An Introduction to ISIS

Michael A. Nowak (MIT-Kavli Institute)
- with useful advice over the years from-
John Houck, John Davis, Dave Huenemoerder, Jörn Wilms

An Introduction to ISIS

(The Greatest Analysis Software Ever Written)

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Data (Spectral) Analysis

- Four major choices: XSPEC, SPEX, Sherpa, ISIS
  - XSPEC is the oldest & most established, so many models will be written with XSPEC in mind
  - SPEX is in some ways a “specialty” package for high-resolution X-ray spectroscopy
  - Sherpa is ≈ the youngest & 2nd most programmable (Sherpa & XSPEC both use Python, but Sherpa was built “ground up” in Python; XSPEC added it later)
  - ISIS is what I use for almost all mathematical analysis (spectra, timing, & other things). It uses the XSPEC models, but can do many other things

SCRIPTS

XSELECT

DS9

CIAO/
DMTOOLS

prism

CFITSIO/
FTOOLS

fv

SAS

XMM

Chandra

Suzaku

Swift

NuSTAR

...

IDL

Custom
Analysis

XRONOS

Timing

SPEX

ISIS

Sherpa

XSPEC

Spectra

"High Level"
Data Analysis

Spacecraft
Specific
Software

Data Storage,
Manipulation,
Visualization

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Spacecraft Specific Software

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...

XMM

"High Level" Data Analysis

XSPEC

Sherpa

ISIS

SPEX

XRONOS

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Timing

Custom Analysis

Custom Analysis

Data Storage, Manipulation, Visualization

CFITSIO/ FTOOLS

CIAO/ DMTOOLS

DS9

Python

Python

S-lang

"High Level" Data Analysis

XSPEC

Sherpa

ISIS

Modules

Custom Analysis

ISIS Philosophy

- All Commands are S-lang Functions or Subroutines
- Models and Data are Just Vectors of Numbers
  - When in Doubt, It's Just Math...
  - No additive/multiplicative (but convolution different)!
- You Should Have Access to and Ability to Manipulate these Numbers
  - Vector Math is Intrinsic to the S-lang Language
- You Should Be Able to Customize Whatever You Want
- With Great Power Comes Great Responsibility
  - ISIS will let you do what you want, but is less likely than XSPEC to try and guess what you want...

```
mnowak%> isis -g

isis> % What follows after % isn't read by the program

isis> print("hello world");       % Commands end with ;
"hello world"

isis> variable a = [0:10];        % Vector math is intrinsic
isis> b = a^2;                    % No declaration on command line
isis> c = log10(sin(b)+exp(a));   % Common math functions exist

isis> plot(a,c);                  % Results can be plotted

isis> id = open_plot("my_first_plot.ps/vcps");
isis>    apj_size; nice_width;
isis>    xlabel("X"); ylabel("Y");
isis>    plot(a,c);
isis> close_plot(id);
```

(I Will Use Orange for Functions I Define in My .isisrc)

```
isis> print
                (
  "hello world"
                )
.
;
"hello world"
```

```
% isn't read by the program

;       % Commands end with ;


        % Vector math is intrinsic
        % No declaration on command line
(a));   % Common math functions exist


                % Results can be plotted

irst_plot.ps/vcps");
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```
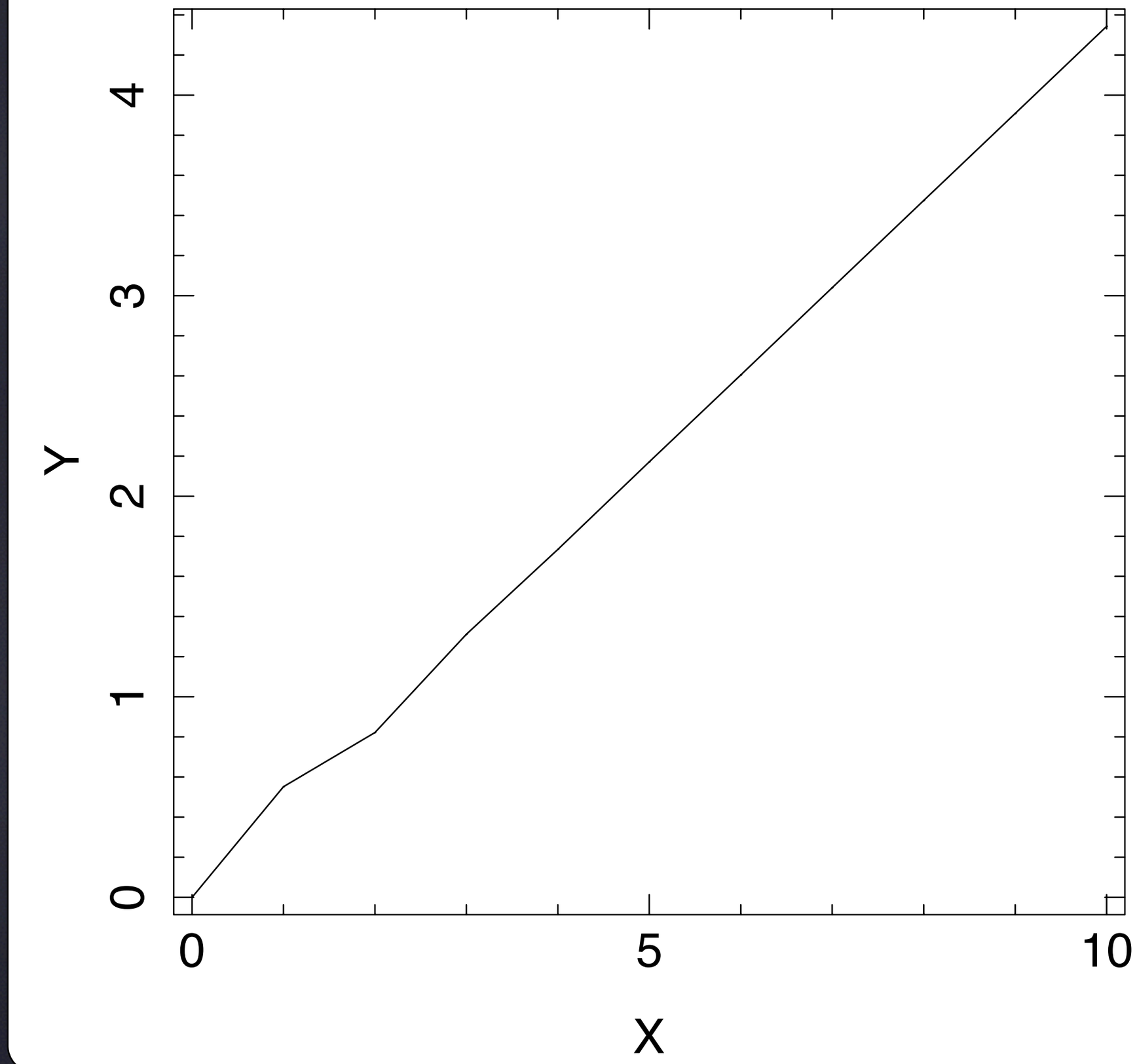

(I Will Use Orange for Functions I Define in My .isisrc)


Y
0
1
2
3
4
0
5
10
X

```
isis> () = evalfile("/path/my_script.sl");
isis> () = evalfile("/path/.isisrc");

isis> public define returns_abc()
      {
         variable a="a";
         variable b="b";
         variable c="c";
         return a,b,c;
      }
isis>

isis> returns_abc;                  % Dump to screen
c
b
a
isis> (a,b,c) = returns_abc();  % Capture output
isis> (,,) = returns_abc();     % Discard output
```

```
isis> () = evalfile("/path/my_script.sl");
```

File: unix%> ~myhome/.isisrc

Many programs look for an “rc” file in your home directory.

.xspecrc, .sherparc, .ciaorc, .xinitrc

These are places where you can put *your customizations*.

.isisrc is a good place to put customizations and programs you will use over and over again. *No recompiling of ISIS is required.*

Environment variable ISIS_HISTORY_FILE keeps a *record of ISIS commands*, which one can scroll backwards through (GNU readline installed).

```
isis> (,,) = returns_abc();      % Discard output
```

```
isis> () = evalfile("/path/my_script.sl");
isis> () = evalfile("/path/.isisrc");

isis> public define returns_abc()
      {
         variable a="a";
         variable b="b";
         variable c="c";
         return a,b,c;
      }
isis>

isis> returns_abc;                  % Dump to screen
c
b
a
isis> (a,b,c) = returns_abc();  % Capture output
isis> (,,) = returns_abc();     % Discard output
```

```
isis> a = [0:10]; b = 3.5; c = "pizza";
isis> who;
a: Integer_Type[11]
b: 3.5
c: pizza

isis> .apropos arf

Found 15 function matches in namespace Global:
_nonstandard_arf_hdu_names all_arfs                    assign_arf
define_arf                 delete_arf                  get_arf
get_arf_exposure           get_arf_info                get_rmf_arf_grid
list_arf                   load_arf                    put_arf
set_arf_exposure           set_arf_info                unassign_arf

Found 6 variable matches in namespace Global:
Allow_Multiple_Arf_Factors Assigned_ARFRMF             Assigned_RMFARF
Ideal_ARF                  Ideal_ARFRMF                Ideal_RMFARF
```

```
isis> .help load_arf
load_arf

 SYNOPSIS
    Load an effective area (ARF) file

 USAGE
    status = load_arf ("filename")

 DESCRIPTION
    This function loads either a FITS Type I or Type II ARF file;
    the updated list of currently loaded ARFs is automatically
    displayed. On return, status is equal to the integer index of
    the ARF just loaded ( status > 0); a return value of status =
    -1 is used to indicate failure.  (For Type II ARF input, a
    return value of zero indicates success).


 SEE ALSO
    load_dataset, list_arf, delete_arf, assign_arf, unassign_arf

isis> alias(“load_arf”,”arf”);
isis> alias(“fit_fun”,”model”);
```

```
isis> pca_id = load_data(“pca.pha”);      % Read pca data
isis> hexte_id =  load_data(“hxt.pha”);  % Read hexte data

isis> % pca_id = 1, hexte_id =2
```

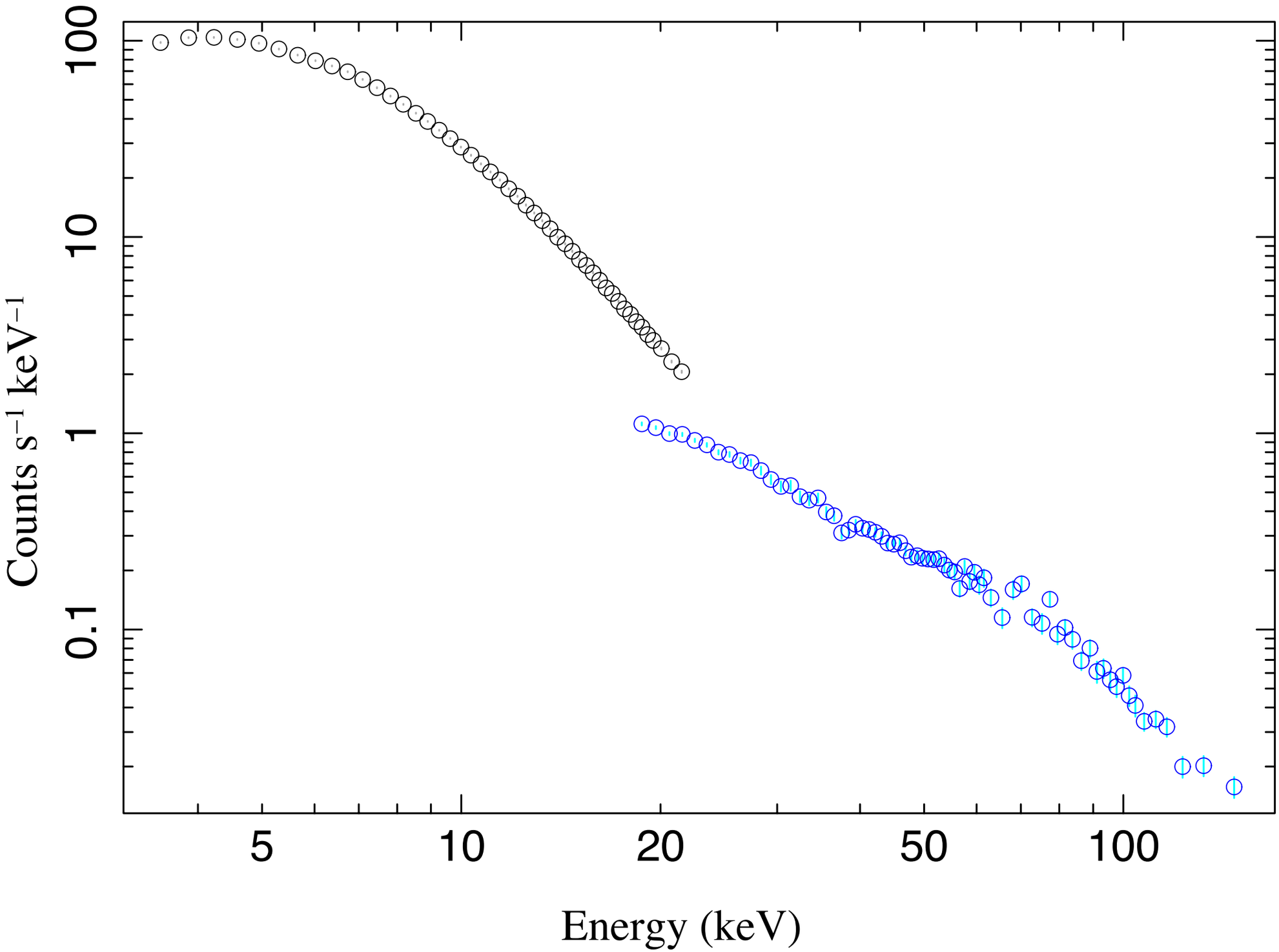
If ARF, RMF, and Background information are in the FITS headers, then these components will also be automatically loaded & associated with spectra.

Data errors are taken from file (STAT_ERR column, combined with SYS_ERR column or keyword), *unless grouping is applied to the data*.

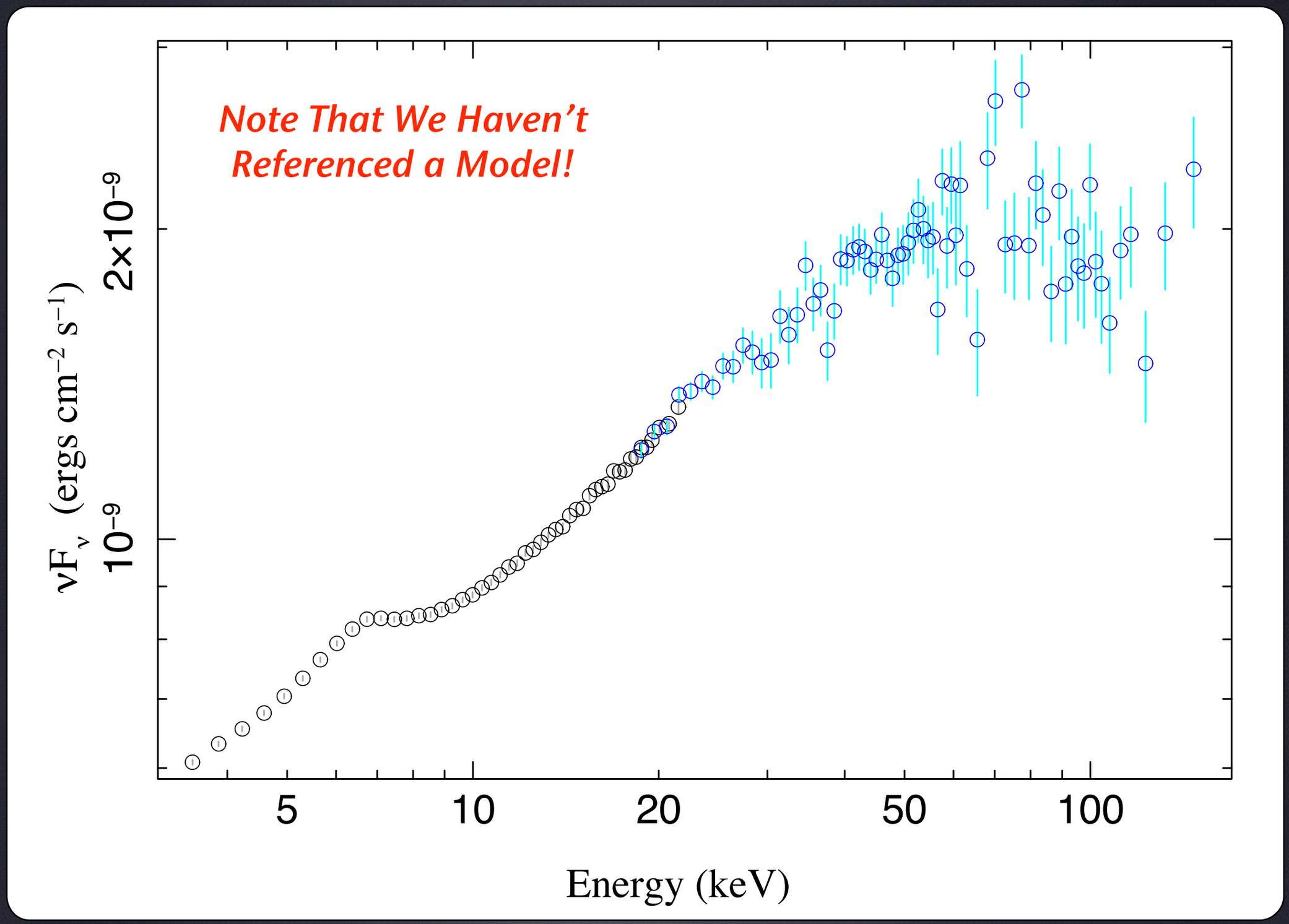
File *grouping will not be automatically applied* unless Isis_Use_PHA_Grouping > 0.

ISIS Let's You Group Data on the Fly!

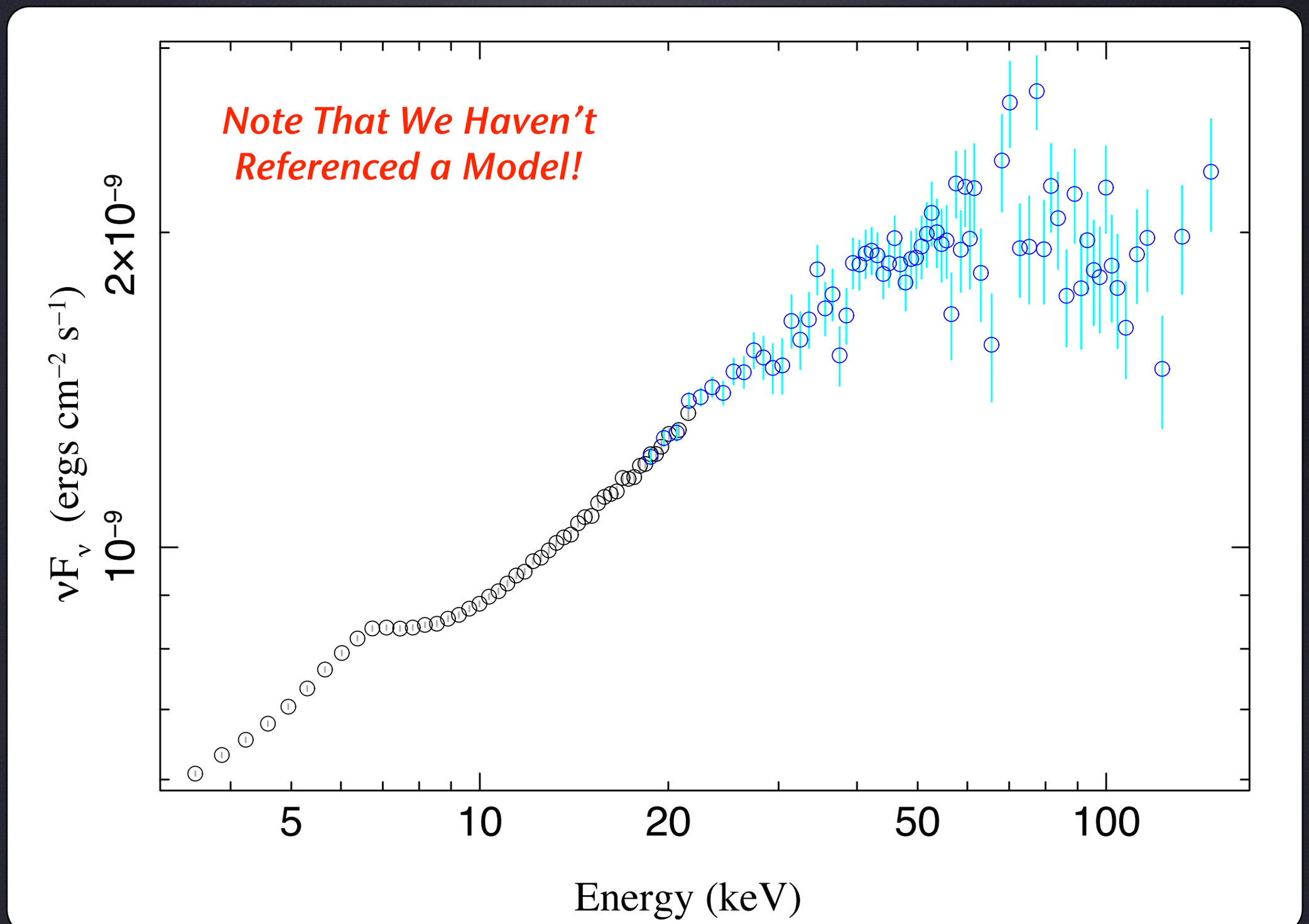
```
isis> group(pca_id; min_sn=4.5, bounds=3, unit="kev");
isis> notice_values(pca_id,3,22; unit="kev");


isis> group(hexte_id; min_sn=8, bounds=18, unit="kev");
isis> notice_values(hexte_id,18,200; unit="kev");

isis> xlog; ylog;
isis> fancy_plot_unit("kev","ergs");

 Also setting ISIS intrinsic plot units to: kev


isis> plot_data({pca_id,hexte_id};dcol={1,4},decol={15,5});
isis> plot_data({1,2};dcol={1,4},decol={15,5});
```


100
10
1
0.1
Counts s^{-1} keV^{-1}
5
10
20
50
100
Energy (keV)

```
isis> plot_unfold({1,2};dcol={1,4},decol={15,5},scale={1,1.07});
```

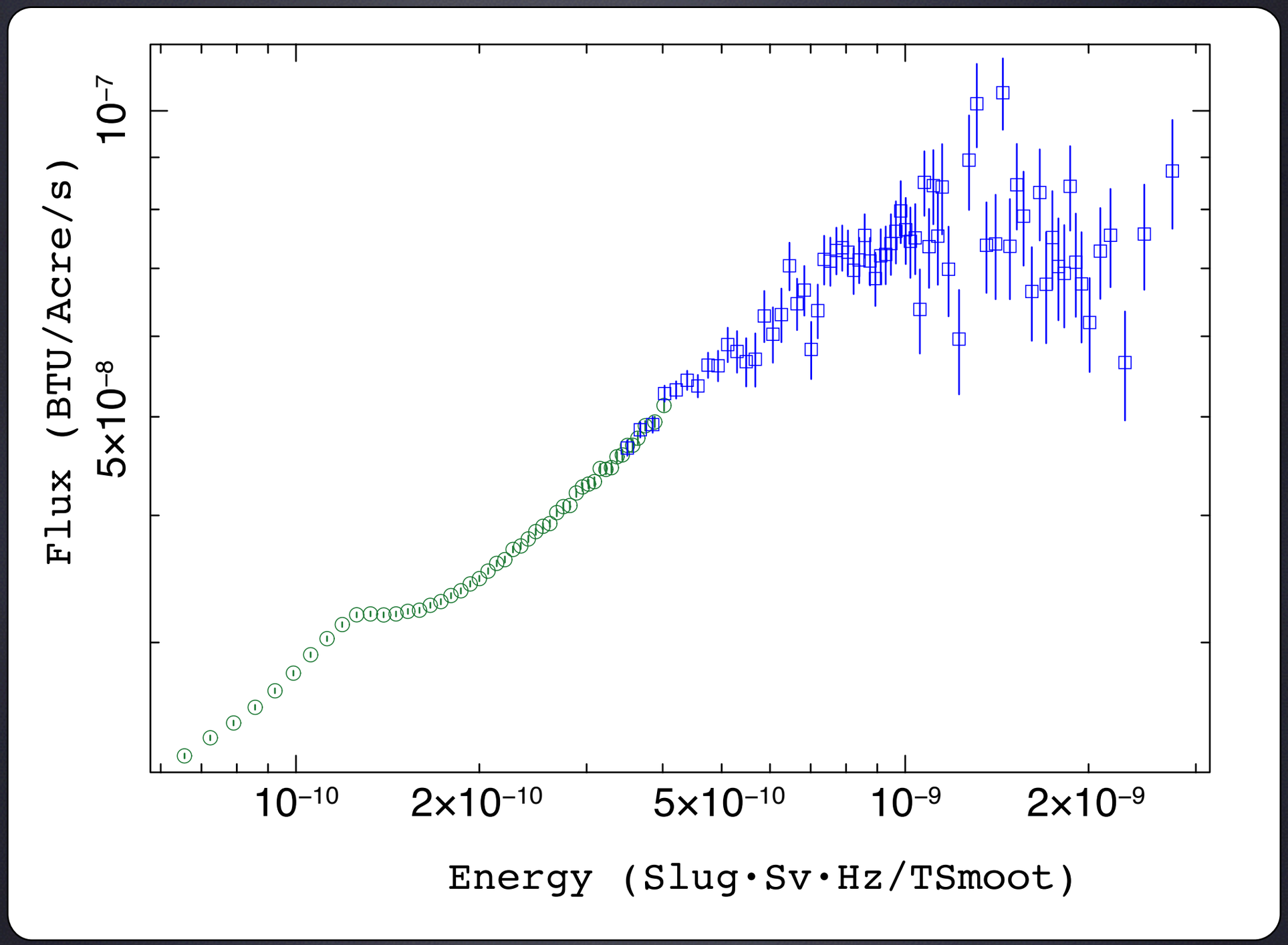


```
isis> plot_unfold({1,2};dcol={1,4},decol={15,5},scale={1,1.07});
```

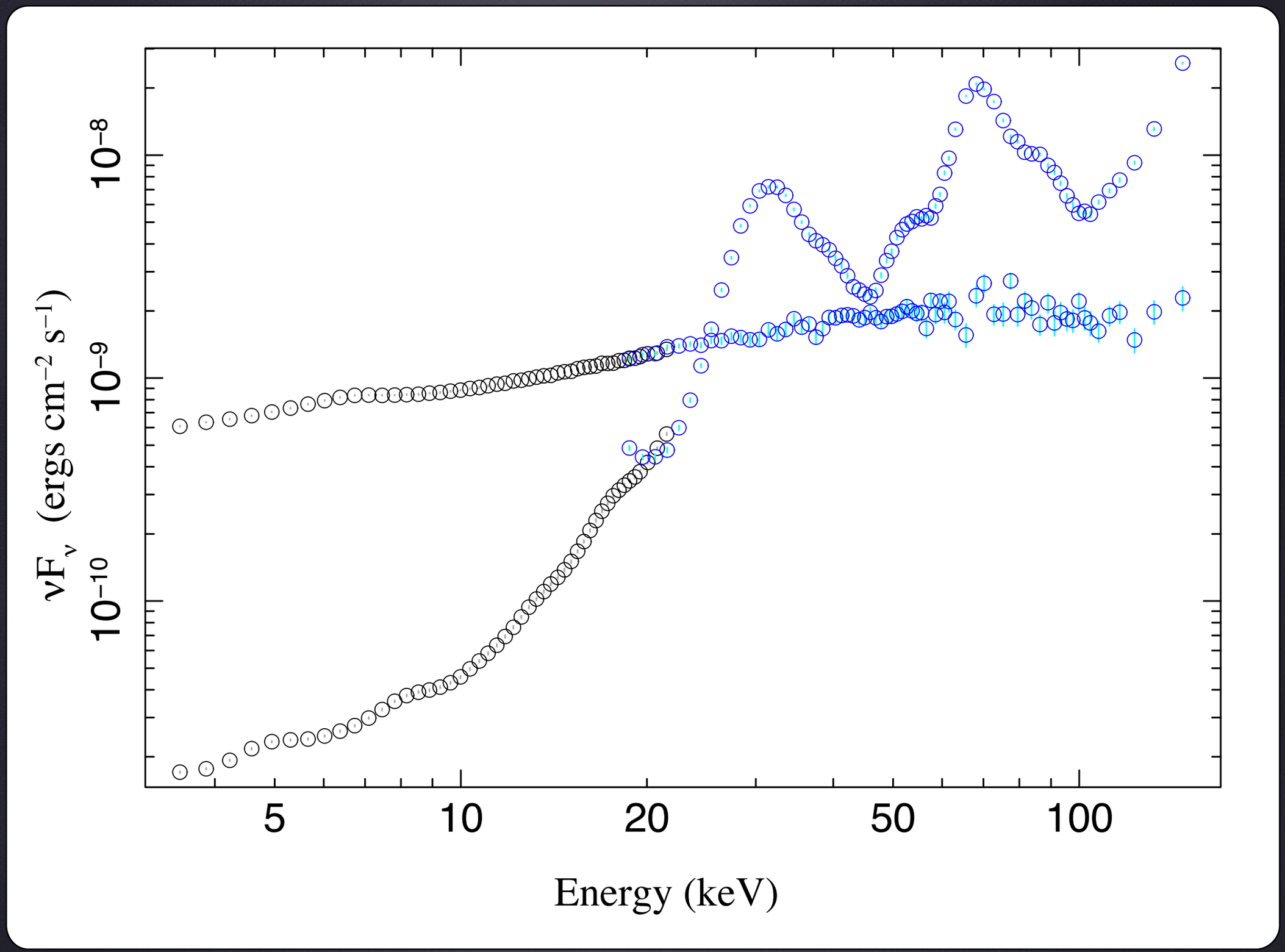


Use with Caution! And Never, Ever, Under Any Circumstances Use the XSPEC: plot eeufs!

```
isis> add_plot_unit("new_energy","new_flux";is_energy=1,
                                    xscale=5.353038e10,yscale=3274.3436);
isis> fancy_plot_unit("new_energy","new_flux");
isis> plot_unfold({1,2};power=3,dsym={4,6},dcol={17,4},
                        xlabel="\\fs Energy (Slug\\.Sv\\.Hz/TSmoot)",
                        ylabel="\\fs Flux (BTU/Acre/s)",scale={1,1.07});
```



```
isis> fancy_plot_unit("kev","ergs");
isis> plot_unfold({1,1,2,2};dcol={1,1,4,4},decol={15,15,5,5},
                            scale={1,1,1.07,1.07},bkg={0,-1,0,-1});
```



```
isis> model("constant(Isis_Active_Dataset)*phabs*highecut*(bknpower+gaussian)");
```

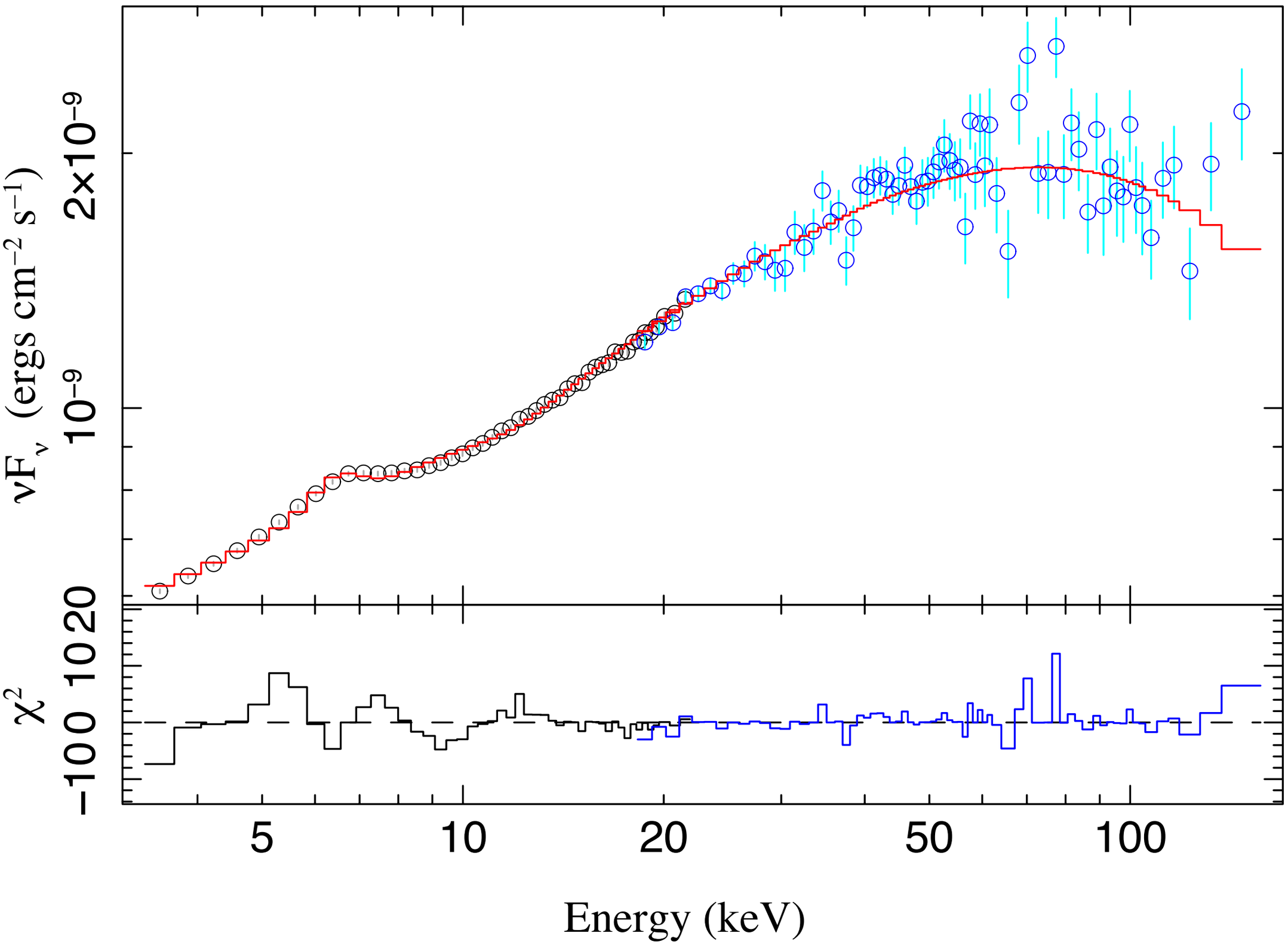
Model is: A Power Law with a "Break" Plus a Line,
that "exponentially rolls over" at high energies,
that is absorbed at low energies,
and
has a different normalization for PCA and HEXTE

Isis_Active_Dataset **is a powerful concept that let's you alter how the model is applied to different data sets, and even allows you to alter how models behave!**

```
isis> list_free;
constant(Isis_Active_Dataset)*phabs*highecut*(bknpower+gaussian)
 idx  param              tie-to  freeze          value           min           max
  2  phabs(1).nH             0       0            0.5             0             5  10^22
  3  highecut(1).cutoffE     0       0             10             8           300  keV
  5  bknpower(1).norm        0       0              1             0          1e+10
  6  bknpower(1).PhoIndx1    0       0            1.8             1             3
  7  bknpower(1).BreakE      0       0             10             8            15  keV
  8  bknpower(1).PhoIndx2    0       0            1.6             1             3
  9  gaussian(1).norm        0       0            0.1             0            10
 10  gaussian(1).LineE       0       0            6.4             6             7  keV
 11  gaussian(1).Sigma       0       0            0.3             0             1  keV
 12  constant(2).factor      0       0      0.9345794          0.75          1.25
```

```
isis> edit_par;     % Starts an editor, or use the commands below ...

isis> set_par("constant(1).factor",1,1);                % Second 1 means => frozen
isis> set_par("phabs(1).nH",0.5,0,0,5);                 % Limited range in search
isis> set_par("high*cutoffE",10,0,8,300);               % Wild cards OK
isis> set_par(4,100,10,0.01,1000);                      % Or use parameter numbers
isis> set_par(6,1.8,0,1,3);                             % Photon Index 1
isis> set_par(7,10,0,8,15);                             % Break Index
isis> set_par(8,1.6,0,1,3);                             % Photon Index 2
isis> set_par(9,0.1,0,0,10);                            % Gaussian Norm
isis> set_par("*LineE",6.4,0,6,7);                      % Line Energy
isis> set_par("*Sigma",0.3,0,0,1);                      % Line Width
isis> set_par("constant(2).factor",1/1.07,0,0.75,1.25);
```

```
isis> () = fit_counts;
 Parameters[Variable] = 12[10]
           Data bins = 118
         Chi-square = 171.7534
   Reduced chi-square = 1.590309

isis> plot_unfold({1,2};dcol={1,4},decol={15,5},scale={1,1/get_par(12)},res=2);
```


νF_ν (ergs cm^{-2} s^{-1})
10^{-9}
2×10^{-9}
χ^2
−10 0 10 20
5
10
20
50
100
Energy (keV)

Confidence Contours are Parallelized!

```
isis> (,) = conf_loop(,1,0.1;save,prefix="best_fit.",num_slaves=2,nice=19);

...

isis> save_par("best_fit.par");
isis> load_par("best_fit.save");

isis> () = eval_counts;
 Parameters[Variable] = 12[10]
            Data bins = 118
          Chi-square = 111.0569
   Reduced chi-square = 1.028305

isis> list_free;
constant(Isis_Active_Dataset)*phabs*highecut*(bknpower+gaussian)
 idx  param                tie-to  freeze          value          min          max
  2  phabs(1).nH               0       0              0            0    0.4477608  10^22
  3  highecut(1).cutoffE       0       0       12.86972     11.55878     13.99137  keV
  5  bknpower(1).norm          0       0      0.2360461    0.2328648    0.240283
  6  bknpower(1).PhoIndx1      0       0       1.628581     1.622399     1.637057
  7  bknpower(1).BreakE        0       0       12.81679     12.11459     13.35711  keV
  8  bknpower(1).PhoIndx2      0       0       1.249342     1.231995     1.269046
  9  gaussian(1).norm          0       0   0.002511571  0.002188707  0.002860817
 10  gaussian(1).LineE         0       0       6.19454     6.083825     6.302416  keV
 11  gaussian(1).Sigma         0       0      0.8079406    0.6850875    0.9338861  keV
 12  constant(2).factor        0       0      0.9480235    0.9355516    0.9613026

isis> plot_unfold({1,2};dcol={1,4},decol={15,5},scale={1,1/get_par(12)},res=2);
```

Confidence Contours are Parallelized!

```
isis> (,) = conf_loop(,1,0.1;save,prefix="best_fit.",num_slaves=2,nice=19);

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 idx  param                tie-to  freeze          value          min          max
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  3   highecut(1).cutoffE       0       0       12.86972     11.55878     13.99137  keV
  5   bknpower(1).norm          0       0      0.2360461    0.2328648     0.240283
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 12   constant(2).factor        0       0      0.9480235    0.9355516    0.9613026

isis> plot_unfold({1,2};dcol={1,4},decol={15,5},scale={1,1/get_par(12)},res=2);
```
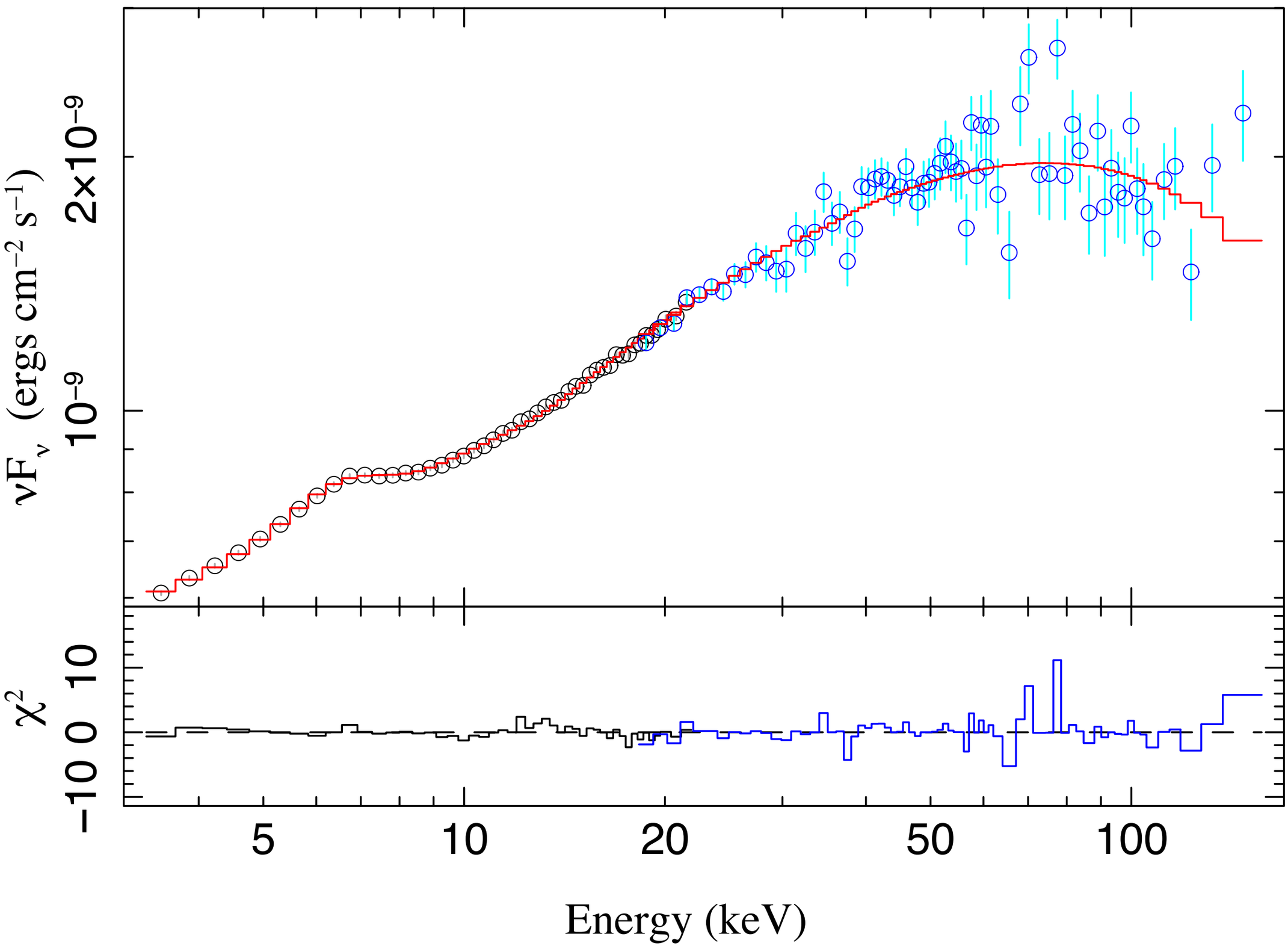
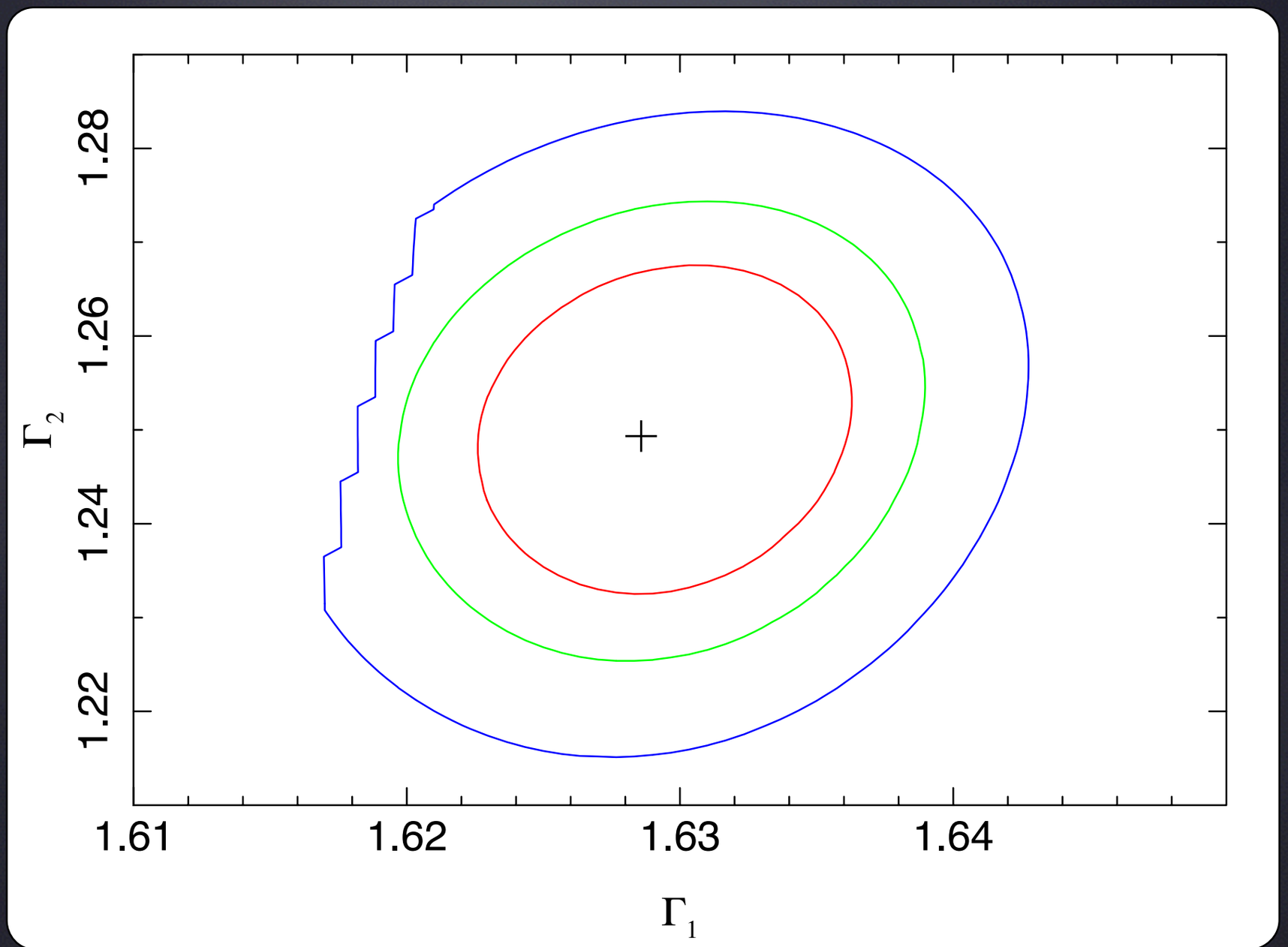

90% Error Bars!


νF_ν (ergs cm^−2 s^−1)
10^−9
2×10^−9
χ^2
−10 0 10
5
10
20
50
100
Energy (keV)

```
isis> variable px = conf_grid(6,1.61,1.65,61);
isis> variable py = conf_grid(8,1.21,1.29,81);
```

Contours are Parallelized

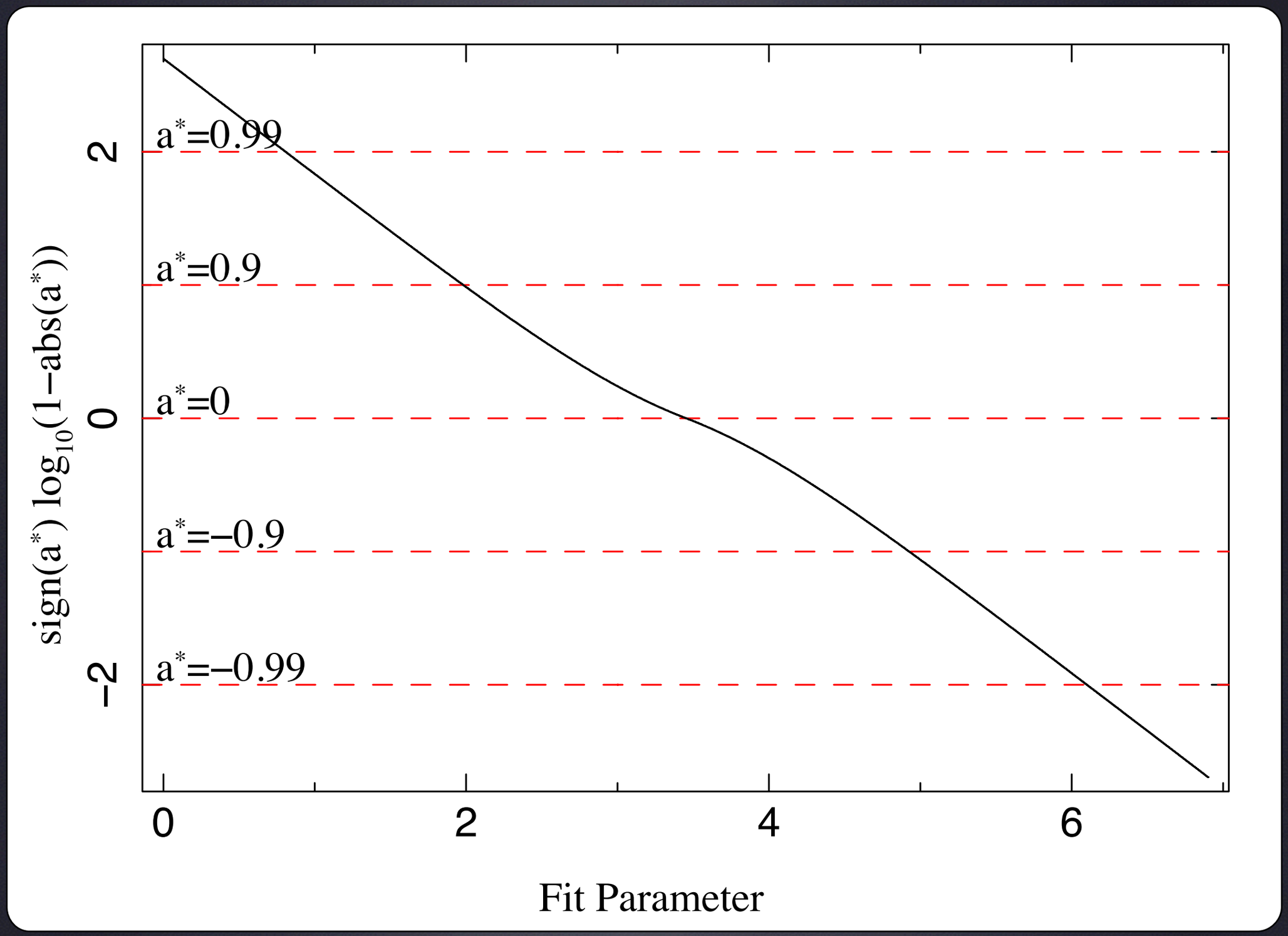
```
isis> variable cntr = conf_map(px,py;flood,num_slaves=2);
isis> xlabel("\\fr\\gG\\d1"); ylabel("\\fr\\gG\\d2");
isis> plot_conf(cntr);
```



- It’s just math! If it makes math sense, it “works”
  - constant*(stuff) – or – (stuff + constant) – or – stuff + 0.*constant
  - isis> model(“(constant-edge)*powerlaw”);
    xspec> model (constant-edge)*powerlaw
  - “Works like math” carries over to parameters using set_par_fun
  - stuff + 0.*(constant(1)+constant(2)+...)
    the constants become “dummy parameters”

- It’s just math! If it makes math sense, it “works”
  - constant*(stuff) – or – (stuff + constant) – or – stuff + 0.*constant
  - isis> model(“(constant-edge)*powerlaw”);
    xspec> model (constant-edge)*powerlaw
  - “Works like math” carries over to parameters using set_par_fun
  - stuff + 0.*(constant(1)+constant(2)+...)
    the constants become “dummy parameters”

set_par_fun(“relconv(1).a” , ”tanh(constant(1).factor - atanh(0.998))”)



Things You Can Control

- Fit methods: “Levenberg-Marquadt” (mpfit) is default, subplex (slow but robust), diffevol (very slow!)
- Fit statistics: χ^2 with Data or Model Variance, Cash statistics, W statistics (script), or *define your own*
  - Cash/W statistics must use certain fit methods (not Levenberg-Marquadt! *Use subplex!*)
- Custom define propagation of errors
- Put values of data & models into vectors; overwrite values of data and data errors
- Get values of responses, effective areas, overwrite

A Note on Backgrounds

- ISIS doesn't "subtract" backgrounds –
  - Total Counts = (Model Prediction) + Background
- We often don't plot total counts, and background can be measured (file) or modeled (back_fun)
- Data statistics are based on the background – *this is a tricky topic*
  - file: increase error for χ^2 data, but not for χ^2 model
  - back_fun: don't increase the error
  - But both these rules sometimes *should* be broken

ISIS Let's You Alter Backgrounds

- A complicated background function I wrote:
  - corfile(indx1, indx2, scale);
  - $Source_1 = Total_1 - Back_1 - scale*(Total_2 - Back_2)$ where errors are a *user-defined* sum in quadrature of *Poisson & Fractional (systematic)* pieces
    - Something I had to write after talking to Phil Uttley, who does RXTE-PCA spectra & timing of AGN
    - Faint Binary + Galactic Ridge + Background & Second Observation Galactic Ridge + Background
- Complicated example of a user-defined function, but ...
- User-defined functions can also be simple

User Defined Functions

```
define zfc_fit(lo,hi,par){
   variable a,f,al,ah,l;
   al = _A(lo);
   ah = _A(hi);
   f = par[1];
   a = par[0]^2 * PI/2./f;
   l = a*f/(al-ah) *  ( atan(al/f) - atan(ah/f) );
   l = reverse(l);
   return l; }
```

ISIS Fit Functions Take/Return *Wavelength Order*, and like XSPEC are Integrated Counts/Bin

$$\mathrm{\_A}(\lambda_{lo},\lambda_{hi}) \Rightarrow \mathrm{keV}_{lo},\mathrm{keV}_{hi}\ ,\ \ \mathrm{\_A}(\mathrm{keV}_{lo},\mathrm{keV}_{hi}) \Rightarrow \lambda_{lo},\lambda_{hi}$$

$$\mathrm{\_A}(x) \ = \ \mathrm{\_A}(1)/\mathrm{reverse}(x)$$

$$\mathrm{\_A}(x,y) \ = \ \mathrm{\_A}(1)/\mathrm{reverse}(y)\ ,\ \mathrm{\_A}(1)/\mathrm{reverse}(x)$$

Going Nuts with User Models

- Rewrite line models: find_line, add_line, delete_line
- model(“powerlaw+lines()”);
  I defined lines()/add_line/delete_line such that
  add_line(“Ne9r”) will:
  - add a guassian line component @13.447 A
  - rename it to “ne9r”
  - place it in existing line list in wavelength order
  - delete_line will remove the component

Resources

- S-lang Scripting Language:
  - http://www.jedsoft.org/slang/
- ISIS Home Page:
  - http://space.mit.edu/CXC/ISIS
- Worked X-ray Fitting Example (& my .isisrc):
  - http://space.mit.edu/home/mnowak/isis_vs_xspec/
- S-lang Timing Analysis Routines:
  - http://space.mit.edu/cxc/analysis/SITAR/
- Remeis ISIS Scripts:
  - http://www.sternwarte.uni-erlangen.de/isis/
- Mail group for asking questions:
  - isis-users@space.mit.edu