Probing Intermittency in the Cosmic Web & SuperWeb

MOCK*ing* HEAVEN

Dick Bond

Zeldovich 100th,
Moscow & Tallin IAU 2014

CIFAR
CANADIAN INSTITUTE FOR ADVANCED RESEARCH

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

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MOCK*ing* HEAVEN

painting the Peak-Patch Picture of Cosmic **CCAT***alogues: Eulerian & Lagrangian halos*

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t/k Sunyaev-Zeldovich application

Zeldovich 100th, Moscow & Tallin IAU 2014

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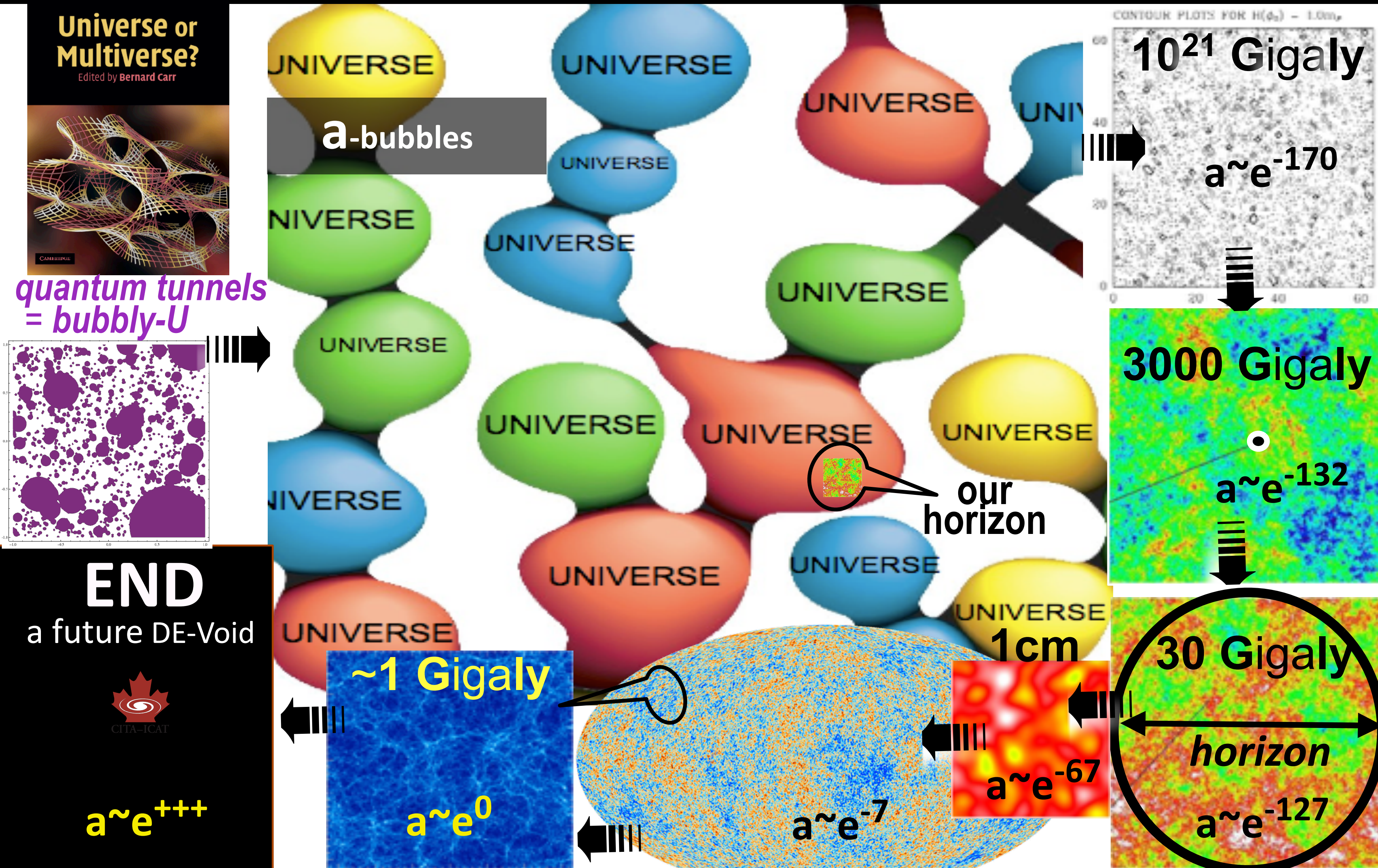
ultra-Ultra Large Scale Structure of the Universe

Horizons: the ultimate-speed constraint on light & information



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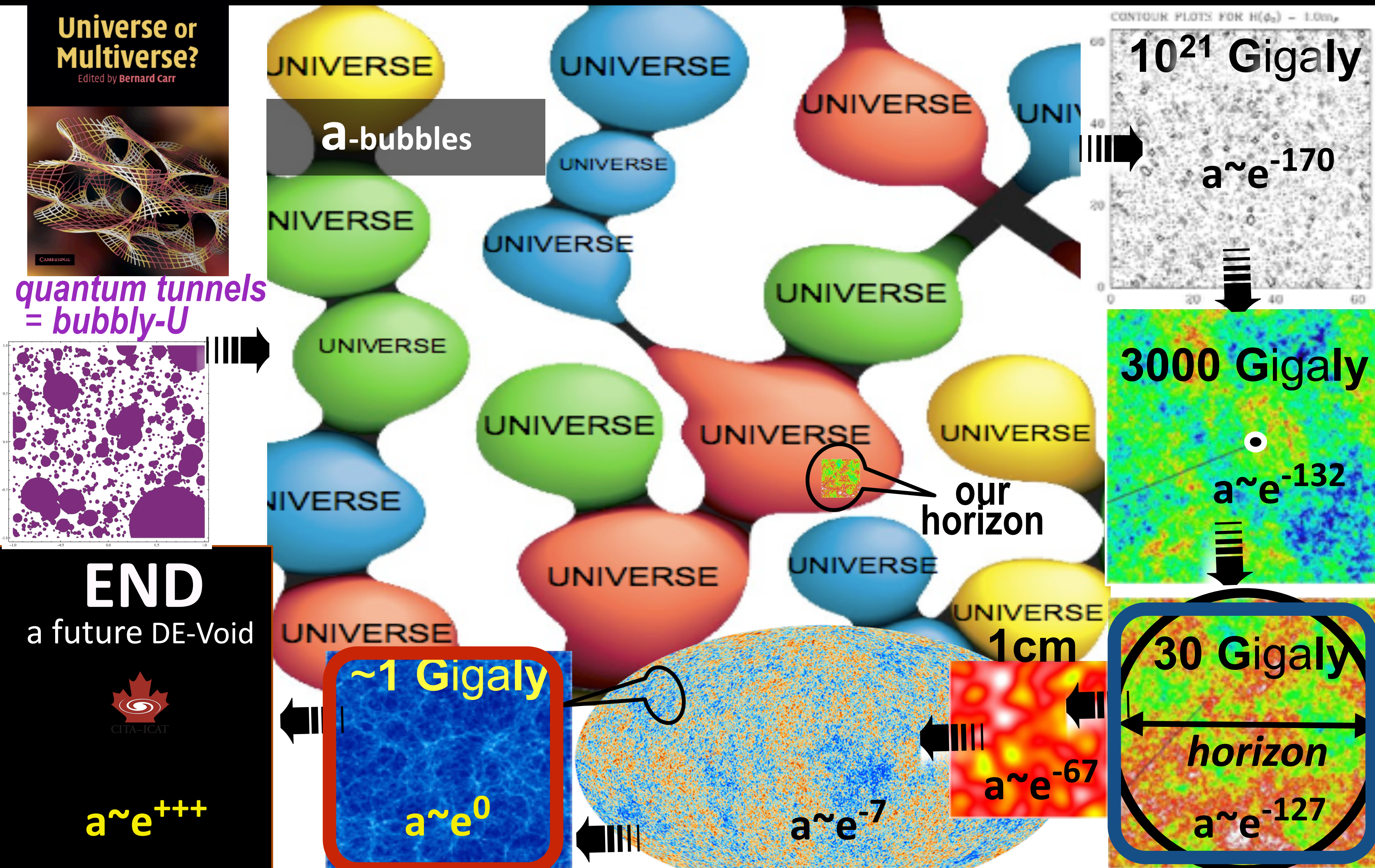


Super-duper LSS & the Super-WEB aka the gravitational potential web ~ primordial 3-curvature web *cf.* the density web ~ strain web

$dX^j = (V^i - HX^i)\, dt + a\mathbf{e}_J{}^j(\mathbf{r},t)\, d\mathbf{r}^J$ $\mathbf{e}_J{}^j \equiv exp(\boldsymbol{\varepsilon})_J{}^j$

$\mathbf{e}$= *drei*bein, triad, deformation tensor, Lagrangian-space metric $a^2\mathbf{e}\mathbf{e}^\dagger$

$\boldsymbol{\varepsilon}$=strain tensor $\propto$ **tidal** tensor $\Rightarrow$ *ln* $\boldsymbol{\rho}/\langle\boldsymbol{\rho}\rangle$= -Trace $\boldsymbol{\varepsilon}$

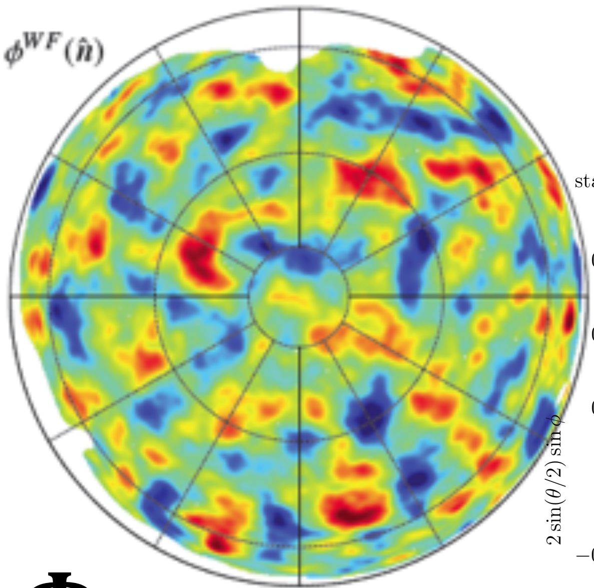
Scale space: resolution = the 5th dimension

Planck1.3 CMB Lensing: reconstructed projected Φ_N gravitational potential

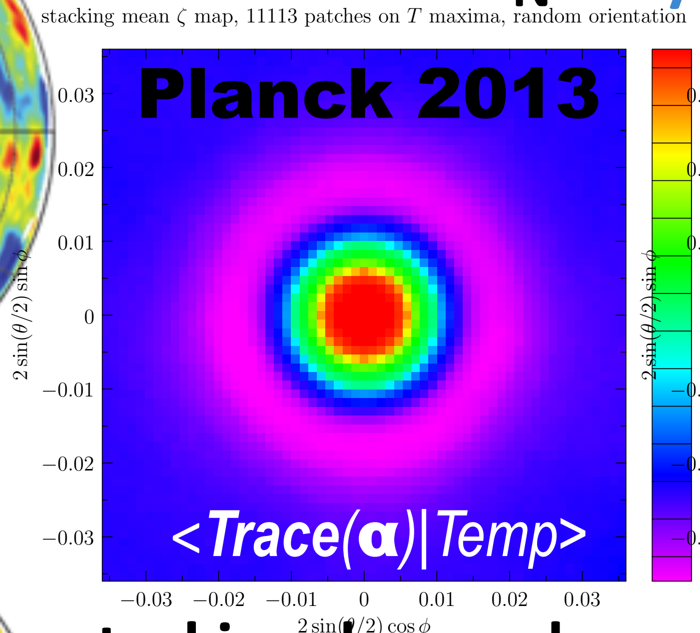
~ dark+baryonic matter map, mean-field map = Wiener filter (beware: fluctuations about mean-field)

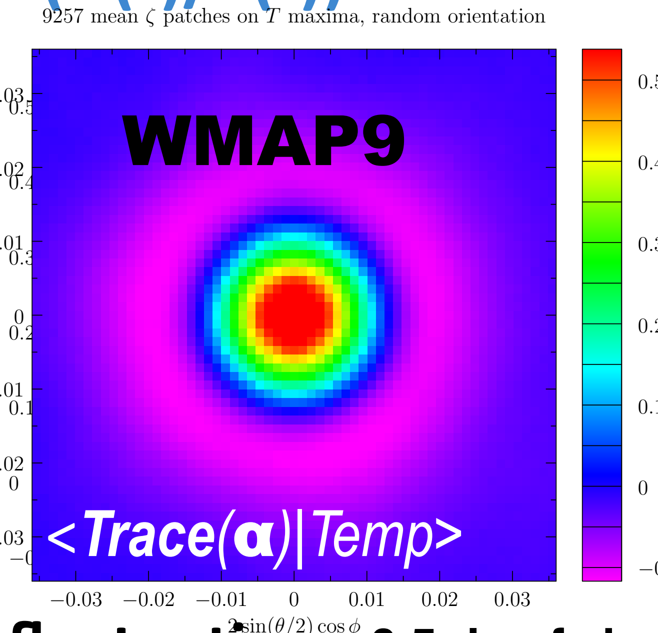
primordial isotropic strain Tr α

Φ_N =-3/5(D(t)/a(t)) Tr α

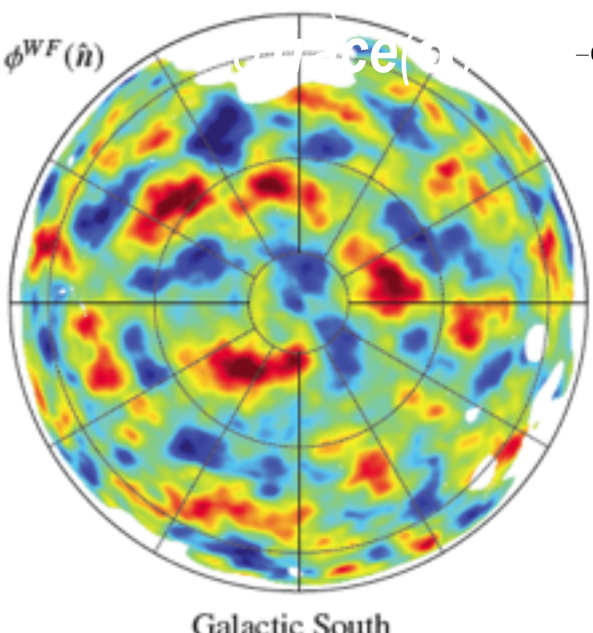


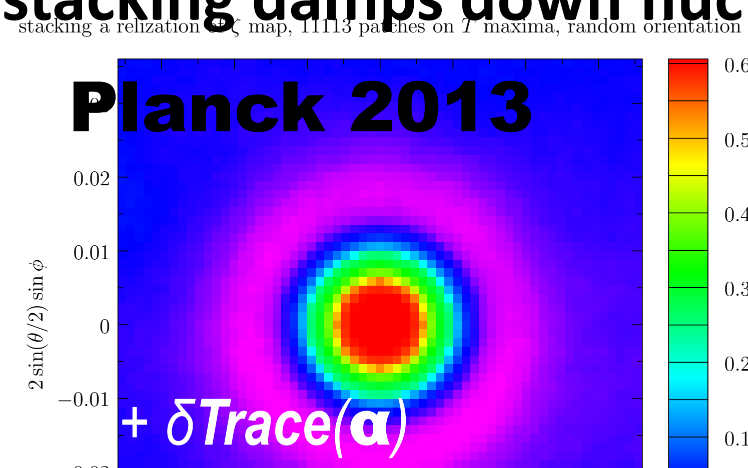
Φ_N





stacking damps down fluctuations, 0.5 deg fwhm





reconstruction of the Early Universe

mean-field

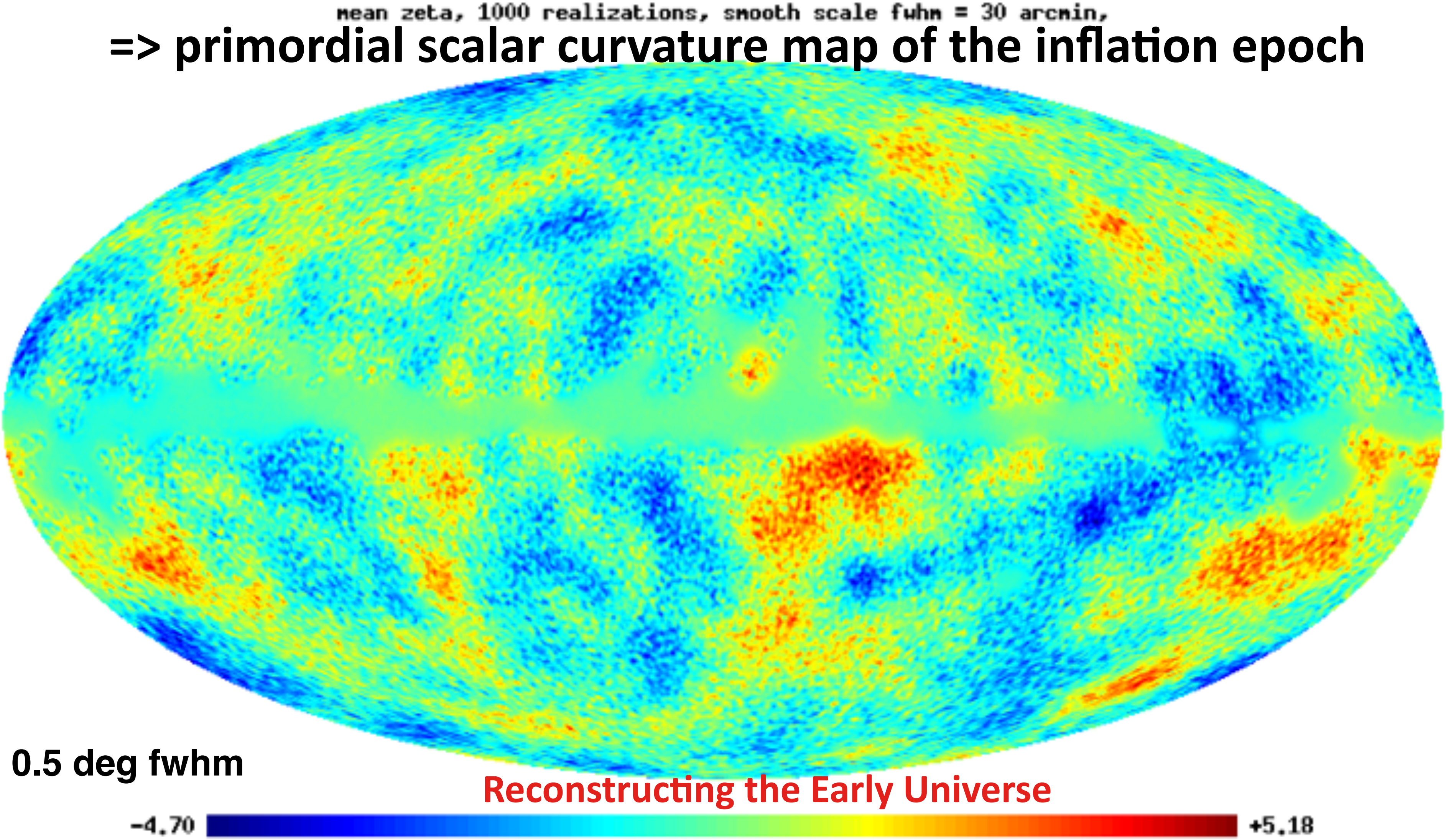
constrained-correlation

Compton differentiable-visibility mask on α

reveals map of **primordial isotropic strain /phonons**

$\int d$ ***visibility****(distance)* ***<Trace(α)|Temp>*** *(angles, distance)*

=> primordial scalar curvature map of the inflation epoch



0.5 deg fwhm

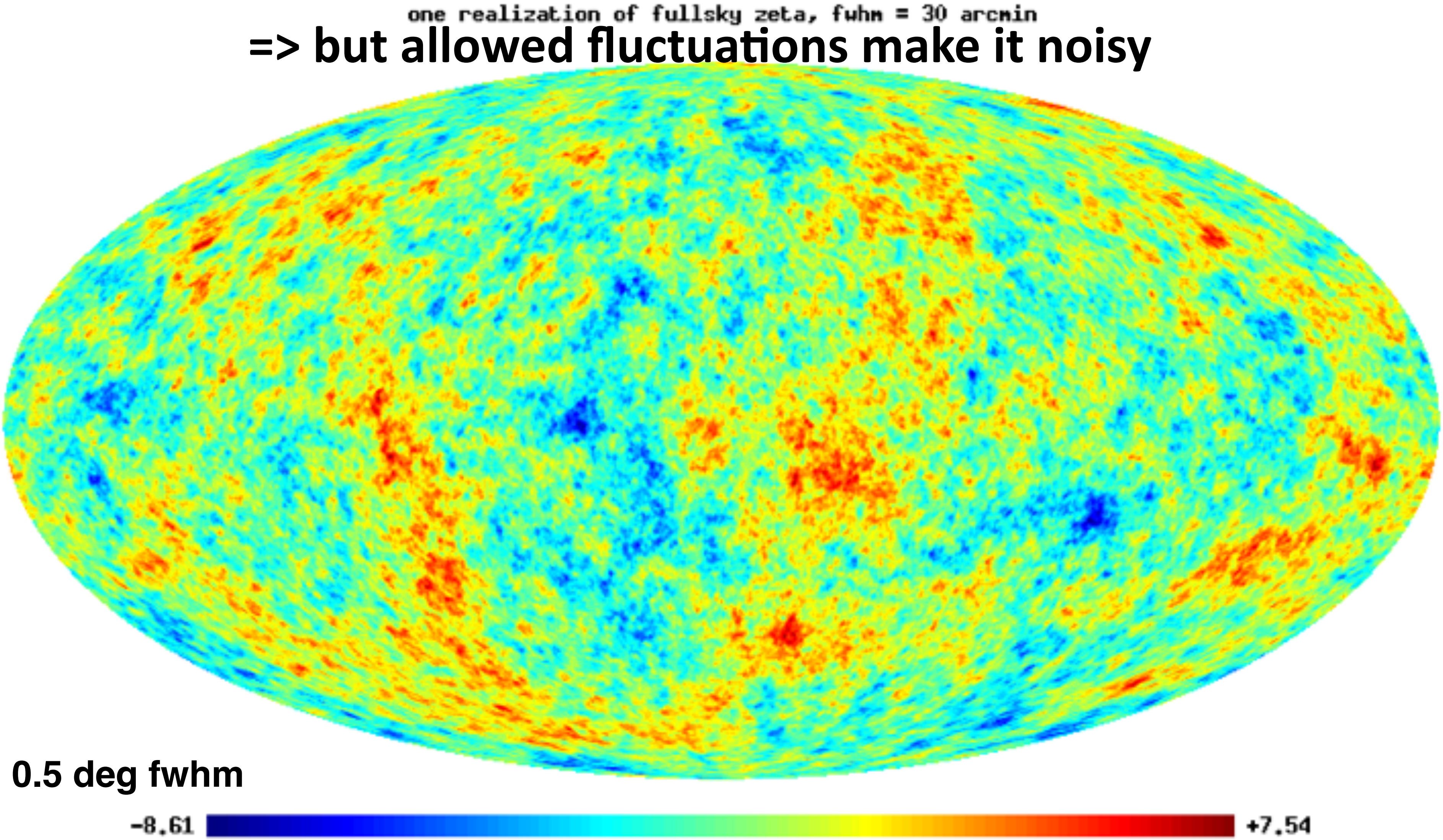
Reconstructing the Early Universe

visibility mask

reveals map of **primordial isotropic strain /phonons**

$\int d$ ***visibility****(distance)* $<\mathbf{Trace}(\boldsymbol{\alpha})|Temp> + \delta\mathbf{Trace}(\boldsymbol{\alpha})$

=> but allowed fluctuations make it noisy



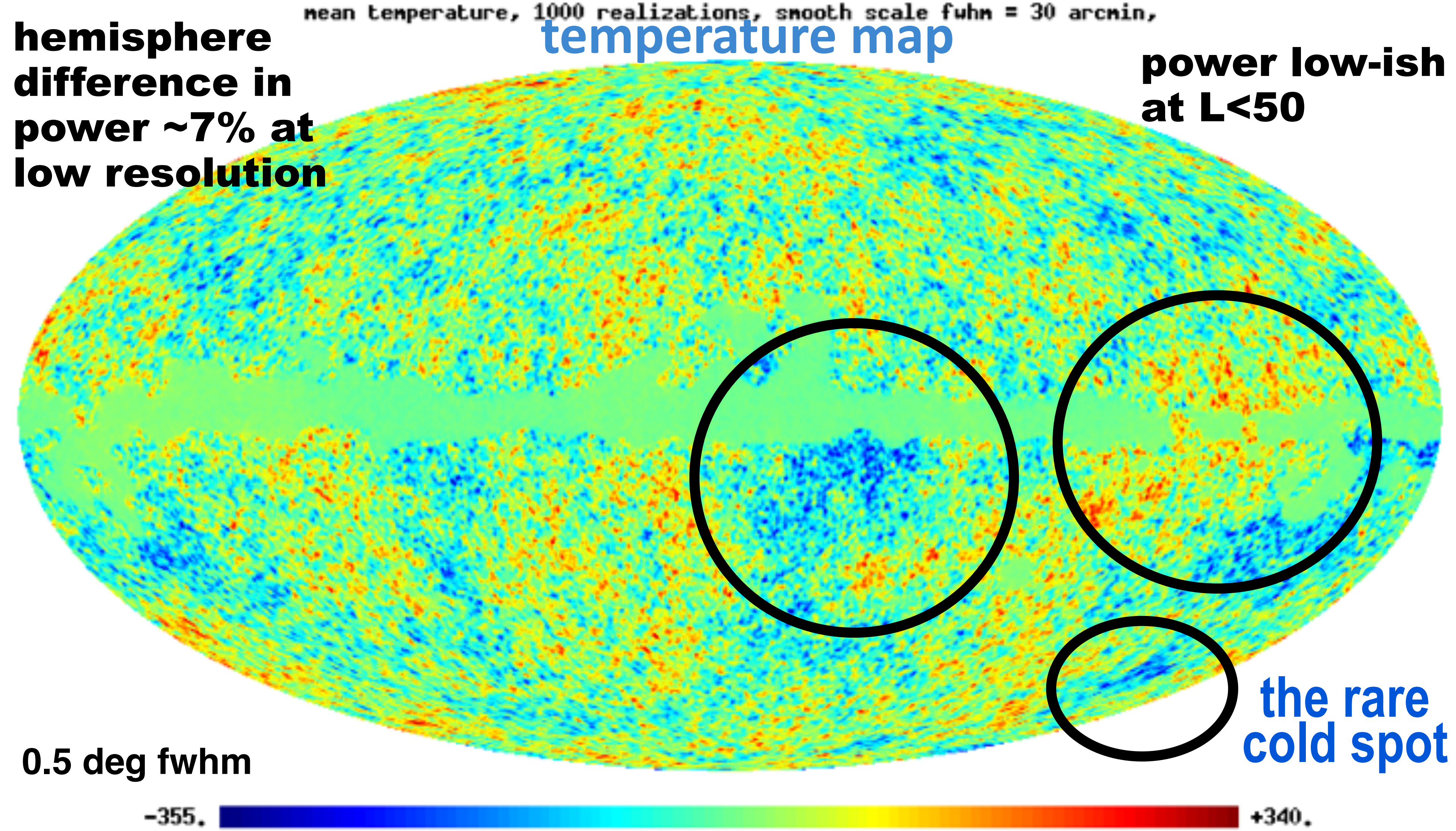
0.5 deg fwhm

Reconstructing the Early Universe

visibility mask

Gaussian to high precision for high multipole, anomalies at low multipoles, non-Gaussian, anisotropic

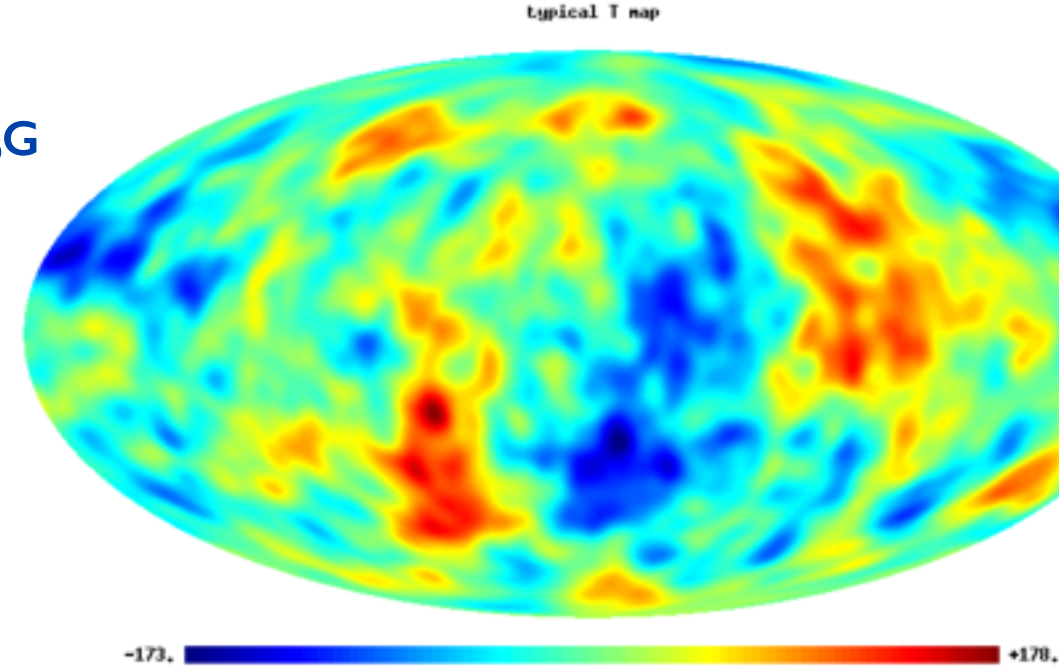
anomalies => inflation COMPLEXITY at t~10^{-36} seconds?



Grand Unified Theory of Anomalies? TBD

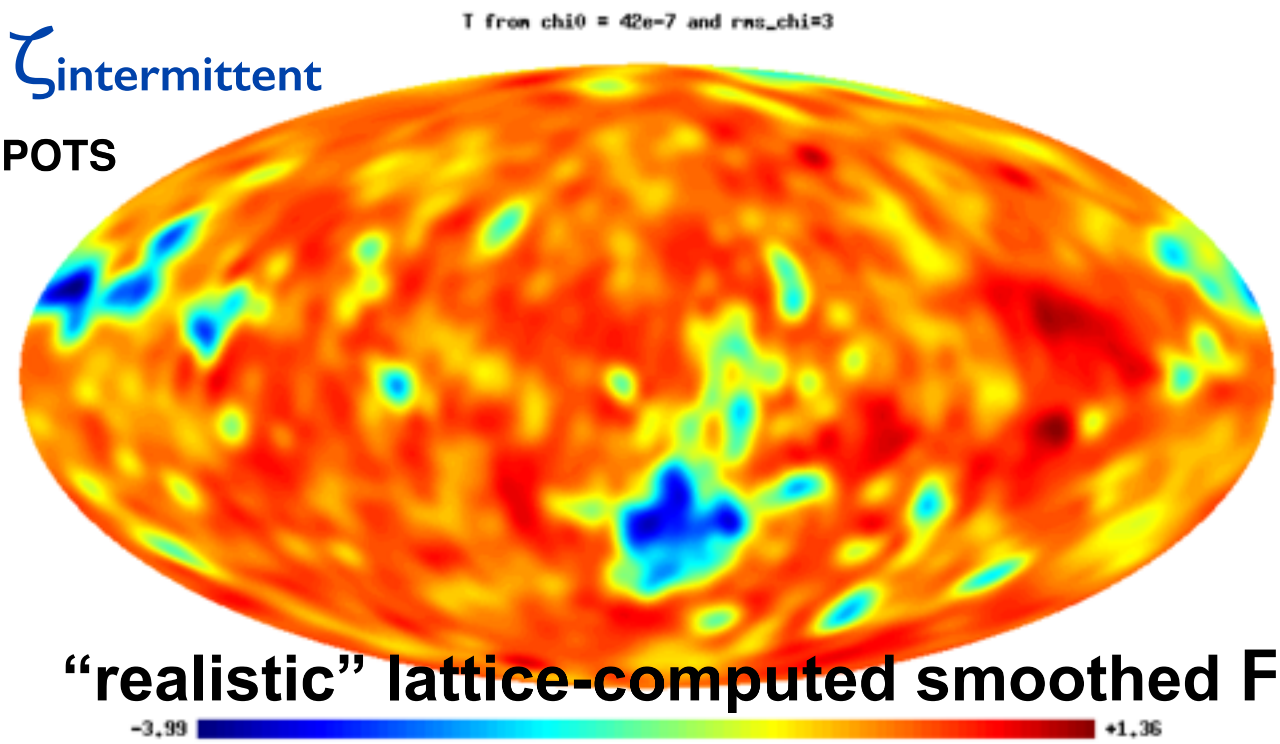
intermittent *strain-power bursts (in curvature)?*

T from ζ_G



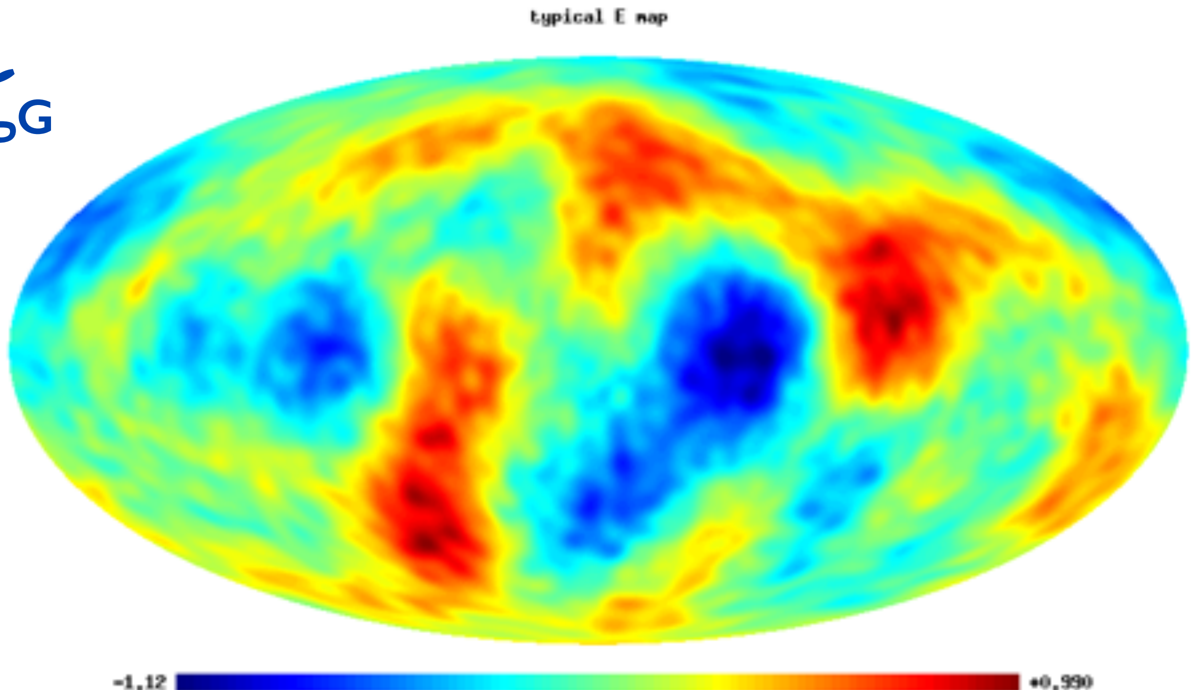
T from $\zeta_{intermittent}$

T COLD SPOTS



“realistic” lattice-computed smoothed F_{NL}

E from ζ_G



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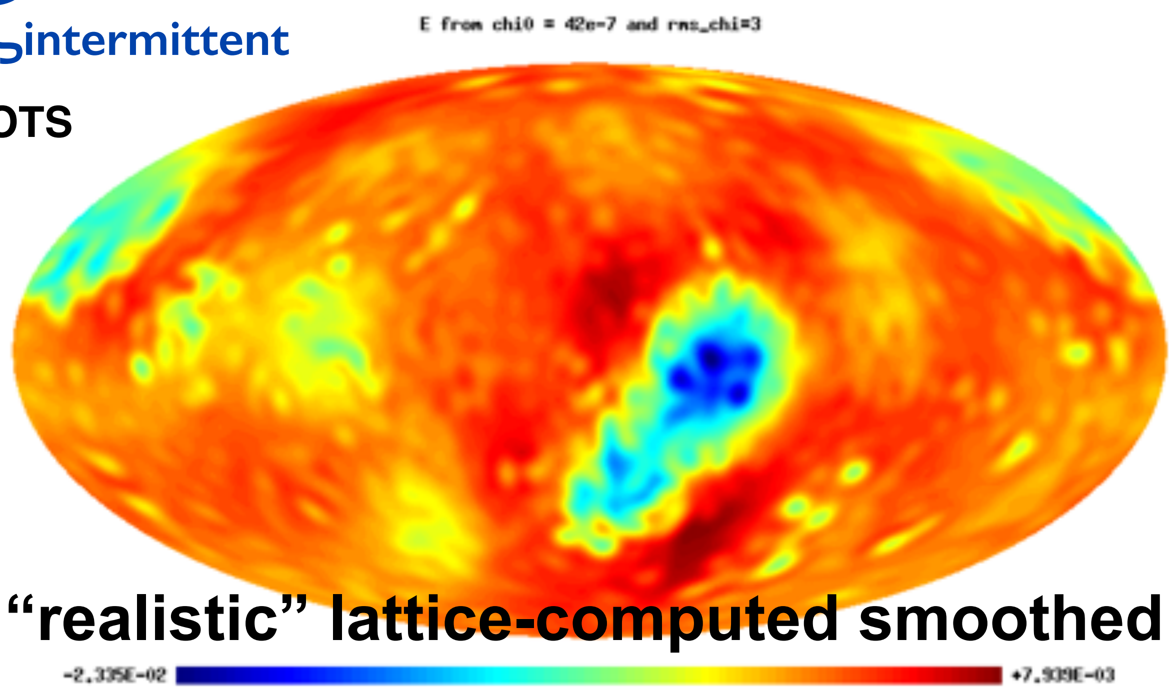
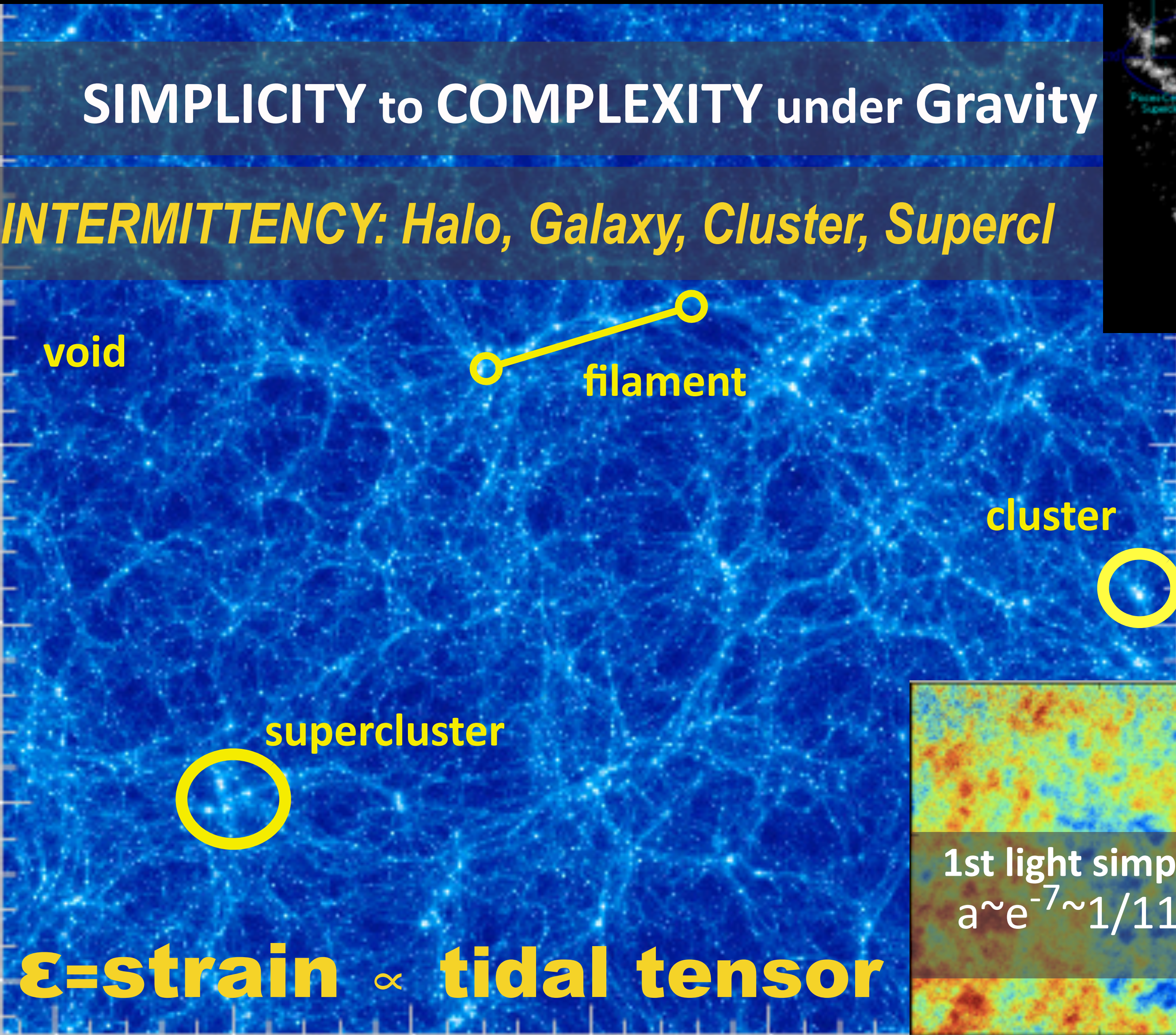
E COLD SPOTS

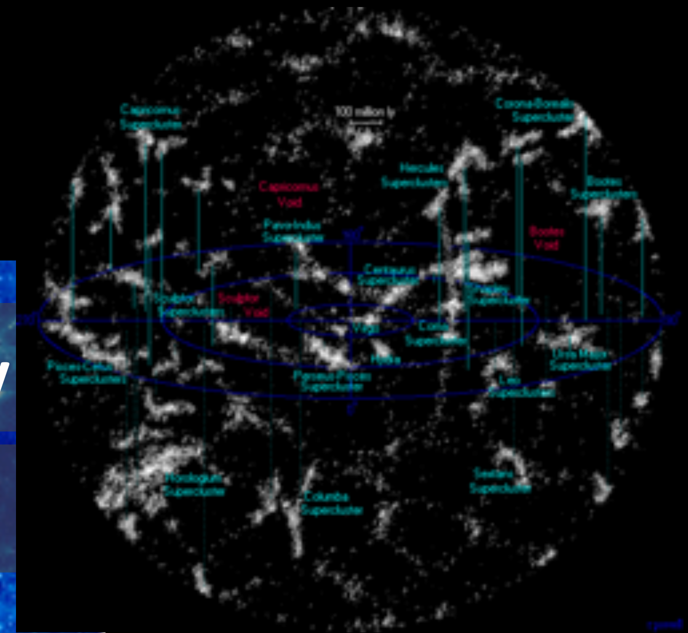


"realistic" lattice-computed smoothed F_{NL}

Simulation of the 7^+ numbers begets the Cosmic Web of clusters

now a~1 & galaxies then a~1/4

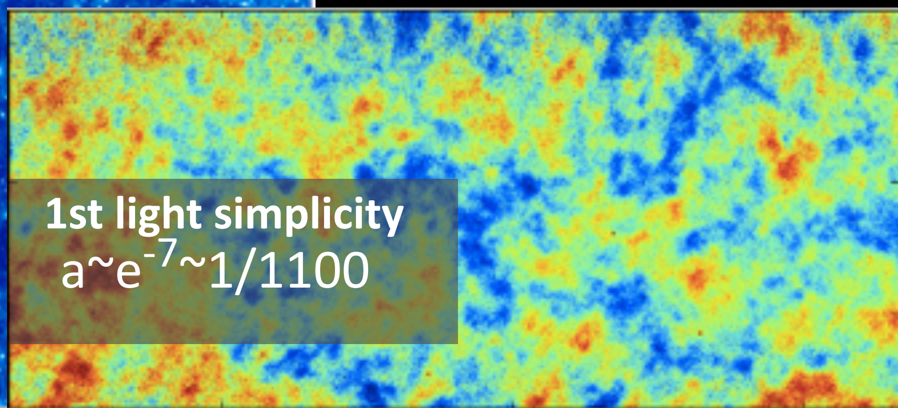




~ billion light years

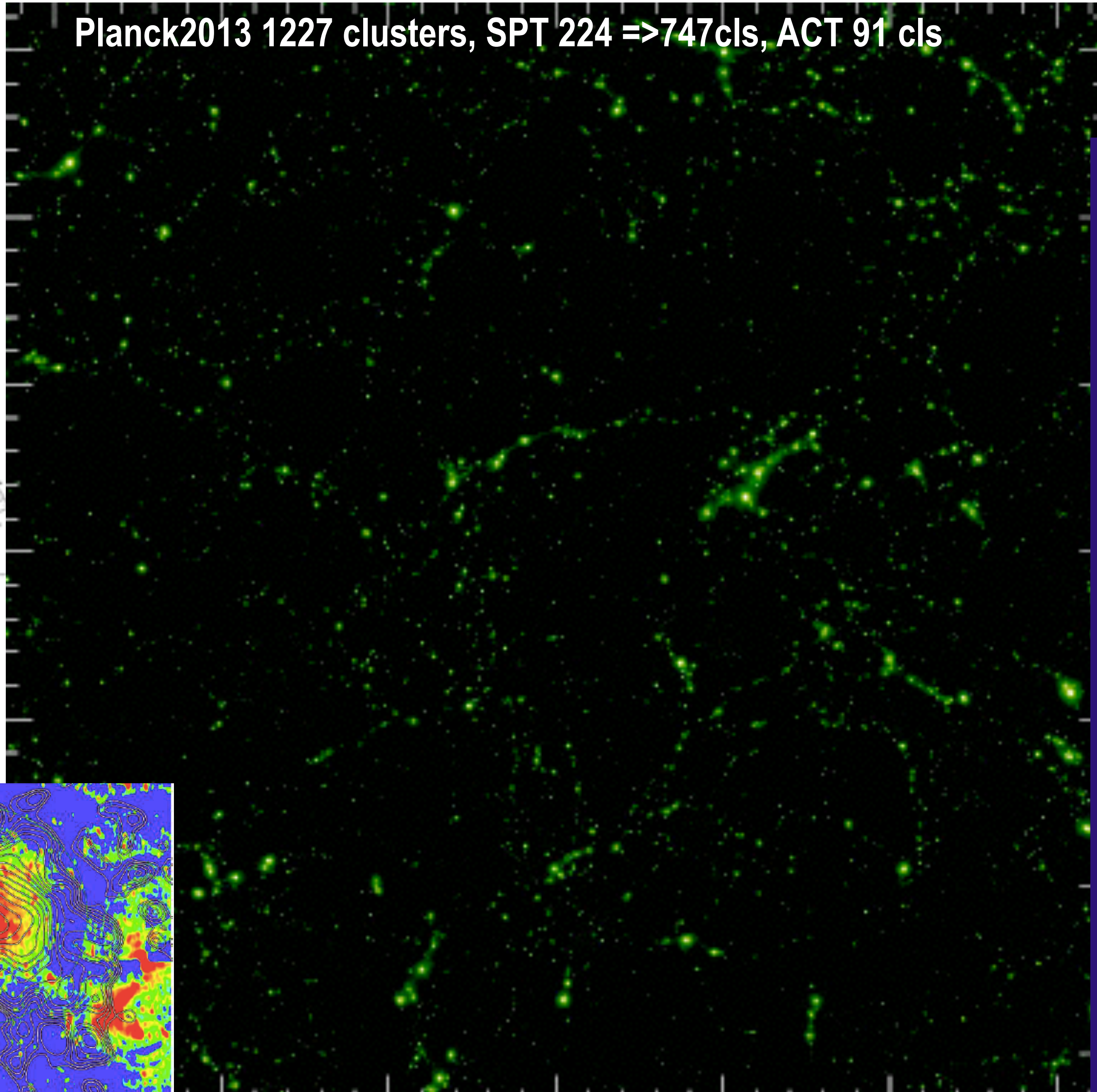
state of the art simulations
a~1 to 1/1.1

ordinary matter
dark matter
dark energy

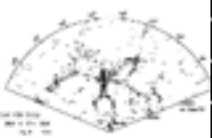


pressure intermittency *in the cosmic web, in cluster-group concentrations probed by* **tSZ**

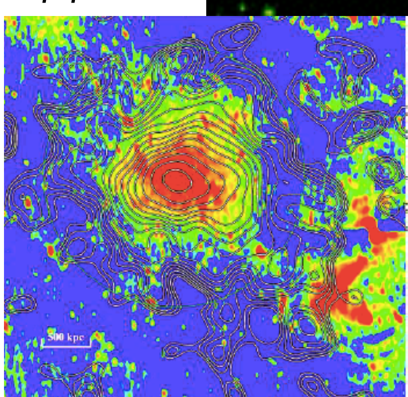
Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)



$p_e(x,t)$



Planck's
Coma
2012.08
pip10



the ***thermal Sunyaev Zeldovich Probe***

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

Compton cooling of hot cosmic web gas

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

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

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

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

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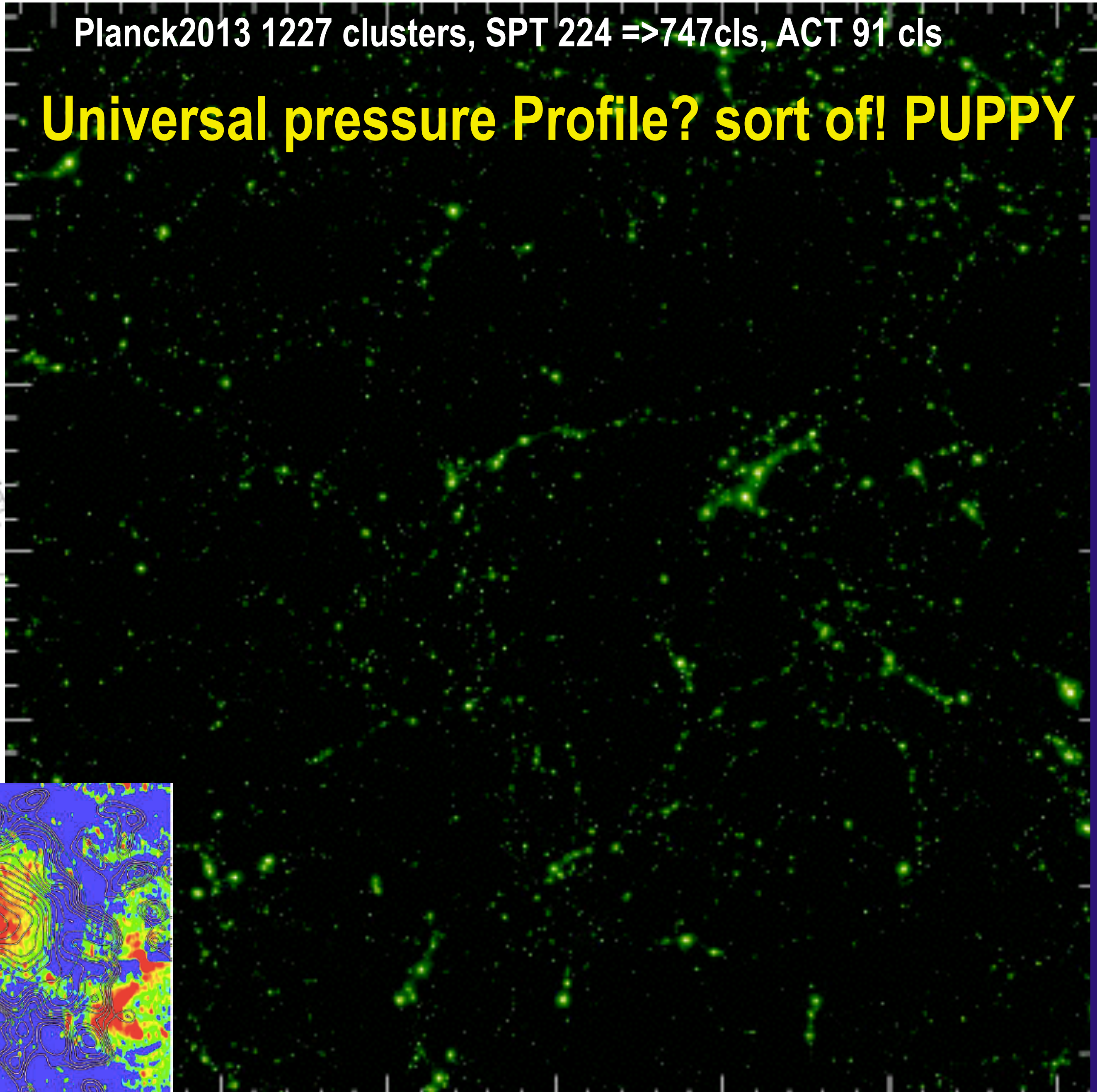

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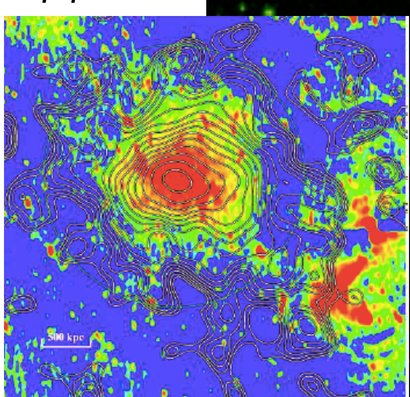

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entropy intermittency *in the cosmic web, via gravitation-induced shocks (then E/S-feedback)*

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

400 Mpc

ΛCDM

WMAP5

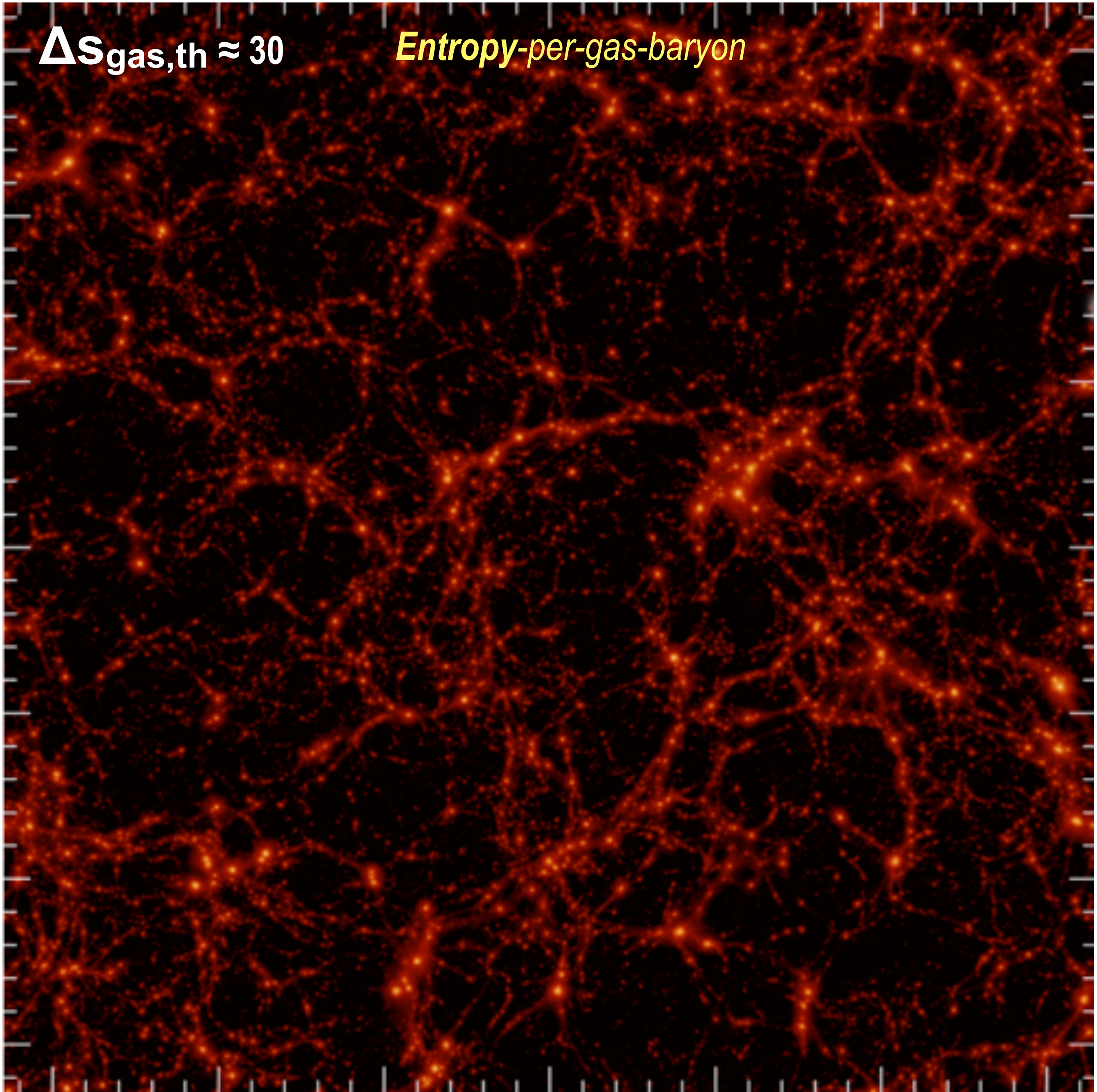
gas pressure

Gadget-3
SF+
SN E+
winds
+CRs

512^3

BBPSS10

BBPS1,2,3,4,5



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

CMB gets entangled in the cosmic web

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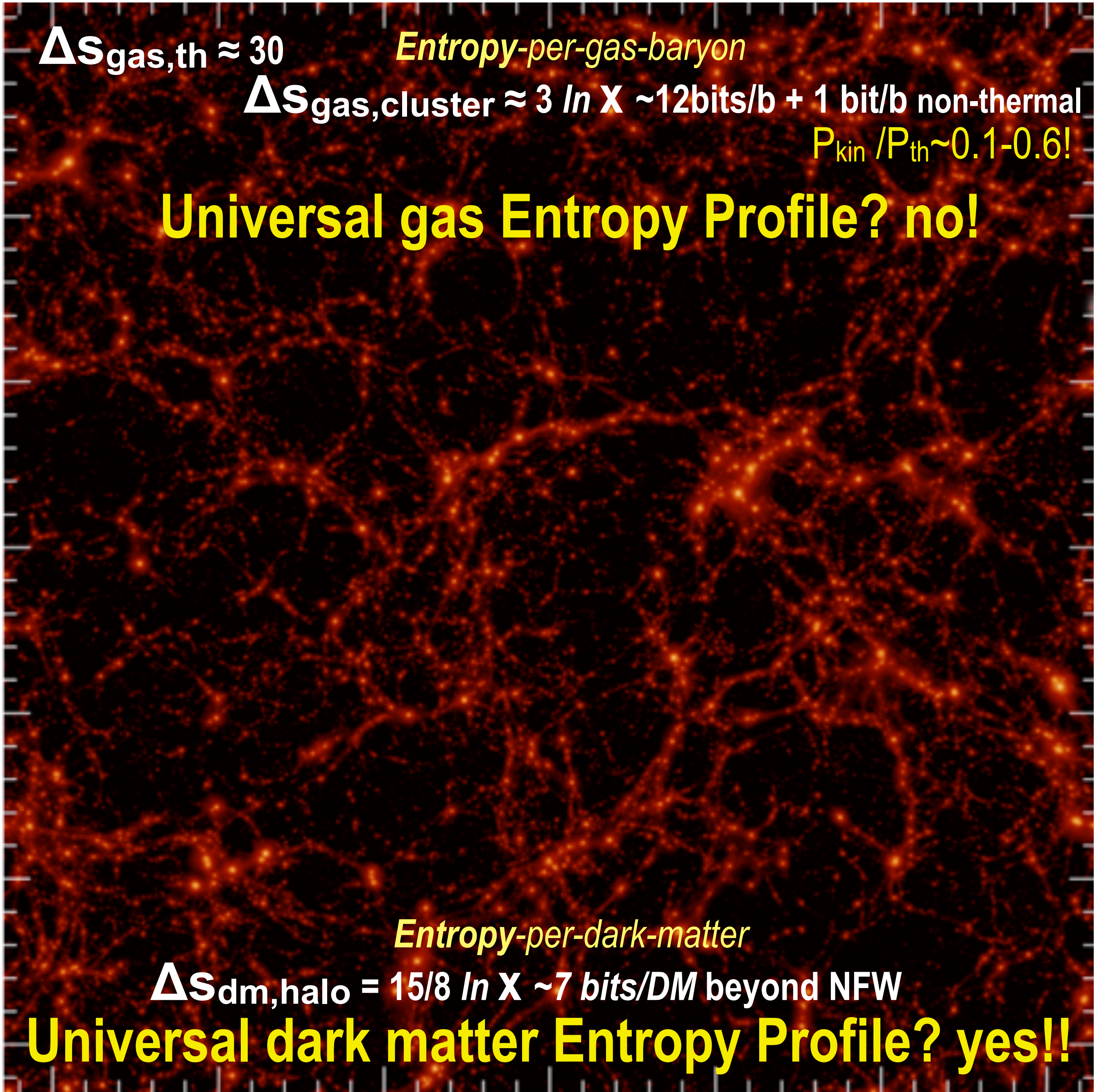
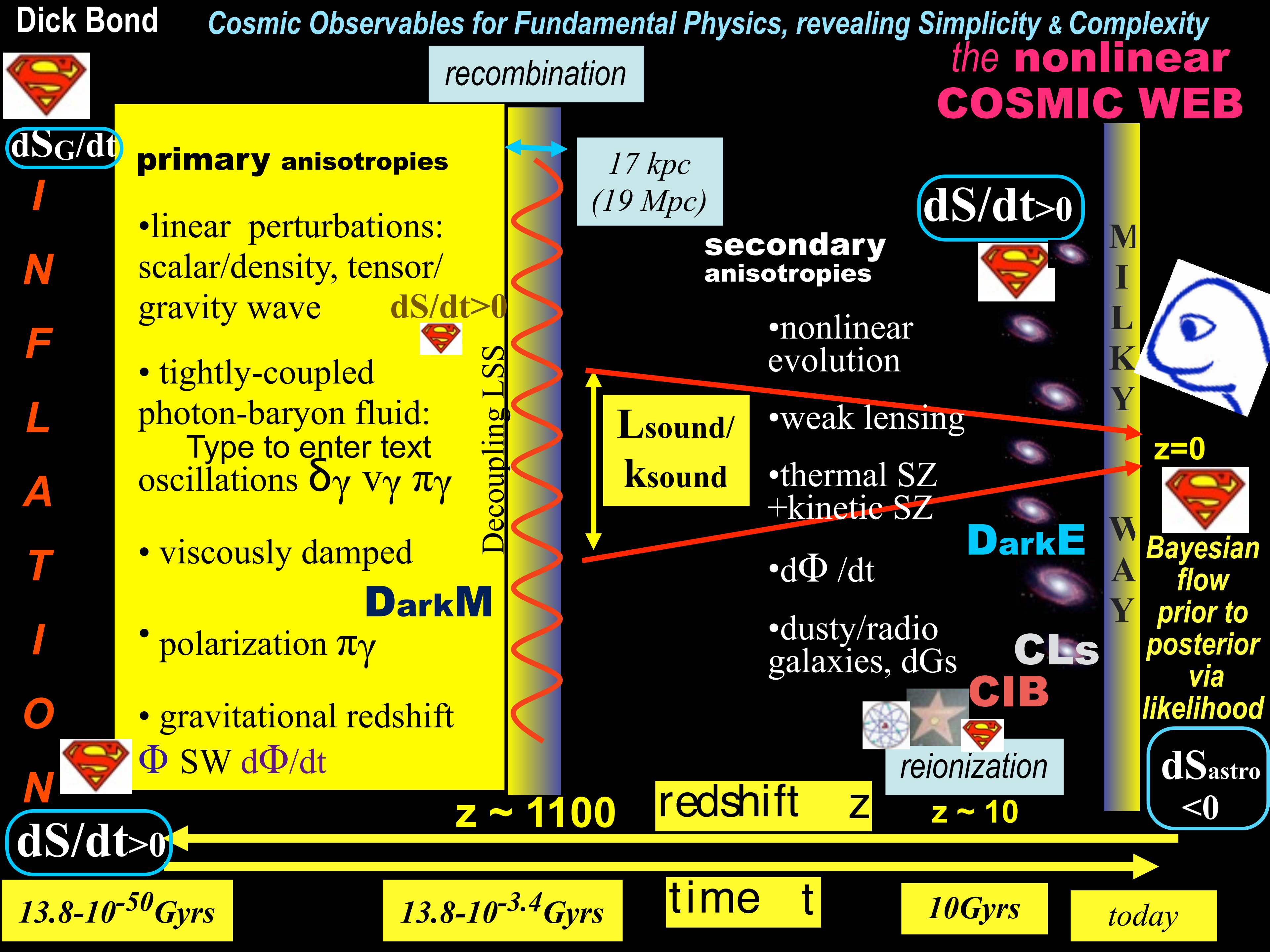
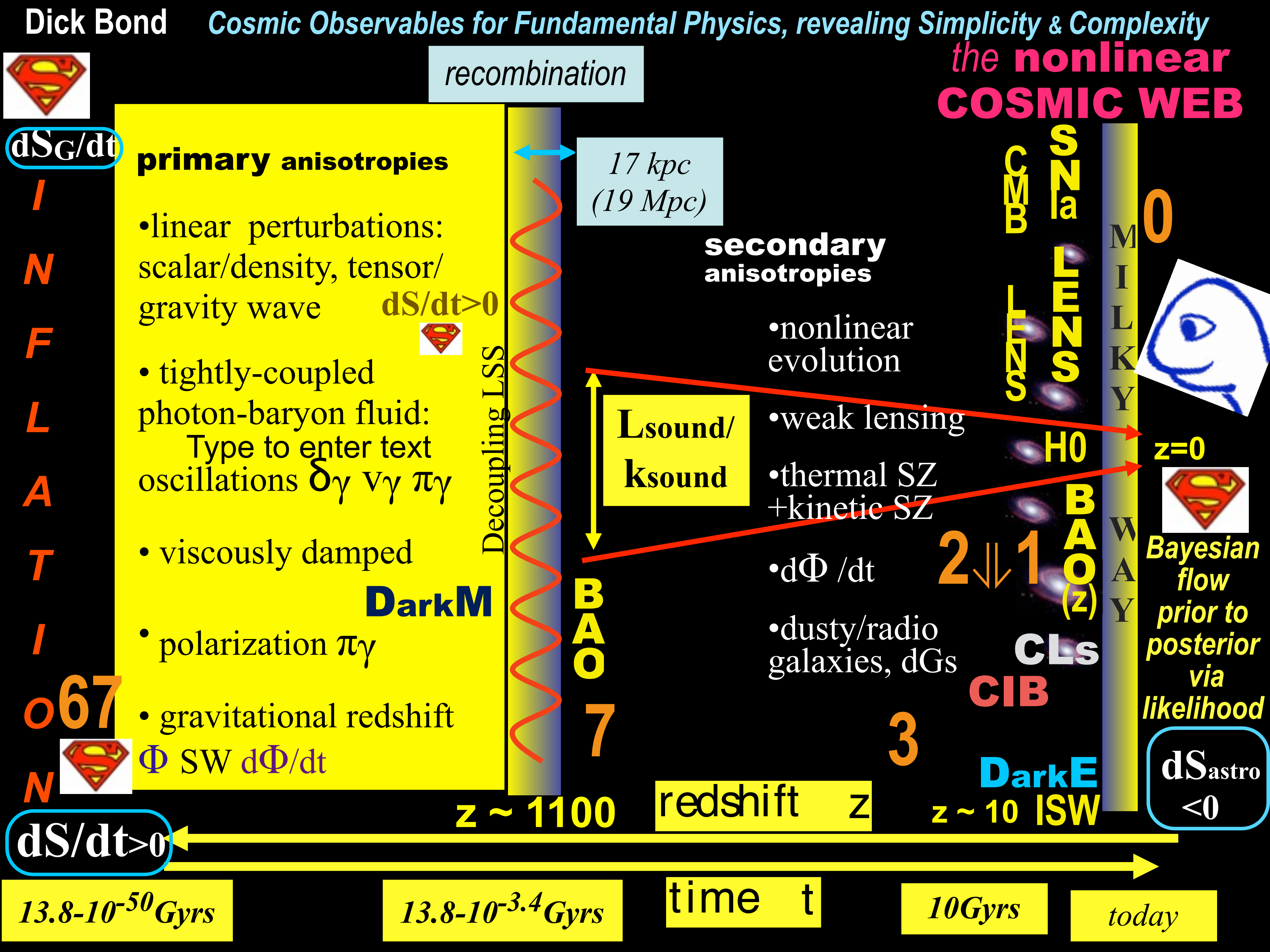




Dick Bond
Cosmic Observables for Fundamental Physics, revealing Simplicity & Complexity
the nonlinear COSMIC WEB
recombination
dSG/dt
INFLATION
primary anisotropies
•linear perturbations: scalar/density, tensor/ gravity wave
dS/dt>0
• tightly-coupled photon-baryon fluid: oscillations δγ vγ πγ
Type to enter text
• viscously damped
DarkM
• polarization πγ
• gravitational redshift
Φ SW dΦ/dt
Decoupling LSS
17 kpc (19 Mpc)
Lsound/ ksound
dS/dt>0
secondary anisotropies
•nonlinear evolution
•weak lensing
•thermal SZ +kinetic SZ
•dΦ /dt
•dusty/radio galaxies, dGs
DarkE
CLs
CIB
reionization
MILKY WAY
z=0
Bayesian flow prior to posterior via likelihood
dSastro <0
z ~ 1100
redshift z
z ~ 10
dS/dt>0
time t
13.8-10^-50 Gyrs
13.8-10^-3.4 Gyrs
10Gyrs
today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•thermal SZ +kinetic SZ
•dΦ /dt
•dusty/radio galaxies, dGs
3
CMB
SN Ia
LENS
LENS
H0
BAO (z)
2⇓1
CLs
CIB
DarkE
0
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Bayesian flow prior to posterior via likelihood
dSastro <0
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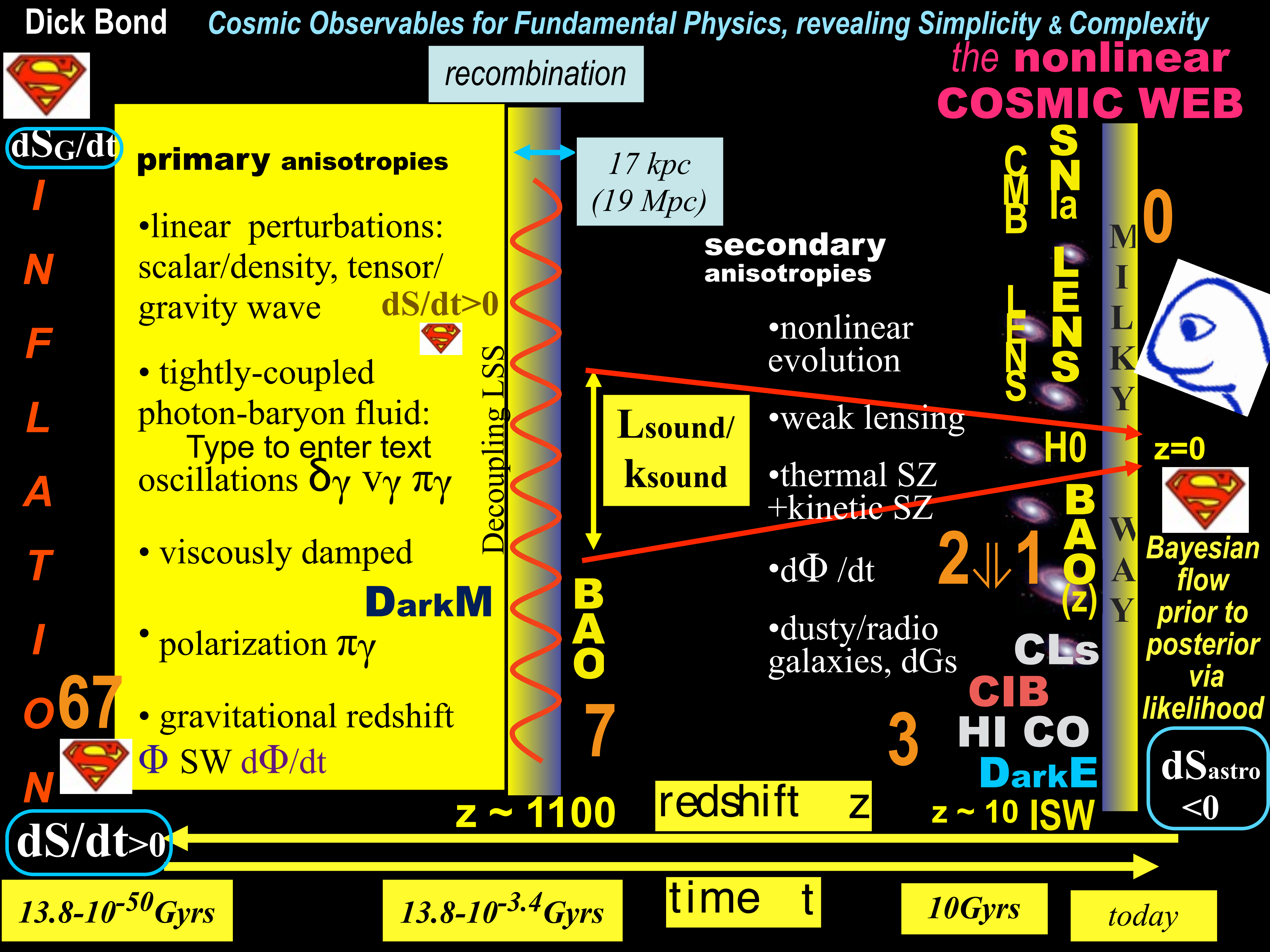

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13.8-10-50Gyrs
13.8-10-3.4Gyrs
10Gyrs
today

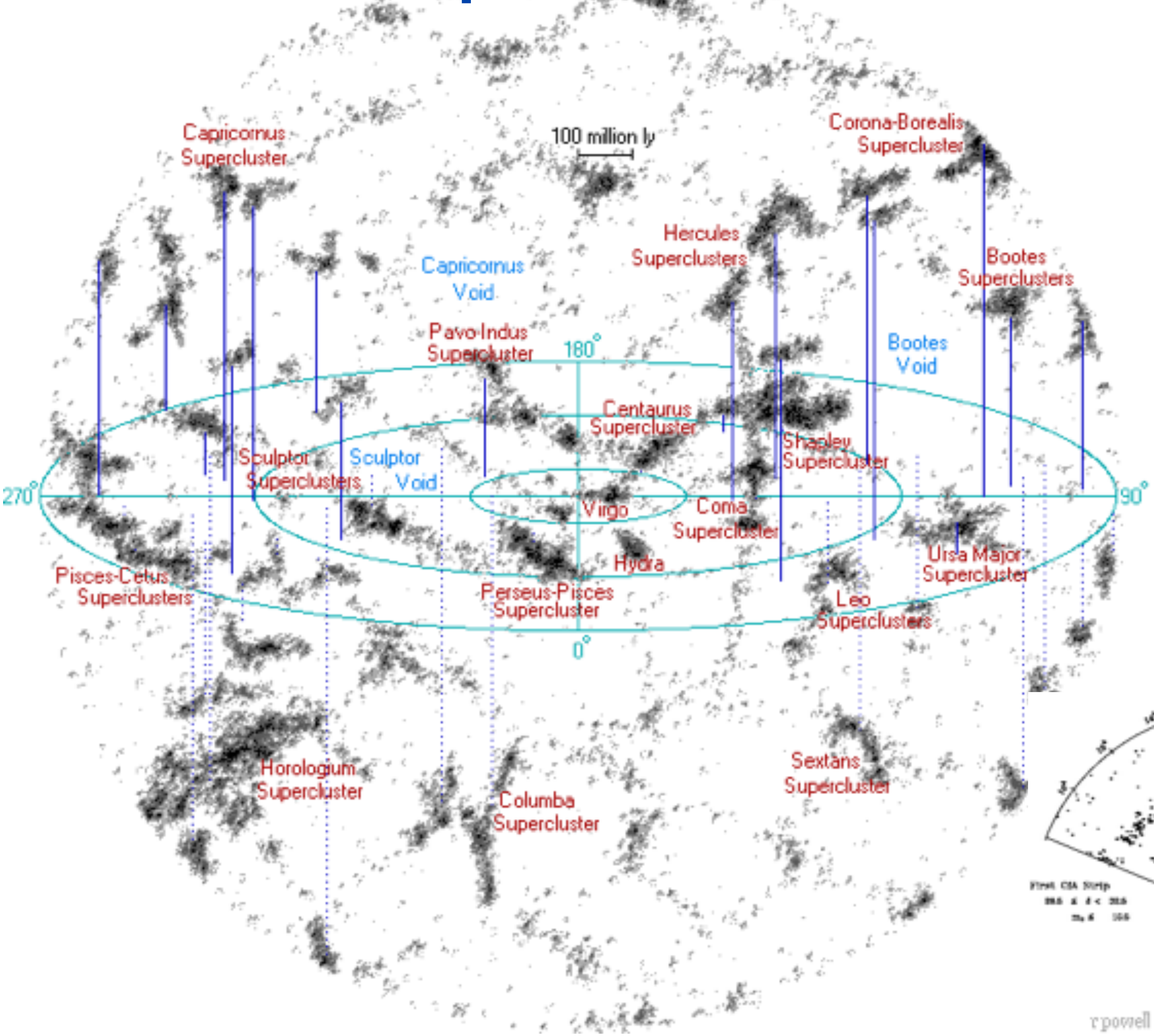
Surveys of the Web(z)

the LSS data bases for cross-correlations

optical z-surveys / weak lensing surveys (CFHT,SDSSx,..,LSST,Euclid,..), small hi-z galaxy surveys (Ly break ...), sub-mm/Cosmic Infared Background surveys (SCUBA, Blast, Herschel, Planck, ACT, SPT .. CCAT), radio (NVSS, FIRST, CHIME, .., SKA, ..), thermal/kinetic Sunyaev-Zeldovich surveys (Planck, ACT, SPT .. CCAT), HI intensity mapping (CHIME, .. SKA), CO intensity mapping (COMA),..

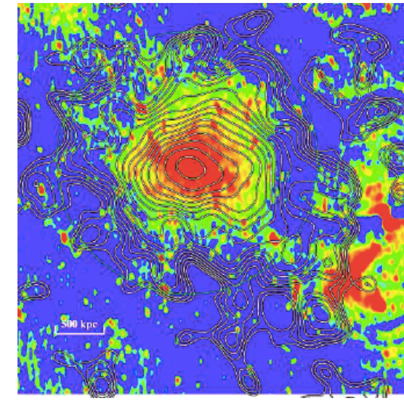
to **a ~ 0.9 via 3D maps**

cosmic web of **nearby superclusters < 1 Giga*ly***



$a = e^{0} = 1$ now *to*

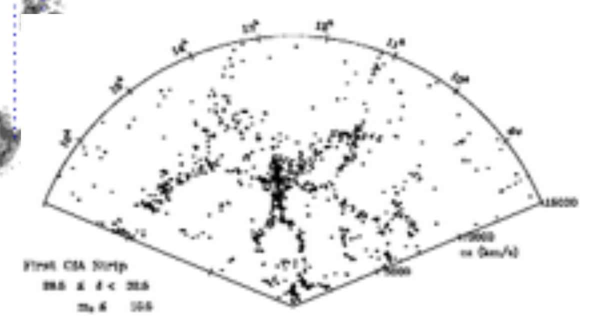
$a \sim e^{-0.1} = 1/1.1$



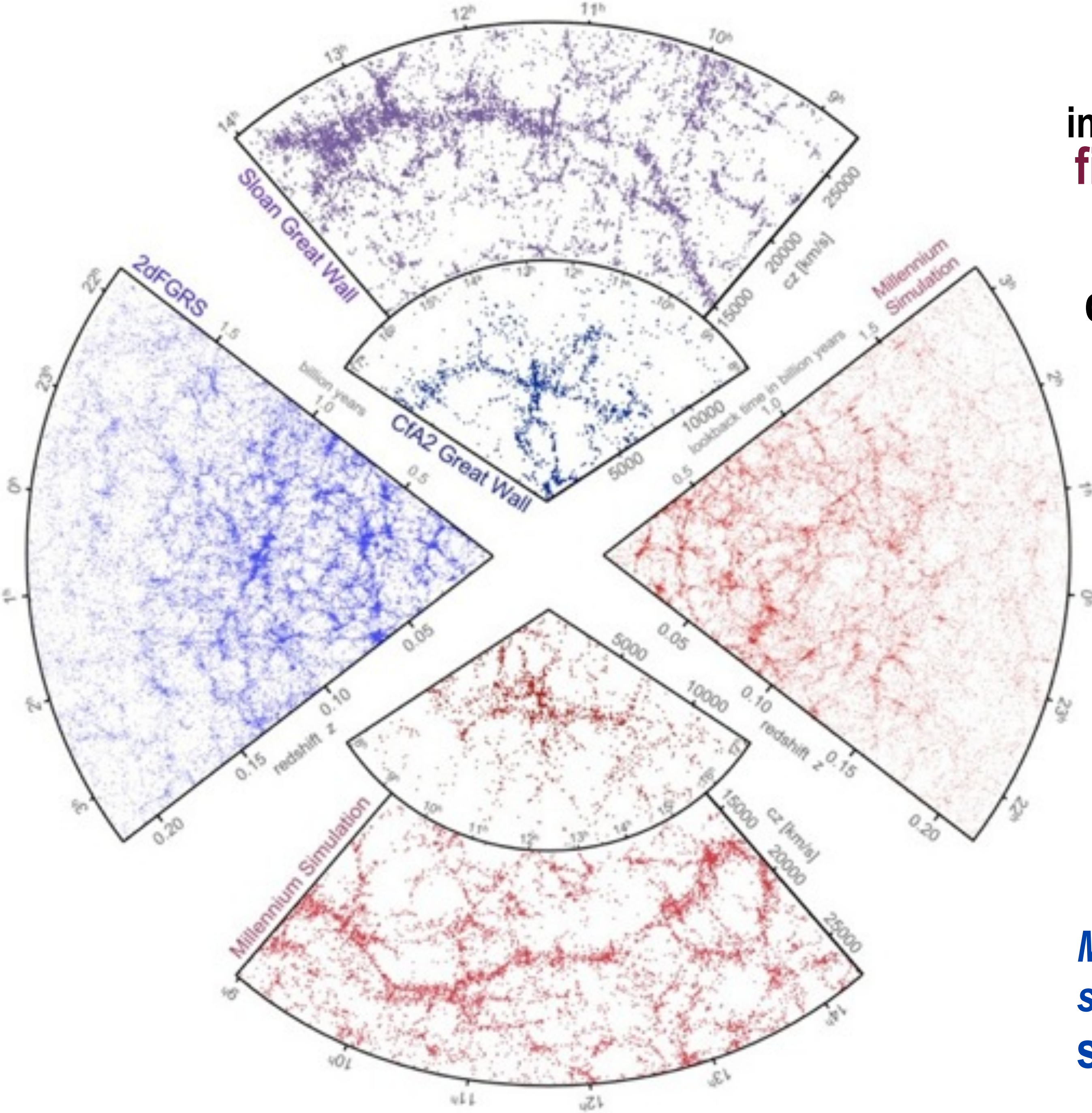
COMA cluster

(100 Mpc, z=0.023)

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



to **a ~ 0.8 via 3D maps**



Collisionless matter

Simulation of the initial Gaussian random field characterized by

7^+ numbers

does indeed beget the

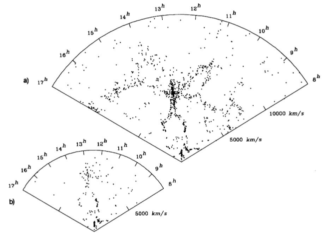
Cosmic Web

Millenium simulation web site "propaganda" on

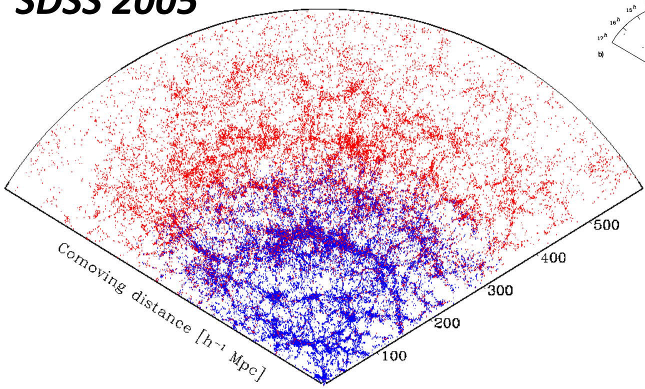
sims *cf.* z-space data

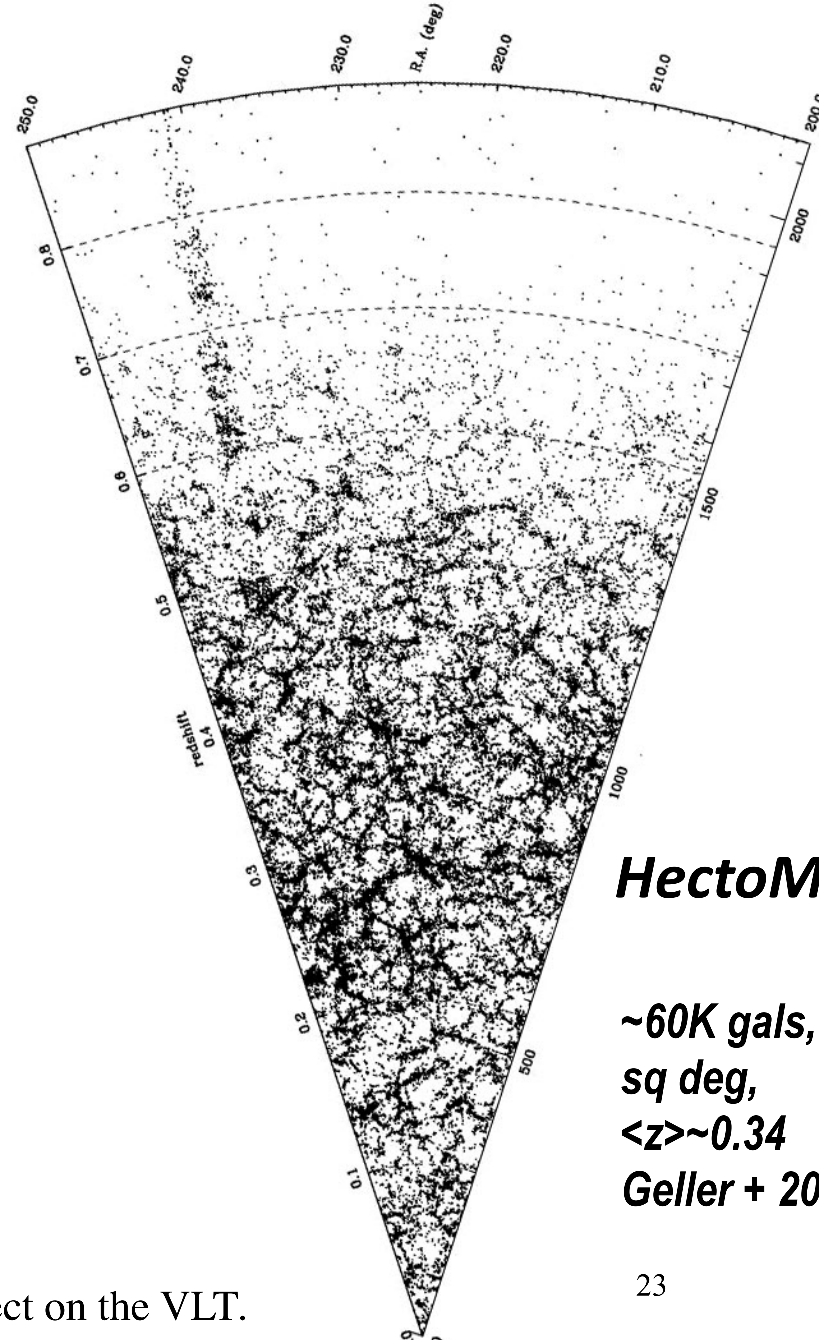
and to **a ~ 0.6 via 3D maps**

CfA 1986



SDSS 2005





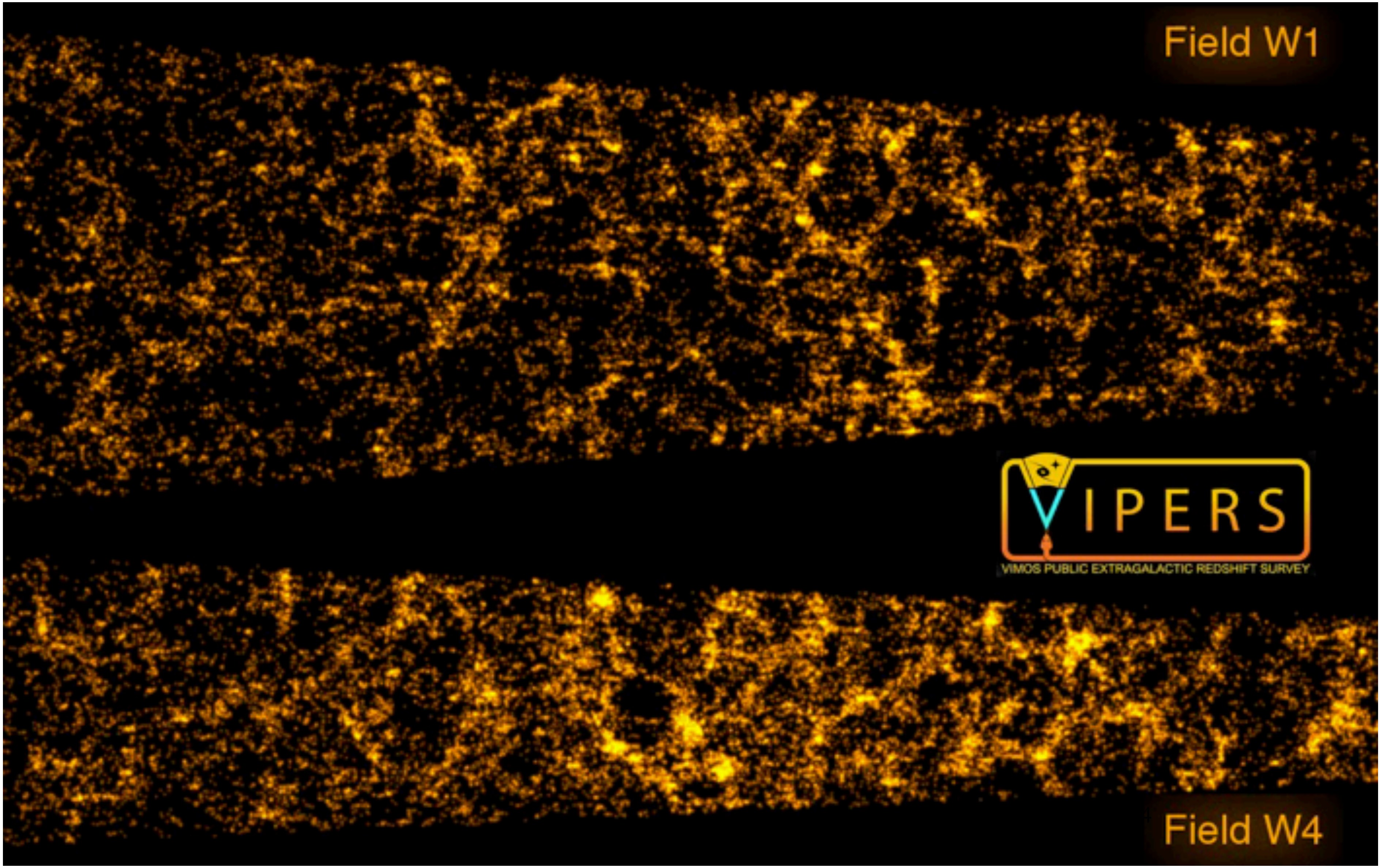
HectoMAP

~60K gals, 50 sq deg, <z>~0.34
Geller + 2013..

- AAT 2dF:
- 2dF QSO redshift survey
- 2 MASS: 2 micron all sky survey
- The VLA FIRST
- ISO nearby Abell cluster survey
- EDisCS: ESO distant clusters survey
- LCRS: The Las Campanas Redshift Survey
- ESP: ESO Slice Project
- CNOC: Canadian
- The CfA redshift survey
- SDSS: Sloan Digital Sky Survey
- DEEP2: deep extragalactic evolutionary probe
- The VIRMOS-VLT Deep Survey (VVDS) project on the VLT.
- The 6dF GS

and to **a ~ 0.7 to 0.5 via 3D maps**

VIPERS using VIMOS@VLT release Oct 4, 2013, 57K redshifts, z=0.45 to z=0.95, 6e7 (h^-1Mpc)^3, higher sampling than LRG BAO surveys Guzzo+13 cover CFHTLS wide fields, 64% done, 24 sq deg



and to the **big f_{sky} future**

Table 4. Summary of current or planned BAO capable spectroscopic surveys. K

Instrument	Telescope	Ref	Nights/ year	No. Galaxies	sq deg	Ops Start	
SDSS I+II	APO 2.5m	1	dedicated	85K LRG	7600	2000	KC
Wiggle-Z	AAT 3.9m	2	60	239K	1000	2007	
BOSS	APO 2.5m	3	dedicated	1.4M LRG + 160K Ly-α	10000	2009	K
HETDEX	HET 9.2m	4	60	1M	420	2014	
eBOSS	APO 2.5m	-	dedicated	600K LRG + 70K Ly-α	7000	2014	KC
MS-DESI	NOAO 4m	5	tbd	32M + 2M Ly-a	18000	2018	KC
SUMIRE PFS	Subaru 8.2m	6	20	4M	1400	2018	J T
4MOST	VISTA 4.1m	7	dedicated	6-20M bright objects	15000	2019	
EUCLID	1.2m space	8	dedicated	52M	14700	2021	

Galaxy And Mass Assembly survey (GAMA) ~375K galaxies in the local Universe over a 360 sq deg

The Primus survey of galaxies at z~1.

Pan-STARRS:

C=china, not canada

UKIRT infrared deep sky survey

DES: the Dark Energy Survey

LSST: the large-aperture synoptic survey telescope

from MS-DESI proposal, MWhite home page

HALOs in the Web(z)

SIMULATIONS

N-body cf. Hydro

Dark Matter

Gas

Stars

Black Holes

FEEDBACK

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

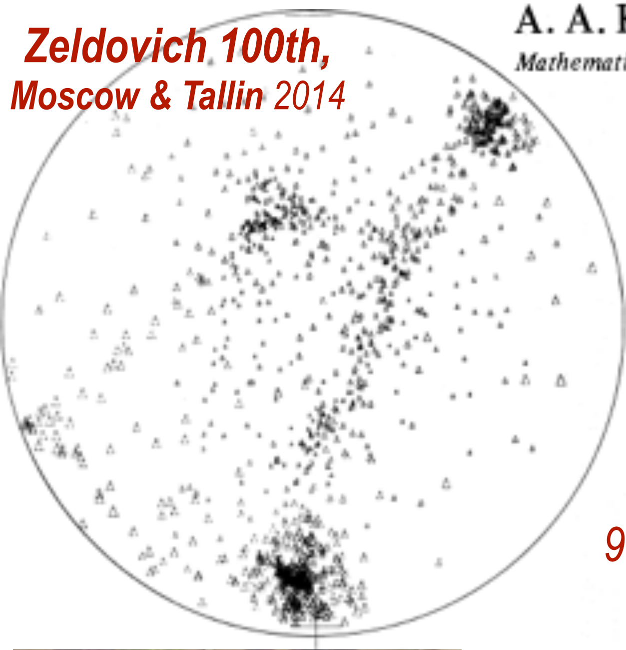
(10+10+20 256^3 SPH gas+DM)

(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*

BBPSS BBPS1,2,3,4,5

Zeldovich 100th,
Moscow & Tallin 2014



A. A. Klypin and S. F. Shandarin *The Keldysh Institute of Applied Mathematics, Academy of Sciences of USSR, Miusskaja Sq. 4, Moscow 125047, USSR*

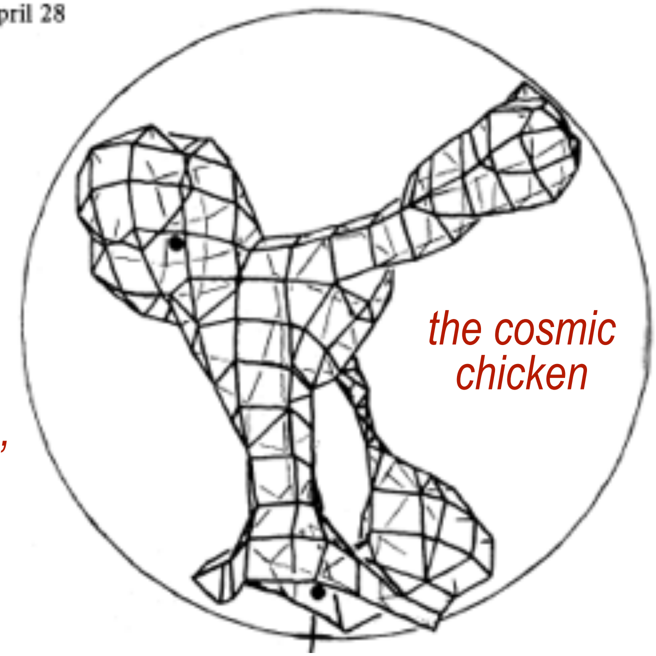
Received 1982 November 15; in original form 1982 April 28

3D numerical model of the Universe

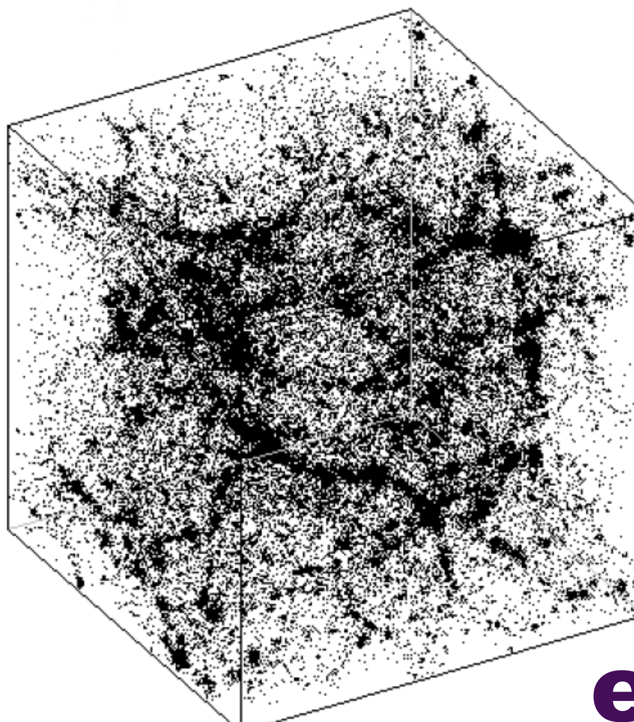
Klypin's vintage 1982
$160h^{-1}$Mpc box 32^3 hDM

It is possible to recognize some webs connecting these 'clusters of galaxies'

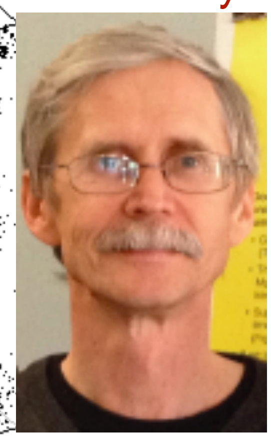
90s Klypin to CITA, 'the west is best'

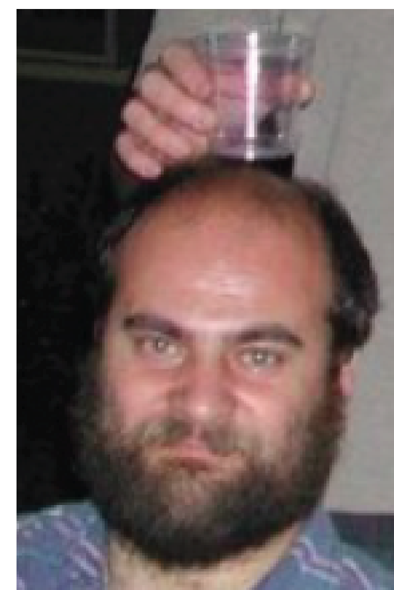


the cosmic chicken

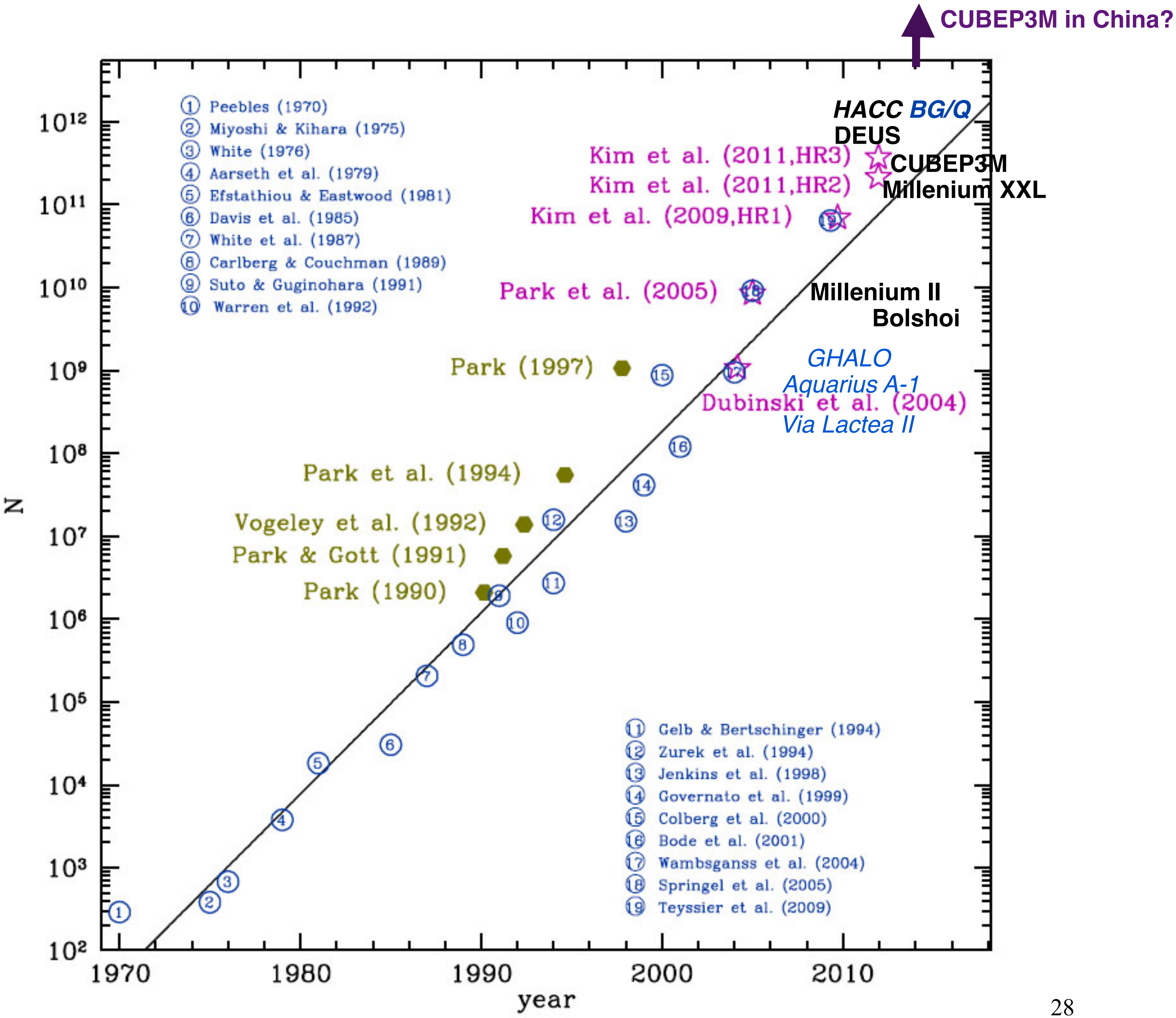


60th bday!'

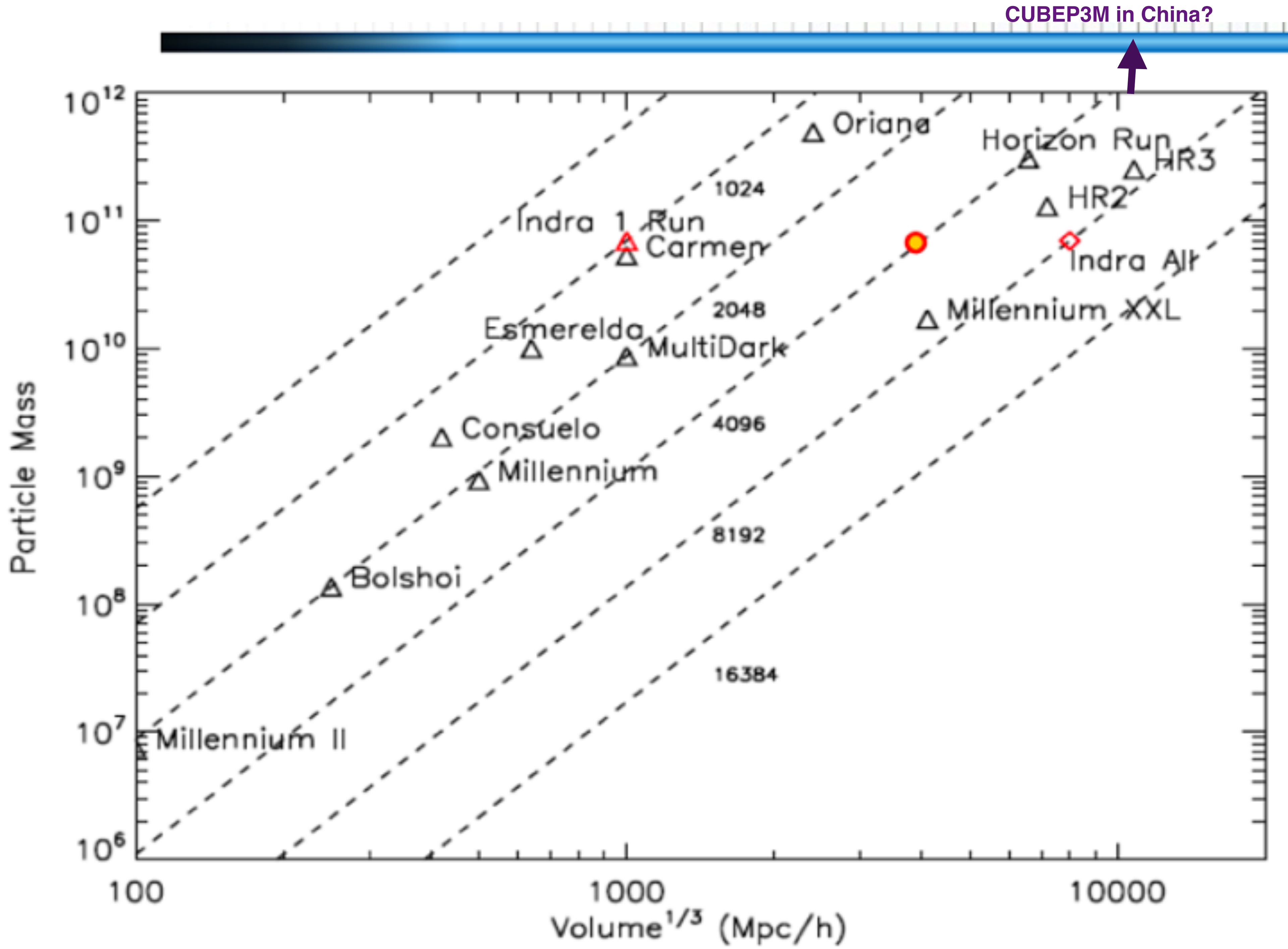




Klypin's vintage 93 $50h^{-1}$Mpc box 128^3 sCDM = **BKP98 web** workhorse; +Couchman AP^3M



(Juhan Kim et al. 2011)



CUBEP3M in China?
Oriana
Horizon Run
HR3
HR2
1024
Indra 1 Run
Carmen
Indra All
2048
Millennium XXL
Esmerelda
MultiDark
Consuelo
4096
Millennium
8192
Bolshoi
16384
Millennium II
Particle Mass
Volume$^{1/3}$ (Mpc/h)
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
100
1000
10000

BigBox Sims By total particle number, N:

BG/Q Run (HACC) 2012
N = 10240^3 L = 9.14 Gpc rsoft = 7 kpc mparticle = 1.9e10 Msun

DEUS FUR (RAMSES) 2012
N = 8192^3 L = 29 Gpc (21 Gpc/h) rsoft = 56 kpc mparticle = 1e12 Msun

Horizon Run 3 (Park et al. TREEPM) 2013 *grew out of Horizon Run 1, N = 4120^3 Kim, Park, Gott, Dubinski 2009@ CITA*
N = 7210^3 L = 15 Gpc (10.82/h Gpc) rsoft = 208 kpc mparticle = 3.4e11 Msun

Emberson et al. in prep (CUBEP3M) 2013-14
N = 6912^3 L = 2.9 Gpc (2/h Gpc) rsoft = 40 kpc mparticle = 3e9 Msun

Millenium XXL (GADGET) 2012
N = 6720^3 L = 4.1 Gpc (3/h Gpc) rsoft = 13.7 kpc mparticle = 8.5e9 Msun

Big Jubilee (CUBEP3M) 2013
N = 6000^3 L = 8.8 Gpc (6/h Gpc) rsoft = 71 kpc (50/h kpc) mparticle = 1.1e11 Msun (7.5e10/h Msun)

Millenium Simulation II (GADGET) 2009
N = 2160^3 L = 140 Mpc (100/h Mpc) rsoft = 1.4 kpc (1/h kpc) mparticle = 9.4e6 Msun

The Bolshoi Simulation (ART) 2011
N = 2048^3 L = 347 Mpc (250/h Mpc) rsoft = 1.4 kpc (1/h kpc) mparticle = 1.9e8 Msun (1.35e8/h Msun)

Indra 2013-14 Gadget2 512 X N = 1024^3 L = 1 Gpc/h box; Data loaded into SQL database, public 1048TB

Millennium 2005 DB is the poster child/ success story – 600 registered users: *N = 10^{10} PB data,* ***VO-oriented, SQL-queryable***

SingleHalo Sims By total particle number, Nhalo:

GHALO (PKDGRAV) 2009
M200 = 1.3e12 Msun (200 times MEAN) mparticle = 1e3 Msun Nhalo = 1.3e9

Aquarius A-1 (GADGET) 2008
M200 = 1.8e12 Msun (200 times MEAN) mparticle = 1.7e3 Msun Nhalo = 1.1e9

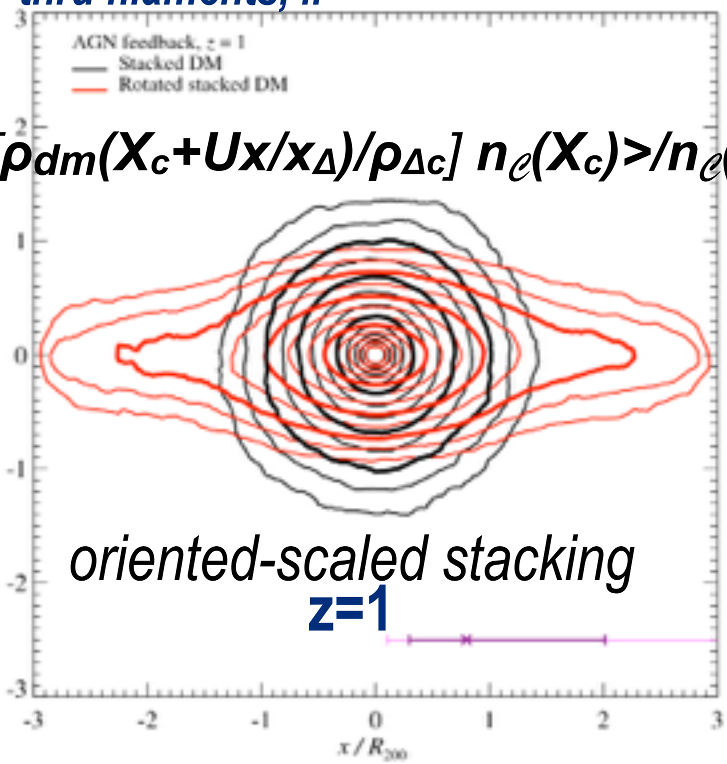
Via Lactea II (PKDGRAV) 2008
M200 = 1.9e12 Msun (200 times MEAN) mparticle = 4.1e3 Msun Nhalo = 4.6e8

HALOs in the Web(z)

the CLUSTER SYSTEM example

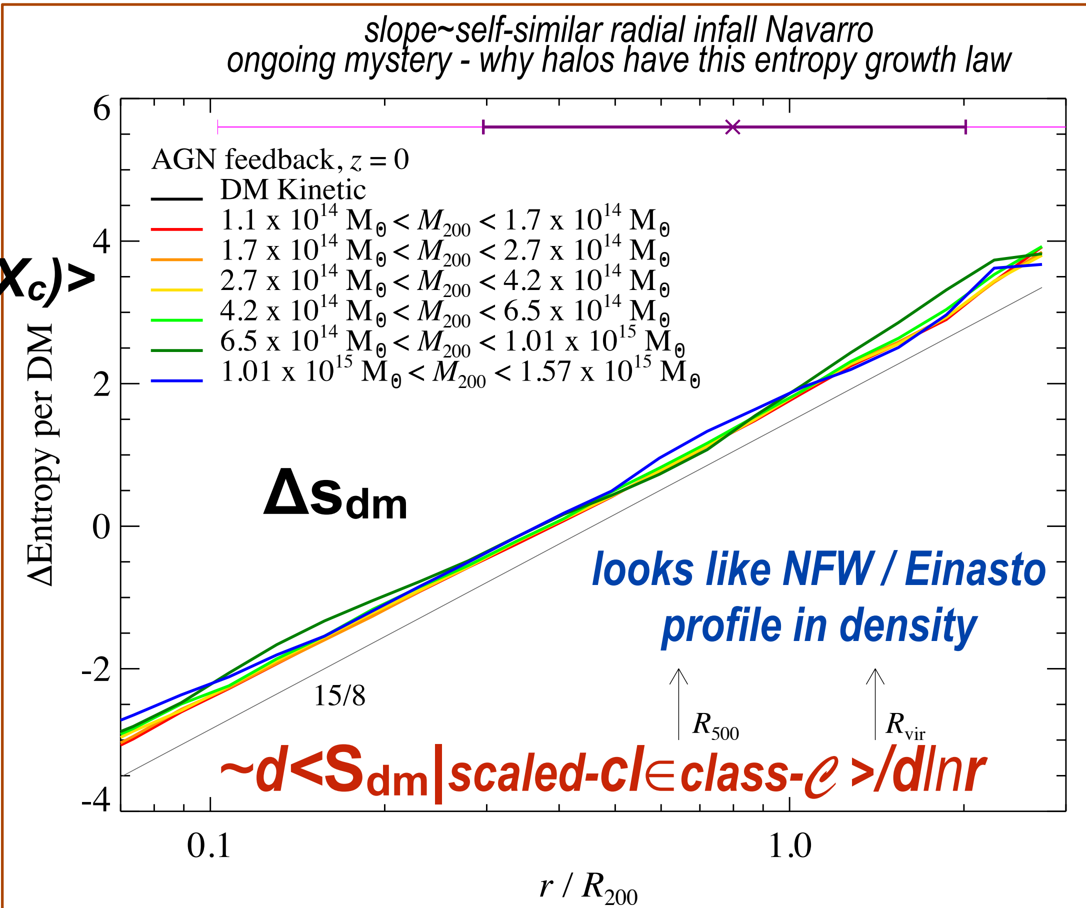
Halos are Complex Systems

sub-halo merger memory,
asphericity, clumping of density,
cosmic web far-field connection thru filaments, ..



$< [\rho_{dm}(X_c+Ux/x_\Delta)/\rho_{\Delta c}]\ n_{\mathscr{C}}(X_c)>/n_{\mathscr{C}}(X_c)>$

Universal dark matter Entropy Profile? yes!!

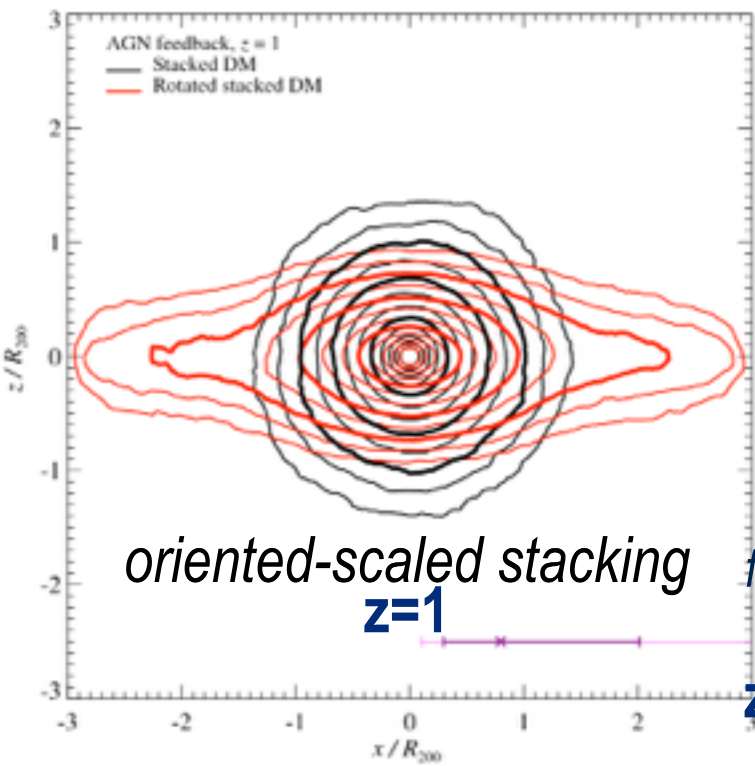


HALOs in the Web(z)

the CLUSTER SYSTEM example

Cluster-Complexity >> Halo-Complexity

Turbulent internal bulk flows /merger memory, **asphericity**, **clumping** of density & **pressure**,
cosmic web far-field connection thru filaments,
FEEDBACK of Entropy& Energy & Momentum from stars, black holes, cosmic rays, ...



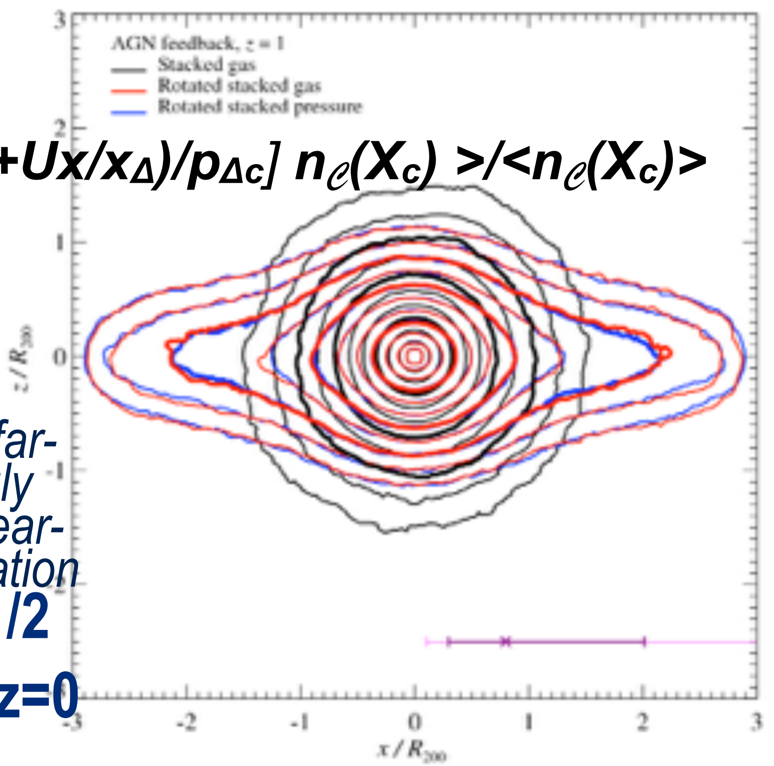
oriented-scaled stacking
z=1

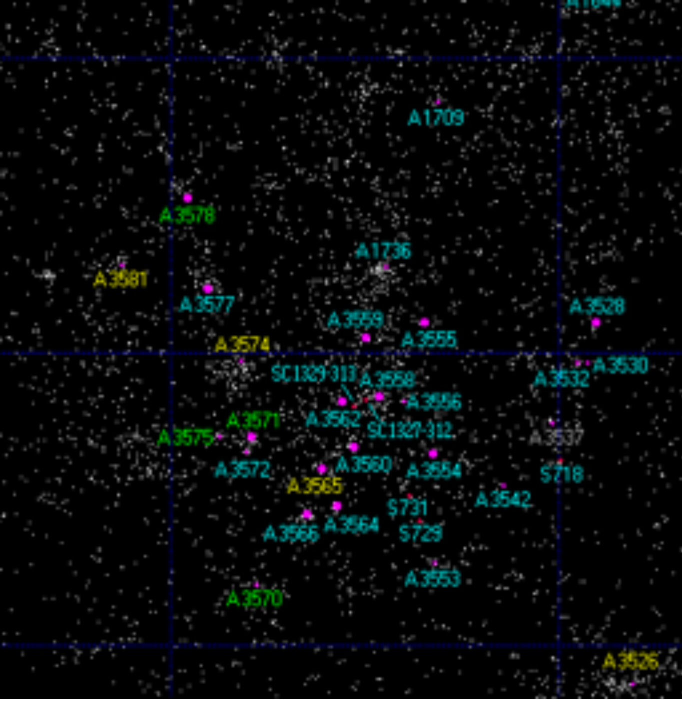
$< [p_g(X_c+Ux/x_\Delta)/p_{\Delta c}]\ n_e(X_c) >/<n_e(X_c)>$

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





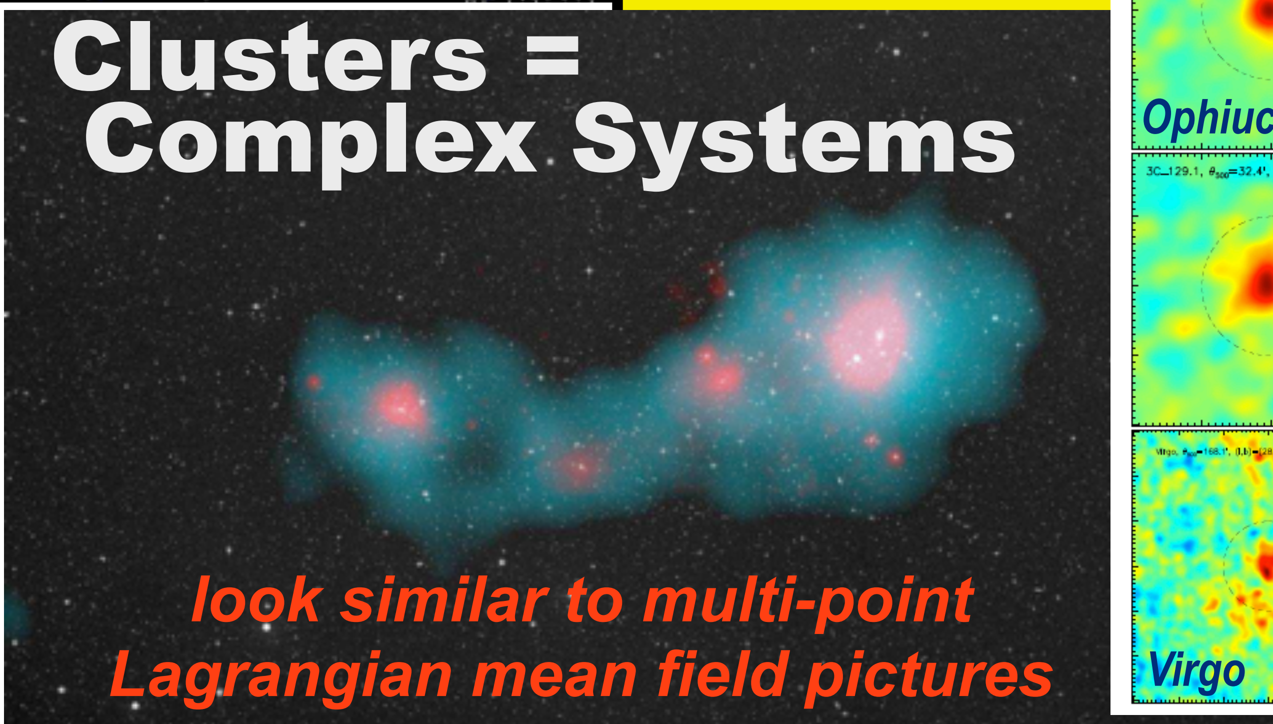
thermal SZ clusters

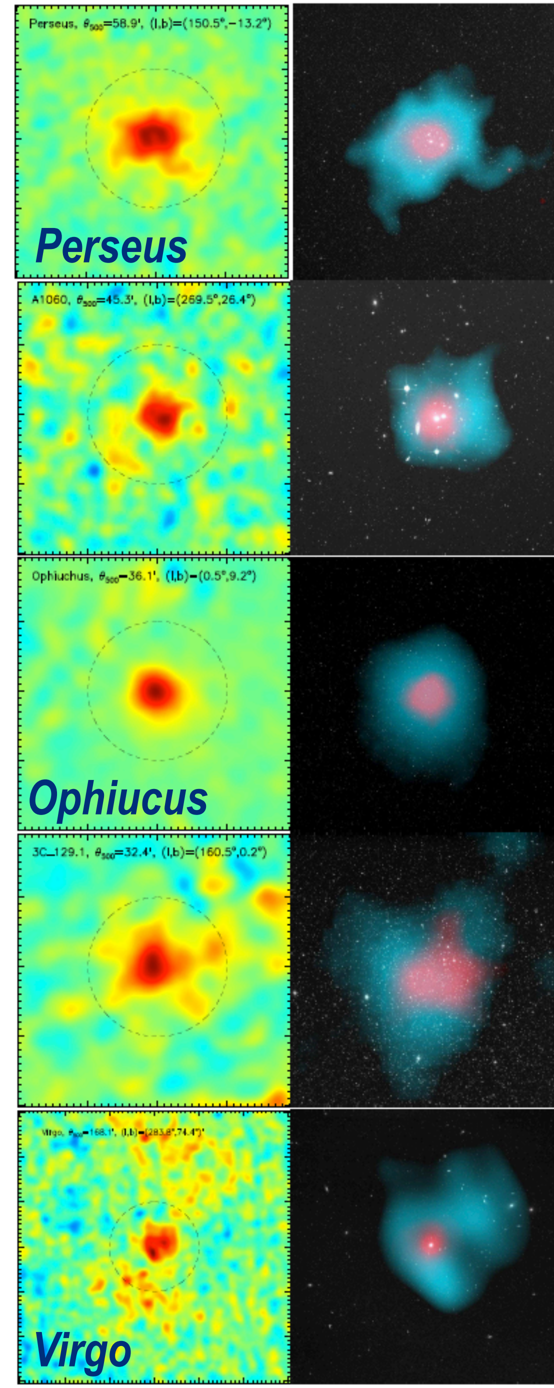
some nearby well-known clusters
from
Perseus to Virgo

Shapley Supercluster

<overdensity> ~5

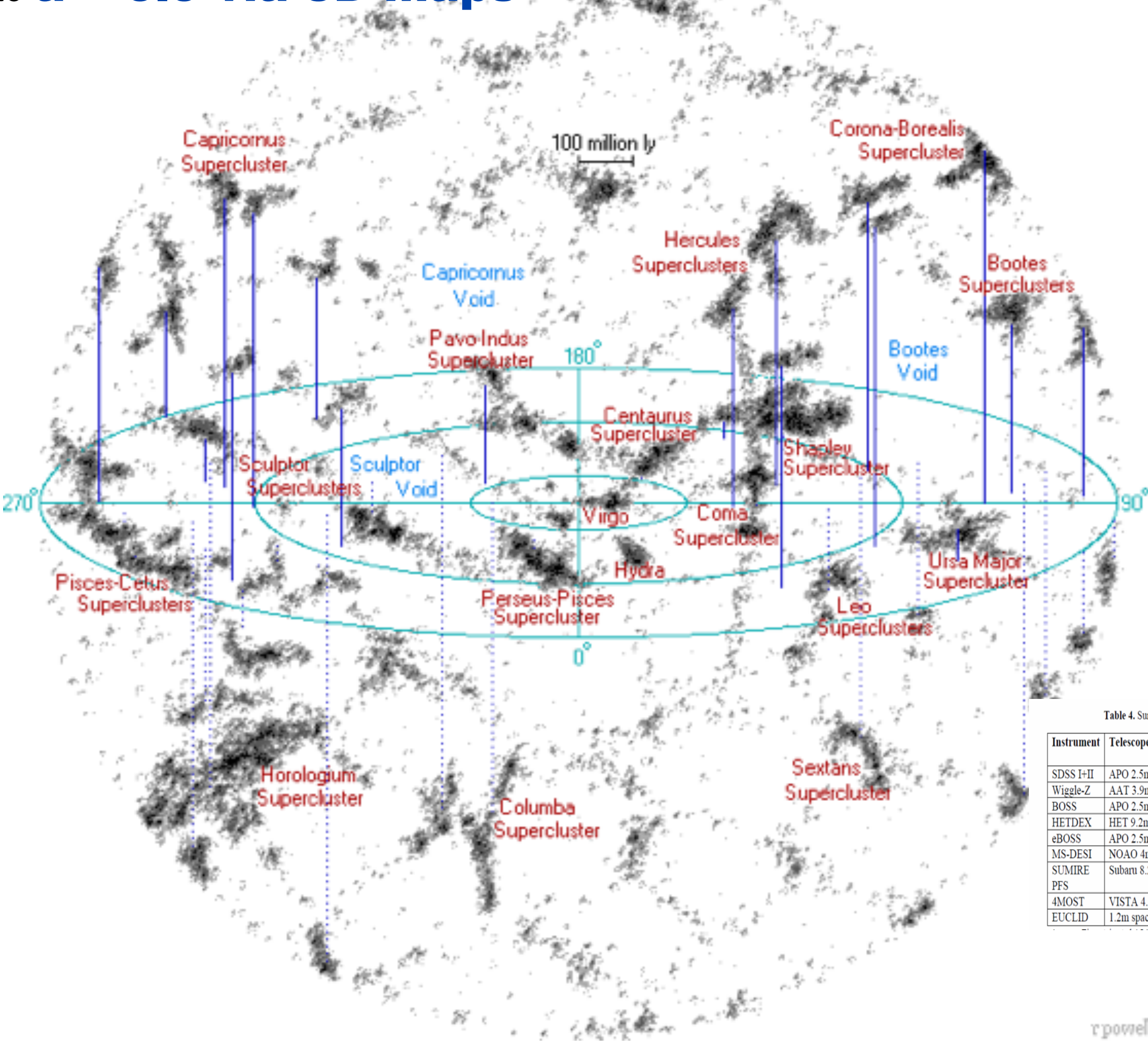
M ~$10^{16.8}$ $M_\odot$





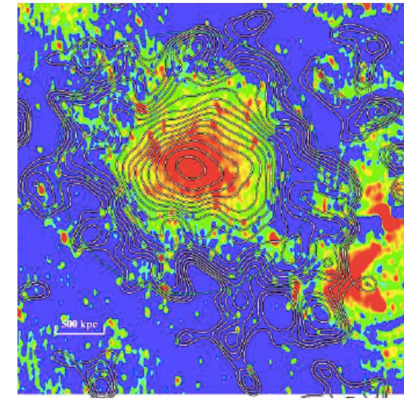
to **a ~ 0.9 via 3D maps**

cosmic web of **nearby superclusters < 1 Giga*ly***



$a = e^{0} = 1$ now *to*

$a \sim e^{-0.1} = 1/1.1$



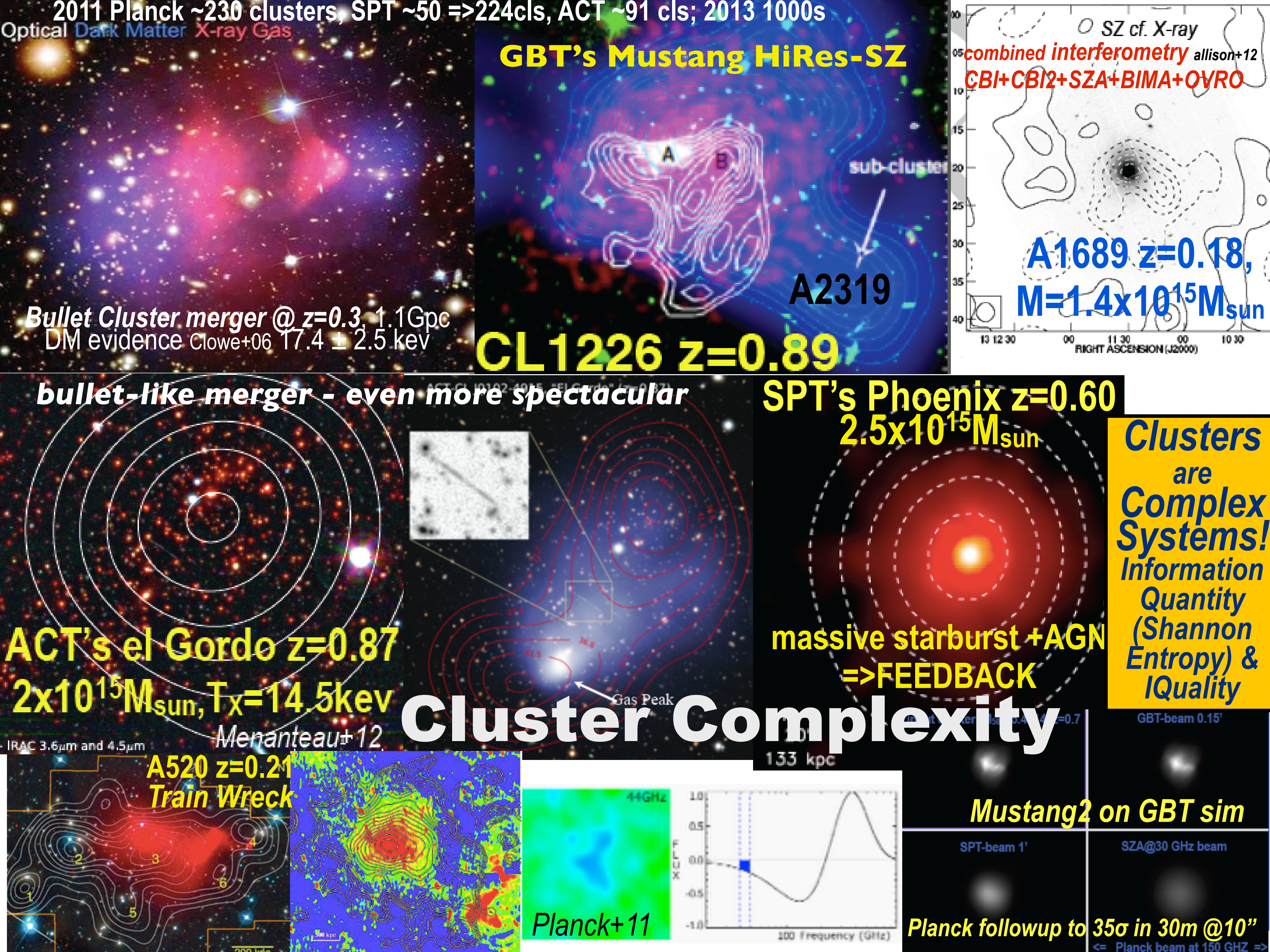
COMA cluster

(100 Mpc, z=0.023)

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

Table 4. Summary of current or planned BAO capable spectroscopic surveys.

Instrument	Telescope	Ref	Nights/ year	No. Galaxies	sq deg	Ops Start
SDSS I+II	APO 2.5m	1	dedicated	85K LRG	7600	2000
Wiggle-Z	AAT 3.9m	2	60	239K	1000	2007
BOSS	APO 2.5m	3	dedicated	1.4M LRG + 160K Ly-α	10000	2009
HETDEX	HET 9.2m	4	60	1M	420	2014
eBOSS	APO 2.5m	-	dedicated	600K LRG + 70K Ly-α	7000	2014
MS-DESI	NOAO 4m	5	tbd	32M + 2M Ly-a	18000	2018
SUMIRE PFS	Subaru 8.2m	6	20	4M	1400	2018
4MOST	VISTA 4.1m	7	dedicated	6-20M bright objects	15000	2019
EUCLID	1.2m space	8	dedicated	52M	14700	2021



2011 Planck ~230 clusters, SPT ~50 =>224cls, ACT ~91 cls; 2013 1000s
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
A
B
sub-cluster
A2319
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 Msun
RIGHT ASCENSION (J2000)
bullet-like merger - even more spectacular
ACT's el Gordo z=0.87
2x10^15 Msun, Tx=14.5kev
Menanteau+12
IRAC 3.6μm and 4.5μm
Gas Peak
SPT's Phoenix z=0.60
2.5x10^15 Msun
massive starburst +AGN
=>FEEDBACK
Clusters
are
Complex
Systems!
Information
Quantity
(Shannon
Entropy) &
IQuality
Cluster Complexity
133 kpc
GBT-beam 0.15'
A520 z=0.21
Train Wreck
44GHz
Planck+11
FLUX
100 Frequency (GHz)
Mustang2 on GBT sim
SPT-beam 1'
SZA@30 GHz beam
Planck followup to 35σ in 30m @10"
<= Planck beam at 150 GHz =>

HALOs in the Web(z)

the CLUSTER SYSTEM example

pressure$(x-x_{cl})$ =

Cross-correlations = Stacking (unoriented, scaled) from **sims & data**

+ residual fluctuations (!!)

PUPPY = Planck universal pressure profile via stacking

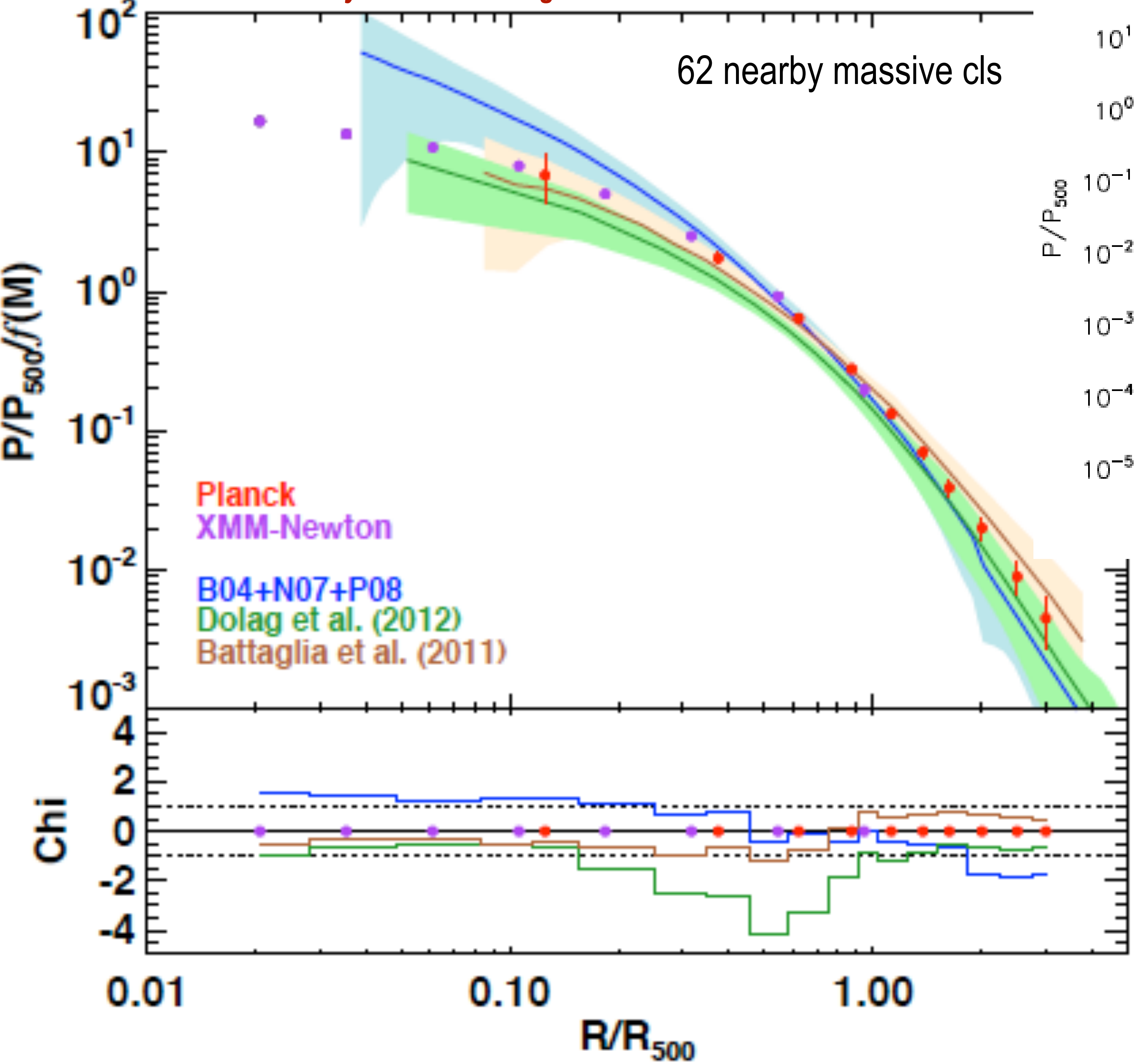
sims => not quite universal (M,z) BBPS2 via stacking

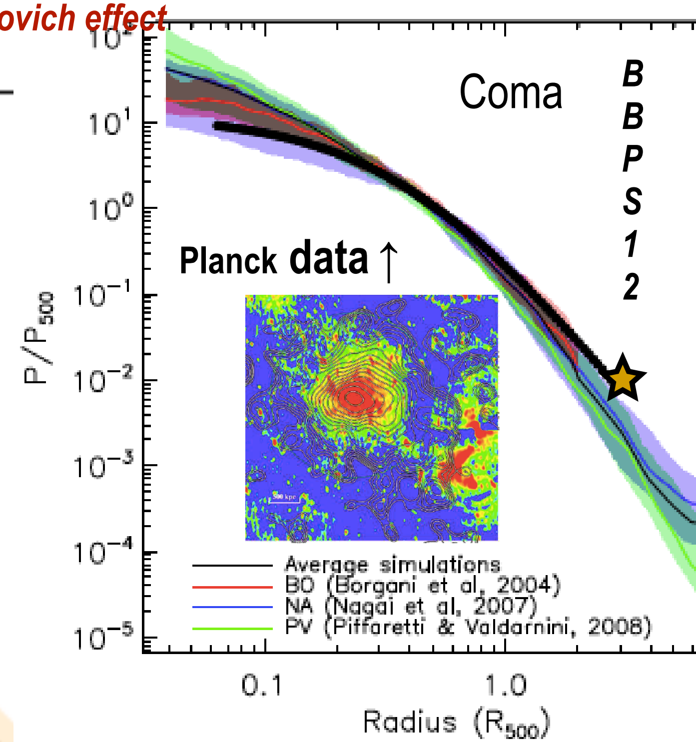
gas entropy = less universal, not bad

DM entropy = universal, NFW-like

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

Planck Intermediate Results. ***V. Pressure profiles of galaxy clusters from the Sunyaev-Zeldovich effect***
Planck intermediate results. ***X. Physics of the hot gas in the Coma cluster*** ***PUPPY***



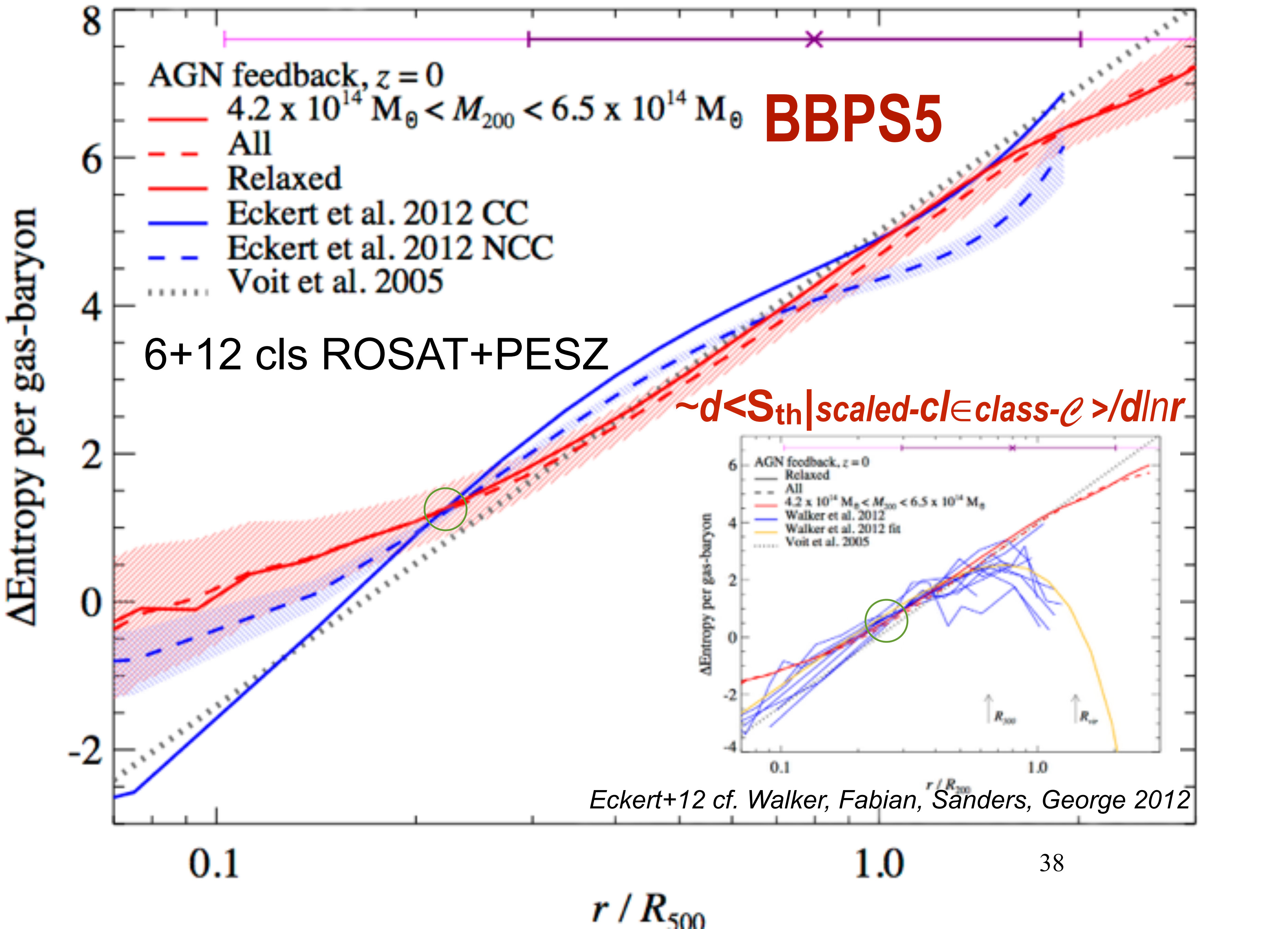


X-ray "universal pressure profile" (Arnaud+10) fails >R_{500}

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

Universal gas **Entropy Profile?** *sort of, but inference from observations is difficult*

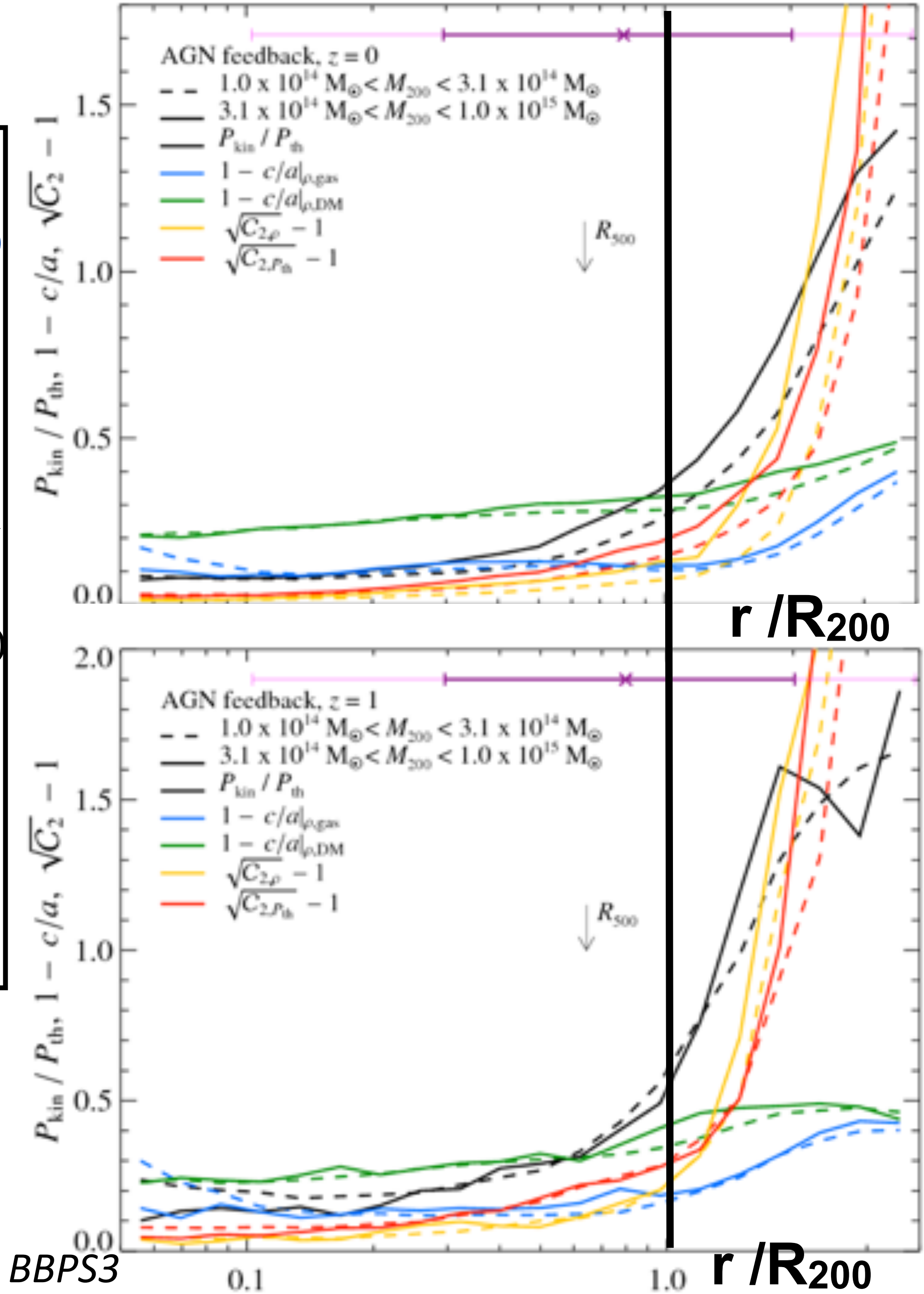


non-thermal/non-equilibrium effects:

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
aka Renyi entropy of order 2

not small @ < **R_{500}**
huge @ < **R_{200}** < **R_{vir}** < **$R_{SZboundary}$**



HALOs in the Web(z)

Cluster/group web MOCKs

Hydro AGN feedback sims

cf.

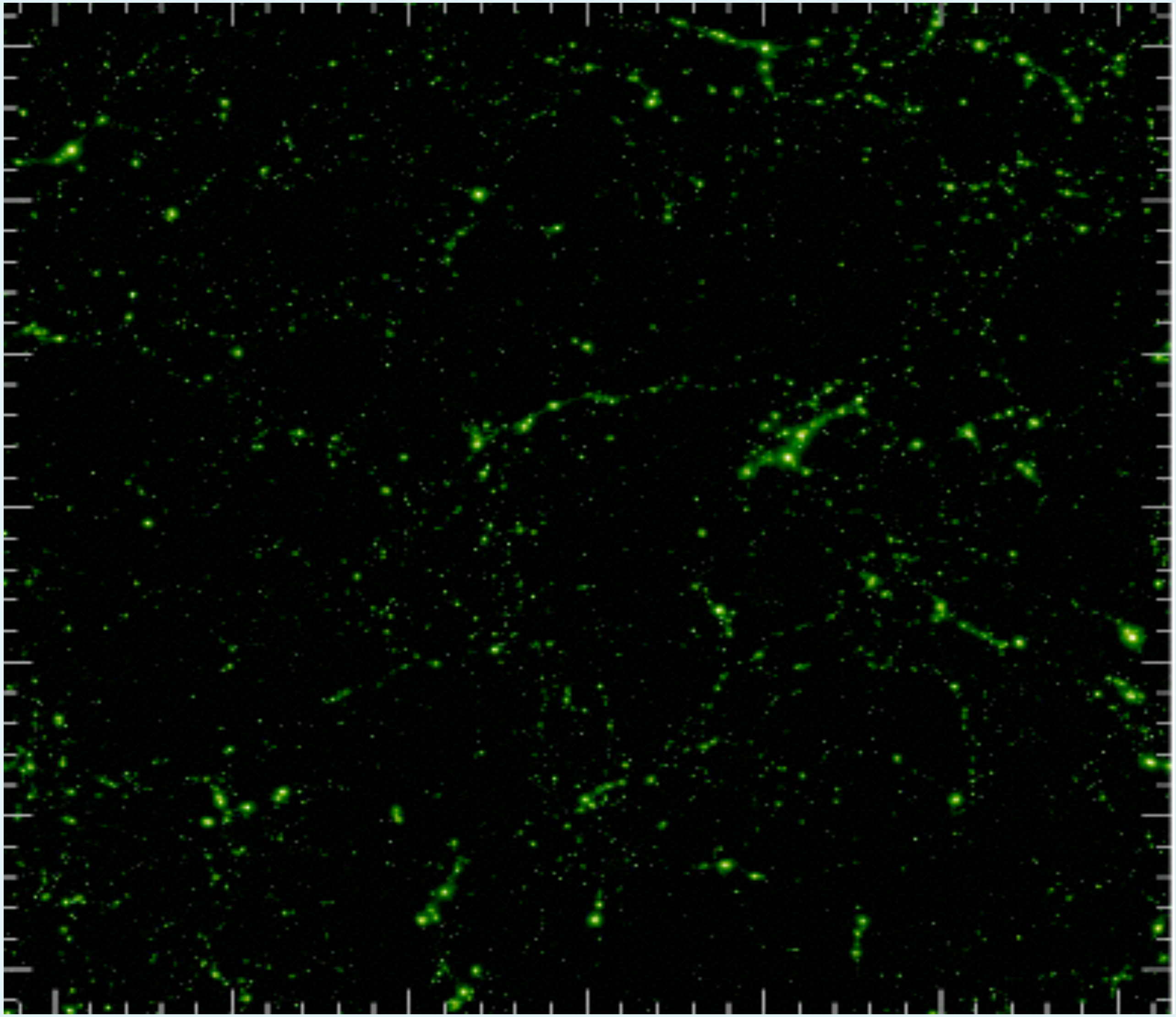
Peak Patches mean-fields from sims

tSZ: rotated translated stacking of 10 periodic boxes

cf. **full light cone PkPatch** non-periodic sim

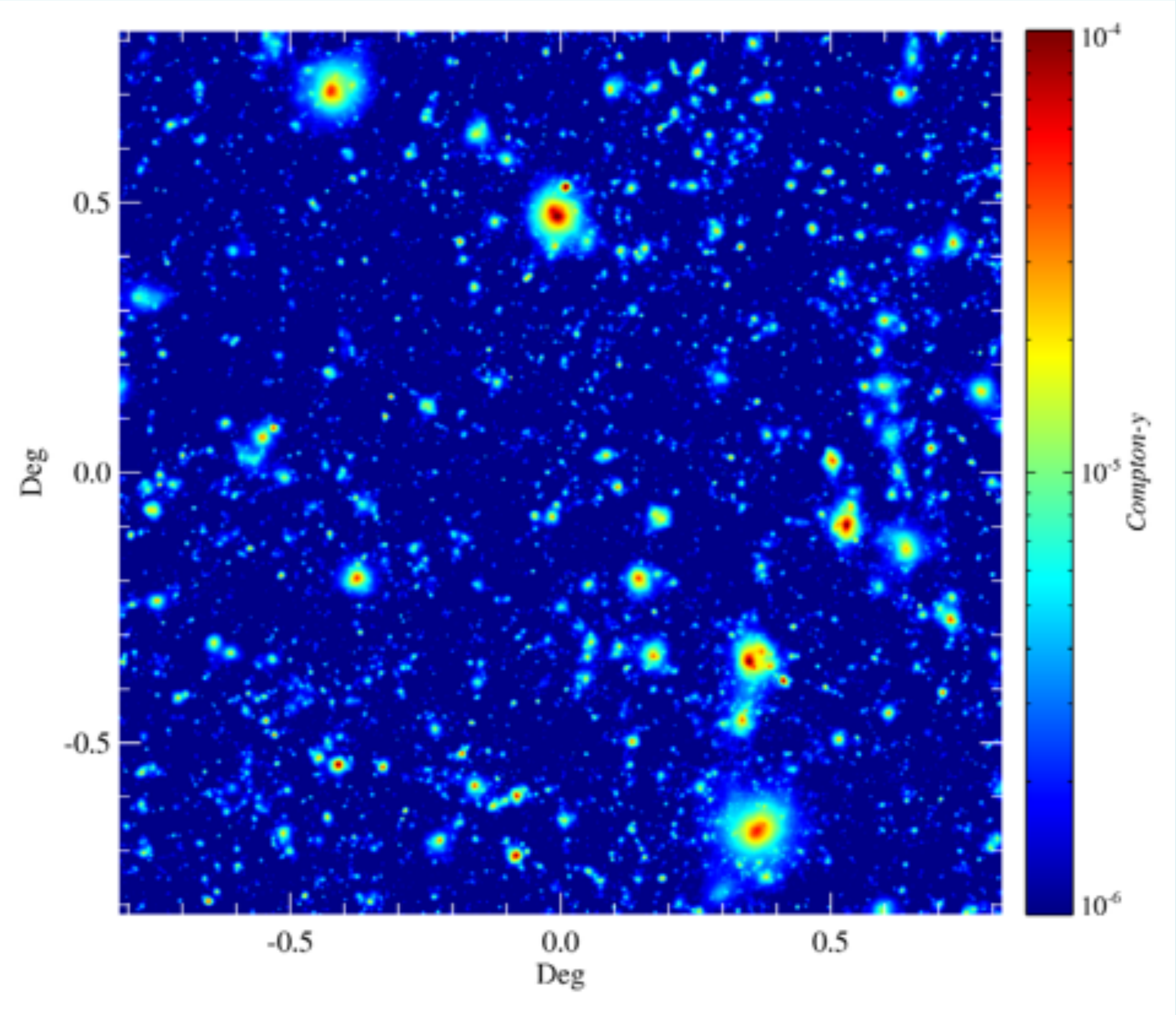
Compton-y map: Feedback

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

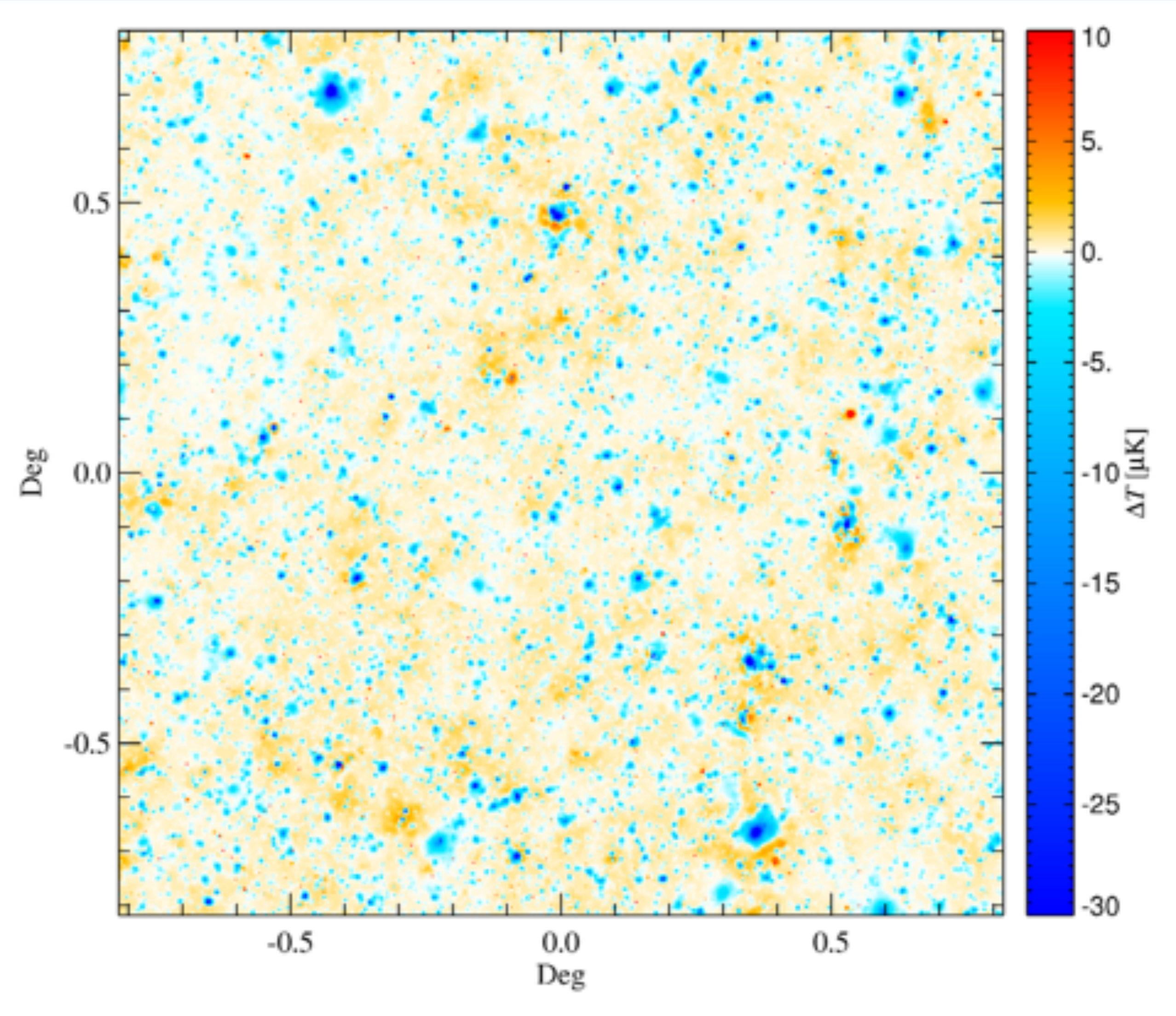


Compton-y map: "adiabatic"

= formation shock entropy from gravitational accretion only



Adiabatic - Feedback



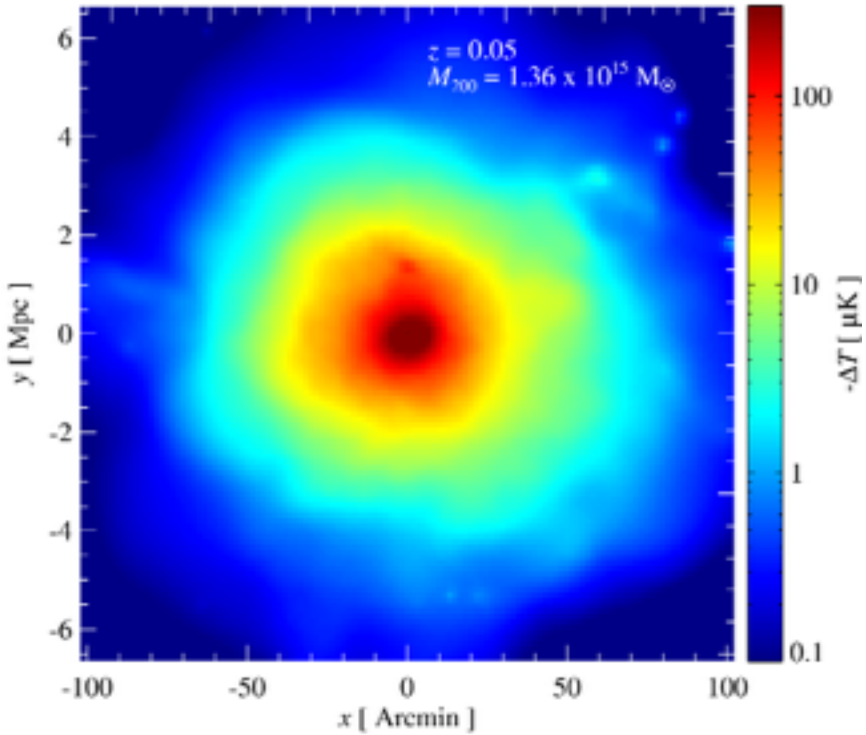
feedback gives "puffier" clusters, with lower core pressures

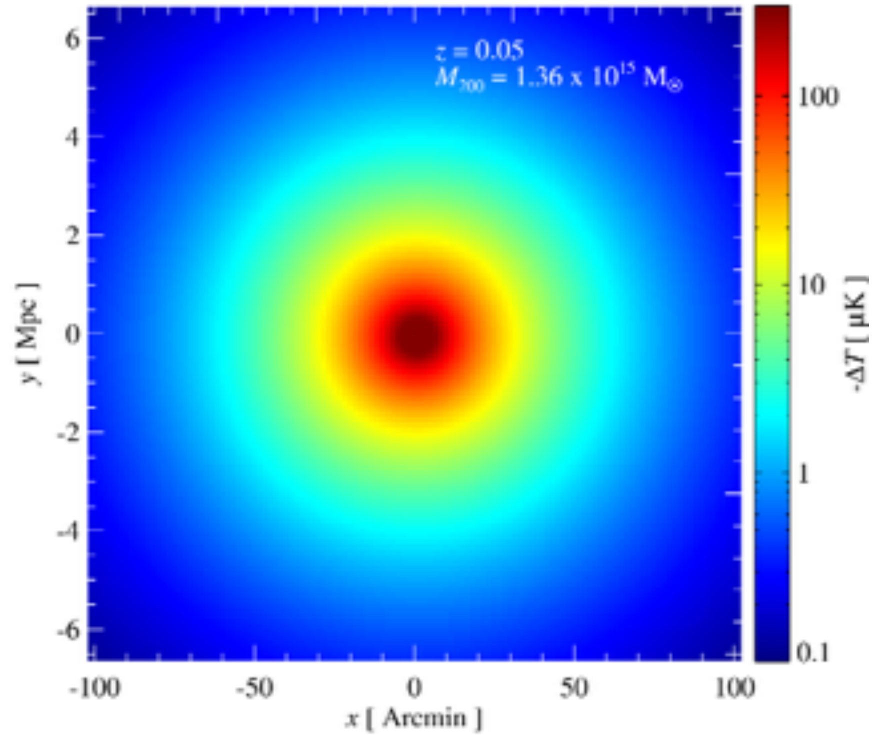
2D pressure exact vs. fit ⇨ pressure sub-structure

***Constrained X-Correlation** Fns = scaled stacked pressure profiles*

***aka** $p = \langle p \mid \{q \in \mathcal{C}\} \rangle + p_f$ (residual "noise") $\langle p \mid \{q \in \mathcal{C}\} \rangle = \langle p q^\dagger \rangle \langle q q^\dagger \rangle^{-1} q$,*

e.g., **p or $\ln p/\langle p \rangle$.** $\langle [p(X_c + U x/x_\Delta)/p_{\Delta c}]\, n_{\mathcal{C}}(X_c) \rangle / \langle n_{\mathcal{C}}(X_c) \rangle$ = ***FormFactor*** (x/x_Δ)



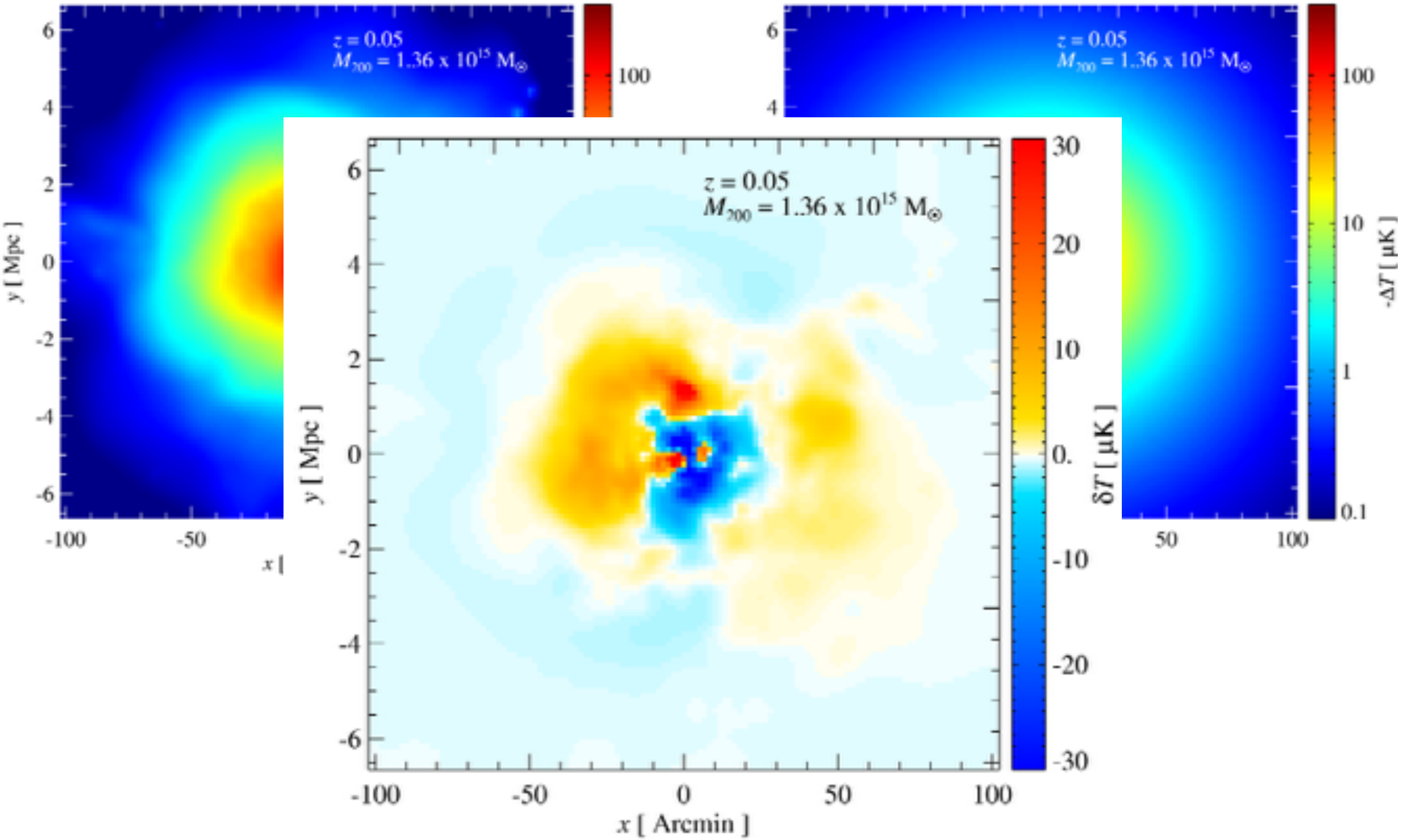


Same cluster (pasted on GNFW according to mass)

@ 30 GHz, z = 0.05 Mass ~10^{15} M_{sun}

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

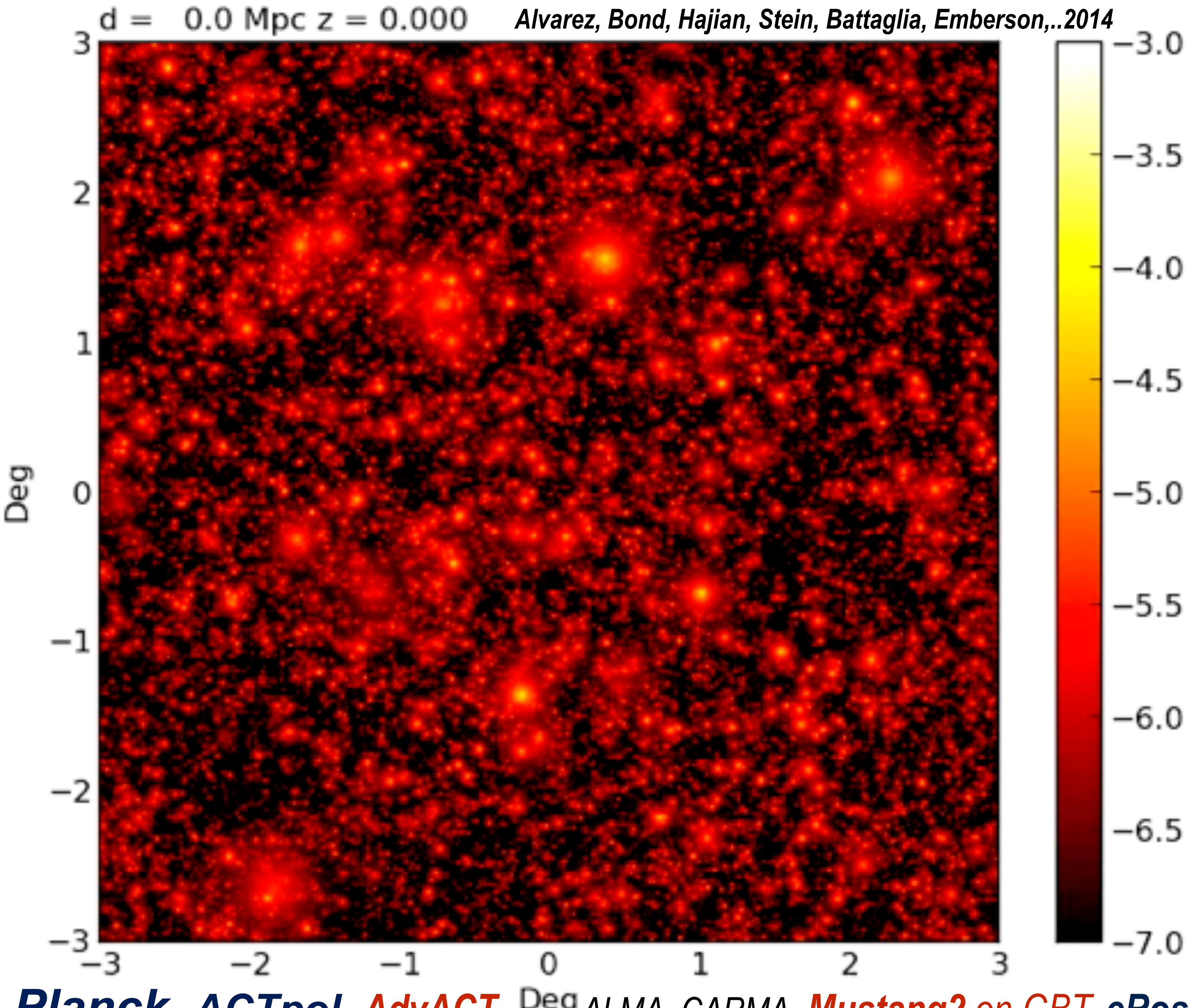
p_f (residual "noise")



Mocking Heaven: lightcone sim for tLCDM. 36 sq deg to z=2

Planck all-sky tSZ mock 1.5 hours on 256 cores on SciNet, 30000 core IBM GPC

Alvarez, Bond, Hajian, Stein, Battaglia, Emberson,..2014



tSZ PkPatch map needs intracluster residual pressure fluctuations & cluster orientation via Lagrangian strain to Eulerian pressure inertia-tensor information for higher tSZ map accuracy.

kSZ PkPatch maps use cluster/ group dominance as in the original moving cluster effect

Planck, ACTpol, AdvACT, *ALMA, CARMA,* ***Mustang2*** *on GBT,* ***eRosita***.. ***COMA, CCAT***.. ***CHIME***

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

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

thermal SZ clusters

QUaD @SP

230 cls => 1227

Planck09.4

52+ bolometers
+ HEMTs @L2
9 frequencies

WMAP @L2 **to 2010**

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

224 (=> **747**)

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

SCUBA2
12000 bolos
JCMT @Hawaii

SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico

80s-**90s**
Ryle
OVRO

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

thermal SZ clusters

QUaD @SP

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

230 cls => 1227

Planck09.4

Planck PSZ, cnts, ymap

861 confirmed, 178 by Planck + 683 known, **most z<.4,**

many ~ $10^{15}M_{sun}$ *0.<z<0.8*

52+ bolometers

+ HEMTs @L2

9 frequencies

WMAP @L2 **to 2010**

Reichardt+12, Benson@ESLAB13

***100 cl cosmology*, 400 with S/N > 5**

now, 747 summer 2013 *2500 deg^2*

2004 2006

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 deg^2, 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

2005 2007

224 (=> **747**)

SPT

1000 bolos

@SPole

Acbar@SP

~1 blind

>96

OVRO /BIMA array

38 cls

SZA@Cal

3 cls (z>1), x?

AMIBA

6 cls

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

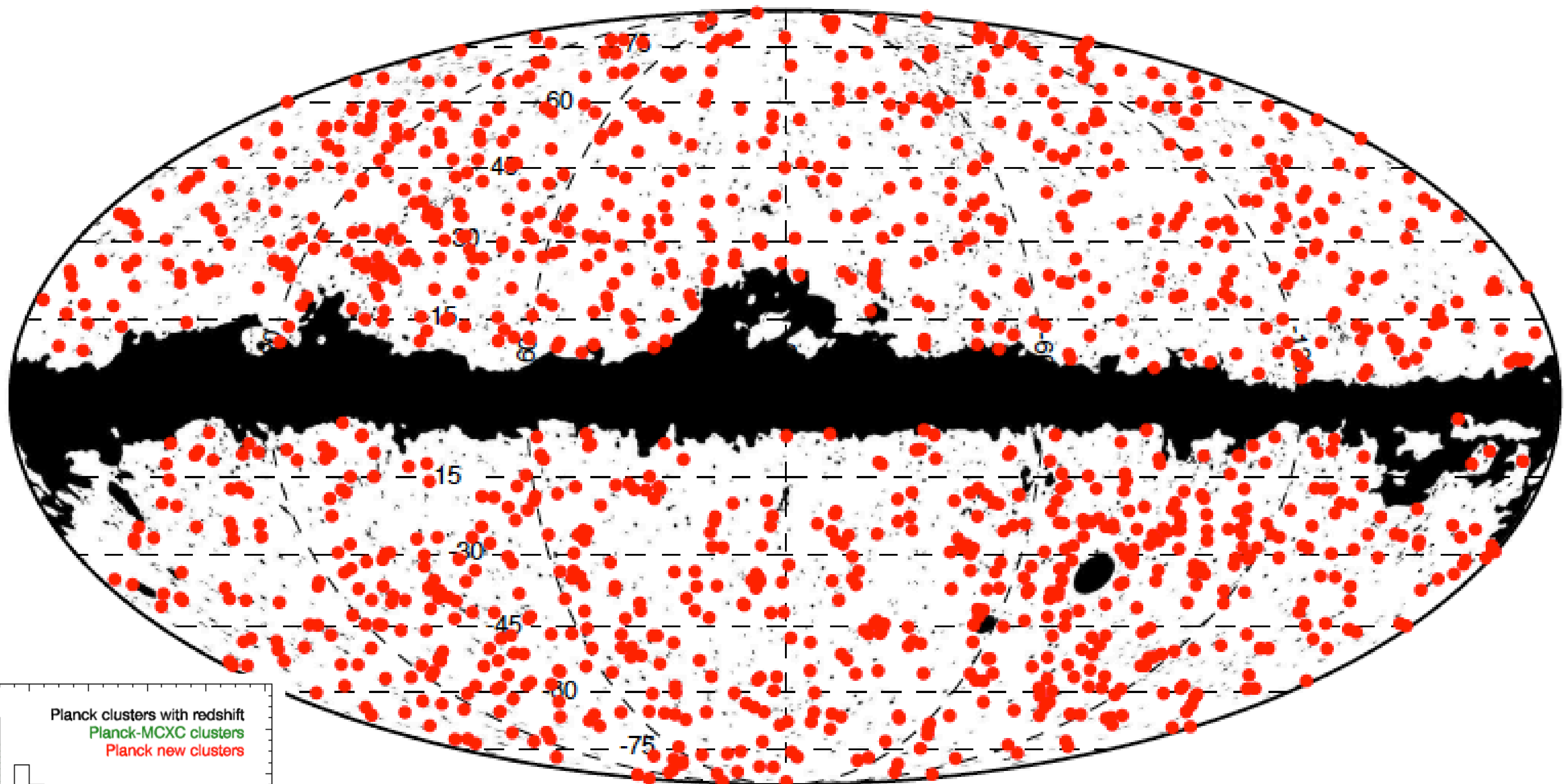
Compton cooling of high pressure / entropy electrons by the CMB

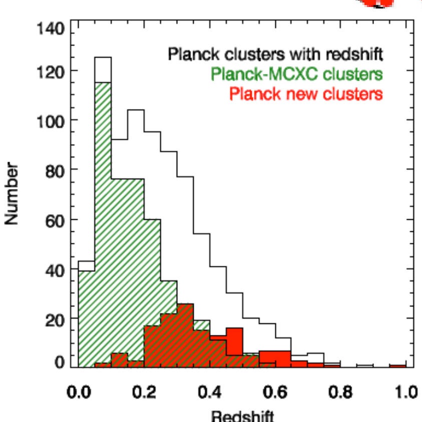
thermal SZ effect **Planck2013 1227 clusters, SPT 224 =>747cls, ACT 91 cls**

PSZ: 1227 clusters, 861 confirmed, 178 by Planck + 683 known, rest in class 1, 2, 3

cf. X-ray sample from ROSAT+ All-sky distribution of MCXC clusters ~1600 *(Piffaretti et 10)*

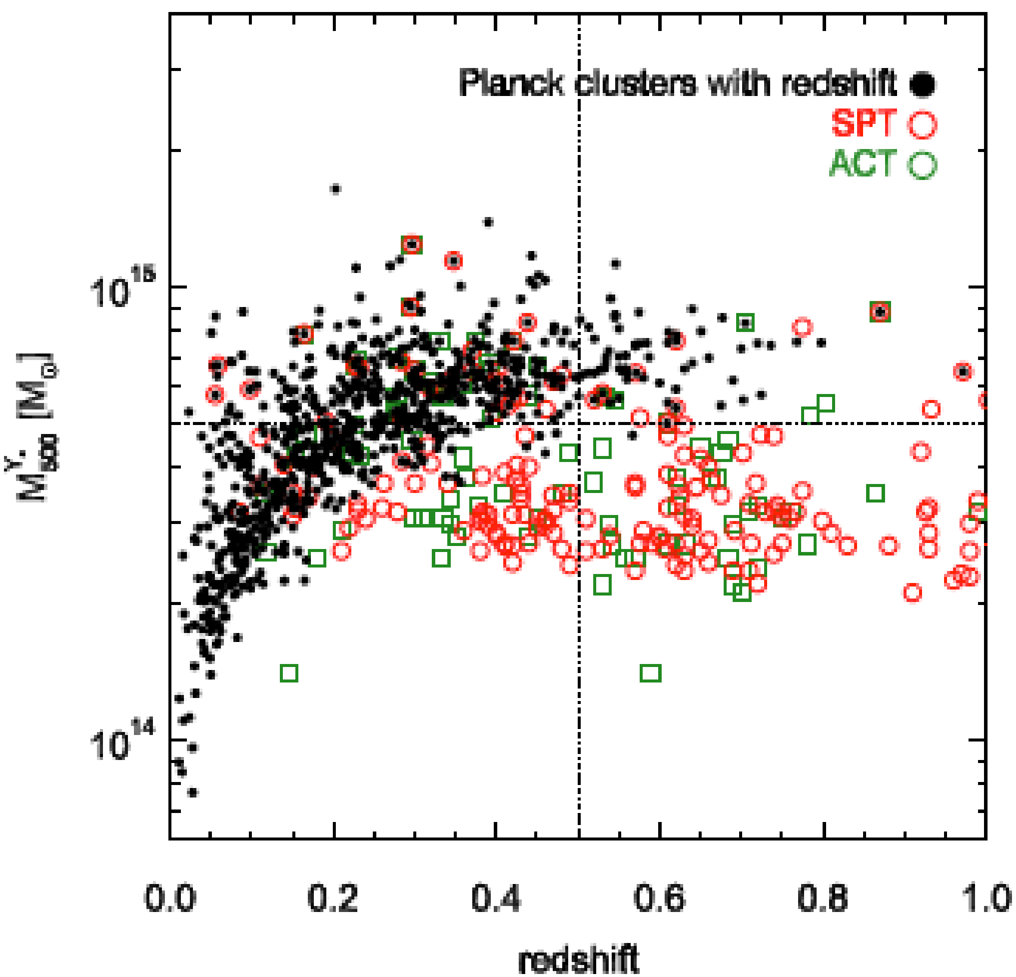
REFLEX, BCS, SGP, NEP, MACS, CIZA, 400SD, 160SD, SHARC, WARPS, EMSS



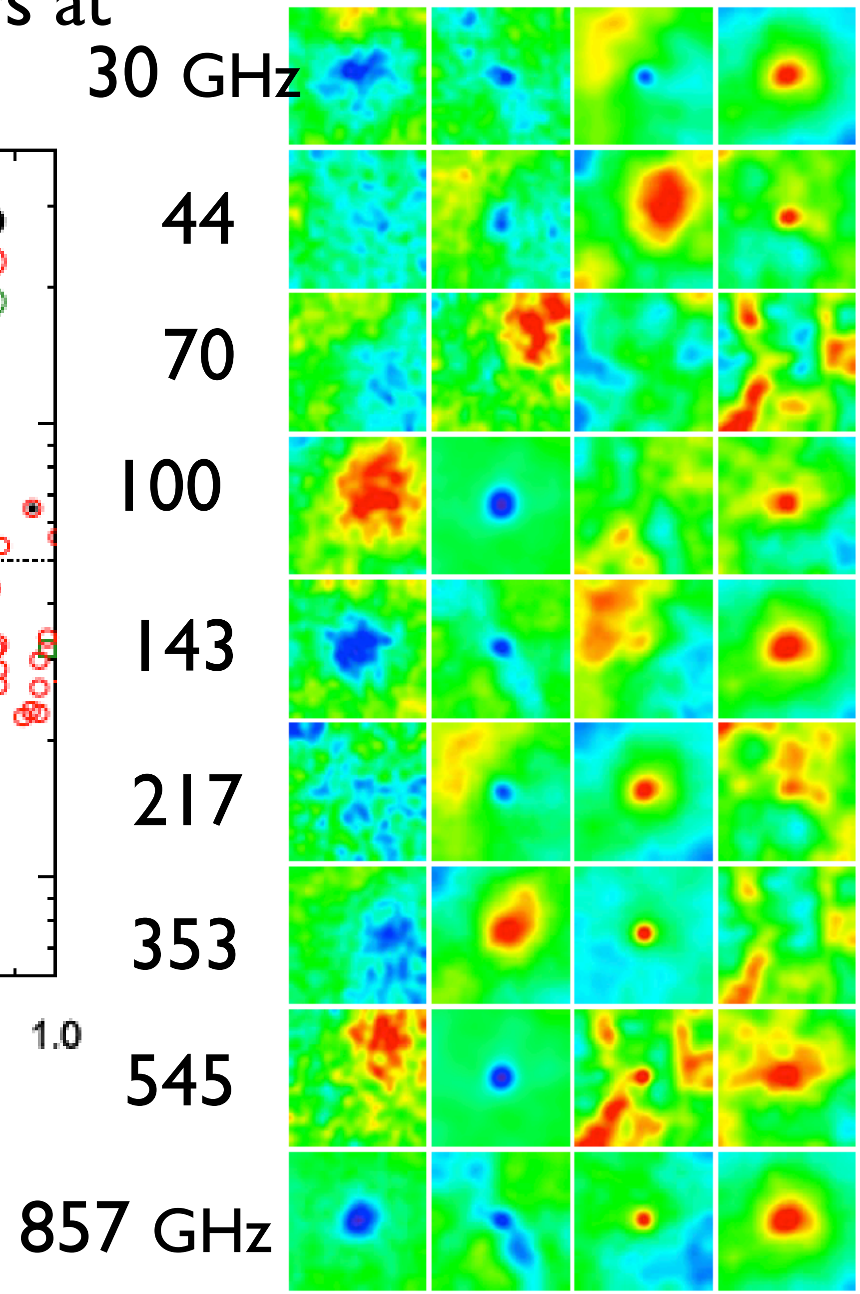


thermal SZ clusters

Planck selects massive clusters at lower z than ACT/SPT



stacked: known-cls C1 C2 C3



HALOs in the Web(z)

Semi-Analytics

Halo Model

= Eulerian Peak Patches

Lagrangian Peak Patches

painting on internal halo physics: DM/gas density, galaxy number density (HOD), pressure, entropy, dust emissivity, HI, CO, ...

for **fast MOnteCKarlos,** vary cosmological contents (DE), non-Gaussianity variants,... *cf. big sims=fixed cosmology, even if 512 of them*

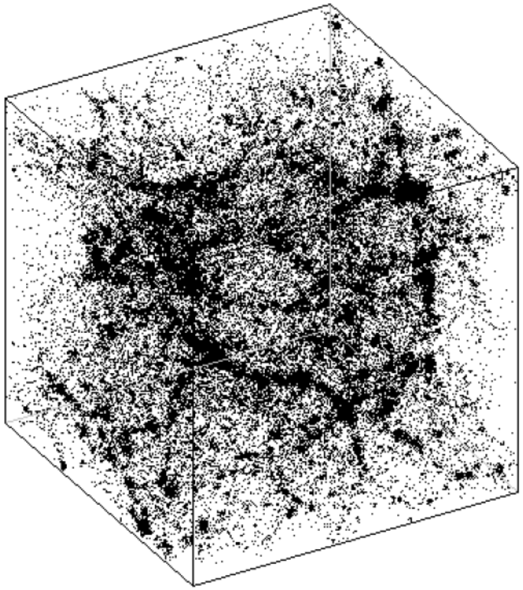
for **understanding the web**

thresholded excursion sets only for 1-point

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

Cosmic Web varies with initial density spectrum tilt

$d\sigma_{\rho L}^2/d\ln k \sim k^{(n+3)}$



neff (k) *varies for ‘standard’ tilted* **Λ***CDM*

~.962 ± .013 small k,

Planck1.3+WP+hiL+BAO

.9608 ± .0054 small k,

-1.3 cluster scale,

-2.3 galaxy scale,

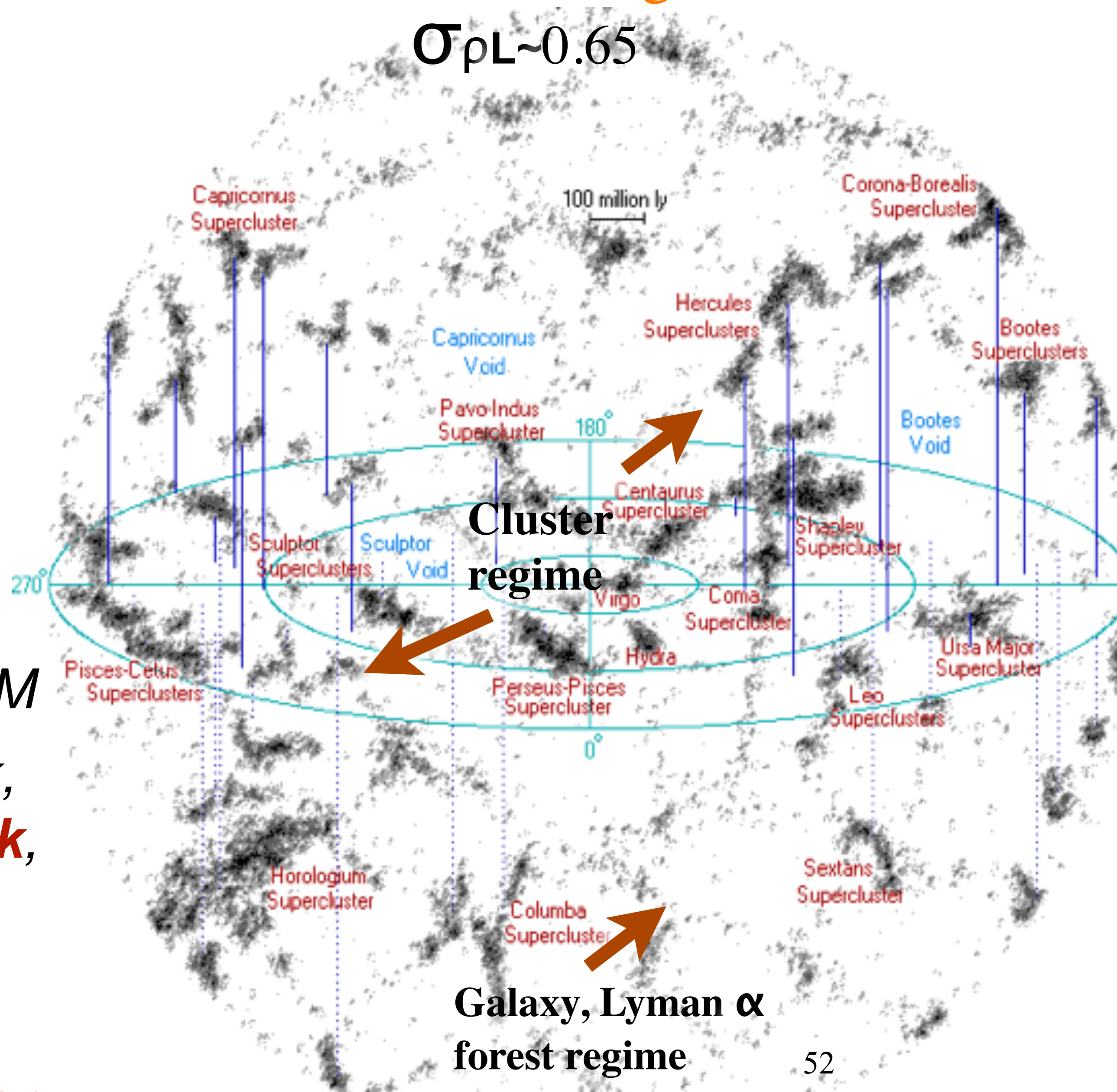
-2.8 Lyman α scale

-3.04 large k, 1st star

percolation threshold contour

smoothing

$\sigma_{\rho L} \sim 0.65$



Cluster regime

Galaxy, Lyman α forest regime

beware: a numerically challenging regime ***extreme LSS tides***

The **Cosmic Web**

B+Kofman+Pogosyan 96-99

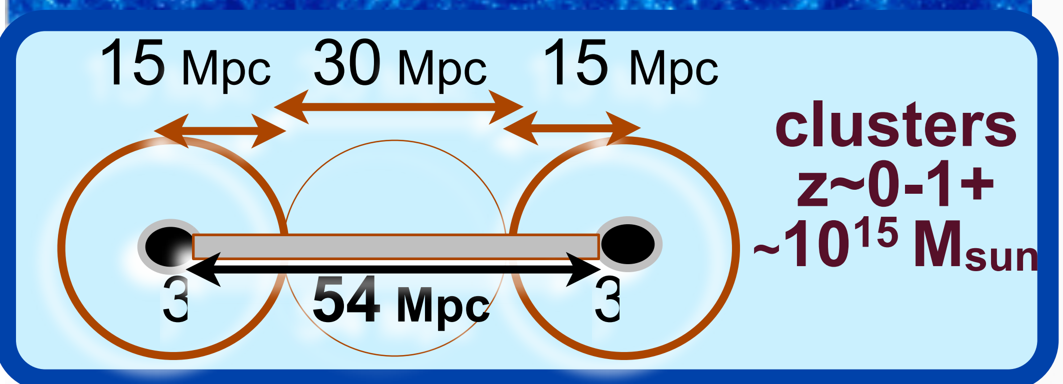
"Molecular" Picture of Filaments & Membranes in LSS

Constrained Correlation Functions

aka $F = \langle F \,|\{q \in \mathcal{C}\}\rangle + F_f$ (residual "noise")

$\langle F \,|\{q \in \mathcal{C}\}\rangle = \langle F q^\dagger \rangle \langle q q^\dagger \rangle^{-1} q$, X-correlation

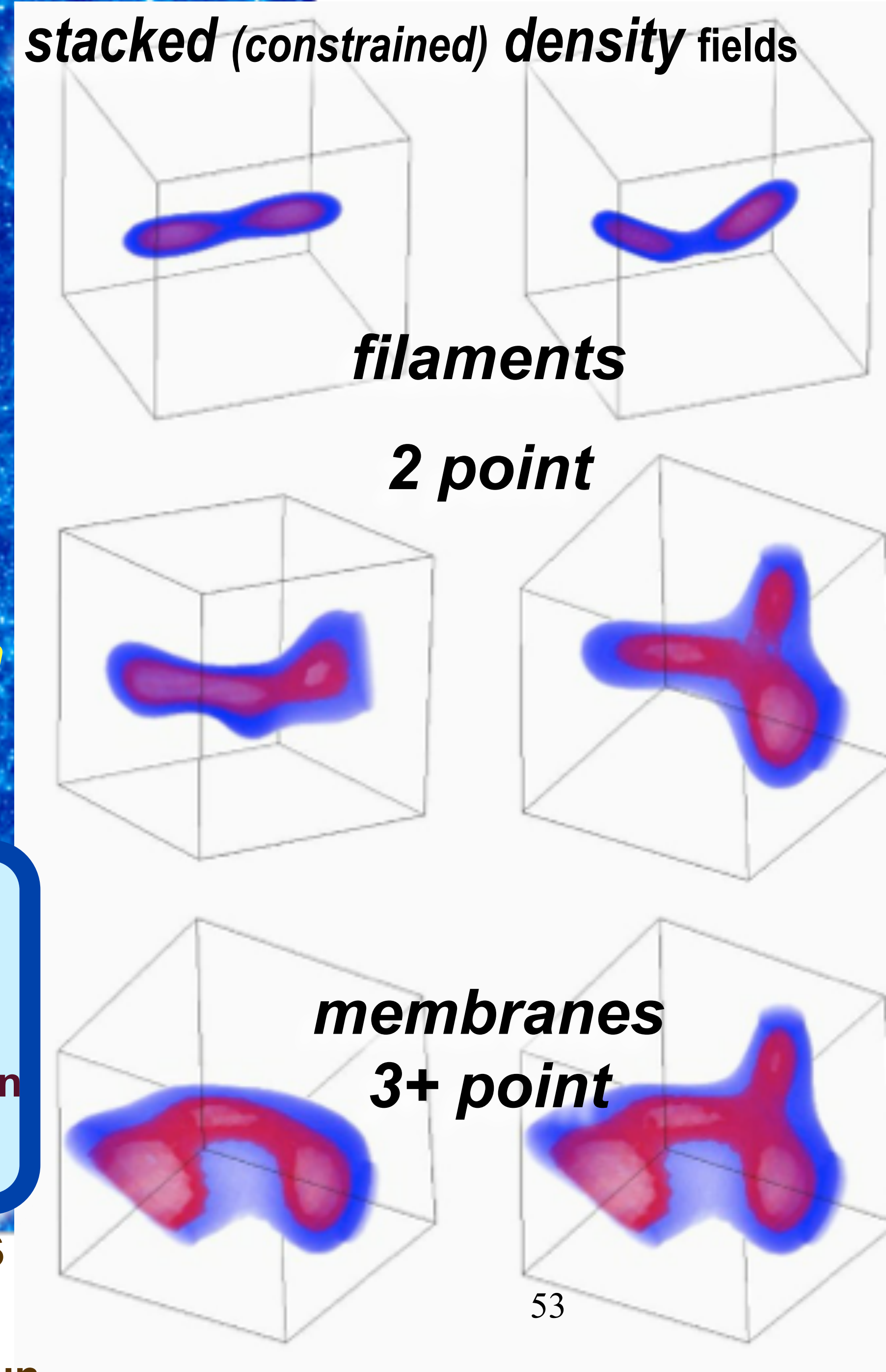
e.g., $F = \ln \rho/\langle\rho\rangle = -\mathrm{Trace}(\epsilon)$



1 Mpc 2 Mpc 1 Mpc

3.6 Mpc

galaxies
z~2-5
$\sim 10^{11.5}$ M_{sun}



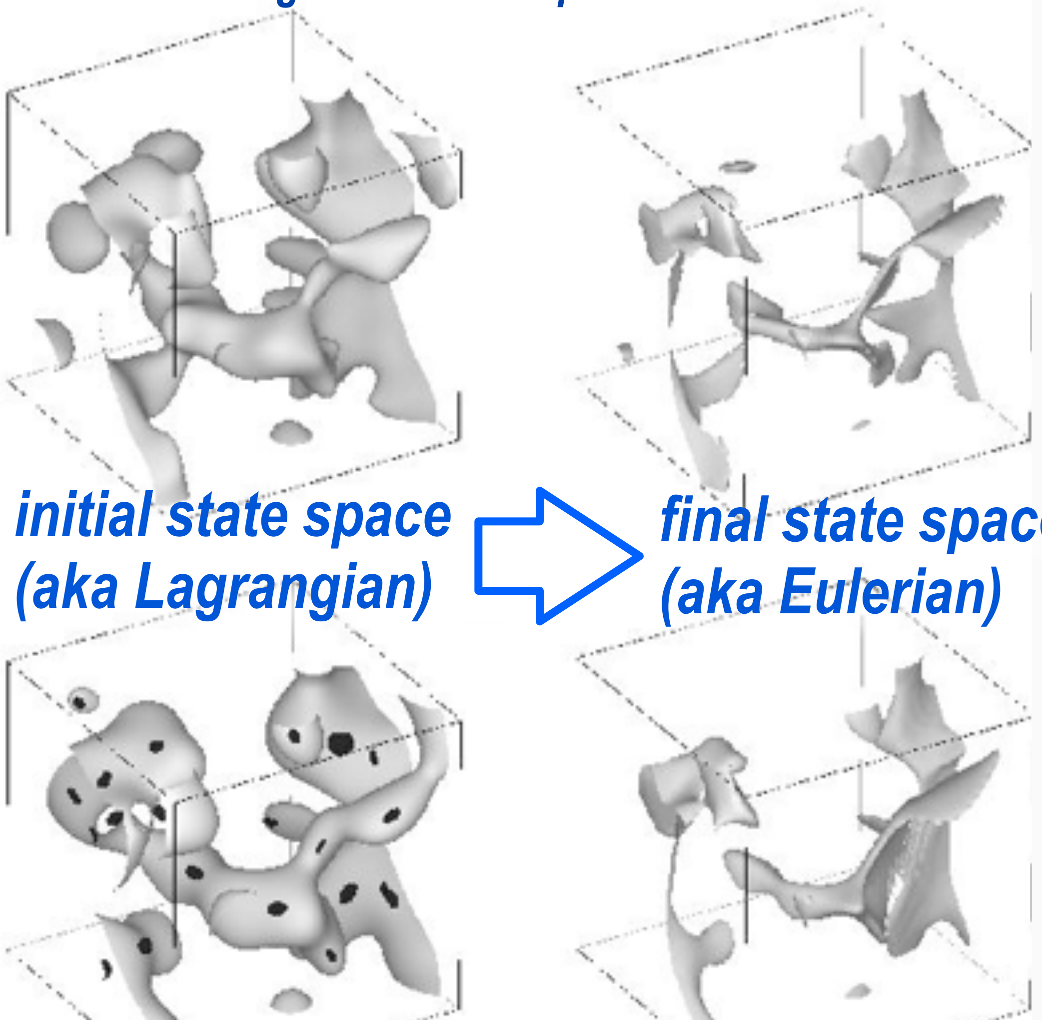
density field **reconstruction** of the filtered web

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

LSS convergence as N_{patch} increases

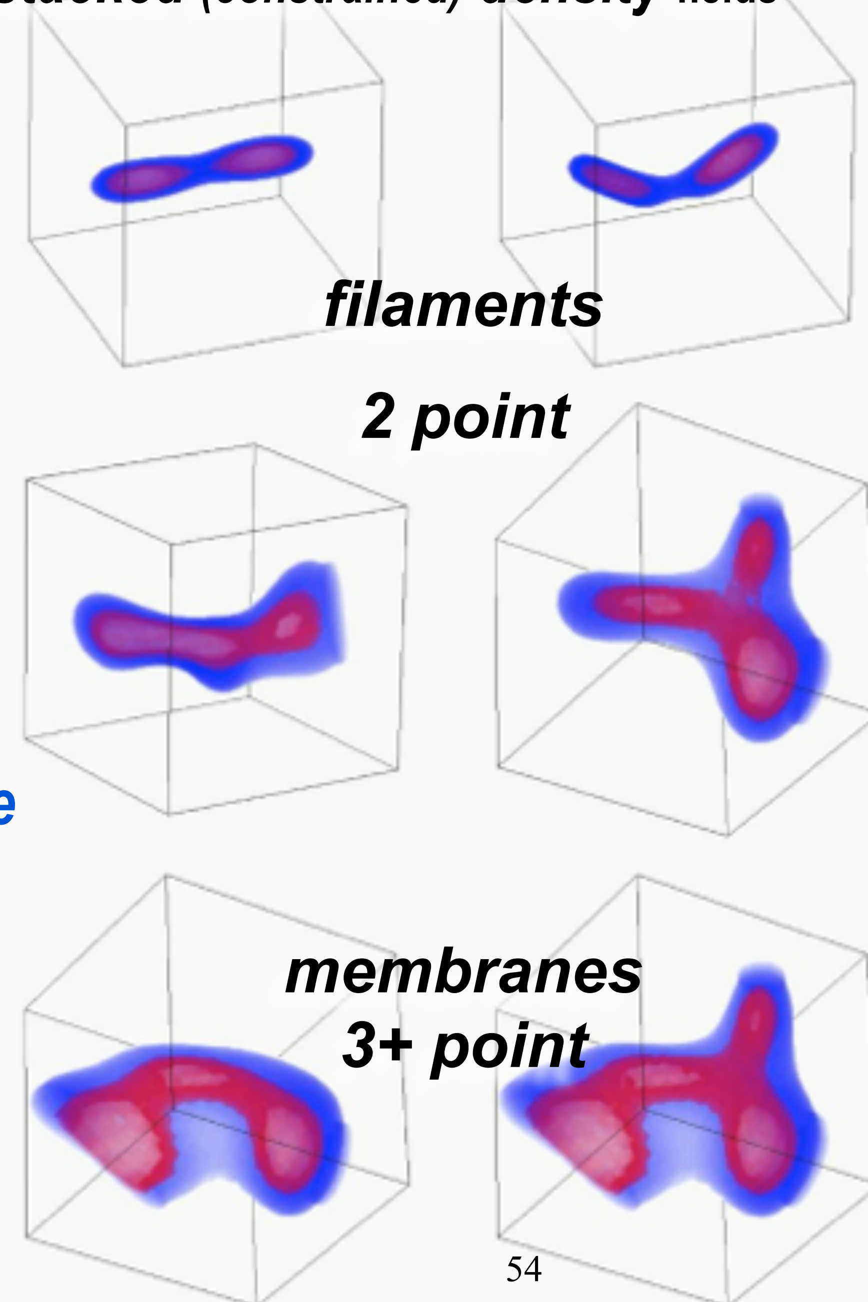
InformationQuality: **clusters encode** the web

interior and high resolution spatial detail <=> more info



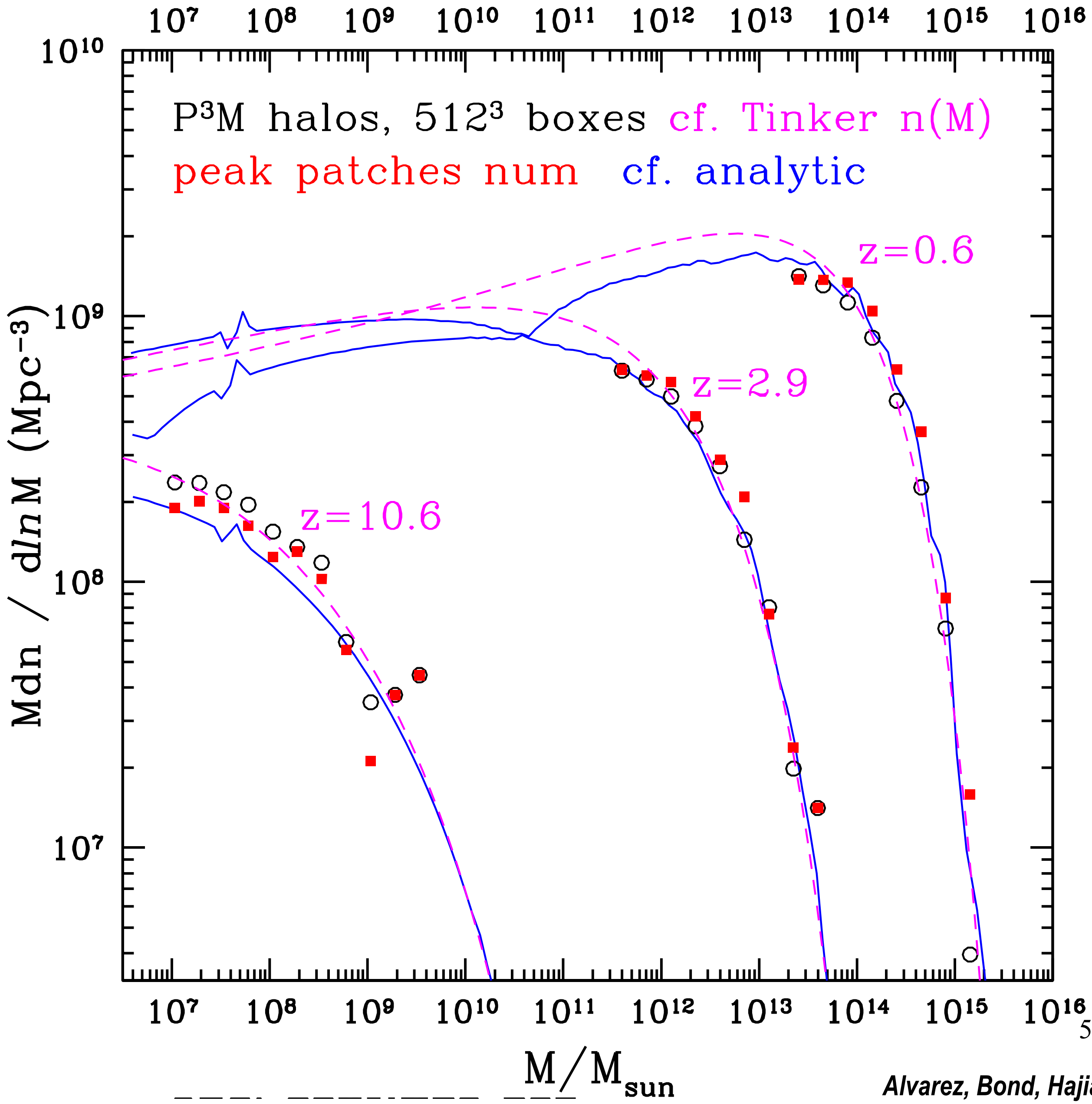
percolation threshold contour

stacked (constrained) **density** fields



Peak patches cf 512^3 CUBEP3M halos using SP-O, boxes are: 857 Mpc, 214 Mpc, 6.43 Mpc

SP-O Halos are exactly **Eulerian-space** Peak Patches



Alvarez, Bond, Hajian, Stein, Emberson 2013

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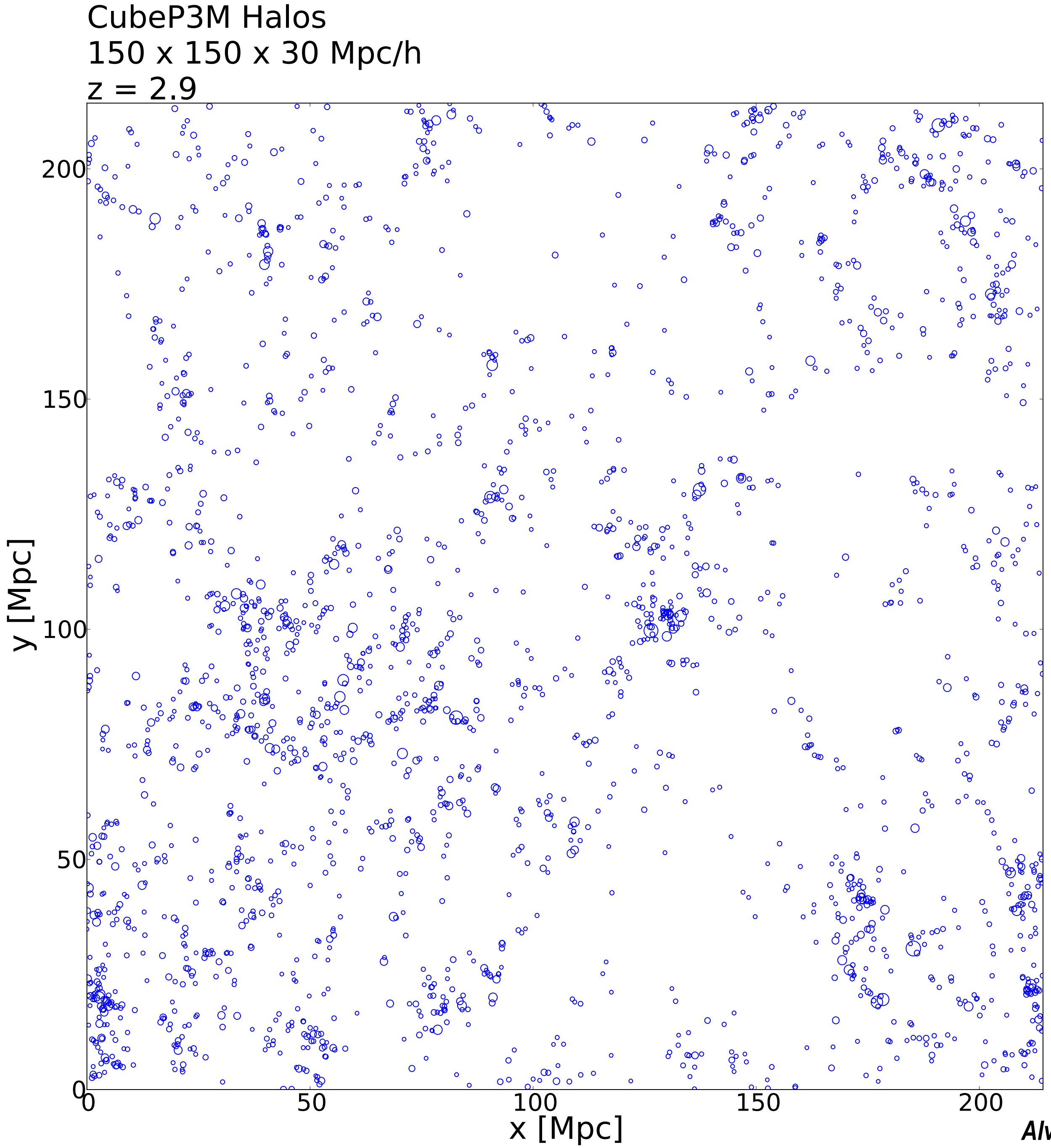

Application to HI, CO, CIB, …

Alvarez, Bond, Hajian, Stein, Emberson 2013

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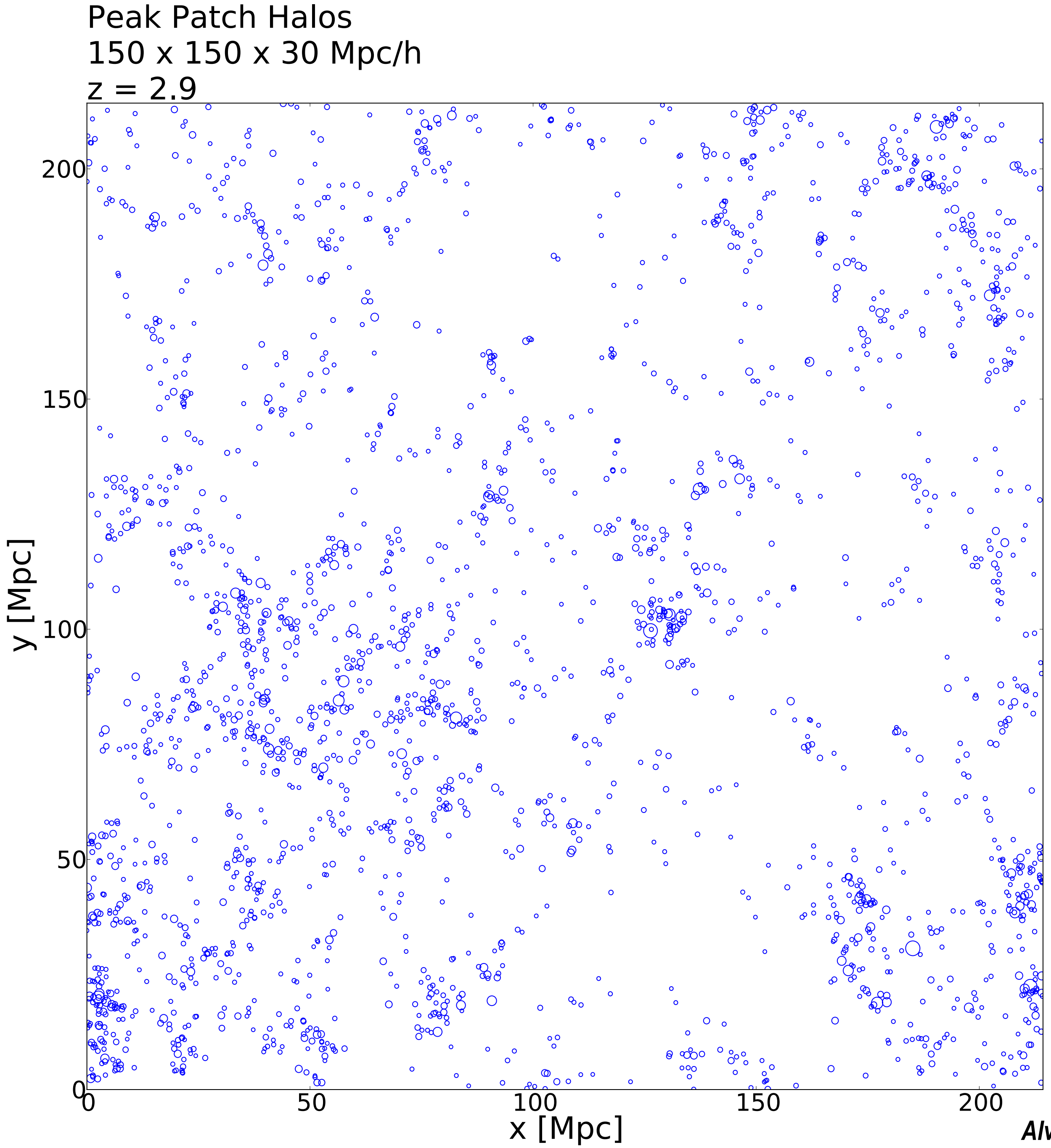
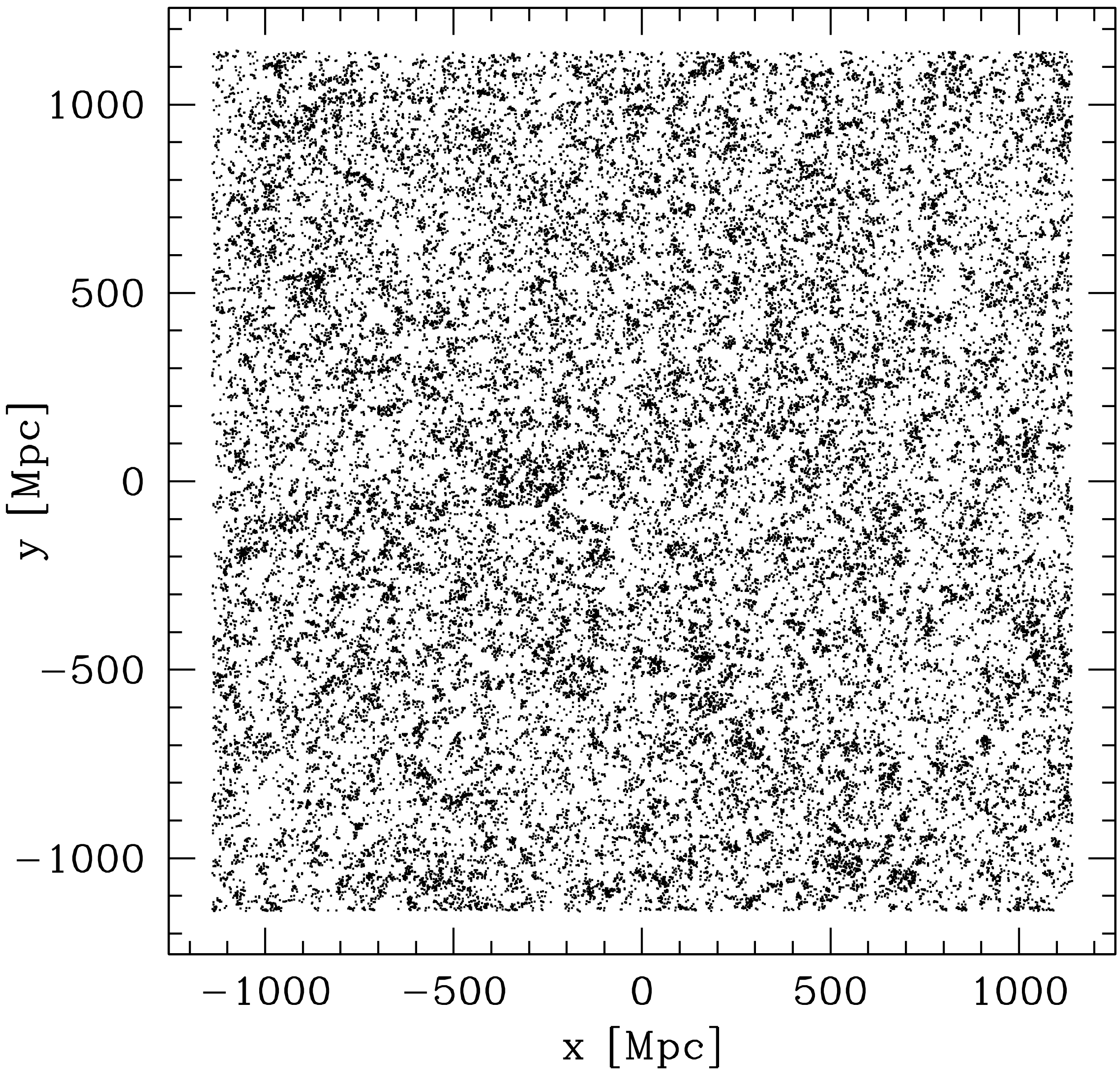


Application to HI, CO, CIB, ...

Alvarez, Bond, Hajian, Stein, Emberson 2013

Application to CO (40 sqdeg) 6000 boxes to tile, only 10 Mpc thick for illustration, but z=2.5-3.5, 640 processes, took 4 hrs



Alvarez, Bond, Hajian, Stein, Emberson 2013

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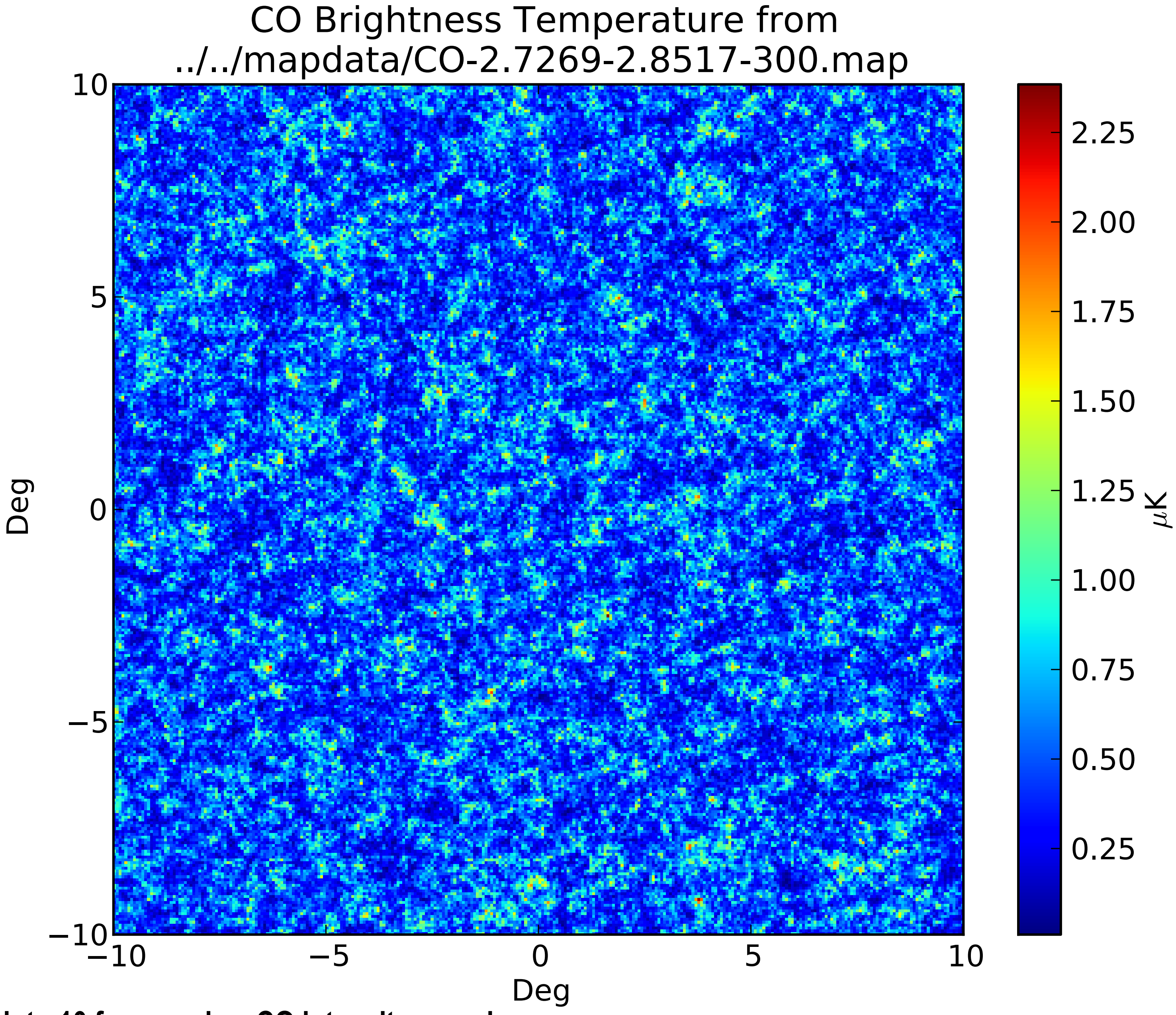
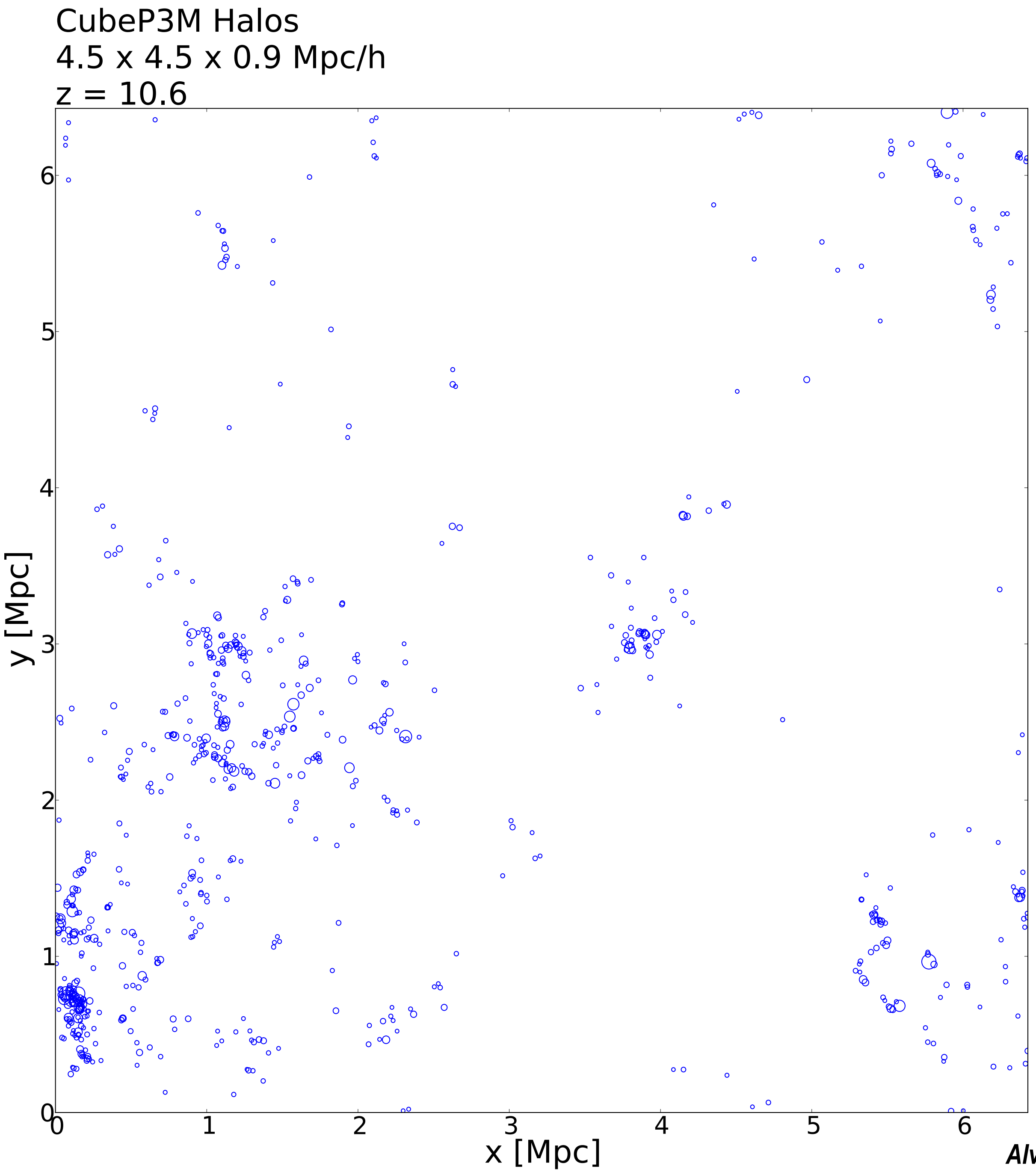


COMA, split into 10 frequencies, CO intensity mapping

Peak patches cf 512^3 CUBEP3M halos using SP-O, boxes are: 857 Mpc, 214 Mpc, 6.43 Mpc



beware: a numerically challenging regime extreme LSS tides

still Peak Patches works!

Application to HI, reionization, first stars & dwarflets

Alvarez, Bond, Hajian, Stein, Emberson 2013

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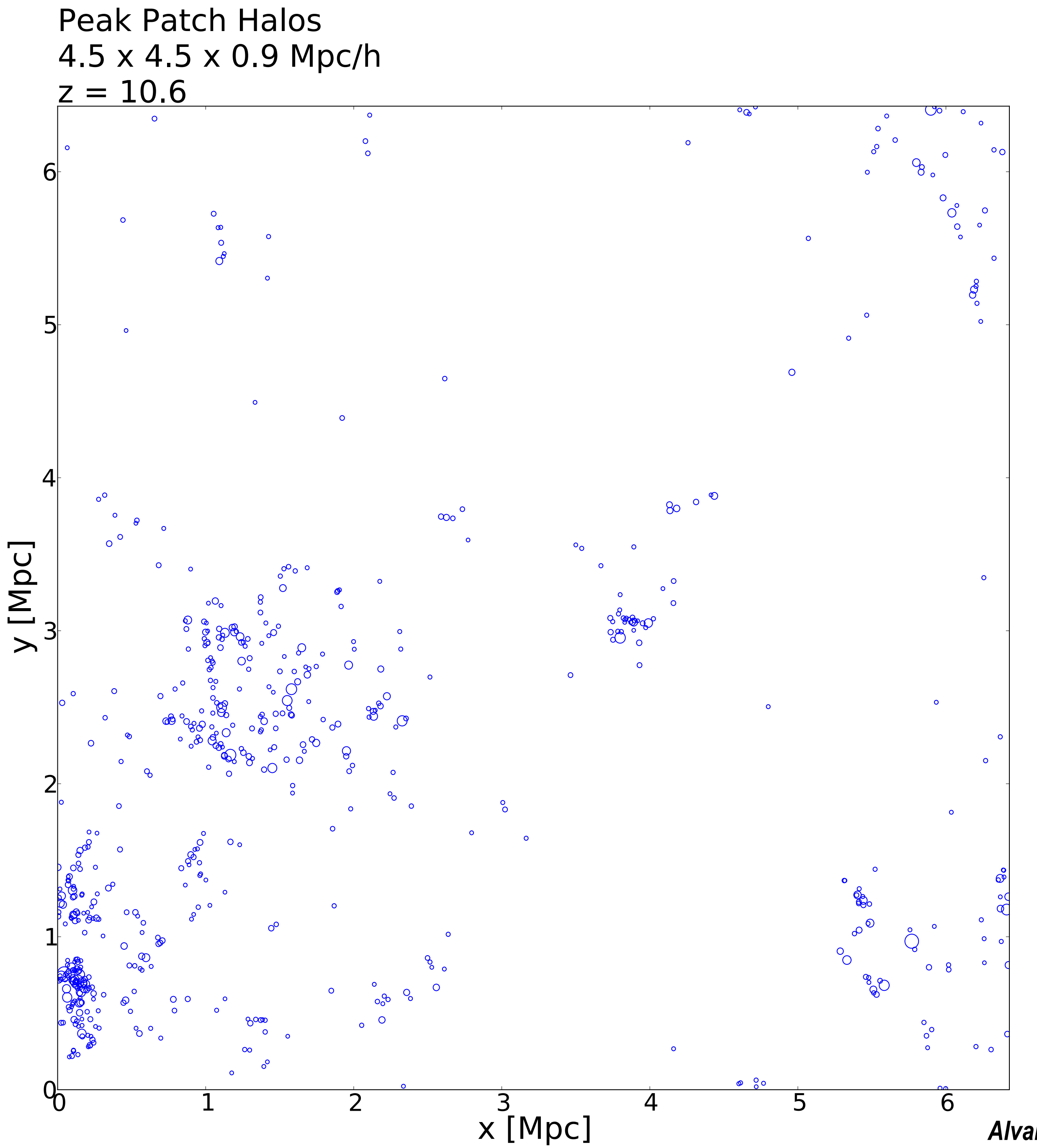


beware: a numerically challenging regime extreme LSS tides

still Peak Patches works!

Application to HI, reionization, first stars & dwarflets

Alvarez, Bond, Hajian, Stein, Emberson 2013

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

C_L^{SZ}

tSZ power spectrum

QUaD @SP

C_L^{SZ}

Planck09.4

52+ bolometers
+ HEMTs @L2
9 frequencies

Planck1.3 matched filter all-sky y-map => C_L^{tSZ}

observed clusters seen, cosmological parameters agree with those from counts!

low L tail from extended nearby cls

WMAP @L2 **to 2010**

2004 — 2005 — 2006 — 2007 — 2008 — 2009 — **LHC** — 2011

2005 C_L^{SZ}

Acbar@SP
~1 blind

>96
OVRO /BIMA array C_L^{SZ}

80s-90s
Ryle
OVRO

SZA@Cal
C_L^{SZ}

AMI

GBT Mustang

AMIBA

APEX
~400 bolos@Chile

2008 C_L^{SZ}

SPT
1000 bolos
@SPole

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

SCUBA2
12000 bolos
JCMT @Hawaii

Bpol @L2

C_L^{SZ}

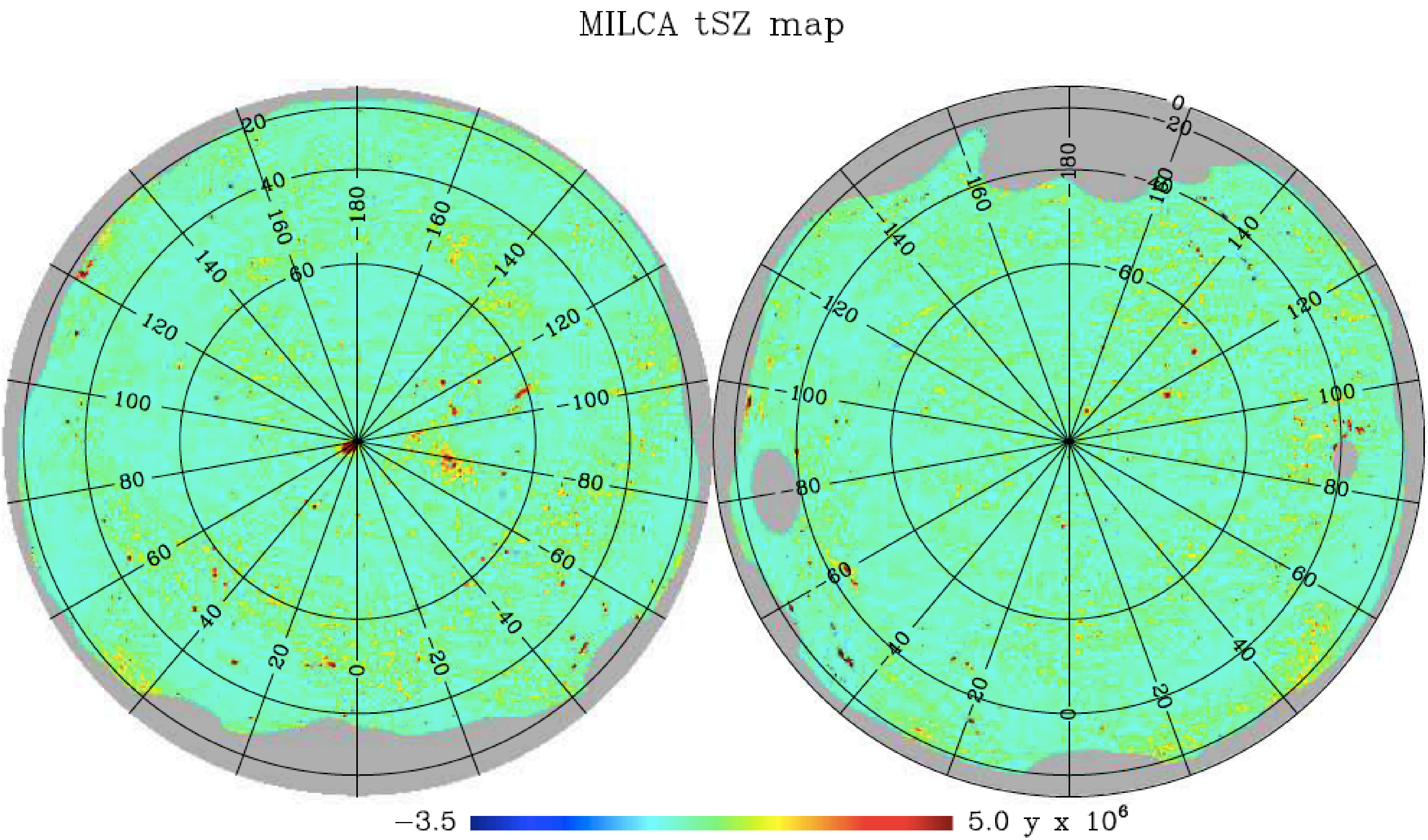
SPTpol
ACTpol

ALMA

CCAT@Chile

LMT@Mexico

SZ power spectrum from ymaps Planck2013 XXI



Adapted component separation algorithms: NILC & MILCA on all HFI channels 100-857 GHz @ 10' res

SEXtractor + MMF and MHW + SEXtractor detected clusters number & flux consistent with PSZ catalogue

tSZ + clustered CIB + Point sources

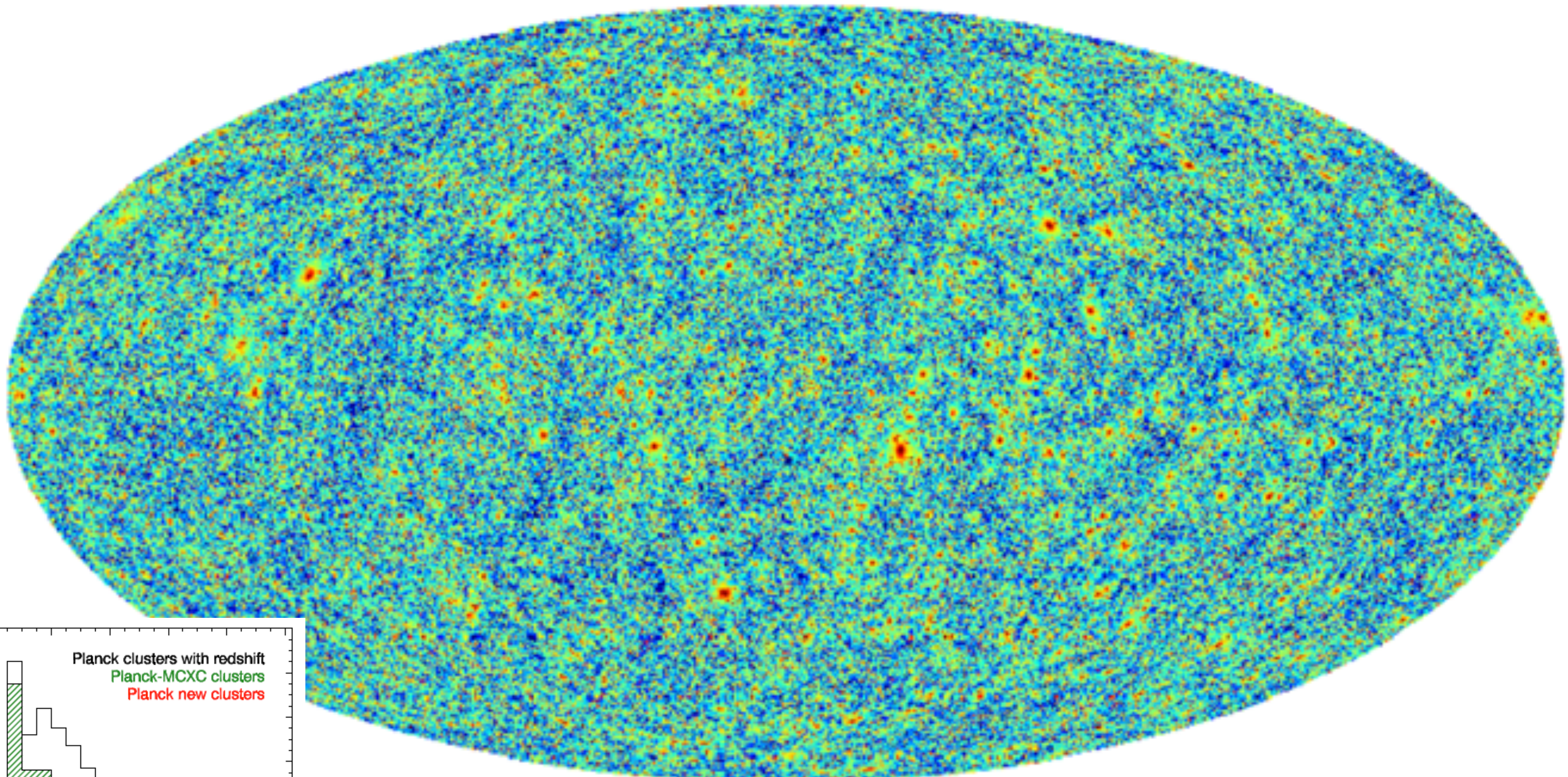
how to characterize map errors?
inhomogeneous, CIB contamination, ..

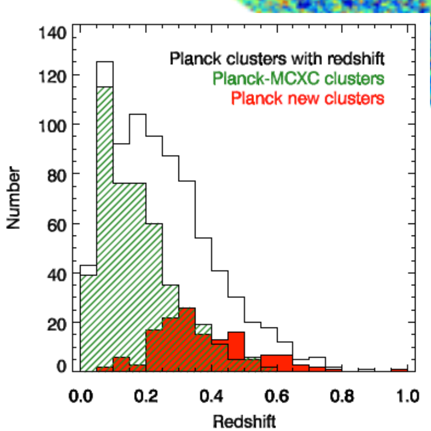
the **Cosmic Web of Clusters**, seen thru Compton cooling of high pressure electrons by the CMB

tSZ effect

Lightcone Simulation of 35000 Clusters > 2×10^{13} M_{sun} to z=0.5 in projected pressure

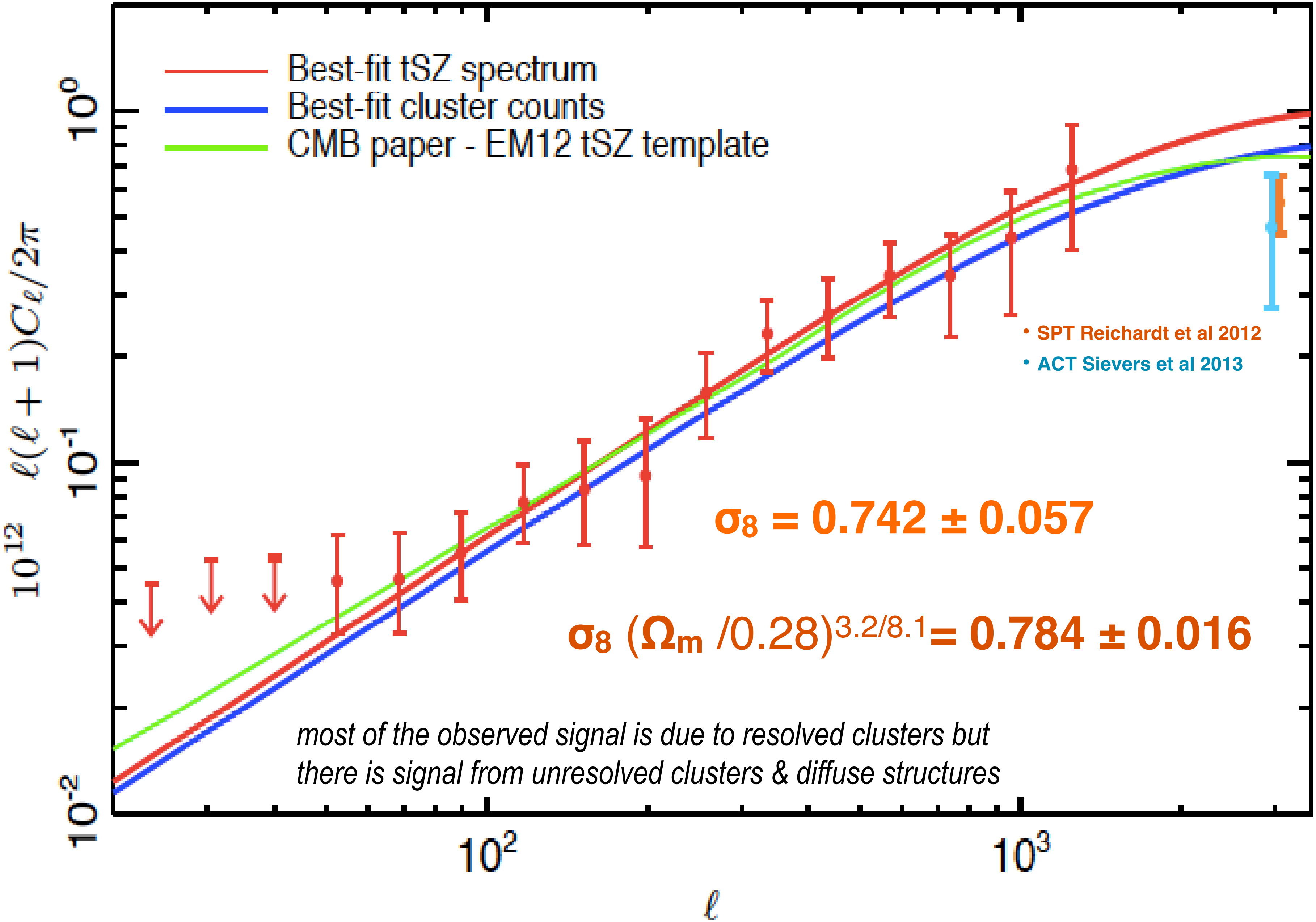
Alvarez, Bond, Hajian, Stein, Battaglia, Emberson,..2014



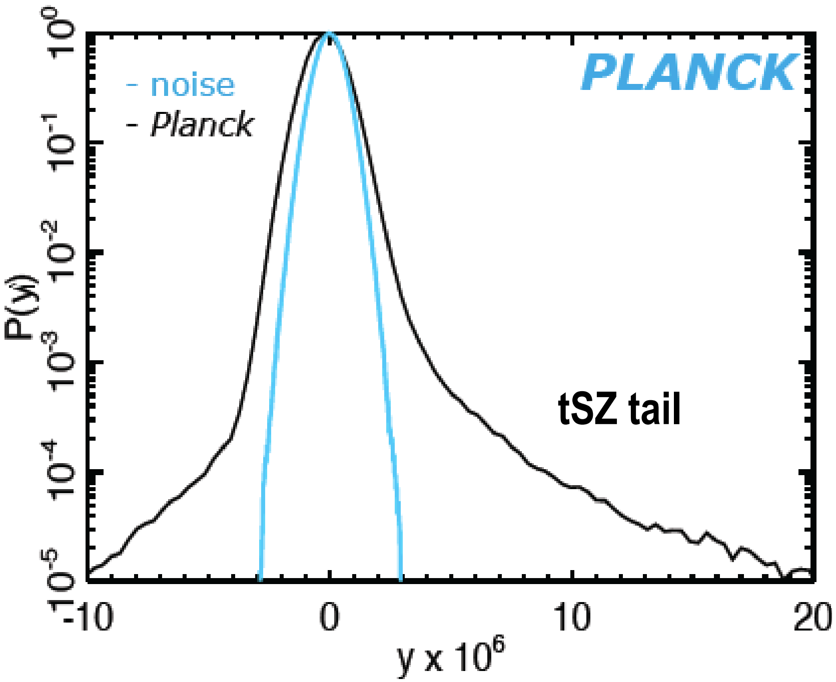


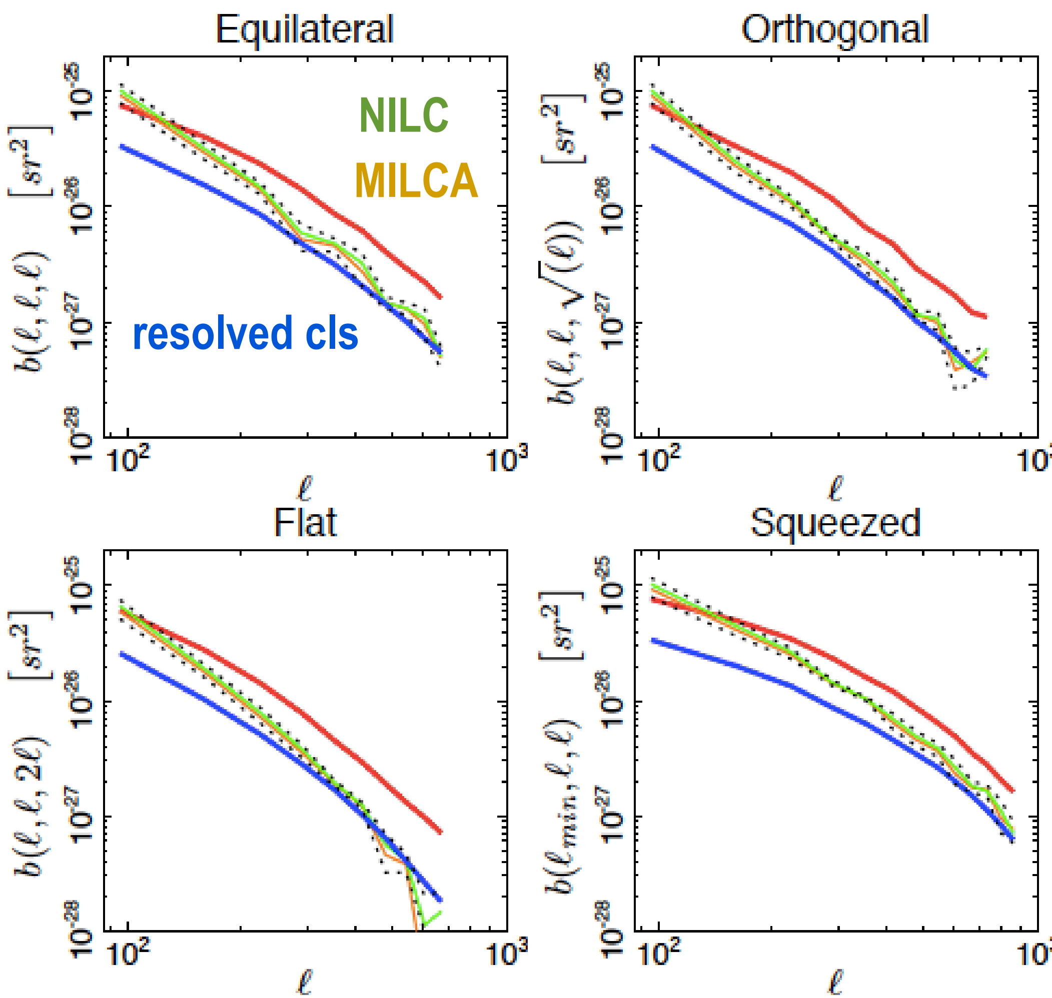
how to characterize map errors? by SIMs
inhomogeneous, CIB contamination, ..

SZ power spectrum from ymaps are consistent with cluster counts cosmology Planck2013 XXI



SZ 1pt PDF and 3 point (bispectrum) from ymaps are consistent Planck2013 XXI



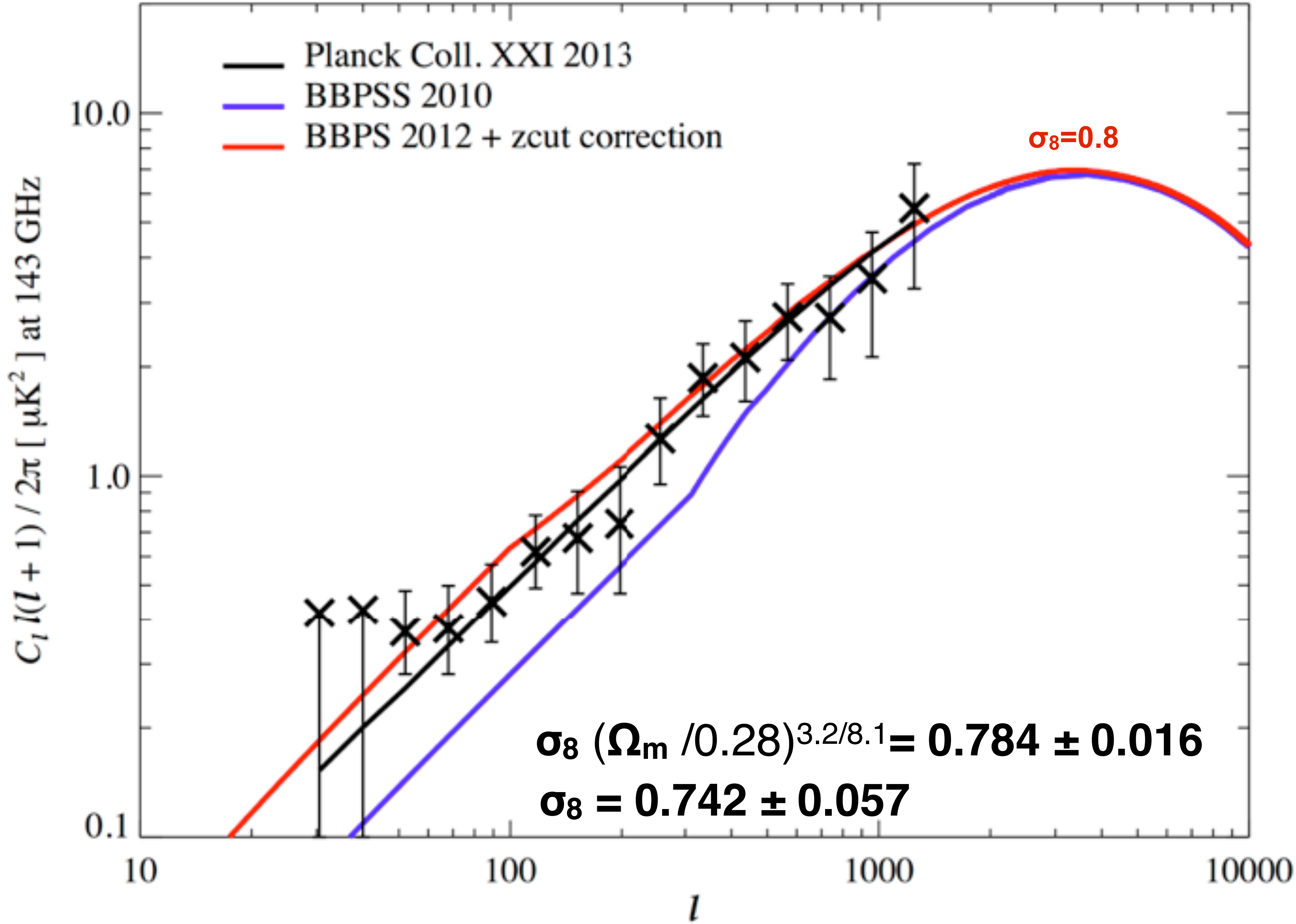


bispectrum amplitude scales as σ_8^{10-12}

=> $\sigma_8 \sim 0.74 \pm 0.04$

SZ power spectrum from ymaps

thermal SZ clusters

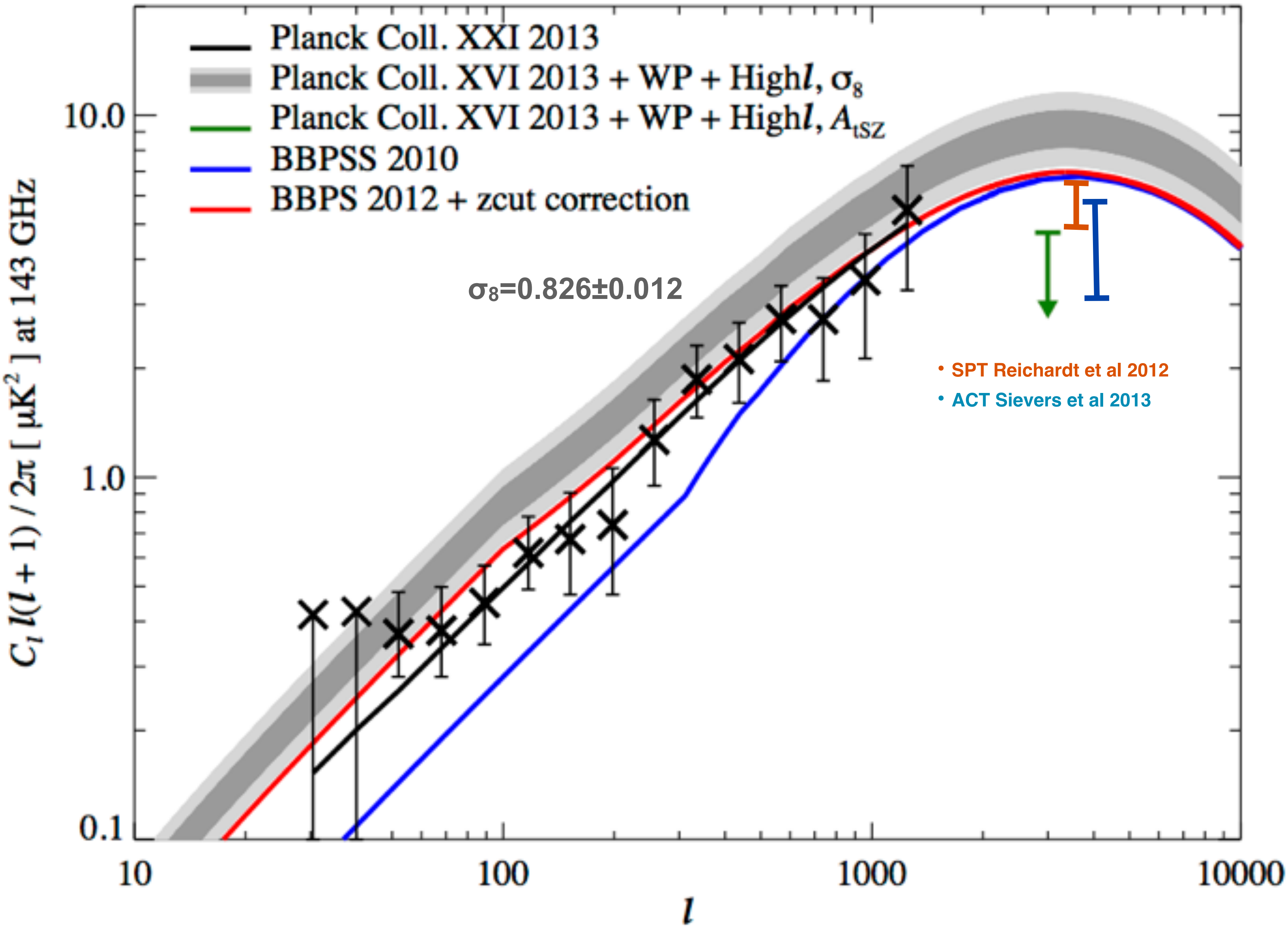


$$\sigma_8 \, (\Omega_m / 0.28)^{3.2/8.1} = 0.784 \pm 0.016$$

$$\sigma_8 = 0.742 \pm 0.057$$

SZ power spectrum from ymaps

thermal SZ clusters



HALOs in the Web(z)

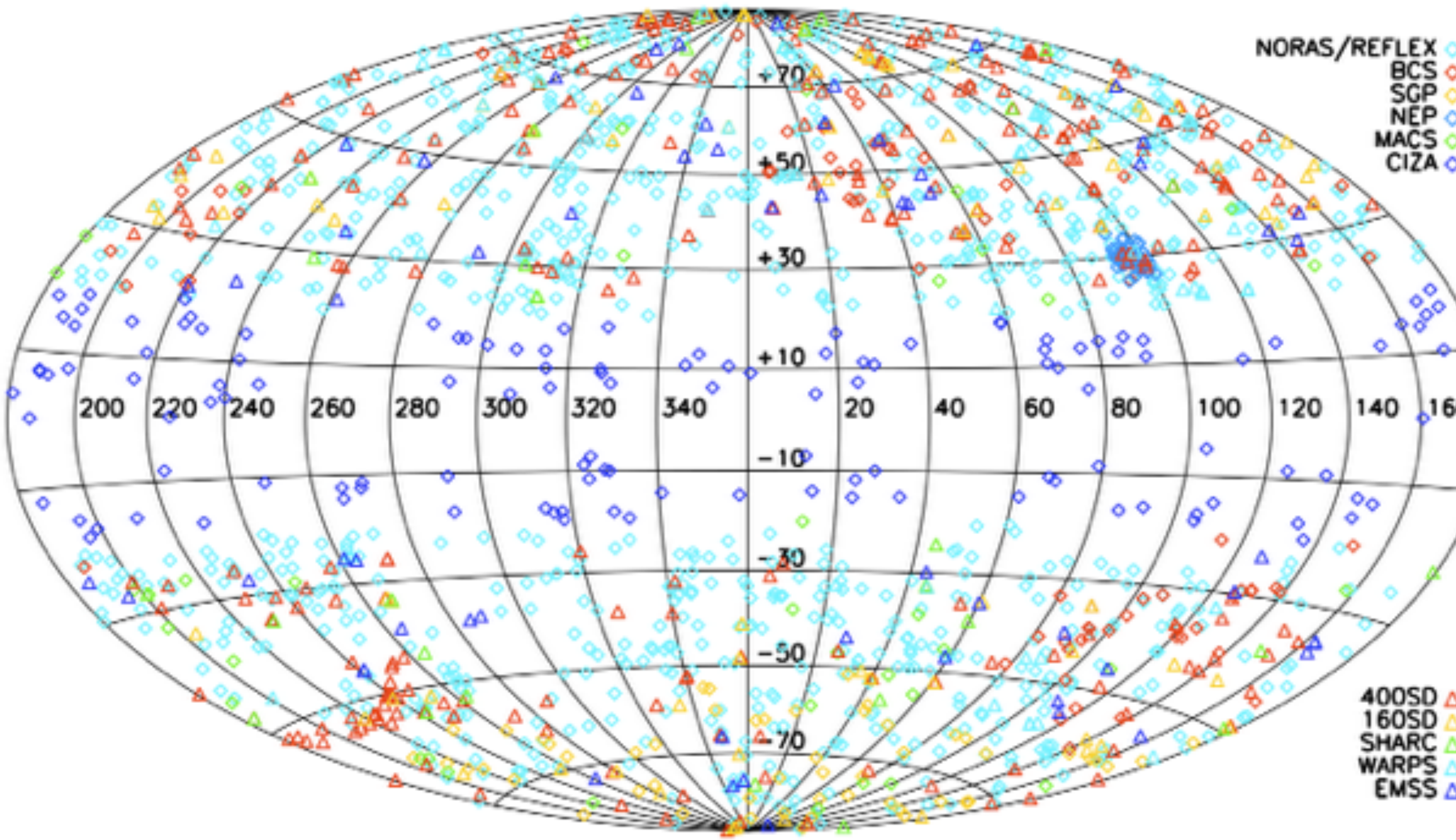
the CLUSTER SYSTEM example

Cross-correlations of X-rays and CMB maps = X-corr power spectra, a path to

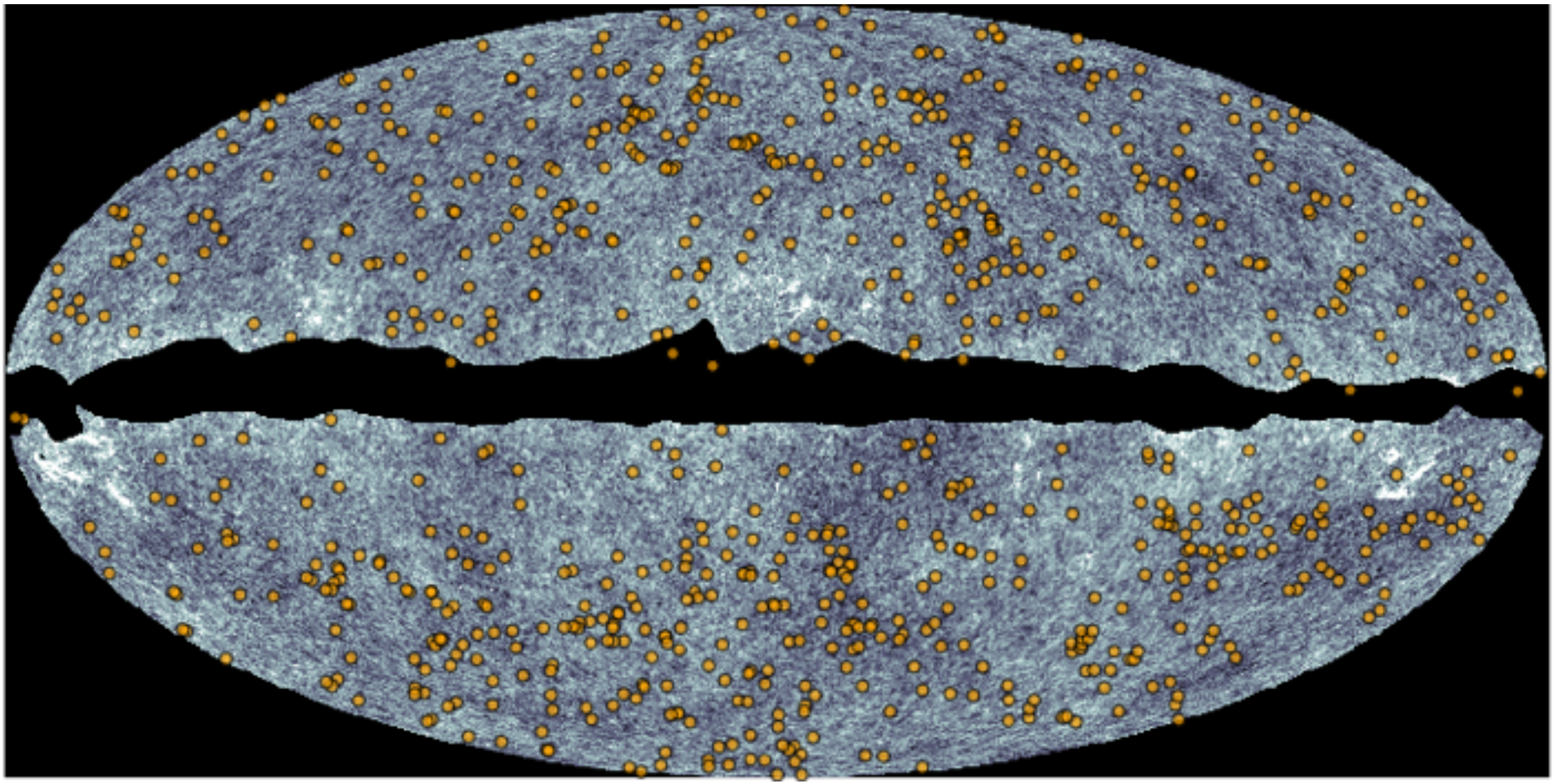
σ_{8SZ} =0.81+-.01 P13+X-SZ

Hajian, Battaglia, Spergel, Bond, Pfrommer, Sievers 2013 **Planck + WMAP9 x ROSAT (RBC subset of MXCC)**

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



Hajian, Battaglia, Spergel, Bond, Pfrommer, Sievers 2013 **Planck + WMAP9 x ROSAT (RBC subset of MXCC)**



Burst of tSZ papers in 2013 Planck

Planck Intermediate Results. XIII. Constraints on peculiar velocities

Planck 2013 results. XXI. Cosmology with the all-sky Planck Compton parameter y-map

Planck 2013 results. XX. Cosmology from Sunyaev–Zeldovich cluster counts

Planck 2013 results. XXIX. Planck catalogue of Sunyaev–Zeldovich sources

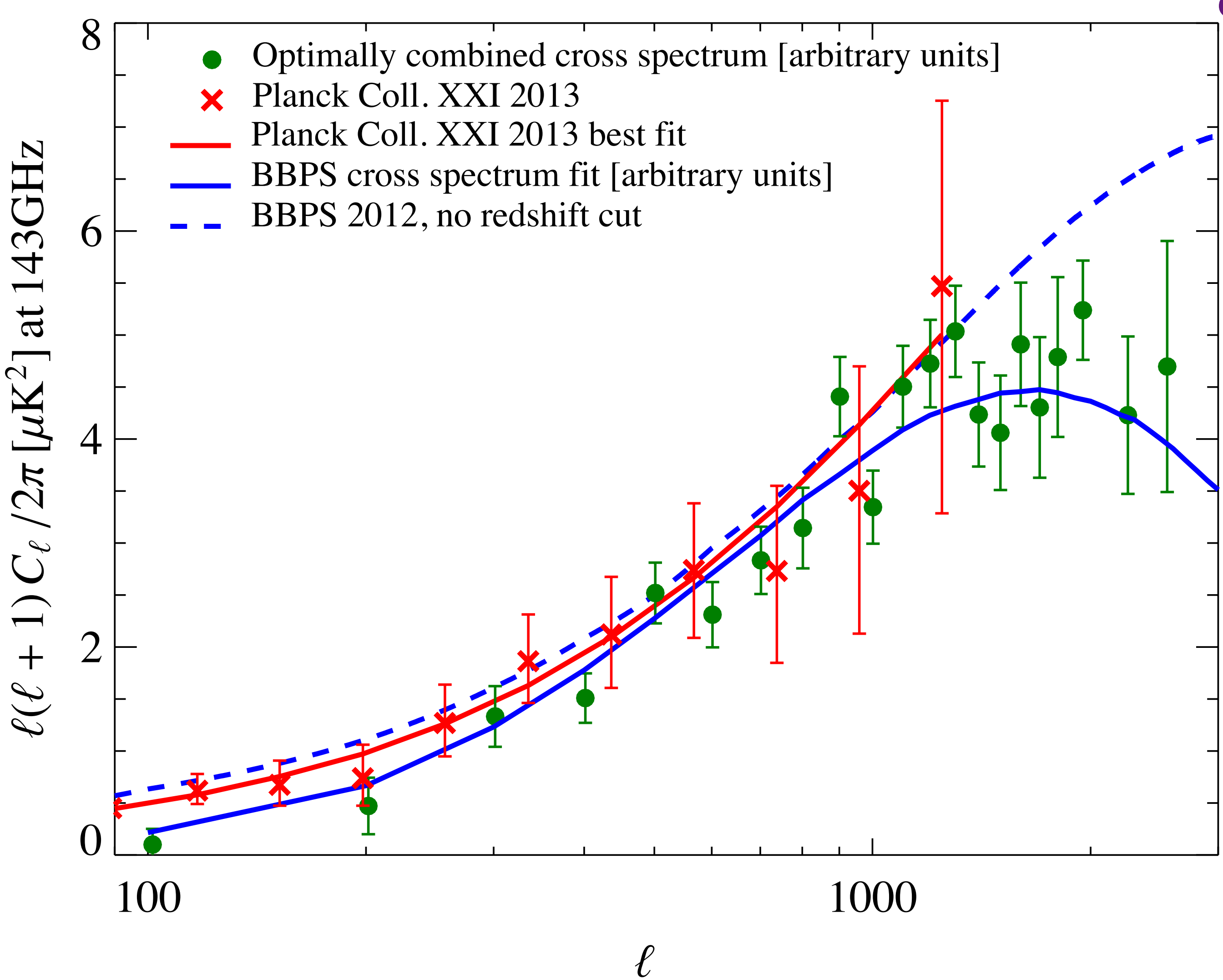
$\sim \sigma_{8SZ}^{7.4}\,\Omega_m^{1.9}$ **for L~ 1000**

$\sigma_{8SZ}\,(\Omega_m/0.30)^{0.26}$ **= 0.80 +- 0.02**

e.g., **= 0.796 +- 0.011** for "AGN feedback"

σ_{8SZ} **= 0.812 +- 0.010 cl+WMAP9**

= 0.812 +- 0.008 cl+Planck2013



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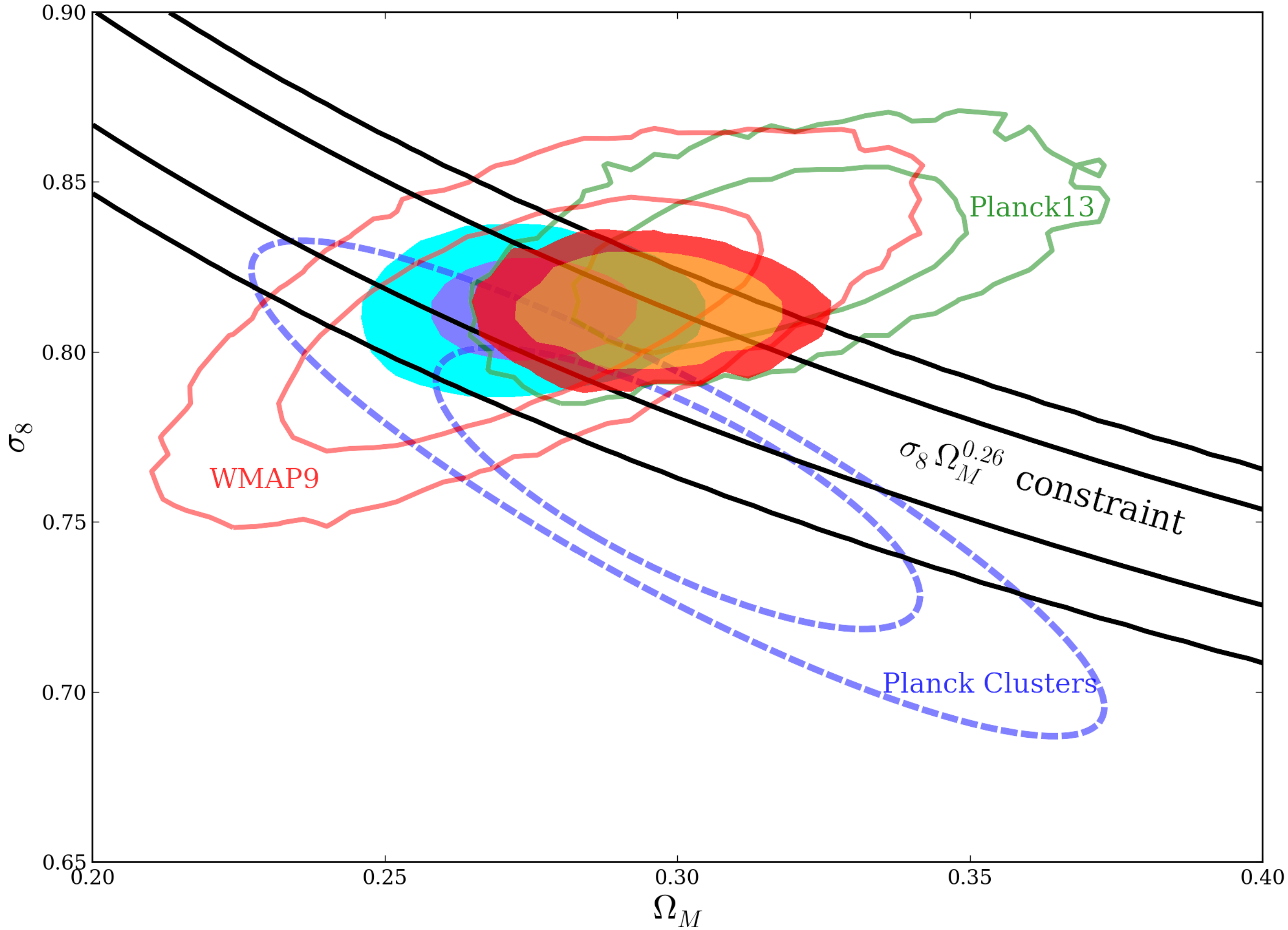

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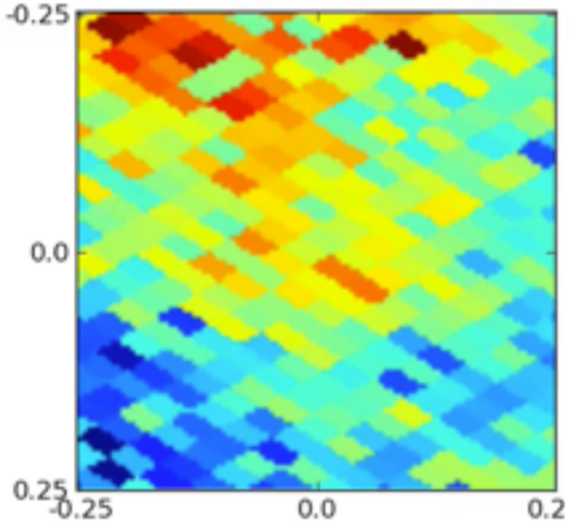
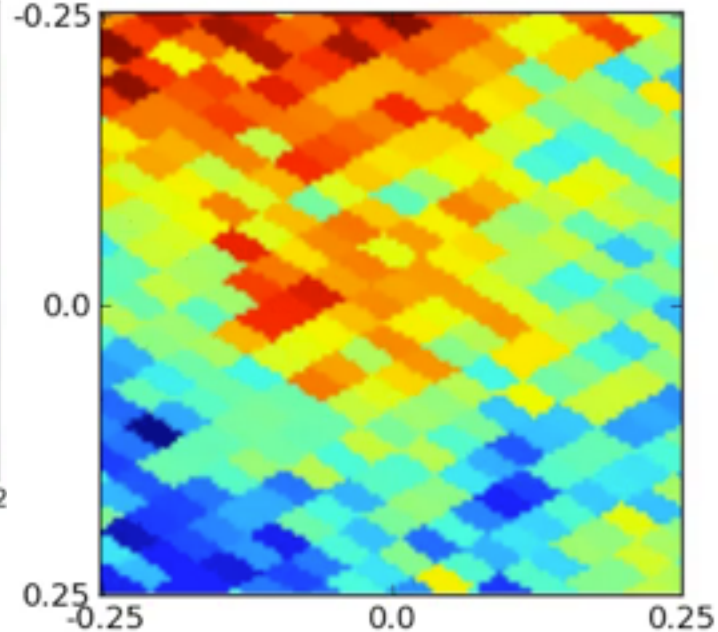
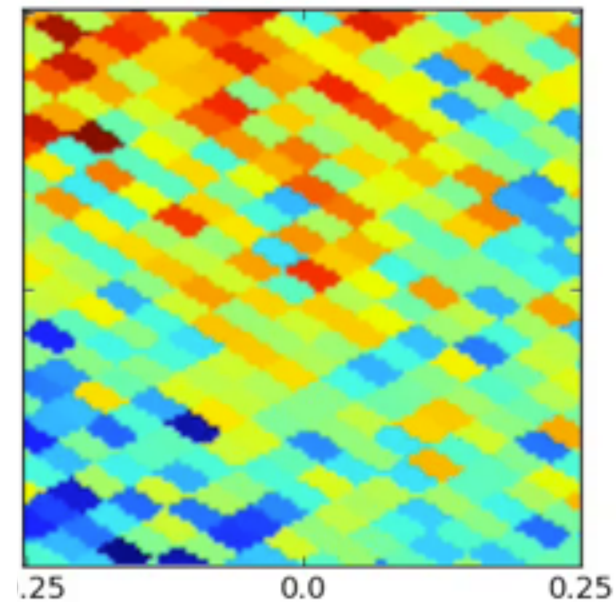
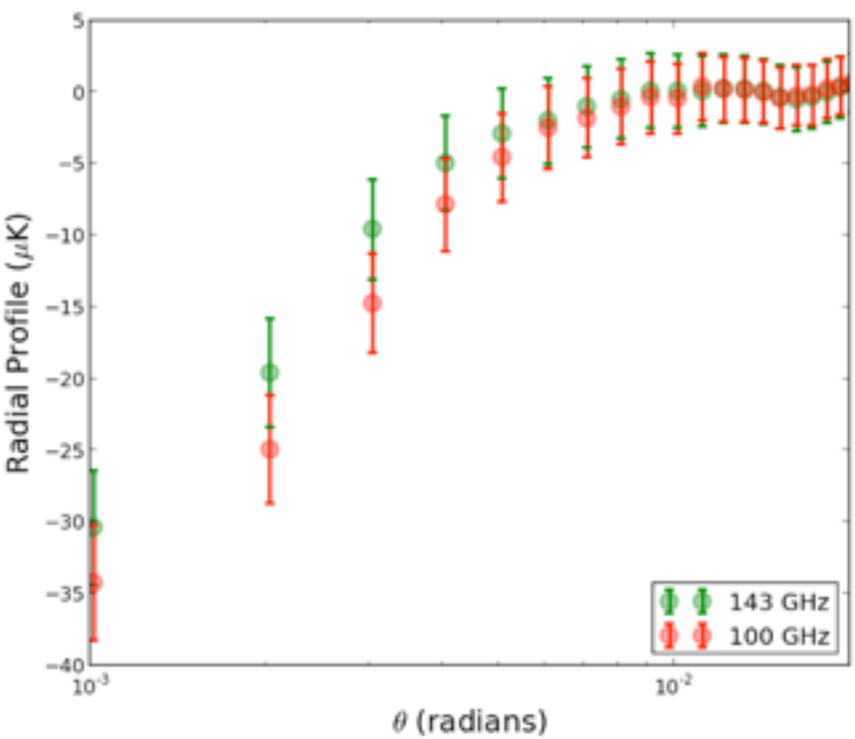


217 GHz







143 GHz

100 GHz

emergence of the cross-correlation

$$\langle \Delta T_{SZ}\,(\theta) | cl \in class\text{-}\mathcal{C} = RBC \rangle$$

from (unscaled) stacking of RBC clusters

@ the tSZ null (220), @ 143=best S/N, @ 100

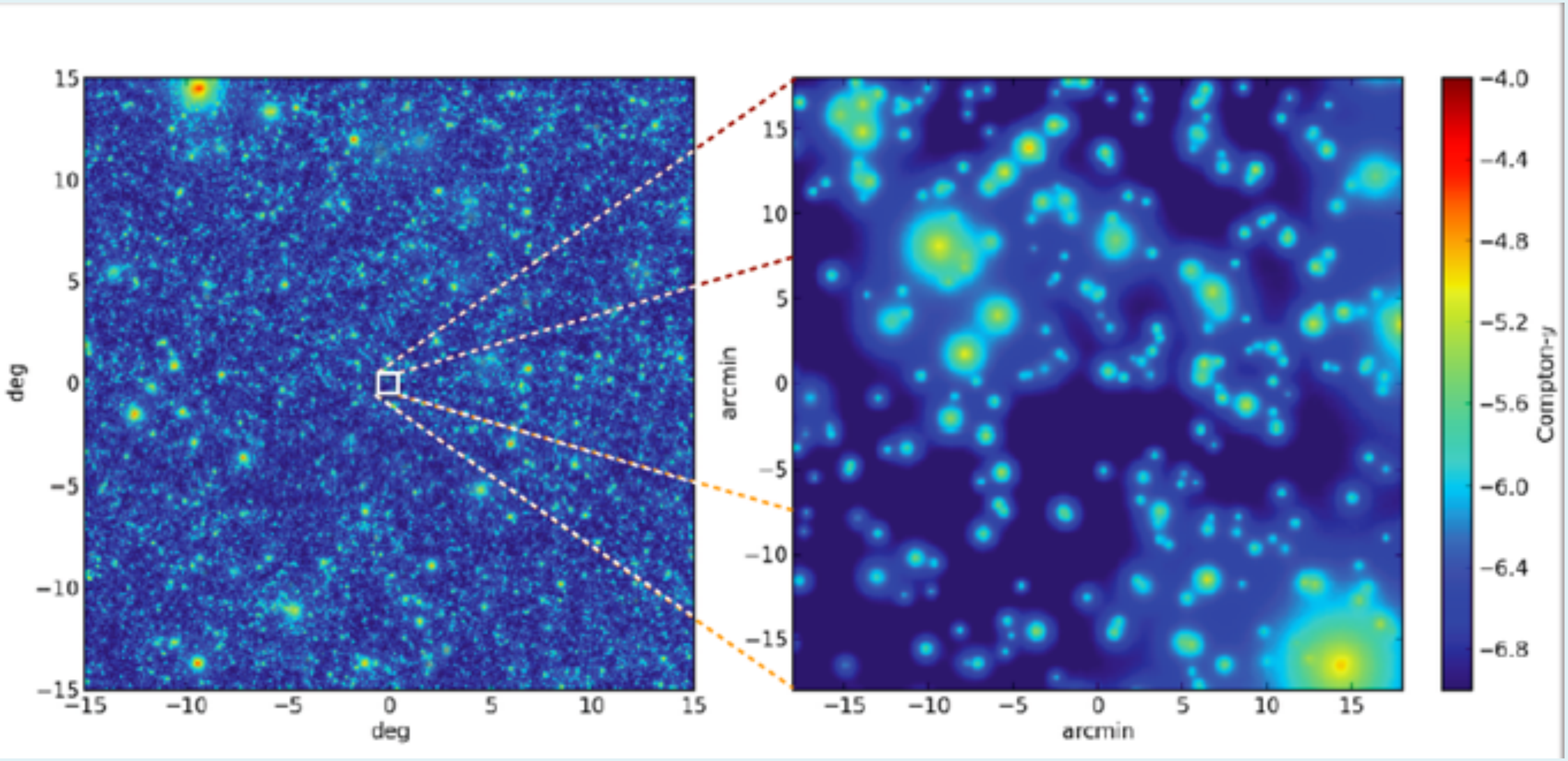
Hajian, Battaglia, Spergel, Bond, Pfrommer, Sievers 2013

Planck + WMAP9 x ROSAT (RBC subset of MXCC)

Compton-y map: Peak Patch

= mean Xcorr pressure field of BBPS2 painted on halos

σ_8=0.75

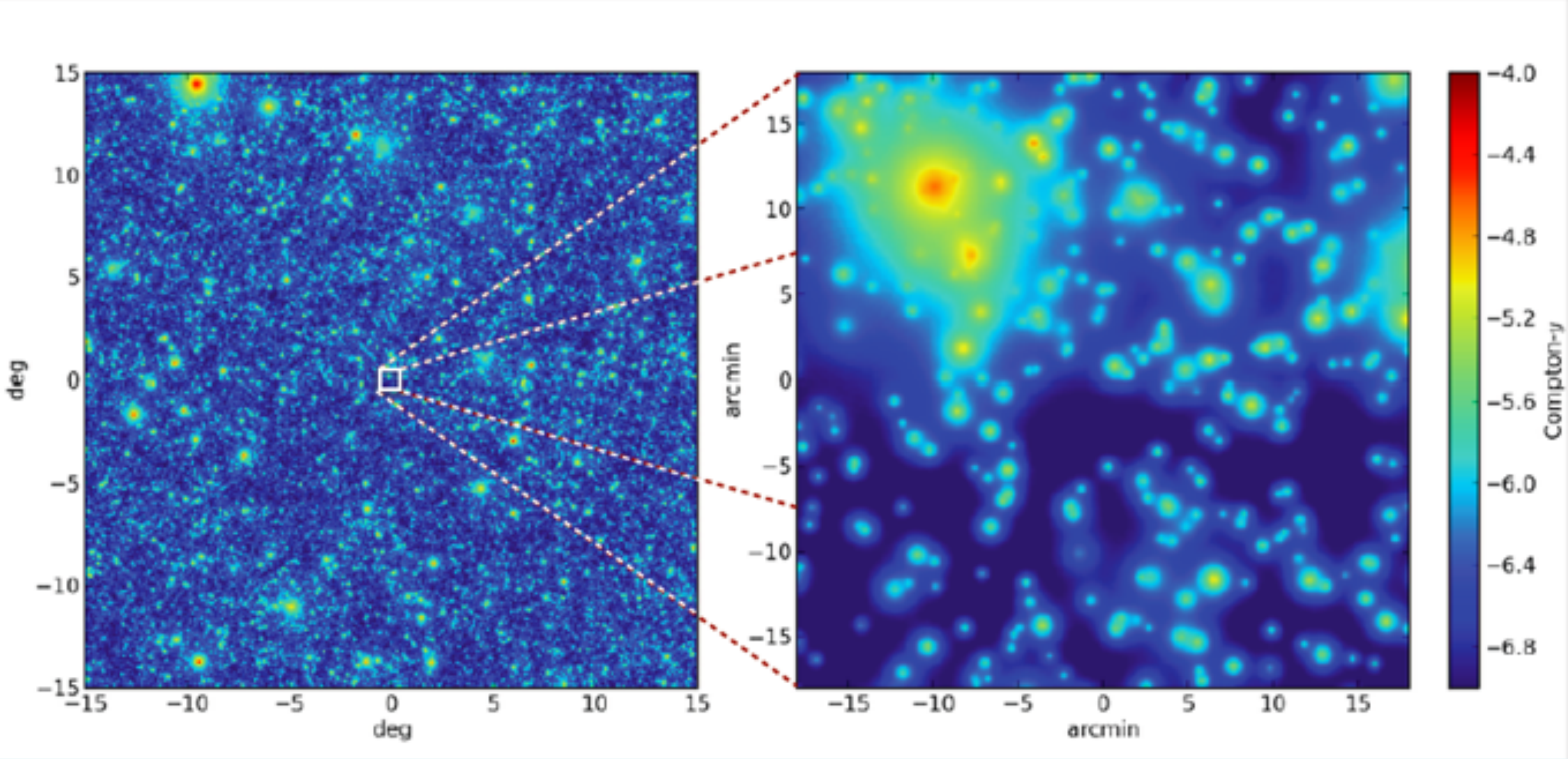


Alvarez, Bond, Hajian, Stein, Emberson 2013

Compton-y map: Peak Patch

= mean Xcorr pressure field of BBPS2 painted on halos

σ_8=0.80

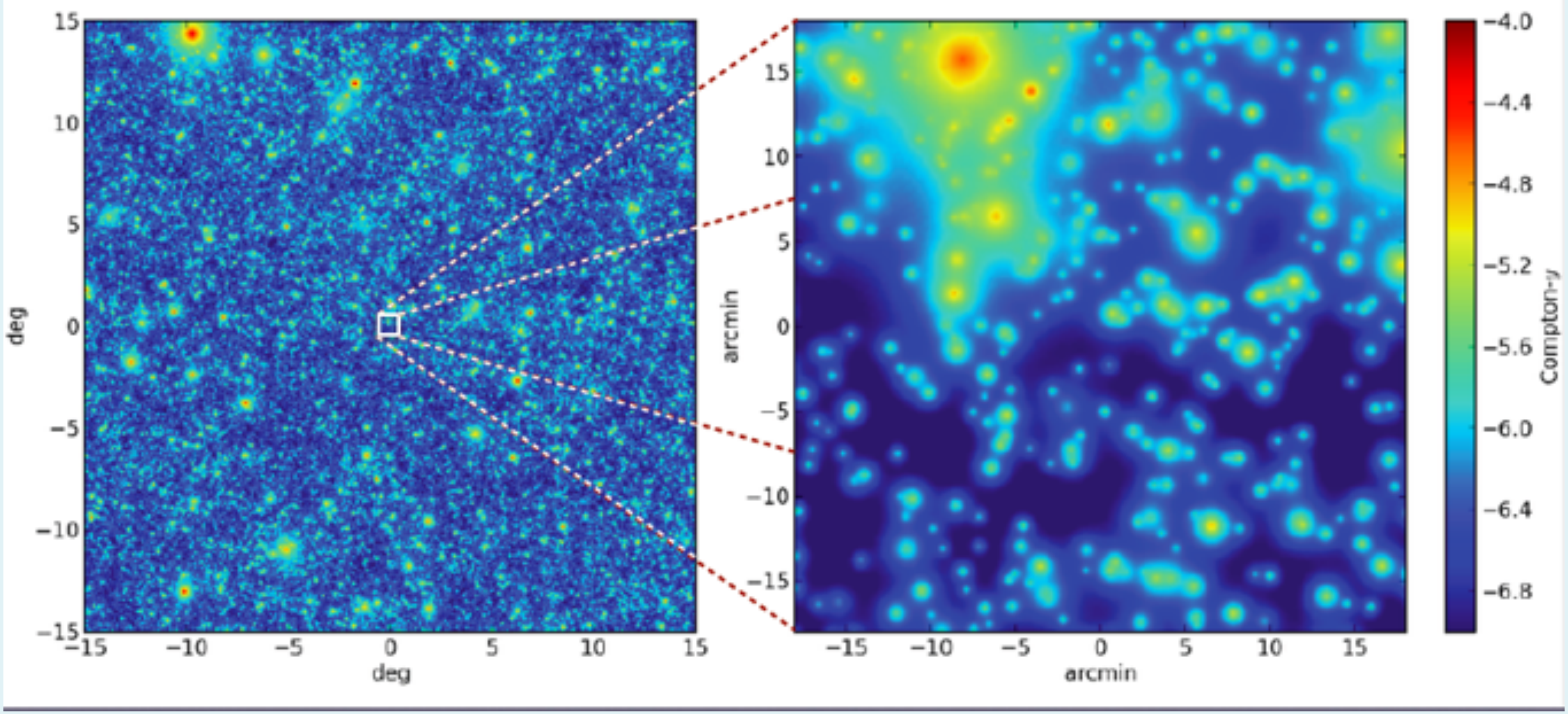


Alvarez, Bond, Hajian, Stein, Emberson 2013

Compton-y map: Peak Patch

= mean Xcorr pressure field of BBPS2 painted on halos

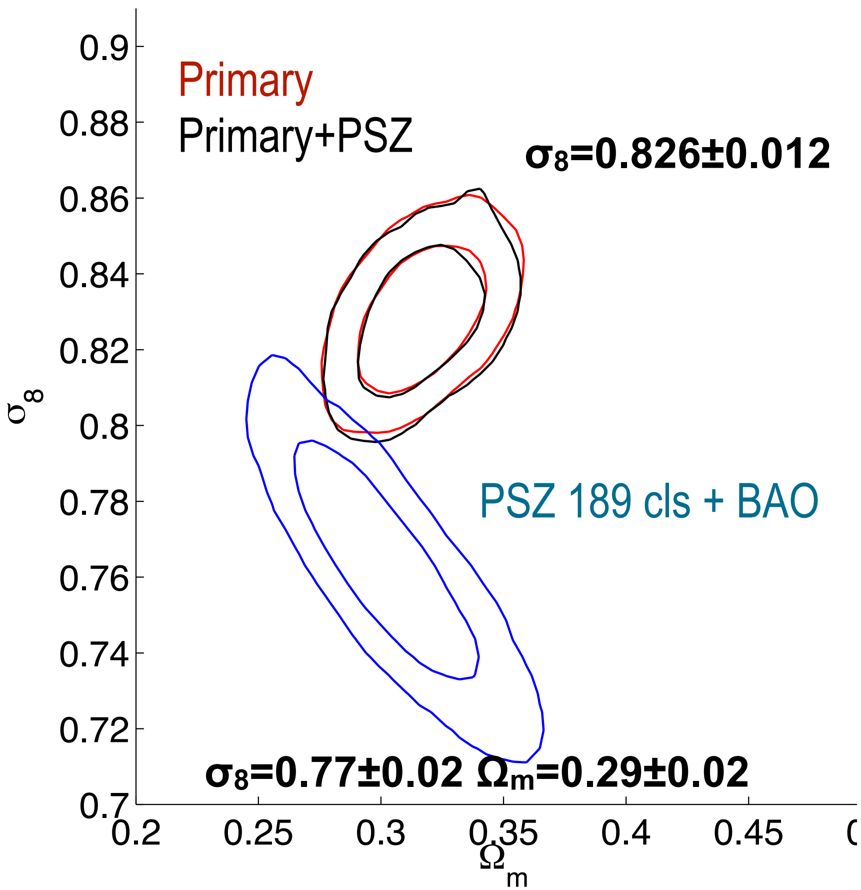
σ_8=0.85



Alvarez, Bond, Hajian, Stein, Emberson 2013

thermal SZ clusters

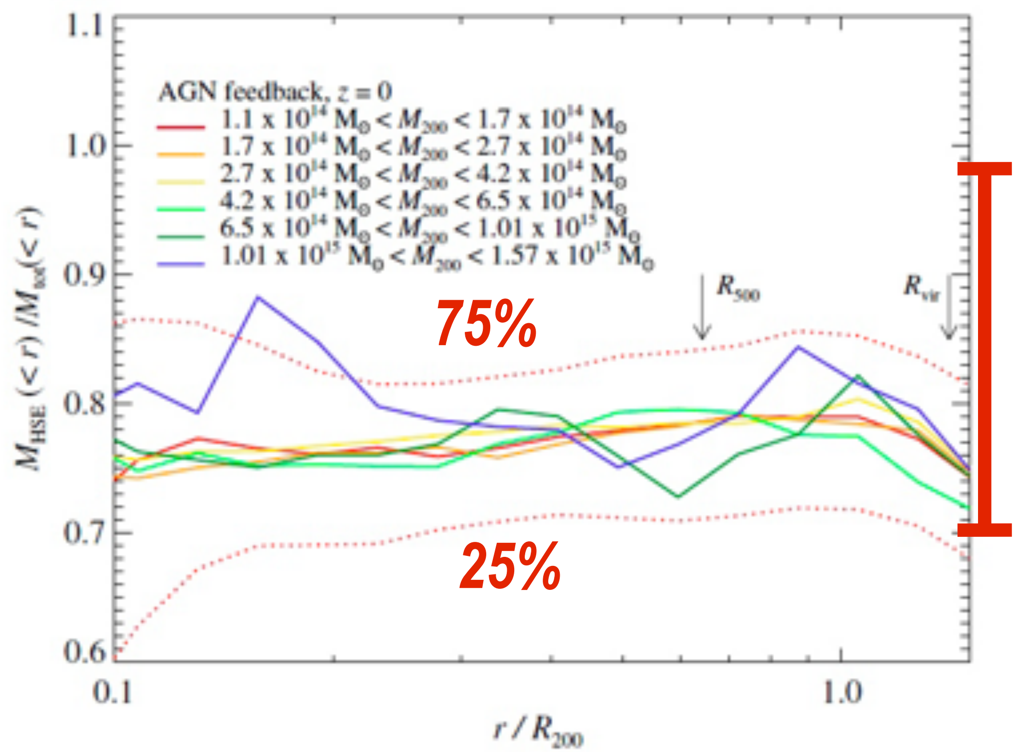
SPT Reichardt+12 different approach cf. ACT Hasselfield+12
X-ray mass proxy cf. dynamical mass proxy (lower bound for σ8, Ωm)
multi-scale S/N likelihood cf. Profile Based Amplitude Analysis single filter 5.9' not matched θ_{500} corrected
ACT and SPT at most mild tension (ACT SZ scaling priors - very broad, would that we knew them better)



Planck2013 XX

$0.7<(MX/M\mathit{true})_{500}<1$ ***TOP HAT HARD prior;***
0.8 default

HSE X Bias b



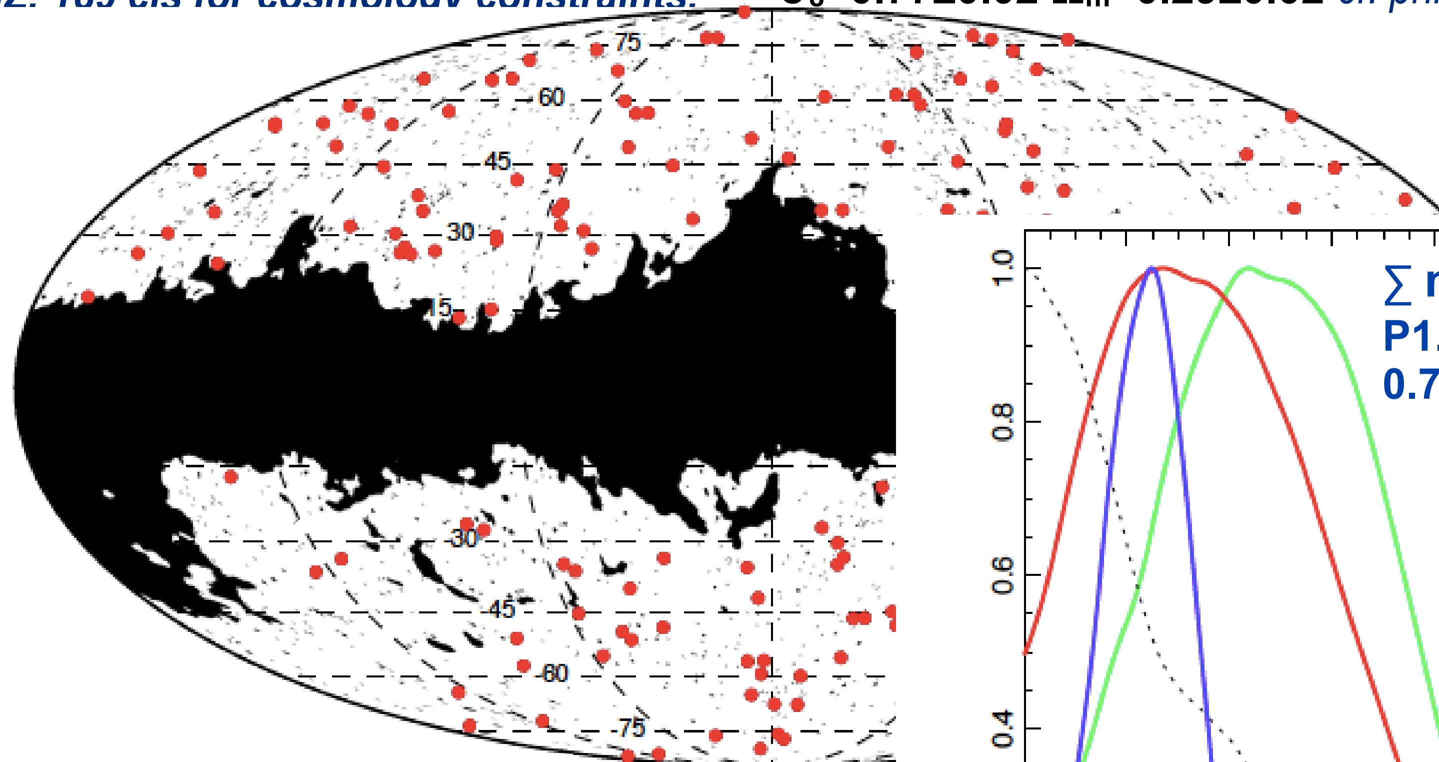
***best theory can do blindly on bX**: not the distribution to use because of sample selection and sub-sample processing*

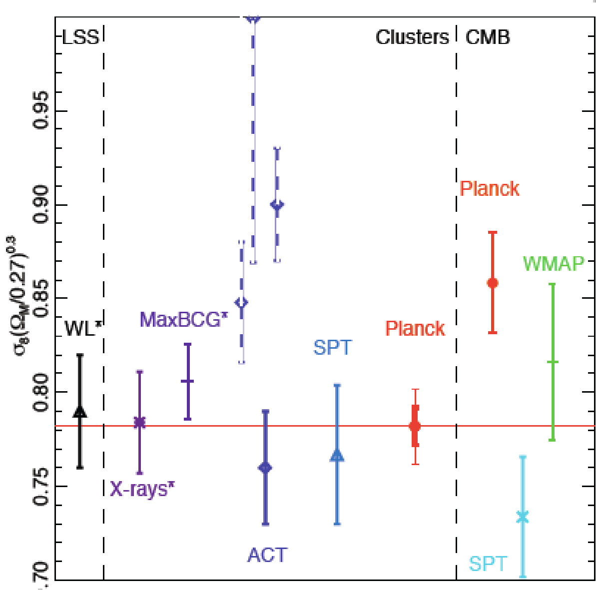
thermal SZ clusters

PSZ: 189 cls for cosmology constraints.

thermal SZ clusters

σ_8=0.77±0.02 Ω_m=0.29±0.02 *cf. primary* σ_8=0.826±0.012





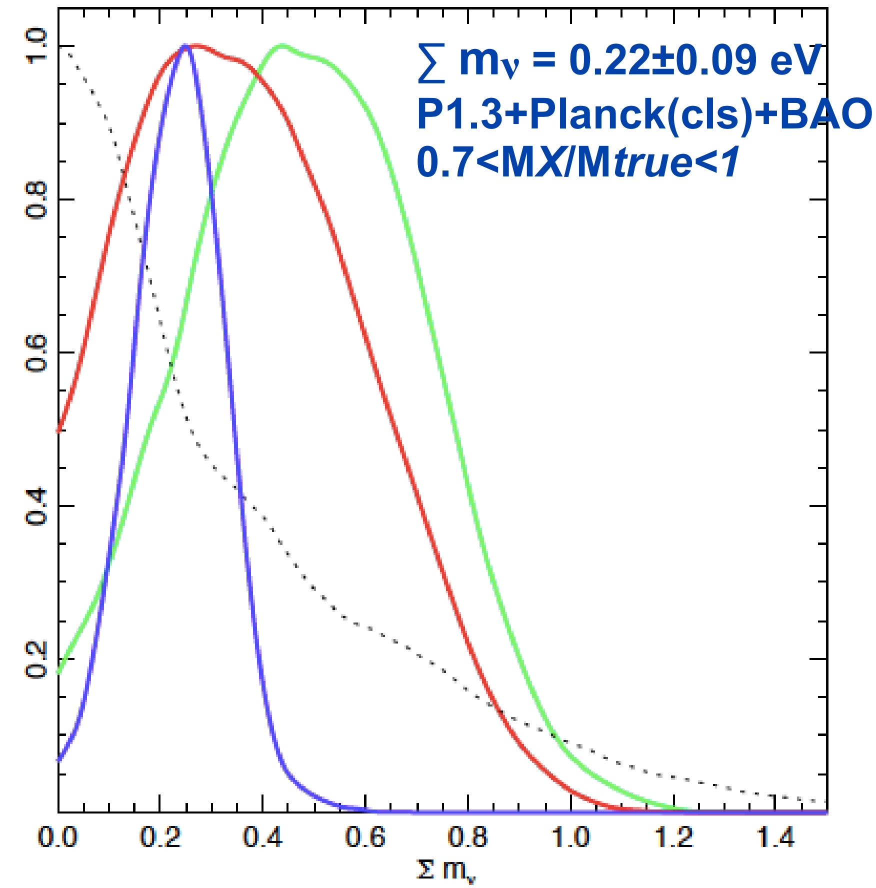
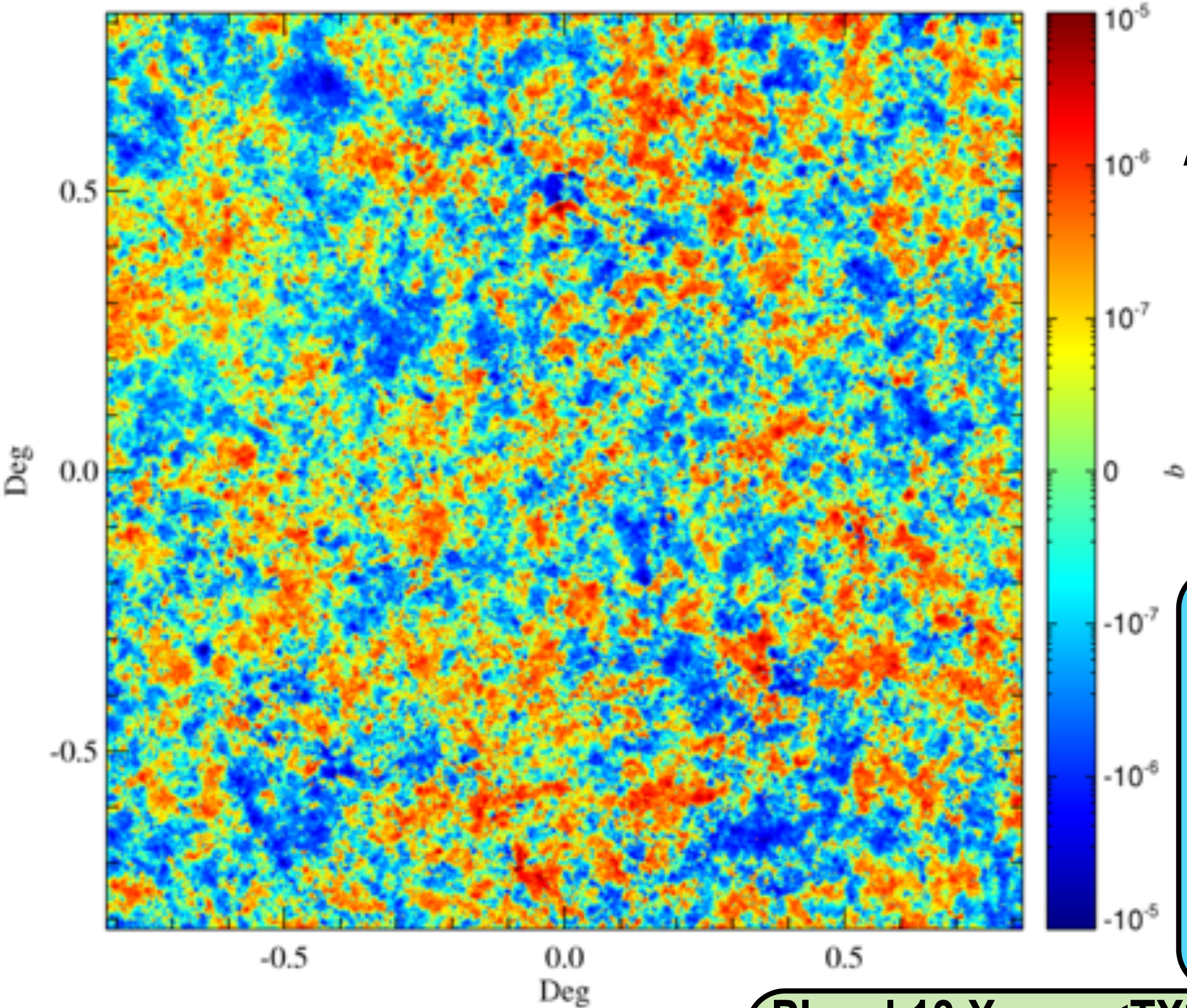


Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1-b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1-b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1-b = 0.8$ (green).

kinetic SZ map *(log)*: Feedback

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



kinetic SZ:

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

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

spectrally degenerate with primary anisotropies

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

ACT x BOSS first kSZ - via Xcorr: $\langle \Delta T \, n_{gal} \rangle$

Hand+ 2012 arXiv/1203.4219 using 7,500 brightest of 27291 luminous BOSS galaxies 220 sq deg overlap with ACT equatorial strip 3x110 sq deg 2008-10 data. $\langle z \rangle \sim 0.5$.

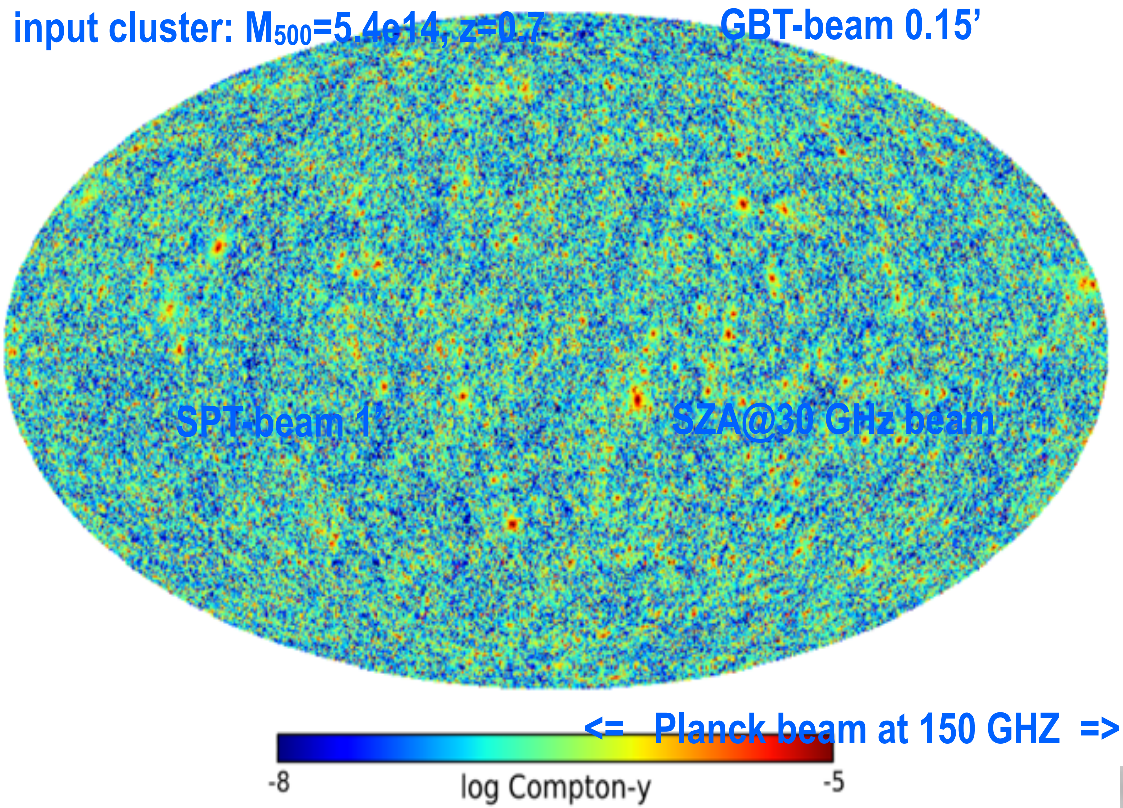
Planck13 Xcorr: $\langle TX \rangle$ MCXC 1750 X-ray cls $\langle z \rangle \sim 0.18$

no *Dark Flow* *~1000 km/s*, **< 254 km/s** 95% CL

BBPS1,2,3,4,5

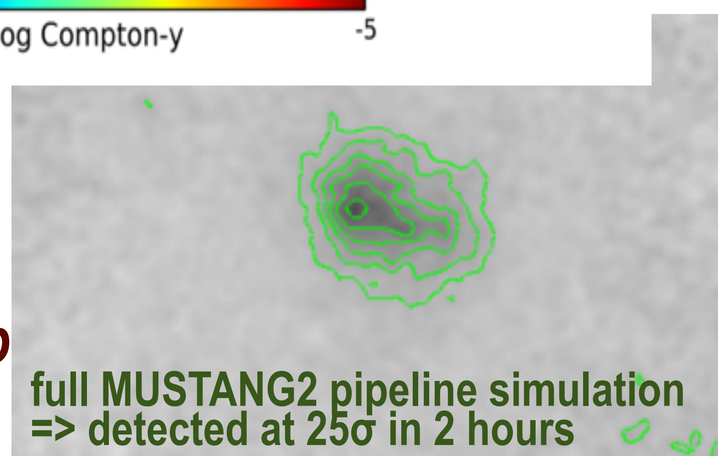
Mustang on GBT 90 GHz 64 bolometer array Imaging SZ @~10" res 4 cls 2010, ~25 Hubble CLASH cls to come Devlin, Mason, ...

future: High-Res SZ sim for MUSTANG2

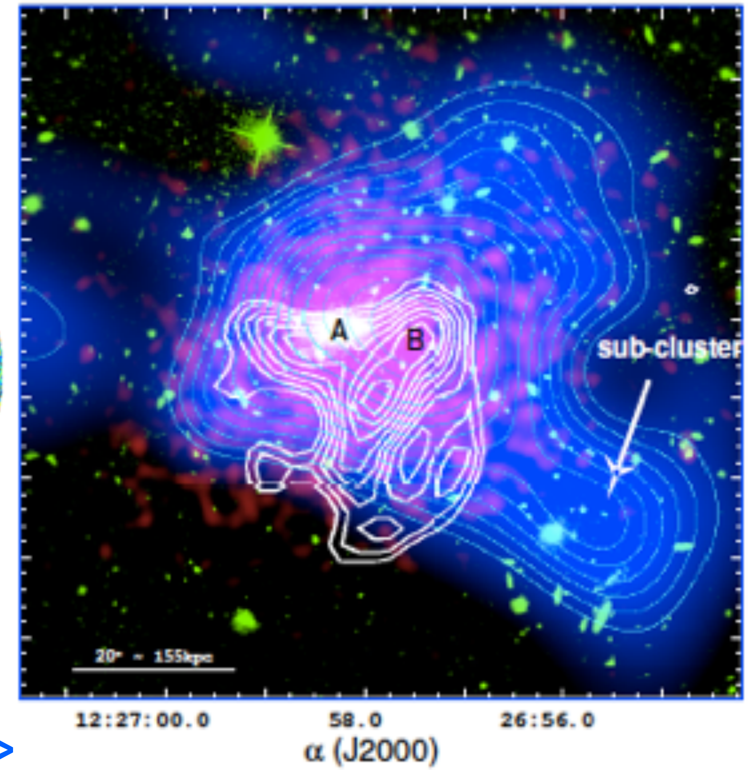


200x mapping speed!
223 cf. 64 pixels, over larger area (5' vs. 40")

=> Planck followup to 35σ in 30m



now: CL1226 z=0.89

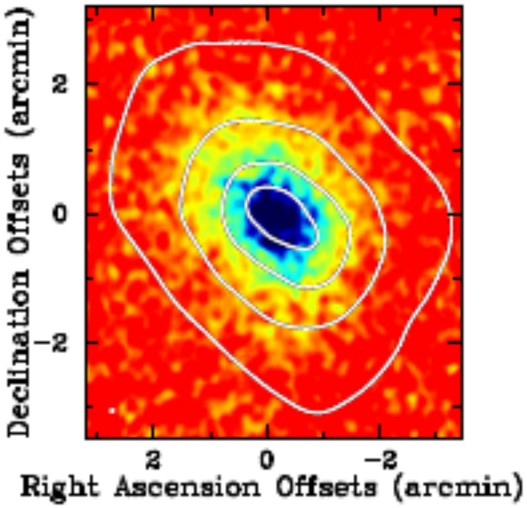


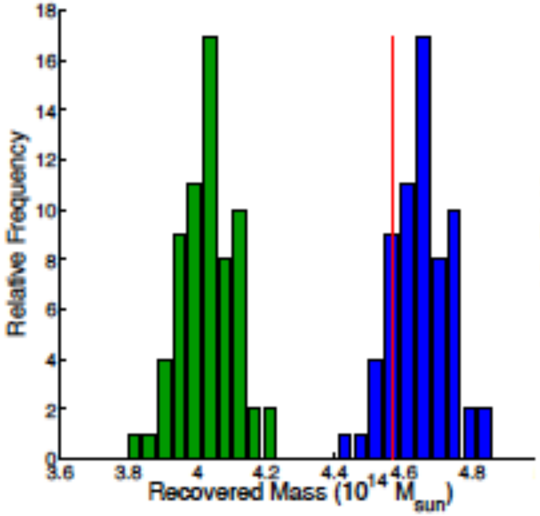
Red Chandra
Blue/cyan weak lens Σ
Green optical
White MUSTANG SZ >3σ

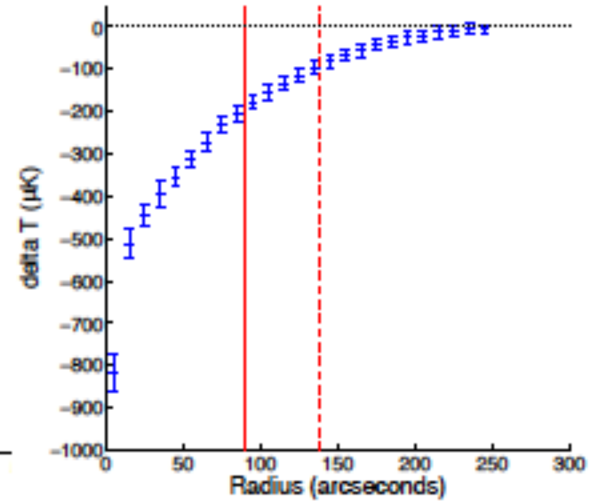
A BCG ~ X-ray peak
B Dark Matter peak
~ lobe of SZ ridge

Mustang2 on GBT 100m or LMT 50m 90 GHz 223 TES bolometer array Imaging SZ @9" /18"res. LMT faster mapping

future: High-Res SZ sim for MUSTANG2







100s of cls to 20" in a season cf. 6 with Mustang1

pressure profiles in 4h of 4.5x1014msun

100h 1 sq deg gps to 0.7x1014msun, order of mag lower than ACT/SPT

15x sensitivity

200x mapping speed!

233 cf. 64 pixels, over larger area (5' vs. 40")

=> rapid hi res followups

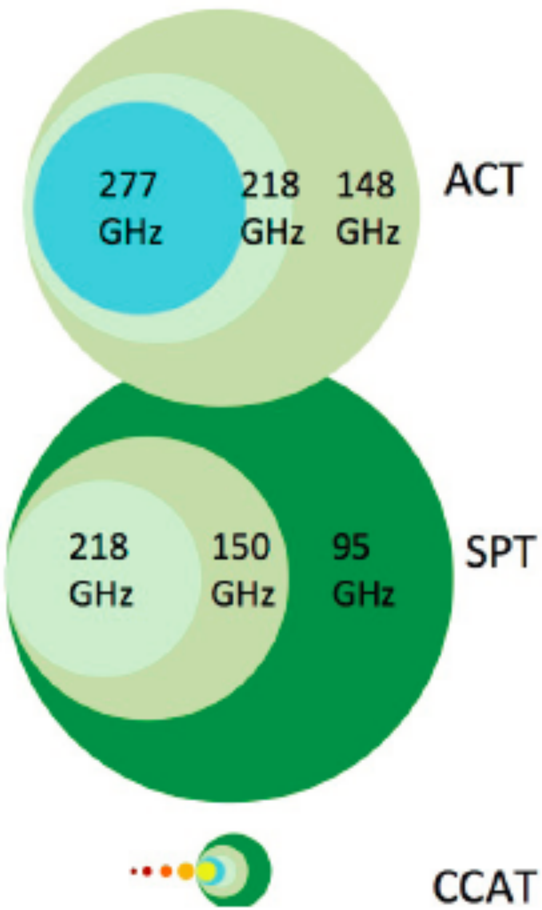
input BBPS cluster: M_{500}=4.5e14, z=0.5

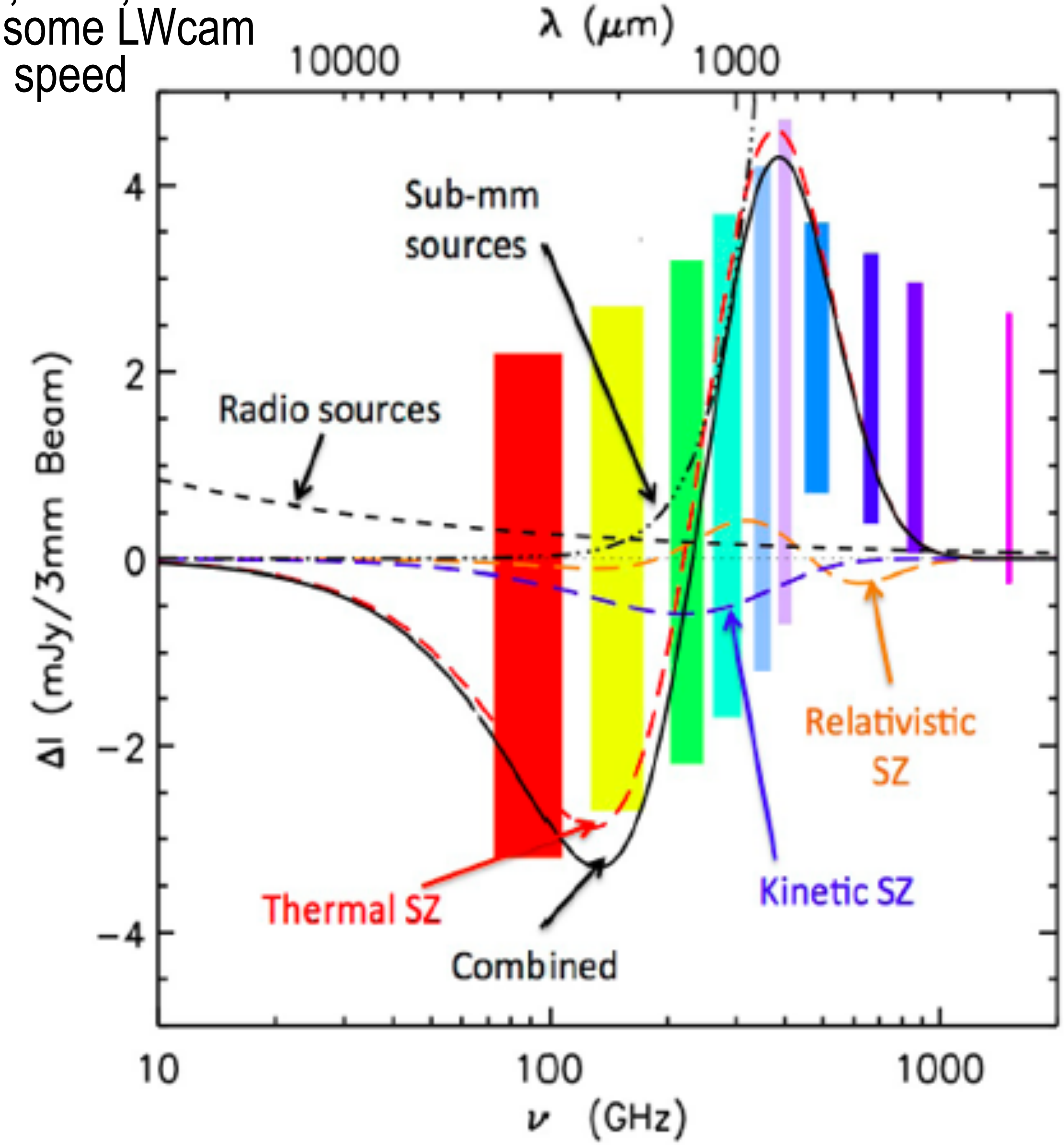
full MUSTANG2 pipeline simulation
=> detected at 46σ in 2 hours

CCAT: 25m mkids detectors

SWcam 857, 667, 484
LWcam 400, 350, 275, 230, 150, 80 GHZ
first light 2018, SWcam with some LWcam frequencies; mapping speed

Imaging SZ @22" @150, 12"@ 275, 8"@ 400





PUPPY and our hydro sims agree: *slower falloff than Arnaud+ X-ray UPP; although there are mass and redshift bin variations, universality is pretty good; variance in pressure profiles is wide*

pressure clumping is not small, *important for SZ- a consequence of merging history*

Universal Entropy Profile? *not as good as PUPPY. obs cf. theory needs work*

rare clusters are still consistent with std ΛCDM*; some highly non-eq, bullet el Gordo ++*

σ_8^{SZ} vs σ_8 tension from P1.3, ACT&SPT **CL,** P1.3 SPT ncl; ACT ncl ok broad scaling bias priors

Σm_ν ~0.2 ev a possibility; mass bias ~1.45 needed; and/or X-ray selection bias

Use physical observables rather than funneling through halo Mass

i.e., not $n_{cluster}(M_{halo}|z)$ but

$n_{cluster}(Y_{SZ}, M_{lens}, Y_X, L_X, T_X, \sigma_v^2, L_{cl,opt}, Rich, \ldots \mid z,$ gold-sample, thresholds)

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

biases in gas fraction estimation => variance large => not robust

these all deliver valuable cosmic gastrophysics.

Can they deliver fundamental physics: dark energy EOS?? σ_8 even? primordial non-Gaussianity??? X cf. opt, sphericalize?? but nice ymap stats C_L^{SZ} PDF, 3pt, counts, X cf. opt, ..

complex systems => theory/obs dispersion/systematics assessment is critical => mock sims for robust measures

kSZ detected, but dark flow constrained

END

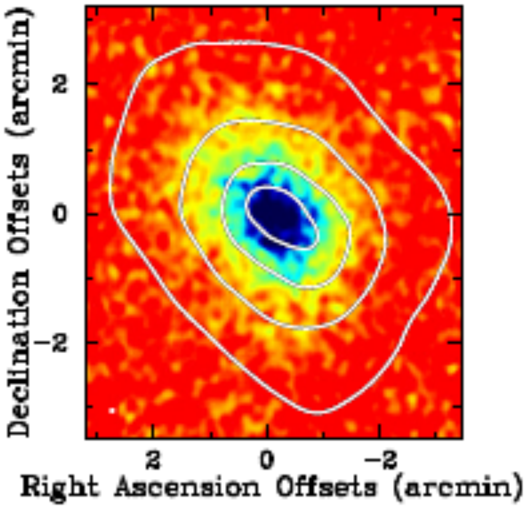
END

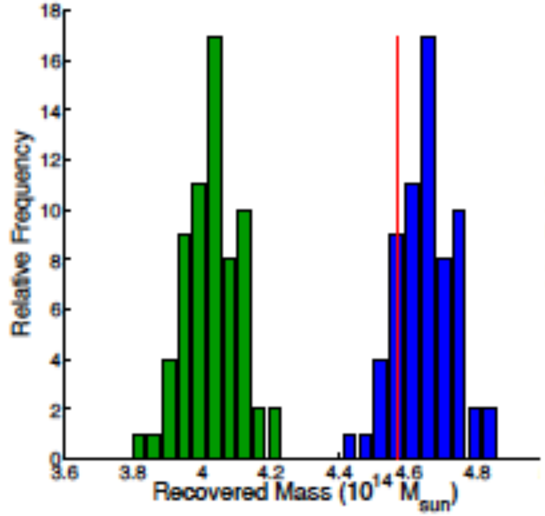
LSS conclusions

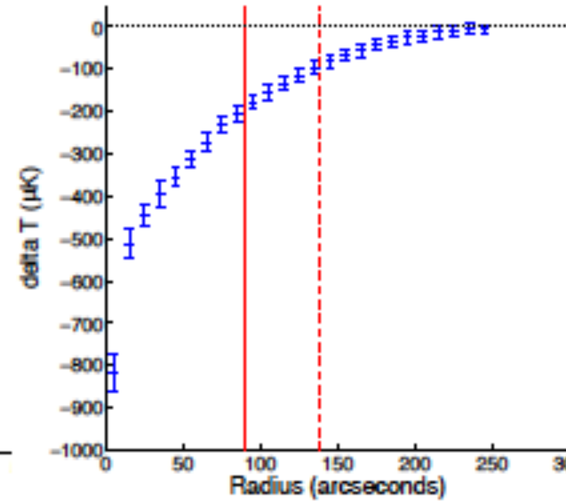
in progressTBD

Mustang2 on GBT 100m or LMT 50m 90 GHz 223 TES bolometer array Imaging SZ @9" /18"res. LMT faster mapping

future: High-Res SZ sim for MUSTANG2







100s of cls to 20" in a season cf. 6 with Mustang1

pressure profiles in 4h of 4.5x1014msun

100h 1 sq deg gps to 0.7x1014msun, order of mag lower than ACT/SPT

15x sensitivity

200x mapping speed!

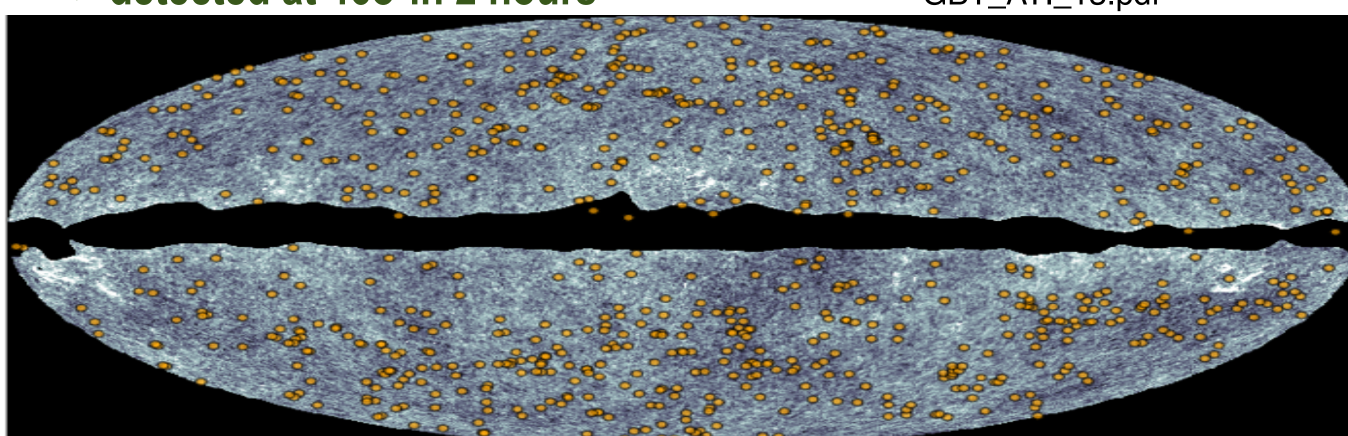
223 cf. 64 pixels, over larger area (5' vs. 40")

=> rapid hi res followups

input BBPS cluster: M_{500}=4.5e14, z=0.5

full MUSTANG2 pipeline simulation
=> detected at 46σ in 2 hours

GBT_ATI_13.pdf



HALOs in the Web(z)

the CLUSTER SYSTEM example

Halos are **Complex Systems**

Painting is an Art Form

Mean-fields(x-x_{cl}) =
Cross-correlations = Stacking
(oriented, scaled) from sims or data

+

residual fluctuations (!!)

MOCKs *are not really real, but still useful*

Universal Pressure profile: d*ln* E_{th}(<r)/d*ln* r

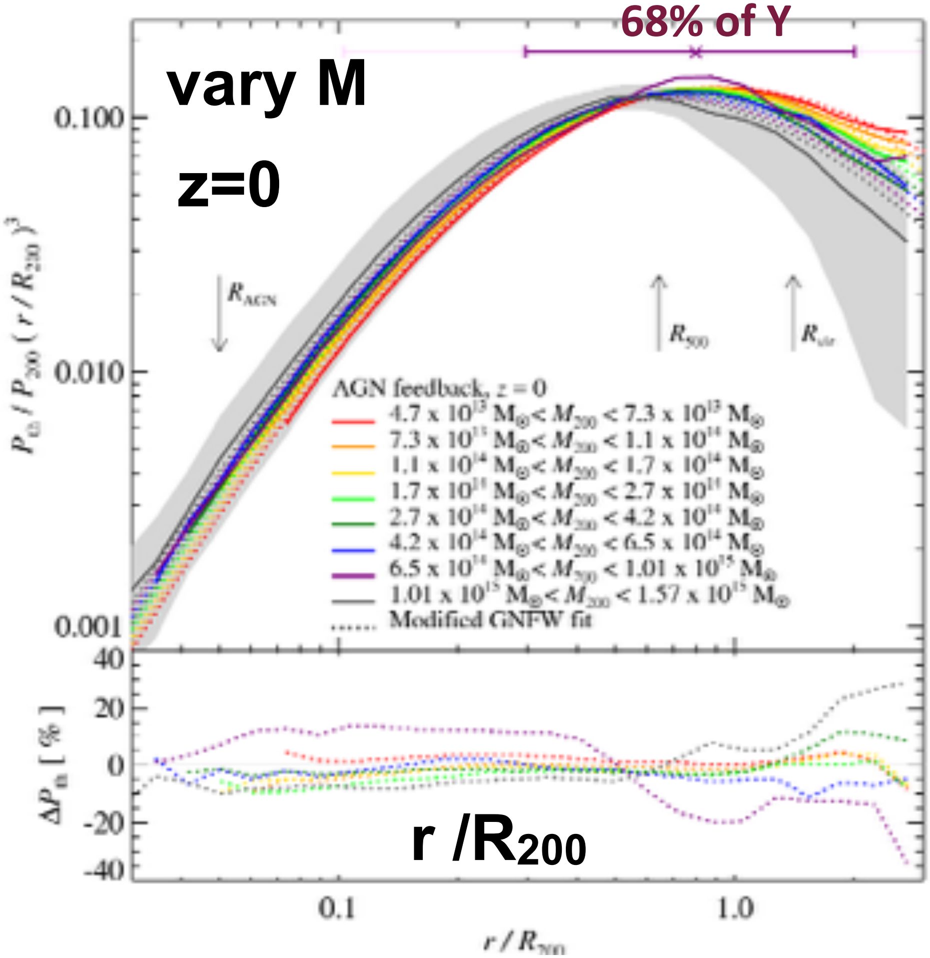
& cluster ENTROPIES: coarse-grained information **Universal Entropy Profile?** *sort of, but inference from observations is difficult*

GNFW-fit(M,z) accuracy <10%

extends Arnaud universal profile PUPPY

~d*ln*<P_{th}V|*scaled-cl∈class-𝒞* >/d*ln*r

68% of Y

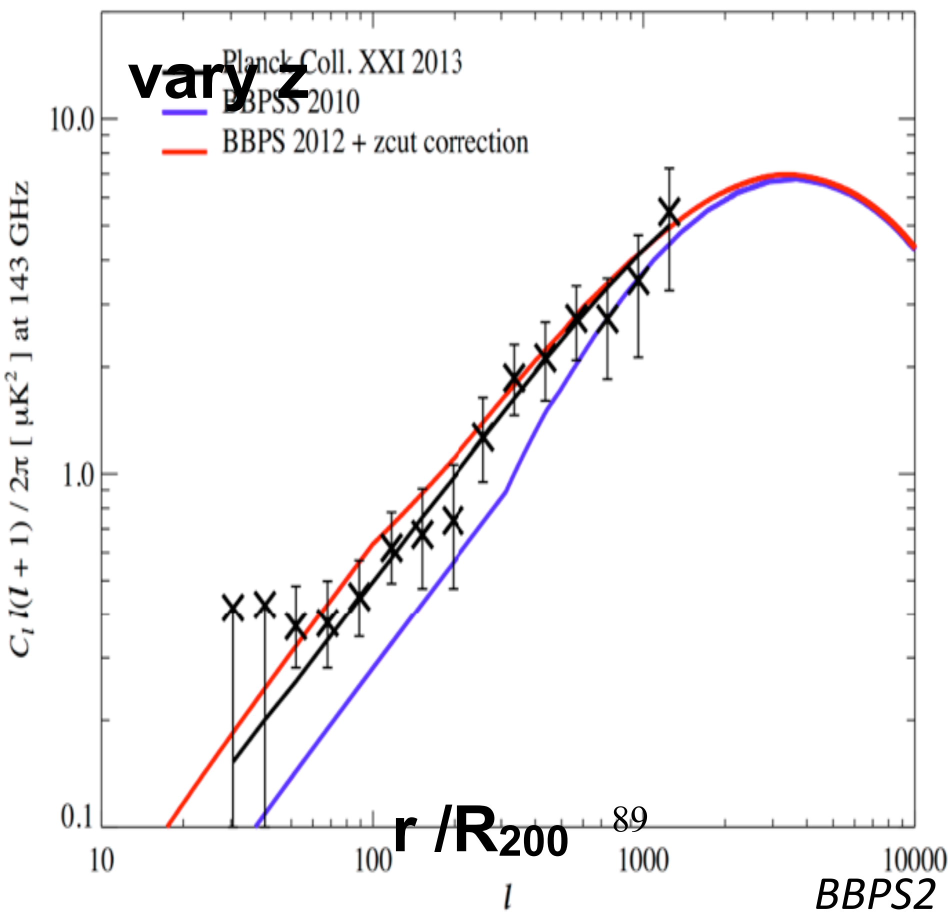


ln p_{th} & *ln* ρ_g & *ln* ρ_{dm} & Φ_{dm+g}

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

but it is p_{tot} *in the virial equation*

68% of Y



BBPS2

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

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

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

CMB gets entangled in the cosmic web

400 Mpc

ΛCDM

WMAP5

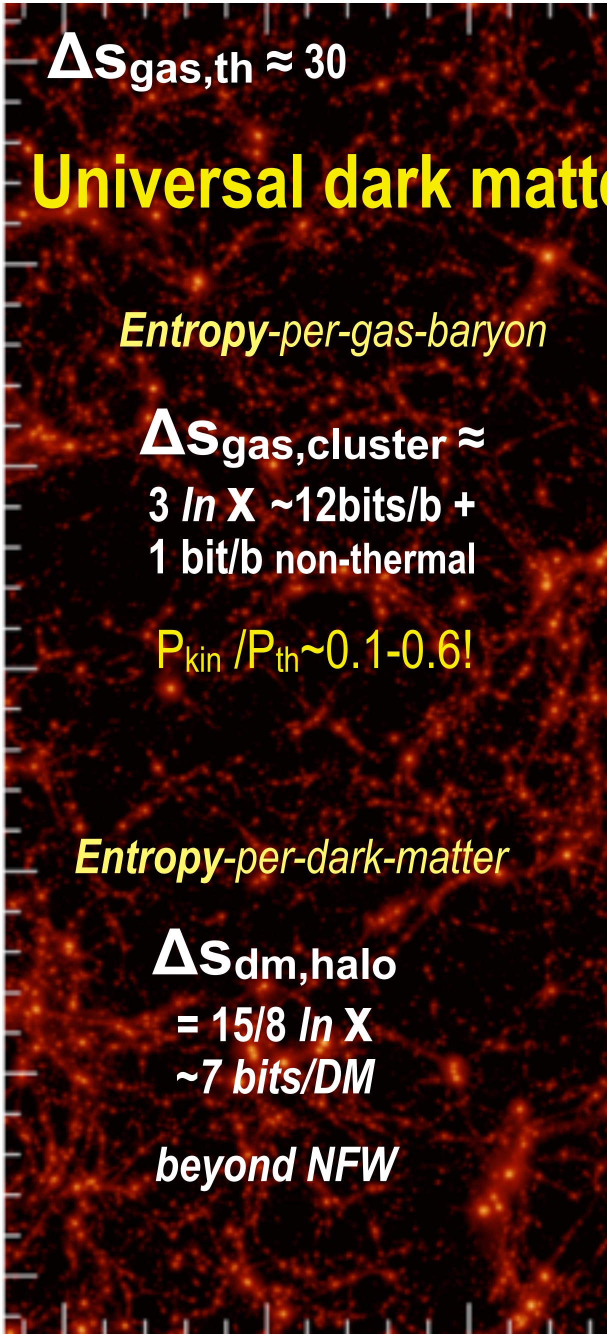
gas pressure

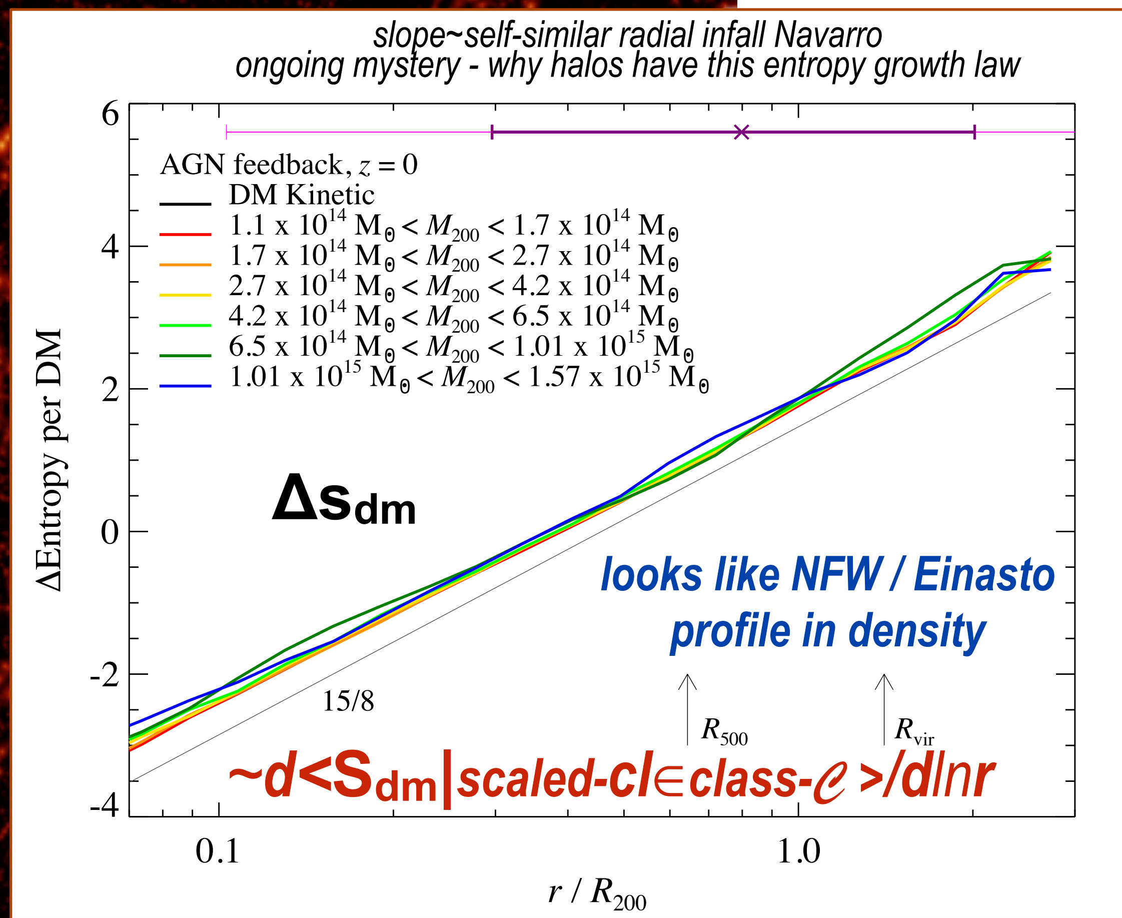
Gadget-3
SF+
SN E+
winds
+CRs

512^3

BBPSS10

BBPS1,2,3,4,5





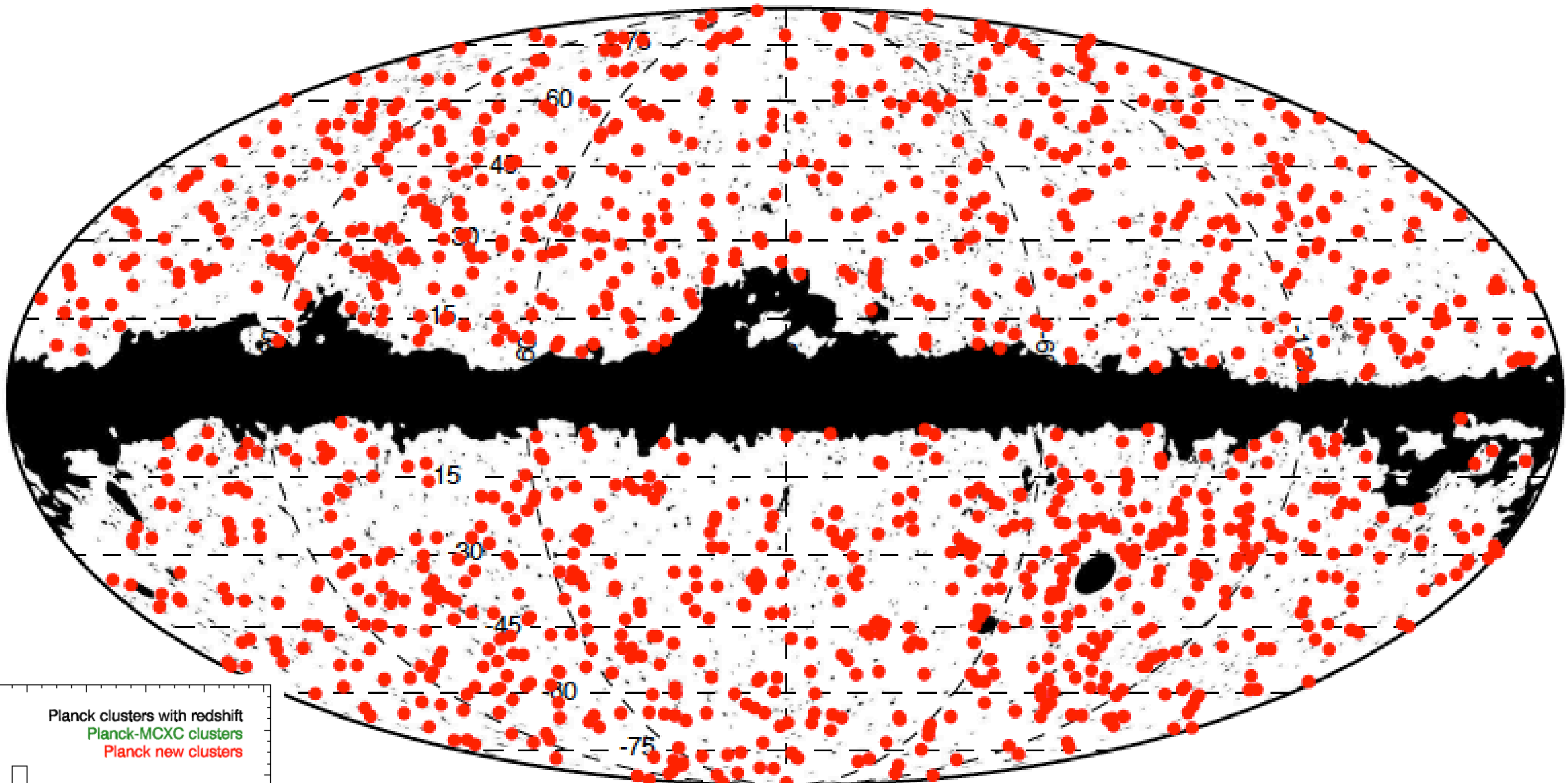
Compton cooling of high pressure / entropy electrons by the CMB

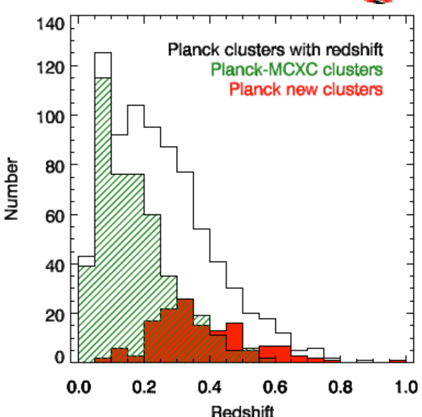
thermal SZ effect **Planck2013 1227 clusters, SPT 224 =>747cls, ACT 91 cls**

PSZ: 1227 clusters, 861 confirmed, 178 by Planck + 683 known, rest in class 1, 2, 3

cf. X-ray sample from ROSAT+ All-sky distribution of MCXC clusters ~1600 *(Piffaretti et 10)*

REFLEX, BCS, SGP, NEP, MACS, CIZA, 400SD, 160SD, SHARC, WARPS, EMSS

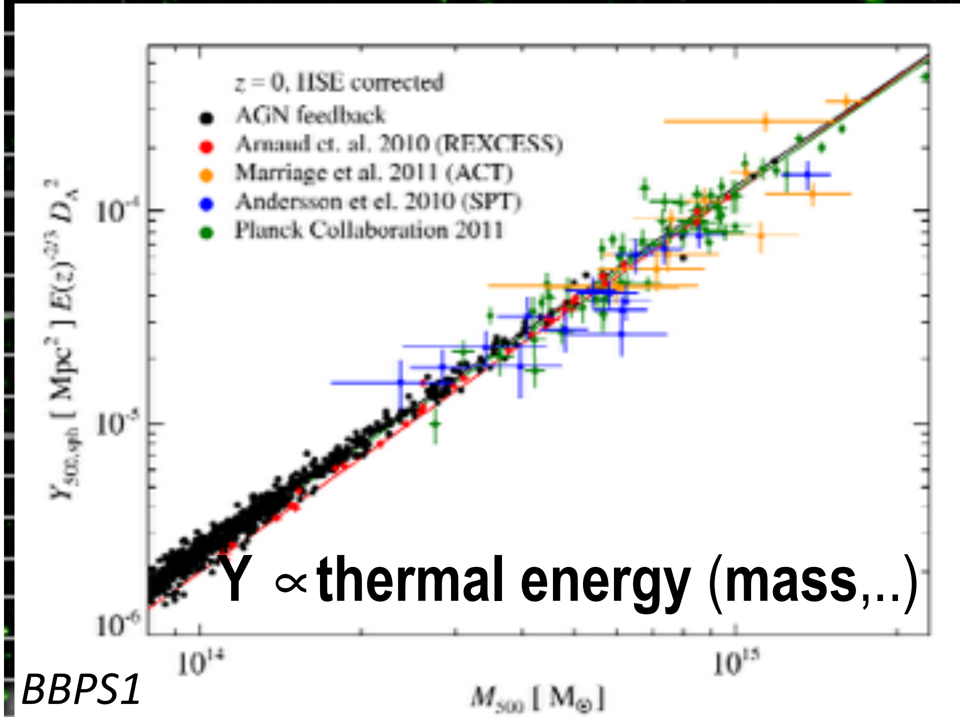




pressure intermittency *in the cosmic web, in cluster-group concentrations probed by* **tSZ**

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

Planck2013 1227 clusters, SPT 224 =>747cls, ACT 91 cls



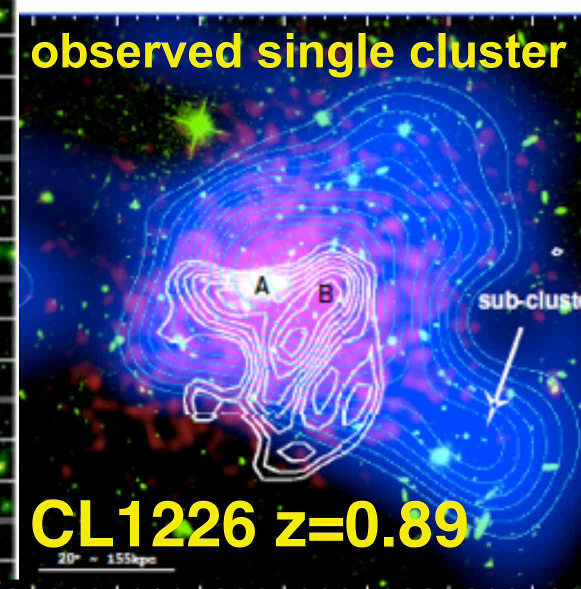
to get **cosmological parameters** from

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

$C_L^{tSZ,kSZ}$

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

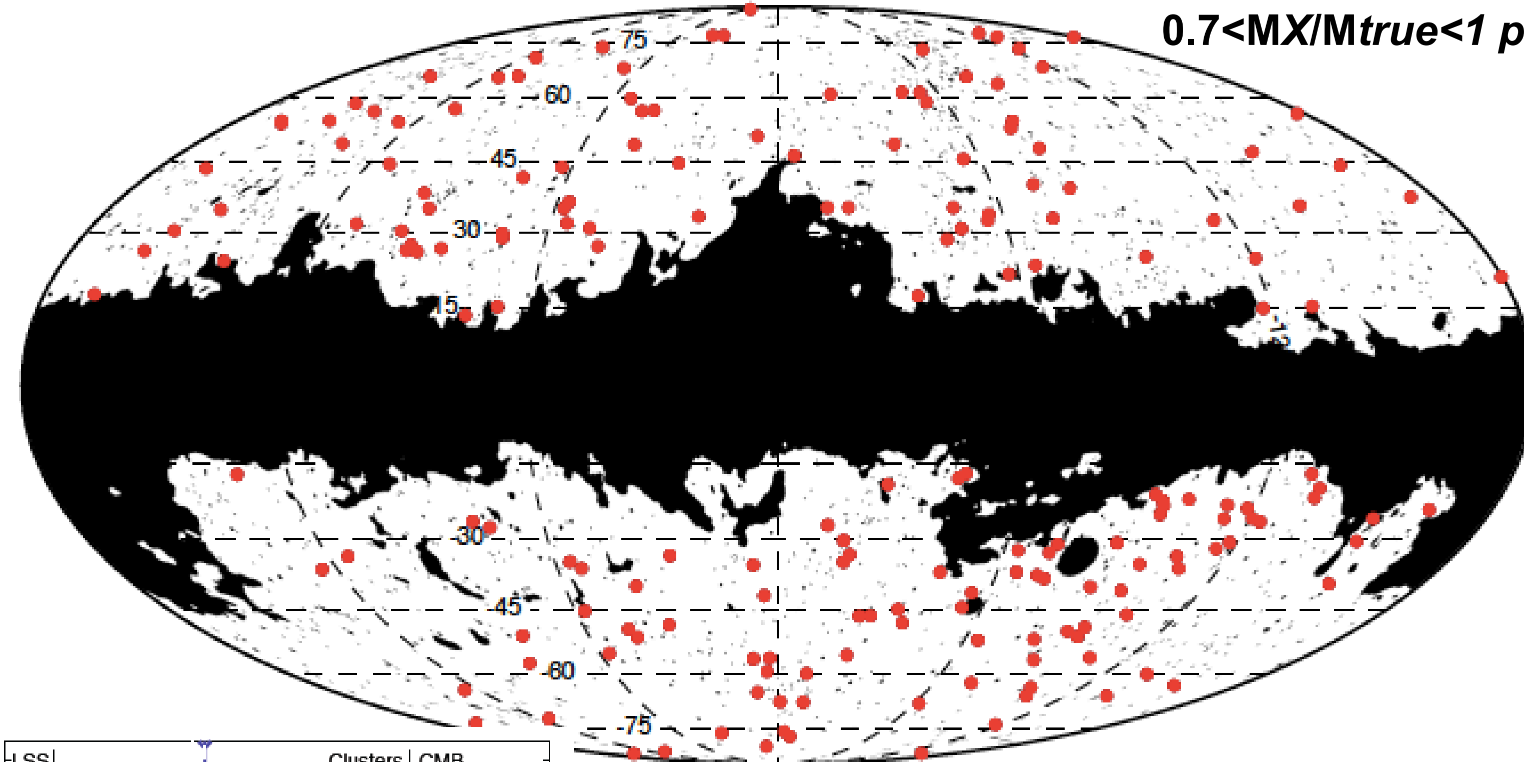
BBPS2



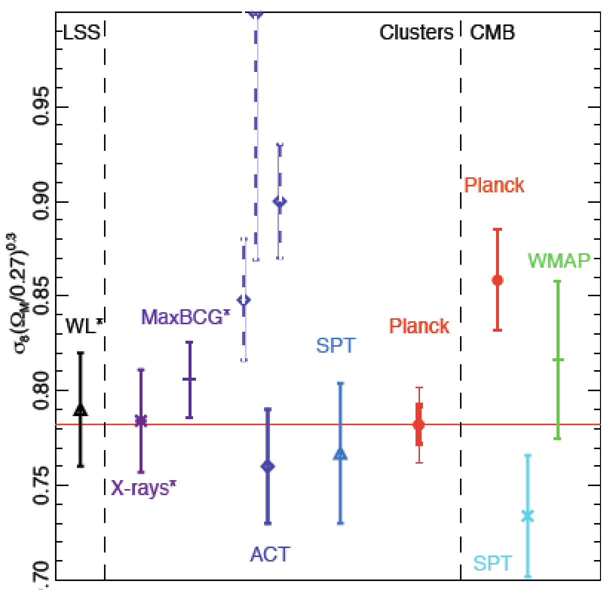
thermal SZ clusters

PSZ: 189 cls for cosmology constraints. **σ_8=0.77±0.02 Ω_m=0.29±0.02** *cf. primary* **σ_8=0.826±0.012**

0.7<MX/Mtrue<1 prior; 0.8 default



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



ACT12 **Hasselfield+12** **15 carefully chosen cls**

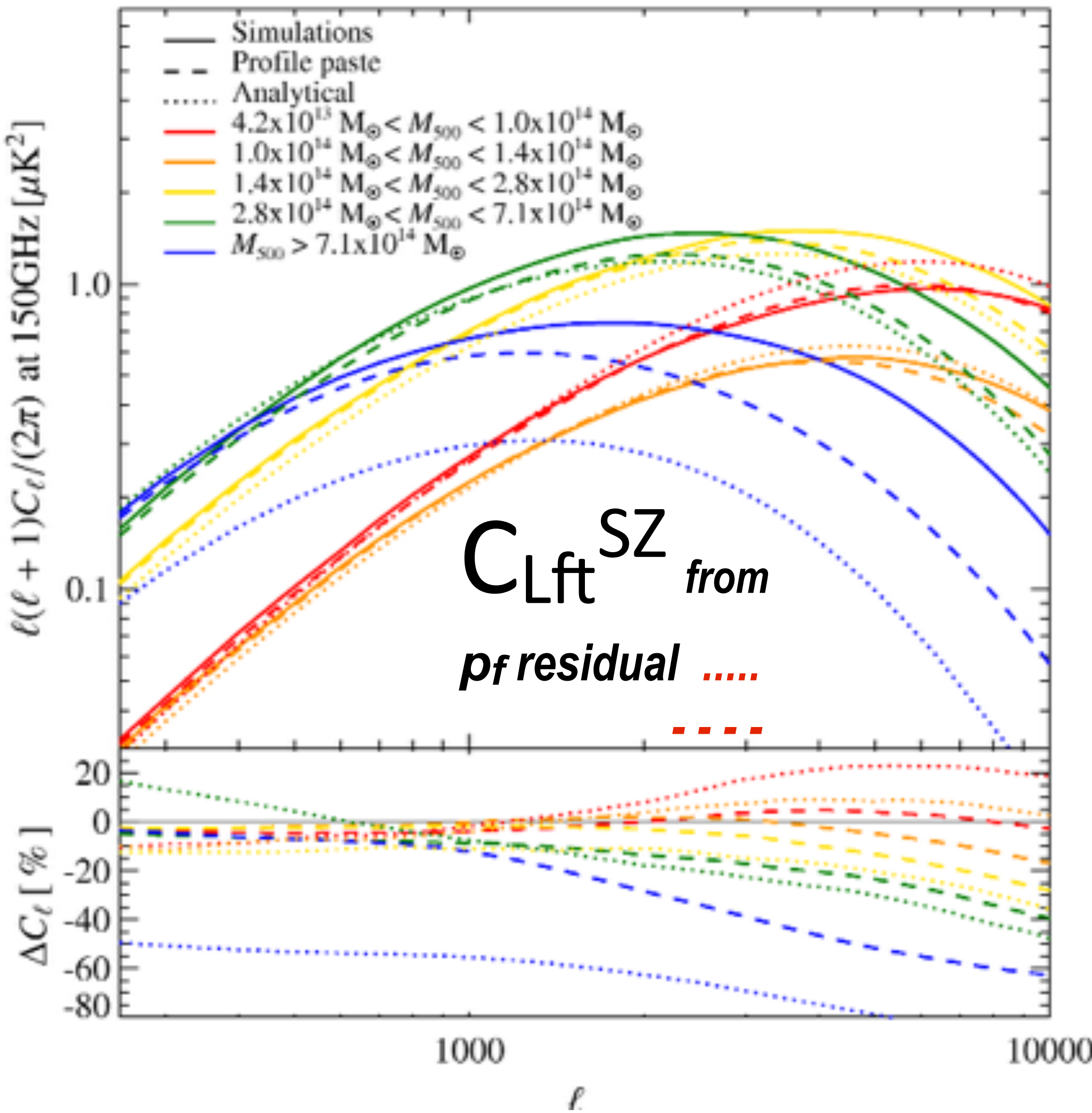
optical dynamical information used *(i.e., not X-ray)*

σ_8=0.829±0.024 Ω_m=0.292±0.025 WMAP7+ACT(cls)

cf. ACT10 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

pressure sub-structure contribution to C_L^{tSZ}



given the cluster catalogue from sims, paint on spherical GNFW-fit (M,z).

scaled X-correlation fn good, not perfect.

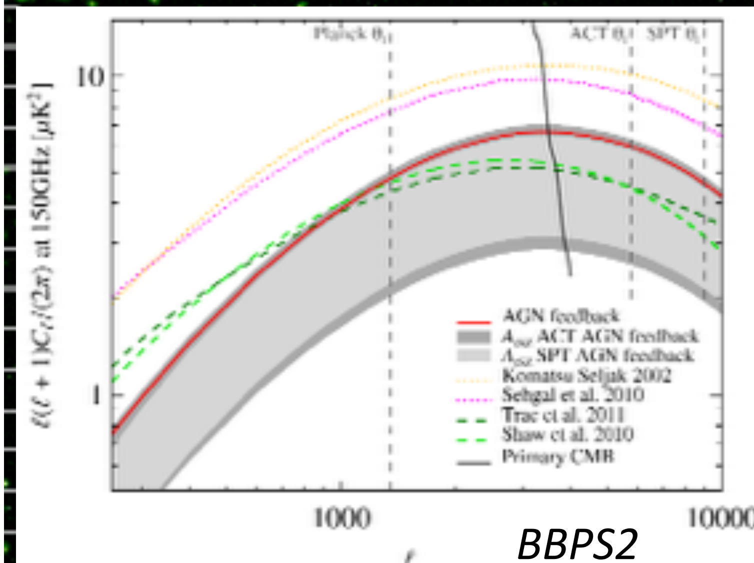
pressure-**sub-structure**

smaller fluctuations if the simulation halos are painted =full analytics

painted on + fit mass function = slightly bigger errors

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

Planck2013 1227 clusters, SPT 224 =>747cls, ACT 91 cls



BBPS2

to get **cosmological parameters** from

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

$C_L^{tSZ,kSZ}$

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

Planck regime, *Δphysics* SZ templates ~degeneracy

Ethermal + Ekin~Egrav/2

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

σ_8^{SZ}

σ_8

mild tension

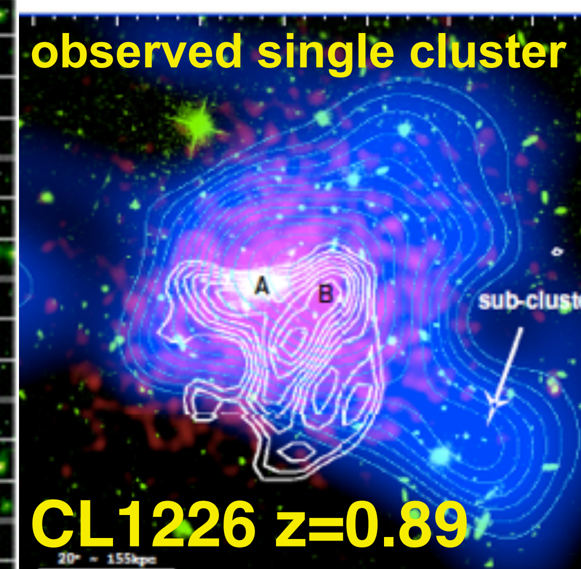
BBPS2

$p_e(x,t)$

ACT's el Gordo z=0.87

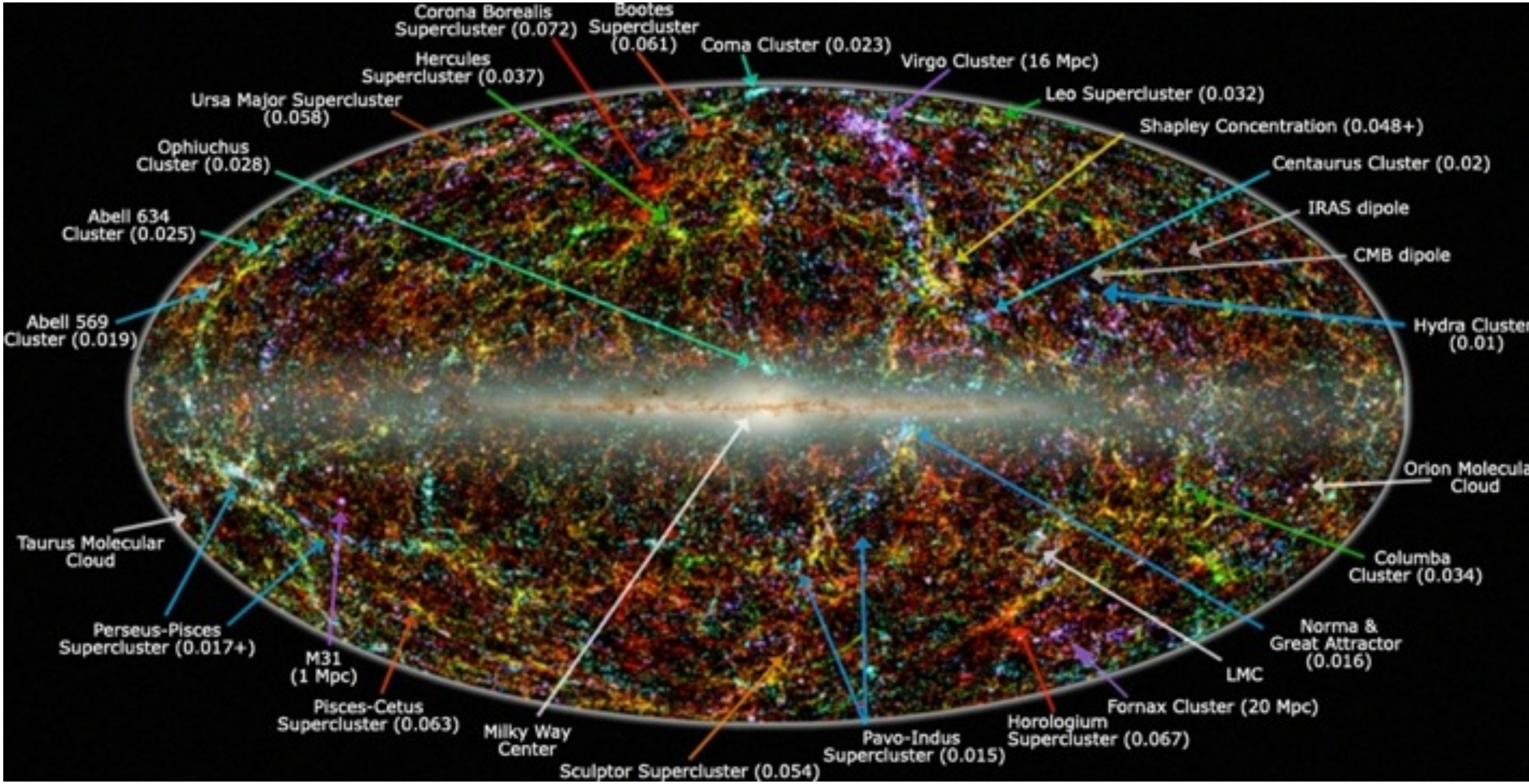
$2x10^{15}M_{sun}, T_X$=14.5kev

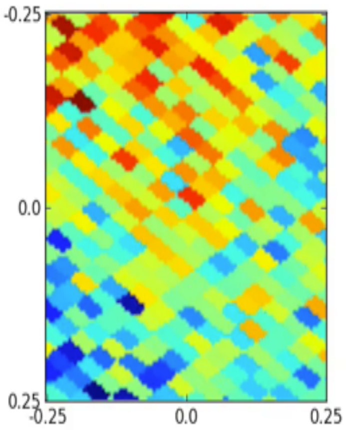
observed single cluster



CL1226 z=0.89

cosmic web of **nearby superclusters** from ***2mass+***





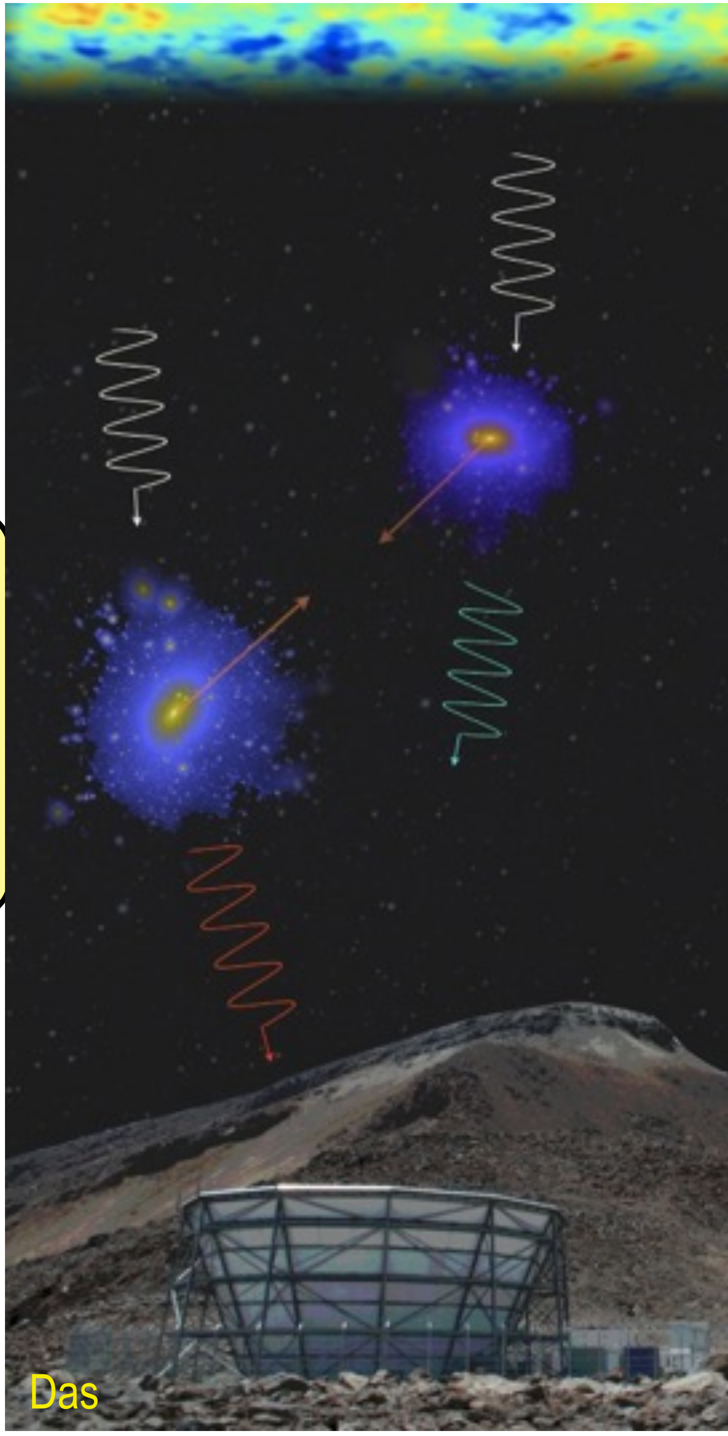
kinetic SZ:

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

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

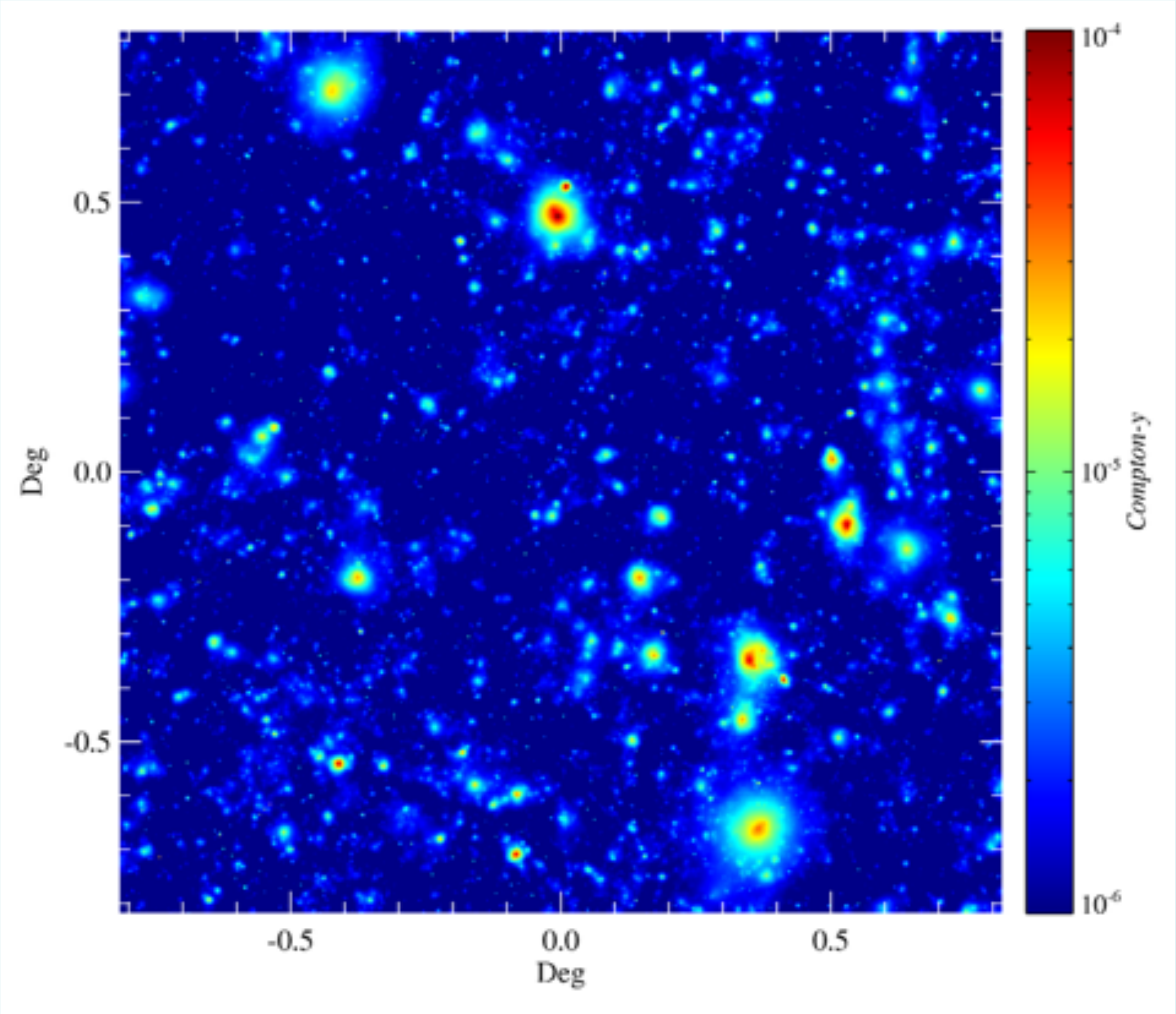
spectrally degenerate with primary anisotropies

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



Compton-y map: Feedback

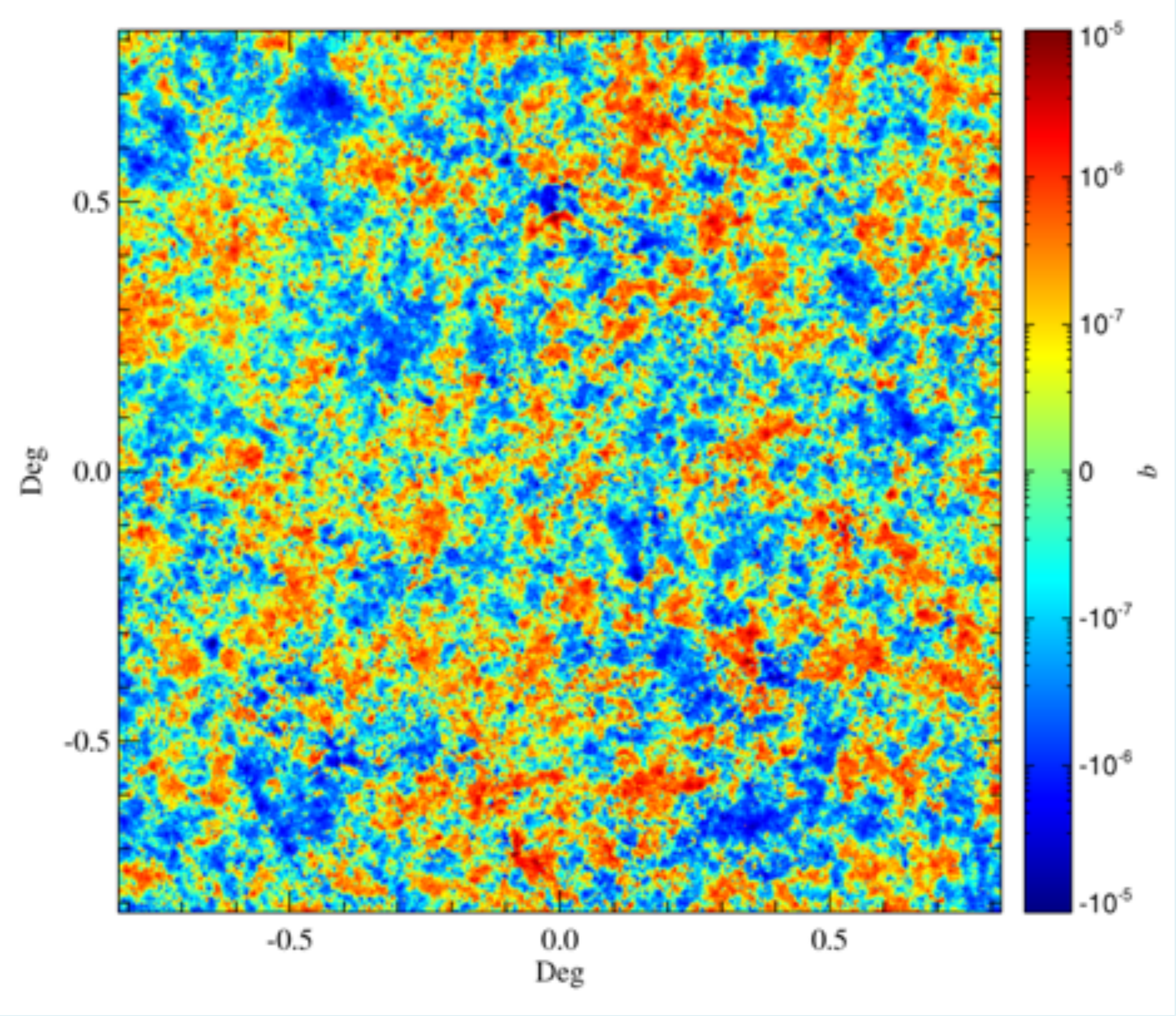
= AGN or Starburst E-feedback + radiative cool + SN energy + wind + (CR)



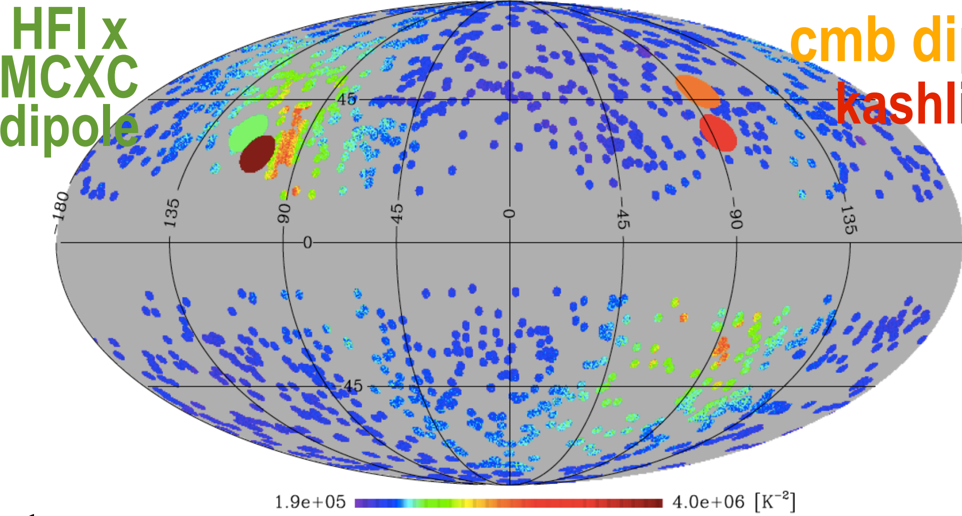
BBPS1,2,3,4,5

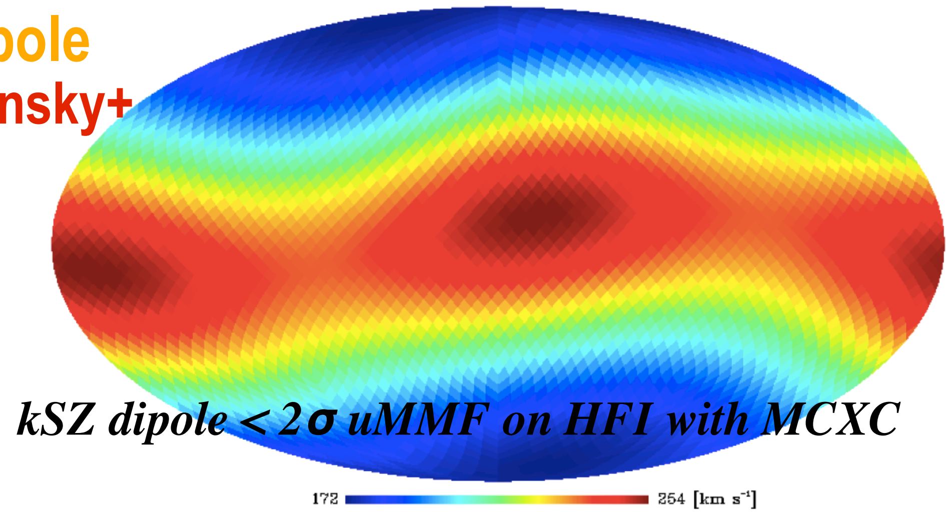
kinetic SZ map *(log)*: Feedback

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



BBPS1,2,3,4,5





kinetic SZ:

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

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

spectrally degenerate with primary anisotropies

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

ACT x BOSS direct detection of the kSZ effect:

Hand+ 2012 arXiv/1203.4219 $<\Delta T \; n_{gal}>$ 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.

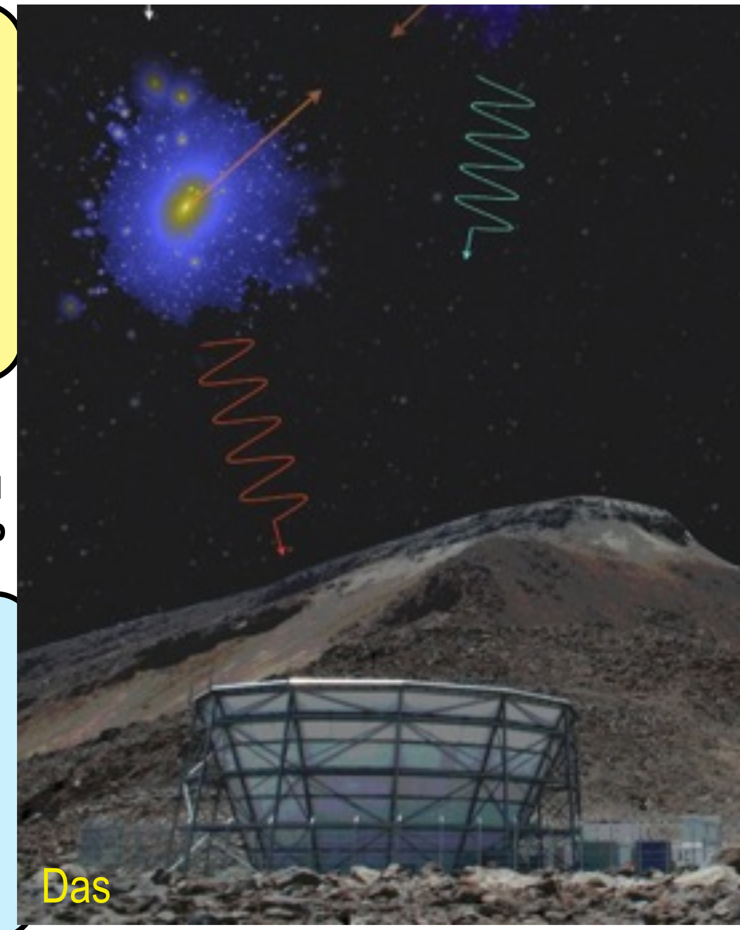
Planck13 X MCXC 1750 X-rays cls

Meta Catalogue of X-ray detected Clusters made for Planck

<z>~0.18, <v_radial> = 72 +- 60 km/s monopole

blind search < 254 km/s 95% CL

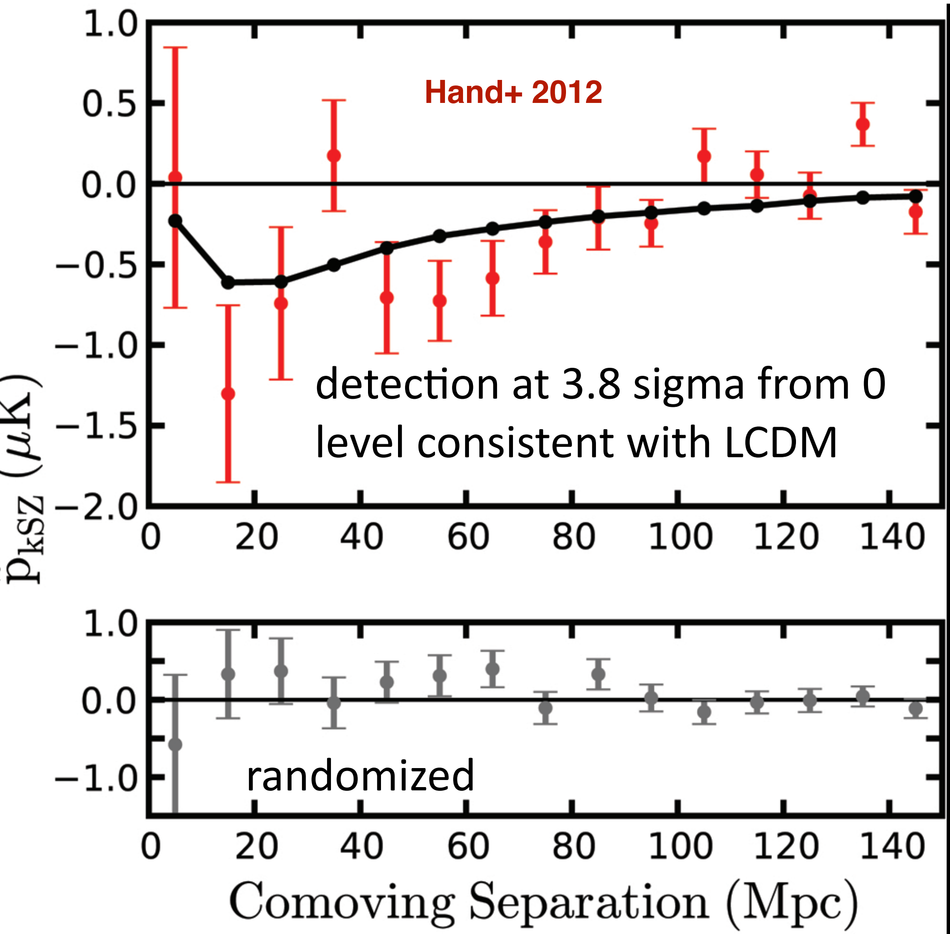
no super-bulk flow *aka the* ***Dark Flow*** *~1000 km/s*



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



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

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

bulk velocity from WMAP7 x Xray-Cls

the Dark Flow

Kashlinsky, Atrio-Barandela, Kocevski & Ebeling08

3σ detection of v ~600 km/s out to z=0.3 towards (*l,b*)= (267°, 34°). 1588 X-cls total

Kashlinsky, Atrio-Barandela & Ebeling12 PhysRep

challenged by:

Keisler 09, Osborne+ 10, Zhang & Stebbins 11, & Mody & Hajian 12 (using Planck & Rosat cls) =>

no significant detection of kSZ signal

bulk velocity from Planck1.3 x Xray-Cls

PIP XIII ~order of mag sensitivity gain, no detection

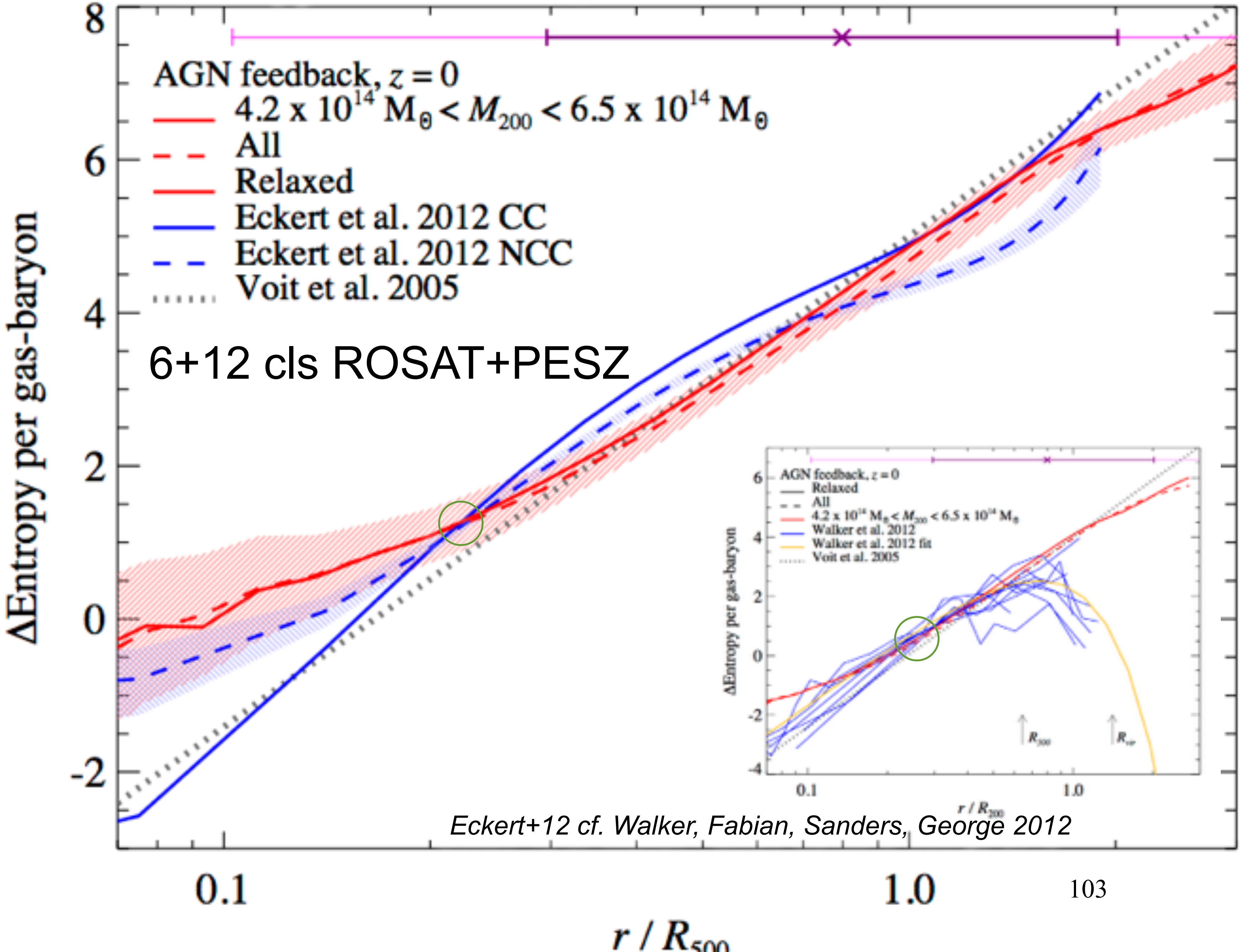
challenged by: *Atrio-Barandela: PIP13 overestimates errors*

the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, 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.

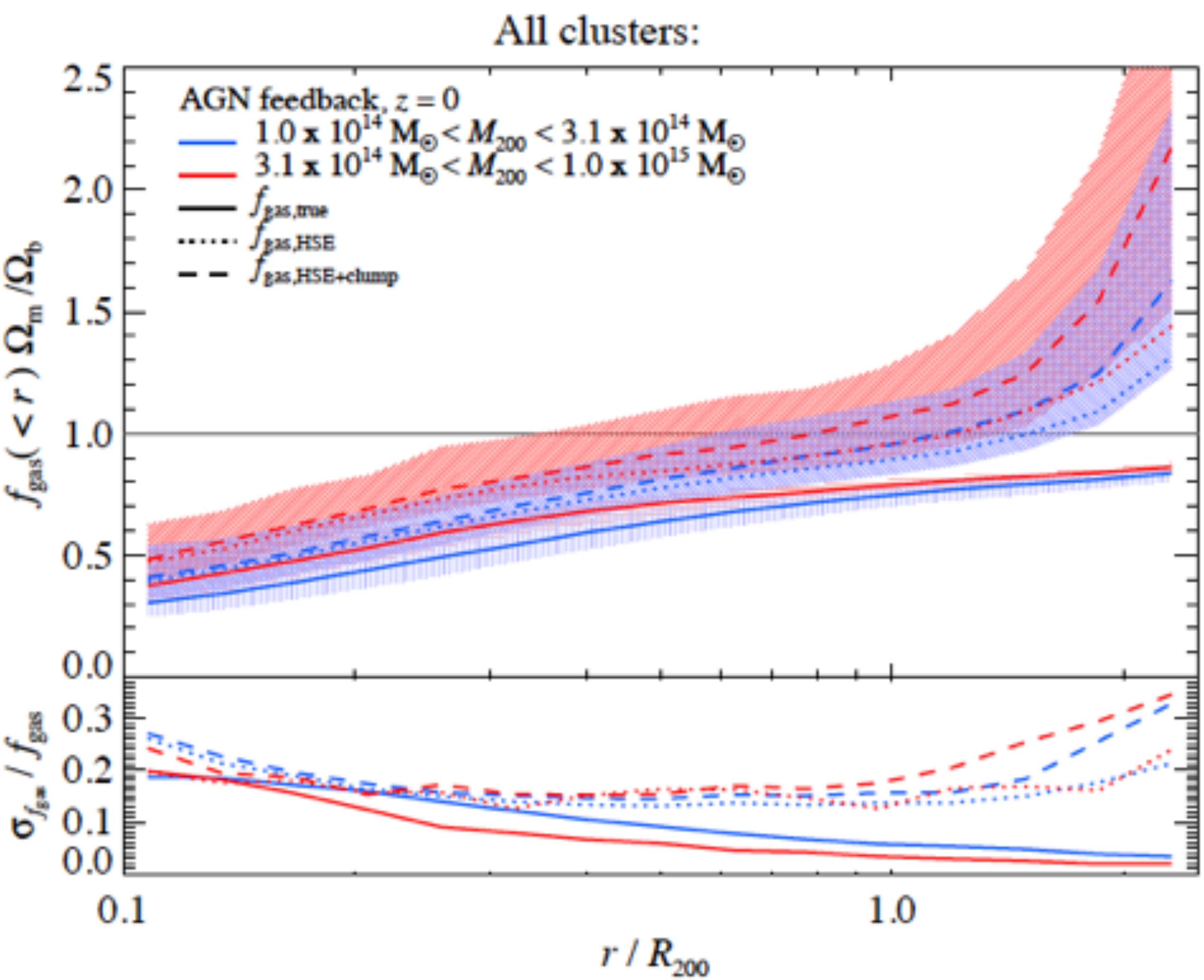
Bond since 1993, Canada since 2001, 1st CSA pre-launch contract 2002-09, post-launch 2010-11, 2011-15

Universal Entropy Profile? *sort of, but inference from observations is difficult*



Eckert+12 cf. Walker, Fabian, Sanders, George 2012

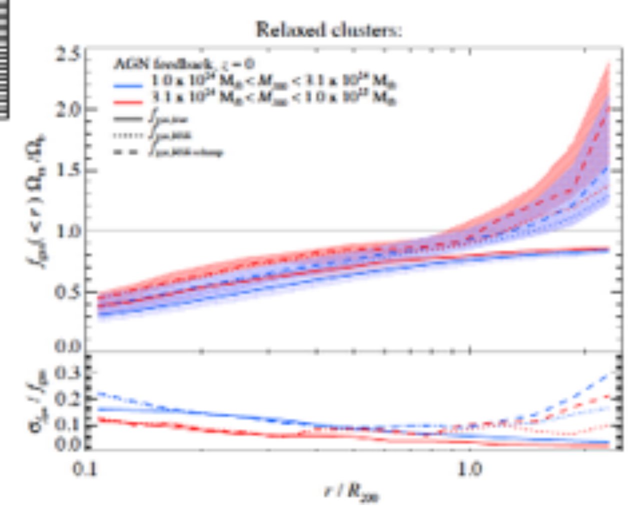
biases in gas fraction estimation in clusters



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).



SZ observations of age in 2010-2011
2011 PEP
Planck early results XII: Cluster Sunyaev-Zeldovich optical scaling relations SDMW@cifar13
Planck Early Results XI: Calibration of the local galaxy cluster Sunyaev-Zeldovich scaling relations
Planck Early Results. X. Statistical analysis of Sunyaev-Zeldovich scaling relations for X-ray galaxy clusters
Planck early results. IX. XMM-Newton follow-up for validation of Planck cluster candidates
Planck Early Results VIII: The all-sky Early Sunyaev-Zeldovich cluster sample 189+ cls
Planck Early Results. VII. The Early Release Compact Source Catalog
2010-11 ACT
The Atacama Cosmology Telescope: Detection of Sunyaev-Zel'dovich Decrement in Groups and Clusters Associated with Luminous Red Galaxies
The Atacama Cosmology Telescope: Sunyaev Zel'dovich Selected Galaxy Clusters at 148 GHz in the 2008 Survey
The Atacama Cosmology Telescope: Cosmology from Galaxy Clusters Detected via the Sunyaev-Zel'dovich Effect
The Atacama Cosmology Telescope: Physical Properties and Purity of a Galaxy Cluster Sample Selected via the Sunyaev-Zel'dovich Effect
The Atacama Cosmology Telescope (ACT): Beam Profiles and First SZ Cluster Maps
The Cosmic Background Imager 2 Taylor+
2013 Combined CBI, SZA, BIMA, and OVRO analysis of the thermal Sunyaev-Zel'dovich Effect in A1689 Alison+ B@cifar13
< *2011* Subdegree Sunyaev-Zel'dovich Signal from Multifrequency BOOMERanG observations
< *2011* High resolution CMB power spectrum from the complete ACBAR data set
2010-12 *also many SPT cluster papers*
2010-13 Battaglia, Bond, Pfrommer, Sievers: theory & hydro sims with feedback
Simulations of the Sunyaev-Zel'dovich Power Spectrum with AGN Feedback BBPSS B@cifar13
Exploring the magnetized cosmic web through low frequency radio emission BBPS
2013 On the Cluster Physics of Sunyaev-Zel'dovich and X-ray Surveys IV: Density and Pressure Clumping due to Infalling Substructures BBPS3 B@cifar13
2013 On the Cluster Physics of Sunyaev-Zel'dovich Surveys III: Information Theoretic View of Clusters and their Non-equilibrium Entropies BBPS5 B@cifar13

< *2011* Galaxy Cluster Astrophysics and Cosmology: Questions and Opportunities for the Coming Decade *white paper*
2010-12 ***MUSTANG2 on GBT proposals*** *Planck cluster followup to 35σ in 1 hr @10” B@cifar13*
2013 CCAT sims

Burst of papers in 2012 Planck, ACT, SPT, theory

Planck Early Results XXVI: Detection with Planck and confirmation by XMM-Newton of PLCK G266.6-27.3, an exceptionally X-ray luminous and massive galaxy cluster at z~1

Planck Intermediate Results. I. Further validation of new Planck clusters with XMM-Newton

Planck Intermediate Results II: Comparison of Sunyaev-Zeldovich measurements from Planck and from the Arcminute Microkelvin Imager for 11 galaxy clusters

Planck intermediate results. III. The relation between galaxy cluster mass and Sunyaev-Zeldovich signal

Planck Intermediate Results. IV. The XMM-Newton validation programme for new Planck galaxy clusters

Planck intermediate results. VI: The dynamical structure of PLCKG214.6+37.0, a Planck discovered triple system of galaxy clusters

Planck Intermediate Results. V. Pressure profiles of galaxy clusters from the Sunyaev-Zeldovich effect ***PUPPY***

Planck intermediate results. X. Physics of the hot gas in the Coma cluster ***PUPPY***

Planck intermediate results. VIII. Filaments between interacting clusters

Planck Intermediate Results. XI: The gas content of dark matter halos: the Sunyaev-Zeldovich-stellar mass relation for locally brightest galaxies

The Atacama Cosmology Telescope: High-Resolution Sunyaev-Zel'dovich Array Observations of ACT SZE-selected Clusters from the Equatorial Strip

The Atacama Cosmology Telescope: ACT-CL J0102-4915 "El Gordo," a Massive Merging Cluster at Redshift 0.87

The Atacama Cosmology Telescope: Dynamical Masses and Scaling Relations for a Sample of Massive Sunyaev-Zel'dovich Effect Selected Galaxy Clusters

Evidence of Galaxy Cluster Motions with the Kinematic Sunyaev-Zel'dovich Effect

The Atacama Cosmology Telescope: A Measurement of the Thermal Sunyaev-Zel'dovich Effect Using the Skewness of the CMB Temperature Distribution

The Atacama Cosmology Telescope: Relation Between Galaxy Cluster Optical Richness and Sunyaev-Zel'dovich Effect

Subaru weak-lensing measurement of a z = 0.81 cluster discovered by the Atacama Cosmology Telescope Survey

The Atacama Cosmology Telescope: Physical Properties of Sunyaev-Zel'dovich Effect Clusters on the Celestial Equator

The Atacama Cosmology Telescope: the stellar content of galaxy clusters selected using the Sunyaev-Zel'dovich effect

The Atacama Cosmology Telescope: Sunyaev-Zel'dovich Selected Galaxy Clusters at 148 GHz from Three Seasons of Data

On the Cluster Physics of Sunyaev-Zel'dovich and X-ray Surveys III: Measurement Biases and Cosmological Evolution of Gas and Stellar Mass Fractions ***BBPS3***

On the Cluster Physics of Sunyaev-Zel'dovich Surveys II: Deconstructing the Thermal SZ Power Spectrum ***BBPS2***

On the Cluster Physics of Sunyaev-Zel'dovich Surveys I: The Influence of Feedback, Non-thermal Pressure and Cluster Shapes on Y-M Scaling Relations ***BBPS1***

Burst of papers in 2013 Planck

Planck Intermediate Results. XIII. Constraints on peculiar velocities

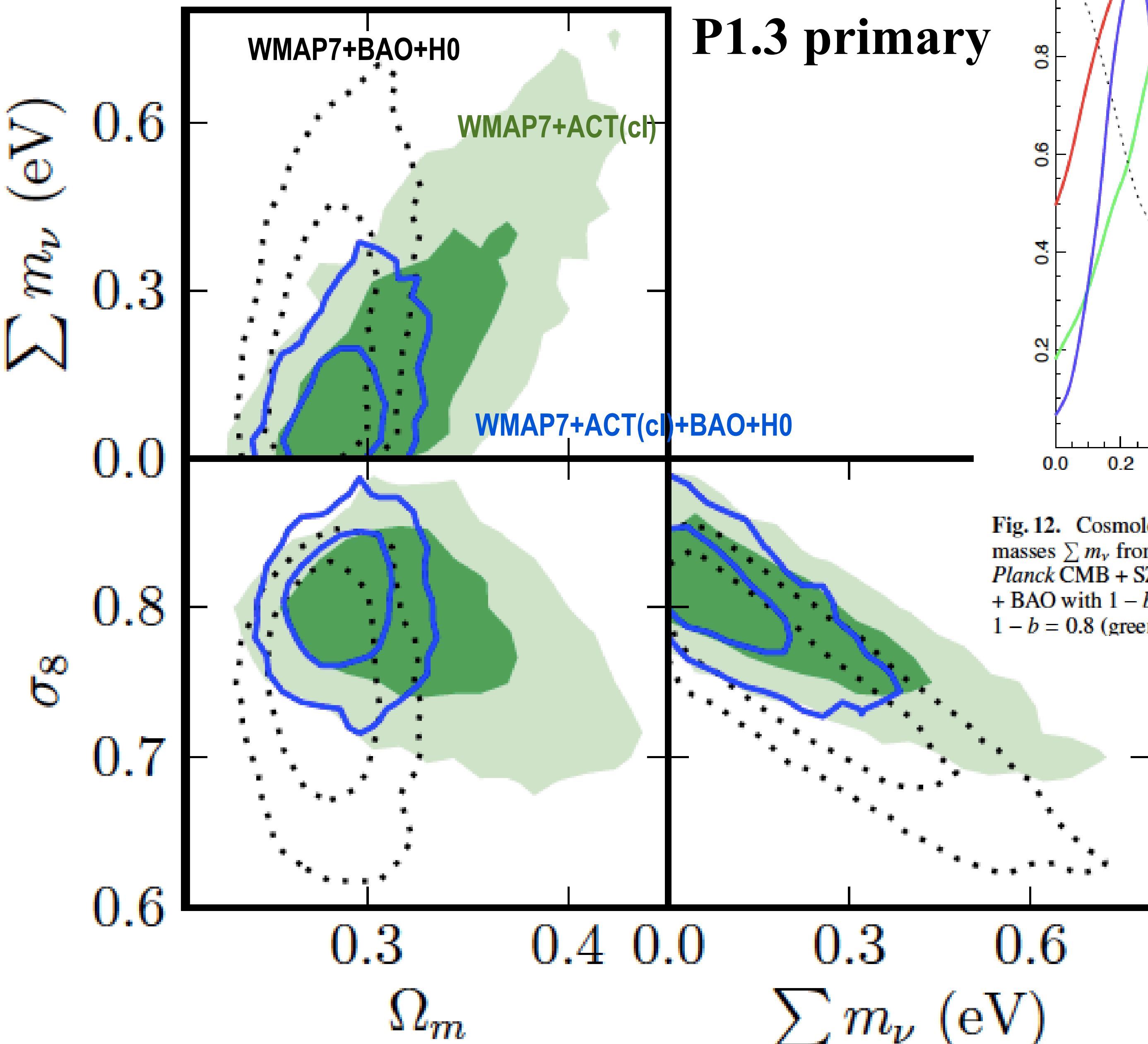
Planck 2013 results. XXI. Cosmology with the all-sky Planck Compton parameter y-map

Planck 2013 results. XX. Cosmology from Sunyaev–Zeldovich cluster counts

Planck 2013 results. XXIX. Planck catalogue of Sunyaev–Zeldovich sources

thermal SZ clusters

Σm_ν <0.230 ev
P1.3 primary



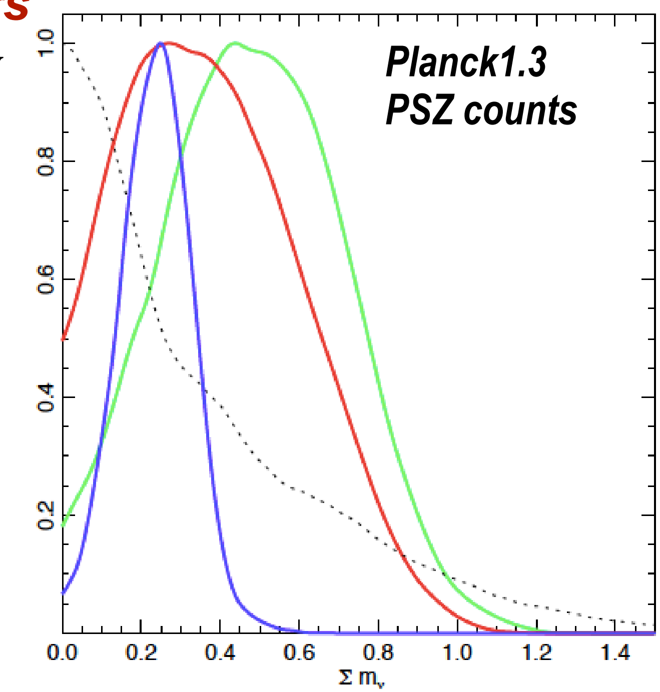
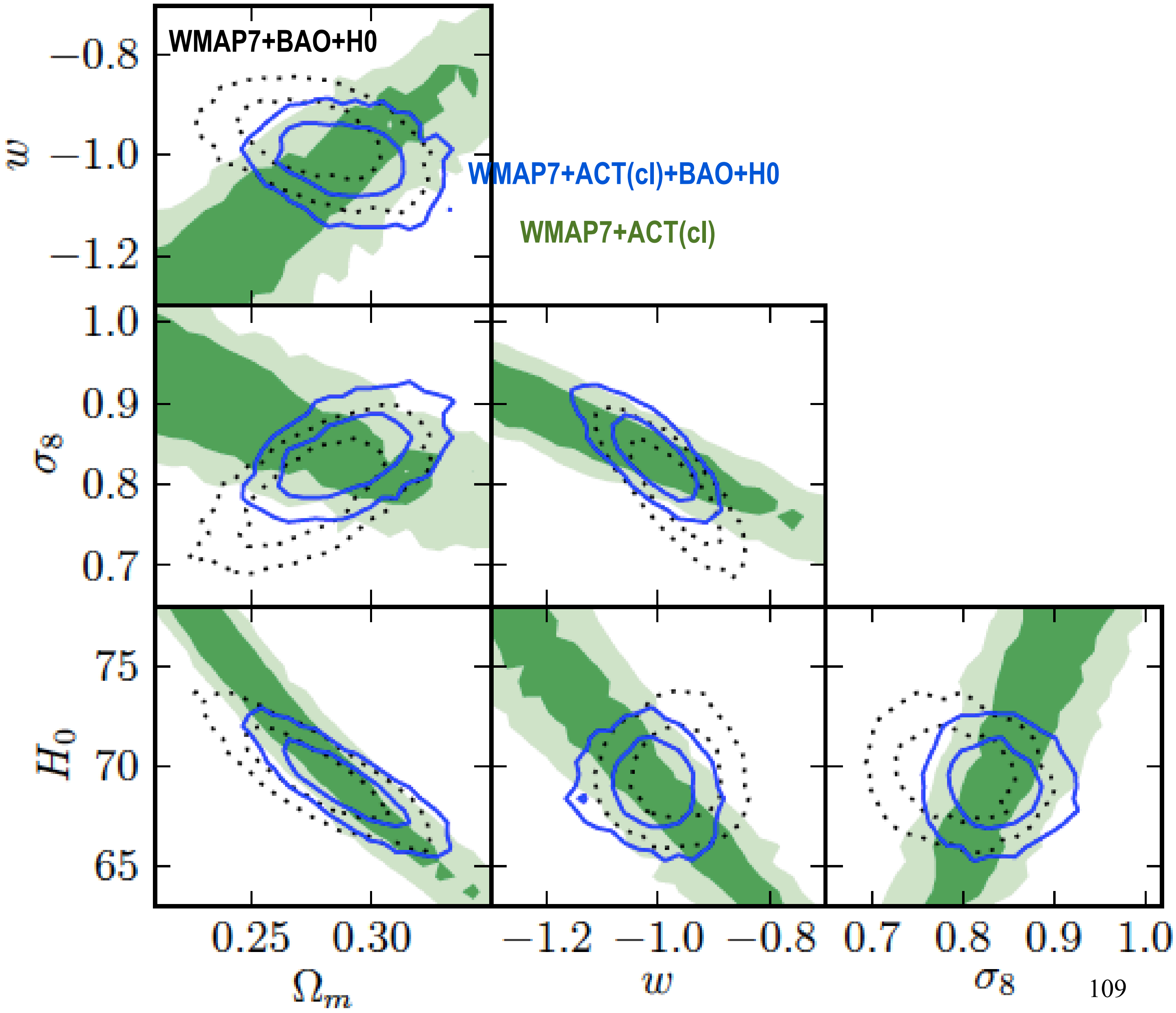


Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1-b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1-b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1-b = 0.8$ (green).

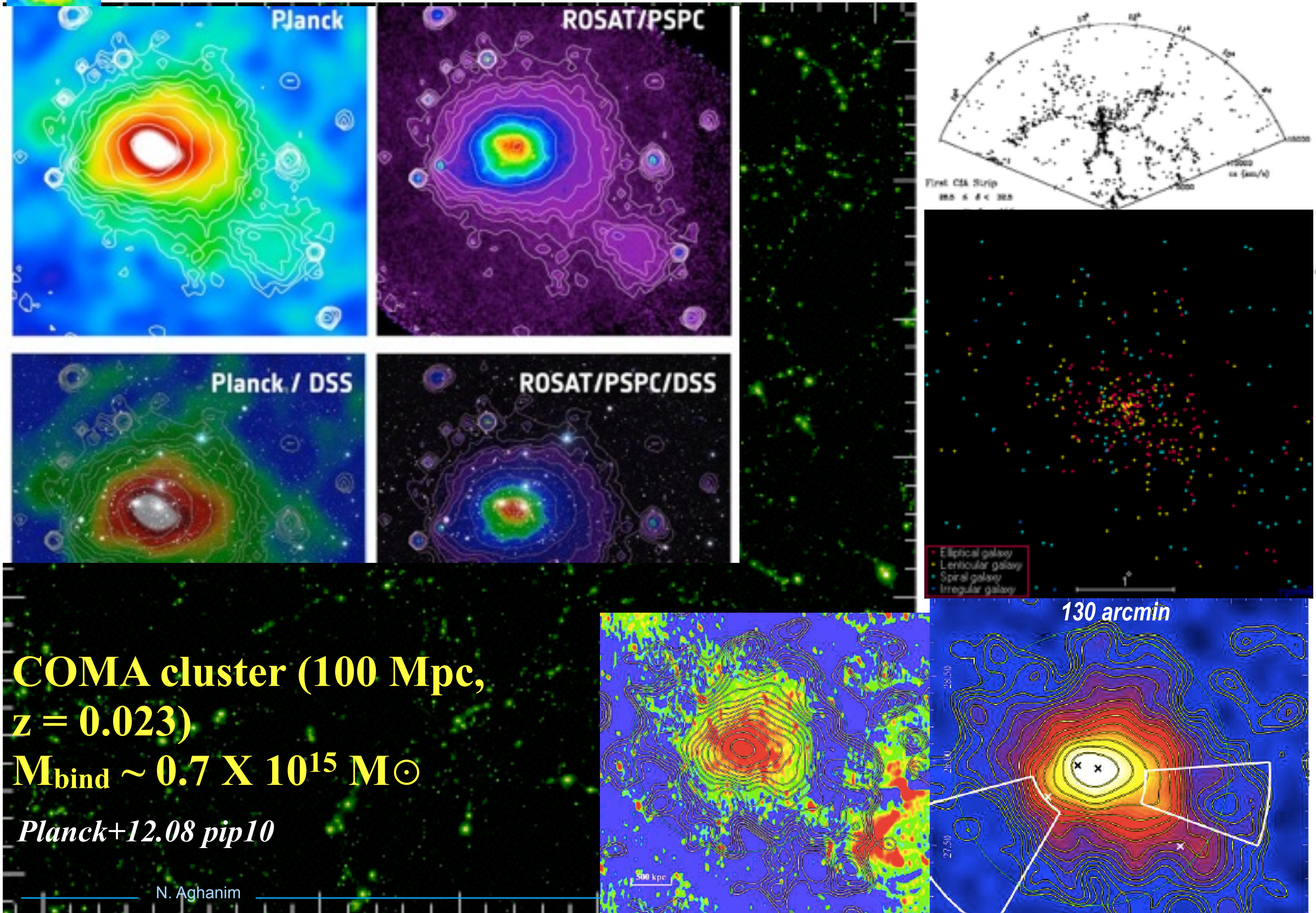
ACT Hasselfield+12

thermal SZ clusters



ACT Hasselfield+12

Planck sees the rarest & most massive clusters over the whole sky e.g., Coma



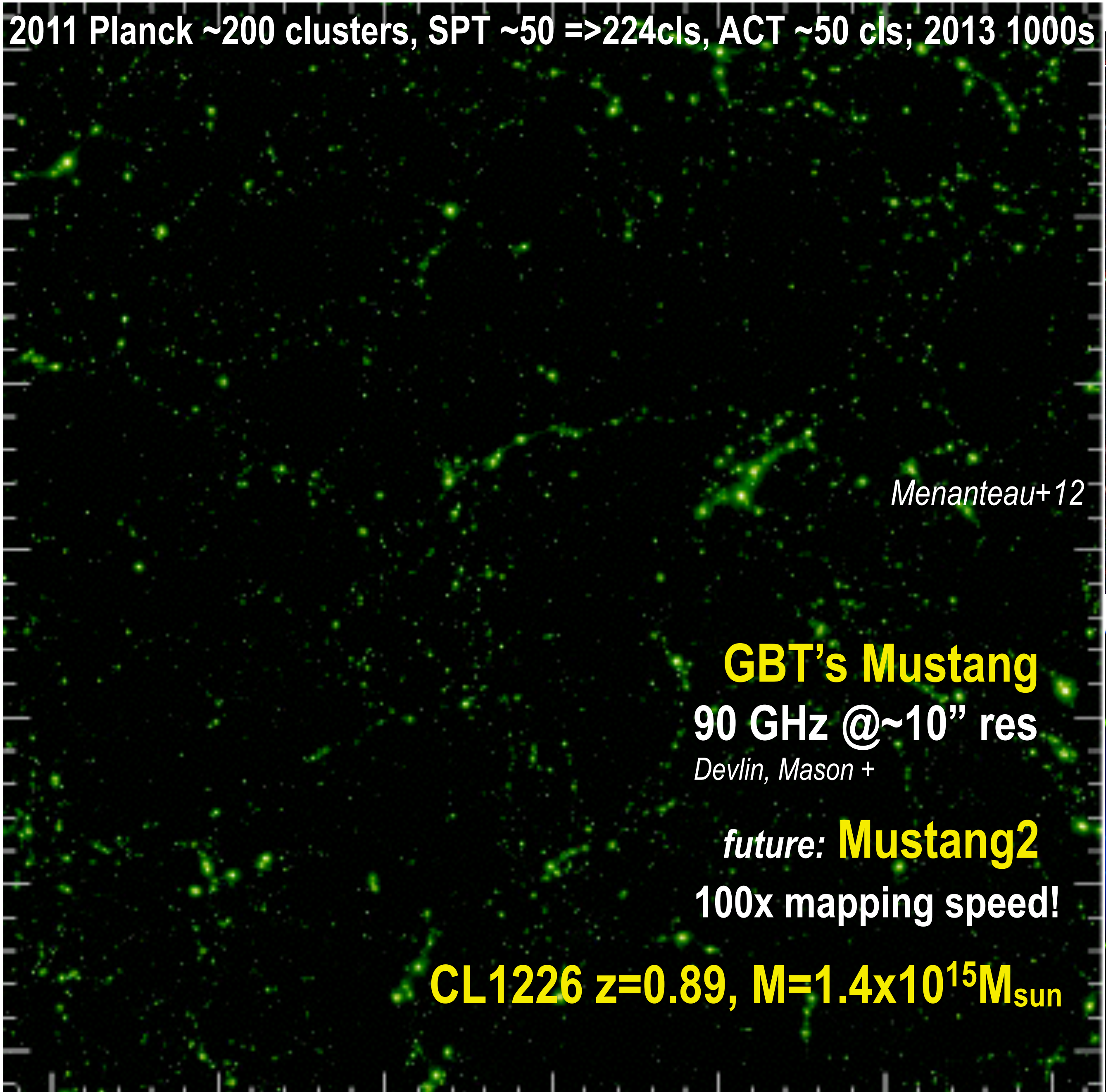
COMA cluster (100 Mpc, z = 0.023)

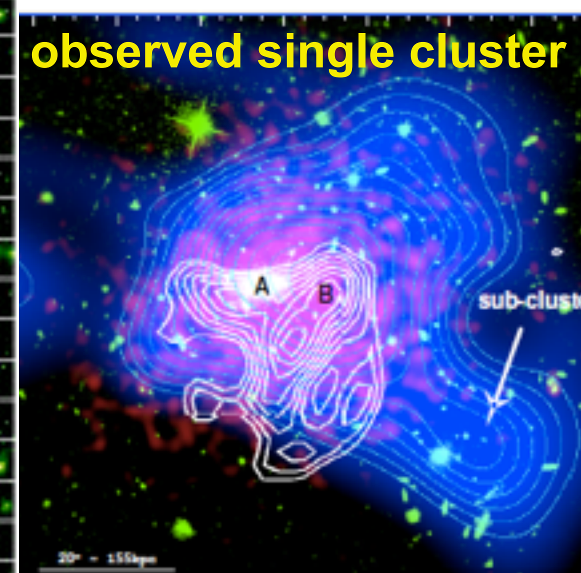
$M_{bind} \sim 0.7 \times 10^{15}\ M_\odot$

Planck+12.08 pip10

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

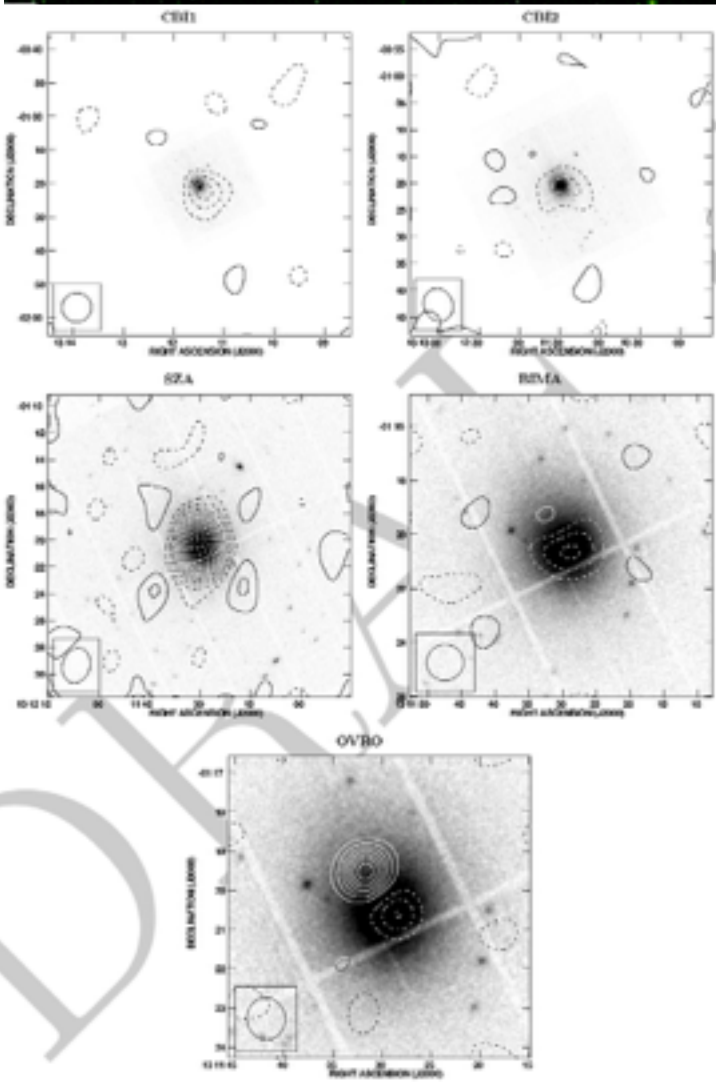
Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)

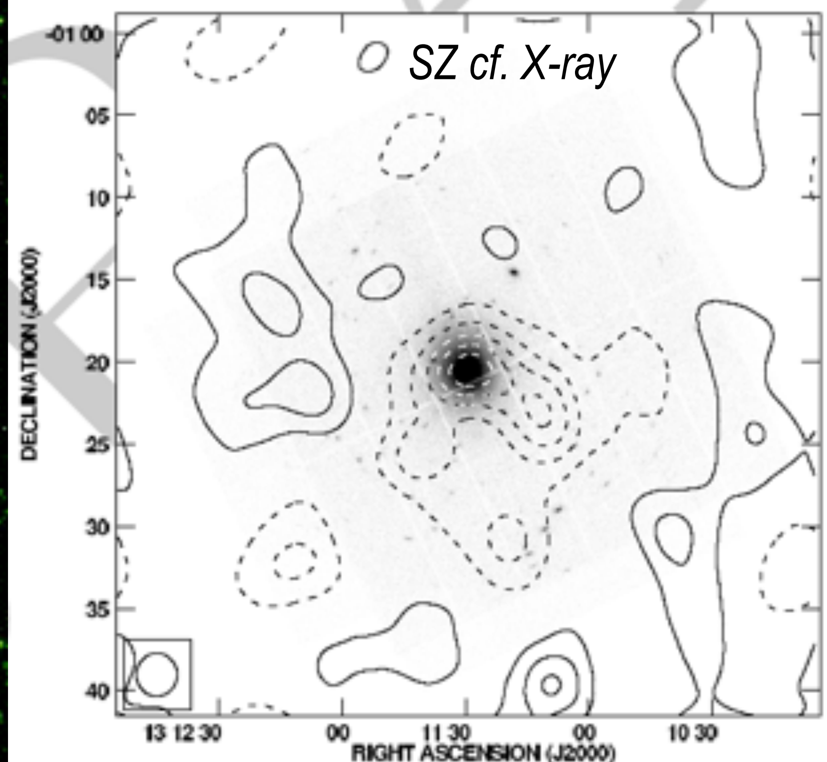


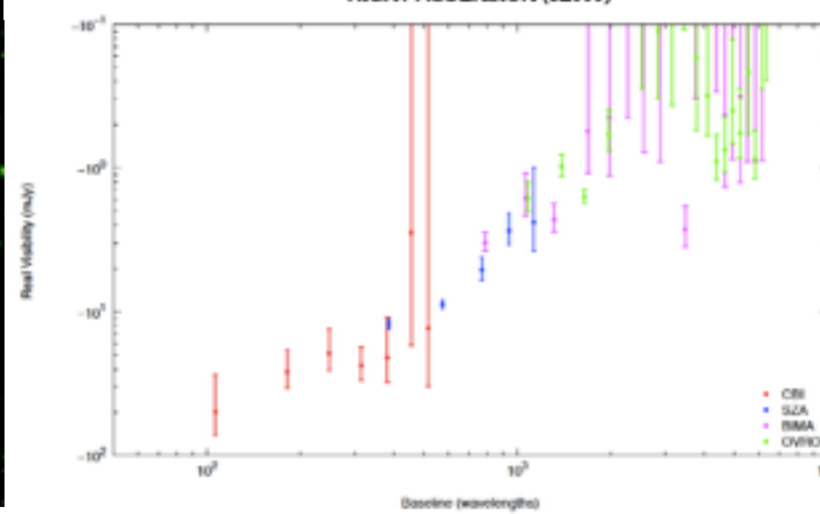


A1689 SZ combine **CBI, CBI2, SZA, BIMA, OVRO interferometry** data

good spatial resolution over a range ~20 *Allison+12*



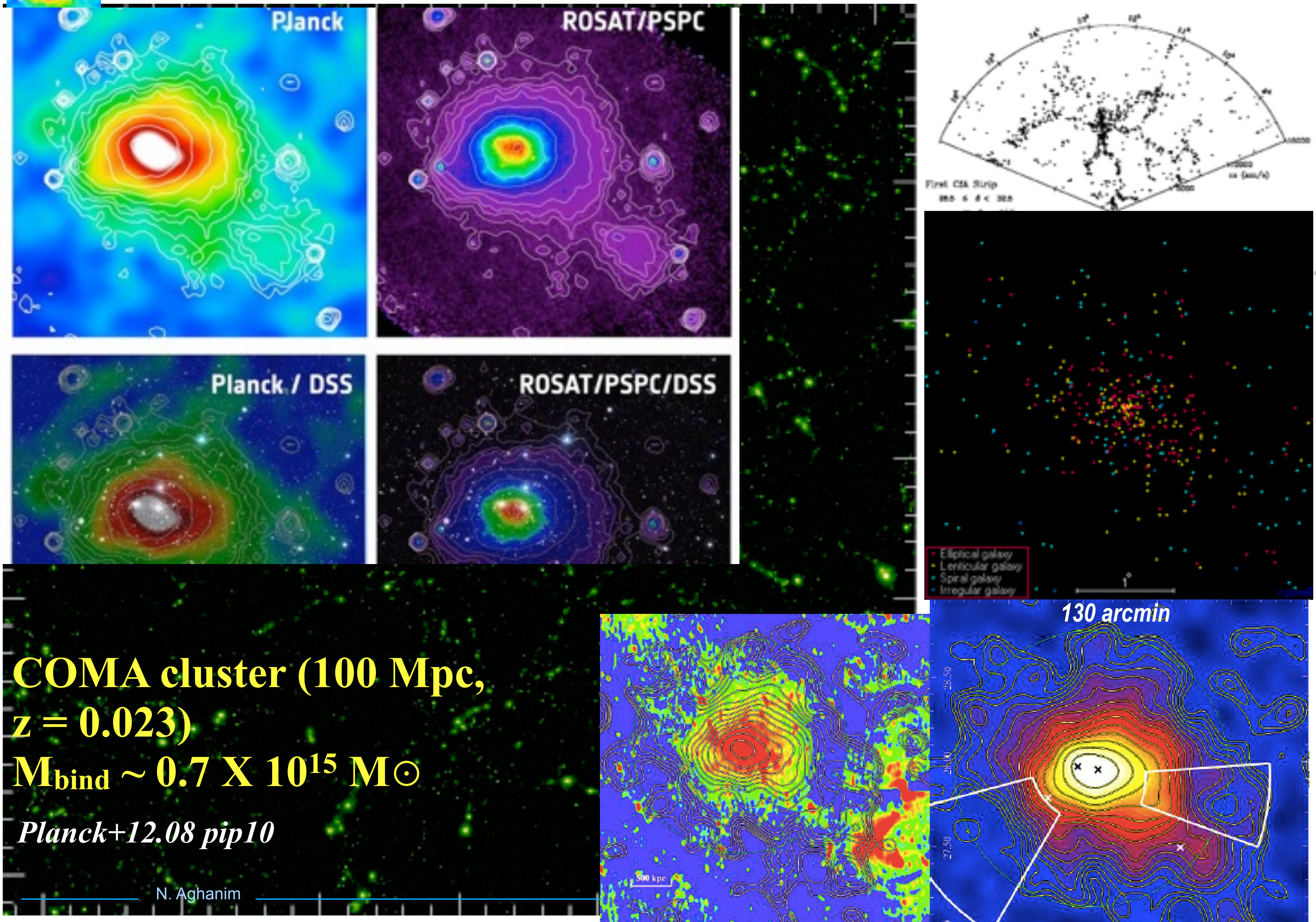




A1689 z=0.18, M=1.4x10^{15}M$_{sun}$

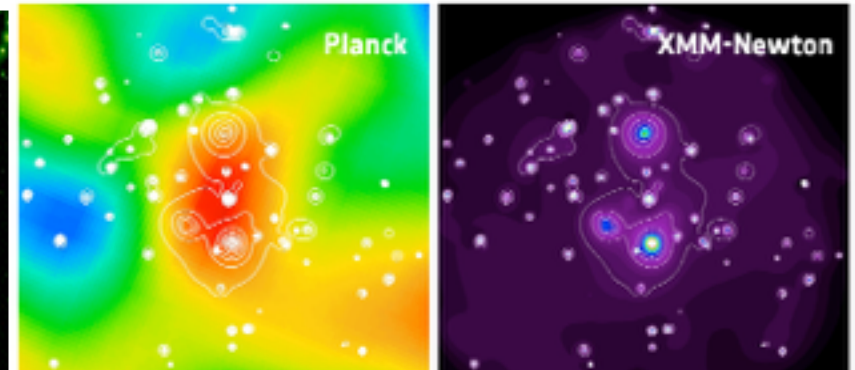
$\langle T_X \rangle$ (9-10.5) kev

Planck sees the rarest & most massive clusters over the whole sky e.g., Coma



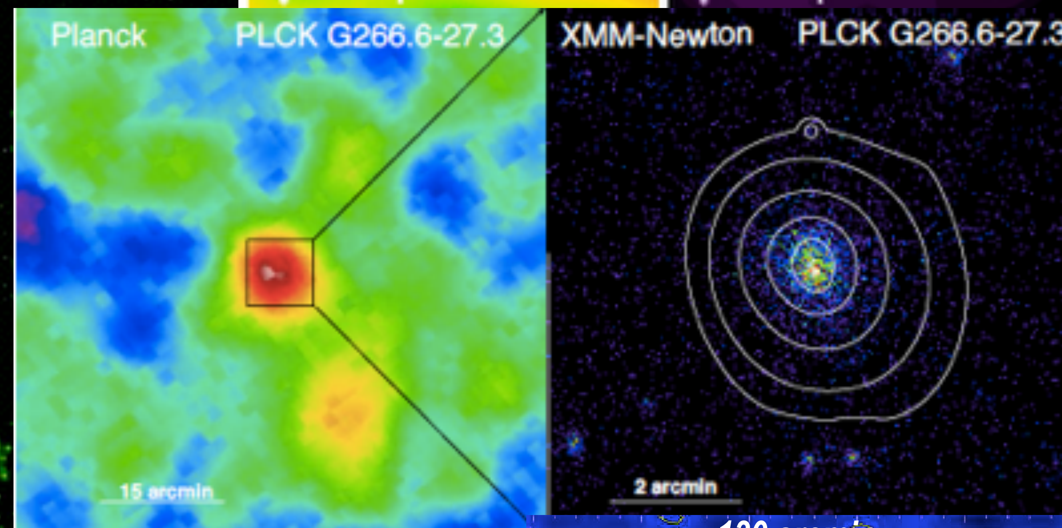
Planck sees the rarest & most massive clusters over the whole sky

Planck+XMM: single clusters, most disturbed; 2 double systems; 2 triple (super-clusters); 0.09 < z < 0.54 *Planck+11.01*



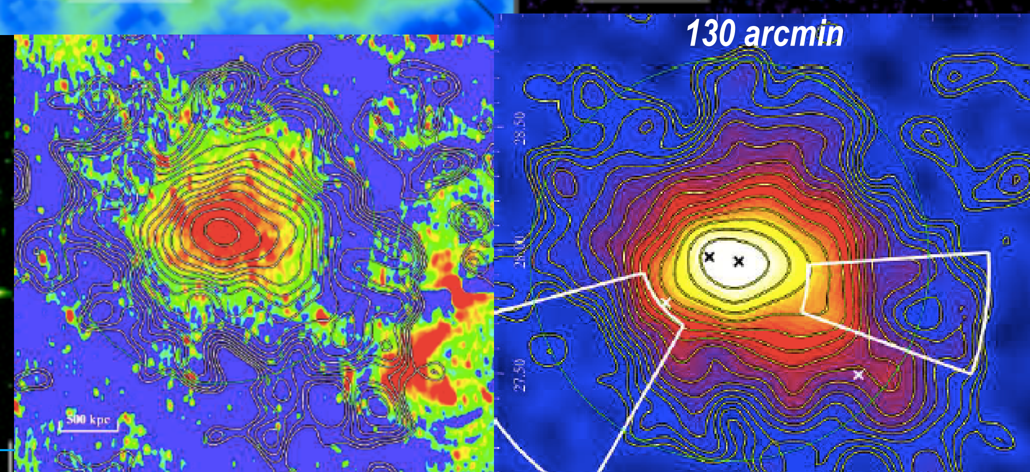
PLCK G266.6−27.3 (z = 0.94 +- 0.02)
$M_{200} \sim (1.5 \pm 0.15) \times 10^{15}\ M_\odot$

Planck+11.06 pep26



COMA cluster (100 Mpc, z =0.023)
$M_{bind} \sim 0.7 \times 10^{15}\ M_\odot$

Planck+12.08 pip10



END

reconstructing ζ *aka* primordial ***scalar curvature*** ***@uniform density***

Bond, Frolov, Huang, Braden, Nolta

Wiener-filtered ζ maps

instead of $\boldsymbol{\zeta}(\mathbf{x})$, $\boldsymbol{\zeta}(\mathbf{k})$, make $\boldsymbol{\zeta}_{LM}(\chi)$, $\chi=|\mathbf{x}|$ & $\boldsymbol{\zeta}_{LM}(k)$, $k=|\mathbf{k}|$ **maps**

$T_{LM\,c,s} \sim \int \zeta_{LM\,c,s}(k)\, U^T_{L\,c,s}(k)\, dk + res \;\sim \int \zeta_{LM\,c,s}(\chi)\, V^T_{L\,c,s}(\chi)\, d\chi + res$

Gaussian stats => $C^{\zeta\zeta}_L(\chi_1,\chi_2)$, $C^{\zeta T}_L(\chi)$, C^{TT}_L

$< \int \mu_b(\chi)\, \zeta_{LM\,c,s}(\chi)\, d\chi \mid a_{LM\,c,s} >$ + *inhomog* **Gaussian fluctuations**

visibility masks $\mu_b(\chi)$ select bands $\Delta\chi_b$ about χ_b ~ decoupling, reionization (also ISW). ∃ only a single-mode $V^T_{L\,c,s}$ direction, fluctuations in orthogonal directions are huge. use the mask for shaped-weighting to control fluctuation-swamping.

full $\zeta_{LM}(k)$ *reconstruction* $<\zeta_{LM}(k) \mid a_{LM}>$ *is fluctuation-swamped*

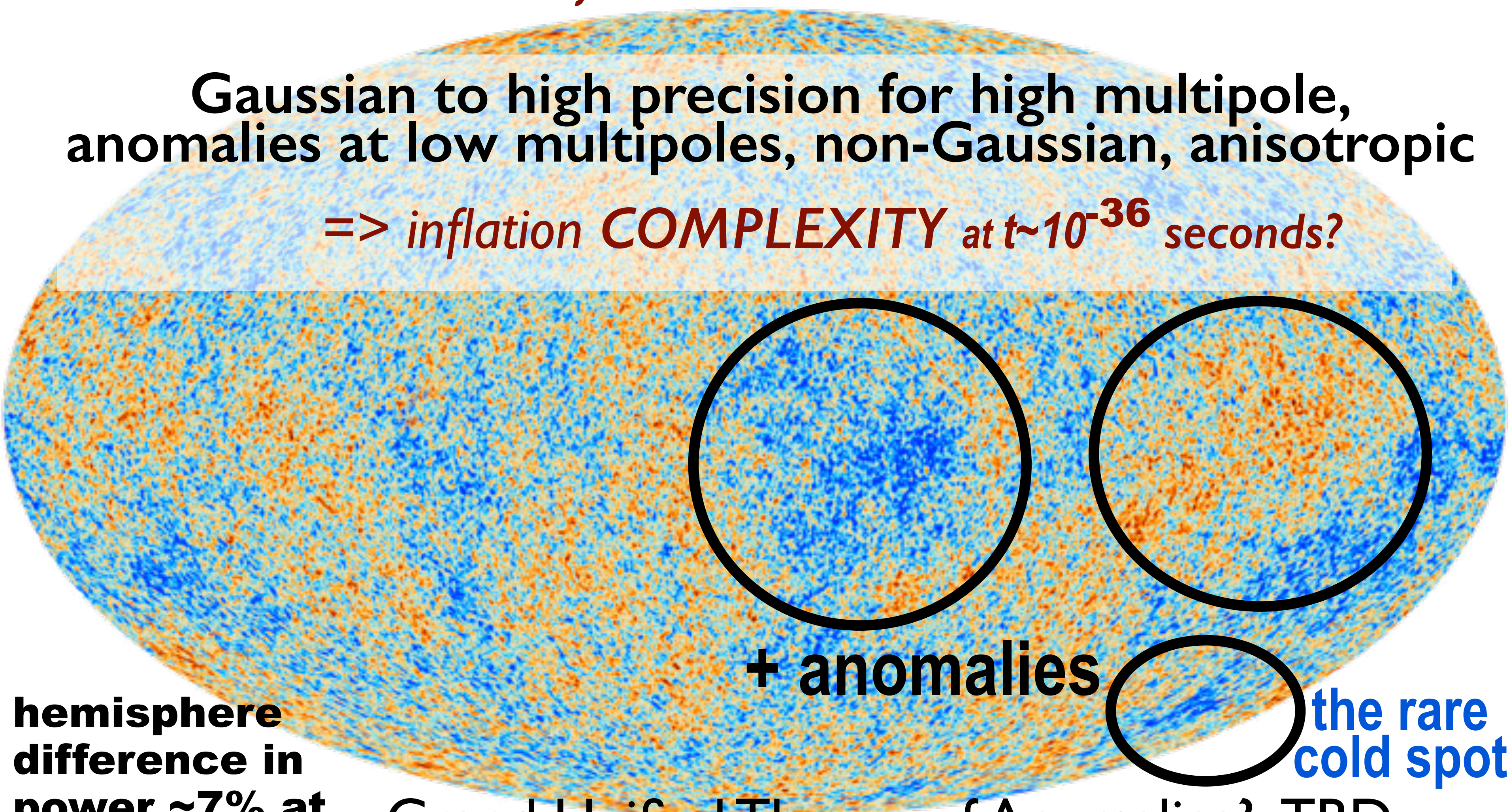
∃ E-pol vector $V^E_{L\,c,s}$ overlaps V^T but it differs enough so reconstruction improves with E-pol

$C^{\zeta E}_L(\chi)$, C^{EE}_L, C^{TE}_L

Planck's primordial light unveiled, March 21, 2013

reveals the SIMPLICITY of primordial cosmic structure

7^{+} numbers, 2+1 are inflation numbers



Gaussian to high precision for high multipole, anomalies at low multipoles, non-Gaussian, anisotropic

=> inflation COMPLEXITY at $t \sim 10^{-36}$ seconds?

+ anomalies

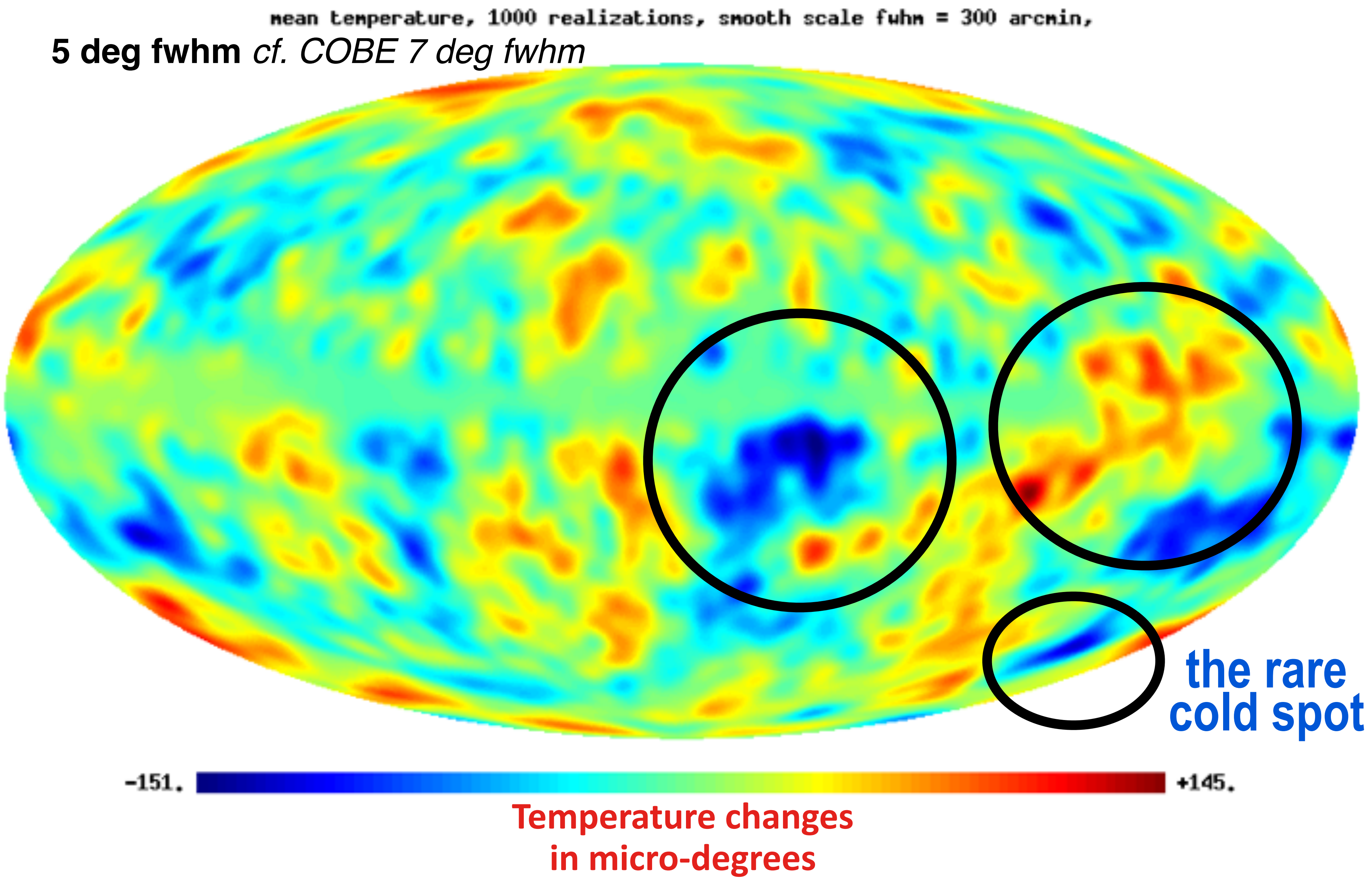
the rare cold spot

hemisphere difference in power ~7% at low resolution

Grand Unified Theory of Anomalies? TBD

intermittent *strain-power bursts (in curvature)?*

temperature map

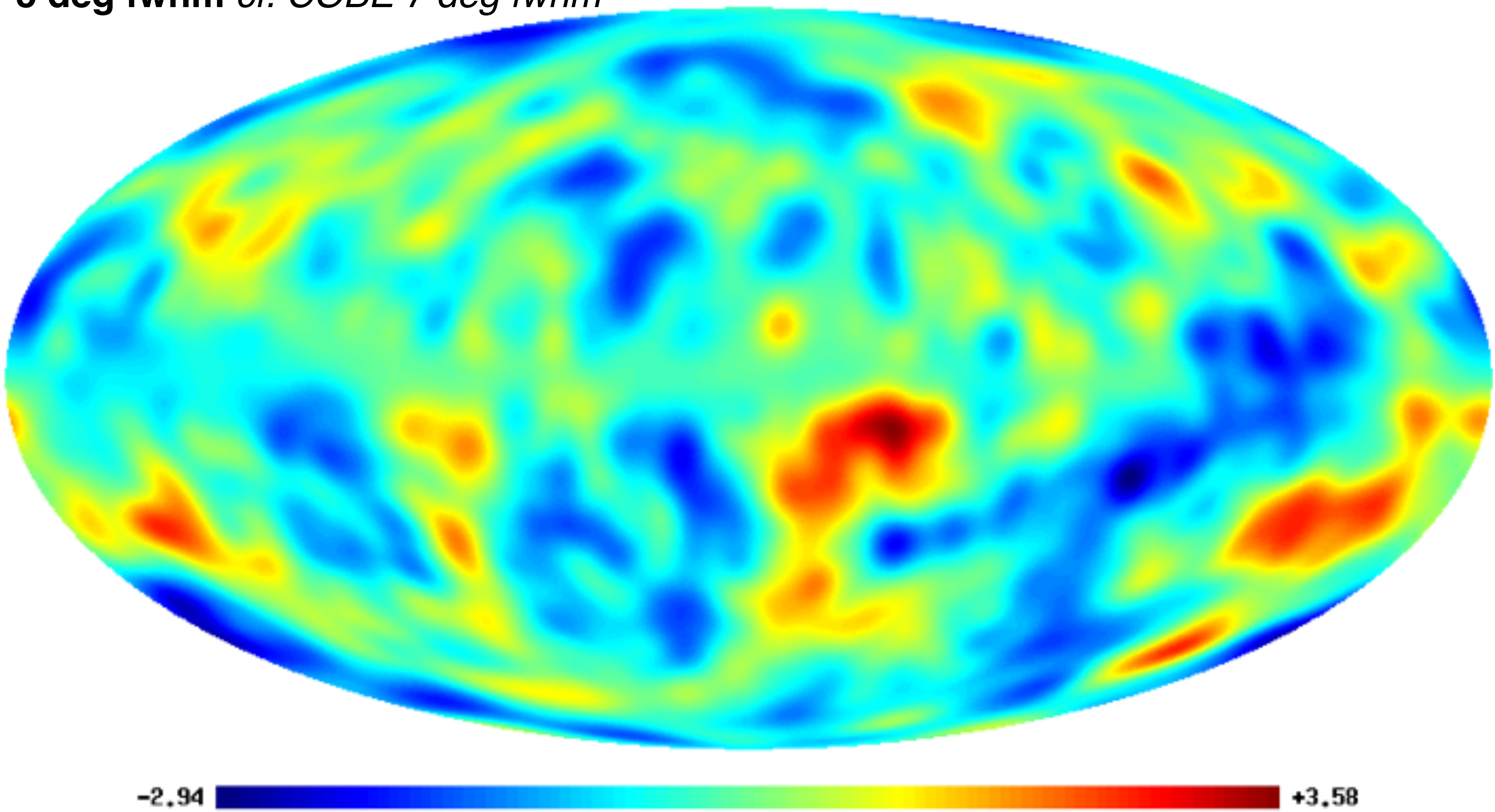


reveals map of **primordial isotropic strain /phonons**

$<Trace(\boldsymbol{\alpha})|Temp>$

mean zeta, 1000 realizations, smooth scale fwhm = 300 arcmin,

5 deg fwhm *cf. COBE 7 deg fwhm*



Reconstructing the Early Universe

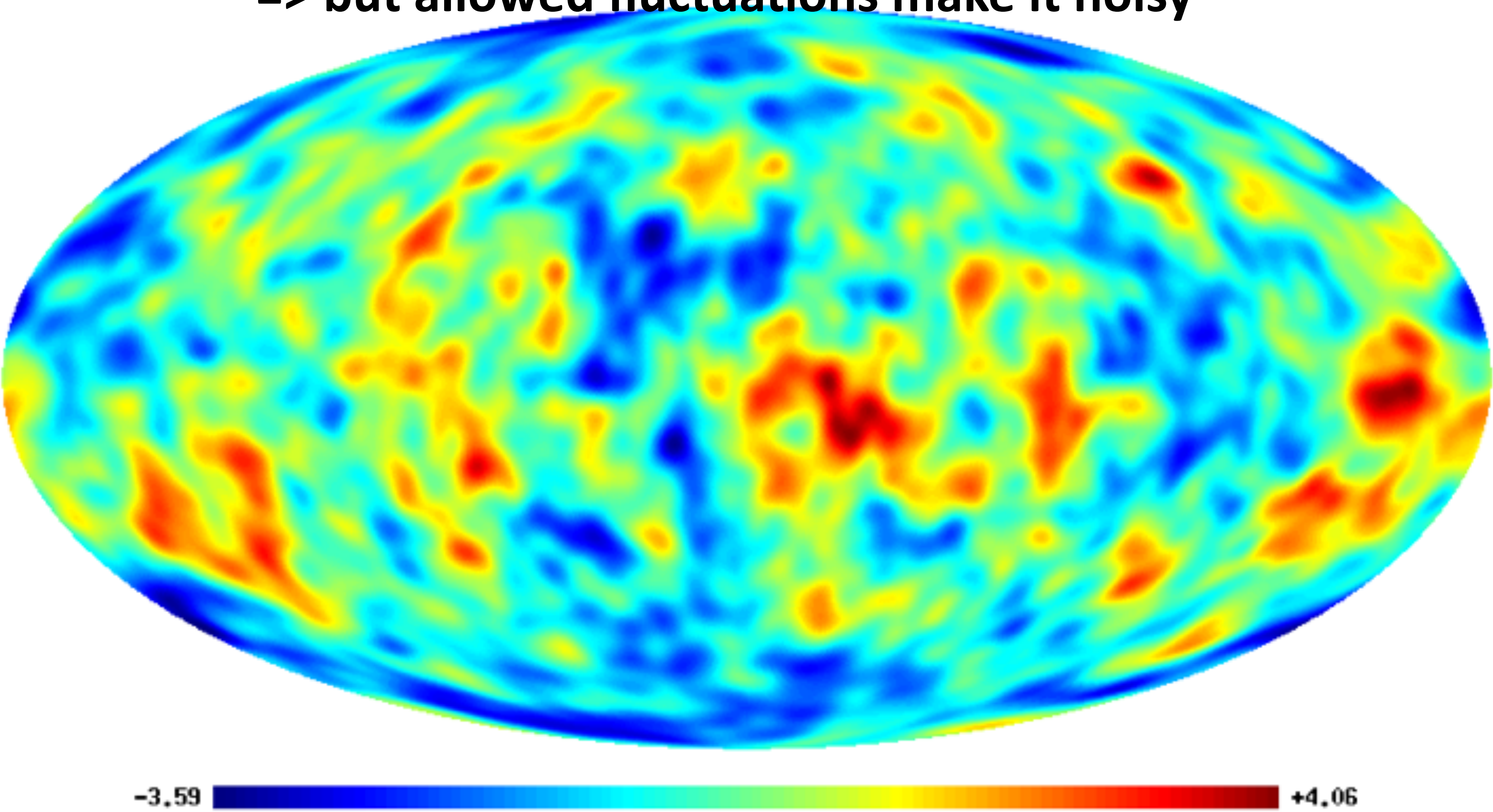
visibility mask

reveals map of **primordial isotropic strain /phonons**

$$\langle \mathbf{Trace}(\boldsymbol{\alpha})|Temp\rangle + \delta\mathbf{Trace}(\boldsymbol{\alpha})$$

one realization of fullsky zeta, fwhm = 300 arcmin

=> but allowed fluctuations make it noisy

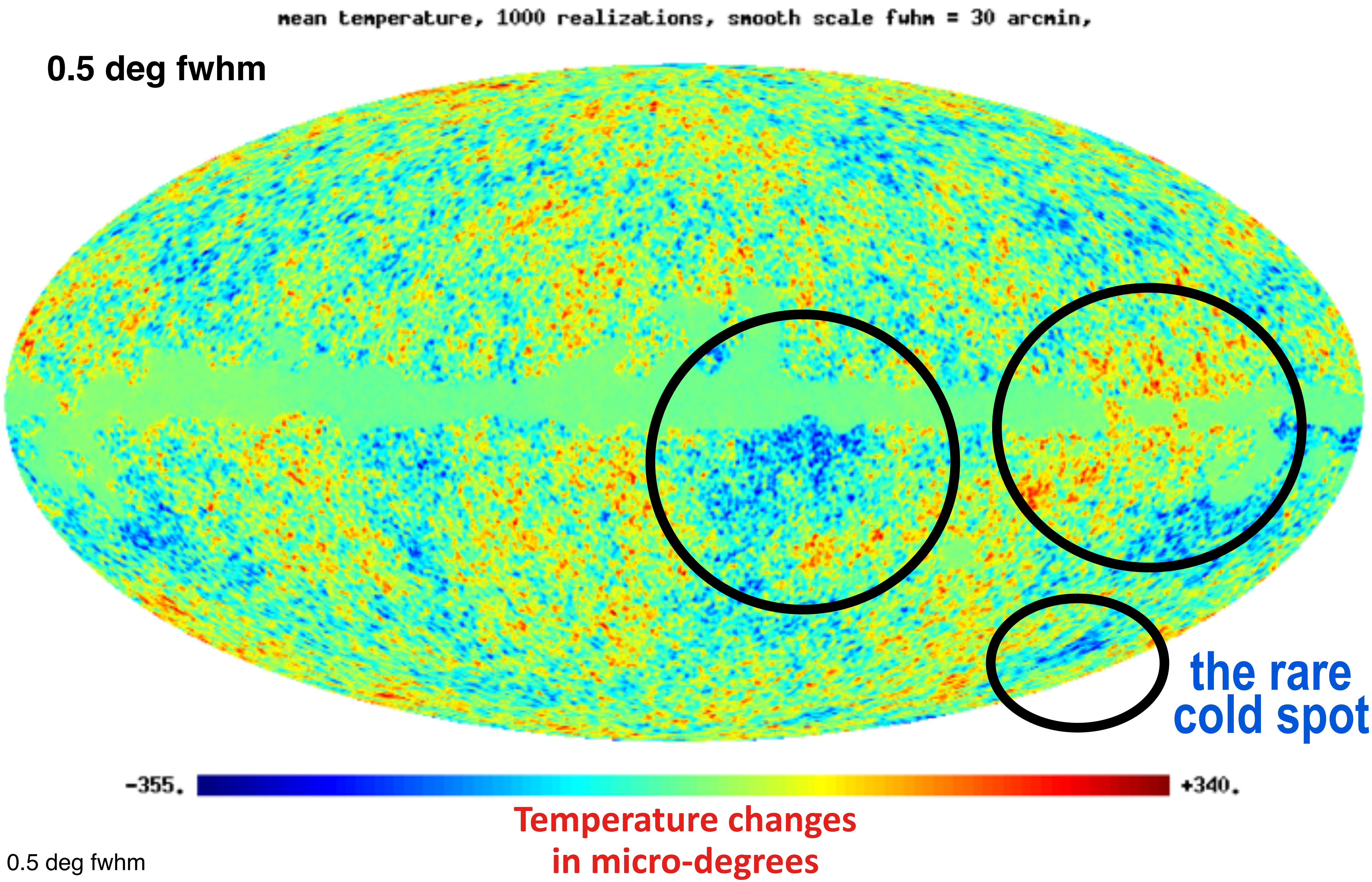


5 deg fwhm cf. COBE 7 deg fwhm

Reconstructing the Early Universe

visibility mask

temperature map



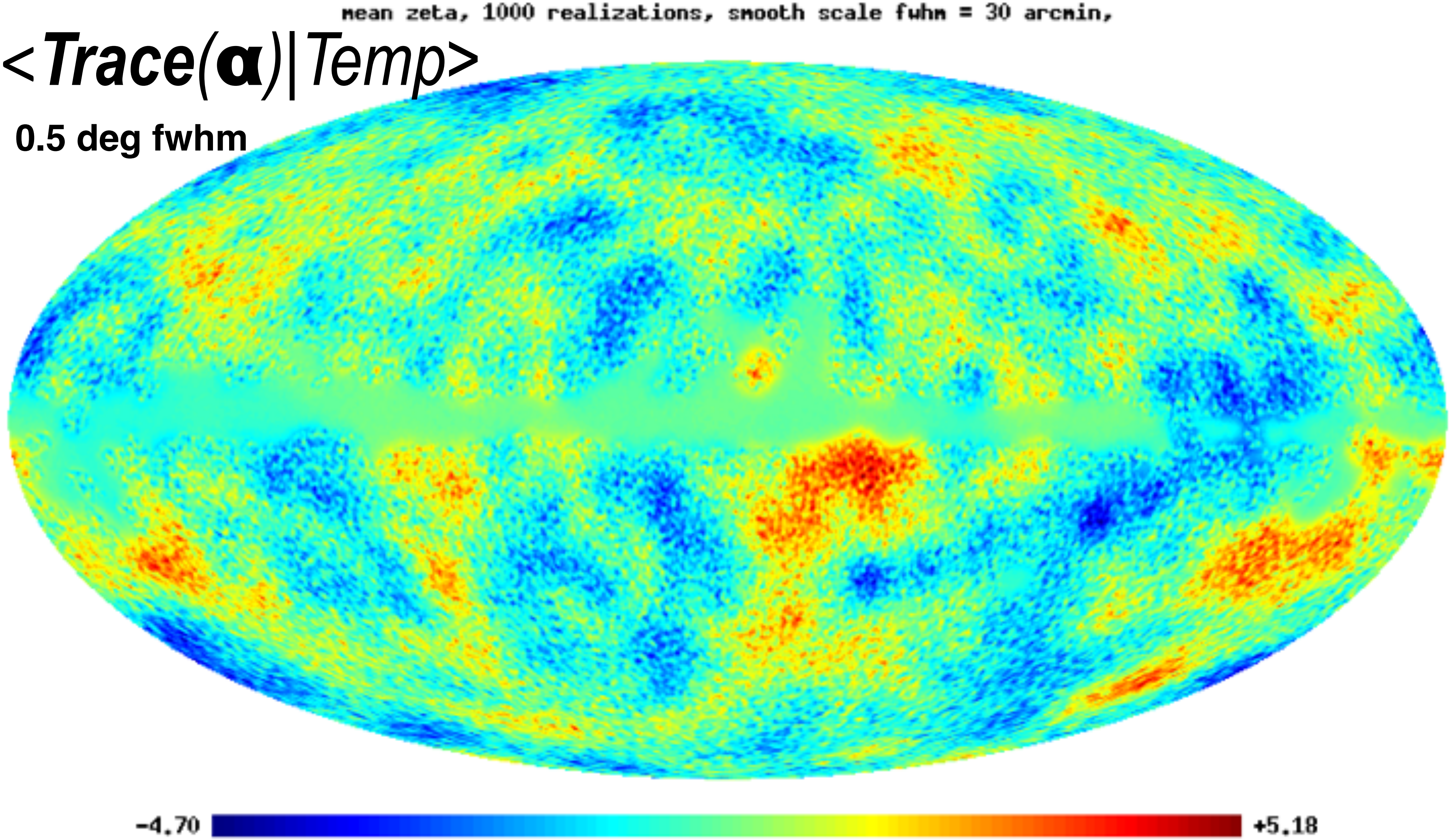
0.5 deg fwhm

reveals map of **primordial isotropic strain /phonons**

=> primordial scalar curvature map of the inflation epoch

$<\boldsymbol{Trace}(\boldsymbol{\alpha})|Temp>$

0.5 deg fwhm



Reconstructing the Early Universe

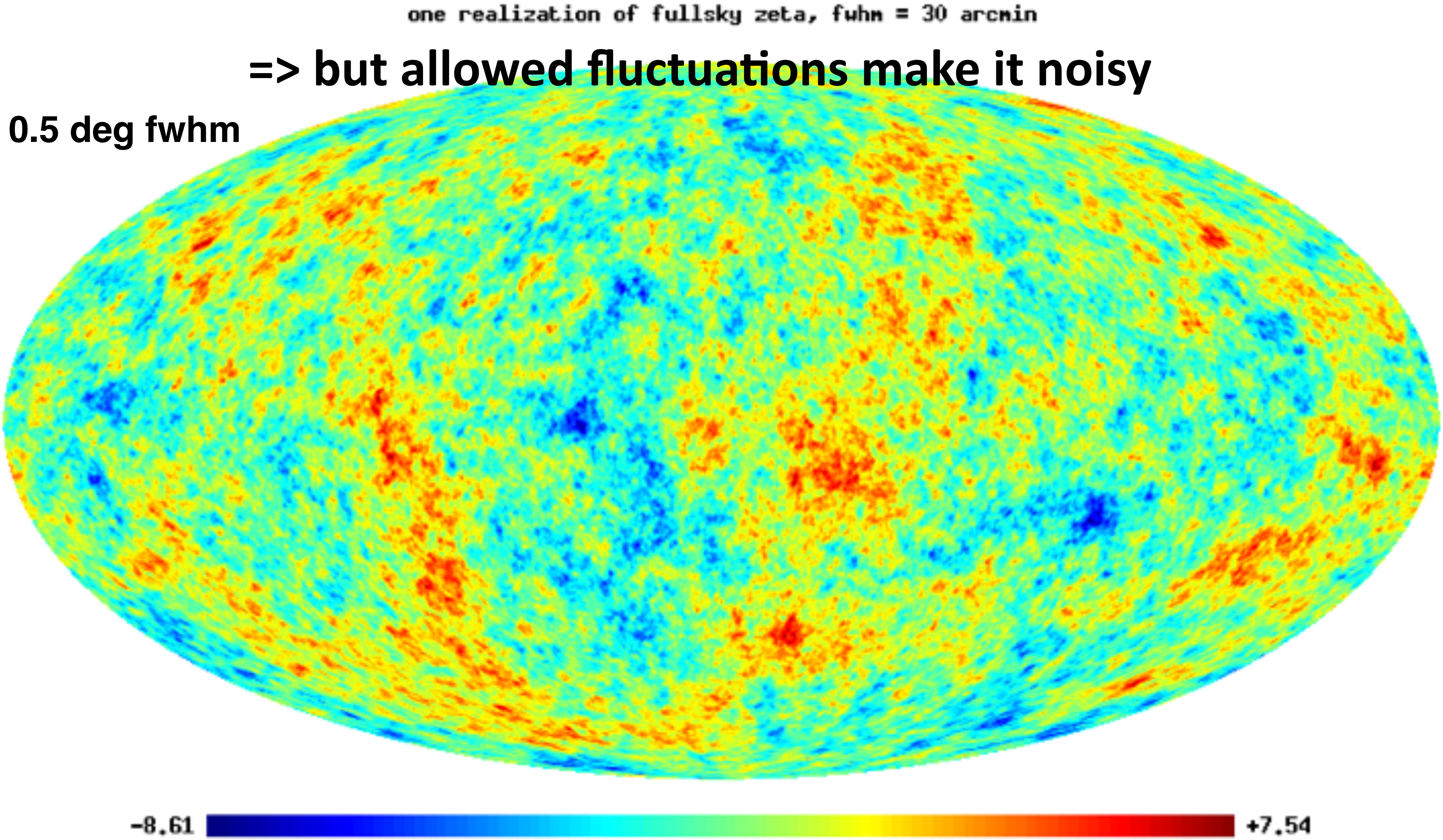
visibility mask

reveals map of **primordial isotropic strain /phonons**

$$\langle \boldsymbol{Trace}(\boldsymbol{\alpha}) | Temp \rangle + \delta \boldsymbol{Trace}(\boldsymbol{\alpha})$$

=> but allowed fluctuations make it noisy

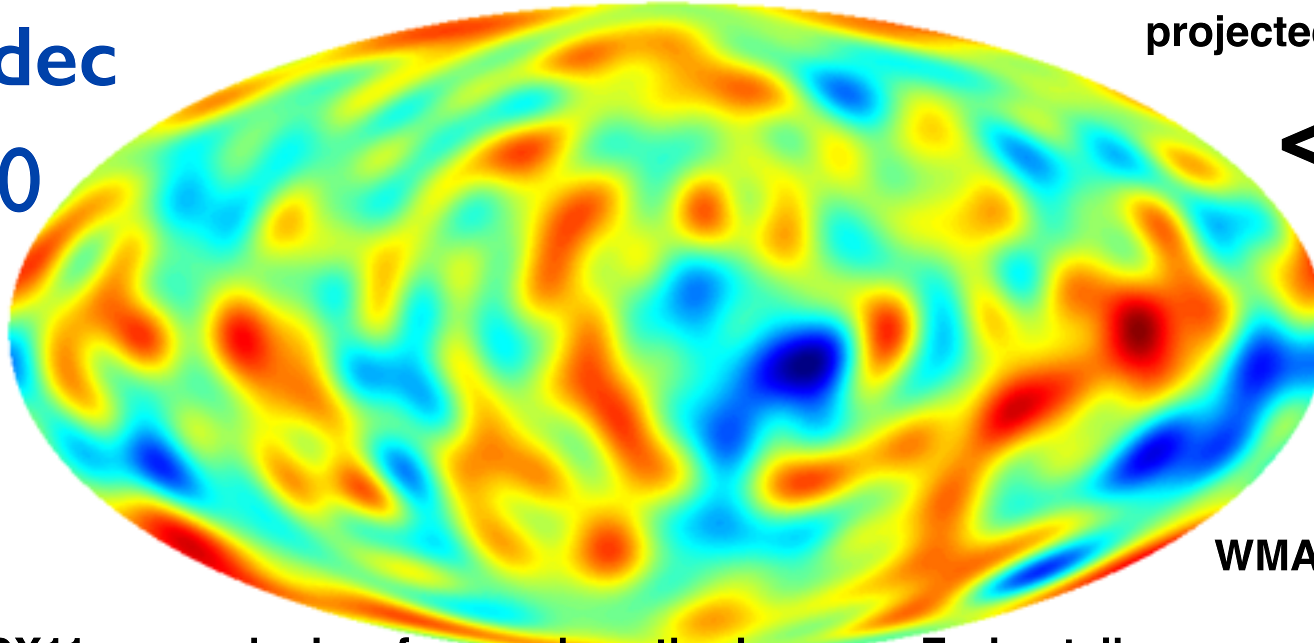
0.5 deg fwhm



Reconstructing the Early Universe **visibility mask**

$\chi_b=\chi_{dec}$

$L_{cut}=20$



projected curvature map

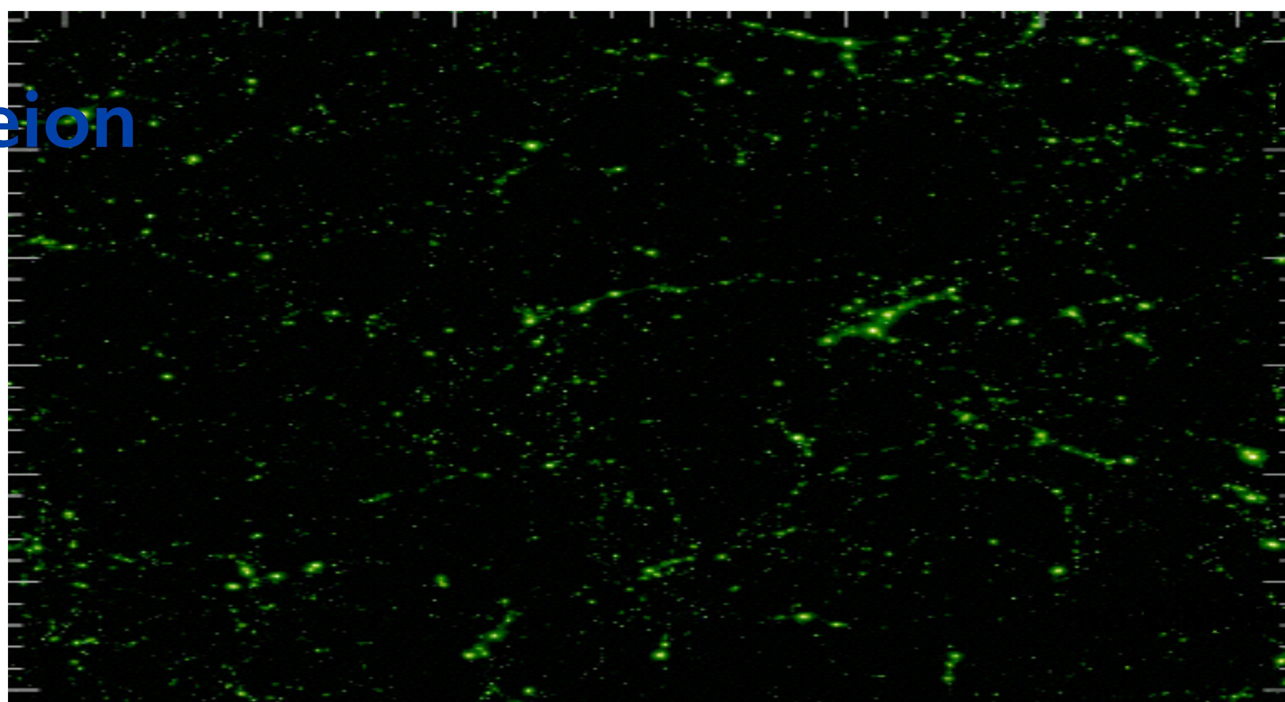
$<\zeta_b|T>$

WMAP T COLD SPOT

SMICA preDX11, unmasked so far, mask methods as per Frolov talk

$\chi_b=\chi_{reion}$

$L_{cut}=20$



$\zeta_b|T>$

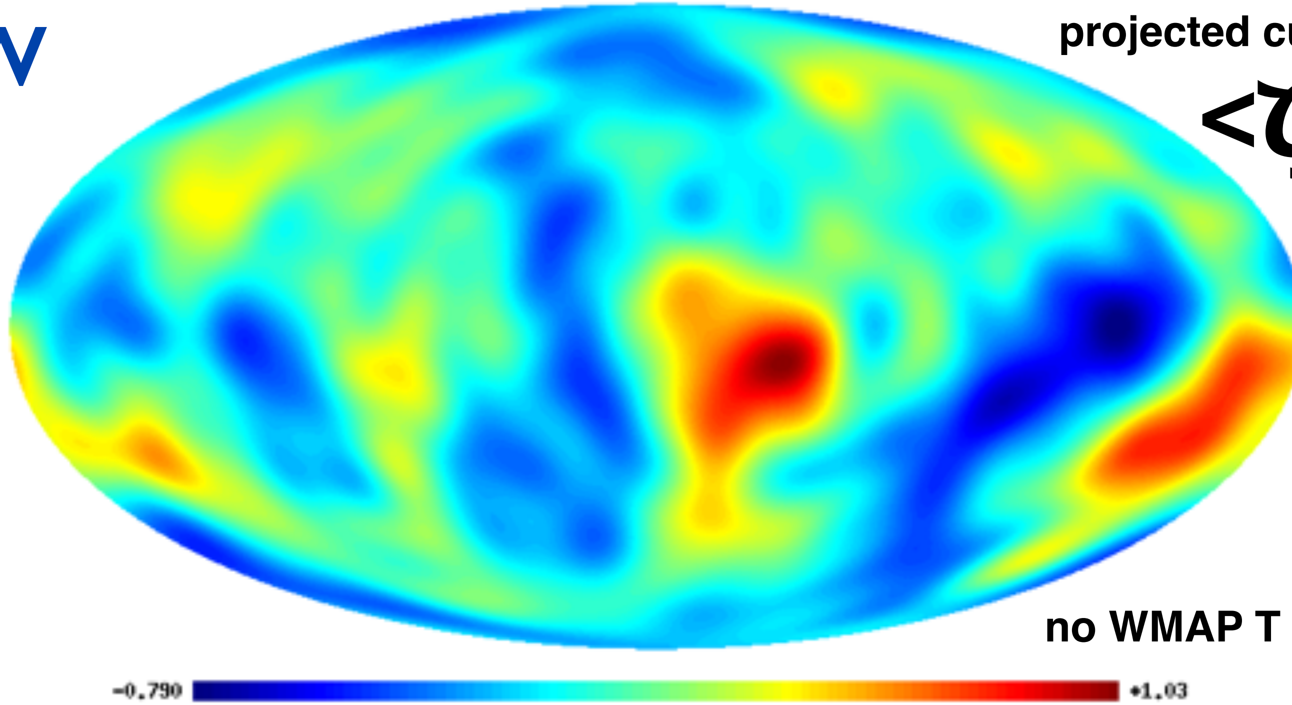
T COLD SPOT

$\chi_b = \chi_{ISW}$

$L_{cut} = 20$

projected curvature map

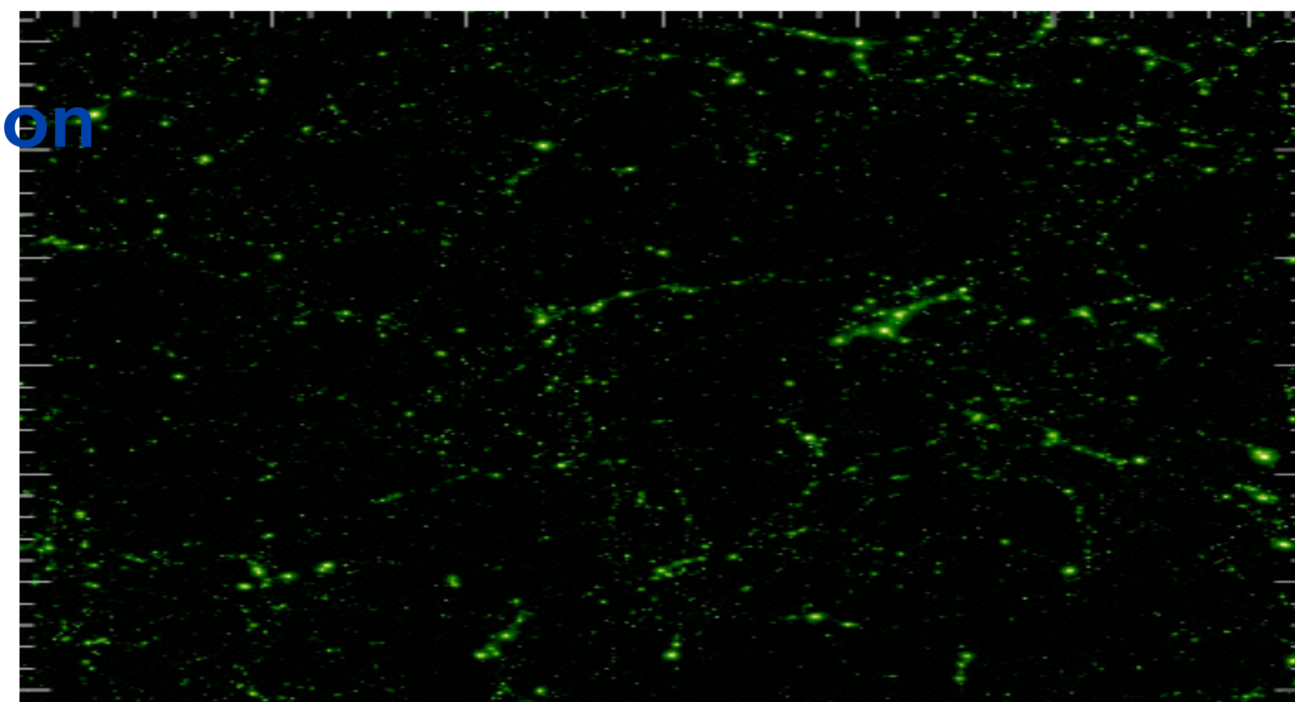
$\langle \zeta_b | T \rangle$



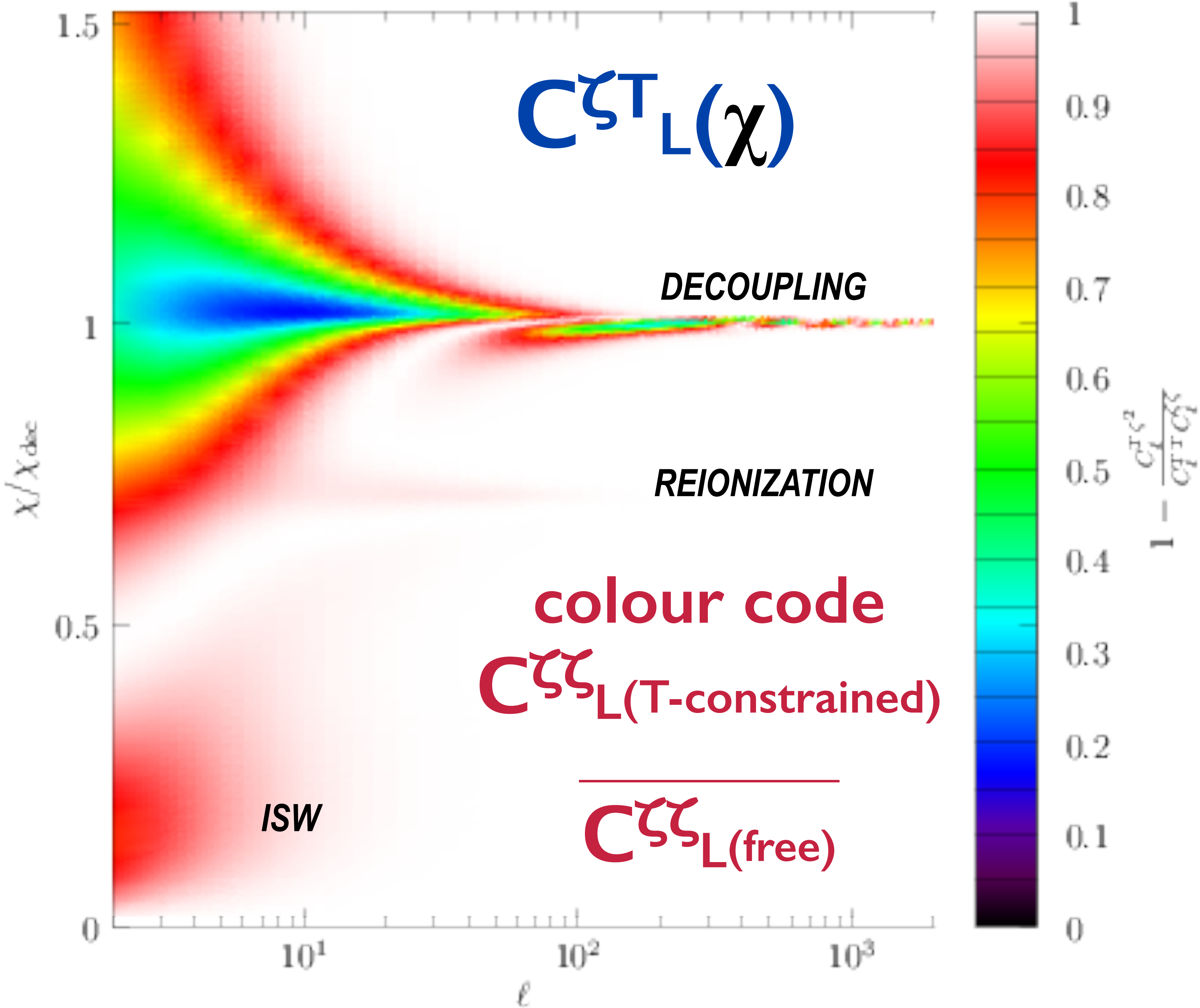
no WMAP T ‘COLD’ SPOT

$\chi_b = \chi_{reion}$

$L_{cut} = 20$



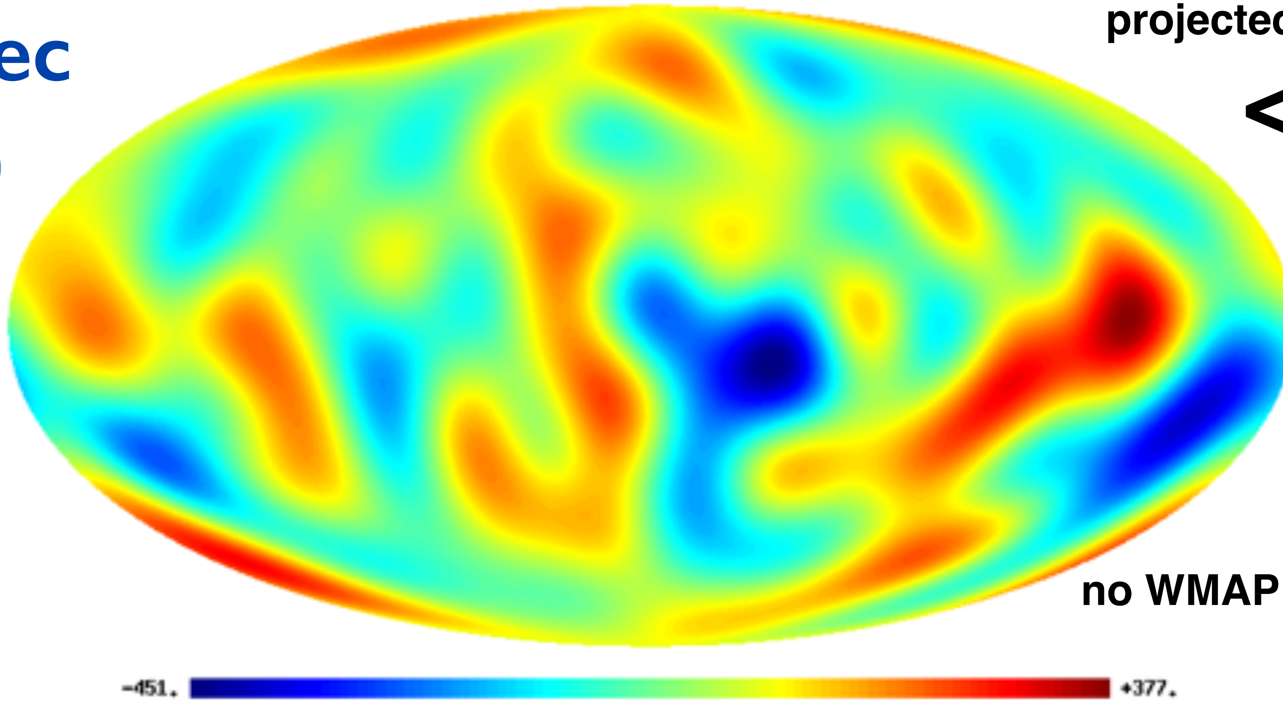
$b | T \rangle$



CζTL(χ)
DECOUPLING
REIONIZATION
ISW
colour code
Cζζ L(T-constrained)
Cζζ L(free)
χ/χdec
ℓ
1.5
1
0.5
0
10^1
10^2
10^3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

$\chi_b=\chi_{dec}$

$L_{cut}=10$



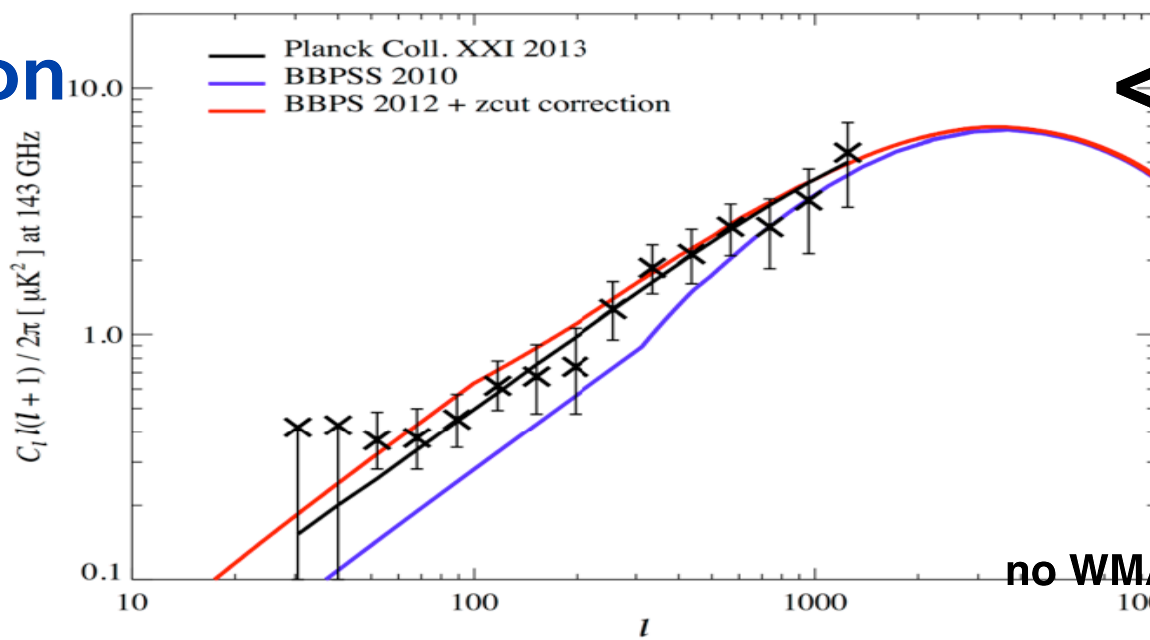
projected curvature map

$<\zeta_b|T>$

no WMAP T COLD SPOT

$\chi_b=\chi_{reion}$

$L_{cut}=10$



$<\zeta_b|T>$

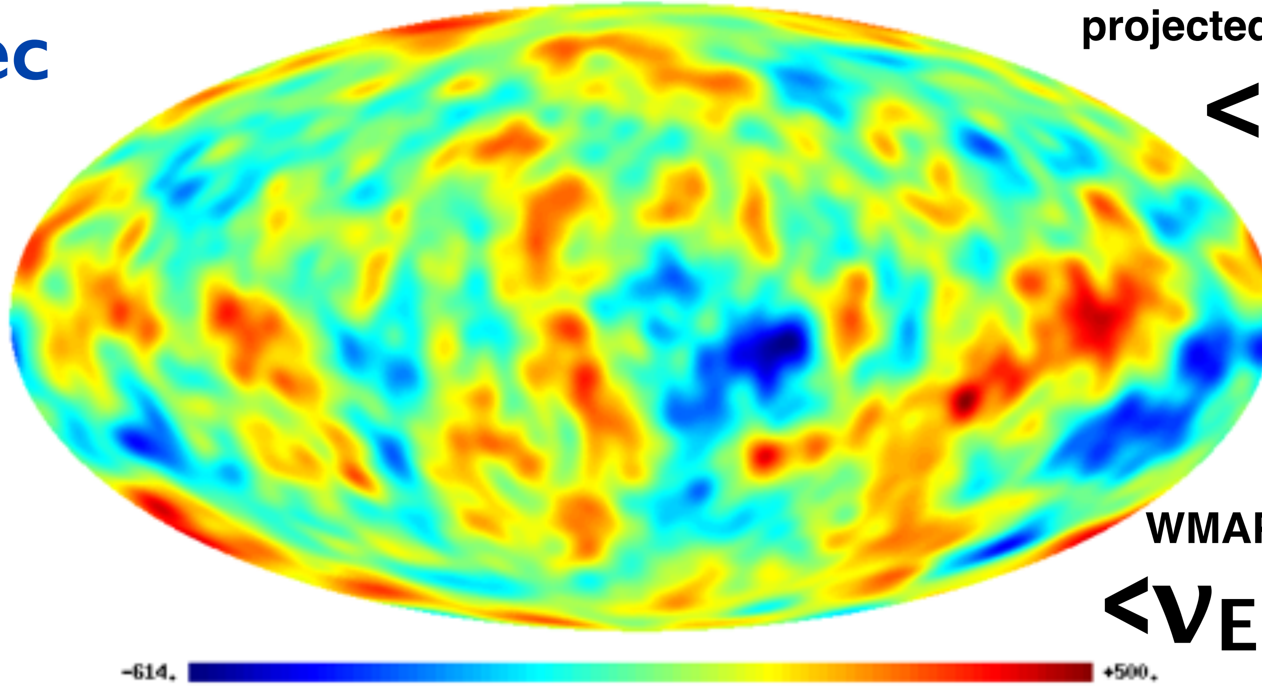
no WMAP T COLD SPOT

$\chi_b = \chi_{dec}$

$L_{cut}=60$

projected curvature map

$<\zeta_b|T>$



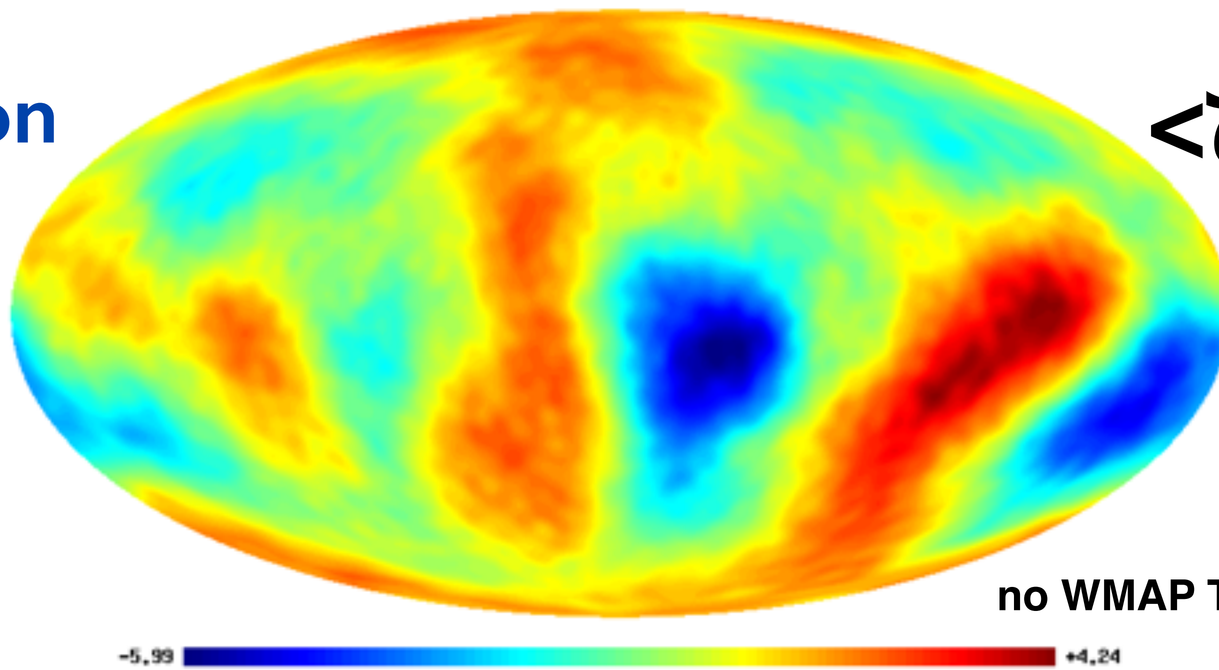
WMAP T COLD SPOT

$<\nu_E|\nu_T>\sim 2$

$\chi_b = \chi_{reion}$

$L_{cut}=60$

$<\zeta_b|T>$

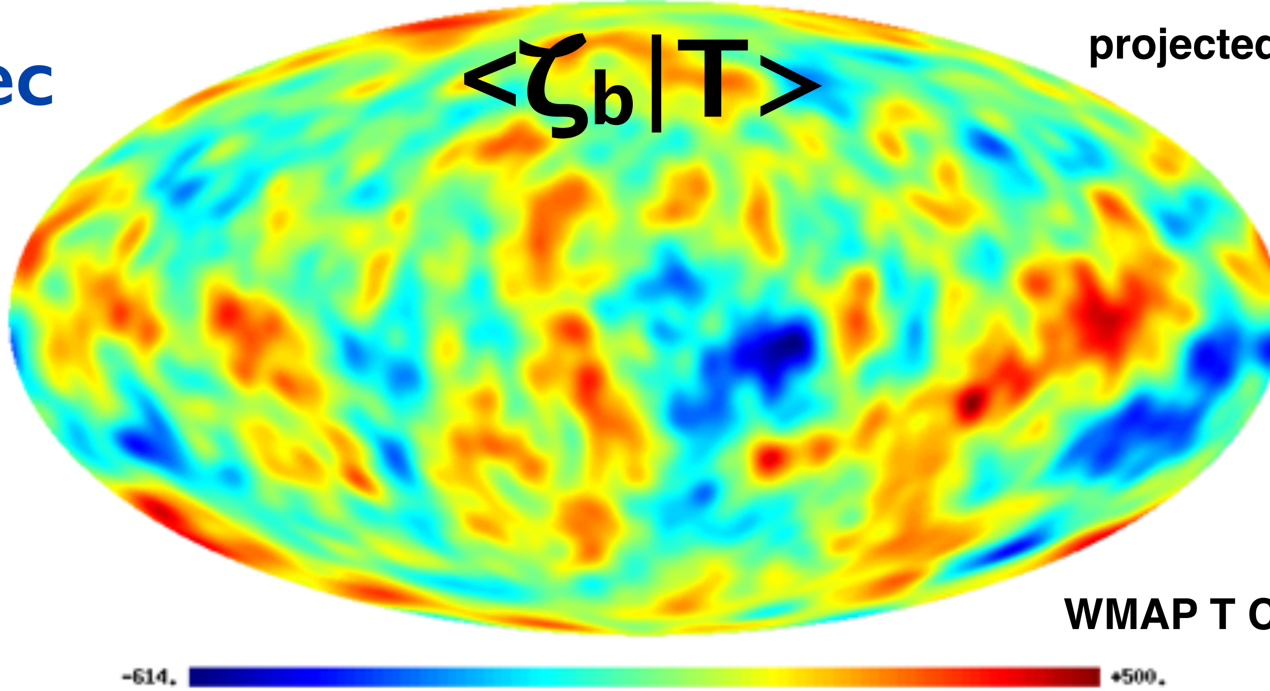


no WMAP T COLD SPOT

$\chi_b = \chi_{dec}$

$L_{cut} = 60$

projected curvature map

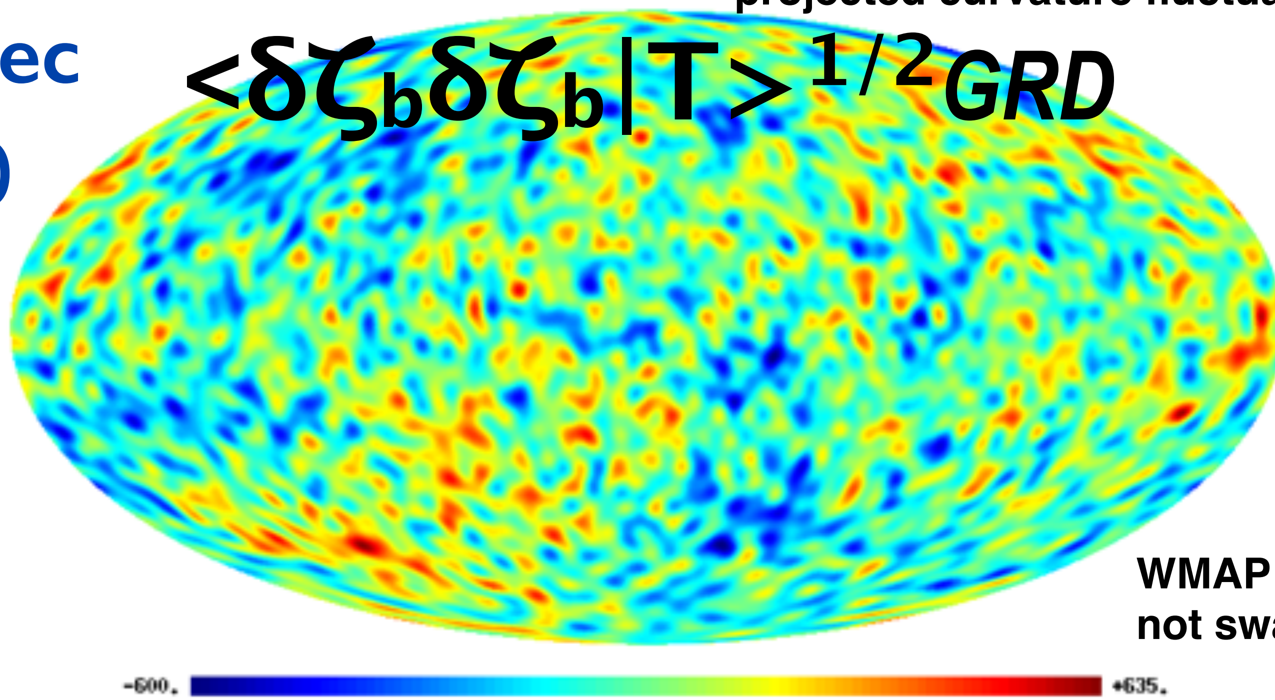


WMAP T COLD SPOT

$\chi_b = \chi_{dec}$

$L_{cut} = 60$

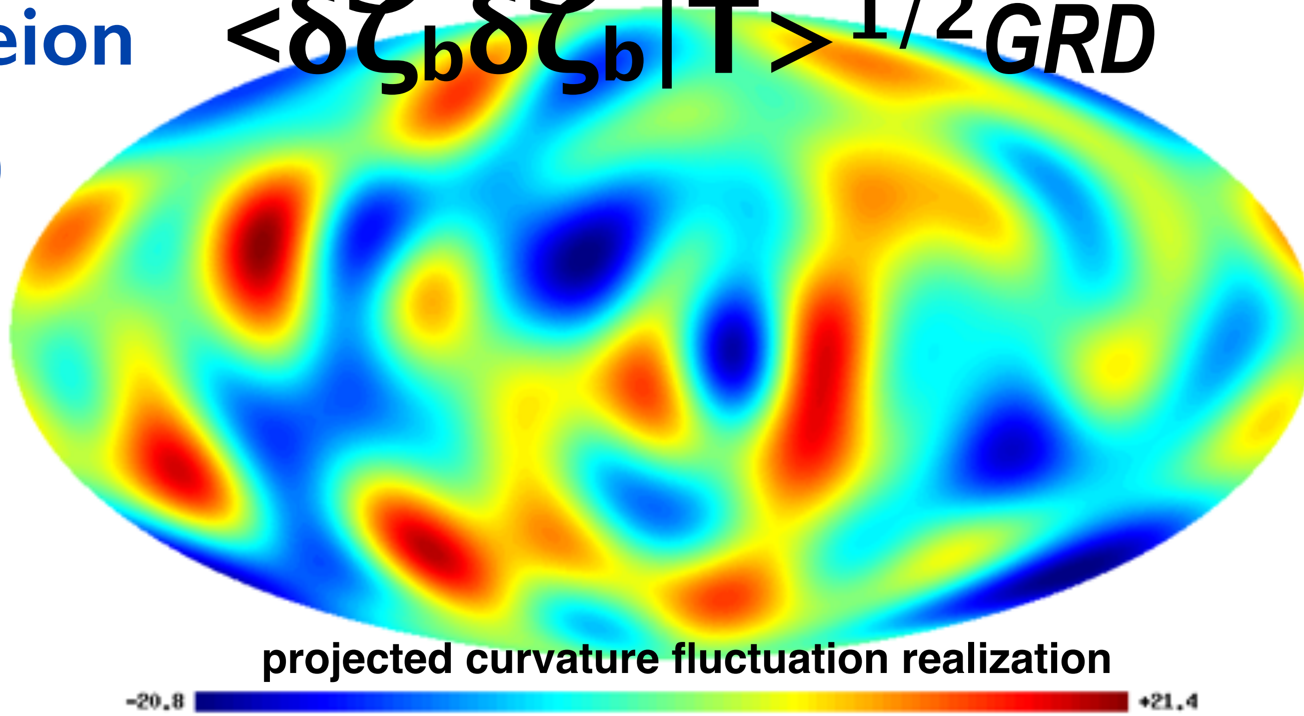
projected curvature fluctuation realization



WMAP T COLD SPOT
not swamped by flucs

$\chi_b = \chi_{reion}$ $\langle \delta\zeta_b \delta\zeta_b | T \rangle^{1/2}$ *GRD*

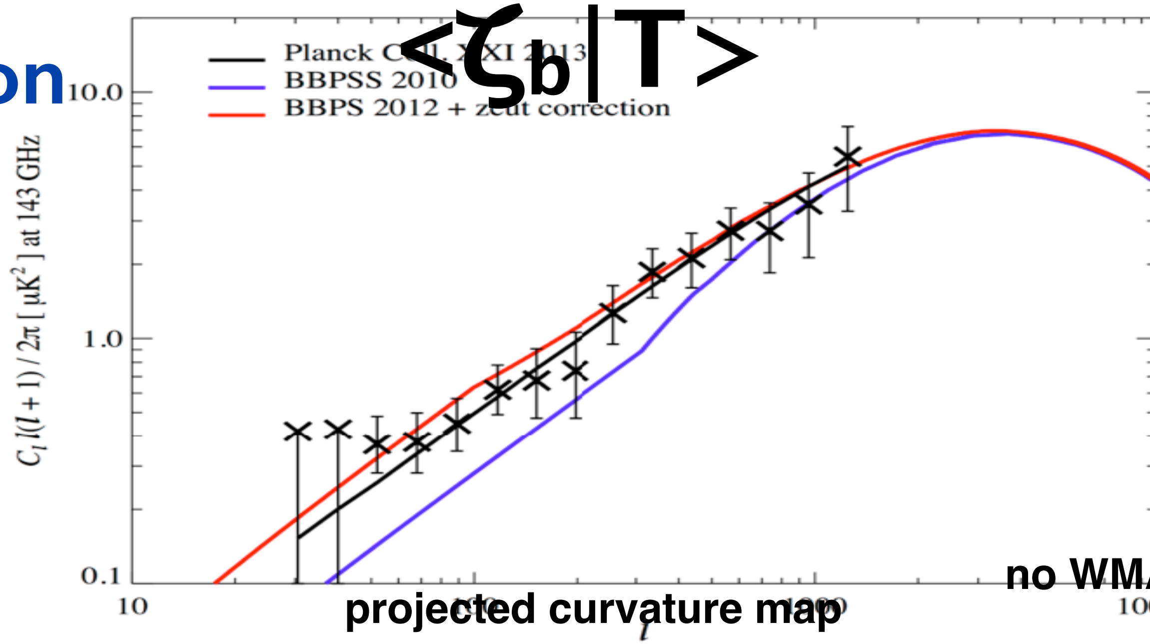
$L_{cut}=10$



$\langle \zeta_b | T \rangle$

$\chi_b = \chi_{reion}$

$L_{cut}=10$



projected curvature map

no WMAP T COLD SPOT

Power Deviation from fiducial $<\zeta|T><\zeta|T> + <\delta\zeta\delta\zeta|T> - <\zeta\zeta|\mathrm{free}>$

byproduct, cf. quadratic $P_{\zeta\zeta}$ *reconstruction, extra* C_s/C_{tot} *& regularizer* $P^{(i)}_{\zeta\zeta}$

Wiener-filtered anisotropic stress *maps, pks & E-pol*

from $< \zeta_{LM\ c,s}(\chi)\ |\ a_{LM\ c,s} >$ **reconstruct**

(1) *actual* Wiener T_{dec} map at decoupling (not T_{now})

(2) *actual* Wiener *anisotropic photon stress-tensor* *(aka quadrupole)* ***at*** χ_{dec} **to *correlate with E-pol*** *(~sources E)*

=> novel Peaks (eigen-$P_T$eaks), statistics, *mean fields*, stacks

"analytic" results exist or derivable, *a la BE87, BM96, BKP97*

complications: other cosmic parameters fixed at maxL value; inhomogeneous generalized noise enters Wiener filters; is error assessment with FFPn adequate?; de-lensing; …

simple proxy for $< (\nabla^{-2} \nabla_i \nabla_j - \delta_{ij}/2)\, T_{dec}\ |\ T_{now} >$ **anisotropic stress**: *if direct transport from* χ_{dec} **then** $(\nabla^{-2} \nabla_i \nabla_j - \delta_{ij}/2)\, T_{now}$

decompose into $Q_T\ U_T\ E_T\ E_T\ P_T\ \psi_T$ akin to $Q\ U\ E\ P\ \psi$, with enhanced peak-stacking correlations, oriented stacks

some work on this, reported by Frolov HFI-CT 13.06

primordial sub-dominant **intermittent nonGaussianity**

Bond, Frolov, Huang, Braden

phonon ~ $\zeta_{NL} = ln(\rho\, a^{3(1+w)})/3(1+w)$ ~ scalar curvature @ uniform density

$\zeta_{NL}(x) = \zeta_G(x) + f_{NL*}\,(\zeta_G^2(x) - \langle\zeta_G^2\rangle)$ **=> $f_{NL*} = 3/5\, f_{NL} - 1$**

$\zeta_{NL}(x) = \zeta_G(x) + F_{NL}(\chi_G)$, inflaton ζ_G & *uncorrelated* isocon χ_G

F_{NL} = *local non-G from modulated preheating caustics*

= a multiple-line spectrum: *spacing = Lyapunov instability coefficient, strength by ?, blending by $\psi_{G,HF}$ marginalization*

a weak quadratic non-G regime => translate f_{NL*} constraint

& a strong non-G regime <= super-bias of the ζ-web

F_{NL} generic if isocon ψ_G is light & inflaton-coupled

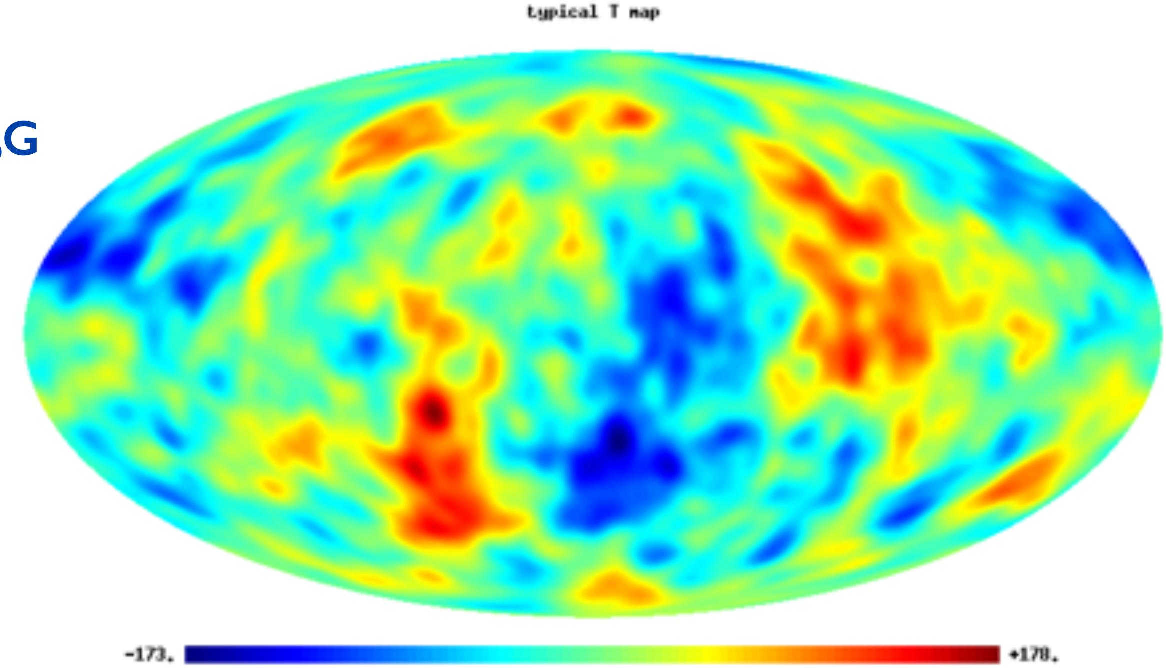
=> search for localized low L extended-sources

=> CONSTRUCTING INTERMITTENT CMB MAPS

"realistic" lattice-computed smoothed F_{NL}

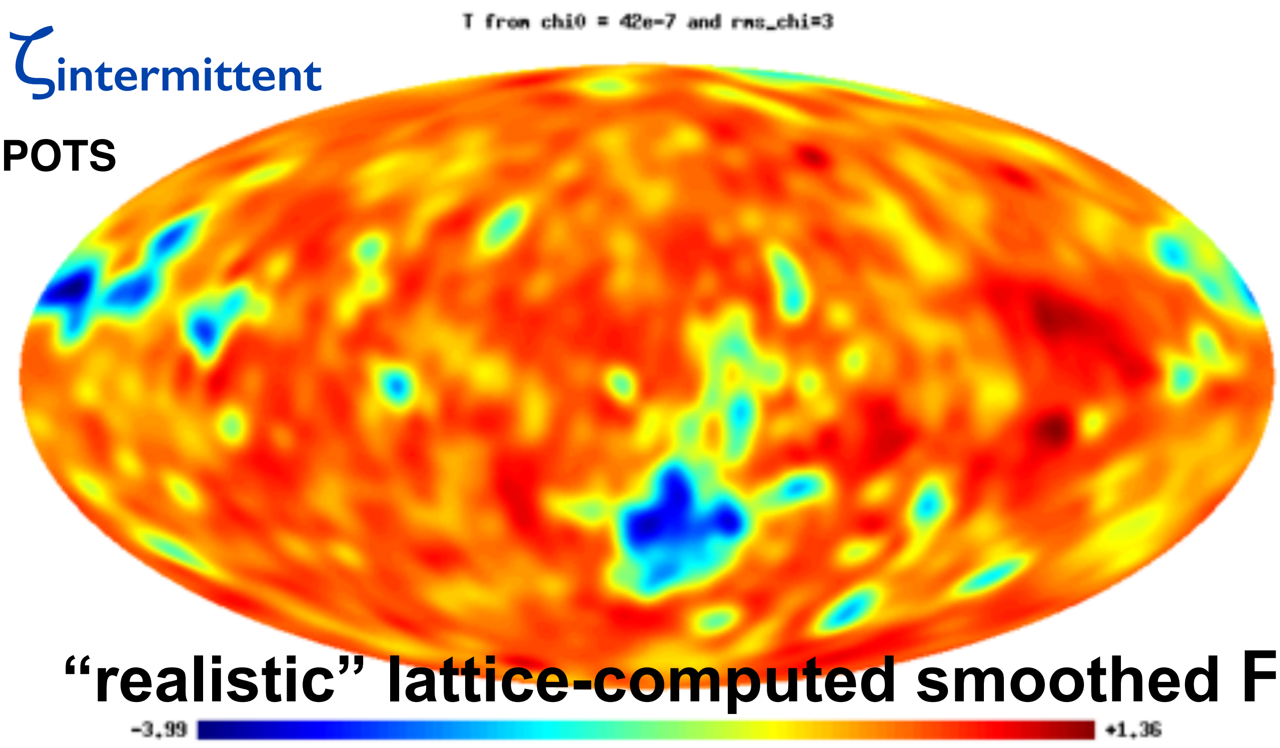
Gaussian lines *(cf. BBKS threshold functions,* **> χ_{crit})**

T from ζ_G



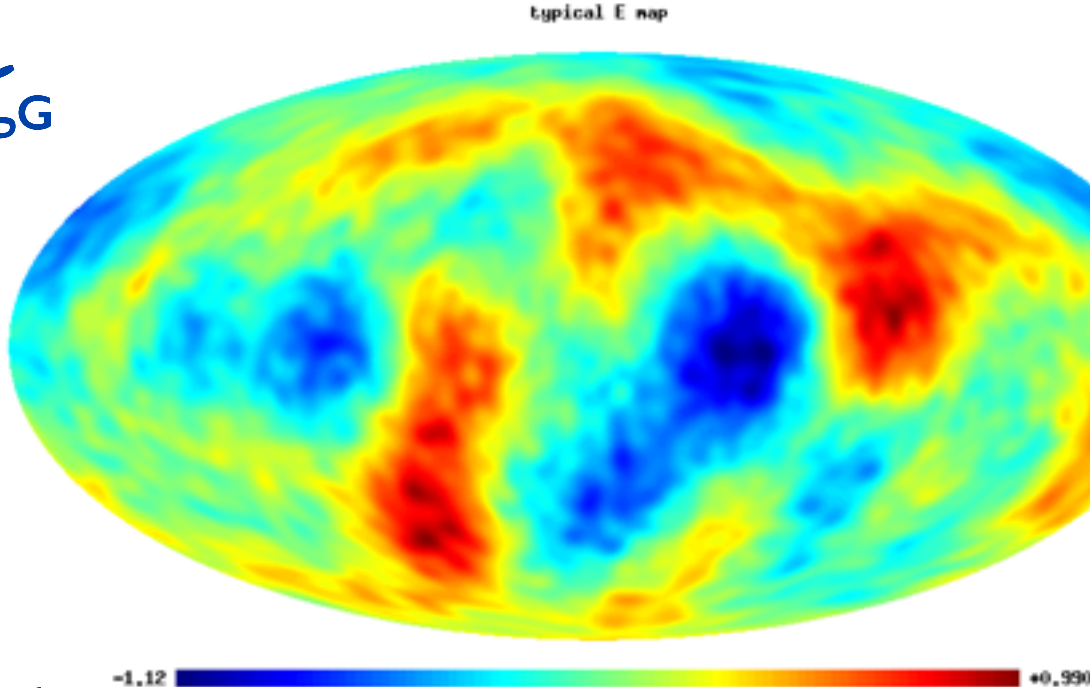
T from $\zeta_{intermittent}$

T COLD SPOTS



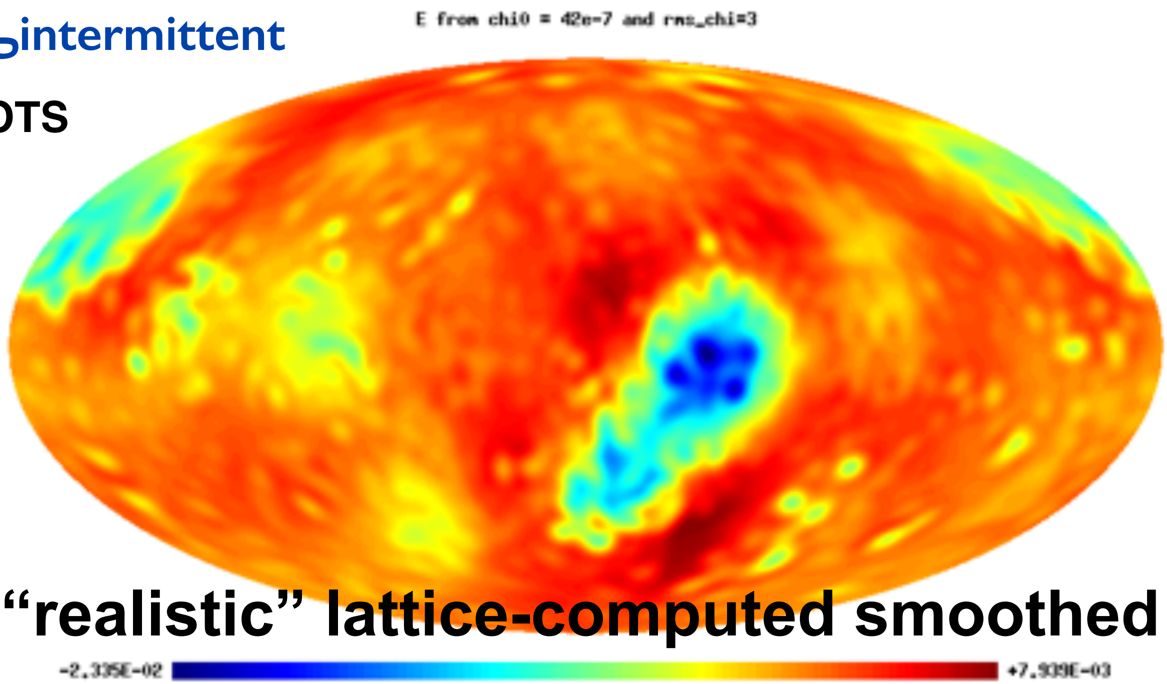
“realistic” lattice-computed smoothed F_{NL}

E from ζ_G



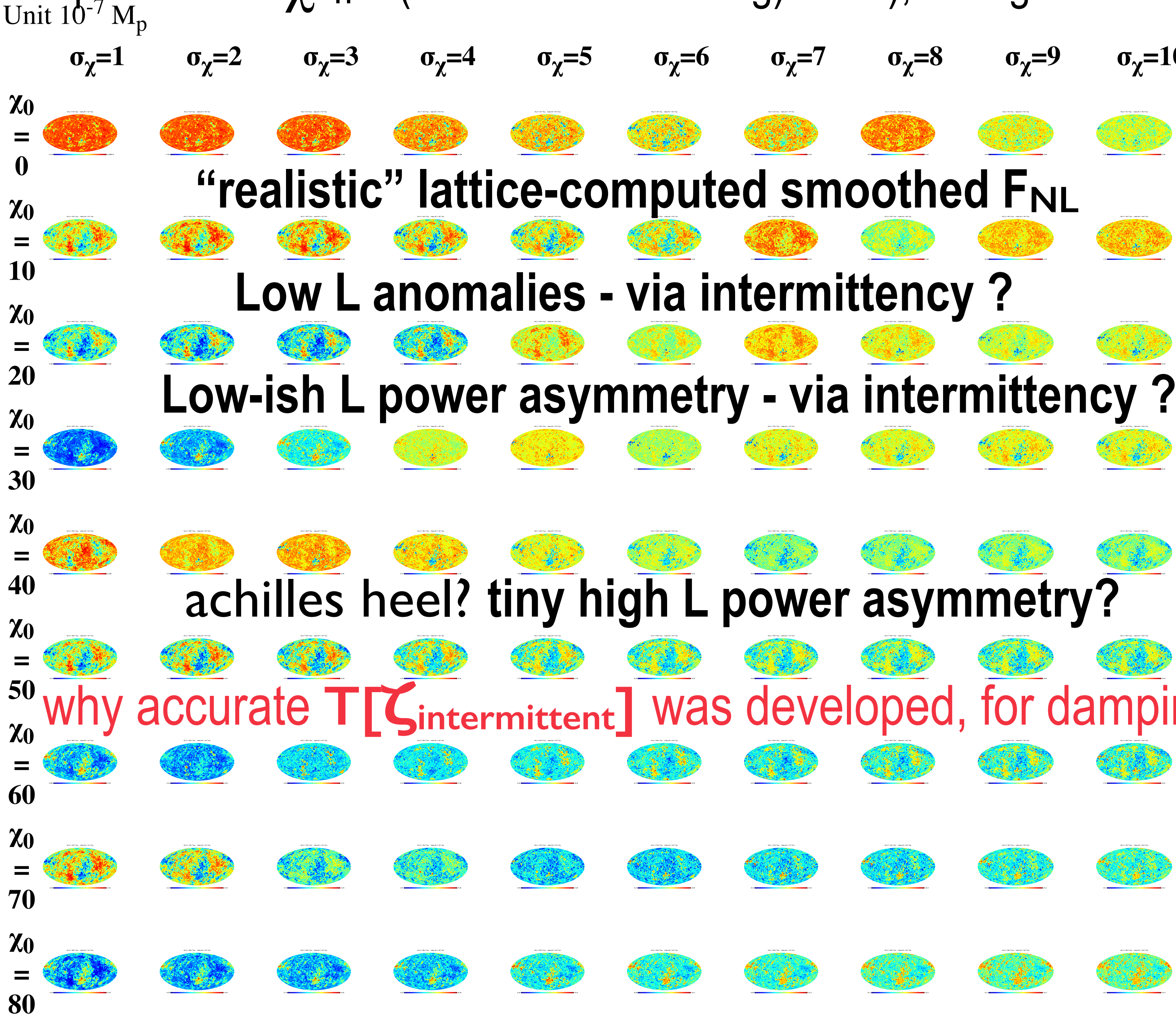
E from $\zeta_{intermittent}$

E COLD SPOTS



“realistic” lattice-computed smoothed F_{NL}

scan super-horizon $\chi_{>h}$ & (LSS/CMB smoothing) width); strength fixed by model



“realistic” lattice-computed smoothed F_{NL}

Low L anomalies - via intermittency ?

Low-ish L power asymmetry - via intermittency ?

achilles heel? **tiny high L power asymmetry?**

why accurate **$T[\zeta_{intermittent}]$** was developed, for damping etc.

END

$a_J^i(r,t)$ **scale-tensor** of the Universe

$$dX^i(r,t) = a_J^i(r,t)\,dr_{eq}^J$$

$$a_J^j \equiv exp(\alpha)_J^j$$

$$\alpha_J^j \equiv \langle ln\ a \rangle \delta_J^j + \varepsilon_J^j$$

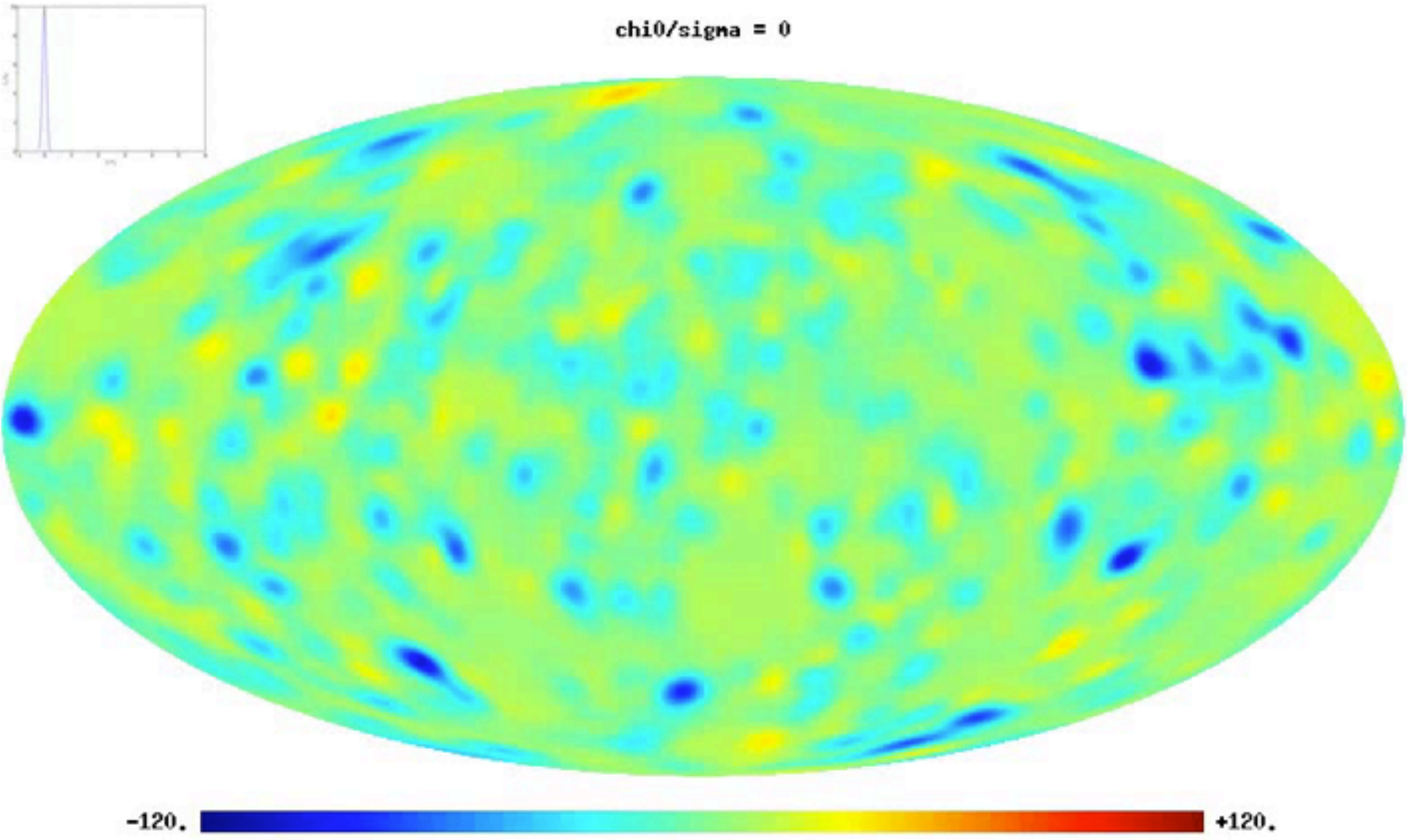
ε=strain tensor

$$dV^i(r,t) = H_J^i(r,t)\,dX^i(r,t)$$

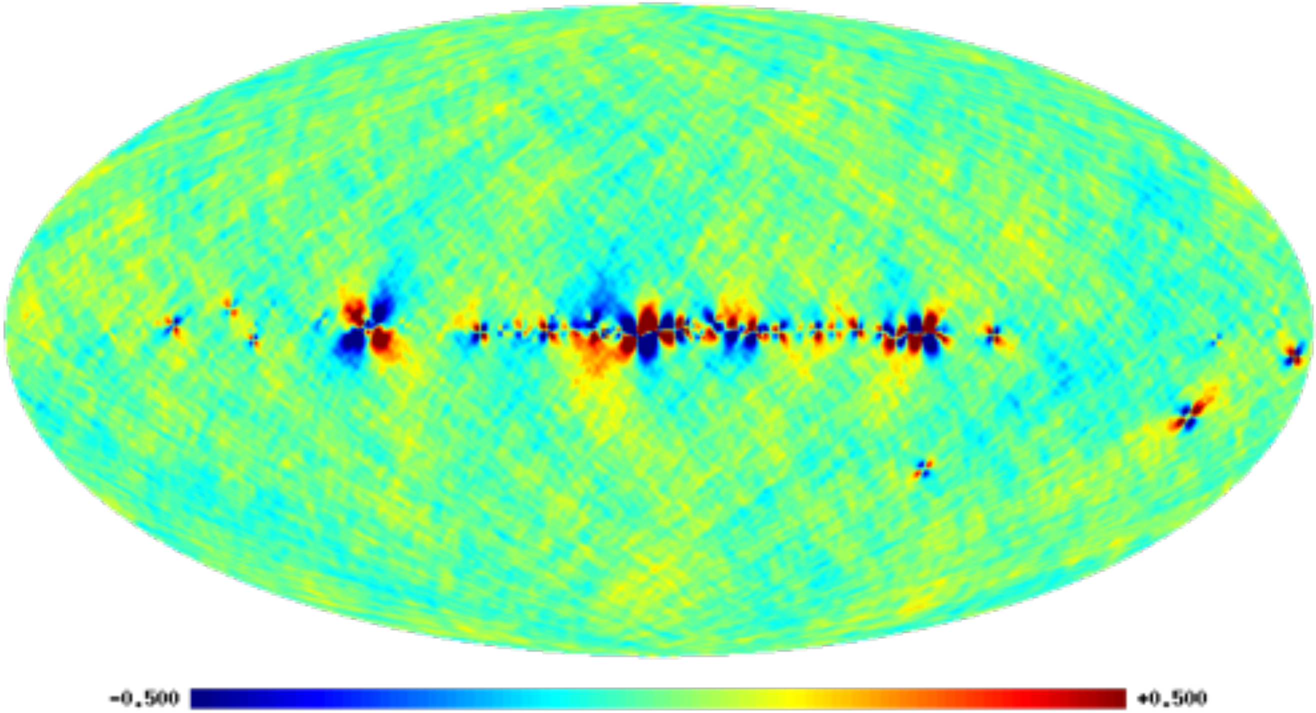
H_J^i=*Hubble aka* ***shear*** =$d\alpha_J^j/dt$

general relativity

phenomenological **Gaussian line:** scan super-horizon $\chi_{>h}$, width, strength

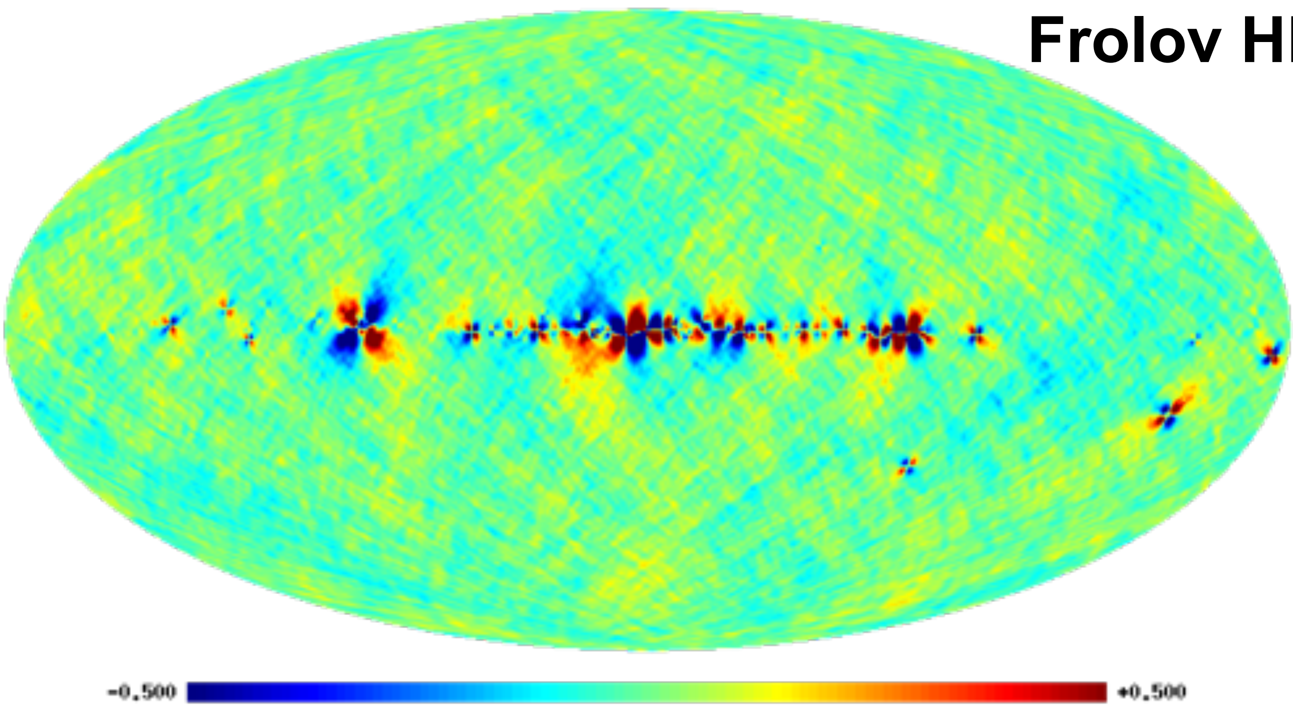


Q_T

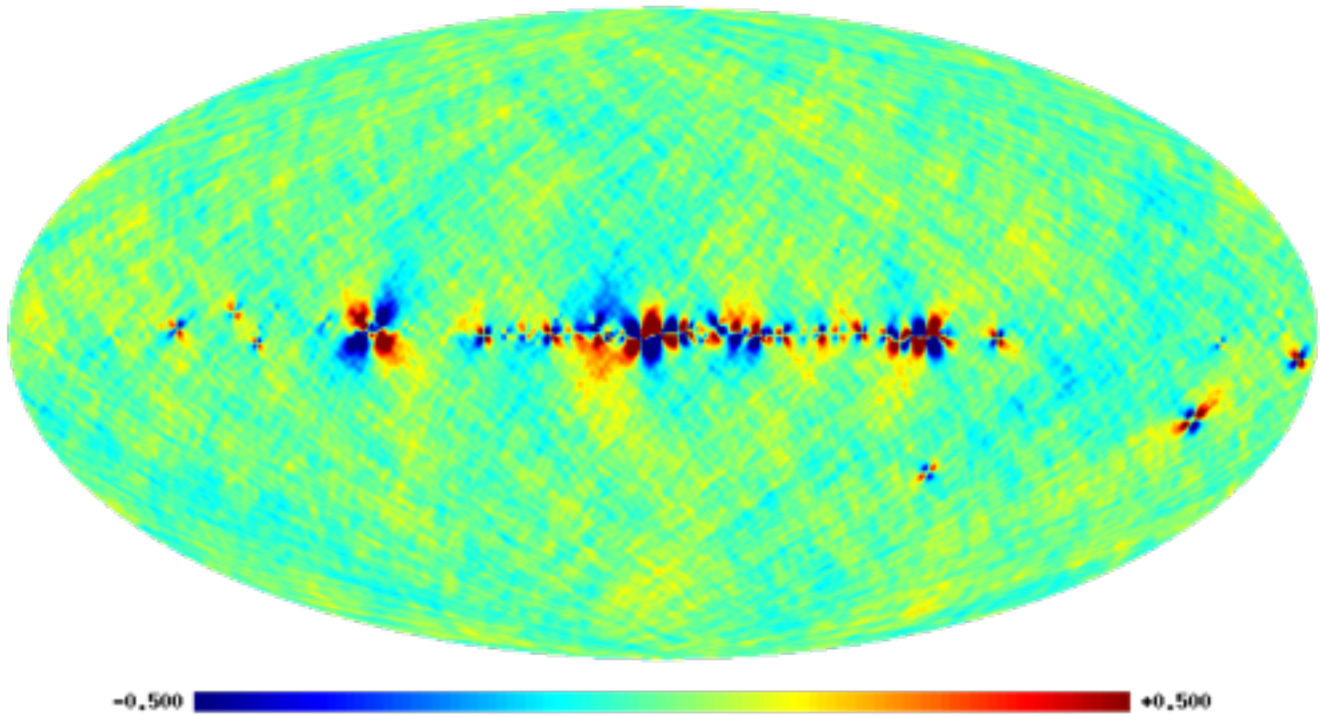


Frolov HFI-CT 13.06

U_T

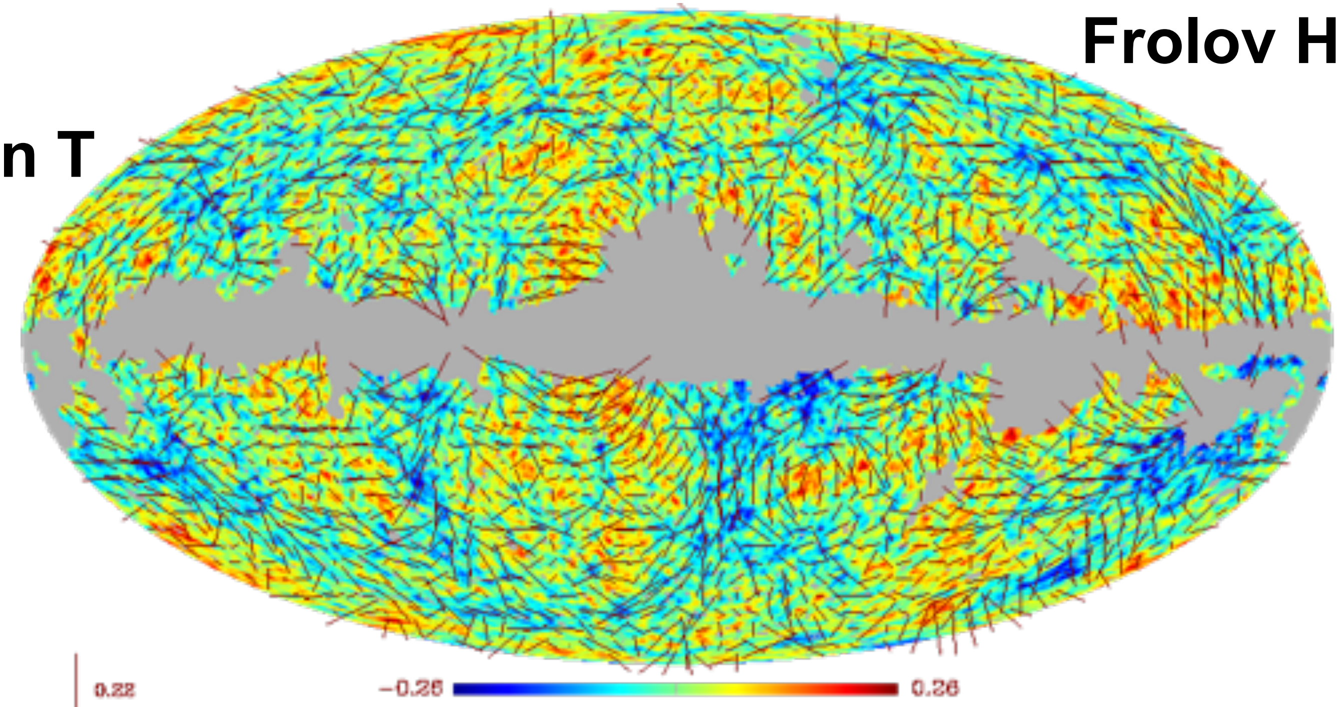


Q_T

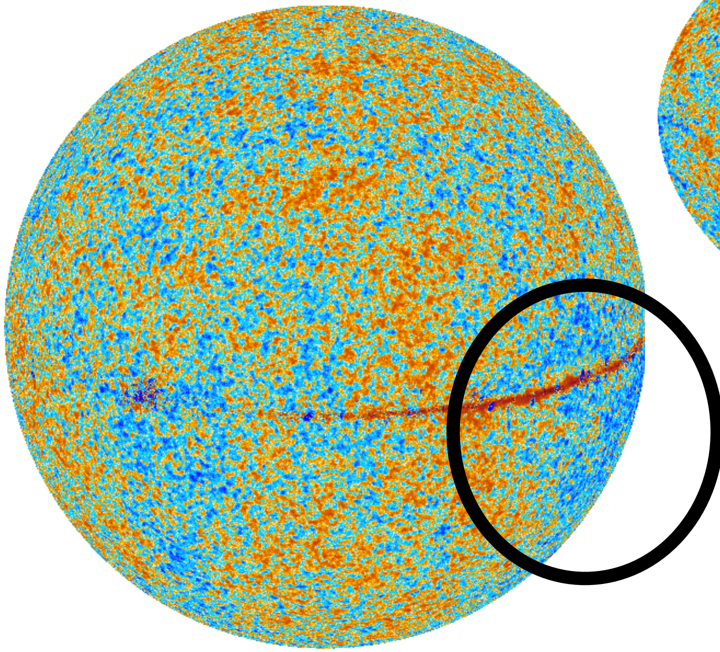


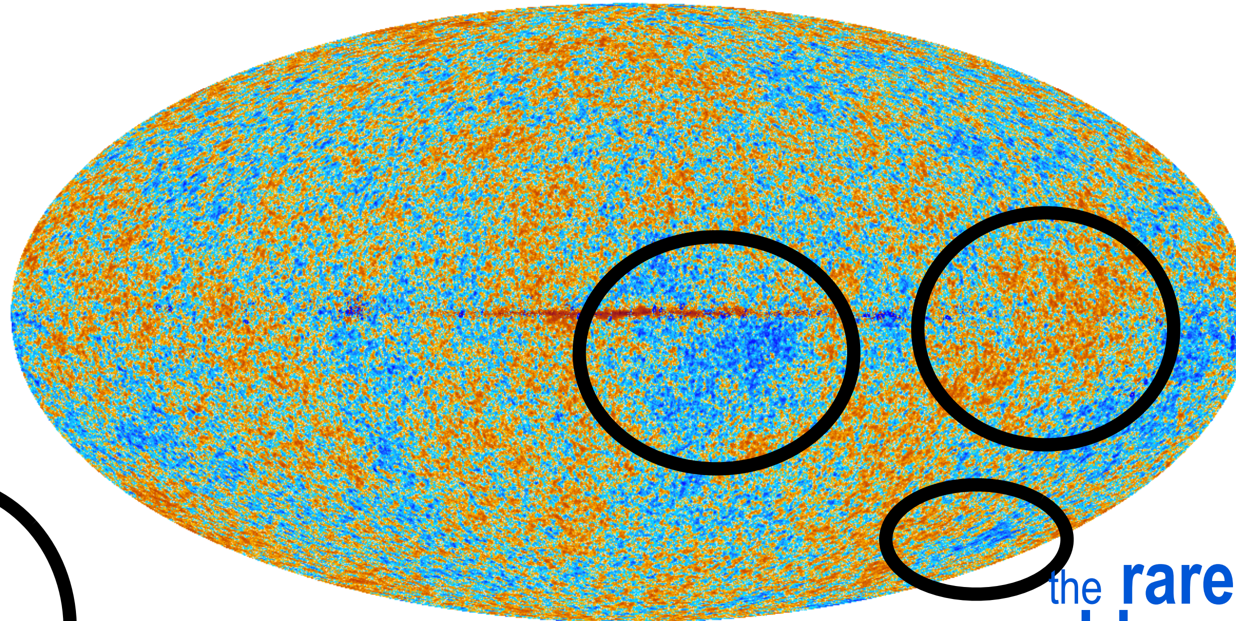
Frolov HFI-CT 13.06

P_T ψ_T on T

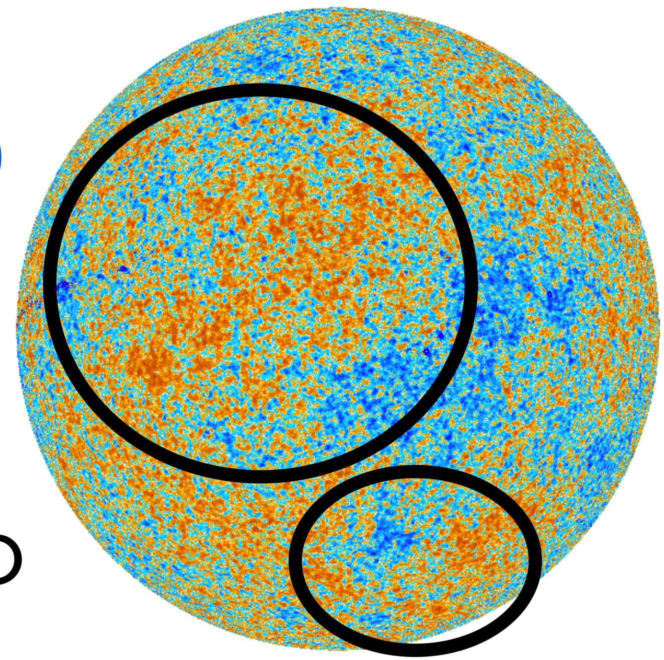


COMPLEXITY *at* **$a \sim e^{-67}$?**





the **rare cold spot**



WHITEN => MASK => FILTER BANK *(SSG42 filter)*
=> EXTRACT PEAKS ***(hierarchical peak patches)***

filter **= extra dimension: scale space analysis ADS of our CFT**

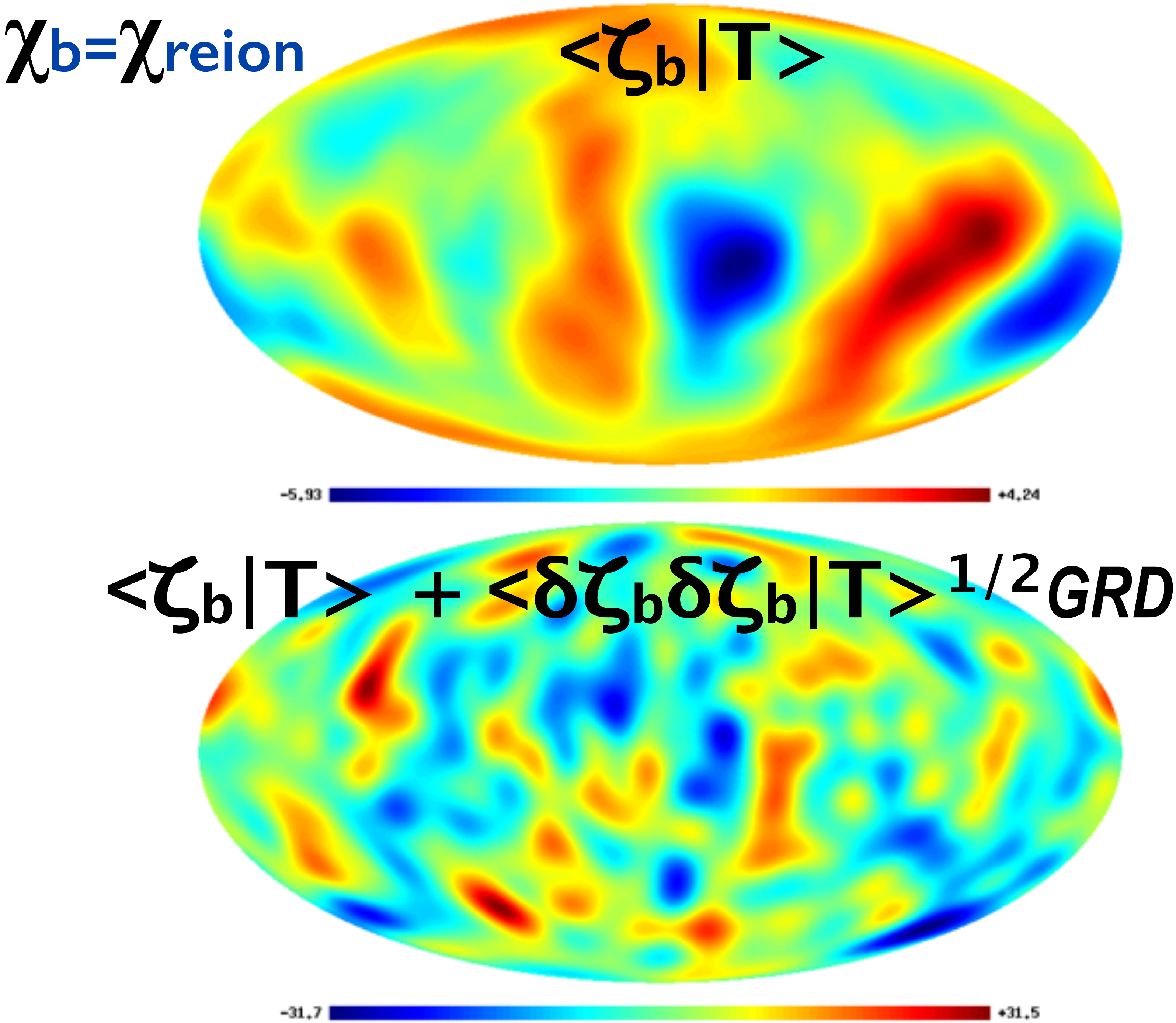
hot & cold peaks ***agree with BE87*** ***Gaussian stats $n_{pk}(<\nu)$***

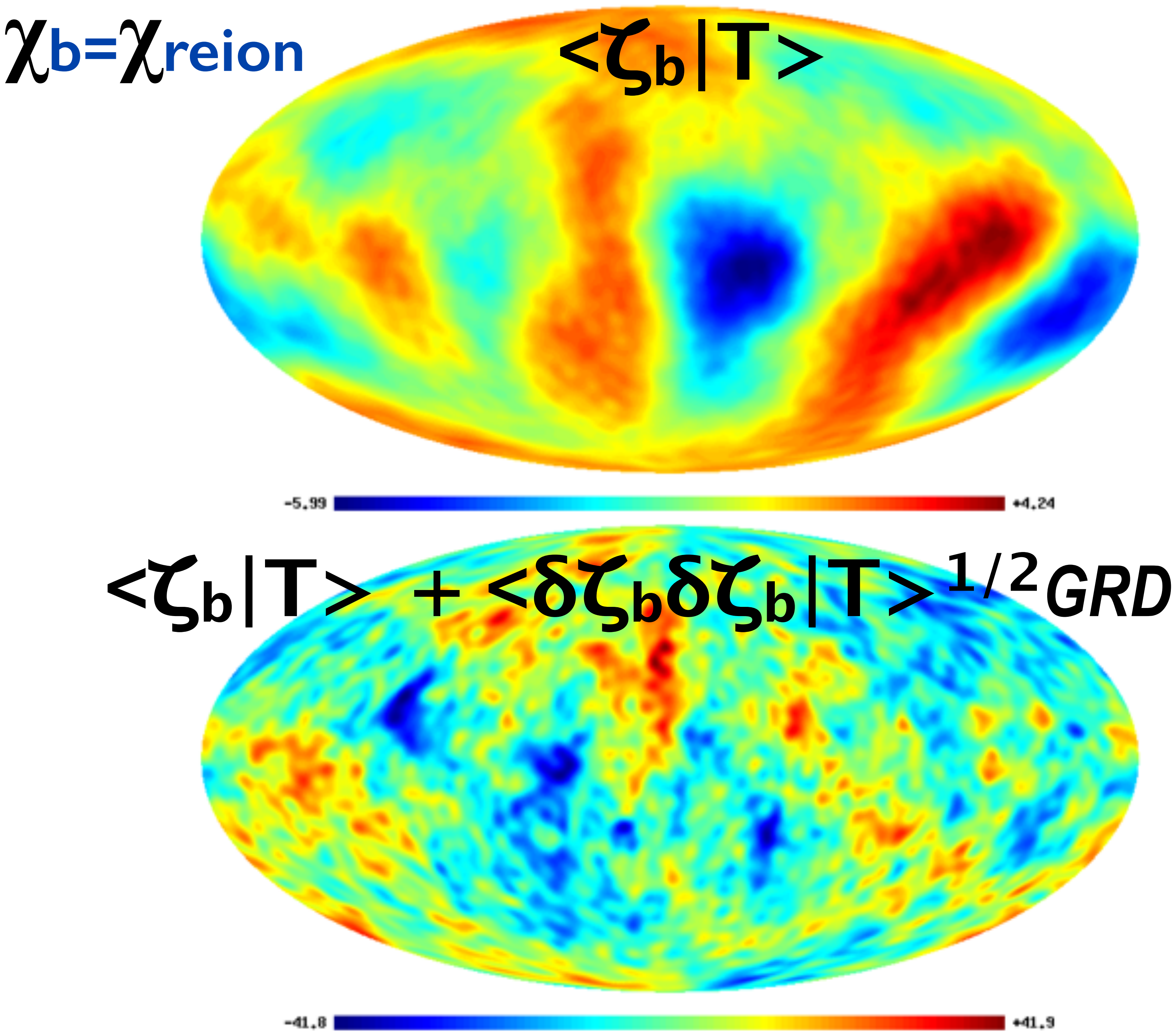
PLANCK2013: 826', 105 peaks, coldest -4.97σ 1:497

WMAP7: 800', coldest -4.87σ significance 1:300

Grand Unified Theory of Anomalies TBD

Anomalies in Polarization? TBD


χb=χreion
<ζb|T>
-5.93
+4.24
<ζb|T> + <δζbδζb|T>1/2GRD
-31.7
+31.5


χb=χreion
<ζb|T>
-5.99
+4.24
<ζb|T> + <δζbδζb|T>1/2GRD
-41.8
+41.9

cluster ELLIPTICITY TENSORS for gas and DM

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

$U_{dm,ij}$ for DM

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

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

rotate to principal axes, scale & stack

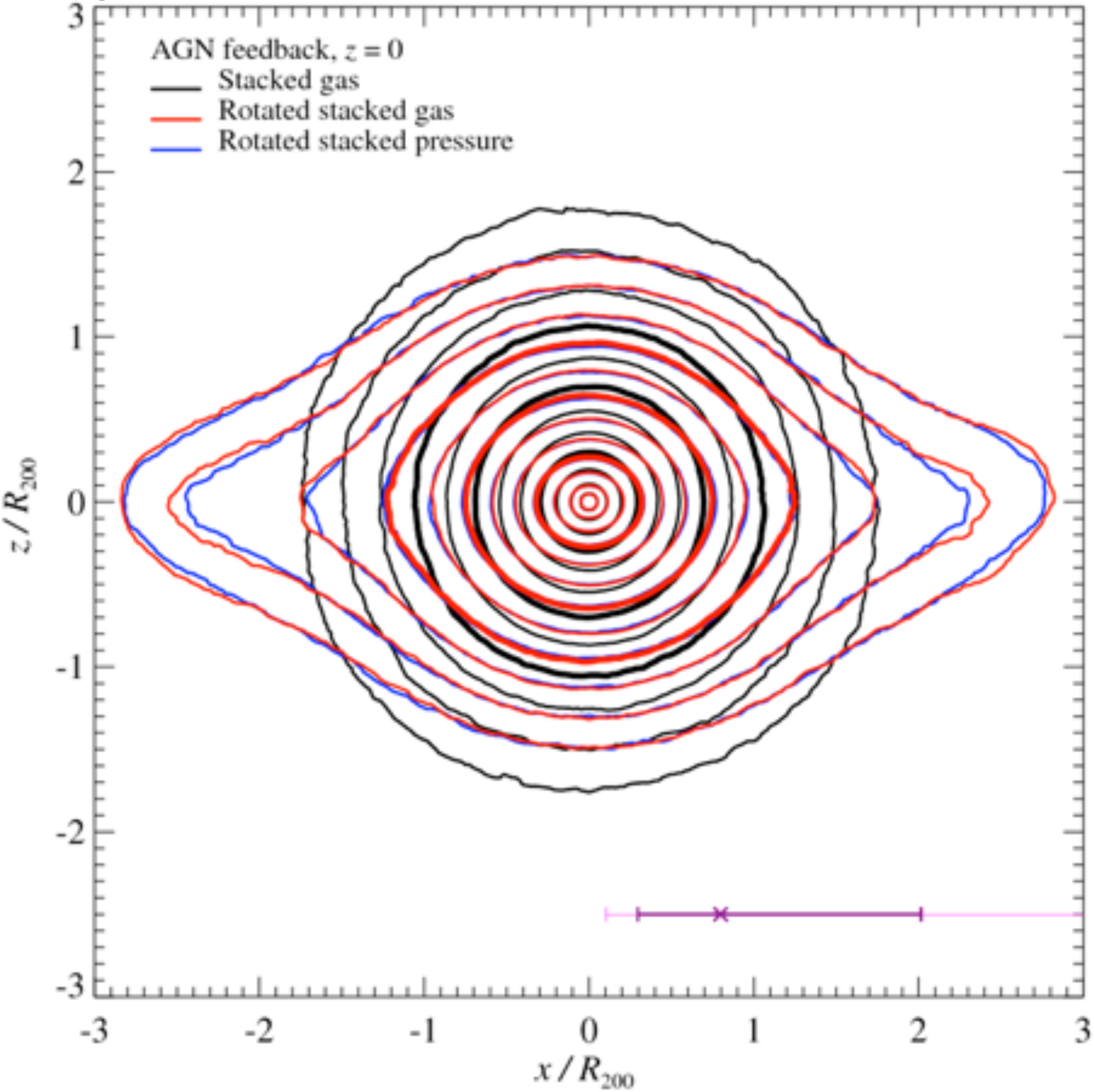
eigenvalues $u_1 > u_2 > u_3 \Rightarrow$

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

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

Halo X-corr Ellipticity ρ_g p_g z=0

$< [\rho_g(X_c+Ux/x_\Delta)/p_{\Delta c}]\ n_{\mathcal{C}}(X_c) >/<n_{\mathcal{C}}(X_c)> = FormFactor(x/x_\Delta)$



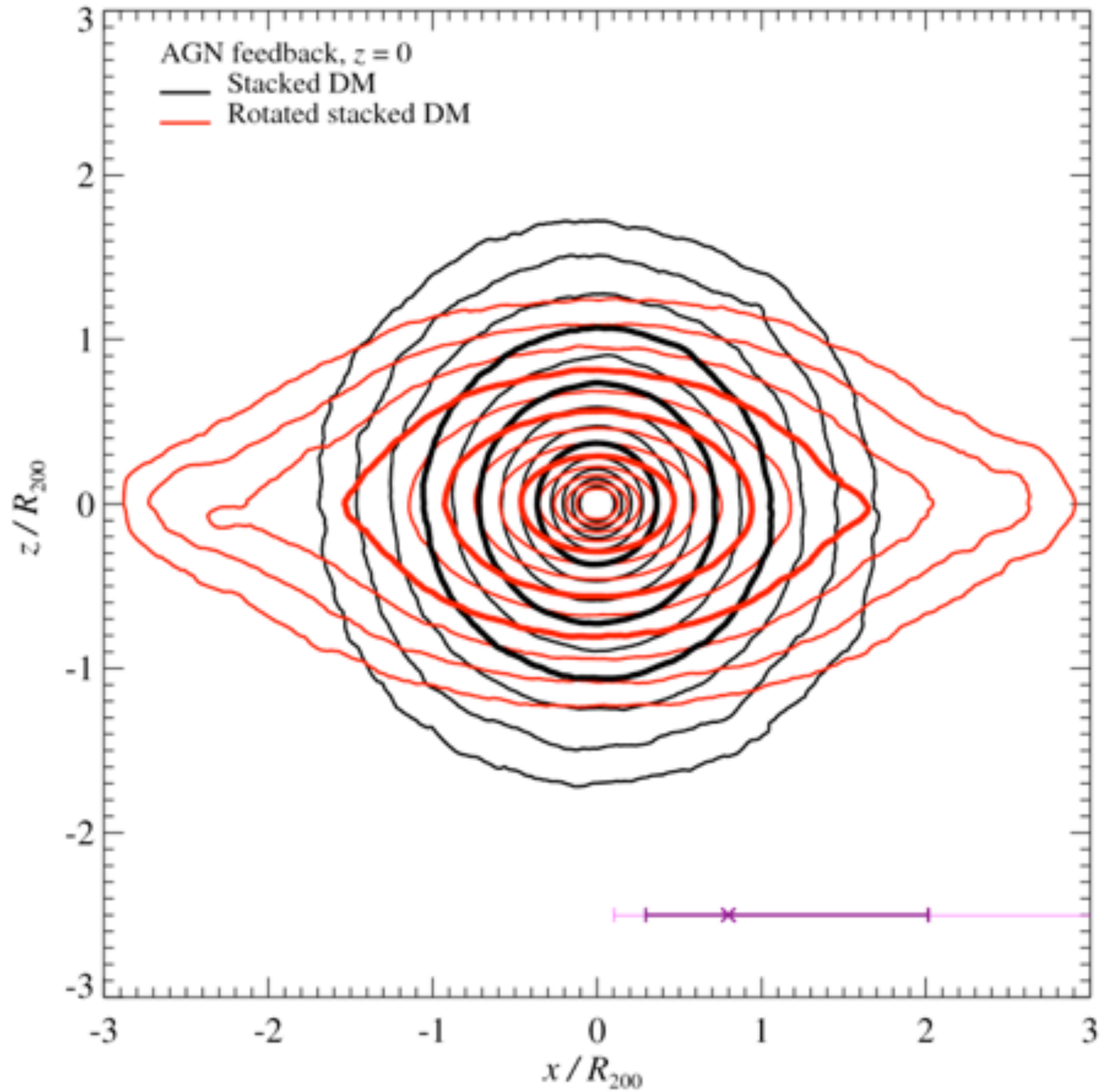
gas in cluster-Y_{SZ} "far-field" is increasingly elongated: a little near-field filament penetration

e(gas) < e(DM) /2

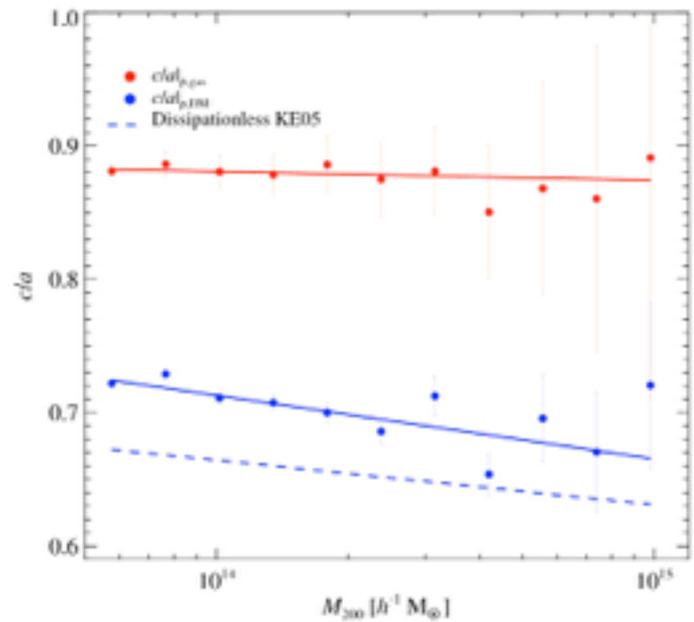
.

Halo X-corr Ellipticity ρ_{dm} z=0

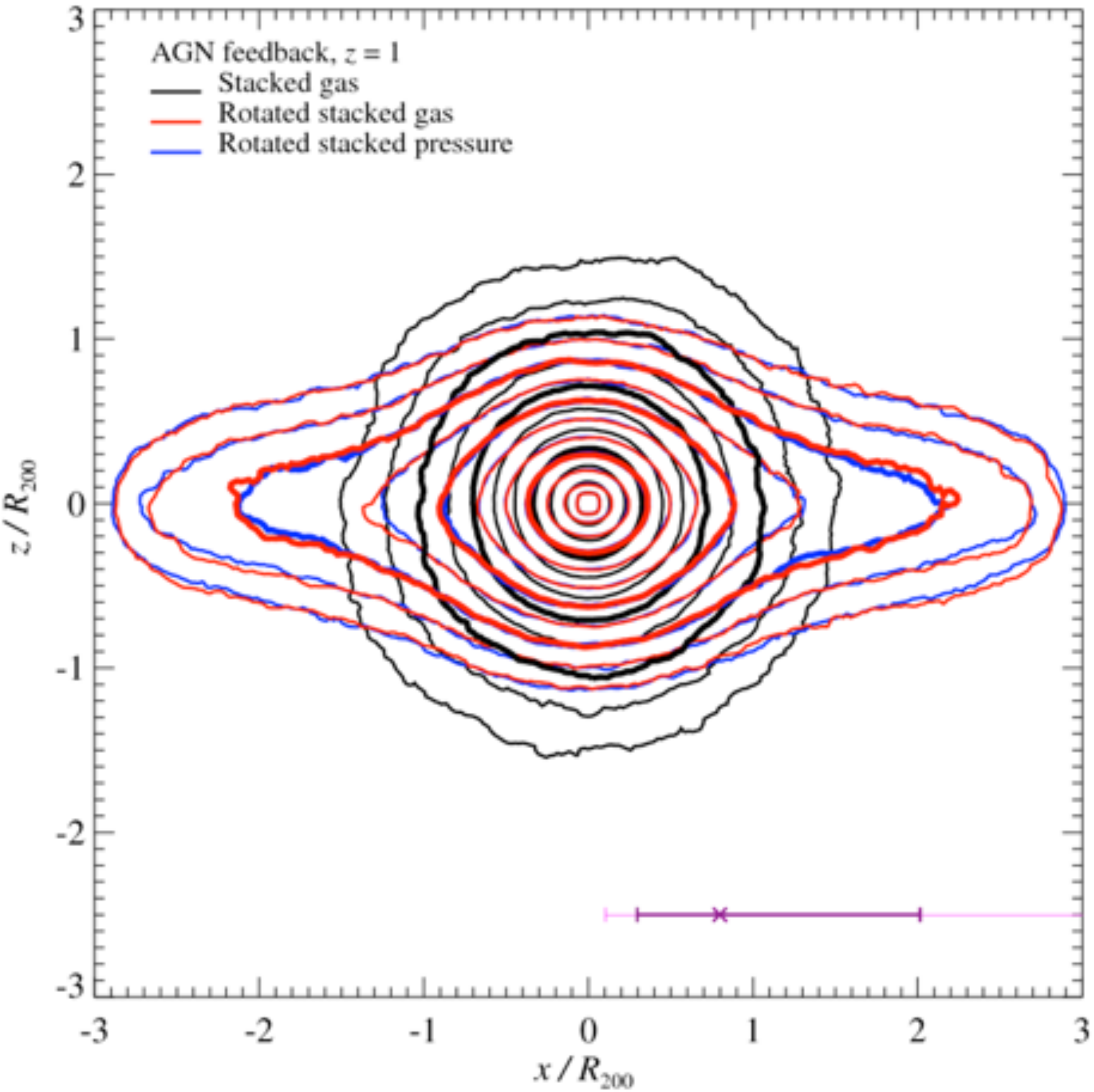
DM in cluster-Y_{SZ} "far-field" is more elongated: a little near-field filament penetration



e(gas) < e(DM) /2



Halo X-corr Ellipticity ρ_g p_g z=1



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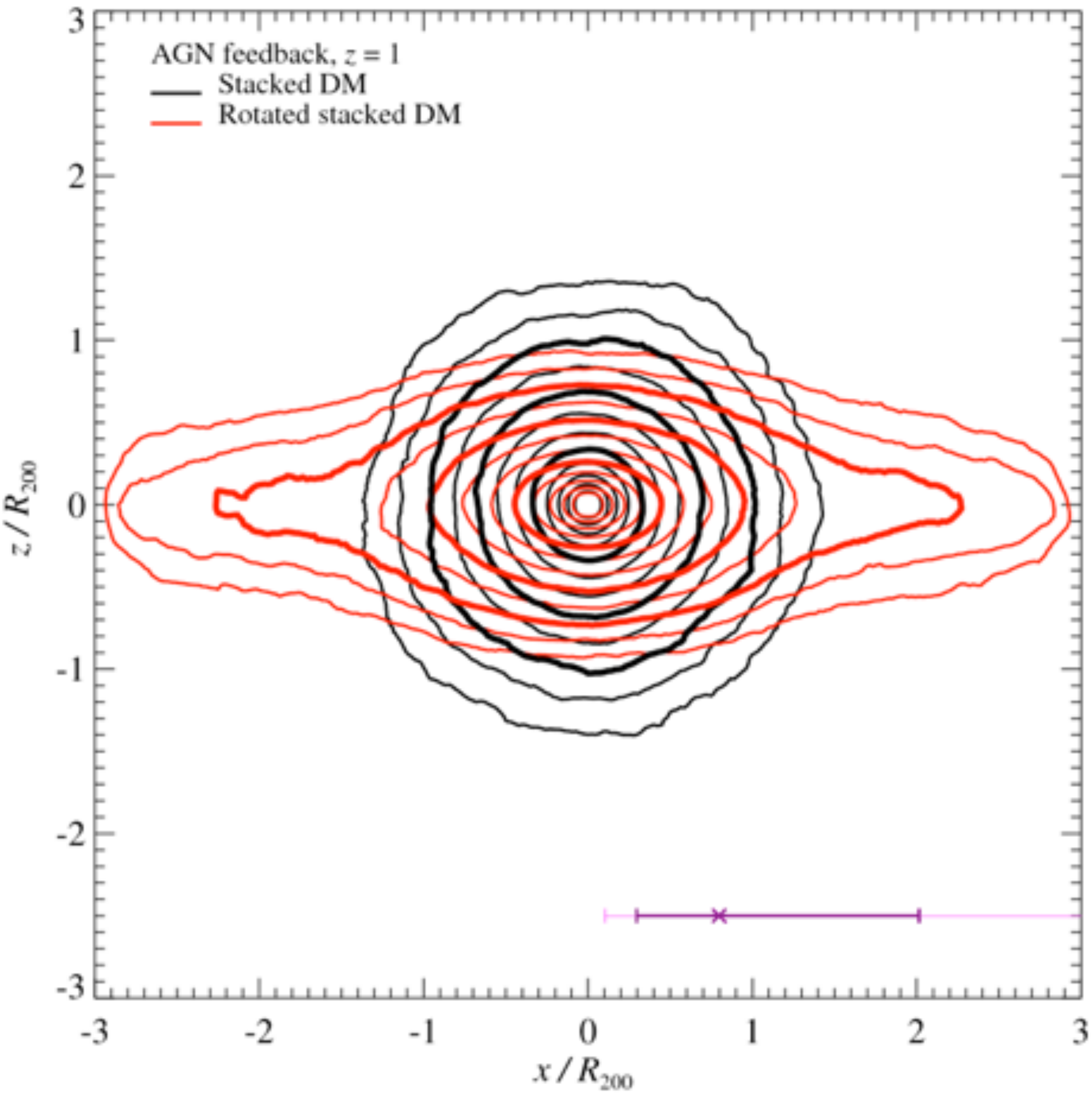
e(gas) < e(DM) /2

z=1 extreme cf. z=0

Halo X-corr Ellipticity ρ_{dm} z=1



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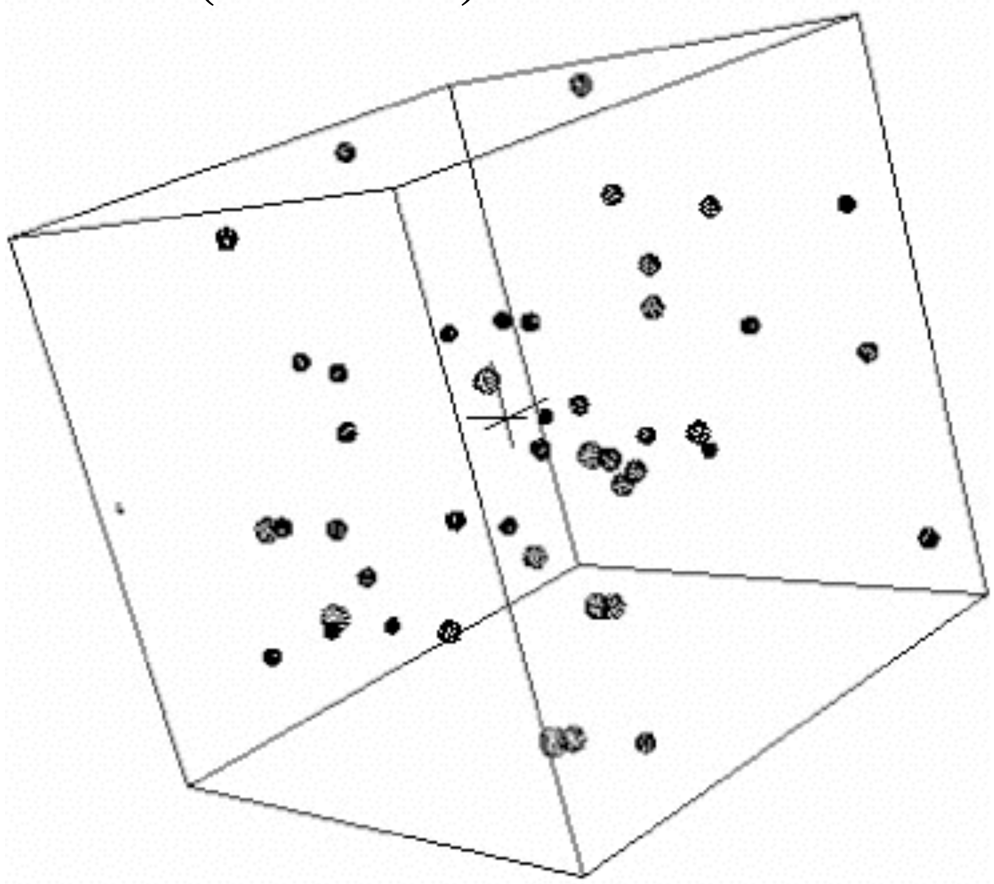
Cluster Peak Patches in Final State Space

(Eulerian)

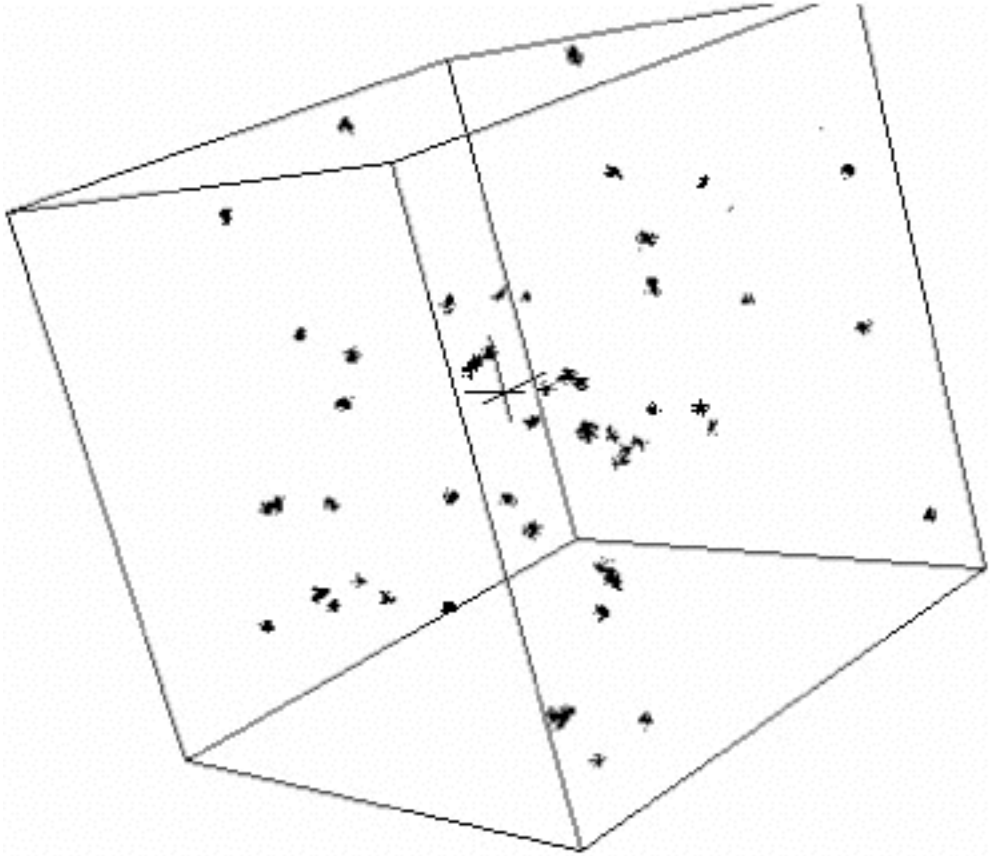


(400 Mpc)^3 simulation

Bond Myers 1991-96

N-body groups
in Final State Space

(Eulerian)



(400 Mpc)^3 simulation

Bond Myers 1991-96

Sunyaev-Zeldovich Simulations and ACT, Planck and SPT Cluster Observations

400 Mpc

ΛCDM

WMAP5

gas density

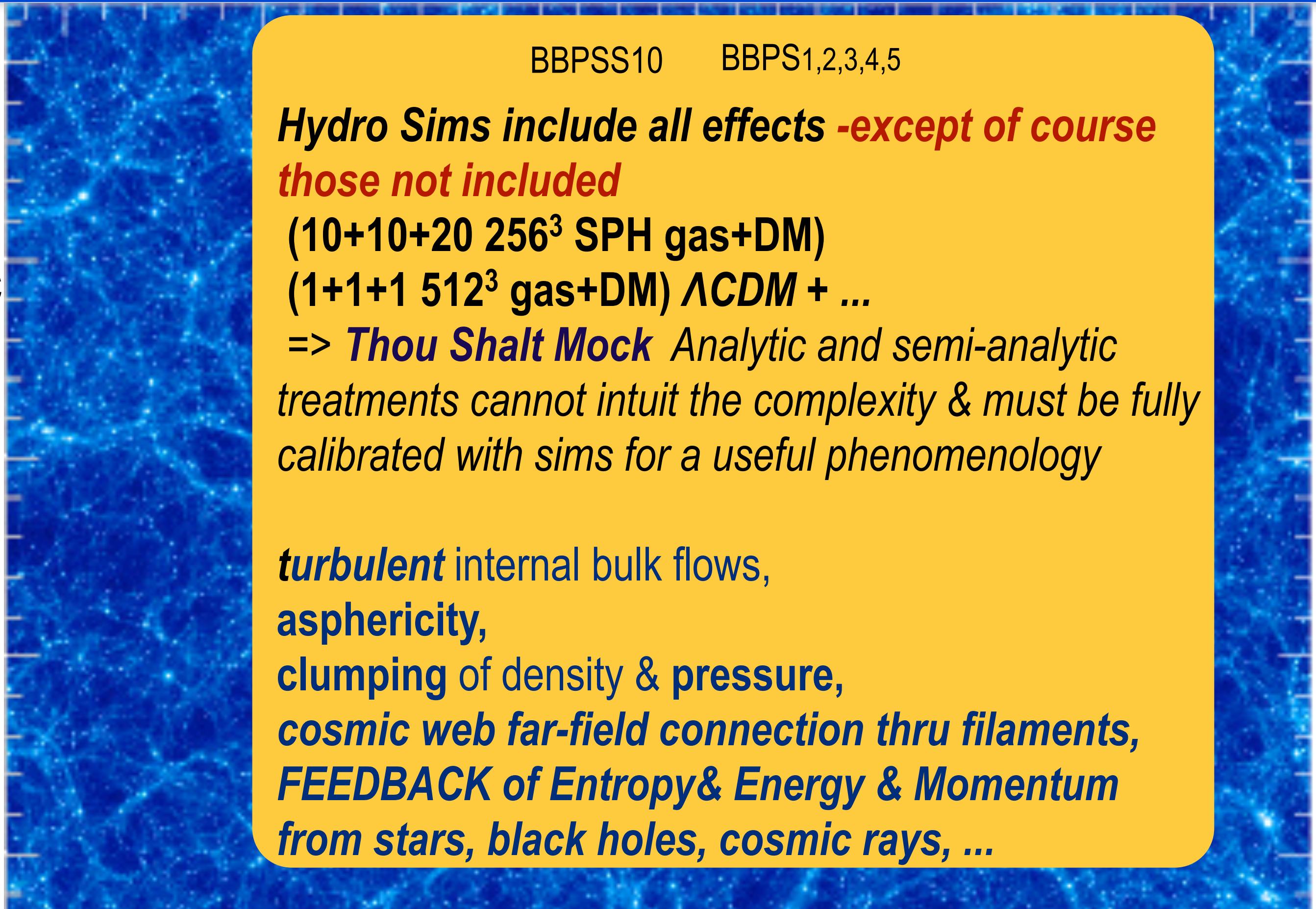
Gadget-3

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,**

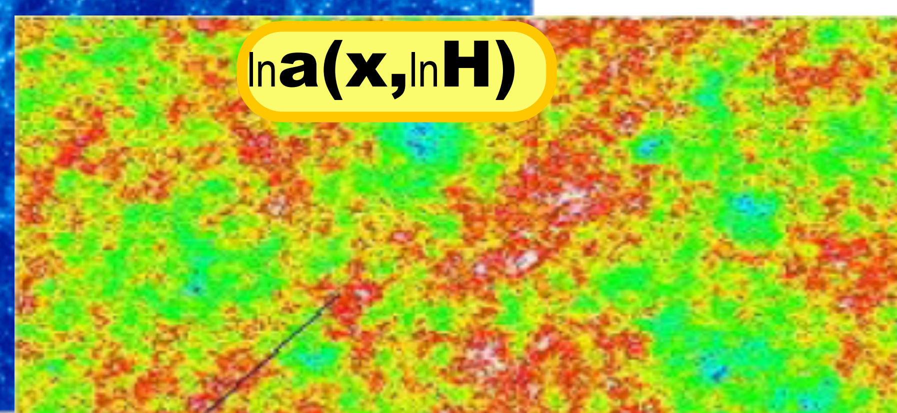
cosmic web far-field connection thru filaments,

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

$\rho_g(x,t)$

a~1

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



Sunyaev-Zeldovich Simulations and ACT, Planck and SPT Cluster Observations

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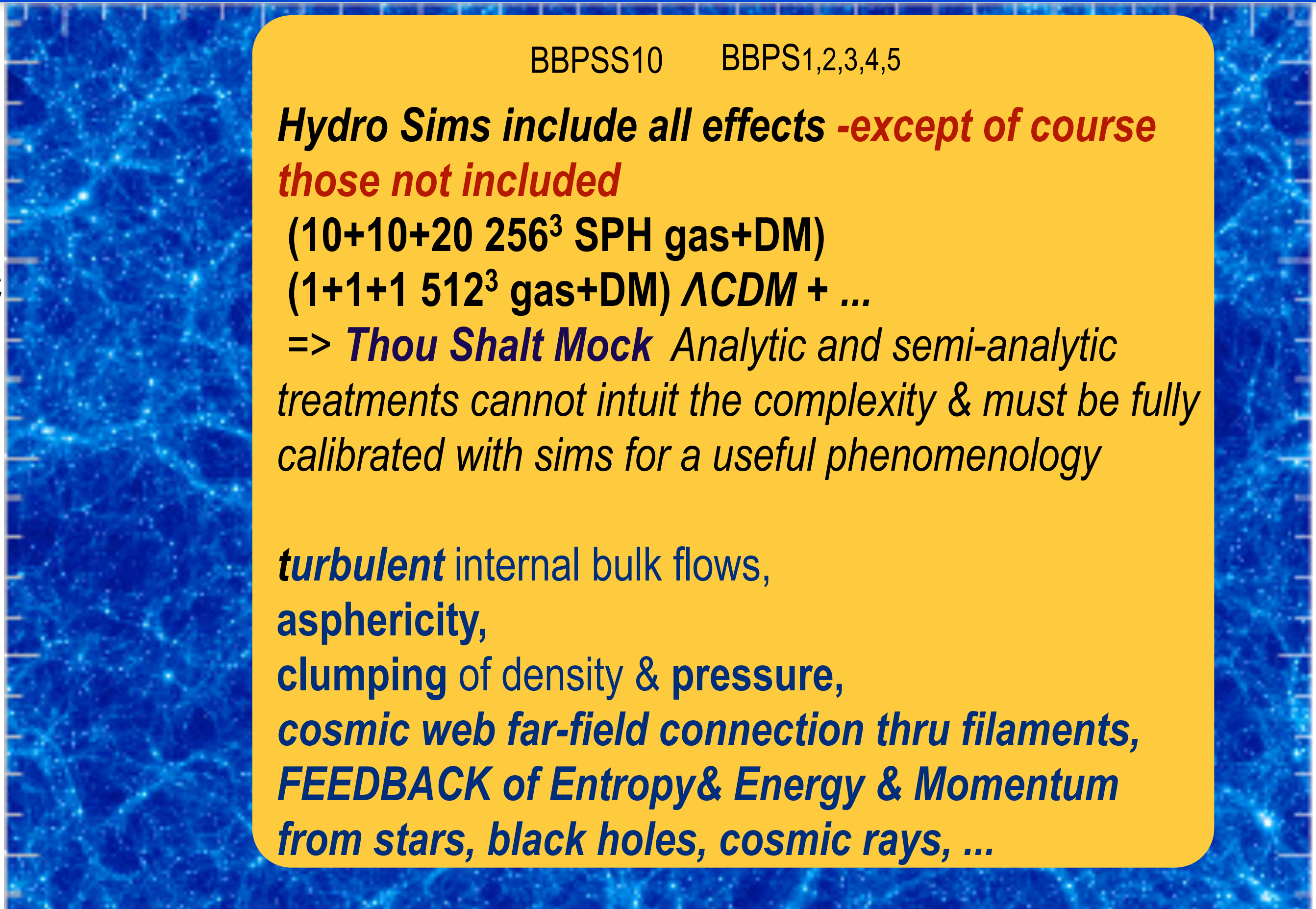

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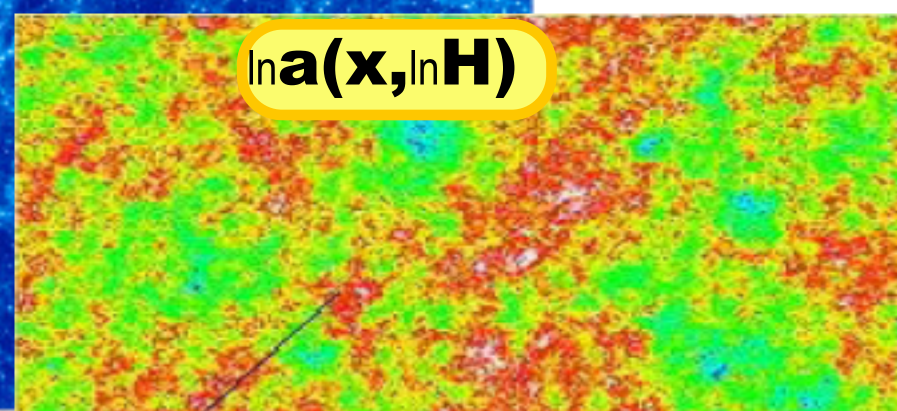
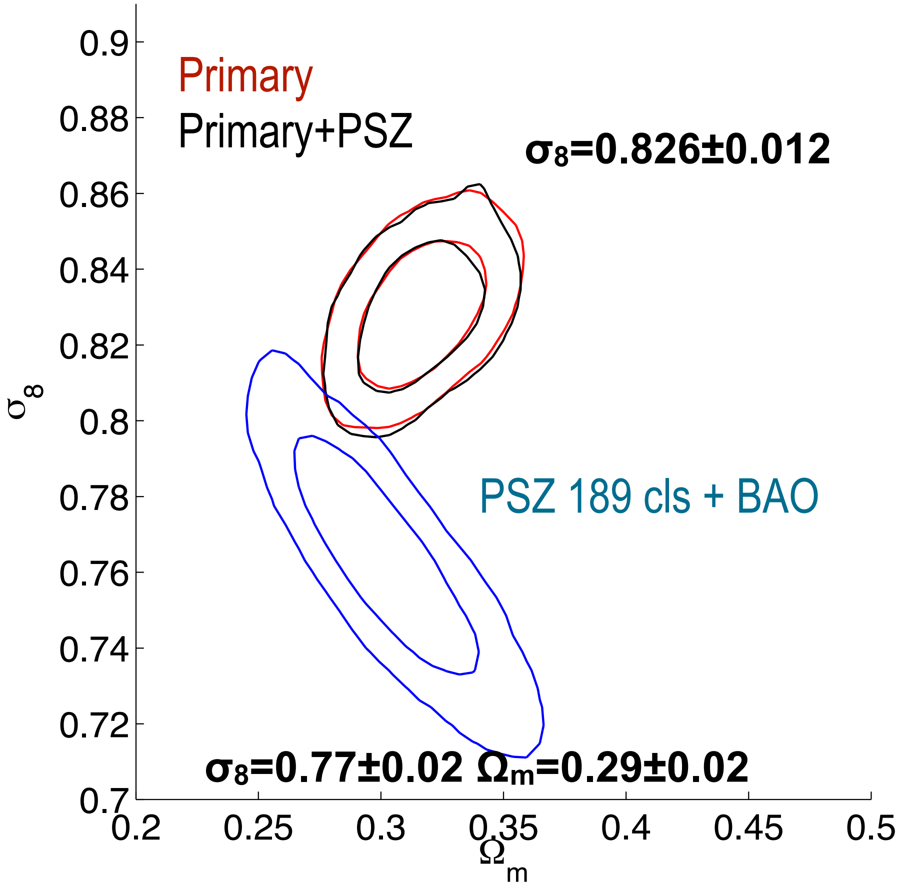


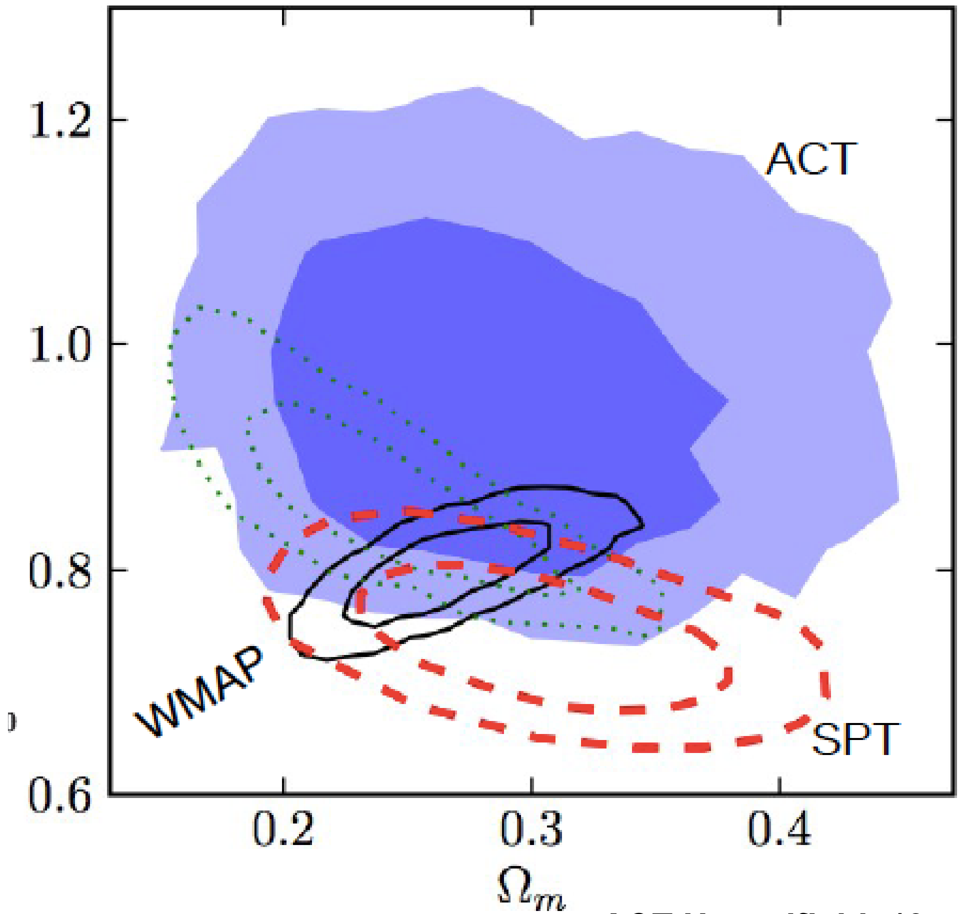
thermal SZ clusters

SPT Reichardt+12 different approach cf. ACT Hasselfield+12
X-ray mass proxy cf. dynamical mass proxy (lower bound for σ8, Ωm)
multi-scale S/N likelihood cf. Profile Based Amplitude Analysis single filter 5.9' not matched θ_{500} corrected
ACT and SPT at most mild tension (ACT SZ scaling priors - very broad, would that we knew them better)



Planck2013 XX

$0.7<(M_X/M_{true})_{500}<1$ *prior; 0.8 default*



ACT Hasselfield+12

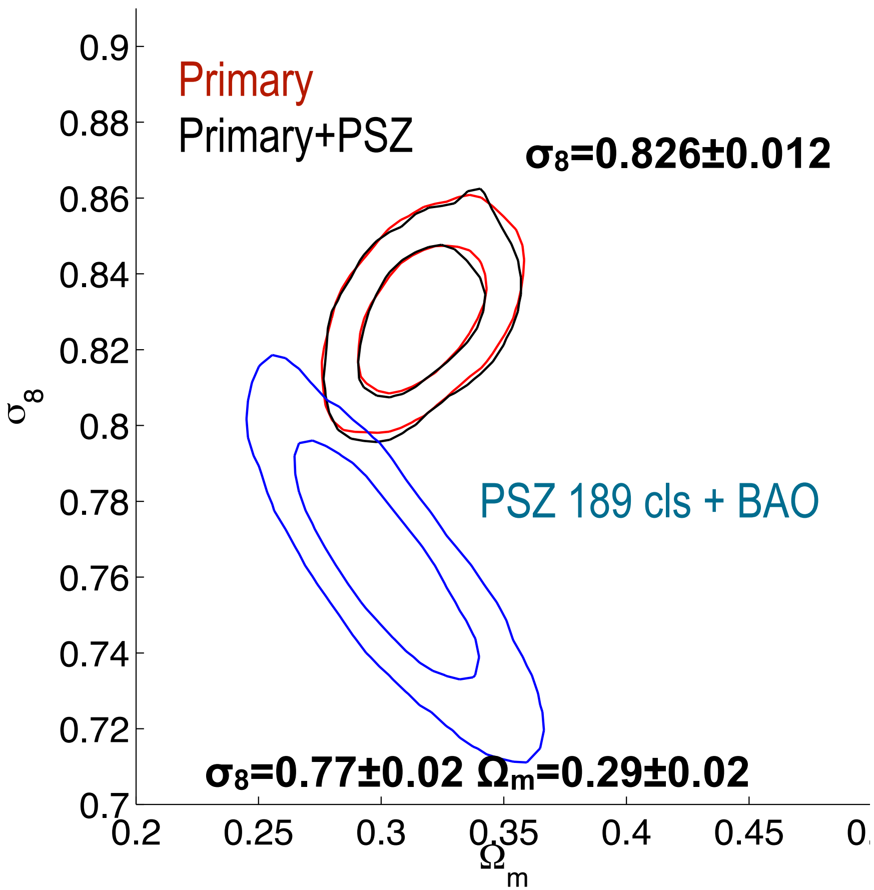
optical **velocity dispersion bias**
β^{dyn}: $(M_{dyn}/M_{true})_{500}$ =1.0±0.15 *prior;*
1.0 default pushes to 1.1±0.12

thermal SZ clusters

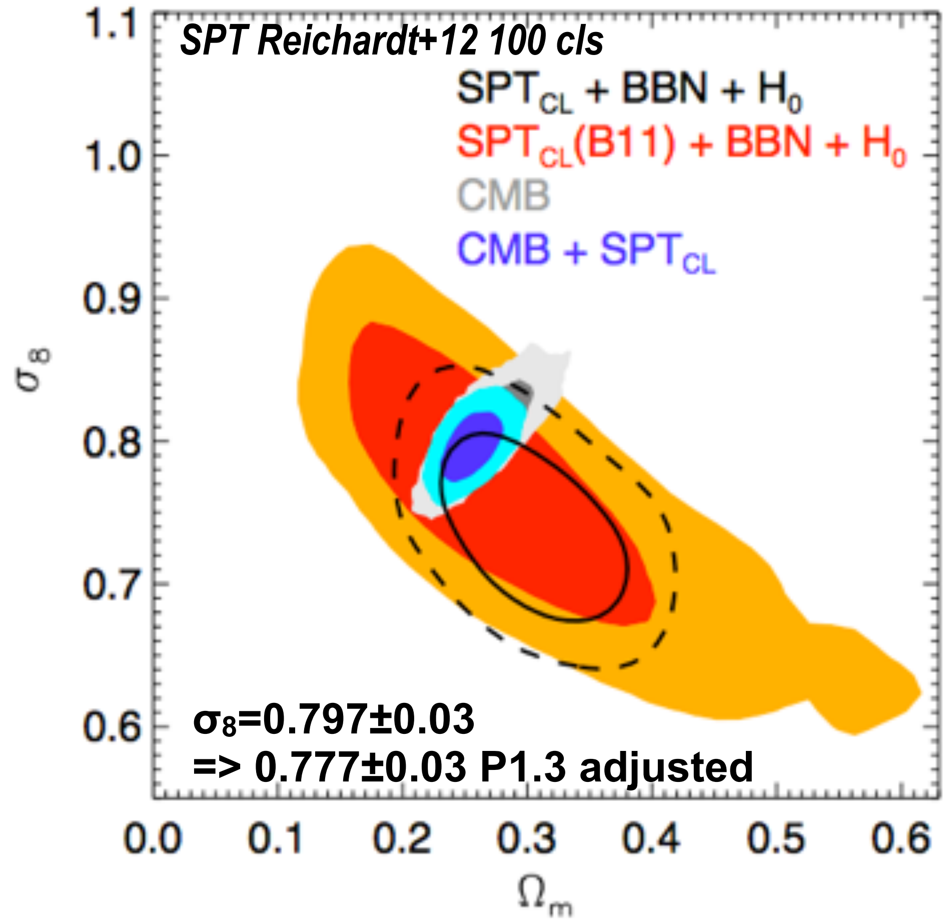
Benson@ESLAB13: SPT has 440 clusters with measured redshifts and SPT S/N > 4.0 full 2500 sq deg catalog in summer 2013

Weak Lensing Mass Calibration

M500(Yx) = (1.02 +/- 0.08) M500(WL) M500(SPT) = **(1.00 +/- 0.08) M500(WL)**



Planck2013 XX

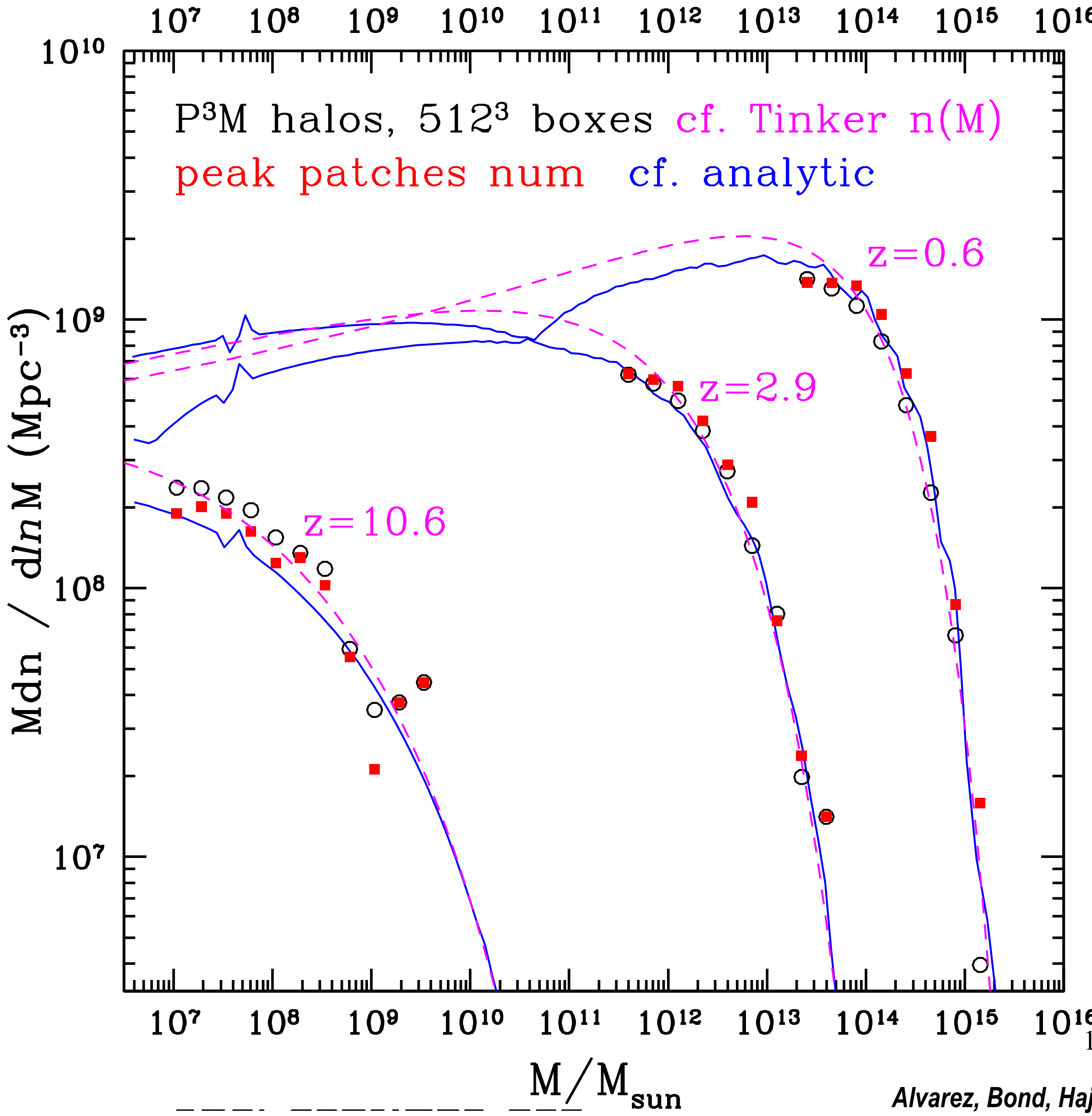


9 Scaling Relation Parameters

$0.7<(MX/Mtrue)_{500}<1$ *prior; 0.8 default*

Peak patches cf 512^3 CUBEP3M halos using SP-O, boxes are: 857 Mpc, 214 Mpc, 6.43 Mpc

SP-O Halos are exactly Eulerian-space Peak Patches



Alvarez, Bond, Hajian, Stein, Emberson 2013