Studying Dark Energy with *eROSITA* Galaxy Clusters

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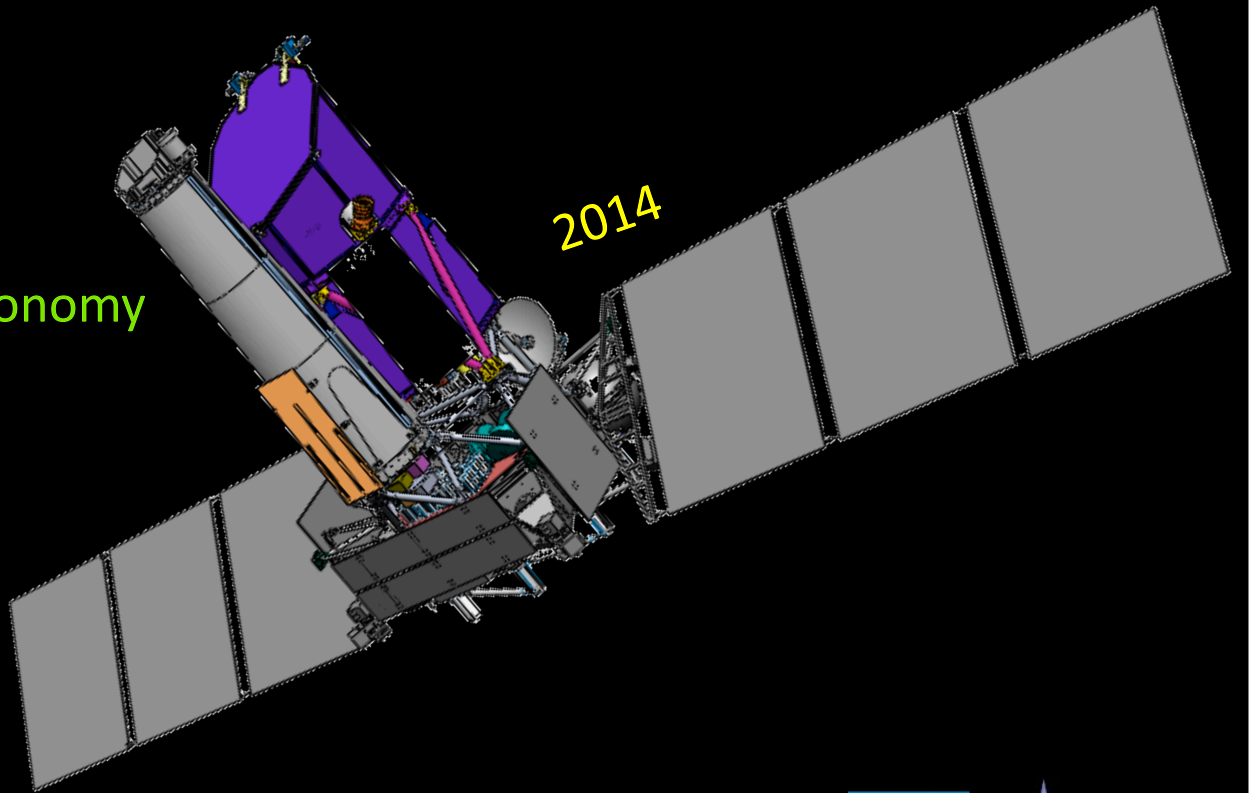
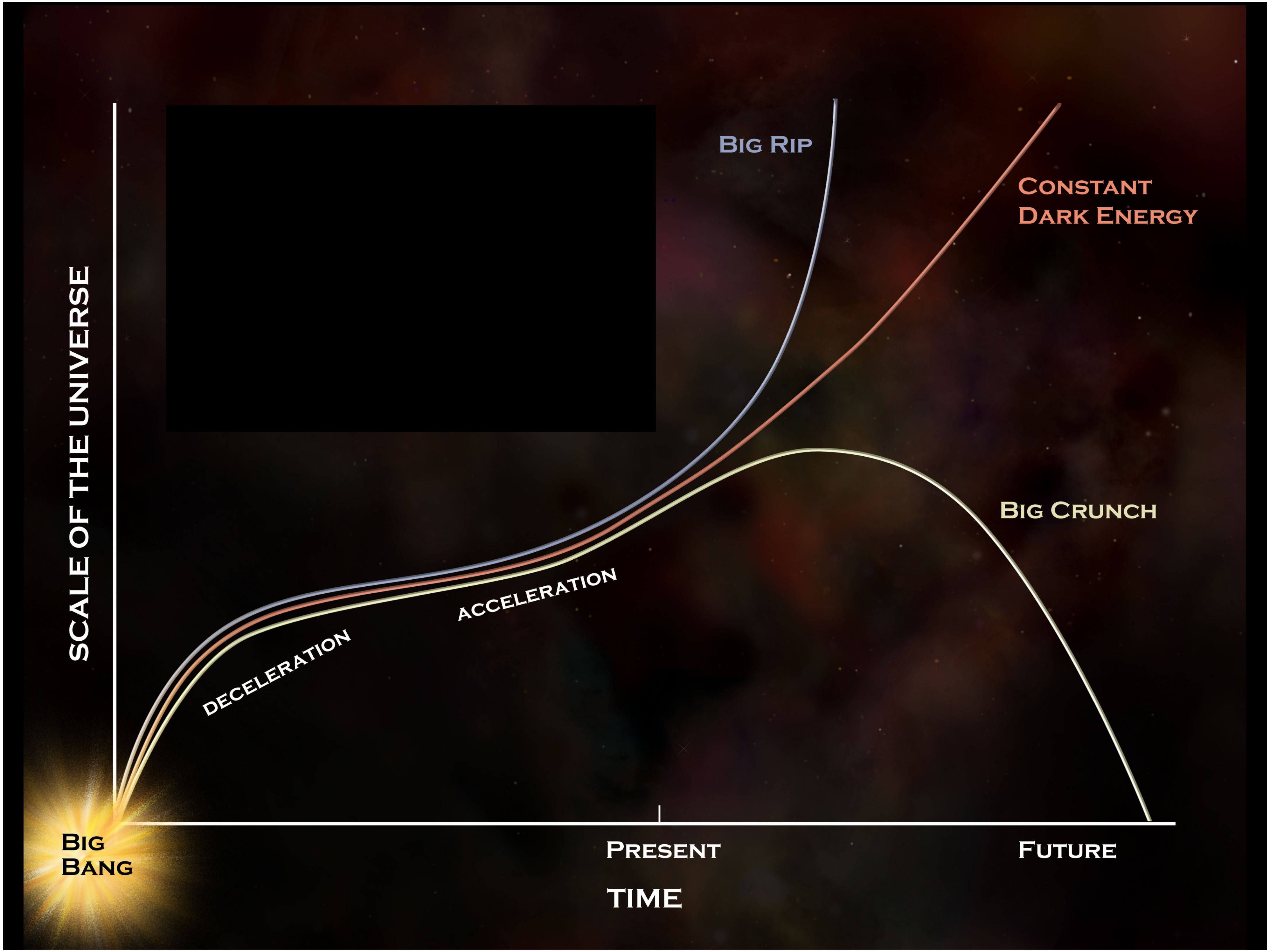
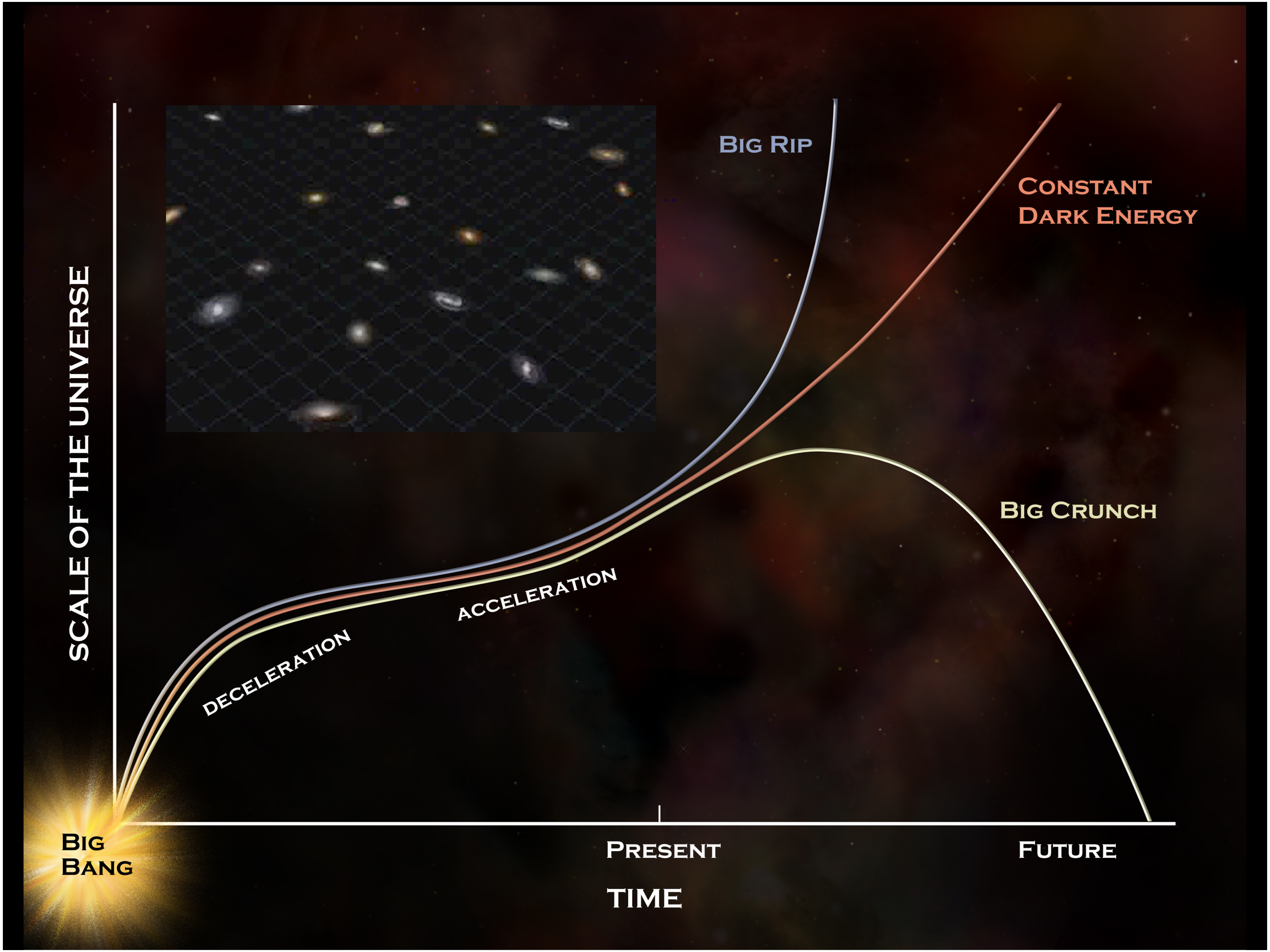
http://dark-energy.net



Overview

- *Conclusion:* With *eROSITA*, we will constrain w_{DE} to <3% 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.


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



Big Rip
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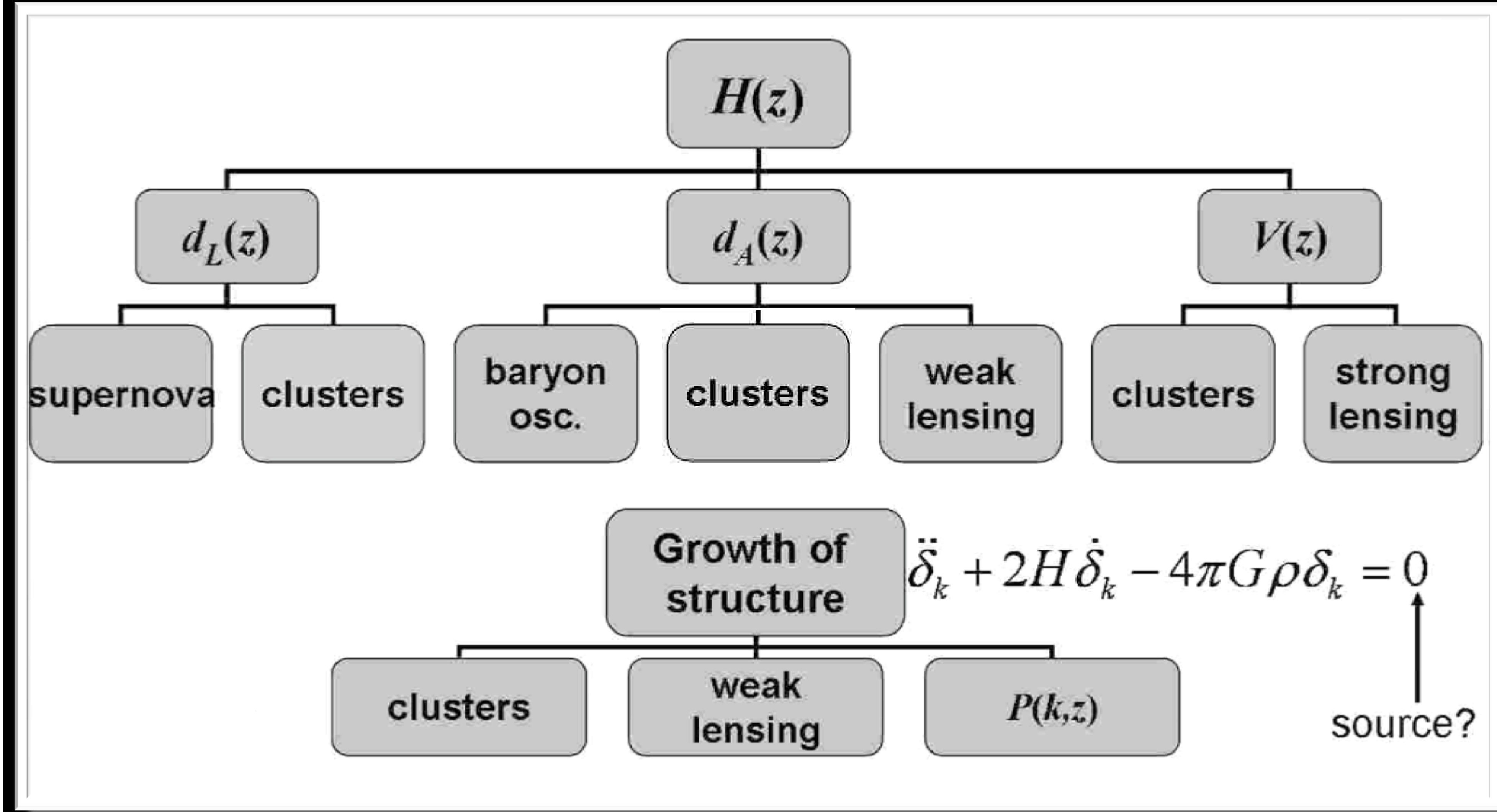
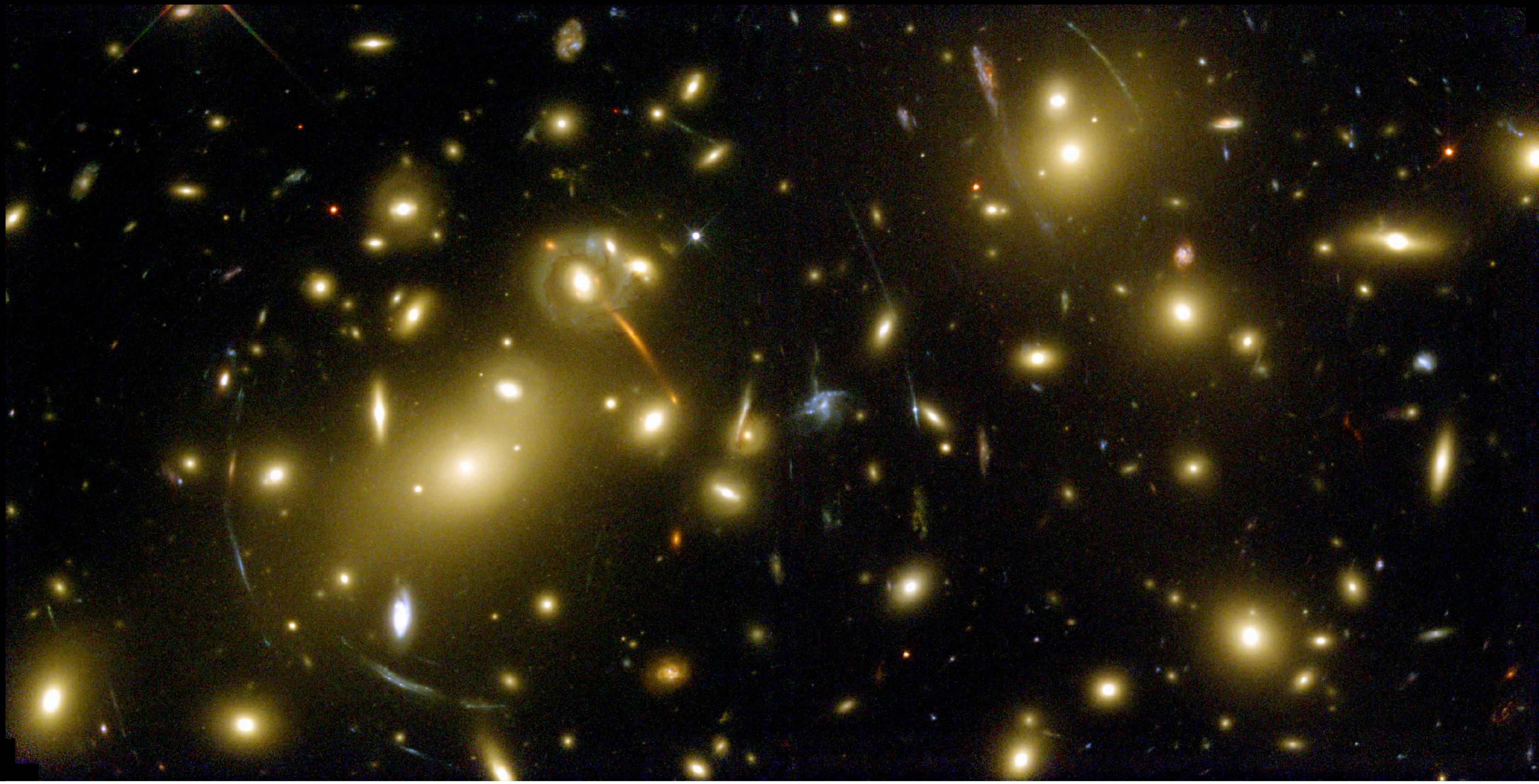
Dark Energy Probes

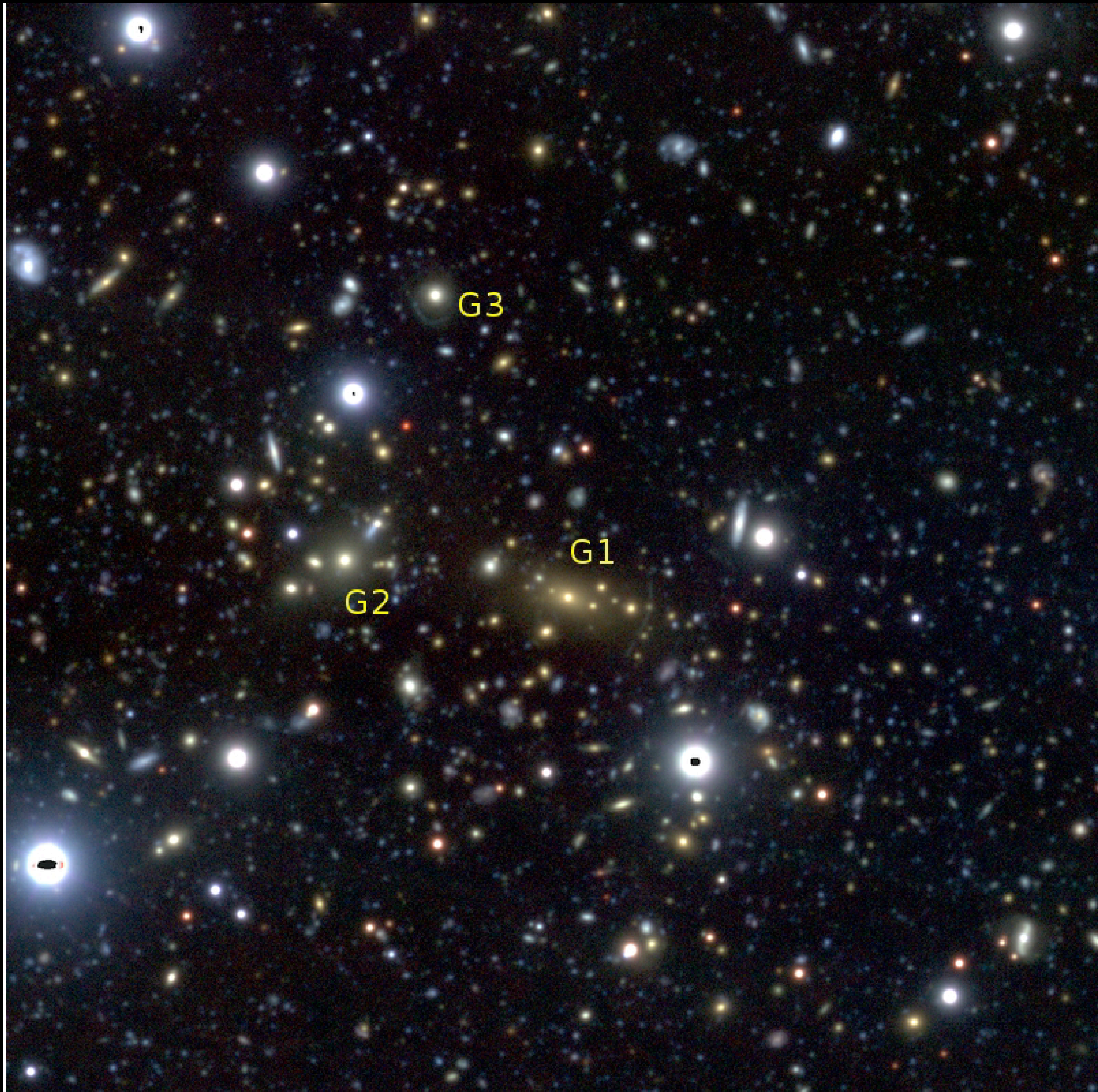


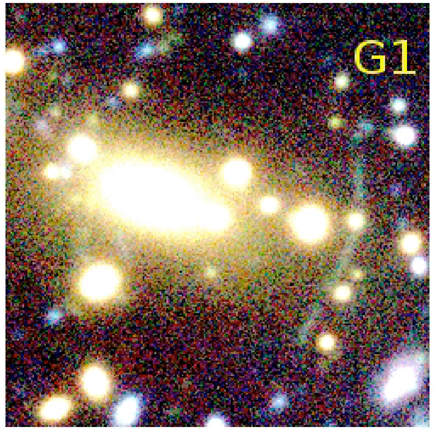
E. Kolb, see also US-DETF report.

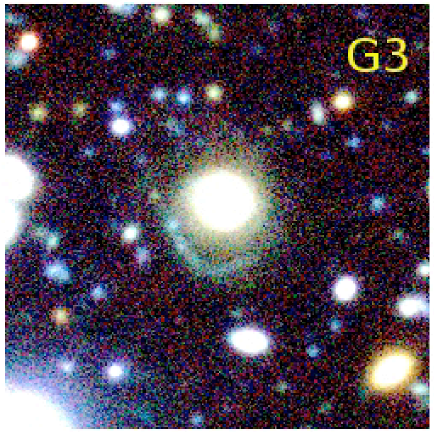
Galaxy Clusters

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

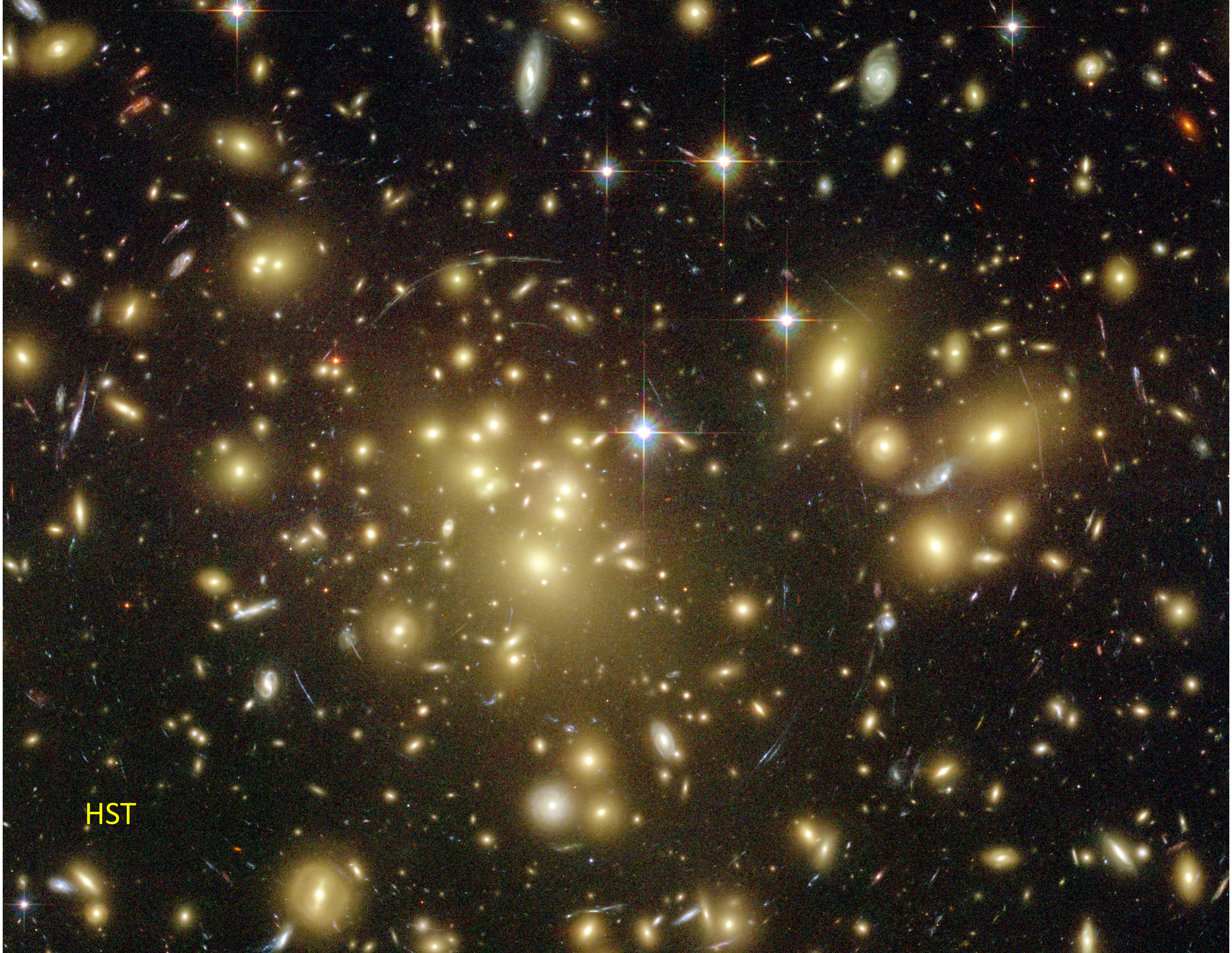






Israel et al. (2010) … photo-z by eye …

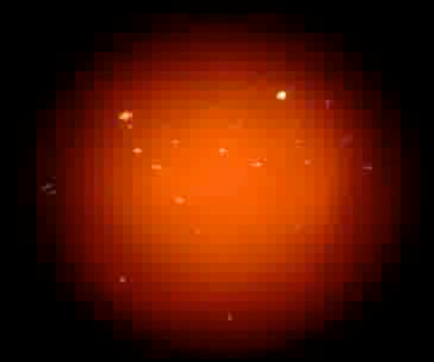

HST

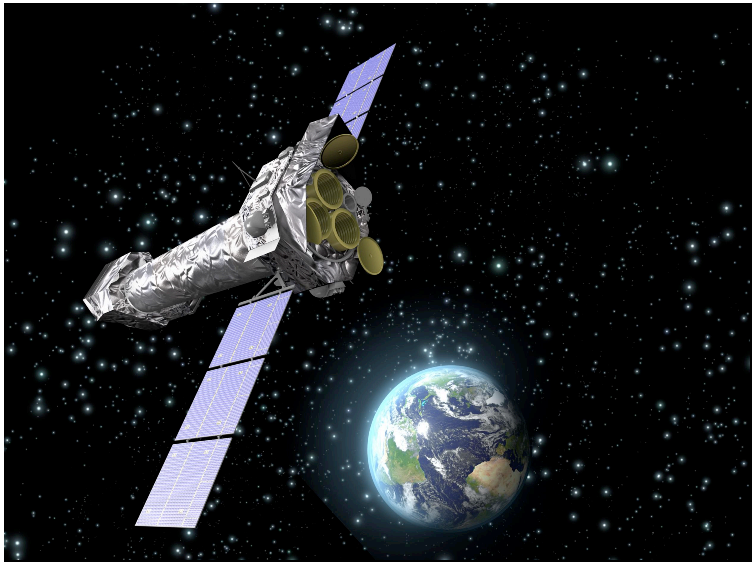

Chandra


HST+Chandra

Intracluster Medium (ICM)

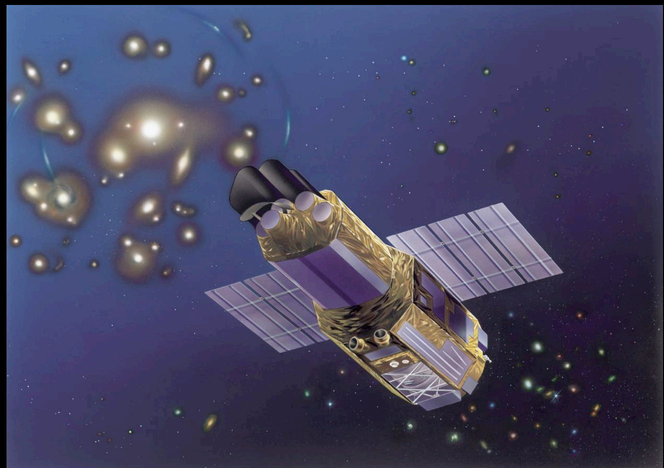
- Hot: $T \sim (10^7\text{–}10^8)$ K; $k_B T \sim (1\text{–}10)$ keV.
- Low density: <0.1 particles/cm^{-3}.
- $M_{\mathrm{ICM}} \sim 10\, M_{\mathrm{stars}}$. $L_X \sim (10^{44}\text{–}10^{45})$ erg/s.
- $M_{\mathrm{total}} \sim 10\, M_{\mathrm{ICM}}$. D ~ 10^7 Lightyears.

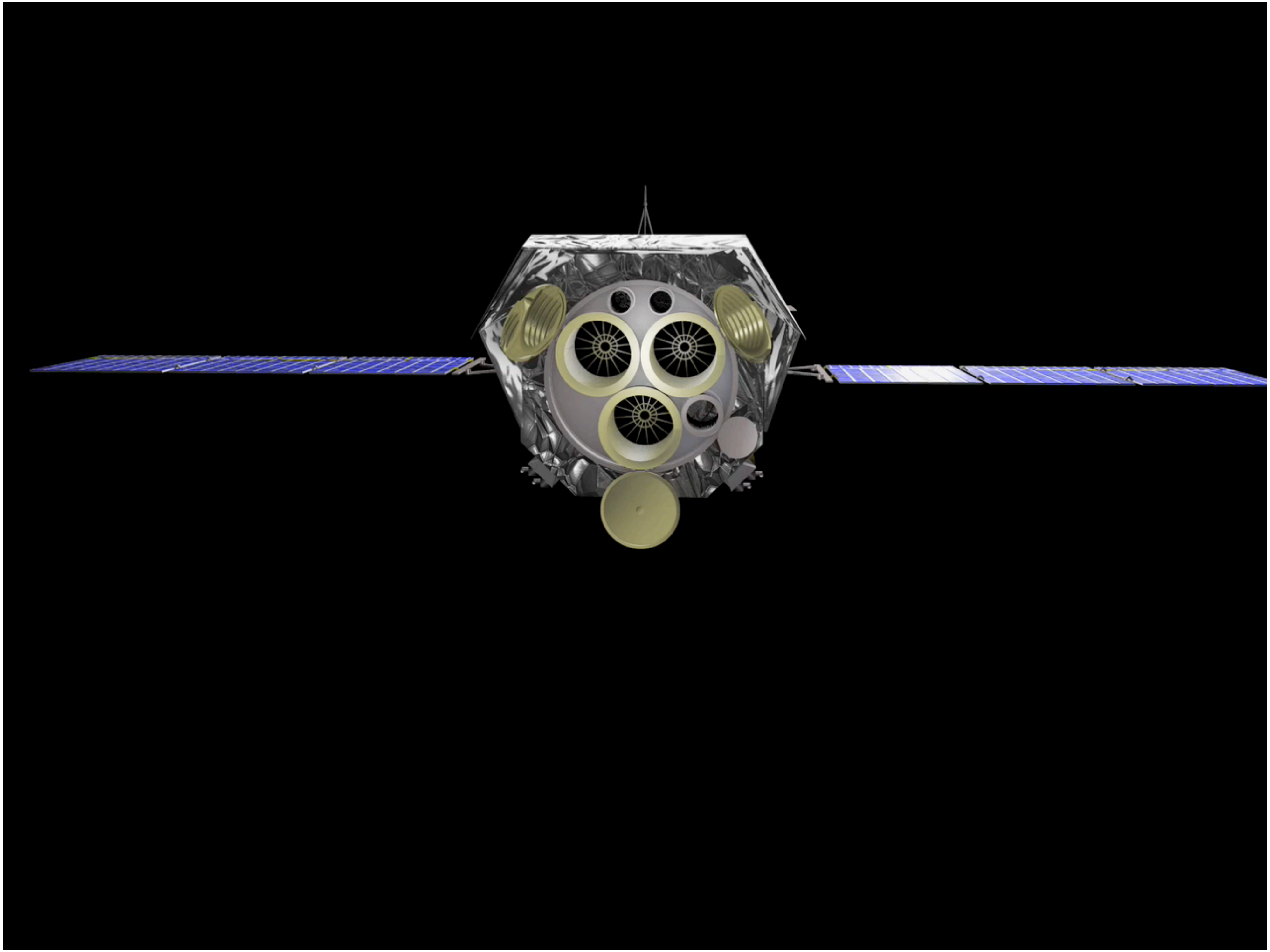




XMM-Newton Launch

European Space Agency





X-Ray Mass Determination

$$\frac{1}{\rho_{\mathrm{gas}}}\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{\mathrm{d}\Phi_{\mathrm{grav}}}{\mathrm{d}r}$$

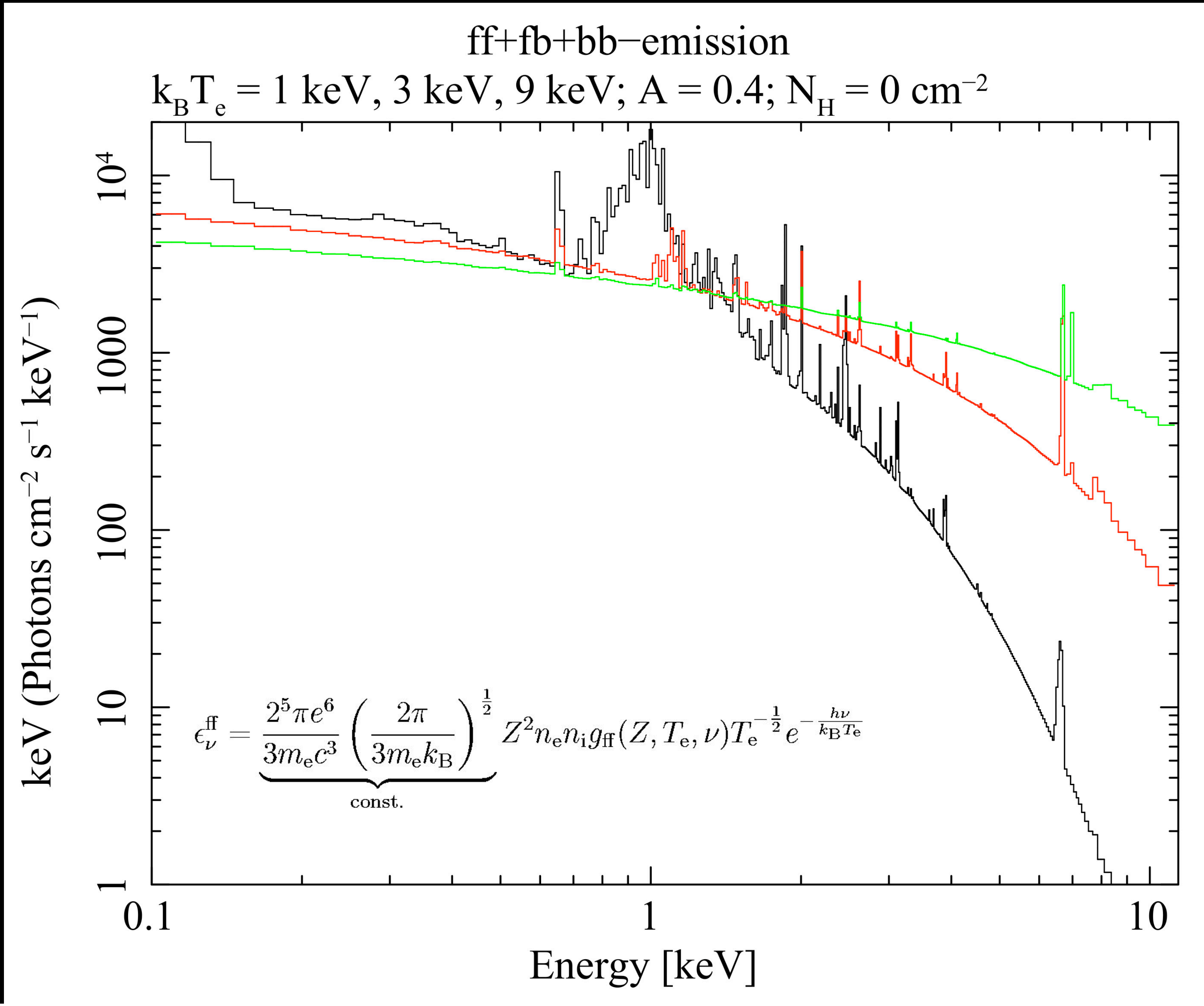
$$P = \frac{k_{\mathrm{B}}}{\mu m_{\mathrm{p}}}\rho_{\mathrm{gas}}T_{\mathrm{gas}}$$

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

$$\frac{1}{\rho_{\mathrm{gas}}}\frac{\mathrm{d}P}{\mathrm{d}r} = \frac{k_{\mathrm{B}}T_{\mathrm{gas}}}{\mu m_{\mathrm{p}}}\frac{1}{r}\left(\frac{\mathrm{d}\ln\rho_{\mathrm{gas}}}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln T_{\mathrm{gas}}}{\mathrm{d}\ln r}\right)$$

$$M_{\mathrm{tot}}(<r) = -\frac{k_{\mathrm{B}}T_{\mathrm{gas}}r}{G\mu m_{\mathrm{p}}}\left(\frac{\mathrm{d}\ln\rho_{\mathrm{gas}}}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln T_{\mathrm{gas}}}{\mathrm{d}\ln r}\right).$$

Gas Temperature and Density



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!

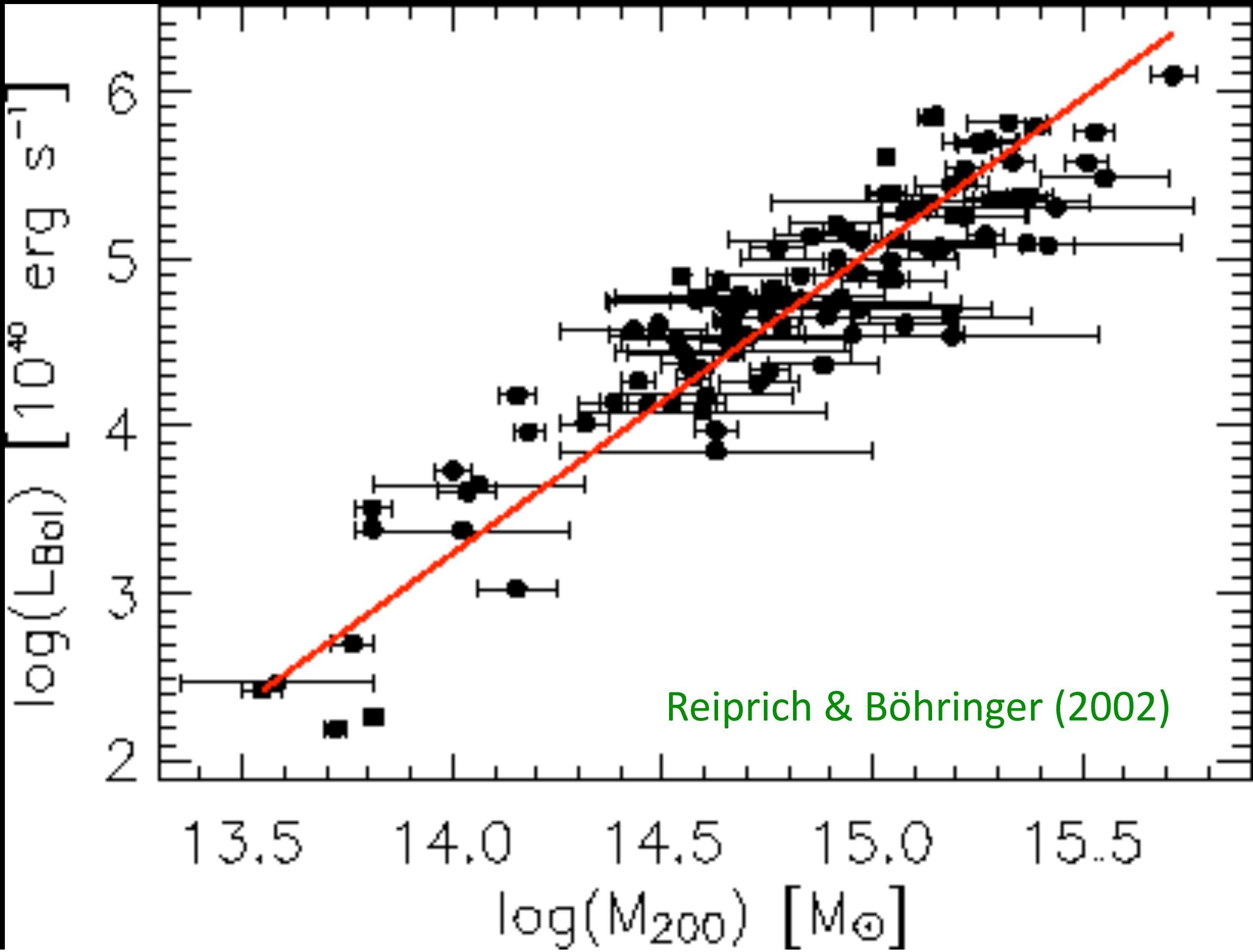
Methods

- 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 $H(z) = H_0\,E(z)$:

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

$$E^2(z) \equiv \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{DE}e^{3\int_0^z [1+w(z')]\mathrm{d}\ln(1+z')} + \Omega$$

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

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

Cluster Mass Function

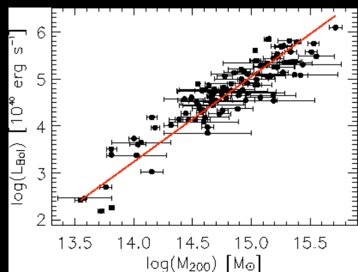
Cluster mass function is *exponentially* sensitive to the growth factor.

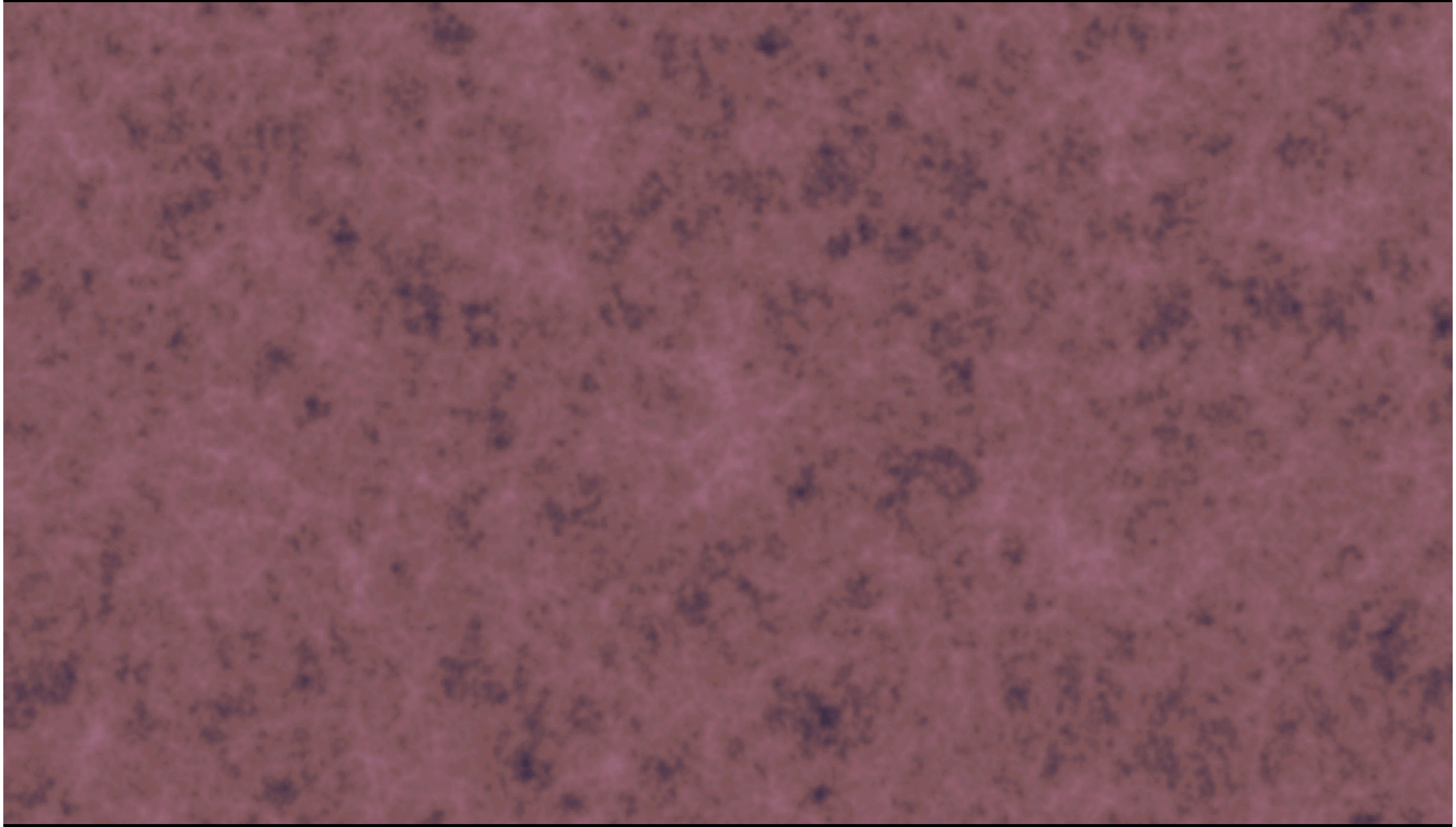
$$\frac{dn(M,z)}{dM} = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}_0}{M}\,\frac{\delta_c^0(z)}{\sigma(M)^2}\left|\frac{d\sigma(M)}{dM}\right|\exp\left(-\frac{\delta_c^0(z)^2}{2\,\sigma(M)^2}\right)$$

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

Accurate masses and search volumes needed.

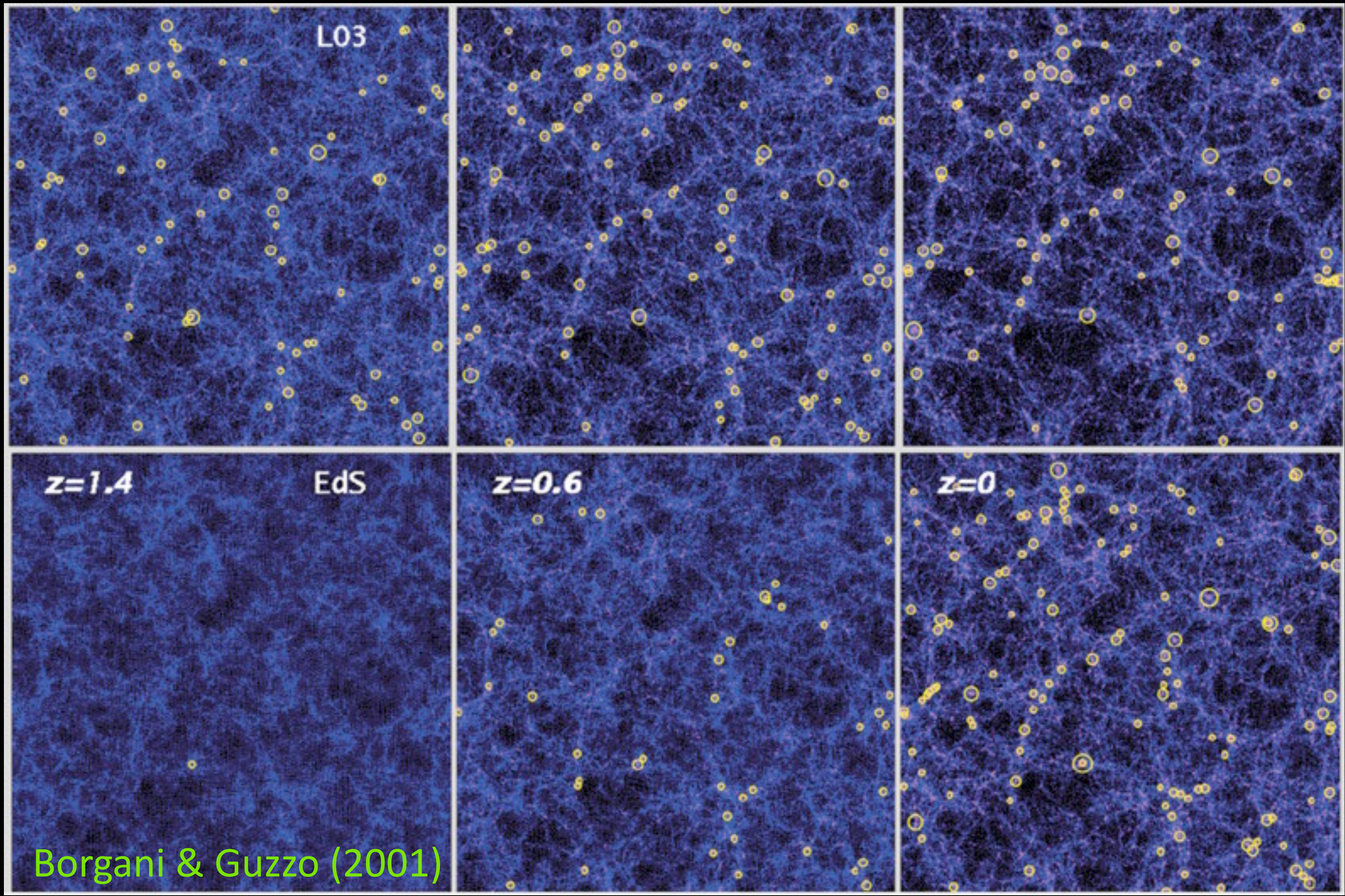
Observable–mass relation is important.

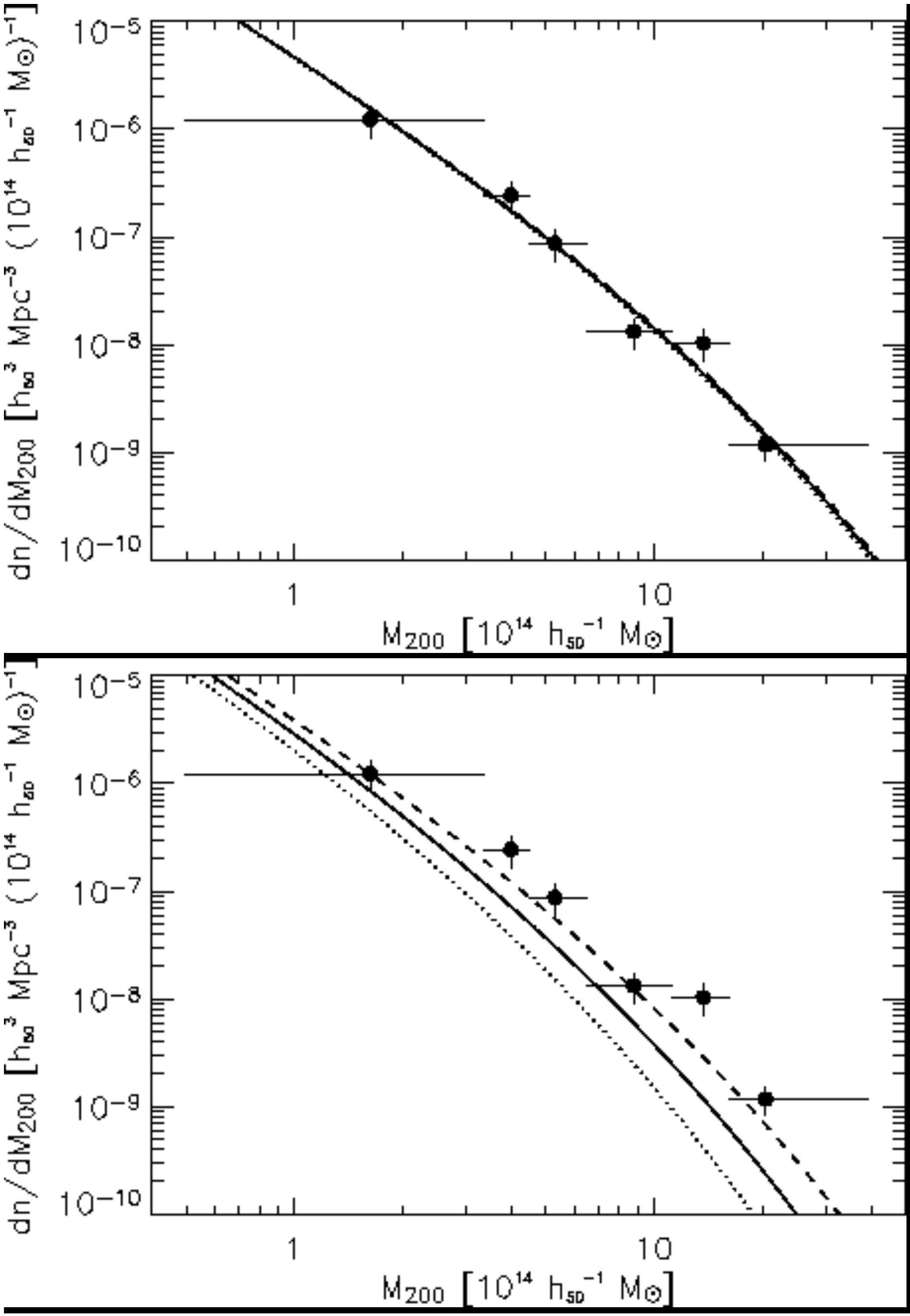




V. Springel

Galaxy Cluster Evolution



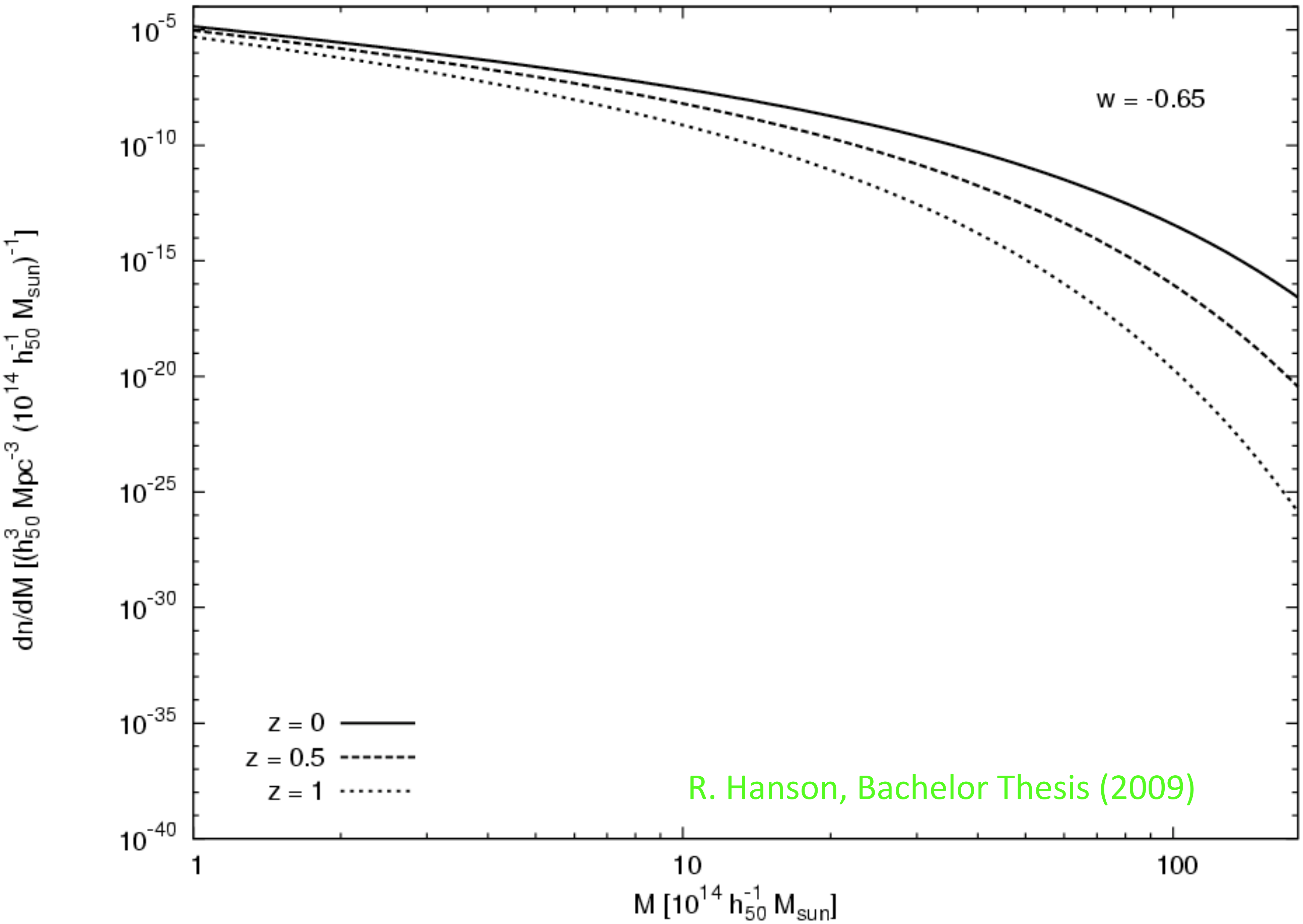


Galaxy cluster mass function

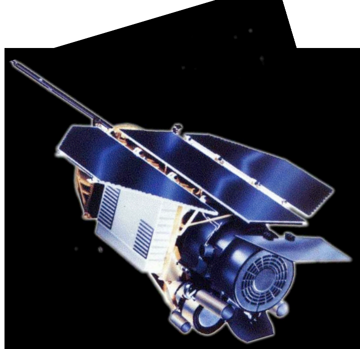
$z = 0.05$

$z = 0.6$

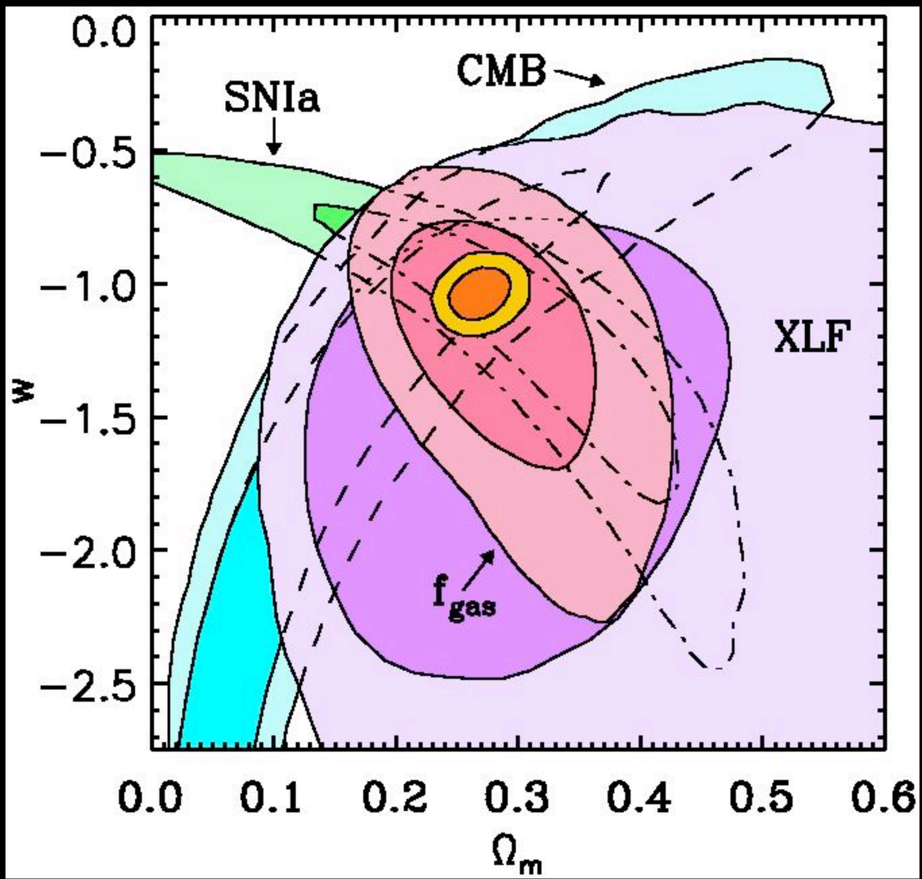
solid: $w = -1$,
dashed: $w = -0.5$,
dotted: $w = -1.25$.

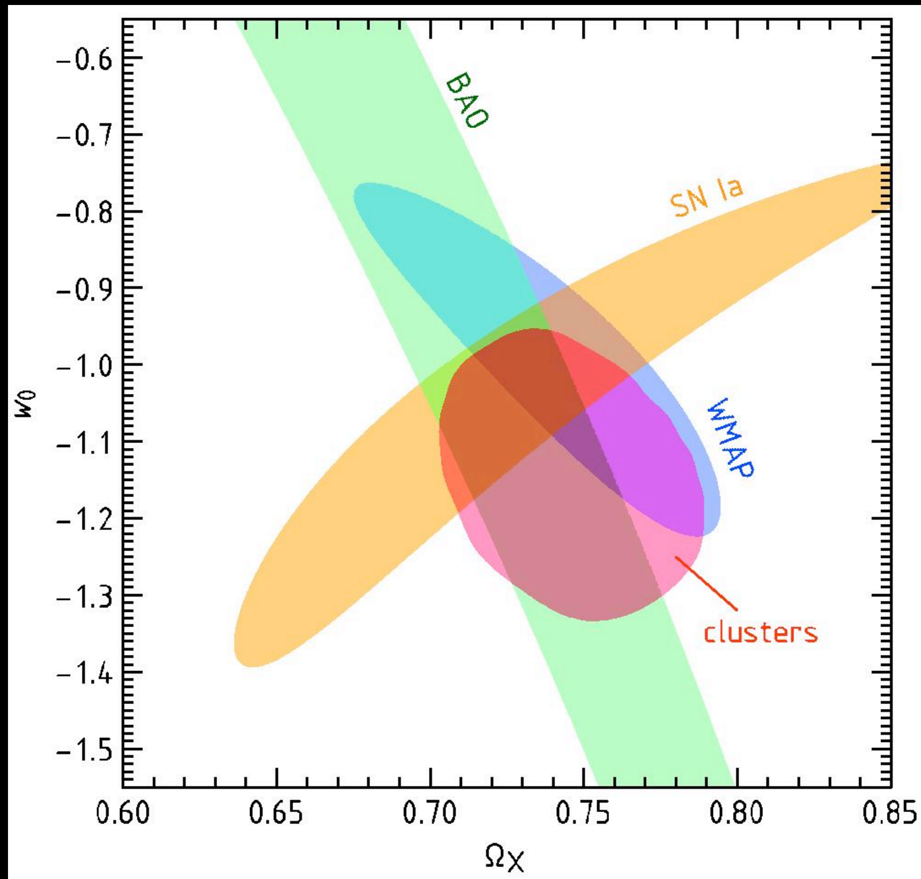


w = -0.65
dn/dM [(h$_{50}^3$ Mpc^{-3} (10^{14} h$_{50}^{-1}$ M$_{sun}$)$^{-1}$]
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
z = 0
z = 0.5
z = 1
R. Hanson, Bachelor Thesis (2009)
1
10
100
M [10^{14} h$_{50}^{-1}$ M$_{sun}$]



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



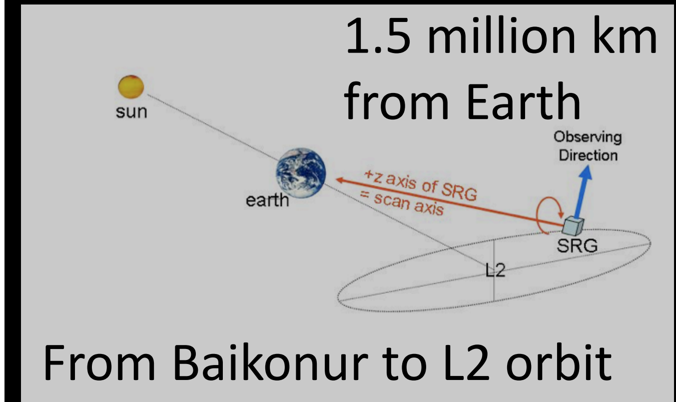


Allen et al. (2008), Mantz et al. (2008, 2010)

Vikhlinin et al. (2009)

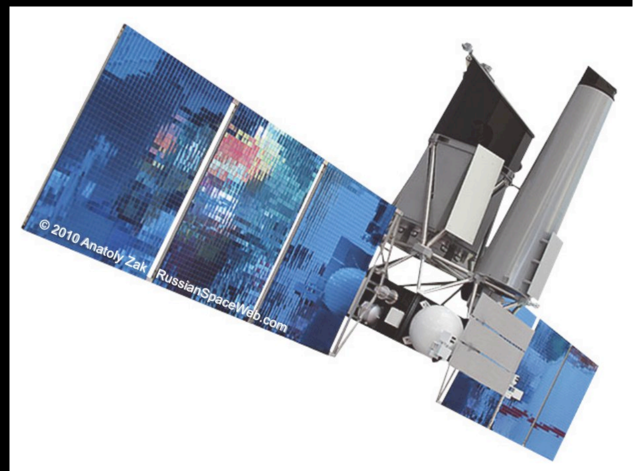
Similar constraints available from SZ cluster surveys.

The (Near) Future: *eROSITA*
~10^5 X-Ray Clusters



Zenit-2SB rocket
Fregat booster

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



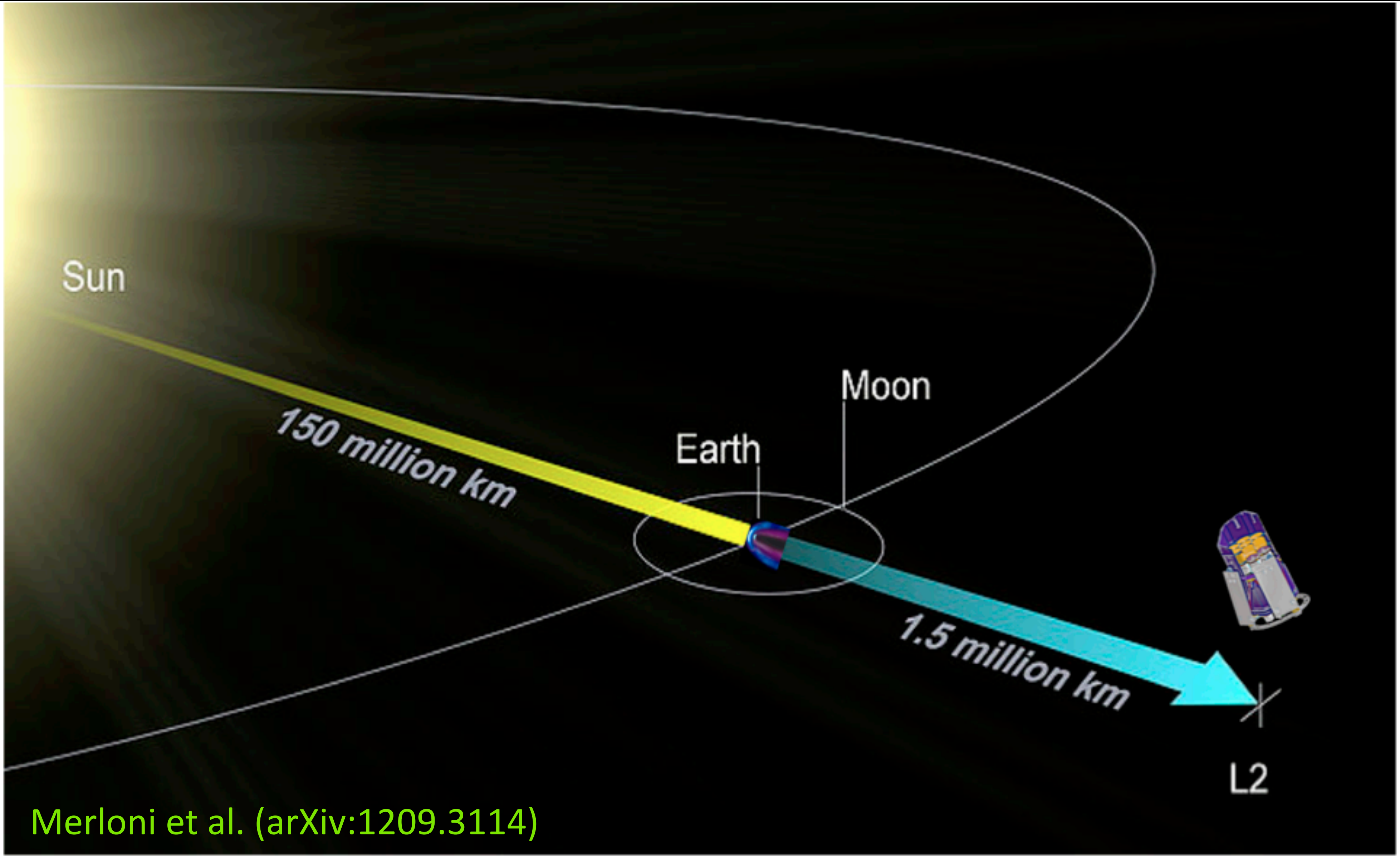
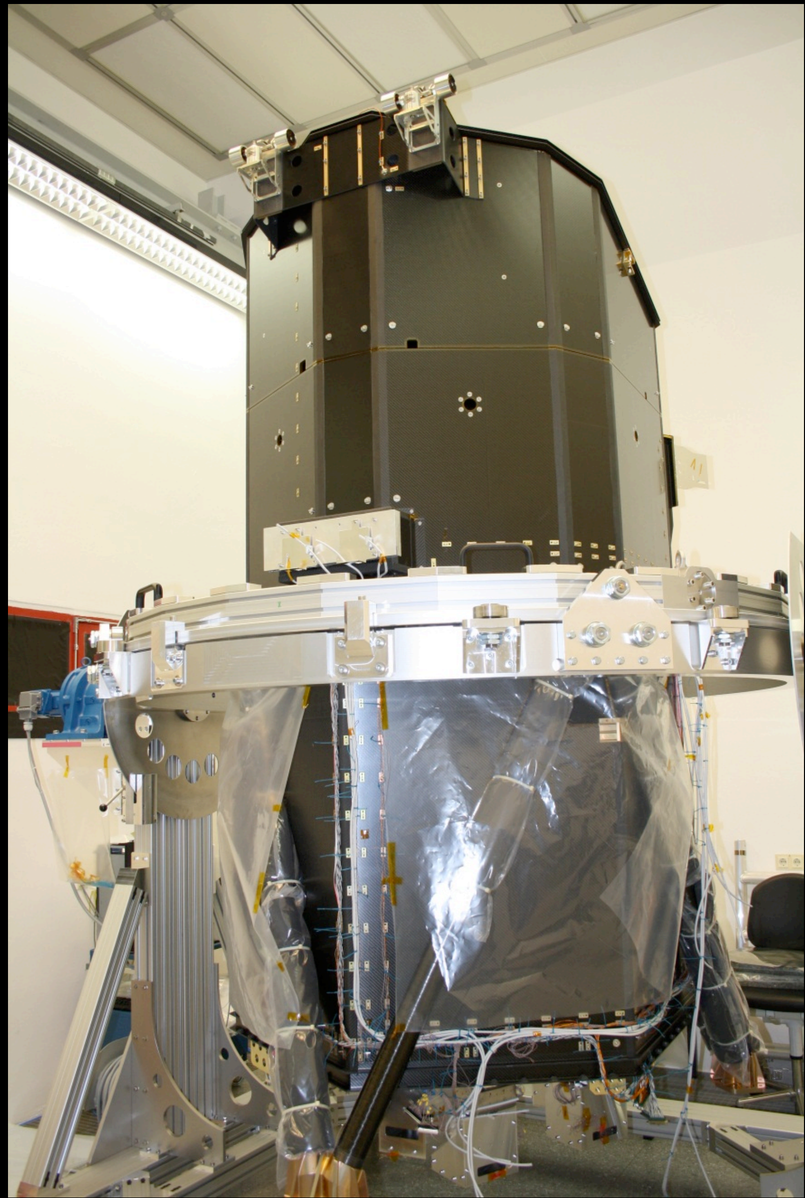
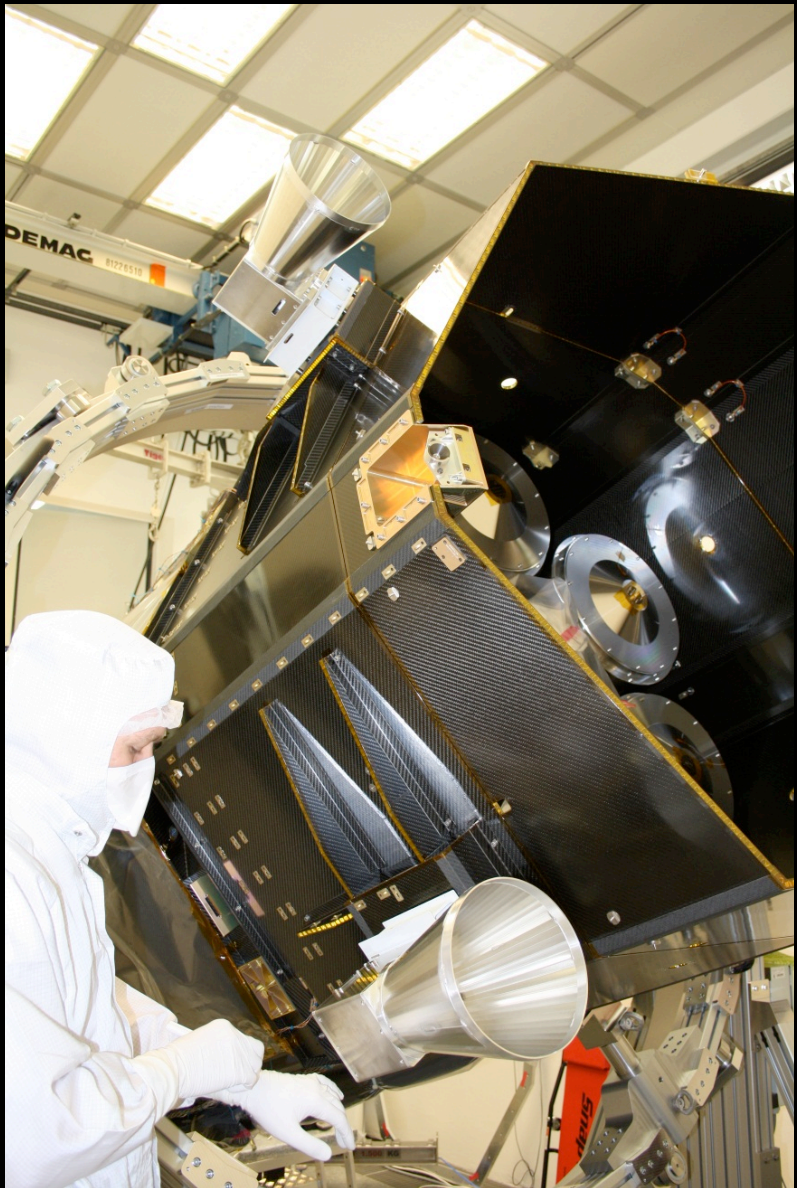


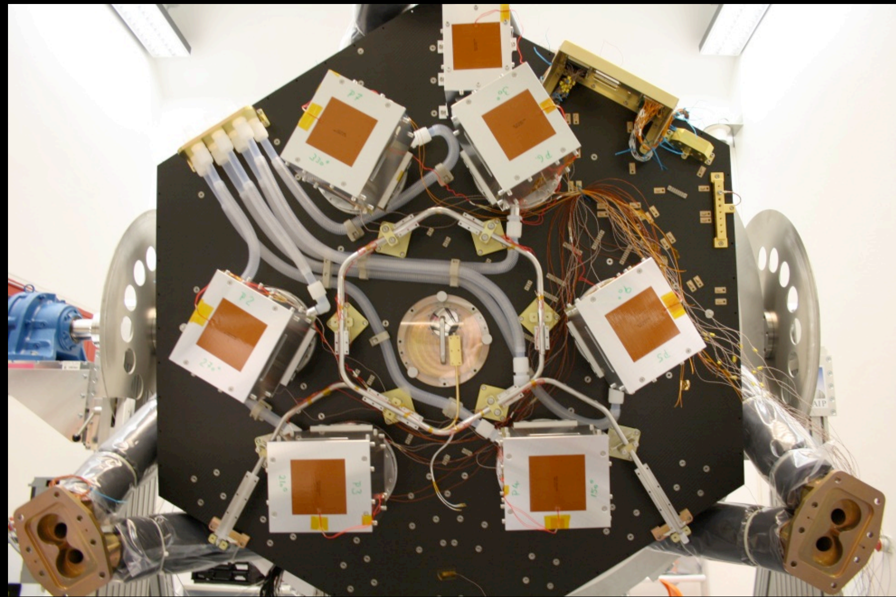
Figure 3.1.1: Schematic view of the location of the L2 orbit of SRG. At the position of the earth, a scaled picture of the geocoronal emission is shown. Unlike any other X-ray satellite launched to date, eROSITA will become the first telescope to observe the X-ray sky from L2, unaffected by geocoronal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

Telescope Structure



From P. Predehl

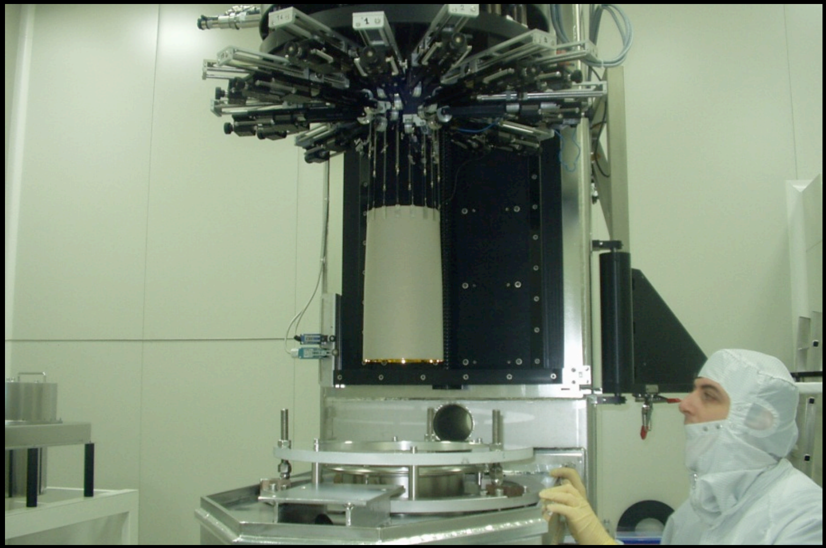




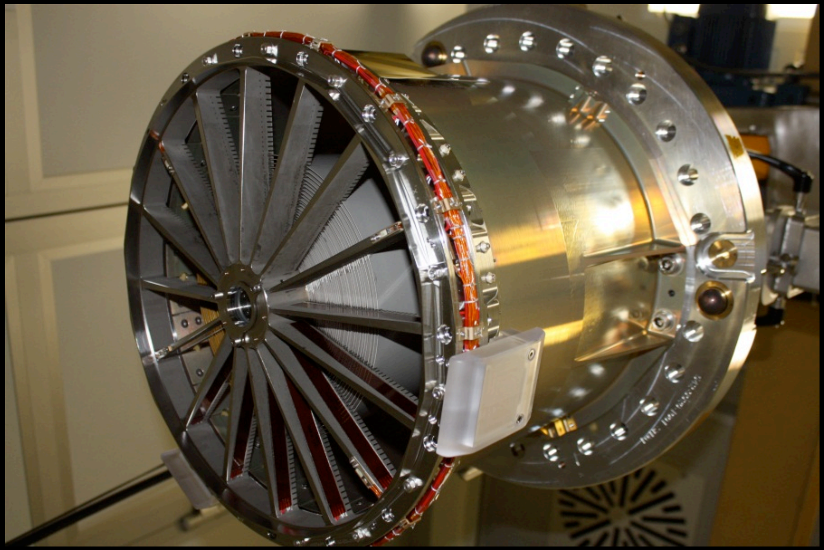
From P. Predehl

Mirror System

Spider Wheel with heaters integrated



VOB in action: Integration of a Shell



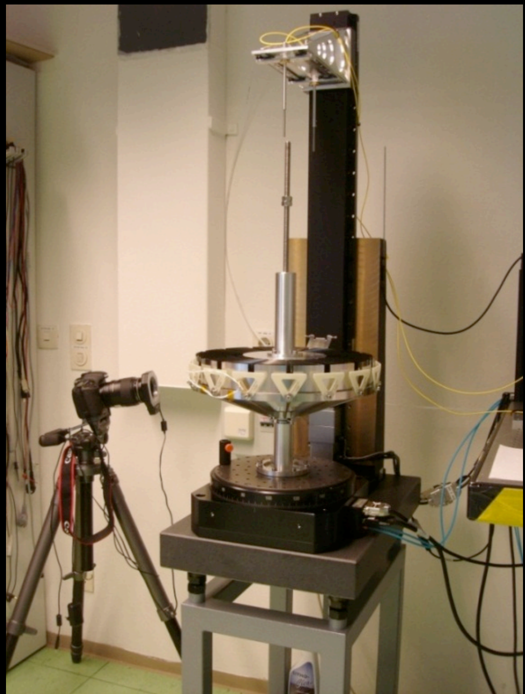
FM-3 Mirror Module with 39/54 shells

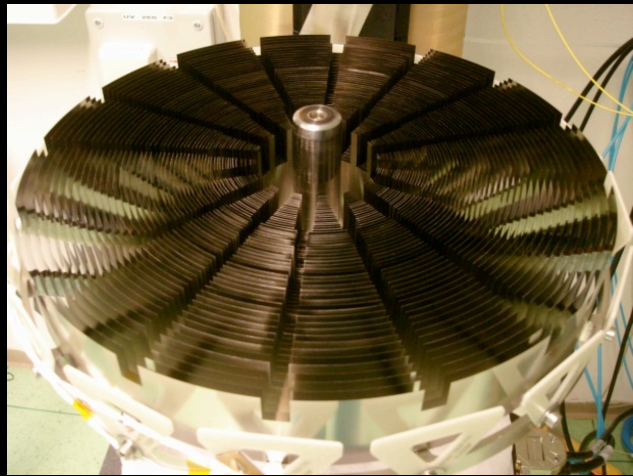
Preparation of PANTER X-ray Tests (FM-3c)

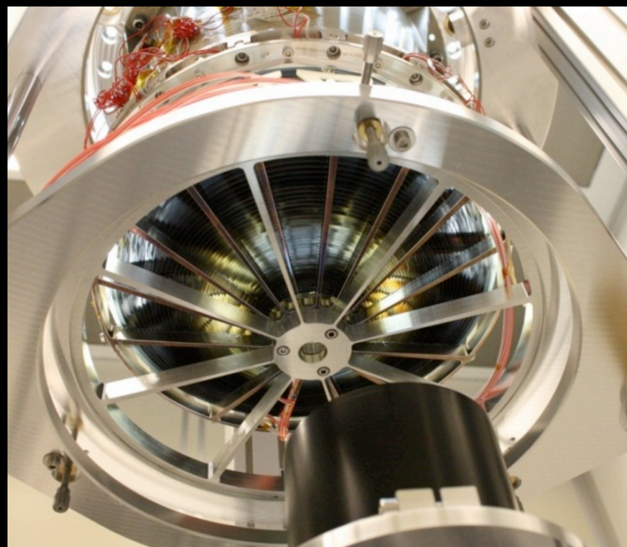
From P. Predehl

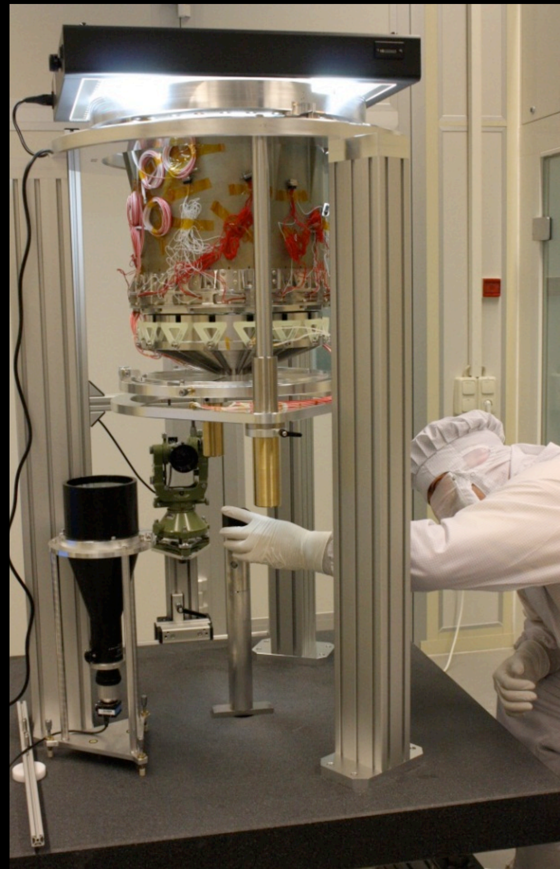
X-ray Baffle

Stand for Integration and
Metrology of Baffle Shells





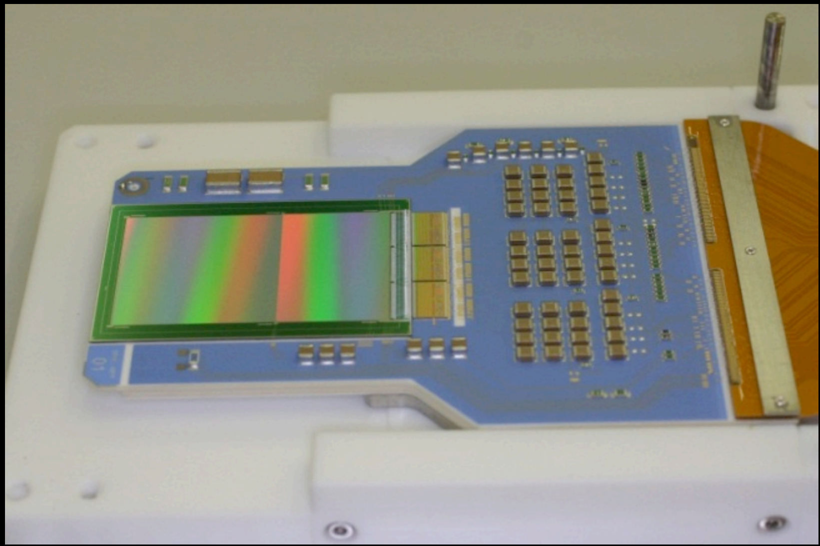




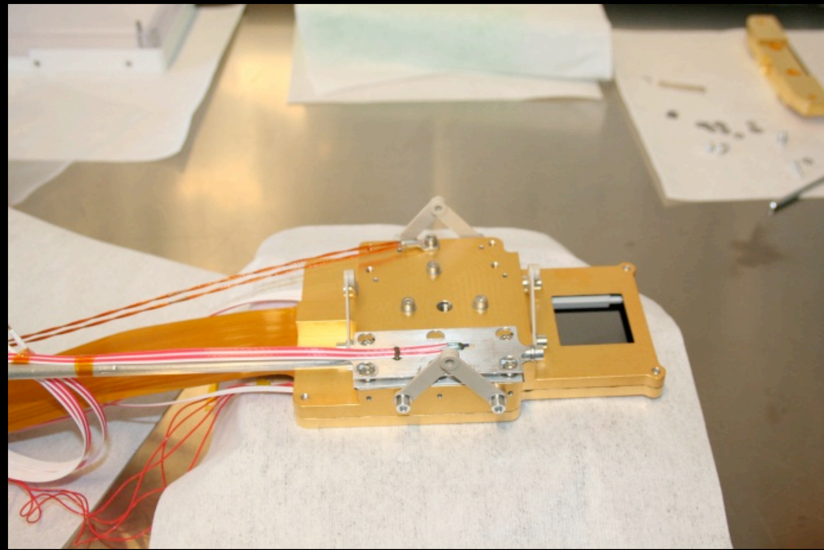
Integration and Metrology of
X-ray Baffle onto Mirror Module

From P. Predehl

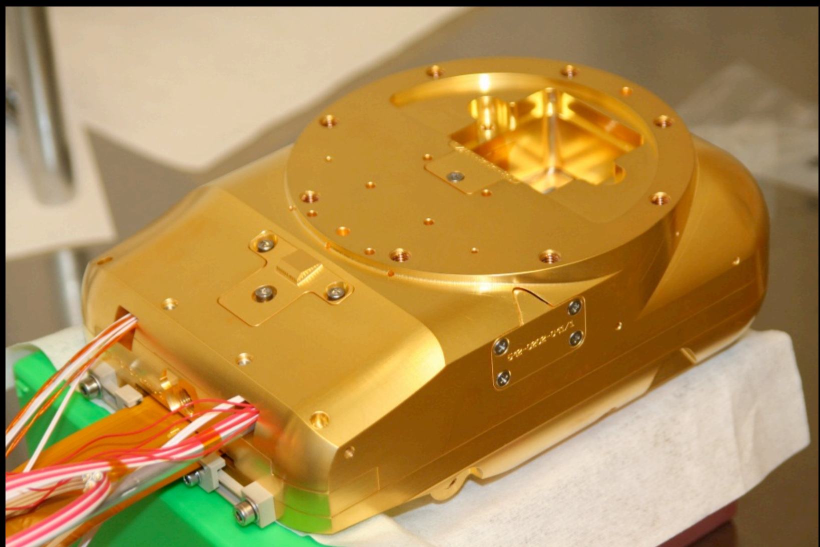
Camera



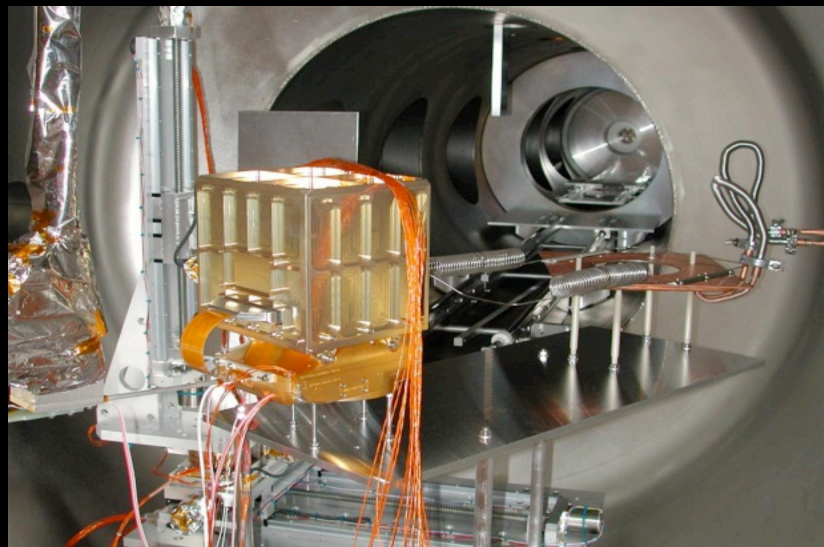
Heart of the Camera: CCD-Module



Cold part of Camera (with test sensors)



Integrated Camera (with massive Copper Housing)

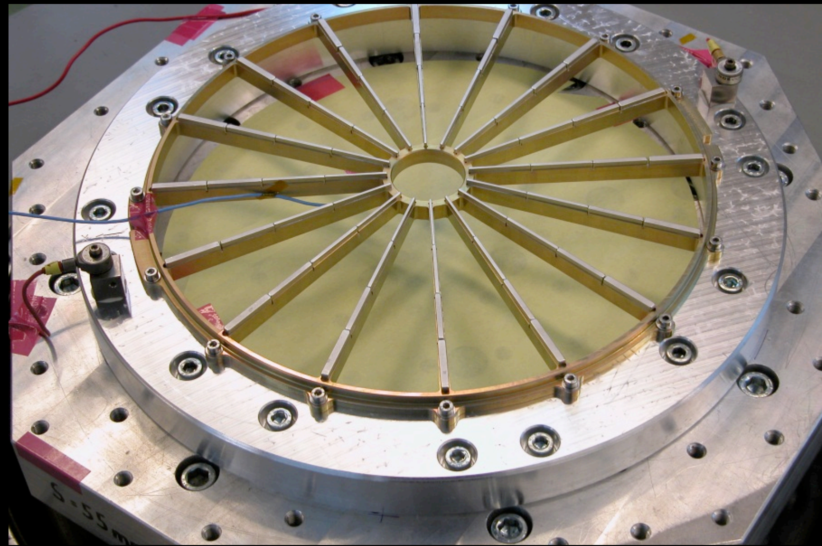


Preparation of Thermal Test

From P. Predehl

Miscellaneous

Filter Wheel

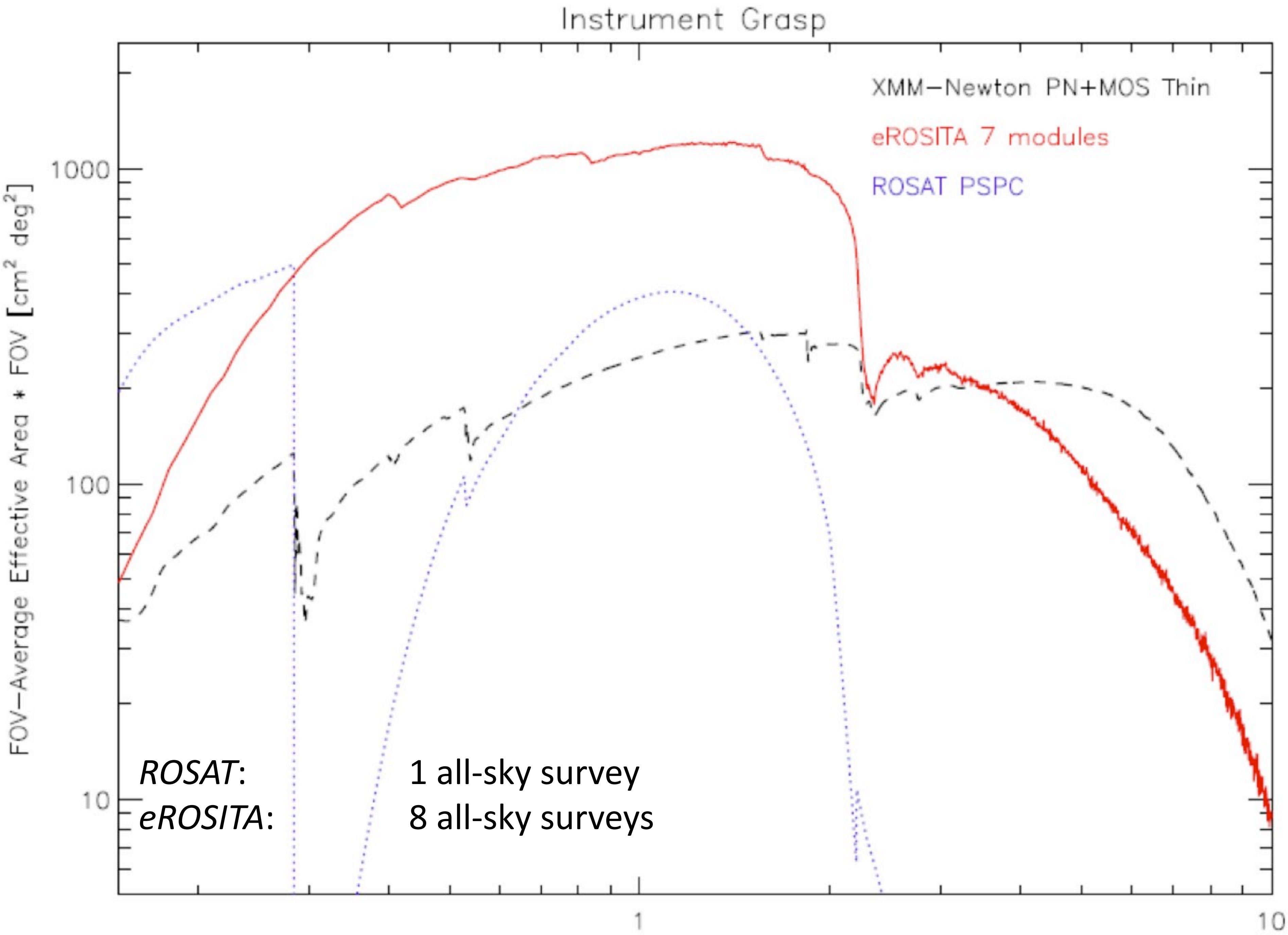


Electron Deflector (on Shaker)

Camera Radiator, upper part with VCHP-Reservoirs

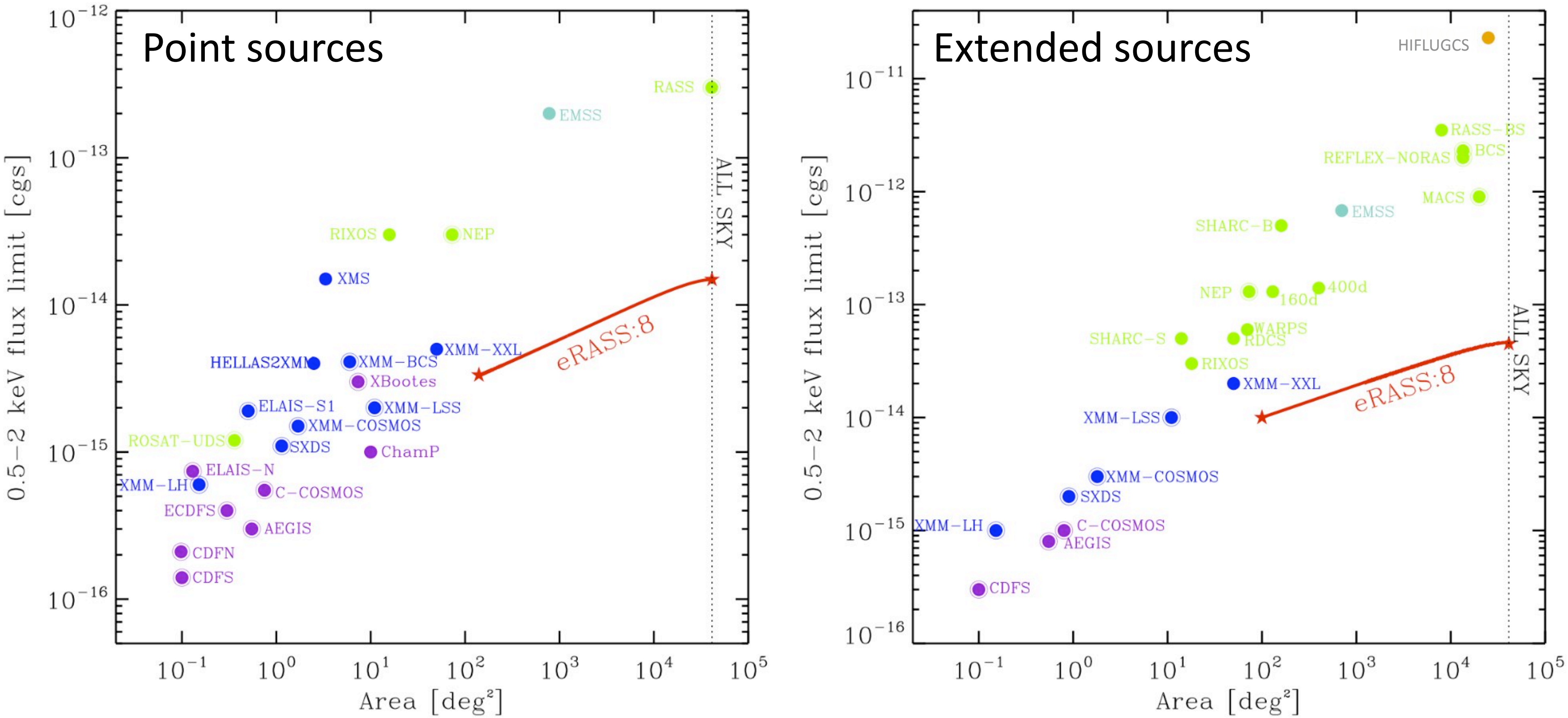
Preparation of Thermal Test with Heatpipe System

From P. Predehl



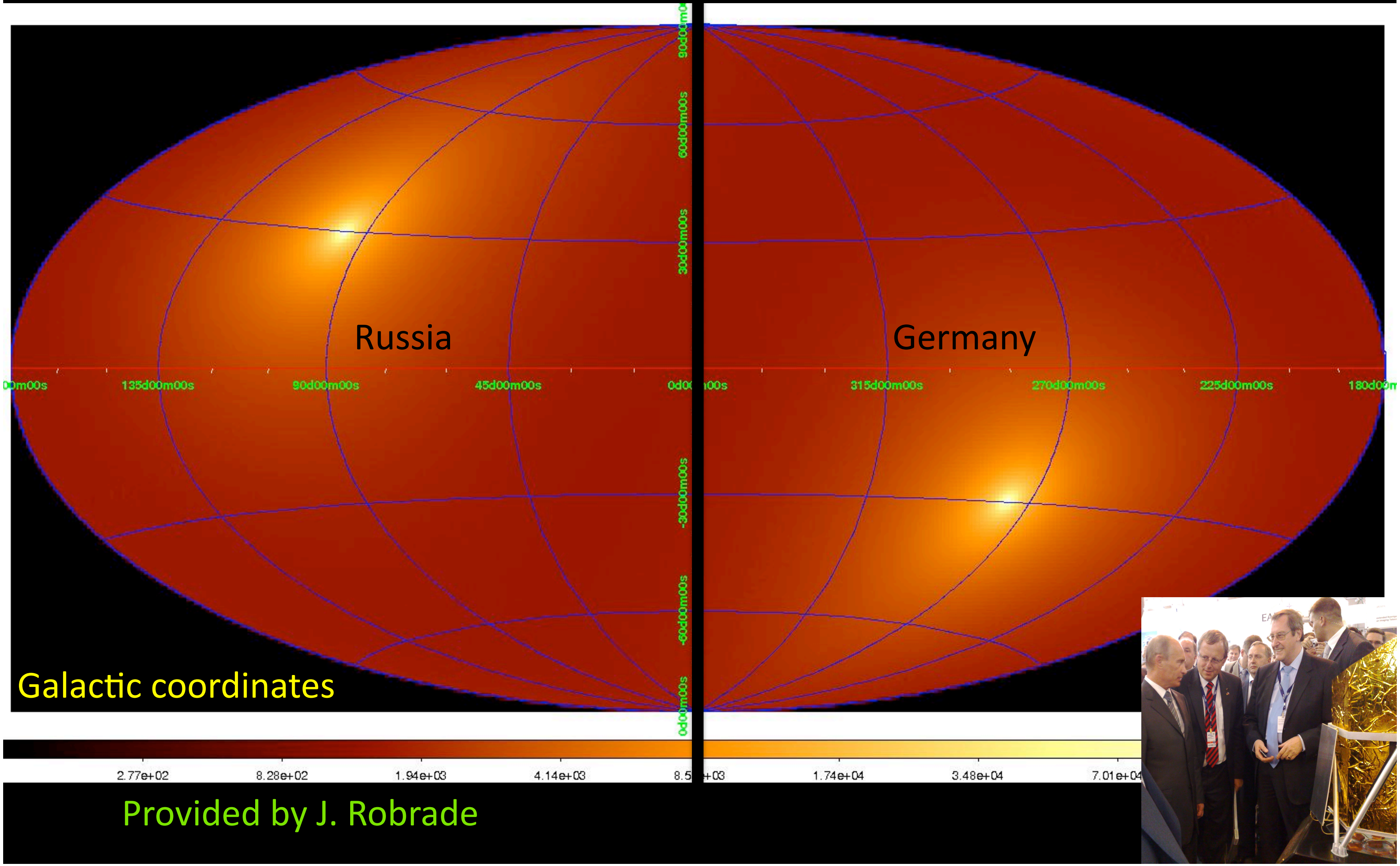
Merloni et al. (arXiv:1209.3114)

Comparison with other Surveys



Adapted from Merloni et al. (arXiv:1209.3114)

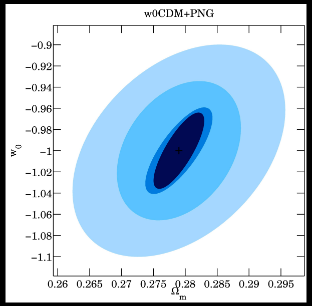
Expected *eROSITA* Exposure Map



Provided by J. Robrade

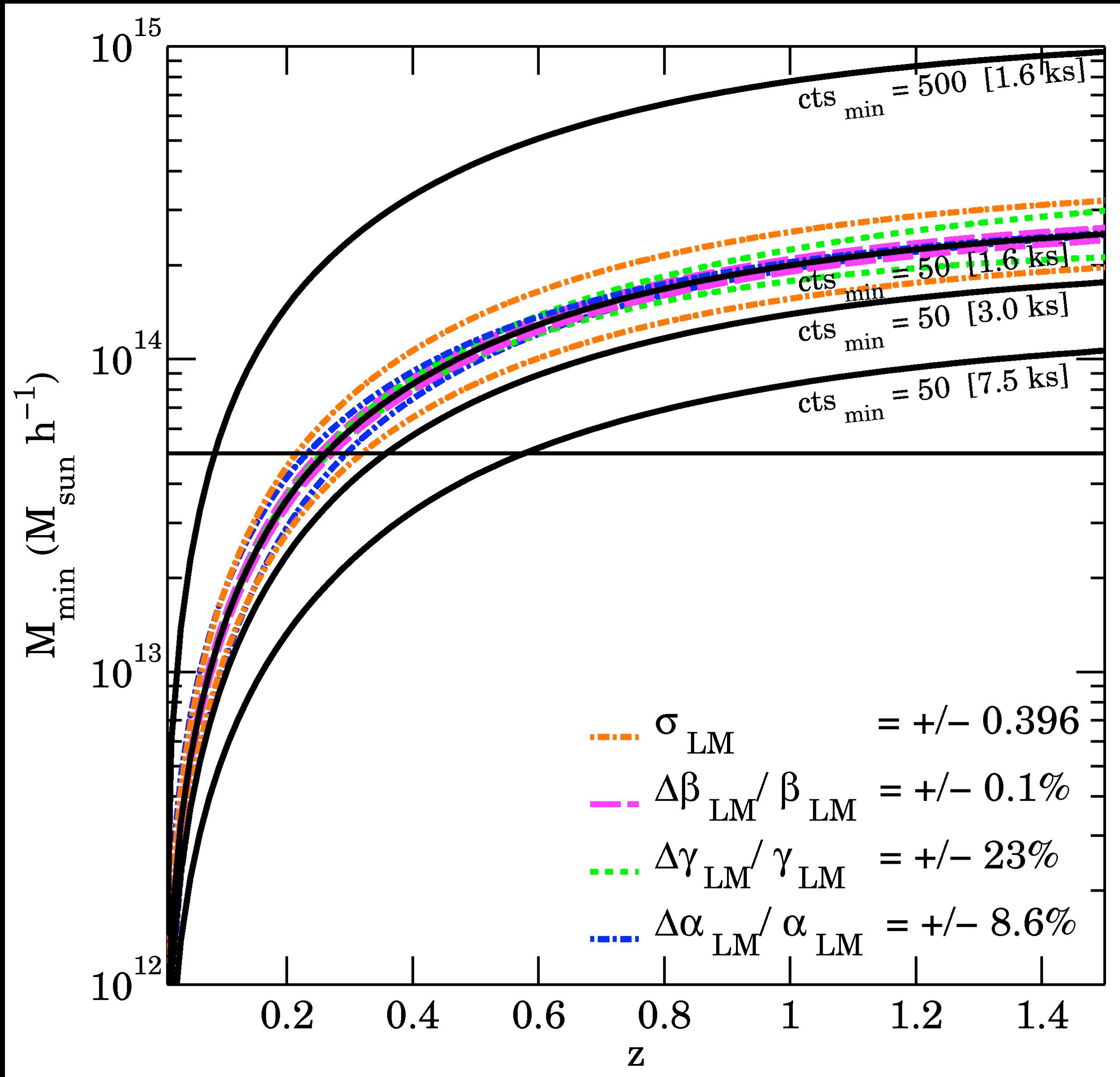
Projected Cosmological Constraints

- *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").

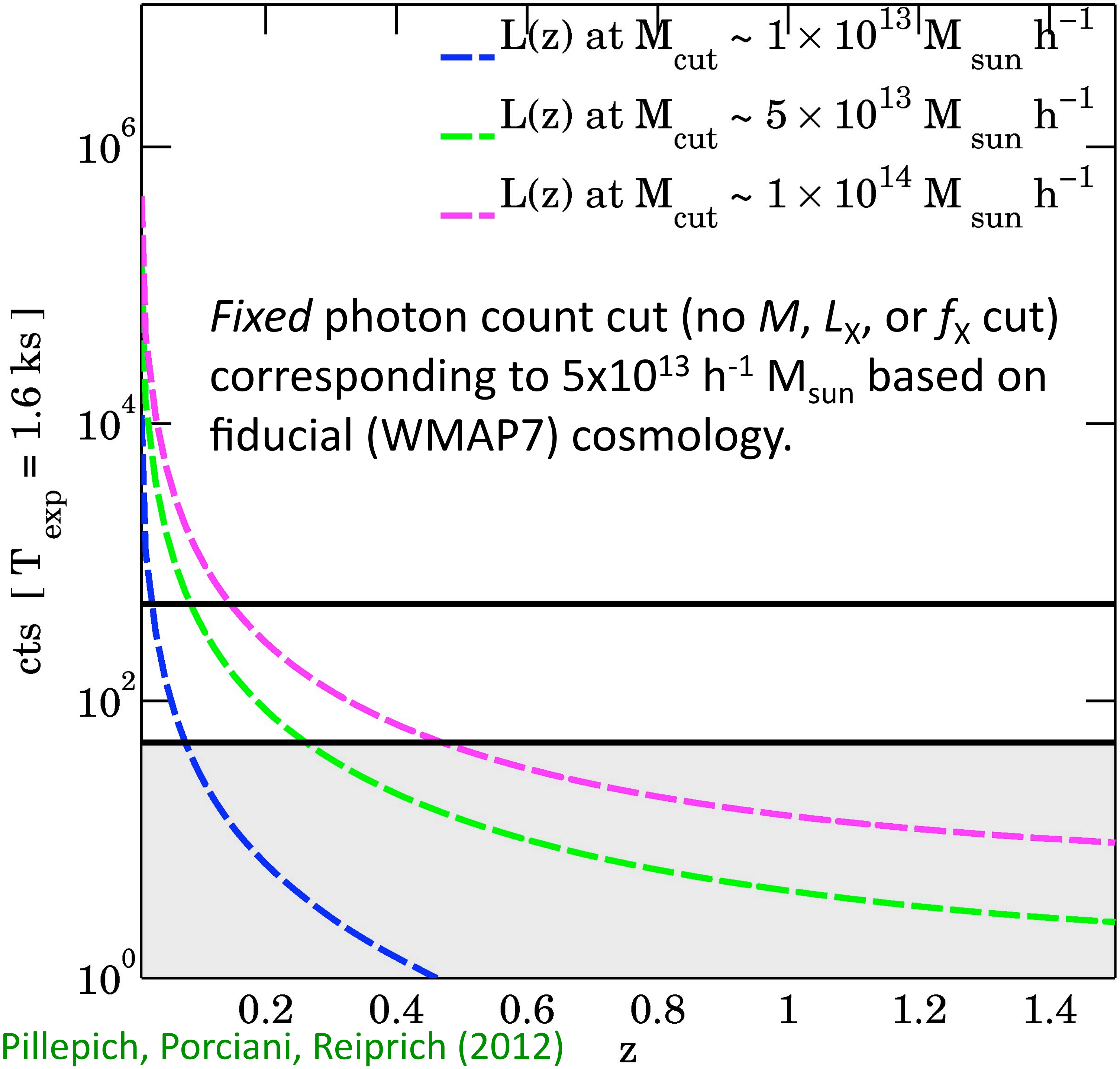


- Take into account expected redshift uncertainty.
- Apply two cosmological tests simultaneously; evolution of (i) cluster mass function and (ii) angular clustering.
- Several assumptions, e.g., hardware works, flat Universe, fiducial cosmology and L_X–M relation, redshifts, one sky for all, ….

Limiting Mass

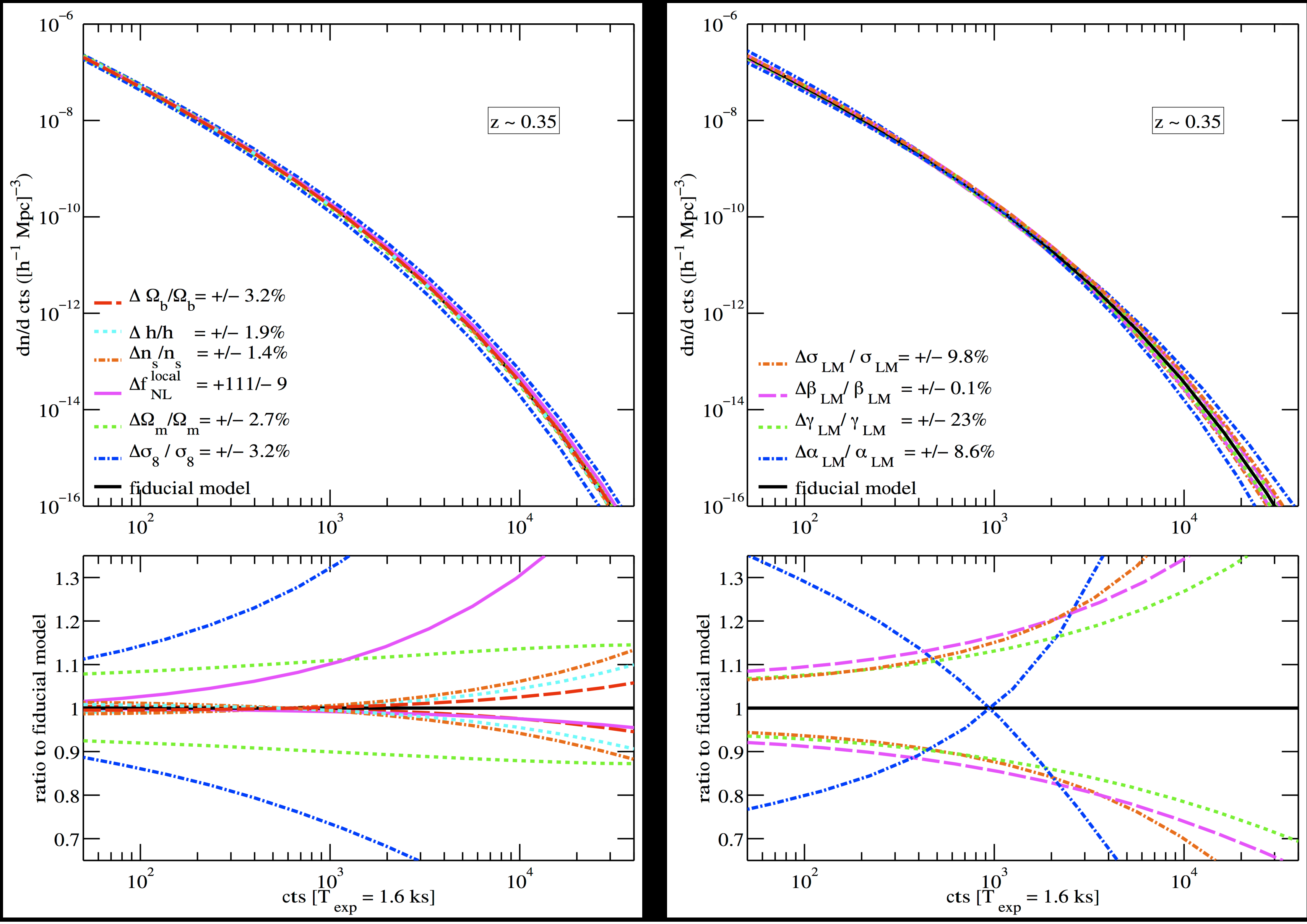


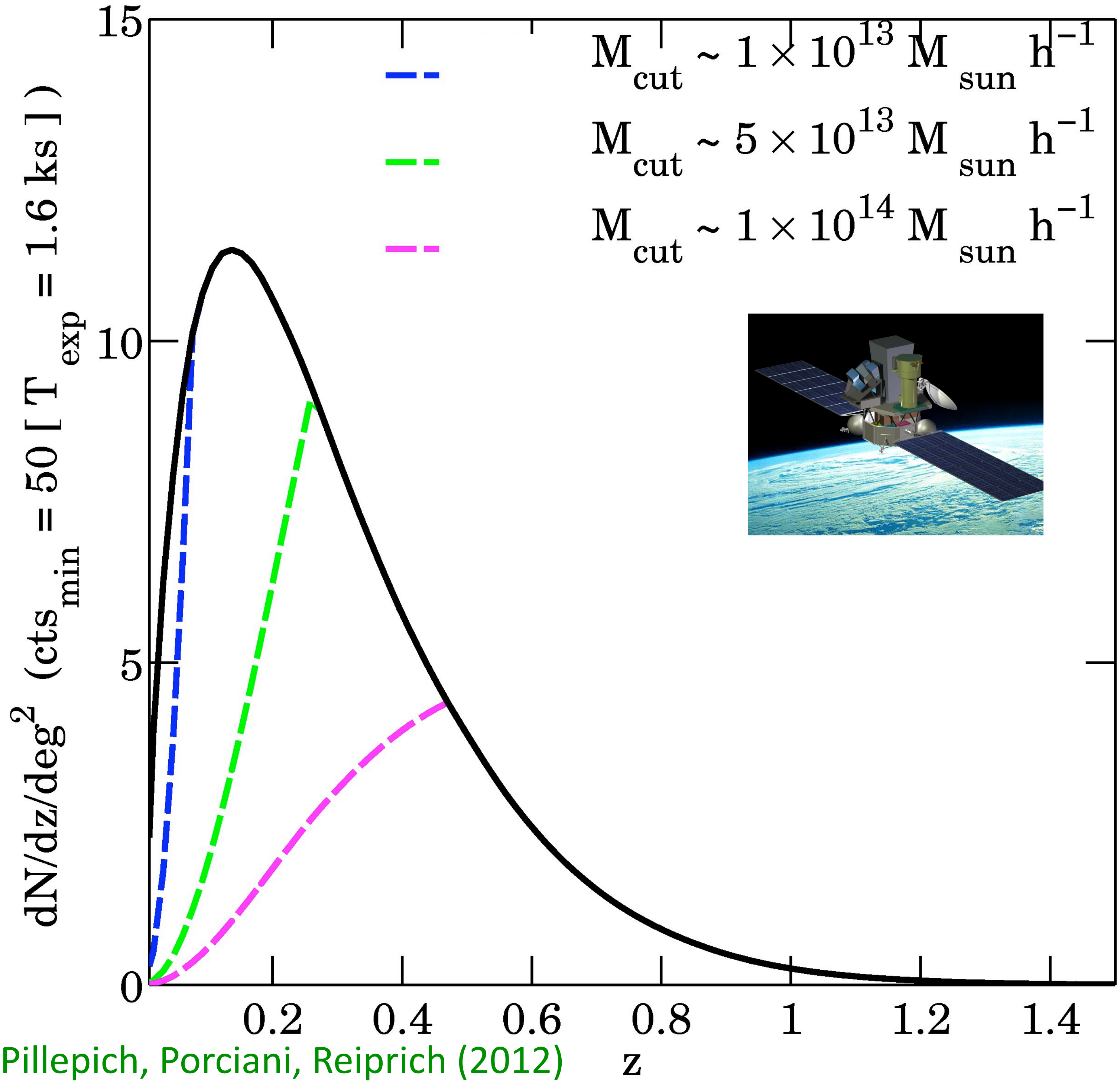
Pillepich, Porciani, Reiprich (2012)



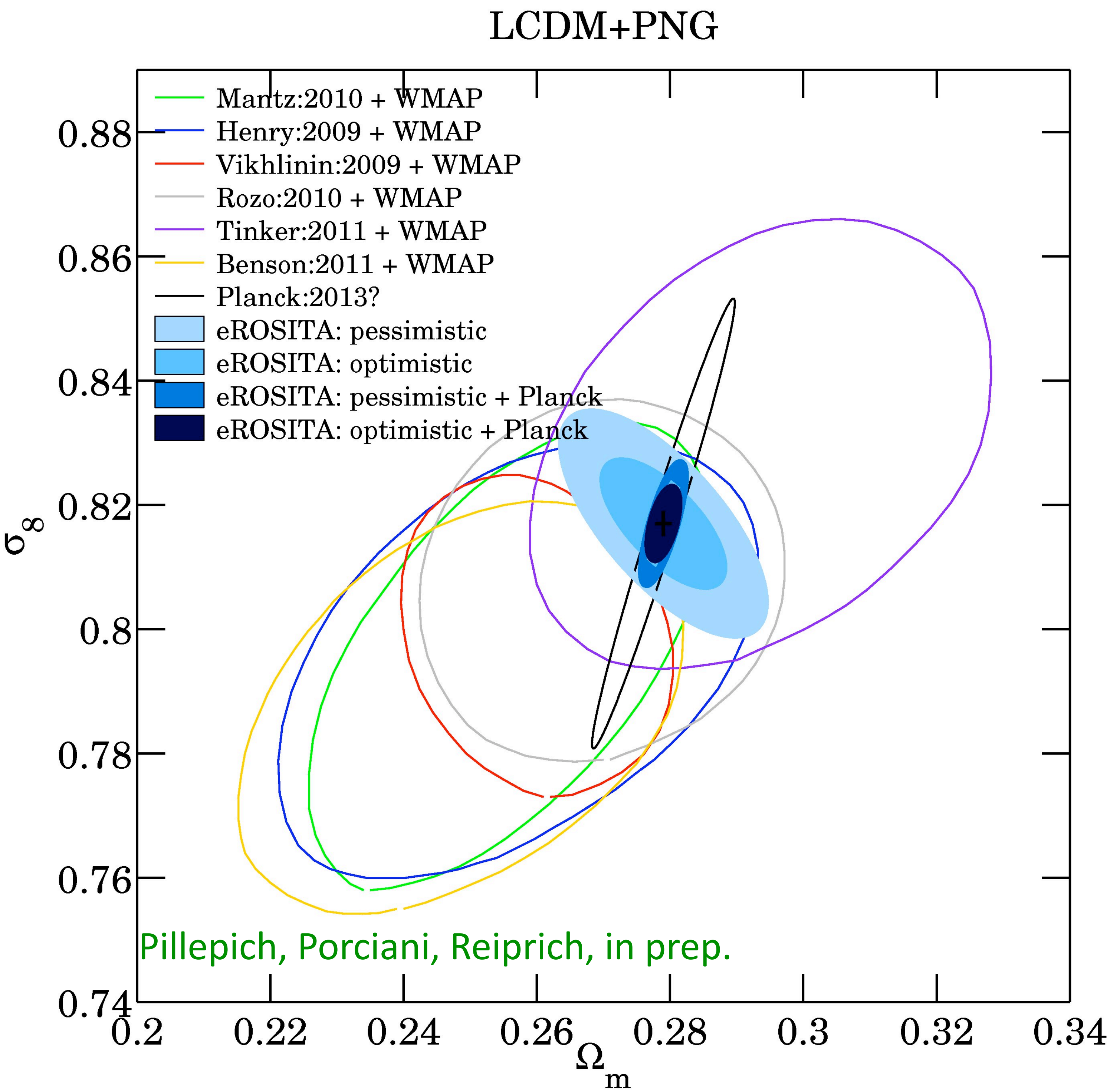
Pillepich, Porciani, Reiprich (2012)

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



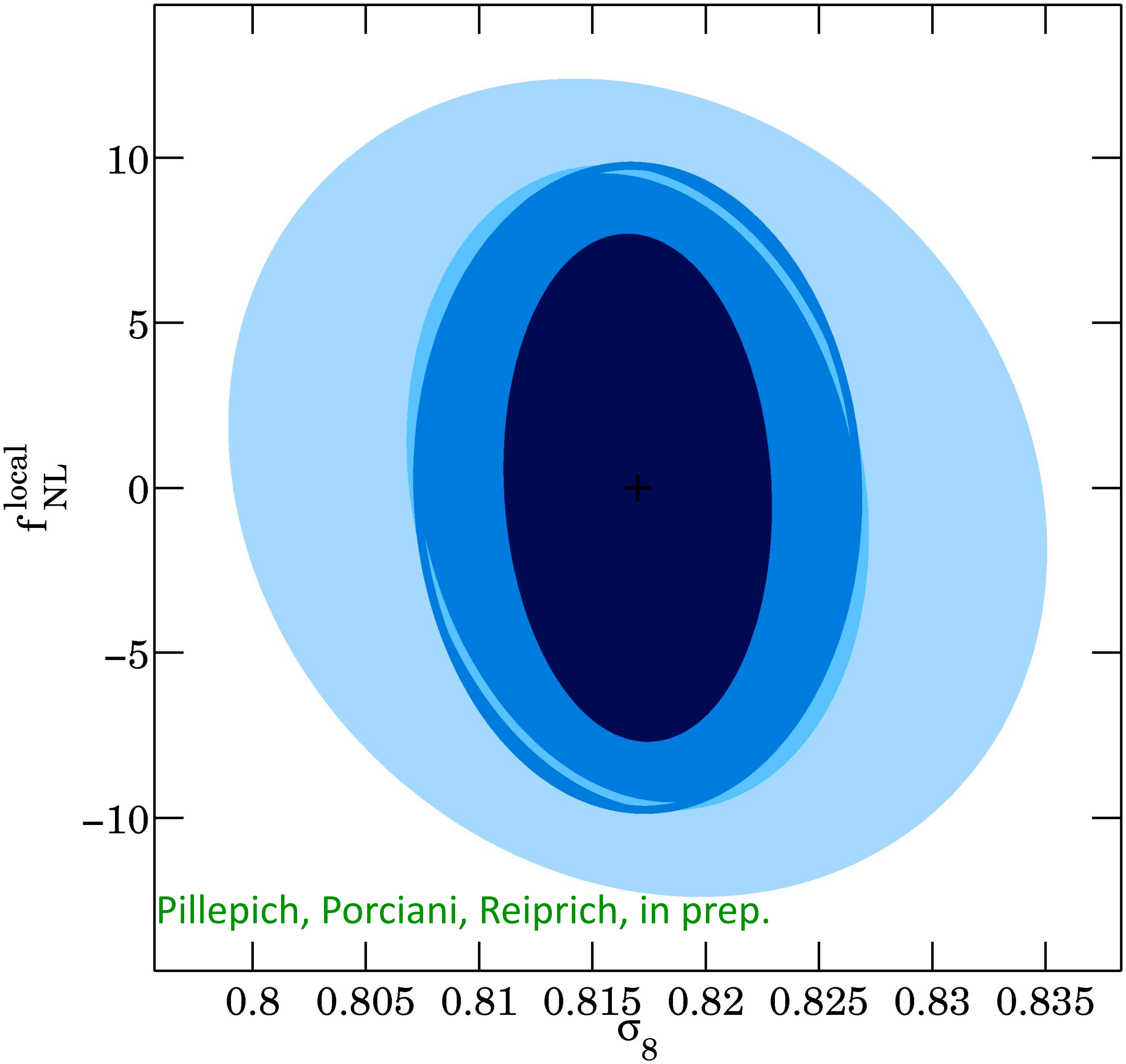


Pillepich, Porciani, Reiprich (2012)



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

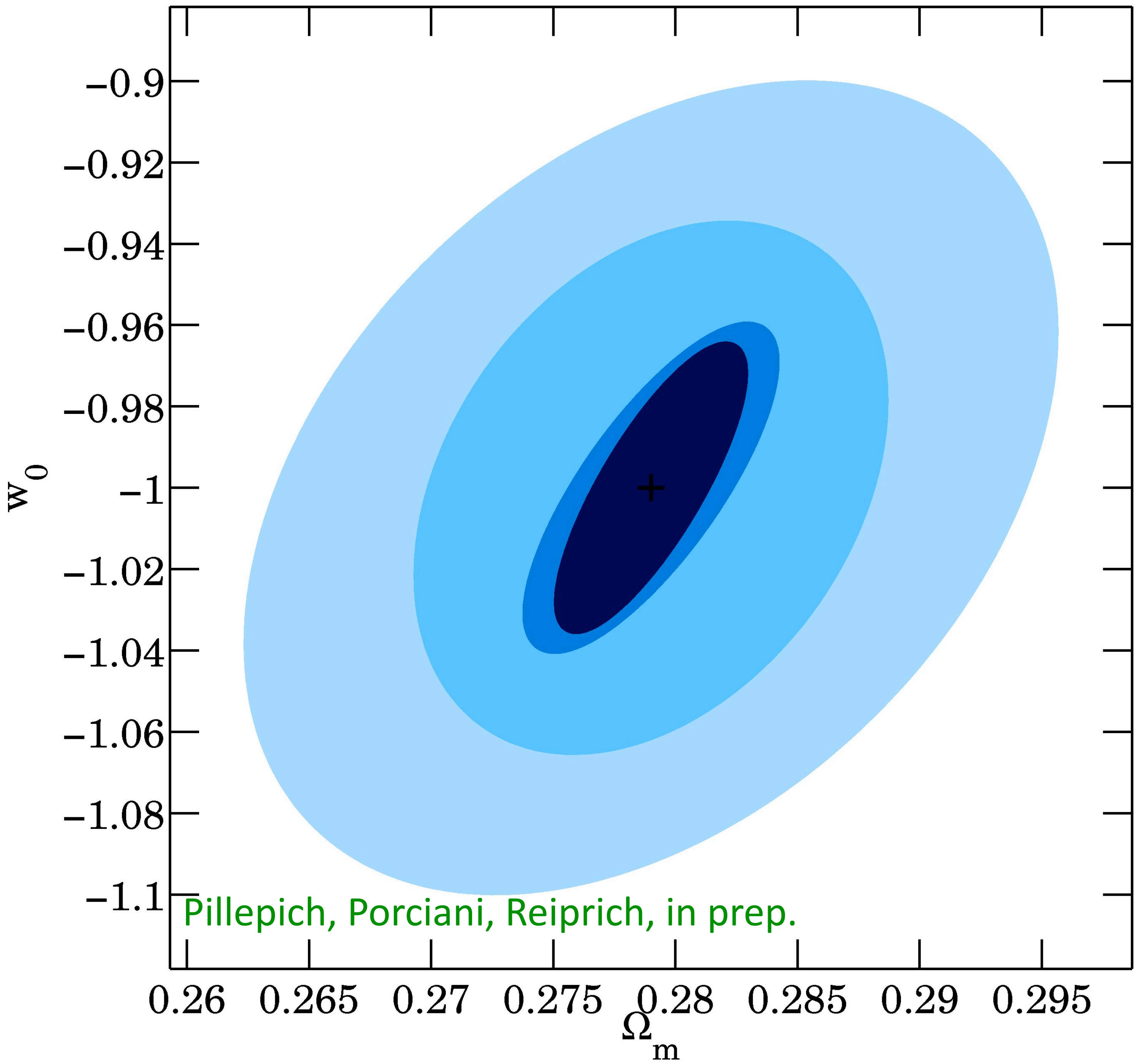
Primordial non-Gaussianity LCDM+PNG



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

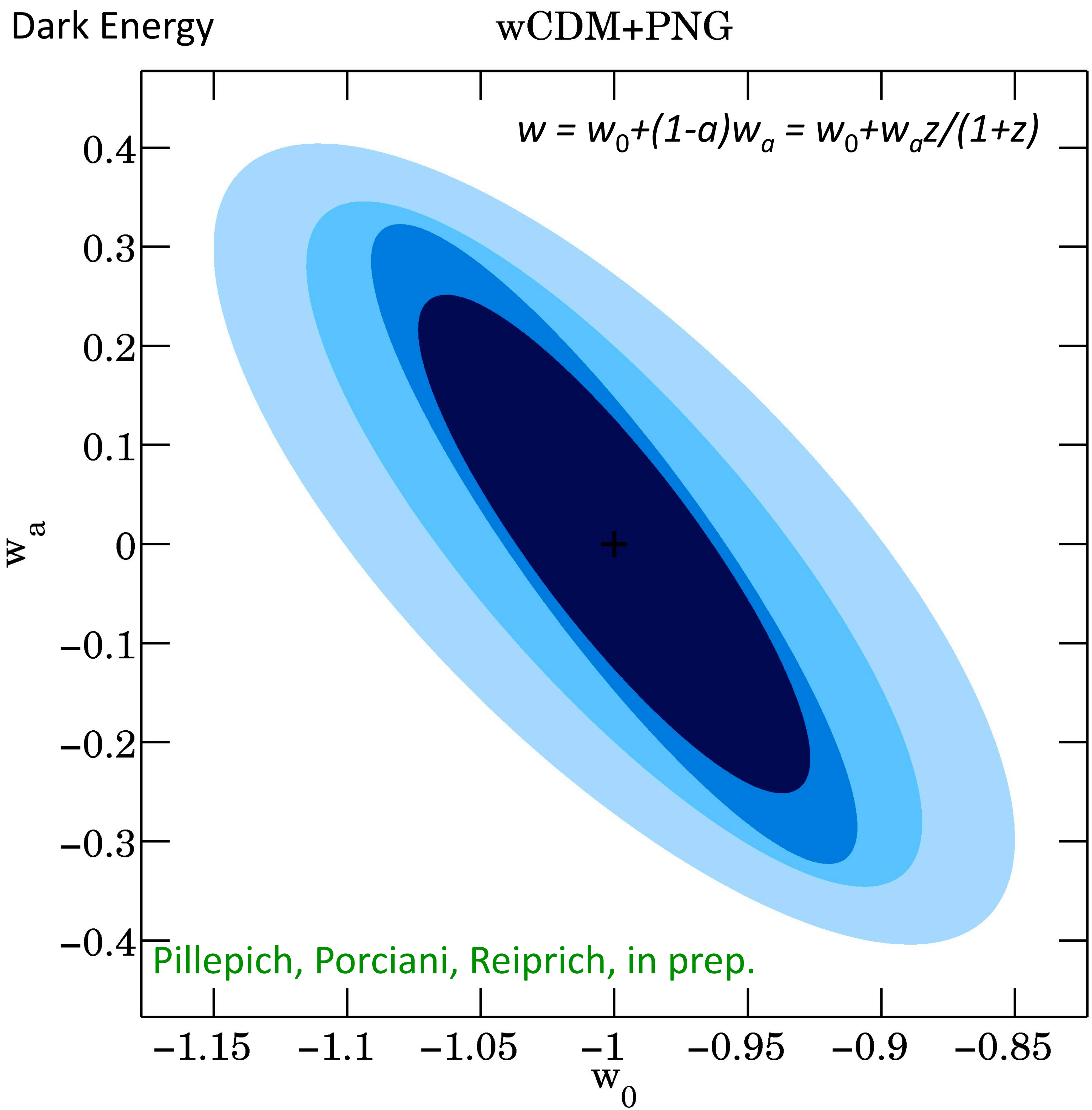
Dark Energy, constant *w*

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)

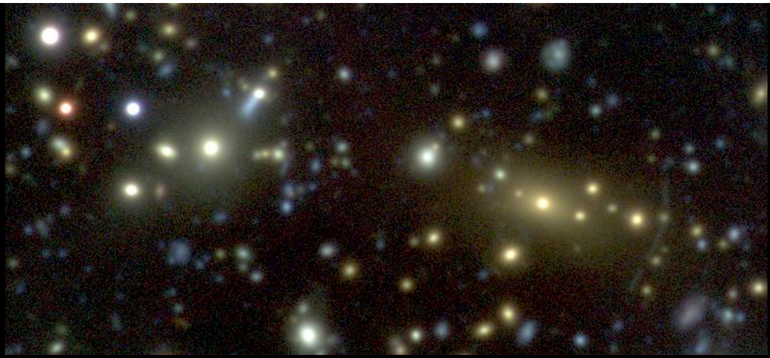
eROSITA Compared to DES and Euclid

Data (Stage IV)	Redshifts	Prior Scenario	Model	Δf_{NL}^{local}	$\Delta\sigma_8$	$\Delta\Omega_m$	Δw_0	Δw_a	$FoM^{DEFT,1\sigma}$
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	-
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	-

>300 for f_{NL}=0

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

Challenges



- Getting redshifts for all clusters. -> X-ray-*z*, photo-*z*, spectro-*z*.
- 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, pointed follow-up observations.
- ….

Summary of Conclusions

- *eROSITA* will be launched in about 2 years.
- It will discover 100k clusters, among them *all* massive ones in the observable Universe.
- It will likely be the first "Stage IV" dark energy probe world-wide.
- It will yield competitive and complementary constraints on dark energy, e.g., Δw_{DE}<3%, but also on modified gravity, neutrinos, primordial non-Gaussianity, ….
- Even tighter constraints possible through low-scatter mass proxies (e.g., *T*) from survey (~10^4 clusters) and pointed phase follow-up.