X-ray Binaries: Spectroscopy & Variability

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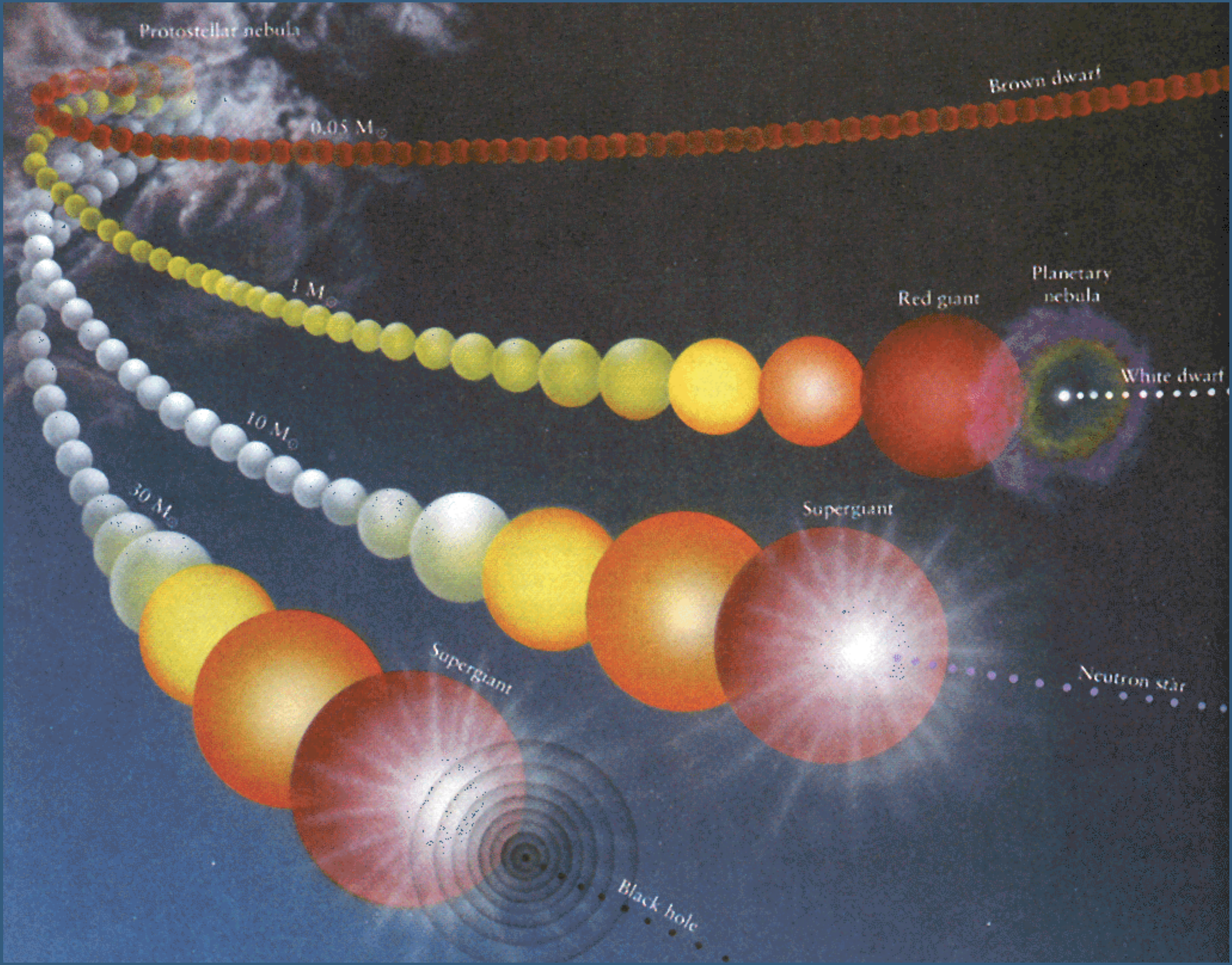
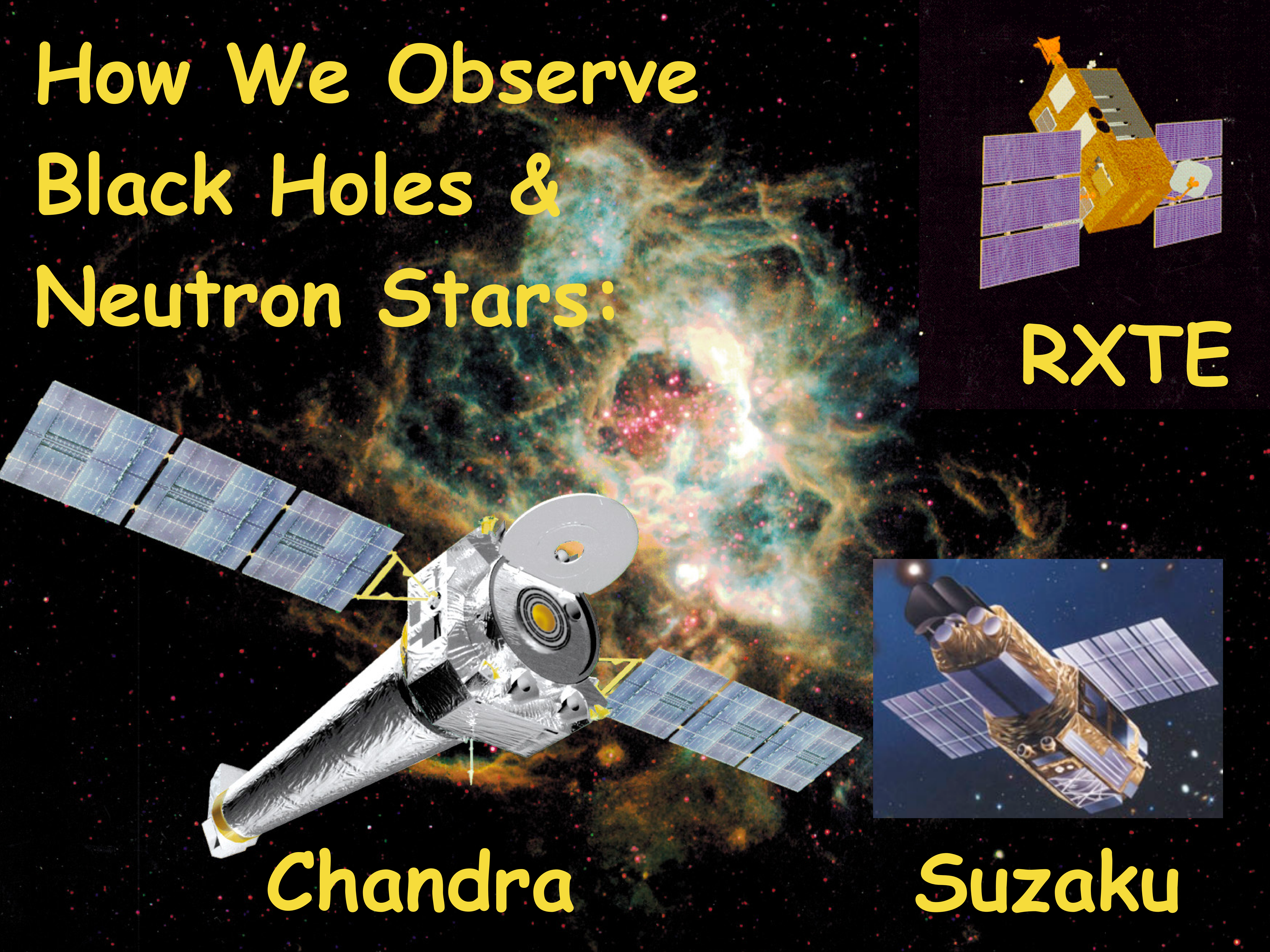
...

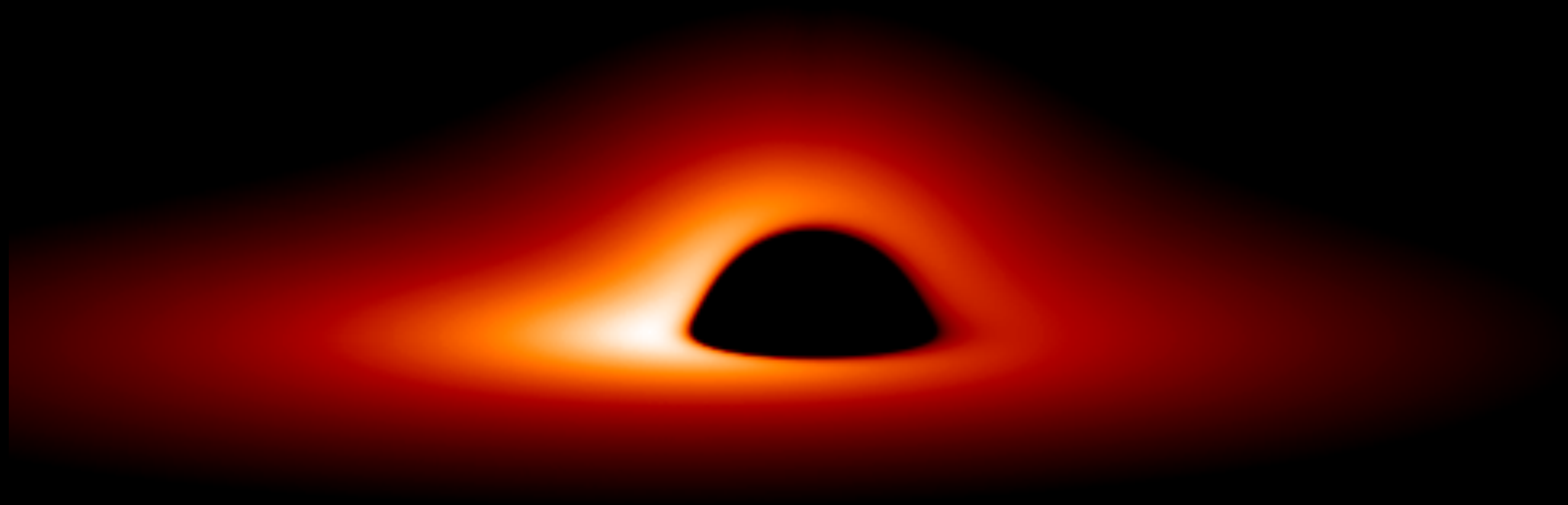

Protostellar nebula
Brown dwarf
0.05 $M_\odot$
1 $M_\odot$
Red giant
Planetary nebula
White dwarf
10 $M_\odot$
30 $M_\odot$
Supergiant
Neutron star
Supergiant
Black hole

Stars End Their Lives as One of Three Kinds of Compact Objects

- ***White Dwarf***: $R \sim R_{Earth}$, $\rho \sim 10^{5 \ldots 6}$ g cm^{-3}
  M < 1.44 Solar Masses (Chandrasekhar Limit)
  Equilibrium between gravity and degeneracy pressure
- ***Neutron Star***: R ~ 10 km , $\rho \sim 10^{13 \ldots 16}$ g cm^{-3}
  1.44 < M < 3 - 4 Solar Masses (Oppenheimer-Volkoff Limit)
- ***Black Hole***: No Stable Configuration above OV-Limit
  Star Collapses,
  Black Hole forms!


How We Observe
Black Holes &
Neutron Stars:
RXTE
Chandra
Suzaku

BLACK HOLES



Described with Only a Few Numbers:

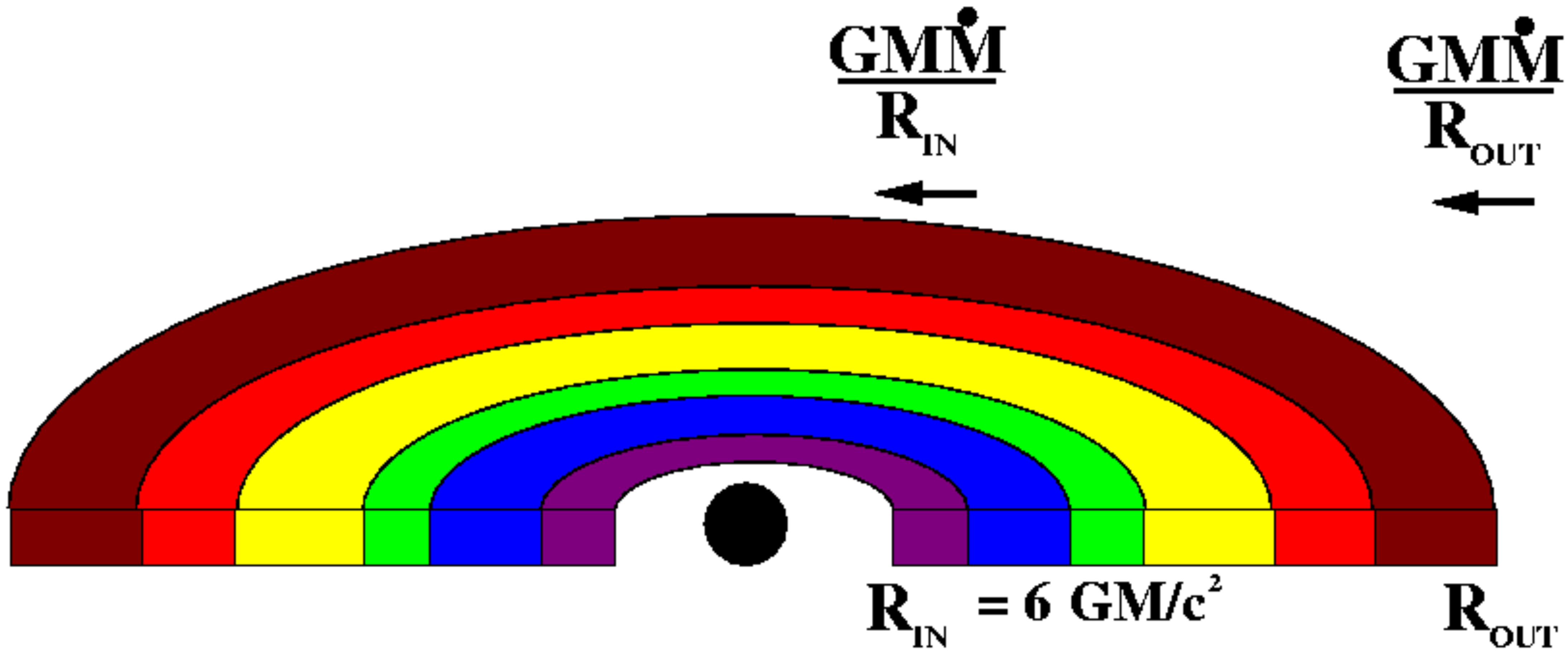
Mass: ? – 10 Billion Suns

Spin: $a = cJ/GM = 0 – 1$

Radius: $2\,GM/c^2 = 3$ km – 200 AU

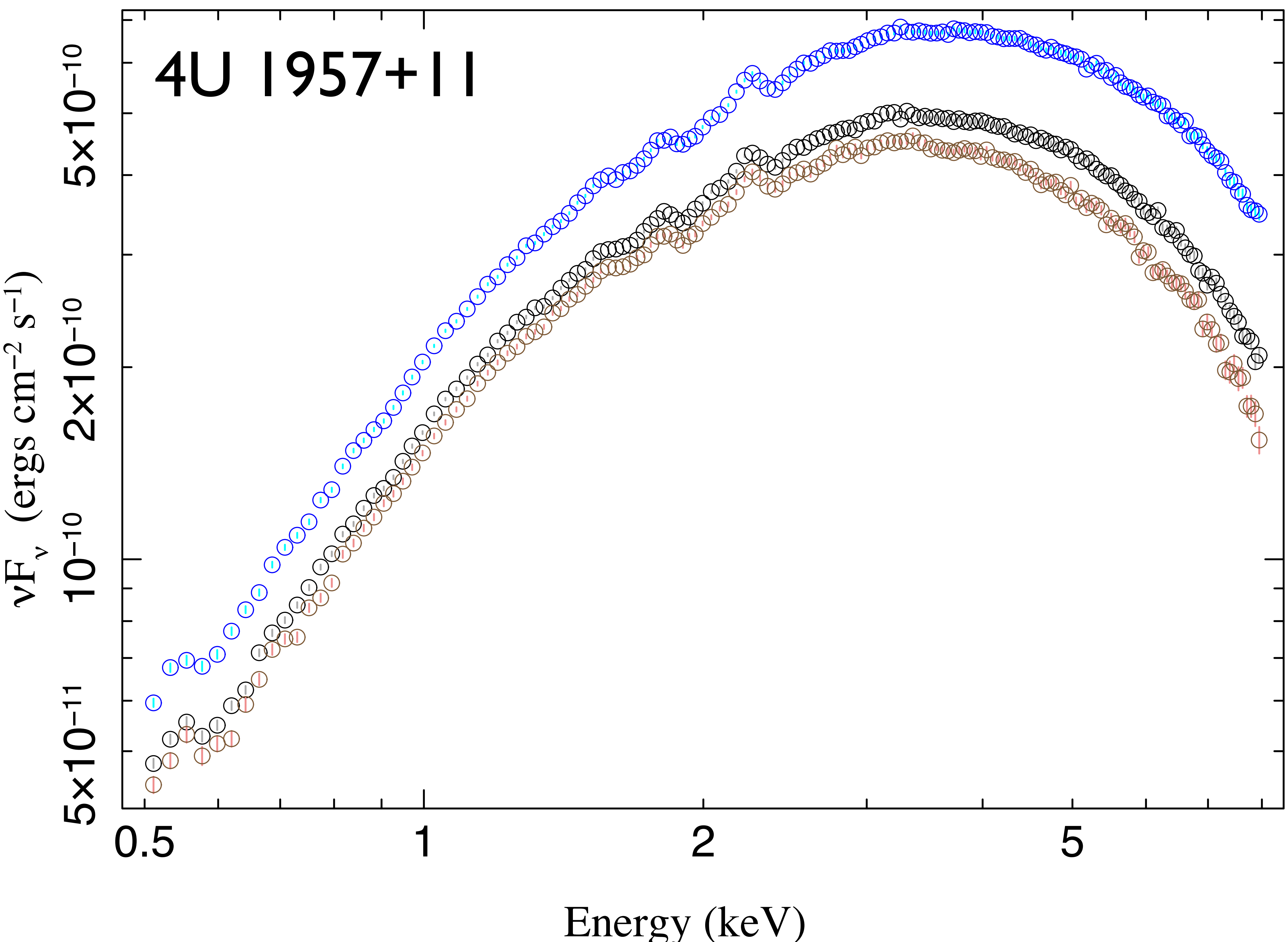
General Relativity Important!

How We Observe Black Holes



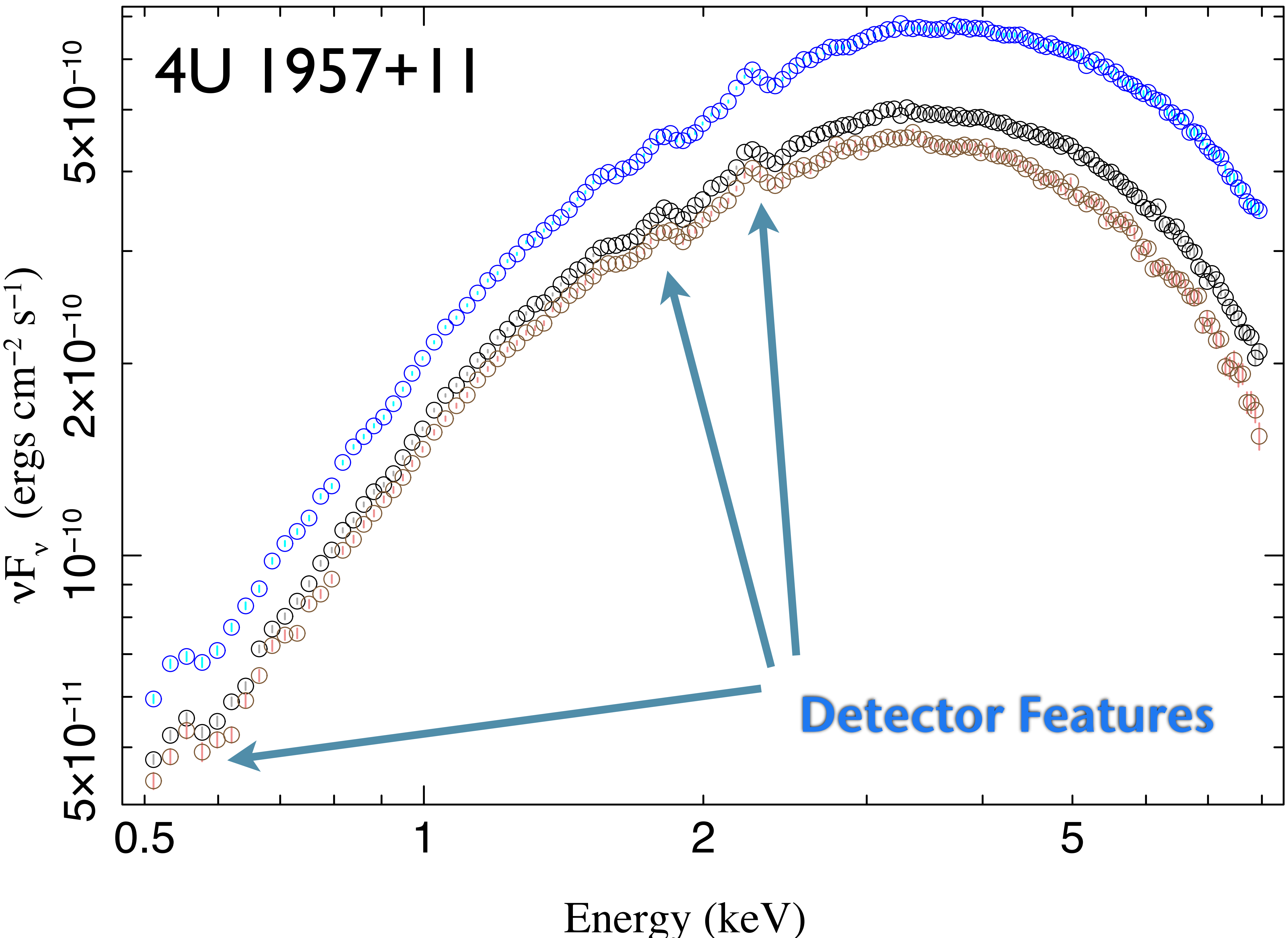
$$L = \frac{GM\dot{M}}{2}\left(\frac{1}{R_{IN}} - \frac{1}{R_{OUT}}\right) = \frac{GM\dot{M}}{2R_{IN}} = \frac{1}{12}\dot{M}c^2$$

Suzaku BHC Observations



(Nowak et al. 2011b)

Suzaku BHC Observations



(Nowak et al. 2011b)

Binaries Can be Bright:

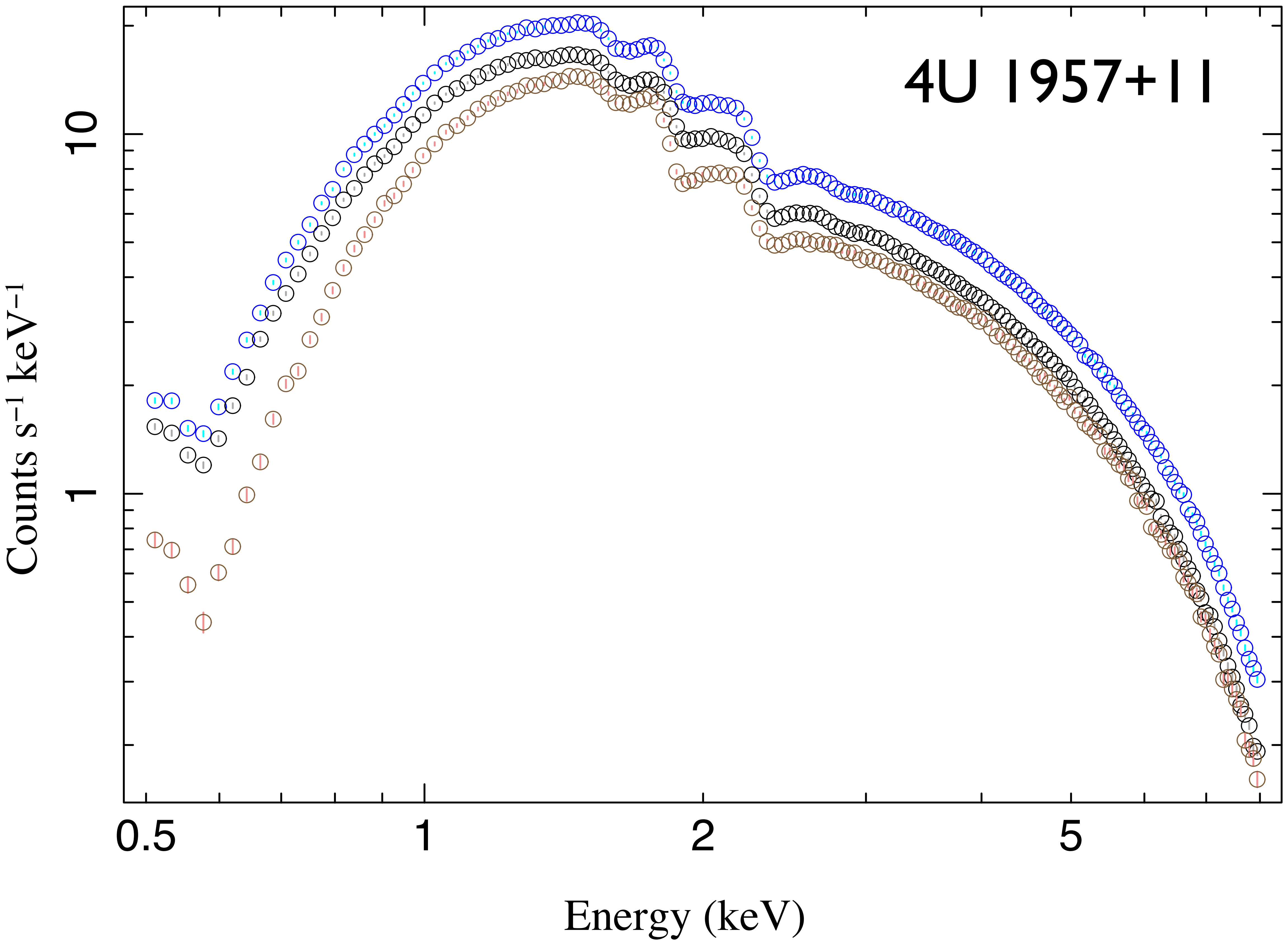
✦ Systematic Errors May Dominate ✦

- Also note that I plotted "flux corrected" data

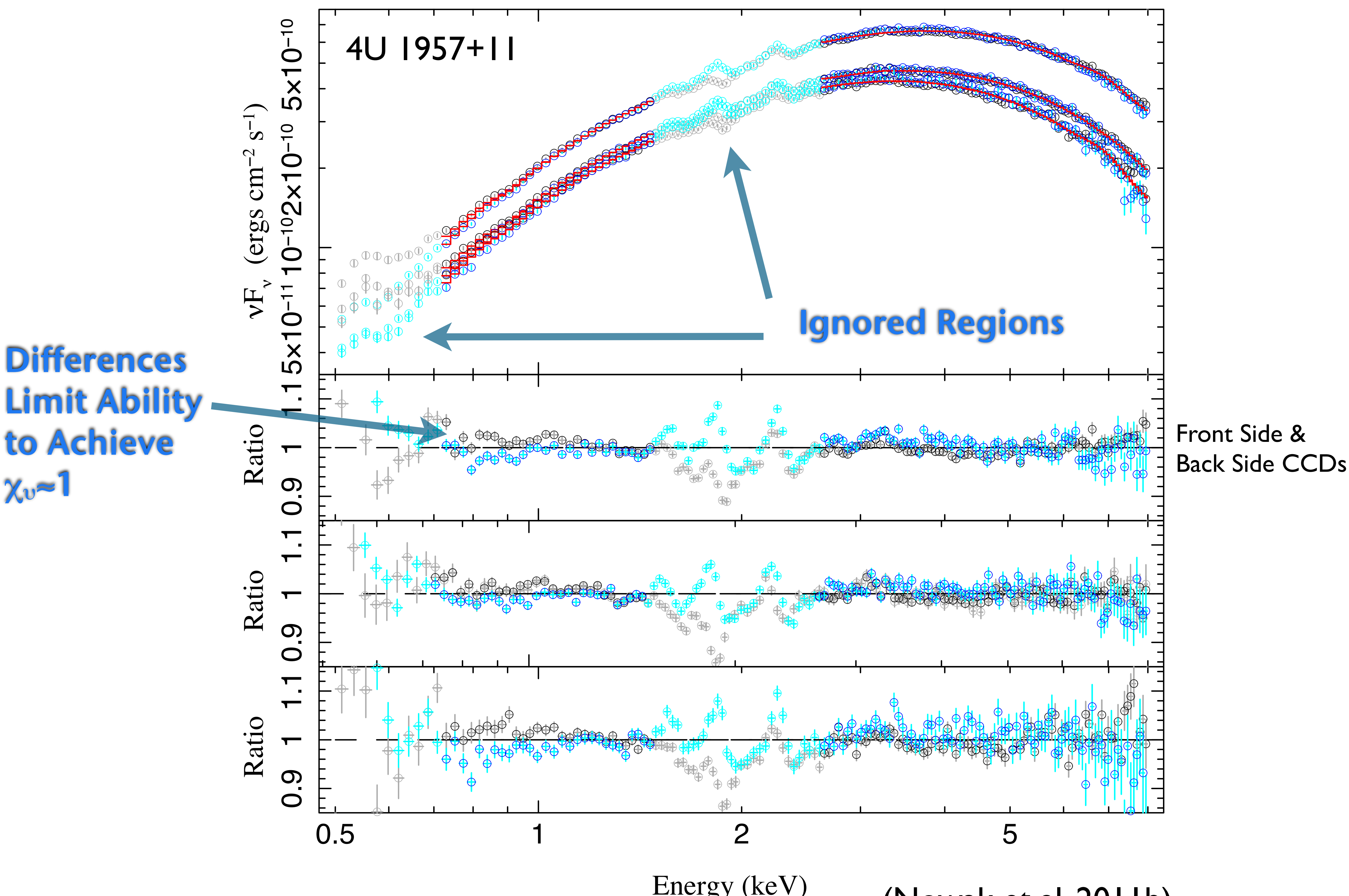
$$\mathcal{F}(h) = \frac{C(h) - B(h)}{T \sum_E R_{hE} A_E}$$

- "Unfolding" spectra is dangerous & potentially misleading
  - XSPEC does it differently; it *imposes your model assumptions* on the unfolded spectrum plot.
  - *Never* plot unfolded spectra the XSPEC way.
- I will do this throughout, but I am a professional!

Suzaku BHC Observations

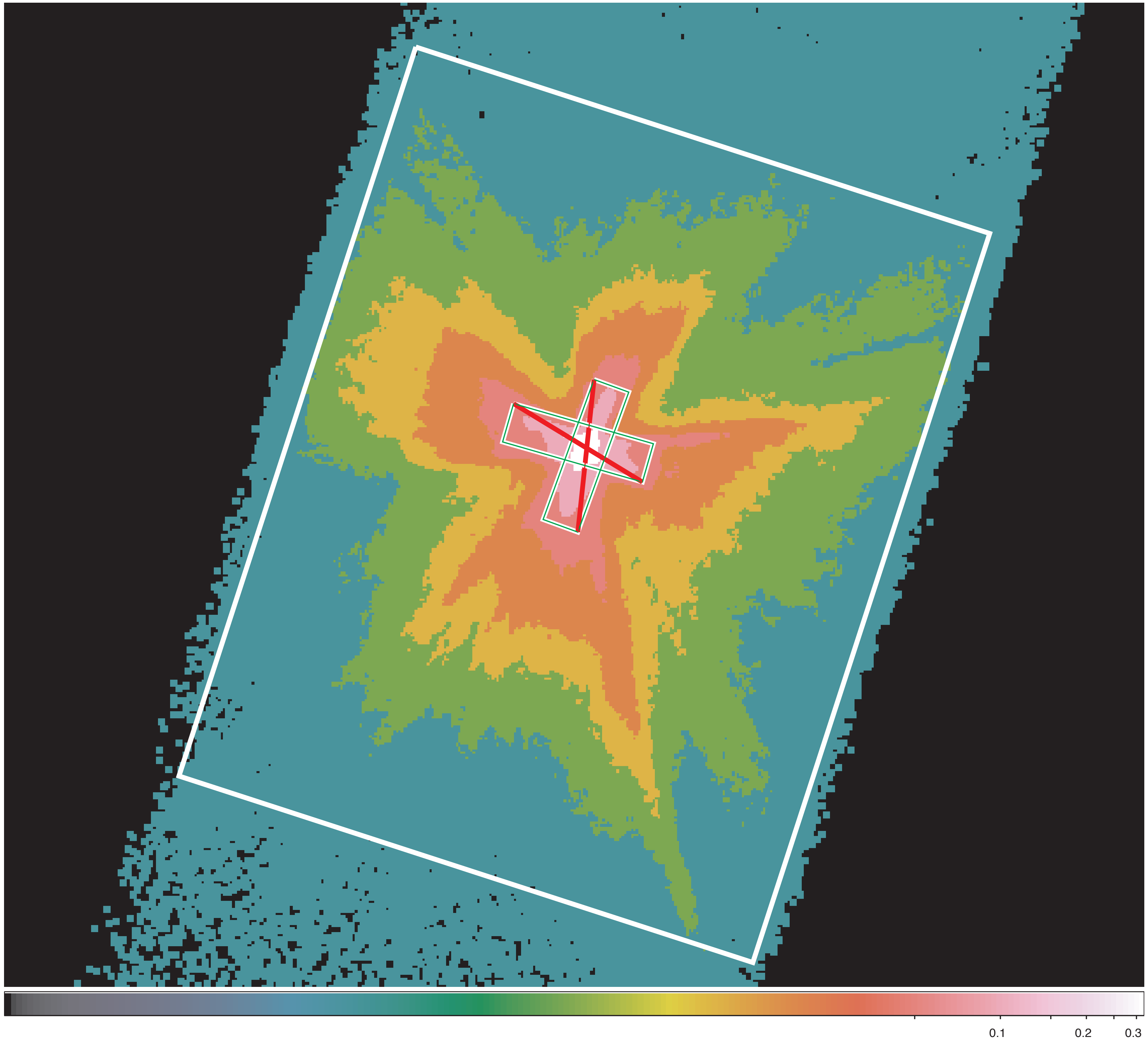


Suzaku BHC Observations



(Nowak et al. 2011b)

Piled-up Data was Ignored



http://space.mit.edu/CXC/software/suzaku/pest.html

In this Case, Disk Normalization was a Key Parameter

- Normalization provides a combination of mass, distance, inclination, and ratio of color temperature to effective temperature ($f_c = T_c/T_{eff}$):

$$\frac{(M/M_\odot)^2 \cos i}{(D/\mathrm{kpc})^2 f_c^4} = 0.0002$$

- Low value (expected 15X larger) argued for some combination of rapid black hole spin, large distance, or that we really don't understand disk atmospheric physics...
- Disk models to try included: diskbb, diskpn, kerrbb, eqpair (=diskpn+Comptonization); Read physics papers to understand their caveats!

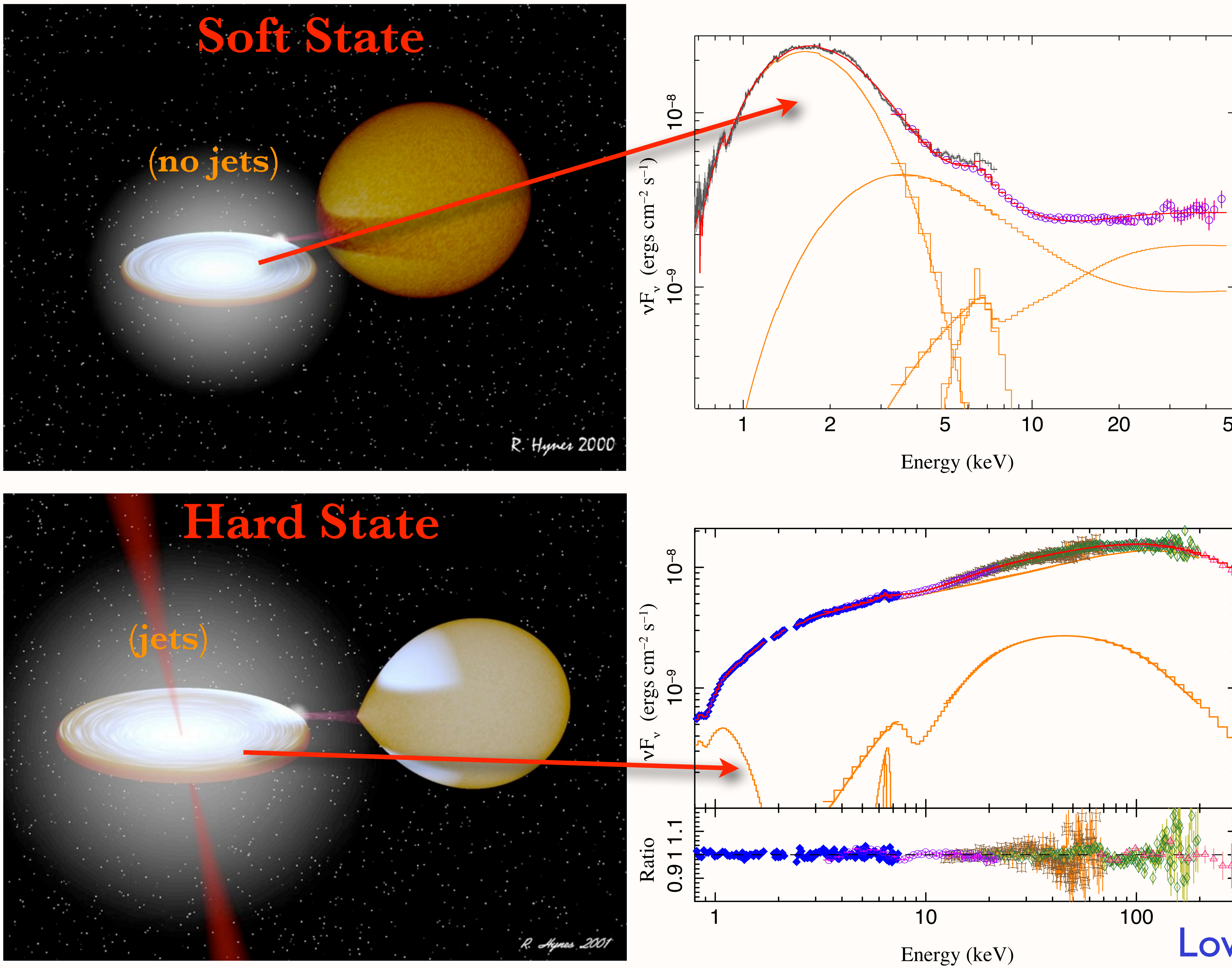
Story is More Complicated:

✦ Black Holes Have "States" with Different Spectral & Variability Properties ✦

- "Soft States" and Low Variability:
  - ★ Probes of GR via disk atmosphere models
- "Hard States" and High Variability:
  - ★ Probes of Coronae and Jets
- "Transitions":
  - ★ Further Probes of GR and Jet Formation

XRB Accretion States

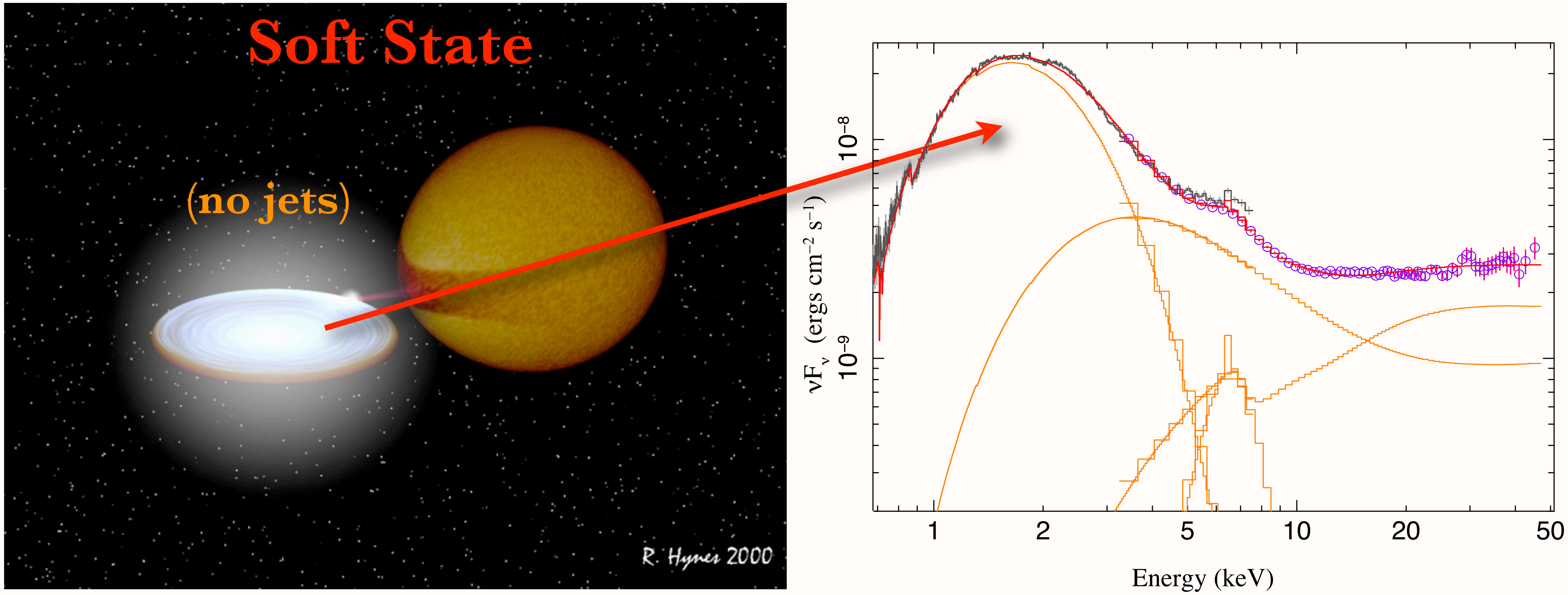
Higher Luminosity

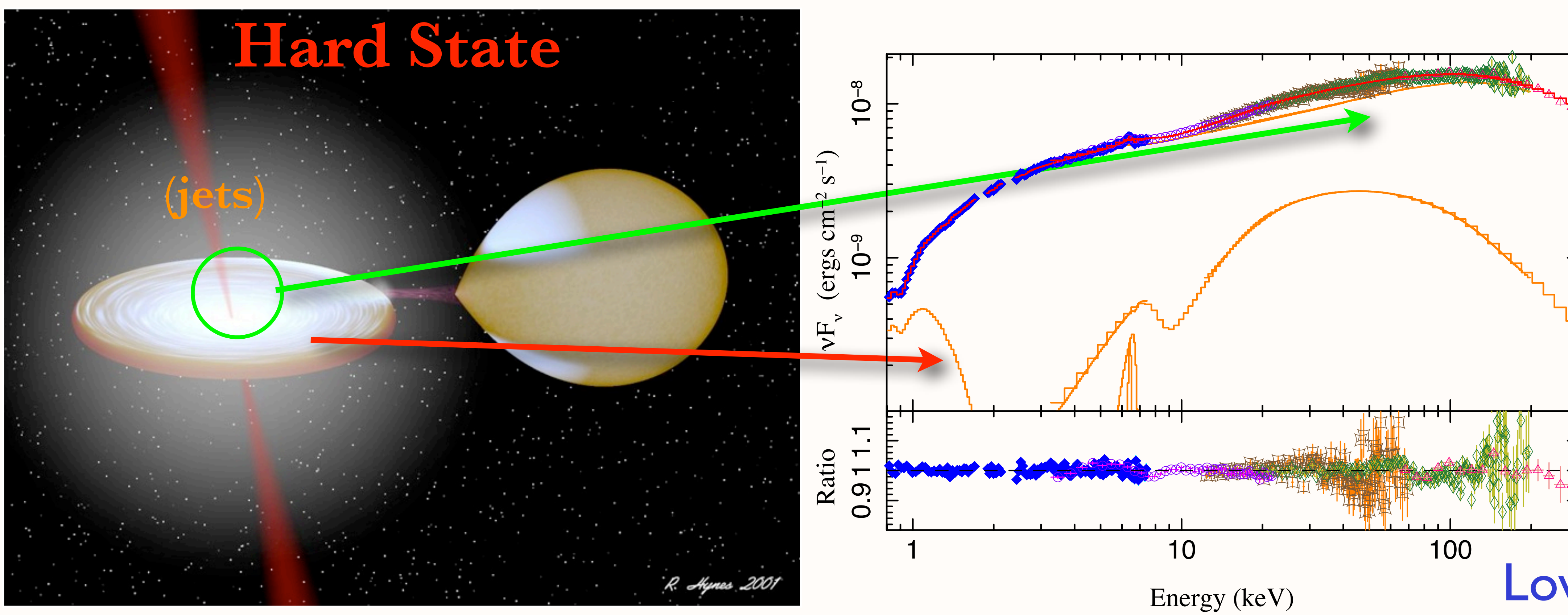


Lower Luminosity

XRB Accretion States

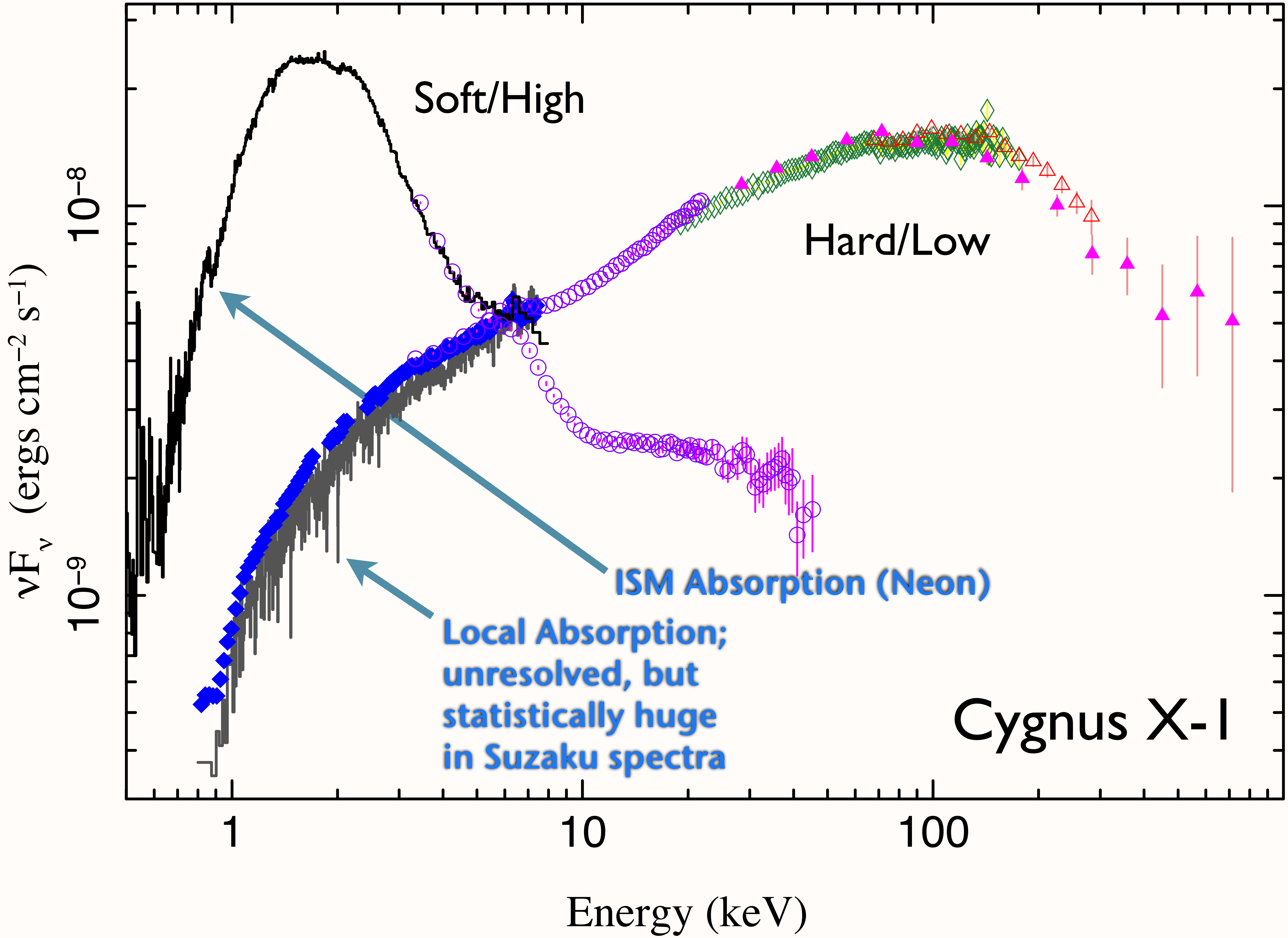
Higher Luminosity





Lower Luminosity

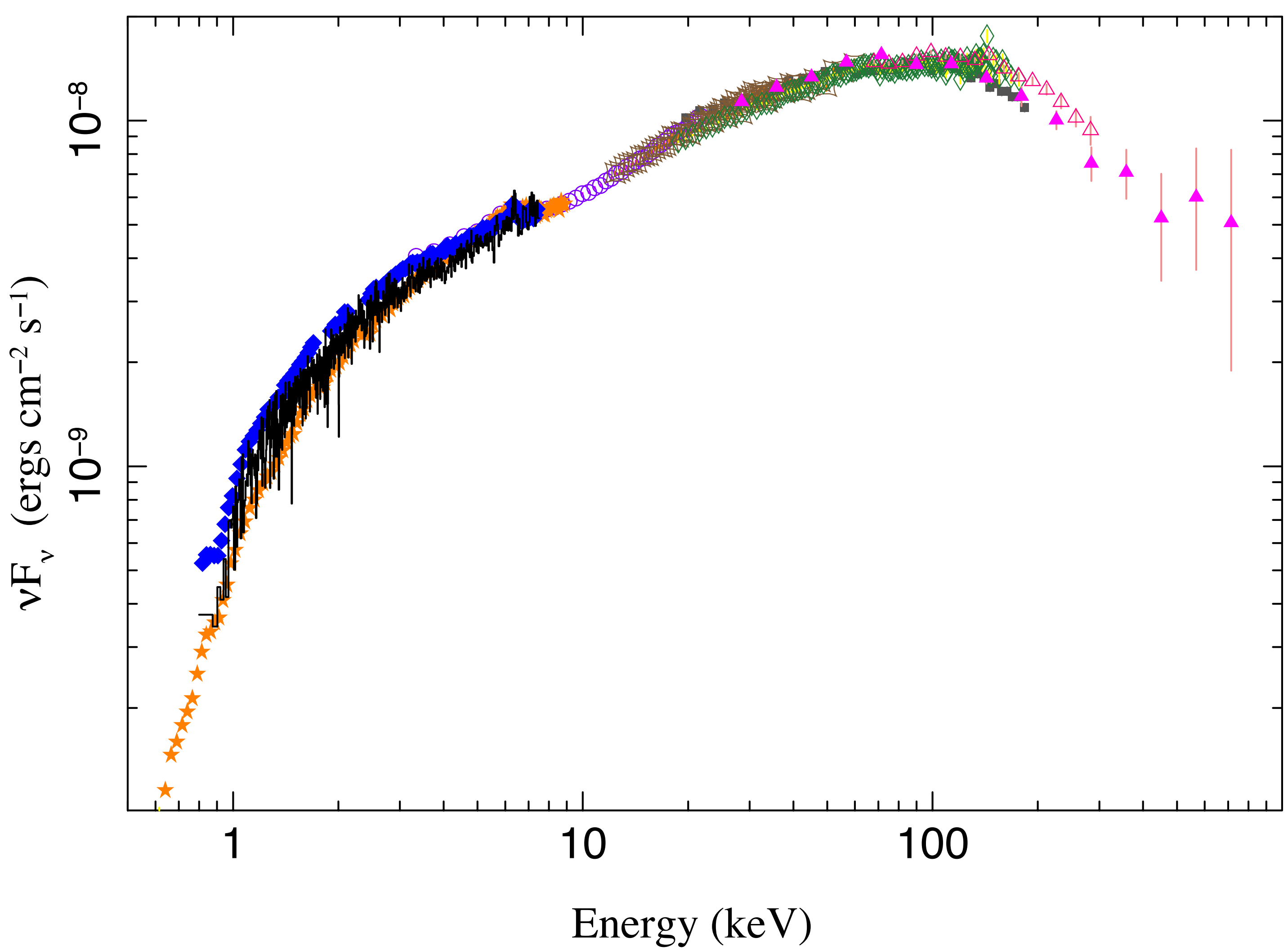
XRB Accretion States



Many Binary Observations are Multi-Detector

- RXTE, Suzaku, INTEGRAL, Swift, ... , are Multi-Detector
- Cross Normalization Constants (*at least*) are Necessary
  - ★ Normalization Constants Range Over ±10-15%

EPIC-PN = 0.78
HEG = 0.89
XIS1 = 0.93
PCA = 1
PIN = 0.97
HEXTE = 0.81
IBIS = 0.82
GSO = 0.88
SPI = 0.97



Binaries Can be Bright II:

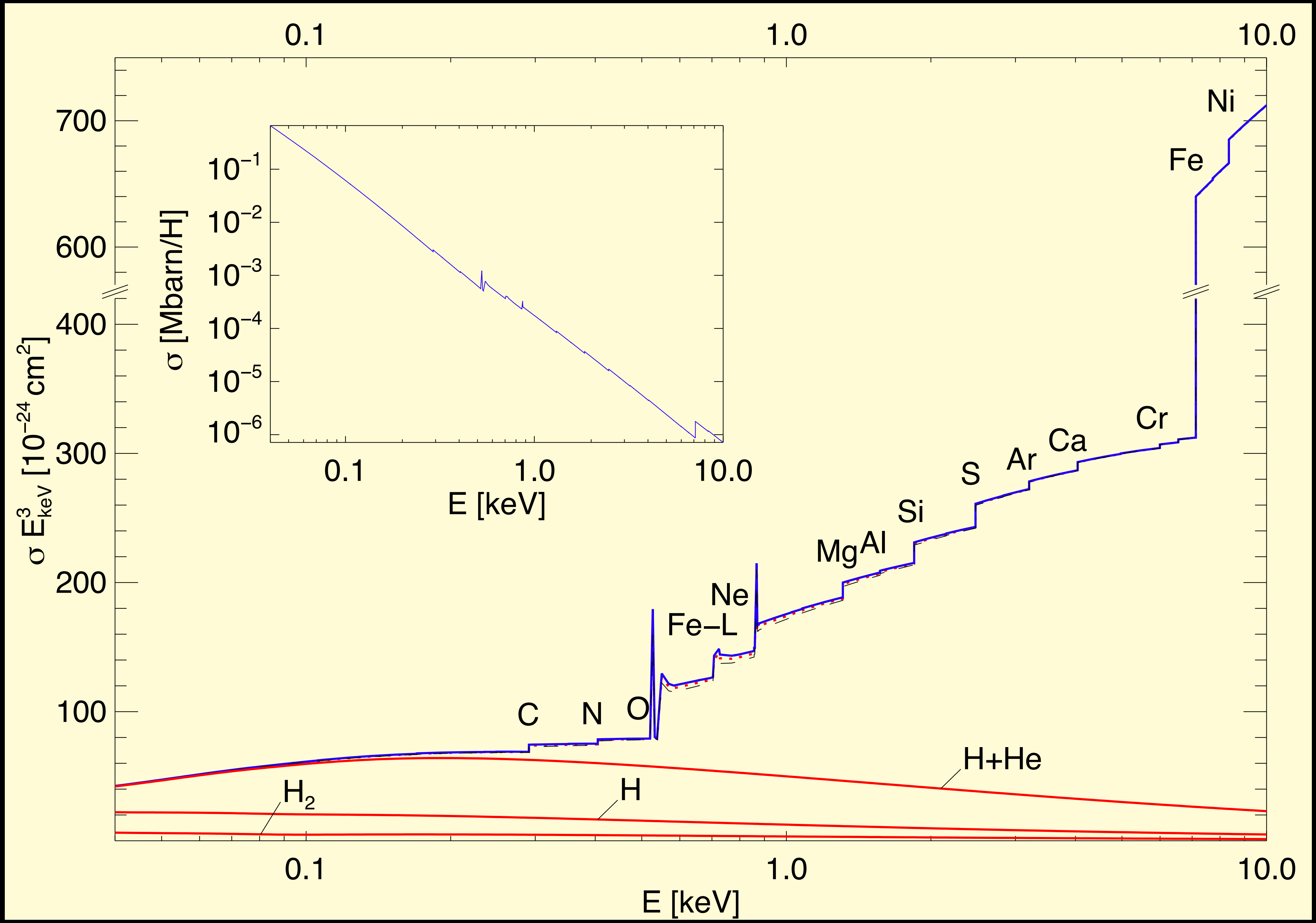
✦ Systematic Errors May Dominate ✦

- In this case, RXTE-PCA error bars were artificially increased by a fractional error (0.5%) to keep it from dominating the fits
- This is a common, but very unsatisfying, practice.
  - No one has had a more clever idea yet ...
  - ... although see Lee et al. 2011, ApJ, 731, 126L ...
  - ... which wouldn't work in this situation anyhow
  - This a project for one of you young, bright, energetic grad students.

Absorption: Depends upon Cross Sections, Abundances, & Model

- Only 23% of X-ray astronomers cite *any* absorption model, 58% of whom cite outdated wabs (Morrison & McCammon 1983)!
- See: http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/ for model of Wilms et al. (2000); use consistent cross sections & abundances (e.g., vern+wilm)
- Be aware that you are fitting metals, but quoting an equivalent hydrogen column (i.e., derived based upon your assumed cross sections, abundances, & model)
- If you are comparing to another waveband, they too are likely quoting an equivalent hydrogen column, and may be measuring something else entirely.

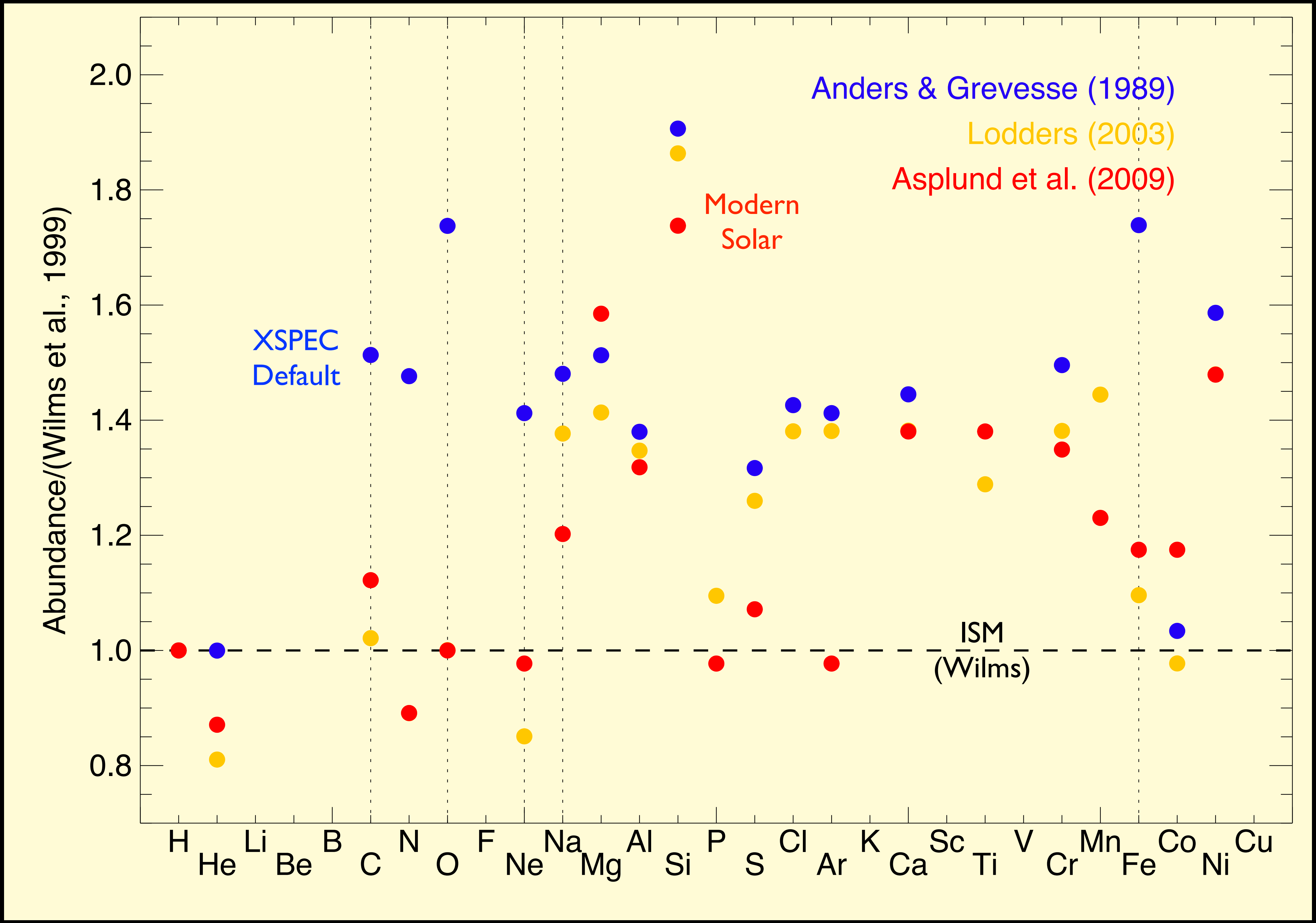
From J. Wilms HEAD Meeting Talk, Hawaii, 2010



Although you use $N_{\rm H}$ to describe the column, what you measure in X-rays is the column of metals.

$\Longrightarrow$ Knowing abundances is important to be able to compare $N_{\rm H}$ measurements from multiwavelength observations.

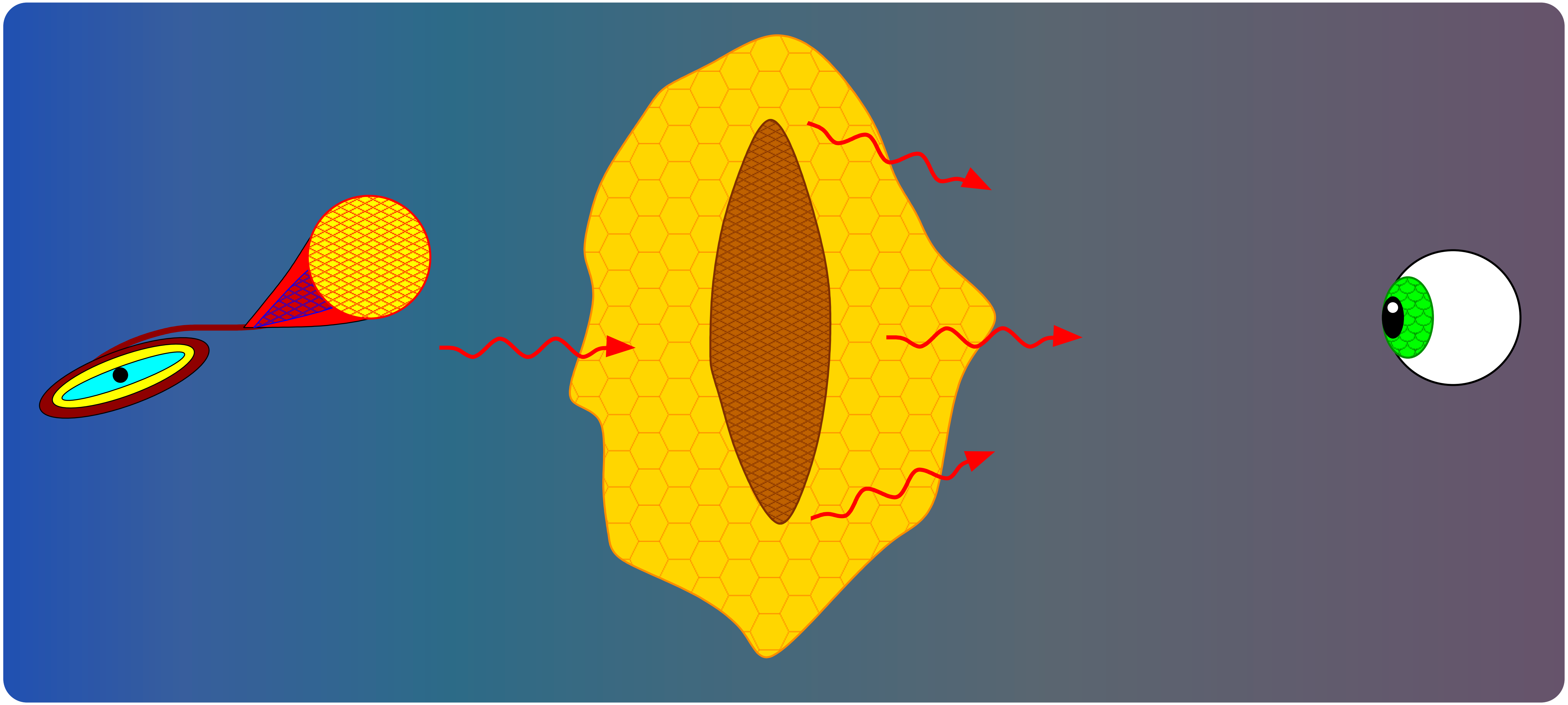
From J. Wilms HEAD Meeting Talk, Hawaii, 2010



"Solar abundances" of Anders & Grevesse (1989): $\sim$40% higher than ISM and $\sim$20% higher than modern solar abundance.

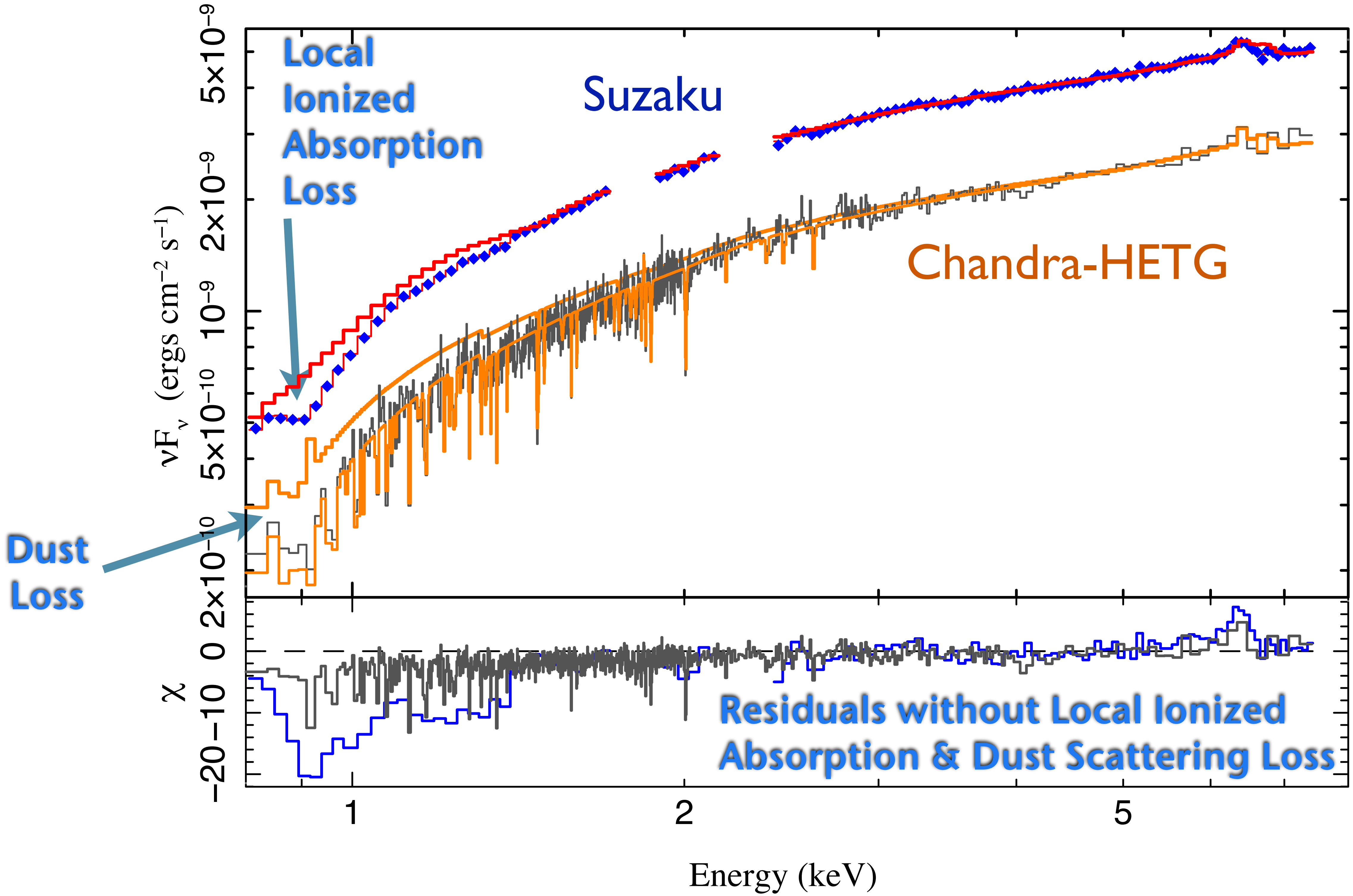
Therefore use Wilms et al. (2000) abundances. Note that Sun is still overabundant wrt. ISM!

Dust Halos: Potential Loss Term for Chandra, Swift & XMM-Newton

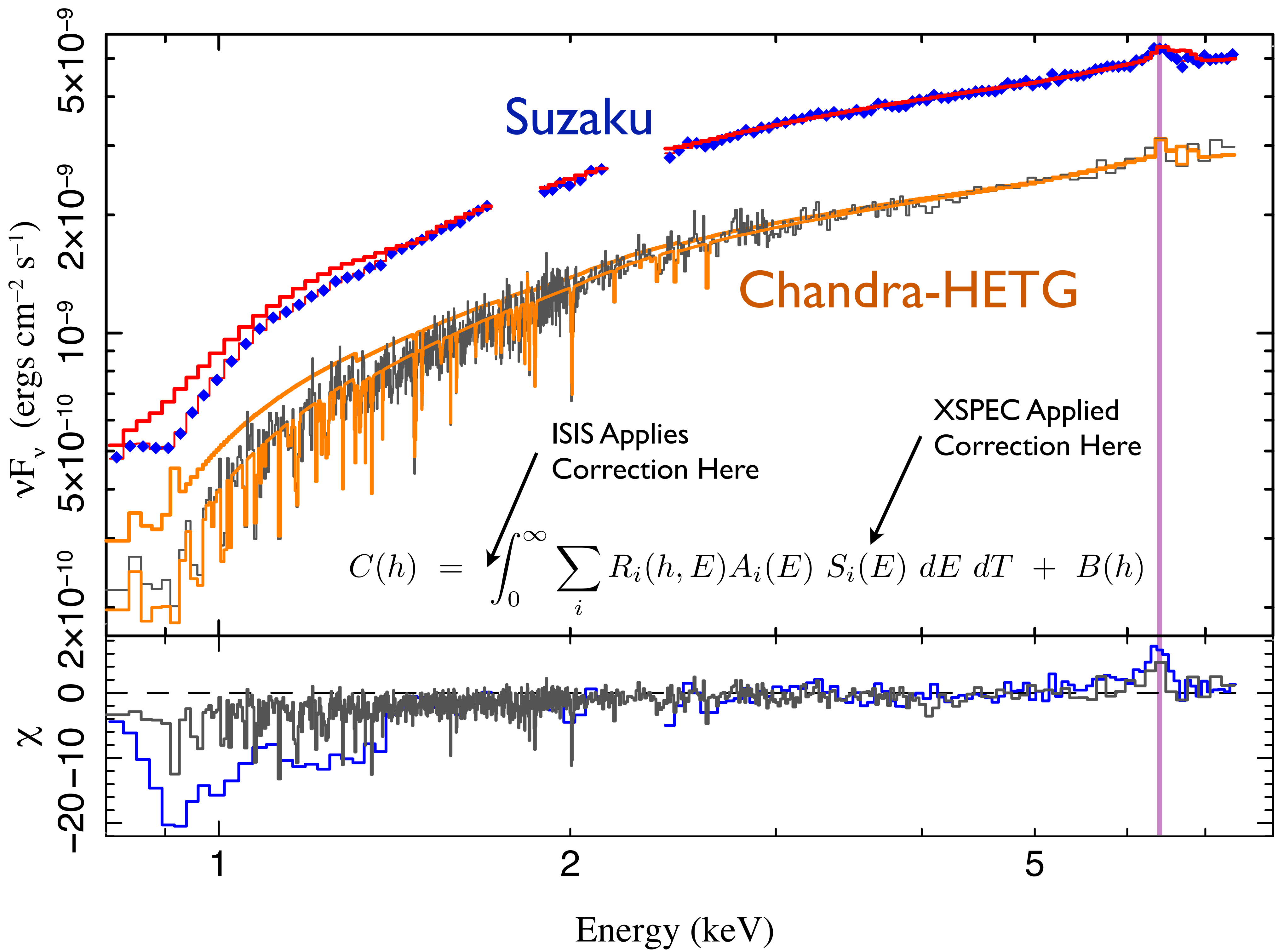


Scatter Back into Line of Sight (Albeit Delayed) for Suzaku, RXTE, etc.

Dust Halos: Potential Loss Term for Chandra, Swift & XMM-Newton

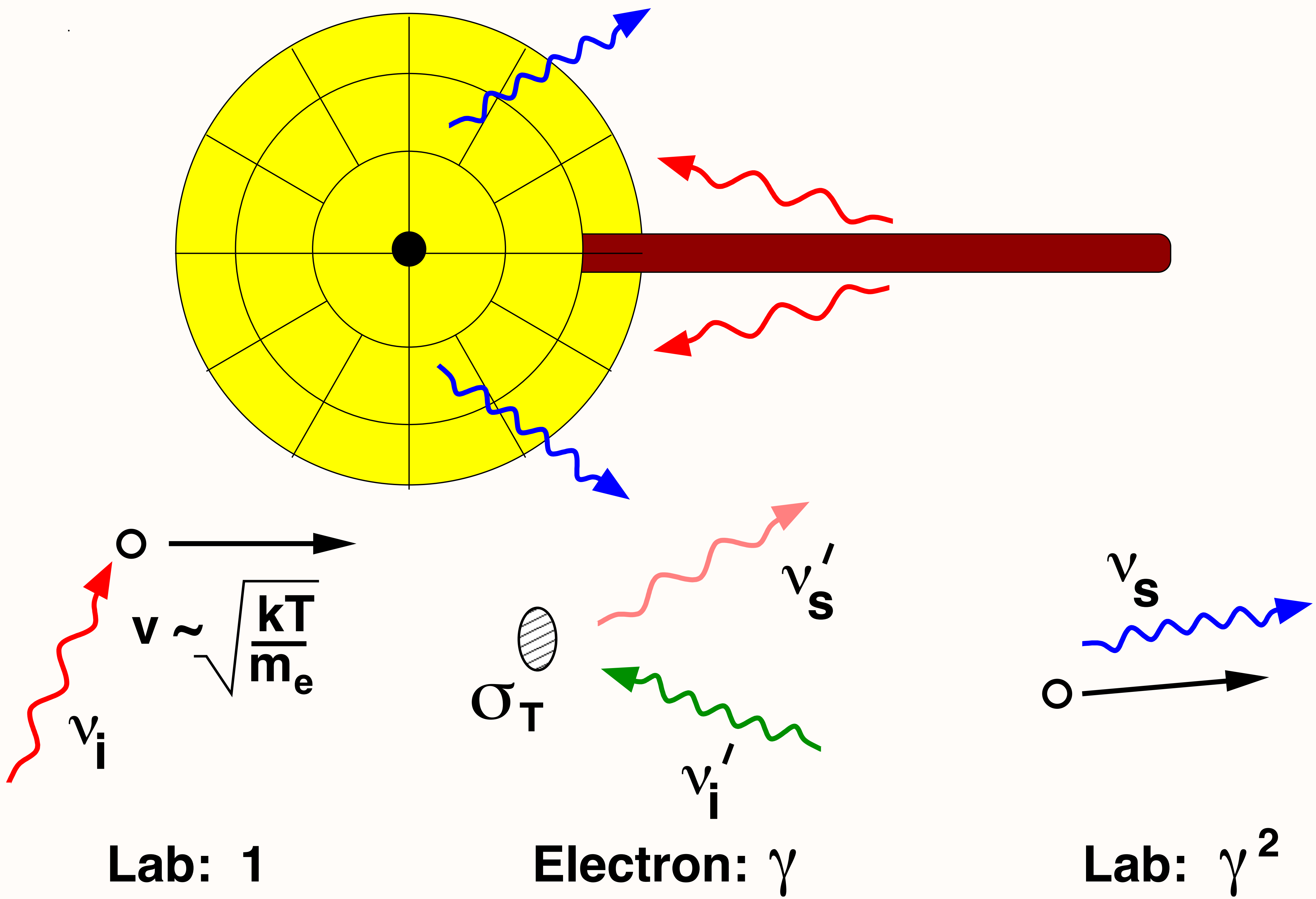


Side Note: For Early Versions of Suzaku Response, Gain Was Off

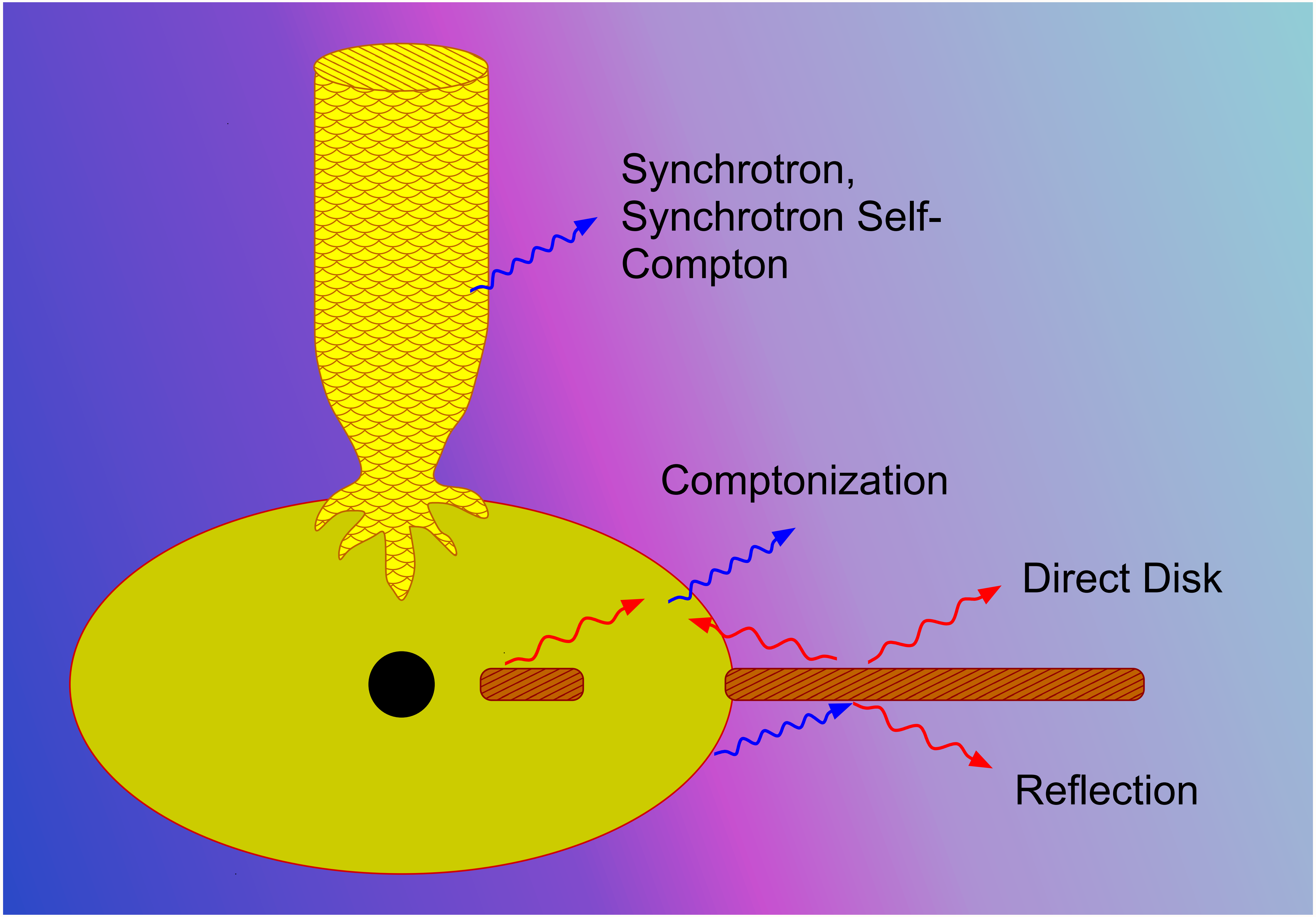


Hard States: Comptonization Paradigm

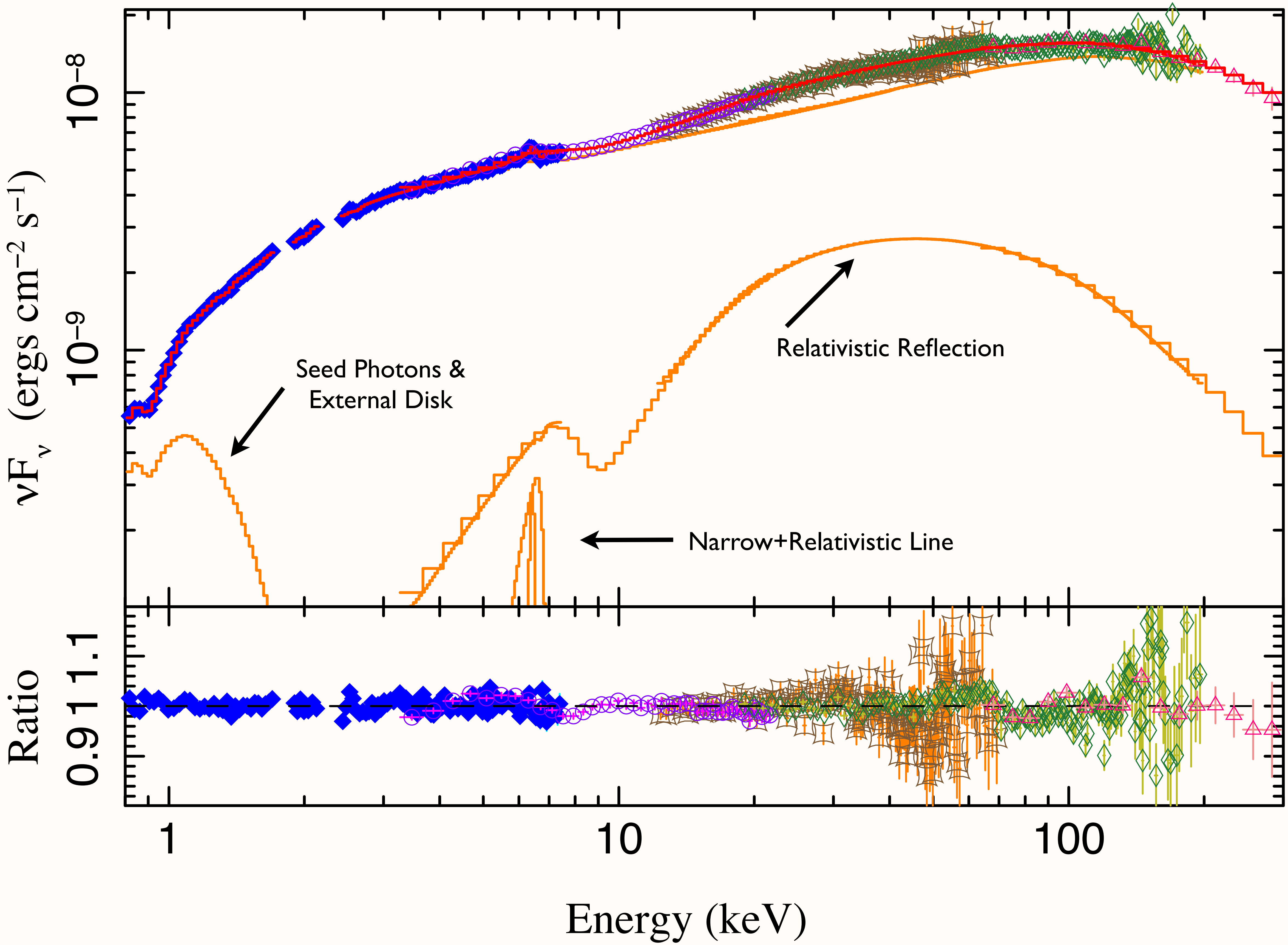
Virial Temperature = $GMm_e/R = m_e c^2/R_G$



Jets May Be Important Too

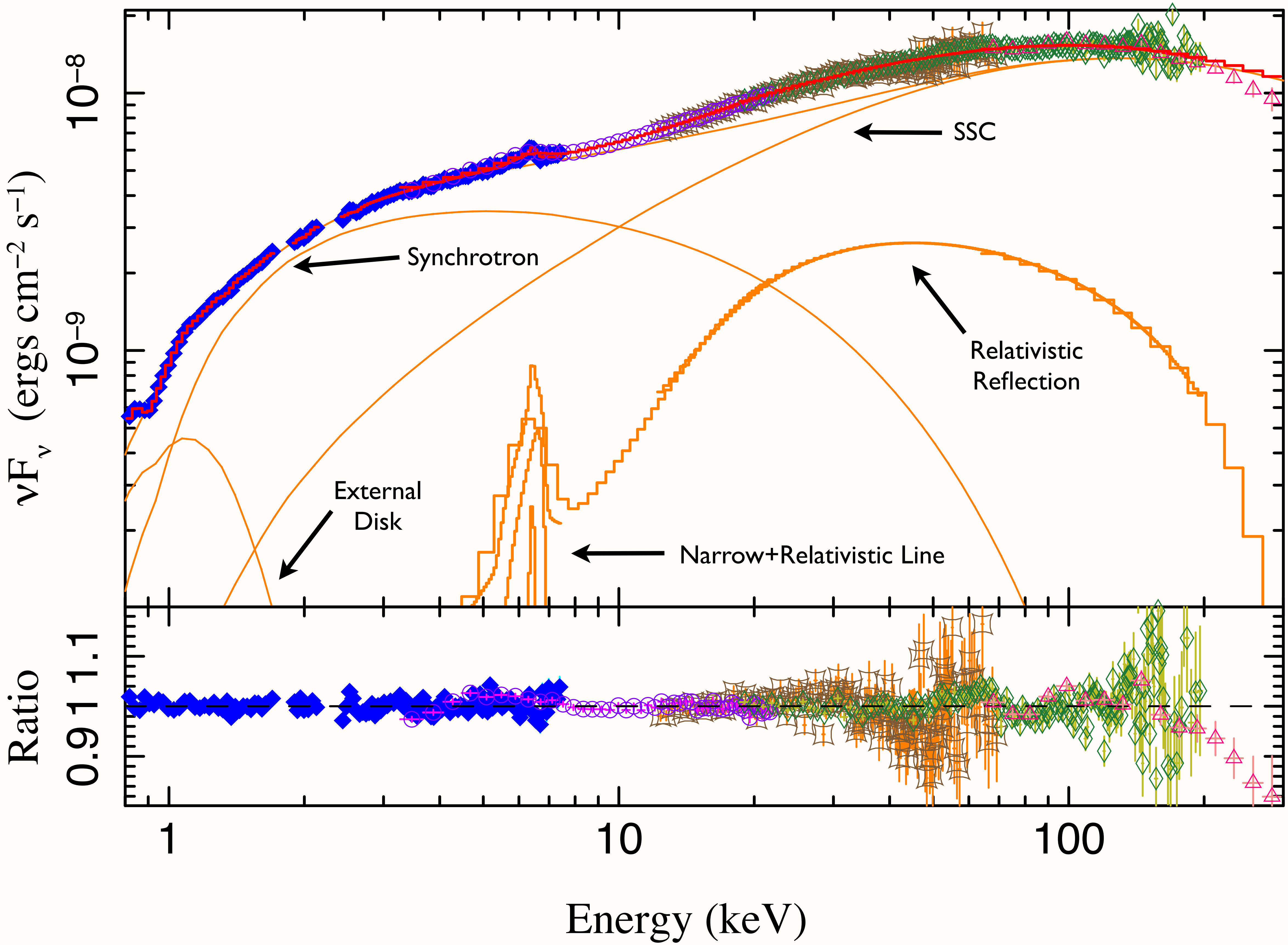


Models Can be Degenerate: Compton



(Nowak et al. 2011, ApJ, 728)

Models Can be Degenerate: Jets



(Nowak et al. 2011, ApJ, 728)

Accounting for Reflection

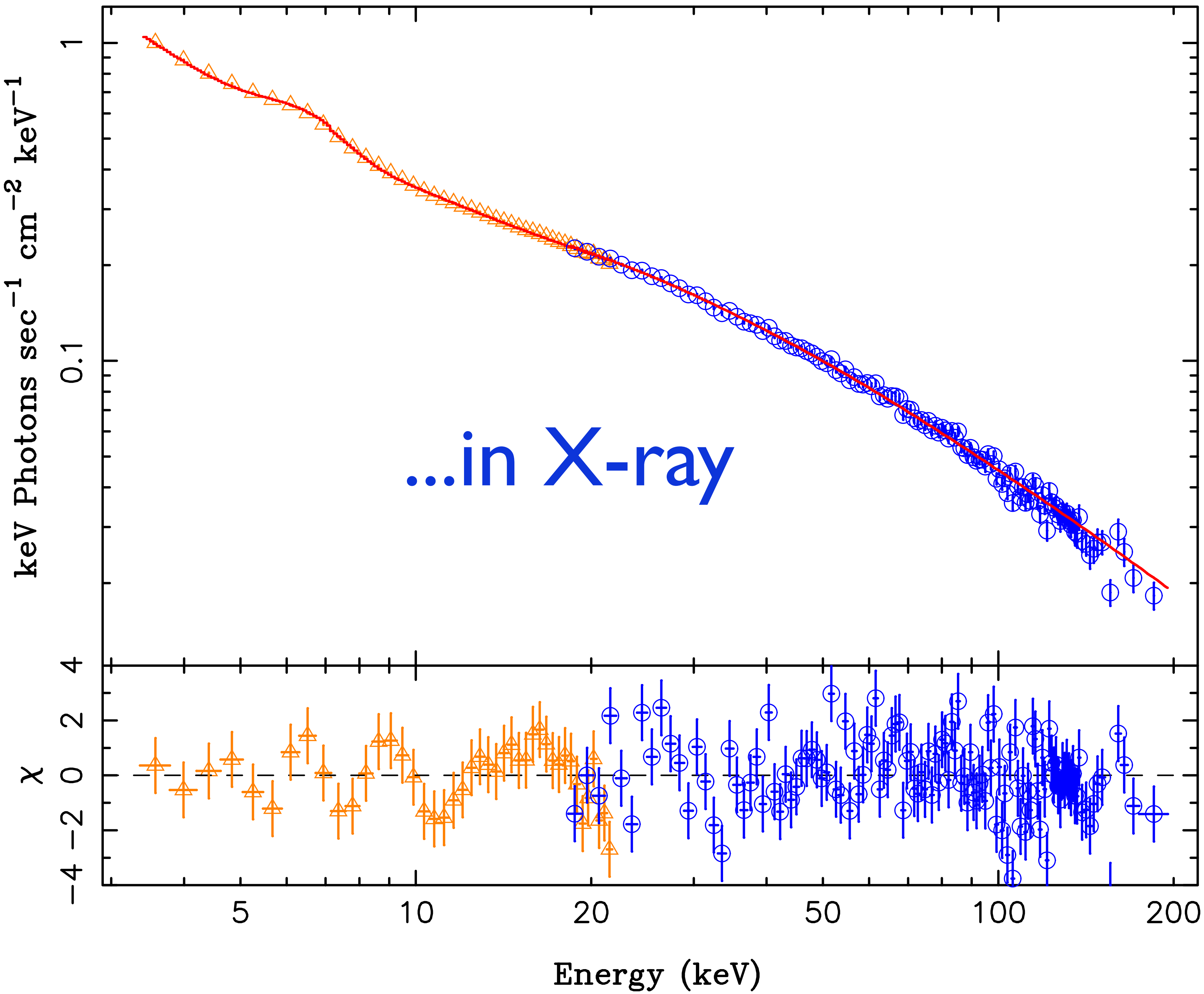
- Reflection spectra between 500 eV – 300 keV rely upon spectra out to 1 MeV! (*Convolution model*)
- Response matrices (usually) do not indicate influence of 1 MeV spectra in noticed band; therefore, analysis programs do not calculate spectra that far out ...
- ... unless you explicitly tell them to. When using convolution models, you often need to *extend the calculation grid*.

Multi-wavelength Fitting:

✦ Radio, IR, & Optical Included via fake Diagonal Response Matrices ✦

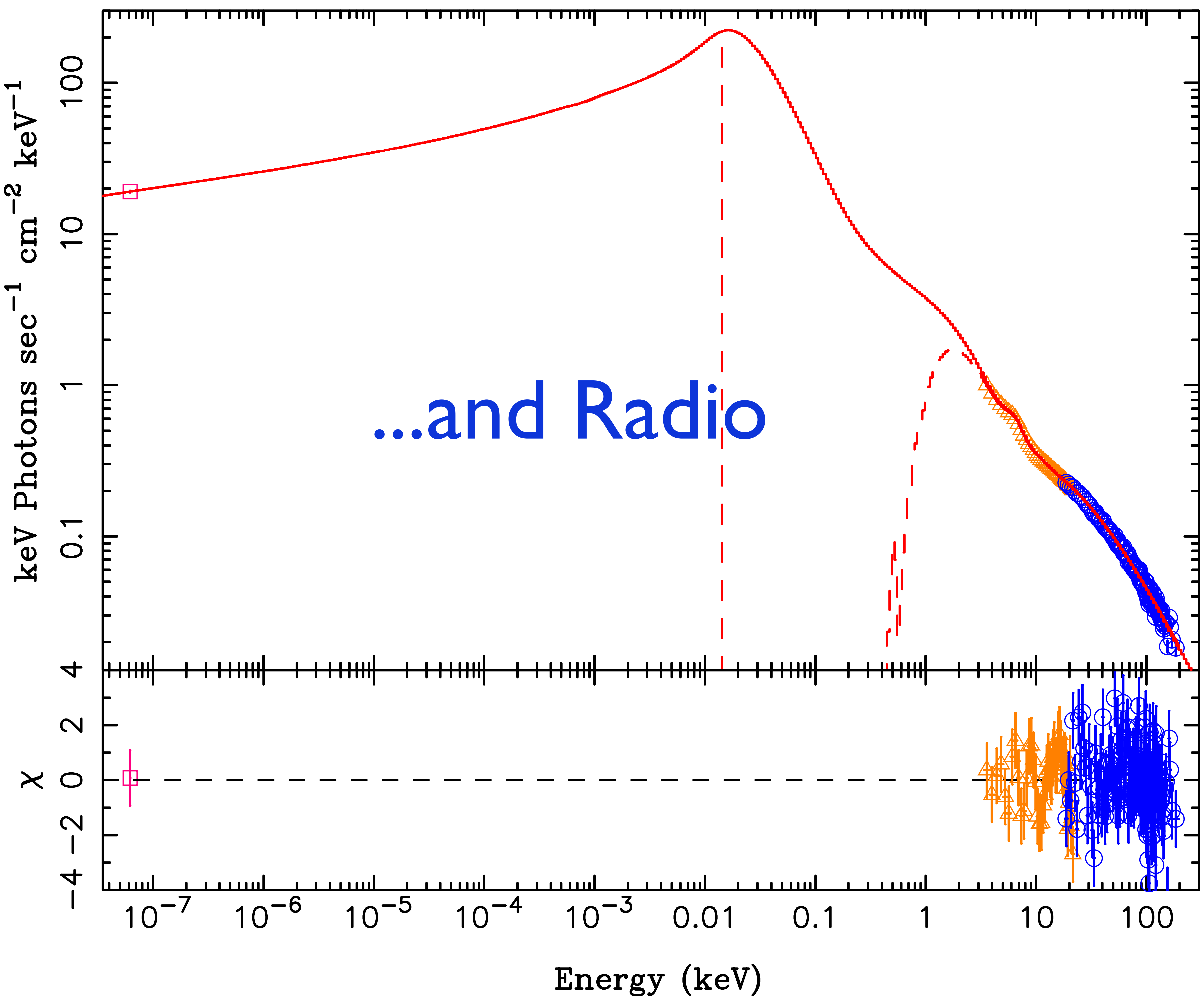
- XSPEC models calculate counts/bin, so if they are used, a "bin width" must be introduced somewhere.
  - ★ One can divide the model by this bin width and fit counts/sec/keV (or counts/sec/A), but it's still there
  - ★ Be careful how you define your error bars/statistics
  - ★ Radio, IR, optical are "flux correcting" their data
- Be careful how you account for "absorption correction" of the non X-ray data!!! (Best not to "correct" other bands.)

Jet Models Fit



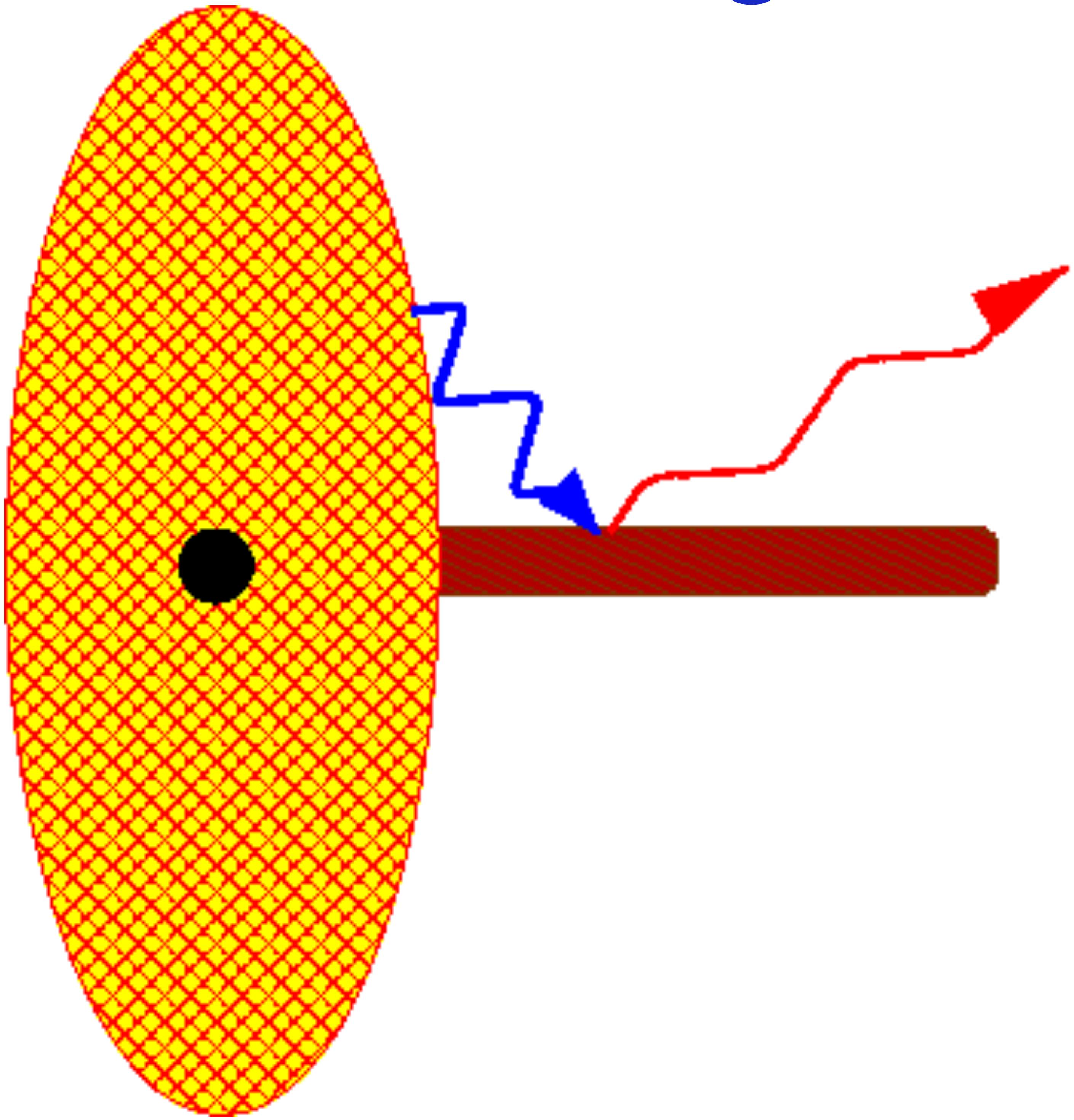
(Markoff, Nowak, Wilms 2005)

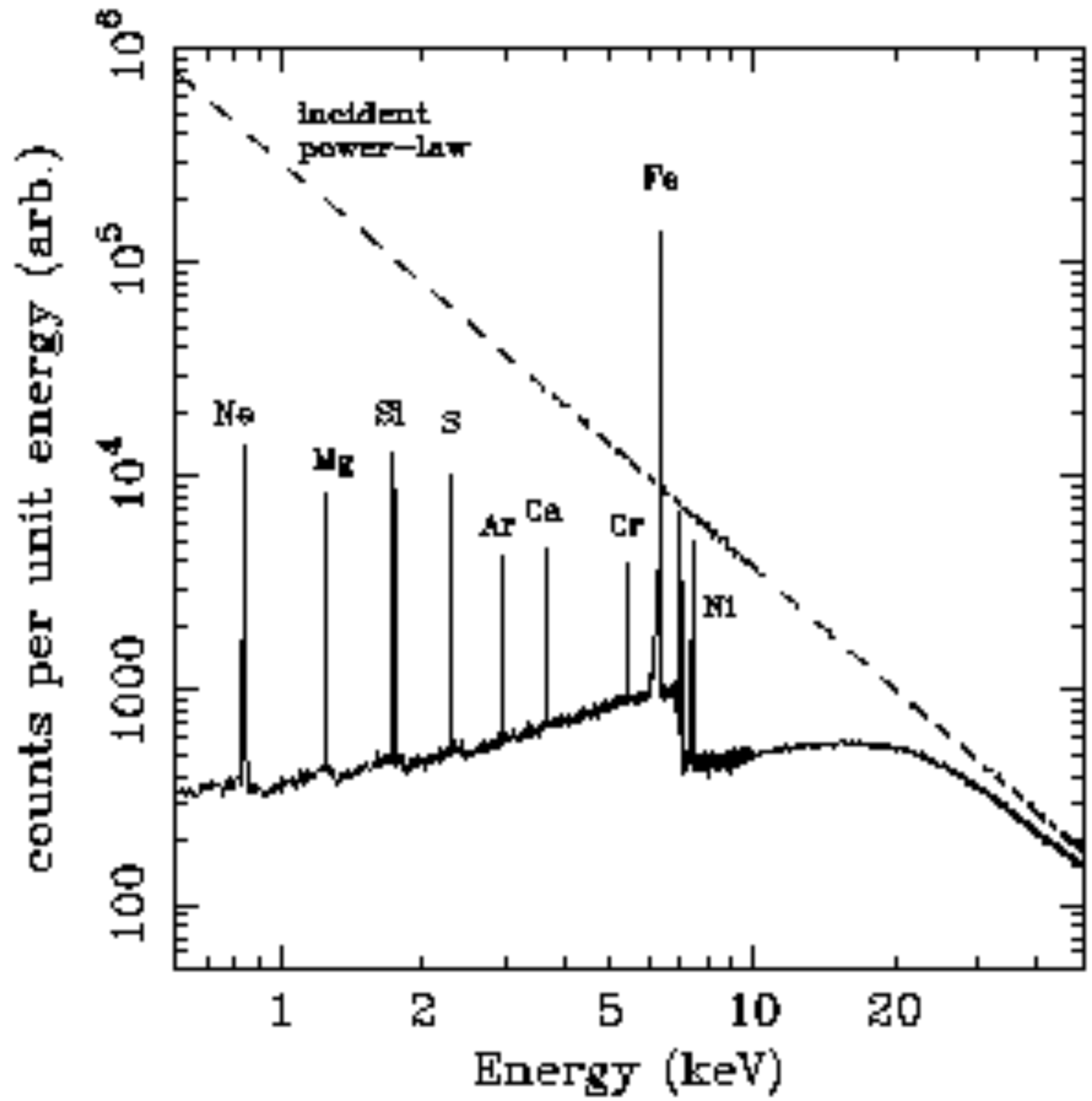
Jet Models Fit



(Markoff, Nowak, Wilms 2005)

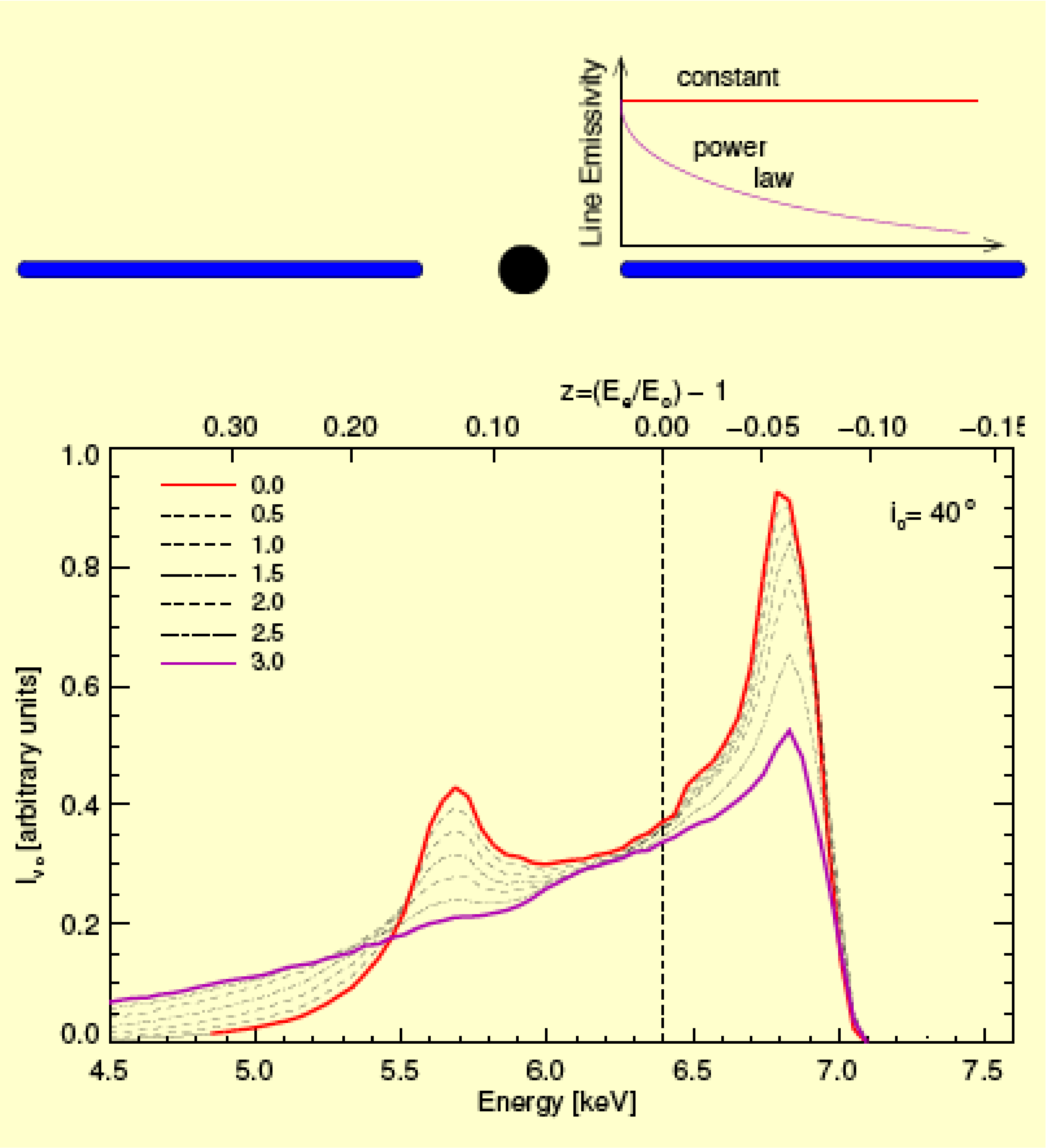
GR Diagnostic: Iron Lines

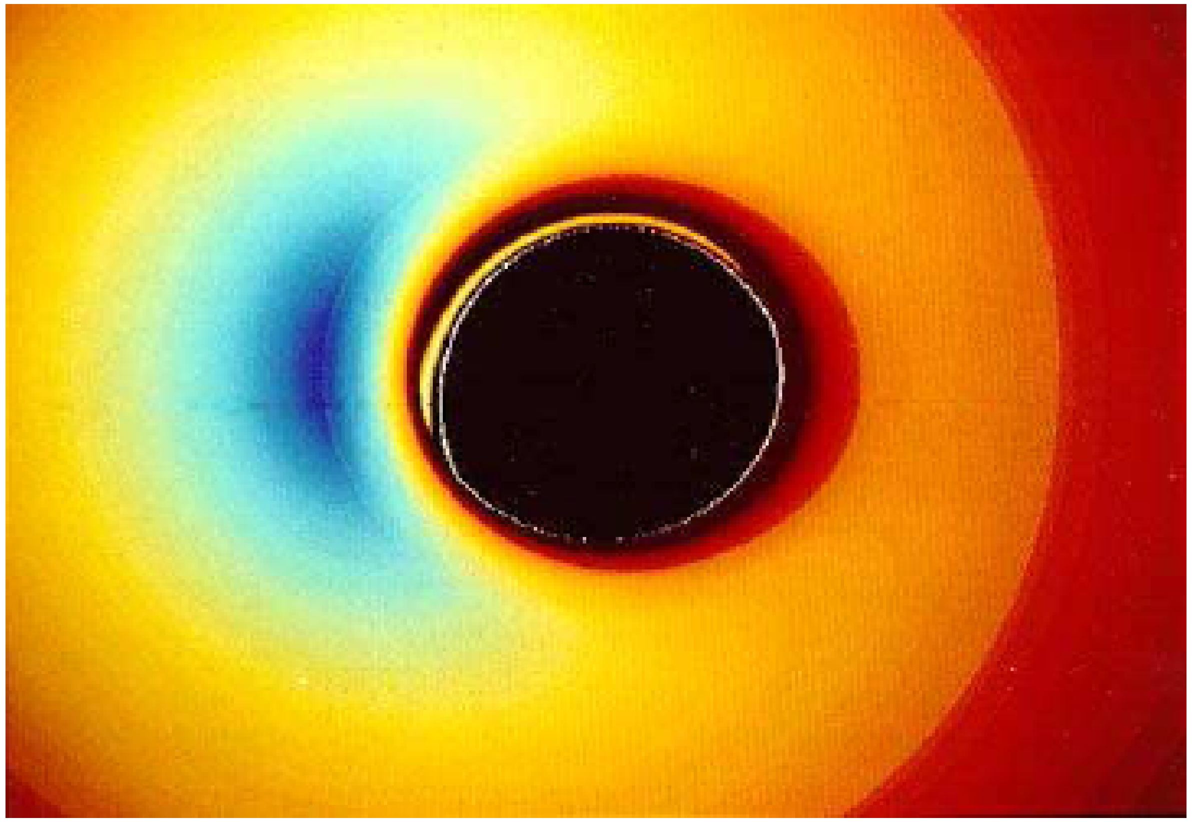




(See "Physics Reports" Review, Reynolds & Nowak 2003)

Relativity Distorts Line Shapes



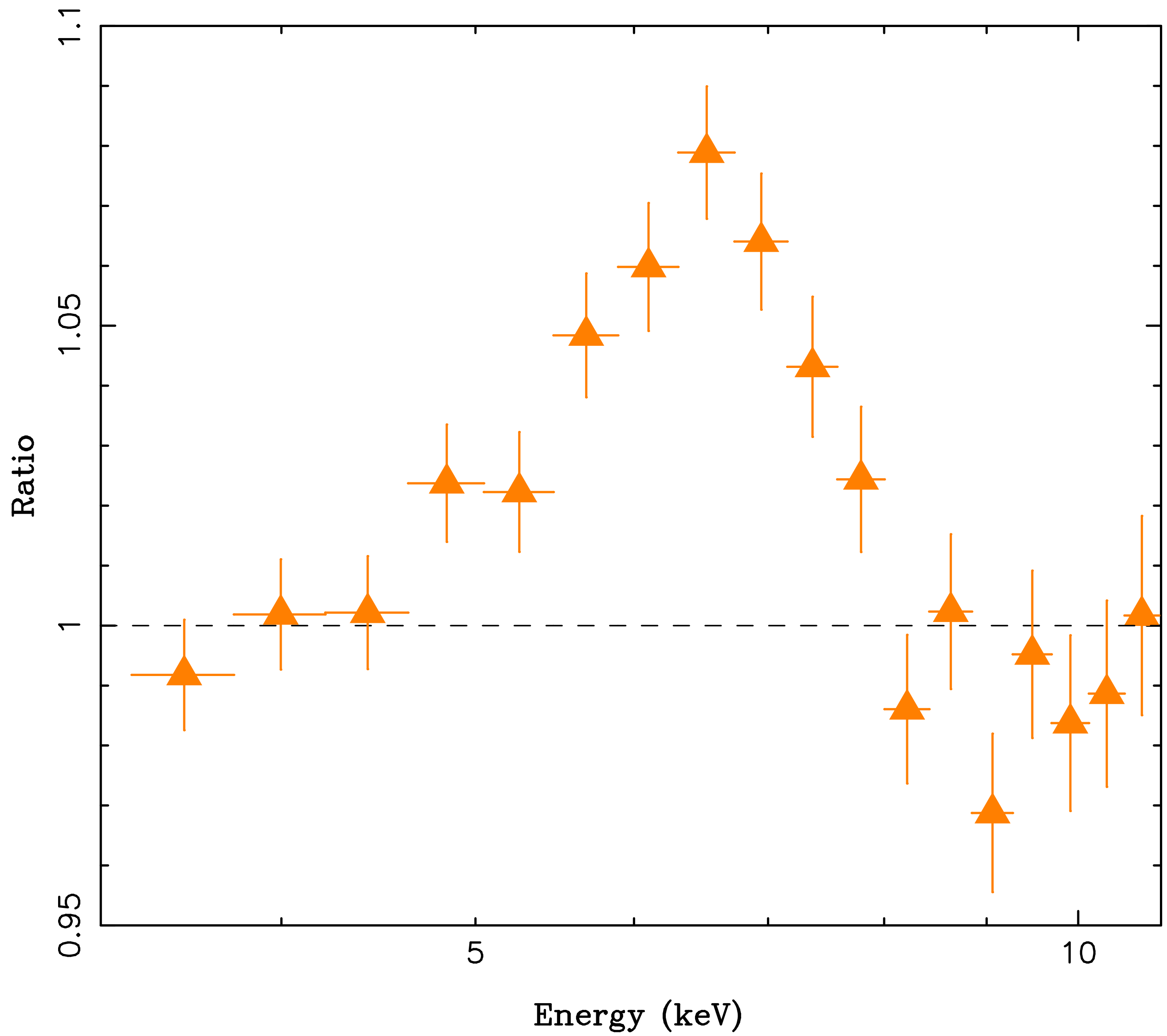


(Perez & Wagoner)

(See "Physics Reports" Review, Reynolds & Nowak 2003)

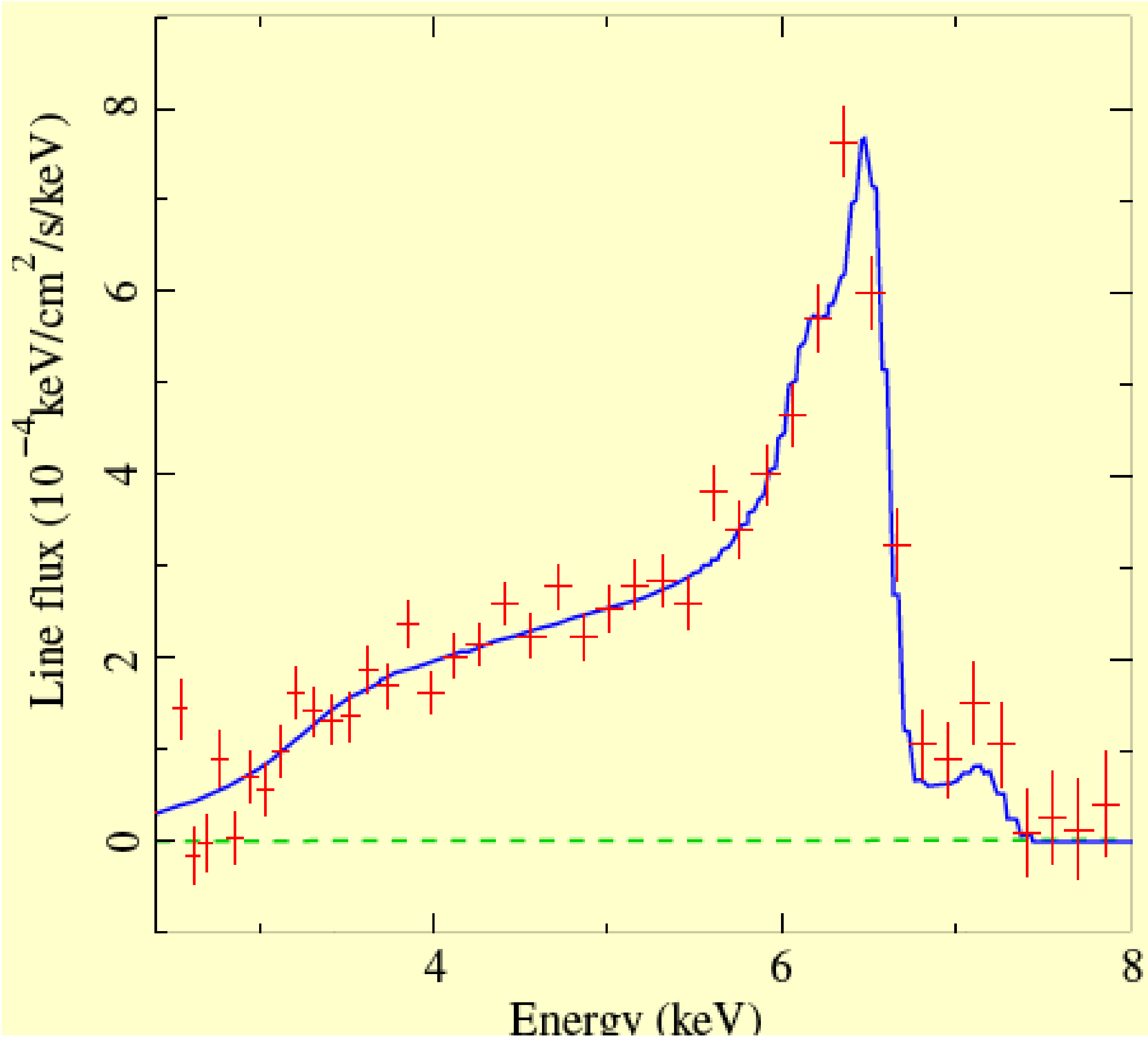
Relativistic Lines Seen in GBHC & AGN

GX 339-4



(Nowak, Wilms, & Dove 2002)

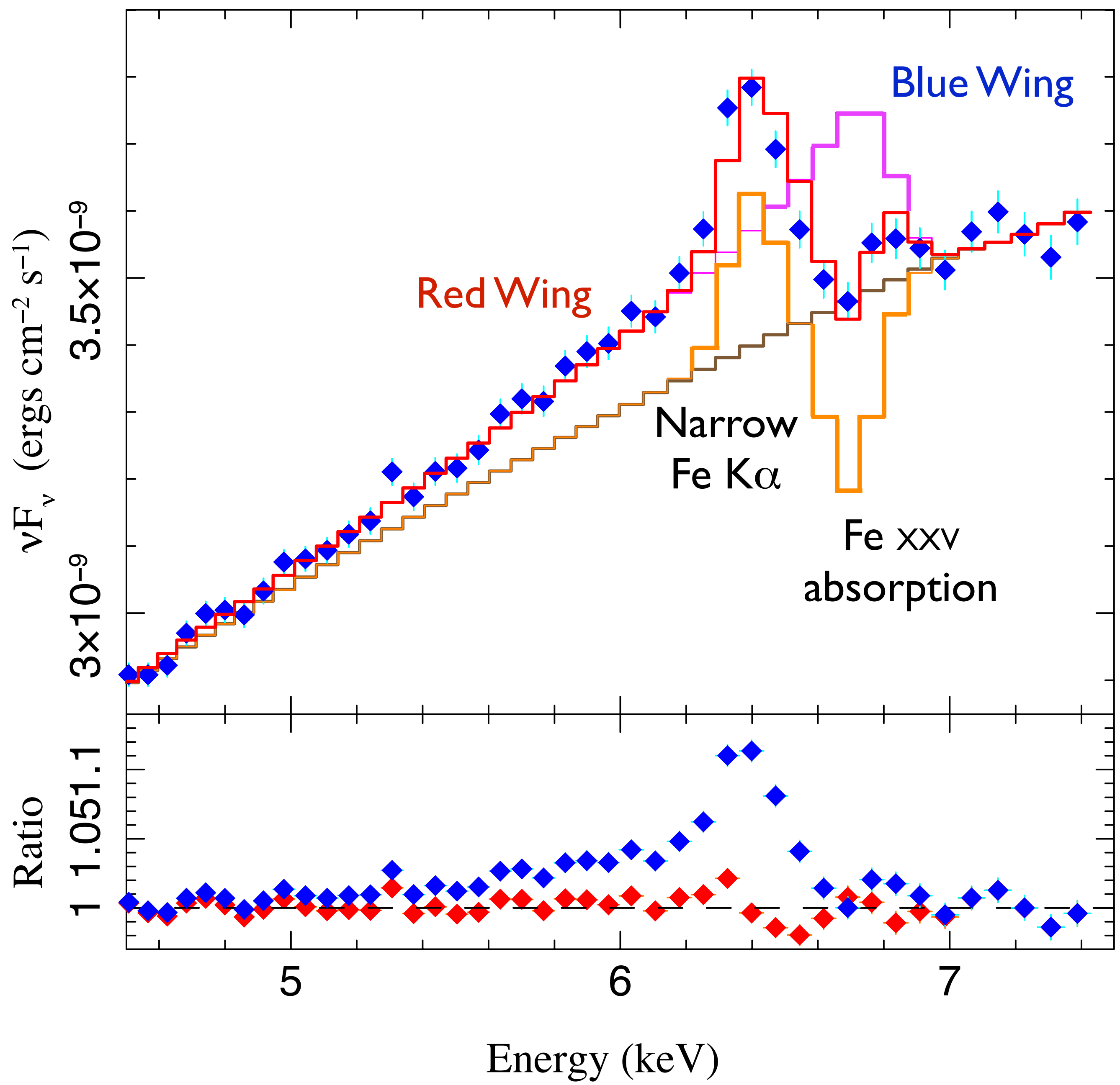
MCG 6-30-15



(Wilms et al. 2001)

(Fabian et al. 2002)

Be Careful with Line Decomposition!



(Nowak et al. 2011, ApJ, 728)

Physical Self-Consistency is as Important as Statistical Quality!

Timing Analysis

$$X_j \equiv \sum_{k=0}^{N-1} x_k \exp(2\pi ijk/N) \quad , \quad j = [-N/2, \ldots, 0, \ldots, N/2]$$

Lightcurve, 0 ... T

Power Spectra:

$$X_j^* X_j = |X_j|^2 \equiv P(f_j) \quad , \quad f_j = \frac{j}{T}$$

Cross Power Spectra:

$$h * g \ (t) \equiv \int_{-\infty}^{\infty} h(\tau) g(t+\tau) \ d\tau$$

$$\mathcal{F}[h * g] = H^*(f) G(f)$$

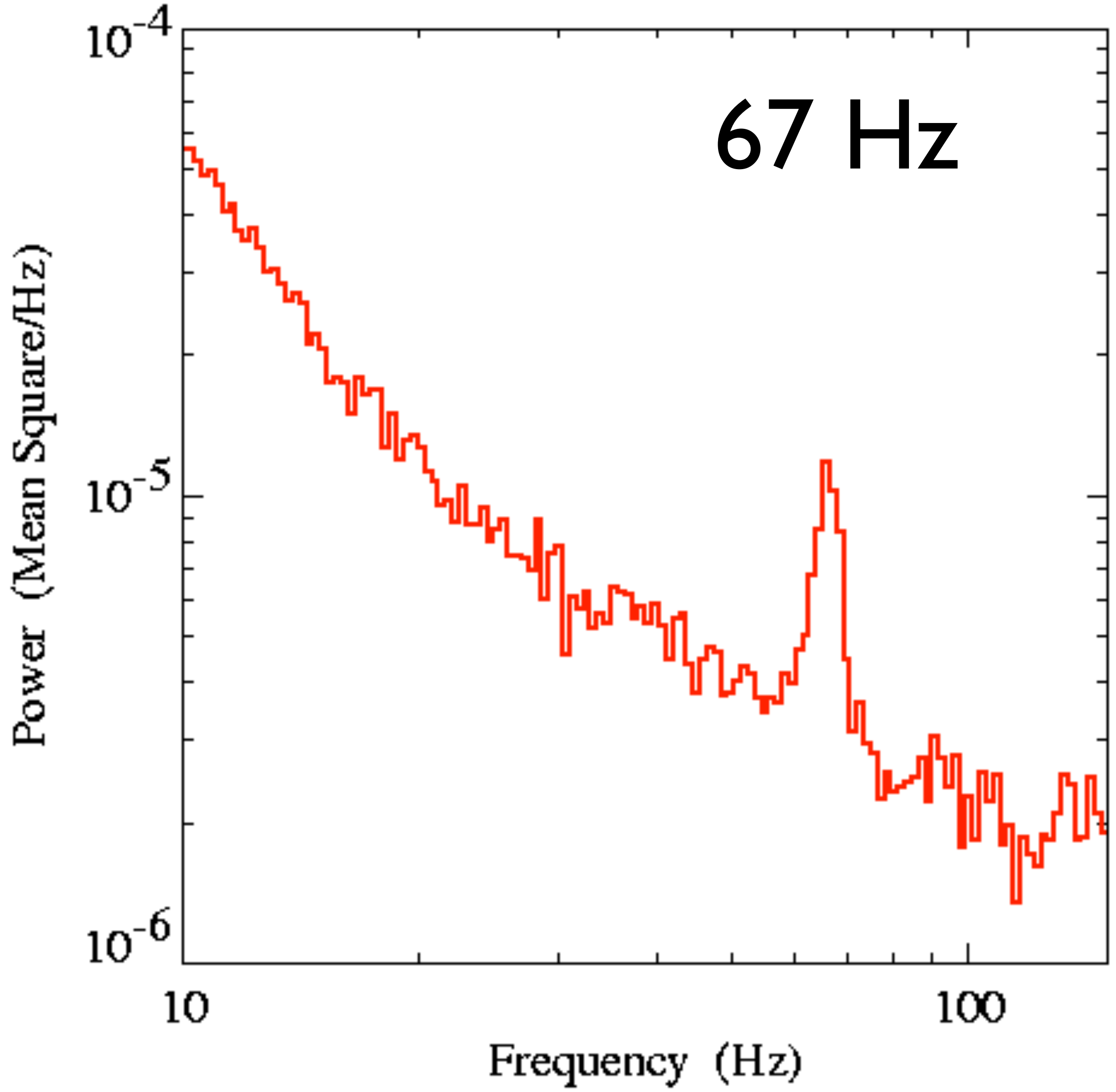
Calculating & Fitting These Often Involve Custom Code!

Timing Analysis

- Power Spectra indicate amplitude of variability, and characteristic frequencies
  - ★ Power can be "broad band", or concentrated over narrow frequencies: quasi-periodic oscillations (QPO)
- Cross Power Spectra indicate the correlation and *time delays* between different lightcurves (i.e., different energy bands) *over a range of Fourier frequencies*
  - ★ Cross power can be trickier to interpret, and require better statistics to calculate. (Poisson noise has a well-defined mean Fourier amplitude, but a random phase.)

Some Soft State BHC Show Stable Oscillations

GRS 1915+105



(Morgan et al. 1997)

ALSO:

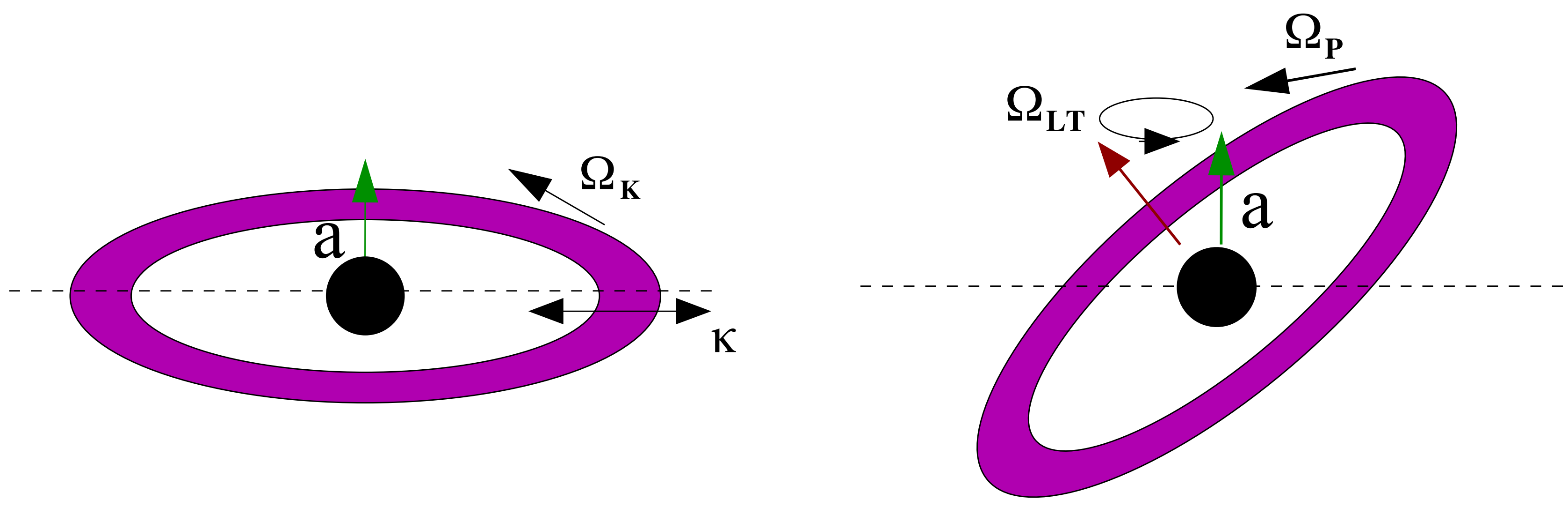
300 & 450 Hz in GRO J1655-40

(Strohmayer 2001)

180 & 270 Hz in XTE J1550-564

(Remillard et al. 2002)

Characteristic Disk Time Scales



- Keplerian Frequency:

$$\Omega_K = (R^{3/2} + a)^{-1}$$

- Lense-Thirring Frequency:

$$\Omega_{LT} = \frac{2a}{R^3}$$

- Radial Epicyclic Frequency:

$$\kappa^2 = \Omega_K^2 \left(1 - \frac{6}{R} + \frac{8a}{R^{3/2}} - \frac{3a^2}{R^2}\right)$$

$$a = \frac{J}{GM/c} = 0 \to 1 \qquad R \to \frac{R}{GM/c^2} \qquad \Omega_K \to \frac{\Omega_K}{c^3/GM}$$

Do Spectral-Temporal Correlations Reveal Geometry?

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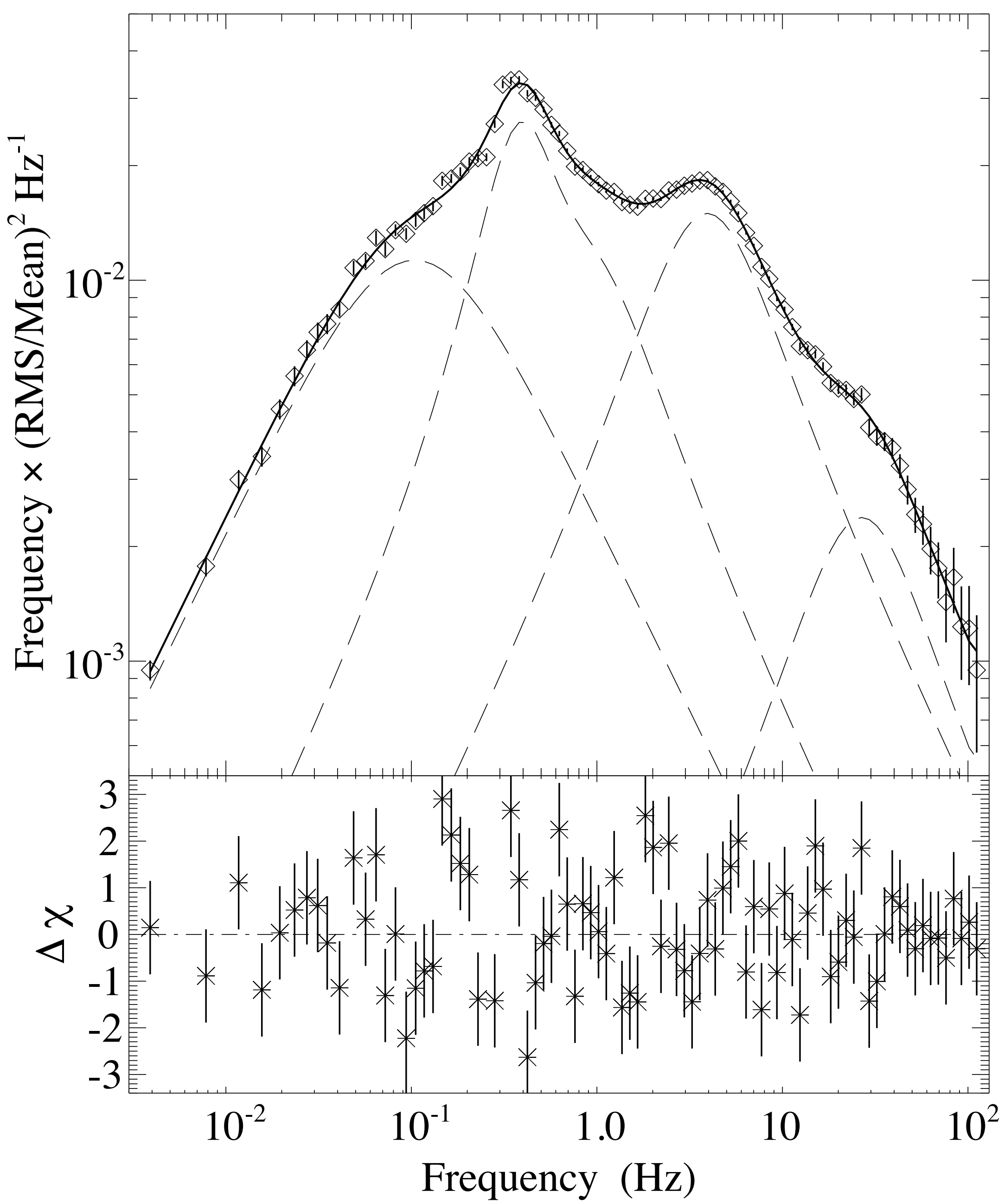
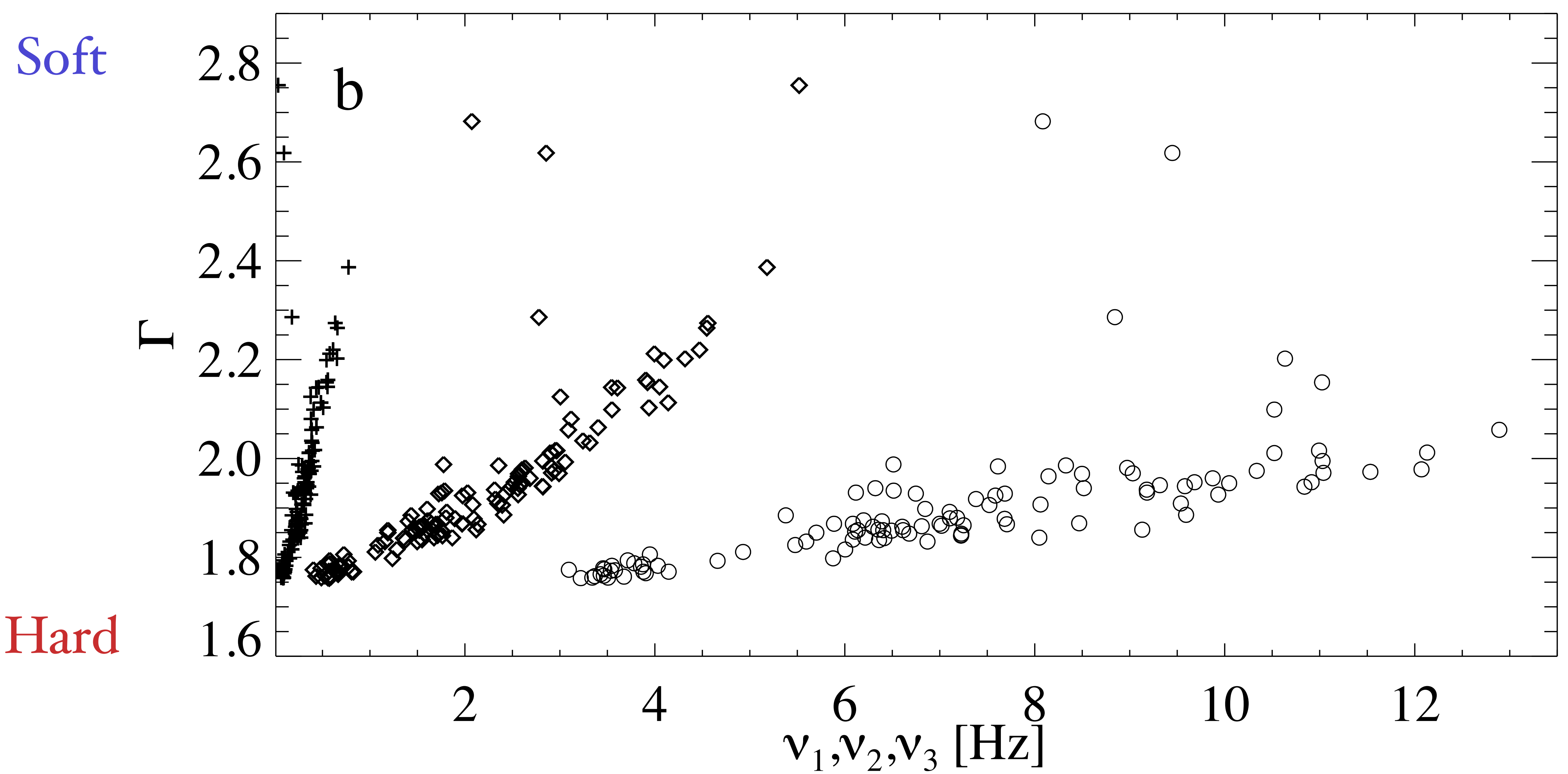


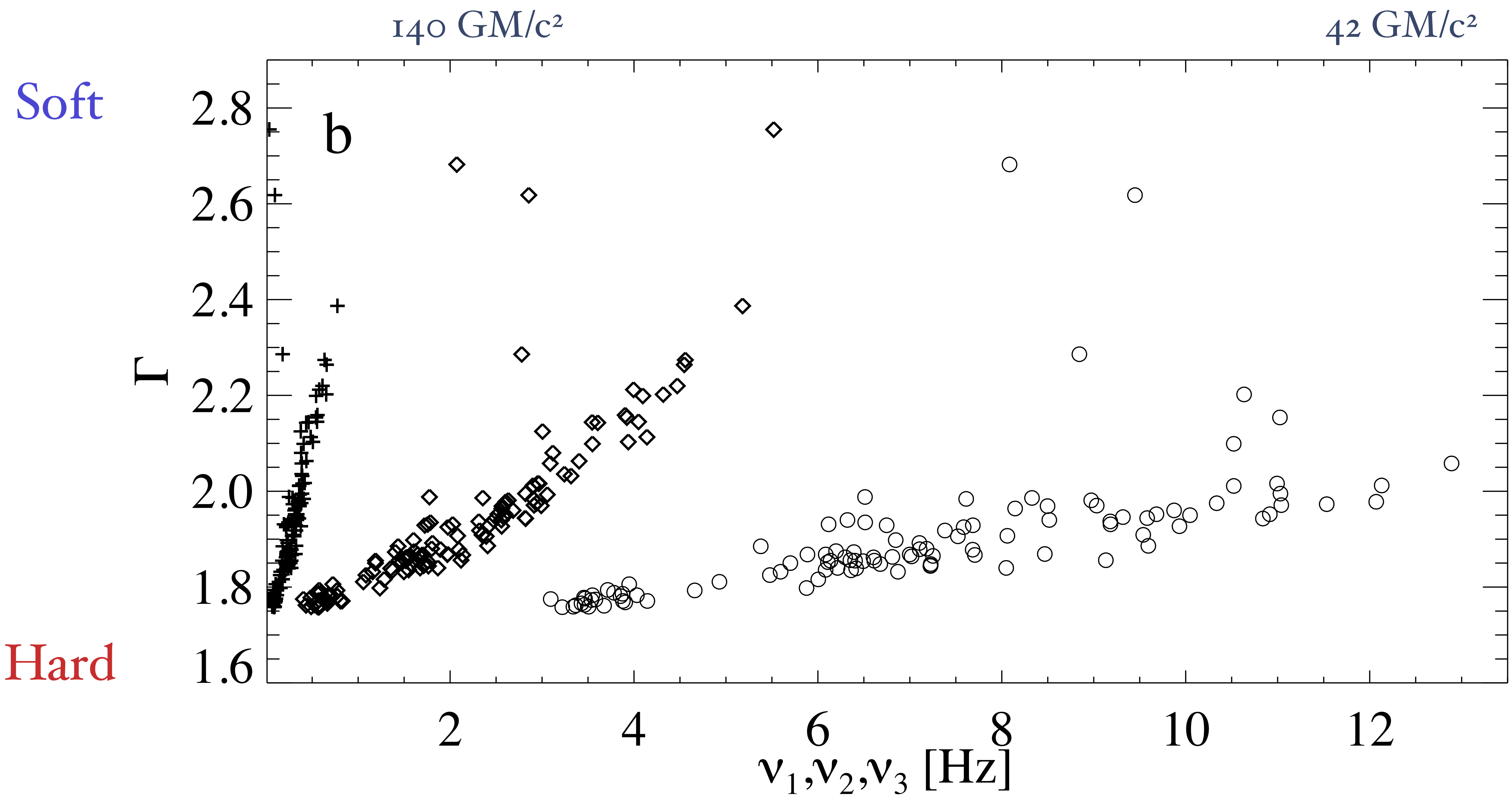
(Nowak 2000)

Do Spectral-Temporal Correlations Reveal Geometry?

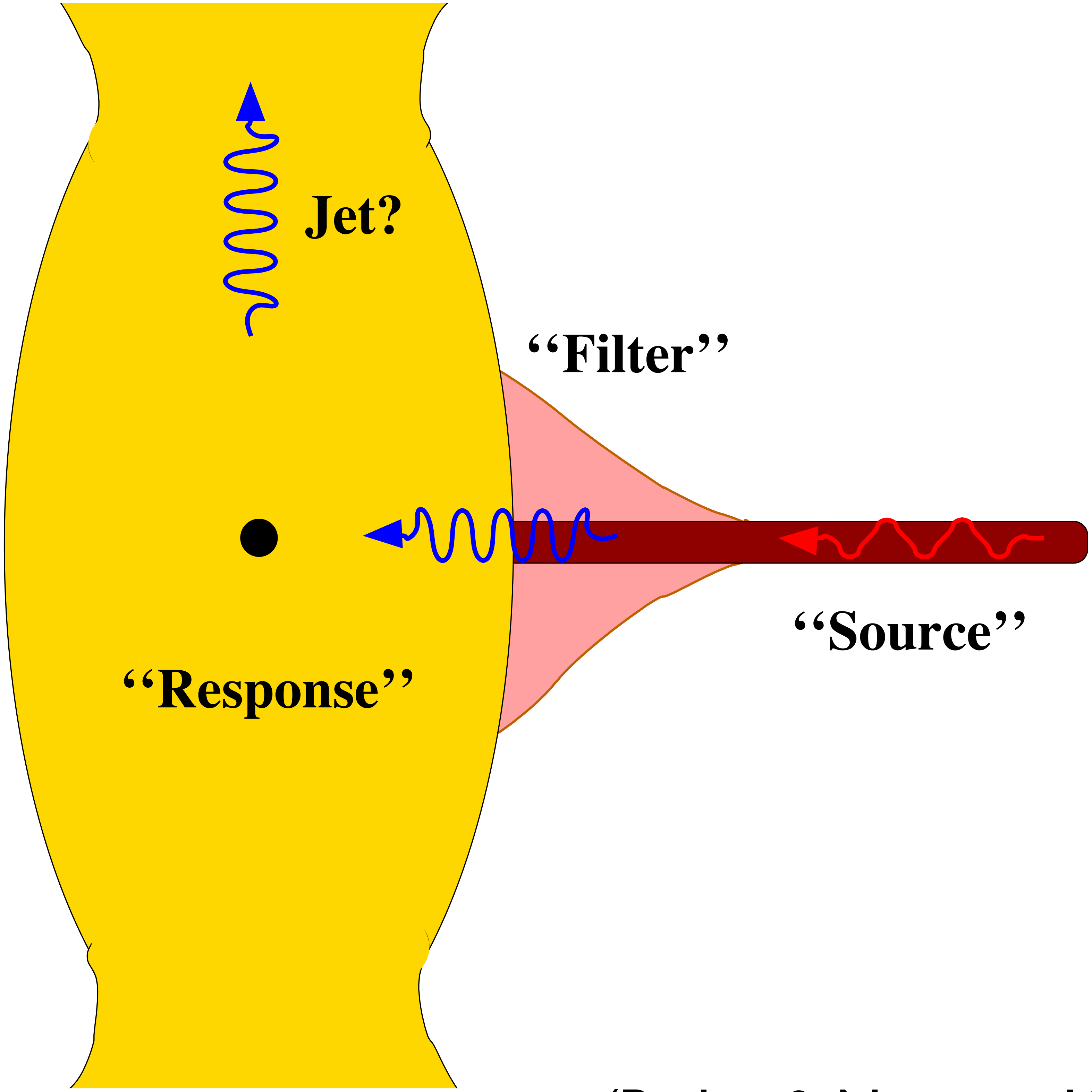


(Pottschmidt et al. 2003)

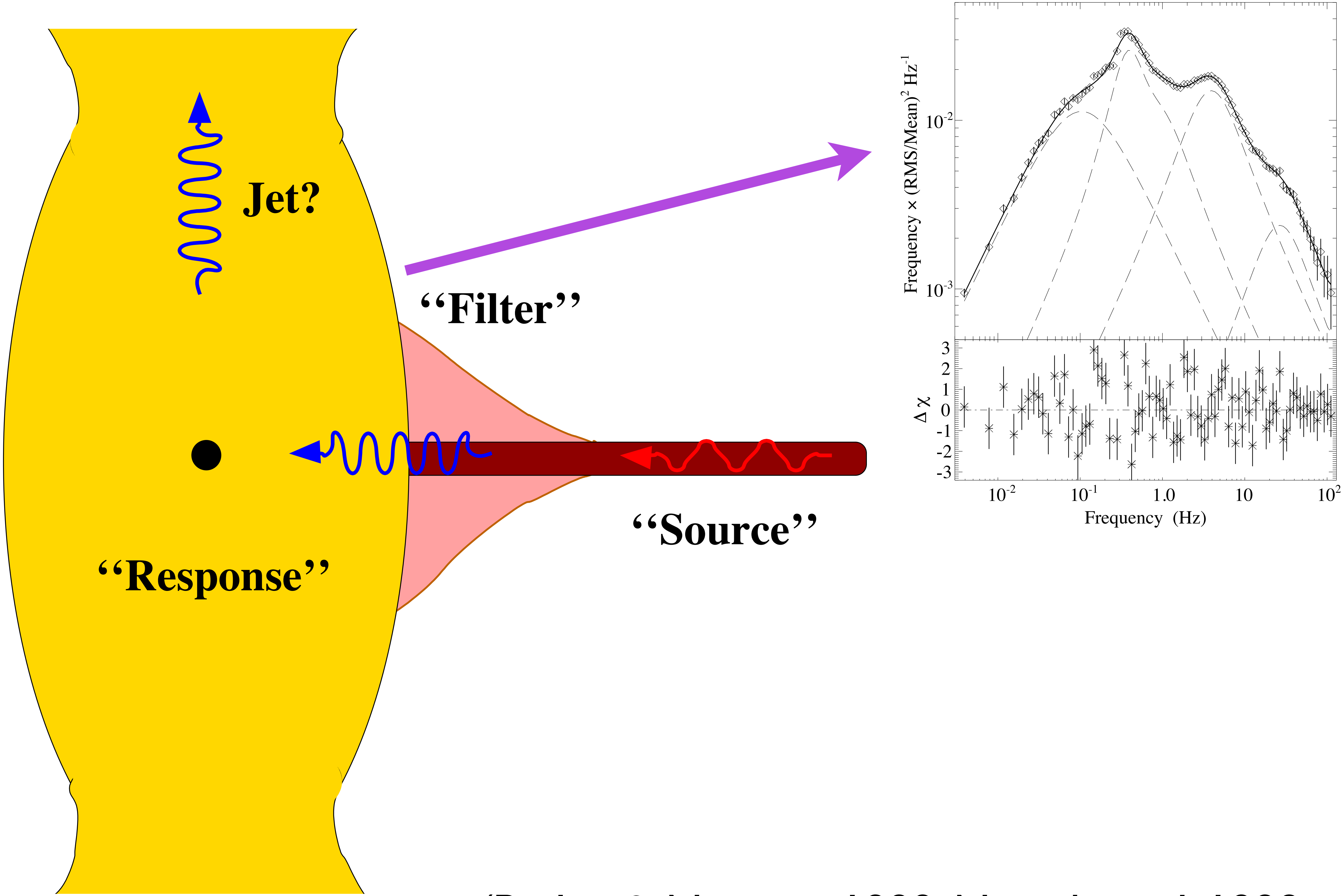
Do Spectral-Temporal Correlations Reveal Geometry?



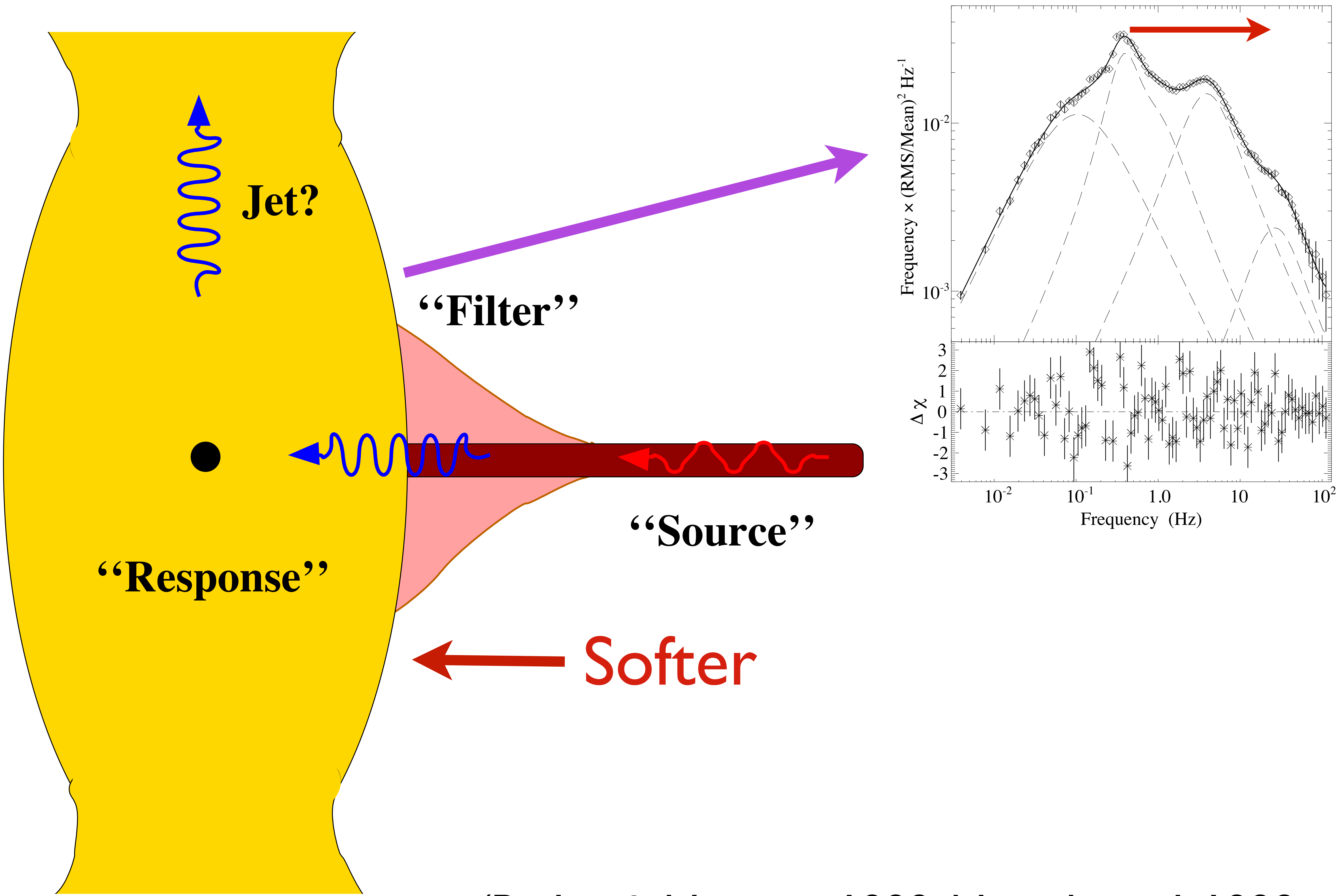
(Pottschmidt et al. 2003)



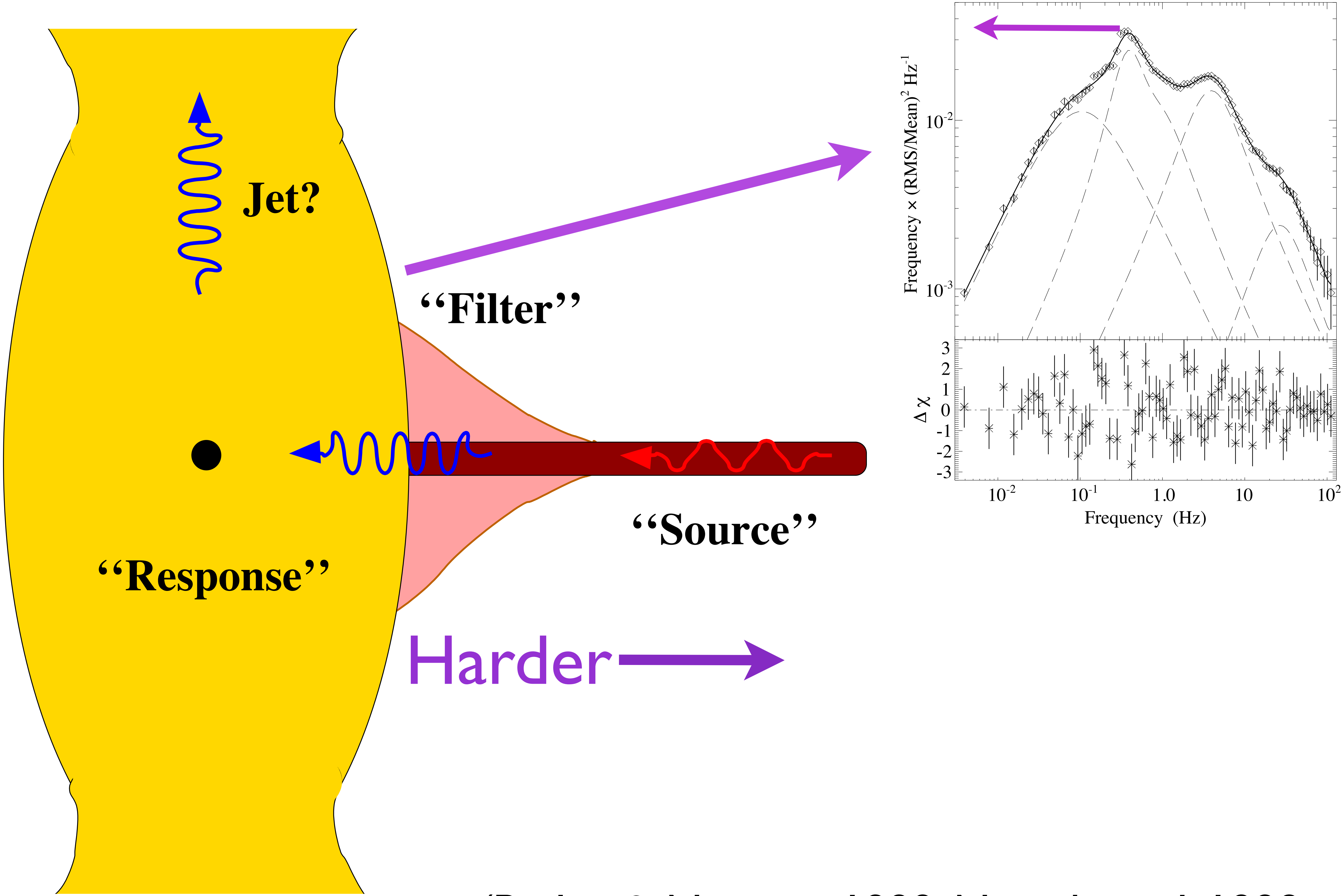
(Psaltis & Norman 1999, Nowak et al. 1998, Miyamoto & Kitamoto 1988)



(Psaltis & Norman 1999, Nowak et al. 1998, Miyamoto & Kitamoto 1988)

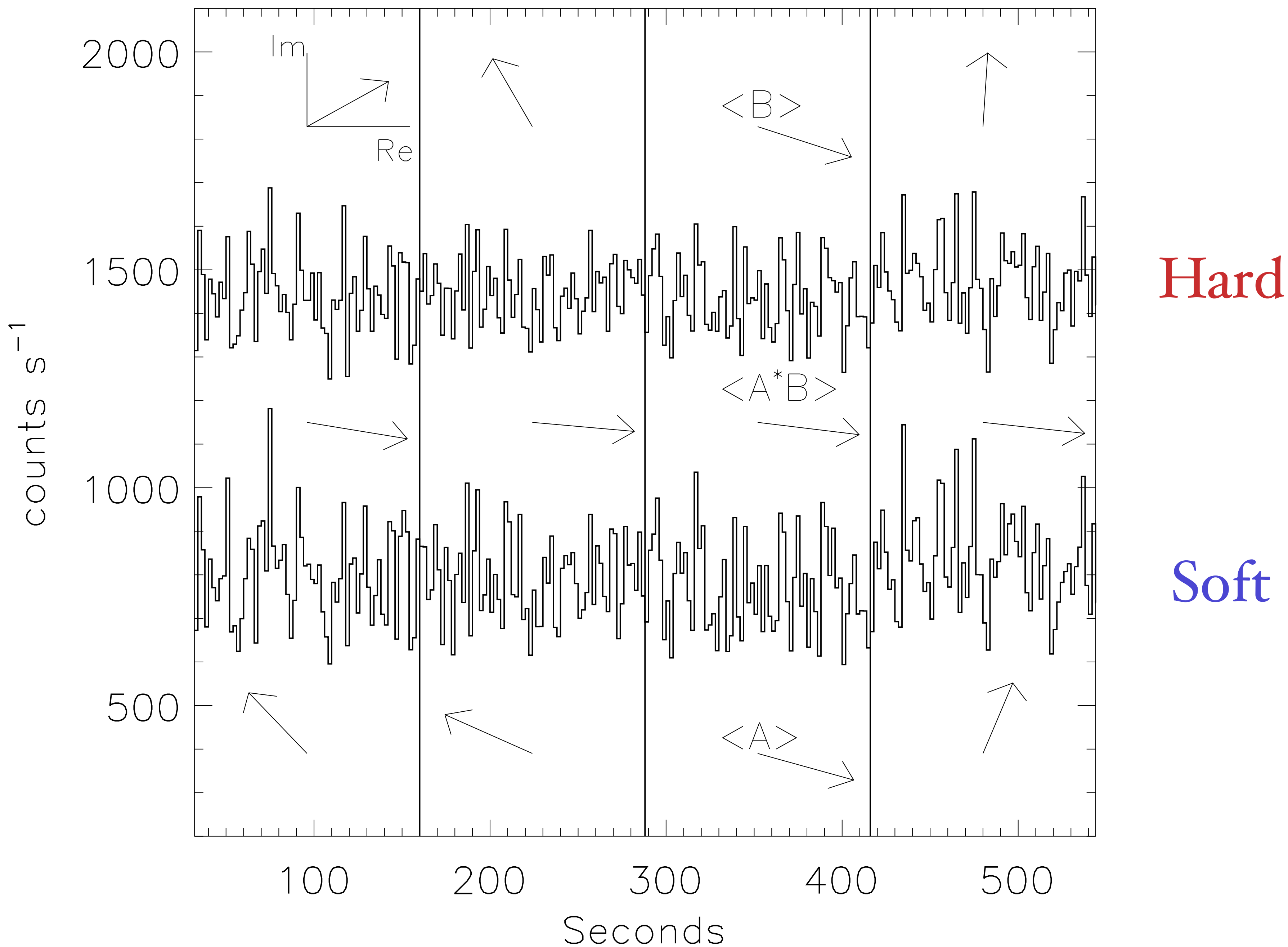


(Psaltis & Norman 1999, Nowak et al. 1998, Miyamoto & Kitamoto 1988)



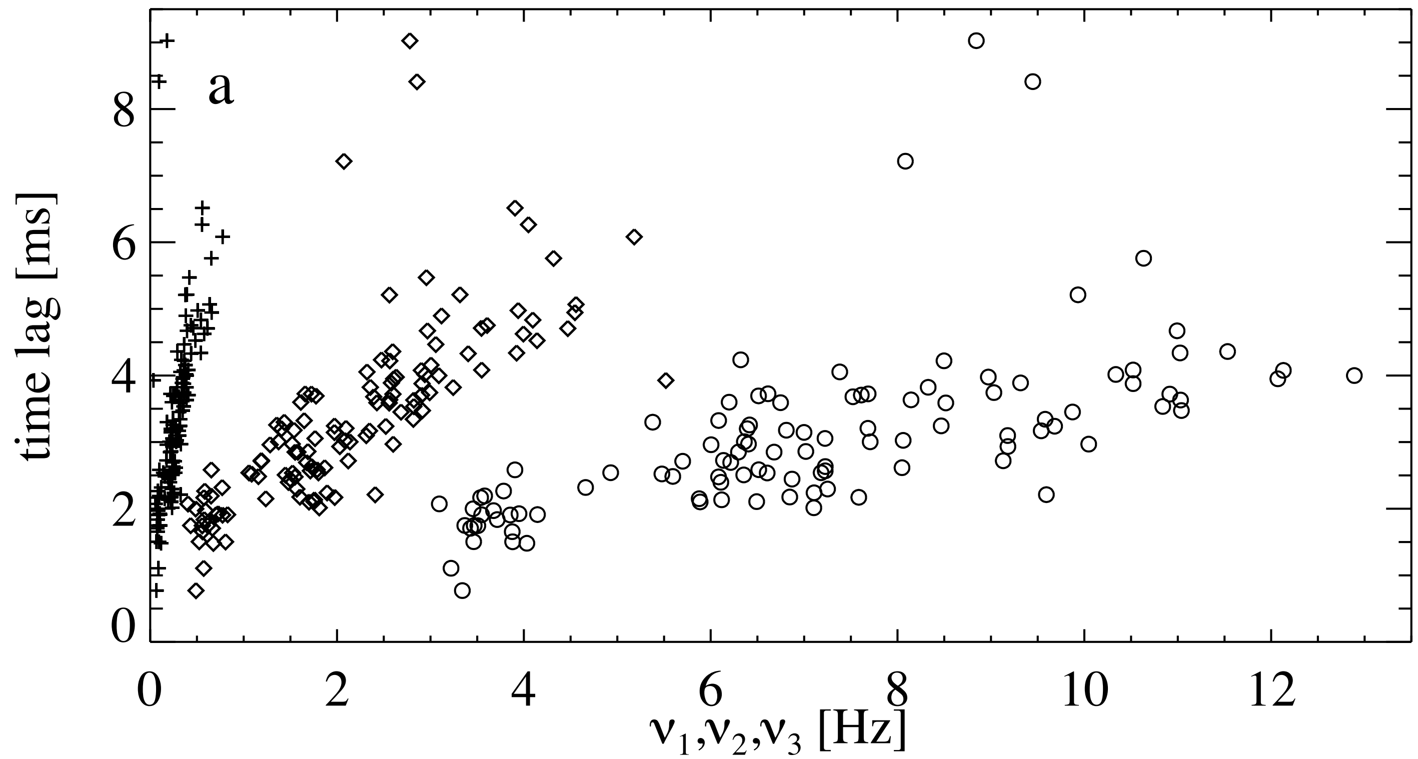
(Psaltis & Norman 1999, Nowak et al. 1998, Miyamoto & Kitamoto 1988)

Fourier Phase/Time Lags

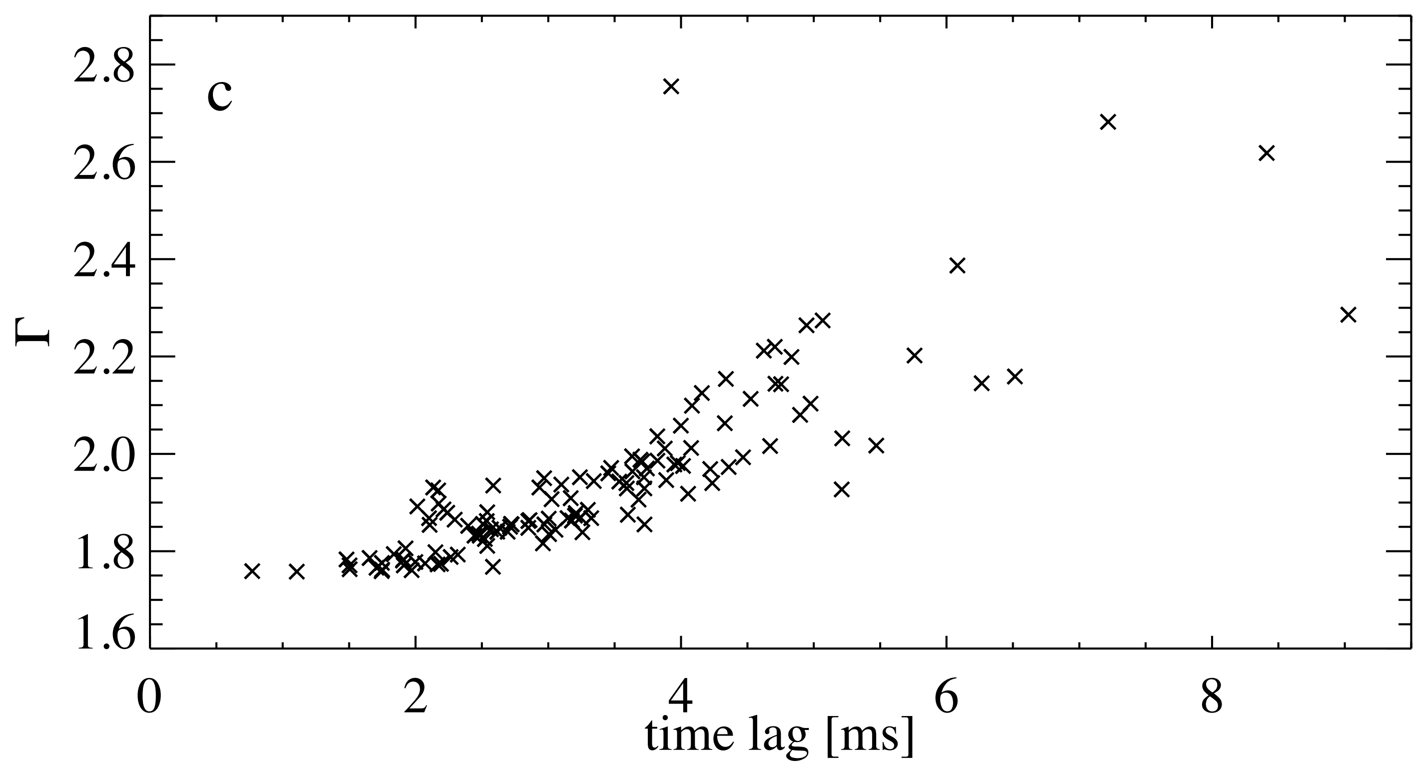


(Nowak et al. 1999)

Fourier Phase/Time Lags



Soft



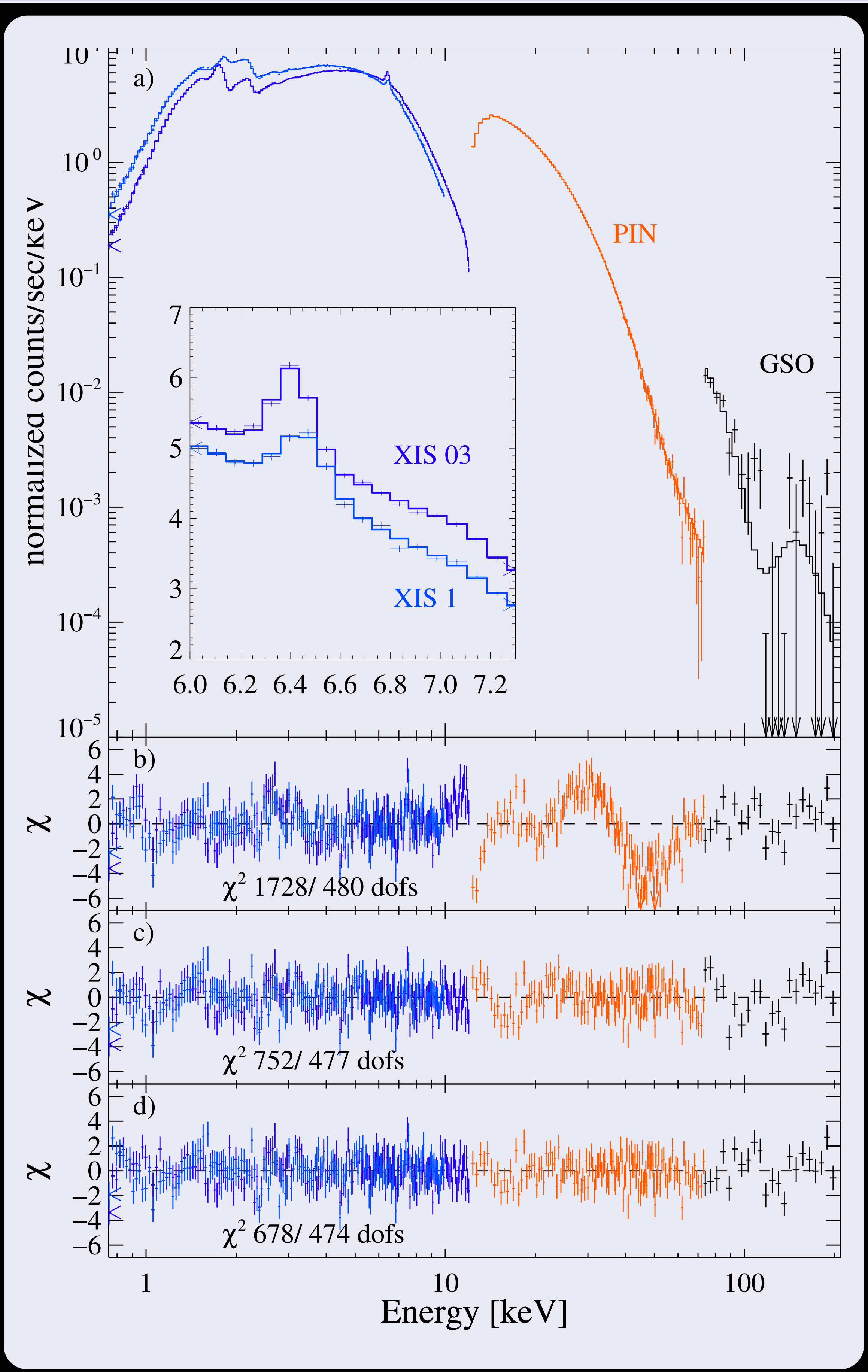
Hard

(Pottschmidt et al. 2003)

Brief Note on Neutron Star Binaries

- Similar concepts & issues arise with neutron star sources
  - Larger population of very bright sources - pileup, systematic errors, etc. are important considerations
- Similar classes of models: disks, coronae, reflection
  - Also blackbodies (boundary layers) & NS surface atmosphere models
- Fun example of high energy spectra: Cyclotron Lines — subject for RXTE-HEXTE, Suzaku-HXD, INTEGRAL
  - Hard X-ray often gets neglected – Fewer counts & smaller effective area instruments, but also ...
  - ftool grppha not equipped – bins by counts *or* channels
  - use isis> group(1;min_sn=5) or sherpa> group_snr(5)
  - Also consider renormalizing background

1A 1118−61: Cyclotron Line Discovery



Courtesy K. Pottschmidt,
Suzaku Workshop, July 2011

3rd Outburst in Source History

500 mCrab:

Suzaku: $58.2^{+0.8}_{-0.4}$ keV

RXTE: $55.1^{+1.6}_{-1.5}$ keV

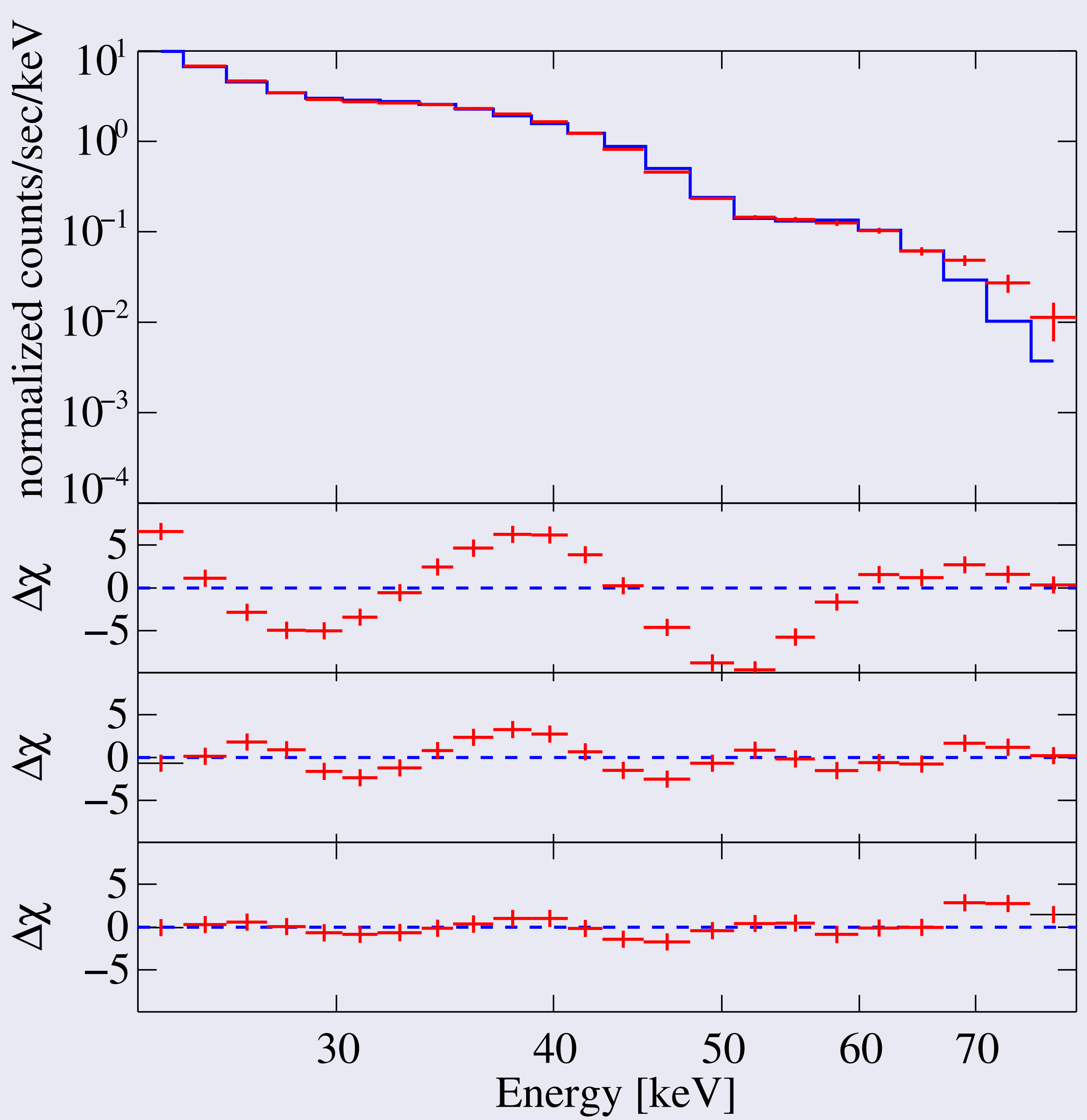
50 mCrab:

Suzaku: $47.4^{+3.2}_{-2.3}$ keV (?)

L dependence important for models.

Suchy, Pottschmidt et al., 2011, ApJ, 733, 15
Doroshenko, Suchy et al., 2010, A&A, 515, 1

CYCLOMC Example



V0332+53, *INTEGRAL*
Schönherr et al., 2007, A&A, 472, 353

Continuum – fdcut

$\Gamma = 0.94$
$E_{cut} = 12.8$ keV
$E_{fold} = 7.5$ keV

Line Model – cyclomc

$B = 3.05 \times 10^{12}$ G
$kT_e = 10.2$ keV
$\tau_{es} = 0.003$, $\mu = 0.06$

Reducing Emission Wings

– bottom illuminated slab
– partial covering

Courtesy K. Pottschmidt,
Suzaku Workshop, July 2011