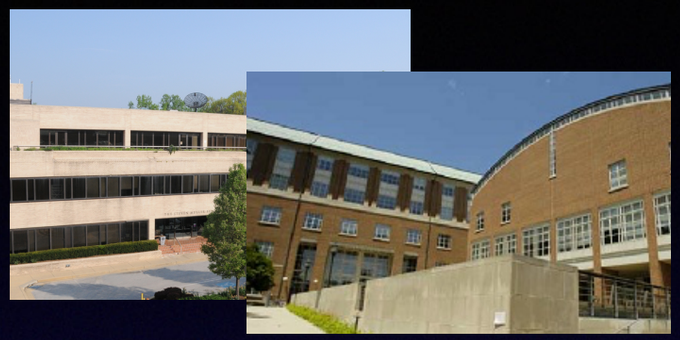
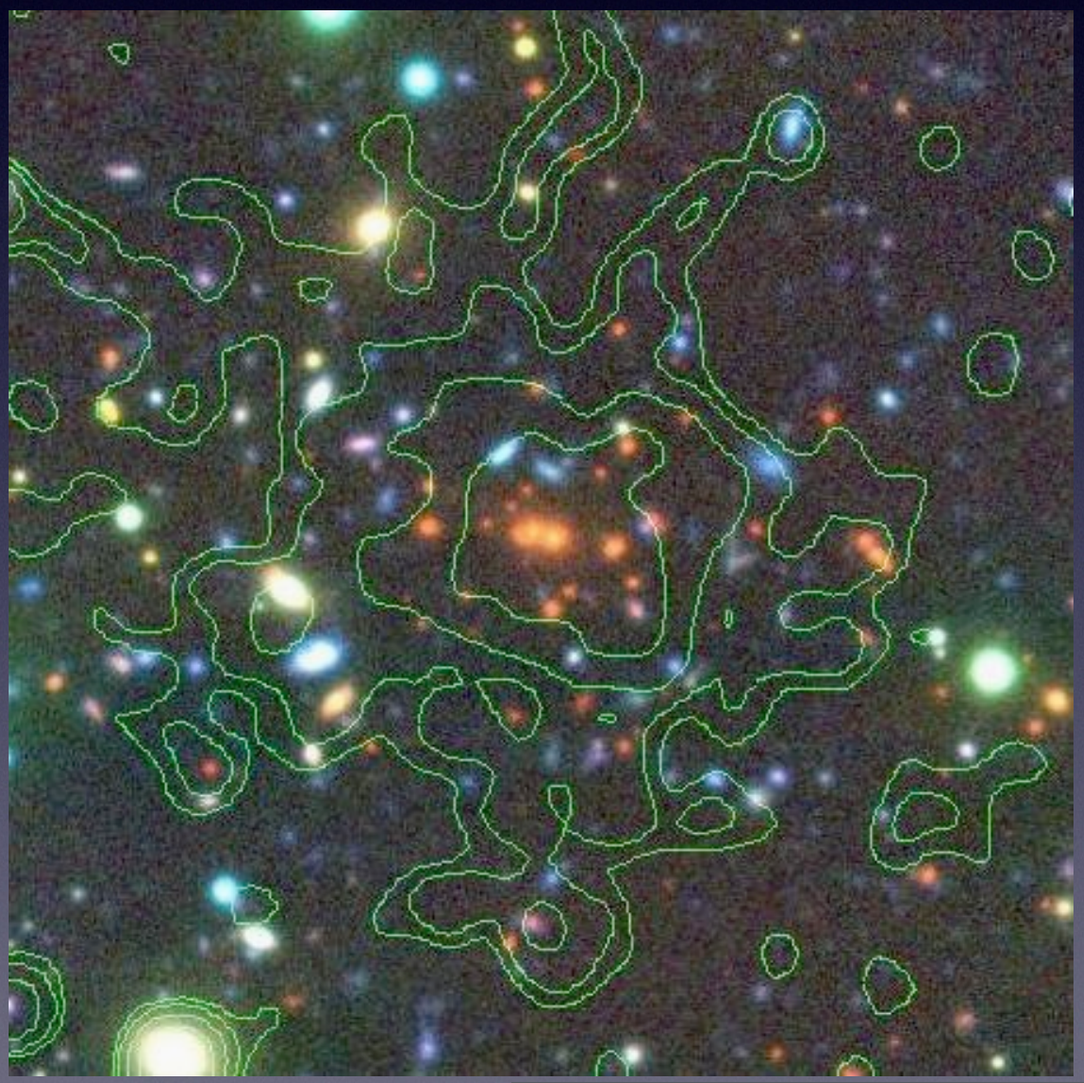
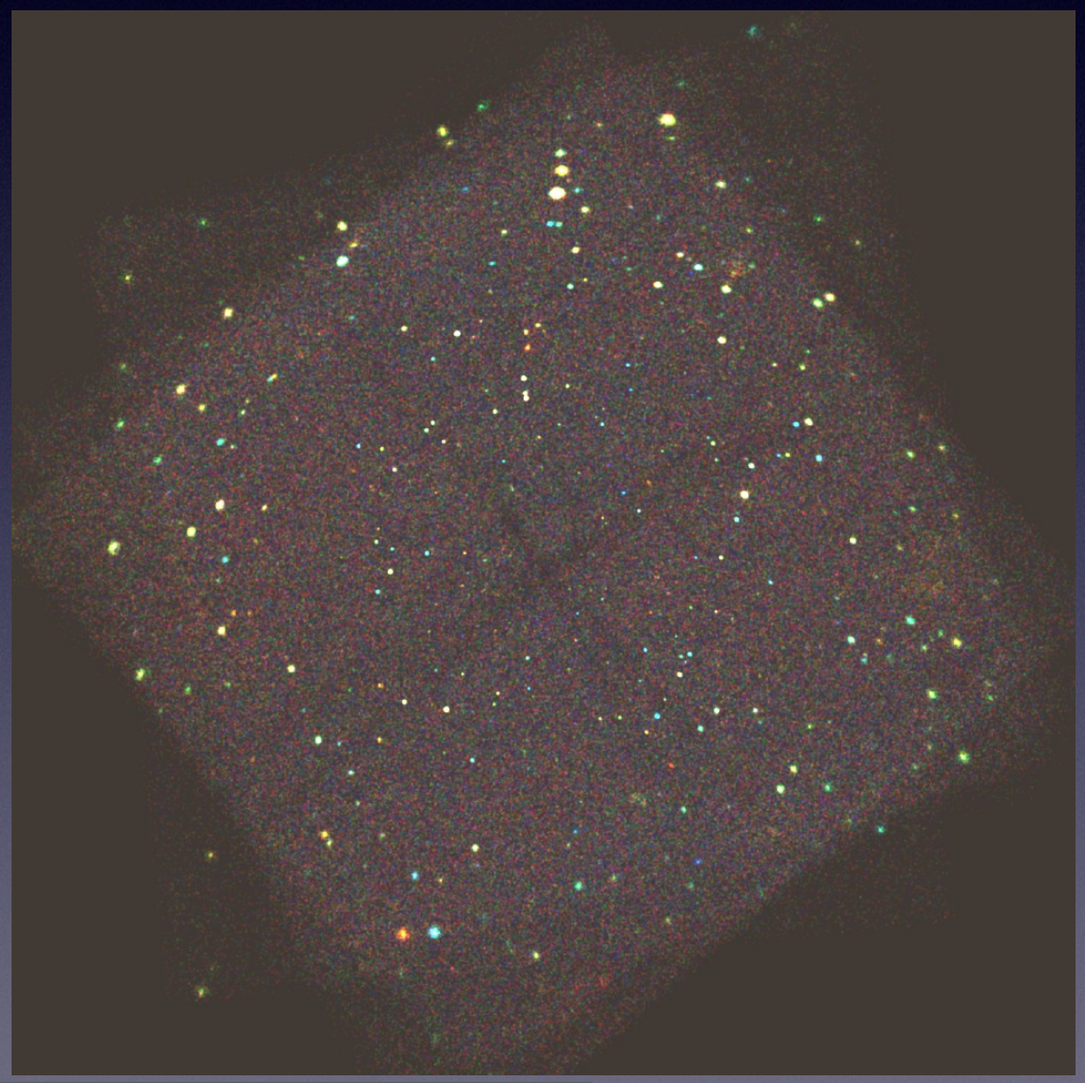
From distant galaxy clusters …
to the Chandra Deep Field South
…from JHU to ESO



Piero Rosati

(Università di Ferrara, IT)

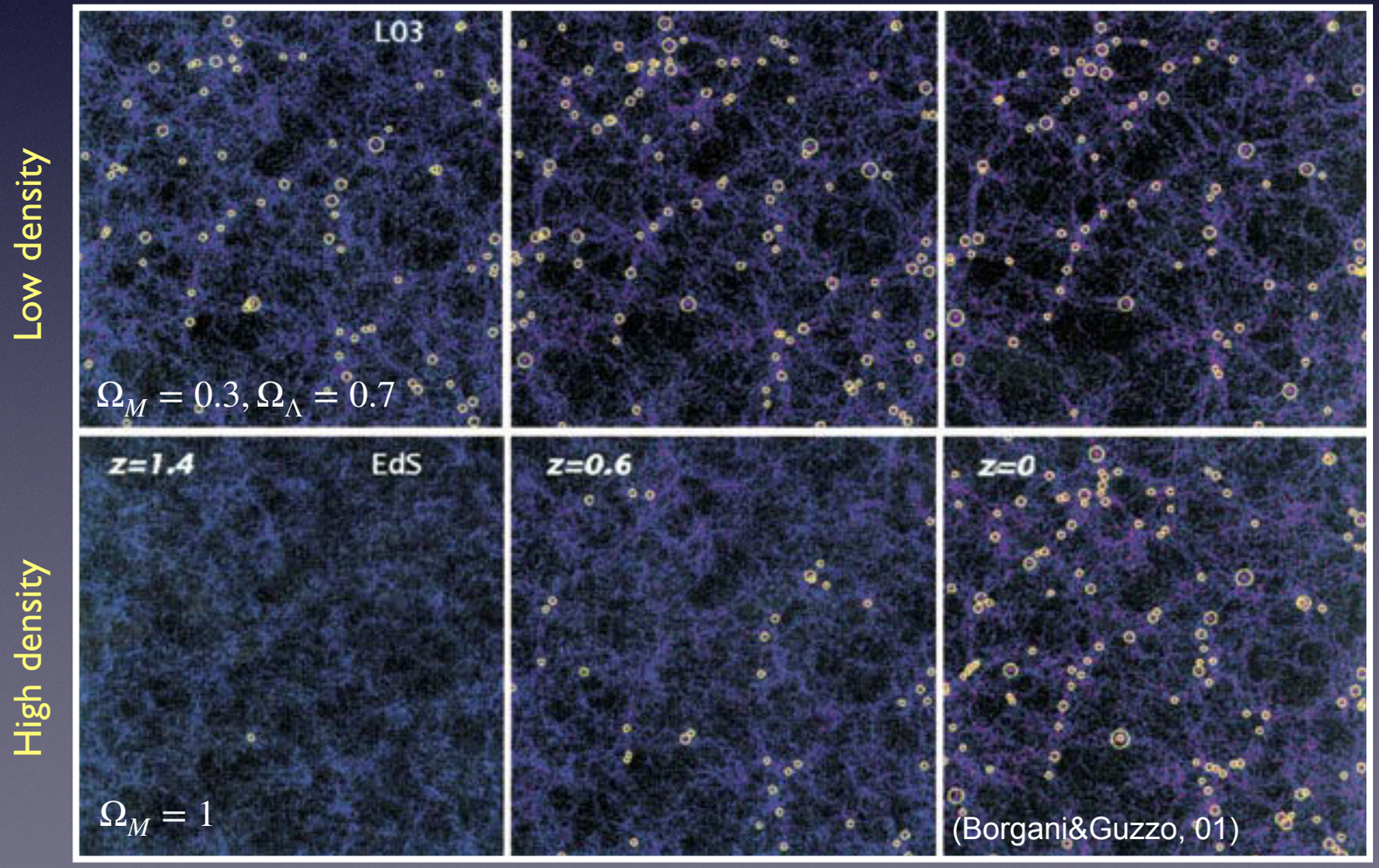




Memorial Symposium to Honor Riccardo Giacconi
Washington DC, May 29-30, 2019

Cluster “evolution” in the early-mid 90s

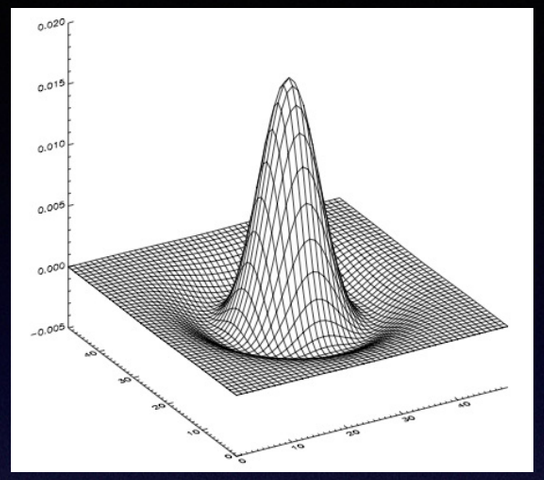
- Confusion reigned in the community about evolution of cluster abundance
- “Tension” on cluster evolution from X-ray (EMSS, Gioia et al. 90) and (small area) optical surveys (Couch et al. 1991, Postman et al. 1996, Carlberg et al. 1997)
- ROSAT mission (1990): great new opportunities for cluster surveys
- Motivation: cluster abundance and correlation function to measure Ω_M and σ_8 (Bahcall et al. 1997,1998)



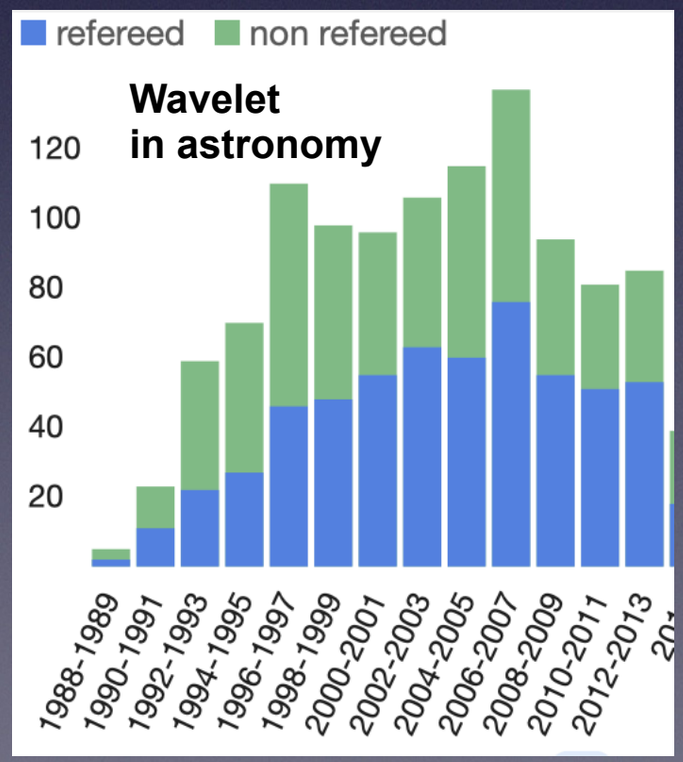
Cluster detection methodology on ROSAT data

- Riccardo's idea for my thesis (JHU, 1991): search for distant clusters in ROSAT data
- The first idea to use wavelet detection algorithms in X-ray astronomy was Riccardo's !

From Sonar data processing technique..
to extended X-ray emission from clusters..!



$$\psi(\frac{r}{a}) = \frac{2}{a^2}[e^{-\frac{r^2}{a^2}} - \frac{1}{2}e^{-\frac{r^2}{2a^2}}]$$



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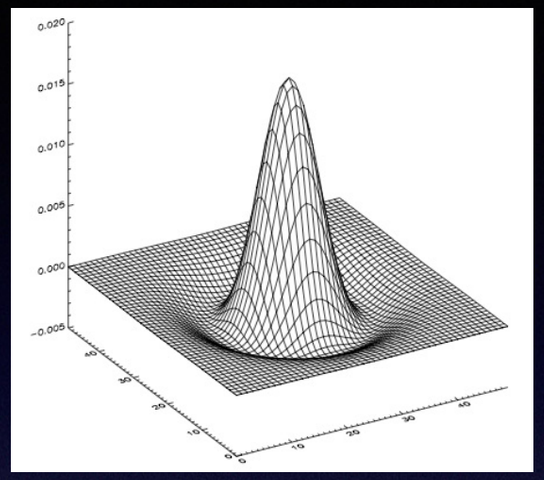

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- ROSAT Deep Cluster Survey (RDCS): searching for extended sources serendipitously in ROSAT deep pointed observations (JHU then ESO) - Co-supervision by Colin Norman@JHU
- >100 candidates clusters
- Intense follow-up program at ESO La Silla and KPNO (1994-2000)

Colin Norman

Cluster "evolution": the solution in the late 90s

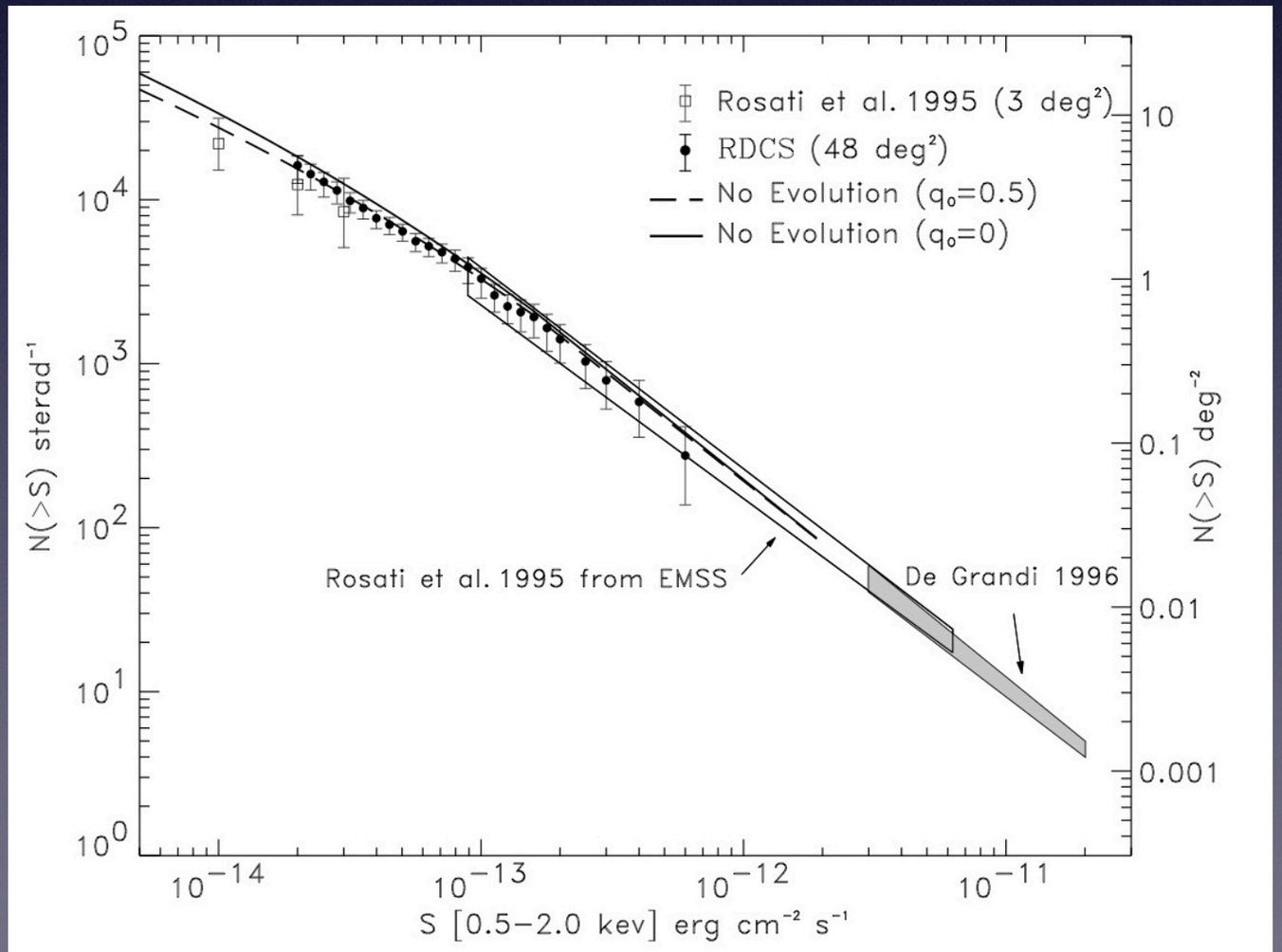
THE *ROSAT* DEEP CLUSTER SURVEY: THE X-RAY LUMINOSITY FUNCTION OUT TO $z = 0.8$

PIERO ROSATI,[1,2,3,4] ROBERTO DELLA CECA,[5] COLIN NORMAN,[2] AND RICCARDO GIACCONI[1]

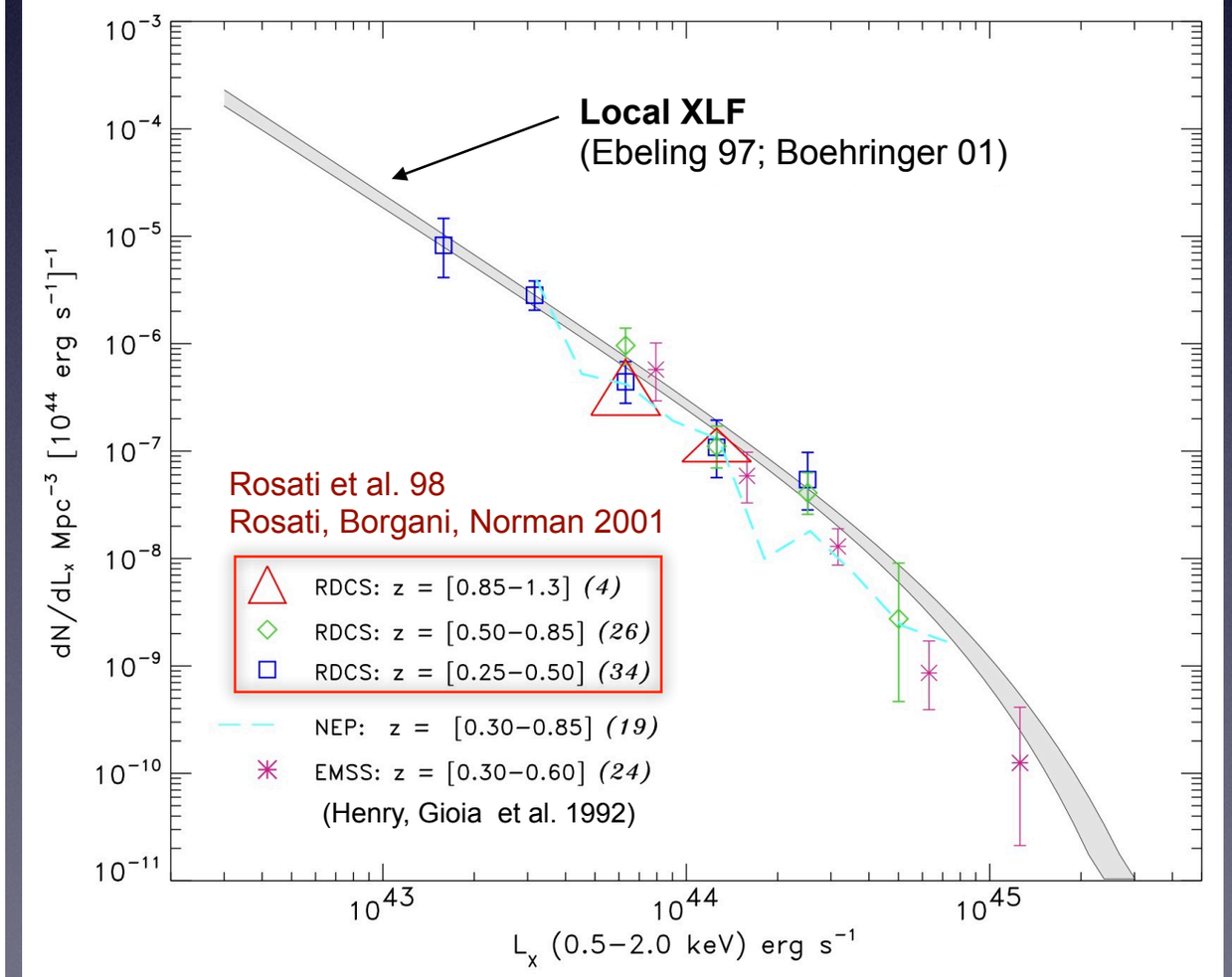
Received 1997 August 7; accepted 1997 October 28; published 1997 November 14 **(ApJ, 392, 760, 1992)**

- No significant evolution of the cluster abundance out to z~1
- Only hint of modest evolution of most massive clusters

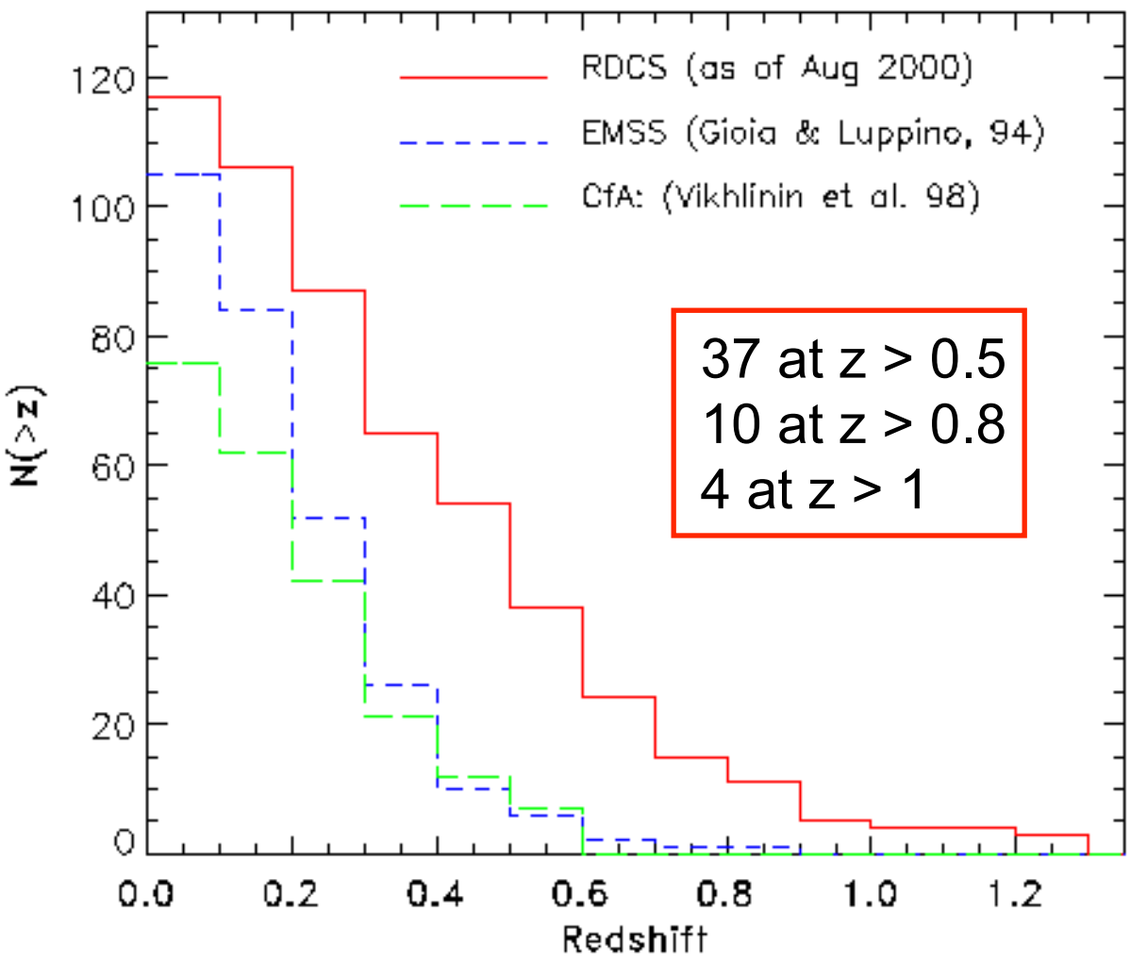
Cluster number counts



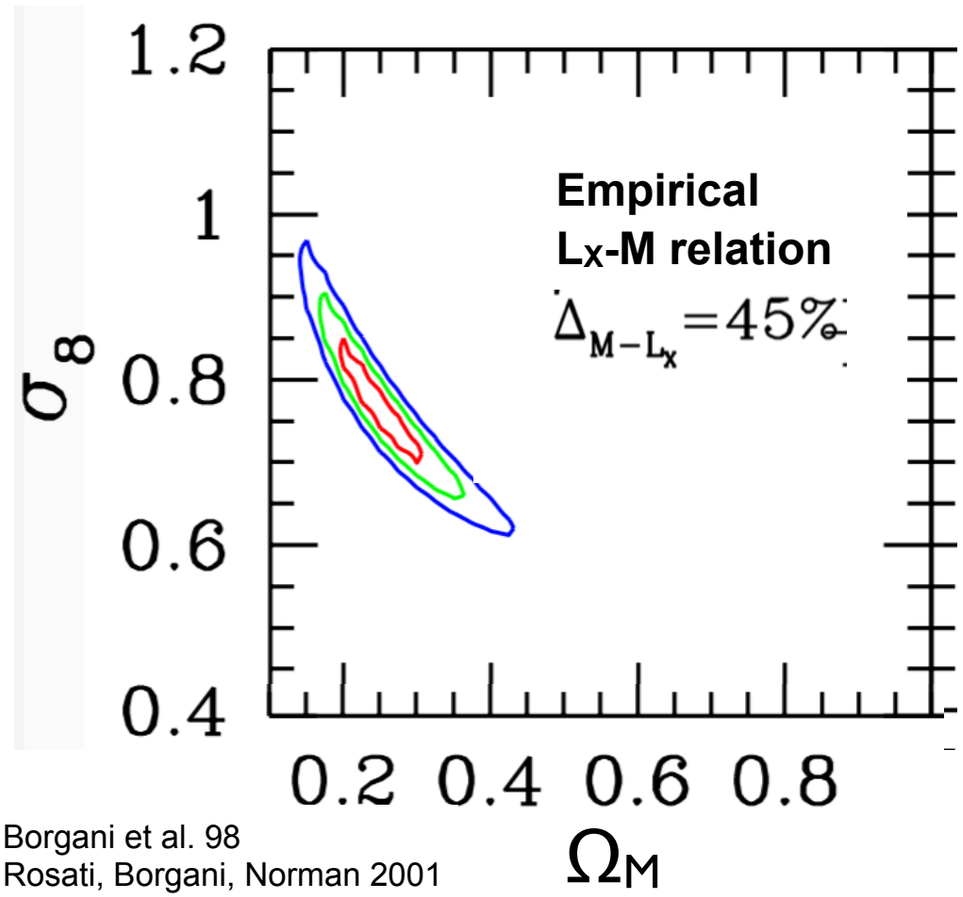
Cluster X-ray Luminosity Function to z~1.2



The population of distant clusters and cosmology



Cosmology with RDCS

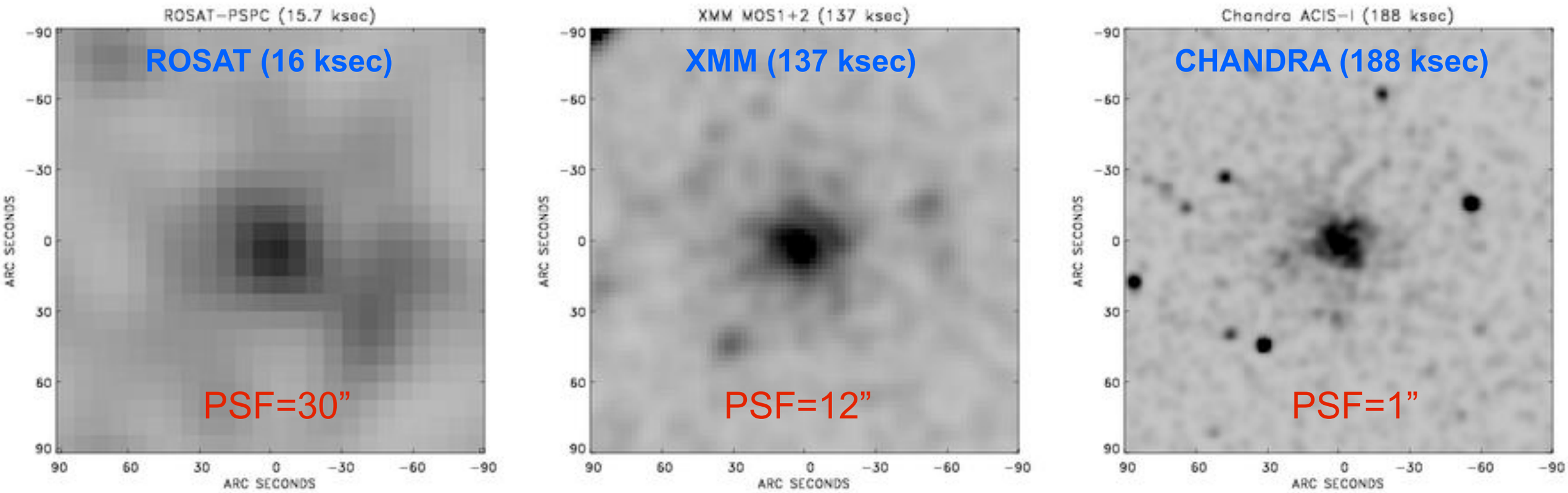


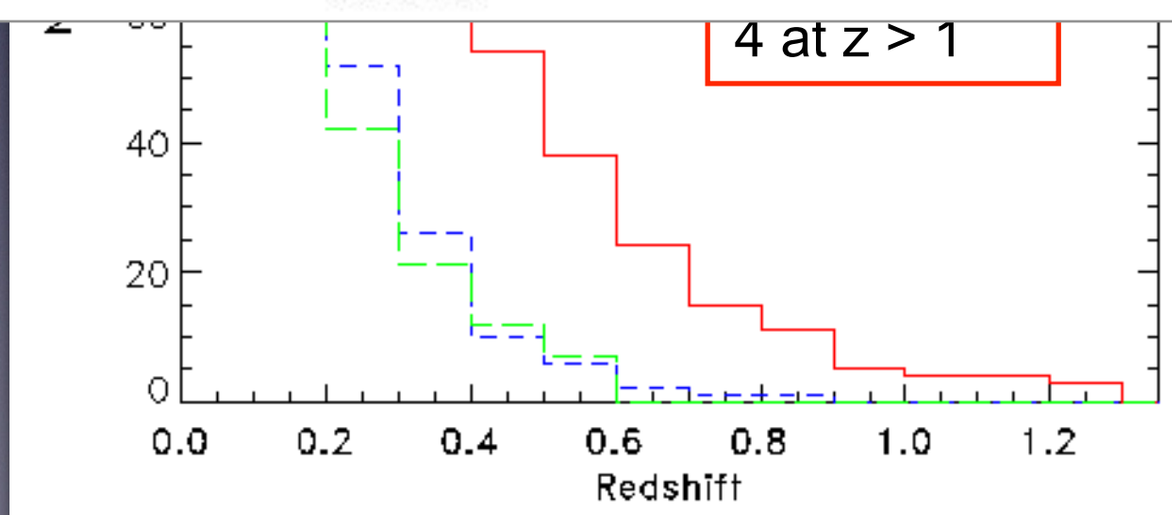
Borgani et al. 98
Rosati, Borgani, Norman 2001

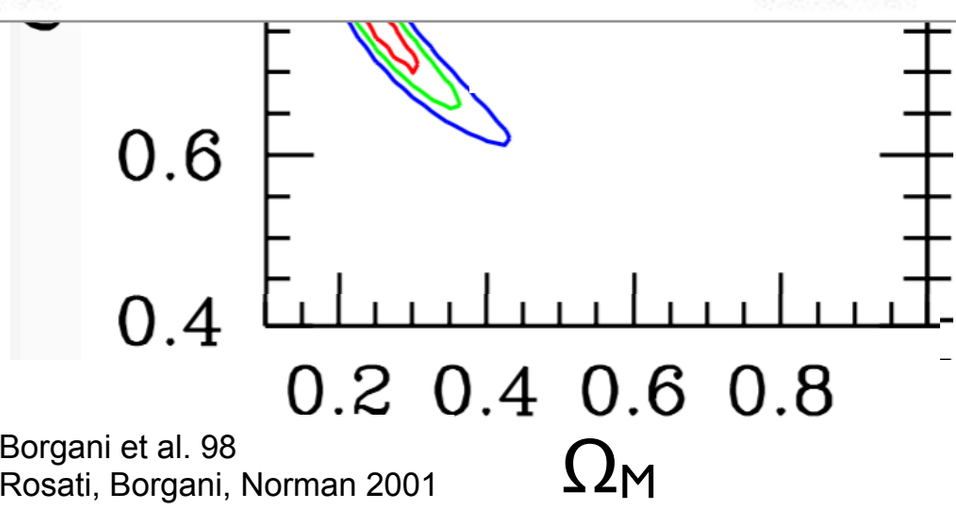
The population of distant clusters and cosmology

Massive ($6\times10^{14}M_{\odot}$) cluster at z=1.24

(RDCS1252, Rosati et al. 04)

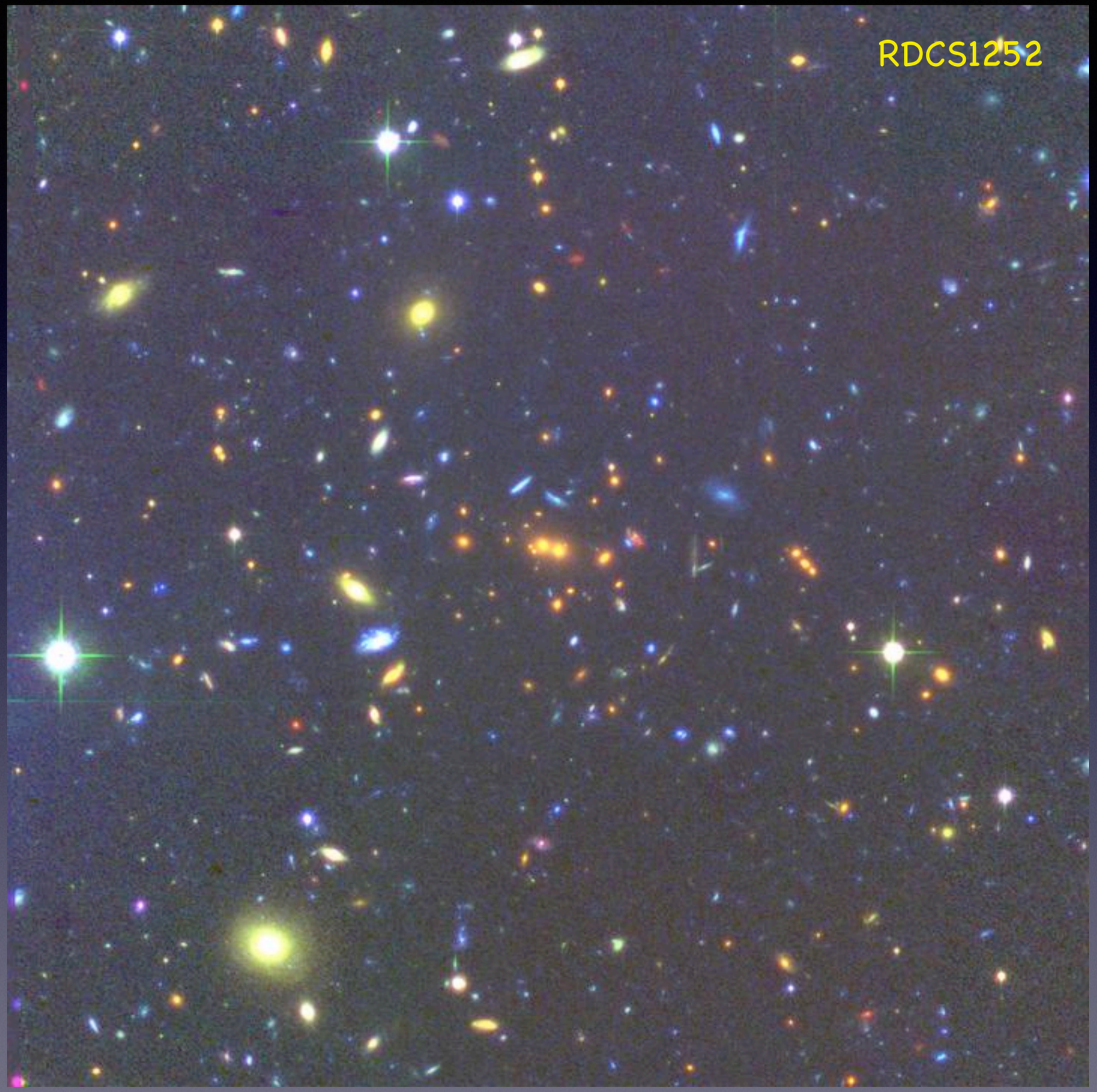




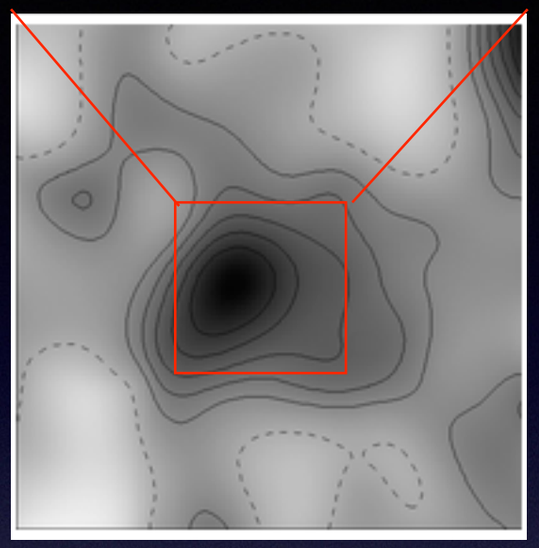


Borgani et al. 98
Rosati, Borgani, Norman 2001

Distribution of baryons and DM in a distant cluster (z=1.24)



Weak Lensing with HST/ACS



Rosati et al. 04, Lombardi et al. 05
Lidman 2005, Demarco et al. 07

- K-band img with VLT/ISAAC
- Spectroscopy with VLT/FORS2

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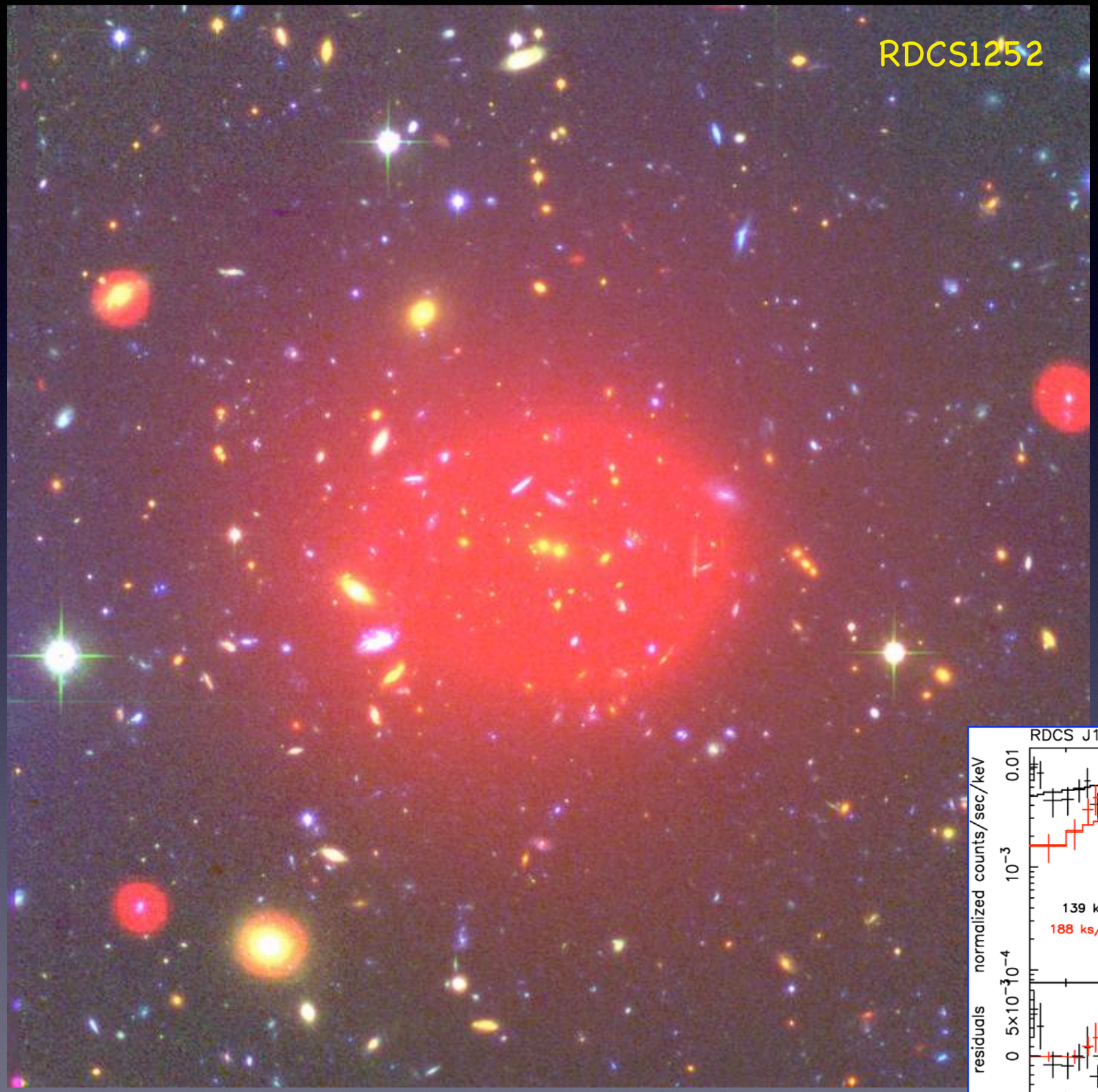

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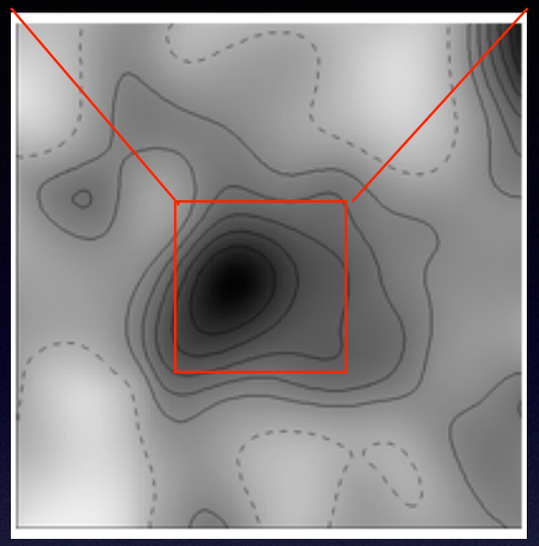

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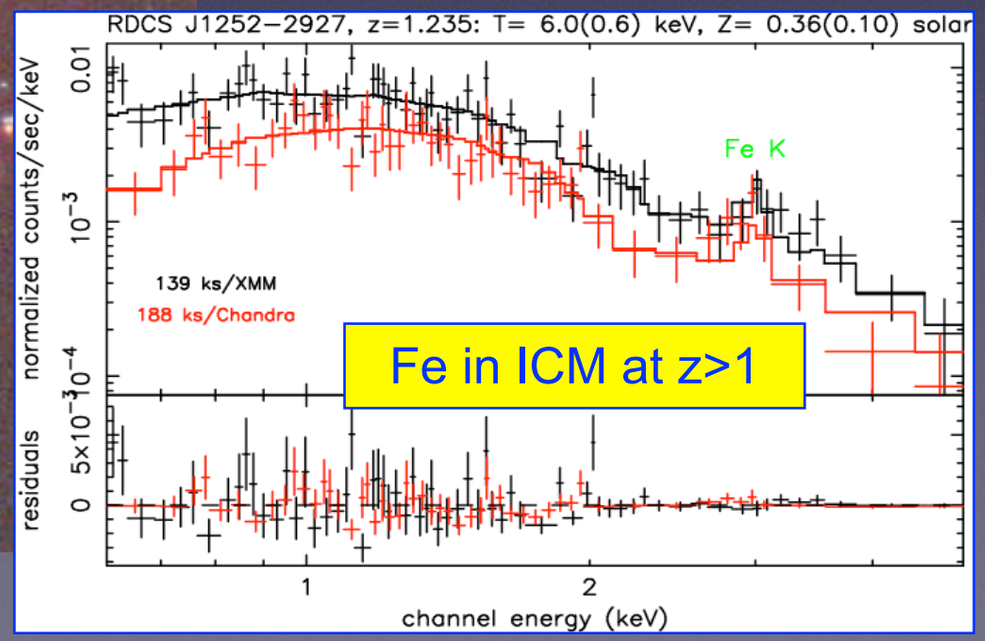
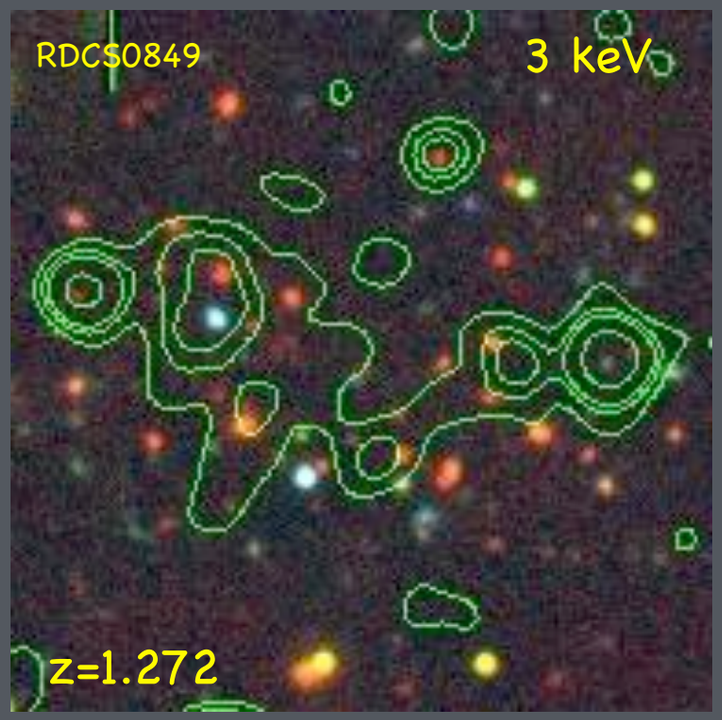
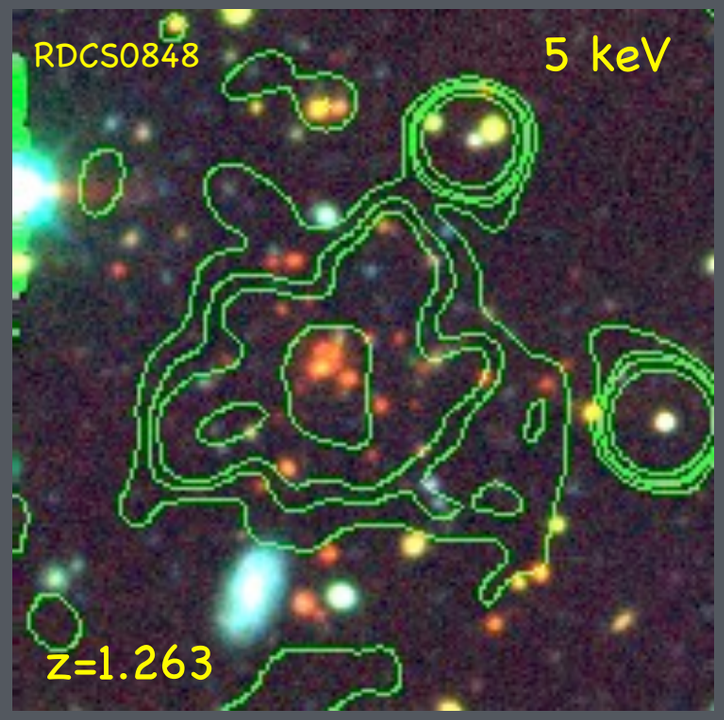
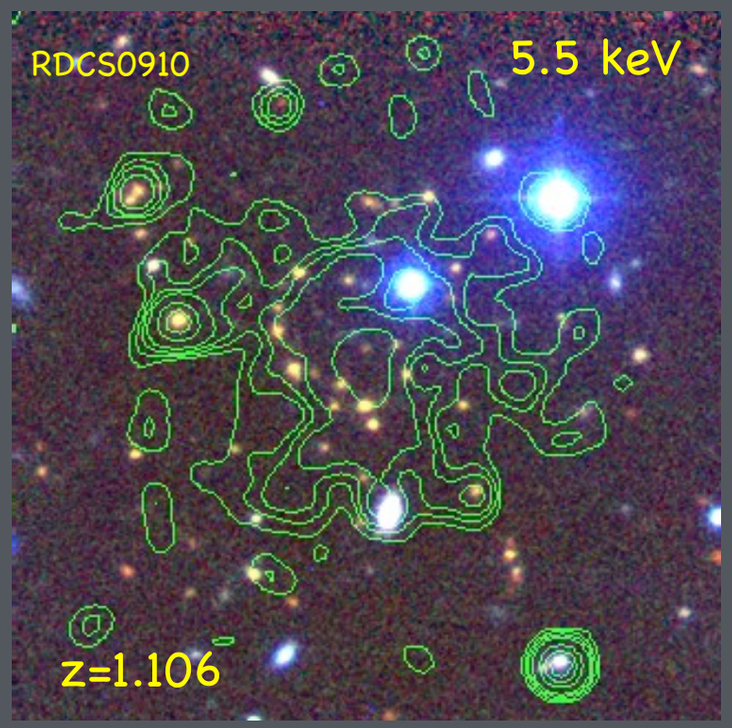


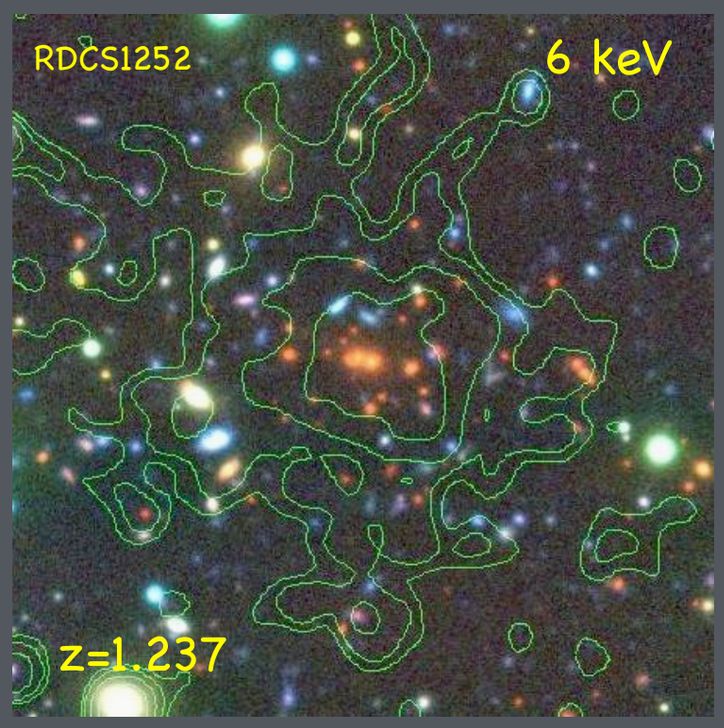
Clusters at z > 1 part of multi-λ campaign





1.5′ ≈ 0.75 Mpc





Rosati et al. 02 (collab. with A.Stanford, P.Eisenhardt)

"To solve definitely the problem of cluster formation and evolution a Wide Field X-ray Telescope is needed"

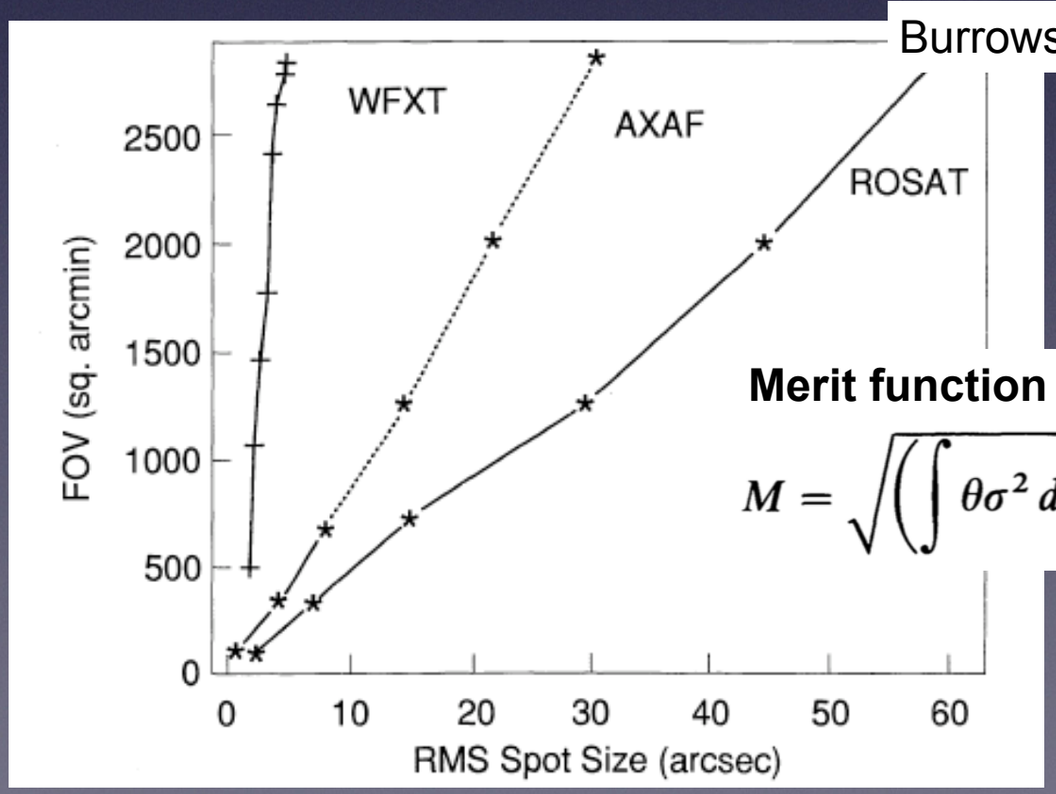
OPTIMAL GRAZING INCIDENCE OPTICS AND ITS APPLICATION TO WIDE-FIELD X-RAY IMAGING

CHRISTOPHER J. BURROWS,[1] RICHARD BURG,[2] AND RICCARDO GIACCONI
Space Telescope Science Institute,[3] 3700 San Martin Drive, Baltimore, MD 21218

Received 1990 April 16; accepted 1991 November 4 **(ApJ, 392, 760, 1992)**

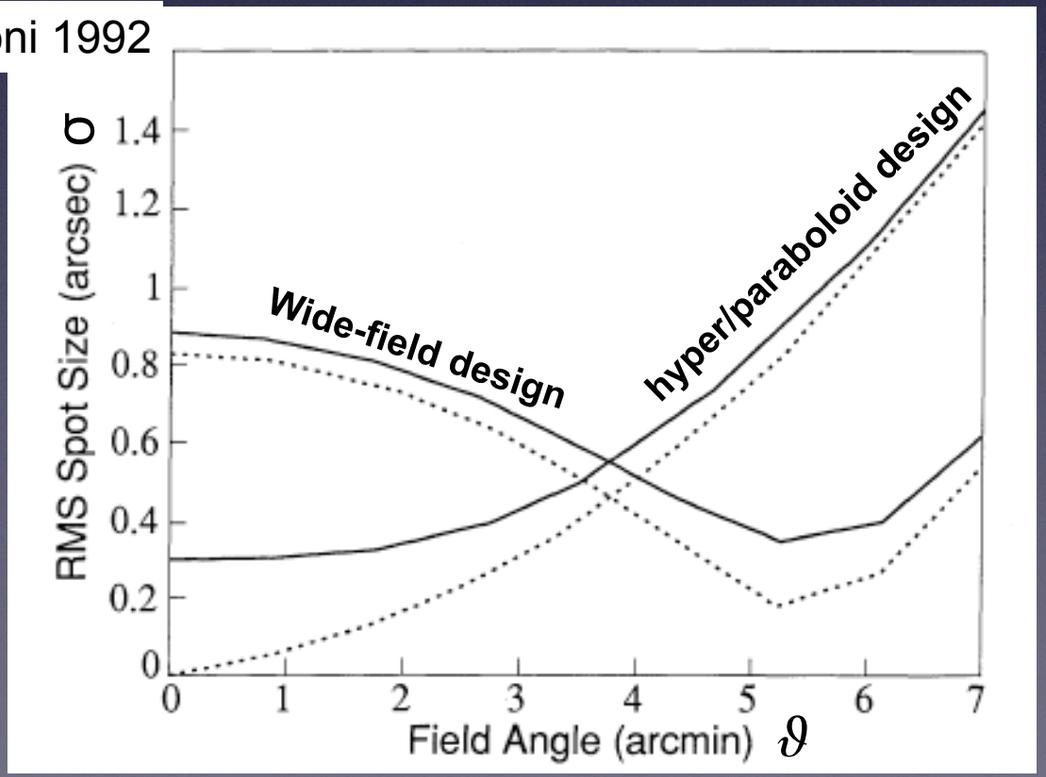
- "*We have developed optical designs to search efficiently for distant X-ray clusters*"
- Science driver: "*survey for distant clusters (z>1) with an Explorer satellite*"
- Polynomial optics design: 1 deg² with a flat ~5" PSF over the entire field
  in other words an "***X-ray Schmidt telescope"***, "*no more difficult to fabricate than existing mirrors*"

Burrows, Burg, Giacconi 1992



Merit function to maximize

$$M = \sqrt{\left(\int \theta\sigma^2\, d\theta\right) \Big/ \left(\int \theta\, d\theta\right)}$$



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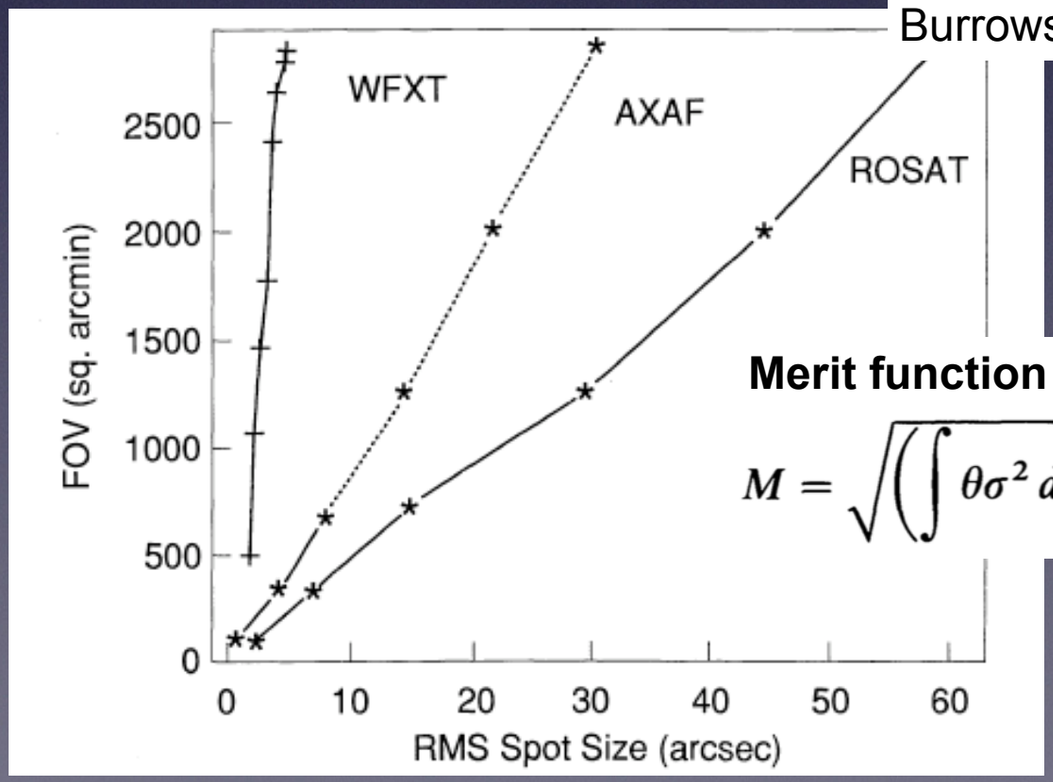

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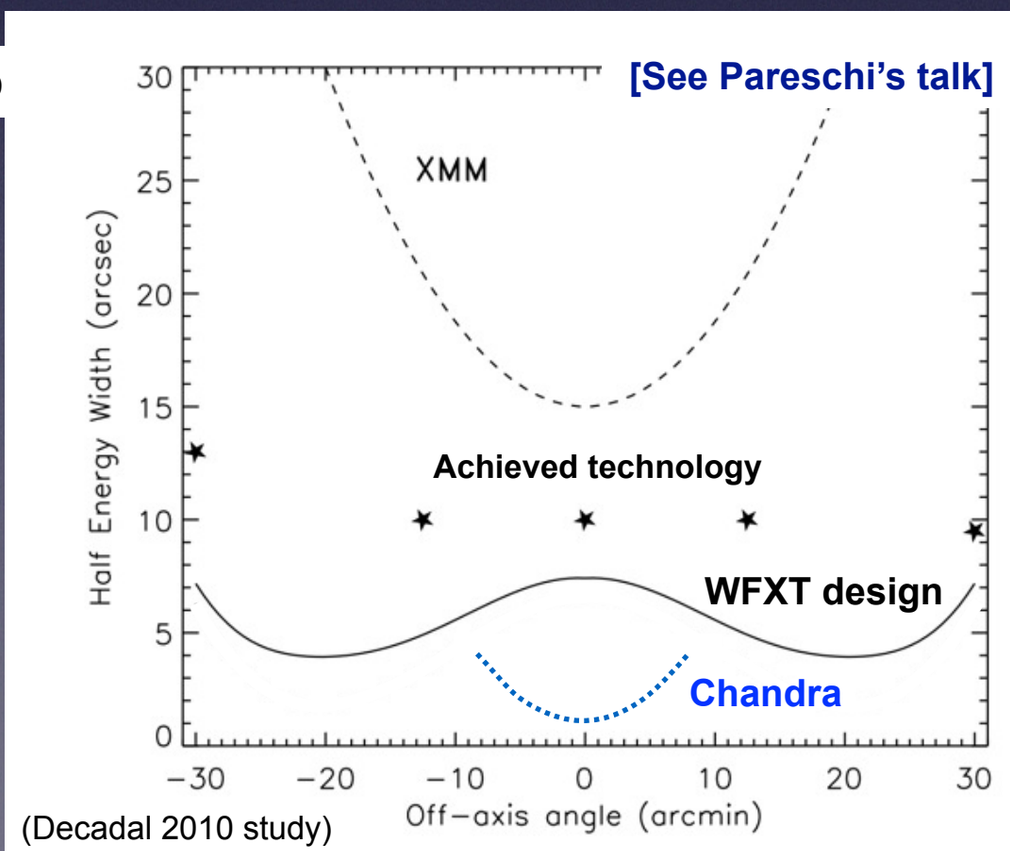
[See Pareschi's talk]



(Decadal 2010 study)

Wide Field X-ray Telescope
(see talks by Chincarini, Gilli, Pareschi)

- NASA-Explorer Proposal in 1995 (PIs: Giacconi, Burg)
  - Basically turned down on the basis of a *prejudice* which dominated the theoretical and observational community in the early-mid 90s…
- Other attempts with ESA/ASI/NASA until 2002 not successful
- Decadal Survey 2010 and other NASA RFIs (2011 PI: Murray).

Regarding your point that WFXT could provide an unbiased survey for clusters of galaxies, to help understand the development of structure in the early universe, the peer panel felt that the proposal did not adequately address the possibility that cluster evolution may be significant at z = 0.3 and more so out to z = 0.5. Estimates in the proposal of the number of sources were based upon the absence of evolution, despite recent publications (including one by some of the Co-Investigators) that suggest the presence of evolution at most redshifts. In the opinion of the reviewers, few clusters would be seen at z greater than 0.5 to 0.75 if evolution is, in fact, important. The result

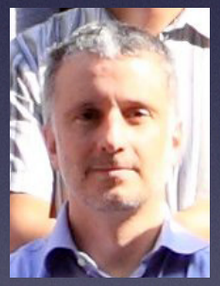
NASA review, Oct 95

Wide Field X-ray Telescope: 2011 design

- Grasp = (A·Ω) = 2-3 order of mag advance over existing or planned missions
- Wide and Deep: incomparably vast survey volume for clusters and AGN at high-z
- Physical source characterization for large samples, no need of optical follow-up
- M-class mission cost envelope, feasible and affordable mirror technology

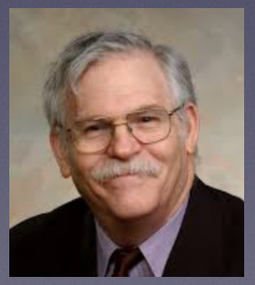
PI: S. Murray

A. Ptak

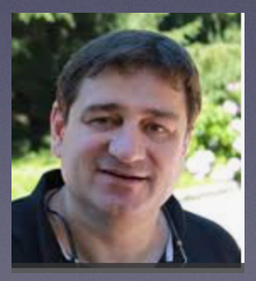


P. Tozzi

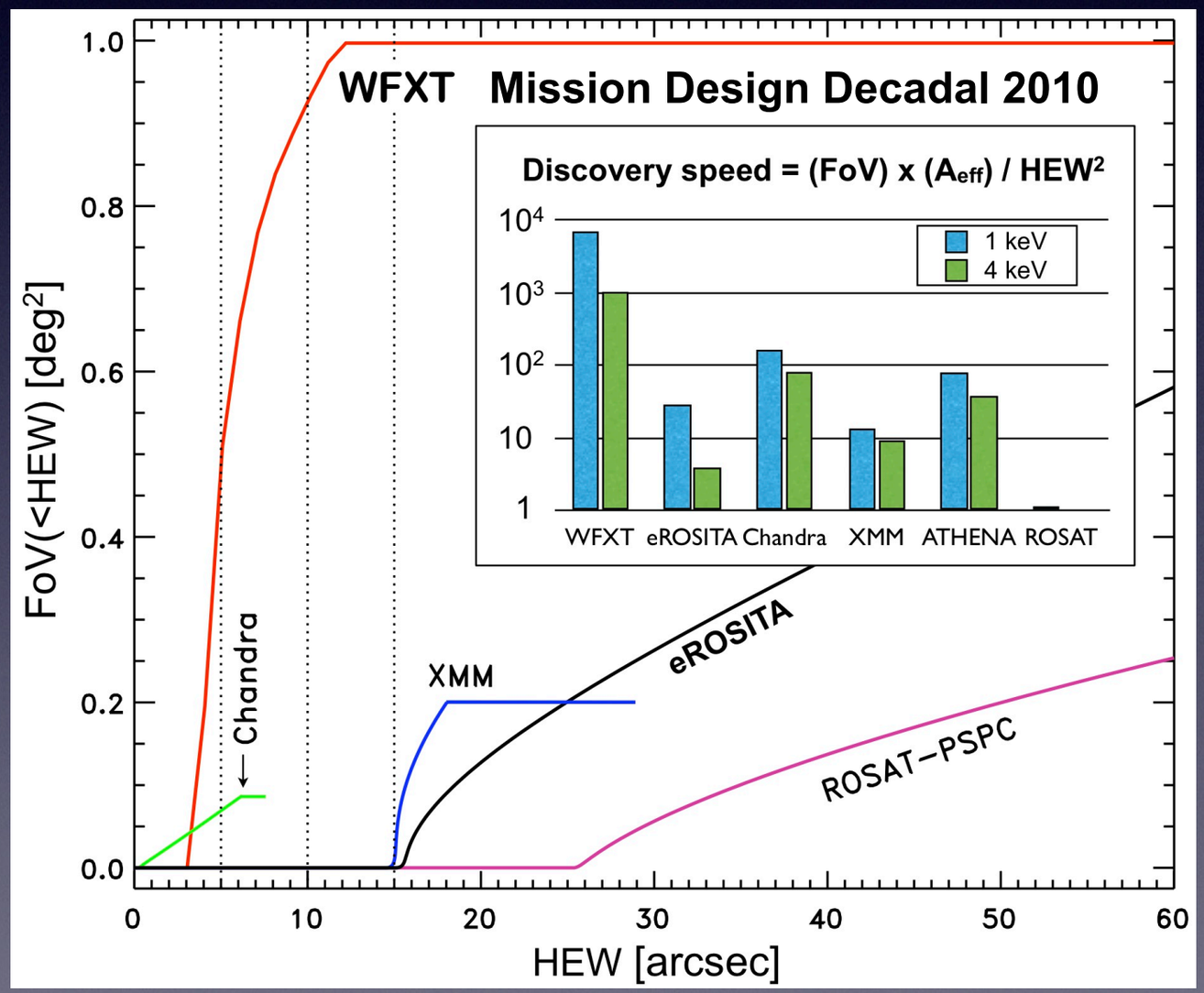
R. Gilli



M. Weisskopf



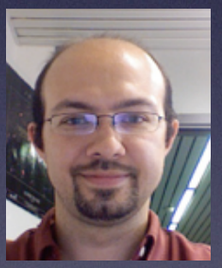
G. Pareschi



Riccardo

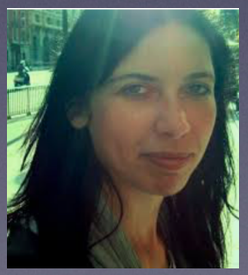
P. Rosati

S. Borgani



M. Paolillo

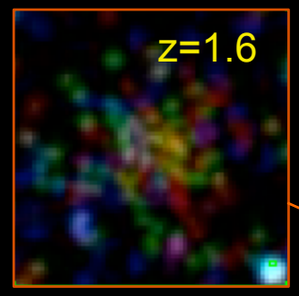
B. Sartori

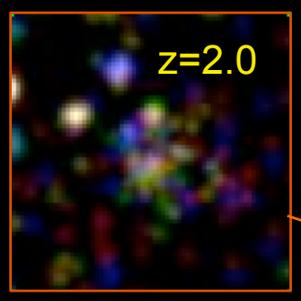


J. Santos

"As always I love to quarrel with you, even if some times you are right" (R. Gilli 2007)

WFXT end-to-end sky simulations



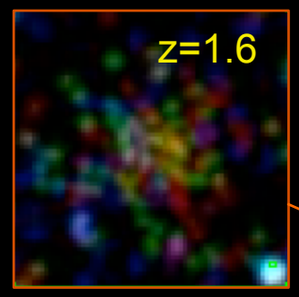


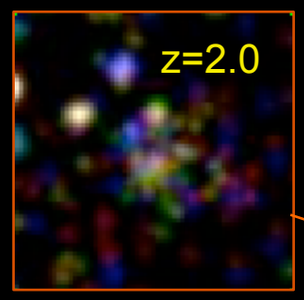
1 deg²

(13 ksec)

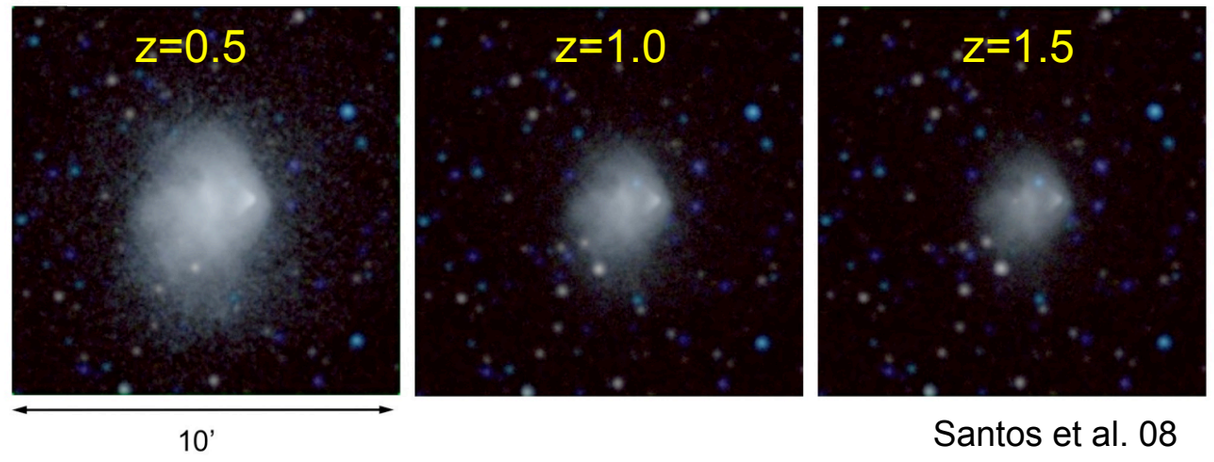
$F_{[0.5\text{-}2\ keV]} = 2\times10^{-16}$ erg/cm²/s (5σ)

WFXT end-to-end sky simulations



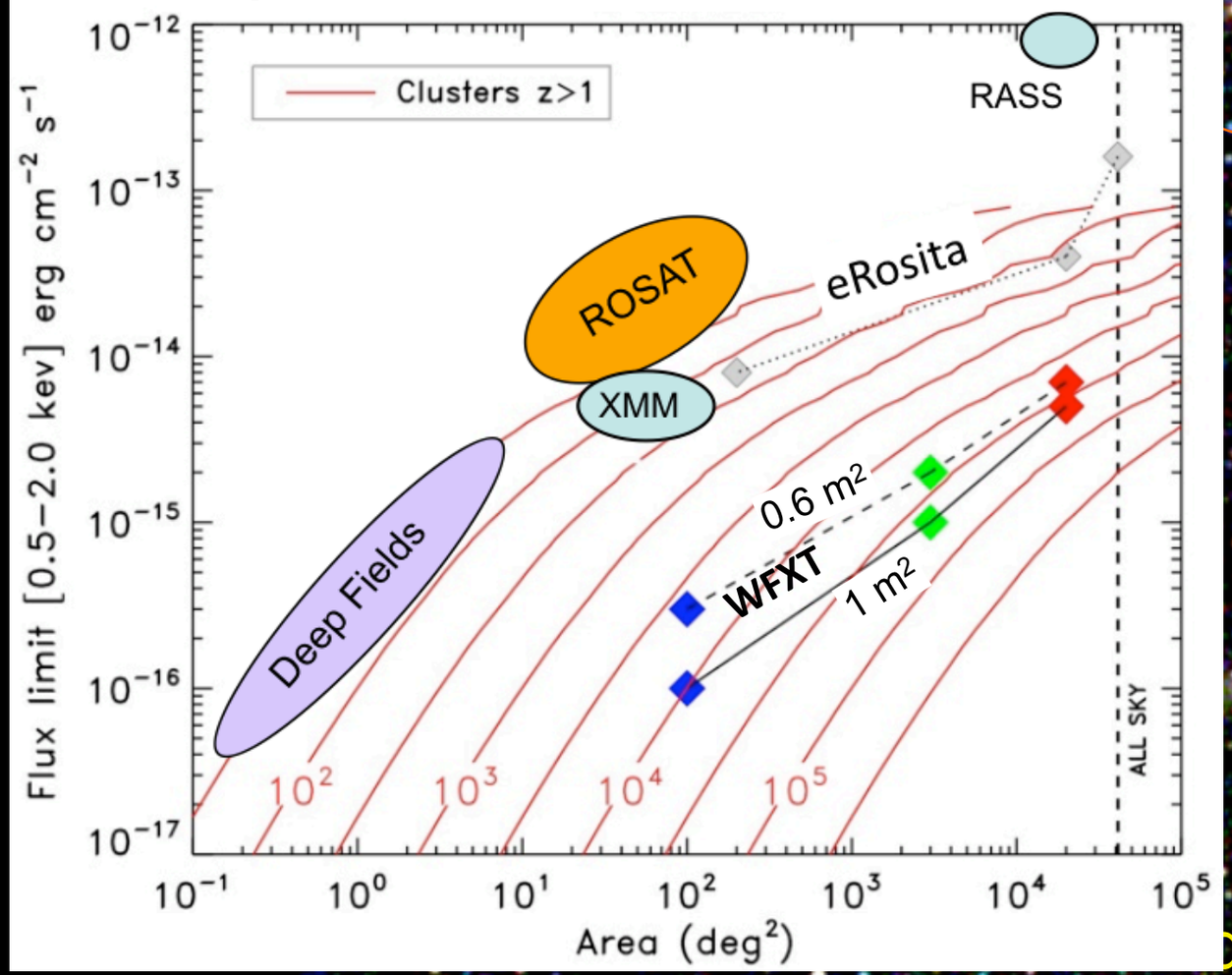


The bullet cluster at high-z



Santos et al. 08

Expected number of clusters at z >1



- ~3×10^5 clusters, 20,000 at z>1 !
- ~20,000 with redshift and temperature !
- Synergy with SZ surveys

~10^7 AGN, >1000 at z>6 (first SMBH)
$\Longrightarrow$ see R. Gilli's talk

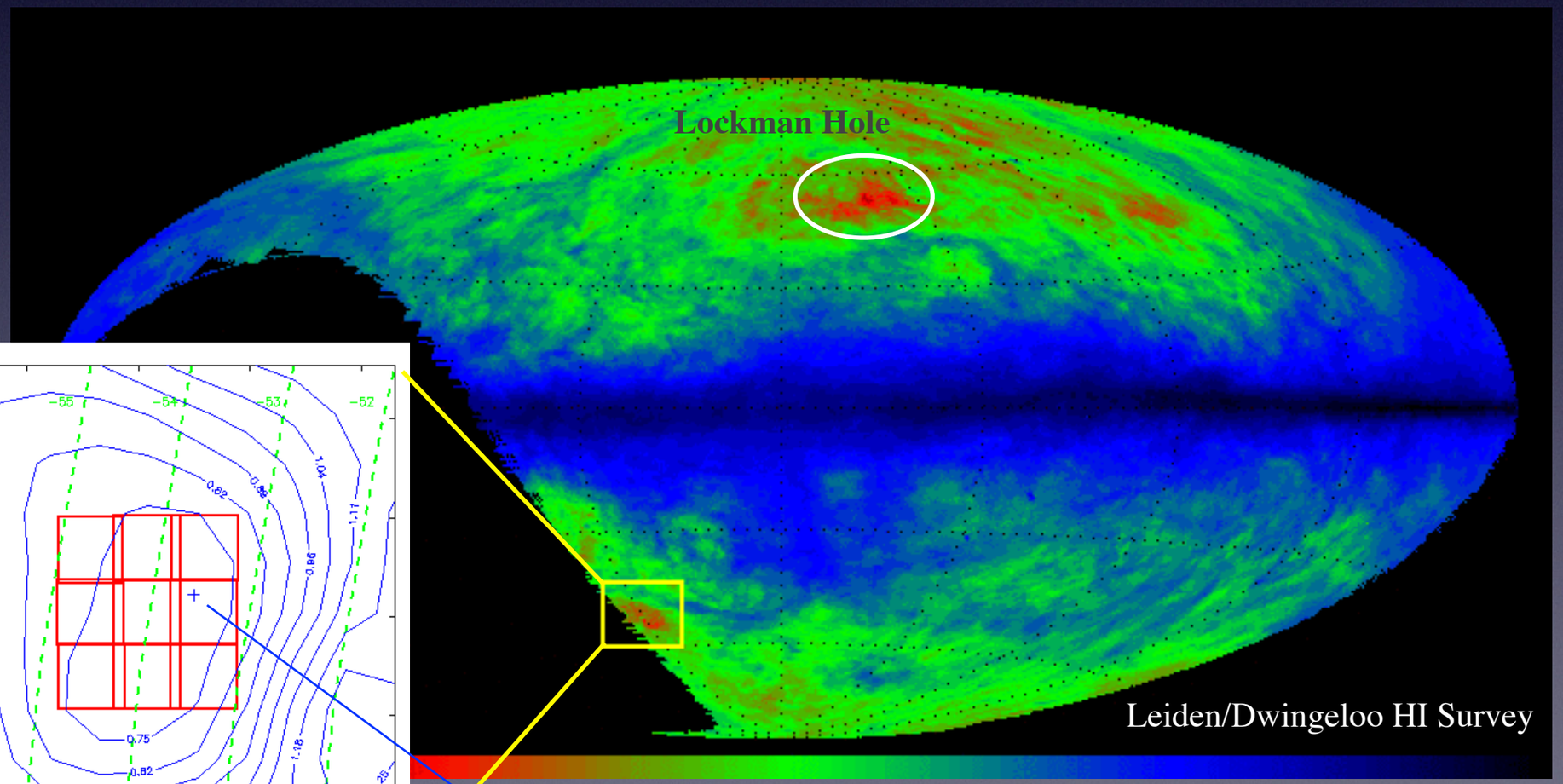
deg²

(13 ksec)

$F_{[0.5\text{-}2\ keV]} = 2\times10^{-16}$ erg/cm²/s (5σ)

Chandra Deep Field selection, planning and execution

- Search for a “South Galactic Hole”, like the Lockman Hole (N_H=0.6x10^{20} cm^{-2})
- No bright stars (<14 mag), no bright X-ray sources from RASS
- VLT should play a central role in the follow-up observations
- Down selection in March 1998: “*we will make glamour in an another field…*”
- First imaging with VLT with the Test Camera and FORS1 (Gilmozzi PI)



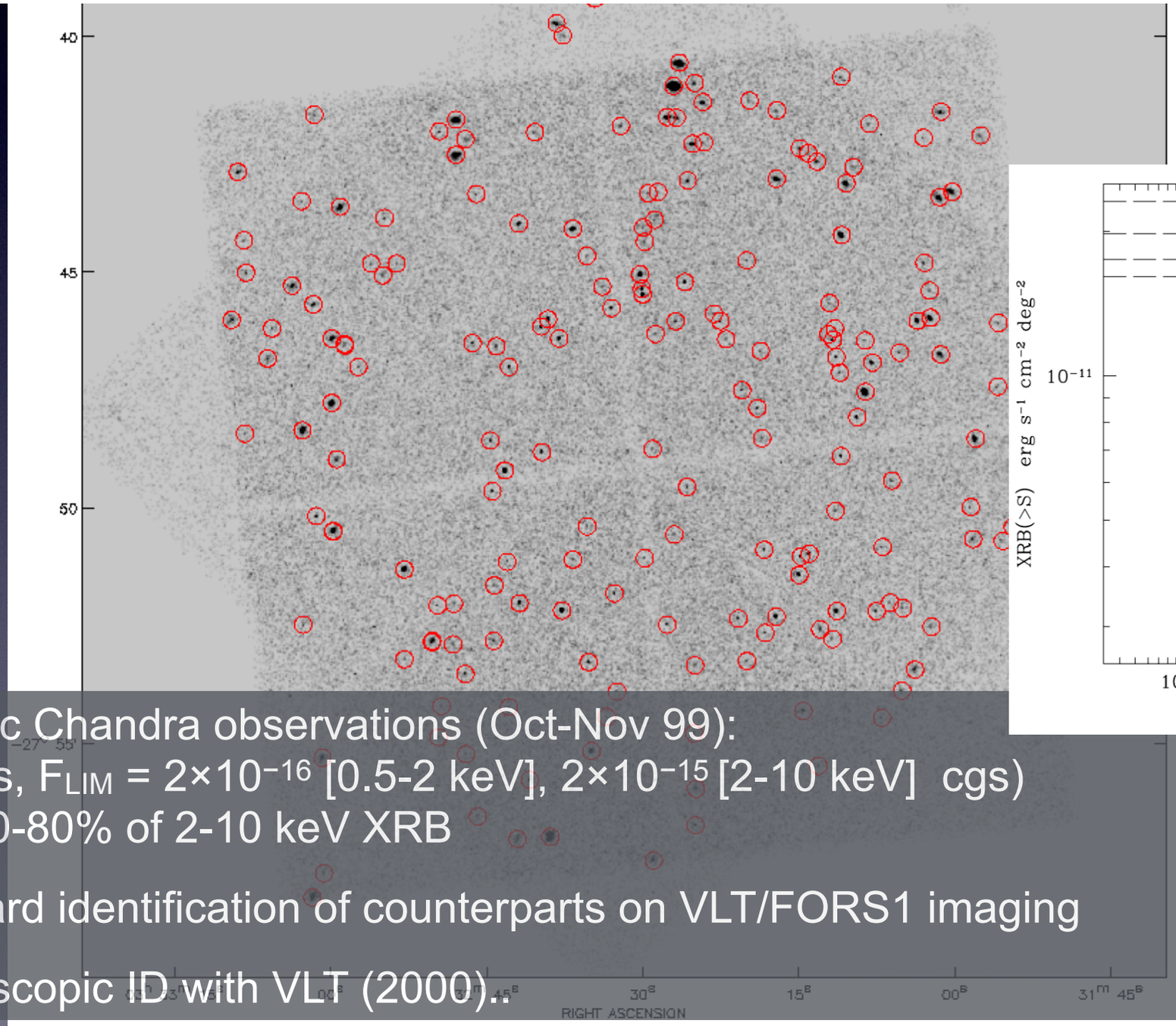
First CDFS results

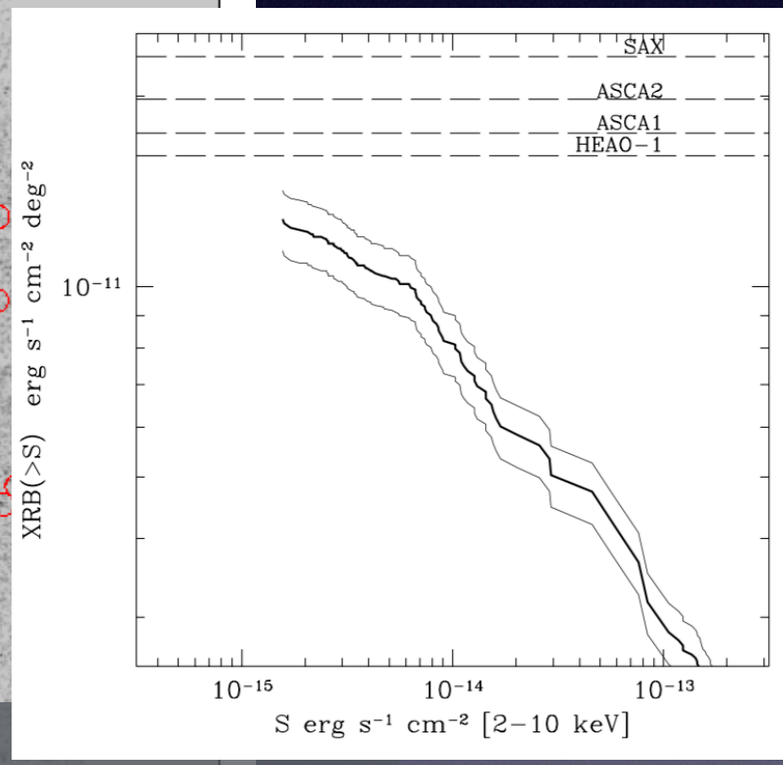
FIRST RESULTS FROM THE X-RAY AND OPTICAL SURVEY OF THE *CHANDRA* DEEP FIELD SOUTH[1]

R. GIACCONI,[2,3] P. ROSATI,[4] P. TOZZI,[2,5] M. NONINO,[5] G. HASINGER,[6] C. NORMAN,[2,7] J. BERGERON,[4] S. BORGANI,[8] R. GILLI,[2,9] R. GILMOZZI,[4] AND W. ZHENG[2]

Received 2000 July 17; accepted 2000 December 20

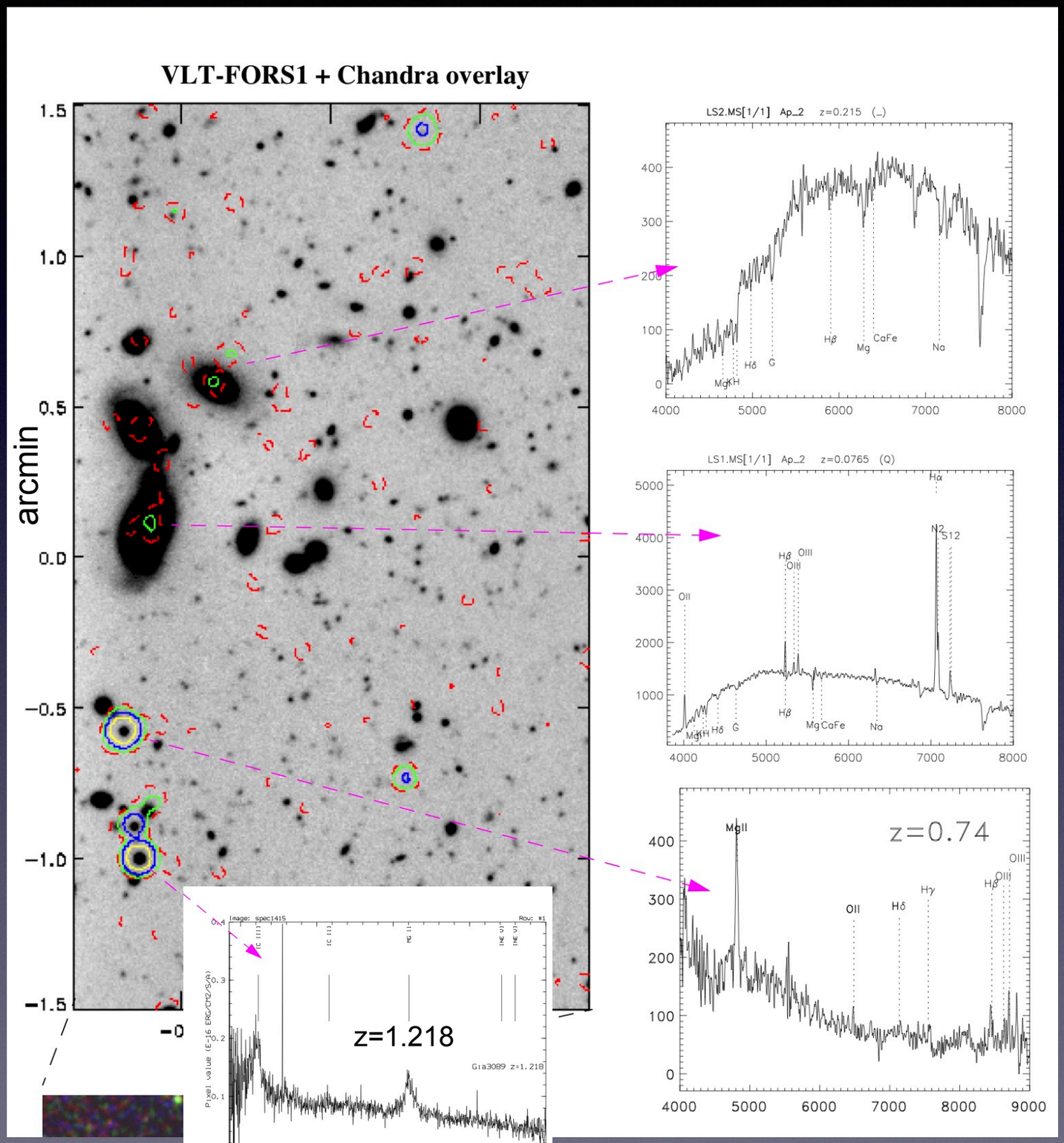
ApJ, 551, 624, 2001





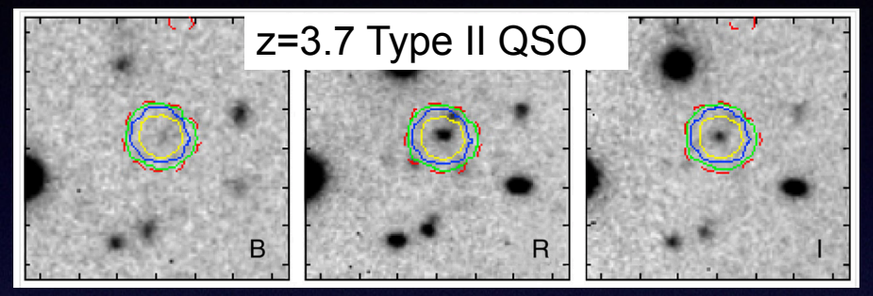
- First 120 ksec Chandra observations (Oct-Nov 99):
  - 160 sources, F_{LIM} = 2×10^{-16} [0.5-2 keV], 2×10^{-15} [2-10 keV] cgs)
  - resolving 60-80% of 2-10 keV XRB
- Straightforward identification of counterparts on VLT/FORS1 imaging
- First spectroscopic ID with VLT (2000)..

First results: VLT spectroscopic follow-up

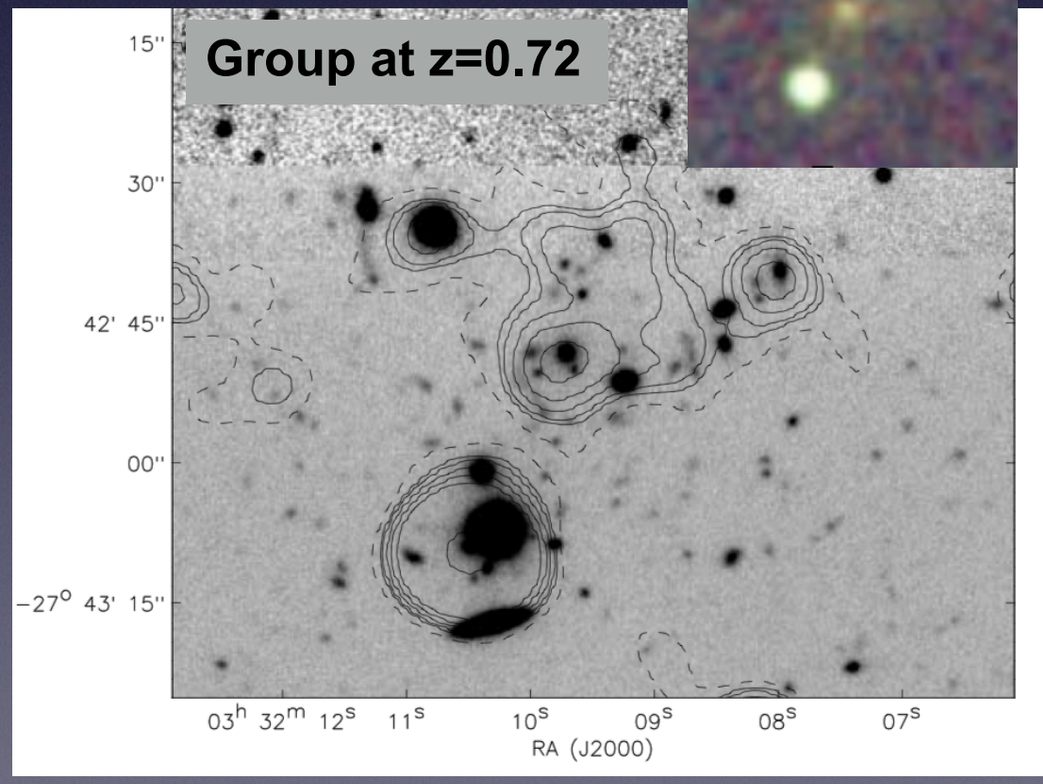


eso0110 — Science Release 13 March 2001

Chandra and the VLT Jointly Investigate the Cosmic X-Ray Background



Giacconi et al. 2002



+ HST/WFPC2 campaign prior to ACS (Schreier et al. 2001)

The 1-Msec exposure

- ~350 sources (f_{LIM} = 5×10^{-17} [0.5-2 keV], 5×10^{-16} [2-10 keV] cgs)
- Up to 90% of the 0.5-2 keV XBR resolved
- First redshift distribution of Type-1/2 AGN $\Longrightarrow$ XRB models
- From 1 to 7 Ms (Brandt et al.): see Roberto Gilli's talk

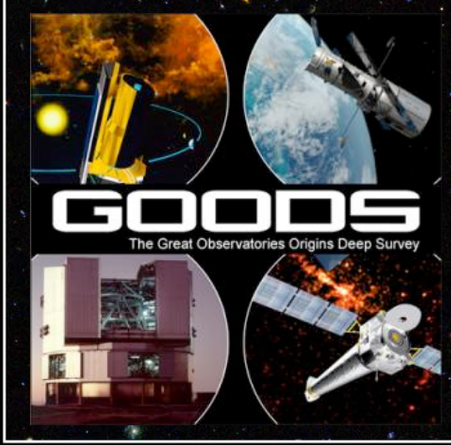
THE CHANDRA DEEP FIELD–SOUTH: THE 1 MILLION SECOND EXPOSURE[1]

P. ROSATI,[2] P. TOZZI,[3] R. GIACCONI[4,5] R. GILLI,[4,6] G. HASINGER,[7] L. KEWLEY,[4] V. MAINIERI,[2,8] M. NONINO,[3] C. NORMAN,[4,9] G. SZOKOLY,[7] J. X. WANG,[4,10] A. ZIRM,[4] J. BERGERON,[2] S. BORGANI,[11] R. GILMOZZI,[2] N. GROGIN,[9] A. KOEKEMOER,[9] E. SCHREIER,[9] AND W. ZHENG[4]

Received 2001 September 18; accepted 2001 October 29

The Impact and Legacy of the CDFS

- CDFS+GOODS (PI: Cesarsky): first experiment of Public Surveys at ESO with contributions from the user community
- VLT U+NIR imaging and panoramic spectroscopy to complement HST data
- Public Advanced Data Products of CDFS stimulated rapid and large scientific exploitation (many high-impact publications), attracted more programs…



Great Observatories Origins Deep Survey • CDF-S
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, The GOODS Team and M. Giavalisco (STScI) • STScI-PRC03-18a

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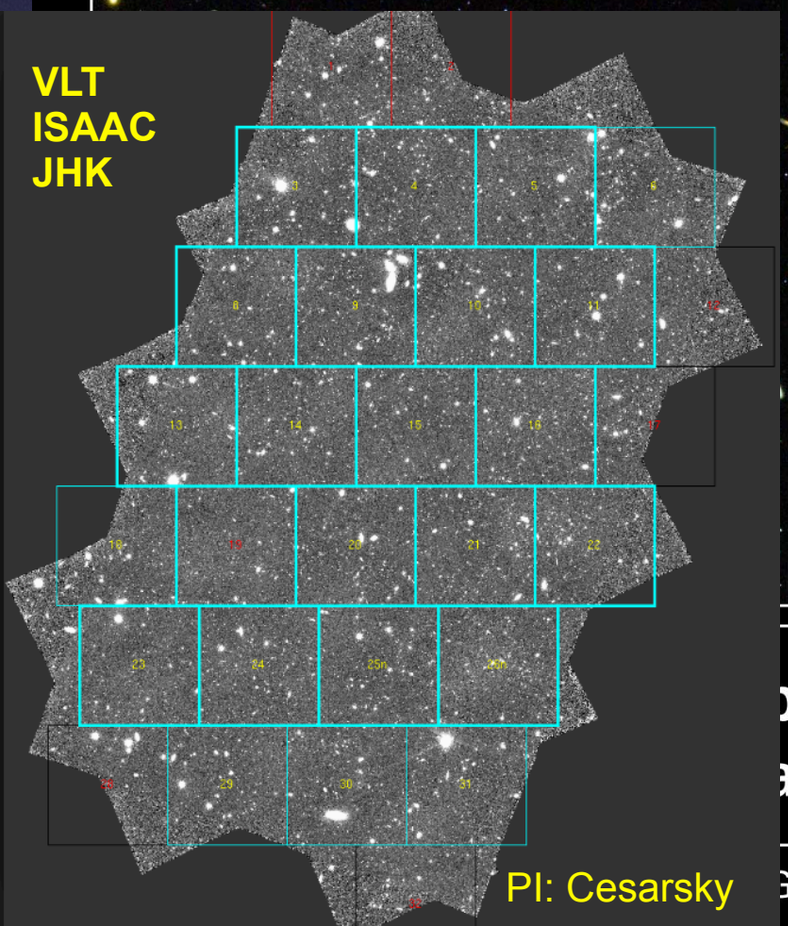
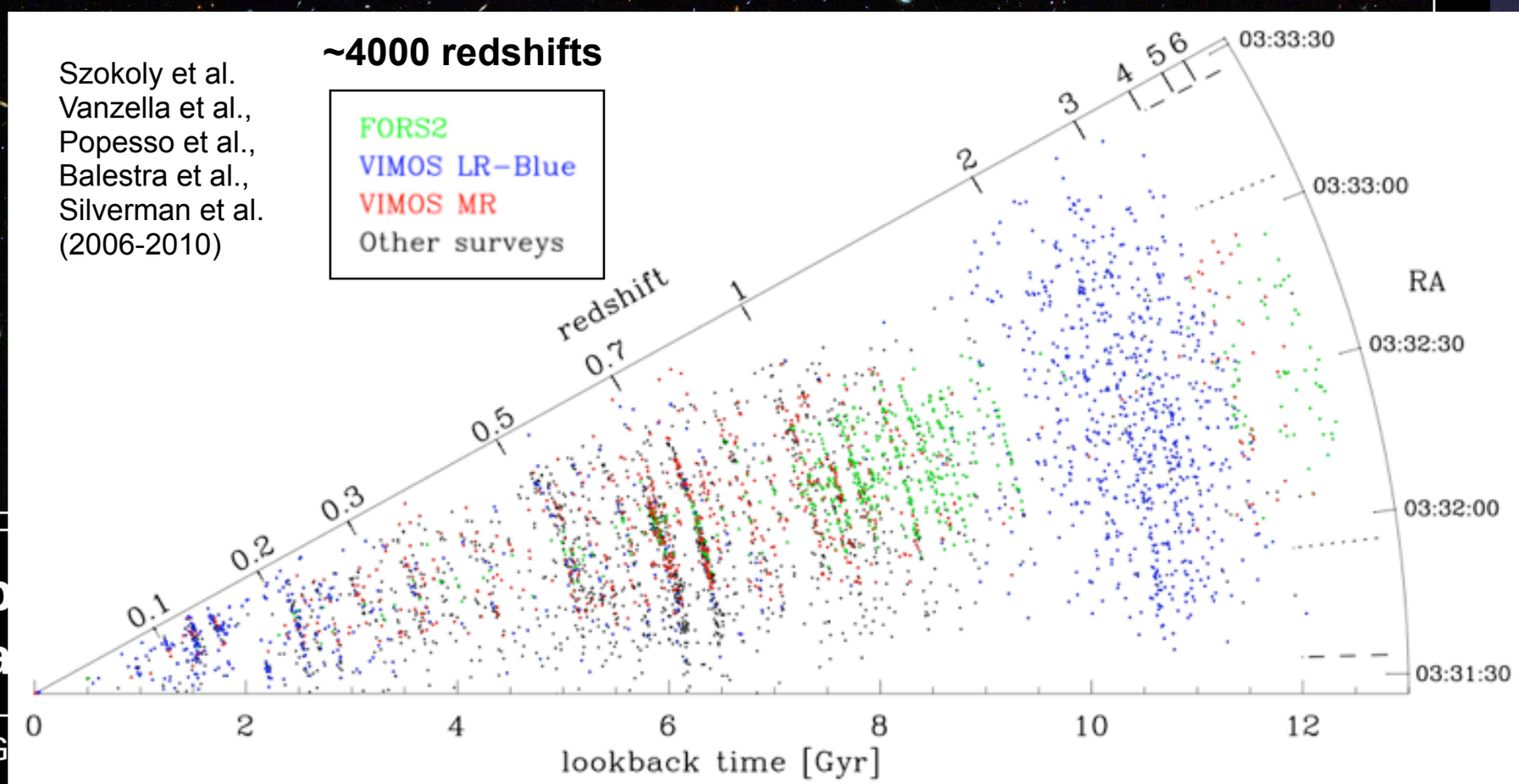
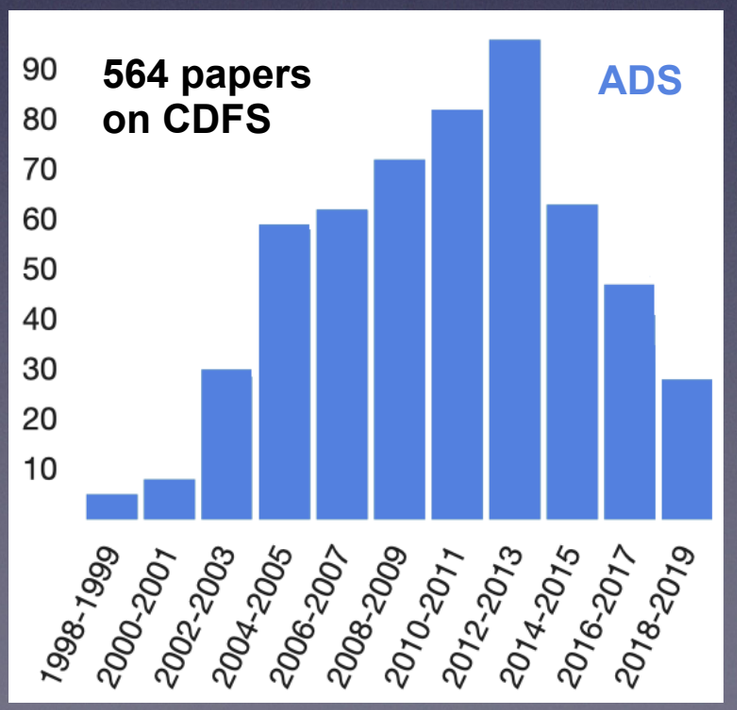




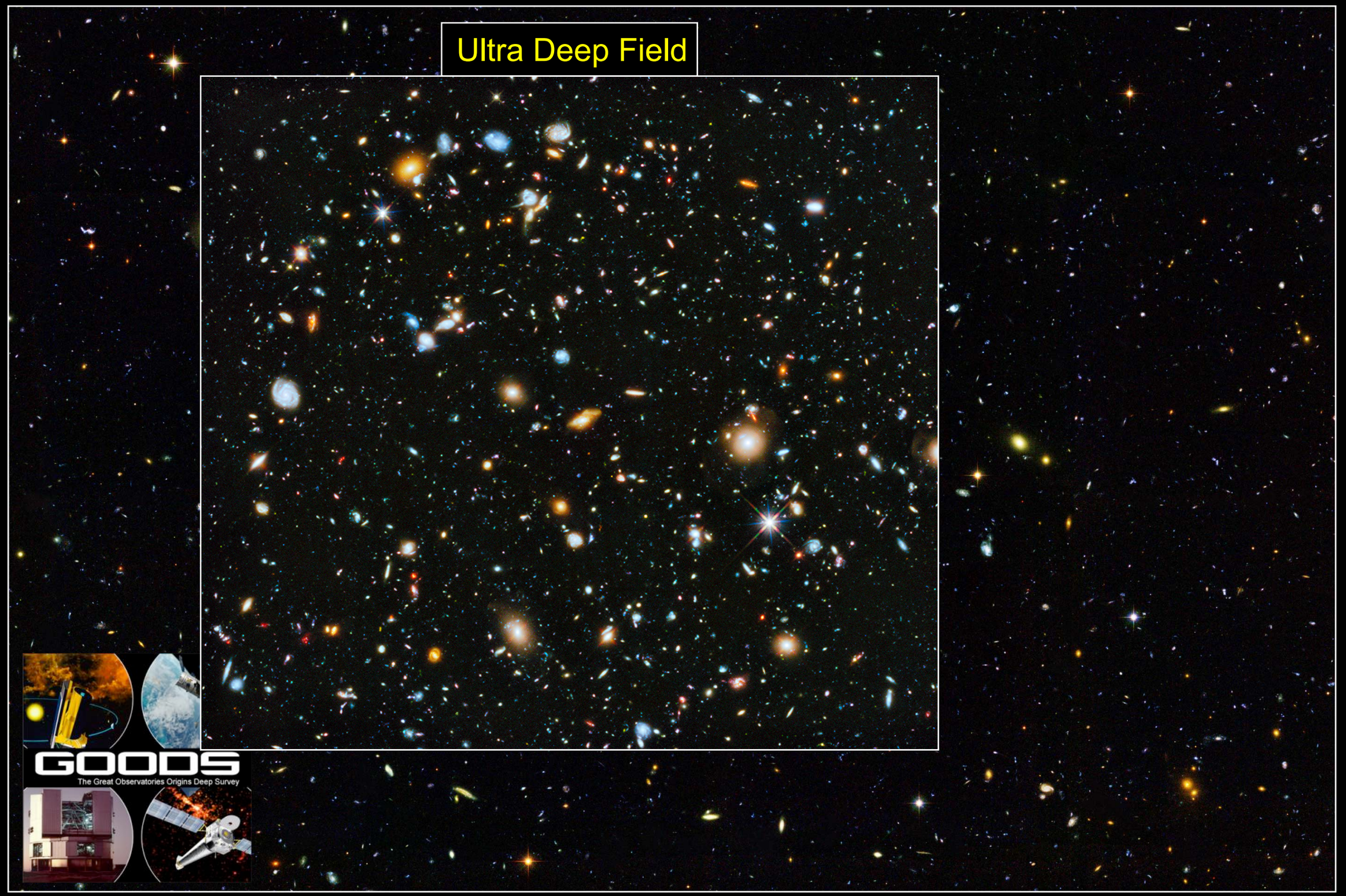
The Impact and Legacy of the CDFS @ESO

- CDFS stimulated one the most intense multi-λ, multi-observatory campaign in astronomy (e.g. VLA survey (PI: K. Kellermann), IR, submm)
- Similar initiatives in other fields launched: COSMOS, CANDELS,…
- Use of ESO facilities on CDFS:
  - 300 independent VLT programs (1999-2018) totalling to 540 nights
    ➜ 10% of VLT science time over 20 years !
  - ESO Survey telescopes (WFI@2.2, VST, VISTA): ~130 nights
  - ALMA: 220 h, 77 programs (~10 independent programs per year)
- 560 refereed articles from CDFS data, 33000 citations (x 2 with GOODS-S)



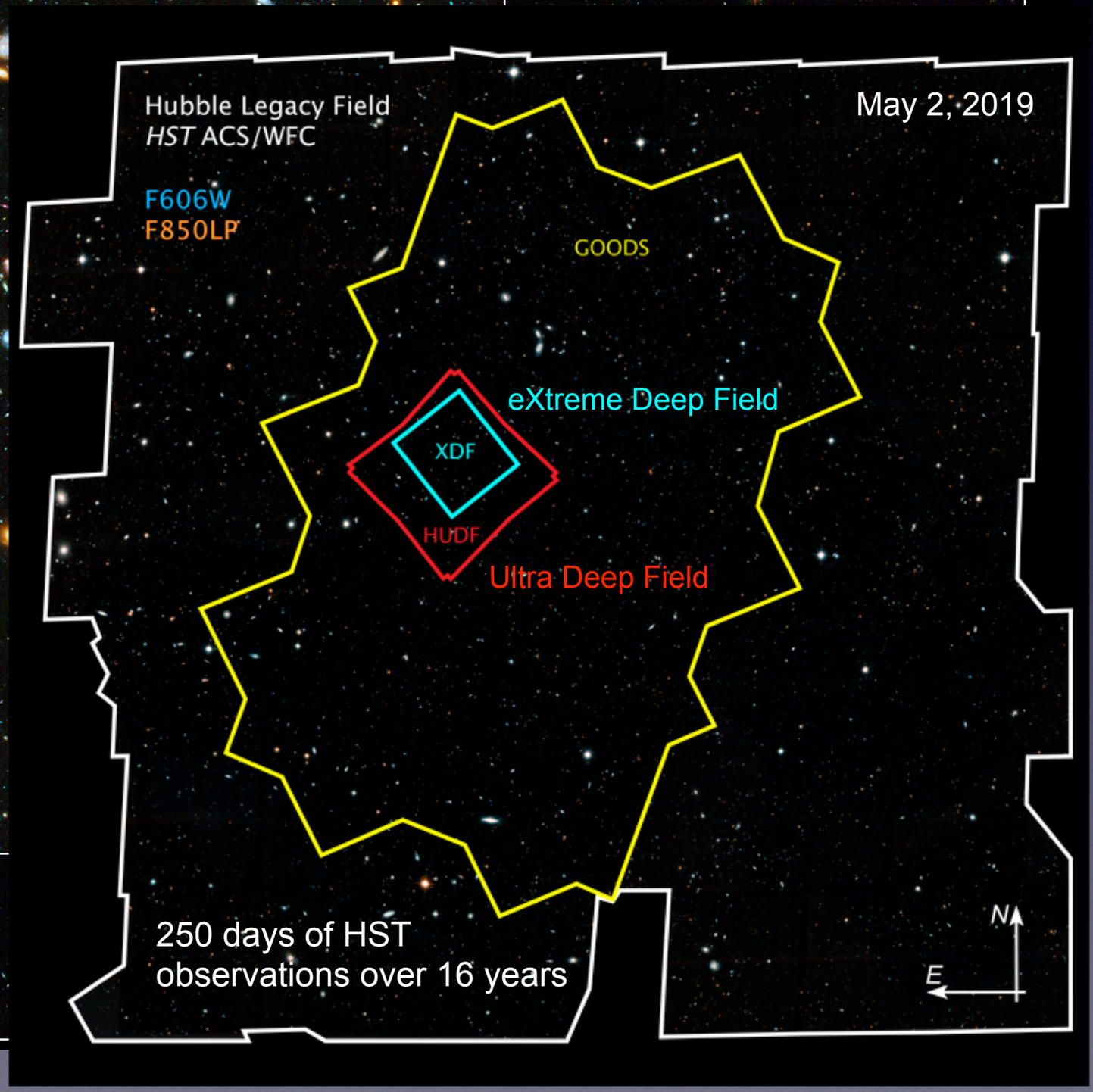
From the CDFS to the Hoary Deep with Hubble

From the CDFS to the Hoary Deep with Hubble



From the CDFS to the Hoary Deep with Hubble

…so much for the "glamour"

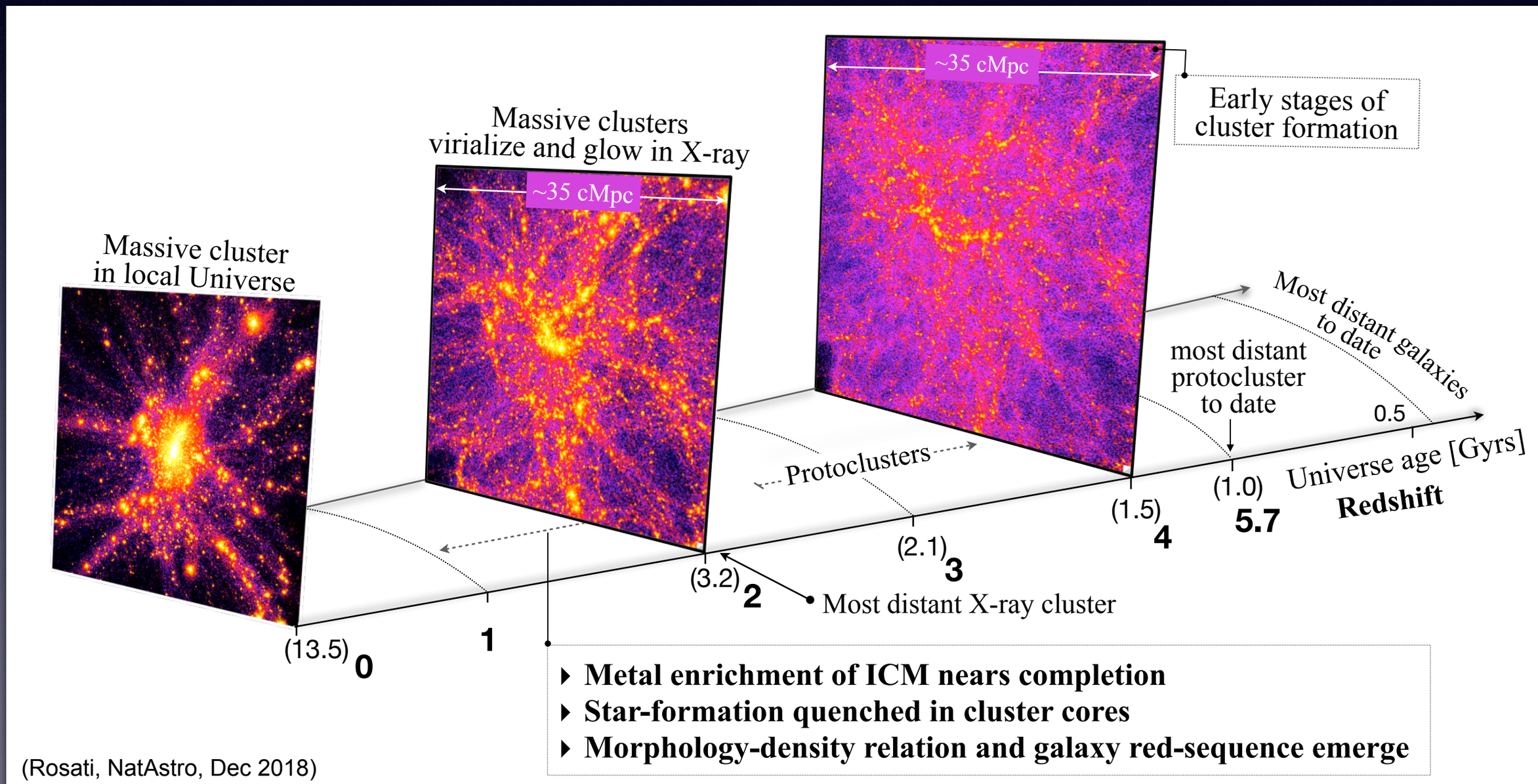


"..understanding Nature requires skill in providing discovery space and care in listening to its replies"

(RG: Sep 2010)

Humble before Nature with a vision, and a plan..!

- Cluster evolution 25 years later: evolution occurs further back in time (z ≫1)
  Nature was indeed more imaginative than us..



(Rosati, NatAstro, Dec 2018)

"..understanding Nature requires skill in providing discovery space and care in listening to its replies"

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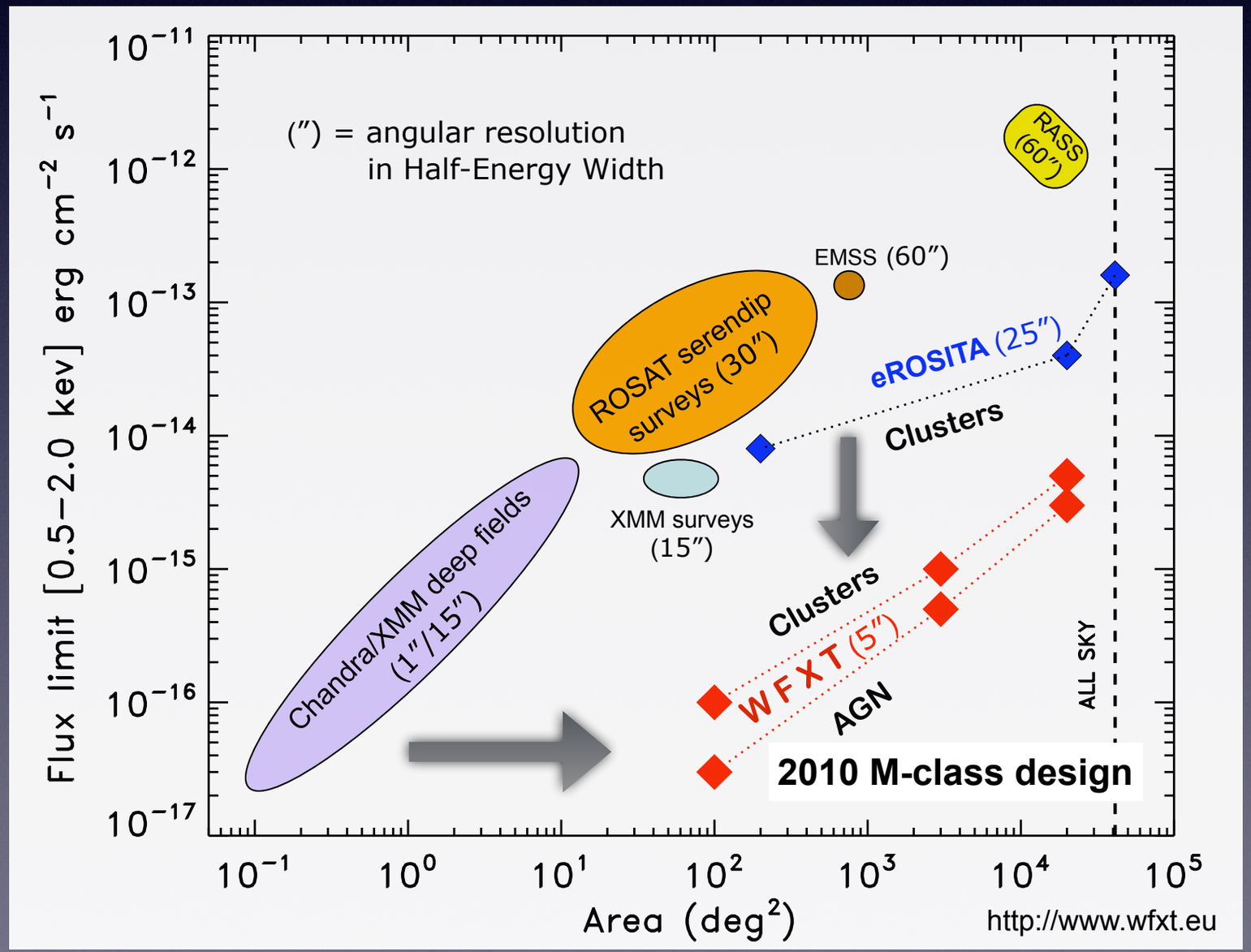
Humble before Nature with a vision, and a plan..!

- Cluster evolution 25 years later: evolution occurs further back in time (z ≫1)
  Nature was indeed more imaginative than us..
- WFXT (RG: "*my best idea*") will preserve its vast discovery power even in 2030:
  X-ray surveys to catch up with area/sensitivity of future surveys (LSST, Euclid, SKA,…)



Tracing Cosmic Evolution with Clusters of Galaxies

Sesto (BZ), Italy − 8-12 July 2019

In memory of Riccardo Giacconi

From my letter to Mirella in January:

…Besides the unparalleled scientific guidance I received, I keep precious record of his ethical principles for our profession and the role it should have in society. All these memories have now become a treasure for me, which I will try to pass on to young generations of scientists.

☞ Retrospective, *Science* (Jan 2019)

SEXTEN CENTER FOR ASTROPHYSICS