


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

Dick Bond

CIAR

the theory of the Sunyaev-Zeldovich Probe of Gas in the Cosmic Web

$\gamma + e \rightarrow \gamma + e$ Compton

$\langle \Delta E_\gamma / E_\gamma \rangle = 4 T_e / m_e c^2 - E_\gamma / m_e c^2$

$\langle (\Delta E_\gamma / E_\gamma)^2 \rangle = 2 T_e / m_e c^2$

thermal SZ: $\Delta T/T = y * (x(e^x+1)/(e^x-1)-4), \; x = h\nu/T_\gamma$

$y = \int n_e (T_e - T_\gamma)/m_e c^2 \, \sigma_T \, d\mathit{los} \sim \int p_e \, d\mathit{line\text{-}of\text{-}sight}$

Compton y-parameter

kinetic SZ: $\Delta T/T = \int n_e \mathbf{v}_{e||} /c \, \sigma_T \, d\mathit{los} \sim \int J_e \, . \, dr$

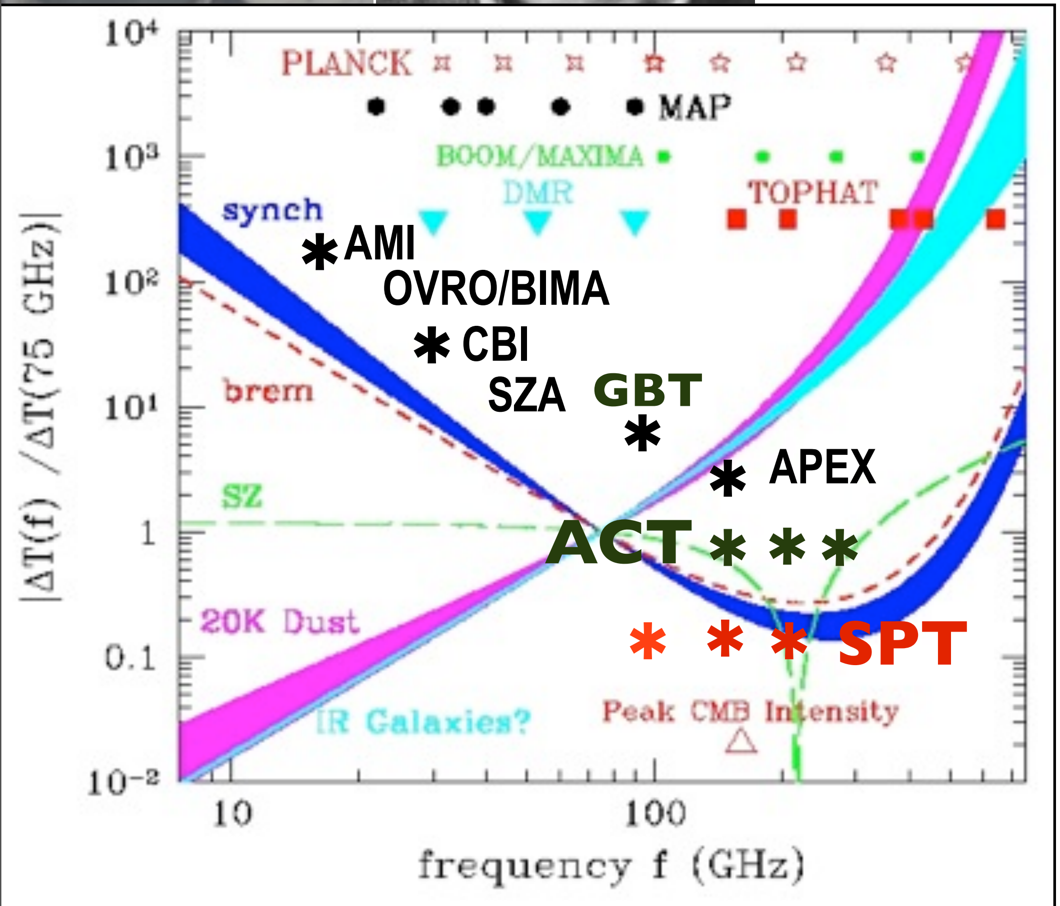
$\int kSZ(\theta,\varphi) d\Omega \sim M_{gas} V_{bulk} / D_A^2$

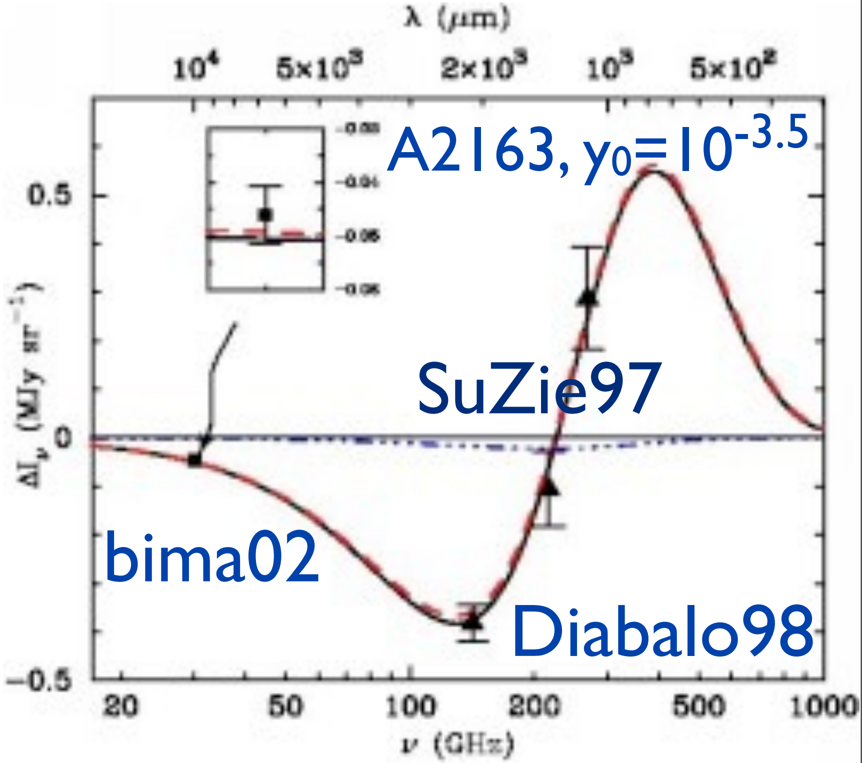
the theory of the Sunyaev-Zeldovich Probe of Gas in the Cosmic Web: $y \sim \int p_e \, d$line-of-sight

$\Delta T/T = y * (x(e^x+1)/(e^x-1)-4)$, $x = h\nu/T_\gamma$

$= -2y$ to xy, **0 @ ν=217 GHz**

$\Delta I_\nu = \Delta T/T * x^4 e^x/(e^x-1)^2$

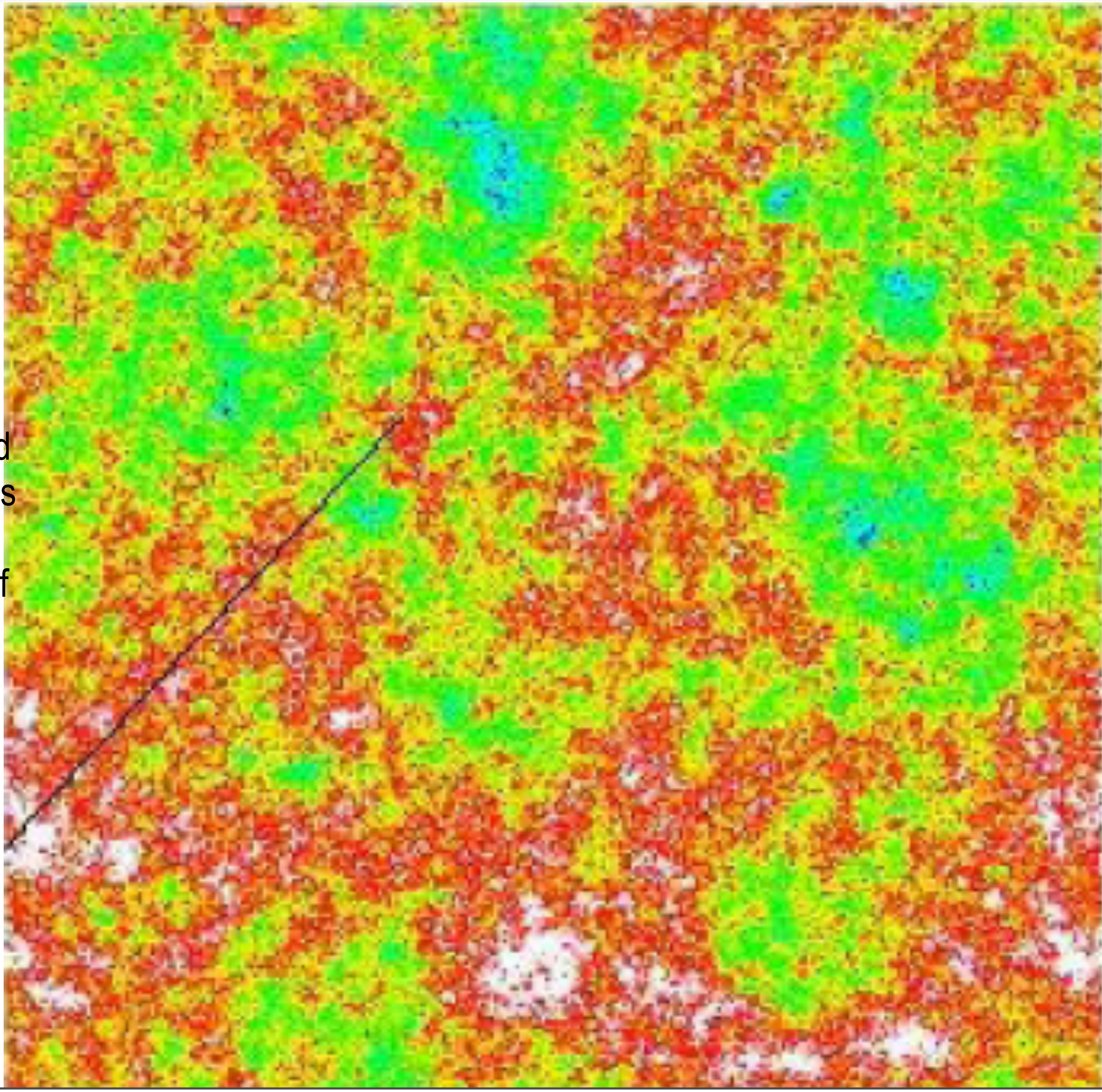




Tuesday, February 22, 2011

fluctuations in the **early universe "vacuum" grow** to *all* **structure**

scalar field fluctuations in the vacuum of the ultra-early Universe



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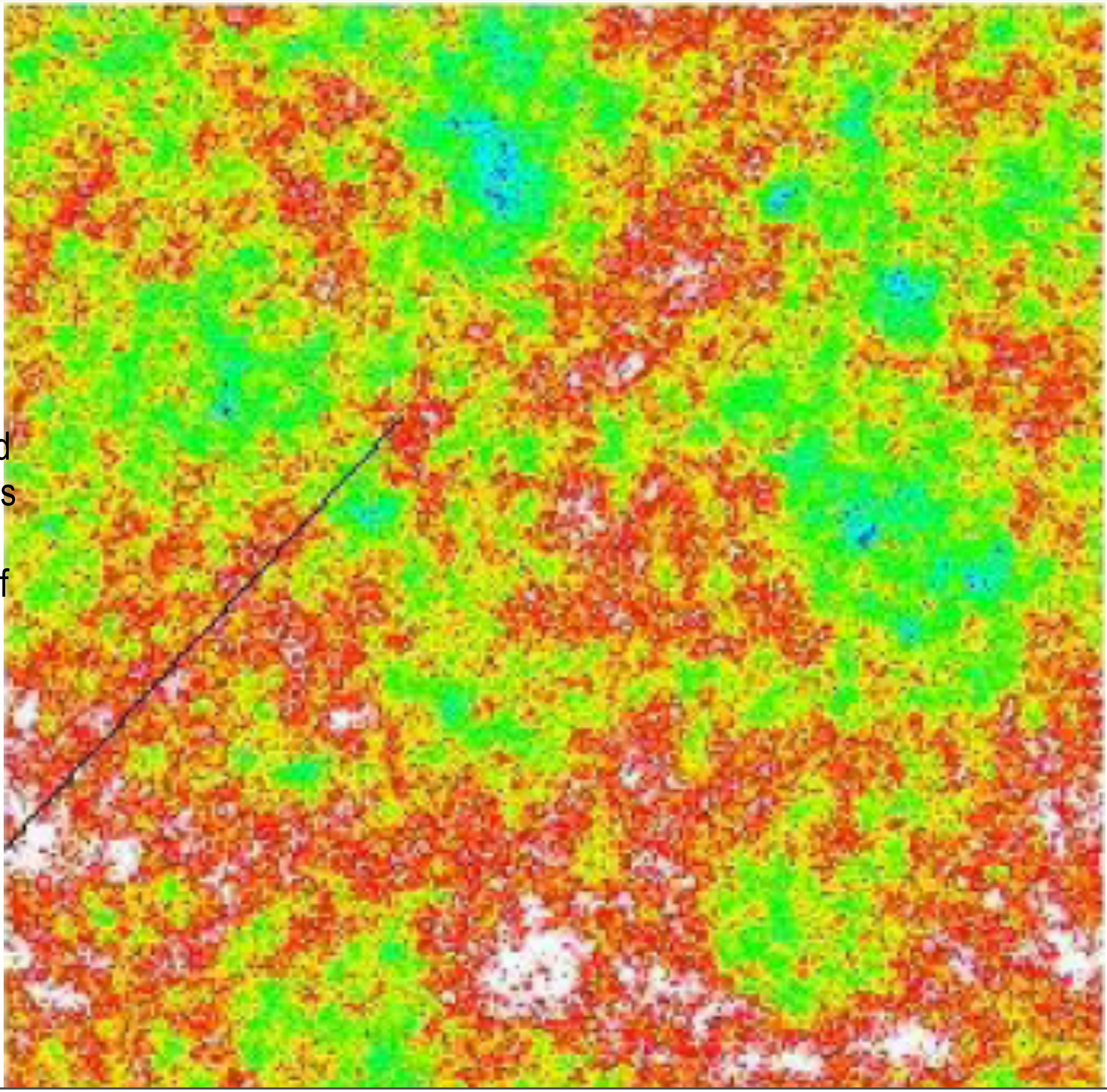


evolve from early U vacuum potential and vacuum noise

fluctuations in the **early universe "vacuum" grow** to ***all*** **structure**

400 Mpc

ΛCDM

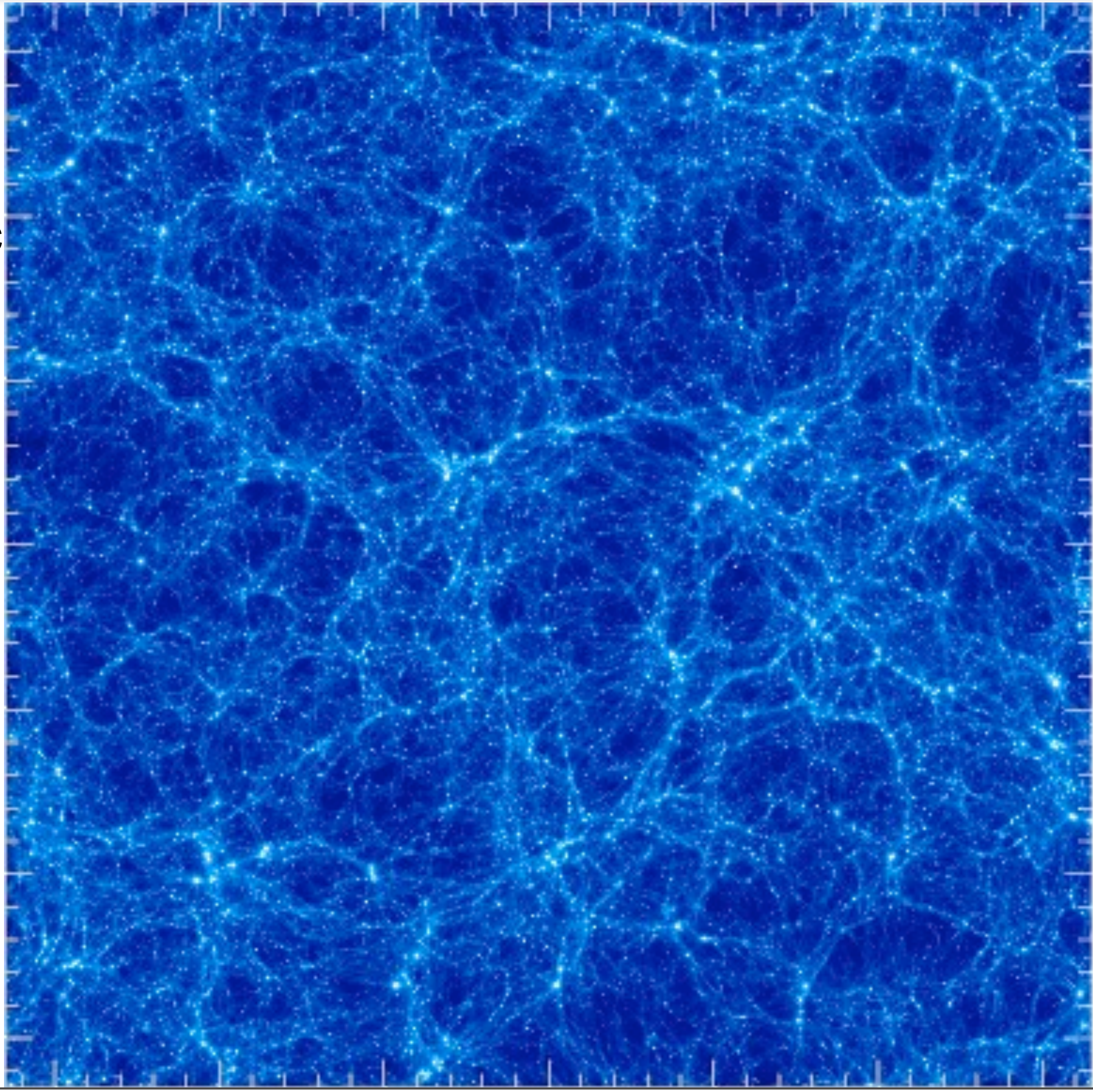
WMAP5

gas density

Gadget-3

SF+ SN E+ winds +CRs

512^3



all this can

evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential aka dark energy

pressure intermittency *in the cosmic web, in cluster-group concentrations probed by* **tSZ**

400 Mpc

ΛCDM

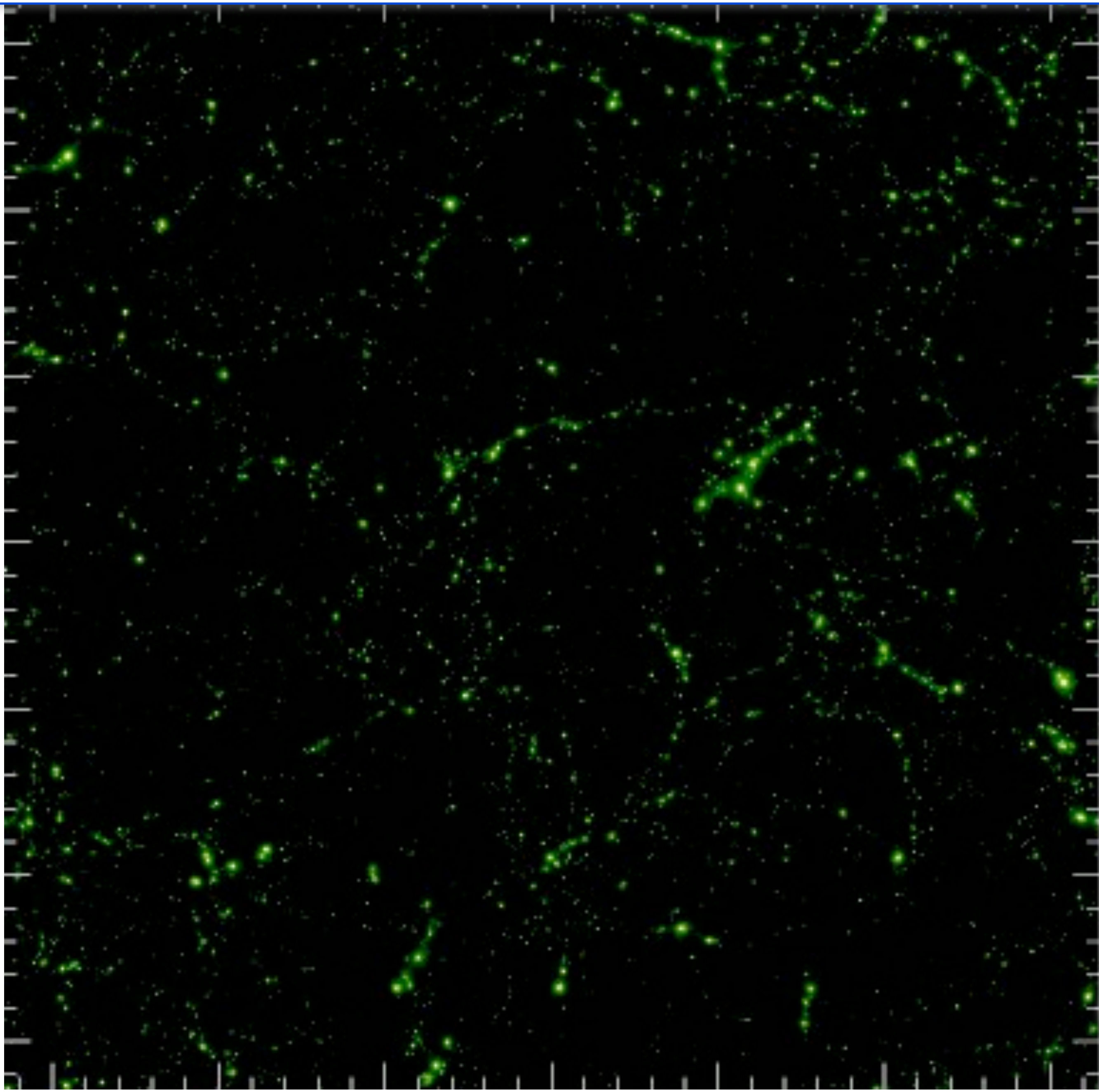
WMAP5

gas pressure

Gadget-3

SF+ SN E+ winds +CRs

512^3



entangled in the cosmic web

descending into the real gastrophysics of cosmic weather

the energetic, turbulent, dissipative, compressive life of the IGM/ICM/ISM

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$y = \int n_e (T_e - T_\gamma)/m_e c^2\, \sigma_T\, d los \sim \int p_e\, d$*line-of-sight*

Compton y-parameter

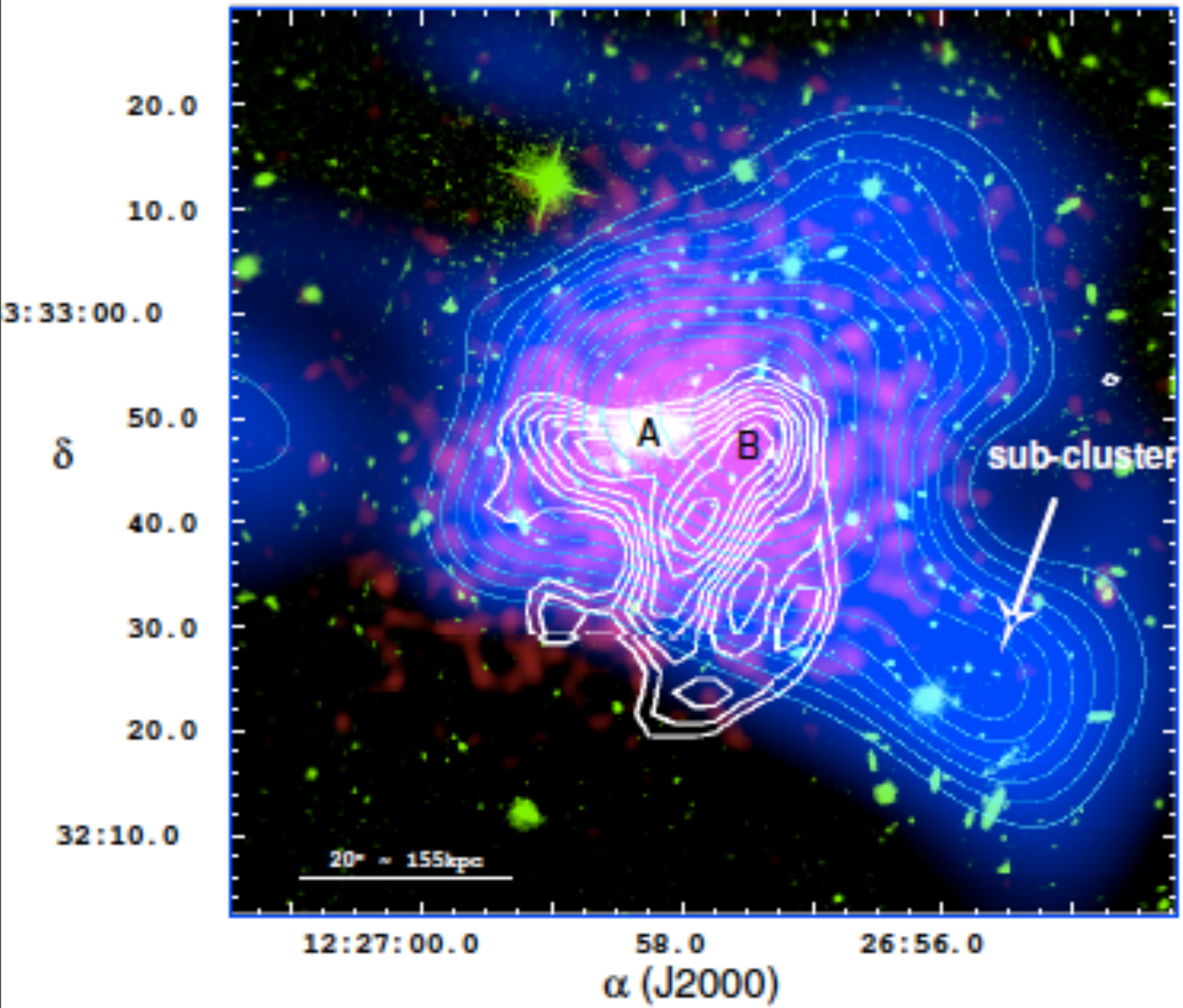
$Y_\Delta = \int y(\theta,\varphi) d\Omega \sim E_{th} / D_A^2 \sim (E_{grav} - 3 P_{kinetic,etc} V + 3 P_s V)/2 D_A^2$

VIRIAL THEOREM: $E_{grav} \sim G M_g M/R \sim M^{5/3}$ **dark matter dominated**

kinetic SZ: $\Delta T/T = \int n_e v_{e||} / c\, \sigma_T\, d los \sim \int J_e . dr$

$\int kSZ(\theta,\varphi) d\Omega \sim M_{gas} V_{bulk} / D_A^2$

Mustang on GBT 90 GHz 64 bolometer array Imaging SZ
@~10" res 4 cls 2010, ~25 Hubble CLASH cls to come Devlin, Mason, ...



CL1226 z=0.89

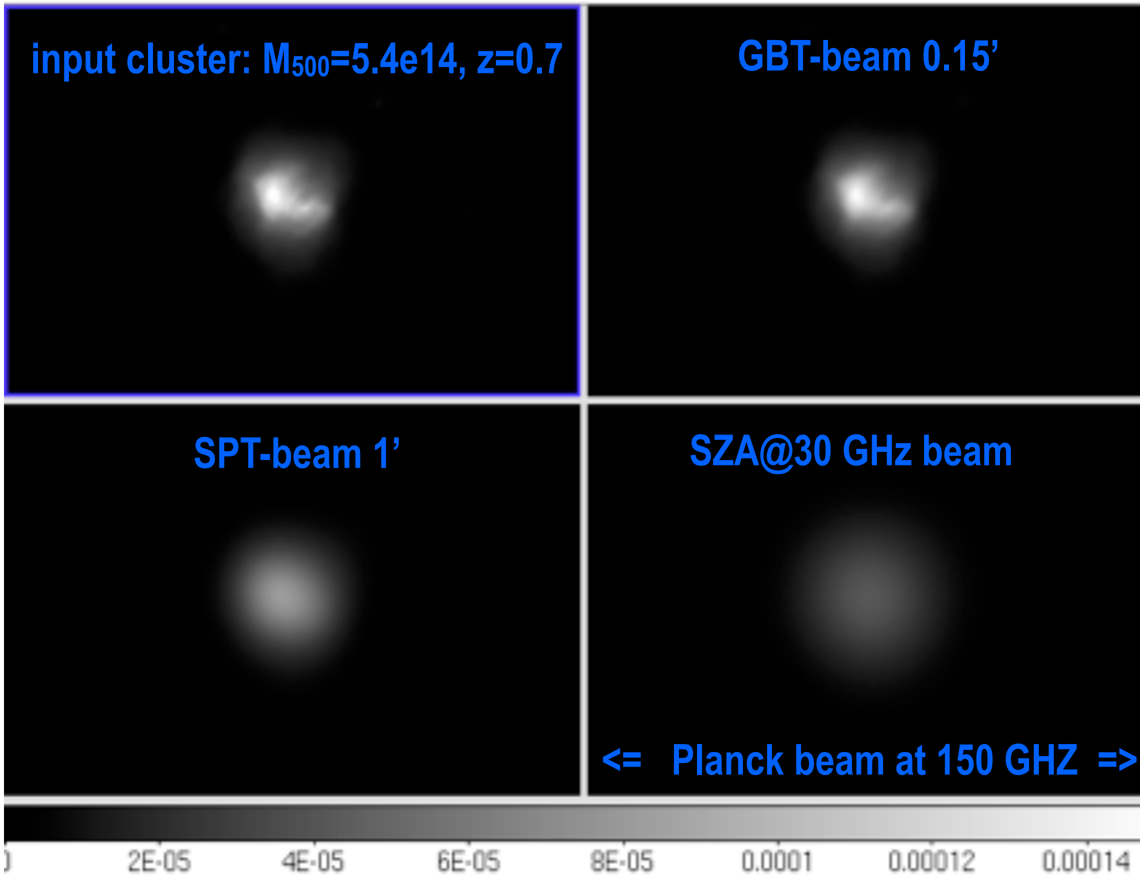
Red Chandra
Blue/cyan weak lens Σ
Green optical
White MUSTANG **SZ >3σ**

A BCG ~ X-ray peak
B Dark Matter peak
~ lobe of SZ ridge

7

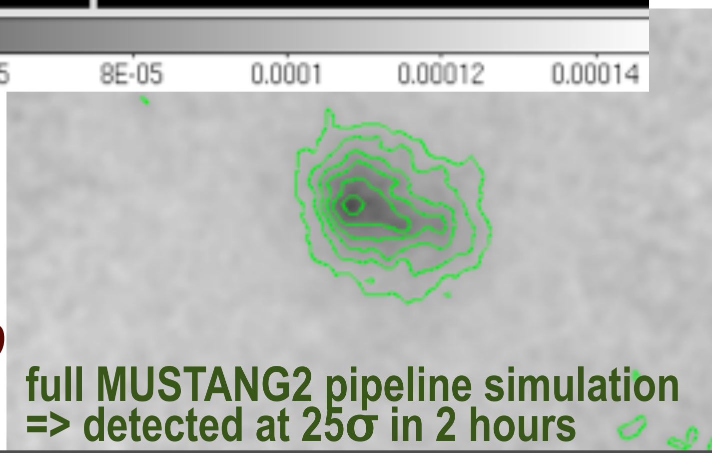
Mustang on GBT 90 GHz 64 bolometer array Imaging SZ @~10” res 4 cls 2010, ~25 Hubble CLASH cls to come Devlin, Mason, ...

future: High-Res SZ sim for MUSTANG2

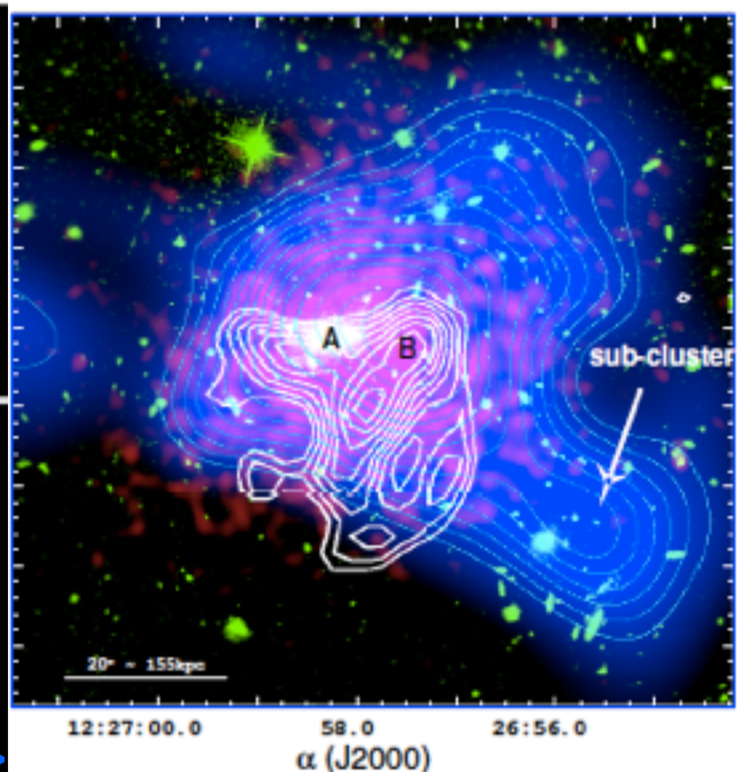


100x mapping speed!
160 cf. 64 pixels, over larger area (5’ vs. 40”)

=> Planck followup to 35σ in 1hr



now: CL1226 z=0.89



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

• **very small angle anisotropies** - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources

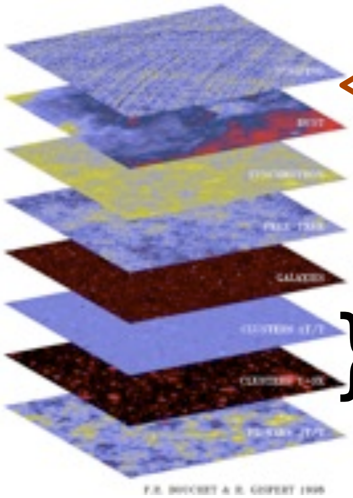
• **small angle anisotropies** - current results, optimal measuring strategies, statistical methods for

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

bond@ ΔT/Tea87: **"clustered shots"** (*aka* **halos** *aka* **bbks86-peaks**) with **spherical 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 2002-11 cf.*
SPH-hydro *(Gadget/Gasoline, MMH, ENZO, ART 2001-11; ITP cluster test 96-00):*
discrepancy from 2002*: big issue was/is: Δ 200 to 20, non-thermal* ***KE/Eth***

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 **half $\langle C_L^{SZ}\rangle_{3000}$** from **z>0.5** & **M<3x10^{14} $M_\odot$ h^{-1}**

CITA-SZ with feedback: *Battaglia, Bond, Pfrommer, Sievers & Sijacki 2010, BBPS 2011a,b,c*

for ACT+SPT+Planck** etal, **urgent to show the cluster-theory-variance as effects are added

07 goal large treePM-sph sims ($\sim 1000^3$ gas+DM)-NOT **08-11** goal 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***;

but *because of **core overcooling and overproduction of stars**, needed a **subgrid** model of **AGN/starburst feedback** in halo cores, calibrated with the (small mass) cluster-BH calculations of Sijacki (with Springel, Pfrommer, ...).* ***Feedback is the essence of Gastrophysical Cosmology. Energy/Momentum driven winds, Relativistic injection.***

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/Starburst feedback model**

AGN feedback + cool + SN E + winds: $\Delta E_{inj} \sim \epsilon \Delta t$ SFR over R_{AGN} in halo centre, episodic above a SFR threshold, $\epsilon_{eff} < \epsilon$: 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% $z<1$

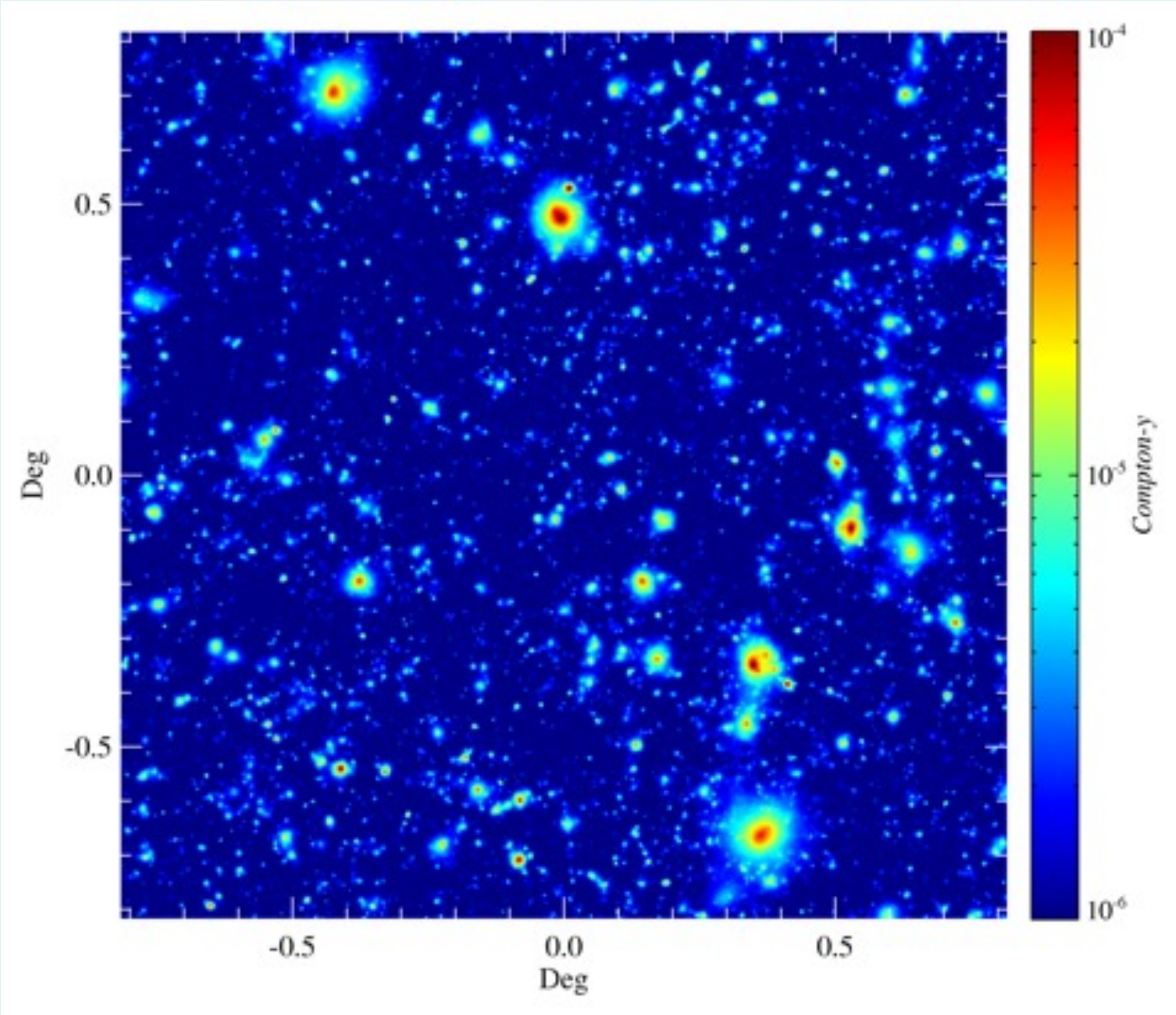
conclusion circa 2011:** ∄ universal panacea to cure cluster cores: highly inhomogeneous, episodic and cluster-history-dependent. if observables are overly sensitive to this, then we become gastrophysical weather reporters and not cosmological gold-sample miners delivering pure cosmic parameters. BUT **most relevant SZ-region $\sim 0.5R_{500}$ to $\sim 3R_{200}$ ⇒ different non-thermal problems:

***kinetic pressure aka "turbulence", pressure/density clumping, asphericity, ...** but we need hydrodynamically-reasonable inner cores hence subgrid feedback (beware of cutouts of overcooled cores)*

"every cluster is a bullet cluster" - or was a bullet

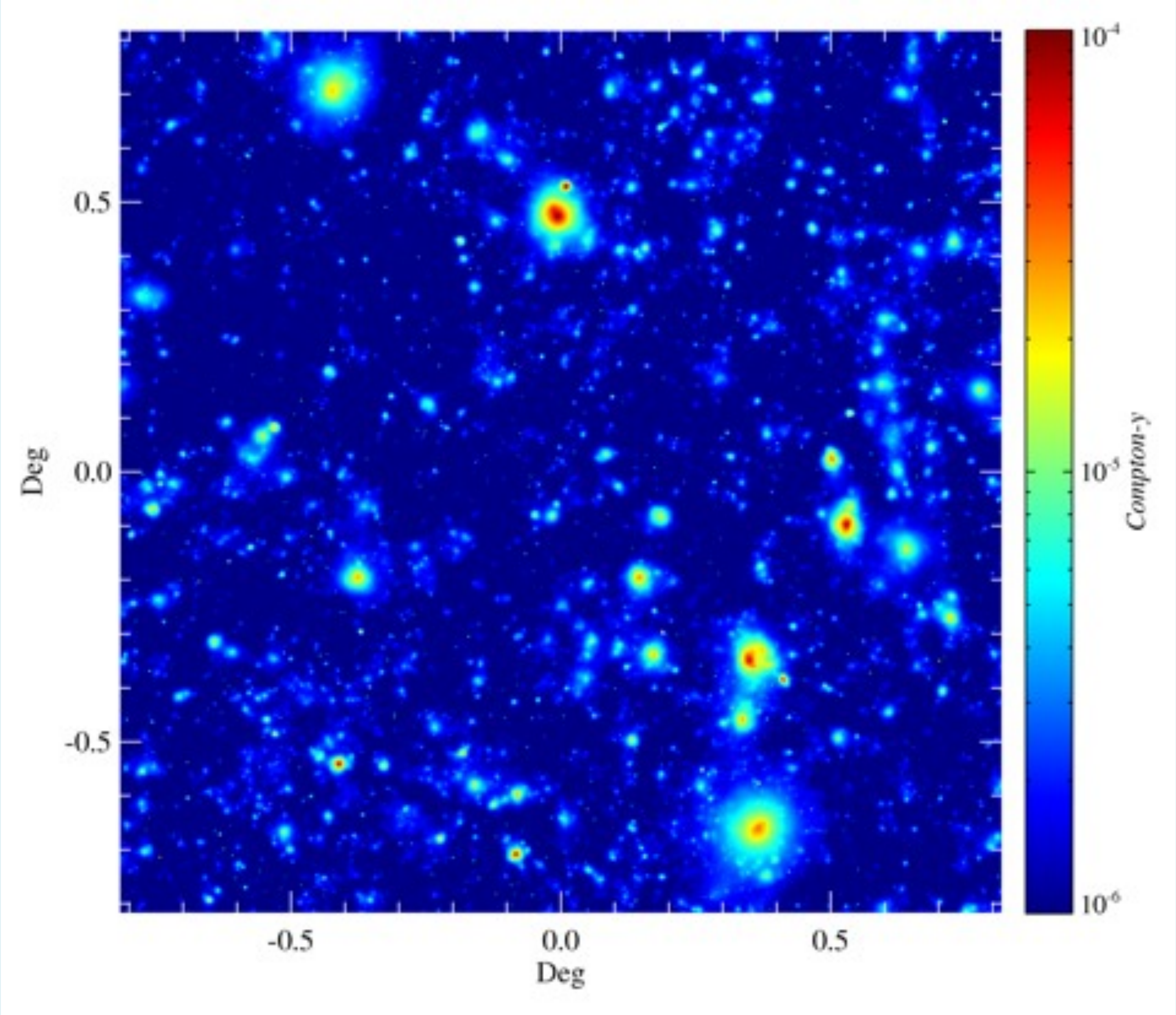
Compton-y map: "adiabatic"

= formation shock entropy from gravitational accretion only

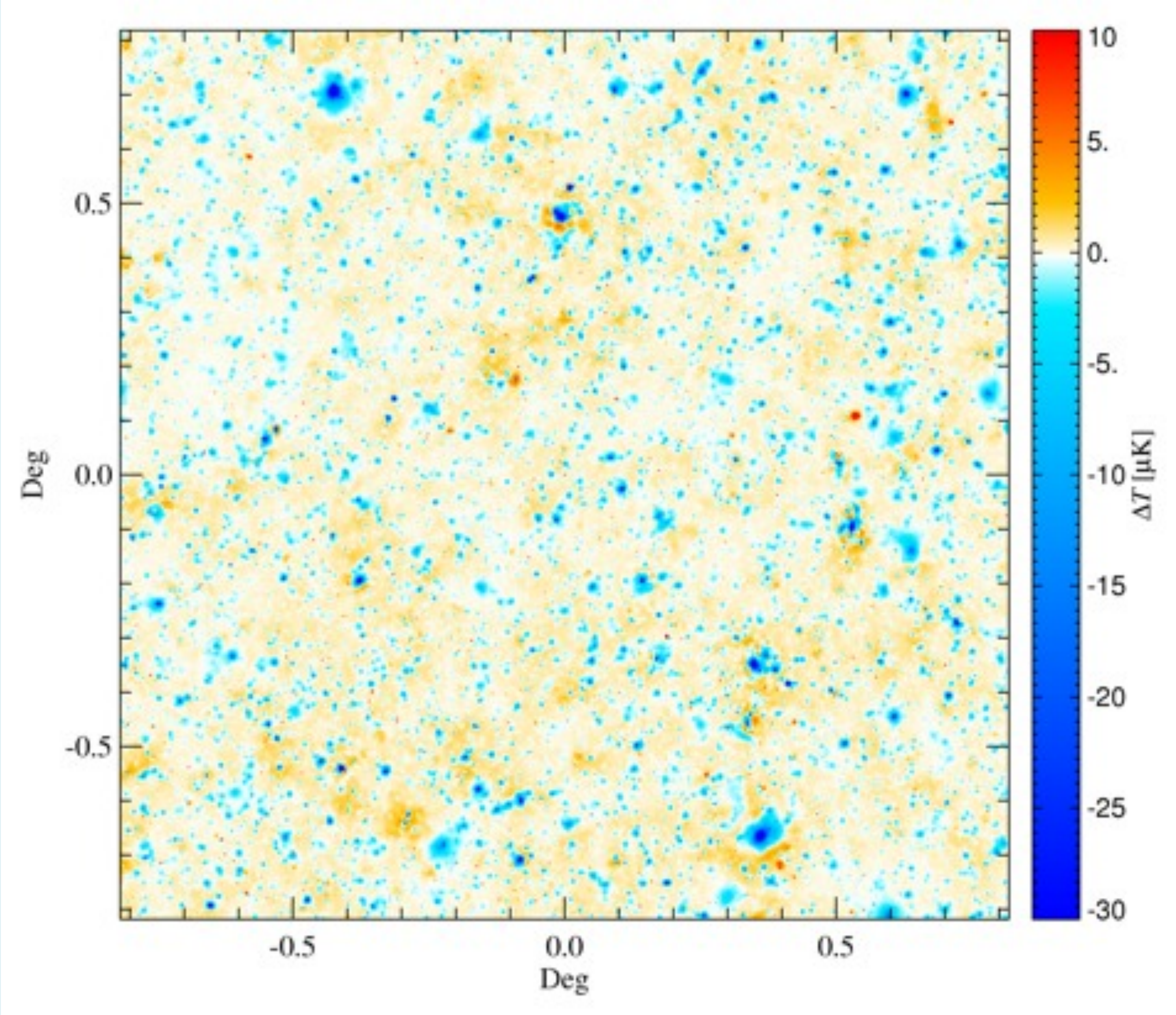


Compton-y map: Feedback

= *AGN or Starburst E-feedback + radiative cool + SN energy + wind + (CR)*



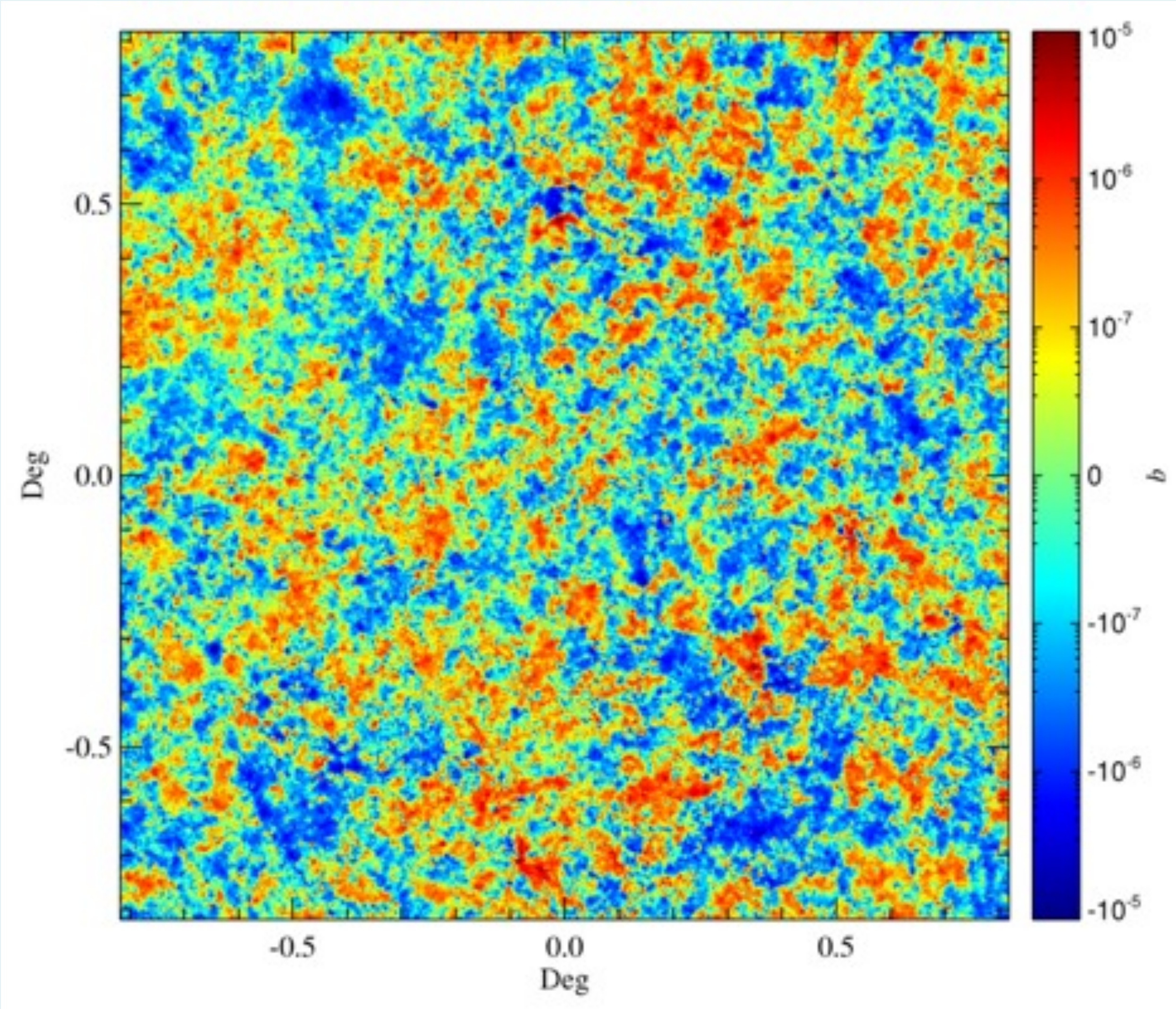
Adiabatic - Feedback



feedback gives "puffier" clusters, with lower core pressures

kinetic SZ map *(log)*: Feedback

= AGN or Starburst E-feedback + radiative cool + SN energy + wind + (CR)



Compton-y map: Feedback

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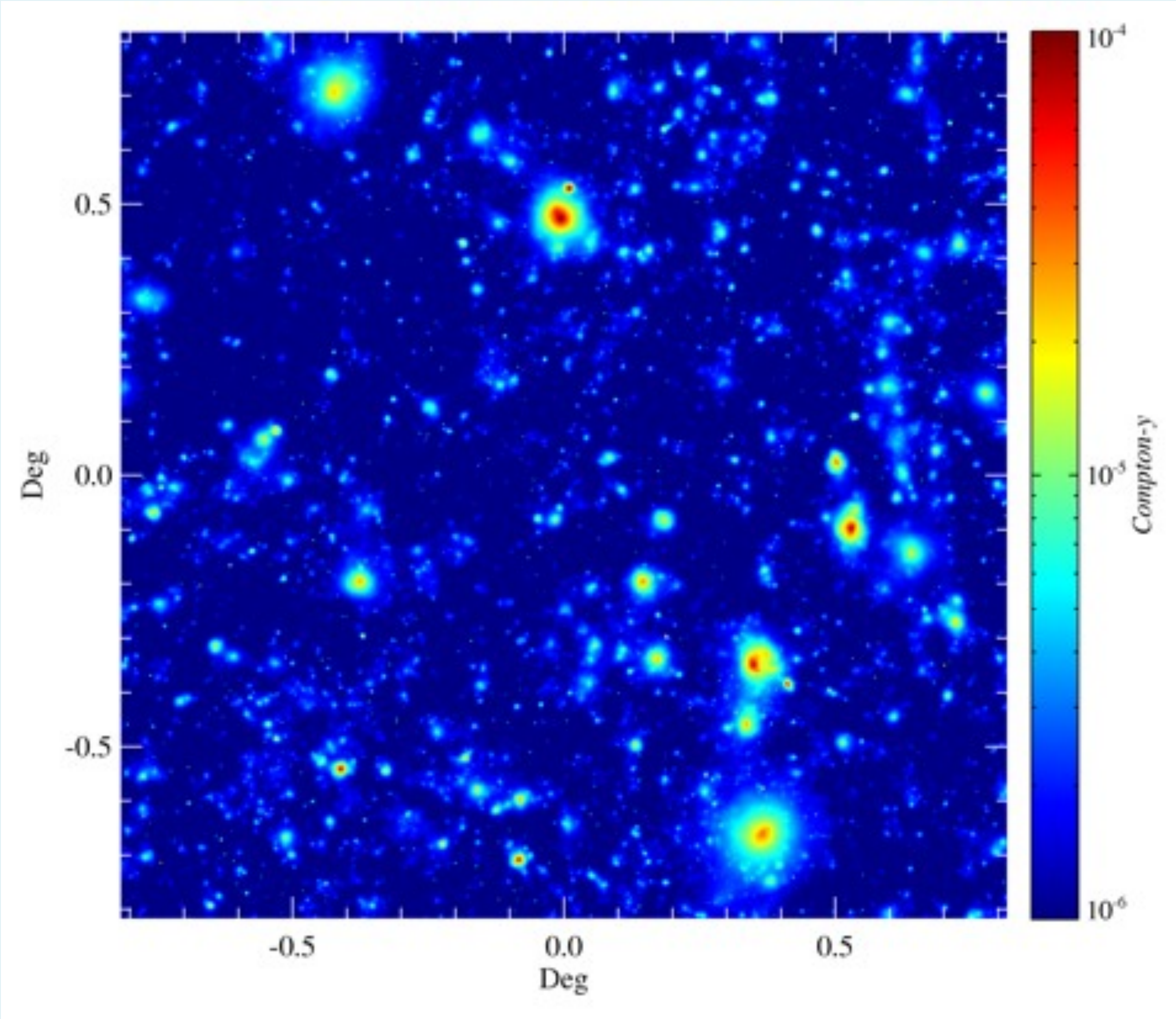
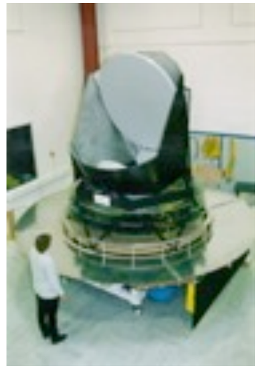


CBI pol to Apr'05 @Chile CBI2

QUaD @SP

Planck09.4

52+ bolometers
+ HEMTs @L2
9 frequencies



WMAP @L2 to 2010

2004 2006 2008 LHC 2011 Bpol @L2

2005 2007 2009

Acbar@SP

AMIBA

SPT
1000 bolos
@SPole

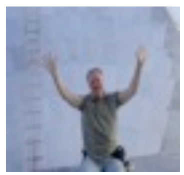
>96
OVRO
/BIMA
array

SZA@Cal

ACT
3000 bolos
3 freqs @Chile

AMI

APEX
~400 bolos@Chile



SCUBA2
12000 bolos
JCMT @Hawaii

SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico

80s-90s
Ryle
OVRO

GBT

CBI pol to Apr'05 @Chile **CBI2**

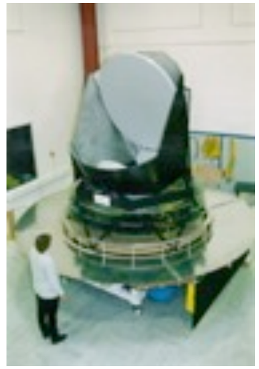
53+35 cls **(>=40)**

QUaD @SP

189 +10 **cls (>=1000)**

Planck09.4

52+ bolometers
+ HEMTs @L2
9 frequencies



WMAP @L2 **to 2010**

2004 2006 2008 **LHC** 2011 **Bpol** @L2

21+26~50 (>=750)

2005 2007 2009

>96
OVRO /BIMA array
38 cls

Acbar@SP
~1 blind

SZA@Cal
3 cls (z>1), x?

AMI
7+1 cls >=50+25

GBT
4 cls (~25 CLASH)

AMIBA
6 cls

APEX
~400 bolos@Chile
~25 cls

SPT
1000 bolos
@SPole

ACT **23+27~50 cls**
3000 bolos
3 freqs @Chile

SCUBA2
12000 bolos
JCMT @Hawaii

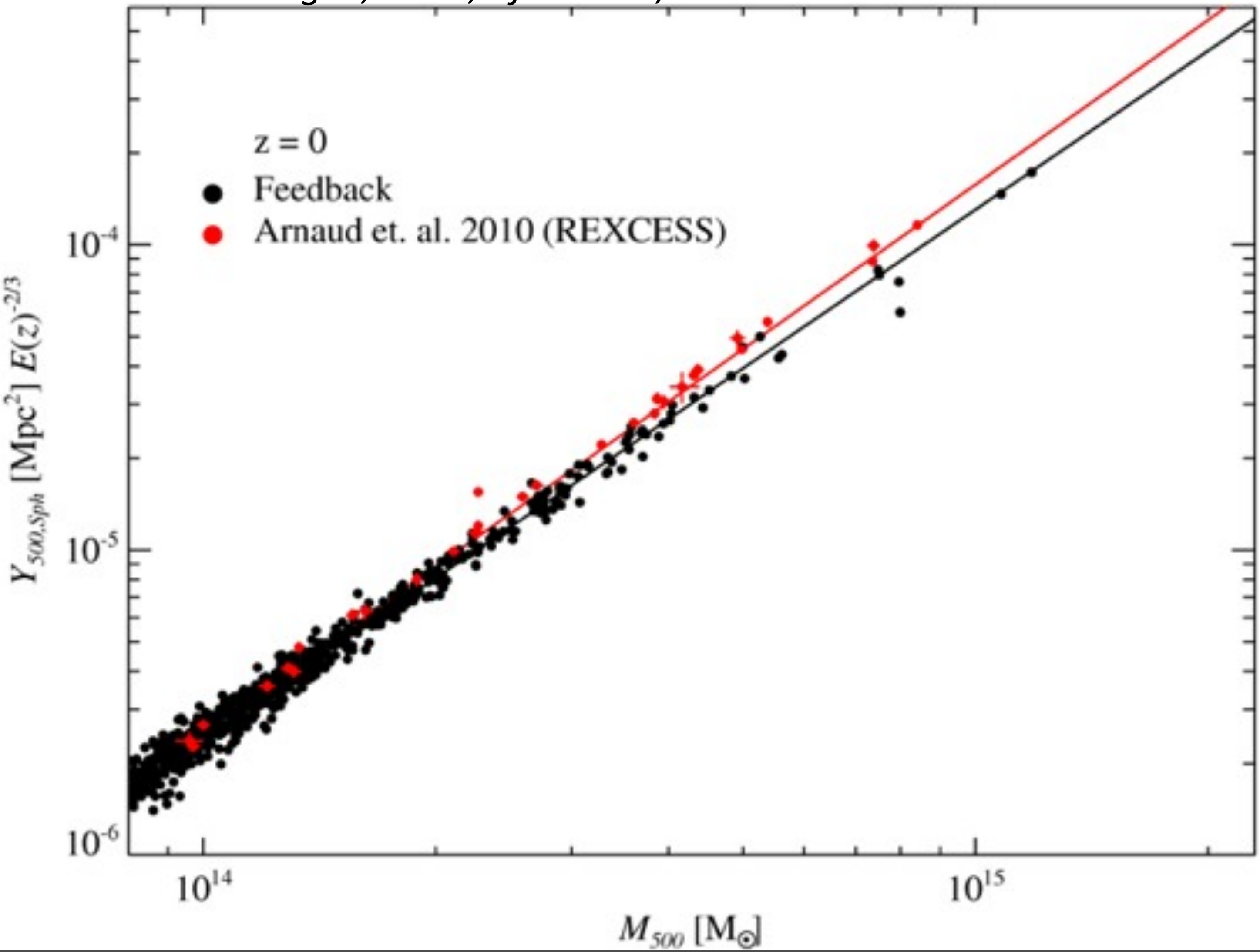
SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico

80s-**90s**
Ryle
OVRO

$Y(<r_\Delta)$-$M(<r_\Delta)$ relation, *where*

$M(<R_\Delta)/V(<R_\Delta)=\Delta\ \rho_{crit}$, Δ=2500, **500**, 200

Battaglia, Bond, Pfrommer, Sievers 11



Planck-ESZ gives **Y_{5R500}**

is Y_{SZ} a good mass proxy in $n_{cl}(M, z)$?
even though virial theorem
Y(e,K/U,...|M)
=> $n_{cl}(Y, z)$

Y(<r_Δ)-M(<r_Δ) relation, *where*

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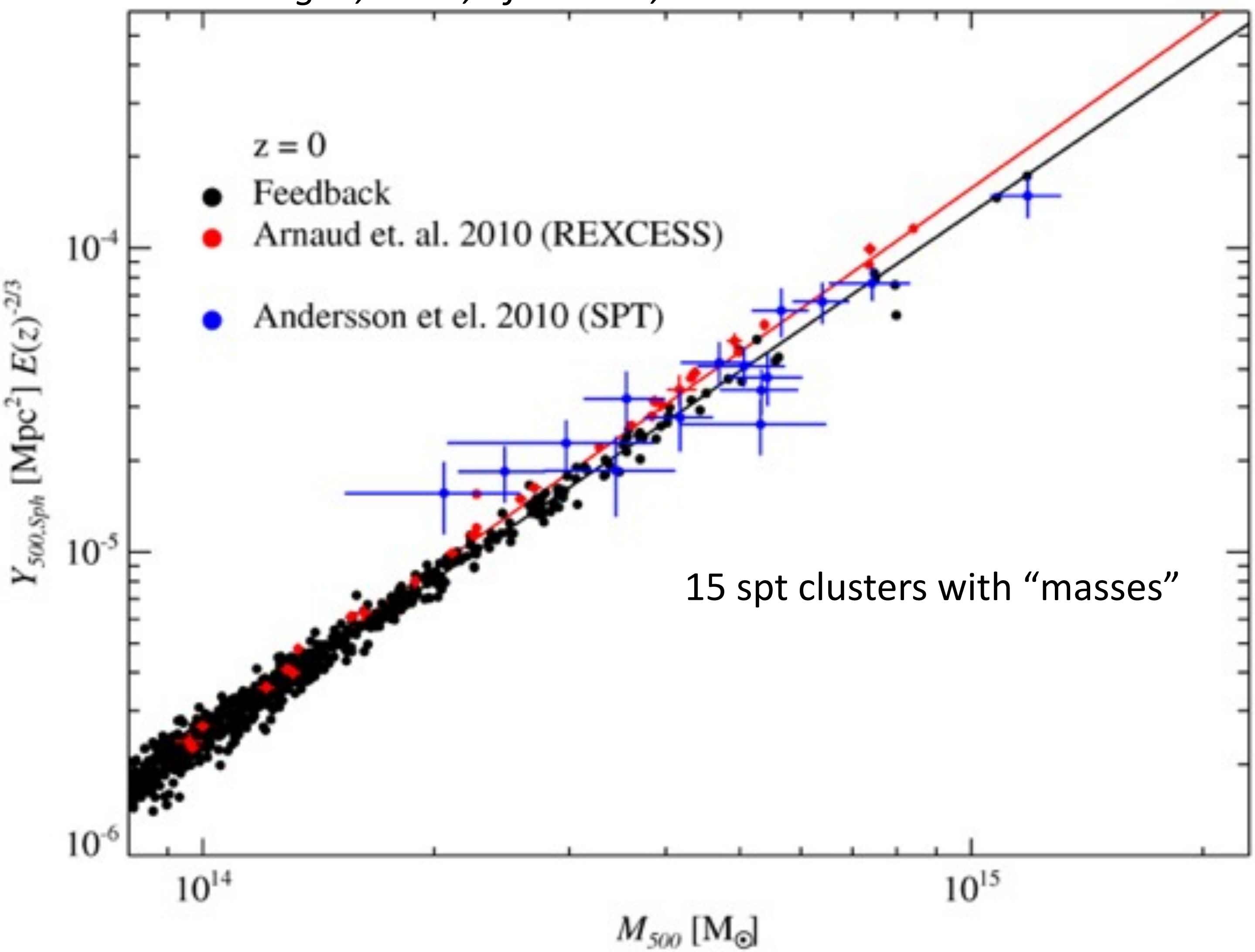
Battaglia, Bond, Pfrommer, Sievers 11



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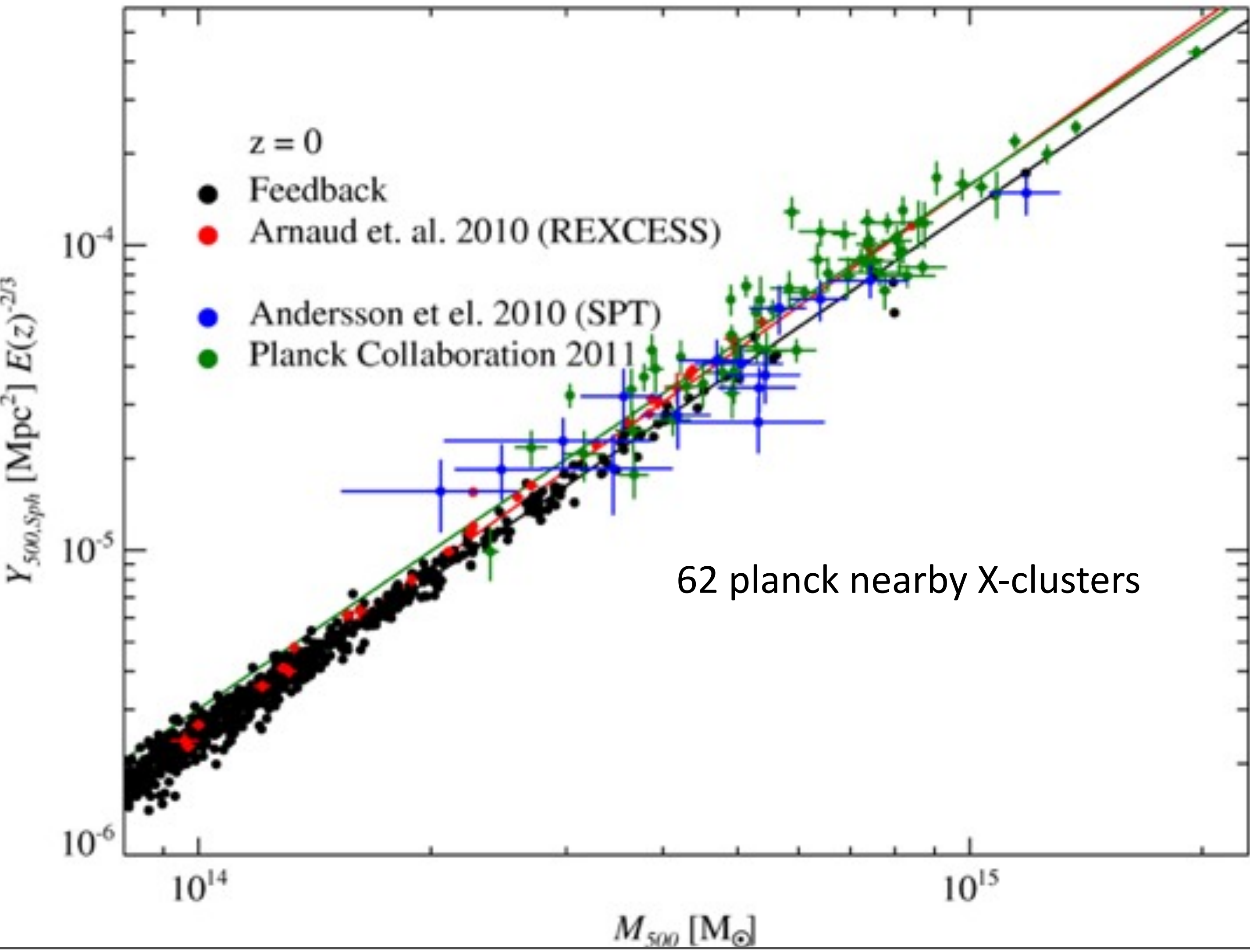

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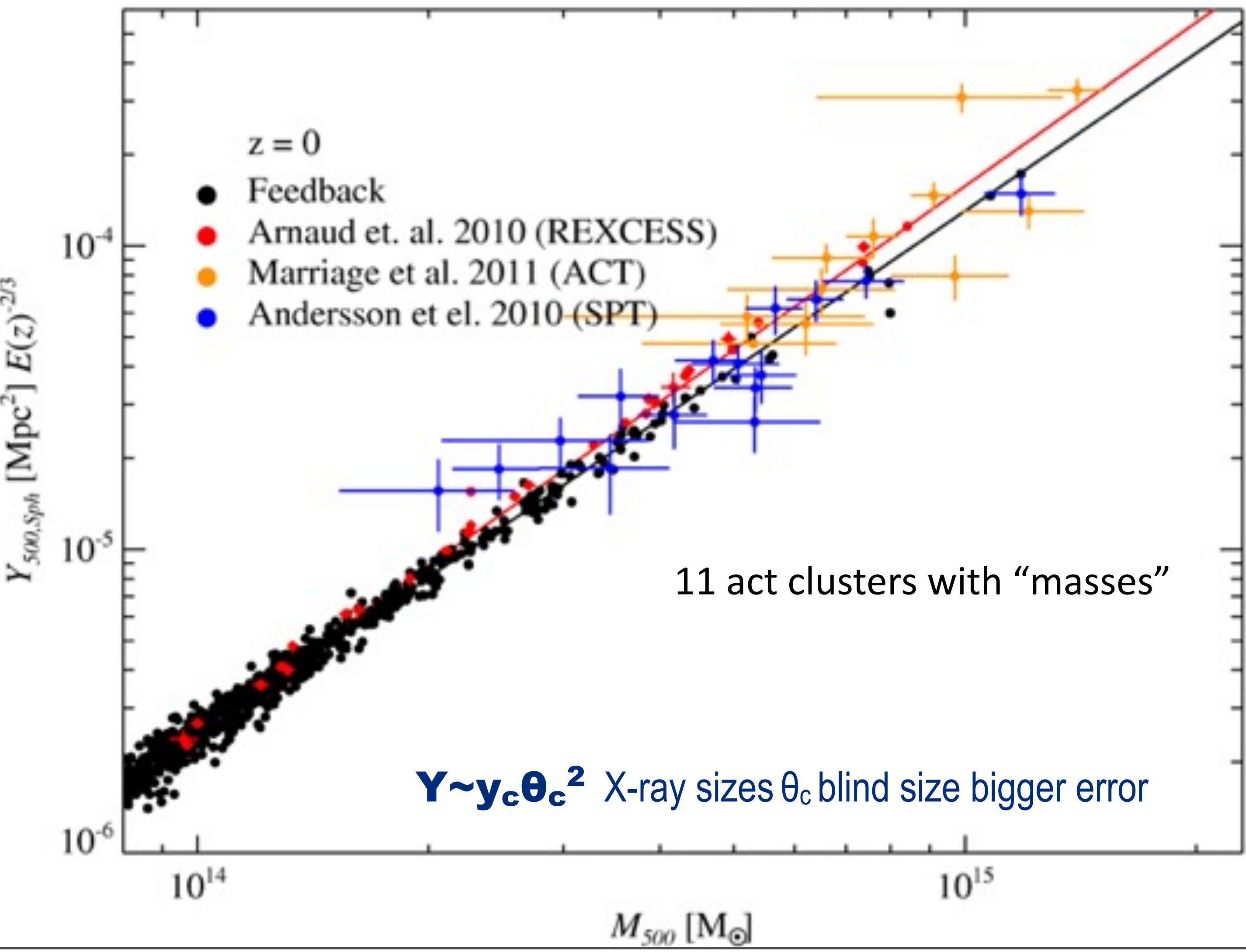
Battaglia, Bond, Pfrommer, Sievers 11



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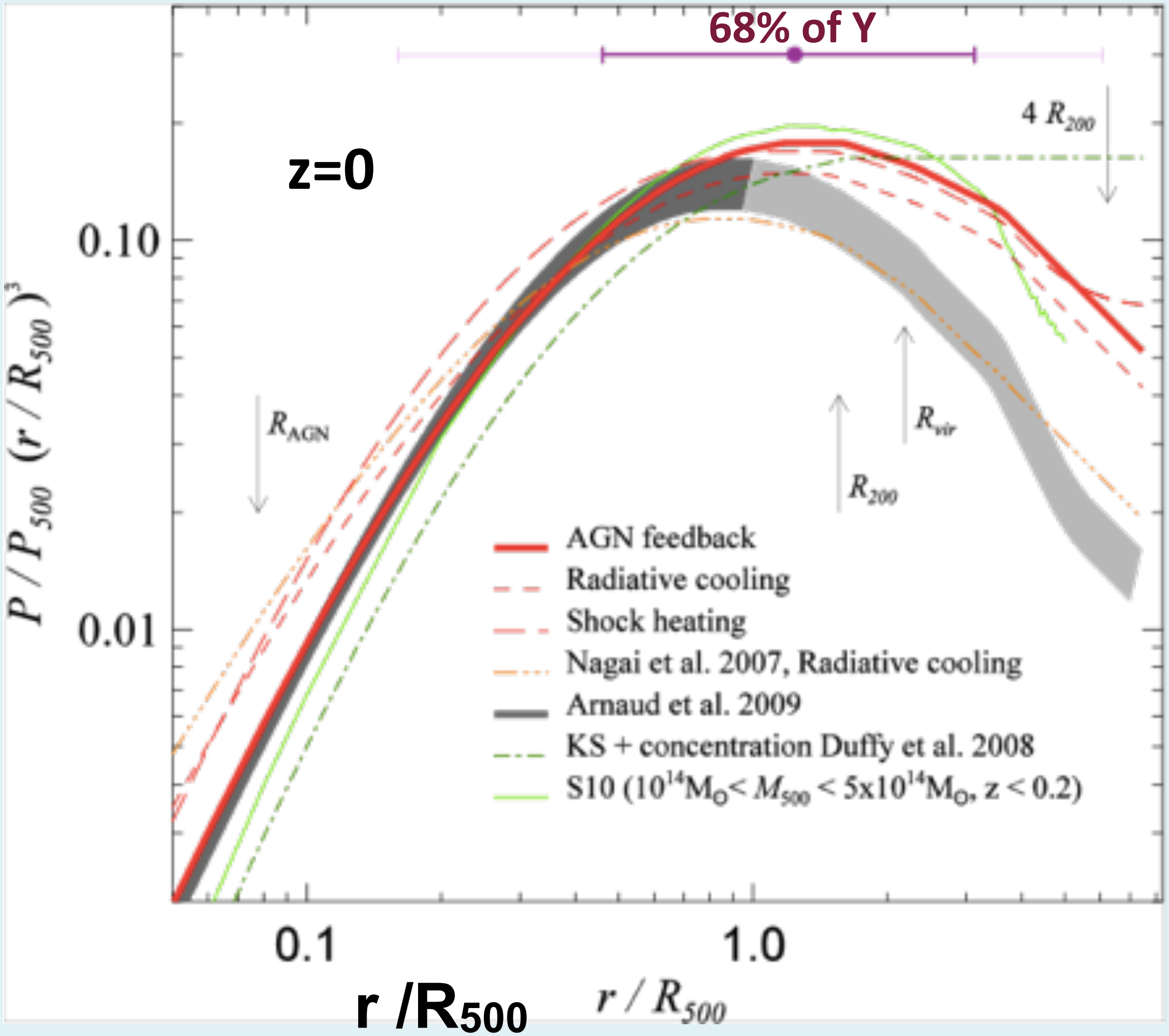
scaled Pressure profiles: d*ln* $E_{th}(<r)$/d*ln* r

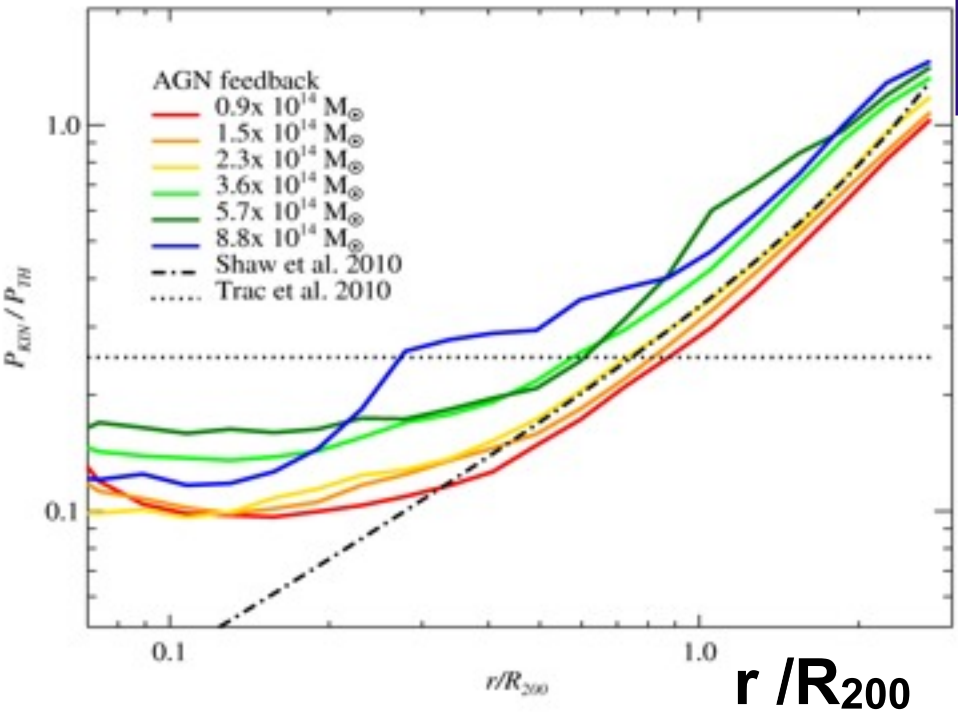
Battaglia, Bond, Pfrommer, Sievers, Sijacki 10



AGN Feedback sims match Arnaud *etal* <X-ray profiles> to data-end ~r_{500} universal?

redshift, mass, ... dependent

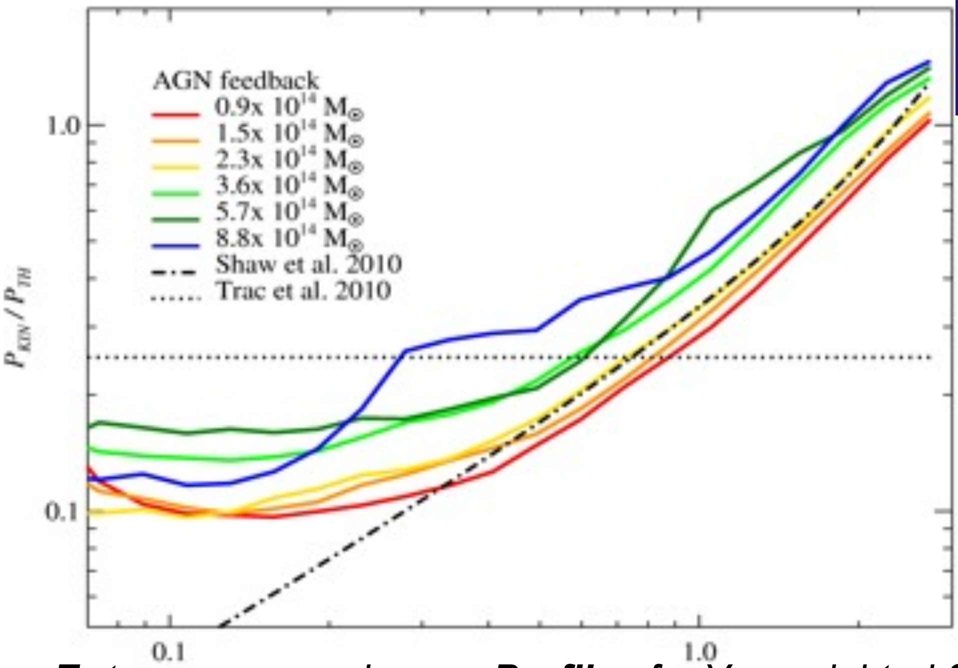
$$\frac{P}{P_\Delta} = \frac{A}{\left[1+\left(\frac{x}{x_c}\right)^{\alpha}\right]^{\gamma/\alpha}}$$



P_{kin} /P_{th}~0.1-0.6!

$<(\Delta v)^2>/c_s^2$ cannot be ignored in HSE $\nabla p_{g,tot}=\rho_g g$

Battaglia, Bond, Pfrommer, Sievers 11



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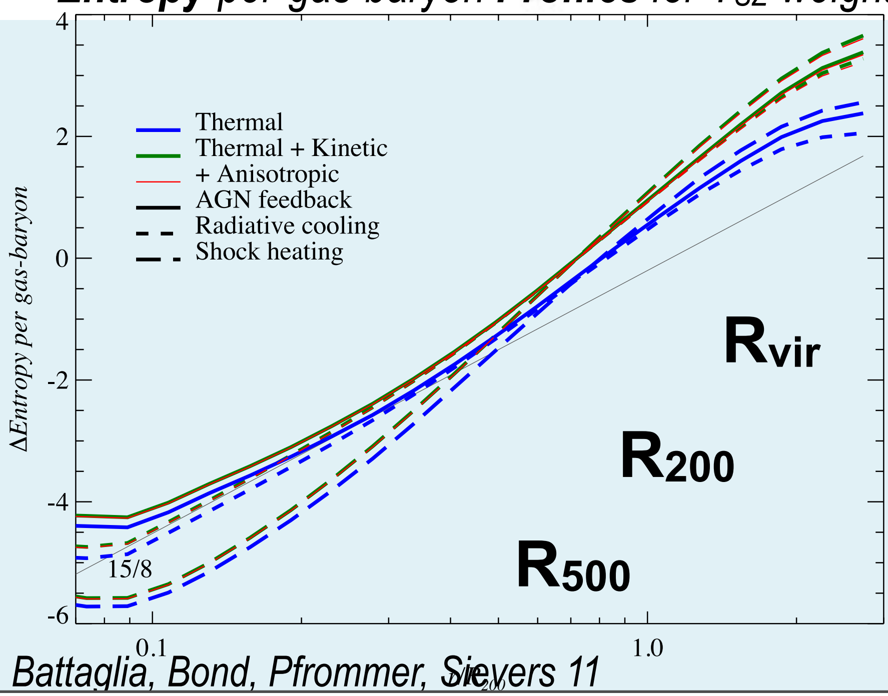
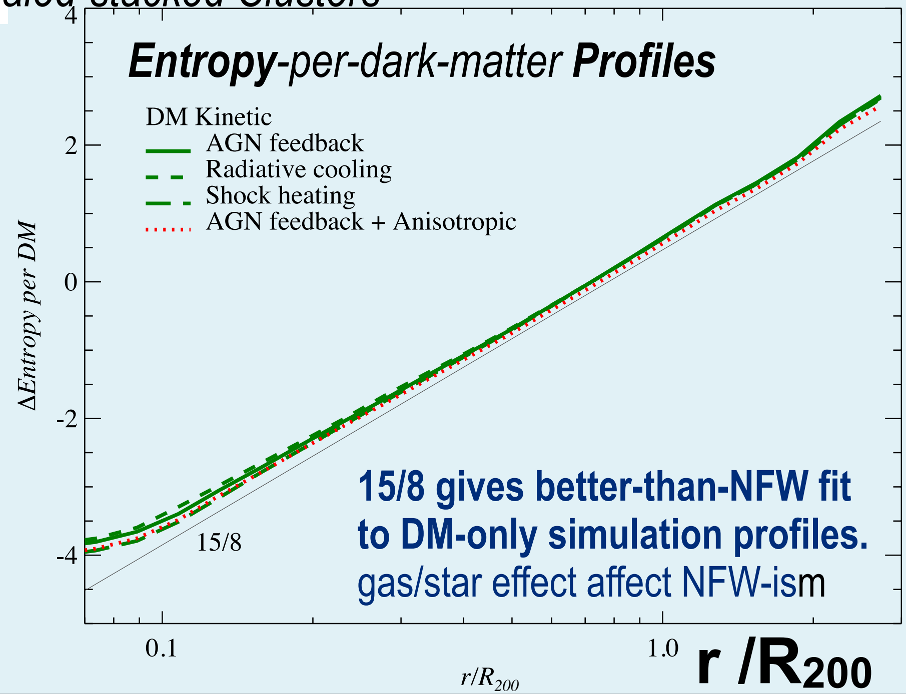
***Entropy**-per-gas-baryon **Profiles** for Y_{SZ}-weighted Scaled-stacked Clusters*

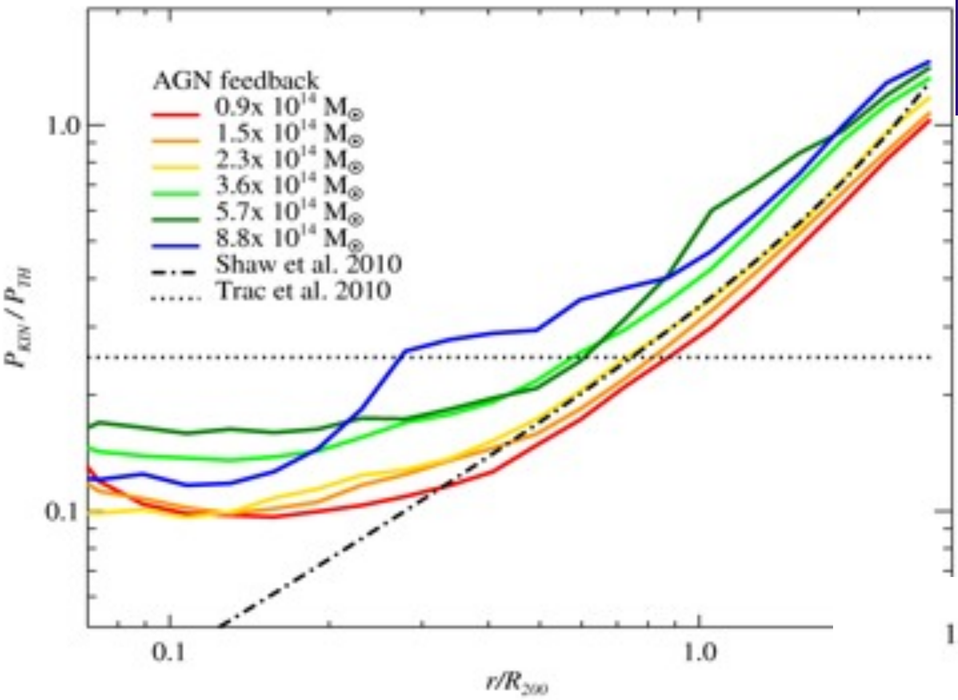




Battaglia, Bond, Pfrommer, Sievers 11

r /R₂₀₀

$P_{kin}/P_{th} \sim 0.1-0.6!$



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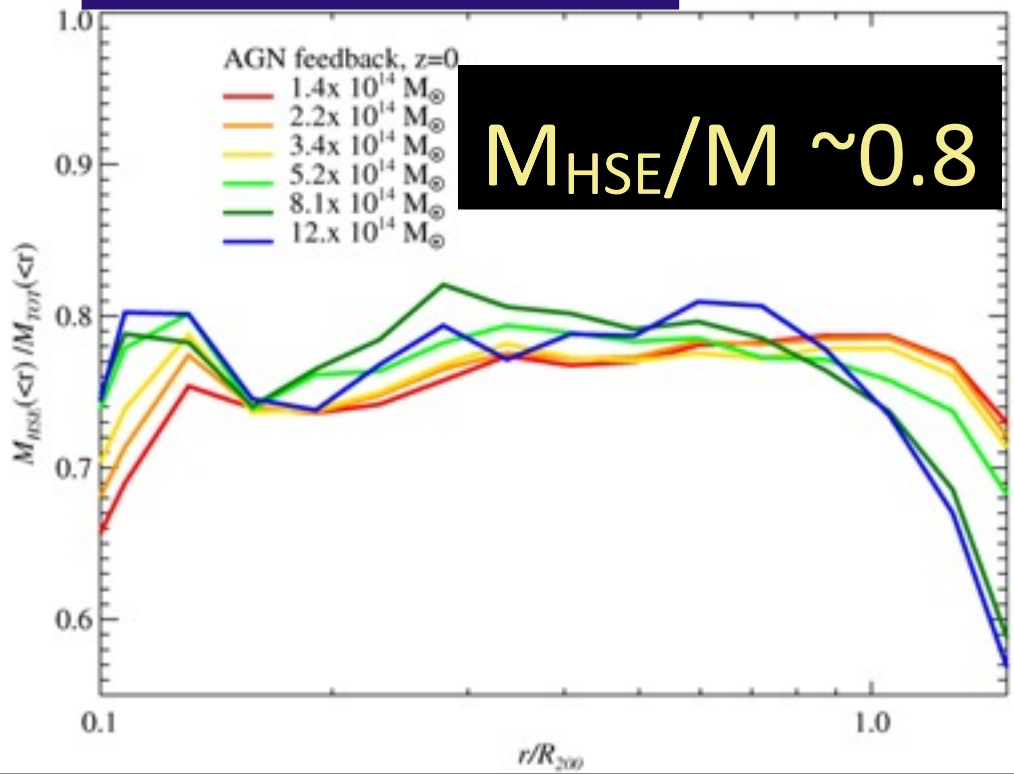
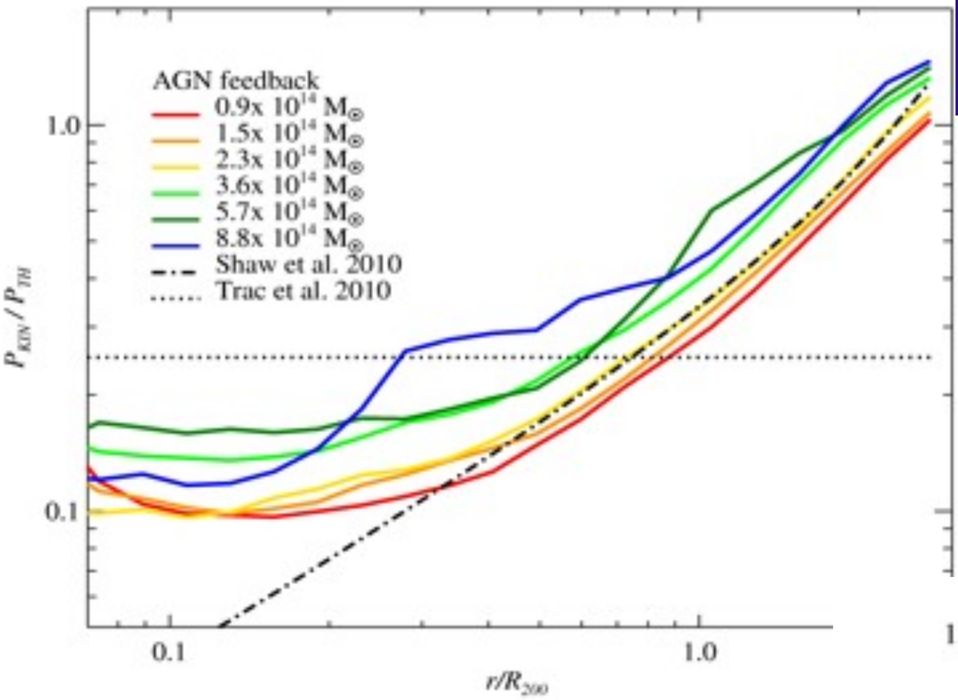


$M_{HSE}/M \sim 0.8$

Battaglia, Bond, Pfrommer, Sievers 11



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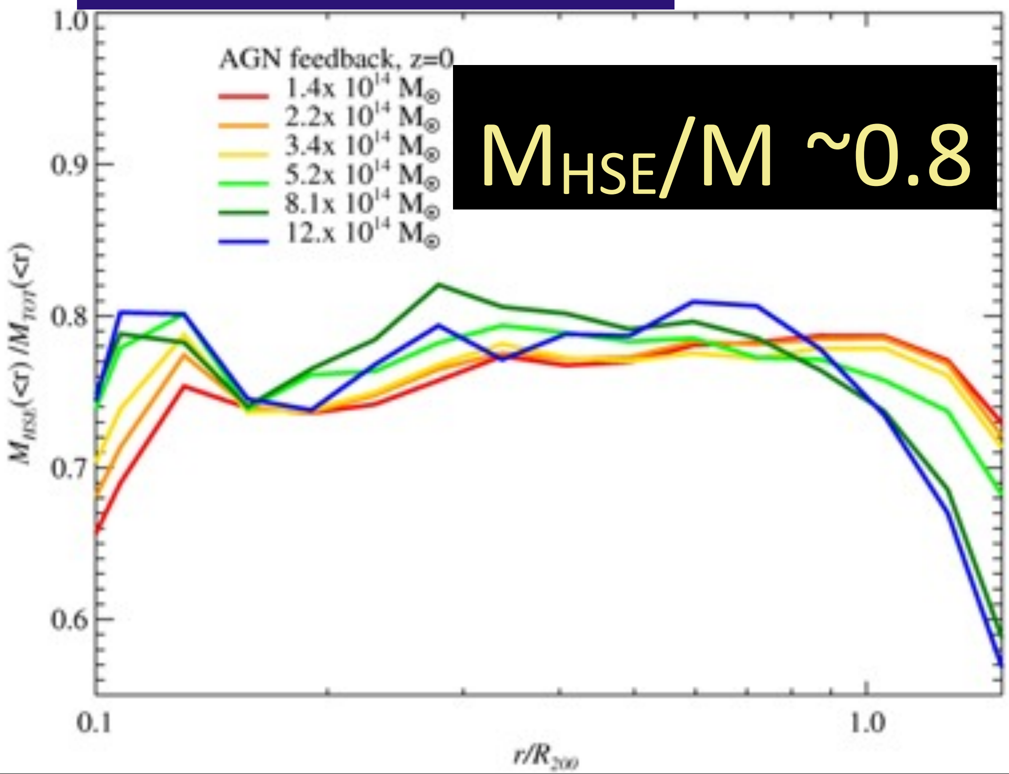


M_{HSE}/M ~0.8

Hydro Sims include all effects
(except of course for those not included).

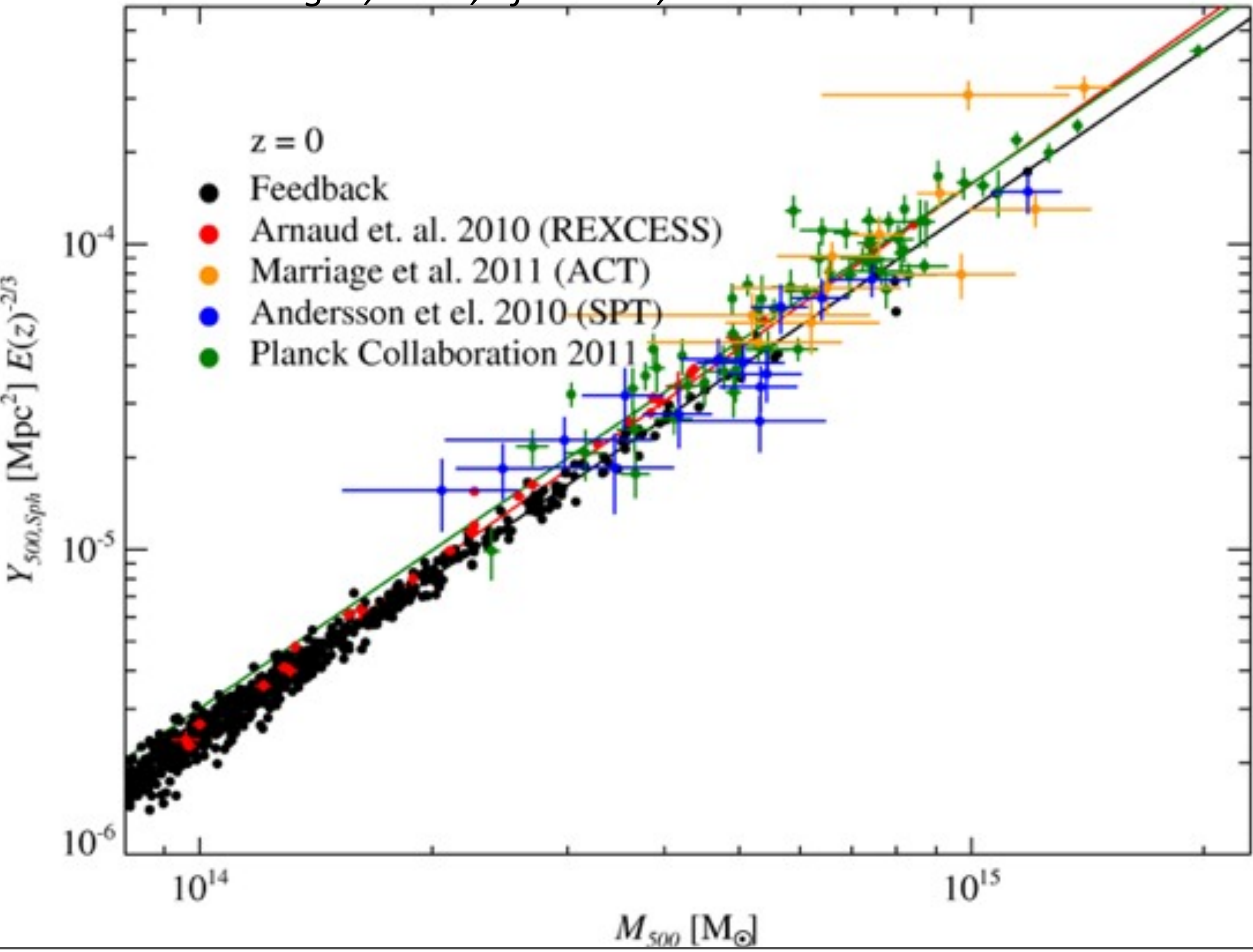
Analytic and semi-analytic treatments must be fully calibrated with sims to give a useful phenomenology.

Battaglia, Bond, Pfrommer, Sievers 11

$Y(<r_\Delta)-M(<r_\Delta)$ relation, *where*

$M(<R_\Delta)/V(<R_\Delta)=\Delta\ \rho_{crit}$, **$\Delta$**=2500, **500**, 200

Battaglia, Bond, Pfrommer, Sievers 11



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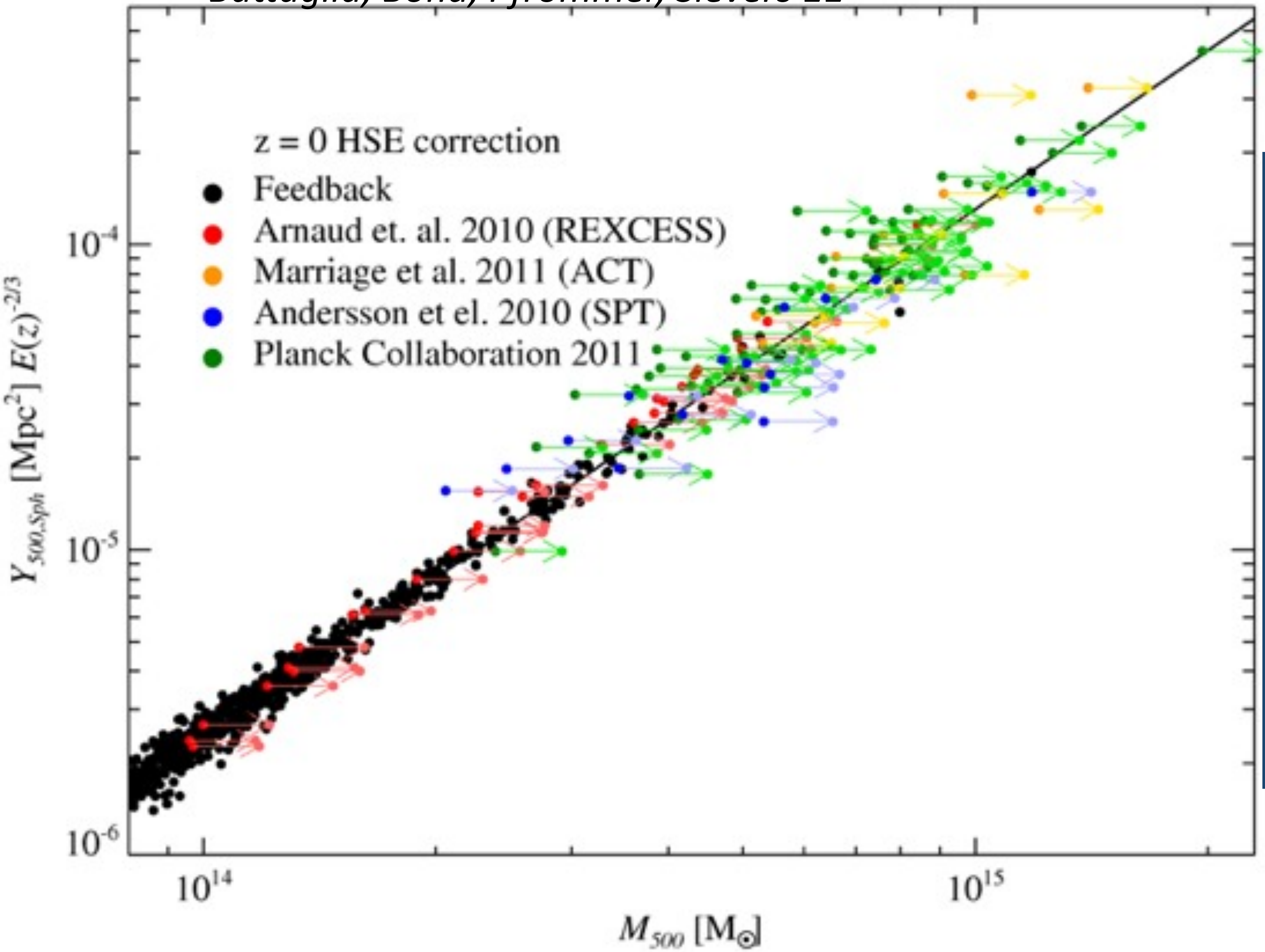

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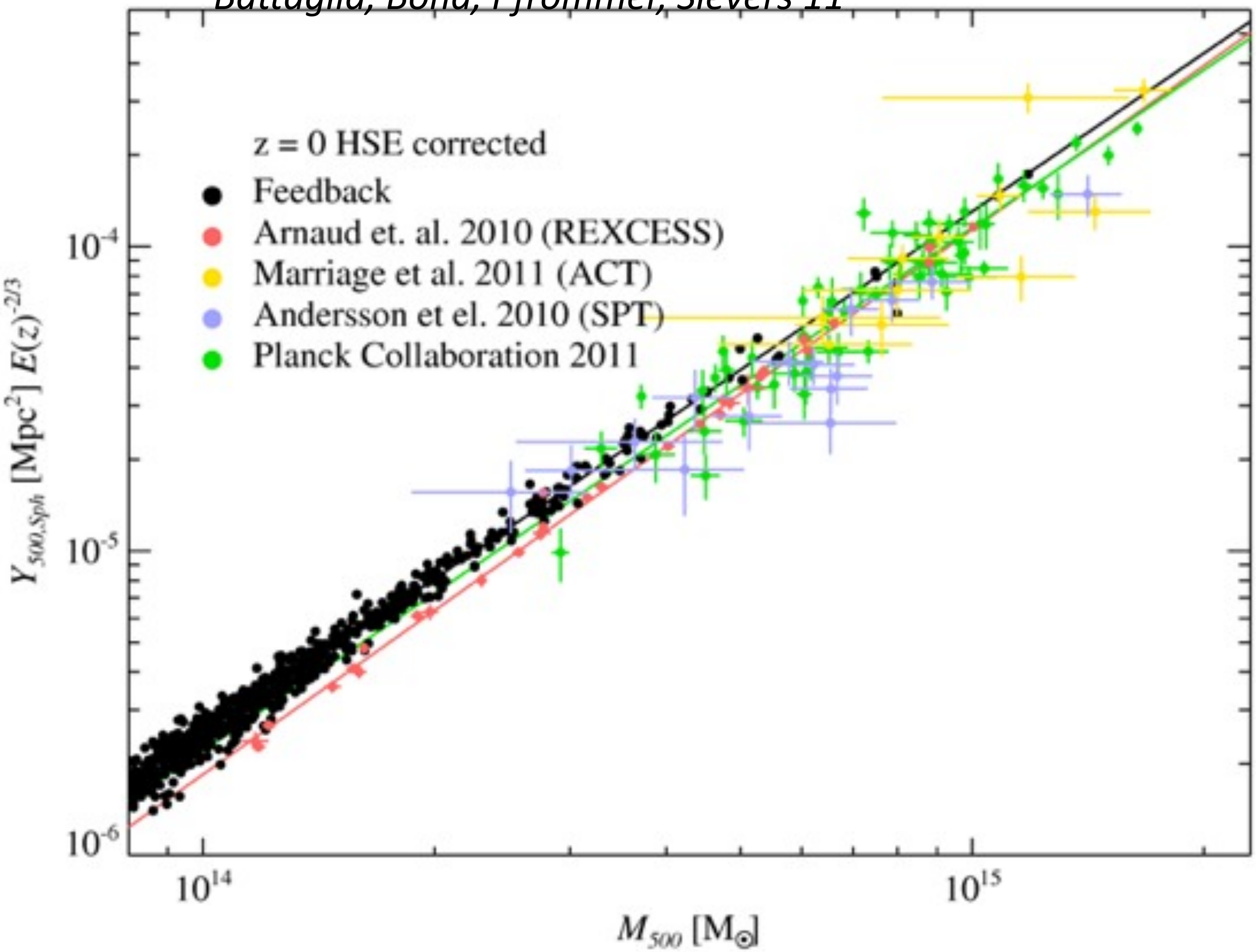
$M(<R_\Delta)/V(<R_\Delta)=\Delta\, \rho_{crit}$, Δ=2500, 500, 200

Battaglia, Bond, Pfrommer, Sievers 11



Planck-ESZ gives **Y_{5R500}**

is Y_{SZ} a good mass proxy in $n_{cl}(M, z)$?

even though good virial theorem $Y(e,K/U,...|M)$

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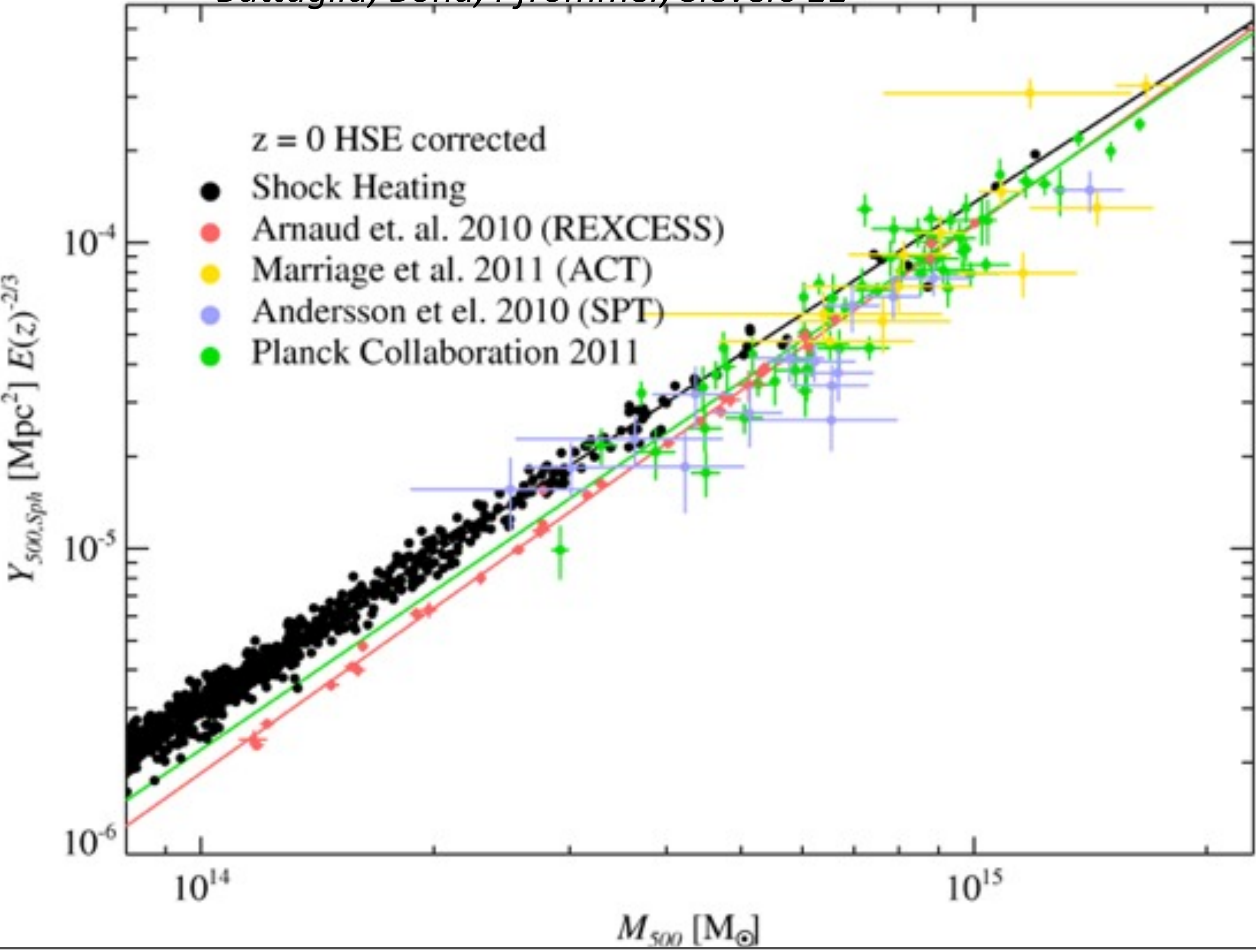
Battaglia, Bond, Pfrommer, Sievers 11



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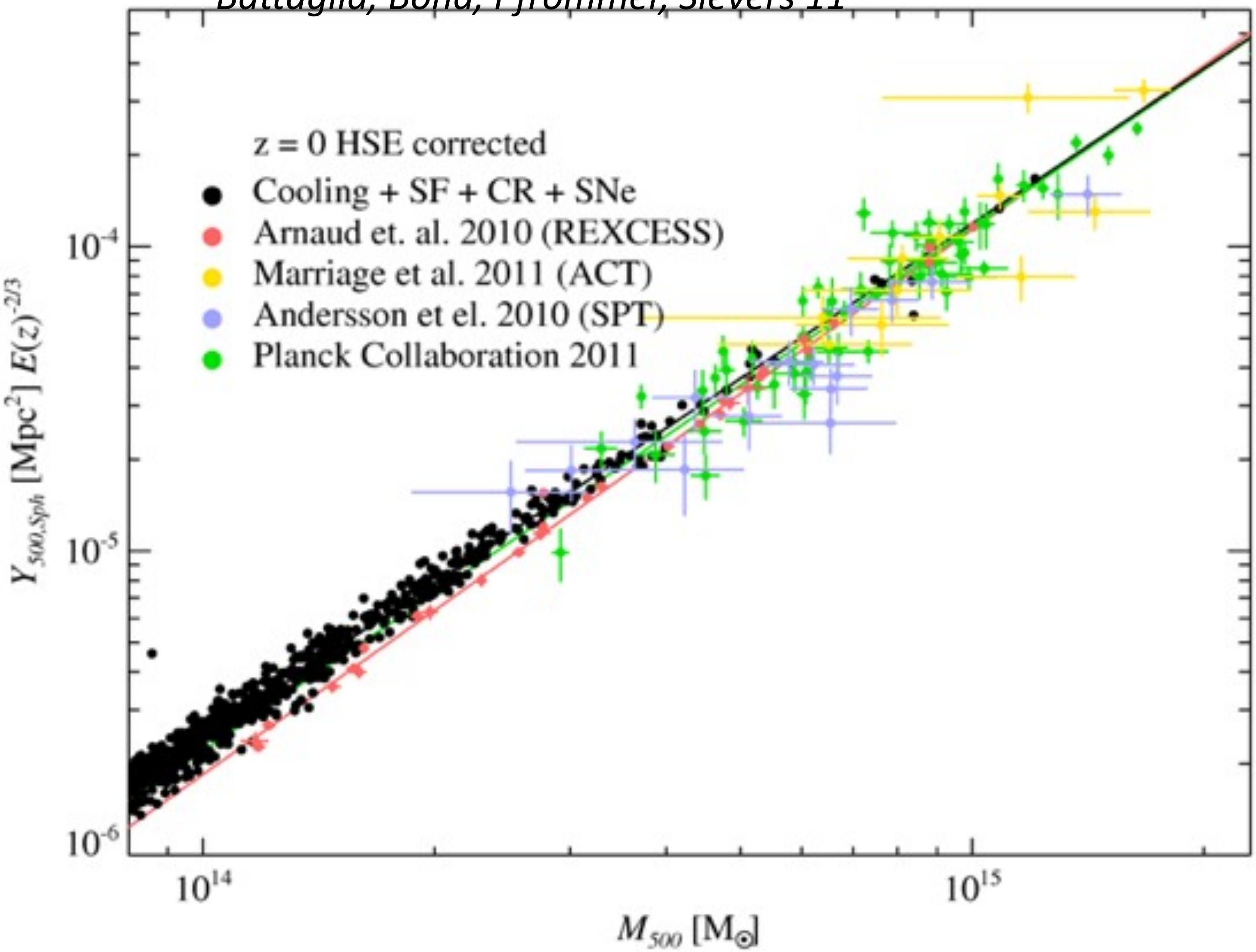

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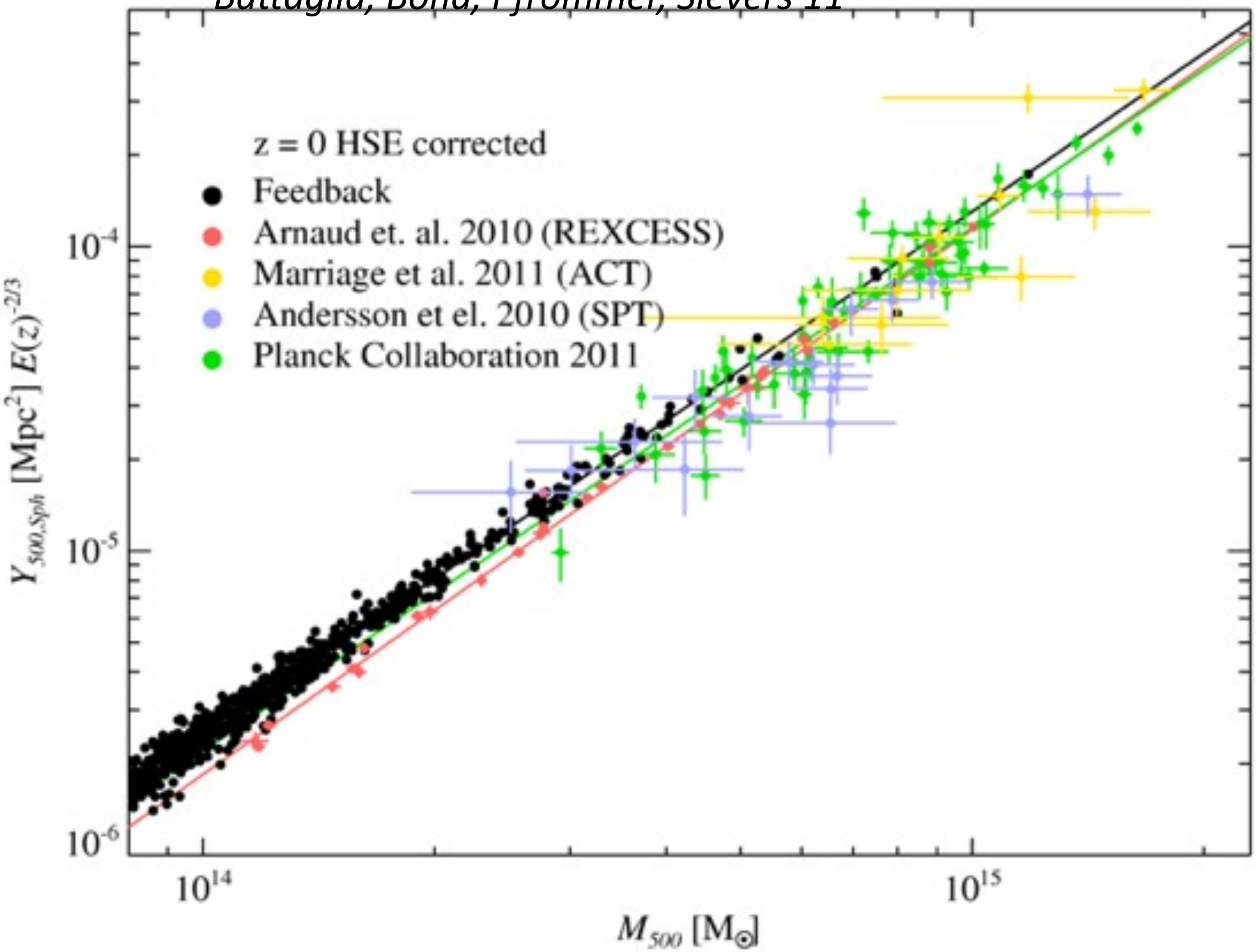

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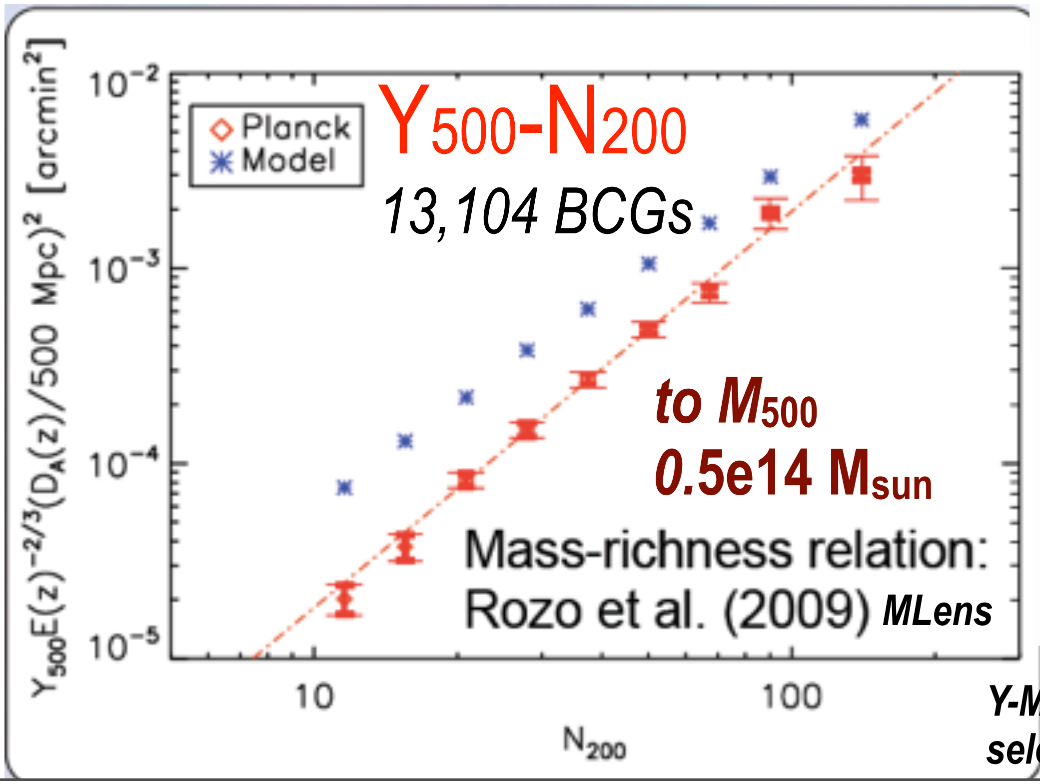
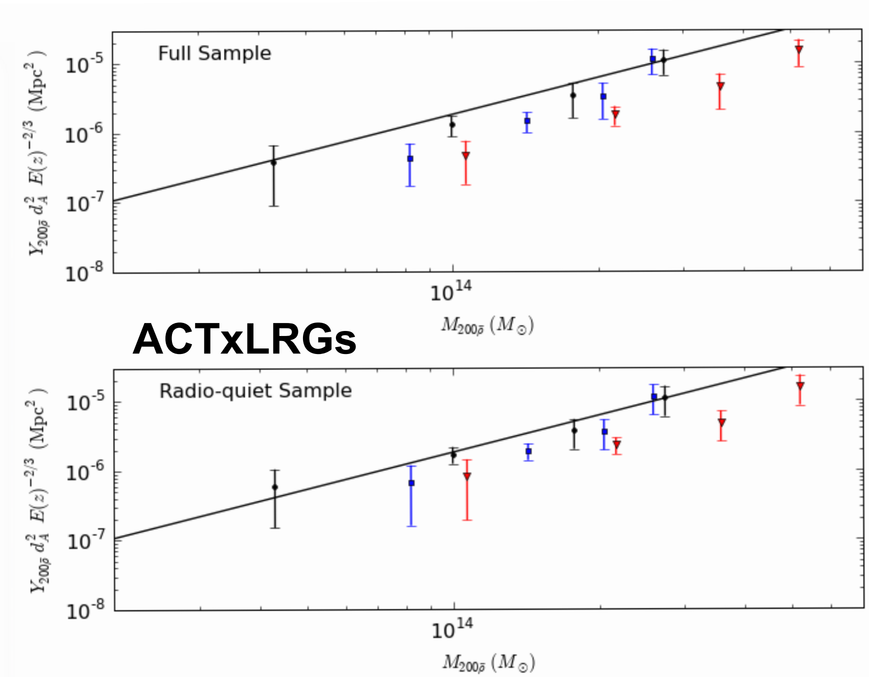
Planck sees the rarest and most massive clusters over the whole sky: 86% with $z<0.3$; masses to $1.5 \times 10^{15}\ M_{sol}$. 90% of the RASS above $M > 9 \times 10^{14}\ M_{sol}$ detected by blind ESZ, 5/21 of new Planck $> 9 \times 10^{14}\ M_{sun}$. **But "stacking" with the multifrequency filter extends the mass range to ~*0.5*e14 M_{sun}**





Y-M offset: Hint for sub-populations? Optical selection? Difference between Mx & MLens & Mbias?...

$Y(<r_\Delta)$-$M(<r_\Delta)$ relation, *where*

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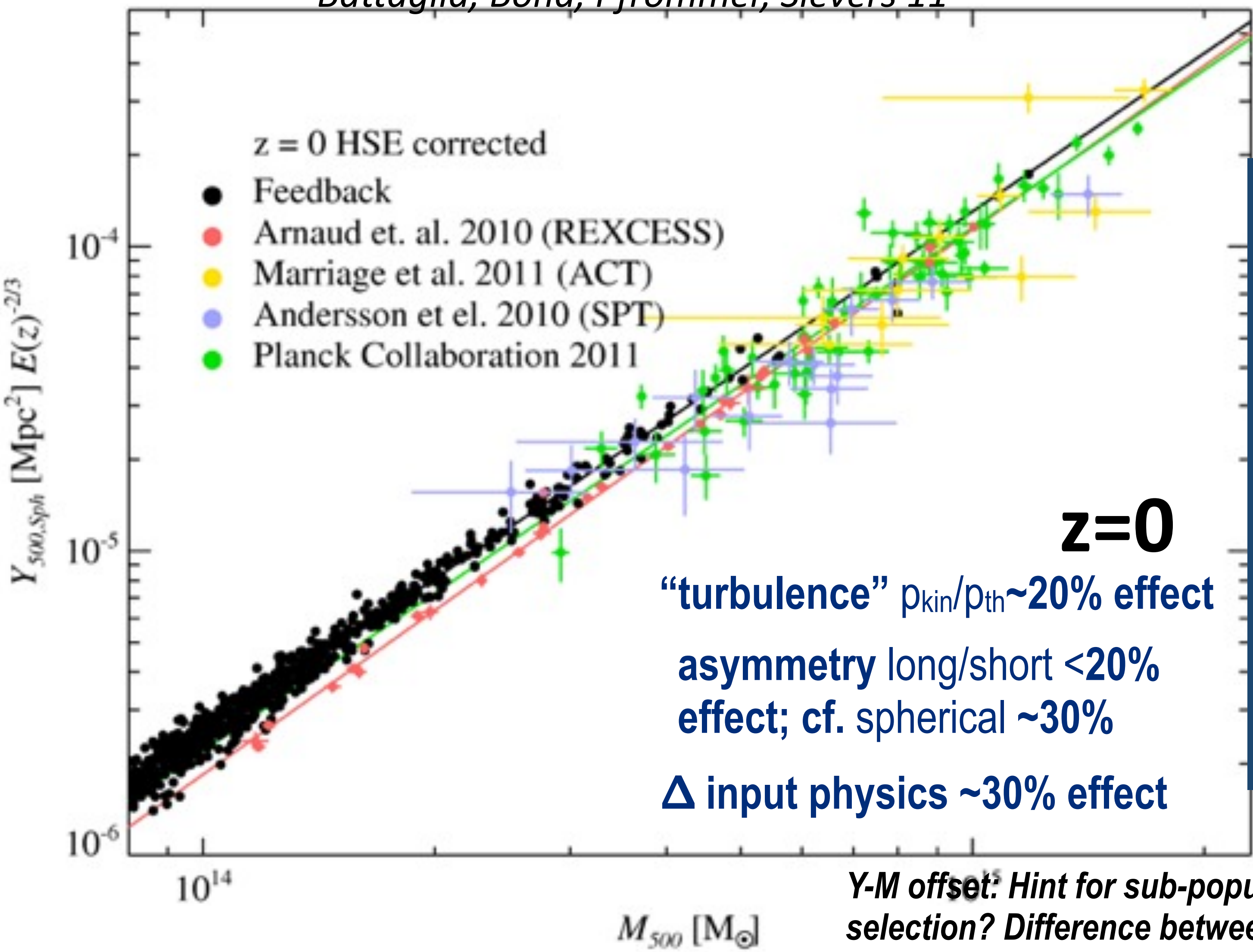

z=0

"turbulence" p_{kin}/p_{th}**~20% effect**

asymmetry long/short <**20% effect; cf.** spherical **~30%**

Δ input physics ~30% effect

Planck-ESZ gives **Y_{5R500}**

is Y_{SZ} a good mass proxy in $n_{cl}(M, z)$?

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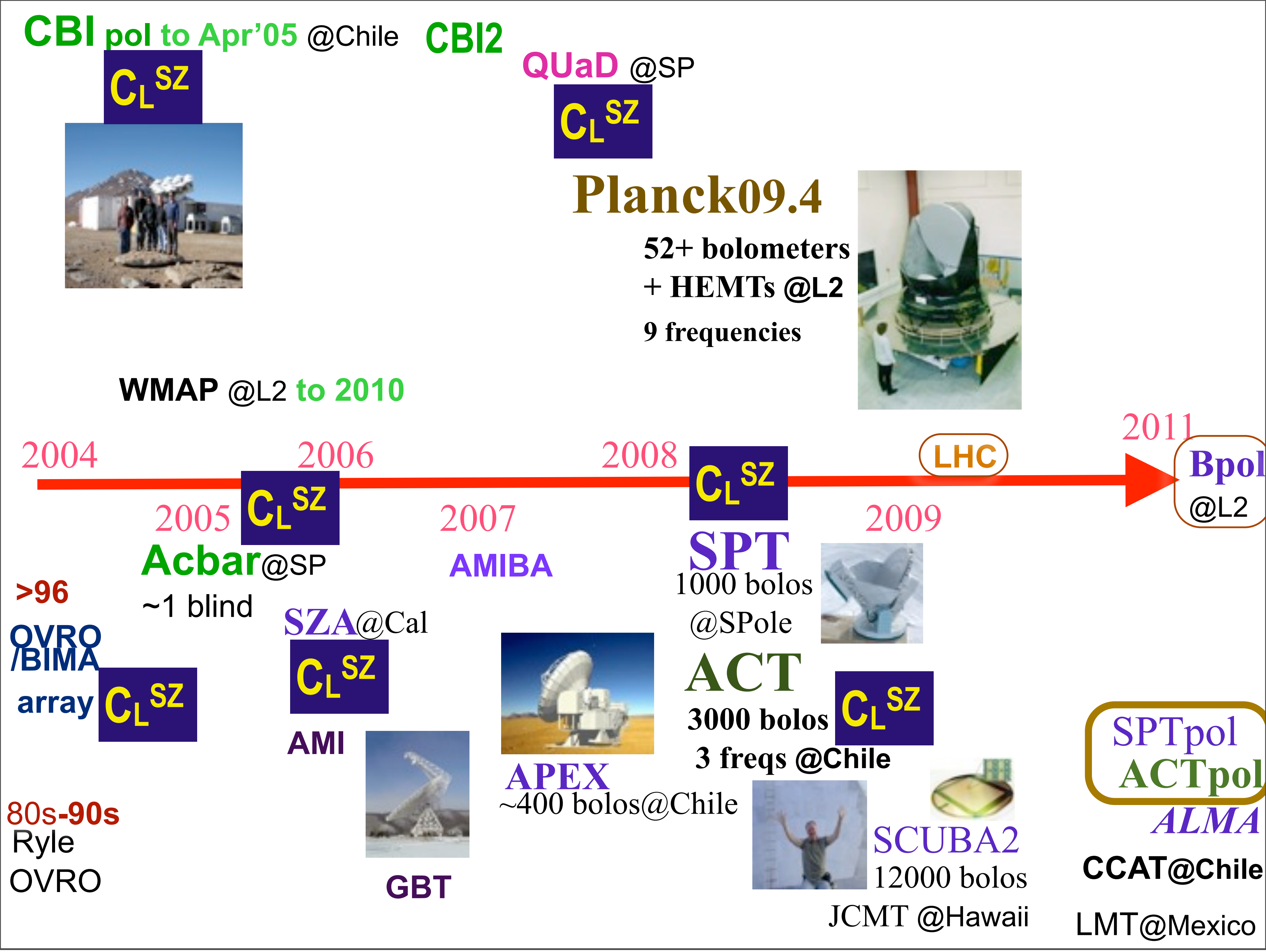
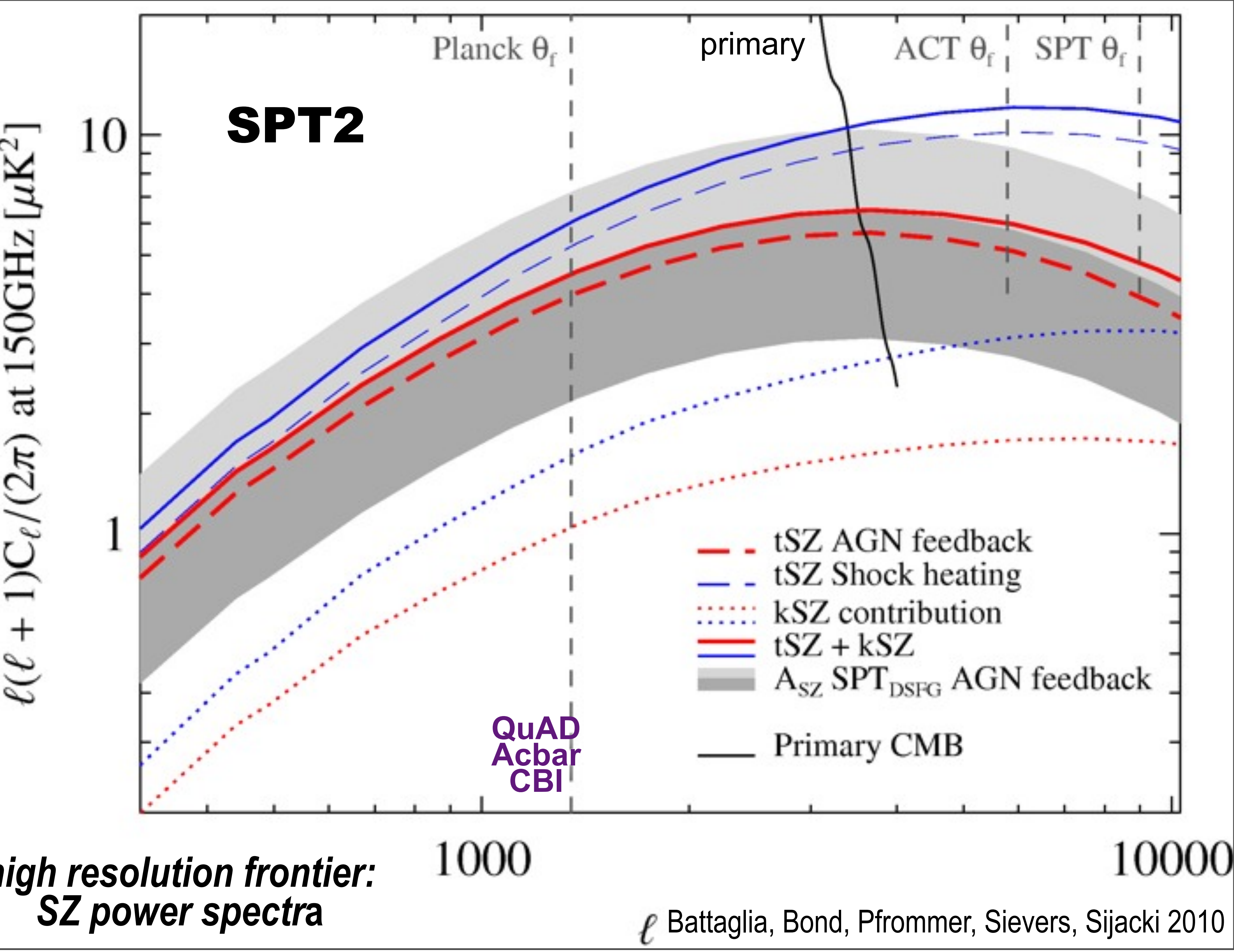
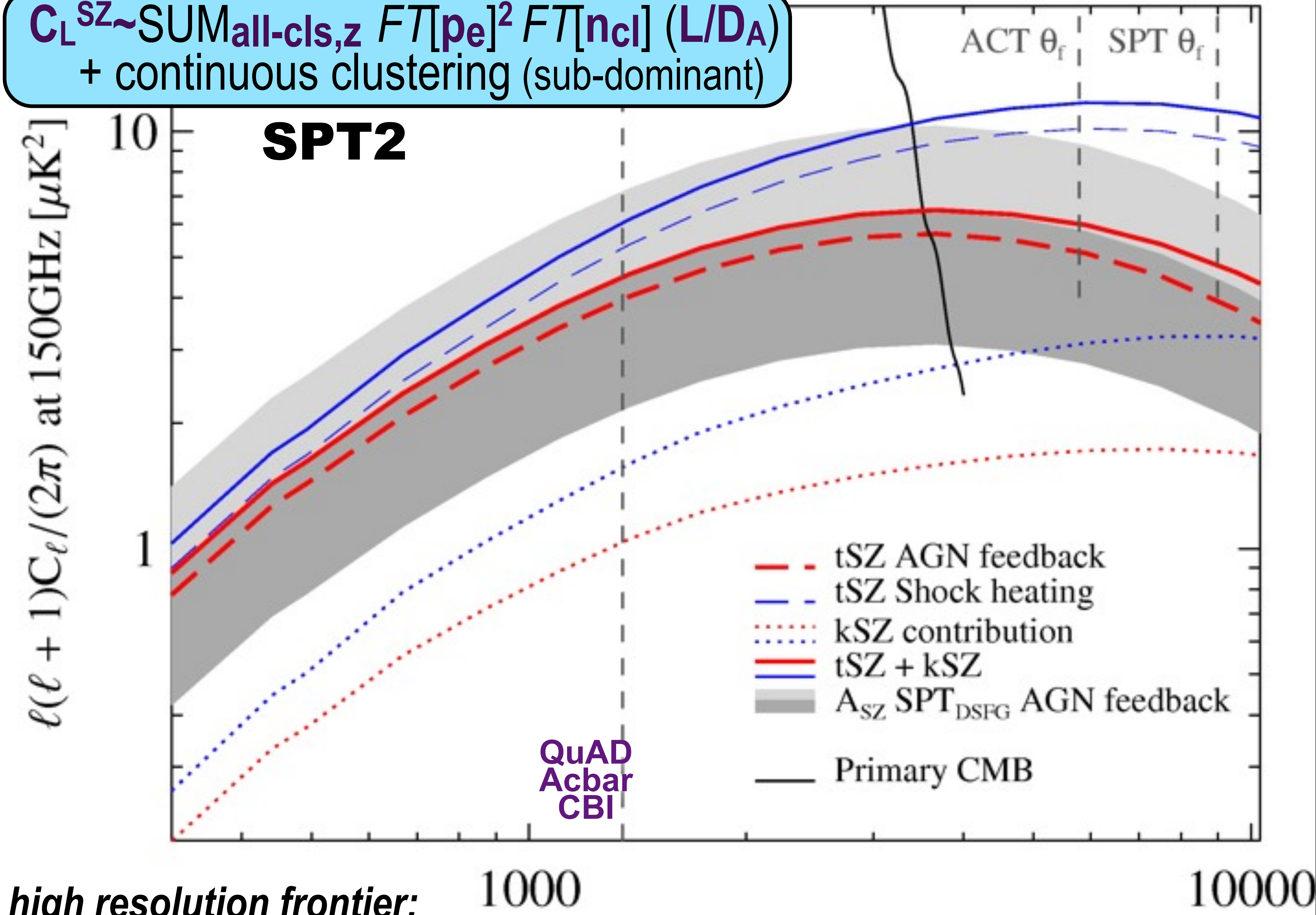

CBI pol to Apr'05 @Chile
CBI2
C_L^{SZ}
QUaD @SP
C_L^{SZ}
Planck09.4
52+ bolometers
+ HEMTs @L2
9 frequencies
WMAP @L2 to 2010
2004
2005
2006
2007
2008
2009
2011
LHC
Bpol
@L2
C_L^{SZ}
Acbar@SP
~1 blind
>96
OVRO
/BIMA
array
C_L^{SZ}
SZA@Cal
C_L^{SZ}
AMI
GBT
AMIBA
APEX
~400 bolos@Chile
C_L^{SZ}
SPT
1000 bolos
@SPole
ACT
3000 bolos
3 freqs @Chile
C_L^{SZ}
SCUBA2
12000 bolos
JCMT @Hawaii
SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico
80s-90s
Ryle
OVRO



high resolution frontier: SZ power spectra

Battaglia, Bond, Pfrommer, Sievers, Sijacki 2010

$C_L^{SZ} \sim SUM_{all\text{-}cls,z}\ FT[p_e]^2\ FT[n_{cl}]\ (L/D_A)$
+ continuous clustering (sub-dominant)



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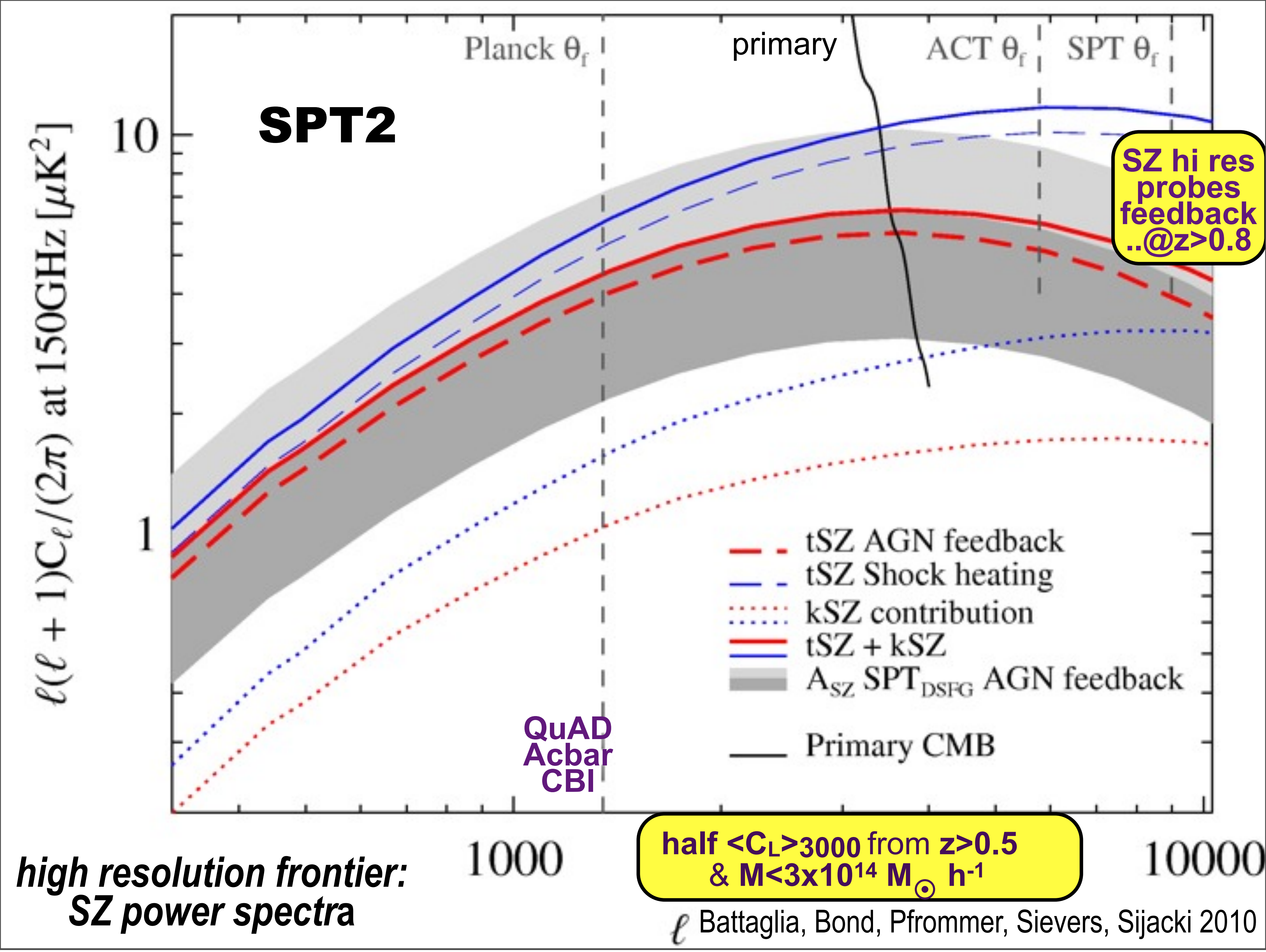

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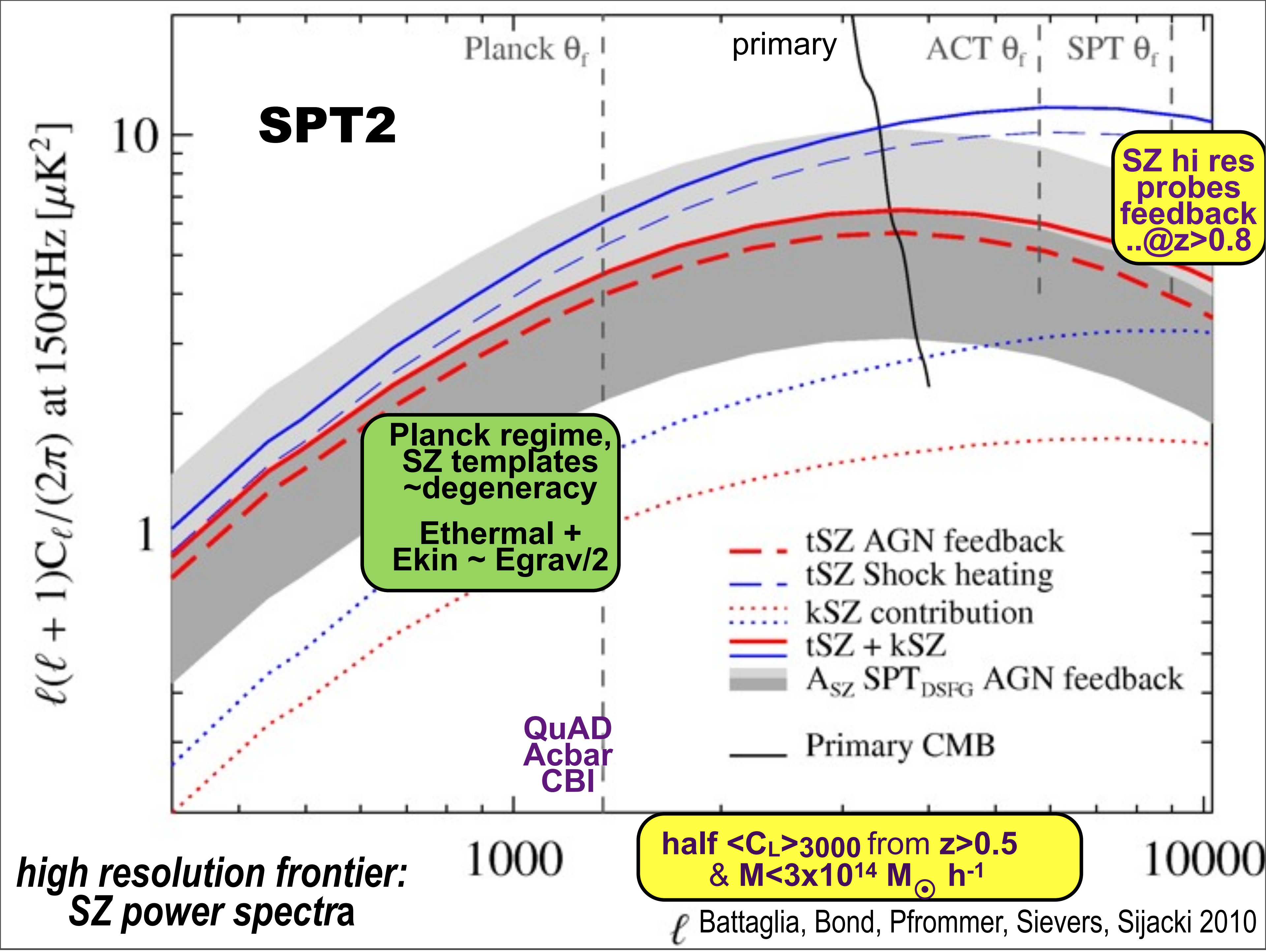

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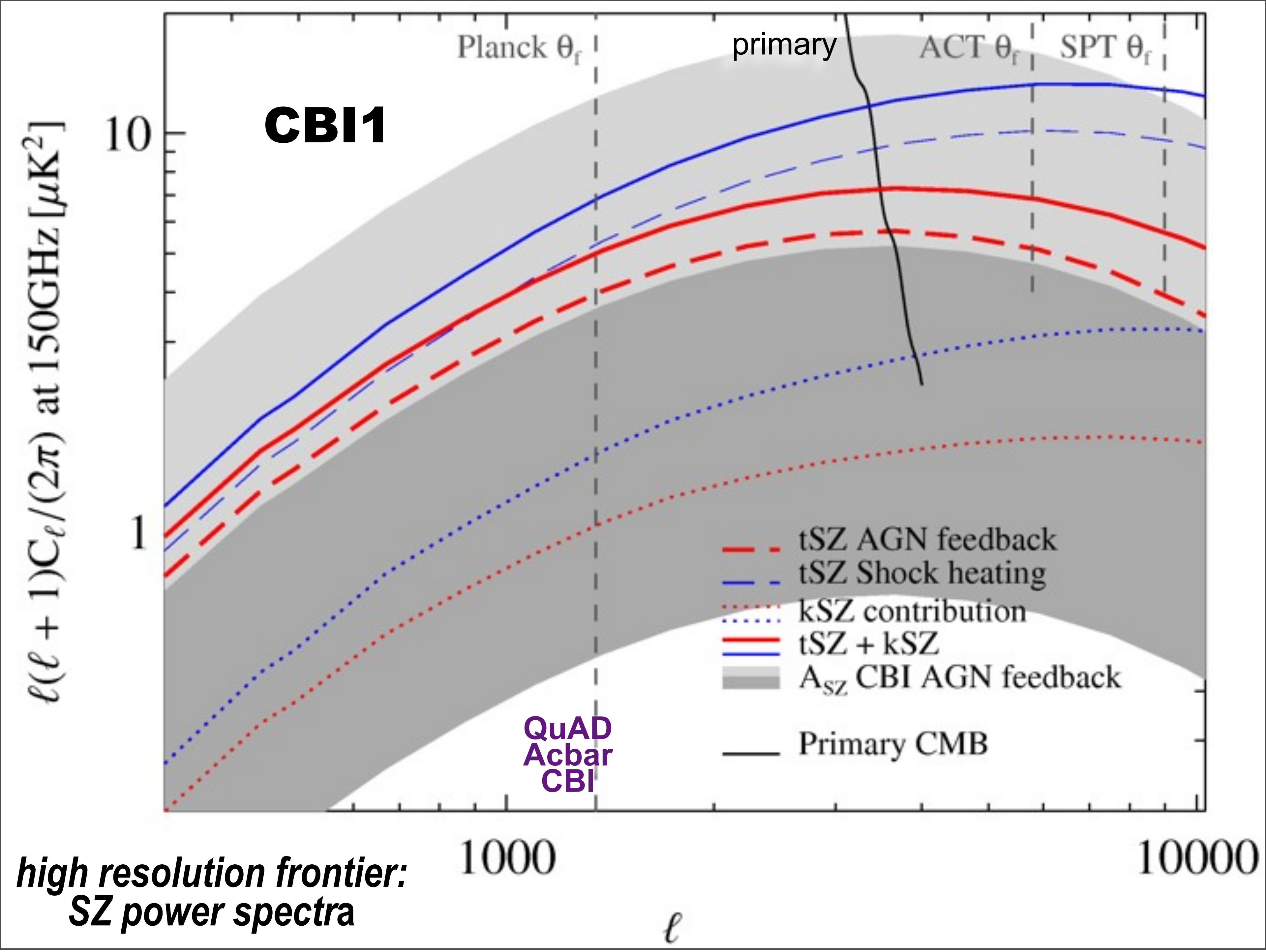

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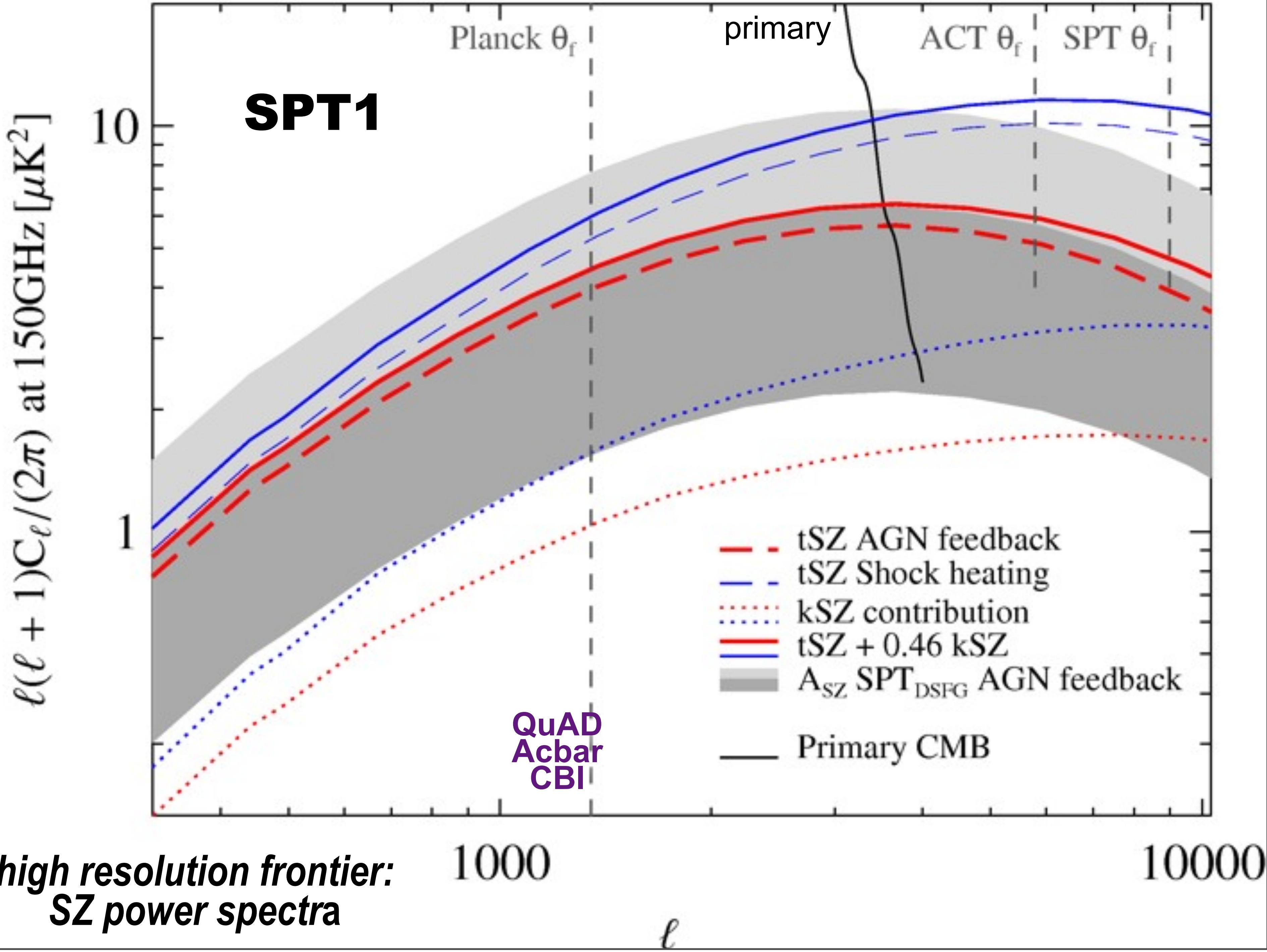

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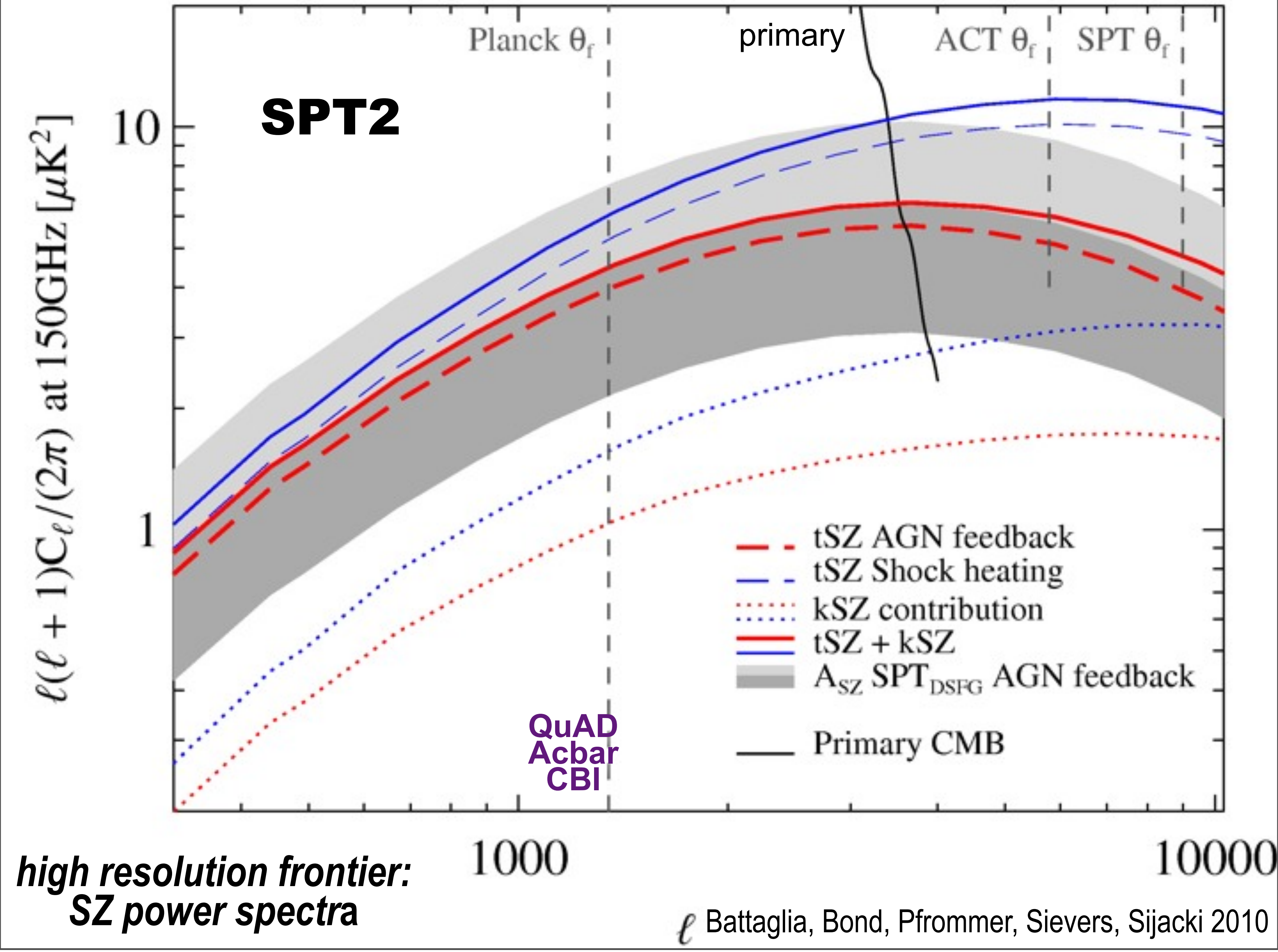

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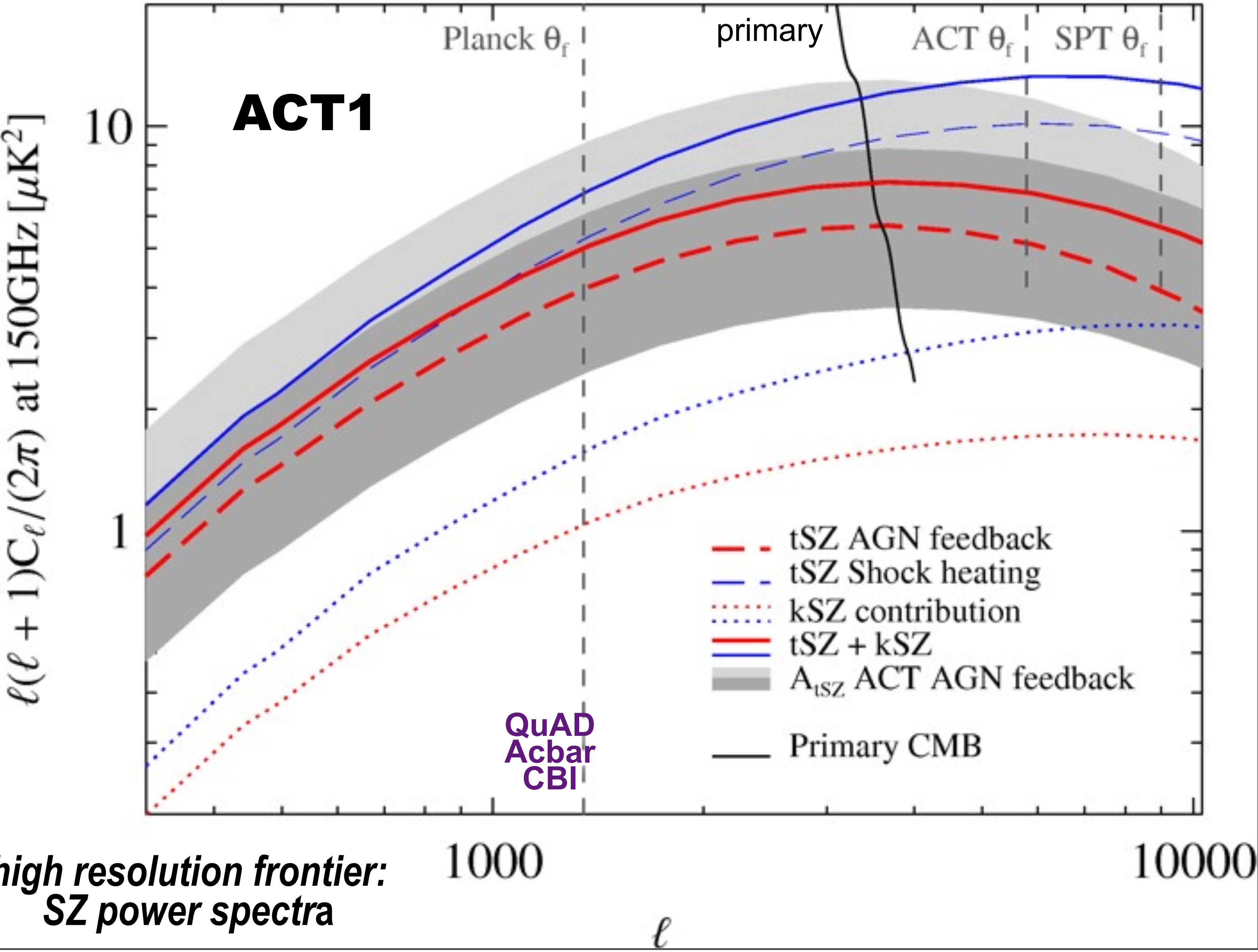
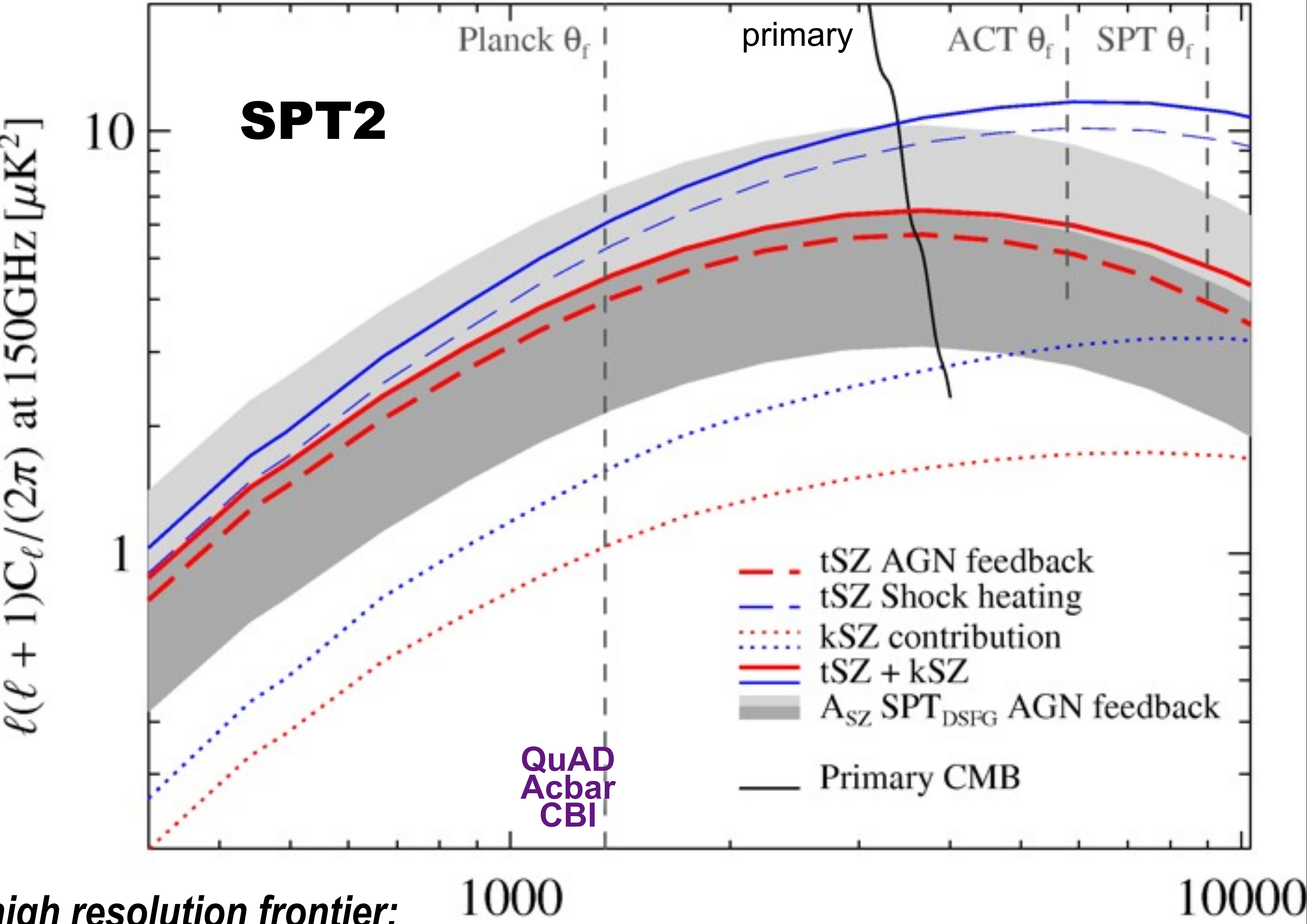


high resolution frontier:
SZ power spectra



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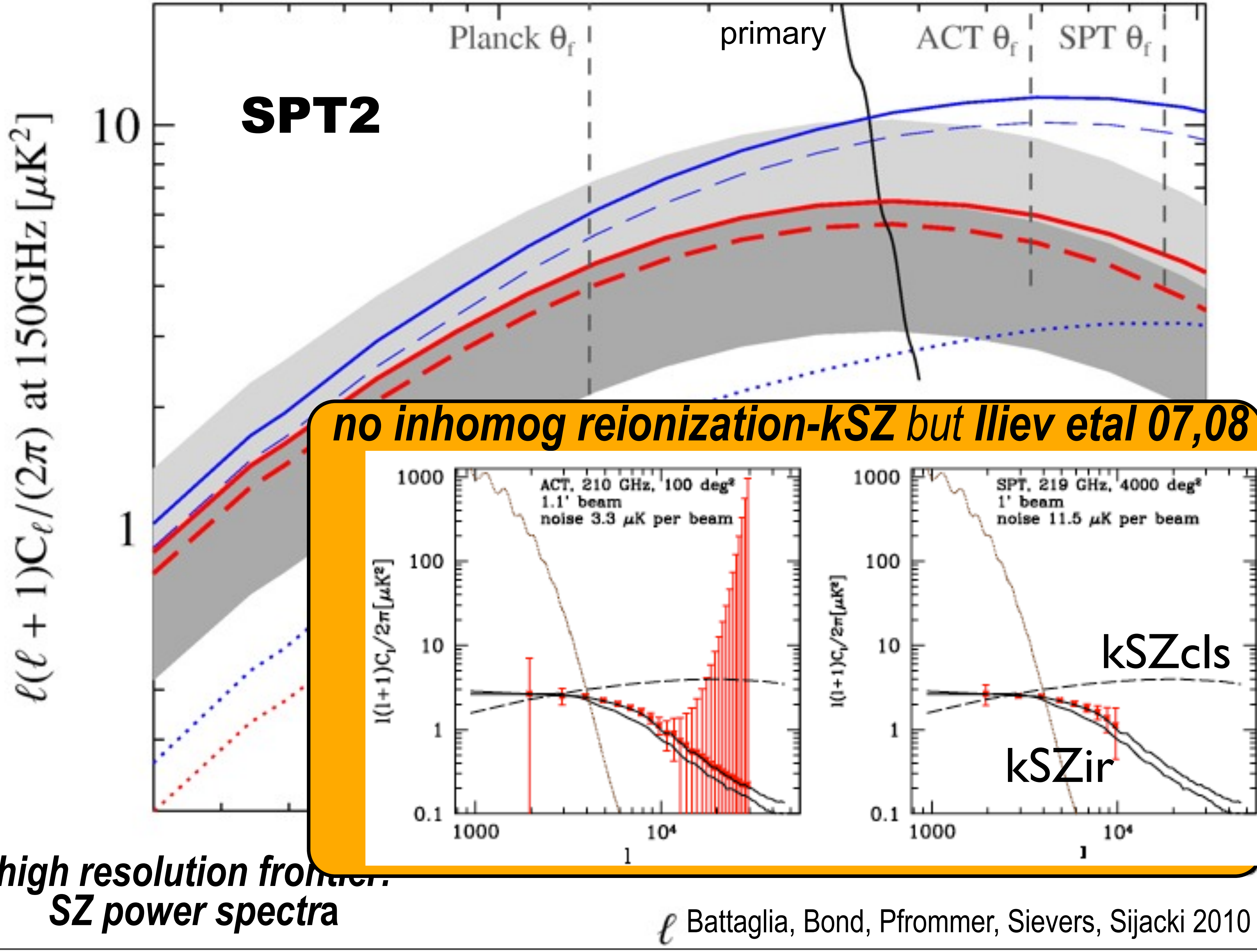

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Battaglia, Bond, Pfrommer, Sievers, Sijacki 2010

$n_{cluster}$

$(Y_{SZ}, M_{lens}, Y_X, L_X, T_X, L_{cl,opt}, R_{ich}, \ldots$

$|$ gold-sample, thresholds)

$+ C_L^{SZ}$(cuts) will deliver valuable

cosmic gastrophysics for sure.

Will it deliver fundamental physics

e.g., the dark energy EOS, primordial

non-Gaussianity??? σ_8 even?

so much for context & theory & forecasts.

on to the results:

Planck, ACT, SPT, Mustang on GBT,

AMI, SZA, APEX, Bolocam,...