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***

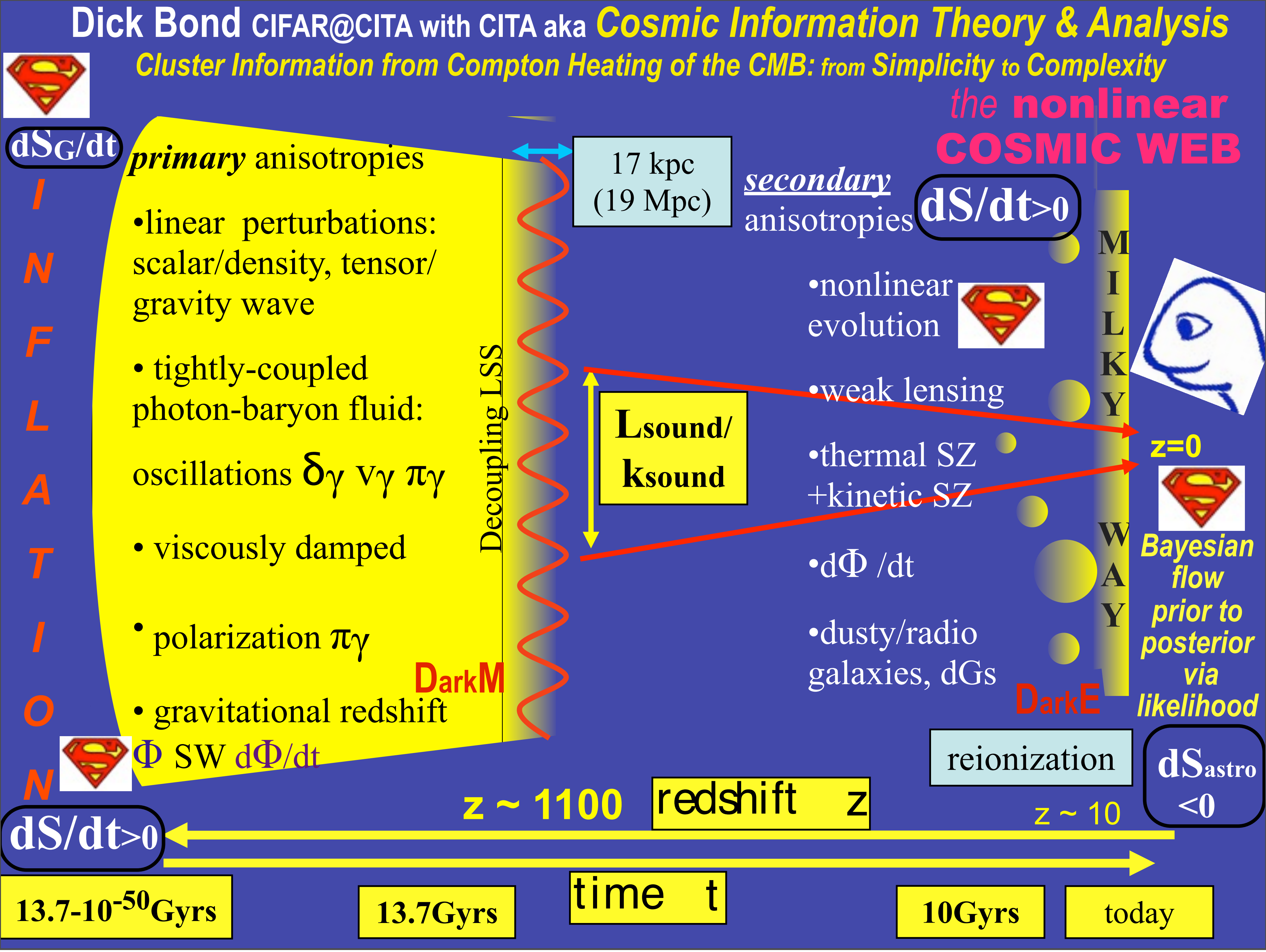
Universe=System+Res =Data+Theory ***en-TANGO-ment***

Dick Bond

Revealing Cosmic Information in Cluster/Group System through the Sunyaev-Zeldovich Effect

Compton upscattering of CMB photons gives a direct probe of the thermal energy of the gas in gravitationally-collapsed nodes of the cosmic web, from the rarest clusters down to the typical groups. I will talk about our current state of cluster theory in relation to SZ observations. In spite of the *long SZ history*, it has only been in the last few years that *ACT, Planck and SPT* have delivered an avalanche of impressive SZ detections 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. *Shannon entropy/information* ideas are used as a theme for this exploration of the non-equilibrium complexity of the cluster/group system.

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*


Dick Bond CIFAR@CITA with CITA aka Cosmic Information Theory & Analysis
Cluster Information from Compton Heating of the CMB: from Simplicity to Complexity
the nonlinear COSMIC WEB
dSG/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
dS/dt>0
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
•dΦ /dt
•dusty/radio galaxies, dGs
DarkE
MILKY WAY
z=0
Bayesian flow prior to posterior via likelihood
reionization
dSastro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
time t
13.7-10^-50Gyrs
13.7Gyrs
10Gyrs
today

fluctuations in the early universe “vacuum” **grow** to ***all*** **cosmic web structure**

$\rho_g(x,t)$

a~1 now

400 Mpc

ΛCDM

WMAP5

gas density

Gadget-3

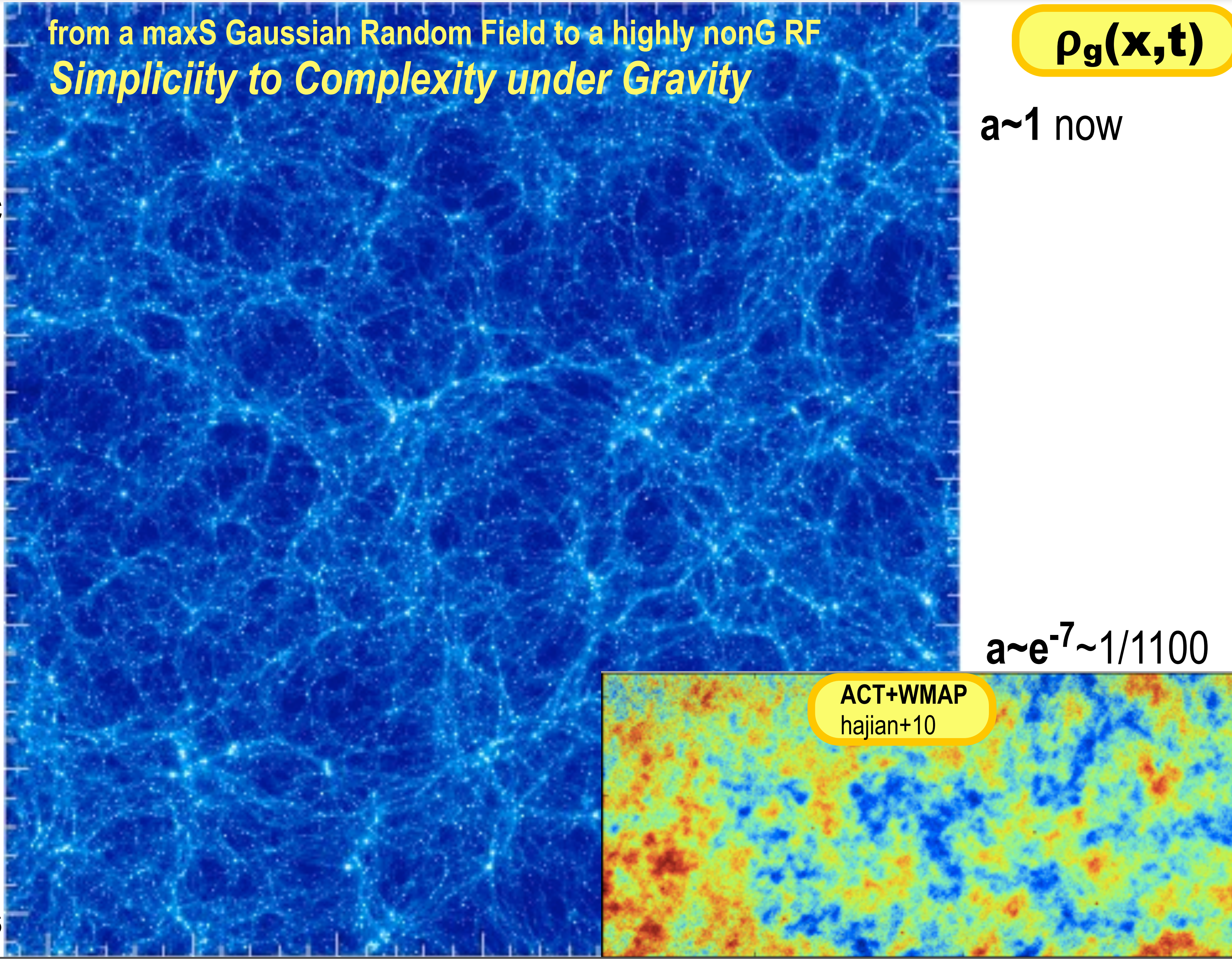
SF+ SN E+ winds +CRs

512^3

BBPSS10

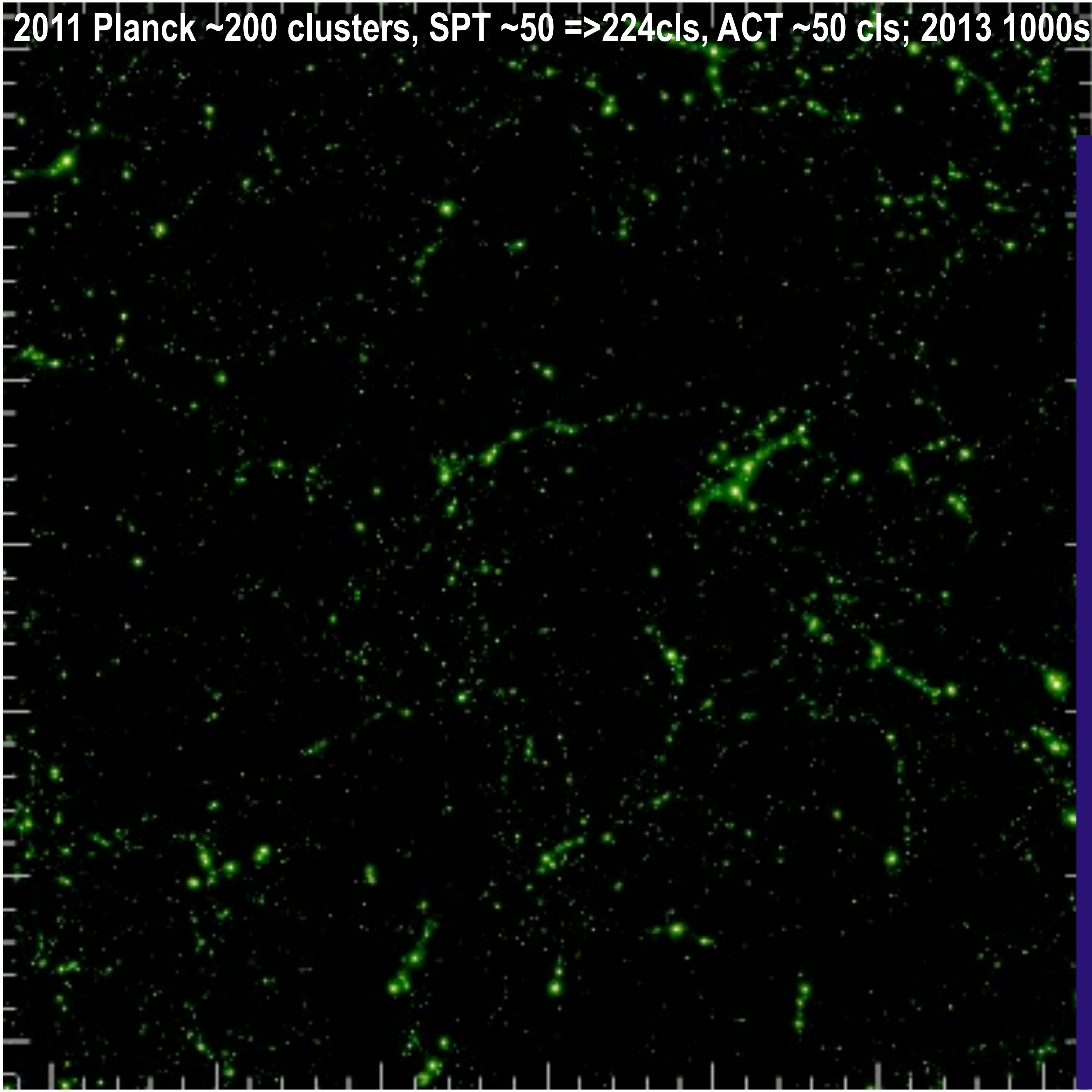
BBPS1,2,3,4,5

a~e^{-7}~1/1100



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

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



$p_e(x,t)$

the thermal Sunyaev Zeldovich Probe

$\gamma + e \rightarrow \gamma + e$ Compton cooling of hot cosmic web gas

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

$$y = \sigma_T \int p_e \, d\text{line-of-sight}$$

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

$$Y_\Delta \sim E_{th} / D_A^2$$

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Secondary Anisotropies
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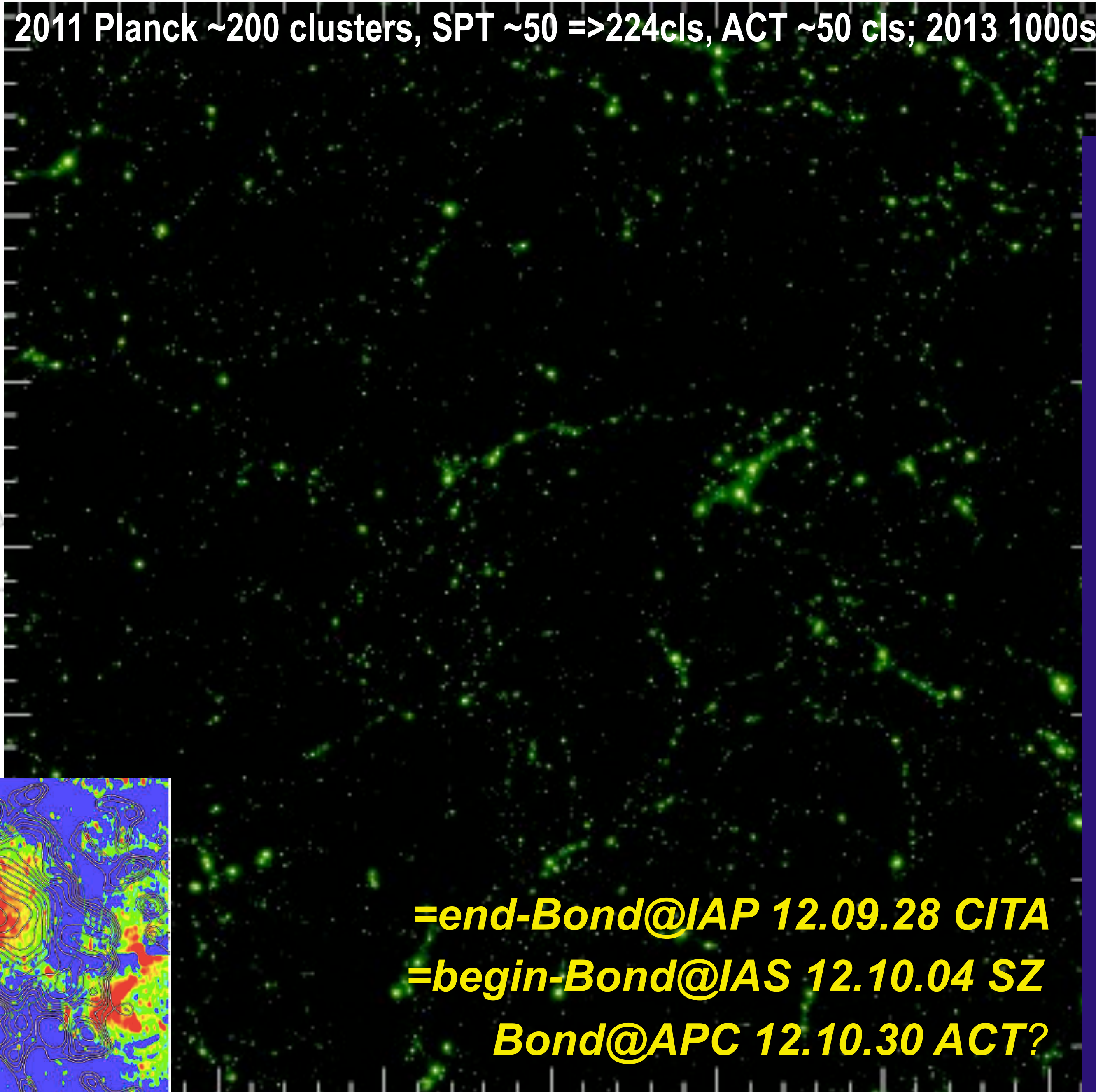

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$<\Delta E_\gamma/E_\gamma>$
$=4T_e/m_ec^2$

$y = \sigma_T \int p_e$ *dline-of-sight*

$\Delta T/T = y *$
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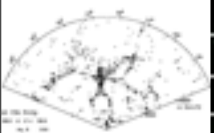
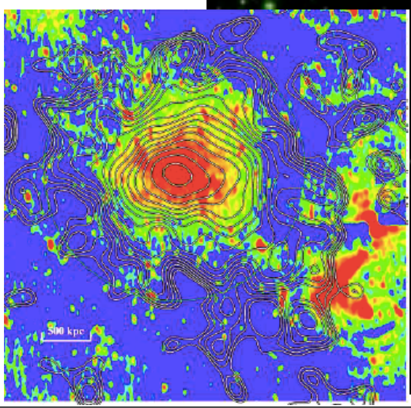
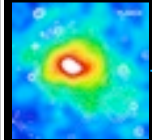


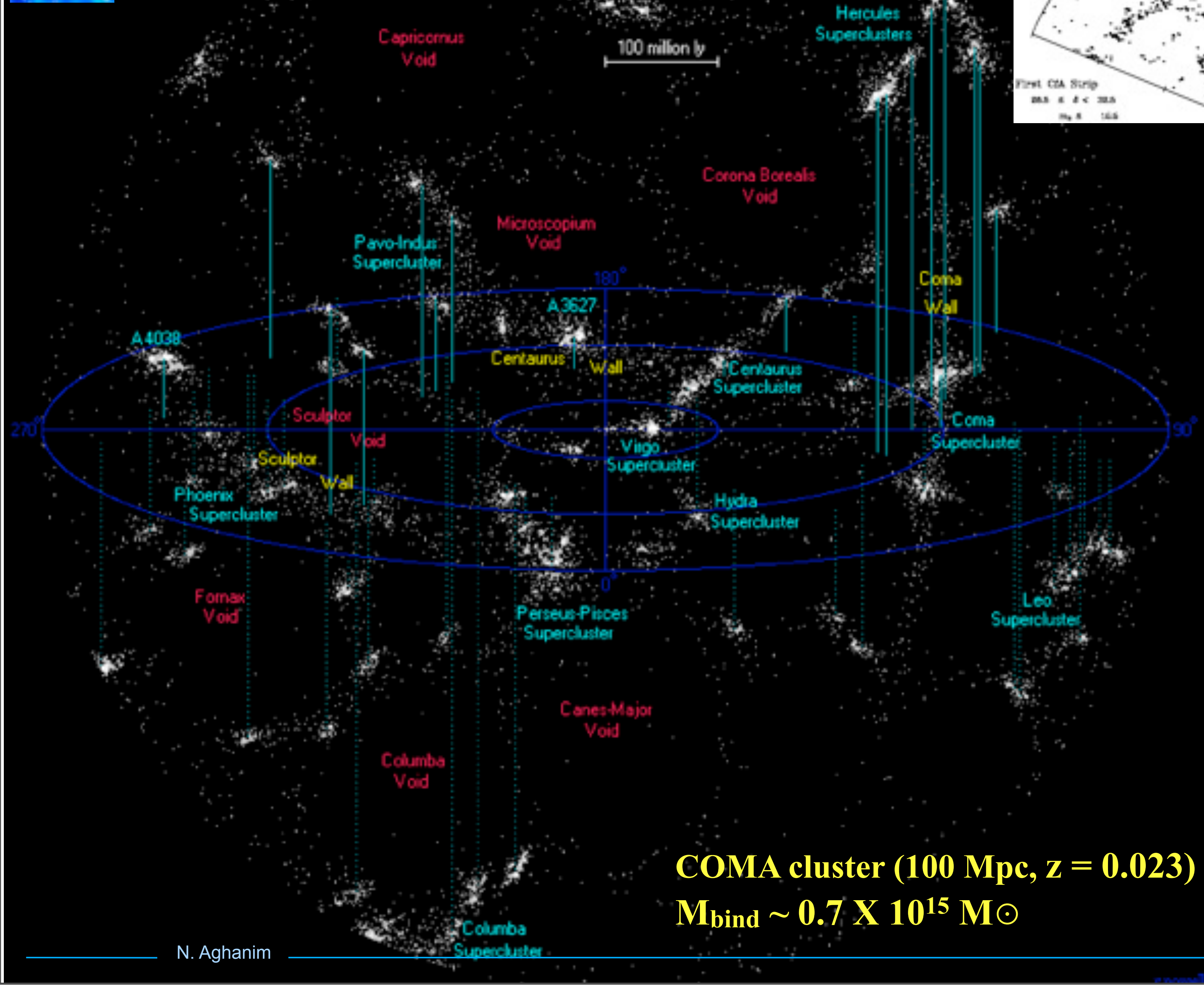
Planck's
Coma
2012.08
pip10

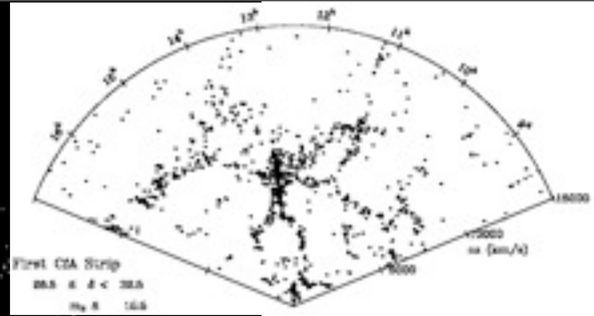


Thursday, 4 October, 12



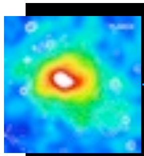
cosmic web of nearby superclusters < 500 M*ly*



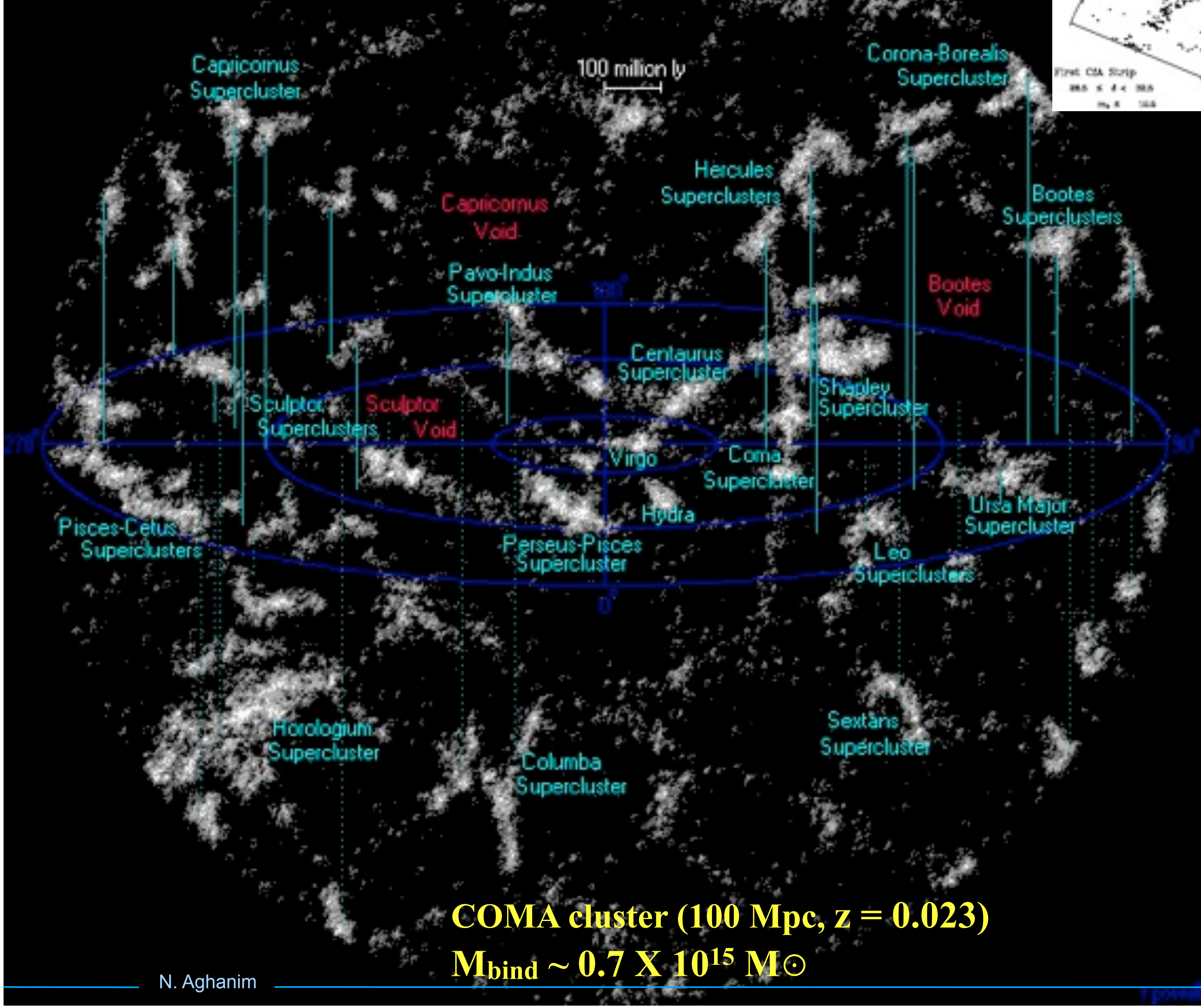


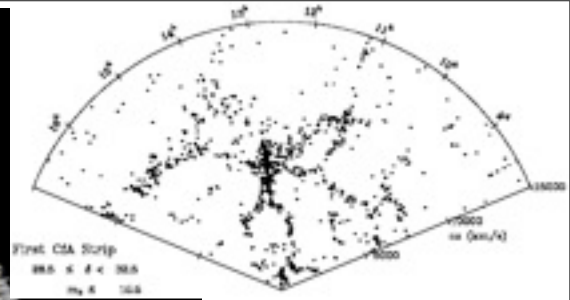
COMA cluster (100 Mpc, z = 0.023)

$M_{bind} \sim 0.7 \times 10^{15}\ M_\odot$



cosmic web of **nearby superclusters < 1000 M*ly***





COMA cluster (100 Mpc, z = 0.023)

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brief ***history*** *of* ***understanding objects*** *& their* ***distribution*** *in the* **cosmic web** *& the* **Sunyaev-Zeldovich** *Probe*

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**

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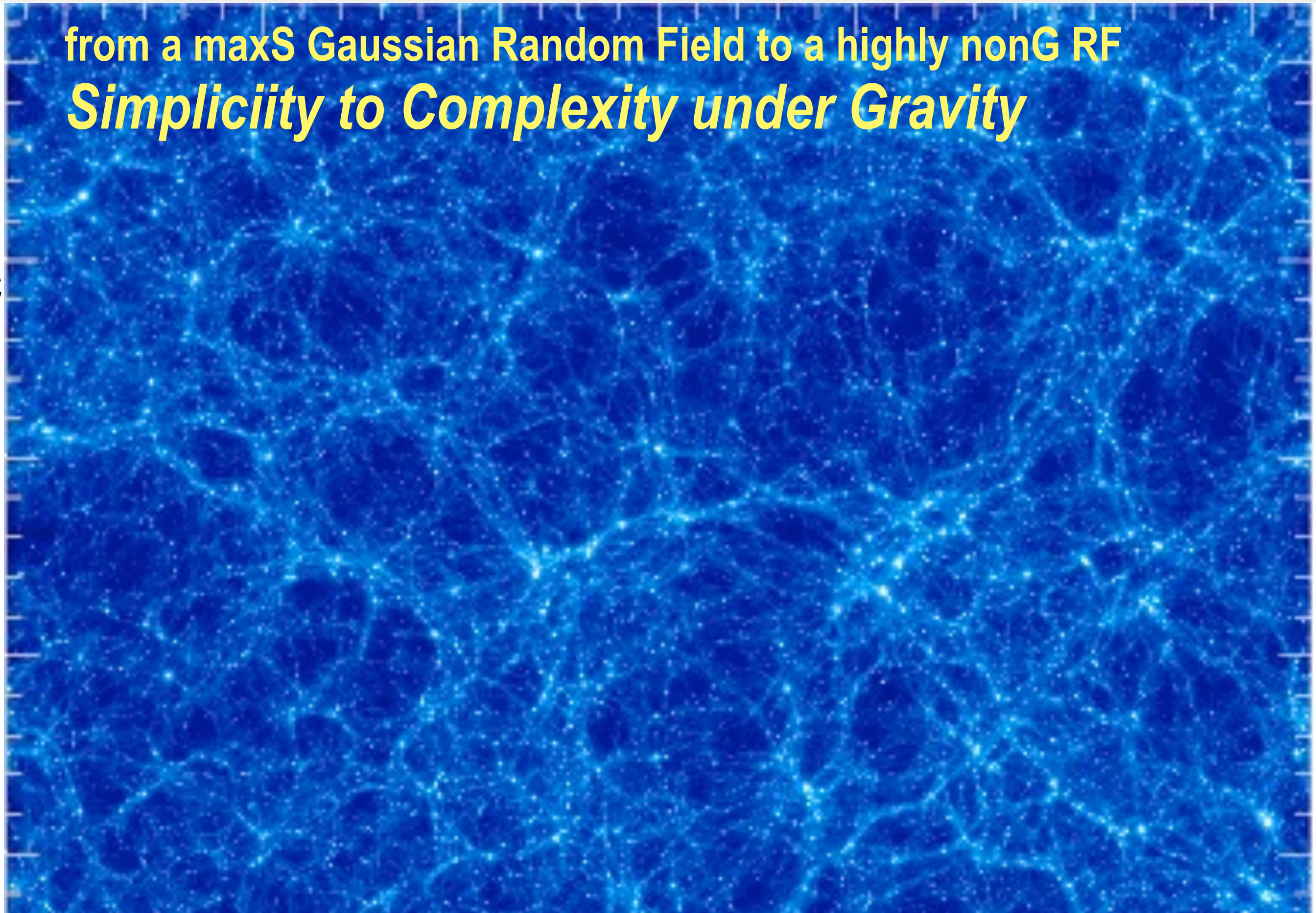
fluctuations in the early universe "vacuum" **grow** to ***all*** **cosmic web structure**



$\rho_g(x,t)$

a~1 now

400 Mpc

ΛCDM

WMAP5

gas density

Gadget-3

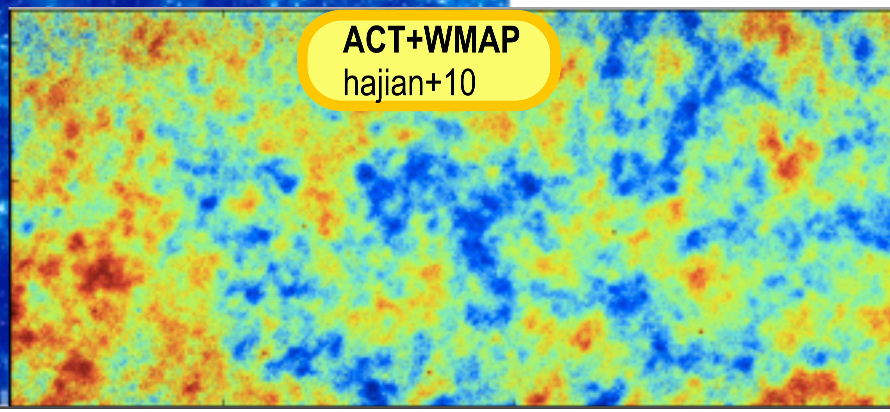
SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4,5

$a \sim e^{-7} \sim 1/1100$



fluctuations in the early universe “vacuum” **grow** to *all* **cosmic web structure**

peak-patches: $\Delta > 100$, *$\ln\rho/\langle\rho\rangle > 2$*, clusters at z ~0-1
are the rare “events” in the medium ⇒ ”intermittency”

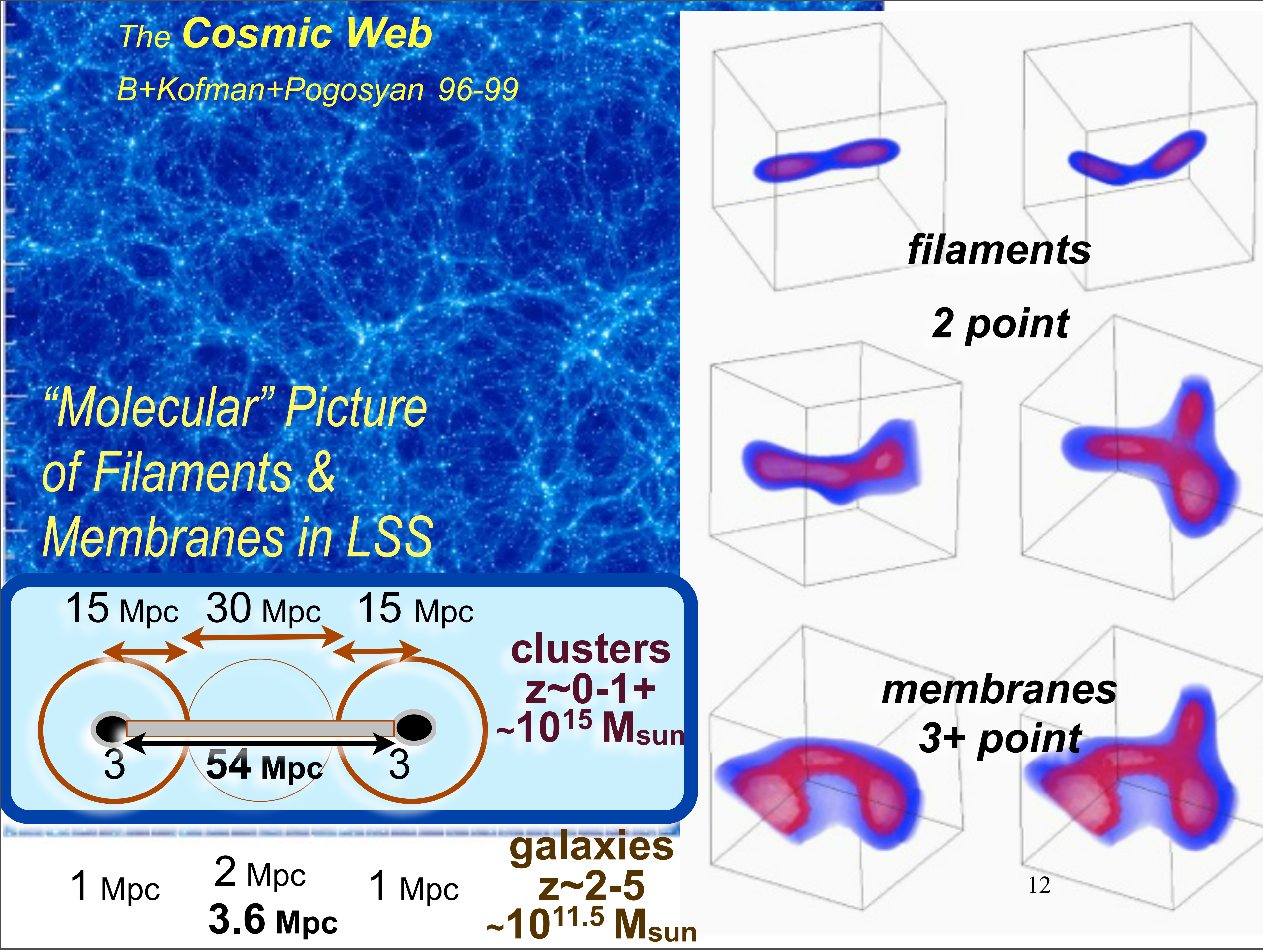
the peak-patches give accurate mass, binding energy, & LSS. *BE / “DM” pressure patches*
initial tidal tensors of the patches orient the web

filaments: $\Delta \sim 5\text{-}10$, *$\ln\rho/\langle\rho\rangle > 2$*, bridge clusters, groups bead the bridges 2-peak constraint of nearly-aligned tidal tensors => **strong bridges**

membranes: $\Delta \sim 2$, *$\ln\rho/\langle\rho\rangle > 1/2$*, intra-filament webbing

3,4,...-peak constraint of “clustering patches’ aka ***superclusters*** ~ *shear-patches*

void-patches: $\Delta < 0.1$ *$\ln\rho/\langle\rho\rangle$-minima*, exact obverse of peak-patches


The Cosmic Web
B+Kofman+Pogosyan 96-99
"Molecular" Picture of Filaments & Membranes in LSS
15 Mpc
30 Mpc
15 Mpc
3
54 Mpc
3
clusters
z~0-1+
~10^15 Msun
1 Mpc
2 Mpc
3.6 Mpc
1 Mpc
galaxies
z~2-5
~10^11.5 Msun
filaments
2 point
membranes
3+ point
12

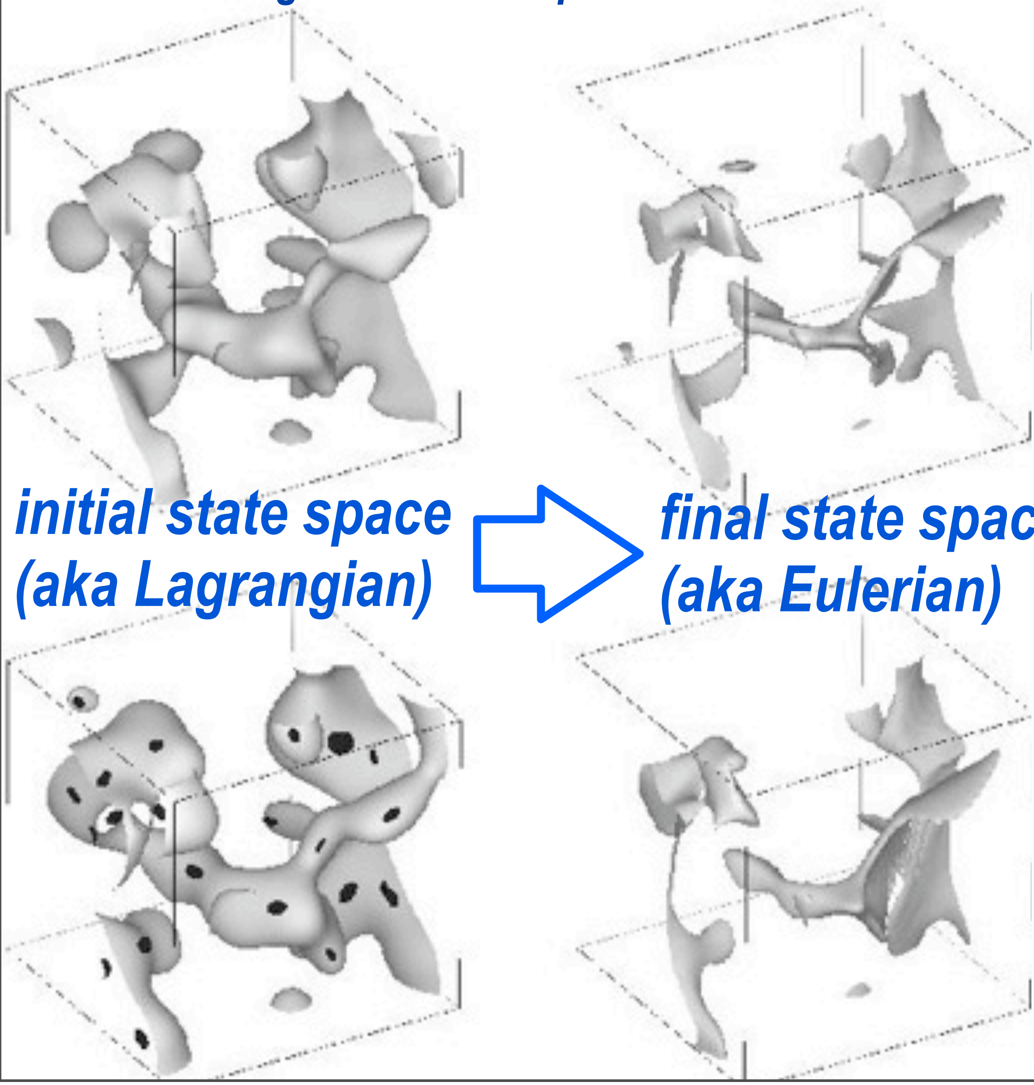
density field **reconstruction** of the filtered web

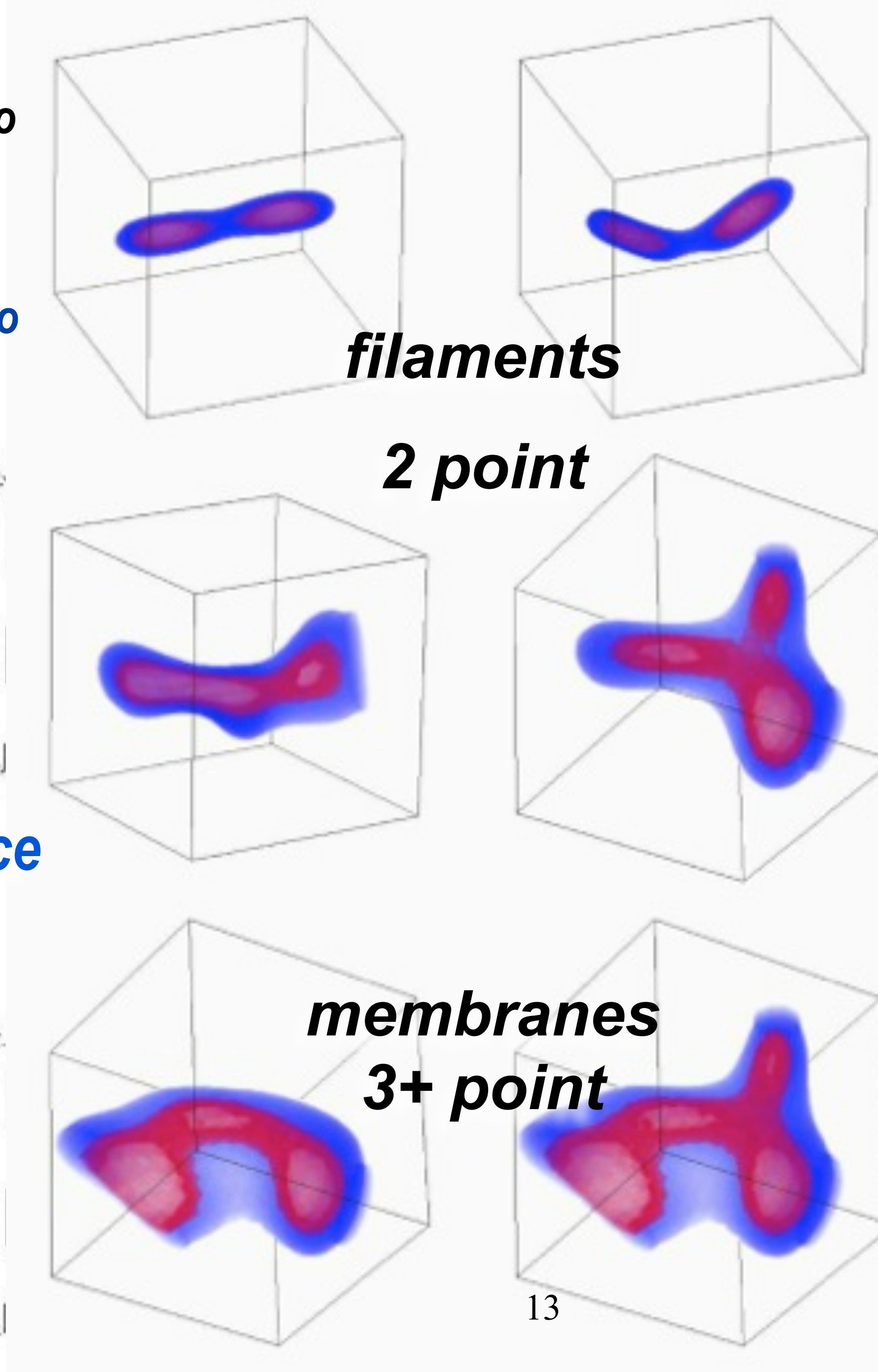
rank-order peak/void-patches(M) minimum info

LSS convergence as N_{patch} increases

InformationQuality: **clusters encode** the web

interior and high resolution spatial detail <=> more info





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

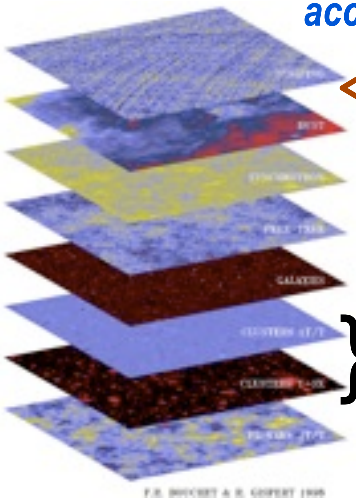
- **very small angle anisotropies** - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- **small angle anisotropies** - current results, optimal measuring strategies, statistical methods for

+ 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 => cosmic web***



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

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

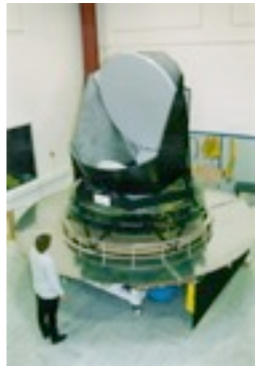
53+35 cls **(>=40)**

QUaD @SP

230 cls (>=1000)

Planck09.4

52+ bolometers
+ HEMTs @L2
9 frequencies



WMAP @L2 **to 2010**

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

2005 2007 **224** (>=750) 2009

Acbar@SP
~1 blind

>96
OVRO /BIMA array
38 cls

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

AMIBA
6 cls

SPT
1000 bolos
@SPole

ACT **23+68~91 cls**
3000 bolos
3 freqs @Chile

AMI
7+1 cls >=50+25

APEX
~400 bolos@Chile
~25 cls

80s-90s
Ryle
OVRO

GBT Mustang
4 cls (~25 CLASH)

SCUBA2
12000 bolos
JCMT @Hawaii

SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico

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

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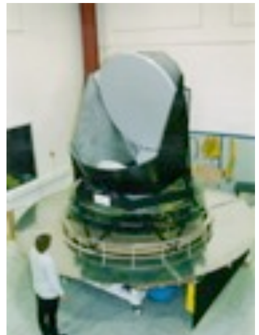

WMAP @L2 **to 2010**

2004 2006 2008

2005 2007

224 (>=750)

New: *Menanteau+12, Hasselfield+12*
ACT Celestial Equator cls, 68 (49+19 in SDSS, half z>.5, 1 z~1.1 $10^{15}M_{sun}$
502 sq deg =>*91 in* *952 deg², 0.1<z<1.3*

100% purity for S/N>5. 60% > 4.5

No significant evidence of SZ/BCG offset
M_{SZ}-N_{200} weak correlation, large scatter

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~1 blind

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6 cls

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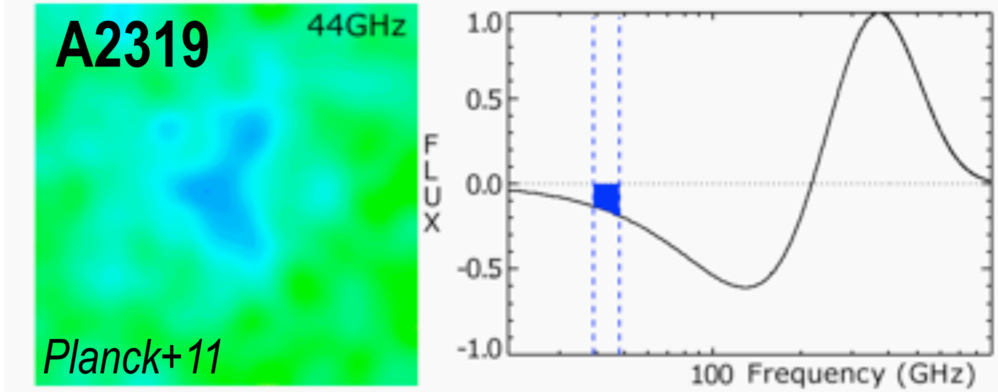
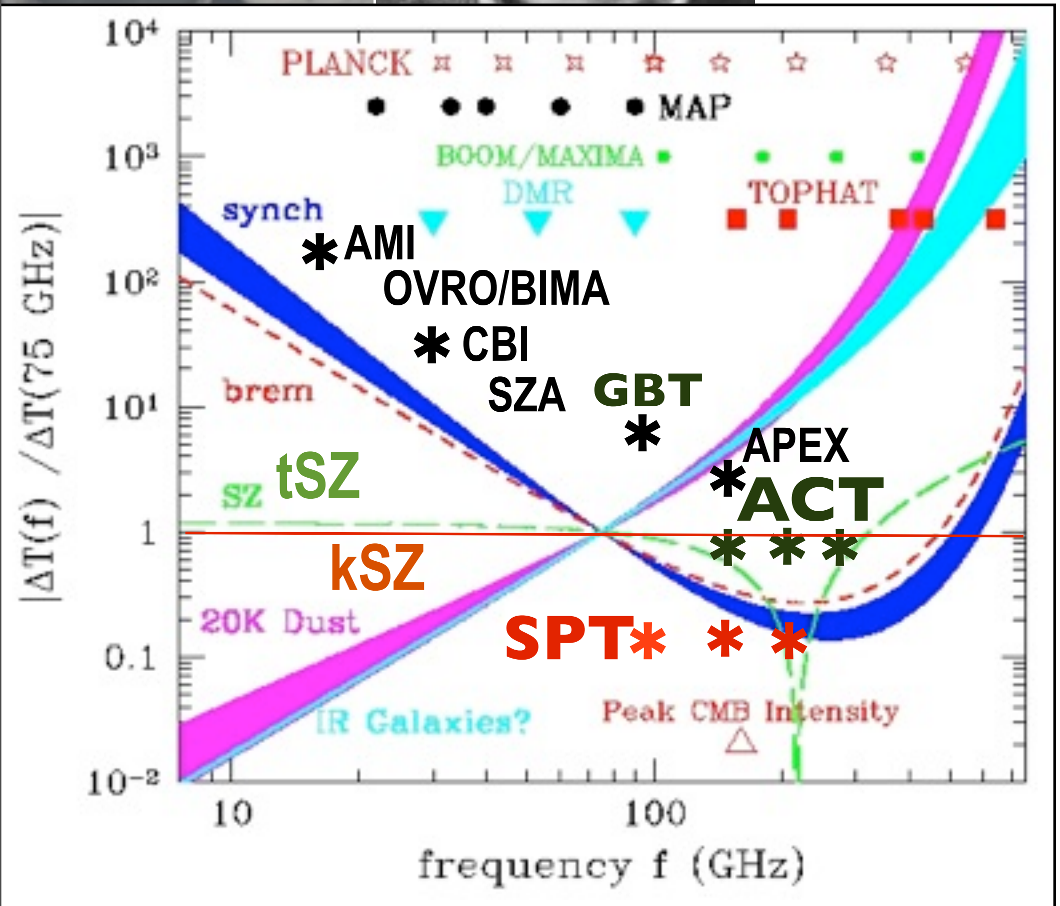
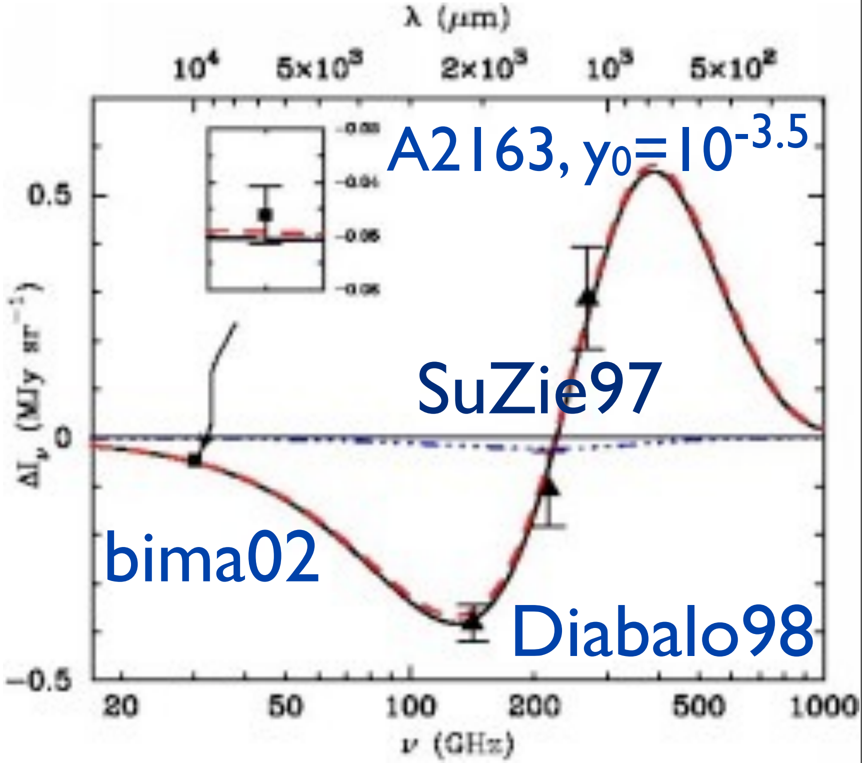


$\Delta T/T = y * (x(e^x+1)/(e^x-1)-4),\ x = h\nu/T_\gamma$

$= -2y$ to xy, 0 @ ν=217 GHz

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

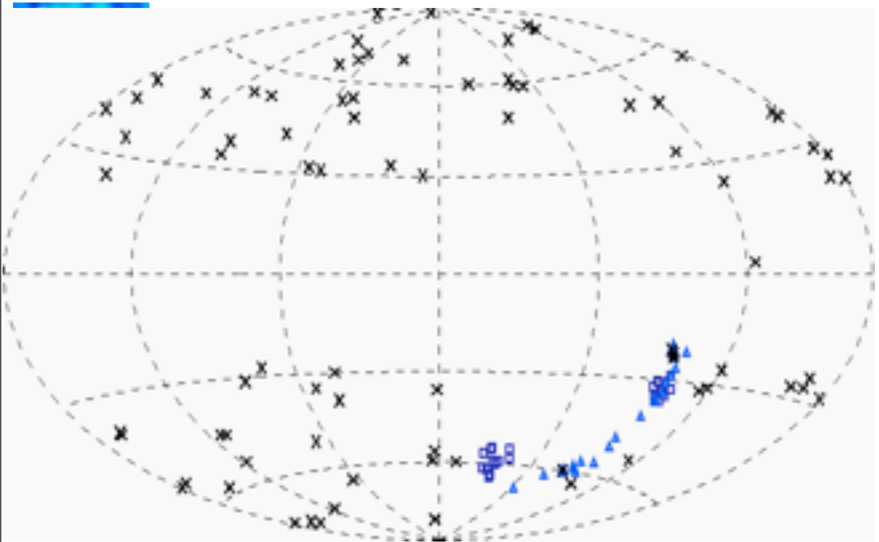




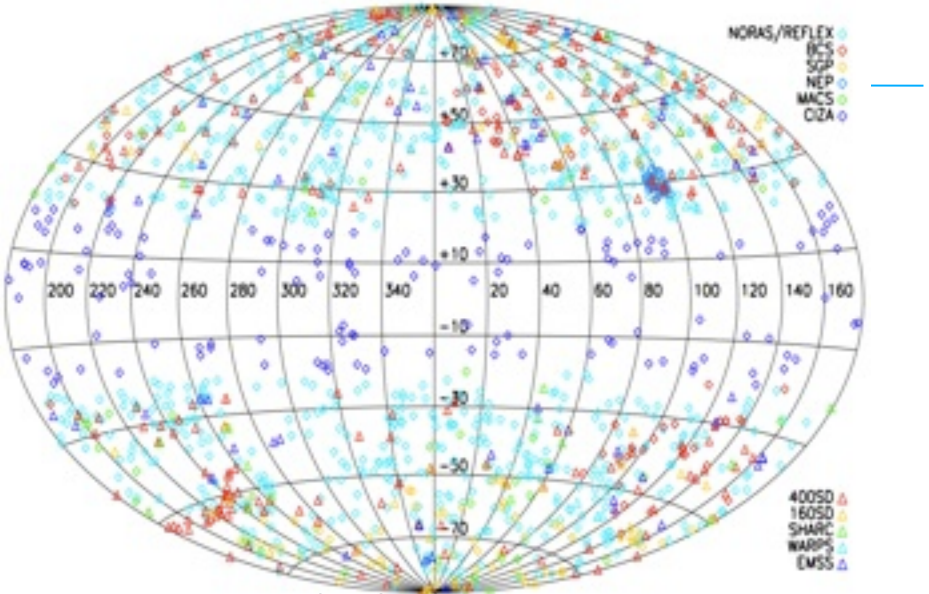
the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

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.

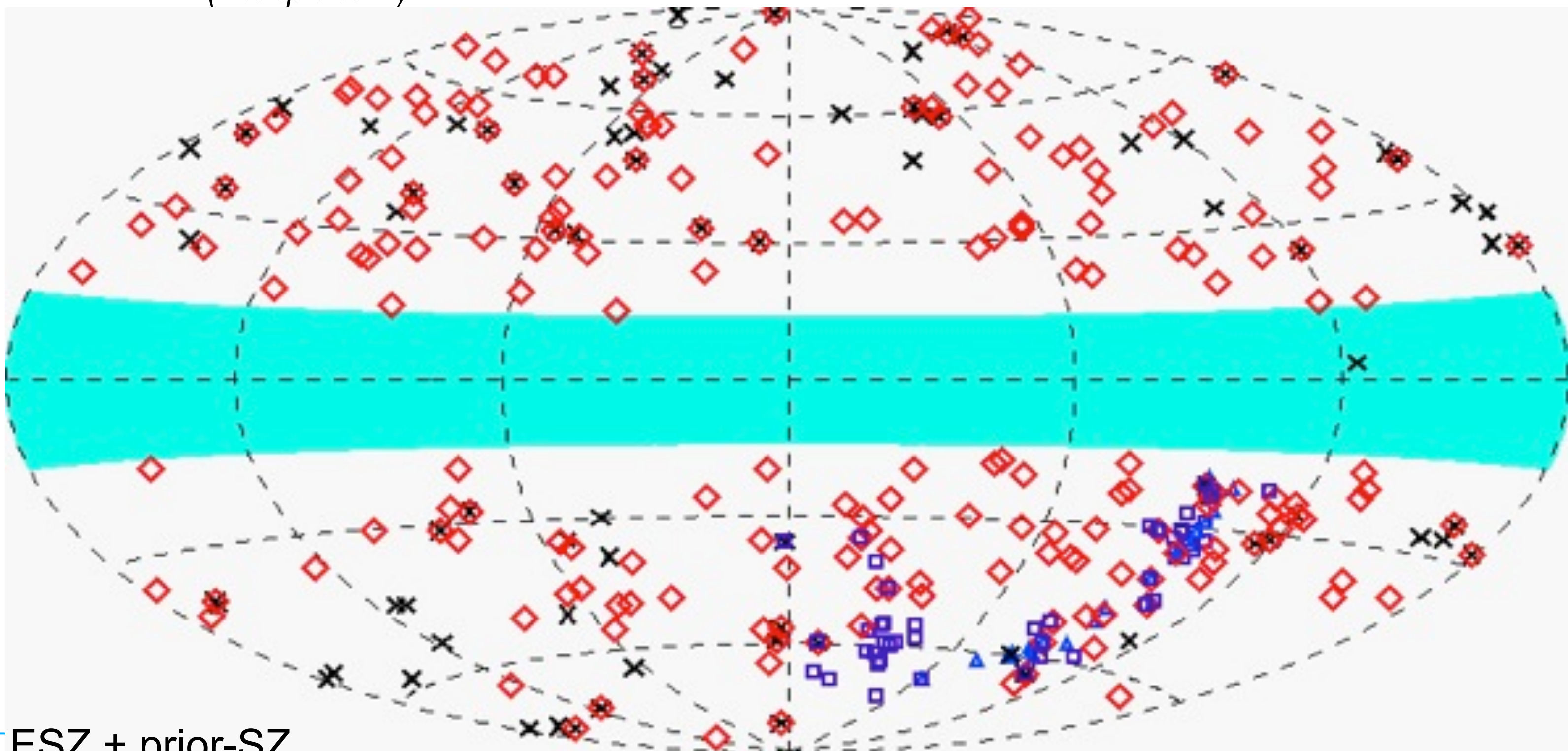
Bond since 1993, Canada since 2001, 1st CSA pre-launch contract 2002-09, post-launch 2010-11, 2011-13



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

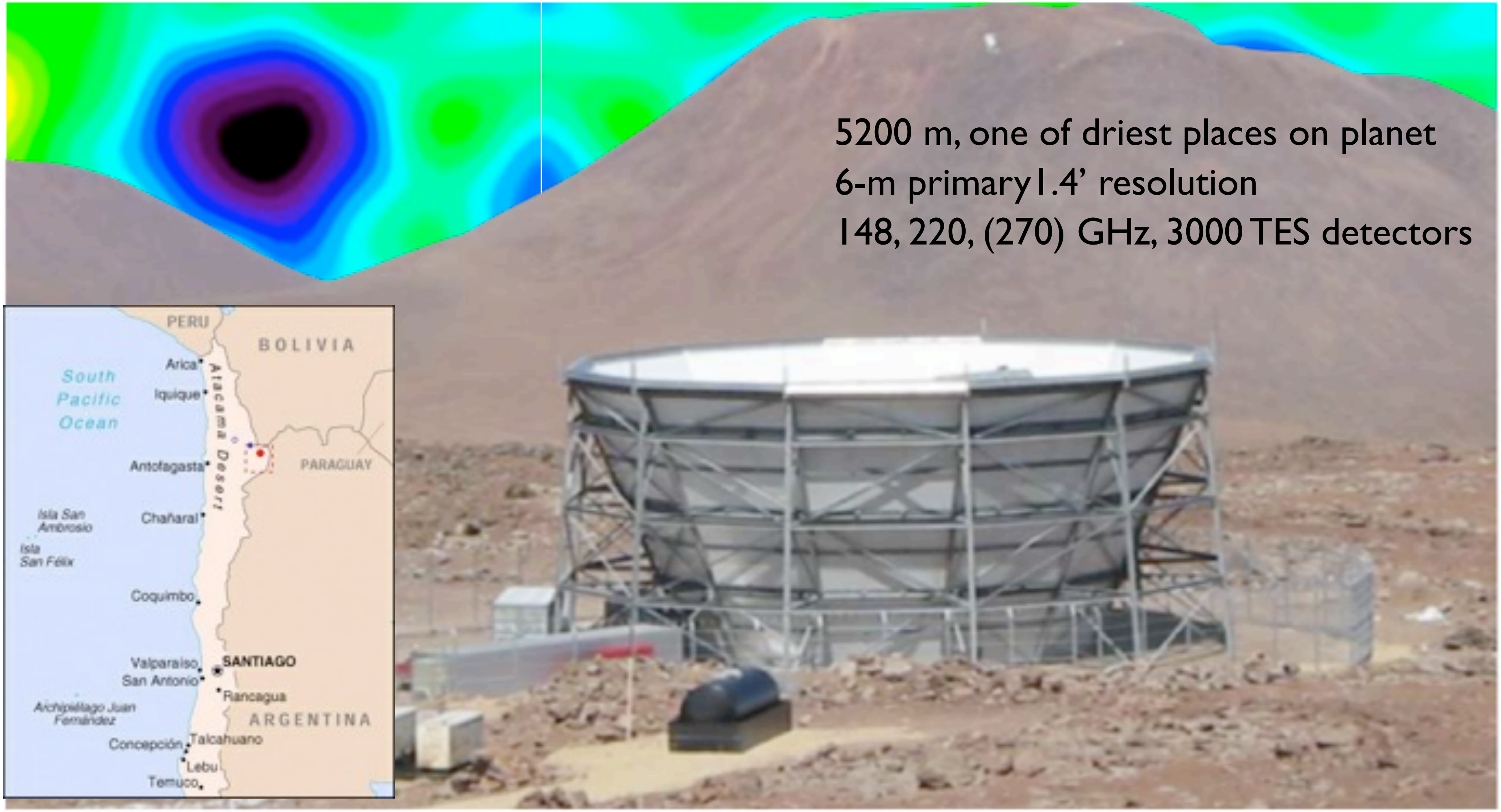


All-sky distribution of MCXC clusters ~1600 *(Piffaretti et 10)*



Planck ESZ + prior-SZ

Cosmology From 17,000 Feet:
Results From the Atacama Cosmology Telescope



CITA–ICAT

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]
* N. Battaglia [8]
* 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 [6,8]
M. Halpern [5]
M. Hasselfield [5]
C. Hernandez-Monteagudo [13,2]
G. Hilton [11]
M. Hilton [14, 15]
* A. D. Hincks [6,8]
R. Hlozek [12, 1]
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 [8,6]
D. Spergel [1]
S.T. Staggs [6]
O. Stryzak [6]
D. Swetz [2]
* E. Switzer [23,6,8]
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]

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[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)
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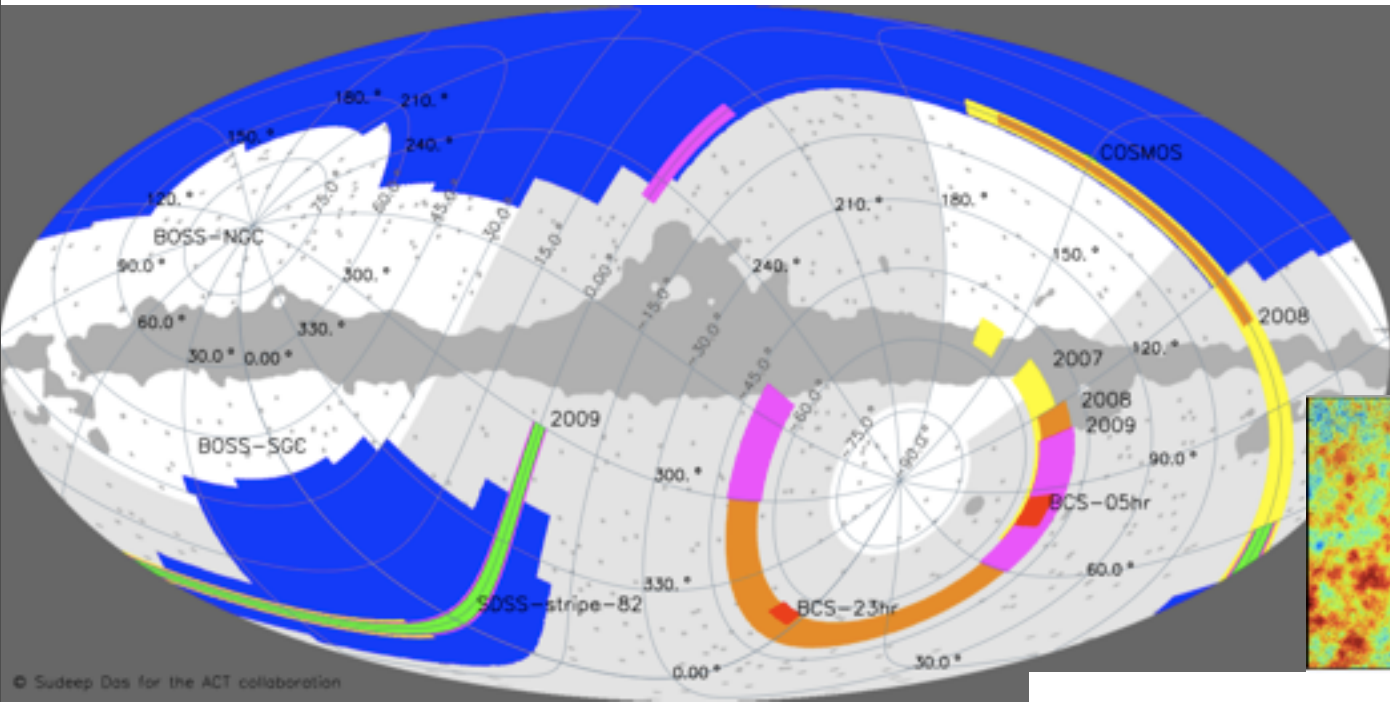
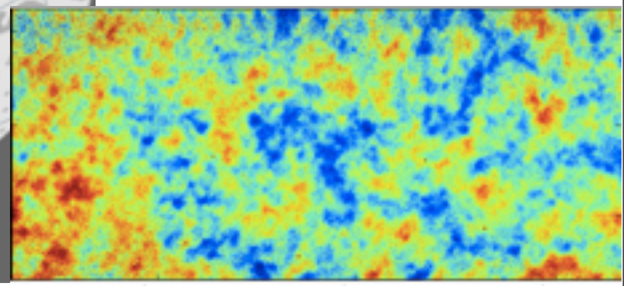
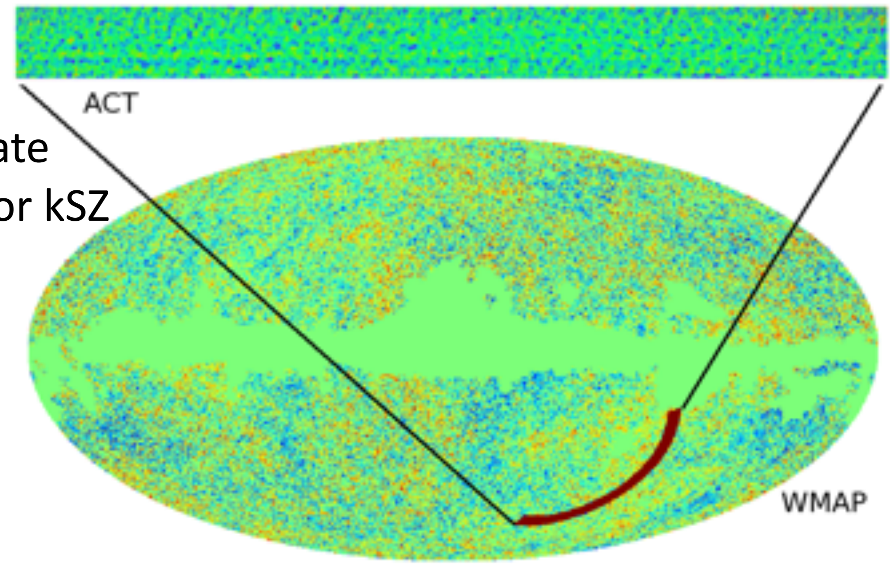
[21] Columbia University (USA)
[22] IPMU (Japan)
[23] KICP, Chicago (USA)
* [24] University of Toronto (Canada)
[25] Haverford College (USA)
[26] West Chester University of Pennsylvania (USA)
[27] Harvard-Smithsonian CfA (USA)
[28] University of Massachusetts, Amherst (USA)
[29] BCCP UC Berkeley and LBL (USA)

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

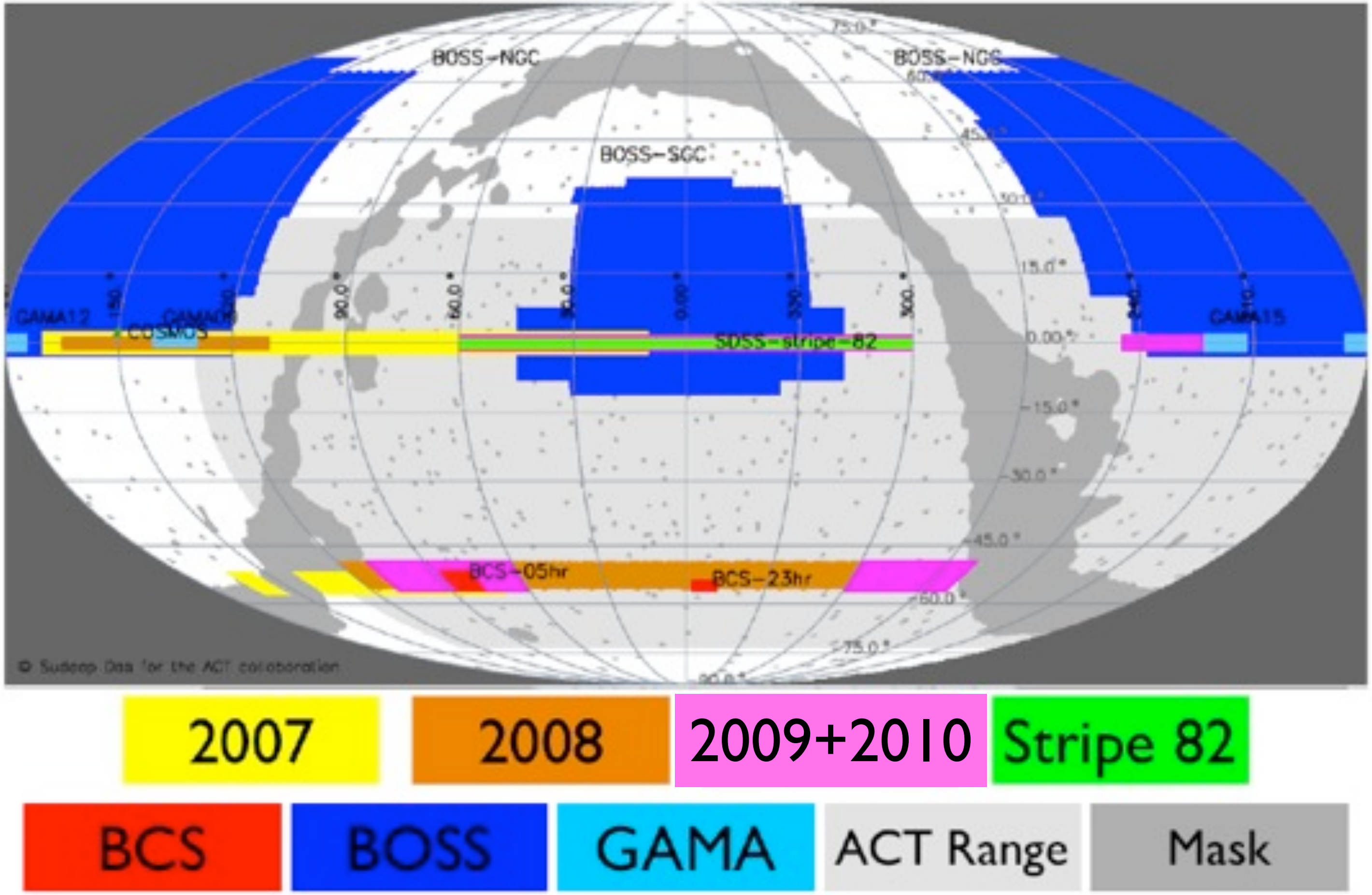


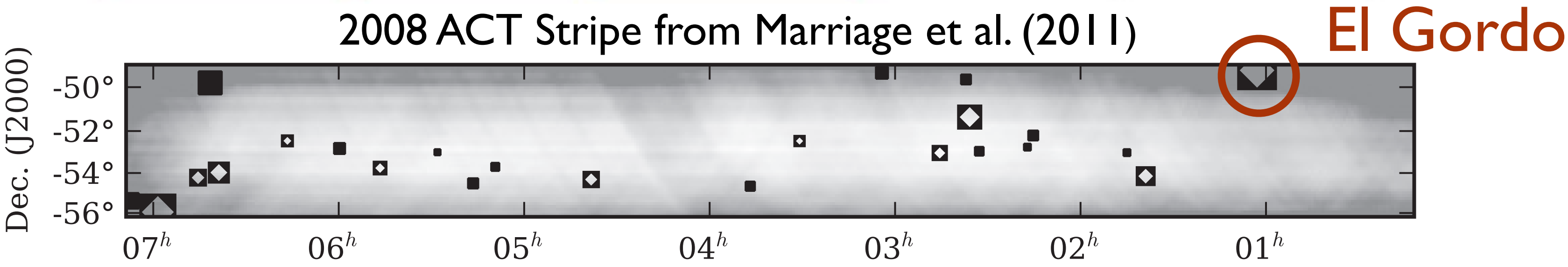

Hajian et al (2010)

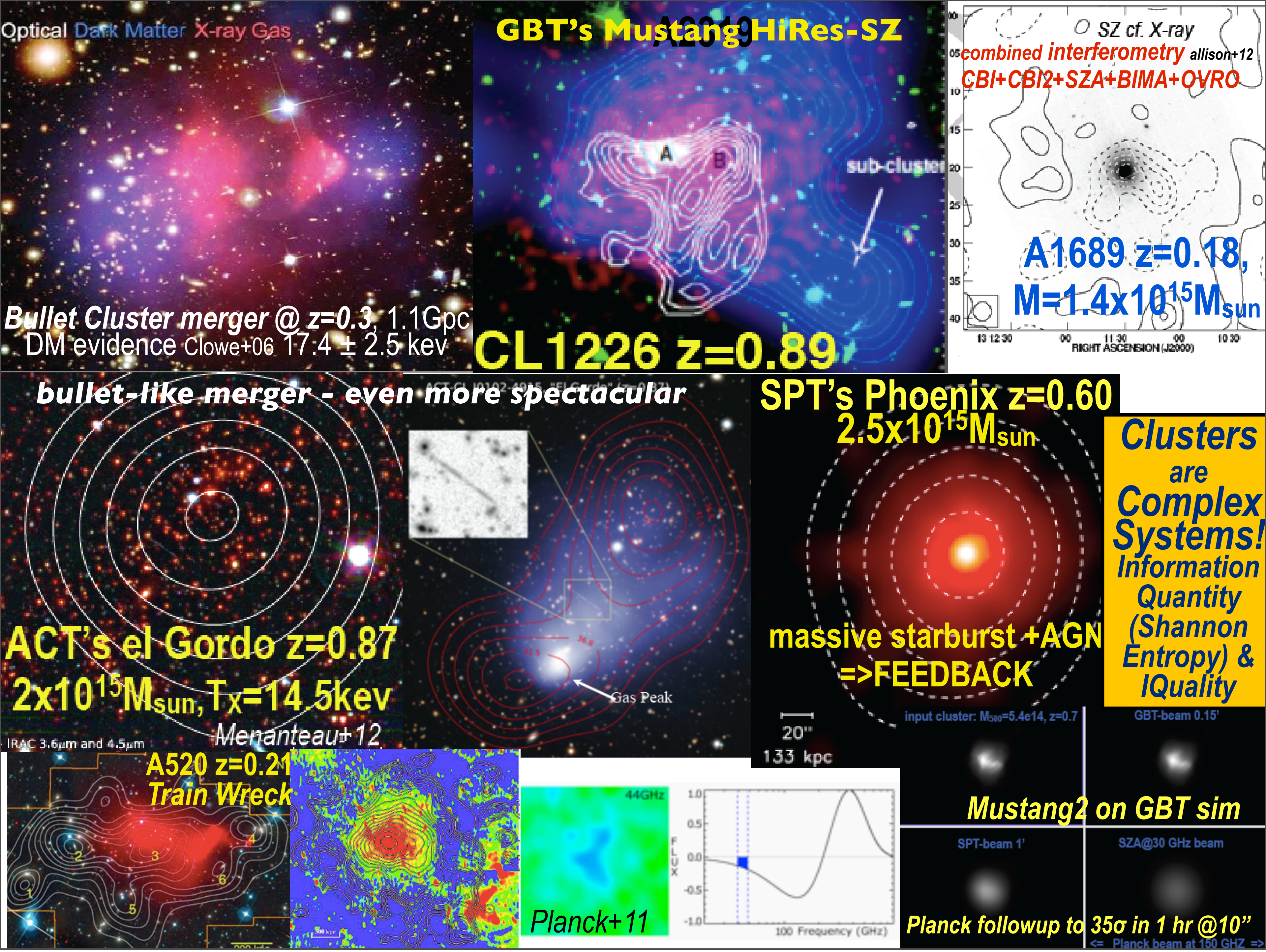


<ACT SZ x other data (opt, X, submm)>, ... X correlate overlaps SDSS III BOSS in the ACT equatorial strip, for kSZ

end observing 2011: ACT completed 3 full seasons, over ~1300 deg^2, maps@CITA.
next step is ACTpol >= 2013






Optical Dark Matter X-ray Gas
Bullet Cluster merger @ z=0.3, 1.1Gpc
DM evidence Clowe+06 17.4 ± 2.5 kev
GBT's Mustang HiRes-SZ
A2019
A
B
sub-cluster
CL1226 z=0.89
SZ cf. X-ray
combined interferometry allison+12
CBI+CBI2+SZA+BIMA+OVRO
A1689 z=0.18,
M=1.4x10^15 M_sun
RIGHT ASCENSION (J2000)
bullet-like merger - even more spectacular
ACT's el Gordo z=0.87
2x10^15 M_sun, Tx=14.5kev
Menanteau+12
IRAC 3.6μm and 4.5μm
Gas Peak
SPT's Phoenix z=0.60
2.5x10^15 M_sun
massive starburst +AGN
=>FEEDBACK
20"
133 kpc
Clusters
are
Complex
Systems!
Information
Quantity
(Shannon
Entropy) &
IQuality
A520 z=0.21
Train Wreck
44GHz
Planck+11
FLUX
100 Frequency (GHz)
input cluster: M500=5.4e14, z=0.7
GBT-beam 0.15'
Mustang2 on GBT sim
SPT-beam 1'
SZA@30 GHz beam
Planck followup to 35σ in 1 hr @10"
<= Planck beam at 150 GHZ =>

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: ΔE_{inj} ~ $\varepsilon \Delta t$ 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

TBD: momentum feedback, relativistic energy/pressure feedback (magnetic fields, cosmic rays)

conclusion circa 2012: ∄ universal panacea *to cure cluster cores: highly inhomogeneous, episodic & cluster-history-dependent. if observables are overly sensitive, 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 ~$3R_{200}$ ⇒ different non-thermal problems: kinetic pressure aka turbulence/internal-bulk-flows, 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, ...***

fluctuations in the early universe “vacuum” **grow** to *all* **cosmic web structure**

400 Mpc

ΛCDM

WMAP5

gas density

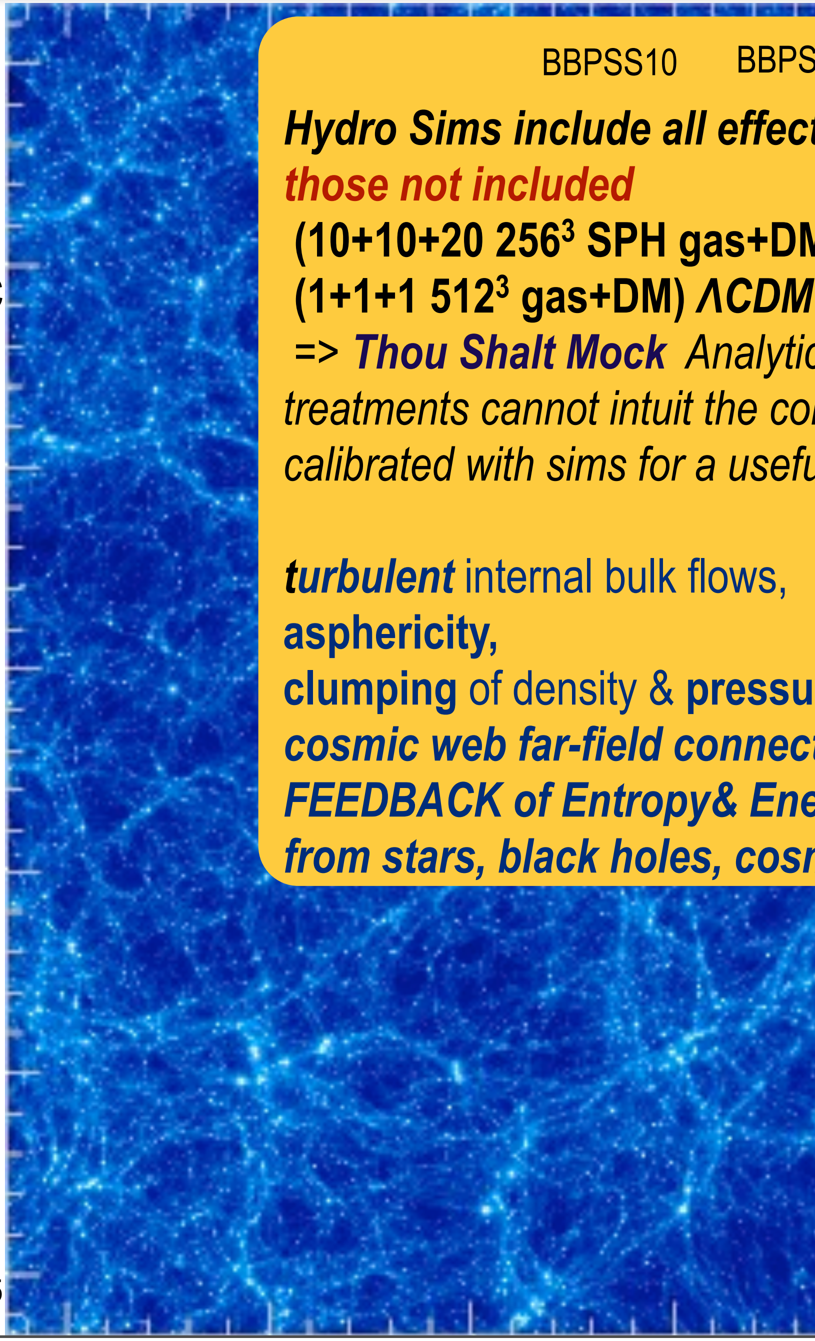
Gadget-3

SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4,5



BBPSS10 BBPS1,2,3,4,5

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

($10+10+20$ 256^3 SPH gas+DM)

($1+1+1$ 512^3 gas+DM) *ΛCDM* + ...

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

turbulent internal bulk flows,

asphericity,

clumping of density & **pressure,**

cosmic web far-field connection thru filaments,

FEEDBACK of Entropy& Energy & Momentum from stars, black holes, cosmic rays, ...

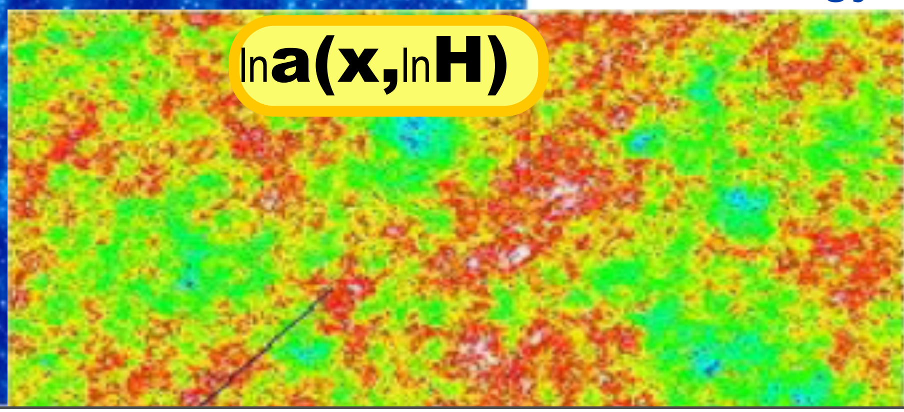
$\rho_g(x,t)$

a~1

evolve from early U vacuum potential and vacuum noise

in the presence of late U vacuum potential aka dark energy

$a\sim e^{-67+}$

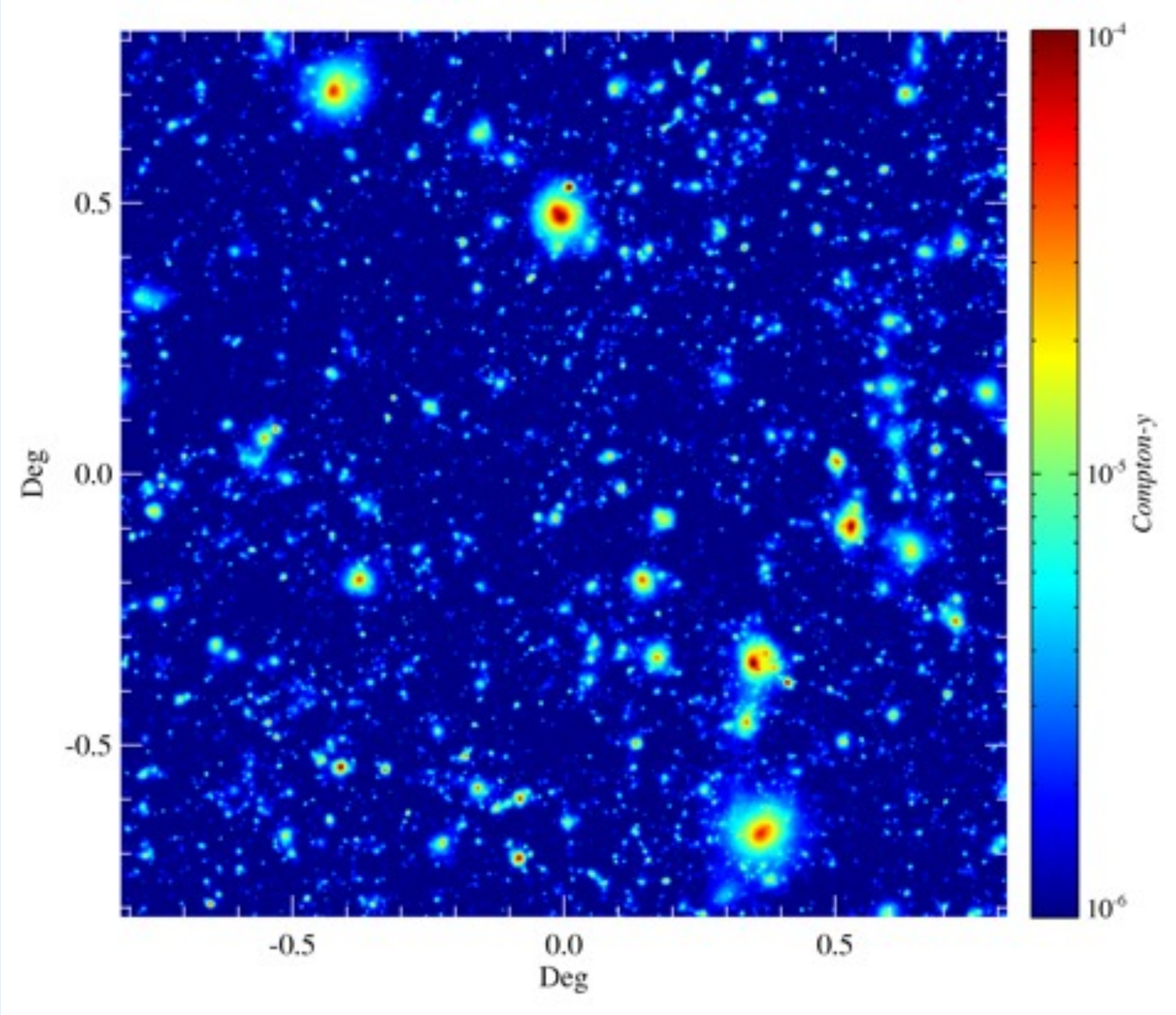


ln a(x, ln H)

Thursday, 4 October, 12

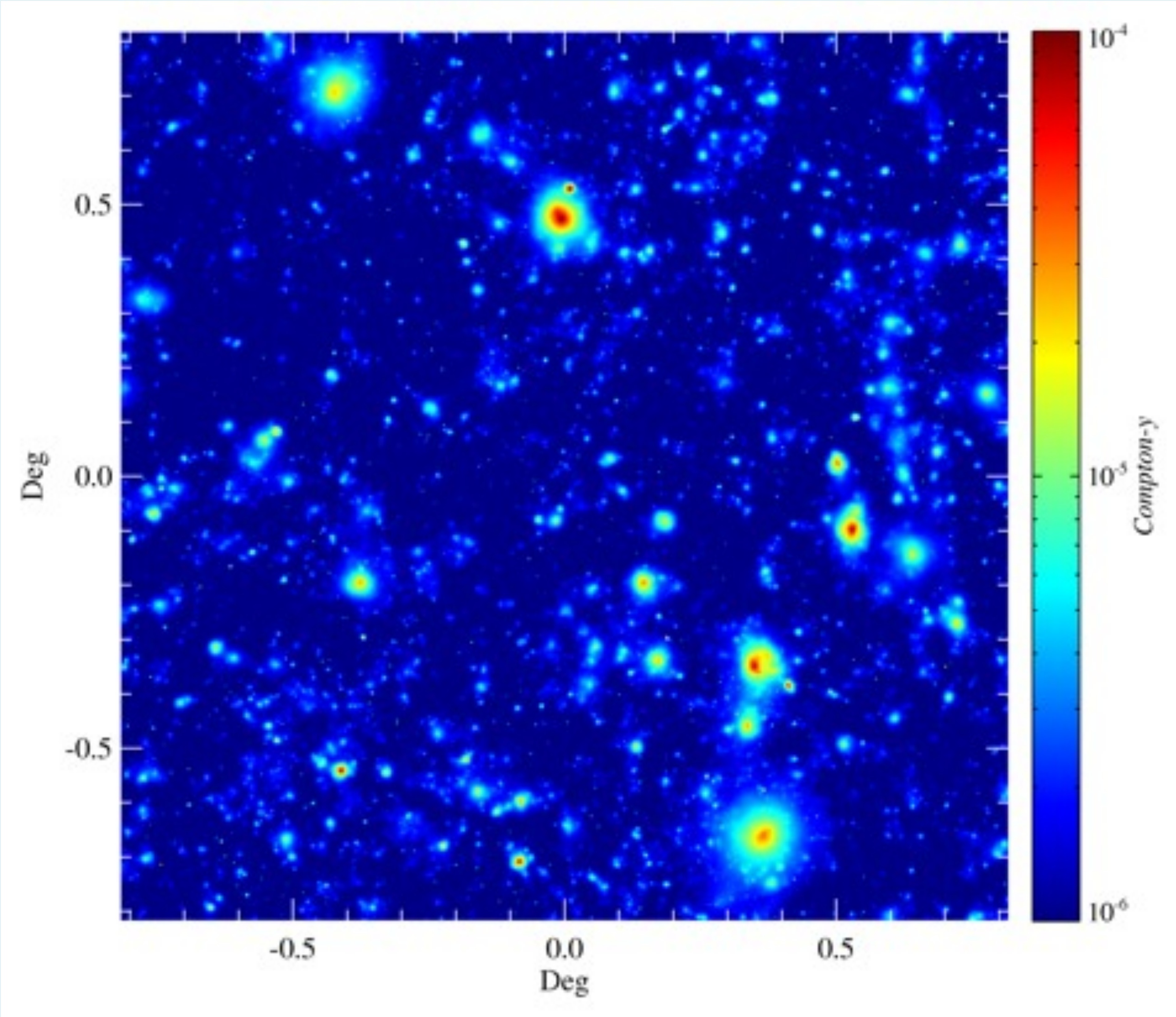
Compton-y map: "adiabatic"

= formation shock entropy from gravitational accretion only

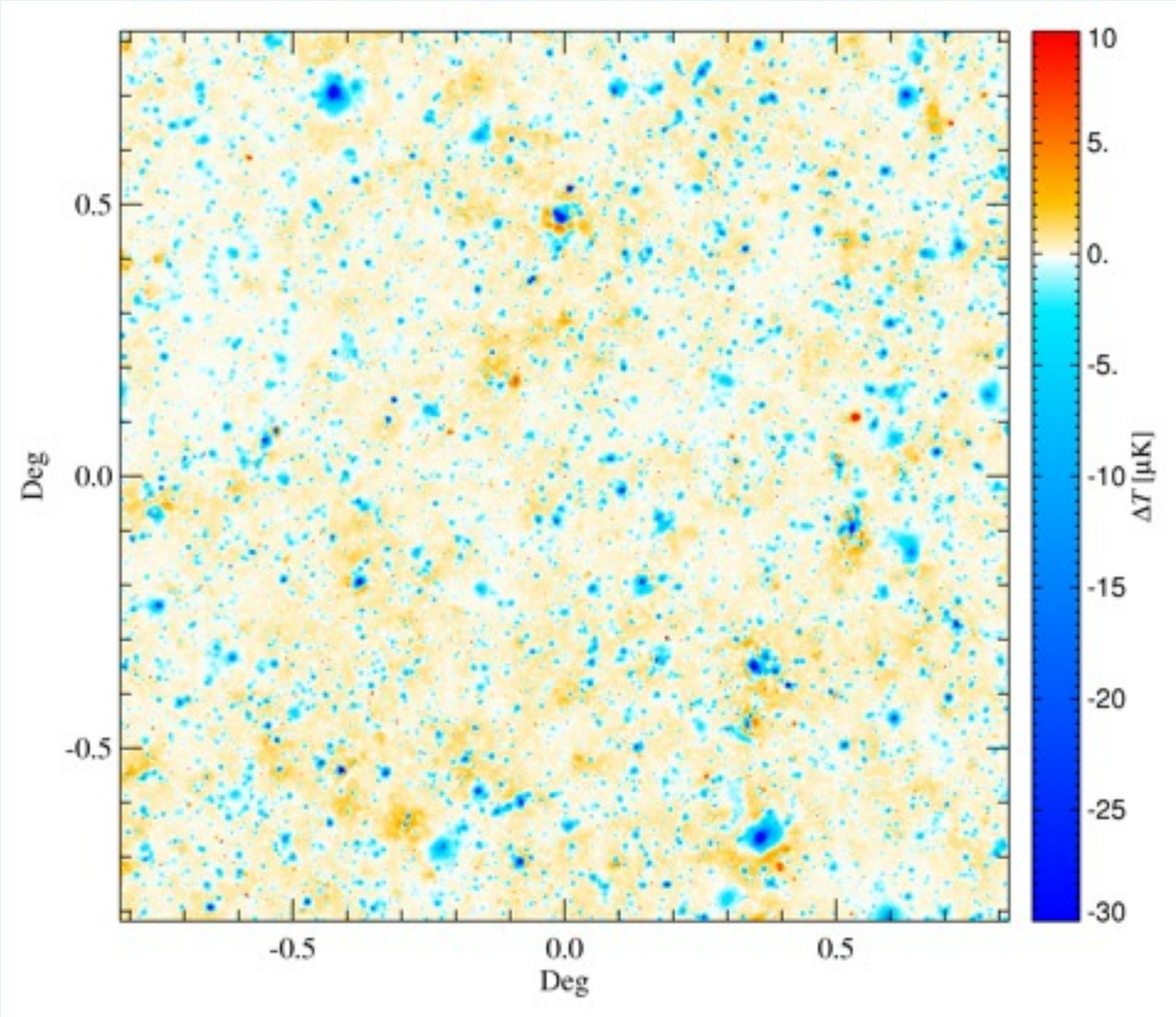


Compton-y map: Feedback

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



Adiabatic - Feedback

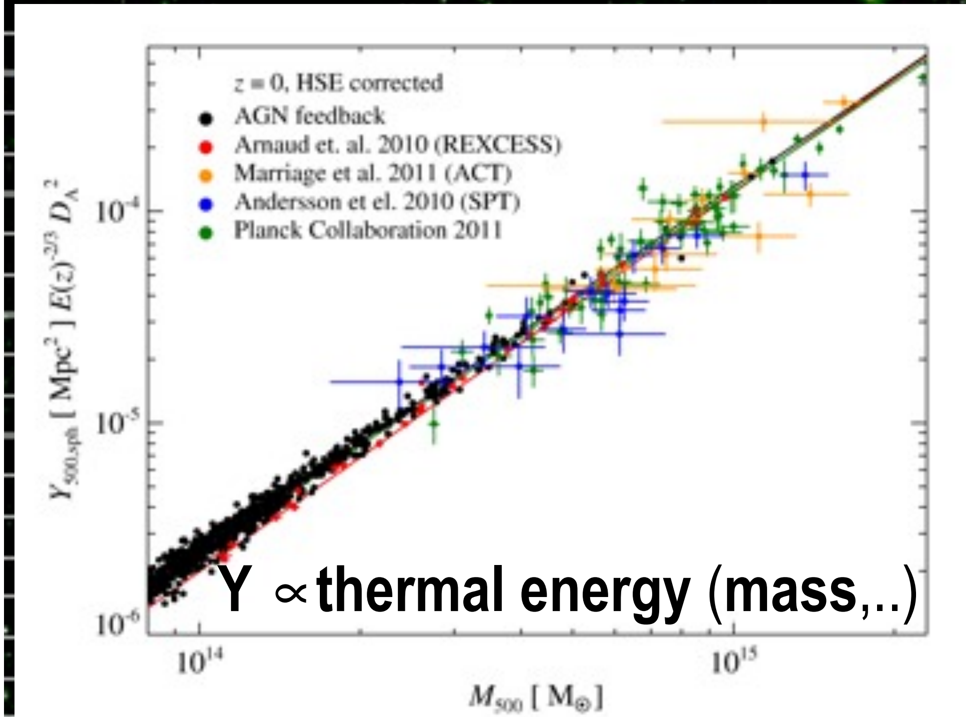


feedback gives “puffier” clusters, with lower core pressures

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

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

2011 Planck ~200 clusters, SPT ~50 =>224cls, ACT ~50 cls; 2013 1000s

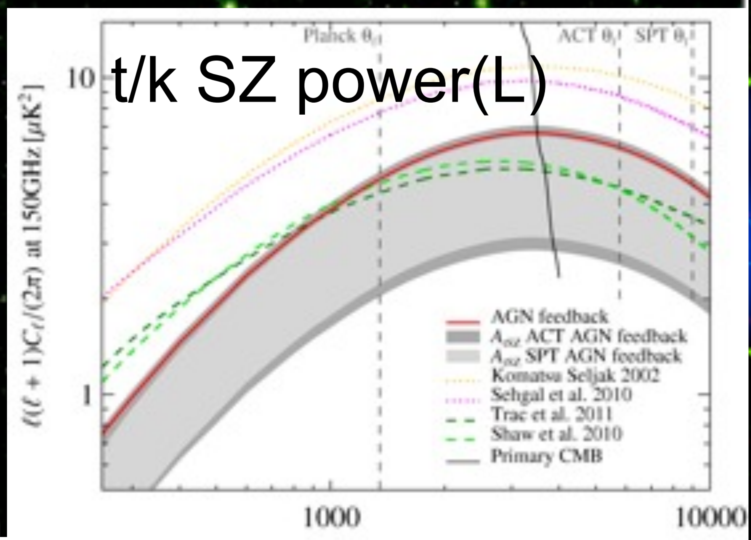


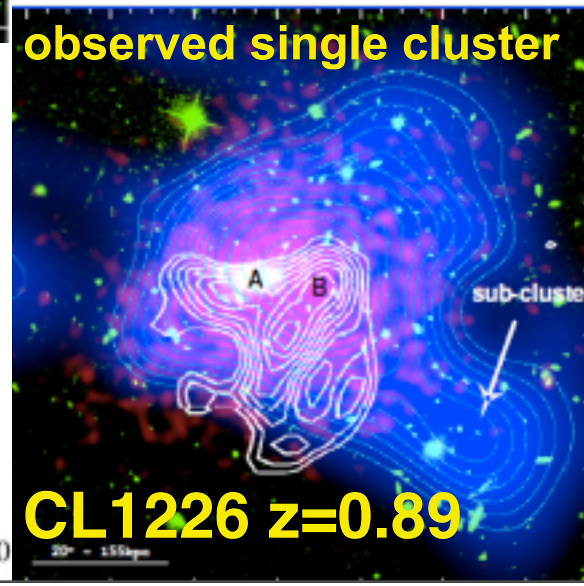
to get **cosmological parameters** from

$n_{cl}(Y(M),z)$ &

$C_L^{tSZ,kSZ}$

cluster complexity => requires **full "mocking"** simulations





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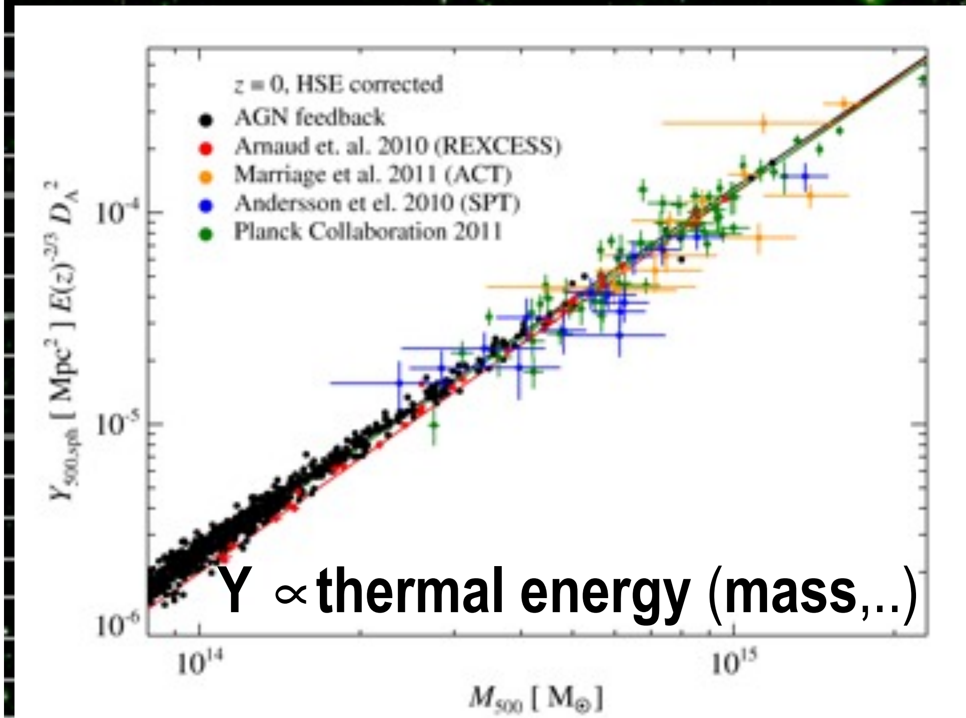


Y ∝ thermal energy (mass,..)

$p_e(x,t)$

ACT's el Gordo z=0.87
$2x10^{15}M_{sun}$, T_X=14.5kev

to get **cosmological parameters** from
$n_{cl}(Y(M),z)$ &
$C_L^{tSZ,kSZ}$
cluster complexity => requires **full "mocking" simulations**

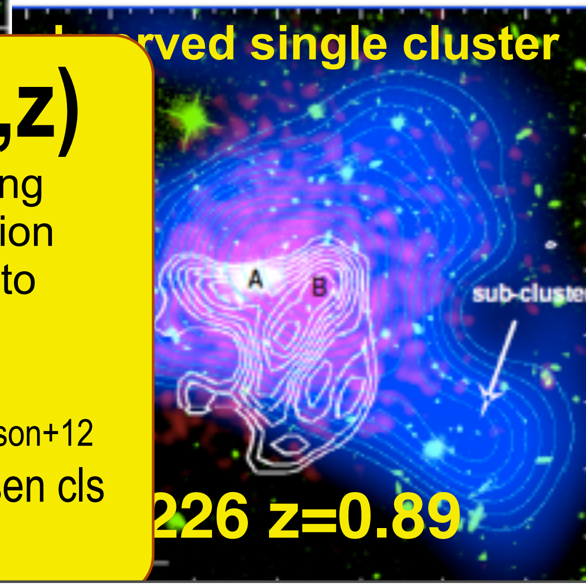
Cosmic Parameters from **$n_{cl}(M,z)$**

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*

SPT similar results with ~20 clusters Benson+12

NEW: ACT Hasselfield+12 15 carefully chosen cls

...rved single cluster



...226 z=0.89

Bond@2004, Second Planck Symposium, Orsay, France, January, *The CMB Landscape circa 2008:* **Mocking Forecasts**

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

increasing sophistication: Monte Carlo selections, contamination of probes, $\mathbf{n_{cl}}$ *(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)

KITP2011@Monsters Inc: 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 e.g., ACT=>ACTpol

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

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

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

$s_X \sim T_e / \rho_g^{2/3}$ & $s_{th} \sim 3Y_T/2 \ln s_X$

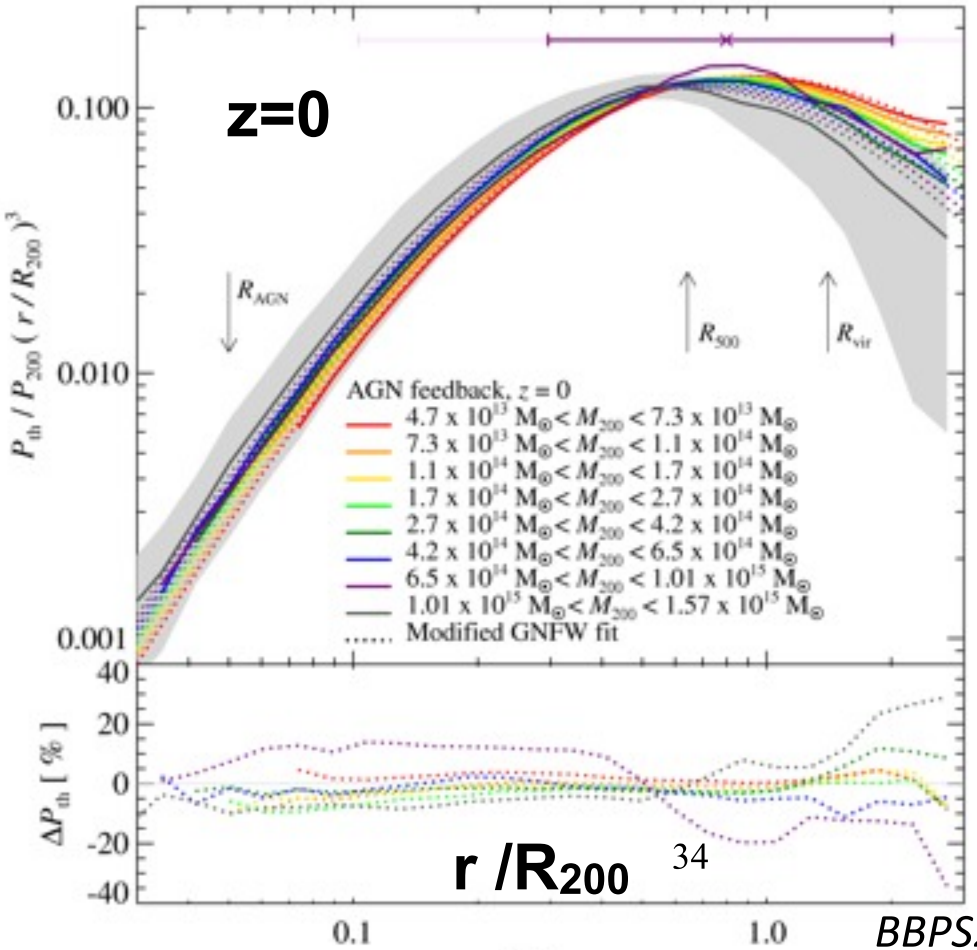
but it is p_{tot} *in the virial equation*
(& $s_{th+kin+clumping+anisotropy}$*)*

& cluster ENTROPIES:
coarse-grained information

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

(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



BBPS2

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

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

$s_X \sim T_e / \rho_g^{2/3}$ & $s_{th} \sim 3Y_T/2 \ ln\ s_X$

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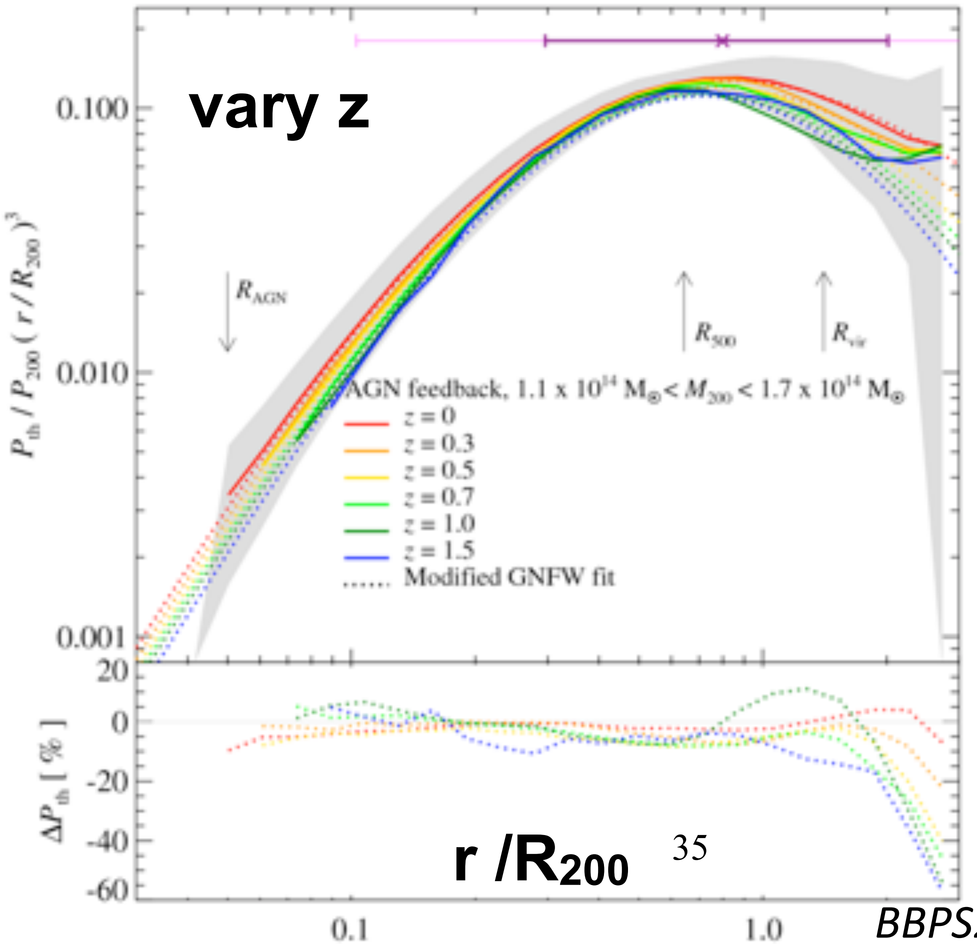
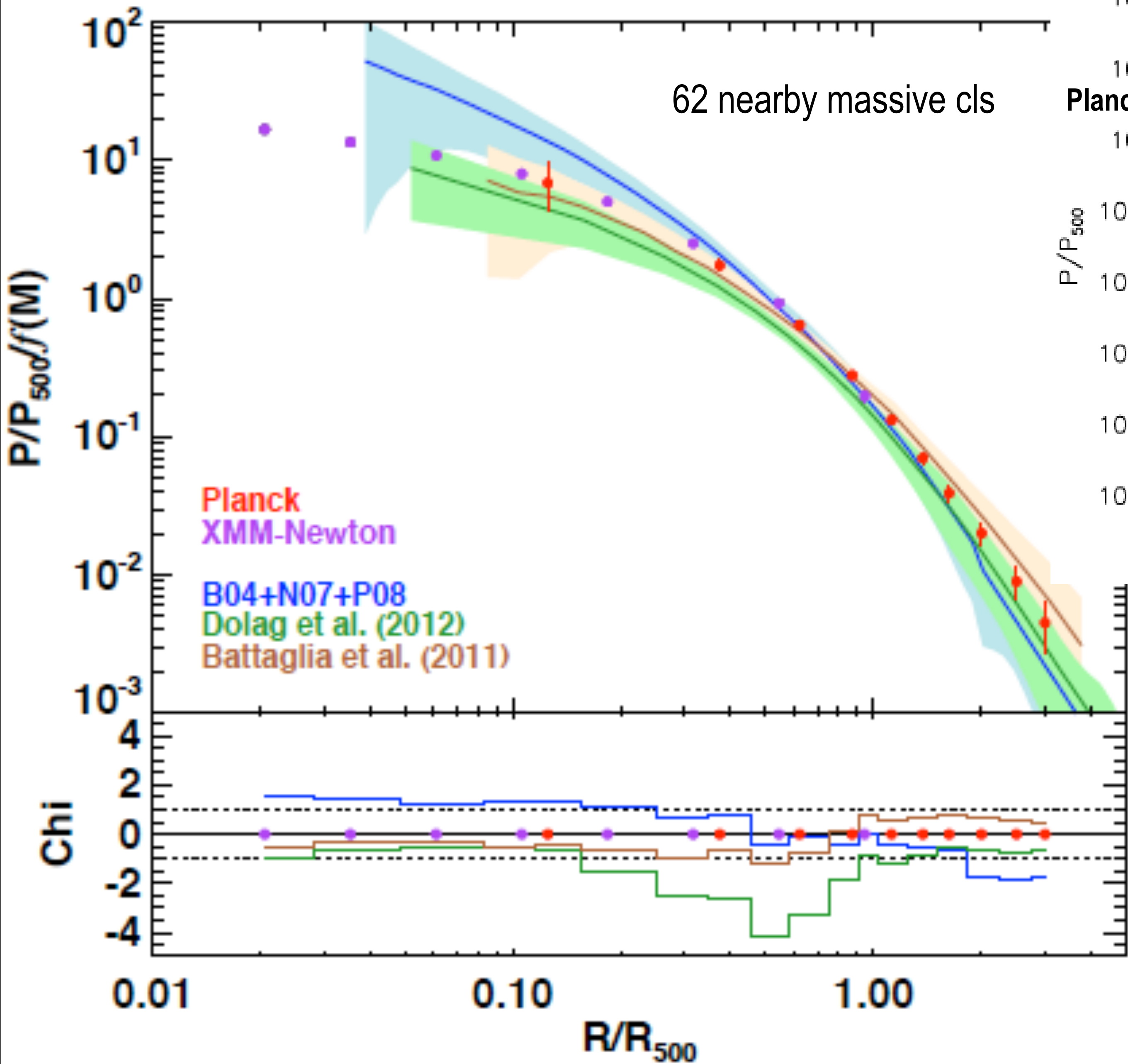
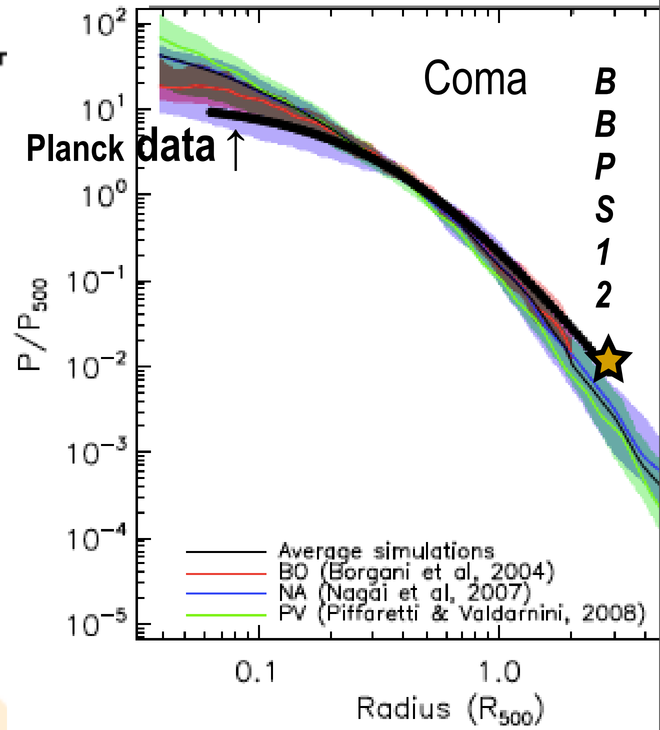


BBPS2

Planck 2012: neo “universal” pressure profile, via SZ from 62 nearby massive cls +Coma





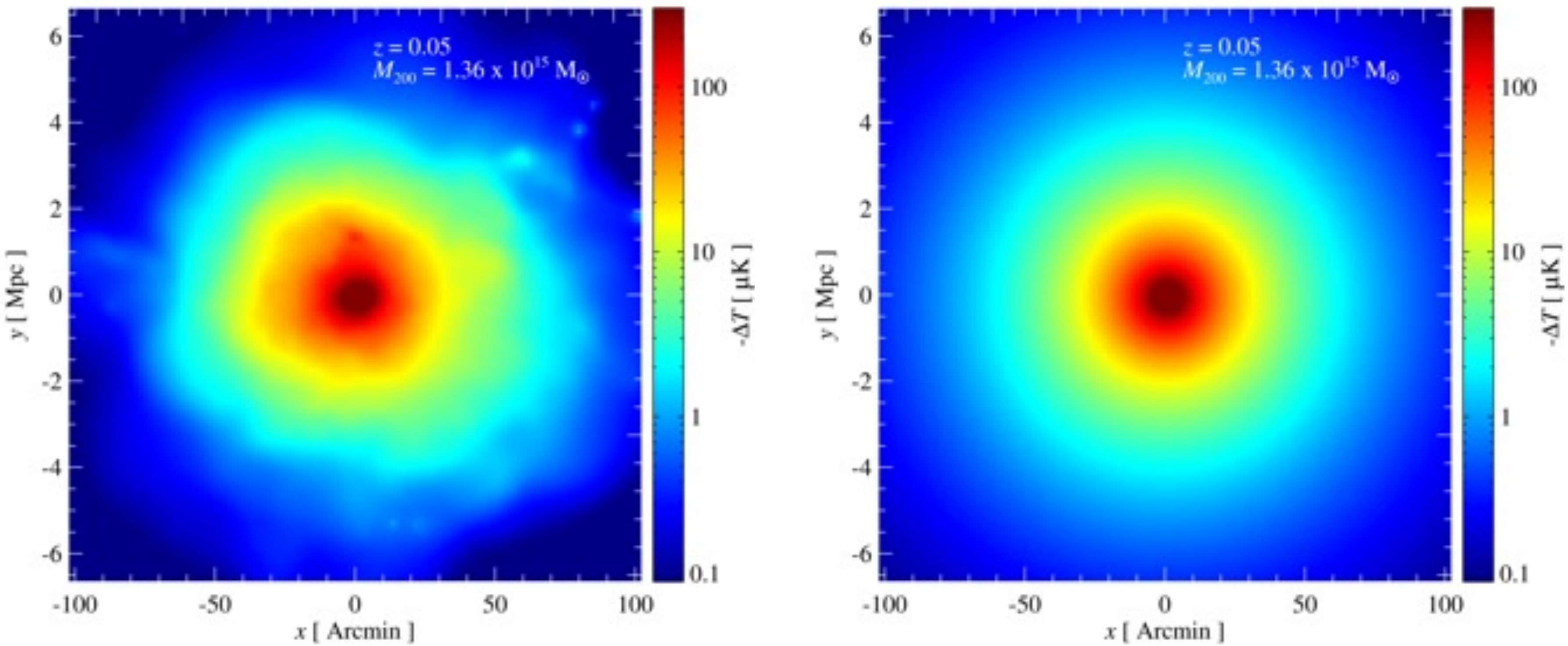
X-ray “universal pressure profile” (Arnaud+10) fails $>R_{500}$

BBPSS11, BBPS12 **AGN feedback pressure profiles fit > R_{500} SZ data better than other hydro sims. nearly “universal”(M,z)**

pressure clumping

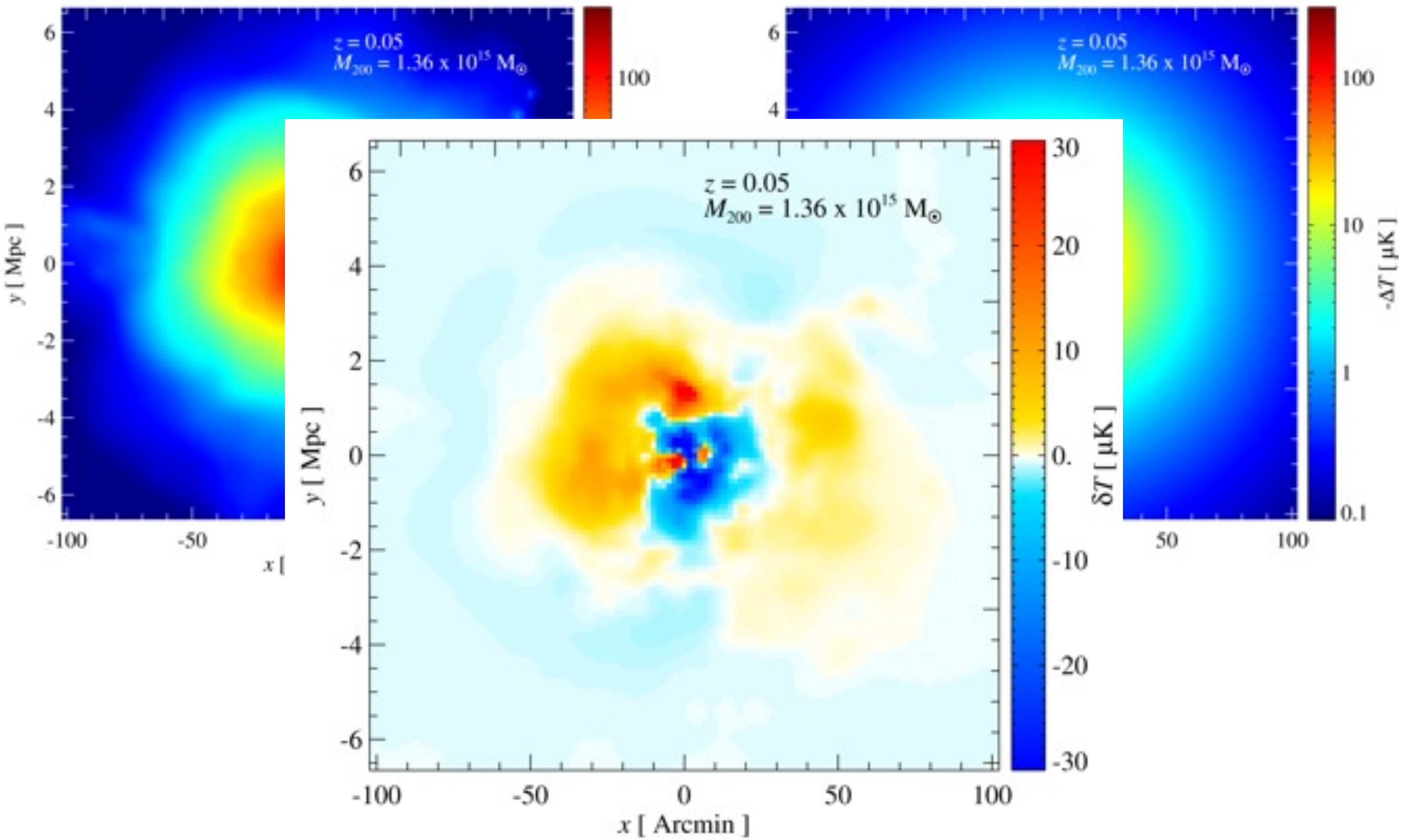
R_{500} ↑ 3 R_{500} => $\delta p/p$ ~0.2 ↑ ~1

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



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

(10+10+20 256^3 SPH gas+DM)

(1+1+1 512^3 gas+DM) *ΛCDM* + ...

=> ***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

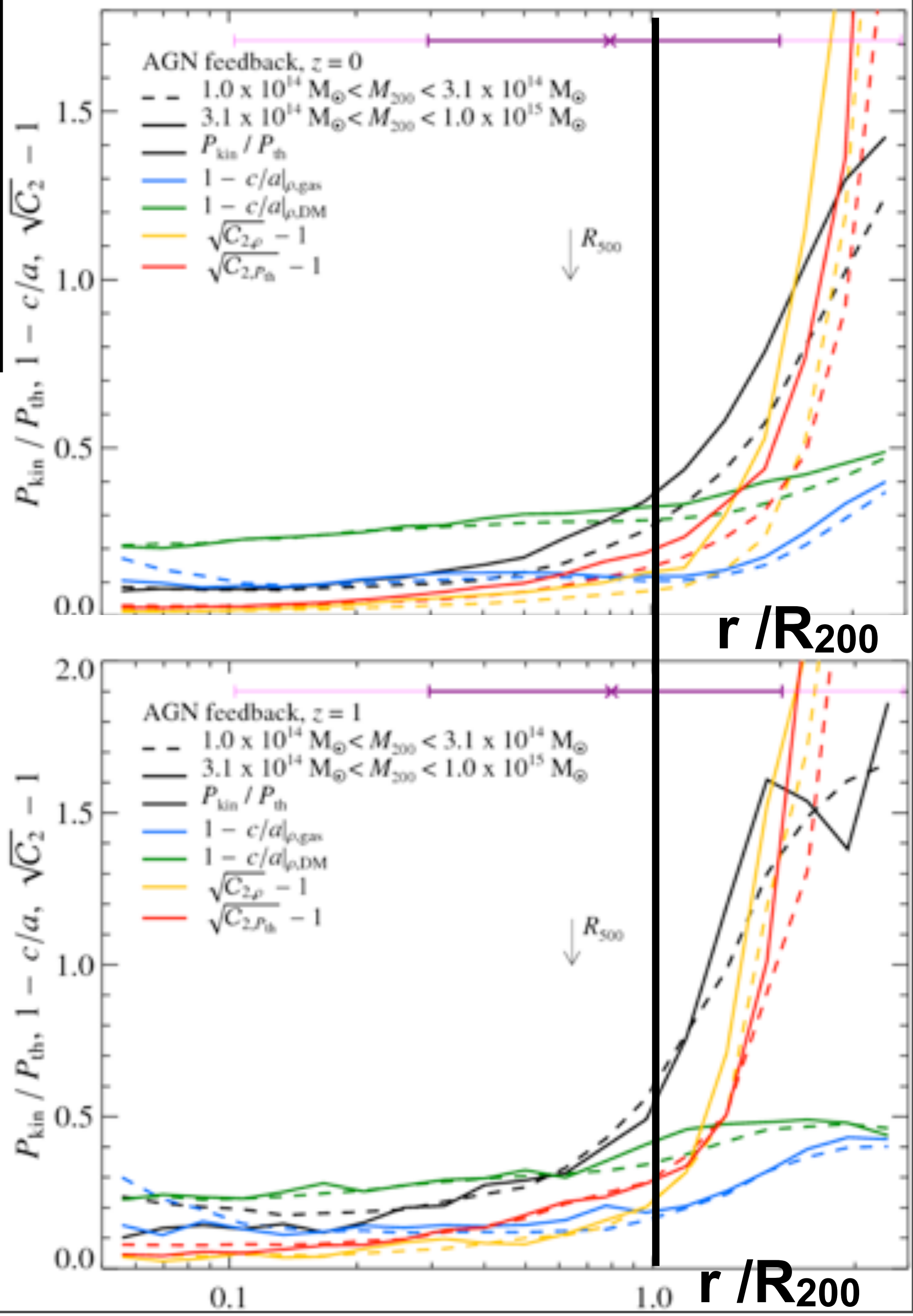
clumping of density & **pressure** (!)

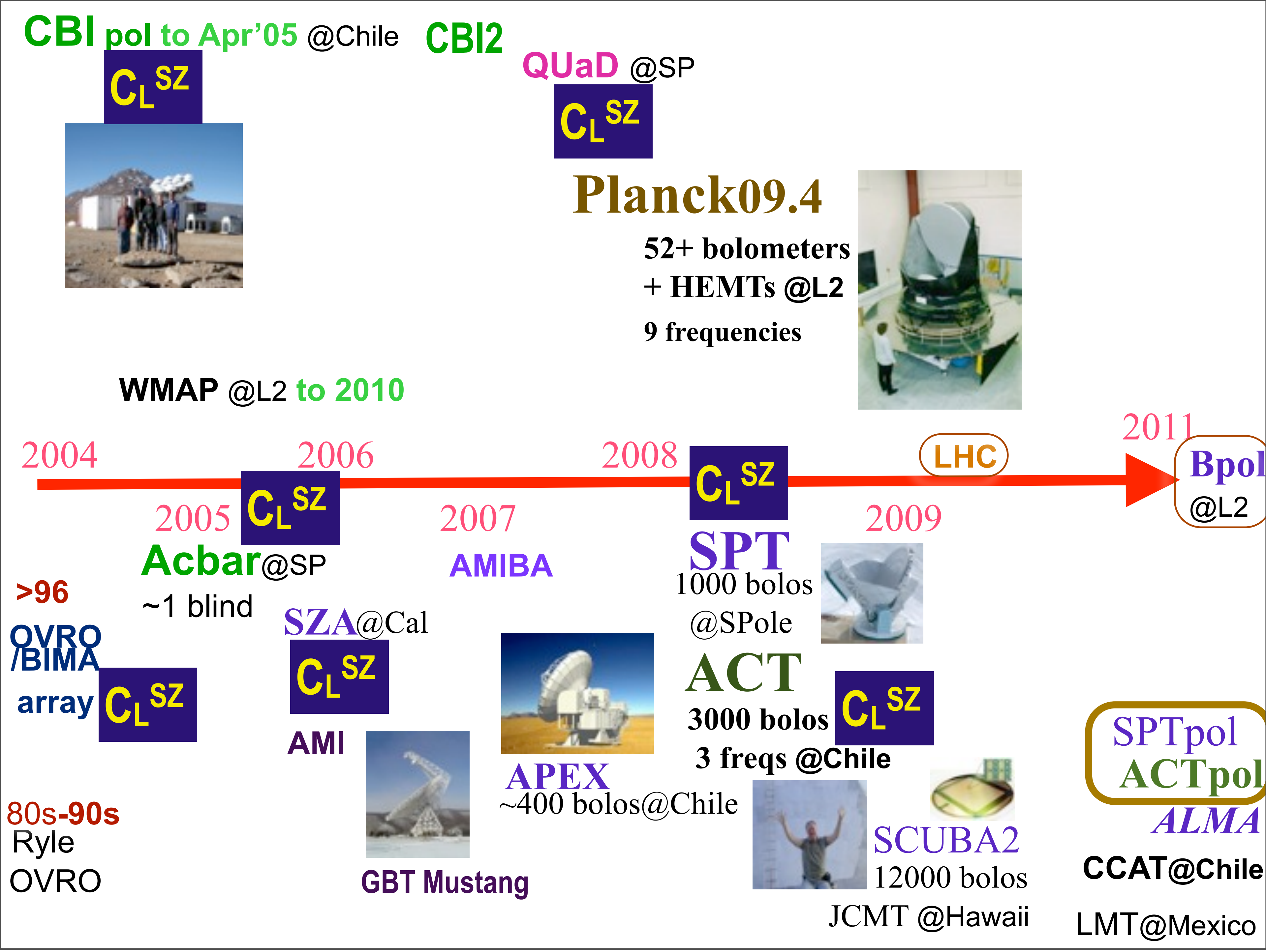
$C_{p2}^{1/2}-1 = \mathrm{sqrt}[\langle p_{th}^2\rangle/\langle p_{th}\rangle^2]-1$

aka Renyi entropy of order 2

not small @ < **R_{500}**

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

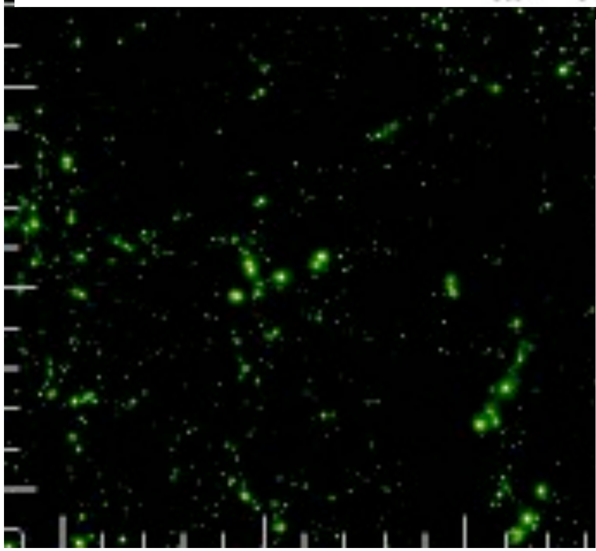


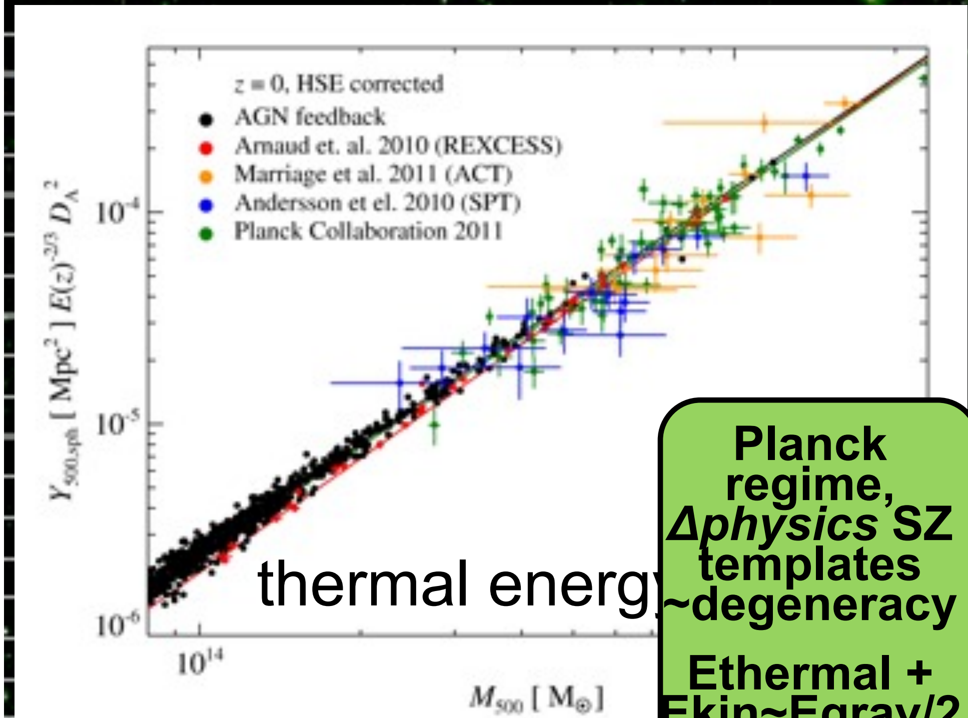

CBI pol to Apr'05 @Chile
CBI2
QUaD @SP
Planck09.4
52+ bolometers
+ HEMTs @L2
9 frequencies
WMAP @L2 to 2010
2004
2005
2006
2007
2008
2009
2011
LHC
Bpol
@L2
Acbar@SP
~1 blind
>96
OVRO
/BIMA
array
SZA@Cal
AMI
AMIBA
SPT
1000 bolos
@SPole
ACT
3000 bolos
3 freqs @Chile
APEX
~400 bolos@Chile
GBT Mustang
SCUBA2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

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

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

2011 Planck ~200 clusters, SPT ~50 =>224cls, ACT ~50 cls; 2013 1000s

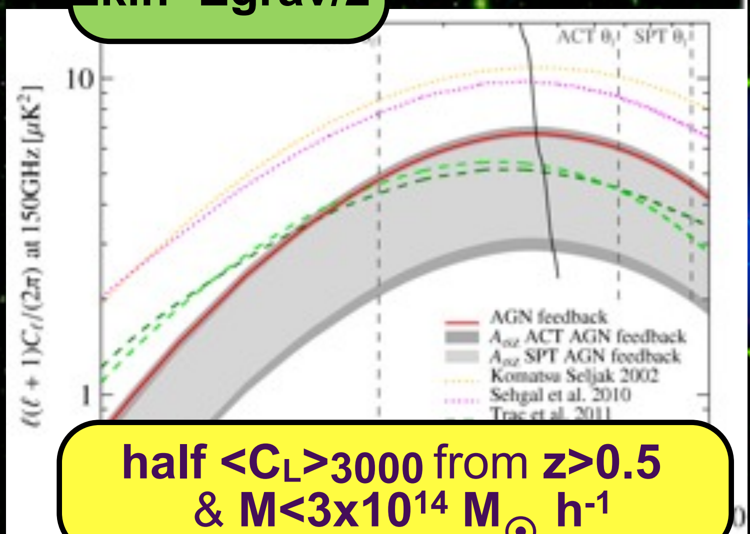




thermal energy

Planck regime,
Δphysics SZ templates
~degeneracy

Ethermal + Ekin~Egrav/2

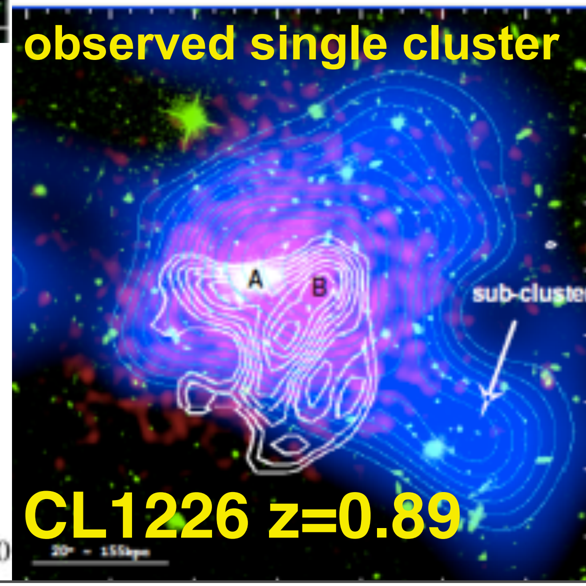


half $\langle C_L \rangle_{3000}$ from $z>0.5$
& $M<3\times10^{14}\ M_\odot\ h^{-1}$

$p_e(x,t)$

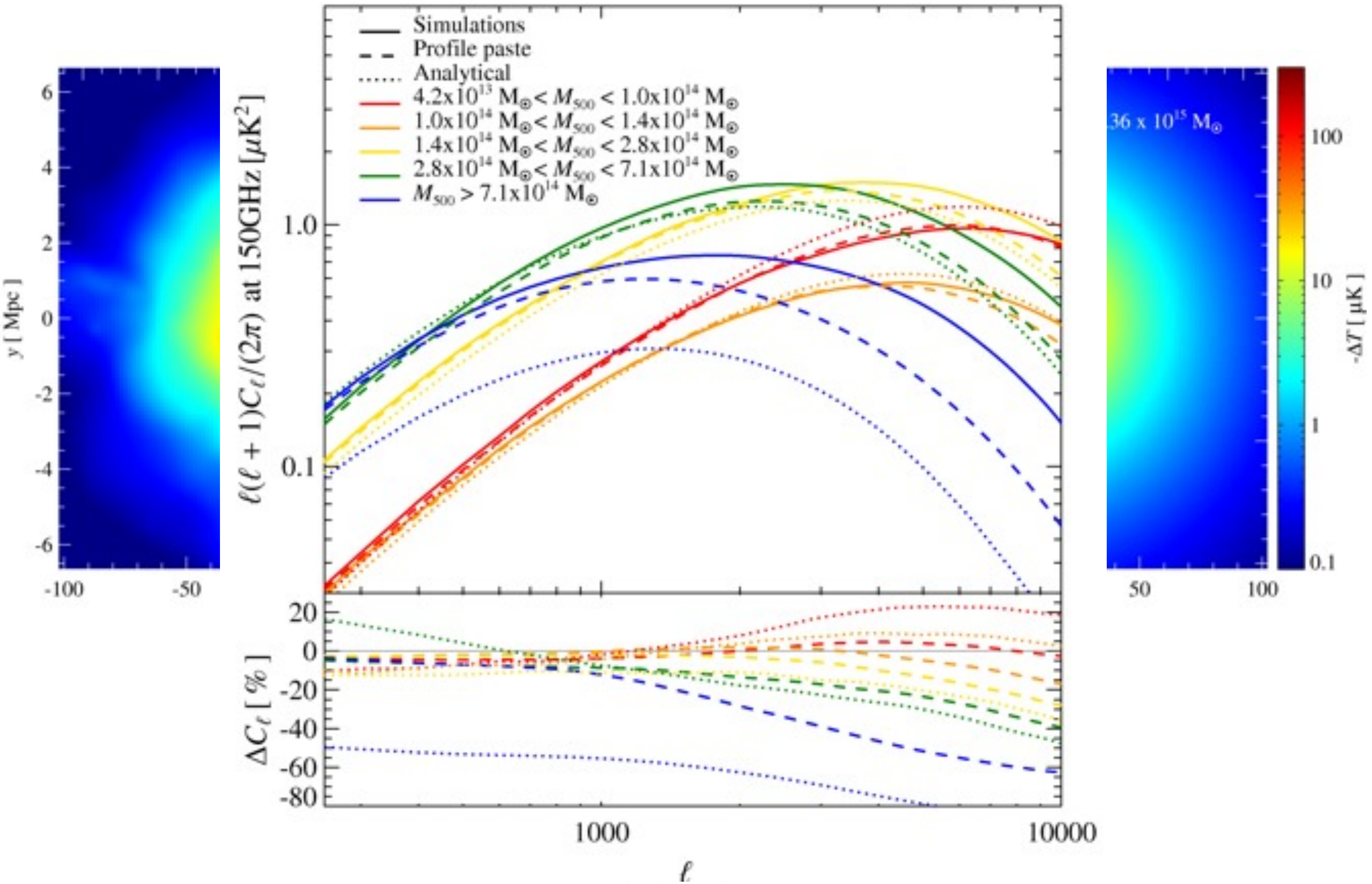
ACT's el Gordo z=0.87
$2\times10^{15} M_{sun}$, T_X=14.5kev

observed single cluster

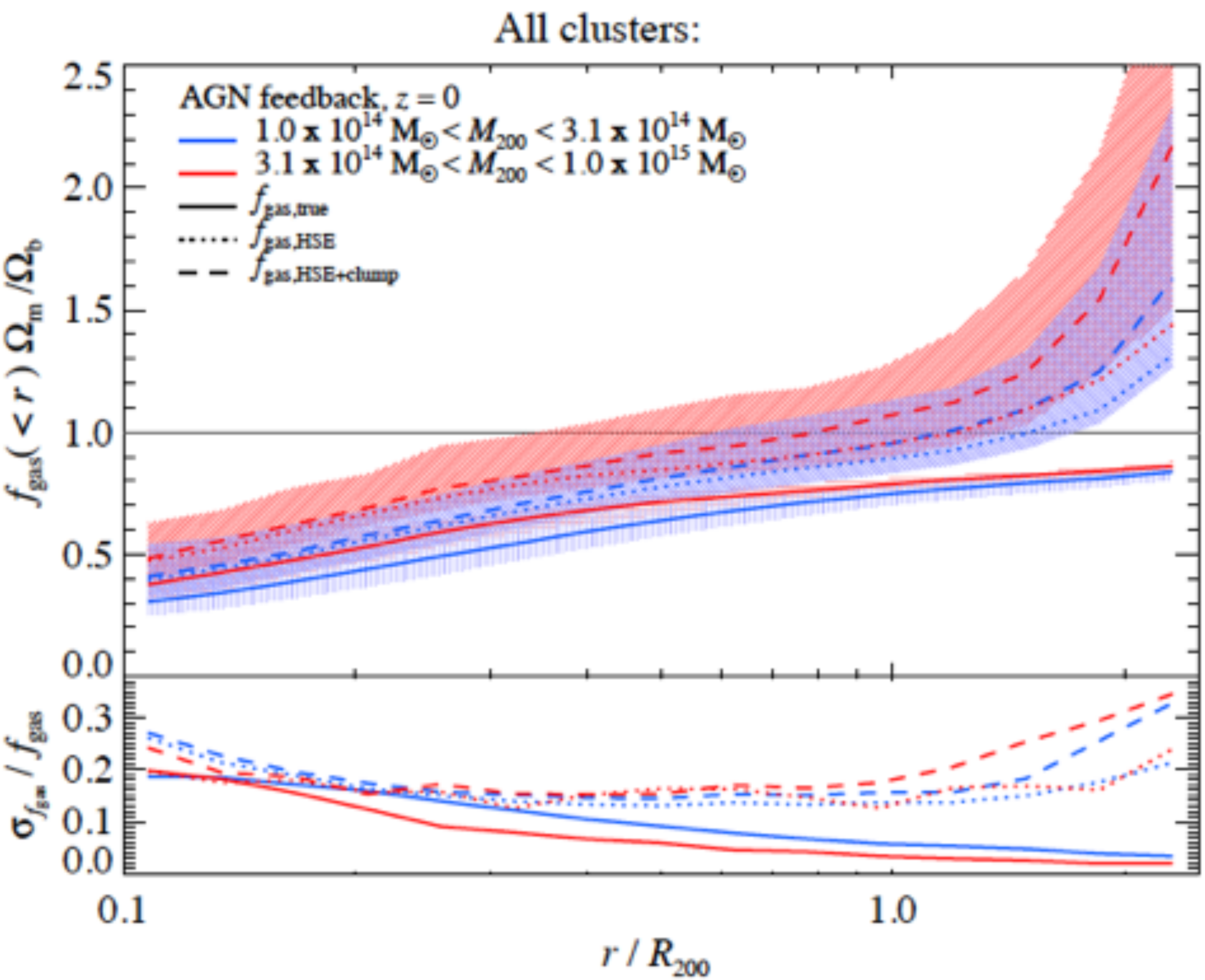


CL1226 z=0.89

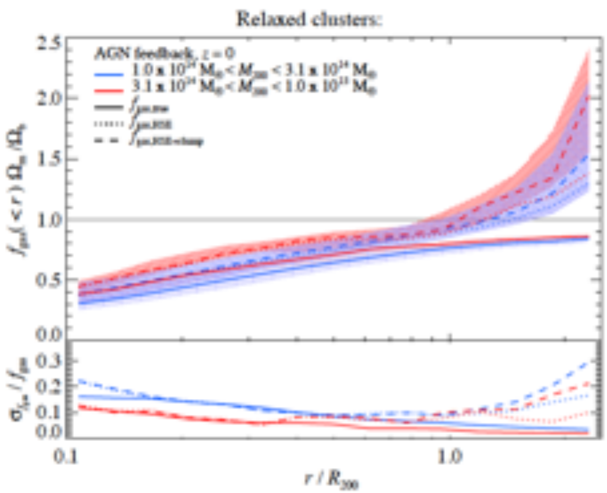
pressure sub-structure contribution to C_L^{SZ}



biases in gas fraction estimation in clusters

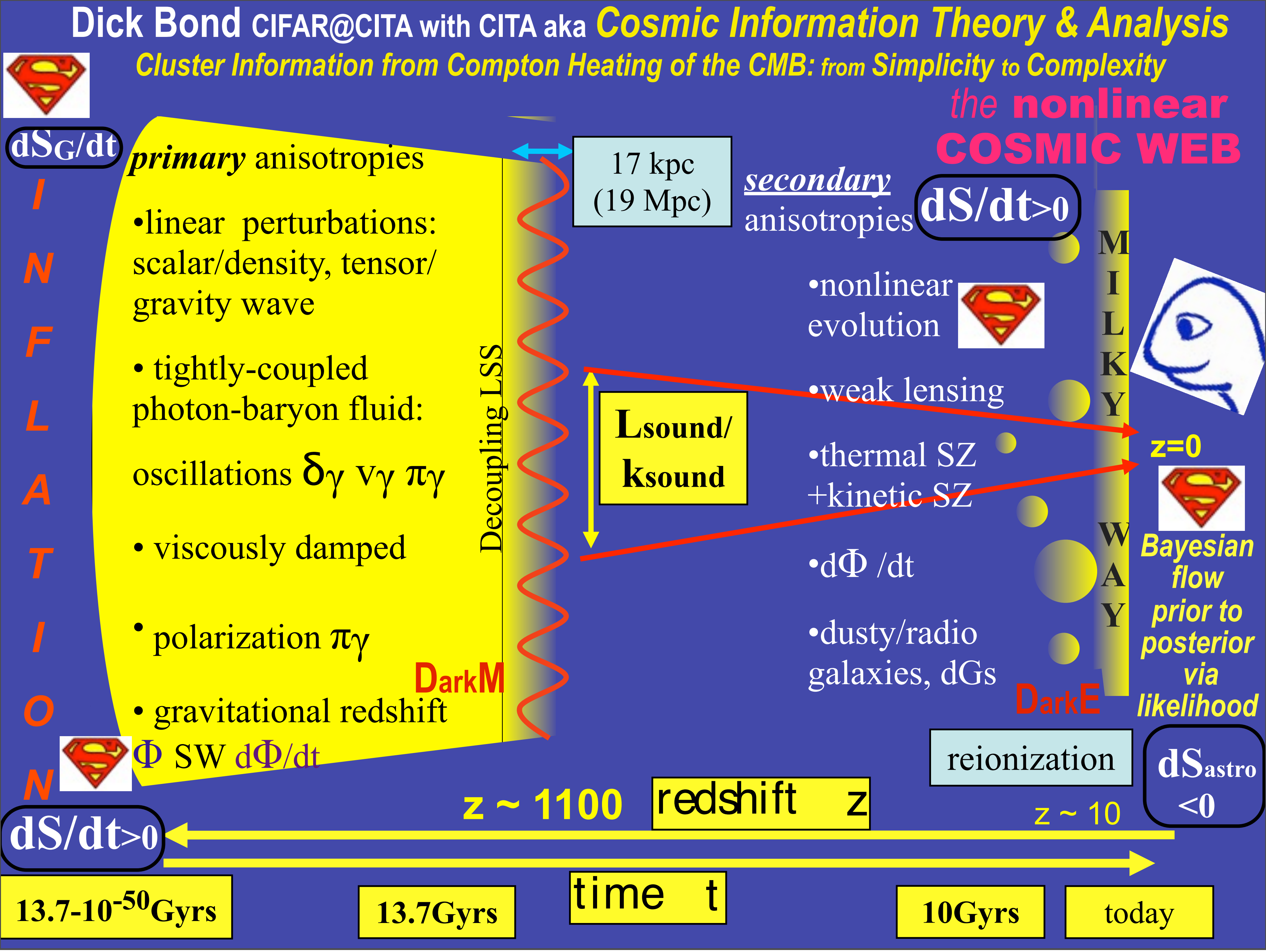


relaxed = third lowest in K/U



bbps3 sims cf.

growing collection of *Suzaku* clusters, consisting of PKS0745-191 (George et al. 2009), Abell 1795 (Bautz et al. 2009), Abell 2204 (Reiprich et al. 2009), Abell 1413 (Hoshino et al. 2010), Abell 1689 (Kawaharada et al. 2010), Abell 2142 (Akamatsu et al. 2011), Perseus (Simionescu et al. 2011), a fossil group RX J1159+5531 (Humphrey et al. 2012), Abell 2029 (Walker et al. 2012), and Hydra A (Sato et al. 2012).


Dick Bond CIFAR@CITA with CITA aka Cosmic Information Theory & Analysis
Cluster Information from Compton Heating of the CMB: from Simplicity to Complexity
the nonlinear COSMIC WEB
dSG/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
dS/dt>0
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
•dΦ /dt
•dusty/radio galaxies, dGs
DarkE
MILKY WAY
z=0
Bayesian flow prior to posterior via likelihood
reionization
dSastro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
time t
13.7-10^-50Gyrs
13.7Gyrs
10Gyrs
today

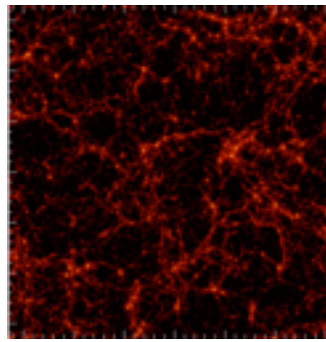
dS/dt 2

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 CIB radiation



dS/dt 2

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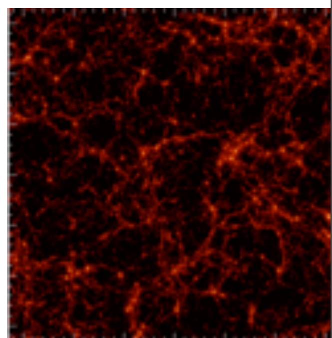


Learning the Cluster Tango

$S_{th,cl} \sim 10^{76}$

cf. $S_{U,m+r} \sim 10^{88.6}$

***Cosmic Hydro Sims** include all effects - except of course those not included Thou Shalt Mock*

(10+10+20 256^3 SPH gas+DM)

(1+1+1 512^3 gas+DM) ΛCDM + ...

nr Sackur-Tetrode: $\Delta s = 1/2 \mathrm{Tr}\, \ln \langle \Delta P_{ij} / \rho \rangle + \ln \rho^{-1}$ *(+clumping+anisotropy..)*

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* **cosmic web structure**

$\rho_g(x,t)$

a~1 now

400 Mpc

ΛCDM

WMAP5

gas density

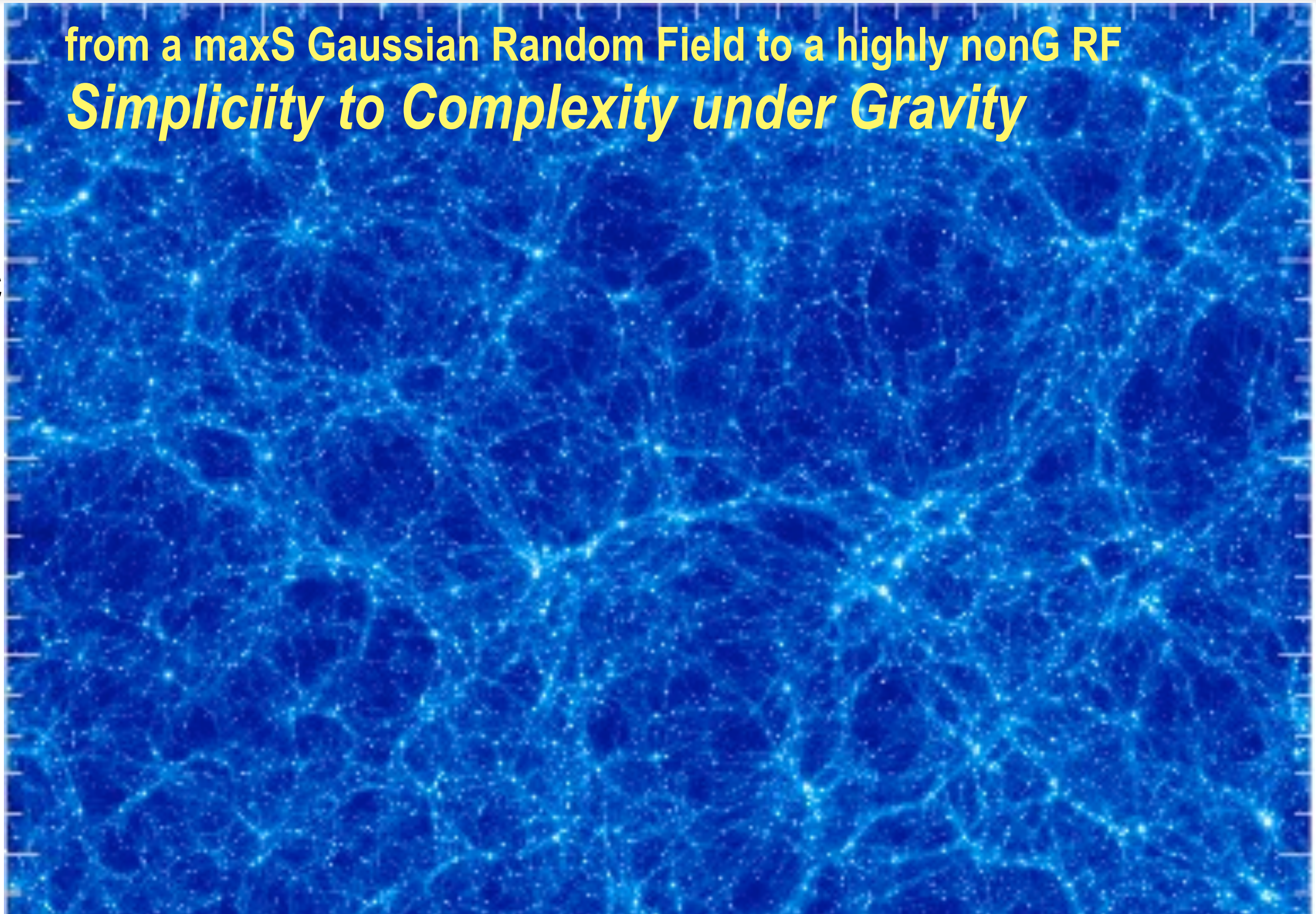
Gadget-3

SF+ SN E+ winds +CRs

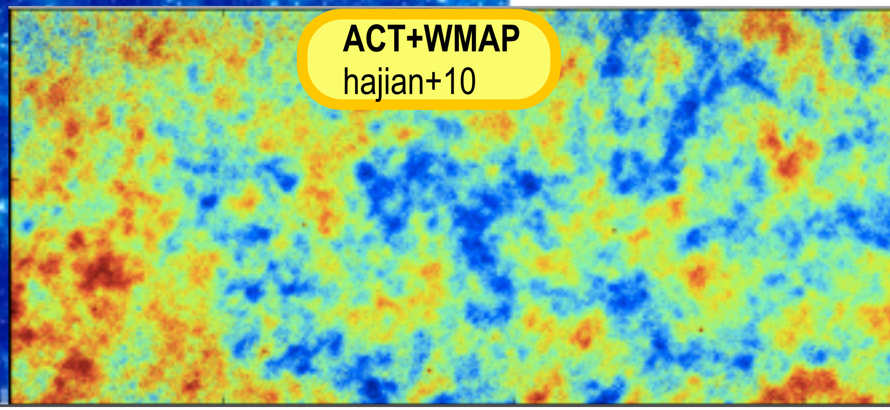
512^3

BBPSS10

BBPS1,2,3,4,5



$a \sim e^{-7} \sim 1/1100$



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

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

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

400 Mpc

ΛCDM

WMAP5

gas pressure

Gadget-3
SF+
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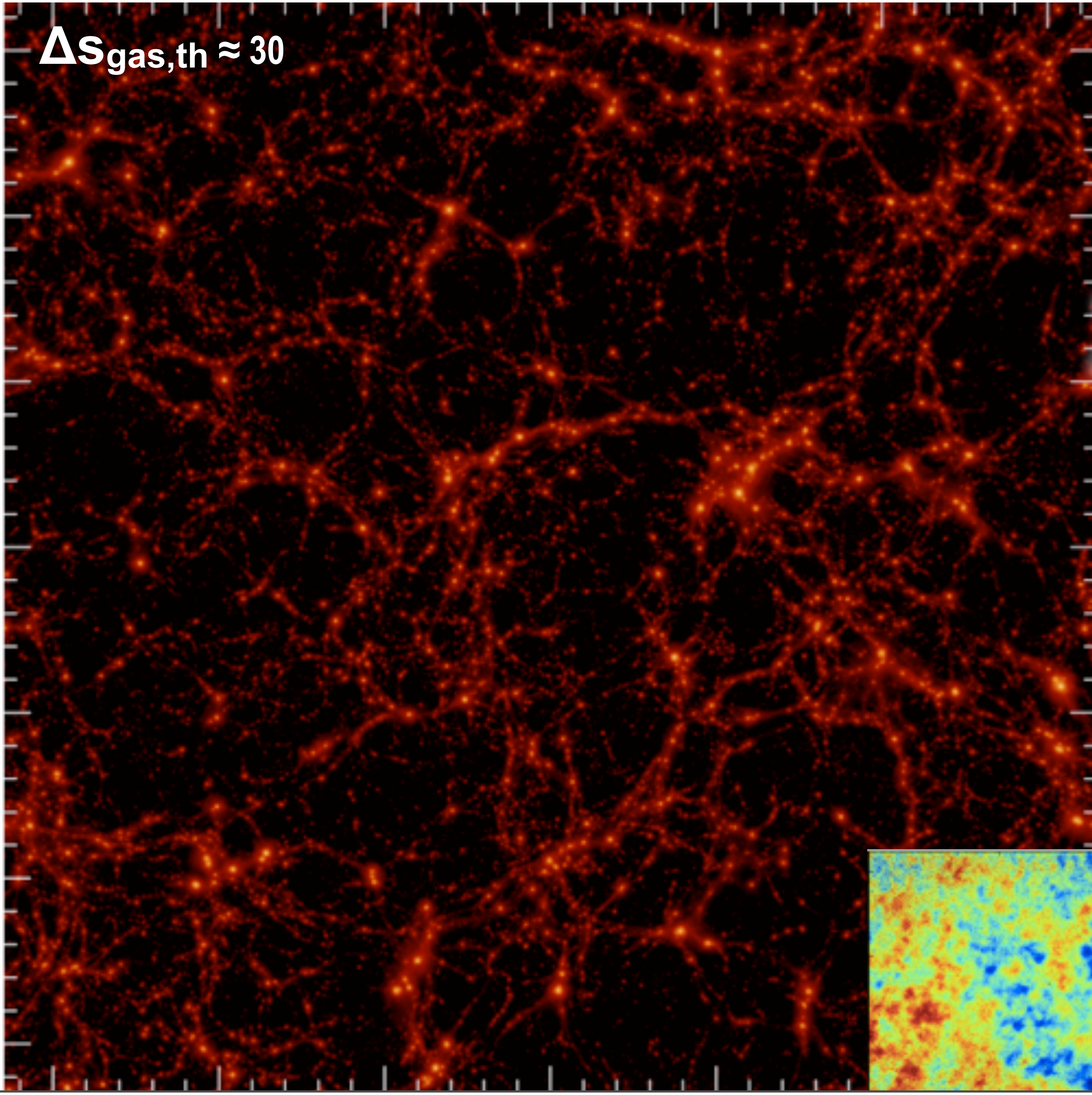
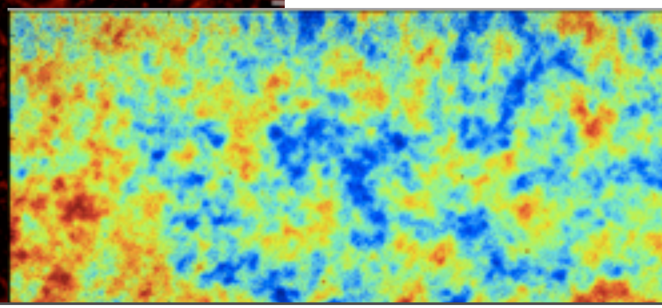


CMB gets entangled in the cosmic web

descending into the real gastrophysics of cosmic weather

the energetic, turbulent, dissipative, compressive

life of the IGM/ICM/ISM



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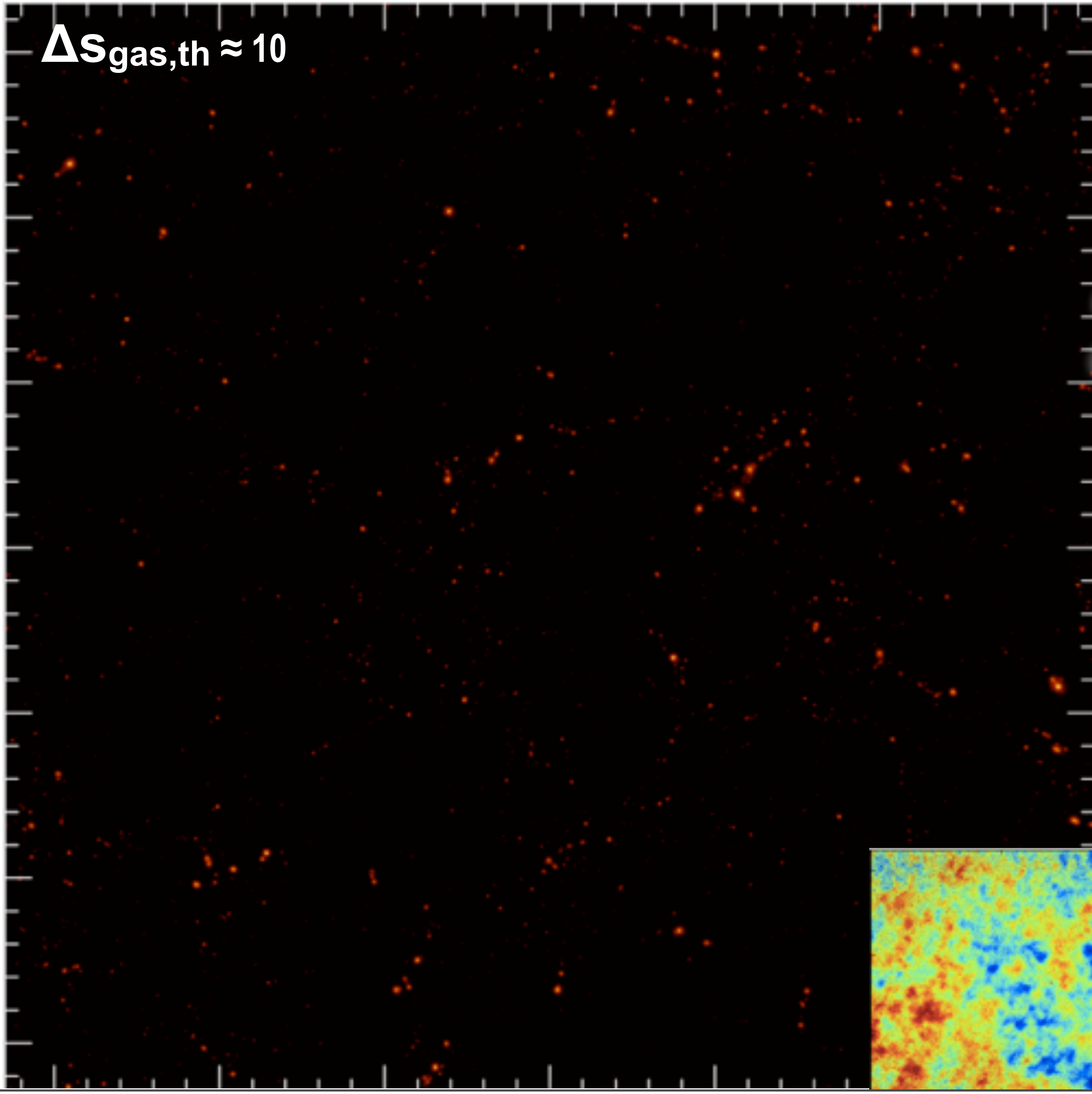

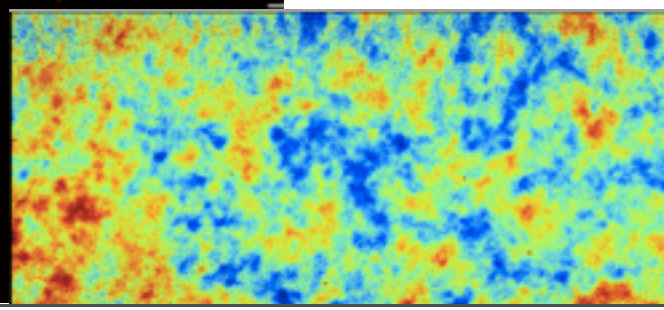

$s_{b,th}(x,t)$

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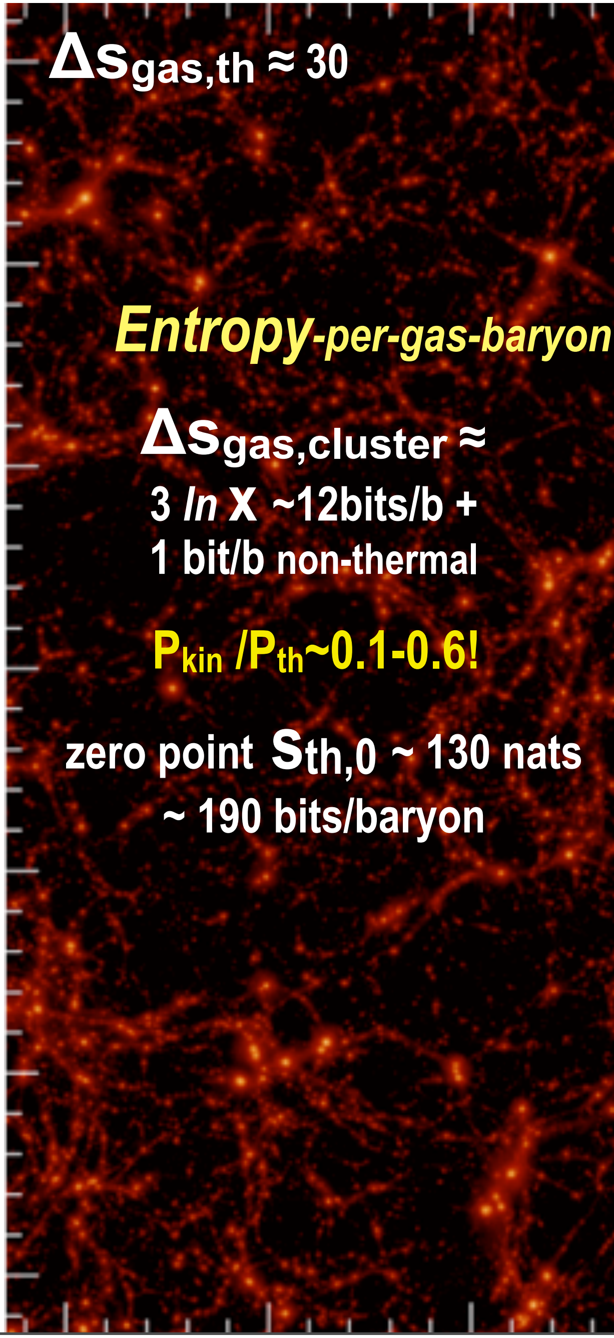


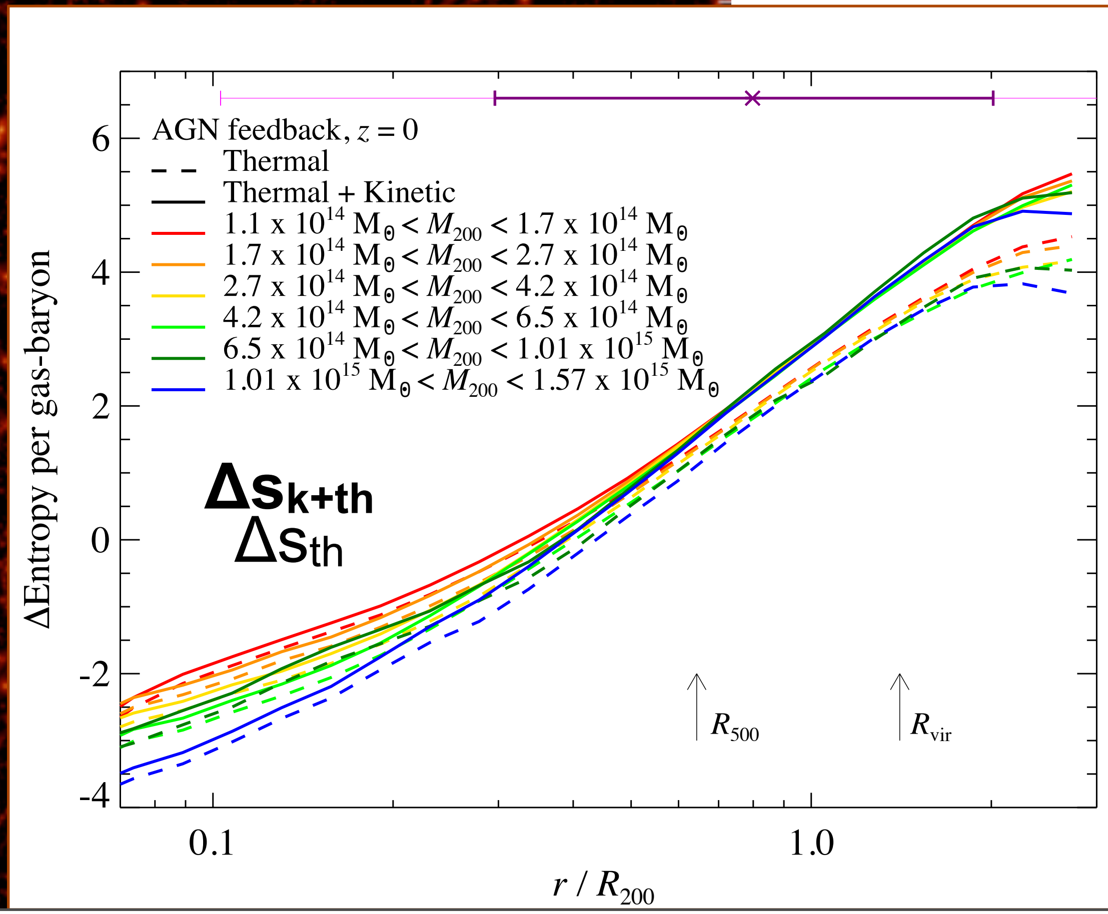
$\Delta s_{gas,th} \approx 30$

Entropy-per-gas-baryon

$\Delta s_{gas,cluster} \approx$
3 *ln* X ~12bits/b +
1 bit/b non-thermal

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

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



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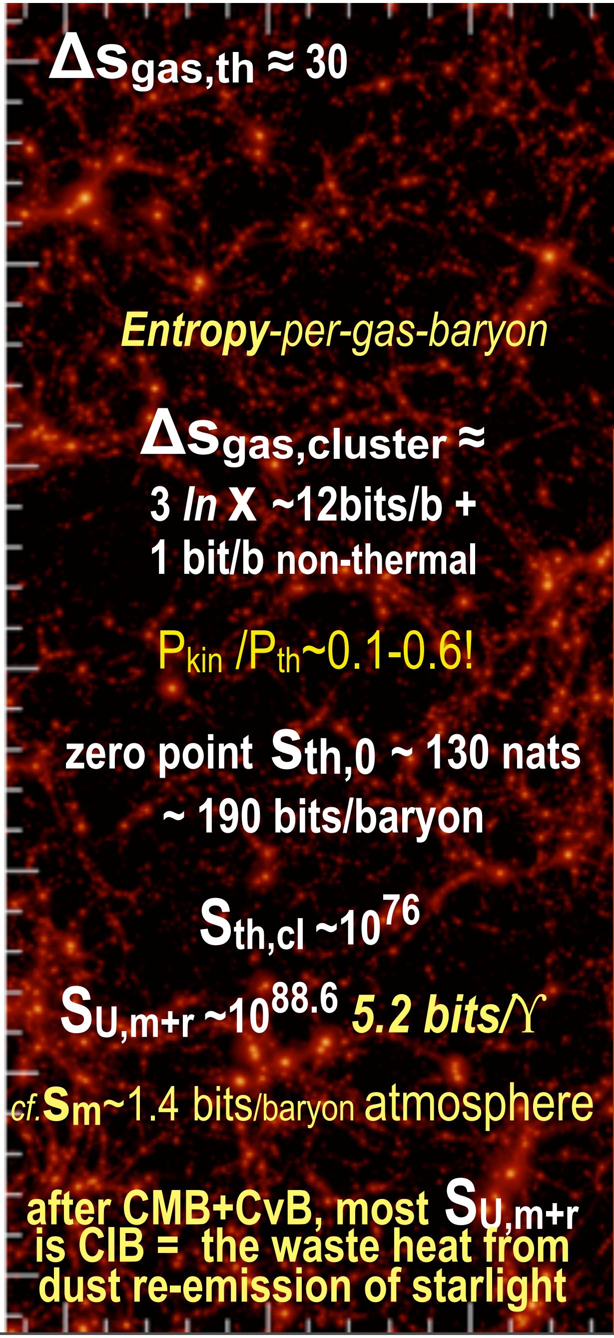

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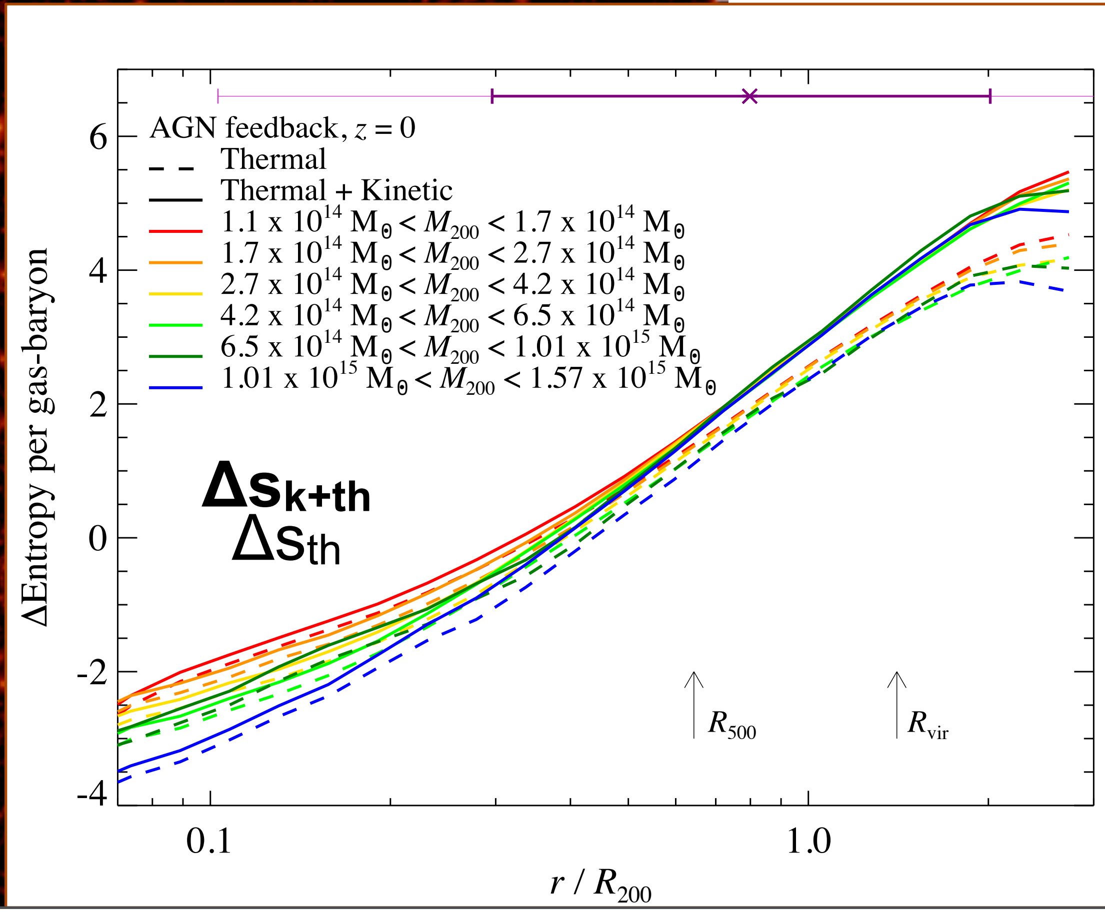
~ 190 bits/baryon

$S_{th,cl} \sim 10^{76}$

$S_{U,m+r} \sim 10^{88.6}$ ***5.2 bits/ϒ***

cf. **S_m**~1.4 bits/baryon atmosphere

after CMB+CvB, most $S_{U,m+r}$ is CIB = the waste heat from dust re-emission of starlight



Thursday, 4 October, 12

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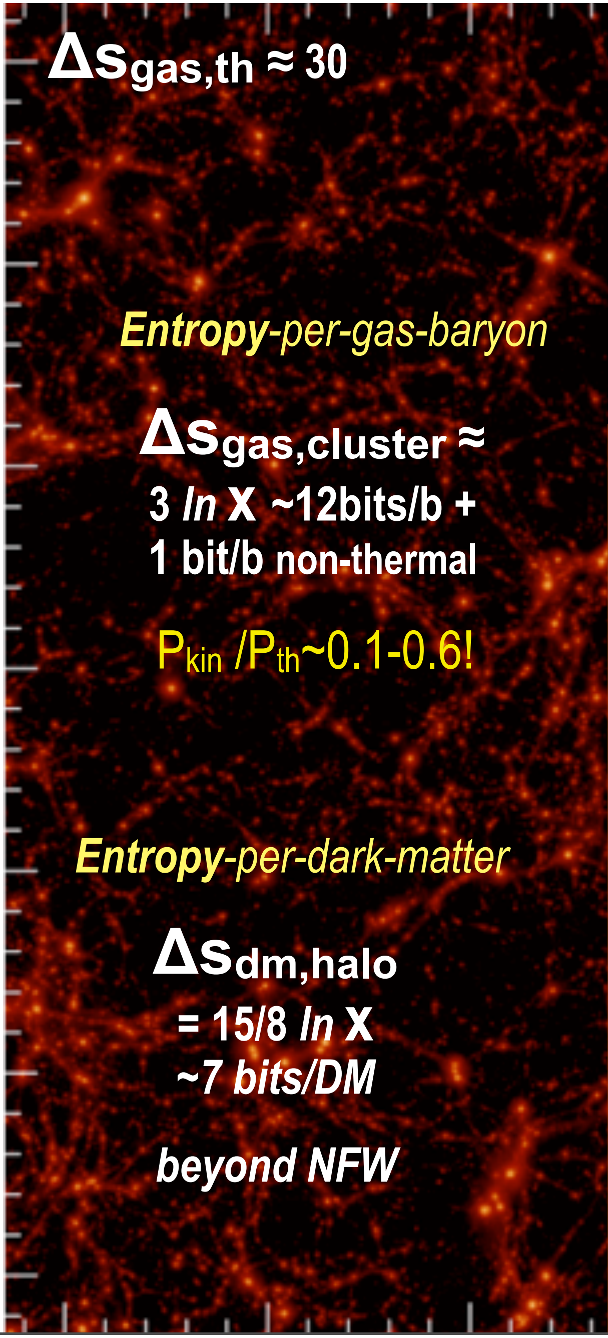
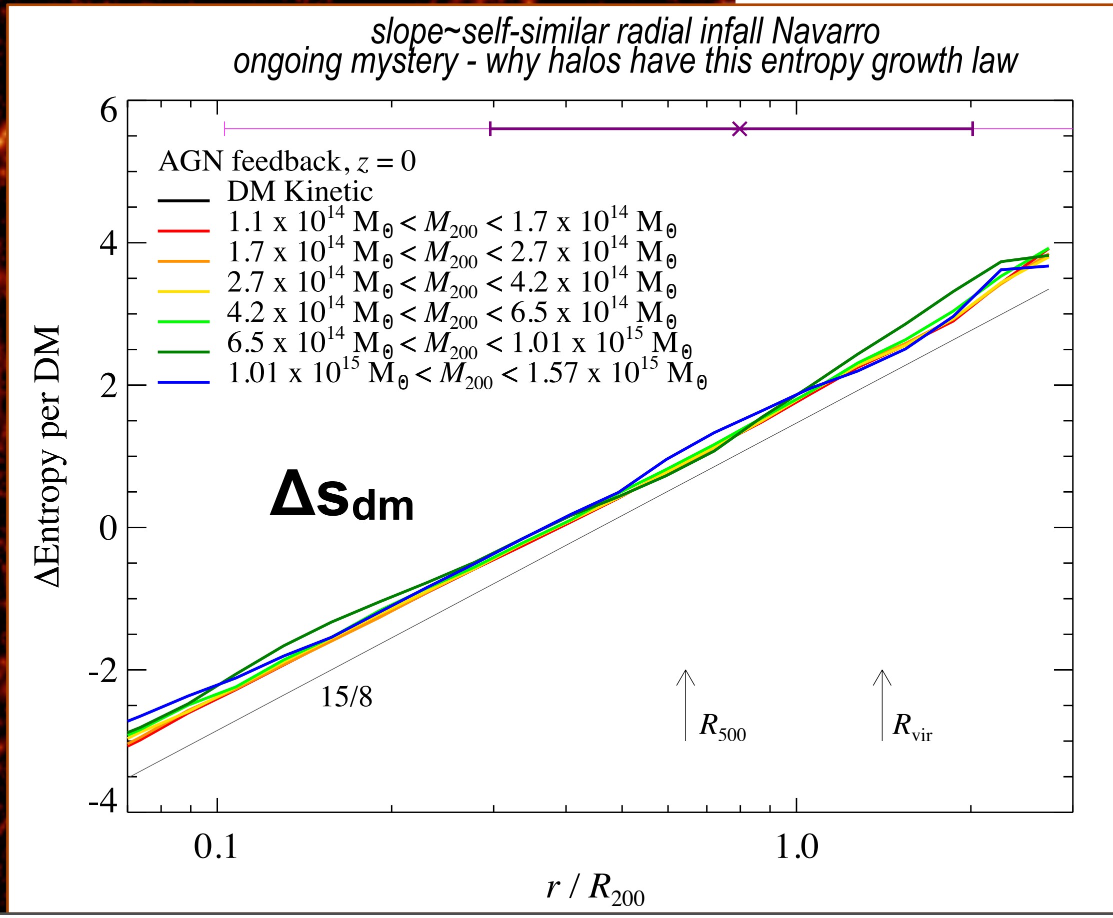
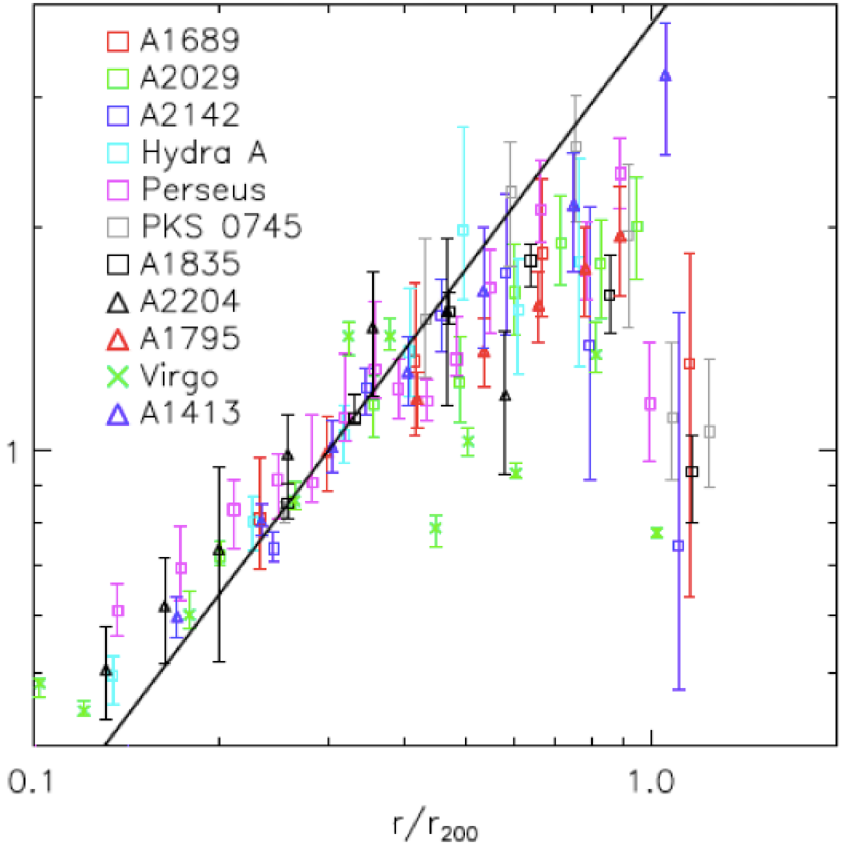
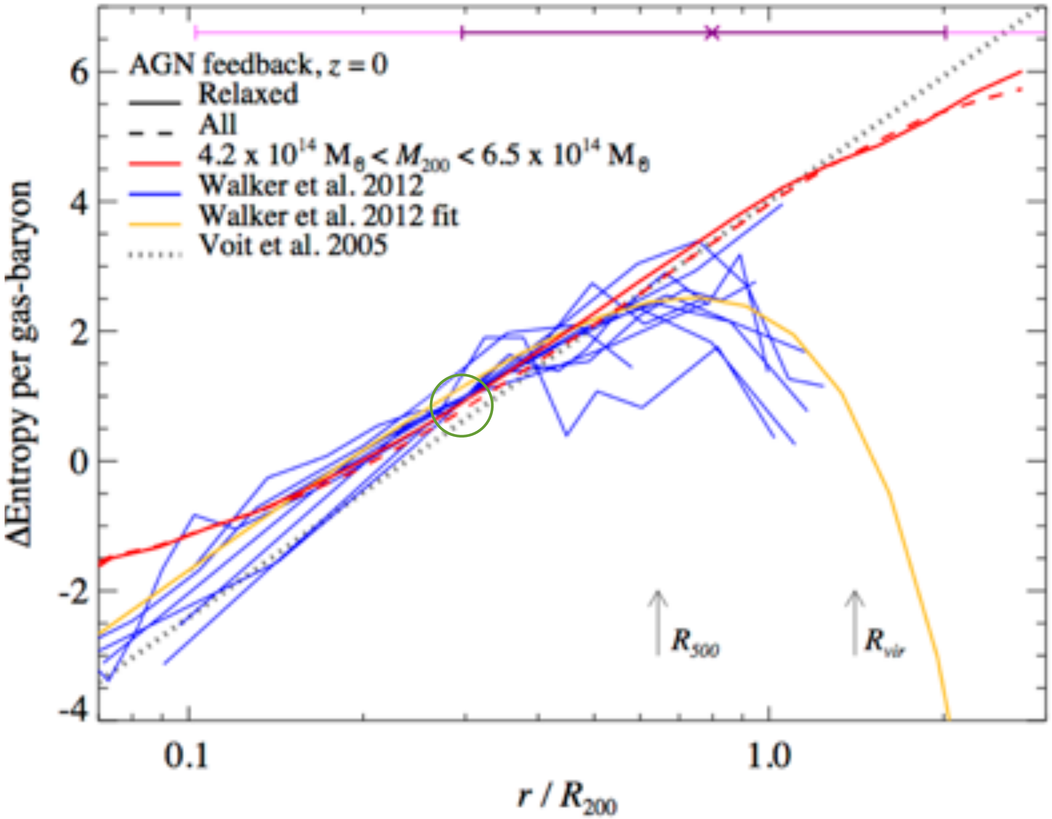




Universal Entropy Profile?

evidence for relaxed cool core clusters Walker, Fabian, Sanders, George 2012





Walker+ form $\mathbf{\Delta s_{gas,cluster} \approx 3\mathit{ln}X - X^2/\mathit{B}}$, *B a fit*

cf. Allison+11,12 $\propto$ $\mathbf{\mathit{ln}\ (1+X^2/X_{S\text{-}core}^2)}$ *used in CMB interferometry analysis*

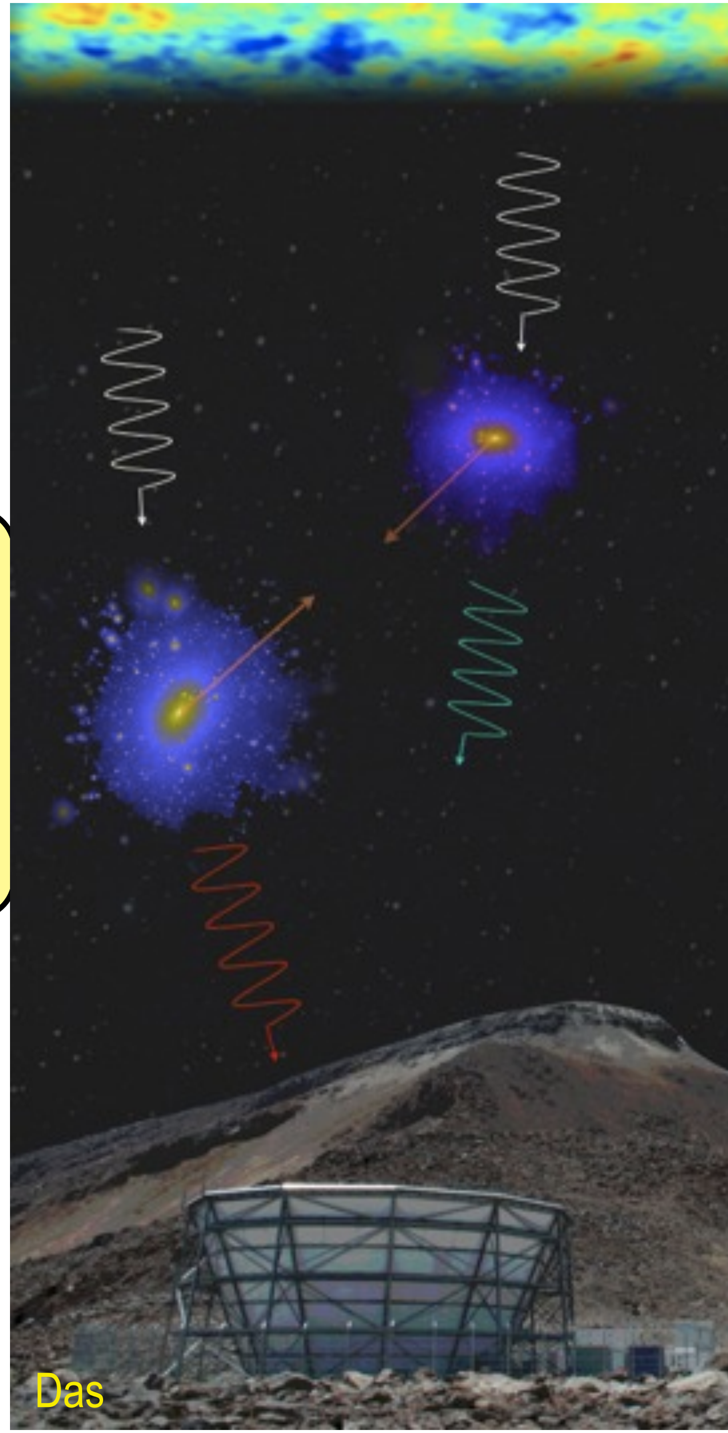
kinetic SZ:

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

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

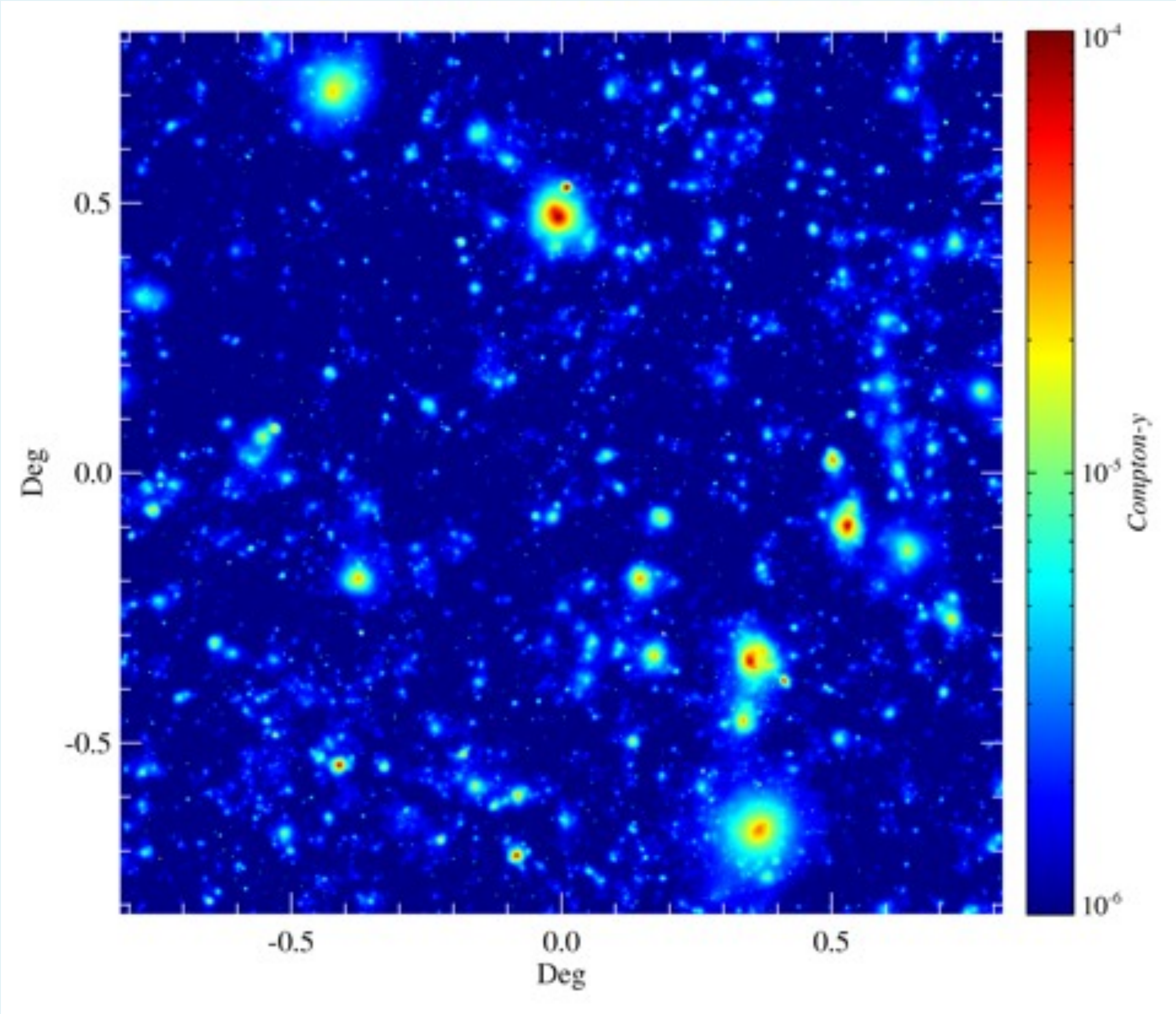
spectrally degenerate with primary anisotropies

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



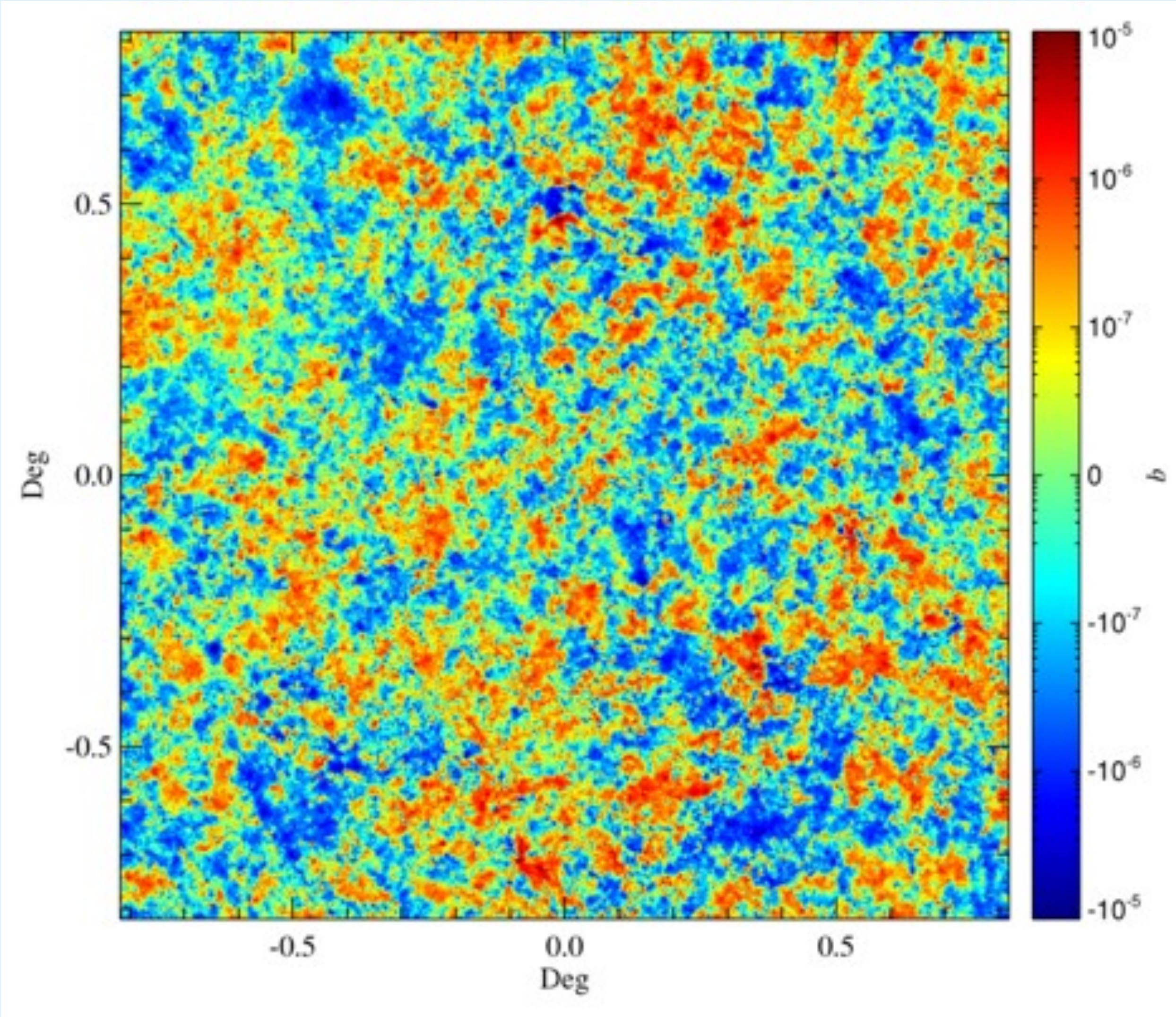
Compton-y map: Feedback

= 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)



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

spectrally degenerate with primary anisotropies

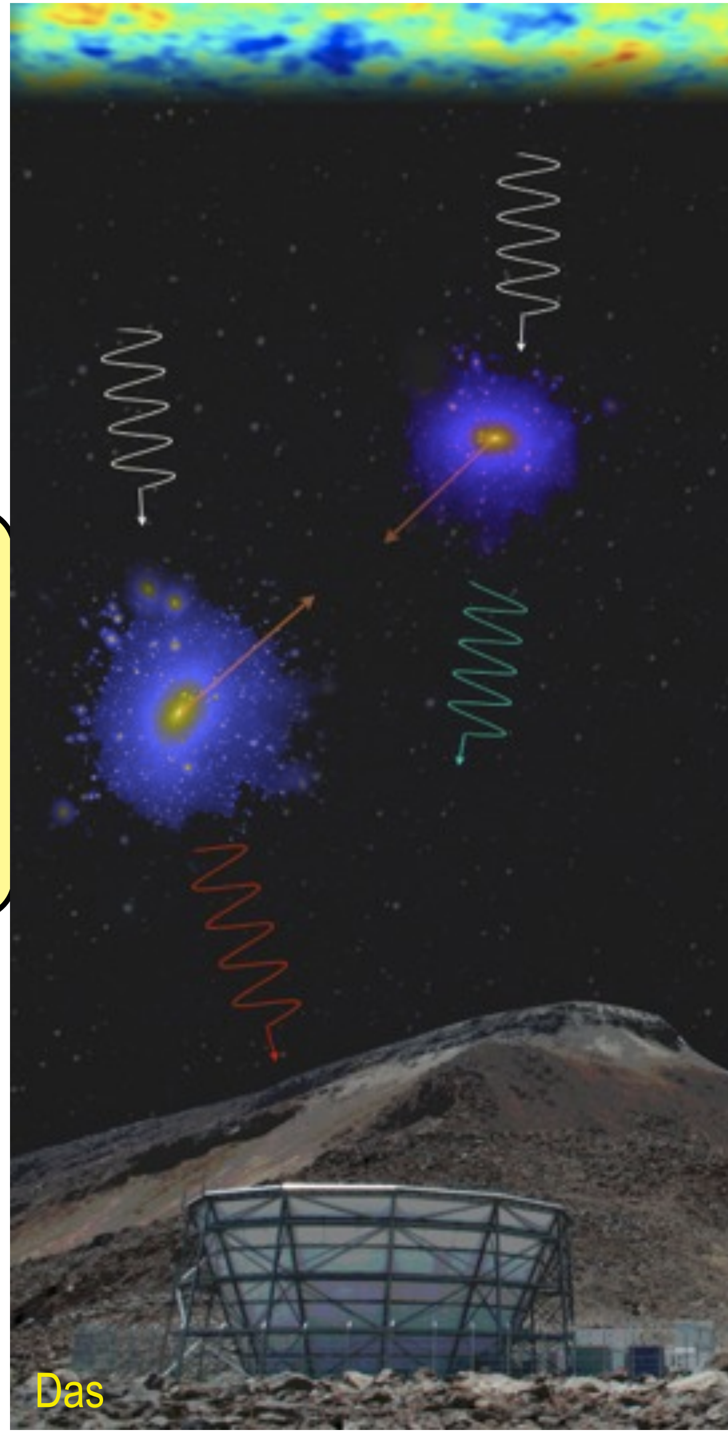
$$\int \mathbf{kSZ}(\theta,\varphi)\mathbf{d}\Omega \sim \mathbf{M}_{\mathbf{gas}}\mathbf{V}_{\mathbf{bulk}} / D_A^2$$

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.

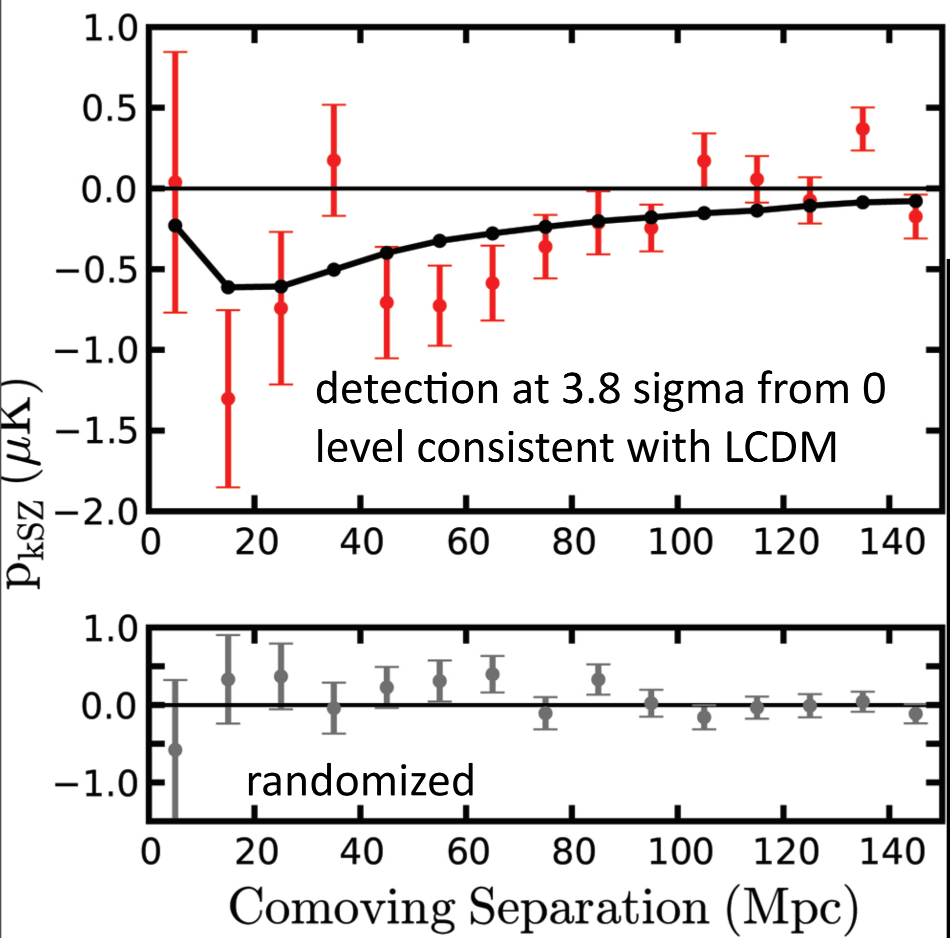
"Like any theoretical scientist proposing an observational effect, I was dreaming for almost 40 years that it would be discovered 'in the next several years,'" Sunyaev said. "It's extremely elegant that the authors were able to choose the most interesting groups of galaxies using the SDSS-III results."



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

$n_{cluster}(M_{halo}|z)$ or $n_{cluster}(Y_{SZ}, M_{lens}, Y_X, L_X, T_X, L_{cl,opt}, R_{ich}, \ldots | z$, gold-sample, thresholds) + C_L^{SZ}(cuts) + $\xi_{cc}(r|n_{cl})$ + f_{gas} deliver valuable cosmic gastrophysics.

Will cls deliver **fundamental physics**

dark energy EOS?? σ_8 even? primordial non-Gaussianity???

theory/obs dispersion/systematics assessment is critical. robust measures

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

$P_{\rho\rho}(k \sim 1/4 h^{-1}\mathrm{Mpc})$ aka σ_8 via n_{cl} f_{gas} ... *ready for prime time? mock-ing!!*

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

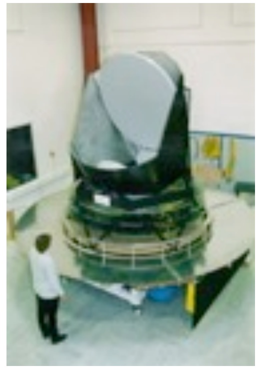
53+35 cls **(>=40)**

QUaD @SP

230 cls (>=1000)

Planck09.4

52+ bolometers
+ HEMTs @L2
9 frequencies



WMAP @L2 **to 2010**

2004 2006 2008 **LHC** 2011

Bpol @L2

2005 2007 **224** (>=750) 2009

>96
OVRO /BIMA array
38 cls

80s-90s
Ryle
OVRO

Acbar@SP
~1 blind

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

AMI
7+1 cls >=50+25

AMIBA
6 cls

APEX
~400 bolos@Chile
~25 cls

GBT Mustang
4 cls (~25 CLASH)

SPT
1000 bolos
@SPole

ACT **23+68~91 cls**
3000 bolos
3 freqs @Chile

SCUBA2
12000 bolos
JCMT @Hawaii

SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico