Active Galactic Nuclei

LOW-RESOLUTION X-RAY SPECTROSCOPY

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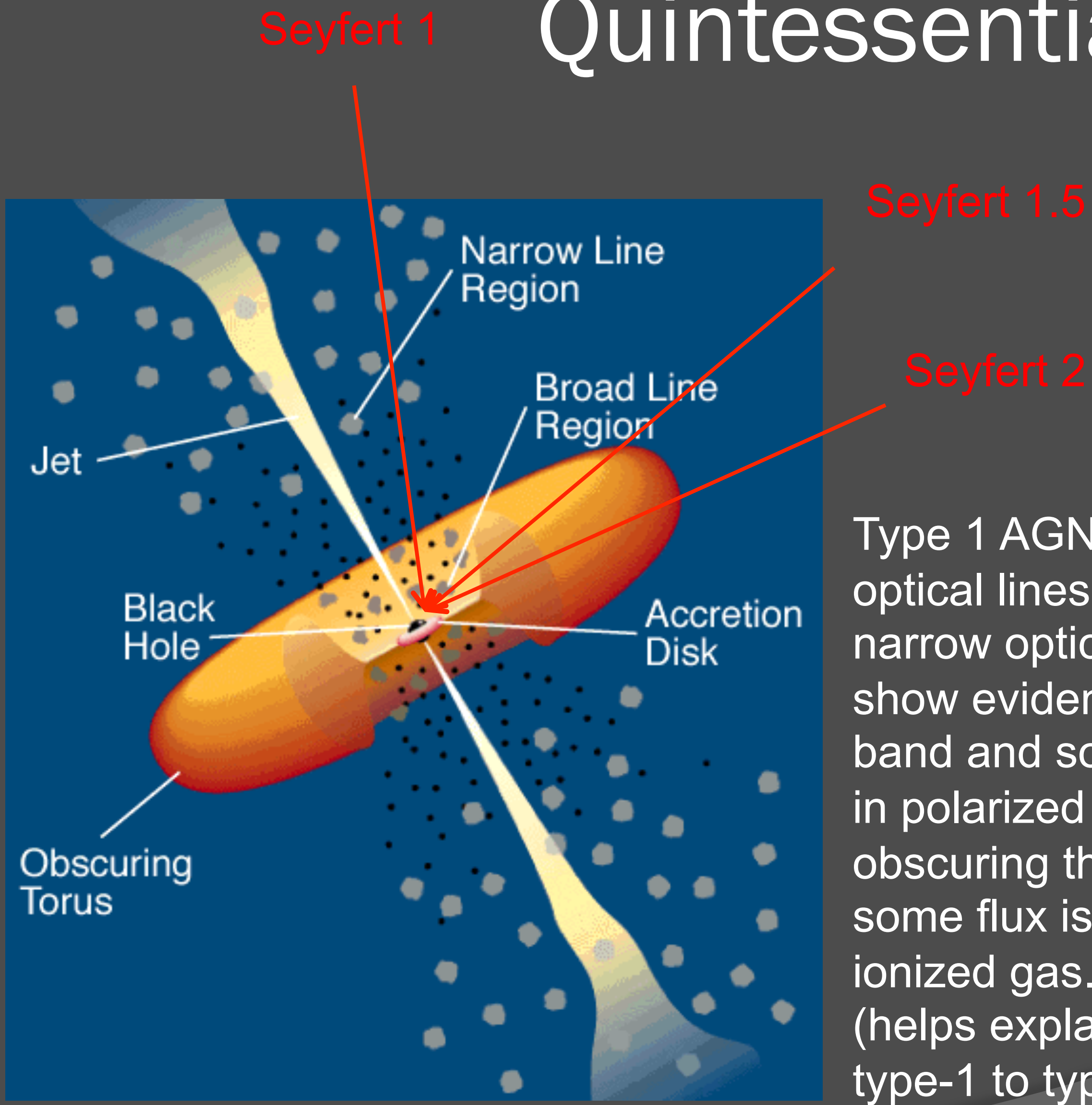
Outline

- AGN X-ray spectral features overview
- CCD resolution spectral fitting
- Examples

Active Galactic Nuclei

- Powered by accretion onto supermassive (M > 10^6 solar mass) black hole
- Accretion disk temperature ~ 10^{5-6} K -> in UV
  - Multi-temperature disk
- Accretion disk forms a corona ala the Sun which inverse-Compton scatters UV photons from accretion disk to X-rays
  - Results in a power-law X-ray spectrum
  - Cuts off at kT of corona
- A “torus” of obscuring gas and dust modifies the spectrum

Quintessential AGN model



Type 1 AGN have broad and narrow optical lines. Type 2 AGN have only narrow optical lines. Type 2 AGN often show evidence of obscuration in the X-ray band and sometimes broad lines are seen in polarized light. Explanation: a torus is obscuring the line of sight in type-2 AGN, some flux is scattered around the torus by ionized gas. Or torus may be clumpy (helps explain AGN that change from type-1 to type-2).

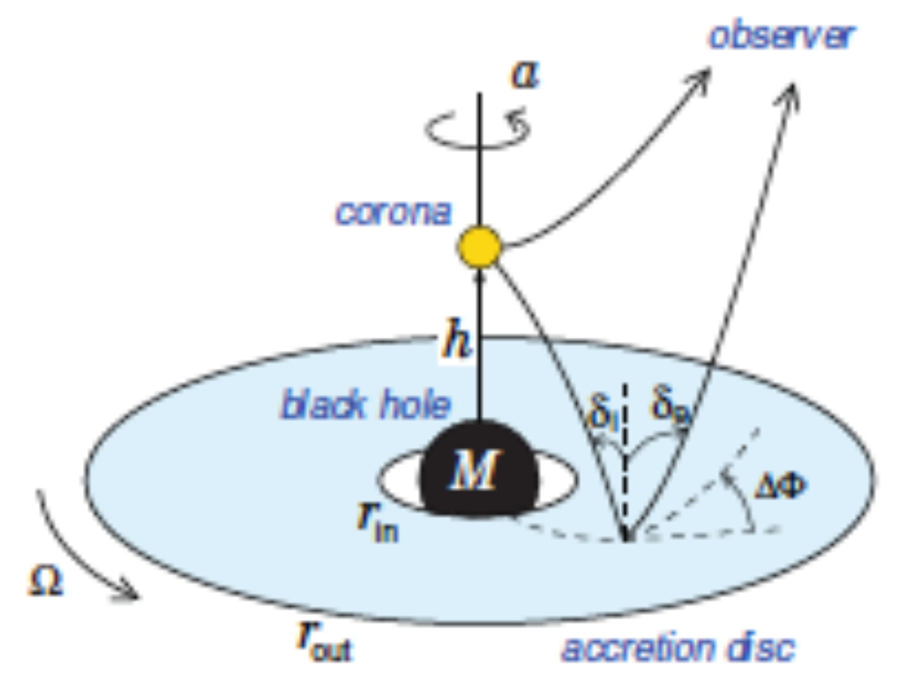
Radio-quiet AGN are called Seyferts.

X-ray Continuum in an AGN

Photons have lower energy than KE of electrons
Compton y parameter:
(avg. fractional energy change per scat.)(mean # of scats.)

Simple derivation of IC power-law (Rybicki & Lightman 1979)
$A = E'/E$
After k scatterings, energy of photon $E_k = EA^k$
Prob. of k scatterings $\sim \tau^k$
$F(E_k) = F(E)\ \tau^k$
$A^k = E_k/E$
$k\ln A = \ln(E_k/E)$
$\tau^k = \tau^{[\ln(Ek/E)/\ln A]} = (E_k/E)^{[\ln\tau\ \ln(Ek/E)/\ln A/\ln(Ek/E)]}$
$F(E_k) = F(E)\ (E_k/E)^{(\ln\tau/\ln A)} = F(E)(E_k/E)^{-\alpha}$
Multiple IC scatterings produces a power-law spectrum

“Lamp Post” model



Dovciak et al. 2011, X-ray Universe Conference

Absorption

$dF = -n\sigma(E)Fdr$ σ = cross section

$$F = F_0 \exp\left[-\sigma \int n(r)dr\right]$$

Transmission through region of constant density:

$F = exp[-nr\sigma(E)]F_0$

Column density = $N_H = \int n(r)dr$

$F/F_0 = \exp(-N_H\sigma) = \exp(-\tau)$

Optically thin = $\tau < 1$
Optically thick = $\tau > 1$

X-ray Cross Sections

X-ray absorption in inter-stellar material mostly due to K-shell photoelectric absorption.

For a given element, $\sigma(E) = 0$ below edge energy, $\propto E^{-3}$ above

Electron scattering $\sigma_T = 6.65 \times 10^{-25}$ cm^{-2}
Scattering is relevant when $N_H\sigma_T \sim 1$
$N_H > 1/\sigma_T = 1 \times 10^{24}$ cm^{-2}

X-ray Cross Section by Element

$$\sigma = \sum_i Z_i \sigma_i$$

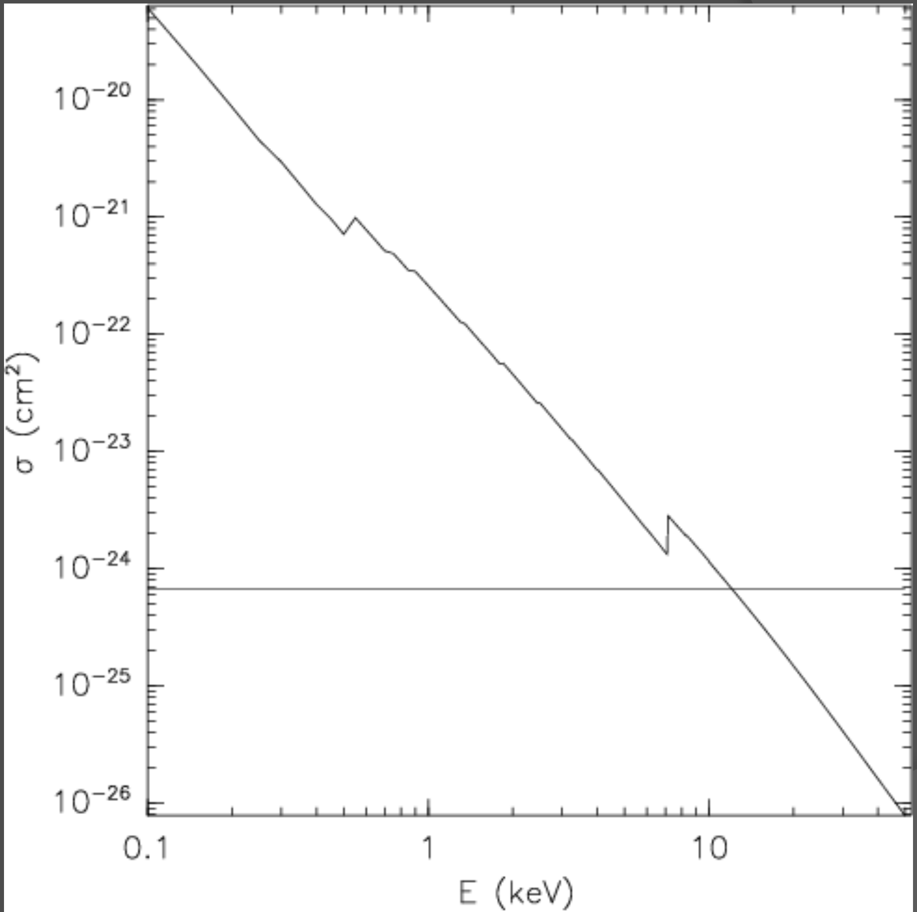
Z_i = abundance of element
i relative to H

Hence N_H gives H column density

Element	Z (rel. abund.)
H	1.00
He	0.0977
C	3.63e-4
N	1.12e-4
O	8.51e-4
Ne	1.23e-4
Na	2.14e-6
Mg	3.80e-5
Al	2.95e-6
Si	3.55e-5
S	1.62e-5
Fe	4.68e-5
Ni	1.78e-6

σ(E)

Optically thin case
E <~ 30 keV, $N_H < 10^{24}$ cm^{-2}
exp($-N_H\sigma_{abs}$)exp($-N_H\sigma_T$)
$\sigma(E) = \sigma_{abs} + \sigma_T$

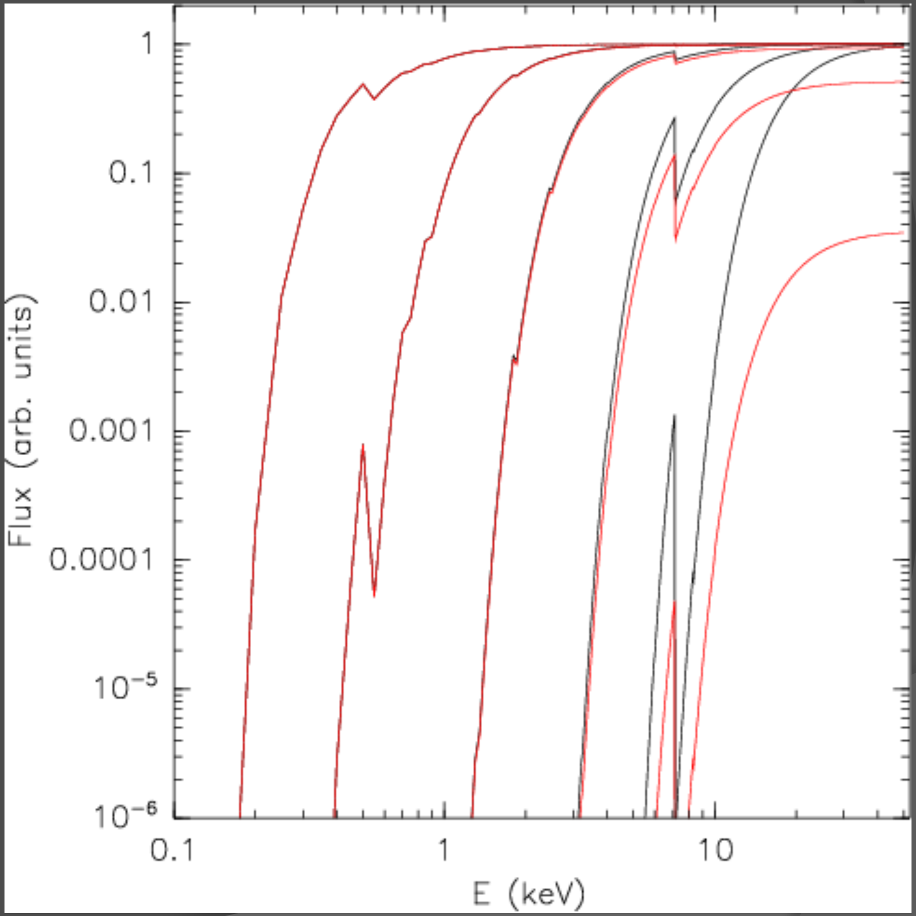


Power-law Spectrum Example

$F(E) = \exp[-N_H\sigma(E)]\, NE^{-\alpha}$

$\sigma = \sigma_{abs}$

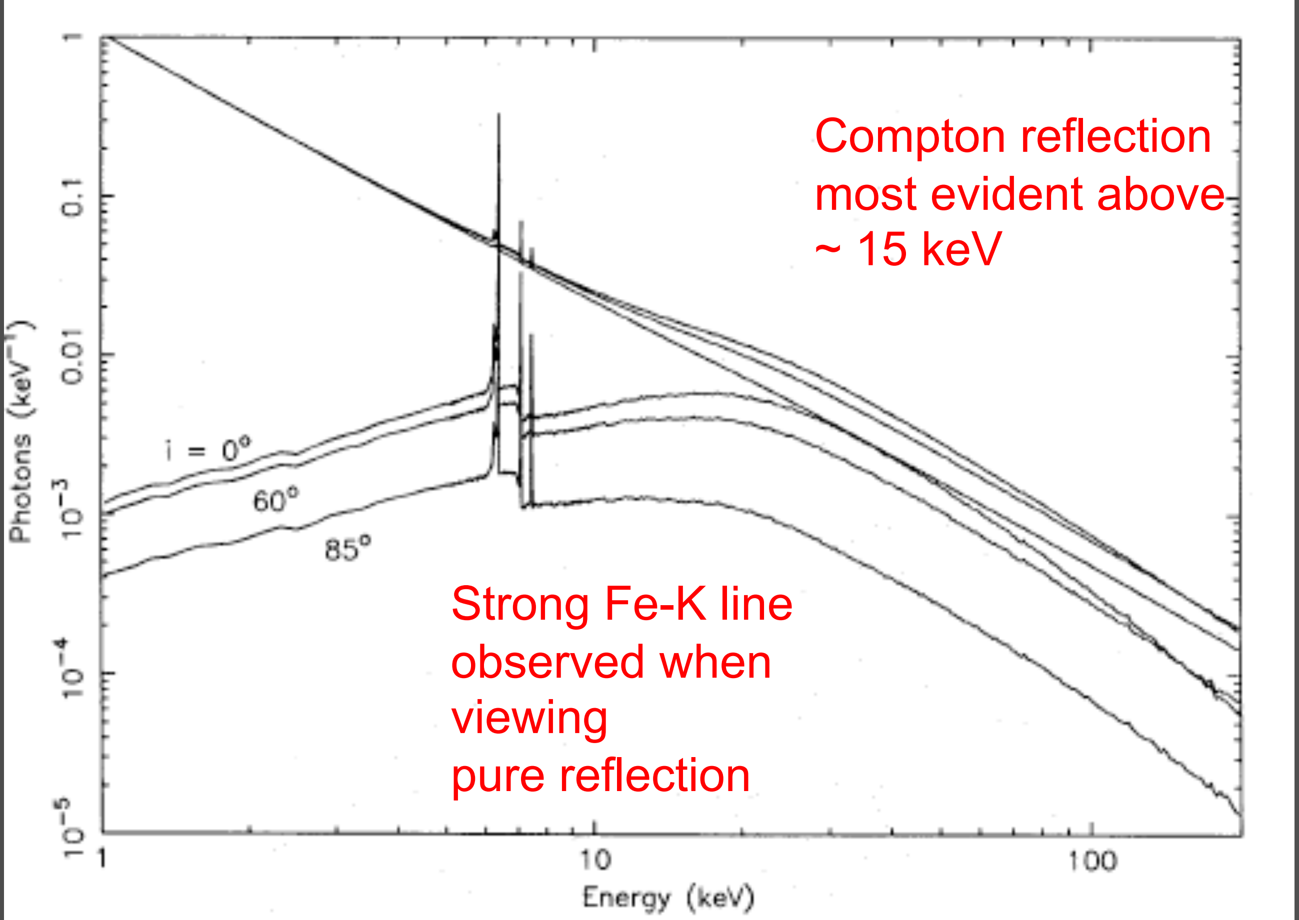
$\sigma = \sigma_{abs} + \sigma_T$



Compton Reflection

Photons impact optically-thick material and scatter back out after traversing ~ τ

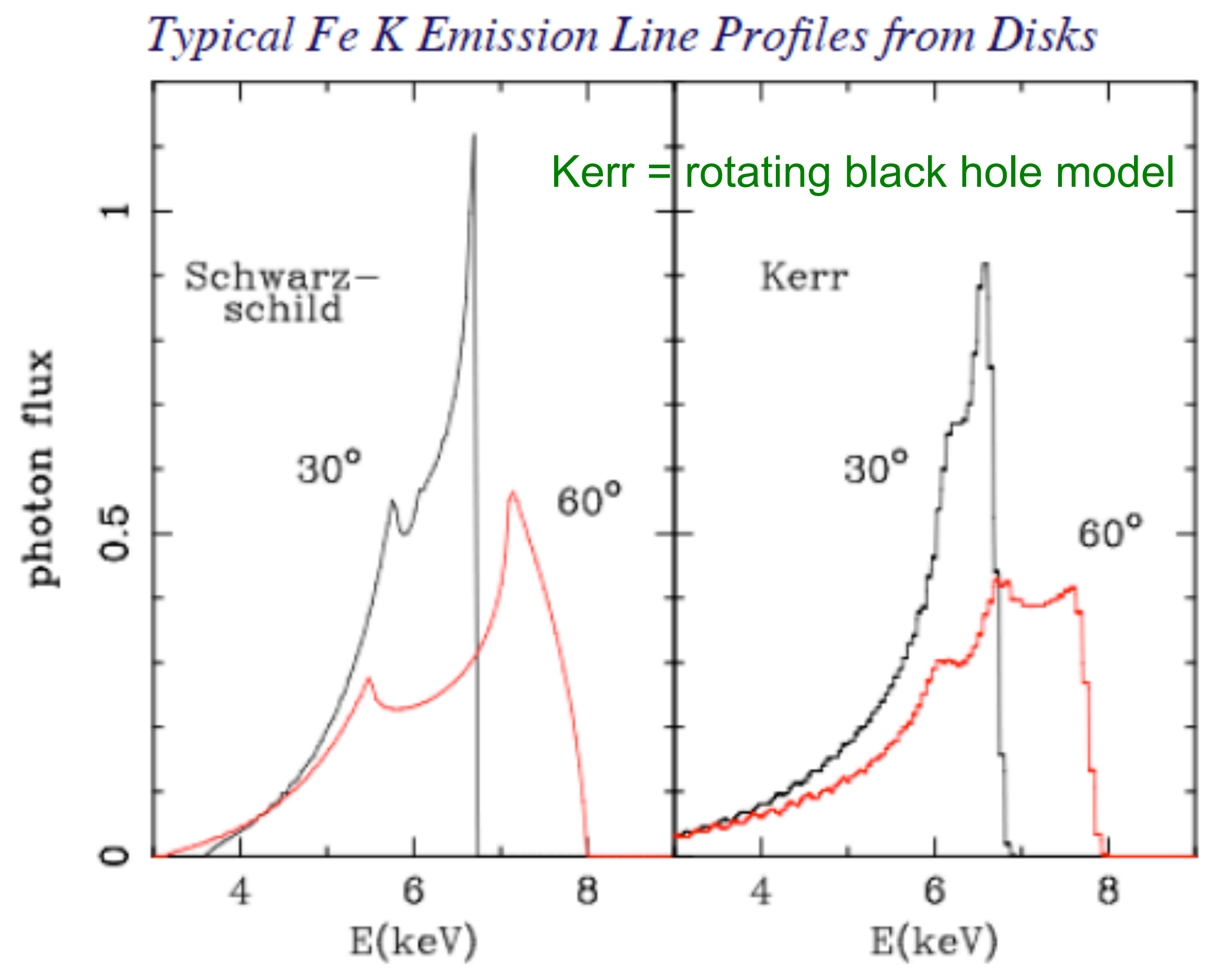
See George & Fabian (1991)



Compton reflection most evident above ~ 15 keV

Strong Fe-K line observed when viewing pure reflection

Figure 12. Reflected and composite (reflected + direct) spectra for a flat, optically thick, non-rotating circular slab illuminated by an isotropic source of primary X-rays located a height h above the centre. The spectra shown are for a disc with $r_{\max} = 10^2 h$ and a power-law incident spectrum with $\Gamma = 1.7$, viewed at inclination angles $i = 0°$, $60°$ and $85°$.



Typical Fe K Emission Line Profiles from Disks

Kerr = rotating black hole model

T. Yaqoob talk at Central Engines of AGN 2006

Simulation by Laura Brenneman

Emission Line Equivalent Width

Two measures of line strength:
  Line flux
  Line equivalent width (EW)

Line flux ~ normalization of the line, depends on distance to AGN

Line EW = line photon flux / continuum at line energy

[line photon flux] = photons/cm^2/s

[continuum] = photons/cm^2/s/keV

[EW] = keV

EW ~ range in E over which continuum must be integrated to produce photons observed in line

$$\int L(E)dE = \int_{E_0 - EW/2}^{E_0 + EW/2} C(E)dE$$

C = continuum, i.e., $N_{PL}E^{-\Gamma}$

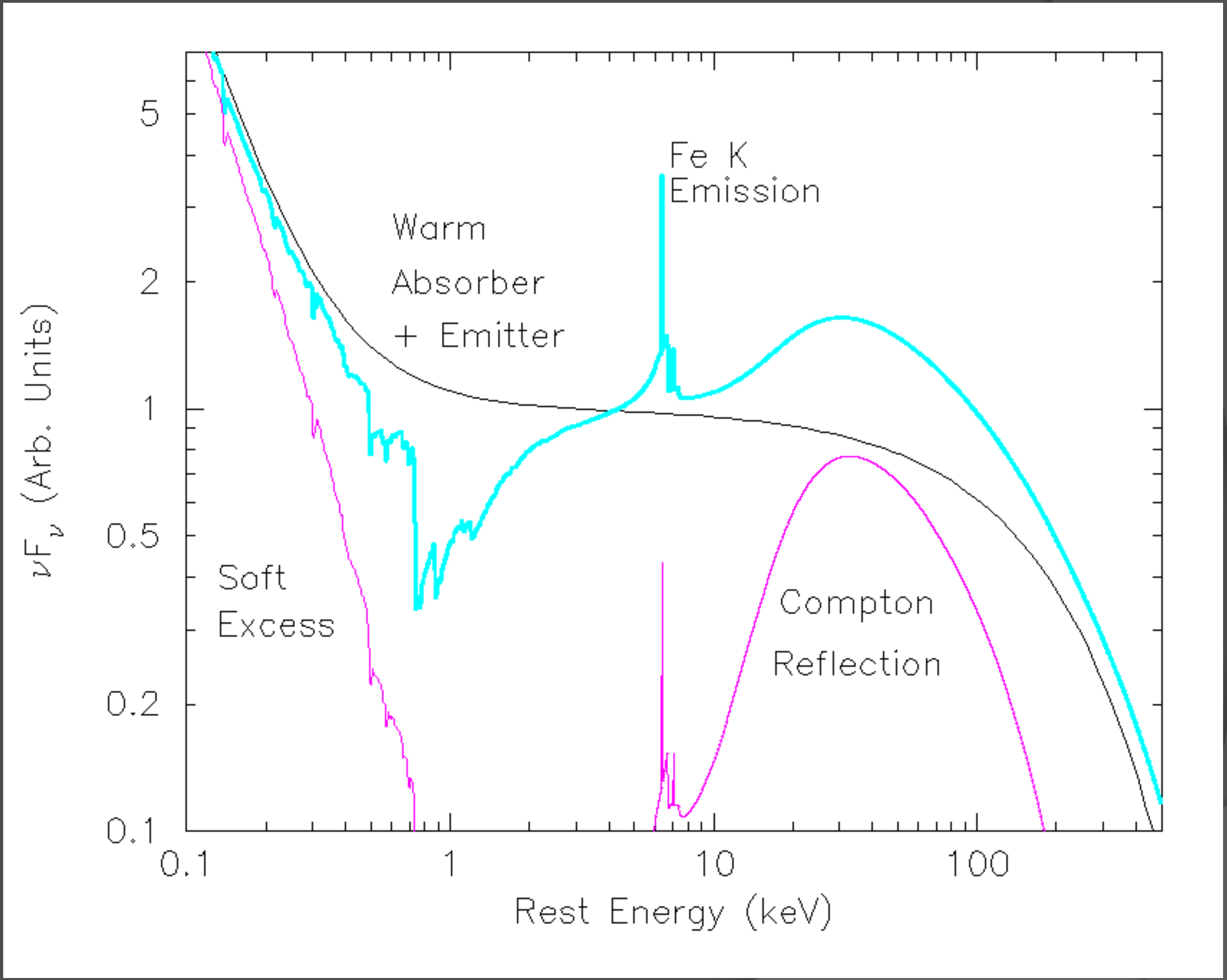
L = line model, e.g., for a Gaussian, $L(E) = N_l \exp[-(E-E_0)^2/2\sigma^2]$

AGN Fe-K Line EWs

- In Seyfert 1s, Fe-K line EWs tend to be ~ 100-400 eV
- In Seyfert 2s, Fe-K line EWs tend to be ~ 100-2000 eV
  - Fe-K EW >> 400 eV is a strong indication of an obscured central source
  - Absence of a high-EW line does not rule out heavy obscuration
    - Line could be washed out by scattered continuum, continuum outside of the AGN, there is no line of sight to reflecting surfaces (e.g., a spherical covering rather than toroidal, etc.)

Other AGN features

- Ionized gas emission lines
  - Photo-ionized outflows
  - Collisionally-ionized gas (star formation)
  - CCD resolution is not sufficient to distinguish these
- Ionized absorber/emitter
  - “warm” absorbers: Oxygen edges around 0.8 keV
- Soft excess
    - Various models under debate, was thought to be tail of disk blackbody emission
- Hot spots: narrow, often transient, emission lines seen near Fe-K



http://www.jca.umbc.edu/~george/html/science/seyferts/seyf1_warmabsorber.shtml

Other Complications

- In practice a simple power-law spectrum is only observed when there are low numbers of counts
- In Seyfert 2s, there is often mixed scattered, reflected and direct flux (for a recent example, see LaMassa et al. 2010)
  - Obscured sources tends to have flatter spectra: lower power-law slope or hard X-ray colors

X-ray Spectral Analysis

- Energy of each event recorded as a “pulse height amplitude” (PHA)

  PHA = aE + b

  a = gain, b = zero point

  Tools like XSPEC can also fit for gain (a,b)

  Spectral resolution = error in measuring E, mainly due counting statistics of ejected electrons

  $\sigma_{PHA} = [n^2 + fE]^{0.5}$ ($n^2 =$ noise term)

Spectral Response

$$m(h) = T \int dE \, \frac{F(E)}{E} A(E) R(E,h)$$

$m(h)$ = expected number of counts at PHA value h

T = exposure time

$A(E)$ = “effective” area of instrument (cm^2)

= geometric area reduced by any attenuation of flux

$R(E,h)$ = line response function = probability of observing photon of energy E at spectral channel h

Spectral Response in Practice

$$m(h) = T \sum_i \Delta E_i \frac{F(E_i)}{E_i} A_i R_{i,h}$$

Pulse height (h) is quantized (by onboard electronics), effective area A computed as a vector, response fn. R computed as matrix.

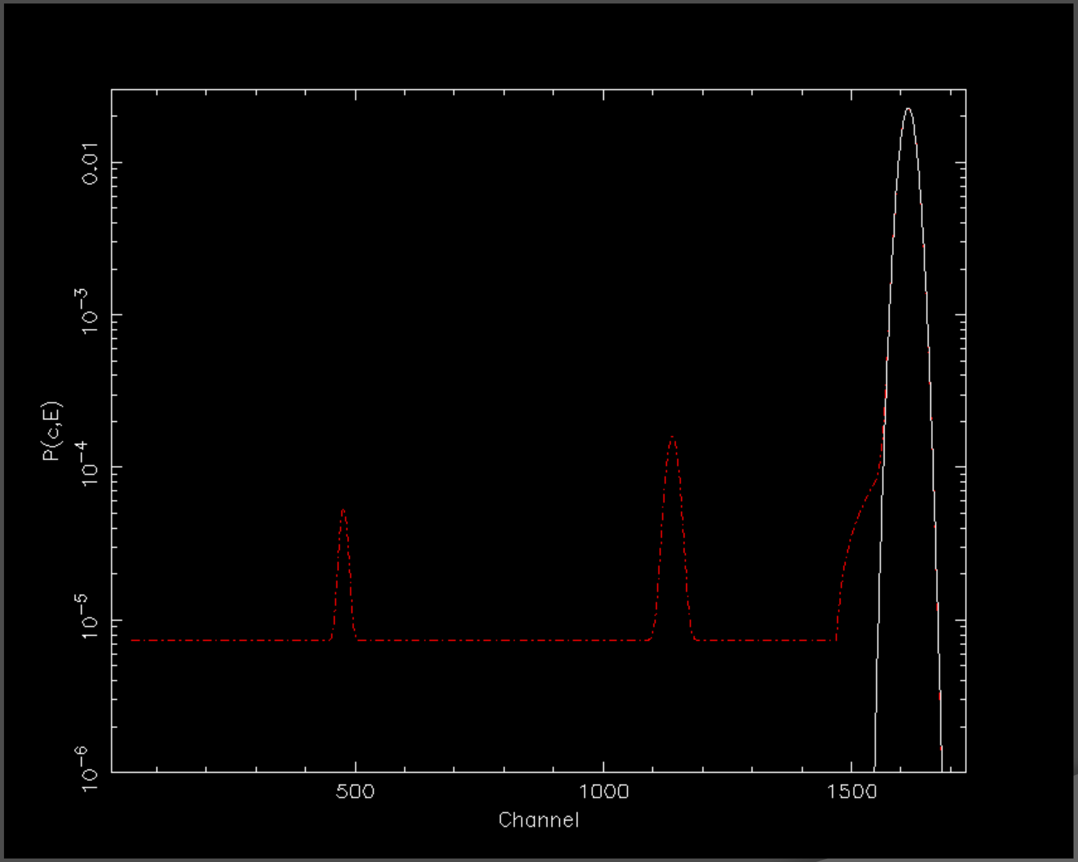
Efficiency of detector QE (“quantum efficiency”) included either in

A ($\Sigma_h R_{i,h}$ = 1) or R ($\Sigma_h R_{i,h}$ = QE).

Spectral Response (Imaging)

- Geometric area in A(E) is due to mirror, attenuation due to reflection efficiency + absorption in telescope (mirror, windows, coatings, etc.)
- Line response function is ~ Gaussian for CCD detectors

Suzaku CCD Line Response at 5.9 keV



X-ray Spectral Fitting

$$m(h) = T \sum_i \Delta E_i \frac{F(E_i)}{E_i} A_i R_{i,h}$$

- The spectral response equation cannot be inverted in a stable way (esp. for X-ray astronomy where there are typically low numbers of photons in each spectral bin)
  - Same problem as trying to “clarify” a blurry picture
- Can we fit spectral features directly and ignore R?
  - Sometimes for high-resolution spectra, but not with low (CCD, CZT, etc) spectra or else many fit parameters will be wrong
- Alternative: forward fitting
  - Vary model, convolve with response to get predicted counts per spectral bin, compare model prediction with data, rinse and repeat

X-ray Spectral Forward Fitting

- Need to minimize difference between $m(h)$ and $c(h)$ (net observed counts = total - background $T(h)$ - $b(h)$)
- Two conventional approaches
  - Bin observed spectrum to 10-20 counts per bin so that Gaussian statistics apply (i.e., error in spectral bin h = $\sigma(h) = T(h)^{-0.5}$), directly subtract background, use χ^2 statistics.
  - Use unbinned spectrum, ignore or model background, use Poisson statistics
  - Hybrid: include background as measured but part of model:
    - P[T(h) | m(h) + b(h)]
      - Probability of observing T(h) total counts given model m and background b (estimated from data)

Gaussian case:
Prob. of observing c(h) for model m(h):

$$P \propto \Pi_h \exp[-(c(h) - m(h))^2/(2\sigma(h)^2)]$$

Maximizing P same as minimizing -log(P)

$$-\log(P) = \Sigma_h [c(h) - m(h)]^2/(2\sigma(h)^2$$

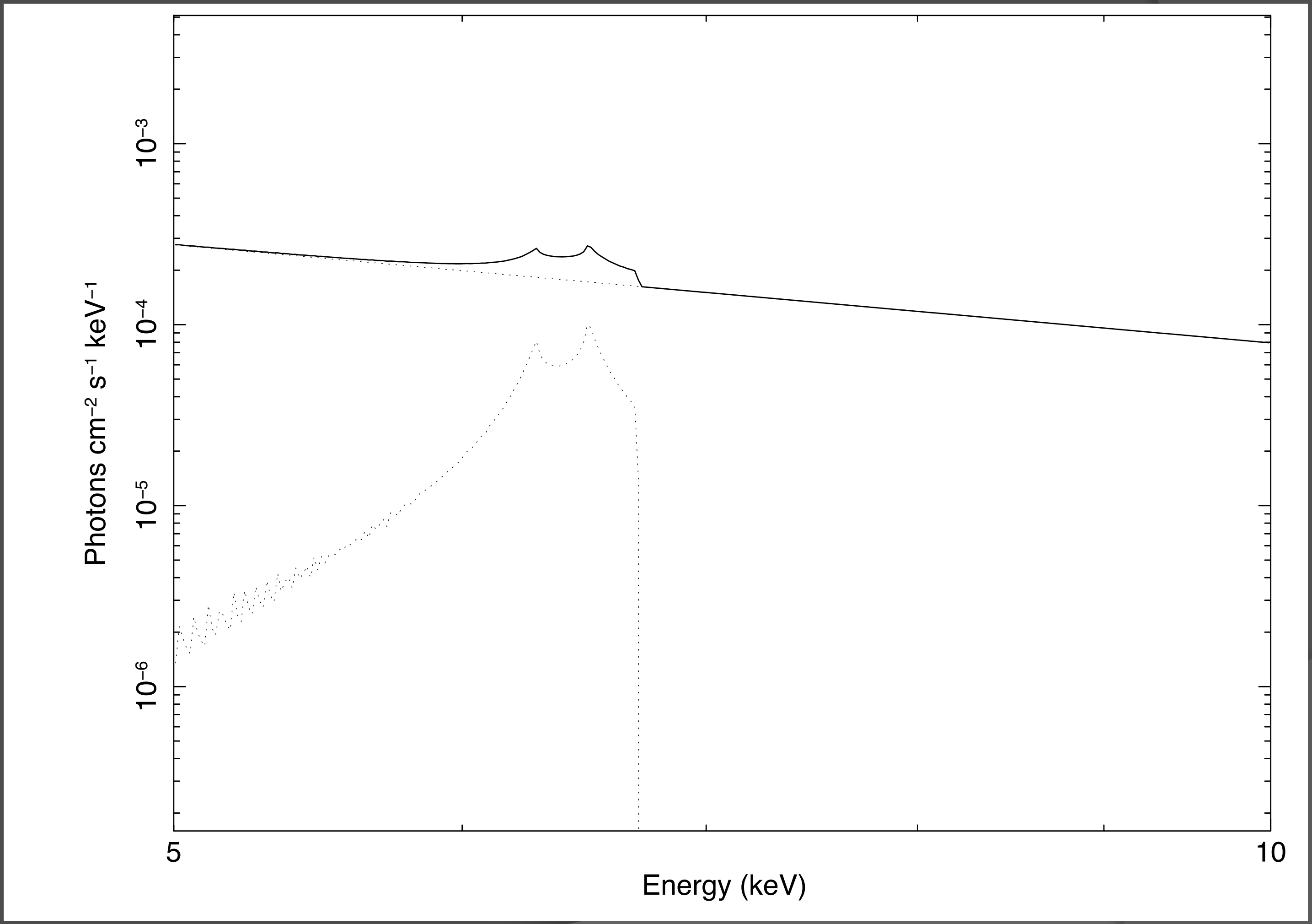
Poisson case:

$$P = \Pi_h \text{Poisson}(T(h), m(h)+b(h))$$

Multiple techniques for optimizing fit statistic and getting confidence regions (Aneta's talk). My personal preference is to use c-statistic with Marquardt-Levenberg minimization and ΔC for errors, then verify with simulations and/or Bayesian MCMC analysis, time-permitting

XSPEC “diskline” model

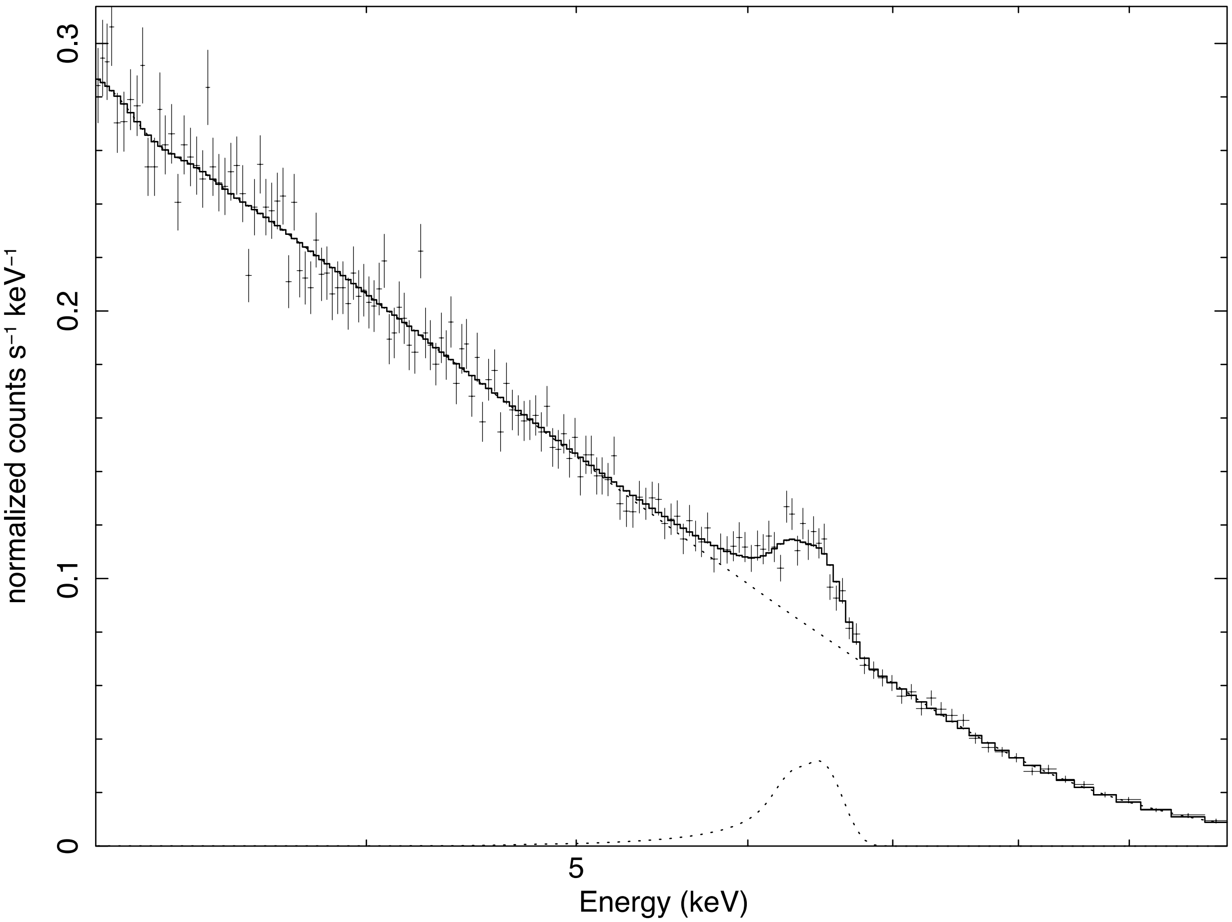
EW = 250 eV
Power-law
with $\Gamma = 1.8$



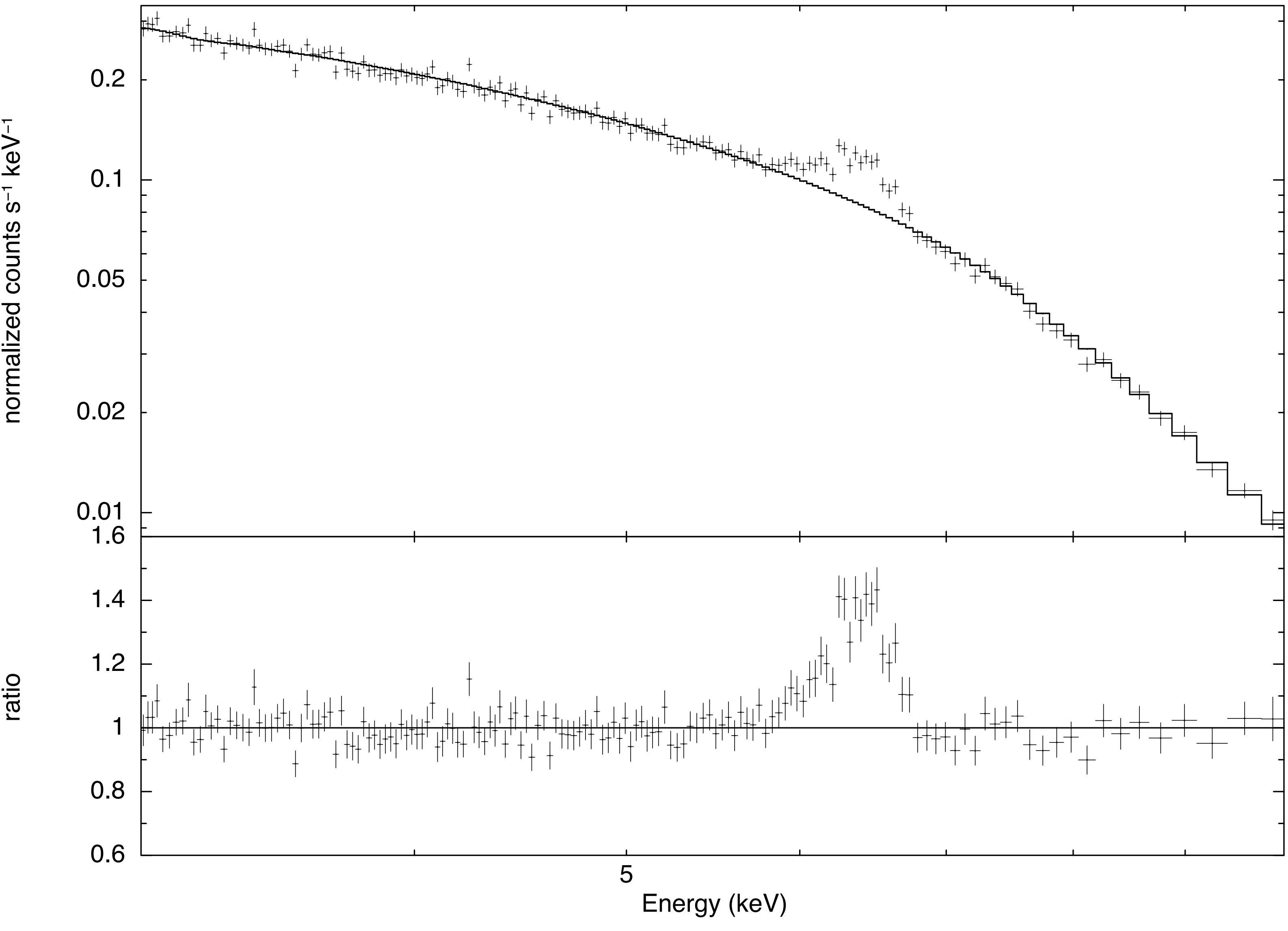
Suzaku Front-Illuminated CCD Simulation

$F(2\text{-}10) = 1.7\times10^{-11}$ ergs cm^{-2} s^{-1}

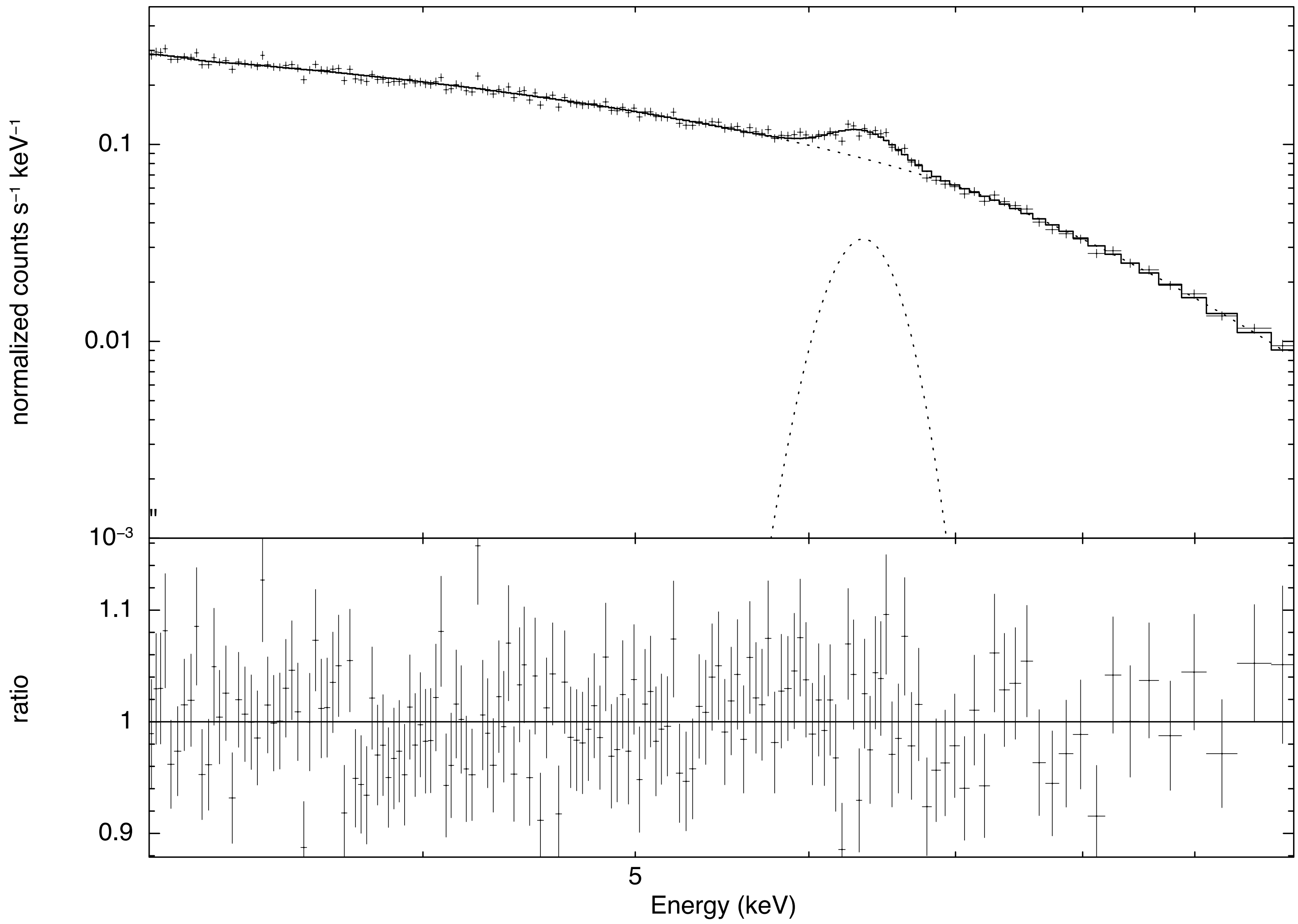
100 ks simulation using “fakeit” in XSPEC, no background



Power-law only fit



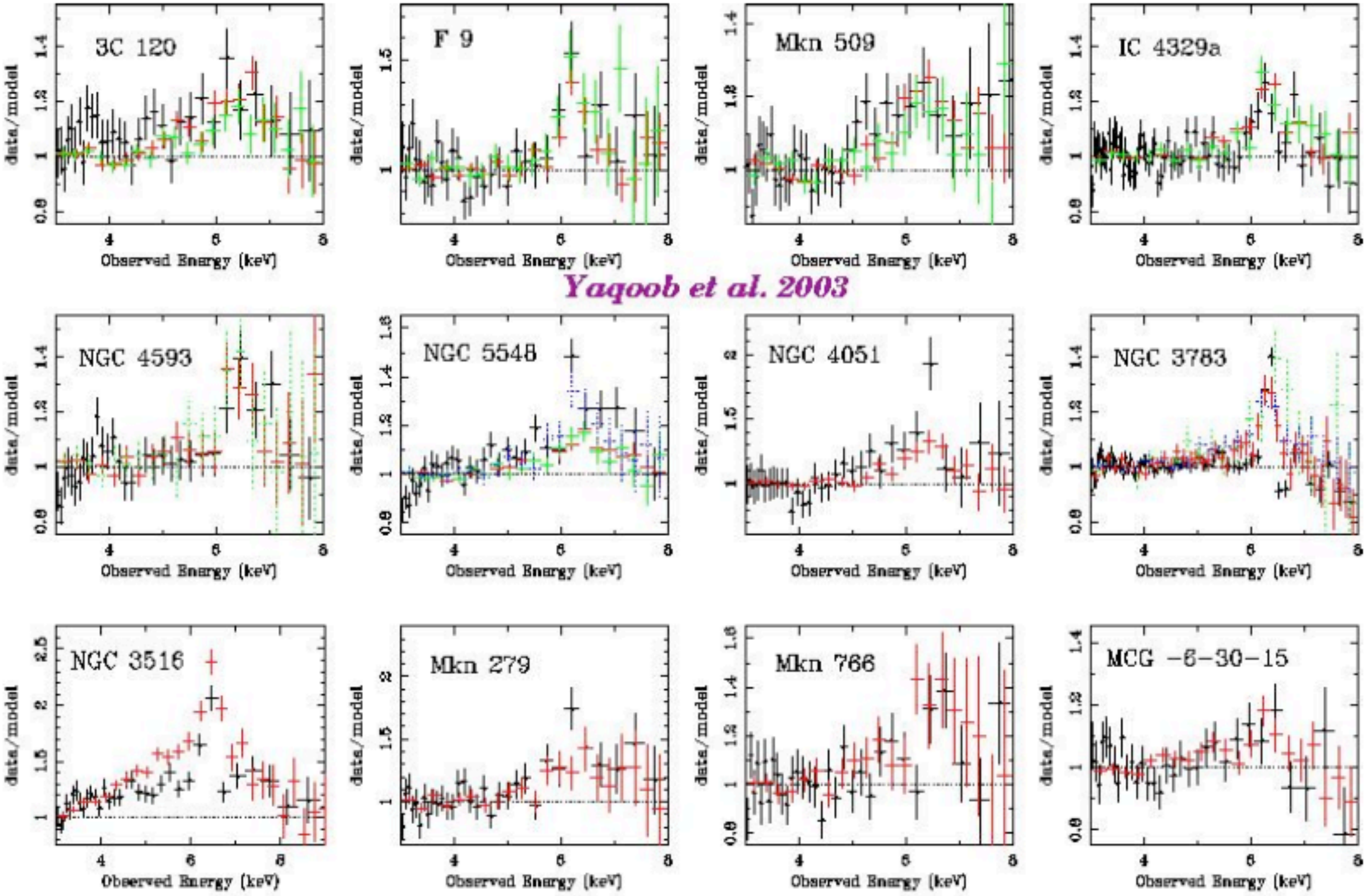
Power-law plus Gaussian fit



C-statistic for power-law fit: 1365
C-statistic for power-law + gaussian fit: 984
Line physical width from fit: 0.20 (0.17-0.24) keV

N.B. error based on $\Delta C = 4.6$, not strictly statistically-correct (Aneta's talk!) but simulations would probably show this is not far off (e.g., Yaqoob 1998: error on EW can be approximated by scaling error on line norm).

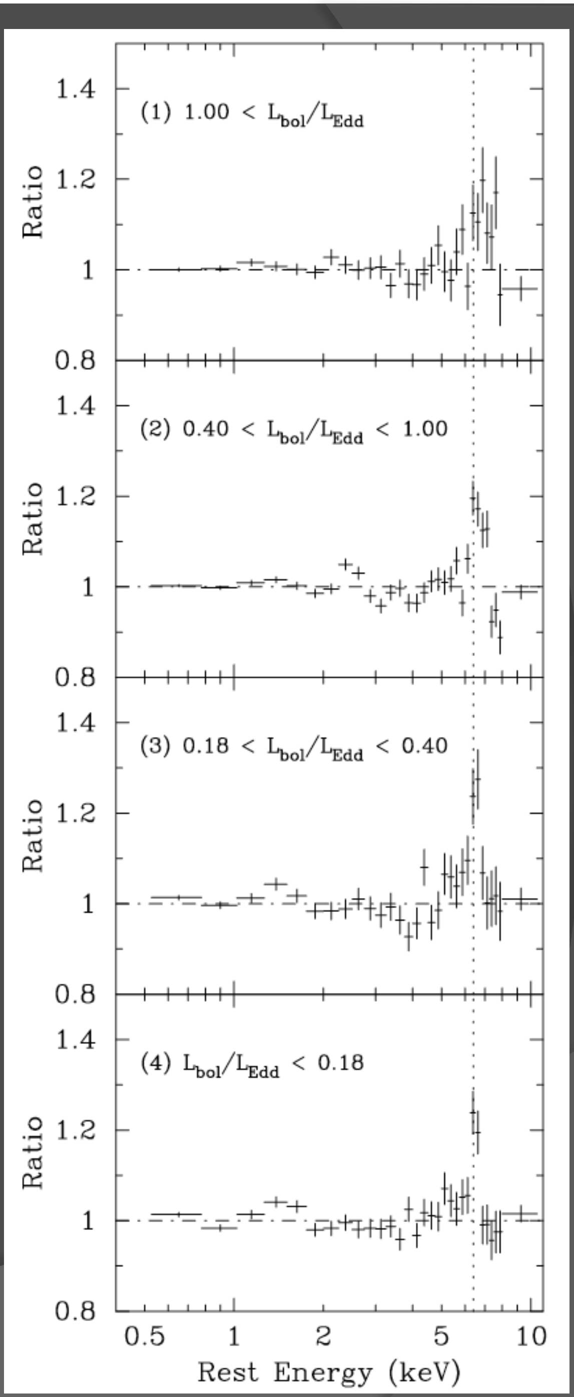
Upshot: a 100 ks Suzaku observation of this hypothetical source might show that there is a broad (physical width > instrumental resolution) Fe-K line but not that this is exclusively consistent with a theoretical disk line



Yaqoob et al. 2003

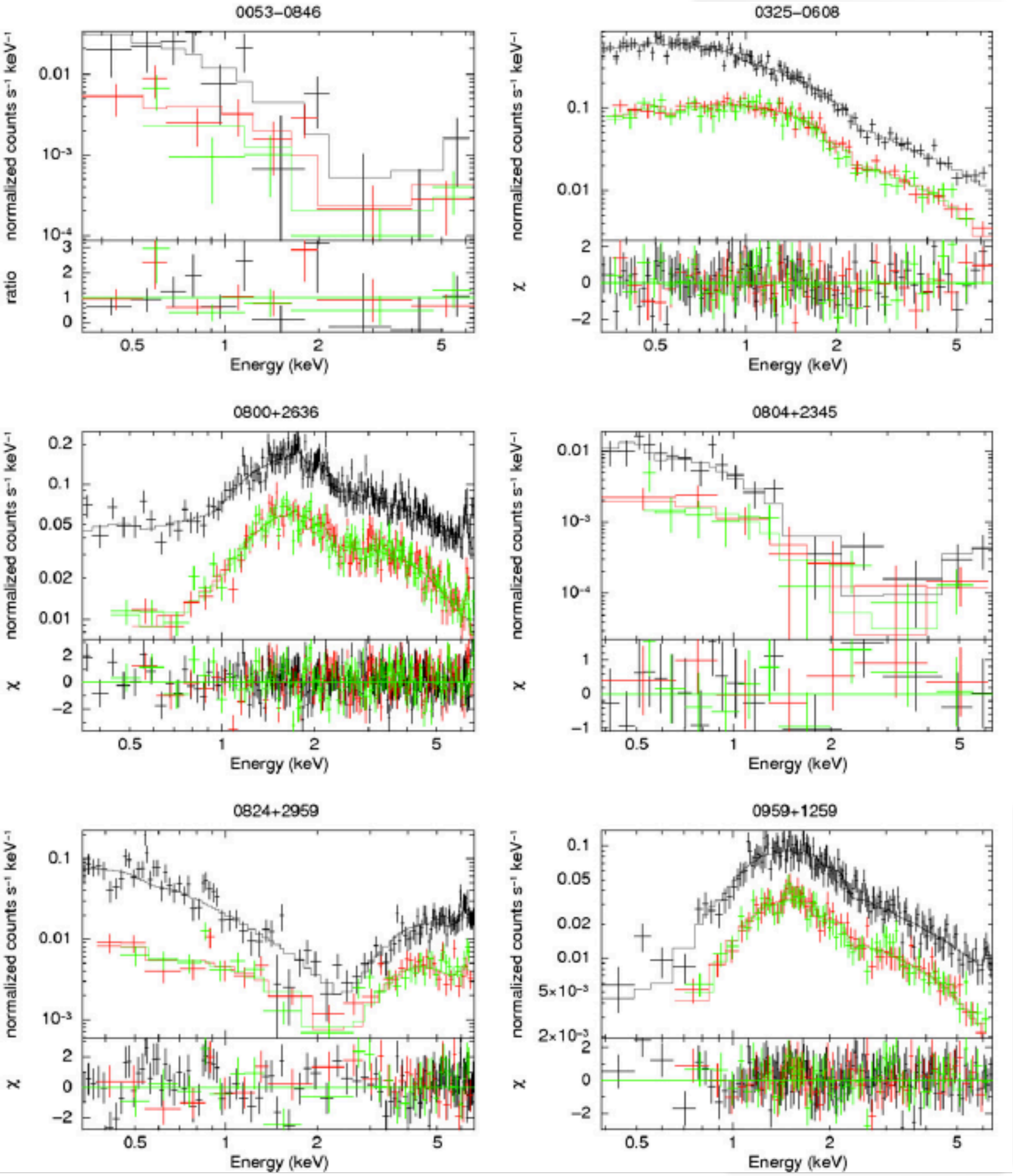
Chandra HEG (BLACK) vs. ASCA S0+S1 (COLORED)

Dependence of Fe-K strength and shape on Accretion rate (Inoue, Terashima, & Ho 2007)



Range of X-ray spectra observed from a complete optically-selected sample of Seyfert 2s (LaMassa et al. 2010)

Fit well with partial covering models, but could soft components be thermal emission? Ionized outflows not directly tied to intrinsic power-law? Need to use physical intuition, background knowledge e.g., star formation very rarely produced luminosities > 10^{42} ergs s^{-1}



XSPEC Models (similar in other fitting packages)

powerlaw – obvious
phabs – absorption not including scattering
plcabs – absorbed power-law including scattering but in an approximate way only valid up to ~ 15 keV, assumes spherical obscuration
pexrav – Compton reflection
gaussian – obvious
diskline, laor(2), kerrdisk – accretion disk line models

To emulate a partial covering (multiple absorbers and scattering), use:
phabs * (const*powerlaw + plcabs)
Optionally tie power-law index in plcabs model to powerlaw model, which would represent elastic scattering (i.e., assumes a highly ionized plasma is acting as a mirror)
const = constant term for scattering fraction, typically 1-10%

Fitting Low-resolution AGN spectra in practice

- Lack of spectral resolution literally blurs distinction between models
- Low numbers of photons often effectively lowers the spectral resolution (e.g., information content of 100 photons over a 10 keV range will low whether data are physically binned or not)
- Care must be taken in assessing significance of features and in model selection (statistics talk later)

Potential Exercises

- Download data from classic Seyfert galaxies (e.g., NGC 3227, Fairall 9, NGC 2992, NGC 4151, Mrk 3) and fit power-law models to 2-10 keV spectrum
  - Watch out for pileup!
  - Add additional absorber, esp. for Sy 2s
  - Compare diskline and gaussian fits to Fe-K
    - Does Fe-K EW vary between observations?
- Repeat Fe-K diskline simulation shown here: how many counts are needed before diskline becomes statistically distinct from a broad Gaussian?
- Simulate partial covering models at various numbers of counts (100, 500, 1000, 5000)
  - Fit with a simple power law, see how “effective” photon index for a simple power-law fit varies with scattering fraction, N_H of the highly absorbed component

Spare Slides

Imagining X-ray Telescopes

- Grazing-incidence optics
  - Often Au or Ir coatings
- Detectors
  - Micro-channel plates (1980s-present) - no energy resolution
    - Einstein, Chandra (1999-present)
  - Imaging proportional counters (1980s) - poor energy res.
    - Einstein, EXOSAT, ROSAT
  - CCDs (1990s-present) - moderate energy res.
    - ASCA, Chandra, XMM-Newton, Suzaku, Swift XRT
  - Gratings (effectively 1999-present) – very good energy res.
    - Chandra, XMM-Newton
  - Calorimeters (2010s-?) - good energy res.
    - Suzaku (but died just before observations started)
    - Astro-H 2014 launch
    - IXO re-envisioned as Athena (ESA) and Con-X-R (US), >2020 launch

Non-Imaging X-ray Detectors

- X-rays detected via ionization
  - Total charge liberated proportional to energy of photon
    - “Proportional counters”
    - Individual photon “events” recorded
- Collimators used to limit field of view (FOV) and reduce background
- Each observation results in spectra (flux vs. energy) and light curves (flux vs. time)
- Still used today (NASA Swift, RXTE, NASA/JAXA Suzaku)