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

25 years cifar

CITA = Cosmic Information Theory & Analysis:
IT from BIT, from BITs in IT, Studying the Cosmic Tango

Universe=System+Res =Data+Theory en-TANGO-ment

Dick Bond

Revealing the Cosmic Information in Clusters through the Sunyaev-Zeldovich Effect

Compton upscattering of CMB photons is a direct probe of the energy of the gas in gravitationally-collapsed objects ranging from the rarest clusters down to the typical groups. I will talk about our current state of SZ observations and cluster theory. In spite of *the long SZ history*, it has only been in the last few years that ACT and Planck teams, to which I belong, and the SPT team, have delivered impressive SZ results that show this probe is now profoundly augmenting the X-ray, optical galaxy and lensing signatures. To unravel the cosmic implications of the SZ data, the *complexity of the cosmic web's cluster/group patches* must be understood, and this requires a large program of *gastrophysical simulations with energy/entropy feedback*, with special attention to cluster outskirts as well as deep interior, whose conclusions I will describe.

***mocking** observations of the cluster/gp system in the cosmic web SciNet*
*massive non-equilibrium **rare events at high z** ACT, SPT, Planck, interferometers, Mustang@GBT*
*3.8σ **direct detection: kinetic SZ effect** of the moving hot gas in the cluster/group system ACTxBOSS*

Cluster Information from Compton Heating of the CMB: ACT, Planck & Theory

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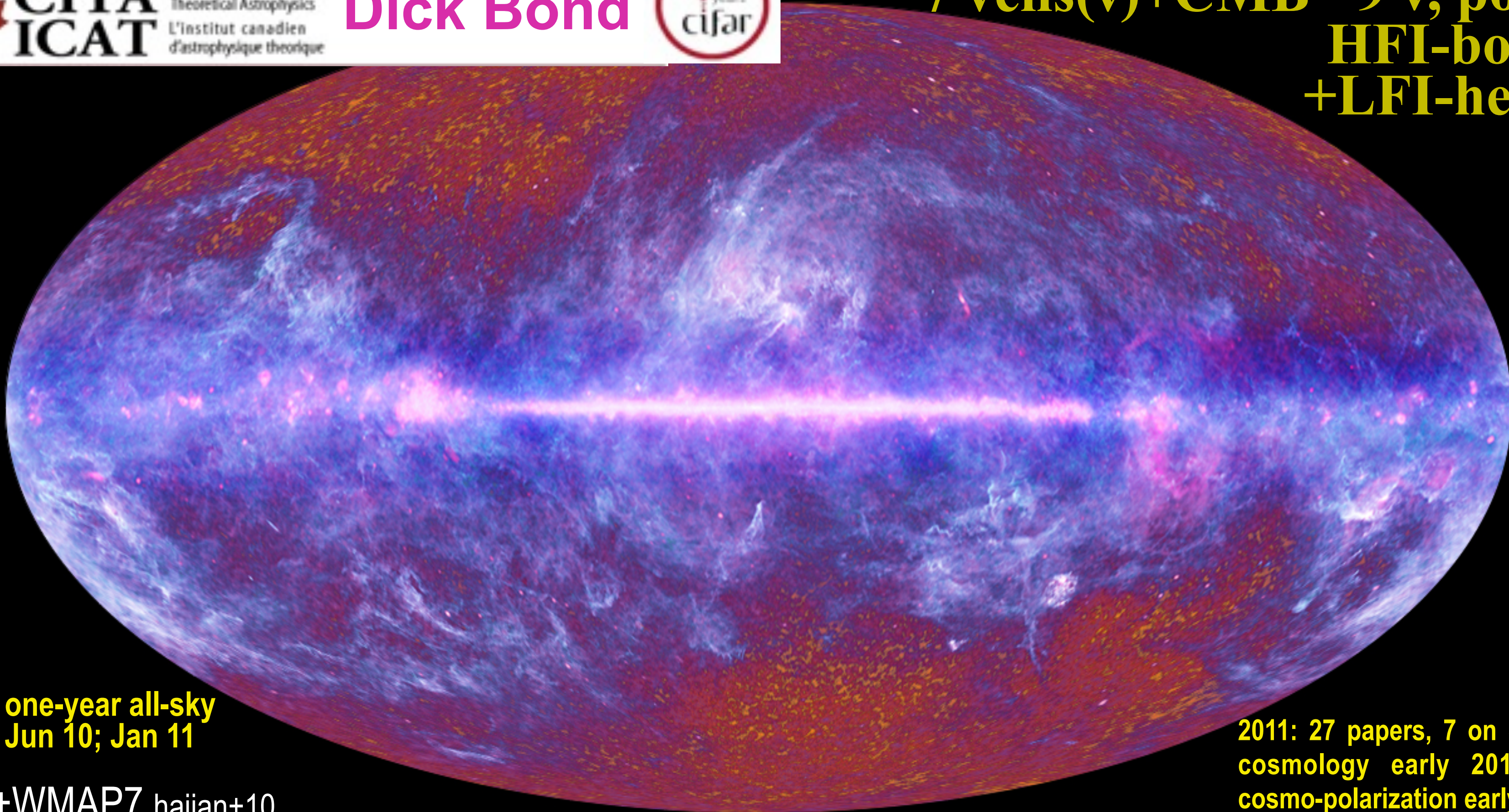
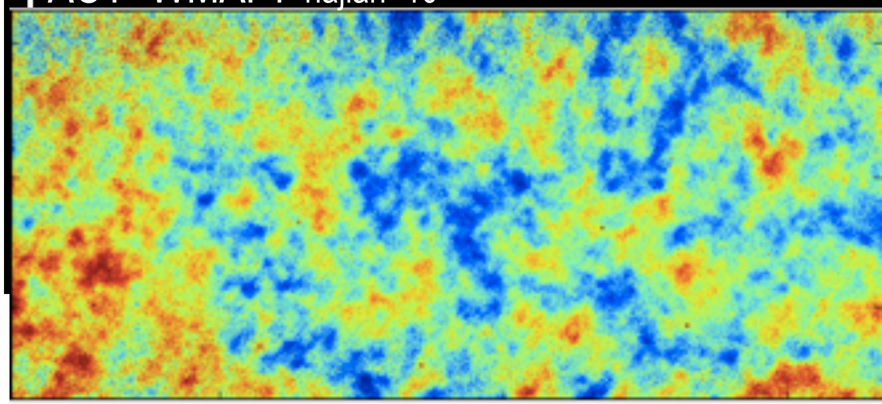
7 veils(ν)+CMB 9 ν, pol, HFI-bolos +LFI-hemts

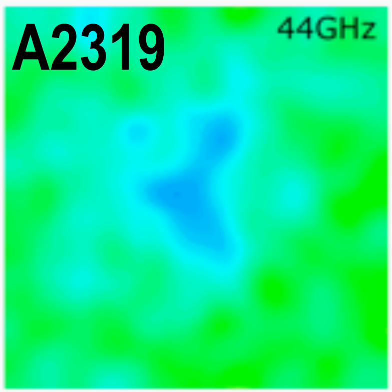


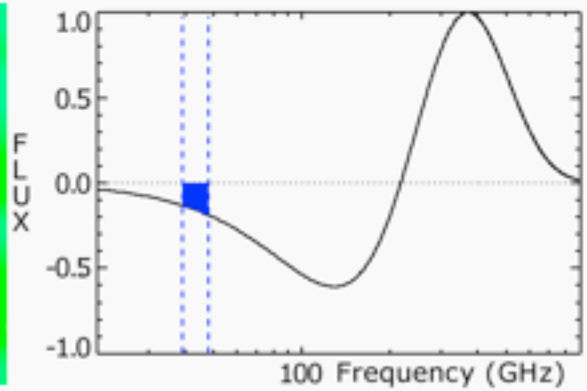
Planck one-year all-sky survey Jun 10; Jan 11

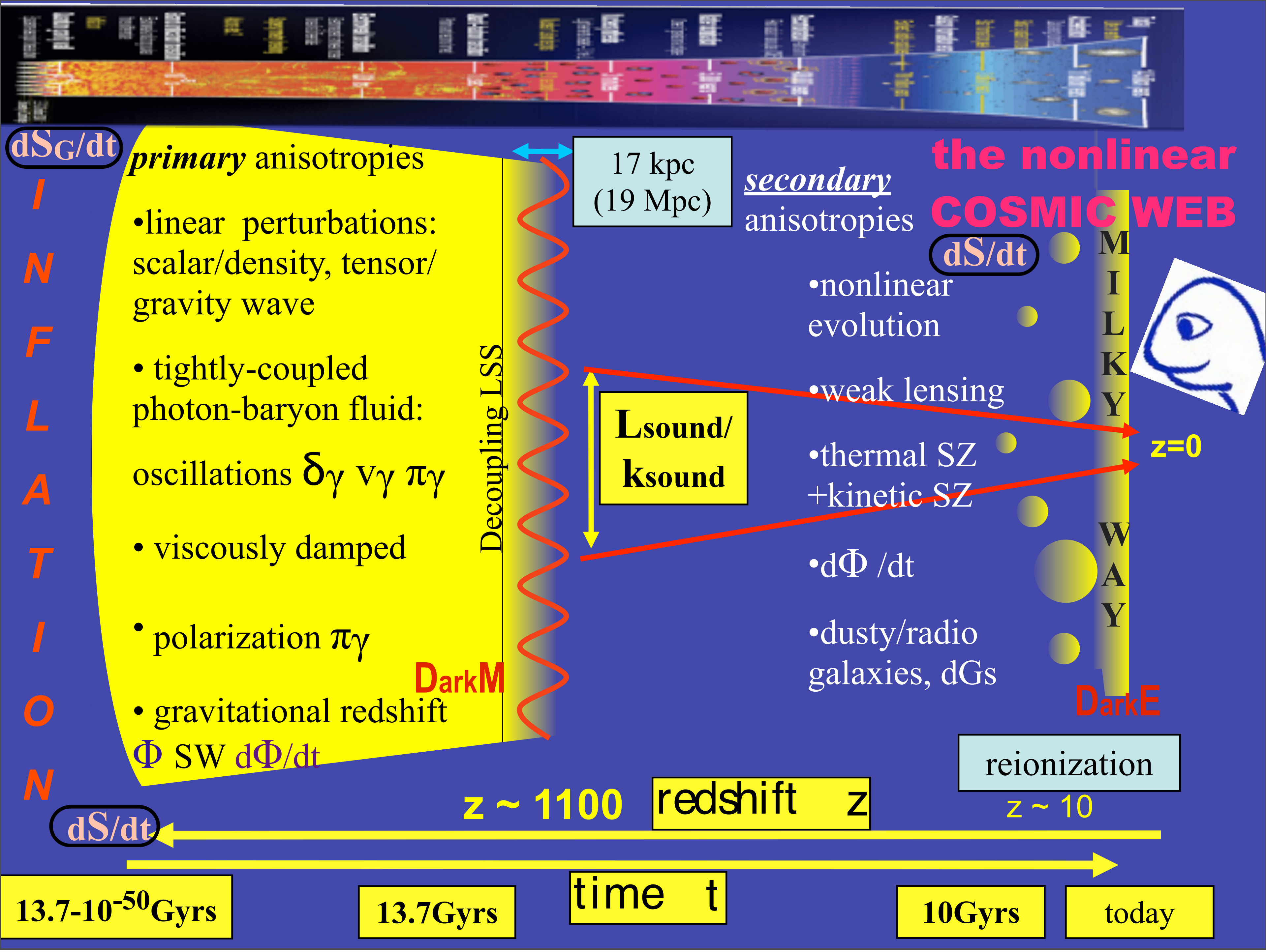
2011: 27 papers, 7 on SZ; first cosmology early 2013, first cosmo-polarization early 2014

ACT+WMAP7 hajian+10







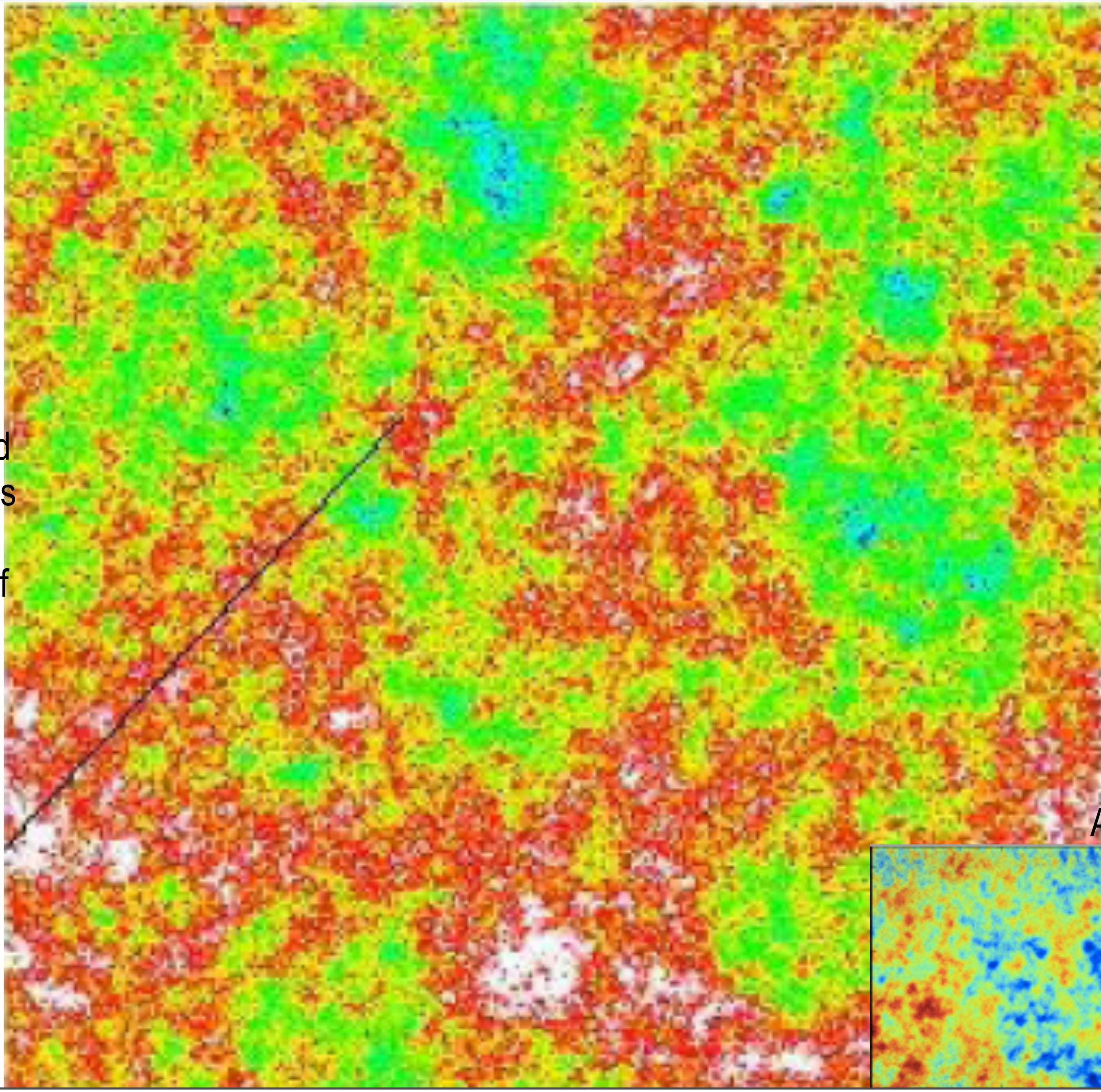


dS_G/dt
INFLATION
primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
• tightly-coupled photon-baryon fluid:
oscillations δγ vγ πγ
• viscously damped
• polarization πγ
• gravitational redshift
Φ SW dΦ/dt
DarkM
Decoupling LSS
17 kpc
(19 Mpc)
Lsound/ ksound
secondary anisotropies
the nonlinear COSMIC WEB
dS/dt
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
•dΦ /dt
•dusty/radio galaxies, dGs
MILKY WAY
z=0
DarkE
reionization
z ~ 10
z ~ 1100
redshift z
dS/dt
time t
13.7-10^-50Gyrs
13.7Gyrs
10Gyrs
today

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

χ

ln a(x, ln H)



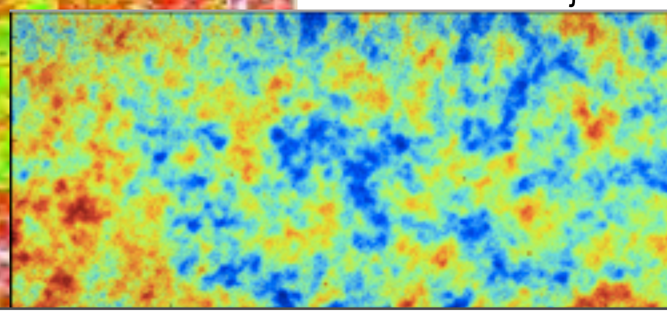
scalar field fluctuations in the vacuum of the ultra-early Universe

pre-heating patch (~1cm)

evolve from early U vacuum potential and vacuum noise

10 Gpc

ACT+WMAP7 hajian+10



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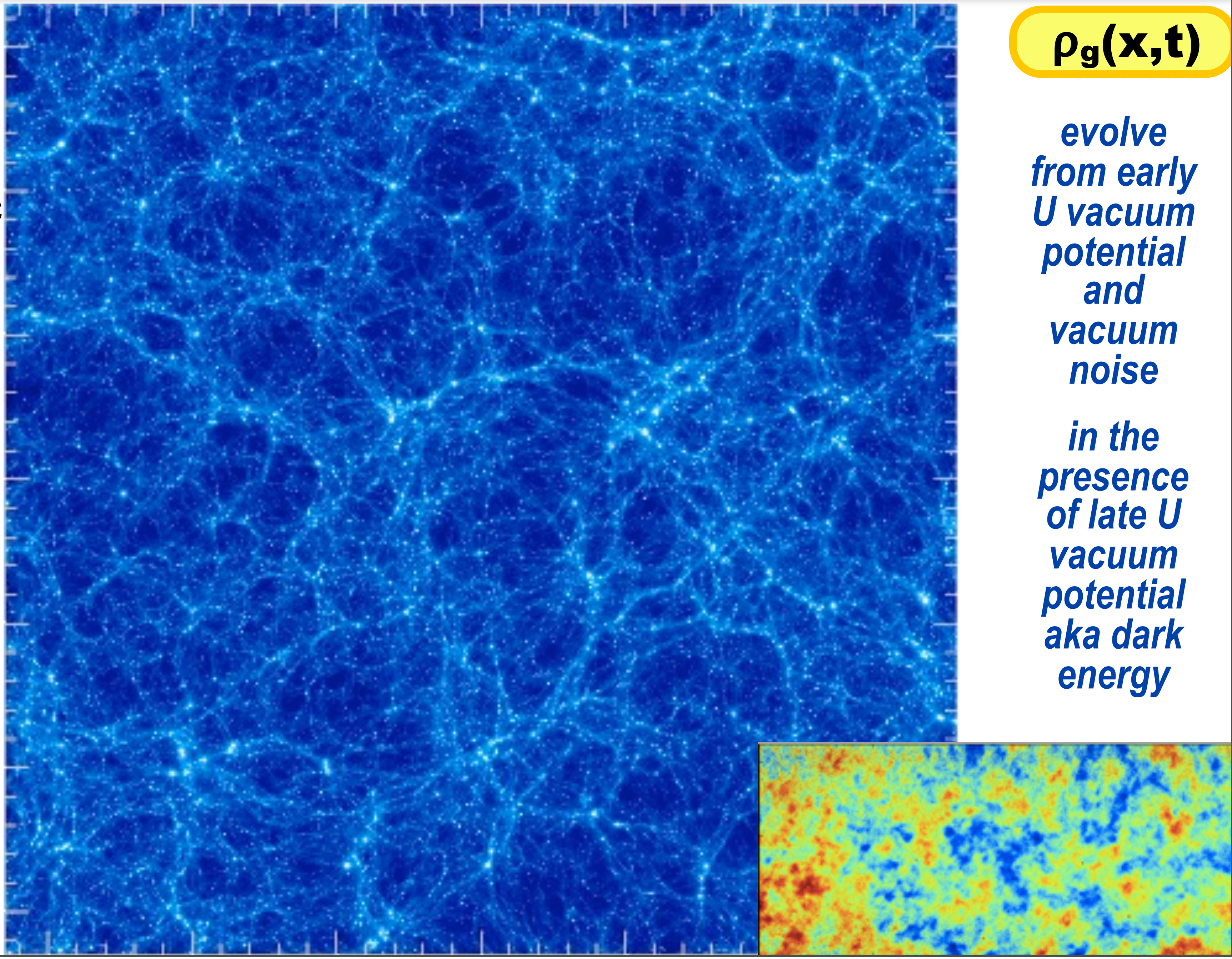


400 Mpc

ΛCDM

WMAP5

gas density

Gadget-3

SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4,5

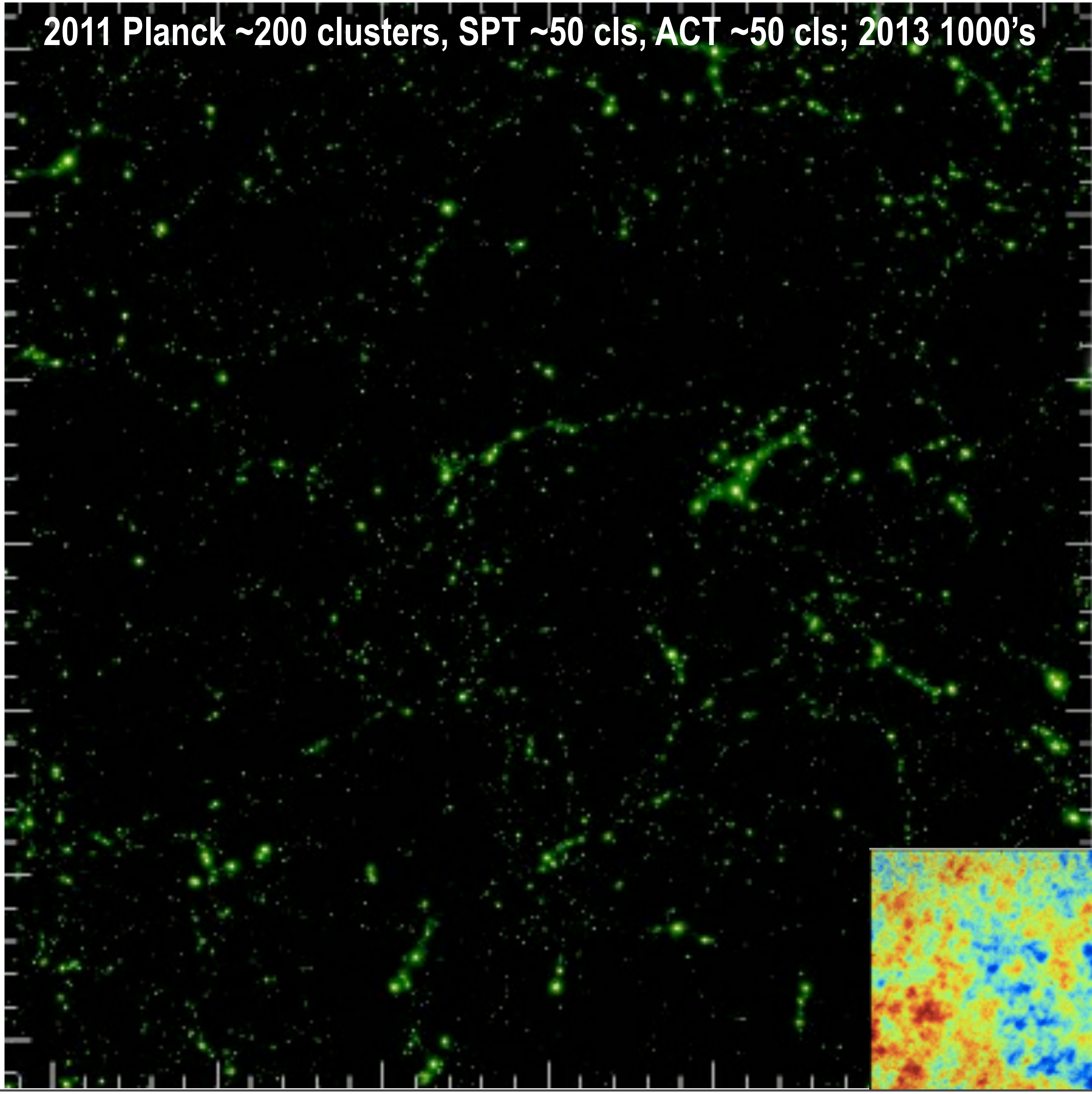
$\rho_g(x,t)$

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**

Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)



400 Mpc

ΛCDM

WMAP5

gas pressure

Gadget-3
SF+
SN E+
winds
+CRs

512^3

BBPSS10

BBPS1,2,3,4,5

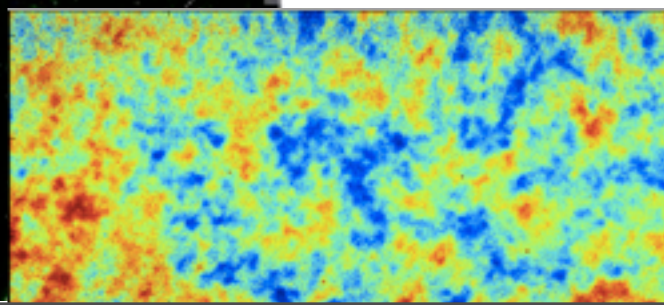
$p_e(x,t)$

CMB gets 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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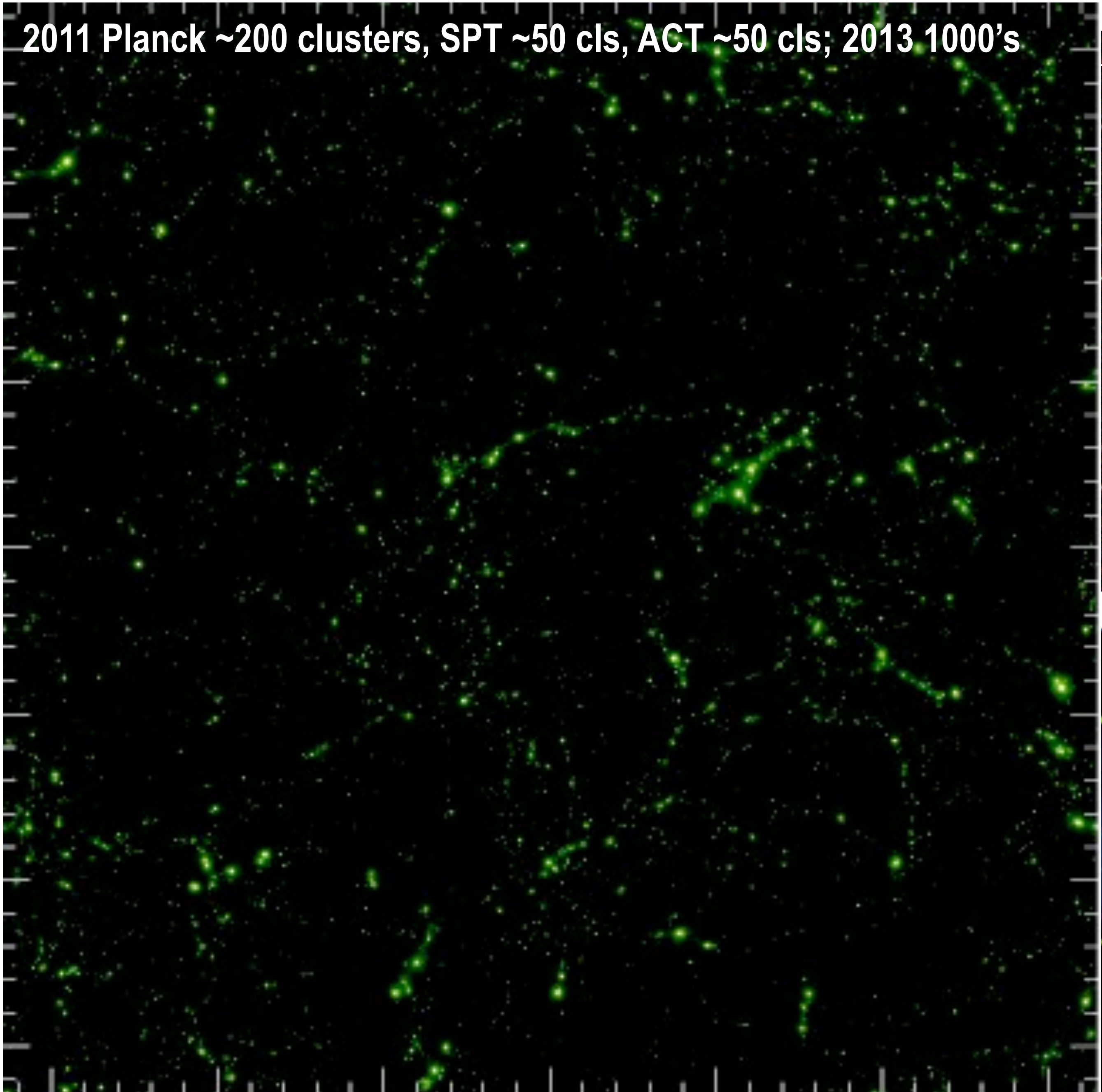
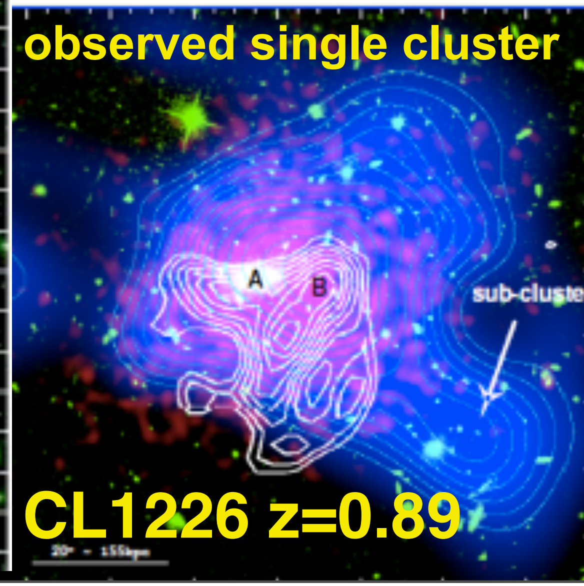
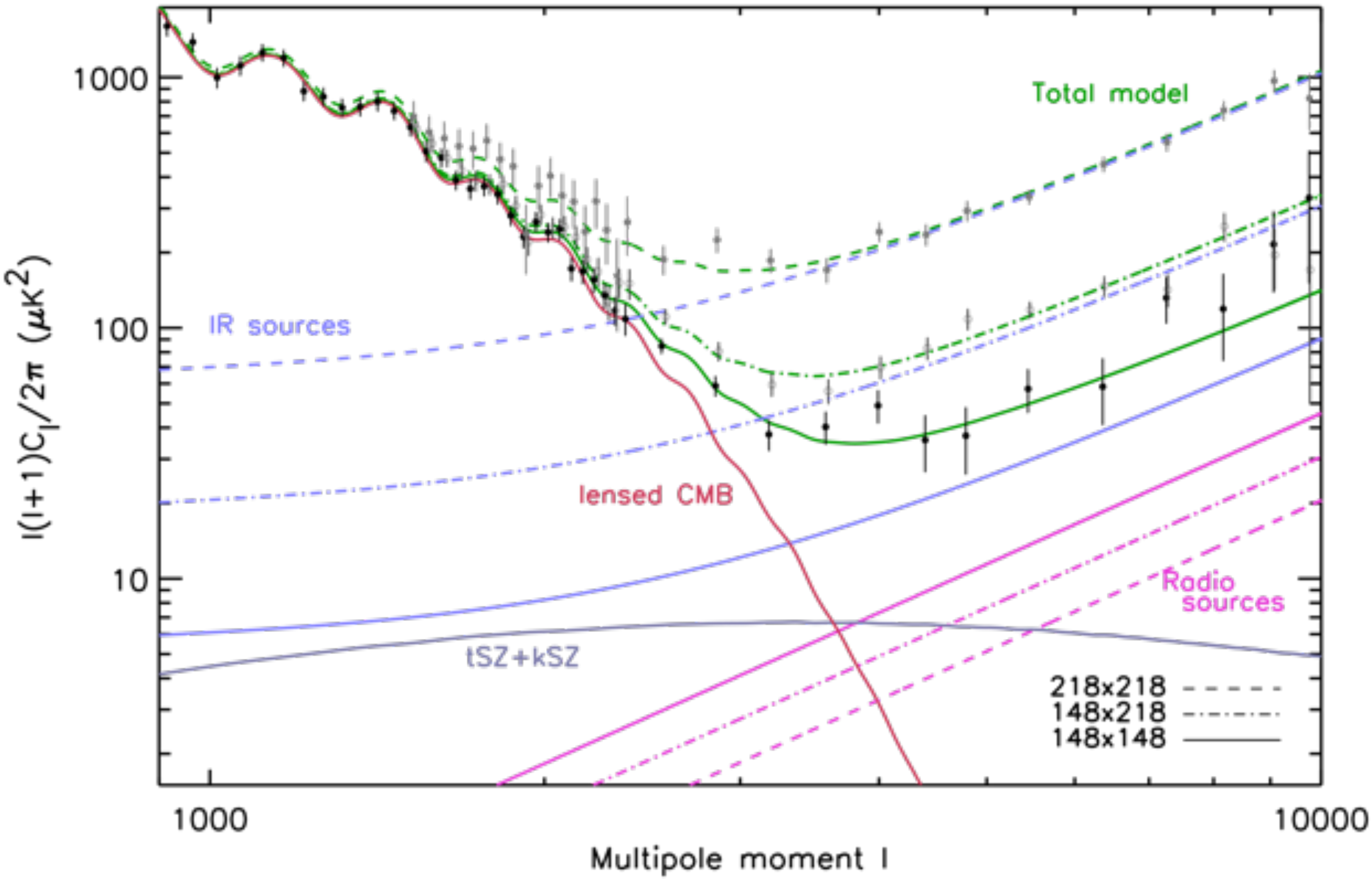




primordial (lensed) CMB + veils, *the veils = radio sources, the CIB, tSZ and kSZ (& Milky Way dust and synchrotron at lower multipoles)*



Dunkley+. 2010

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CIAR

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

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

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

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

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

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

Compton y-parameter

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

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

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$$<\Delta E_\gamma/E_\gamma> = 4T_e/m_ec^2 - E_\gamma/m_ec^2$$

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Compton y-parameter

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

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

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

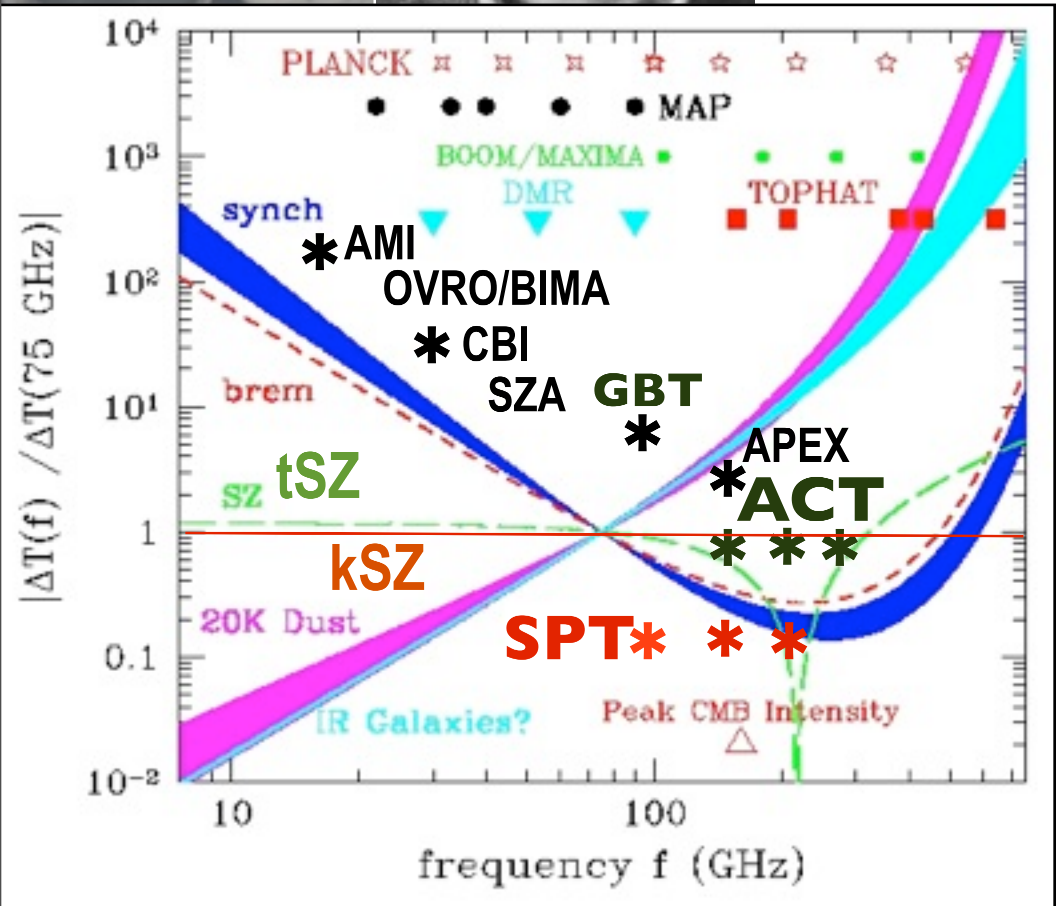
$\int kSZ(\theta,\varphi) d\Omega \sim M_{gas} V_{bulk} / D_A^2$

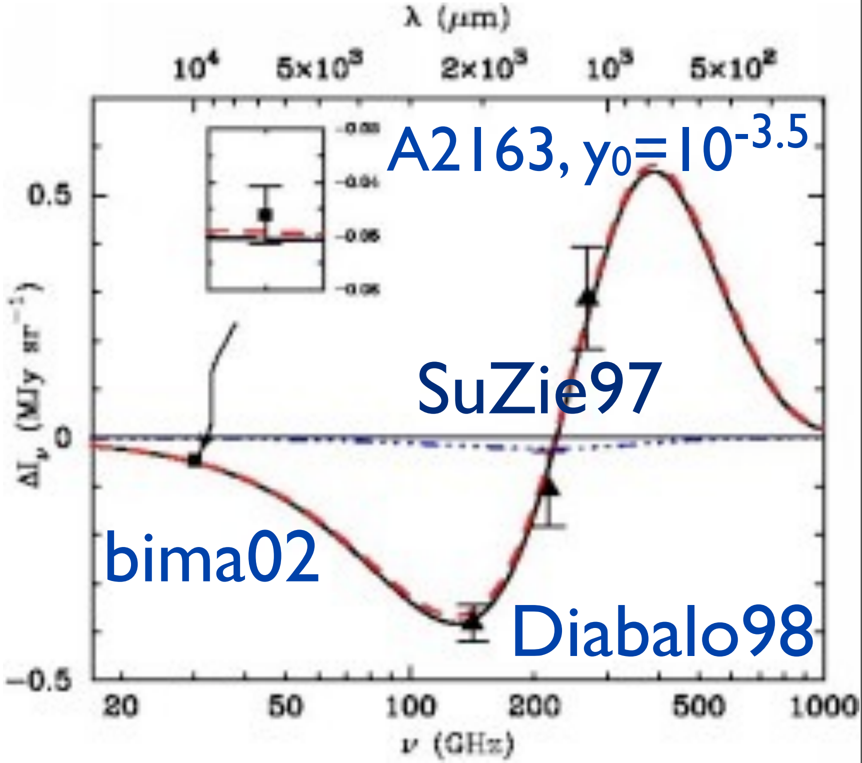
the theory of the Sunyaev-Zeldovich Probe of Gas in the Cosmic Web: $y \sim \int p_e$ dline-of-sight

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

$= -2y$ to xy, 0 @ $\nu = 217$ GHz

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





Synergy between Clusters & other cosmological probes

$n_{cluster}$

$(Y_{SZ}, M_{lens}, Y_X, L_X, T_X, L_{cl,opt}, R_{ich}, \ldots$ | z, gold-sample, thresholds)

+ C_L^{SZ}(cuts) + $\xi_{cc}(r|n_{cl})$ delivers

valuable cosmic gastrophysics.

Will it deliver fundamental physics

e.g., the dark energy EOS, primordial non-Gaussianity??? σ_8 even?

cluster/gp system used since 80s: Xtra power ξ_{cc} ξ_{cg} => xCDM

P_{pp}(.25h/Mpc) aka σ_8 via n_{cl} f_{gas} ... *ready for prime time? mock-ing!!*

ambient SZ in pancake model SBS83; hdm ruled out by clusters FDW83; SZ from clusters, explosions, superconducting cosmic strings B88; ambient SZ pix B89

“clustered shots” (*aka* **halos** *aka* **bbks86-peaks**) ⇒ **peak patches BM91-96, SZ/CIB was the target**

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

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

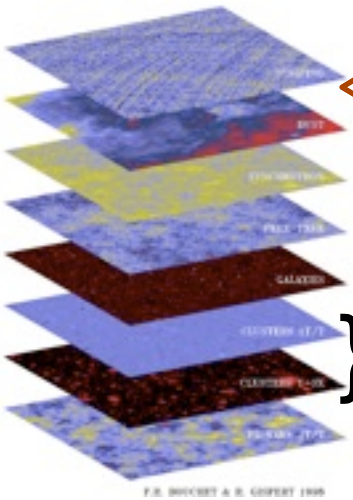
• **small angle anisotropies** - current results, optimal measuring strategies, statistical methods for

+ 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 2002-12 cf.* ***SPH-hydro*** (***Gadget/Gasoline***, *MMH, ENZO, ART, RAMESES 2001-12;* ***ITP cl test*** *96-00):* ***discrepancy 2002+****: big issue was/is: Δ 500 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}**


cifar@05 mt tremblant, quebec:
the dangers of probing high peaks

in praise of **mocking** the **cluster/gp system** *with*

*increasing sophistication: Monte Carlo selections, contamination of probes, **n_{cl}** (what's happening, Mass++), & ... MC mock-observations & systematics, **end-to-end sims a la CMB expts***

cluster near, intermediate (> r500) & far (>r200) field

internal bulk flows aka turbulence

ratty edges from filament inflow

anisotropy $\neq$ spherical

line of sight contaminants for cylindrical measures

clumping, subhalos, ...

radio galaxies / AGN / BCG inside

other galaxies inside

background galaxies

short distance complexities in a coarse-grained world (e.g., unstable multiphase cooling cores)

@Monsters Inc: good movement in this direction, e.g., ACT, Planck, SPT, DES, X..., an industry arises, Mockers Inc.

need: fast + numerous MC, but informed by high res full simulations

beware, although DM-dominated the gas/stars are - of course - highly biased inside the clusters, painting/splattering dark matter halo potential wells (e.g., $\mathbf{p_e}(F_N(x))$ can never be accurate; e.g., DM ellipticity >> gas ellipticity

SciNet

Simulate Universes *from ultra-early beginnings to ultimate end. turning 6 parameter LCDM theories into Petabits. Fields on a lattice, Linear Theory, Linear perturbation evolution for primary CMB, pure N-body, Gastrophysical complexity, feedback, transport.* **Mock** data

Process Data *compressing the Petabit+ raw observed CMB+LSS information into high quality bits.* **ACT maps >20 CPU-Mhrs solve for 10^{10} params from $>10^{12}$ data pts**

SciNet @UofT:

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

CITA-SZ with feedback: *Battaglia, Bond, Pfrommer, Sievers & Sijacki 2010, BBPS 2011-12 1,2,3,4,5*

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

07 goal large treePM-sph sims (~1000^3 gas+DM)-NOT **08-12** 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: $\Delta E_{inj} \sim \varepsilon \Delta t$ 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 2012: $\nexists$ *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 tSZ-region ~$0.5R_{500}$ to ~$3R_{200}$ $\Rightarrow$ different non-thermal problems:***

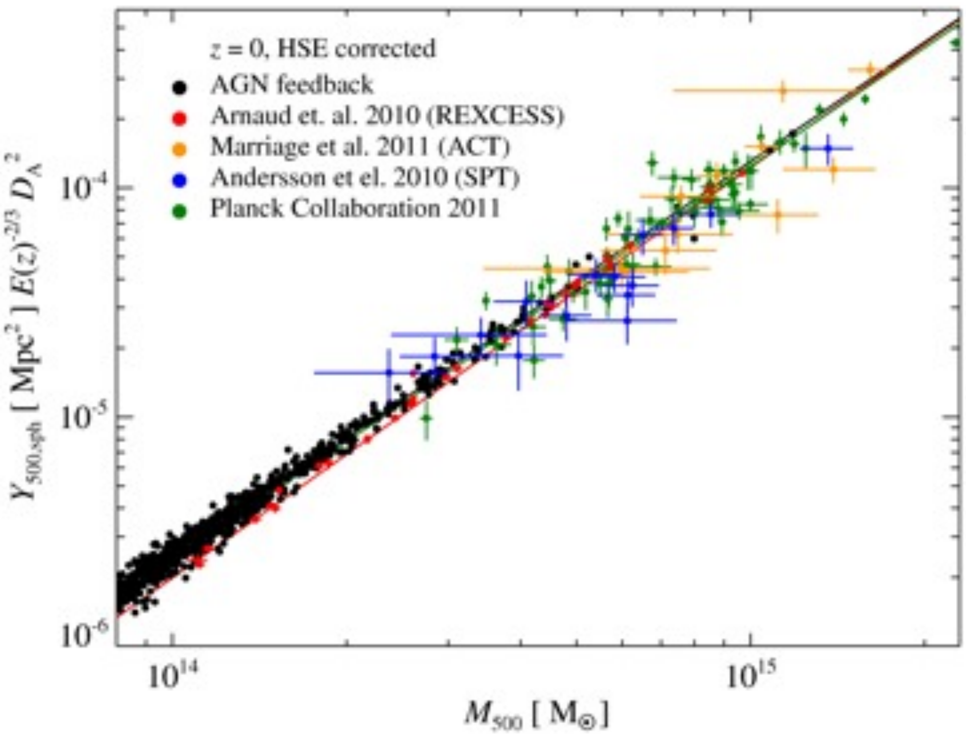
kinetic pressure aka "turbulence", pressure/density clumping, asphericity, ... *but we need hydrodynamically-reasonable inner cores hence subgrid feedback (beware of cutouts of overcooled cores)*

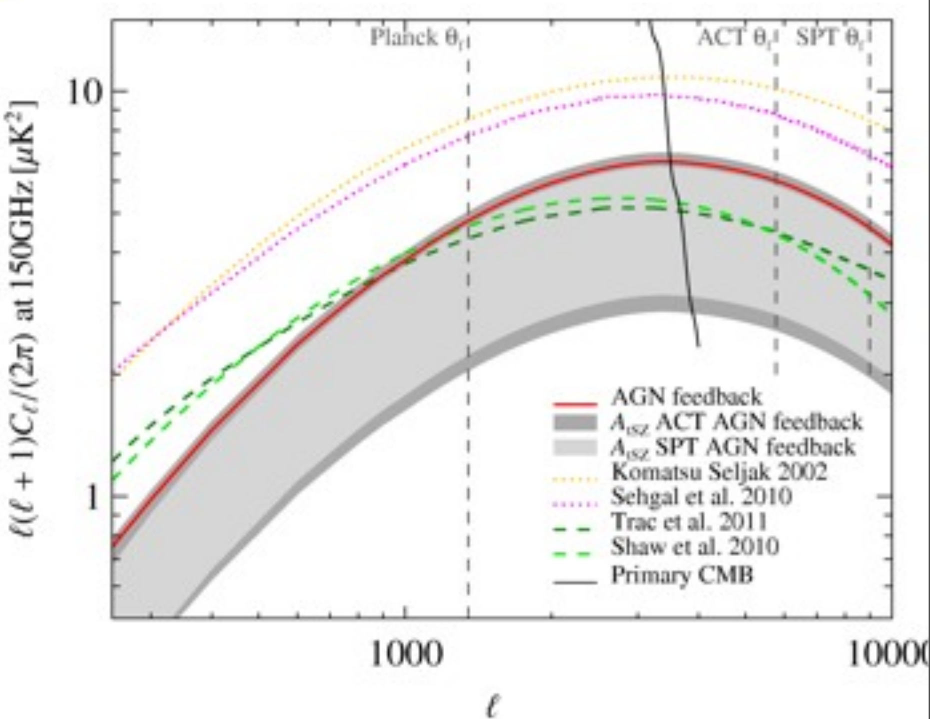
"every cluster is a Bullet cluster" - or was a bullet in its past, el Gordo, A520, ...

Cluster Coarse-Grained Feedback Sims cf. SZ data ACT, SPT, Planck

Cluster counts $n_{cl}(M(Y))dM$ + tSZ/kSZ Power spectra

Battaglia, Bond, Pfrommer, Sievers 2011-12: I,II,III,IV,V; BBPS+Sijacki 2010





both are sensitive to gastrophysics:
resolution, feedbacks(M,z), kinetic <δVδV†> cf. thermal pressure, <δXδX†>anisotropy, p&ρ-clumping, non-equilibrium cluster-outskirts

Hydro Sims include all effects -except of course those not included

=> Thou Shalt Mock Analytic and semi-analytic treatments cannot intuit these & must be fully calibrated with sims for a useful phenomenology

non-thermal/non-equilibrium effects:

Summary: the **running** with **r/R_{200}**

aka resolution (e.g., $d\ln E_{th}(<r)/d\ln r$)

of effects influencing **$Y_{SZ500}(M)$** & **C_L^{tSZ}** for low & high **M** @ z=0, 1

turbulent internal bulk flows **P_{kin}/P_{th}**

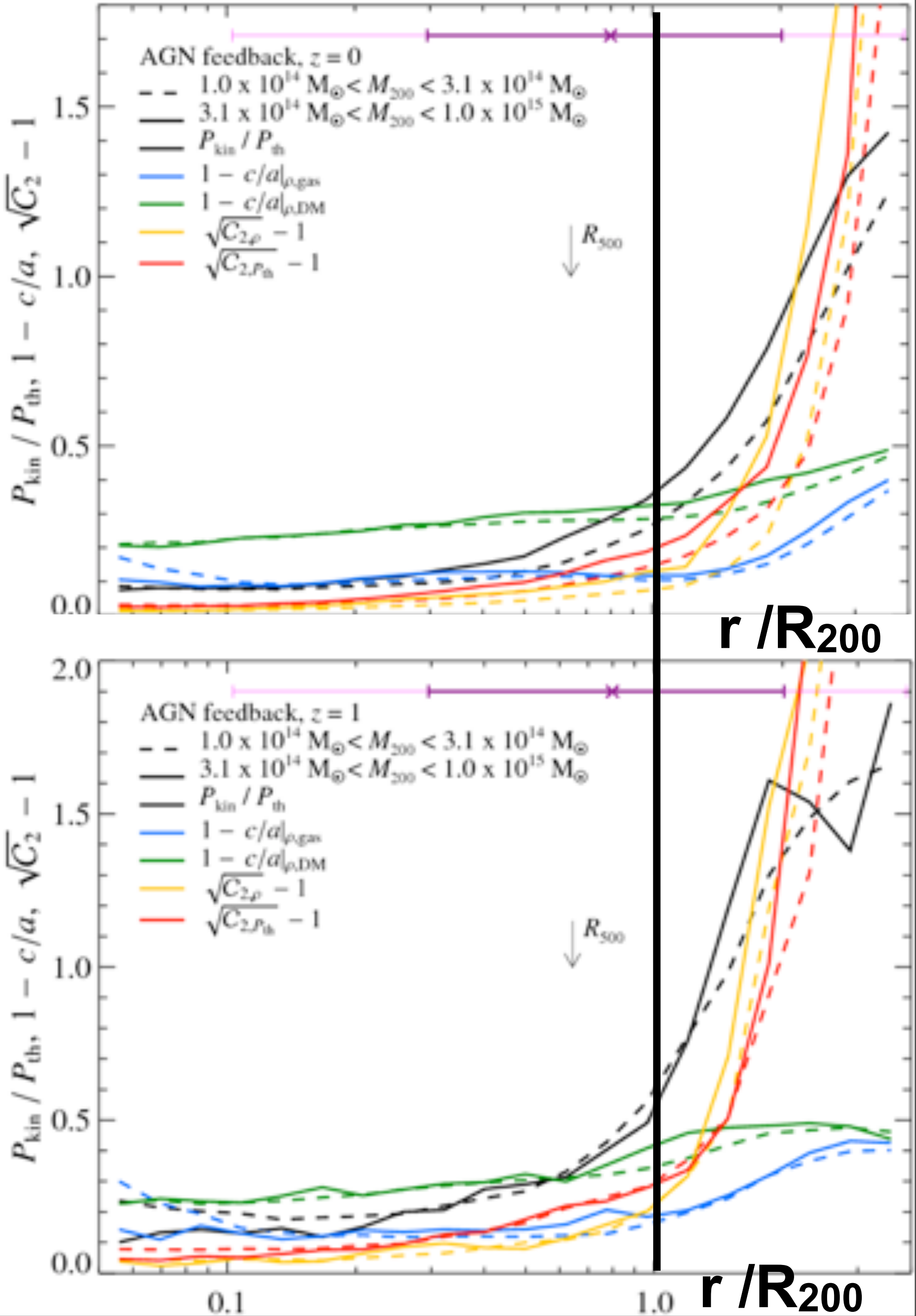
asphericity 1-c/a gas cf. DM

clumping of density & **pressure** (!)

$C_{p2}^{1/2}-1 = \mathrm{sqrt}[\langle p_{th}^2\rangle/\langle p_{th}\rangle^2]-1$

not small @ < R_{500}

huge @ < R_{200} < R_{vir} < $R_{SZboundary}$



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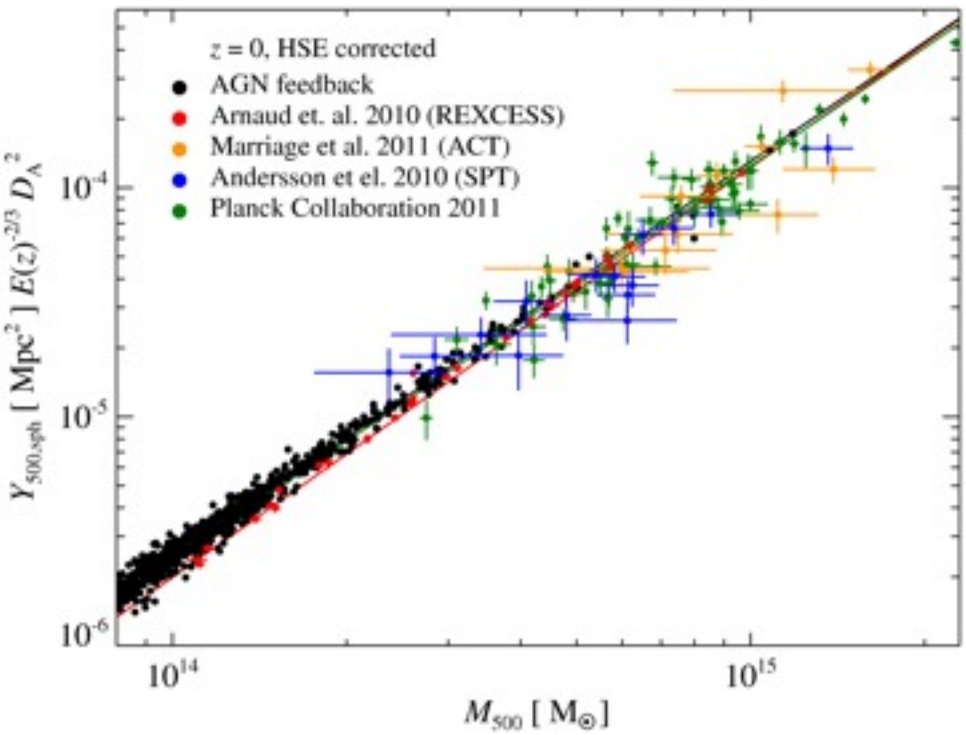

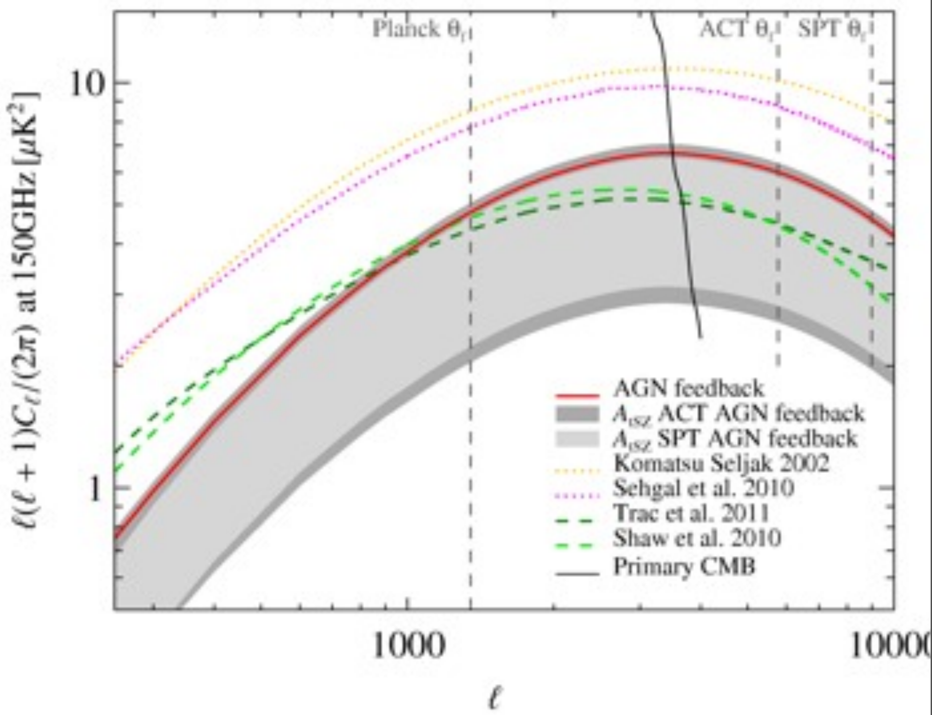

"turbulence" p_{kin}/p_{th}**~20% effect**

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

Δ input physics ~30% effect

Pressure subclumping & asphericity pushes C_L^{tSZ} up by ~10-20% over L~2000-8000

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

$\ln p_{th}$ & $\ln \rho_g$ & $\ln \rho_{dm}$ & Φ_{dm+g}

$s_X \sim T_e / \rho_g^{2/3}$

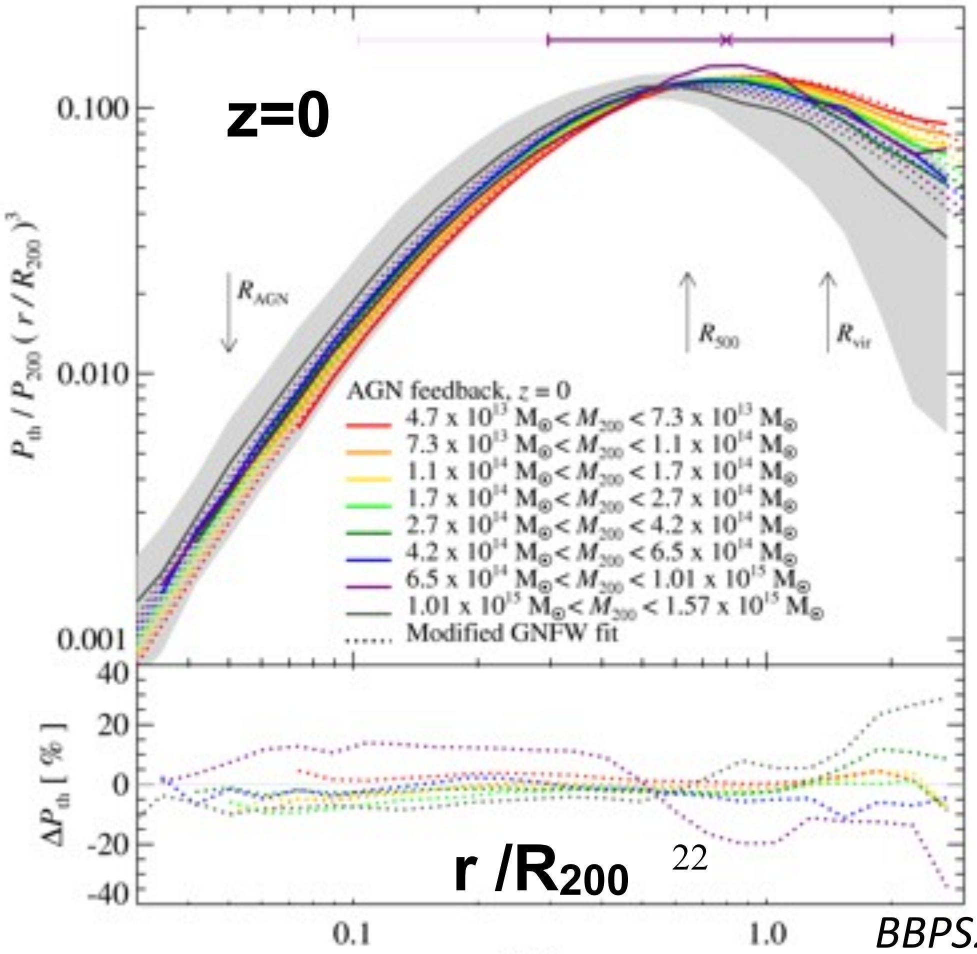
but it is p_{tot} *in the virial equation (& more)*

(10+10+20 256^3 gas+DM)
(1+1+1 512^3 gas+DM) *ΛCDM*
***sphericalize-scale-stack* cluster profiles, with Y_{SZ} weighting, also M & z bins.**

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 to **rotate-into-principal-axes - scale-stack*** **profiles**

& cluster ENTROPIES: coarse-grained information

GNFW-fit(M,z) accuracy <10%
extends Arnaud universal profile



BBPS2

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

ln p_{th} & *ln* ρ_g & *ln* ρ_{dm} & Φ_{dm+g}

$s_X \sim T_e / \rho_g^{2/3}$

but it is p_{tot} *in the virial equation (& more)*

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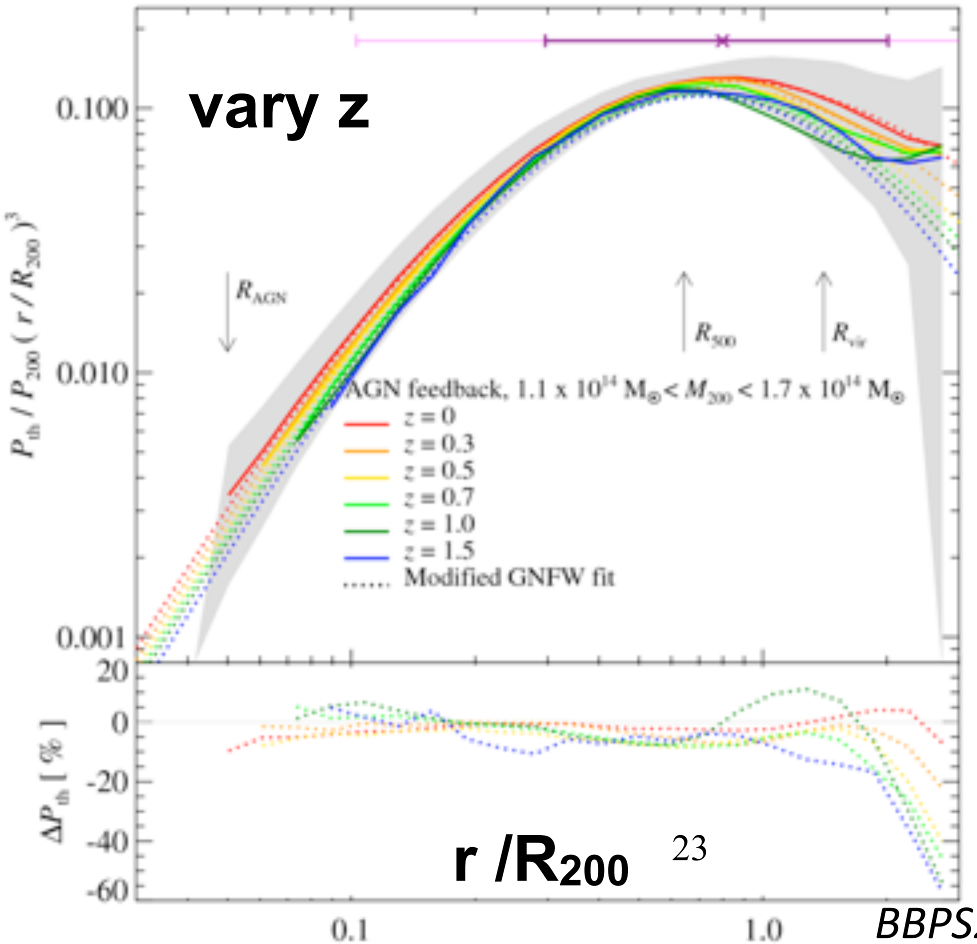

BBPS2

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CBI pol to Apr'05 @Chile CBI2

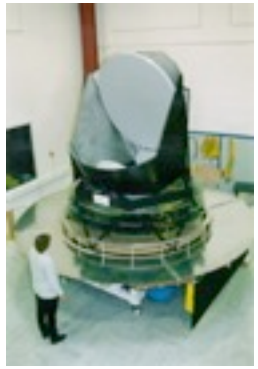
53+35 cls (>=40)

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

Acbar@SP
~1 blind

>96

OVRO
/BIMA
array

38 cls

SZA@Cal

3 cls (z>1), x?

AMIBA

6 cls

AMI

7+1 cls >=50+25

GBT Mustang

4 cls (~25 CLASH)

APEX
~400 bolos@Chile

~25 cls

SPT
1000 bolos
@SPole

ACT

23+27~50 cls

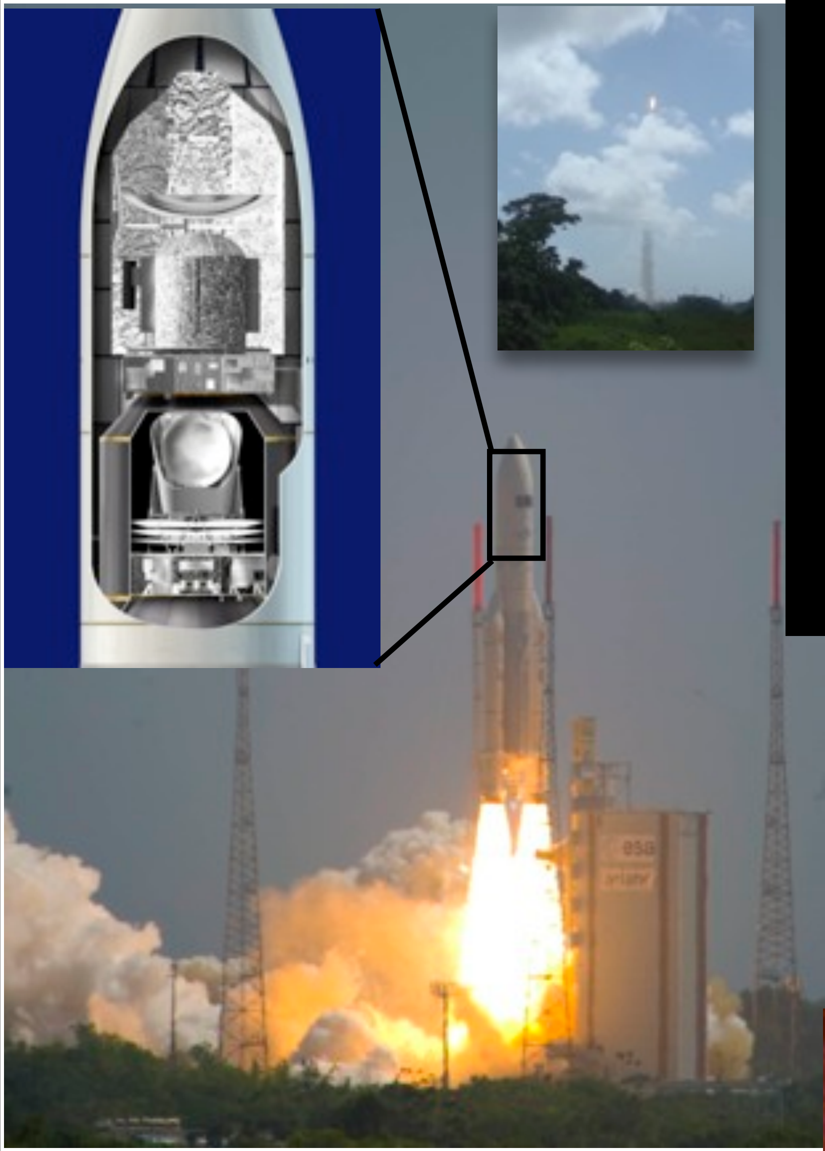
3000 bolos
3 freqs @Chile

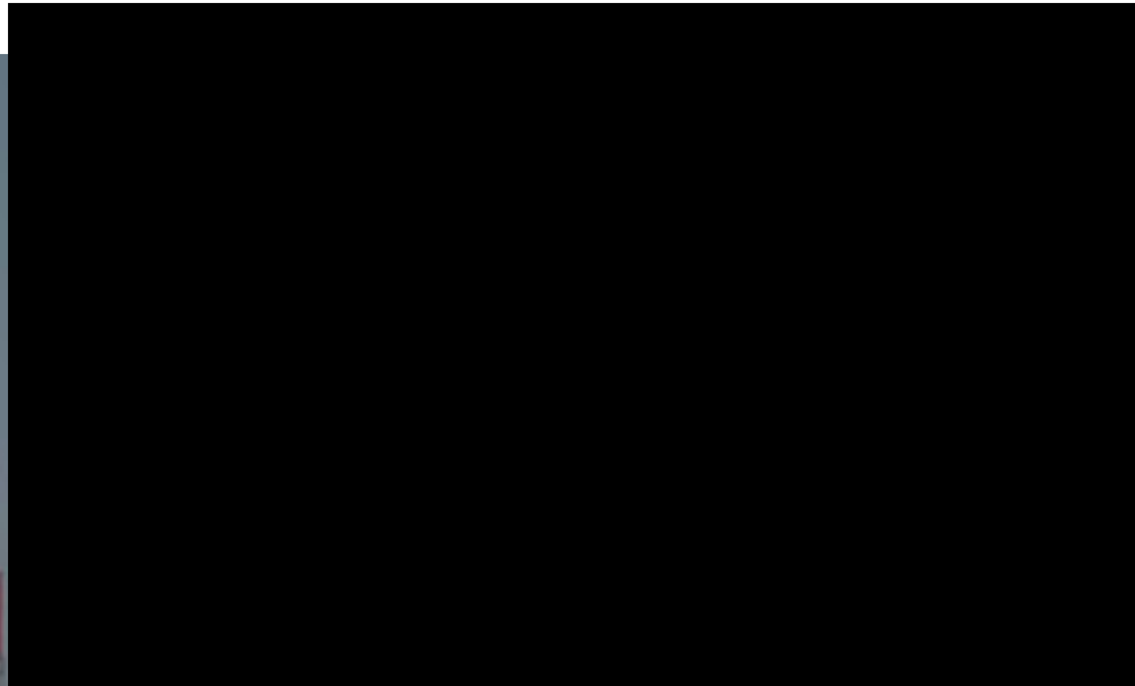
SCUBA2
12000 bolos
JCMT @Hawaii

80s-90s
Ryle
OVRO

SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico

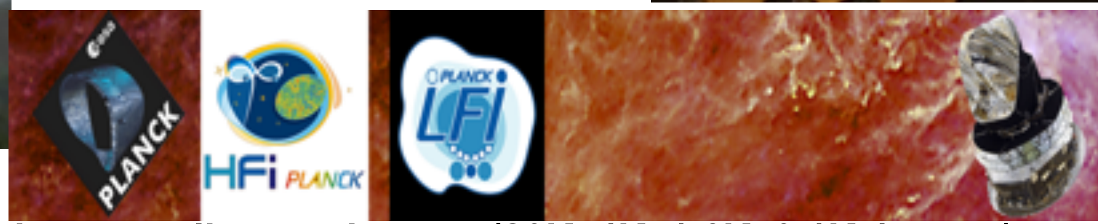
Planck+Herschel Launch May14 09 Fr. Guiana





1.5m telescope, HFI bolometers @6freq <100mK, LFI HEMTs@3freq, some bolometers & all HEMTS are polarization sensitive

HFI+LFI **performance** to **spec** or better

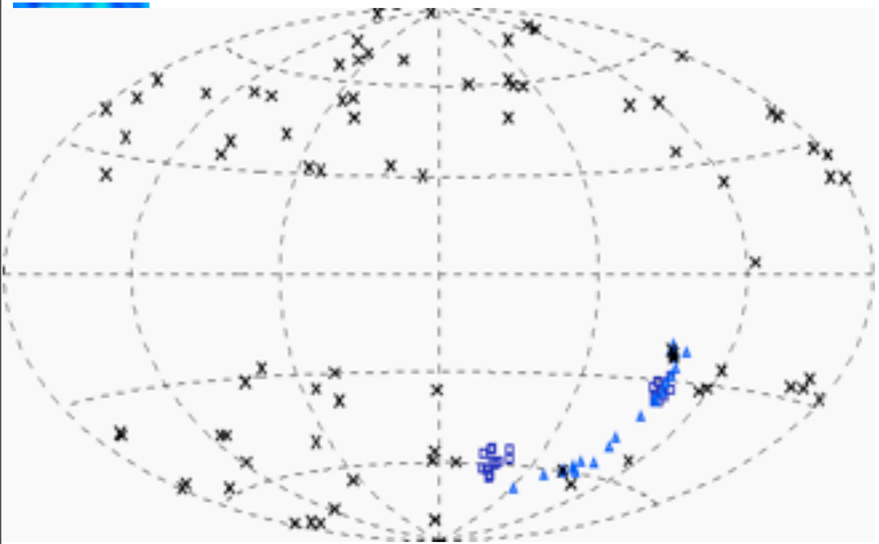


Left earth at ~10 km/s, 1.5 million km in 45 days, cooling on the way (20K, 4K, 1.6K, 0.1K 4 stage).
@L2 on July 2 09 -almost no trajectory correction @operational temp; Survey started on Aug 13 09
spin@1 rpm, 40-50 minutes on the same circle, covers all-sky in ~6 month, ~2.43 years to Jan14,2012

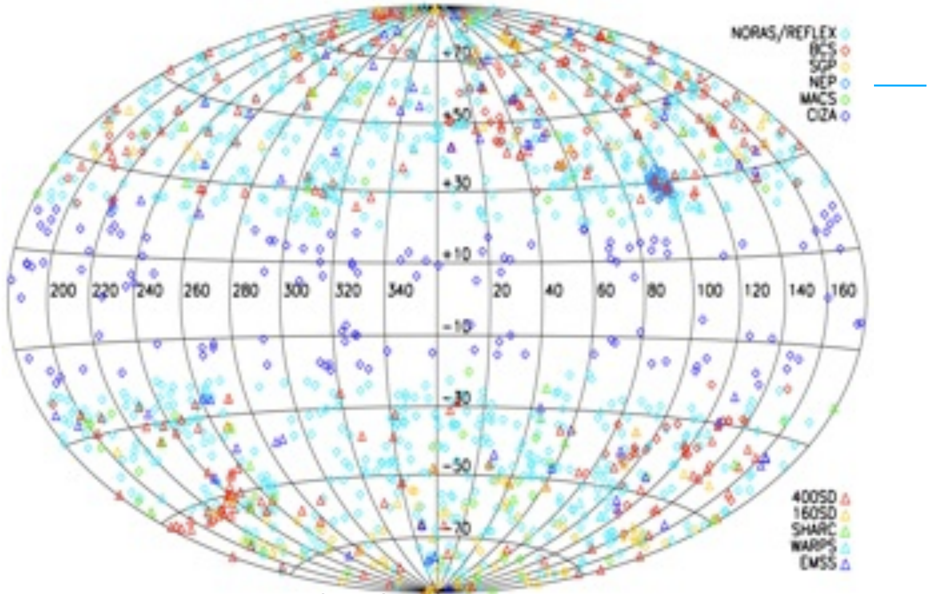
the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency -- ESA -- with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

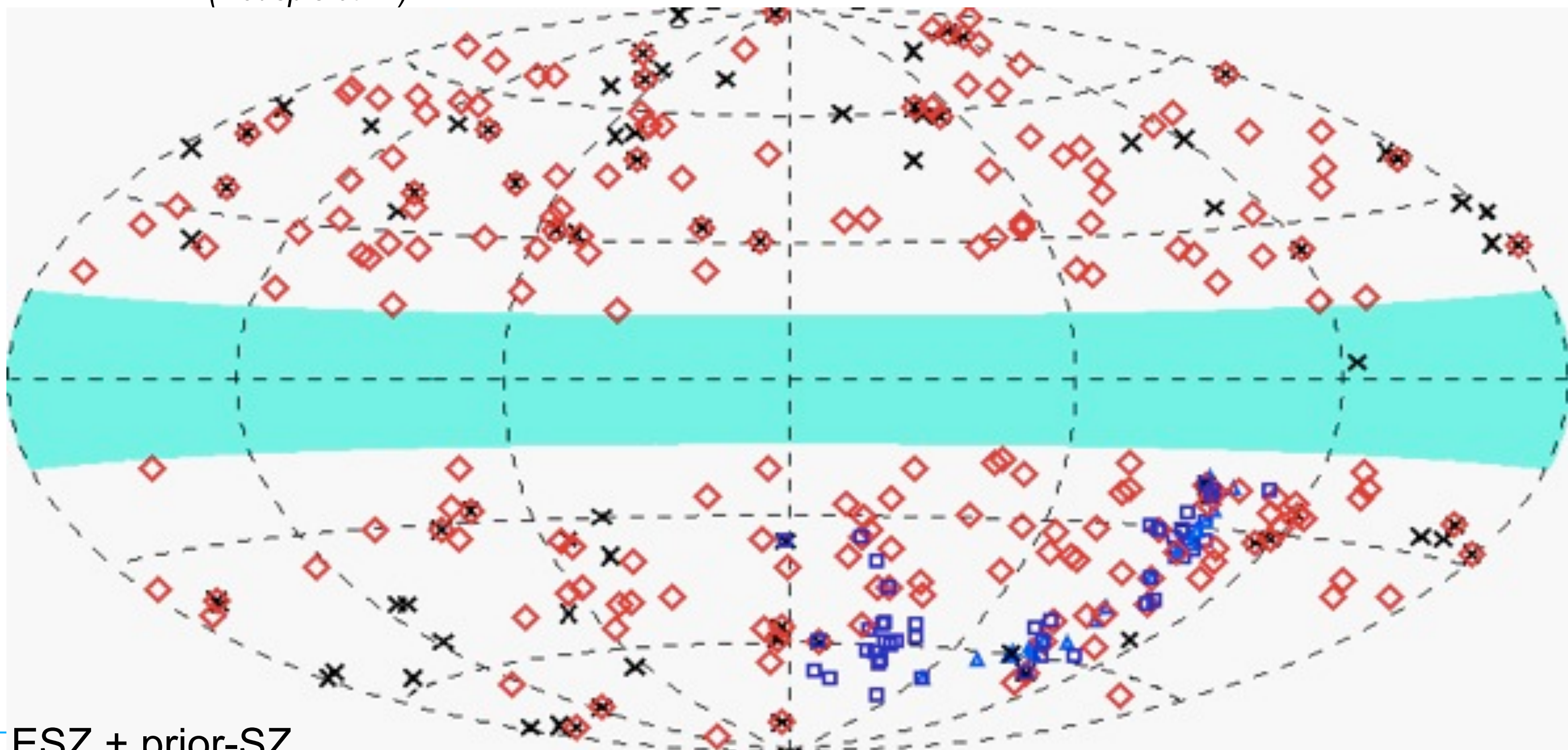
Bond since 1993, Canada since 2001, 1st CSA pre-launch contract 2002-09, post-launch 2010-11, 2011-13



All-sky compilation of first generation SZ clusters
(Douspis et 11)



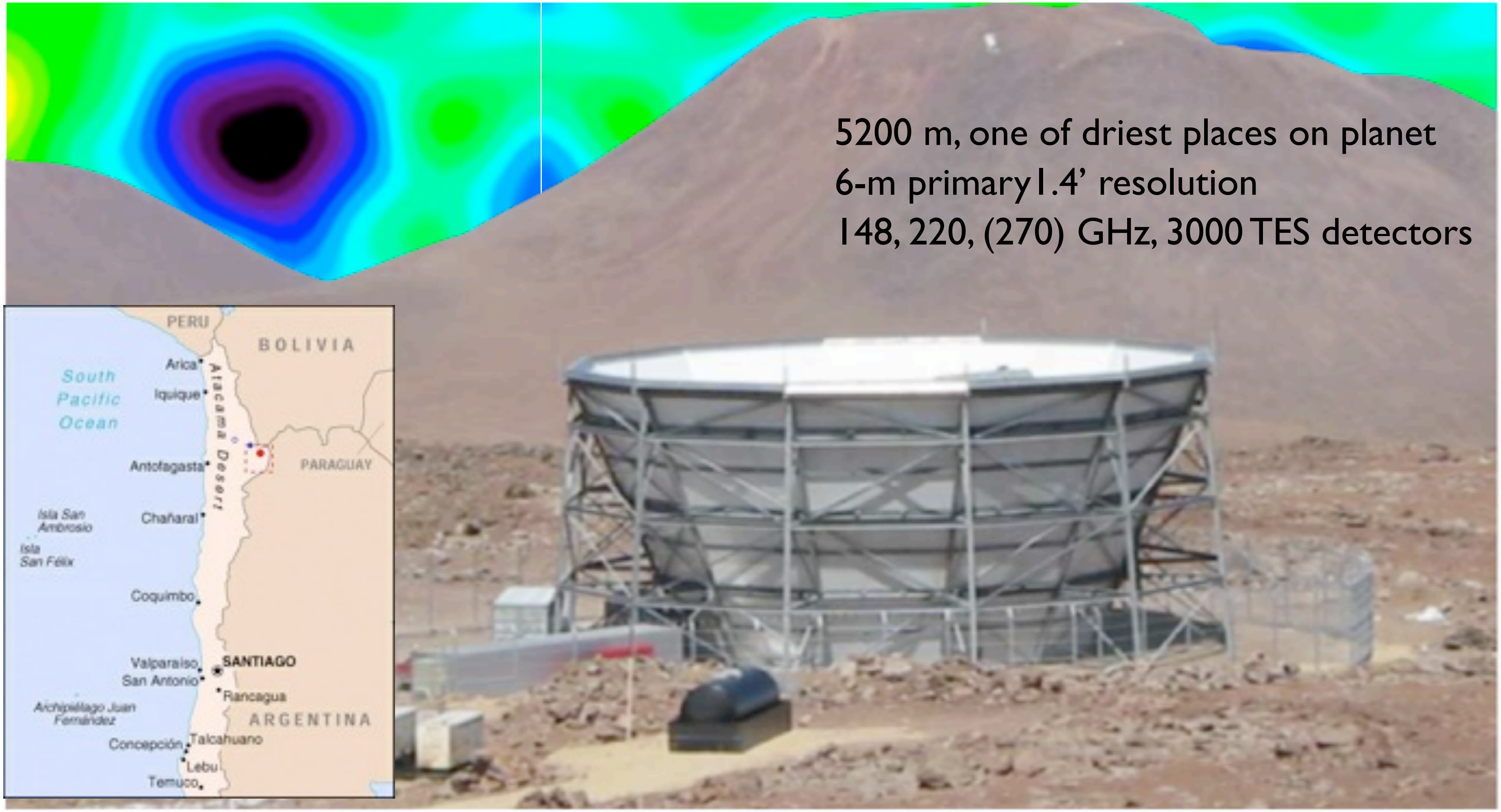
All-sky distribution of MCXC clusters ~1600 *(Piffaretti et 10)*



Planck ESZ + prior-SZ

Cosmology From 17,000 Feet:

Results From the Atacama Cosmology Telescope

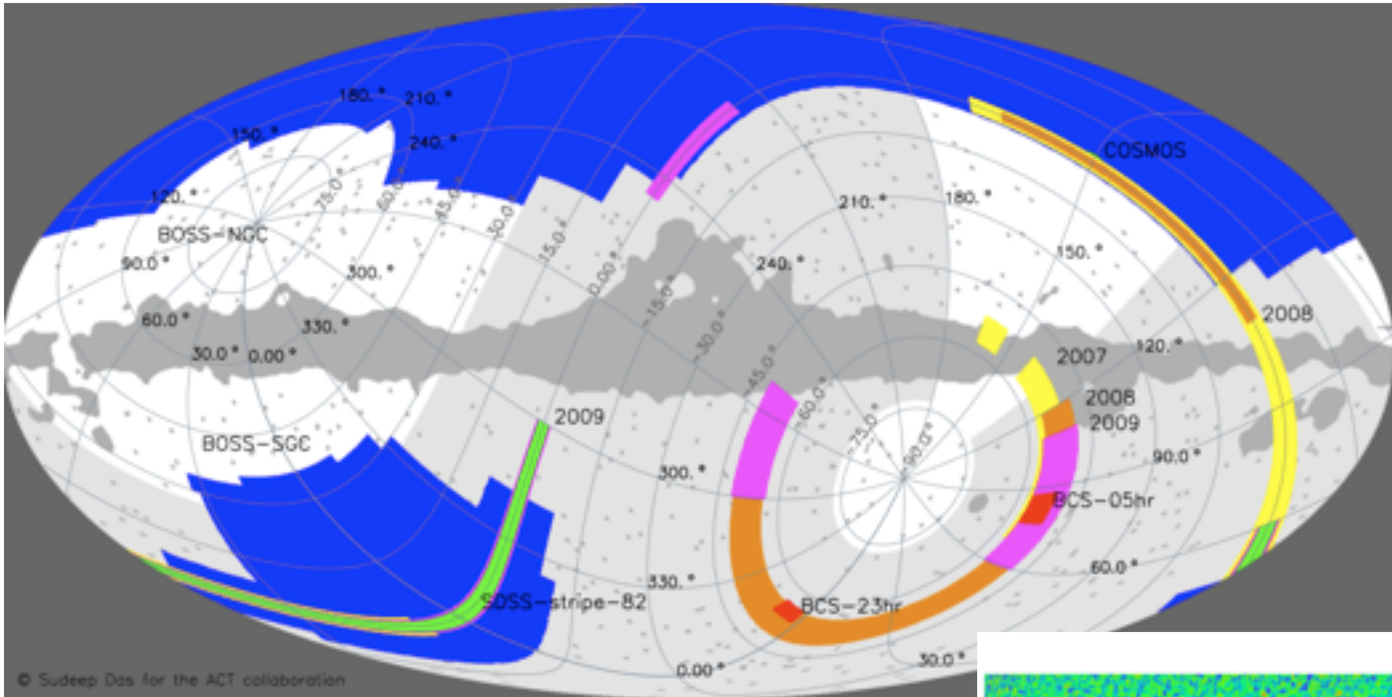


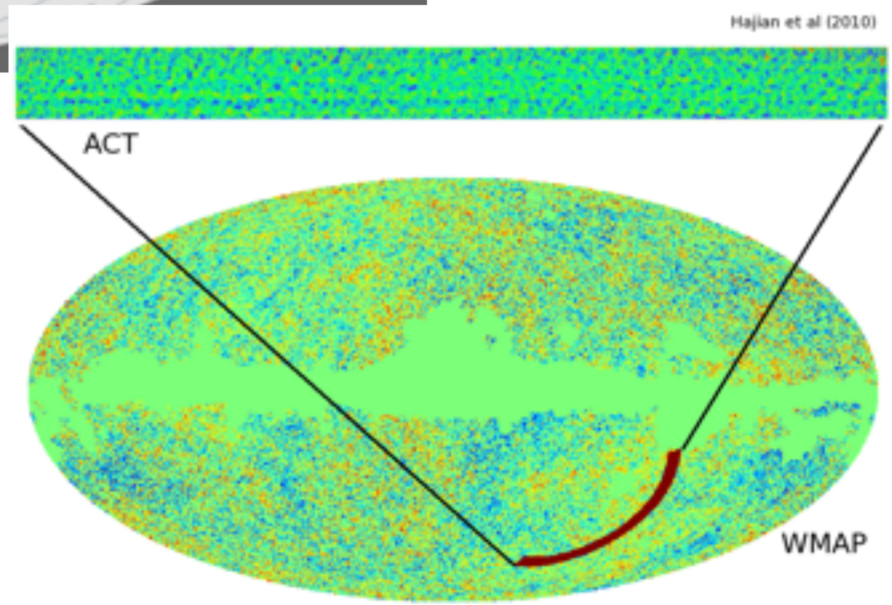
CMB@CITA: Boomerang, Acbar, CBI1,2, WMAP, **Planck, ACT, Spider, Blast, & ACTpol, ABS, QUIET2;**
GBT-Mustang2, CARMA/SZA, SCUBA2, ALMA, CCAT. CMB@CIFAR: these + APEX , SPT, SPTpol, EBEX

V. Acquaviva [1,2]
P. Ade [3]
P. Aguirre [4]
M. Amiri [5]
J. Appel [6]
E. Battistelli [7,5]
J. R. Bond [8]
B. Brown [9]
B. Burger [5]
J. Chervenak [10]
S. Das [29,6,1]
M. Devlin [2]
S. Dicker [2]
W. B. Doriese [11]
J. Dunkley [12,6,1]
R. Dunner [4]
T. Essinger-Hileman [6]
R.P. Fisher [6]
J.W. Fowler [6]
A. Hajian [6]
M. Halpern [5]
M. Hasselfield [5]
C. Hernandez-Monteagudo [13,2]
G. Hilton [11]
M. Hilton [14, 15]
A. D. Hincks [6]
R. Hlozek [12]
K. Huffenberger [16,6]
D. Hughes [17]
J. P. Hughes [18]
L. Infante [4]
K.D. Irwin [11]
N. Jarosik [6]
R. Jimenez [19]
J.B. Juin [4]
M. Kaul [2]
J. Klein [2]
A. Kosowsky [9]
J.M. Lau [20,6]
M. Limon [21]
Y.T. Lin [22,1,4]
R. Lupton [1]
T.A. Marriage [1,6]
D. Marsden [2]
K. Martocci [23,6]
P. Mauskopf [3]
F. Menanteau [18]
K. Moodley [14]
H. Moseley [10]
B. Netterfield [24]
M.D. Niemack [11,6]
M.R. Nolta [8]
L.A. Page (PI) [6]
L. Parker [6]
B. Partridge [25]
H. Quintana [4]
B. Reid [19,1]
N. Sehgal [20,18]
J. Sievers [8]
D. Spergel [1]
S.T. Staggs [6]
O. Stryzak [6]
D. Swetz [2]
E. Switzer [23,6]
R. Thornton [26,2]
H. Trac [27,1]
C. Tucker [3]
L. Verde [19]
R. Warne [14]
G. Wilson [28]
E. Wollack [10]
Y. Zhao [6]

[1] Princeton University Astrophysics (USA)
[2] University of Pennsylvania (USA)
[3] Cardiff University (UK)
[4] Pontifica Universidad Catolica de Chile (Chile)
[5] University of British Columbia (Canada)
[6] Princeton University Physics (USA)
[7] University of Rome “La Sapienza” (Italy)
[8] CITA, University of Toronto (Canada)
[9] University of Pittsburgh (USA)
[10] NASA Goddard Space Flight Center (USA)
[11] NIST Boulder (USA)
[12] Oxford University (UK)
[13] Max Planck Institut fur Astrophysik (Germany)
[14] University of KwaZulu-Natal (South Africa)
[15] South African Astronomical Observatory
[16] University of Miami (USA)
[17] INAOE (Mexico)
[18] Rutgers (USA)
[19] Institute de Ciencies de L’Espai (Spain)
[20] KIPAC, Stanford (USA)
[21] Columbia University (USA)
[22] IPMU (Japan)
[23] KICP, Chicago (USA)
[24] University of Toronto (Canada)
[25] Haverford College (USA)
[26] West Chester University of Pennsylvania (USA)
[27] Harvard-Smithsonian CfA (USA)
[28] University of Massachusetts, Amherst (USA)
[29] BCCP UC Berkeley and LBL (USA)

end observing 2011: ACT completed 3 full seasons, over ~1300 deg^2, **maps@CITA.**
next step is ACTpol

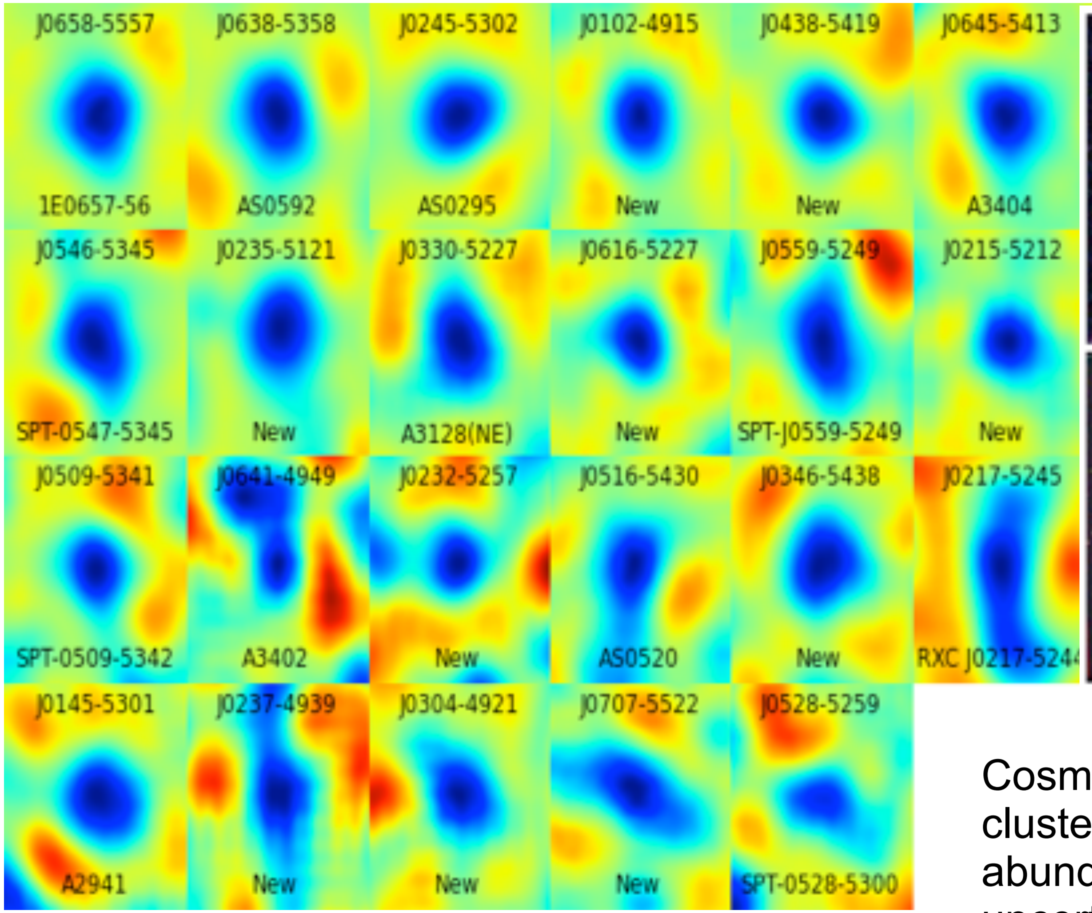




<ACT SZ x other data (opt, X, submm)>, ...
X correlations
e.g., note overlap with SDSS III BOSS in the ACT equatorial strip, used for kSZ

23+ Galaxy Clusters Found by ACT via SZ Signal

Marriage+ 10



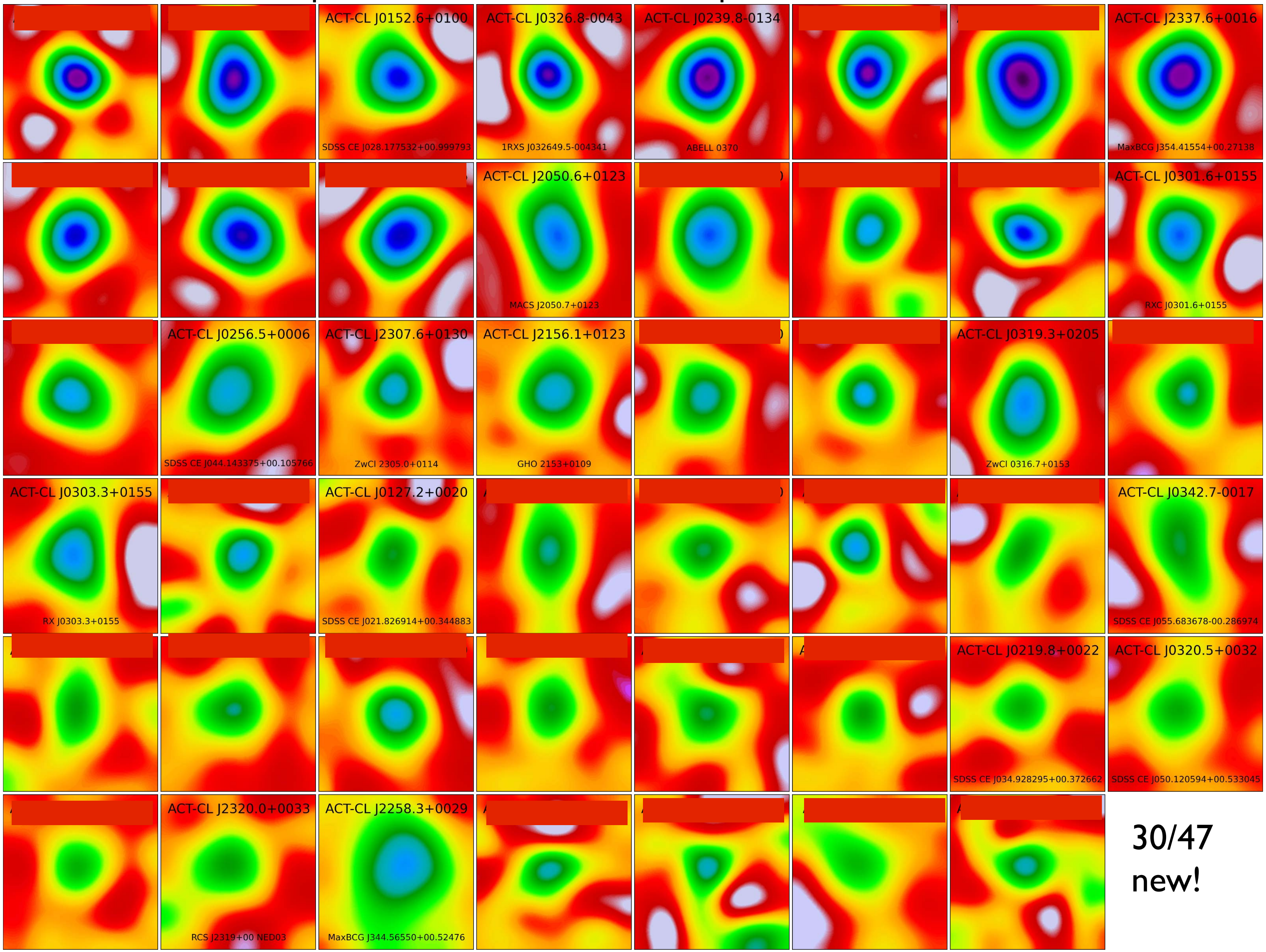
Optical Observations Menanteau+10

With the ACT equatorial strip, ~50 clusters

Cosmic Parameters from 9 confirmed clusters (Sehgal+10) using cluster abundances => mass calibration still too uncertain (e.g. σ_8=0.82±0.05 to 0.85±0.12). attempt at Dark Energy equation of state, but little leverage

Optically Confirmed Equatorial Clusters

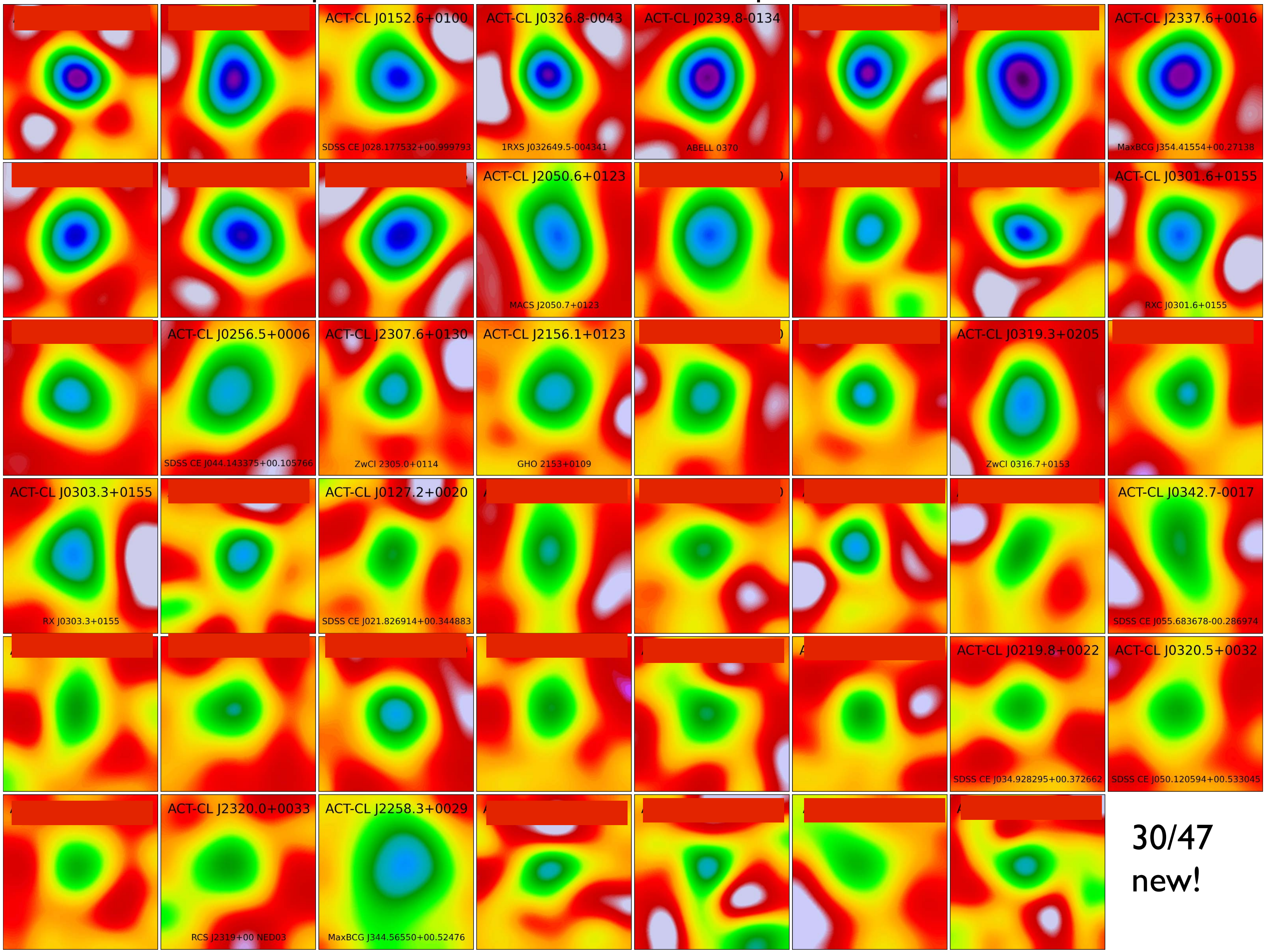
some SZA follow-up Riess+ 11 further follow-up on GBT+SZA



30/47
new!

Optically Confirmed Equatorial Clusters

some SZA follow-up Riess+ 2011 further follow-up on GBT+SZA



30/47 new!

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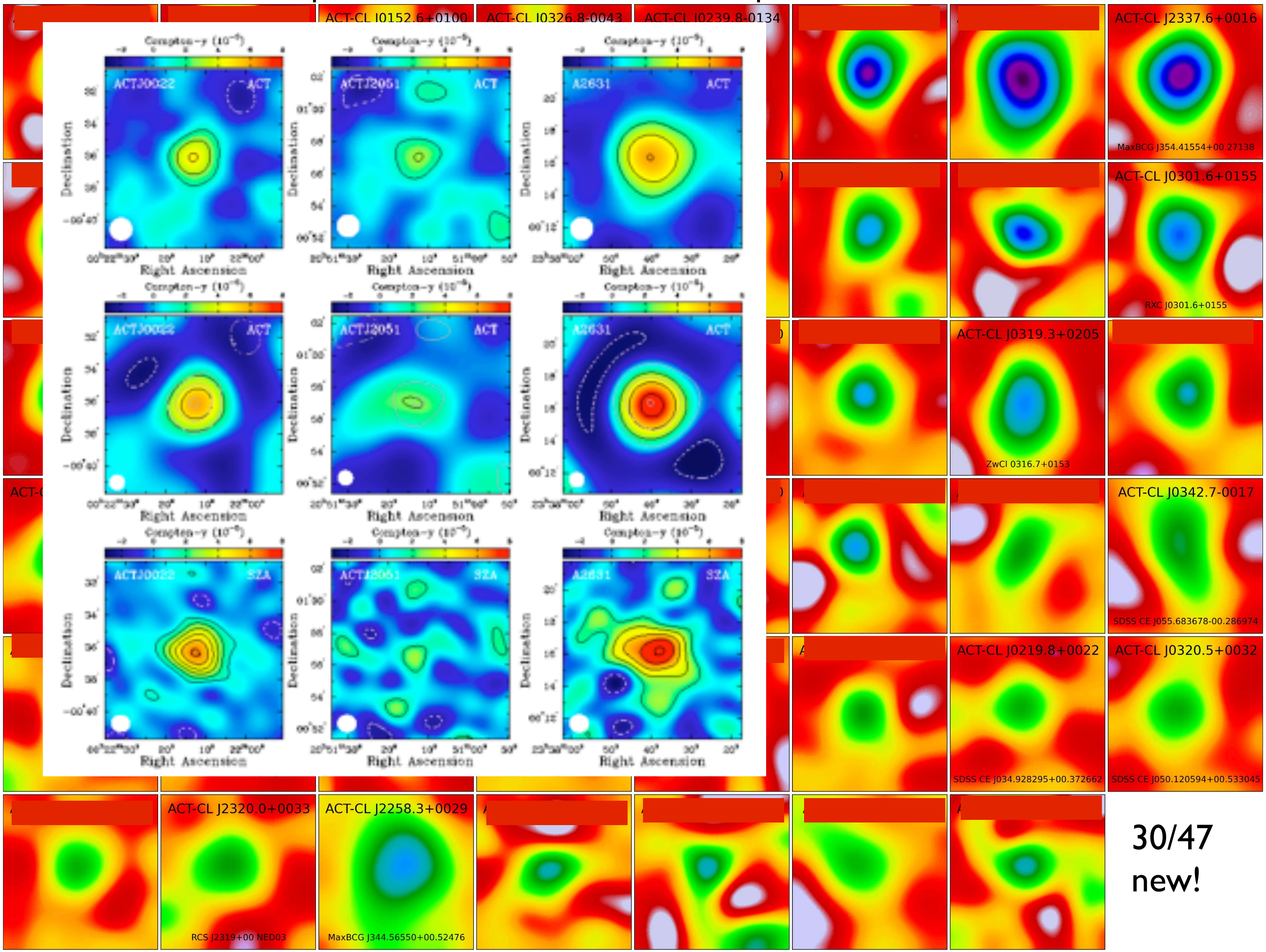
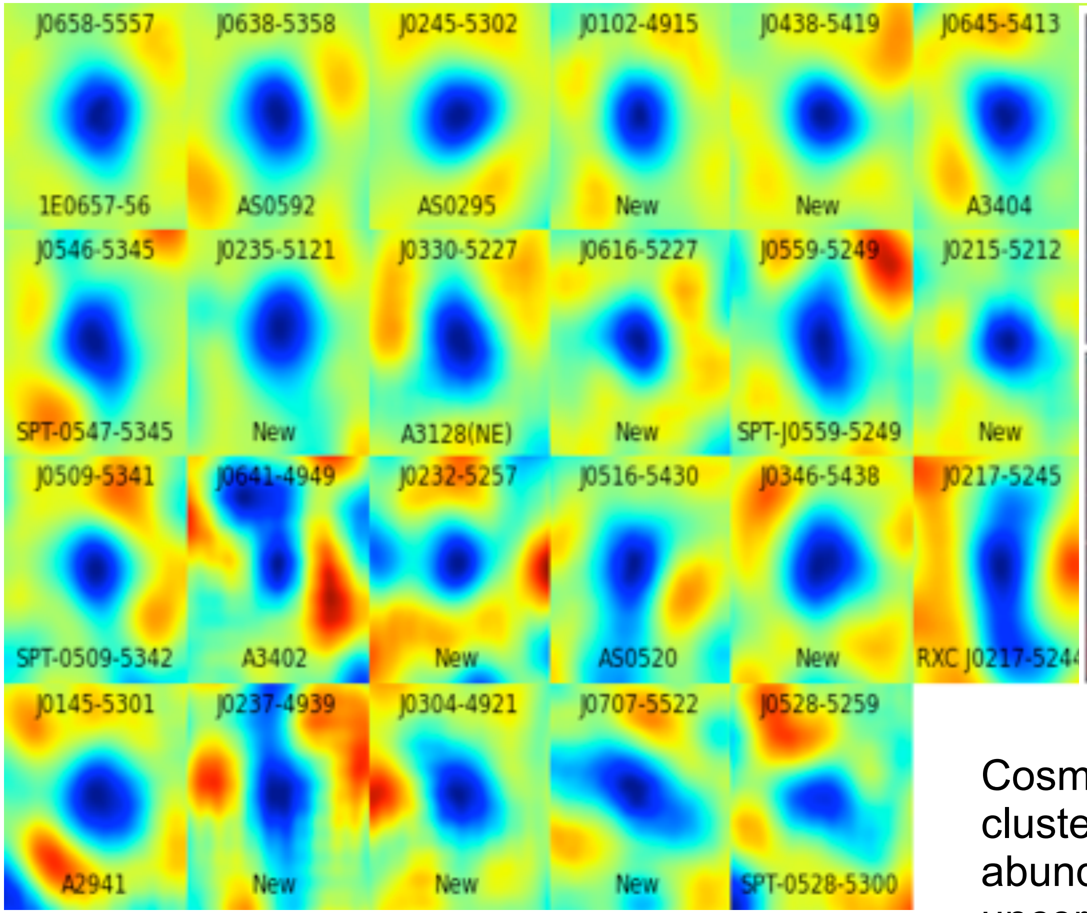


30/47
new!

23+ Galaxy Clusters Found by ACT via SZ Signal

Marriage+ 10



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With the ACT equatorial strip, ~50 clusters

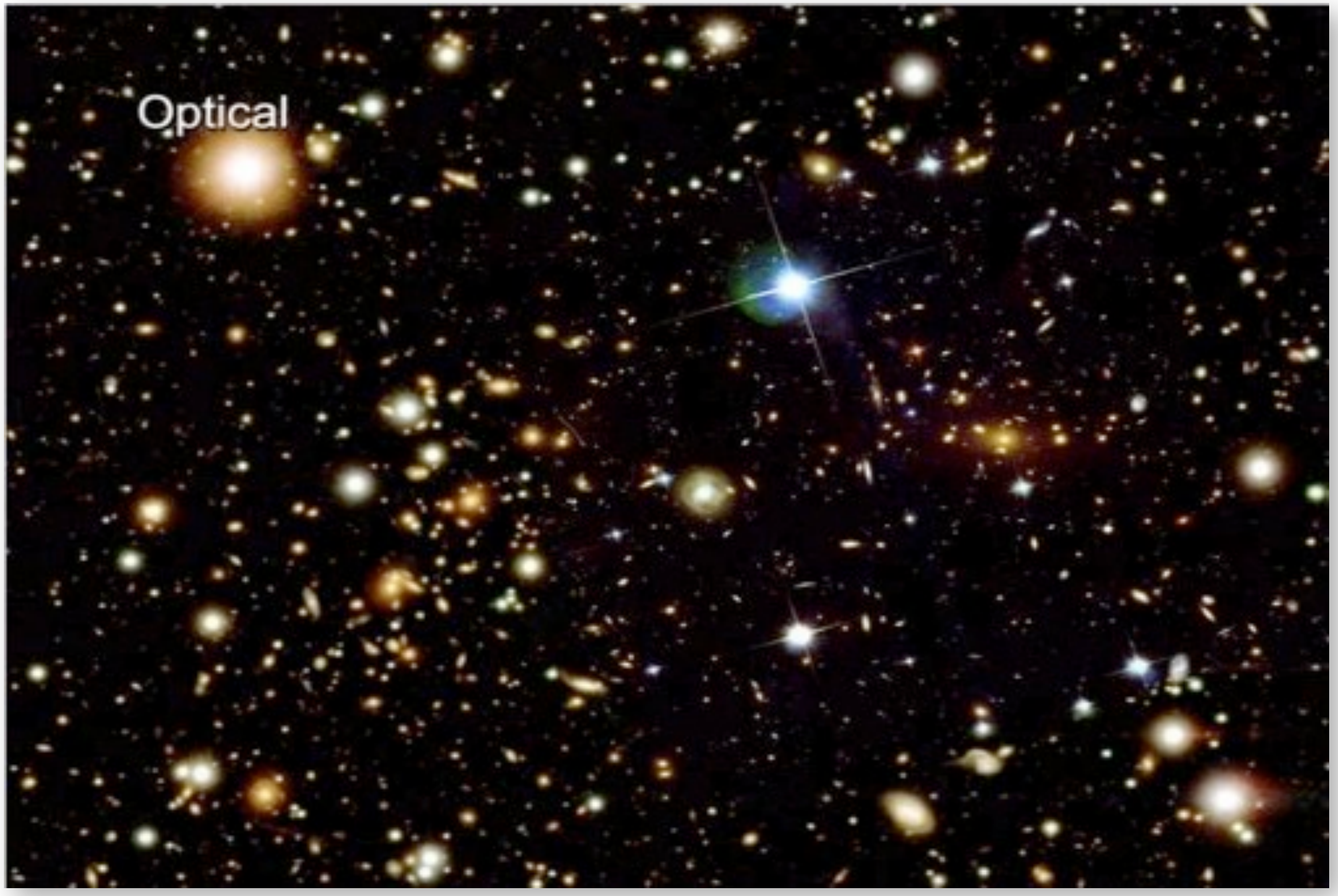
Menanteau+12, "bullet"-like Cluster at z~0.87, discovered in 2009 data by Menanteau+10, highest SZ in 755 sq deg Marriage+11, much follow-up

the Bullet Cluster merger @ z~0.3: evidence for DM

Clowe et al.(2006)

"every cluster is a Bullet cluster" - or was a bullet in its past, ***el Gordo, A520, ...***

the Bullet Cluster merger @ z~0.3: evidence for DM



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"every cluster is a Bullet cluster" - or was a bullet in its past, el Gordo, A520, ...

"*El Gordo*," Multi-wavelength Observations

Menanteau+ 12

- Detected in 2008 ACT maps of Southern Strip (Menanteau+10, Marriage+11)
  - Strongest SZ decrement over 755 deg^2 (South + Equator) & in ACT+SPT: 2800 deg^2

=> SZ mass, yT_{CMB} - *Mass*

- Optical follow-up: **89 redshifts**
  - Imaged (*griz*) at SOAR/SOI Dec 09
  - VLT/FORS2 MOS 10*hrs* + Imaging 2*hrs* Jan11

=> dynamical mass, σ_{gal}-*M*

- *Chandra* X-ray Observations
  - ACIS-I, 60 ks, observed 27 Jan 2011

=> X-ray mass, *Lx-M*, *Tx-M*, *Yx-M*

- Spitzer IRAC follow-up
  - Imaged at 3.6 μm and 4.5 μm

=> Stellar mass

optical, X-ray, SZ mass ~agree, combine =>

$$M_{200} = (2.16 \pm 0.32) \times 10^{15}\, h_{70}^{-1} M_{\odot}$$

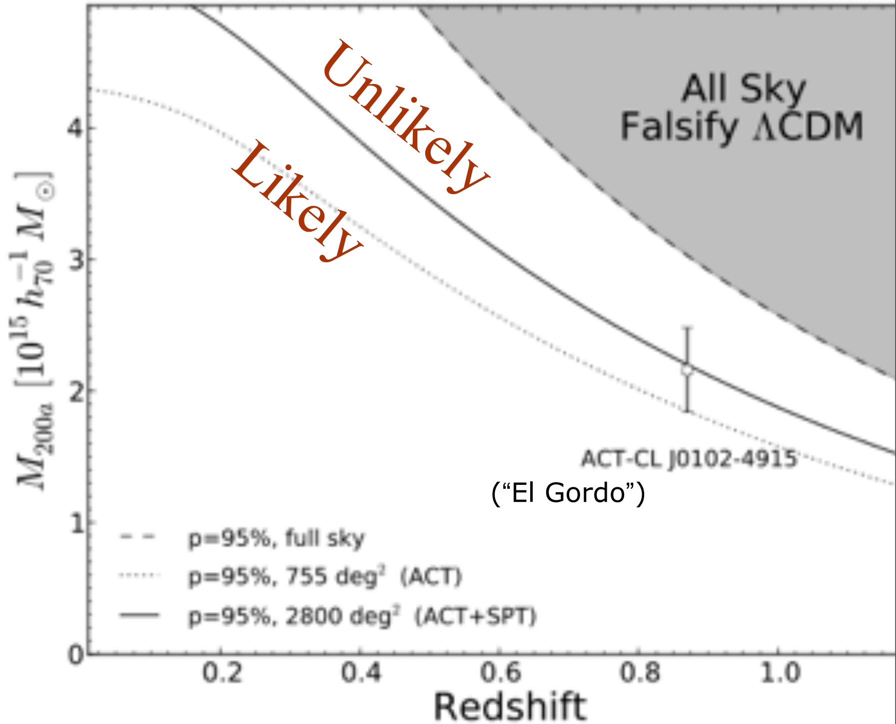
is El Gordo too rare for ΛCDM? no, even if ~virialized

Combined Mass from optical+X-ray+SZ: *ACT*

$M_{200} = (2.16 \pm 0.32) \times 10^{15}\, h_{70}^{-1} M_\odot$

1321 +- 106 km/s; 14.5 +- 1 kev

Menanteau et al. (2012, ApJ, 748,7)



some other rare SZ events

SPT-CL J2106-5844 (z=1.14) *SPT*

$M_{200} = (1.27 \pm 0.21) \times 10^{15}\, h_{70}^{-1}\, M_\odot$

CL J1226+3332 (z=0.89) *Mustang*

$M_{200} = (1.38 \pm 0.20) \times 10^{15}\, h_{70}^{-1}\, M_\odot$

A1689 **(z = 0.18)** *CBI+CBI2+BIMA+OVRO+SZA*

M_{vir} = (1.4-2) X 10^{15} M⊙

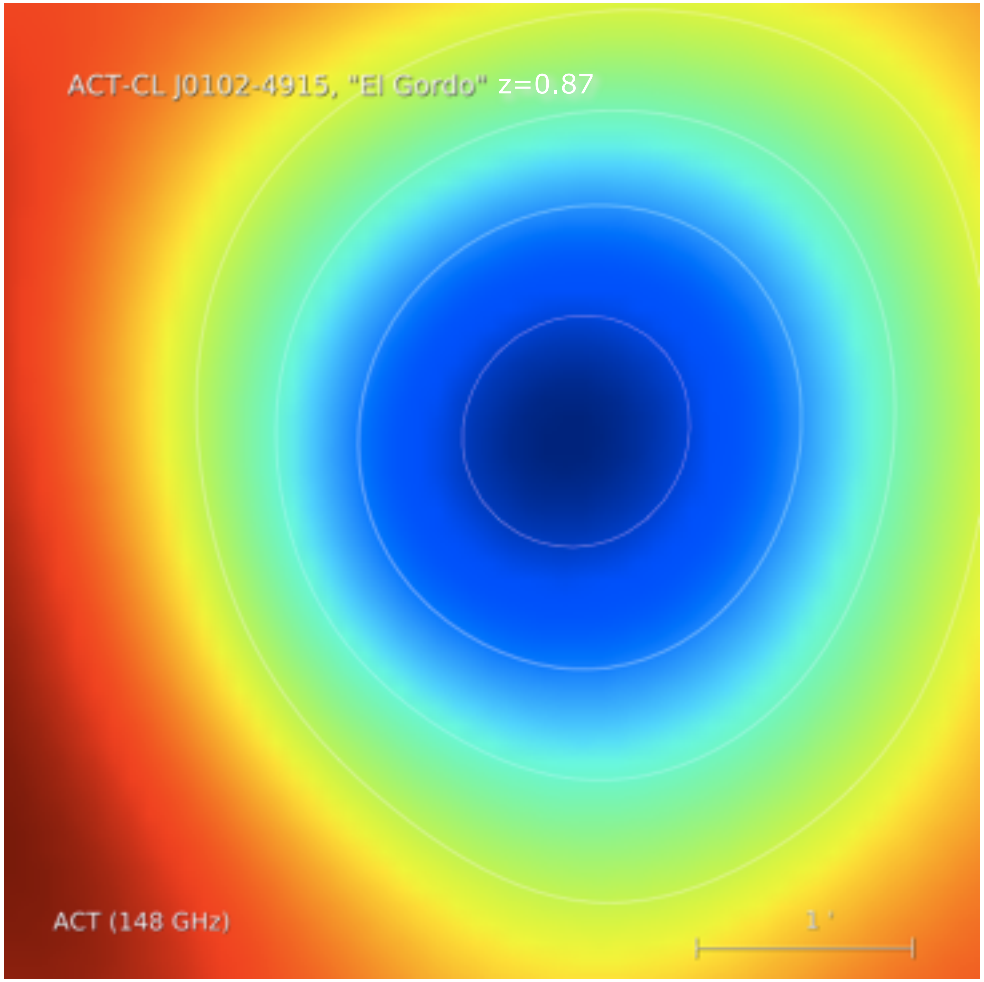
PLCK G266.6−27.3 **(z = 0.94 +- 0.02)** *Planck+11 26*

M_{200} ~ (1.5 +- 0.15) X 10^{15} M⊙

A520 z=0.21 Train Wreck Cluster *WkLens+Opt+X*

use Mortonson+11 exclusion curves for ΛCDM & quintessence DE. assumes nature of n(M,z) objects

A Violent Merger in "El Gordo"



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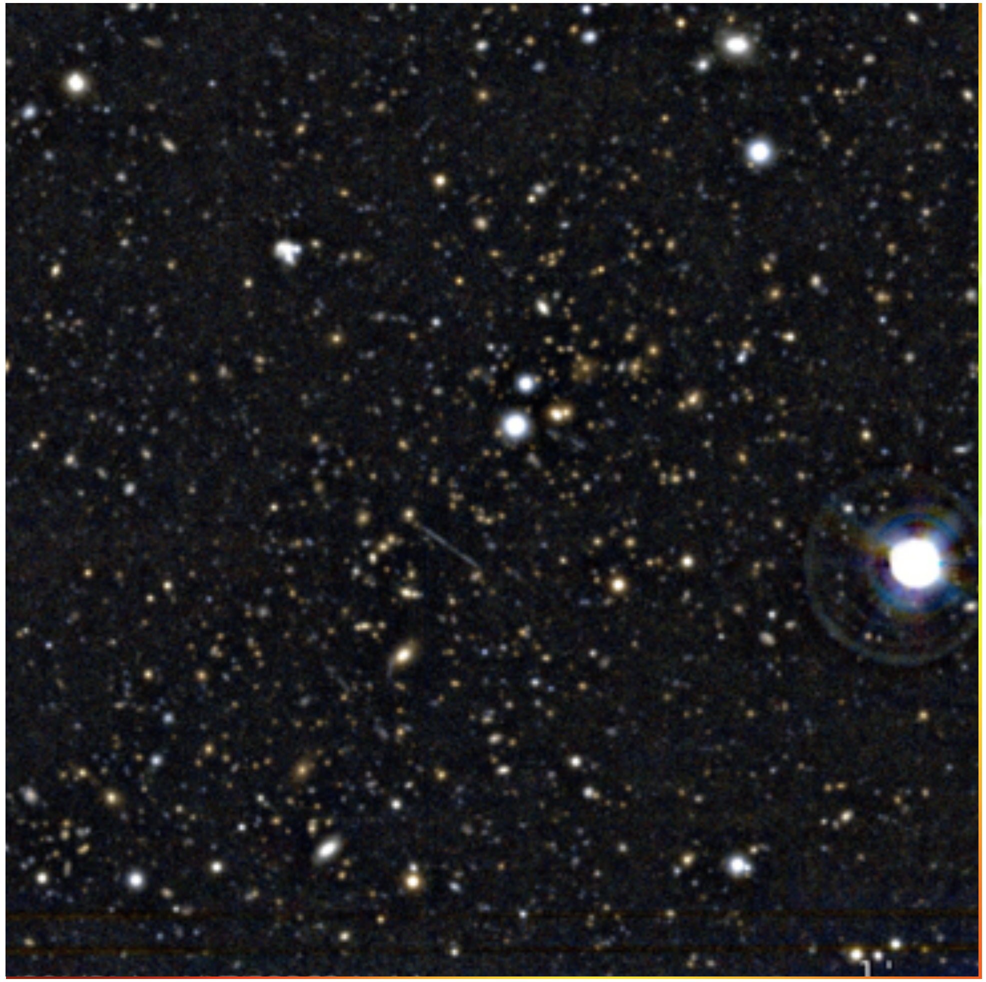
A Violent Merger in “El Gordo”



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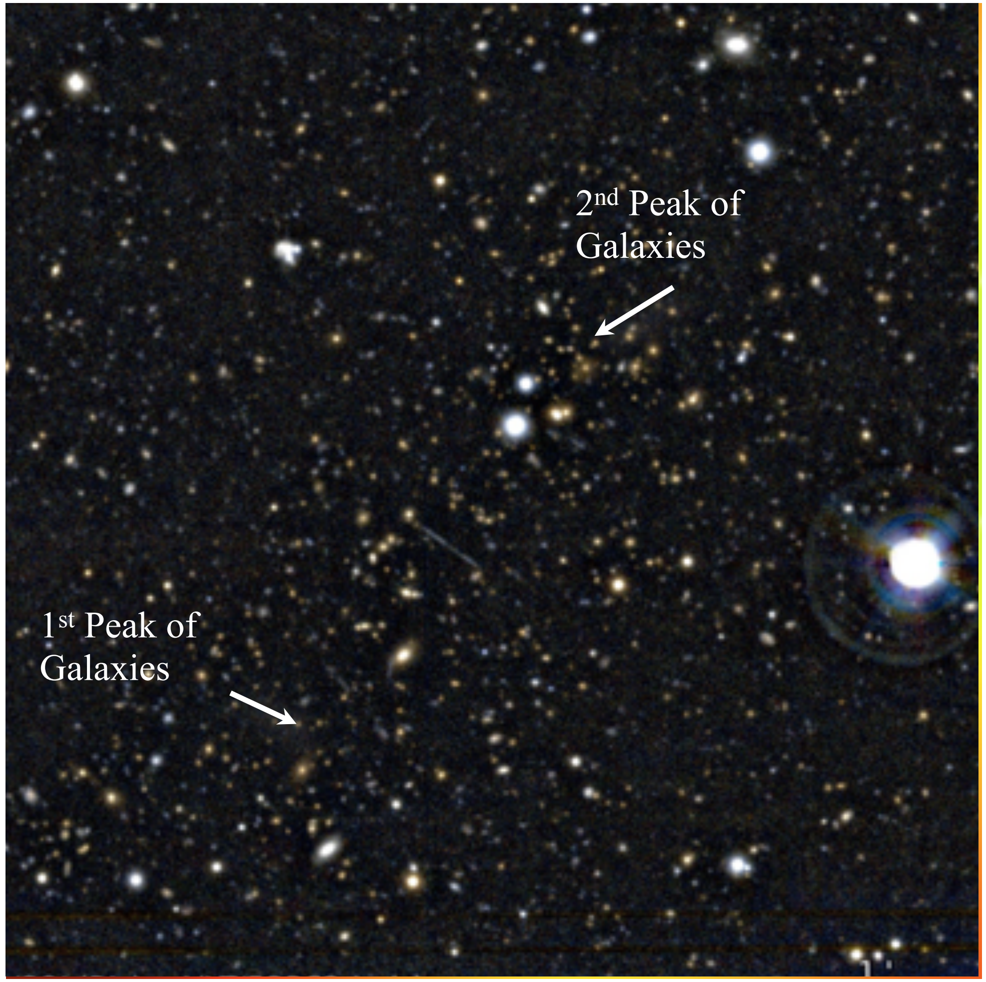
A Violent Merger in “El Gordo”

The galaxies in “El Gordo” mostly lie in two distinct groups

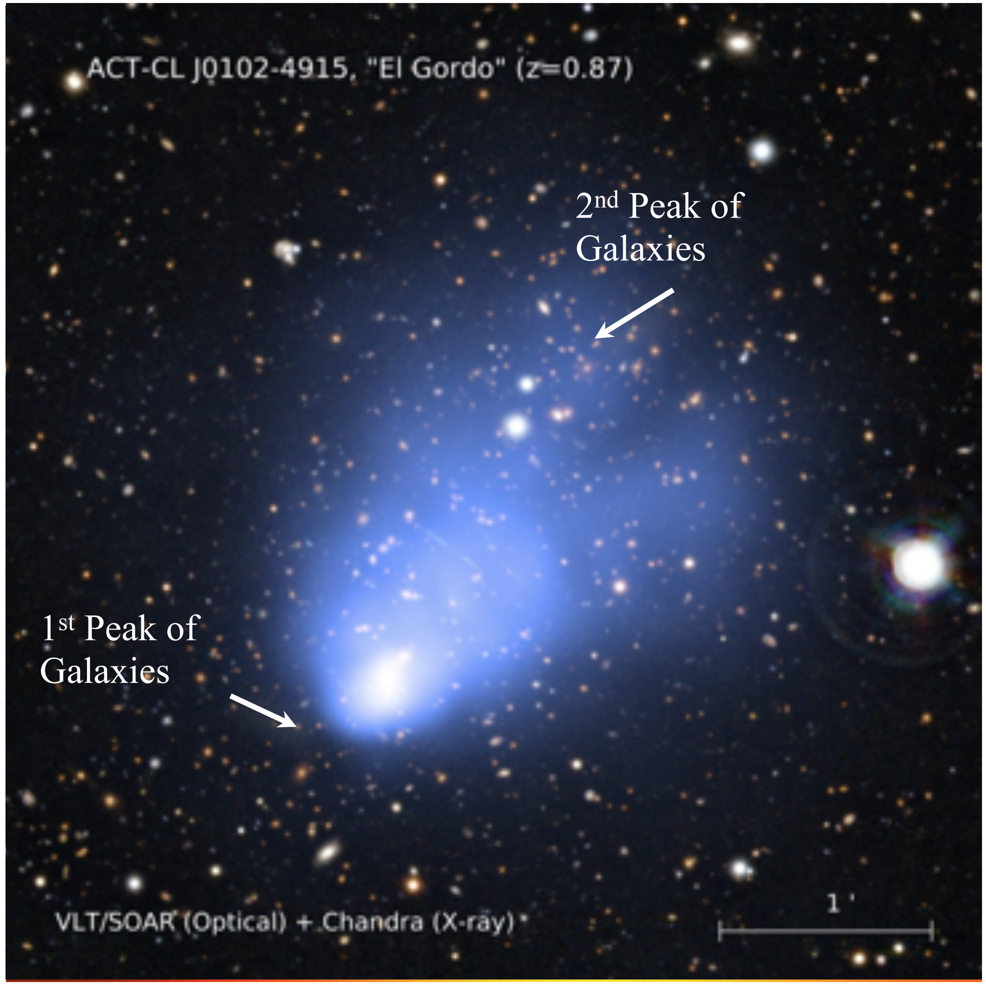


Menanteau et al. (2012, ApJ, 748,7)

A Violent Merger in "El Gordo"

The galaxies in "El Gordo" mostly lie in two distinct groups

X-ray emission mostly between these 2 groups, with a bright offset Gas Peak (a merging core) & a Wake



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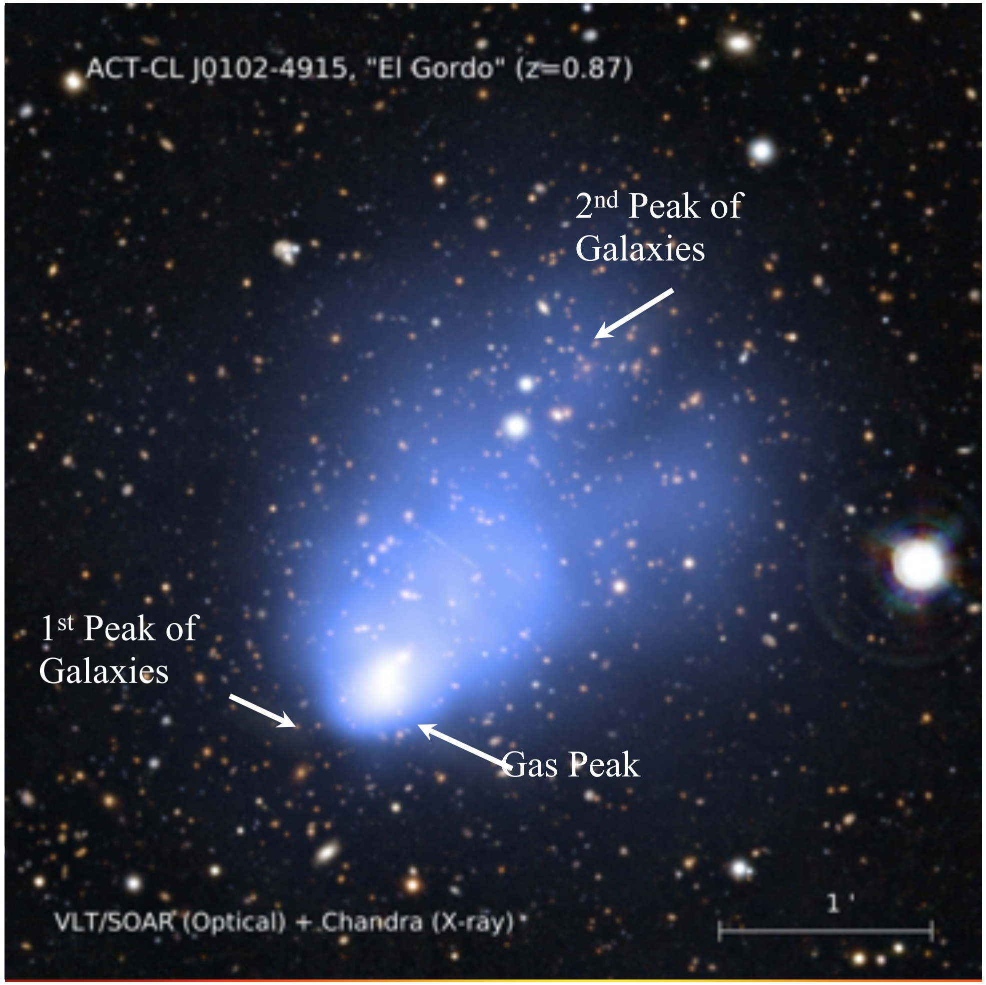

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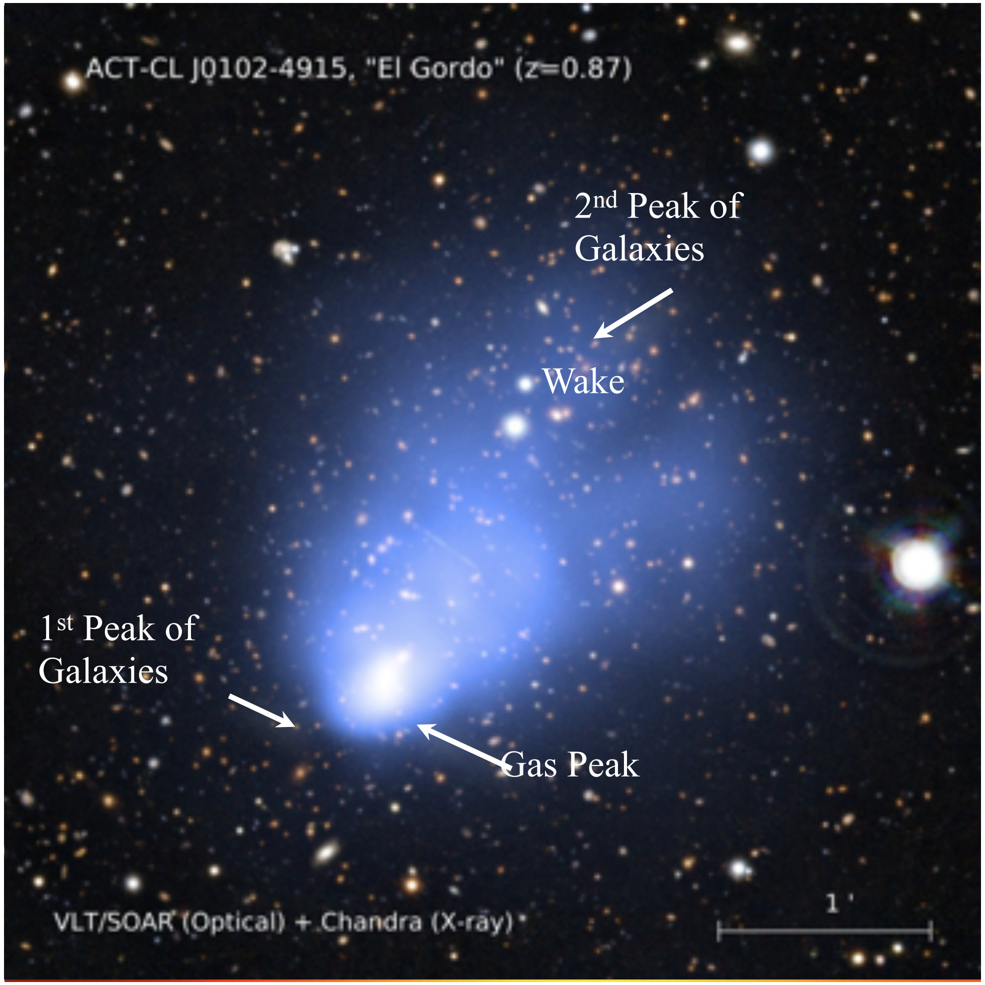

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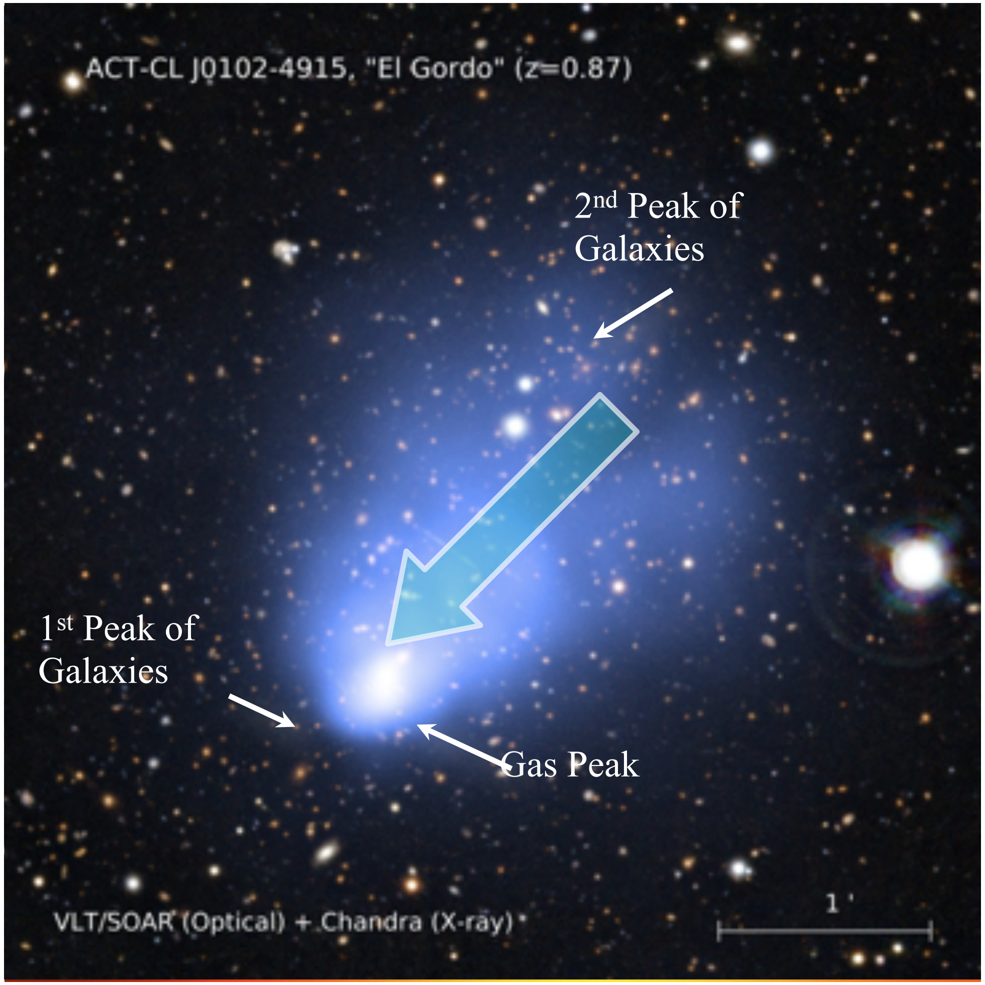

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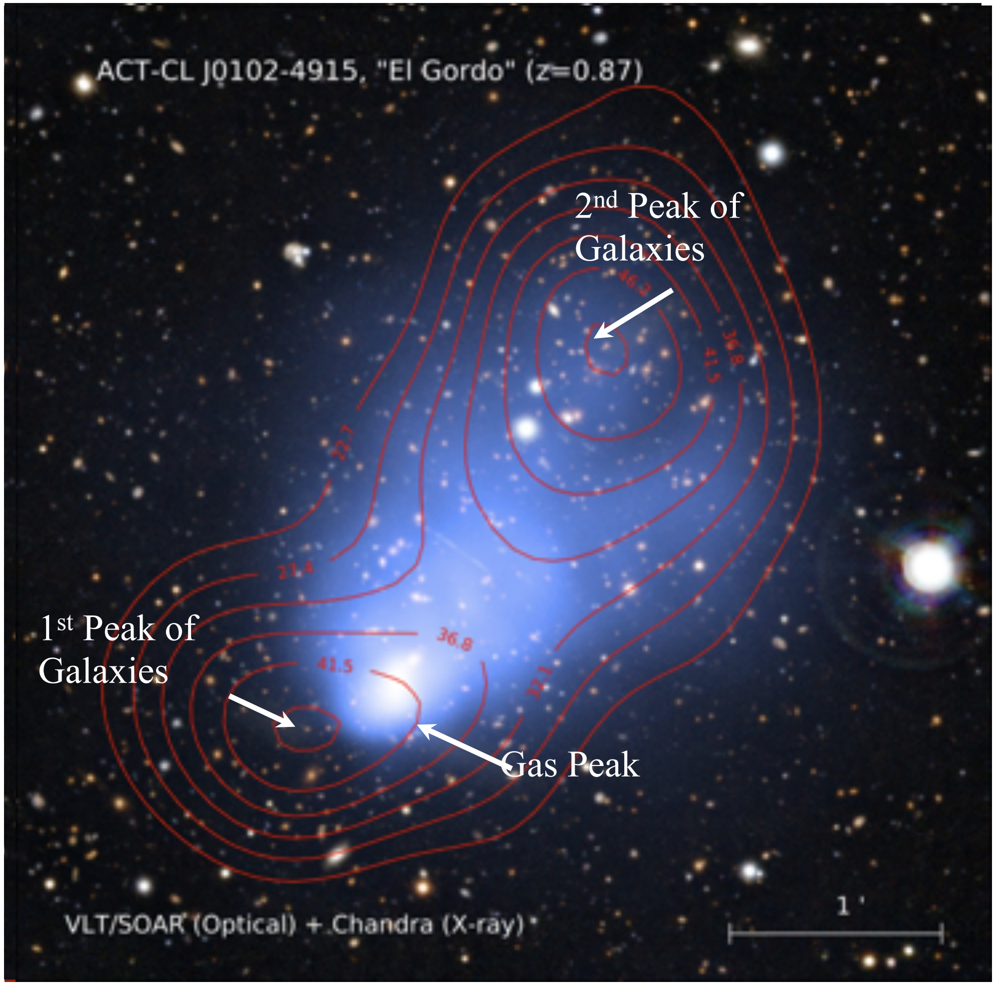
Galaxy distribution peak ahead of the Gas Peak in the direction of the merger – a spatial separation like that seen in the Bullet Cluster



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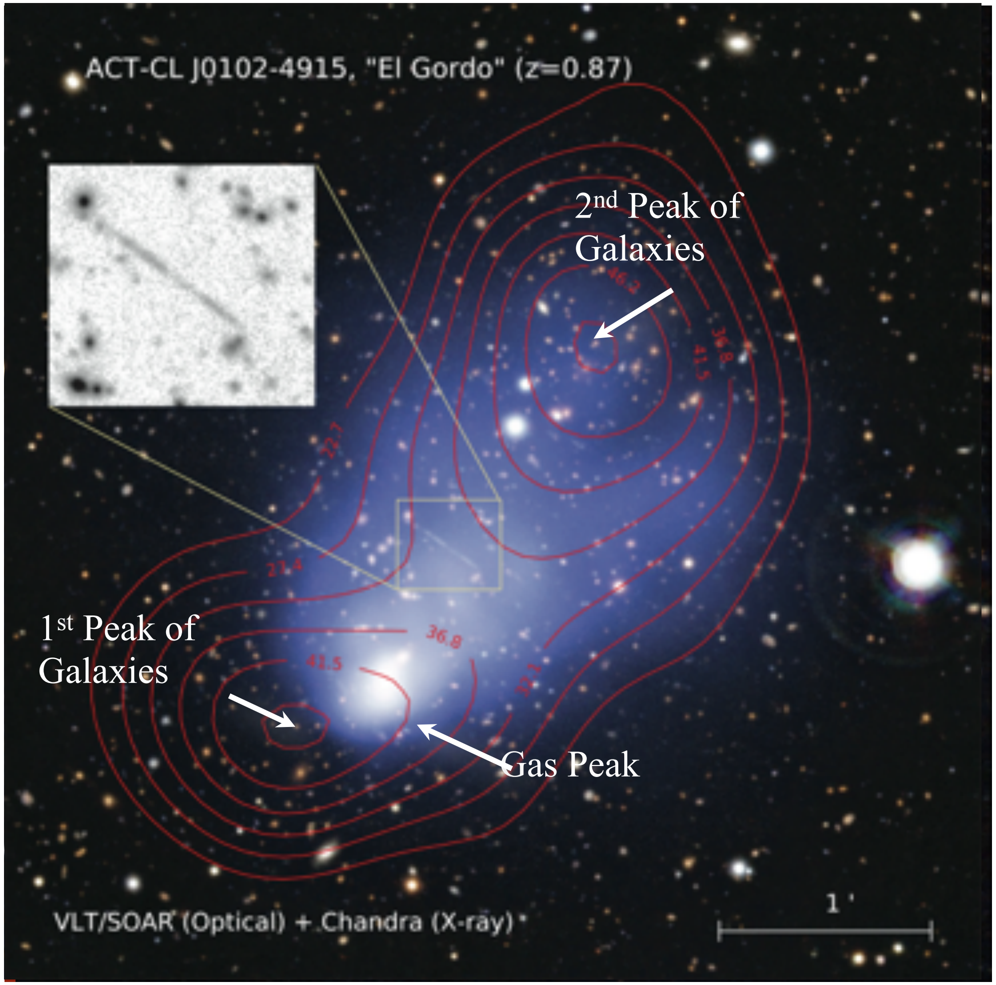

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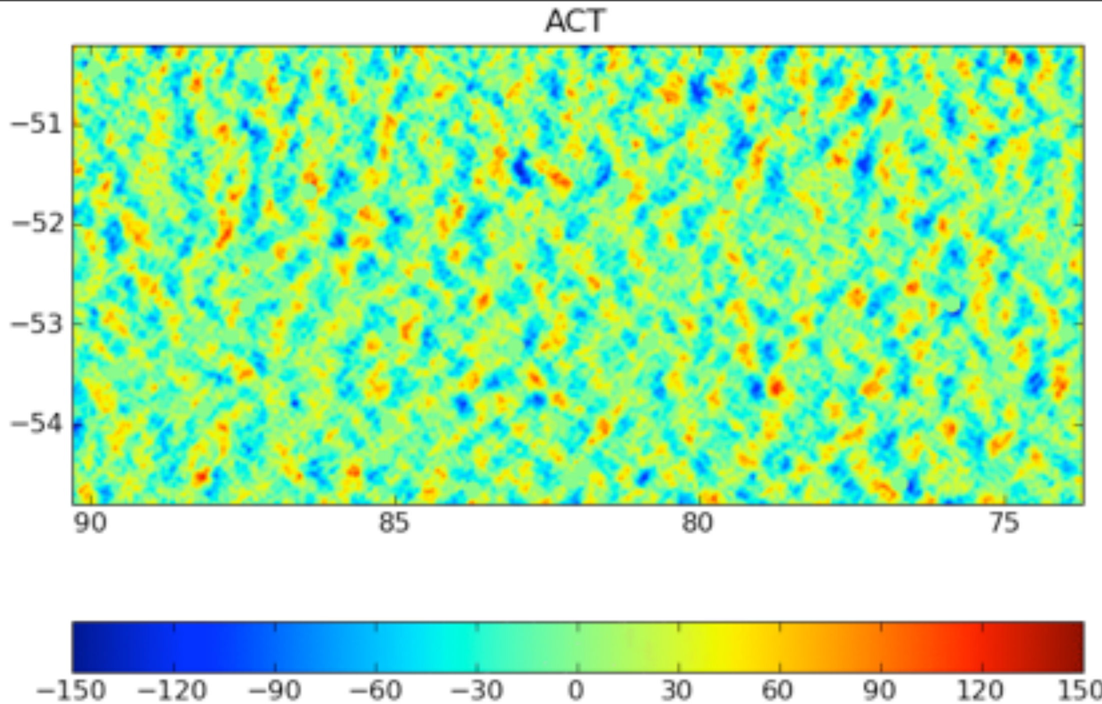
SPT *(2500 sq deg)*=>SPT-pol



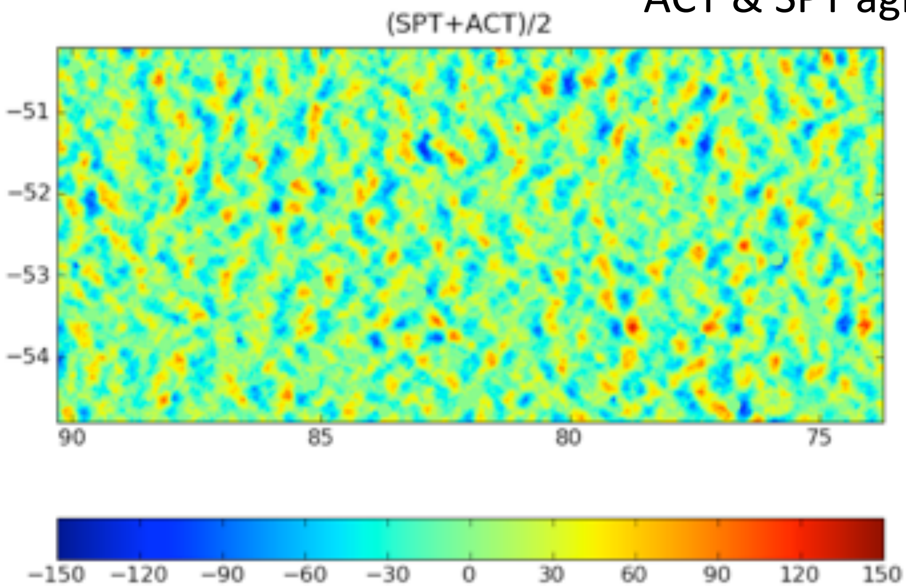
SPT clusters ~50, ~500 detected

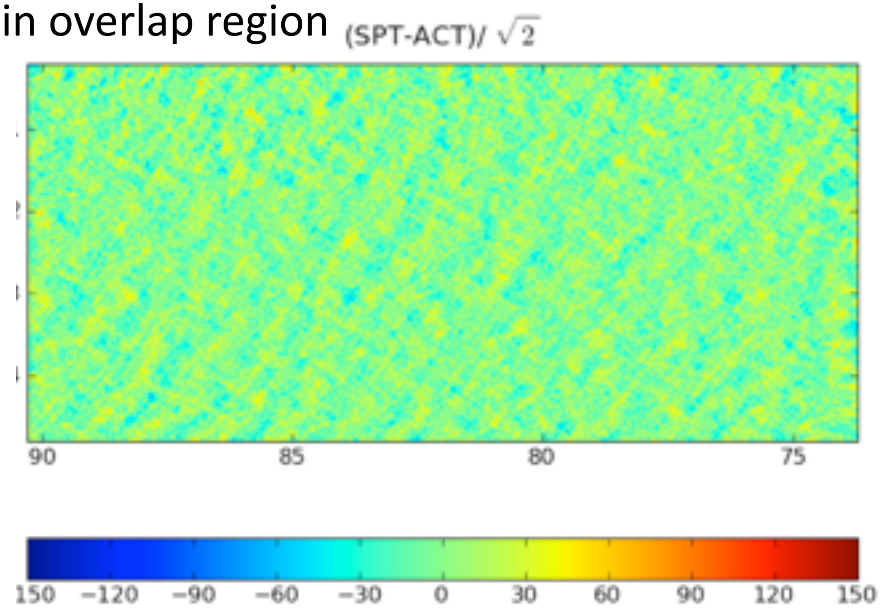
andersson+11 (15), vanderlinde+11 (21), foley+11 (z=1.14), benson+12

rare event: SPT-CL J2106-5844 (z=1.14)

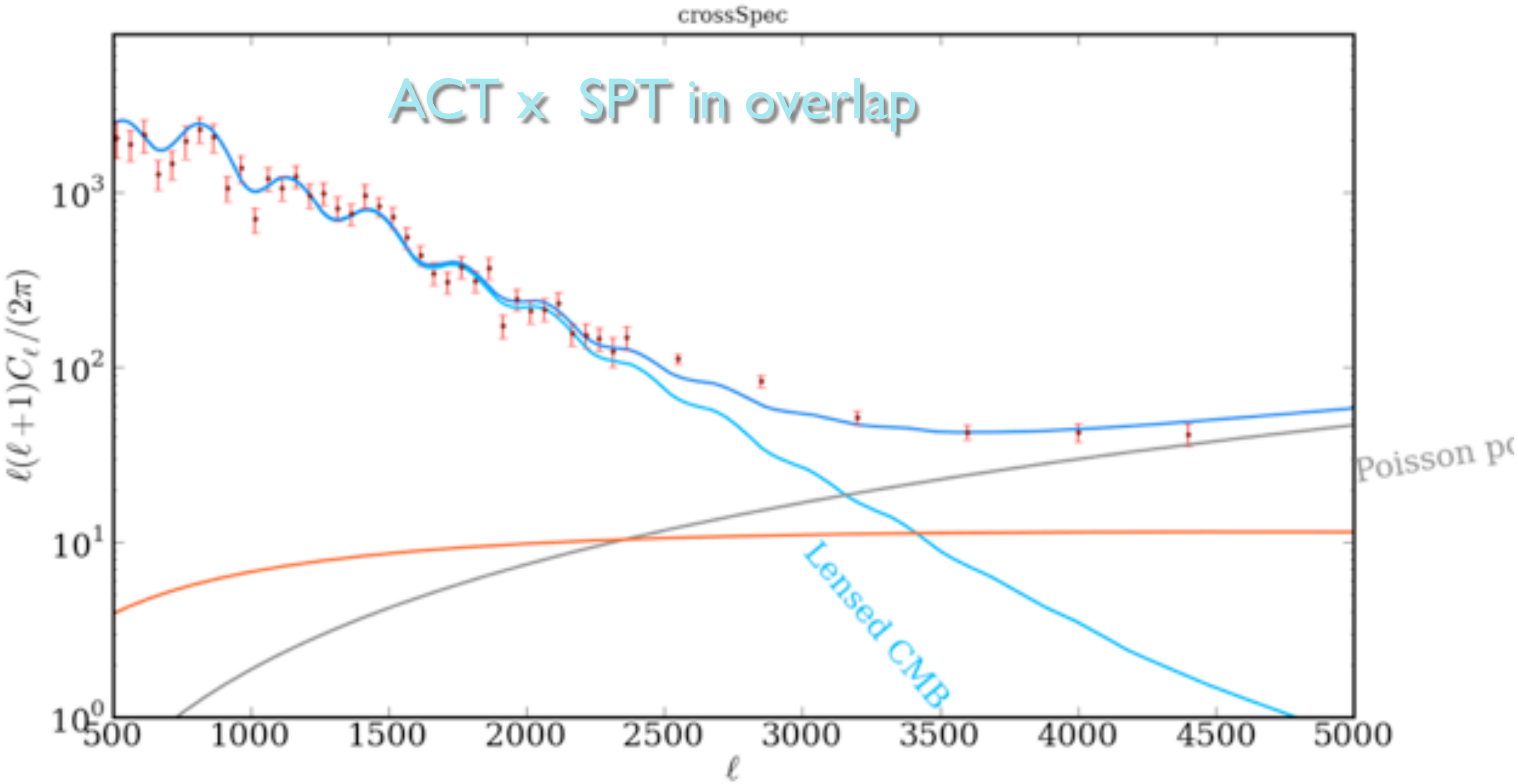
$M_{200} = (1.27 \pm 0.21) \times 10^{15}\, h_{70}^{-1}\, M_\odot$

ACT & SPT agree in overlap region



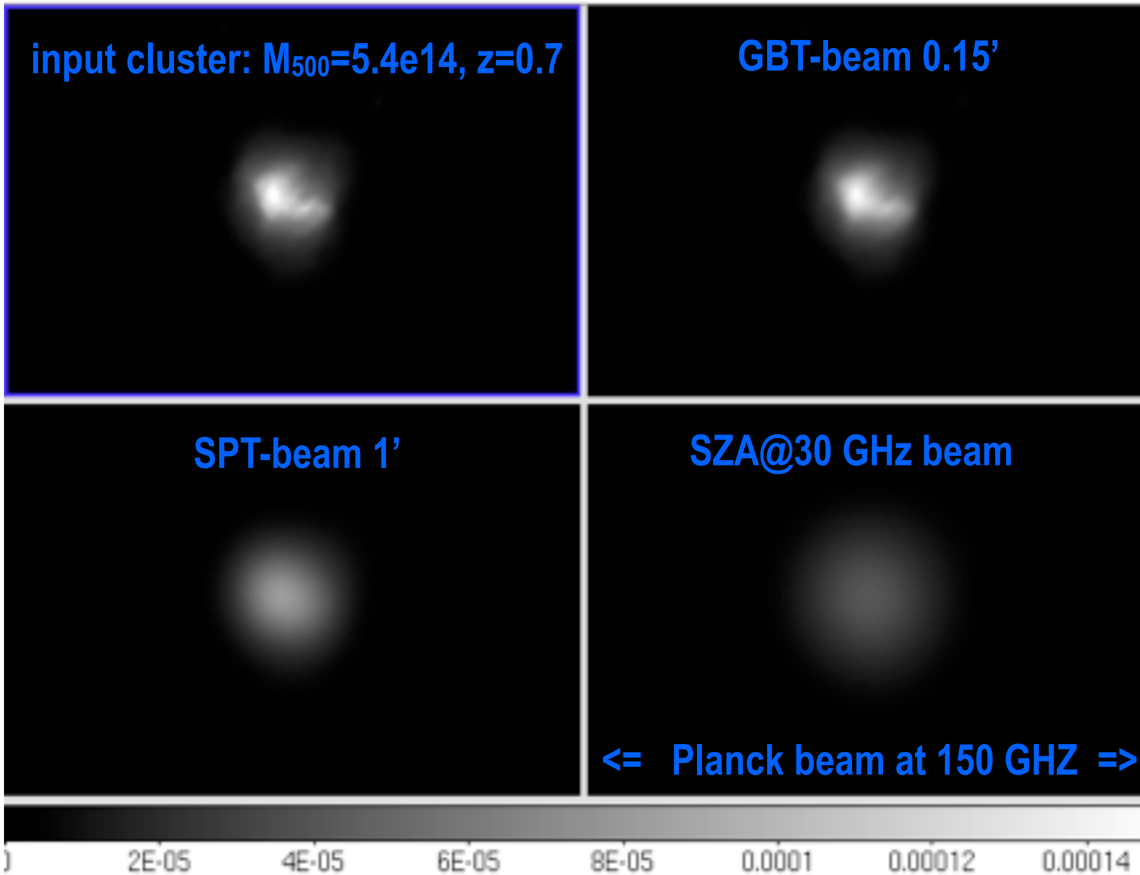


SPT & ACT agree in detail



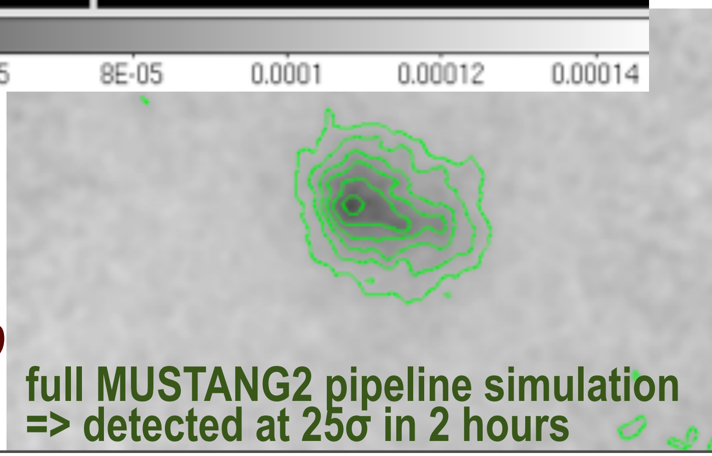
Mustang on GBT 90 GHz 64 bolometer array Imaging SZ @~10" res 4 cls 2010, ~25 Hubble CLASH cls to come Devlin, Mason, ...

future: High-Res SZ sim for MUSTANG2

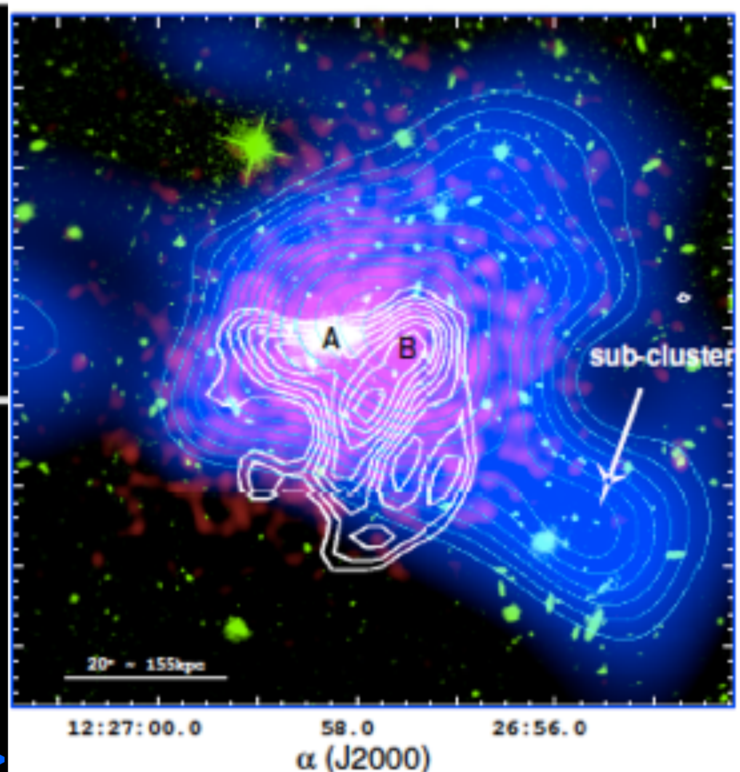


100x mapping speed!
160 cf. 64 pixels, over larger area (5' vs. 40")

=> Planck followup to 35σ in 1hr



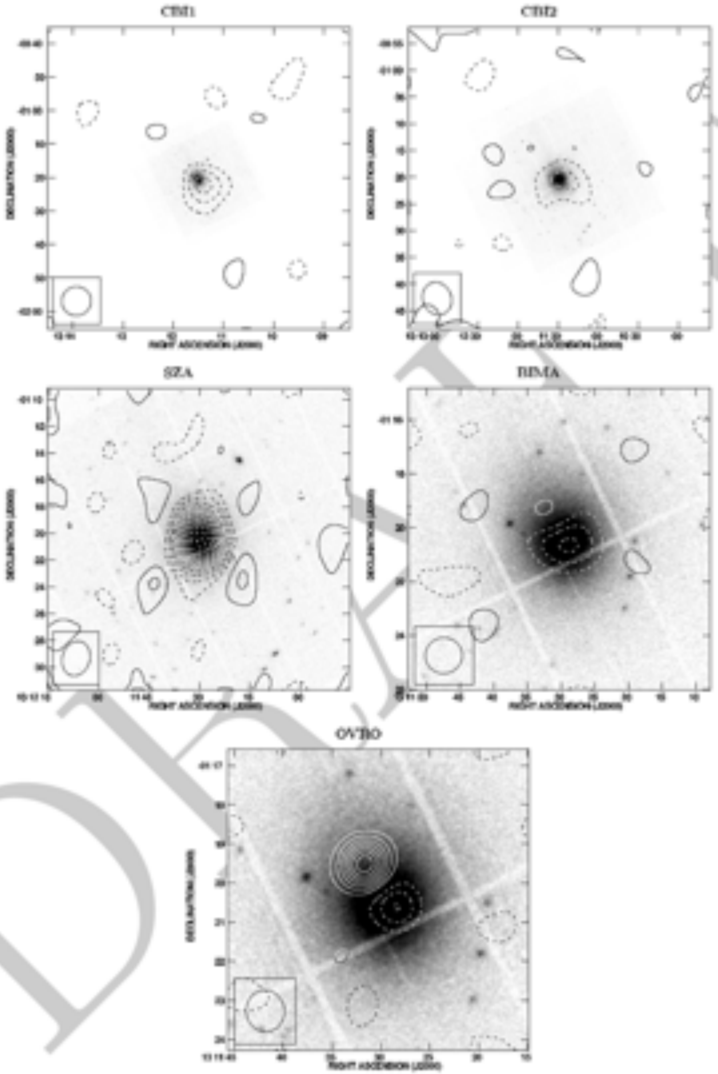
now: CL1226 z=0.89

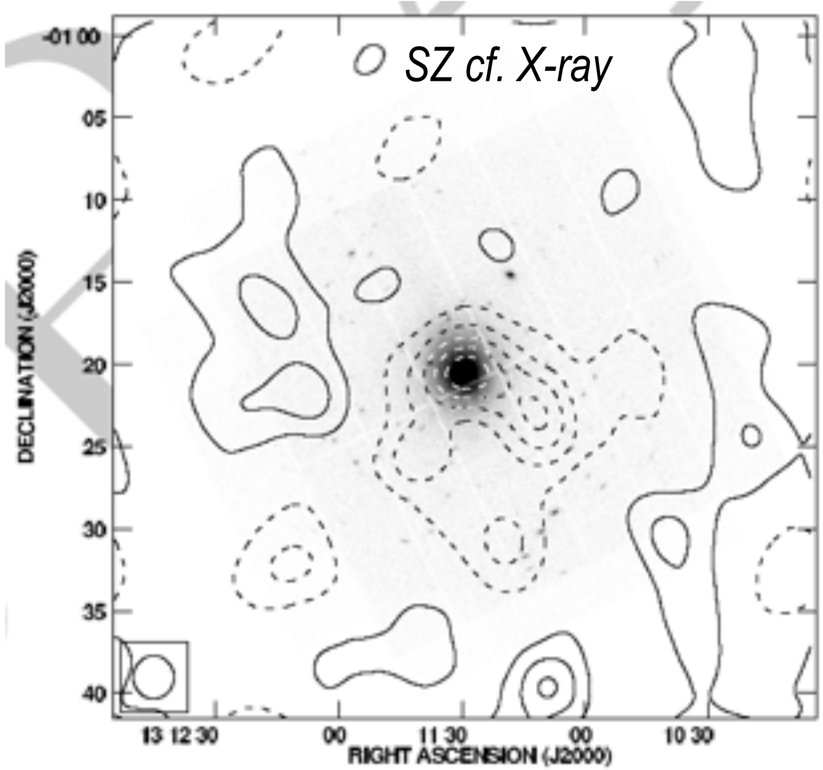


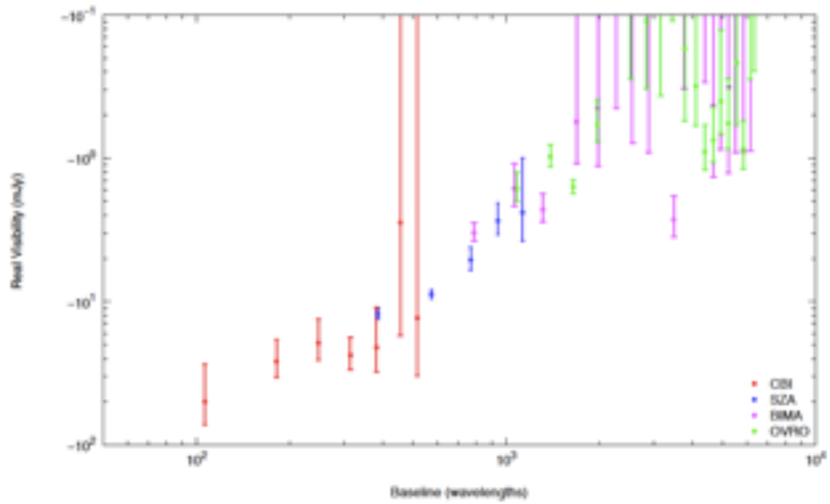
Red Chandra
Blue/cyan weak lens Σ
Green optical
White MUSTANG SZ >3σ

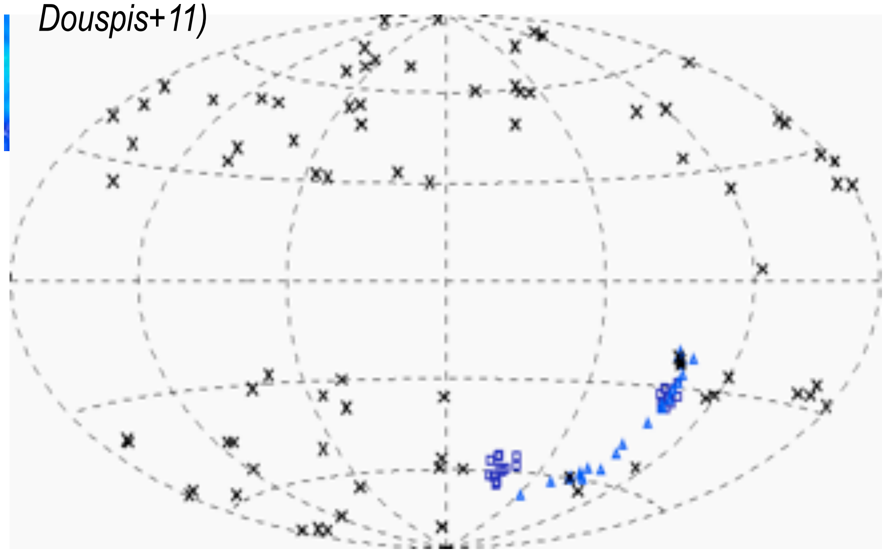
A BCG ~ X-ray peak
B Dark Matter peak
~ lobe of SZ ridge

A1689 [$z = 0.18$ **M_{vir} = (1.4-2) X 10^{15} M⊙** <T_X> (9-10.5) kev] SZ combining **CBI, CBI2, SZA, BIMA, OVRO interferometry** data gives good spatial resolution over a range ~20 *Allison+12*

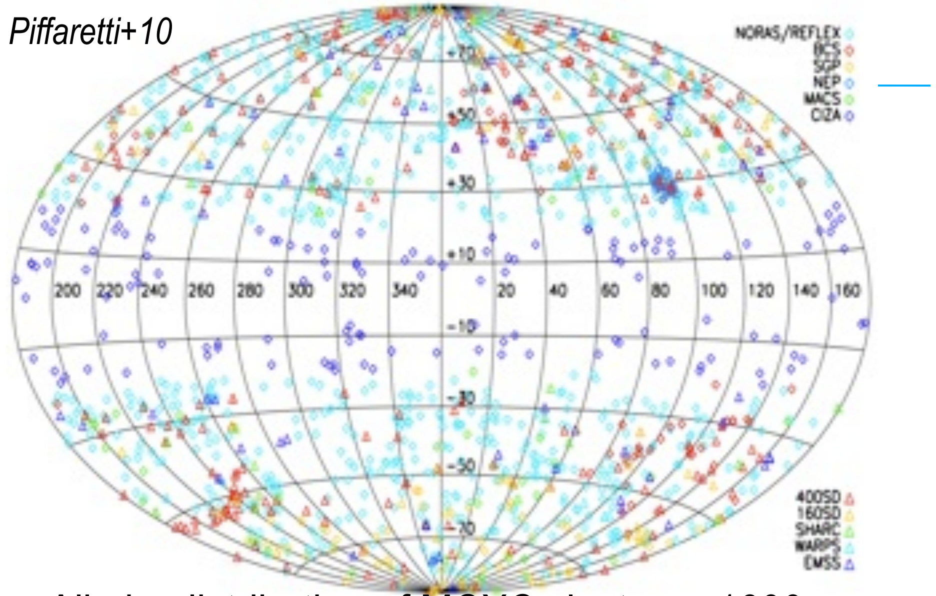






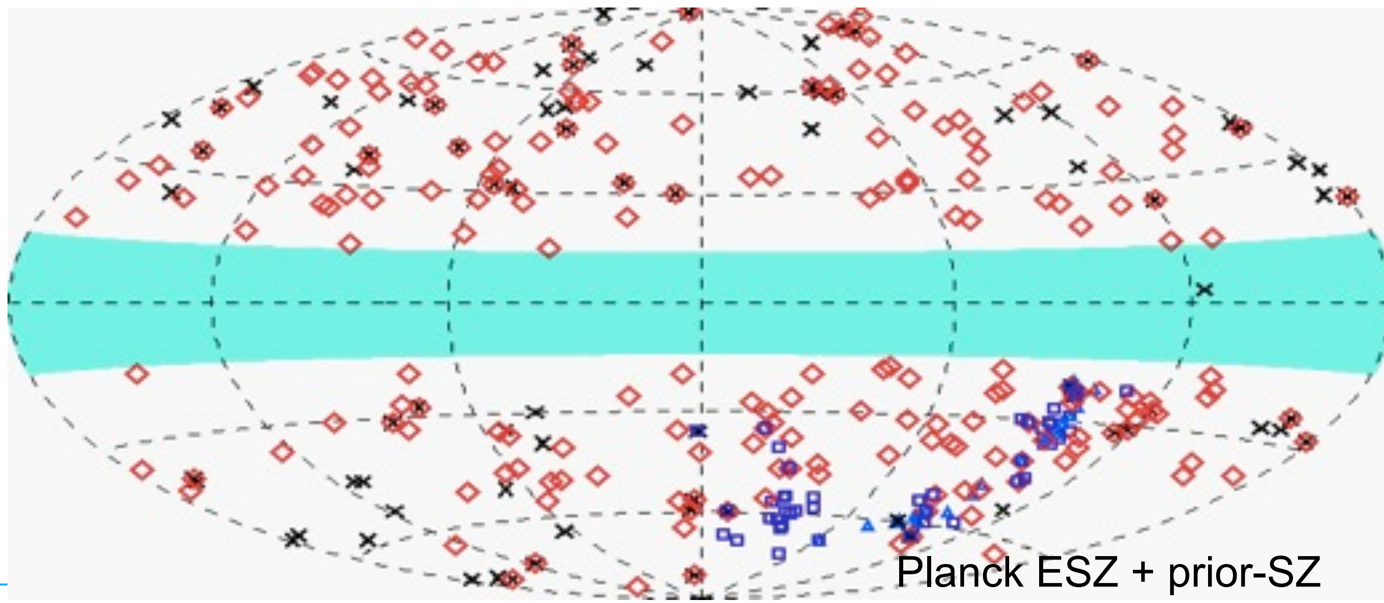


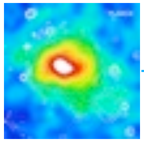
All-sky compilation of first generation SZ clusters



All-sky distribution of MCXC clusters ~1600

ESZ 20 new + 169 in X/Opt cats (& ~80% new in SZ, $E_{thermal}$ view) PlanckXMM dedicated time on newbies ~95% reliable, validation, S/N ~ 6 cut + cross-correlate with X/SDSS-BCG catalogues:
YM scaling relations as expected for X-ray cls, apparent SZ deficit for optical cls [&ACTxSDSS-LRGs]

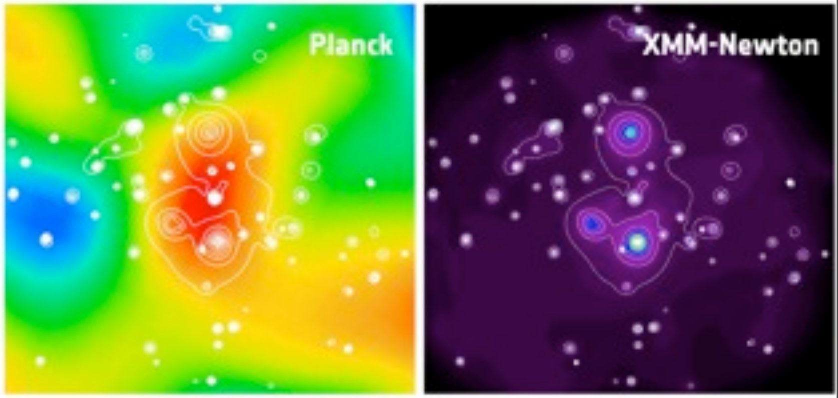


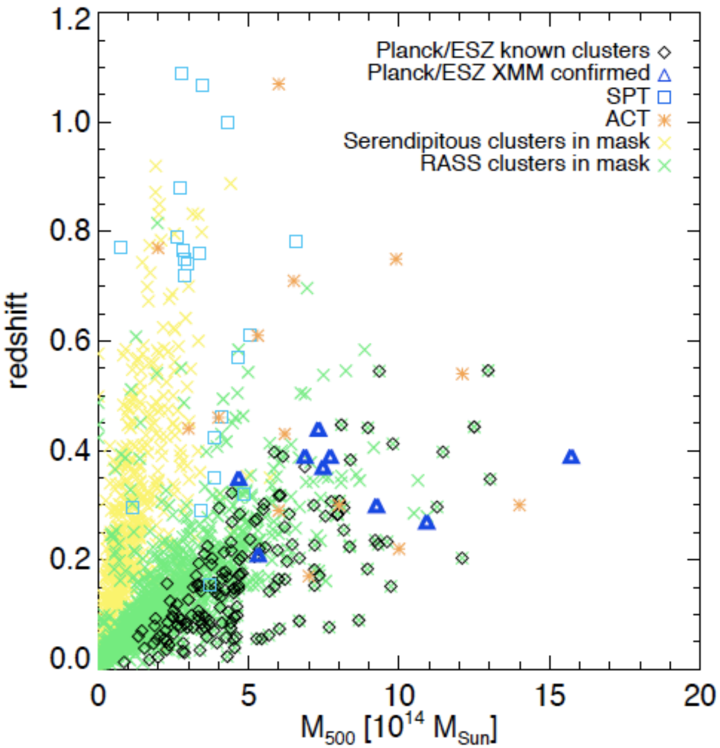


Planck sees the rarest & most massive clusters over the whole sky:

small/moderate redshifts (86% with z<0.3); masses to 1.5×10^{15} M_{sol}. 90% of the RASS above M > 9×10^{14} M_{sol} detected by blind ESZ, 5/21 of new Planck clusters have M > 9×10^{14} M_{sol}.

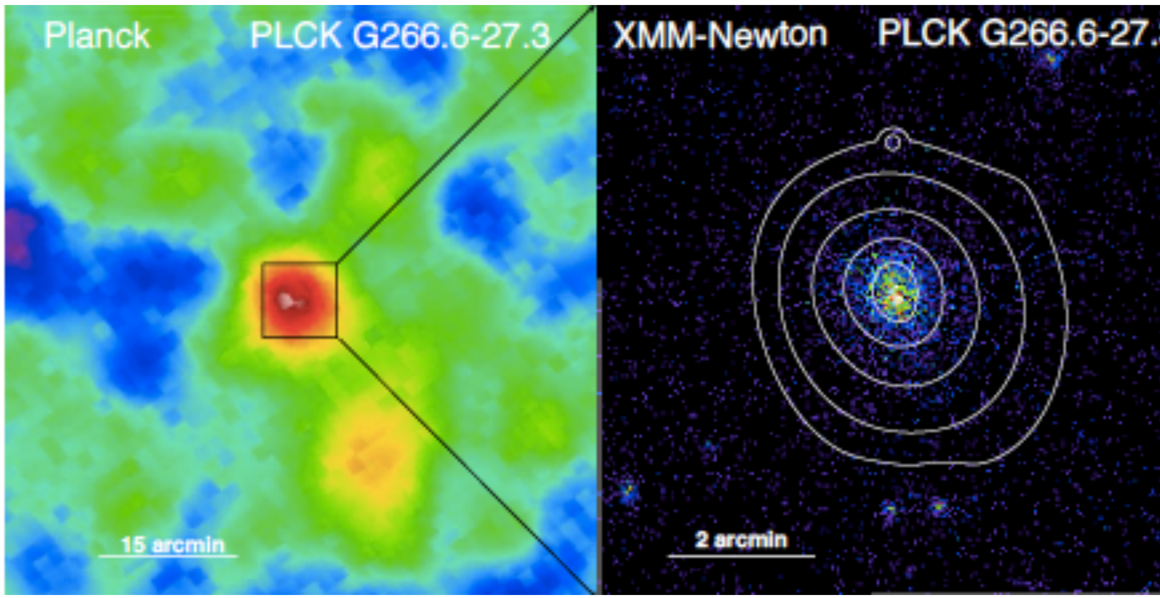
XMM-*Newton followups: Jan11* **25 candidates observed: 21 confirmed** → ***~85% success rate; 17 single clusters, most disturbed; 2 double systems; 2 triple (super-cluster) systems; 0.09 < z < 0.54; Dec11 second XMM followup Planck paper; soon one more.***





PLCK G266.6−27.3 **(z = 0.94 +- 0.02)** *Planck+11.6 26*

M_{200} ~ (1.5 +- 0.15) X 10^{15} $M_\odot$

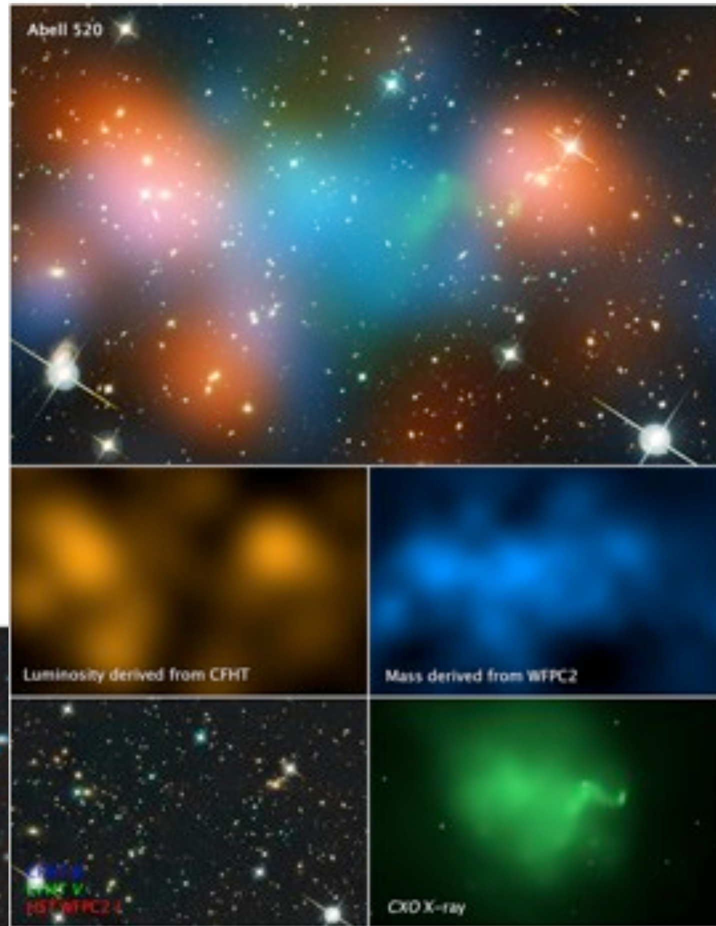


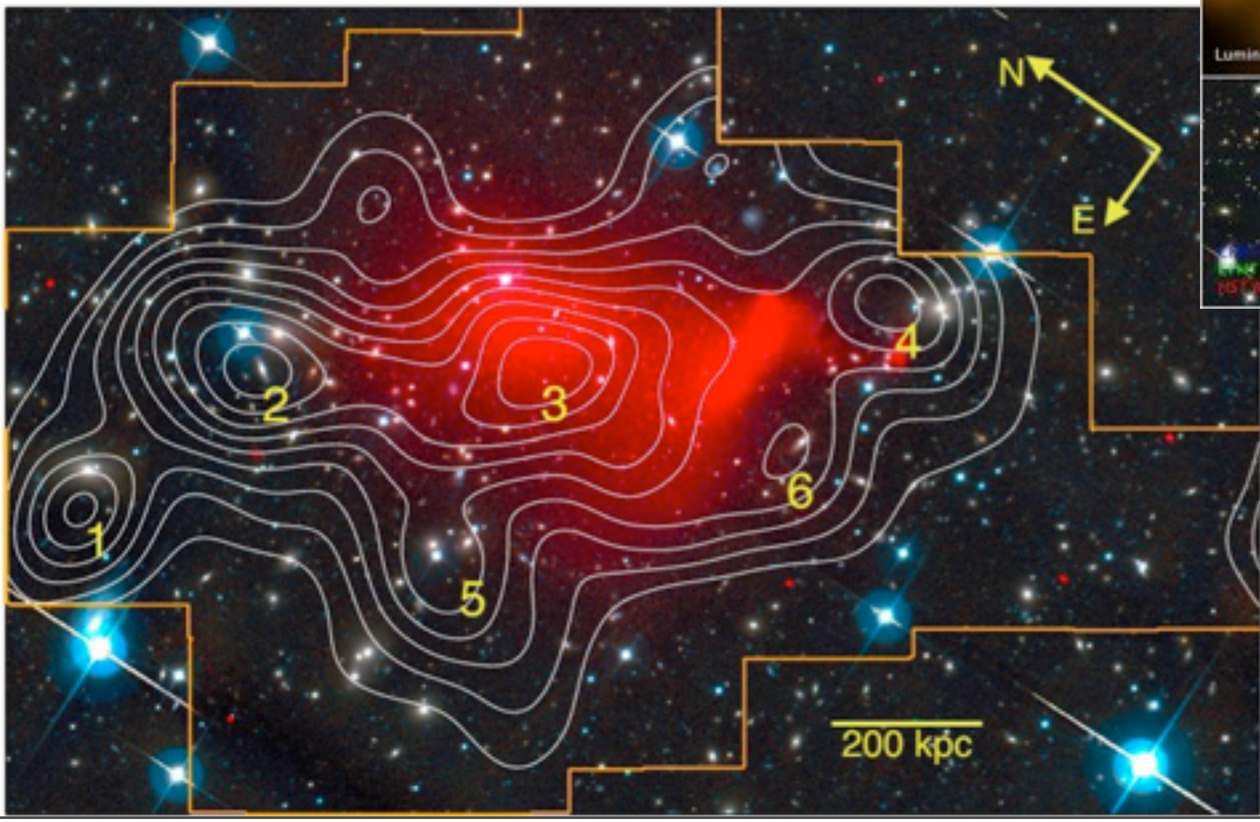
A520 z=0.21 Train Wreck Cluster

Markevitch+05

Mahdavi+07

Jee+ 12 weak lensing dark core, many sublumps, filament?, complex merge (*or funny collisional DM?)*





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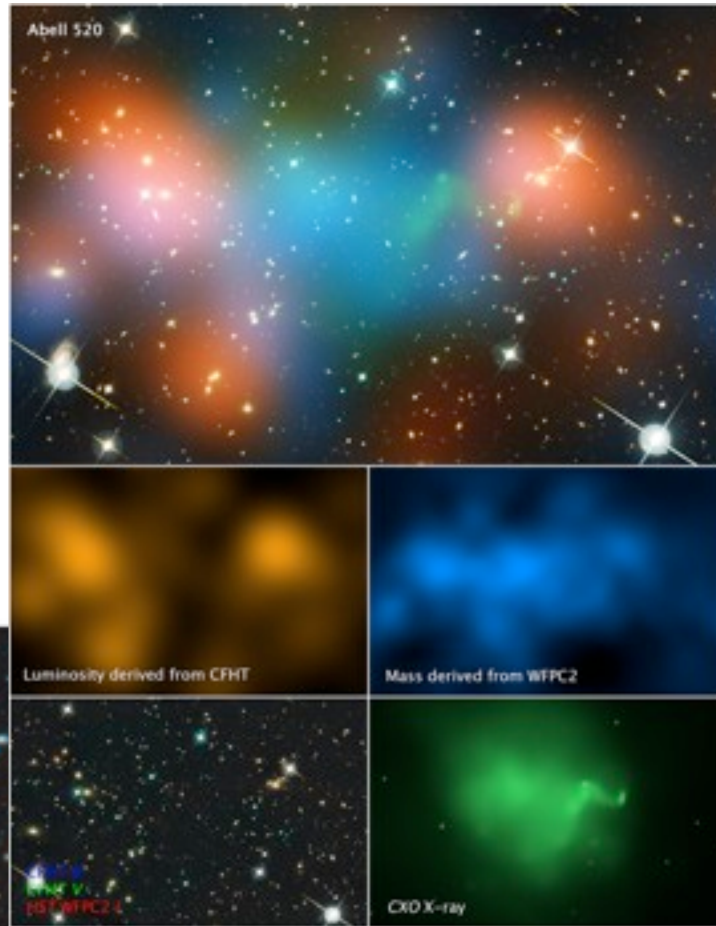
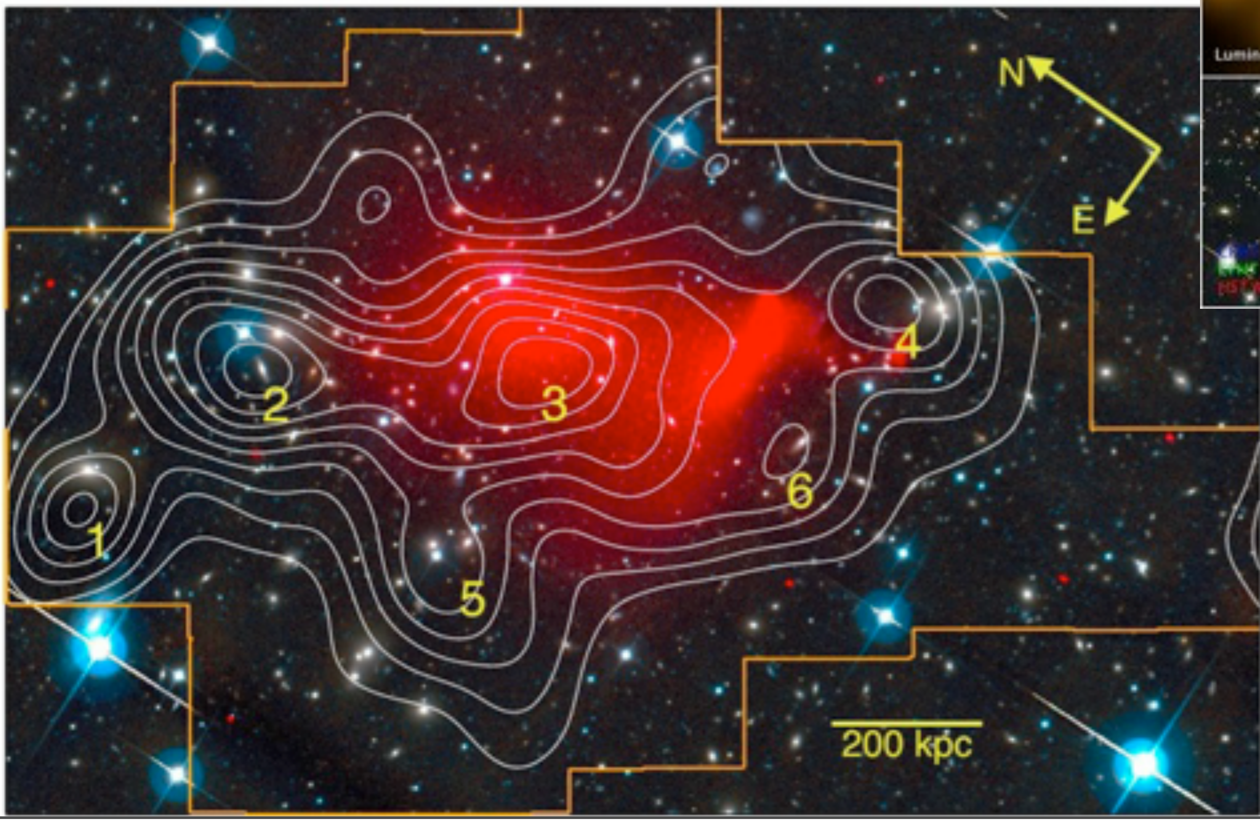




Hydro Sims include all effects -except of course those not included

=> *Thou Shalt Mock Analytic and semi-analytic treatments cannot intuit these & must be fully calibrated with sims for a useful phenomenology*

non-thermal/non-equilibrium effects:

Summary: the **running** with **r/R$_{200}$**

aka resolution (e.g., d*ln* E$_{th}$(<r)/d*ln* r)

of effects influencing **Y$_{SZ500}$(M)** &

C$_L^{tSZ}$ for low & high **M** @ z=0, 1

turbulent internal bulk flows **P$_{kin}$/P$_{th}$**

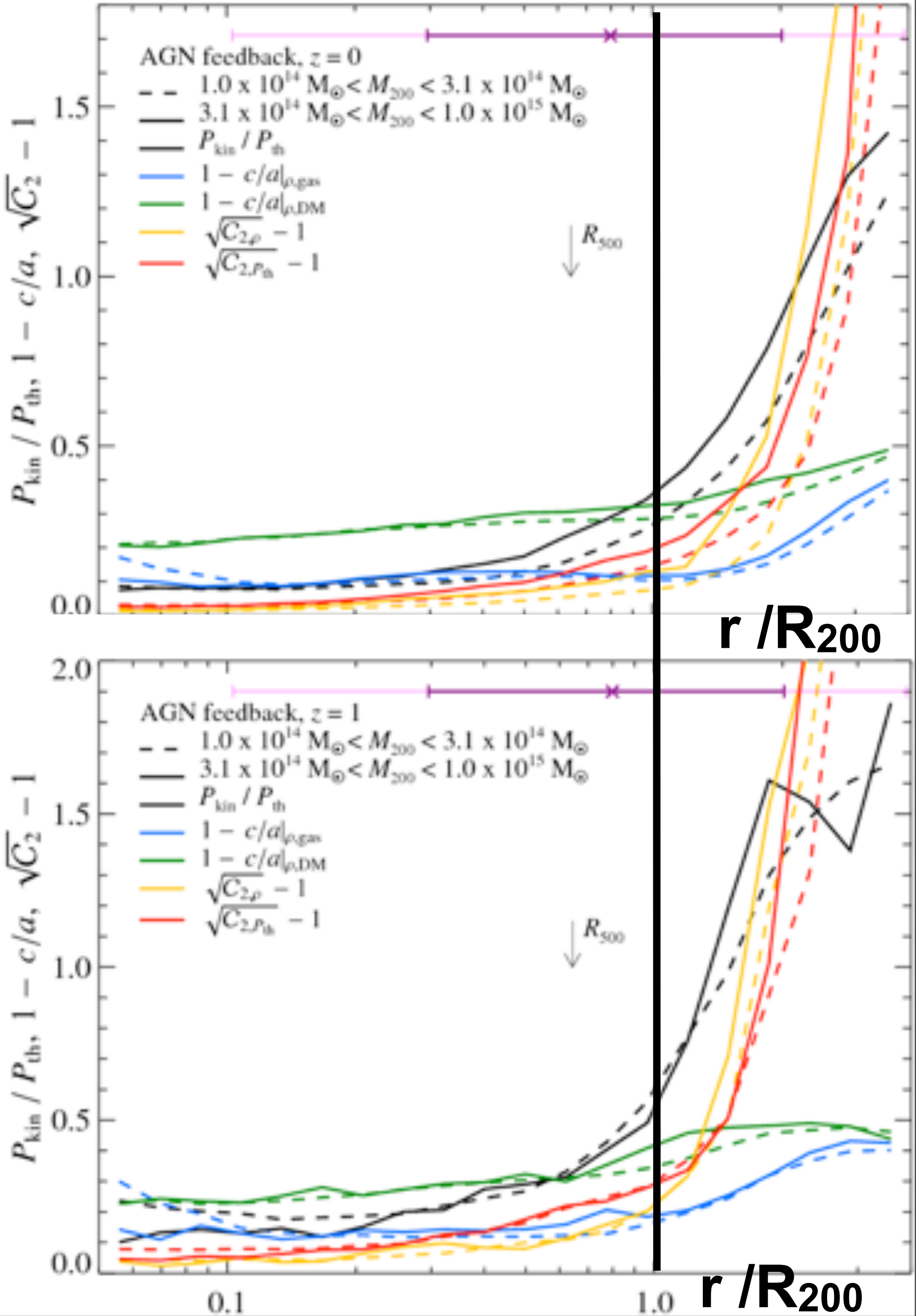
asphericity 1-c/a gas cf. DM

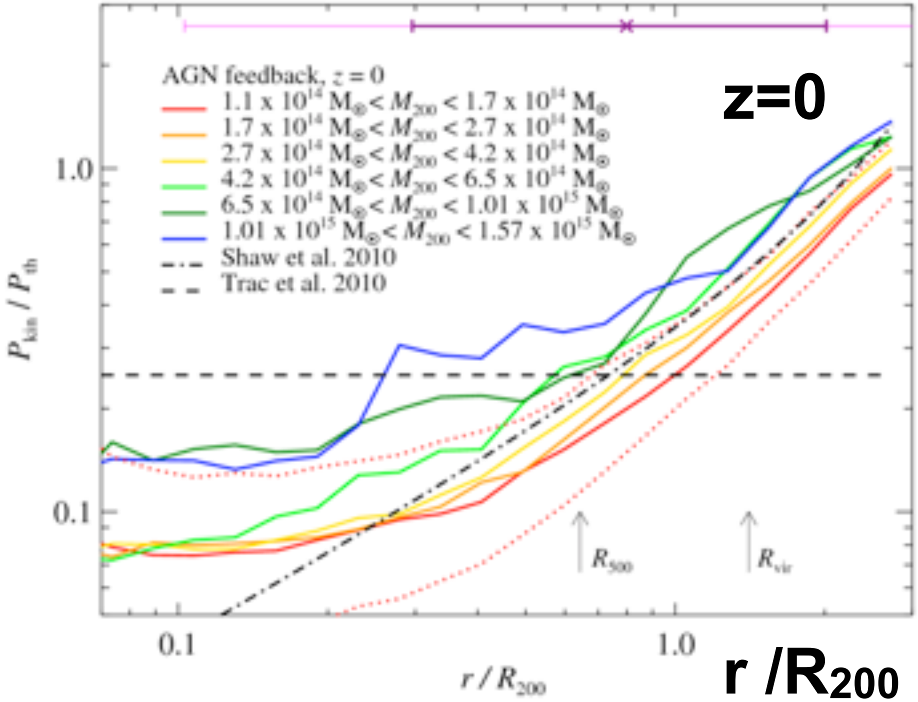
clumping of density & **pressure** (!)

$C_{p2}^{1/2}$ -1 = sqrt[<p_{th}^2>/<p_{th}>^{2}]-1

not small @ < **R$_{500}$**

huge @ < **R$_{200}$** < **R$_{vir}$** < **R$_{SZboundary}$**

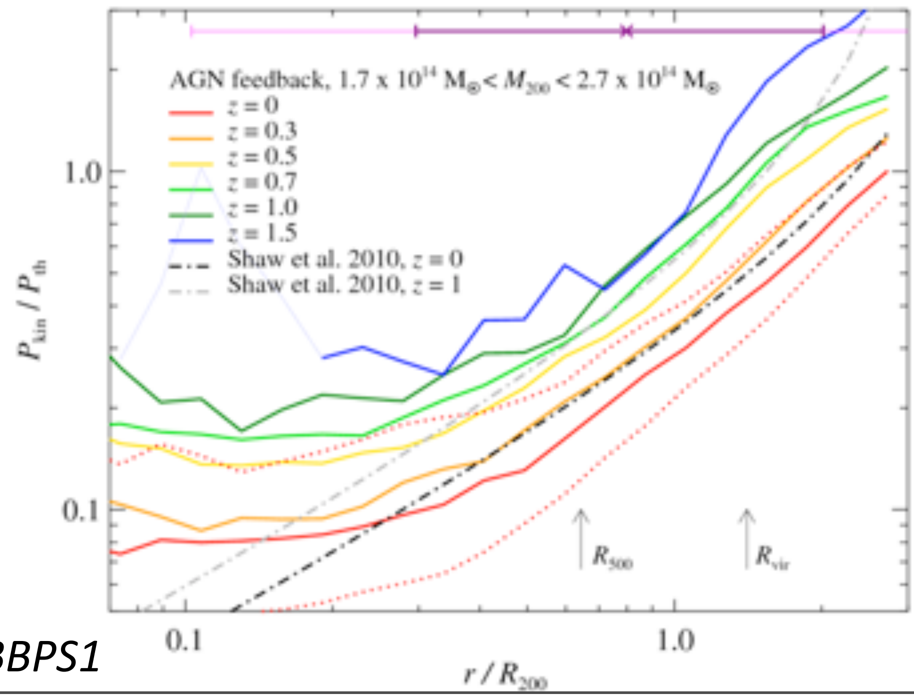




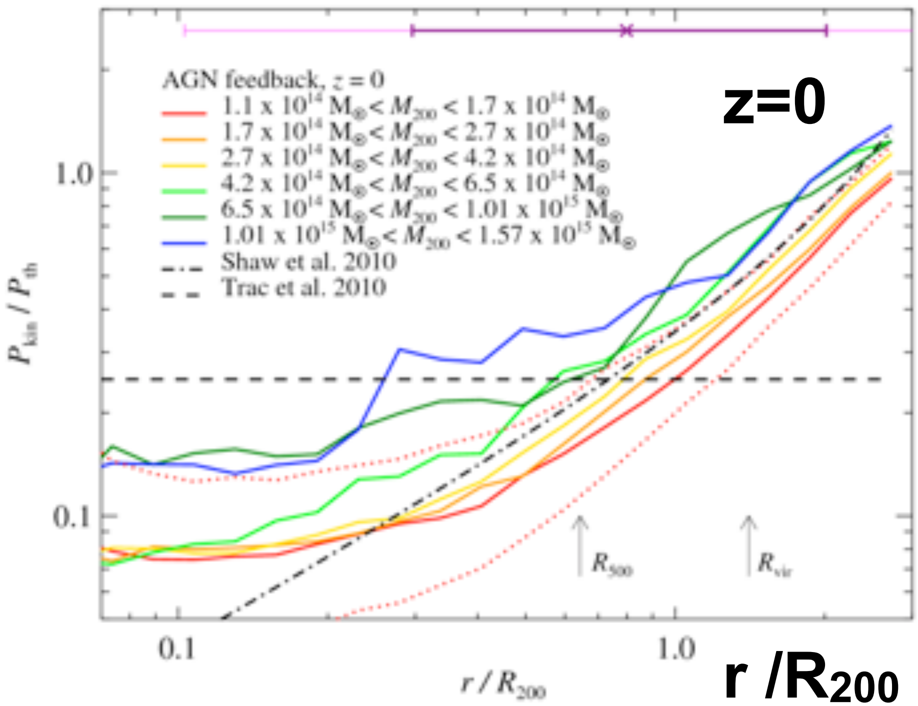
P_{kin} /P_{th} (M,z)~0.1-1+!

=> $<(\Delta v)^2>/c_s^2$ cannot be ignored in HSE

$\nabla p_{g,tot}=\rho_g g$



BBPS1

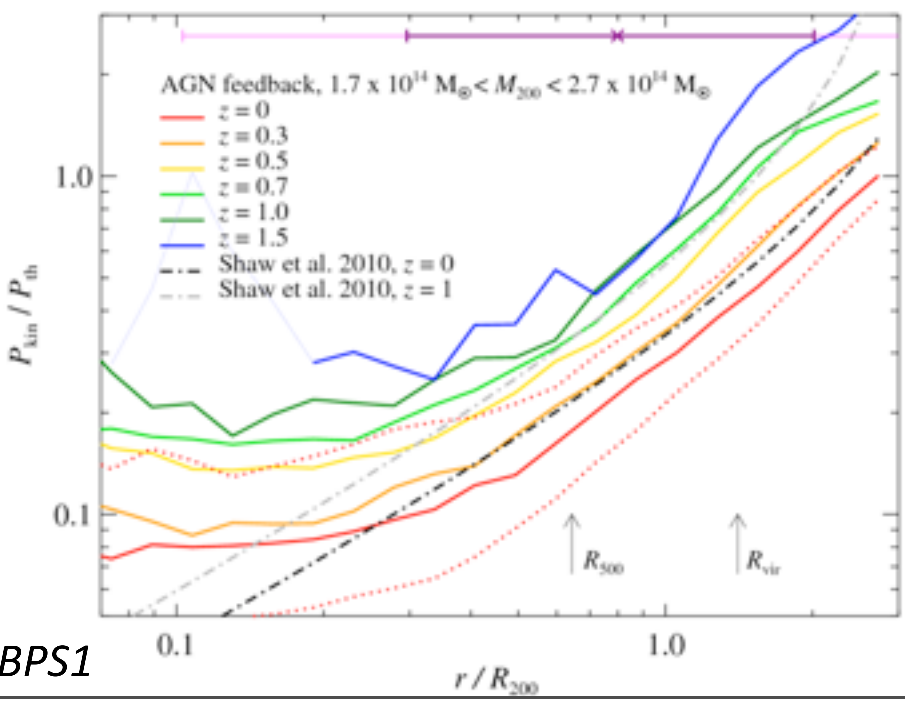


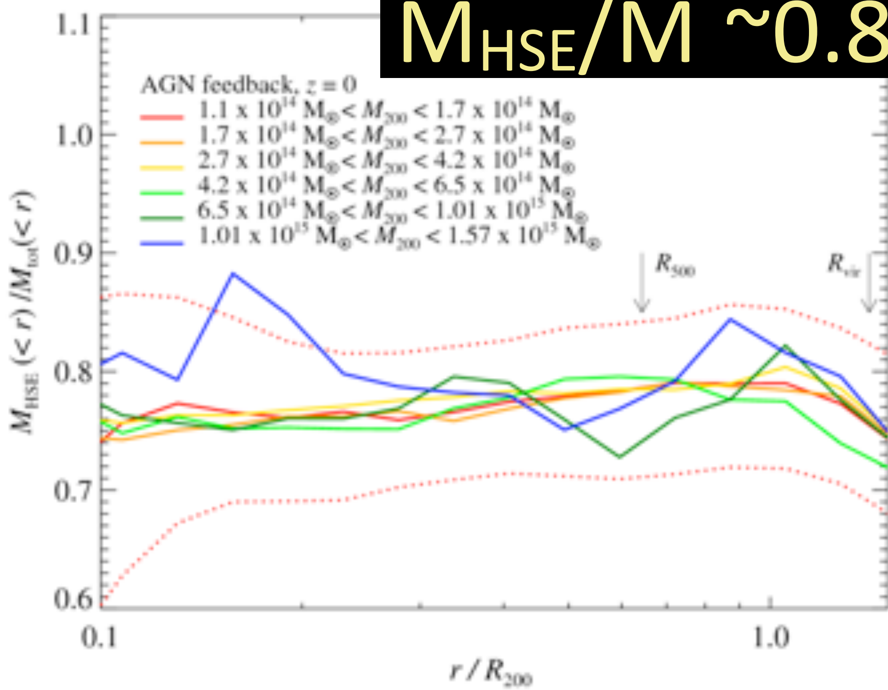
P_{kin} /P_{th} (M,z)~0.1-1+!

=> $\langle(\Delta v)^2\rangle/c_s^2$ cannot be ignored in HSE

$\nabla p_{g,tot}=\rho_g g$

M_{HSE}/M ~0.8





BBPS1

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 moment of inertia*
$w(x)=1$ or $w(x)= 1/x^2$ (does not overweight the outskirts) => similar

$U_{dm,ij}$ 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)

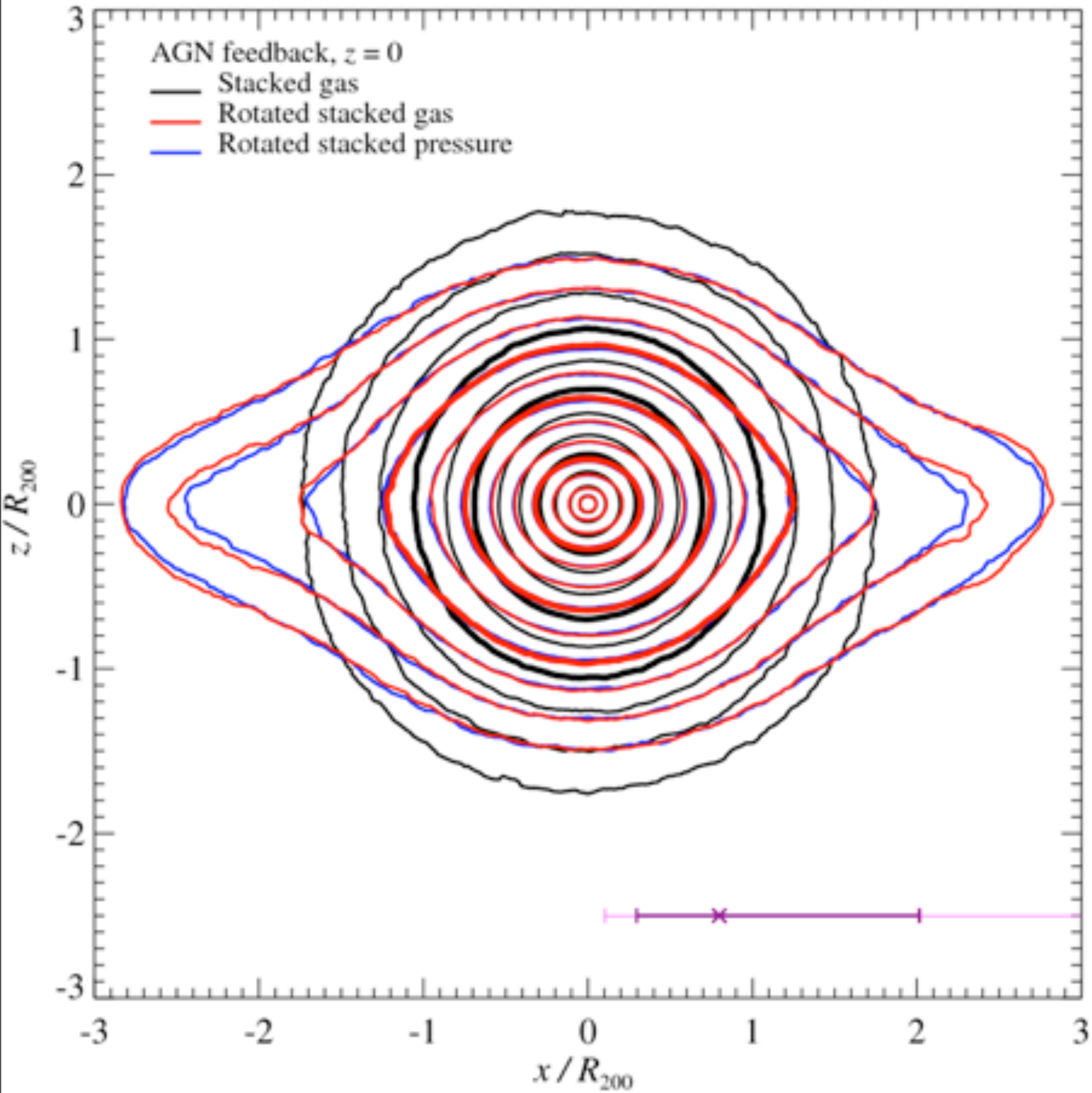
rotate to principal axes, scale & stack

eigenvalues $u_1 > u_2 > u_3 \Rightarrow$

ellipticity $e = (u_1-u_3)$ */2Trace***U,**

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

Ellipticity ρ_g z=0



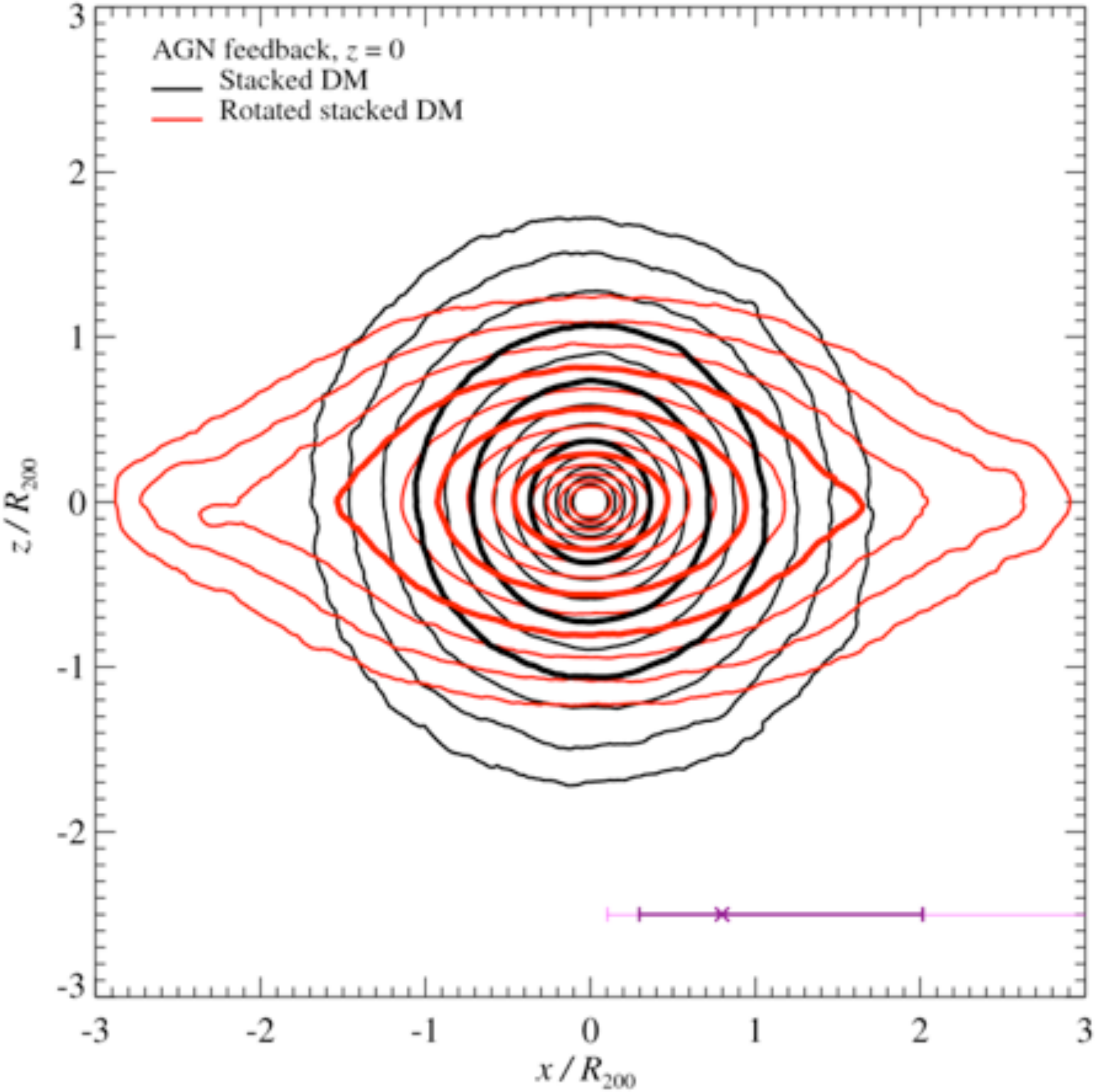
gas in cluster-Y_{SZ} "far-field" is increasingly elongated: a little near-field filament penetration

e(gas) < e(DM) /2

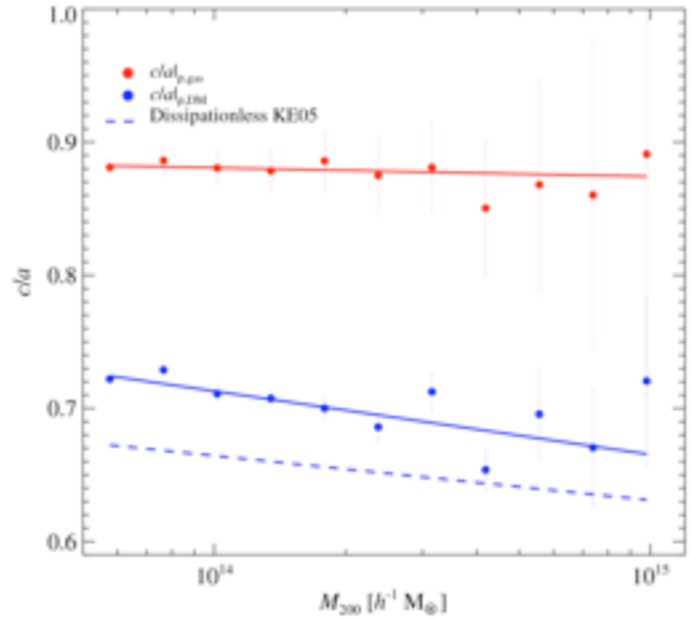
.

Ellipticity ρ_{dm} z=0

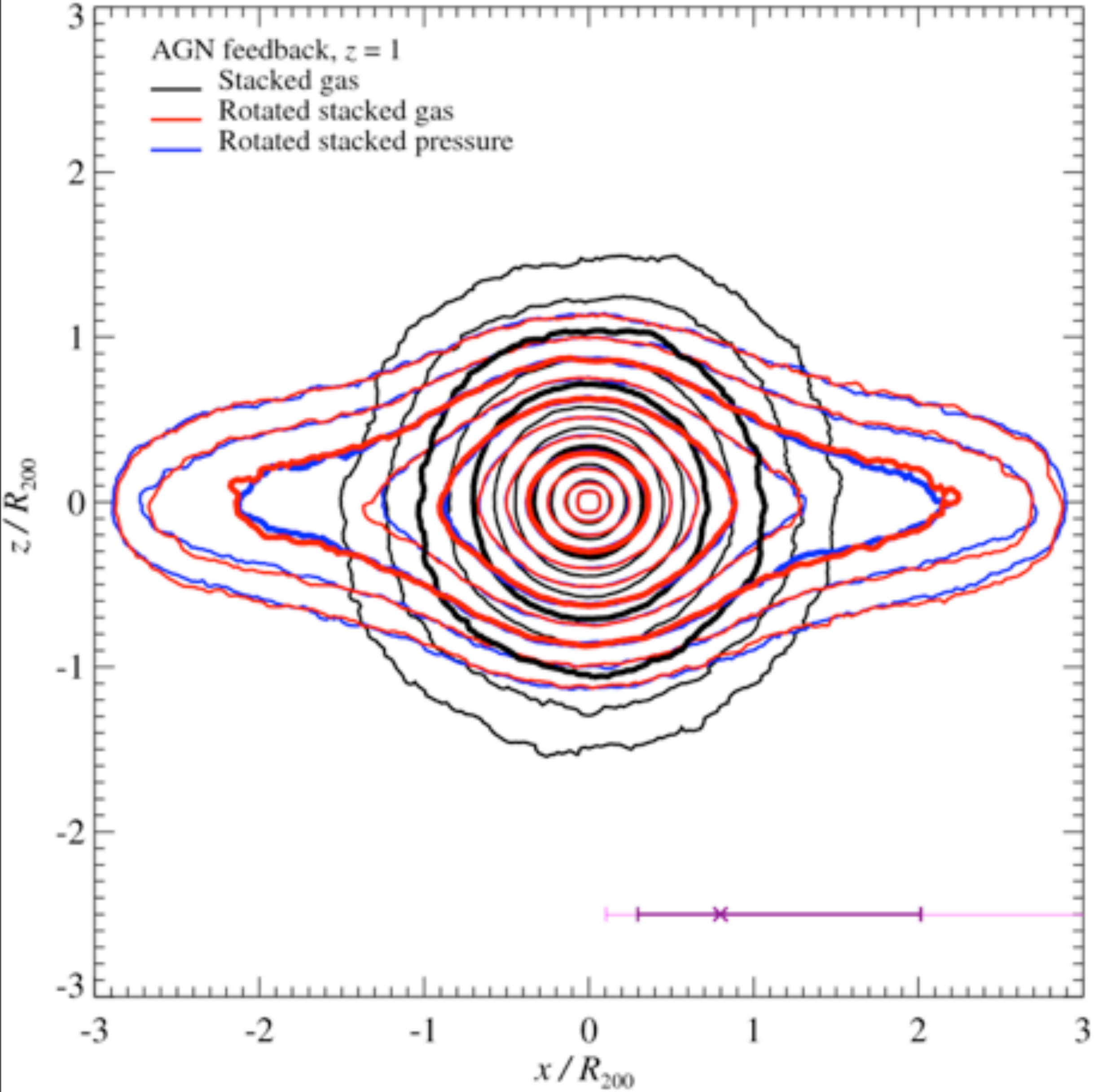
DM in cluster-Y_{SZ} "far-field" is more elongated: a little near-field filament penetration



e(gas) < e(DM) /2



Ellipticity ρ_g z=1

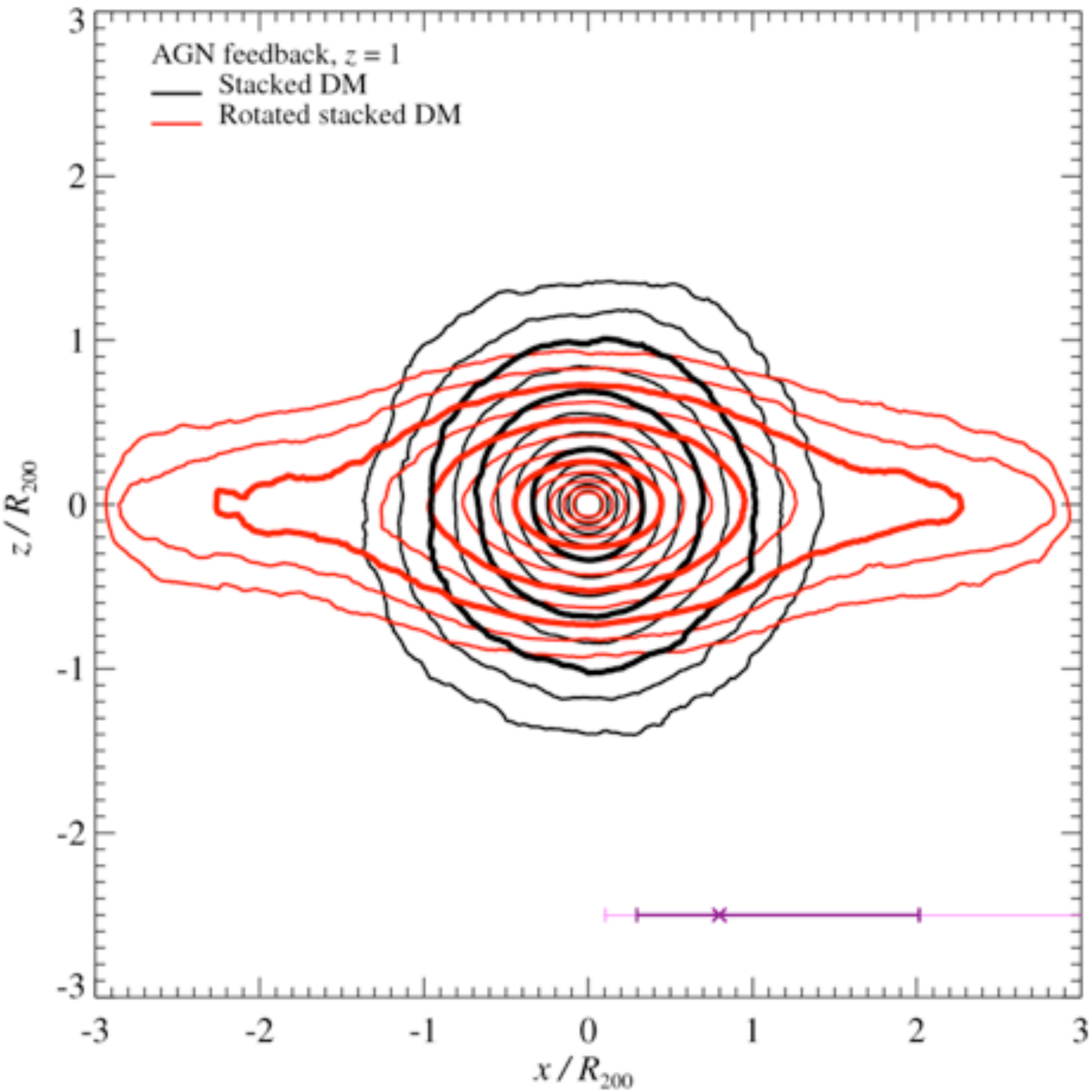


gas in cluster-Y_{SZ} "far-field" is increasingly elongated: a little near-field filament penetration

e(gas) < e(DM) /2

z=1 extreme cf. z=0

Ellipticity ρ_{dm} z=1



DM 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

*d**S**/dt* 2

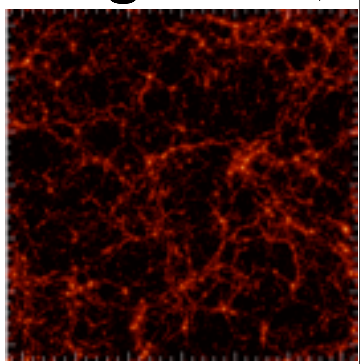
Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)

how most of the entropy in baryons & dark matter was generated

strain waves break => clusters/groups (galaxies/dwarfs) in the cosmic web collapse => shocked gas & extreme nonlinear phase space entanglement of dark matter / stars

then the baryons feed back entropy: exploding stars, accreting black holes, dusty radiation,

... who, what, where,when, why?



morphs *into the nonlinear* ***Cosmic Web: clusters, filaments, voids; galaxies*** **(SZ)**

gastrophysical simulations with feedback from AGN / starbursts / SN .. confront CMB+LSS data

dS/dt 2

how most of the entropy in baryons & dark matter was generated

strain waves break => clusters/groups (galaxies/dwarfs) in the cosmic web collapse => shocked gas & extreme nonlinear phase space entanglement of dark matter / stars

then the baryons feed back entropy: exploding stars, accreting black holes, dusty radiation

Studying the Cosmic Tango** Universe=System+Res =Data+Theory **en-TANGO-ment

BBPS5, .. measure all non-thermal/non-equilibrium complexity with coarse-grained constrained Shannon entropies for clusters/protocls: thermal +kinetic tensor +asymmetry tensor + clumping, includes entropy of dark matter!

fine-*macro-small*-grain 10^6 baryons in cubic metres cf. **sph--*macro-large*- grain 10^{65} baryons. ~26 dims per sph-grain, huge dimensional reduction, scaled-radial-*resolution*-grain further dim reduction. entanglement of fine & coarse & EFT. feedback.**

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

$\rho_g(x,t)$

400 Mpc

ΛCDM

WMAP5

gas density

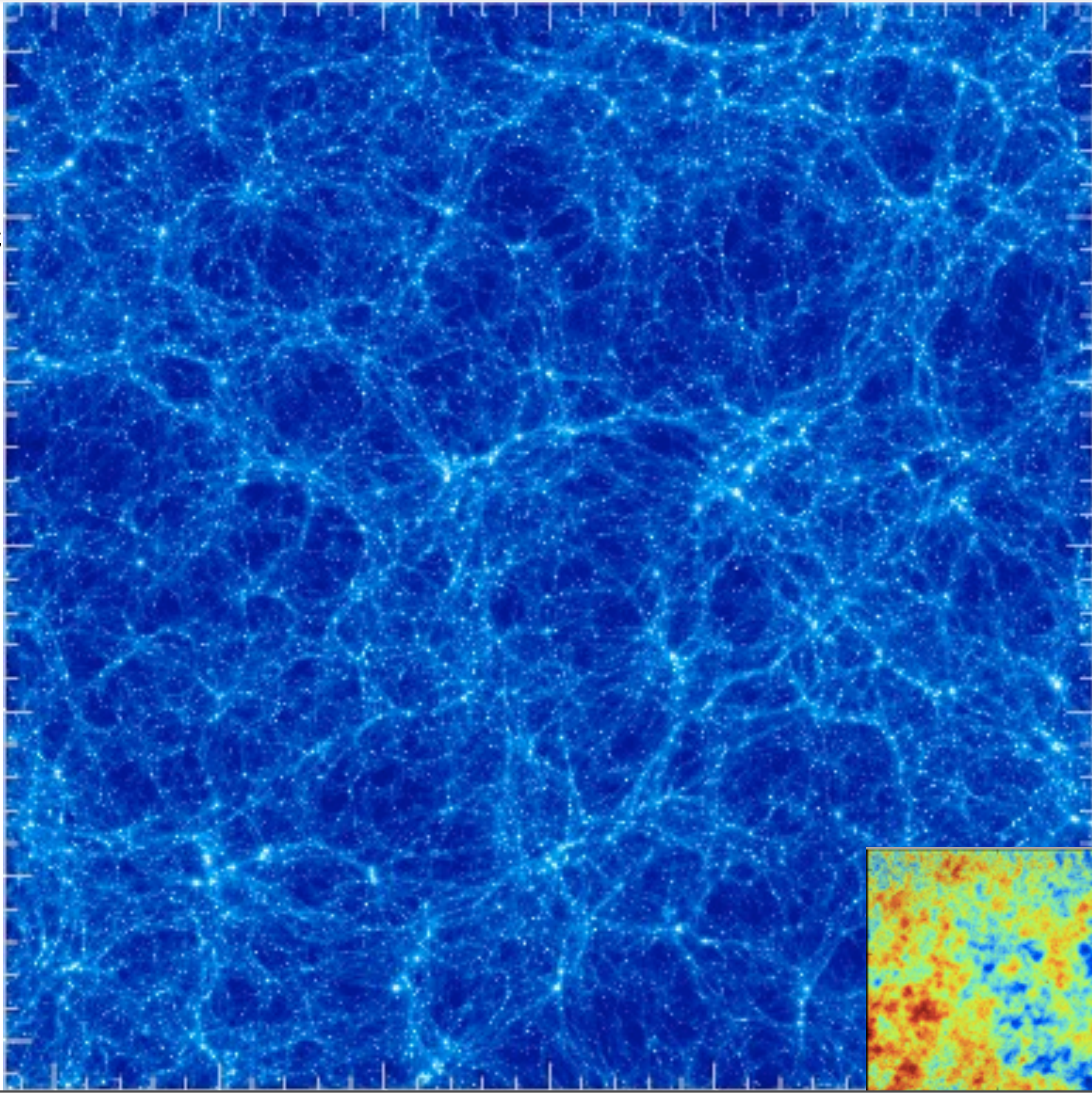
Gadget-3

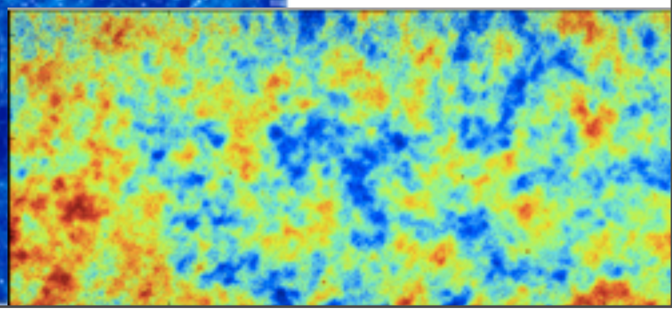
SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4





evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential aka dark energy

entropy intermittency *in the cosmic web, via gravitation-induced shocks (then E/S-feedback)*

Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)

400 Mpc

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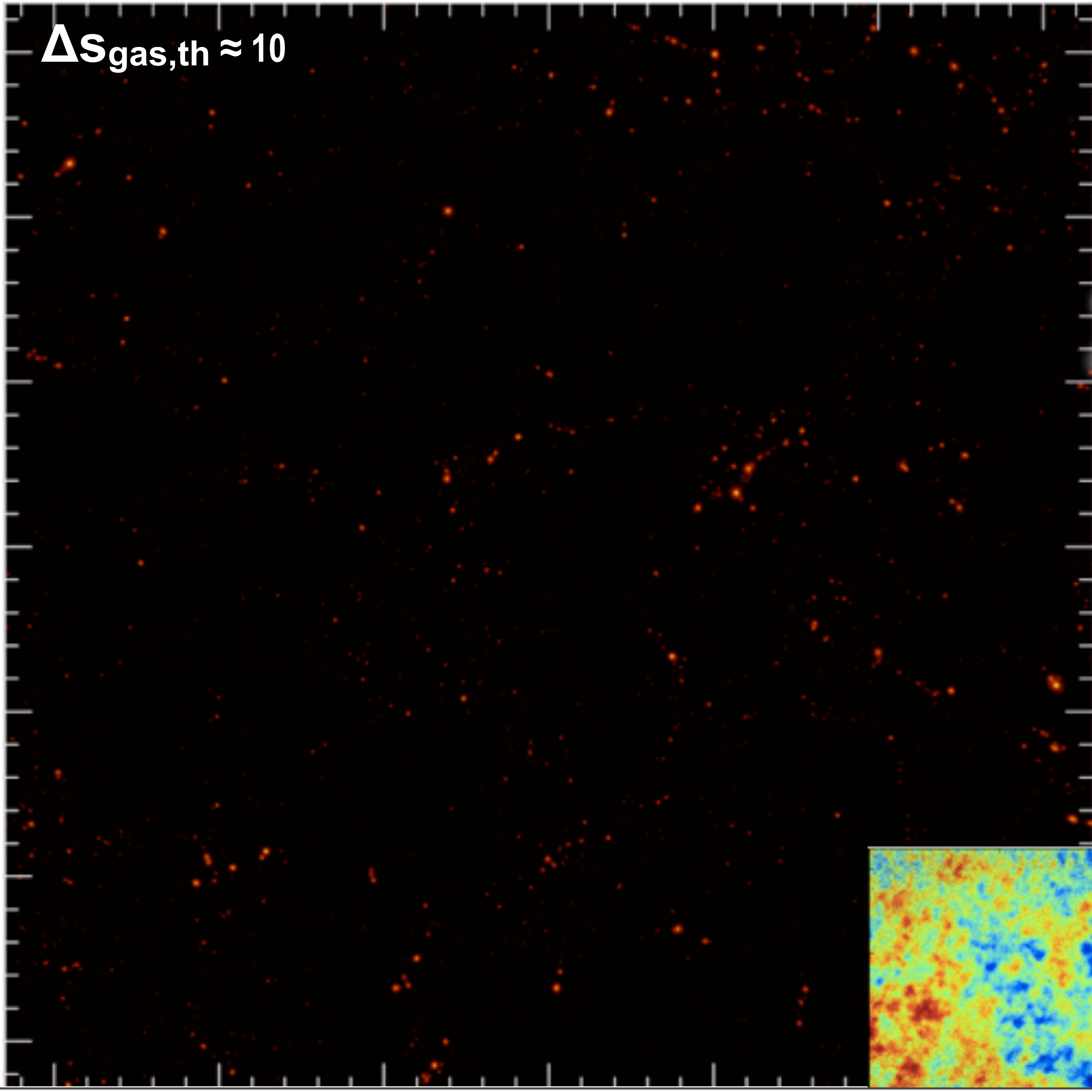


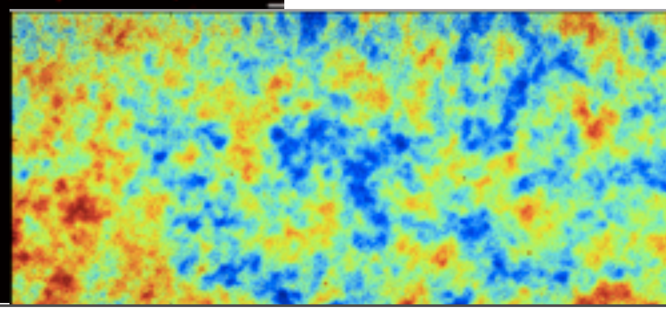
$s_{b,th}(x,t)$

CMB gets 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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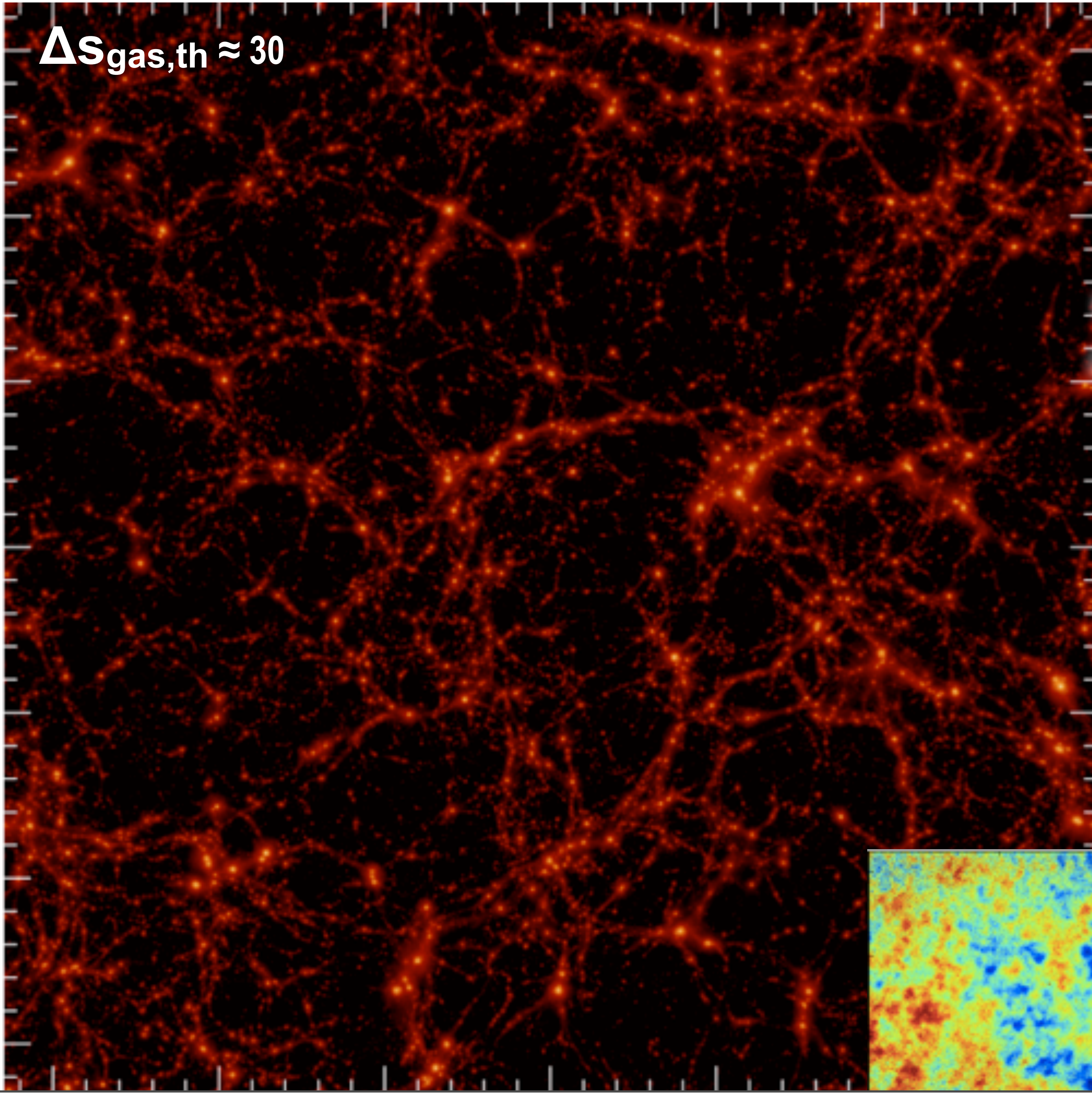

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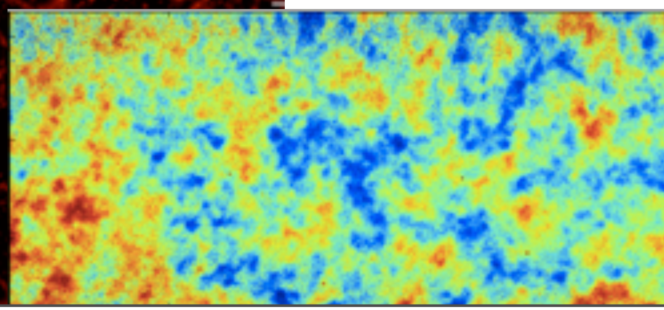

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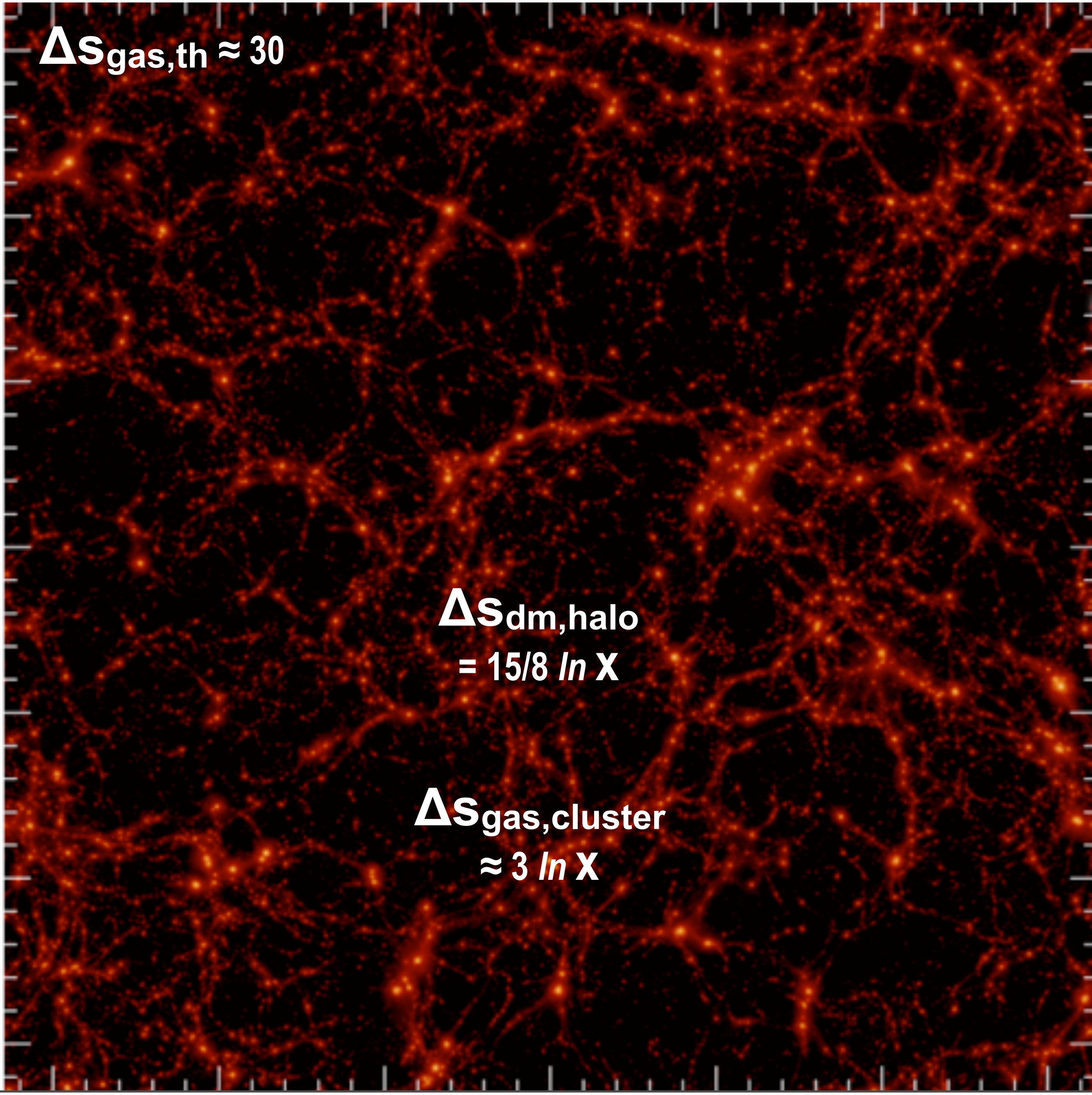


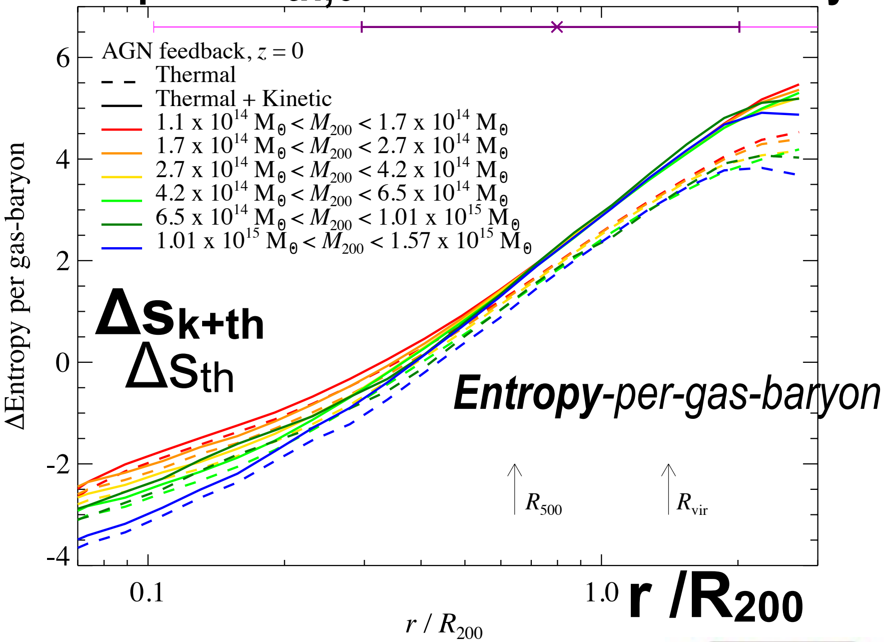
$s_{b,th}(x,t)$

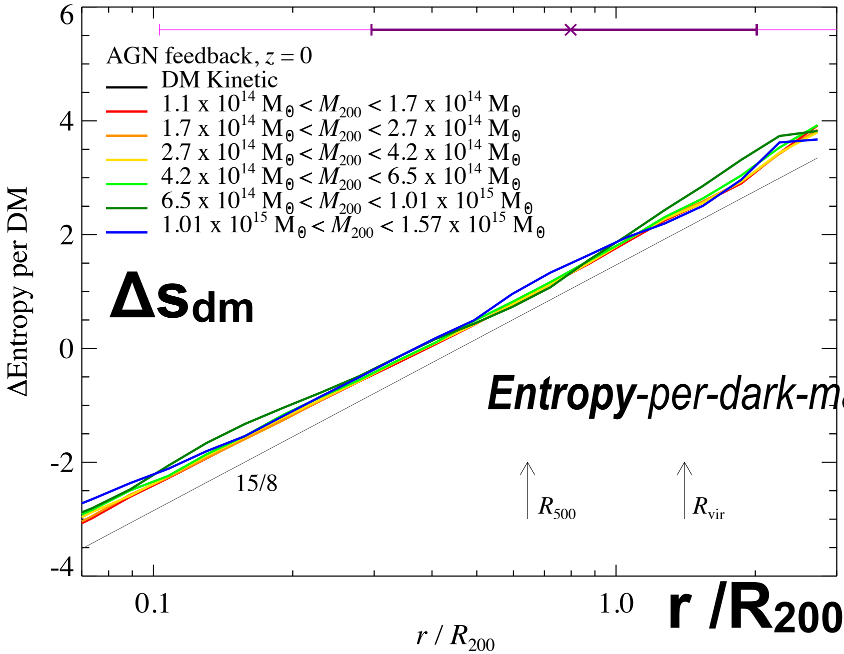
CMB gets entangled in the cosmic web

non-equilibrium and non-thermal ***Entropy Profiles (M | z=0) for Mass-binned Scaled Stacked Clusters***

zero point $s_{th,0}$ ~ 130 nats ~ 190 bits/baryon

BBPS5





slope~3.04 =X-ray Voit

slope~15/8 =self-similar radial infall Navarro

better-than-NFW fit to DM-only simulation density profiles.

gas/star effect affect NFW-ism.

ongoing mystery - why halos have this entropy growth law

P_{kin} / P_{th}~0.1-1+!

$<(\Delta v)^2>/c_s^2$ affects hydrostatic equilibrium

*gps-**cls** ~150-**190 bits/baryon**,* **Δs_{th}~*12 bits/b ;* s_{kin+th}-s_{th}~*1bit/b***

Δs_{dm} = 1/2 Tr *ln*<(p_{kin} I + Π_{kin}) /ρ_{dm}> - *ln* ρ_{dm} *~7 bits/DM*

zero point depends on type of DM, WIMP or axion or ...

cf. **$s_{\gamma+v}$ / n_b ~*1.66x10^10*/(1+δ_b) bits/b**

cf. **AGN's black hole entropy S_{bh} = $M_{bh}^2/2M_P^2$** ~10^{22} **S_b;** but **τ_{bh}** ~ 10^{120}yrs

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

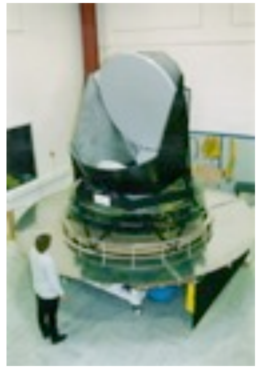
C_L^{SZ}

QUaD @SP

C_L^{SZ}

Planck09.4

52+ bolometers
+ HEMTs @L2
9 frequencies



WMAP @L2 **to 2010**

2004 — 2005 — 2006 — 2007 — 2008 — 2009 — 2011 → **Bpol** @L2

LHC

2005 C_L^{SZ}

Acbar@SP
~1 blind

>96
OVRO /BIMA array C_L^{SZ}

SZA@Cal C_L^{SZ}

AMI

GBT Mustang

2007 **AMIBA**

APEX
~400 bolos@Chile

2008 C_L^{SZ}

SPT
1000 bolos
@SPole

ACT C_L^{SZ}
3000 bolos
3 freqs @Chile

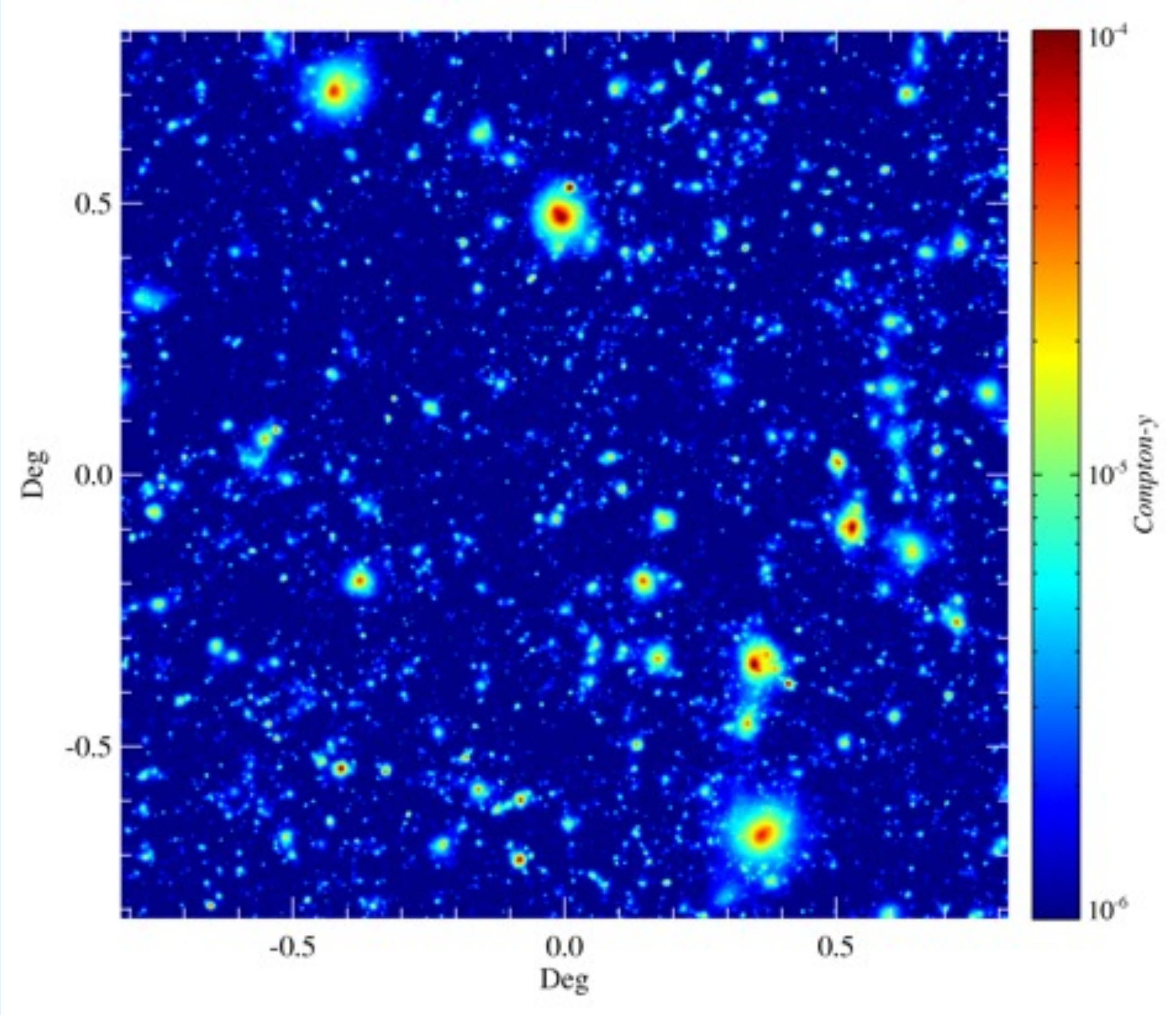
SCUBA2
12000 bolos
JCMT @Hawaii

SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico

80s-90s
Ryle
OVRO

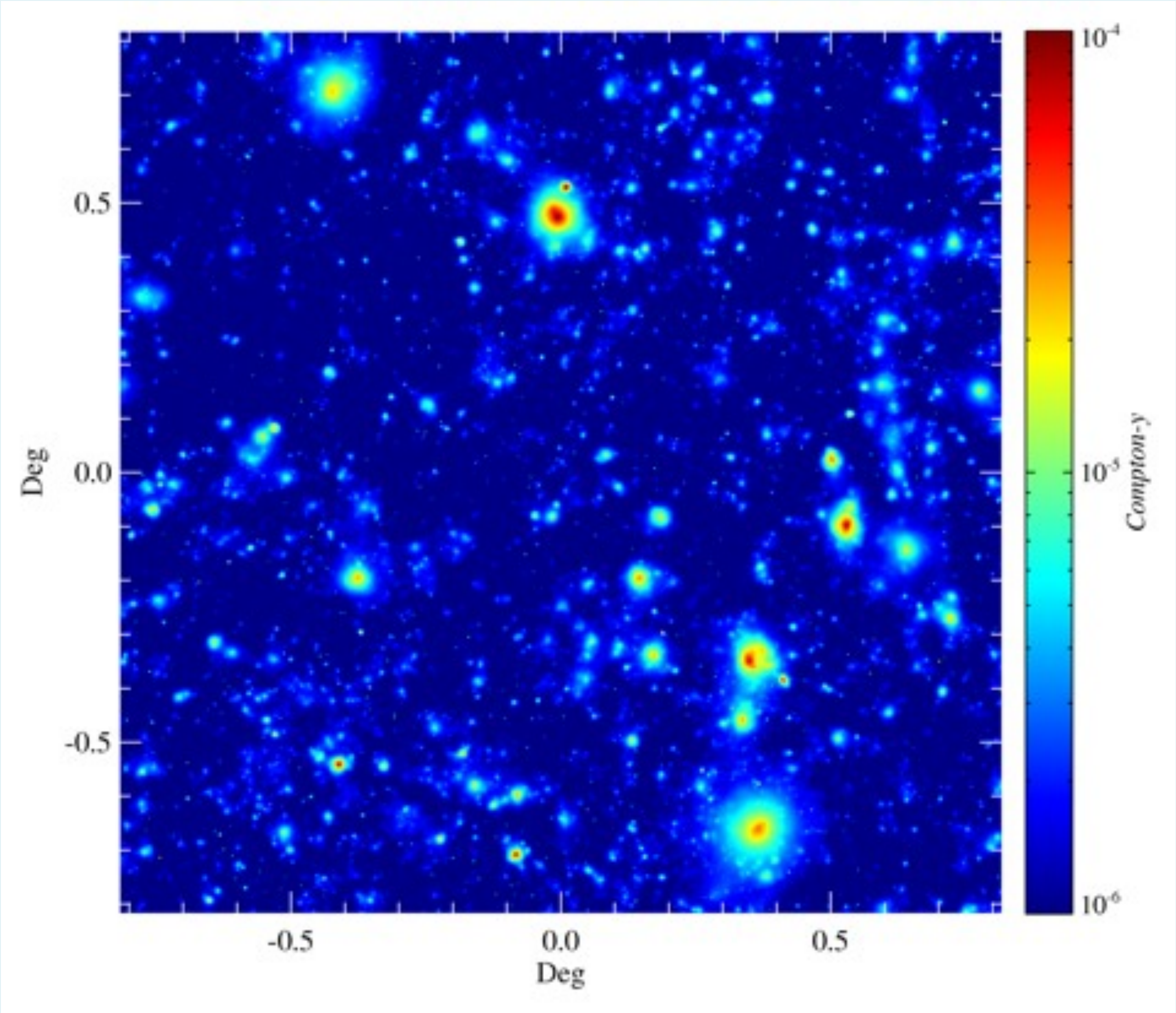
Compton-y map: "adiabatic"

= formation shock entropy from gravitational accretion only

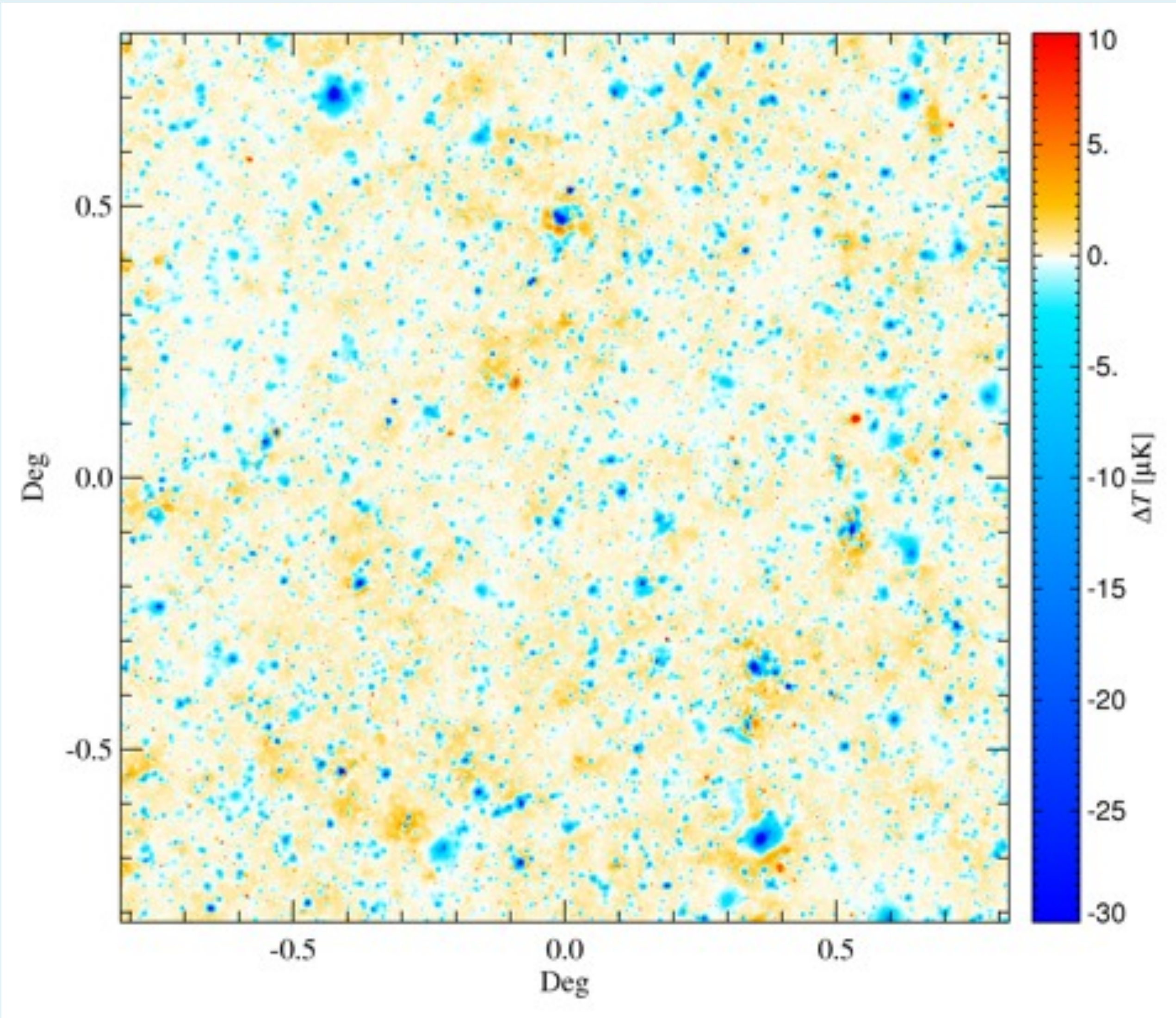


Compton-y map: Feedback

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



Adiabatic - Feedback

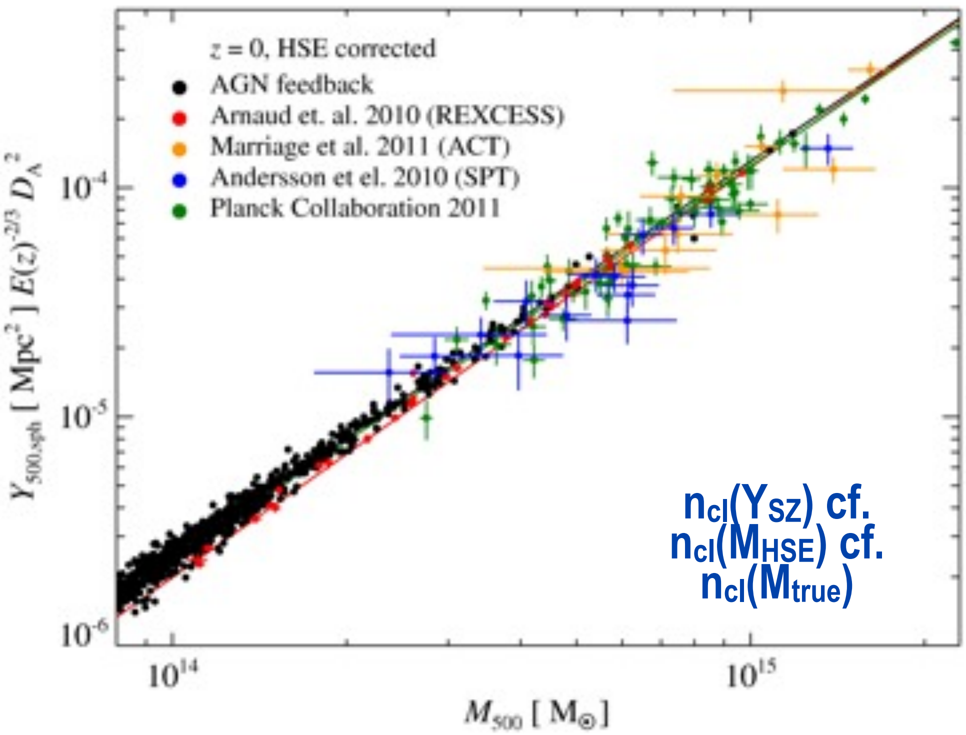


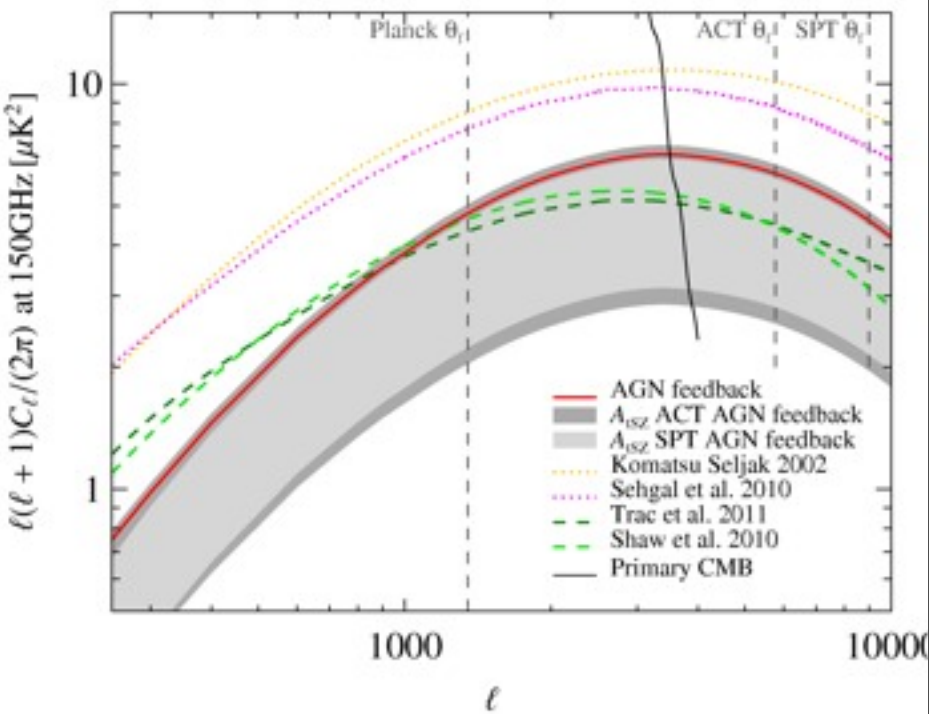
feedback gives “puffier” clusters, with lower core pressures

Cluster Coarse-Grained Feedback Sims cf. SZ data ACT, SPT, Planck

Cluster counts $n_{cl}(M(Y))dM$ + tSZ/kSZ Power spectrum

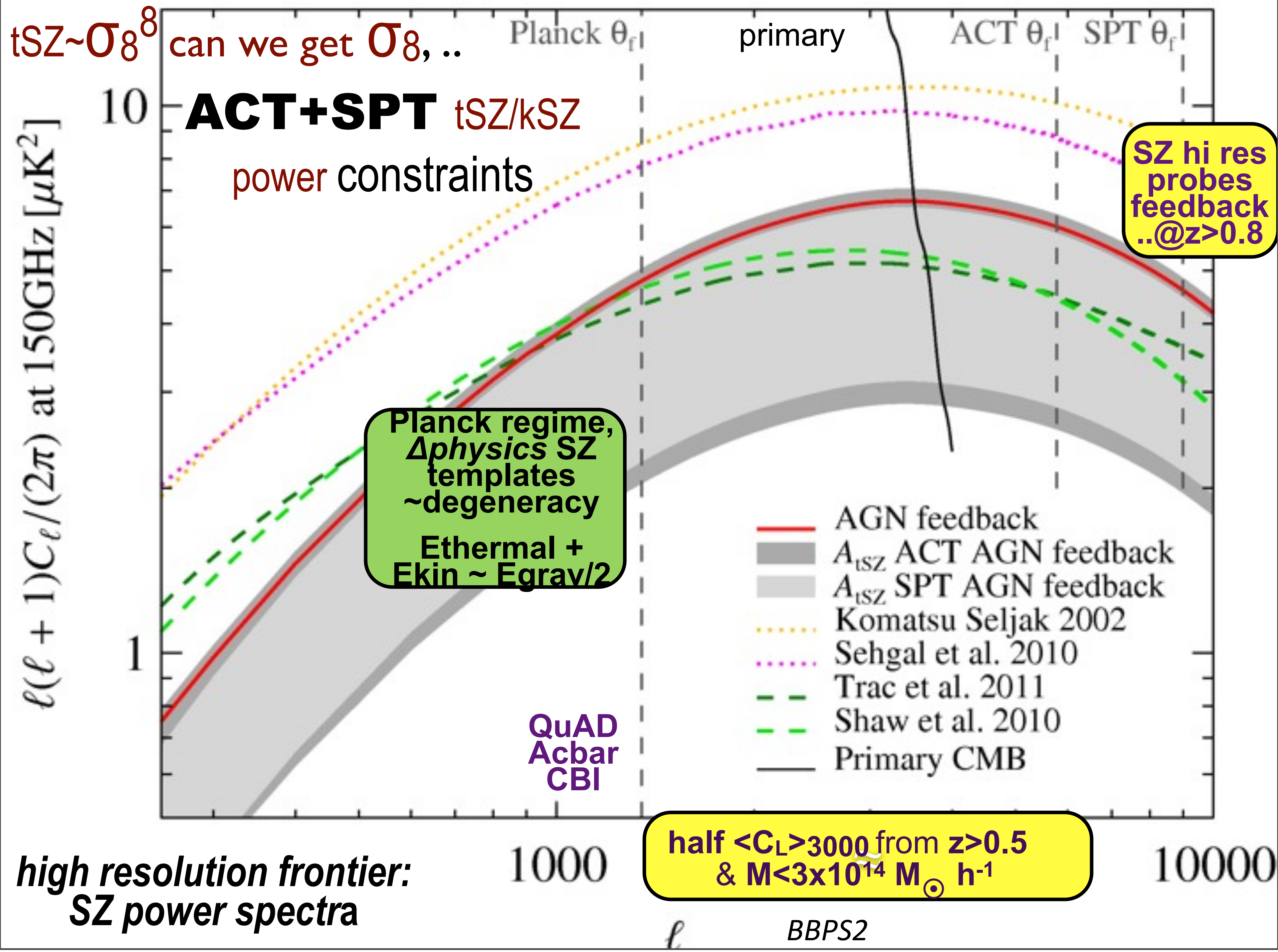
Battaglia, Bond, Pfrommer, Sievers 2011: I,II,III,IV; BBPS+Sijacki 2010



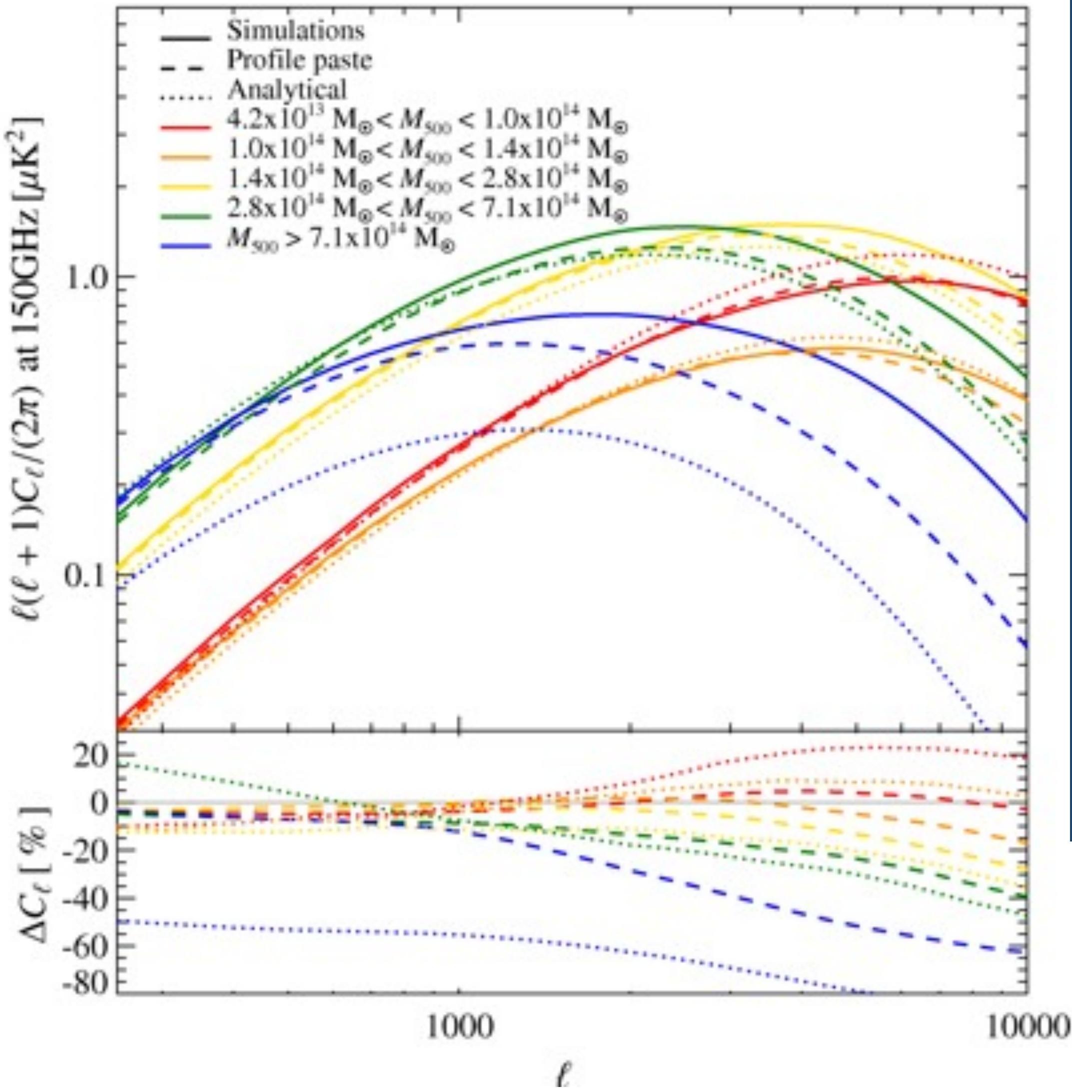


YSZ-M (Planck, ACT) and YX-M (ROSAT) offset when stacked at optical positions (e.g., maxBCG). Optical selection issue? Mx cf. MLens cf. Mbias?...

σ_8SZ a little low cf. $\sigma_8$primary (ACT,SPT) but within ~1 sigma with feedback, KS02-style analytics were way off, corrected in response to our sims, now fully calibrated by us. full ACT data is being analyzed now. Planck CLSZ will come in Jan 2013.


tSZ~σ8^8 can we get σ8, ..
ACT+SPT tSZ/kSZ
power constraints
Planck θf
primary
ACT θf
SPT θf
SZ hi res probes feedback ..@z>0.8
ℓ(ℓ + 1)Cℓ/(2π) at 150GHz [μK²]
10
1
Planck regime, Δphysics SZ templates ~degeneracy
Ethermal + Ekin ~ Egrav/2
QuAD
Acbar
CBI
AGN feedback
AtSZ ACT AGN feedback
AtSZ SPT AGN feedback
Komatsu Seljak 2002
Sehgal et al. 2010
Trac et al. 2011
Shaw et al. 2010
Primary CMB
1000
10000
ℓ
half <CL>3000 from z>0.5
& M<3x10^14 M⊙ h^-1
high resolution frontier:
SZ power spectra
BBPS2

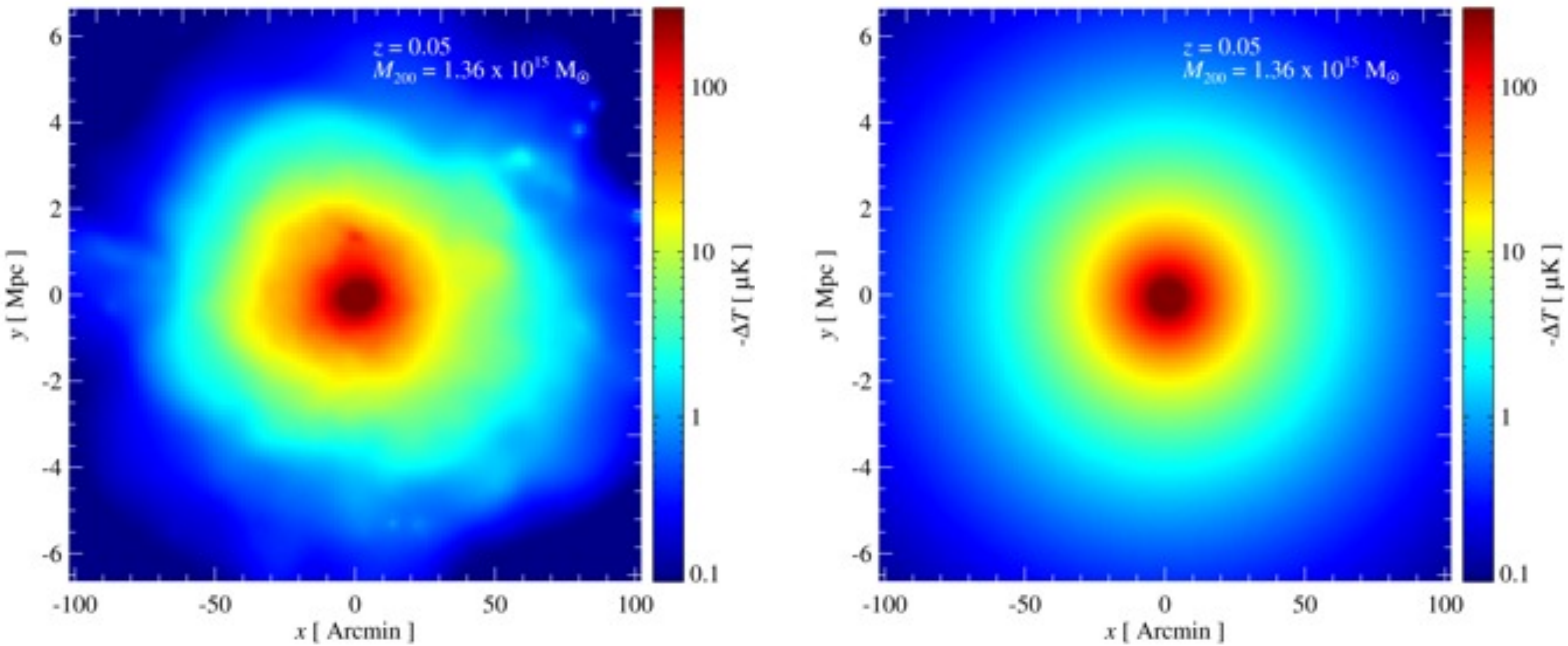
pressure sub-structure contribution to C_L^{SZ}



given the cluster catalogue from sims, paint on spherical GNFW-fit (M,z). good, not perfect.

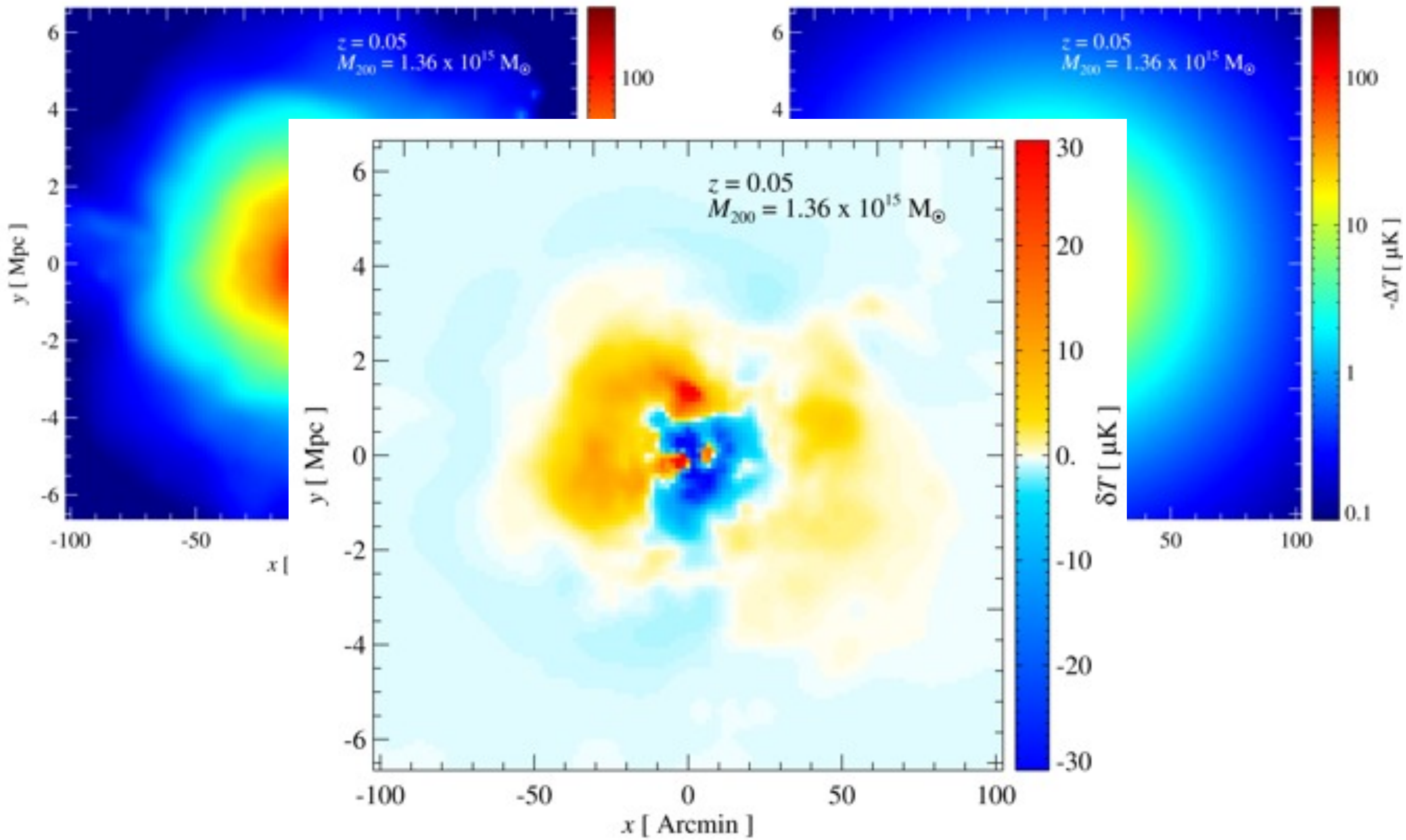
pressure-**sub-structure** the bigger difference cf. full analytics is due to mass function

2D pressure exact vs. fit ➪ pressure sub-structure



Same cluster (pasted on GNFW according to mass) @ 30 GHz, $z = 0.05$ Mass ~10^{15} M_{sun}

2D pressure exact vs. fit ➪ pressure sub-structure



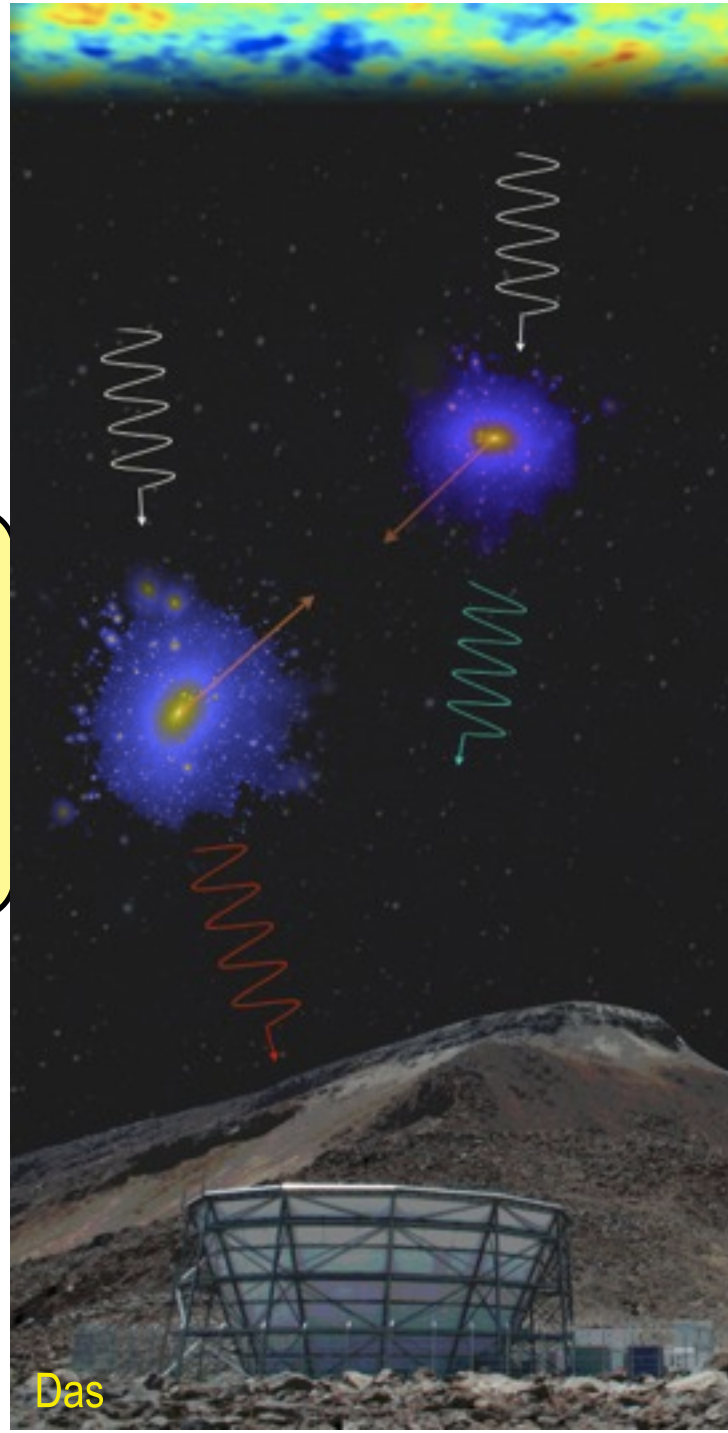
kinetic SZ:

$$\Delta T/T = \int n_e \, \mathbf{v}_{e||} / c \, \sigma_T \, d\,los$$

$$\sim \int J_e \, . \, dr$$

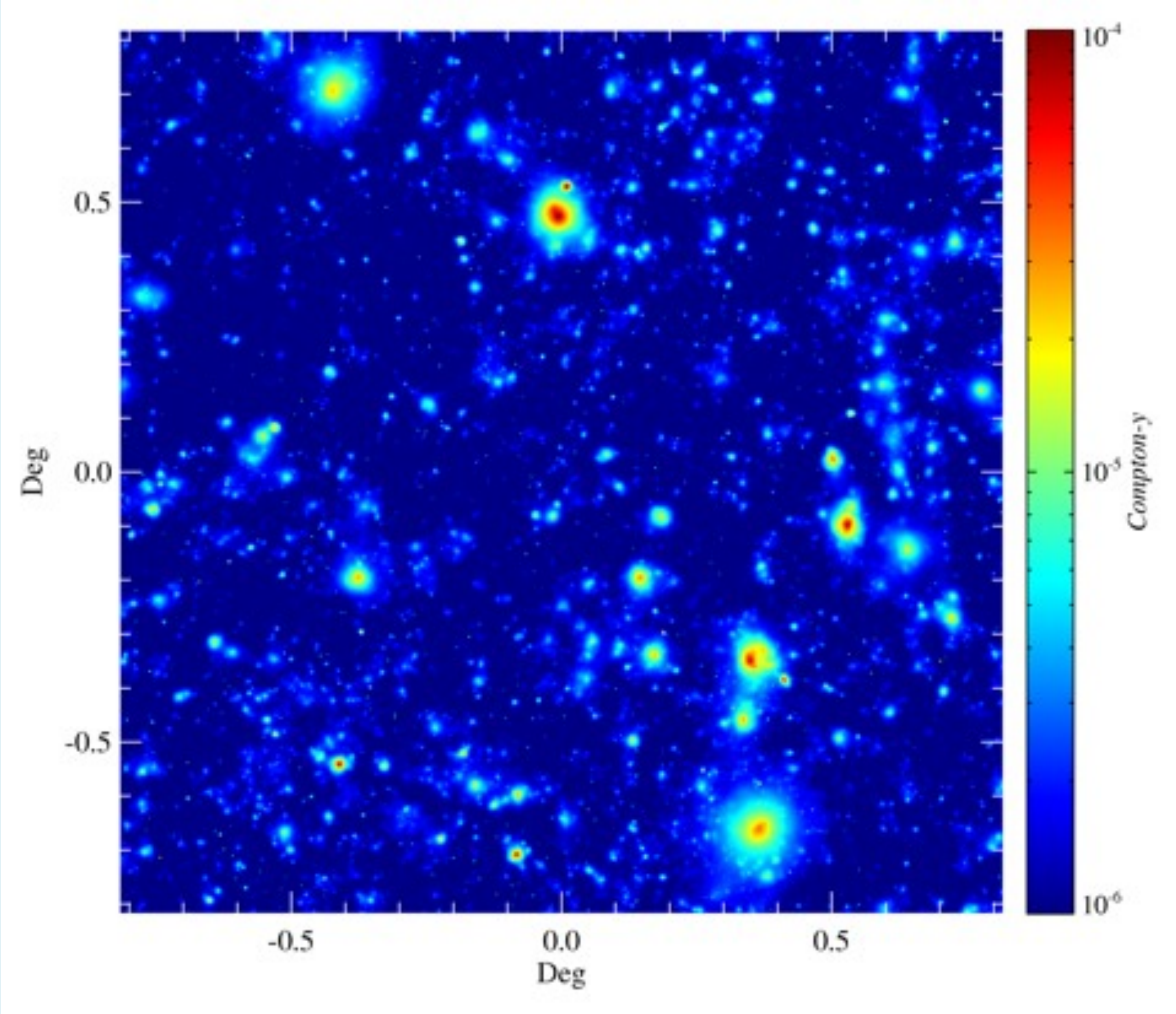
spectrally degenerate with primary anisotropies

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



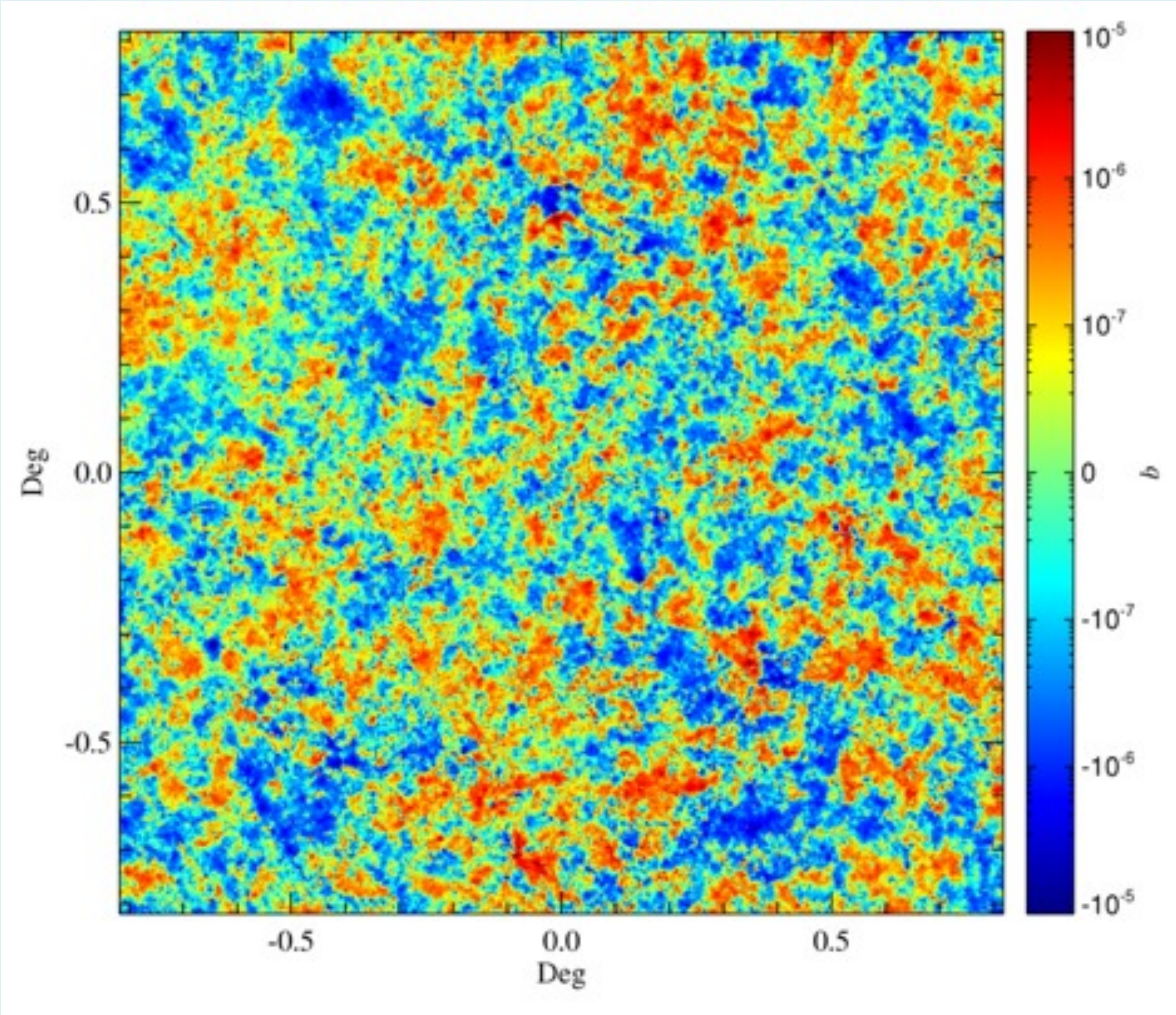
Compton-y map: Feedback

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



kinetic SZ map *(log)*: Feedback

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



kinetic SZ:

$$\Delta T/T = \int n_e \, \mathbf{v}_{e||} /c \, \sigma_T \, dlos$$

$$\sim \int J_e \cdot dr$$

spectrally degenerate with primary anisotropies

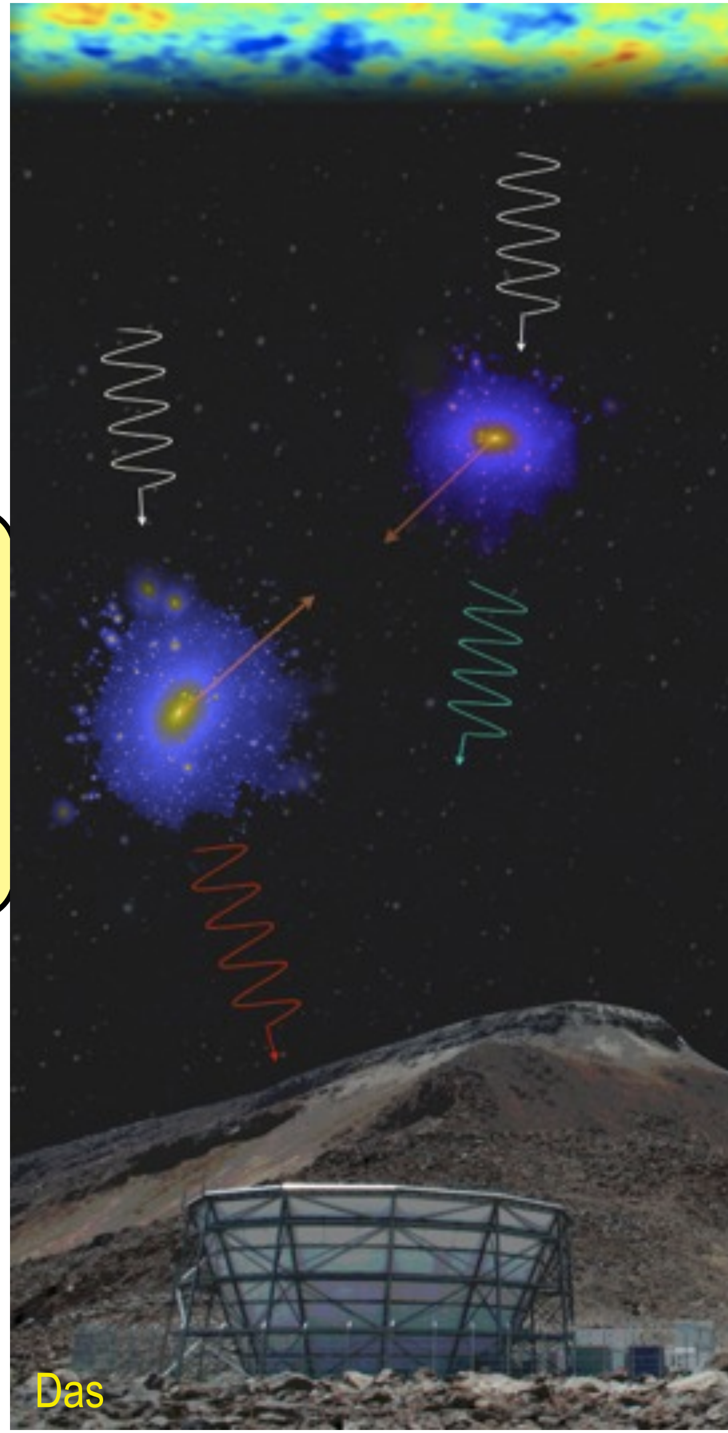
$$\int \mathbf{kSZ}(\theta,\varphi)\mathbf{d\Omega} \sim \mathbf{M_{gas} V_{bulk}} / D_A^2$$

ACT x BOSS direct detection of the kSZ effect:

Hand+ 2012 arXiv/1203.4219 i.e. Mar 20

$<\Delta T \; ng>$ using 7,500 brightest of 27291 luminous BOSS galaxies 220 sq deg overlap with ACT equatorial strip 3x110 sq deg 2008-10 data. <z>~0.5.

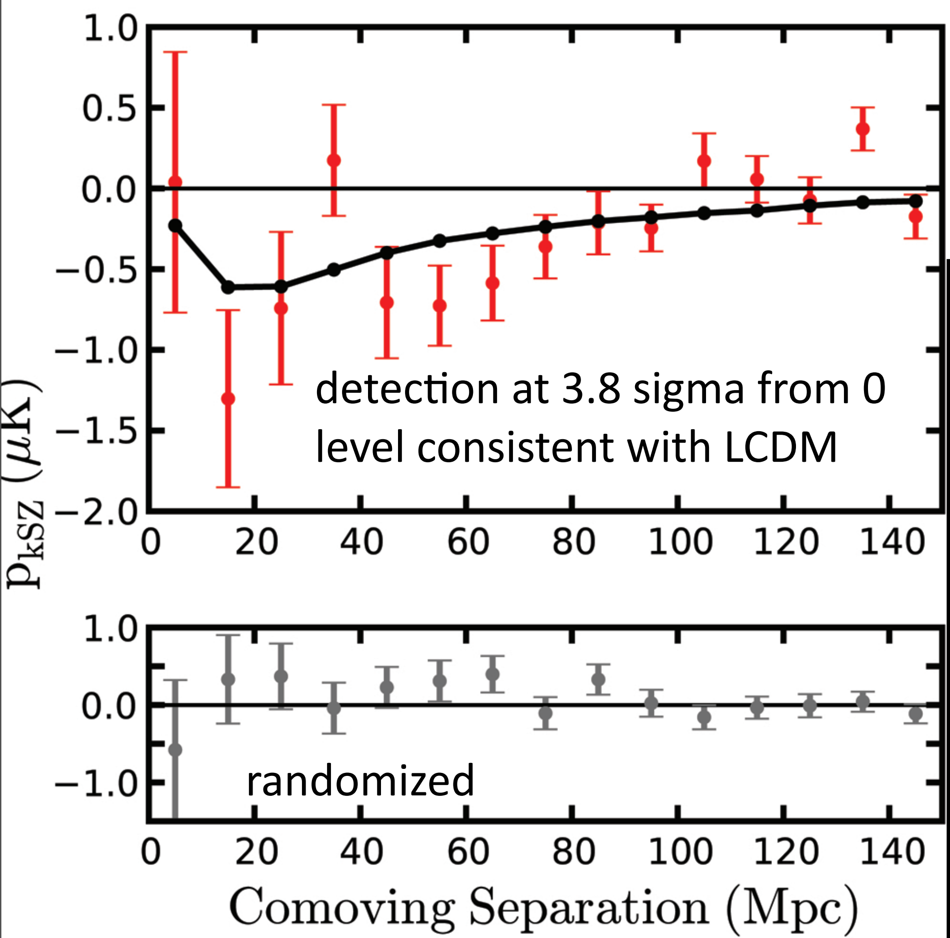
"Like any theoretical scientist proposing an observational effect, I was dreaming for almost 40 years that it would be discovered 'in the next several years,'" Sunyaev said. "It's extremely elegant that the authors were able to choose the most interesting groups of galaxies using the SDSS-III results."



kinetic SZ map *(log)*: Feedback

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

pair-wise velocities (momenta) statistic from **ACT x Opt-Cls/Gps** ~BOSS bright galaxies



$$\tilde{p}_{\rm pair}(r) = \frac{\sum_{i<j}(\mathbf{p}_i \cdot \hat{\mathbf{r}}_i - \mathbf{p}_j \cdot \hat{\mathbf{r}}_j)c_{ij}}{\sum_{i<j} c_{ij}^2}$$

$$c_{ij} \equiv \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2} = \frac{(r_i - r_j)(1+\cos\theta)}{2\sqrt{r_i^2 + r_j^2 - 2r_i r_j \cos\theta}},$$

bulk velocity from **WMAP7 x Xray-Cls**

Kashlinsky, Atrio-Barandela, Kocevski & Ebeling08 reported a ***3σ detection of v ~600 km/s to z=0.3*** towards along *(l,b)*= (267°, 34°). ***the Dark Flow***

Kashlinsky, Atrio-Barandela & Ebeling12 PhysRep

Keisler 09, Osborne+ 10, Zhang & Stebbins 11, & Mody & Hajian 12 (using Planck & Rosat cls) - ***no significant detection of kSZ signal***

Planck x Clusters: ~order of mag sensitivity gain

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

25 years cifar

CITA = Cosmic Information Theory & Analysis:
IT from BIT, from BITs in IT, ***Studying the Cosmic Tango***

Dick Bond

Universe=System+Res =Data+Theory ***en-TANGO-ment***

Revealing the Cosmic Information in Clusters through the Sunyaev-Zeldovich Effect

Compton upscattering of CMB photons is a direct probe of the energy of the gas in gravitationally-collapsed objects ranging from the rarest clusters down to the typical groups. I will talk about our current state of SZ observations and cluster theory. In spite of *the long SZ history*, it has only been in the last few years that ACT and Planck teams, to which I belong, and the SPT team, have delivered impressive SZ results that show this probe is now profoundly augmenting the X-ray, optical galaxy and lensing signatures. To unravel the cosmic implications of the SZ data, the *complexity of the cosmic web's cluster/group patches* must be understood, and this requires a large program of *gastrophysical simulations with energy/entropy feedback*, with special attention to cluster outskirts as well as deep interior, whose conclusions I will describe.

mocking *observations of the cluster/gp system in the cosmic web* SciNet **internal bulk, p-clump, anis, Δphys**
massive non-equilibrium ***rare events at high z*** ***el Gordo++*** *ACT, SPT, Planck, interferometers, Mustang@GBT*
3.8σ direct detection: kinetic SZ effect *of the moving hot gas in the cluster/group system* ***ACTxBOSS***