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 6.32.1 (August 2023) – xspec V12.13.1
  https://heasarc.gsfc.nasa.gov/docs/software/heasoft/

- Supported architectures:
  - macOS
  - PC Linux – Ubuntu, Fedora, Redhat Enterprise

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

xspec

```
xspec> data 3C33_r3_c20.pi
xspec> ignore bad
xspec> ignore **-0.3 7.-**

xspec> cpd /xw
xspec> plot ldata
xspec> 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 onboard 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
```

Fraction of Src counts/Total counts

loaded back and response files

(Total) Data counts

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

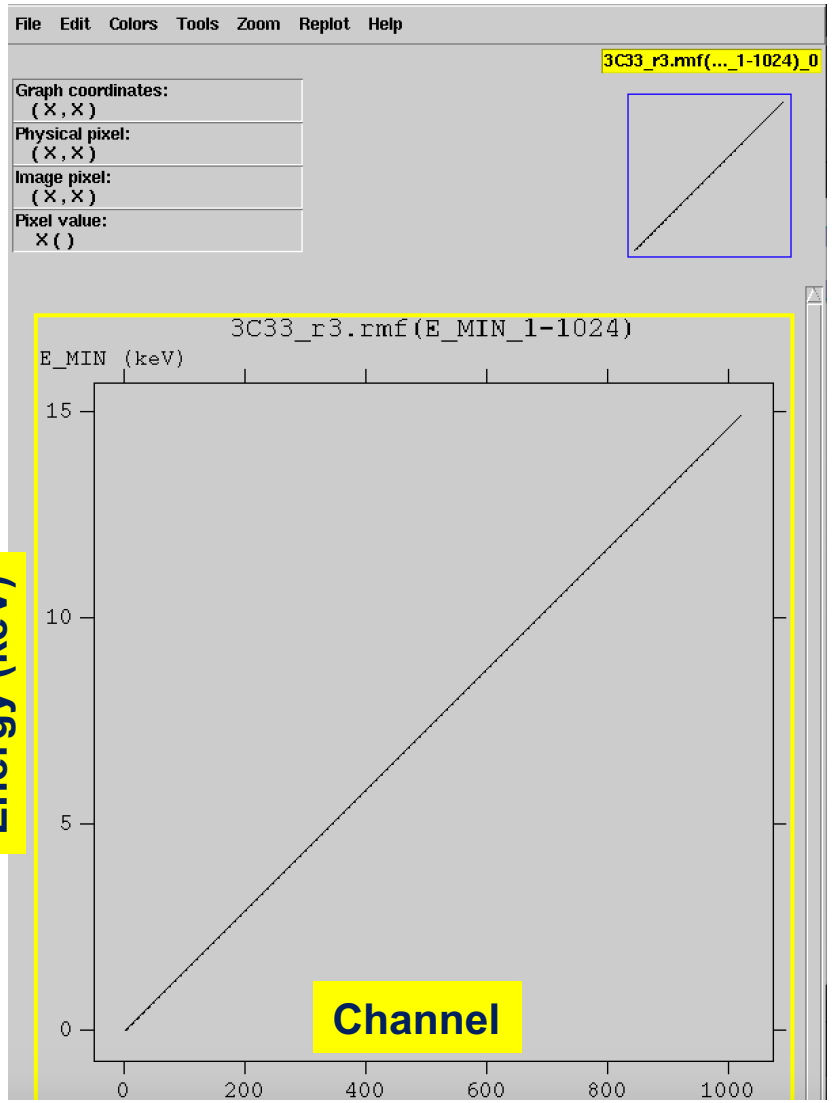
- fv 3C33_r3.rmf

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

Select	CHANNEL	E_MIN	E_MAX
	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



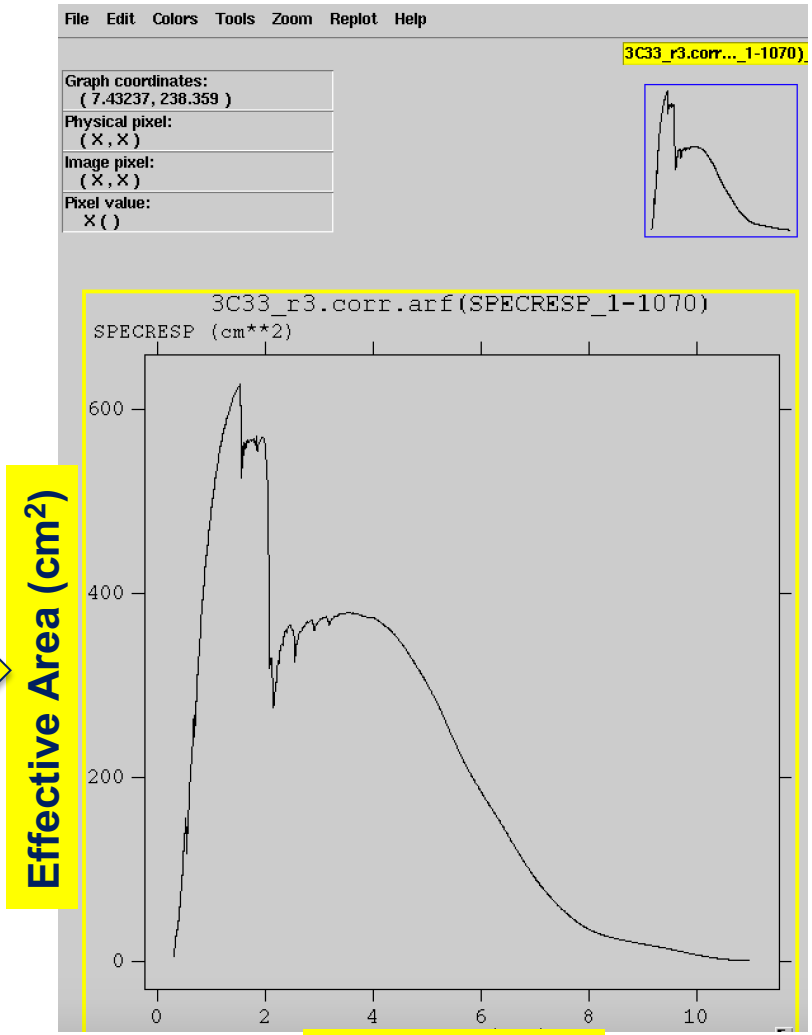
Response matrices: ARF

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

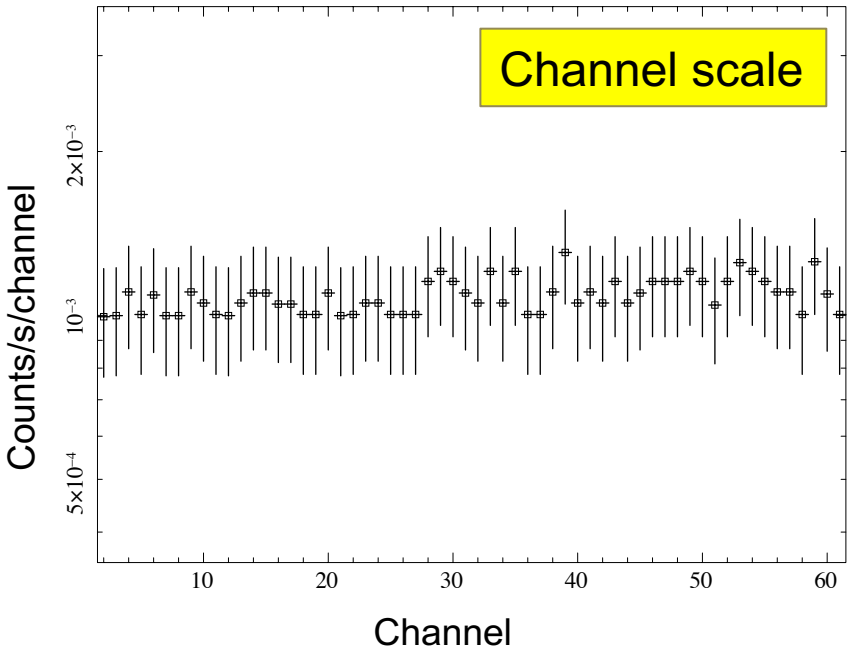
Select	ENERG_LO	ENERG_HI	SPECRESP	PSF_FRAC
All	1E	1E	1E	1D
Invert	keV	keV	cm**2	
	Modify	Modify	Modify	Modify
1	3.000000E-01	3.100000E-01	3.886596E+00	9.729960747434E-01
2	3.100000E-01	3.200000E-01	1.144929E+01	9.729424863851E-01
3	3.200000E-01	3.300000E-01	1.601507E+01	9.728888978671E-01
4	3.300000E-01	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

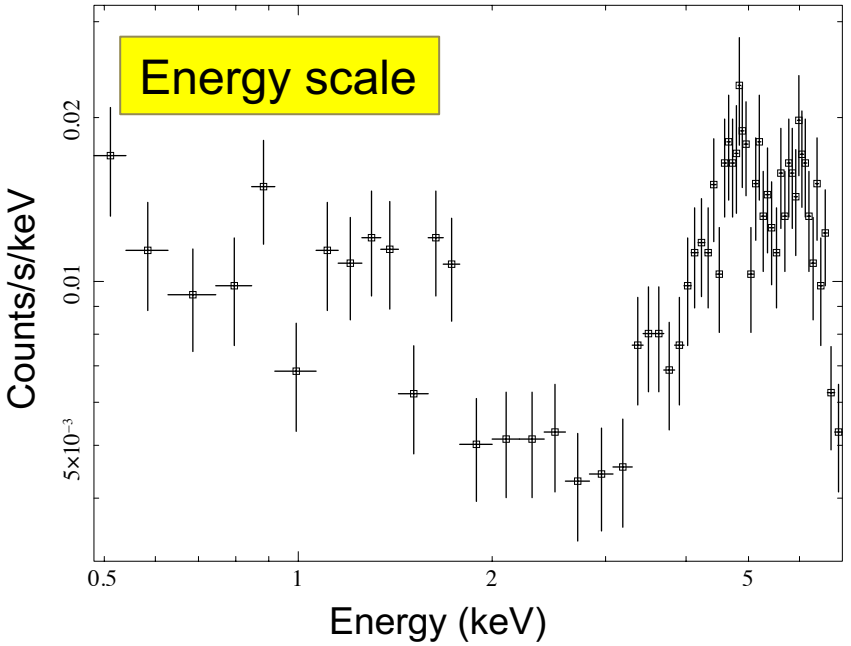


PSF_FRAC: a sort of aperture correction (see EEF concept)

`xspec>` setplot energy

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



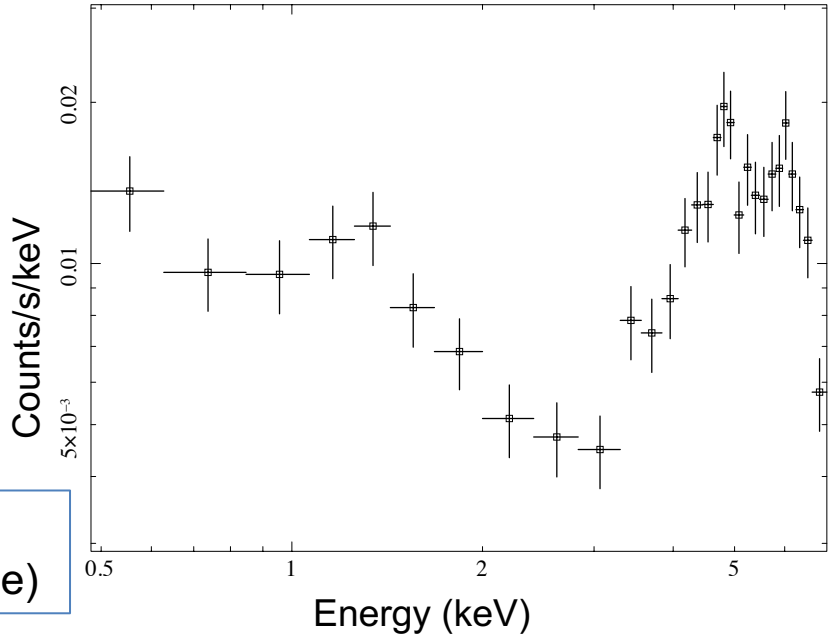


`xspec>` setplot rebin 5 12

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)

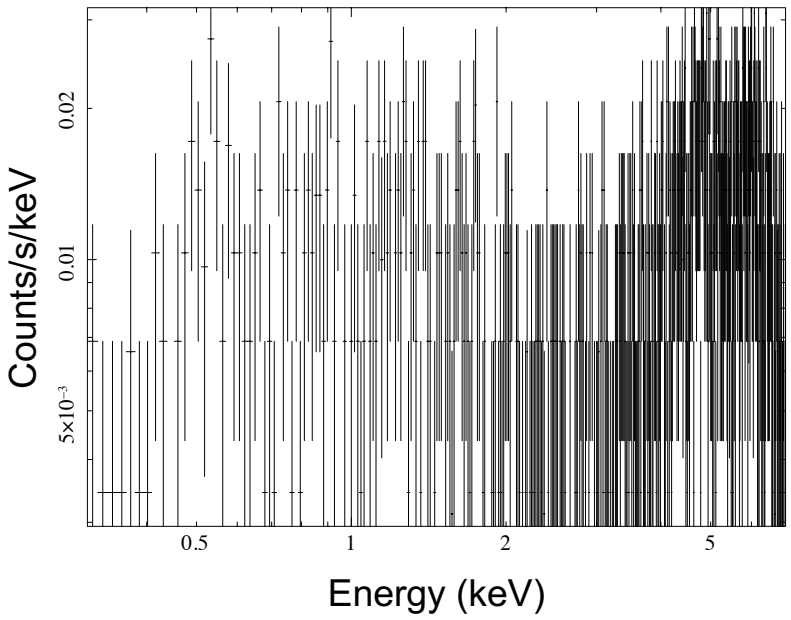
What does ‘binning’ (grouping) mean?

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)

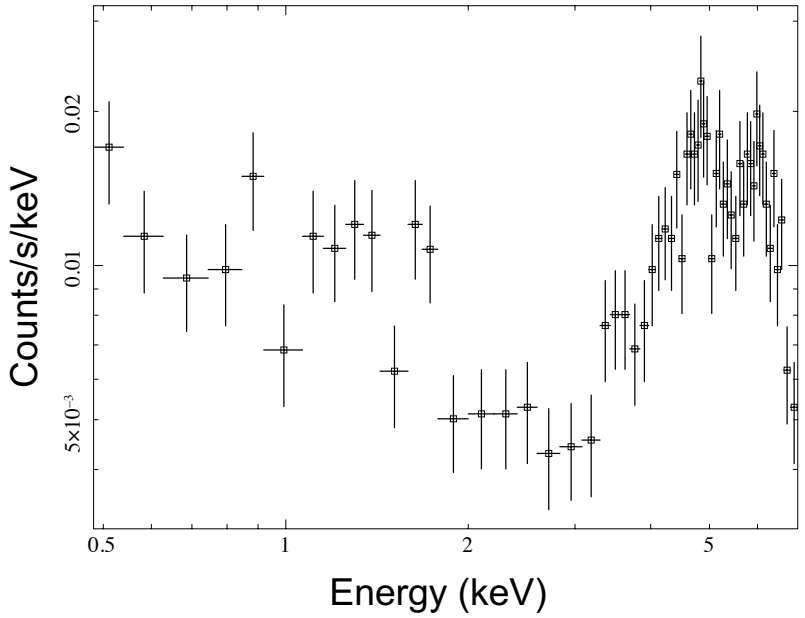
Using the ftool *grppha* (or similar), we can require that each spectral bin contains at least a given number of counts (see step 1a)

“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

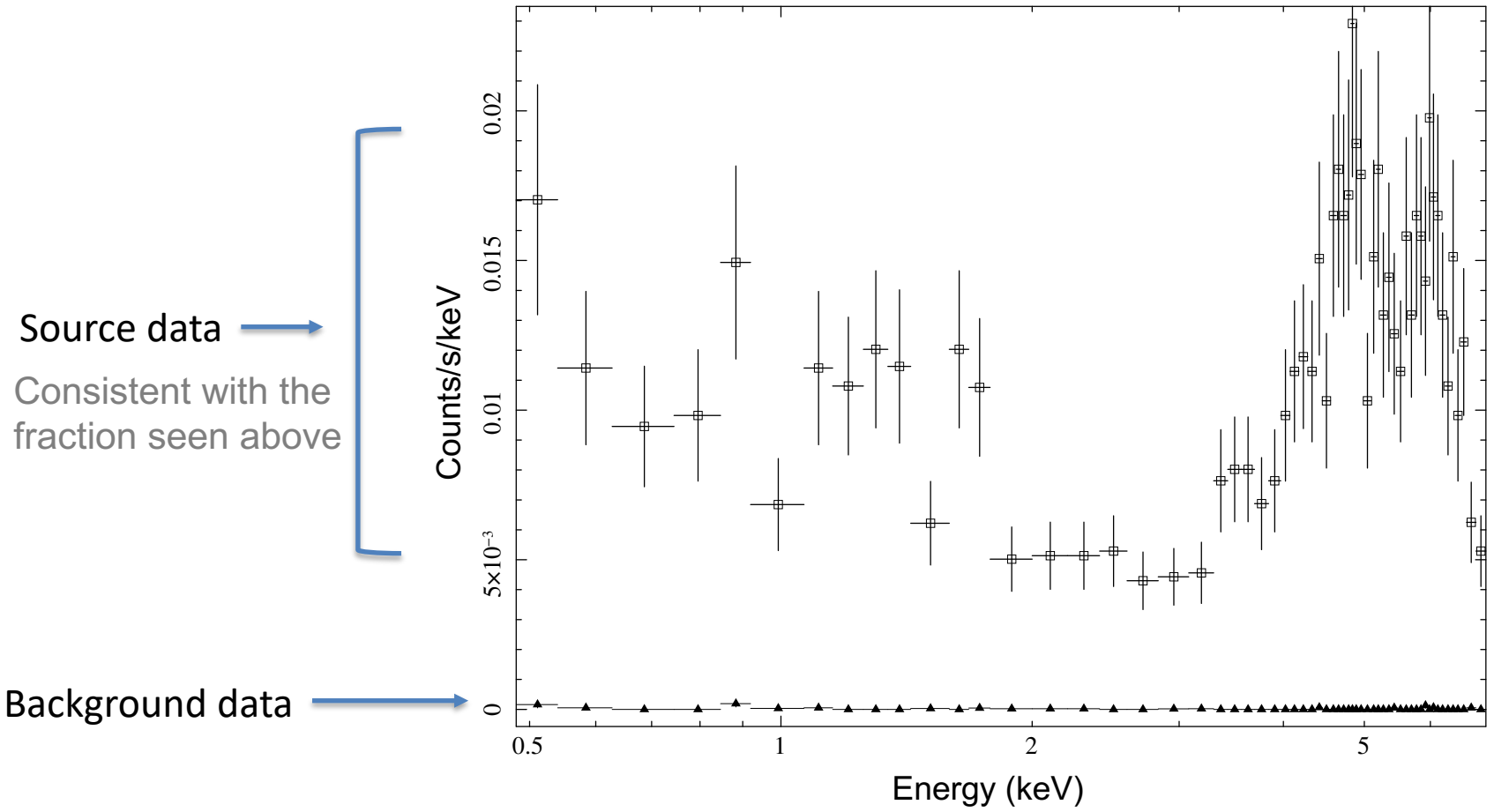
Source vs. background data

```
xspec> setplot command r y
xspec> setplot background
xspec> plot
xspec> setplot noback
```

Rescale the y axis

Plot source and background data

Go back and plot only the source data



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	nteea	nthComp	optxagn	optxagnf	pegpwrlw
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	vnpshock	vpshock	vraymond	vrnei
vsedov	vvapec	vvgnei	vvnei	vvnpshock	vvpshock
vvrnei	vvsedov	zagauss	zbbody	zbremss	zgauss
zpowerlw					

Multiplicative models

SSS_ice	TBabs	TBgrain	TBvarabs	absori	acisabs
cabs	constant	cyclabs	dust	edge	expabs
expfac	gabs	heilin	highecut	hrefl	lyman
notch	pcfabs	phabs	plabs	pwab	recorn
redden	smedge	spexpcut	spline	swind1	uvred
varabs	vphabs	wabs	wndabs	xion	zTBabs
zbabs	zdust	zedge	zhighect	zigm	zpcfabs
zphabs	zredden	zsmdust	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      rgsxsrc
      simpl      zashift      zmshift

Mixing Models:
      ascac       projct       suzpsf       xmmpsf

Pile-up Models:
     pileup
```

Example:
model phabs*(powerlaw+gaussian)

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

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

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

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

        >> 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
```

Your source's coordinates (3C33 here)

$N_{H,Gal}=2.96\times10^{20}$ 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
               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
========================================================================
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
------------------------------------------------------------------------


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.
```

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

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

parameter number

number of the component

Model: pha(po)

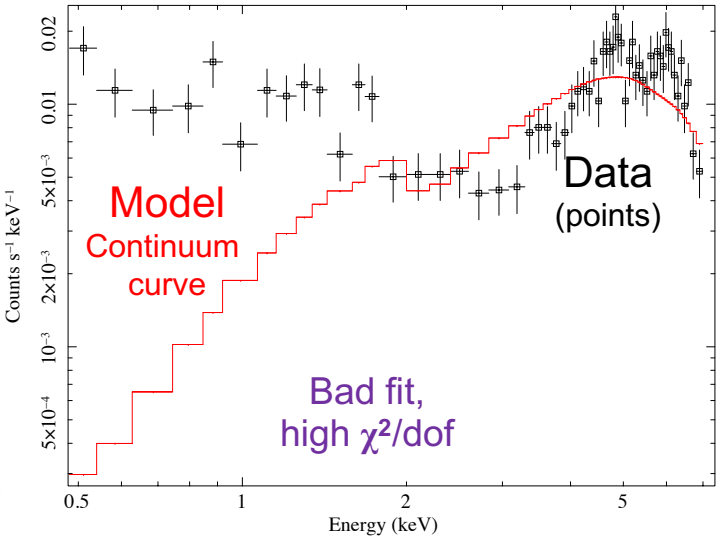
```
xspec> query yes
xspec> renorm
xspec> fit 100
```

to allow a preliminary "adjustment"

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; see also tutorial on Statistics)

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

Model: pha(po)

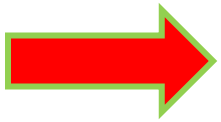
To evaluate the goodness of the fit: the χ^2 statistical test

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

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

- S_i = src counts in the I={1,…,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 the 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 ⇔ Gaussian statistics
Unbinned data, C-statistics ⇔ Poisson statistics

χ^2 in a nutshell

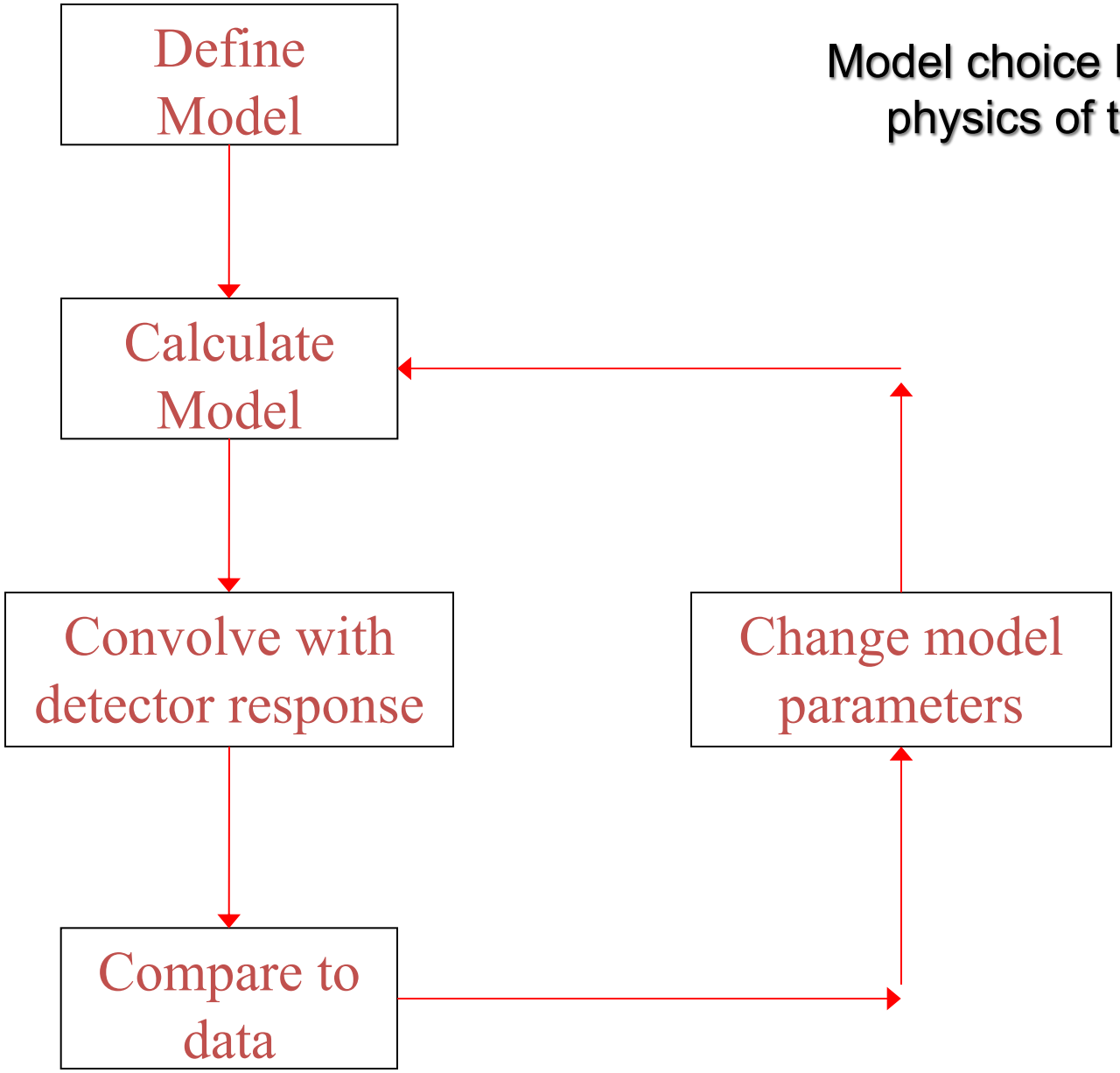
Reduced χ^2 large ←→ P(χ^2) small

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

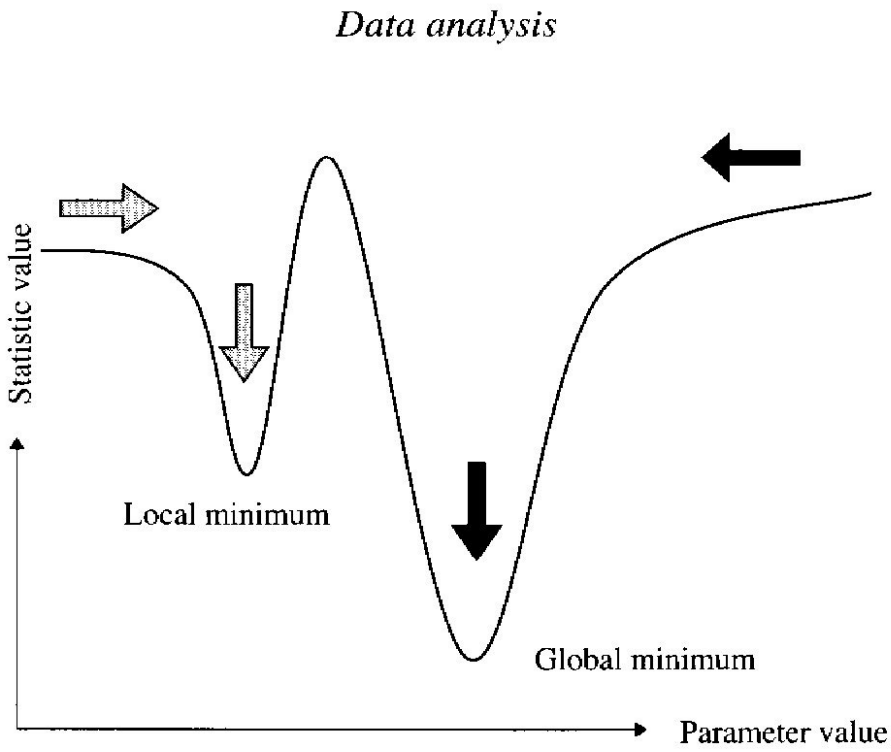
Reduced χ^2 small ←→ P(χ^2) large

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

Forward-fitting algorithm



Global vs. local minimum



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 miminum, 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?

Model: pha(po+po)

xspec> fit 100

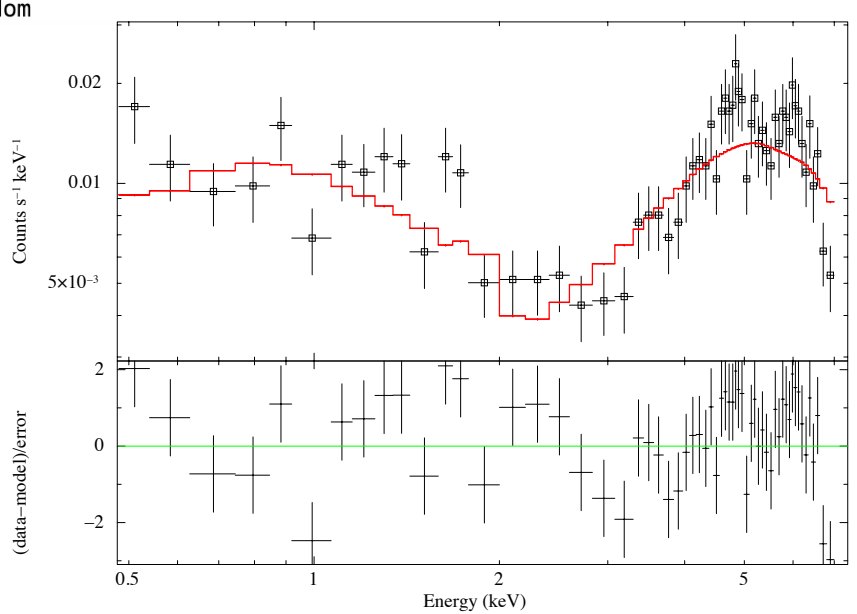
```
========================================================================
Model phabs<1>(powerlaw<2> + powerlaw<3>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   phabs      nH         10^22    2.96000E-02  frozen
   2    2   powerlaw   PhoIndex            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
------------------------------------------------------------------------

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
```

ONE QUESTION:
are all the derived parameters physically acceptable?

We will come back on this later…

xspec> plot ldata delchi

delchi = (data-model)/error



The χ^2 /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 σ=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.

========================================================================
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

------------------------------------------------------------------------
```

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

→ After the inclusion of N_H,is the newly derived photon index (parameter 6, component 4) more consistent with what is expected in case of an AGN (Γ=1.8-2)?

Model: pha(po+zpha(po))

xspec> fit 100

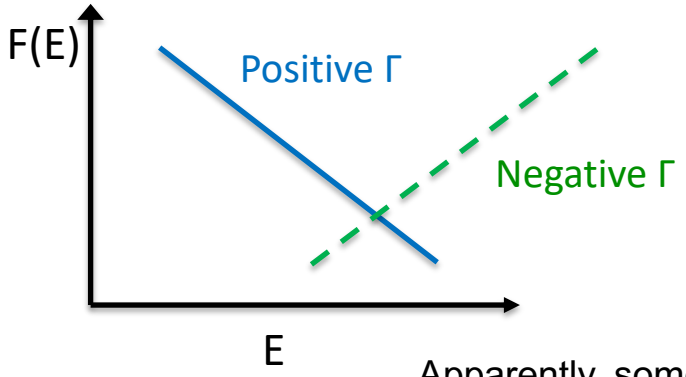
```
========================================================================
Model phabs<1>(powerlaw<2> + zphabs<3>*powerlaw<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   phabs      nH         10^22    2.96000E-02  frozen
   2    2   powerlaw   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
```

χ^2/dof=76.0/55 now → improvement in the fit

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

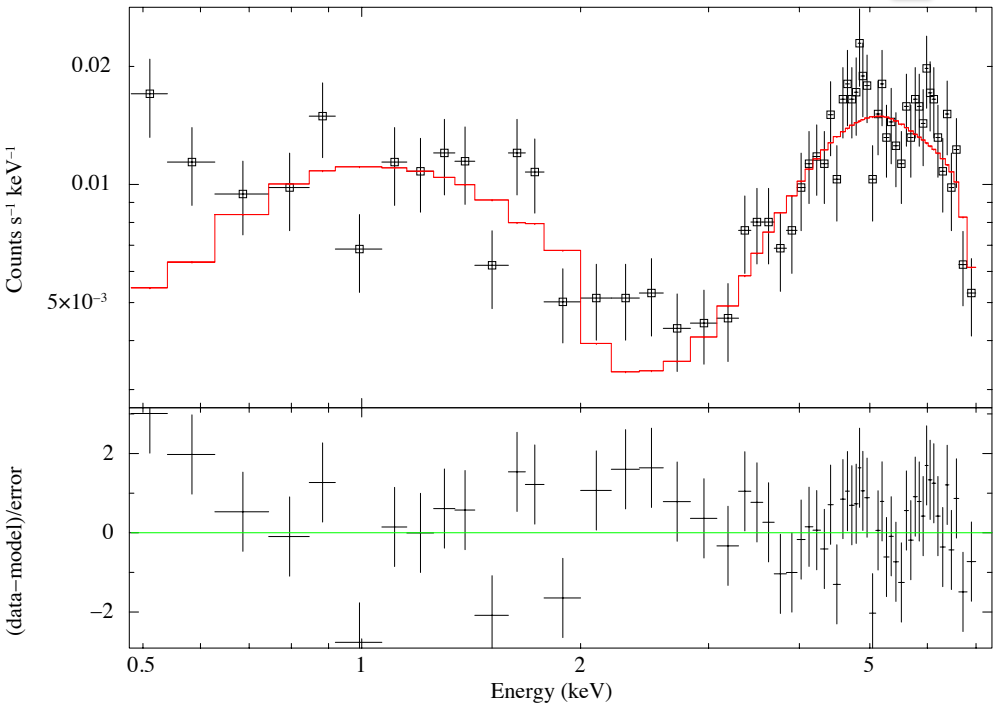
→ likely, the hard-band powerlaw and the column density are *degenerate parameters*, hence constraining both over the limited hard band of Chandra is challenging

VIABLE 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 5b)



Apparently, some line-like residuals around 6 keV

xspec> plot ldata delchi



Model: pha(po+zpha(po))

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

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

------------------------------------------------------------------------
```

I have included a narrow (σ=10 eV, fixed) line at the expected rest-frame energy of the neutral iron Kα transition (6.4 keV)

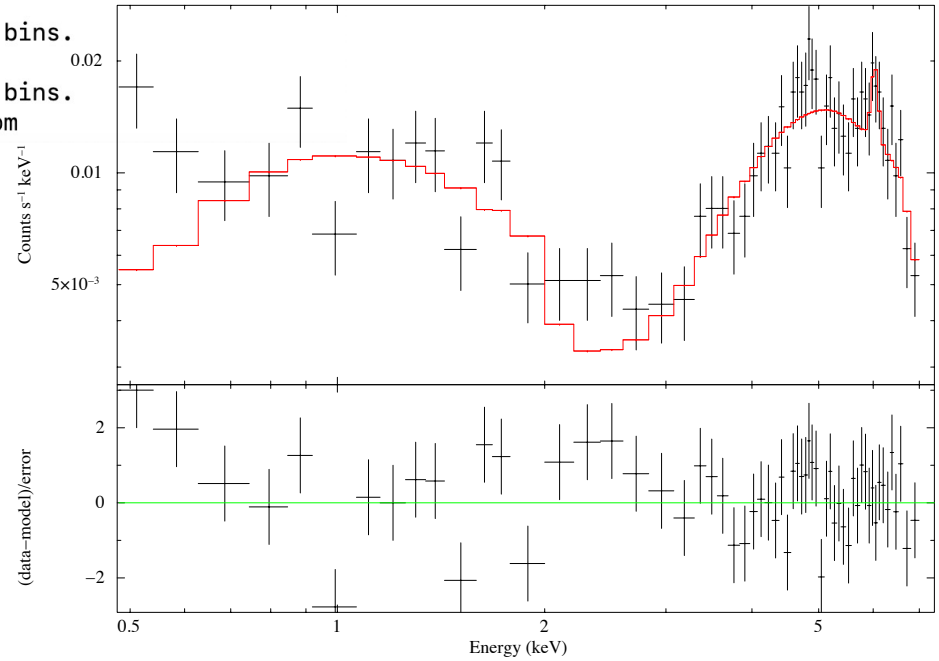
Model: pha(po+zpha(zgauss+po+))

xspec> 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
------------------------------------------------------------------------
```

xspec> plot ldata delchi

```
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

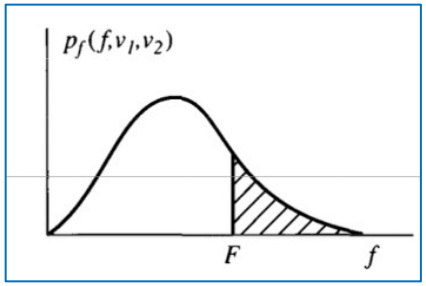
Model: pha(po+zpha(zgauss+po+))

Step 4: the F-test

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

- **Model 1**: double powerlaw + obscuration: χ^2 /dof=76.0/55
- **Model 2**: double powerlaw + obscuration + **iron emission line**: χ^2 /dof=69.7/53

$\Delta\chi^2/\Delta dof=6.3/2$



Large F value → low probability (of exceeding that value, see tables) → highly significant improvement due to the additional component (see also the lesson on Statistics)

```
xspec> ftest 69.7 53 76.0 55
```

χ^2 (model2) dof (model 2) χ^2 (model1) dof (model1)

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

→ The iron line has low significance: P(real line)=1−0.10095~0.90 → ~1.6σ

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

$$P_f(f;\upsilon_1,\upsilon_2) = \frac{\chi_1^2/\upsilon_1}{\chi_2^2/\upsilon_2}$$

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

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)

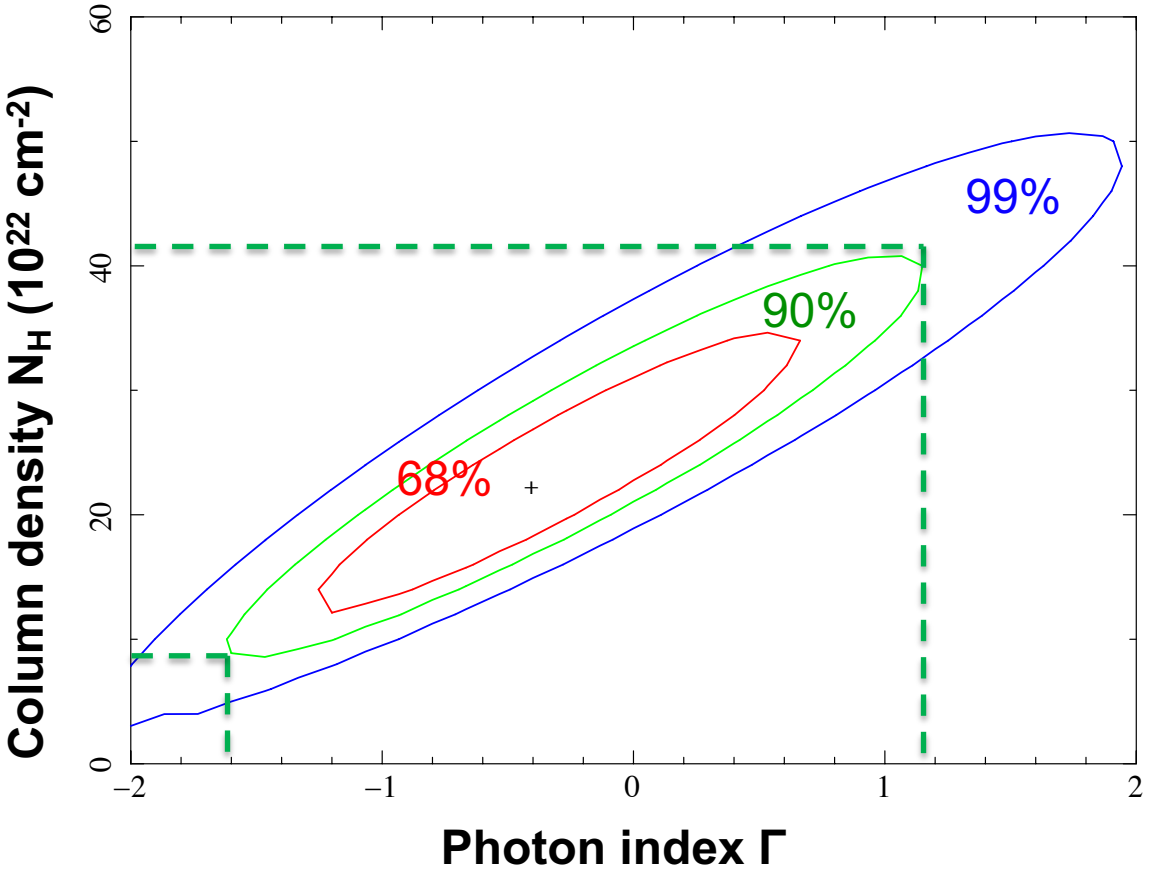
at each step
(in the process of 'moving' through the selected ranges of the two parameters)

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

Chi-Squared	Delta Chi-Squared	PhoIndex 10		nH 4	
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

→ Parameters involved in the fit

`xspec>` plot contour



- 90% confidence level: the photon index varies in the range ~ [−1.6, 1.2], while the column density varies in the interval ~ [9−41] ×10^{22} 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

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

- χ^2_α: χ^2 confidence limits (*values in steppar*)
- χ^2_{min}: minimim χ^2 value (best fit, *69.7 in the previous example*)
- $\Delta\chi^2$
- α: level of confidence
- ν: degrees of freedom

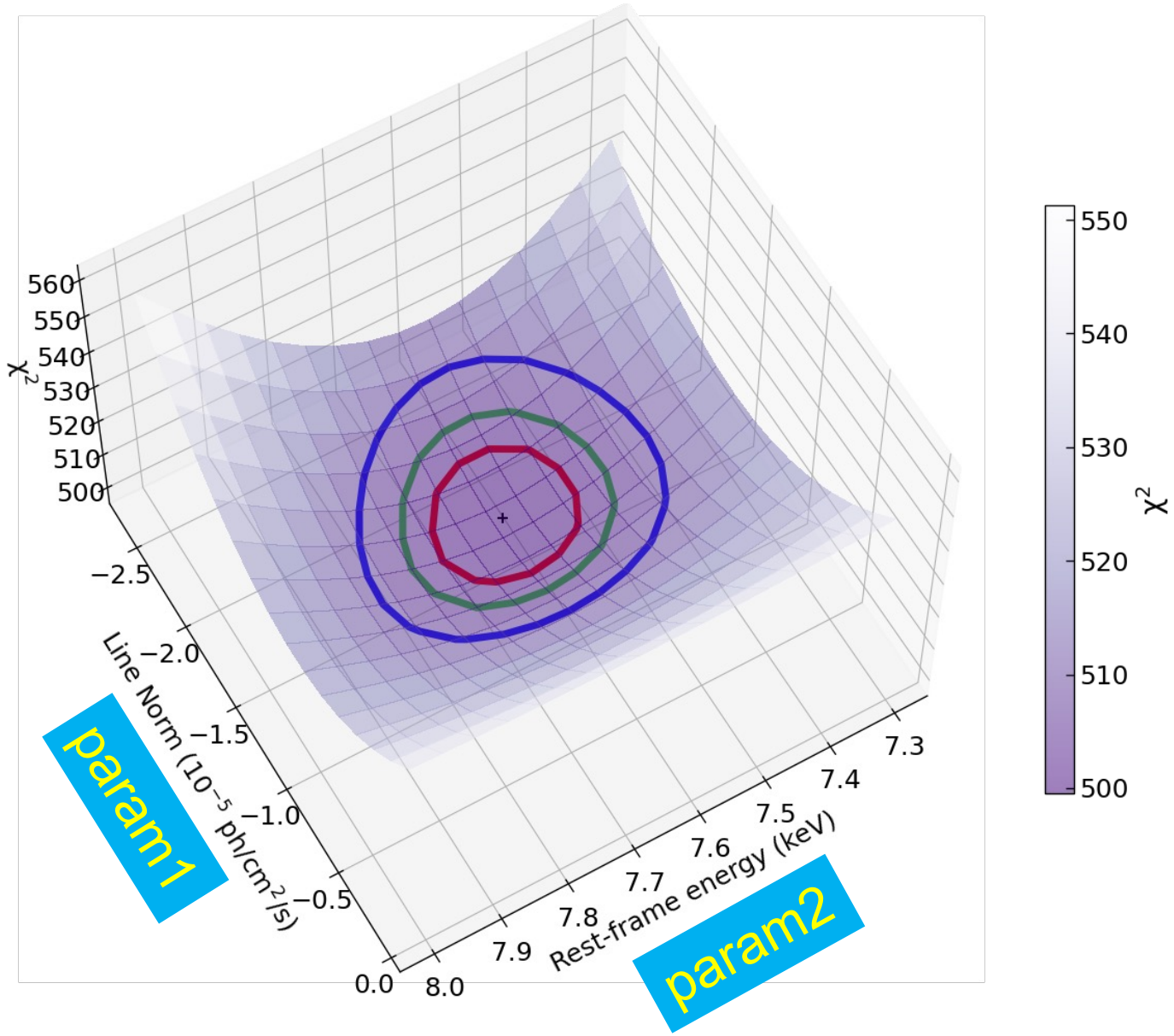
We will further discuss this Δ later in the slides

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

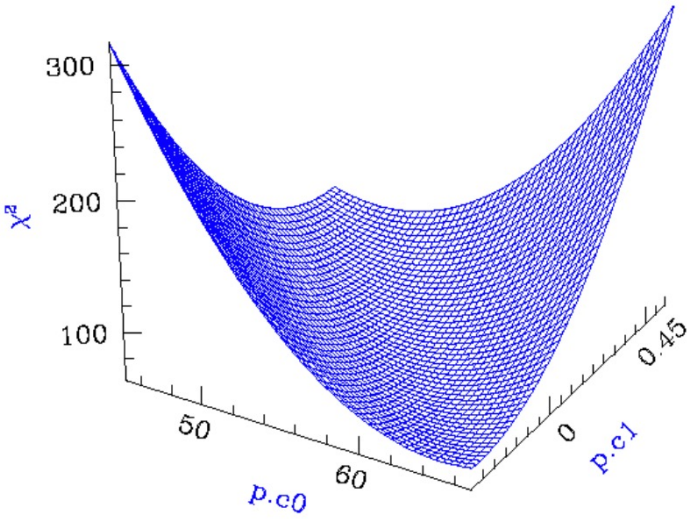
Avni 1976

CONSTANTS FOR CALCULATING CONFIDENCE REGIONS

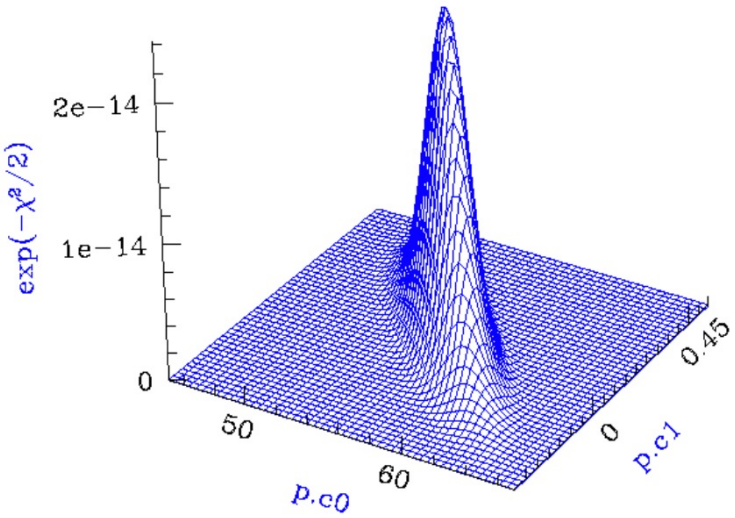
α (%)	q (No. of Interesting Parameters) 1	2	3
68.....	1.00	2.30	3.50
90.....	2.71	4.61	6.25
99.....	6.63	9.21	11.30



Courtesy of E. Bertola

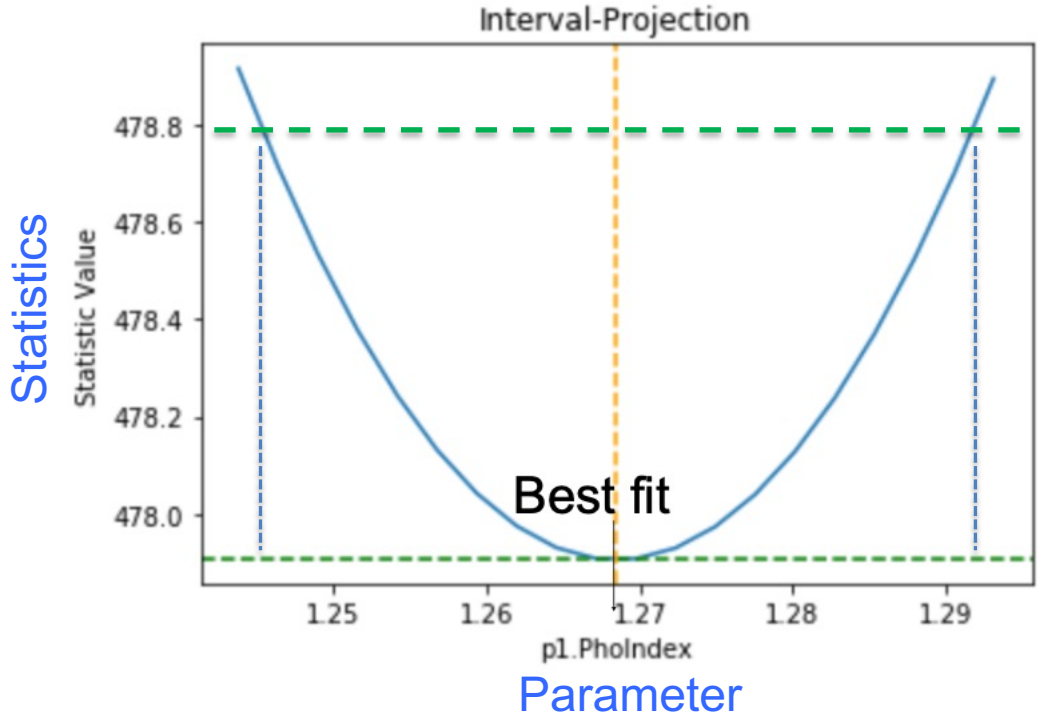


Calculating Confidence Limits means Exploring the Parameter Space - Statistical Surface



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).

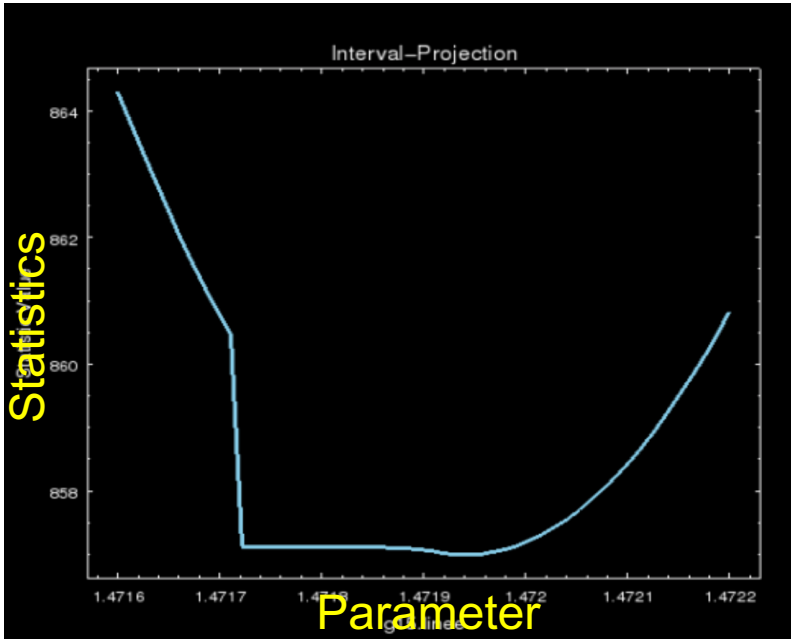
Credits: A. Siemiginowska



Well-behaved surface
(Gaussian, one parameter)

$\Delta\chi^2=1$ (68% conf. level)

Not well-behaved surface
(not Gaussian)



Credits: A. Siemiginowska

Step 5b: towards the final fitting solution

`xspec>` 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
------------------------------------------------------------------------
```

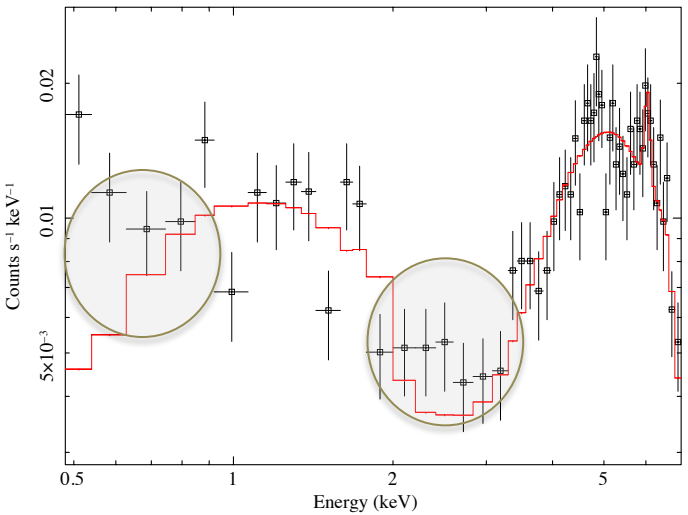
`xspec>` fit 100

```
========================================================================
Model phabs<1>(powerlaw<2> + zphabs<3>(zgauss<4> + powerlaw<5>)) Source N
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+))
$\Gamma_1=\Gamma_2$

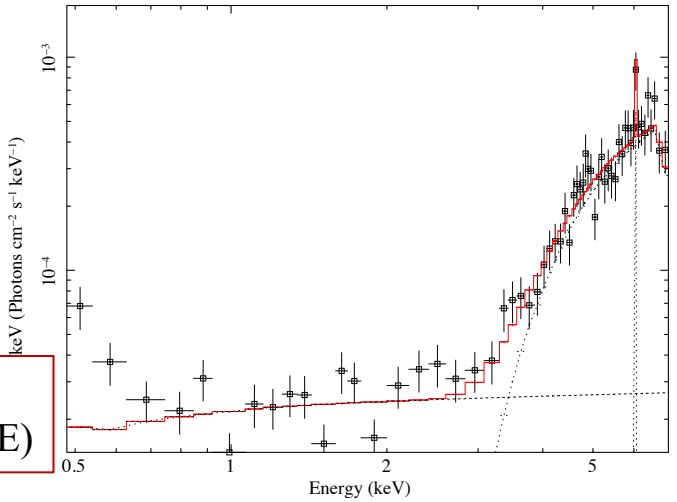
- Some residuals in the soft band and around 2 keV, where the soft and hard components ‘connects’ each other
- The photon index is still (nominally) lower than expected → reflection component needed (but not accounted for in this tutorial)

`xspec>` plot ldata



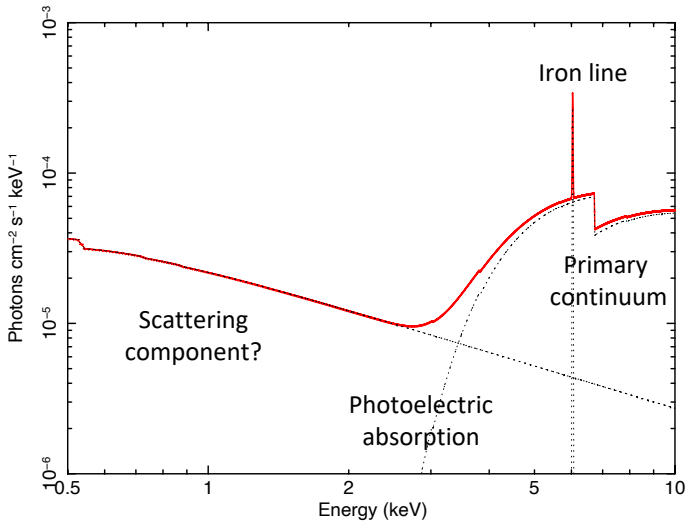
Convolution with the response matrix

`xspec>` plot eeufspec



Unfolded spectrum in E F(E)

`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
------------------------------------------------------------------------

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
```

These are the errors at 1σ for that parameter

$\Delta\chi^2$ as a Function of Confidence Level and Degrees of Freedom

	ν					
p	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
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

1 parameter of interest

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.

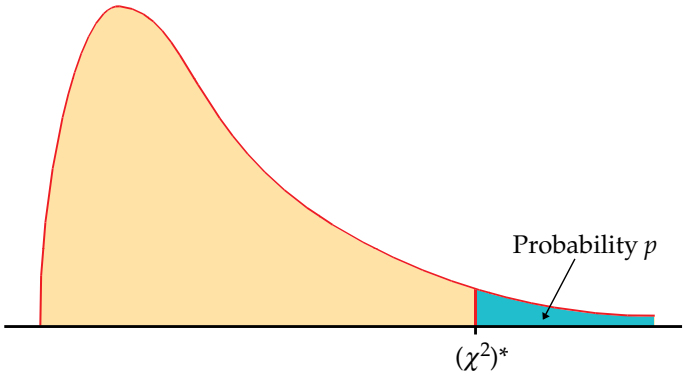


TABLE F

χ^2 distribution critical values

Parameters of interest →

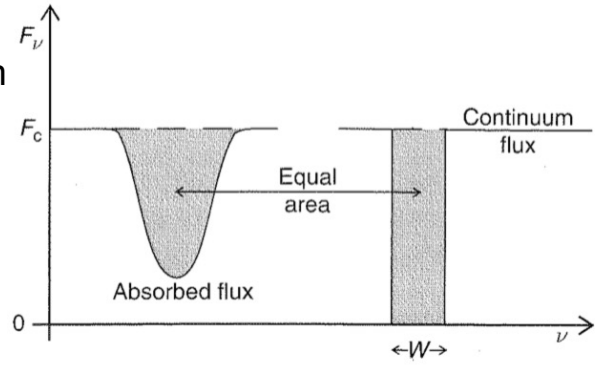
	Tail probability p			**.10**				**.01**				
df	.25	.20	.15	.10	.05	.025	.02	.01	.005	.0025	.001	.0005
1	1.32	1.64	2.07	2.71	3.84	5.02	5.41	6.63	7.88	9.14	10.83	12.12
2	2.77	3.22	3.79	4.61	5.99	7.38	7.82	9.21	10.60	11.98	13.82	15.20
3	4.11	4.64	5.32	6.25	7.81	9.35	9.84	11.34	12.84	14.32	16.27	17.73
4	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

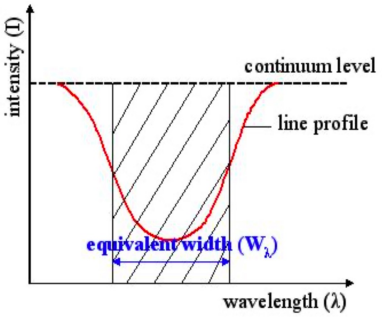
Uncertainties on the line EW measurement. I

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)

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

$$W_\nu = \int_{\nu_1}^{\nu_2} \frac{F_C - F_\nu}{F_C} d\nu$$ 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 conistent 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/cm^2/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 keV)=3.9 [3.3−4.2]×10^{-12} erg/cm^2/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
------------------------------------------------------------------------


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)
```

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**

$\mathrm{Log}F_{2\text{-}10\ \mathrm{keV}} = -11.45\ [-11.49, -11.41] \rightarrow F_{2\text{-}10\ \mathrm{keV}} = 3.5\ [3.2\text{–}3.9] \times 10^{-12}$ erg/cm^2/s
consistent with the 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

```
xspec> addcomp 5 clumin
xspec> [...]; 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
------------------------------------------------------------------------


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)
```

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**

$\mathrm{LogL_{2\text{-}10\ keV}}$= 43.90 [43.82 − 43.97]
→ $L_{2\text{-}10\ keV}$=7.9 [6.6−9.3]×10^{43} 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]