The Empirical ("3C50") Background Model

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NICER Data Analysis Workshop

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Outline

Reference: "An Empirical Background Model for the *NICER* X-ray Timing Instrument", submitted to AJ (v2)

https://drive.google.com/file/d/1HhgFa5422y__fkc_SXpIVKs_7dB2UUDR/view?usp=sharing

- **Need for *NICER* Background (BG) Modeling**
- **3C50 Model Parameters**
- **Library Spectra for ISS Night**
- **Supplementary Library for ISS Daytime**
- **Performance Assessments**
- **Model Improvements, 2021**

Background Context

- *NICER* Detectors & Field of View
  - 52 operating (of 56), co-pointing, on-target, single-channel Detectors (Detector packages are called “Focal Plane Modules” (FPMs))
  - Metal Collimator limits X-ray FOV to radius = 1mm (3.17 arcmin; captures 90% of PSF) forcing short path to anode (active Si radius = 2.8 mm)
  - Event lists always merge target X-rays with all BG events
  - *NICER* observes 7 BKGD_* fields (no sources) to assist modeling

- Model Parameters
  - Use measurements unaffected by target X-rays (strategy of 3C50)
  - Use environmental parameters (Space Weather Model / next talk)

Background Context

reminders from Craig's talks:

1. Each *NICER* event has entries for (relevant to BG models):
   - Event Flags (on/off bits): overshoots (energy saturated), undershoots (detector resets), forced triggers (monitors 0.0 keV), et al.
   - PI (energy in units of 10 eV) and PI_ratio (= PI / PI_fast)

   The first line of defense against particle BG: exclude overshoots

   The NICER pipeline excludes overshoots, undershoots & forced triggers when making cleaned event lists: $obsid/xti/event_cl/ni$obsid_cl.evt.gz

2. Optical light leak in ISS-daytime causes intrusion of noise events

   This can be considered as an additional component in a BG model

Background Context

- Pre-launch BG analyses predicted:
  - low rate from cosmic X-ray BG (< 0.3 c / s / 56 FPMs, 0.4 - 8 keV) away from the polar horns in ISS orbit
  - in-band (0.4-12 keV) events from particles would arise from their clipping the edges of active Si ... events recognizable by PI_ratio?

- The plane of PI (energy) versus PI_ratio (ratio PI/PI_fast) has implications for spatial distribution of BG components
  - Events originating near center of detector: PI_ratio ~ 1.0
  - Events below collimator and near edge of detector: P_ratio > 1.5

  (charge diffusion in long path to anode elongates pulse, while short measuring window for fast chain truncates integration for long pulses (i.e. measures lower keV, leading to increased PI_ratio))

3C50 model arises from this context

Bright Source in PI_RATIO vs. PI

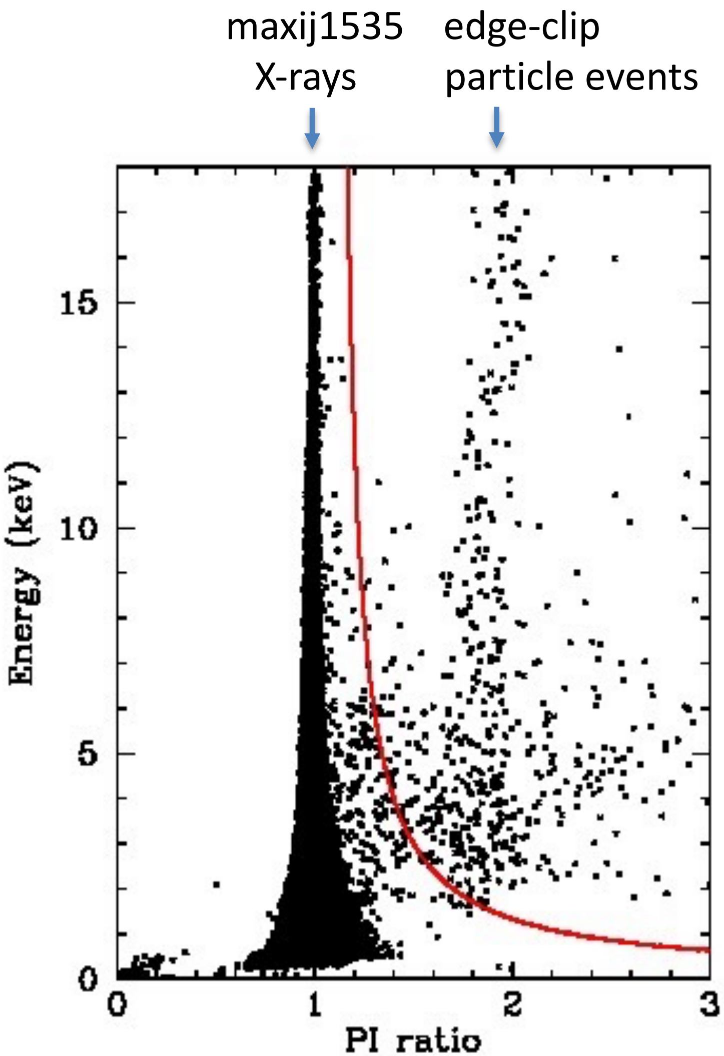
MAXI J1535-571

876 s GTI starting
2017 Sep 12 23:20 UT

intensity ~ 7500 c/s

“trumpet line” selected
(left of red): 6.5 M events

rejected (right of line)
~800 events



PI_RATIO = keV (slow chain) / keV (fast chain)

PI_RATIO & Background Events

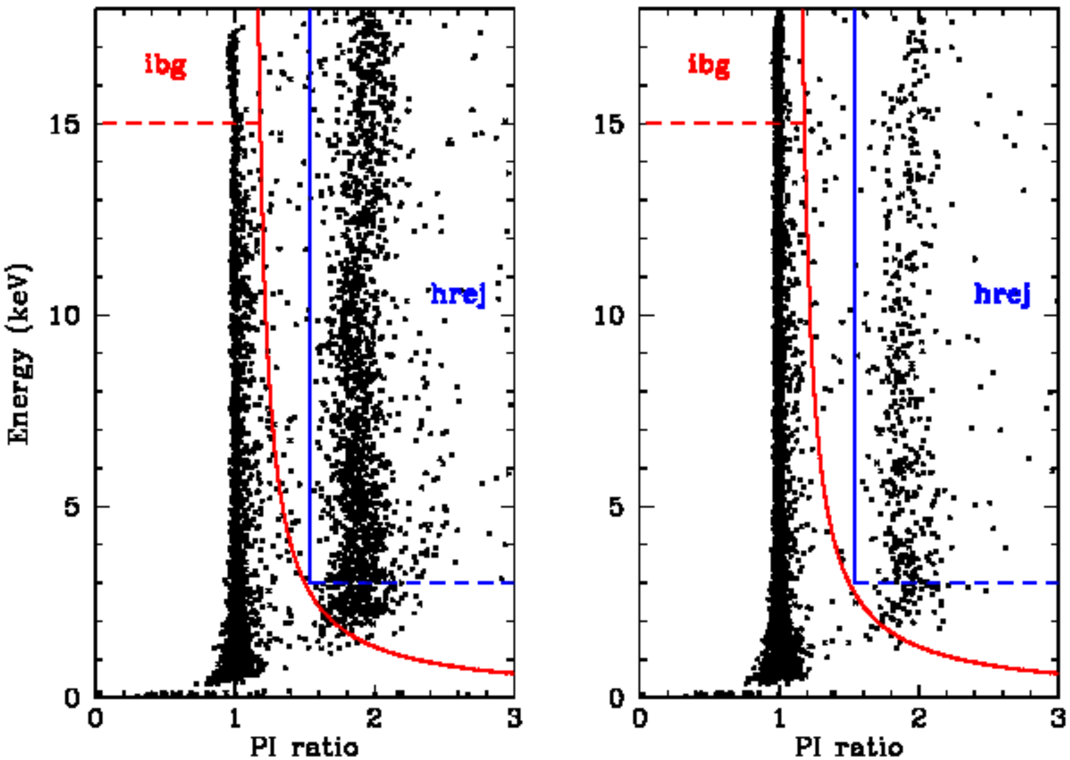
Background contains in-focus & spatially extended components that can vary independently ; Left: *hrej > ibg*; Right: *ibg >> hrej*

red curve: pipeline selection line (to left) for in-focus events

ibg: events "in focus", but at 15-18 keV, which is beyond the eff. area of the optics

hrej: rejected events from particles near detector edge

ibg and ***hrej*** represent different types of particle events

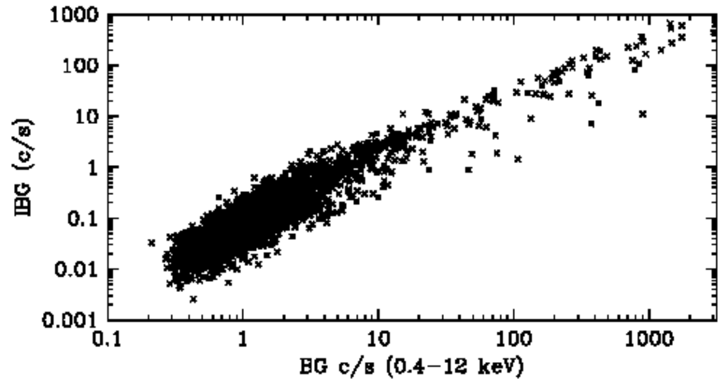


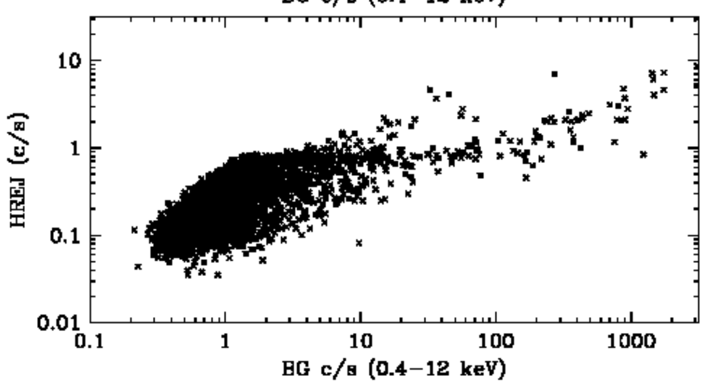
PI_RATIO = keV (slow chain) / keV (fast chain)

Background Data

In-focus background rate (R_{BG}) and spectrum (0.2-12 keV) is what BG models must predict

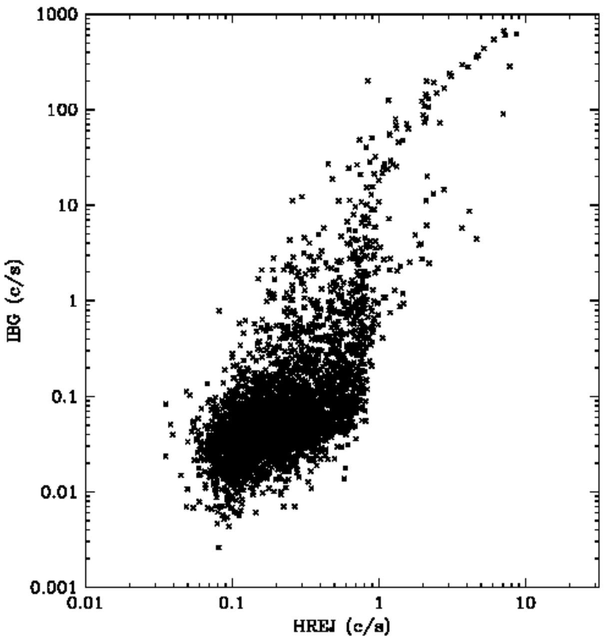
How do (***ibg, hrej***) correlate with $\boldsymbol{R_{BG}}$?





R_{BG} > 2.0 c/s for 82% of 3556 GTIs
….extent more than polar horns

Do (***ibg, hrej***) correlate with each other?



Model Strategy

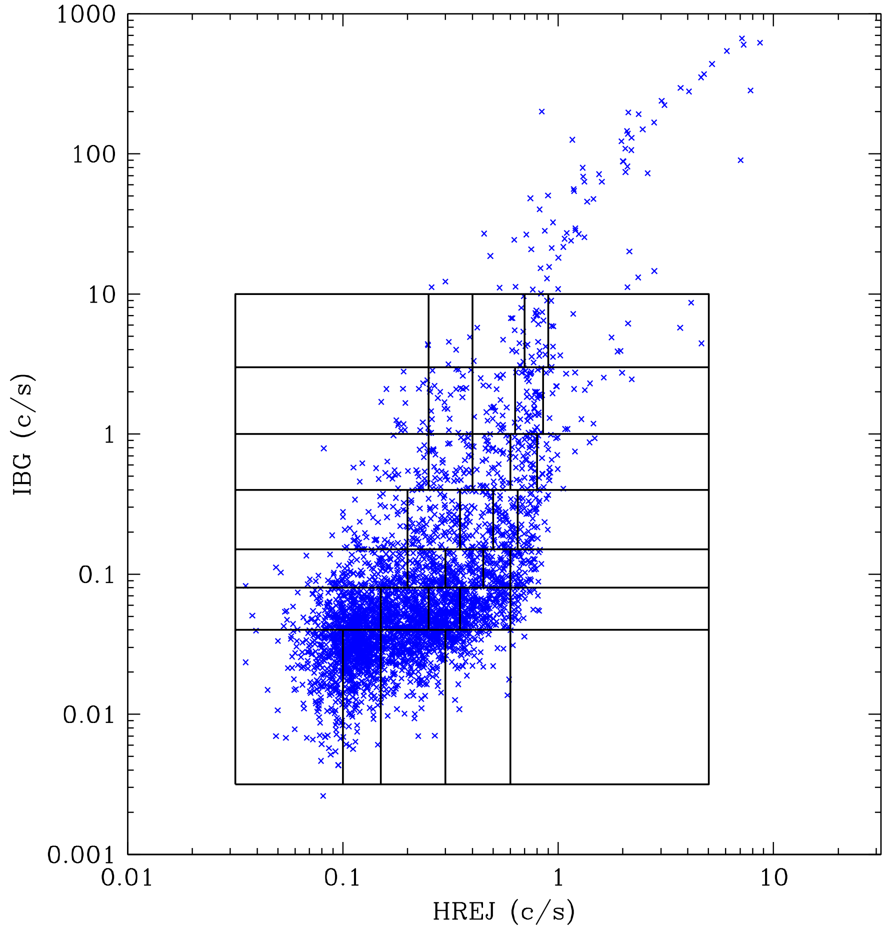
NICER

Define a Library of Spectra for grid in (***ibg, hrej***) for ISS Night

Soft Excess during ISS Daytime creates need for independent 3rd model; parameter

7 cells in *ibg*
5 cells in *hrej*
and extreme BG conditions are beyond the model

Library spectra are the average spectra within each cell



3C50 Strategy

- 3C50 Model
  - Two parameters (***ibg, hrej***) to build a Stage 1 Library of BG Spectra for ISS Night (instrument in darkness)
  - Each GTI_i: use (ibg_i, $hrej_i$) and N_{FPM} to choose stage 1 spectrum
  - Normalize library choice *= ibg_i / ibg_{lib}
  - Additional parameter, based on ***nz***, noise rate 0.0-0.25 keV), use Stage 1 residuals to build Stage 2 Library for ISS Daytime, when optical leaks create a soft excess due to increased noise
  - Each GTIi: use nz_i and N_{FPM} to choose library spectrum and then normalize by nz_{lib}/nz_i

- Performance Assessments
  - Residuals when BG-subtracting the BG observations
  - Light curves of Calibration X-ray sources

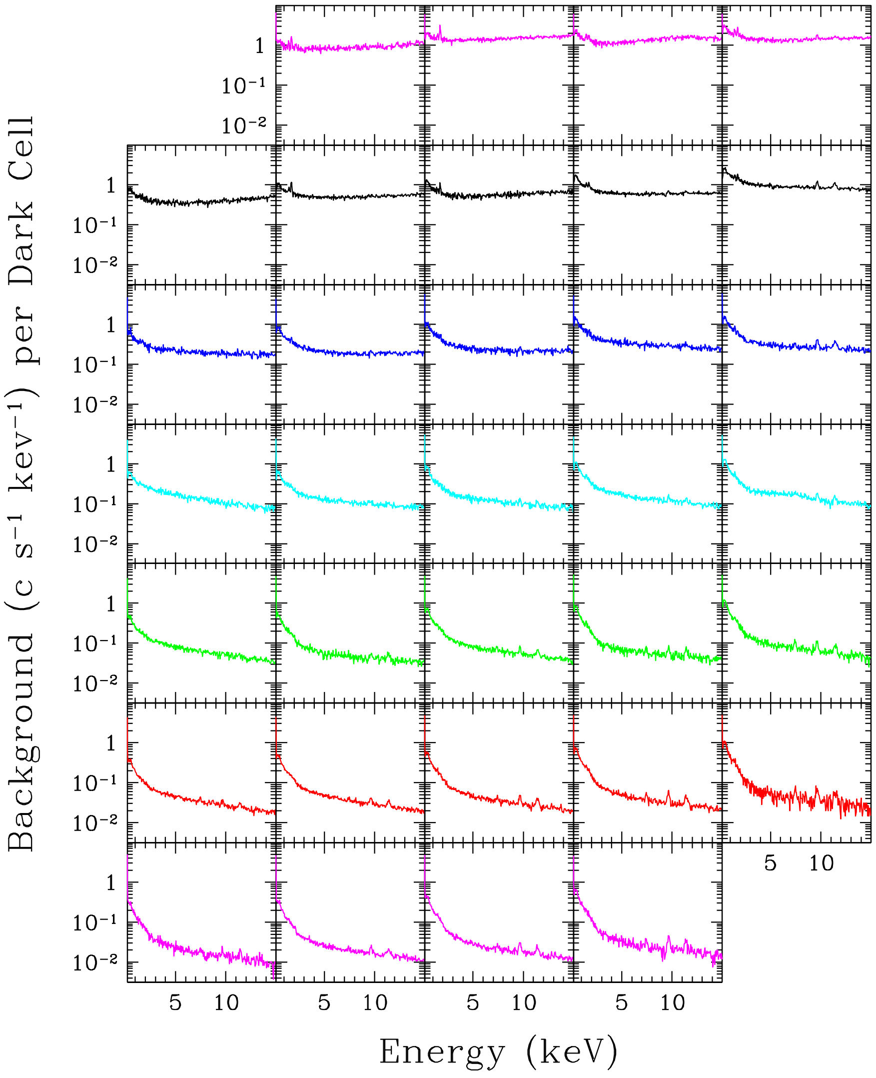
Library: Night [IBG, HREJ]

Model 3C50 Night Library

Based on 50 best FPMs (exclude 14 and 34)

Stronger emission lines and soft peak are seen with increasing ***hrej*** (left to right)

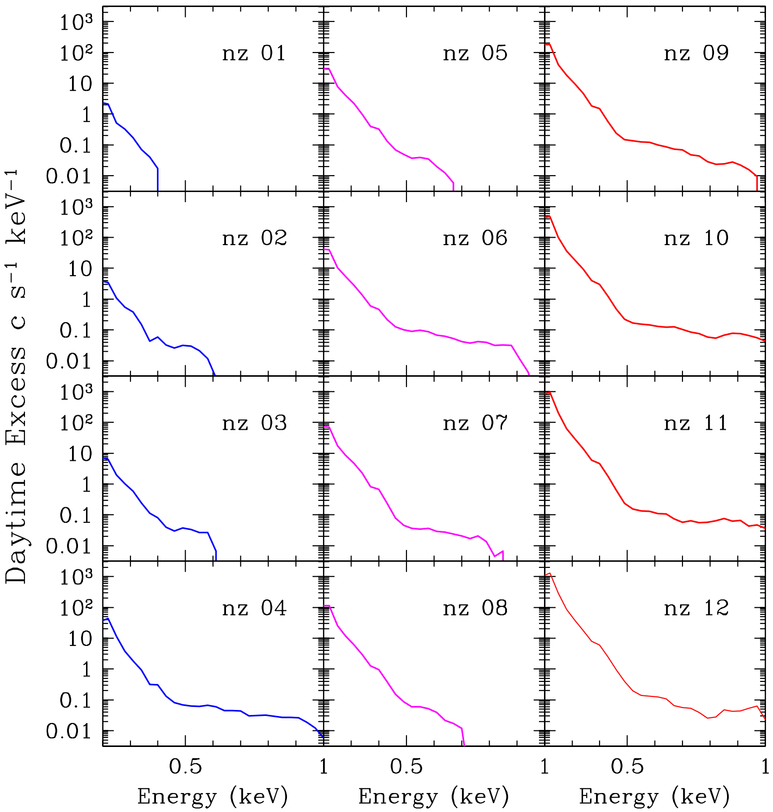
BG spectra are much brighter and harder with increasing ***ibg*** (vertical) ; different type of particles?



Model 3C50 Daytime Library

Stage 1 model (only) residuals are is averaged for 12 intervals in ***nz*** (count rate at 0.0–0.25 keV)

Soft excess has increasing extension into target keV range, with increasing ***nz***



3C50 BG calculator in ftools

- 3C50 Implemented with "***nibackgen3C50***", by Mike Loewenstein
  - Supported by NICER Guest Observer Facility
  - HEASARC compliant ; will become formal HEASoft ftool
  - to download and install, visit

  https://heasarc.gsfc.nasa.gov/docs/nicer/tools/nicer_bkg_est_tools.html

- Usage: investigation framework
  - Each call to *nibackgen3C50* produces one BG spectrum (pha file)
  - Users need to define investigation framework
    - by ObsID?, i.e., the daily set of GTIs on a given target, **or**
    - shorter timescale? (recommend intervals > 100 s to limit normalization noise ; make cleaned event lists as associated GTI file per interval
  - Input to *nibackgen3C50* drives the matching of BG files & framework
    - input by ***obsid*** parameter, **or**
    - input by ***ufafile*** and ***clfile*** parameters

nibackgen3C50

- Usage: additional considerations
  - Data : Library gain calibrations (keyword GCALFILE) should match
    - parameter ***gainepoch*** shortcuts: 2020 = nixtiflightpi20170601v005.fits ; 2021 = the current GCALFILE nixtiflightpi20170601v006.fits ; etc.
      Note: these two are ~interchangeable, with no differences below 12 keV
    - Libraries made for earlier epochs, but accuracy is better in 2020/2021
    - Note: the *NICER* archive was not revised for each new gain epoch ; use *nicerl2* to bring old observations up to current calibrations
  - Numbers of FPMs used in data analyses
    - 50 FPMs were used for all BKGD_* spectra selected to create the model libraries, ignoring active FPMs 14 and 34
    - To control FPM selections, users can list FPMs to be ignored (***fpmofflist***)
    - Library boundaries are based on 52 FPMs, and the measured parameter values (*ibg, hrej, nz*) are linearly rescaled for that purpose
    - Normalizations of selected library spectra (*ibg and nz,* if nz_{52} > 200 c/s) are performed with raw values, to properly match the input spectra, and so corrections must be made later if the number of selected FPMs does not match the chosen response file.

nibackgen3C50

- nibackgen3C50 internal parameters
  - In the general, the input files may cover more than one GTI, but the tool will never cross GTI boundaries (gaps can be hours) when computing model parameter values
  - Thus, the BG spectrum is usually computed for sub-intervals, and the exposure-weighted average is the final BG output
  - ***dtmin, dtmax*** control sub-intervals, if intervals other than GTIs is preferred
  - Each sub interval: tool retrieves (*ibg, hrej, nz*) values to select, normalize, and combine (if two stages needed) library spectra, using calls to “mathpha”.
  - In addition to the BG spectrum the tool retrieves the total (source + BG) spectrum from the same input files

BG Model Assessment

Full 3C50 Model Residuals: **Daytime, Nighttime**

Model works best when BG is low (R_{BG} < 2 c/s ; 82% of BKGD GTIs)

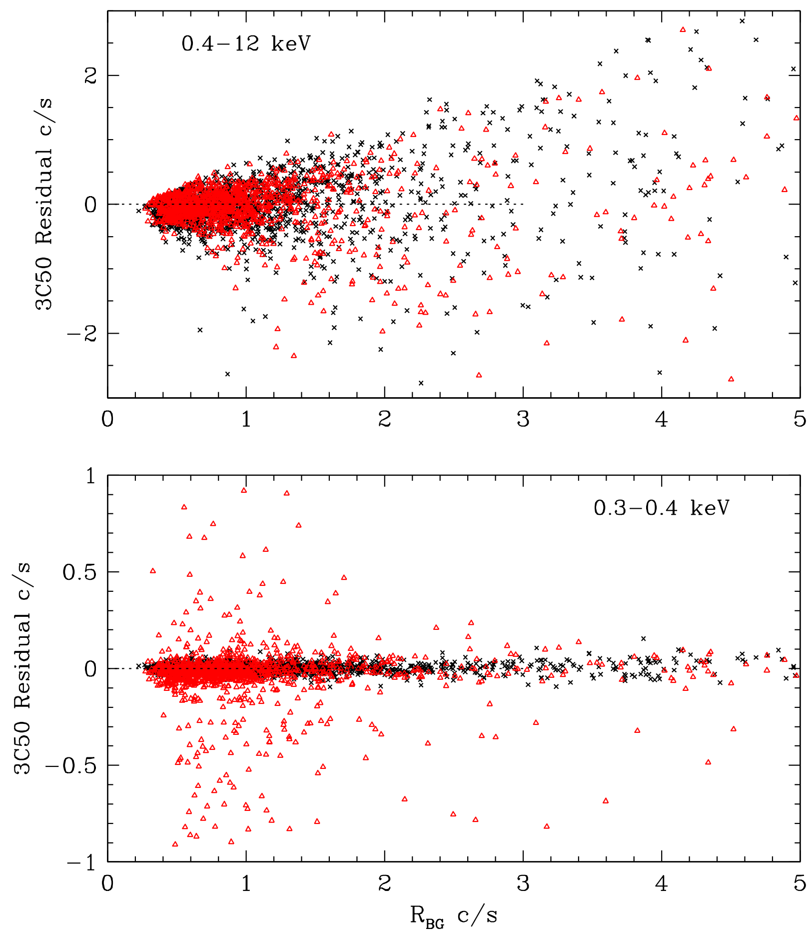
with level 2 filtering in diagnostic bands (**see paper & next slides**),

NICER detection limit (3σ) in a single GTI:

1.20 c/s at 0.4-12 keV (0.1 mCrab)

0.51 c/s at 0.3-2.0 keV.

in 10 ks searches, the detection limits are a factor ~4 lower.



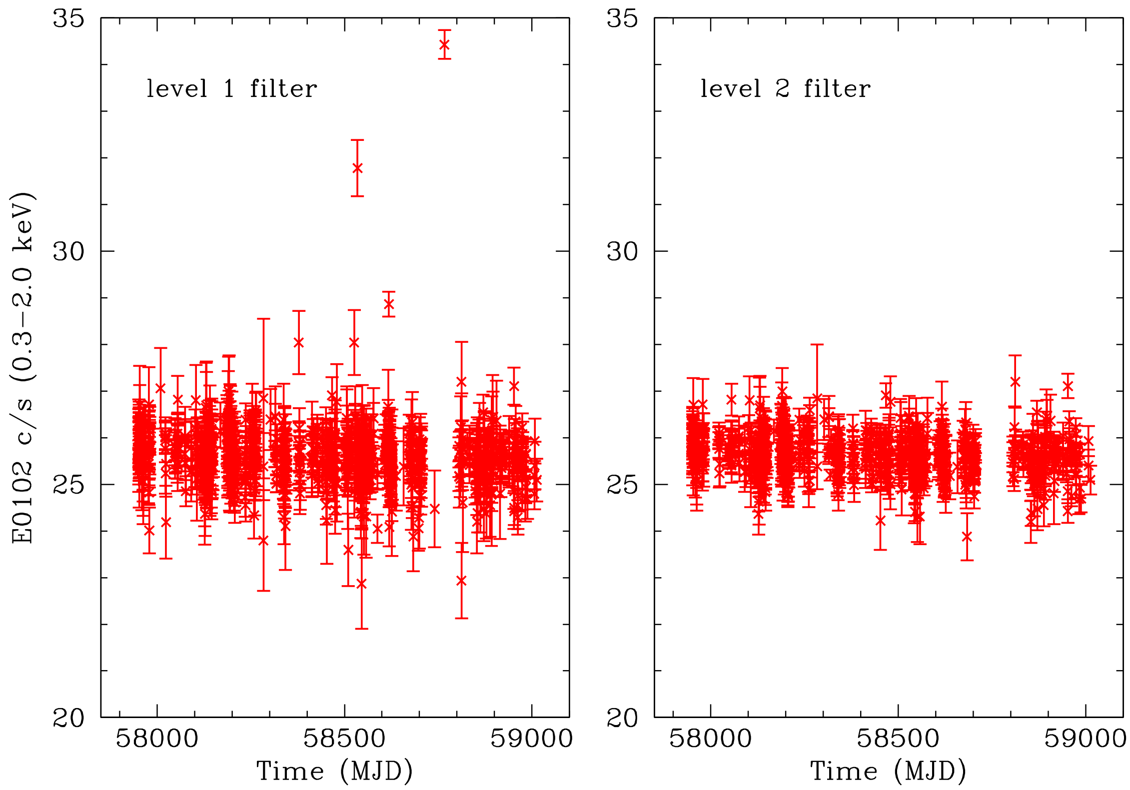
Quality Filtering

- Quality filtering can be performed with the background-subtracted target spectra (subscript “net”)
  - Background residuals can be >> source intensitites at either ends of the spectrum
  - $S0_{net}$ (0.2-0.3 keV) is quality check on $S1_{net}$ (0.3-0.4 keV)
  - hbg_{net} (13-15 keV) is quality check on high-energy end of BG model prediction

- Ballpark filter criteria (see 3C50 model paper):
  - Level 1 filter (all but the brightest, hardest few sources):
    $-30.0 < S0_{net} < 30.0)$ c/s && $(-0.5 < hbg_{net} < 0.5))$ c/s
  - Level 2 filter (sources 20-300 c/s):
    $-10.0 < S0_{net} < 10.0)$ c/s && $(-0.1 < hbg_{net} < 0.1))$ c/s
  - Level 3 filter (sources < 20 c/s):
    $-2.0 < S0_{net} < 2.0)$ c/s && $(-0.05 < hb_{gnet} < 0.05))$ c/s
  - Level 3-soft (sources very faint and not detectable above 2 keV)
    add D-band (4-12 keV) criterion : $-0.5 < D_{net} < 0.5$ c/s

BG Model Assessment

Example of BG-subtracted light curves and data filtering on 1E 0102-75 (SNR in the SMC, used as a calibration source)



For 941 NICER GTIs (408 ks), level 1 filtering (95% of data) yields 25.60 ± 0.62 c/s,

while level 2 filtering (85% of data) gives 25.63 ± 0.42 c/s,

and the rms statistical uncertainty is 0.32 c/s.

Empirical Model 2021

NICER

Revisions 2021:

- Replace ***hrej*** with ***COR_SAX*** (see Fig. 14 of paper)
- Revert definition of ***nz*** back to 0.0-0.2 keV
- Investigate ways to avoid the Poisson uncertainty in ***ibg*** (low count rates) which adds re-normalization noise for GTIs < 100 s.
- Find the additional parameter(s) that will improve the model

  Leading candidate is the angle between camera and the particle stream, which depends on the pitch angle and magnetic latitude.