Analysis of low surface brightness sources with EPIC

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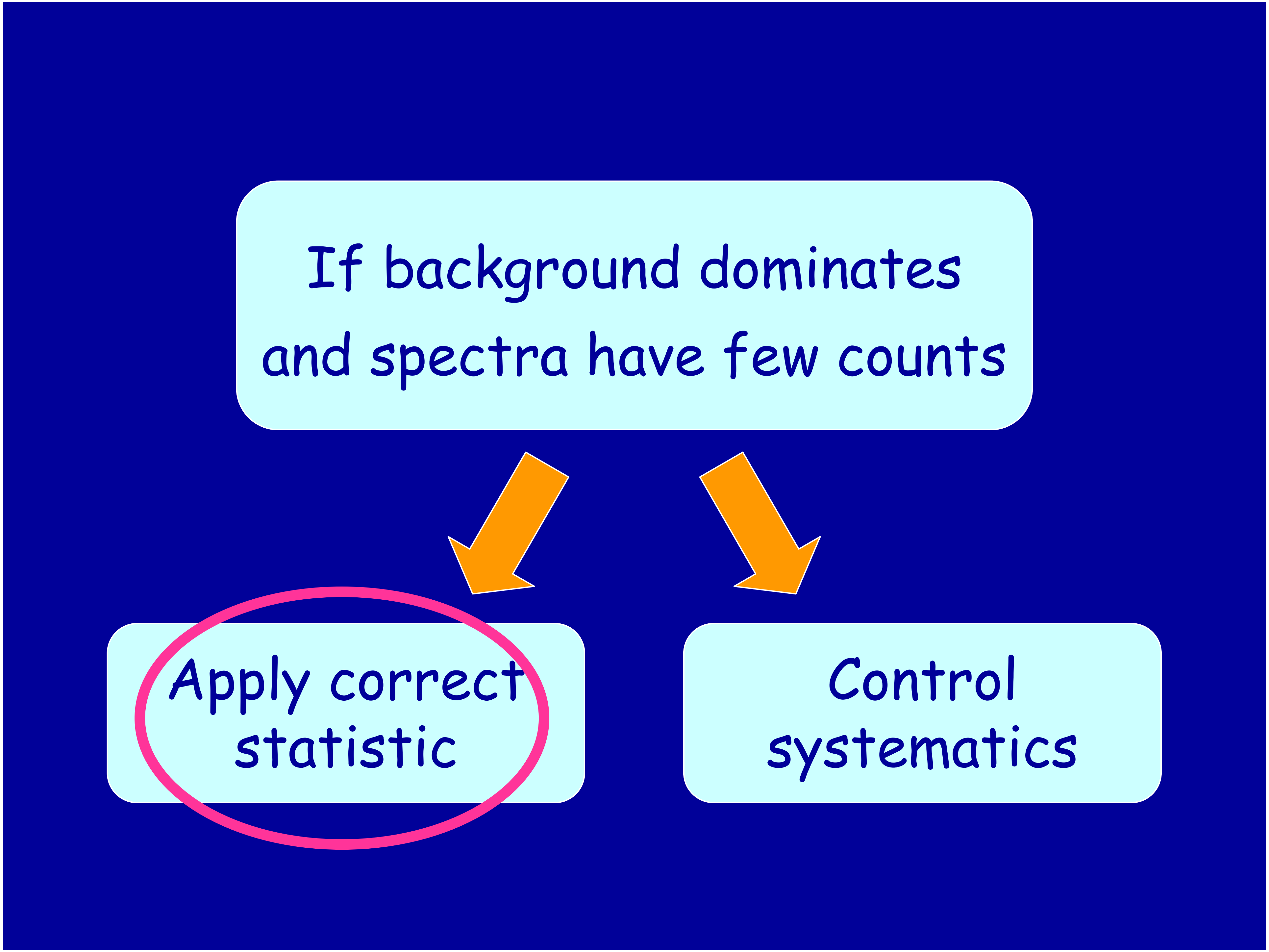
SOMMARIO

1) Proprietà generali di ammassi e ICM
   Temperatura, massa ed altre osservabili

2) Meccanismi di formazione
   Il raffreddamento del core

3) I profili di temperatura
   EPIC e il problema del fondo
   Incertezze statistiche e sistematiche
   Conclusioni e prospettive future


If background dominates
and spectra have few counts
Apply correct
statistic
Control
systematics

APPLY THE CORRECT STATISTIC

The counting process of the number of photons collected by a detector during a time interval is a typical example of a **Poisson process**

A spectrum is univocally defined by the **observed** counts, O_i, in each channel

Given a model, the **expected** counts, E_i, in each channel can be calculated

APPLY THE CORRECT STATISTIC

The probability, P, of obtaining a particular spectrum follows a **Poisson distribution** and is a function of the model parameters, α:

$$P(\alpha) = \prod_{i=1}^{N} \frac{E_i^{O_i}(\alpha)\exp\left(-E_i(\alpha)\right)}{O_i!}$$

APPLY THE CORRECT STATISTIC

Given a measured spectrum,
astronomers wish to determine
the **best set of** model **parameters**

The **maximum likelihood** method
determines the parameters which maximize P

One is likely to collect those data
which carry the highest chance to be collected

The **Cash** (Cash, 1979) and the χ^2 statistics
are based on these concepts

The former is more **appropriate**
when analyzing **low count spectra**

THE χ^2 STATISTIC

The χ^2 is based on the **hypothesis** that each spectral bin contains a sufficient number of counts to make the **deviations** of the observed from the expected counts **have a Gaussian distribution**

Table 2. Weighted averages of temperature best fit values compared to the input value and relative differences $\Delta T/T_0$, using different channel groupings.

N_{bin} [a]	kT_0 [b]	kT [c]	$\Delta T/T_0$ [d]
400	7.00	6.99±0.01	-0.1%
100	7.00	6.95±0.01	-0.7%
25	7.00	6.89±0.01	-1.6%

Notes: [a] counts per bin; [b] input temperature in keV; [c] measured temperature in keV; [d] relative difference.

THE χ^2 STATISTIC

This hypothesis is satisfied only for **very large** counts per bin

Every kind of channel grouping implies **loss** of spectral **information**

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MAXIMUM LIKELIHOOD ESTIMATORS

The Cash and the χ^2 statistics are based
on maximum likelihood methods

From the literature (e.g. Eadie 1971)
it is well known that:

ML estimators could be **biased**
especially in the case of
highly **non linear model** parameters
(e.g. kT of a bremsstrahlung model)

Bias: difference between expected and true value

THERMAL SOURCE ONLY CASE

Table 1. Weighted averages of temperature best fit values compared to the input value and relative differences $\Delta T/T_0$, using different exposure times and statistics.

		χ^2		Cash	
Exp. [a]	kT_0 [b]	kT [c]	$\Delta T/T_0$ [d]	kT [c]	$\Delta T/T_0$ [d]
1000	7.00	6.89±0.01	-1.6%	7.00±0.01	+0.0%
100	7.00	6.83±0.01	-2.4%	7.03±0.01	+0.4%
10	7.00	6.76±0.03	-3.4%	6.91±0.02	-1.3%
5	7.00	6.59±0.04	-5.9%	6.81±0.03	-2.7%

Notes: [a] exposure time in kiloseconds; [b] input temperature in keV; [c] measured temperature in keV; [d] relative difference.

Bias appears for low count spectra

The Cash estimator is **asymptotically unbiased**

COMPARISON - χ^2 vs. CASH

	χ^2	Cash
Distribution	Gaussian	Poisson
Channel grouping	Often required (binned data)	Not necessary (unbinned data)
Goodness of fit	Easy to evaluate	Montecarlo simulation
Validity	Approximation for large counts	Works also for few counts
Diffusion	Large	Scarce

INTRODUCING A BACKGROUND

When using the Cash statistic
the background has to be modeled (Cash, 1979)

Source dominates (first six rows)

Bkg dominates (last six rows)

			sub-χ^2		mod-C	
Ring	Exp. [a]	kT_0 [b]	kT [c]	$\Delta T/T_0$ [d]	kT [c]	$\Delta T/T_0$ [d]
1.0′-1.5′	100	5.00	4.84±0.01	-3.2 %	4.96±0.01	-0.8%
1.0′-1.5′	100	7.00	6.78±0.02	-3.1 %	6.97±0.02	-0.4%
1.0′-1.5′	100	9.00	8.69±0.02	-3.4 %	8.97±0.03	-0.3%
1.0′-1.5′	10	5.00	4.81±0.03	-3.8 %	4.82±0.03	-3.6%
1.0′-1.5′	10	7.00	6.78±0.05	-3.1 %	6.79±0.05	-3.0%
1.0′-1.5′	10	9.00	8.68±0.11	-3.6 %	8.62±0.08	-4.2%
4.5′-6.0′	100	5.00	3.95±0.01	-21.0 %	4.71±0.02	-5.8%
4.5′-6.0′	100	7.00	5.24±0.02	-25.1 %	6.44±0.03	-8.0%
4.5′-6.0′	100	9.00	6.43±0.02	-28.6 %	8.10±0.04	-10.0%
4.5′-6.0′	10	5.00	3.02±0.03	-39.6 %	3.20±0.03	-36.0%
4.5′-6.0′	10	7.00	3.68±0.04	-47.4 %	3.77±0.04	-46.1%
4.5′-6.0′	10	9.00	4.11±0.05	-54.3 %	4.50±0.06	-50.0%

The bias depends on:
1) the background contribution
2) the spectrum total number of counts

WORK IN PROGRESS…

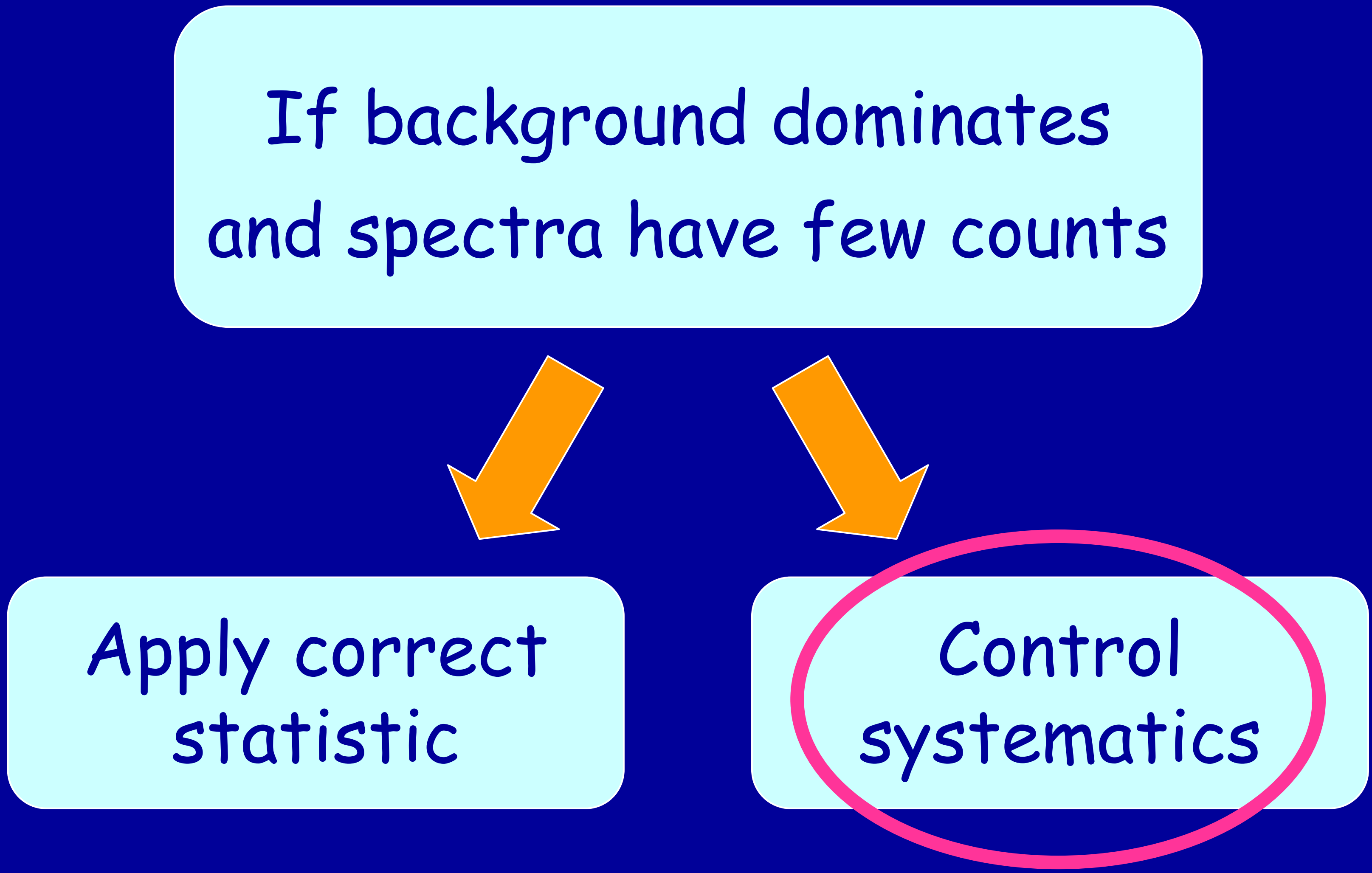
For the realistic case
no definitive solution has been found

Quick and dirty solution: the triplet method

Correct the posterior probability density functions
(Leccardi & Molendi, 2007 A&A submitted)

Long term solution: ?

Find different estimators (e.g. 1/kT, log(kT), …)
Explore the Bayesian approach


If background dominates and spectra have few counts
Apply correct statistic
Control systematics

SYSTEMATIC UNCERTAINTIES

Imperfect MOS-pn cross-calibration

Defective background knowledge

The energy band is very important

SYSTEMATIC UNCERTAINTIES

Measuring the temperature of hot GC

Using the energy band beyond 2 keV

- ✓ Cross-calibration is relatively good
- ✓ Internal background continuum is well described by a power law
- ✓ Al and Si fluorescence lines are excluded
- ✓ Local X-ray background is negligible

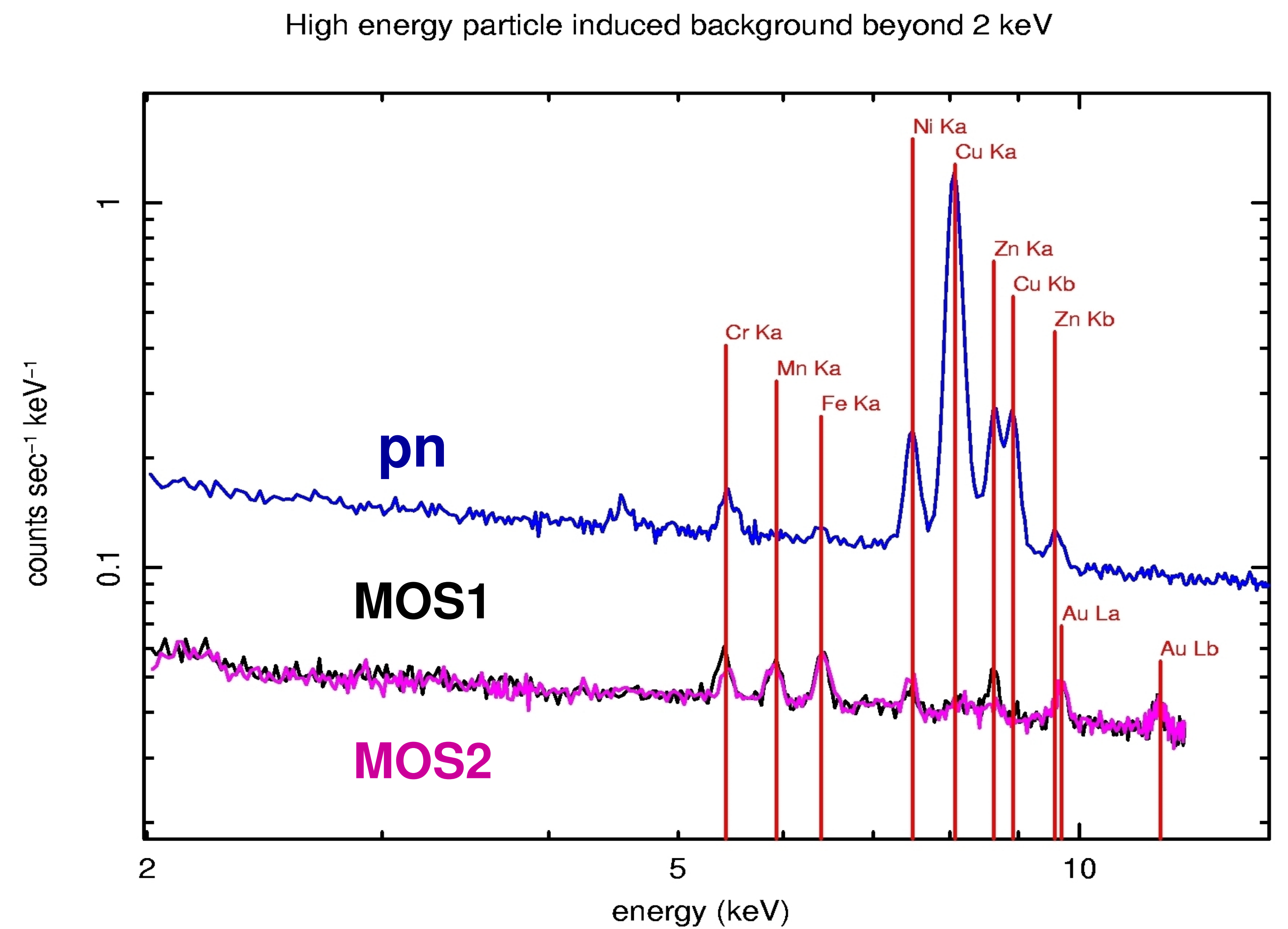
BACKGROUND BEYOND 2 keV

I. Internal background: continuum and lines

II. (Quiescent) soft protons

III. Cosmic X-ray background

INTERNAL BACKGROUND



INTERNAL BKG: CONTINUUM

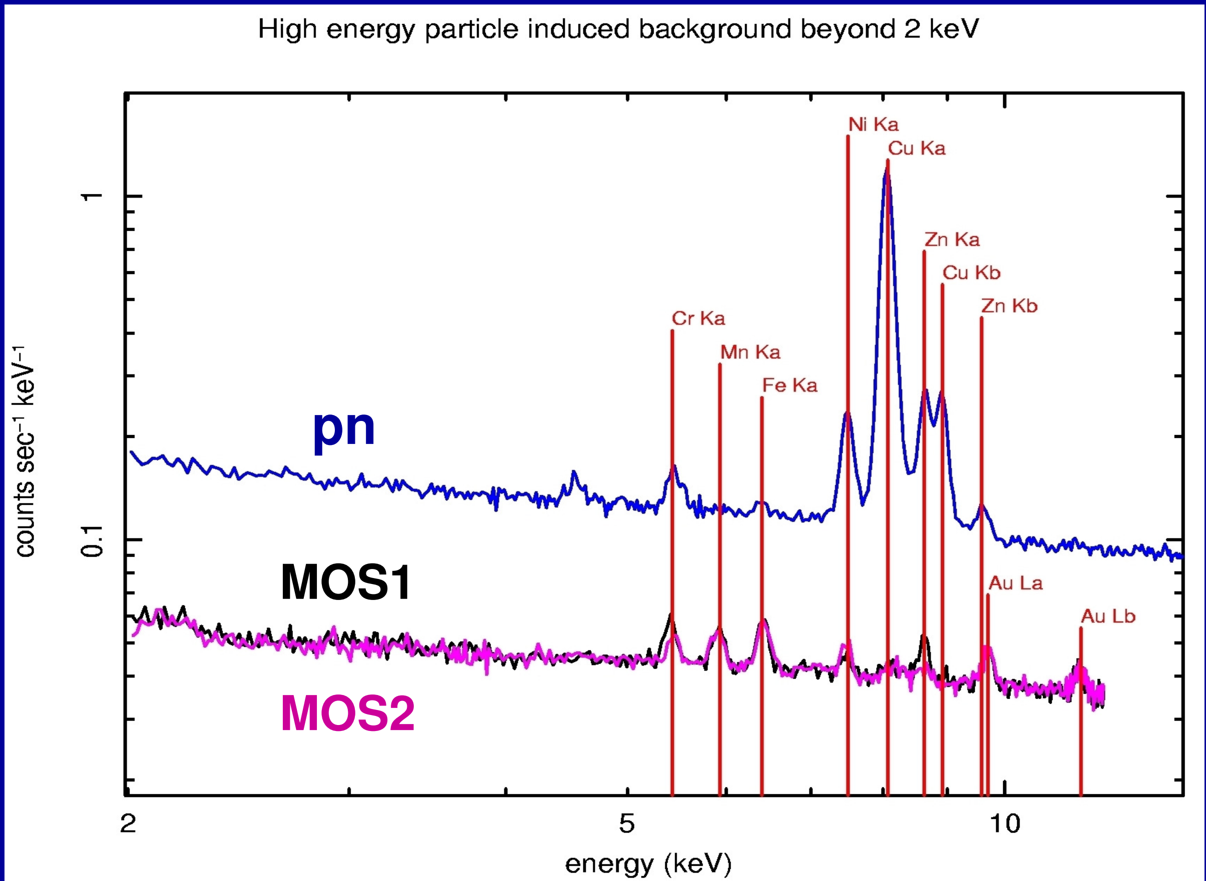
When analyzing different observations
we found typical variations
of 15% for PL normalization
and negligible variations for PL index

PL index is ~0.23 for MOS and ~0.33 for pn
it does not show spatial variations

MOS: SB is roughly constant over all detector
pn: SB presents a hole due to electronic board,
inside the hole the continuum is more intense

INTERNAL BKG: LINES

When analyzing different observations
we found typical variations of the norm of the lines
of the same order of the associated statistical error



MOS
weak lines

pn
intense
Ni-Cu-Zn
blend lines

THE R PARAMETER

$$R = \frac{cr_{IN}}{cr_{OUT}}$$

R depends only on the selected inner region and on the instrument

R is independent of the particular observation

R is roughly equal to the area ratio for MOS, not for pn

Once measured the PL normalization out of the FOV, this **scale factor** allows to estimate rather precisely the PL normalization in the selected region of the FOV for every observation.

SOFT PROTONS

I. Light curve in a hard band (beyond 10 keV) and GTI filtering with a semi-fixed threshold

II. Light curve in a soft band (2-5 keV) and GTI filtering with a 3 σ threshold

III. IN/OUT ratio to evaluate the contribution of quiescent soft protons

Caveat !

Extended sources which fill the whole FOV and emit beyond 5-6 keV

SOFT PROTONS

Goal:

estimate QSP contribution for MOS spectra

Stack many blank field observations (~1.5 Ms)

Use the Cash statistic → Background modeling

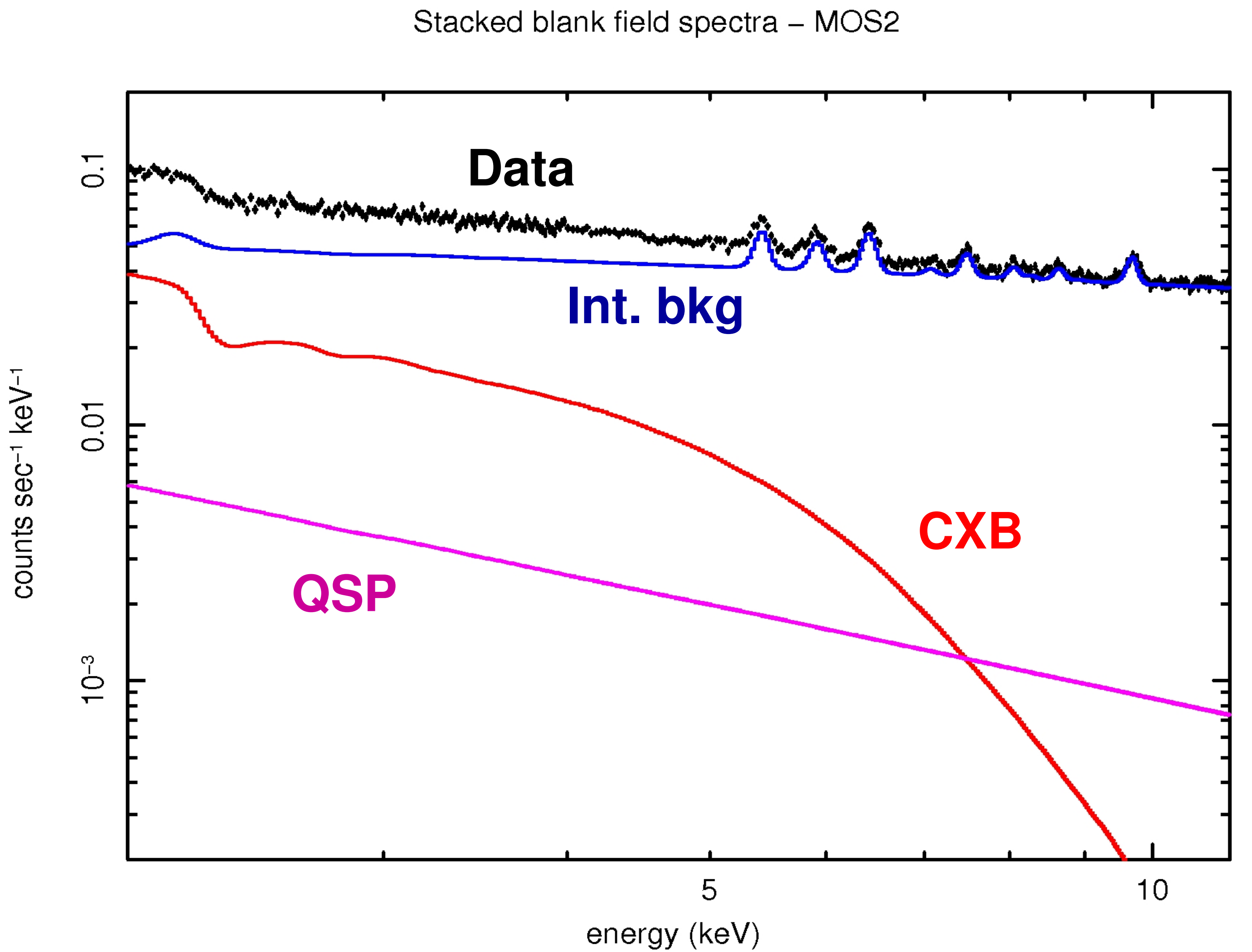
Model the total spectrum

CXB + QSP + Int. bkg continuum + Int. Bkg lines

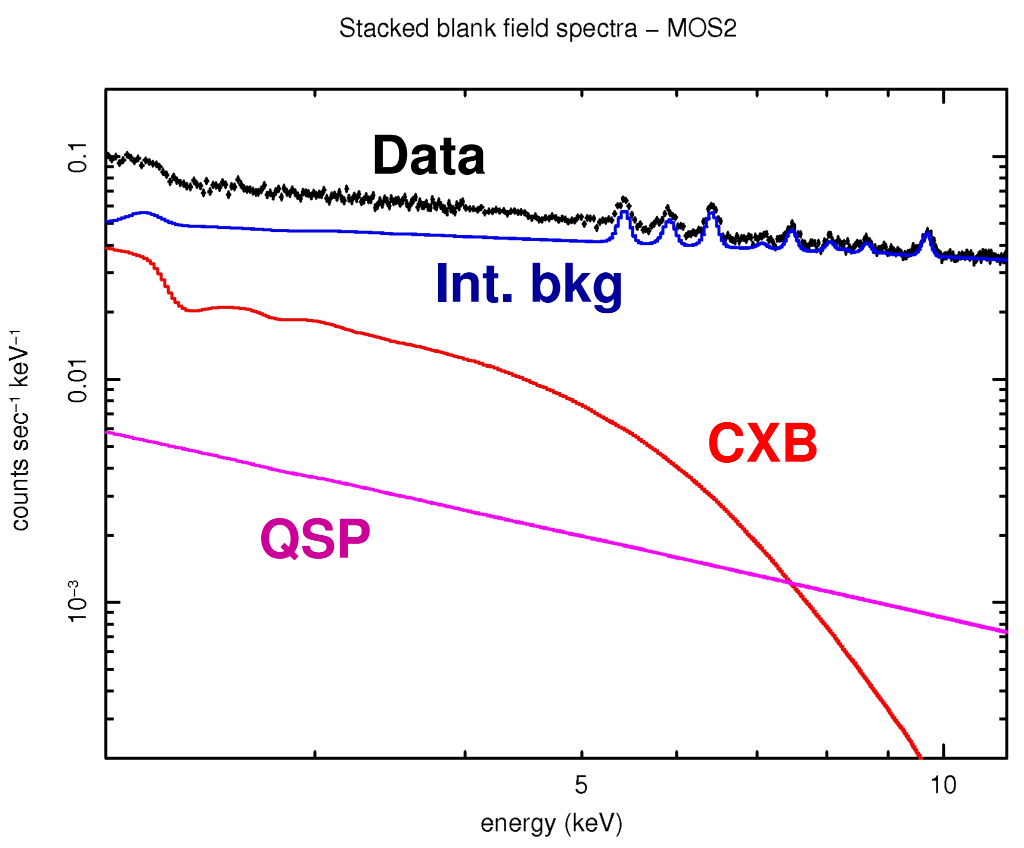
with

PL + PL/b + PL/b + (several) GA/b

SOFT PROTONS & COSMIC BKG



SOFT PROTONS & COSMIC BKG



Int. bkg continuum is fixed

-PL index from CLOSED

-PL norm = R*$norm_{OUT}$

Int. bkg line norm is free

QSP and CXB parameters are free

We measure both CXB and QSP components

SOFT PROTONS & COSMIC BKG

Work in progress

Soft proton index is poorly constrained,
conversely the normalization uncertainty is 15%

CXB uncertainties are rather large
because we are modeling 3 components

	Index	Norm
QSP[a]	1.4±0.4	6.2±0.9 @ 7.5 keV
CXB[a]	1.47±0.07	2.3±0.2 @ 3 keV *
CXB[b]	1.52±0.04	2.68±0.03 @ 3 keV *
CXB[c]	1.41±0.06	2.46±0.09 @ 3 keV *

* CXB norm is expressed in photons cm^{-2} s^{-1} sr^{-1} keV^{-1}

SOFT PROTONS & COSMIC BKG

We eliminate QSP component and fit the same data only with CXB and int. bkg

The index is substantially unchanged, norm increases by 15% due to QSP not to real CXB, uncertainties are strongly reduced

	Index	Norm
QSP[a]	1.4±0.4	6.2±0.9 @ 7.5 keV
CXB[a]	1.47±0.07	2.3±0.2 @ 3 keV *
CXB[b]	1.52±0.04	2.68±0.03 @ 3 keV *
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* CXB norm is expressed in photons cm^{-2} s^{-1} sr^{-1} keV^{-1}

SOFT PROTONS & COSMIC BKG

De Luca & Molendi have used renormalized background subtraction

Results are consistent
the difference could be due to the cosmic variance (~7%)

We can infer that also this result could be biased by 10-15%
and the uncertainties could be too small

	Index	Norm
QSP[a]	1.4±0.4	6.2±0.9 @ 7.5 keV
CXB[a]	1.47±0.07	2.3±0.2 @ 3 keV *
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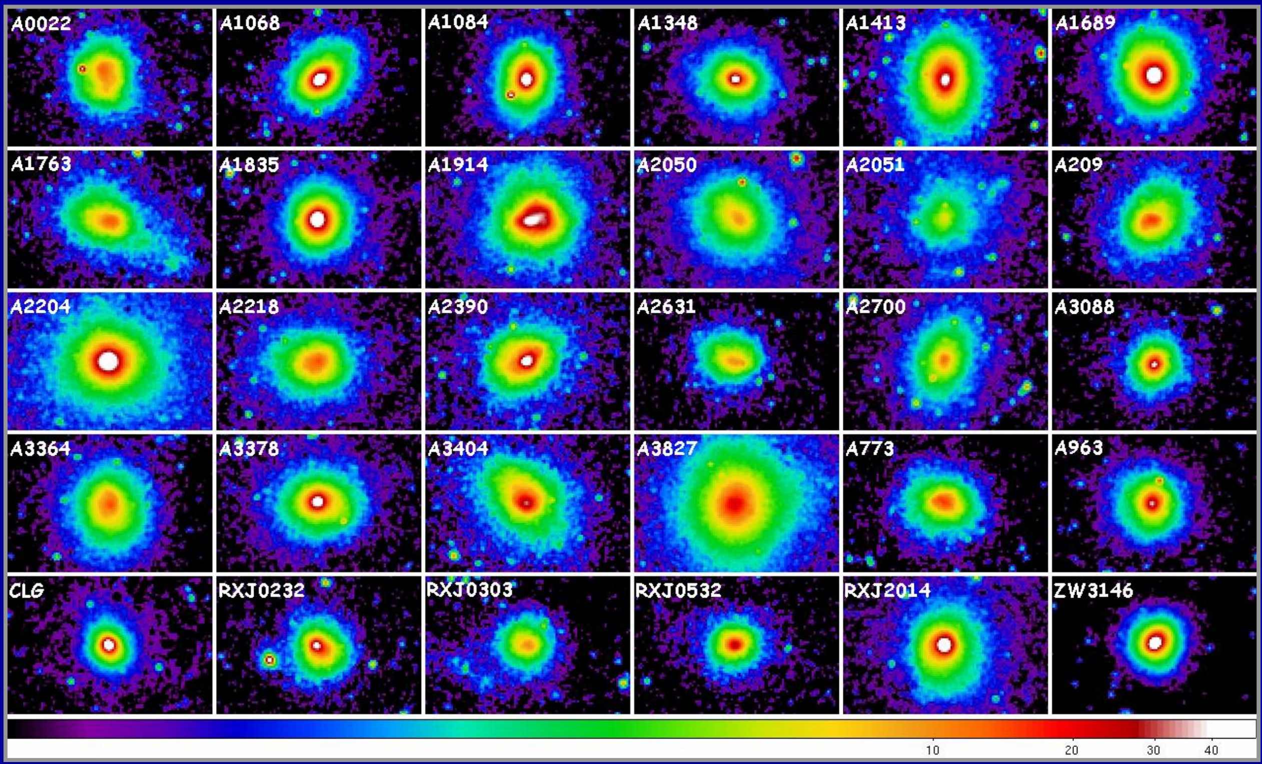
* CXB norm is expressed in photons $cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}$

Goal:

measure temperature profiles of hot intermediate redshift galaxy clusters

Intermediate redshift	0.092 < z < 0.291
High temperature	kT > 4 keV



OUR TECHNIQUE

Galaxy clusters are extended sources.

They fill the FOV (intermediate redshift)
but in outer regions thermal emission is very small,
therefore IN/OUT technique is reliable.

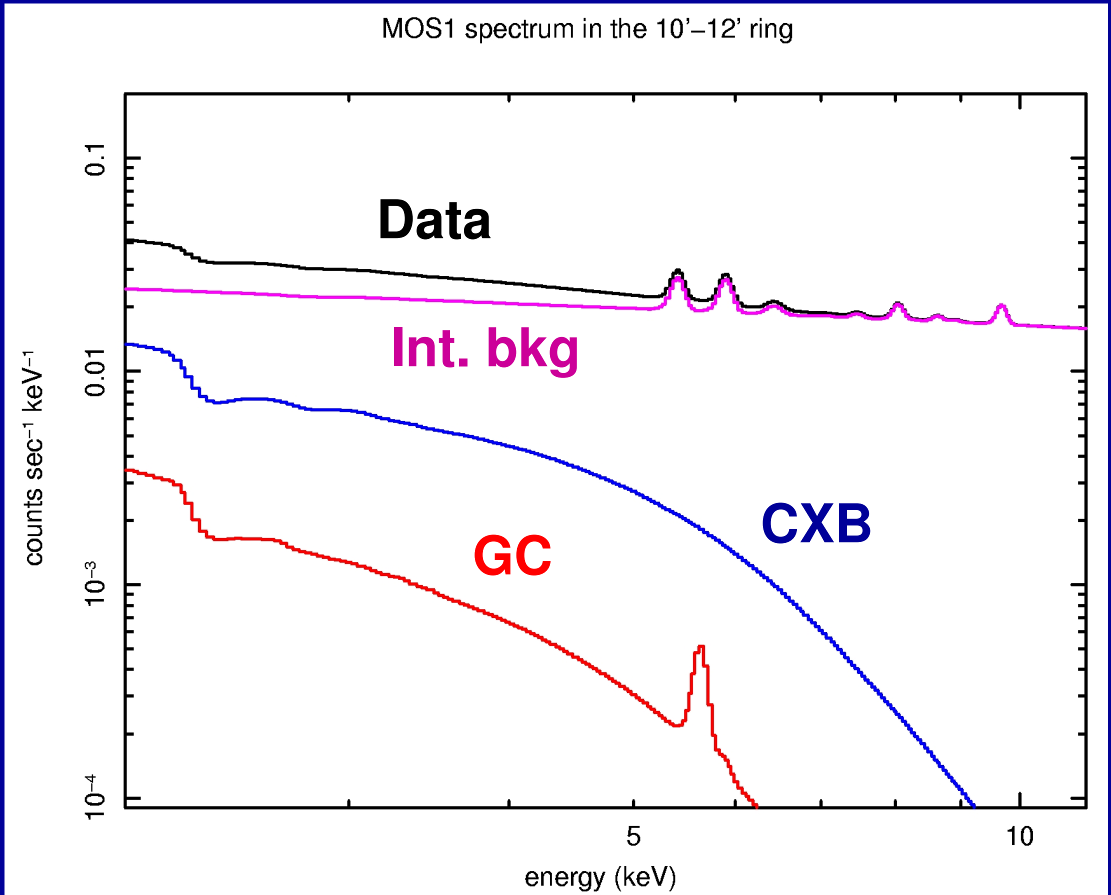
They are hot → exponential cutoff at high energies,
therefore we use the energy band beyond 2 keV.

We use the Cash statistic (more suitable than χ^2).

Cash statistic requires background modeling.

OUR TECHNIQUE NOW

We consider an external ring (10′-12′ in FOV)
to estimate the norm of CXB and int. bkg



GC is fixed
(iterative estimate)

Int. bkg and CXB:
index fixed
norm free

QSP is excluded:
- degeneracy
- int. bkg and CXB contain also information on QSP

OUR TECHNIQUE NOW

We rescale so called CXB and int. bkg norm
to the inner regions using area ratio

In the inner regions CXB and int. bkg norm
are semi-fixed:
they are allowed to vary in a small range
around the rescaled values

Montecarlo simulations tell us
how important is the systematic introduced

We found a bias of ~5-10% in the ring 5′-7′
where the background dominates

IN THE FUTURE…

If we find a tight relation between
the IN/OUT ratio and the QSP normalization,
we could model and fix the bulk
of QSP component.

This could reduce the bias of 5-10%.

We will implement simulations to evaluate
which is the best procedure and
to quantify the intensity of introduced bias.