from **SuperWeb simplicity** to **complex Intermittency** in the **Cosmic Web**

Zeldovich 100th, Tallin IAU 308 2014

Dick Bond

CIFAR
CANADIAN INSTITUTE FOR ADVANCED RESEARCH

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

На здоровье
Terviseks

Z70,ZES82
AZS82
e_J^j

from **SuperWeb simplicity** to **complex Intermittency** in the **Cosmic Web**

MOCK*ing* HEAVEN

painting the Euler/Lagrange Peak-Patch Picture of Cosmic ACTalogues aka halos (N-body/pp+hydro sims/HOD/obs)

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*or **blockage** from **gastrophysical indigestion?***

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Super-duper LSS & the Super-WEB aka the primordial 3-curvature web aka the phonon/isotropic strain = volume deformation web

$ln\,\rho(x,t)/\langle\rho\rangle|_V$ $\quad$ $ln\,V/\langle V\rangle|_\rho = 3\,ln\,a(x,t)|_\rho$

$\zeta(x,t) = \int (dE+pdV)/E \quad /\langle 3(1+p/\rho)\rangle(t)$

BST83, SBB89, SB90,91, B95, Bond+Braden2014 ζ for preheating

$\zeta(x,t) = (ln\,\rho(x,t) + \int (1+p/\rho)(x,t)\, d\,ln\,a^3(x,t)) \;/\langle 3(1+p/\rho)\rangle(t)$

cf. the density web ~ strain web ~ gravitational potential web

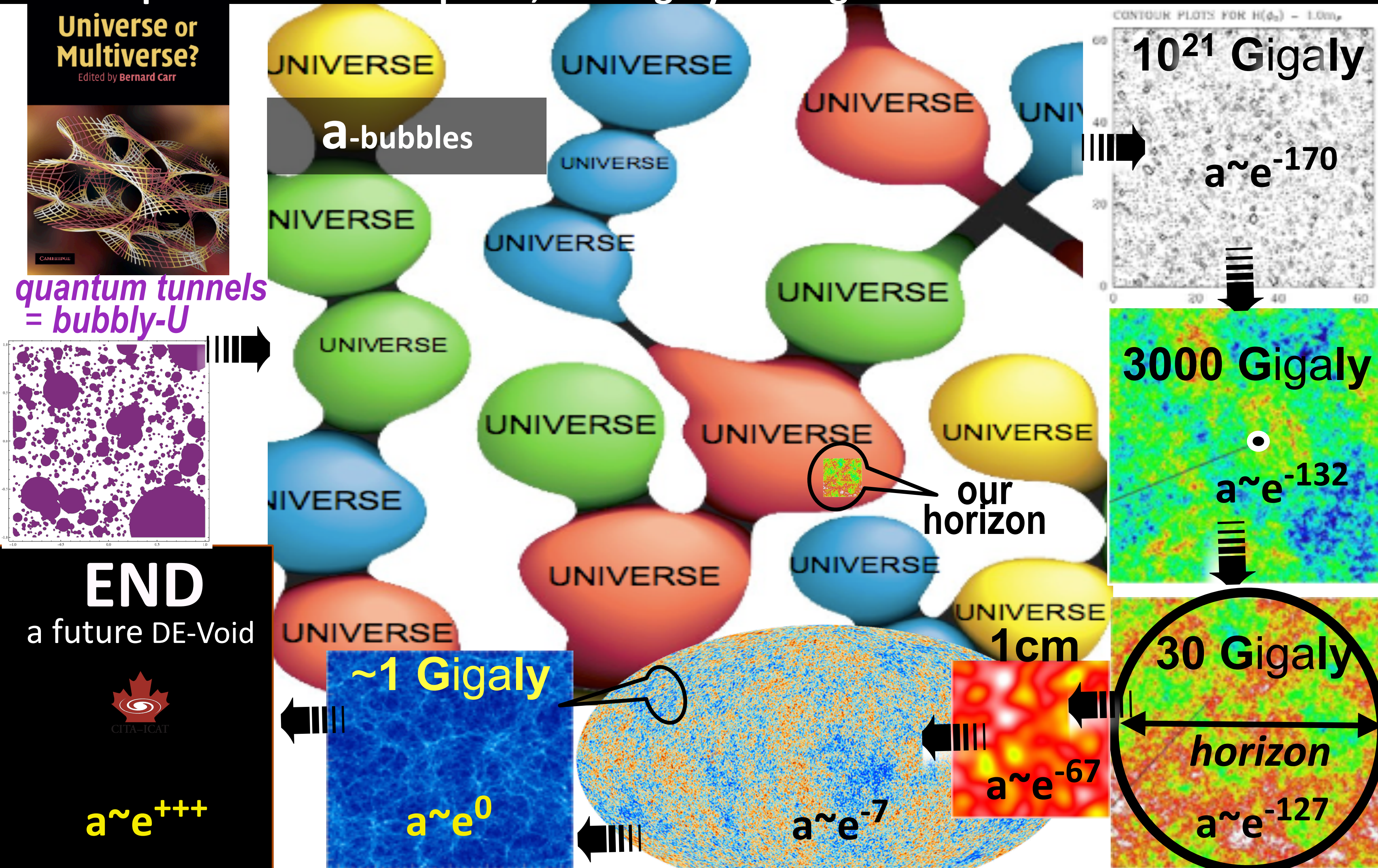
$-\,ln\,\rho/\langle\rho\rangle = \text{Trace}\; ln\; e_J{}^j = ln\,V/\langle V\rangle|_\rho$

cold $\langle p/\rho\rangle \sim 0$ => $\zeta(x,t\,|cdm)$ *conserved before shell crossing (preheating)*

SuperWeb of ultra-Ultra Large Scale Structure of the Universe

Horizons: the ultimate-speed constraint on light & information

a highly strained & stressed state in the universe at large (very, very), randomly simple in our Hubble patch, and highly entangled in the small to medium



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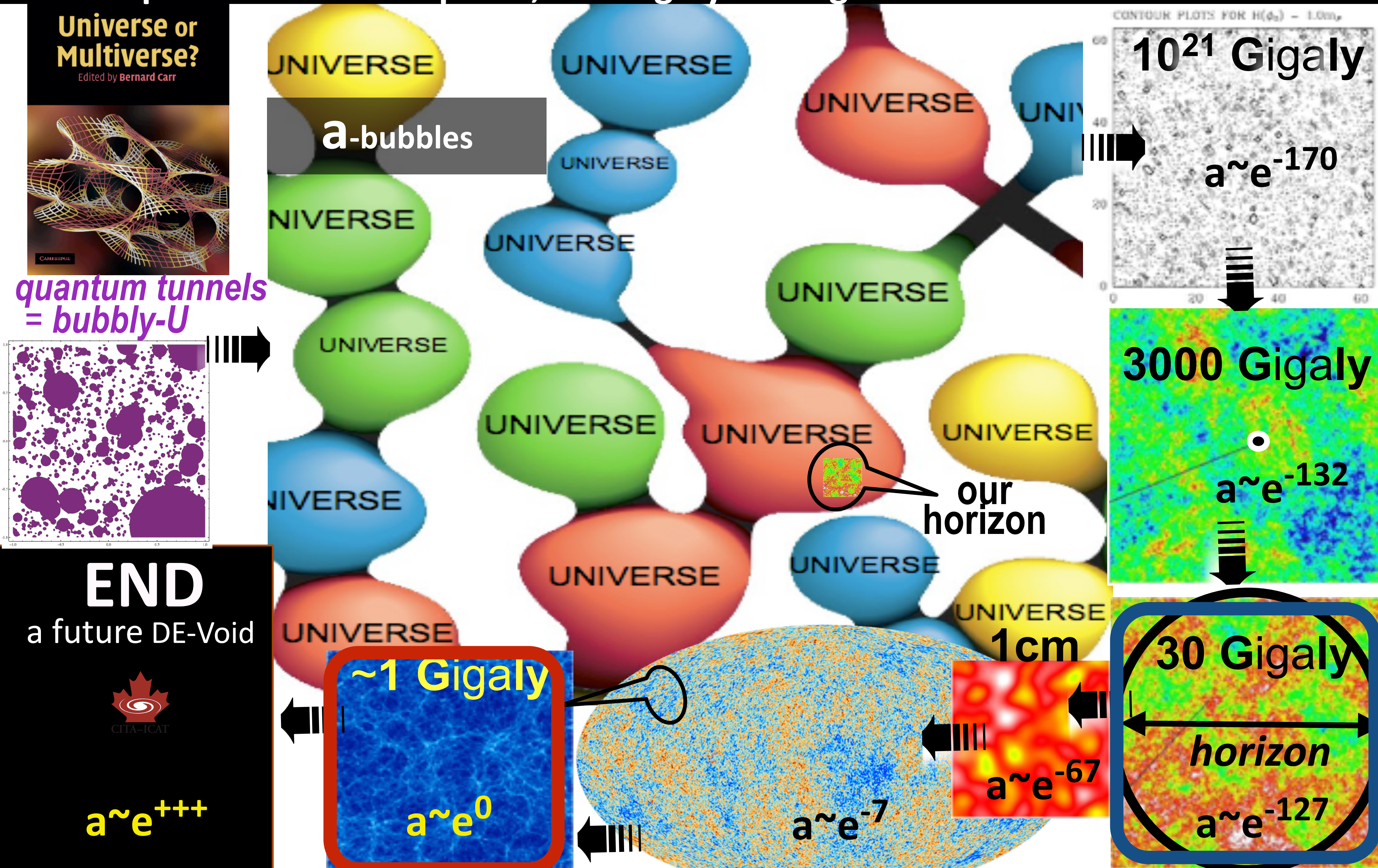
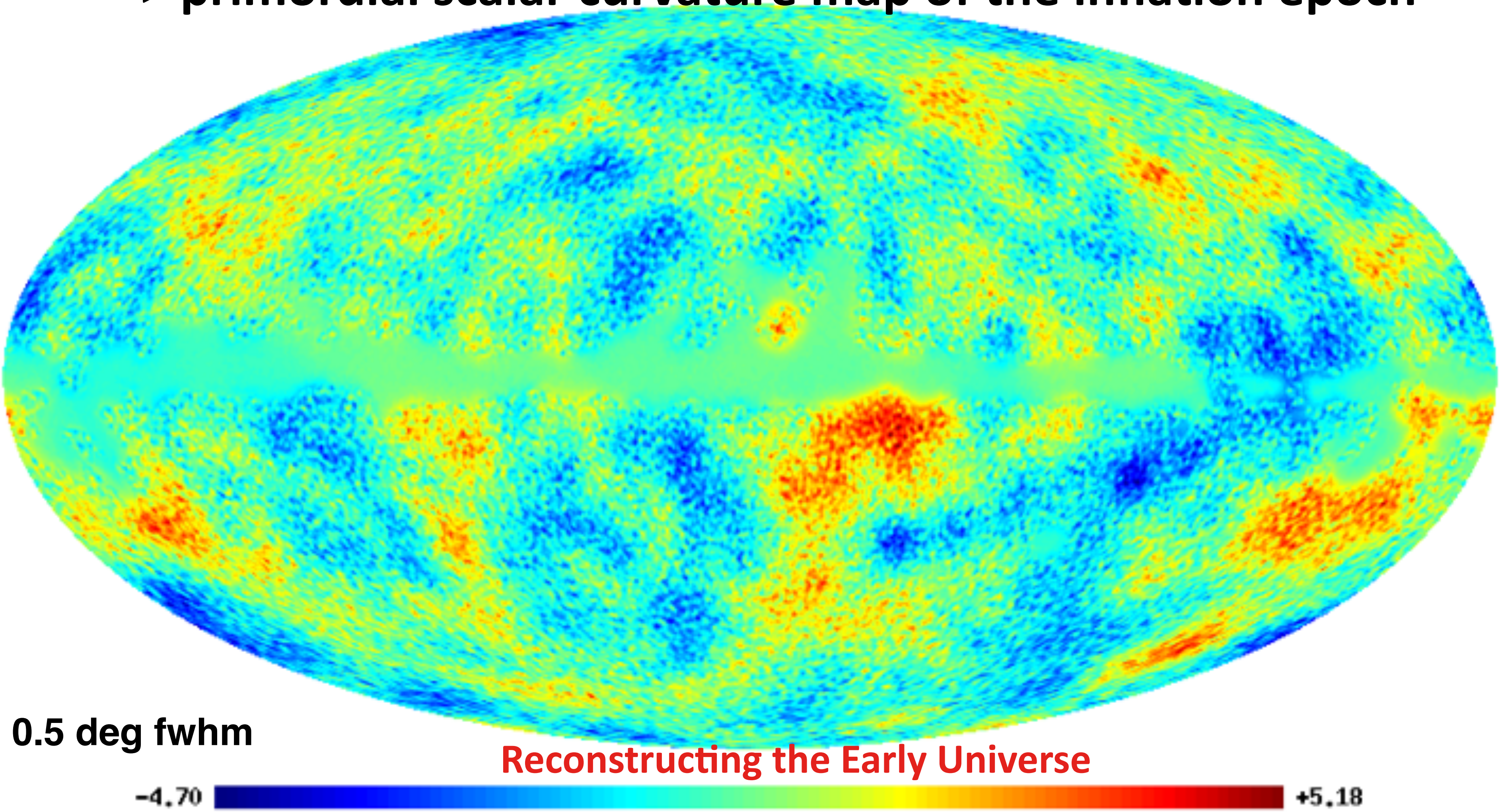


Planck reveals map of **primordial isotropic strain /phonons**

$\int d$ ***visibility***(*distance*) <ζ |*Temperature*> (*angles, distance*)

mean zeta, 1000 realizations, smooth scale fwhm = 30 arcmin,

=> primordial scalar curvature map of the inflation epoch



0.5 deg fwhm

Reconstructing the Early Universe

visibility mask

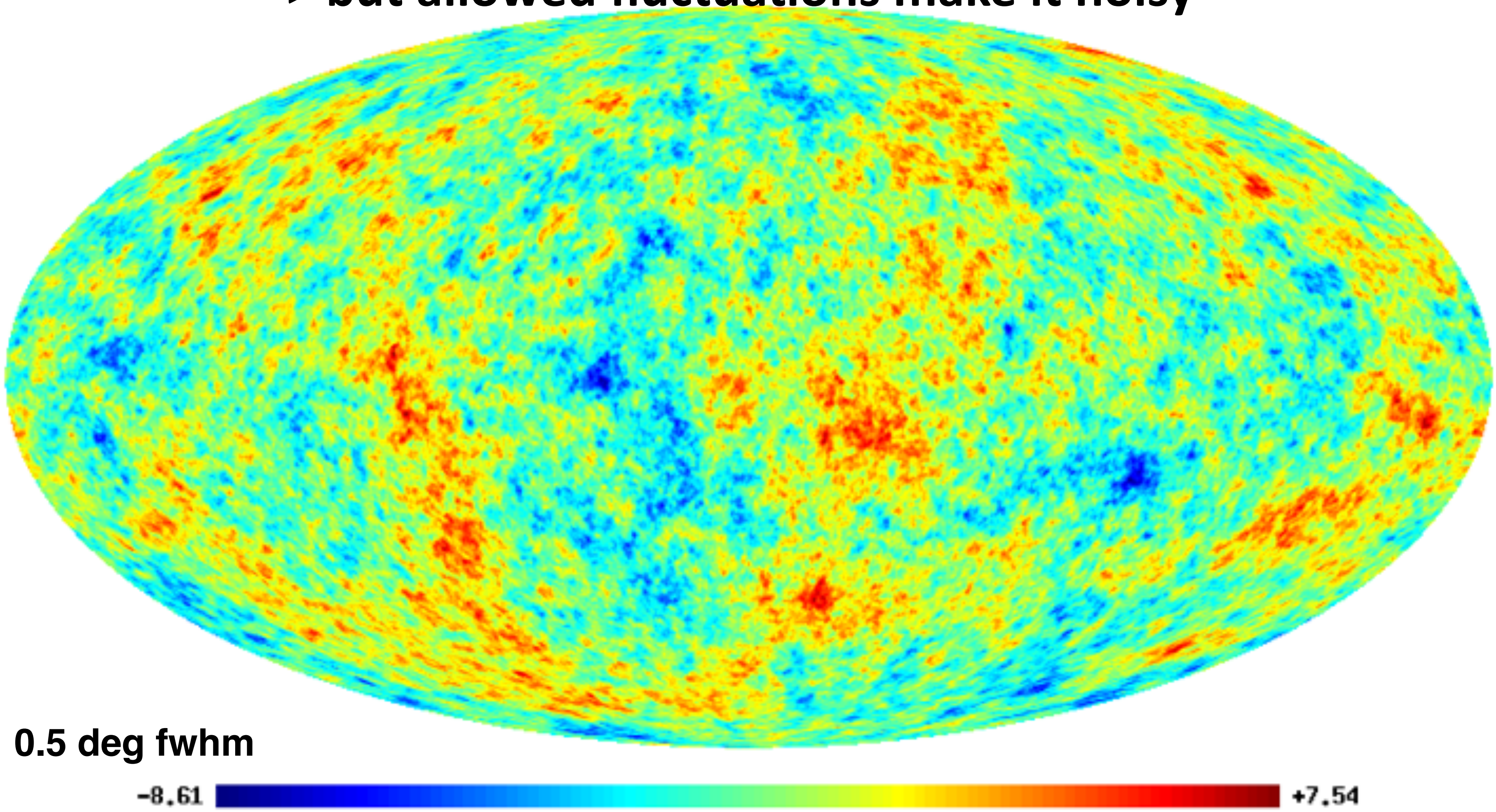
Bond, Braden, Frolov, Huang 2014

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

$\int d$ ***visibility***(*distance*) $< \zeta \,|\, Temperature > + \, \delta\zeta$

one realization of fullsky zeta, fwhm = 30 arcmin

=> but allowed fluctuations make it noisy



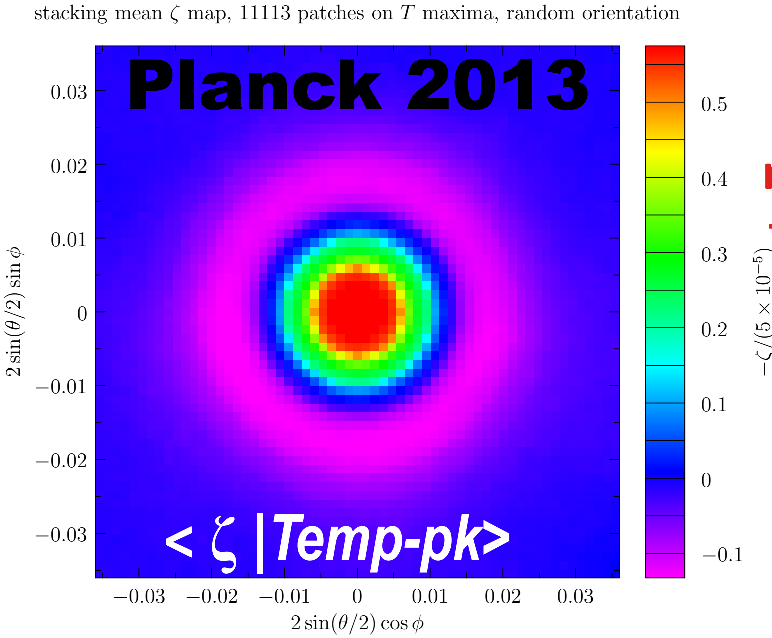
0.5 deg fwhm

Reconstructing the Early Universe

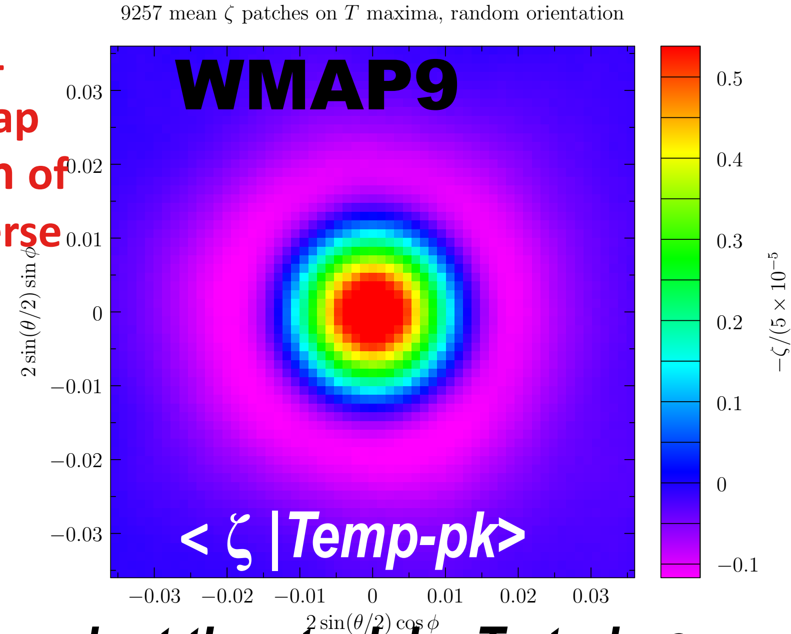
Bond, Braden, Frolov, Huang 2014

visibility mask

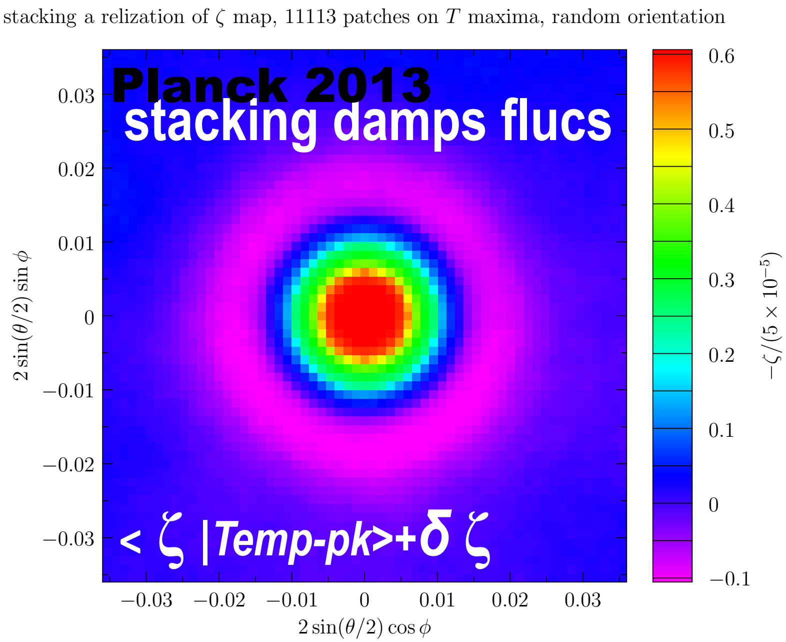
primordial isotropic strain ζ : $\Phi_N \sim -3/5(D(t)/a(t))$ *Transfer** ζ



mean-field constrained-correlation map reconstruction of the Early Universe

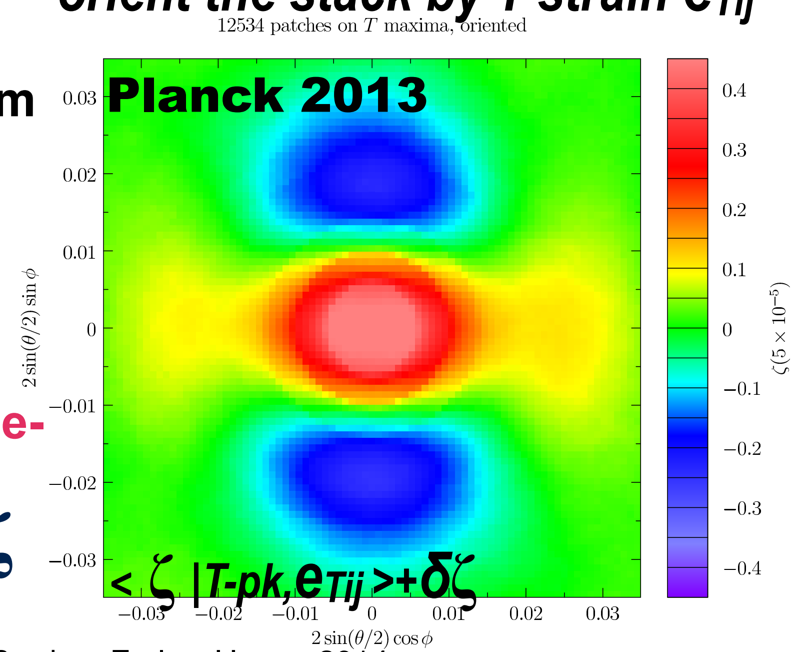


orient the stack by T-strain e_{Tij}



0.5 deg fwhm

Compton differentiable-visibility mask on ζ

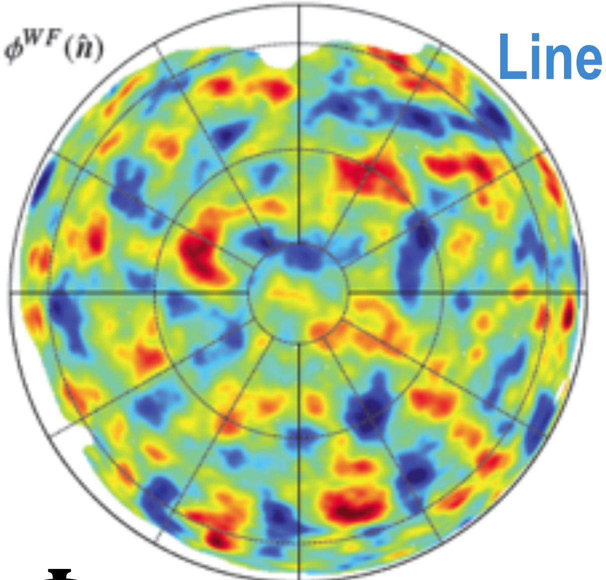


Bond, Braden, Frolov, Huang 2014

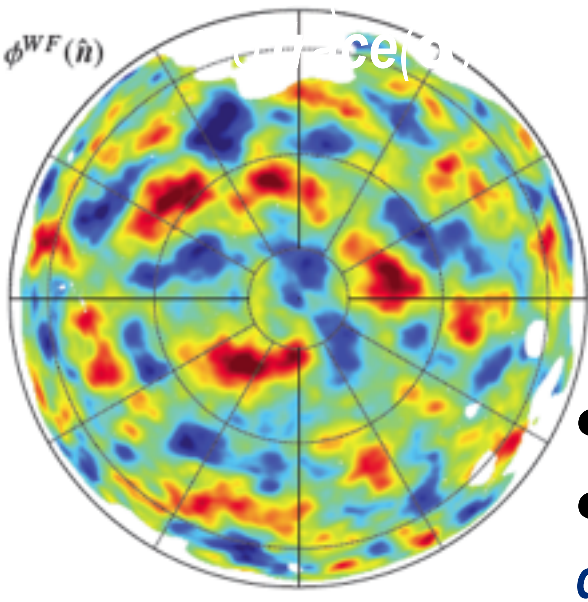
Planck1.3 CMB Lensing: reconstructed projected Φ_N gravitational potential

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

Linear Φ_N ~ -3/5(D(t)/a(t)) *Transfer** *ln* **a(x,t)**|$_\rho$

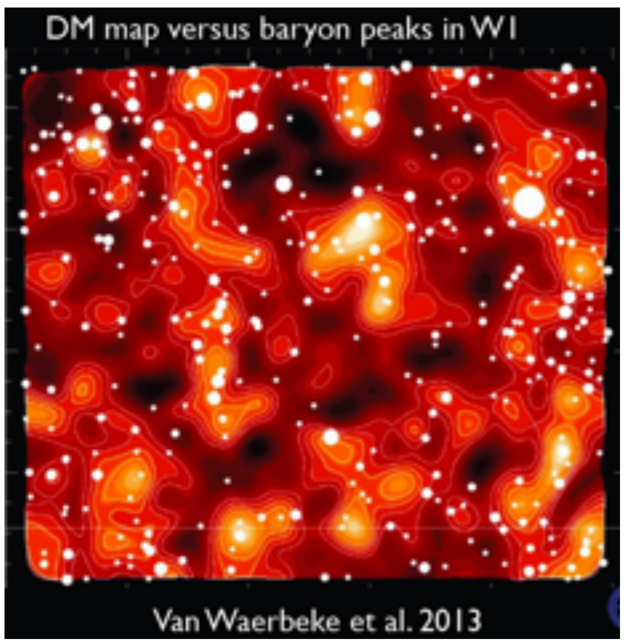


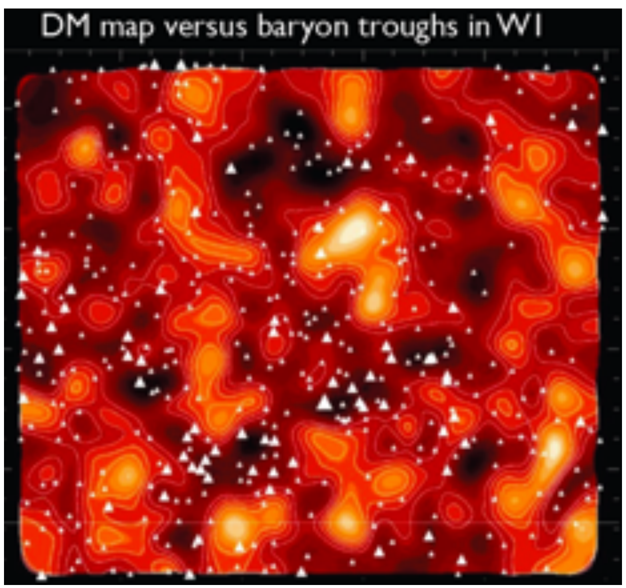
Φ_N Galactic North



Galactic South

CFHTlens Ludo+13 reconstructed projected density, could turn it into a Φ_N gravitational potential map





Φ_N map from velocity: flows

Φ_N map from galaxy z-surveys *modulo* **bias, *z-space distortion, nonlinear 'entropy'/heat,*** *gas dissipation/feedback*

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

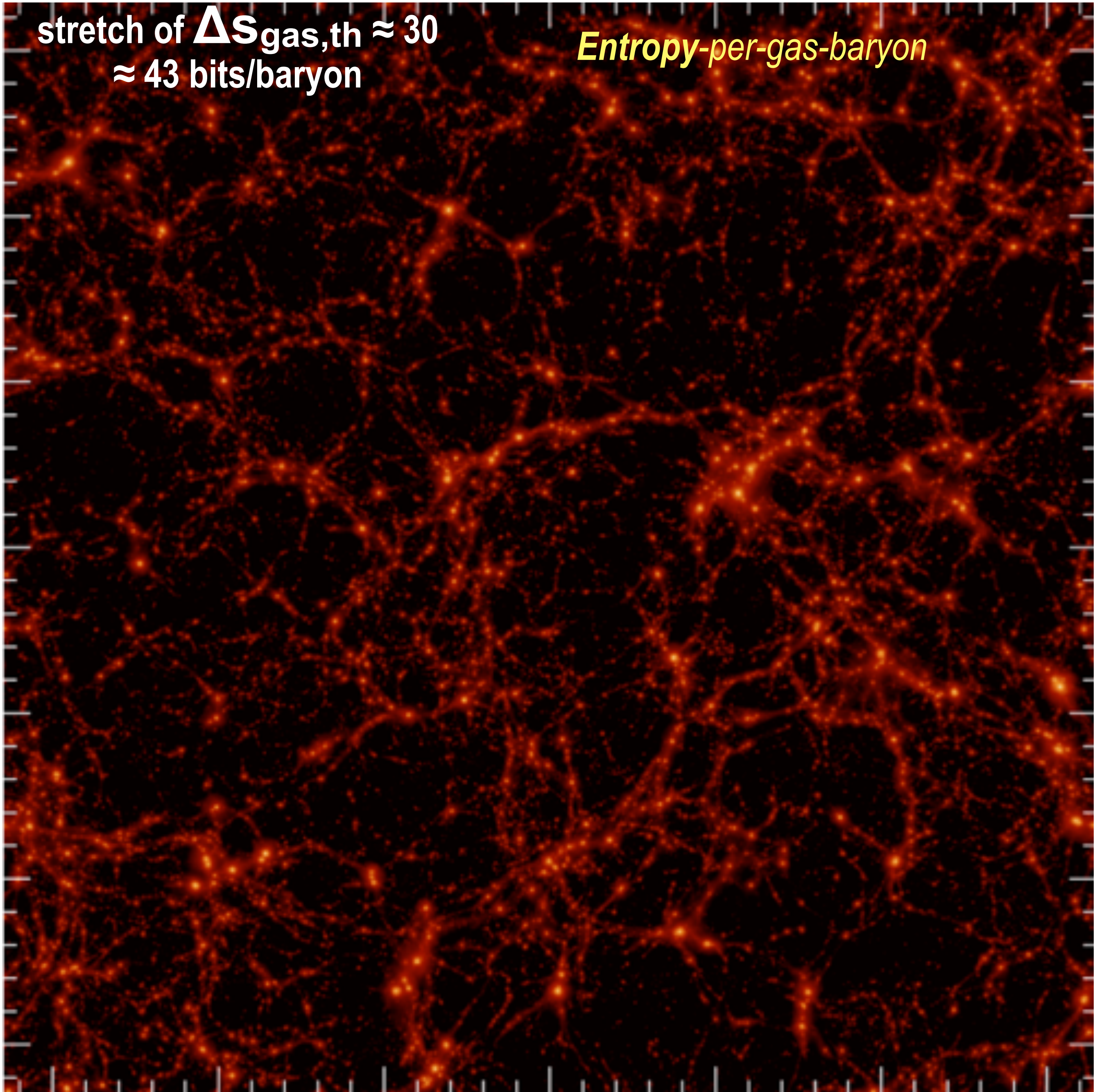
gas pressure

Gadget-3
SF+
SN E+
winds
+CRs

512^3

BBPSS10

BBPS1,2,3,4,5



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

baryons get entangled in the cosmic web

Let there be HEAT

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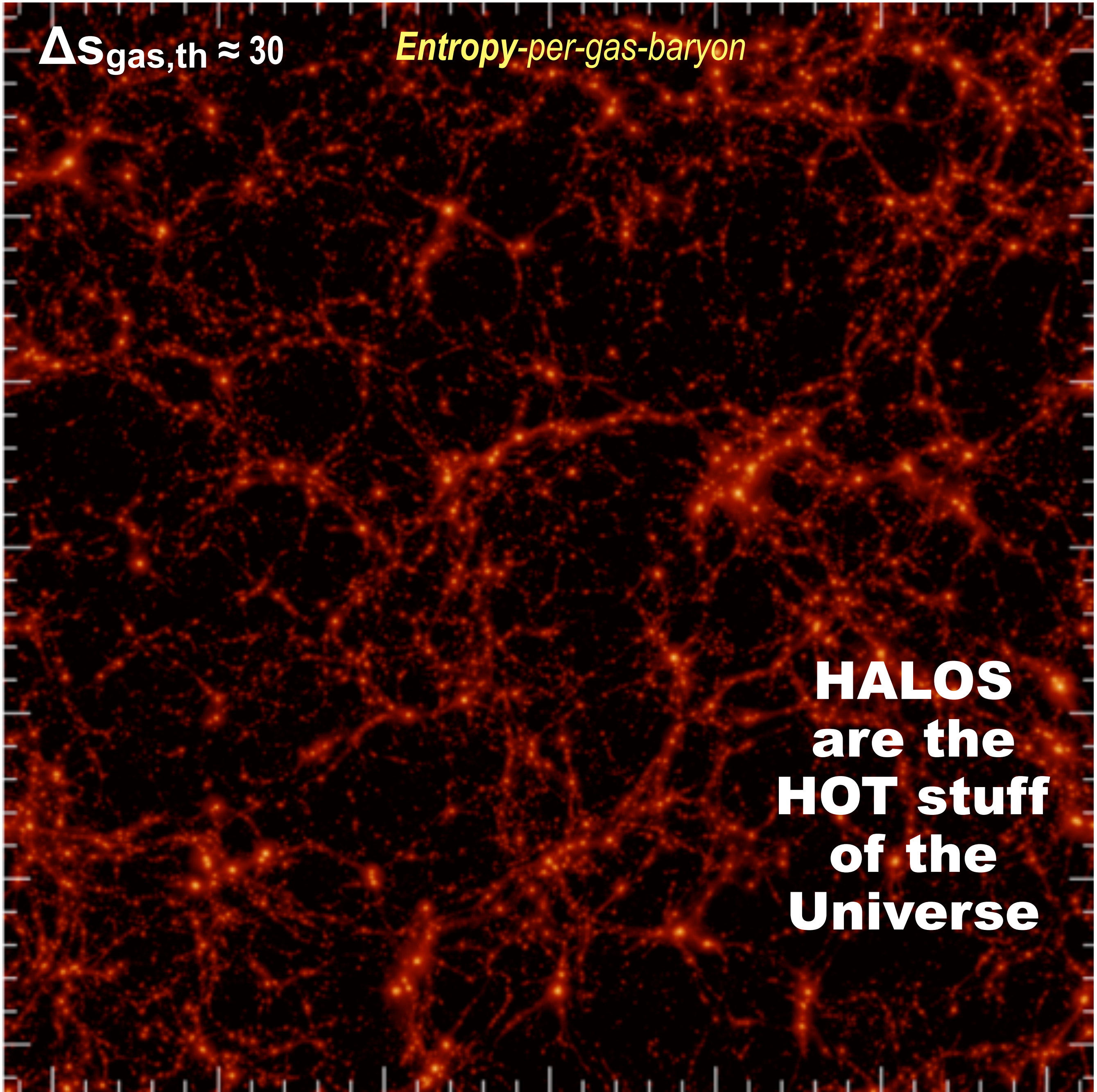


$s_{b,th}(x,t)$

baryons get entangled in the cosmic web

Let there be HEAT

$\rho_g(x,t)$

$\rho_{stars}(x,t)$

$p_e(x,t)$

$I_\nu(x,t)$

$n_{dust}(x,t)$

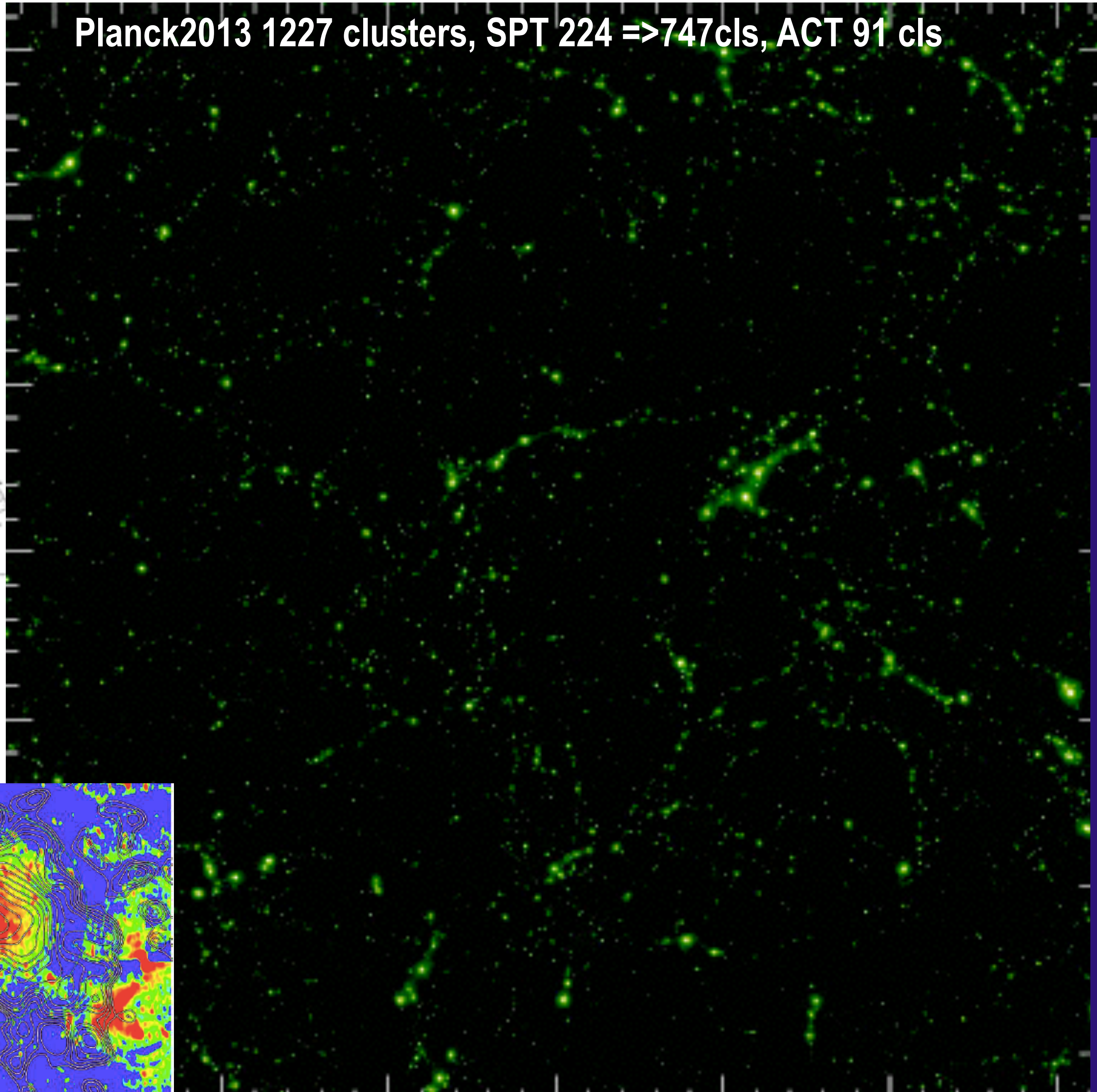
non-Gaussian CDM entanglement

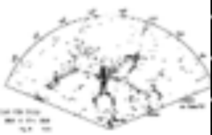
$\rho_{dm}(x,t)$

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

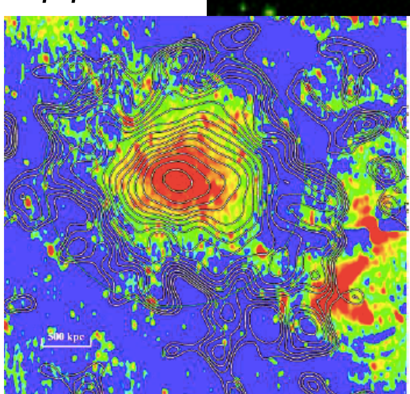
Secondary Anisotropies
(tSZ, kSZ, WL, reion, CIB; hydro)

$p_e(x,t)$





Planck's
Coma
2012.08
pip10



the thermal Sunyaev Zeldovich Probe

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

Compton cooling of hot cosmic web gas

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

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

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

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

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

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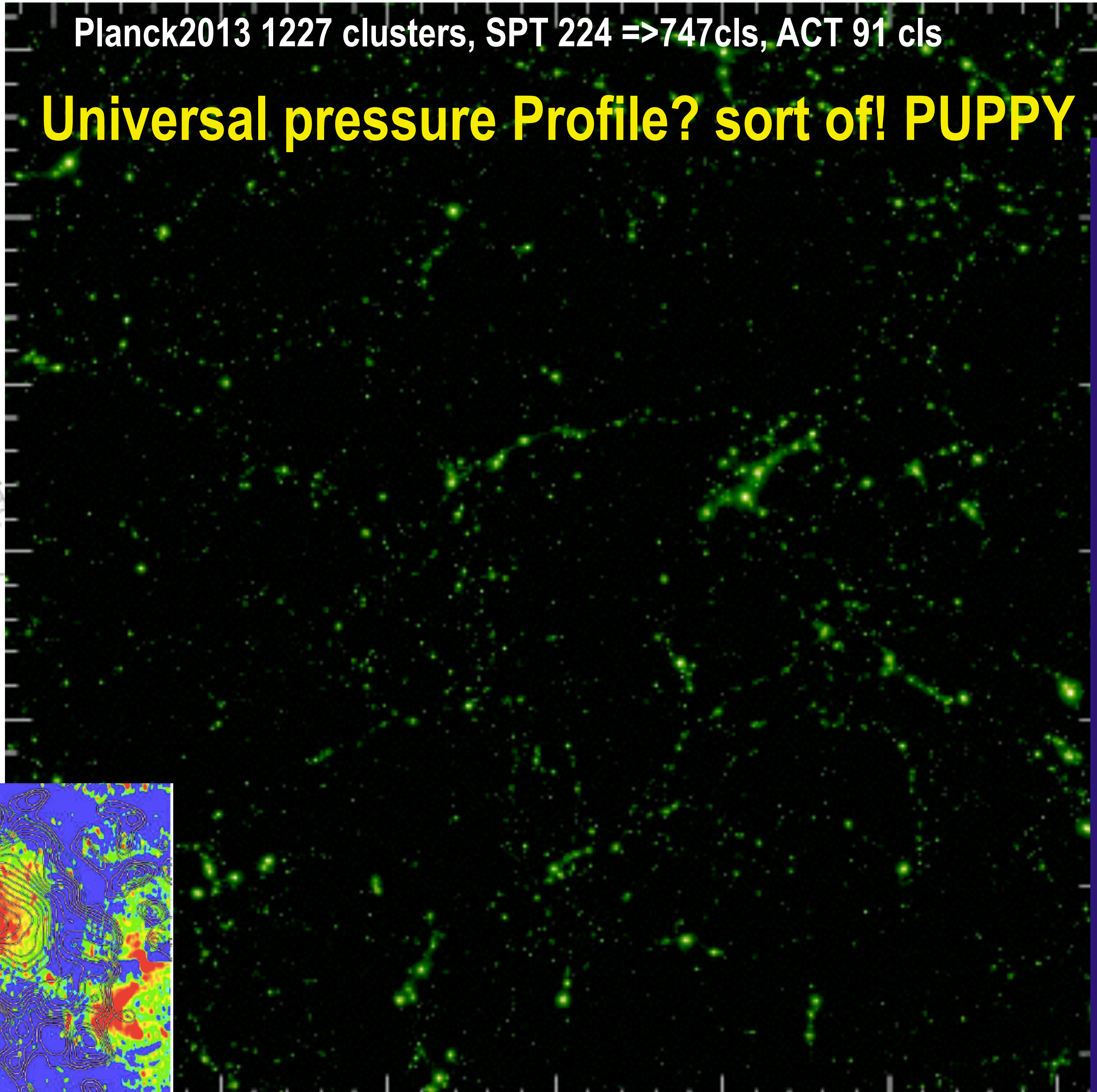

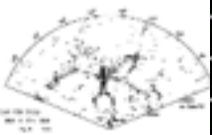

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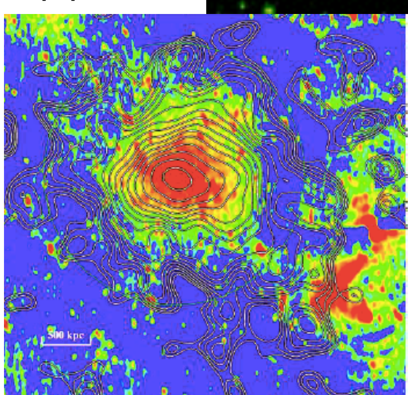

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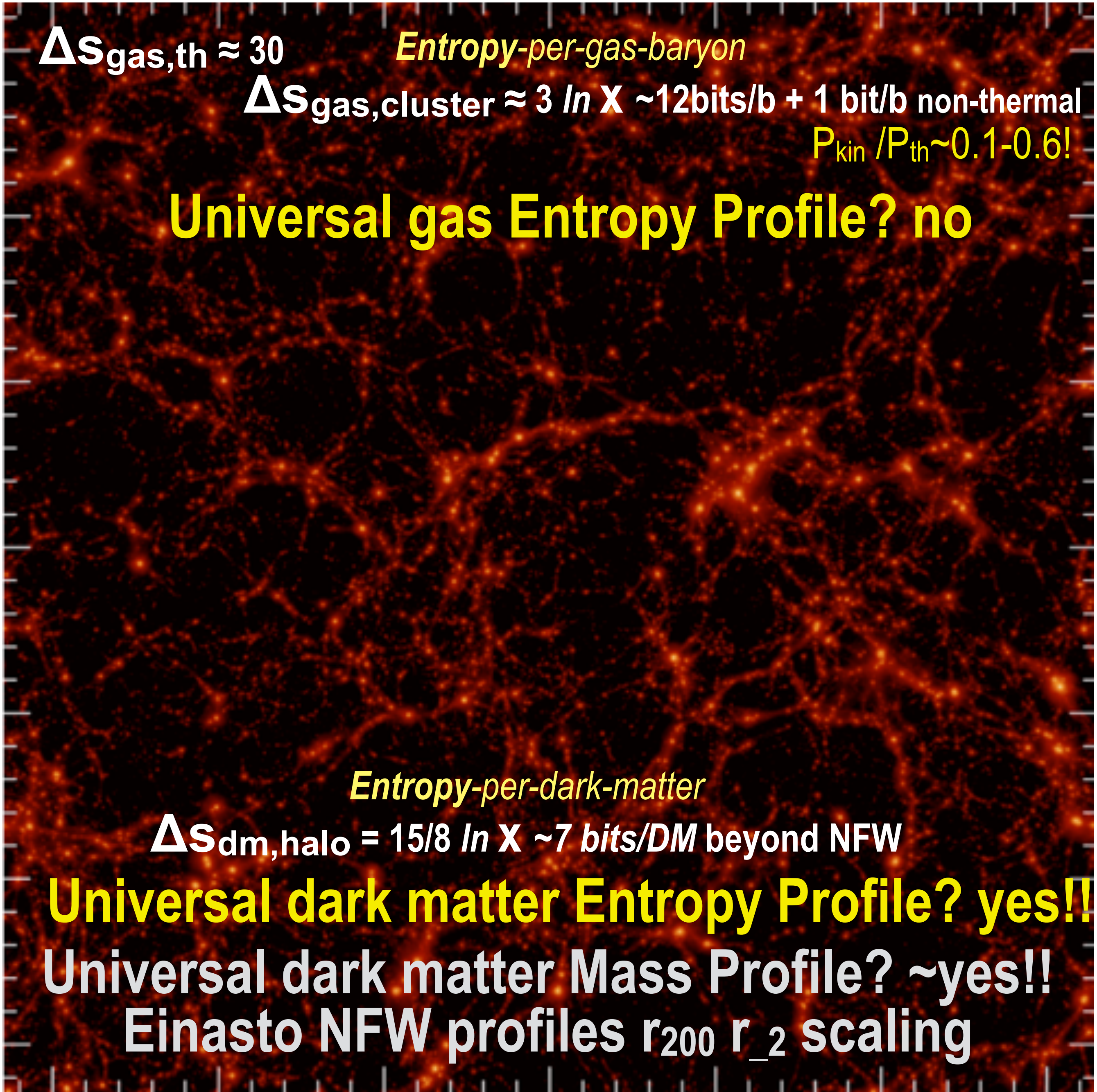


$s_{b,th}(x,t)$

dark matter gets entangled in the cosmic web

Let there be coarse-grained HEAT

HALOS are the HOT stuff of U

Surveys of the Web(z)

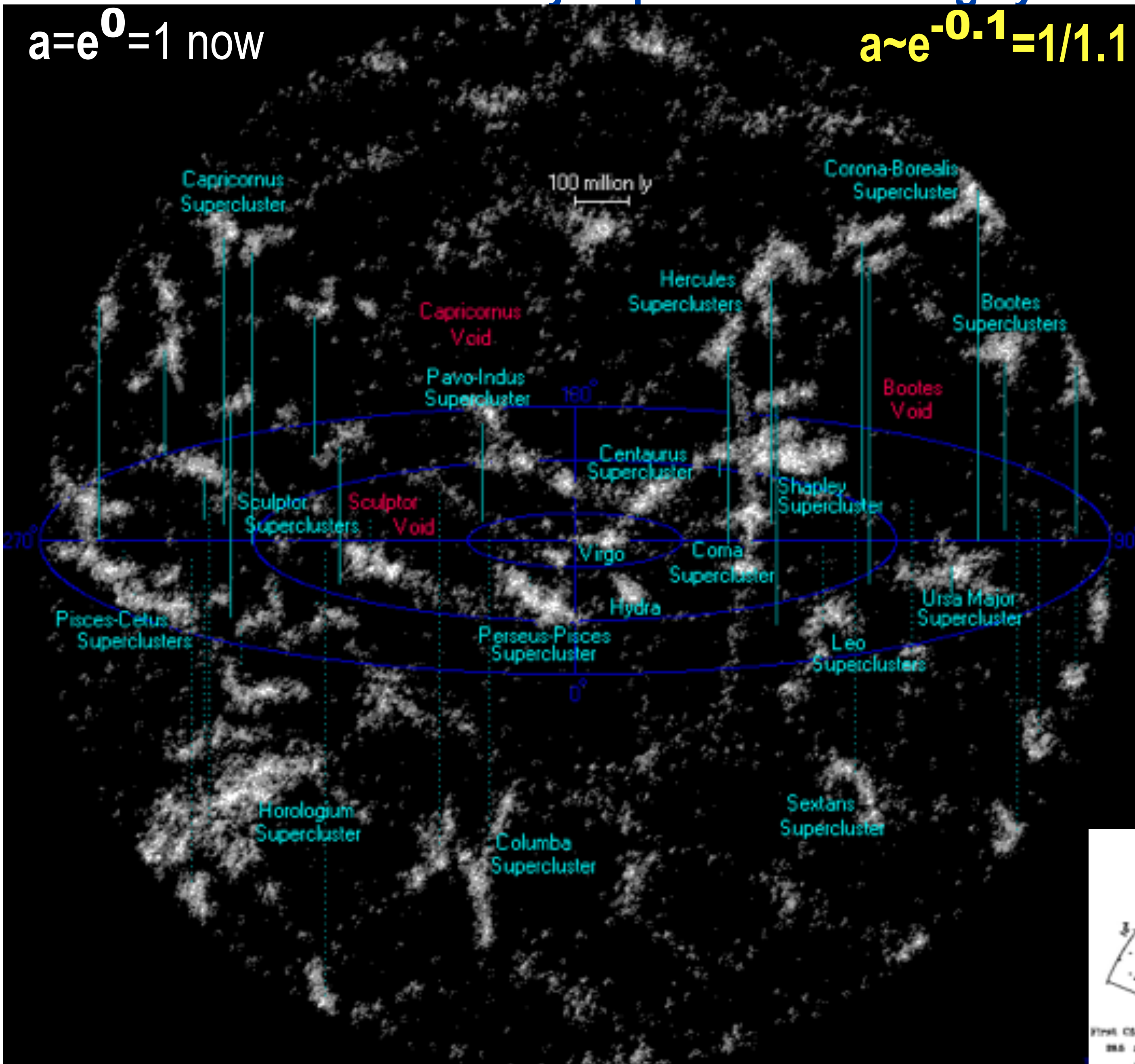
the LSS data bases for

fundamental physics &/or **cosmic weather**

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 < Giga*lyr



70s adiabatic pancake (physical filter) *Doroshkevich*

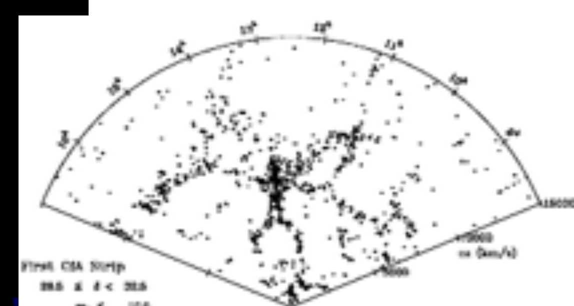
cf.

70s isoc B/BH (power law CorrFn) *Basko*

miracle of CDM = grand unification of east & west ideas with ~ HSZ spectrum

emergence of superclusters

Peebles vs. 70s Einasto+.. 80 + Oort +



Emergence of the Cosmic Web

a Vintage 98 slide in praise of superclusters & their role in LCDM

CorBor & Coma superclusters in the Century z-survey

(Geller etal 98)

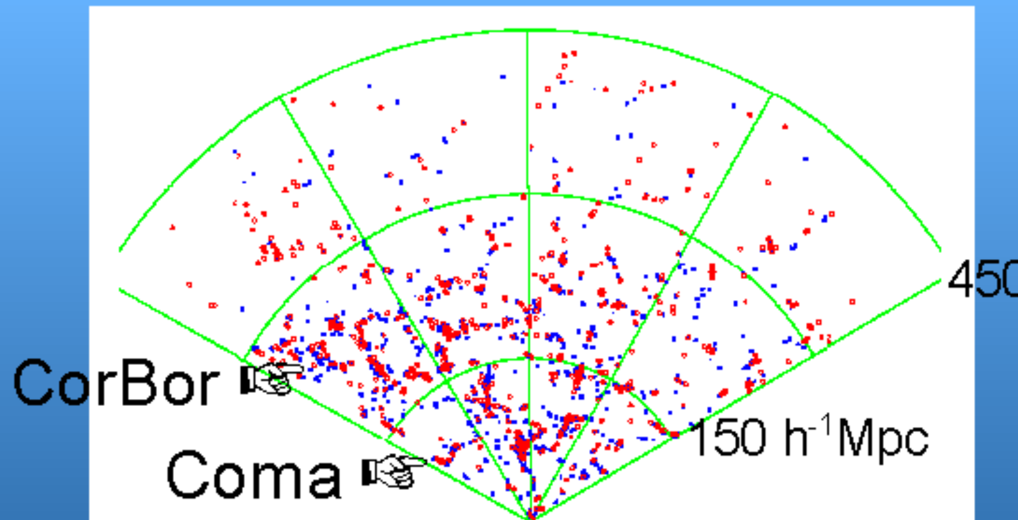


Fig. Plate 1.— Cone diagram for the Century Survey. The right ascension runs from 8.5^h to 16.5^h and the radial green lines are at 2 hour intervals. The outer boundary of the plot is at 45,000 km s^{-1} and the green lines at constant velocity mark 15,000 km s^{-1} intervals. Blue points represent spiral galaxies; yellow ones are early types. In the gray-green regions there is a mix of types.

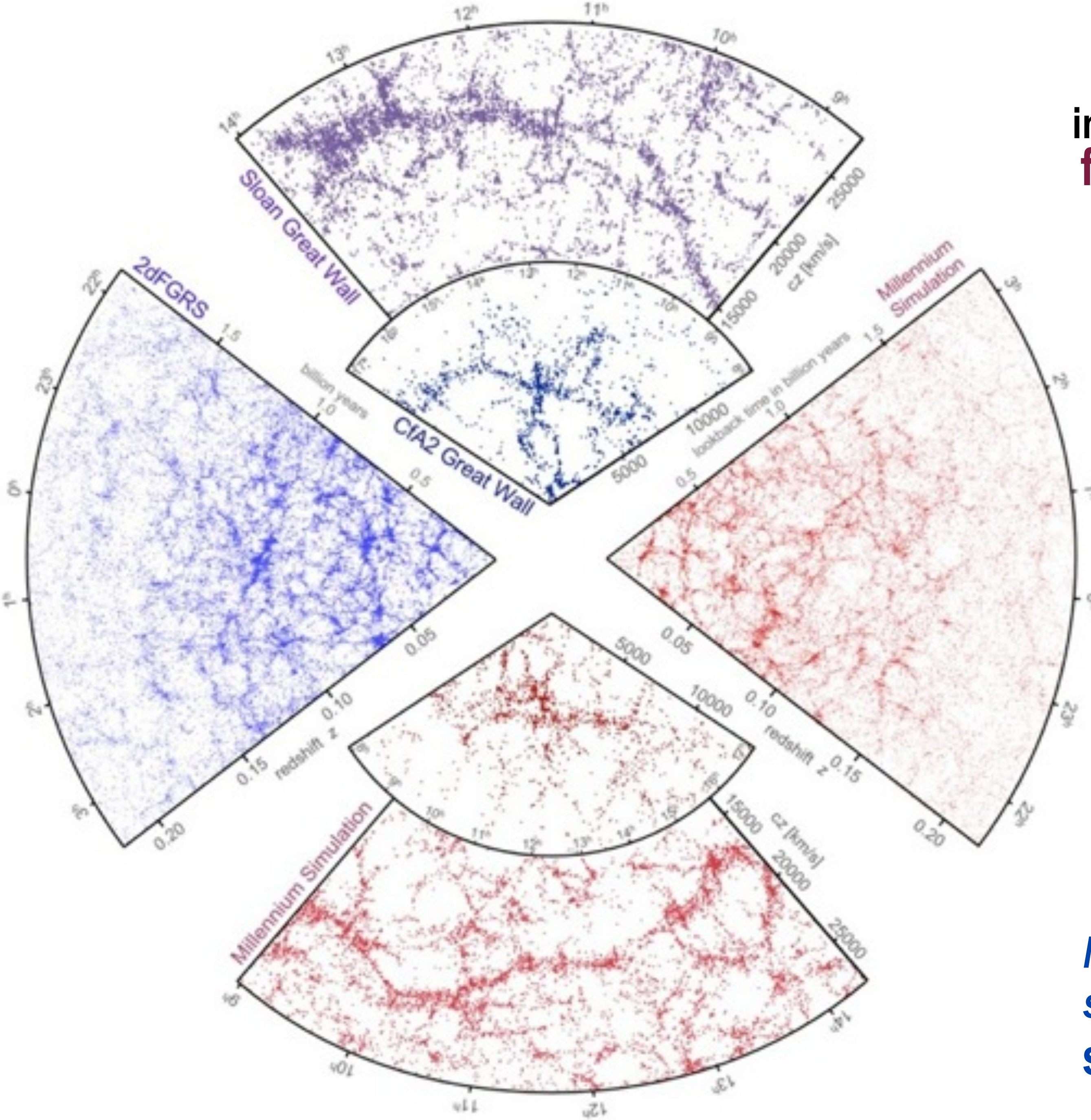
CorBor: biggest scl in Northern Sky 7 cls, $M \approx 4 \times 10^{16}\ h^{-1}M_\odot$

$M/L_B(<20h^{-1}\mathrm{Mpc}) \approx 560\ h L_\odot/M_\odot \Rightarrow \Omega \approx 0.36 \pm 0.1$ Small, Ma, Sargent, Hamilton 98

Hercules: 3 cls, $.8\times10^{16}\ h^{-1}M_\odot$, 530 $\Rightarrow \Omega \approx 0.34 \pm 0.1$ Barmby,Huchra 98

Shapley: 20 cls, $\gtrsim 10^{16}\ h^{-1}M_\odot$, core+web Bordelli etal,, Drinkwater etal

c.f. CNOCl 14cls $\Rightarrow \Omega \approx 0.19 \pm 0.06 \pm 0.04$ Carlberg etal 96,97 to **a ~ 0.8 via 3D maps**



Collisionless matter

Simulation of the initial Gaussian random field characterized by

7⁺ numbers

does indeed beget the

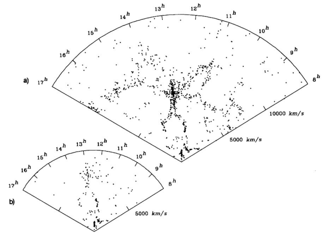
Cosmic Web

Millenium simulation web site "propaganda" on

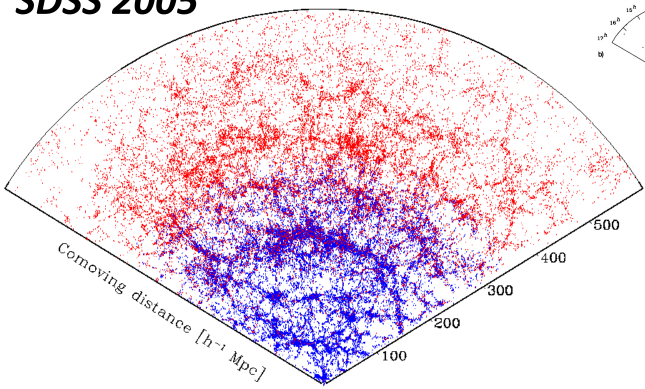
sims *cf.* z-space data

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

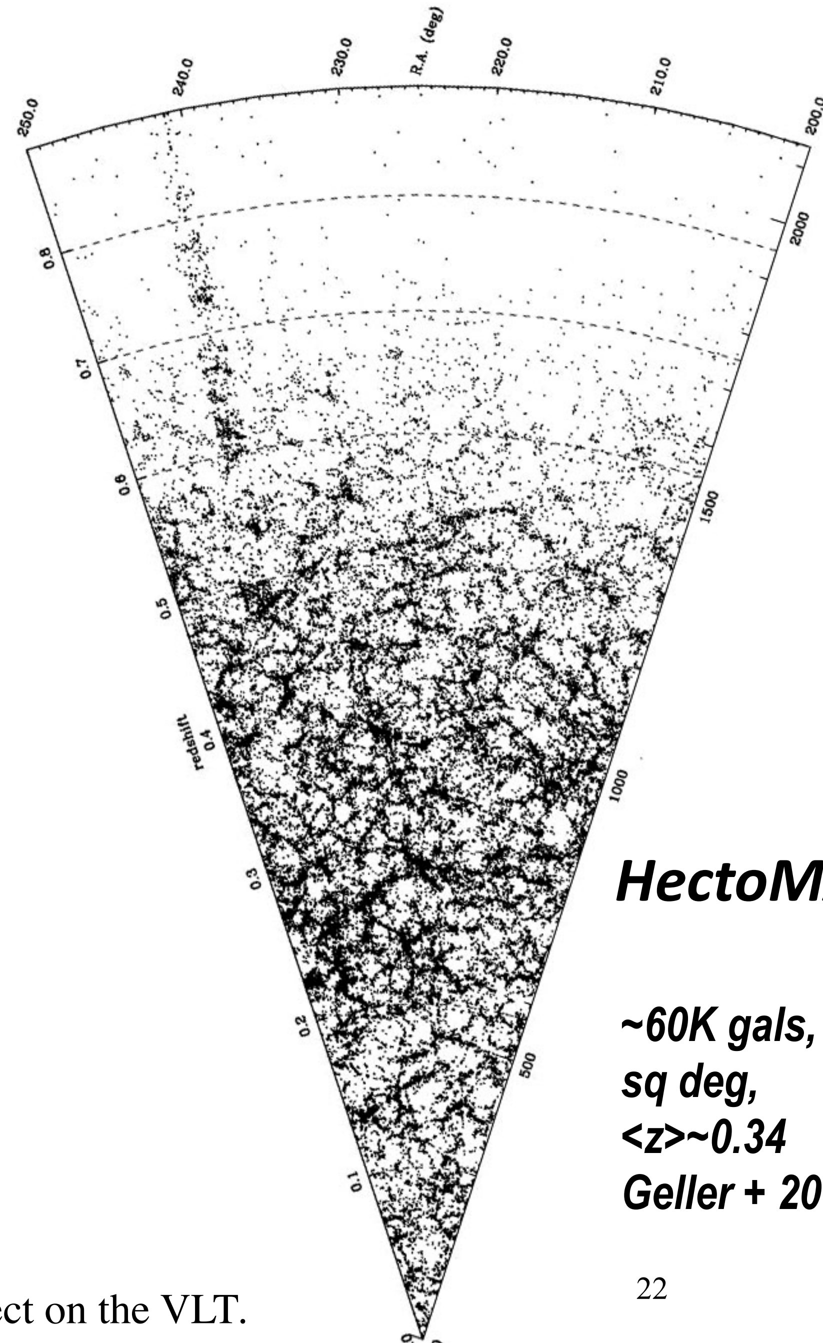
CfA 1986



SDSS 2005



- [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]

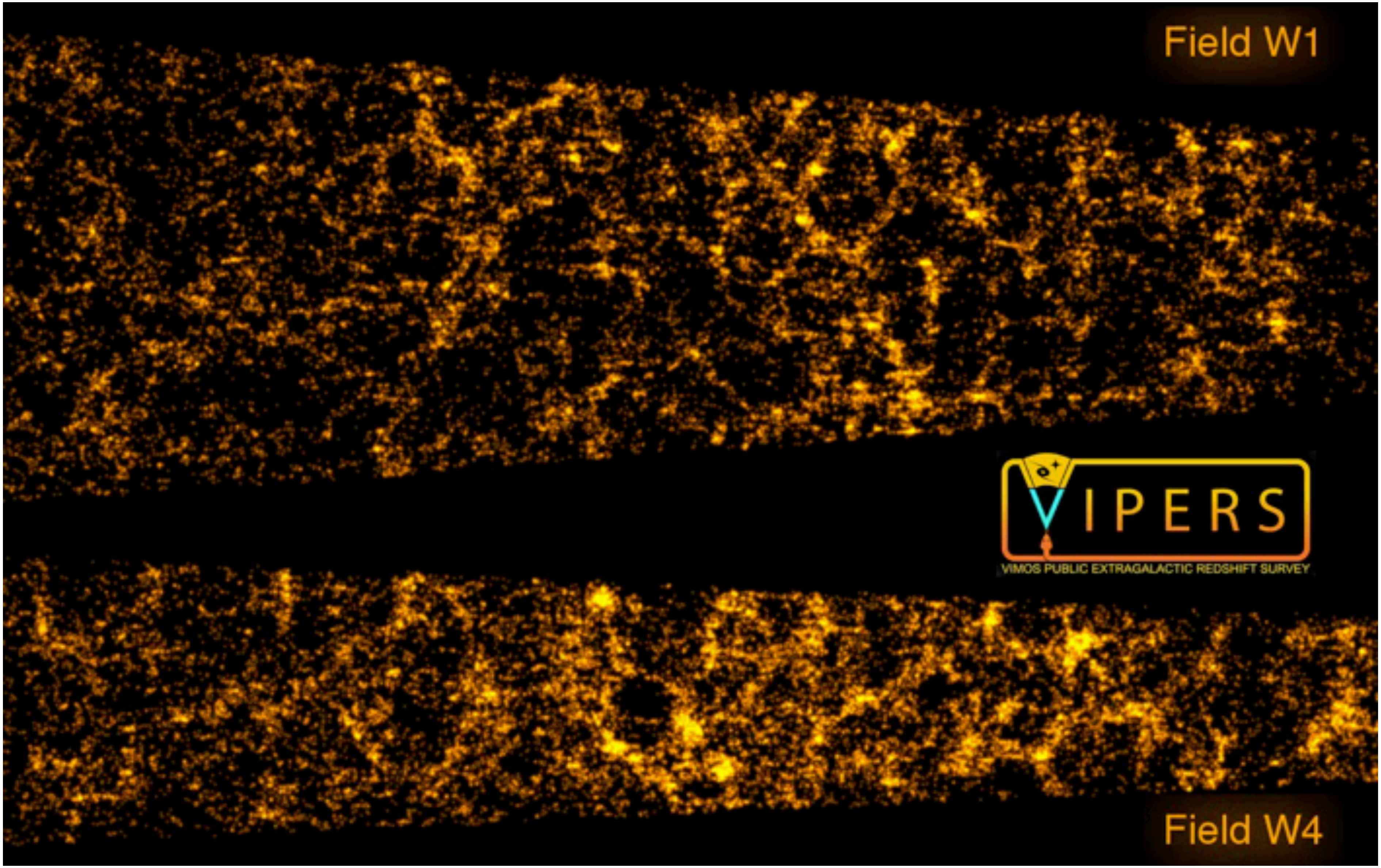


HectoMAP

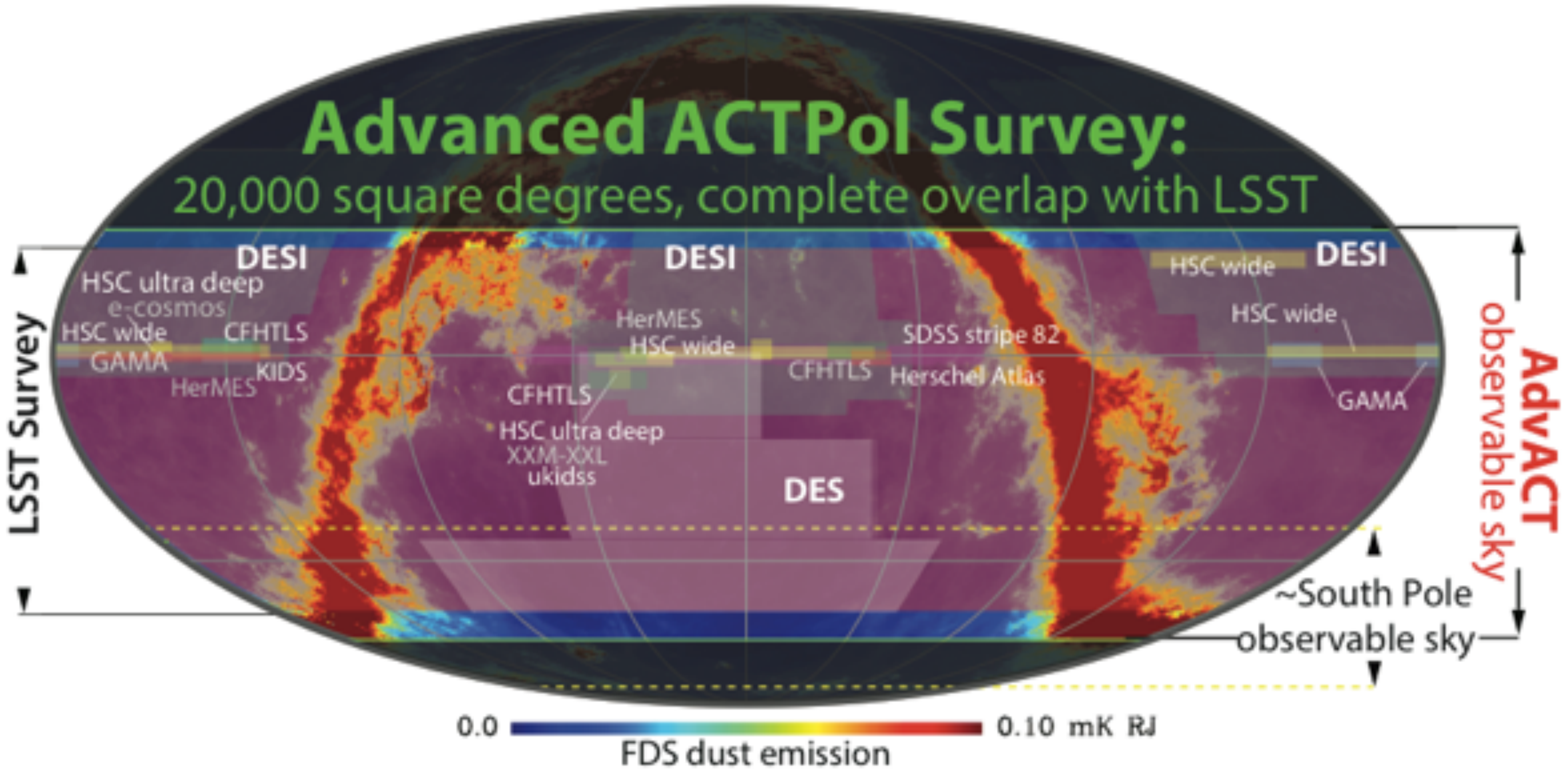
~60K gals, 50 sq deg, <z>~0.34
Geller + 2013..

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



Advanced ACTPol (AdvACT) Observations



- ~20,000 deg^2 survey (f_{sky}~0.5) with complete LSST overlap as well as DES, ALMA, and other observatories located in Chile
- Substantial overlap with spectroscopic surveys (SDSS, PFS, DESI)
- ~ 20K SZ clusters + y-map + kSZ (clusters/reionization)

LSS & the Strain-WEB

aka the gravitational tidal web

~ 3-curvature web

strain power spectrum ~ **density** power spectrum

$$dX^j = (V^i - HX^i)\, dt + a\, e_J{}^j(r,t)\, dr^J$$

$$e_J{}^j \equiv exp(\varepsilon)_J{}^j \qquad \alpha_J{}^j \equiv \varepsilon_J{}^j - \ln a\, \delta_J{}^j$$

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

ε=strain tensor ∝ **tidal** tensor (linear) ⇒ $-\ln \rho/\langle\rho\rangle$ = Trace ε

Scale space: resolution = the 5th dimension

the fluctuation-background split aka peak-background split
our Effective Field Theory, coarse-grain rules LSS, but
fine-grain talks to coarse-grain: halo substructure

Lagrange good on unentangled unHEATed coarse-grained scales but Euler for fine-grain

4+1 dimensions => the ADS to our CRFT => scale dreibein => 4+6 dimensions

brief history of understanding objects and their distribution in the cosmic web

80s: M **scale space** *ln*R_f 3+1D => 4+1D our ADS to CRFT => 9+1D ε

80s: objects=**peaks** of filtered GR initial linear **density** field BBKS..; **clustered shots & bias**

B88a,b,89.. BM91,93a,b,c,94,B96, big unpublished 'preprints' BM93-97,BKP98a,b,BKPW98,BW01

~~90s: threshold-based **excursion sets** & 1-pt statistics of "dark matter" halos BCEK,...~~

lnR_f => resolution as pseudo-imaginary-time $\sigma_{\rho L}{}^2$

imported ***Stochastic Inflation*** ideas of Bond +Salopek 90, 91 into LSS *Langevin, Smoluchowski, Fokker-Planck, barriers, ..*

90s: the **peak-patch picture of cosmic catalogues** BM96a,b,c: tidal/strain fields $\varepsilon^j{}_J(r_{pk},t,R_{pk})$ fundamental in evolution; ***accurate mass & spatial structure determination cf. SP-O gps***; shearing patch simulations BW96-99-02, BWKP99

1. INTRODUCTION BM96a =BM93 preprint

One might wonder why we put effort into approximate descriptions of cosmic structure formation given the tremendous recent and promised advances in computing power. Surely the not very distant future will bring computations of arbitrarily large simulation volumes with arbitrarily high resolution using arbitrarily adaptive hydrodynamical and *N*-body techniques. That will be so. But even so, we need a physical language to discuss the outcomes.

For the all important rare events in the medium, such as massive clusters now and bright galaxies at high redshift, the appropriate idiom is the flowing peak patch at which grand constructive interferences in density and velocity waves mark out the sites of collapse. And radiating outward from the peak-patch core are filaments and sheets that too are rare. The structure may finally fade into the root-mean-square fluctuations in the medium as coherence in the phases fades into randomness. Or the structure may blend into another peak patch, for rare constructive interferences tend to be clustered. No image from the cosmology of the 1980s was as powerful as the CfA picture of Coma and its Great Wall, the paradigm for a peak patch and its environs.

90s: the **cosmic web** of interconnected filaments, membranes & voids, with $\varepsilon^j{}_J$-oriented peak-patches playing a determining role BKP98 ⇒ **"molecular" picture** of large scale structure

all collapses in a hierarchy are warm not cold, becoming hotter as phase space tubes further wind. vs AZS82 & pro BKP98

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 + ...

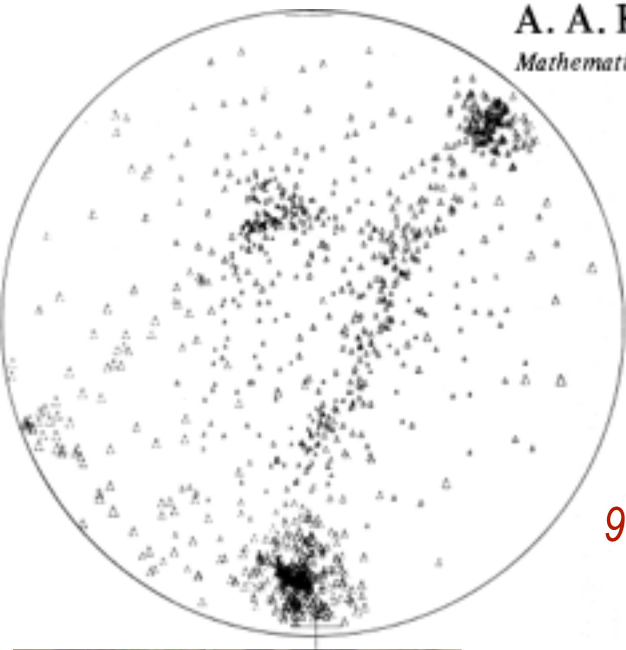
=> *Thou Shalt Mock* *Analytic and semi-analytic treatments cannot intuit the complexity & must be fully calibrated with sims for a useful phenomenology*

BBPSS BBPS1,2,3,4,5

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

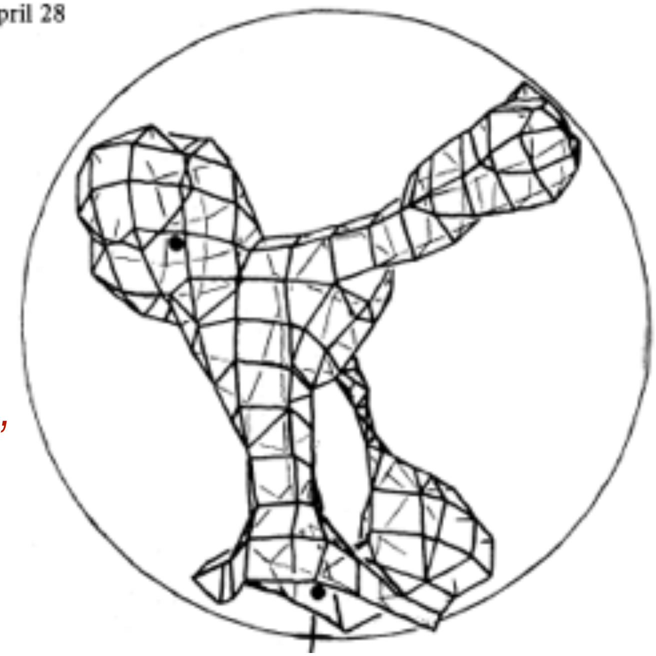
3D numerical model of the Universe

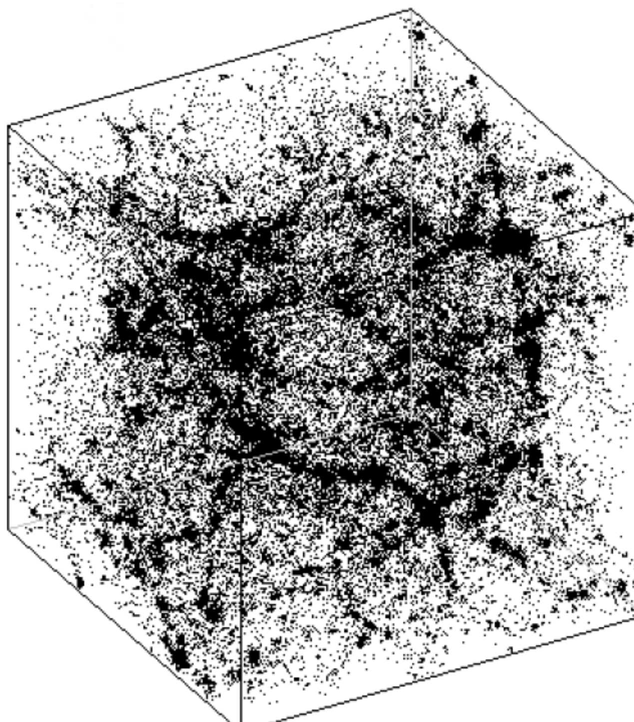


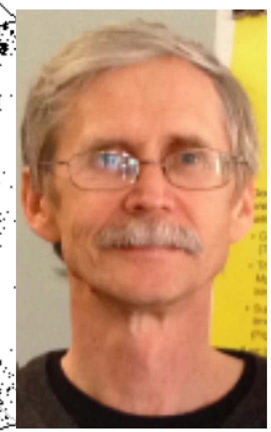
Klypin's vintage 82
160h^{-1}Mpc box 32^3 hDM

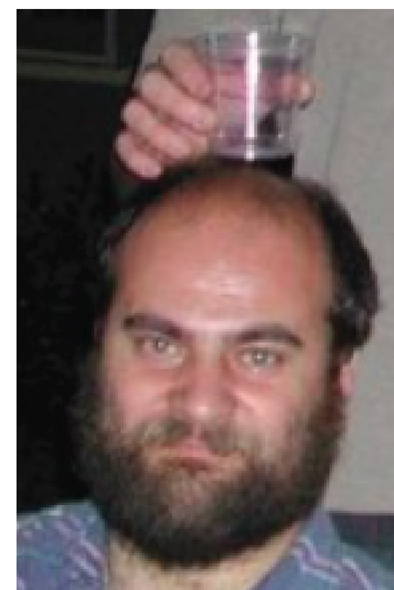
It is possible to recognize some webs connecting these 'clusters of galaxies'

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

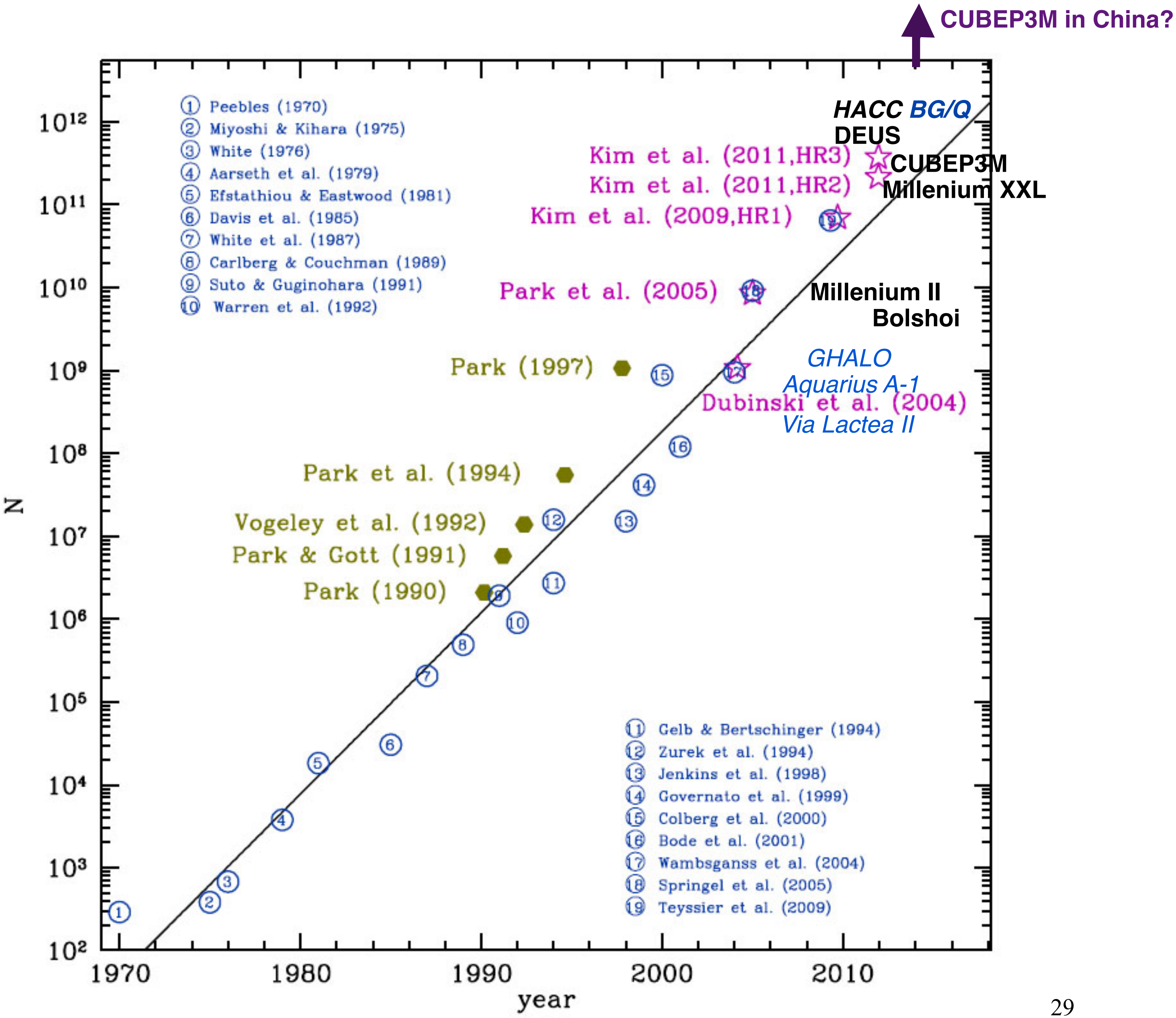








Klypin's vintage 93 50h^{-1}Mpc box 128^3 sCDM = BKP98 web workhorse, *Couchman's 128^3 for BM91-96*



(Juhan Kim et al. 2011)

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*

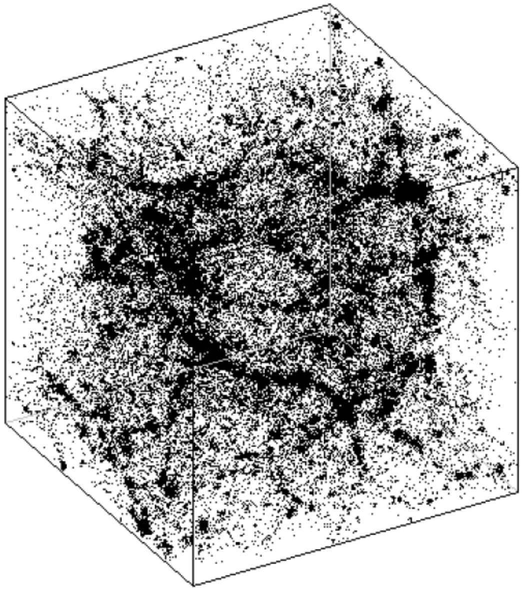
for understanding the web

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 ΛCDM*

~.962 ± .013 small k,

Planck1.3+WP+hiL+BAO

***.9608 ± .0054 small k**,*

-1.3 cluster scale,

-2.3 galaxy scale,

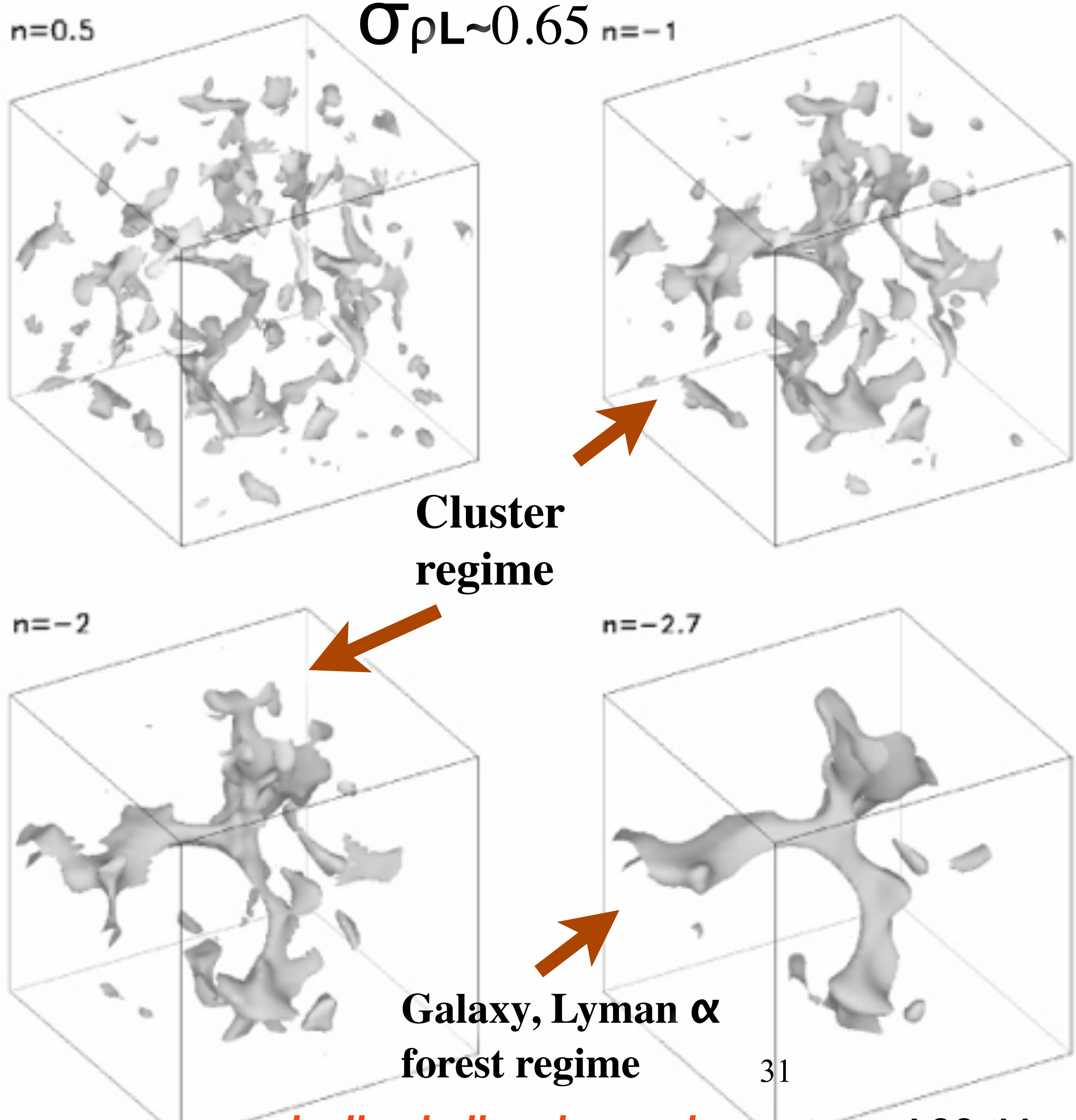
-2.8 Lyman α scale

-3.04 large k, 1st star

percolation threshold contour

smoothing

$\sigma_{\rho L}$~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 LSS
Filaments & Membranes

Constrained Correlation Functions

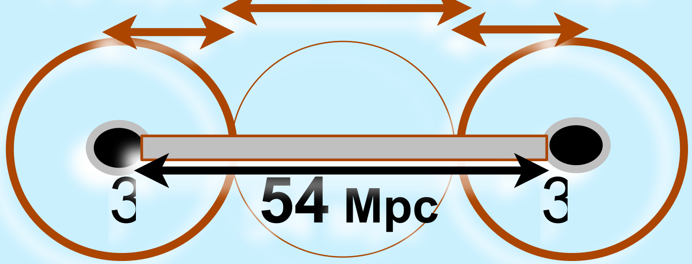
aka $F = \langle F \,|\{q \in \mathcal{C}\}\rangle + F_f$ ***(residual "noise")***

$\langle F \,|\{q \in \mathcal{C}\}\rangle = \langle F q^\dagger \rangle \langle q q^\dagger \rangle^{-1} q = \chi_{Fq} * q,$

χ_{Fq} **F's susceptibility to q a LRT Xcorrelation**

stack for χ_{Fq} e.g., **halo model** for ρ, p χ_{pn}

complete hierarchical representation of a random field by mean fields of a patch/sub-patch point process; peak patches are just stage 1; band-limited sub-patches, sub-sub patches …
but F(r,t) dynamical merger trees are better

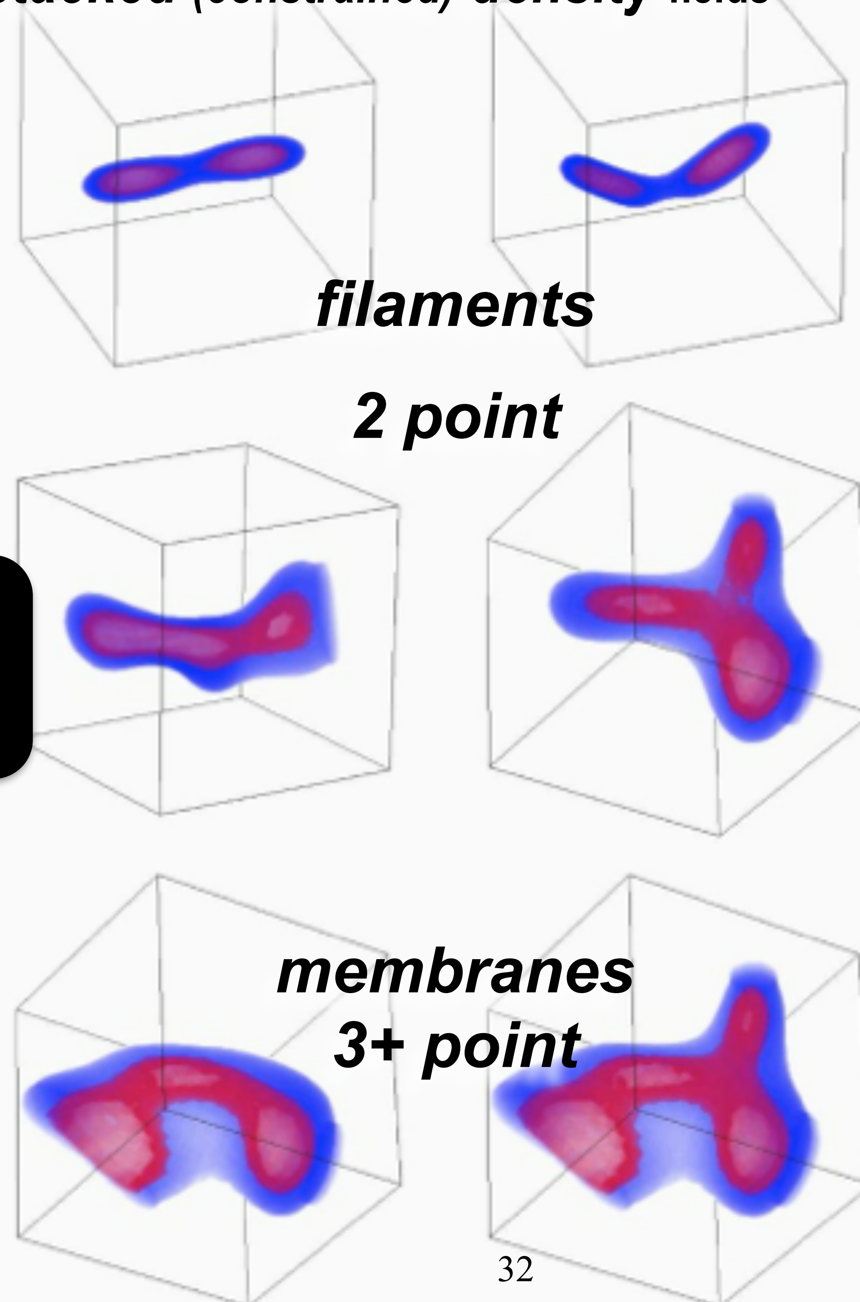


clusters
z~0-1+
$\sim 10^{15}$ M_{sun}

1 Mpc   2 Mpc   1 Mpc
3.6 Mpc

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

stacked (constrained) ***density*** fields



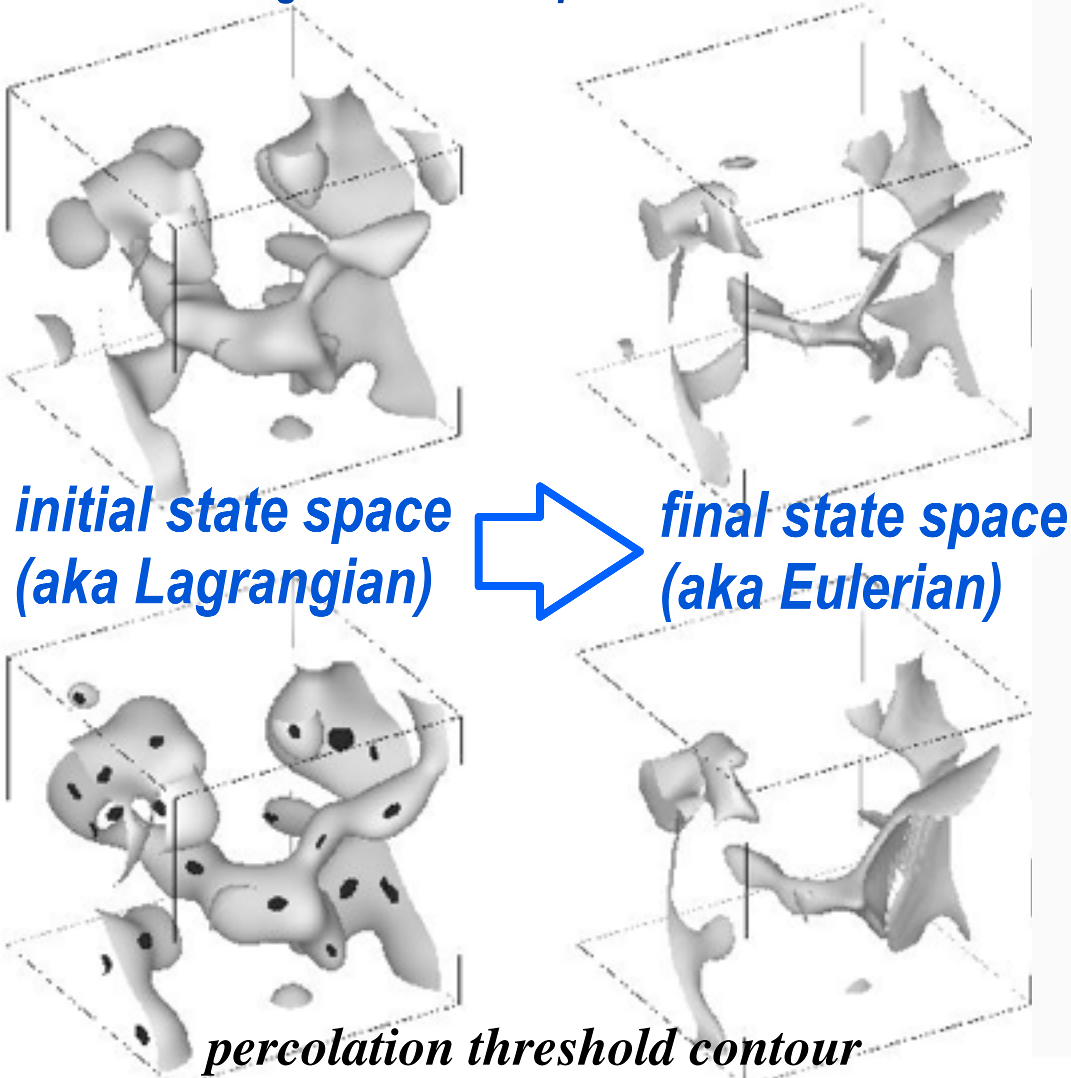
density field **reconstruction** of the filtered web

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

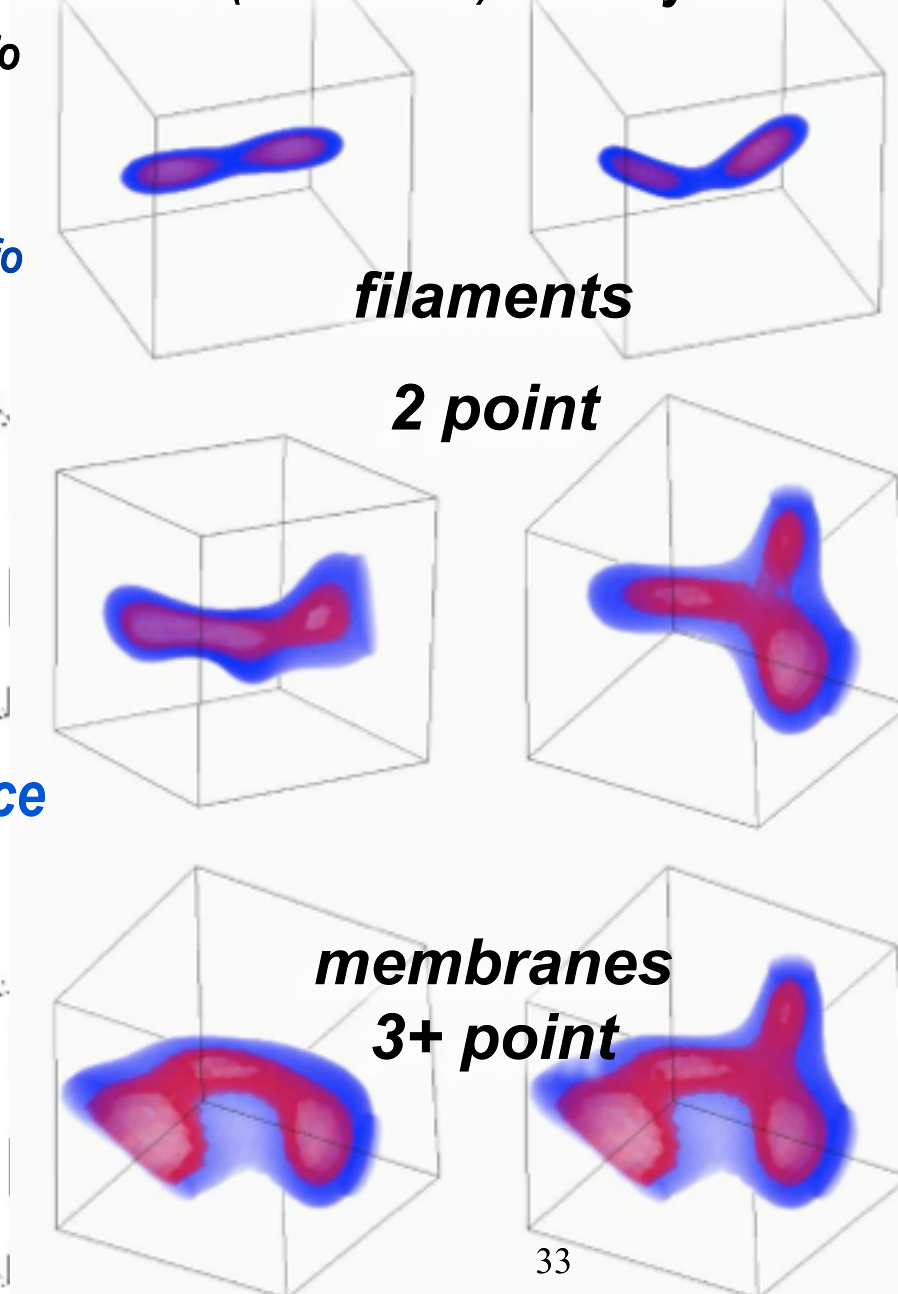
LSS convergence as N_{patch} increases

InformationQuality: ***clusters encode*** *the web*

interior and high resolution spatial detail <=> more info



stacked (constrained) **density** fields



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

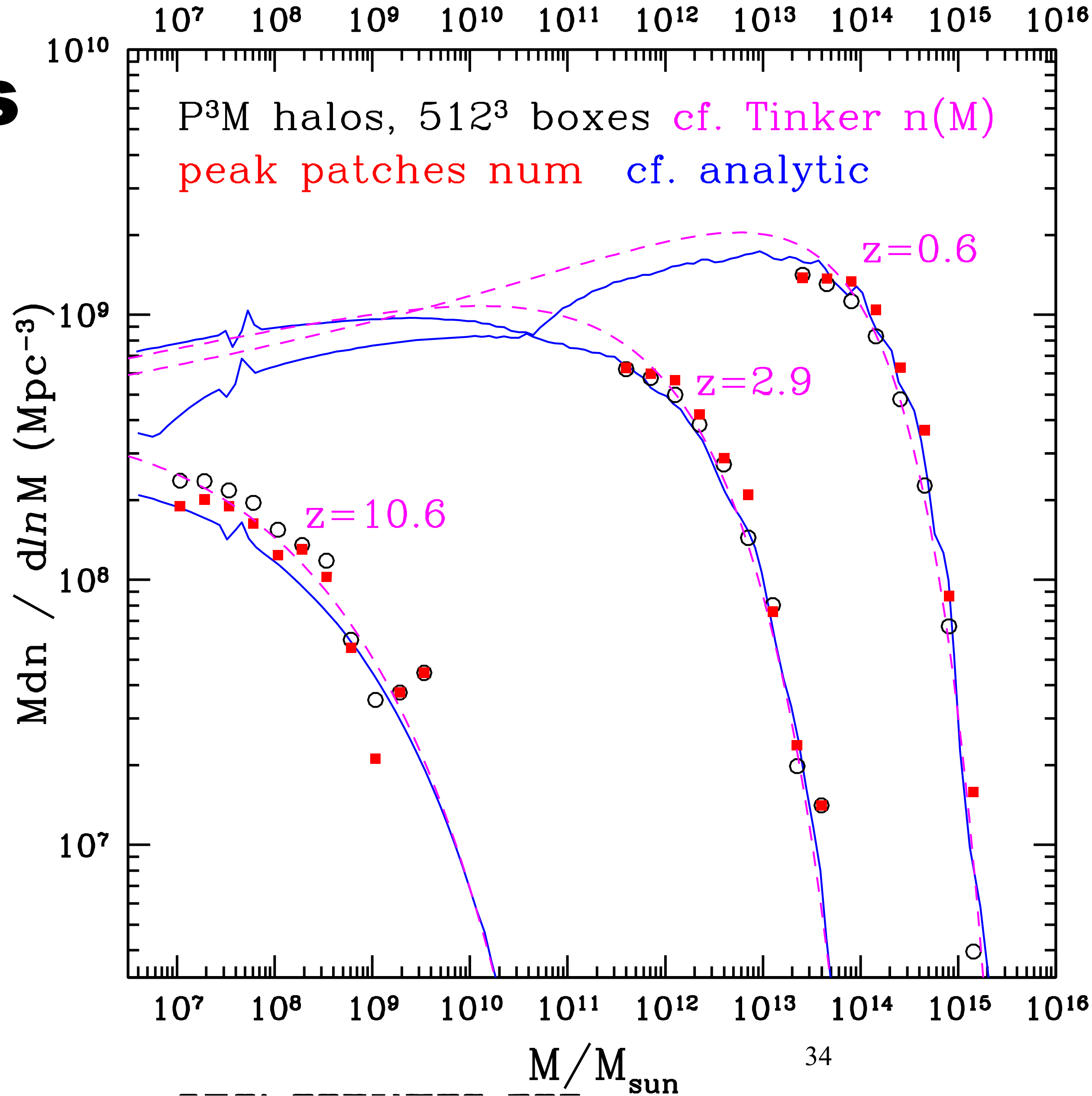
SP-O Halos are exactly Eulerian-space Peak Patches

abundances of halos is understood

numerically & analytically

Euler *cf.* Lagrange

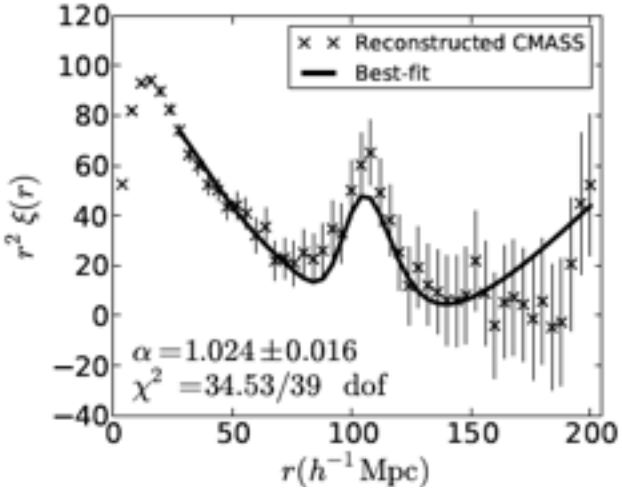
PeakPatches

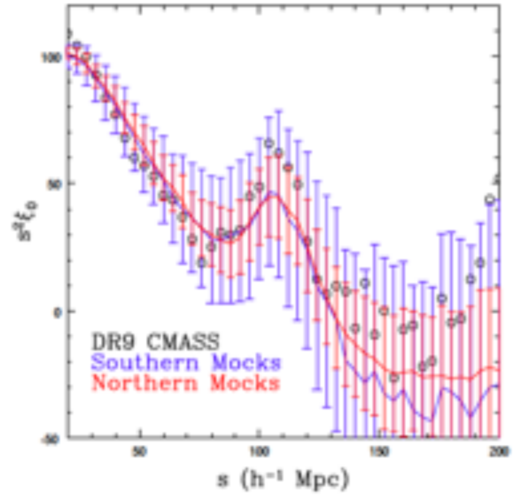


Alvarez, Bond, Hajian, Stein, Emberson 2013

BIAS & 2-point clustering of halos is understood numerically & analytically: move via L1PT + L2PT

BAO in SDSS-III BOSS DR9 galaxies





targets: $\gamma(r) = -d\,ln\,\xi_{gg} \, -d\,ln\,r$ + BAO

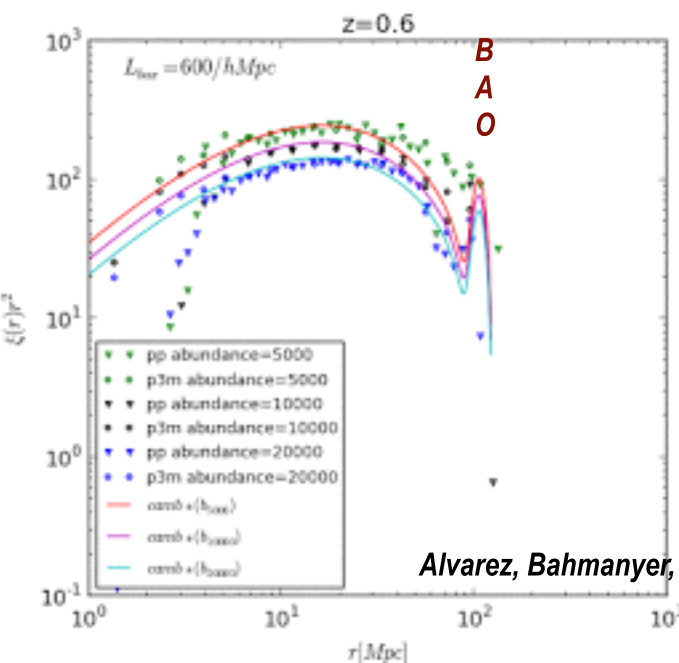
SDSS-III BOSS data cf.

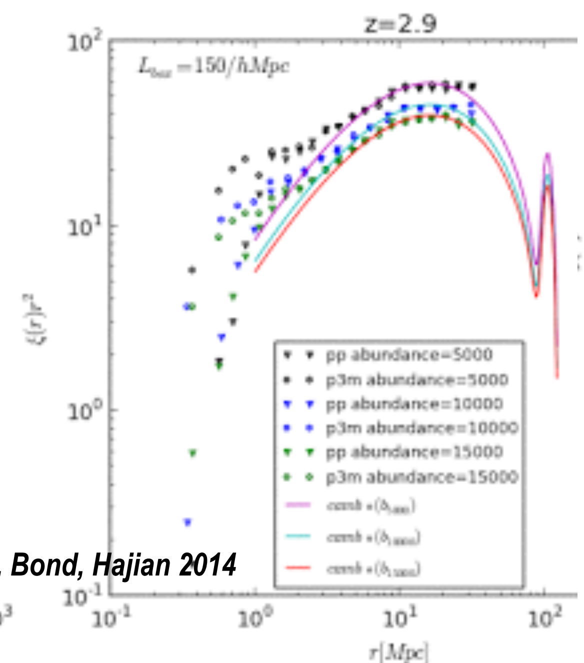
Manera+12 600 L2PT +HOD sims

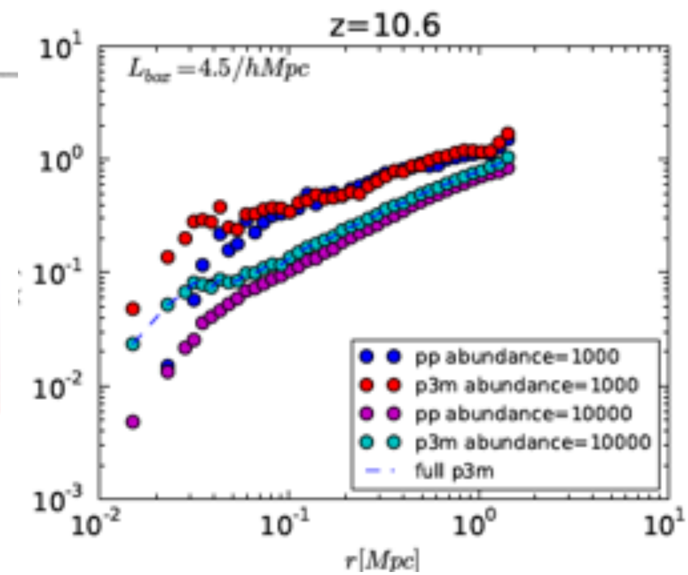
PkPatch fast & better halo masses

SP-O Halos are exactly Eulerian-space Peak Patches

Peak patches cf 512^3 CUBEP3M halos using SP-O, boxes are: 600, 150, 4.5 h^{-1}Mpc



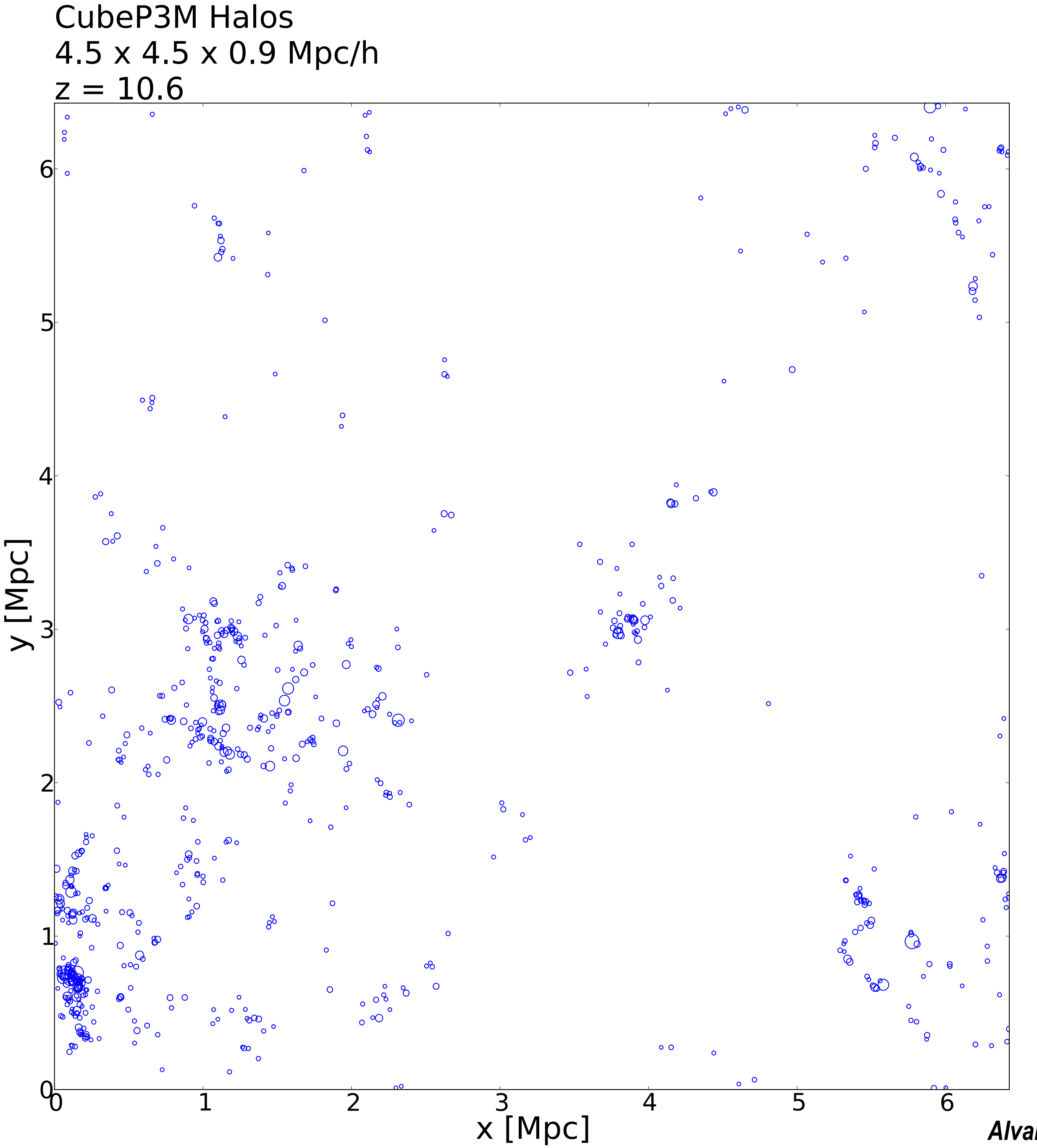




Alvarez, Bahmanyer, Bond, Hajian 2014

hi-z challenge: flat power per e-fold
periodic BC => box scale truncated

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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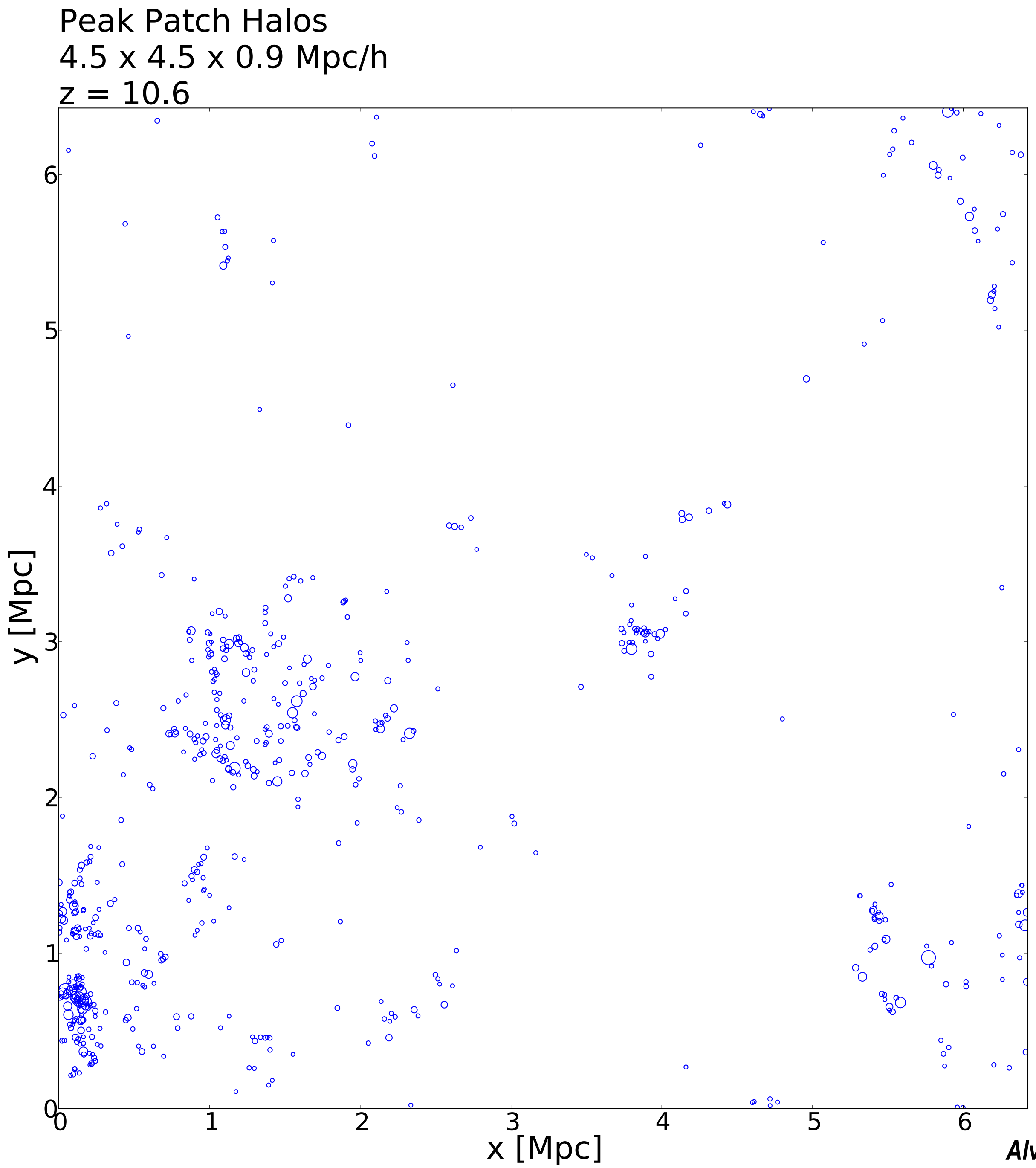

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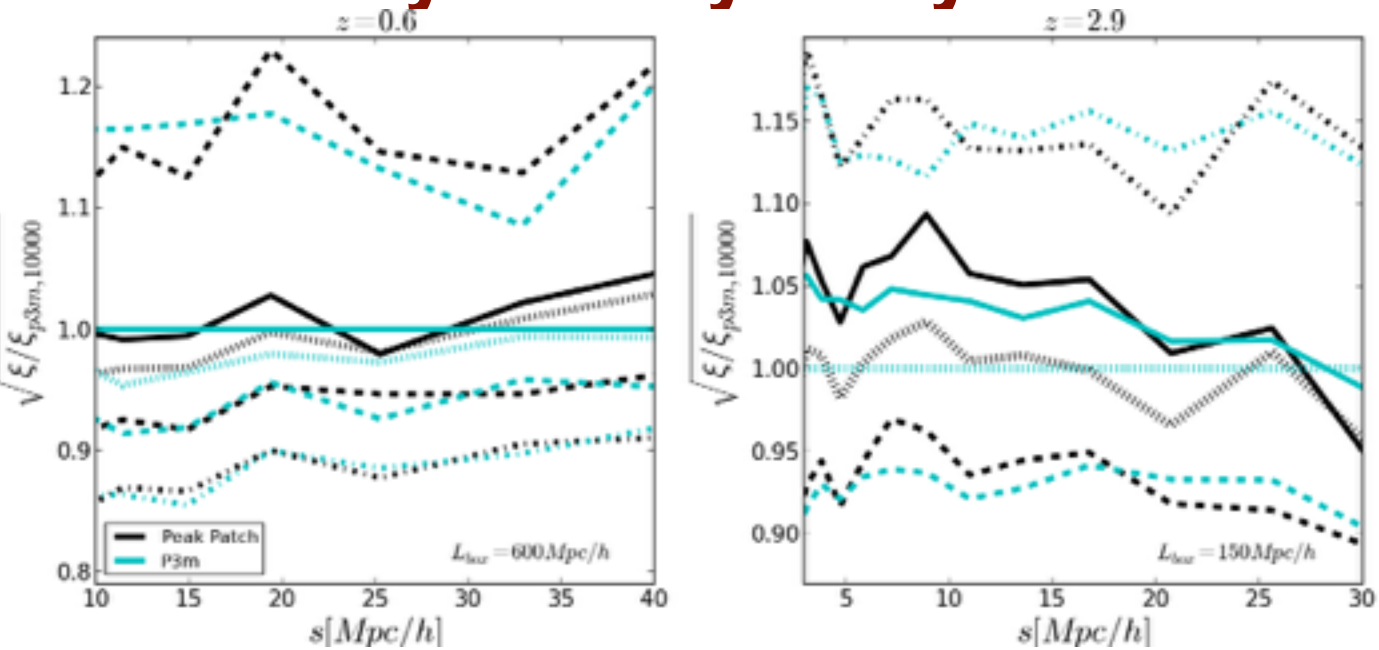

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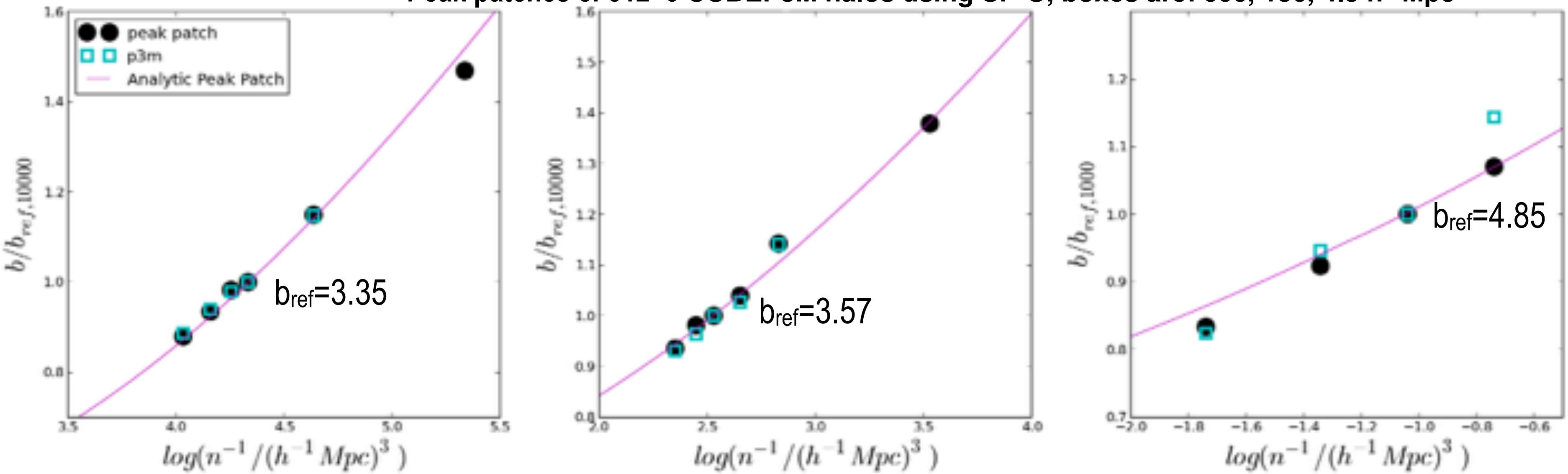


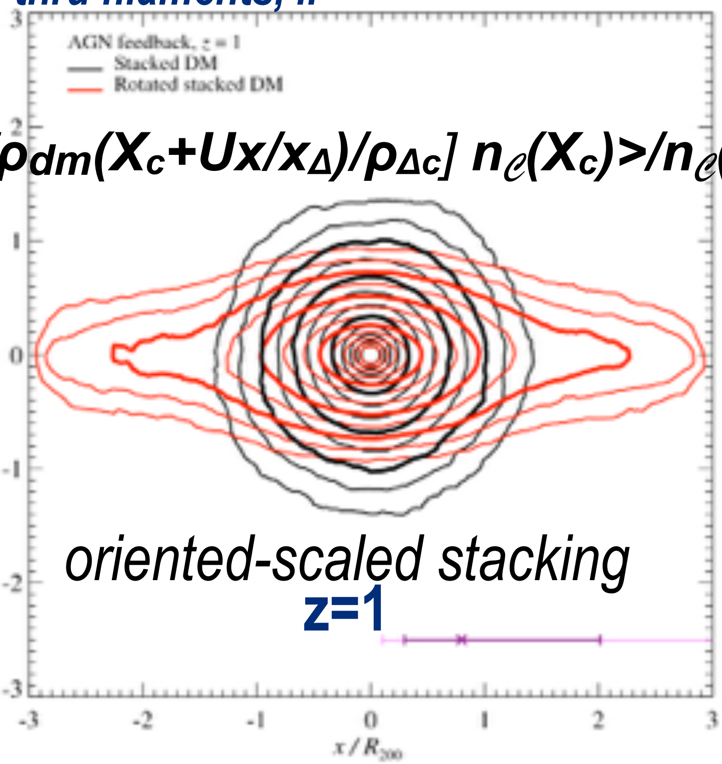
HALOs in the Web(z)

the CLUSTER SYSTEM example

Halos are Complex Systems

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

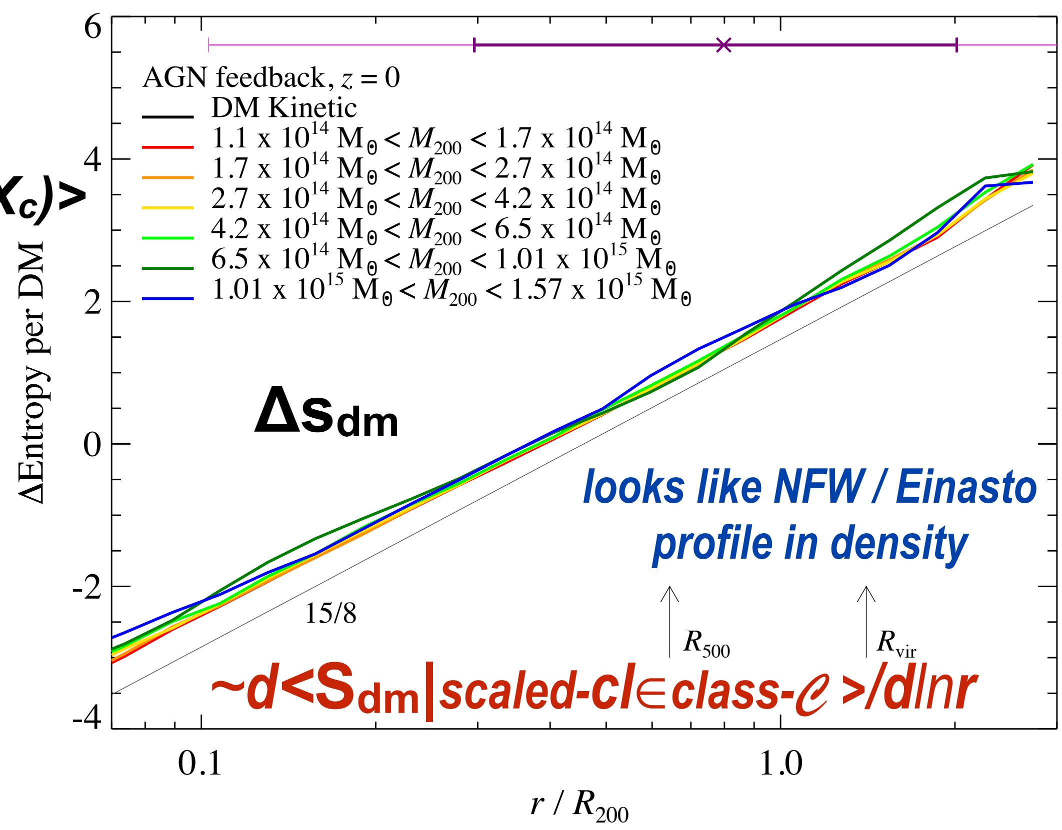
$< [\rho_{dm}(X_c+Ux/x_{\Delta})/\rho_{\Delta c}]\ n_{\mathscr{C}}(X_c)>/n_{\mathscr{C}}(X_c)>$



oriented-scaled stacking
z=1

Universal dark matter Entropy Profile? yes!!

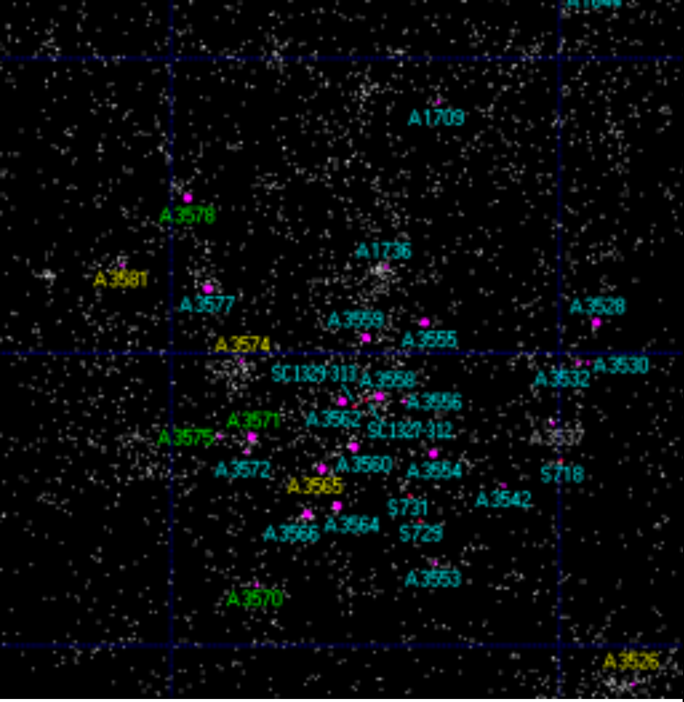
slope~self-similar radial infall Navarro
ongoing mystery - why halos have this entropy growth law



Δs_{dm}

looks like NFW / Einasto profile in density

$\sim d\langle S_{dm} | \text{scaled-cl} \in \text{class-}\mathscr{C} \rangle / d\ln r$



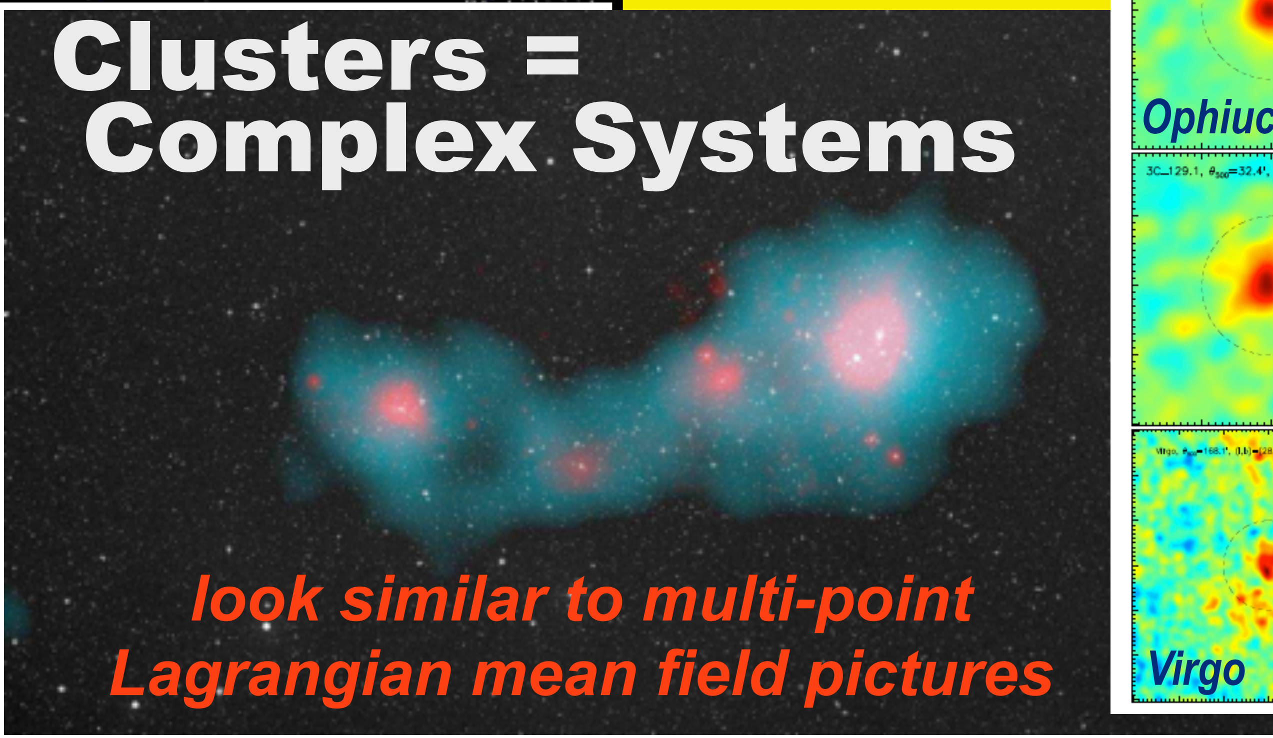
thermal SZ clusters

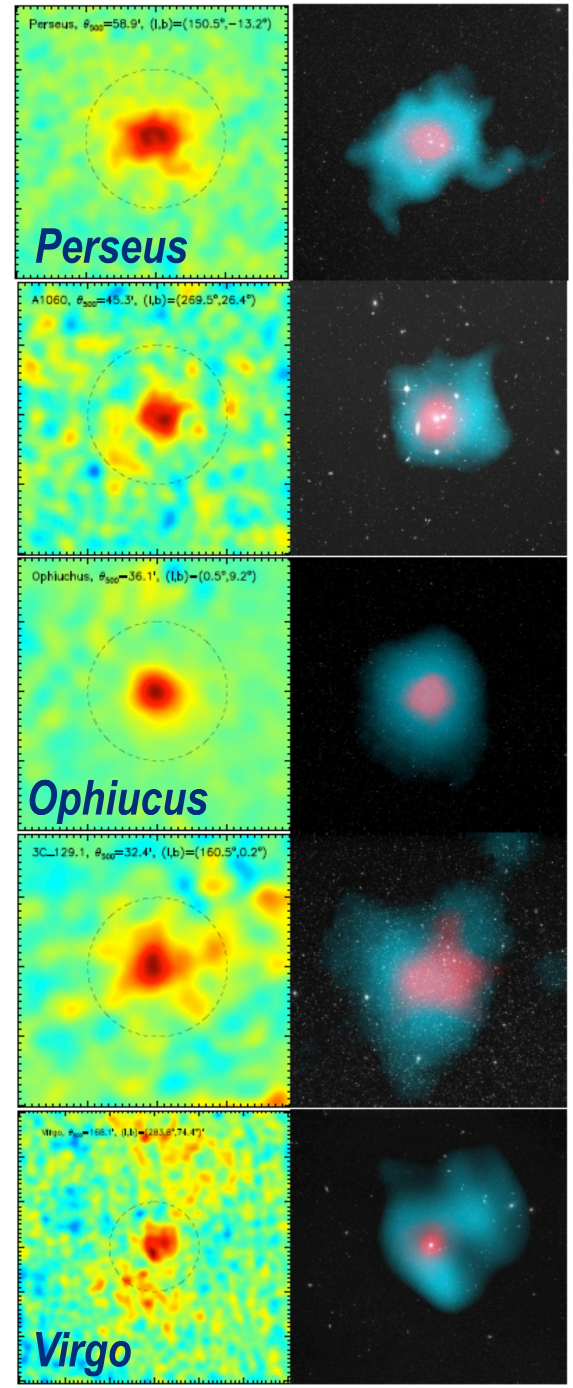
some nearby well-known clusters from Perseus to Virgo

Shapley Supercluster

<overdensity> ~5

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





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

2005 2007 224 (=> **747**) 2009

>96
OVRO /BIMA array
38 cls

80s-90s
Ryle
OVRO

Acbar@SP
~1 blind

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

AMI
7+1 cls >=50+25

AMIBA
6 cls

APEX
~400 bolos@Chile
~25 cls

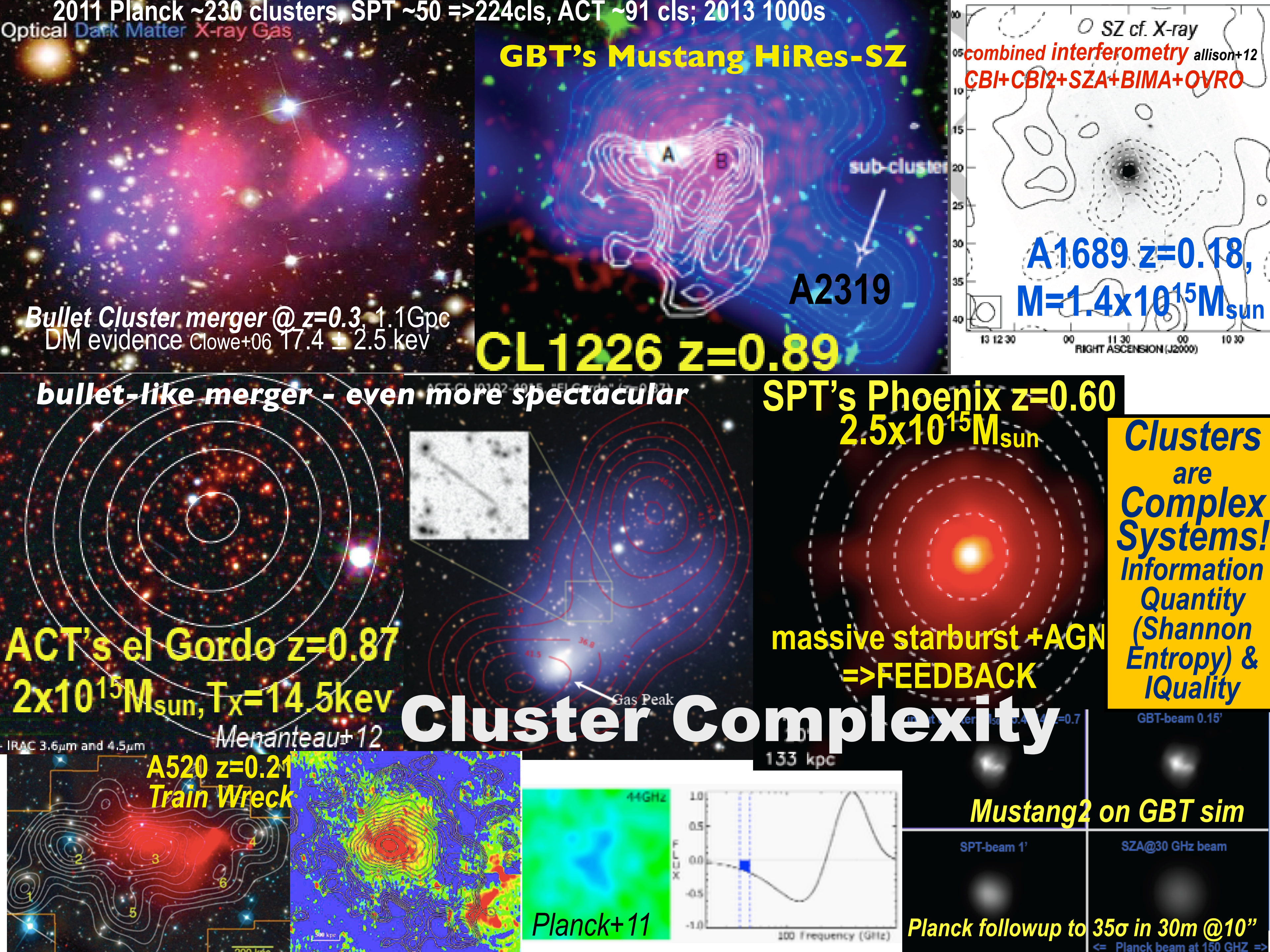
GBT Mustang
4 cls (~25 CLASH)

SPT
1000 bolos
@SPole

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

SCUBA2
12000 bolos
JCMT @Hawaii

SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico



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

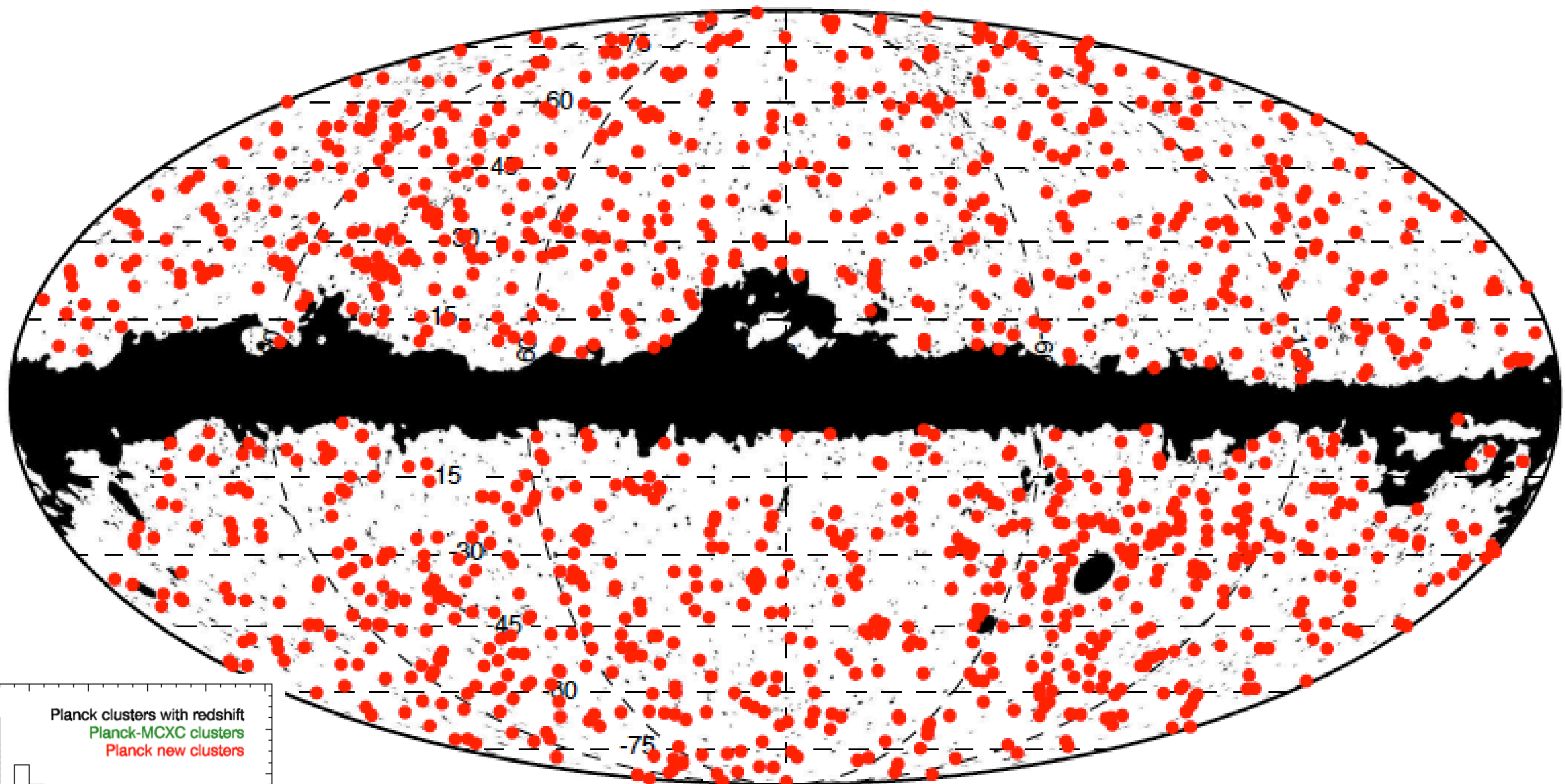
Compton cooling of high pressure / entropy electrons by the CMB

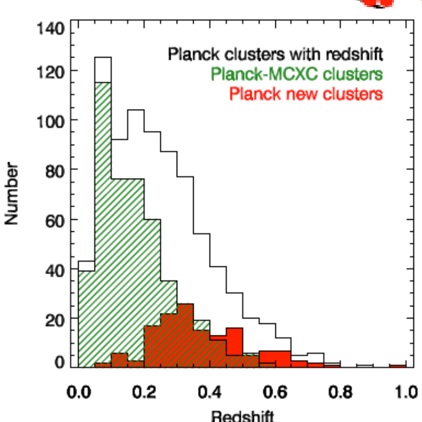
thermal SZ effect **Planck2013 1227 clusters, SPT 224 =>747cls, ACT 91 cls**

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





HALOs in the Web(z)

SIMULATIONS

N-body using **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

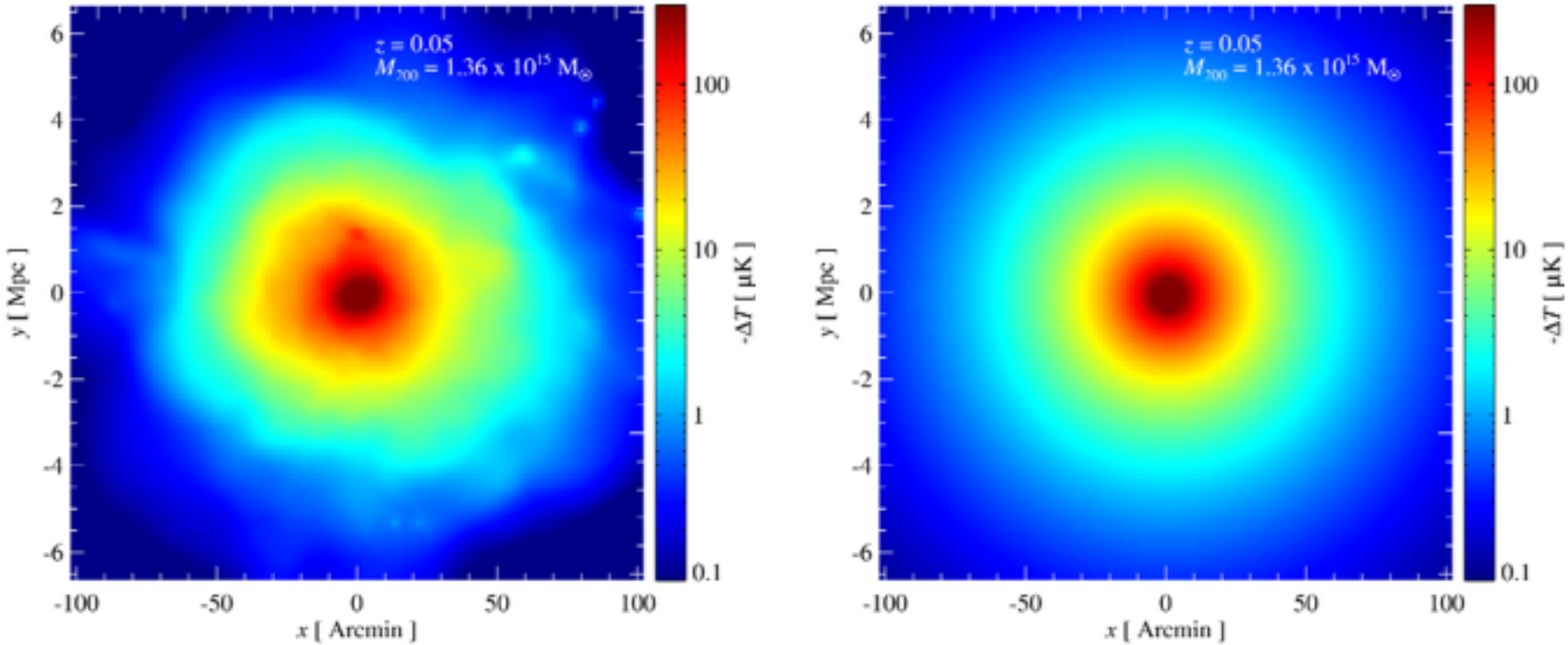
fundamental physics from the cluster web? or a gastrophysical indigestion blockage?

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

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

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

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

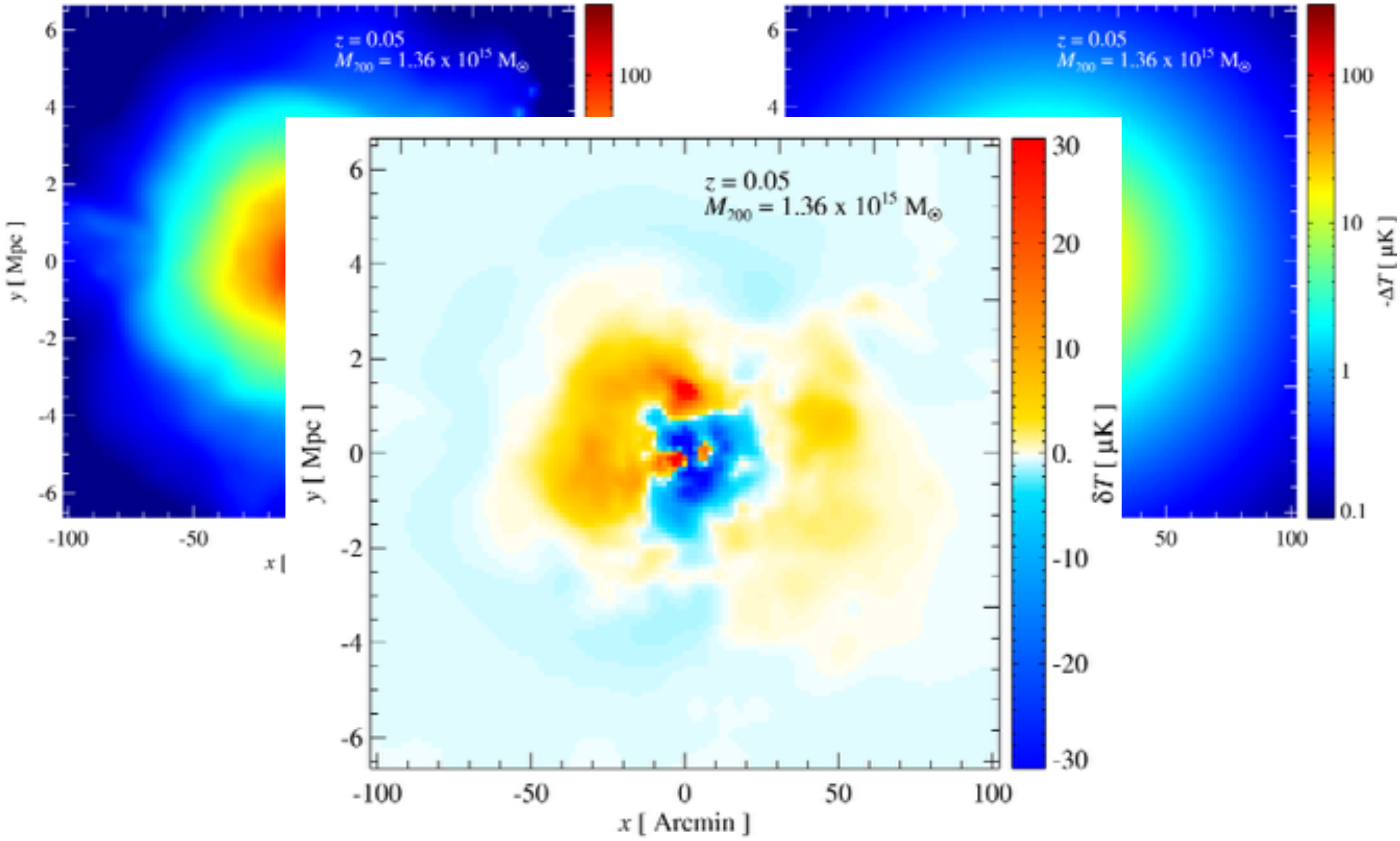


Same cluster (pasted on GNFW according to mass)

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

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

p_f (residual "noise")



HALOs in the Web(z)

SIMULATIONS

E or L Peak-Patches

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using Hydro

Gas

Stars

Black Holes

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BBPSS BBPS1,2,3,4,5

fundamental physics from the cluster web? or a gastrophysical indigestion blockage?

the **Cosmic Web of Clusters**, seen thru

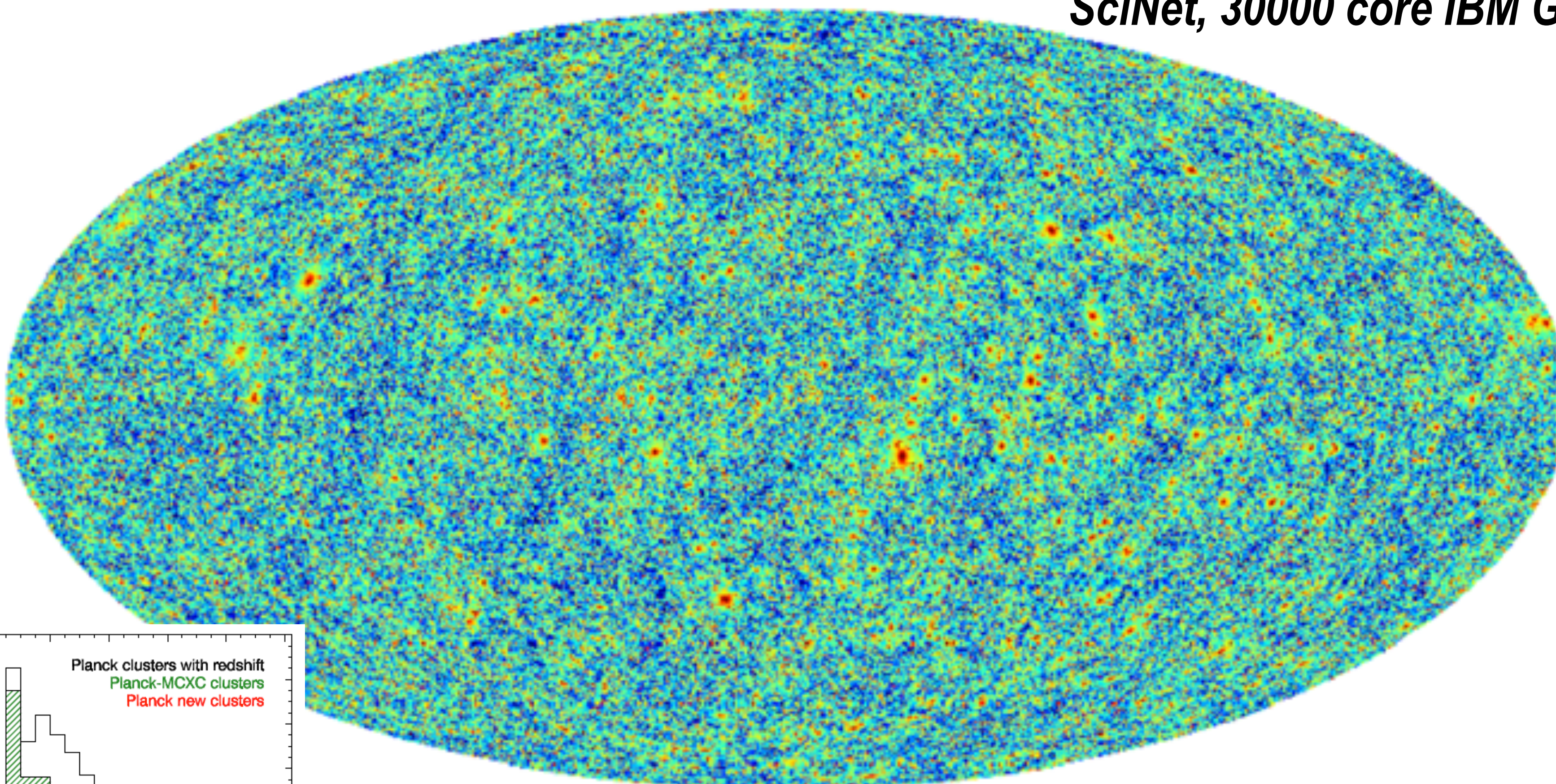
Compton cooling of high pressure electrons by the CMB

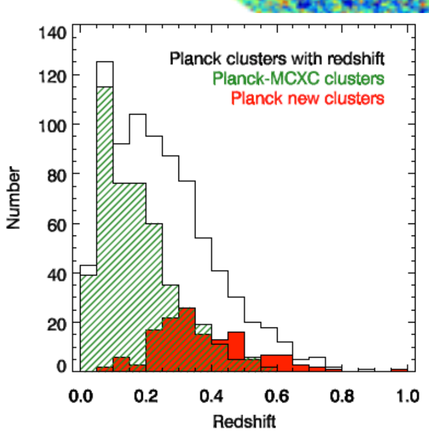
tSZ effect

Lightcone Simulation of 35000 Clusters > 1.5×10^{13} M_{sun} to z=0.5 in projected pressure

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

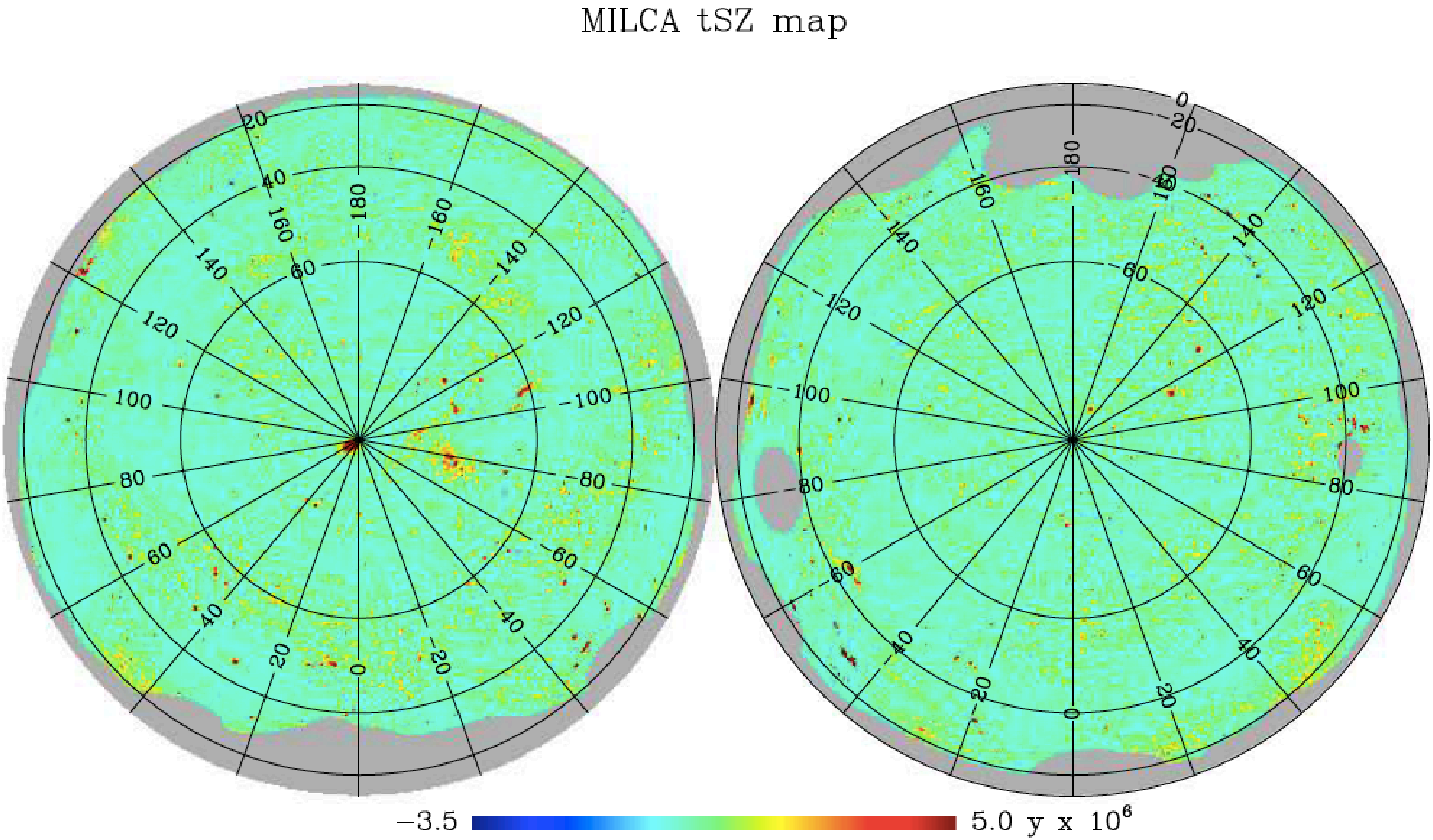
1.5 hours on 256 cores on SciNet, 30000 core IBM GPC





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

SZ power spectrum from ymaps Planck2013 XXI; *also van Waerbeke, Hinshaw & Murray 13, Hill & Spergel 13*



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, .. ***via Mocks***

HALOs in the Web(z)

Cluster/group web MOCKs

Hydro AGN feedback sims

cf.

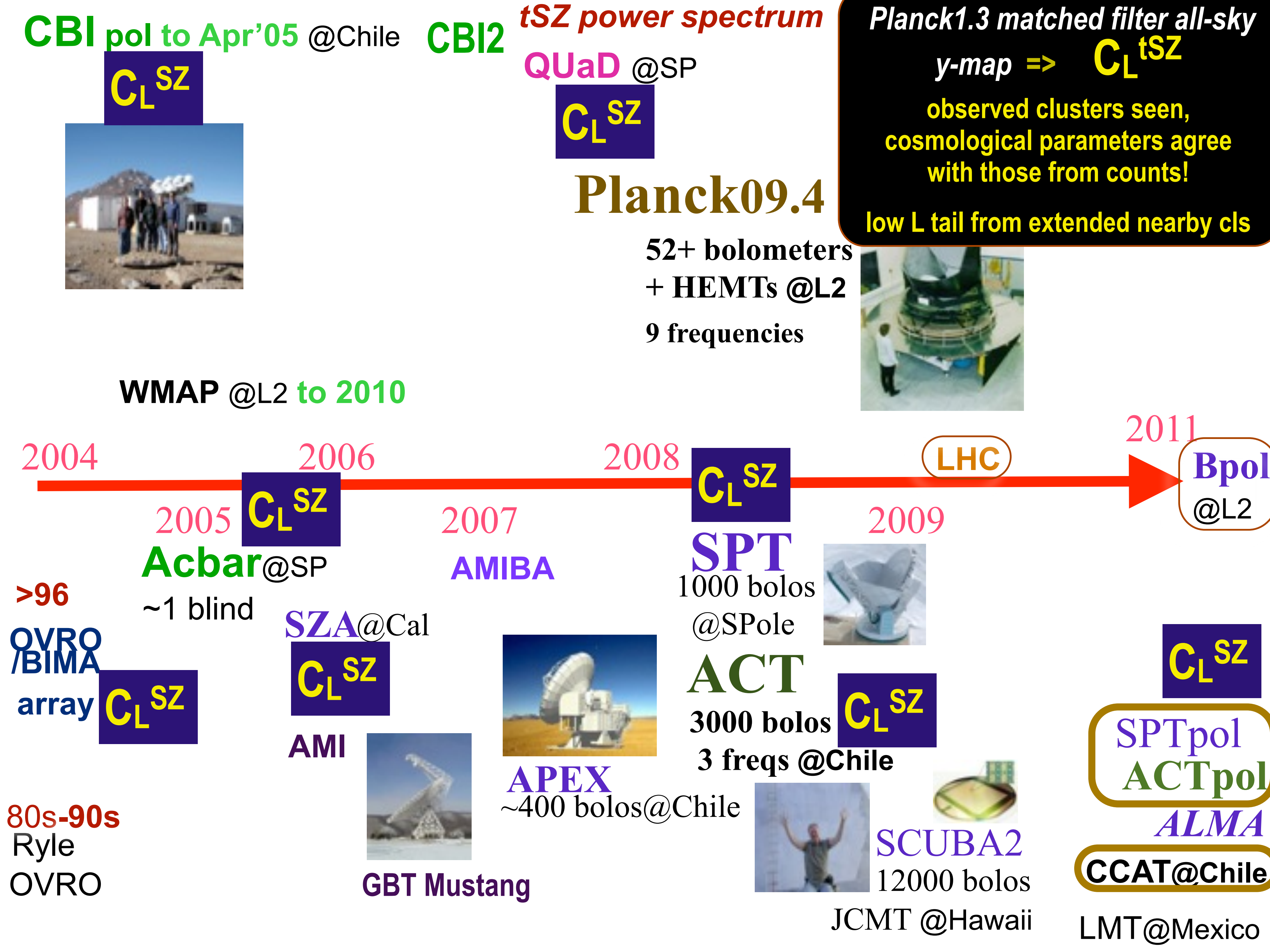
Peak Patches mean-fields from sims

tSZ: rotated translated stacking of 10 periodic boxes

cf. full light cone PkPatch non-periodic sim

Alvarez, Bond, Hajian, Battaglia + ***2014 peak patches cf. BBPS***
Hajian, Alvarez, Bond 2014: ***machine learning of complex multidimensional selection functions***

fundamental physics from the cluster web? or a gastrophysical indigestion blockage?


CBI pol to Apr'05 @Chile
C_L^{SZ}
CBI2
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
2011
LHC
Bpol
@L2
C_L^{SZ}
Acbar@SP
~1 blind
>96
OVRO
/BIMA
array
C_L^{SZ}
SZA@Cal
C_L^{SZ}
AMI
AMIBA
GBT Mustang
APEX
~400 bolos@Chile
C_L^{SZ}
SPT
1000 bolos
@SPole
ACT
3000 bolos
3 freqs @Chile
C_L^{SZ}
SCUBA2
12000 bolos
JCMT @Hawaii
C_L^{SZ}
SPTpol
ACTpol
ALMA
CCAT@Chile
LMT@Mexico
80s-90s
Ryle
OVRO

HALOs in the Web(z)

the CLUSTER SYSTEM example

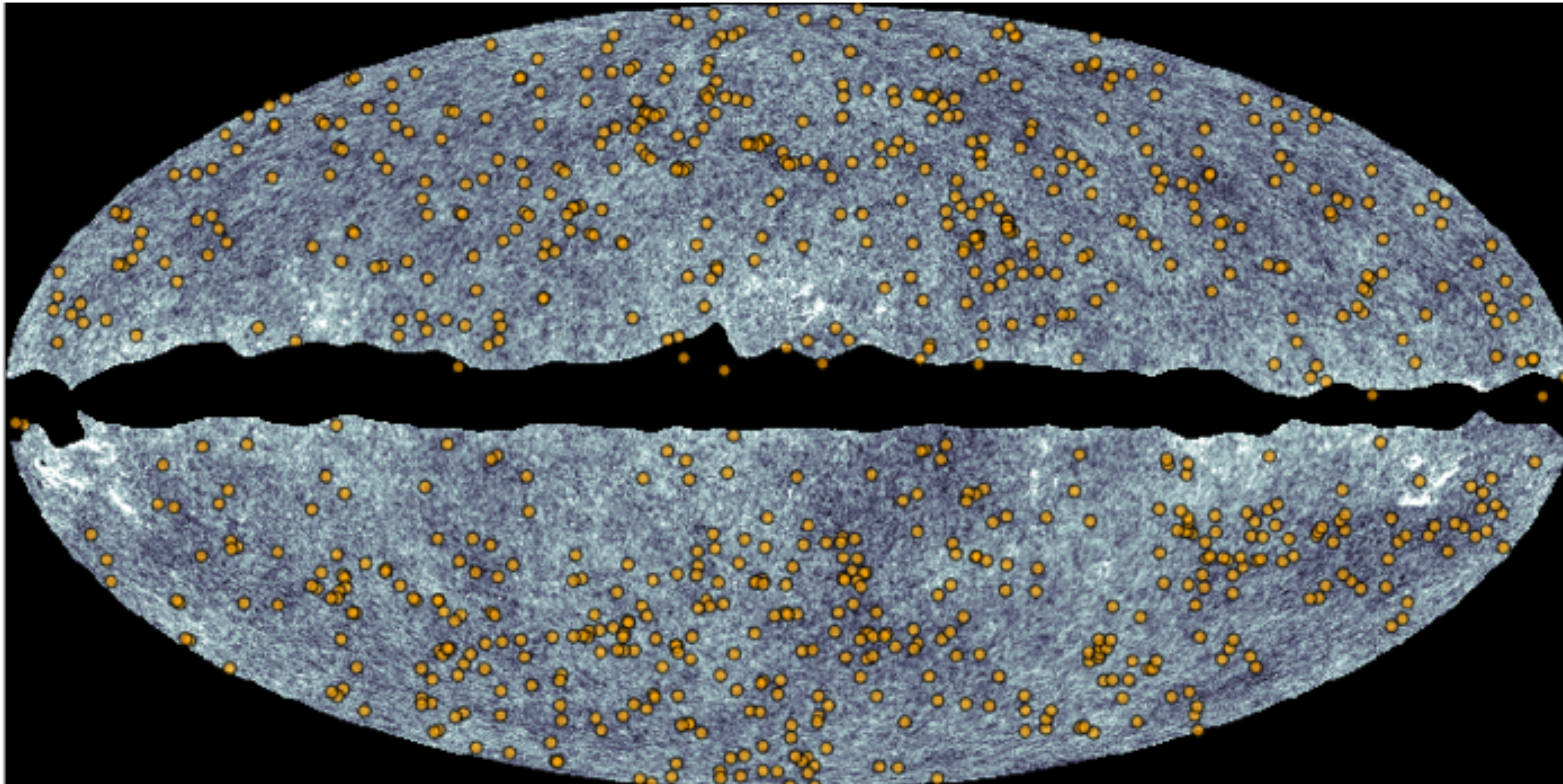
Cross-correlations of X-rays and CMB maps = X-corr power spectra, a path to

σ_{8SZ} =0.81 ± .01 P13+X-SZ

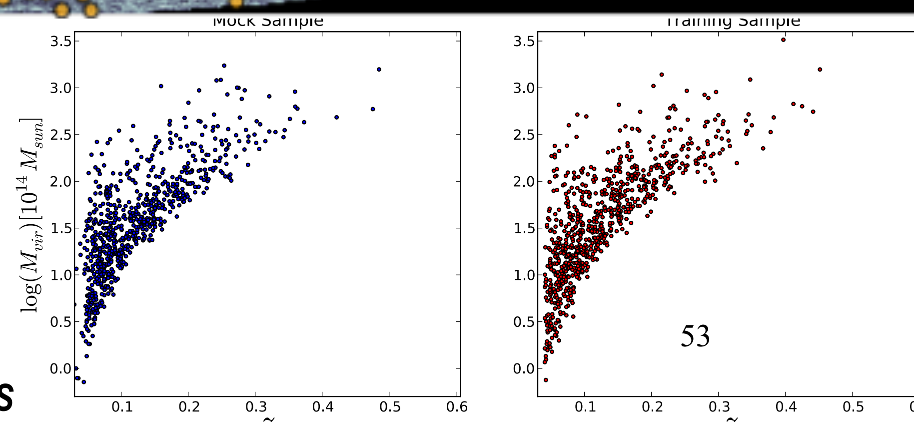
Hajian, Battaglia, Spergel, Bond, Pfrommer, Sievers 2013 **Planck + WMAP9 x ROSAT (RBC subset of MXCC)**

fundamental physics from the cluster web? or a gastrophysical indigestion blockage?

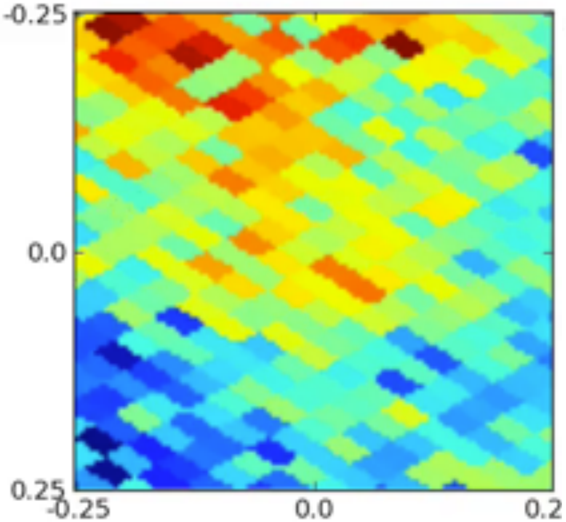
Hajian, Battaglia, Spergel, Bond, Pfrommer, Sievers 2013 **Planck + WMAP9 x ROSAT (RBC subset of MXCC)**



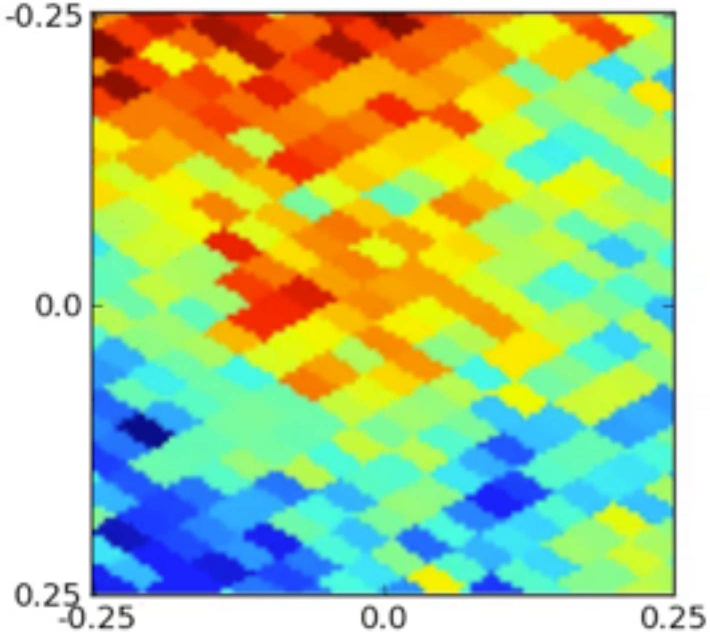
Hajian, Alvarez, Bond 2014: ***machine learning of the RBC sample using all sky Planck peak-patch mocks with BPSS p-profiles painted on.***



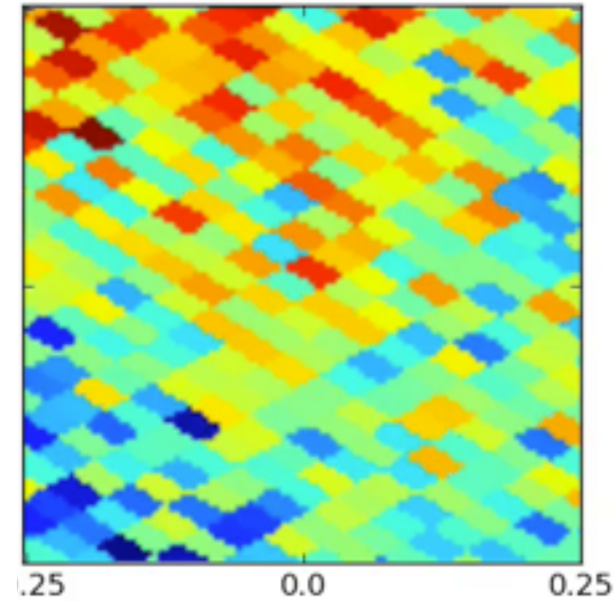
Alvarez, Bond, Hajian, Battaglia + ***2014 peak patches cf. BBPS***



217 GHz

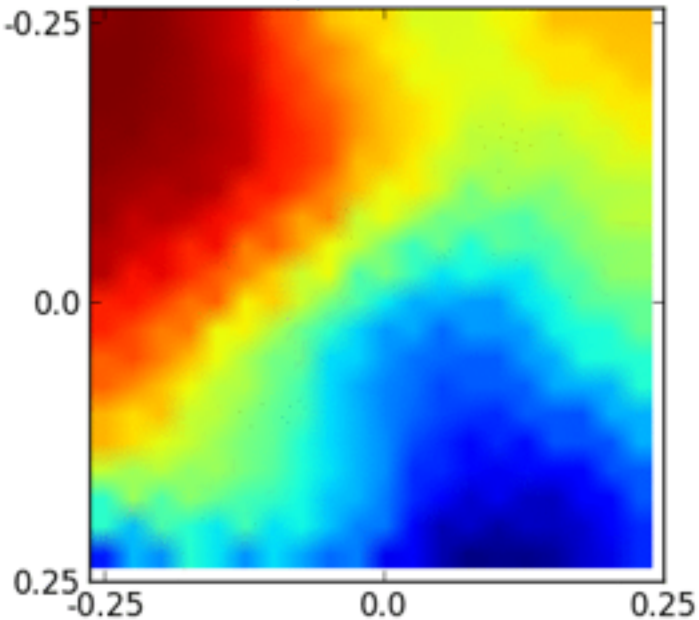


143 GHz



100 GHz

simulated stack of a sample machine-learned RBC catalogue in the Planck213 all-sky BBPS-pressure/X-ray peak-patch cluster/group mock



emergence of the cross-correlation

<ΔT$_{SZ}$ *(θ)|cl∈class-𝒸 =RBC*>

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)

Alvarez, Bond, Hajian, Battaglia + ***2014 peak patches cf. BBPS***
Hajian, Alvarez, Bond 2014: ***machine learning***

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"

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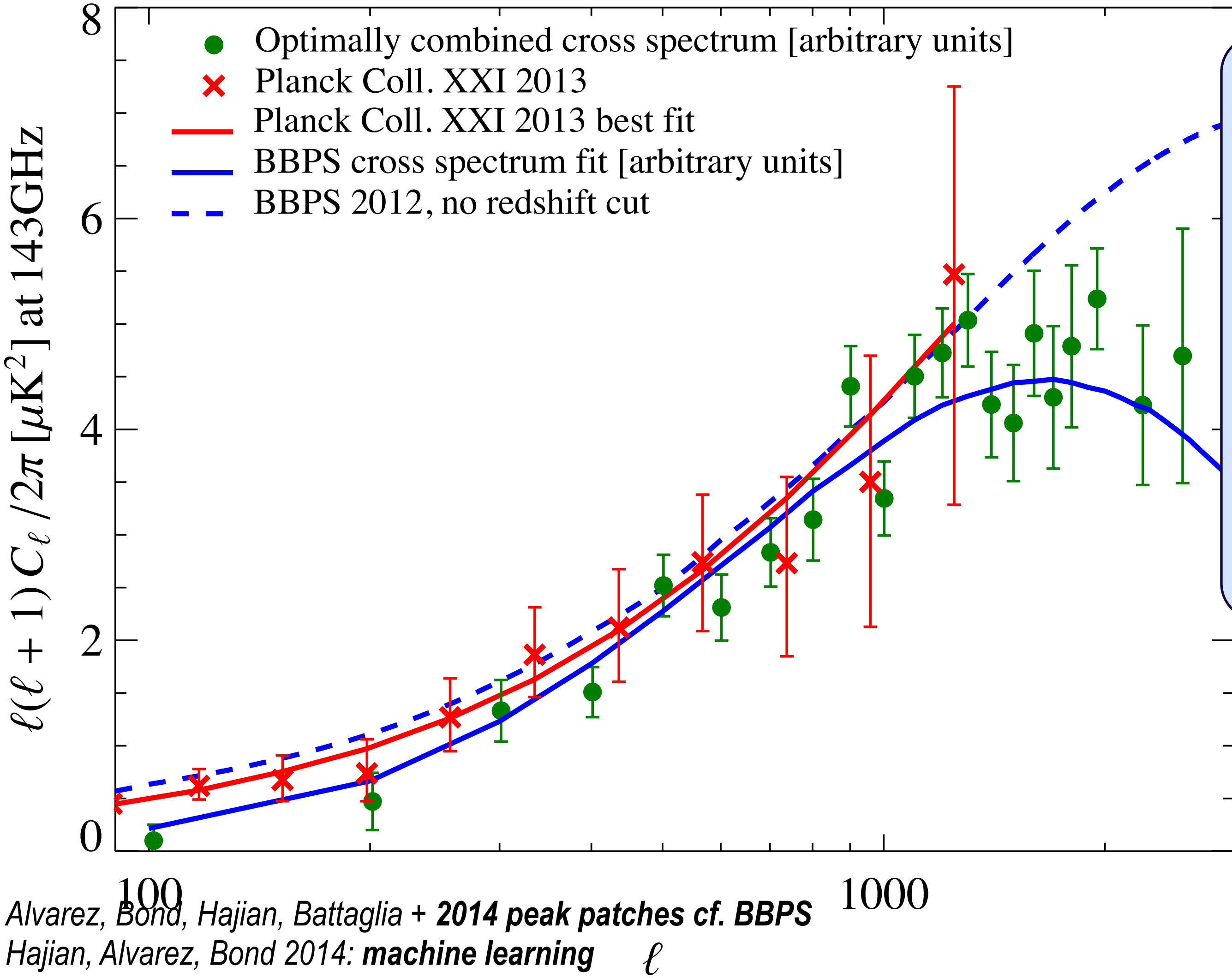

Tension: primary CMB
σ_8**=0.826±0.012**

cf. **clusters:**
σ_{8SZ} **= 0.77±0.02 Planck13**

cf. **X-ray RBC x Planck13**
σ_{8SZ} **= 0.812 +- 0.010 cl+WMAP9**
= 0.812 +- 0.008 cl+Planck13

P13/WMAP9 primary needed to break σ_{8SZ} Ω_m ***degeneracy***

gastrophysical problems for cls?
or higher ν mass
gastrophysical relief

Alvarez, Bond, Hajian, Battaglia + ***2014 peak patches cf. BBPS***
Hajian, Alvarez, Bond 2014: ***machine learning***

fundamental physics from the cluster web? or a gastrophysical indigestion blockage?

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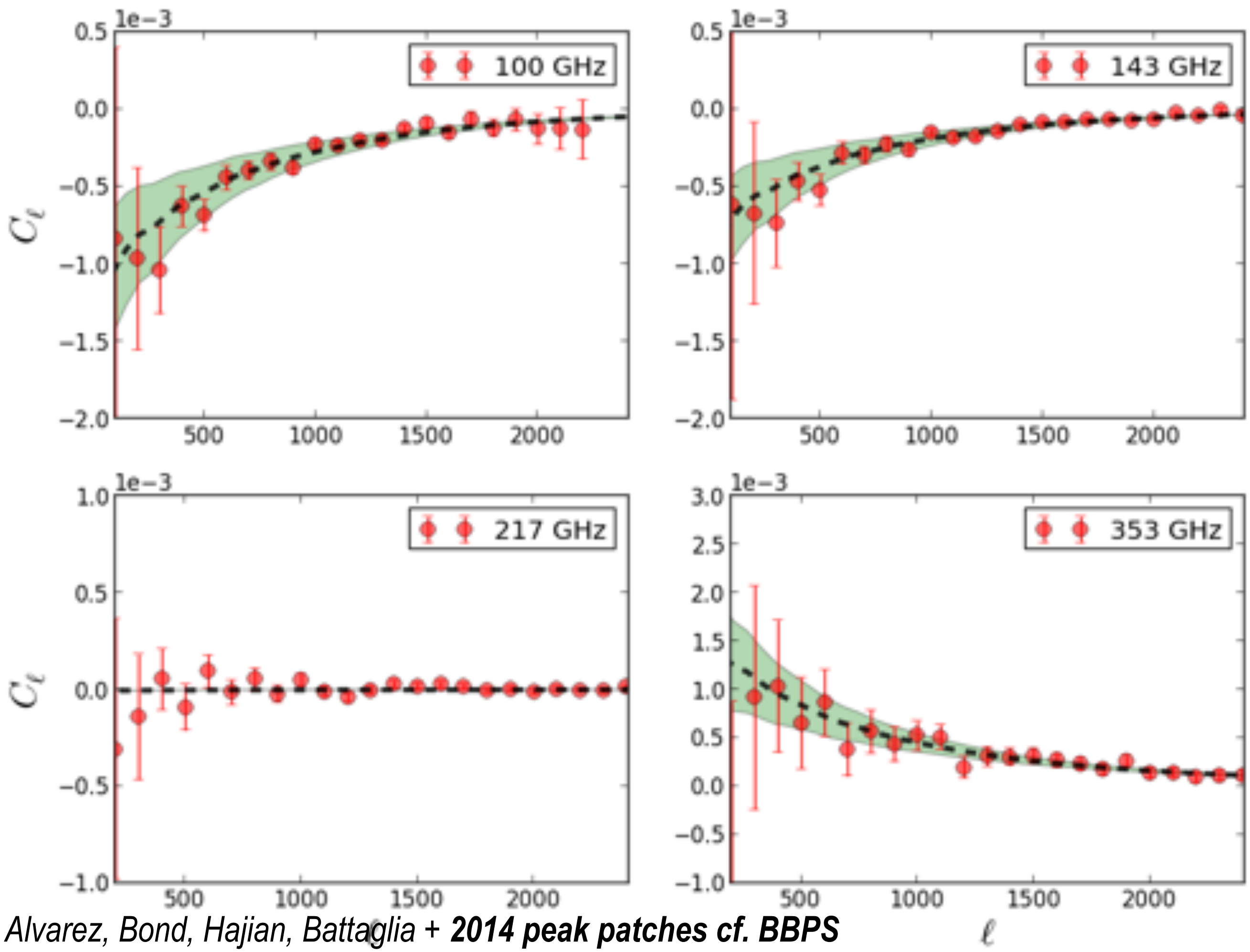

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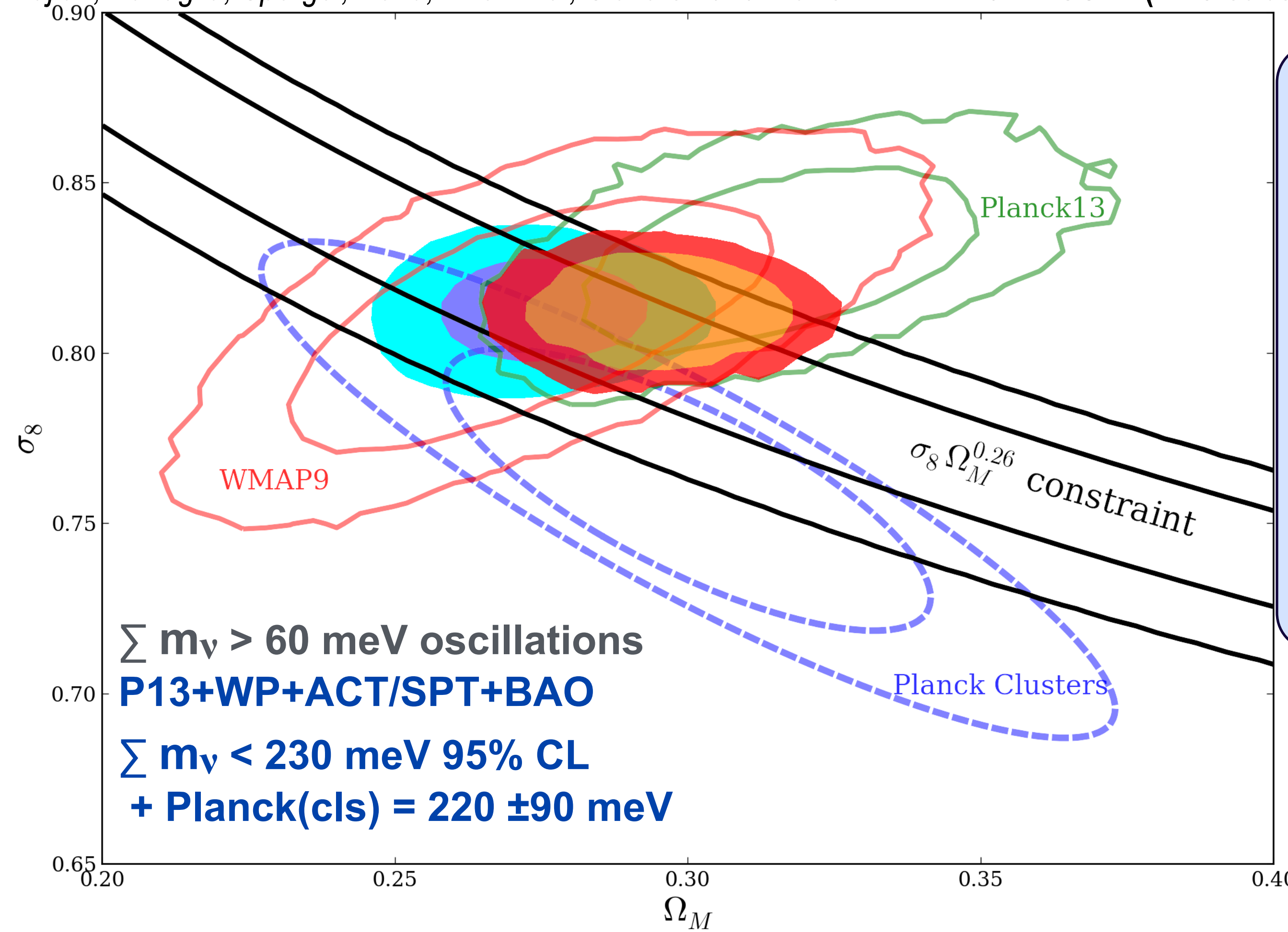

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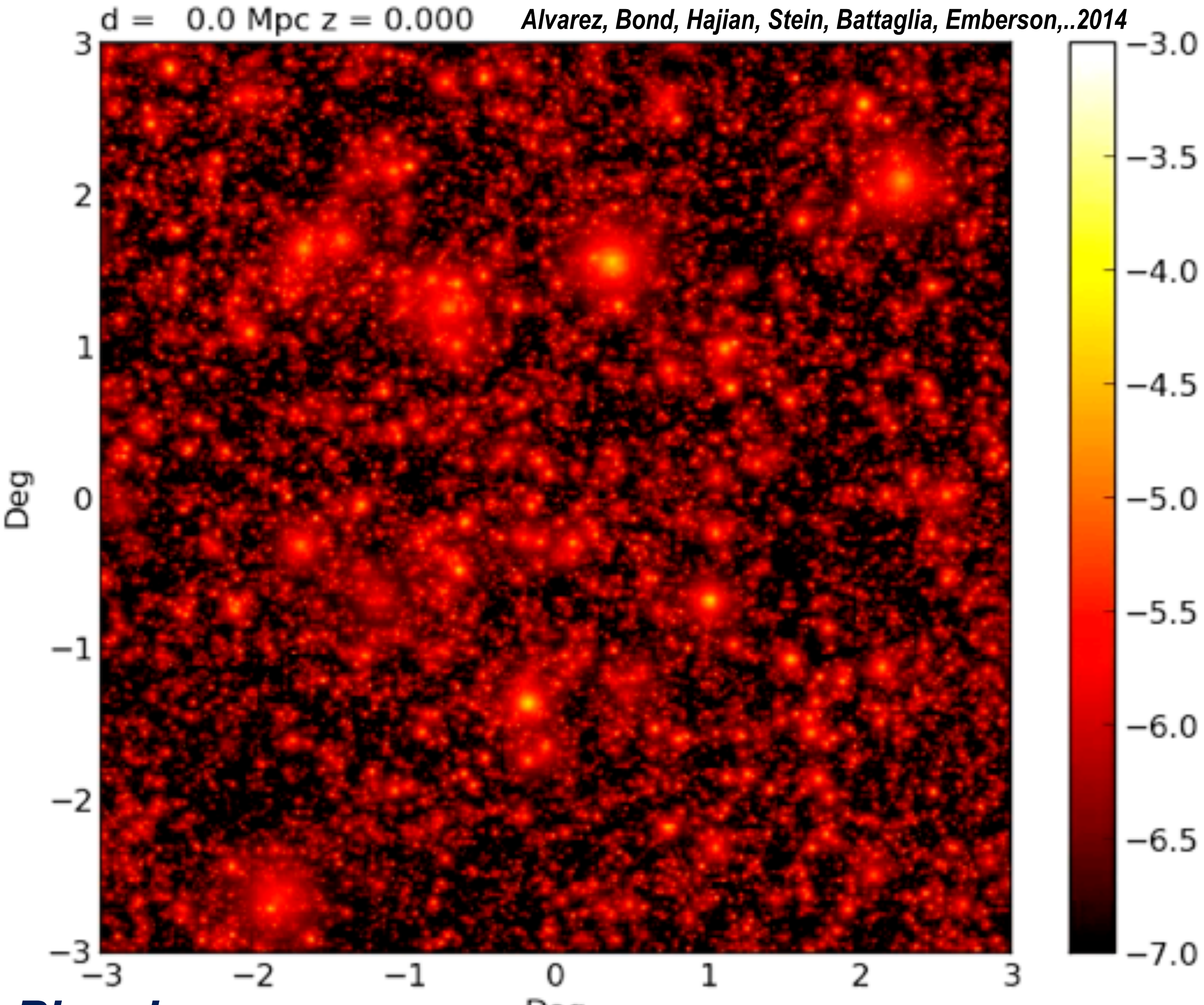
fundamental physics from the cluster web? or a gastrophysical indigestion blockage?

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



for higher map accuracy tSZ PkPatch map needs: 1. intracluster residual pressure fluctuations & 2. cluster orientation via map of Lagrangian strain to Eulerian pressure inertia-tensor

kSZ Peak-Patch maps use cluster/group dominance =moving cluster effect of Sunyaev + *Zeldovich*

see Calabrese+14 for AdvACT forecast on Reionization Epoch kSZ *Alvarez, Battaglia, Iliev etc. mocking reion kSZ*

mock large z-surveys, HOD
CO, HI intensity mapping
CIB, CIB-tSZ correlation, …

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