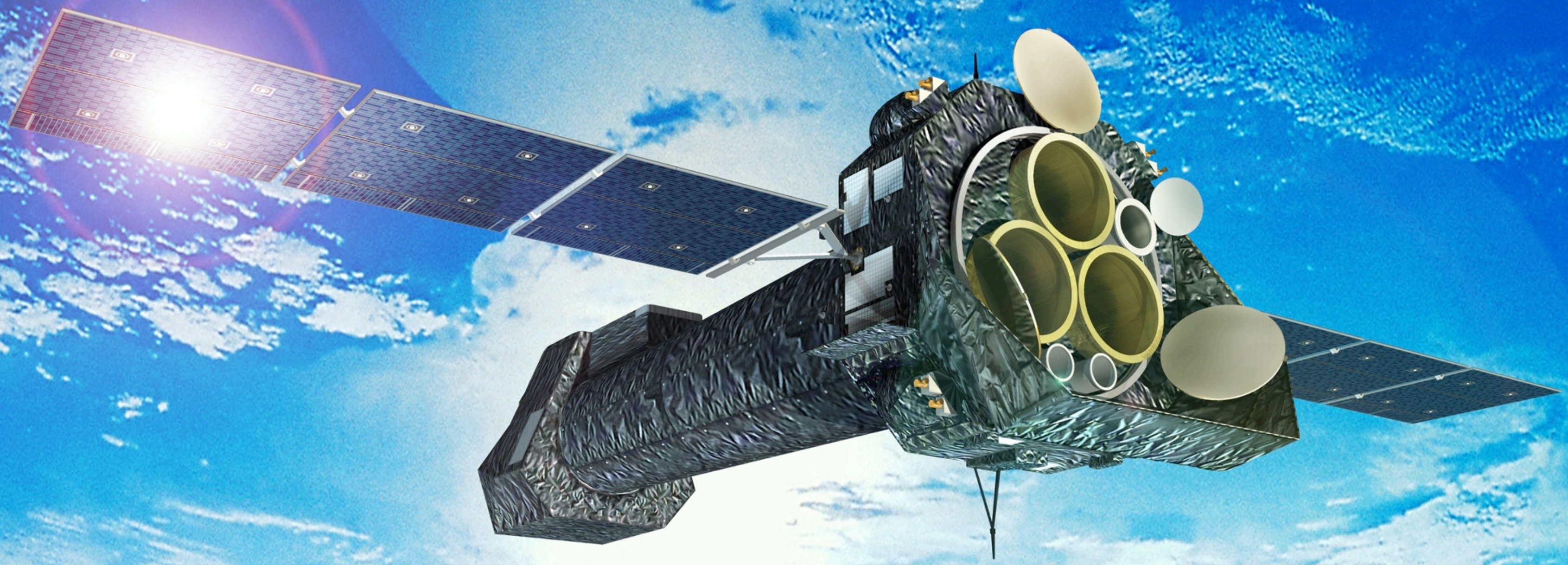
IACHEC

International Astronomical Consortium for High Energy Calibration

12th IACHEC meeting

27 – 30 March 2017, UCLA (Lake Arrowhead, USA)

An empirical method for improving the XMM-Newton/EPIC-pn RMF and ARFs



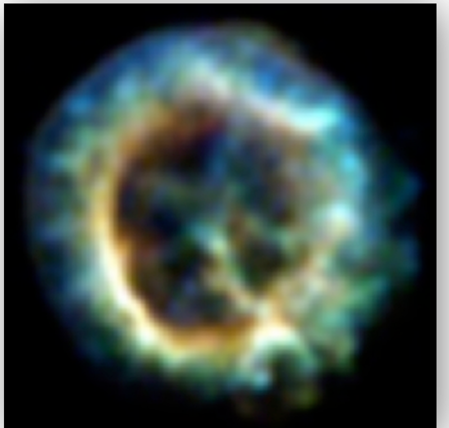
Konrad Dennerl - Max Planck Institute for extraterrestrial Physics – Garching - Germany

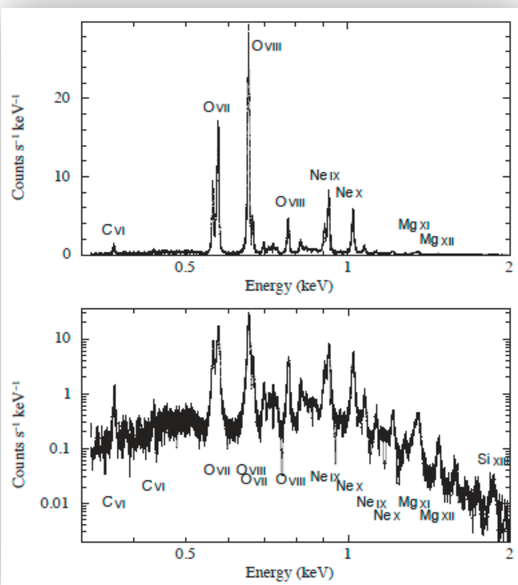
A&A 597, A35 (2017)

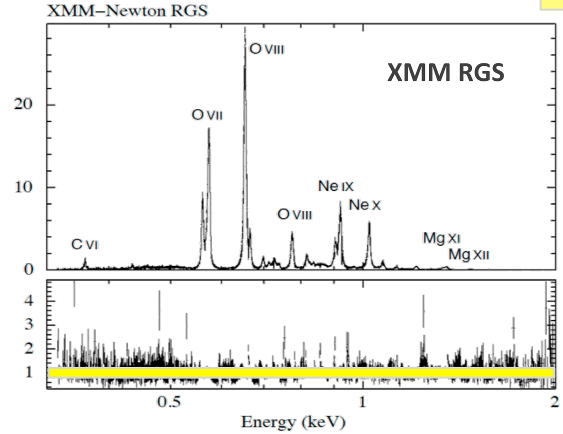
SNR 1E 0102.2-7219 as an X-ray calibration standard in the 0.5–1.0 keV bandpass and its application to the CCD instruments aboard *Chandra*, *Suzaku*, *Swift* and *XMM-Newton*

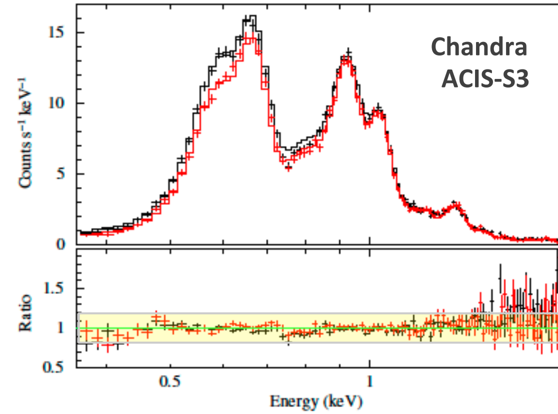
Paul P. Plucinsky[1], Andrew P. Beardmore[2], Adam Foster[1], Frank Haberl[3], Eric D. Miller[4], Andrew M. T. Pollock[5], and Steve Sembay[2]

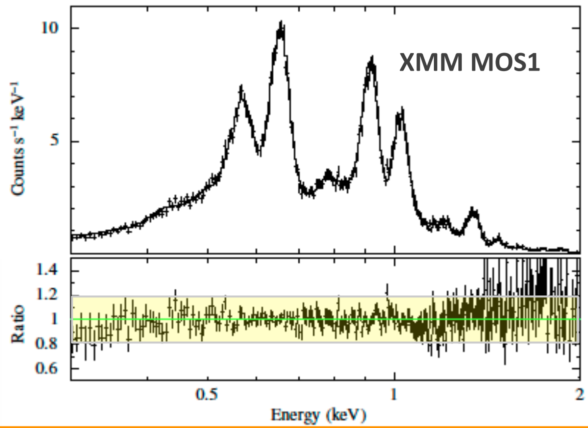
± 20%

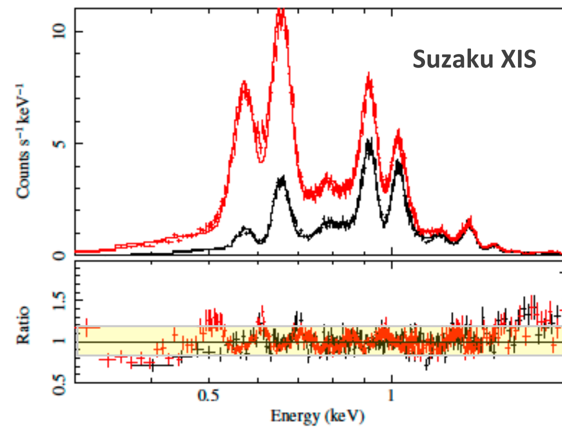


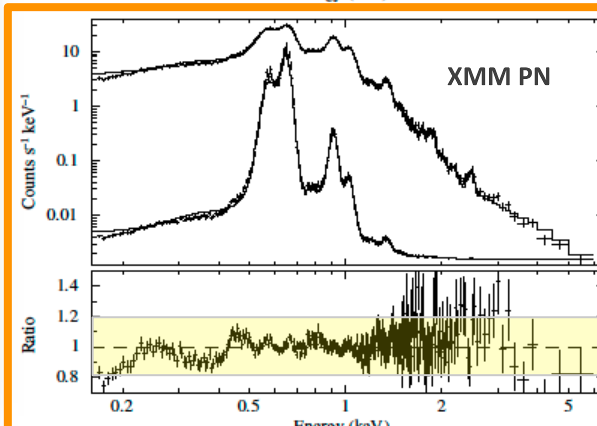


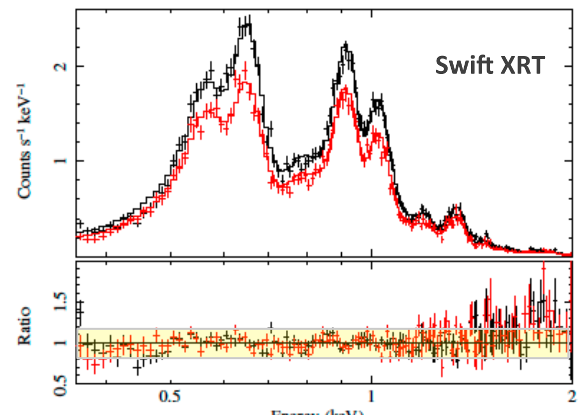






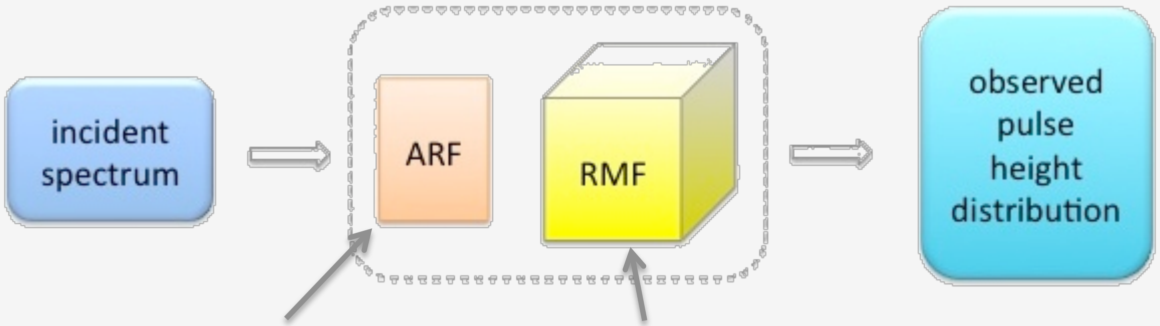






General properties of the ARF and RMF

ARF: „Ancillary Response File", RMF: „Redistribution Matrix File"



EPIC pn: 2067 vector elements 2067 x 4096 matrix elements

RMF @ EPIC pn: 4096 adu bins from 0.0 to 20.5 ‚keV' („EBOUNDS")
2067 eV bins from 50 eV to 16 keV

EPIC pn RMF: 8.5 million matrix elements → **HUGE** parameter space!
EPIC pn ARFs: 3 x 2067 elements → comparatively trivial

→ find appropriate RMF parametrization and try to optimize it..

Empirical modeling of the EPIC pn RMF

Step 1

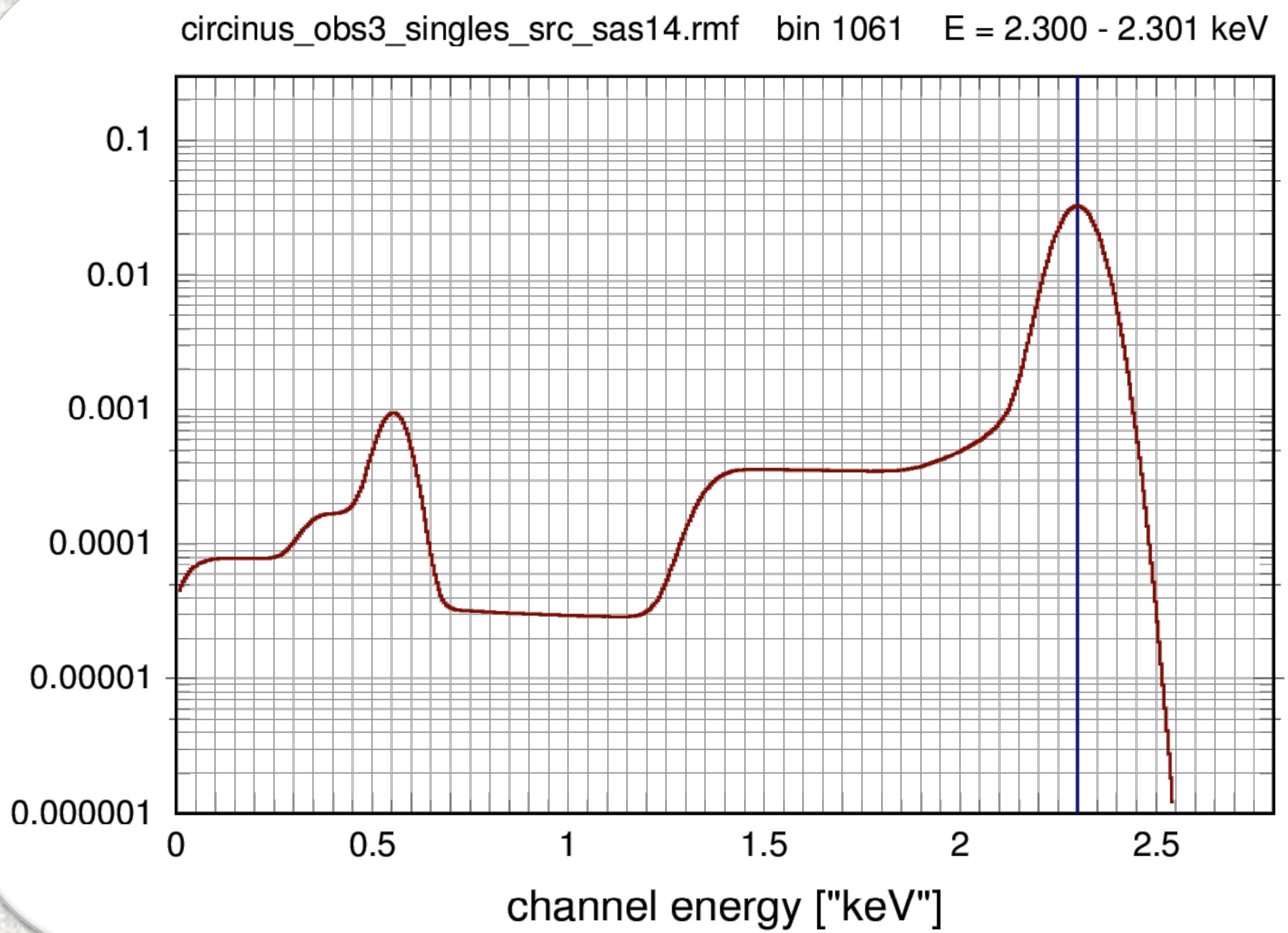
- extract a suitable number (39) of „spectra“ from an EPIC pn RMF
- find a generic mathematical function which is capable of reproducing all of them
- determine the fit parameters individually for each of the 39 spectra
- tighten their energy dependence by applying a „spectral stabilizer“
- find for each parameter a mathematical function which reproduces its energy dependence
- compose the empirical RMF by evaluating this function at each (channel,energy) bin

→ faster computation of the RMF
→ direct access to its „shaping components“

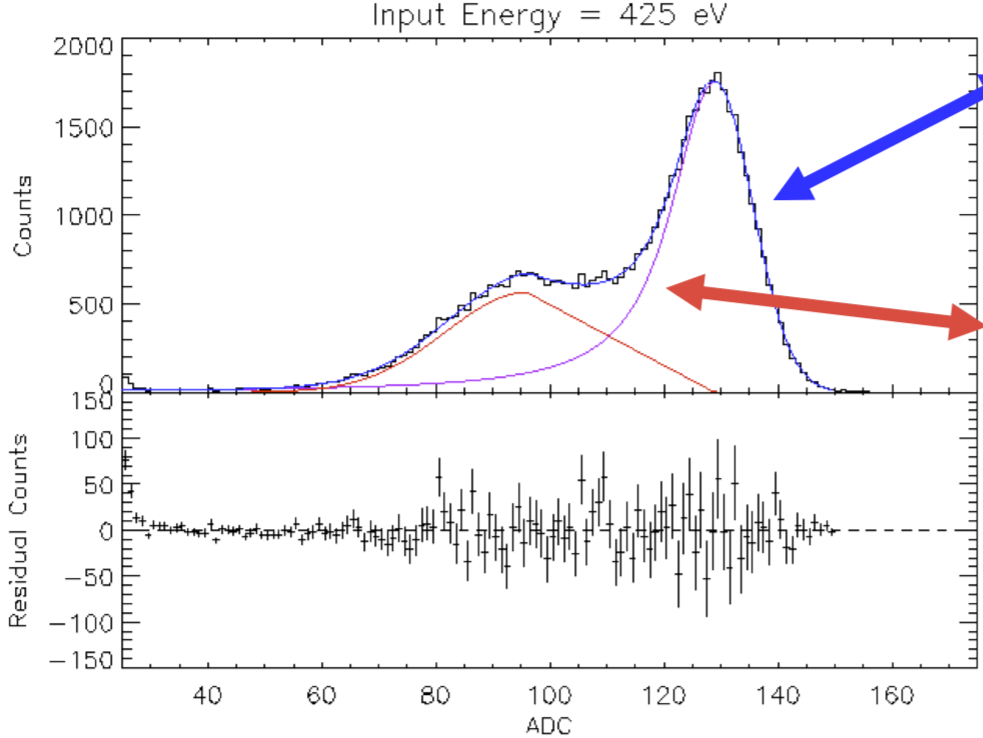
Step 2

- change the energy dependence of the parameters
- compute modified RMFs
- fit them to pairs of „reliable“ model spectra and observed spectra
- improve the RMF

Model Parameters for the EPIC pn RMF



Descriptive Model: The VRMF Model



Main Peak

Blue Wing:
Gaussian

Red Wing:
Voigt Function

= Gaussian convolved with a Lorentian.

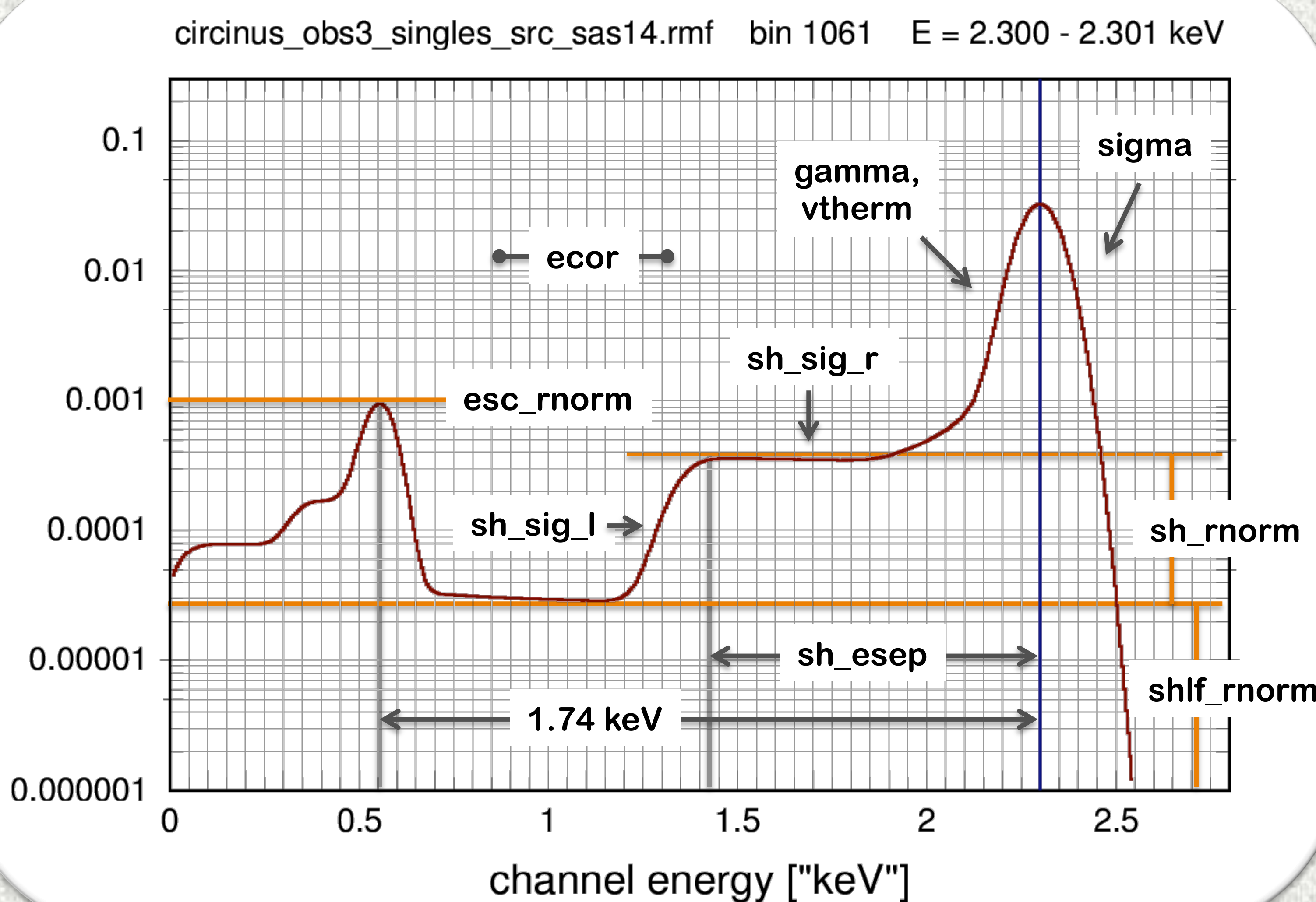
Dampening factor
= 0 (Gaussian)
> 0 (Lorentz-like)

XMM
EPIC
MOS

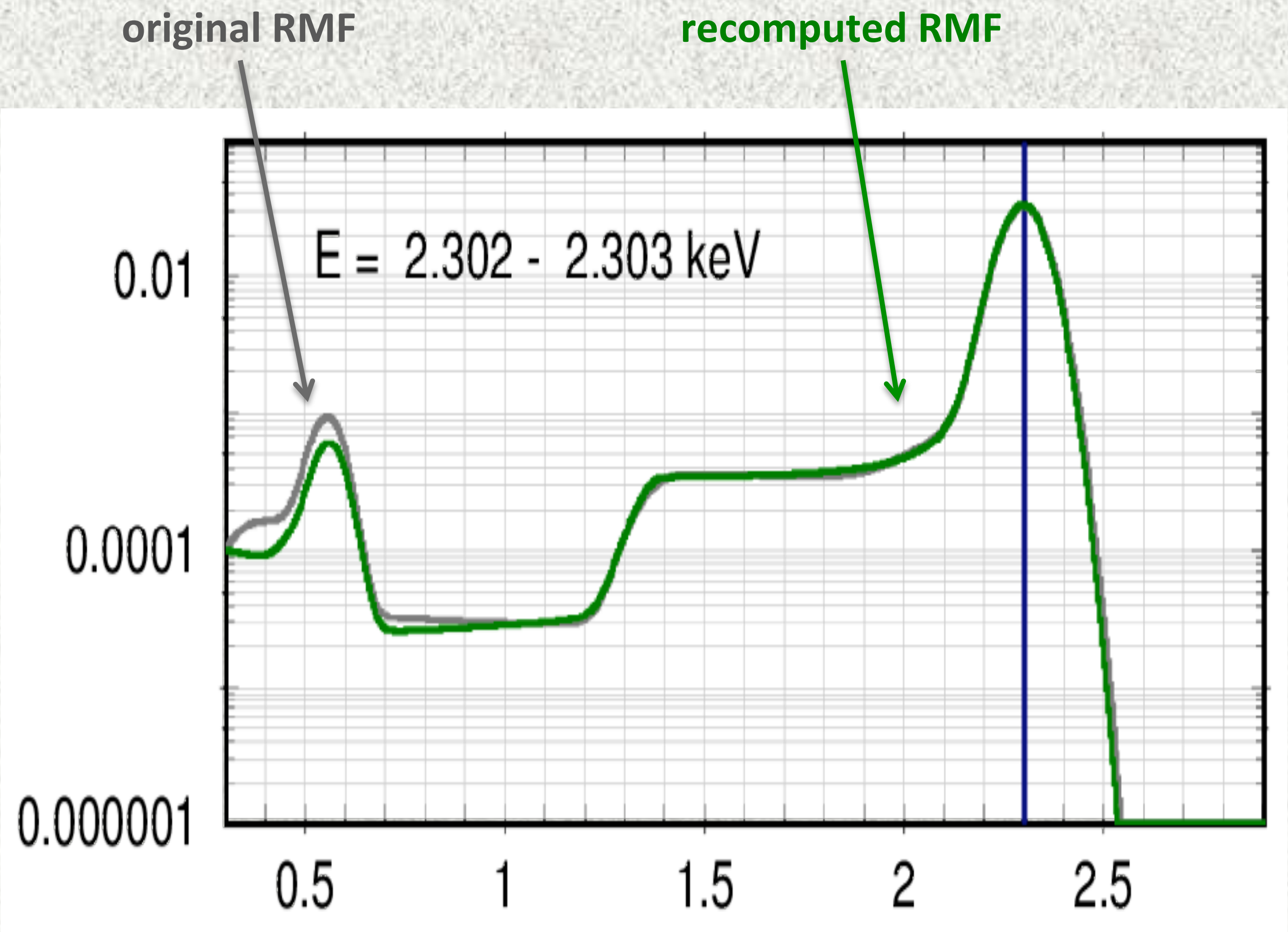
Steve Sembay (sfs5@star.le.ac.uk)
Mallorca 01/04/09

University of Leicester

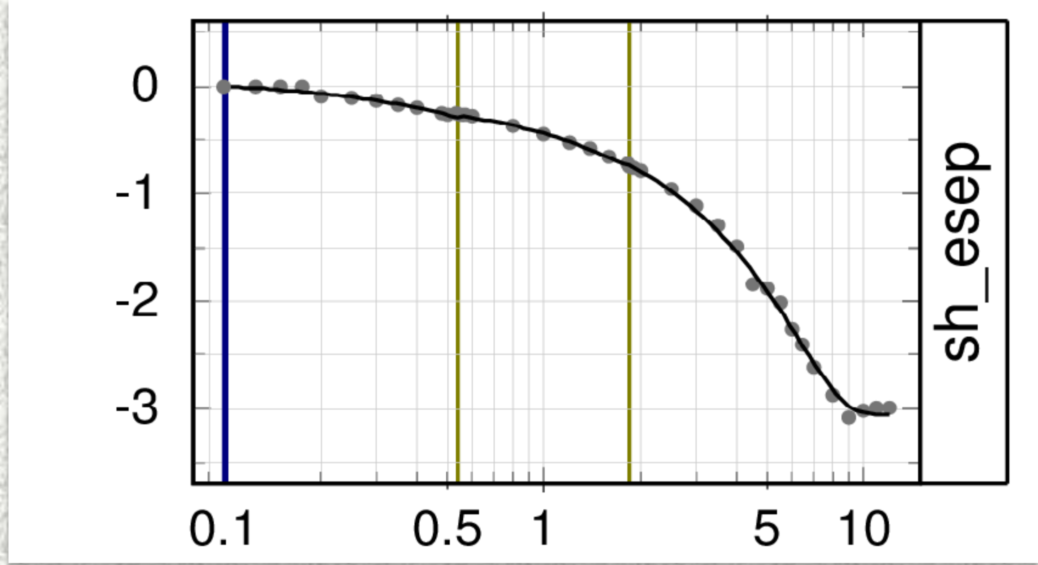
Modeling the EPIC pn RMF at individual energies



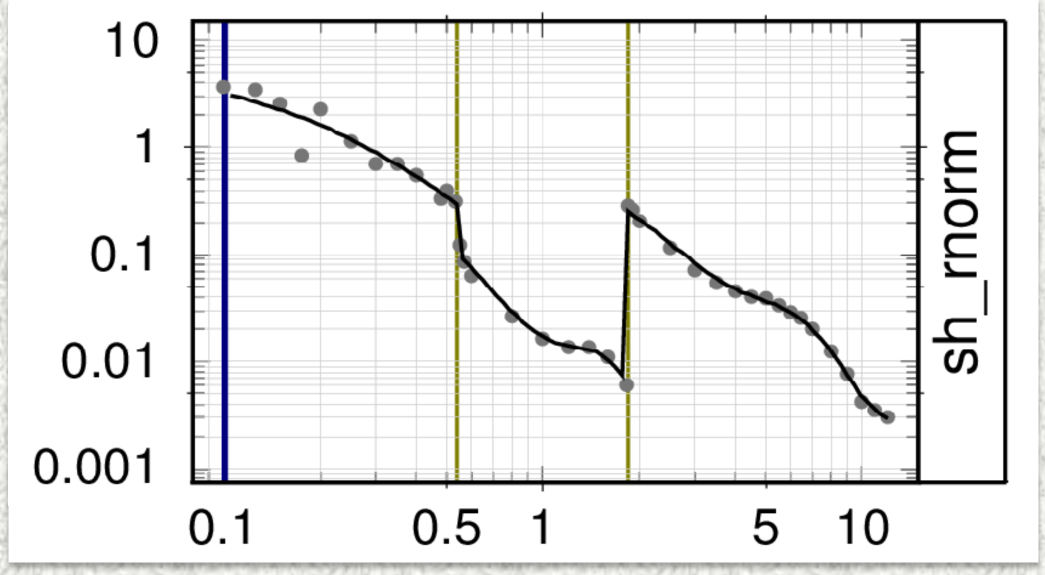
Comparison: original and recomputed RMF @ 2.3 keV



Modeling the energy dependence of the RMF parameters for EPIC pn

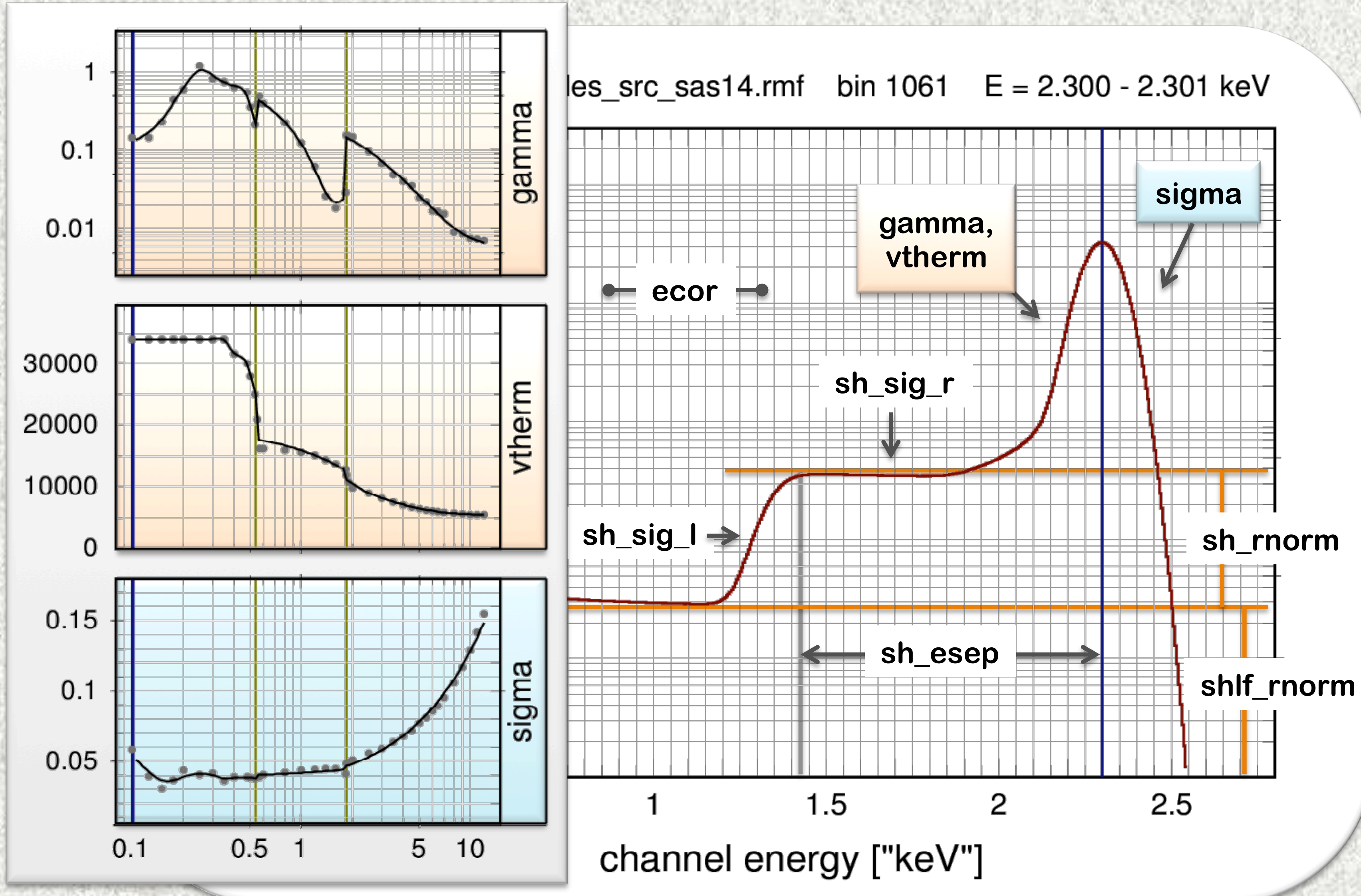


approximating spline



approximating segmented spline

Modeling the EPIC pn RMF at individual energies



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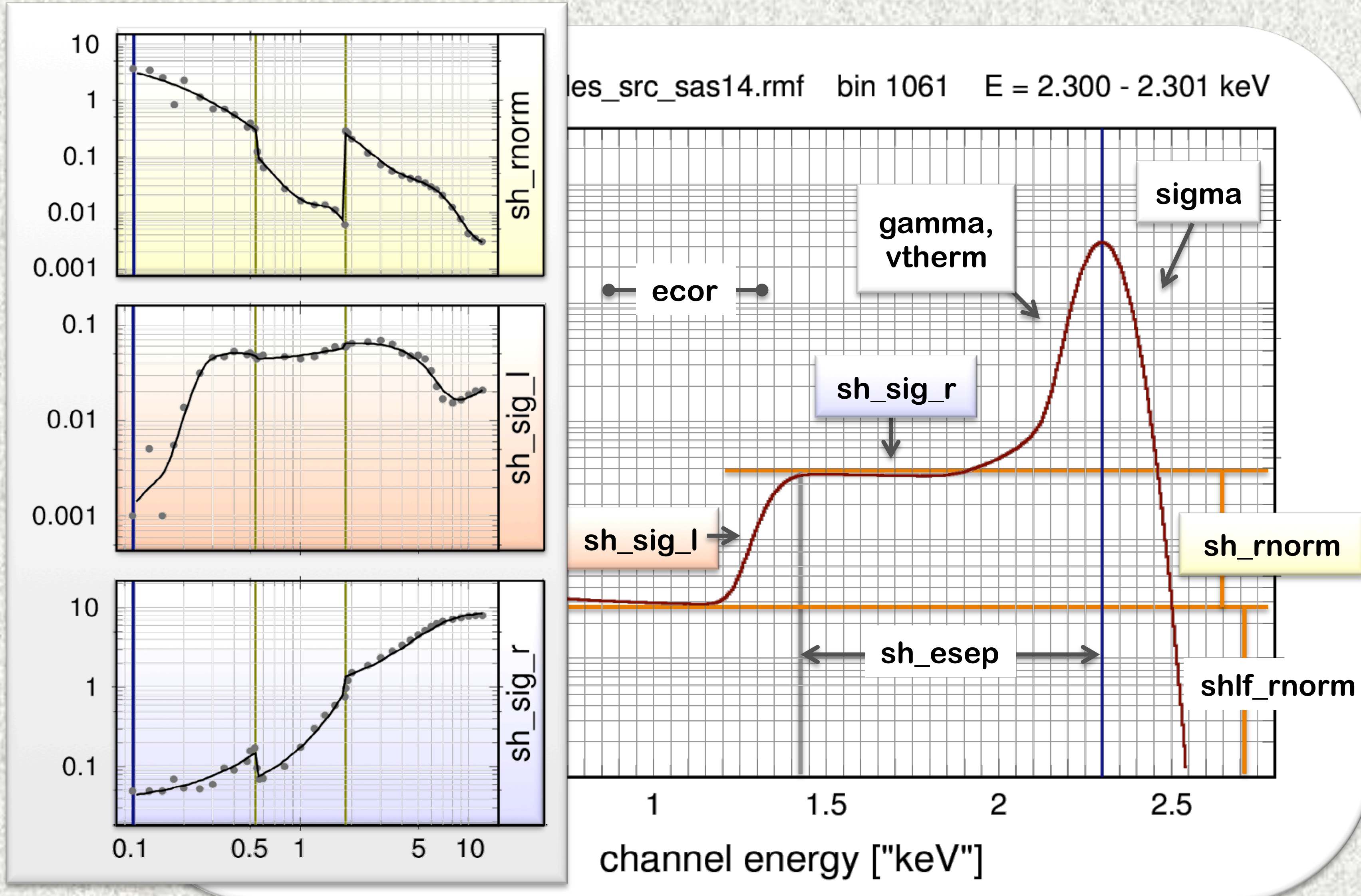

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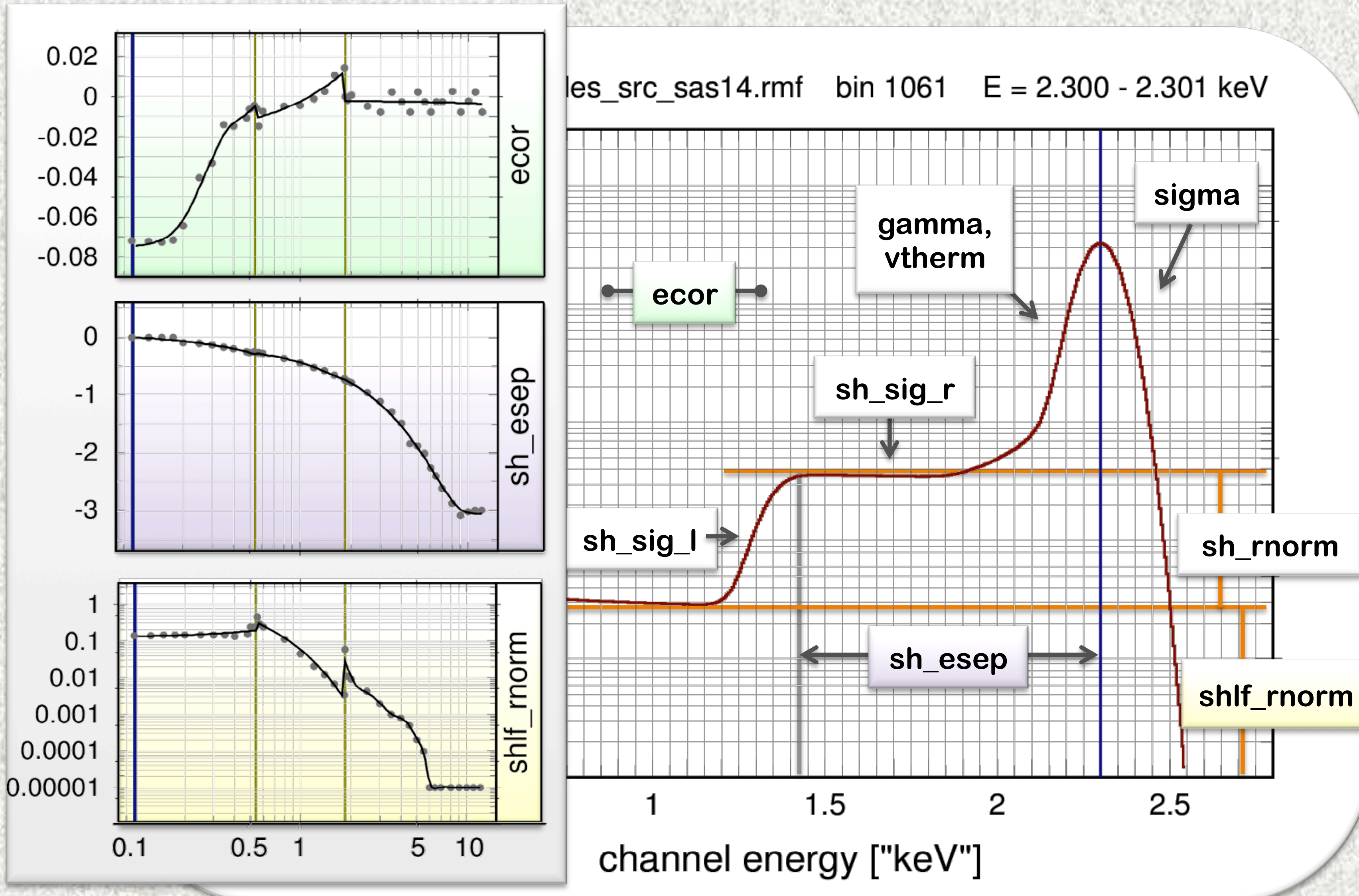

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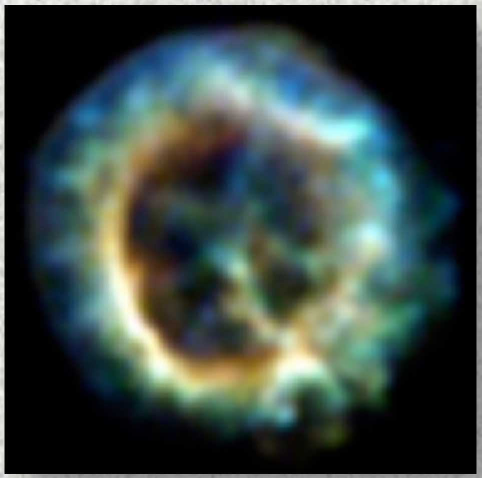
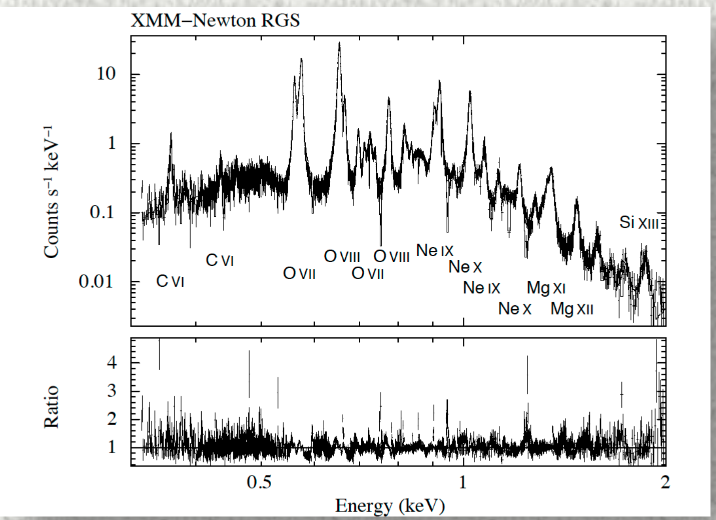
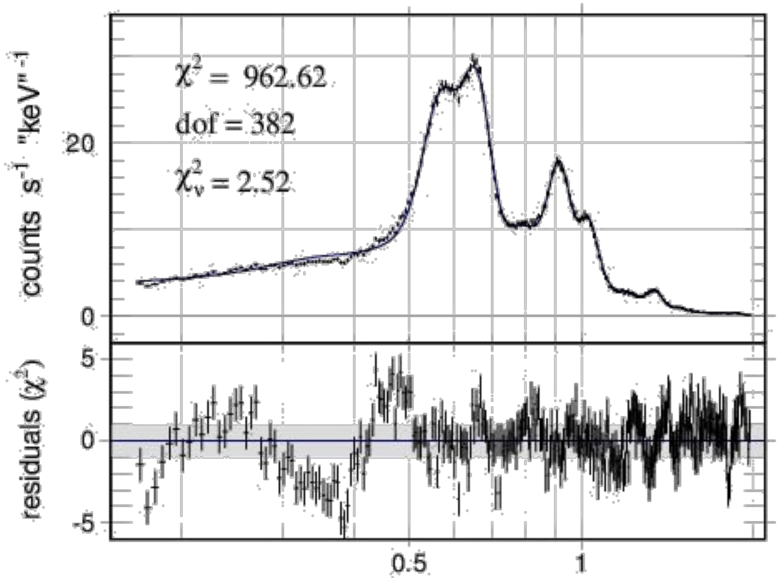


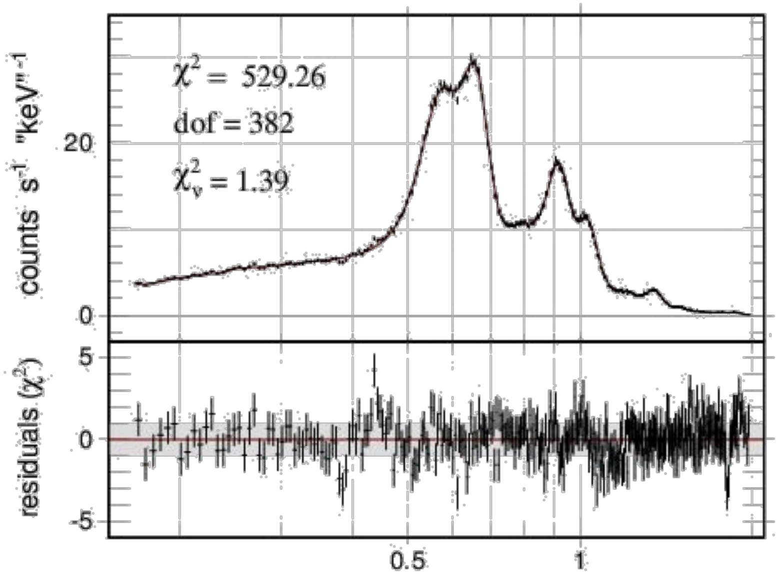
Improving the EPIC pn RMF

SNR 1E0102

proof of concept







Challenge: finding appropriate models

The quality of RMF/ARF improvement is directly related to the confidence of spectral models

e.g. is there a second thermal component in the spectrum of RXJ 1856 ?

Reliable „technical" reference models are essential

→ IACHEC !

Challenge: finding suitable data

XMM-Newton / EPIC-pn

full frame
ext. full frame
large window
small window
timing
burst

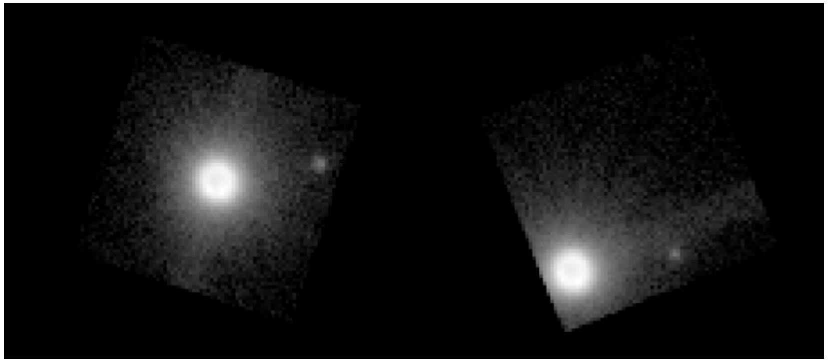
thin filter
medium filter
thick filter

time
of the
observation

position
on the
CCD

example: 1E 0102

2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
1x	2x	1x	1x	1x	2x	2x	2x	2x	1x	1x	3x	2x	2x	2x

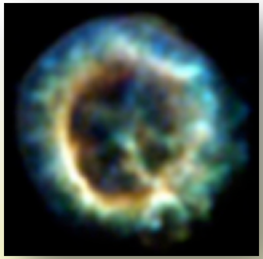


thin
medium
thick

centered position
boresight position

Selected calibration observations

general strategy: start at **low energies, below the escape peak of Si** (1.7 keV)



1E 0102-72

SW, **medium**, 2011-04-20, 23 ks

SW, **thin**, 2014-10-20, 30 ks

SW, **medium**, 2014-10-20, 30 ks

RXJ 1856.6-3754

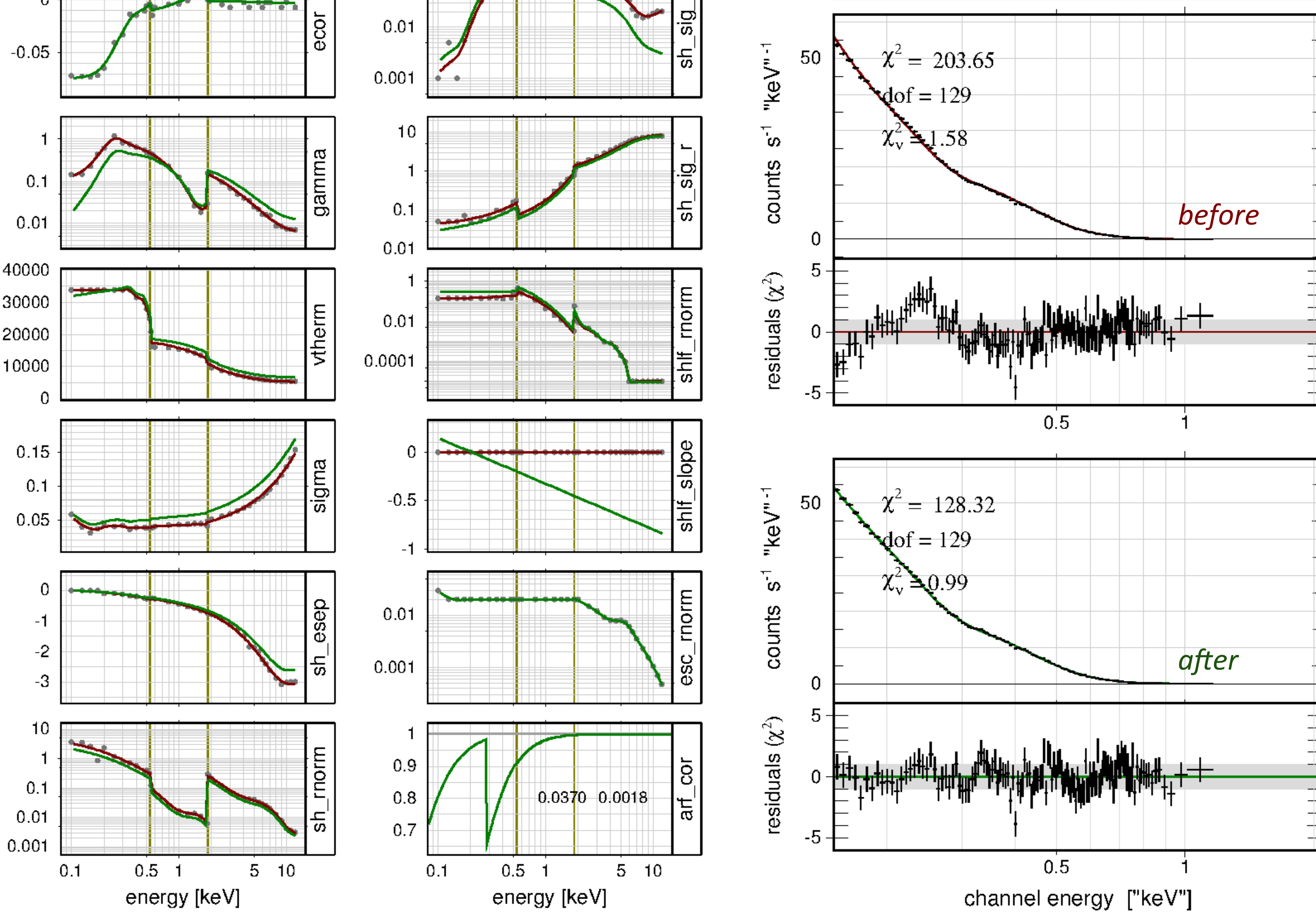
SW, **thin**, 2014-09-18/19, 78 ks

ζ Puppis

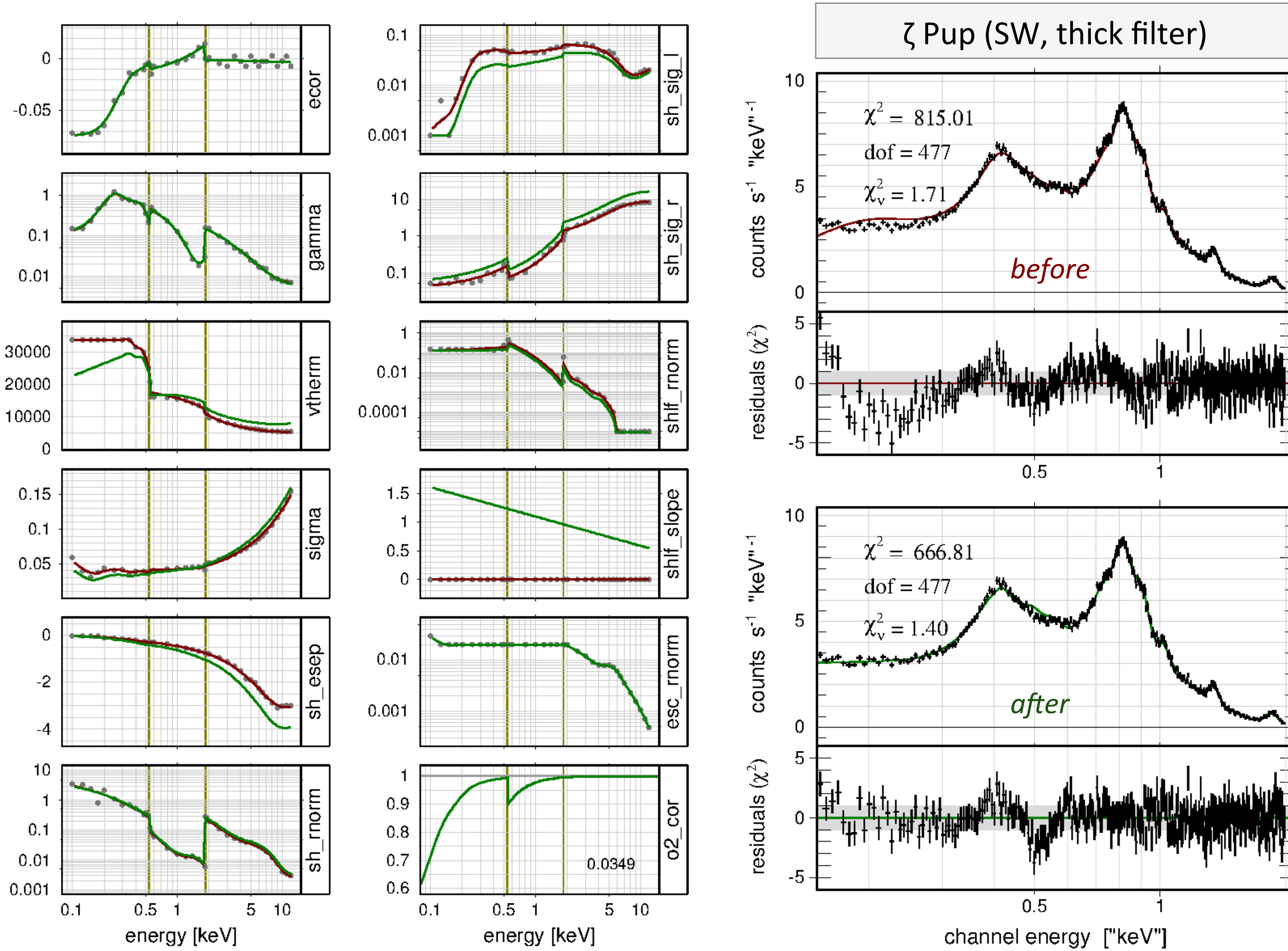
SW, **thick**, 2013-10-08, 67 ks

RXJ 1856.6-3754 (SW, thin filter)

RXJ 1856 (SW, thin filter)



ζ Puppis (SW, thick filter)

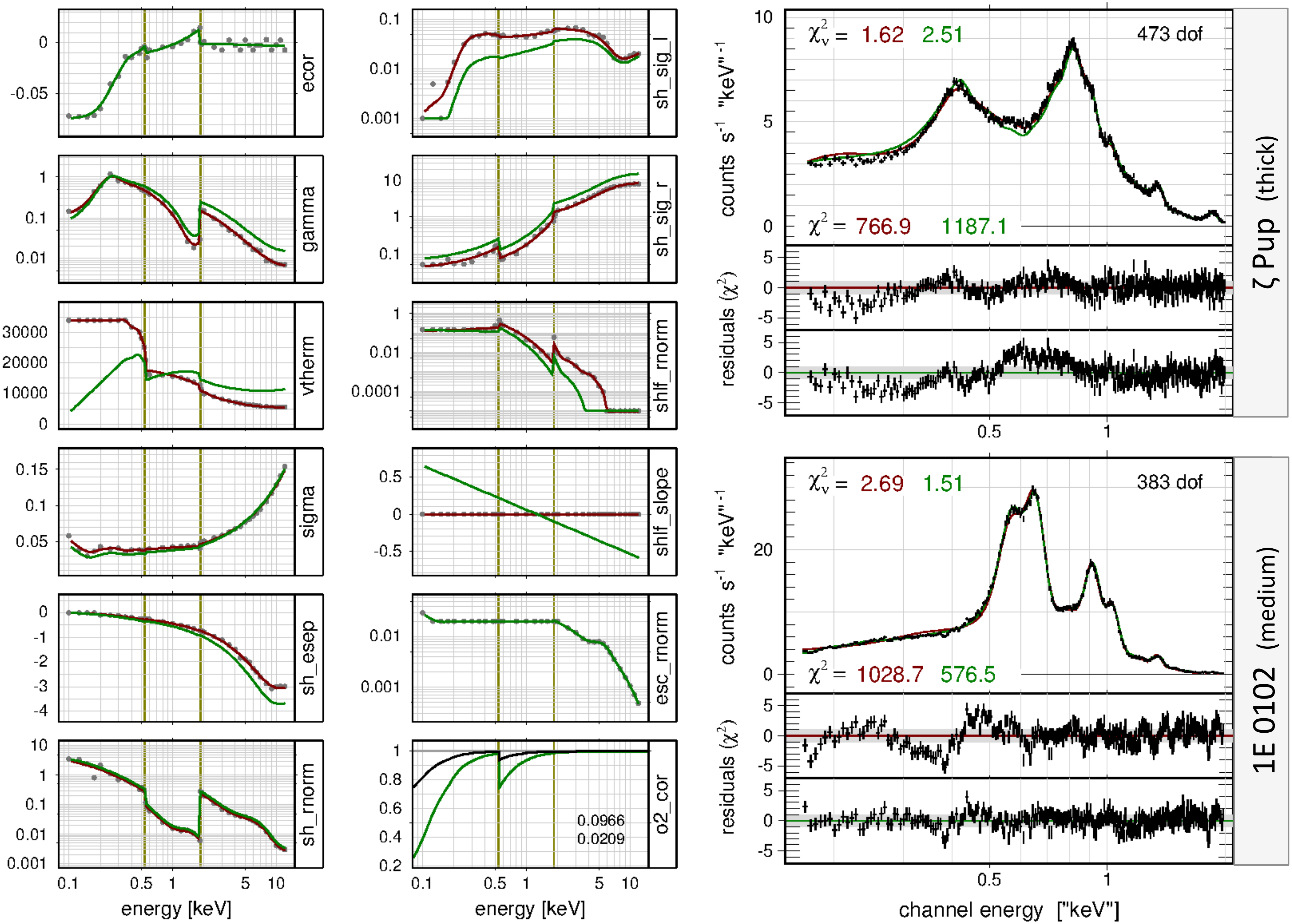


ζ Pup (SW, thick filter)
ecor
gamma
vtherm
sigma
sh_esep
sh_rnorm
sh_sig_l
sh_sig_r
shlf_rnorm
shlf_slope
esc_rnorm
o2_cor
0.0349
energy [keV]
χ² = 815.01
dof = 477
χ²ν = 1.71
before
χ² = 666.81
dof = 477
χ²ν = 1.40
after
counts s⁻¹ "keV"⁻¹
residuals (χ²)
channel energy ["keV"]

ζ Puppis (SW, thick filter)

&

1E 0102-72 (SW, medium filter)



ecor
gamma
vtherm
sigma
sh_esep
sh_rnorm
energy [keV]
sh_sig_l
sh_sig_r
shlf_rnorm
shlf_slope
esc_rnorm
o2_cor
0.0966
0.0209
energy [keV]
χ^2_ν = 1.62 2.51
473 dof
χ^2 = 766.9 1187.1
counts s^{-1} "keV"$^{-1}$
residuals (χ^2)
ζ Pup (thick)
χ^2_ν = 2.69 1.51
383 dof
χ^2 = 1028.7 576.5
1E 0102 (medium)
channel energy ["keV"]

Interim result:
algorithm works well,
but resulting RMF depends
heavily on assumed spectral models

Is there any possiblity to expose the CCD
to a known X-ray spectrum ?

Currently no, but for XMM/EPIC
we can modify the incident spectrum
in a controlled way!

There is a filter wheel..

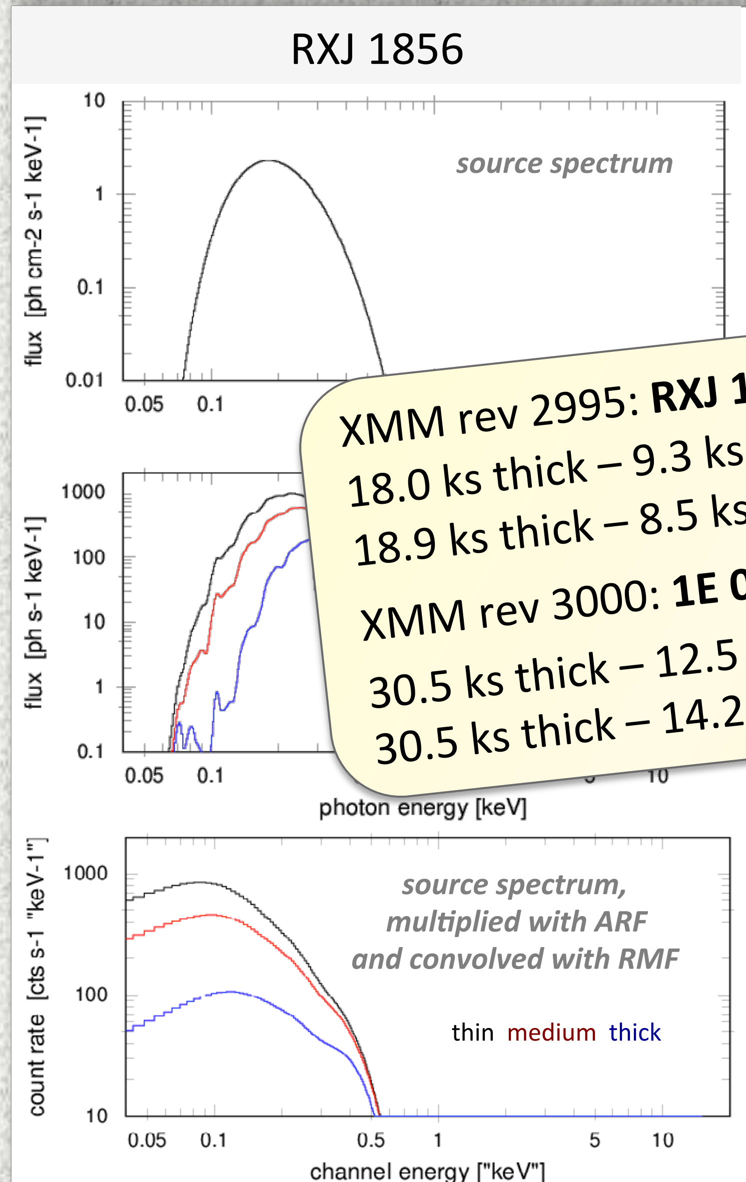
Idea: observe the same
(temporally constant, soft, non piled-up)
X-ray source(s) with all available filters and fit the spectra simultaneously with the same RMF

General strategy:

- make this calibration measurement **as robust as possible** by minimizing any possible disturbances: observe
  - at (almost) the same time
  - at the same position on the detector
  - with the same readout mode

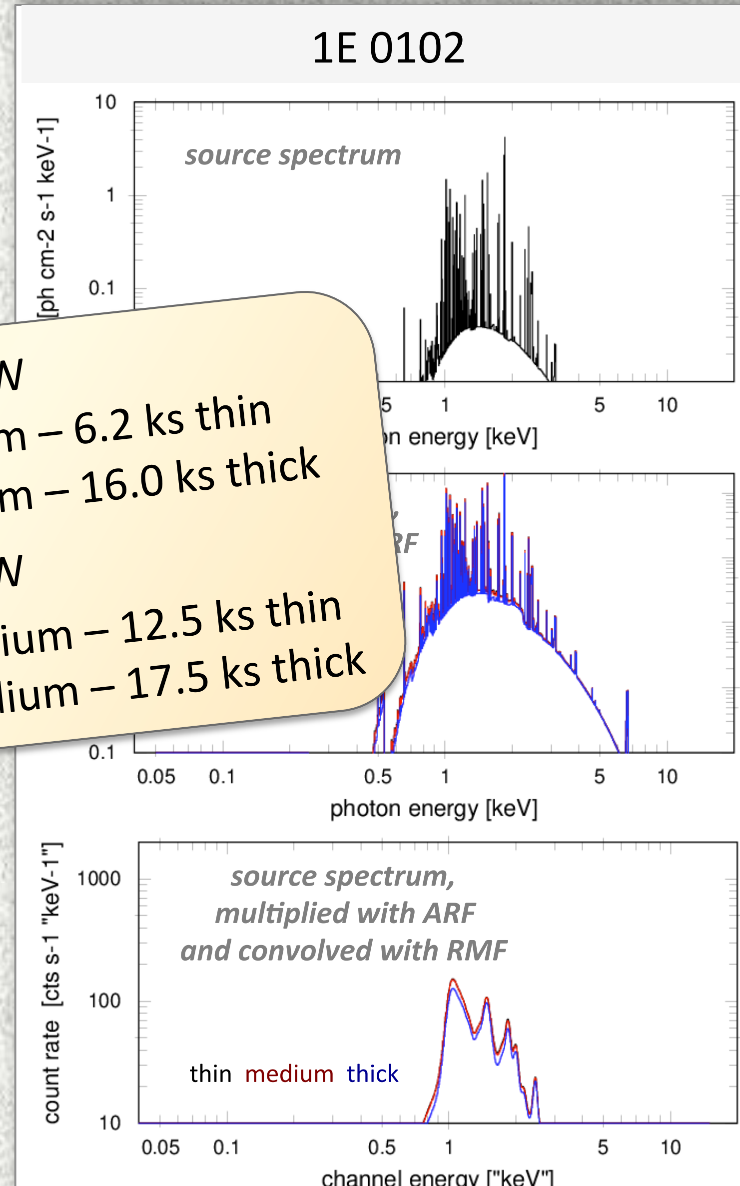
→ „controlled experiment"
→ by-product: check of the ARF

- to make this even more robust (vs. any short-term changes), repeat the same filter sequence immediately afterwards, e.g.
  thick – medium – thin -- thick – medium – thin



XMM rev 2995: **RXJ 1856**, SW
18.0 ks thick – 9.3 ks medium – 6.2 ks thin
18.9 ks thick – 8.5 ks medium – 16.0 ks thick

XMM rev 3000: **1E 0102**, SW
30.5 ks thick – 12.5 ks medium – 12.5 ks thin
30.5 ks thick – 14.2 ks medium – 17.5 ks thick



Looking behind the scences ..

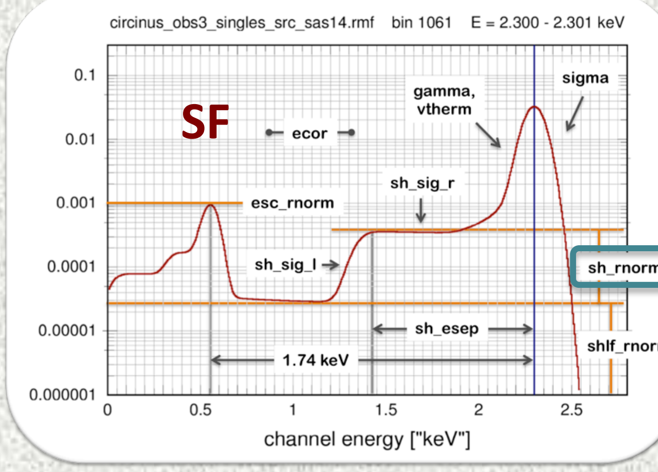
RMF refinement method

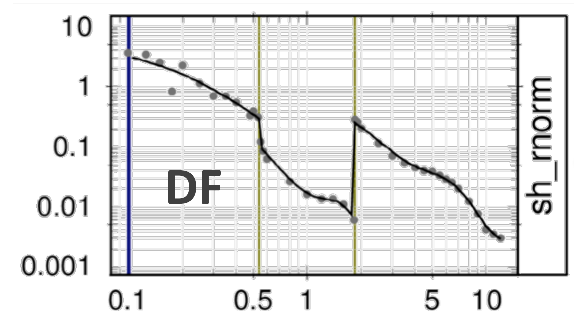
(ARF refinement comparatively trivial)

1) Compose the RMF of **shaping functions SF** which are determined by **shaping parameters SP**:

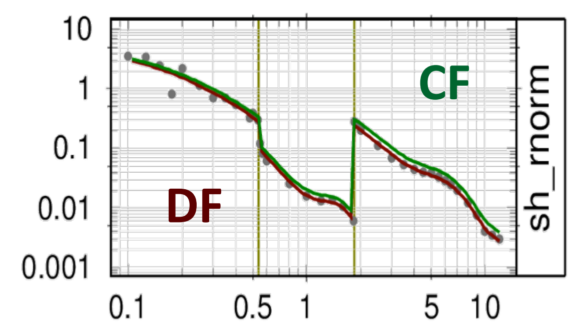
- main peak: *gamma, vtherm, sigma*
- shoulder: *sh_rnorm, sh_sigl, sh_sigr, sh_esep*
- shelf: *shlf_rnorm, shlf_slope*
- escape peak: *another 9 parameters*

and determine **deformation functions DF** to model the energy dependence of the shaping functions, and reproduce an existing RMF

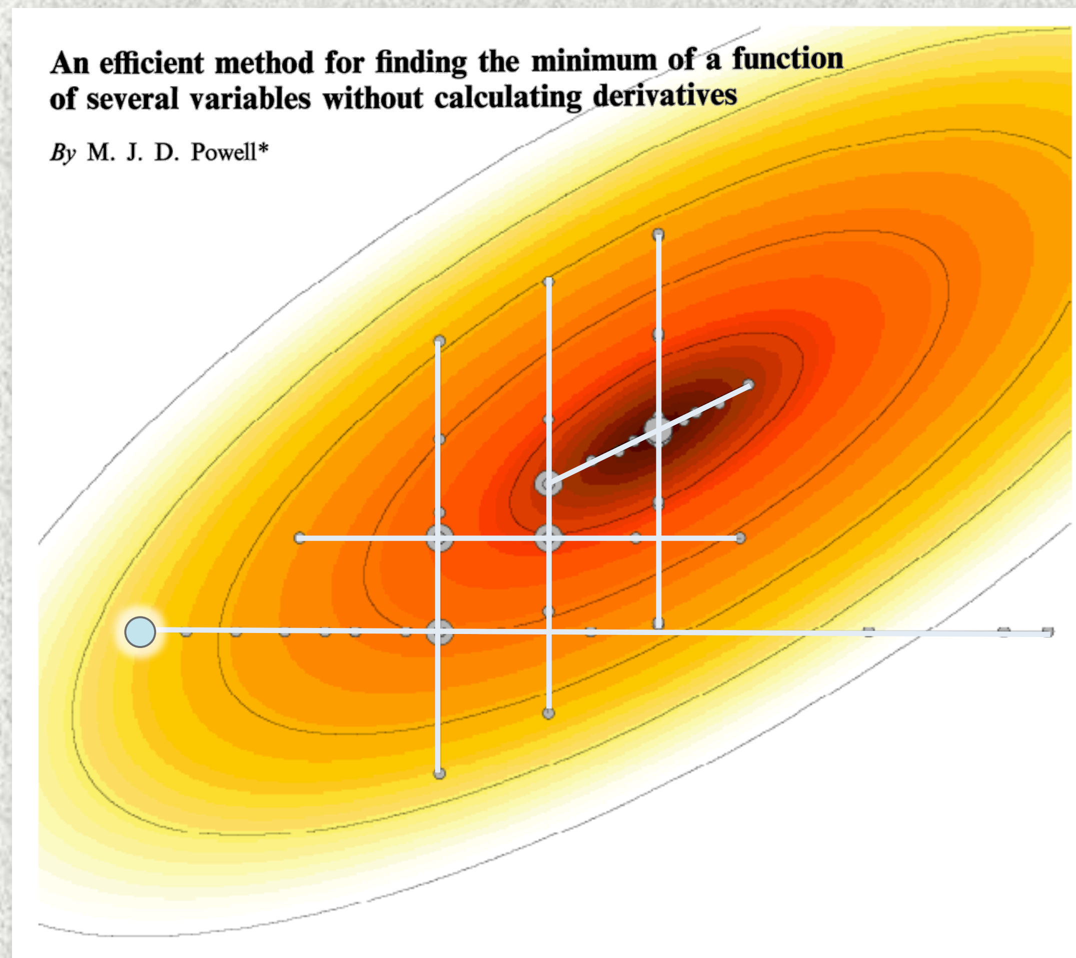


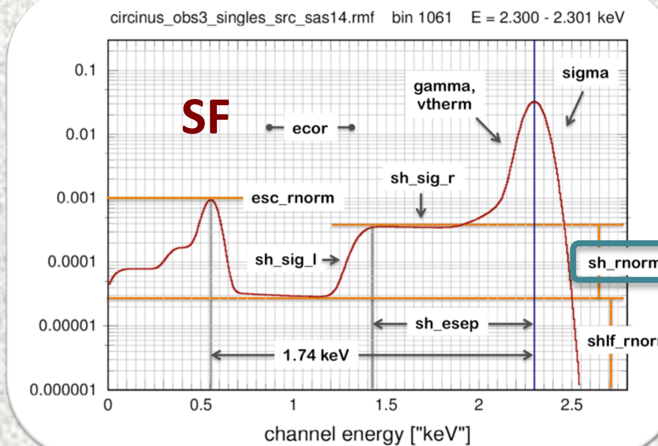


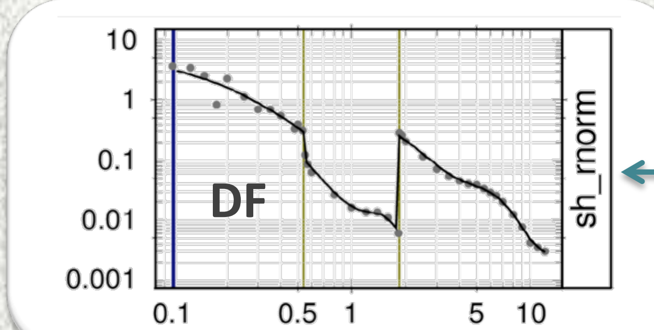
2) Apply **correction functions CF** to the deformation functions DF, recompute the RMF, use this RMF for (simultaneously) fitting X-ray spectra with spectral **model functions MF** (with plausible spectral **model parameters MP**), and compute the goodness of the fit.
Vary the **correction parameters CP** (and the correction functions CF) in order to maximize the goodness of the fit.

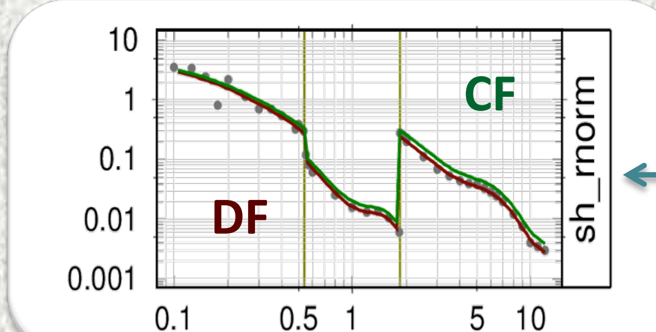


RMF refinement method







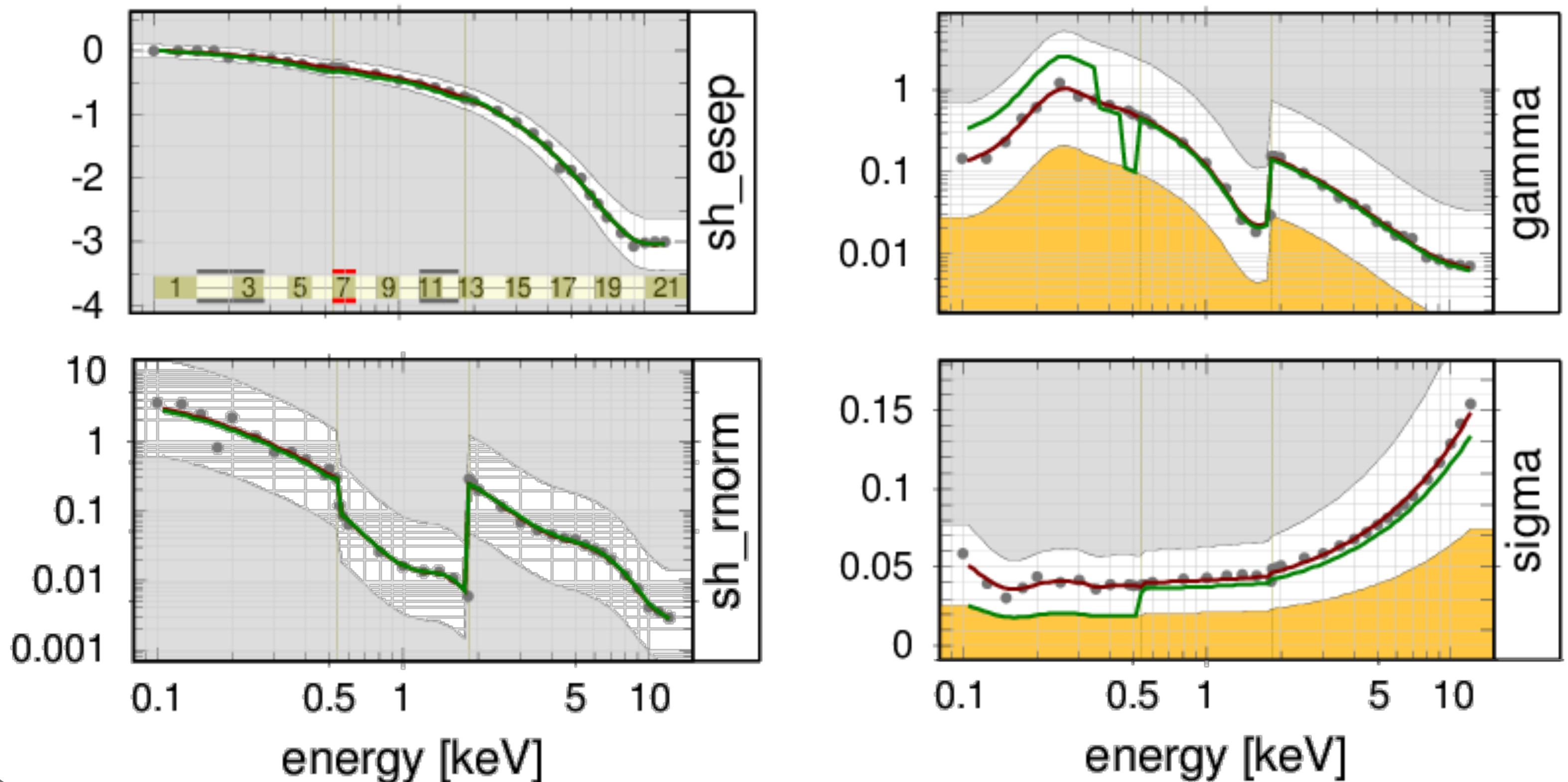


Vary the **correction parameters CP** (and the correction functions CF) in order to maximize the goodness of the fit.

RMF refinement method

Challenge: constraining the **correction functions CF**

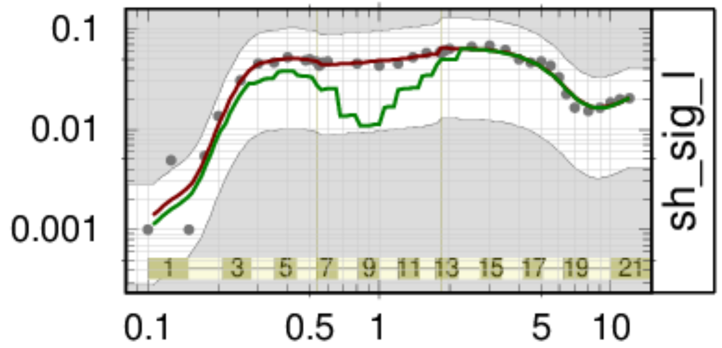
Solution: define appropriate corridors and „discourage“ any attempt to leave them by adding penalties to the goodness of the fit if values lie outside, scale the penalties with distance from the allowed region

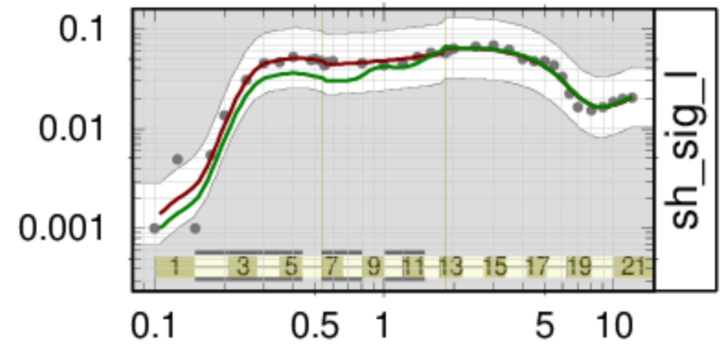


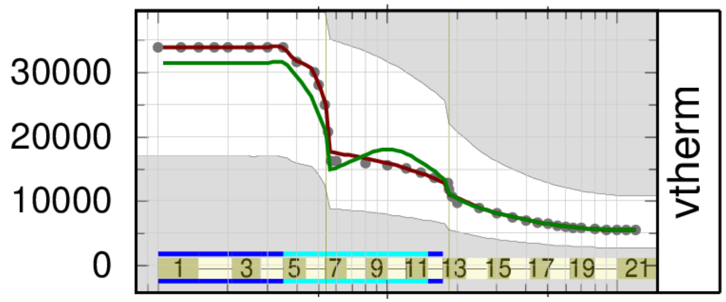
RMF refinement method

Challenge: finding the **correction functions CF**
(not just the parameters **CP**, but the functions themselves!)

Solution: divide the energy range into small intervals and compute for each interval an appropriate correction







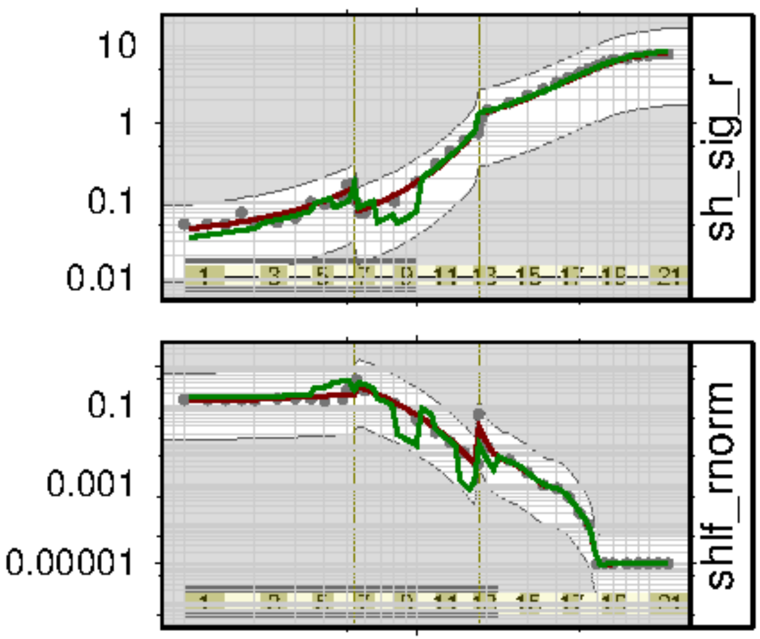
the correction can either be applied stepwise or in a smoothed way by using spline interpolation

RMF refinement method

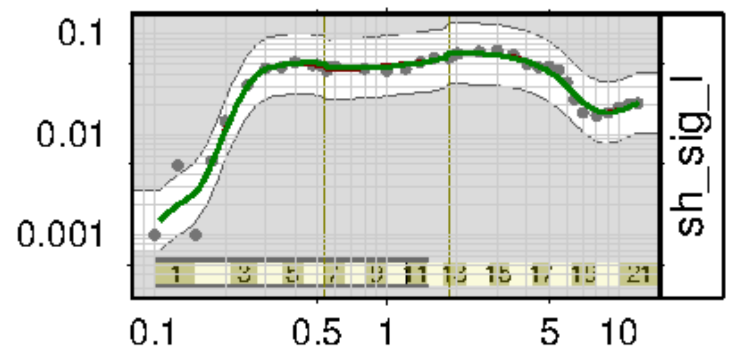
Challenge: „stabilizing“ the correction functions **CF**
(different parameter combinations can lead to similar fit quality)

Solution: include CF smoothness as an additional criterion for the goodness of the fit (i.e., add „roughness penalty“)

*starting with a „rough“ **CF***



*starting with a smooth **CF***



the „roughness penalty“ has to be applied „gently“ in order to ensure that minimizing the spectral fit is the dominant goal

RMF refinement method

Challenge: how to keep an overview (in total > 1000 parameters!)

- **19 shaping functions SF** with a total of **19 shaping parameter SP**;
  the energy dependence of each SP is determined by a deformation function DF
- the **19 DFs** are computed from a total of **555 deformation parameters DP**,
  which were derived by simultaneously fitting 39 EPIC-pn „RMF samples“
  with 117 free and 438 fixed/tied parameters
- **19 correction functions CF**, each determined by up to 21 adjustable CPs,
  yielding a total of **399 correction parameters CPs**
- spectral fits:
  - 1E 0102: **208 model parameters MP_1**, with 4 of them free + **gain offset**
  - RXJ 1856: **3 model parameters MP_2,** with 1-3 of them free + **gain offset**
- in addition for the 3 ARFs: (thick, medium, thin):
  - **3 x 2 adjustable parameters** for C-K and O-K absorption
  - **up to 21 adjustable parameters** for correcting the fraction of singles

→ up to **19 x 21 + 6 = 405 adjustable correction parameters** in total
→ necessity to **fix/tie/couple** a subset of the correction parameters
→ necessity to **constrain** the correction functions
→ necessity to **control** the spectral fit results

Solution: concise graphical summary

Simultaneous fit to
RXJ 1856 and 1E0102
in three filters each

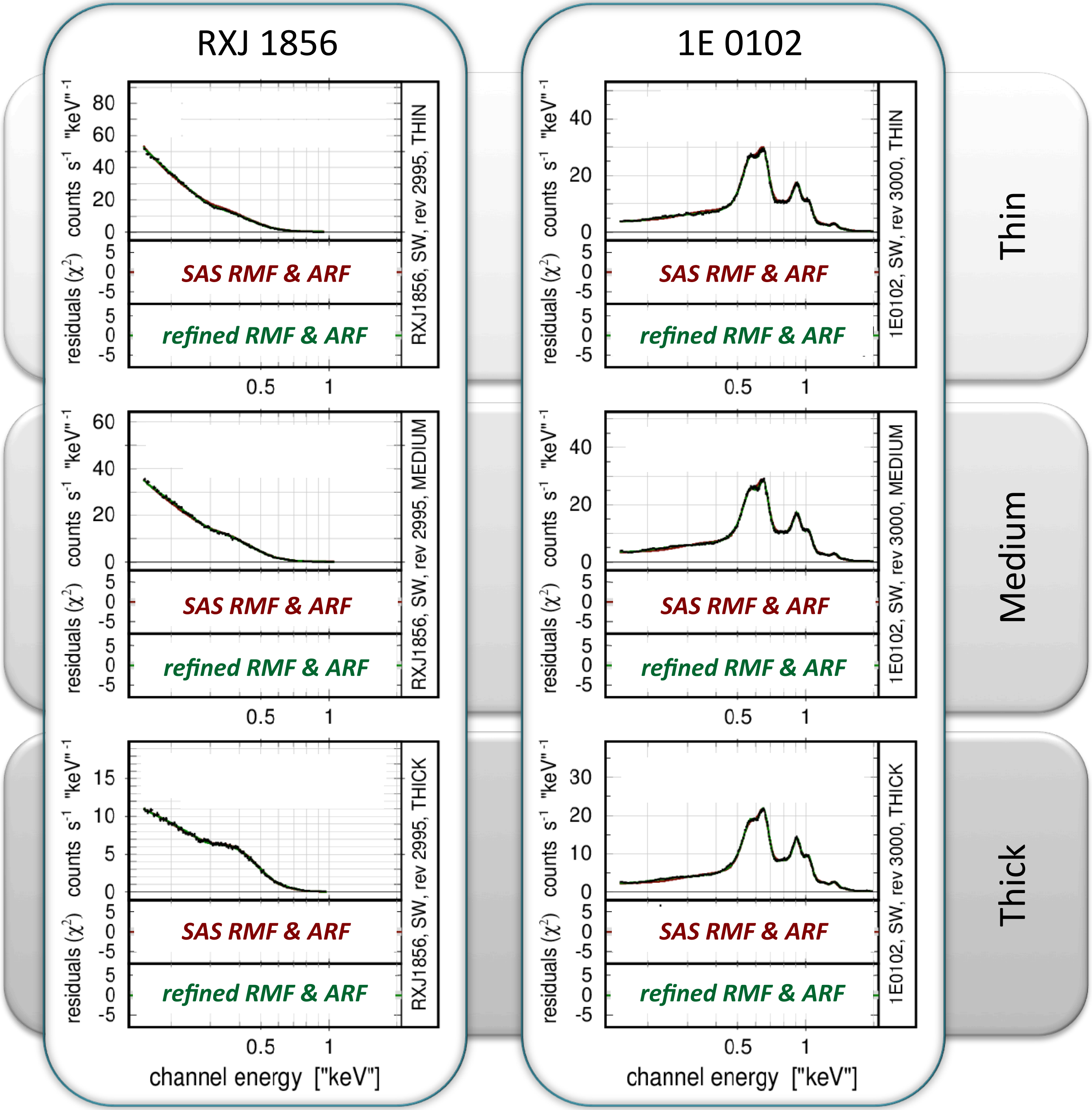
using the same
model spectrum
for each source,
with no normalization
between the filters

and

1 RMF + 3 ARFs

⇩

significant
improvement
possible !



Simultaneous fit to RXJ 1856 and 1E0102 in three filters each

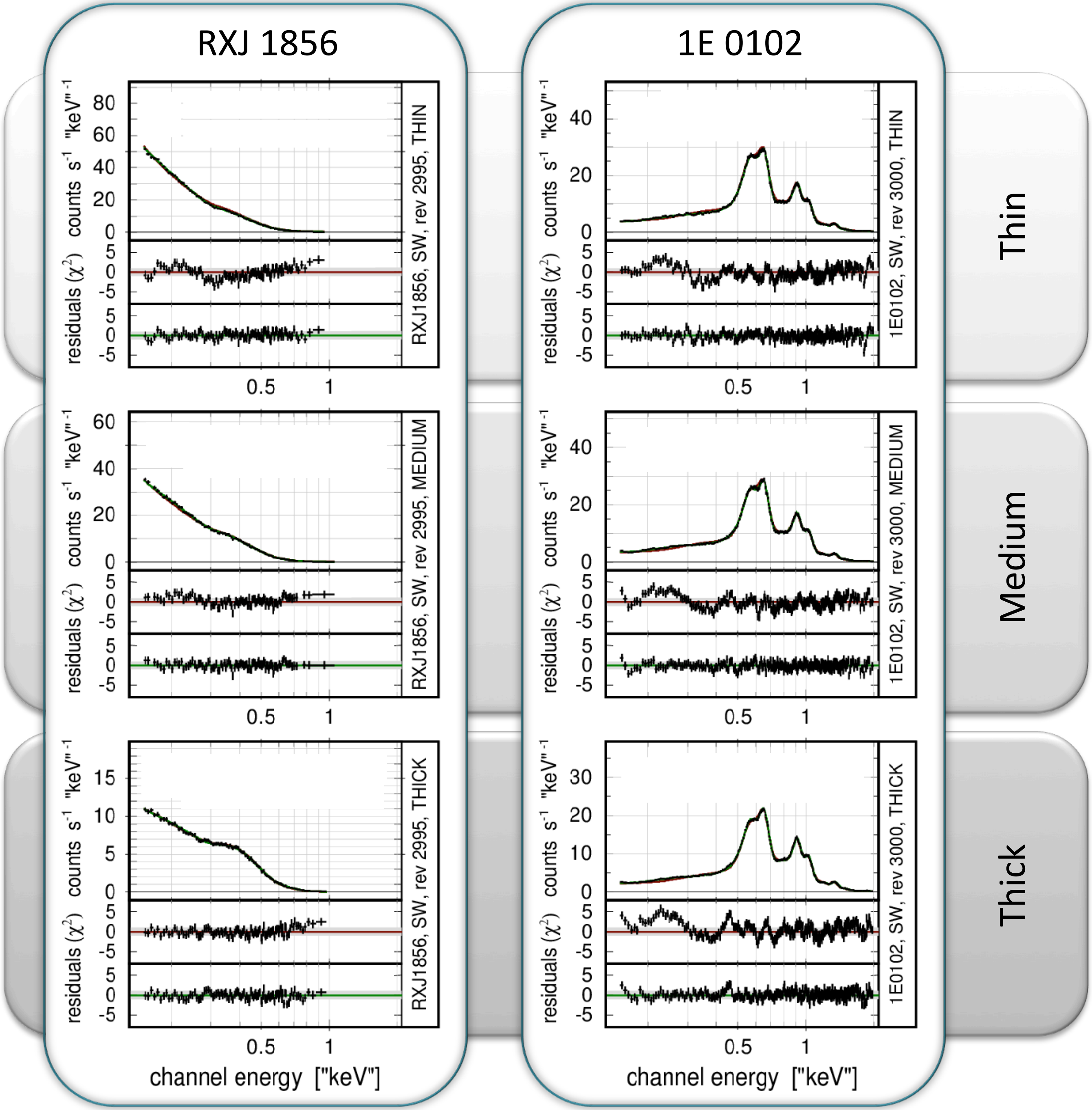
using the same model spectrum for each source, with no normalization between the filters

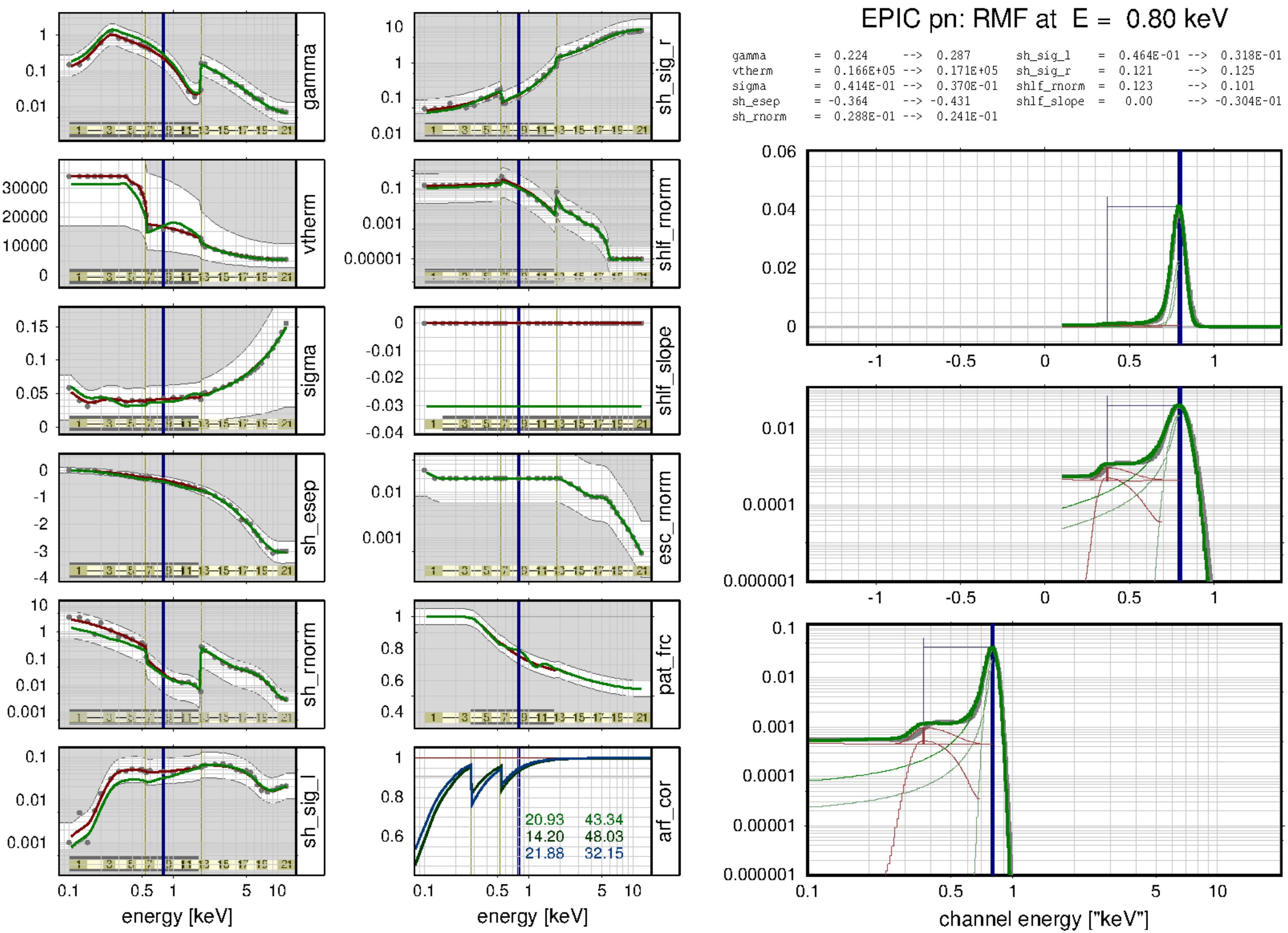
and

1 RMF + 3 ARFs

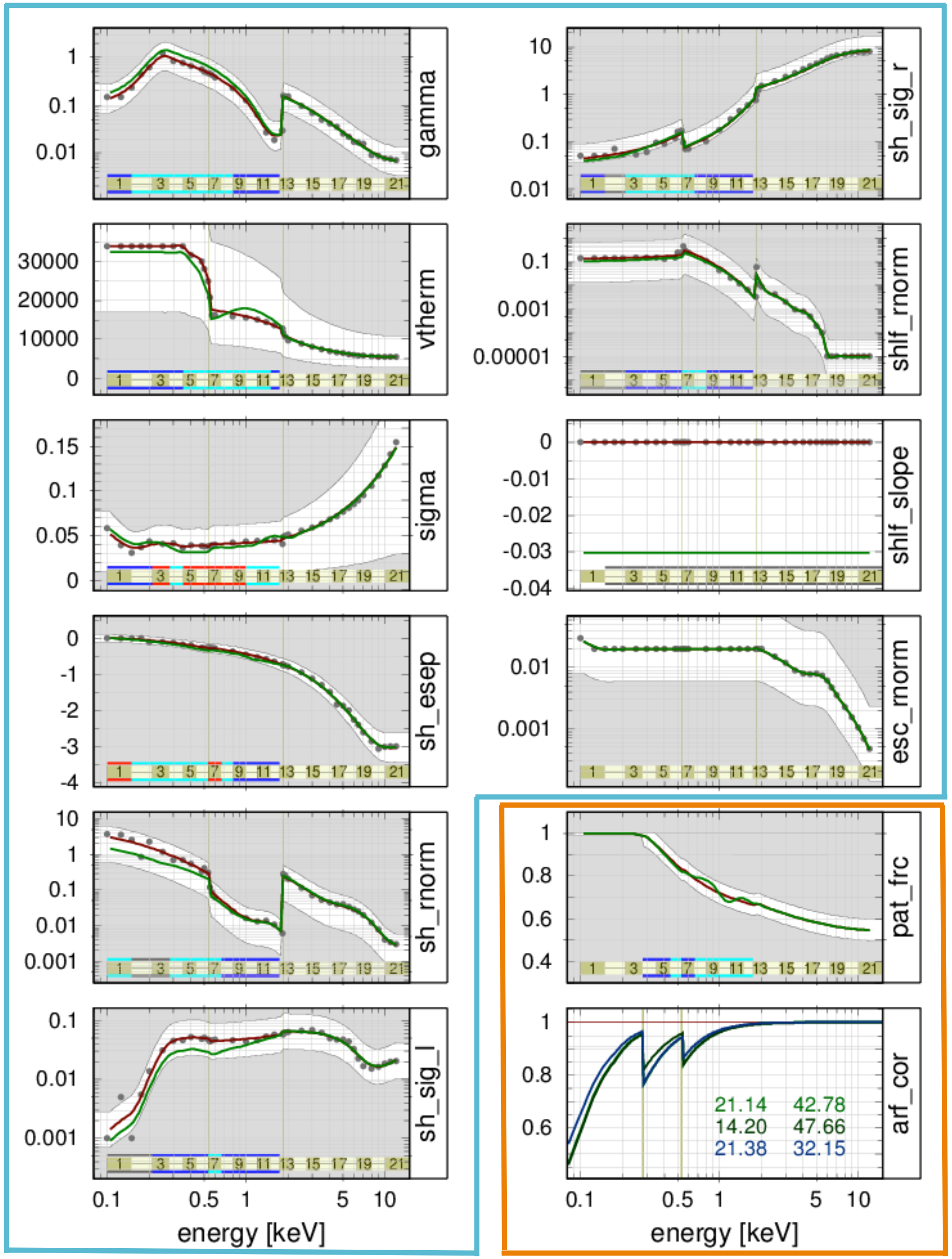
⇩

significant improvement possible !




EPIC pn: RMF at E = 0.80 keV
gamma = 0.224 --> 0.287
vtherm = 0.166E+05 --> 0.171E+05
sigma = 0.414E-01 --> 0.370E-01
sh_esep = -0.364 --> -0.431
sh_rnorm = 0.288E-01 --> 0.241E-01
sh_sig_l = 0.464E-01 --> 0.318E-01
sh_sig_r = 0.121 --> 0.125
shlf_rnorm = 0.123 --> 0.101
shlf_slope = 0.00 --> -0.304E-01
gamma
vtherm
sigma
sh_esep
sh_rnorm
sh_sig_l
sh_sig_r
shlf_rnorm
shlf_slope
esc_rnorm
pat_frc
arf_cor
20.93 43.34
14.20 48.03
21.88 32.15
energy [keV]
energy [keV]
channel energy ["keV"]

RMF and ARF refinement: parameters



X-ray spectra: model, data, results

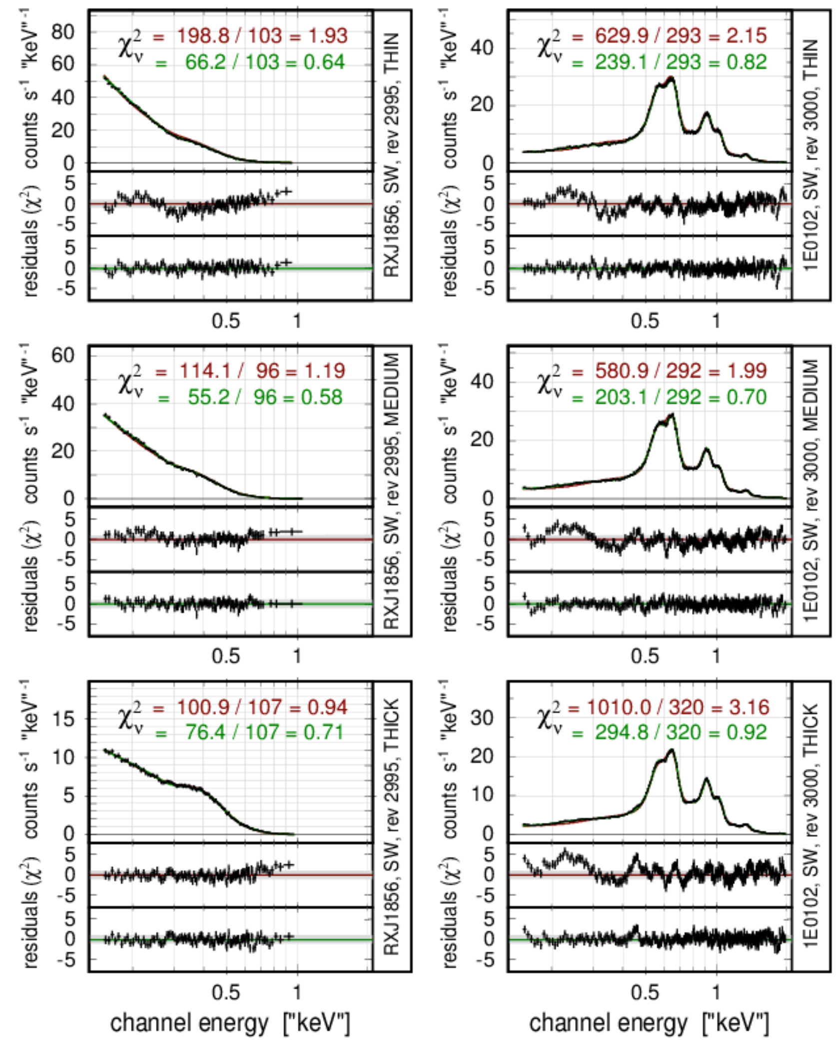
RXJ1856

bbodyrad: kT = 0.062 keV
bbodyrad: norm = 0.207E+06
gain: offset = -1.3 eV

n_H == 7 x 10^{19} cm^{-2}

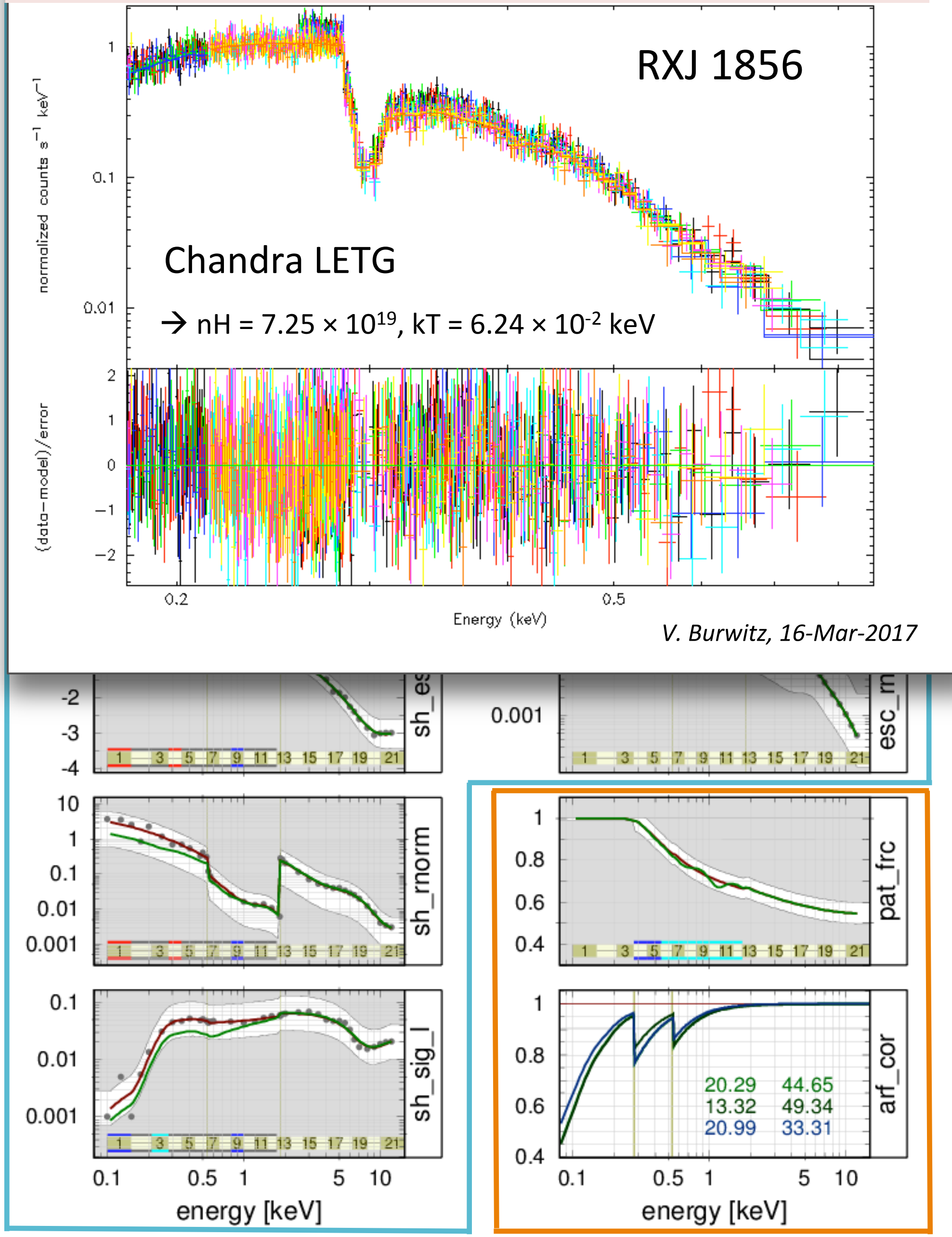
1E0102

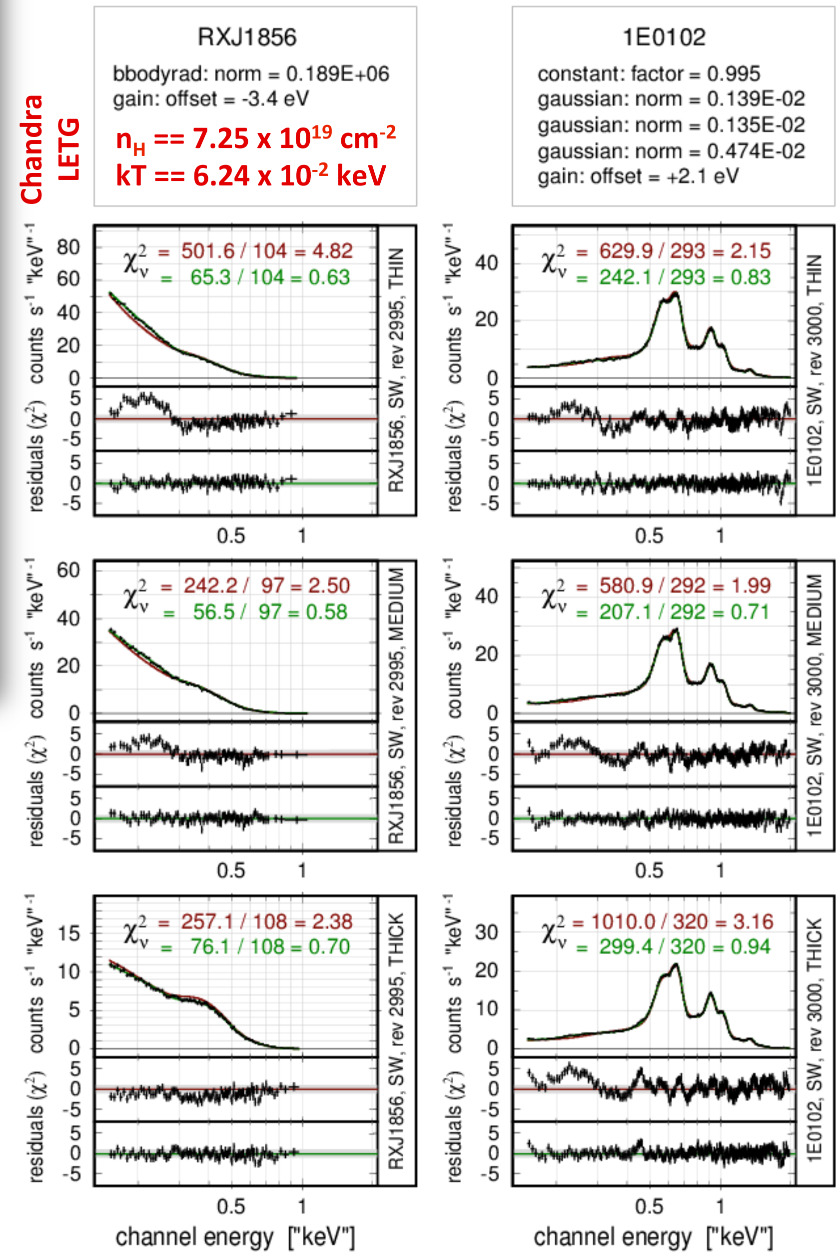
constant: factor = 0.981
gaussian: norm = 0.139E-02
gaussian: norm = 0.134E-02
gaussian: norm = 0.471E-02
gain: offset = +1.8 eV



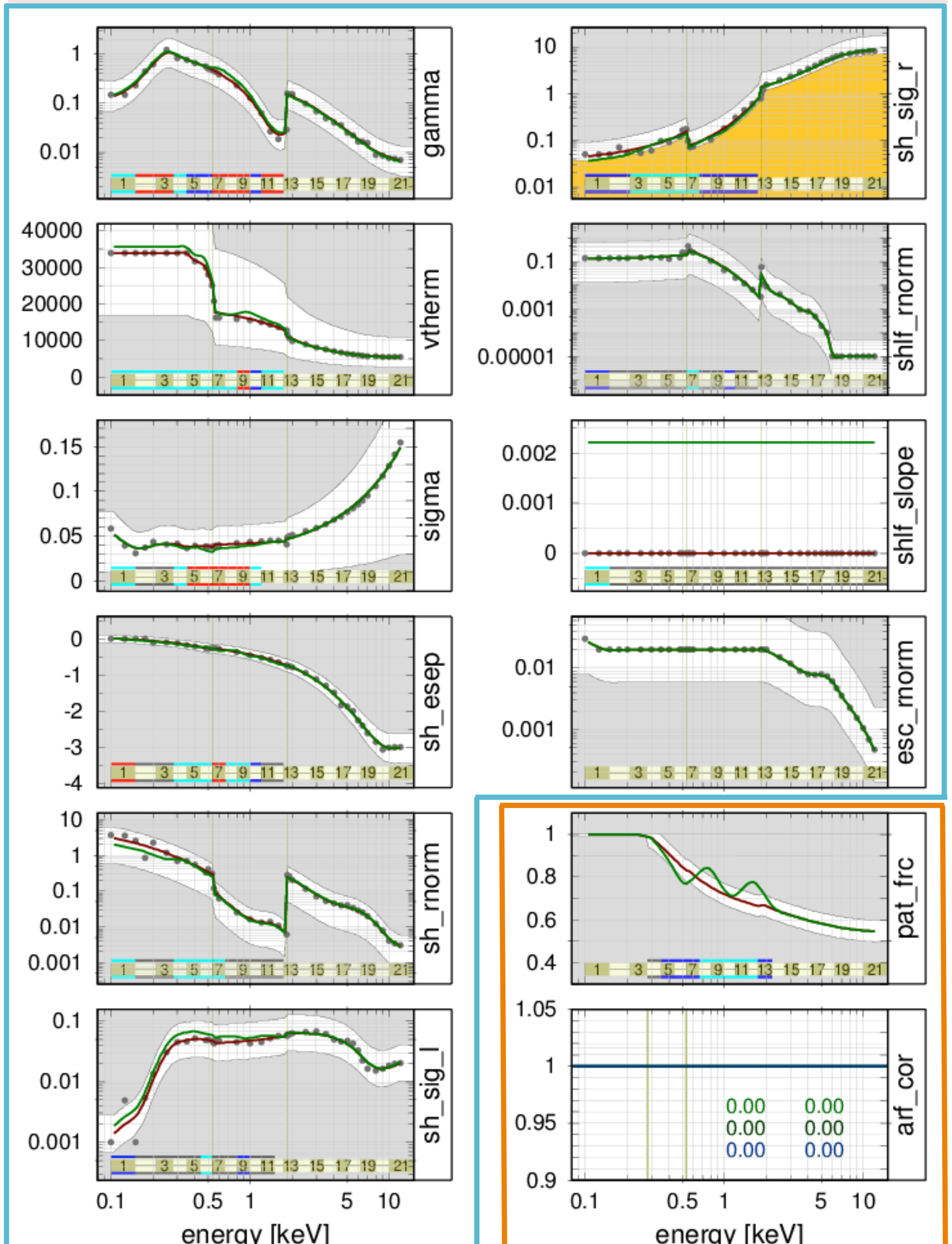
X-ray spectra: model, data, results

XMM/EPIC-pn: bbodyrad: norm = 1.89 x 10^5
Chandra LETGS: bbodyrad: norm = 1.58 x 10^5





XMM/EPIC-pn: bbodyrad: norm = 1.93 x 10^5
Chandra LETGS: bbodyrad: norm = 1.58 x 10^5

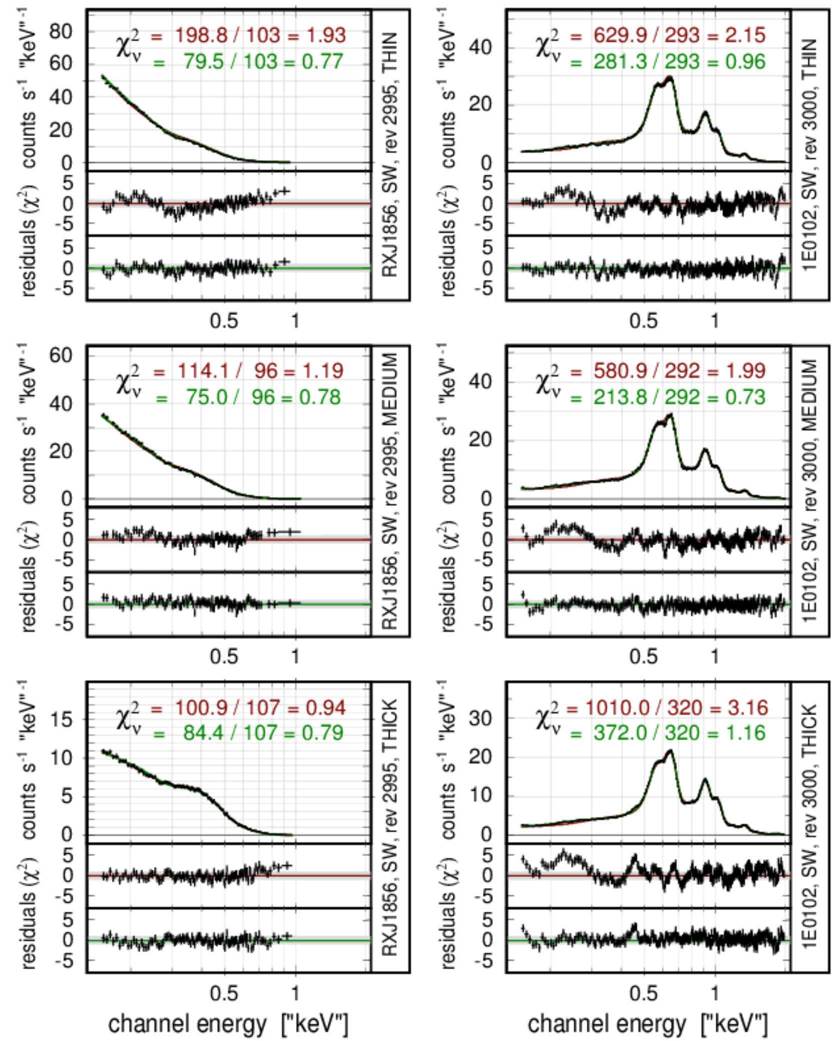


X-ray spectra: model, data, results

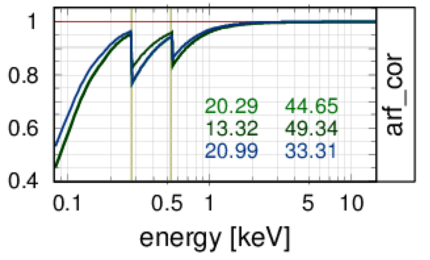
RXJ1856
bbodyrad: kT = 0.061 keV
bbodyrad: norm = 0.193E+06
gain: offset = -1.4 eV

n_H == 7 x 10^{19} cm^{-2}

1E0102
constant: factor = 0.877
gaussian: norm = 0.146E-02
gaussian: norm = 0.141E-02
gaussian: norm = 0.465E-02
gain: offset = +2.3 eV



What might cause any additional (apparent?) low energy absorption ?



modeled by absorption from C and O

Could the absorption around the O-K edge be caused by a larger thickness of the SiO_2 layer ?

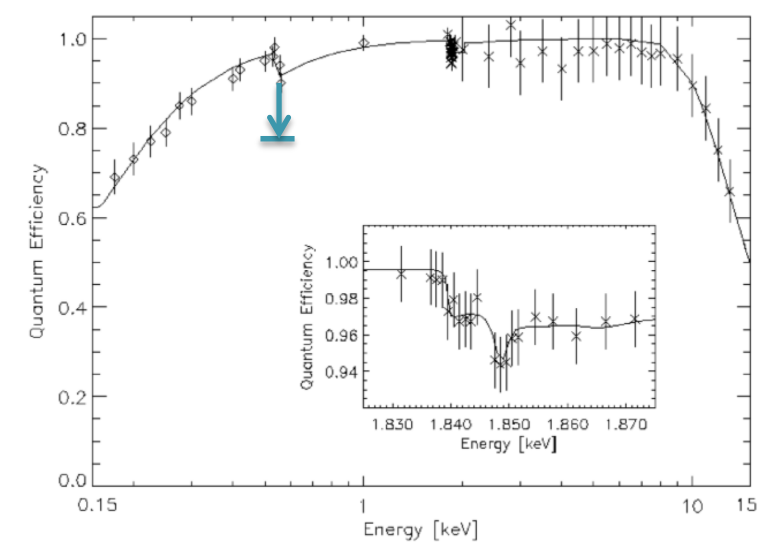


Figure 28: *Quantum efficiency of the EPIC pn CCD chips as a function of photon energy (Strüder et al., 2001, A&A, 365, L18, Fig. 5).*

→ not likely

What about absorption around C-K ?

ARF components

ARF („Ancillary Response File“)

= mirror effective area

* filter transmission
* CCD quantum efficiency
* fraction of single pixel events
* threshold induced cutoff

Calibration of the first XMM Flight Mirror Module
II - Effective Area

Ph. Gondoin[a], B. Aschenbach[b], M. Beijersbergen[a], R. Egger[b]
F. Jansen[a], Y. Stockman[c], J.P. Tock[c]

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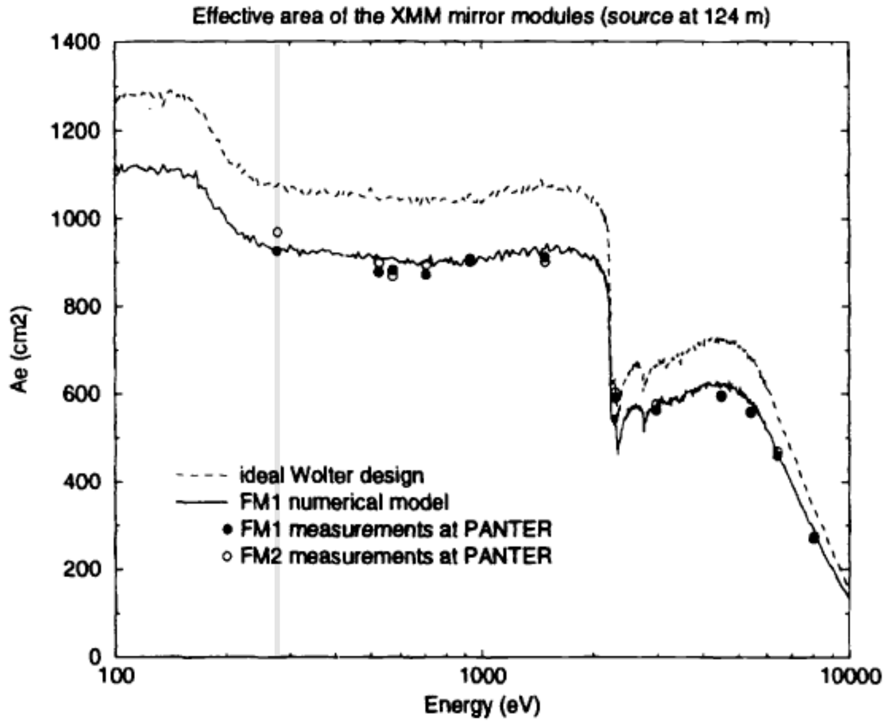
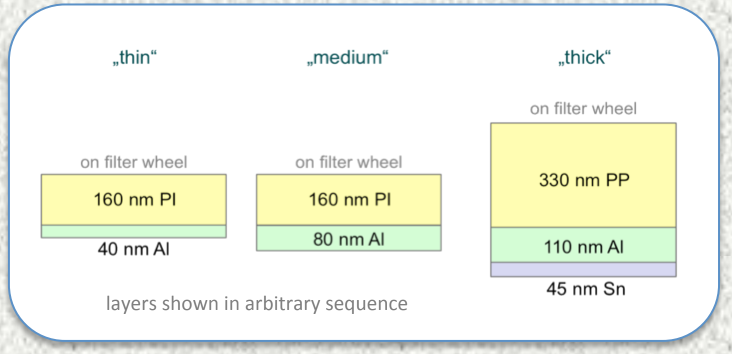
[b] Max-Planck Institute fur Extraterrestrische Physik, 8046 Garching, Germany
[c] Centre Spatial de Liege, B-4031 Liege, Belgium



ARF components



ARF („Ancillary Response File")

= mirror effective area

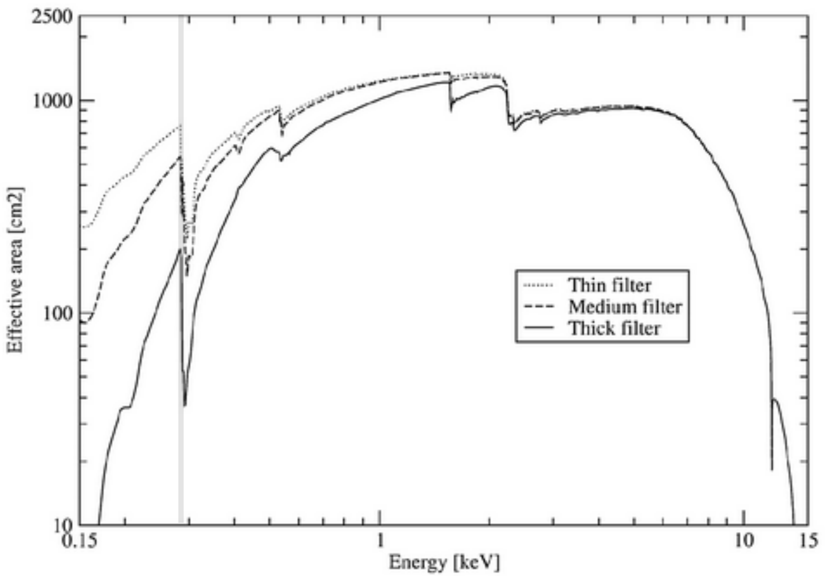
* filter transmission

* CCD quantum efficiency

* fraction of single pixel events

* threshold induced cutoff

https://www.cosmos.esa.int/web/xmm-newton/technical-details-epic



The EPIC pn effective area for each of the optical blocking filters and without a filter

ARF components

ARF („Ancillary Response File")

= mirror effective area

* filter transmission

* CCD quantum efficiency

* fraction of single pixel events

* threshold induced cutoff

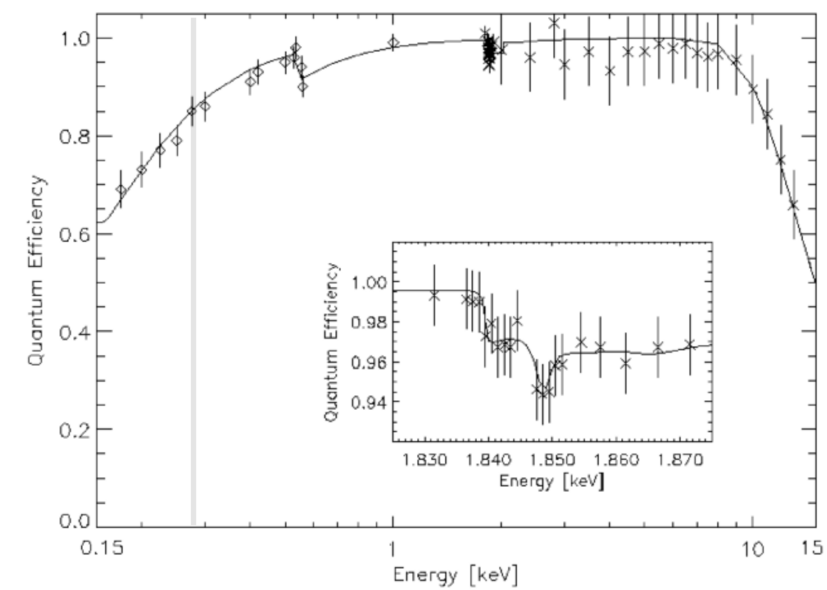


Figure 28: *Quantum efficiency of the EPIC pn CCD chips as a function of photon energy (Strüder et al., 2001, A&A, 365, L18, Fig. 5).*

ARF components

ARF („Ancillary Response File“)

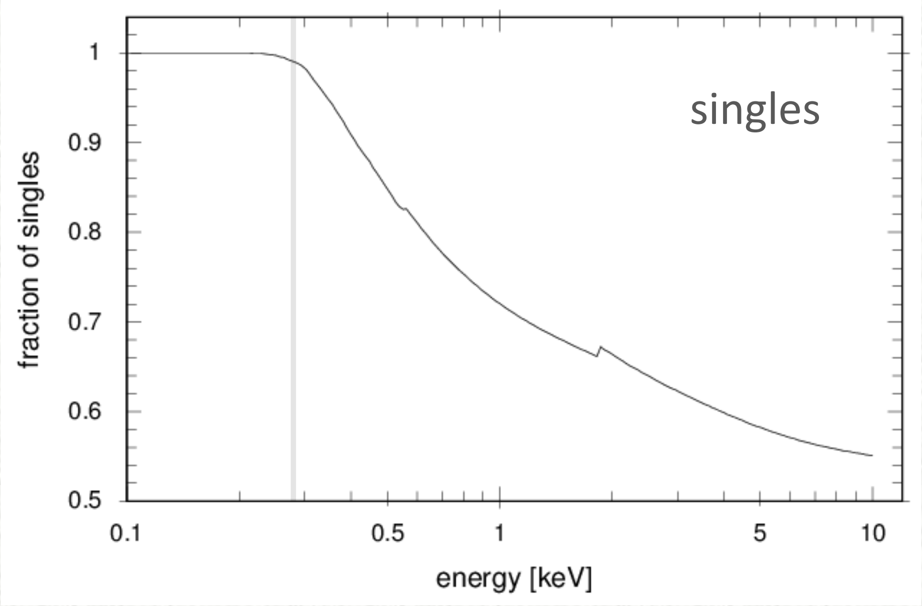
= mirror effective area

* filter transmission

* CCD quantum efficiency

* fraction of single pixel events

* threshold induced cutoff



ARF components

ARF („Ancillary Response File“)

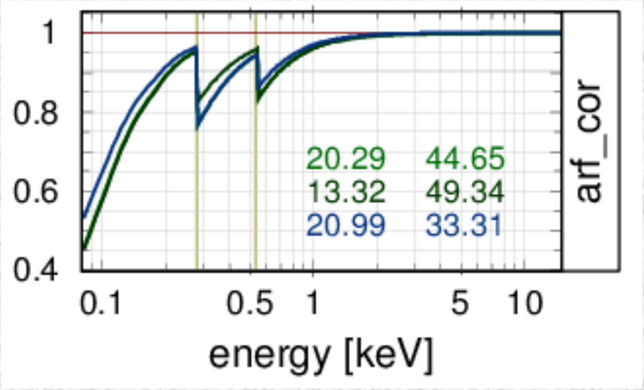
= mirror effective area

* filter transmission

* CCD quantum efficiency

* fraction of single pixel events

* threshold induced cutoff



→ sensitivity may drop to ~50% close to the low energy threshold!

Summary and Outlook

Current status:

Significant RMF & ARF improvements could be obtained for all three filters with two soft (<2 keV) X-ray sources exhibiting complementary spectra, without any renormalization between the filters

Future work:

extend RMF refinement to

- **higher energies** (where the treatment of the escape peak becomes important)
- other **readout modes**: LW, FF, eFF, TI, BU
- full XMM-Newton **time span** (CTI induced trends in energy resolution)
- other **detector positions** (CTI induced trends in energy resolution)

then:

- **interpolate** temporal and positional dependencies by suitable functions
- determine an appropriate **scaling** between the readout modes

Method:

simultaneous fits to suitable X-ray targets with complementary spectra, using ‚reliable' spectral models

→ **IACHEC !**

An empirical method for improving the XMM-Newton/EPIC-pn RMF and ARFs

Konrad Dennerl - Max Planck Institute for extraterrestrial Physics – Garching - Germany