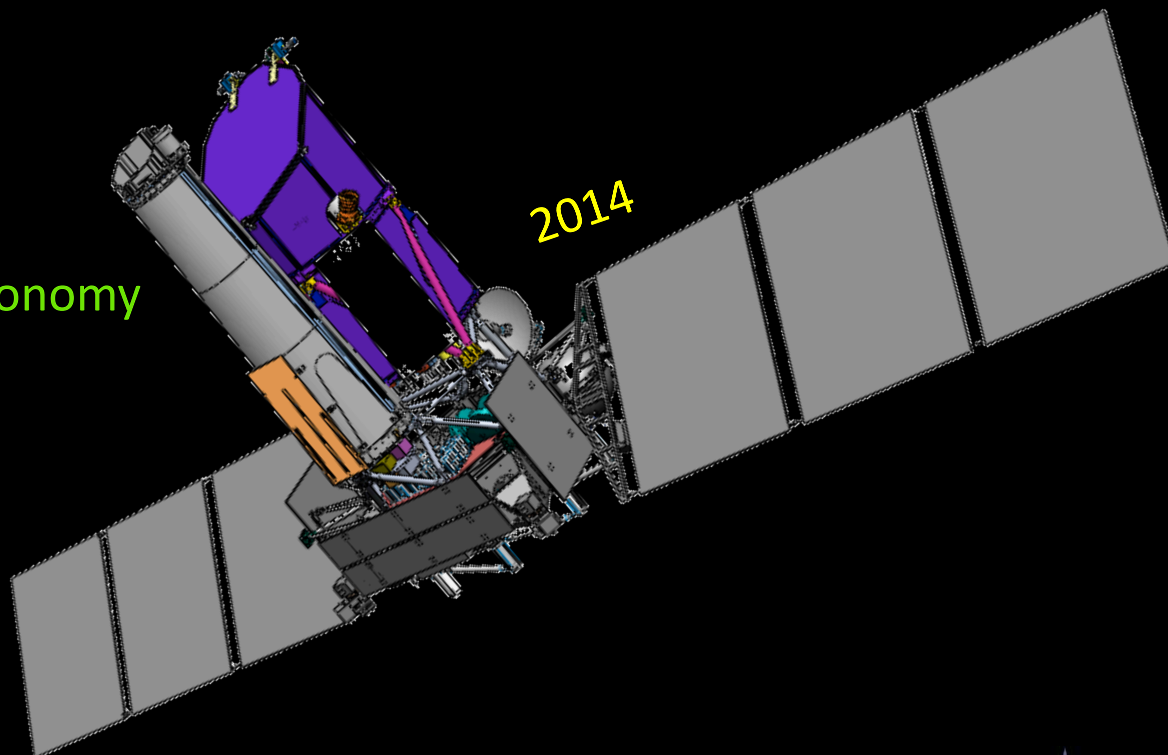
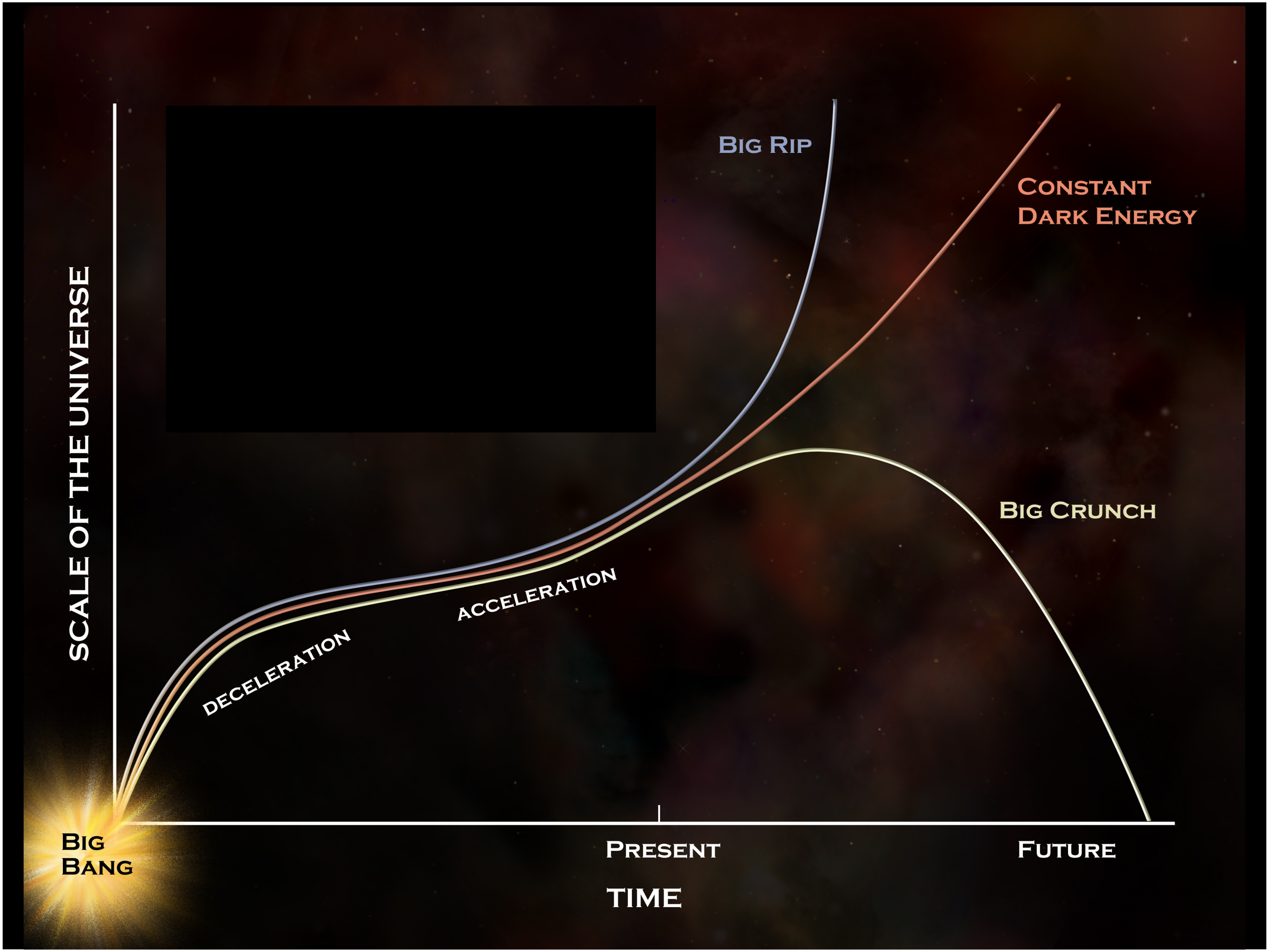
Cluster Cosmology and Prospects for *eROSITA*

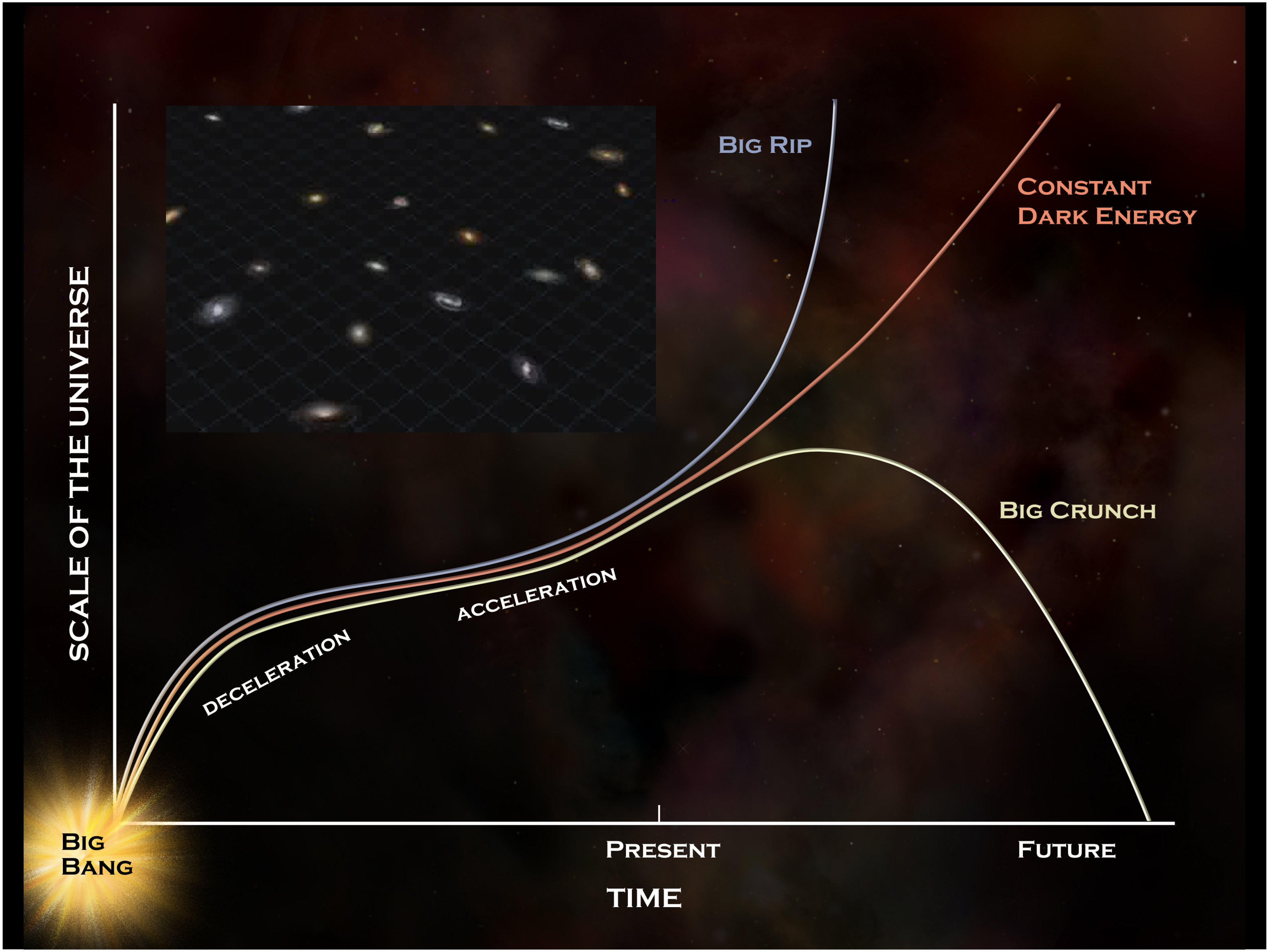


Thomas Reiprich
Argelander Institute for Astronomy
Bonn University
http://dark-energy.net

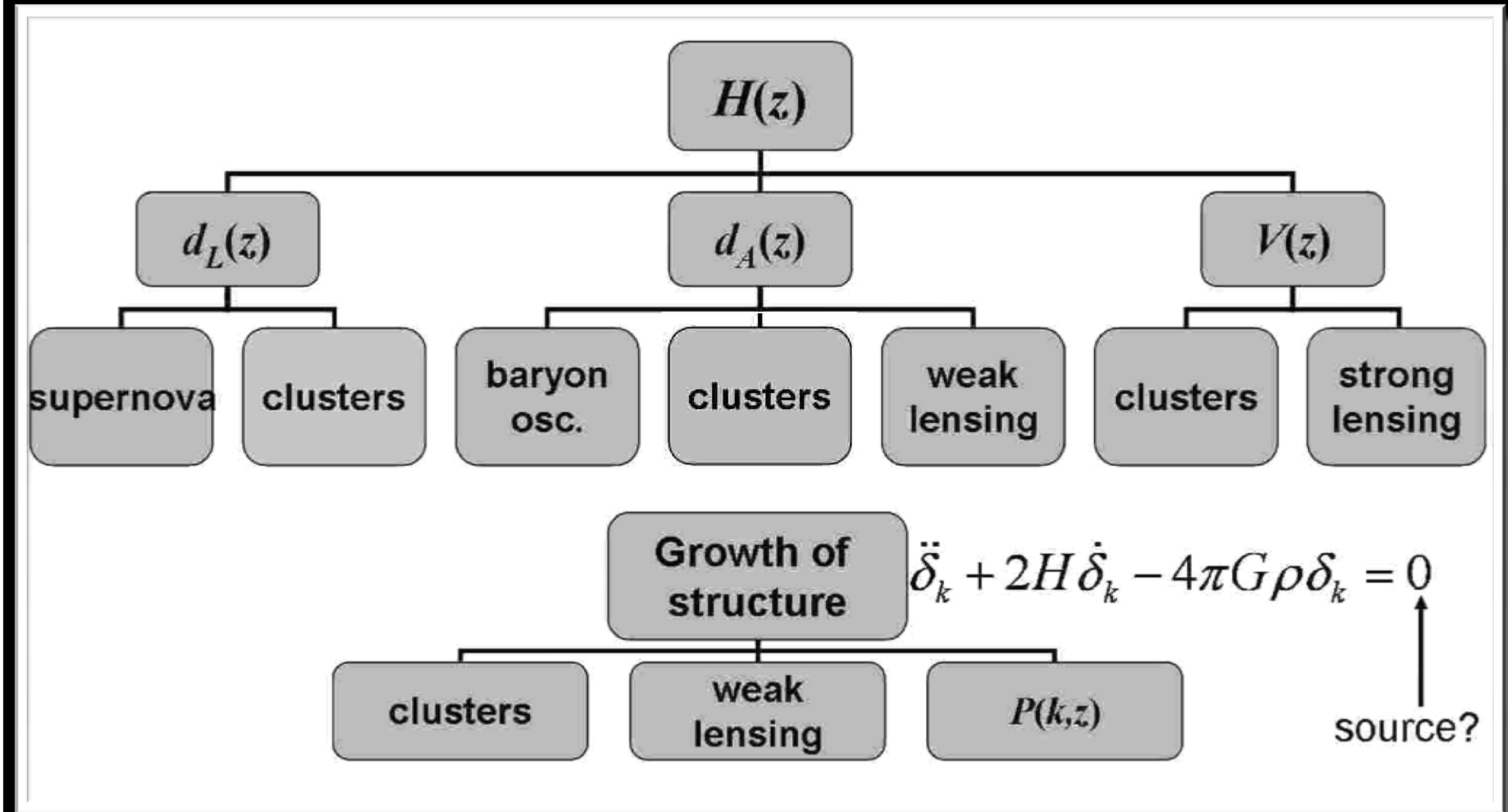
Overview

- *Conclusion:* We will constrain w_{DE} to <3% with *eROSITA* using ALL massive galaxy clusters in the observable Universe.
- What are clusters?
- How can they be used to constrain cosmological parameters?
- Why use X-rays to study them?
- What is *eROSITA*?
- Forecasts and comparison to other DE probes.


[redacted]
Big Rip
Constant
Dark Energy
Big Crunch
Scale of the Universe
Deceleration
Acceleration
Big
Bang
Present
Future
Time


Big Rip
Constant
Dark Energy
Big Crunch
Scale of the Universe
deceleration
acceleration
Big
Bang
Present
Future
Time

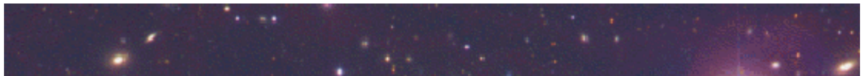
Dark Energy Probes

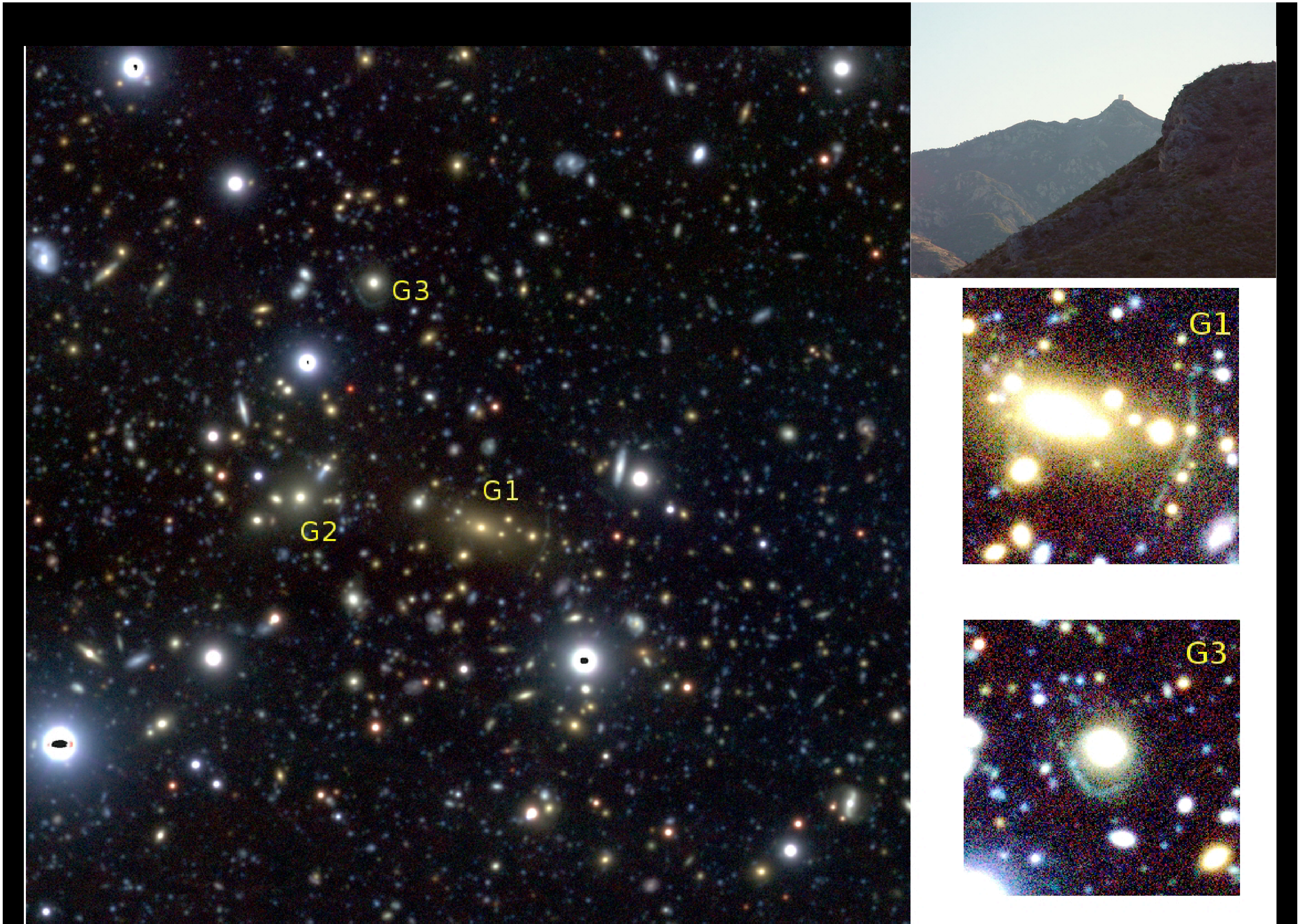


E. Kolb, see also US-DETF report.

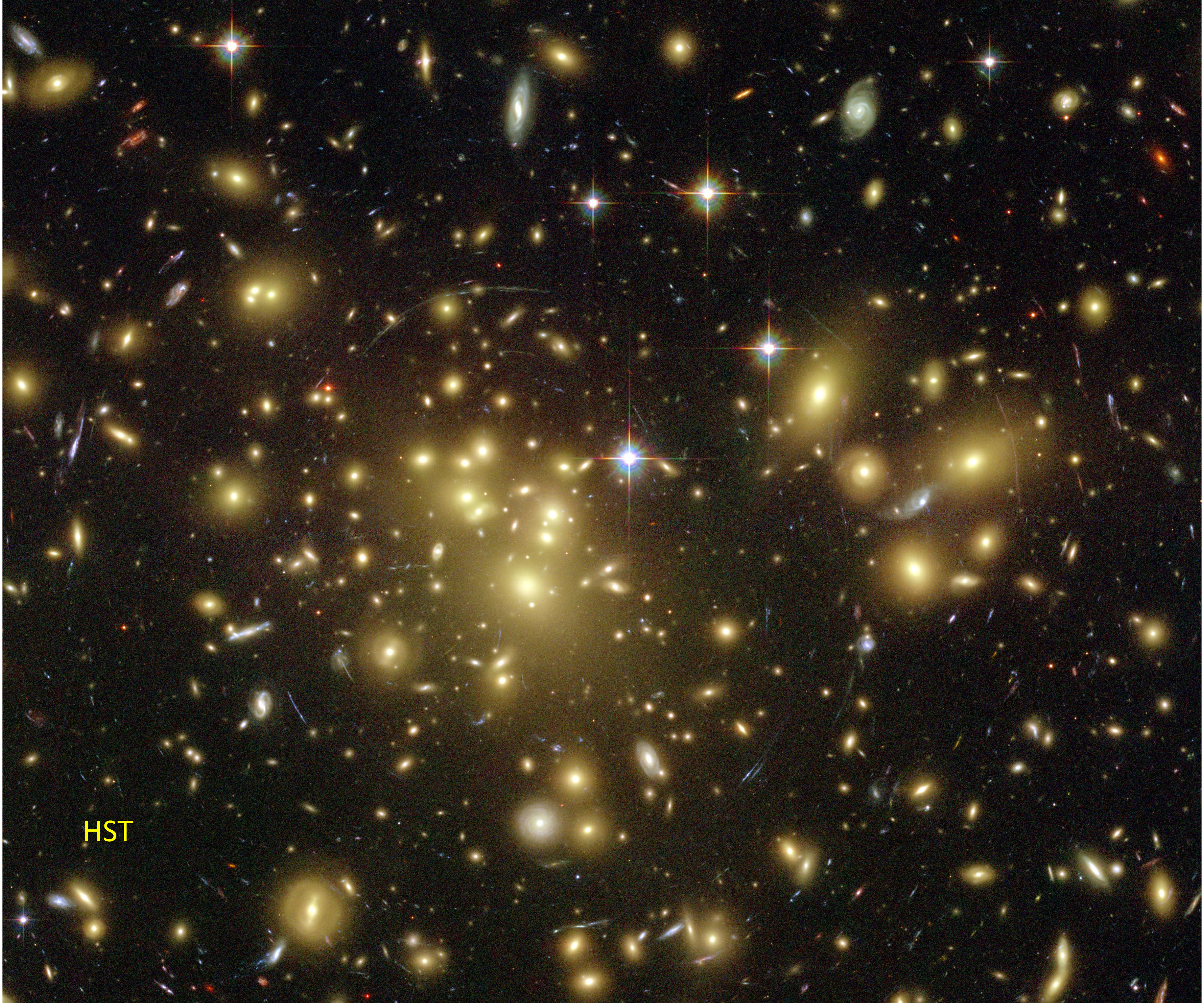
Galaxy Clusters

- Clusters of ~1,000 galaxies.
- Largest, most massive (~10^{15} $M_{\odot}$) collapsed objects in the Universe.





Israel et al. (2010)

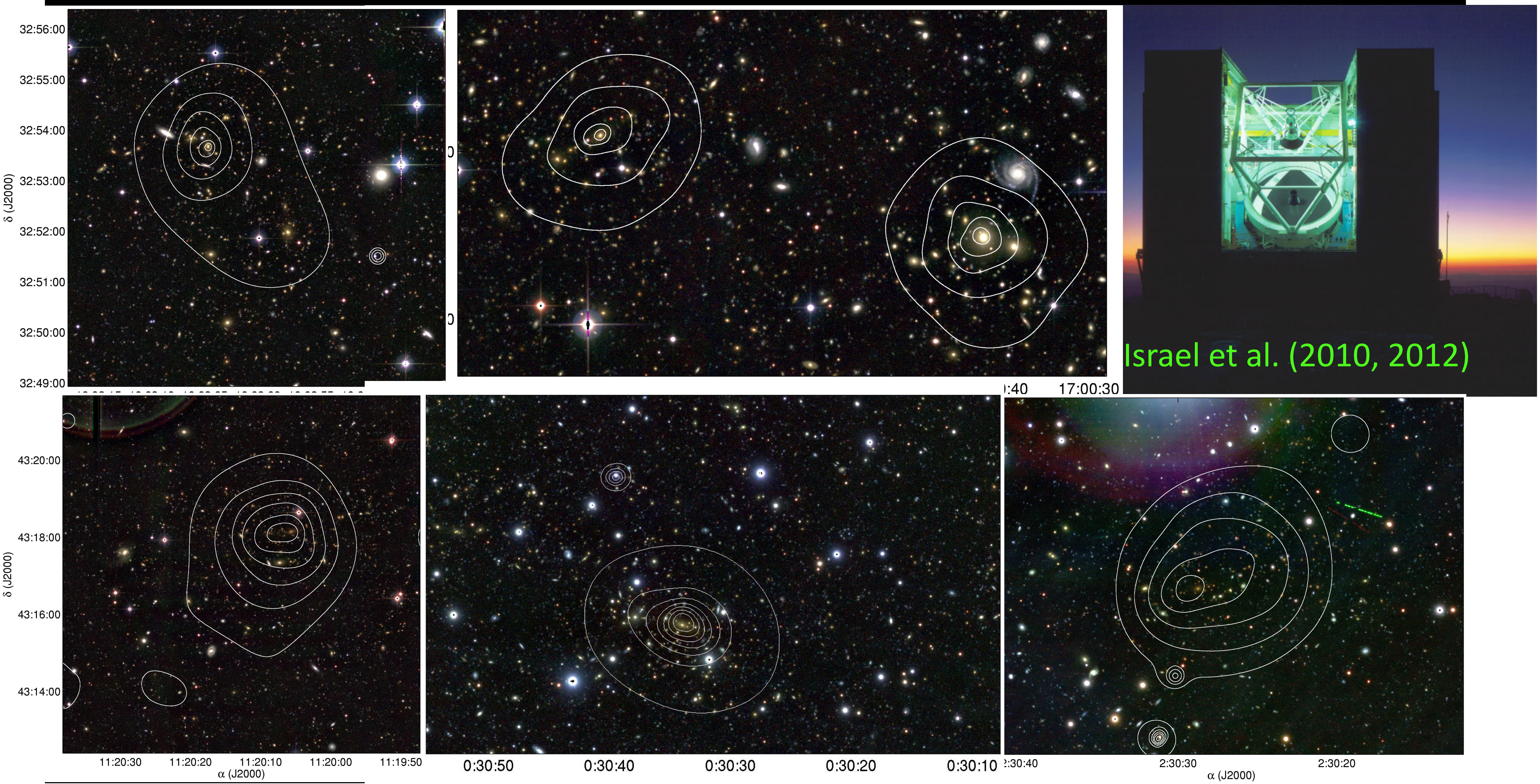

HST


Chandra


HST+Chandra


SDSS+Chandra

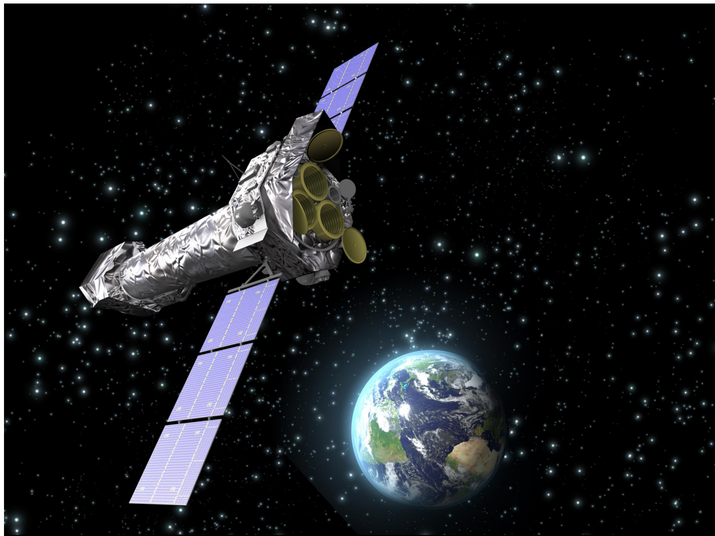
Weak Lensing Observations of 400d Galaxy Clusters



z=0.45 (left) & foreground cluster at

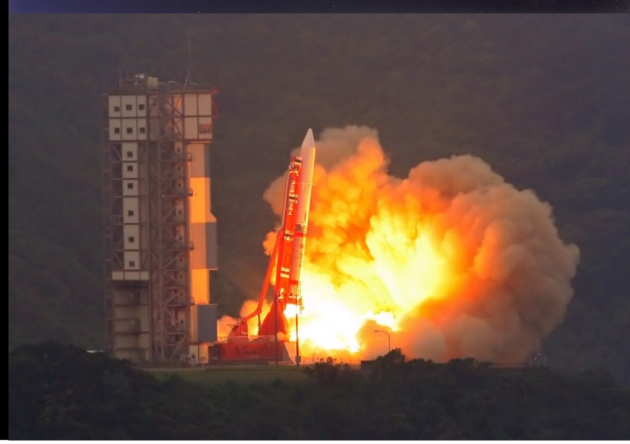
Intracluster Medium (ICM)

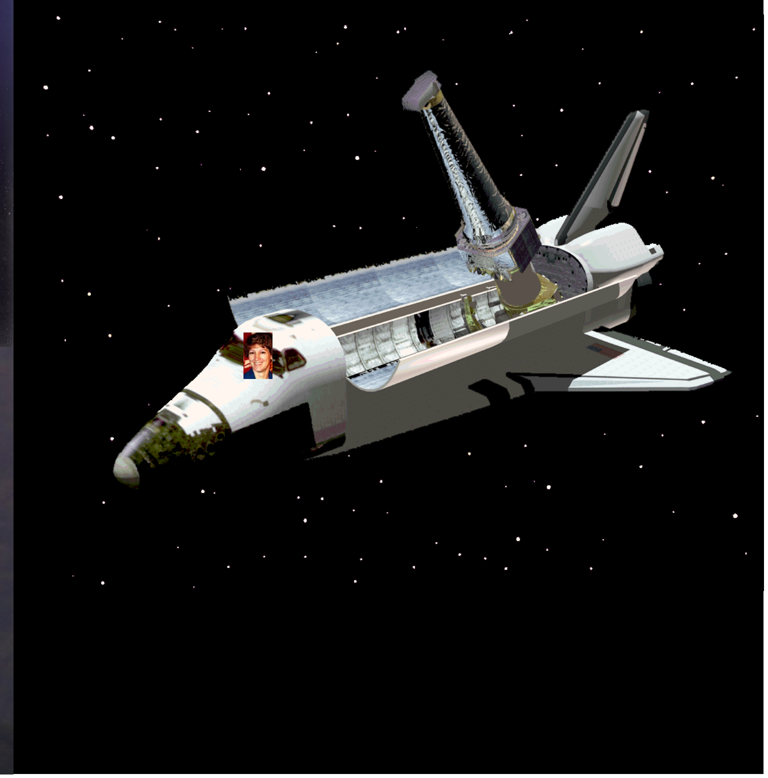
- Hot: $T \sim (10^7$–$10^8)$ K; $k_B T \sim (1$–$10)$ keV.
- Low density: <0.1 particles/cm^{-3}.
- $M_{\mathrm{ICM}} \sim 10\ M_{\mathrm{stars}}$. $L_X \sim (10^{44}$–$10^{45})$ erg/s.
- $M_{\mathrm{total}} \sim 10\ M_{\mathrm{ICM}}$. D ~ 10^7 Lightyears.

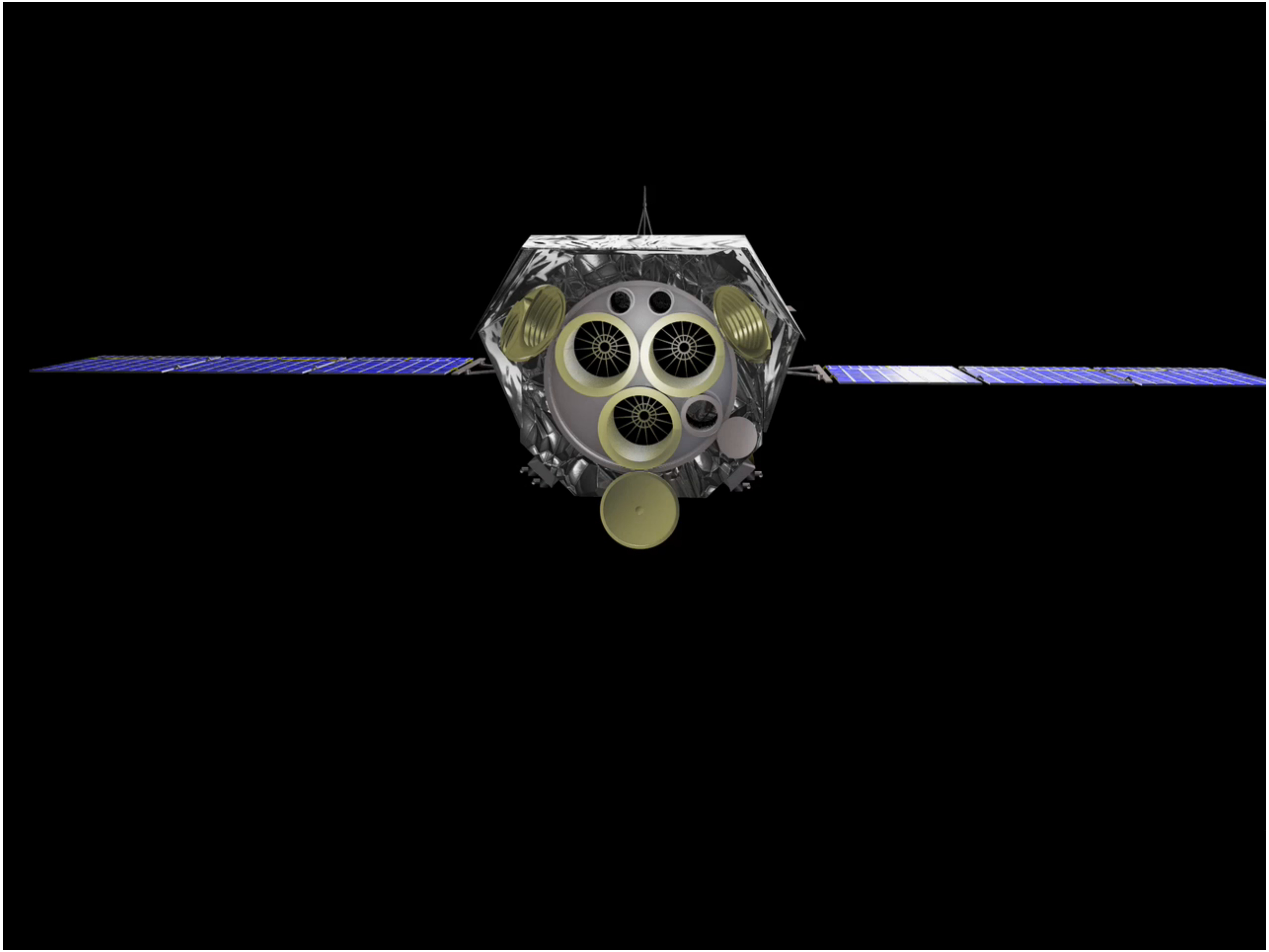


XMM-Newton Launch

European Space Agency







X-Ray Mass Determination

$$P = \frac{k_B}{\mu m_p} \rho_{gas} T_{gas}$$

$$\frac{1}{\rho_{gas}} \frac{dP}{dr} = -\frac{d\Phi_{grav}}{dr}$$

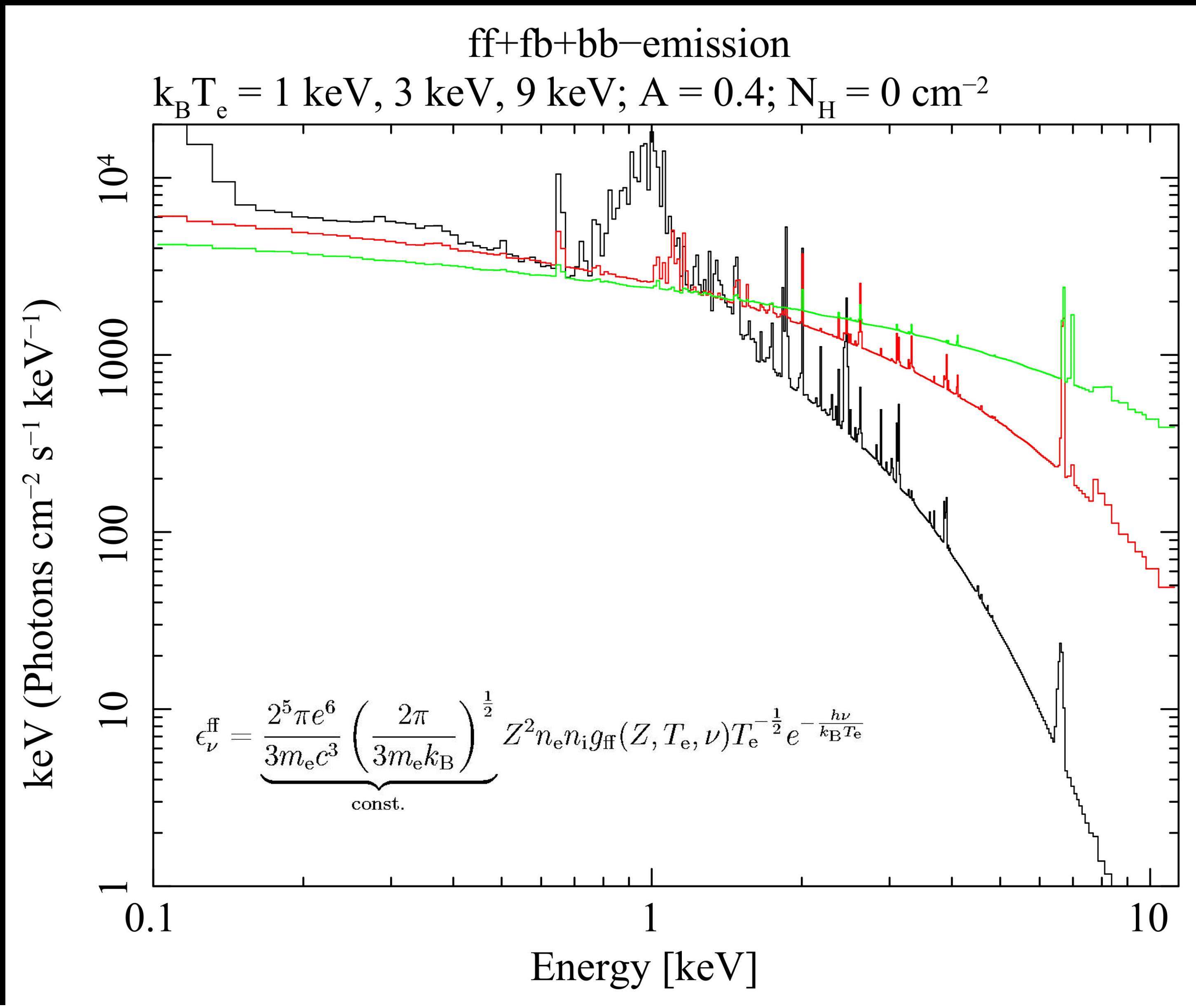
$$\frac{d\Phi_{grav}}{dr} = \frac{G M_{tot}(<r)}{r^2}$$

$$\frac{1}{\rho_{gas}} \frac{dP}{dr} = \frac{k_B T_{gas}}{\mu m_p} \frac{1}{r} \left(\frac{d \ln \rho_{gas}}{d \ln r} + \frac{d \ln T_{gas}}{d \ln r} \right)$$

$$M_{tot}(<r) = -\frac{k_B T_{gas} r}{G \mu m_p} \left(\frac{d \ln \rho_{gas}}{d \ln r} + \frac{d \ln T_{gas}}{d \ln r} \right).$$

$$PV = N k_B T$$

Gas Temperature and Density



$$\epsilon = n_e n_H \Lambda(T, A)$$

Why Use Clusters for Cosmology? Great History!

- First evidence for dark matter (30s).
- Strongest evidence for Ω_M<1 (90s).
- First evidence for σ_8<0.9 (00s).
- Clearest evidence for existence of dark matter and its small interaction cross section (00s).
- First Stage IV dark energy probe (10s).

Why Use Clusters for Cosmology? Versatile and Multi-λ!

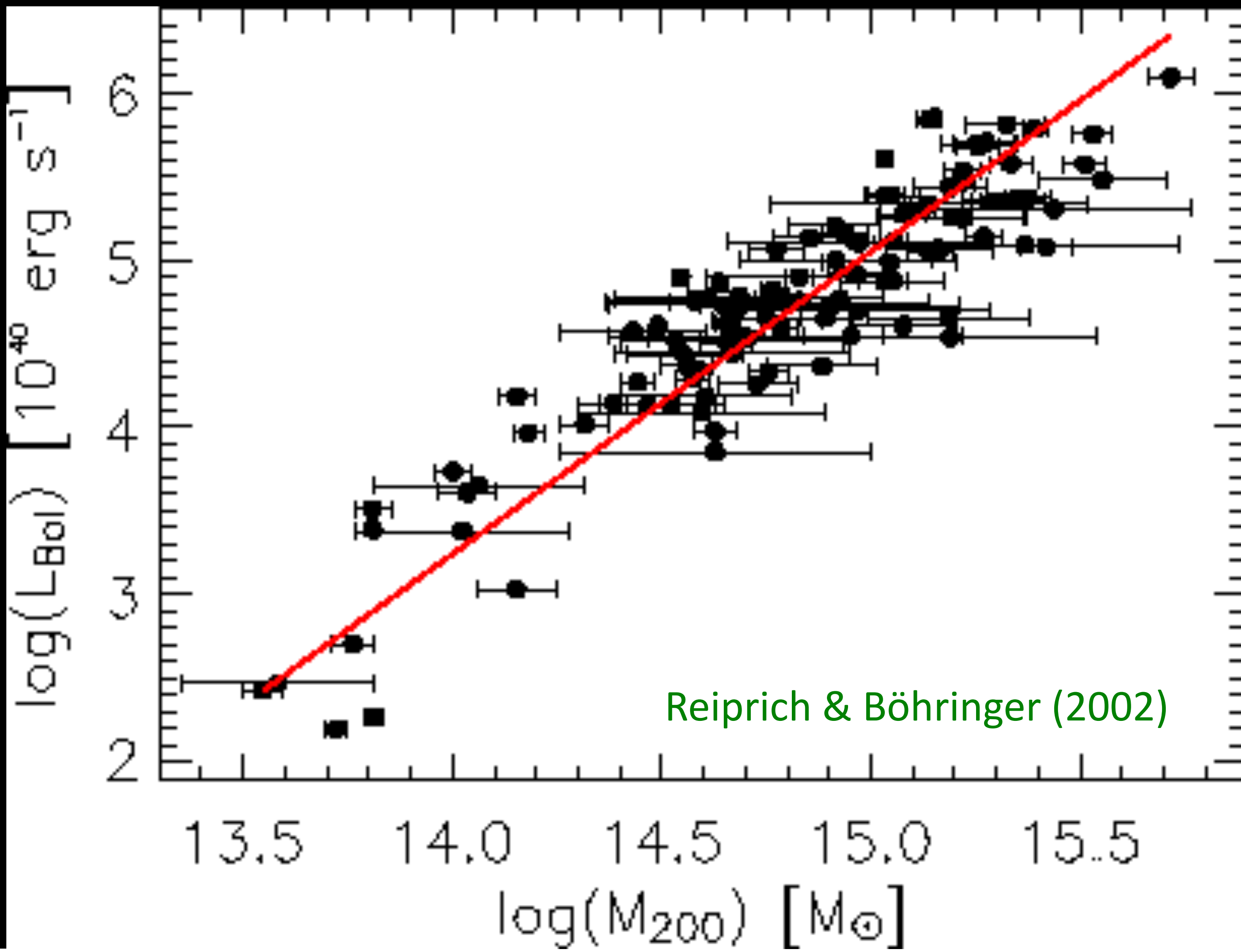
Methods

- Baryons (fraction, *apparent* evolution),
- M/L * luminosity density,
- power spectrum (normalization, shape, evolution, baryonic wiggles),
- mergers (frequency, evolution),
- SZ + X-rays $\Rightarrow H_0$,
- mass function (amplitude, shape, evolution),
- ….

Wavebands

- Optical/infrared (galaxies, lensing),
- Sub-/mm (SZ-effect),
- Radio (radio halos / relics, WATs / NATs),
- gamma rays (?),
- X-rays,
- ….

As we'll see, masses important; selection observable, L_X, correlates well with mass.



Why is Cluster Growth Sensitive to Underlying Cosmology?

Galaxy Cluster Evolution and Equation of State of Dark Energy

- Growth of structure depends on expansion rate; i.e., on the Hubble parameter $H(z) = H_0\, E(z)$:

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta$$

$$E^2(z) \equiv \Omega_{\rm r}(1+z)^4 + \Omega_{\rm m}(1+z)^3 + \Omega_{\rm k}(1+z)^2 + \Omega_{\rm DE}e^{3\int_0^z [1+w(z')]\,{\rm d}\ln(1+z')} + \Omega$$

- $H(z)$ depends on equation of state, $w = p/(\rho c^2)$.

- Evolution of cluster number density depends on *w*!
- And on whether or not the first equation needs to be modified.

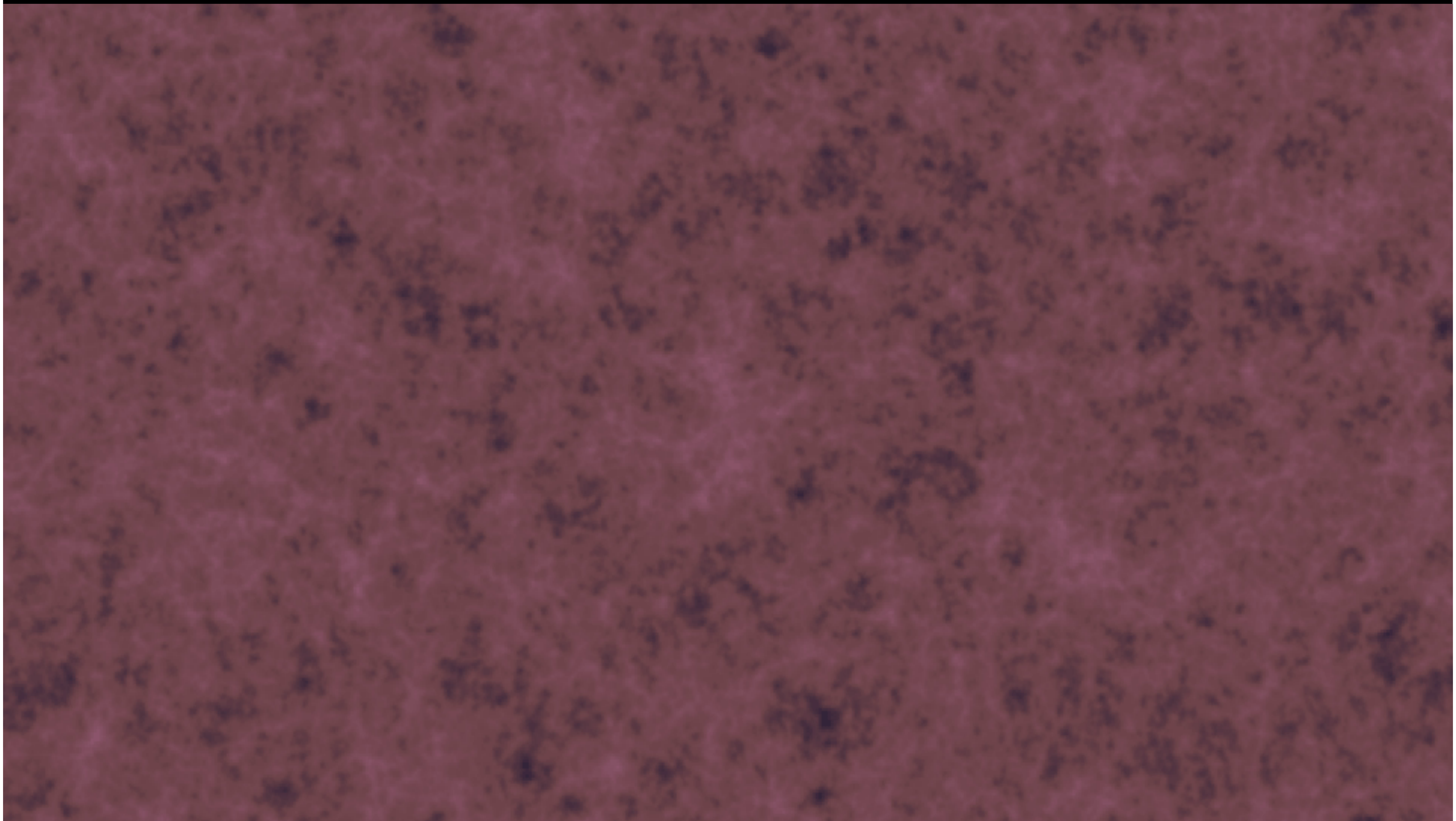
Cluster Mass Function

Cluster mass function is *exponentially* sensitive to the growth factor.

$$\frac{dn(M,z)}{dM} = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}_0}{M}\,\frac{\delta_c^0(z)}{\sigma(M)^2}\left|\frac{d\sigma(M)}{dM}\right|\exp\left(-\frac{\delta_c^0(z)^2}{2\,\sigma(M)^2}\right)$$

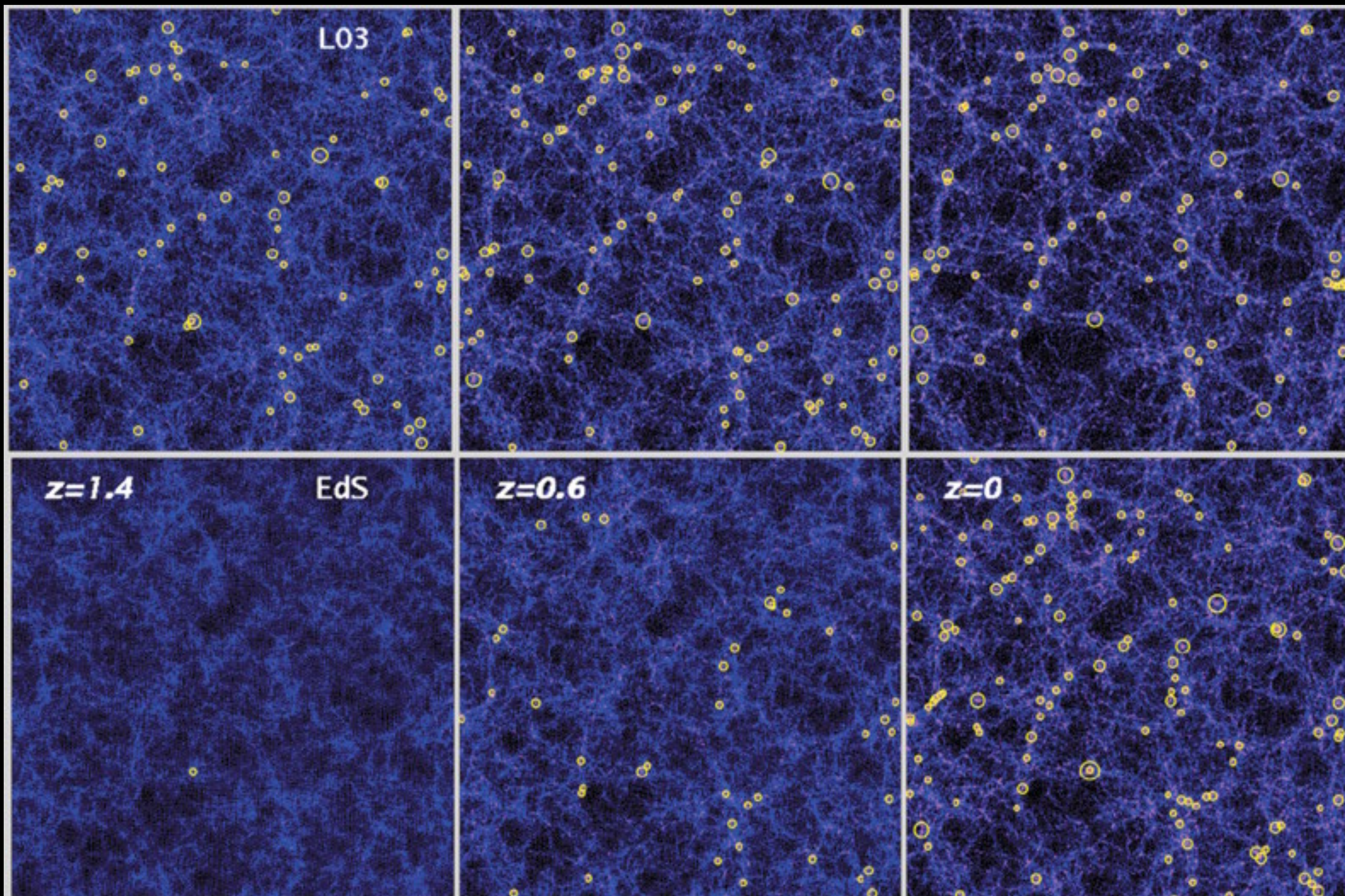
This has been known since the 70's (e.g., Press & Schechter).

Accurate masses and search volumes needed.
Observable–mass relation is important.

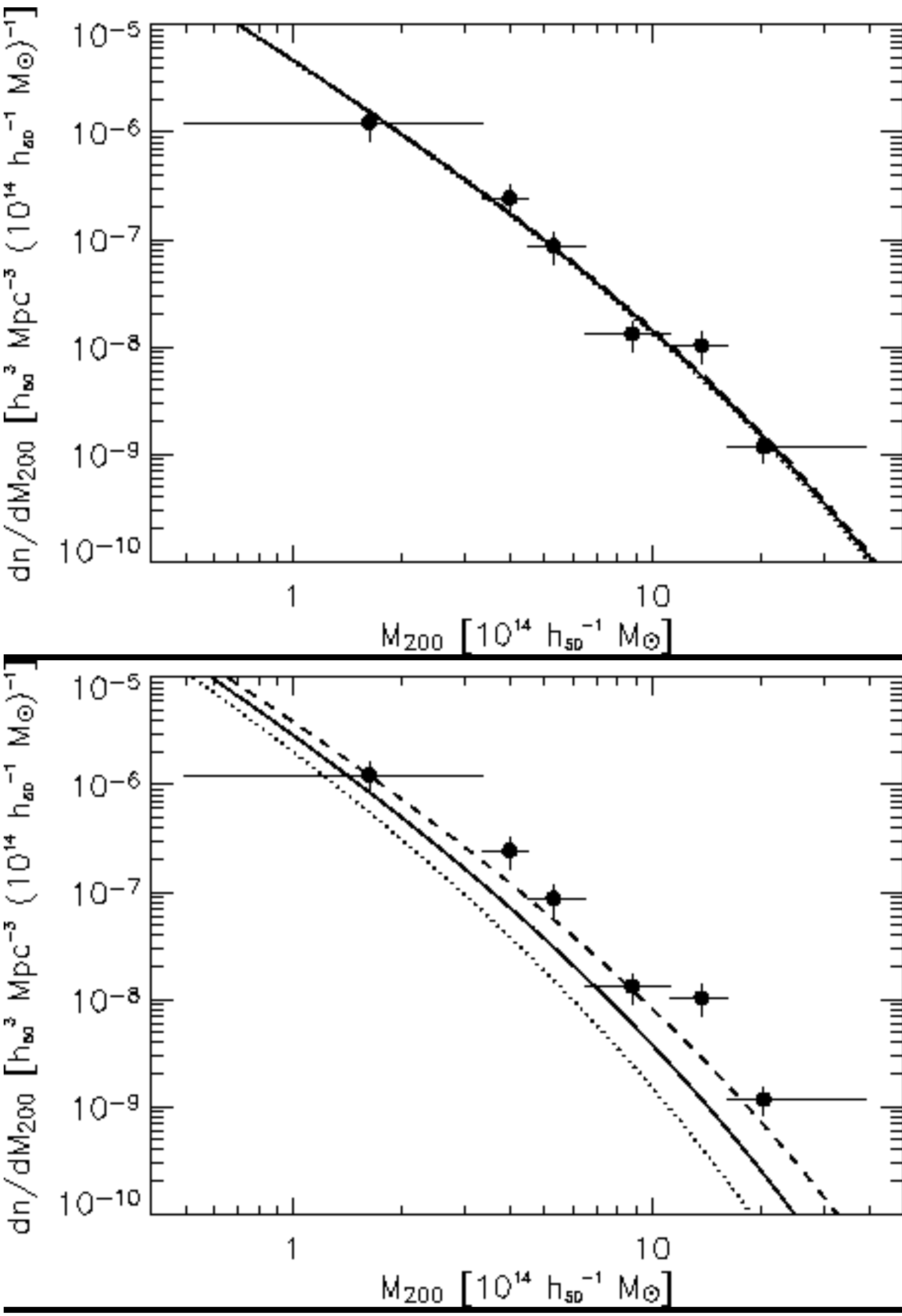


V. Springel

Galaxy Cluster Evolution



Borgani & Guzzo (2001)

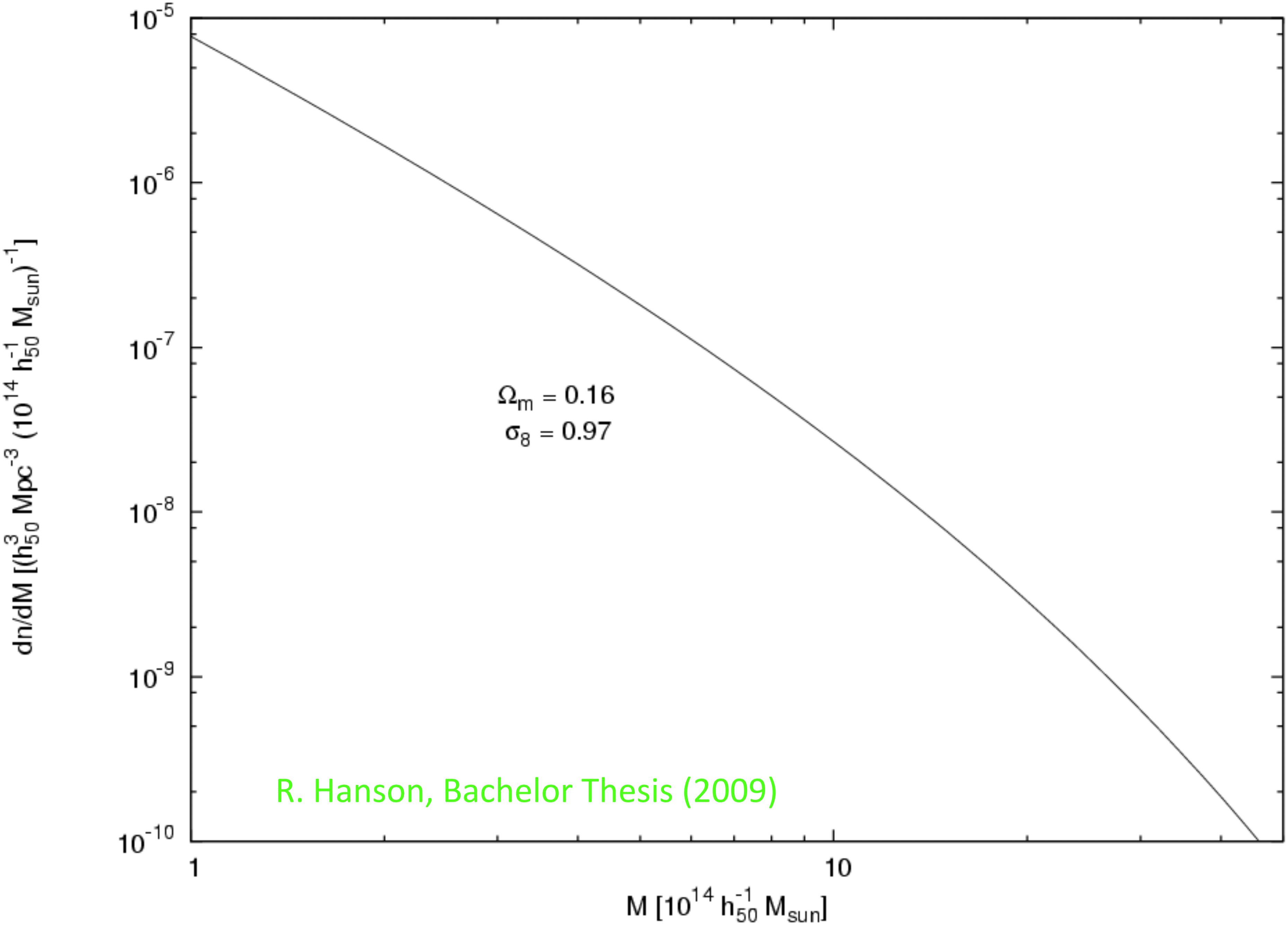


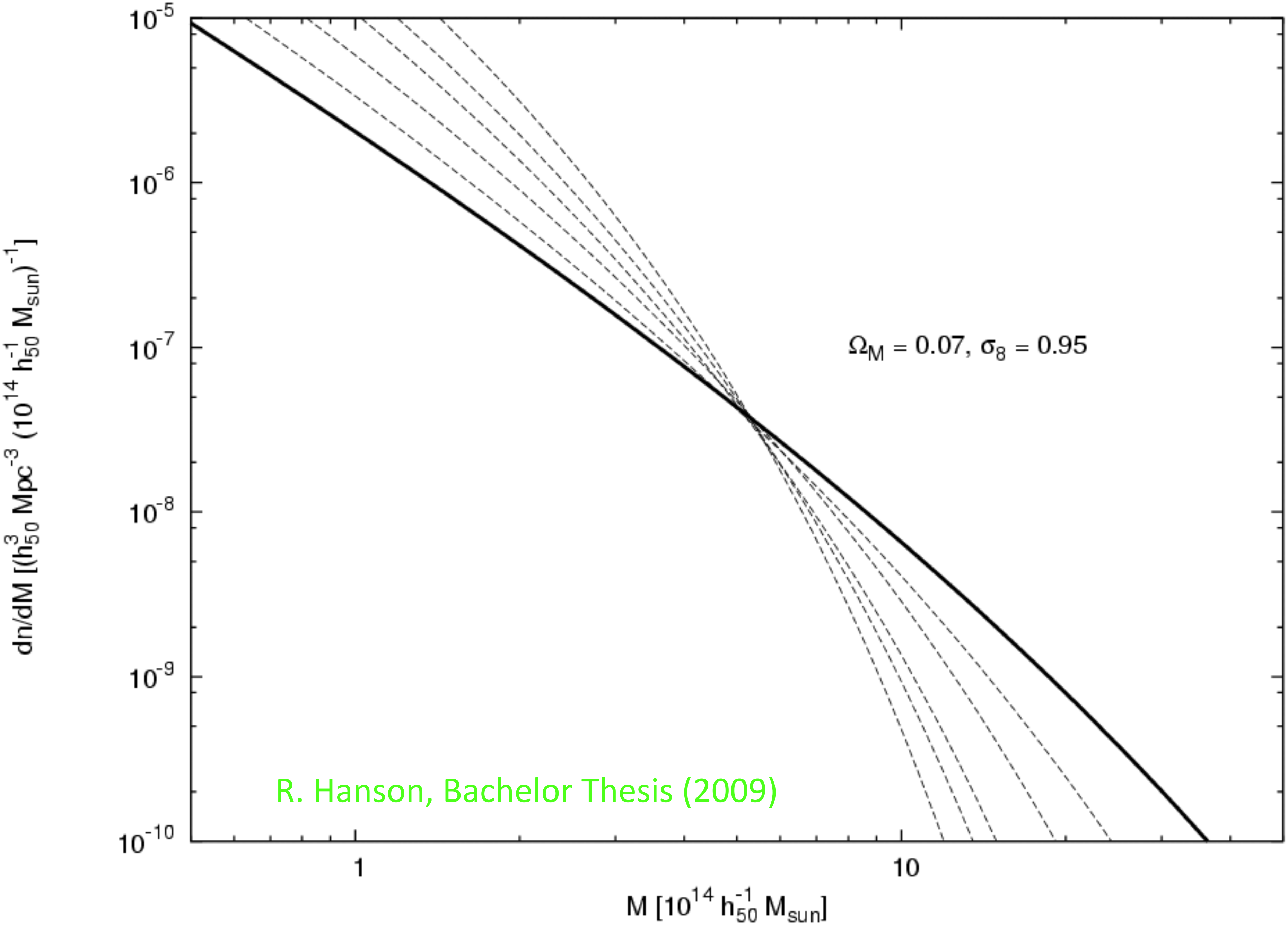
Galaxy cluster mass function

$z = 0.05$

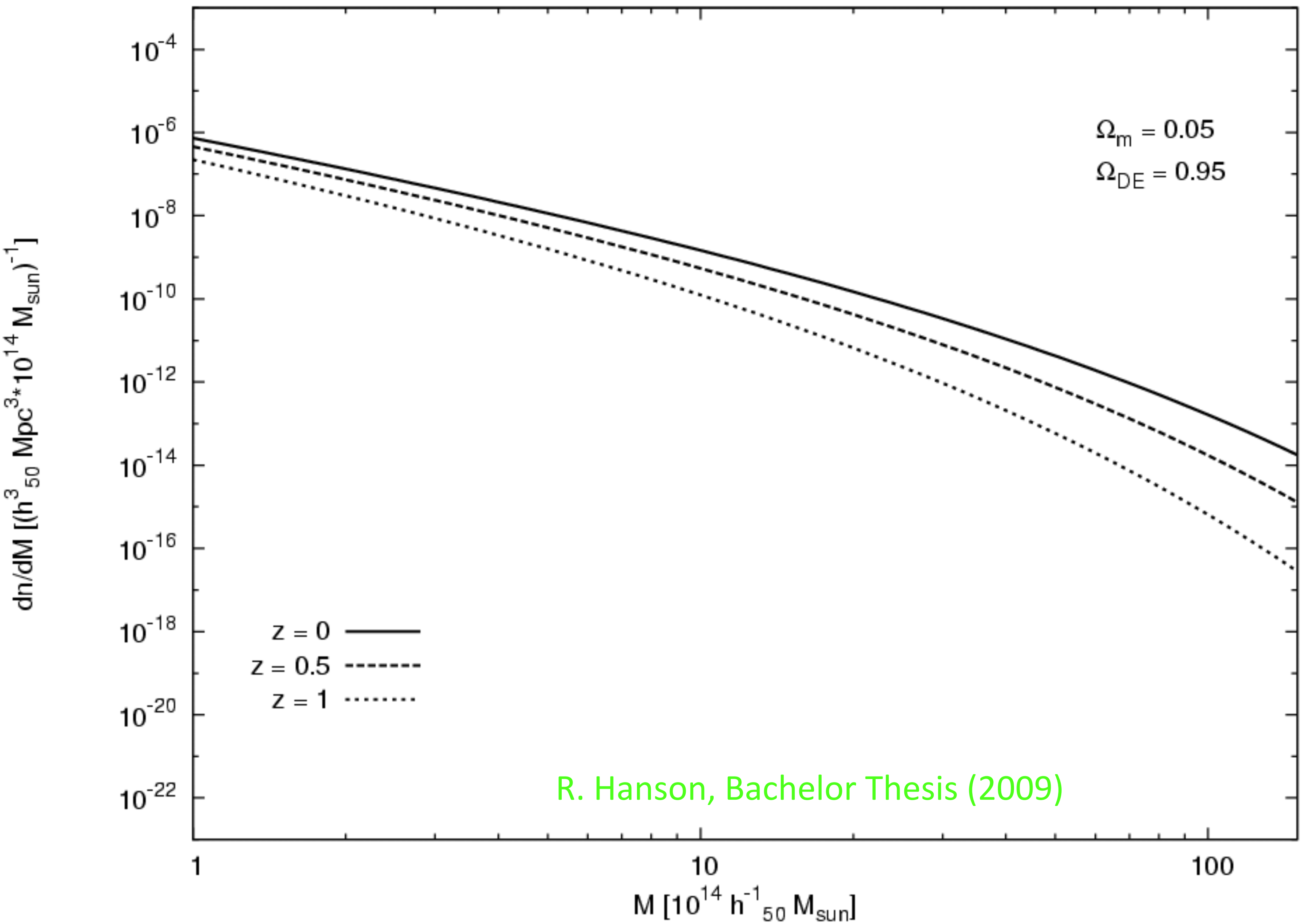
$z = 0.6$

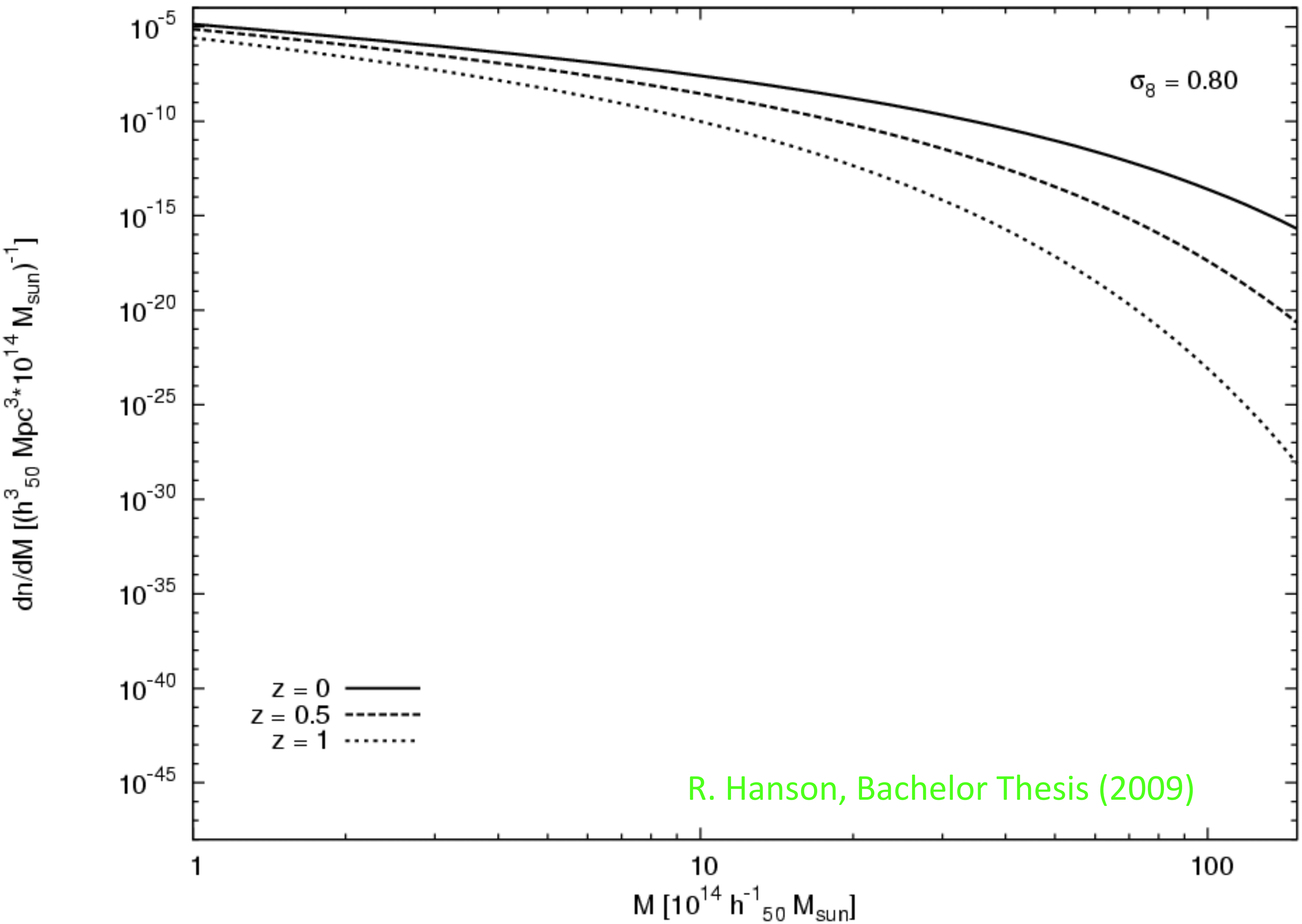
solid: $w = -1$,
dashed: $w = -0.5$,
dotted: $w = -1.25$.


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
dn/dM [(h_{50}^3 Mpc^{-3} (10^{14} h_{50}^{-1} M_{sun})$^{-1}$]
$\Omega_m = 0.16$
$\sigma_8 = 0.97$
R. Hanson, Bachelor Thesis (2009)
1
10
M [10^{14} h_{50}^{-1} M_{sun}]

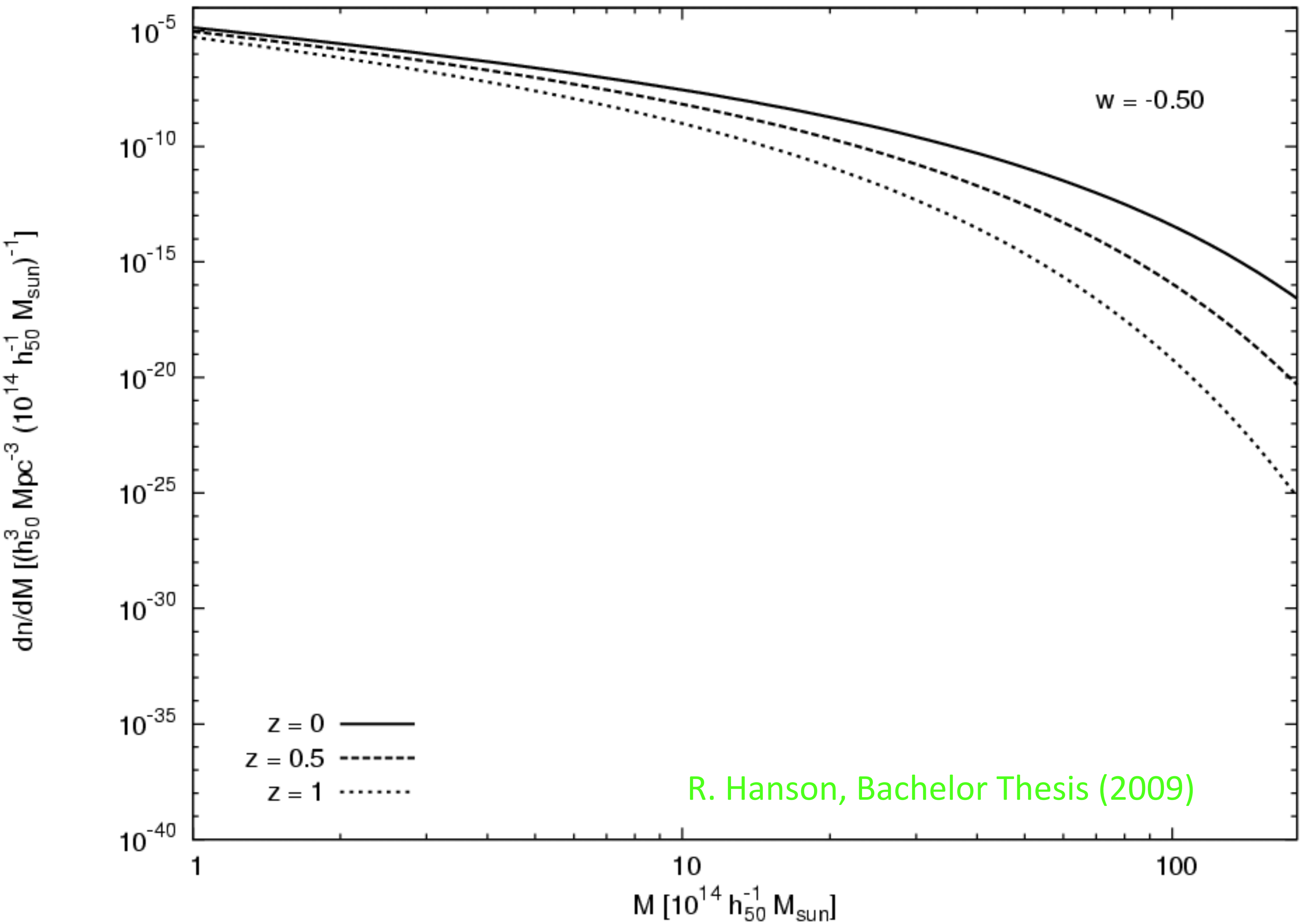


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
dn/dM [(h_{50}^{3} Mpc^{-3} (10^{14} h_{50}^{-1} M_{sun})$^{-1}$]
$\Omega_M = 0.07,\ \sigma_8 = 0.95$
R. Hanson, Bachelor Thesis (2009)
1
10
M [10^{14} h_{50}^{-1} M_{sun}]

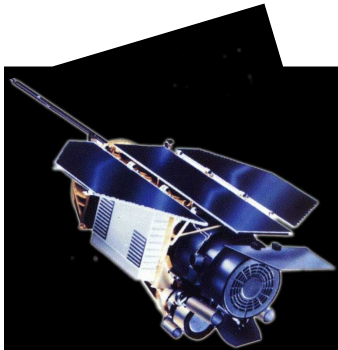

dn/dM [(h^3_50 Mpc^3*10^14 M_sun)^-1]
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
1
10
100
M [10^14 h^-1_50 M_sun]
Ω_m = 0.05
Ω_DE = 0.95
z = 0
z = 0.5
z = 1
R. Hanson, Bachelor Thesis (2009)



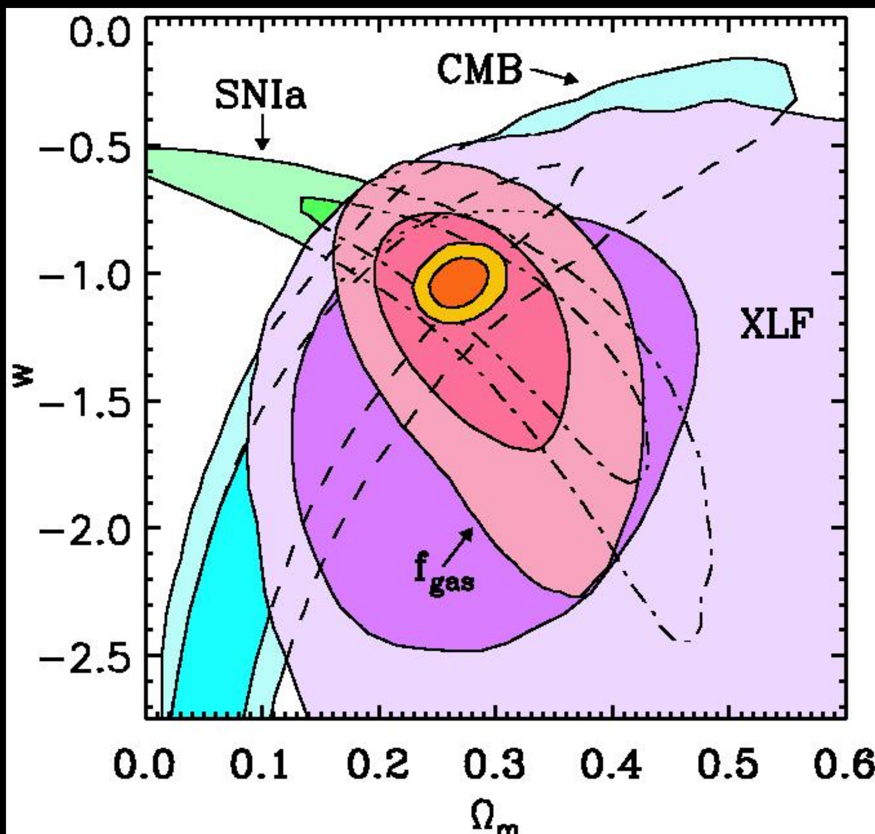
σ8 = 0.80
dn/dM [(h^3_50 Mpc^3*10^14 M_sun)^-1]
M [10^14 h^-1_50 M_sun]
10^-5
10^-10
10^-15
10^-20
10^-25
10^-30
10^-35
10^-40
10^-45
1
10
100
z = 0
z = 0.5
z = 1
R. Hanson, Bachelor Thesis (2009)

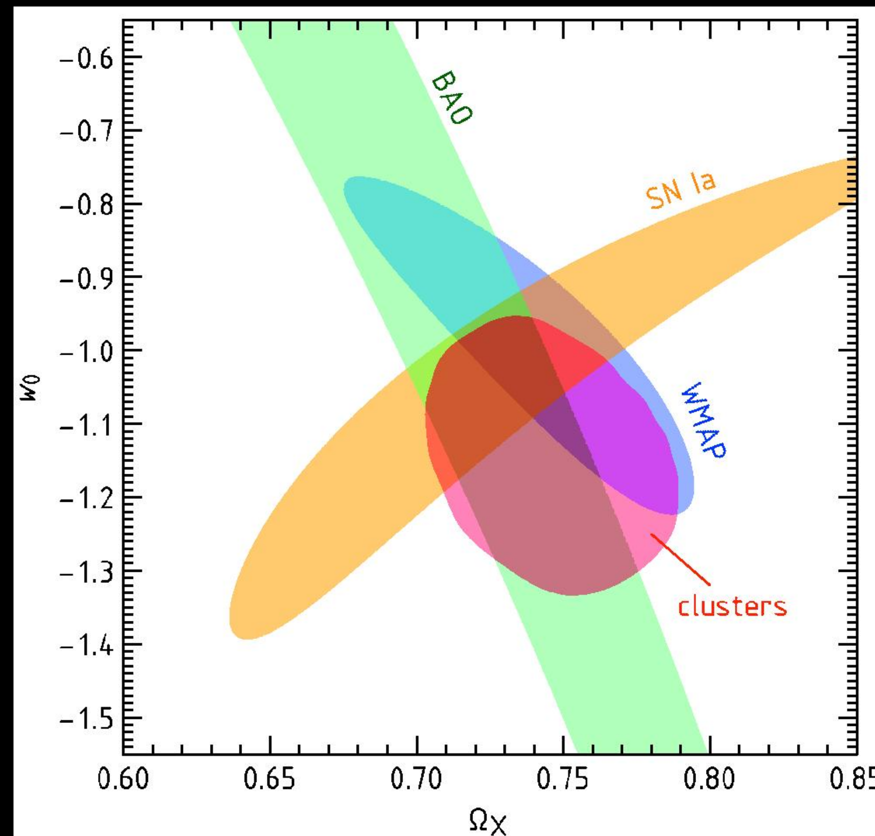


dn/dM [(h$_{50}^{3}$ Mpc^{-3} (10^{14} h$_{50}^{-1}$ M$_{sun}$)$^{-1}$]
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
1
10
100
M [10^{14} h$_{50}^{-1}$ M$_{sun}$]
w = -0.50
z = 0
z = 0.5
z = 1
R. Hanson, Bachelor Thesis (2009)



Current Constraints on *w* from ~10^2 X-Ray Clusters



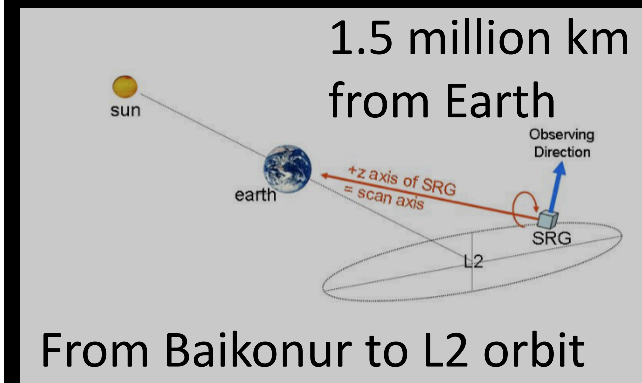


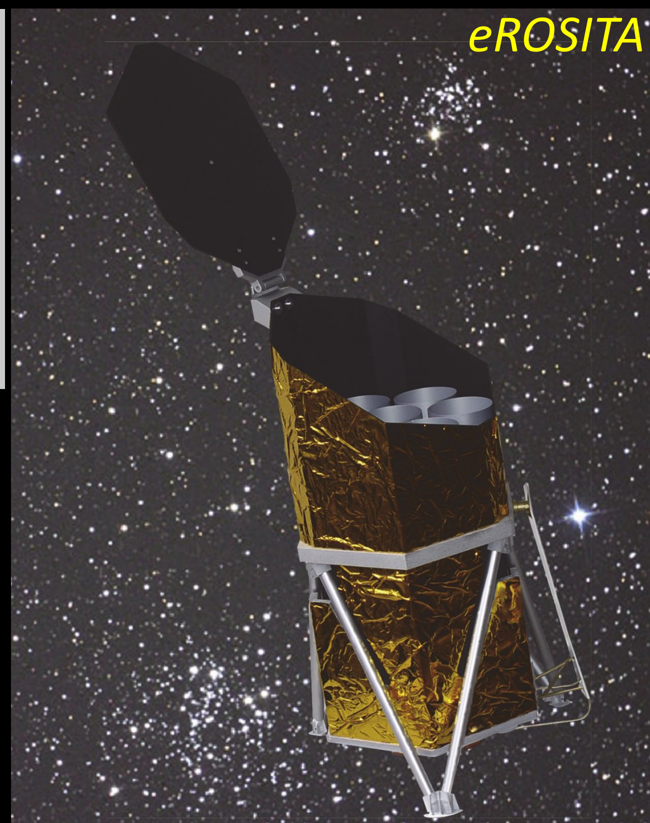
Allen et al. (2008), Mantz et al. (2008, 2010)

Vikhlinin et al. (2009)

Similar constraints available from SZ cluster surveys.

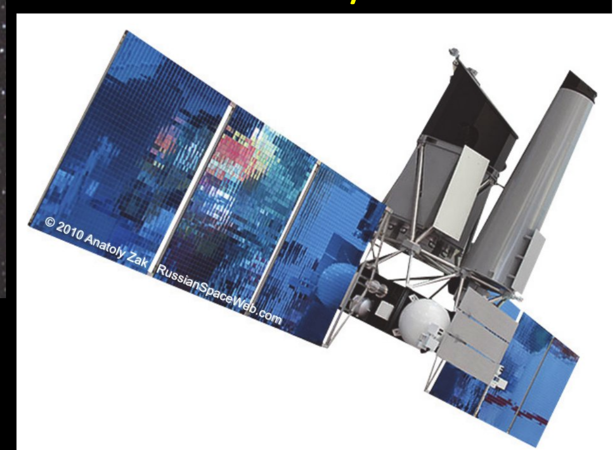
The (Near) Future: *eROSITA*





Zenit-2SB rocket
Fregat booster

Spektr-RG mission
Navigator platform
ART-XC / *eROSITA*



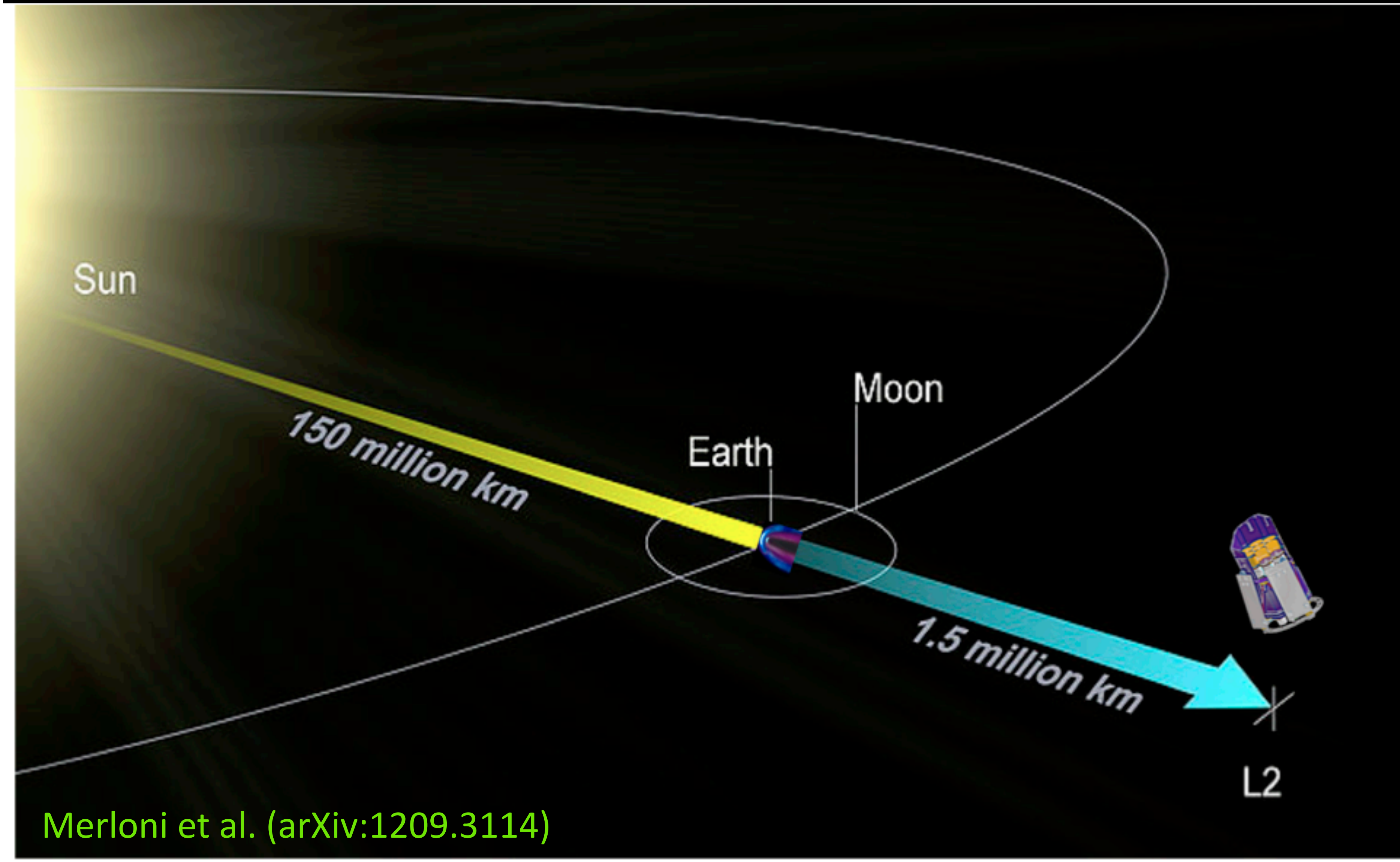
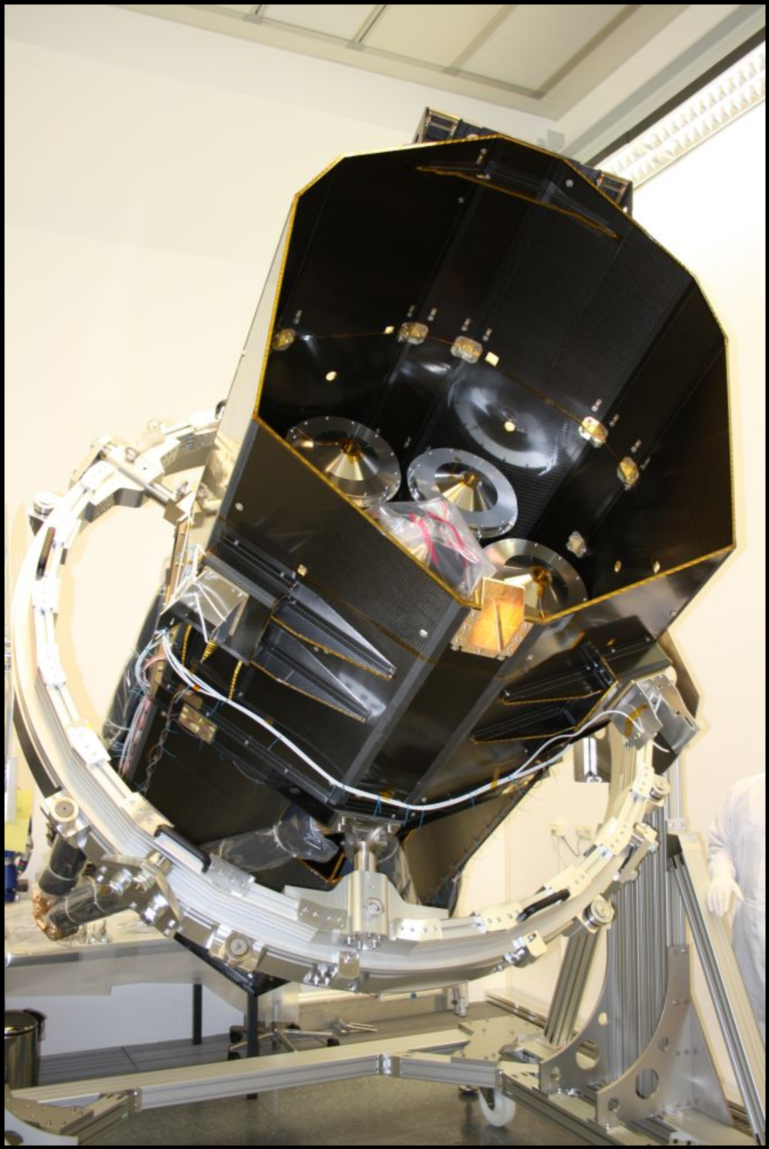
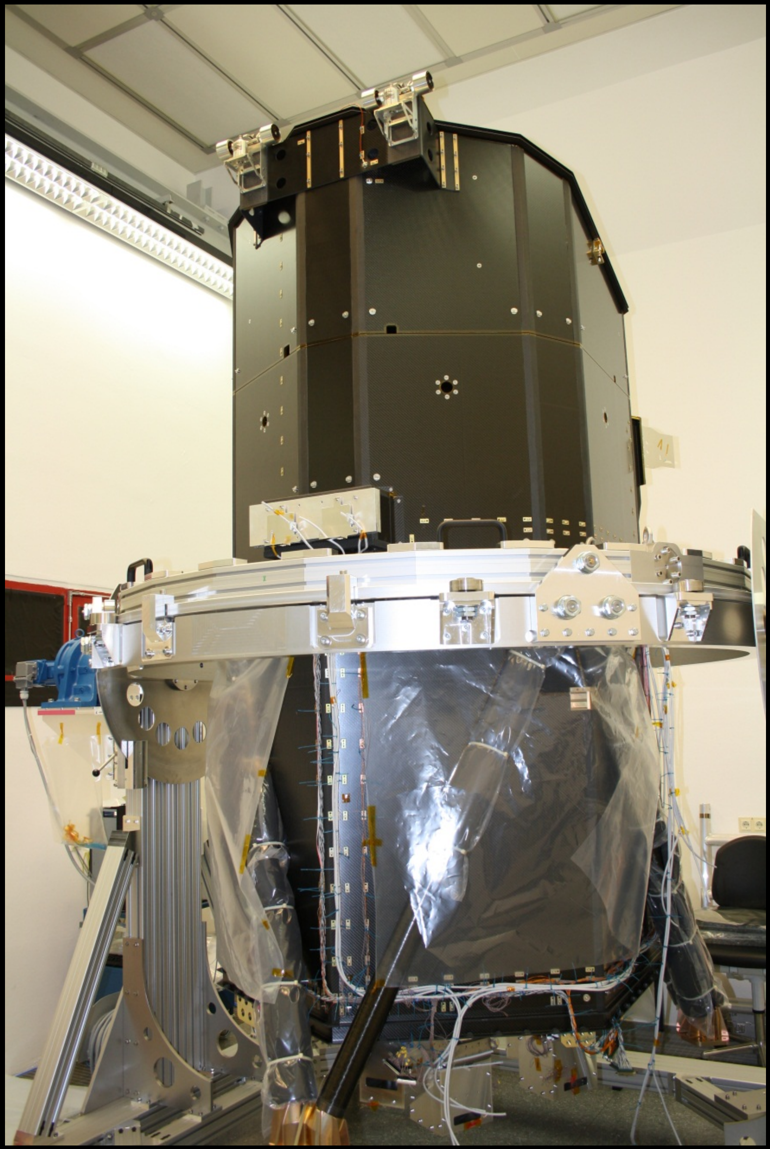


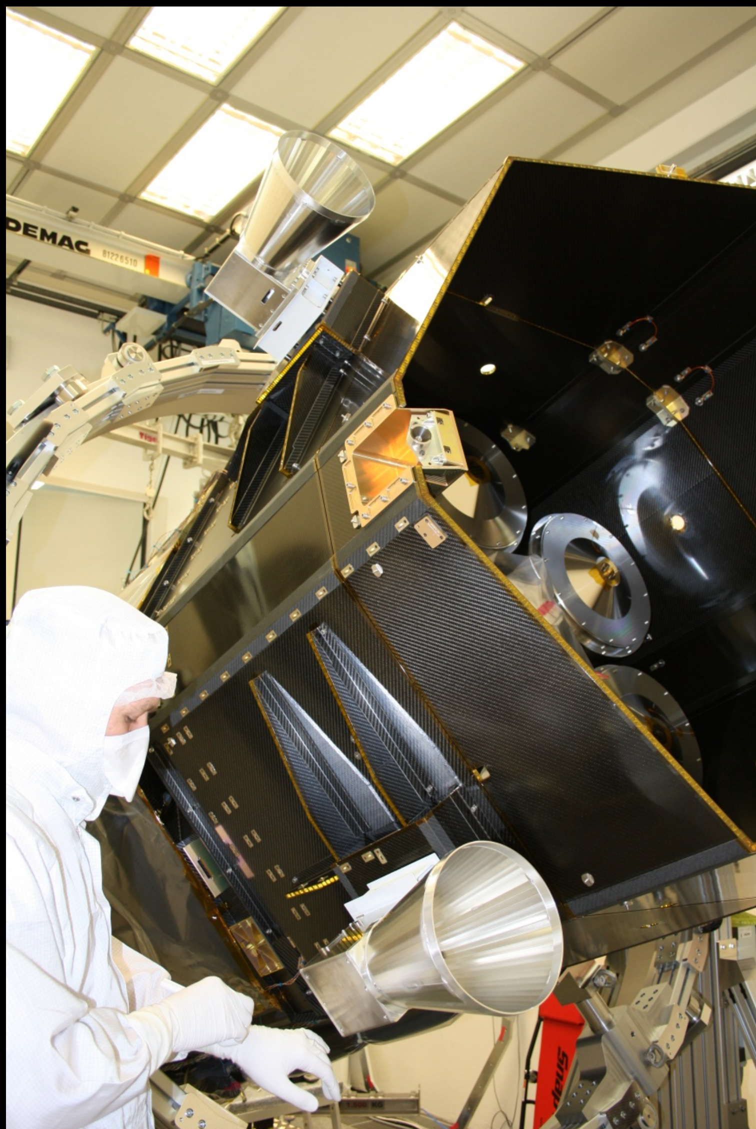
Figure 3.1.1: Schematic view of the location of the L2 orbit of SRG. At the position of the earth, a scaled picture of the geocoronal emission is shown. Unlike any other X-ray satellite launched to date, eROSITA will become the first telescope to observe the X-ray sky from L2, unaffected by geocoronal X-ray emission (composite image courtesy of K. Dennerl).

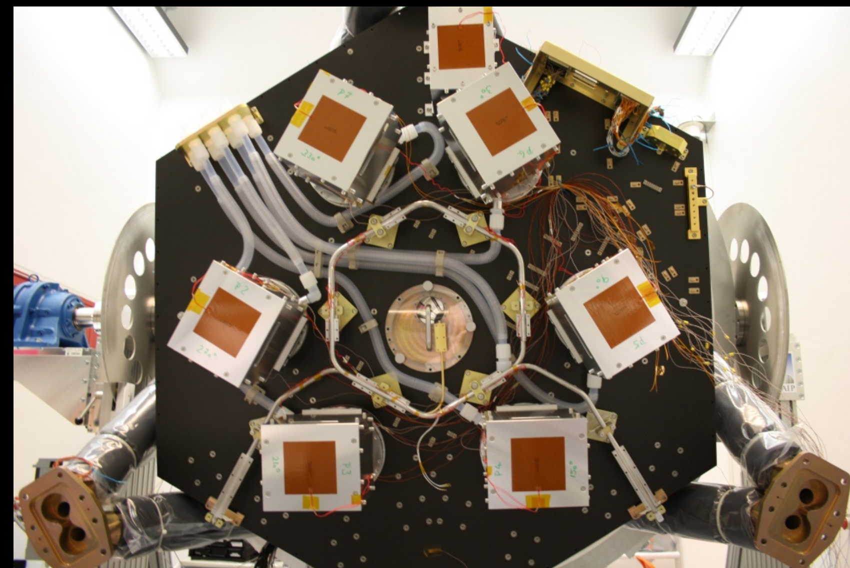
Telescope Structure





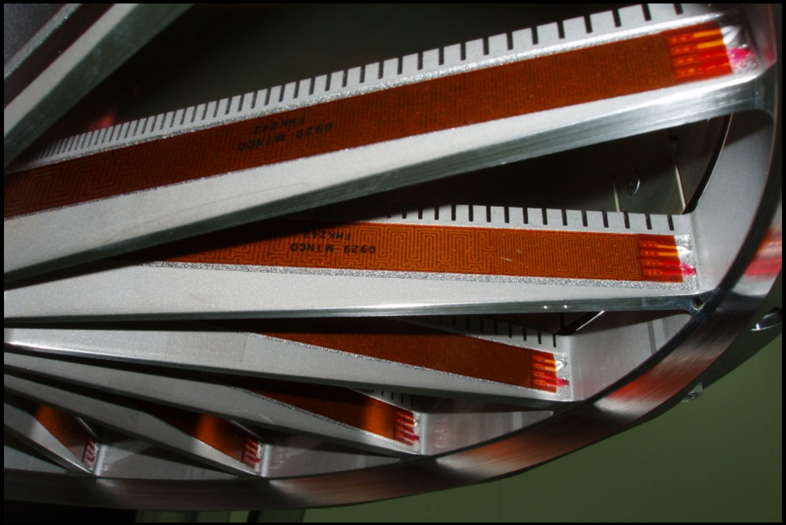
From P. Predehl



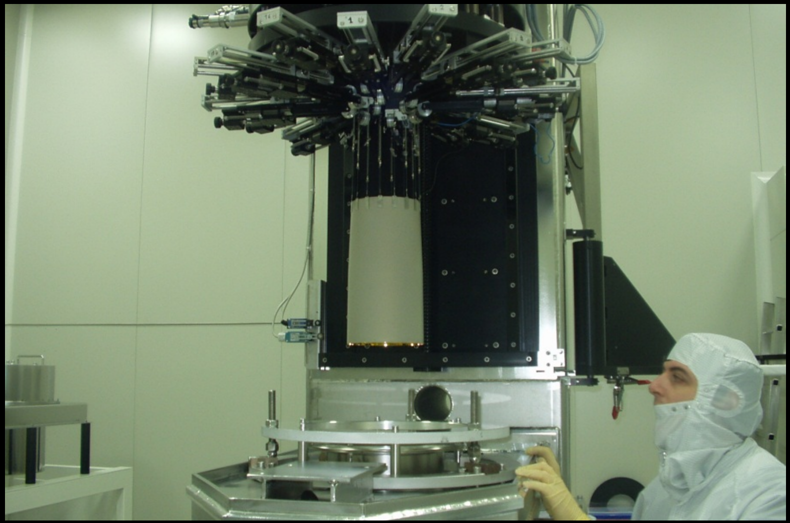


From P. Predehl

Mirror System



Spider Wheel with heaters integrated



VOB in action: Integration of a Shell

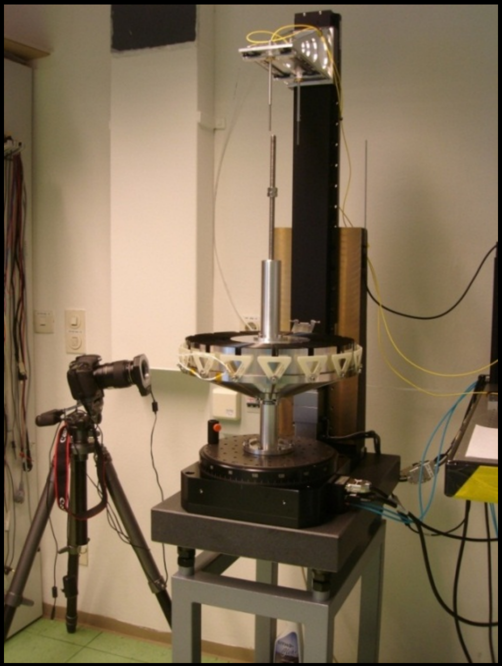
FM-3 Mirror Module with 39/54 shells

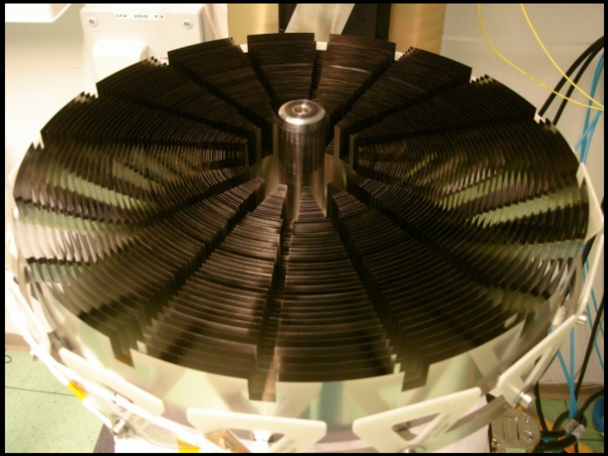
Preparation of PANTER X-ray Tests (FM-3c)

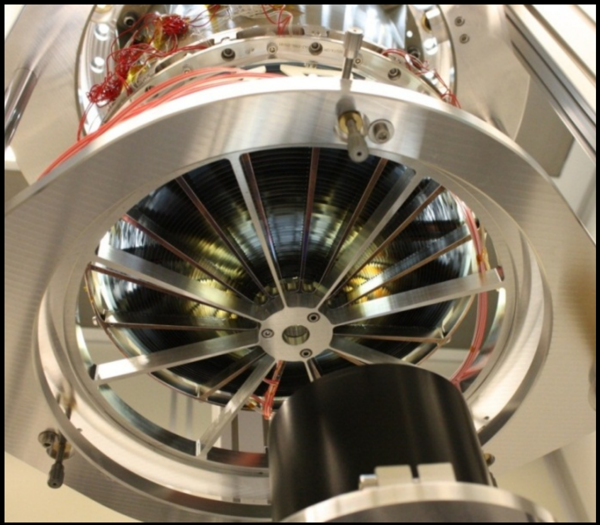
From P. Predehl

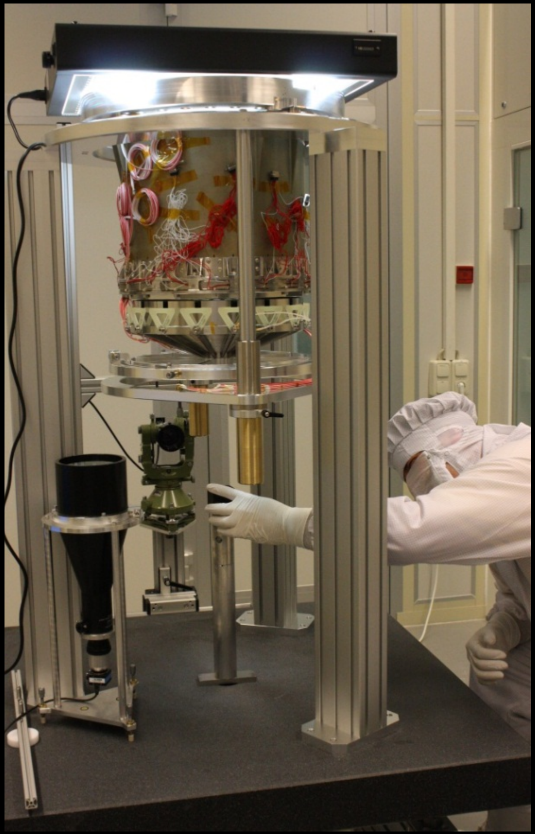
X-ray Baffle

Stand for Integration and
Metrology of Baffle Shells





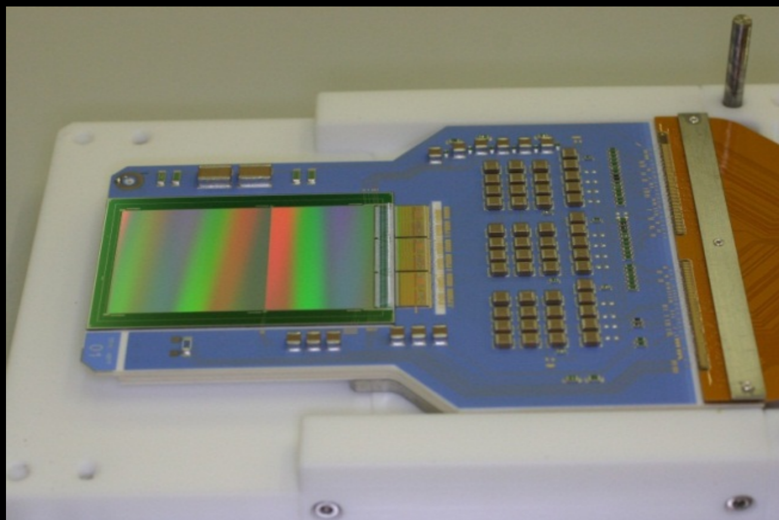




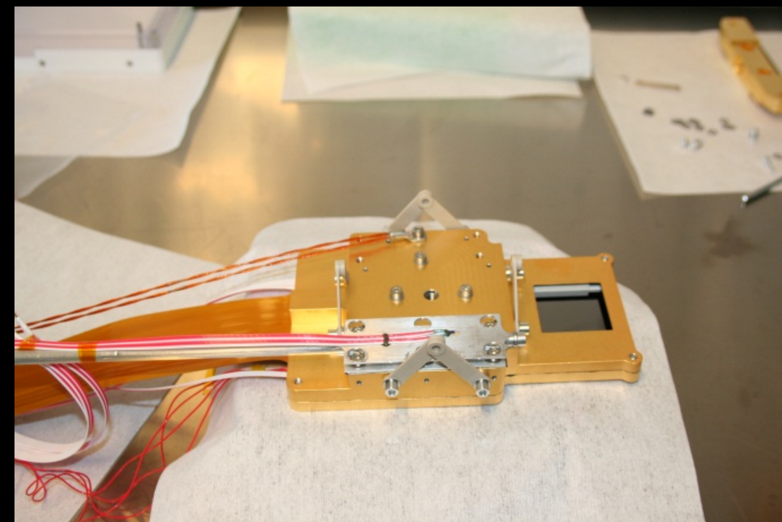
Integration and Metrology of
X-ray Baffle onto Mirror Module

From P. Predehl

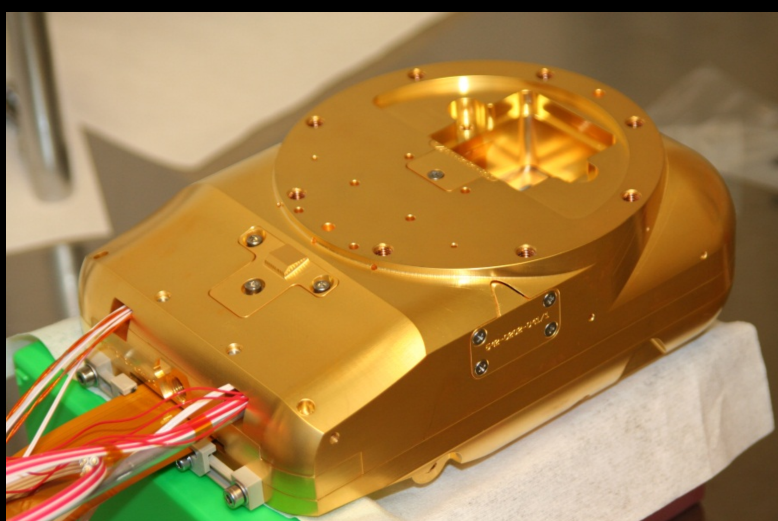
Camera



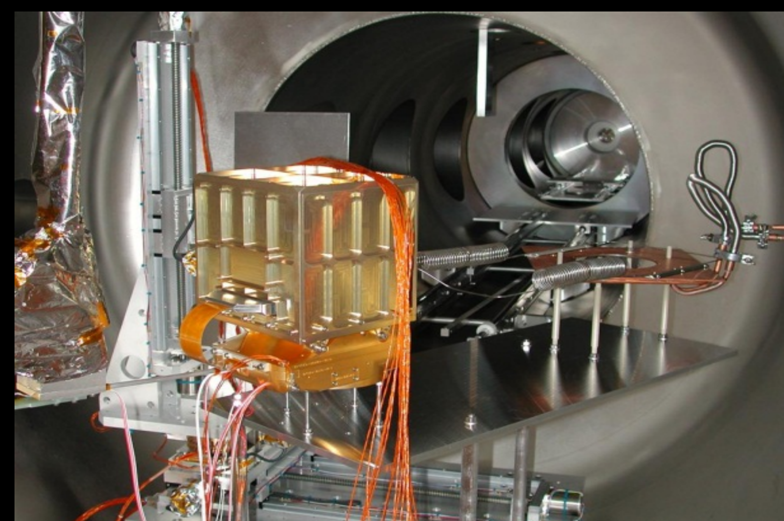
Heart of the Camera: CCD-Module



Cold part of Camera (with test sensors)



Integrated Camera (with massive Copper Housing)

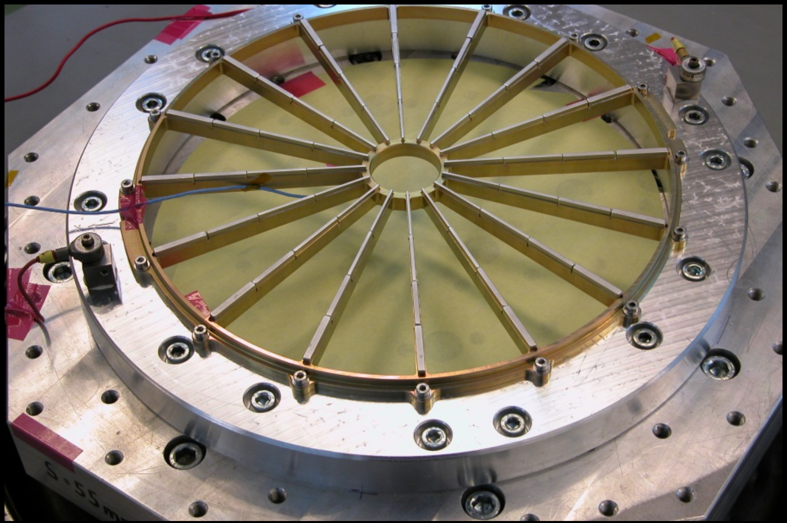


Preparation of Thermal Test

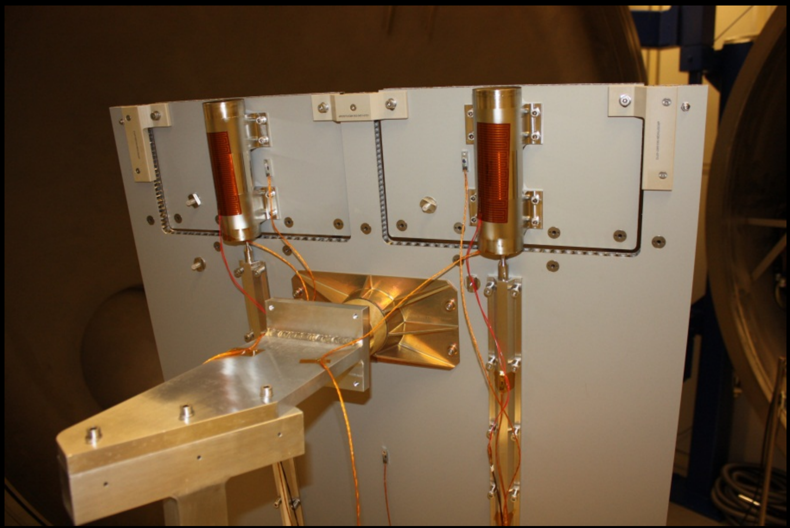
From P. Predehl

Miscellaneous

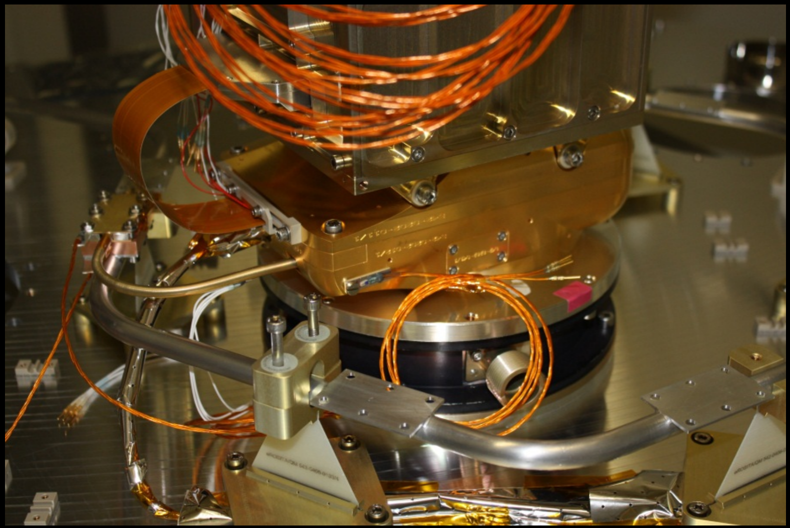
Filter Wheel



Electron Deflector (on Shaker)

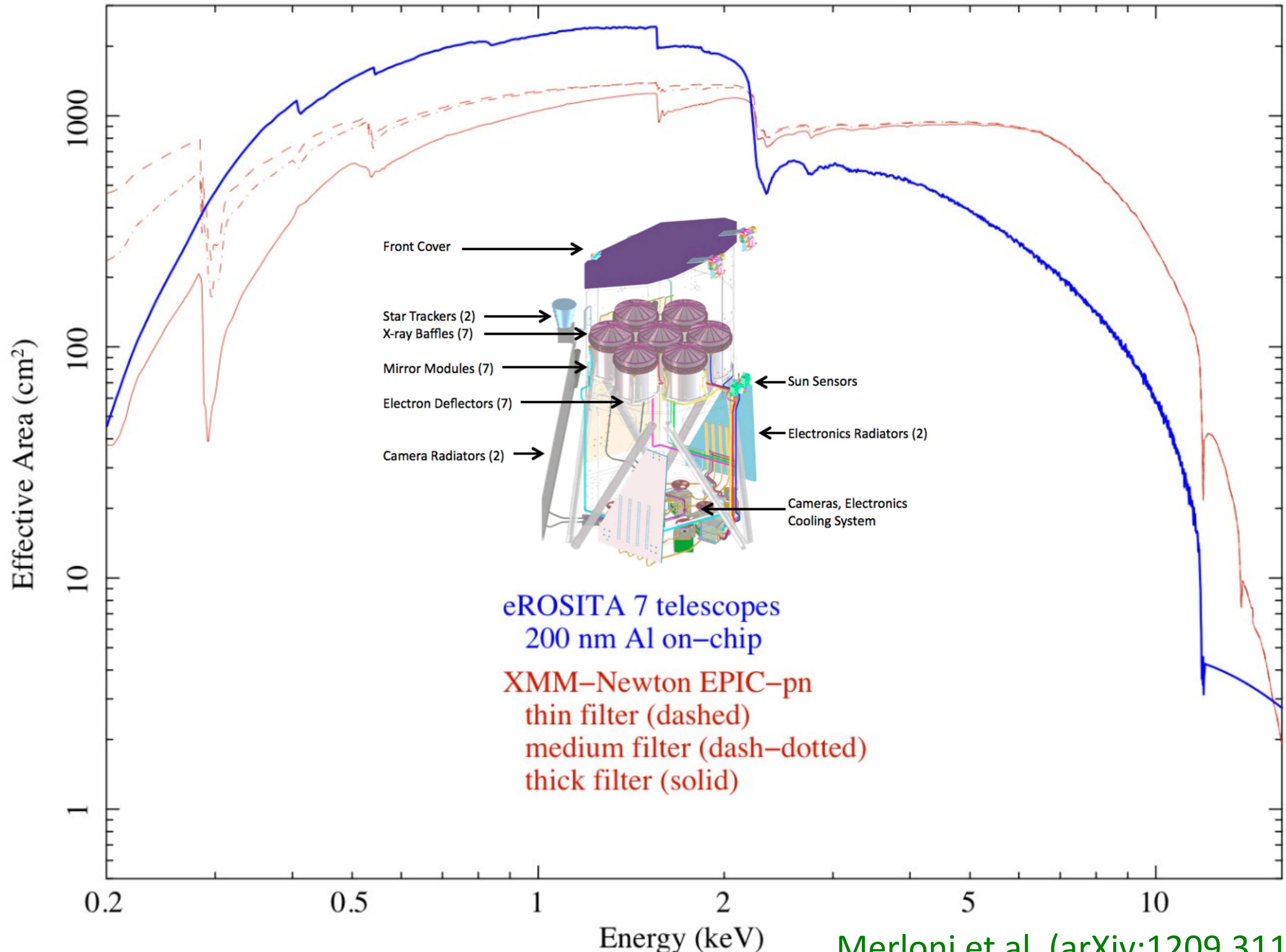


Camera Radiator, upper part with VCHP-Reservoirs

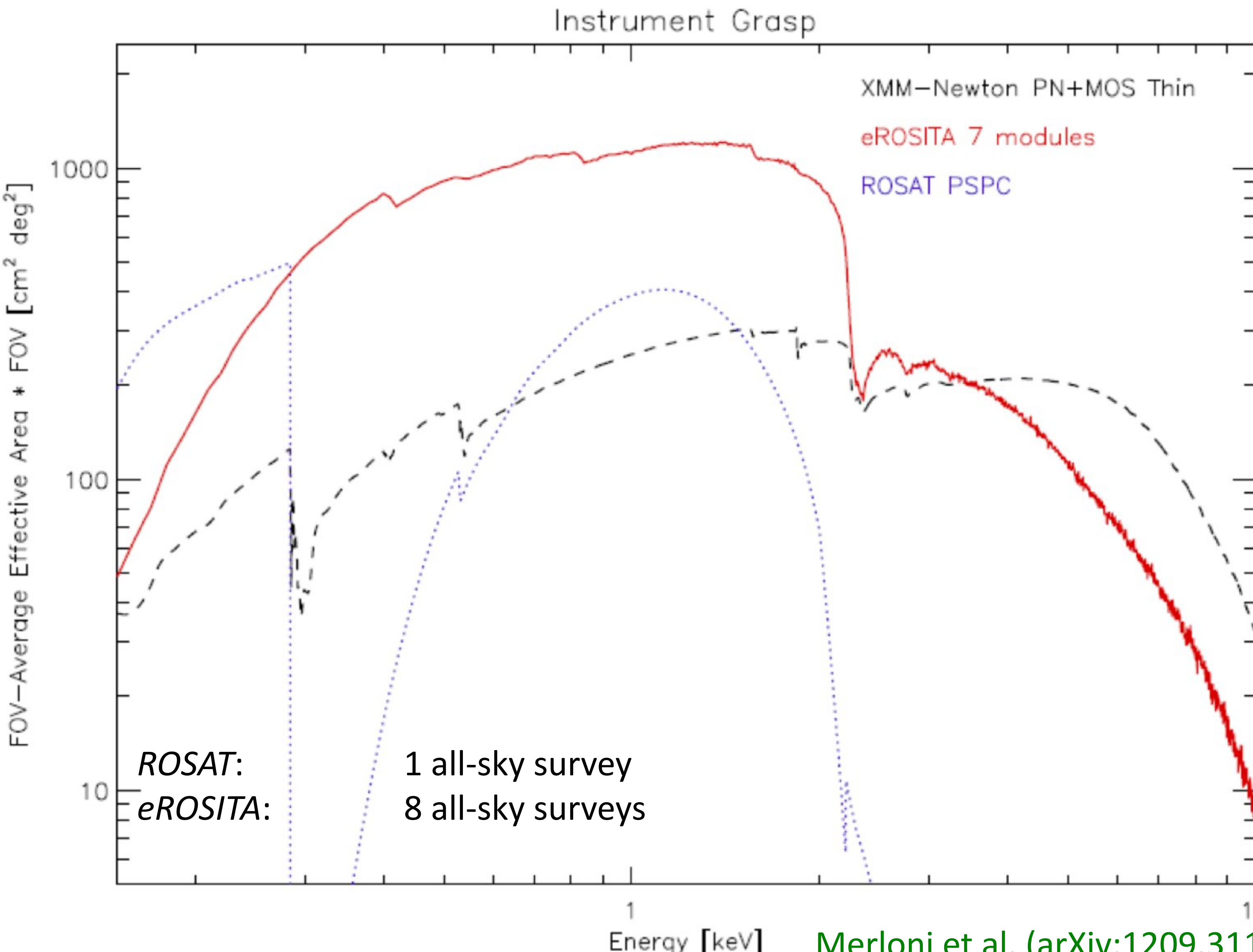


Preparation of Thermal Test with Heatpipe System

From P. Predehl

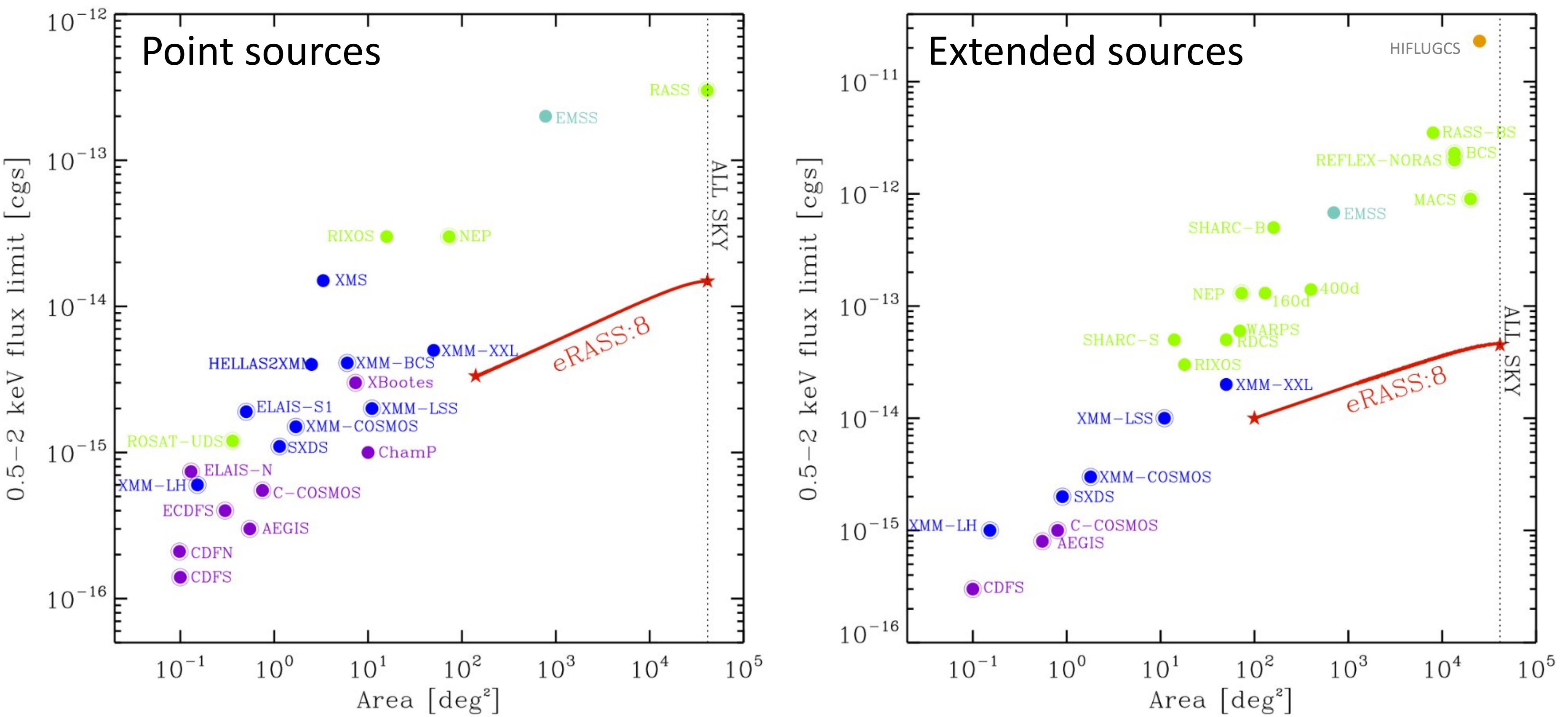


Merloni et al. (arXiv:1209.3114)



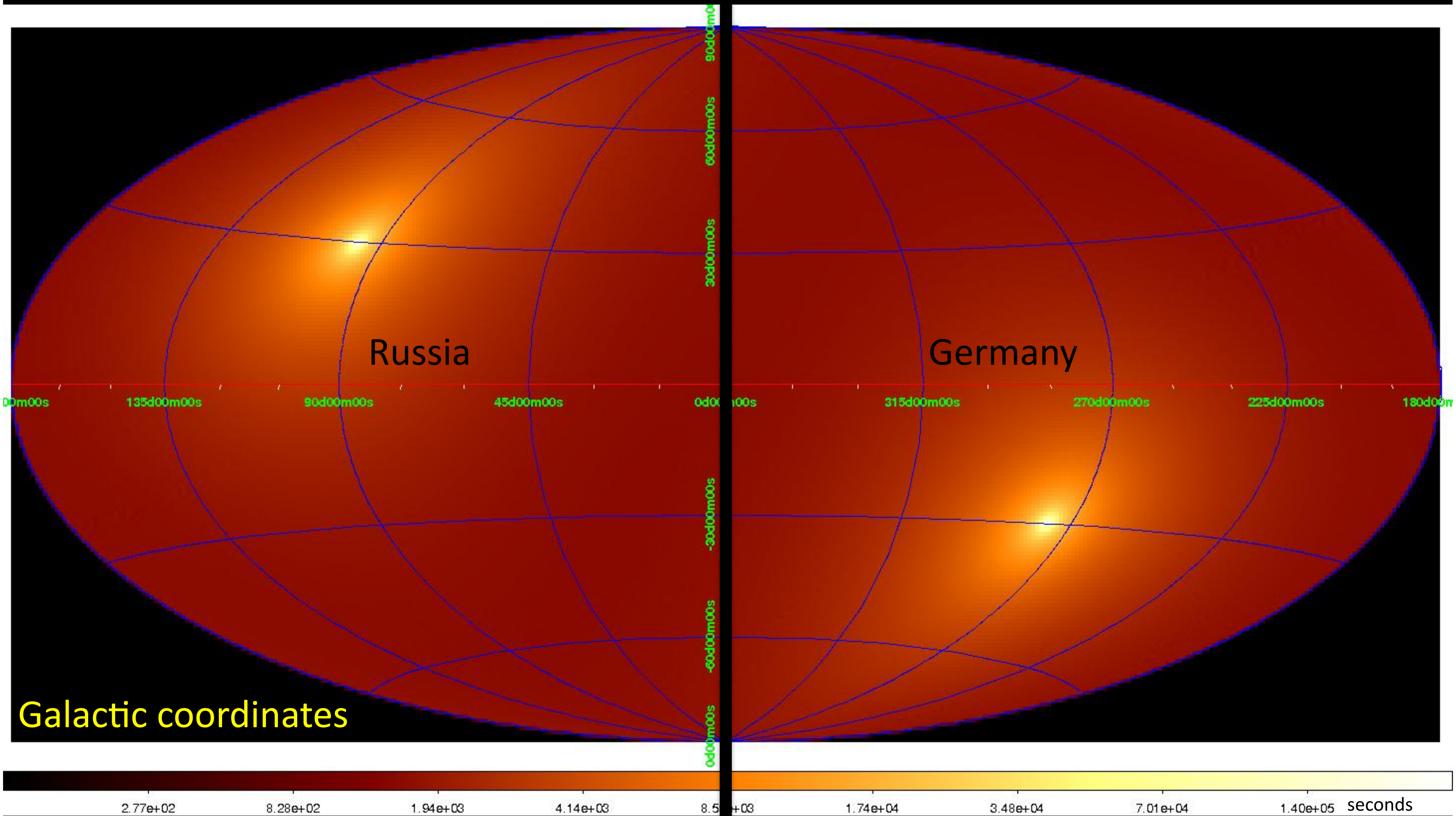
Merloni et al. (arXiv:1209.3114)

Comparison with other Surveys



Adapted from Merloni et al. (arXiv:1209.3114)

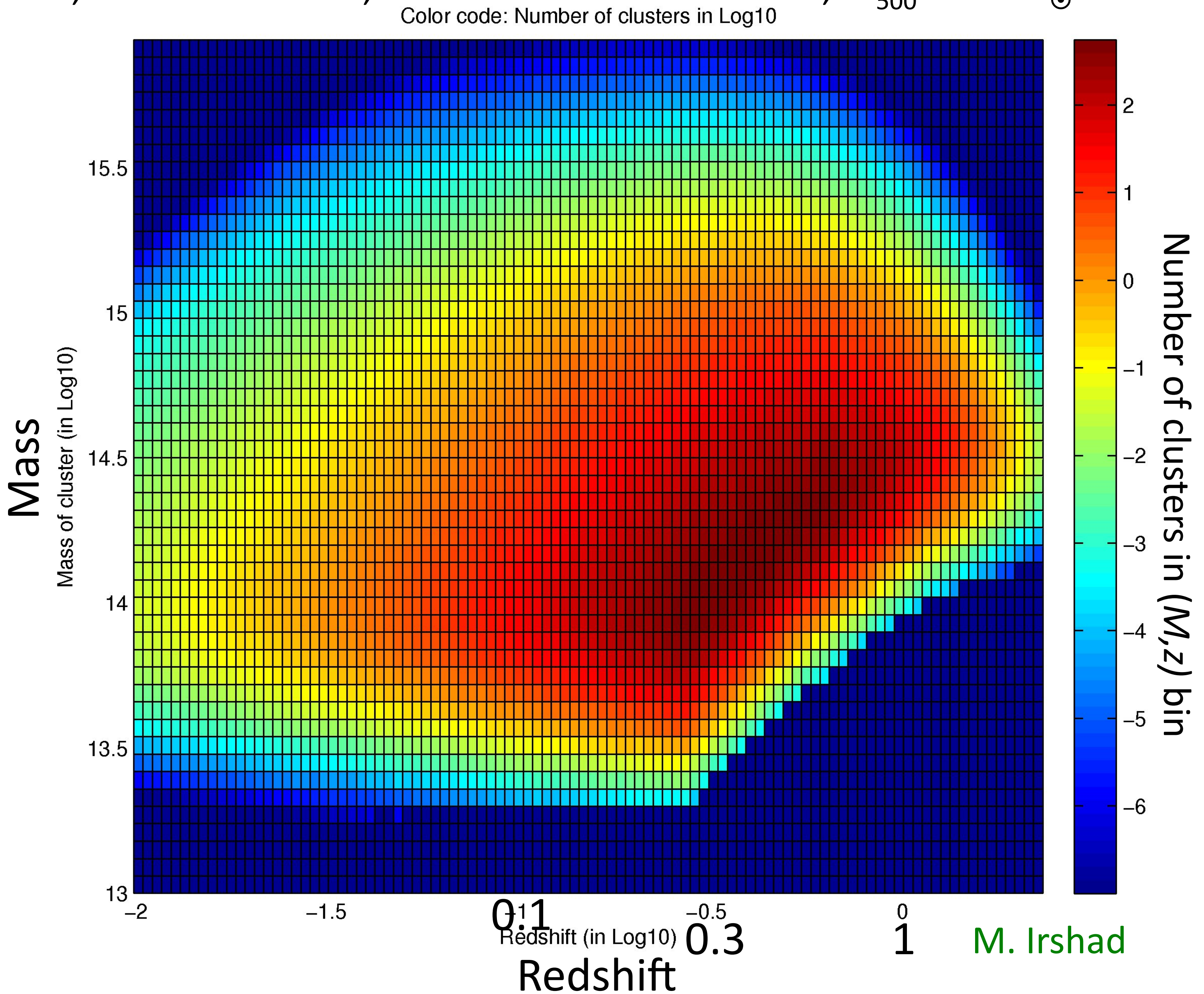
Expected *eROSITA* Exposure Map



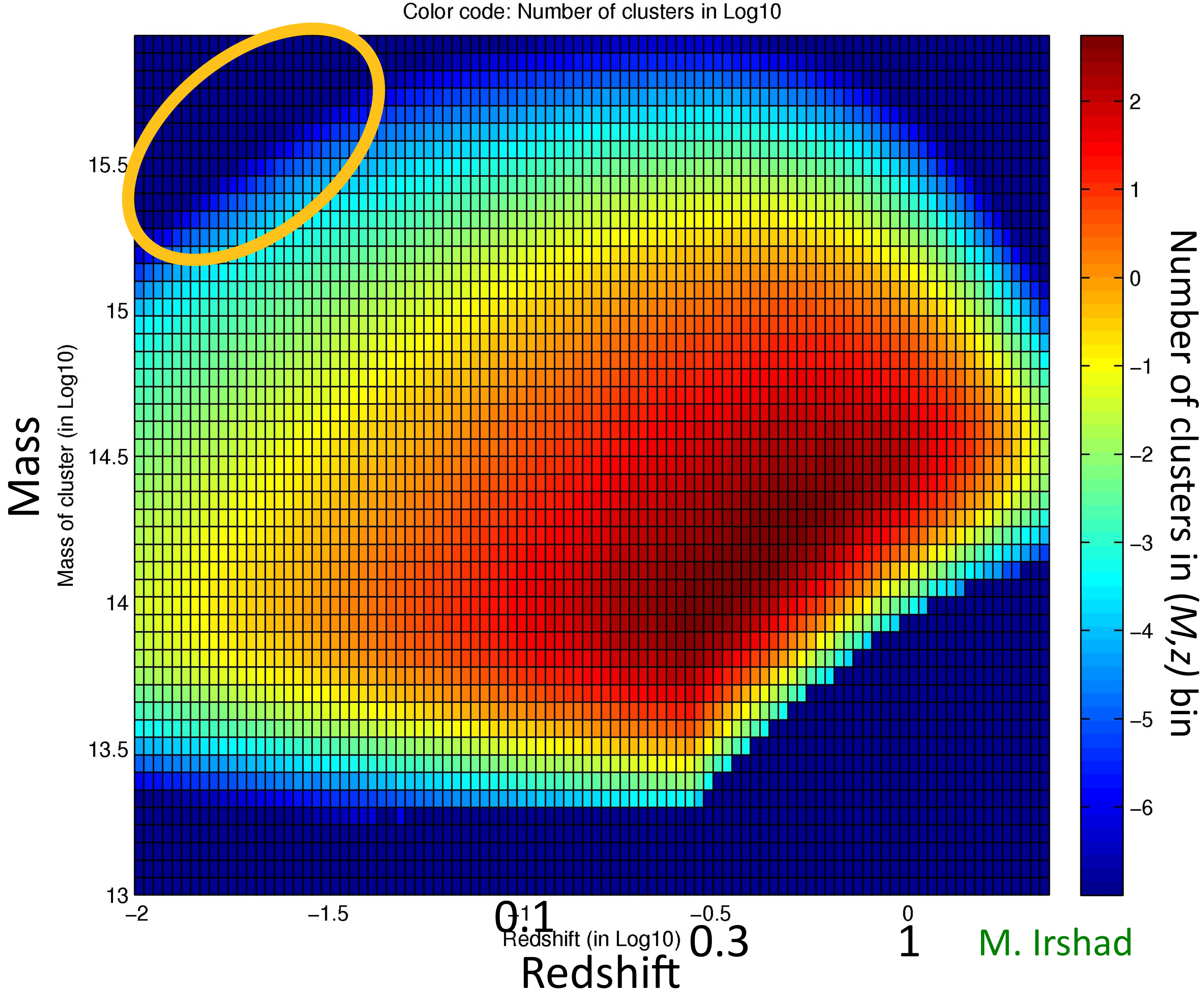
Provided by J. Robrade

How Many Clusters with what Mass at which Redshift will *eROSITA* Discover?

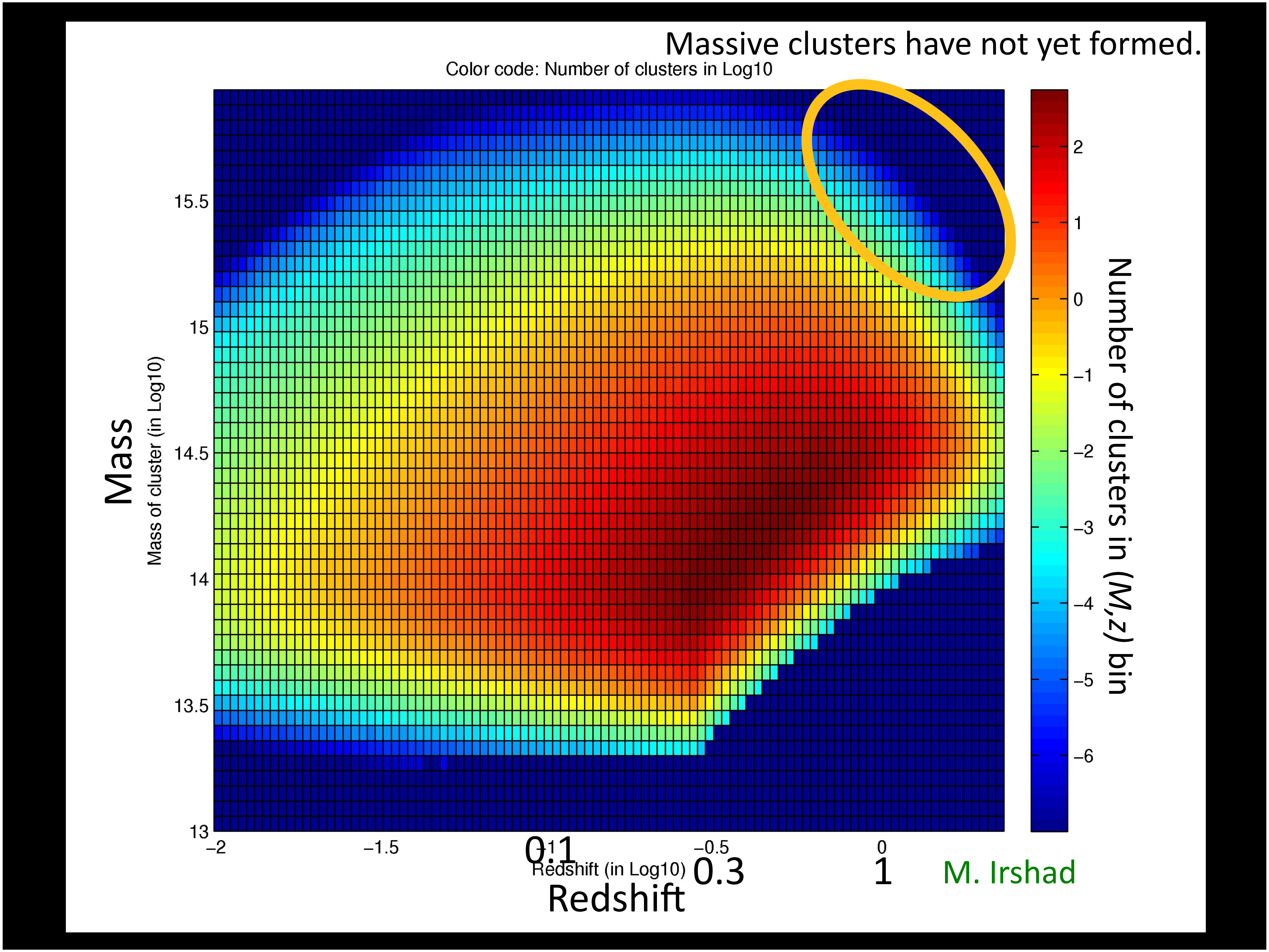
~100,000 clusters total, most clusters around z~0.3, M_{500}~10^{14} $M_{\odot}$.

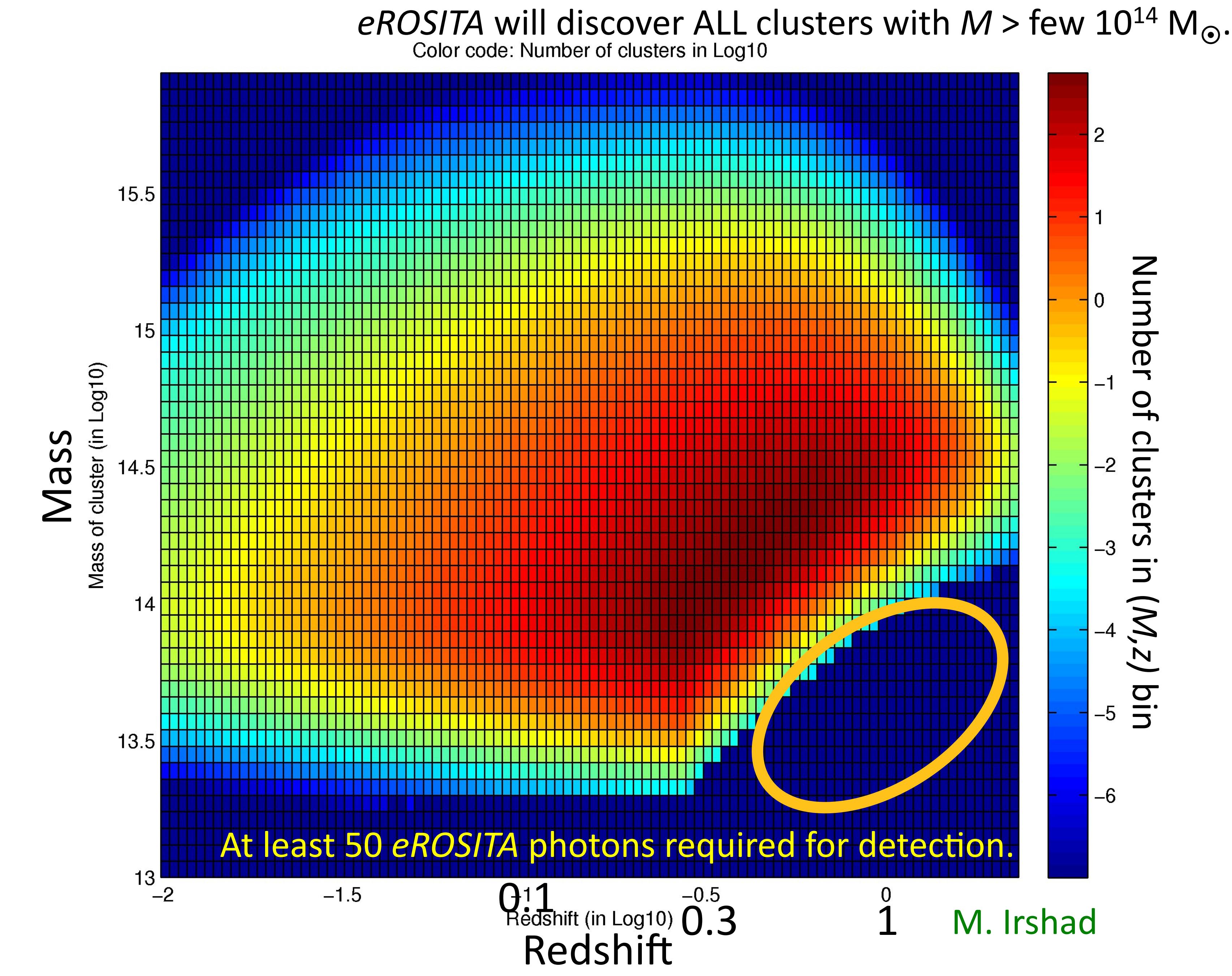


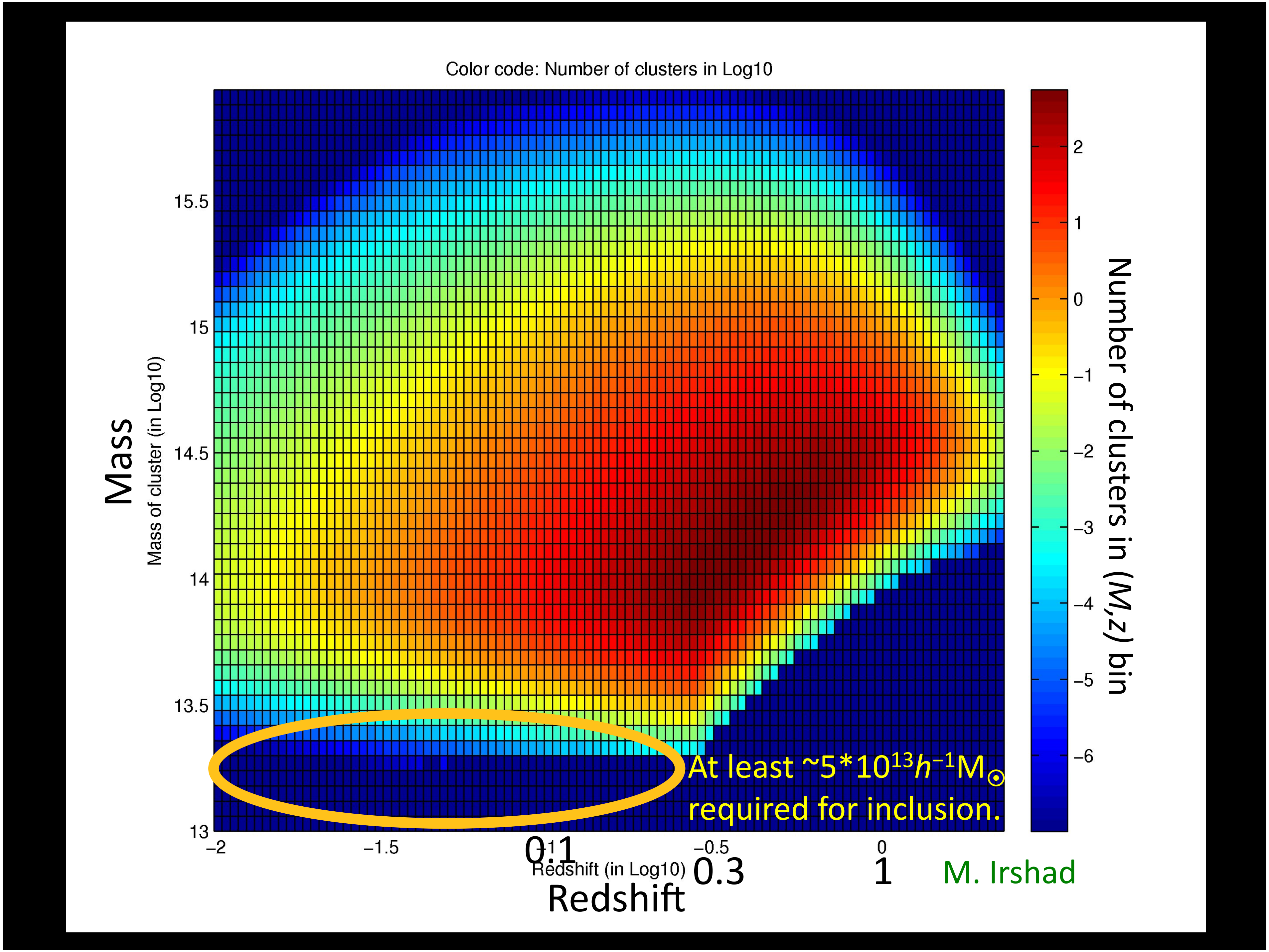
Volume too small for rare massive clusters.



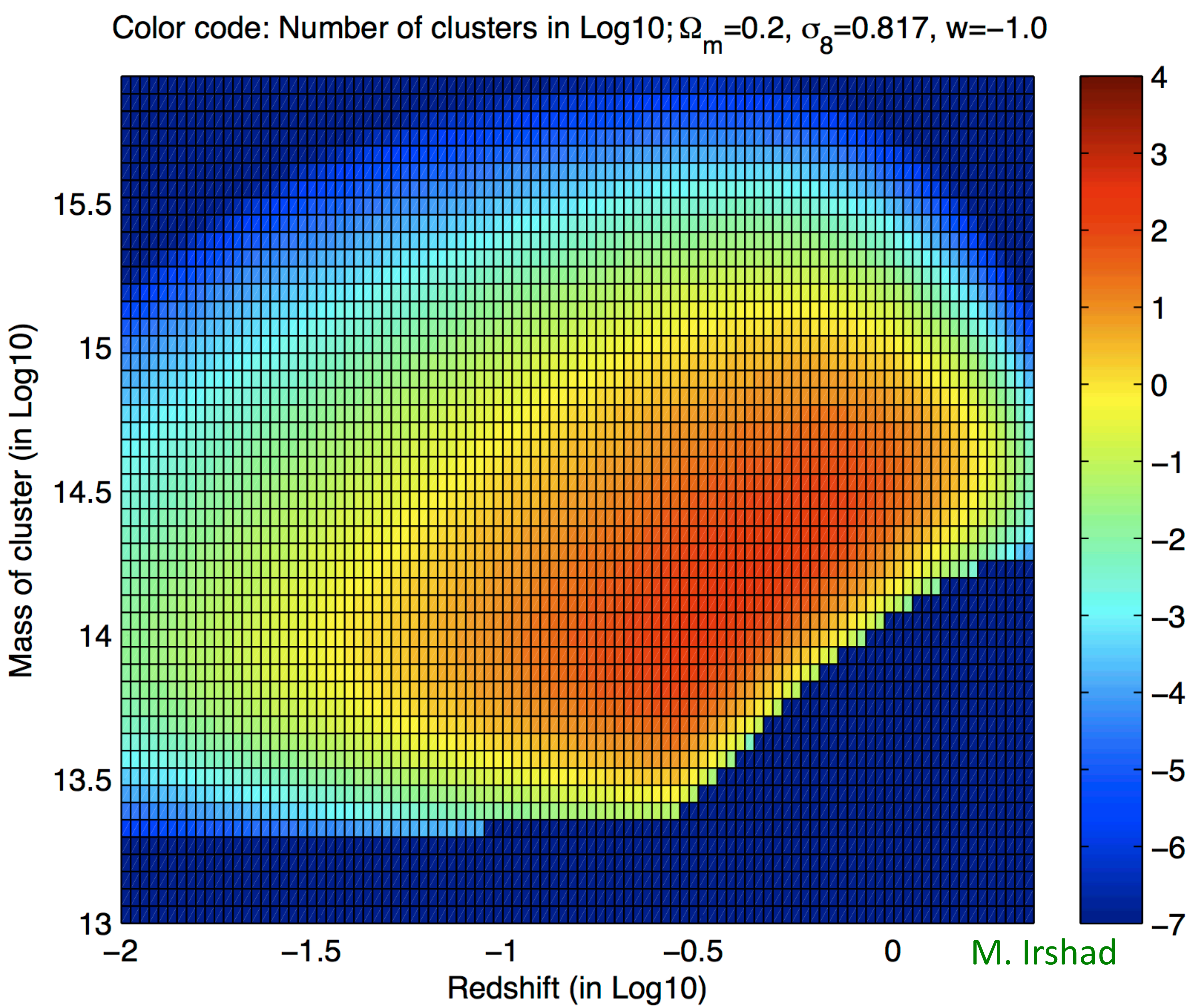
M. Irshad


Massive clusters have not yet formed.
Color code: Number of clusters in Log10
Mass
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
0.1
0.3
1
Redshift (in Log10)
Redshift
2
1
0
−1
−2
−3
−4
−5
−6
Number of clusters in (M,z) bin
M. Irshad

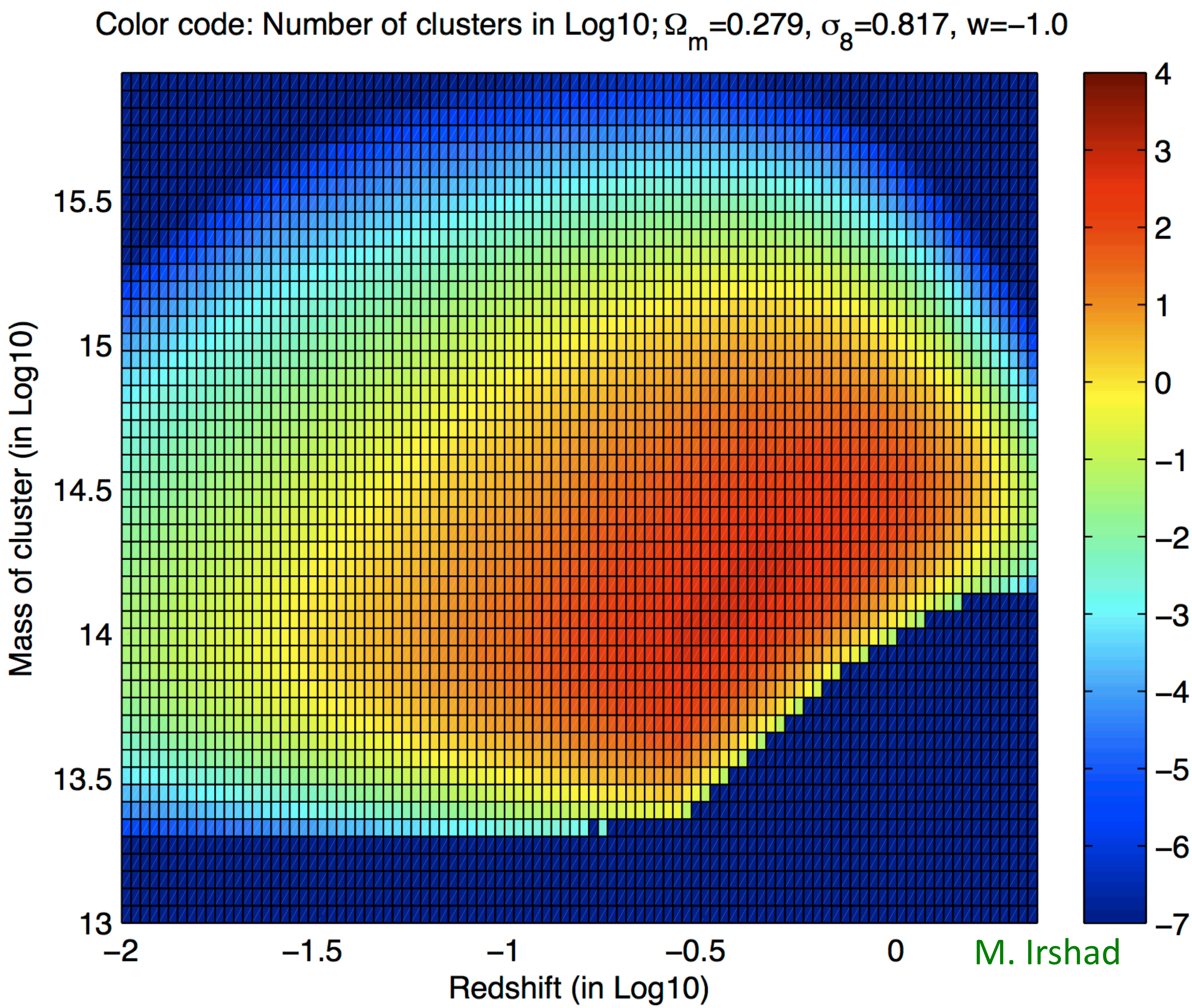

eROSITA will discover ALL clusters with *M* > few 10^{14} $M_{\odot}$.
Color code: Number of clusters in Log10
Mass
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
0.1
0.3
1
Redshift (in Log10)
Redshift
2
1
0
−1
−2
−3
−4
−5
−6
Number of clusters in (*M*,*z*) bin
At least 50 *eROSITA* photons required for detection.
M. Irshad



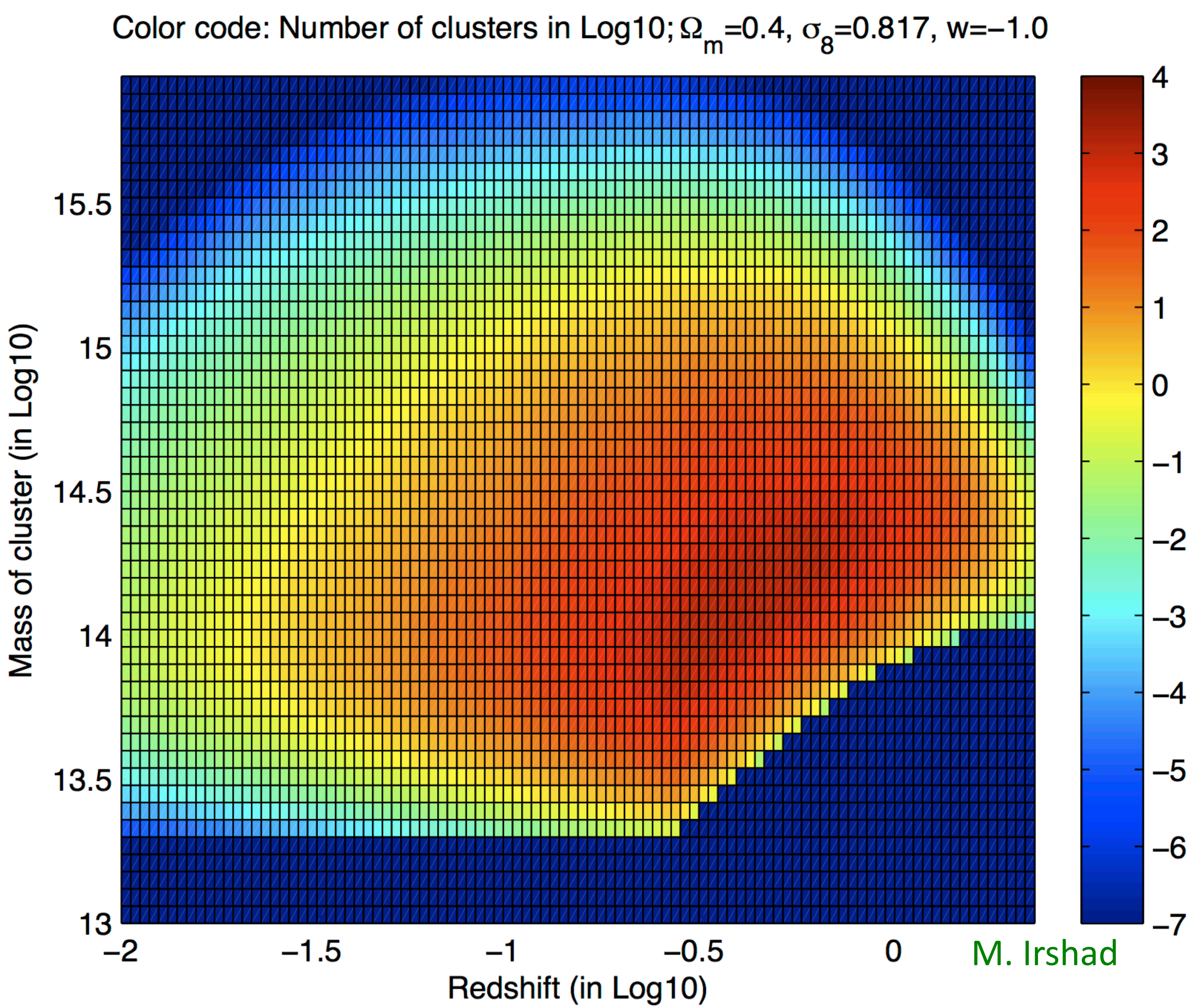
Color code: Number of clusters in Log10
Mass
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
0.1
0.3
1
Redshift (in Log10)
Redshift
2
1
0
−1
−2
−3
−4
−5
−6
Number of clusters in (M,z) bin
At least ~5*10^13 h^−1 M☉
required for inclusion.
M. Irshad

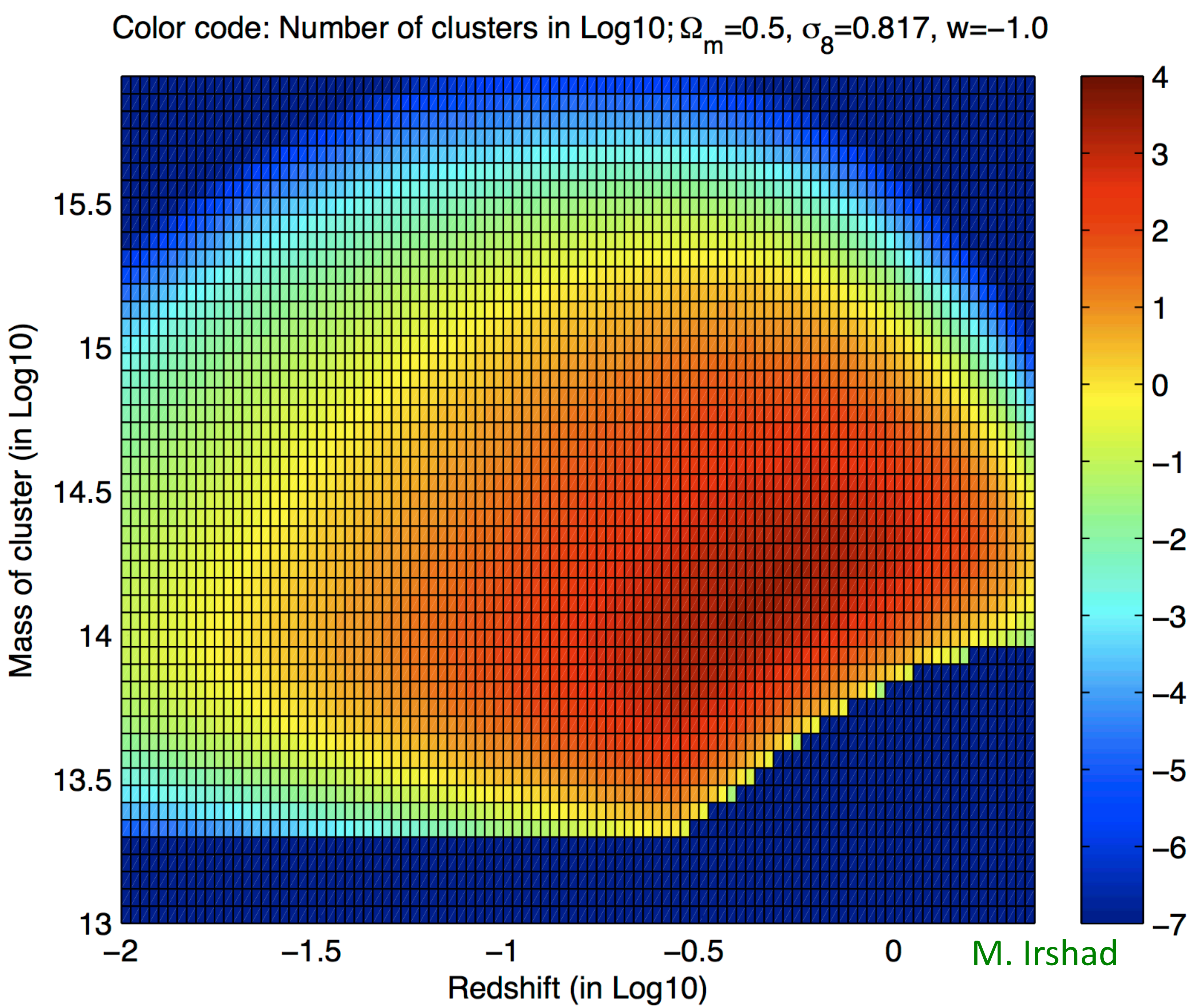


Color code: Number of clusters in Log10; Ω_m=0.2, σ_8=0.817, w=−1.0
Mass of cluster (in Log10)
13
13.5
14
14.5
15
15.5
Redshift (in Log10)
−2
−1.5
−1
−0.5
0
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

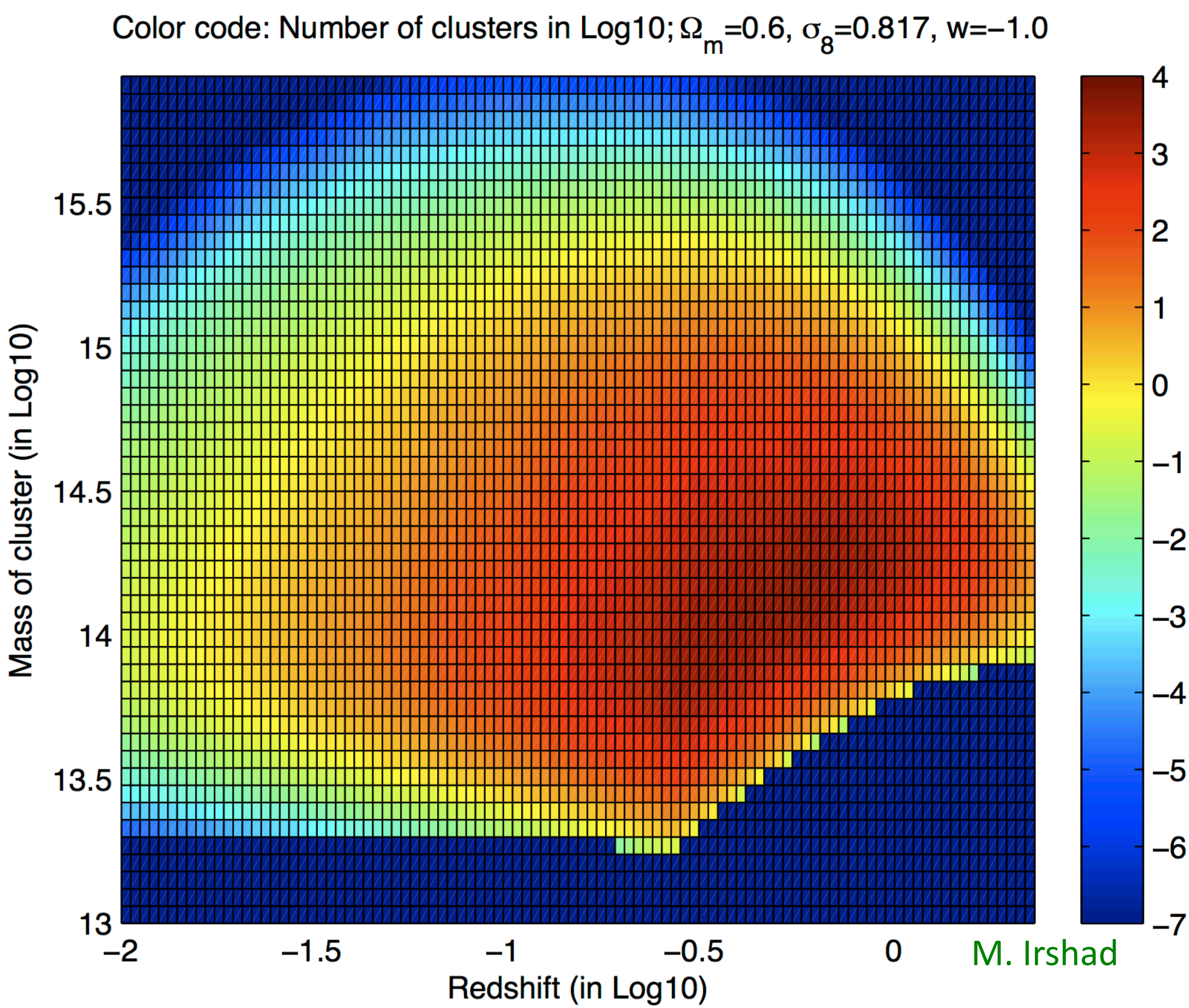


Color code: Number of clusters in Log10; Ω_m=0.279, σ_8=0.817, w=−1.0
Mass of cluster (in Log10)
13
13.5
14
14.5
15
15.5
Redshift (in Log10)
−2
−1.5
−1
−0.5
0
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

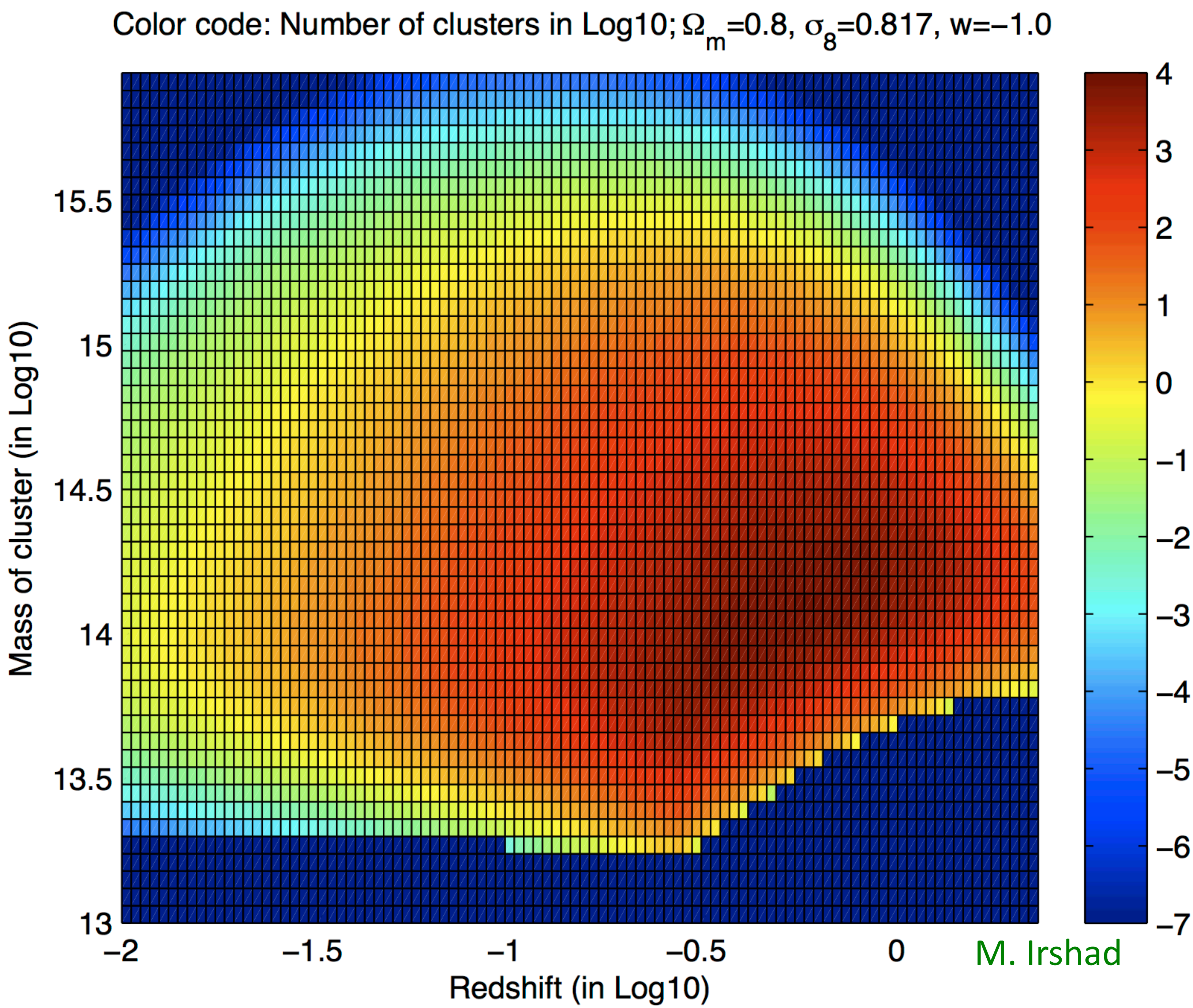

Color code: Number of clusters in Log10; Ω_m=0.4, σ_8=0.817, w=−1.0
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad



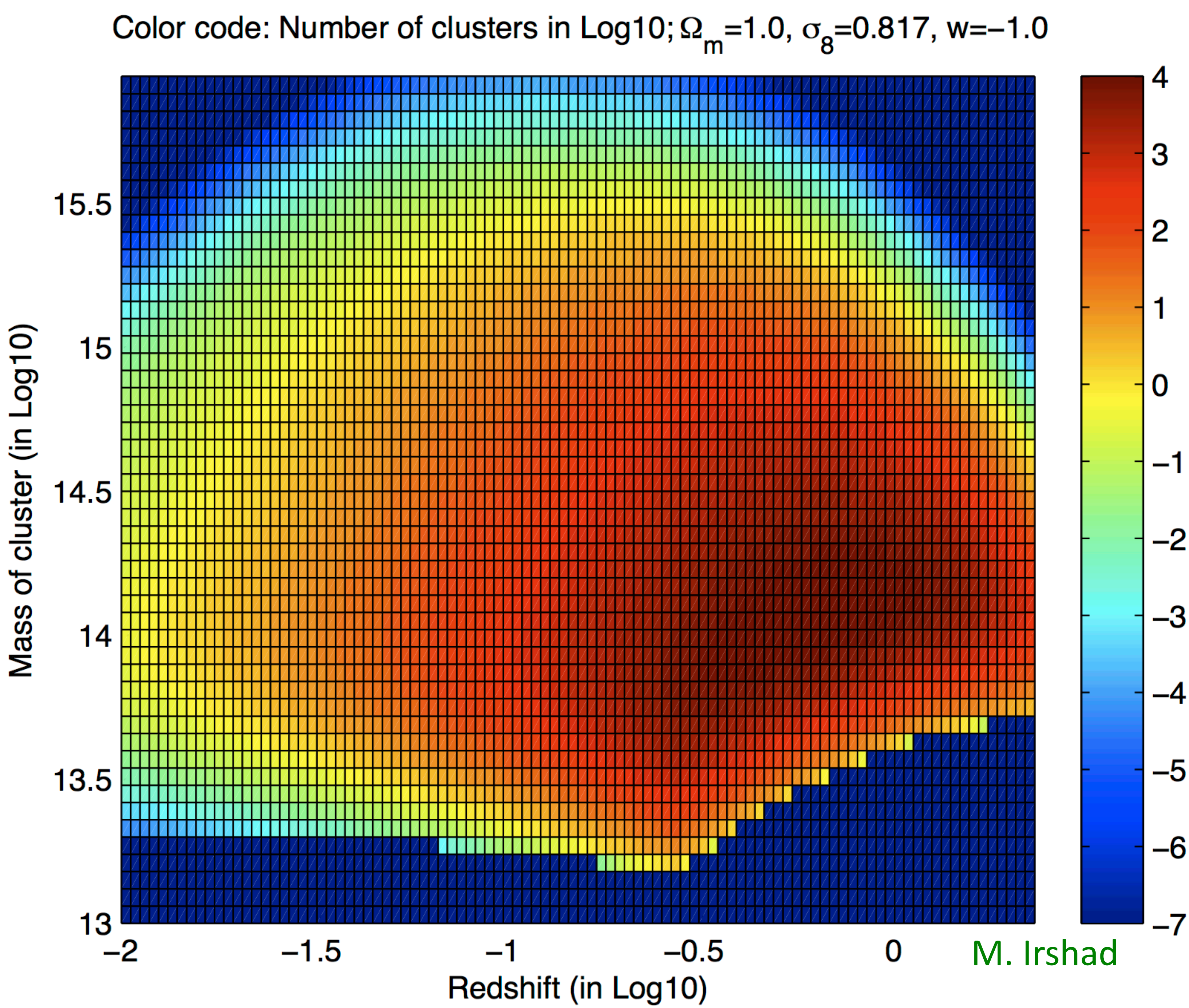
Color code: Number of clusters in Log10; Ω_m=0.5, σ_8=0.817, w=−1.0
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

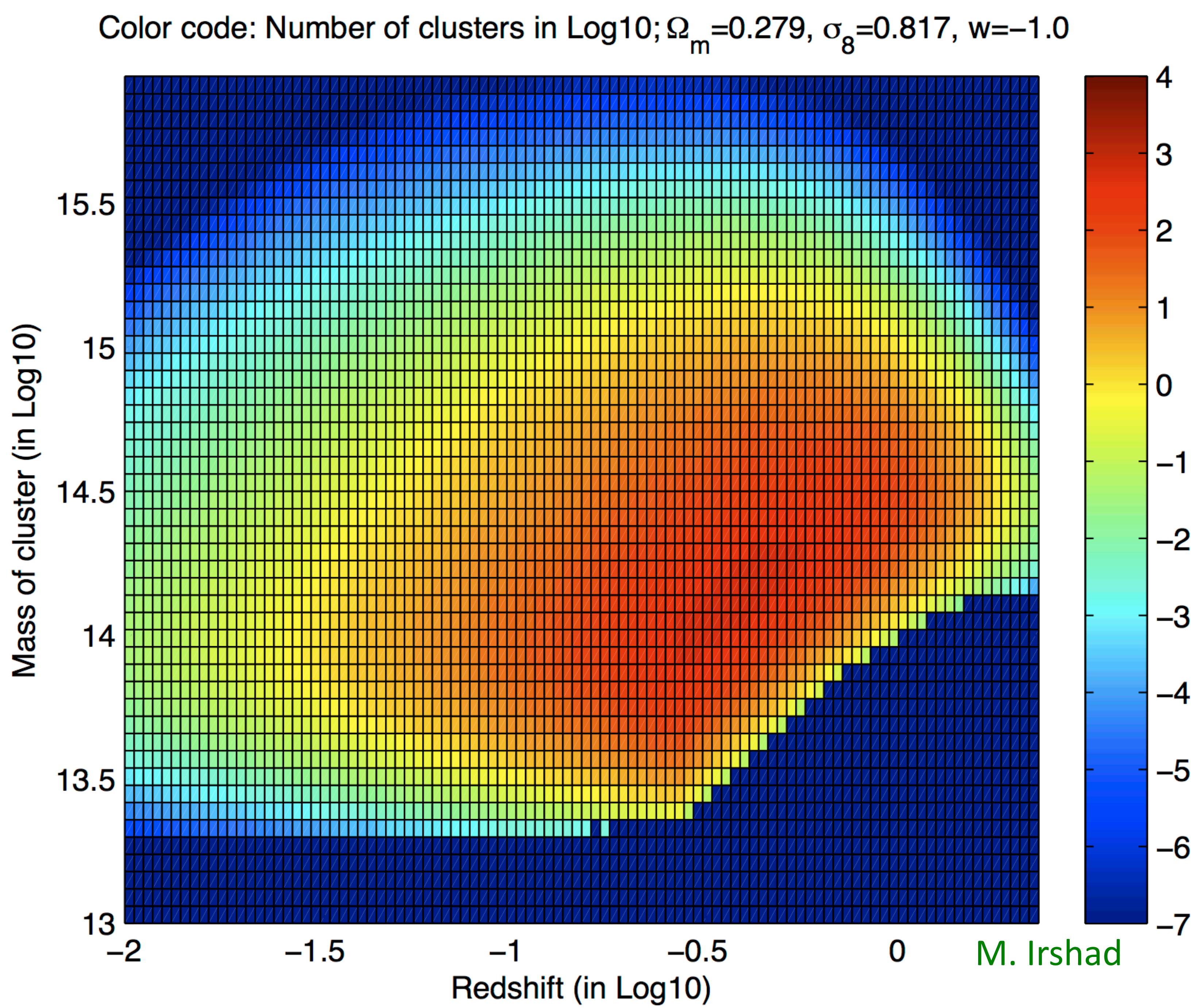


Color code: Number of clusters in Log10; Ω_m=0.6, σ_8=0.817, w=−1.0
Mass of cluster (in Log10)
13
13.5
14
14.5
15
15.5
Redshift (in Log10)
−2
−1.5
−1
−0.5
0
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

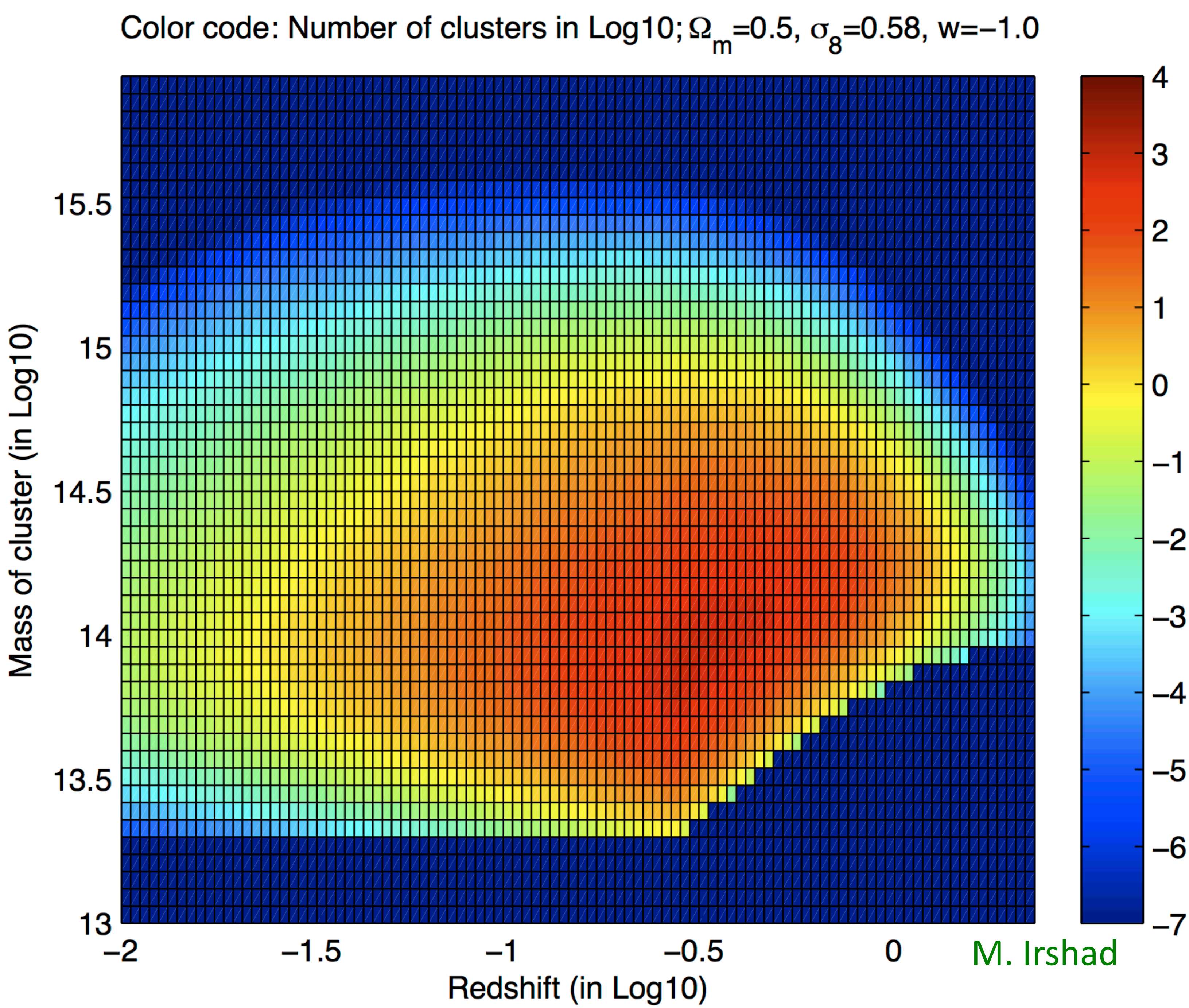


Color code: Number of clusters in Log10; Ω_m=0.8, σ_8=0.817, w=−1.0
Mass of cluster (in Log10)
Redshift (in Log10)
13
13.5
14
14.5
15
15.5
−2
−1.5
−1
−0.5
0
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

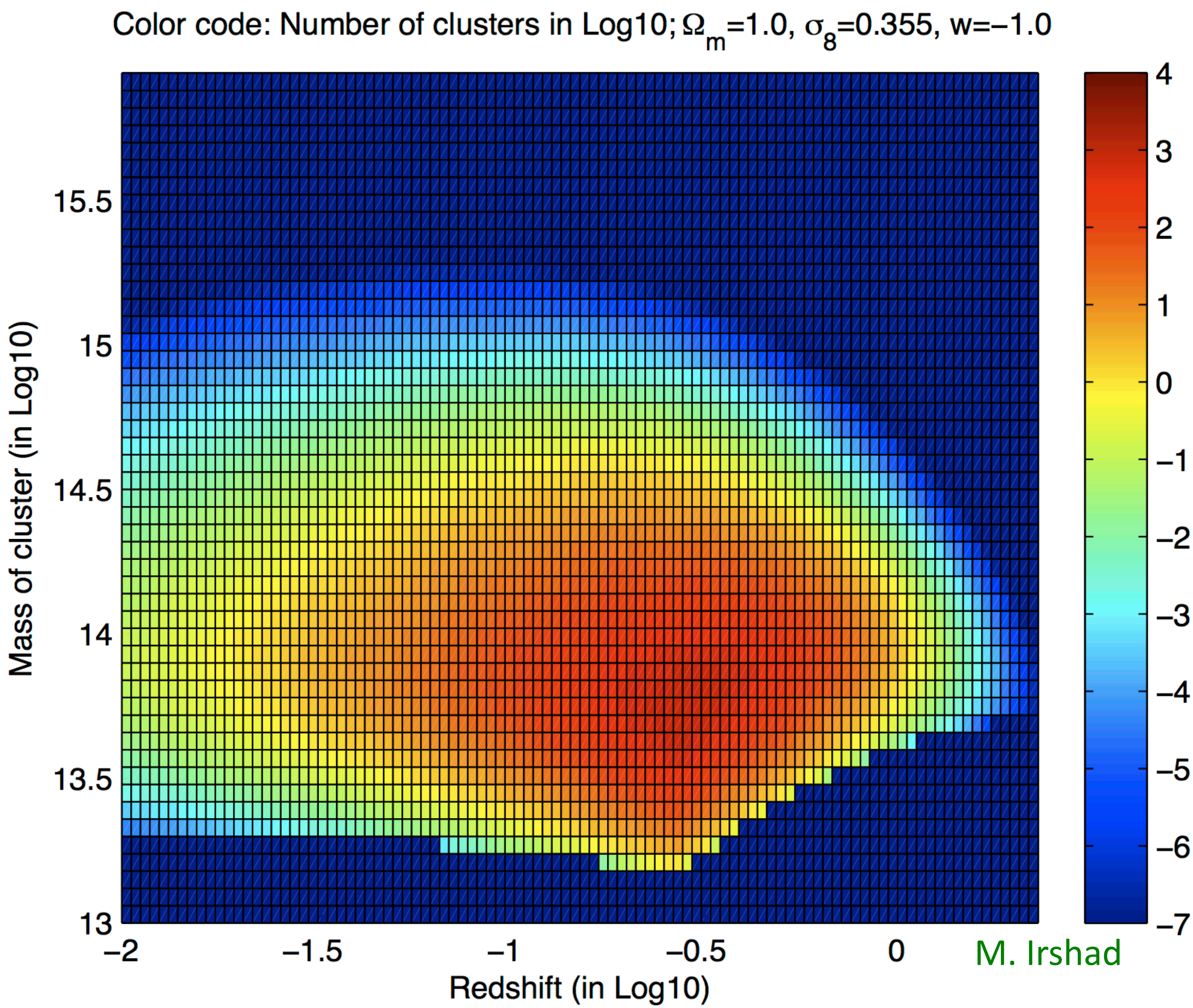

Color code: Number of clusters in Log10; Ω_m=1.0, σ_8=0.817, w=−1.0
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

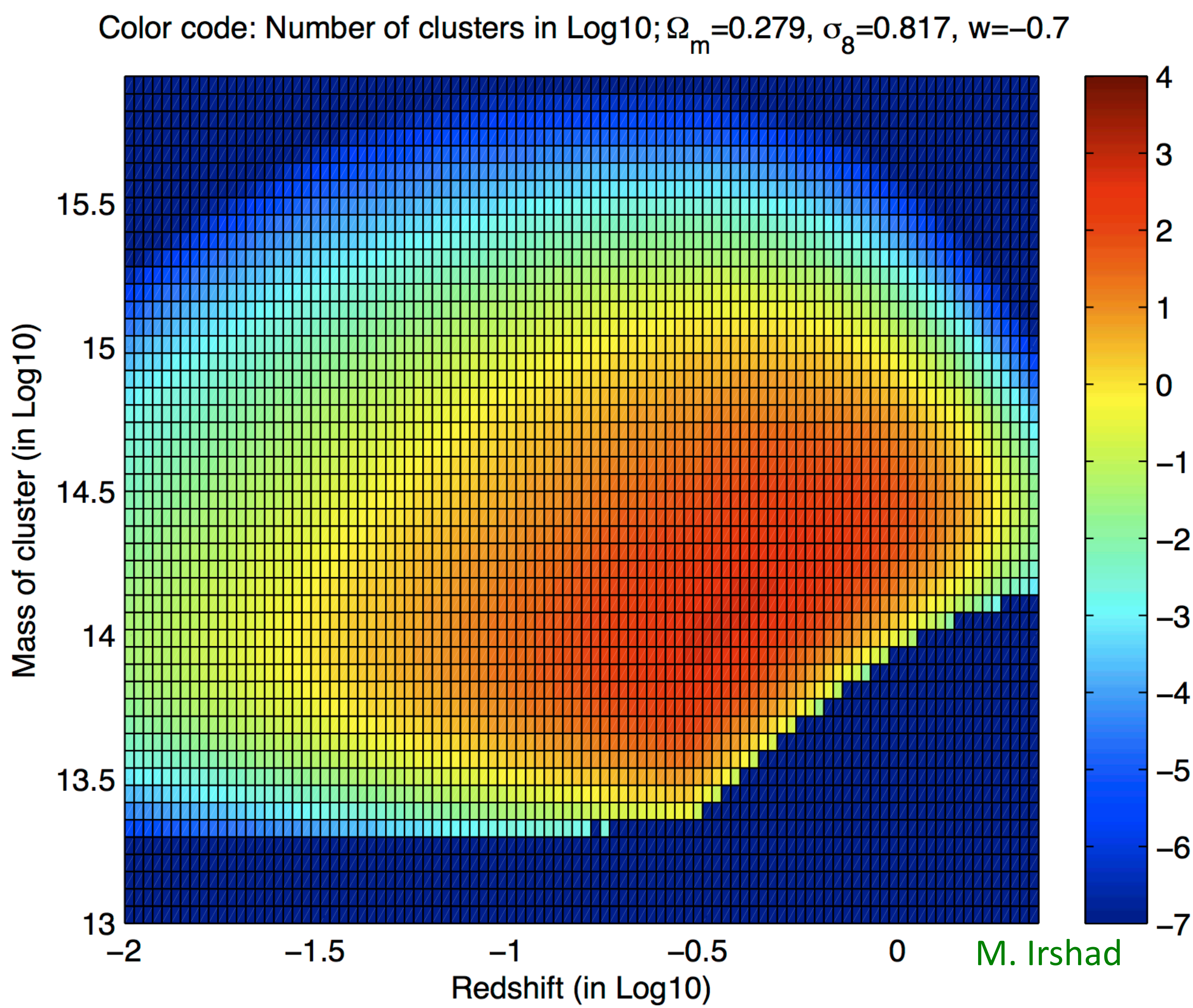


Color code: Number of clusters in Log10; Ωm=0.279, σ8=0.817, w=−1.0
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

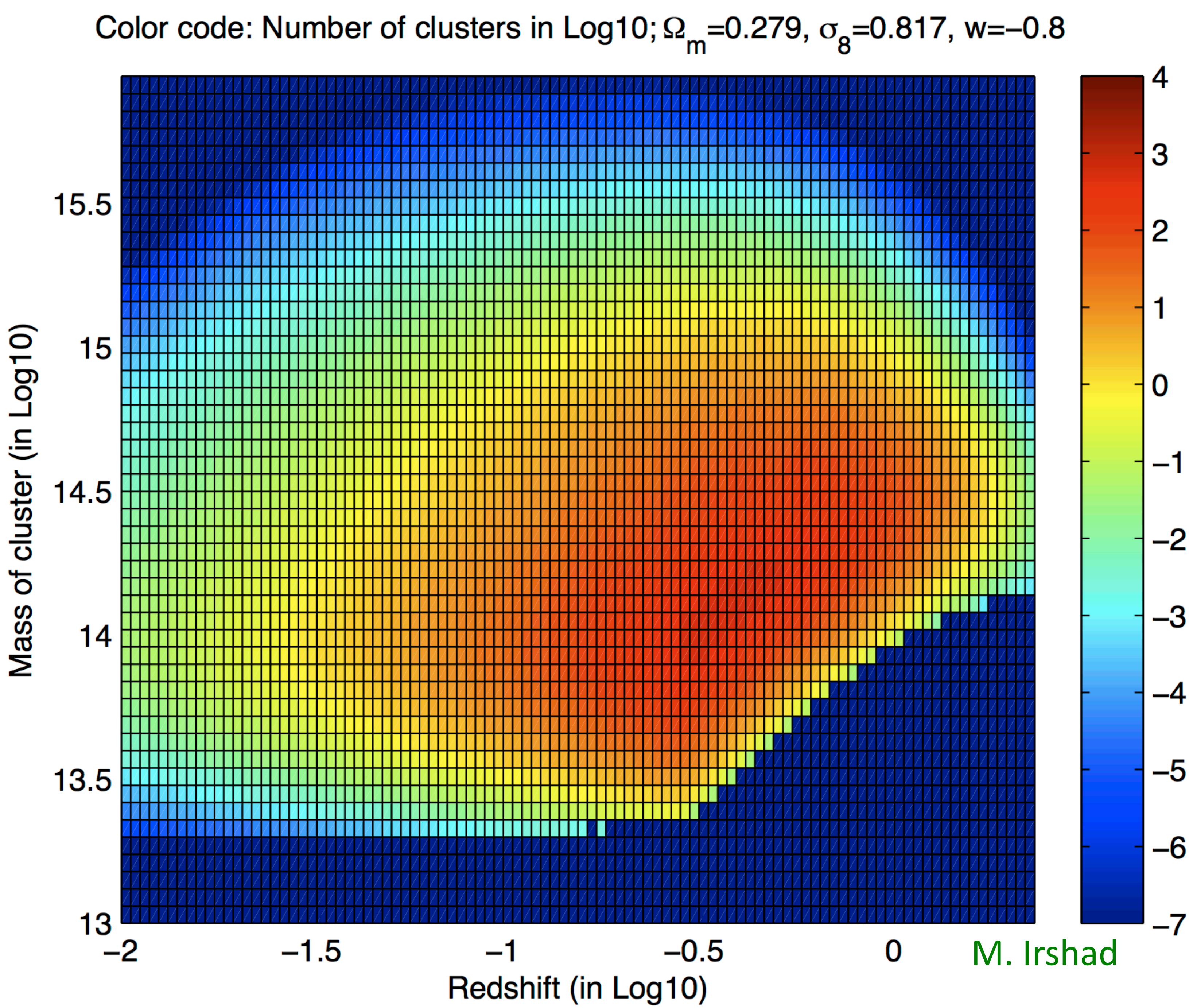


Color code: Number of clusters in Log10; Ω_m=0.5, σ_8=0.58, w=−1.0
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

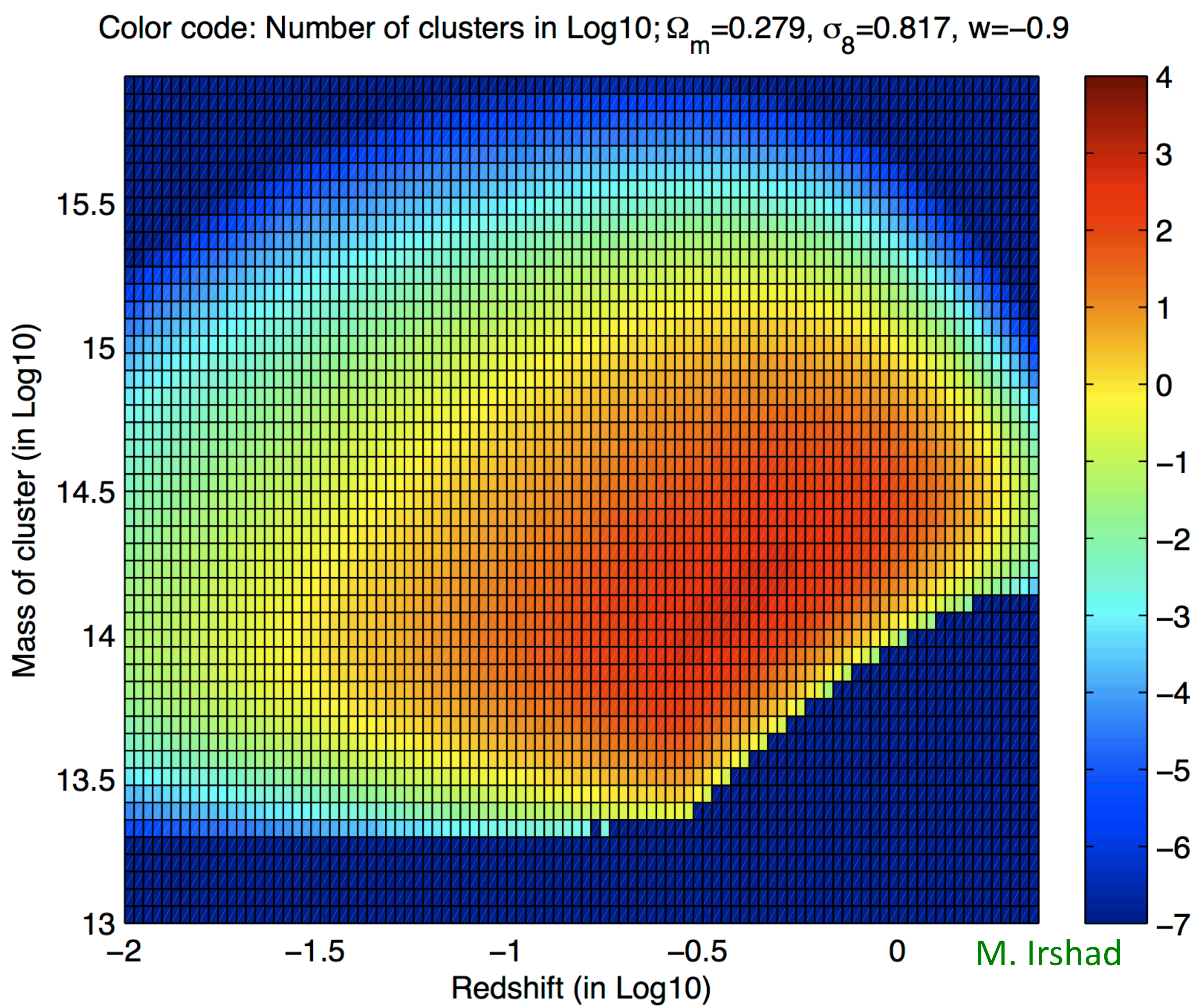

Color code: Number of clusters in Log10; Ωm=1.0, σ8=0.355, w=−1.0
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad



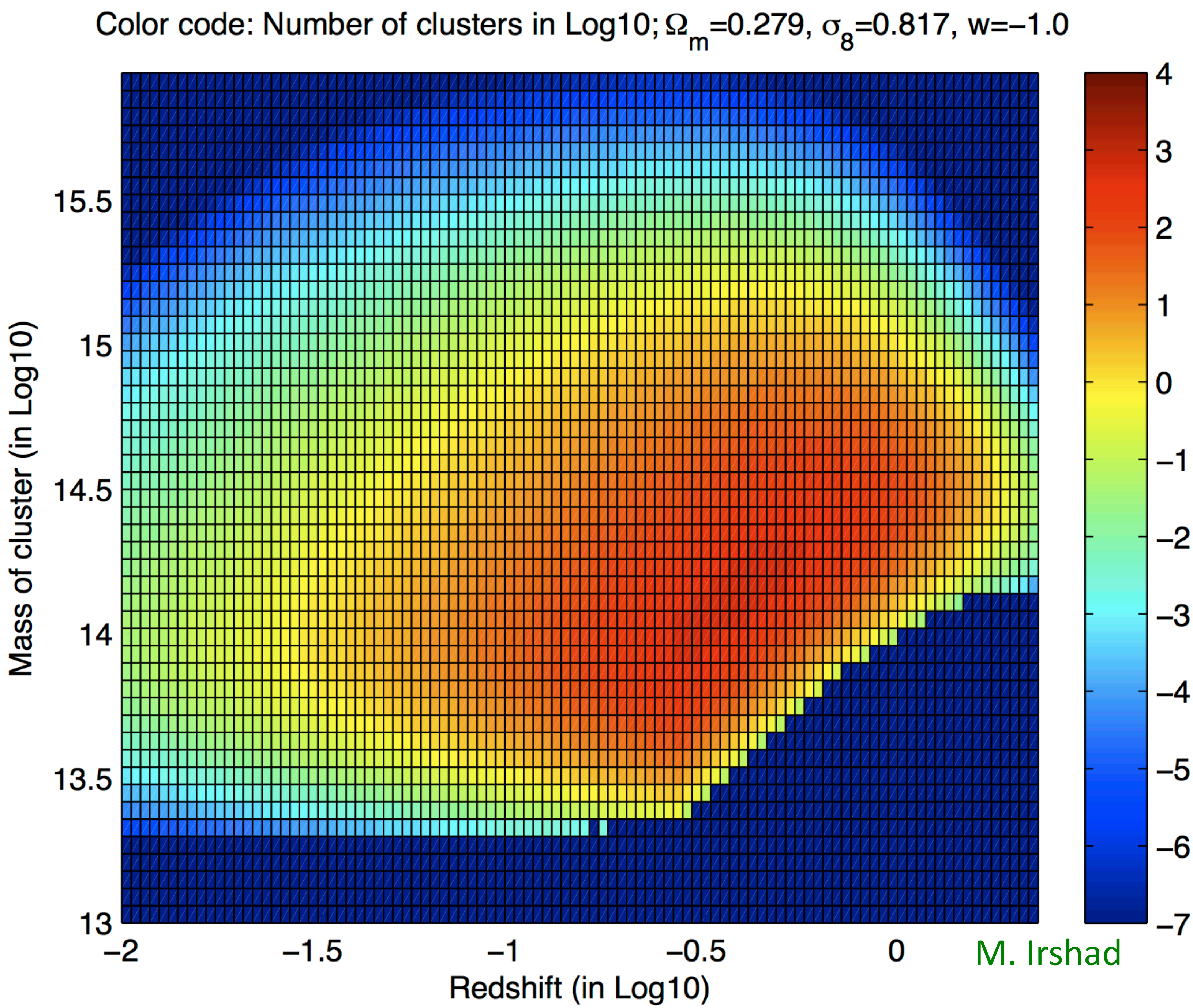
Color code: Number of clusters in Log10; Ωm=0.279, σ8=0.817, w=−0.7
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
Mass of cluster (in Log10)
Redshift (in Log10)
M. Irshad

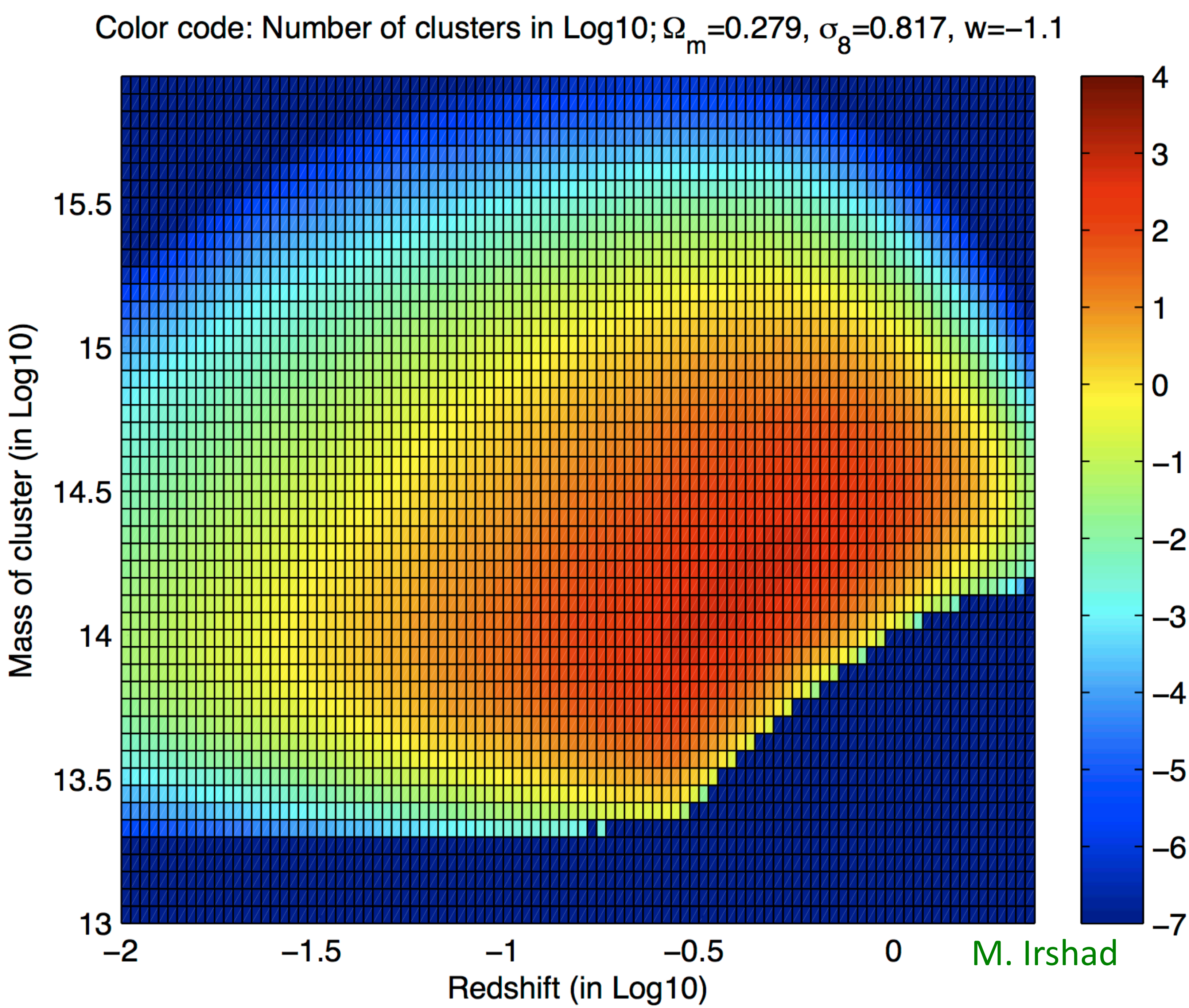


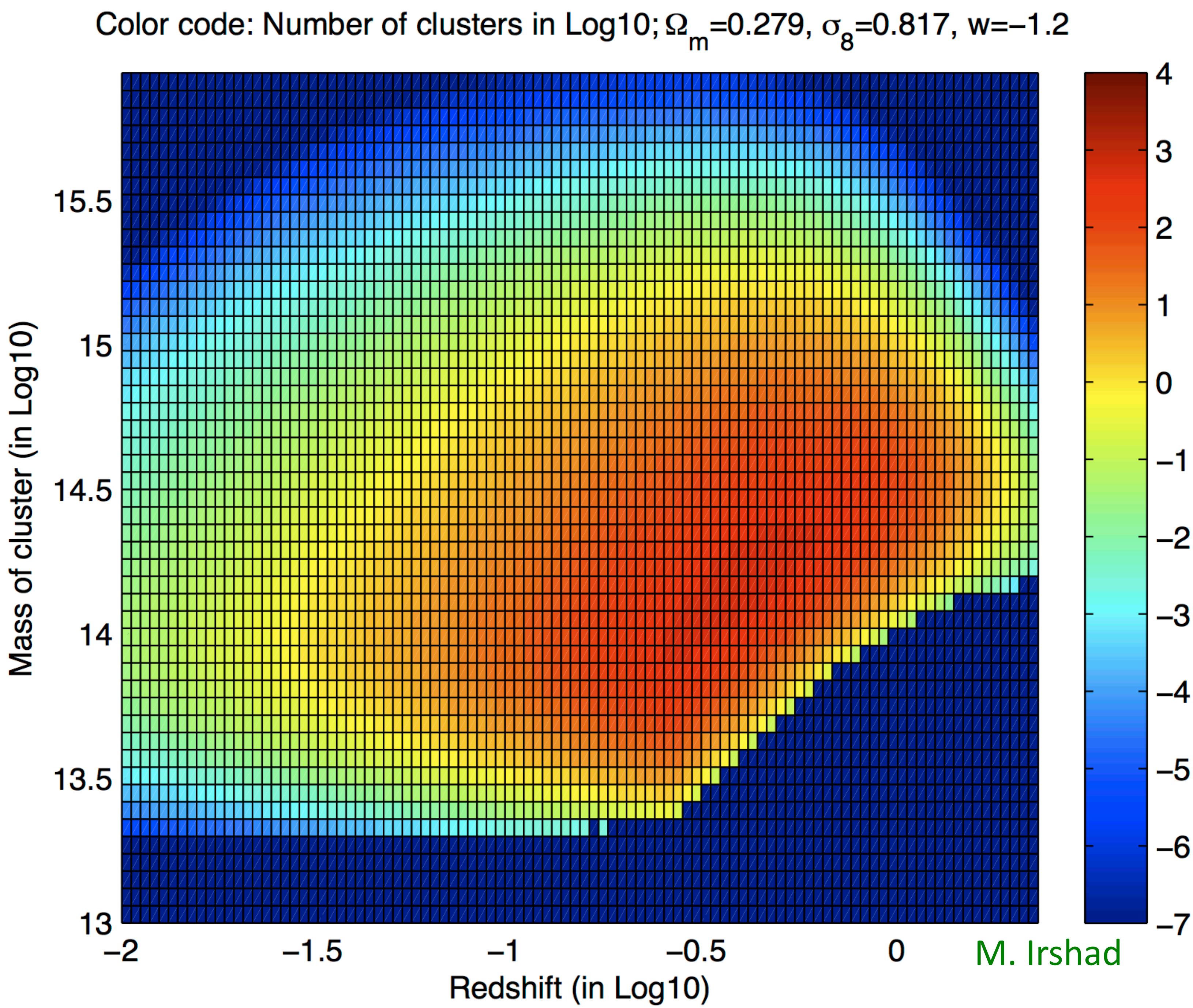
Color code: Number of clusters in Log10; Ω_m=0.279, σ_8=0.817, w=−0.8
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

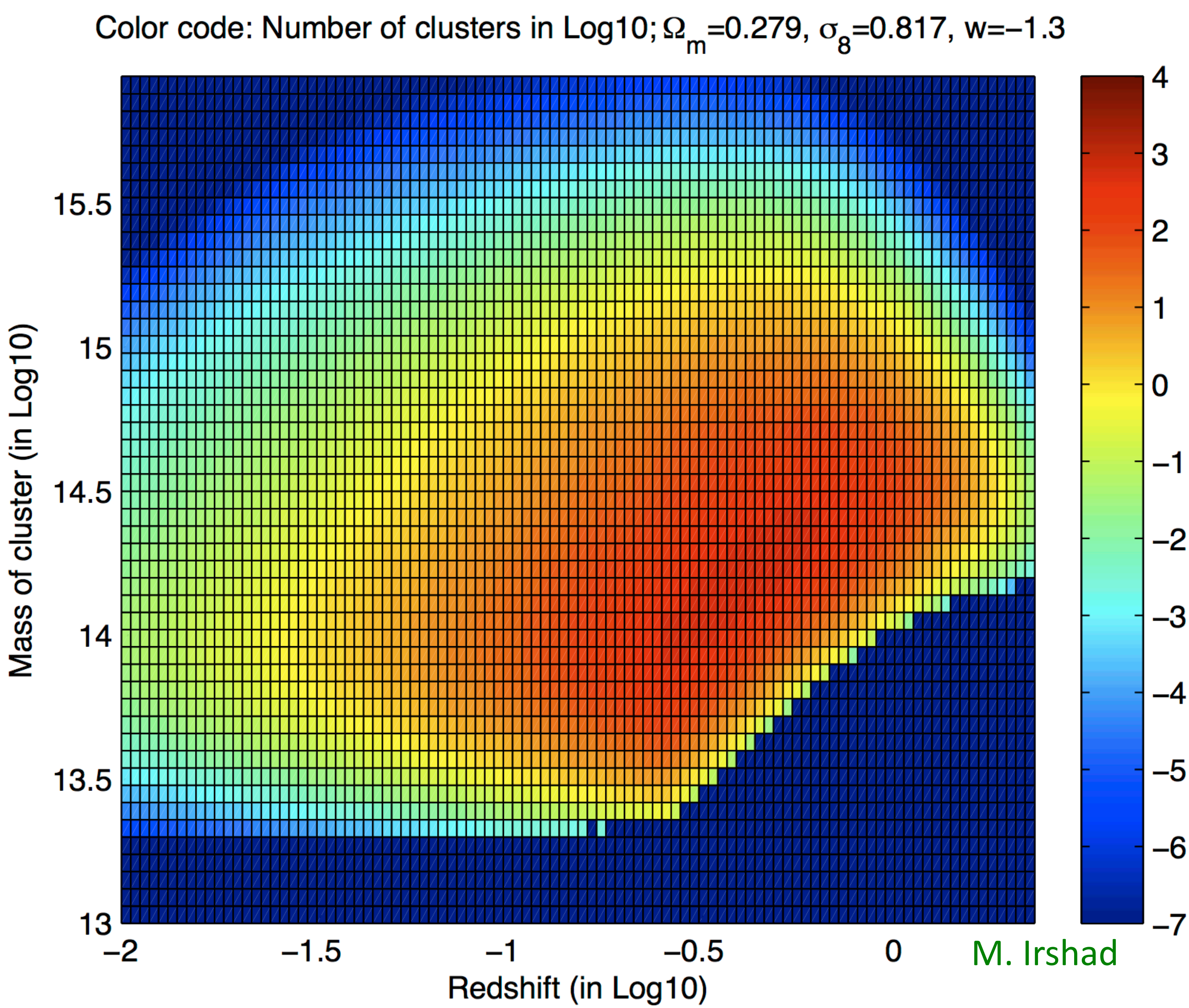


Color code: Number of clusters in Log10; Ω_m=0.279, σ_8=0.817, w=−0.9
Mass of cluster (in Log10)
13
13.5
14
14.5
15
15.5
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad


Color code: Number of clusters in Log10; Ω_m=0.279, σ_8=0.817, w=−1.0
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad


Color code: Number of clusters in Log10; Ωm=0.279, σ8=0.817, w=−1.1
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

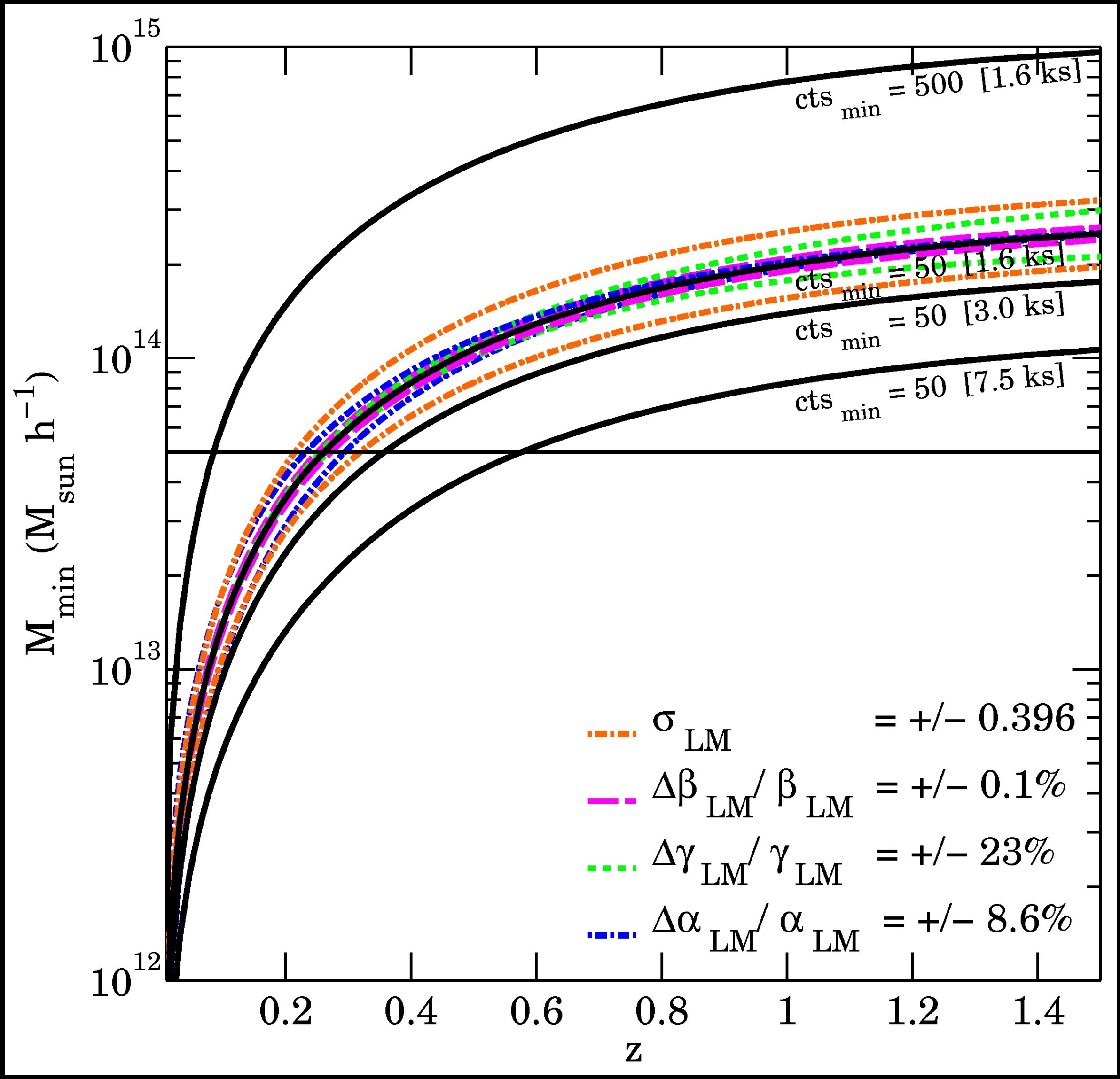

Color code: Number of clusters in Log10; Ωm=0.279, σ8=0.817, w=−1.2
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad


Color code: Number of clusters in Log10; Ωm=0.279, σ8=0.817, w=−1.3
Mass of cluster (in Log10)
15.5
15
14.5
14
13.5
13
−2
−1.5
−1
−0.5
0
Redshift (in Log10)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
M. Irshad

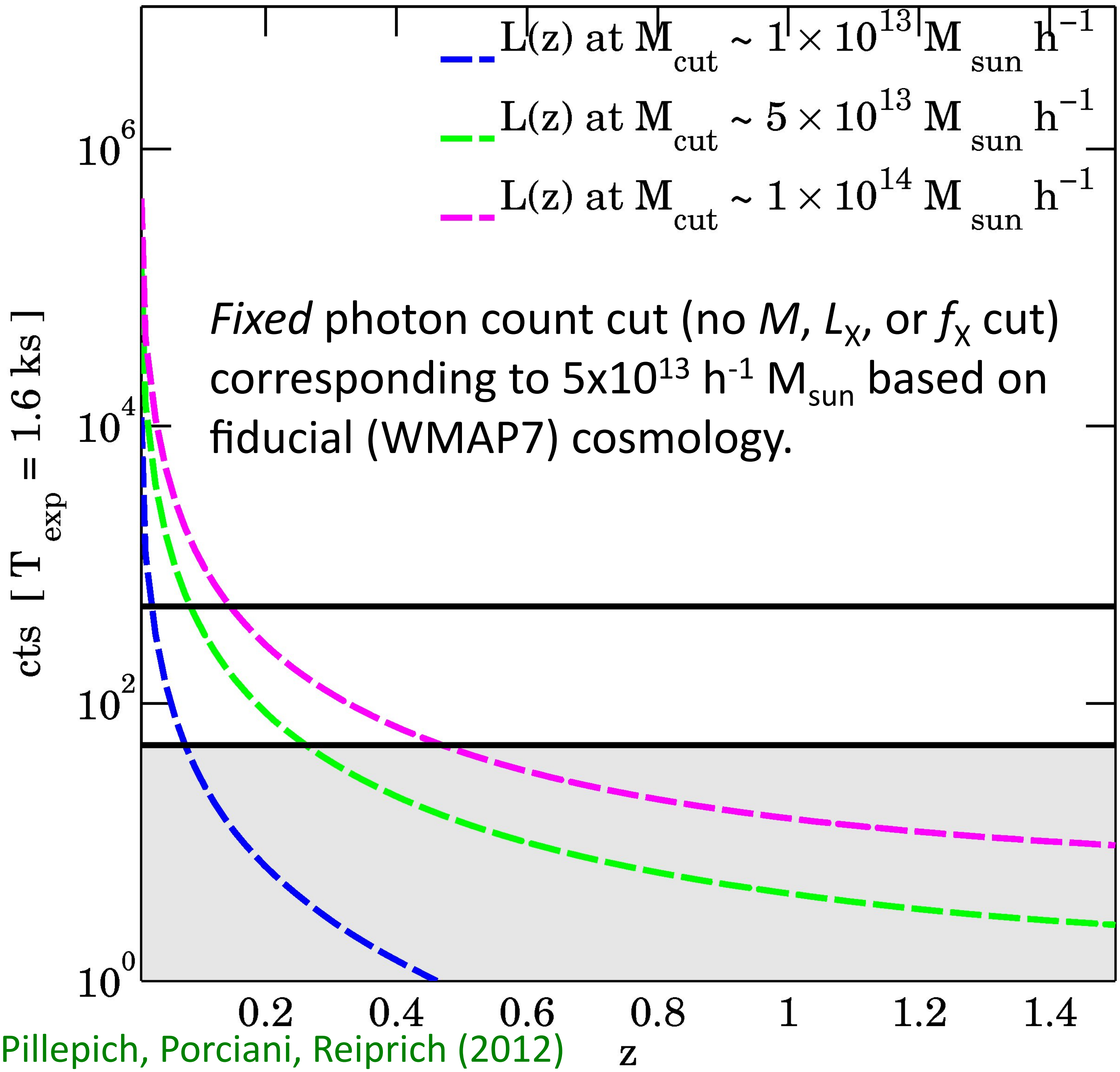
Projected Cosmological Constraints

- *eROSITA*-specific forecasts, taking into account photons registered at detector; assume that clusters get detected if at least 50 source photons received.
- Include cluster physics; scatter in L_X–M relation accounted for, fit scaling relation parameters simultaneously with cosmology ("self-cal").
- Take into account expected redshift uncertainty.
- Apply two cosmological tests simultaneously; evolution of (i) cluster mass function and (ii) angular clustering.
- Several assumptions, e.g., hardware works, flat Universe, fiducial cosmology and L_X–M relation, redshifts, one sky for all, ….

Limiting Mass

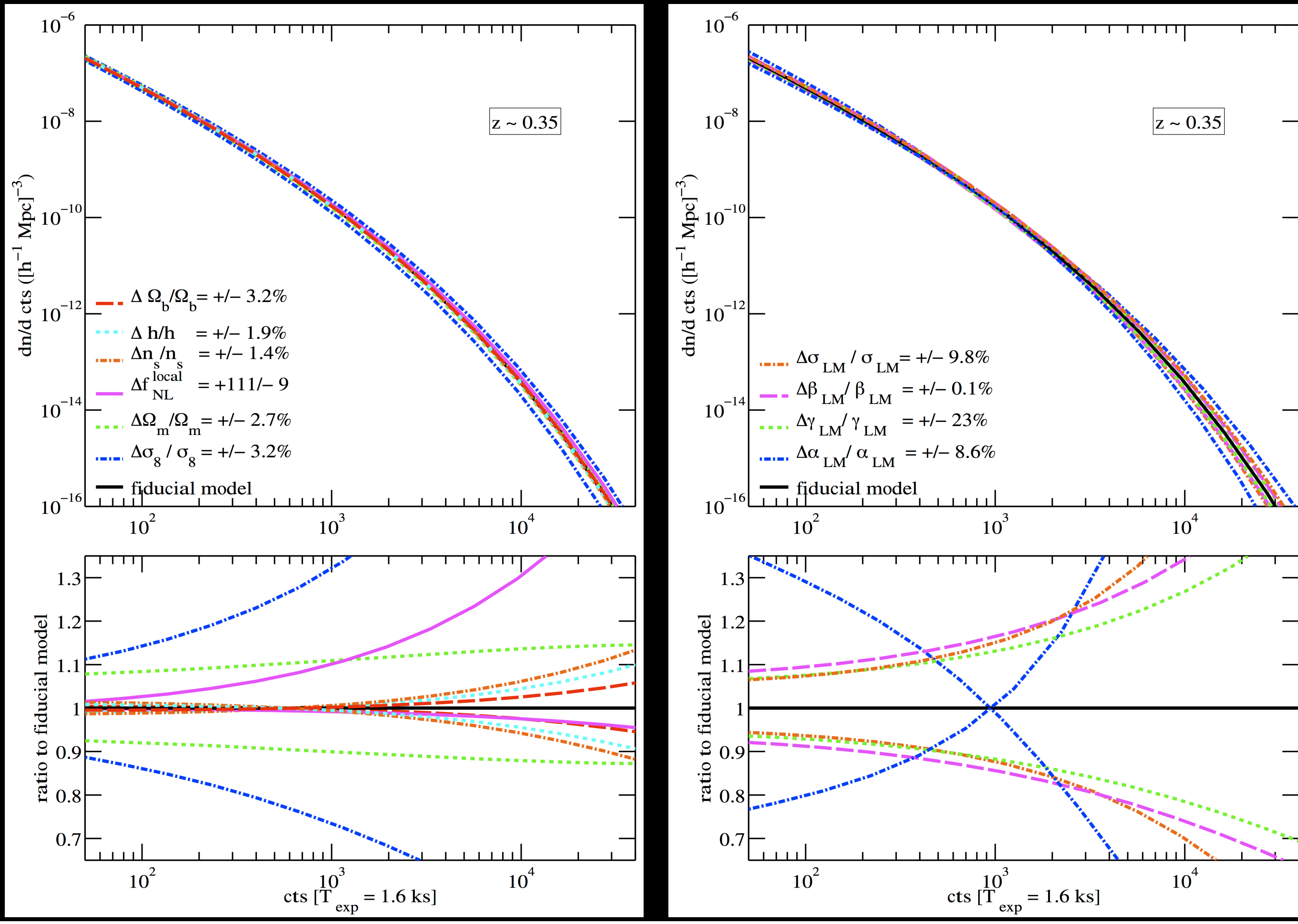


Pillepich, Porciani, Reiprich (2012)

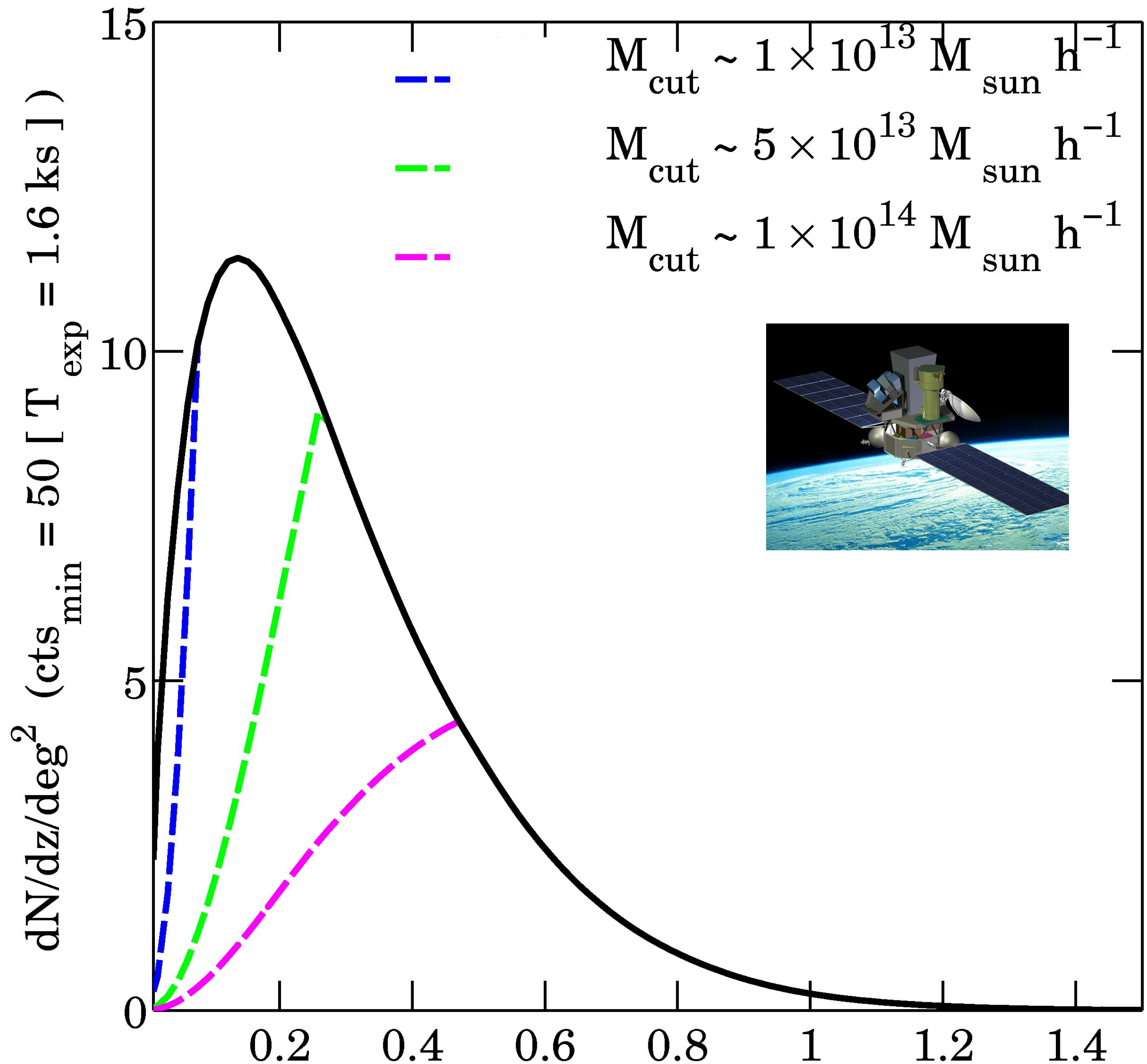


Pillepich, Porciani, Reiprich (2012)

Close to actual experiment: predict cluster abundance as function of X-ray photons detected on *eROSITA* CCDs

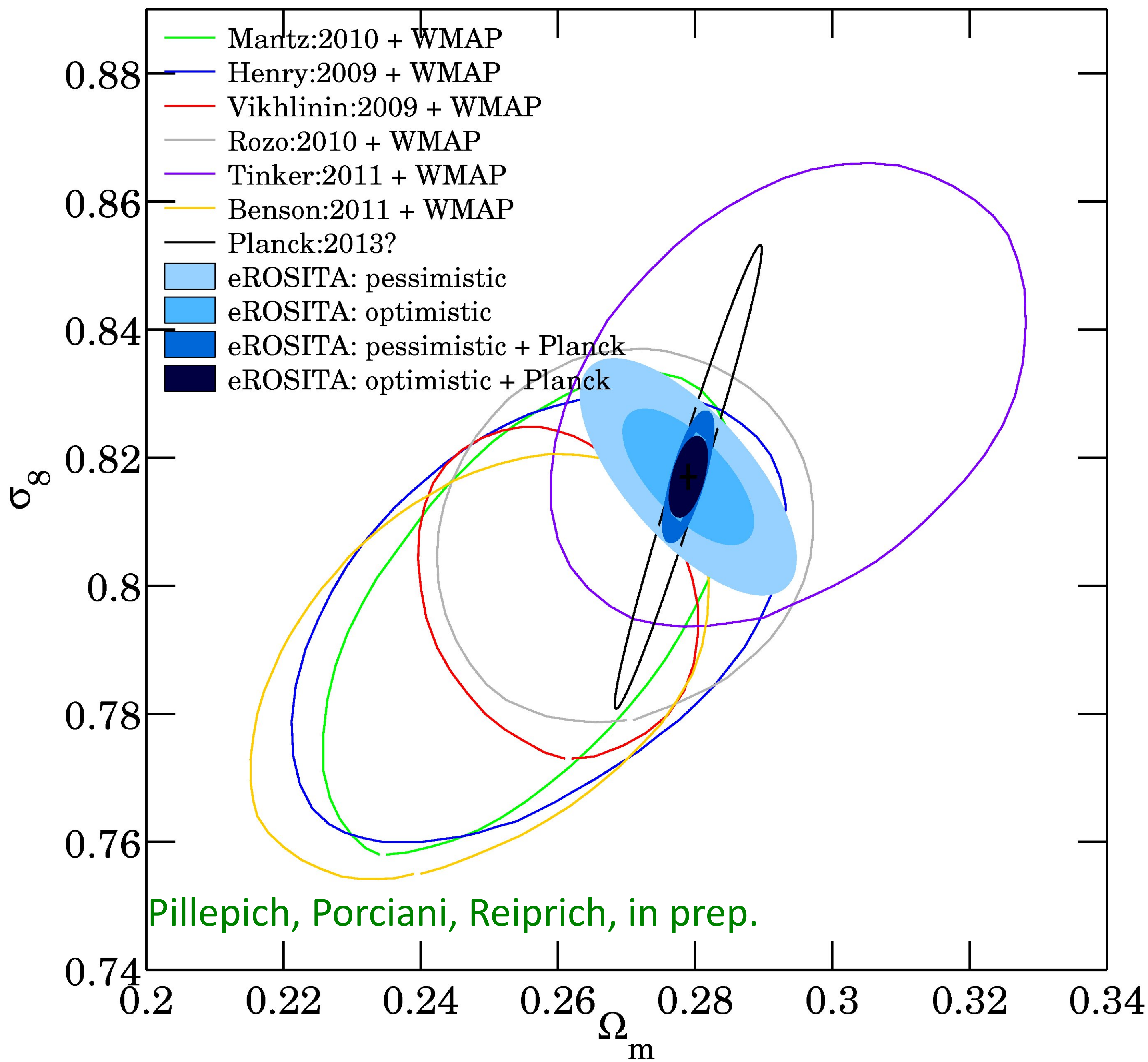


Pillepich, Porciani, Reiprich (2012)



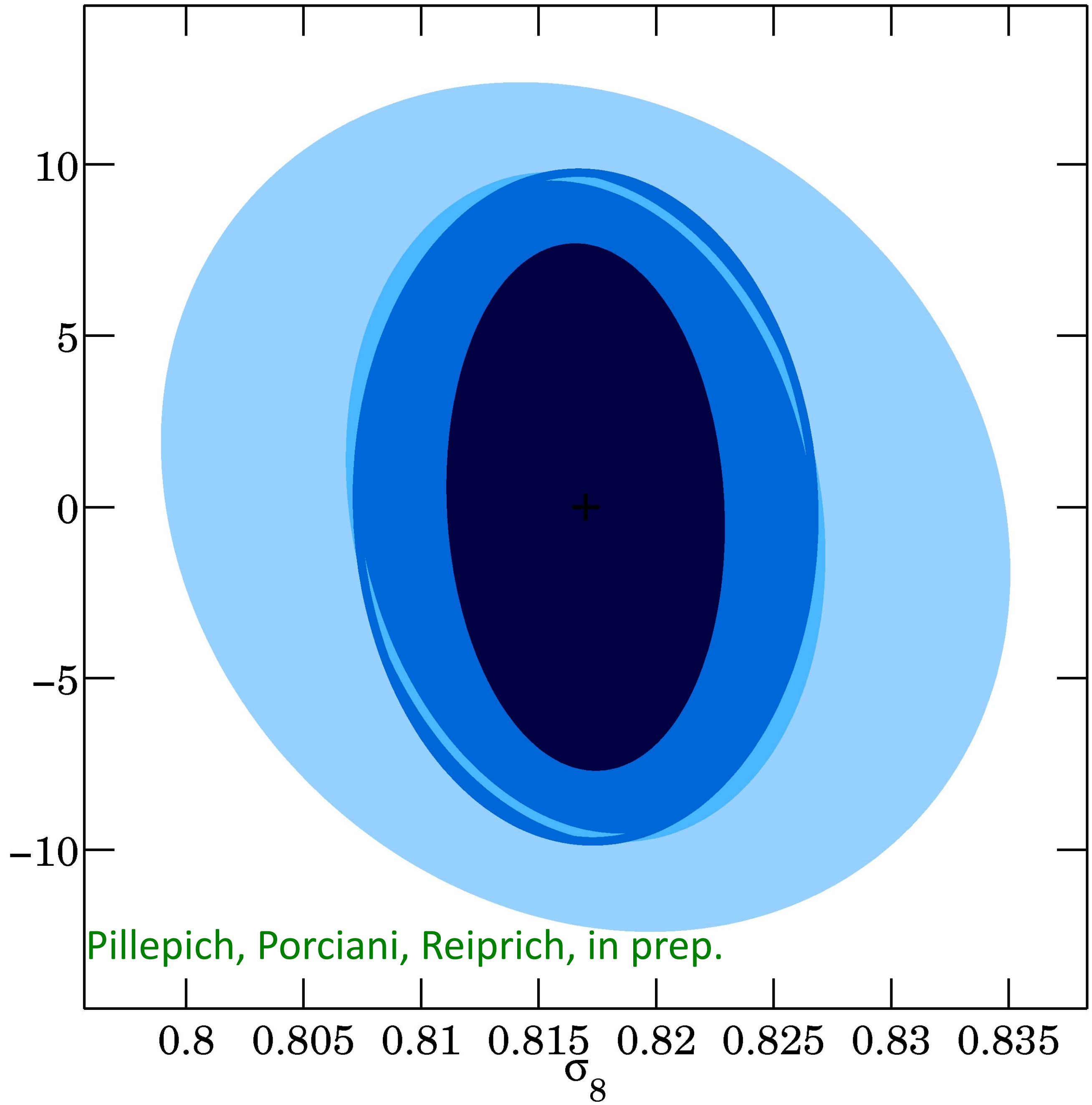
Pillepich, Porciani, Reiprich (2012)

LCDM+PNG



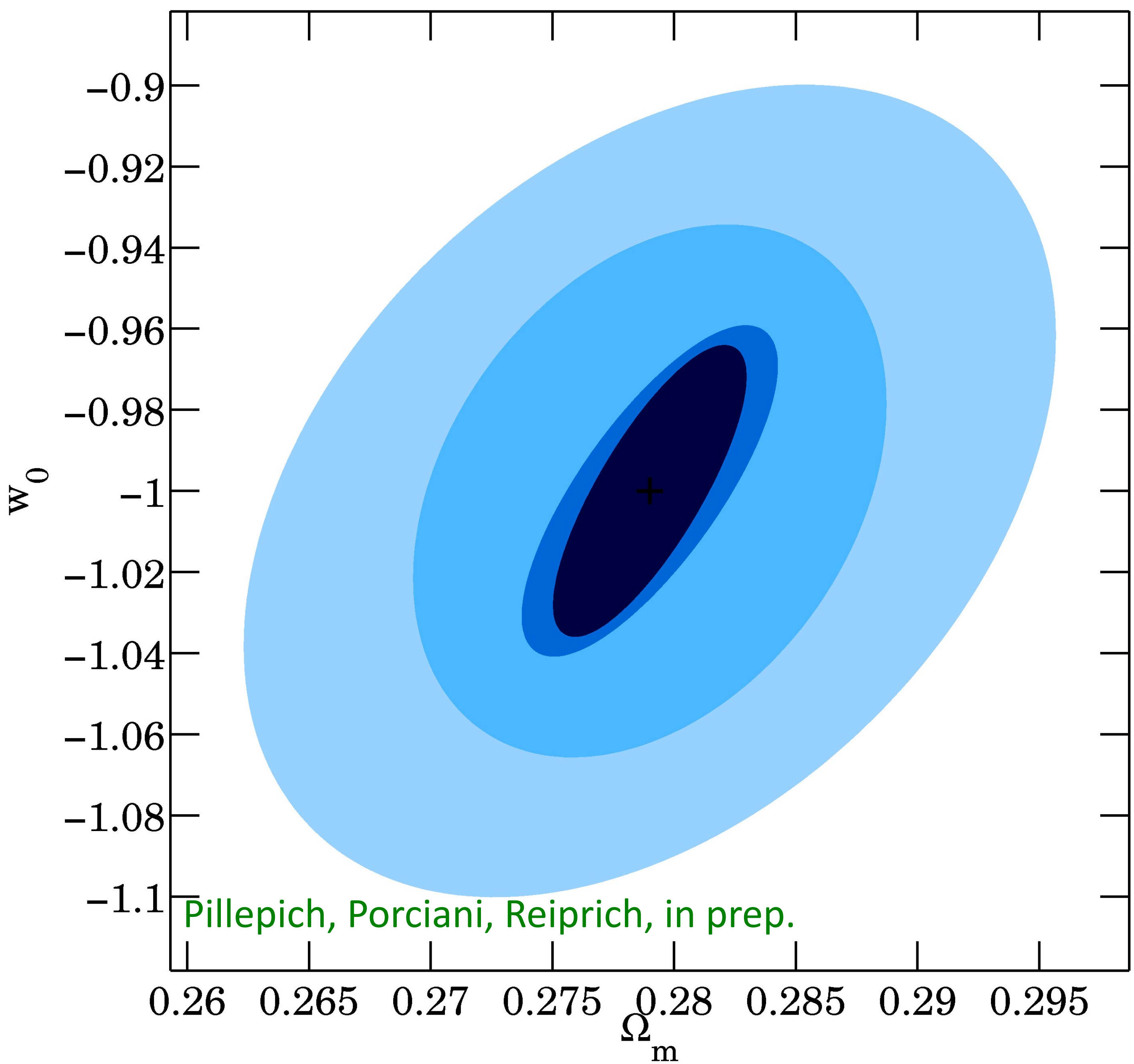
See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

Primordial non-Gaussianity LCDM+PNG



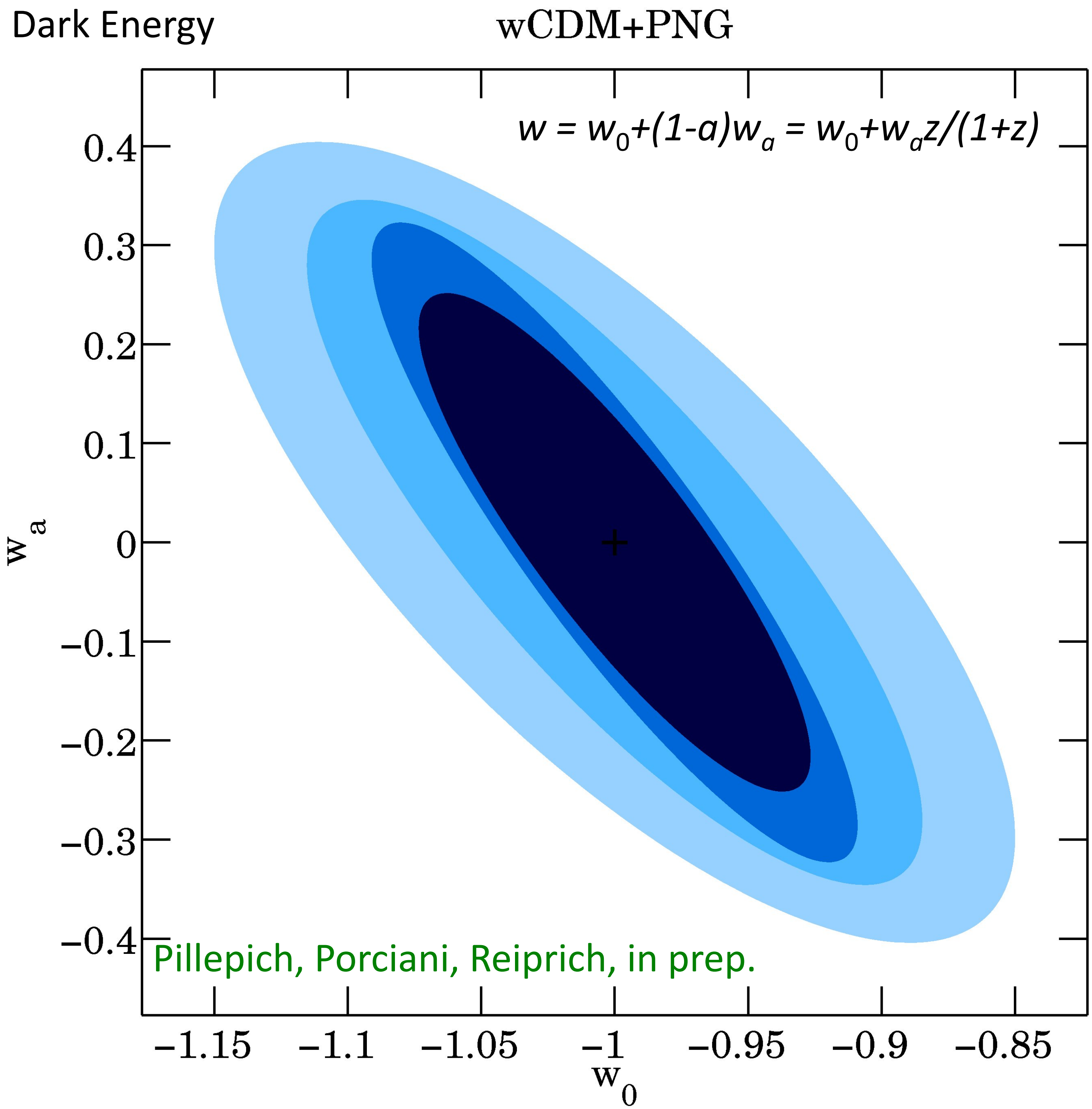
See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

Dark Energy, constant *w*   w0CDM+PNG



See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

Dark Energy



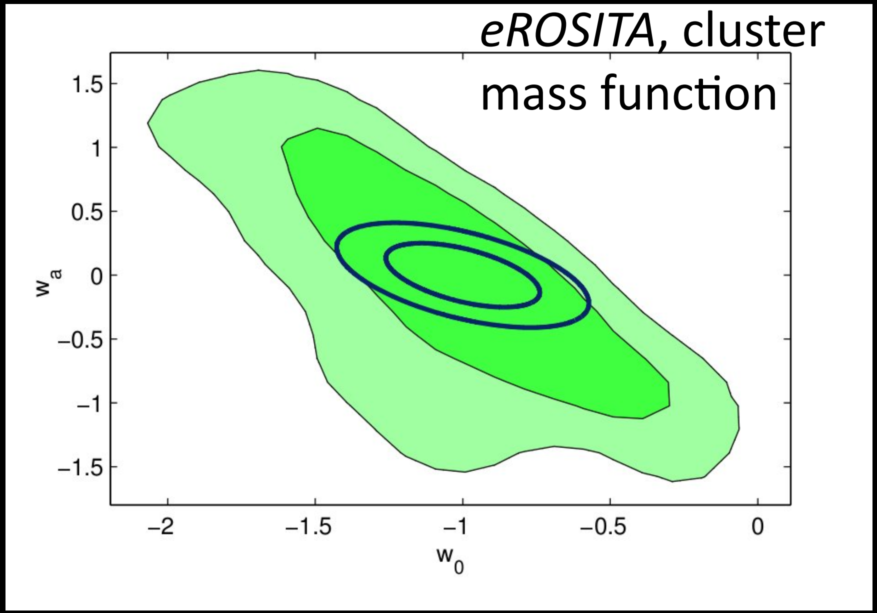
See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

eROSITA Compared to DES and Euclid

Data	Redshifts	Prior Scenario	Model	Δf_{NL}^{local}	$\Delta\sigma_8$	$\Delta\Omega_m$	Δw_0	Δw_a	$FoM^{DEFT,1\sigma}$
Stage IV									
eROSITA	photo-z	Pessimistic	LCDM+PNG	8.1	0.012	0.0101	-	-	-
eROSITA	spectro-z	Optimistic	LCDM+PNG	6.4	0.007	0.0060	-	-	-
eROSITA + Planck	photo-z	Pessimistic	LCDM+PNG	6.5	0.006	0.0021	-	-	-
eROSITA + Planck	spectro-z	Optimistic	LCDM+PNG	5.0	0.004	0.0015	-	-	-
eROSITA	photo-z	Pessimistic	w0CDM+PNG	8.2	0.016	0.0109	0.066	-	-
eROSITA	spectro-z	Optimistic	w0CDM+PNG	6.6	0.009	0.0063	0.043	-	-
eROSITA + Planck	photo-z	Pessimistic	w0CDM+PNG	6.9	0.007	0.0034	0.026	-	-
eROSITA + Planck	spectro-z	Optimistic	w0CDM+PNG	5.6	0.005	0.0025	0.023	<3%	-
eROSITA	photo-z	Pessimistic	wCDM+PNG	8.2	0.018	0.0120	0.098	0.27	57.4
eROSITA	spectro-z	Optimistic	wCDM+PNG	6.6	0.011	0.0066	0.075	0.23	103.1
eROSITA + Planck	photo-z	Pessimistic	wCDM+PNG	7.0	0.007	0.0036	0.059	0.21	179.4
eROSITA + Planck	spectro-z	Optimistic	wCDM+PNG	5.7	0.006	0.0026	0.048	0.16	263.3
DES Stage III	photo-z	WL+2D photometric	wCDM+PNG	8.6	0.009	0.0082	0.093	0.61	- (>300 for f_{NL}=0)
DES + Planck	photo-z	WL+2D photometric	wCDM+PNG	8.2	0.009	0.0074	0.090	0.35	-
Euclid Stage IV	photo-z	WL+2D photometric	wCDM + PNG	4.7	0.005	0.0048	0.054	0.32	-
Euclid	spectro-z	WL+2D spectroscopic	wCDM + PNG	5.7	0.005	0.0051	0.051	0.35	-
Euclid + Planck	photo-z	WL+2D photometric	wCDM + PNG	4.5	0.005	0.0044	0.052	0.20	-
Euclid + Planck	spectro-z	WL+2D spectroscopic	wCDM + PNG	5.3	0.005	0.0037	0.035	0.15	-

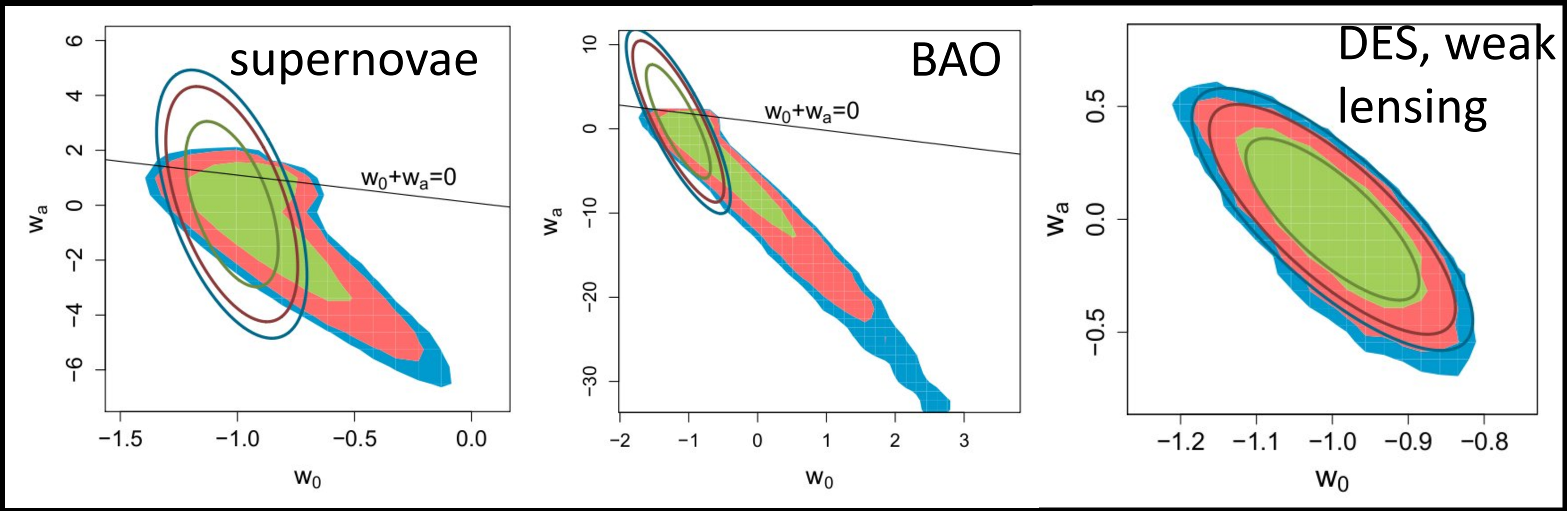
Pillepich, Porciani, Reiprich, in prep.; Merloni et al. (arXiv:1209.3114).
DES and Euclid from Giannantonio et al. 2012.

Fisher vs MCMC Forecasting for Redshift-Dependent Equation of State



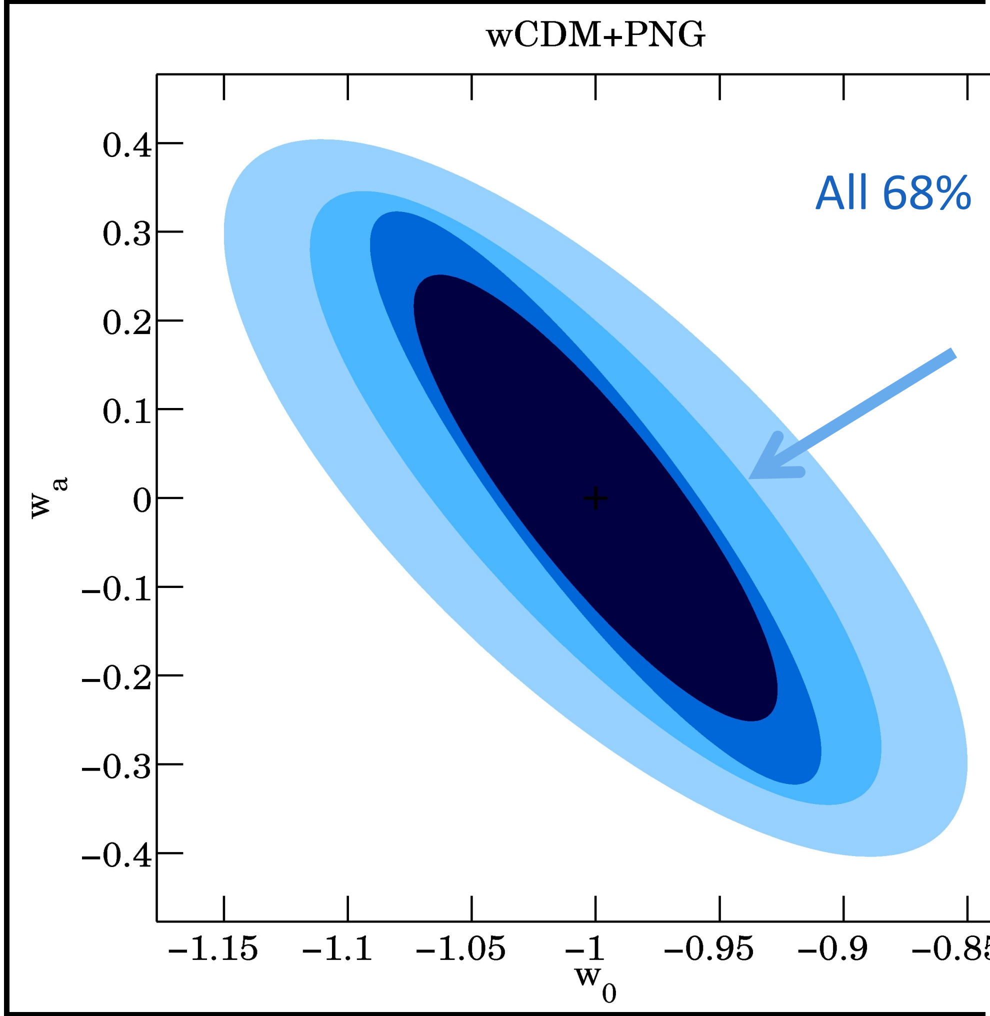
S. Khedekar
PhD thesis (2011)

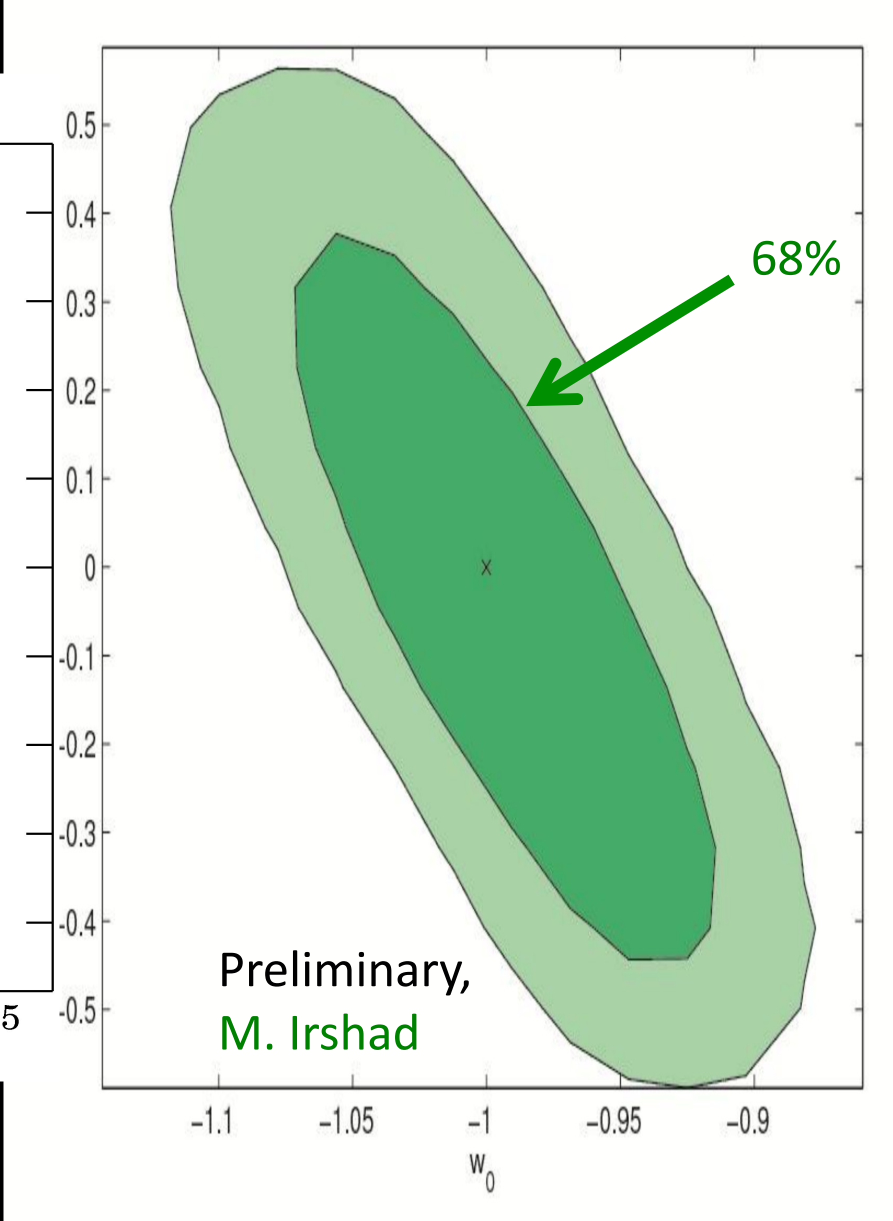
Wolz et al. (2012)



Fisher Matrix

MCMC

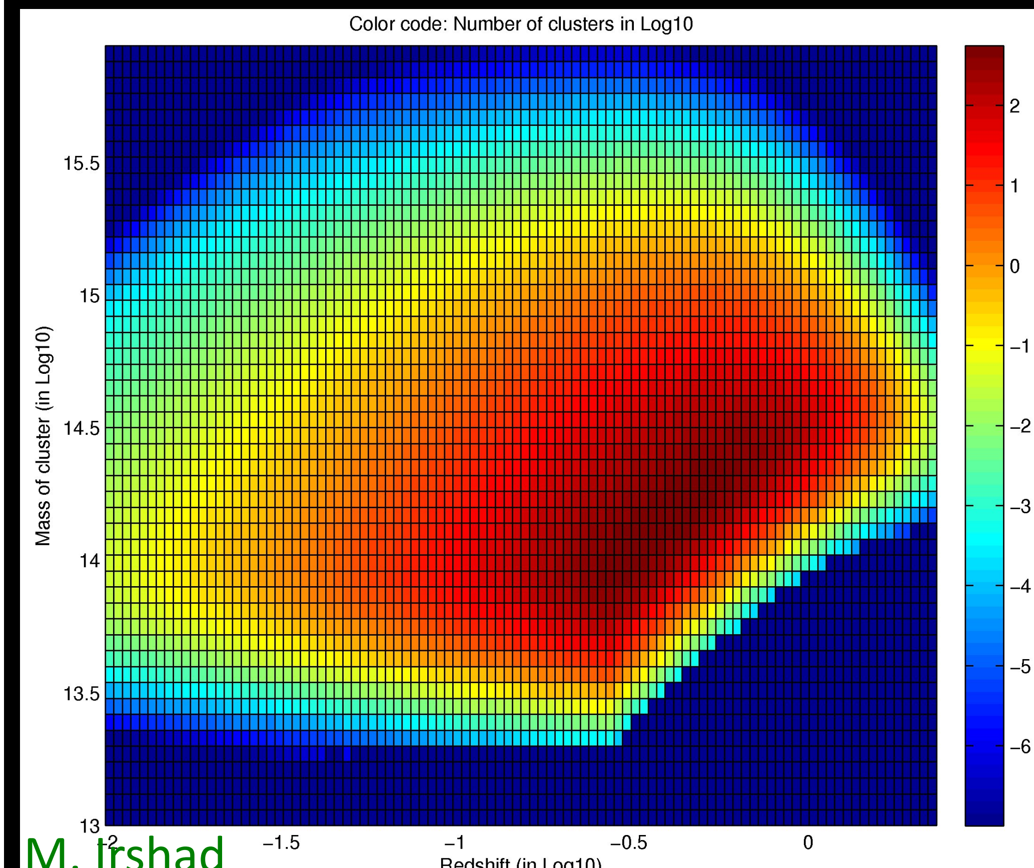


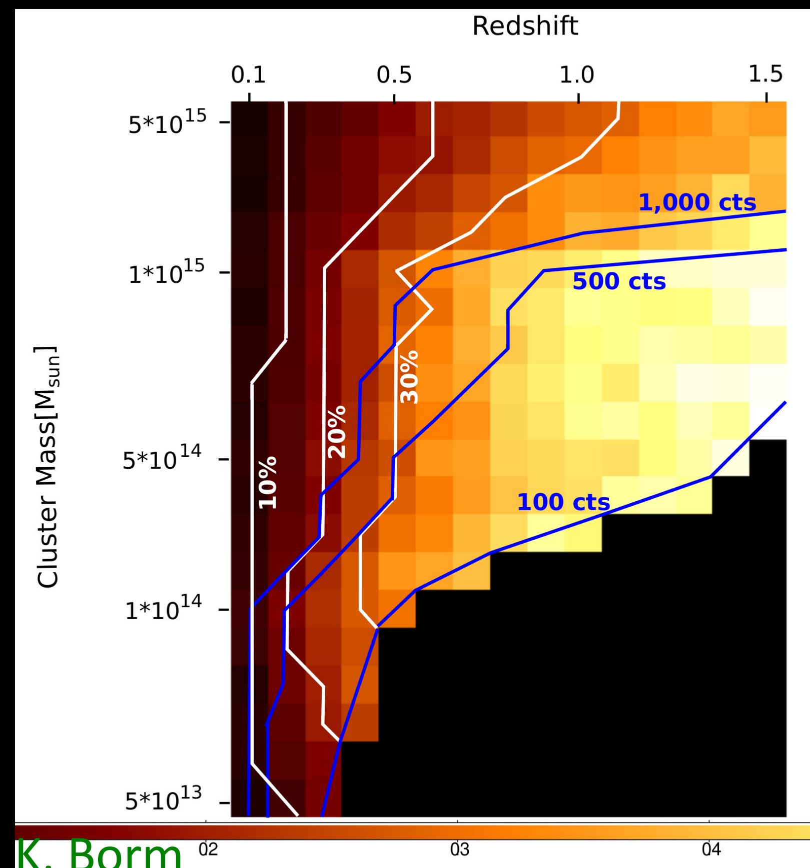


NOT a proper comparison since different assumptions used – but looks promising!

There's more than L_X!
$\Delta T/T \leq 10\%$ and $\Delta z/(1+z) \leq 10\%$ for ~10^4 clusters, directly from survey.

Talk Katharina Borm tomorrow.



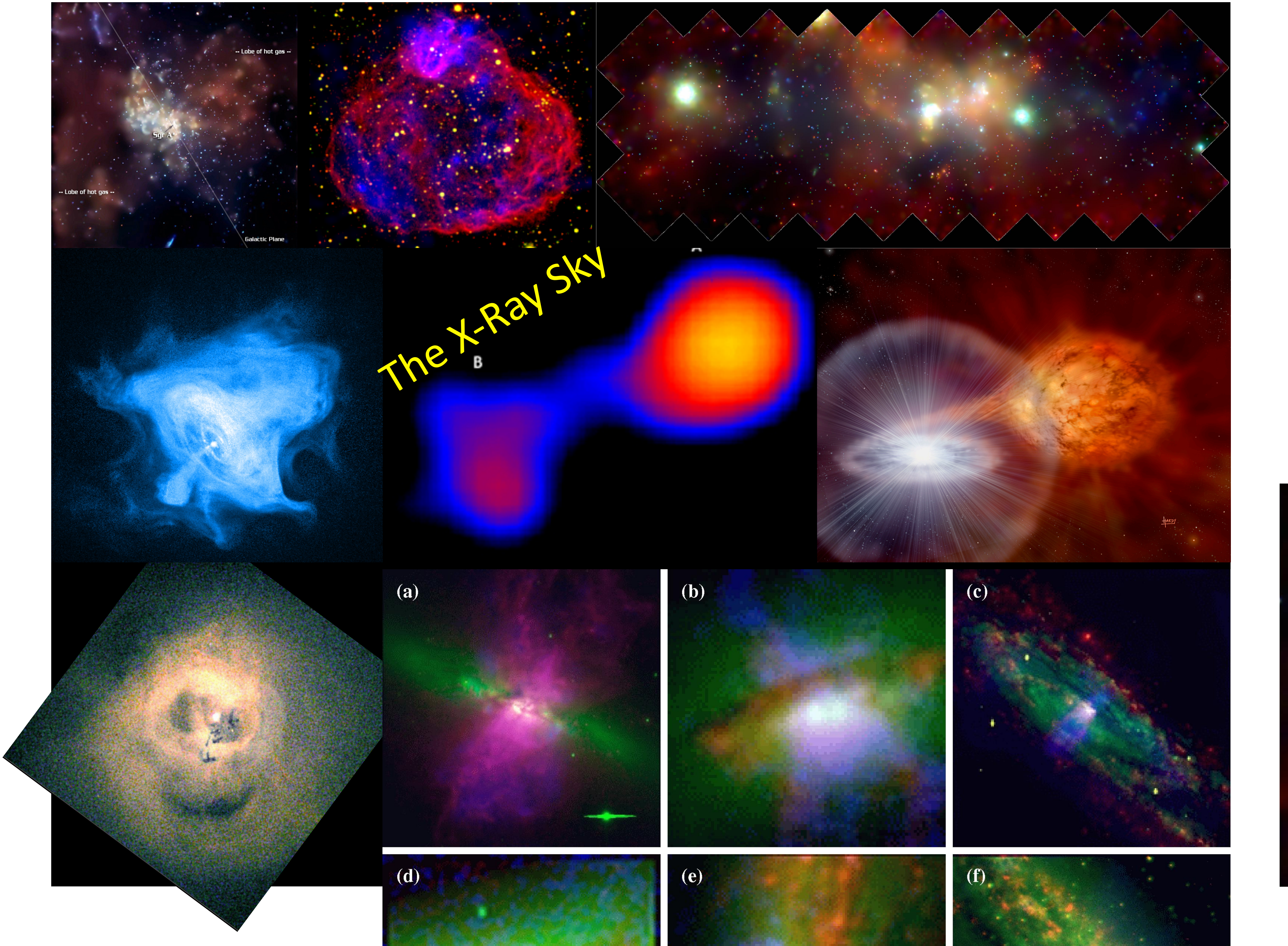


Challenges

- Getting redshifts for all clusters (X-ray-*z*, photo-*z*, spectro-*z*). -> Talk Hans, Katharina.
- L_X-M relation might be more complex (e.g., mass and redshift dependent scatter). -> Multiwavelength mass-calibration program.
- Handling AGN (X-ray–emitting supermassive black holes) contamination. -> Detailed simulations of the *eROSITA* sky.
- ….

Summary of Conclusions

- *eROSITA* will likely be the first "Stage IV" dark energy probe world-wide. It will yield competitive and complementary constraints, e.g., Δw_{DE}<3%.
- Fisher forecasts seem consistent with MCMC.
- Even tighter constraints possible through low-scatter mass proxies (e.g., *T*) from survey (~10^4 clusters) and pointed phase follow-up.
- Launch in two years, *now* is the time to prepare cosmological analysis pipelines to constrain dark energy, f_{NL}, modified gravity, neutrino masses, ….


The X-Ray Sky
-- Lobe of hot gas --
Sgr A*
-- Lobe of hot gas --
Galactic Plane
B
(a)
(b)
(c)
(d)
(e)
(f)