

XSPEC Tutorial and Statistics

Basic steps for X-ray spectral analysis

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Where can I find XSPEC?

- XSPEC is part of the NASA HEASoft software suite (FTOOLS)
- The latest version is HEASoft 6.301 (April 2022) – xspec V12.12.1

<https://heasarc.gsfc.nasa.gov/docs/software/heasoft/>

- Supported architectures:
 - macOS/Mac OS X M1/ARM
 - PC Linux – Ubuntu (or other Debian-based Linux)
 - PC Linux – Fedora (or other RPM-based Linux)

XSPEC is a command-driven, interactive, X-ray spectral-fitting program, designed to be completely detector-independent

Alternatively: **Sherpa**

<https://cxc.cfa.harvard.edu/sherpa/>

Outline

- ☐ 'Grouping' the data. Loading data in xspec & setup commands
- ☐ Response matrices
- ☐ A quick journey through models in xspec
- ☐ Binned vs. unbinned data
- ☐ Starting model & spectral fit
- ☐ Evaluation of the goodness of the fit
- ☐ Gaussian vs. Poissonian regime
- ☐ Adding spectral components
- ☐ F-test
- ☐ Contour plots
- ☐ Final fitting solution
- ☐ Errors on the parameters
- ☐ Fluxes and luminosities (and errors)
- ☐ Save/restore working session
- ☐ Some additional and useful commands

Step 1a: 'grouping' spectra (if not already done)

Once X-ray spectra are extracted and response matrices are produced – see Chandra and XMM-Newton Tutorials – four files (fits format) are needed within XSPEC

Chandra ACIS-S data in this example

- source spectrum 3C33_r3.pi
- background spectrum 3C33_r3_bkg.pi
- ARF response matrix 3C33_r3.corr.arf
- RMF response matrix 3C33_r3.rmf

Before loading these files in XSPEC, it is better to:

- (1) 'associate' a source spectrum with its background file and response matrices (RMF and ARF); this is done automatically for Chandra by running the ciao tool *specextract*;
- (2) group the spectral counts using a binning of e.g. 20 counts/bin (depending on the source photon statistics and the 'sampling' of the instrument spectral resolution) and allow application of the χ^2 **statistics** (it is required to be in the Gaussian regime in each spectral bin).

Alternatively, in low-photon counting regime, use unbinned (or binned to 1 count/bin) data and **Cash statistics**

input src spectrum output src spectrum list of commands

chkey: change key param in the spectrum fits file

- **grppha** 3C33_r3.pi 3C33_r3_c20.pi comm="**group min 20** & chkey BACKFILE
3C33_r3_bkg.pi & chkey ANCRFILE 3C33_r3.corr.arf & chkey RESPFILE 3C33_r3.rmf & exit"
→ 3C33_r3_c20.pi

Name all of the files properly!

Step 1b: loading data in XSPEC and “setup” commands

xspect

xspect> data 3C33_r3_c20.pi

xspect> ignore bad

xspect> ignore **-0.3 7.-**

xspect> cpd /xw

xspect> plot ldata

xspect> setplot command r y

- load the grouped spectrum (produced in step 1a)
- ignore spectral bins flagged as bad (typically, at low/high E)
- ignore spectral bins below 0.3 keV and above 7 keV (to be verified on the data, check src. vs. back level)
- change the plotting device (e.g., on screen here; on PS file)
- plot the data in log scale
- rescale the y axis

Energy: with “.”

Otherwise: interpreted as channels if integer (conversion made via the RMF)

- The ‘-’ sign indicates a range
- **: means ‘everything’

Loading multiple datasets

In case of **multiple datasets**: adoption of the same model to carry out a simultaneous X-ray spectral analysis (taking advantage of the ‘increased’ photon statistics)

all spectra are fits files (irregardless of the name, as .pi here)

```
xspec> data 1:1 spectrum1.pi 2:2 spectrum2.pi 3:3 spectrum3.pi
```

load all datasets at the same time

```
xspec> ignore 1-3:**-0.3 7.0-**
```

select the proper energy range for all datasets (1-3)

```
xspec> cpd /xw
```

```
xspec> plot ldata
```

When **multiple datasets** are used, remember to place in front of all models the **constant model** [e.g., mo **cons**(pha*po+...)]. This takes into account:

- (a) cross-calibration uncertainties among different instruments of the same telescope (typically, a few percent) and different instruments of different telescopes;
- (b) some possible source flux variability in case of multiple observations not taken simultaneously.

The first constant should be fixed to 1, the others are left free to vary (i.e., are part of the fitting process).

xspec> show all

XSPEC version: 12.12.1
Build Date/Time: Thu Mar 31 20:12:13 2022

1 file 1 spectrum
Spectrum 1 Spectral Data File: 3C33_r3_c20.pi
Net count rate (cts/s) for Spectrum:1 6.520e-02 +/- 1.811e-03 (99.8 % total)
Assigned to Data Group 1 and Plot Group 1
Noticed Channels: 2-61
Telescope: CHANDRA Instrument: ACIS Channel Type: PI
Exposure Time: 1.992e+04 sec
Using fit statistic: chi
Using Background File 3C33_r3_bkg.pi
Background Exposure Time: 1.992e+04 sec
Using Response (RMF) File 3C33_r3.rmf for Source 1
Using Auxiliary Response (ARF) File 3C33_r3.corr.arf
Spectral data counts: 1301 (Total) Data counts

Fraction of
Src counts/Total counts
loaded back and
response files

Source net (i.e. background-subtracted) **counts** = data counts × fraction =
=1301 × 0.998 → in this case the source dominates the signal

Possible binning choices depending on the source photon statistics:

- have enough counts (e.g., 20-25) in each bin and then apply the χ^2 statistics;
- one count/bin and apply the Cash statistics (C-stat, named W-stat if background is subtracted);
- 'sampling' the spectral resolution of the data

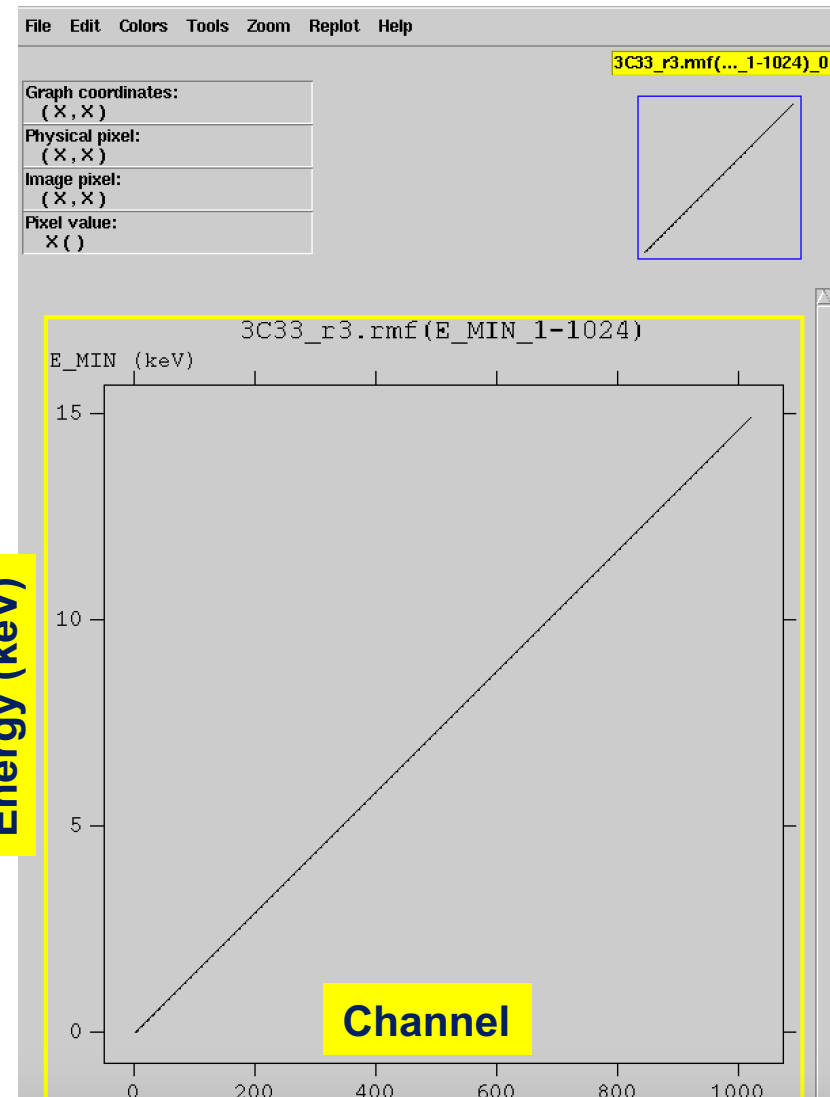
Response matrices: RMF

RMF: links the instrumental channel scale with the physical energy (wavelength) scale

- fv 3C33_r3.rmf

File Edit Tools Help				
Index	Extension	Type	Dimension	View
0	Primary	Image	0	Header Image Table
1	MATRIX	Binary	6 cols X 1070 rows	Header Hist Plot All Select
2	EBOUNDS	Binary	3 cols X 1024 rows	Header Hist Plot All Select

File Edit Tools Help			
	CHANNEL	E_MIN	E_MAX
Select	1J	1E	1E
All	channel	keV	keV
Invert	Modify	Modify	Modify
1	1	7.300000E-03	1.460000E-02
2	2	1.460000E-02	2.920000E-02
3	3	2.920000E-02	4.380000E-02
4	4	4.380000E-02	5.840000E-02
5	5	5.840000E-02	7.300000E-02
6	6	7.300000E-02	8.760000E-02
7	7	8.760000E-02	1.022000E-01
8	8	1.022000E-01	1.168000E-01
9	9	1.168000E-01	1.314000E-01
10	10	1.314000E-01	1.460000E-01
11	11	1.460000E-01	1.606000E-01
12	12	1.606000E-01	1.752000E-01
13	13	1.752000E-01	1.898000E-01
14	14	1.898000E-01	2.044000E-01
15	15	2.044000E-01	2.190000E-01
16	16	2.190000E-01	2.336000E-01
17	17	2.336000E-01	2.482000E-01
18	18	2.482000E-01	2.628000E-01
19	19	2.628000E-01	2.774000E-01
20	20	2.774000E-01	2.920000E-01



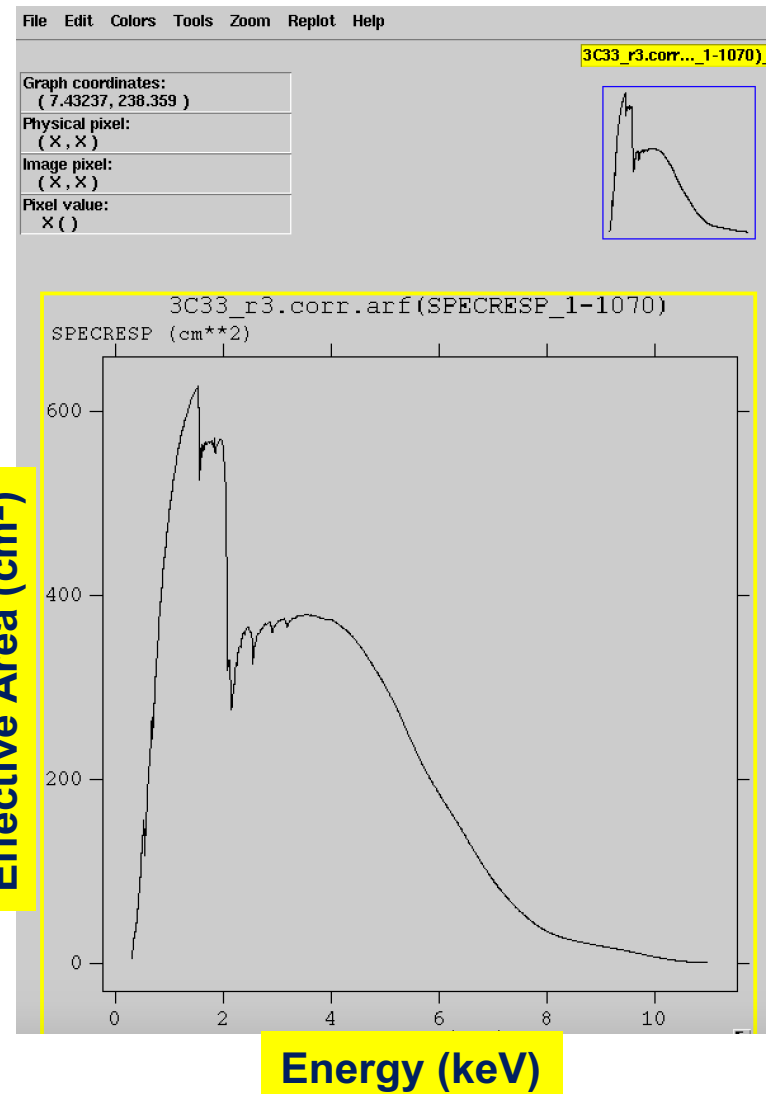
Response matrices: ARF

ARF: indicates the effective response (hence sensitivity) of the mirrors+instrument at a given source position on the detector

- fv 3C33_r3.corr.arf

File Edit Tools Help				
Select	ENERG_LO	ENERG_HI	SPECRESP	PSF_FRAC
<input checked="" type="checkbox"/> All	1E	1E	1E	1D
	keV	keV	cm**2	
<input type="checkbox"/> Invert	Modify	Modify	Modify	Modify
1	3.000000E-01	3.100000E-01	3.886596E+00	9.729960747434E-01
2	3.100000E-01	3.200000E-01	1.144929E+01	9.729424863851E-01
3	3.200000E-01	3.300000E-01	1.601507E+01	9.728888978671E-01
4	3.300000E-01	3.400000E-01	2.089009E+01	9.728353095087E-01
5	3.400000E-01	3.500000E-01	2.528668E+01	9.727817211504E-01
6	3.500000E-01	3.600000E-01	2.901072E+01	9.727281326324E-01
7	3.600000E-01	3.700000E-01	3.212375E+01	9.726745442740E-01
8	3.700000E-01	3.800000E-01	3.583970E+01	9.726209559157E-01
9	3.800000E-01	3.900000E-01	4.098644E+01	9.725673675574E-01
10	3.900000E-01	4.000000E-01	4.640701E+01	9.725137790394E-01
11	4.000000E-01	4.100000E-01	4.873587E+01	9.724601906810E-01
12	4.100000E-01	4.200000E-01	5.367477E+01	9.724066023227E-01
13	4.200000E-01	4.300000E-01	6.376080E+01	9.723530138047E-01
14	4.300000E-01	4.400000E-01	7.226711E+01	9.722994254463E-01
15	4.400000E-01	4.500000E-01	7.973080E+01	9.722458370880E-01
16	4.500000E-01	4.600000E-01	8.869151E+01	9.721922485700E-01
17	4.600000E-01	4.700000E-01	9.731506E+01	9.721386602116E-01
18	4.700000E-01	4.800000E-01	1.062349E+02	9.720850718533E-01
19	4.800000E-01	4.900000E-01	1.150116E+02	9.720314833353E-01
20	4.900000E-01	5.000000E-01	1.239493E+02	9.719778949770E-01

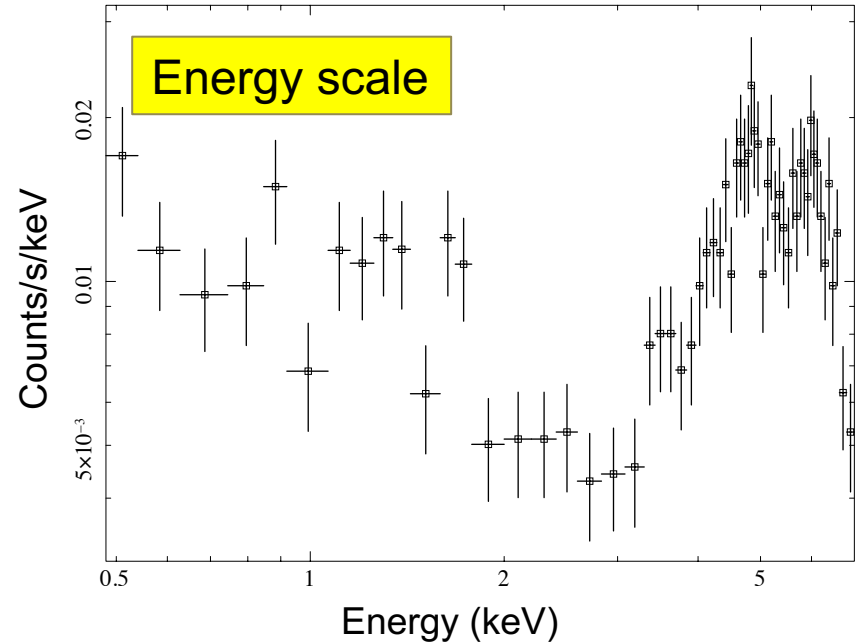
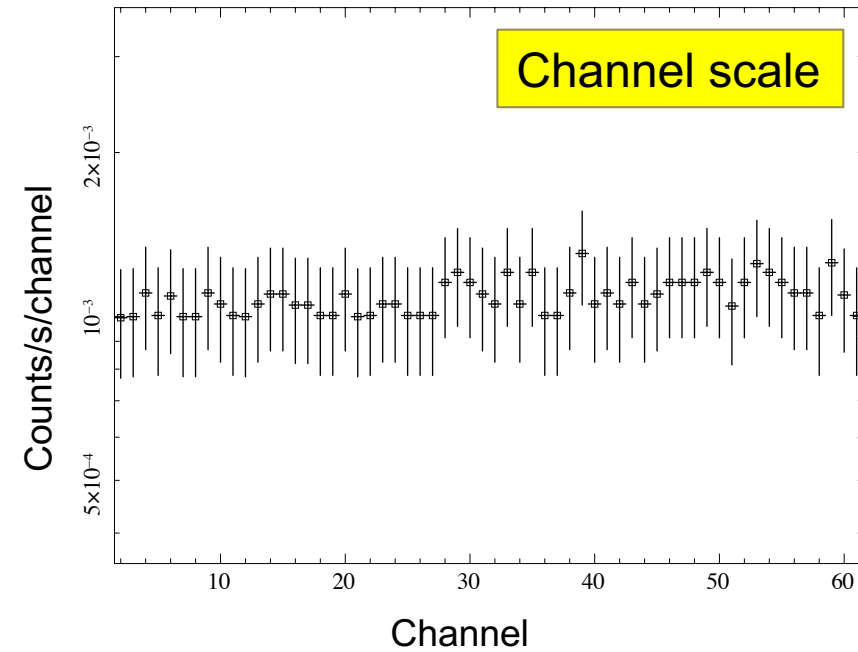
Effective Area (cm²)



PSF_FRAC: a sort of aperture correction (see EEF concept)

```
xspec> setplot energy
```

Channel scale = instrument scale
Energy scale = “physical” scale



```
xspec> setplot rebin 5 12
```

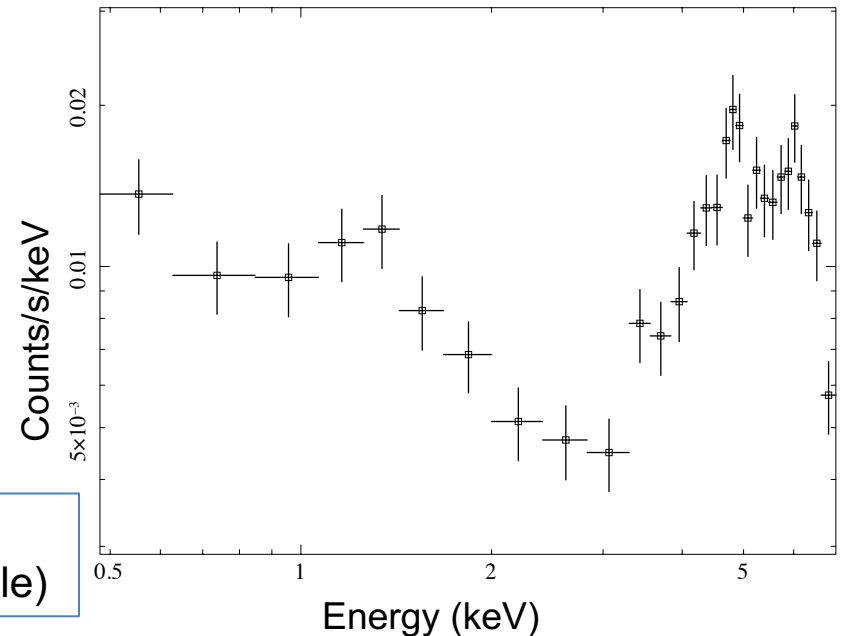


minimum significance in
the new bin

maximum number of
bins to be combined

(just for plotting purposes)

Spectrum in channels vs. spectrum in energy:
they are linked via the RMF (redistribution matrix file)



What does ‘binning’ (grouping) mean?

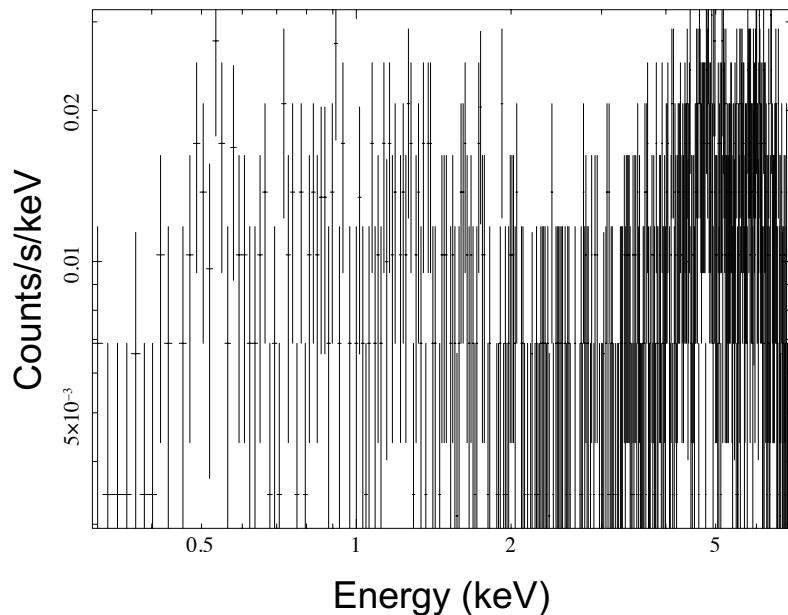
To apply the χ^2 test, we need that in every bin the statistics is nearly in the Gaussian regime, i.e., there is a sufficiently high number of counts in each spectral bin (datapoint)

Using the tool *grppha* (or similar), we can require that each spectral bin contains at least a given number of counts (see step 1a)

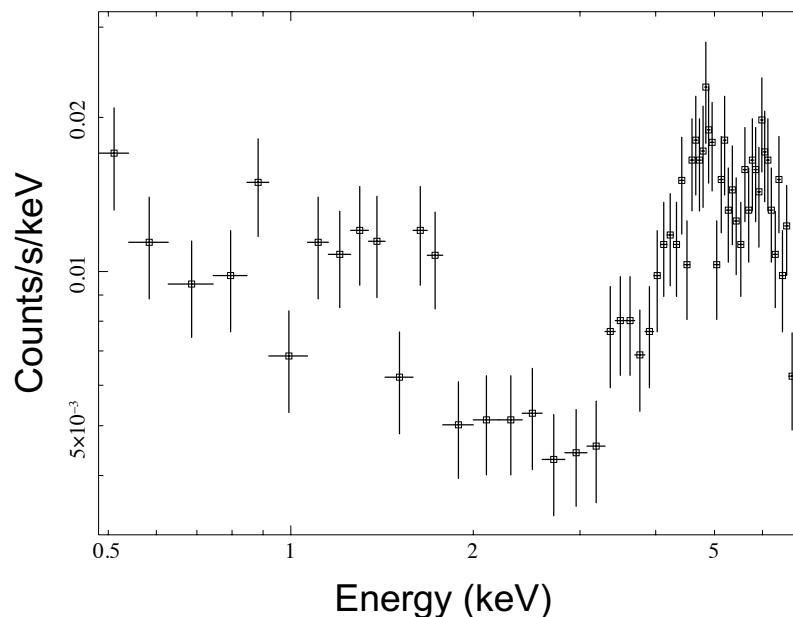
“original” distribution of the counts (note: here scale=energy)



Example of **unbinned spectrum**



The same, now **binned spectrum**



Good photon statistics: it is suggested to rebin the data and apply χ^2

Step 2: 'families' of xspec models

XSPEC models used like in math operations

Additive models

agauss	apec	bapec	bbody	bbodyrad	bexrav
bexriv	bkn2pow	bknpower	bmc	bremss	bvapec
bvvapec	c6mekl	c6pmekl	c6pvmkl	c6vmekl	cemekl
cevmkl	cflow	complS	compPS	compST	compTT
compbb	compmag	comptb	compth	cplinear	cutoffpl
disk	diskbb	diskir	diskline	diskm	disko
diskpbb	diskpn	eplogpar	eqpair	eqtherm	equil
expdec	ezdiskbb	gadem	gaussian	gnei	grad
grbm	kerrbb	kerrd	kerrdisk	laor	laor2
logpar	lorentz	meka	mekal	mkcflow	nei
npshock	nsa	nsagrav	nsatmos	nsmax	nsmaxg
nsx	ntea	nthComp	optxagn	optxagnf	pegpwr1w
pexmon	pexrav	pexriv	plcabs	posm	powerlaw
pshock	raymond	redge	refsch	rnei	sedov
sirf	smaug	srcut	sresc	step	vapec
vbremss	vequil	vgadem	vgnei	vmcflow	vmeka
vmekal	vnei	vnpschok	vpshock	vraymond	vnei
vsedov	vvapec	vvnei	vvnei	vvnpshock	vvpschok
vvrnei	vsedov	zagauss	zbbody	zbremss	zgauss
zpowerlw					

Multiplicative models

SSS_ice	TBabs	TBgrain	TBvarabs	absori	acisabs
cabs	constant	cyclabs	dust	edge	expabs
expfac	gabs	heilin	highcut	hrefl	lyman
notch	pcfabs	phabs	plabs	pwab	recorn
redden	smedge	spexcut	spline	swind1	uvred
varabs	vphabs	wabs	wndabs	xion	zTBabs
zbabs	zdust	zedge	zhigcut	zigm	zpcfabs
zphabs	zredden	zsmidust	zvarabs	zvfeabs	zvphabs
zwabs	zwndabs	zxipcf			

Syntax:

M1*M2*(A1+A2+M3*A3)

M=multiplicative model: modifies incident flux

A=additive model: source of emission

Other models

Convolution Models:

cflux	cpflux	gsmooth	ireflect	kdblur	kdblur2
kerrconv	lsmooth	partcov	rdblur	reflect	rgxsxsrc
simpl	zashift	zmshift			

Mixing Models:

ascac	projct	suzpsf	xmmpsfs
-------	--------	--------	---------

Pile-up Models:

pileup

Example:

model phabs*(powerlaw+gaussian)

$$M(E) = \exp[-n_H \sigma(E)]$$

$$A(E) = KE^{-\alpha}$$

$$A(E) = K \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right)$$

Suggestion: 'starting' model for **AGN emission**:
powerlaw modified by Galactic (MW)
absorption

Step 3a: starting model + spectral fit

Absorption due to our Galaxy (MW): you need to **include it in all spectral models**. All photons pass through our own Galaxy

```
xspec> nh
```

```
>>>>>> NH version 3
Equinox (d/f 2000)[2000]
RA in hh mm ss.s or degrees[159.386] 01 08 52.86
DEC in dd mm ss.s or degrees[56.171] 13 20 14.2
```

Your source's coordinates (3C33 here)

```
>> Using map h1_nh_HI4PI.fits
```

```
LII , BII 129.448839 -49.313559
Requested position at X and Y pixel 932.06 321.88
Search nH in 12 X 12 pixels box
Each pixel is 0.083 deg 0.083 deg
```

RA	DEC	Dist(deg)	nH
17.2521	13.2623	0.0812	2.93E+20
17.1710	13.2564	0.0940	2.89E+20
17.2913	13.3530	0.0709	3.03E+20
17.2101	13.3472	0.0140	2.95E+20
17.1289	13.3413	0.0890	2.91E+20

nH calculated using all points within 0.1000 deg from input position

```
h1_nh_HI4PI.fits >> Average nH (cm**-2) 2.94E+20
h1_nh_HI4PI.fits >> Weighted average nH (cm**-2) 2.96E+20
```

$N_{\text{H,Gal}} = 2.96 \times 10^{20} \text{ cm}^{-2}$

Alternatively (web tool): <https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl>
based on the HI4PI Survey (N.B. Bekhti et al. 2016, A&A, 594, A116)

Suggestion: start with a simple modeling (as a powerlaw modified by Galactic absorption)

xspec> **mo pha*po**

pha: accounts for the Galactic N_H (multiplicative model)
po: powerlaw model (additive model) for the primary AGN comp.

It is possible to provide values to the parameters at every step of the fitting process

[XSPEC12>mo pha*po

Input parameter value, delta, min, bot, top, and max values for ...							
	1	0.001(	0.01)	0	0	100000	1e+06
[1:phabs:nH>2.96e-2	-1	0.01(	0.01)	-3	-2	9	10
[2:powerlaw:PhoIndex>1.9	1	0.01(	0.01)	0	0	1e+20	1e+24
[3:powerlaw:norm>1e-5							

-1 means frozen parameter (the same as using the

-1 means frozen parameter (the same as using the command freeze # of the parameter; opposite: thaw)

Model phabs<1>*powerlaw<2> Source No.: 1					Active/On	
Model	Model	Component	Parameter	Unit	Value	
par	comp					
1	1	phabs	nH	10^22	2.96000E-02	frozen
2	2	powerlaw	PhoIndex		1.90000	+/- 0.0
3	2	powerlaw	norm		1.00000E-05	+/- 0.0

Alternatively, you may assign later a value to a parameter using
xspec> **newpar 2 1.9**

Fit statistic : Chi-Squared 1084.55 using 60 bins.
Test statistic : Chi-Squared 1084.55 using 60 bins.
Null hypothesis probability of 3.89e-189 with 58 degrees of freedom
Current data and model not fit yet.

parameter number number of the component

Model: pha(po)

```
xspec> query yes
```

```
xspec> renorm
```

 to allow a preliminary “adjustment”

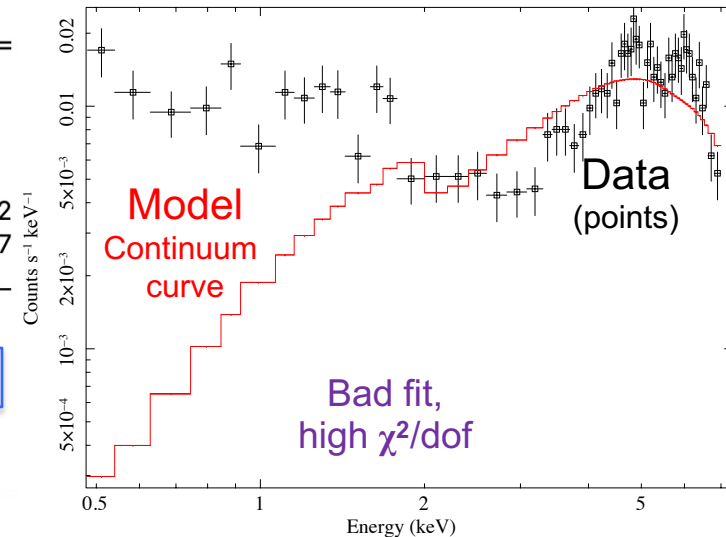
```
xspec> fit 100
```

 fit 100 times

```
=====
Model phabs<1>*powerlaw<2> Source No.: 1 Active/On
Model Model Component Parameter Unit Value
par comp
  1 1 phabs nH 10^22 2.96000E-02 frozen
  2 2 powerlaw PhoIndex -1.50855 +/- 8.78563E-02
  3 2 powerlaw norm 3.82238E-06 +/- 4.89638E-07
=====
```

```
Fit statistic : Chi-Squared 250.22 using 60 bins.
Test statistic : Chi-Squared 250.22 using 60 bins.
Null hypothesis probability of 1.03e-25 with 58 degrees of freedom
```

Bad fit in the soft and in the hard part of the spectrum



dof=degrees of freedom=(number of datapoints – number of free parameters)=60-2=58

- χ^2/dof close to unity means that it is a good fit (here: 250/58: not in this case!) – see lesson on statistics and the following slides
- Null hypothesis probability=probability that the model is a good representation of the datapoints (i.e., good if close to 1)

All the adopted models should be physically motivated according to the known source (multi-wavelength) properties & classification

Model: pha(po)

To evaluate the goodness of the fit: the χ^2 statistical test

Test to compare the observed distribution of the results with that expected

$$\chi^2 = \sum_{k=1}^n \frac{(O_k - E_k)^2}{\sigma_k^2}$$

O_k =observed values (spectral datapoints)

E_k =expected values (model)

σ_k =error on the measured values (error on each spectral bin)

k =number of datapoints (bins after rebinning)

$$\chi^2 / dof \approx 1$$



the observed and expected
distributions are similar

Applicability of χ^2 statistics

χ^2 statistic

$$S = \sum_i \left(\underbrace{S_i}_{O_K} - \underbrace{B_i t_s / t_b}_{E_K} - \underbrace{m_i t_s}_{\sigma_K} \right)^2 / \left((\sigma_S)_i^2 + (\sigma_B)_i^2 \right)$$

- S_i = src counts in the $I=\{1, \dots, N\}$ data bins with exposure t_s ;
- B_i = background counts with exposure t_b ;
- m_i = model predicted count rate;
- $(\sigma_S)^2$ and $(\sigma_B)^2$ = variance on the src and background counts, typically estimated by S_i and B_i

BUT

the χ^2 statistic fails in low-counting regime
(few counts in each data bin)

Alternative solutions in case of low photon statistics

- i. To rebin the data so that each bin contains a large enough number of counts

BUT: loss of information and dependence on the rebinning method adopted

- ii. To modify S so that it performs better in low-count regime (e.g., by estimating the variance for a given data bin using the average counts from the surrounding bins; Churazov+96)

BUT: it would need Montecarlo simulations to properly support the result

- iii. To construct a **maximum-likelihood estimator** based on the Poisson distribution of the detected counts (Cash79; Wachter+79). ML means finding the best fit of parameters that maximizes the Poisson likelihood

```
xspec> statistic chi (default)  
xspec> statistic cstat
```

Binned data, χ^2 statistics	\Leftrightarrow Gaussian statistics
Unbinned data, C-statistics	\Leftrightarrow Poisson statistics

χ^2 in a nutshell

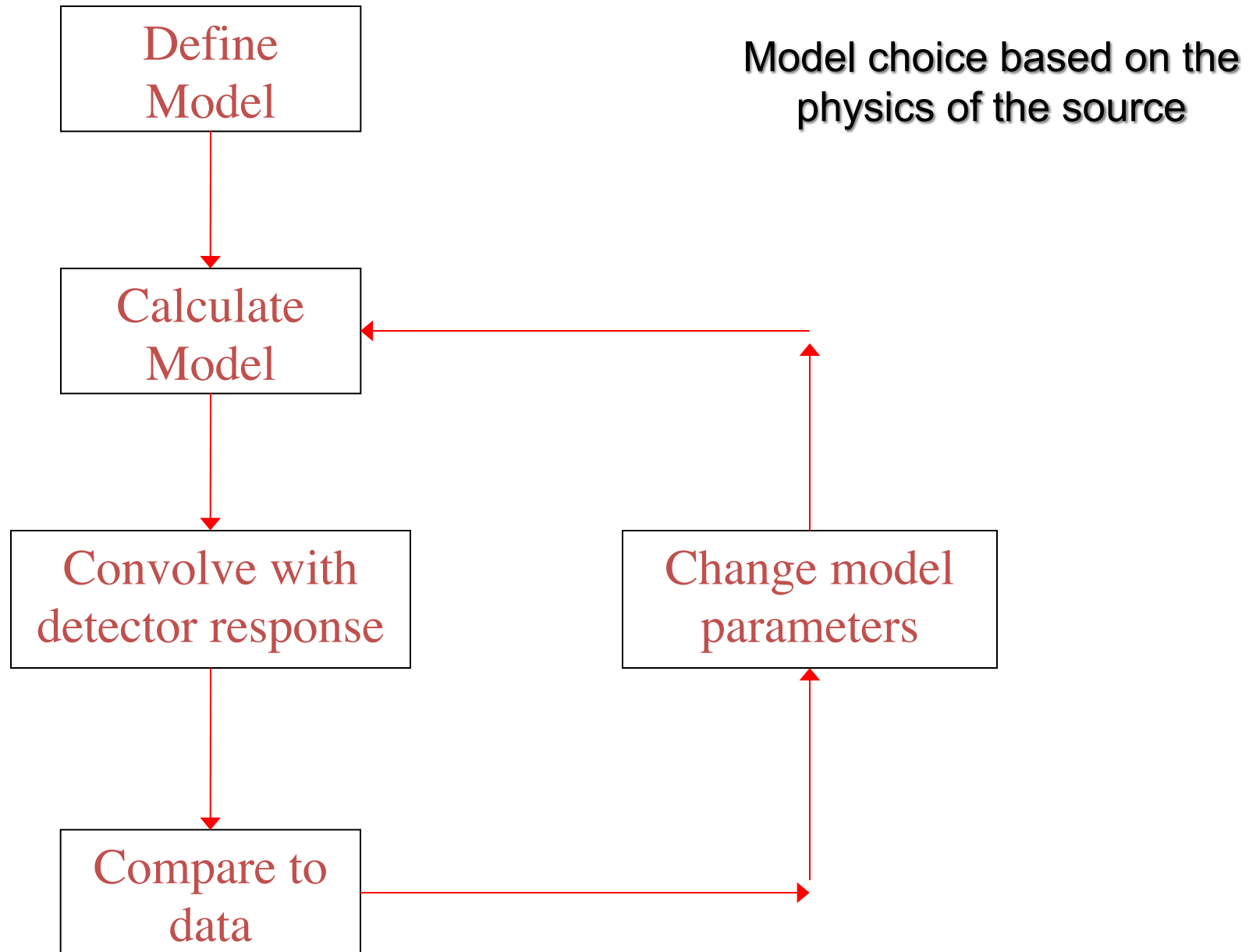
Reduced χ^2 large \leftrightarrow $P(\chi^2)$ small

- a. Errors are under-estimated
- b. The model does not describe the data correctly

Reduced χ^2 small \leftrightarrow $P(\chi^2)$ large

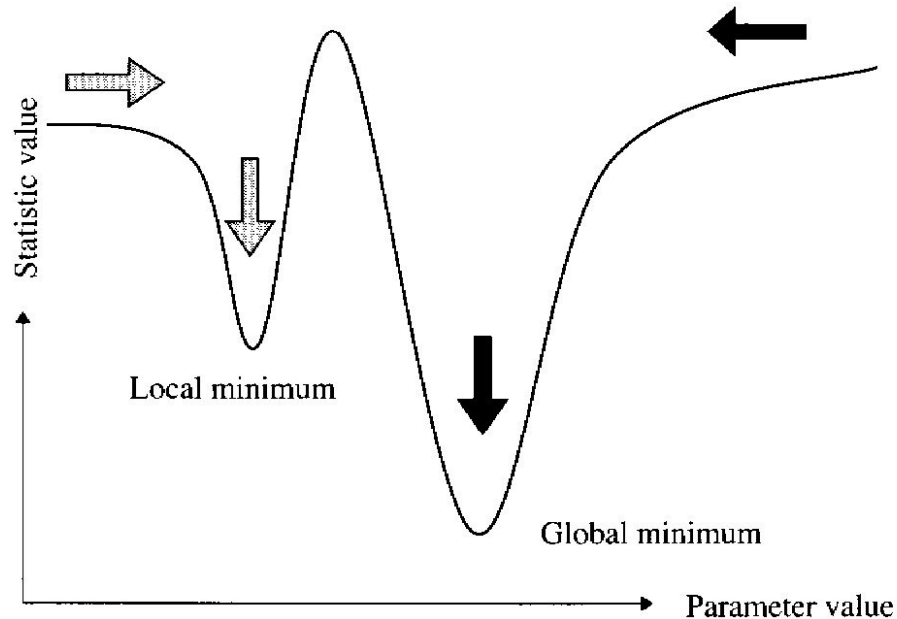
- c. Errors are over-estimated
- d. Were data “selected” in a particular way?

Forward-fitting algorithm



Global vs. local minimum

Data analysis



If the fit process is started at the “right place”, then it will converge to the true minimum

The more complicated the model and the more highly correlated the parameters, then the more likely that the algorithm will hardly find the true minimum

To ‘move’ the fit from a local minimum, you can change some of the parameters using the *newpar* command and then fit again

Step 3b: adding components and fit. I

`xspec> addcomp 2 powerlaw` adding a powerlaw as # component (#=order in the model)

Input parameter value, delta, min, bot, top, and max values for ...

1	0.01(	0.01)	-3	-2	9	10
2:powerlaw:PhoIndex>1.8						
1	0.01(	0.01)	0	0	1e+20	1e+24
3:powerlaw:norm>1e-5						

Fit statistic : Chi-Squared 164.18 using 60 bins.

Test statistic : Chi-Squared 164.18 using 60 bins.
Null hypothesis probability of 1.47e-12 with 56 degrees of freedom
Current data and model not fit yet.

```
=====
Model phabs<1>(powerlaw<2> + powerlaw<3>) Source No.: 1 Active/On
Model Model Component Parameter Unit Value
par comp
1 1 phabs nH 10^22 2.96000E-02 frozen
2 2 powerlaw PhoIndex 1.80000 +/- 0.0
3 2 powerlaw norm 1.00000E-05 +/- 0.0
4 3 powerlaw PhoIndex -1.50636 +/- 0.0
5 3 powerlaw norm 3.83424E-06 +/- 0.0
```

Inclusion of an additional powerlaw
component to account for the residuals
observed at low energies:
scattering component? phenomenological
(simplistic) parameterization of something
different?

xspec> fit 100

```
=====
Model phabs<1>(powerlaw<2> + powerlaw<3>) Source No.: 1   Active/On
Model Model Component Parameter Unit      Value
par  comp
 1    1    phabs      nH          10^22    2.96000E-02 frozen
 2    2    powerlaw   PhoIndex      2.11546 +/- 0.253295
 3    2    powerlaw   norm          2.21887E-05 +/- 1.76027E-06
 4    3    powerlaw   PhoIndex     -2.27030 +/- 0.157493
 5    3    powerlaw   norm          1.11704E-06 +/- 2.92660E-07
=====
```

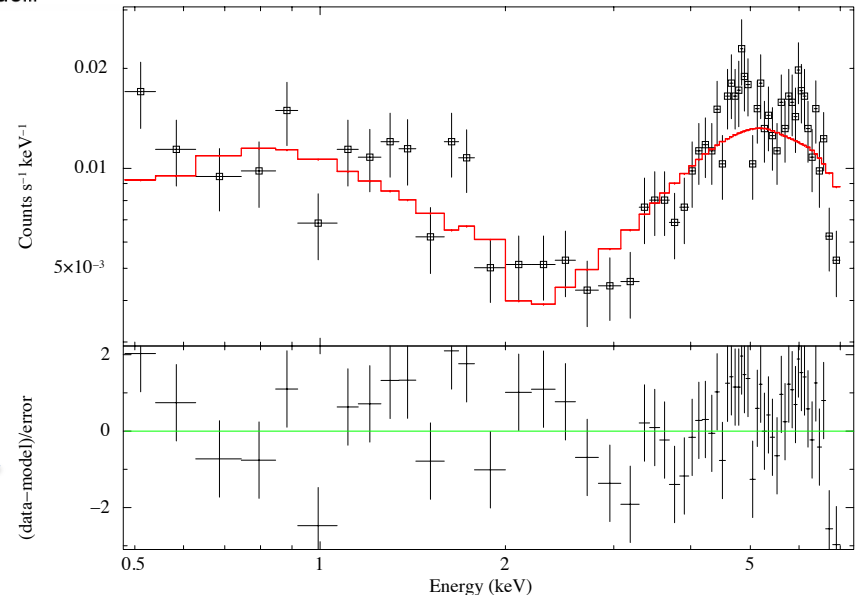
ONE QUESTION:
are all the derived parameters physically
acceptable?

We will come back on this later...

```
Fit statistic : Chi-Squared      89.24      using 60 bins.
Test statistic : Chi-Squared      89.24      using 60 bins.
Null hypothesis probability of 3.13e-03 with 56 degrees of freedom
```

xspec> plot ldata delchi

delchi = (data-model)/error →



The $\chi^2/\text{dof}=89.2/56$ is much lower than previous one and the model more properly reproduces the observed spectral datapoint distribution.
There are yet *some residuals* (bottom panel: data-model, i.e. deviations in units of $\sigma=\text{stat. error}$)

Model: pha(po+po)

Step 3b: adding components and fit. II

xspec> addcomp 3 zpha adding zpha=absorption intrinsic to the source as third component

```
Input parameter value, delta, min, bot, top, and max values for ...
      1      0.001(      0.01)      0      0      100000      1e+06
[4:zphabs:nH>1
      0      -0.01(      0.01)      -0.999      -0.999      10      10
[5:zphabs:Redshift>0.06
      z=0.06
```

```
Fit statistic : Chi-Squared      93.47      using 60 bins.
Test statistic : Chi-Squared      93.47      using 60 bins.
Null hypothesis probability of 9.34e-04 with 55 degrees of freedom
Current data and model not fit yet.
```

Justification: the inverted slope of the continuum (negative photon index) may be ascribed to the presence of obscuration

```
=====
Model phabs<1>(powerlaw<2> + zphabs<3>*powerlaw<4>) Source No.: 1 Active/On
Model Model Component Parameter Unit Value
par comp
  1 1 phabs nH 10^22 2.96000E-02 frozen
  2 2 powerlaw PhoIndex 2.11546 +/- 0.253295
  3 2 powerlaw norm 2.21887E-05 +/- 1.76027E-06
  4 3 zphabs nH 10^22 1.00000 +/- 0.0
  5 3 zphabs Redshift 6.00000E-02 frozen
  6 4 powerlaw PhoIndex -2.27030 +/- 0.157493
  7 4 powerlaw norm 1.11704E-06 +/- 2.92660E-07
-----
```

→ Is the newly derived photon index (after the inclusion of N_{H} ; parameter 6, component 4) more consistent with what is expected in case of an AGN ($\Gamma=1.8-2$)?

Model: pha(po+zpha(po))

xspect> fit 100

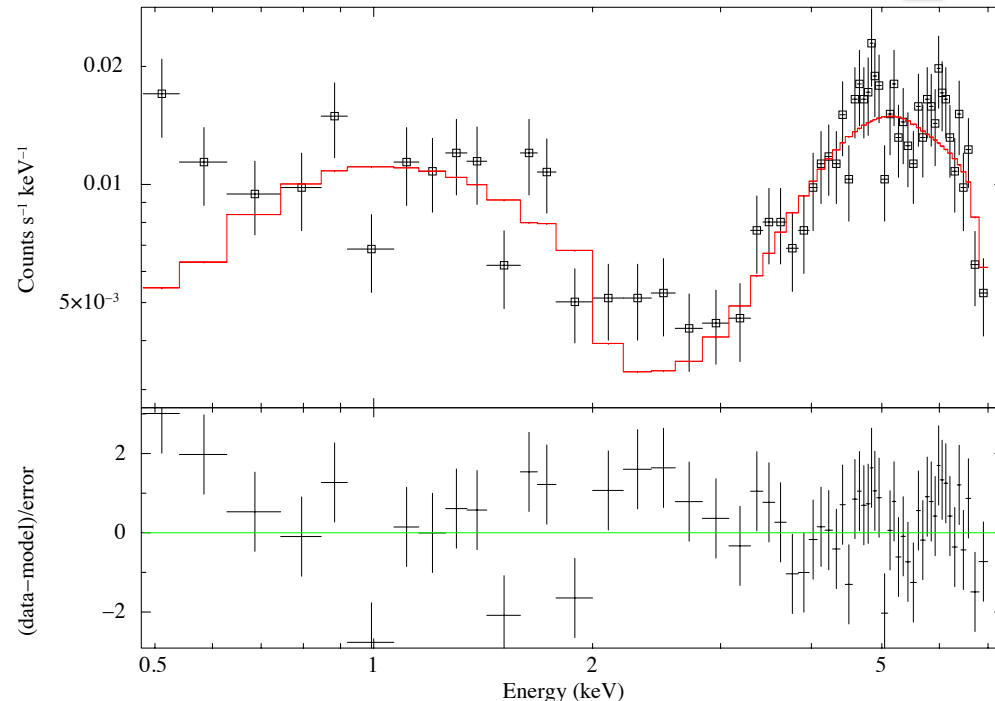
=====							
Model phabs<1>(powerlaw<2> + zphabs<3>*powerlaw<4>)					Source No.:	1	Active/On
Model	Model	Component	Parameter	Unit	Value		
par	comp						
1	1	phabs	nH	10^22	2.96000E-02	frozen	
2	2	powerlaw	PhoIndex		1.14238	+/-	0.161801
3	2	powerlaw	norm		2.45188E-05	+/-	1.69217E-06
4	3	zphabs	nH	10^22	22.0419	+/-	5.59213
5	3	zphabs	Redshift		6.00000E-02	frozen	
6	4	powerlaw	PhoIndex		-0.539341	+/-	0.528688
7	4	powerlaw	norm		3.81227E-05	+/-	3.43217E-05

Fit statistic : Chi-Squared 76.04 using 60 bins.
 Test statistic : Chi-Squared 76.04 using 60 bins.
 Null hypothesis probability of 3.16e-02 with 55 degrees of freedom

Apparently, some line-like residuals around 6 keV



xspect> plot ldata delchi



Model: pha(po+zpha(po))

$\chi^2/\text{dof}=76.0/55$ now \rightarrow improvement in the fit

However, the photon index (parameter 6, component 4) is still negative

\rightarrow likely, the hard-band powerlaw and the column density are *degenerate parameters*, hence constraining both over the limited hard band of Chandra is challenging

VIALE SOLUTIONS:

Link the photon indices of the two powerlaw as in the case of Thomson scattering in the soft band) – see the following slides

Step 3b: adding components and fit. III

xspec> addcomp 4 zgauss adding zgauss=emission line as fourth component

```
Input parameter value, delta, min, bot, top, and max values for ...
      6.5      0.05(      0.065)      0      0      1e+06      1e+06
[6:zgauss:LineE>6.4
      0.1      0.05(      0.001)      0      0      10      20
[7:zgauss:Sigma>0.01,-1
      0      -0.01(      0.01)      -0.999      -0.999      10      10
[8:zgauss:Redshift>0.06
      1      0.01(      0.01)      0      0      1e+20      1e+24
[9:zgauss:norm>1e-6
```

I have included a narrow ($\sigma=10$ eV, fixed) line at the expected rest-frame energy of the neutral iron K α transition (6.4 keV)

```
Fit statistic : Chi-Squared      74.92      using 60 bins.
Test statistic : Chi-Squared      74.92      using 60 bins.
Null hypothesis probability of 2.54e-02 with 53 degrees of freedom
Current data and model not fit yet.
```

```
=====
Model phabs<1>(powerlaw<2> + zphabs<3>(zgauss<4> + powerlaw<5>)) Source No.: 1   Active/On
Model Model Component Parameter Unit Value
par comp
  1    1    phabs      nH        10^22  2.96000E-02 frozen
  2    2    powerlaw   PhoIndex      1.14238 +/- 0.161801
  3    2    powerlaw   norm          2.45188E-05 +/- 1.69217E-06
  4    3    zphabs     nH        10^22  22.0419 +/- 5.59213
  5    3    zphabs     Redshift      6.00000E-02 frozen
  6    4    zgauss     LineE        keV    6.40000 +/- 0.0
  7    4    zgauss     Sigma        keV    1.00000E-02 frozen
  8    4    zgauss     Redshift      6.00000E-02 frozen
  9    4    zgauss     norm          1.00000E-06 +/- 0.0
 10    5    powerlaw   PhoIndex      -0.539341 +/- 0.528688
 11    5    powerlaw   norm          3.81227E-05 +/- 3.43217E-05
-----
```

Model: pha(po+zpha(zgauss**+po+))**

xspecc> fit 100

=====						
Model phabs<1>(powerlaw<2> + zphabs<3>(zgauss<4> + powerlaw<5>)) Source No.: 1 Active/On						
Model	Model	Component	Parameter	Unit	Value	
par	comp					
1	1	phabs	nH	10^22	2.96000E-02	frozen
2	2	powerlaw	PhoIndex		1.15143	+/- 0.161868
3	2	powerlaw	norm		2.45395E-05	+/- 1.69157E-06
4	3	zphabs	nH	10^22	22.2581	+/- 5.75947
5	3	zphabs	Redshift		6.00000E-02	frozen
6	4	zgauss	LineE	keV	6.39238	+/- 4.48975E-02
7	4	zgauss	Sigma	keV	1.00000E-02	frozen
8	4	zgauss	Redshift		6.00000E-02	frozen
9	4	zgauss	norm		1.08538E-05	+/- 4.45599E-06
10	5	powerlaw	PhoIndex		-0.392248	+/- 0.555082
11	5	powerlaw	norm		4.82903E-05	+/- 5.22882E-05

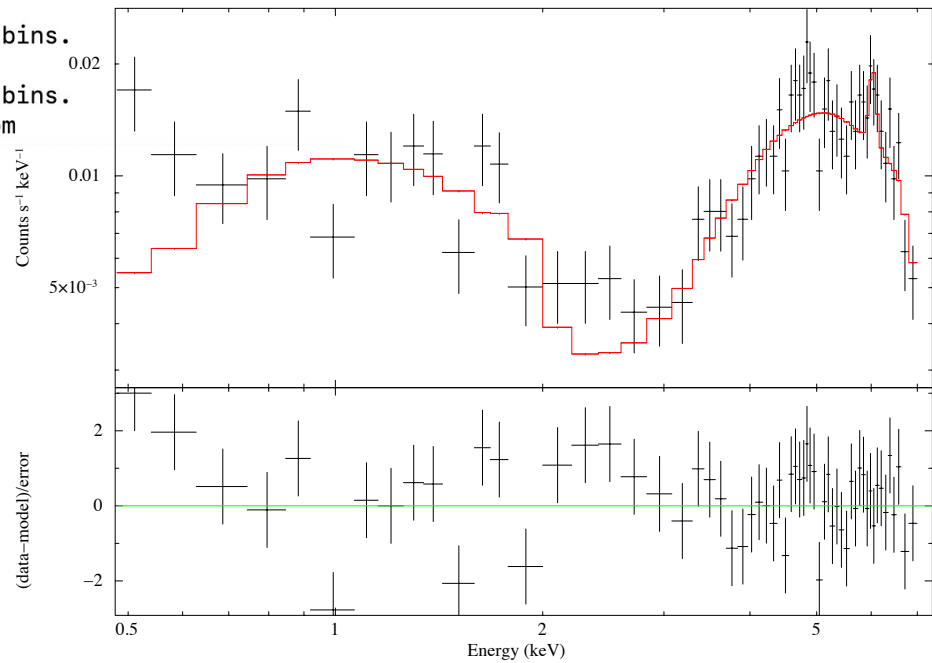
Fit statistic : Chi-Squared 69.70 using 60 bins.
Test statistic : Chi-Squared 69.70 using 60 bins.
Null hypothesis probability of 6.17e-02 with 53 degrees of freedom

Is the added component (the line in this case) statistically significant?
How much significant?



F test

xspecc> plot ldata delchi



Model: pha(po+zpha(zgauss+po+))

Step 4: the F-test

(here applied to estimate the statistical significance of the inclusion of an emission line)

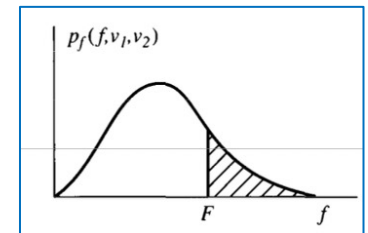
- **Model 1**: double powerlaw + obscuration: $\chi^2/\text{dof}=76.0/55$
- **Model 2**: double powerlaw + obscuration + **iron emission line**: $\chi^2/\text{dof}=69.7/53$



$$\Delta\chi^2/\Delta\text{dof}=6.3/2$$

xspect> ftest 69.7 53 76.0 55

$\chi^2(\text{model2})$ $\text{dof}(\text{model 2})$ $\chi^2(\text{model1})$ $\text{dof}(\text{model1})$



Large F value \rightarrow low probability
(of exceeding that value, see tables)
 \rightarrow highly significant improvement
due to the additional component

```
[XSPEC12>ftest 69.7 53 76.0 55  
F statistic value = 2.39527 and probability 0.10095
```

\rightarrow The iron line has low significance: $P(\text{real line})=1-0.10095\sim0.90 \rightarrow \sim1.6\sigma$

Use the F-test to evaluate the improvement to a spectral fit due to the assumption of a different model, with additional terms

Conditions:

(a) the simpler model is nested within the more complex model;

(b) the extra parameters have Gaussian distribution (not truncated by the parameter space boundaries) – BUT see also Protassov+02 on caveats

$$P_f(f; v_1, v_2) = \frac{\chi_1^2 / v_1}{\chi_2^2 / v_2}$$

$$\propto \Delta \chi^2 / k$$

The larger this ratio,
the larger the improvement
in the spectral fitting

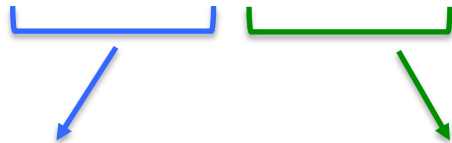
*k=number of additional
parameters*

Step 5a: contour plots and error computation

Use the *steppar* command to compute errors simultaneously for two parameters and visualize them using contour plots - it performs a fit while stepping the values of two parameters through a given range

Here: photon index (param. 10) vs. column density (param. 4)

```
xspec> stepp 10 -2 2 30 4 0 60 30
```



Parameter 10 is stepped from
value -2 to 2 in 30 steps

Parameter 4 is stepped from
value 0 to 60 (units of 10^{22} cm^{-2})
in 30 steps

It provides how one parameter varies wrt. another parameter (i.e., the error range for sets of parameters)

Useful also to understand whether two spectral parameters are correlated (not necessarily from a physical point of view)

at each step
(in the process of 'moving'
through the selected
ranges of the two
parameters)

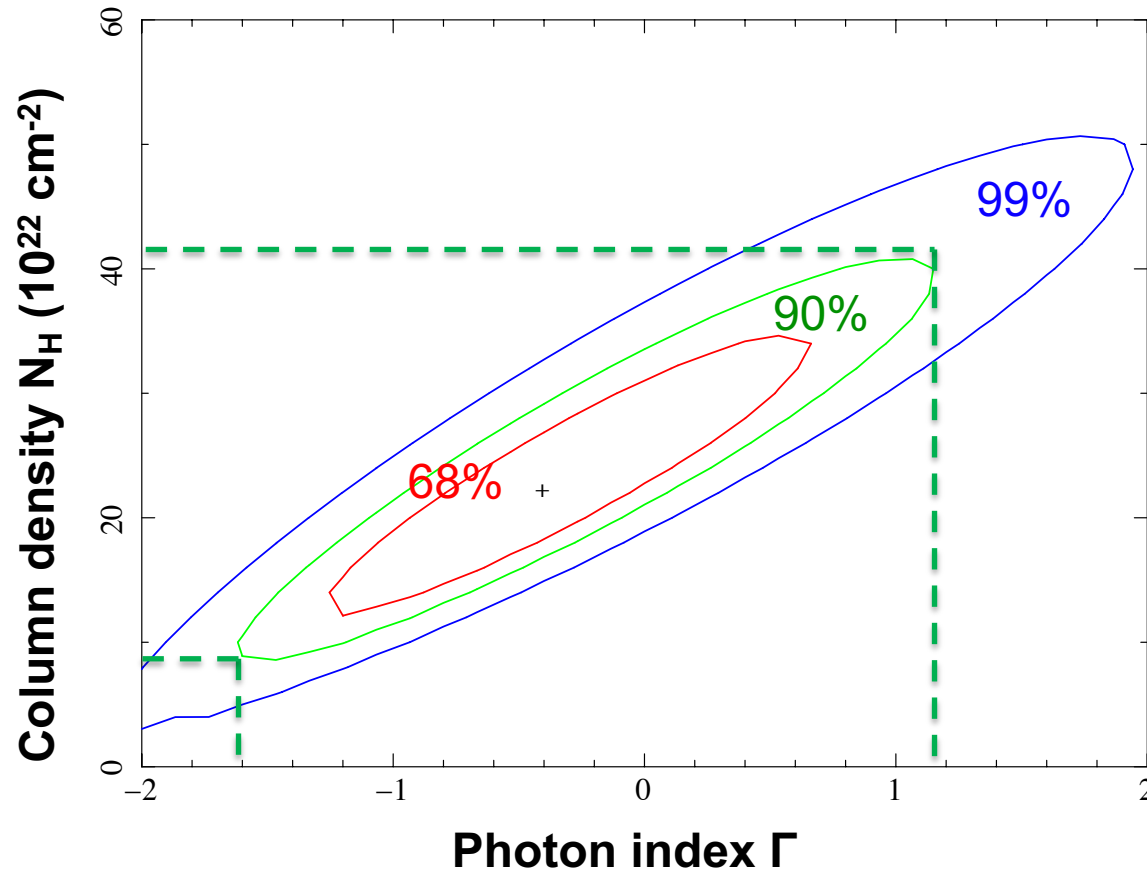
Variations in χ^2 (hence, $\Delta\chi^2$)
wrt. best-fitting solution

Chi-Squared	Delta Chi-Squared	PhoIndex 10	nH 4
-------------	----------------------	----------------	---------

Parameters involved in the fit

82.257	12.553	0	-2	0	0
97.112	27.408	1	-1.6	0	0
130.85	61.143	2	-1.2	0	0
186.48	116.78	3	-0.8	0	0
265.11	195.4	4	-0.4	0	0
363.95	294.25	5	0	0	0
474.76	405.06	6	0.4	0	0
585.89	516.18	7	0.8	0	0
687.28	617.57	8	1.2	0	0
772.51	702.81	9	1.6	0	0
840.9	771.2	10	2	0	0
462.99	393.28	10	2	1	6
406.58	336.87	9	1.6	1	6
347.9	278.19	8	1.2	1	6
288.93	219.23	7	0.8	1	6
232.32	162.61	6	0.4	1	6
181.08	111.38	5	0	1	6
138.18	68.48	4	-0.4	1	6
105.93	36.229	3	-0.8	1	6
85.501	15.797	2	-1.2	1	6
76.667	6.963	1	-1.6	1	6
77.912	8.2079	0	-2	1	6
83.7	13.996	0	-2	2	12
74.987	5.2834	1	-1.6	2	12

xspec> plot contour



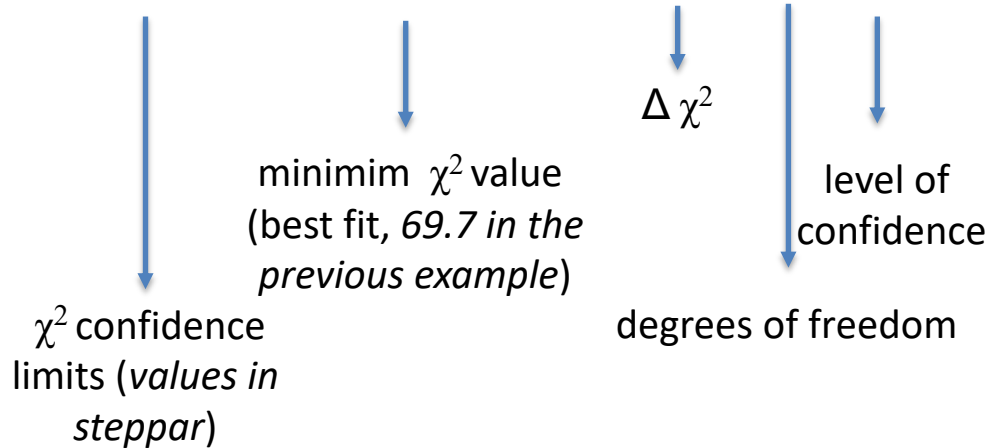
- 90% confidence level: the photon index varies in the range $\sim [-1.6, 1.2]$, while the column density varies in the interval $\sim [9-41] \times 10^{22} \text{ cm}^{-2}$
- The photon index and the column density are degenerate parameters
- We can decide to link the photon indices of the two powerlaws (as in case of scattering)

The meaning of contour plots/confidence regions

The *contour plots* define a confidence region in the parameter space (i.e., the “statistical surface”) within which the true parameters lie with a certain confidence (hence, 68, 90, 99% in XSPEC by default). They represent regions of constant probability

$$\chi^2_{\alpha} = \chi^2_{min} + \Delta(\nu, \alpha)$$

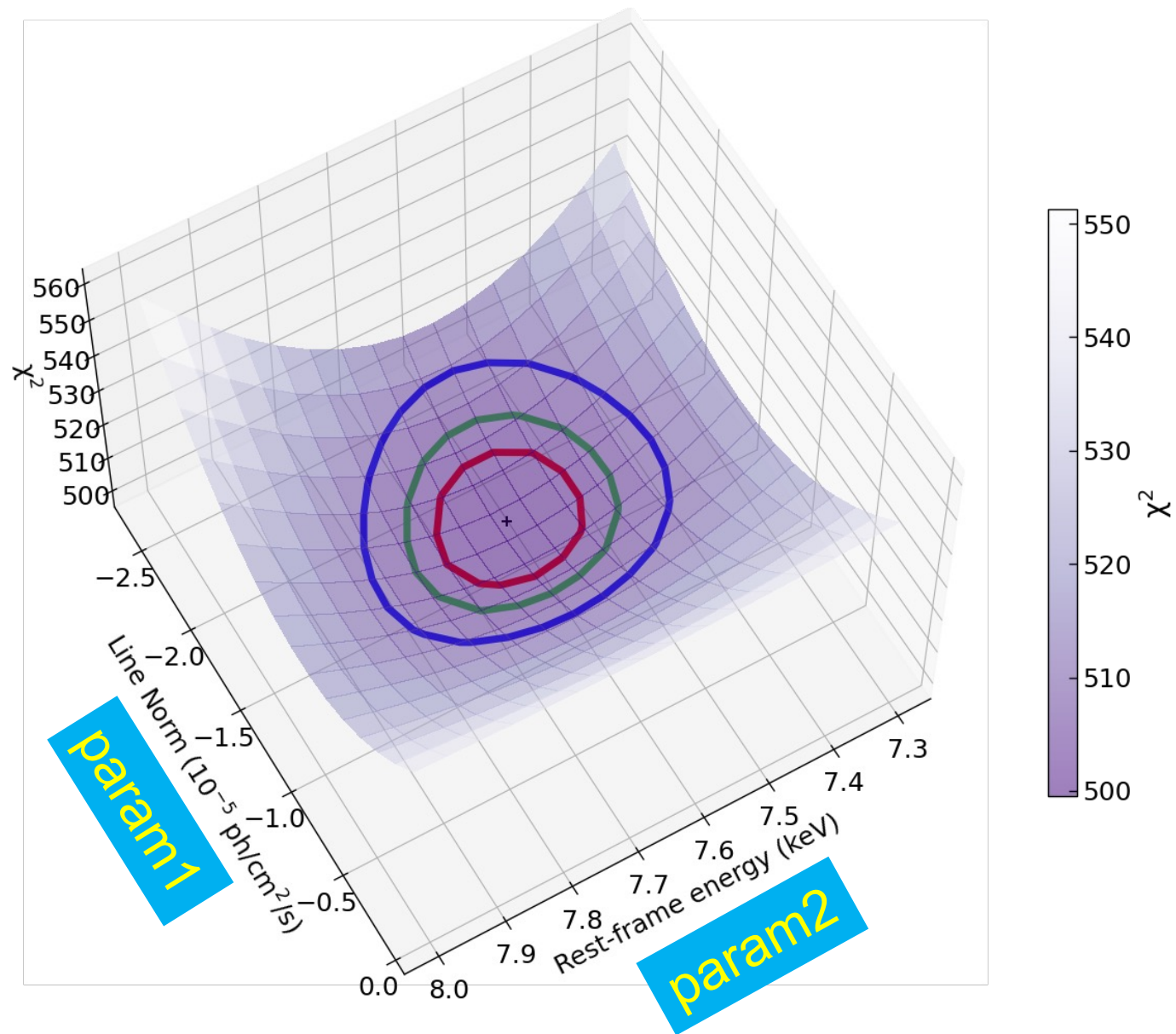
We will further discuss this Δ later in the slides



Δ depends only on the number of parameters involved in the fit (see previous slides)

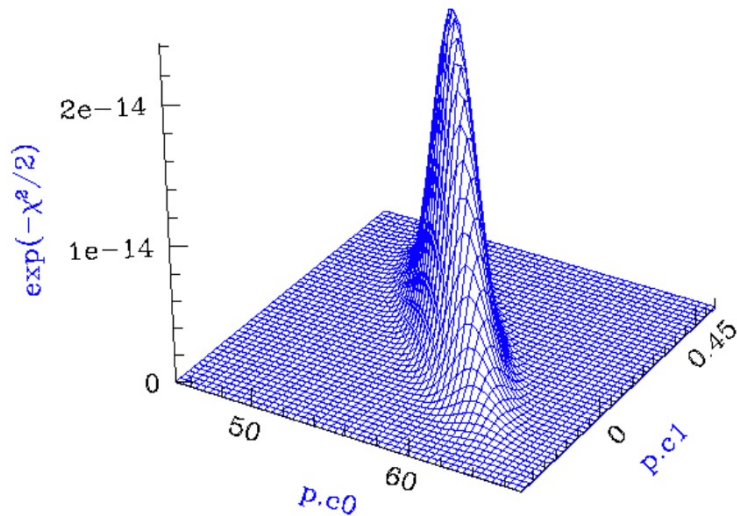
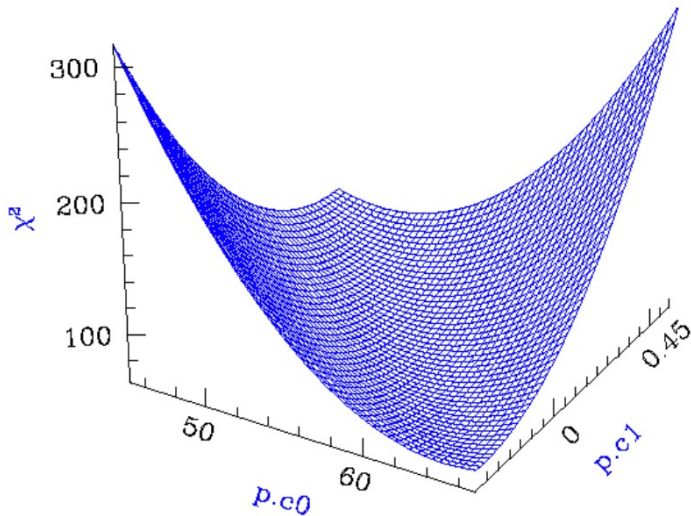
Avni 1976

CONSTANTS FOR CALCULATING CONFIDENCE REGIONS			
α (%)	q (NO. OF INTERESTING PARAMETERS)		
	1	2	3
68.....	1.00	2.30	3.50
90.....	2.71	4.61	6.25
99.....	6.63	9.21	11.30



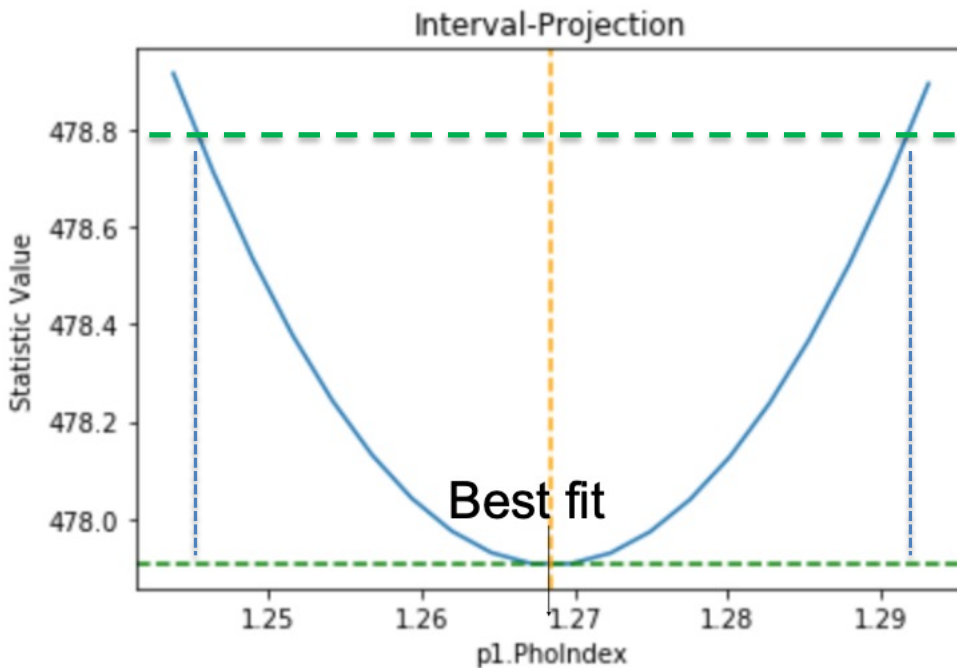
Courtesy of E. Bertola

Calculating Confidence Limits means Exploring the Parameter Space - Statistical Surface



Example of a “**well-behaved**” statistical surface in parameter space, viewed as a multi-dimensional paraboloid (χ^2 , top), and as a multi-dimensional Gaussian ($\exp(-\chi^2/2) \approx L$, bottom).

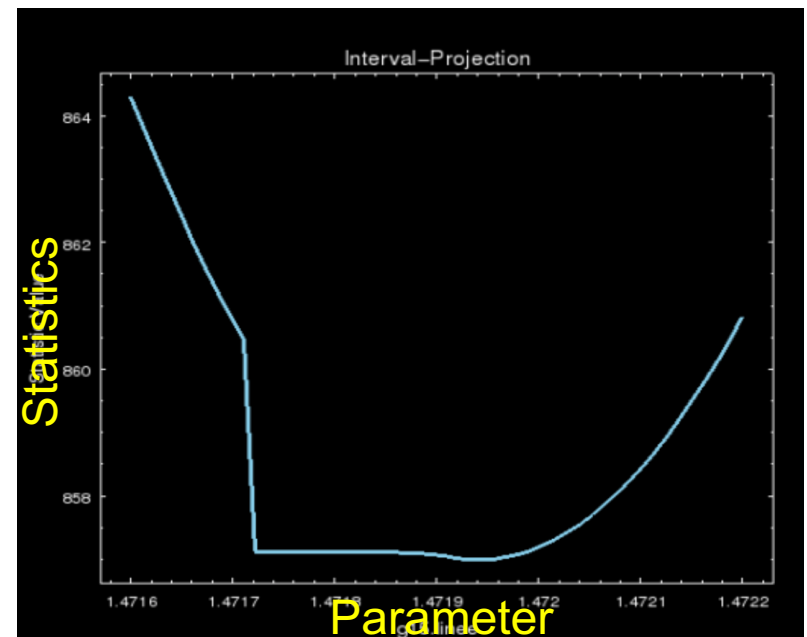
Statistics



Well-behaved surface
(Gaussian, one parameter)

$$\Delta\chi^2=1$$

Not well-behaved surface
(not Gaussian)



Parameter

Step 5b: towards the final fitting solution

xspect> newpar 2 = 10

We link the photon index of the secondary (soft) component to that of the primary one (as expected in case of scattering)

```
=====
Model phabs<1>(powerlaw<2> + zphabs<3>(zgauss<4> + powerlaw<5>)) Source No.: 1   Active/On
Model Model Component   Parameter   Unit      Value
par  comp
  1    1   phabs         nH          10^22     2.96000E-02   frozen
  2    2   powerlaw      PhoIndex      -0.392248   = p10
  3    2   powerlaw      norm          2.45395E-05   +/-  0.0
  4    3   zphabs         nH          10^22     22.2581      +/-  0.0
  5    3   zphabs         Redshift      6.00000E-02   frozen
  6    4   zgauss         LineE         keV        6.39238      +/-  0.0
  7    4   zgauss         Sigma         keV        1.00000E-02   frozen
  8    4   zgauss         Redshift      6.00000E-02   frozen
  9    4   zgauss         norm          1.08538E-05   +/-  0.0
 10    5   powerlaw      PhoIndex      -0.392248   +/-  0.0
 11    5   powerlaw      norm          4.82903E-05   +/-  0.0
=====
```

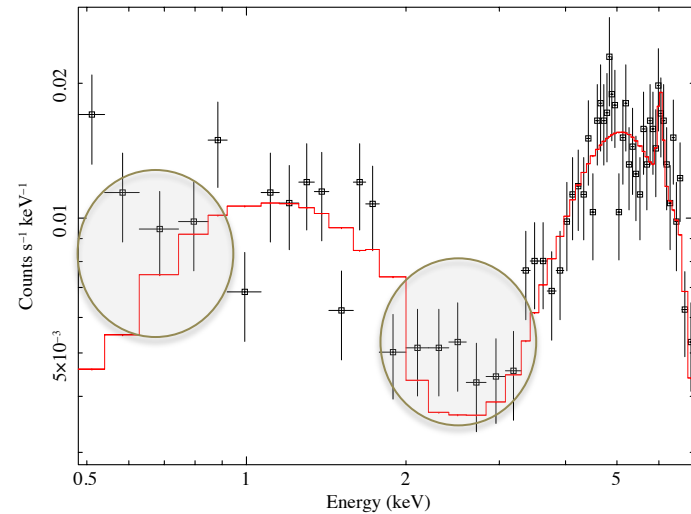
xspect> fit 100

```
=====
Model phabs<1>(powerlaw<2> + zphabs<3>(zgauss<4> + powerlaw<5>)) Source No.: 1   Active/On
Model Model Component   Parameter   Unit      Value
par  comp
  1    1   phabs         nH          10^22     2.96000E-02   frozen
  2    2   powerlaw      PhoIndex      0.935292     = p10
  3    2   powerlaw      norm          2.35020E-05   +/-  1.69263E-06
  4    3   zphabs         nH          10^22     37.6379      +/-  2.73295
  5    3   zphabs         Redshift      6.00000E-02   frozen
  6    4   zgauss         LineE         keV        6.39929      +/-  4.51006E-02
  7    4   zgauss         Sigma         keV        1.00000E-02   frozen
  8    4   zgauss         Redshift      6.00000E-02   frozen
  9    4   zgauss         norm          1.43843E-05   +/-  5.6
 10    5   powerlaw      PhoIndex      0.935292     +/-  0.1
 11    5   powerlaw      norm          6.78472E-04   +/-  1.8
=====
```

Model: pha(po+zpha
(zgauss+po+))
 $\Gamma_1 = \Gamma_2$

- Some residuals in the soft band and around 2 keV, where the soft and hard components 'connects' each other
- The photon index is still (nominally) lower than expected \rightarrow reflection component needed (but not accounted for in this tutorial)

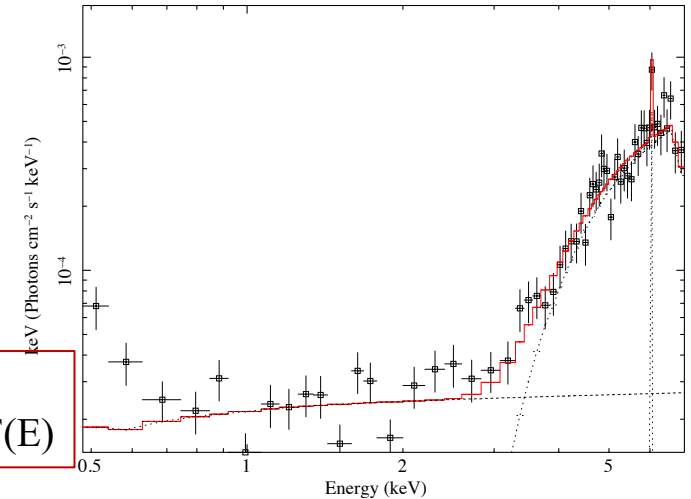
xspec> plot ldata



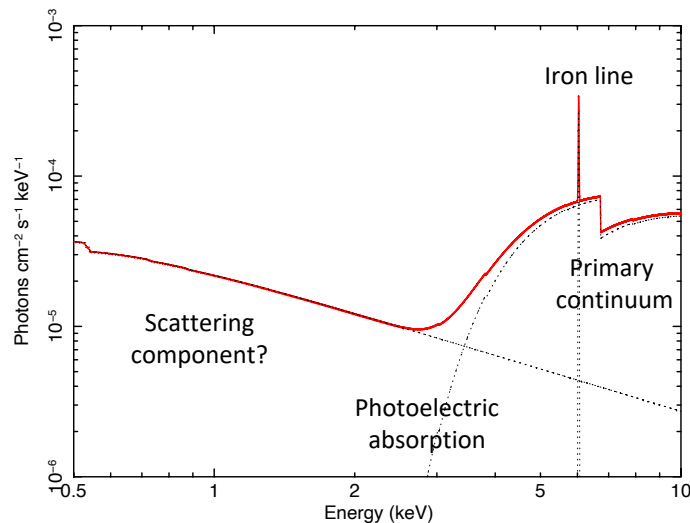
Convolution with
the response
matrix

Unfolded
spectrum in $E F(E)$

xspec> plot eeufs



xspec> plot model



Step 5c: estimate of parameters uncertainties

To compute errors: *error* and *uncertainty* commands in xspec

```
=====
```

Model	phabs<1>	*powerlaw<2>	+ zphabs<3>	(zgauss<4>	+ powerlaw<5>)	Source	No
Model	Model	Component	Parameter	Unit	Value		
par	comp						
1	1	phabs	nH	10 ²²	2.96000E-02	frozen	
2	2	powerlaw	PhoIndex		0.935354	= p10	
3	2	powerlaw	norm		2.35026E-05	+/- 1.69262E-06	
4	3	zphabs	nH	10 ²²	37.6728	+/- 2.73288	
5	3	zphabs	Redshift		6.00000E-02	frozen	
6	4	zgauss	LineE	keV	6.39928	+/- 4.51013E-02	
7	4	zgauss	Sigma	keV	1.00000E-02	frozen	
8	4	zgauss	Redshift		6.00000E-02	frozen	
9	4	zgauss	norm		1.43840E-05	+/- 5.64652E-06	
10	5	powerlaw	PhoIndex		0.935354	+/- 0.137424	
11	5	powerlaw	norm		6.78558E-04	+/- 1.83102E-04	

These are the errors
at 1 σ for that
parameter

Fit statistic : Chi-Squared 73.33 using 60 bir

Test statistic : Chi-Squared 73.33 using 60 bir

Null hypothesis probability of 4.11e-02 with 54 degrees of freedom

$\Delta\chi^2$ as a Function of Confidence Level and Degrees of Freedom						
p	ν					
	1	2	3	4	5	6
68.3%	1.00	2.30	3.53	4.72	5.89	7.04
90%	2.71	4.61	6.25	7.78	9.24	10.6
95.4%	4.00	6.17	8.02	9.70	11.3	12.8
99%	6.63	9.21	11.3	13.3	15.1	16.8
99.73%	9.00	11.8	14.2	16.3	18.2	20.1
99.99%	15.1	18.4	21.1	23.5	25.7	27.8

xspec> error 4 4=number of the parameter, N_H here

Parameter	Confidence Range	(2.706)
4	33.101 42.8442	(-4.57177, 5.17145)

By default, xspec computes errors at the 90% confidence level (2.706) for one parameter of interest (Avni 1976; Lampton et al. 1976) – it is the Δ parameter seen before

Confidence	sigma	delta_chi-square	1 parameter of interest
68.3%	1.0	1.00	
90.0%	1.6	2.71	
95.5%	2.0	4.00	
99.0%	2.6	6.63	
99.7%	3.0	9.00	

Ex. 1: Error at **90%** confidence level
for one parameter of interest:
xspec> error **2.71** #param

Ex. 2: Error at **90%** confidence level
for two parameters of interest:
xspec> error **4.61** #param

Ex. 3: Error at **99%** confidence level
for one parameter of interest:
xspec> error **6.63** #param

1 parameter of interest: as only one parameter at each time would vary

Table entry for p is the critical value $(\chi^2)^*$ with probability p lying to its right.

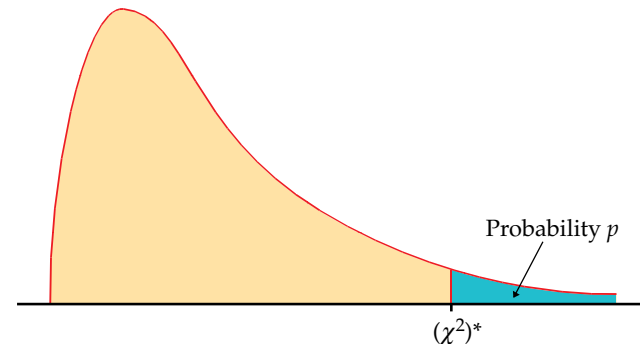


TABLE F												
χ^2 distribution critical values												
	Tail probability p											
df	.25	.20	.15	.10	.05	.025	.02	.01	.005	.0025	.001	.0005
1	1.32	1.64	2.07	2.71	3.84	5.02	5.41	6.63	7.88	9.14	10.83	12.12
2	2.77	3.22	3.79	4.61	5.99	7.38	7.82	9.21	10.60	11.98	13.82	15.20
3	4.11	4.64	5.32	6.25	7.81	9.35	9.84	11.34	12.84	14.32	16.27	17.73
4	5.39	5.99	6.74	7.78	9.49	11.14	11.67	13.28	14.86	16.42	18.47	20.00
5	6.63	7.29	8.12	9.24	11.07	12.83	13.39	15.09	16.75	18.39	20.51	22.11

Parameters of interest →

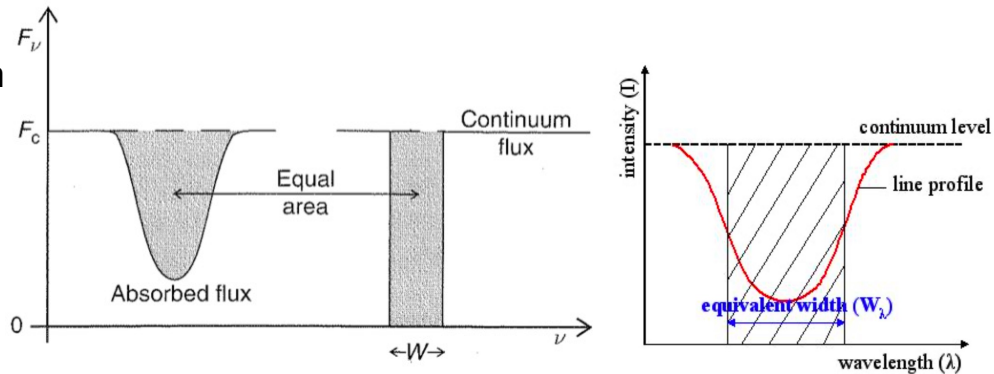
Uncertainties on the line EW measurement. I

Wavelength/frequency space definition [Angstrom/keV units]

EW is a measure of how prominent a line is (F_λ , F_ν) wrt. the continuum (F_C)

$$W_\lambda = \int_{\lambda_1}^{\lambda_2} \frac{F_C - F_\lambda}{F_C} d\lambda \quad \text{Units=Angstrom}$$

$$W_\nu = \int_{\nu_1}^{\nu_2} \frac{F_C - F_\nu}{F_C} d\nu \quad \text{Units=eV}$$



```
xspec> eqw 4
```

#=model component associated with the Gaussian line

Data group number: 1

Additive_group equiv width for Component 4: 0.100872 keV

```
xspec> eqw 4 err 100 90
```

EW including errors at 90% confidence level doing 100 trials

Data group number: 1

Additive group equiv width for Component 4: 0.100872 keV

Parameter distribution is derived from fit covariance matrix.

Equiv width error range: 0.0414912 - 0.184698 keV

EW=101 [41–185] eV

Uncertainties on the line EW measurement. II

Alternatively: assuming that the dominant contribution to the EW error comes from the line intensity (so, limited contribution from the uncertainty on the continuum emission), one can (1) compute the 90% error on the line normalization, (2) place the upper 90% value as line normalization and (3) type *eqw* again (without fitting), then (4) place the lower 90% value as line normalization and (5) type *eqw* again (without fitting)

```
=====
Model phabs<1>*powerlaw<2> + zphabs<3>(zgauss<4> + powerlaw<5>) Source No
Model Model Component Parameter Unit Value
par comp
  1 1 phabs nH 10^22 2.96000E-02 frozen
  2 2 powerlaw PhoIndex 0.935354 = p10
  3 2 powerlaw norm 2.35026E-05 +/- 1.69262E-06
  4 3 zphabs nH 10^22 37.6728 +/- 2.73288
  5 3 zphabs Redshift 6.00000E-02 frozen
  6 4 zgauss LineE keV 6.39928 +/- 4.51013E-02
  7 4 zgauss Sigma keV 1.00000E-02 frozen
  8 4 zgauss Redshift 6.00000E-02 frozen
  9 4 zgauss norm 1.43840E-05 +/- 5.64652E-06
 10 5 powerlaw PhoIndex 0.935354 +/- 0.137424
 11 5 powerlaw norm 6.78558E-04 +/- 1.83102E-04
```

xspec> error 9

```
9 4.95654e-06 2.36522e-05 (-9.42745e-06,9.2682e-06)
```

EW=101 [35–166] eV
Totally consistent with the
previous value



```
XSPEC12>ne 9 2.36522e-05
```

```
Fit statistic : Chi-Squared 76.24 using 60 bins.
```

```
Test statistic : Chi-Squared 76.24 using 60 bins.
```

```
Null hypothesis probability of 2.48e-02 with 54 degrees of freedom
```

```
Current data and model not fit yet.
```

```
XSPEC12>eqw 4
```

```
Data group number: 1
```

```
Additive group equiv width for Component 4: 0.165868 keV
```

```
XSPEC12>ne 9 4.95654e-06
```

```
Fit statistic : Chi-Squared 76.34 using 60 bins.
```

```
Test statistic : Chi-Squared 76.34 using 60 bins.
```

```
Null hypothesis probability of 2.43e-02 with 54 degrees of freedom
```

```
Current data and model not fit yet.
```

```
XSPEC12>eqw 4
```

```
Data group number: 1
```

```
Additive group equiv width for Component 4: 0.0347591 keV
```


Step 6: source flux and luminosity

xspec> flux 2 10 flux in the observed-frame 2–10 keV band
xspec> newpar 4 0 absorption set to 0
xspec> lum 2 10 0.06 luminosity in the rest-frame 2–10 keV band
 z=0.06

command *cosmo* to change the cosmology

```
[XSPEC12>flux 2 10
  Model Flux 0.00035807 photons (3.8799e-12 ergs/cm^2/s) range (2.0000 - 10.000 keV)
[XSPEC12>ne 4 0

Fit statistic   : Chi-Squared                327095.1      using 60 bins.

Test statistic  : Chi-Squared                327095.1      using 60 bins.
Null hypothesis probability of 0.0e+00 with 54 degrees of freedom
Current data and model not fit yet.
[XSPEC12>lum 2 10 .06
Model Luminosity 8.2876e+43 ergs/s (2.0000 - 10.000 keV rest frame)
(z = 0.0600 H0 = 70.0 q0 = 0.00 Lambda0 = 0.730)
```

- ☐ **Flux** is *observed* (typically, no correction for absorption) and in the *observed-frame band* (units: erg/cm²/s)
- ☐ **Luminosity** needs to be *intrinsic/de-absorbed* (so, put $N_H = 0$ and do **not** fit again) and is reported in the *source rest frame* (units: erg/s)

Uncertainties on fluxes and luminosities. I

`xspec> flux 2 10 error 100 90` (100 trials to compute the error at 90% c.l., 2–10 keV band)

```
XSPEC12>flux 2 10 error 100 90
```

Parameter distribution is derived from fit covariance matrix.

Model Flux 0.00035807 photons (3.8799e-12 ergs/cm^2/s) range (2.0000 – 10.000 keV)

Error range 0.0003102 – 0.0003806 (3.310e-12 – 4.166e-12) (90.00% confidence)

$$F(2-10 \text{ keV}) = 3.9 [3.3-4.2] \times 10^{-12} \text{ erg/cm}^2/\text{s}$$

For what concerns the luminosity, we cannot apply the same method: if we place $N_H=0$ to have intrinsic values, xspec requires the data to be fit again



cflux and *clumin* commands

Uncertainties on fluxes and luminosities. II

- **cflux** and **clumin** are multiplicative model components.
- cflux (clumin) are placed in front of model component(s). At least one of the additive models should have the normalization fixed (frozen) to a non-zero value.
- cflux/clumin must be treated as the other model components (as part of the fit)
- Example: model pha***cflux***zpha*pow

```
xspec> addcomp 3 cflux
```

```
Input parameter value, delta, min, bot, top, and max values for ...
      0.5      -0.1(      0.005)      0      0      1e+06      1e+06
4:cflux:Emin>2
      10      -0.1(      0.1)      0      0      1e+06      1e+06
5:cflux:Emax>10
      -12      0.01(      0.12)     -100     -100      100      100
6:cflux:lg10Flux>-12
```

Setting the range (2-10 keV)
where the flux is computed

```
xspec> freeze 14      fix the powerlaw normalization (as required by the cflux tool)
```

```
xspec> fit 100
```

Uncertainties on fluxes and luminosities. III

=====

Model phabs<1>*powerlaw<2> + cflux<3>*zphabs<4>(zgauss<5> + powerlaw<6>)						
Model	Model	Component	Parameter	Unit	Value	
par	comp					
1	1	phabs	nH	10^22	2.96000E-02	frozen
2	2	powerlaw	PhoIndex		0.935615	= p13
3	2	powerlaw	norm		2.35038E-05	+/- 1.69261E-06
4	3	cflux	Emin	keV	2.00000	frozen
5	3	cflux	Emax	keV	10.0000	frozen
6	3	cflux	lg10Flux	cgs	-11.4505	+/- 2.32119E-02
7	4	zphabs	nH	10^22	37.6633	+/- 2.73227
8	4	zphabs	Redshift		6.00000E-02	frozen
9	5	zgauss	LineE	keV	6.39925	+/- 4.50821E-02
10	5	zgauss	Sigma	keV	1.00000E-02	frozen
11	5	zgauss	Redshift		6.00000E-02	frozen
12	5	zgauss	norm		1.43960E-05	+/- 6.89801E-06
13	6	powerlaw	PhoIndex		0.935615	+/- 0.137435
14	6	powerlaw	norm		6.79101E-04	frozen

Boundaries for the computation

Emin=2 keV

Emax=10 keV

lg10Flux is the log of the flux in the observed energy range Emin-Emax

The **powerlaw normalization** has been **frozen**

Fit statistic : Chi-Squared 73.33 using 60 bins.

Test statistic : Chi-Squared 73.33 using 60 bins.

Null hypothesis probability of 4.11e-02 with 54 degrees of freedom

XSPEC12>error 6

Parameter Confidence Range (2.706)

6 -11.4923 -11.41 (-0.0418036, 0.0405441)

$\text{LogF}_{2-10 \text{ keV}} = -11.45 [-11.49, -11.41] \rightarrow F_{2-10 \text{ keV}} = 3.5 [3.2-3.9] \times 10^{-12} \text{ erg/cm}^2/\text{s}$
consistent with previous value within errors

Uncertainties on fluxes and luminosities. IV

For what concerns the X-ray luminosity, it must be computed as *intrinsic* (de-absorbed), i.e. placing $N_H=0$ without subsequent fitting the spectrum. However, errors can be computed only using **clumin**. It works similarly to *cflux*.

Example: model pha*zpha*clumin*pow

xspect> addcomp 5 clumin

xspect> [...]; fit 100

```
=====
Model phabs<1>*powerlaw<2> + zphabs<3>(zgauss<4> + clumin<5>*powerlaw<6>) :
Model Model Component Parameter Unit Value
par comp
 1 1 phabs nH 10^22 2.96000E-02 frozen
 2 2 powerlaw PhoIndex 0.935227 = p14
 3 2 powerlaw norm 2.35016E-05 +/- 1.69269E-06
 4 3 zphabs nH 10^22 37.6737 +/- 2.73077
 5 3 zphabs Redshift 6.00000E-02 frozen
 6 4 zgauss LineE keV 6.39933 +/- 4.51252E-02
 7 4 zgauss Sigma keV 1.00000E-02 frozen
 8 4 zgauss Redshift 6.00000E-02 frozen
 9 4 zgauss norm 1.43828E-05 +/- 5.64716E-06
10 5 clumin Emin keV 2.00000 frozen
11 5 clumin Emax keV 10.0000 frozen
12 5 clumin Redshift 6.00000E-02 frozen
13 5 clumin lg10Lum cgs 43.8978 +/- 3.64824E-02
14 6 powerlaw PhoIndex 0.935227 +/- 0.137412
15 6 powerlaw norm 6.79101E-04 frozen
```

Boundaries for the computation

Emin=2 keV

Emax=10 keV

lg10Lum is the log of the luminosity in the rest-frame energy range

Emin-Emax

The **powerlaw normalization** has been **frozen**

Fit statistic : Chi-Squared 73.33 using 60 bins.

Test statistic : Chi-Squared 73.33 using 60 bins.

Null hypothesis probability of 4.11e-02 with 54 degrees of freedom

[XSPEC12]>error 13

Parameter Confidence Range (2.706)
13 43.8227 43.9725 (-0.0749676,0.0748433)

$$\text{Log}L_{2-10 \text{ keV}} = 43.90 [43.82 - 43.97]$$

$$\rightarrow L_{2-10 \text{ keV}} = 7.9 [6.6 - 9.3] \times 10^{43} \text{ erg/s}$$

Step 7: save data+model and 'recover' all in XSPEC later

To save the current data + model you may use the command

```
xspec> save all po_zpha_po_zgauss
```

A file po_zpha_po_zgauss.xcm is saved with model and data (name these files properly!)

To recover the settings + data + model later, you can use the command

```
xspec> @po_zpha_po_zgauss.xcm
```

```
xspec> fit
```

XSPEC will ask you to fit the data again

Other possibly useful commands – some already discussed

in XSPEC

- `setplot rebin #1 #2` (to rebin the data; #1 indicates the number of σ)
- `show all`
- `show files`
- `show notice`
- `script filename` [save all the commands in a file (filename here; default: `xspec.xcm`)]
- `save model bestmodel.xcm` (save only the best fit model, without the data)
- `setplot command redshift #` (set the energy axis to redshift # of the source)
- `setplot background; plot` (plot the background; to remove it: `setplot noback; plot`)

In IPLOT (plotting environment for XSPEC)

`xspec> iplot`

- `time off` (to remove the date in the bottom-right part of the plot)
- `csize 2` (character size)
- `msize` (marker size)
- `label top` (title of the plot)
- `label filename` (title of the file)
- `hardcopy nomefile.ps/cps` (save a figure)
- `plot`
- `wen namefile` [writes two files (`.qdp` and `.pco`), one with data and the other with plot settings]