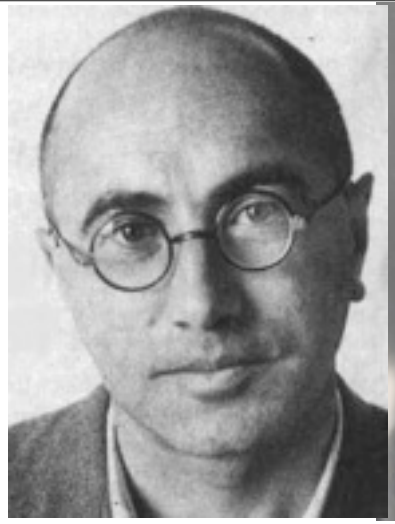
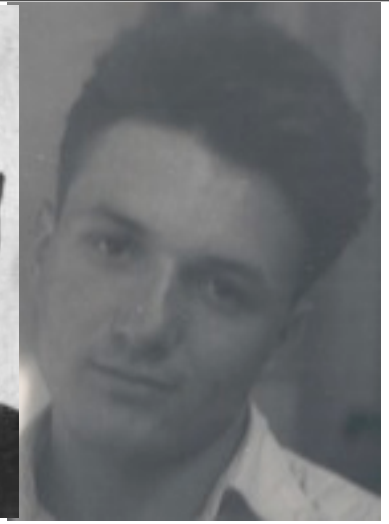



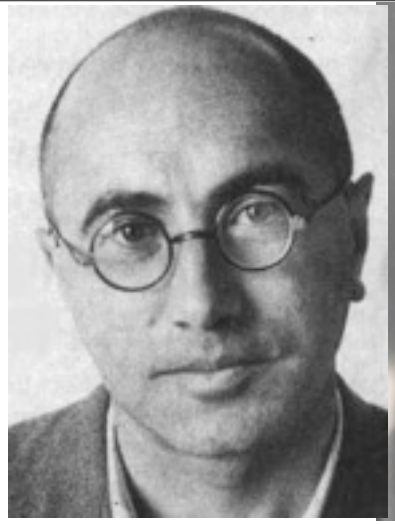
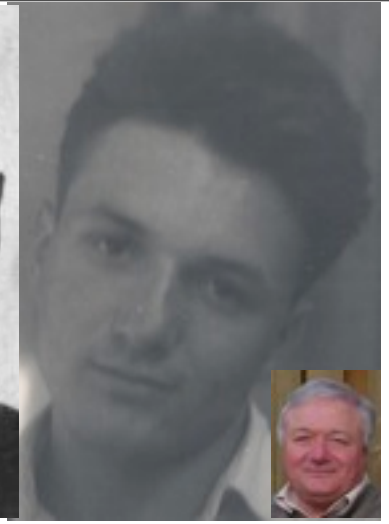
CITA ICAT Canadian Institute for Theoretical Astrophysics / L'institut canadien d'astrophysique theorique

Dick Bond

CIAR

the Power in Sunyaev & Zeldovich, then & now

The Impact for ACT +Planck+SPT of AGN Feedback on SZ Power Spectra

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(Linear) primary CMB anisotropies *are strongly damped by photon-baryon shear viscosity at high L > 1000, where* ***secondary anisotropies from the weakly and strongly nonlinear cosmic web dominate.*** *In order of dominance:* ***thermal Sunyaev-Zeldovich effect*** *(Compton scattering of CMB off hot gas, unique frequency signature),* ***CMB weak lensing*** *(smooths out peaks and troughs, no frequency signature),* ***kinetic Sunyaev-Zeldovich*** *effect (Thomson scattering of CMB off moving ionized gas, at high and low redshift), & more.* ***Extragalactic radio*** *(synchrotron) and* ***infrared sources*** *(dust emission) are important (frequency signatures, complex). Galactic foregrounds strongest at low L.*

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To get n_s, m_ν etc., from cosmic parameter estimation of the primary CMB anisotropy power, the statistics of secondary power must be fully incorporated ⇒ need to know accurately.

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2ndary signals are also cosmic-info-loaded: density **power spectra** in gas and dark matter. **Dark energy equation of state** from **large SZ cluster samples** (measures their thermal energy, related by virial equation to DM+gas gravitational energy) (& **CMB weak lensing**).

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Delta T over Tea Toronto May 1987: first dedicated CMB conference, exptalists +theorists, primary+secondary ΔT/T

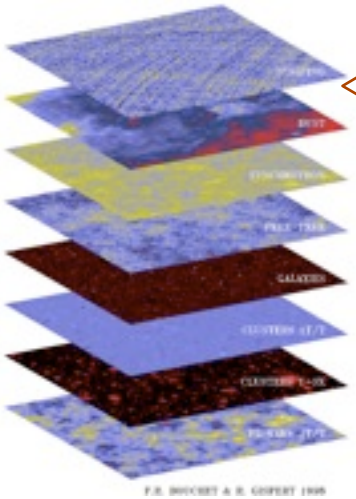
- very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- small angle anisotropies - current results, optimal measuring strategies, statistical methods for

+ effect of energy injection / explosions on LSS- a big pre-COBE forecast issue

bond@ ΔT/Tea87: "clustered shots" (bbks86-peaks for halos) with **pressure profiles** *via binding energy (not mass) but beta-profiles with core scaling and old X-ray beta's*

BUT spherical collapse - *too many cls* **&** **non-dynamical masses** - *high M's too low*

⇒ peak patches BM91-96 ***tidal fields - virial mass from homogeneous ellipsoid dynamics, accurate cluster positions, masses, binding energies, clustering***



e..g, ***application to Planck sims 90s,*** *CBI, AMIBA, ..*

constrained supercluster **treePM-SPH** ***sim*** **of ΛCDM +cooling: largest k-range of its time** (>> Virgo sim) ***SZ in supercls may give us the outskirts of cls & gps, not filaments (unless ∃ large gas E-outflows)*** ***B+Kofman+Pogosyan+Wadsley 97/99***

painting halos with analytic Y_{SZ} & pressure form factors cf. SPH-hydro: the discrepancy existed from 2002 (a big issue was/is the overdensity 200 to 20 far-field & non-equilibrium)

What sort of objects in the cosmic web dominate the SZ effect?

Δ_{cut}= 200, 120, 60, 20 then convergence, pick up far-field of clusters and groups,+ a little into filaments ***(unless ∃ large gas E-outflows into filaments)***

What is the redshift range that contributes to the SZ effect?

all from 0 to ~2

CITA-SZ with feedback: *Battaglia, Bond, Pfrommer, Sievers & Sijacki 2010*

the expts: **CBI, ACBAR to L~2500+, BIMA ~6000, Quad to 2000+, *Planck* ~ 2000, SZA ~ 4000, *APEX, ACT & SPT* to ~10000, eventually SPTpol and ACTpol. + *high res follow-ups GBT, SZI, ALMA, CCAT, ...***

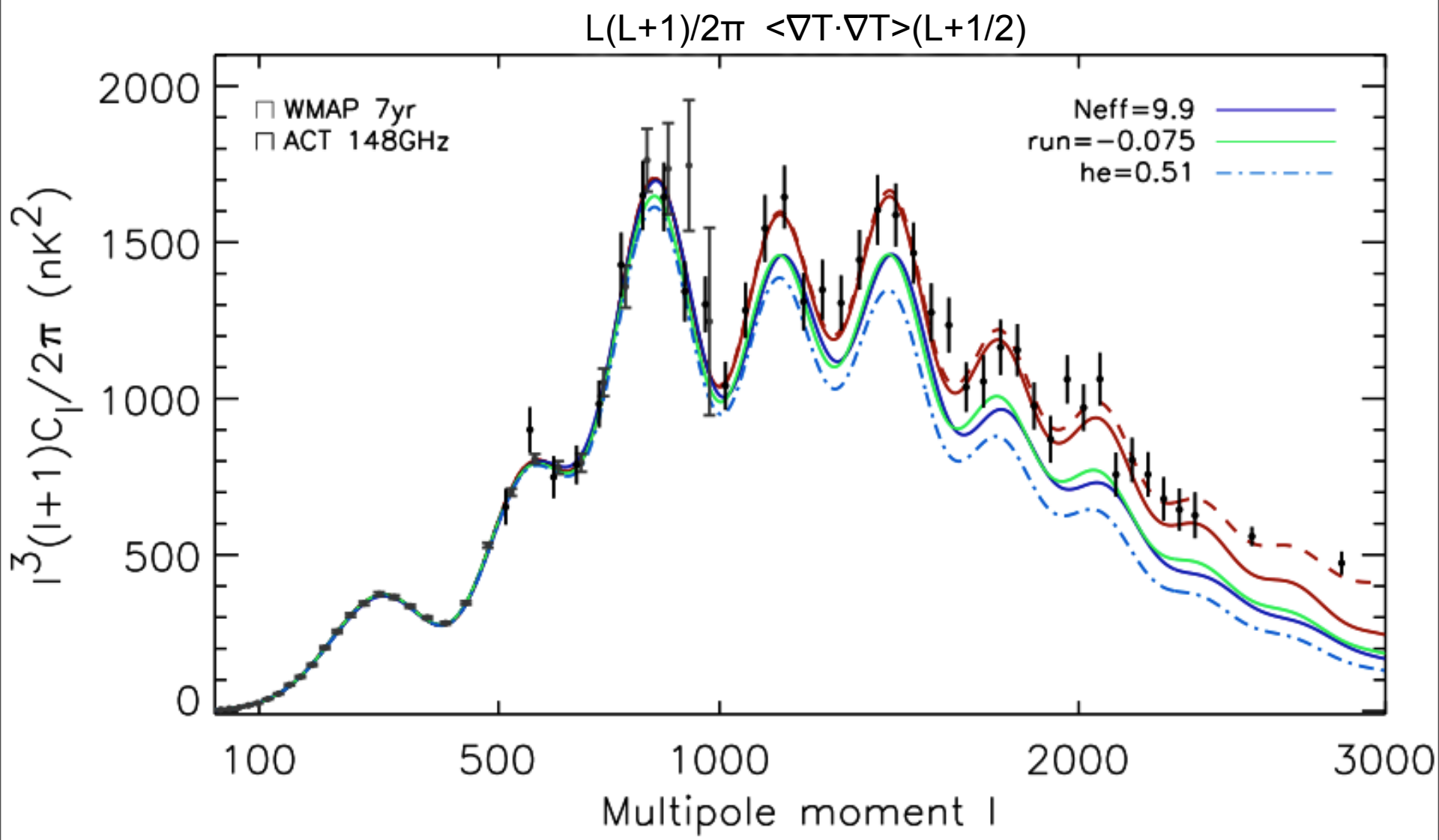
⇒ urgent to show the range of C_L^{SZ} as effects are added

Oct07: do large treePM-sph sims (>700^3 gas+DM)-NOT instead 512^3 & 256^3 & single-hi-res-cls

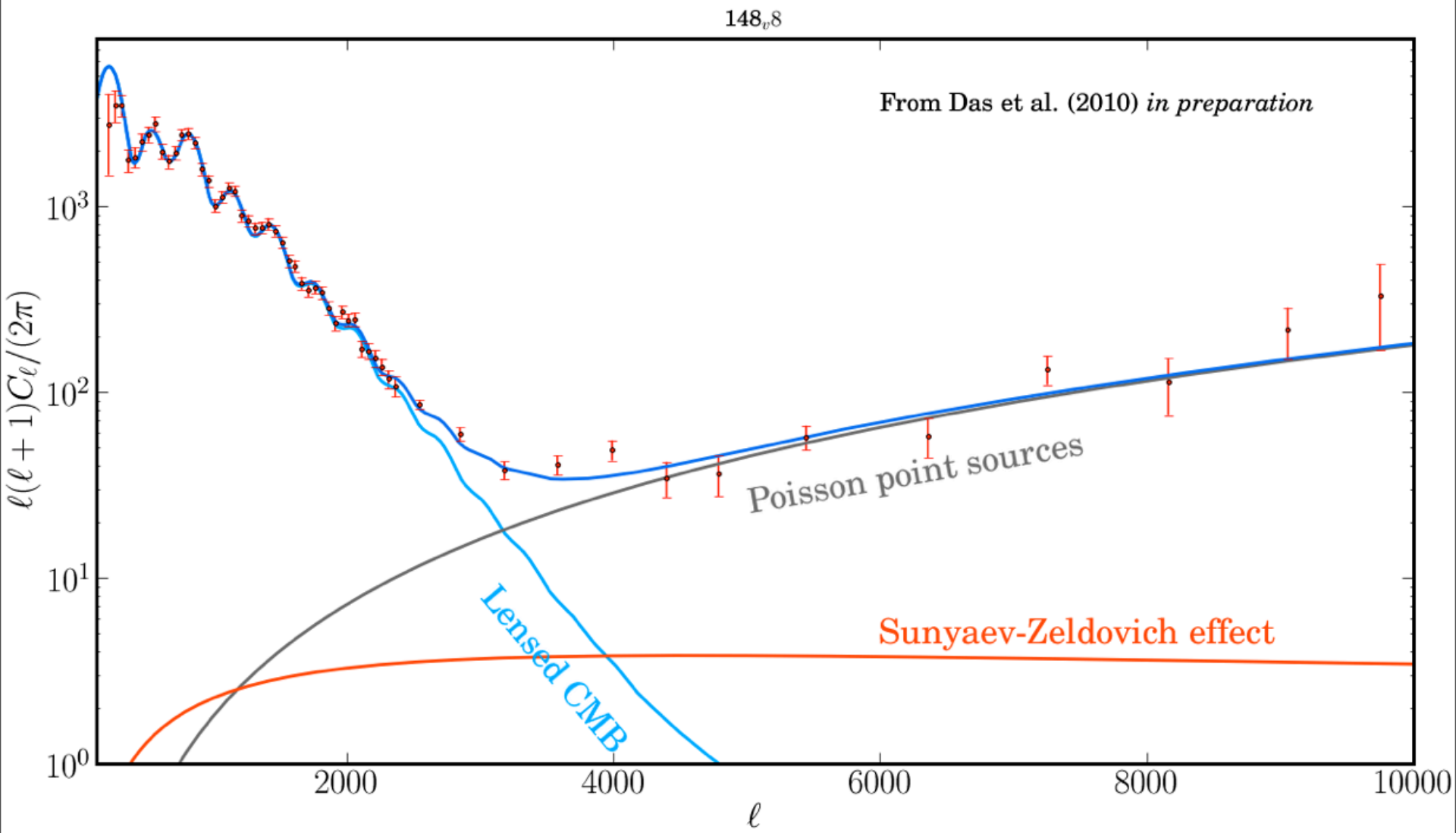
shock heat only "adiabatic"*; cool+SN E; cool + SN E + winds; *cool + SN E-feedback + winds + CRs from cluster shocks;

AGN feedback + cool + SN E + winds: $\Delta E_{inj} \sim \varepsilon \Delta t$ SFR over R_{AGN} in halo centre, episodic above a SFR threshold, $\varepsilon_{eff} < \varepsilon$

ACT@5170m


L(L+1)/2π <∇T·∇T>(L+1/2)
WMAP 7yr
ACT 148GHz
Neff=9.9
run=−0.075
he=0.51
$l^3(l+1)C_l/2\pi$ (nK^2)
2000
1500
1000
500
0
100
500
1000
2000
3000
Multipole moment l

ACT@5170m


148$_{\nu}$8
From Das et al. (2010) *in preparation*
$\ell(\ell+1)C_\ell/(2\pi)$
10^3
10^2
10^1
10^0
2000
4000
6000
8000
10000
ℓ
Poisson point sources
Lensed CMB
Sunyaev-Zeldovich effect

ACT@5170m

148
10^3
10^2
10^1
10^0
$\ell(\ell+1)C_\ell/(2\pi)$
2000
4000
6000
8000
10000
ℓ
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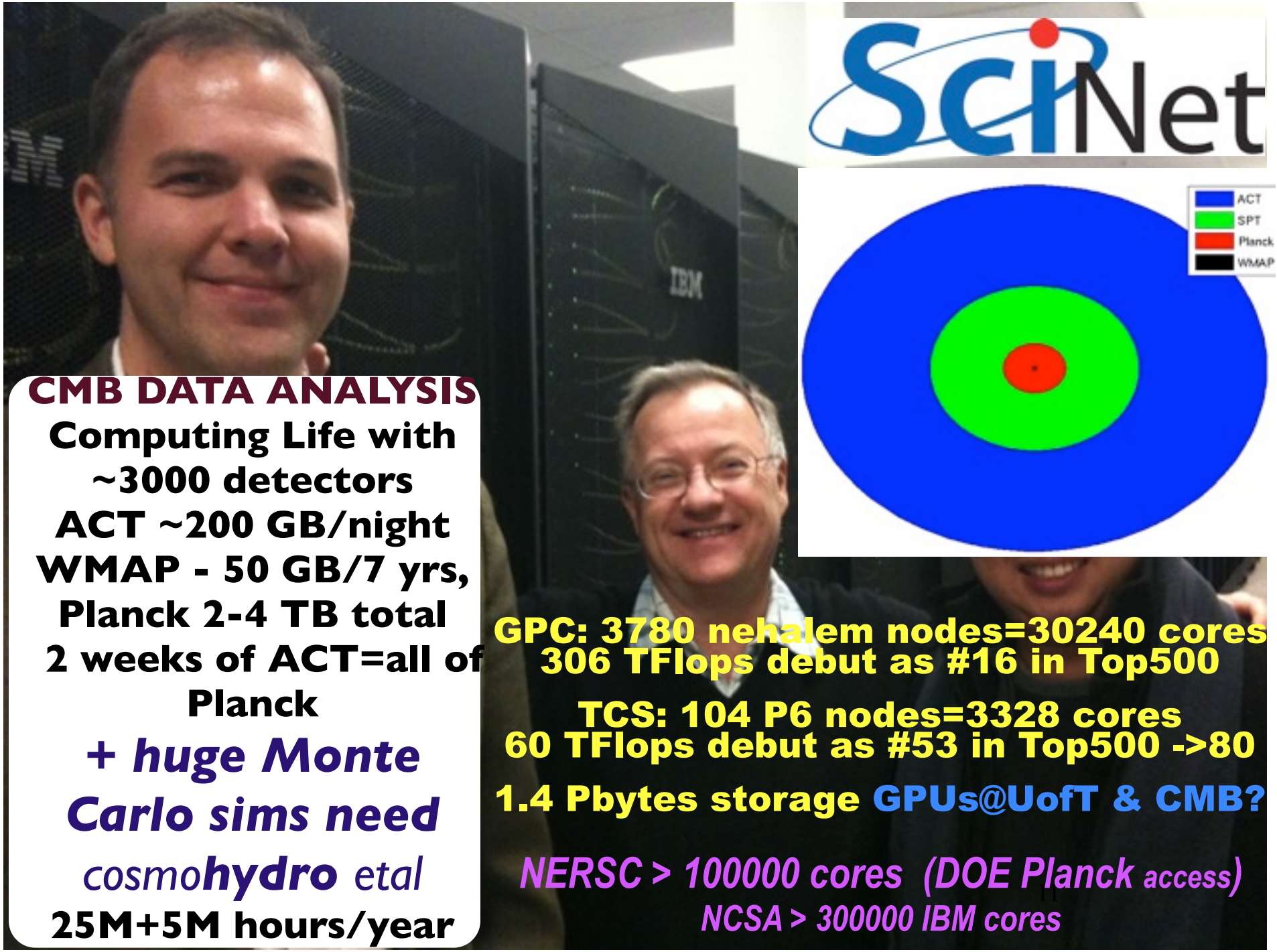

SciNet
ACT
SPT
Planck
WMAP
CMB DATA ANALYSIS
Computing Life with
~3000 detectors
ACT ~200 GB/night
WMAP - 50 GB/7 yrs,
Planck 2-4 TB total
2 weeks of ACT=all of
Planck
+ huge Monte
Carlo sims need
cosmohydro etal
25M+5M hours/year
GPC: 3780 nehalem nodes=30240 cores
306 TFlops debut as #16 in Top500
TCS: 104 P6 nodes=3328 cores
60 TFlops debut as #53 in Top500 ->80
1.4 Pbytes storage GPUs@UofT & CMB?
NERSC > 100000 cores (DOE Planck access)
NCSA > 300000 IBM cores

400 Mpc ΛCDM

WMAP5

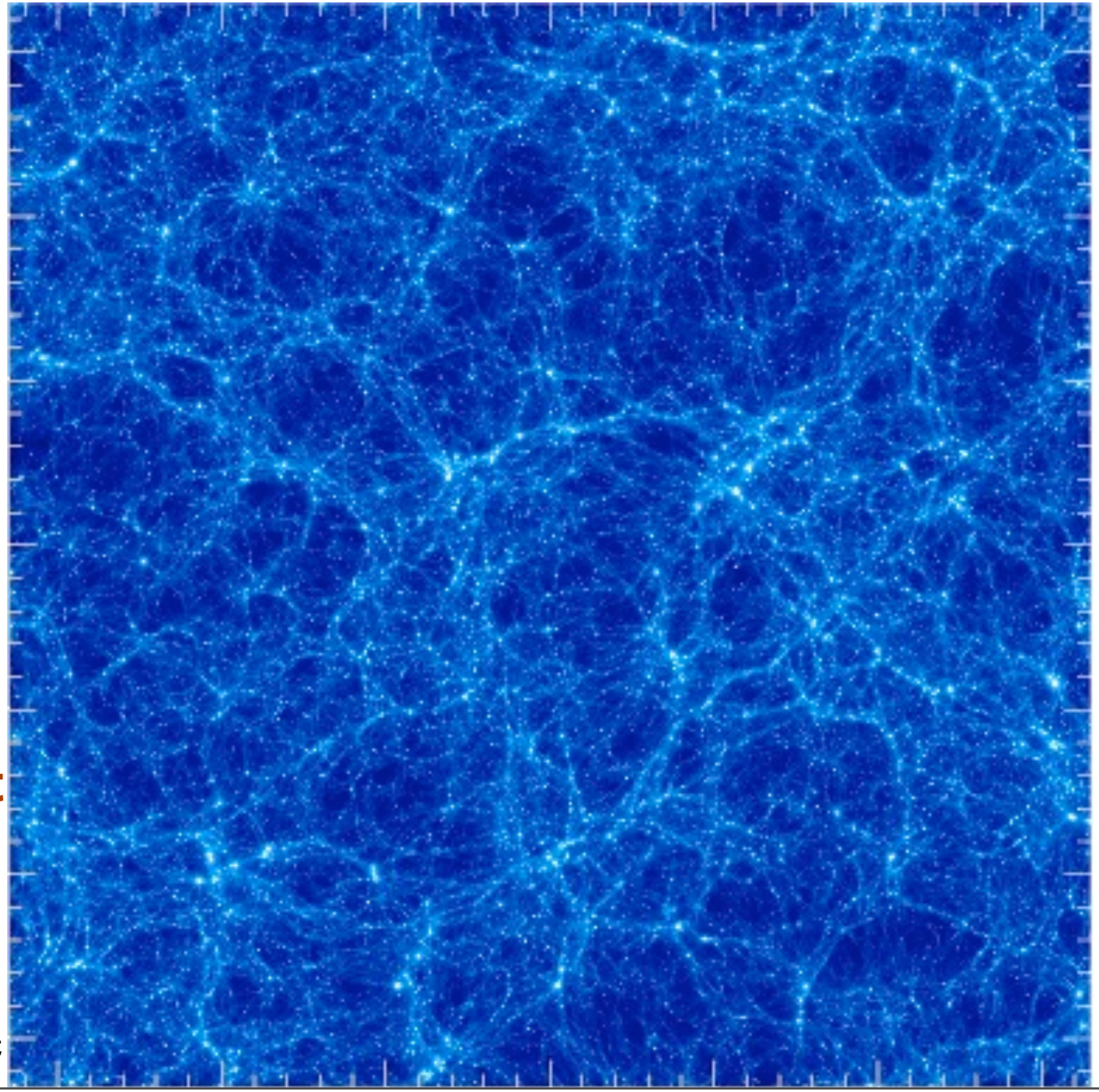
gas density

Gadget-3 SF+ SN E+ winds +CRs

512^3 also

& AGN E-input +all

& shock-adiabatic



CMB gets entangled in the cosmic web

aka the descent into the real astronomy of IGM/ISM weather, dust storms & turbulent times

400 Mpc

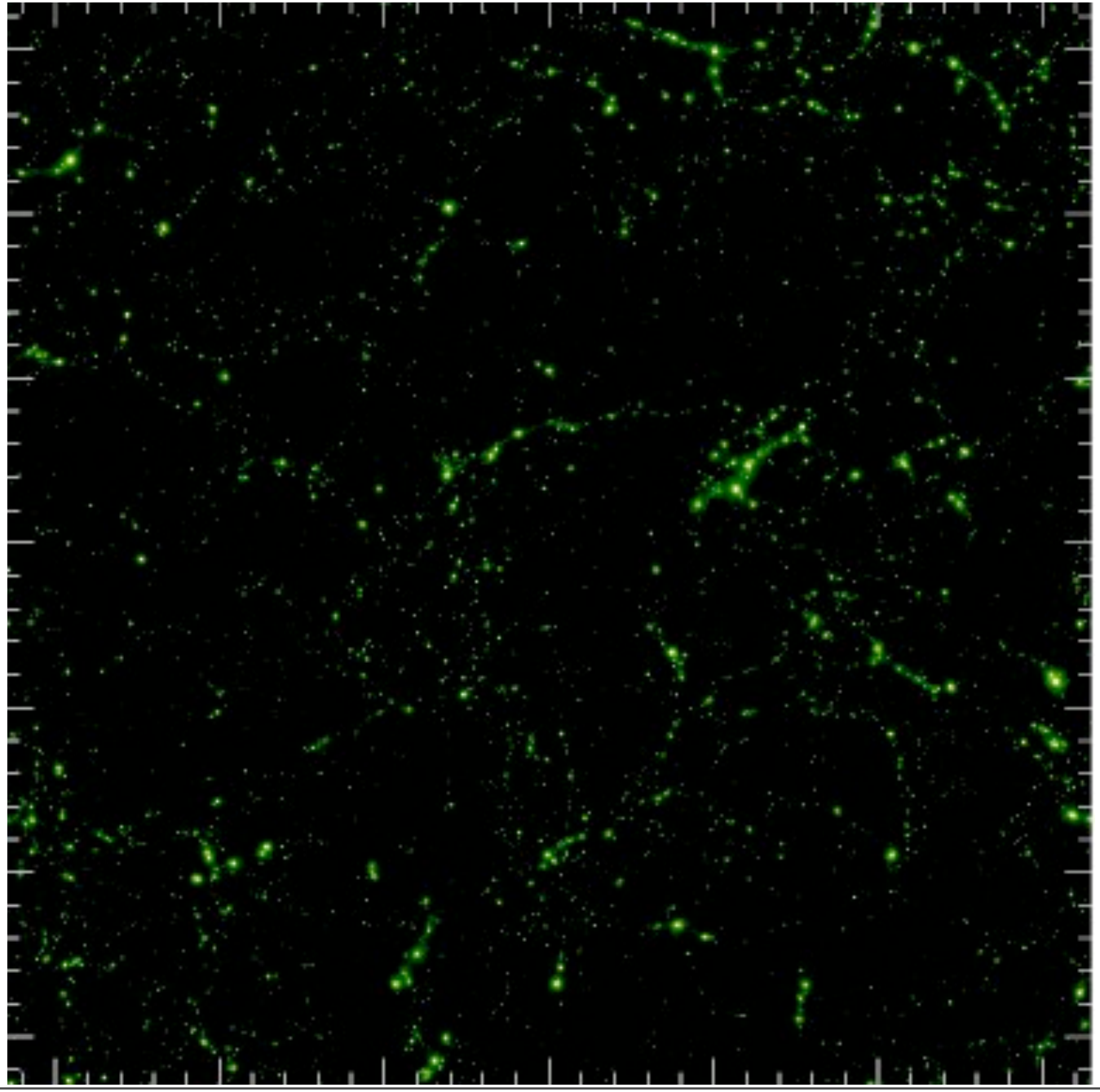
ΛCDM

WMAP5

gas pressure

Gadget-3 SF+ SN E+ winds +CRs

512^3



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CITA-SZ with feedback: *Battaglia, Bond, Pfrommer, Sievers & Sijacki 2010*

for ACT+SPT+Planck, urgent to show the range of C_L^{SZ} as effects are added

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shock heat only "adiabatic"; **cool+SN E; cool + SN E + winds;** ***cool + SN E-feedback + winds + CRs from cluster shocks***;

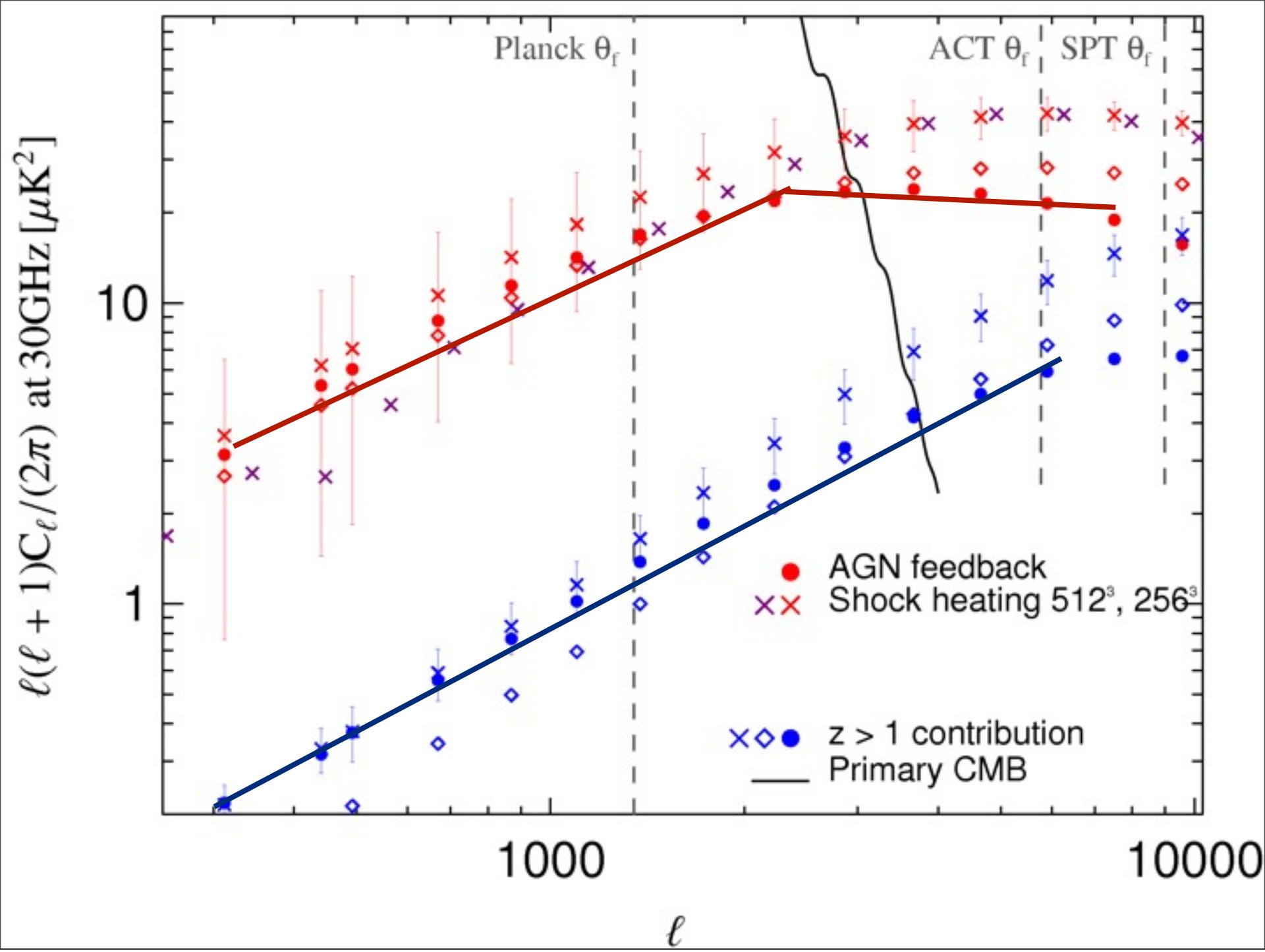
but *because of* ***core overcooling and overproduction of stars****, waited for a* ***subgrid*** *model of* ***AGN feedback*** *in cluster cores, to be calibrated with the (small mass) cluster-BH calculations of Sijacki (with Springel, Pfrommer, ...)*

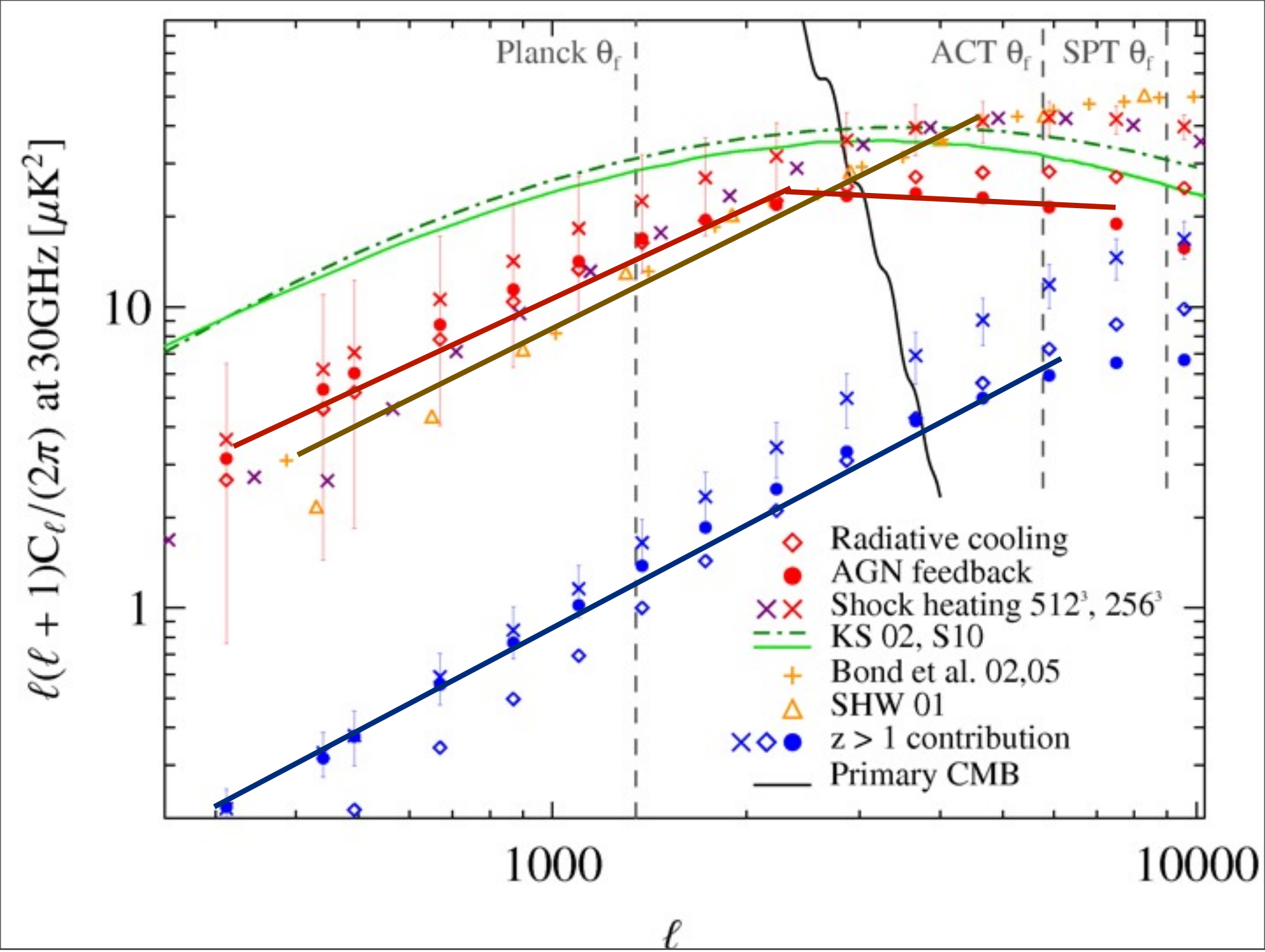
full Sijacki-resolution was/is ~ infeasible for single massive clusters, and certainly strongly infeasible for big-box statistically useful samples, & also itself is just a subgrid model hence our **exploratory subgrid BH feedback model**

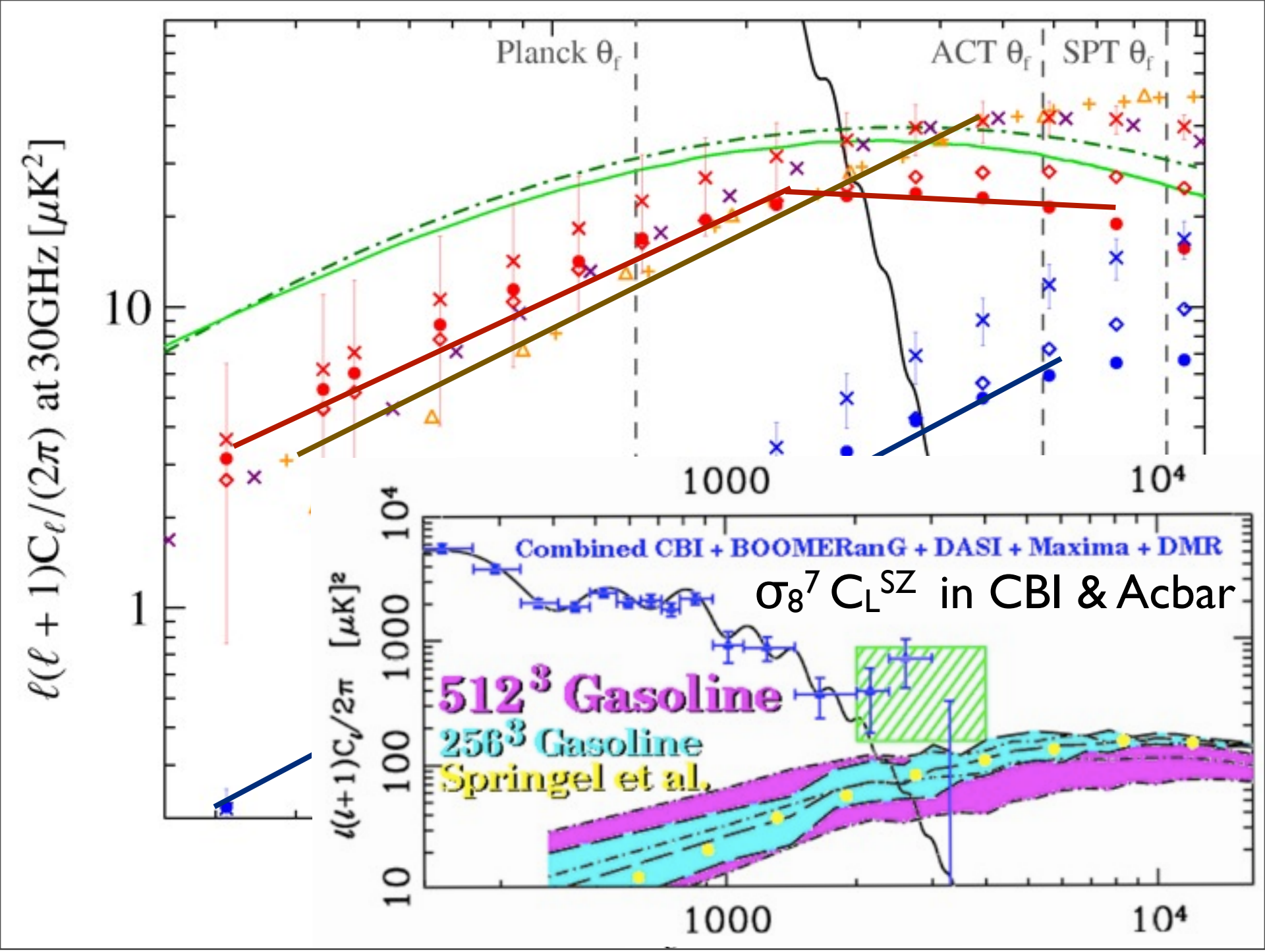
AGN feedback + cool + SN E + winds: $\Delta E_{inj} \sim \varepsilon \Delta t$ SFR over R_{AGN} in halo centre, episodic above a SFR threshold, $\varepsilon_{eff} < \varepsilon$: most E_{inj} above z=2, so much freedom to minimize ε_{eff} e.g., E_{inj} 58% at $z > 2$, 23% in $1 < z < 2$ 19% z<1

conclusion circa 2010: $\nexists$ *universal panacea to cure cluster cores: episodic and cluster-history-dependent. if observables are overly sensitive to this, then we become gastrophysical weather reporters and not cosmological gold-sample miners delivering pure cosmic parameters. BUT most relevant SZ-region* ***~$0.5R_{500}$ to ~$3R_{200}$*** $\Rightarrow$ *different set of non-thermal problems.*

we do need a hydrodynamically-reasonable inner core (beware of cutouts from overcooled cores)


Planck θ_f
ACT θ_f
SPT θ_f
$\ell(\ell+1)C_\ell/(2\pi)$ at 30GHz [μK^2]
10
1
1000
10000
ℓ
AGN feedback
Shock heating 512^3, 256^3
z > 1 contribution
Primary CMB

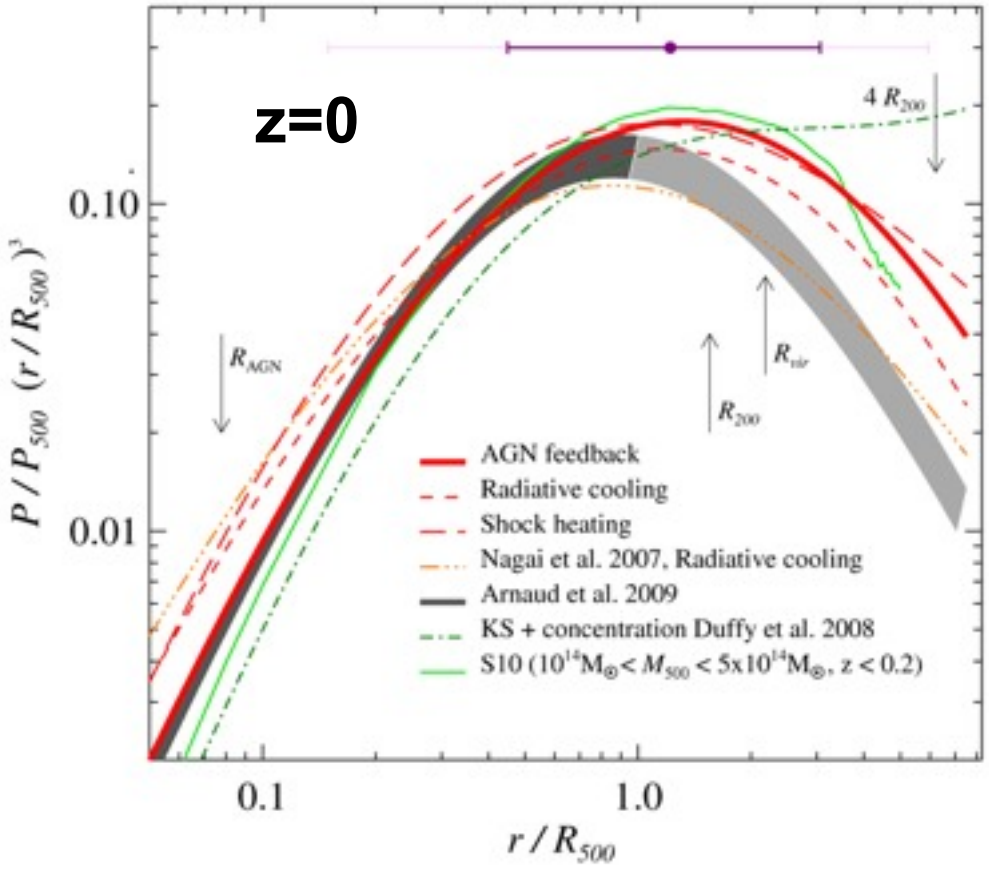

Planck θf
ACT θf
SPT θf
10
1
1000
10000
ℓ
ℓ(ℓ + 1)Cℓ/(2π) at 30GHz [μK²]
Radiative cooling
AGN feedback
Shock heating 512³, 256³
KS 02, S10
Bond et al. 02,05
SHW 01
z > 1 contribution
Primary CMB


Planck θ_f
ACT θ_f
SPT θ_f
$\ell(\ell+1)C_\ell/(2\pi)$ at 30GHz [μK^2]
10
1
1000
10^4
Combined CBI + BOOMERanG + DASI + Maxima + DMR
$\sigma_8^7 C_L^{SZ}$ in CBI & Acbar
512^3 Gasoline
256^3 Gasoline
Springel et al.
$\ell(\ell+1)C_\ell/2\pi$ [μK]^2
10
100
1000
10^4
1000
10^4

(10 256^3 gas+DM) ΛCDM *spherialize-scale-stack* cluster profiles, with Y_{SZ} weighting, also z (& type) bins. *types=??*

for fast MCMC C_L^{SZ}(cosmic & internal-cl parameters) with nonG statistics a la peak patch or ..
includes all non-th & non-eq effects

better: *rotate-into-principal-axes - scale-stack* profiles



(10 256^3 gas+DM) ΛCDM *spherical-scale-stack* cluster profiles, with Y_{SZ} weighting, also z (& type) bins. *types=??*

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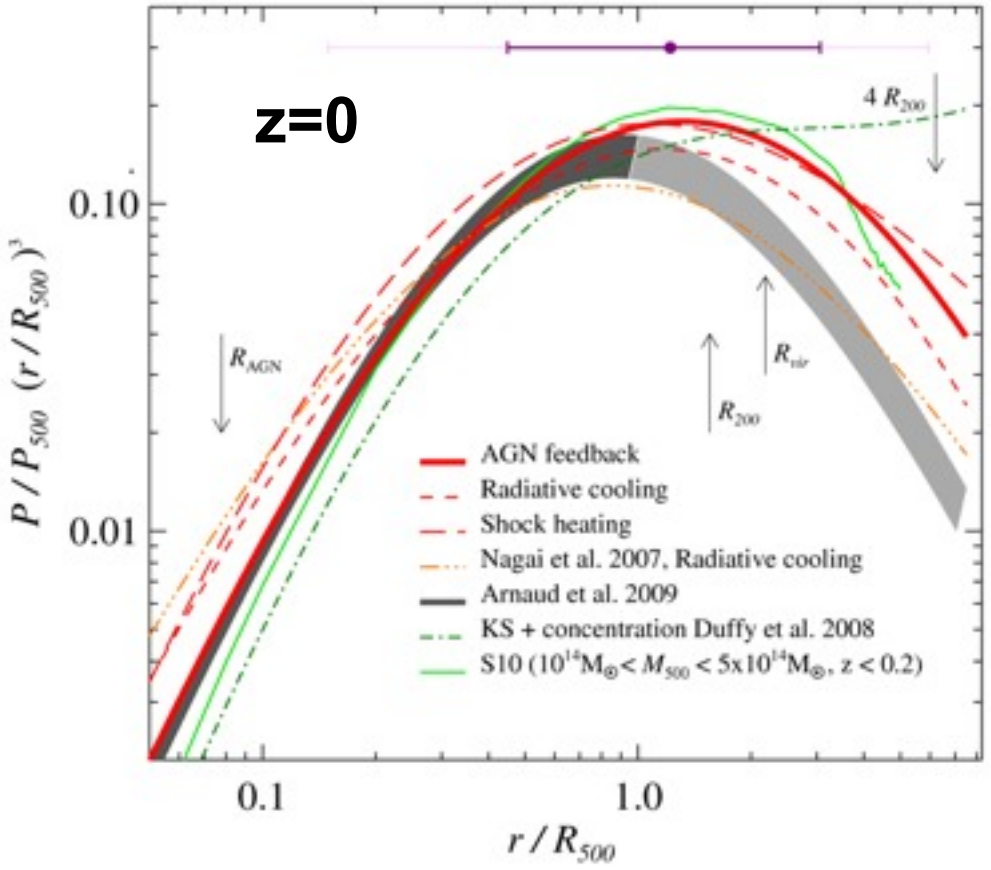


cluster ENTROPIES with INTERNAL BULK KINETIC ENERGY

s per particle **= $\int$[-f ln f +f] dVdV_p / $\int$f dVdV_p** *(MB corrected for BE/FD)*

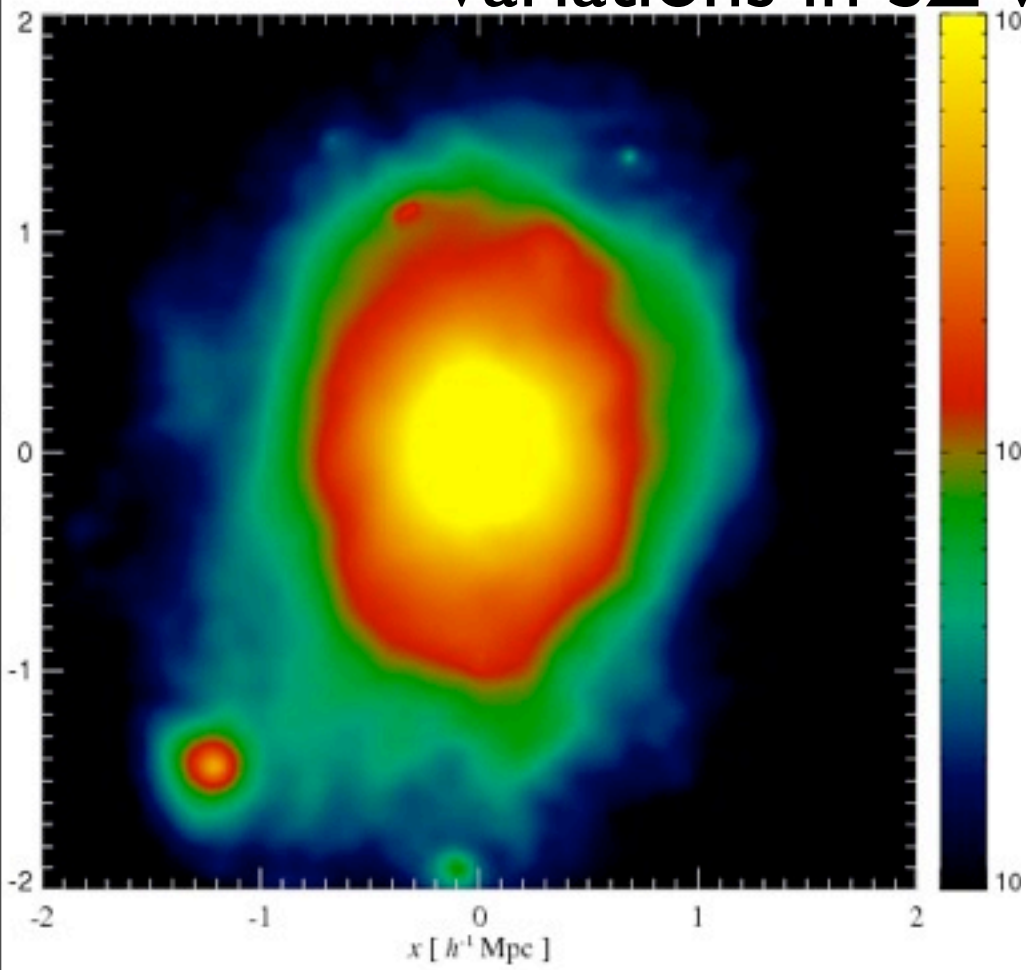
$$\Delta s_{th} = Y_T\ 3/2\ (ln\ p_{th} - 5/3\ ln\ \rho_g), \quad Y_T = \sum Y_A$$

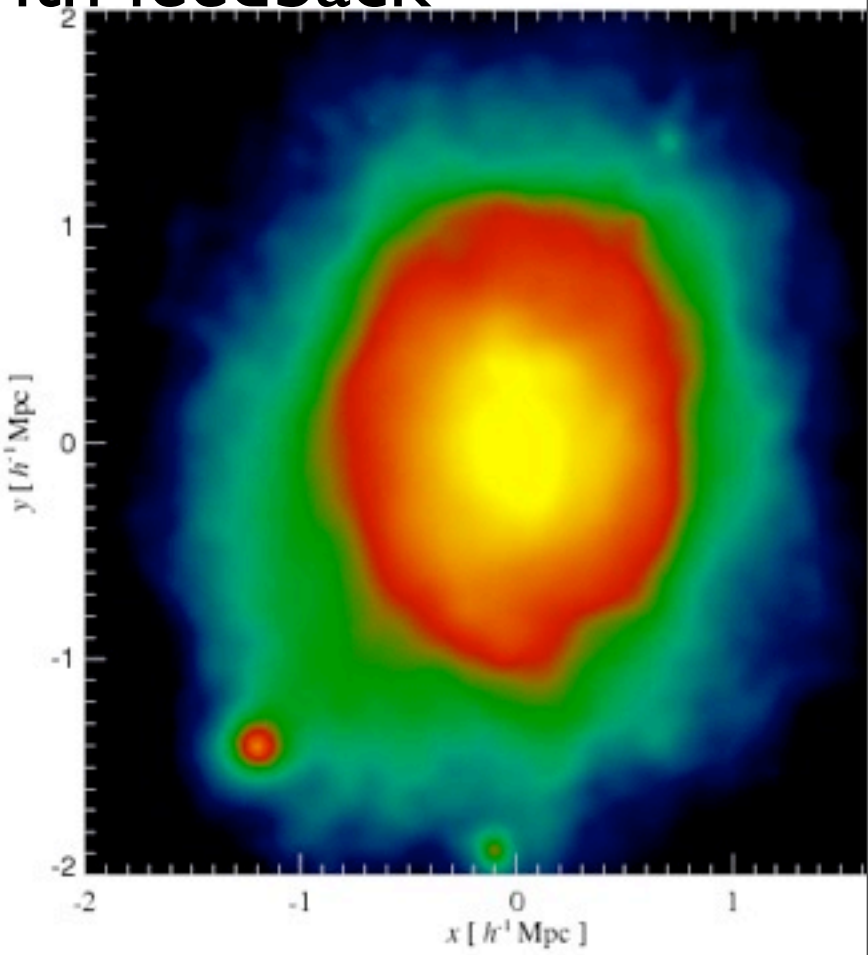
$$\Delta s_{tot} - \Delta s_{th} = \sum Y_A\ 1/2\ \mathrm{Trace}\ ln(\ I + m_A/m_p\ (p_{kin}\ I + \Pi_{kin})/p_{th}\ )$$

entropy-per gas-baryon cf. entropy-per-DM-particle

$$\Delta s_{dm} = 3/2\ (ln\ (p_{kin}\ I + \Pi_{kin})/3 - 5/3\ ln\ \rho_{dm})$$

Variations in SZ with feedback



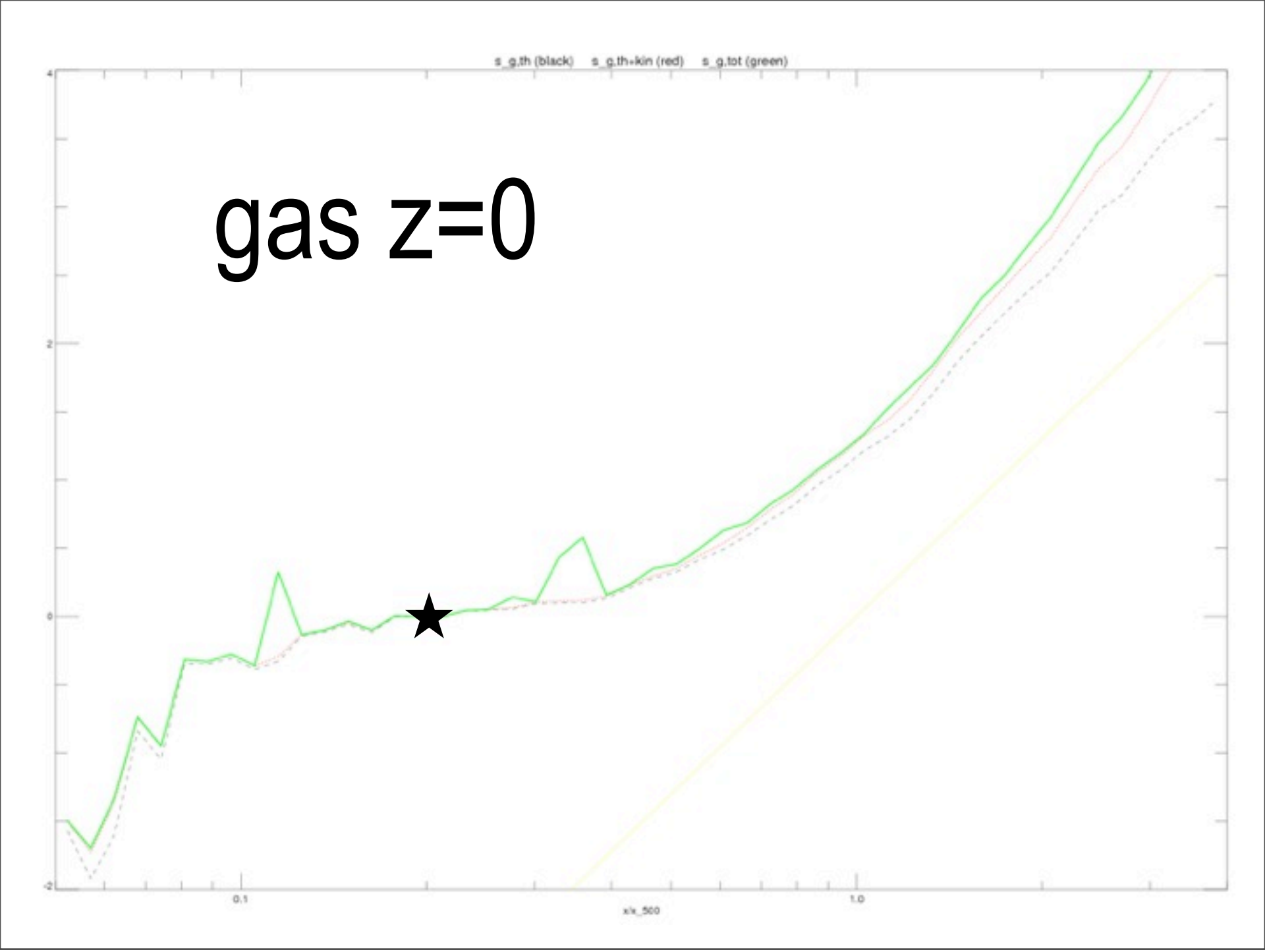


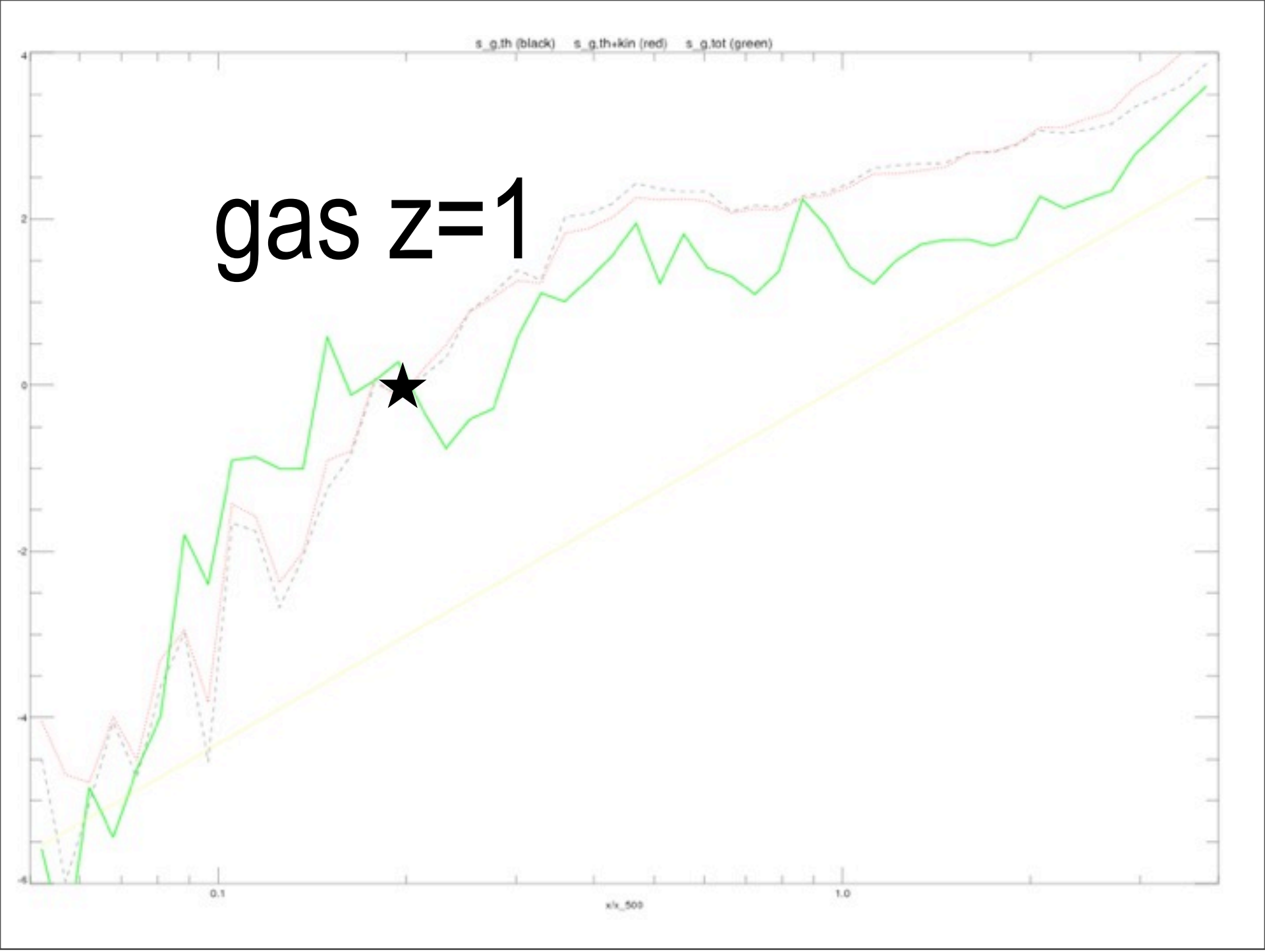
+ gas cooling + star formation +CR

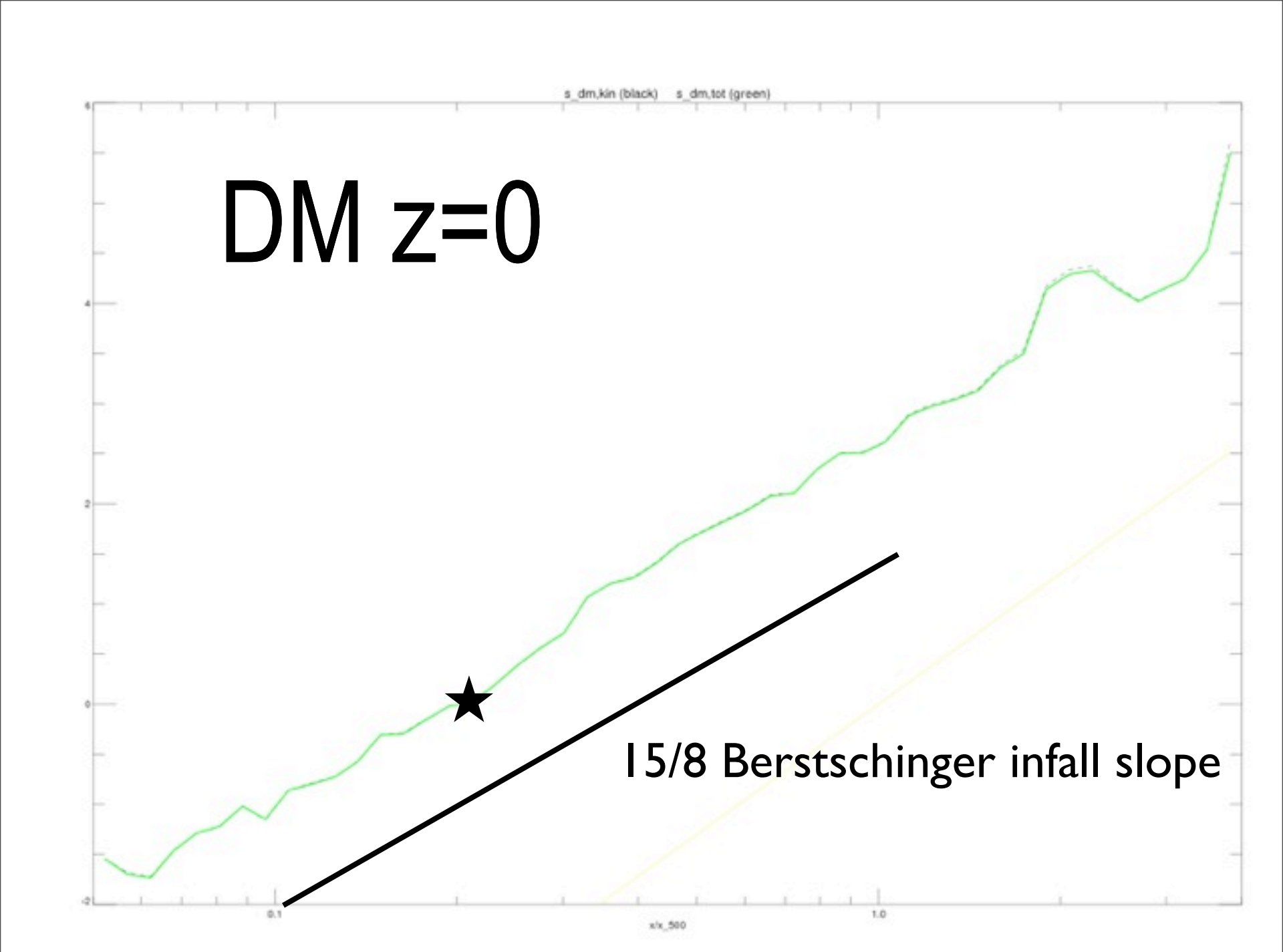
+ "AGN" feedback

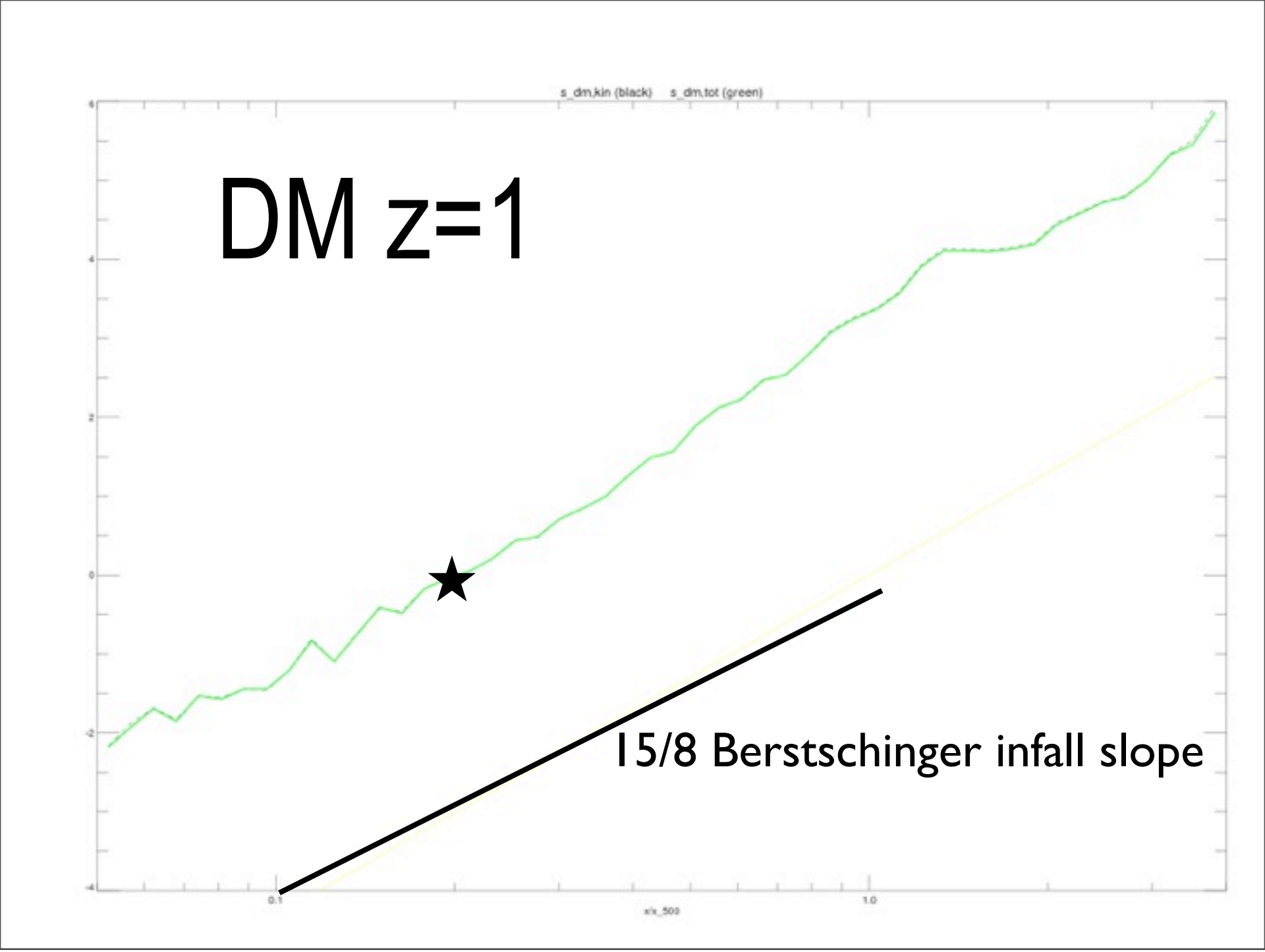
high res ICM follow-ups are essential to make a robust subgrid algorithm (& a cluster catalogue for cosmology ...)

Battaglia, Bond, Pfrommer, Sievers, Sijacki 2010 ~20 hi res *+JunLong* 40x2 hi-res vary ΔE_{inj}


s_g.th (black) s_g.th+kin (red) s_g.tot (green)
gas z=0
4
2
0
-2
0.1
1.0
x/x_500


s_g.th (black) s_g.th+kin (red) s_g.tot (green)
gas z=1
4
2
0
-2
-4
-6
0.1
1.0
x/x_500


s_dm,kin (black) s_dm,tot (green)
DM z=0
15/8 Berstschinger infall slope
6
4
2
0
-2
0.1
1.0
x/x_500

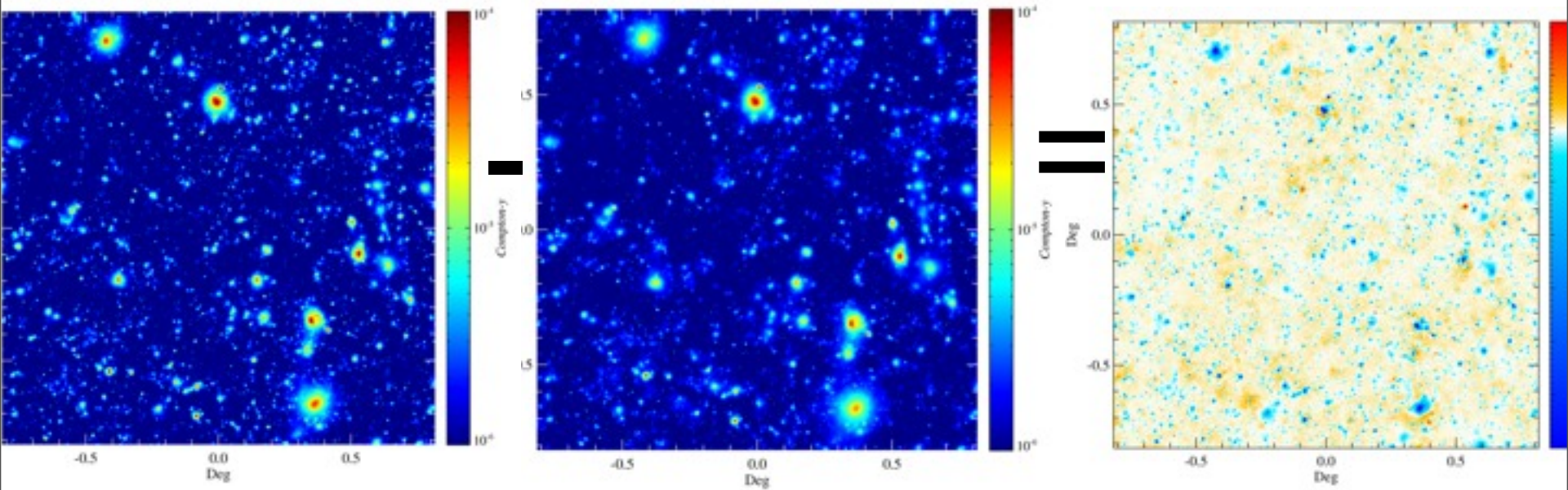

s_dm,kin (black) s_dm,tot (green)
DM z=1
15/8 Berstschinger infall slope
0.1
1.0
x/x_500

CITA SZ templates with feedback *Battaglia, Bond, Pfrommer, Sievers, Sijacki 2010*

256^3 workhorse sims, 10 x 3cases

rotate and translate periodic boxes at many z-bins - sample lots and lots of virtual maps to compute the mean and variance of C_L^{SZ}

512^3 box sims ~ 8 **256^3** box sims, but stats for 10 is much better



shock heat only - *adiabatic*

AGN E-feedback + radiative cool + SN energy + winds

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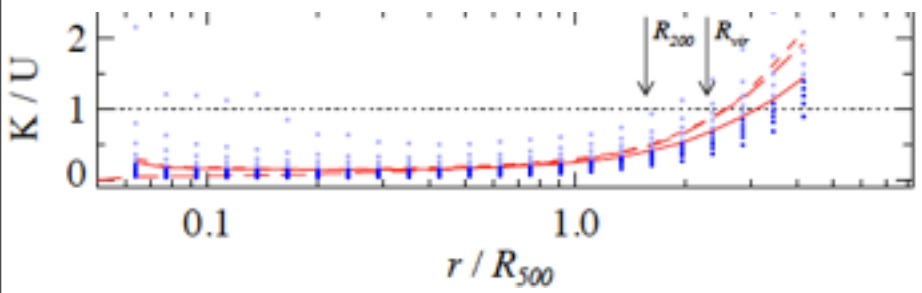
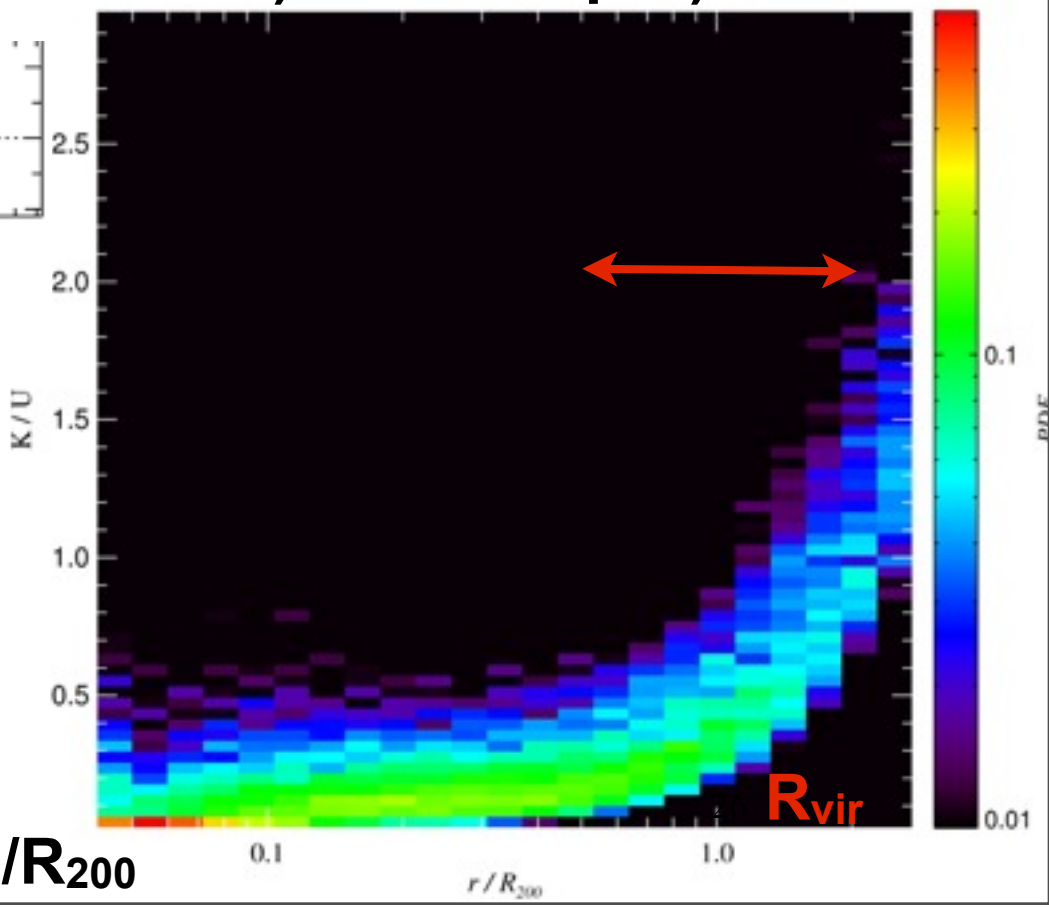
$$\Delta s_{dm} = 3/2\, (\mathit{ln}\ (p_{kin}\, I + \Pi_{kin})/3 - 5/3\ \ln \rho_{dm})$$

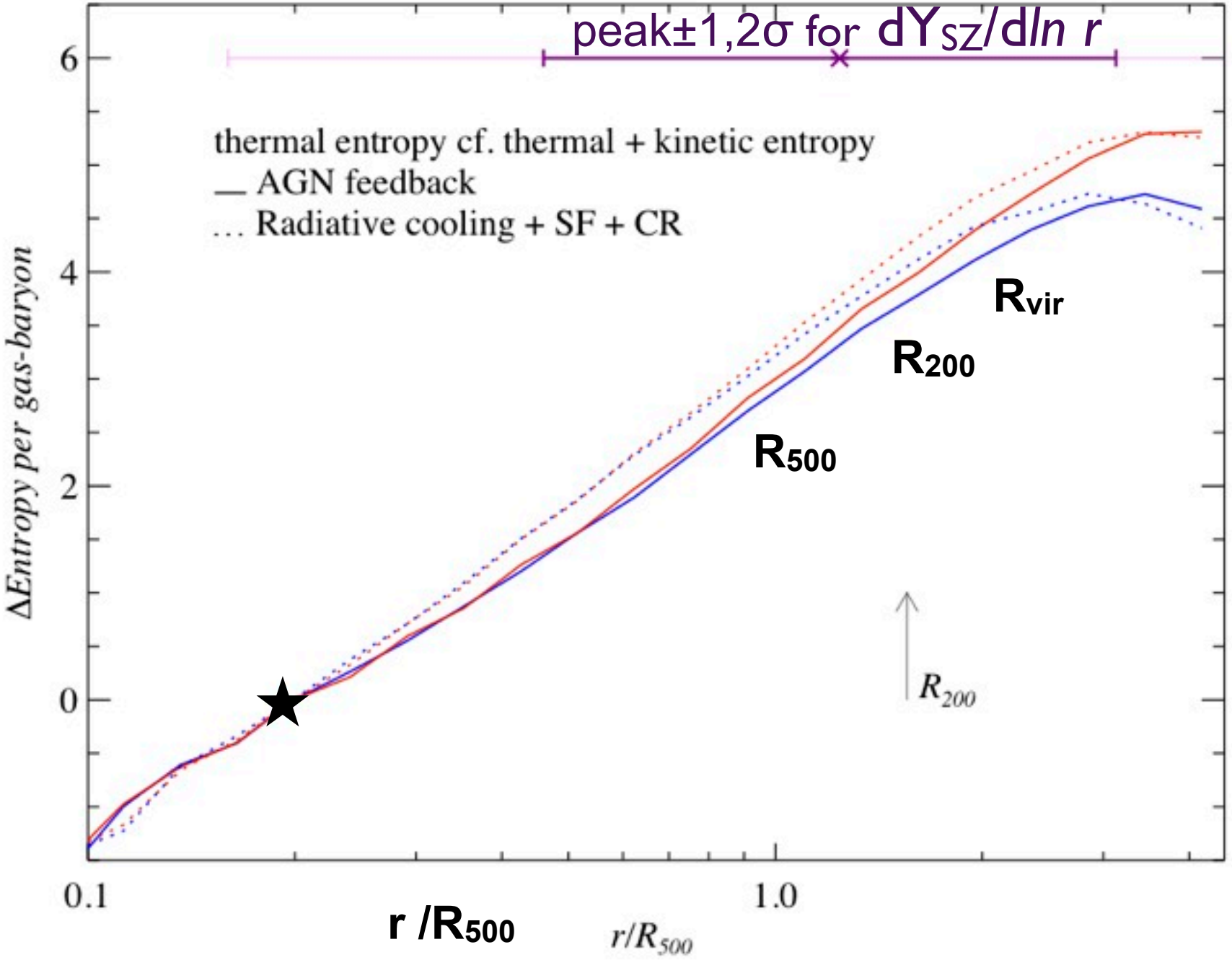


probability distribution for
$\int p_{kin} / \int p_{th}\ (<r)$ *vs.* r/R_{200}



r /R_{200}

Entropy Profiles for Y_{SZ}-weighted Scaled Stacked Clusters



cluster ELLIPTICITY TENSORS for gas and DM

$U_{g,ij} = \int dm_g\, x_i\, x_j\, w(x) / \int dm_g\, x^2\, w(x)$, *weight $w(x) = 1/x^2$ (does not overweight the outskirts) cf. moment of inertia $w(x)=1$*

$U_{dm,ij}$ for DM

($U_{p,ij} = \int dPV\, x_i\, x_j\, w(x) / \int dPV\, x^2\, w(x)$, $dPV = pdV$

p_{th} for SZ, p_{tot} for virial equation & cluster masses)

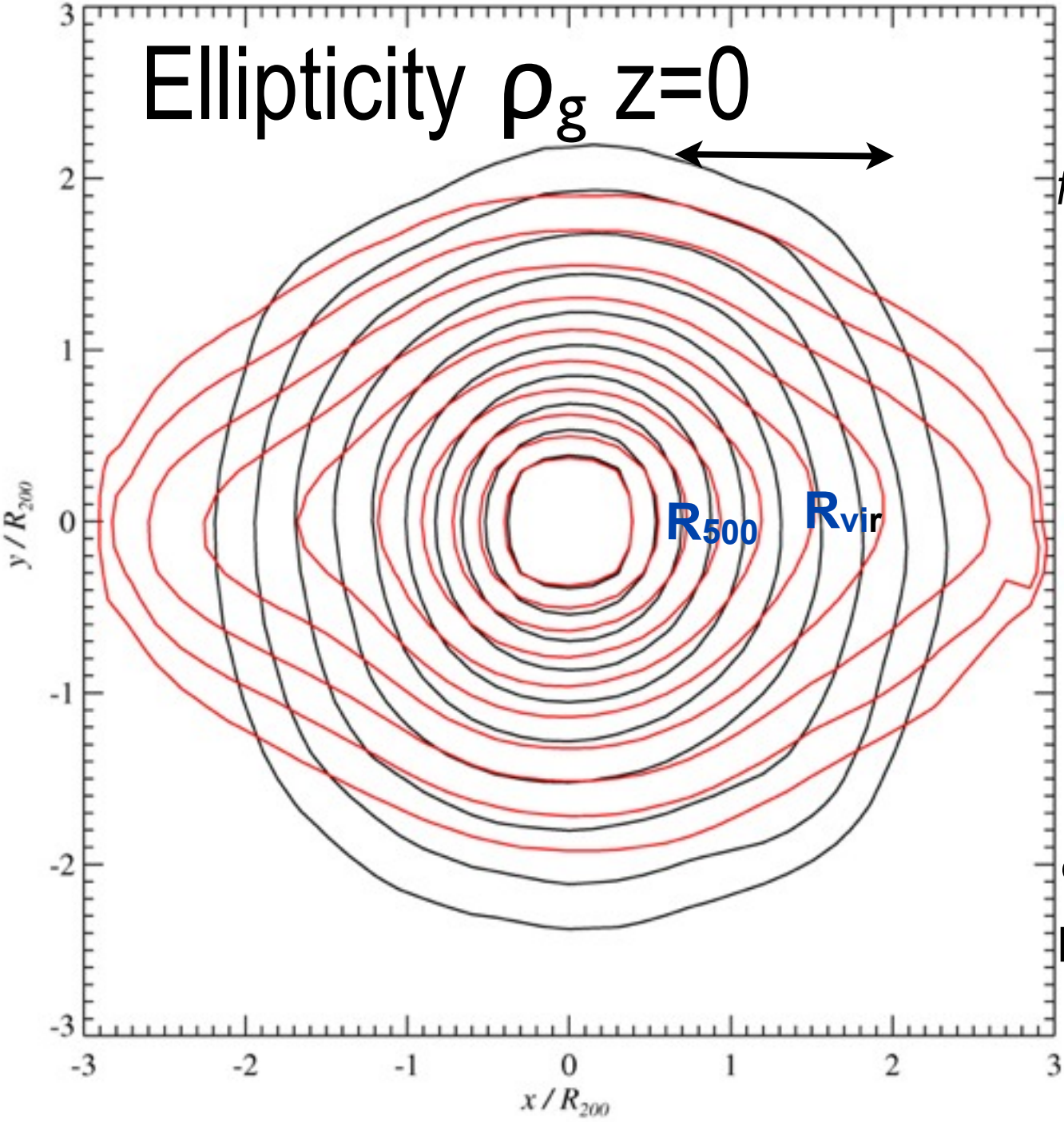
rotate to principal axes, scale & stack

eigenvalues $u_1 > u_2 > u_3 \Rightarrow$

ellipticity e = $(u_1 - u_3)$ *I2Trace***U,**

prolaticity *(if >0, oblaticity if <0)* **p = $(u_1 - 2u_2 + u_3)$** *I2Trace***U**

Ellipticity ρ_g z=0



gas in cluster-Y_{SZ} "far-field" is increasingly elongated: a little near-field filament penetration

e(gas) < e(DM) /2

.

e(<x_{500}) =0.040±.019

DM =0.092±.028

e(<x_{200}) =0.040±.019

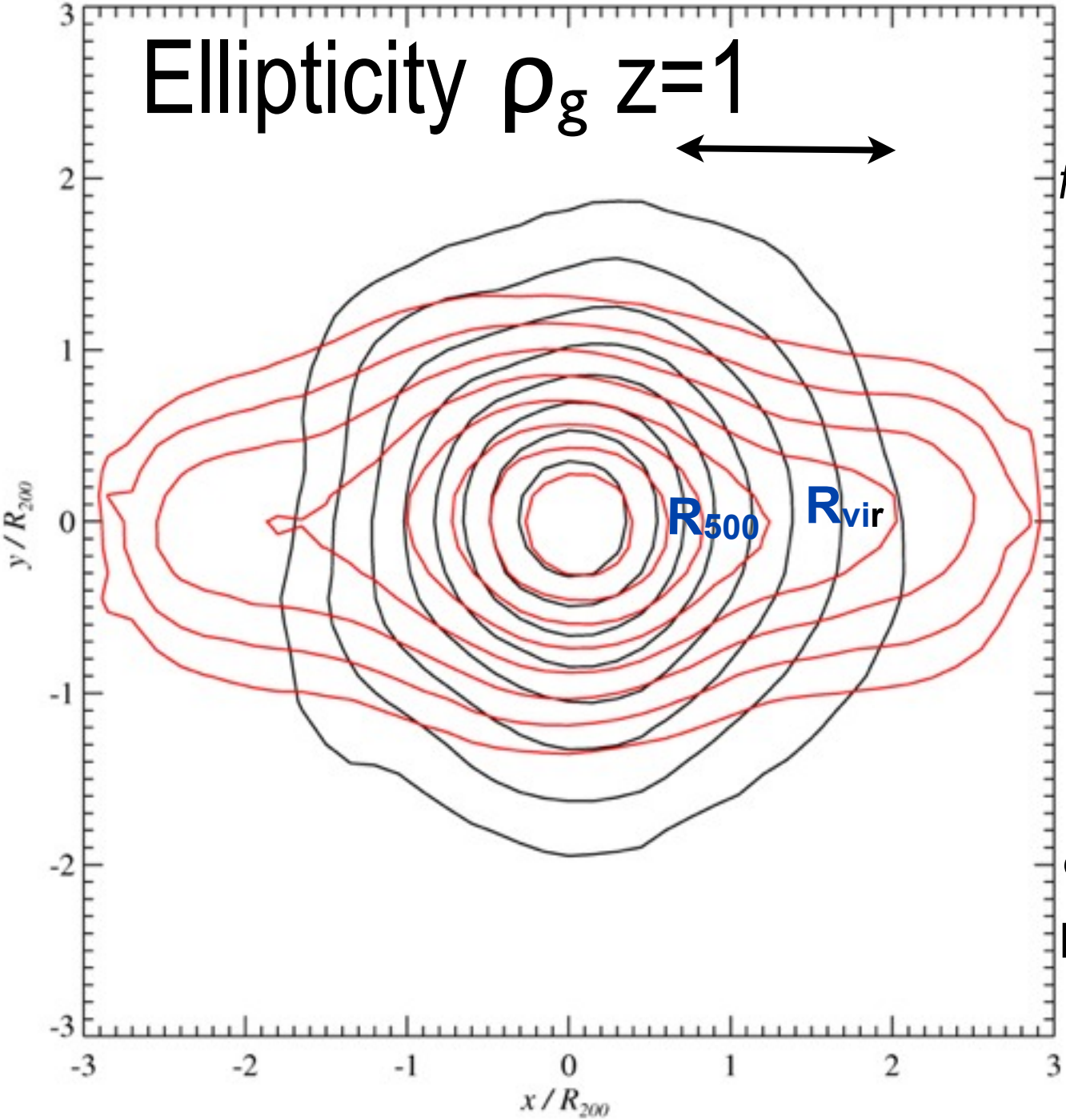
DM =0.096±.029

e(<3x_{200})=0.065±.031

p(<3x_{200})=0.029±.034

p(<x_{200})=0.009±.021

Ellipticity ρ_g z=1



gas in cluster-Y_{SZ} "far-field" is increasingly elongated: a little near-field filament penetration

e(gas) < e(DM) /2

z=1 extreme cf. z=0

e(<x_{500}) =0.052±.040

DM =0.106±.039

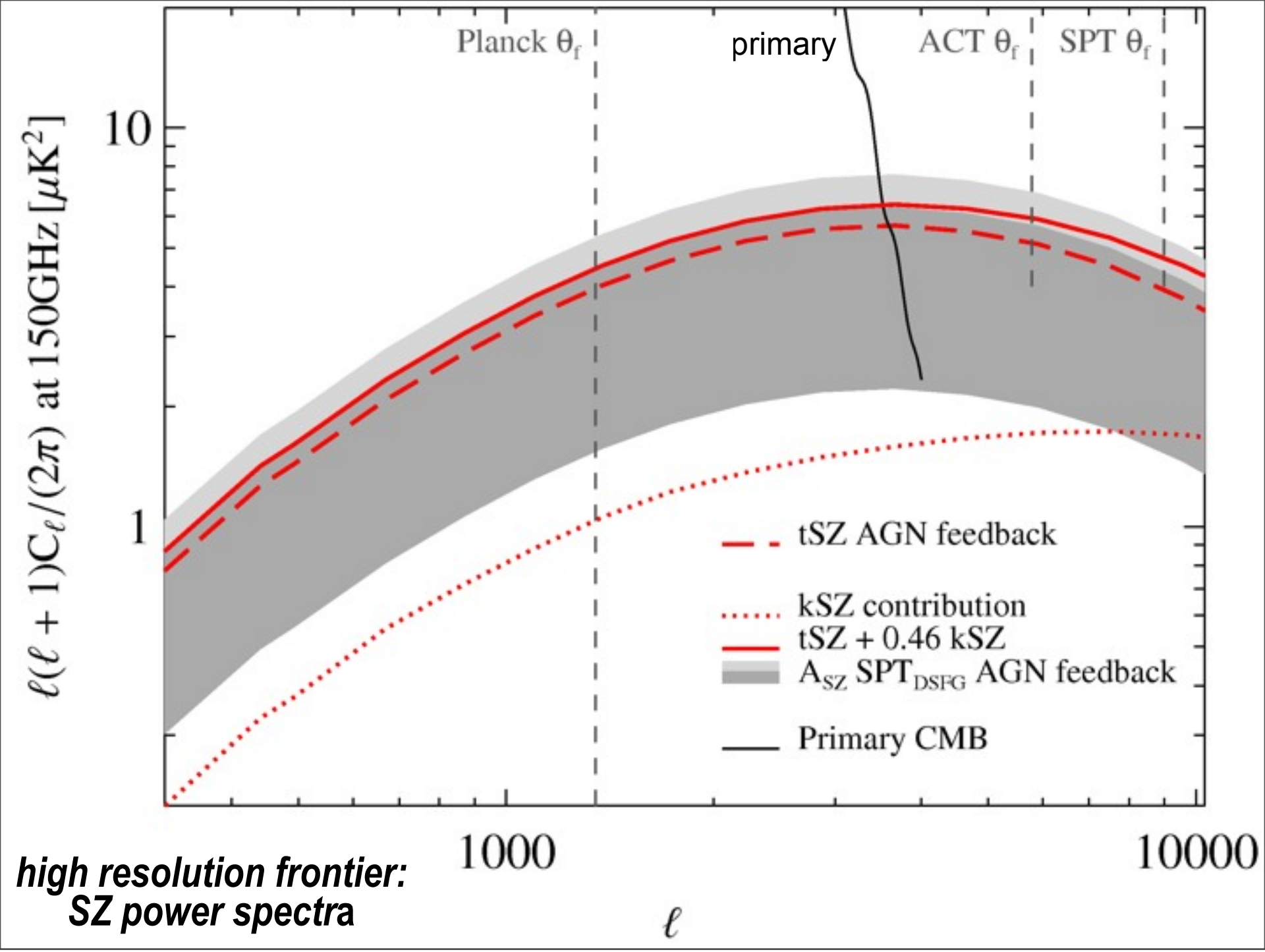
e(<x_{200}) =0.056±.041

DM =0.111±.041

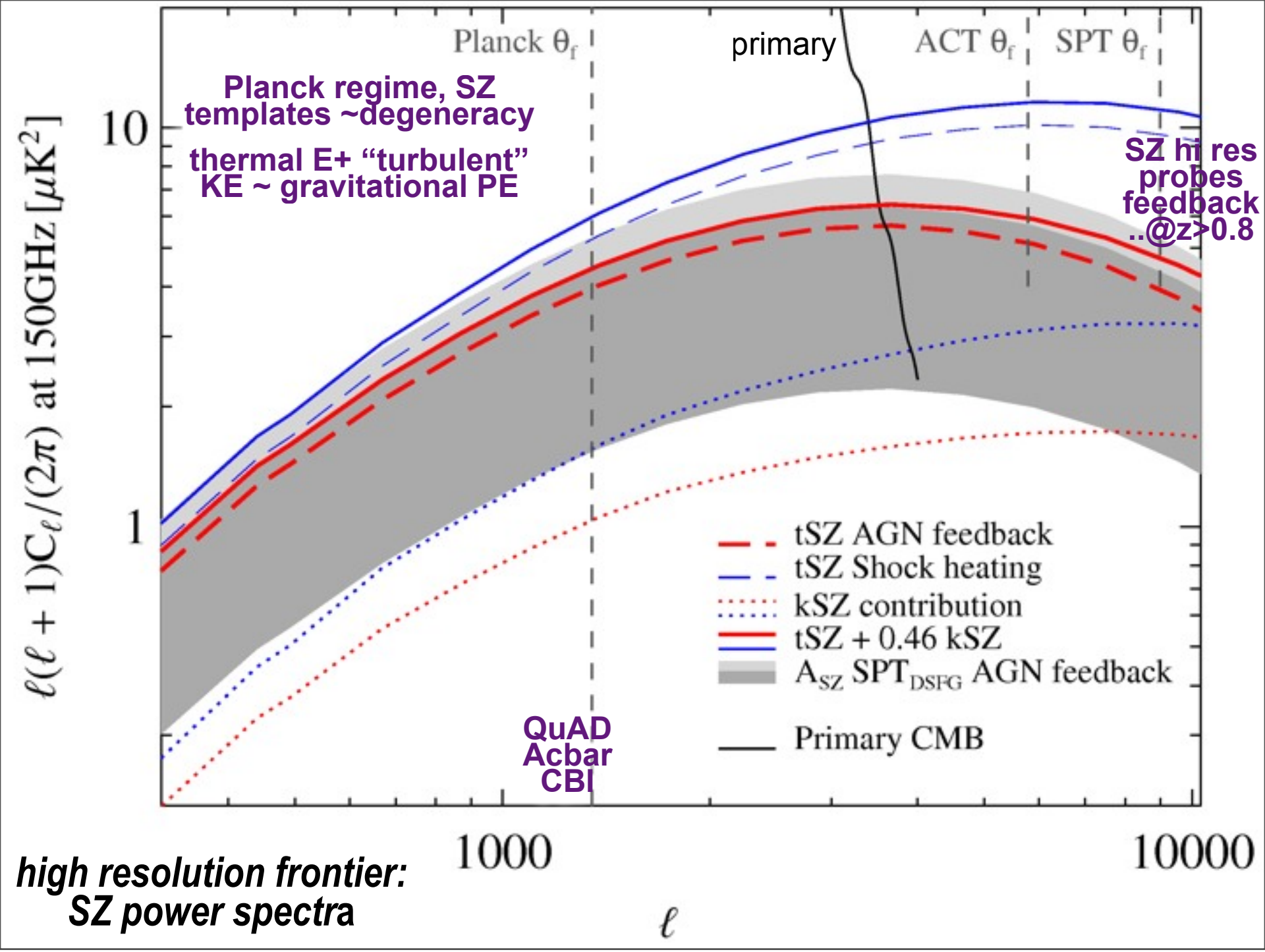
e(<3x_{200})=0.113±.035

p(<3x_{200})=0.044±.051

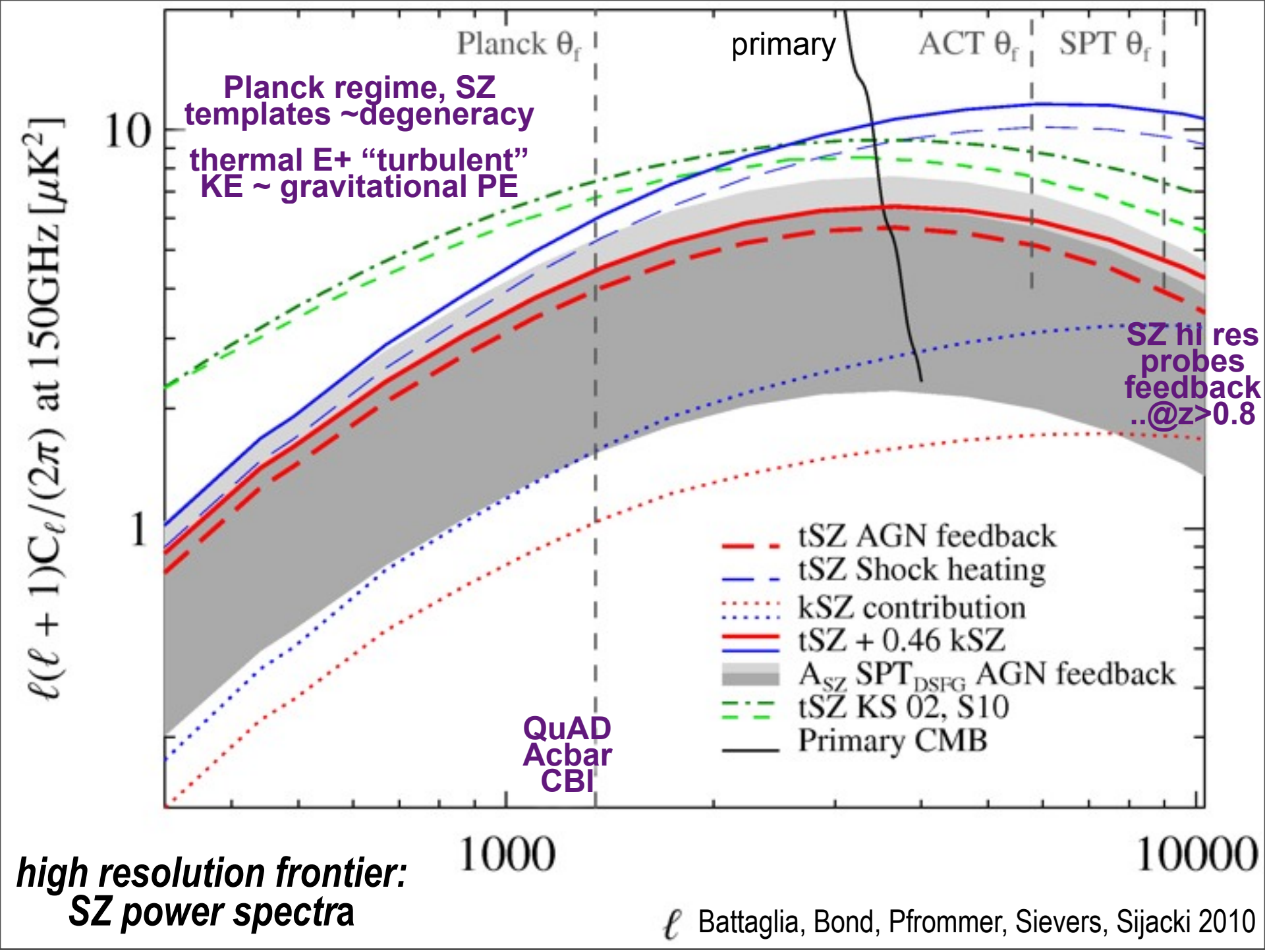
p(<x_{200})=0.021±.046



high resolution frontier:
SZ power spectra

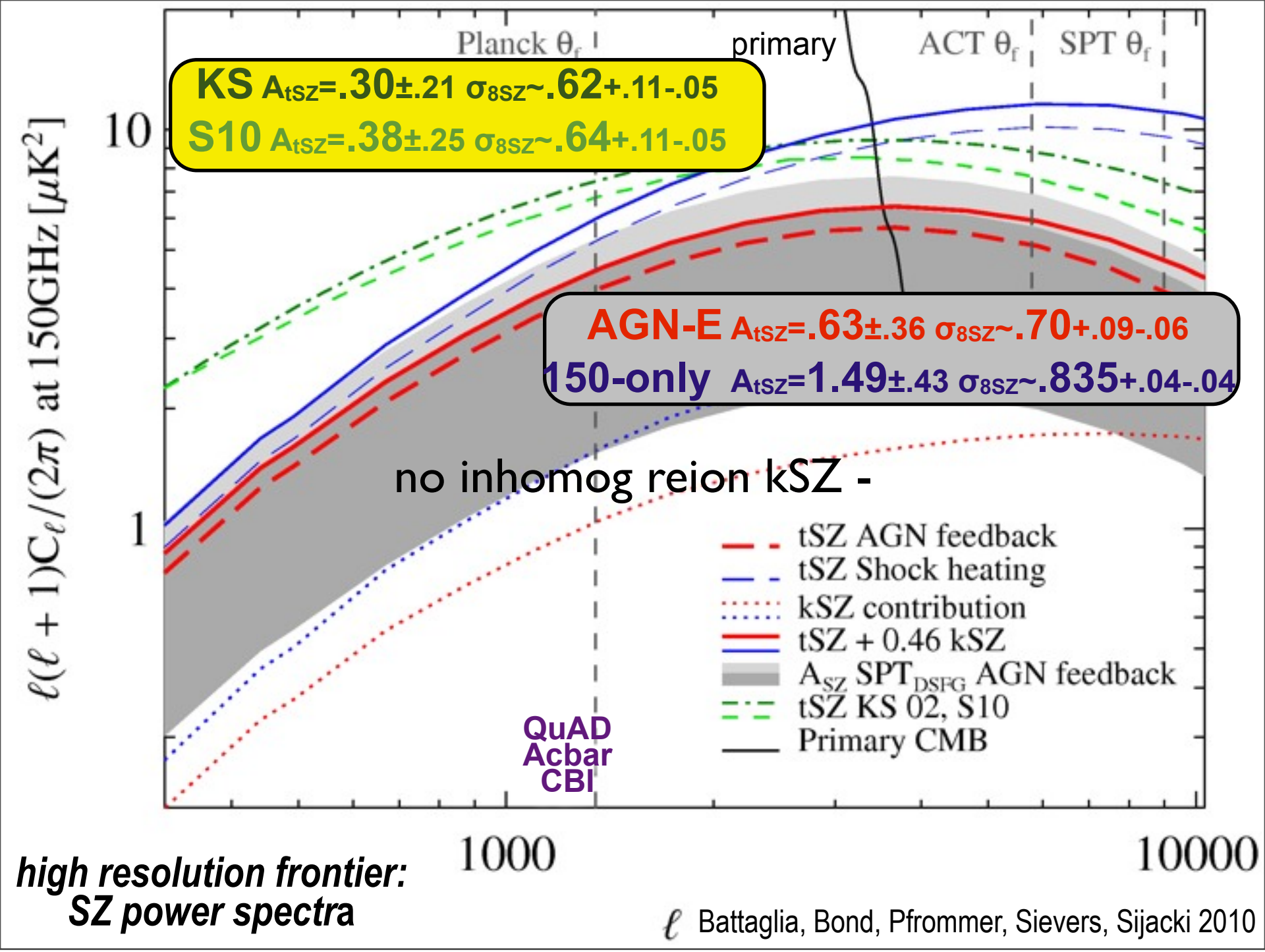


high resolution frontier: SZ power spectra



high resolution frontier: SZ power spectra

Battaglia, Bond, Pfrommer, Sievers, Sijacki 2010



high resolution frontier:
SZ power spectra

Battaglia, Bond, Pfrommer, Sievers, Sijacki 2010

Planck θ_f | primary | ACT θ_f | SPT θ_f

KS A_{tSZ}=.30±.21 σ_{8SZ}~.62+.11-.05

S10 A_{tSZ}=.38±.25 σ_{8SZ}~.64+.11-.05

AGN-E A_{tSZ}=.63±.36 σ_{8SZ}~.70+.09-.06

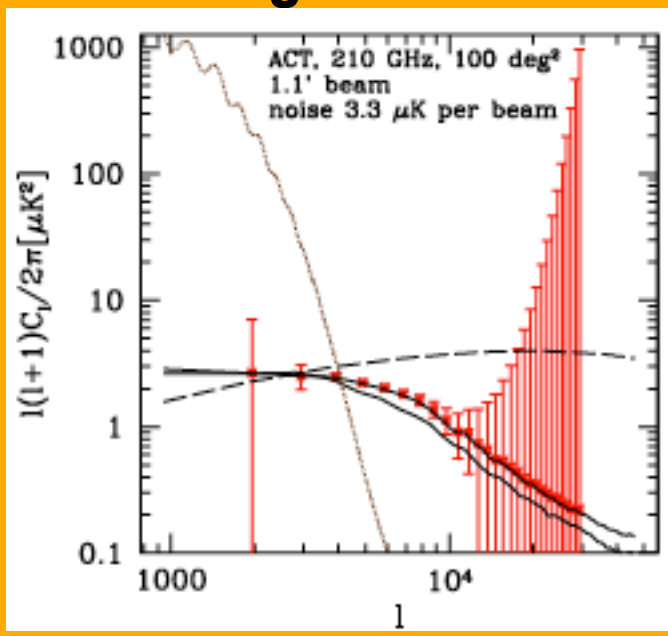
150-only A_{tSZ}=1.49±.43 σ_{8SZ}~.835+.04-.04

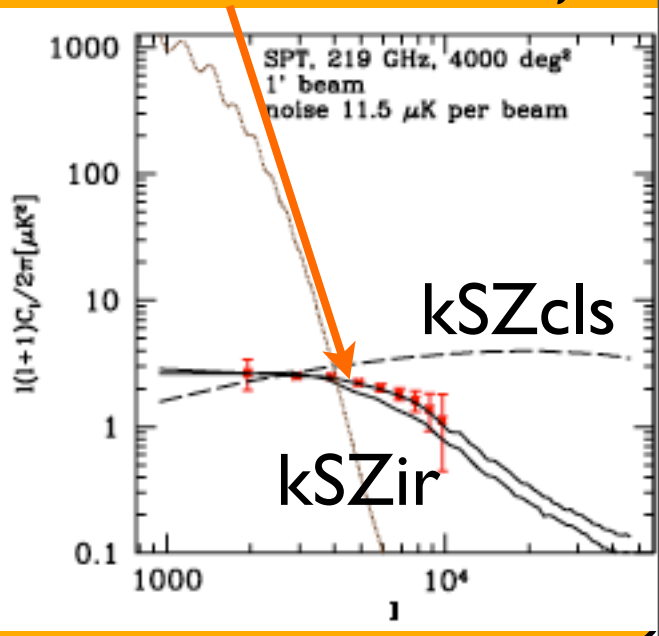
$\ell(\ell+1)C_\ell/(2\pi)$ at 150GHz [μK^2]

10

1

no inhomog reionization-kSZ** but **Iliev etal 07,08





high resolution frontier: SZ power spectra

ℓ Battaglia, Bond, Pfrommer, Sievers, Sijacki 2010

much TBD

max entropy to get an "optimal" ellipticity tensor?

$$\Delta S = \int [[-f \ln f + f] - [-f \ln f_{model} + f_{model}]] \, dV dV_p$$