

X-ray Spectral fitting of BHXRBS by TCAF FITS file:

- I. A brief summary of TCAF Spectral Model
- II. An introduction to the TCAF fits file(s), fitting within XSPEC
- III. A Tale of Two *Constraints*: On fits and of the model

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Workshop on *Two Component Advective Flows (TCAF): Fitting Procedure and Results for Stellar and supermassive black holes.*
ICSP, India
2024.09.25

X-ray Spectral fitting of BHXRBS by TCAF FITS file:

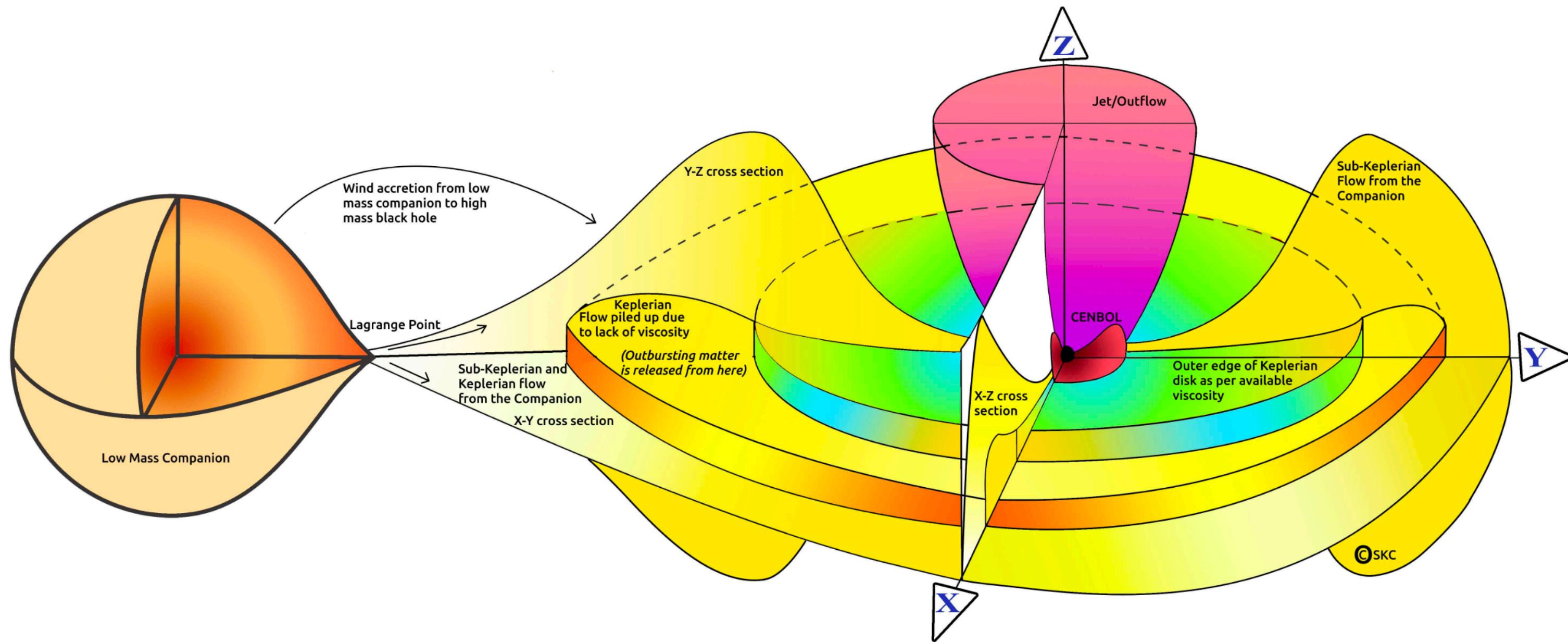
I. A brief summary of TCAF Spectral Model

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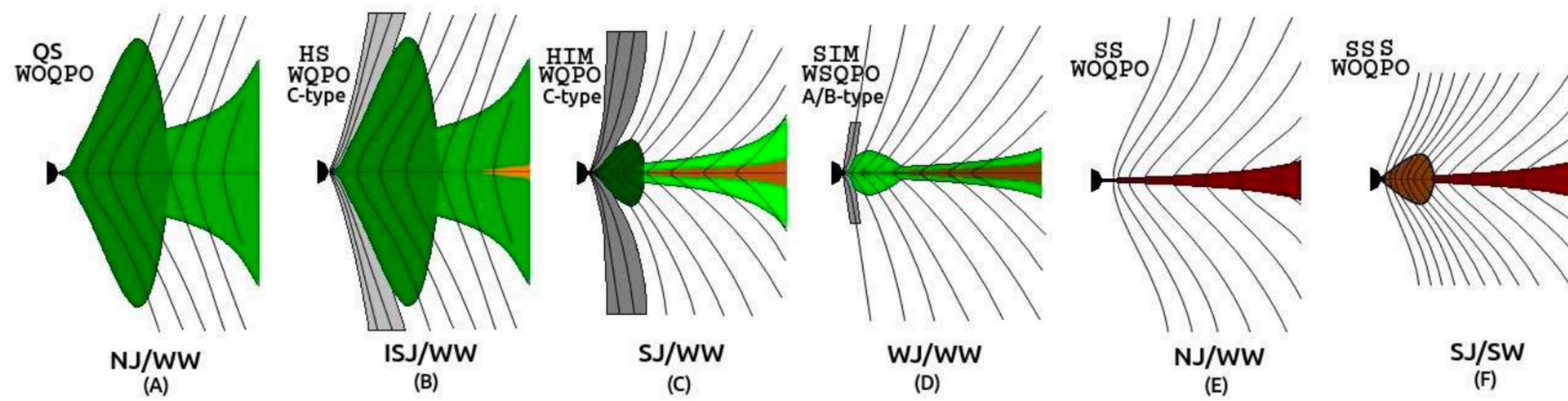
Workshop on *Two Component Advection Flows (TCAF): Fitting Procedure and Results for Stellar and supermassive black holes.*
ICSP, India
2024.09.25

A Unified Accretion-Ejection Mechanism



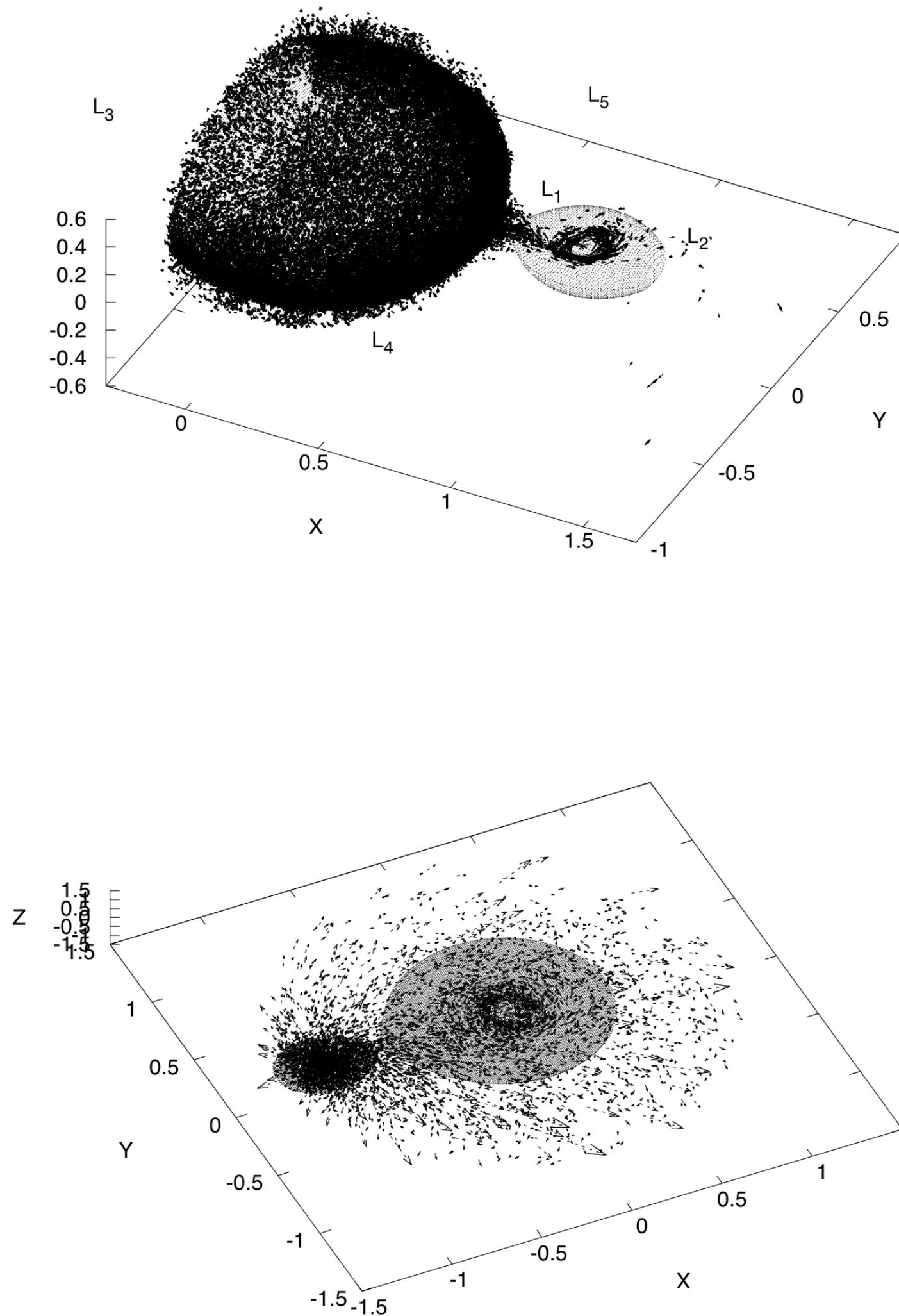
- ▶ Two Component Advective Flow around black holes.
- ▶ Flow Parameters: \dot{m}_d , \dot{m}_h , X_s , R

A Unified Outburst Mechanism

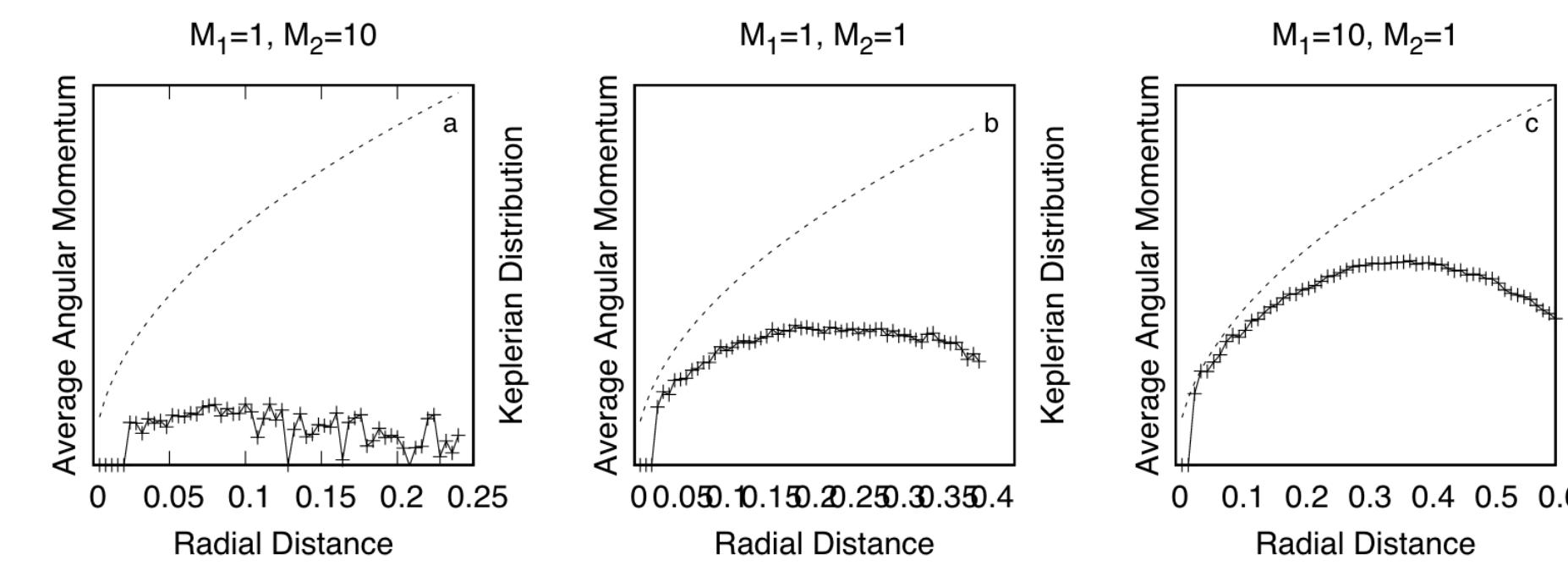


- ▶ TCAF as a general flow configuration across different spectral states.

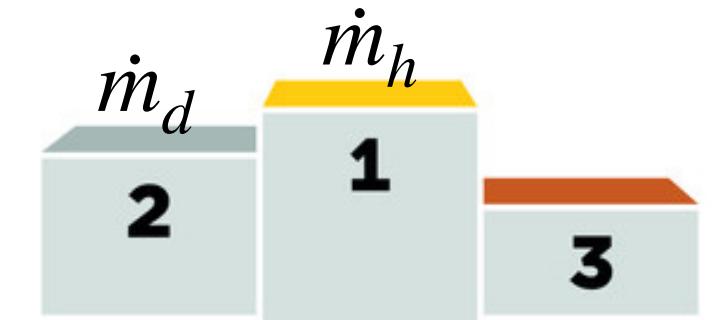
A Unified Accretion-Ejection Mechanism



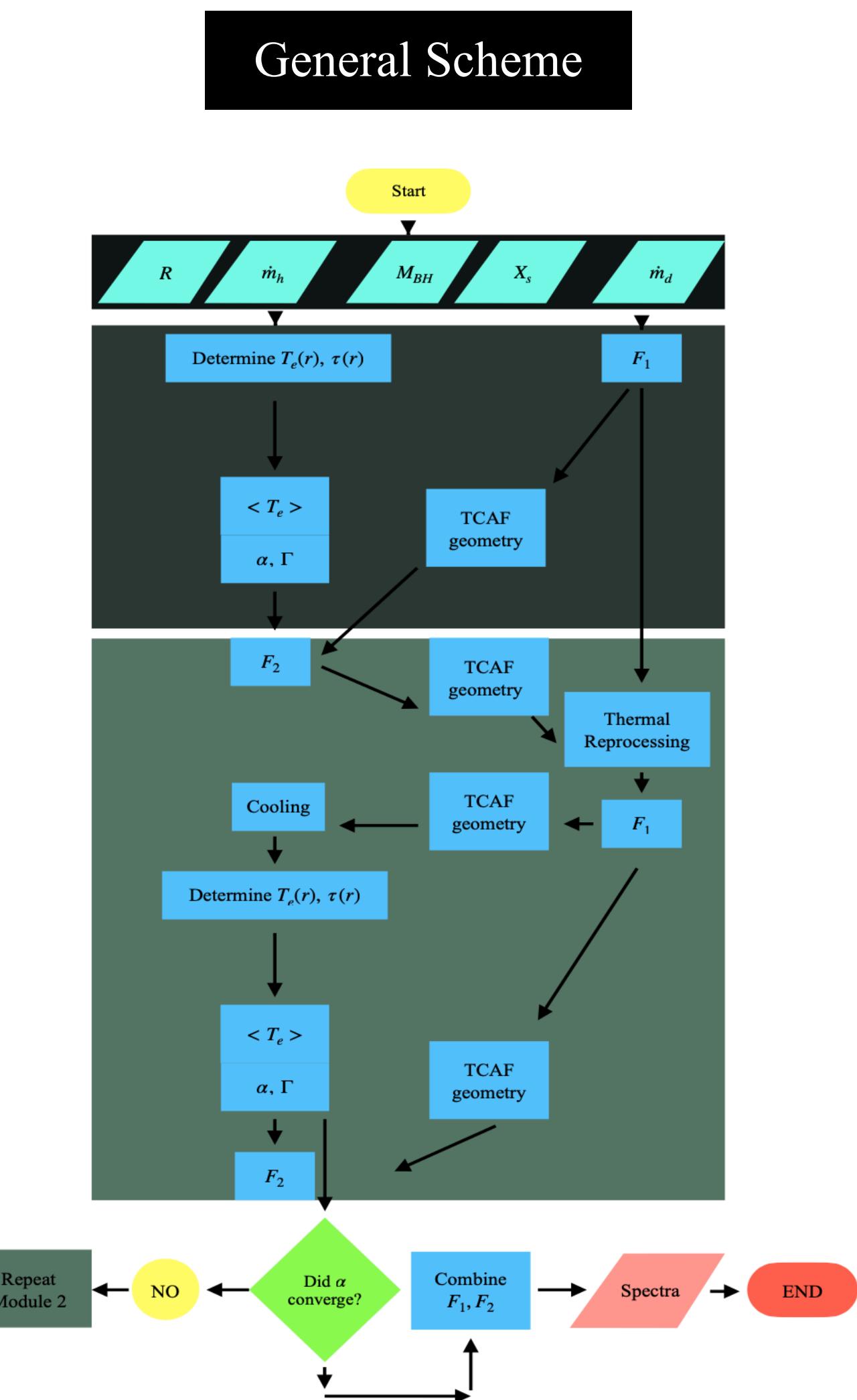
- ▶ HMXBs: Wind captured easily around Roche Lobe/ L_1 point.



- ▶ LMXBs: Winds from all directions captured.



TCAF Spectral Code



X-ray Spectral fitting of BHXRBS by TCAF FITS file:

II. An introduction to the TCAF fits file(s), fitting within XSPEC

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TCAF Fits File

Summary Window

The screenshot shows the fv: Summary window for the file TCAF_v0.3.2_R1.fits. The window has a menu bar with File, Edit, Tools, and Help. Below the menu is a table with four rows. The first row contains the index (0), extension (Primary), type (Image), and dimension (0). The second row contains index (1), extension (PARAMETERS), type (Binary), and dimension (10 cols X 5 rows). The third row contains index (2), extension (ENERGIES), type (Binary), and dimension (2 cols X 549 rows). The fourth row contains index (3), extension (SPECTRA), type (Binary), and dimension (2 cols X 276480 rows). To the right of the table is a "View" section with five buttons: Header, Image, Table, Hist, Plot, All, and Select.

Index	Extension	Type	Dimension	View				
0	Primary	Image	0	Header	Image	Table		
1	PARAMETERS	Binary	10 cols X 5 rows	Header	Hist	Plot	All	Select
2	ENERGIES	Binary	2 cols X 549 rows	Header	Hist	Plot	All	Select
3	SPECTRA	Binary	2 cols X 276480 rows	Header	Hist	Plot	All	Select

Parameter Space

The screenshot shows the fv: Binary Table window for the file TCAF_v0.3.2_R1.fits[1]. The window has a menu bar with File, Edit, Tools, and Help. Below the menu is a table with 12 columns labeled NAME, METHOD, INITIAL, DELTA, MINIMUM, BOTTOM, TOP, MAXIMUM, NUMBVALS, and VALUE. The first row shows the column headers. The second row shows the column types: 12A, J, E, E, E, E, E, E, J, and 24E. Below the table are several "Modify" buttons. The table itself contains 5 rows of data. At the bottom of the window are "Go to:" and "Edit cell:" fields.

NAME	METHOD	INITIAL	DELTA	MINIMUM	BOTTOM	TOP	MAXIMUM	NUMBVALS	VALUE
Select	12A	J	E	E	E	E	E	J	24E
All	Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	ndotd	1	2.000000E-03	1.696996E-01	1.000000E-03	1.000000E-03	8.000000E+00	8.000000E+00	24
2	ndoth	1	2.000000E-03	1.696996E-01	1.000000E-03	1.000000E-03	8.000000E+00	8.000000E+00	24
3	mbh	0	8.000000E+00	3.333333E+00	5.000000E+00	5.000000E+00	1.500000E+01	1.500000E+01	4
4	xs	1	1.000000E+02	7.650730E-02	8.000000E+00	8.000000E+00	4.600000E+02	4.600000E+02	24
5	R	0	1.500000E+00	7.375000E-01	1.050000E+00	1.050000E+00	4.000000E+00	4.000000E+00	5

<https://heasarc.gsfc.nasa.gov/ftools/fv/>

- ▶ Using any standard *fits* file viewer.
- ▶ In terminal: fv
“TCAF_v0.3.2._R1.fits”
- ▶ Summary Window > View > Parameters > All: parameter space.
- ▶ Why? Check the soft and **hard bounds**. Check the **number of grid points**.

TCAF Fits File

Energy Domain

Left Table (30 rows):

	ENERG_LO	ENERG_HI
1	1.309381E-04	1.351146E-04
2	1.351146E-04	1.394244E-04
3	1.394244E-04	1.438716E-04
4	1.438716E-04	1.484606E-04
5	1.484606E-04	1.531961E-04
6	1.531961E-04	1.580826E-04
7	1.580826E-04	1.631250E-04
8	1.631250E-04	1.683282E-04
9	1.683282E-04	1.736973E-04
10	1.736973E-04	1.792378E-04
11	1.792378E-04	1.849549E-04
12	1.849549E-04	1.908544E-04
13	1.908544E-04	1.969421E-04
14	1.969421E-04	2.032240E-04
15	2.032240E-04	2.097062E-04
16	2.097062E-04	2.163953E-04
17	2.163953E-04	2.232976E-04
18	2.232976E-04	2.304201E-04
19	2.304201E-04	2.377699E-04
20	2.377699E-04	2.453540E-04
21	2.453540E-04	2.531801E-04
22	2.531801E-04	2.612558E-04
23	2.612558E-04	2.695891E-04
24	2.695891E-04	2.781881E-04
25	2.781881E-04	2.870615E-04
26	2.870615E-04	2.962179E-04
27	2.962179E-04	3.056664E-04
28	3.056664E-04	3.154163E-04
29	3.154163E-04	3.254771E-04
30	3.254771E-04	3.358589E-04

Right Table (549 rows):

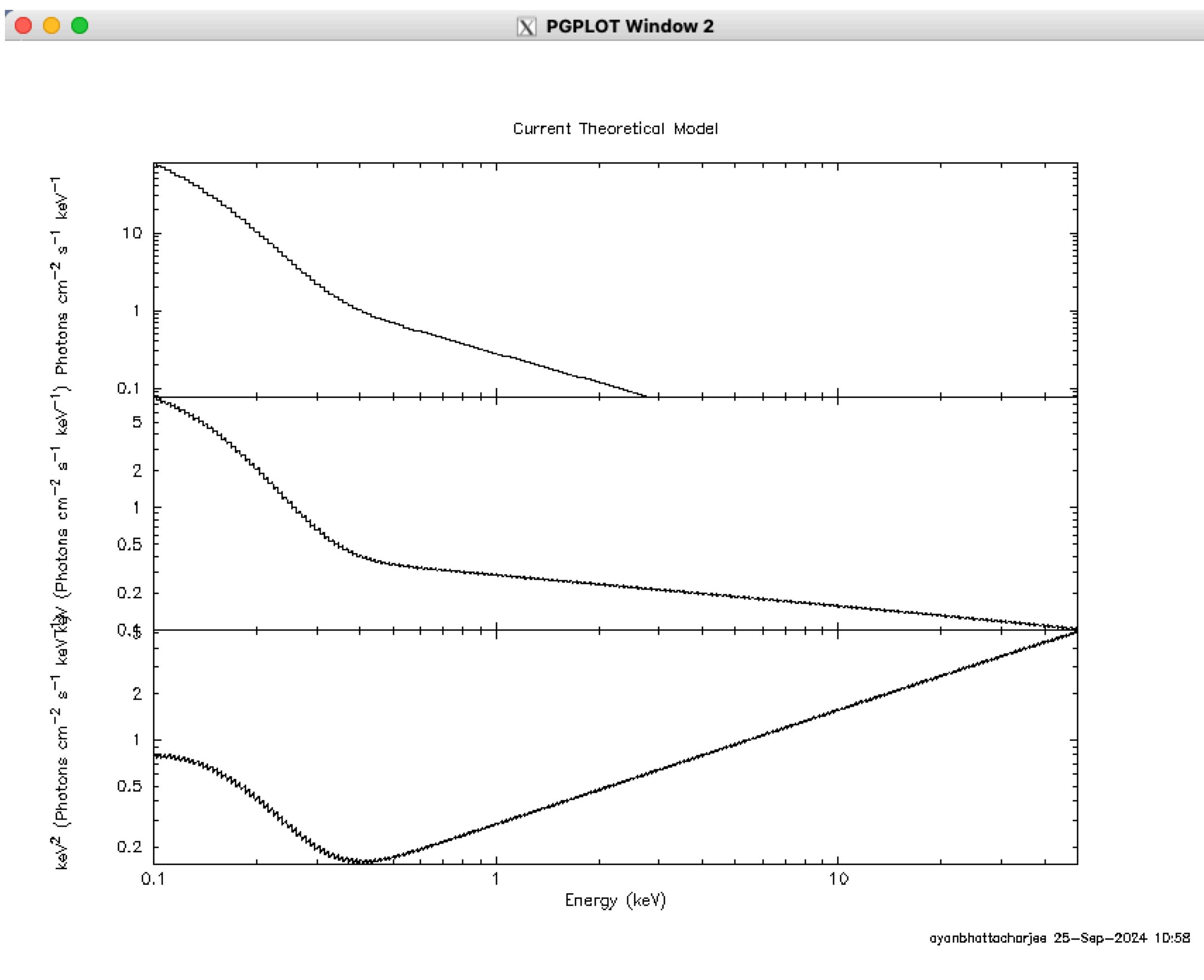
	ENERG_LO	ENERG_HI
520	1.564367E+03	1.614266E+03
521	1.614266E+03	1.665756E+03
522	1.665756E+03	1.718889E+03
523	1.718889E+03	1.773716E+03
524	1.773716E+03	1.830292E+03
525	1.830292E+03	1.888673E+03
526	1.888673E+03	1.948916E+03
527	1.948916E+03	2.011081E+03
528	2.011081E+03	2.075229E+03
529	2.075229E+03	2.141422E+03
530	2.141422E+03	2.209727E+03
531	2.209727E+03	2.280211E+03
532	2.280211E+03	2.352943E+03
533	2.352943E+03	2.427995E+03
534	2.427995E+03	2.505440E+03
535	2.505440E+03	2.585357E+03
536	2.585357E+03	2.667822E+03
537	2.667822E+03	2.752917E+03
538	2.752917E+03	2.840727E+03
539	2.840727E+03	2.931338E+03
540	2.931338E+03	3.024839E+03
541	3.024839E+03	3.121323E+03
542	3.121323E+03	3.220883E+03
543	3.220883E+03	3.323620E+03
544	3.323620E+03	3.429634E+03
545	3.429634E+03	3.539029E+03
546	3.539029E+03	3.651913E+03
547	3.651913E+03	3.768398E+03
548	3.768398E+03	3.888599E+03
549	3.888599E+03	4.012634E+03

- ▶ Using any standard *fits* file viewer.
- ▶ In terminal: fv
“TCAF_v0.3.2._R1.fits”
- ▶ Summary Window > View > Energies > All: parameter space.
- ▶ Why? Check the upper/lower limits.
Check the **resolution at any energy**.

<https://heasarc.gsfc.nasa.gov/ftools/fv/>

TCAF Fits File

Plotting the SED



- ▶ Using XSPEC.
- ▶ In terminal: model atable{TCAF_v0.3.2._R1.fits}

```
TCAF Session > xspec
XSPEC version: 12.14.0h
Build Date/Time: Wed Jul 10 21:31:06 2024

XSPEC12>model atable{TCAF_v0.3.2_R1.fits}

Input parameter value, delta, min, bot, top, and max values for ...
  0.002   0.1697( 2e-05)   0.001   0.001     8     8
1:TCAF:mdotd>0.1
  0.002   0.1697( 2e-05)   0.001   0.001     8     8
2:TCAF:mdoth>1.0
  8   3.33333( 0.08)      5       5    15    15
3:TCAF:mbh>10.0
  100  0.0765073( 1)      8       8    460    460
4:TCAF:xs>100.0
  1.5   0.7375( 0.015)    1.05   1.05     4     4
5:TCAF:R>3.0
  1   0.01( 0.01)        0       0  1e+20  1e+24
6:TCAF:norm>1.0

=====
Model atable{TCAF_v0.3.2_R1.fits}<1> Source No.: 1 Active/Off
Model Model Component Parameter Unit Value
par comp
  1   1   TCAF      mdotd      0.100000 +/- 0.0
  2   1   TCAF      mdoth      1.000000 +/- 0.0
  3   1   TCAF      mbh       10.000000 +/- 0.0
  4   1   TCAF      xs        100.000000 +/- 0.0
  5   1   TCAF      R         3.000000 +/- 0.0
  6   1   TCAF      norm      1.000000 +/- 0.0

XSPEC12>pl mo emo eemo
XSPEC12>cpd /xw
XSPEC12>pl mo emo eemo
XSPEC12>
```

Fitting with the TCAF *Fits* File

Loading the Data

```
TCAF SESSION> xspec
XSPEC version: 12.11.0
Build Date/Time: Thu Jun 25 15:05:33 2020

XSPEC12>cpd /xw
XSPEC12>data xp50137010500
xp50137010500.rsp.gz  xp50137010500_b2c.lc.gz  xp50137010500_n2a.lc.gz  xp50137010500_n2e.lc.gz  xp50137010500_s2c.lc.gz
xp50137010500_b2.pha.gz  xp50137010500_b2d.lc.gz  xp50137010500_n2b.lc.gz  xp50137010500_s2.pha.gz  xp50137010500_s2d.lc.gz
xp50137010500_b2a.lc.gz  xp50137010500_b2e.lc.gz  xp50137010500_n2c.lc.gz  xp50137010500_s2a.lc.gz  xp50137010500_s2e.lc.gz
xp50137010500_b2b.lc.gz  xp50137010500_n1.lc.gz  xp50137010500_n2d.lc.gz  xp50137010500_s2b.lc.gz
XSPEC12>data xp50137010500_s2.pha.gz

1 spectrum in use

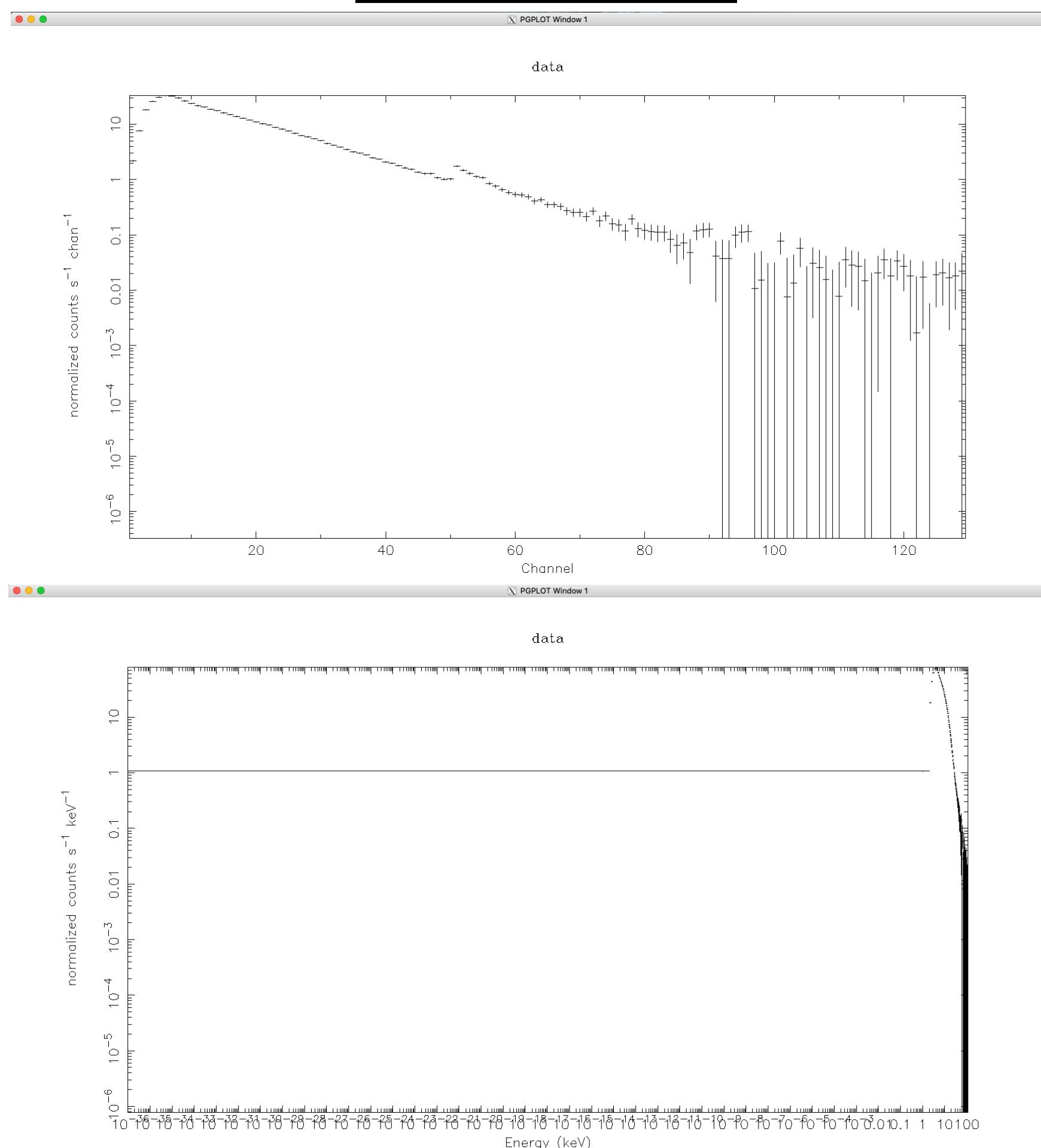
Spectral Data File: xp50137010500_s2.pha.gz Spectrum 1
Net count rate (cts/s) for Spectrum:1 5.289e+02 +/- 6.891e-01 (79.3 % total)
Assigned to Data Group 1 and Plot Group 1
Noticed Channels: 1-129
Telescope: XTE Instrument: PCA Channel Type: PHA
Exposure Time: 1696 sec
Using fit statistic: chi
Using Background File          xp50137010500_b2.pha
Background Exposure Time: 1696 sec
Using Response (RMF) File      xp50137010500.rsp for Source 1

XSPEC12>
```

- ▶ Using XSPEC.
- ▶ Essential files:
 - ▶ 1. Source spectrum
 - ▶ 2. Background spectrum
 - ▶ 3. Response file (to convert channel > energy)

Fitting with the TCAF *Fits* File

Visualising the Data



- ▶ Using XSPEC.
- ▶ Essential files:
 - ▶ 1. Source spectrum
 - ▶ 2. Background spectrum
 - ▶ 3. Response file (to convert channel > energy)

```
TCAF SESSION> xspec
XSPEC version: 12.11.0
Build Date/Time: Thu Jun 25 15:05:33 2020

XSPEC12>cpd /xw
XSPEC12>data xp50137010500
xp50137010500.rsp.gz  xp50137010500_b2c.lc.gz  xp50137010500_n2a.lc.gz  xp50137010500_n2e.lc.gz  xp50137010500_s2c.lc.gz
xp50137010500_b2e.gz  xp50137010500_b2d.lc.gz  xp50137010500_n2b.lc.gz  xp50137010500_s2e.pha.gz  xp50137010500_s2d.lc.gz
xp50137010500_b2a.lc.gz  xp50137010500_b2e.lc.gz  xp50137010500_n2c.lc.gz  xp50137010500_s2a.lc.gz  xp50137010500_s2e.lc.gz
xp50137010500_b2b.lc.gz  xp50137010500_n1.lc.gz  xp50137010500_n2d.lc.gz  xp50137010500_s2b.lc.gz
XSPEC12>data xp50137010500_s2.pha.gz

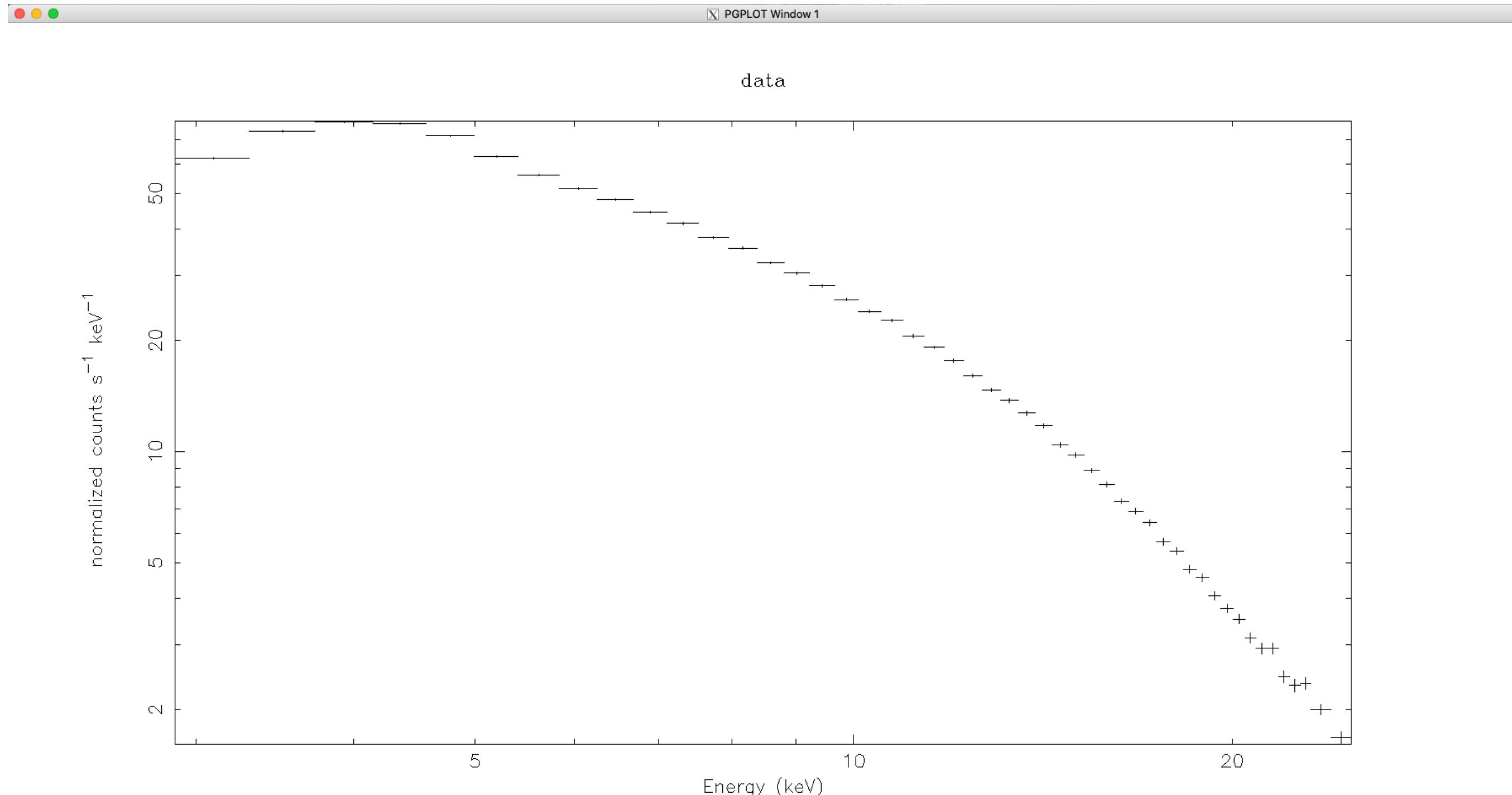
1 spectrum in use

Spectral Data File: xp50137010500_s2.pha.gz Spectrum 1
Net count rate (cts/s) for Spectrum:1 5.289e+02 +/- 6.891e-01 (79.3 % total)
Assigned to Data Group 1 and Plot Group 1
Noticed Channels: 1-129
Telescope: XTE Instrument: PCA Channel Type: PHA
Exposure Time: 1696 sec
Using fit statistic: chi
Using Background File: xp50137010500_b2.pha
Background Exposure Time: 1696 sec
Using Response (RMF) File: xp50137010500.rsp for Source 1

XSPEC12>p1 ld
XSPEC12>p1 ld
XSPEC12>setplot e
XSPEC12>p1 ld
XSPEC12>
```

Fitting with the TCAF *Fits* File

Choosing the Range



- ▶ Using XSPEC.
- ▶ Select the range of interest:
- ▶ Ignore **set of channels** out of region of interest

```
TCAF SESSION> xspec
XSPEC version: 12.11.0
Build Date/Time: Thu Jun 25 15:05:33 2020
XSPEC12>cpd /xw
XSPEC12>data xp50137010500
xp50137010500.rsp.gz  xp50137010500_b2c.lc.gz  xp50137010500_n2a.lc.gz  xp50137010500_n2e.lc.gz  xp50137010500_s2c.lc.gz
xp50137010500_b2.pha.gz  xp50137010500_b2d.lc.gz  xp50137010500_n2b.lc.gz  xp50137010500_s2.pha.gz  xp50137010500_s2d.lc.gz
xp50137010500_b2a.lc.gz  xp50137010500_b2e.lc.gz  xp50137010500_n2c.lc.gz  xp50137010500_s2a.lc.gz  xp50137010500_s2e.lc.gz
xp50137010500_d2b.lc.gz  xp50137010500_n1.lc.gz  xp50137010500_n2d.lc.gz  xp50137010500_s2b.lc.gz
XSPEC12>data xp50137010500_s2.pha.gz

1 spectrum in use

Spectral Data File: xp50137010500_s2.pha.gz Spectrum 1
Net count rate (cts/s) for Spectrum: 1 5.289e+02 +/- 6.891e-01 (79.3 % total)
Assigned to Data Group 1 and Plot Group 1
Noticed Channels: 1-129
Telescope: XTE Instrument: PCA Channel Type: PHA
Exposure Time: 1696 sec
Using fit statistic: chi
Using Background File xp50137010500_b2.pha
Background Exposure Time: 1696 sec
Using Response (RMF) File xp50137010500.rsp for Source 1

XSPEC12>pl ld
XSPEC12>pl ld
XSPEC12>setplot e
XSPEC12>pl ld
XSPEC12>ig **-2.5 25.0-**
    3 channels (1-3) ignored in spectrum # 1
    77 channels (53-129) ignored in spectrum # 1

XSPEC12>
```

Fitting with the TCAF *Fits* File

Loading the Model

```

/usr/bin/clear
XSPEC12>model phabs*atable{/Users/ayanhattacharjee/WORKSPACE/WORKSNB/PROJECTS/TCAFMANUAL/TCAFVN/FITSFILES/TCAF_v0.3.2_R1.fits}
Input parameter value, delta, min, bot, top, and max values for ...
   1    0.001(     0.01)      0      0    100000    1e+06
1:phabs:nH>0.013 -1
   0.002    0.1697(   2e-05)    0.001    0.001      8      8
2:TCAF:mdotd>0.005
   0.002    0.1697(   2e-05)    0.001    0.001      8      8
3:TCAF:mdoth>0.25
   8    3.33333(    0.08)      5      5    15    15
4:TCAF:mbh>6.99 -1
   100    0.0765073(     1)      8      8    460    460
5:TCAF:xs>70.0
   1.5    0.7375(    0.015)    1.05    1.05      4      4
6:TCAF:R>3.0
   1    0.01(     0.01)      0      0    1e+20    1e+24
7:TCAF:norm>29.67 -1

=====
Model phabs<1>*atable{/Users/ayanhattacharjee/WORKSPACE/WORKSNB/PROJECTS/TCAFMANUAL/TCAFVN/FITSFILES/TCAF_v0.3.2_R1.fits}<2> Source No.: 1 Active
/On
Model Model Component Parameter Unit      Value
par comp
  1  1  phabs      nH      10^22  1.30000E-02 frozen
  2  2  TCAF       mdotd    5.00000E-03 +/- 0.0
  3  2  TCAF       mdoth    0.250000 +/- 0.0
  4  2  TCAF       mbh     6.99000 frozen
  5  2  TCAF       xs      70.0000 +/- 0.0
  6  2  TCAF       R       3.00000 +/- 0.0
  7  2  TCAF       norm    29.6700 frozen

Fit statistic : Chi-Squared          57792.10      using 49 bins.
Test statistic : Chi-Squared        57792.10      using 49 bins.
Null hypothesis probability of 0.00e+00 with 45 degrees of freedom
Current data and model not fit yet.
XSPEC12>

```

Use local path

- ▶ Using XSPEC.
- ▶ Select the fits file as a Table model.
- ▶ Use preferred models for absorption due to ISM.
- ▶ Freeze the parameters not to be varied: freeze “parameter number” or by adding “-1” as delta
- ▶ Keep n_H fixed if prior observation exists.
- ▶ Keep “norm” fixed based on distance and angle of observation measurement (if any).

Fitting with the TCAF *Fits* File

Setting Error Limits

```

/usr/bin/clear
XSPEC12>model phabs*atable{/Users/ayanbhattacharjee/WORKSPACE/WORKSNB/PROJECTS/TCAFMANUAL/TCAFVN/FITSFILES/TCAF_v0.3.2_R1.fits}
Input parameter value, delta, min, bot, top, and max values for ...
   1    0.001(     0.01)      0      0    100000    1e+06
1:phabs:nH>0.013 -1
   0.002    0.1697(   2e-05)    0.001    0.001      8      8
2:TCAF:mdotd>0.005
   0.002    0.1697(   2e-05)    0.001    0.001      8      8
3:TCAF:mdoth>0.25
   8    3.33333(   0.08)      5      5    15    15
4:TCAF:mbh>6.99 -1
   100   0.0765073(      1)      8      8    460    460
5:TCAF:xs>70.0
   1.5    0.7375(   0.015)    1.05    1.05      4      4
6:TCAF:R>3.0
   1    0.01(     0.01)      0      0    1e+20    1e+24
7:TCAF:norm>29.67 -1

=====
Model phabs<1>*atable{/Users/ayanbhattacharjee/WORKSPACE/WORKSNB/PROJECTS/TCAFMANUAL/TCAFVN/FITSFILES/TCAF_v0.3.2_R1.fits}<2> Source No.: 1 Active
/On
Model Model Component Parameter Unit      Value
par comp
 1 1 phabs      nH      10^22  1.3000E-02 frozen
 2 2 TCAF       mdotd    5.00000E-03 +/- 0.0
 3 2 TCAF       mdoth    0.250000 +/- 0.0
 4 2 TCAF       mbh      6.99000 frozen
 5 2 TCAF       xs       70.0000 +/- 0.0
 6 2 TCAF       R        3.00000 +/- 0.0
 7 2 TCAF       norm     29.6700 frozen

Fit statistic : Chi-Squared          57792.10      using 49 bins.
Test statistic : Chi-Squared        57792.10      using 49 bins.
Null hypothesis probability of 0.00e+00 with 45 degrees of freedom
Current data and model not fit yet.
XSPEC12>systematic 0.005
  Model systematic error set to 0.005
XSPEC12>query yes
XSPEC12>

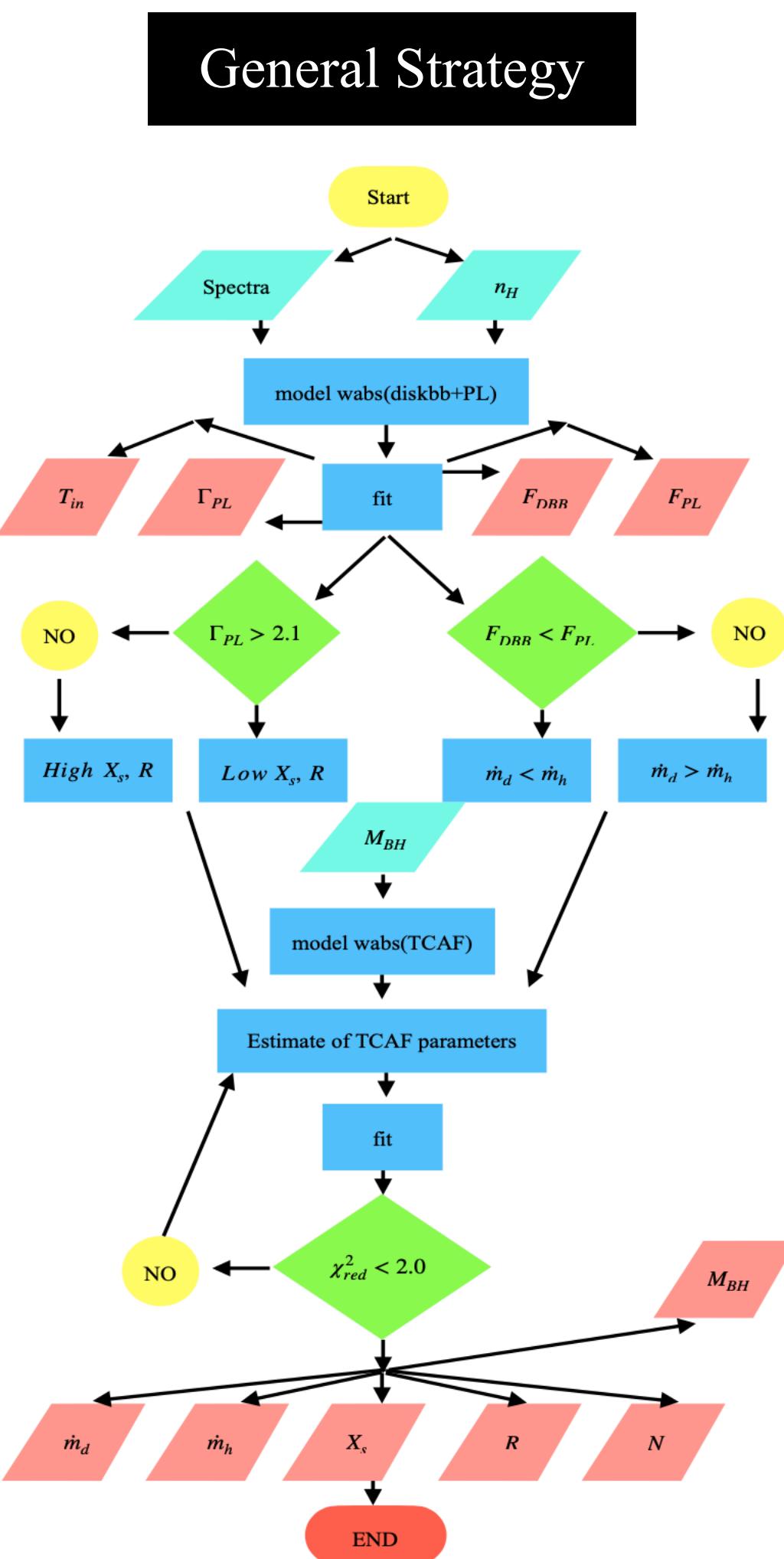
```

Based on data

To remove y/n prompts

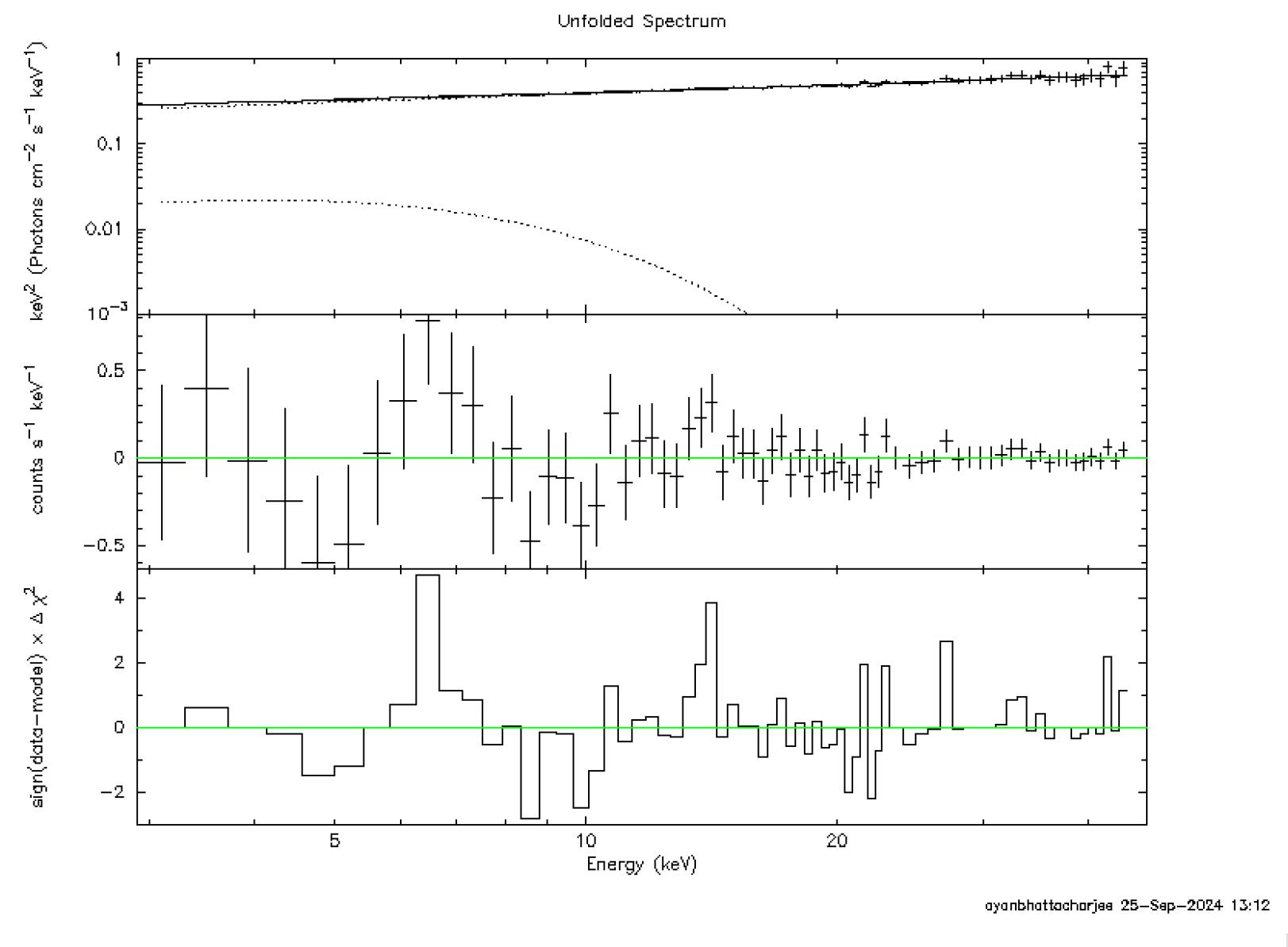
- ▶ Using XSPEC.
- ▶ Choose appropriate systematic error: 0.5% here, can be lower for recent observations.
- ▶ To remove y/n prompts, use “Query yes”. To check each steps more carefully, do not turn this flag on.

Fitting with the TCAF *Fits* File



Fitting with the TCAF *Fits* File

Initial Guess



```
=====
Model phabs<1>(cflux<2>*diskbb<3> + powerlaw<4>) Source No.: 1 Active/On
Model fractional systematic error = 0.005
Model Model Component Parameter Unit      Value
par comp
 1 1 phabs      nH      10^22   1.30000E-02 frozen
 2 2 cflux      Emin    keV     2.50000   frozen
 3 2 cflux      Emax    keV     10.0000   frozen
 4 2 cflux      lg10Flux cgs    -10.3990 +/- 0.123145
 5 3 diskbb     Tin     keV     1.74295 +/- 0.109689
 6 3 diskbb     norm    -       0.353506 frozen
 7 4 powerlaw   PhoIndex -       1.66218 +/- 1.44981E-02
 8 4 powerlaw   norm    -       0.179492 +/- 7.34367E-03

Fit statistic : Chi-Squared           53.97   using 71 bins.
Test statistic : Chi-Squared        53.97   using 71 bins.
Null hypothesis probability of 8.75e-01 with 67 degrees of freedom
```

```
=====
Model phabs<1>(diskbb<2> + cflux<3>*powerlaw<4>) Source No.: 1 Active/On
Model fractional systematic error = 0.005
Model Model Component Parameter Unit      Value
par comp
 1 1 phabs      nH      10^22   1.30000E-02 frozen
 2 2 diskbb    Tin     keV     1.74291 +/- 0.109661
 3 2 diskbb    norm    -       0.353451 +/- 0.117685
 4 3 cflux      Emin    keV     2.50000   frozen
 5 3 cflux      Emax    keV     45.0000   frozen
 6 3 cflux      lg10Flux cgs    -8.71670 +/- 2.21915E-03
 7 4 powerlaw   PhoIndex -       1.66219 +/- 1.45125E-02
 8 4 powerlaw   norm    -       0.179495 frozen

Fit statistic : Chi-Squared           53.97   using 71 bins.
Test statistic : Chi-Squared        53.97   using 71 bins.
Null hypothesis probability of 8.75e-01 with 67 degrees of freedom
```

- ▶ Using XSPEC.
- ▶ Select the model of interest:
 - ▶ We use diskbb+powelaw.
- ▶ Check F_{BB} and F_{PL} to estimate initial accretion rates.

Fitting with the TCAF *Fits* File

Initial Fits

```

XSPEC12>fit 100
Warning: renorm - no variable model to allow renormalization
          Parameters
Chi-Squared |beta|/N   Lvl      2:mdotd    3:mdoth    5:xs       6:R
1474.16     3.19559e+06 -3      0.00381290   0.258457   63.5793   3.24841
1180.7      552530      -3      0.00639696   0.253581   66.1274   3.09402
55.1442     357826      -4      0.00725196   0.253120   65.2023   3.07945
53.6829     3759.36     -4      0.00750481   0.252526   65.6336   3.07074
53.5732     3903.46     -4      0.00754296   0.252450   66.0540   3.07867
53.5724     328.708     -2      0.00754330   0.252451   66.0584   3.07878
=====
Variances and Principal Axes
          2      3      5      6
4.3919E-10| -0.9798 -0.1998 0.0002 -0.0080
1.1327E-06|  0.1999 -0.9789 0.0005 -0.0431
7.8815E+01| -0.0008 0.0437 -0.0561 -0.9975
6.6324E+05| -0.0000 -0.0030 -0.9984 0.0560
=====
Covariance Matrix
          1      2      3      4
1.738e-04 2.469e-02 9.061e+00 -4.456e-01
2.469e-02 6.214e+00 2.002e+03 -1.157e+02
9.061e+00 2.002e+03 6.612e+05 -3.707e+04
-4.456e-01 -1.157e+02 -3.707e+04 2.158e+03
=====
Model phabs<1>*atable{/Users/ayanhattacharjee/WORKSPACE/WORKSNB/PROJECTS/TCAFMANUAL/TCAFVN/FITSFILES/TCAF_v0.3.2_R1.fits}<2> Source No.: 1 Active
/On
Model Model Component Parameter Unit      Value
par comp
 1 1 phabs      nh      10^22  1.30000E-02 frozen
 2 2 TCAF        mdotd   7.54330E-03 +/- 1.31829E-02
 3 2 TCAF        mdoth   0.252451  +/- 2.49285
 4 2 TCAF        mbh     6.99000  frozen
 5 2 TCAF        xs      66.0584  +/- 813.112
 6 2 TCAF        R       3.07878  +/- 46.4532
 7 2 TCAF        norm    29.6700  frozen
=====
Fit statistic : Chi-Squared           53.57  using 49 bins.

```

- ▶ Using XSPEC.
- ▶ Fit using: fit #number of iterative steps
- ▶ Or use “fit” to run until minimum χ^2 is obtained.

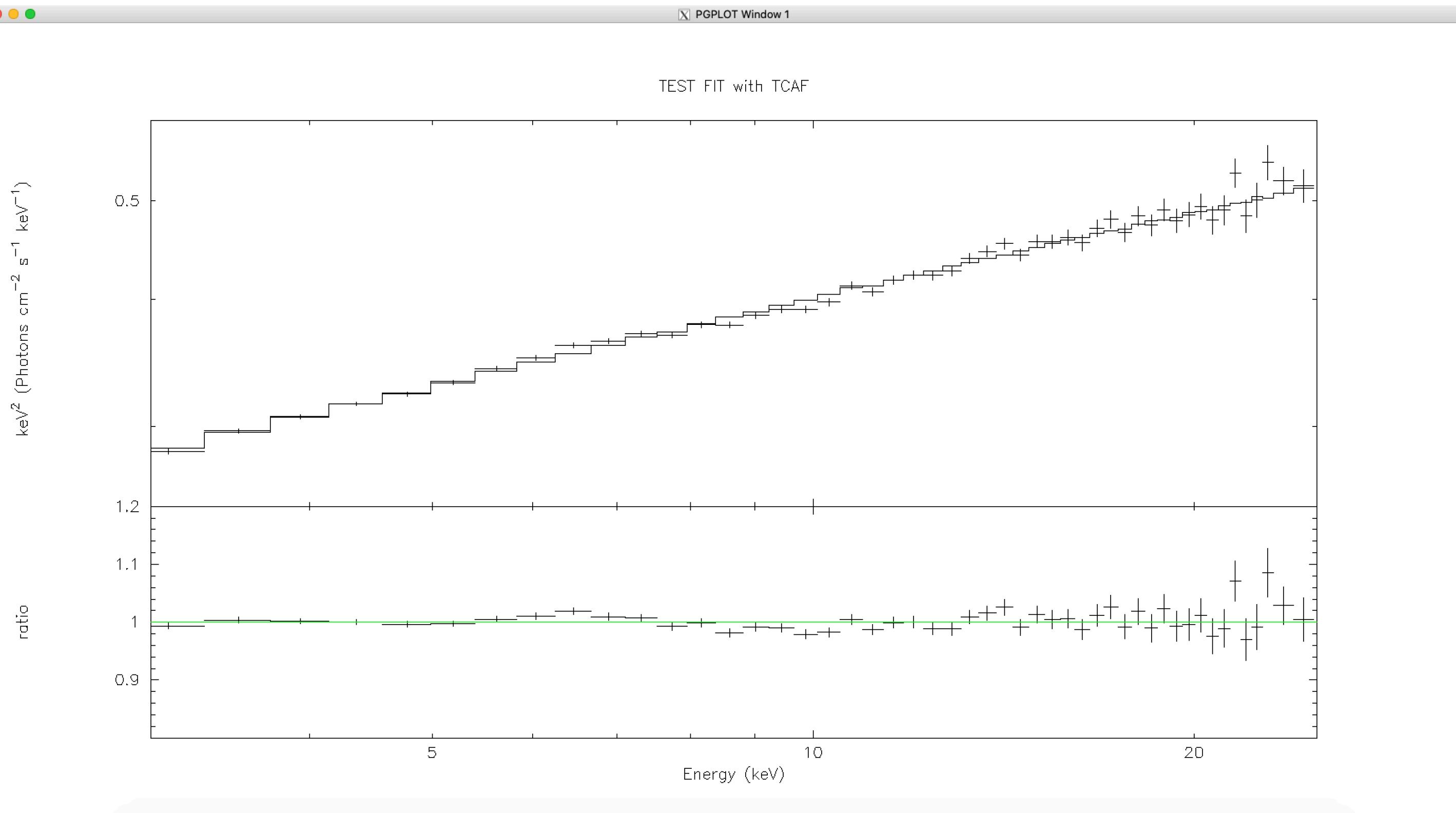
```

Null hypothesis probability of 1.78e-01 with 45 degrees of freedom
XSPEC12>fit
Warning: renorm - no variable model to allow renormalization
          Parameters
Chi-Squared |beta|/N   Lvl      2:mdotd    3:mdoth    5:xs       6:R
53.5724     48.7154     -2      0.00754357   0.252451   66.0636   3.07886
=====
Variances and Principal Axes
          2      3      5      6
4.3929E-10| -0.9798 -0.1998 0.0002 -0.0080
1.1325E-06|  0.1999 -0.9789 0.0005 -0.0431
7.9151E+01| -0.0008 0.0437 -0.0562 -0.9975
6.6487E+05| -0.0000 -0.0030 -0.9984 0.0561
=====
Covariance Matrix
          1      2      3      4
1.739e-04 2.476e-02 9.072e+00 -4.471e-01
2.476e-02 6.246e+00 2.019e+03 -1.164e+02
9.072e+00 2.810e+03 6.628e+05 -3.725e+04
-4.471e-01 -1.164e+02 -3.725e+04 2.173e+03
=====
Model phabs<1>*atable{/Users/ayanhattacharjee/WORKSPACE/WORKSNB/PROJECTS/TCAFMANUAL/TCAFVN/FITSFILES/TCAF_v0.3.2_R1.fits}<2> Source No.: 1 Active
/On
Model Model Component Parameter Unit      Value
par comp
 1 1 phabs      nh      10^22  1.30000E-02 frozen
 2 2 TCAF        mdotd   7.54357E-03 +/- 1.31882E-02
 3 2 TCAF        mdoth   0.252451  +/- 2.49924
 4 2 TCAF        mbh     6.99000  frozen
 5 2 TCAF        xs      66.0636  +/- 814.107
 6 2 TCAF        R       3.07886  +/- 46.6119
 7 2 TCAF        norm    29.6700  frozen
=====
Fit statistic : Chi-Squared           53.57  using 49 bins.
Test statistic : Chi-Squared         53.57  using 49 bins.
Null hypothesis probability of 1.78e-01 with 45 degrees of freedom
XSPEC12>

```

Fitting with the TCAF *Fits* File

Fitting the Data



- ▶ Using XSPEC.
- ▶ Fit using: fit #number of iterative steps
- ▶ Or use “fit” to run until minimum χ^2 is obtained.

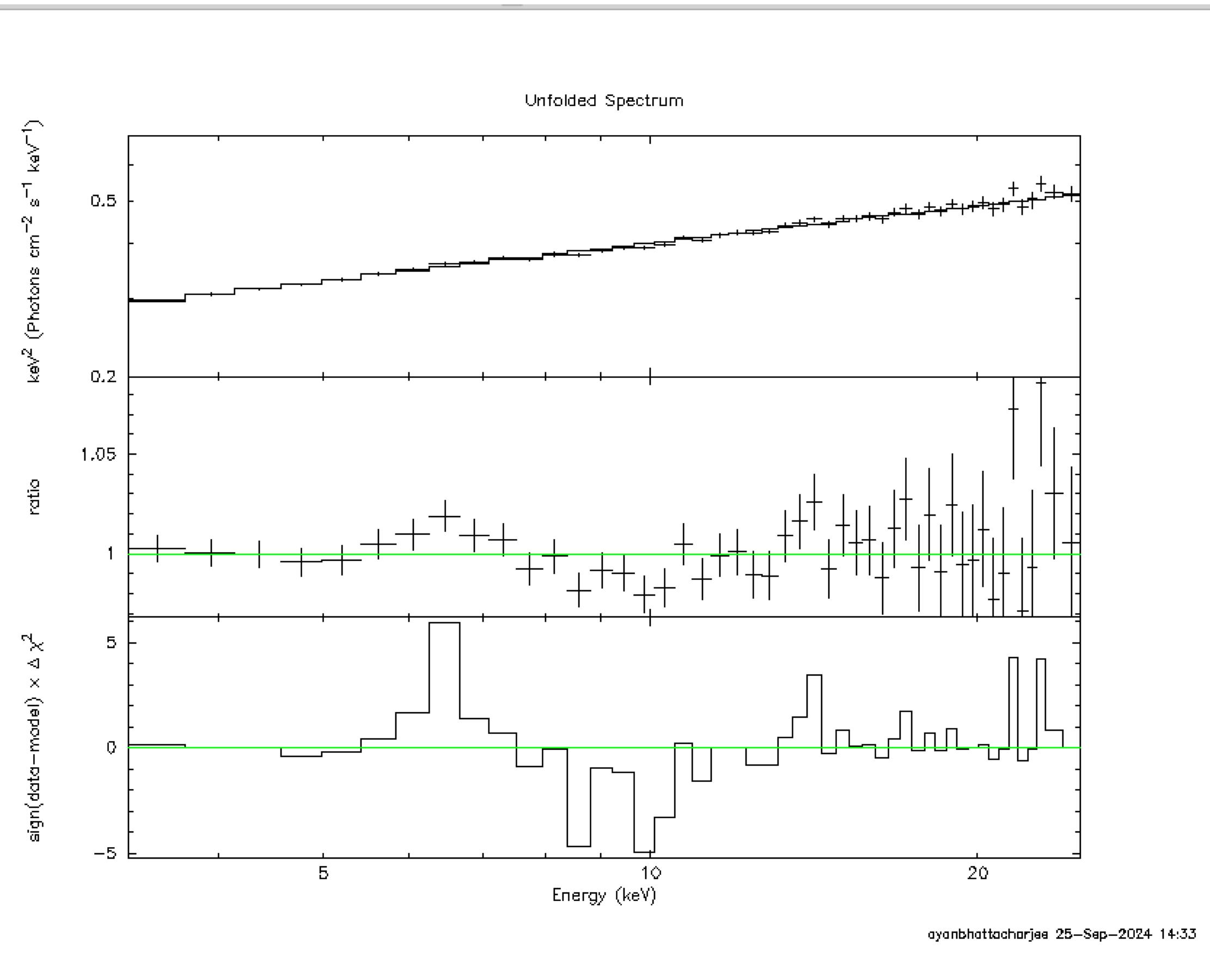
```

Chi-Squared |beta|/N   Lv1    2:mdotd   3:mdoth   5:xs     6:R
52.4691   1233.28   -2    0.00764516   0.252287  66.2557  3.07585
52.469   79.0469   -2    0.00764600   0.252287  66.2675  3.07596
=====
Variances and Principal Axes
      2      3      5      6
4.7971E-10 | -0.9787 -0.2053  0.0002 -0.0082
1.2987E-06 |  0.2054 -0.9777  0.0065 -0.0438
1.0411E+02 | -0.0008  0.0437 -0.0555 -0.9975
9.6931E+05 | -0.0000 -0.0029 -0.9985  0.0555
=====
Covariance Matrix
      1      2      3      4
3.492e-04  4.506e-02  1.650e+01 -8.326e-01
4.506e-02  8.634e+00  2.855e+03 -1.631e+02
1.650e+01  2.855e+03  9.663e+05 -5.367e+04
-8.326e-01 -1.631e+02 -5.367e+04  3.085e+03
=====
Model phabs<1>*atable{/Users/ayanbattacharjee/WORKSPACE/WORKSNB/PROJECTS/TCAFMANUAL/TCAFVN/FITSFILES/TCAF_v0.3.2_R1.fits}<2> Source No.: 1 Active
/On
Model Model Component Parameter Unit      Value
par comp
  1 1 phabs      nH      10^22  1.3000E-02 frozen
  2 2 TCAF       mdotd   7.64600E-03 +/- 1.86863E-02
  3 2 TCAF       mdoth   0.252287 +/- 2.93835
  4 2 TCAF       mbh      6.99000 frozen
  5 2 TCAF       xs       66.2675 +/- 983.016
  6 2 TCAF       R        3.07596 +/- 55.5466
  7 2 TCAF       norm     29.6700 frozen
=====
Fit statistic : Chi-Squared          52.47   using 48 bins.
Test statistic : Chi-Squared         52.47   using 48 bins.
Null hypothesis probability of 1.79e-01 with 44 degrees of freedom
XSPEC12>save all TCAF_TEST_FITS.xcm
XSPEC12>save model TCAF_TEST_MODEL.xcm
XSPEC12>

```

Fitting with the TCAF *Fits* File

Check: data/model



<https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html>
<https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/node330.html#AppendixPLT>

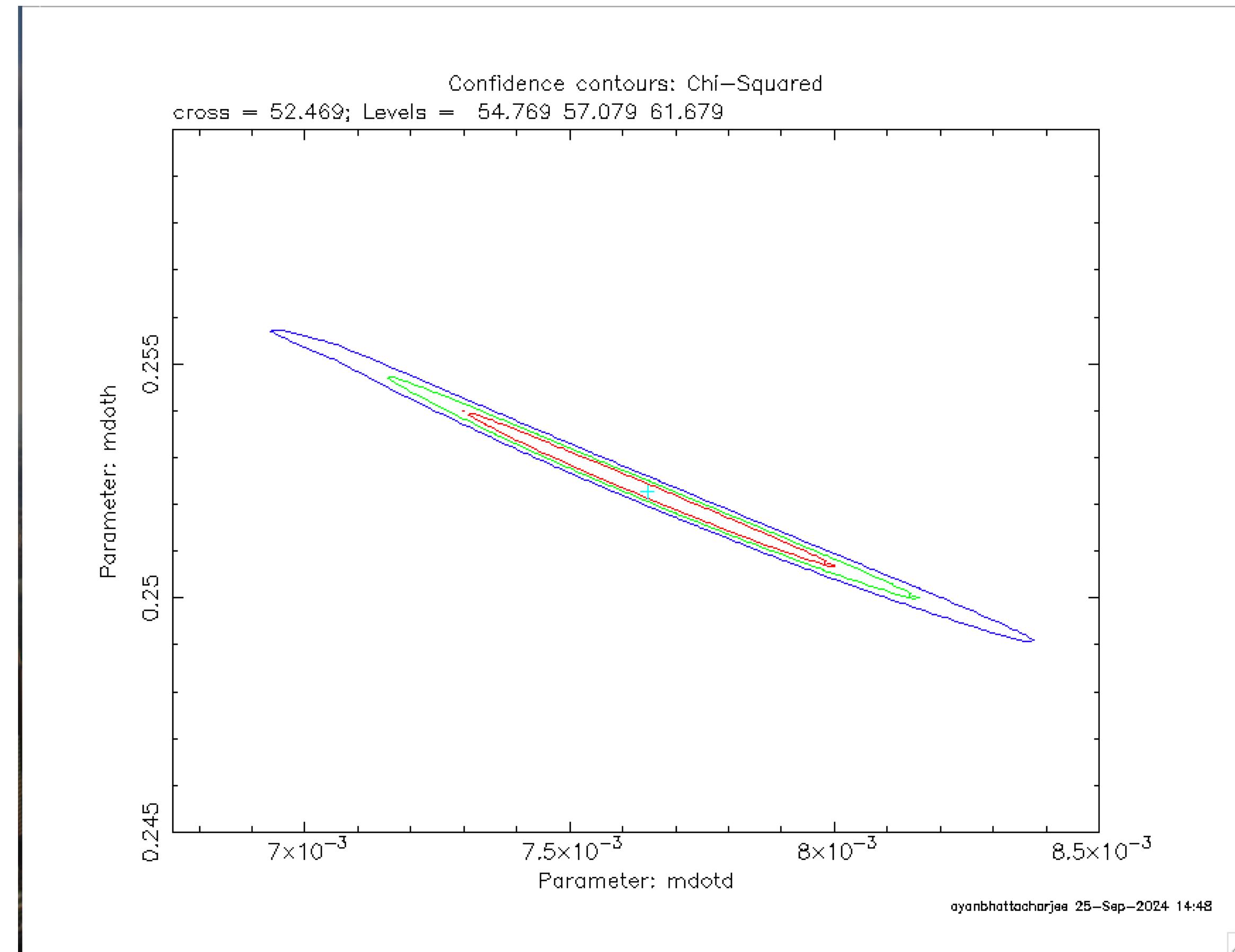
- ▶ Using XSPEC.
- ▶ Visualising the fit: quantifying data vs model
 - ▶ Unfolded spectrum
 - ▶ Ratio of data vs model
 - ▶ $\Delta\chi^2$ vs energy.

```
XSPEC12>pl eeuf rat chi
XSPEC12>ipl
PLT> r y 0.001 1.0
PLT> r y 0.01 1.0
PLT> r y 0.1 1.0
PLT> r y 0.1 0.5
PLT> r y 0.1 0.7
PLT> r y 0.2 0.7
PLT> q
XSPEC12>setpl e
XSPEC12>pl eeuf rat chi
XSPEC12>ipl
PLT> r y 0.2 0.7
PLT> wd TCAF_TEST_FITS_data.qdp
PLT> h TCAF_TEST_FITS_data.eps/cps
```

- ▶ Using PGPlot/iplot: Alter plot specifications.
- ▶ Extracting fitted data:
 - ▶ wd (for ascii),
 - ▶ h (for image).

Fitting with the TCAF *Fits* File

Quality of Fits



- ▶ Using XSPEC.
- ▶ Checking if true minima: using “steppar”
 - ▶ Choose a narrow range of parameters around fitted value.
 - ▶ Choose 2 parameters at time, freeze the rest.
 - ▶ Use high number of steps.

```
XSPEC12>freez 5 6
Fit statistic : Chi-Squared          52.47    using 48 bins.

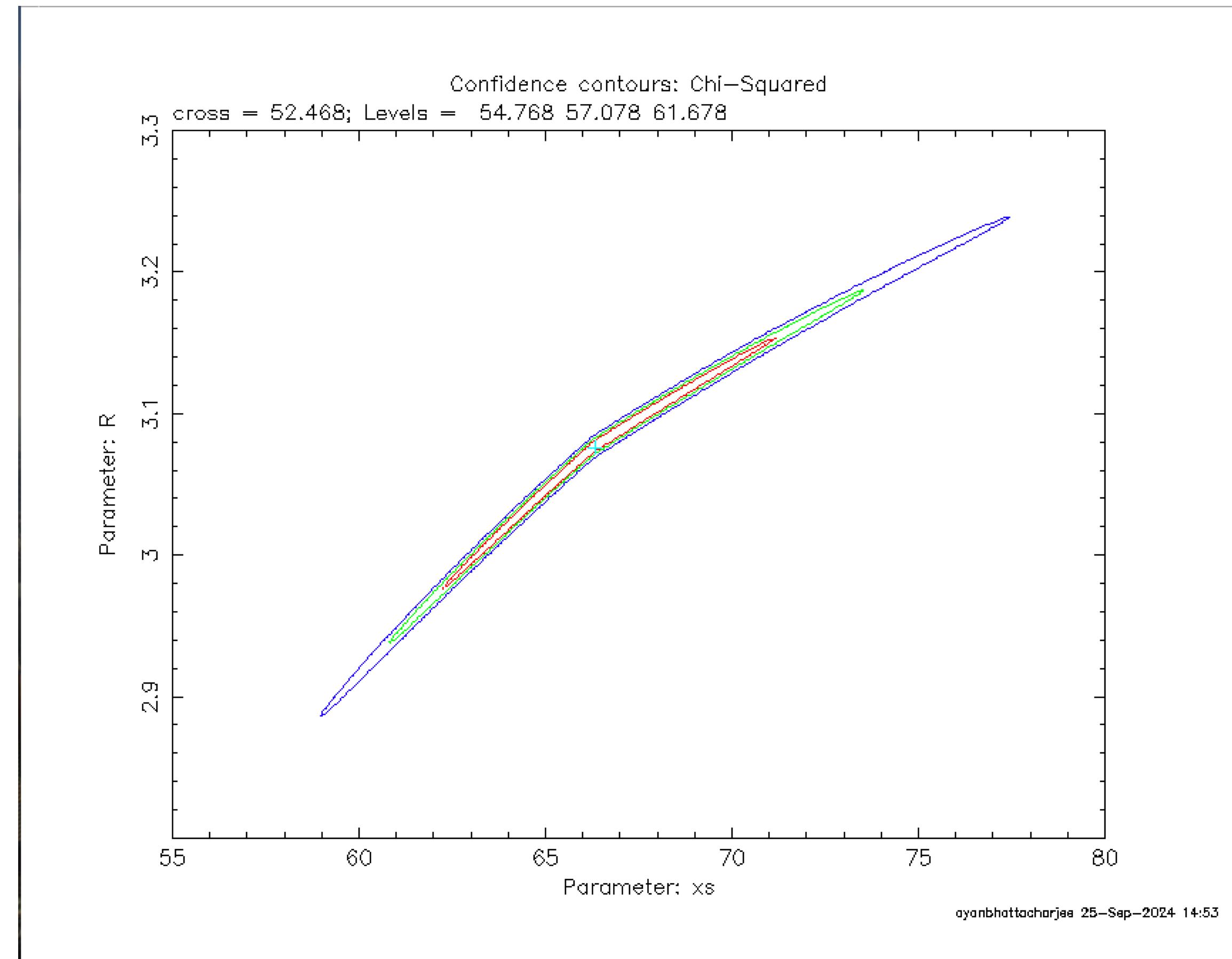
Test statistic : Chi-Squared          52.47    using 48 bins.
Null hypothesis probability of 2.38e-01 with 46 degrees of freedom
Current data and model not fit yet.
XSPEC12>steppar 2 0.006 0.009 300 3 0.24 0.27 300
```

```
XSPEC12>iplot
[PLT> r x 6.75e-3 8.75e-3
[PLT> r x 6.75e-3 8.5e-3
[PLT> r y 0.245 0.26
PLT>
```

- ▶ Using PGPlot/iplot: Alter plot specifications.
- ▶ Extracting fitted data:
 - ▶ wd (for ascii),
 - ▶ h (for image).

Fitting with the TCAF *Fits* File

Quality of Fits



<https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html>

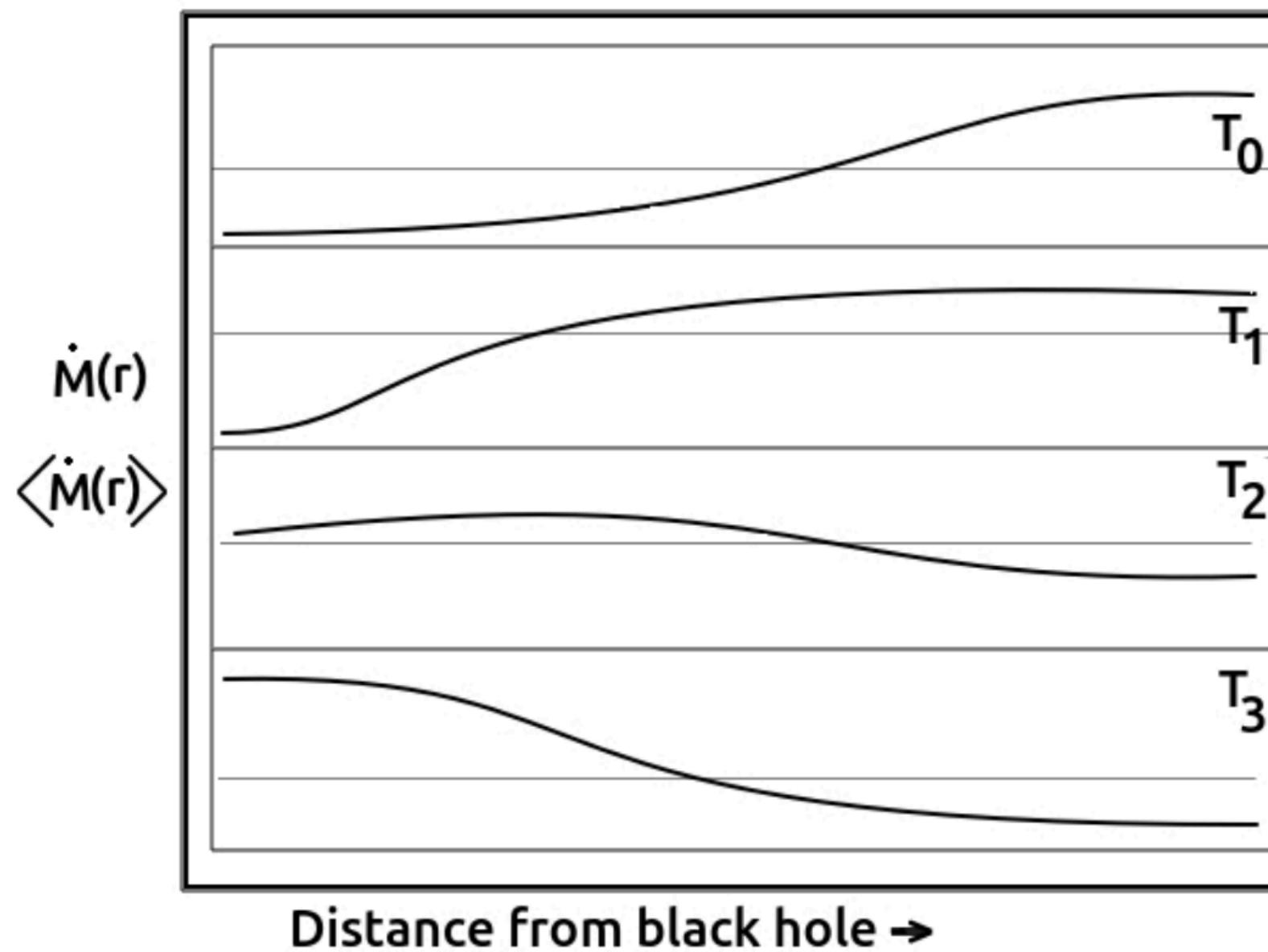
- ▶ Using XSPEC.
- ▶ Checking if true minima: using “steppar”
 - ▶ Choose a broad range first > check local/global minima.
 - ▶ Choose narrow range of parameters around fitted value > Obtain smoother $\Delta\chi^2$ contour.
 - ▶ Choose 2 parameters at time, freeze the rest.
 - ▶ Use high number of steps.

```
XSPEC12>steppar 5 55.0 80.0 300 6 2.8 3.3 300
```

- ▶ Using PGPlot/iplot: Alter plot specifications.
- ▶ Extracting fitted data:
 - ▶ wd (for ascii),
 - ▶ h (for image).

Caveats

- **Radiative Components:** No synchrotron emission, Fe Line emission or Comptonization of Fe line.
- **Geometrical Components:** JeTCAF includes base of jet, but present TCAF code only used CENBOL.
- **Temporal Variations:** Smaller time scale or larger amplitude fluctuations are not included in this steady state solution.



Key Points

- Sub-Keplerian flows around black holes, across different mass scales and companion masses, are the **default** mode of accretion. In quiescent states, the flow configuration is ‘halo dominated’ and thus, higher value of \dot{m}_h is expected.
- During an outburst, or for persistently bright sources, higher flux requires more photons, which is efficiently supplied by a disk. Onset of higher viscosity (beyond the critical value), triggers the formation and sustains the disk component. In such scenarios, a higher \dot{m}_d is expected, which varies over time.
- Due to the interplay of \dot{m}_d (supplier of soft photons), and \dot{m}_h (supplier of hot electrons; Compton cloud), the shock location X_s changes (propagating, oscillating).

X-ray Spectral fitting of BHXRBS by TCAF FITS file:

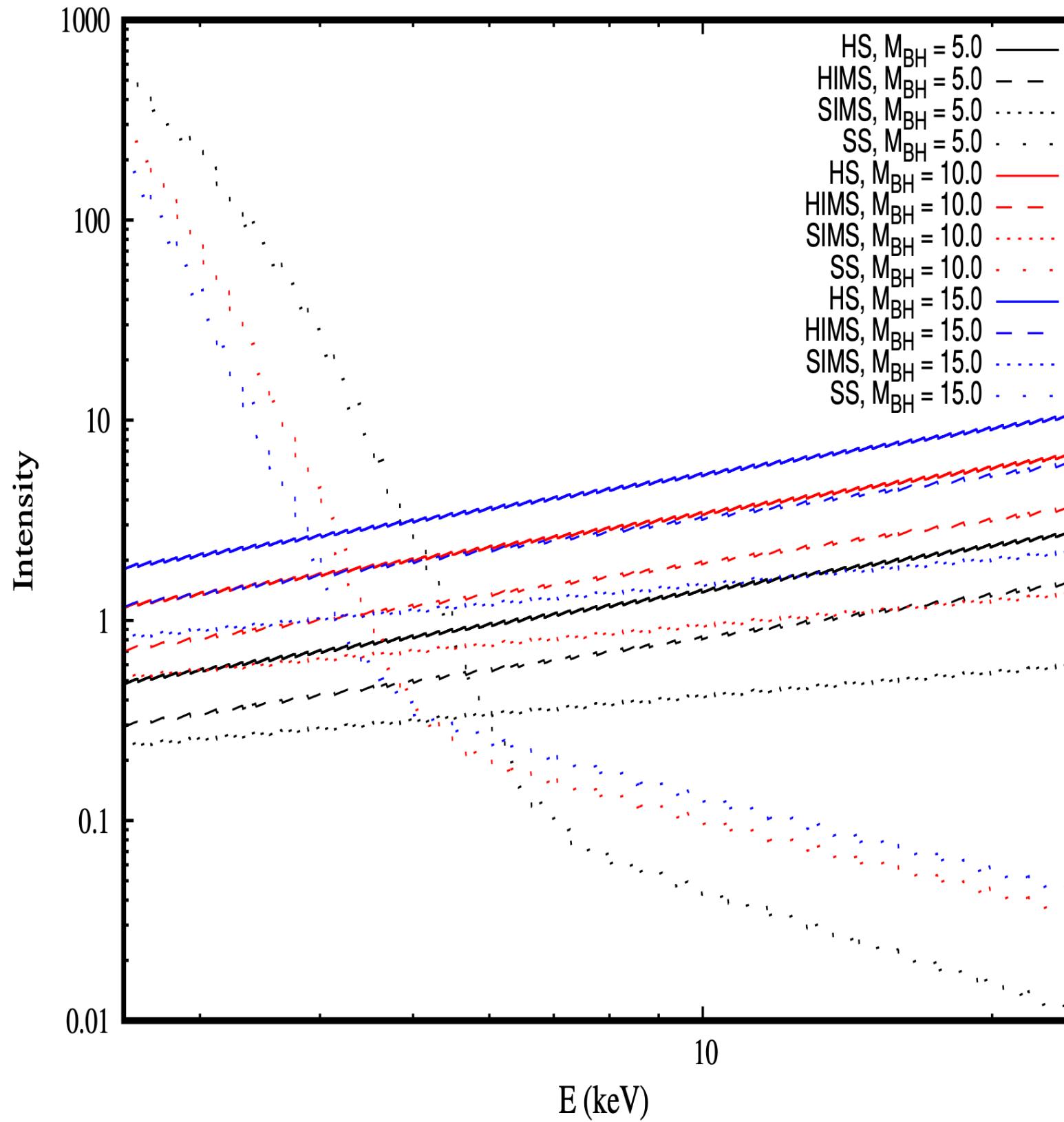
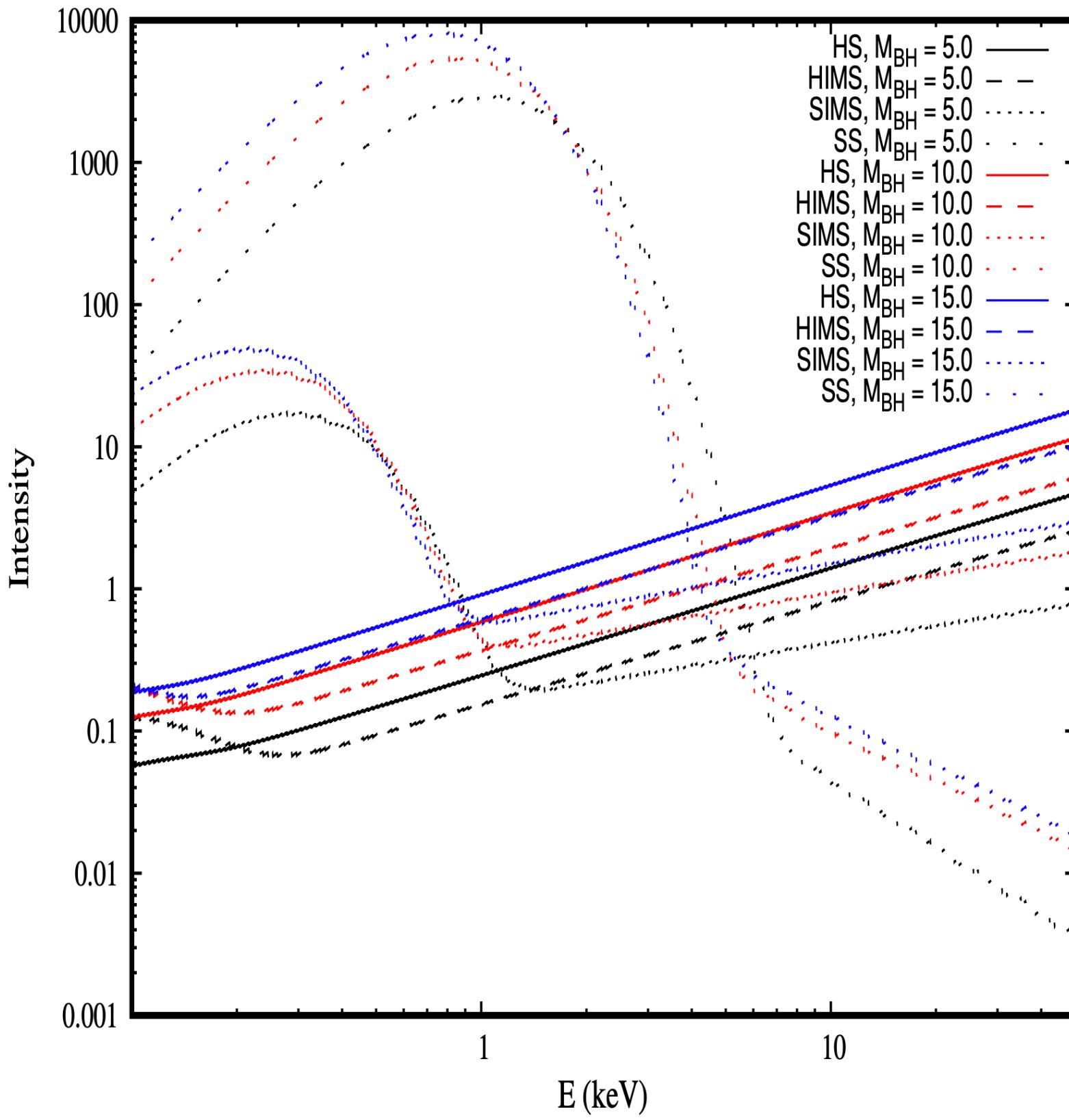
III. A Tale of Two *Constraints*: On fits and of the model

Ayan Bhattacharjee

Ulsan National Institute of Science and Technology, Republic of Korea

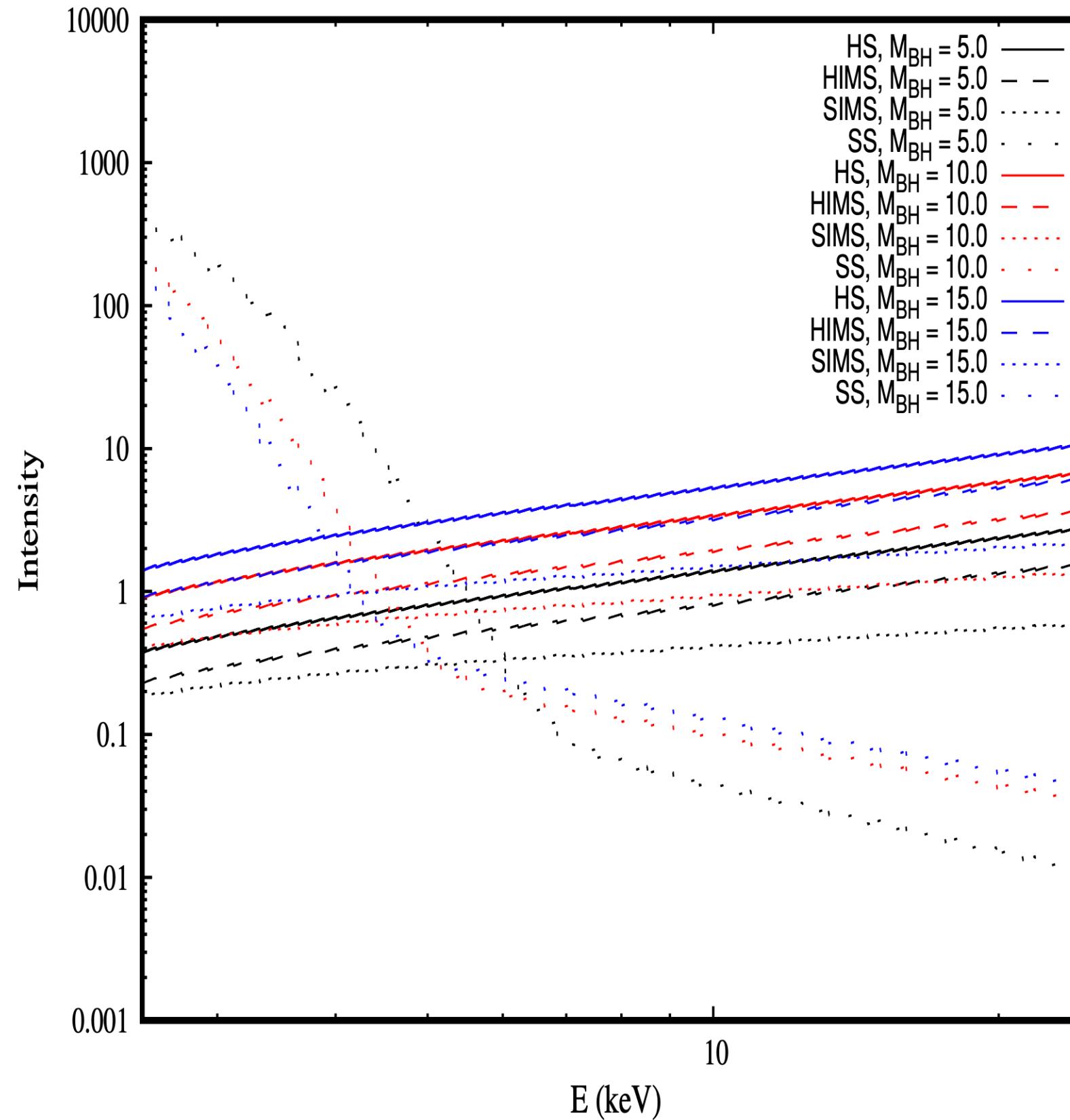
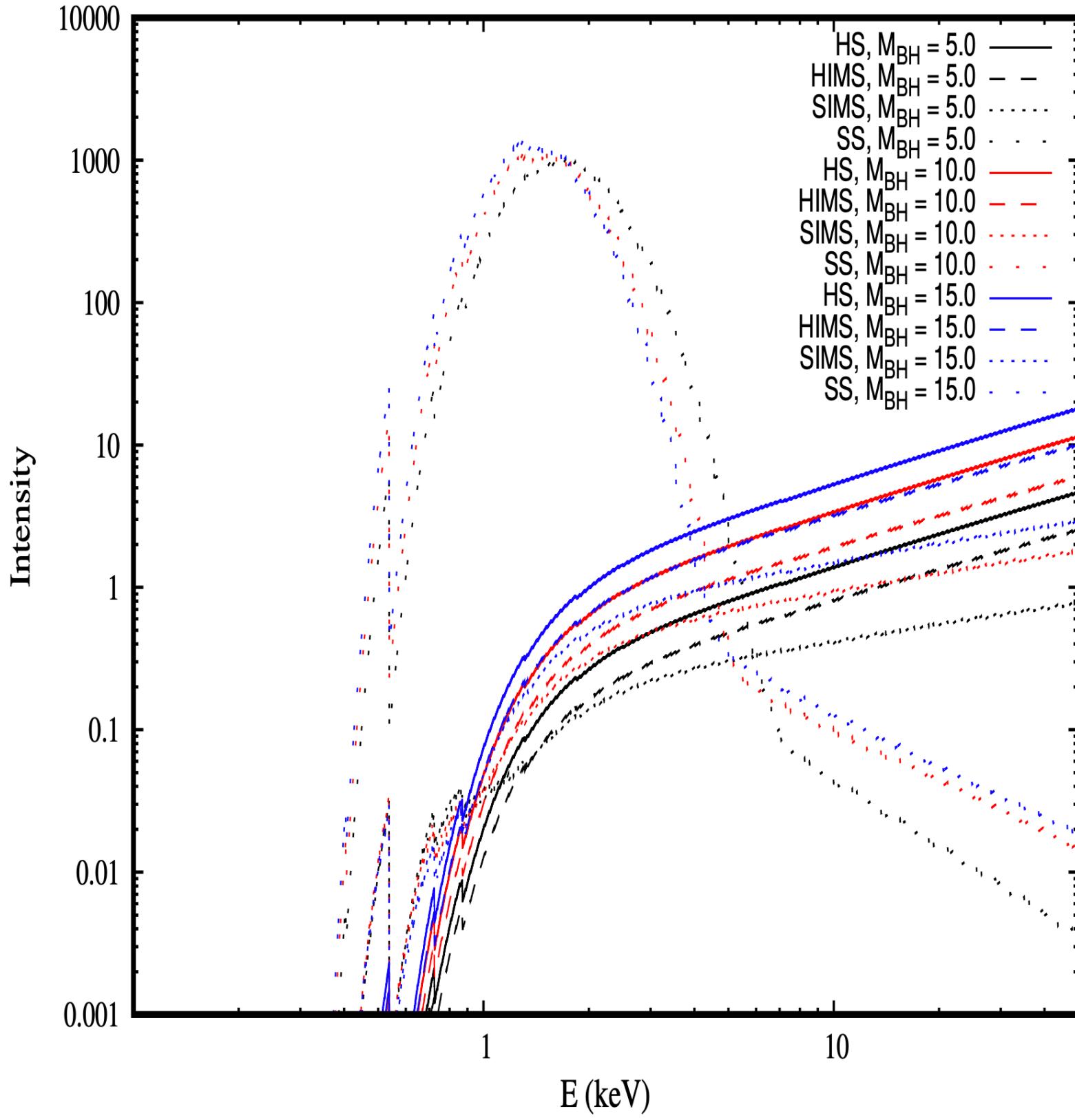
Workshop on *Two Component Advective Flows (TCAF): Fitting Procedure and Results for Stellar and supermassive black holes.*
ICSP, India
2024.09.25

Constraint 1: Limited Energy Range



- ▶ Features of the modified multicolour disk and Comptonized spectra spreads over a large energy range.
- ▶ Instrument energy band is limited.
 - ▶ Truncation errors.
 - ▶ Apparent degeneracy.
- ▶ Fixes:
 - ▶ Larger energy range, multi-messenger observation (as long as $\Delta t_{spec,E1} \sim \Delta t_{spec,E2}$).
 - ▶ Using data with higher signal-to-noise ratio.
 - ▶ Using precise normalisation from distance and angle measurements.

Constraint 2: Absorption due to ISM



- ▶ Absorption: $E < 3\text{keV}$.
 - ▶ Loss of information of source spectra.
 - ▶ Higher chances of apparent degeneracies.

- ▶ Fixes:
 - ▶ Using spectra from very different states to maximise differences.
 - ▶ High resolution data and modelling of absorption for $E < 3\text{keV}$.

Constraint 3: Inclusion of Additive Components

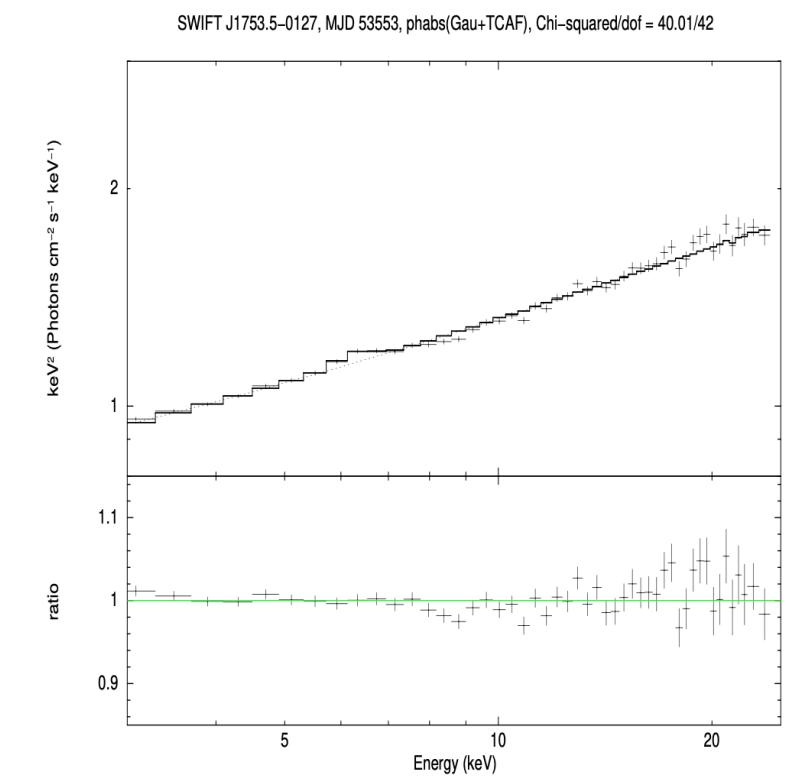


Figure 2.6: TCAF parameters for the fit: $\dot{m}_d = 0.837$, $\dot{m}_h = 0.450$, $X_s = 35.25$, $R = 1.05$. The Fe-line required a Gaussian component: $E_1 = 6.21$, $\sigma_1 = 0.36$, $N_1 = 0.001$.

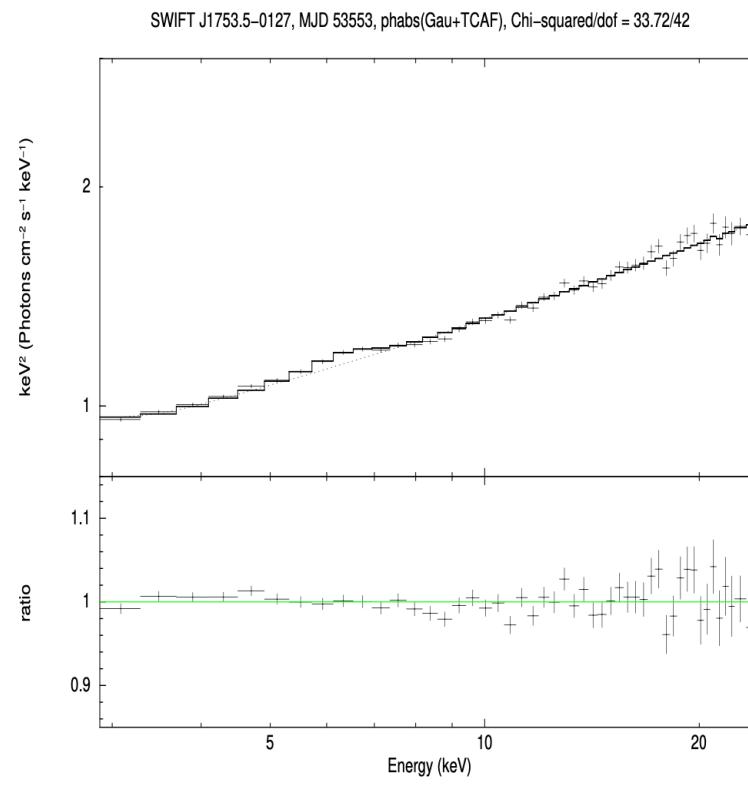


Figure 2.8: TCAF parameters for the fit: $\dot{m}_d = 0.991$, $\dot{m}_h = 3.617$, $X_s = 32.75$, $R = 1.18$. The Fe-line required a Gaussian component: $E_1 = 6.20$, $\sigma_1 = 0.63$, $N_1 = 0.002$.

- ▶ For line emission, e.g. Fe K line, Gaussian or Laor profiles are used.
- ▶ Narrow vs Broad line:
 - ▶ Flux redistributed at low E region
 - ▶ Apparent degeneracy.
- ▶ Fixes:
 - ▶ Consistency check with theory of TCAF: \dot{m}_d/\dot{m}_h based on state.
 - ▶ Coupled or more physical line emission models.

Thank You!