Detecting Galaxy Clusters in (Simulated) SZ Surveys

SUMMARY

- Structure Formation
- Cosmological dependence of mass function
- Sky surveys
- Simulated sky surveys as a tool to develop and test cluster detection algorithms & assess the impact on flux measure and completeness of:
  - cluster properties (morphology, substructure)
  - instrument configuration (beam size, frequency choice)

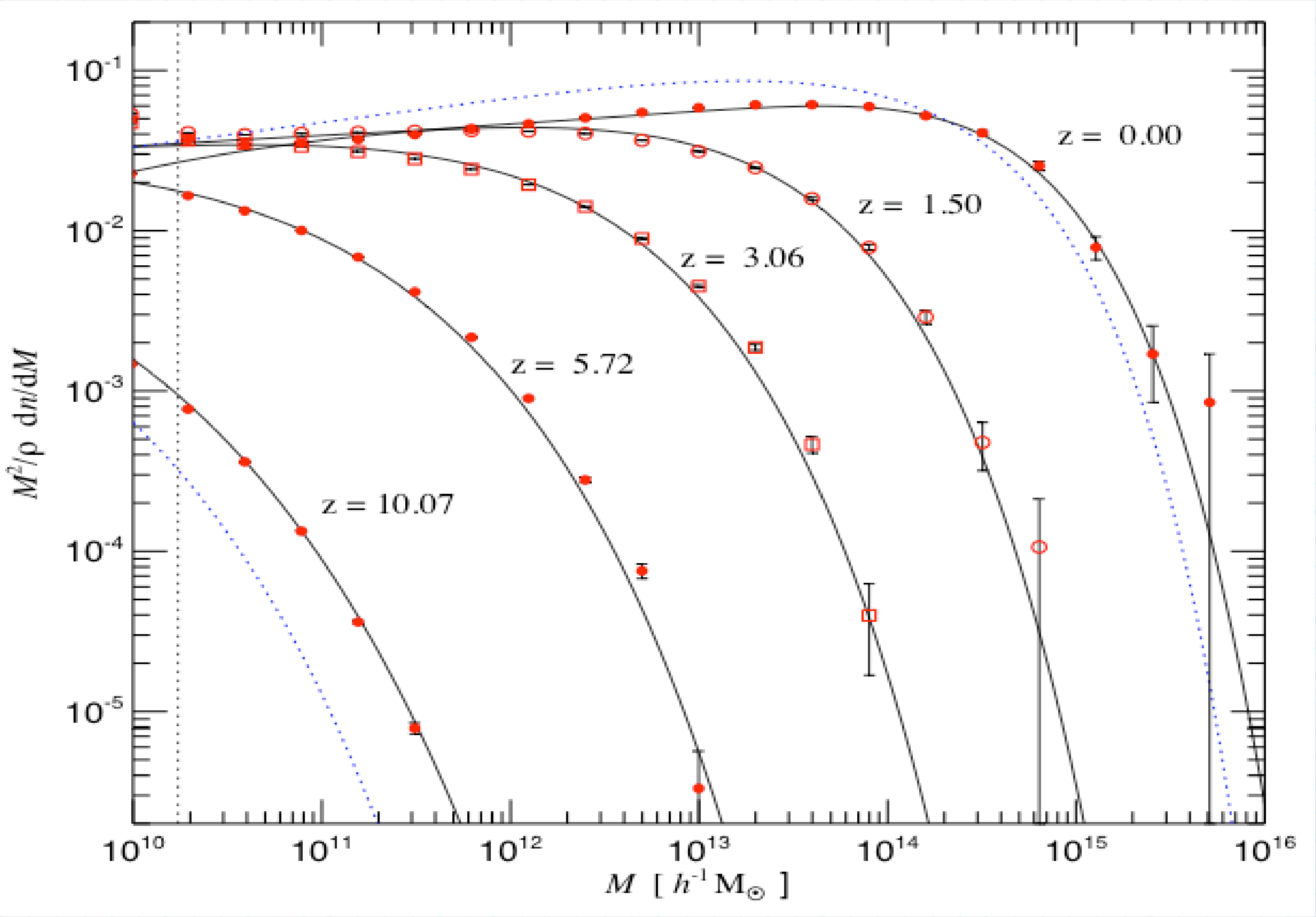
Mass distribution of halos

* CDM predicts hierarchical structure scheme:
    1. low mass perturbation collapse first
    2. merge to form more massive structures
* abundance of halos as a function of mass and redshift important quantity in cosmology
* Analytic predictions via Press-Schecter formalism (and subsequent variants) (Press & Schechter, 1974; Bond et al. 1992; Lacey & Cole 1994; Sheth & Tormen 1999; Jenkins et al. 2001)
    - smooth linear density field on range of mass scales
    - assume fraction of space contained within regions above some critical density, δ_c, is contained within collapsed objects
    - use δ_c = 1.686 (from spherical collapse)

$$\frac{dn(M,z)}{dM} = -\sqrt{\frac{2}{\pi}}\frac{\rho_0}{M}\frac{\delta_c}{\sigma^2(M,z)}\frac{d\sigma(M,z)}{dM}\exp\left(-\frac{\delta_c^2}{2\sigma^2(M,z)}\right)$$

The N-body era

- Concerted effort over the last 15 years to simulation formation of structure and measure halo mass function [Cole & Lacey, 1993; Lacey & Cole, 1994; Governato et al. 1999; **Sheth & Tormen 1999**, Jenkins et al. 01; Springel et al. 05; Warren et al. 07)



Springel et al. (2005)

- Jenkins et al. (01) demonstrated the form of the mass function is **independent* of epoch and cosmological parameters**

*in CDM, and depending on your definition of halo mass

Cosmological dependence

$$\frac{dn}{dM}(z, M) = -0.316 \frac{\rho_{m,0}}{M} \frac{d\sigma_M}{dM} \frac{1}{\sigma_M} \exp\left\{ - \left| 0.67 - \log[D(z)\sigma_M] \right|^{3.82} \right\}$$

* Mass density
* Power-law dependence on fluctuation amplitude
* Power-law dependence on linear growth factor

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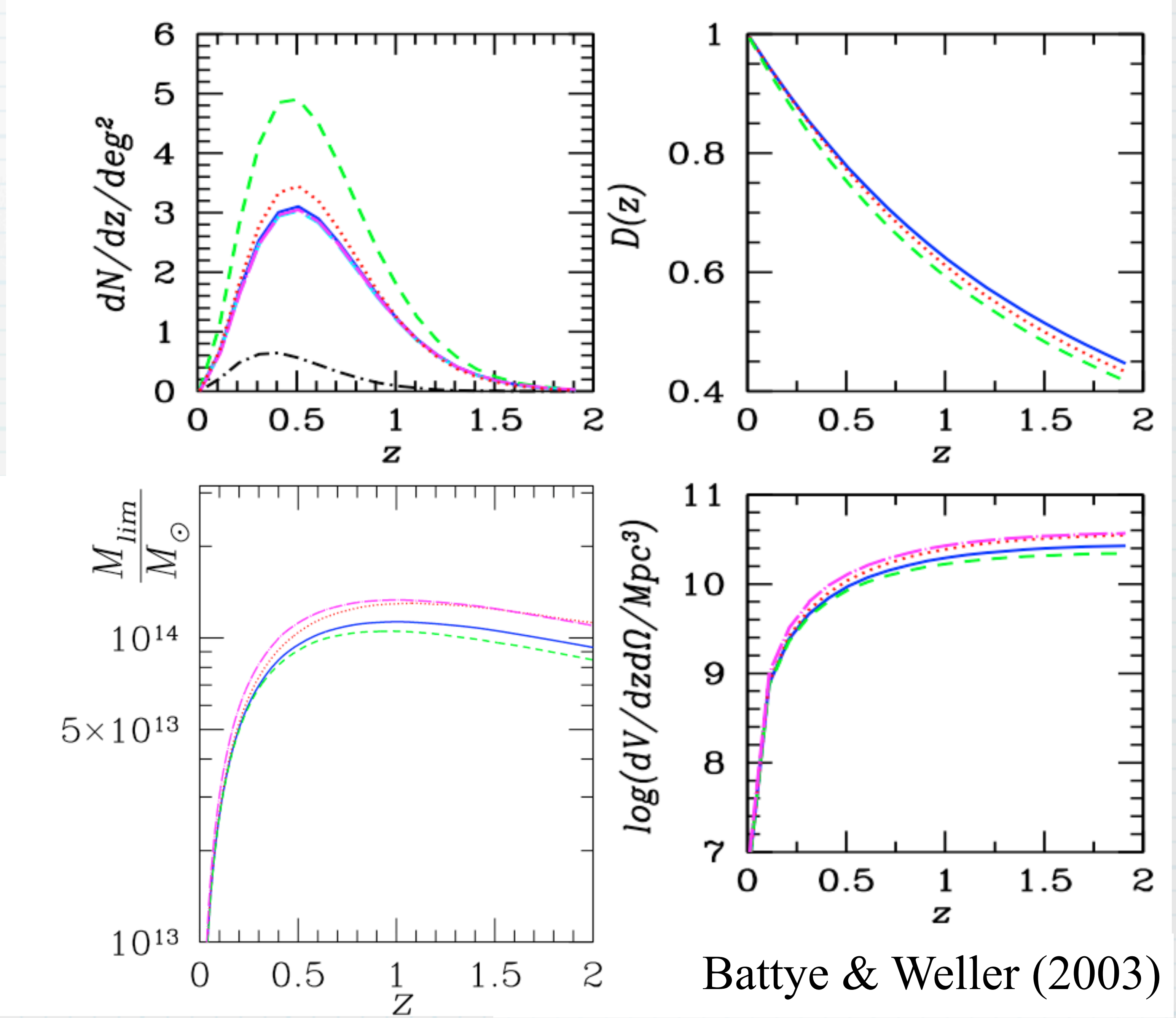
Sky-surveys

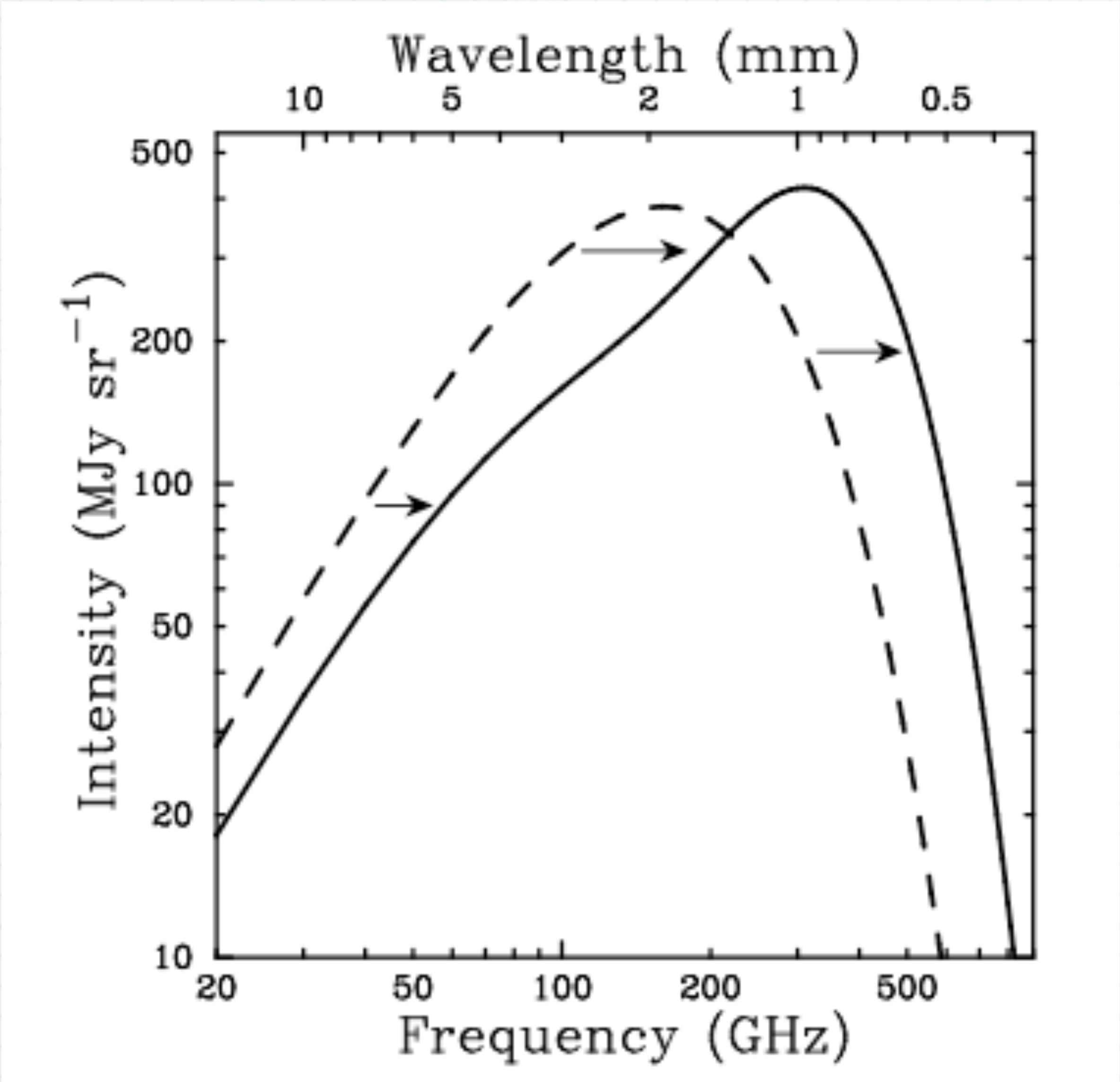
$$\Delta N(z) = \Delta\Omega \int_{z-\Delta z/2}^{z+\Delta z/2} dz \frac{d^2V}{d\Omega dz} \int_{M_{\rm lim}}^{\infty} \frac{dn}{dM}\, dM$$

* Survey sky coverage
* Redshift bins
* Volume element
* Limiting mass of survey (redshift dependent)
* Cosmology dependence driven by volume element and mass function



Battye & Weller (2003)

Sunyaev-Zel'dovich Flux



Carlstrom et al. 2002

- Inverse Compton Scattering: $e^- + \gamma \rightarrow e^- + \gamma$
- Surface brightness insensitive to redshift

$$\left(\frac{\Delta T}{T_{CMB}}\right)_{tsz} \equiv yY_0 = y(X coth(X/2) - 4)$$

$$y(\theta) = \frac{k_B \sigma_T}{m_e c^2} \int n_e T_e dl$$

For isothermal, spherically collapsed clusters in virial equilbrium (e.g. Battye & Weller, 03)

$$Y = \int_0^{\theta_{vir}} y(\theta) d\Omega \propto f_{gas} M_{vir}^{5/3} E(z)^{2/3}$$

scatter 10-20% (depending on which simulations you believe)

Simulated SZ Sky Surveys (SSSS)

- lightcone N-body simulations
- Identify halos
- add intra-cluster gas

simulation step

TPM code: (Bode et al. 03)
Gas model: (Ostriker et al. 05)
$\sigma_8 = 0.77$, $\Omega_M = 0.26$

- ray trace
- add noise (CMB, instrument, SZ bg)

synthetic maps

- filter images -- find clusters
- catalogue crossmatch
- measure Y-func

cluster detection

multifrequency matched filter
(Haenault & Tegmark, 96, Herranz et al. 02, Melin et al. 06)

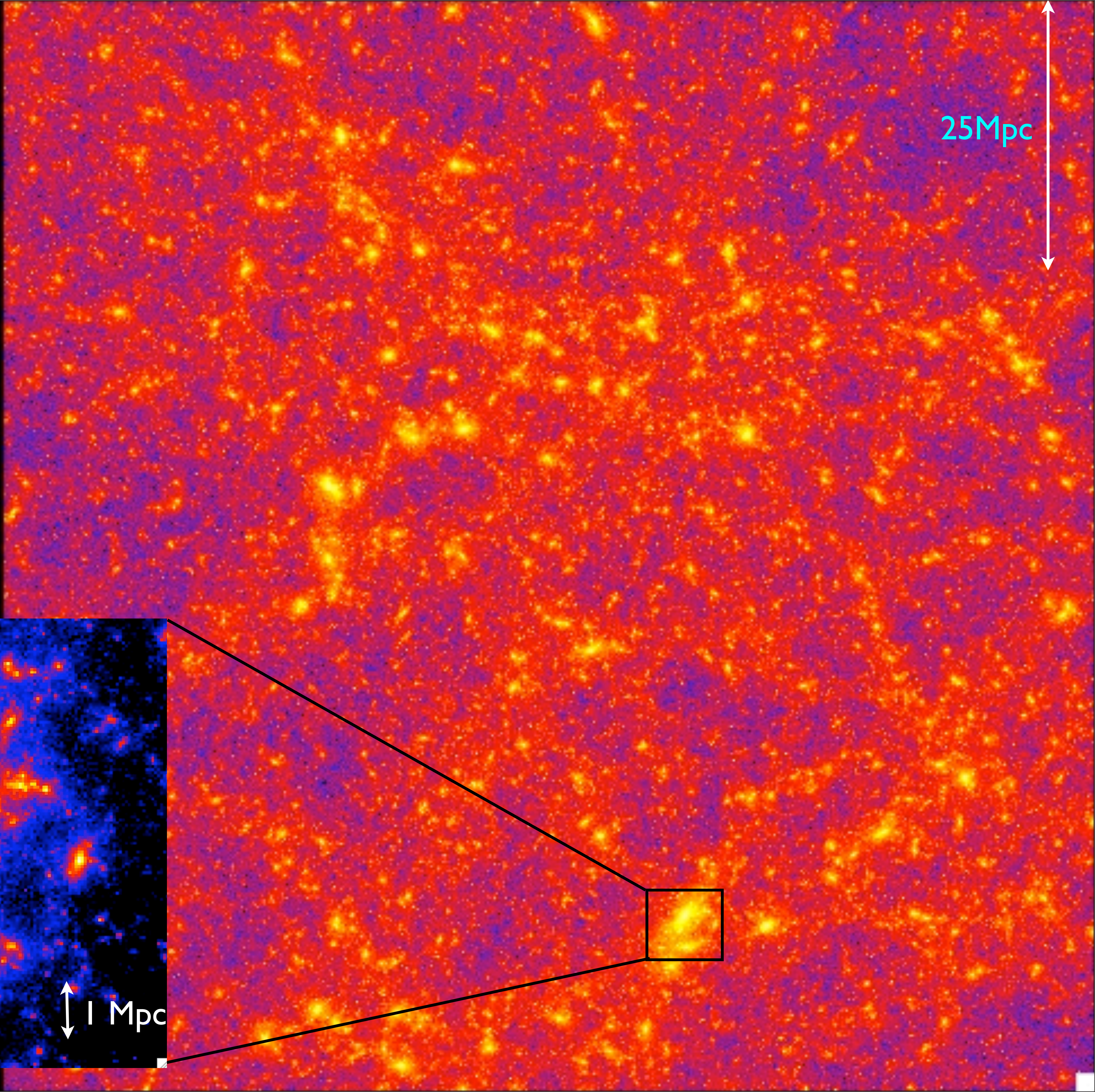
$$y_{obs}(\theta) = y_0 \left(1 + \left(\frac{x}{\theta_c}\right)^2\right)^{-1/2}$$

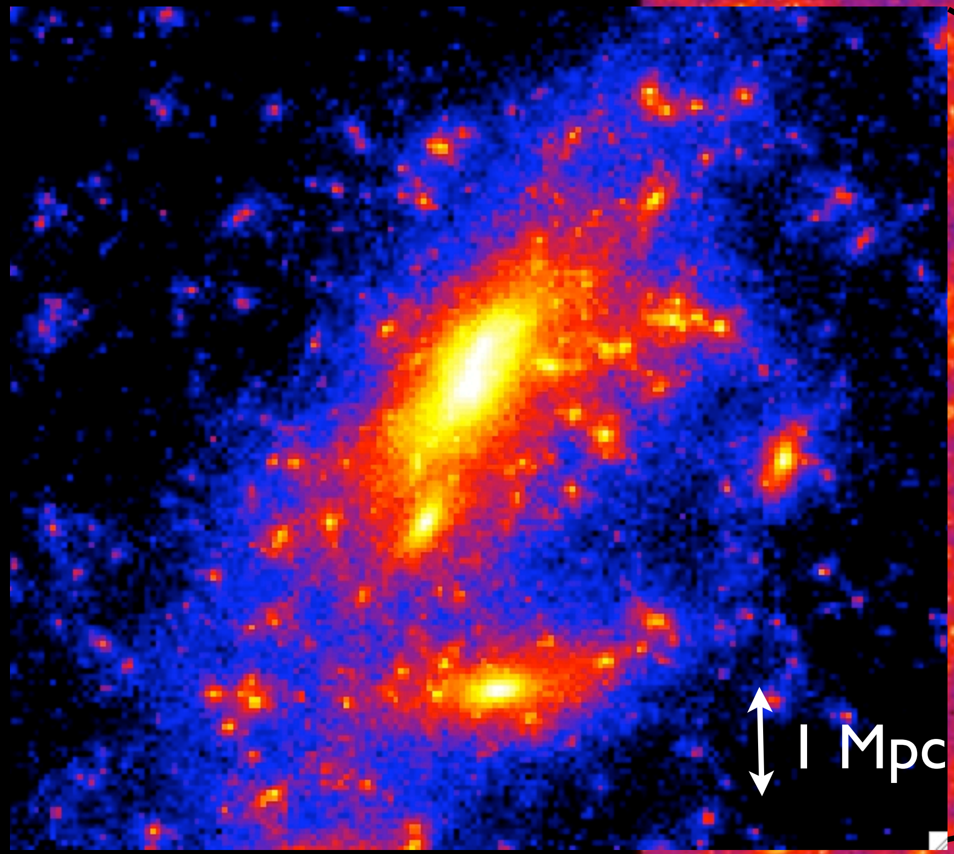
2×10^9 particles

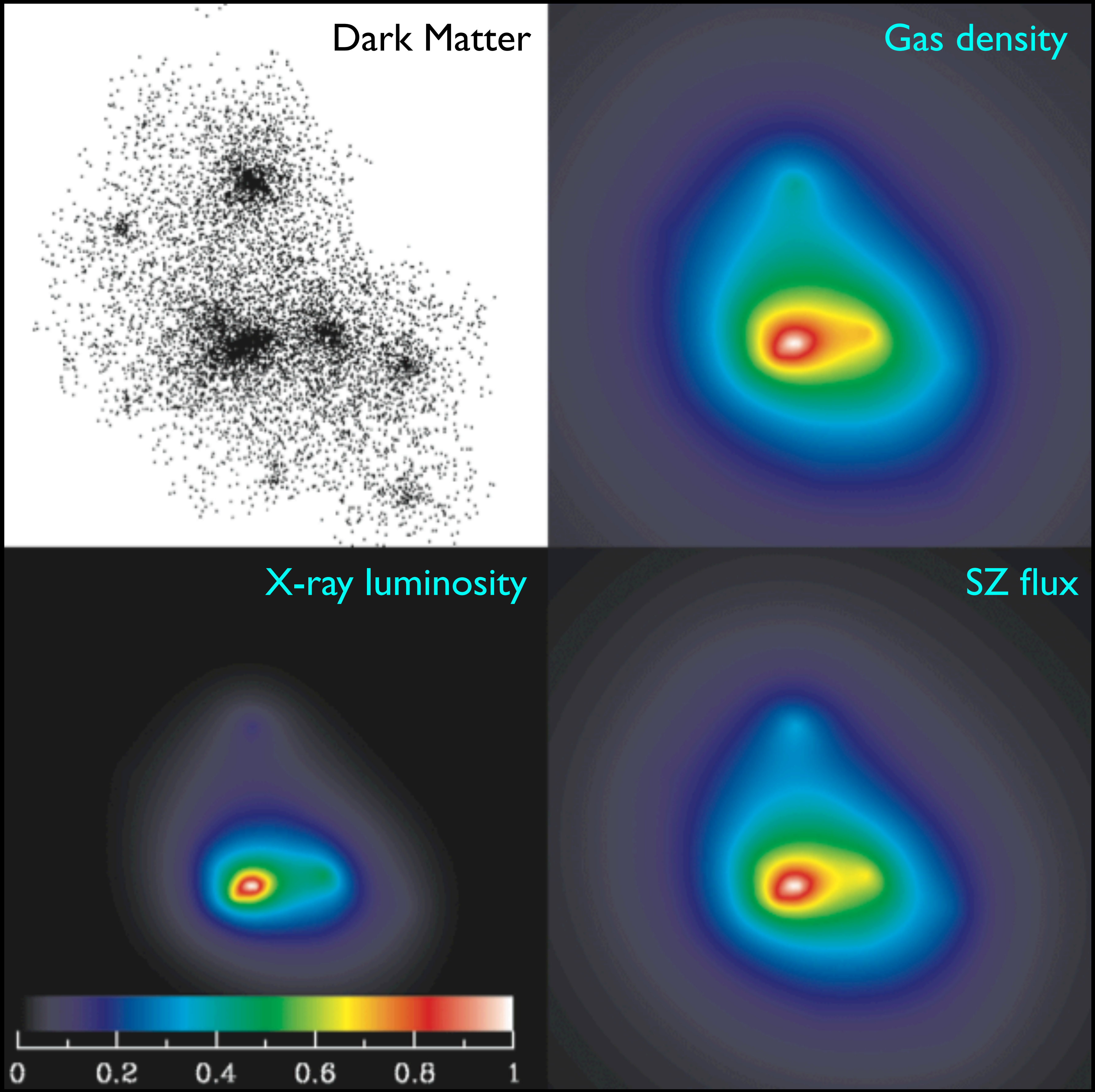
Box side length
2 Gpc

TPM code
(Bode et al. 03)

$(\Omega_\mathrm{M}, \Omega_b, H_0, \sigma_8) =$
$(0.26, 0.044, 72, 0.77)$






Dark Matter
Gas density
X-ray luminosity
SZ flux
0
0.2
0.4
0.6
0.8
1

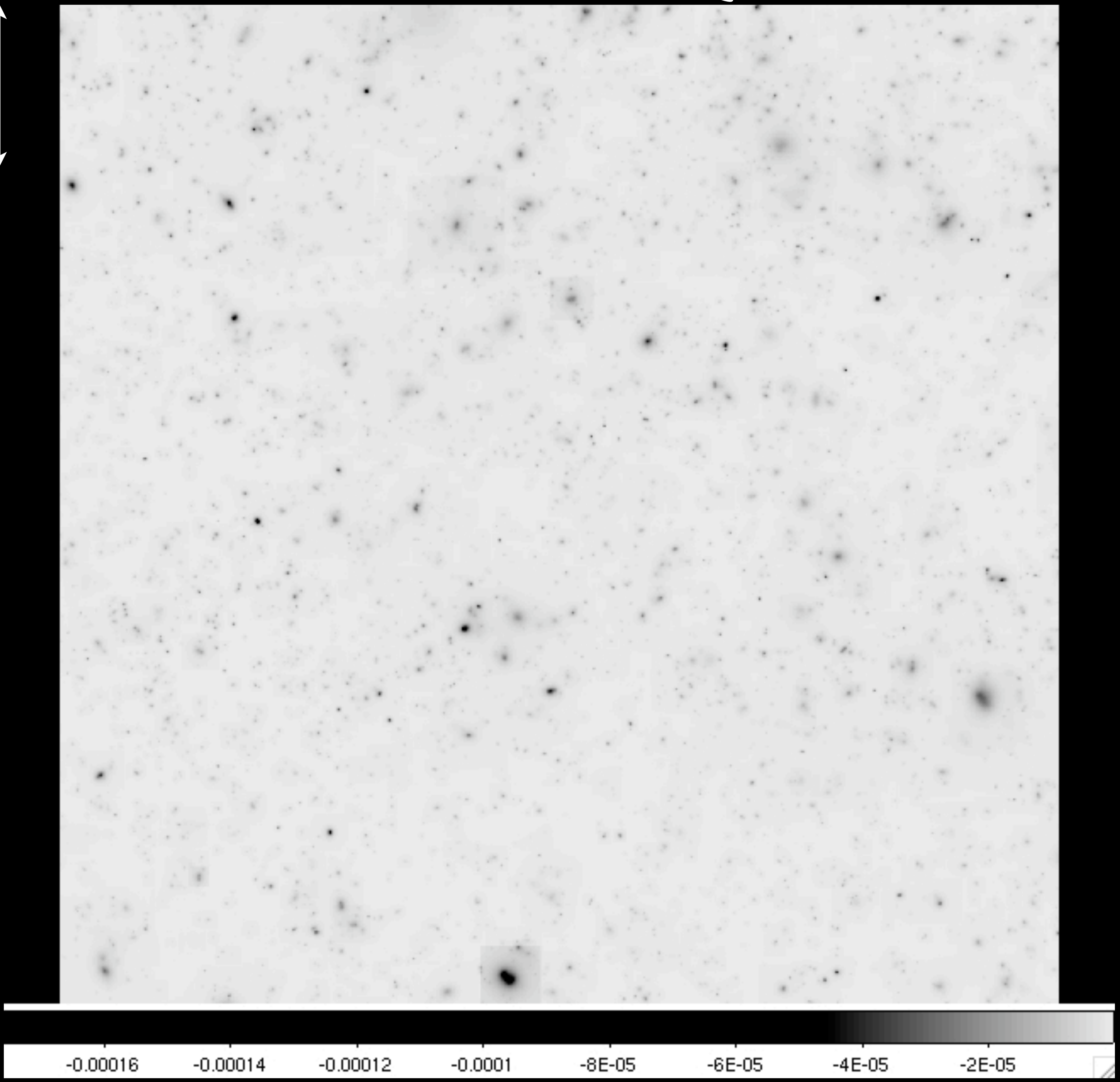
SZ skymaps

1 deg

$\nu = 150\text{Ghz}$

$1'$ beam

pixel noise:
12.5 μK/1'



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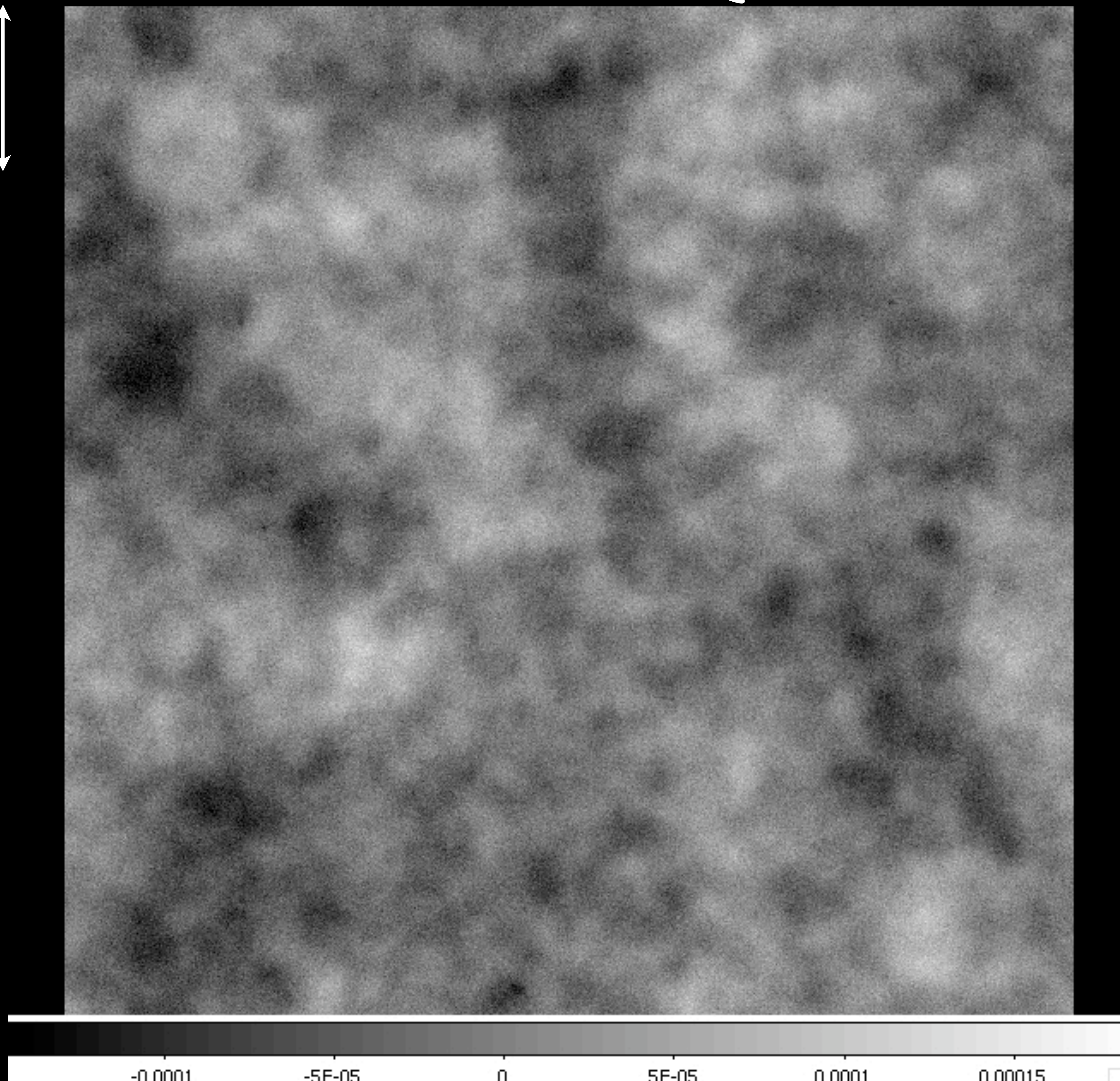
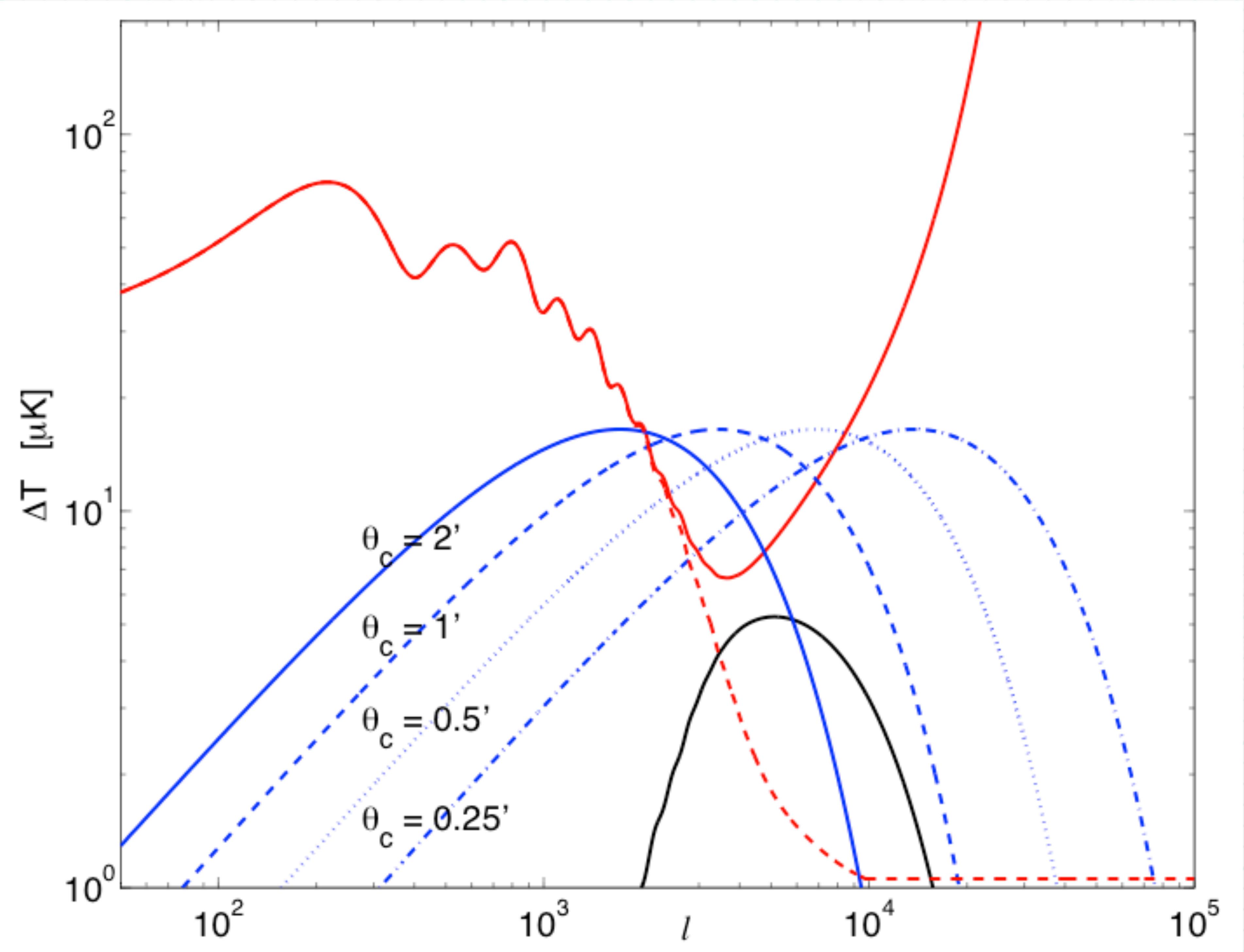


Map Filtering

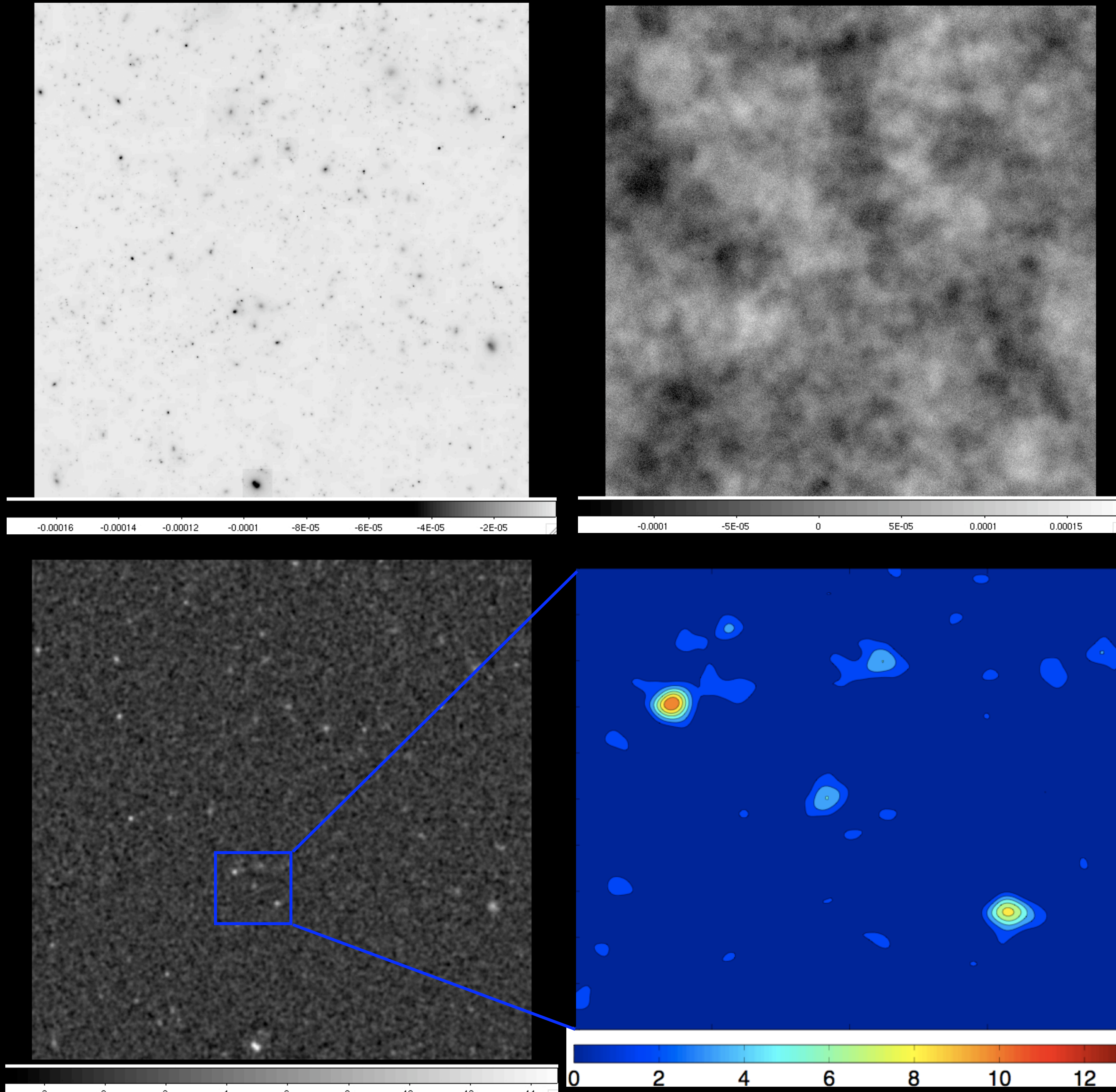


$$S_{\theta_c}(x) = y_0 \left(1 + \left(\frac{x}{\theta_c}\right)^2\right)^{-1/2} \longrightarrow 2\pi\theta_c \frac{\exp\left(-\theta_c l\right)}{l}$$

SZ only

full map

filtered
1 arcmin



Mock surveys

- two sky map realizations (each 396 deg^2)
  - full gas model
  - beta model profiles
- simulate two surveys configurations

	freq (Ghz)	Noise (μK arcmin^2)	Beam size (FWHM)	N clusters S/N > 5
SPTa	[90, 150, 220]	[25, 12.5, 25]	[1.67, 1, 0.7]	405
SPTb	[150, 220, 265]	[12.5, 25, 25]	[1, 0.7, 0.6]	557

Catalogue Cross-Matching

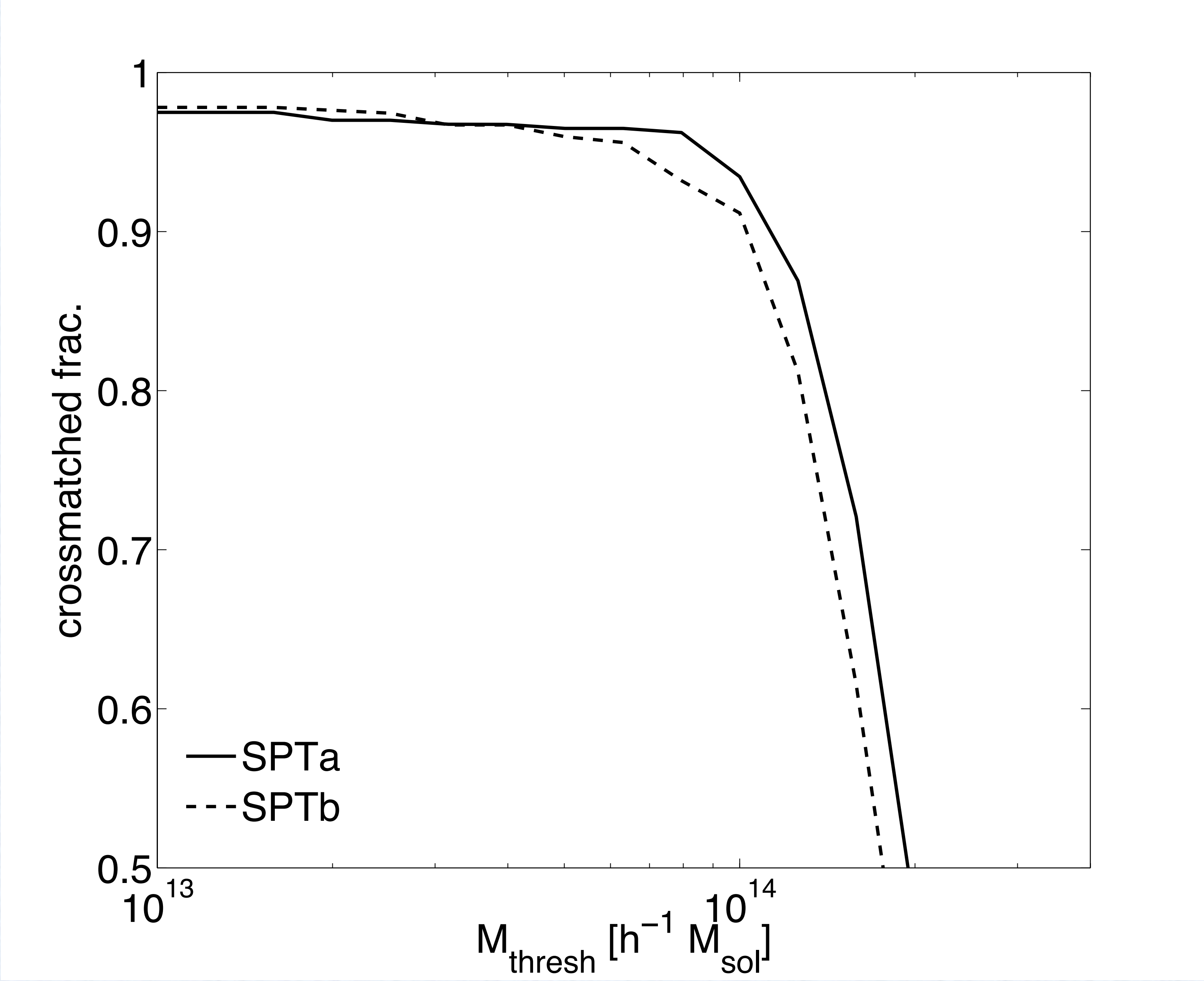
- Aim to find true counter-parts of image clusters
  - to compare true vs measured properties
  - investigate impact of cross-matching on catalogue completeness and purity
- compare peak signal position of image cluster against angular position of potential minimum of catalogue cluster

$$\Delta x = |r_{im} - r_{\Phi_{min}}|$$

- Successful match if $\Delta x < r_{tol}$

Crossmatching

- find $r_{tol} = 1.5'$ is optimal C.M. radius
- beam smearing can shift cluster centres by ~1′
- approx 3 % of candidates ‘fake’ detections



- Smaller beam enables detection of lower mass clusters
- However, slight increase in number of contaminants

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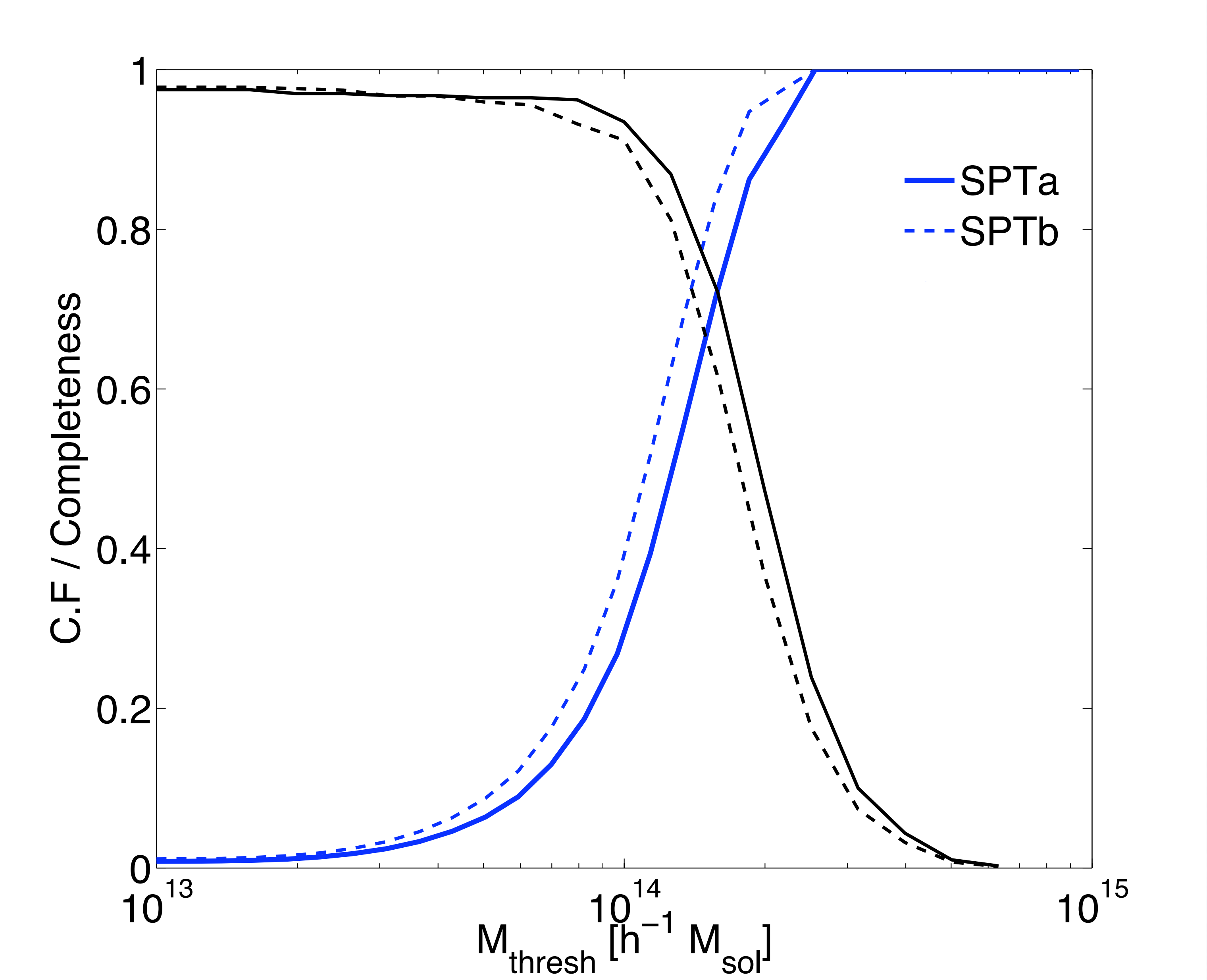

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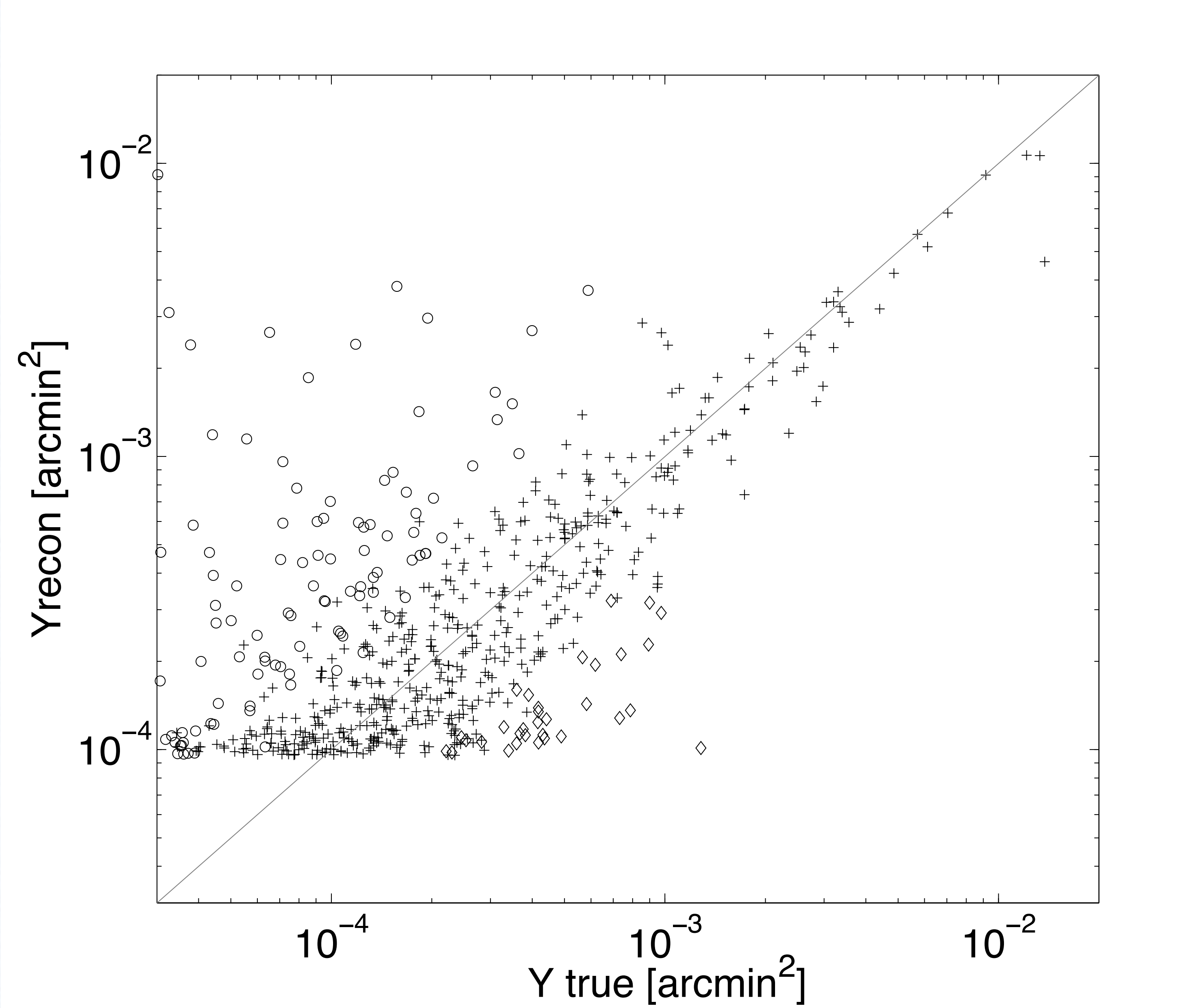
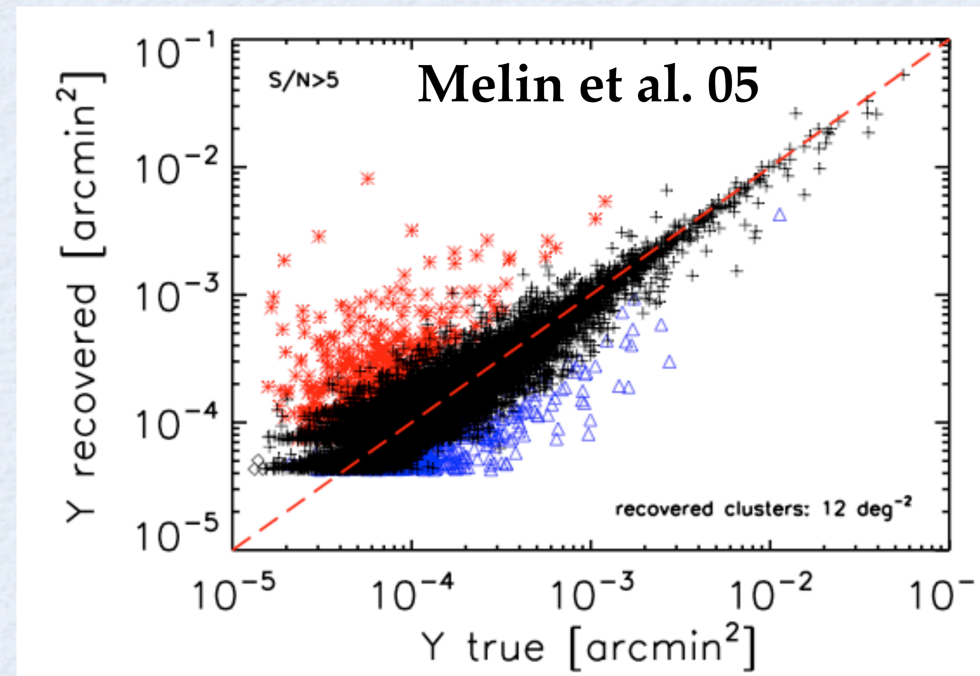
Flux Measurements



$$Y(\theta) = \int_0^{\theta} y(\theta) d\Omega$$

$$y_{obs}(\theta) = y_0 \left(1 + \left(\frac{x}{\theta_c}\right)^2\right)^{-1/2}$$



- Large scatter, even using β-model runs
- Error due to poor estimation of core radius, θ_c

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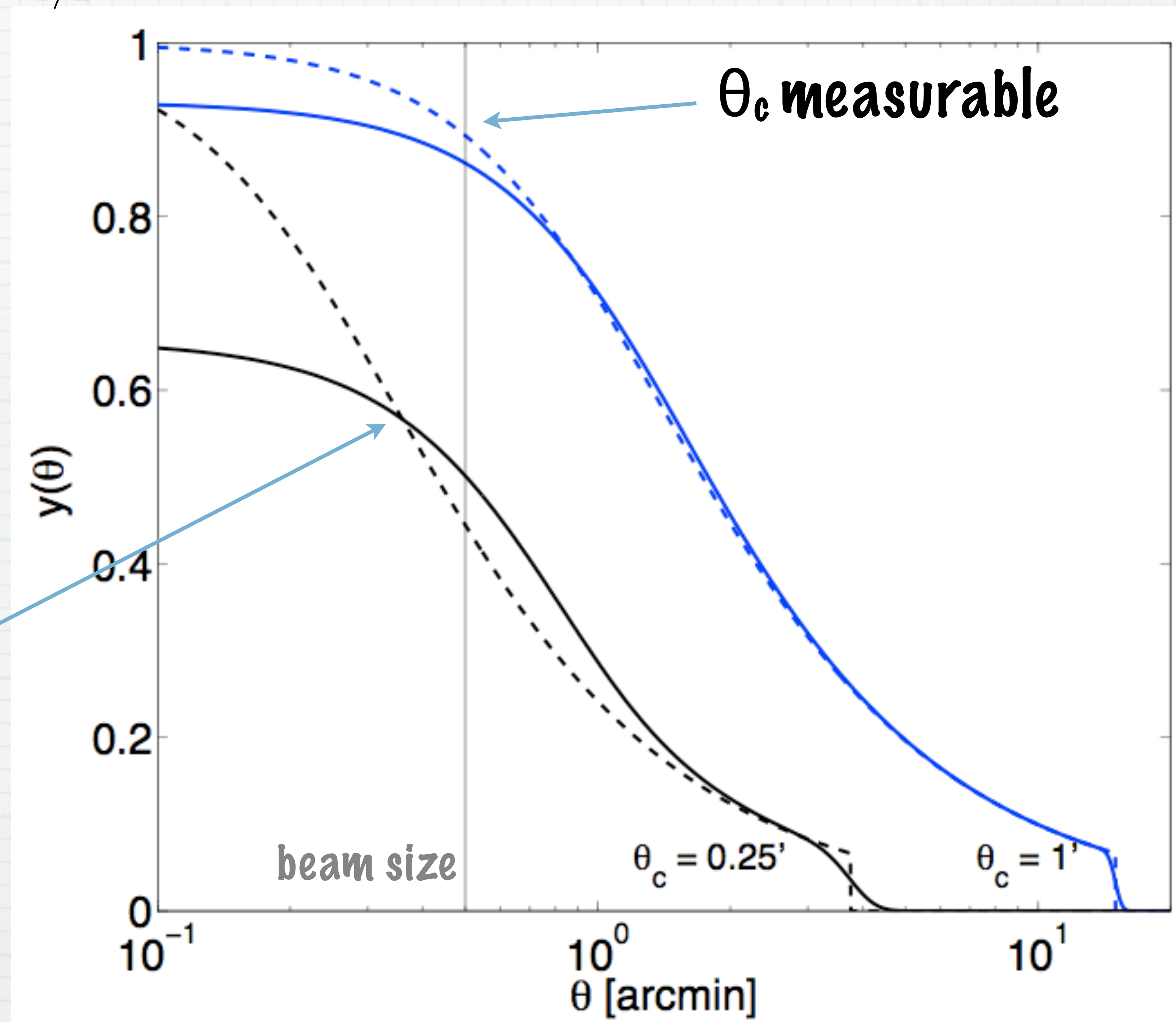


- We can not accurately measure radial profiles of clusters of scale angular size < beam size

BEAM-AVERAGED FLUX

- Really, y_0 is a measure of the average flux within a single beam area
- For clusters with $\theta_c > \theta_{beam}$, $y\pi\theta_{beam}^2$ is the integrated flux within a single beam

$$y_0 \pi \theta_{beam}^2 = f(z) Y_{200} \;, \qquad f(z) = \frac{\int_0^{\theta_{beam}} y(\theta)\theta d\theta}{\int_0^{\theta_{200}} y(\theta)\theta d\theta} \propto d_A(z)^2 / R_{200}^2$$

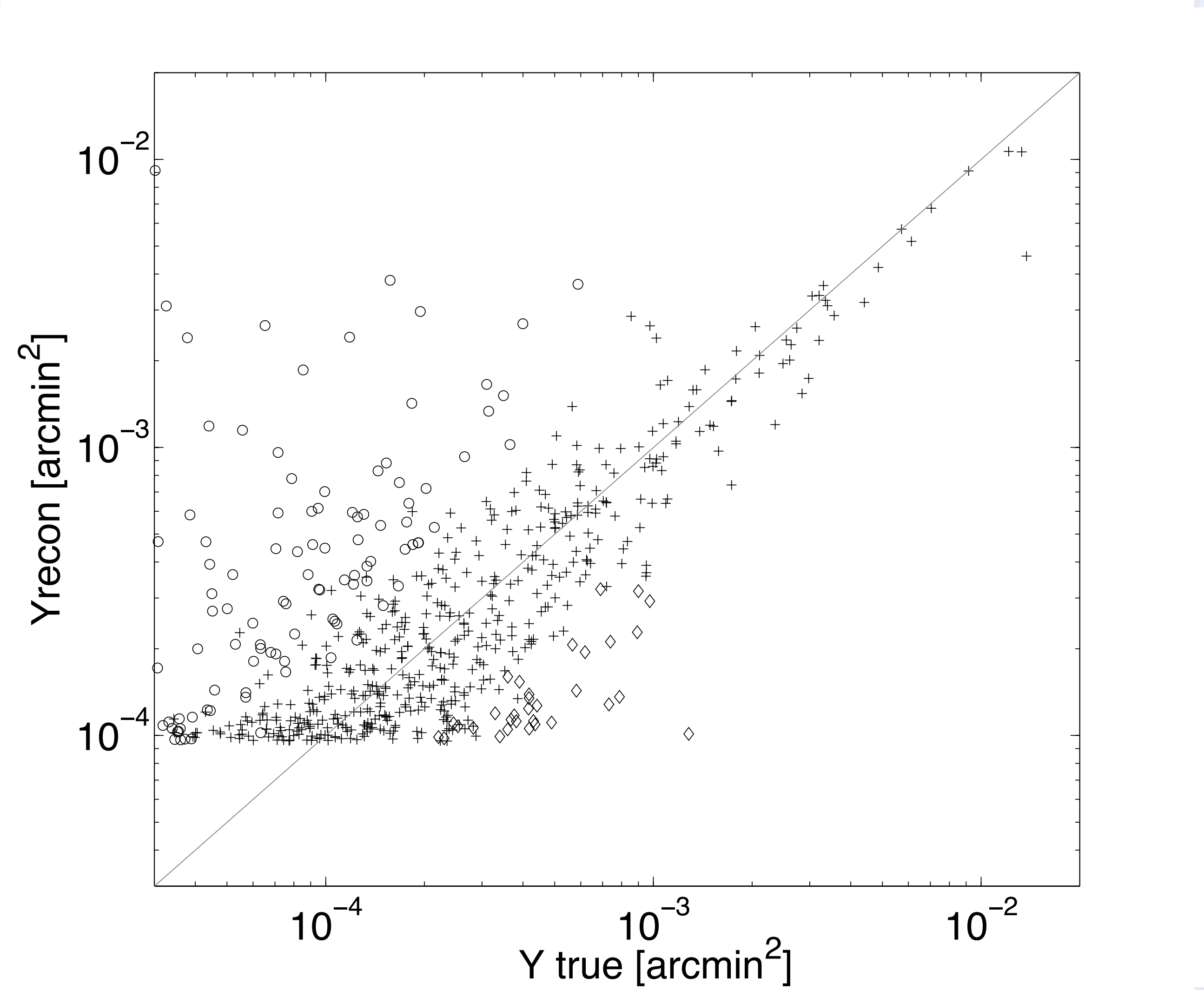
- Use Y_b parameter as estimate of cluster Y_{200}

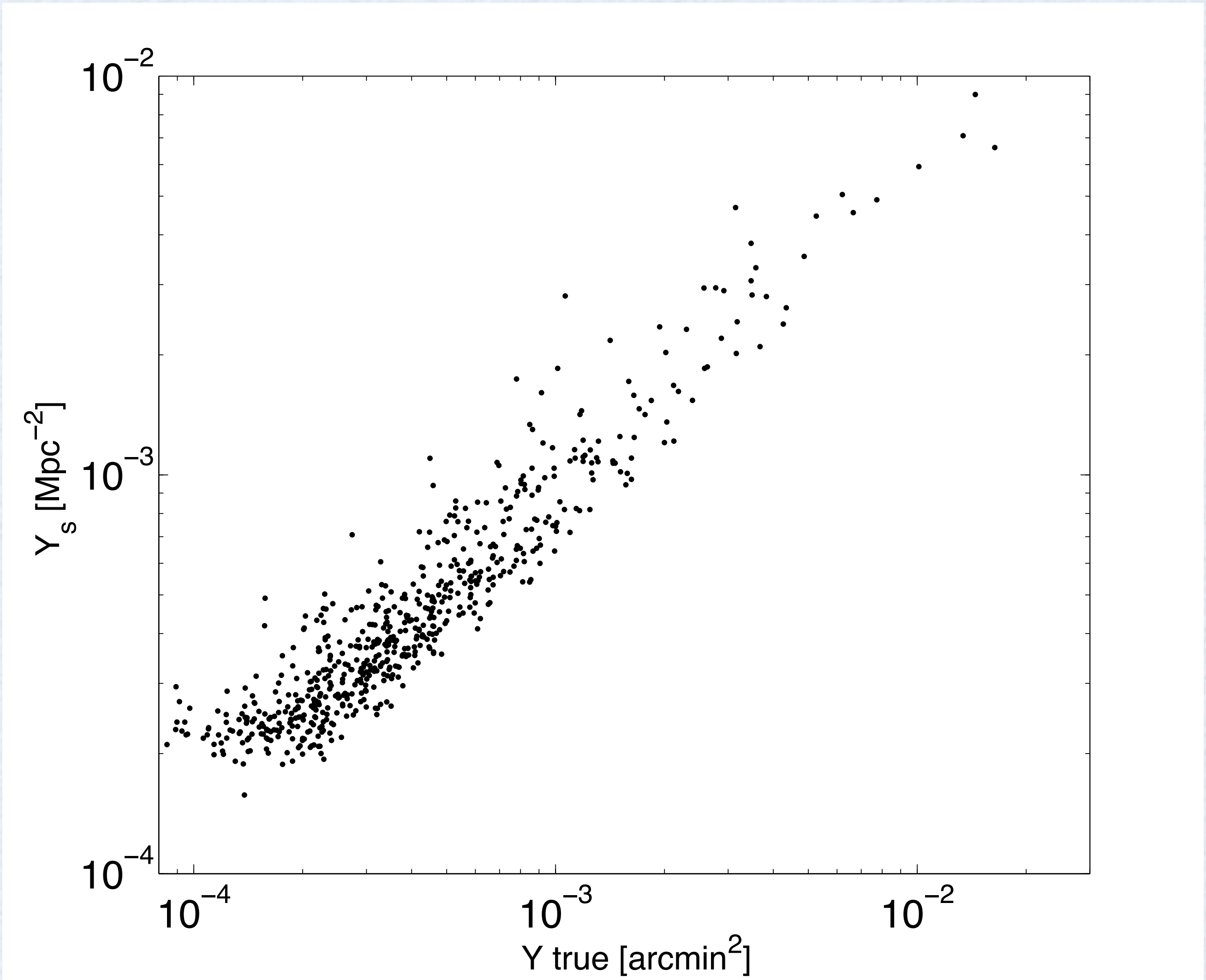
$$Y_b = y_0 E(z)^{-2/3} / d_A(z)^2$$

- Require correction to y_c for clusters with $\theta_c < \theta_{beam}$ due to degeneracy between matched filter estimates of y_c and θ_c

Surface Flux Density

beta-model runs





reconstruction method

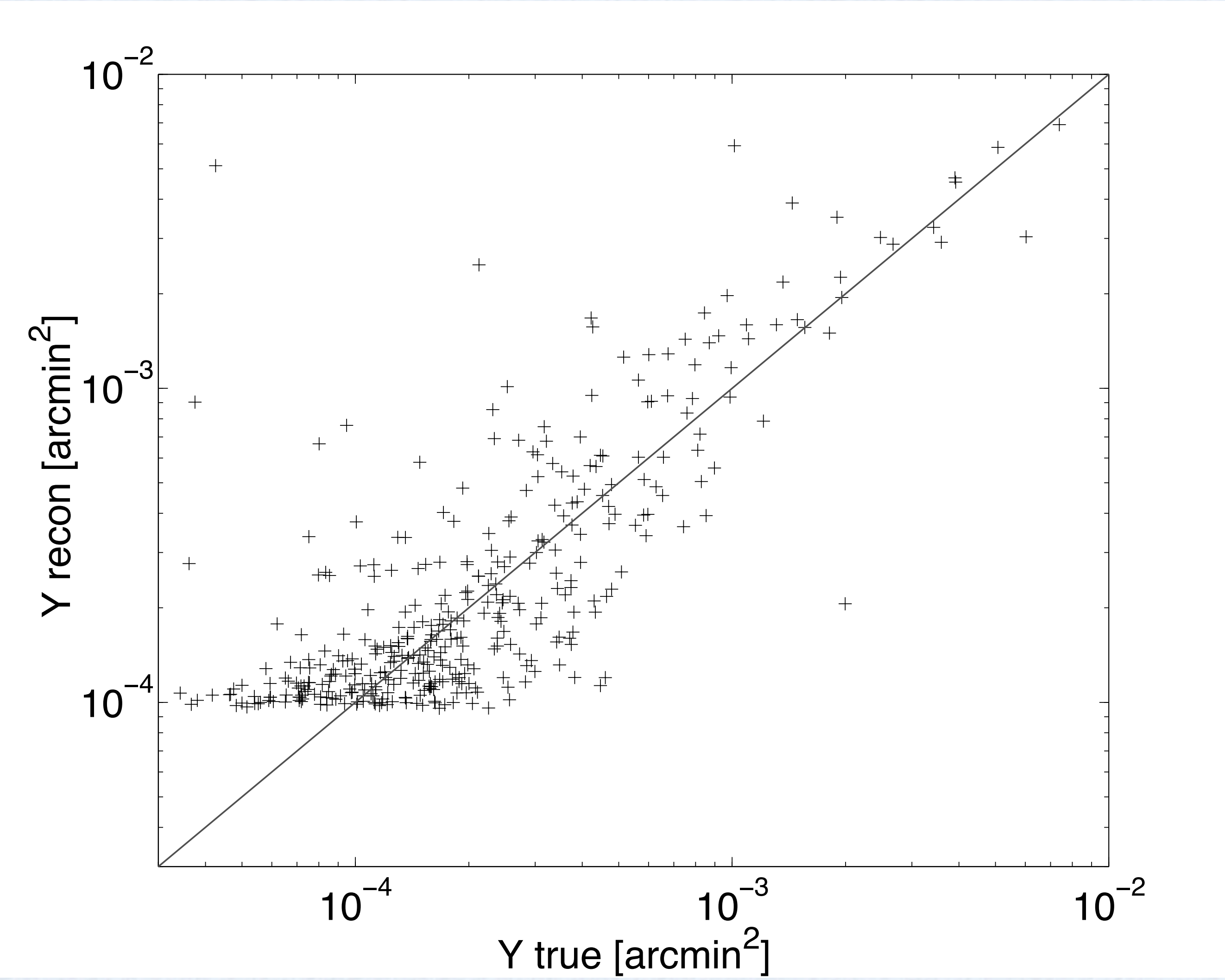
$$Y_\theta = y_0 \int_0^\theta ((1 + (\theta/\theta_c)^2)^{-1/2} \theta d\theta$$

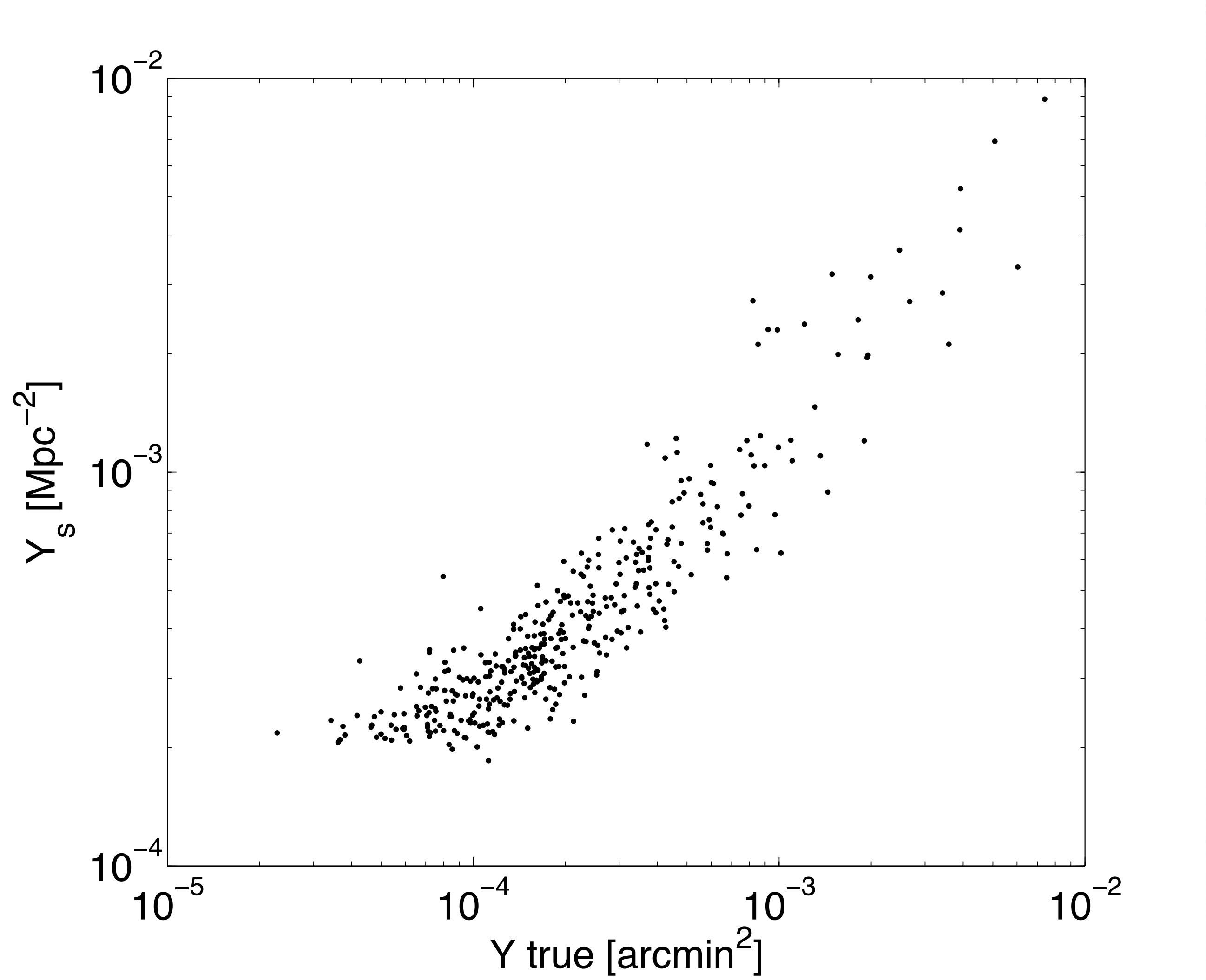
beam average flux density

$$Y_b = y_0 E(z)^{-2/3} / d_A(z)^2$$

Surface Flux Density

full gas model





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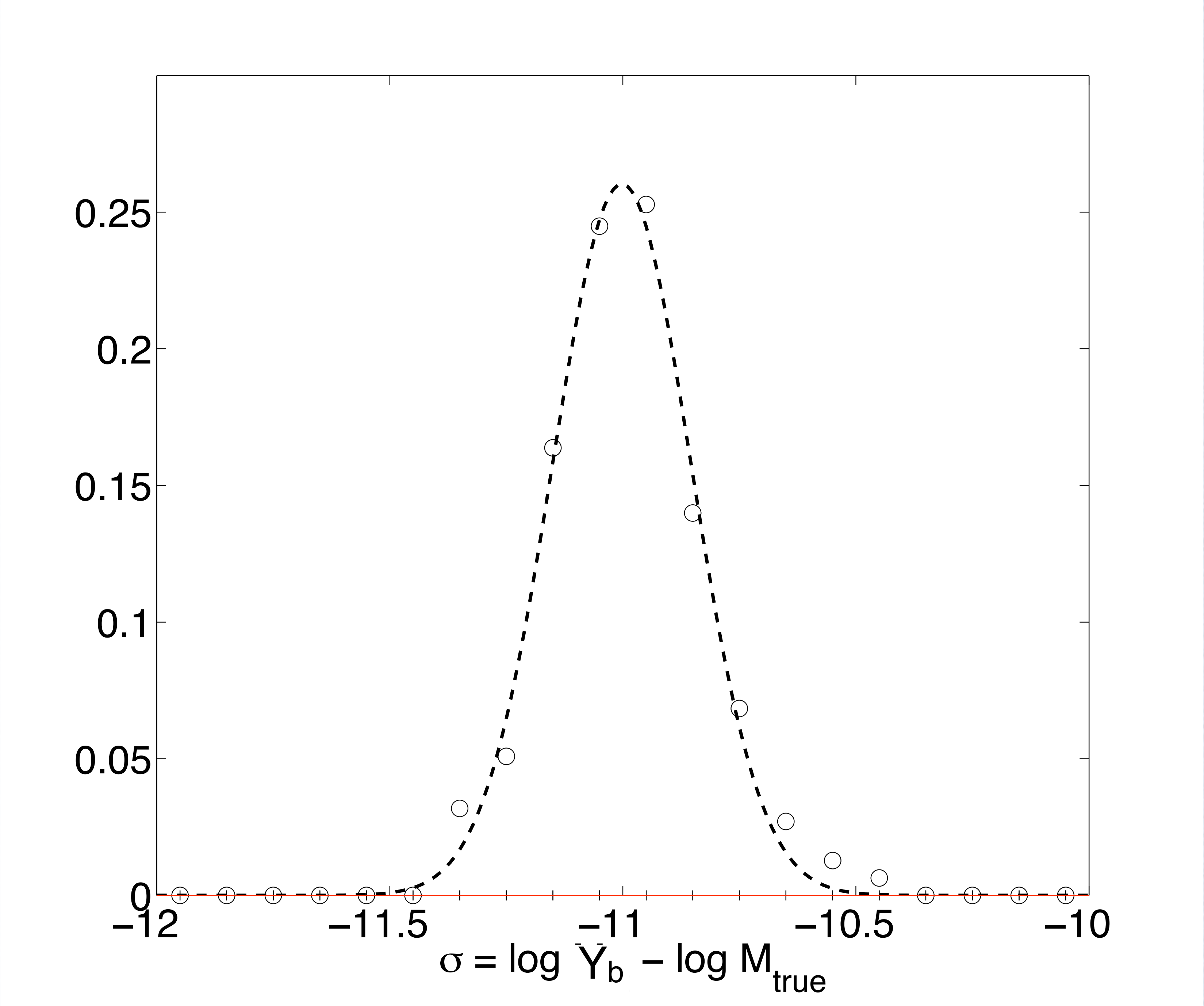
Y_B VS MASS

β-model (black,--) : 17.4%

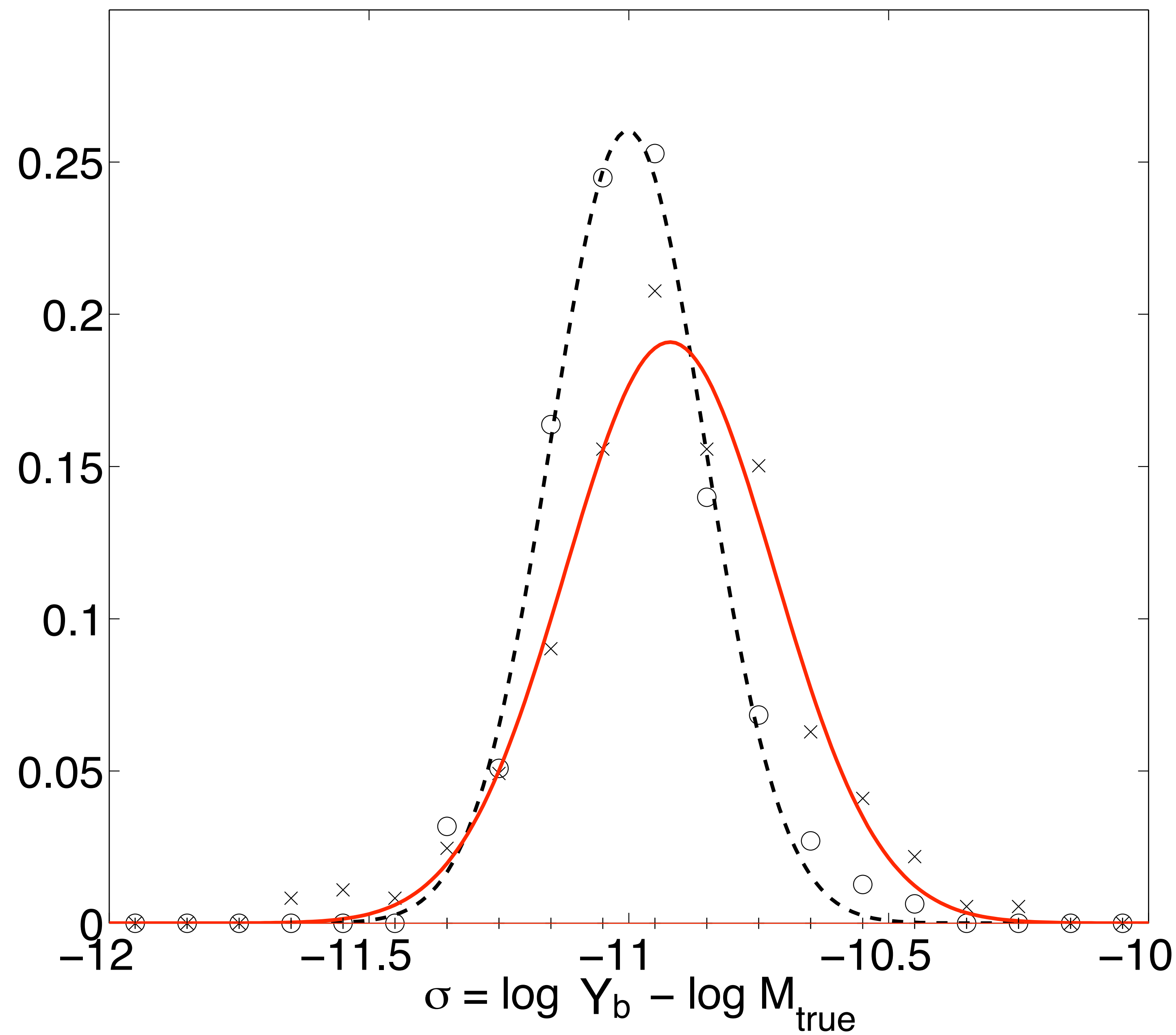


$$\frac{M_{200}}{10^{14}h^{-1}M_{sol}} = A[E(z)^{-2/3}Y_b d_A(z)^2]^{\sigma}$$

Yb vs Mass

β-model (black,--) : 17.4%

Gas Model, SPTa, (red) : 23.3%



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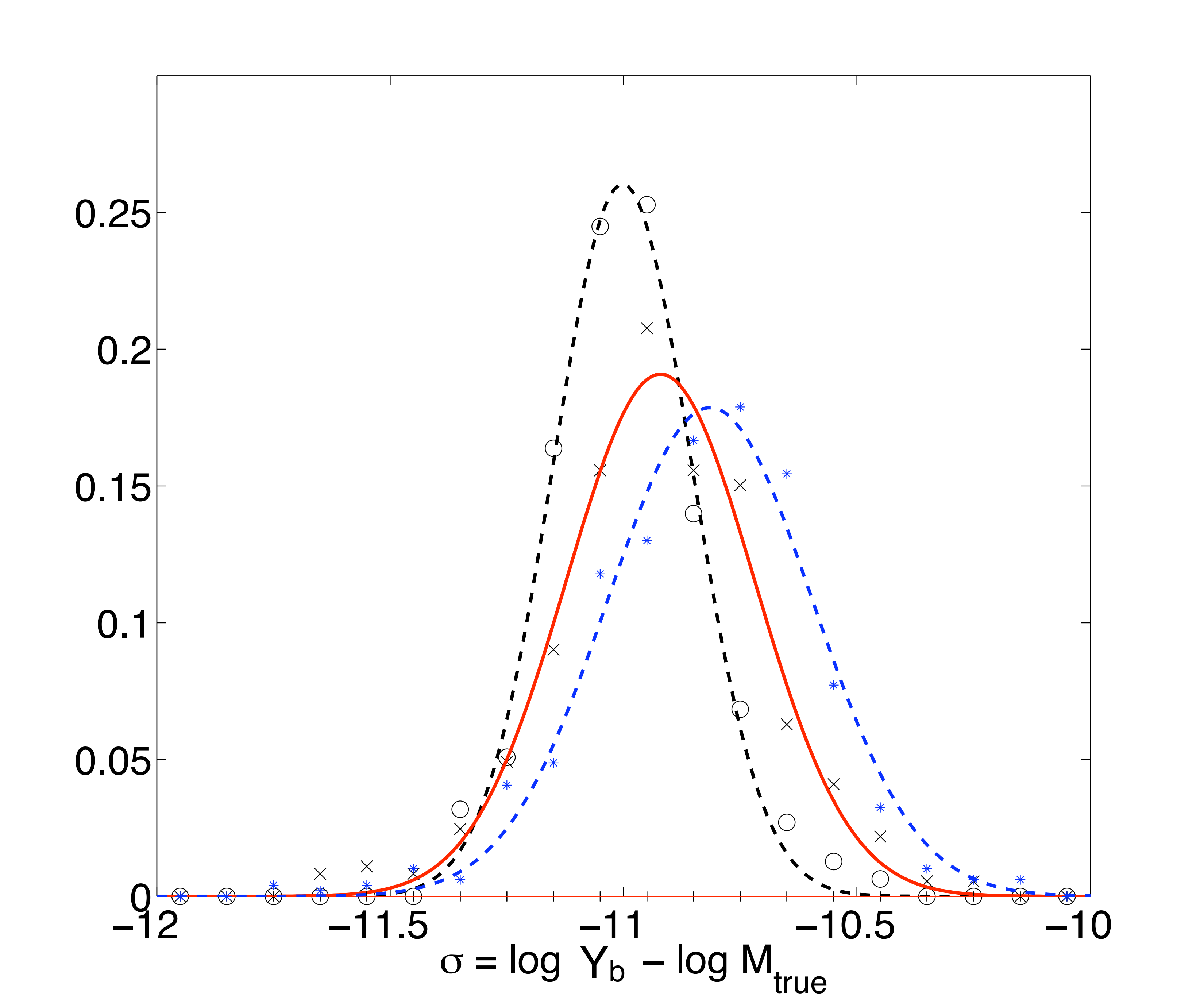
Gas Model, SPTb, (blue --) : 25.0%



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Y_B vs Mass

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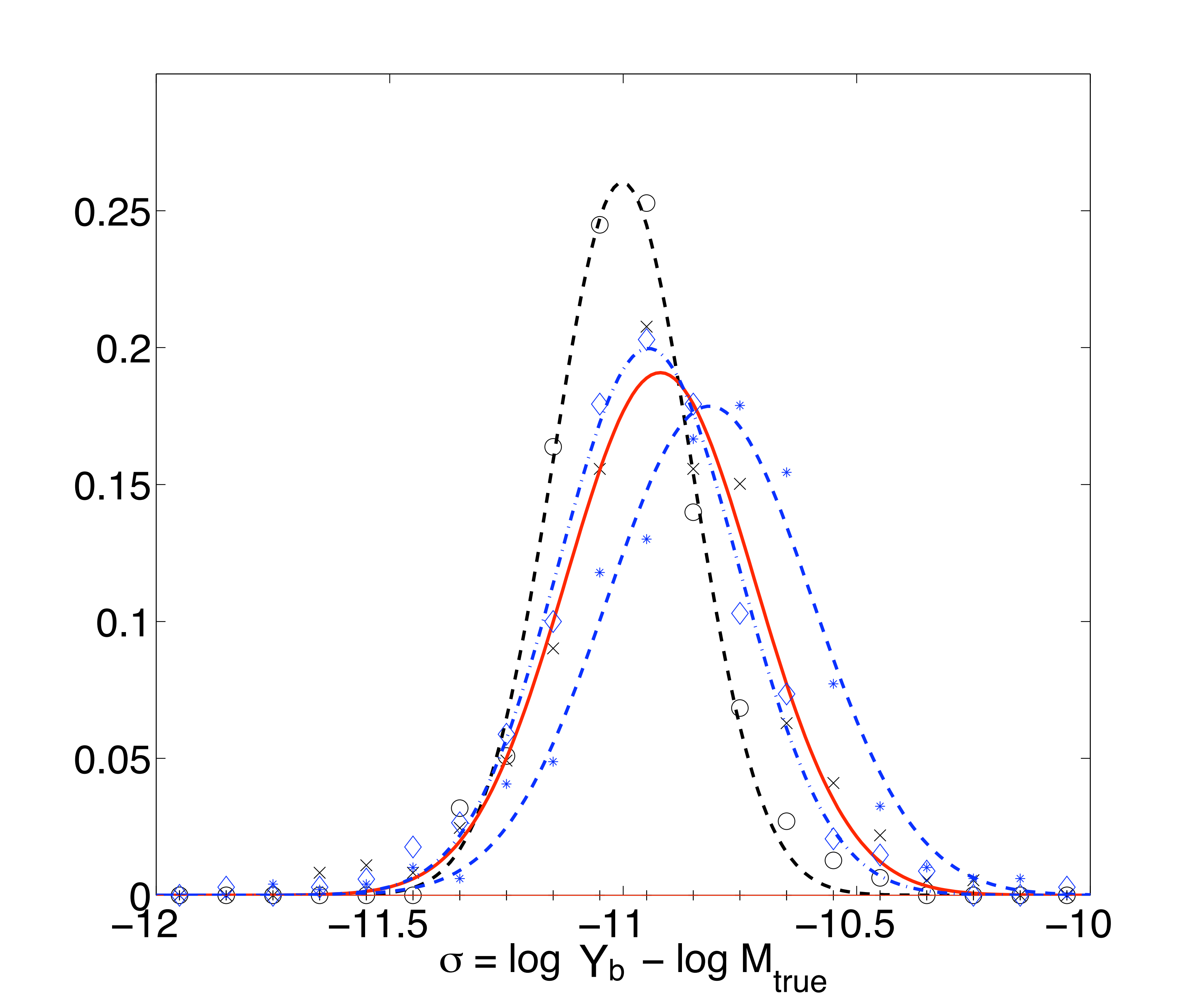
Gas Model, SPTb, (blue --) : 25.0%

Gas Model, ci. sy (blue -.) : 22.5%



$$\frac{M_{200}}{10^{14}h^{-1}M_{sol}} = A[E(z)^{-2/3}Y_b d_A(z)^2]^{\sigma}$$

Y_B VS MASS

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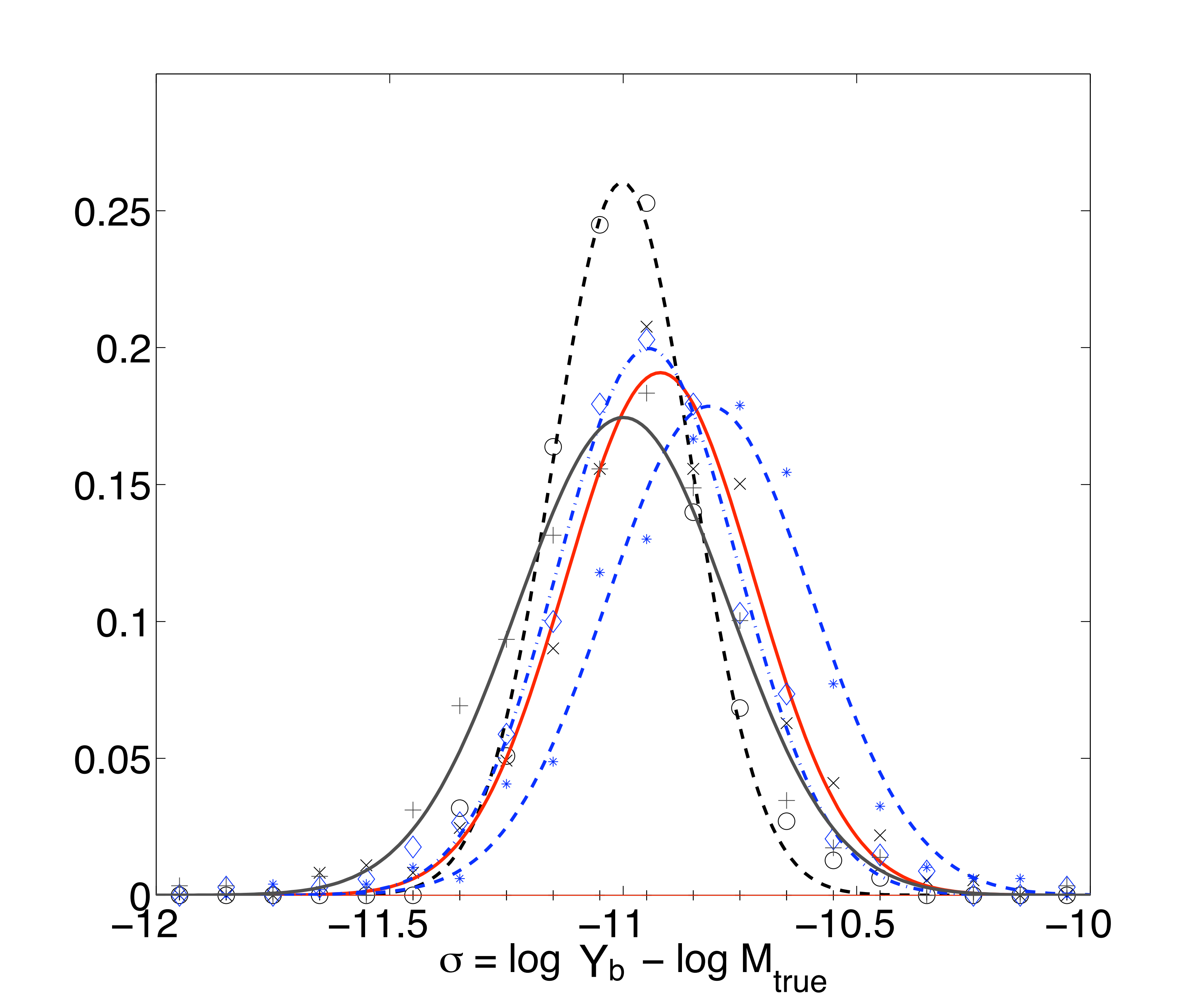
Gas Model, SPTb, (blue --) : 25.0%

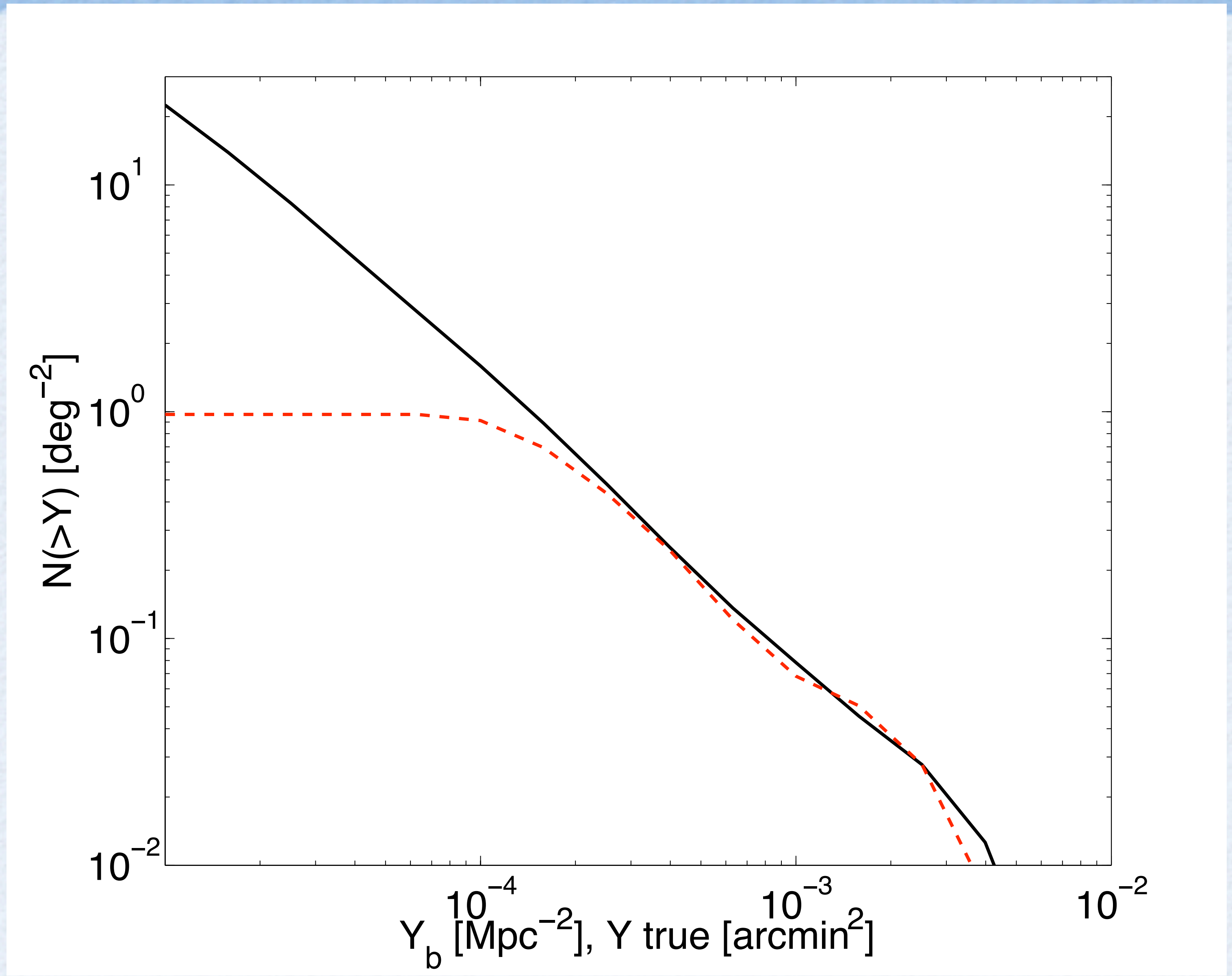
Gas Model, ci. sy (blue -.) : 22.5%

Hi FB Model, SPTa, (grey) : 25.0%



$$\frac{M_{200}}{10^{14}h^{-1}M_{sol}} = A[E(z)^{-2/3}Y_b d_A(z)^2]^{\sigma}$$

Self-Calibration



- self-calibration uses shape of mass-function to calibrate Y-M scaling relation
- Need to place strong priors on cosmic evolution of s.r.

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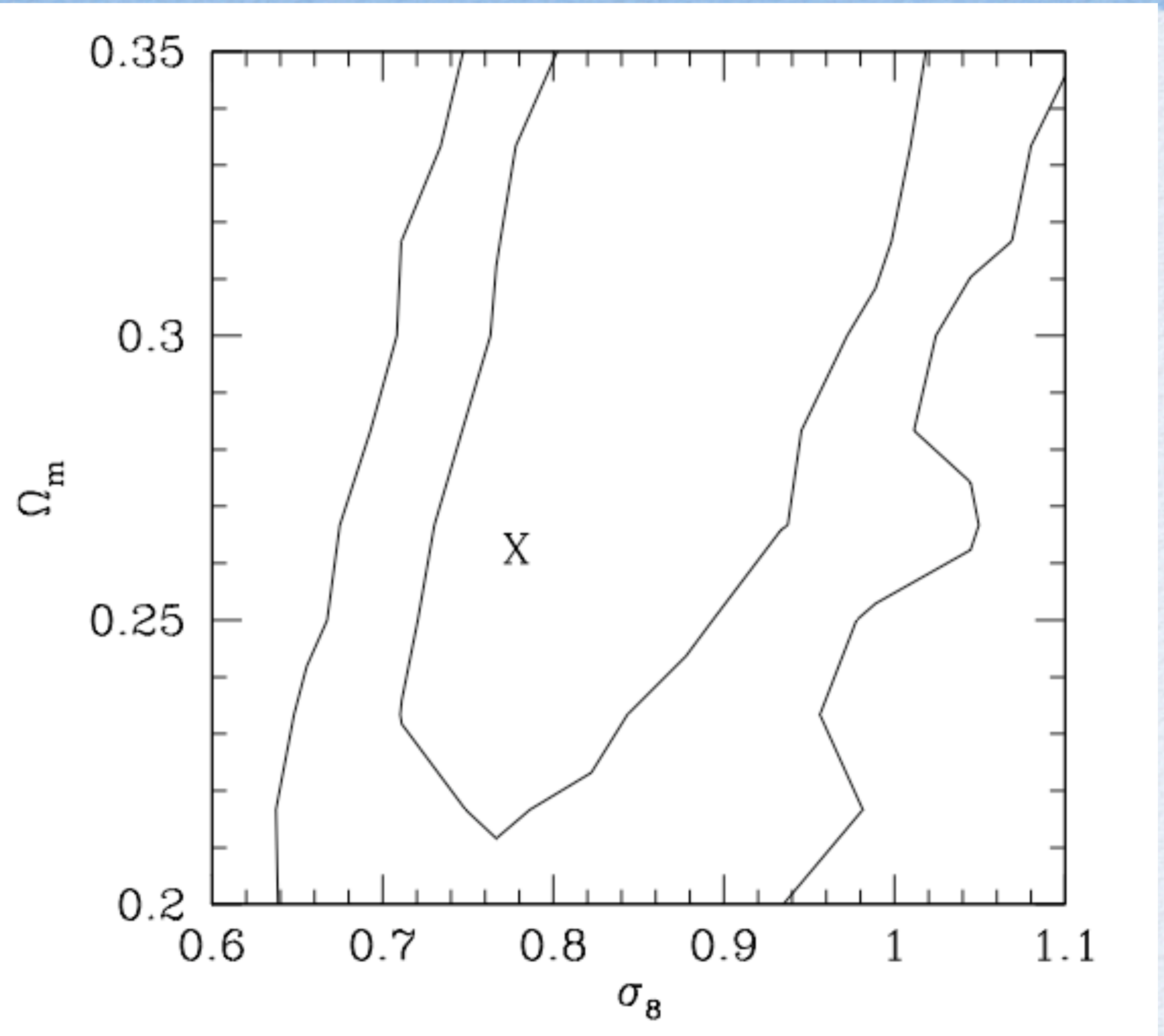

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Summary

- Produce sky maps of ~400 sq. deg. of simulated lightcone ($\sigma_8 = 0.77$, $\Omega_M = 0.26$)
- Using multifrequency matched filter find 1 cluster/deg.^{2} at S/N > 0.5 for 18μK instrument noise
- 3% contaminants (mergers, substruct., l.o.s. confusion). Removed by optical crossmatch with r_{tol}=1.5′
- completeness at 90% for $M_{200} > 2\text{x}10^{14}\ h^{-1}\ M_{sol}$
- yield slightly improved using smaller beam
- Y averaged within beam area provides most accurate estimate of cluster integrated flux (~24% scatter vs M_{200})

$3 \times 10^{14} M_\odot, \; z = 0.5$