Spectral Fitting with NICER: Best Practices

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NICER Data Analysis Workshop

May 11, 2021

Outline

- Preface: First High Throughput Coverage in Soft X-rays
- Data Preparation
- Response Files
- Systematic error
- Absorption models; adding atomic edges
- Spectral modeling of the Crab Nebula
- Script-fitting Large Numbers of Spectra
- Modeling BH Binaries
- Fitting problems & poor BG prediction
- Conclusions

Spectral Analyses with NICER

- **New performance regime**
  - some sources: millions of counts below 2 keV
  - very sensitive to ISM absorption details
  - some strongly detected pulsars: 0.1 c/s, 0.3-2 keV
  - subtle BG components in soft X-rays
  - programs with thousands of GTIs (like RXTE)
  - with all the complications of lines, edges, and Si spectral resolution (like X-ray CCD instruments)

→ climb the learning curve

Data Preparation

- Background Modeling (talks earlier today)
- Grouping Bins (the grppha problem)
  - Control Oversampling (PI bins at 10 eV are too small)

    Common in NICER Science Team: group to oversample by factor ~ 3
    Suggestion from Jack Steiner:

PI Bin Start	PI Bin End	Binsize
1	20	2
21	248	3
249	600	4
601	1200	5
1201	1494	6

  - Control minimum counts per bin (e.g. MINCOUNT = 25)

Problem: conventional ftool "grppha" can't do both (one undoes the other)

Data Preparation

- Solutions to “grppha” binning limitations
  - Set controlled oversampling, but pull back maximum keV of fit (not desirable ; loses information)
  - Craig’s has adapted and is testing “ftgrouppha” to combine the two needs for grouping
  - Jack Steiner has an idl tool to rewrite pha file with the combined tasks of grouping

please stay tuned to postings from NICER on public access to these tools

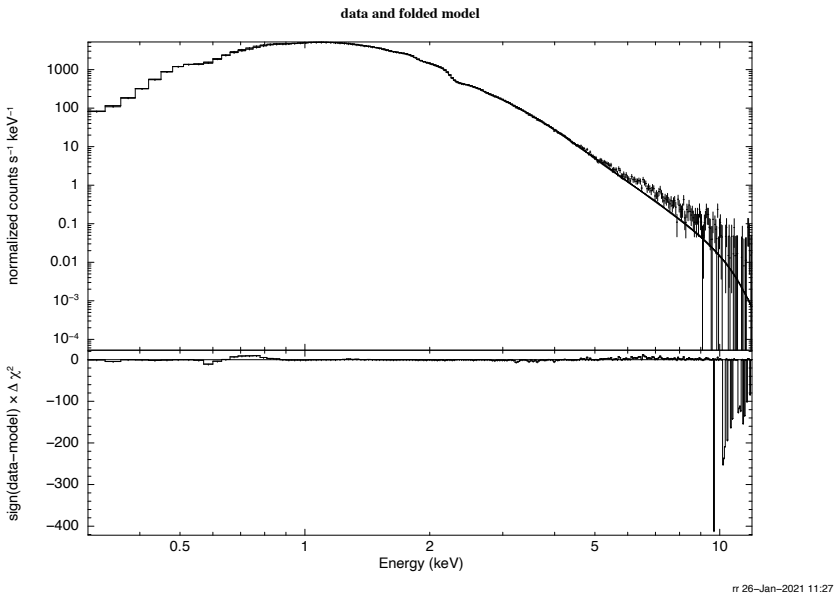
Data Preparation

Simple Illustration of need for MINCOUNT

MAXI J1727-203 (GTI 0019, fit 0.3-12.0 keV ; syserr 0.02

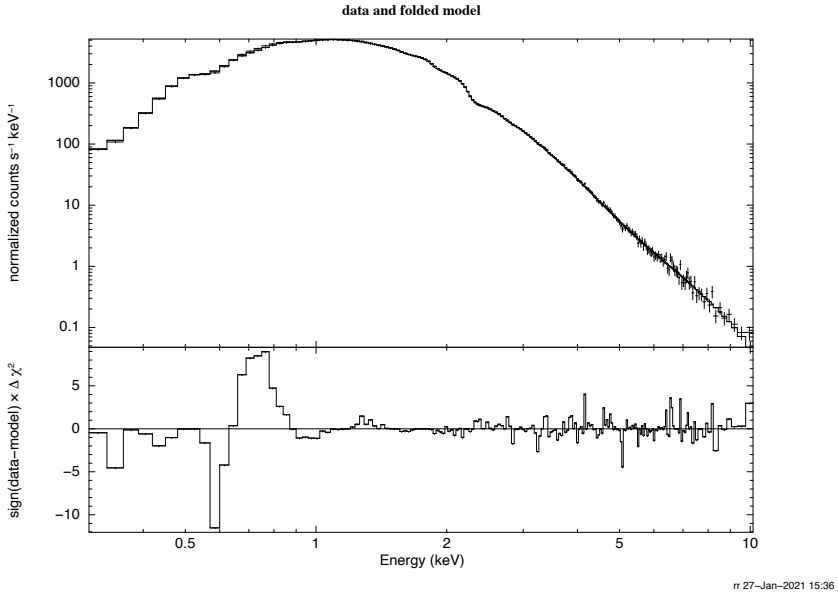
group to oversample by 3 only

$X_\nu = 10.9 \quad \Gamma = 4.5$



group to oversample by 3 AND group min=25
(done with Jack Steiner's idl tool)

$X_\nu = 0.90 \quad \Gamma = 2.9$



Response Files

- Current response files in $CALDB for 52 FPMs:

  nixtiref20170601v002.rmf, nixtiaveonaxis20170601v004.arf

  I used the response calculator to make:
  nixtiref20170601v002-array50.rmf (excluding 14 and 34)
  nixtiaveonaxis20170601v004-array50.arf (excluding 14, 34)

  → both sets work very well (hard to see differences 50 vs. 52)

Systematic Error & Absorption

- Consensus from Calibration Tests and Science : Set to 1% and explore residuals (grppha “systematics 1-1500 0.01”)
- For the ISM absorption, Use tbabs in the spectral model and “abundances wilms”
- If “glitches” show up, as in previous slide, try adding edges

  Oxygen 0.56 keV
  Fe L 0.71 keV
  Ne-K 0.87 keV
- See Craig’s talk: consider using “tbfeo” or tbvarabs” to allow abundances to vary
- Real world complications: Some NICER publications pull up syserr to 2%

Fitting the Crab Nebula

- Craig covered Crab spectral fits in his talk on Monday
- It is important to know that the fit is significantly more complicated by edges and other spectral features, compared to RXTE (2.8-60 keV)
- Not recommended to start here, without guidance
- Some Bright black hole binaries are smoother and easier to learn from

Fitting Black Hole Binaries

First examples of fitting large data sets:

Alabarta et al. 2020 (MNRAS, 497, 3896)
"X-ray spectral & timing evolution of MAXI J1727-203 with NICER"
done with older calibration: nixtiref20170601v001.rmf

Cuneo et al 2020 (MNRAS, 496, 1001)
"A NICER look at the state transitions of the black hole candidate MAXI J1535-571 during its reflares"
done with older calibration: nixtiref20170601v001.rmf

Zhang et al. 2020 (MNRAS, 499, 851)
"NICER observations reveal that the X-ray transient MAXI J1348-630 is a black hole X-ray binary"
Analyses done with nicer v1.02.rmf

+2021 in press, e.g., **Jana et al.** (MAXIJ0637) ; Yao et al. (AT2019wey)

Automating Fitting Scripts

make a generic script: e.g., fit_ezdisk_simpl_maxj1727.xcm

```
# Return TCL results for XSPEC commands.
set xs_return_result 1
query on
# Open the file to put the results in.
set fileid [open fit_ezdisk_simpl.log a]
setplot energy
# Set up the model.
ignore 0.0-0.3 10.0-**
abund wilm

mo tbabs(simpl(ezdisk))
0.406 0.0
2.1
0.1
1
0.5
10.0
fit 50000
cpd /ps
plot ldata chi
# Print out the result to the file.
tclout filename
puts $fileid "file: $xspec_tclout"
tclout  model
```

.... continued

```
puts $fileid "$xspec_tclout"
tclout param 1
puts $fileid "par1:  $xspec_tclout"
tclout sig 1
puts $fileid "sig1:  $xspec_tclout”
tclout param 2
puts $fileid "par2:  $xspec_tclout"
tclout sig 2
puts $fileid "sig2:  $xspec_tclout"
tclout param 3
puts $fileid "par3:  $xspec_tclout"
tclout sig 3
puts $fileid "sig3:  $xspec_tclout"
tclout param 4
puts $fileid "par4:  $xspec_tclout"
tclout sig 4
puts $fileid "sig4:  $xspec_tclout"
tclout param 5
puts $fileid "par5:  $xspec_tclout"
tclout sig 5
puts $fileid "sig5:  $xspec_tclout"
tclout stat
scan $xspec_tclout "%f" mychi
puts $fileid "chi $mychi"
tclout dof
scan $xspec_tclout "%d" mydof
puts $fileid "dof $mydof"
# Reset the model.
model none
# Close the file.
close $fileid
```

Quick-Fit Scripts

2. turn list of spectra into script to run the model on each one, e.g.:

> more run_fit_ezdisk_simpl.go

```
data smrbgsub_cl50_0001.pha ; @fit_ezdisk_simpl_maxj1727.xcm ; mv pgplot.ps pgplot_0001.ps
data smrbgsub_cl50_0002.pha ; @fit_ezdisk_simpl_maxj1727.xcm ; mv pgplot.ps pgplot_0002.ps
data smrbgsub_cl50_0003.pha ; @fit_ezdisk_simpl_maxj1727.xcm ; mv pgplot.ps pgplot_0003.ps
…..etc
data smrbgsub_cl50_0173.pha ; @fit_ezdisk_simpl_maxj1727.xcm ; mv pgplot.ps pgplot_0173.ps
```

3. xspec12> @ run_fit_ezdisk_simpl.go

→ **results all packed into fit_ezdisk_simpl.log**

parse & tabulate the fit parameters with your favorite ASCII tools (e.g., grep, paste, awk)

MAXI J1727-203

Alabarta et al. 2020

60 NICER Spectra

nixtiref20170601v001.rmf

… and paired 2017 .arf

fit: 0.3–10.0

group: 30 eV bins plus min=25

syserr: 0.3-2.0 0.05; 2.0-10.0 0.01

TBABS(NTHCOMP+DISKBB))

N_H = 0.437 (x10^{22} cm^{-2}) fixed

Comp. kT_e = 1000 (keV) fixed

X_ν 1.16 (whole data set)

Quick-script (RR) 2021

173 GTIs

nicer-rmf6s-array50.rmf

nicer-consim135p-array50.arf

fit: 0.3–12.0

group: oversample=3 plus min=20

0.3-0.55 0.02; 0.55-0.85 0.05; 0.85-12.0 0.02

TBABS(SIMPL(EZDISK))

0.401 (after one pass with N_H free)

N/A

avg. 0.98 [170] + 3 GTIs X_ν > 2.5

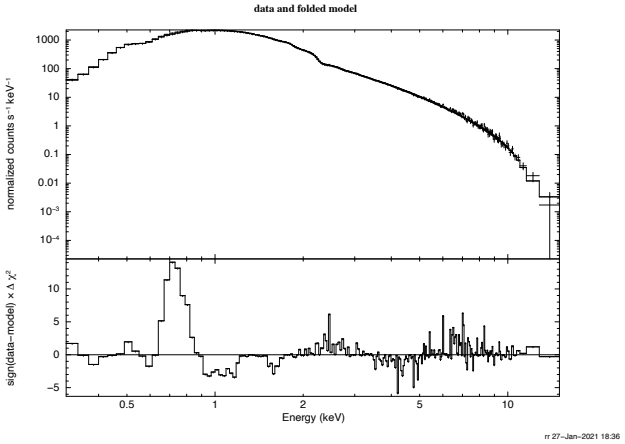
MAXI J1727-203

Quick-script 2021 Residuals

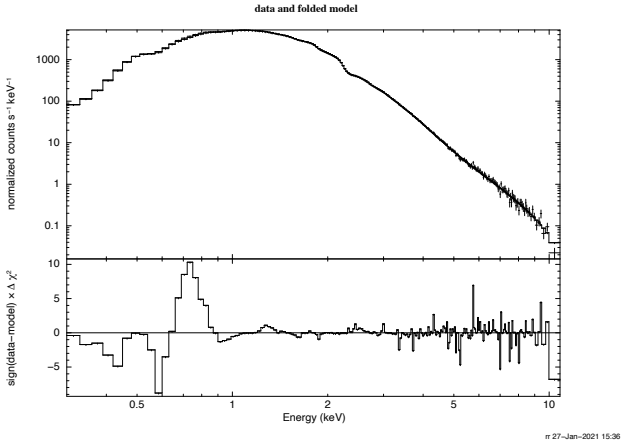
syserr: 0.3-12.0 0.02

Glitches at edges (O edge)

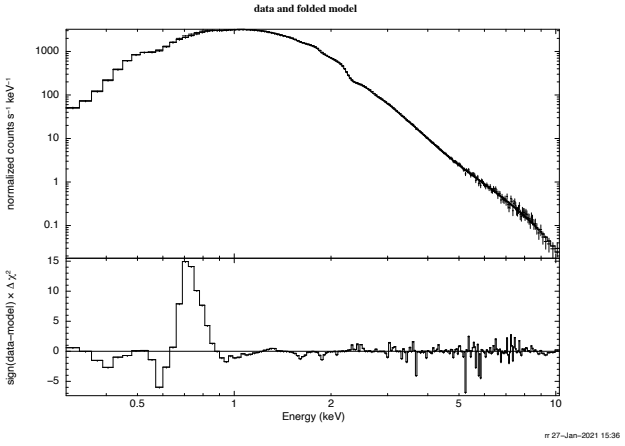
002 early IS



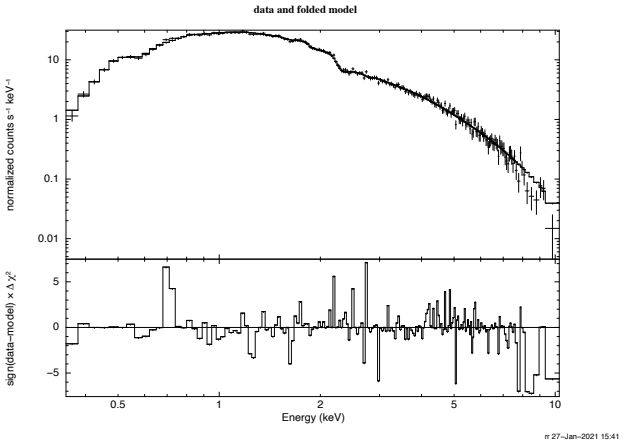
021 thermal (soft) state



045 later IS



090 hard state



MAXI J1727-203

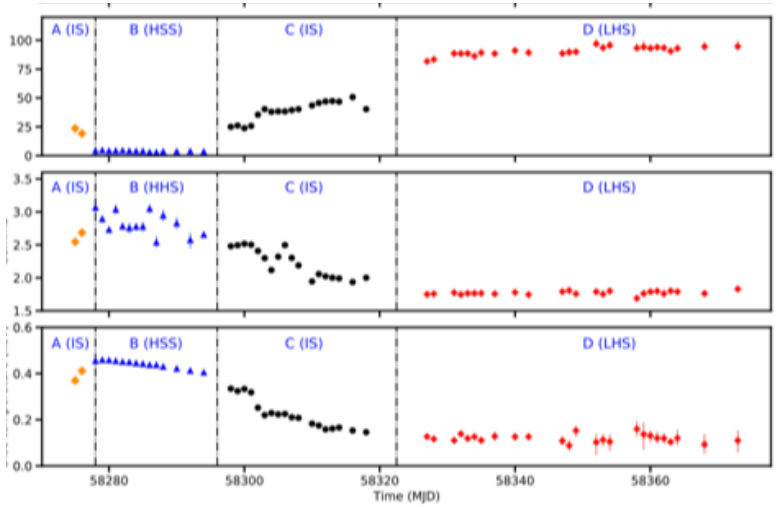
Ron quick-fit:

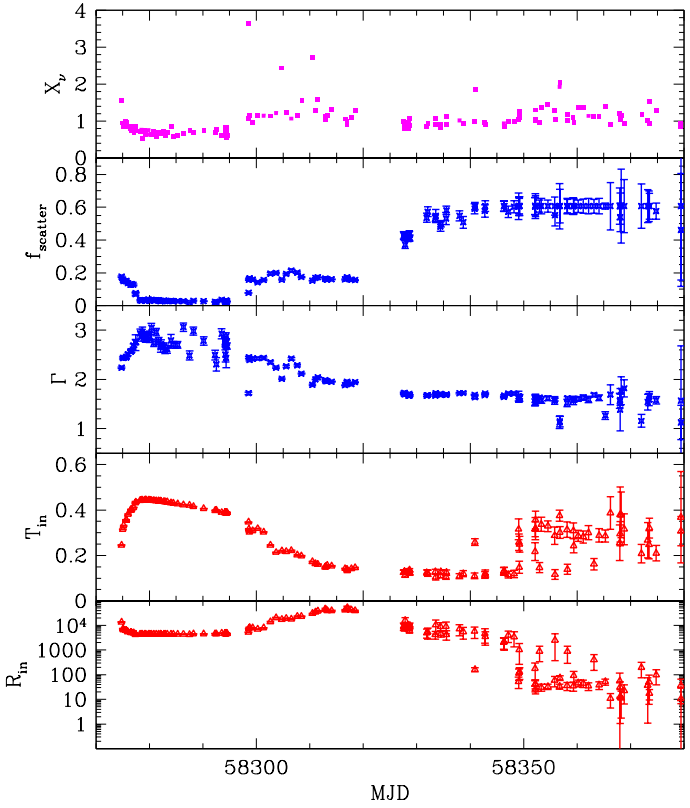
Alabarta et al.:

percent comp. E.

Γ

T_{in}





→ still iterations and science interpretation remaining, but analyses and iterations are scripted to be efficient

Kappa^1 Ceti fitting problems

Kenji Hamaguchi reported GTIs with fitting problems:
Time-Sliced Spectral Analyses of Stellar X-ray Data

K^1 Ceti: G5 V at 9.2 pc
ObsIDs [64]: 2300020101 – 0135 ; 3230020101 – 0129

How does photometric quality screening ($S0_{net}$, hbg_{net}) compare with Kenji's problem GTIs?

total GTIs:	211	
number within BG model limits:	206	
Level 1 screening	201	$-20.0 < s1_{net} < 20.0$; $-0.5 < hbg_{net} < 0.5$
Level 2 screening	199	$-5.0 < s1_{net} < 5.0$; $-0.1 < hbg_{net} < 0.1$

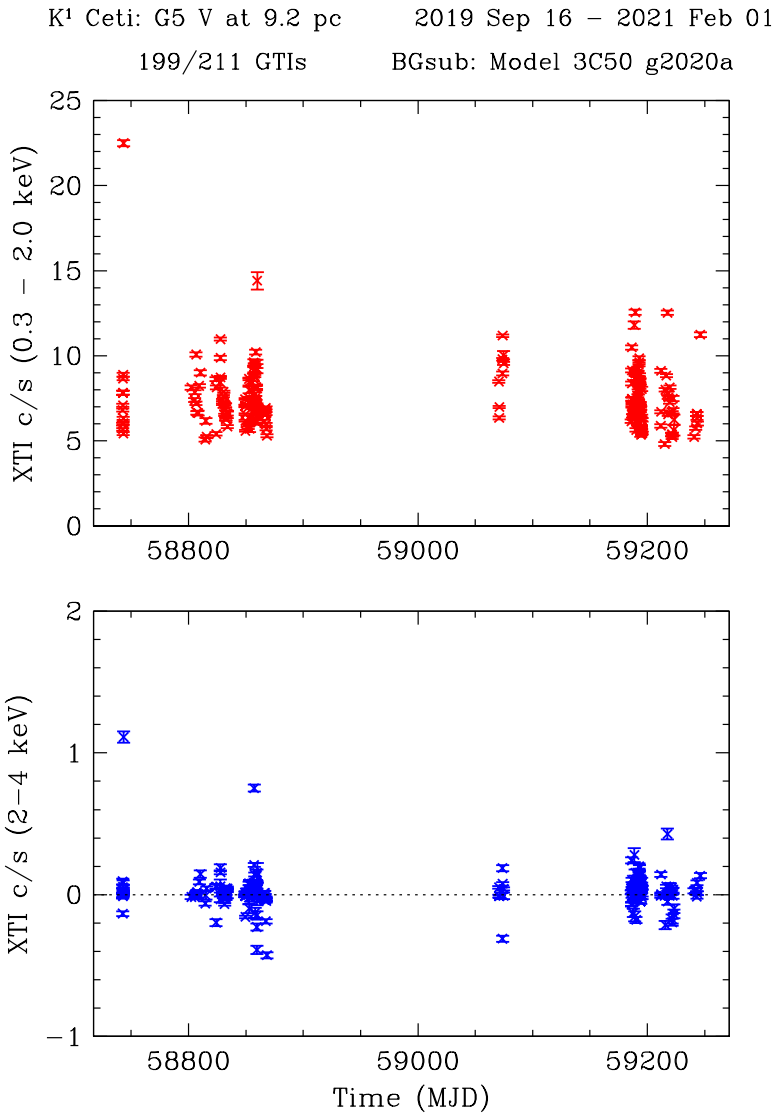
$s0_{net}$: background-subtracted rate at 0.2-0.3 keV
hbg_{net} : background-subtracted rate at 13-15 keV

Kappa^1 Ceti

K^1 Ceti: G5 V at 9.2 pc

NICER with level 2 filter

- soft spectrum
- detection above 2 keV in flares



Kappa^1 Ceti

K^1 Ceti: G5 V at 9.2 pc

Group	ObsID	Interval (NICER TIME)			RR GTI#	Level 2 filter	C_{net} (2-4 keV)	D_{net} (4-12)
191206	2300020113	187152309	187152935	Interval 1	0026	OK	-0.197	0.020
200117	2300020133	190912247	190913162	Interval 3	0098	OK	-0.043	-0.063
	2300020133	190917829	190918741	Interval 4	0099	OK	-0.033	0.080
201202	3300020107	218445309	218446023	Interval 1	0119	OK	-0.069	-0.044
	3300020111	218779926	218780471	Interval 13	0142	OK	-0.602	-1.168

Conclusions:

- **Filtering does not remove the 5 bad intervals found by Kenji**
- **Only the fifth interval has anomalous negative C/D bands**
- **Bad spectral fits (Chi-square) are cause for ADDITIONAL screening**
- **Valuable cases to test future BG models**

Fairall 9 fitting problems

Ed Cackett & Ethan Partington reported fitting problems for ESO113-G45 (Fairall 9), after binning level-2 filtered spectra in intervals of intensity

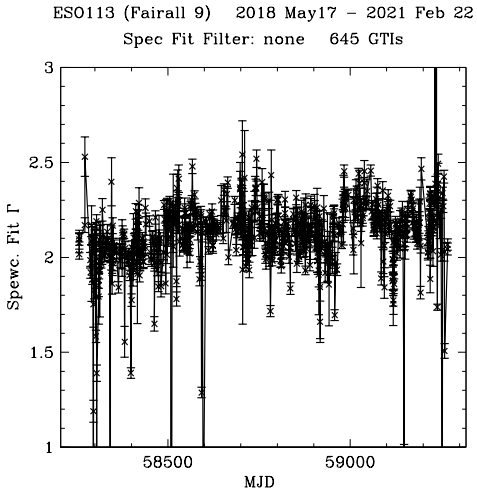
Compare Filtering with bad spectral fits when each GTI is fit with the adopted model (power law + absorption + soft excess)

	$S0_{net}$; hbg_{net} #GTIs		quality spectral fits #GTIs
total GTIs	645		645
level 1 filter	28	$\chi^2_\nu > 5.0$	7
level 2 filter	68	$\chi^2_\nu > 1.5$	36
level 2 selected	549	good-fit selected	603

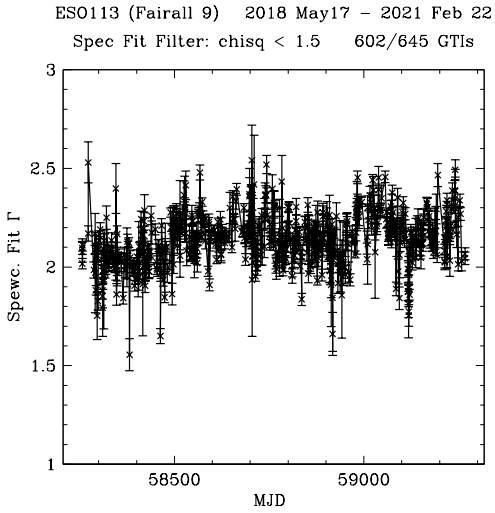
….but, again, filtered GTIs and bad-fit GTIs only partially overlap!

Specrum Filtering: χ^2_ν

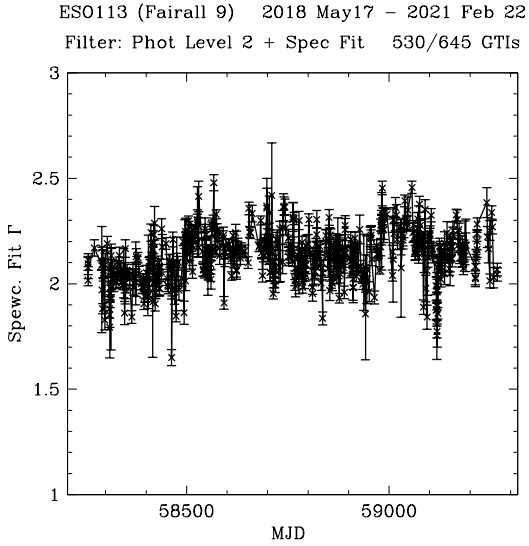
NONE



chisq < 1.5



chisq < 1.5 + PHOT level 2



Advice: Filter on both bg-sub phot. and per-GTI spectral fits before combining spectra

Next: Close the loop on Fairall 9 : combine only phot-spec-filtered spectra
Take closer look at phot/spec filter overlaps and non-overlaps

Conclusions

- Spectral fitting convolves accuracy limit of gain, background subtraction, response files (detectors), and ancillary files (optics) …. hence the last to mature
- NICER is now doing well with spectral fitting & large data sets.
- Sdvised to fit individual GTIs and remove cases with bad χ_ν^2, in addition to those removed via SO_{net}. hbg_{net} filtering (…important, prior to combining data)
- Feedback of user experiences with spectral fits is welcome (send to Calibration and background teams)