X
X
L

The ultimate
XMM extragalactic survey

die Kunst über in der Wissenschaft

Latest results from The XMM-XXL survey

The cosmological analysis of X-ray cluster surveys

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Service d'Astrophysique du CEA

Outline

1. Reminder: clusters and cosmology

2. The XXL survey

3. Critical for cosmology : the cluster selection function

4. Results from the XXL survey

5. Forward cosmological analysis by modeling observable parameters only

1. Clusters and cosmology

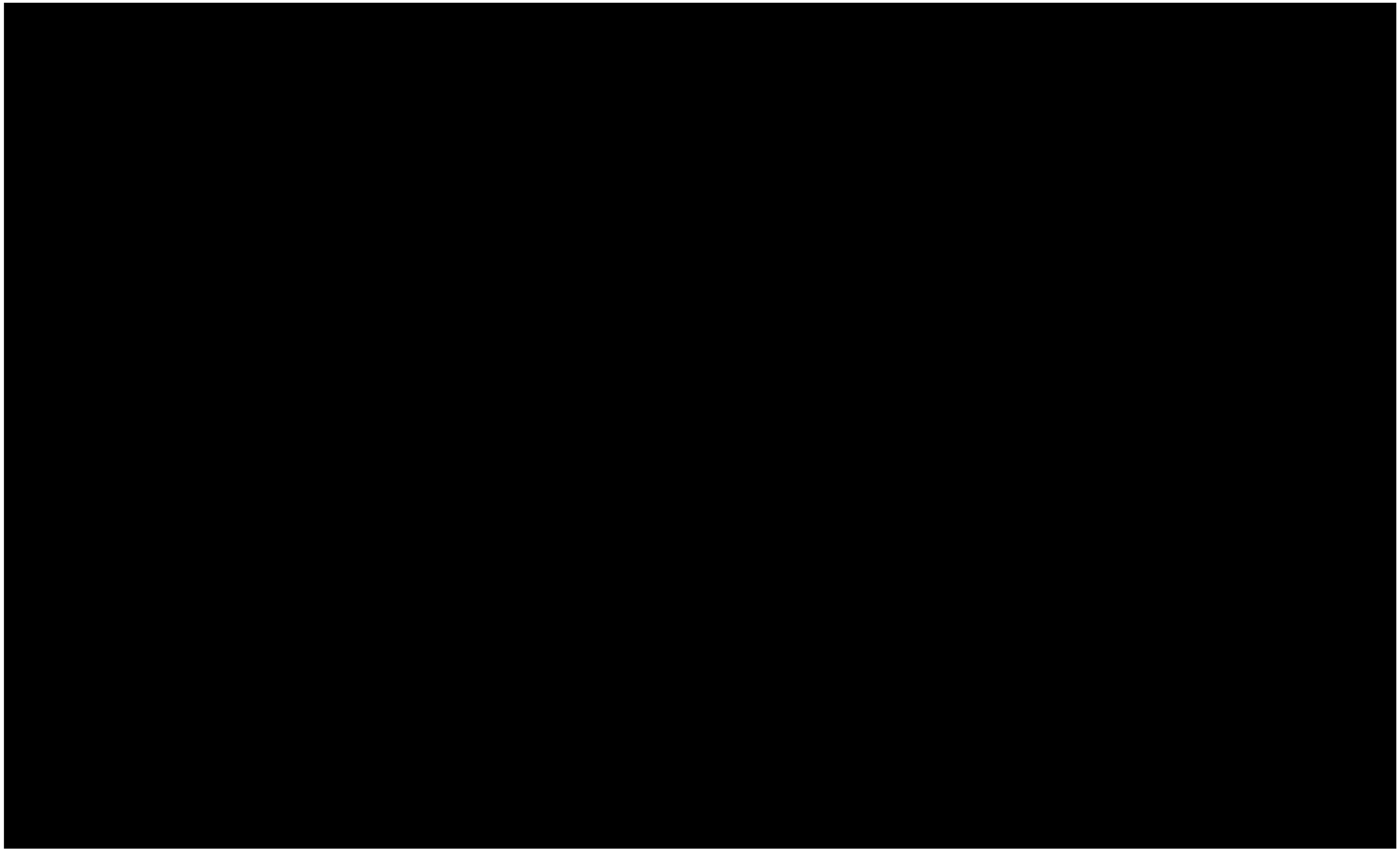
Cosmology ?

- Field of astrophysics that studies the universe as a **whole**

  (density, finite-infinite, structure, topology, nature and amount of 'dark' material, fate . . .)

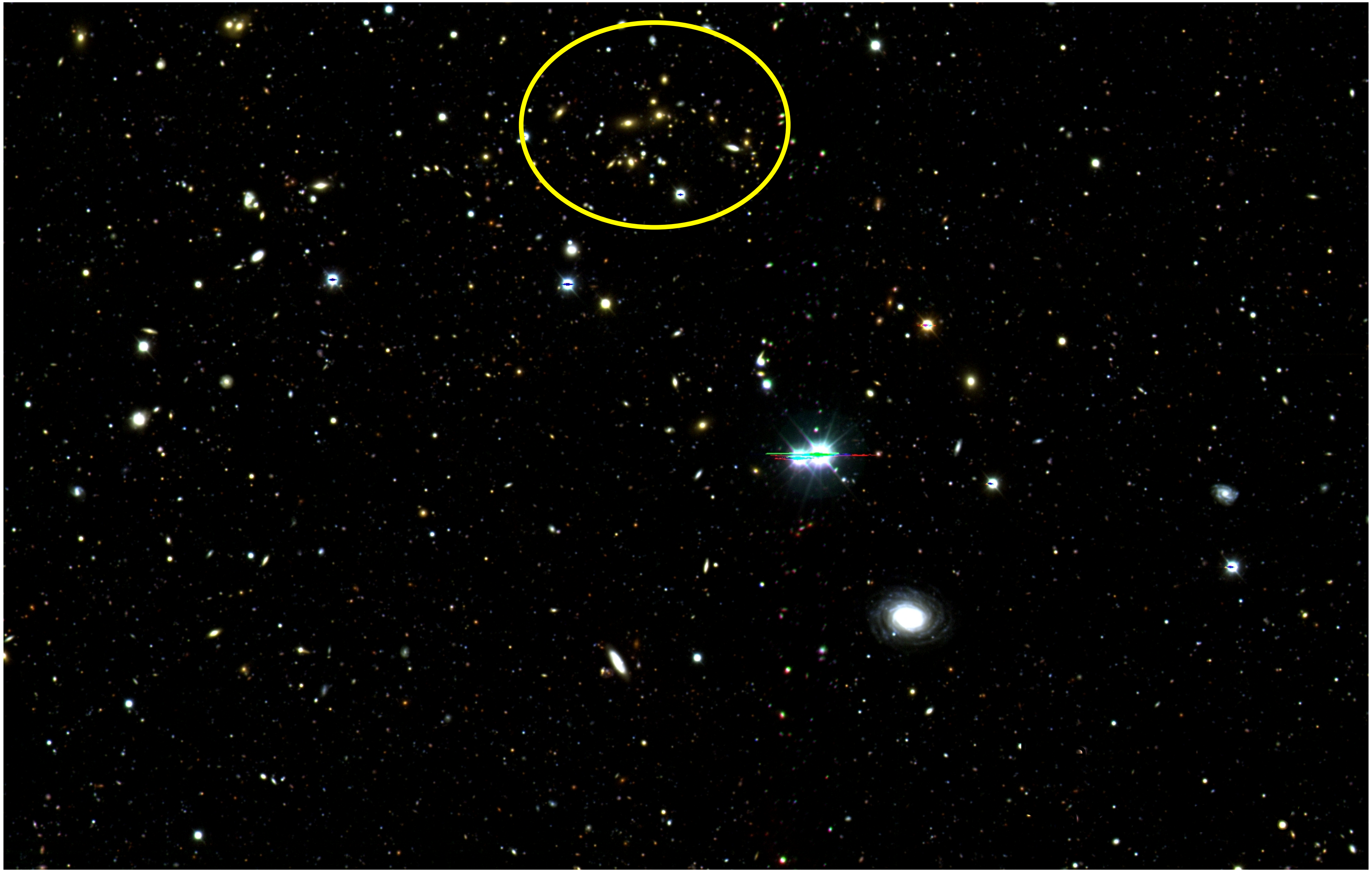
- Science of "empty fields"

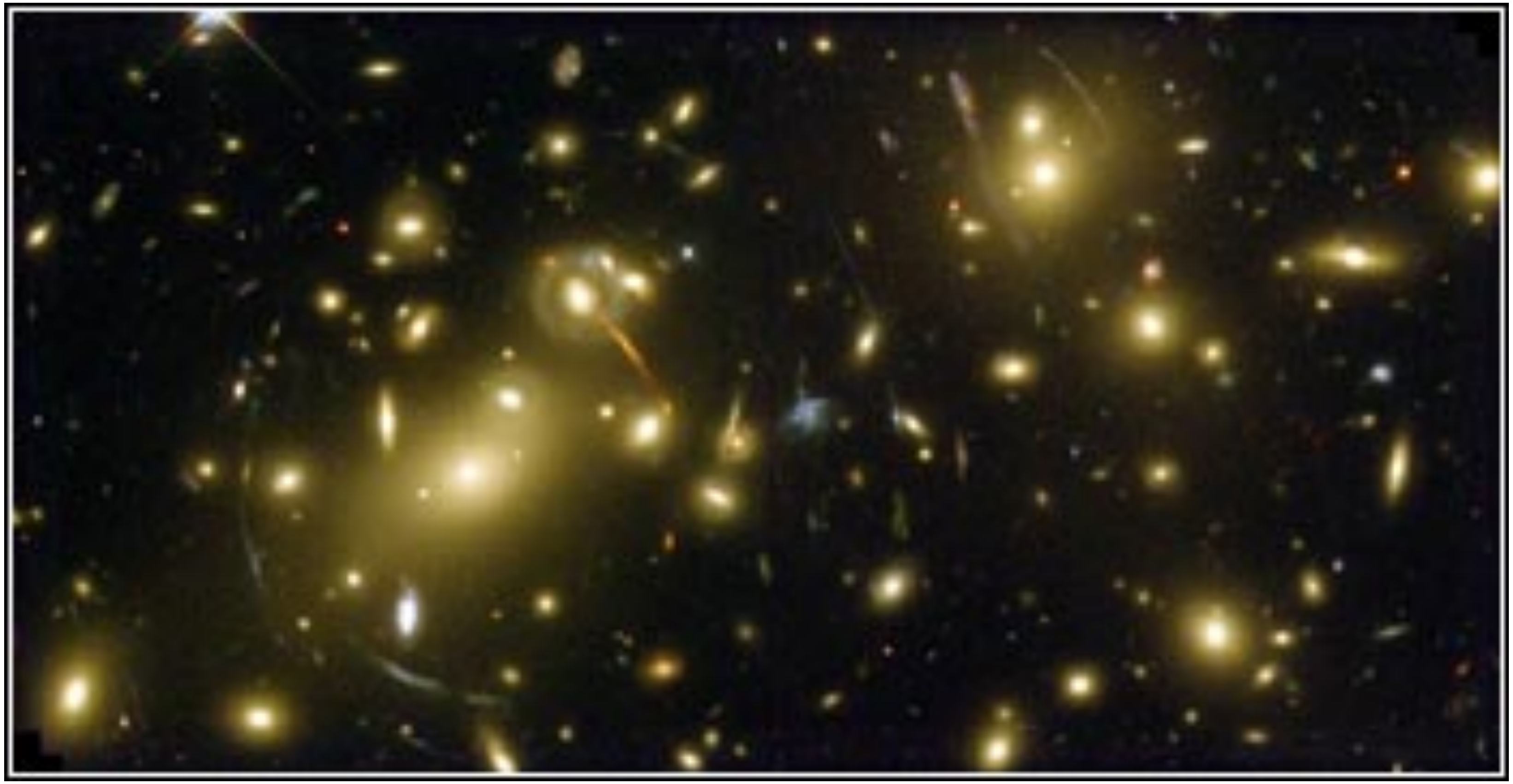
An empty field:



Long exposures with a large telescope …… ➔

The sky in the optical band

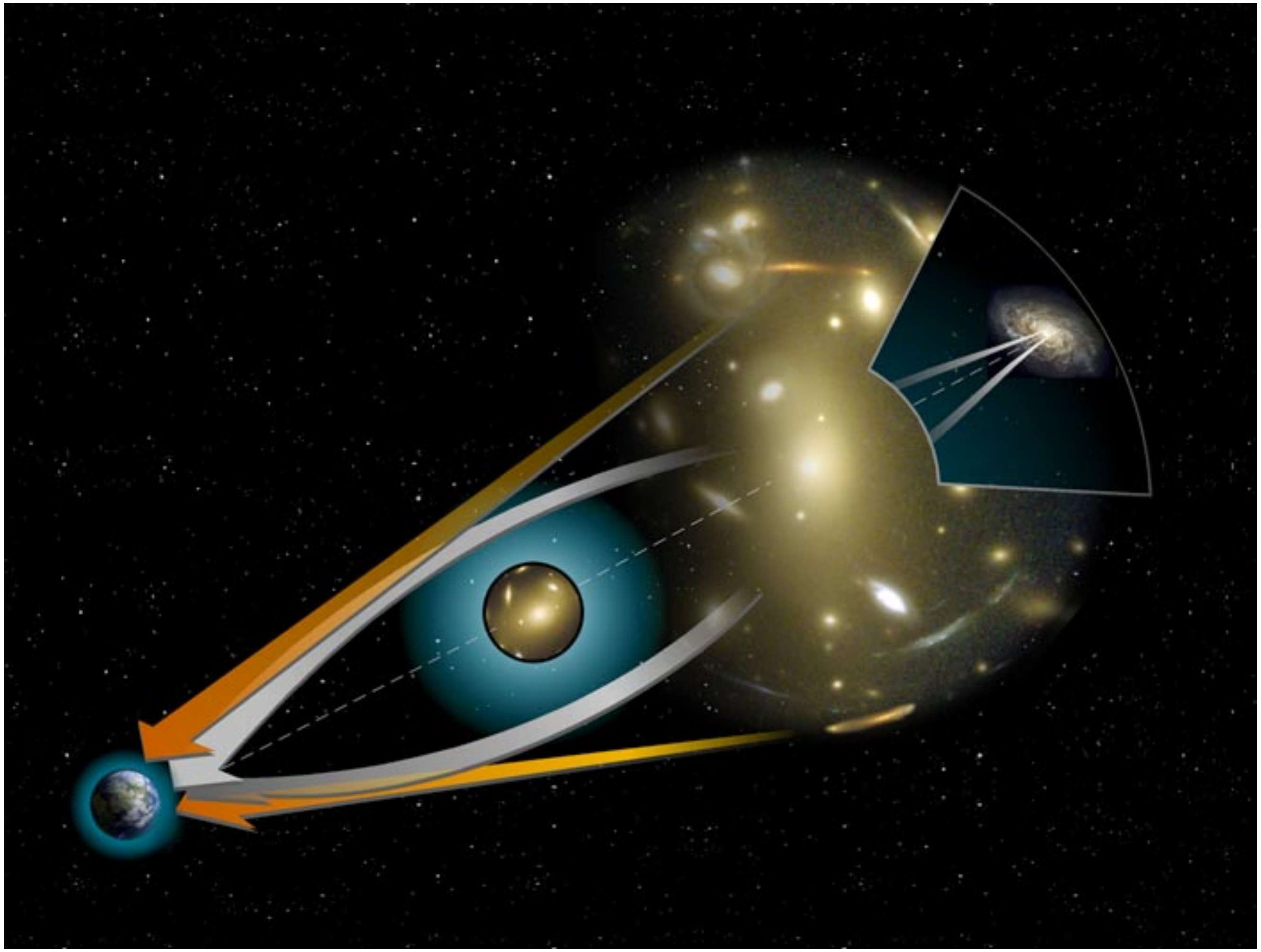




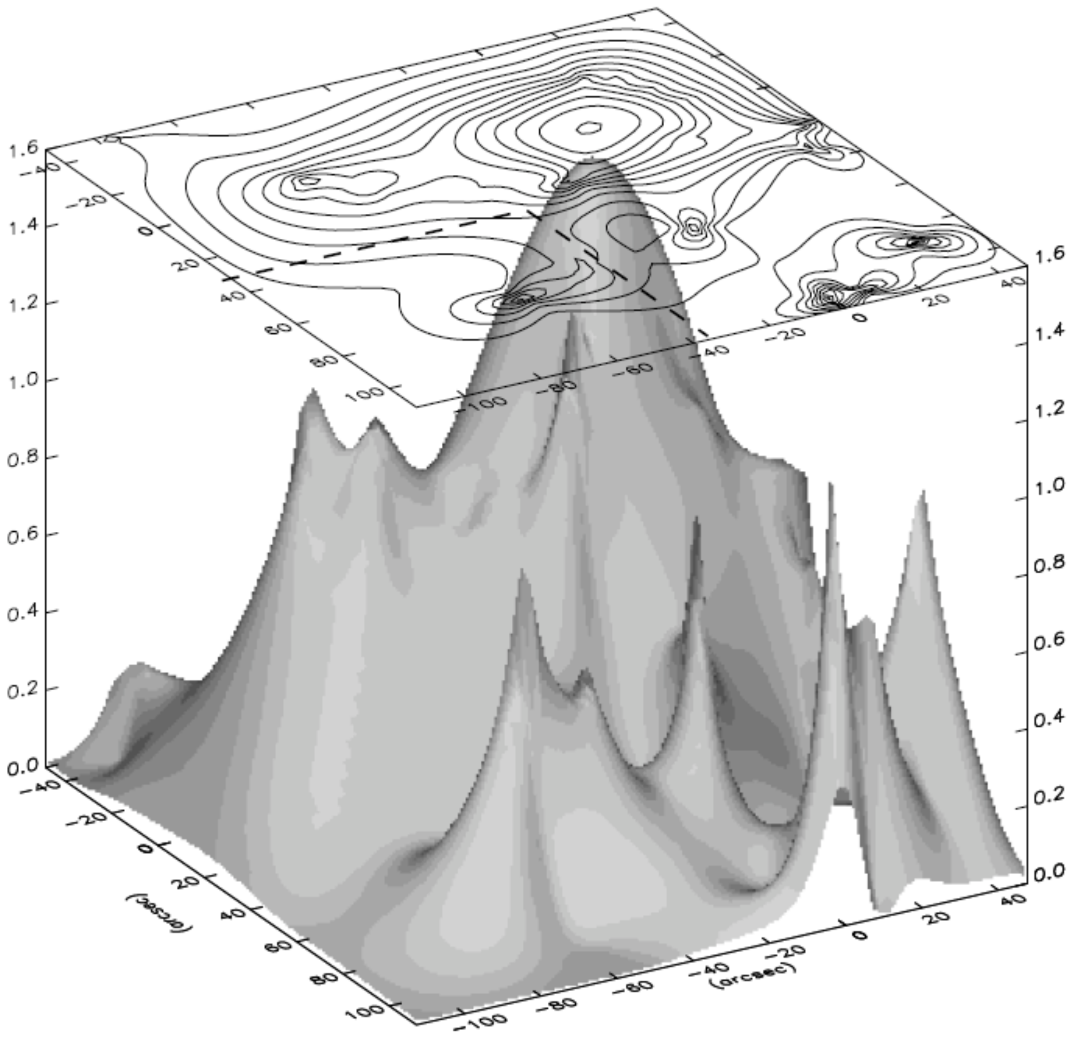
The center of A2218 as seen by the HST

$z = 0.176$

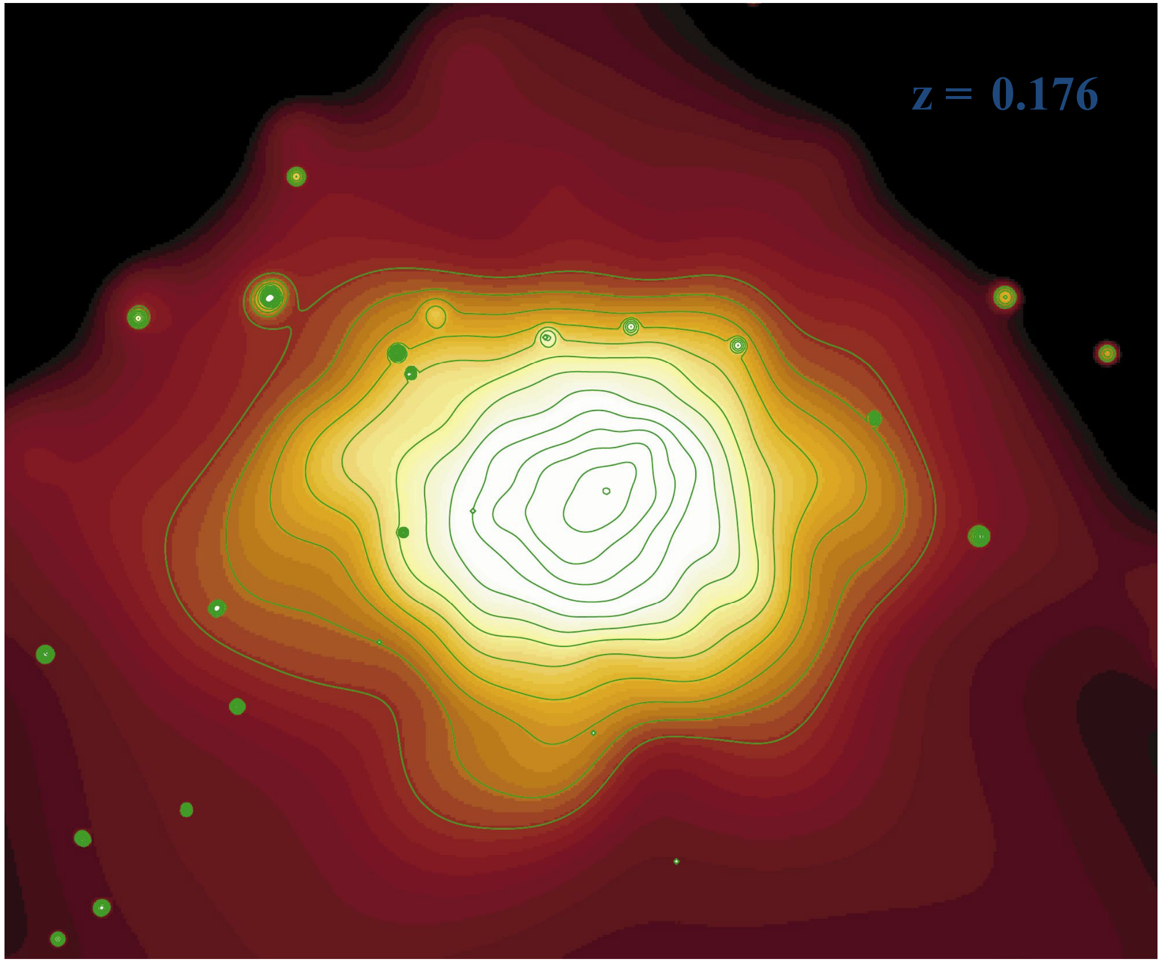
The dark matter acts as a lens



The shear measurement allows us to measure (total) cluster masses

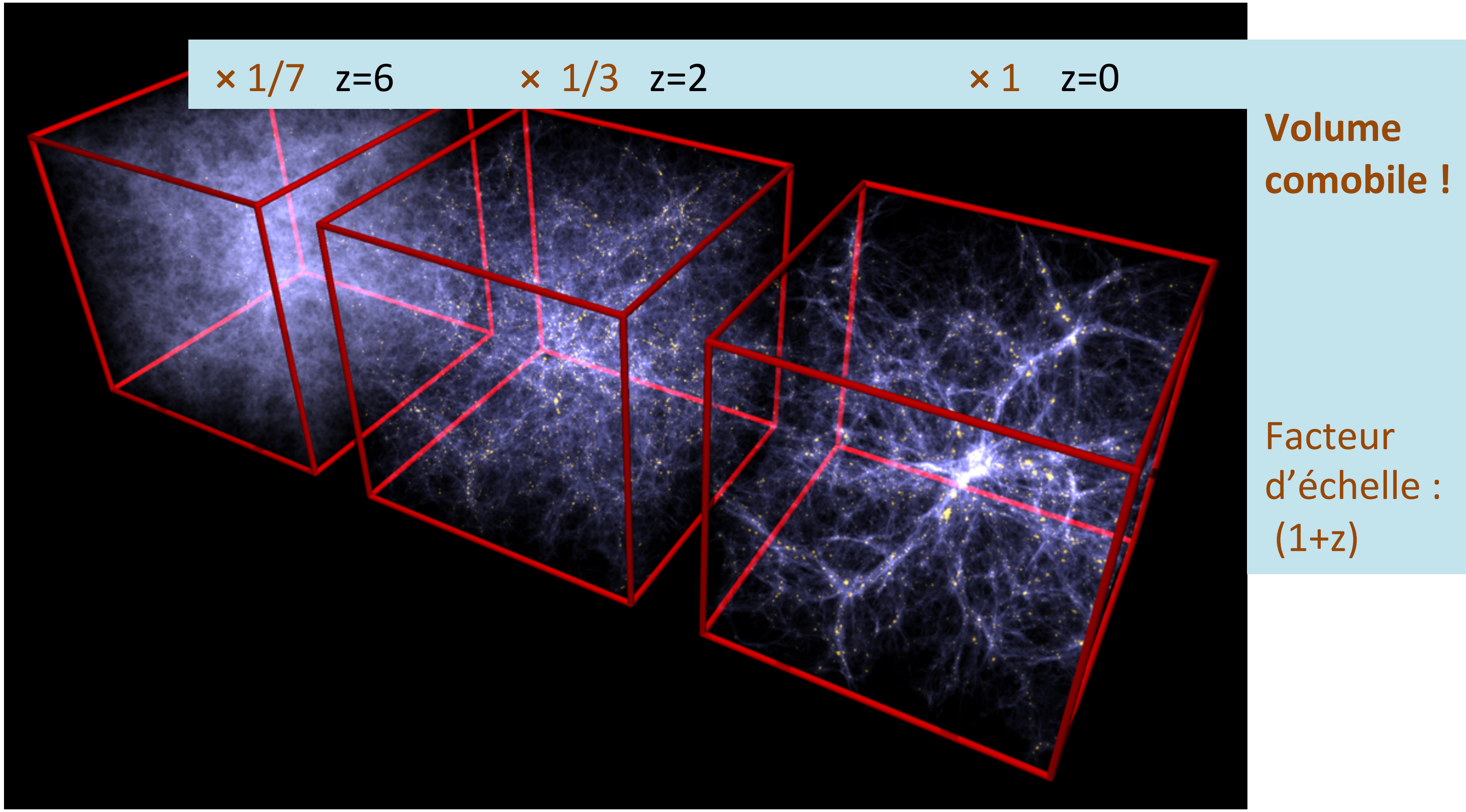


X-ray image of A2218

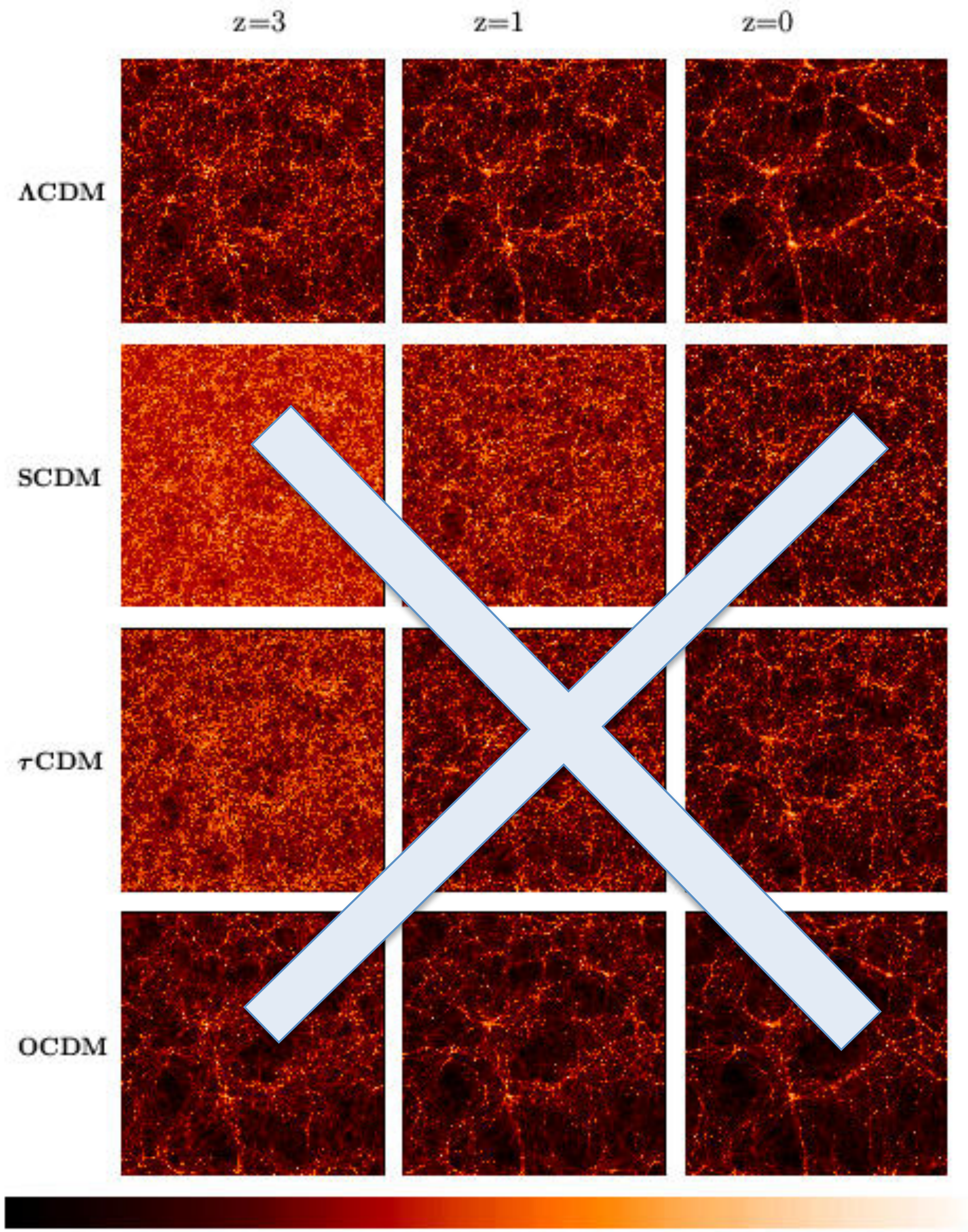


Gaz

T ~ 50 million degrees



Why to compare the structure of the universe at different epochs?



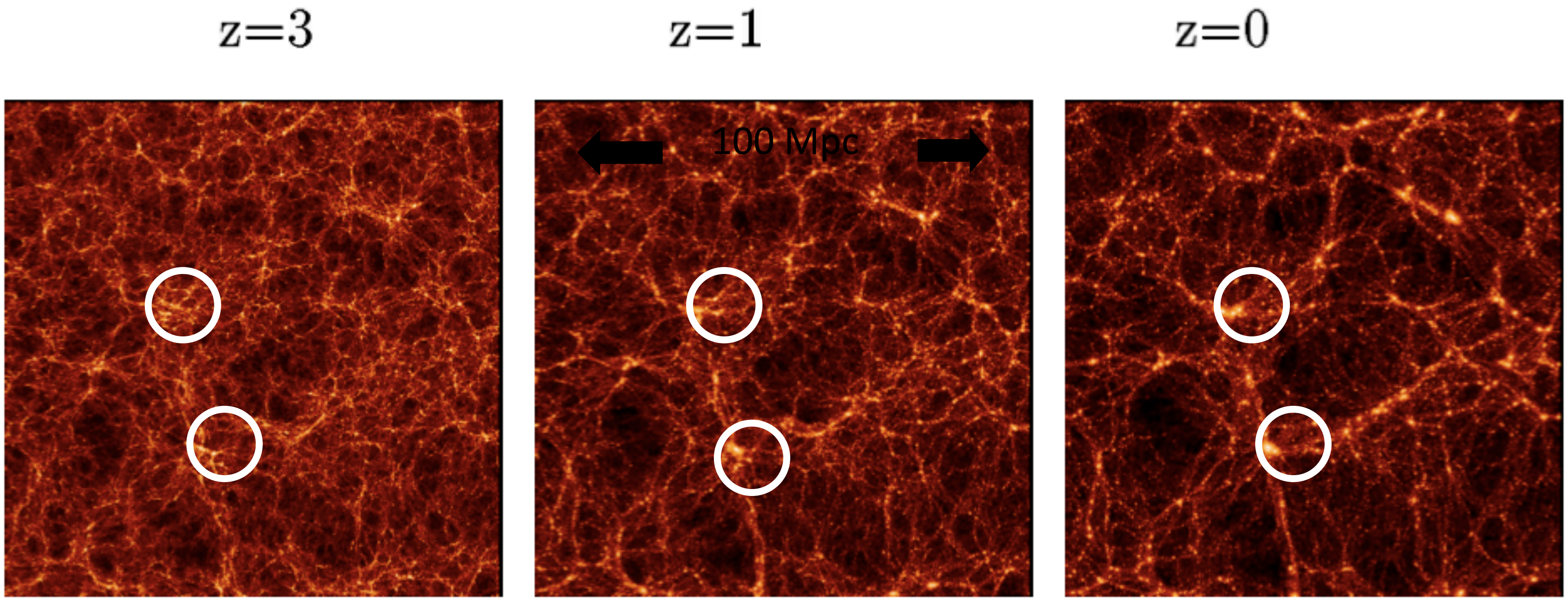
The VIRGO Collaboration 1996

The structure of the universe

for different cosmological models

Simulations: Dark matter only

Clusters of galaxies
= nodes of the cosmic structre



Most massive objects in the universe

=> cosmology

FILM

EVOLUTION OF INTER-GALACTIC GAS

blue : cold red : hot box size : 50 Mpc

By HORIZON – Mare Nostrum

Why searching for clusters in the X-ray band ?

- The source density is much lower than in the optical or in the IR
- Projection effects are negligible
- Two types of sources:
  - pointlike : AGN (~ 300 / deg^2)
  - extended : clusters of galaxies (~ 10 /deg^2)
- A first mass estimate can be obtained thanks to the gas temperature

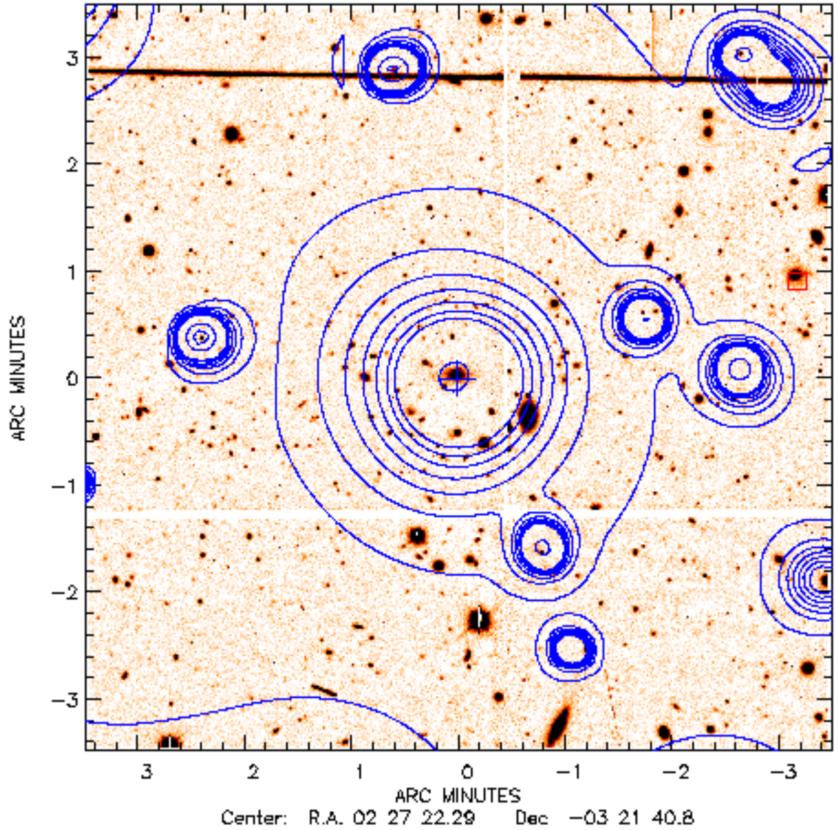
To make things clear… and exciting!

- In galaxy clusters, the mass of galaxies is neglible:
  - Galaxies 5%
  - Gas 15%
  - Dark Matter 80%

- Mean density of the ICM is ~ 1 atom/liter
  - 5 times emptier than the best vacuum obtained on Earth
  - But the total gas mass of a cluster is ~ 10^{14} Mo!

- With XMM, we collect ~ 1 cluster photon per minute for clusters at z ~ 0.5
  - Typically 100-500 photons per cluster in 10 ks
  - Less than the number of galaxies in clusters!

X-ray emission from clusters



Background image : CFHT i

Blue contours : XMM

XXL in short:

1) FIND

~ 500 X-ray clusters

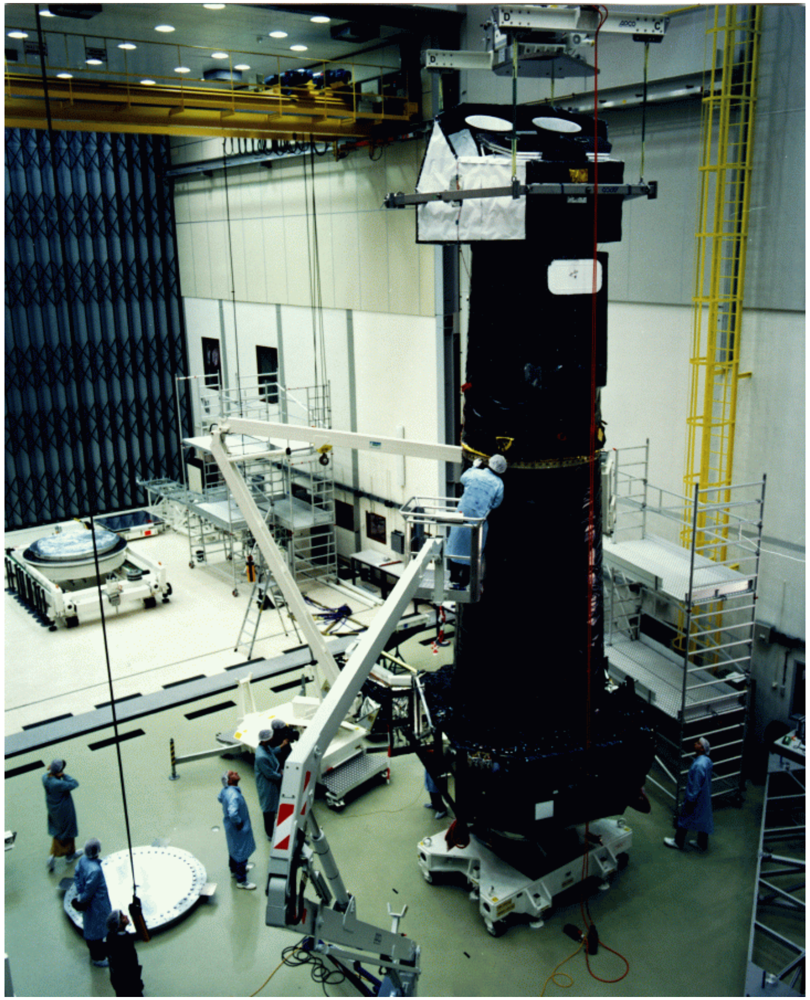
in 50 deg^2

2) DO COSMOLOGY

X-ray clusters ~ 5% of the source population

2.a The XMM-XXL survey
lay-out

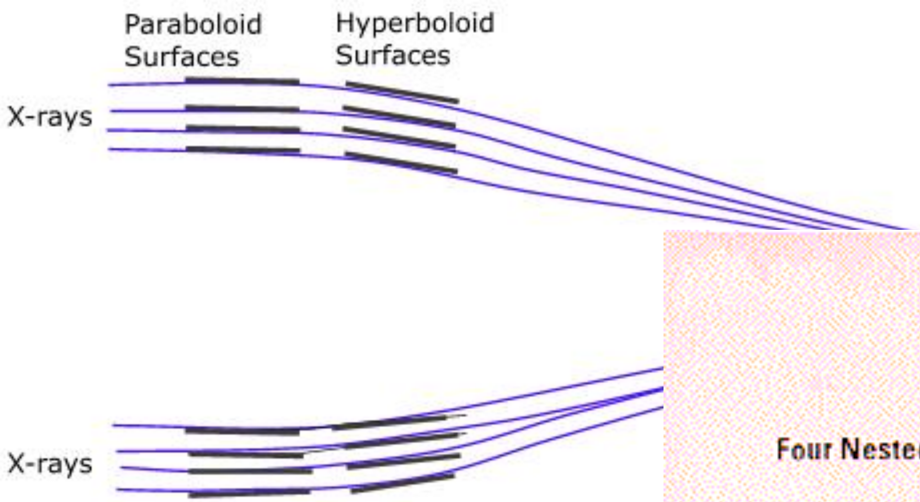
XMM

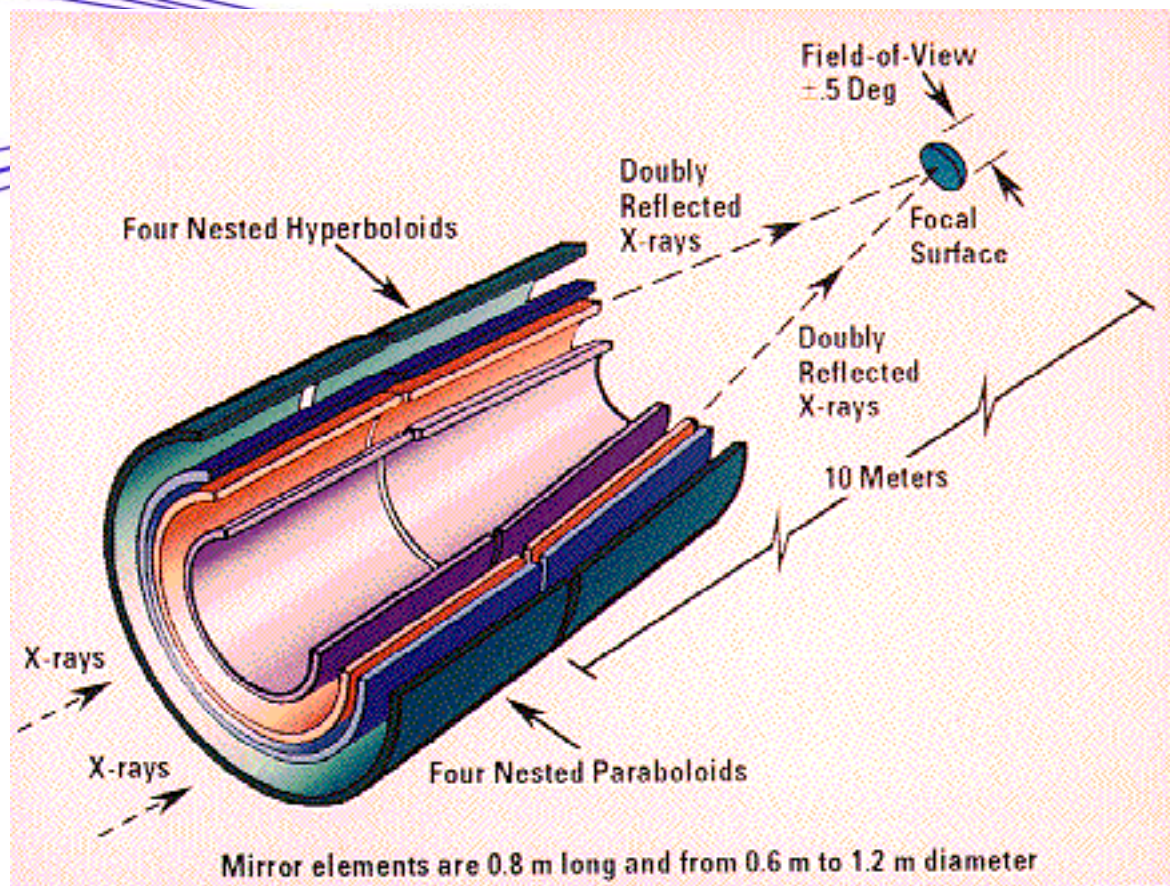


The largest ESA telescope
0.1-10 keV (~100-1 Å)

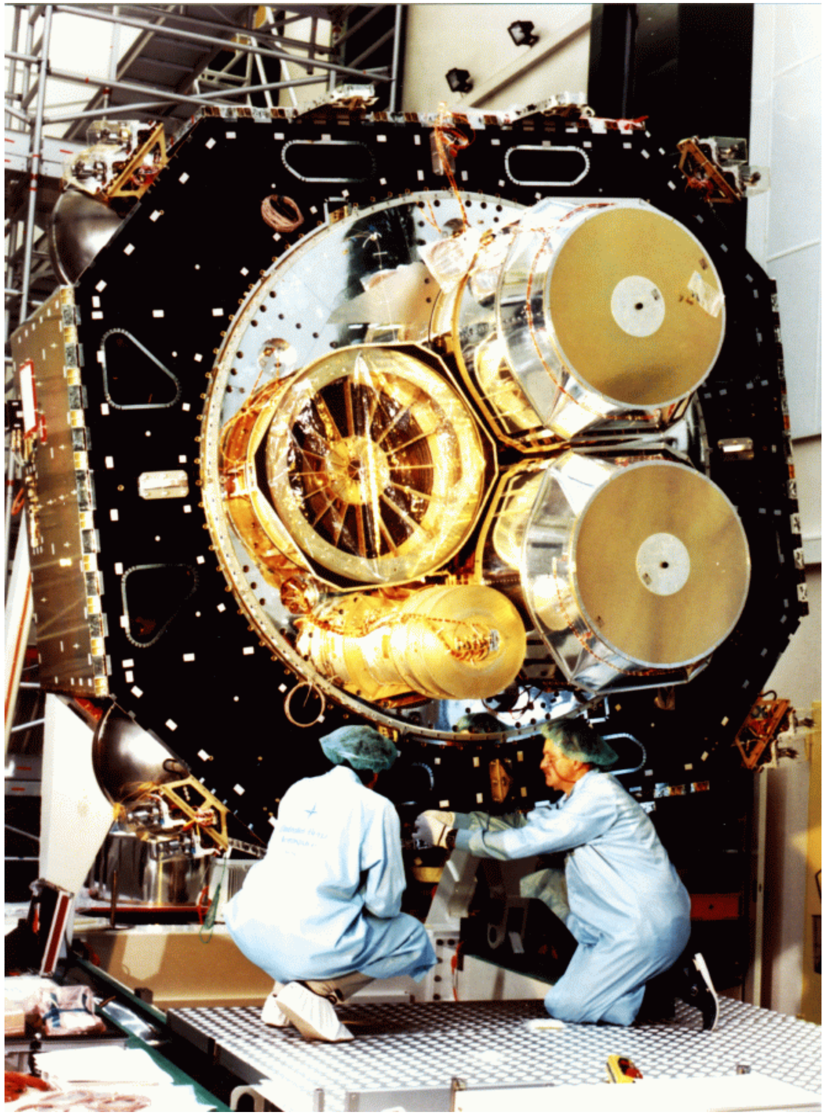
Launched: 1999

collect and focus X-ray light



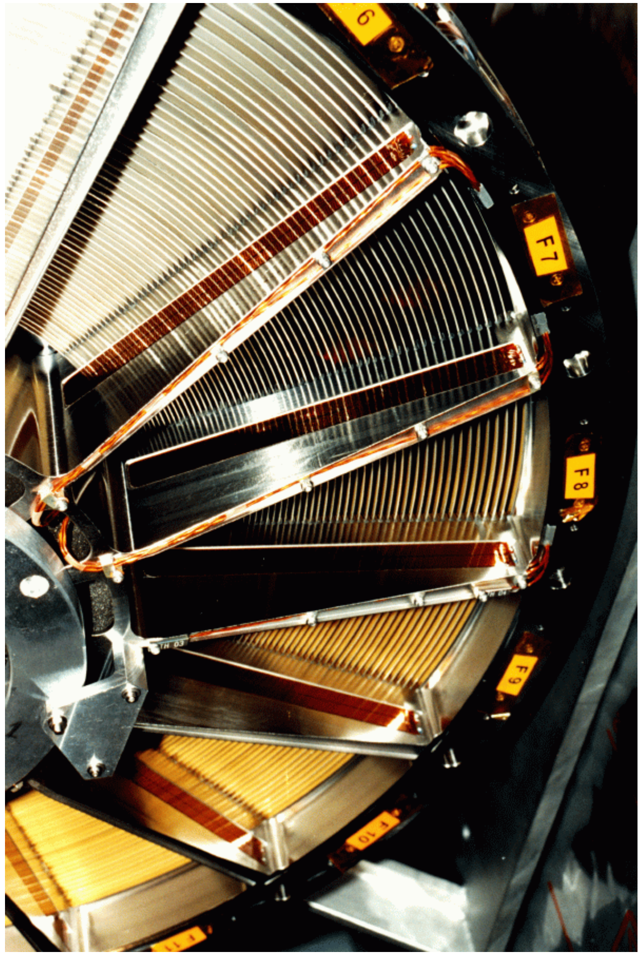


Grazing incidence:
Wolter telescope

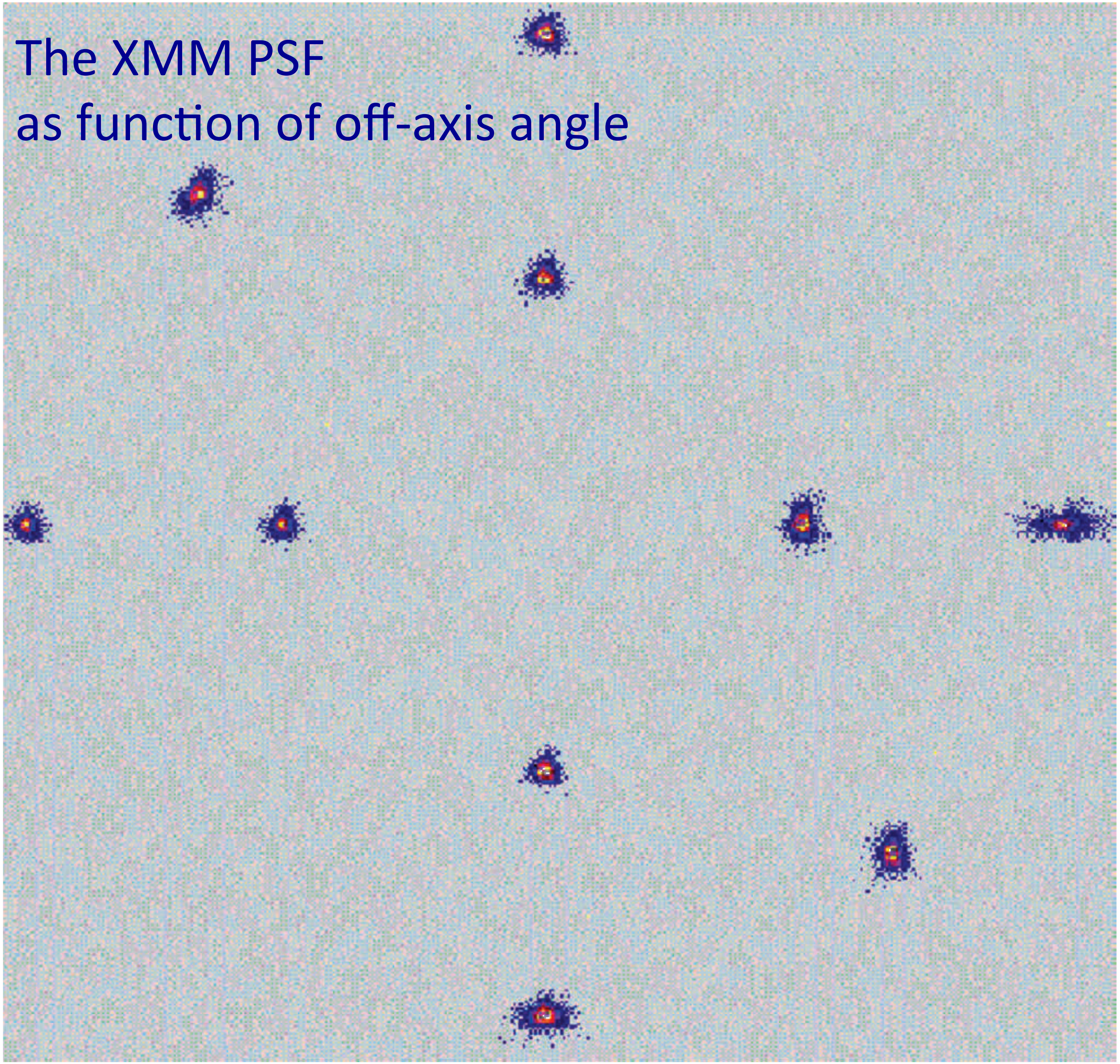


3 X-ray telescopes

58 nested mirror shells



The XMM PSF
as function of off-axis angle



Field of view:
30 arcmin diam.

Photon counting mode.
we register:

- Arrival time
- Position
- Energy

The XXL survey in short

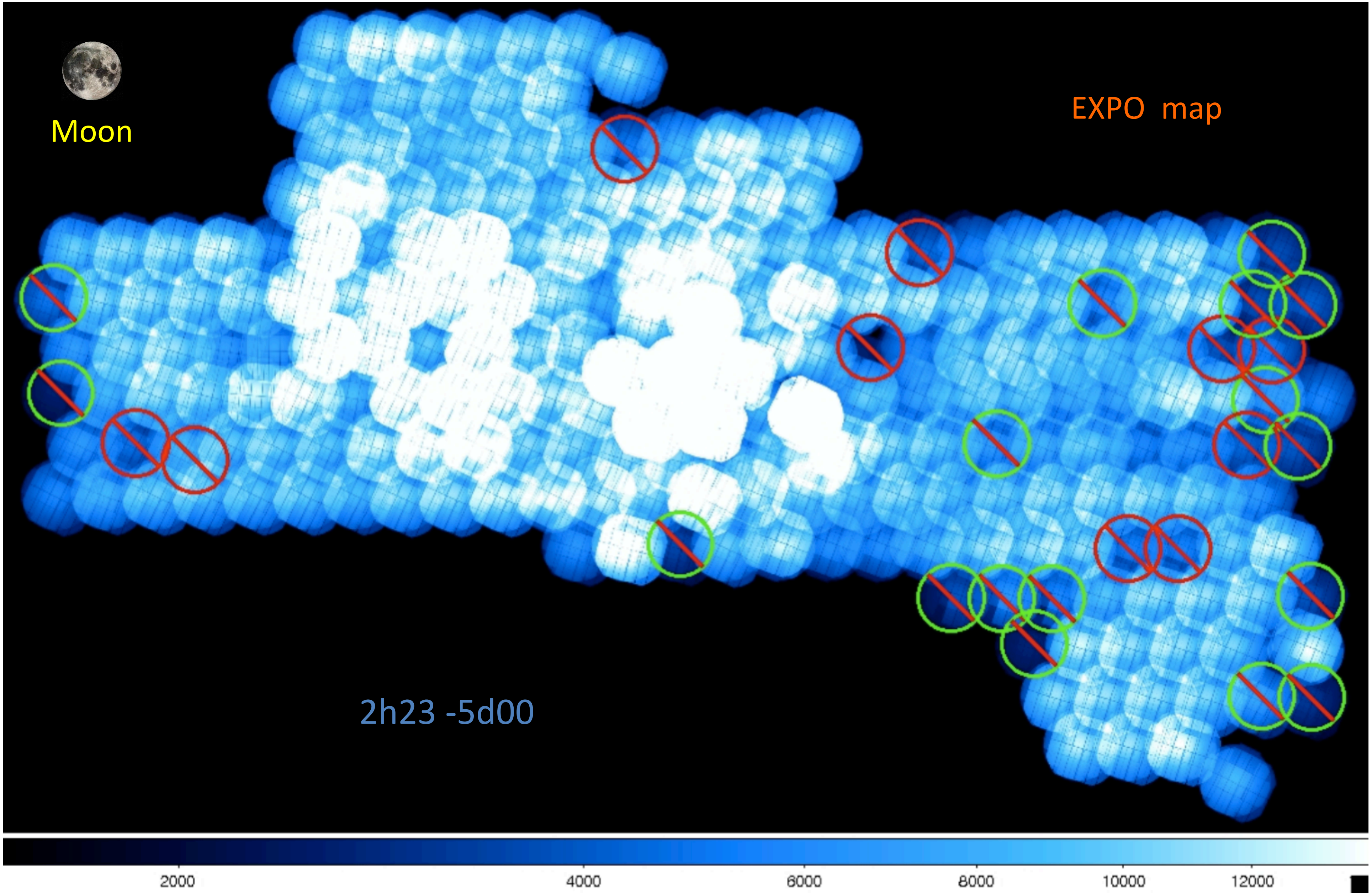
The largest XMM programme to date:

- 6.9 Ms of XMM time
- ~ 100 collaborators
- 1$^{\text{st}}$ series of 15 papers published in 2016
- 2$^{\text{nd}}$ 20 2018

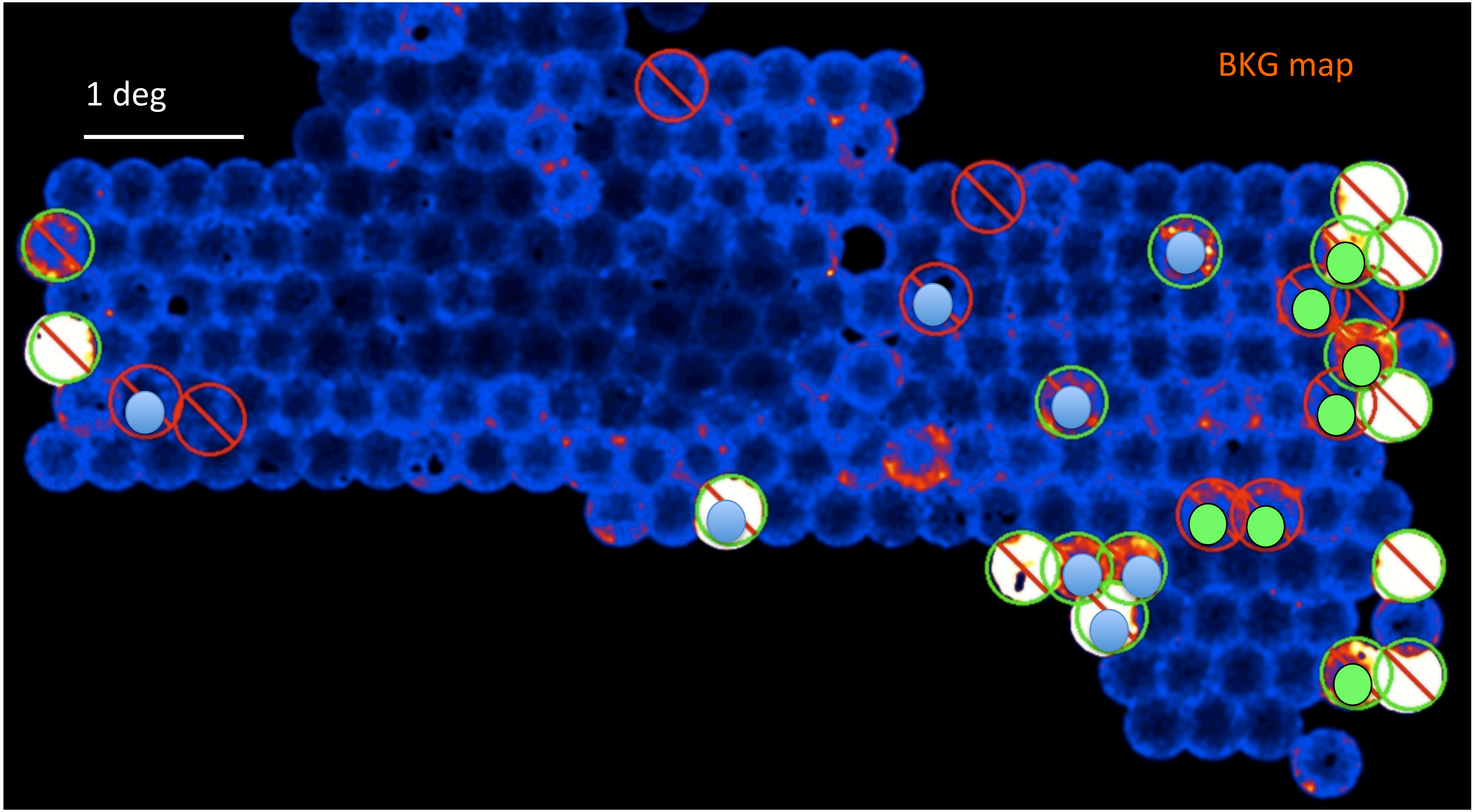
- ~ 500 clusters
- Over 20 000 AGN

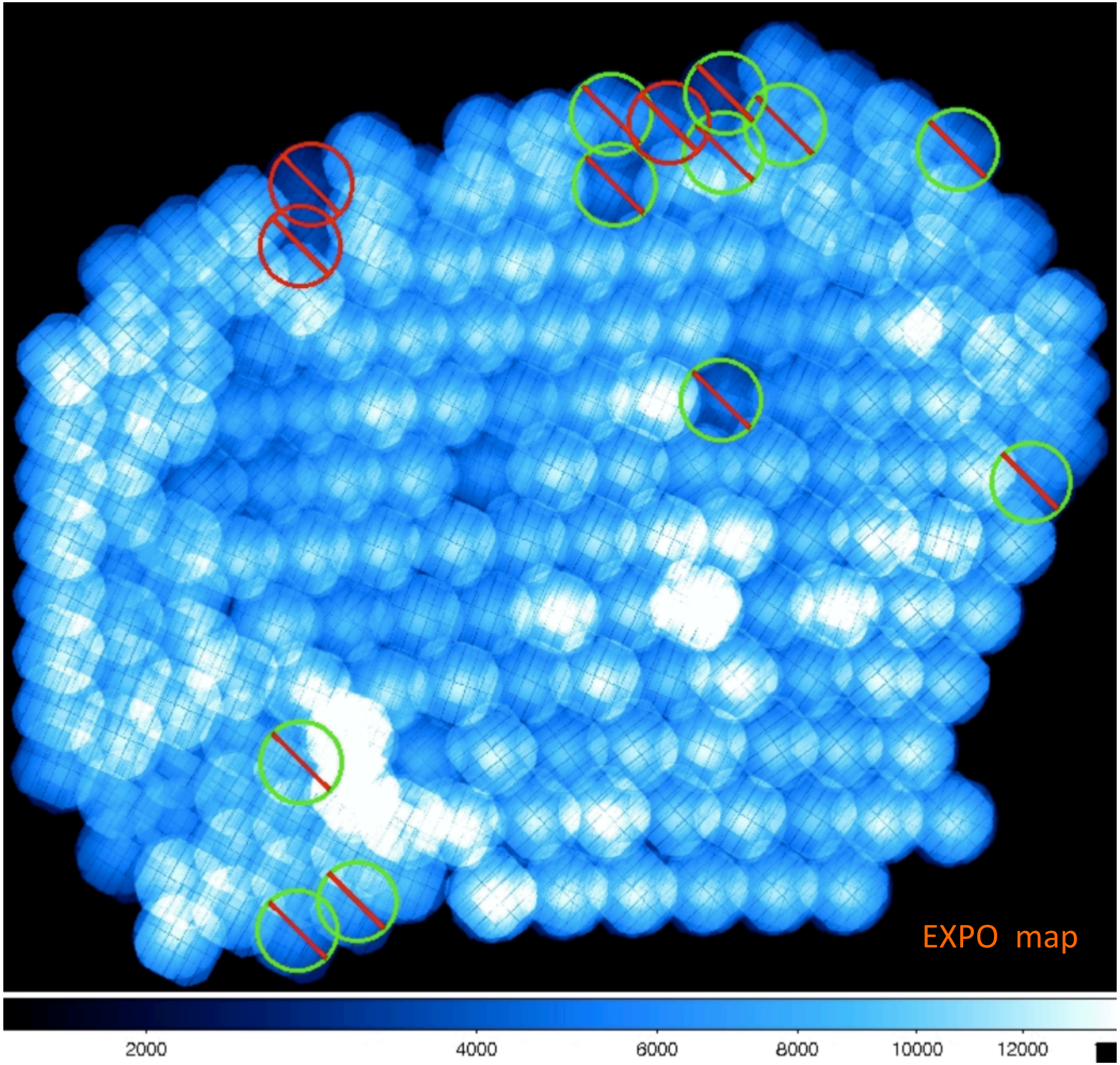
Primary goal : cosmology with the 0<z<1 clusters

XXL-N 25 deg^2



XXL-N

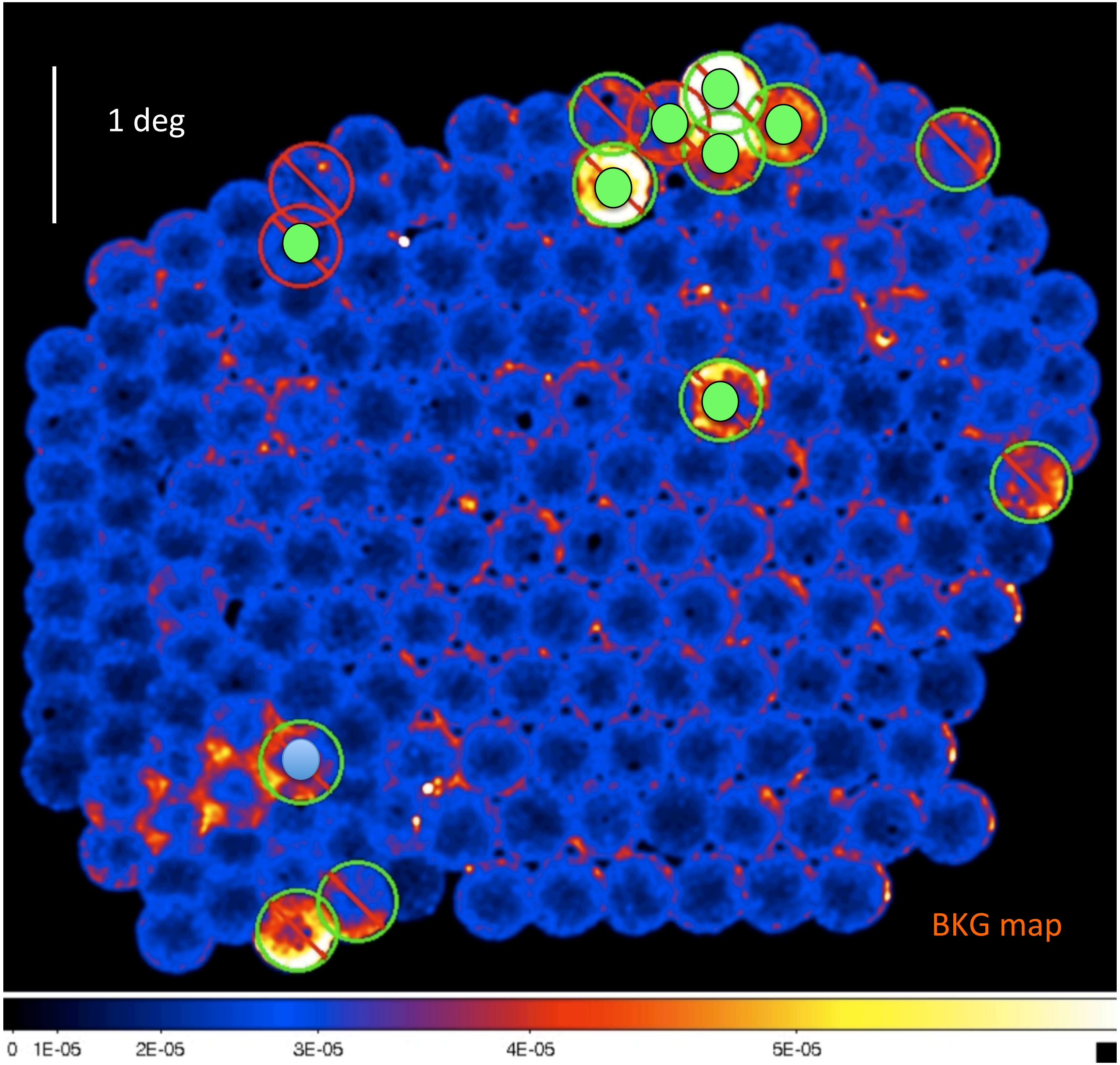




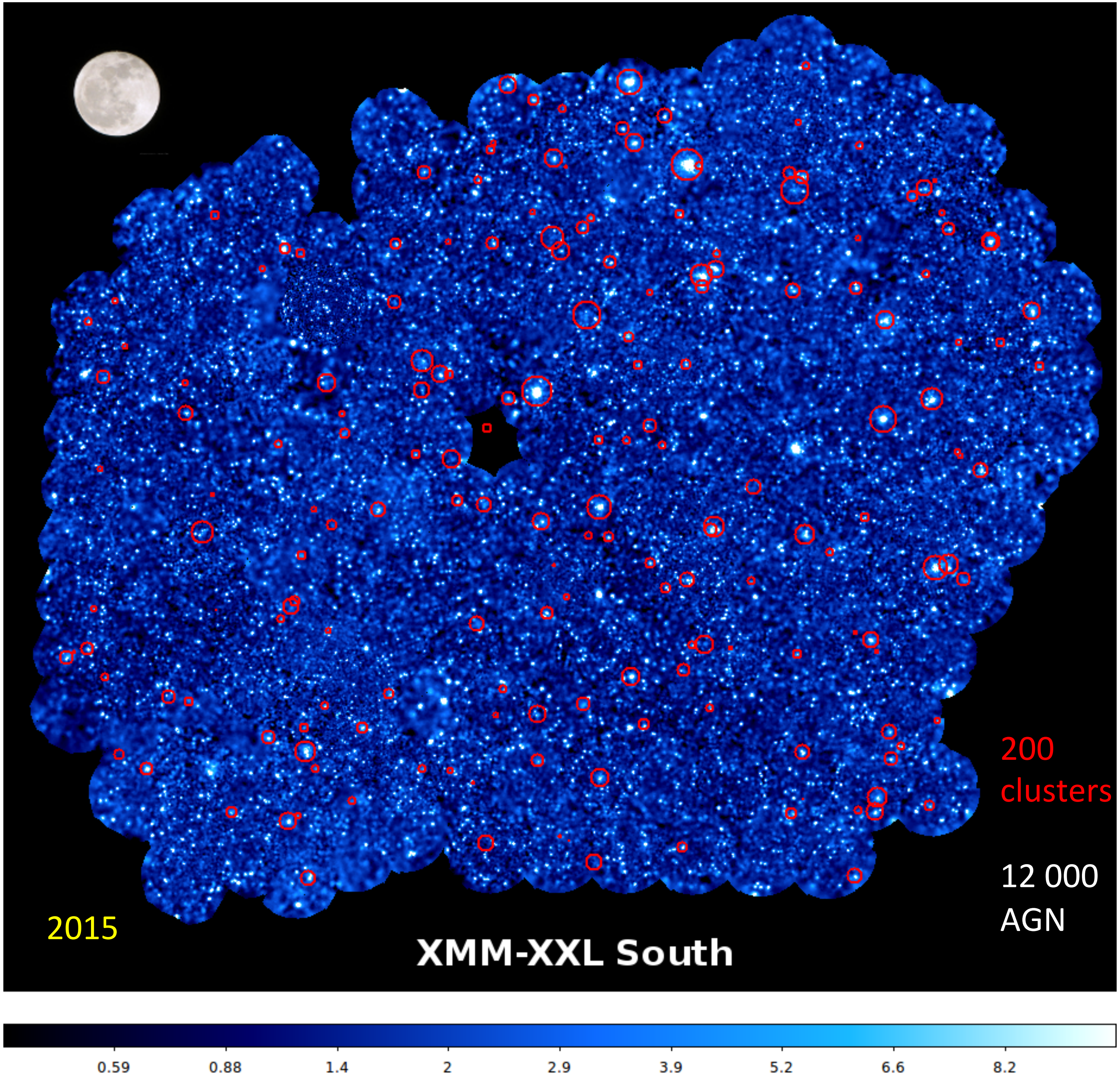
XXL-S
25 deg^2

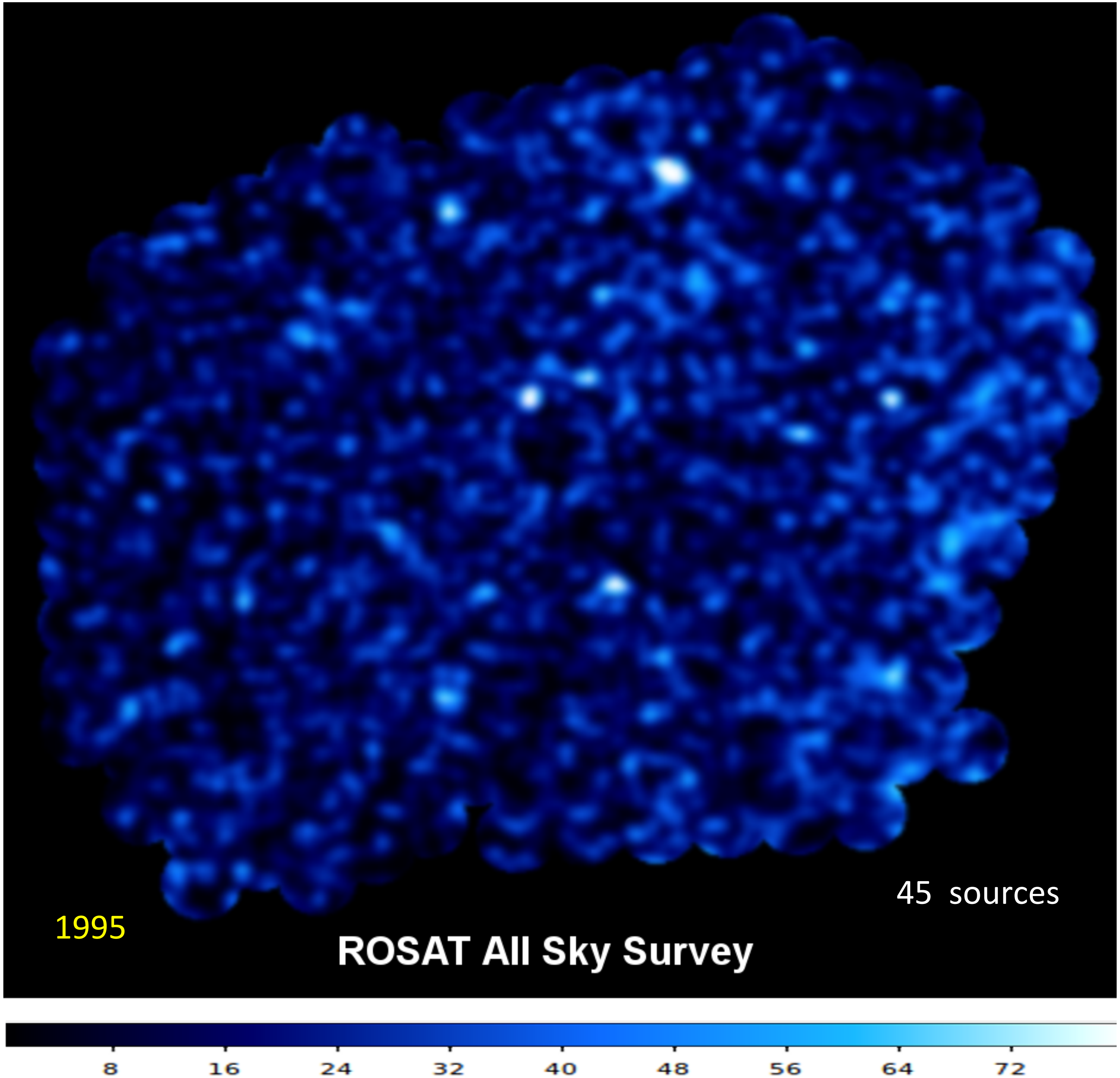
23h30 -55d00

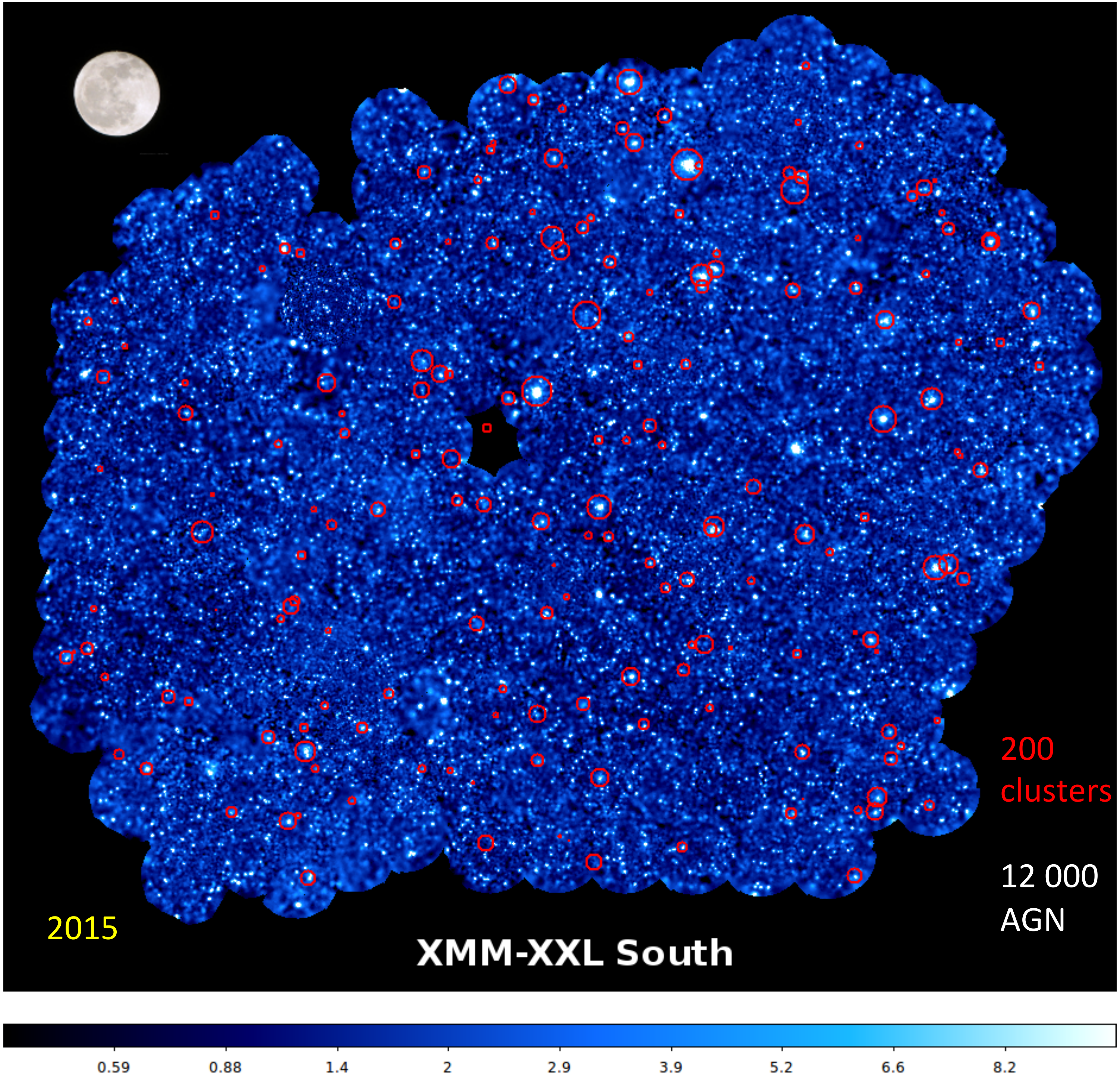
within the SPT
100 deg2
Deep Field



XXL-S


200
clusters
12 000
AGN
2015
XMM-XXL South
0.59
0.88
1.4
2
2.9
3.9
5.2
6.6
8.2


45 sources
1995
ROSAT All Sky Survey
8
16
24
32
40
48
56
64
72


200
clusters
12 000
AGN
2015
XMM-XXL South
0.59
0.88
1.4
2
2.9
3.9
5.2
6.6
8.2

Not a flux limit !

~ surface brightness limited

2.b The XXL survey

selection function

The 2-step XXL pipeline

1. Source detection on the wavelet filtered photon image

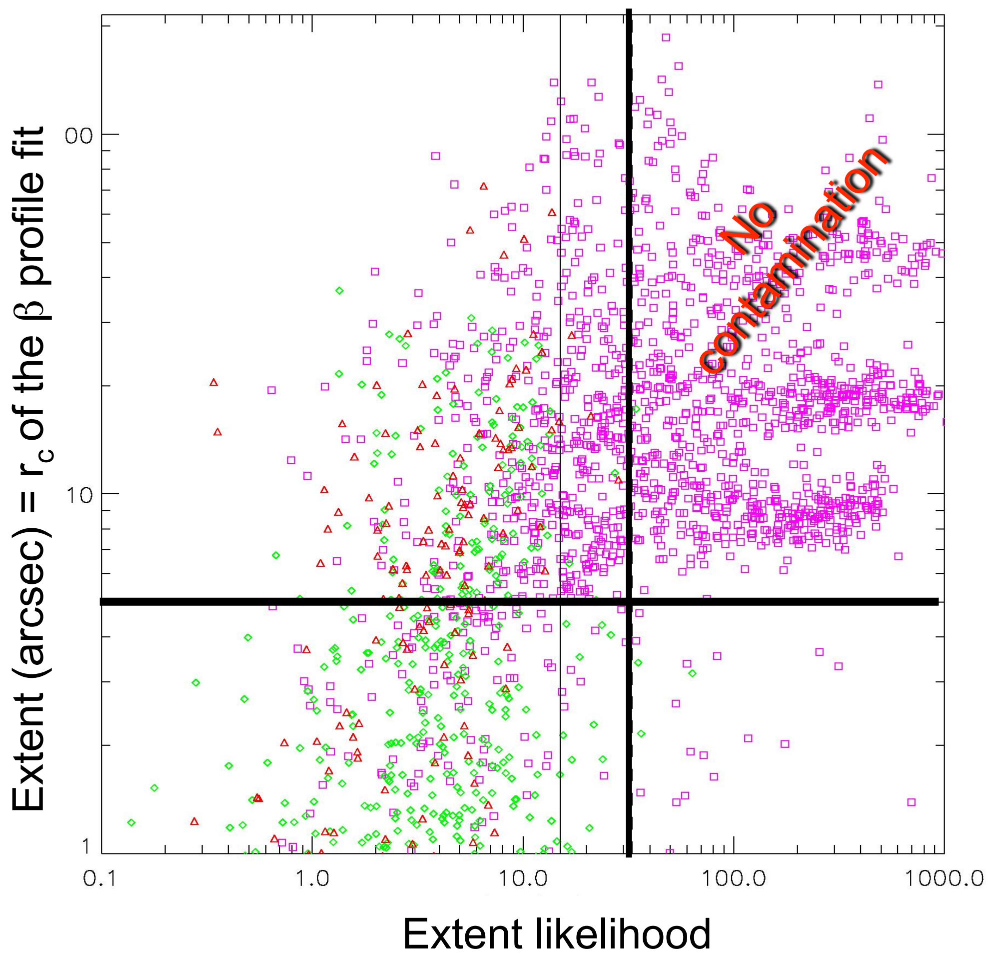
2. Each source is examined by a LH analysis. Two models are tested:
   1. PSF: normalisation
   2. Extended source: $\beta = 2/3$, r_c, normalisation

→ The source selection is made in the pipeline parameter output space

The cluster selection process

2 classes of extended X-ray sources

Green = AGNs   Magenta = clusters   Red = Spurious



Class 1 (C1):

~ 4/deg^2

no contamination

Class 2 (C2) – fainter objects:

~ 5 more / deg^2

+ 5 false det.

50% contamination

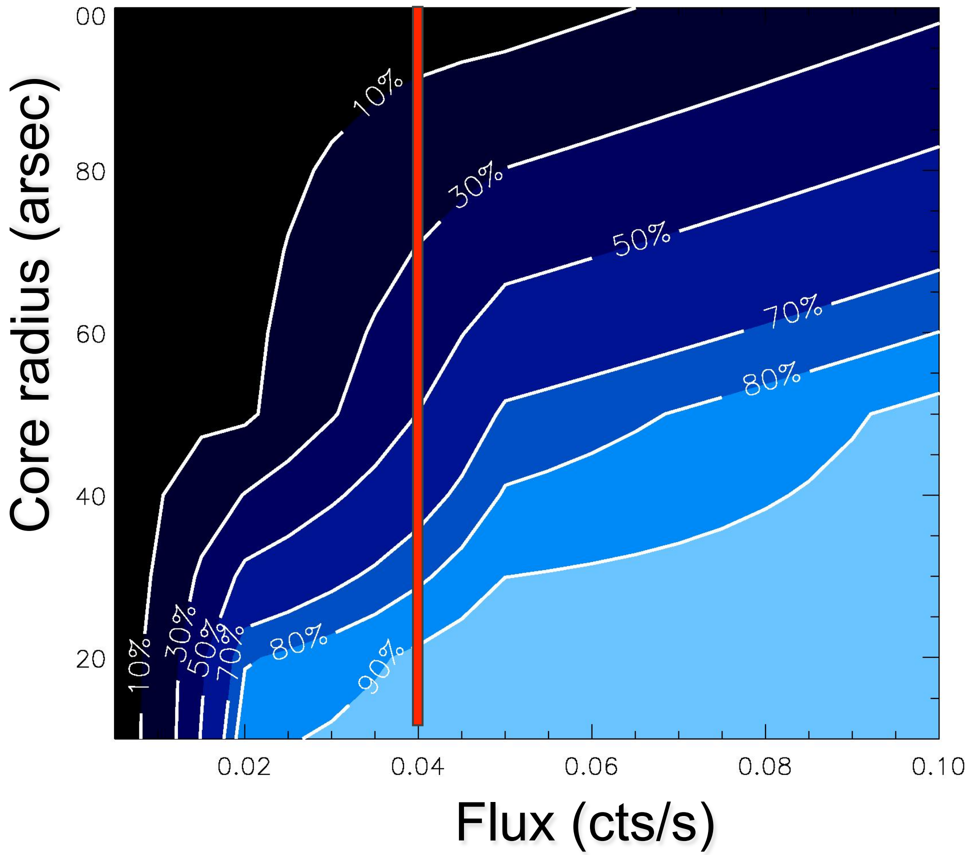
Pacaud et al 2006

Detection rates

from analytical simulations

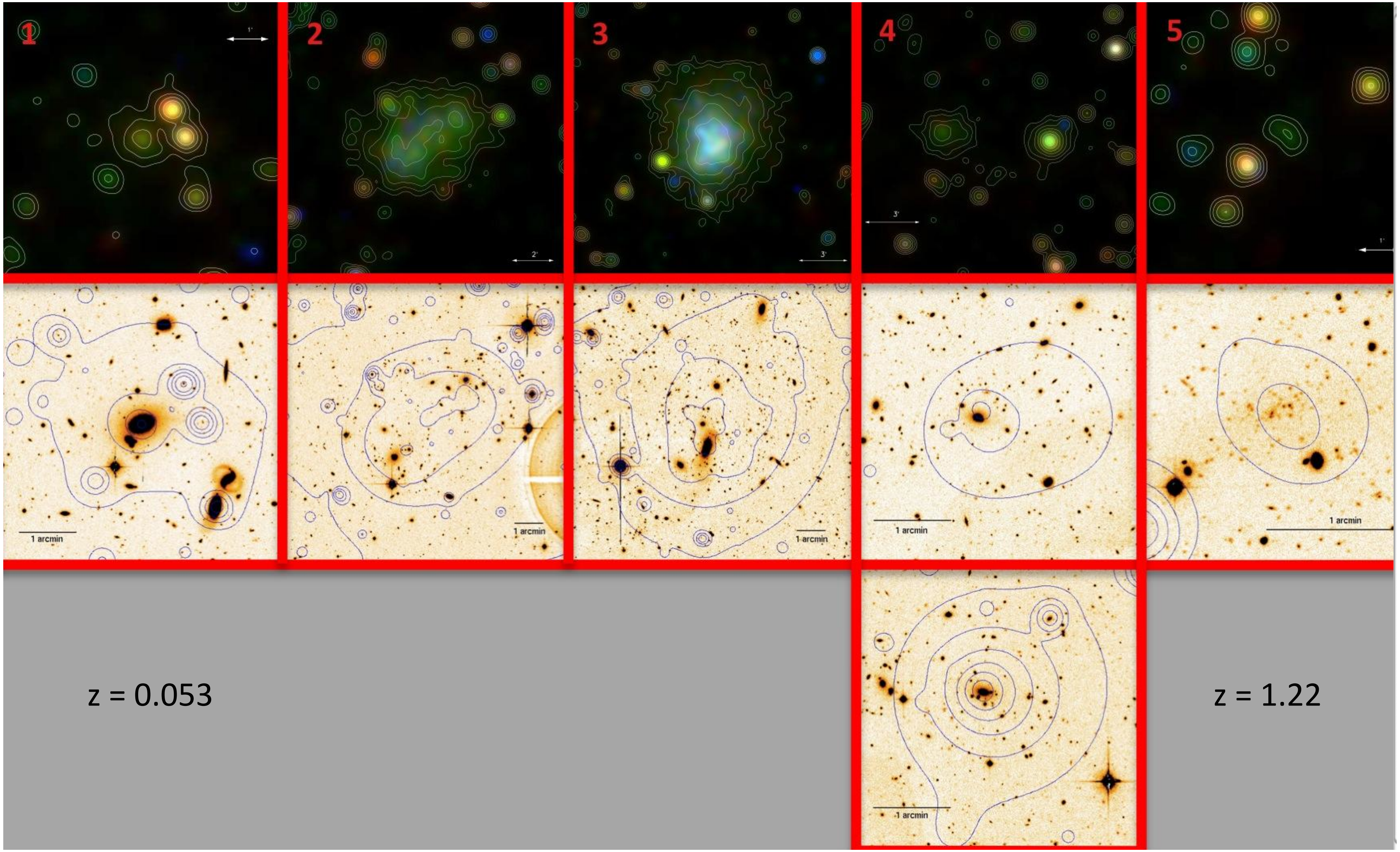
Class 1 sample : < 5% contamination

Not a flux limit !

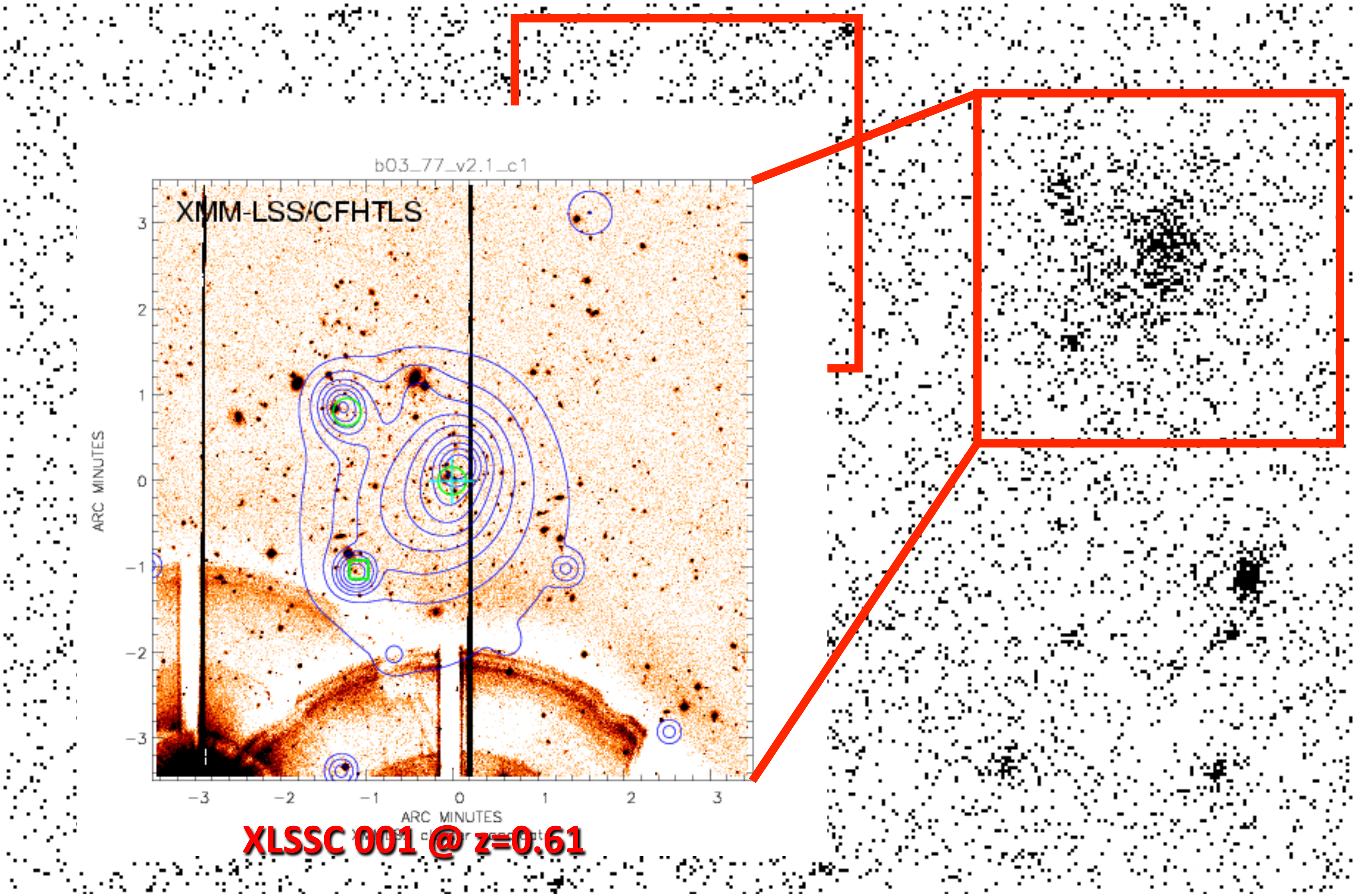


Pacaud et al 2006

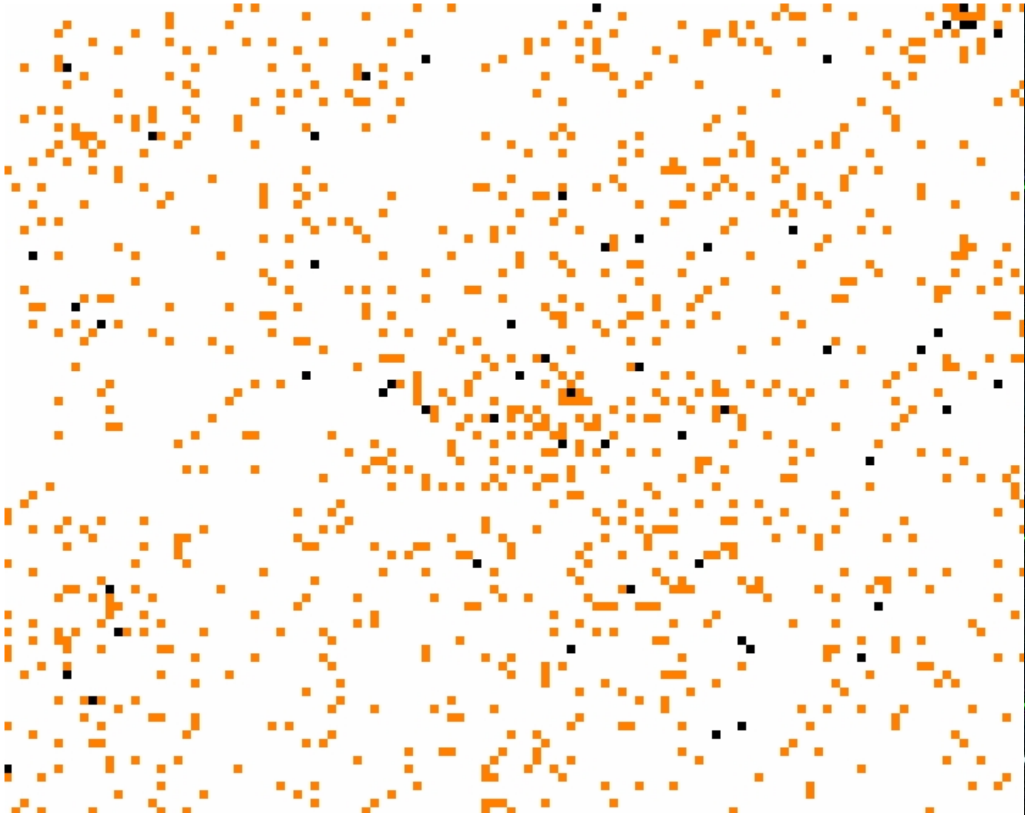
XXL clusters of galaxies
and their optical counterpart (CFHTLS)

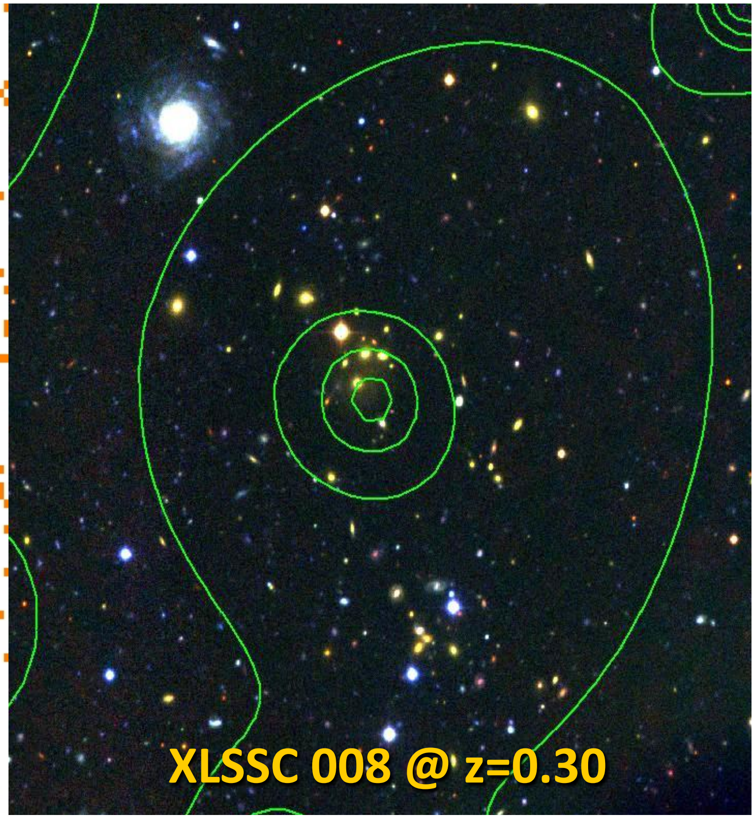


An XMM image (10ks) of an 'empty field'



An XMM image (10ks) of an ‘empty field’





Working with these data: difficult !

: misleading (Poisson statistics)

: ambitious

… but feasible

Summary

the selection function is solely based on output pipeline parameters

=

no physics

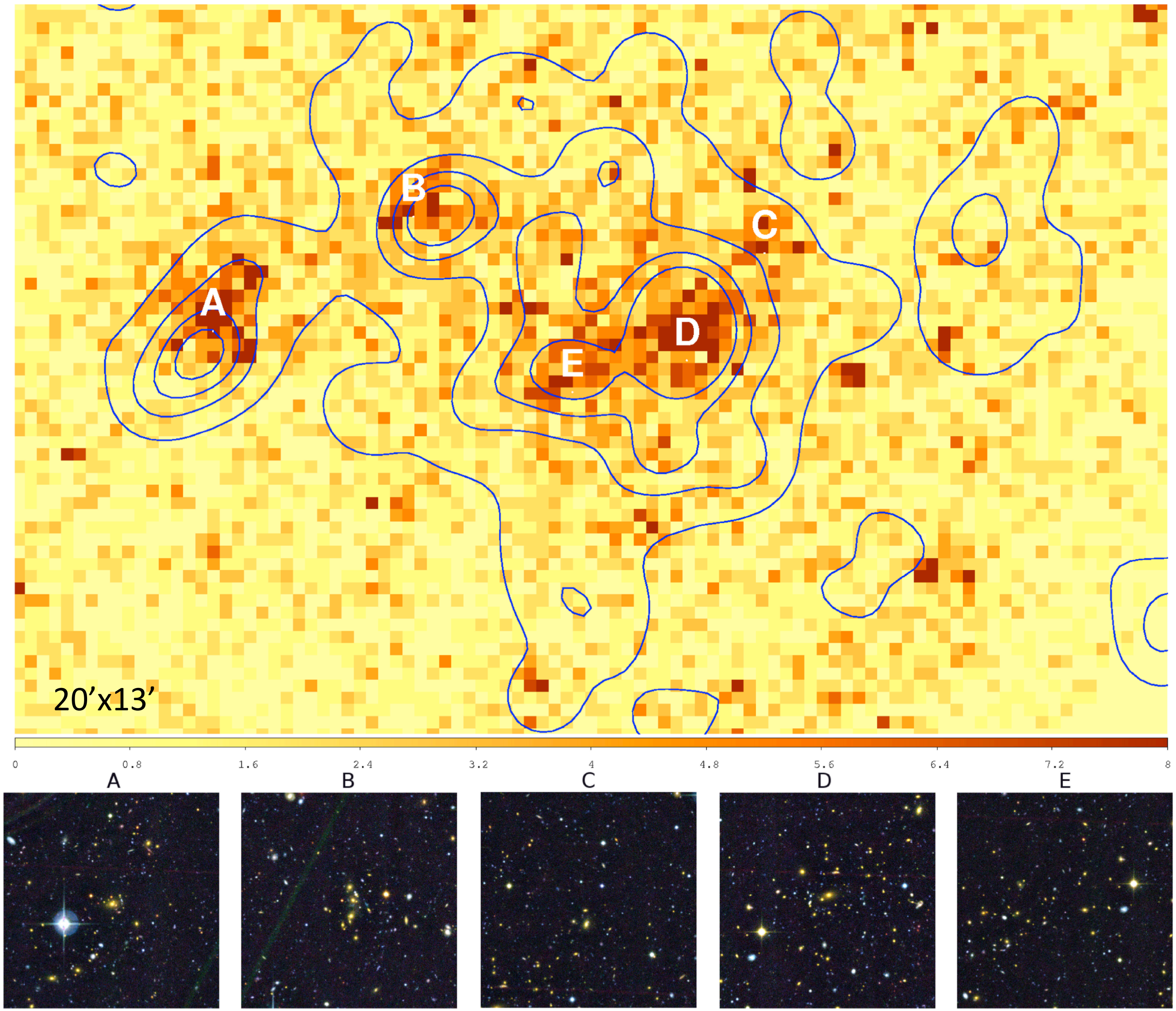
no cosmological dependence

4. RESULTS

1st series 2016

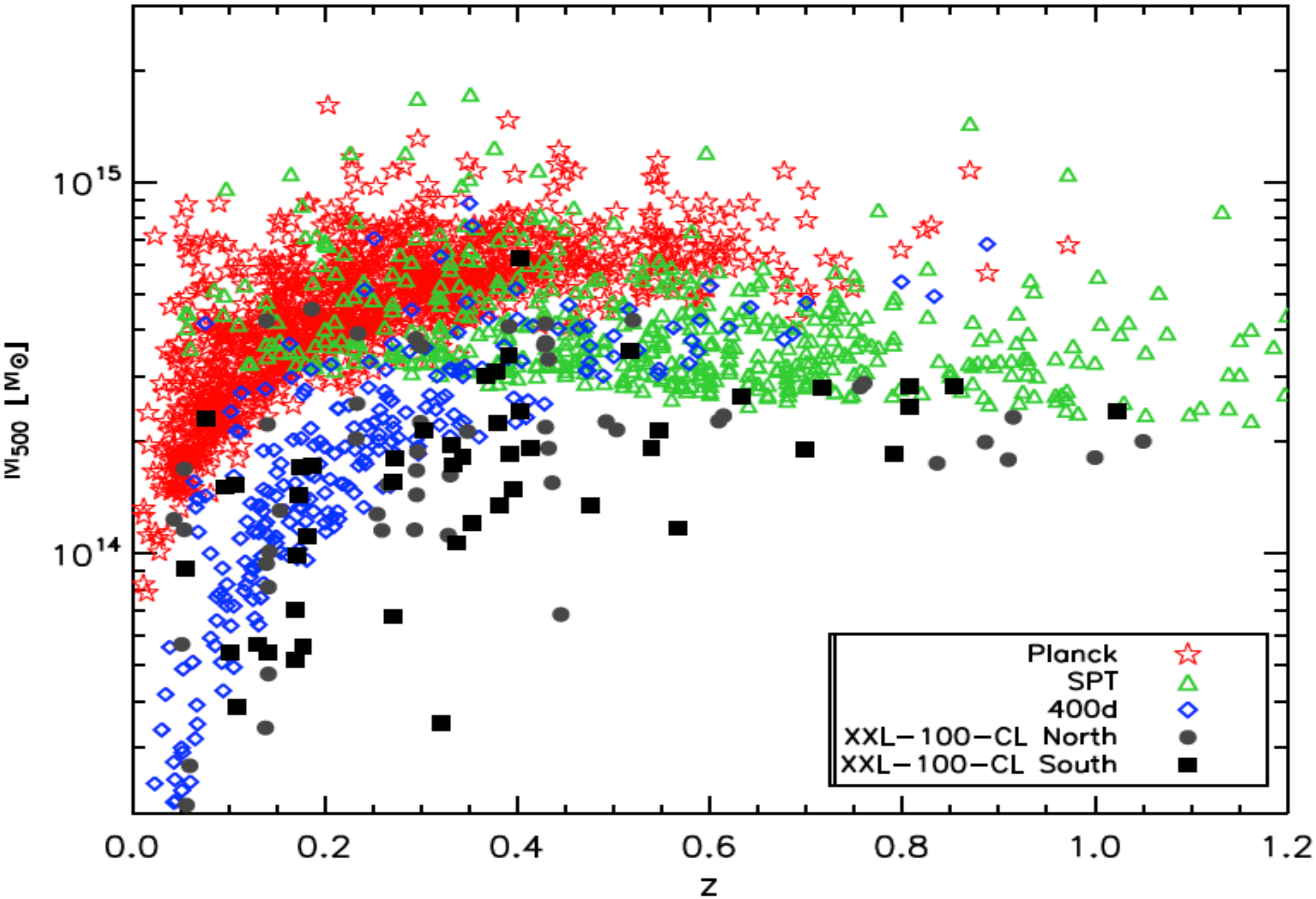
15 papers

Discovery of a super group at z=0.5



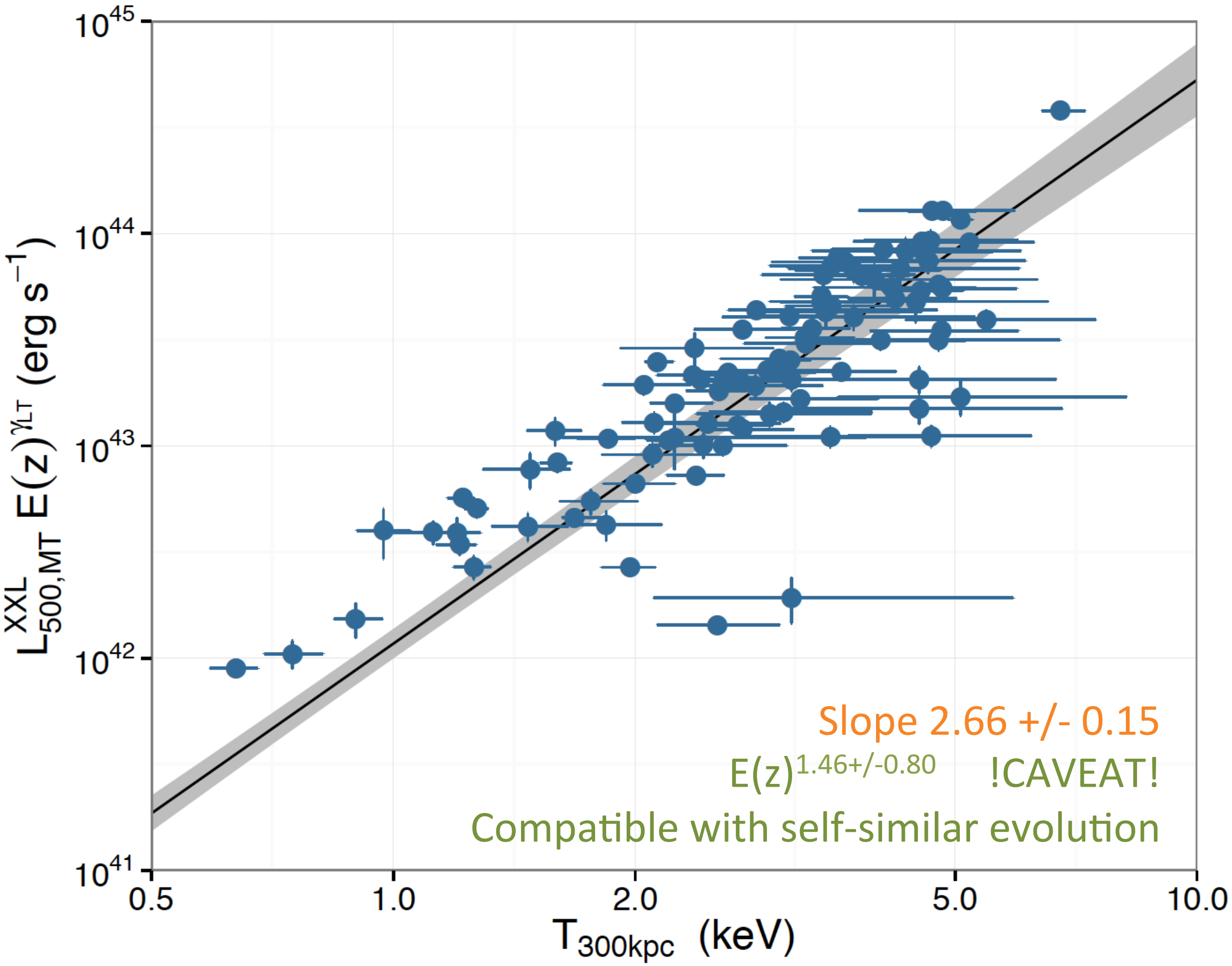
Cluster mass range

XXL paper II : 100 brightest clusters *Pacaud et al, A&A 2106*



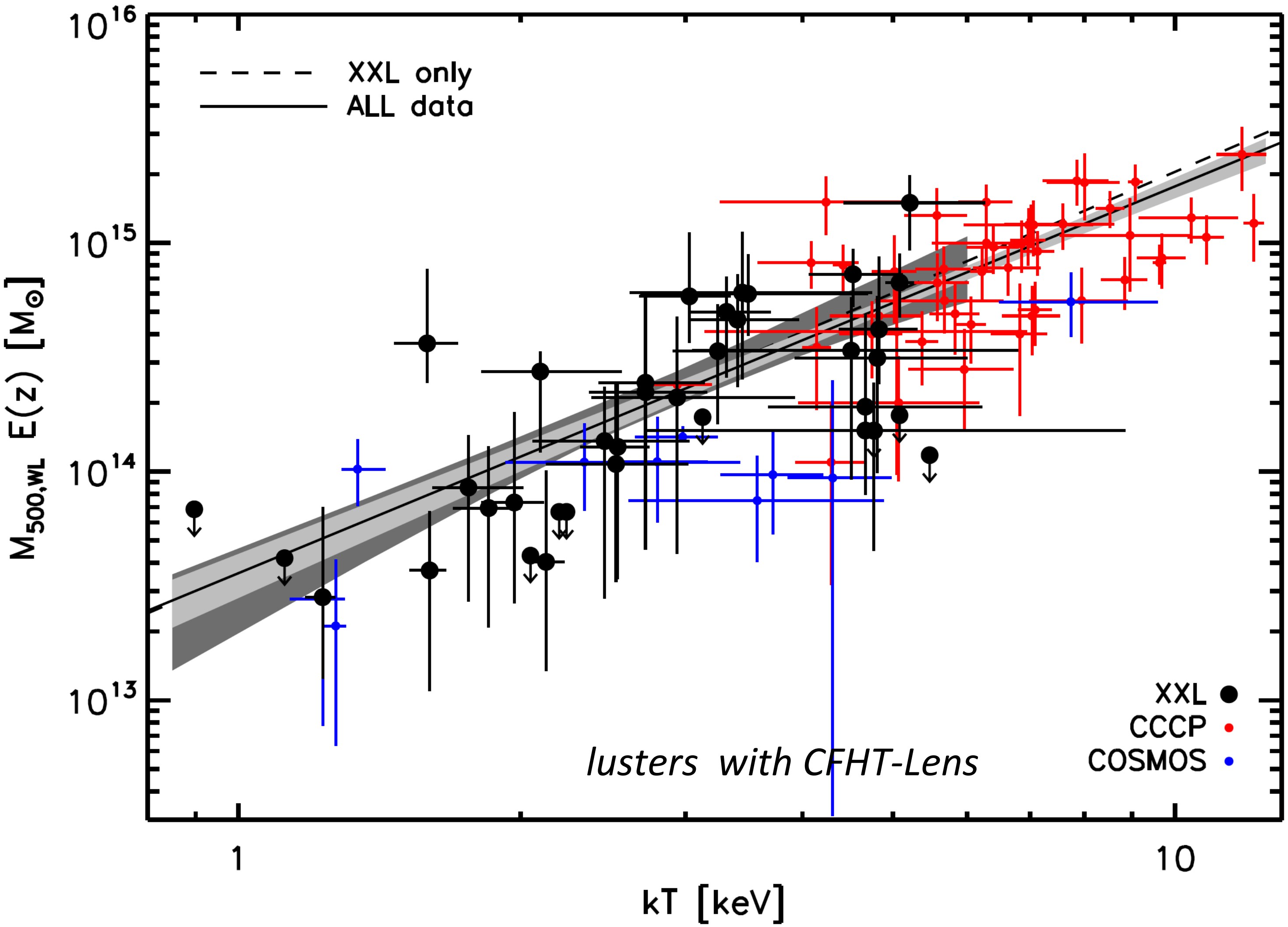
Cluster L-T relation

XXL paper III   Giles, Maughan et al 2016



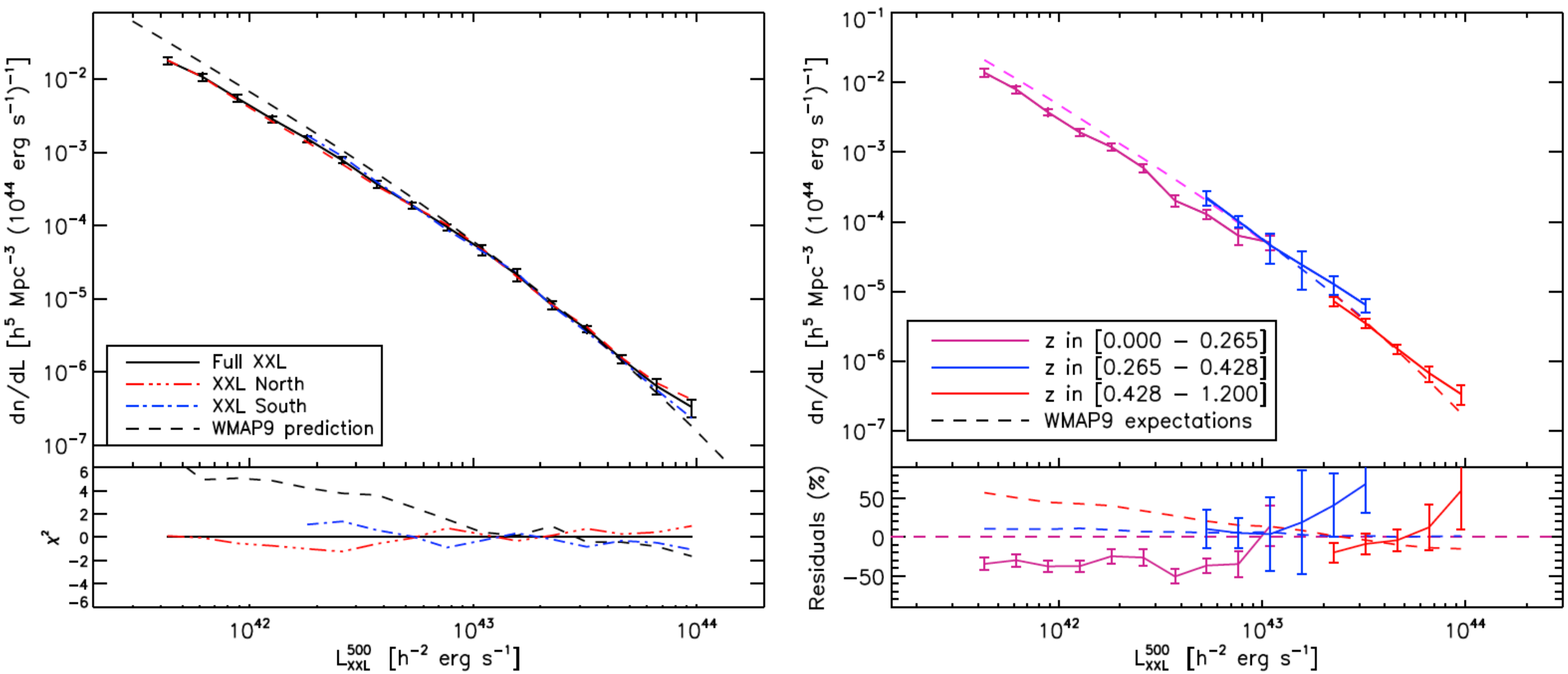
Cluster M-T relation

XXL paper IV   Lieu, Smith et al 2016



Cluster luminosity function

XXL paper II   Pacaud, Clerc et al 2016



No evolution for $F(L_x)$!

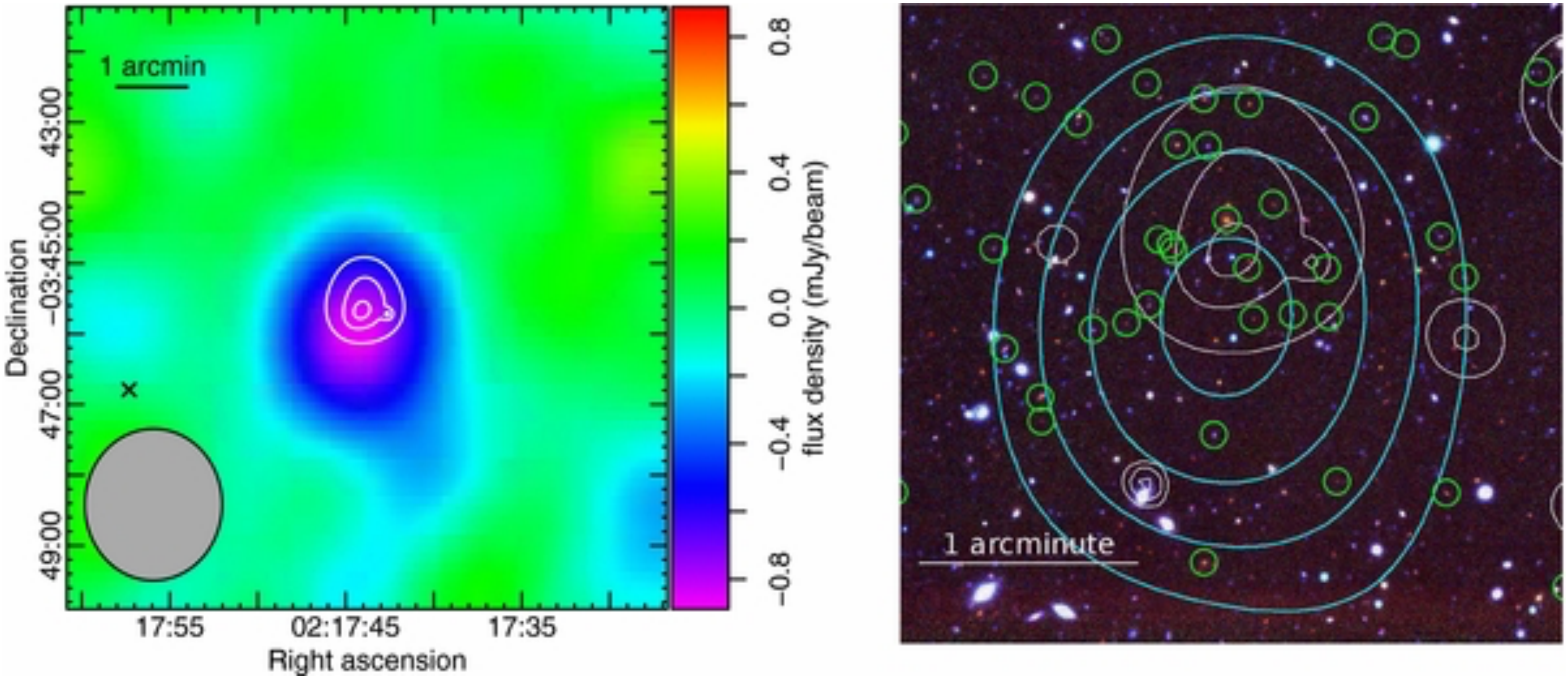
XLSSC-122

Mantz at al 2014

XXL paper V

z-phot~1.9

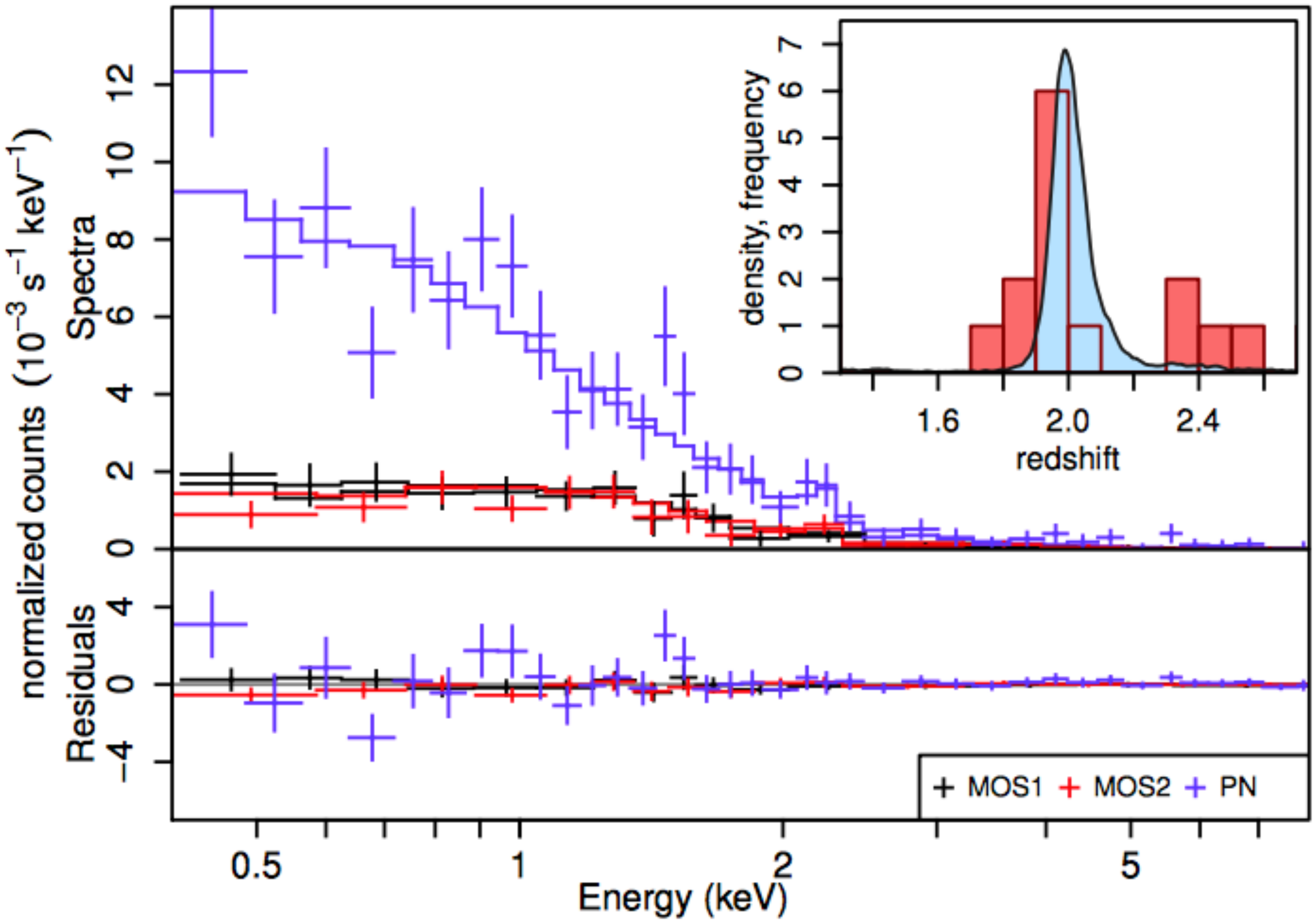
CARMA XMM CFHT



Redshift confirmation by deep XMM obs.

Mantz et al, 2017, A&A in press

XXL paper XVII



z = 2.0

kT =
5.0 ± 0.7 keV

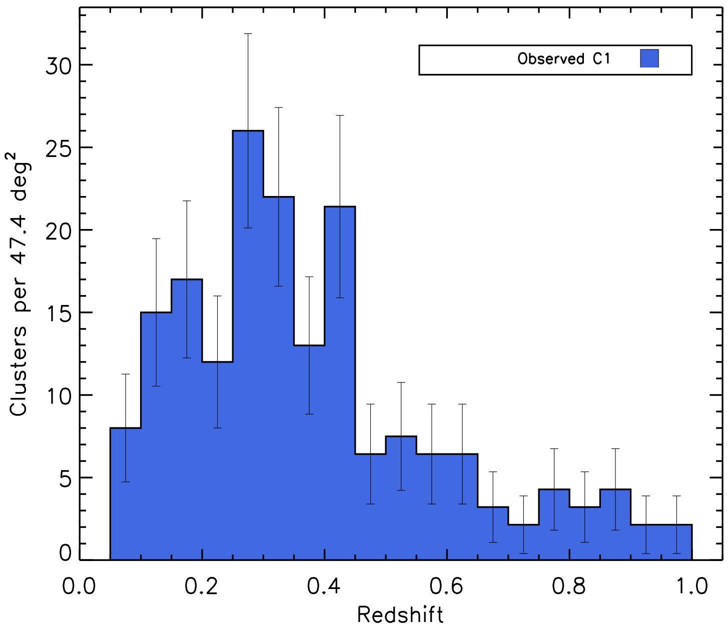
The SZ-X offset remains

Second series : A&A 2018
20 papers

- Catalogue of 365 clusters
- Catalogue of 20 000 AGN
- AGN and galaxy environement studies
- Cluster cosmological analysis

Cluster sample and observables

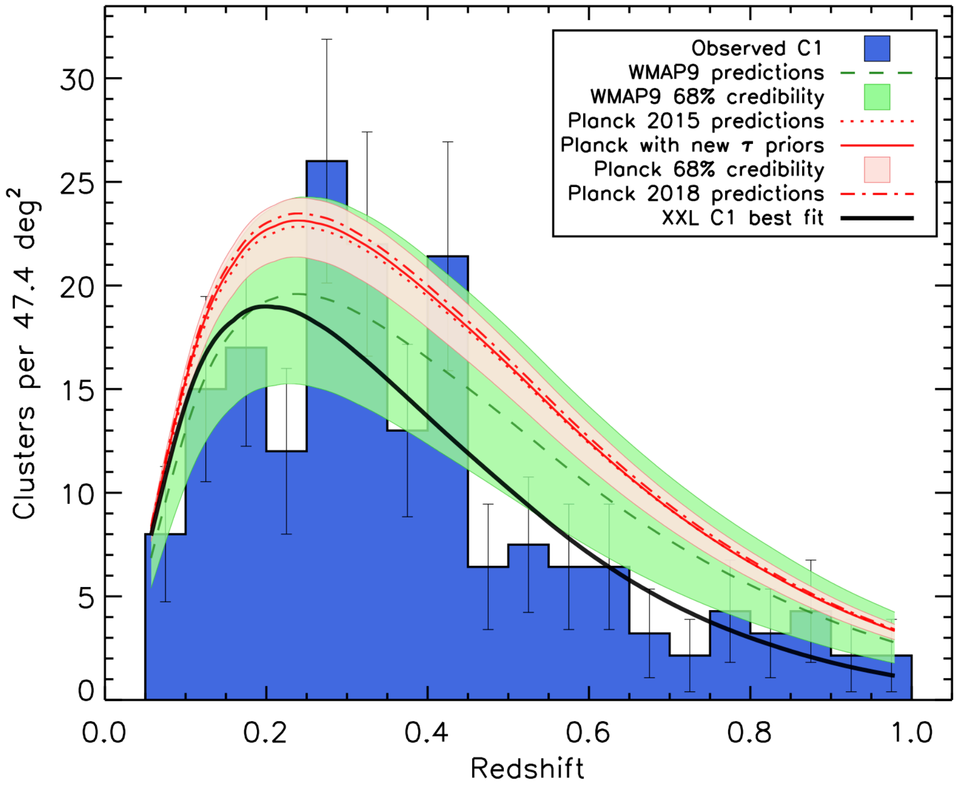
- Based on the XXL C1 sample of the XXL 2nd release (Adami et al. 2018)
- Cosmological constraints from the cluster density in redshift space (dn/dz), restricting to the redshift range [0.05-1.0] :
    - 178 clusters with measured redshifts
    - 5 clusters without a measured redshift – modeled as a 6.6% incompleteness for z>0.4



$M_{500} \sim 5\ 10^{13} – 3\ 10^{14}$

XXL paper XXV , Pacaud et al 2108

Comparison with CMB predictions



Using our best-fit scaling relations

<u>CMB overestimates the cluster density</u>

WMAP9 model : **+37%**

Planck15 model : **+ 61%**

Results very much comparable to the Planck SZ clusters !

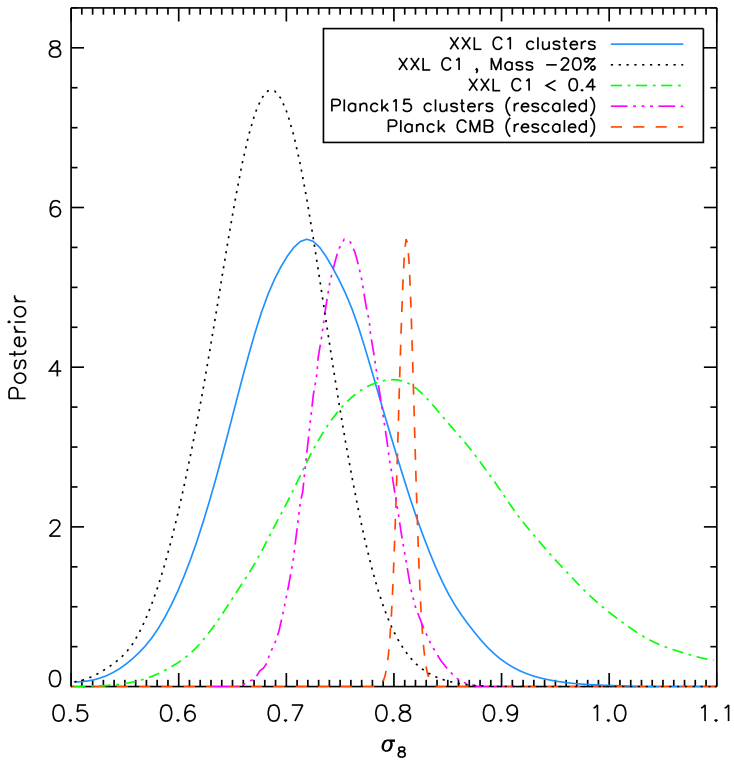
How significant is this discrepancy ?

Which cosmology do the XXL C1 clusters favour ?

XXL paper XXV , Pacaud et al 2108

Flat ΛCDM analysis

- We ran MCMC chains based the likelihood of the predicted redshift density.
- Priors on Ω_b and n_s included to stabilize the convergence.
- Additional weak prior on h = 0.7 +/- 0.1
- Cosmic variance accounted for as gaussian fluctuations on the total counts



A low value of $\boldsymbol{\sigma_8}$**=0.72±0.07** is prefered

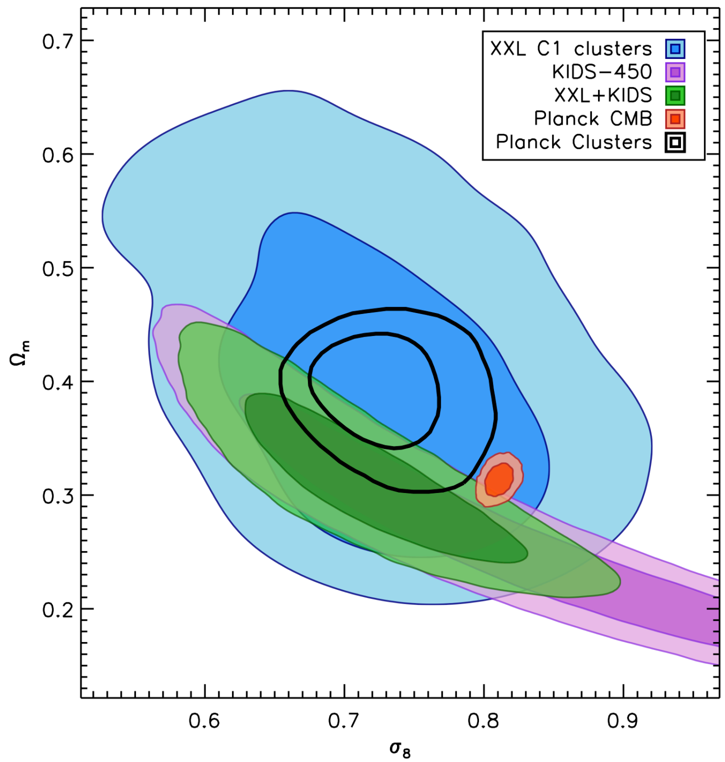
σ_8 driven low by the density at z>0.4

Results **comparable with Planck15** clusters but for a **different M_{500} and z regime**

XXL paper XXV , Pacaud et al 2108

XXL/CMB comparison in Flat ΛCDM

- Errors are still larger than the Planck SZ cluster analysis (using only redshift distribution, conservative assumptions on scaling laws and half as many clusters)
- Tension with Planck CMB remains unsignificant at this stage ($<0.1\sigma$)



XXL-C1 + KiDS-450 yield tighter constraints :

$\Omega_m=0.31\pm0.05$, $\sigma_8=0.72\pm0.06$

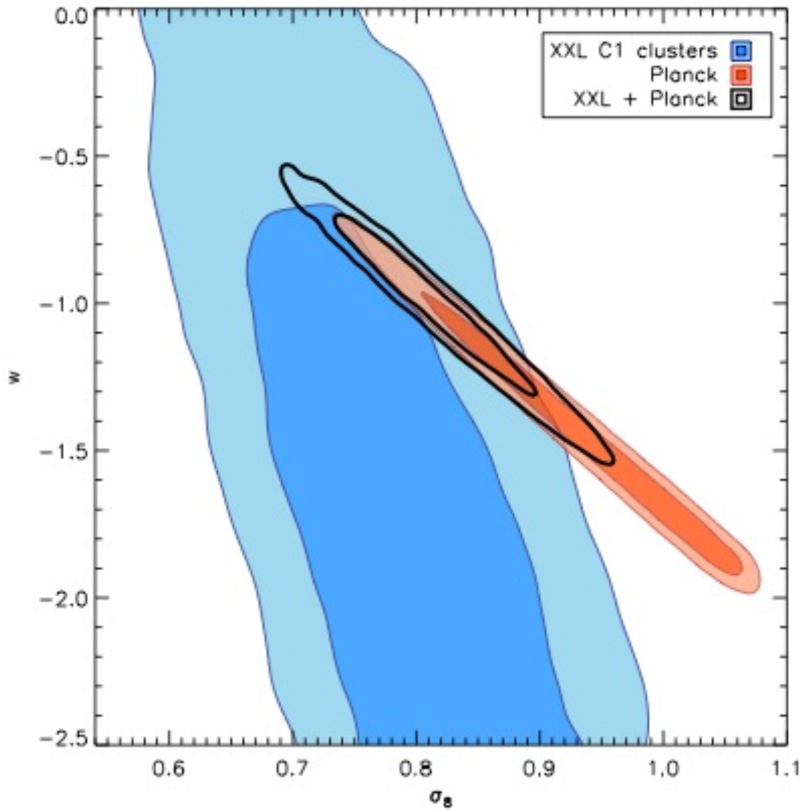
But tensions are similar that for KiDS alone (see Hildebrandt 2017)

Despite the low cluster density, everything seems compatible with Planck CMB results

XXL paper XXV , Pacaud et al 2108

wCDM constraints

- For dark energy models (w=Cst), Planck CMB constraints are weaker
- Even with the early analysis, XXL can already improve constraints on w
    - Planck 2015 : $w = -1.44 \pm 0.3$
    - **Planck + XXL :** $\boldsymbol{w = -1.02 \pm 0.2}$
- Still no significant tension ($\sim 0.5\sigma$), despite best fit offsets
- The combination of clusters and CMB disfavours phantom DE models



XXL paper XXV , Pacaud et al 2108

The 3D cluster-cluster ξ

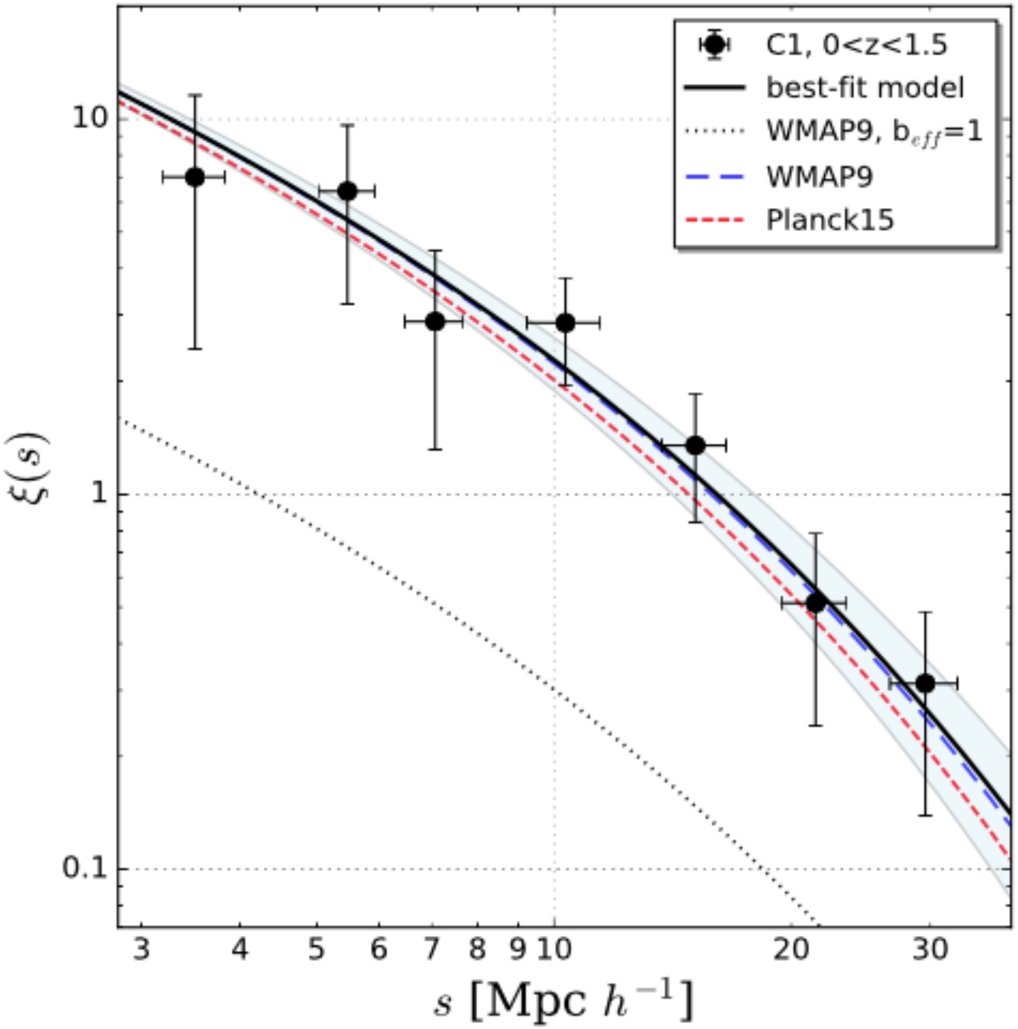


Fig. 3. Redshift-space 2PCF of the C1 XXL clusters at $z < 1.5$ (black dots) compared to the best-fit model, i.e. the median of the MCMC posterior distribution (black solid line). The shaded area shows the 68% uncertainty on the posterior median. The derived best-fit model correlation length is $s_0 = 16 \pm 2\, h^{-1}$ Mpc.

XXL paper XVI , Marulli et al 2018

NOW:
Inventory of the systemactic errors

- Accuracy of the mass calibration
- Average cluster shape (β = 2/3)   (sel. funct.)
- Effect of ‘peaked’ clusters (sel. funct.)
- Scatter in the scaling relations
- Uncertainties in the theoretical mass function

➔ Will be adressed in the final analysis with the complete cluster sample (~400 objects) along with numerical simulations

3. X-ray cluster forward cosmology modelling

Clerc et al 2012
Pierre et al 2017
Valotti et al 2018

X-ray cluster cosmology

- **Old route:**

Flux, Temp => Mass => dn/dM/z => compare with theory

Masses - and scaling relations - must be computed for each tested cosmology

- **Quick way:**

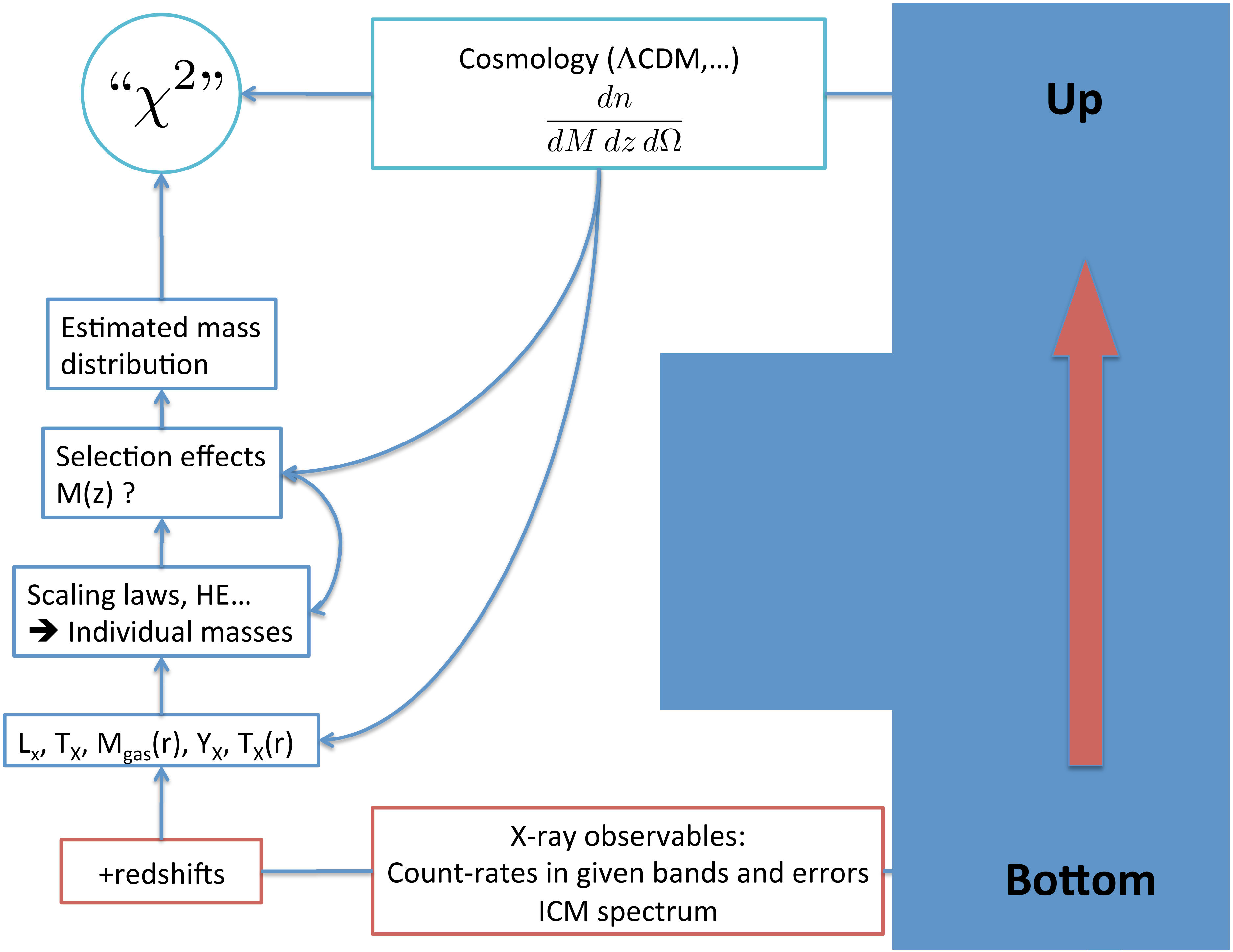
Work in directly in the observed parameter space

➔ Predicted X-ray colour-magnitude diagrams

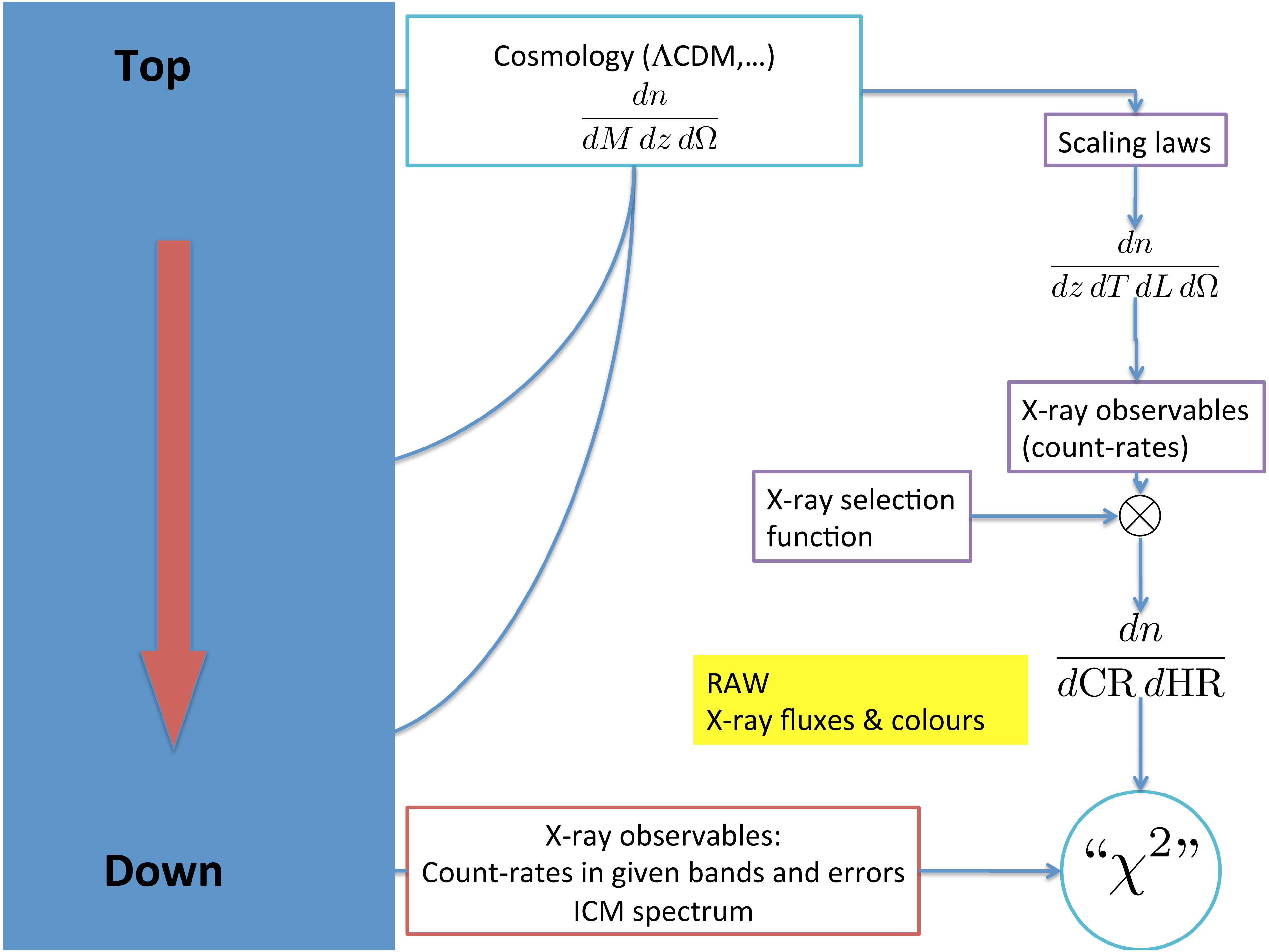
Clerc et al 2012, Pierre et al 2017, Valotti et al 2017

Fit simultaneously:

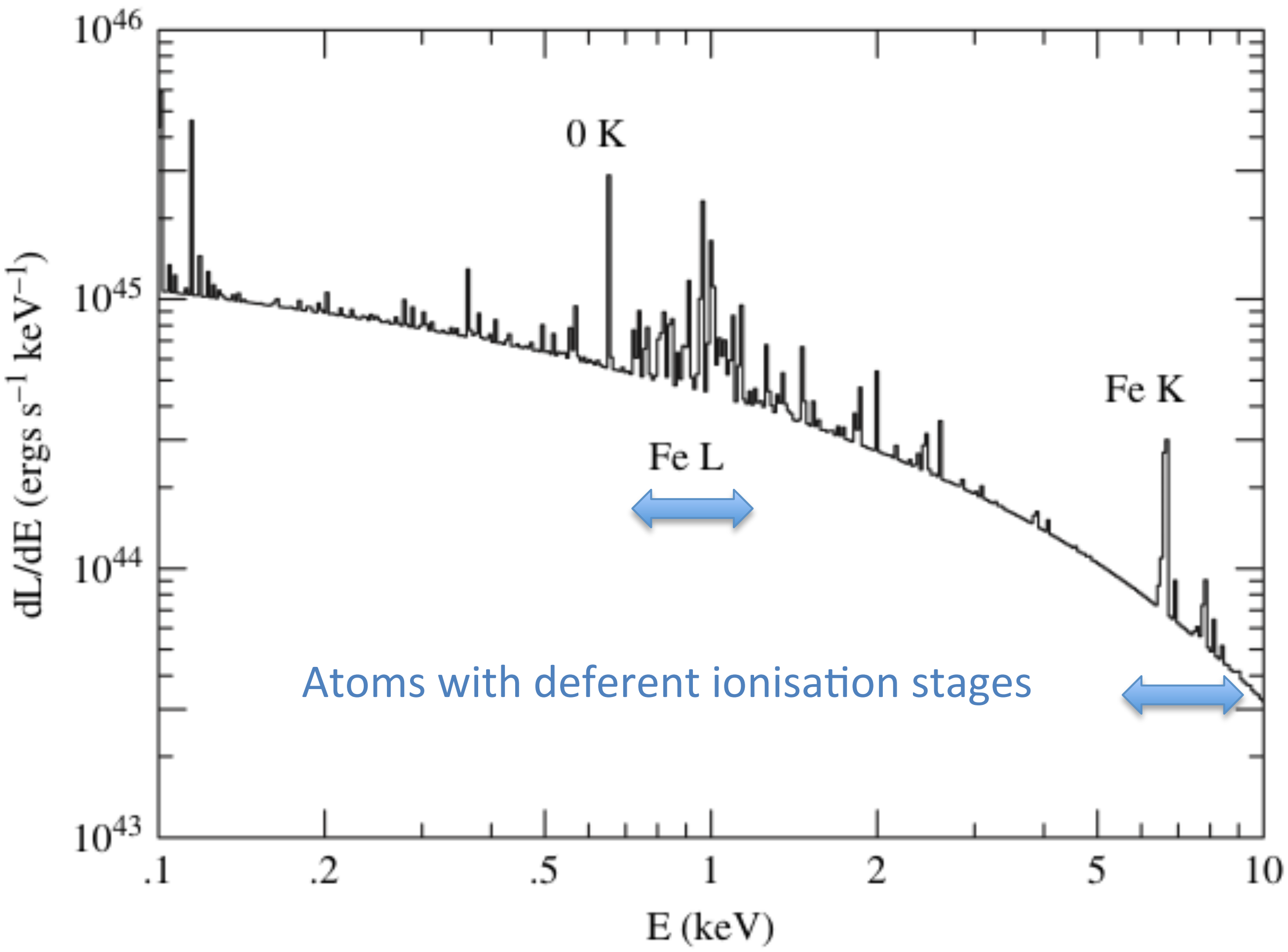
cosmology - cluster physics & evolution - selection effects



"χ^2"
Cosmology (ΛCDM,...)
$\frac{dn}{dM\,dz\,d\Omega}$
Up
Estimated mass distribution
Selection effects M(z) ?
Scaling laws, HE…
➔ Individual masses
L_X, T_X, $M_{gas}(r)$, Y_X, $T_X(r)$
+redshifts
X-ray observables:
Count-rates in given bands and errors
ICM spectrum
Bottom


Top
Down
Cosmology (ΛCDM,...)
$\frac{dn}{dM\,dz\,d\Omega}$
Scaling laws
$\frac{dn}{dz\,dT\,dL\,d\Omega}$
X-ray observables (count-rates)
X-ray selection function
$\frac{dn}{d\mathrm{CR}\,d\mathrm{HR}}$
RAW
X-ray fluxes & colours
X-ray observables:
Count-rates in given bands and errors
ICM spectrum
"χ^2"

X-ray emission complex



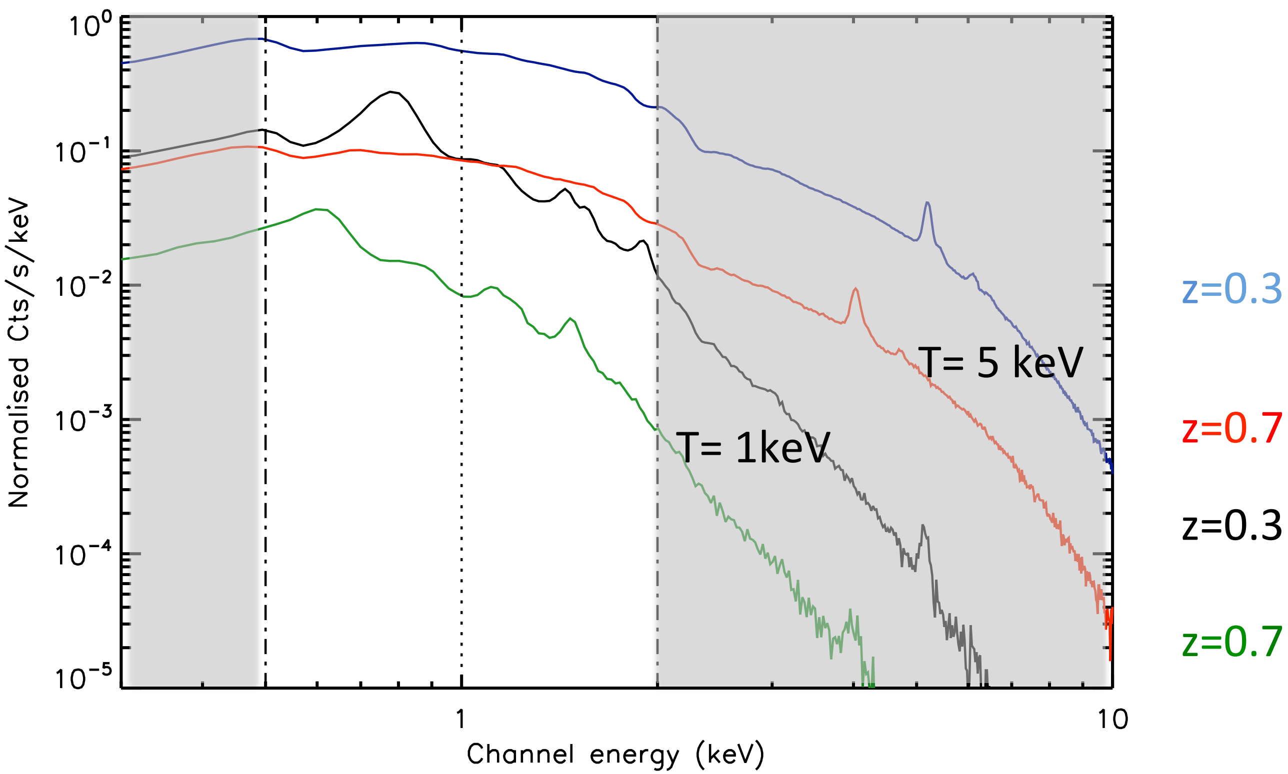
Cluster spectrum = bremsstrahlung continuum + emission lines

Example :
Iron
Atomic number: 26

Stable isotopes
54
56 92%
57
58

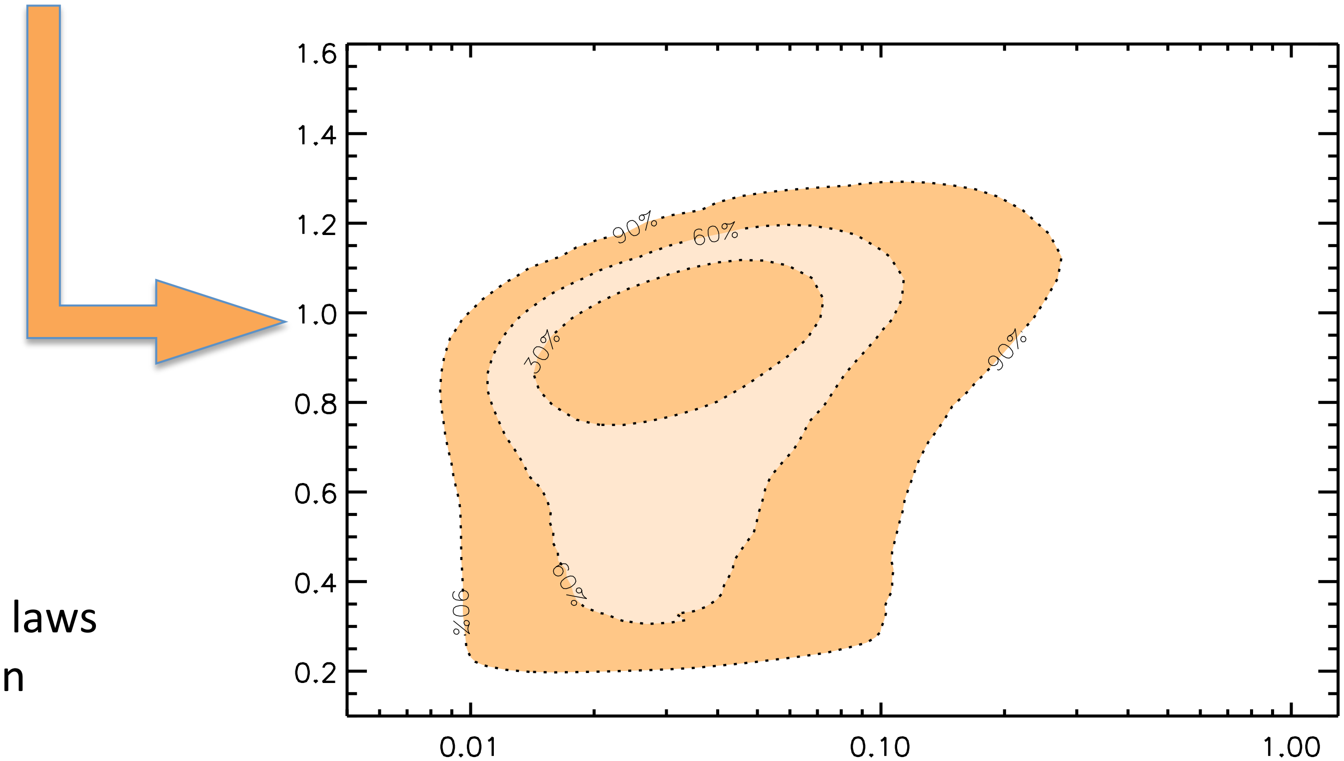
Raw XMM cluster spectra

- CR in [0.5-2] keV ~ Magnitude
- HR = [1-2]/[0.5-1] ~ Colour



The CR-HR distribution

[1-2] keV / [0.5-1] keV hardness ratio (HR)



[0.5-2] keV Count-rate (CR, cts/s)

Diagram computed for :

WMAP5 cosmology

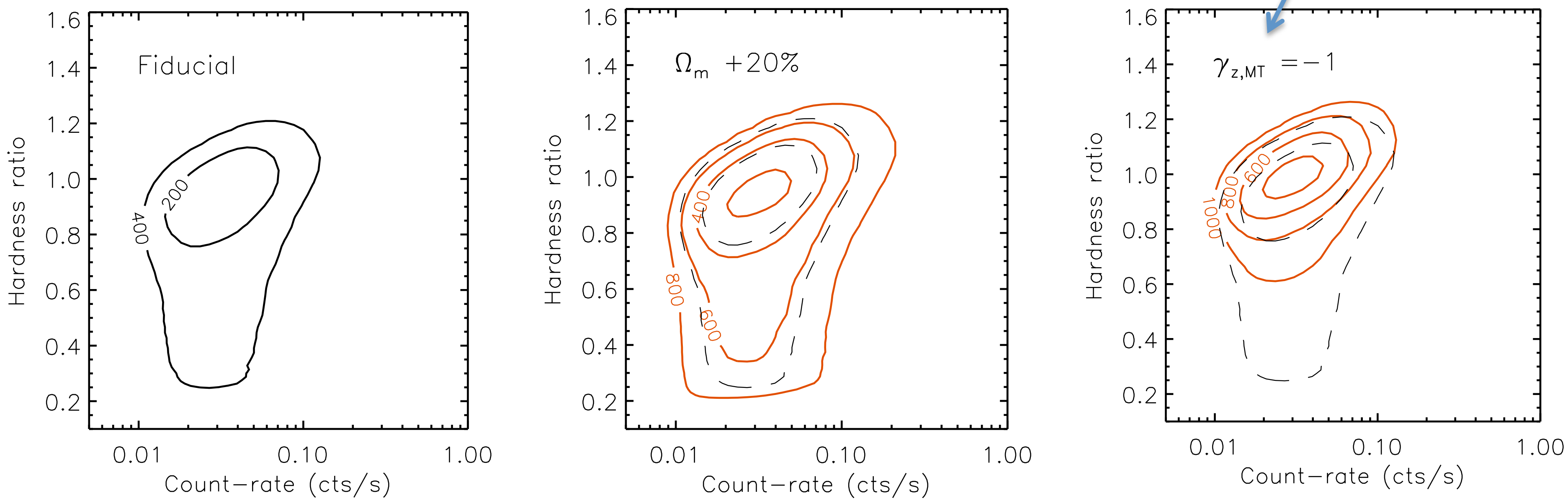
C1 selection

Local cluster scaling laws

Self-similar evolution

100 deg^2

Non self-similar evolution



The selected
X-ray observable cluster parameters

1. XMM count-rate in [0.5-2] keV
2. XMM 'hardness ratio' : CR[1-2] / CR[0.5-1]
3. Apparent size : core radius of the β-profile
4. Redshift

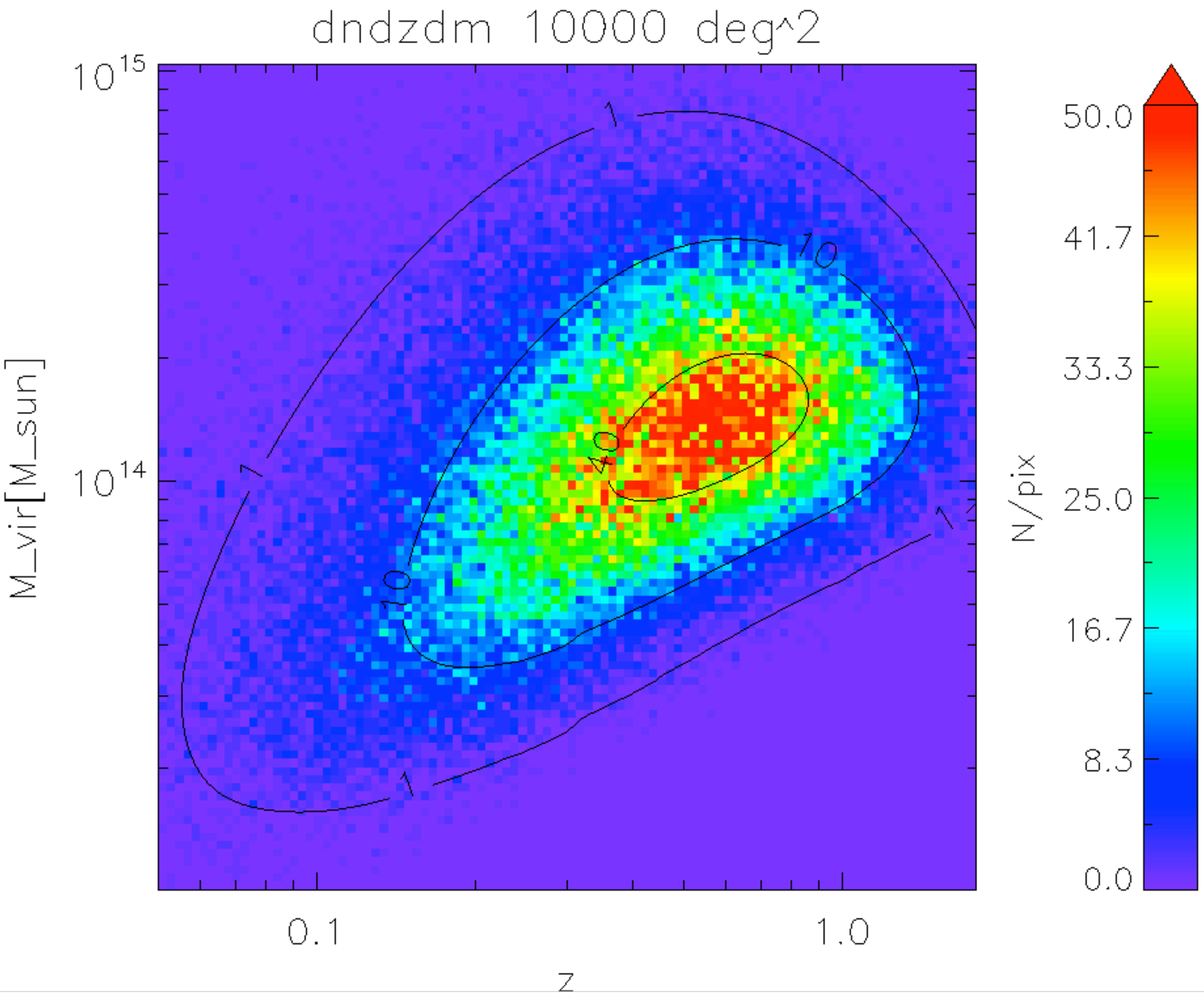
- Useful: the selection is expressed in terms of 1+3

$\Rightarrow$ We project the predicted [M-z] space into the 4D [CR-HR-Rc-z] space for any cosmology + scaling relations

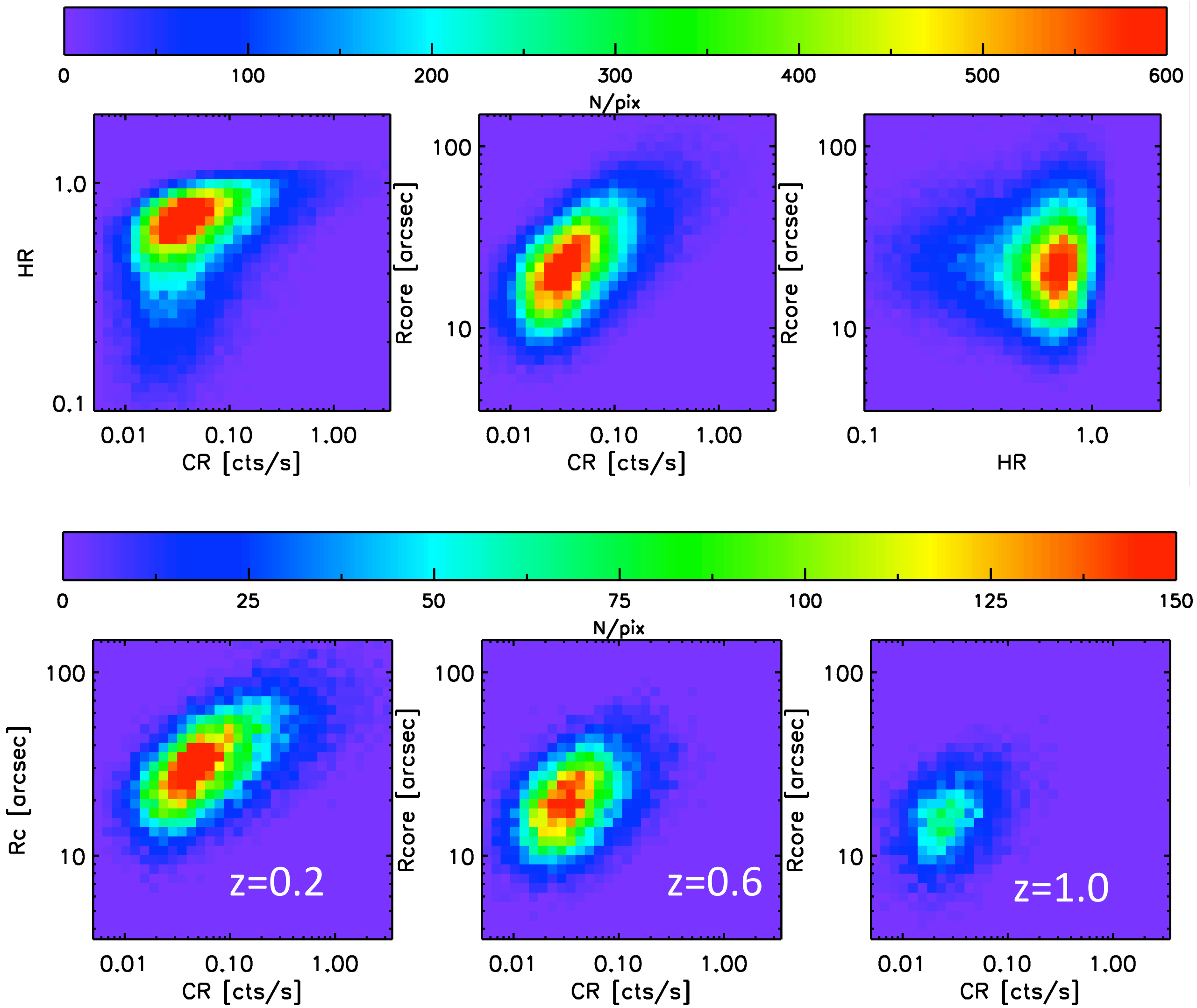
$\Rightarrow$ Fit to the observed 4D diagram

The M-z plane (10,000 deg^2)

for the selected C1 clusters



Projection into the 4D observational space



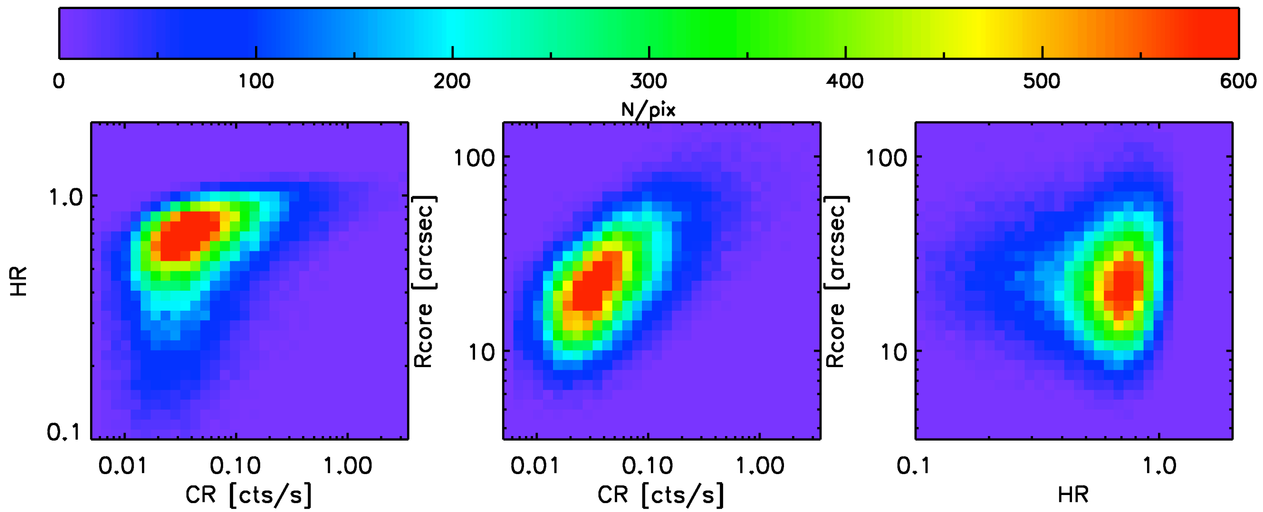
CR, HR, Rc

integrated over z

Rc-CR
intergated over HR

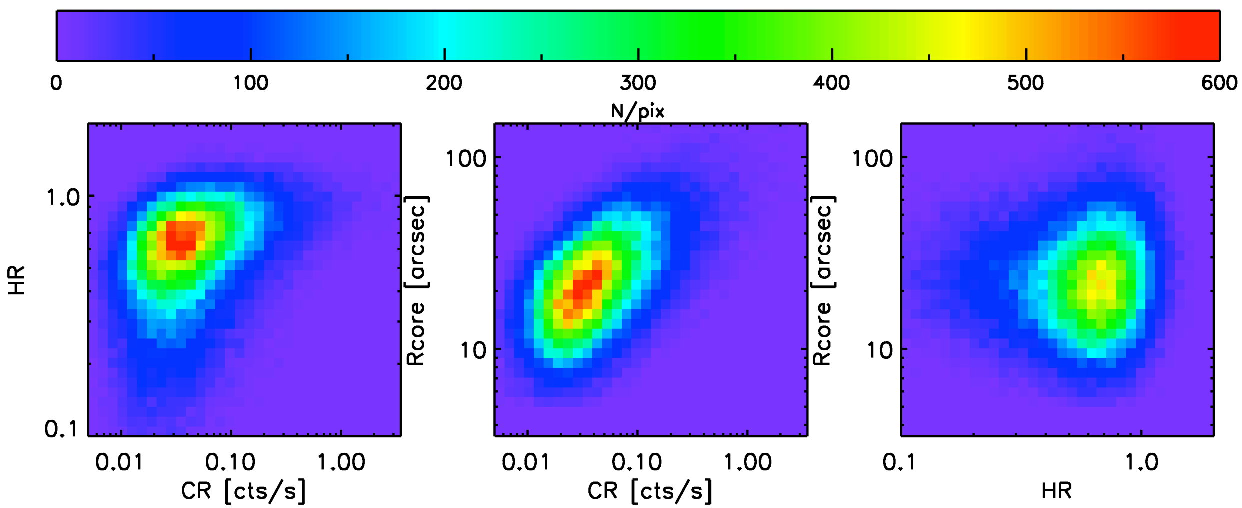
3 z-slices

Easy: introducing error measurements



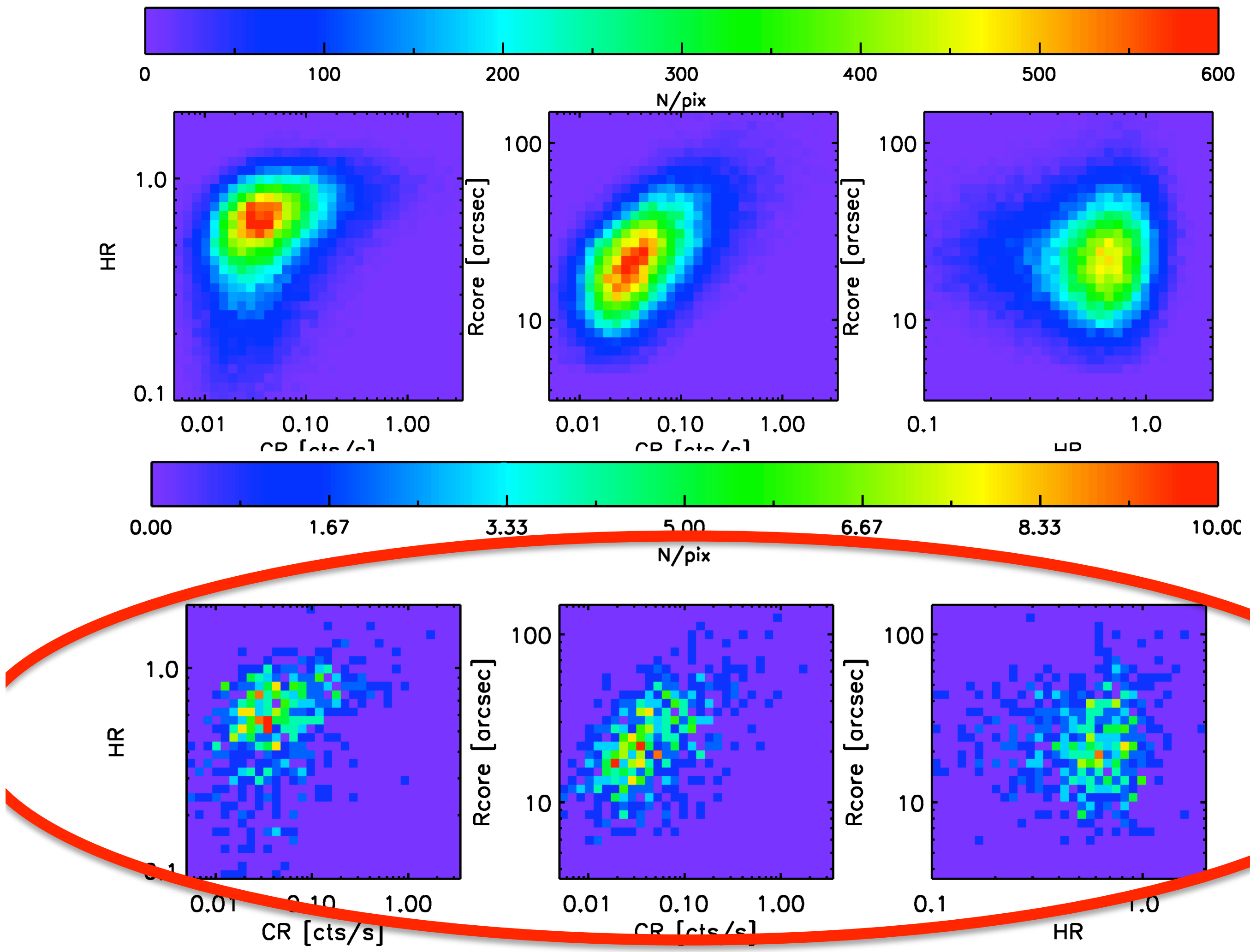
CR, HR, Rc

integrated over z



+ 20% err
on all parameters

Reducing the area



10,000 deg^2

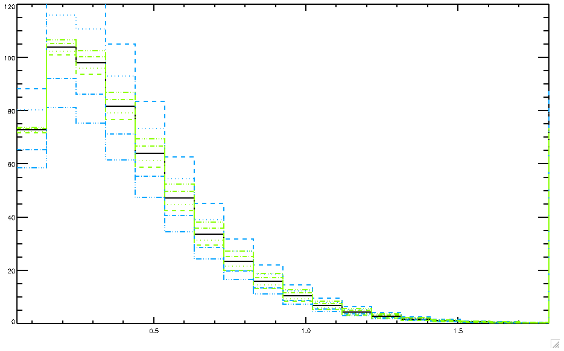
This is what we fit in 4D

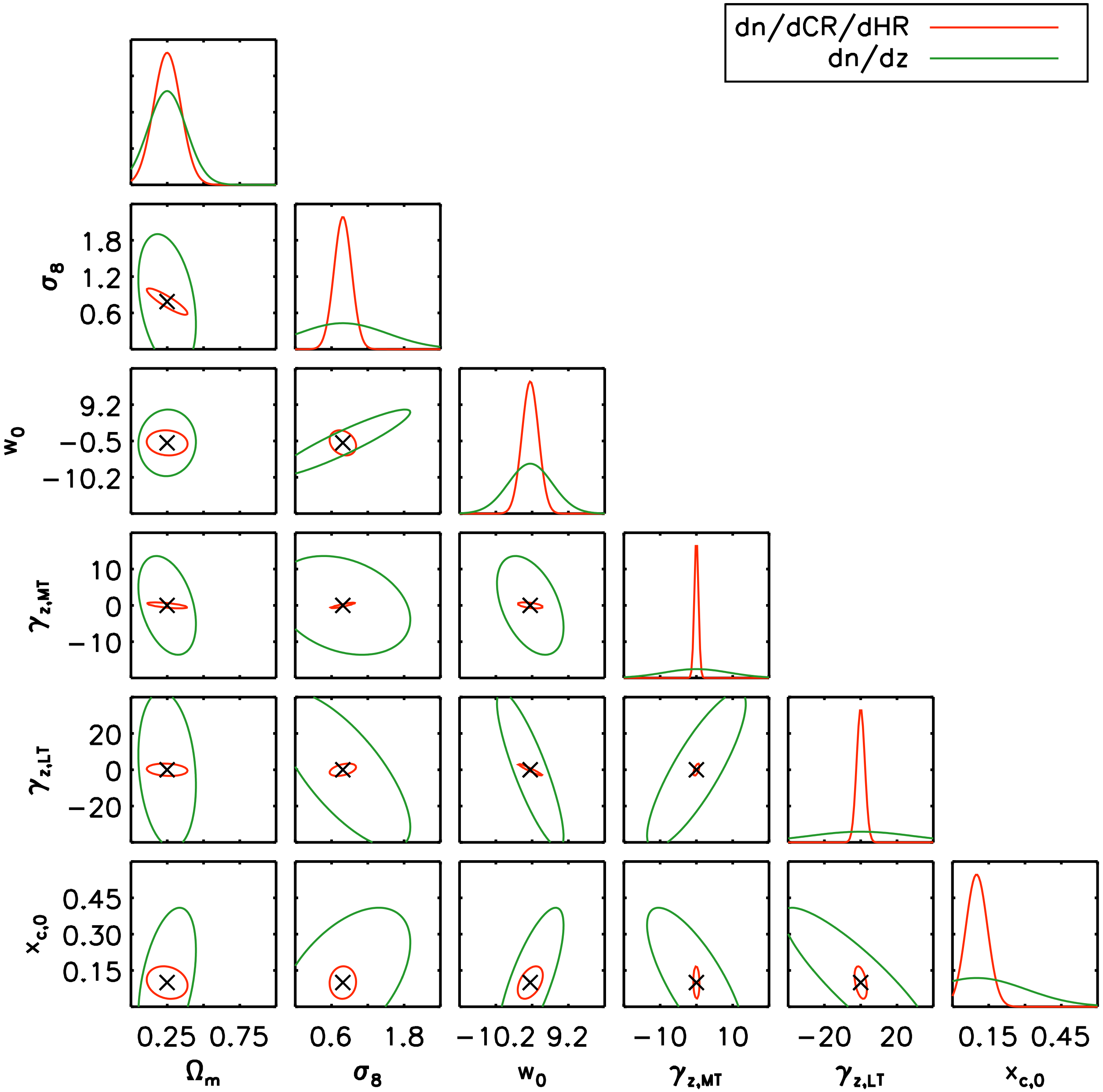
100 deg^2

Comparison with the standard approaches

(Fisher analysis)

1) CR-HR vs dn/dz

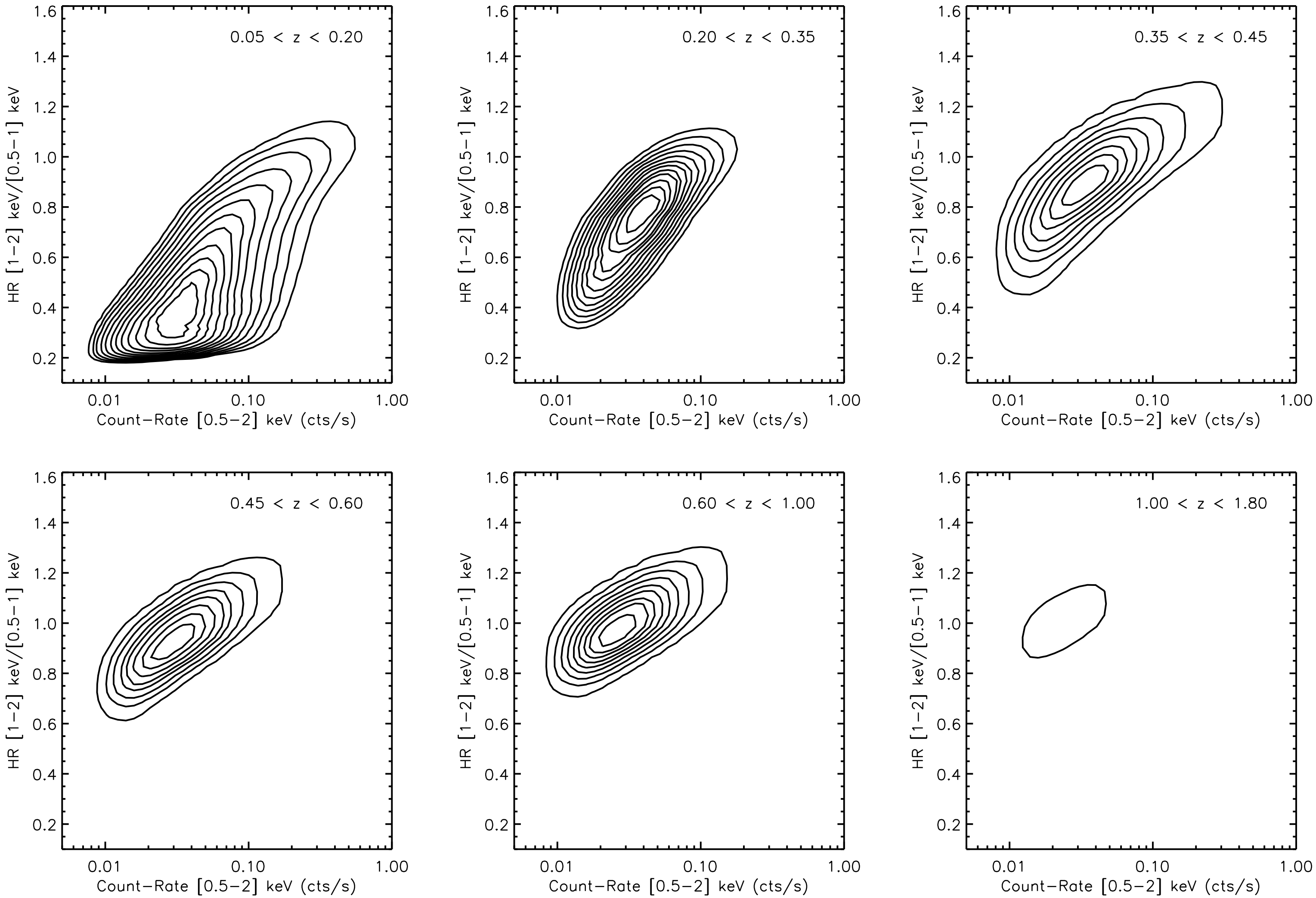




Does not need redshifts!

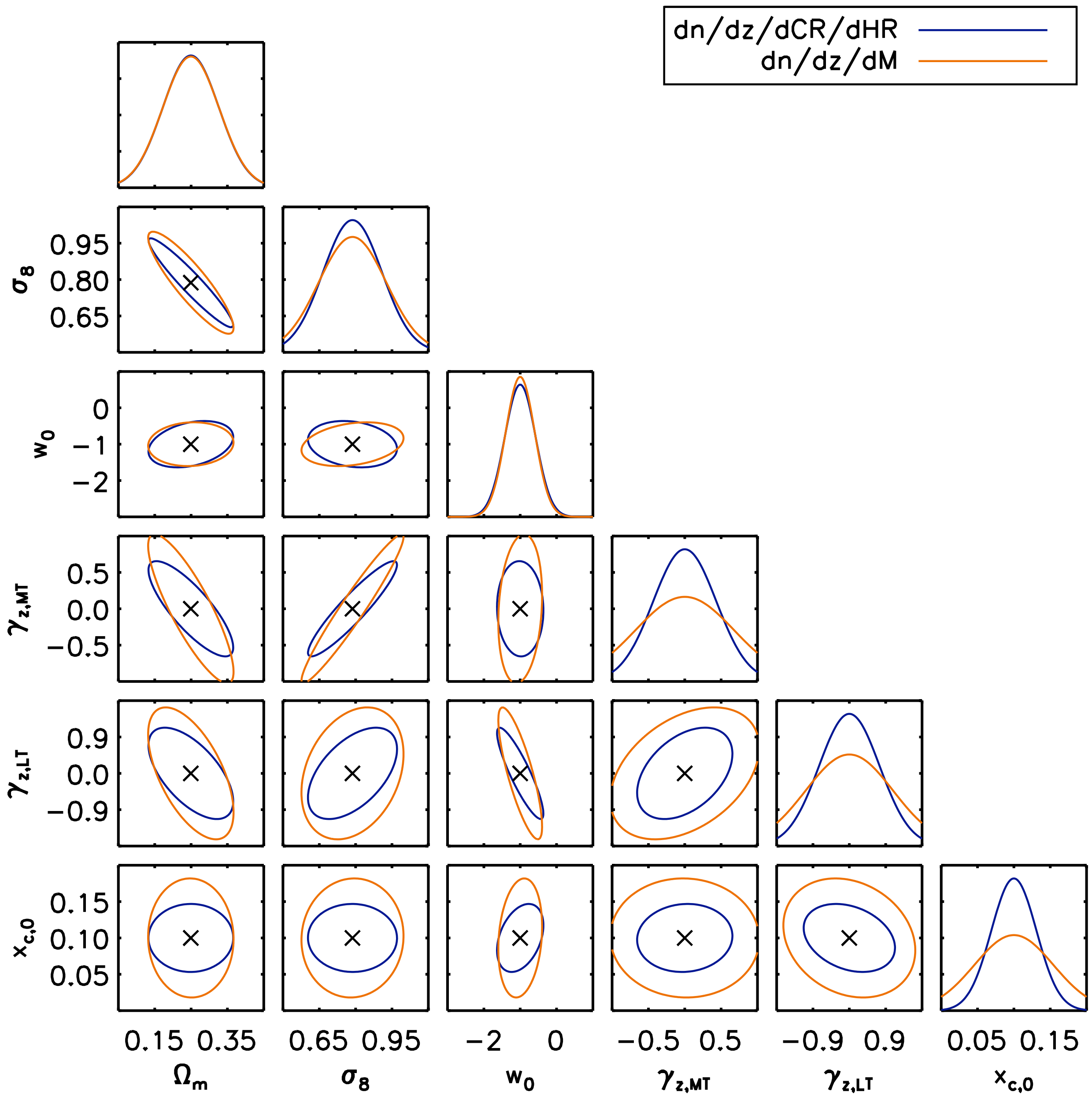
Adding redshifts

➔ 4th dimension to the diagram



Adding redshifts
(photo-z are sufficient)

2) CR-HR-dz
vs
N(M, z)



Processing of 700 deg^2
~ 9000 fake XMM observations
(Aardvark simulations)

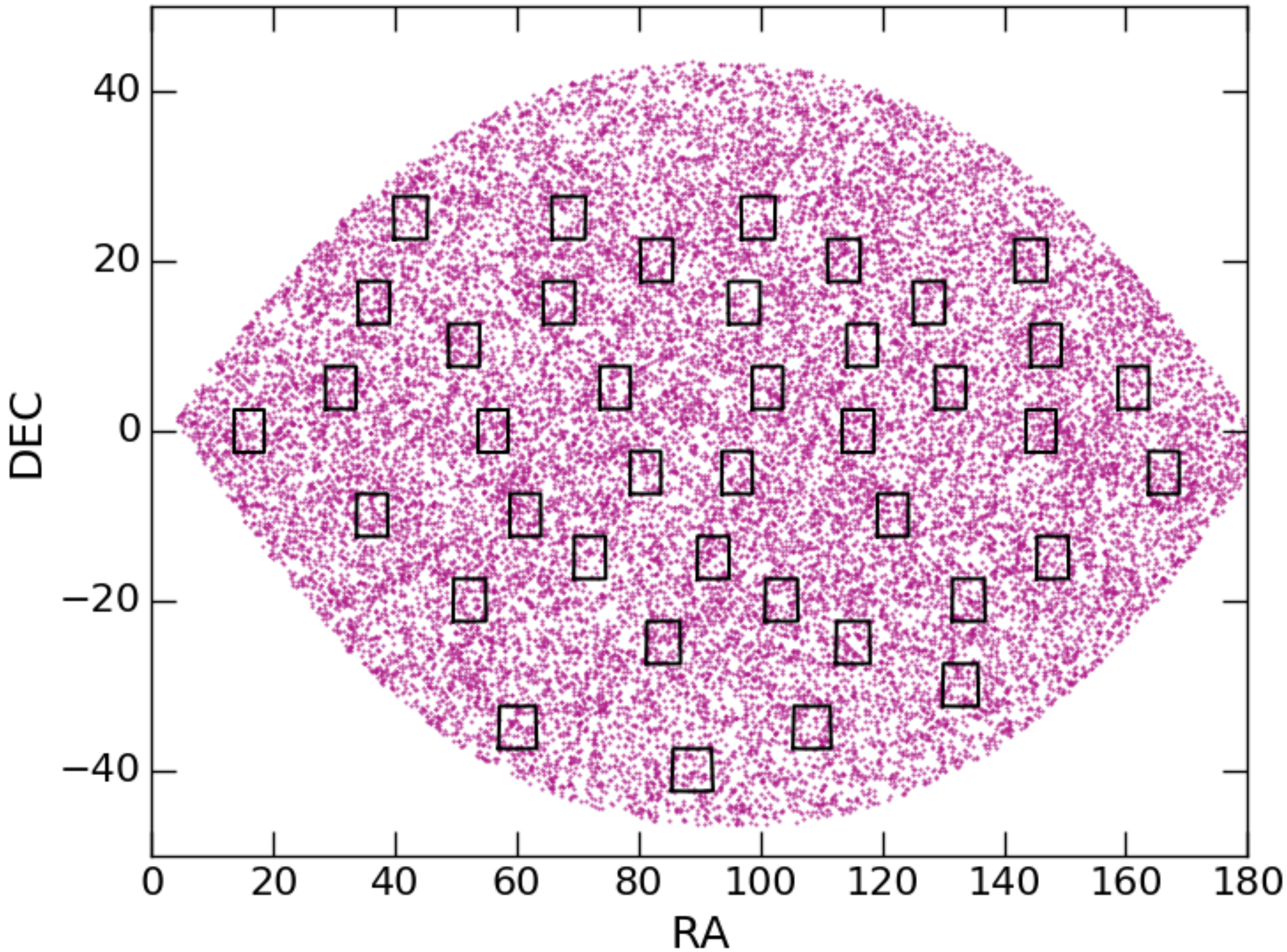
- Selection of the C1 clusters
- Construction of te CR-HR-Rc-z diagrams

- Analyses   with +/- free parameters
  - MCMC
  - Amoeba
  - Check Fisher analysis

The 700 deg^2 simulations

DM: Aardwark

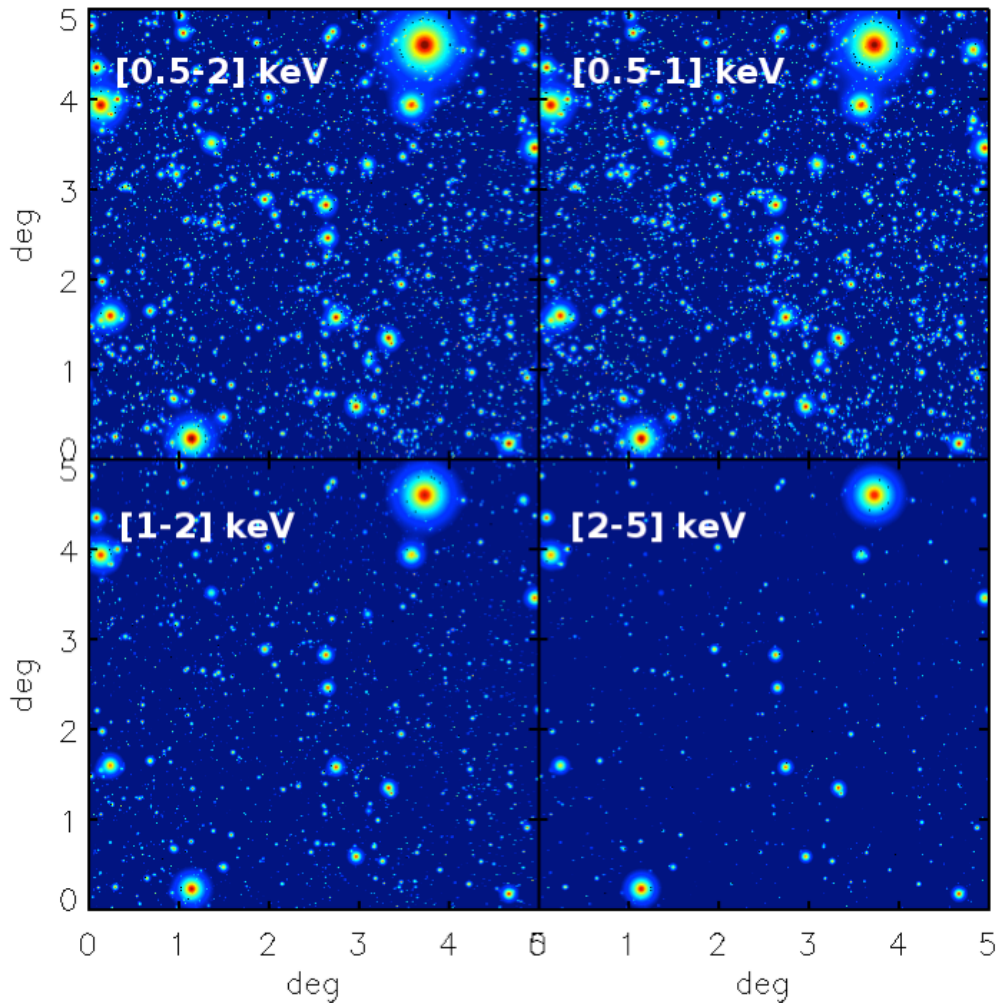
39 x 25deg^2 fields



Emissivity map: one 5x5 deg^2 field

Gas painting : A. Farahi, G. Evrard (Michigan)

X-ray image: L. Faccioli (Saclay)



A few results (a)

ID	Observable combination	Fitted parameters	$<p>$ MCMC	*best-10* Amoeba	Toy catalogues[x10] Amoeba	Fisher analysis
A1	CR-HR$_1$	Ω_m	$0.249^{+0.014}_{-0.019}$	0.245	0.234±0.019	0.23 ± 0.013
		σ_8	0.823±0.014	0.825	0.830±0.018	0.83 ± 0.012
		$x_{c,0}$	$0.285^{+0.033}_{-0.034}$	0.290	0.232±0.024	0.24 ± 0.031
		w_0	$-1.117^{+0.212}_{-0.218}$	-1.037	-1.204±0.296	-1.00 ± 0.246
A2	CR-HR$_1$-r$_c$	Ω_m	0.222±0.010	0.220	0.226±0.013	0.23 ±0.012
		σ_8	$0.846^{+0.011}_{-0.010}$	0.846	0.832±0.015	0.83 ± 0.011
		$x_{c,0}$	$0.240^{+0.011}_{-0.013}$	0.247	0.248±0.014	0.24 ± 0.017
		w_0	$-1.009^{+0.153}_{-0.144}$	-0.969	-0.980±0.198	-1.00 ± 0.21
A3	z−CR-HR$_1$-r$_c$	Ω_m	0.219 ±0.005	0.218	0.229±0.004	0.23 ± 0.005
		σ_8	0.852±0.009	0.854	0.832±0.009	0.83 ± 0.009
		$x_{c,0}$	0.240±0.003	0.239	0.240±0.003	0.24 ± 0.003
		w_0	$-0.990^{+0.029}_{-0.027}$	-0.990	-1.041 ±0.033	-1.00 ± 0.032
A4	CR-HR$_1$-HR$_2$-r$_c$	Ω_m	$0.228^{+0.008}_{-0.009}$	0.227	0.226± 0.013	0.23 ± 0.008
		σ_8	$0.844^{+0.008}_{-0.009}$	0.843	0.833 ± 0.012	0.83 ± 0.010
		$x_{c,0}$	$0.226^{+0.008}_{-0.009}$	0.229	0.247 ± 0.012	0.24 ± 0.009
		w_0	$-1.166^{+0.148}_{-0.146}$	-1.121	-0.975 ± 0.195	-1.00 ± 0.113

Table 6. Summary table for the cosmological analysis of the Aardvark C1 CLEAN catalogue over 711 deg^2. The first column gives the run ID. The second column lists the signal variables used in the fit and the third one, the subset of free parameters. The fourth and fifth columns show the results from the MCMC analysis at the 68% confidence level and from the Amoeba best-10 fit, respectively. The sixth column shows the results obtained by running Amoeba over 10 toy catalogues of 700 deg^2, for which the mass function is taken to be Tinker's. The last column shows the Fisher analysis forecast for 1σ errors .

A few results (b)

Parameter	MCMC fit	Amoeba *best-10*	Fisher analysis
Ω_m	0.228 ±0.020	0.207	0.23 ±0.025
σ_8	0.876 ±0.073	0.814	0.83 ±0.156
w_0	-0.981 ±0.053	-0.940	-1.00 ±0.065
x_c	0.249 ±0.016	0.258	0.24 ±0.034
σ_{x_c}	0.500 ±0.019	0.504	0.50 ±0.023
α_{MT}	1.538 ±0.096	1.453	1.49 ±0.169
γ_{MT}	0.268 ±0.136	0.162	0.00 ±0.244
C^{MT}	0.502 ±0.140	0.490	0.46 ±0.297
σ_{MT}	0.258 ±0.133	0.112	0.10 ±0.206

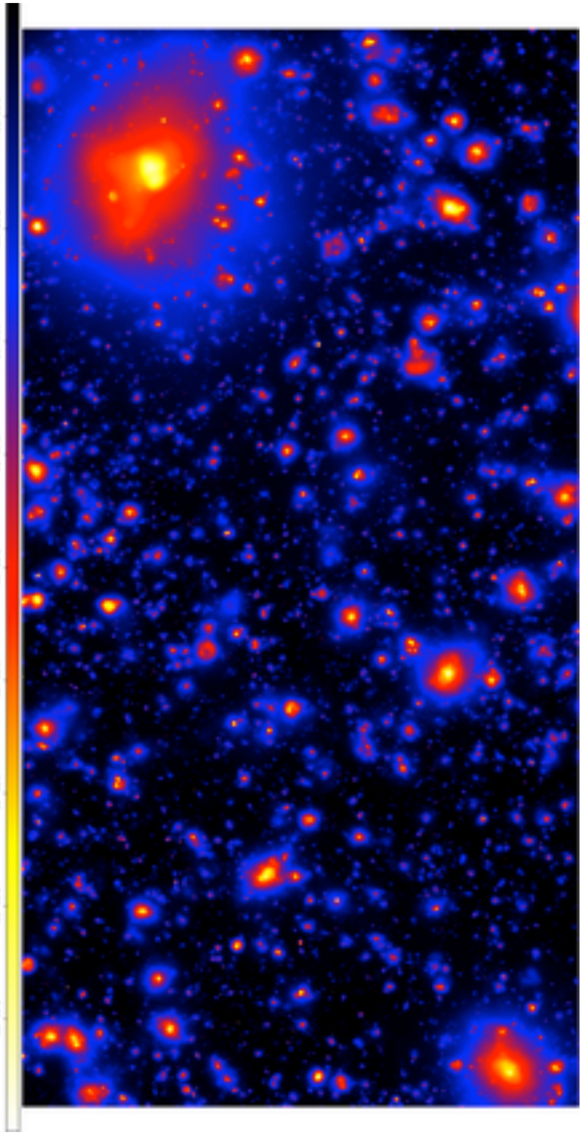
Table 7. Fit results (z–CR-HR-r_c) over the 711 deg^2 Aardvark C1 CLEAN catalogue when cosmological and cluster physics parameters are let free.

Next and final step before the full cosmological analysis

- Compute a more realistic selection function using hydrodynamical simulations
- In order to evaluate the systematic uncertainties
  - Cluster irregular shapes
  - Cooling flows
  - Physical AGN contamination

Cosmos-OWLS simulation

Le Brun, McCarthy et al 2014



1x2 deg^2 field

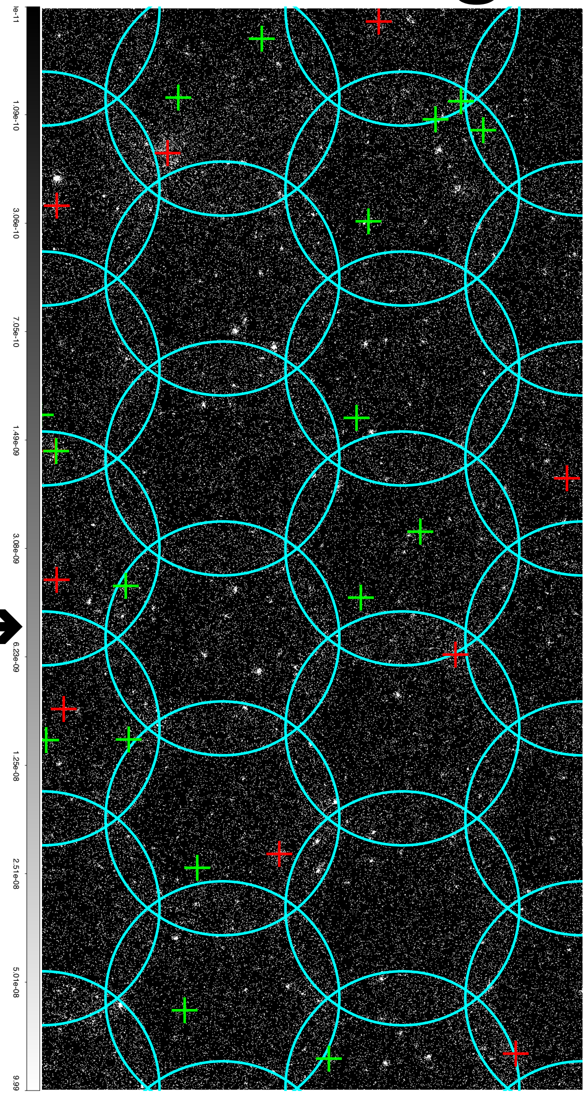
← Input = hot gas

Output = XMM photon image →

All instrumental effects and background components are taken into account

AGN are added

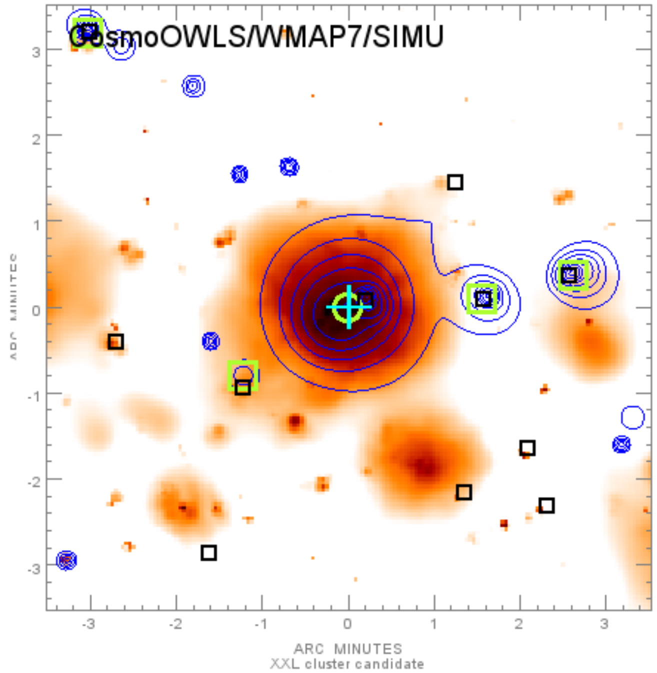
XMM image



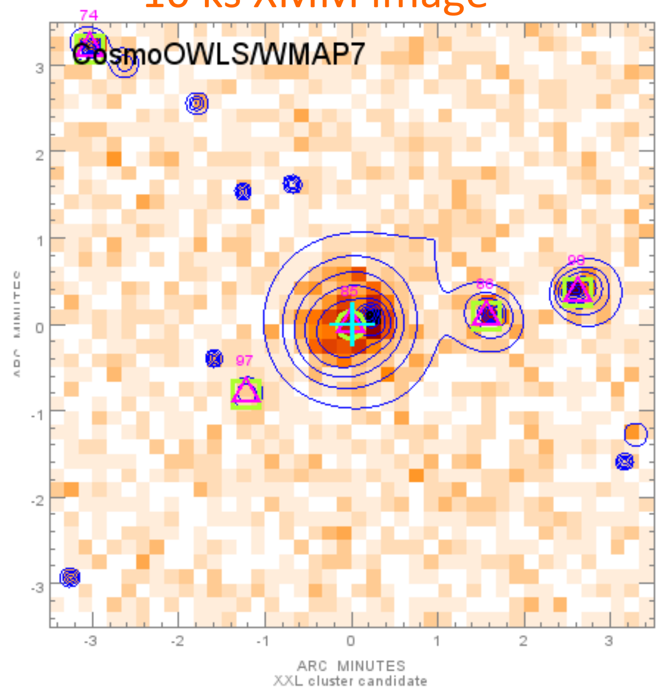
X-ray pipeline output

Cosmo-OWLS simulations, *Le Brun et al 2014*
AGN X-ray contribution, XXL paper XIX *Koulouridis et al 2018*

X-ray emissivity



10 ks XMM image



7'x7' image centered on a z = 0.95 cluster ; M_{500} = 3.5 10^{14}M
– the black squares are the in-situ simulated AGN

5. Summary and conclusion

Summary

- 50 deg2 - 500 clusters – 25 000 AGN
- A selection function exclusively based on observed parameters.
- The 2018 cosmological analysis shows a cluster deficit wrt CMB predictions.
- A new cosmological method based on the forward modelling of observables
- Stay tuned for the up-coming XXL 3rd release!

Next future

- A great deal of information is expected from the confrontation with hydrodynamical simulations

- At a later stage, simulations will allow us to by-pass the scaling-relation formalism (as well as the mass function) in the cosmological analysis of X-ray clusters.

→ results = cosmology + non gravitational energy inputs in the ICM

→ Implement CNN in the cosmological analysis