HICOSMO

X-ray analysis of a complete sample of galaxy clusters

Gerrit Schellenberger

Hot spots in the XMM sky:
Cosmology from X-ray to Radio

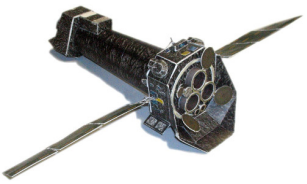
Μύκονος
June 15, 2016

Argelander-Institut für Astronomie

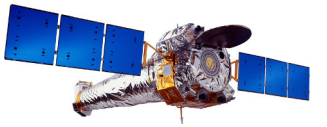
Bonn-Cologne Graduate School of Physics and Astronomy

IMPRS astronomy & astrophysics Bonn and Cologne

CfA Smithsonian Astrophysical Observatory

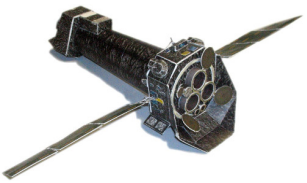


Outline



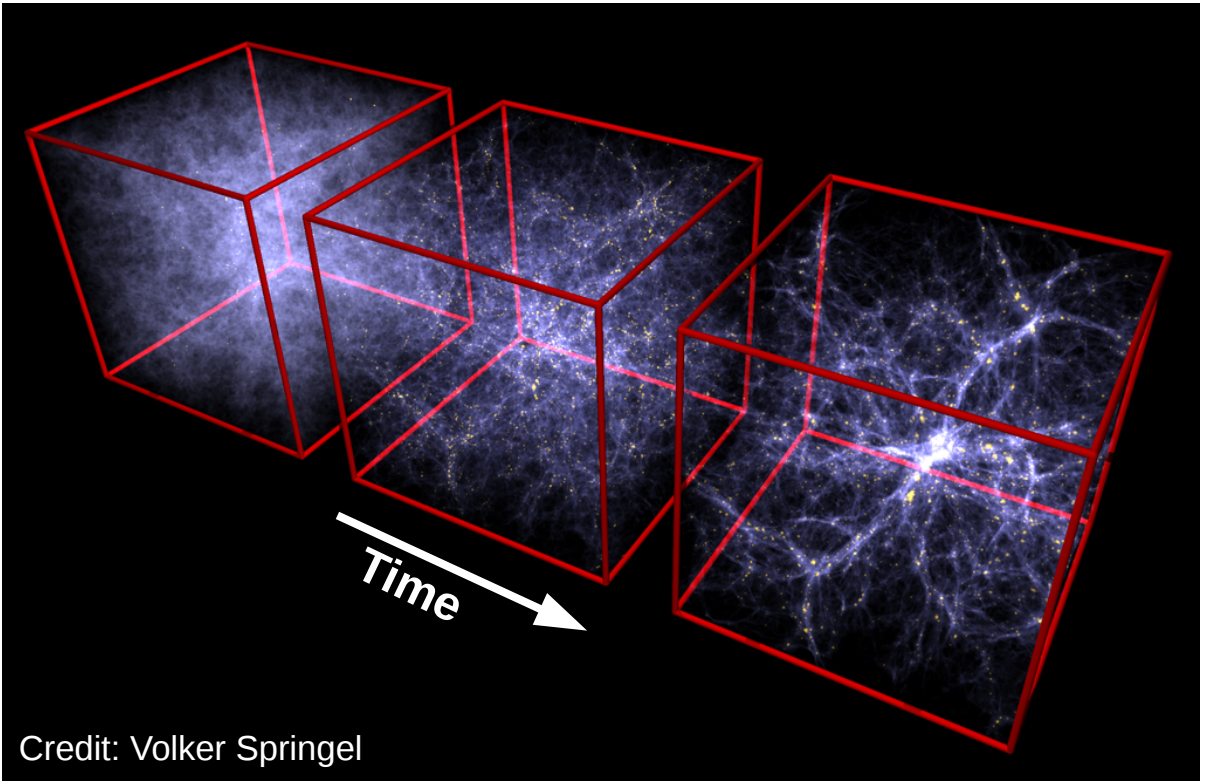
- Introduction
  - Cosmology
  - HIFLUGCS

- Cosmology with HIFLUGCS
  - Data analysis
  - Total mass estimates
  - Cosmological results
  - X-ray calibration uncertainties



Introduction

Cosmology and structure formation

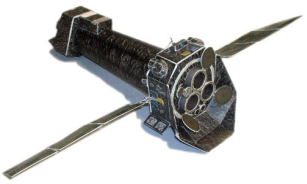


Credit: Volker Springel

- Energy composition of the Universe leads to structure formation scenario

  → Overdensities collapse due to gravity

- Today: Number density → Halo Mass Function



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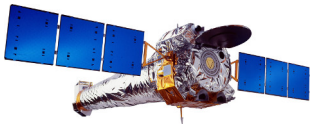

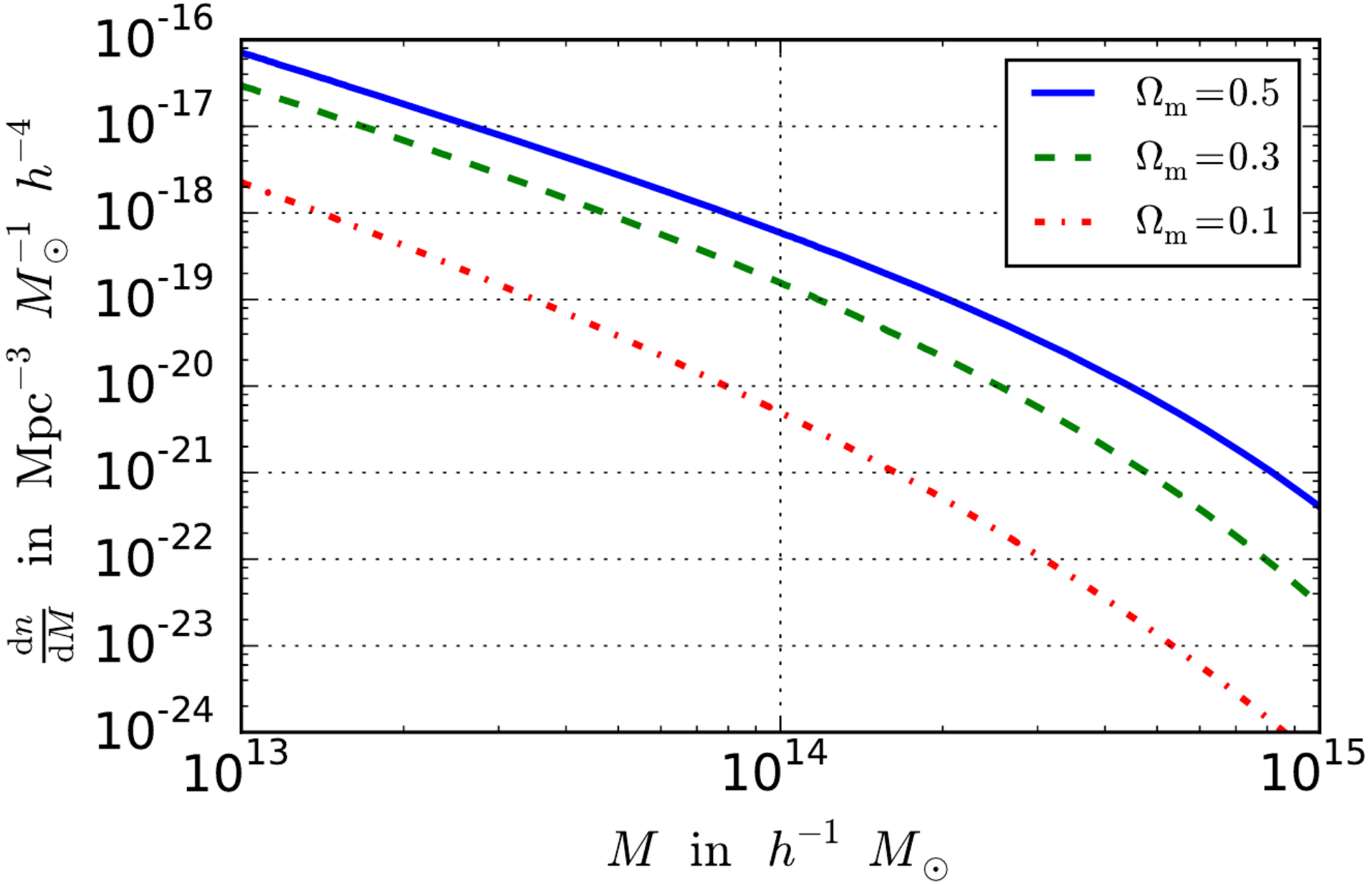

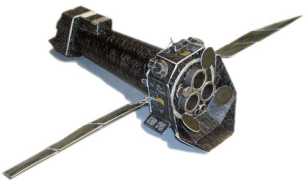

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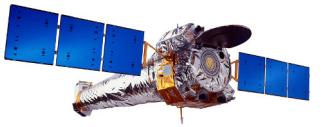

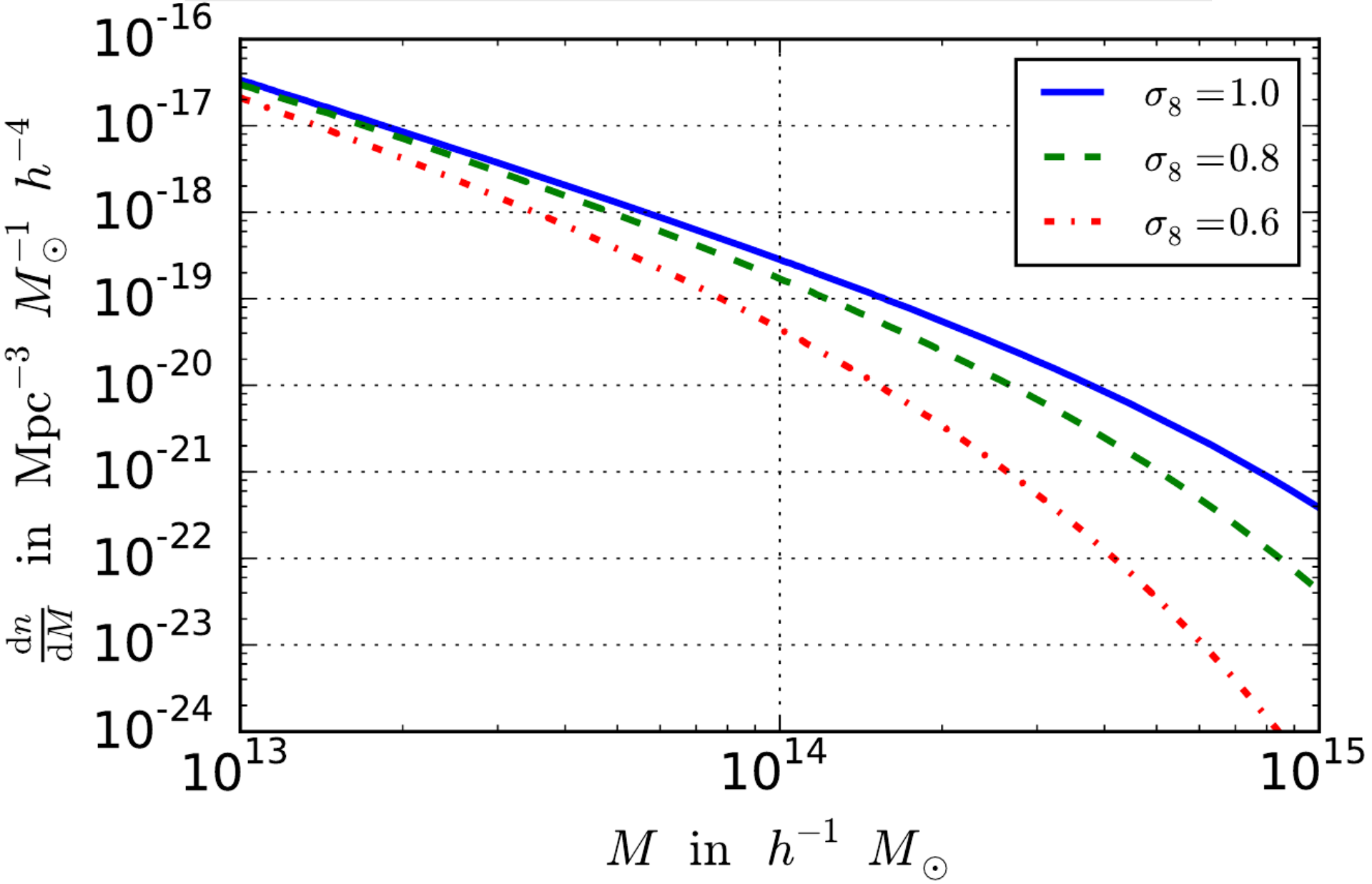

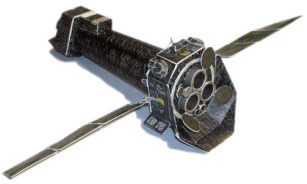

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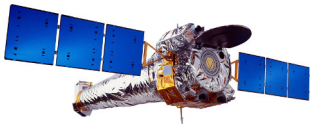
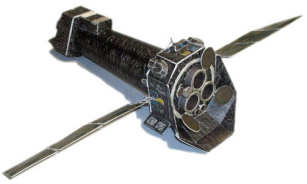


Total gravitating Mass

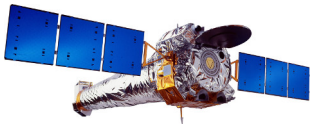
- Total mass assuming hydrostatic equilibrium
- Temperature and density profile needed

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

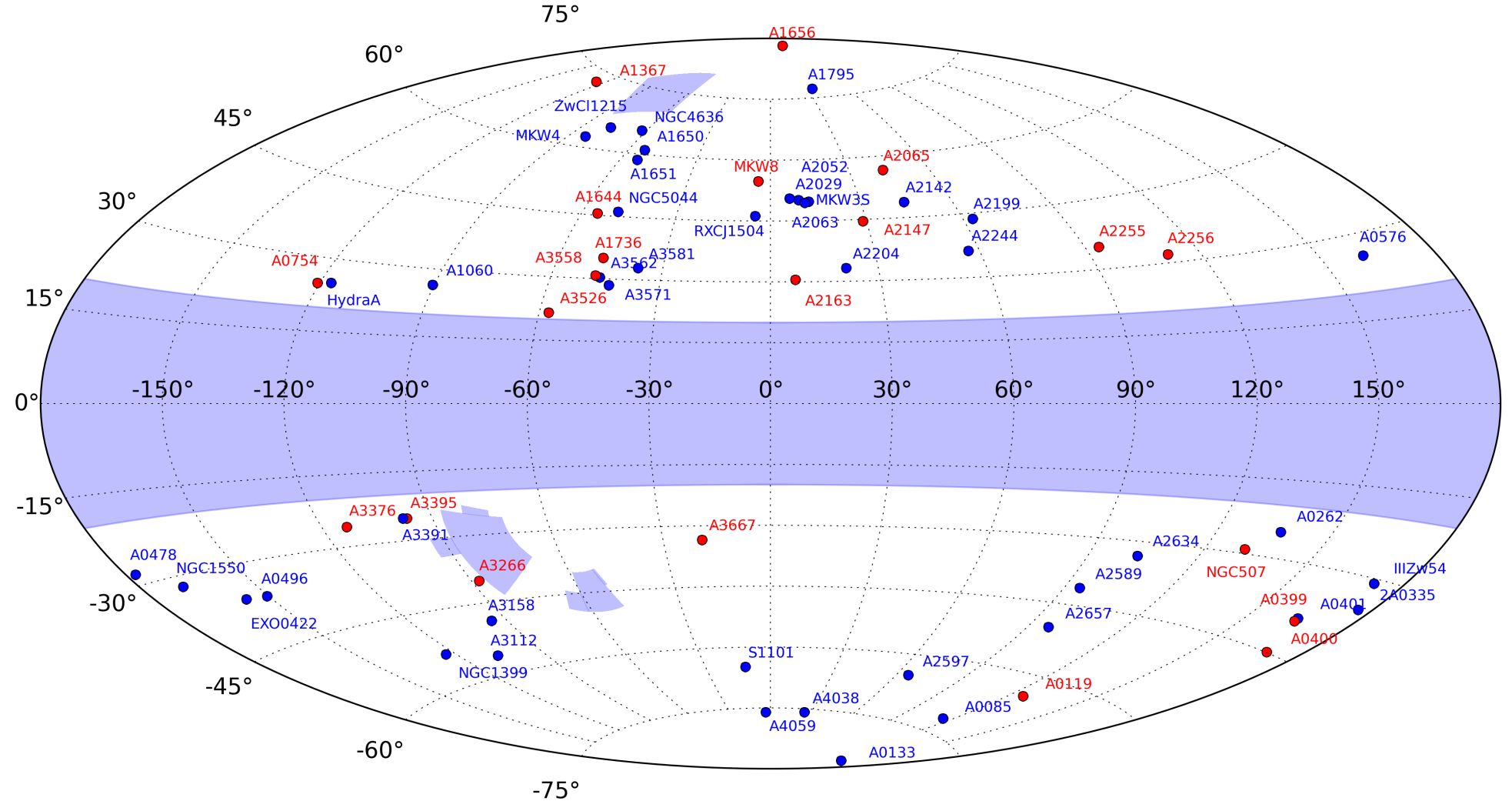
- Each cluster analyzed individually
- LM scaling relation derived self-consistently from same sample



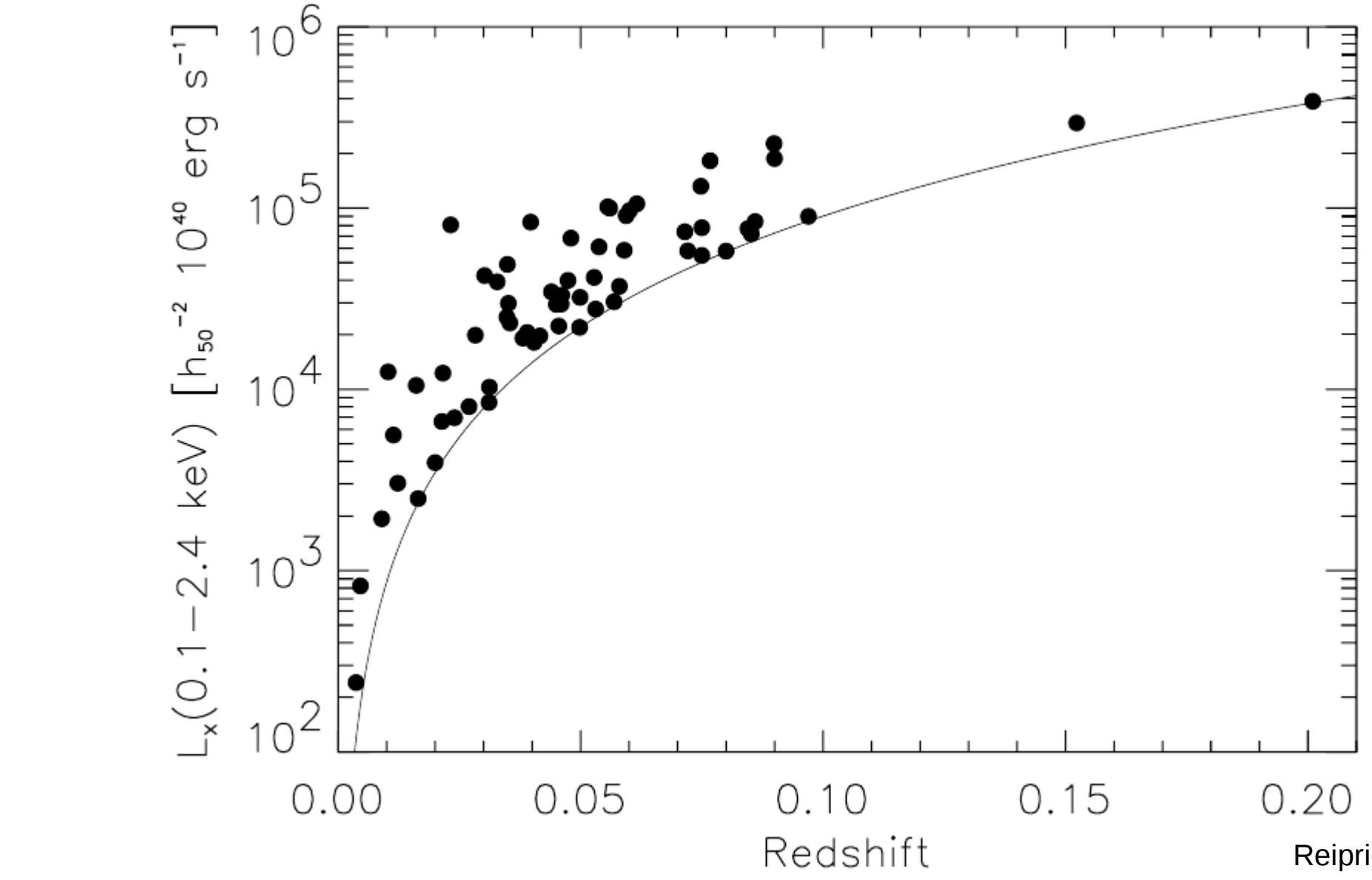
HIFLUGCS



- Flux limited ($2 \cdot 10^{-11}$ erg s^{-1} cm^{-2}), complete and selected from ROSAT
- 64 very bright and nearby galaxy clusters
- All HIFLUGCS clusters observed (many several times) with Chandra

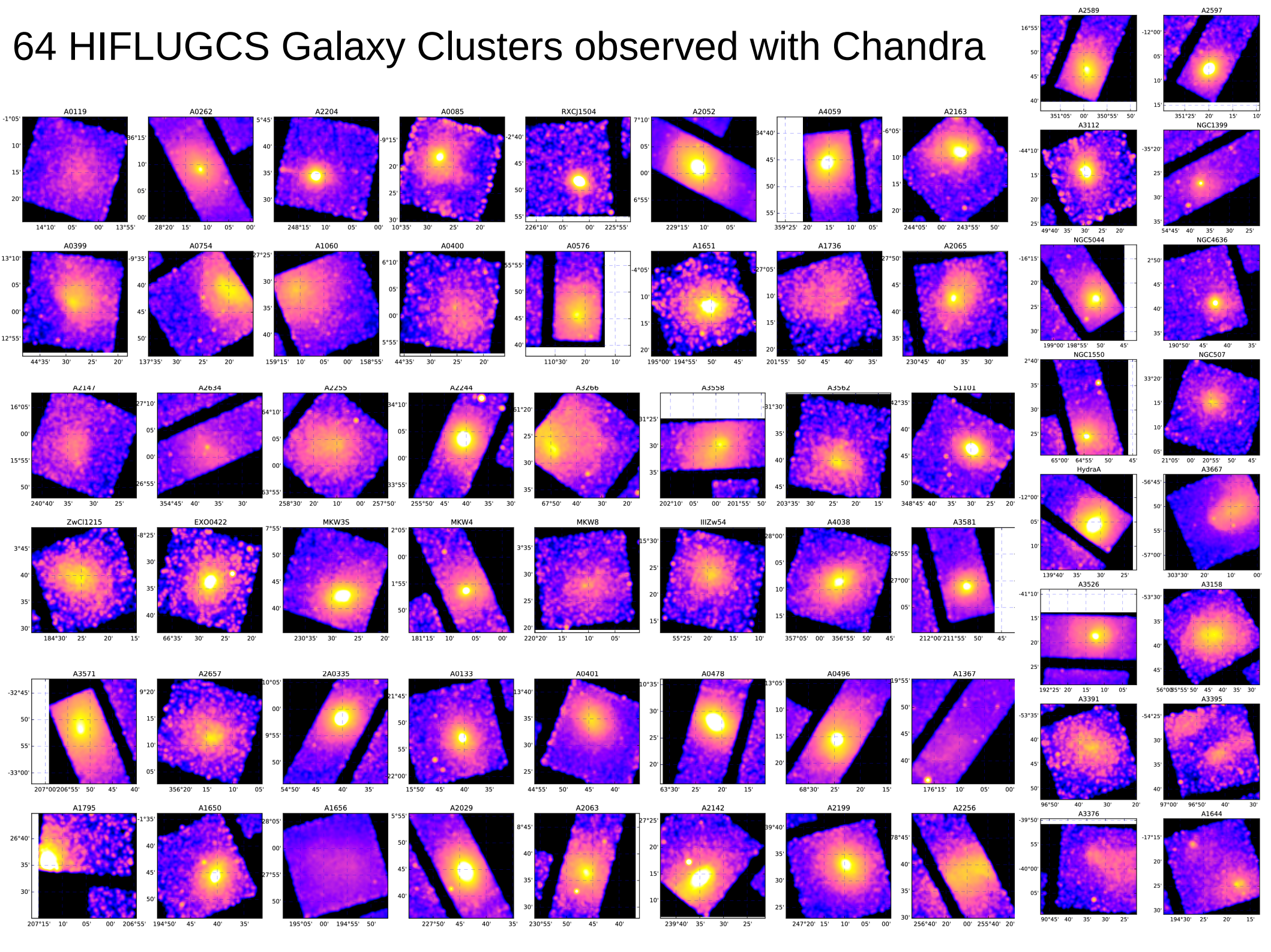


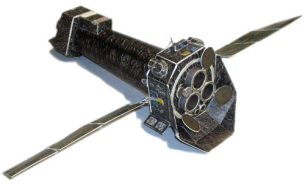
HIFLUGCS



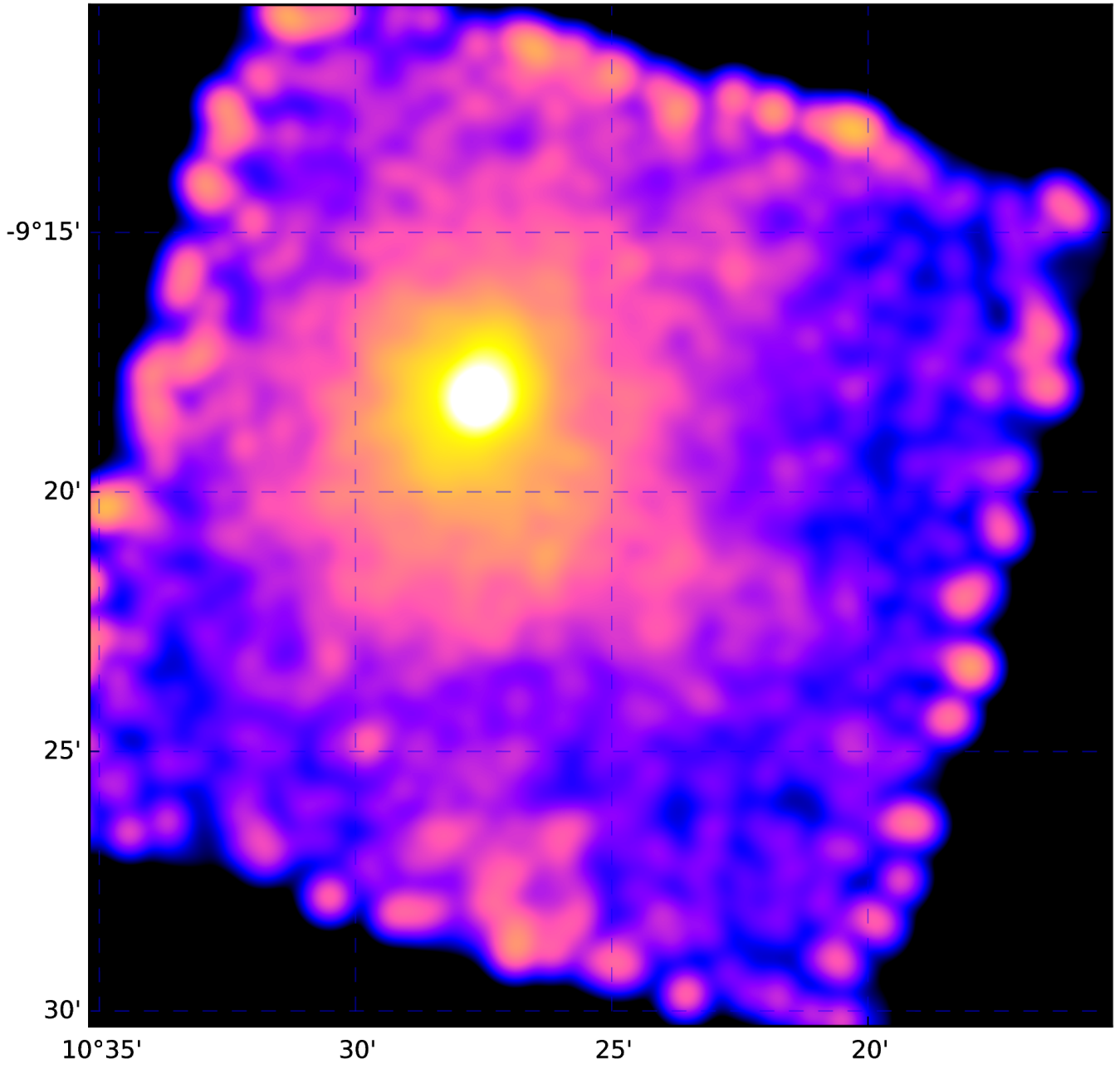
Reiprich+02

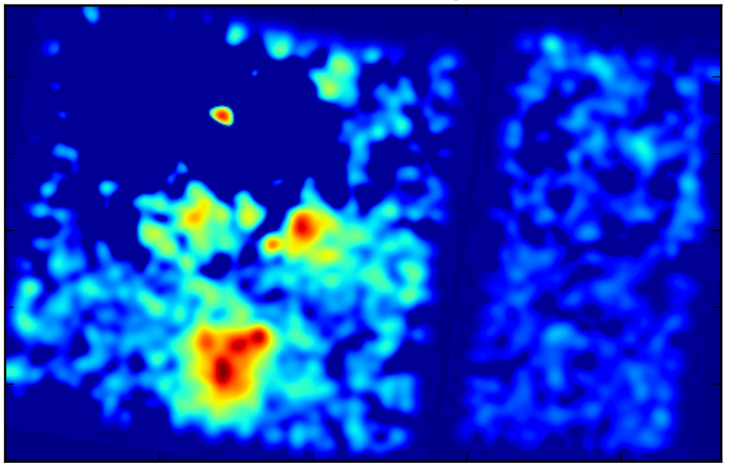
64 HIFLUGCS Galaxy Clusters observed with Chandra

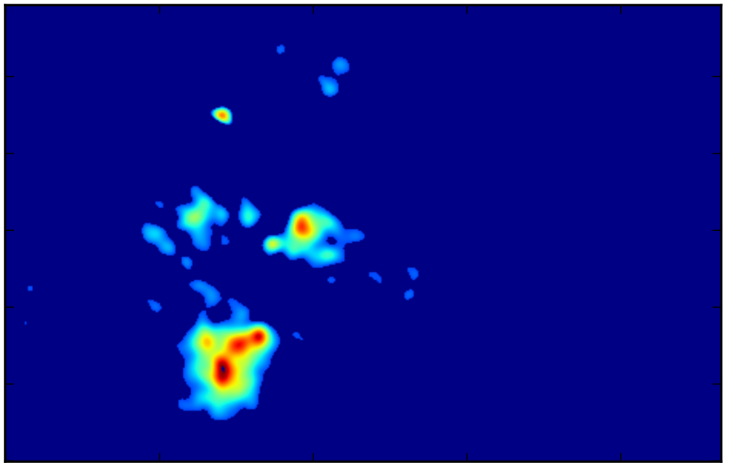




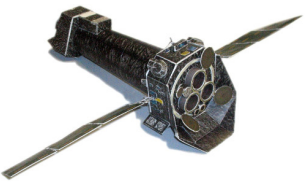
Removing Substructure

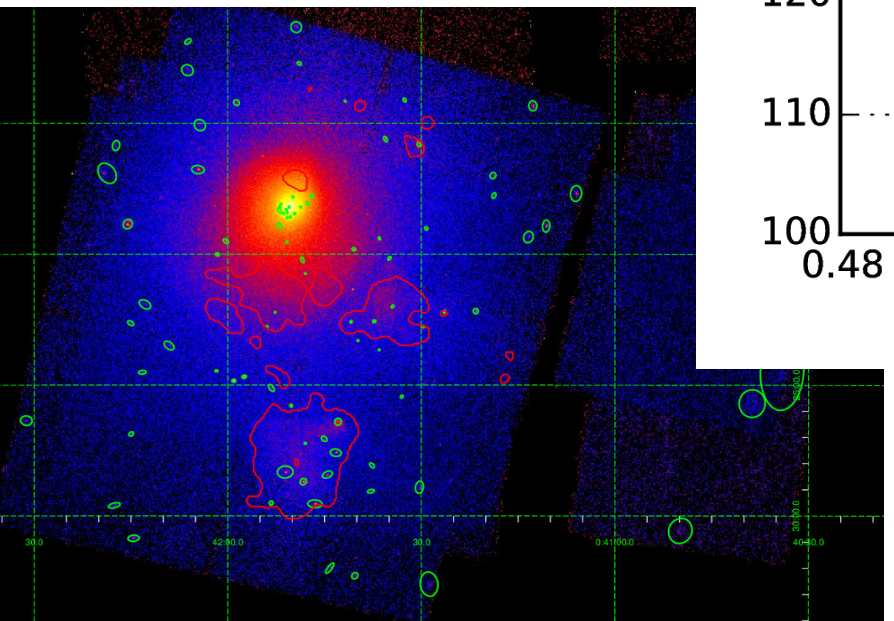


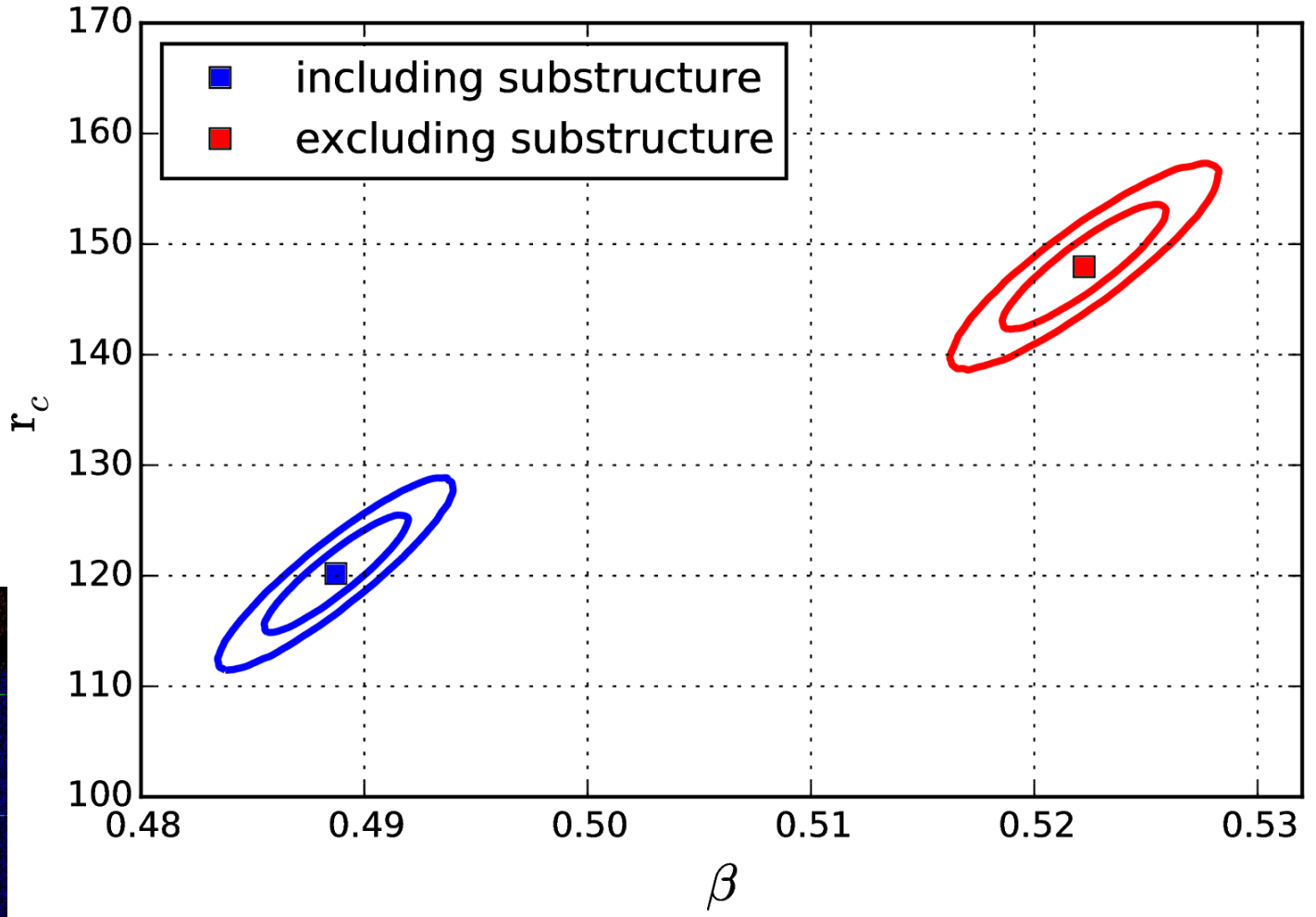


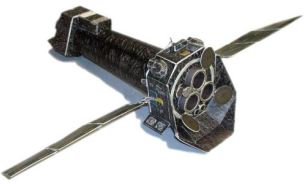


Substructure









Appropriate temperature parametrization

1. Smoothly joined power laws:

$$T(r) = \frac{1}{(\{1/[t_1(r)]\}^s + \{1/[t_2(r)]\}^s)^{1/s}},$$

$$t_i(r) = T_{i,100}\left(\frac{r}{100\ \mathrm{kpc}}\right)^{p_i}, \quad i = 1, 2. \qquad (4)$$

5 free parameters

2. Power laws mediated by an exponential:

$$T(r) = T_0 + t_1(r)e^{-(r/r_p)^\gamma} + t_2(r)\left(1 - e^{-(r/r_p)^\gamma}\right),$$

$$t_i(r) = T_i\left(\frac{r}{r_0}\right)^{p_i}, \quad i = 1, 2. \qquad (5)$$

8 free parameters

3. The Allen et al. (2001) rising profile joined to a falling temperature profile by an exponential cutoff,

$$T(r) = t_1(r)e^{-(r/r_p)^\gamma} + t_2(r)\left(1 - e^{-(r/r_p)^\gamma}\right),$$

$$t_1(r) = a + T_1\left[\frac{(r/r_1)^{p_1}}{1 + (r/r_1)^{p_1}}\right],$$

$$t_2(r) = b + T_2\left[\frac{1}{1 + (r/r_2)^{p_2}}\right]. \qquad (6)$$

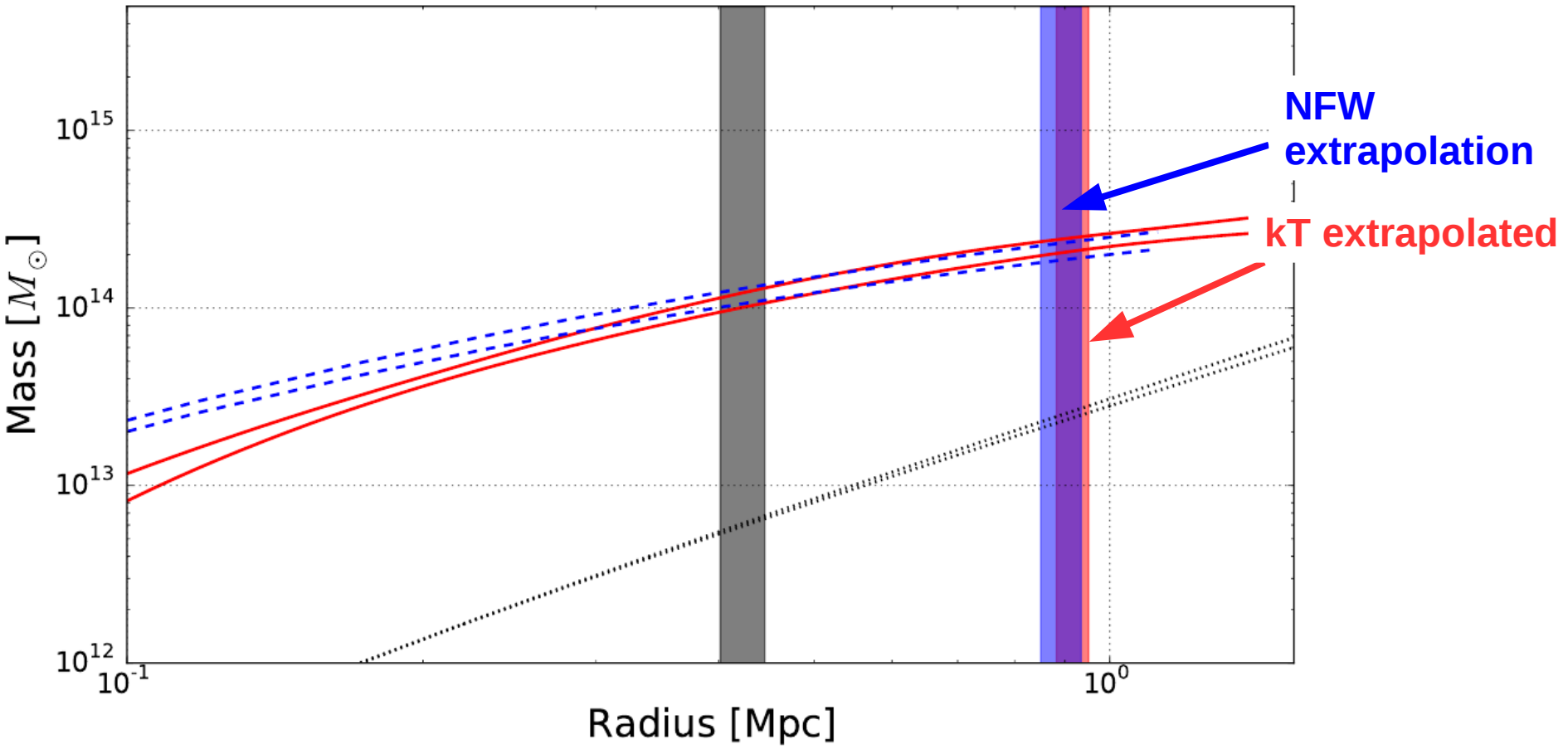
10 free parameters

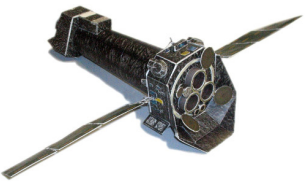
Gastaldello+07

Mass extrapolation

For most clusters extrapolation of temperature profile needed

Extrapolation of the measured temperature profile or NFW fit to the mass profile





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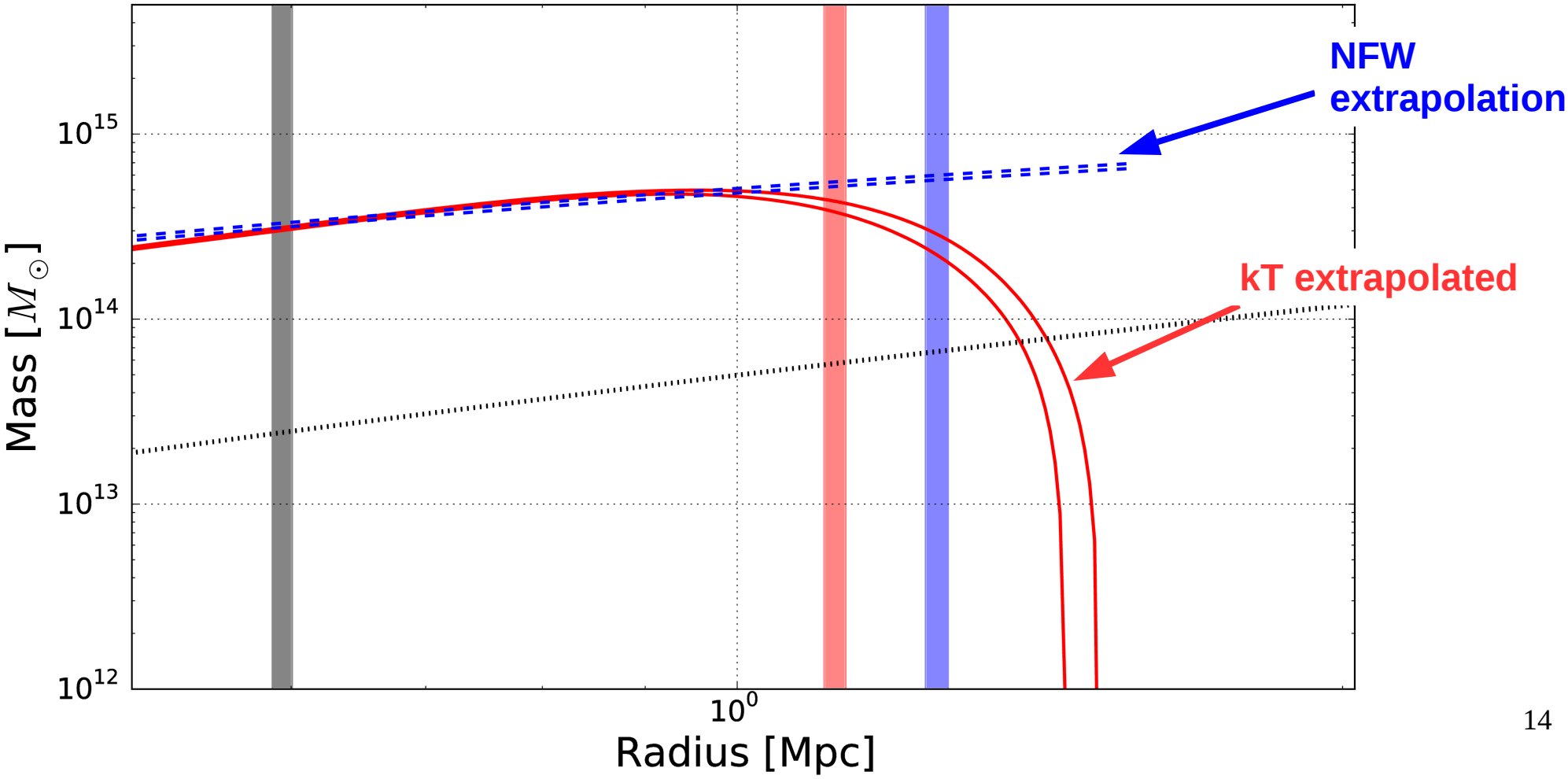
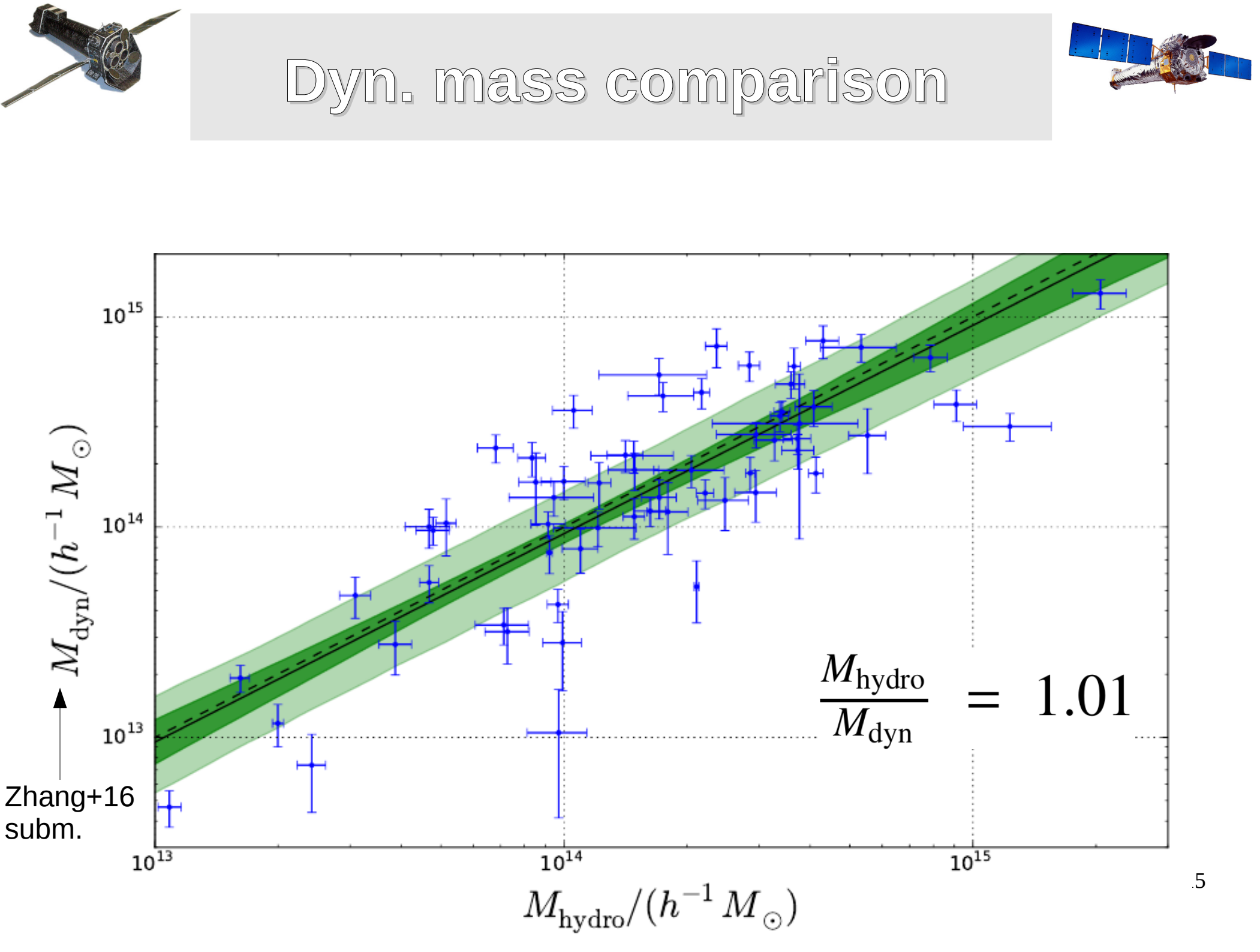
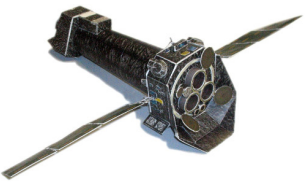


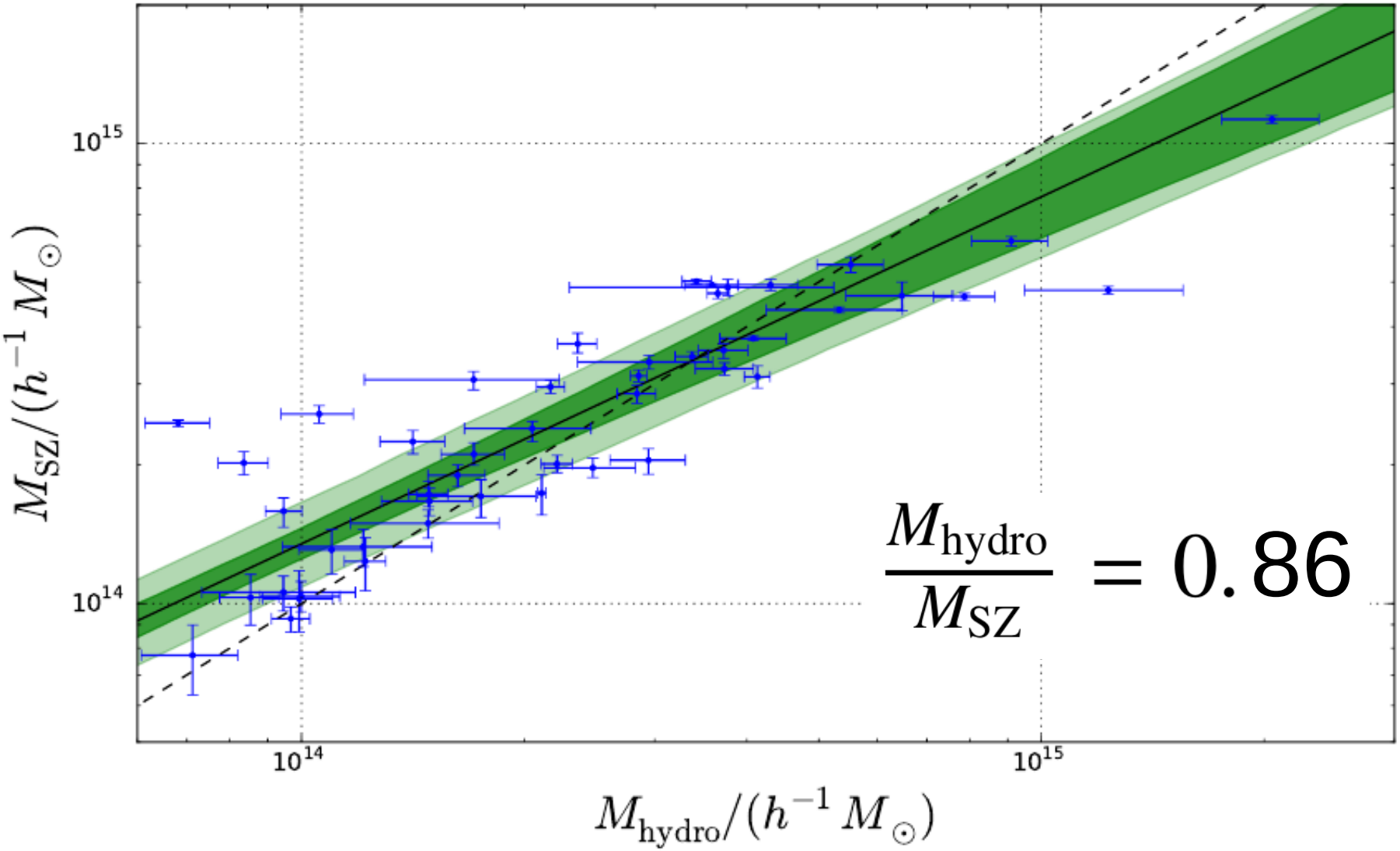
Dyn. mass comparison



Zhang+16 subm.

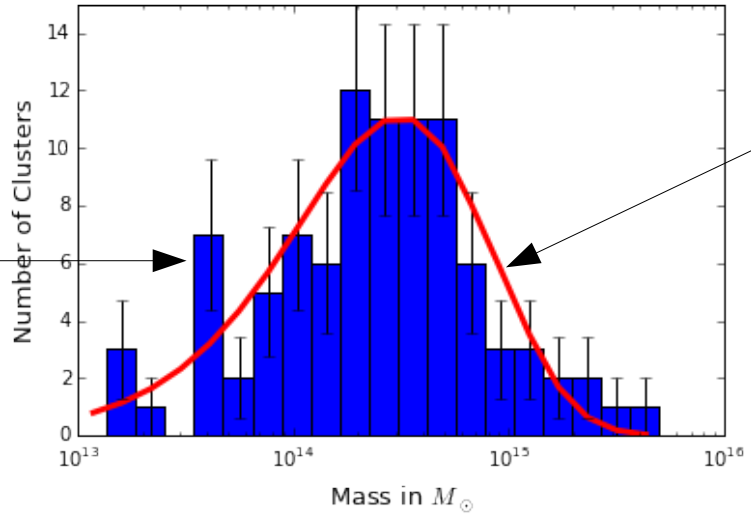


Planck SZ mass comparison



Cosmology

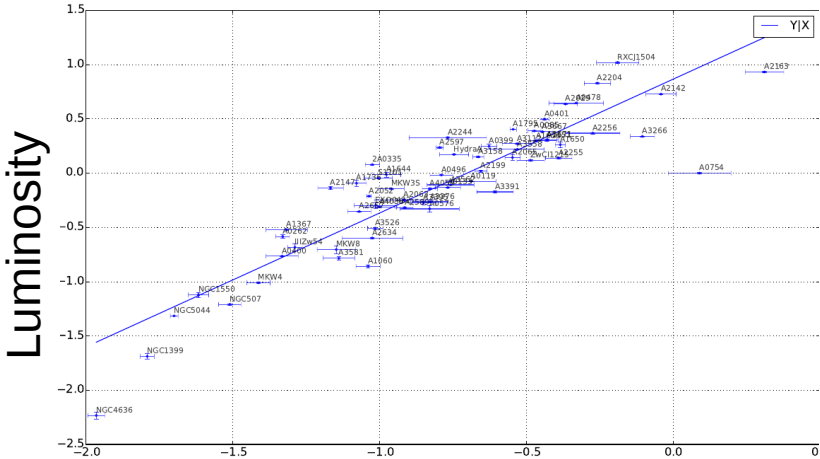
Observations



Model

Tinker+08 Mass Function

LM relation to select clusters



Likelihood function:
(Mantz+10,15)

$$\mathcal{L}(\hat{M}, \hat{L}, N_{\rm det}) = \underbrace{\frac{\langle N \rangle^N \, e^{-\langle N \rangle}}{N!}}_{\text{Poisson}} \cdot \underbrace{\frac{N!}{N_{\rm det}!\, N_{\rm mis}!} \, p^{N_{\rm det}} \, (1-p)^{N_{\rm mis}}}_{\text{Binomial}} \cdot \underbrace{\prod_{i=1}^{N_{\rm det}} \tilde{P}_i}_{\text{observational probability}}$$

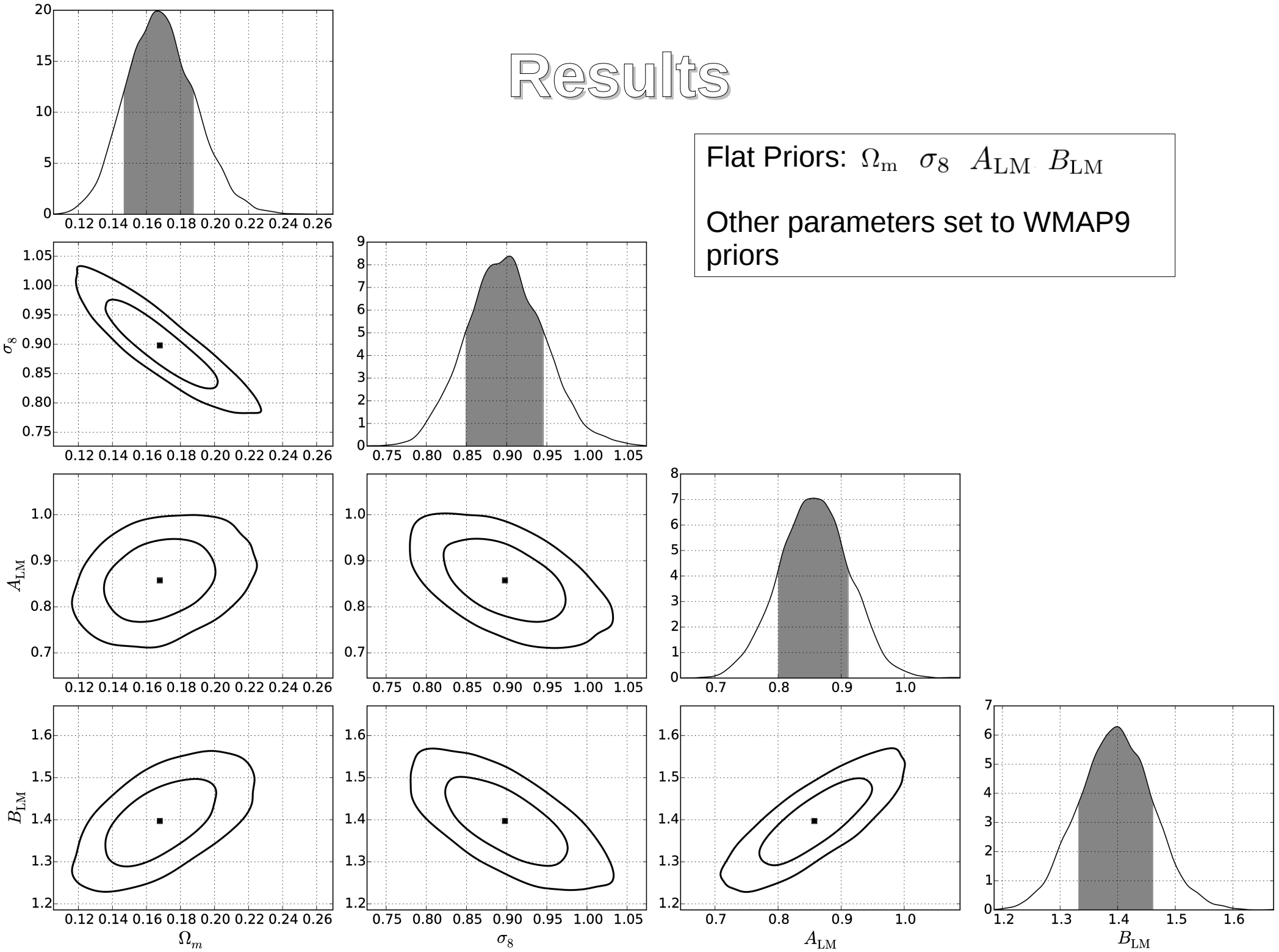
<N> - clusters predicted from HMF

p - Probability to detect clusters

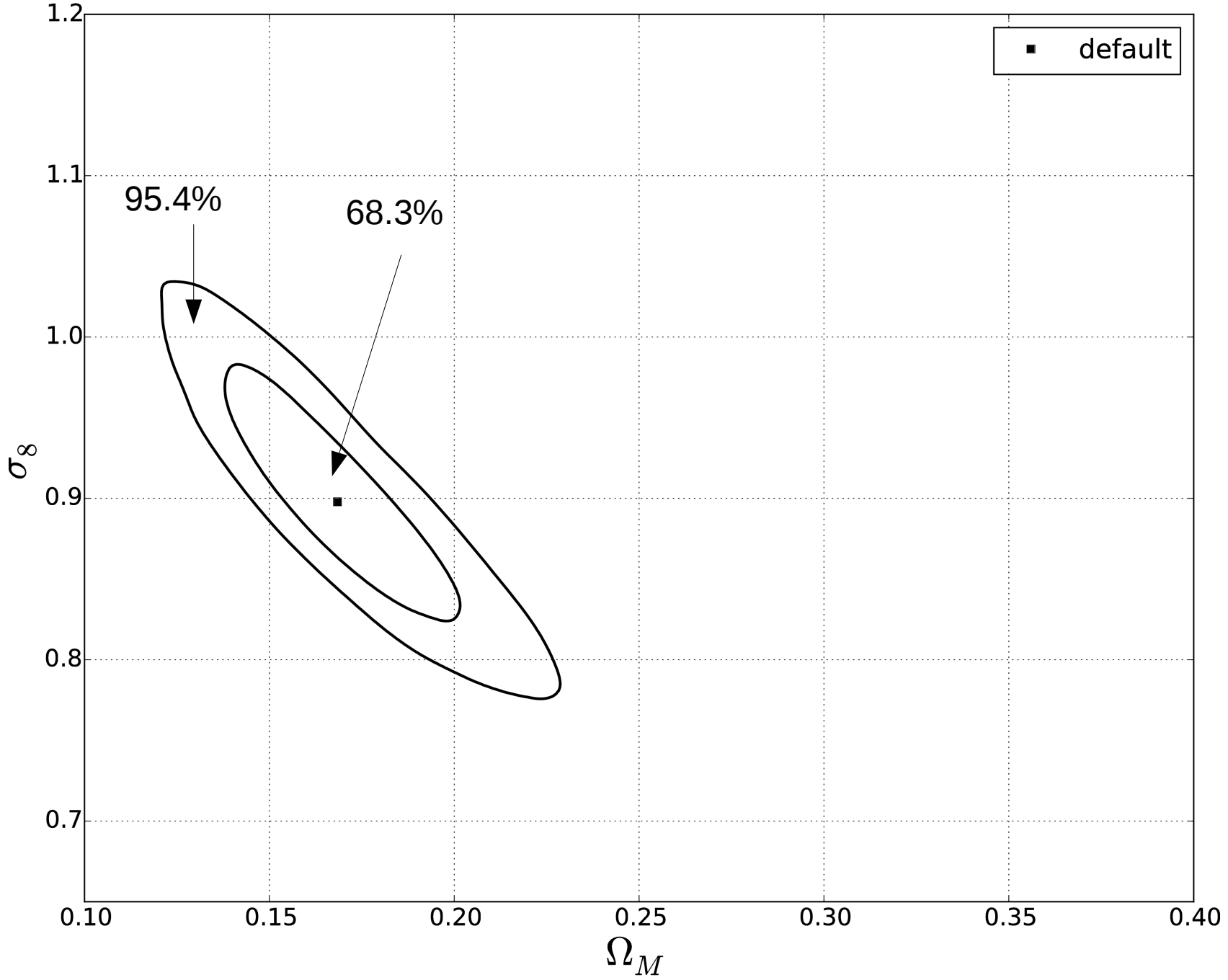
Results

Flat Priors: $\Omega_{\rm m}$ σ_8 $A_{\rm LM}$ $B_{\rm LM}$

Other parameters set to WMAP9 priors



Cosmological results



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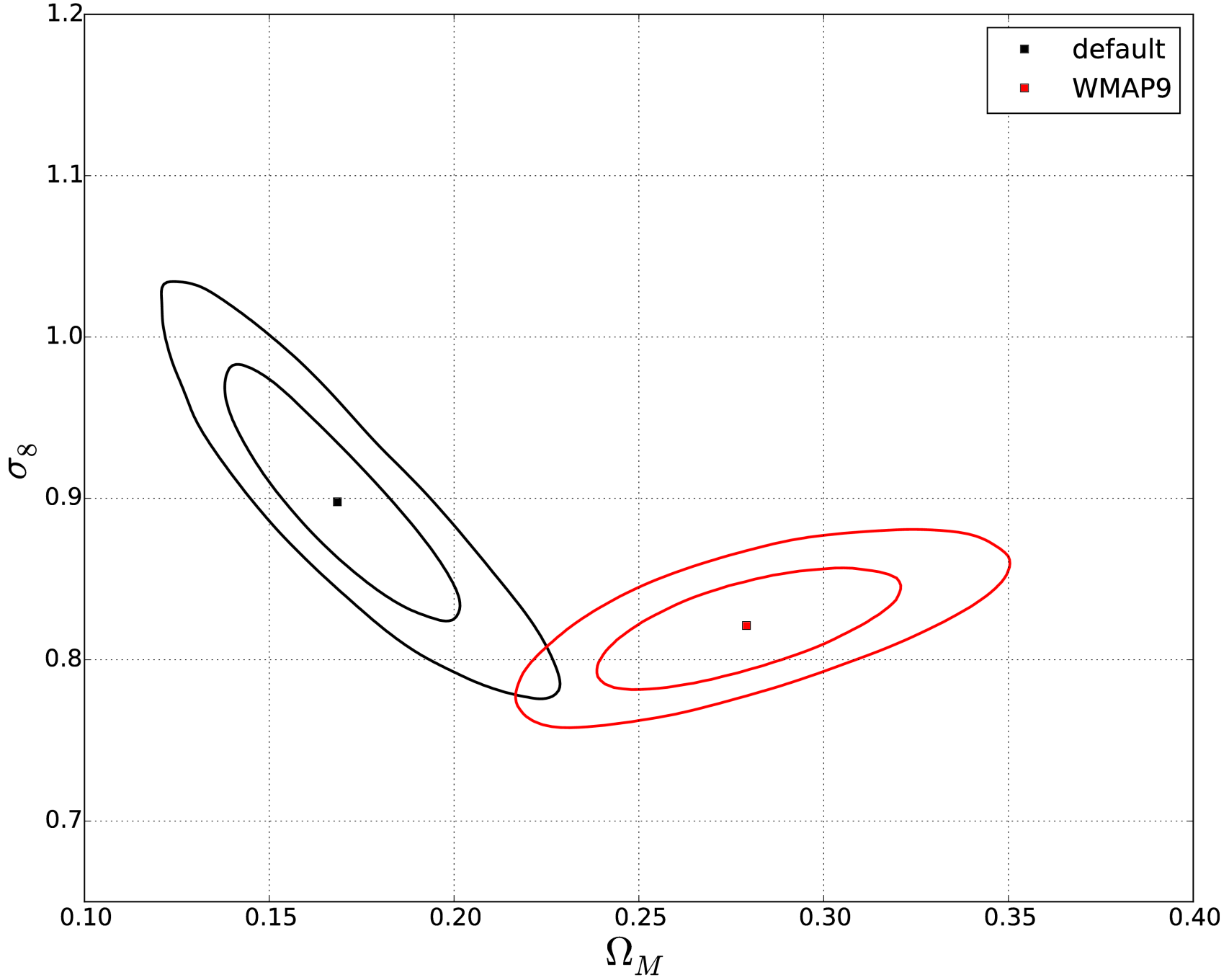

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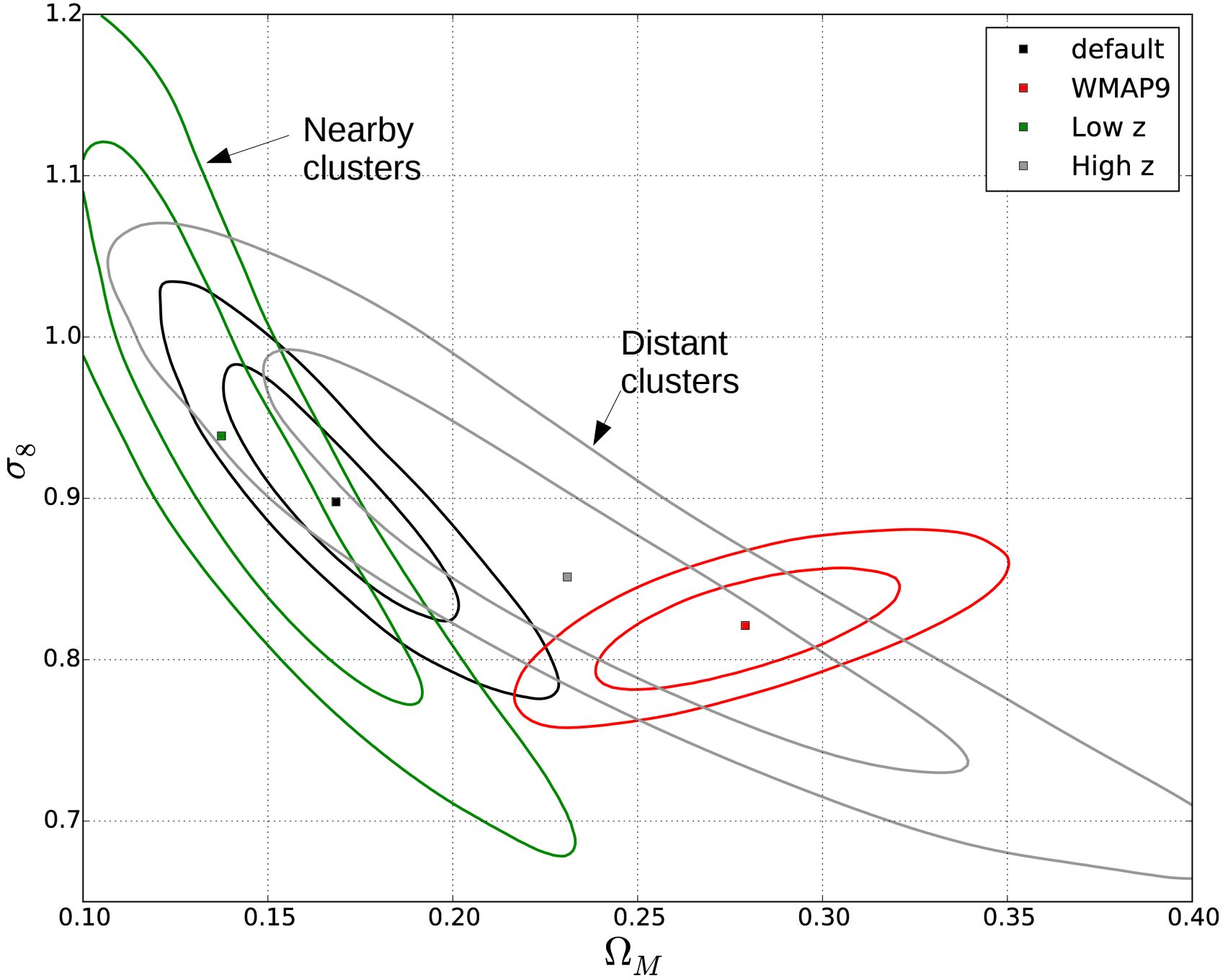

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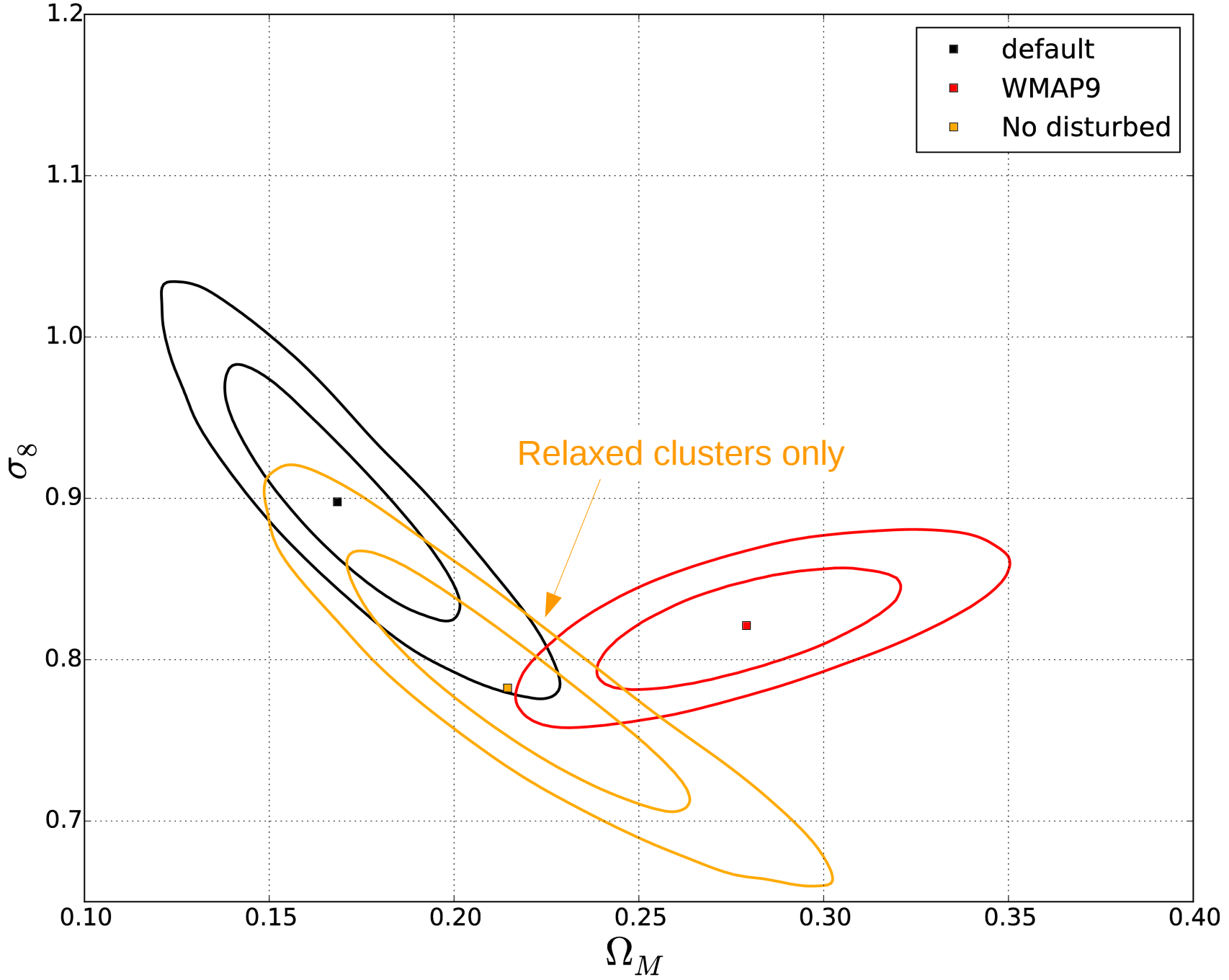
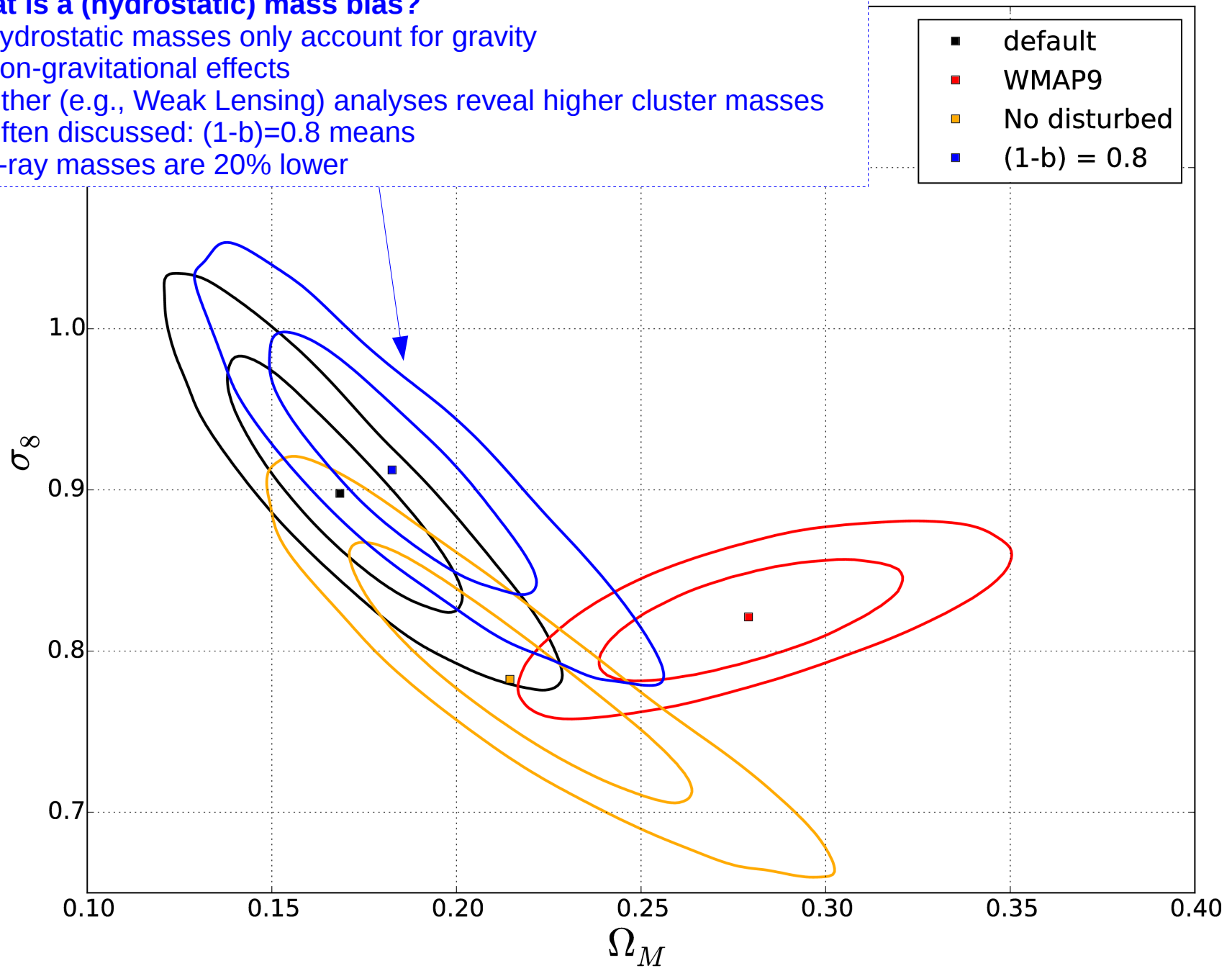


Cosmological results

What is a (hydrostatic) mass bias?

- Hydrostatic masses only account for gravity
- Non-gravitational effects
- Other (e.g., Weak Lensing) analyses reveal higher cluster masses
- Often discussed: (1-b)=0.8 means
- X-ray masses are 20% lower



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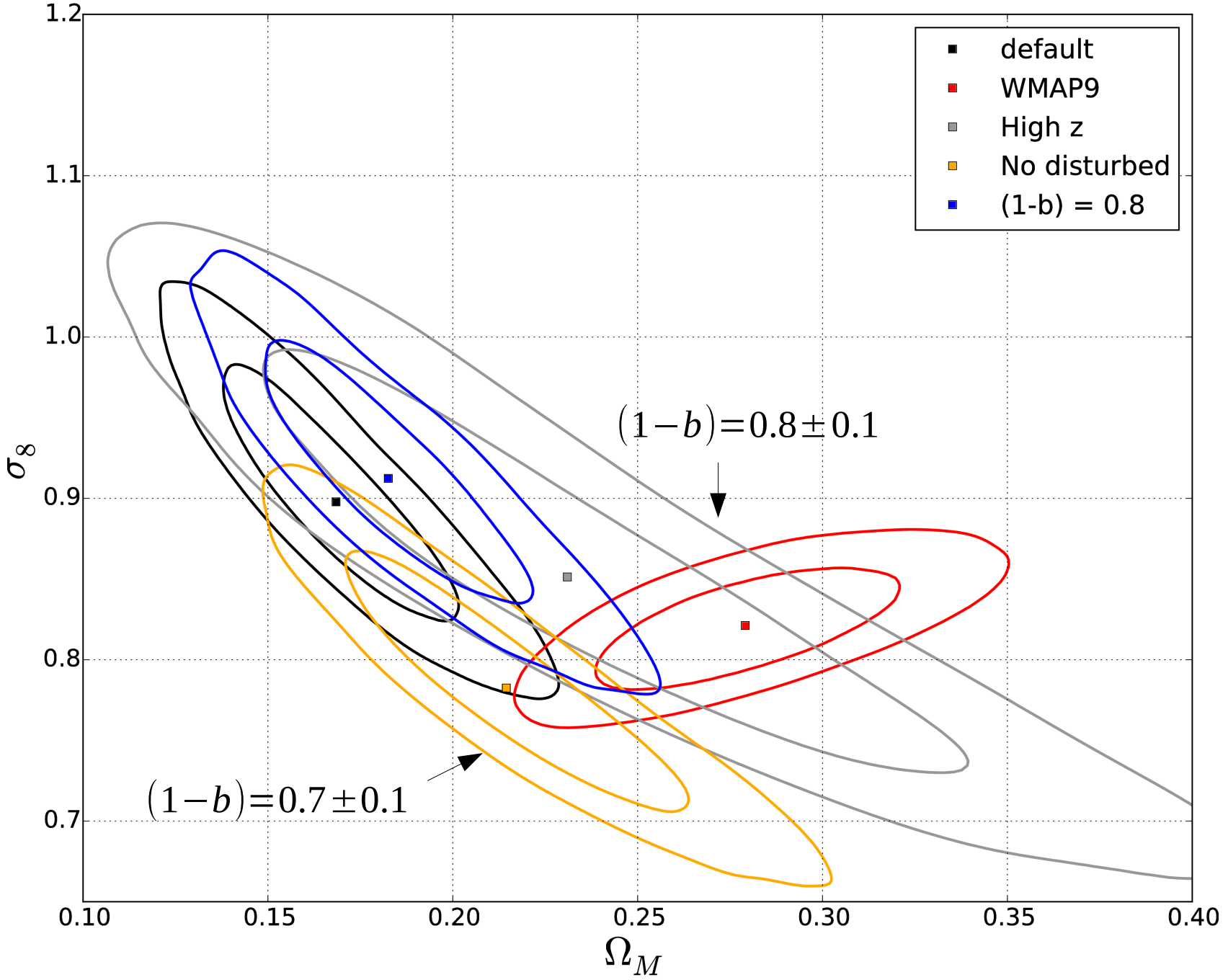

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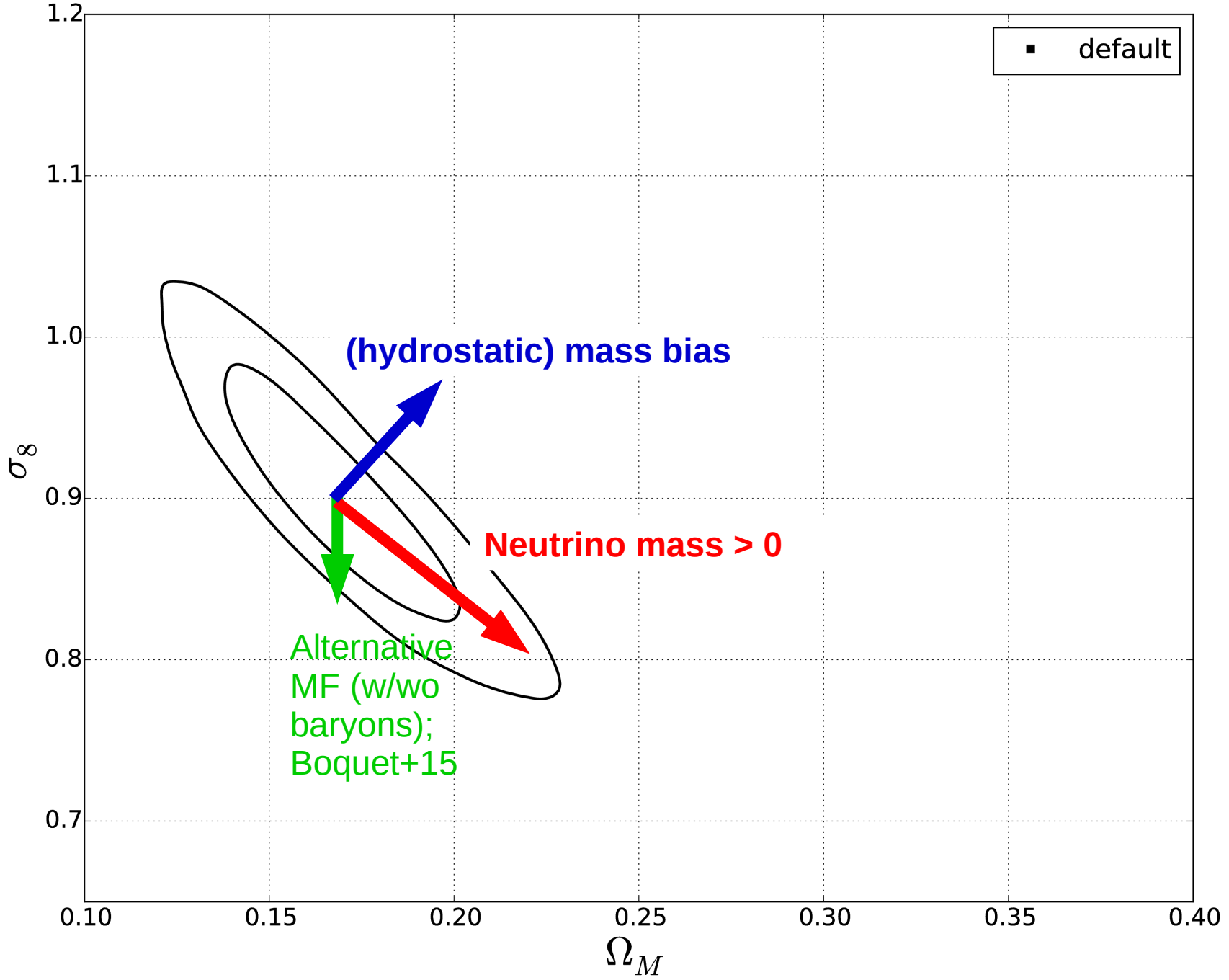
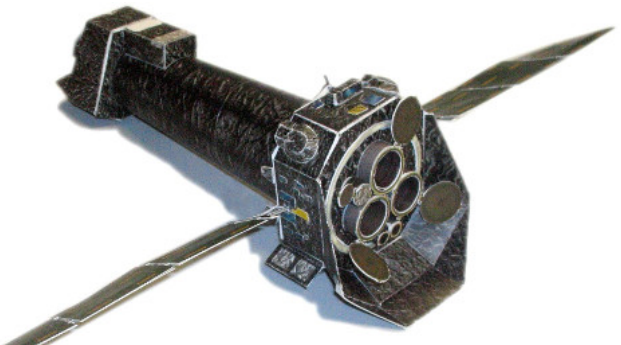


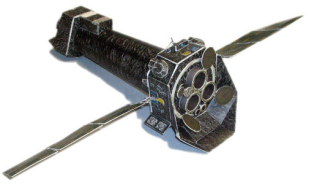
IACHEC
International Astronomical Consortium for High Energy Calibration

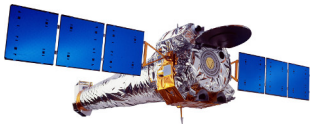
Do different instruments give consistent results?

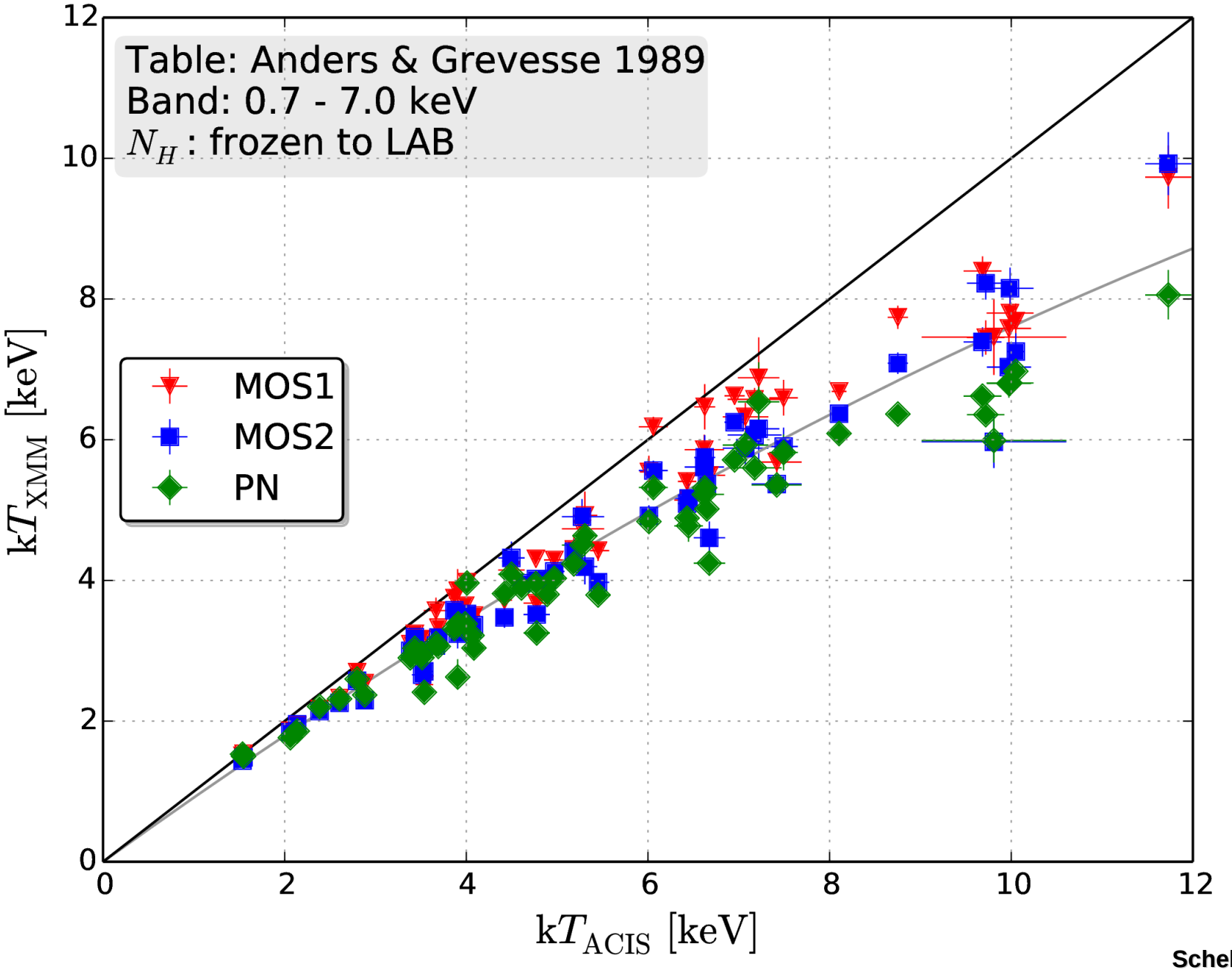
Cross calibration of X-ray instruments



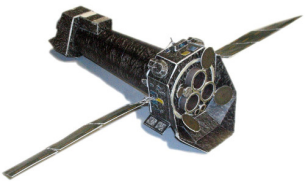
Temperatures



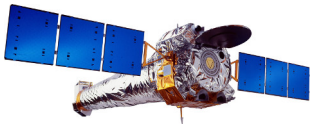




Schellenberger+2015



Summary



- First time: Individually determined X-ray cluster masses for cosmology
  - 196 observations with 7.6 Ms
  - Temperature profiles for every cluster
  - Best observed cluster sample
  - Several tests to estimate systematics in Ω_M, σ_8 results

Systematics

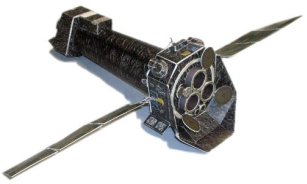
Substructure
- Can bias surface brightness fits
- One of the longest X-ray tails found in Zwicky 8338

Sample composition
- Selection effects
- Dynamically disturbed systems and/or galaxy groups bias (0.04)

Instruments
- XMM-Newton – Chandra have systematic temperature differences (0.01)
- Mainly soft energy band is affected

Other tests: (Ω_M change)
Neutrino mass (0.02)
Galaxy group incompleteness (0.06)
Different extrapolations (0.05)
Different radii (0.06)

Non-linear LM relation (0.03)
Planck & dynamical masses (< 0.005)
Alternative halo mass function (< 0.005)
Hydrostatic mass bias (0.005)
Gas mass



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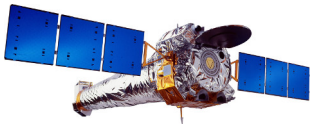

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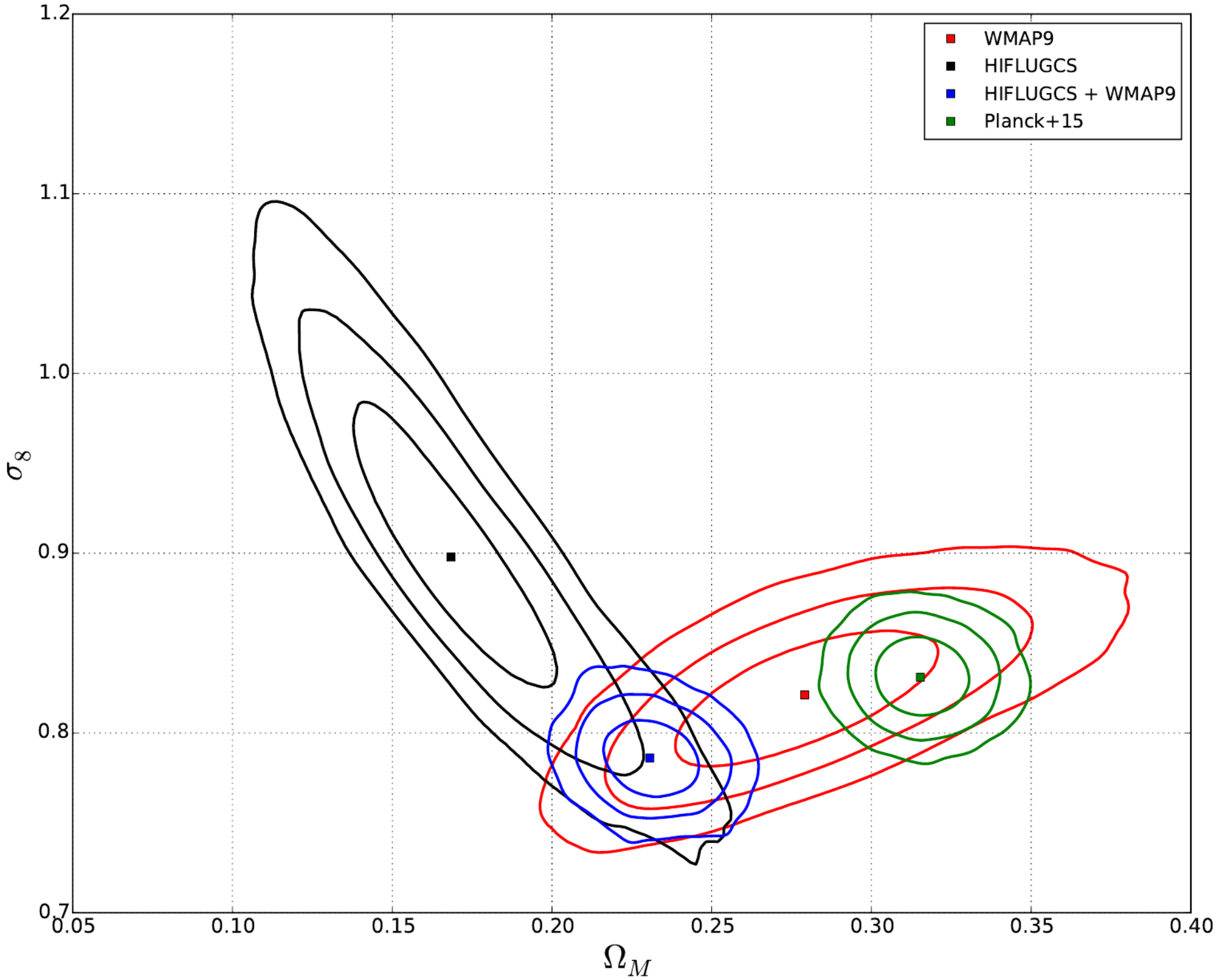
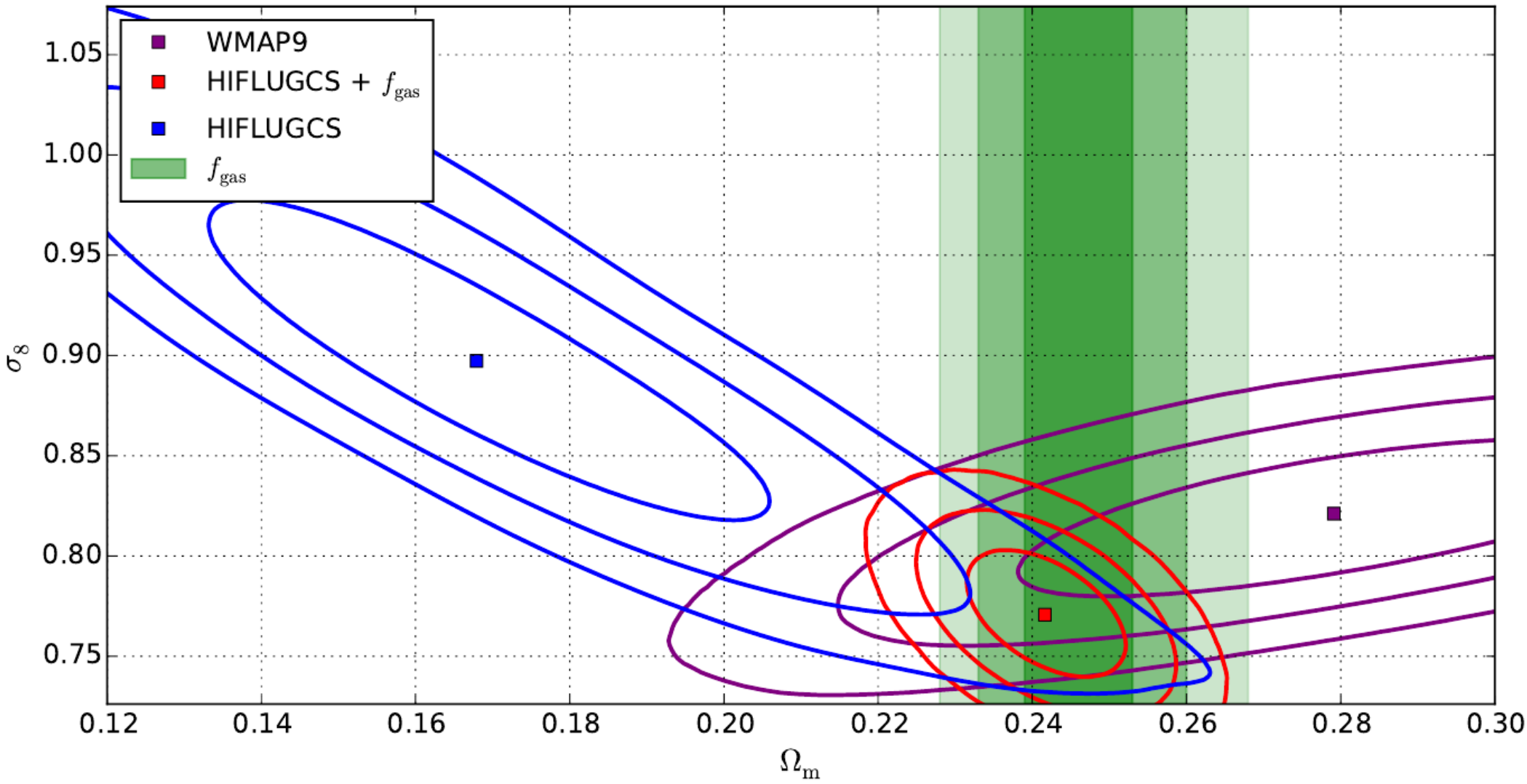
$$\Omega_M = 0.17 \pm 0.02(\text{stat.}) \pm 0.11(\text{syst.})$$

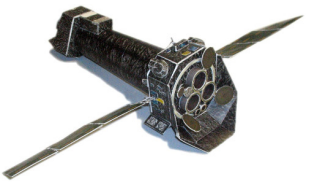
Other tests: (Ω_M change)

Neutrino mass (0.02)
Galaxy group incompleteness (0.06)
Different extrapolations (0.05)
Different radii (0.06)

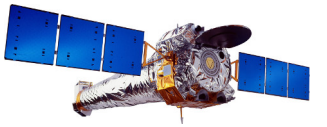
Non-linear LM relation (0.03)
Planck & dynamical masses (< 0.005)
Alternative halo mass function (< 0.005)
Hydrostatic mass bias (0.005)
Gas mass


WMAP9
HIFLUGCS
HIFLUGCS + WMAP9
Planck+15
1.2
1.1
1.0
0.9
0.8
0.7
σ_8
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Ω_M


WMAP9
HIFLUGCS + $f_{\rm gas}$
HIFLUGCS
$f_{\rm gas}$
1.05
1.00
0.95
0.90
0.85
0.80
0.75
σ_8
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
$\Omega_{\rm m}$



Gas mass fraction

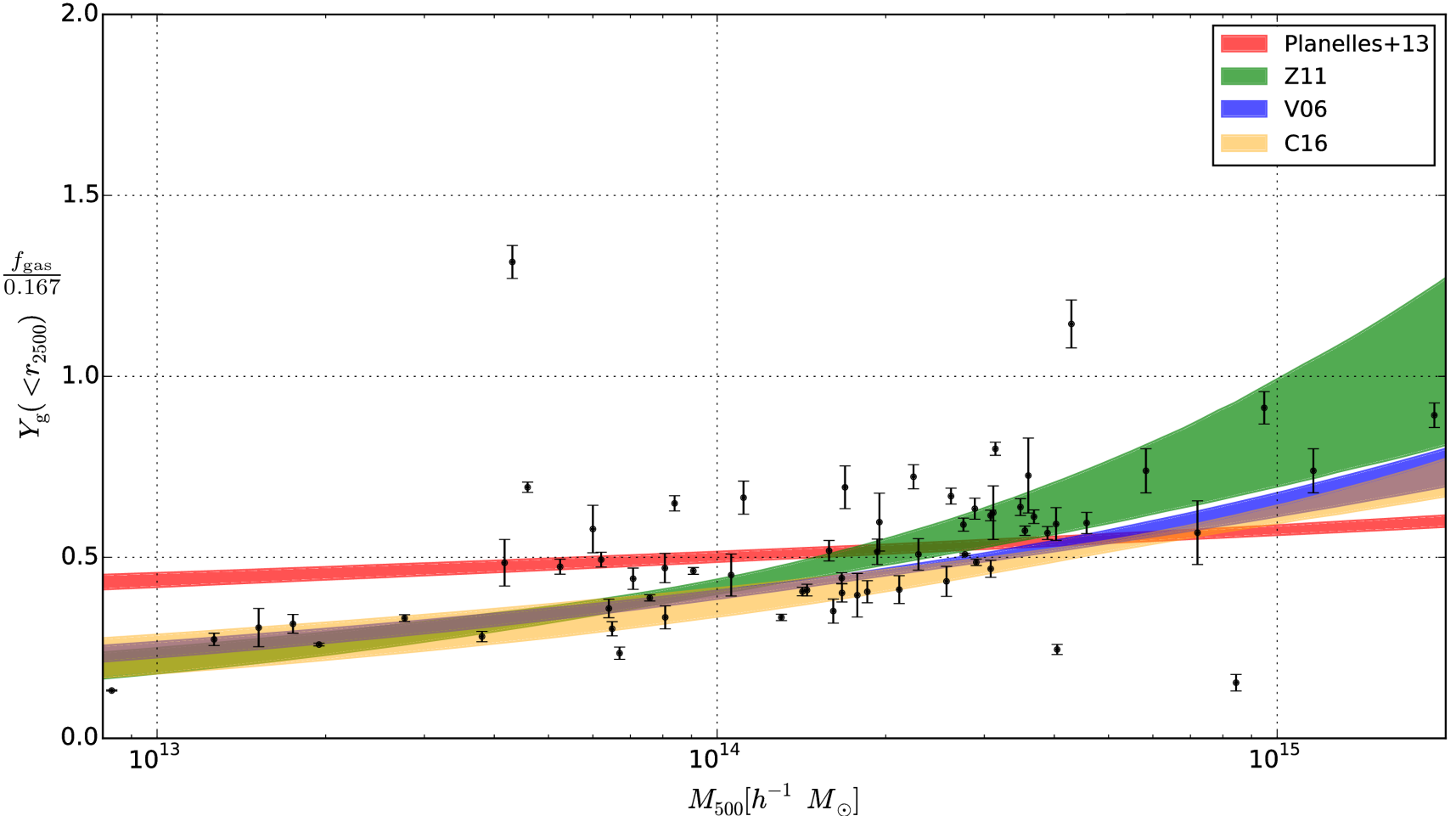


Comparing gas mass fractions with simulations (Planelles+13)

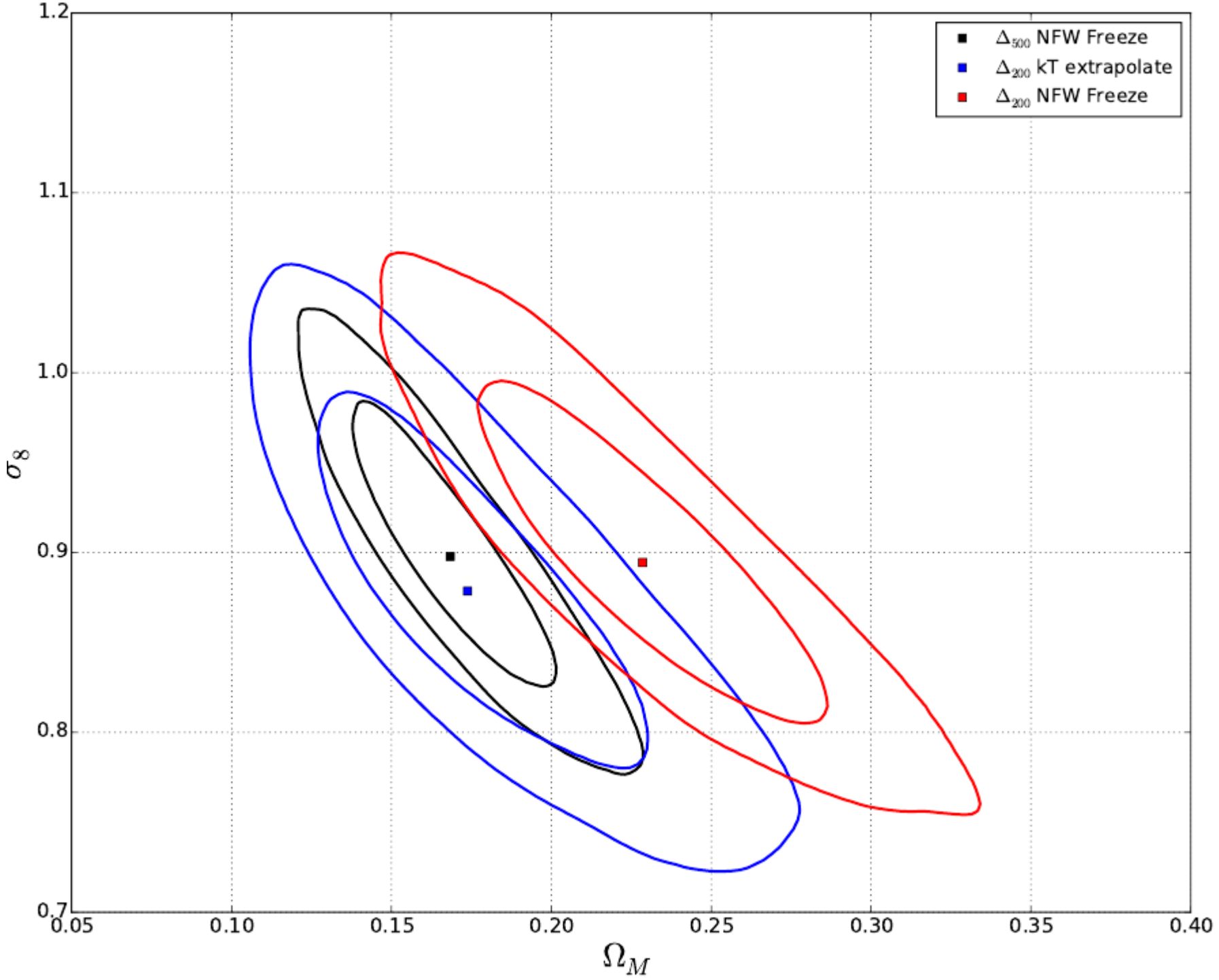
$$f_{\rm gas}^{\Lambda{\rm CDM}} = Y_{\rm g}\, A^{\Lambda{\rm CDM}}\, \frac{\Omega_{\rm b}}{\Omega_{\rm m}} \left(\frac{d_{\rm A}^{\Lambda{\rm CDM}}(z)}{d_{\rm A}(z)} \right)^{1.5}$$

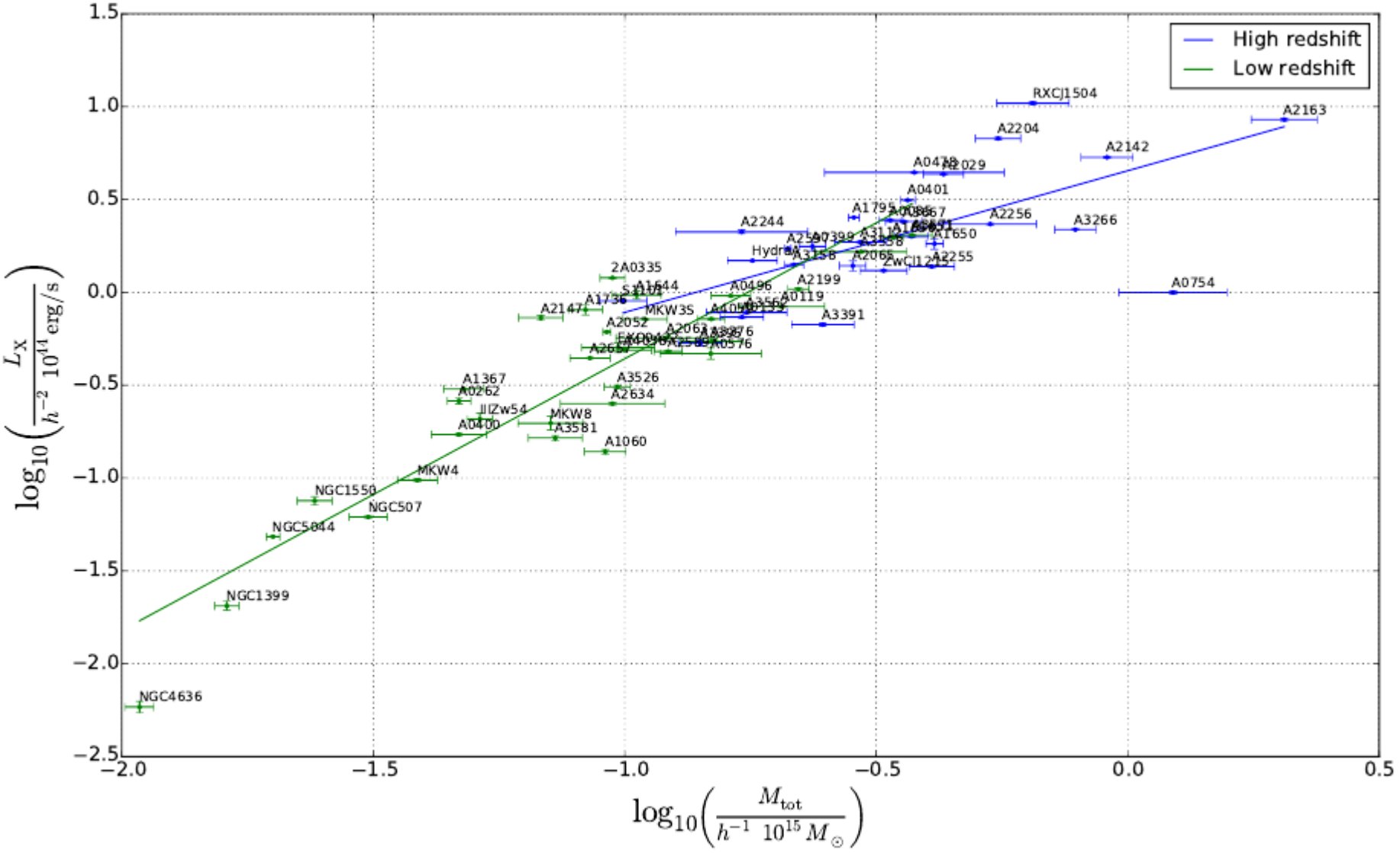
$$Y_{\rm g} = Y_{0,{\rm g}}(1+\alpha z) \left(\frac{M_{500}}{5\times10^{14}\,{\rm h}^{-1}\,{\rm M}_\odot} \right)^{\beta} \left(\frac{\Delta}{500} \right)^{\gamma}$$

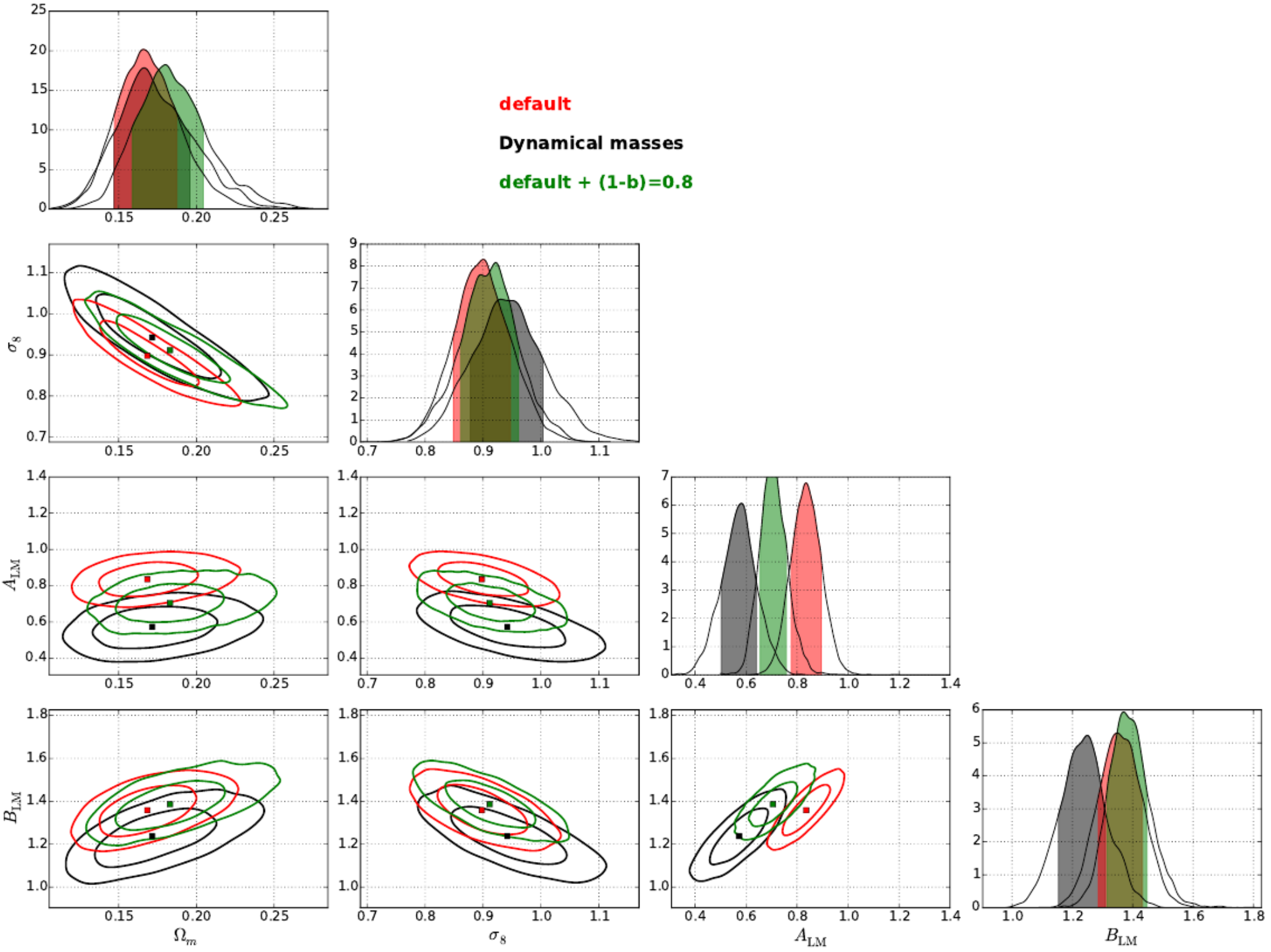
$Y_{\rm g} = \frac{f_{\rm gas}}{0.167}$

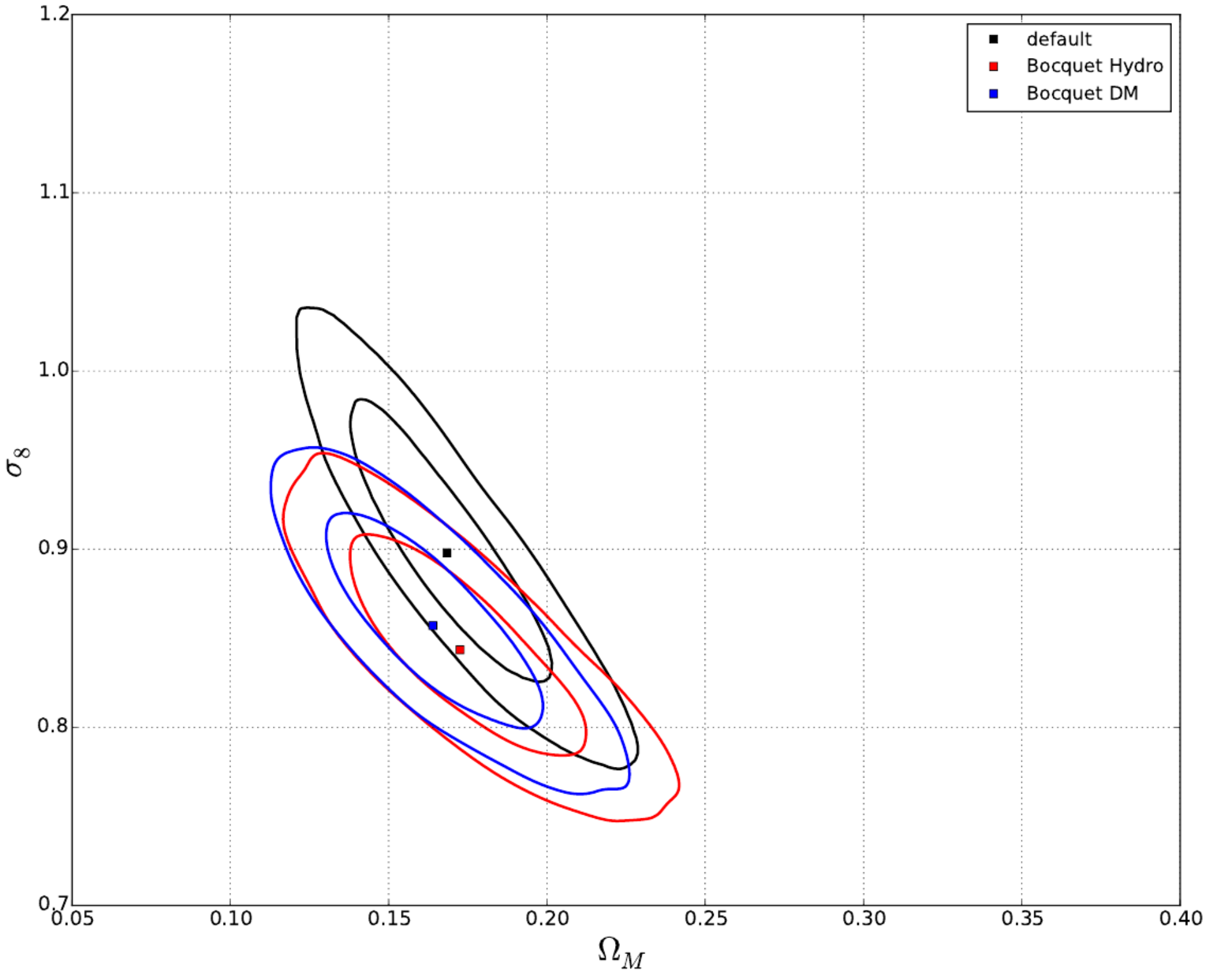


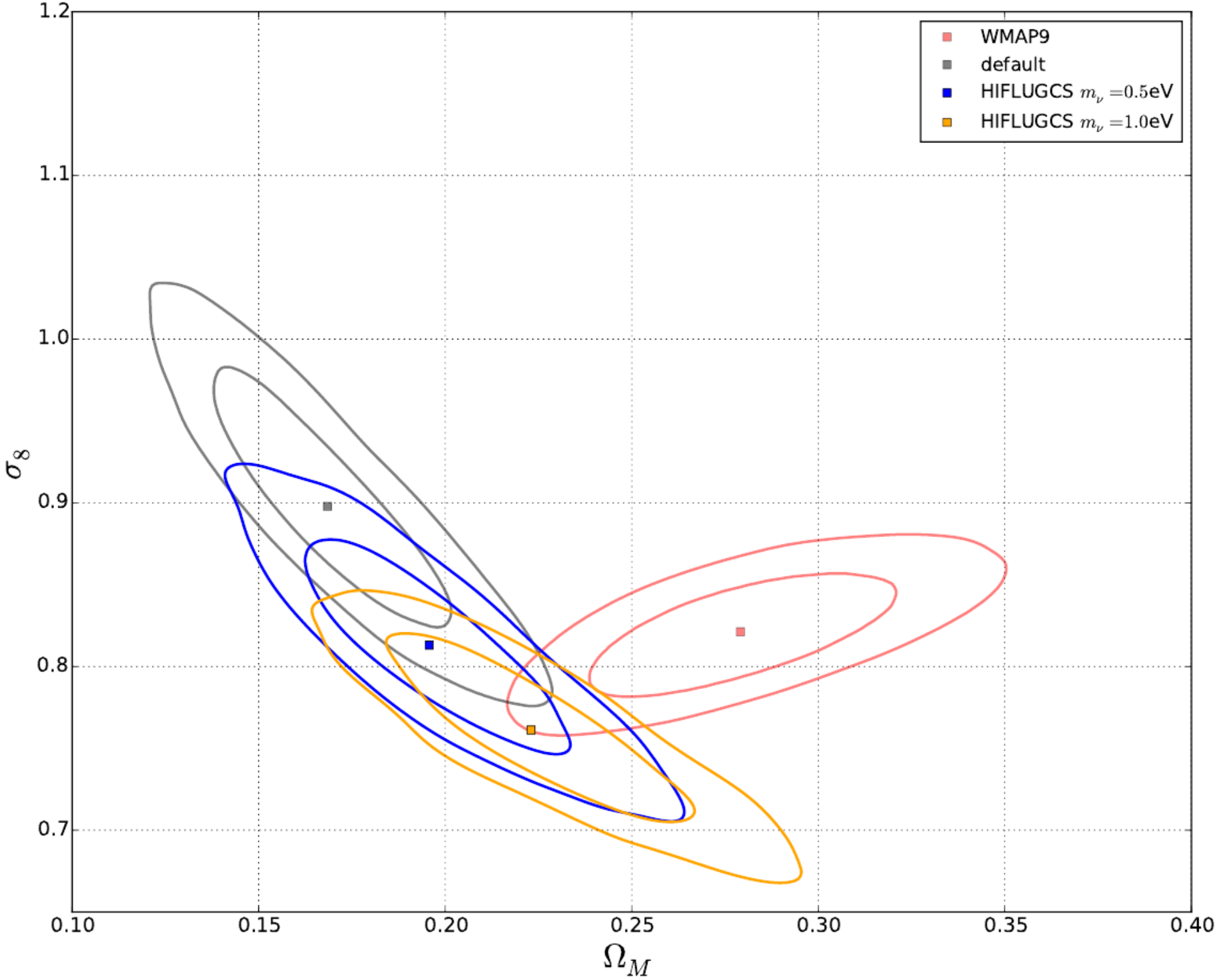
Setup	Ω_m	σ_8	A_{LM}	B_{LM}	σ_{LM}
HIFLUGCS + WMAP9	$0.234^{+0.010}_{-0.010}$	$0.785^{+0.014}_{-0.013}$	$0.867^{+0.054}_{-0.052}$	$1.448^{+0.056}_{-0.053}$	0.26
High-z	$0.200^{+0.065}_{-0.047}$	$0.889^{+0.088}_{-0.091}$	$0.696^{+0.071}_{-0.068}$	$1.182^{+0.142}_{-0.131}$	0.24
Low-z	$0.150^{+0.039}_{-0.028}$	$0.914^{+0.134}_{-0.121}$	$1.244^{+0.107}_{-0.106}$	$1.627^{+0.101}_{-0.100}$	0.22
25% Groups	$0.223^{+0.033}_{-0.029}$	$0.820^{+0.057}_{-0.052}$	$0.767^{+0.057}_{-0.056}$	$1.242^{+0.072}_{-0.069}$	0.26
50% Groups	$0.198^{+0.028}_{-0.026}$	$0.854^{+0.058}_{-0.053}$	$0.796^{+0.059}_{-0.056}$	$1.291^{+0.072}_{-0.070}$	0.26
80% Groups	$0.178^{+0.024}_{-0.022}$	$0.884^{+0.054}_{-0.052}$	$0.811^{+0.058}_{-0.058}$	$1.318^{+0.069}_{-0.066}$	0.26
Broken Powerlaw	$0.141^{+0.021}_{-0.019}$	$0.988^{+0.072}_{-0.068}$	$1.254^{+0.133}_{-0.132}$	$1.697^{+0.128}_{-0.122}$	[a] $0.995^{+0.112}_{-0.106}$
$(1-b) = [0.7, 1]$	$0.174^{+0.026}_{-0.021}$	$0.938^{+0.066}_{-0.061}$	$0.725^{+0.082}_{-0.079}$	$1.336^{+0.071}_{-0.068}$	0.26
$(1-b) = 0.8$	$0.177^{+0.025}_{-0.021}$	$0.950^{+0.058}_{-0.055}$	$0.694^{+0.054}_{-0.052}$	$1.338^{+0.070}_{-0.068}$	0.26
High-z + $(1-b) = [0.7, 1]$ + WMAP9	$0.280^{+0.023}_{-0.020}$	$0.822^{+0.021}_{-0.019}$	$0.635^{+0.089}_{-0.090}$	$1.281^{+0.123}_{-0.111}$	0.26
No disturbed	$0.213^{+0.034}_{-0.028}$	$0.784^{+0.056}_{-0.052}$	$0.981^{+0.073}_{-0.075}$	$1.516^{+0.086}_{-0.086}$	0.26
No disturbed + $(1-b) = 0.8$	$0.224^{+0.036}_{-0.031}$	$0.828^{+0.057}_{-0.057}$	$0.837^{+0.064}_{-0.066}$	$1.524^{+0.085}_{-0.087}$	0.26
No disturbed + $(1-b) = [0.7, 1]$ + WMAP9	$0.271^{+0.023}_{-0.021}$	$0.816^{+0.021}_{-0.021}$	$0.727^{+0.119}_{-0.104}$	$1.581^{+0.064}_{-0.061}$	0.26
Planck SZ Masses	$0.234^{+0.042}_{-0.033}$	$0.790^{+0.051}_{-0.052}$	$0.980^{+0.055}_{-0.053}$	$1.606^{+0.107}_{-0.095}$	$0.197^{+0.025}_{-0.021}$
Dynamical Masses	$0.171^{+0.027}_{-0.021}$	$0.944^{+0.063}_{-0.062}$	$0.573^{+0.068}_{-0.072}$	$1.236^{+0.079}_{-0.078}$	0.35
Bocquet DM	$0.163^{+0.024}_{-0.021}$	$0.857^{+0.041}_{-0.041}$	$0.827^{+0.056}_{-0.055}$	$1.339^{+0.069}_{-0.070}$	0.26
Bocquet Hydro	$0.171^{+0.024}_{-0.021}$	$0.845^{+0.038}_{-0.039}$	$0.822^{+0.057}_{-0.057}$	$1.334^{+0.066}_{-0.065}$	0.26
$\sum m_\nu = 0.5\,\mathrm{eV}$	$0.187^{+0.024}_{-0.020}$	$0.850^{+0.045}_{-0.045}$	$0.827^{+0.060}_{-0.058}$	$1.343^{+0.066}_{-0.071}$	0.26
$\sum m_\nu = 1.0\,\mathrm{eV}$	$0.215^{+0.026}_{-0.023}$	$0.794^{+0.040}_{-0.039}$	$0.839^{+0.059}_{-0.059}$	$1.354^{+0.070}_{-0.069}$	0.26

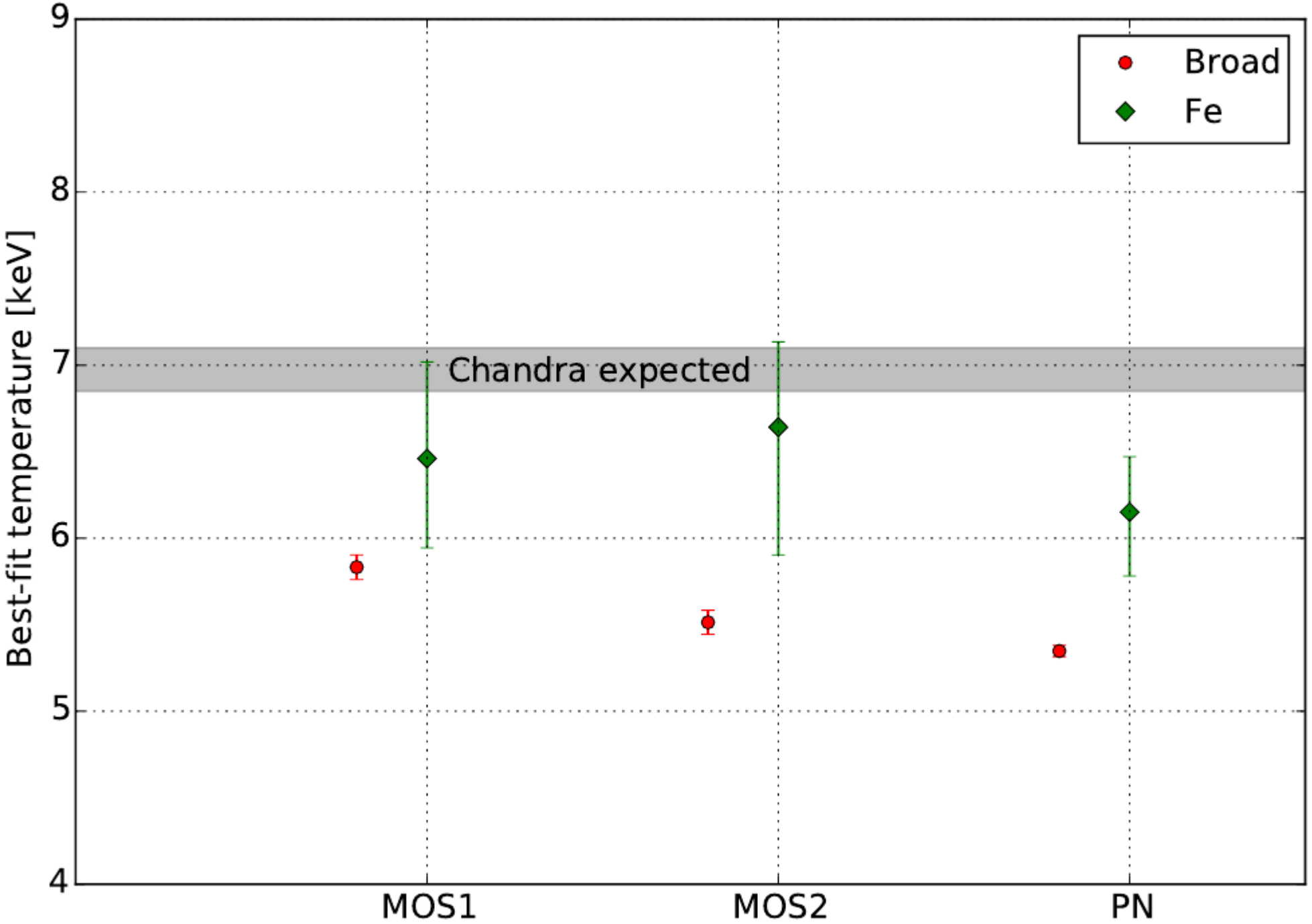

Δ_{500} NFW Freeze
Δ_{200} kT extrapolate
Δ_{200} NFW Freeze
1.2
1.1
1.0
0.9
0.8
0.7
σ_8
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Ω_M

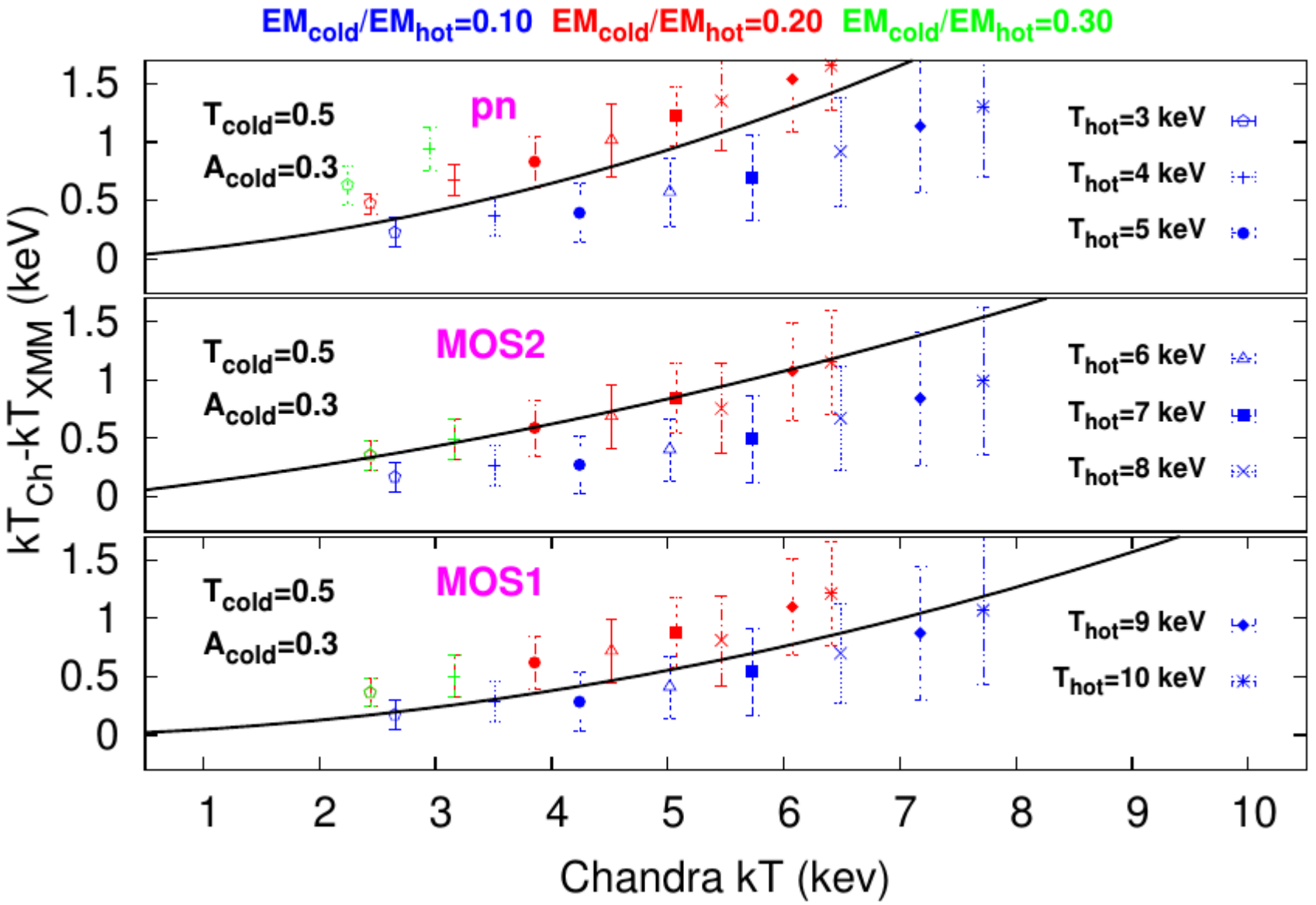

High redshift
Low redshift
RXCJ1504
A2163
A2204
A2142
A0401
A2244
A2256
A3266
A1650
A2255
A0754
A2199
A0119
A3391
A0496
A1644
A1736
A2147
MKW3S
A2052
A0576
2A0335
A1367
A0262
A3526
A2634
IIZw54
MKW8
A0400
A3581
A1060
MKW4
NGC1550
NGC507
NGC5044
NGC1399
NGC4636
$\log_{10}\left(\frac{L_X}{h^{-2}\ 10^{44}\ \mathrm{erg/s}}\right)$
$\log_{10}\left(\frac{M_{tot}}{h^{-1}\ 10^{15}\ M_\odot}\right)$

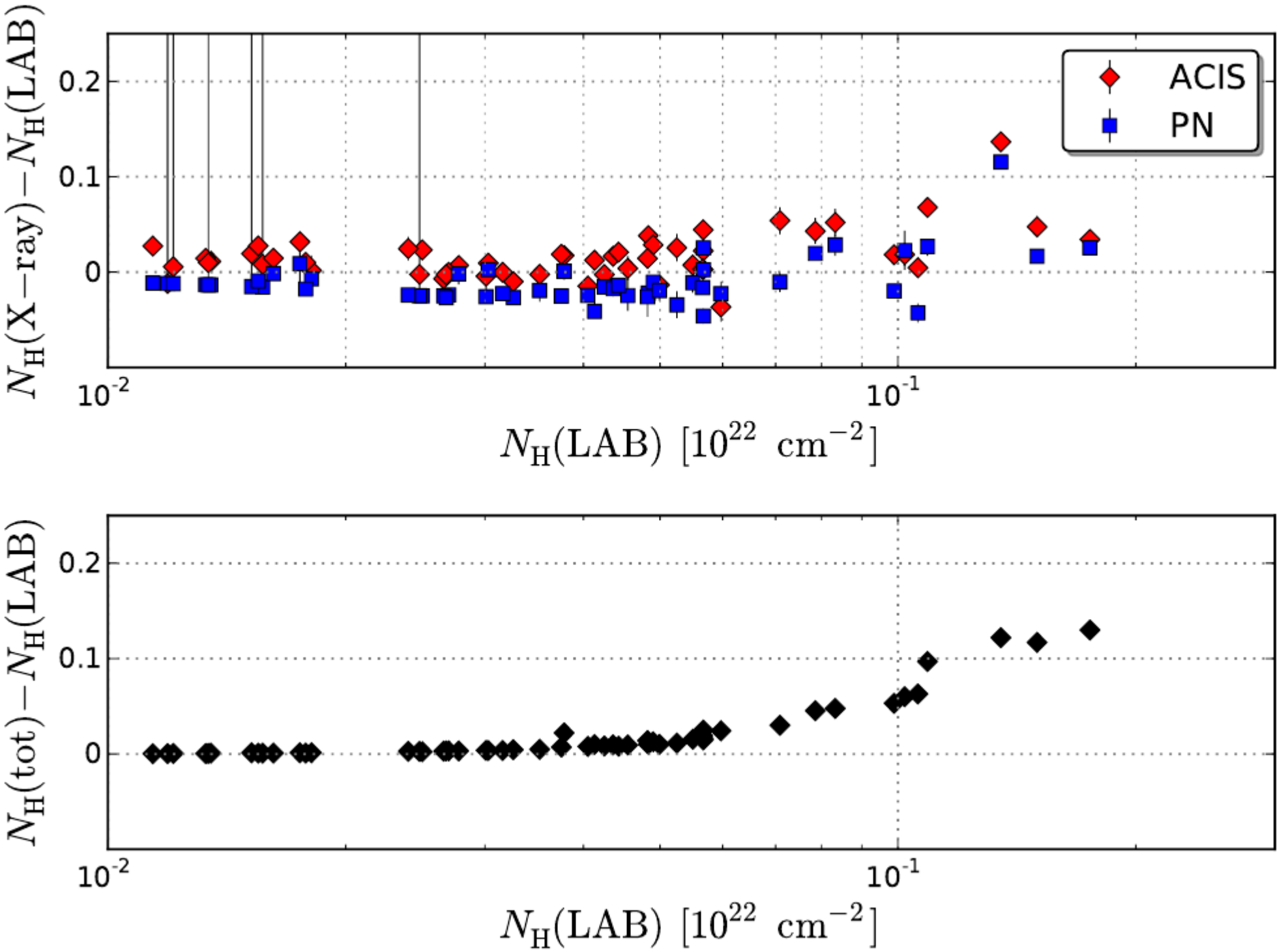

default
Dynamical masses
default + (1-b)=0.8
Ω_m
σ_8
$A_{\rm LM}$
$B_{\rm LM}$


default
Bocquet Hydro
Bocquet DM
1.2
1.1
1.0
0.9
0.8
0.7
σ_8
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Ω_M

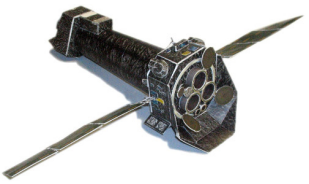

WMAP9
default
HIFLUGCS m_ν =0.5eV
HIFLUGCS m_ν =1.0eV
1.2
1.1
1.0
0.9
0.8
0.7
σ_8
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Ω_M

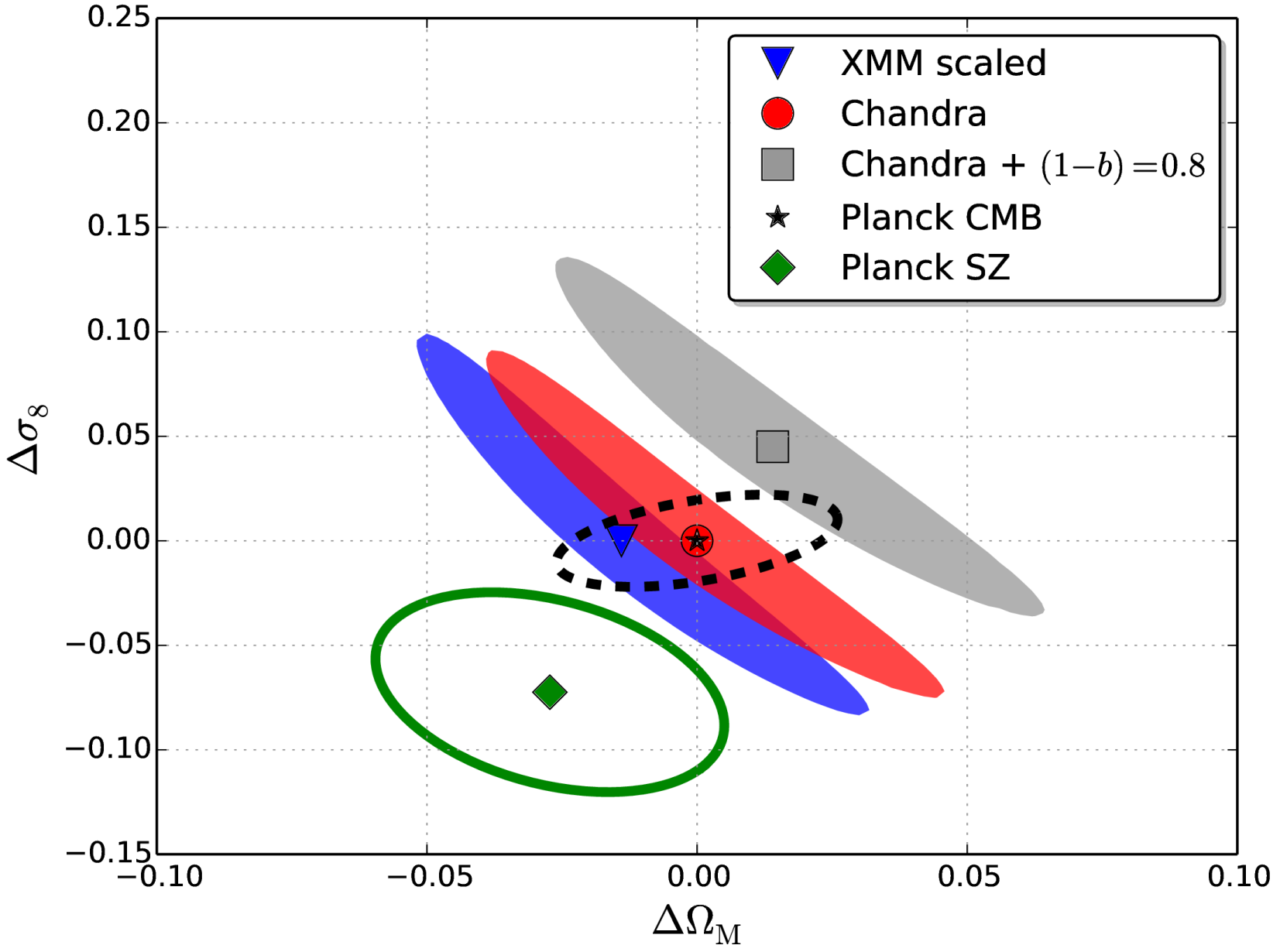

Broad
Fe
Chandra expected
Best-fit temperature [keV]
9
8
7
6
5
4
MOS1
MOS2
PN


EMcold/EMhot=0.10
EMcold/EMhot=0.20
EMcold/EMhot=0.30
pn
MOS2
MOS1
Tcold=0.5
Acold=0.3
Thot=3 keV
Thot=4 keV
Thot=5 keV
Thot=6 keV
Thot=7 keV
Thot=8 keV
Thot=9 keV
Thot=10 keV
kTCh-kTXMM (keV)
Chandra kT (kev)


ACIS
PN
$N_{\rm H}({\rm X-ray}) - N_{\rm H}({\rm LAB})$
$N_{\rm H}({\rm tot}) - N_{\rm H}({\rm LAB})$
$N_{\rm H}({\rm LAB})$ $[10^{22}$ cm$^{-2}]$
0.2
0.1
0
10^{-2}
10^{-1}

Cosmology




XMM scaled
Chandra
Chandra + $(1-b)=0.8$
Planck CMB
Planck SZ
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.10
−0.05
0.00
0.05
0.10
$\Delta\sigma_8$
$\Delta\Omega_M$