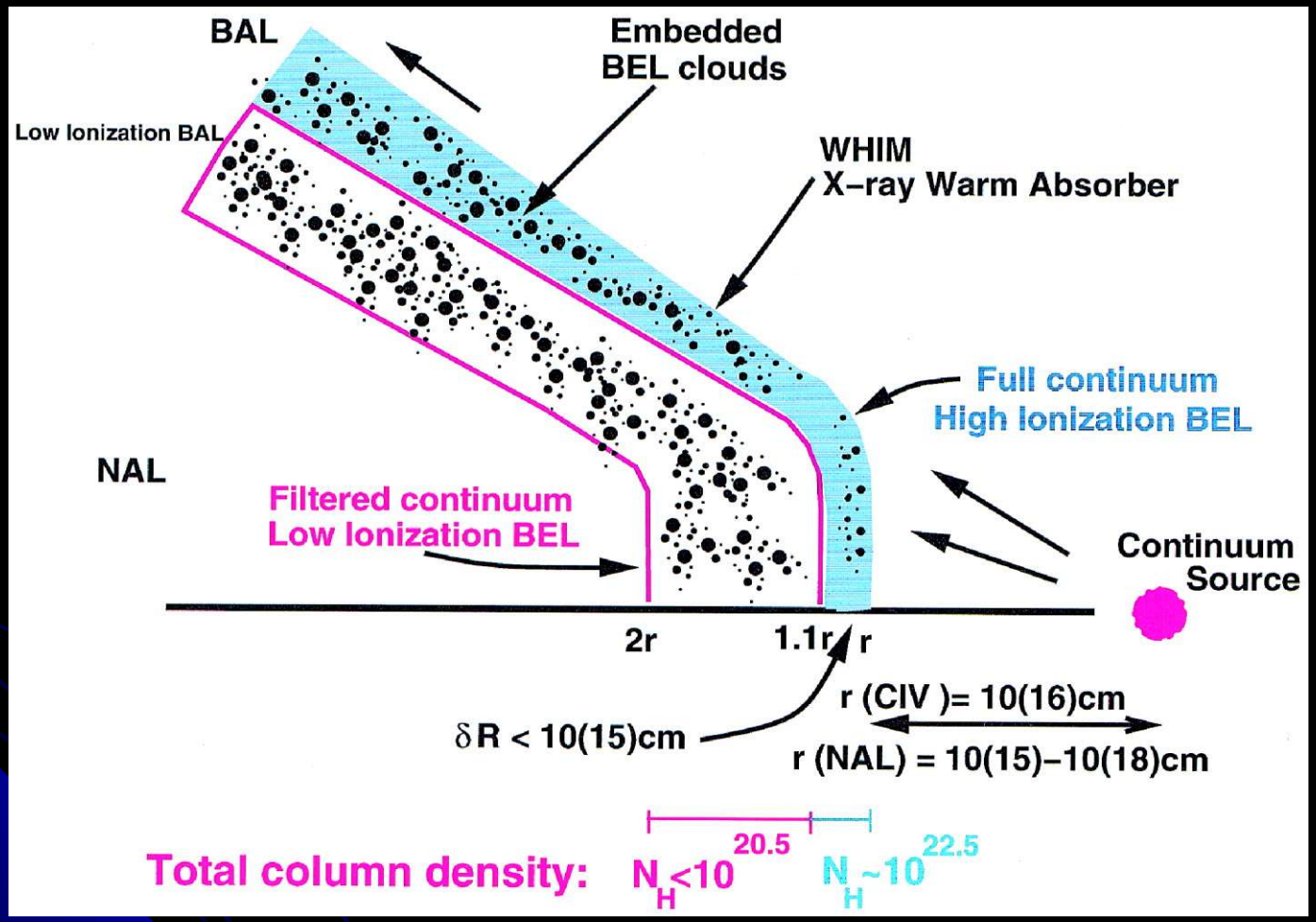


Elvis Structure for Quasars



Elvis 2000 [122 ADS citations]

Elvis Structure for Quasars



Elvis 2000 [122 ADS citations]

Comparison of Elvis with Urry & Padovani

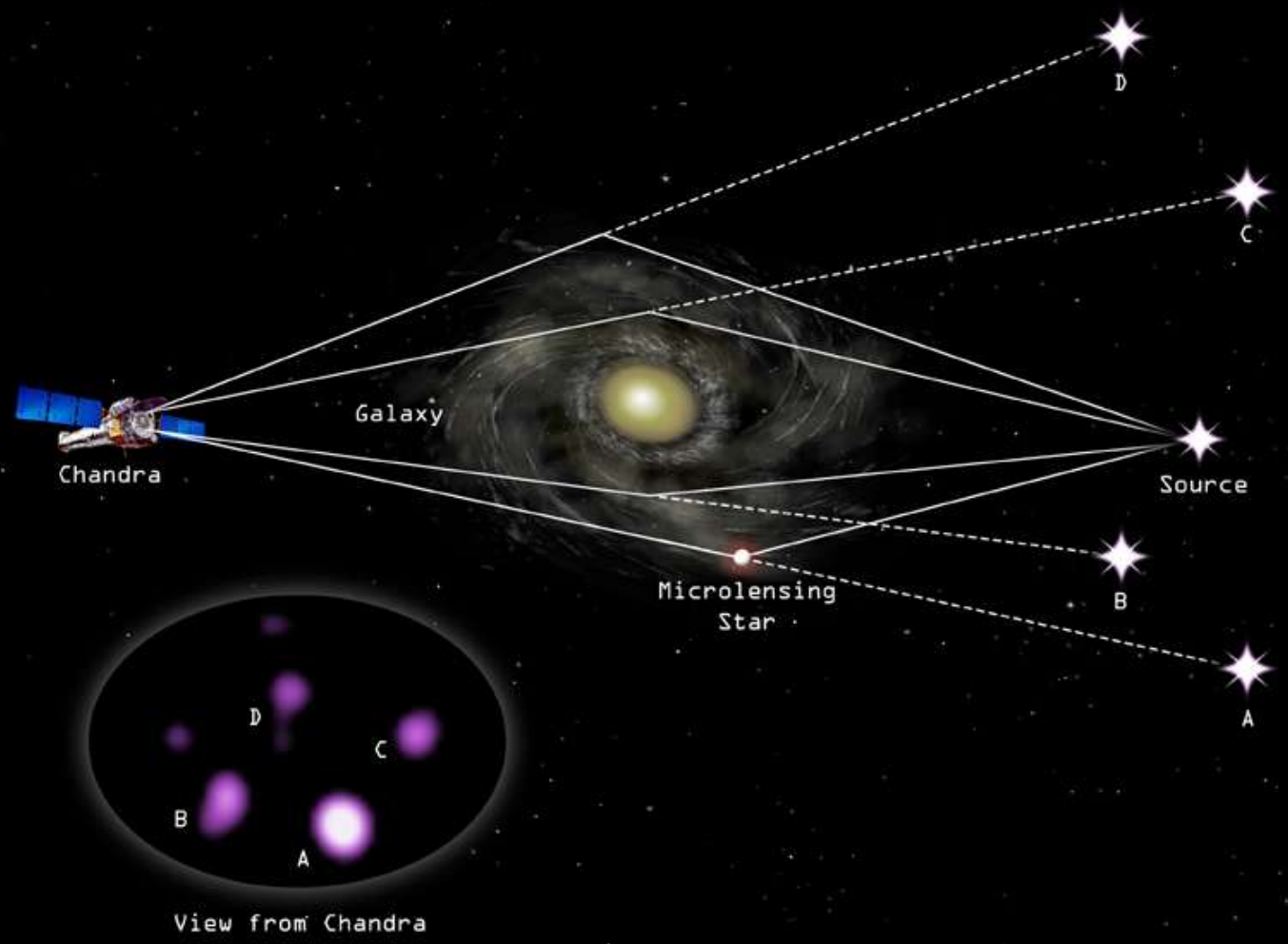
~25 citations / year

~70 citations / year

BALQSO in X-rays: UM425

- BAL phenomenon – outflowing ionized material – well-characterized in optical but optical lines saturated so determining ionization state difficult
- X-ray data give an important complement to optical:
  - Key X-ray transitions are less saturated over a wide range of column density and ionization
  - Models predict presence of warm-hot ionizing medium in BAL flows
- UM425 was identified in a Chandra survey of 10 bright BALQSOs
  - Brightest in sample by a factor of two – 46 cts/ksec!
  - Known to have OVI absorption, indicating high-ionization material
  - Suspected gravitational lens – another BALQSO (4.5 mags fainter) at same redshift was 6.5 arcsec away. But.. no lensing galaxy known despite efforts
- In AO3 we were awarded a 110 ksec ACIS-S observation of UM425
  - Goals – Best spectrum of a BALQSO, investigate lensing, cluster?

Gravitational lensing



Gravitational lensing

Lens an Astrophysicist!

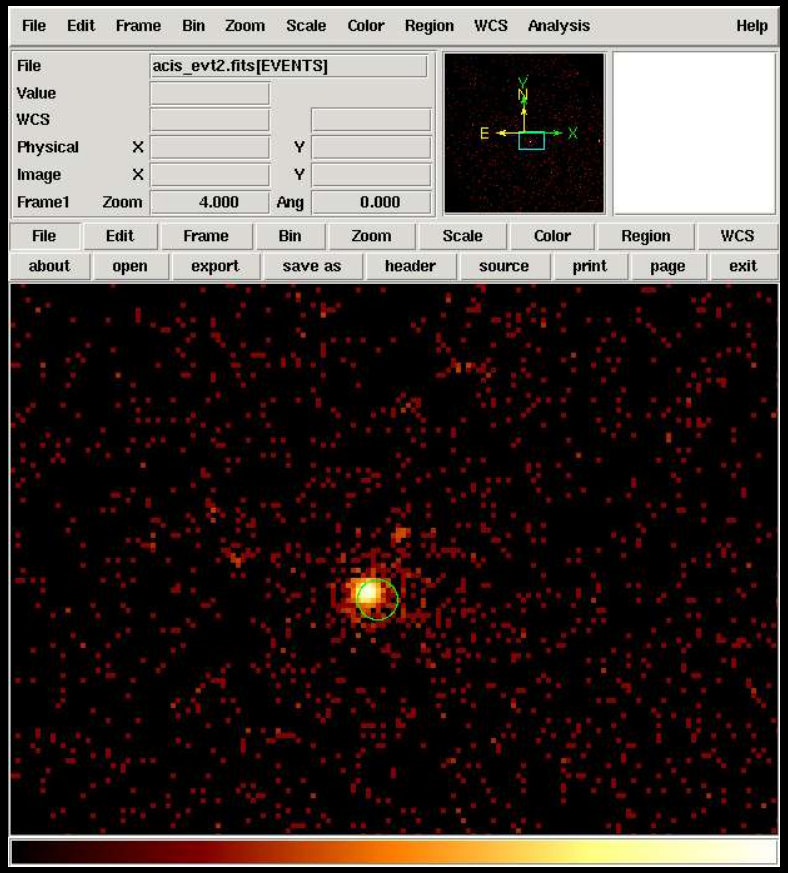
http://theory2.phys.cwru.edu/~pete/GravitationalLens/GravitationalLens.html

UM425 data: First look

- After initial data preparation steps (e.g. http://asc.harvard.edu/ciao/threads/data.html for Chandra data), view the event data in ds9
- Make life easier for you and your collaborators by *scripting* the ds9 commands with the XPA interface[1]

```
alias ds9set 'xpaset -p ds9'

ds9set file 'acis_evt2.fits[events][energy=300:8000]'
ds9set pan to 4142 4048 physical
ds9set zoom to 4
ds9set cmap BB
ds9set scale log
ds9set regions format ciao
echo "circle(11:23:20.7,+01:37:47,4)" | xpaset ds9 regions
```



- Issues: Source offset and some “fuzz”?

[1]http://hea-www.harvard.edu/RD/ds9/ref/xpa.html

UM425 data: First look – *cont'd*

- Identification of two point sources with UM425A and B can be firmly established by including optical image (WFPC)

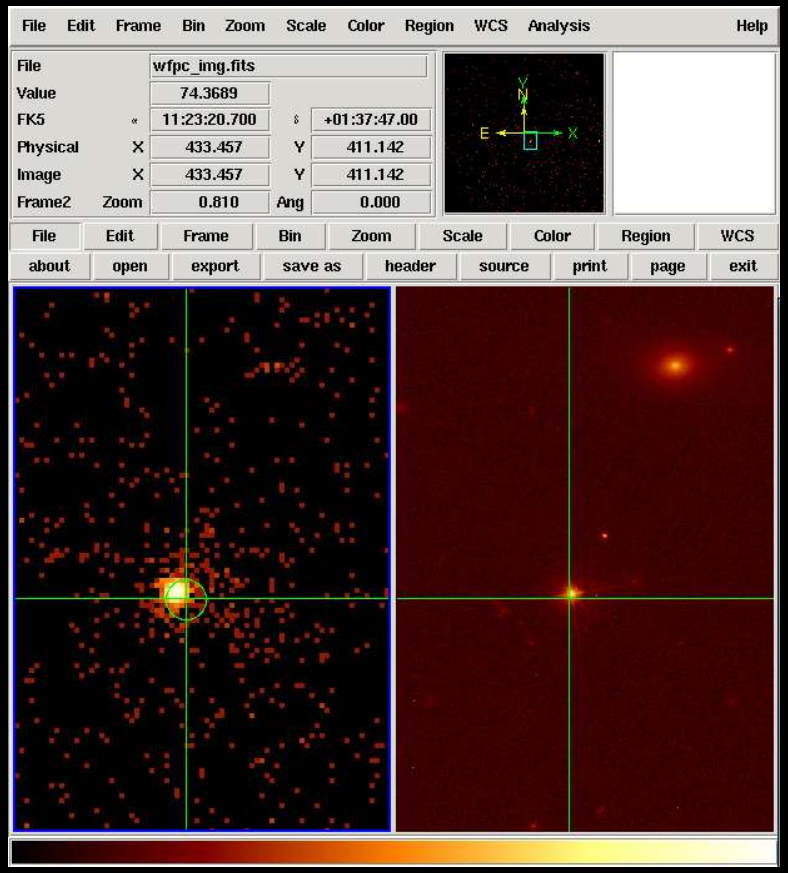
Generate soft Chandra image

```
ds9set file 'acis_evt2.fits[events][energy=300:2500]'
ds9set pan to 4142 4048 physical
ds9set zoom to 4
ds9set cmap BB
ds9set scale log
ds9set regions format ciao
echo "circle(11:23:20.7,+01:37:47,4)" | xpaset ds9 regions
```

Add WFPC image to new frame

```
ds9set tile yes
ds9set frame new
ds9set file wfpc_img.fits
ds9set cmap BB
ds9set scale log
ds9set scale mode zmax

ds9set frame 1
ds9set match frames wcs
ds9set mode crosshair
ds9set lock crosshairs wcs
ds9set crosshair 11:23:20.7 +01:37:47 wcs fk5
ds9set cursor 0 0
```

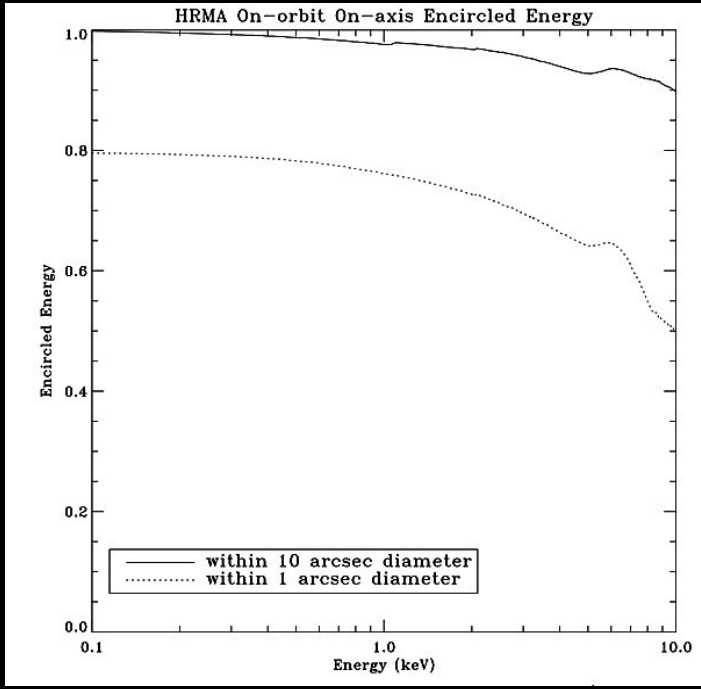


Low Resolution Spectral Analysis – High Counts

- First goal: understand the X-ray spectrum of the bright UM425A
- With ~5000 counts this is one of the highest S/N X-ray observations of a BALQSO
- Science drivers
  - Is the hard powerlaw typical of other z~1 RQ QSOs?
  - What is the intrinsic absorbing column?
  - Is the absorption “warm” or “cold”?
- Analysis issues
  - Source and background extraction regions
  - Pileup
  - Fit models
  - Fit statistics and minimization methods

Source and background extraction regions

- Source extraction region is commonly set to include ~95% of source photons near 1-2 keV
- X-ray mirror PSF is broader for hard photons (scattering)
- For XMM the analysis tools calculate ARF based on extraction region
- For Chandra, standard tools currently do not account for extraction region size
  - Need to be aware of this effect
  - 1" diameter (on-axis) => $\Delta\Gamma \sim 0.10$
  - 10" diameter (on-axis) => $\Delta\Gamma \sim 0.02$
  - User tools exist to correct ARF[1]



- For background, usually choose a large source-free annulus. If not available use pre-made background files
- Evaluate source contamination

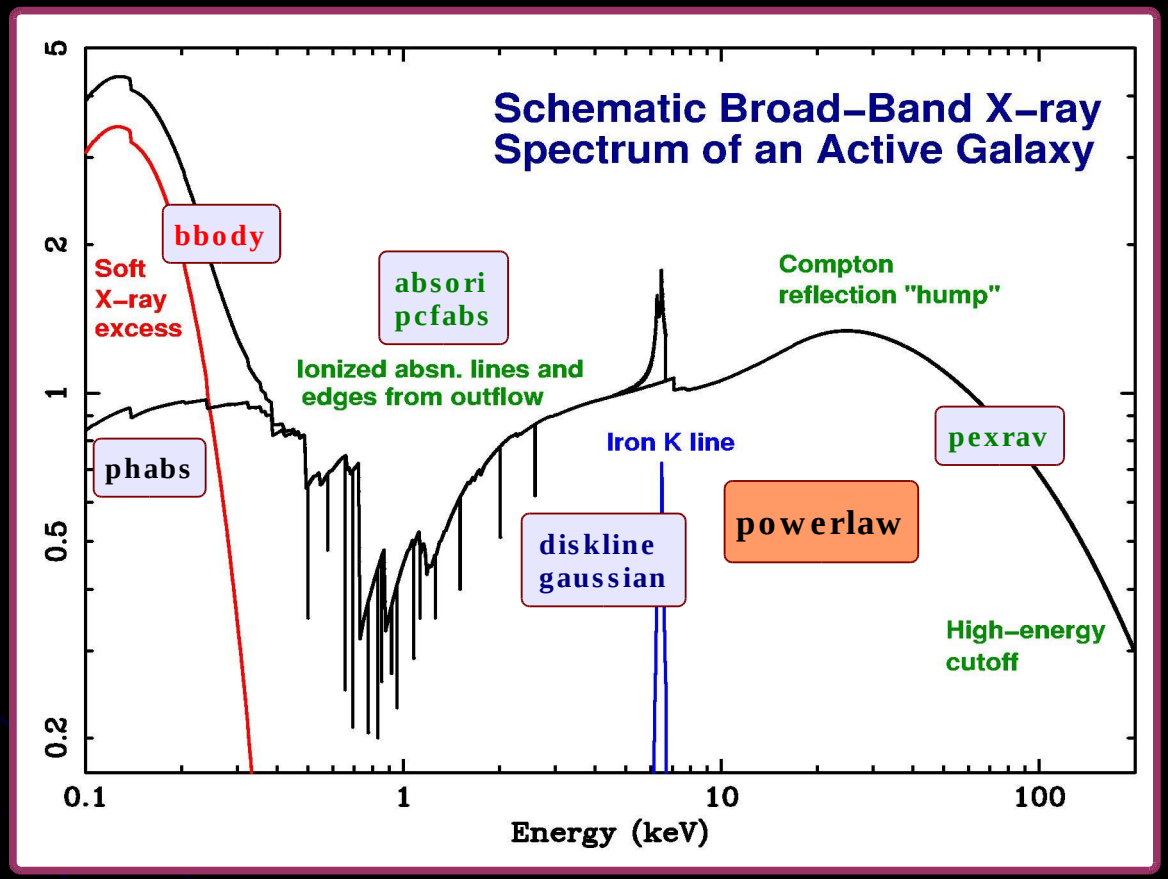
[1]http://www.astro.psu.edu/xray/acis/recipes/non_www_scripts/xpsf/xpsf.pro

The dreaded pileup issue

- Multiple photon events within a single or adjacent pixels during a single readout can cause either energy or grade migration
- For bright sources this causes distortion in the image and spectrum
- An initial estimate of pileup for ACIS can easily be made with PIMMS. For XMM the SAS tool epatplot can be used as a diagnostic.
- For moderate pileup in ACIS there is a CIAO thread[1] that gives details of how to include the jdpileup model[2] in fitting
- For strong pileup, the only option may be to excise the core and fit using only the wings. This introduces serious issues related to PSF energy dependence and assumptions in ARF generation.
- In the case of UM425A, the pileup fraction was estimated at 6%. Applying the jdpileup model to our fitting produced no statistically significant change in the fit parameters.

[1] http://cxc.harvard.edu/sherpa/threads/pileup
[2] http://space.mit.edu/~davis/pileup2001.html

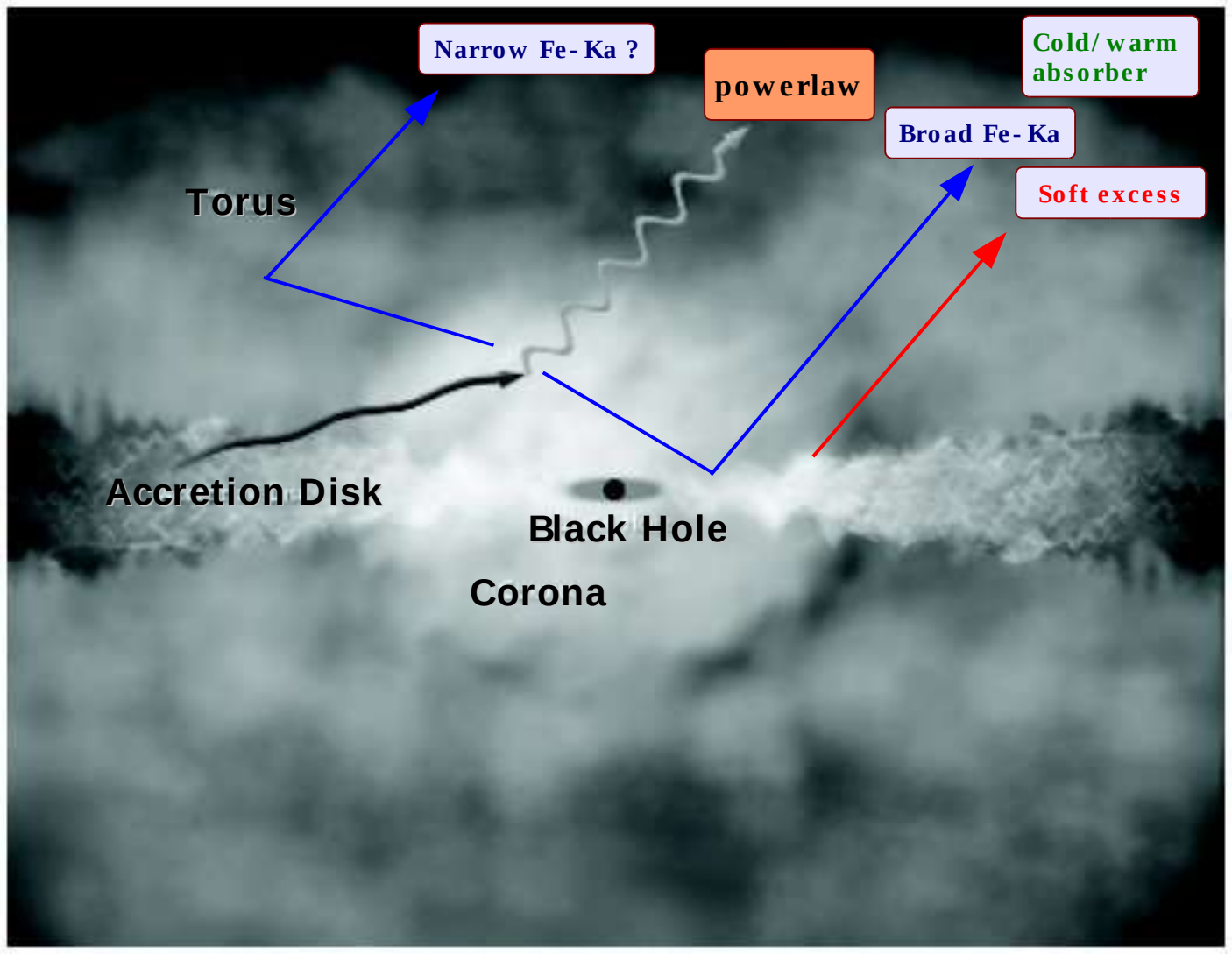
Common "Off the Shelf" low-resolution models for AGN



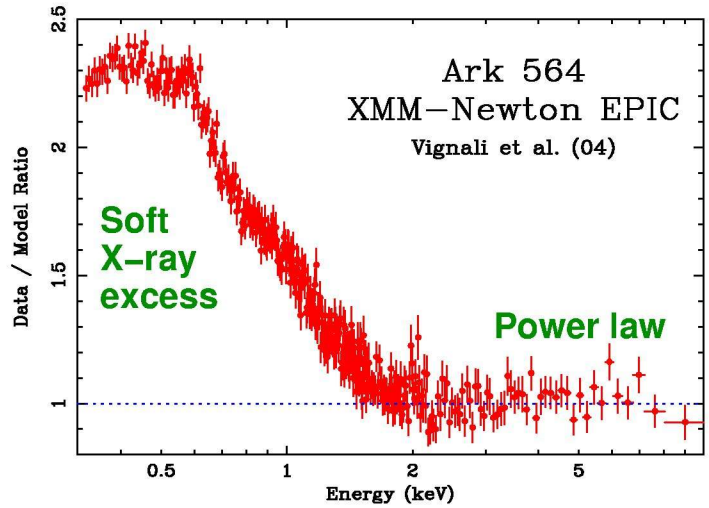
Adapted from http://www.astro.psu.edu/users/niel/papers/aas204-invited.pdf by N. Brandt

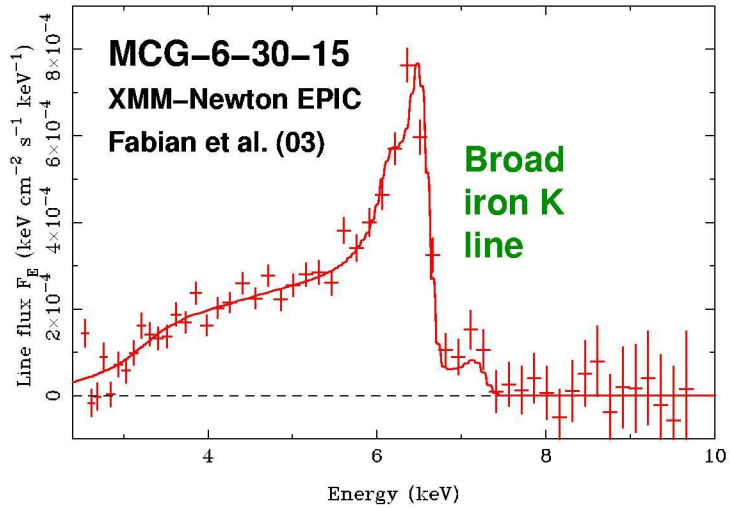
A different view of X-ray emission

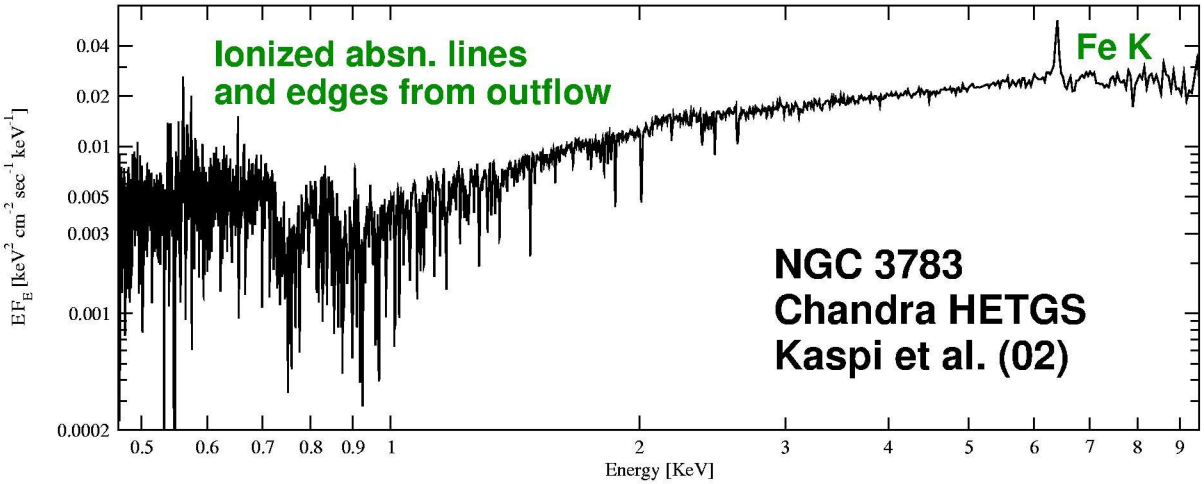
Galactic absorption



AGN spectral features







Also unidentified features

Also substantial jet−linked X−rays in radio−loud AGN

http://www.astro.psu.edu/users/niel/papers/aas204-invited.pdf

Spectral fitting options

- Common options for X-ray spectral analysis are XSPEC and Sherpa
- As for other analysis tasks, scripting all fits and plot generation will save much time in the long run
- Fit statistic (e.g. Chi Gehrels, Chi Primini, Model Variance, Data Variance, Cash, C-stat, etc)
- Optimization method (Levenberg-Marquardt, Migrad, Powell, Monte-*, Grid-*)
- Binned or unbinned?

Binned	Unbinned
Subtract background	Model background
Well-defined goodness of fit	C-stat
Intuitive visual plot of model vs. data	Not easy
Gaussian assump. invalid < ~20 cts/bin	No restrictions
Fit statistic needs consideration	Cash is robust, unbiased
Generally faster	Slower

Experiment with different options!

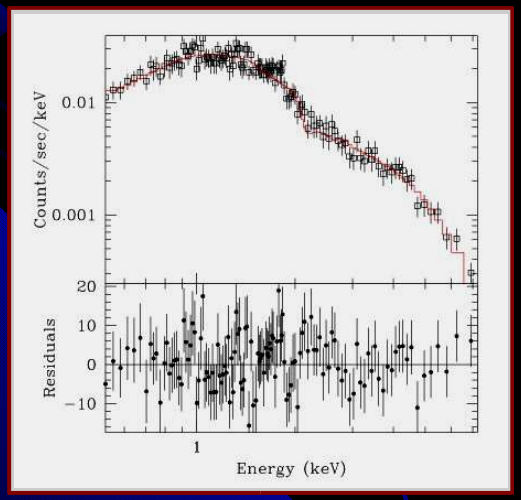
UM425A spectral fit results

- Used Sherpa, L-M optimization, and the χ^2 data-variance statistic with the spectrum binned to a minimum of 30 counts/bin

X-RAY SPECTRAL FIT PARAMETERS FOR UM 425A

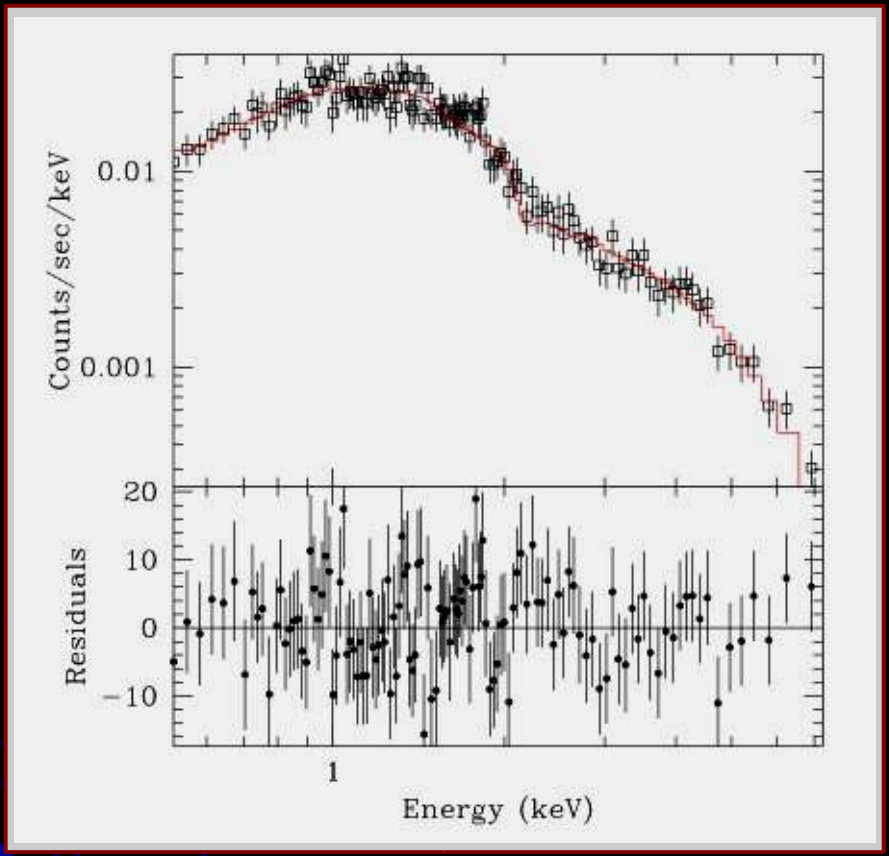
Model	Γ (a)	Amplitude (b)	$N_{H,z}$ (c)	Other (d)	Flux (e)	χ^2 (DOF)
Gal N_H (fixed)	1.43 ± 0.04	5.3 ± 0.2	...	...	3.7 ± 0.1	430.5(122)
$N_H(z = 1.465)$	1.78 ± 0.08	7.9 ± 0.6	1.1 ± 0.2	...	3.4 ± 0.1	145.3(121)
Part. Cov. $N_H(z = 1.465)$	1.99 ± 0.13	10.4 ± 1.6	3.8 ± 1.2	$f_{PC} = 0.73 \pm 0.06$	3.4 ± 0.1	122.2(120)
Warm absorber (CLOUDY)	2.00 ± 0.06	11.6 ± 2.0	10.0 ± 1.5	$U = 1.76 \pm 0.04$	3.4 ± 0.1	126.3(120)

NOTES: Uncertainties are 90% confidence limits. (a) Power law photon index. (b) Power law normalization in units of 10^{-5} photons cm^{-2} s^{-1} keV^{-1} at 1 keV (c) Absorbing column in units 10^{22} cm^{-2} at quasar redshift. (d) f_{PC} is the partial covering fraction, U is the $\log_{10}$ of the dimensionless CLOUDY ionization parameter (e) Model flux (0.3-8 keV) in units 10^{-13} ergs cm^{-2} s^{-1}



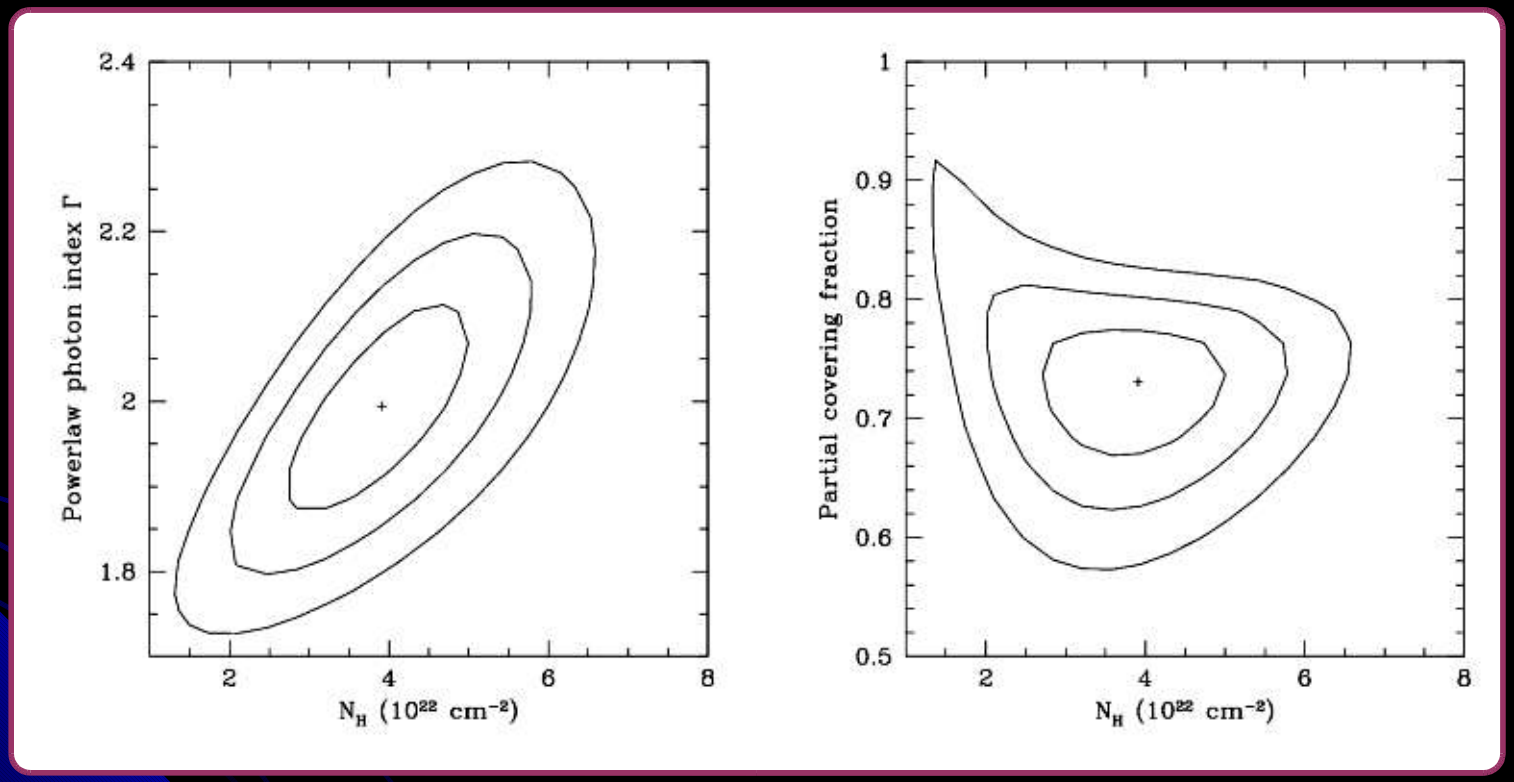
UM425A spectral fit results

- Best fit models (warm absorber and partially-covering neutral absorber) are both acceptable, with no significant residuals



UM425A spectral fit results

- Absorbing column NH is highly correlated with powerlaw photon index and somewhat correlated with partial covering fraction



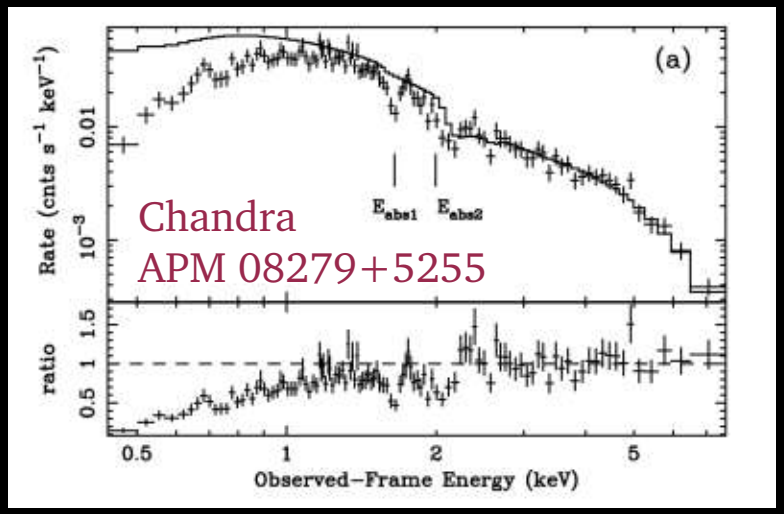
- Parameter error bars often don't tell the whole story

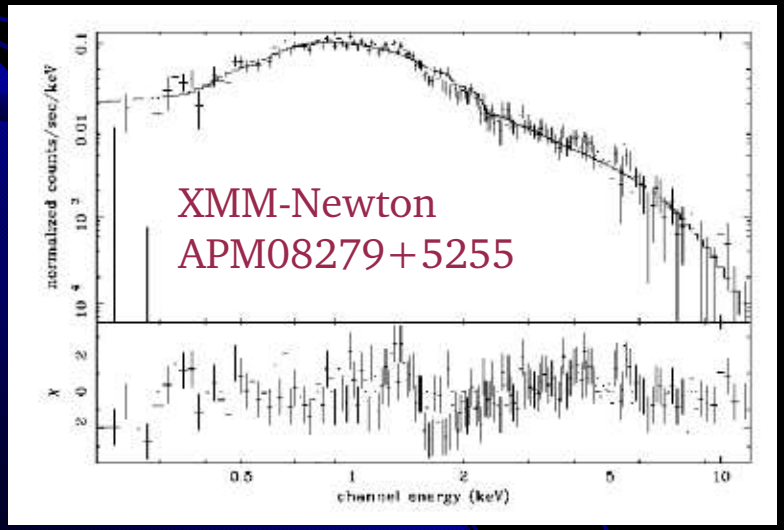
UM425A spectral fit results – Conclusions

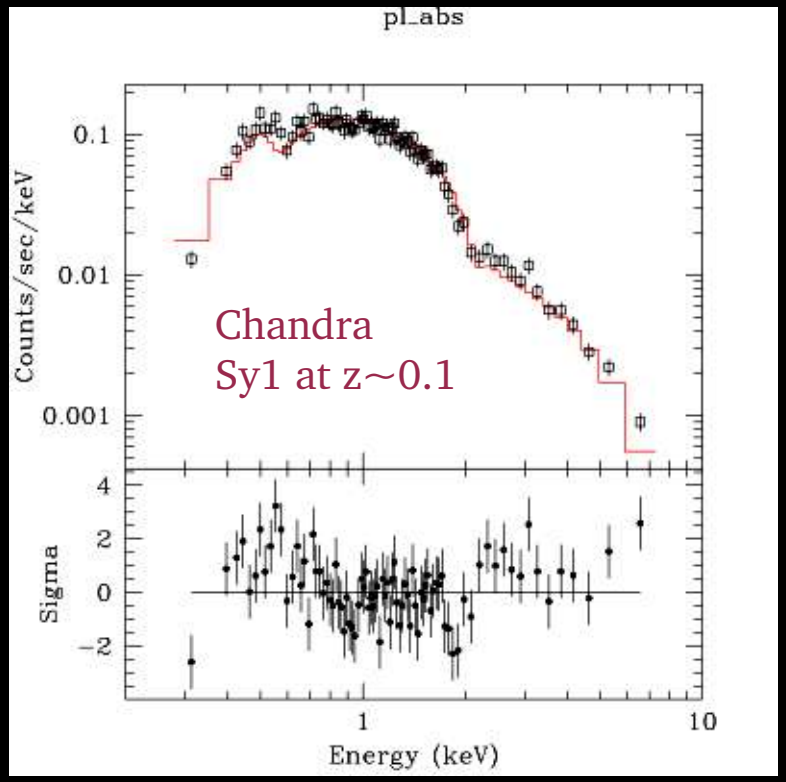
- Apart from the intrinsic absorbing column ($N_H \sim 3\text{-}10 \times 10^{22}$), UM425 is a very typical $z \sim 1.5$ radio-quiet QSO
  - Power law photon index $=2.0\pm0.1$
  - Optical to X-ray flux ratio is $\alpha_{ox}=1.6$
- This argues against the hypothesis that BALQSOs are a special evolutionary state of AGN, e.g. young by analogy with NL Sy-1s
- The ionization state of the X-ray obscuring material is not constrained. If neutral then partial covering is required.

UM425A spectral fit results – Conclusions

- No X-ray BAL troughs in UM425A from highly ionized Fe, as seen in APM 08279+5255 (z=3.91) and PG 1115+080[1]







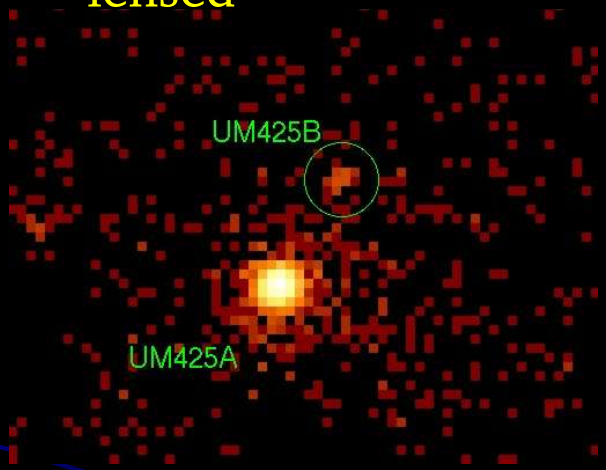
[1]Chartas et al 2002,2003; Hasinger et al. 2002

UM425A spectral fit results – Conclusions

- BALQSOs present a significant observational challenge in X-rays
  - Most are at moderate to high redshift ($z > \sim 0.5$)
  - Faint – none have been observed with gratings
  - Interesting spectral region (e.g. OVII) gets shifted into energy range where detector has low effective area and is poorly calibrated. For UM425, OVII is coincident with instrumental Carbon edge (284 eV).
  - Gravitationally lensed sources are the best prospect (Chartas)
  - Not burdened with excessive S/N

UM425B spectral fitting

- UM425B has about 29 counts, a factor of ~170 less than UM425A
- Optical magnitude difference of 4.5 ⇒ expect a factor of ~60 if lensed



Have no fear, Cash is here!

- Even with 29 counts is possible to fit a spectrum with 1 parameter (plus norm)
- Do unbinned fitting with Cash statistics
- If you have some physical insight into the system (a *prior),* fitting a 1-parameter model is better than a hardness ratio

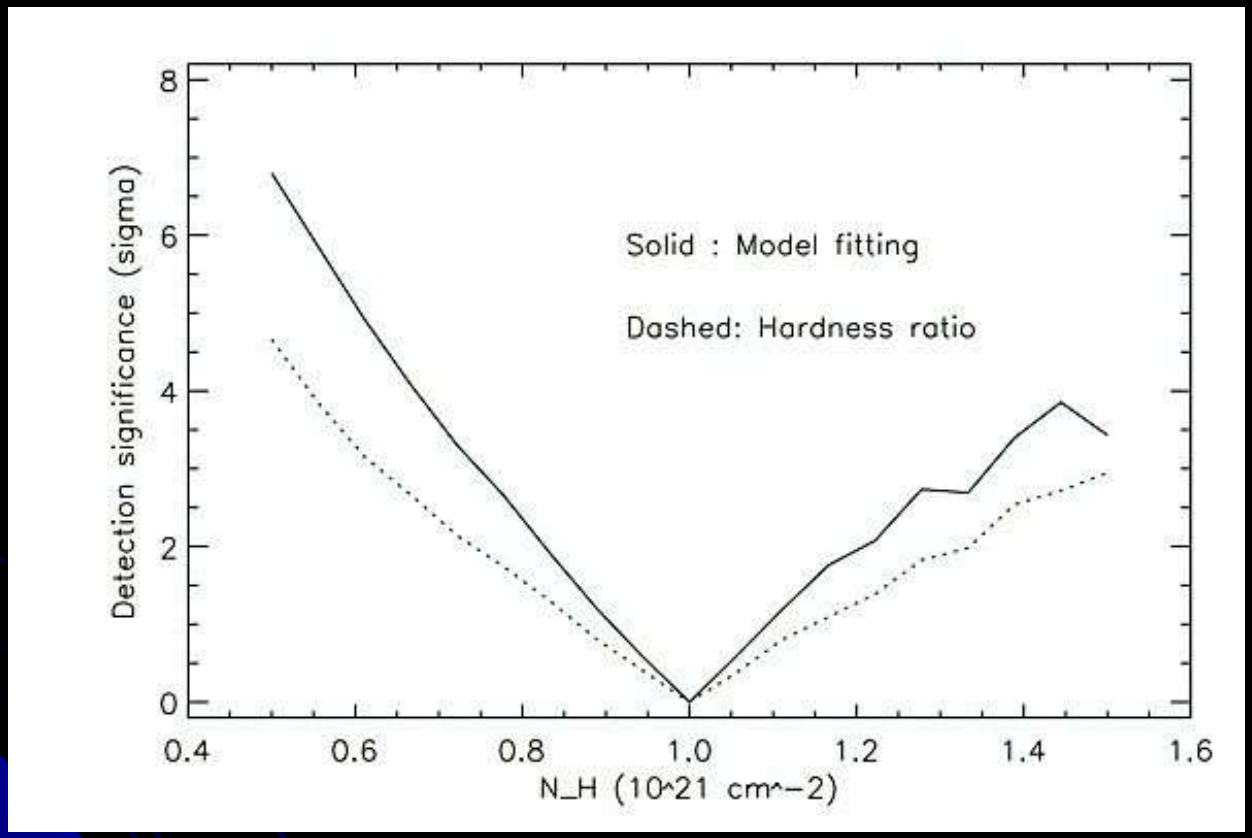
- Fit for intrinsic neutral absorber (N_H) and normalization, assuming same photon index Γ=2.0 as in UM425A
- Result is N_H=2.0x10^{23} or a factor of 5 > neutral fit for UM425A
- Absorbing columns differ by more than 3-σ

Hardness ratios

- Hardness ratio HR = (H-S)/(H+S) is commonly used as a 1-parameter characterization of spectral shape
  S = Soft band counts
  H = Hard band counts
- Often used in low count situations or surveys with many sources
- Advantage: Easy to calculate
- Disadvantages:
  - Uncertainty is hard to calculate in low-counts regime: Fun trick to stump your local statistician! Mortals need to do Monte-Carlo sims
  - Needs correction factors: Galactic absorption, detector, off-axis angle, time-dependent response
  - Typically need to convert back to a source model anyway
  - Ignores any prior information you might have, e.g. thermal or powerlaw spectrum. (Without any prior, HR gives no physical information)
  - Lower S/N than fitting

Hardness ratios

Compare model fitting to HR for simulated data with differing values of absorption



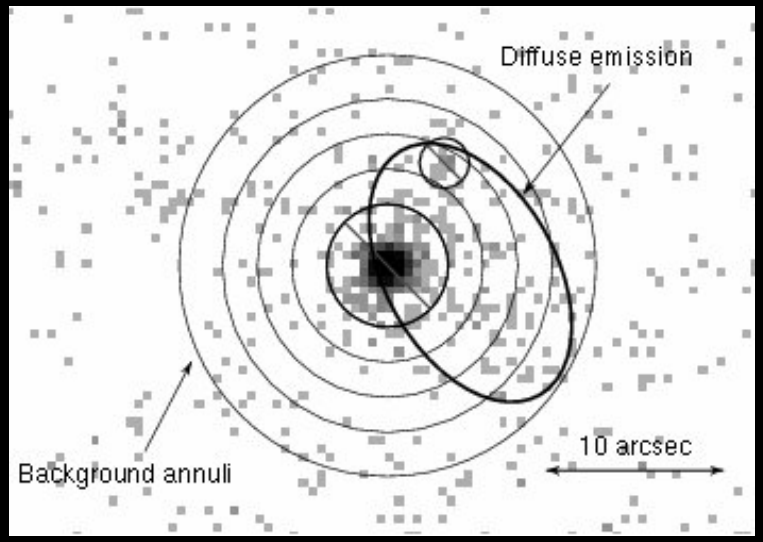
Hardness ratios

If you absolutely must… HR uncertainty can be estimated by Monte-Carlo:

- Drawing from the Poisson distribution with means S and H (observed values), create simulated S and H and form an ensemble of simulated HR values.
- Then calculate your favorite statistics on that distribution, e.g. mean, 90% limits, etc
- This is a “frequentist” approach with assumes observed S and H are the true values
- Prefer to calculate P(HR | S,H). This is difficult, but code exists.

Image analysis

- UM425 field contains diffuse emission
- Consistent with gravitational lensing
- Analysis of weak diffuse emission (~200 counts) in presence of strong point source (few thousand counts) is difficult!



- Simple method relying on PSF axial symmetry gives a lower limit of 51 ± 13 counts
- Cannot rely on eyeball estimates of emission extent

Image analysis – *gettin' fancy*

- Total flux from diffuse emission key to testing gravitational lens theory

Assume typical cluster parameters (T, abundances) and scaling relations

flux ⇒ luminosity ⇒ mass ⇒ gravitational lens splitting

- Basic idea:
  - Use ChaRT and MARX to generate decent PSF model
  - For smoothed image, go through a complex dance with dmfilth (excising hole in image) and csmooth using the real data and the PSF model to subtract PSF outside the hole. Direct subtraction leaves huge residuals
  - For radial profile, same idea but skip smoothing
  - See Green et al. 2005 (astro-ph/0505248) for the gory details.

Image analysis

- Diffuse emission extends out to ~30 arcsec and has ~180 counts, more than three times the initial lower limit based on the "by-eye excess"

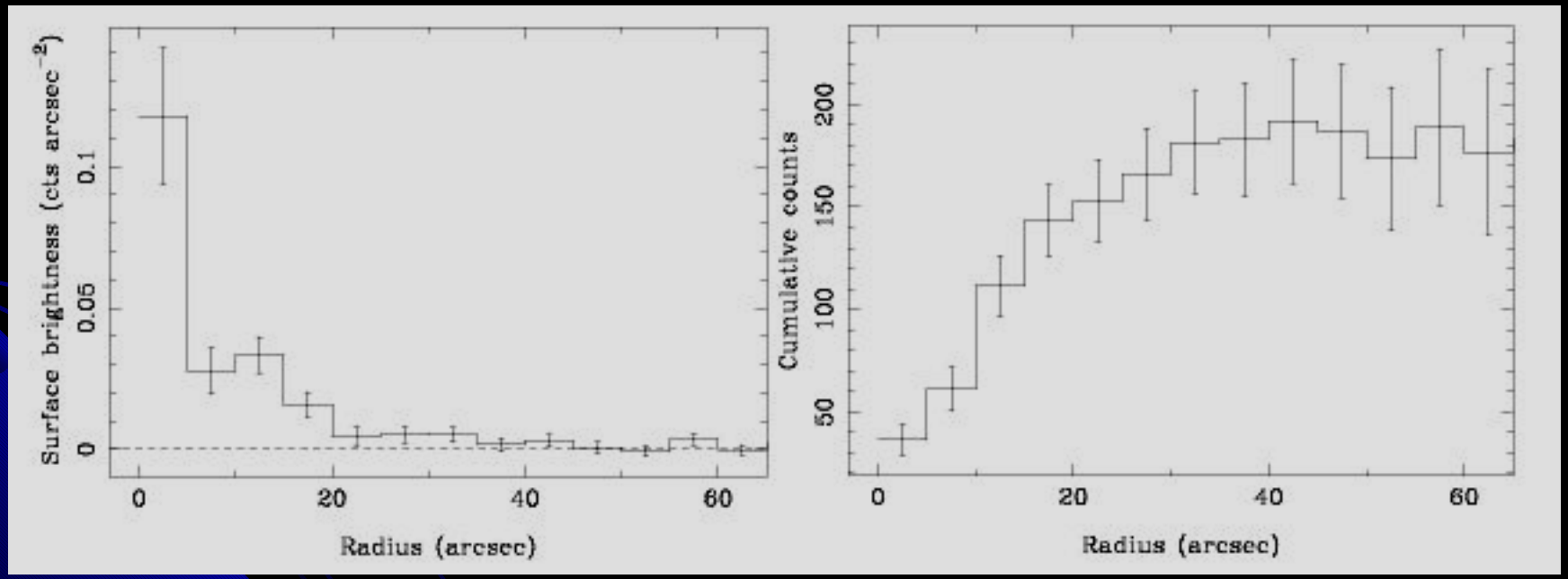
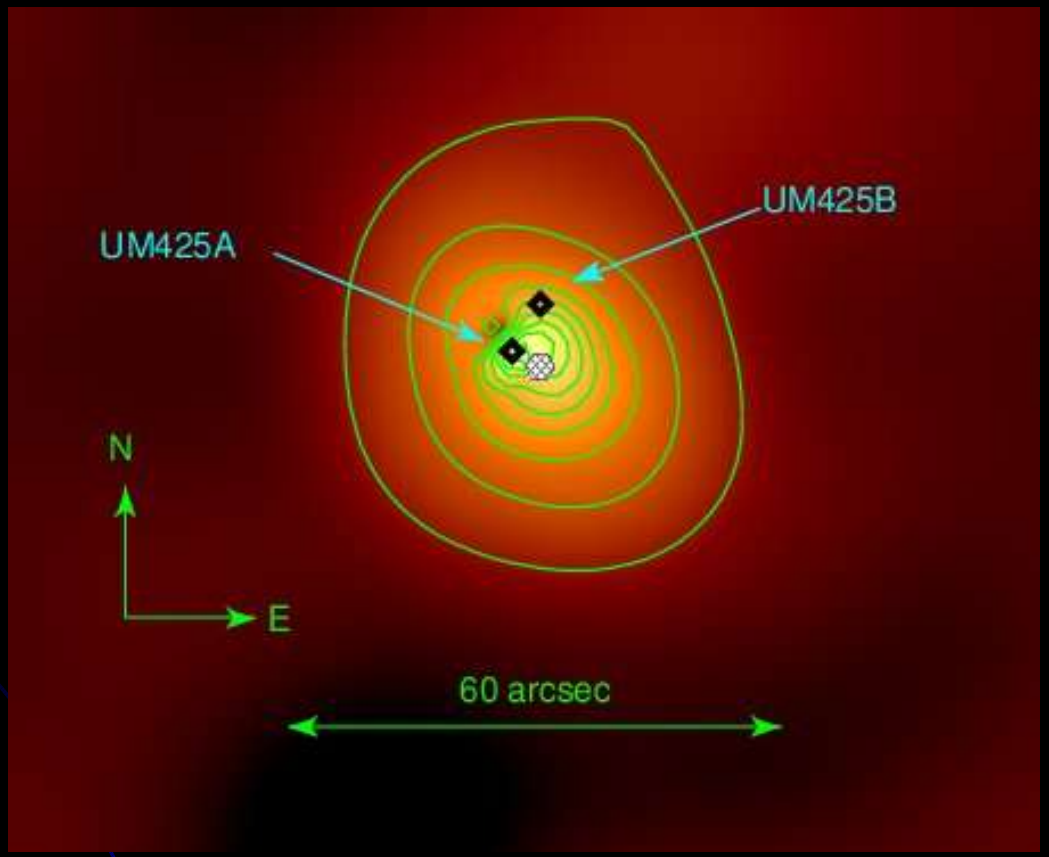


Image analysis

- Cluster emission not centered near UM425B where it would be expected for gravitational lensing
- Cluster is not relaxed – perhaps dark matter distribution different from X-ray emitting mass?



UM425 – What's the deal?

- UM425A (bright component) is an otherwise normal QSO which is absorbed (~3-10 x 10^{22})
- We do not know the ionization (warm or neutral?)
- If UM425B is a lensed image, the absorption is 5 times higher
  - Time delay
  - Different sightline. Scale is interesting
- Diffuse emission, offset from both UM425A and B
  - Flux corresponds cluster with enough mass to create lens splitting
- But is there really a cluster there?
- YES – Green et al. 2005 found 9 galaxies at z=0.77 in the field
- So the problem is solved?
- Well... need either unusual lens or unusual galaxy (M/L > 80)

Lensing and microlensing in AGN

- Lensing (macrolensing by foreground galaxies/clusters) offers:
  - Magnified views (perhaps 50-100 times)
  - Views of sources at different sightlines[1,2]
  - Views at different times
- Microlensing by stars in a foreground lensing galaxy acts as a transient magnifying glass
- Typical microlensing scale is well-matched to accretion disk size
- Chartas et al 2004 detected what appears to be amplification of the Fe-Kα emitting region in one of the four cloverleaf images

[1]Green et al. 2005 (astro-ph/005248)
[2]Chelouche 2003

Summary

- Blah Blah Blah