The Past, Present & Future of Random Fields in Cosmology

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25 years cifar

What is the Universe made of & how was it, is it & will it be distributed?

NOW: baryons/leptons + (cold-ish) dark matter + dark energy/inflaton + tiny curvature energy
(+photons+light neutrinos + *gravity waves*). *??a bit of strings/textures/PBHs??* ***web of galaxies/clusters***

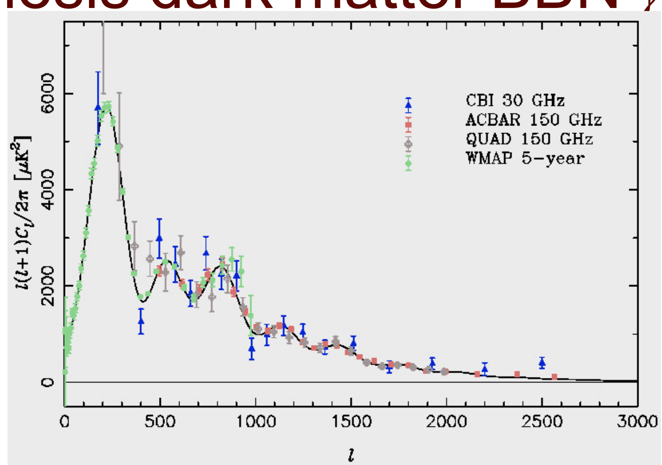
THEN: coherent inflaton /**"vacuum" energy** + **zero-point fluctuations** in all fields (*Gaussian RF*) & then preheat via mode coupling to incoherent cascade to thermal equilibrium soup

very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic baryogenesis dark matter BBN γdec **dark energy**

$V_{\mathrm{eff}}(\psi_{\mathrm{inf}})$?
$K_{\mathrm{eff}}(\psi_{\mathrm{inf}})$?

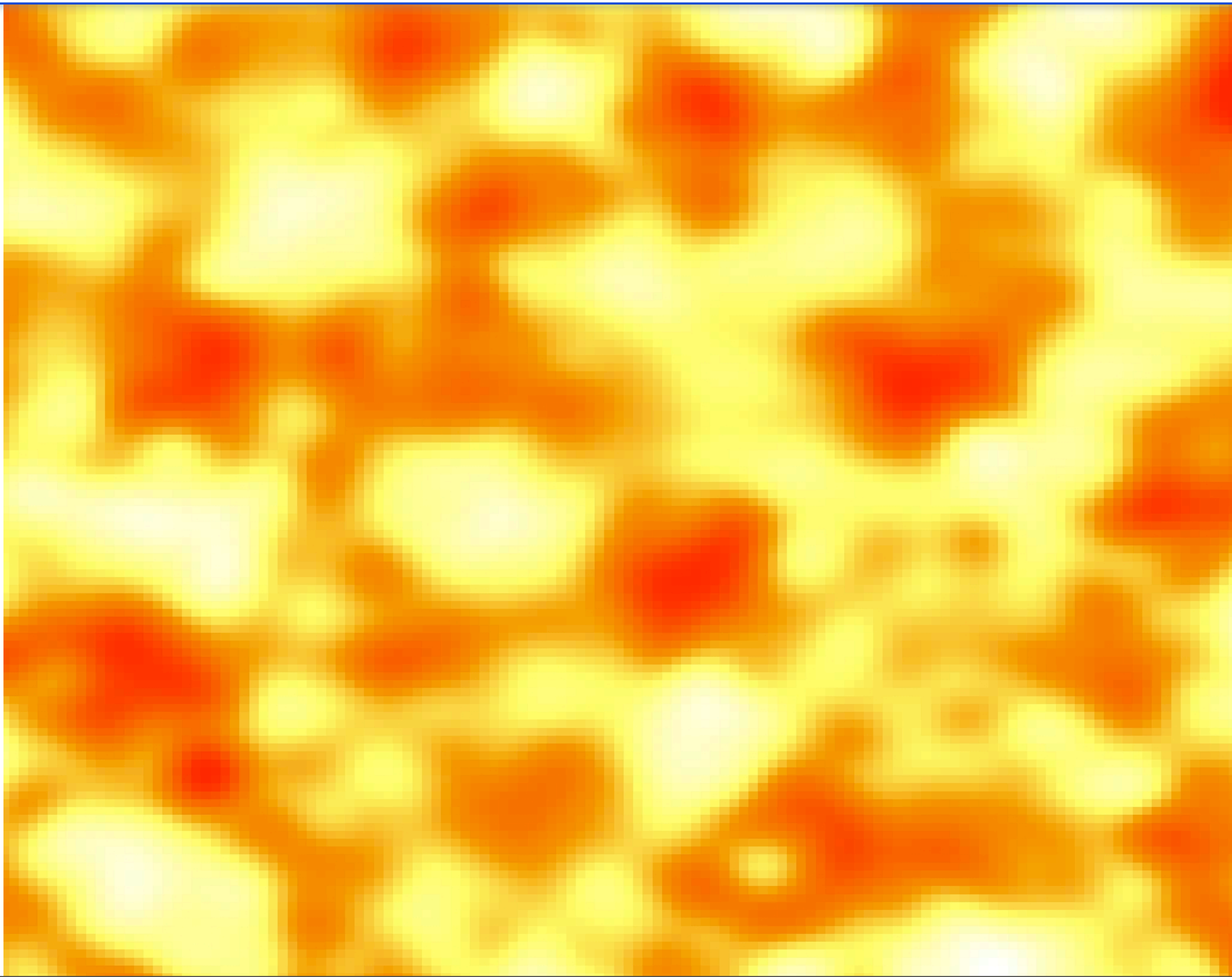


$V_{\mathrm{eff}}(\psi_{\mathrm{inf}})$?
$K_{\mathrm{eff}}(\psi_{\mathrm{inf}})$?

cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de} \sim H^2 M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

nonlinear Gas & Dark Matter Structure in the Cosmic Web the cluster/gp web "now", the galaxy/dwarf system "then"



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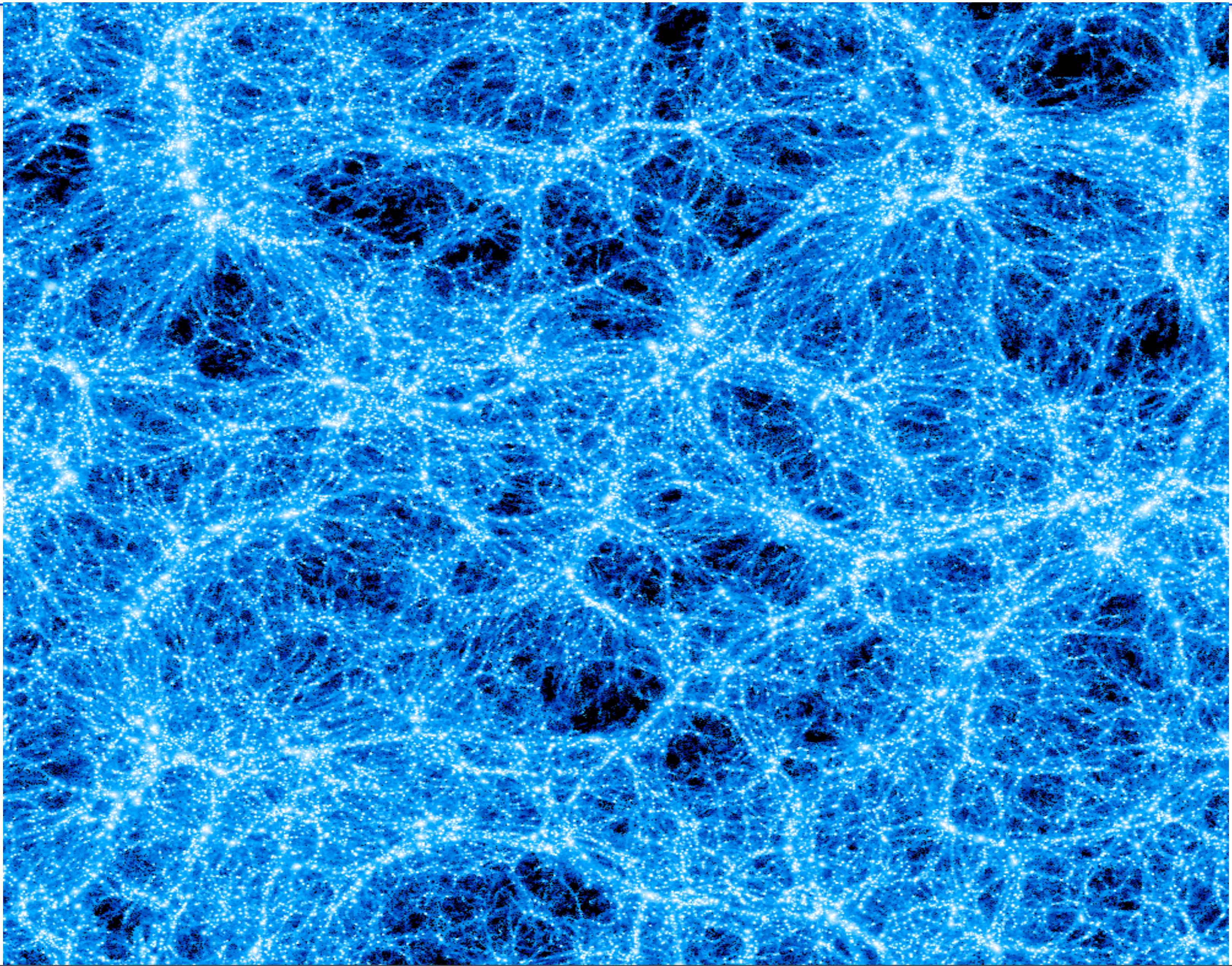
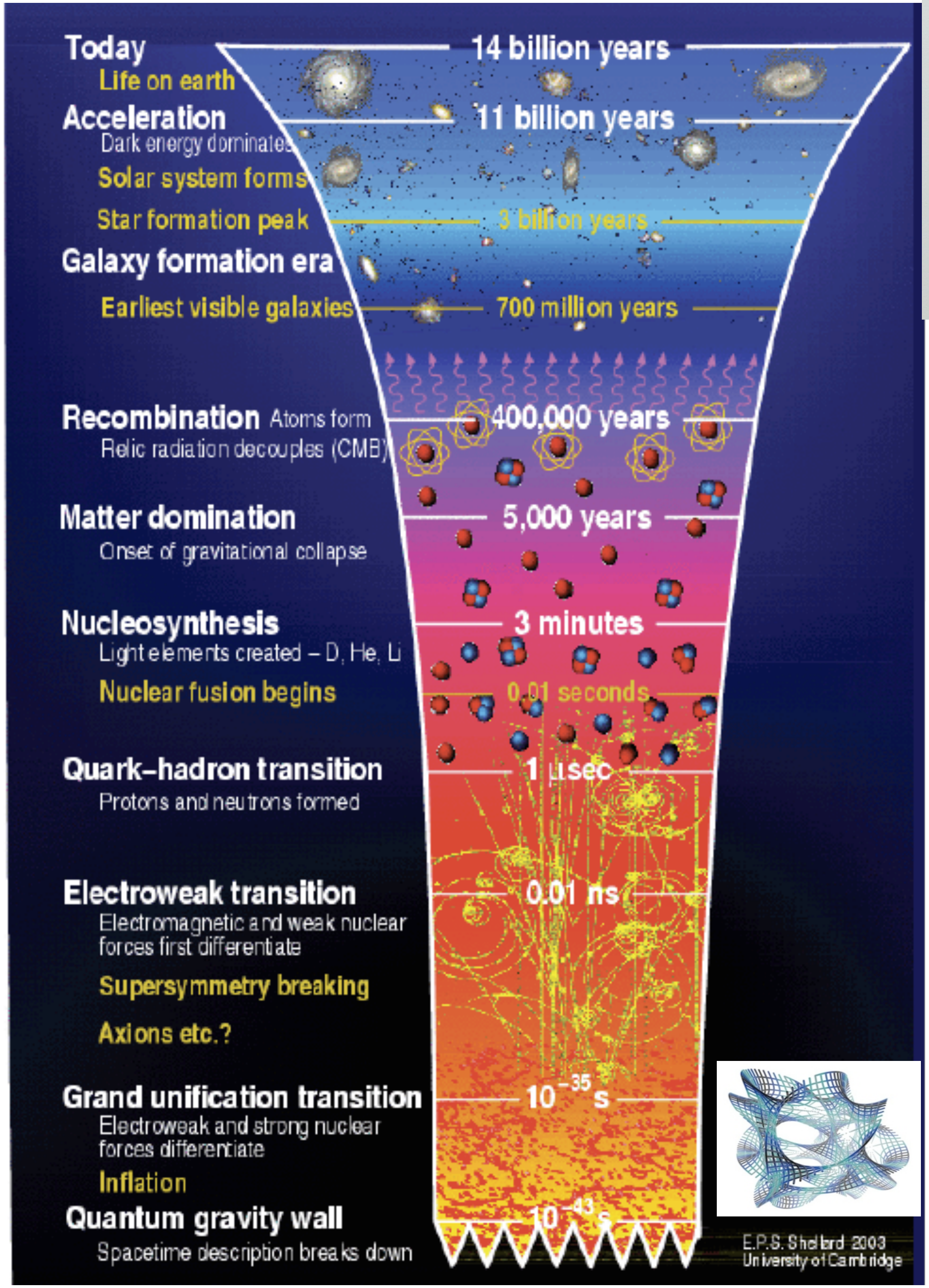
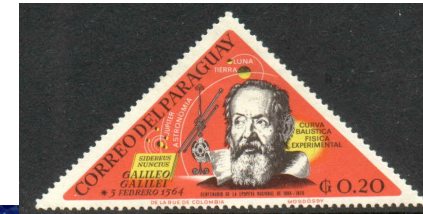
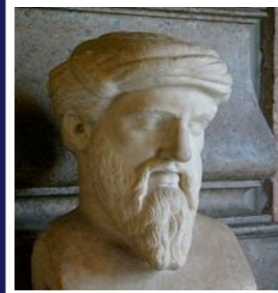




IT from BIT





the Meaning may change but the Facts will remain

FLUCTUATION GENERATOR → **LINEAR AMPLIFIER** → **NONLINEAR DISSIPATIVE AMPLIFIER**

statistically homogeneous & isotropic Gaussian Random Fields => 2-point power spectra fns of 3D wavenumber $|\mathbf{k}|$

quantum noise

$P_\Phi(k)$, $P_{GW}(k)$

$\Delta T_{(LM)}$

$P_\rho(k)$, $P_{\mathbf{v}}(k)$

$P_{gal}(k)$, $P_{cl}(k)$

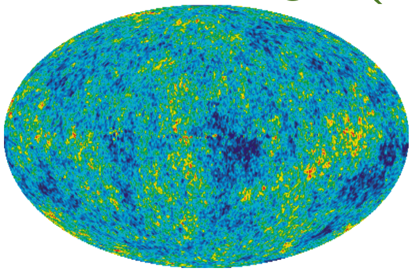
gastro-physics

aka “sub-grid” aka astronomy

nonlinear objects of various types & their clustering properties, N-point statistics

n_{gal} n_{cl} ..

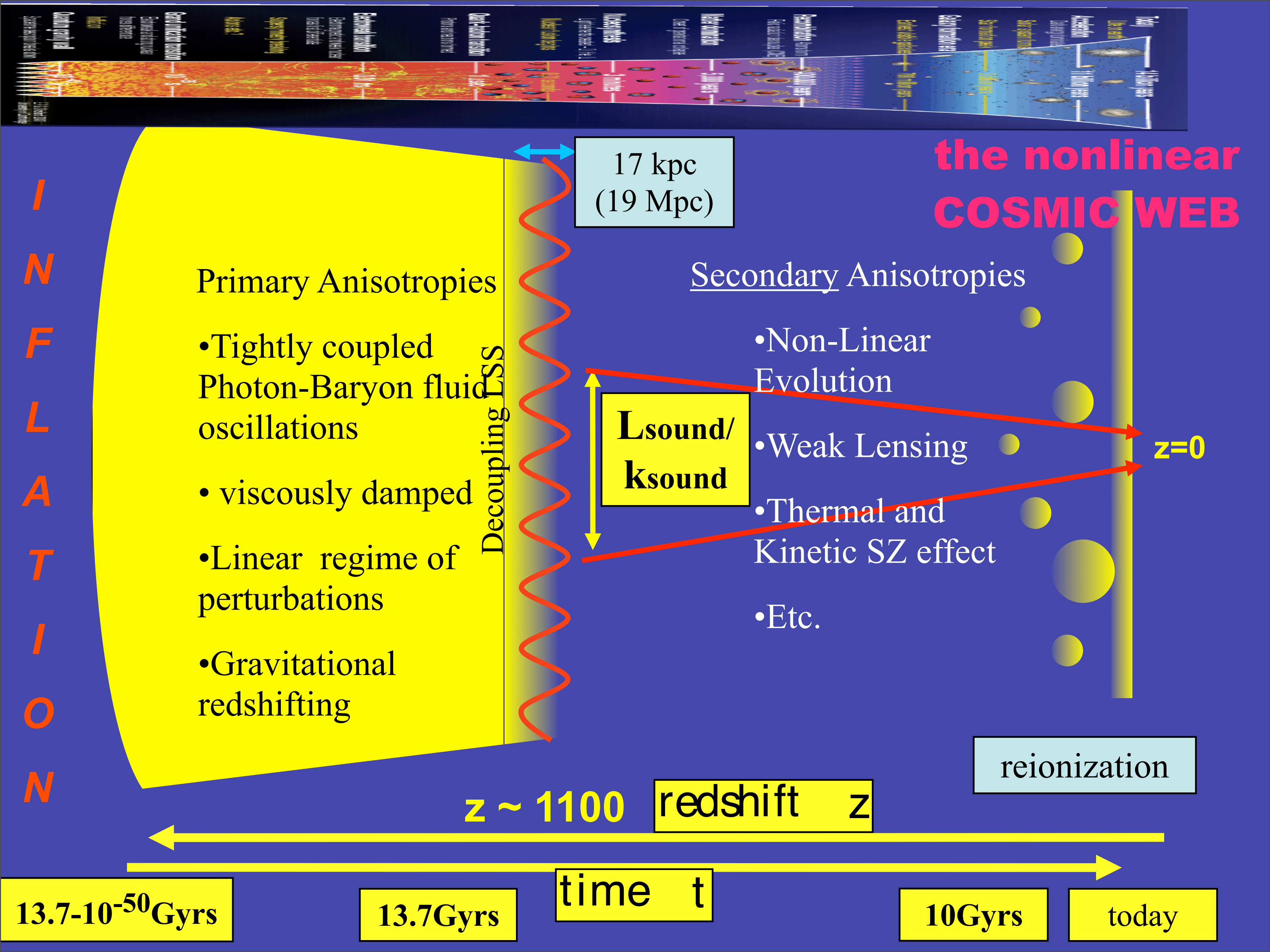
n_{halos} n_{peaks}



Cosmic Microwave Background Radiation

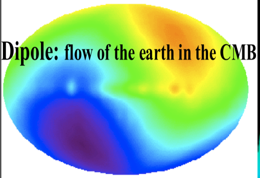
statistically isotropic all-sky GRF on the 2-sphere

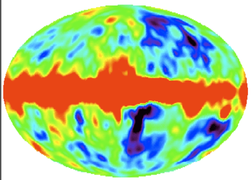
$C_L = \langle |\Delta T_{(LM)}|^2 \rangle$, $k_{2D} \sim L+1/2$



17 kpc
(19 Mpc)
the nonlinear
COSMIC WEB
I N F L A T I O N
Primary Anisotropies
•Tightly coupled
Photon-Baryon fluid
oscillations
• viscously damped
•Linear regime of
perturbations
•Gravitational
redshifting
Decoupling LSS
Lsound/
ksound
Secondary Anisotropies
•Non-Linear
Evolution
•Weak Lensing
•Thermal and
Kinetic SZ effect
•Etc.
z=0
reionization
z ~ 1100
redshift z
time t
13.7-10^-50Gyrs
13.7Gyrs
10Gyrs
today

CMB

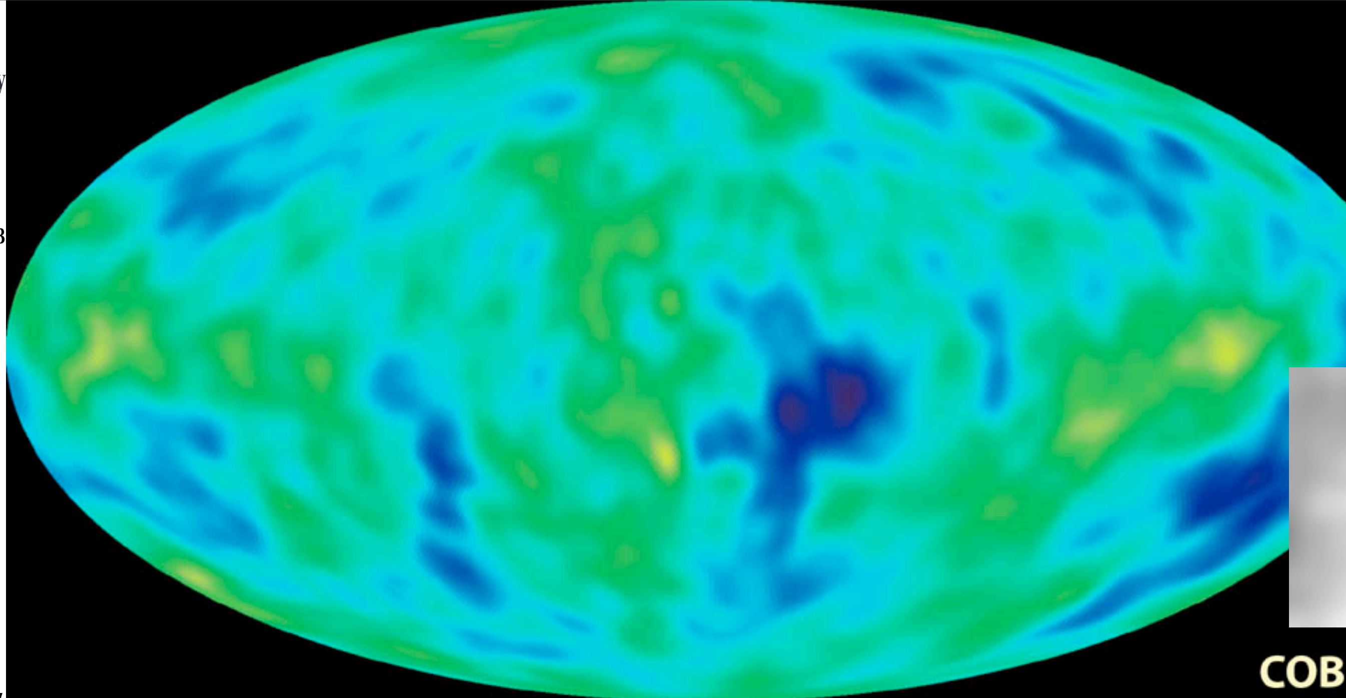


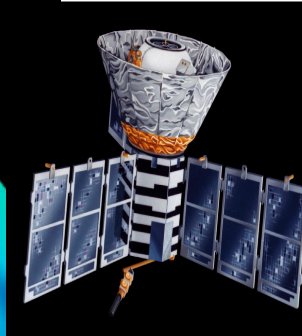


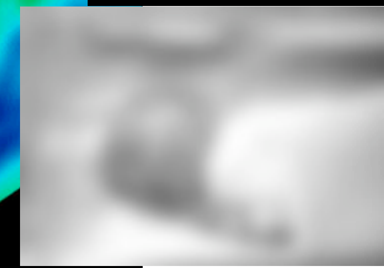
COBE/DMR:
CMB + Galactic @7^0

is this a statistically isotropic Gaussian random field, when account is taken of the Milky Way emissions & extra-galactic sources?

yes! maybe?

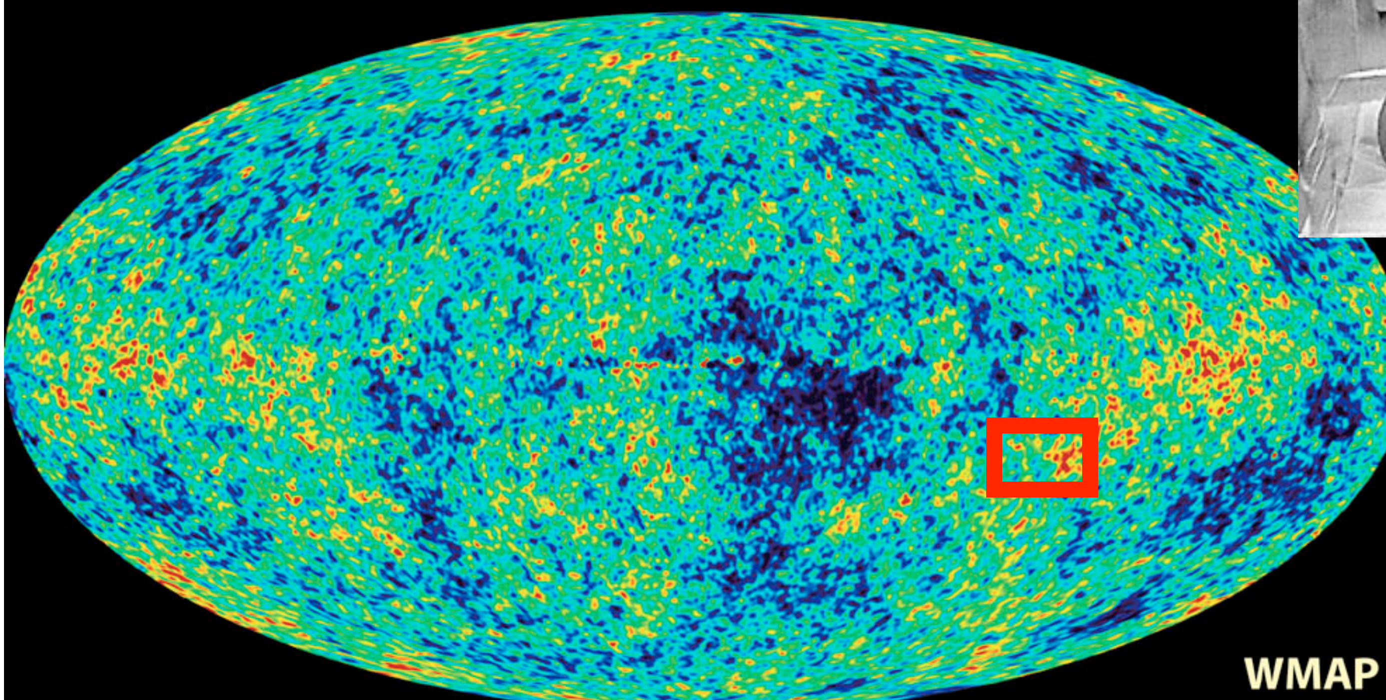


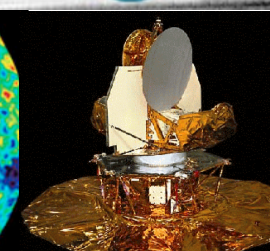




COBE

1992/96

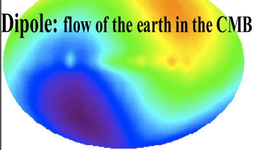


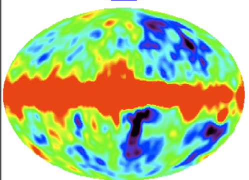


WMAP

Feb03
Mar06
Mar08

Dipole: flow of the earth in the CMB





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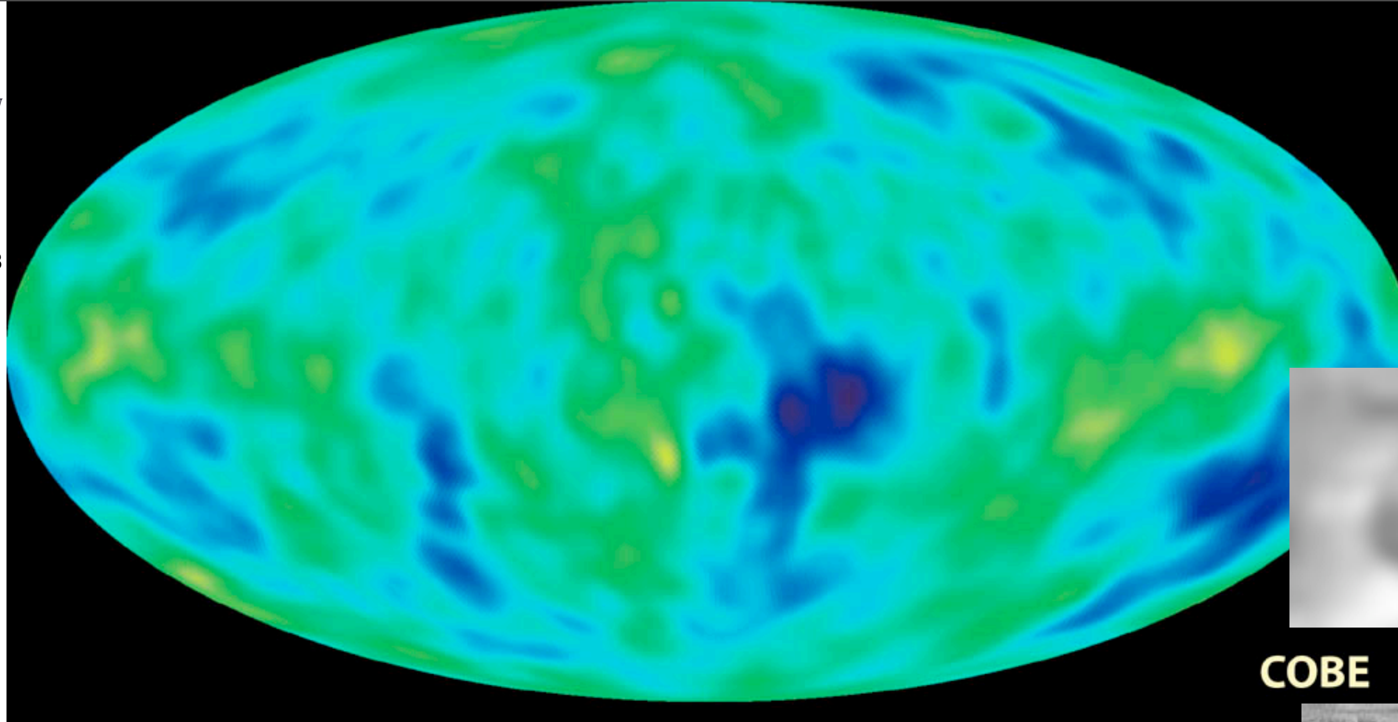
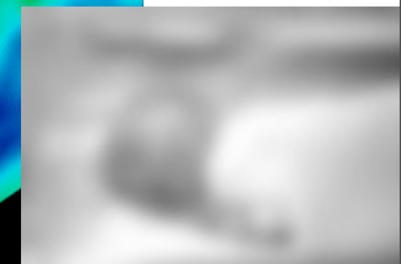
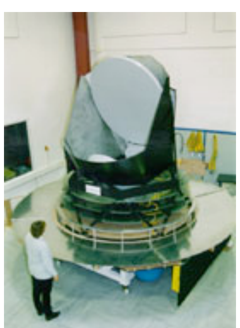
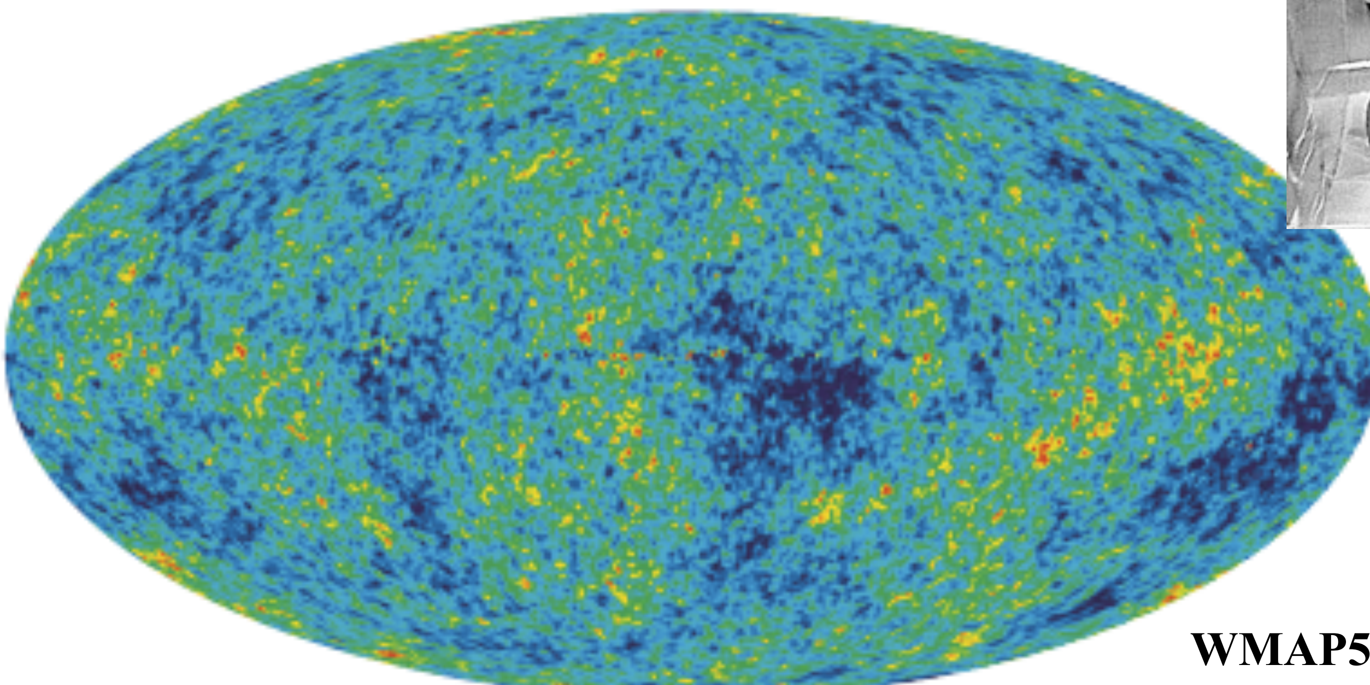




1992/96

Planck satellite April09 launch





WMAP5

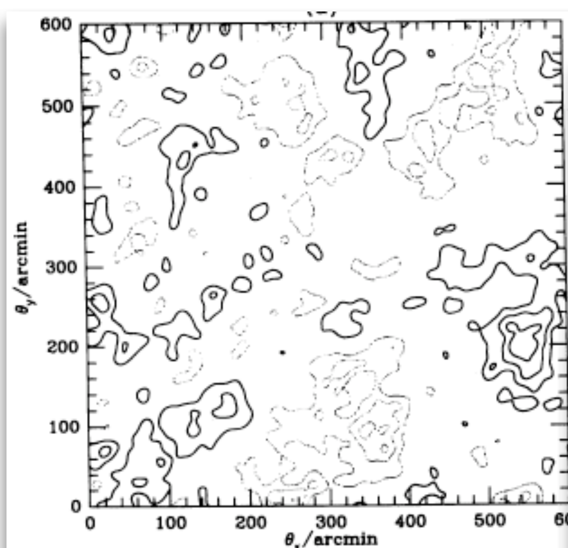
Feb03
Mar06
Mar08

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

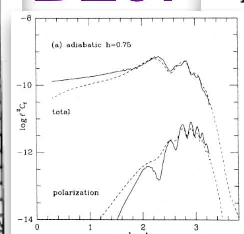
Primary Cosmic Microwave Background Radiation ~ a statistically isotropic all-sky GRF on the 2-sphere $C_L = \langle|\Delta T_{(LM)}|^2\rangle$ *with target* C_L *shapes*

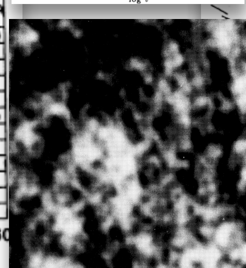
A tentative list of topics organized according to angular scale, with theory and observation intertwined, is:

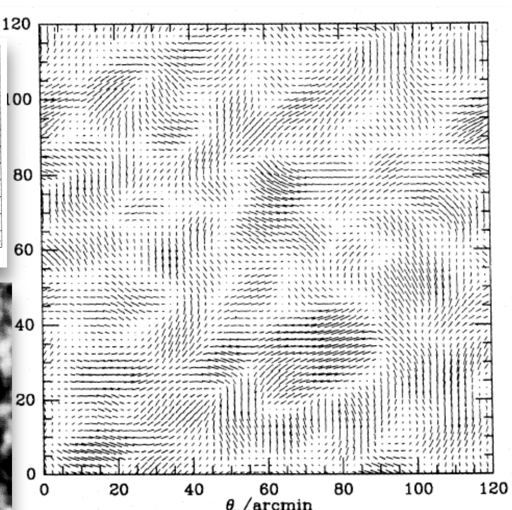
- very small angle anisotropies - VLA results, secondary fluctuations via the Sunyaev-Zeldovich effect, primeval dust emission, and radio sources
- small angle anisotropies - current results, optimal measuring strategies, statistical methods for small signals in larger noise, which universes can we rule out, the reheating issue, future detectors and techniques, CMB map statistics, polarization
- intermediate and large angle anisotropies - $5^o - 10^o$ results, future experiments at $\sim 1^o$, COBE and other large angle analyses, theoretical $C(\theta)'s$ and their angular power spectra, Sachs-Wolfe effect in open Universes, the isocurvature CDM and baryon stories, $\Delta T/T$ from gravitational waves, the cosmic string story.



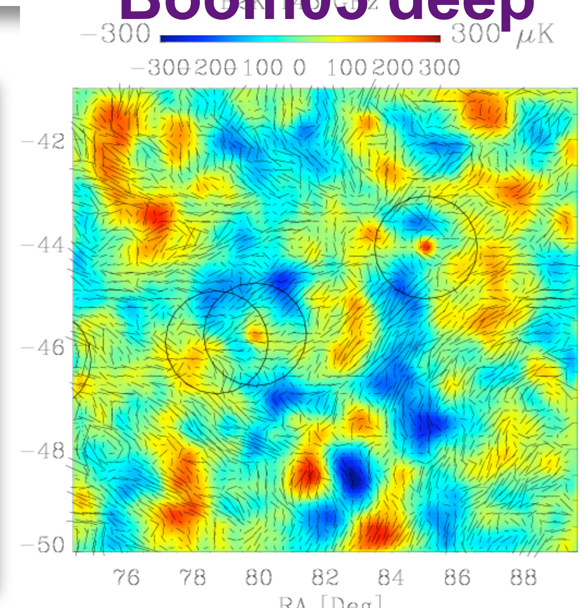
BE87







Boom05 deep

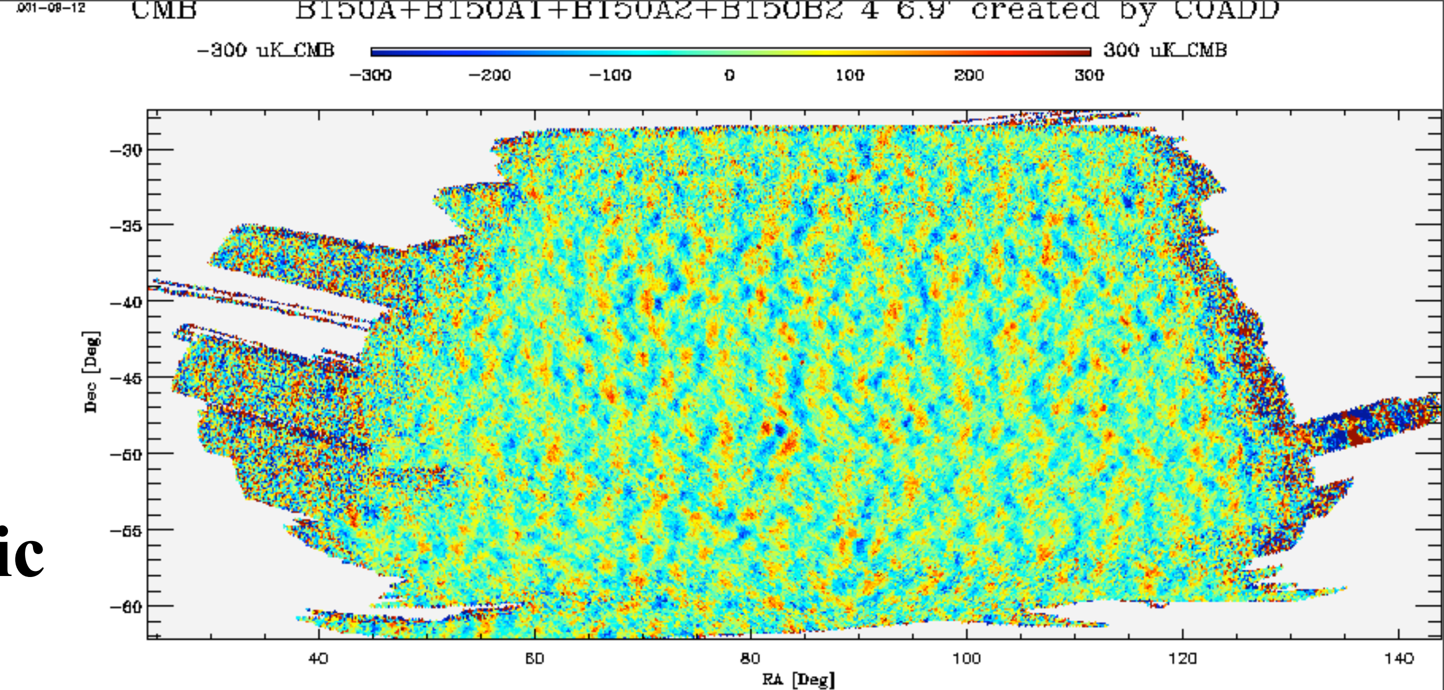


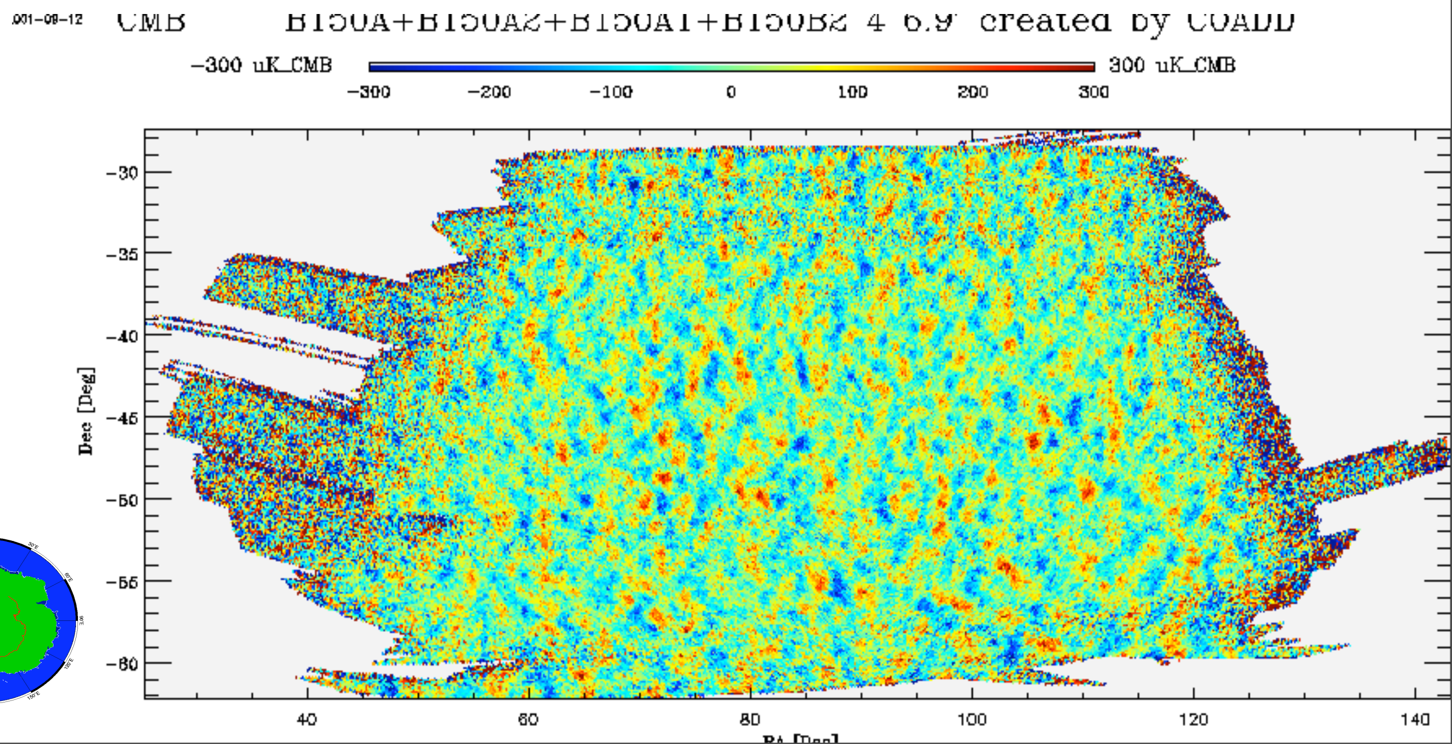
Boomerang @150GHz is (nearly) Gaussian: Simulated vs Real

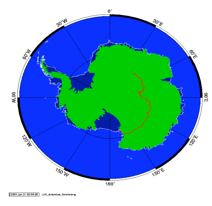
thermodynamic CMB temperature fluctuations

2.9% of sky

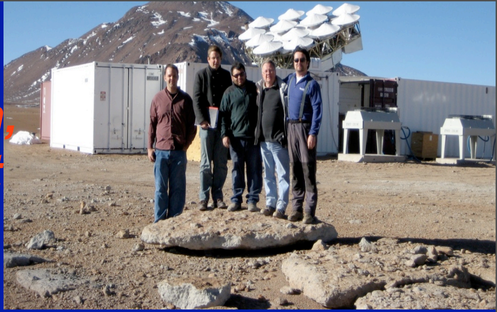
ΔT~30 ppm





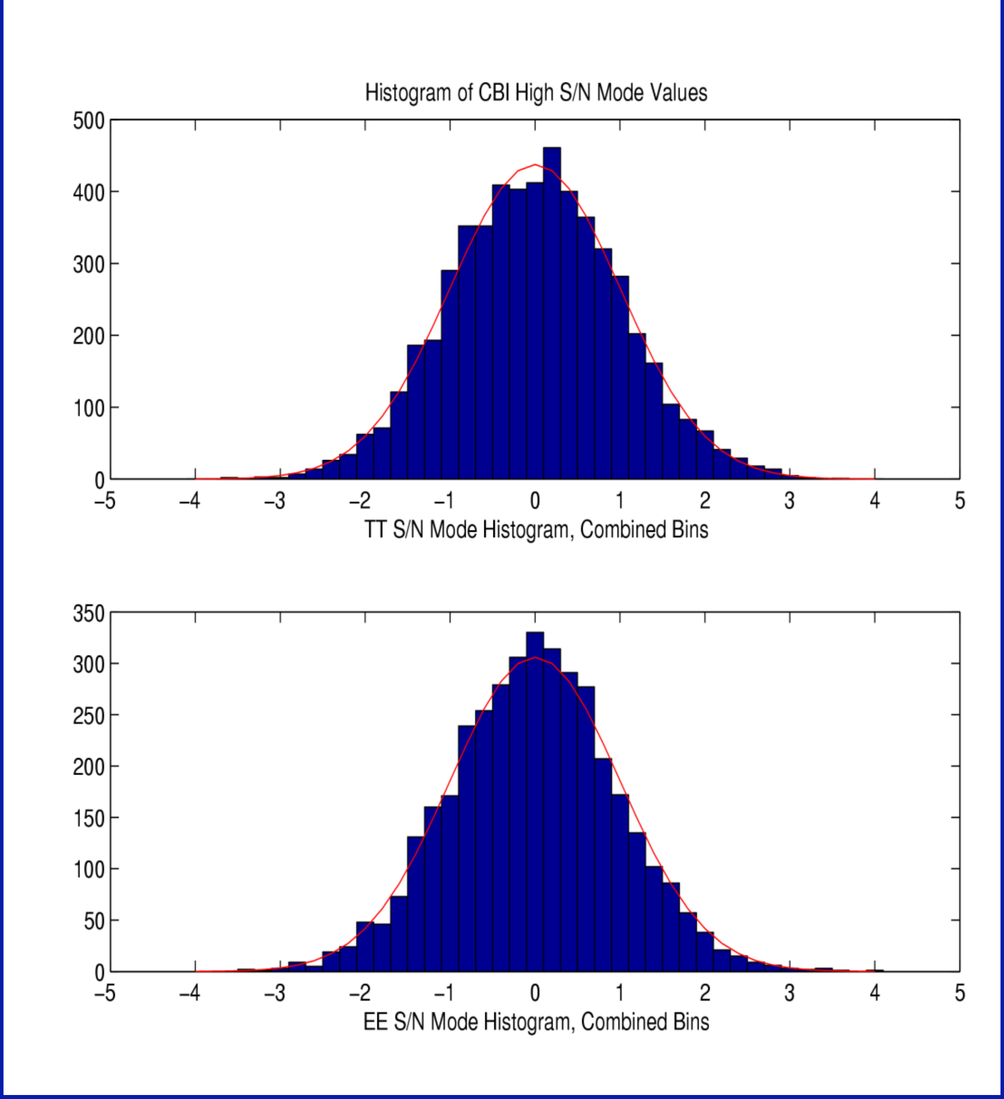


All non-primary CMB components are non-Gaussian: extragalactic radio and submm sources; Galactic synchrotron, bremsstrahlung & dust emission, CMB-upscattering from hot gas in clusters, gravitational lensing of the CMB, ...



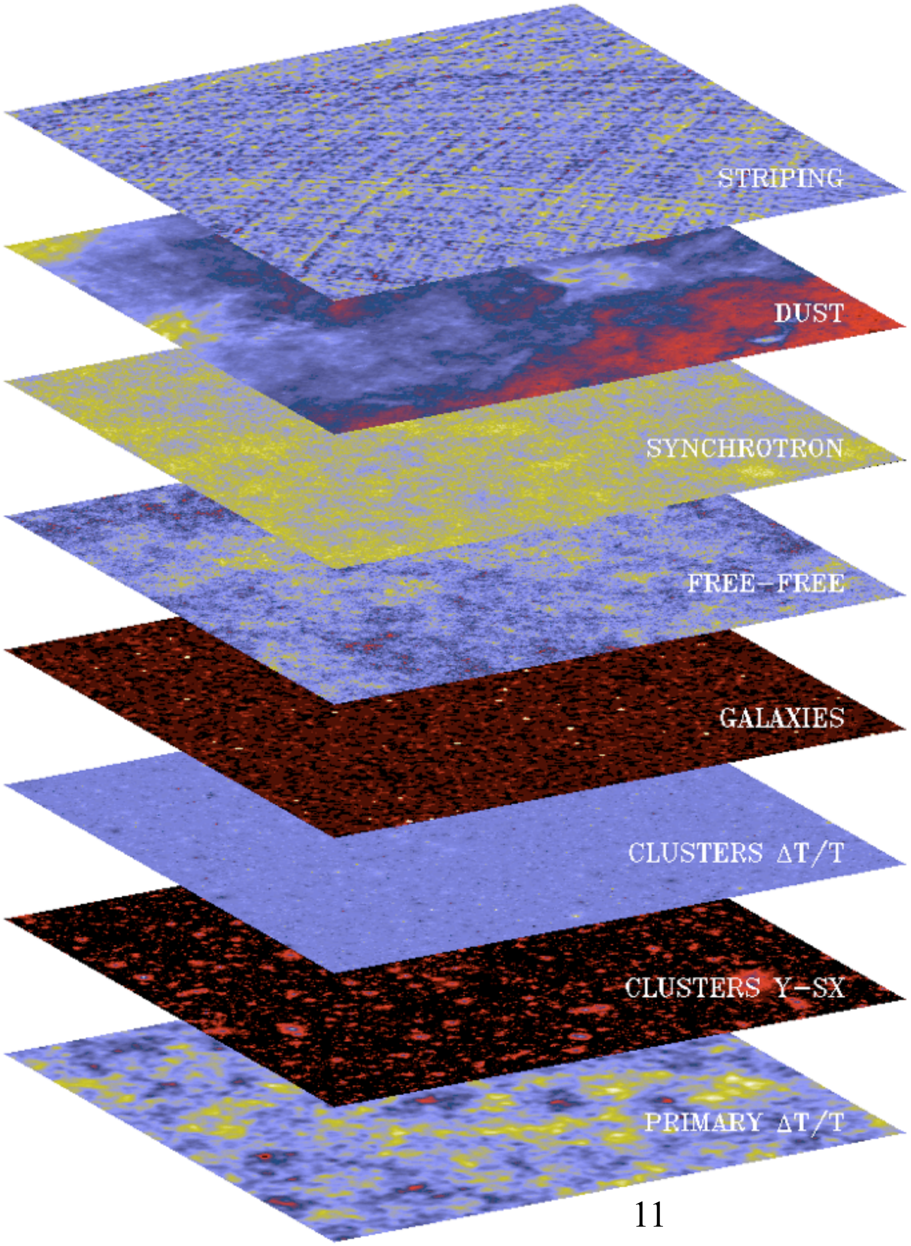
even the high resolution Cosmic Background Imager ΔT is ~ Gaussian, & so is its CMB polarization signal

- Method: Decompose data (with extragalactic radio sources removed) into uncorrelated S/N eigenmodes for each bin; Pick out modes expected to have signal; Check distribution for non-Gaussianity
- We kept 5500 modes for TT ΔT, 3800 for EE polarization
- all are consistent with Gaussian
- first check of EE polarization

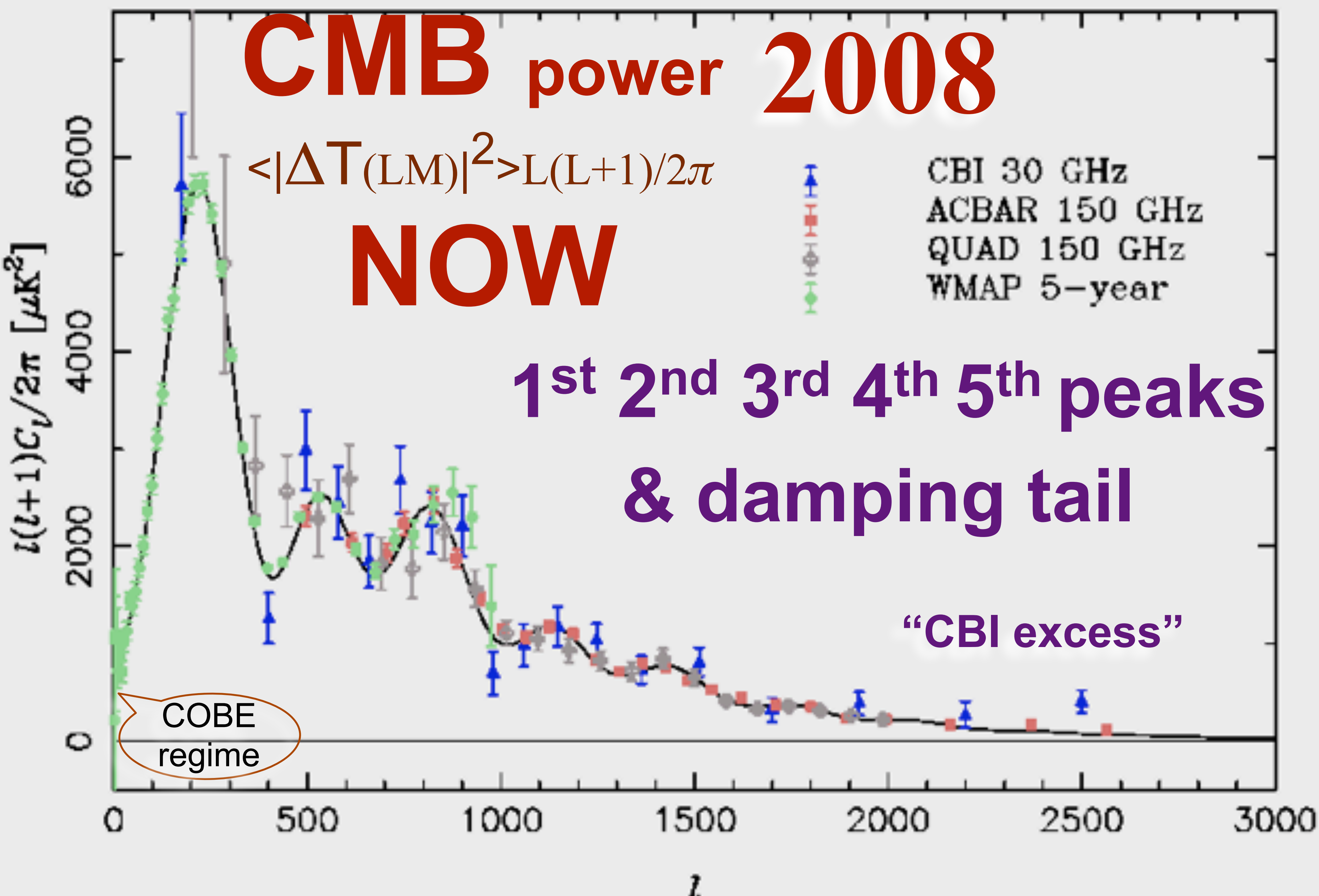


the quest for primordial non-Gaussianity within the primary CMB requires exquisite foreground removal, whether inflation-induced or cosmic-string-induced, ...

striping
dust
synchrotron
bremsstrahlung
dusty galaxies
kinetic SZ
thermal SZ
PRIMARY



F.R. BOUCHET & R. GISPERT 1998



Sievers etal 2009 Jan astroph

⇒ exquisite & increasingly precise determination of cosmic parameters

dark matter abundance Ω_m=0.268 +.012 -.012

	January 2000	January 2002	June 2002	January 2003	March 2003
$\Omega_{cdm}h^2$	$0.198^{+0.088}_{-0.080}$	$0.130^{+0.031}_{-0.028}$	$0.124^{+0.026}_{-0.025}$	$0.125^{+0.021}_{-0.022}$	$0.111^{+0.010}_{-0.010}$

CMB-only history (weak-h prior). LSS-then drove to near current

$\Omega_{dm}h^2$ 0.1145 +-0.0023 CMBall+WL+LSS+SN+Lya

$\Omega_b h^2$ 0.0233 +- 0.0005 ordinary matter abundance (baryons)

$\Rightarrow \rho_{dm}/\rho_b$ =5.1

Ω_Λ	$0.34^{+0.28}_{-0.24}$	$0.52^{+0.17}_{-0.20}$	$0.53^{+0.17}_{-0.19}$	$0.57^{+0.14}_{-0.19}$	$0.73^{+0.06}_{-0.10}$

CMB-only history (weak-h prior). LSS-then drove to near current value

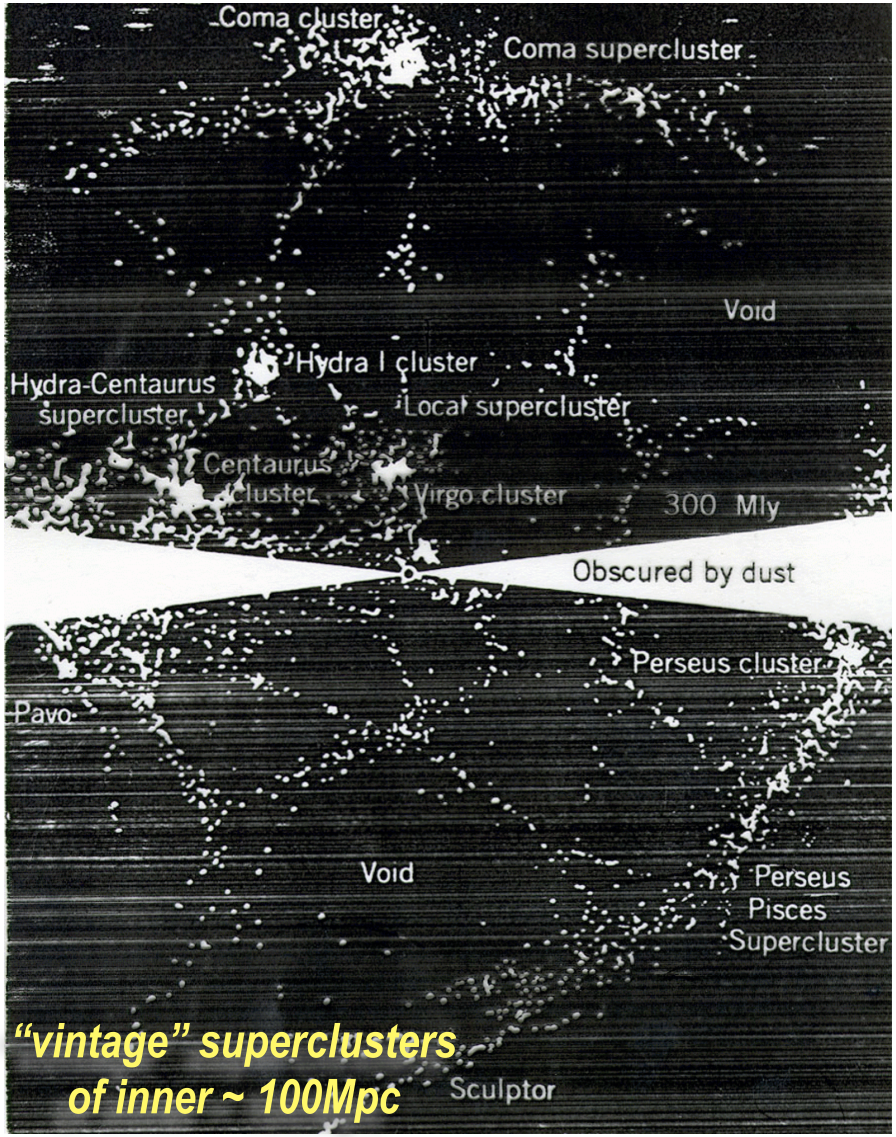
dark energy abundance Ω_Λ=0.736 +.012 -.012

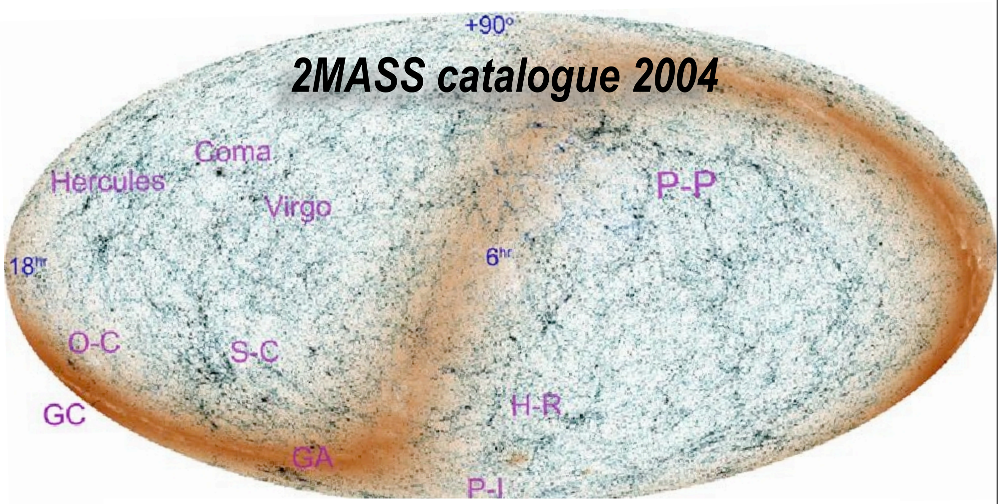
& H_0 = 72 +-1 CMBall+WL+LSS+SN+Lya

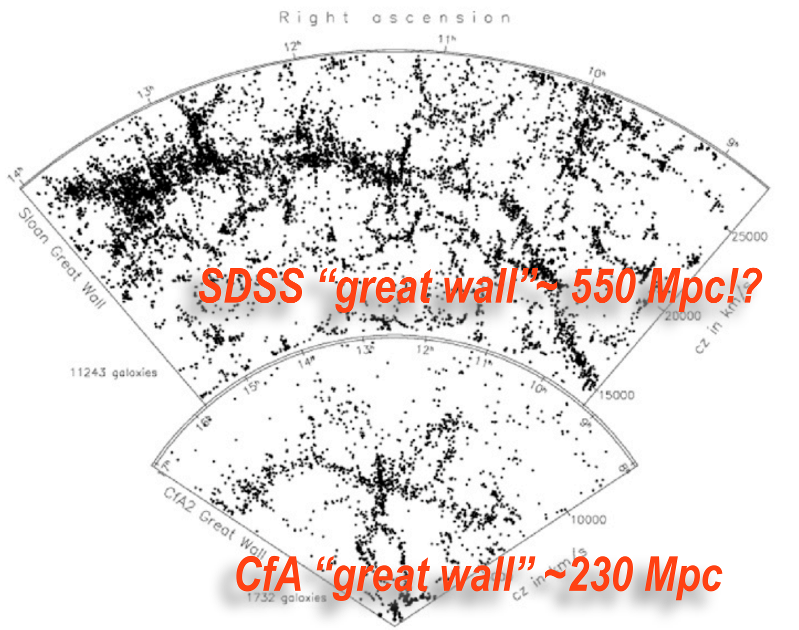
$\Rightarrow \rho_m/\rho_{de}$ =.30

ε=-dlnH/dlna=1+q: now =3/2[Ω_{m0} +(1+w)(1-Ω_{m0})] ~0.40?, to 0?

Cosmic Web & Superclustering: a natural consequence of the gravitational instability of a hierarchical Gaussian random density field







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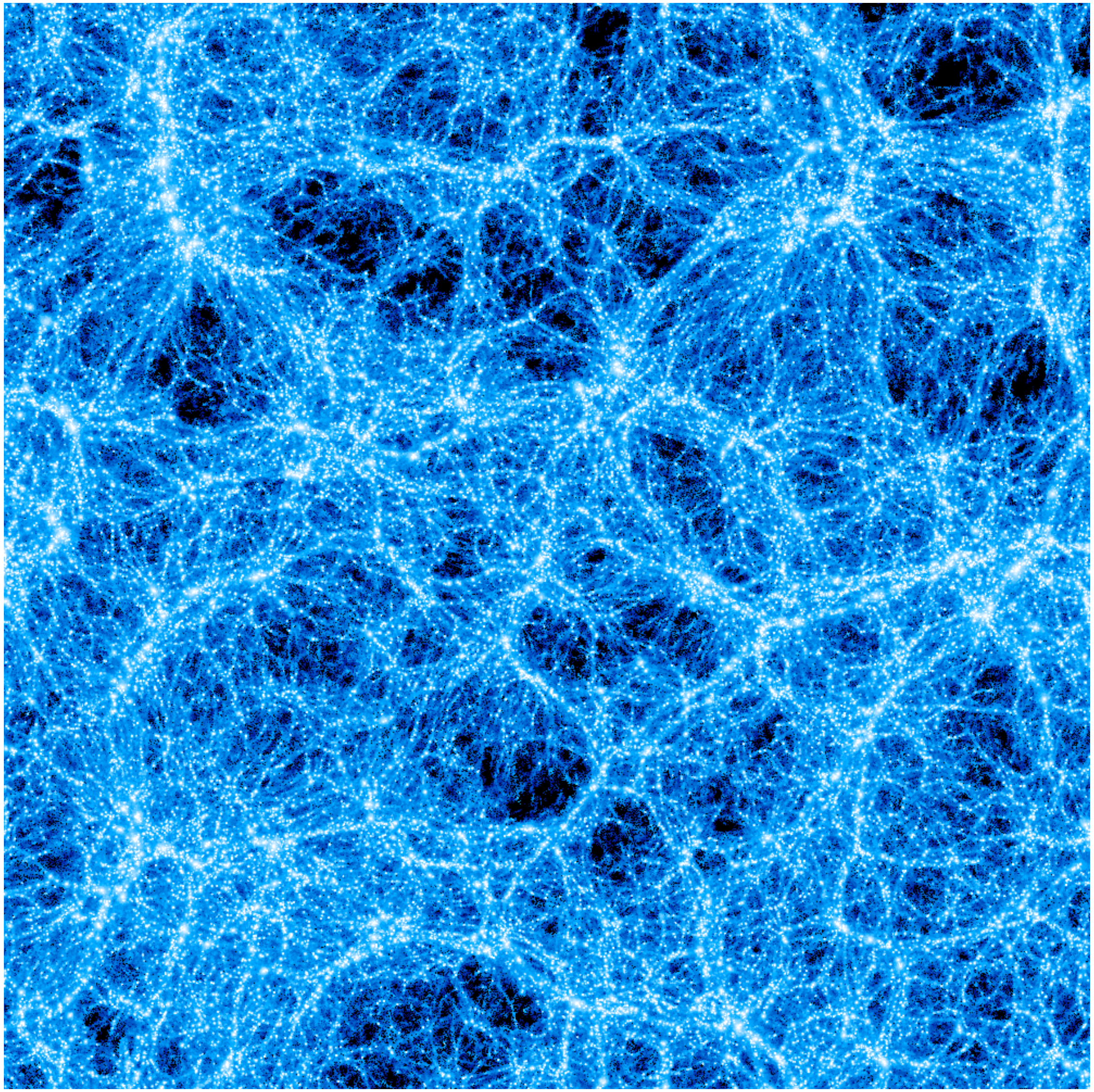
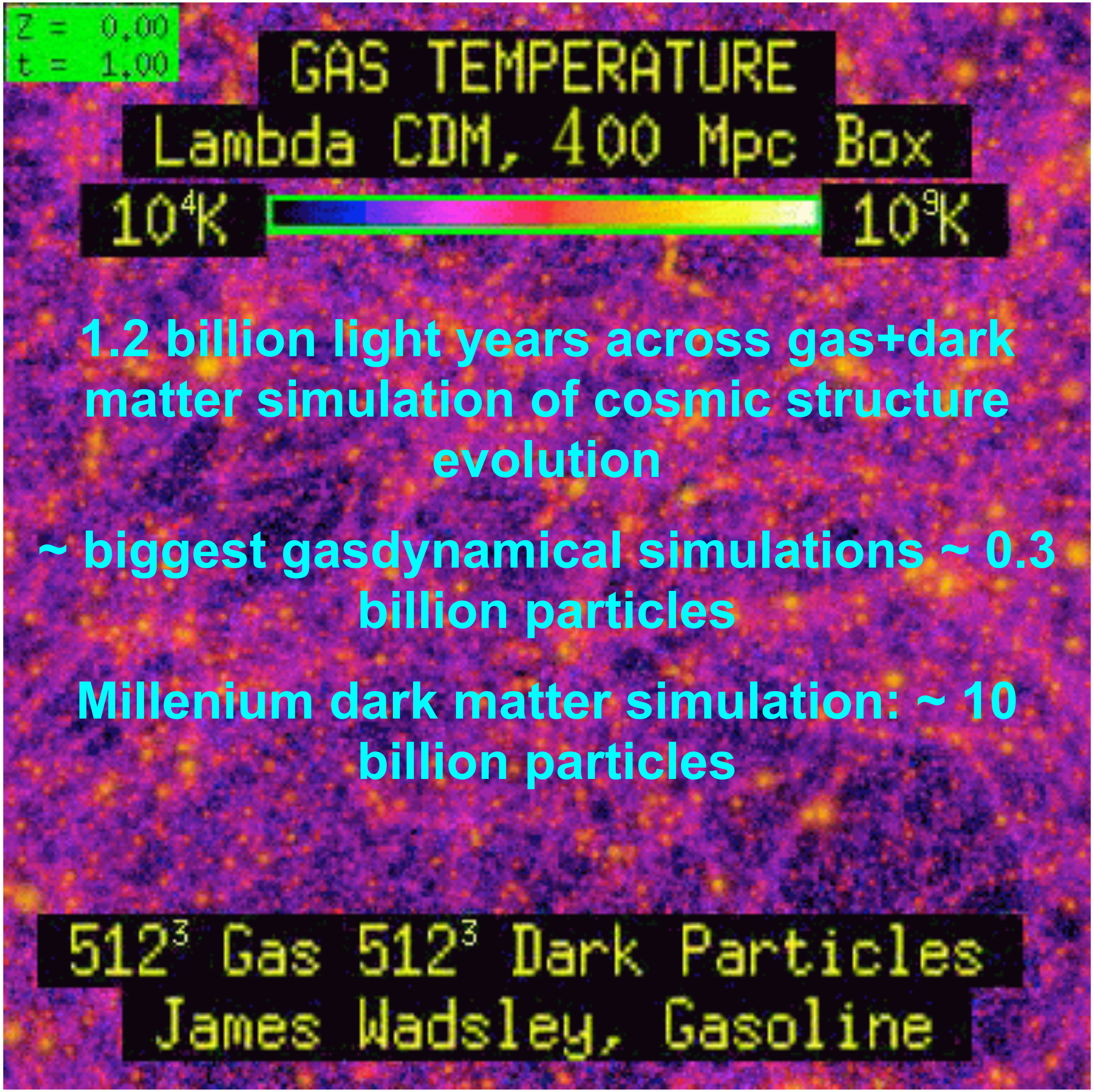


ΛCDM 400 Mpc treeSPH

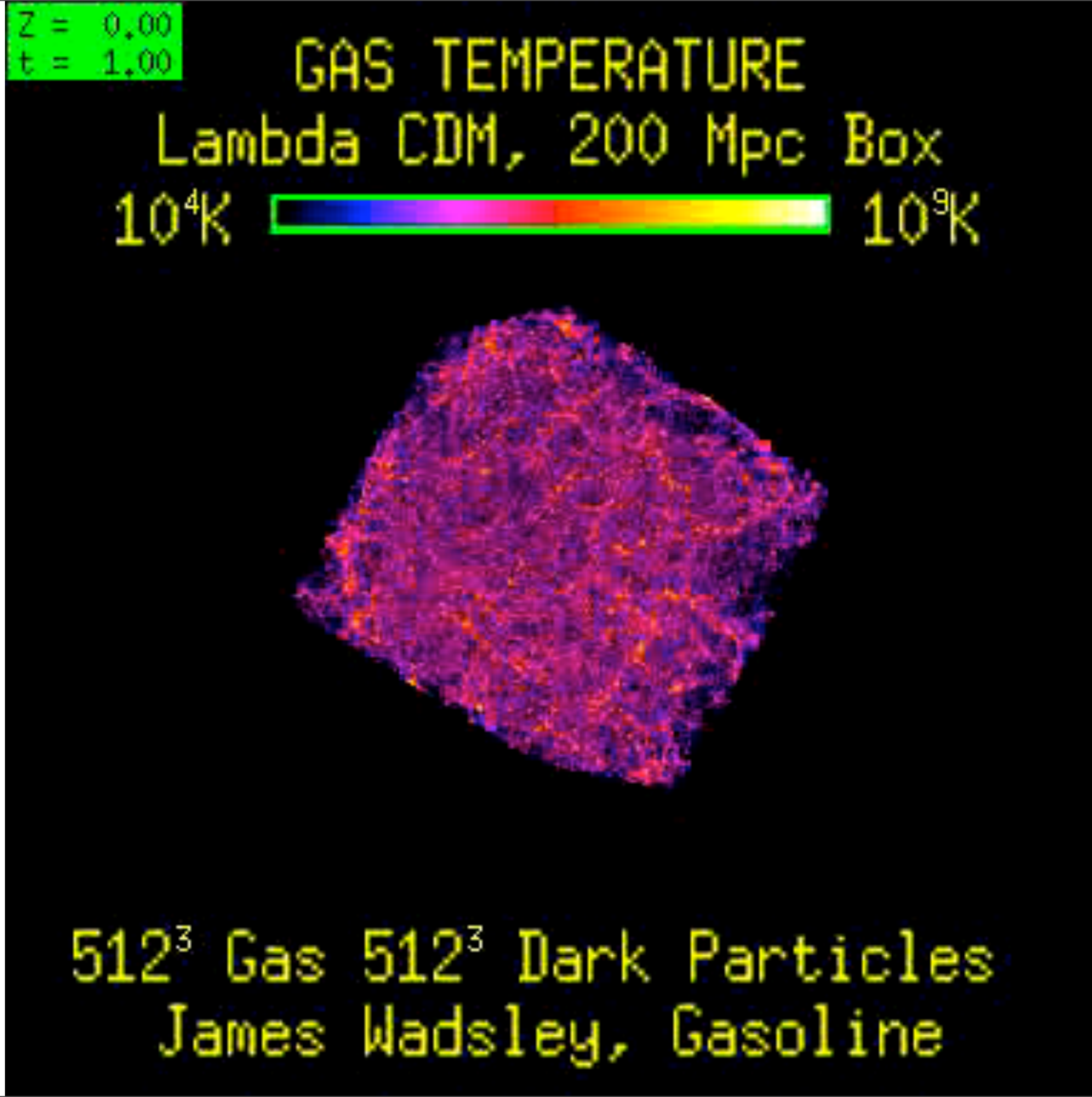
512^3 gas+CDM particles

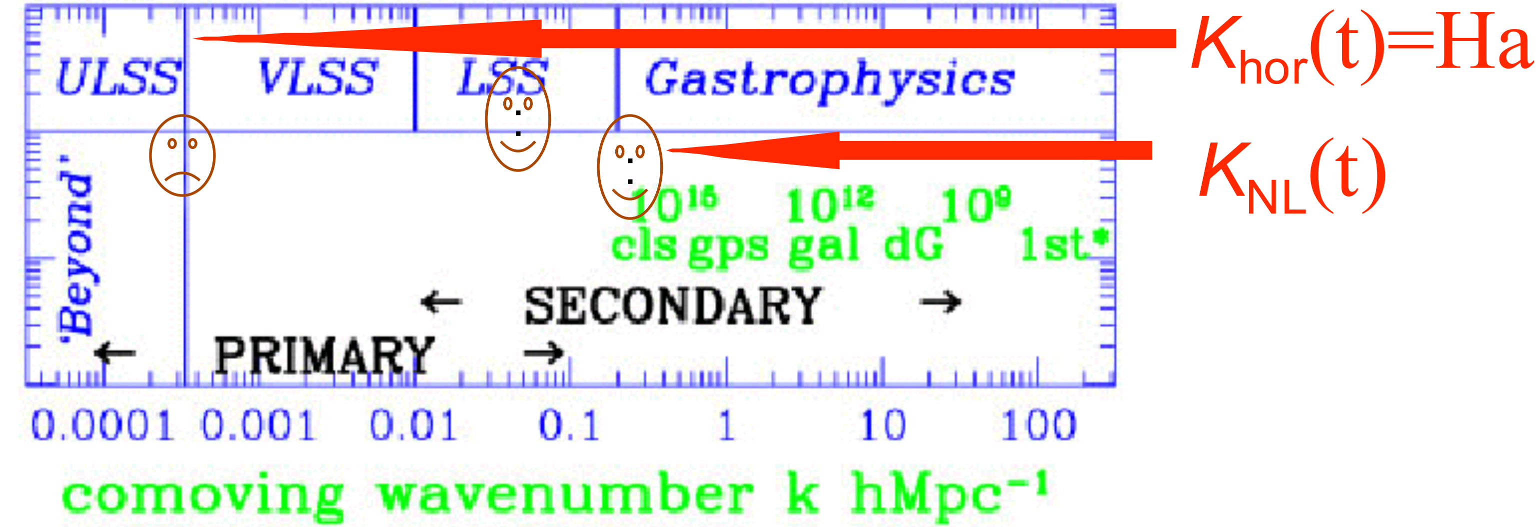


1.2 billion light years across gas+dark matter simulation of cosmic structure evolution

~ biggest gasdynamical simulations ~ 0.3 billion particles

Millenium dark matter simulation: ~ 10 billion particles


Z = 0.00
t = 1.00
GAS TEMPERATURE
Lambda CDM, 200 Mpc Box
10^4K
10^9K
512^3 Gas 512^3 Dark Particles
James Wadsley, Gasoline



$$\lambda_{phys} = 2\pi\bar{a}(t)/k, \quad \bar{a} = 1 \text{ now}$$

Cosmic Spatial Length Scale (unwrinkled)

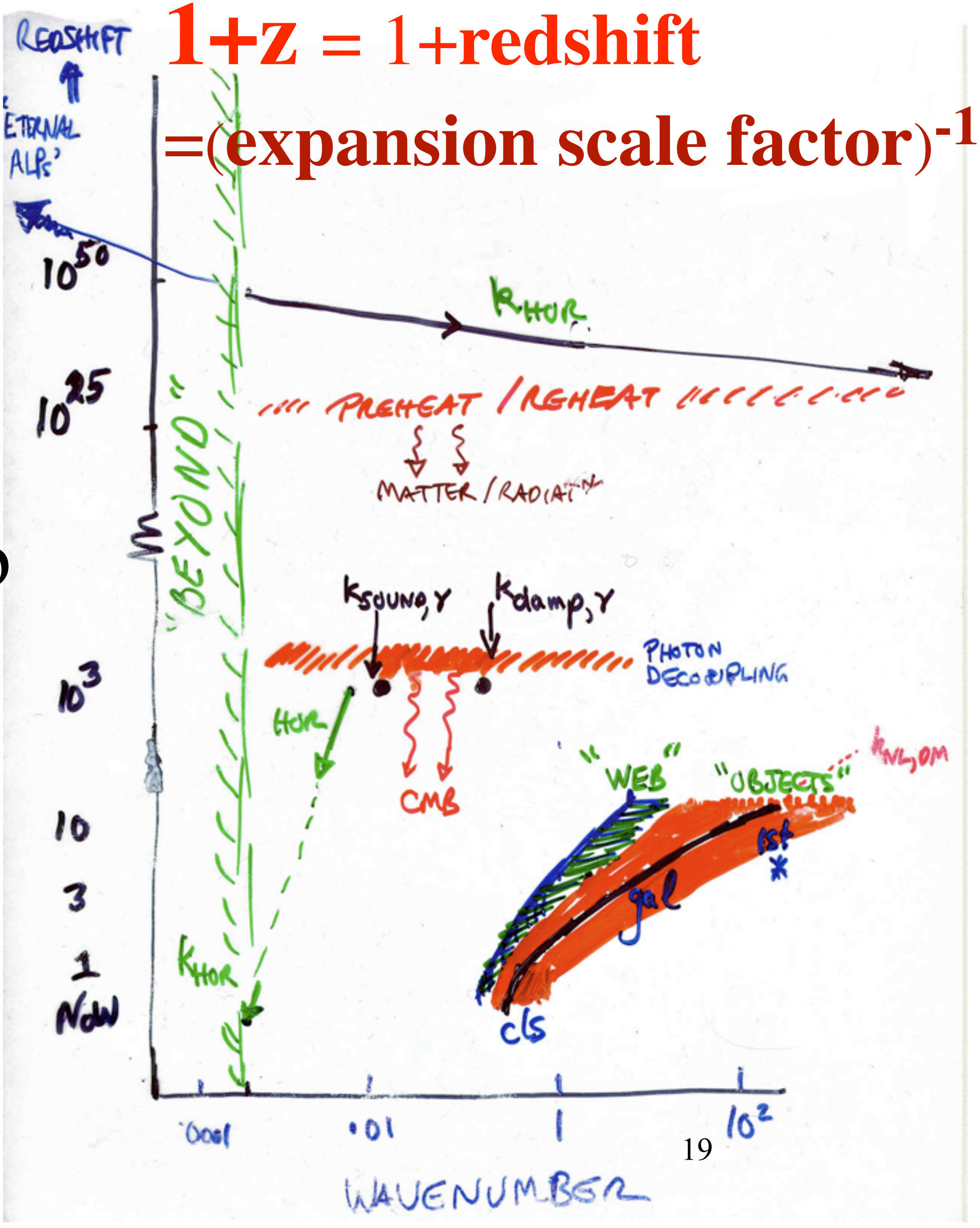
Momentum Space PROBES

$1+z$ = 1+redshift
=(expansion scale factor)$^{-1}$

Redshift *vs* wavenumber:

k_{NL} & the cosmic web

"virialized" collapsed objects bridged by a network of filaments, membranes & voids



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

50s Neyman&Scott point process of galaxies - Poissonian ideas; 70s Peebles etal: 2-pt & 3-pt correlation functions in angular in the Shane-Wirtanen galaxy catalogue; 80s APM catalogue Efstathiou etal; 50s-80s Abell cluster catalogue & 2-point cg and cc; 80s: superclusters are real, large voids exist. 3D redshift surveys CfA ⇒ 2dF, SDSS,COSMOS

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70s: Doroshkevich, Shandarin, Zeldovich: 1st order Lagrangian dynamics, statistics of 1D collapsing entities (caustics & pancakes) in a GRF; 80s: Arnold, Shandarin & Zeldovich: influential picture of 1st order catastrophes;1D⇒2D⇒3D pancake⇒filament⇒cluster flows

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

80s: hot, warm & **cold** collisionless **dark matter** paradigm ⇒***x**CDM*

87: ***X***= s /H0 / Λ / Open/ is /is+ad/ h-c/ h+/ b/ b / **Λ+b** / Op+b /τ /BSI /BSI2

90s-00s: data settled on *X*= Λ +tilt ⇒ *dark-energy* +tilt

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80s: hot, warm & **cold** collisionless **dark matter** paradigm ⇒***x**CDM*

$\mathbf{X}(\mathbf{r},t) = a(t)\,(\mathbf{r} - \mathbf{s}(\mathbf{r},t))$ general map of a cold medium, onto multi-stream map;
$dX^i/a = (V^i-HX^i)/a\,dt + \mathbf{e}^i{}_l(r,t)dr^l = v_{pec}{}^i dt + (\delta^i{}_l+\varepsilon^i{}_l(r,t))dr^l$; $\mathbf{v}_{pec}=-\Delta\Phi_P$,
where $\rho_m/<\rho_m> = 1+\delta_m = 1/\det(1+\varepsilon) \Rightarrow \ln \rho/<\rho> = -\mathrm{Trace}\ln(1+\varepsilon)$; $\varepsilon =$ **strain tensor**

Lagrangian 1st order linear $\mathbf{s}(\mathbf{r},t)=D(t)\mathbf{s}(\mathbf{r})=D(t)\nabla\psi_s(\mathbf{r})$ separable 1-1 & onto => caustics,
$\Delta\psi_S=\delta_L=-\mathrm{Tr}\,\varepsilon = \Phi_P\,(a/D)/4\pi G<\rho_m>a^3$, ε~tidal tensor: velocity potential $\Psi_{V}=-dD/dt\,\psi_S$, ε~shear

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

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where $\rho_m/\langle\rho_m\rangle = 1+\delta_m = 1/\det(1+\varepsilon) \Rightarrow \ln\rho/\langle\rho\rangle = -\mathrm{Trace}\,\ln(1+\varepsilon)$; $\varepsilon =$ **strain tensor**

Lagrangian 1st order linear $\mathbf{s}(\mathbf{r},t) = D(t)\mathbf{s}(\mathbf{r}) = D(t)\nabla\psi_s(\mathbf{r})$ separable 1-1 & onto => caustics,

$\Delta\psi_S = \delta_L = -\mathrm{Tr}\,\varepsilon = \Phi_P\,(\mathbf{a/D})/4\pi G\langle\rho_m\rangle a^3$, ε~tidal tensor: velocity potential $\Psi_V = -dD/dt\,\psi_S$, ε~shear

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

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

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

90s: the **cosmic web** of interconnected filaments, membranes & voids, with $\varepsilon^{i}{}_{l}$ -oriented peak-patches playing a determining role BKP98 $\Longrightarrow$

"molecular" picture of large scale

peak-patches $\delta > 100$, massive galaxies at z ~ 3

are the rare “events” in the medium ⇒ ”intermittency”

(dwarf galaxies at higher z, groups then clusters at lower z)

filaments $\delta \sim$ 5-10, bridge massive galaxies, dwarfs

bead the bridges & there are smaller dwarf bridges

2-peak constraint of nearly-aligned tidal tensors **=> strong bridges**

membranes $\delta \sim 2$ intra-filament webbing

3,4,...-peak constraint of “clustering patches’ of peaks

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

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

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peak-patches $\delta > 100$, massive galaxies at $z \sim 3$ are the rare "events" in the medium ⇒ "intermittency" (dwarf galaxies at higher z, groups then clusters at lower z)

filaments $\delta \sim 5\text{-}10$, bridge massive galaxies, dwarfs bead the bridges & there are smaller dwarf bridges

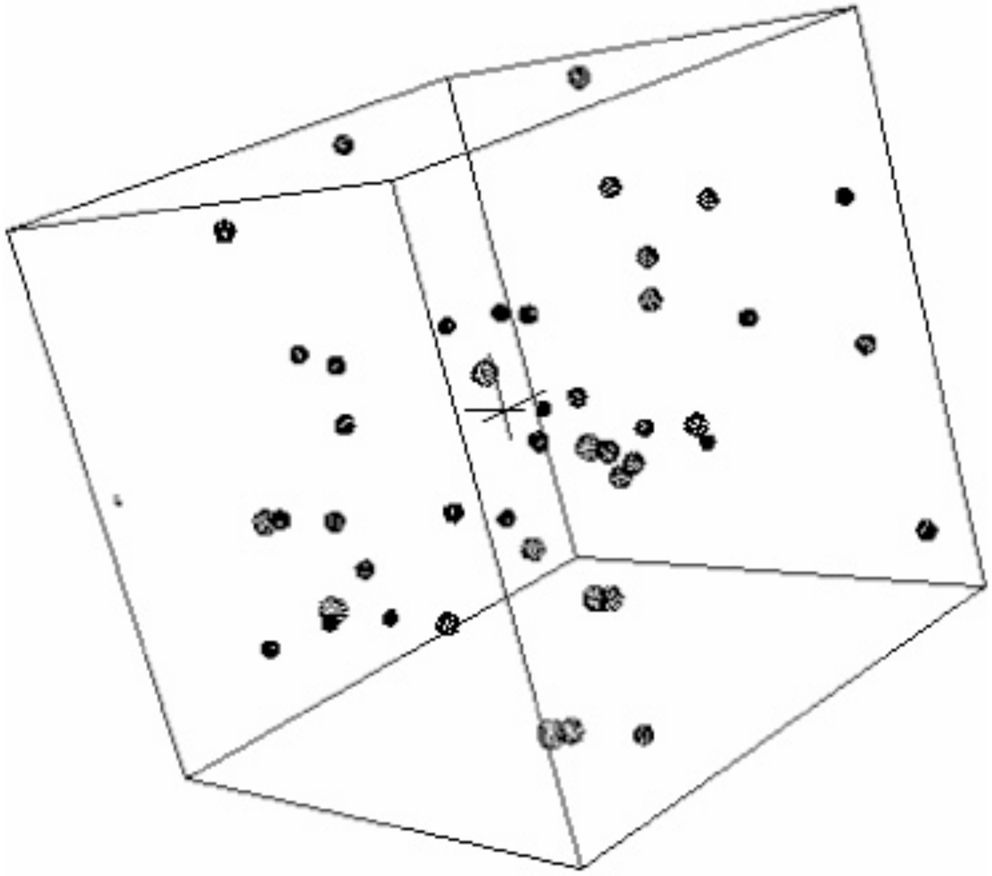
2-peak constraint of nearly-aligned tidal tensors **=> strong bridges**

membranes $\delta \sim 2$ intra-filament webbing

3,4,...-peak constraint of "clustering patches' of peaks

Cluster Peak Patches in Final State Space

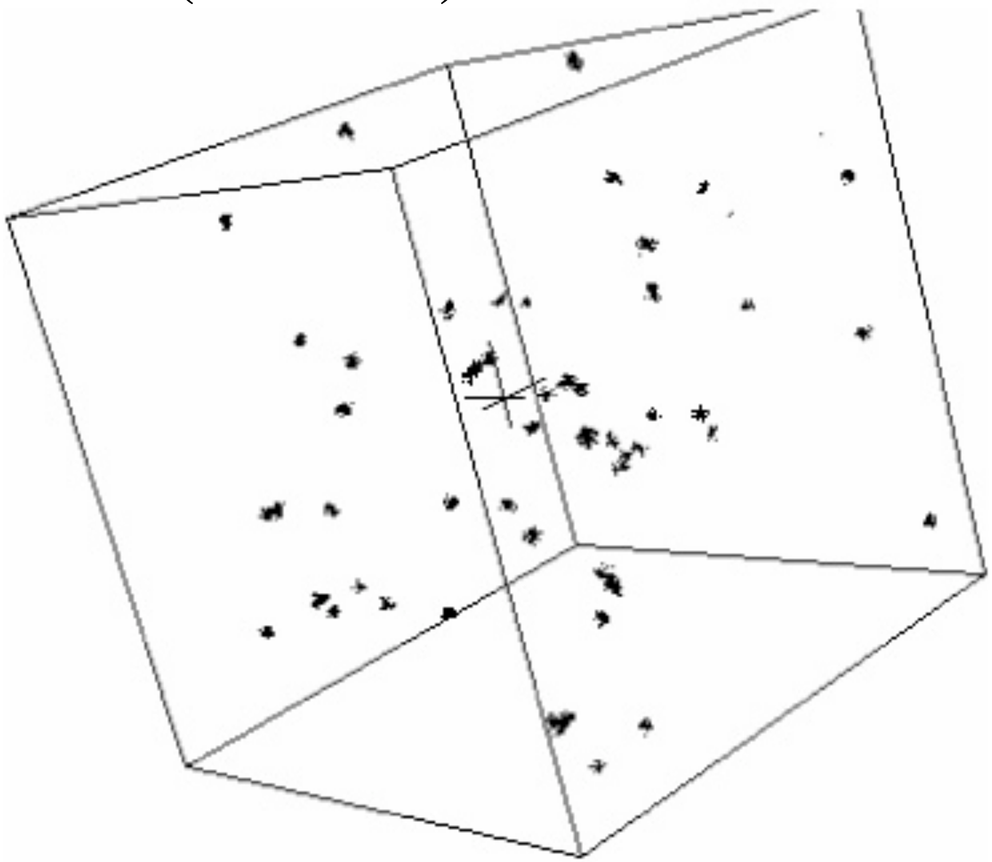
(Eulerian)



(400 Mpc)^3 simulation

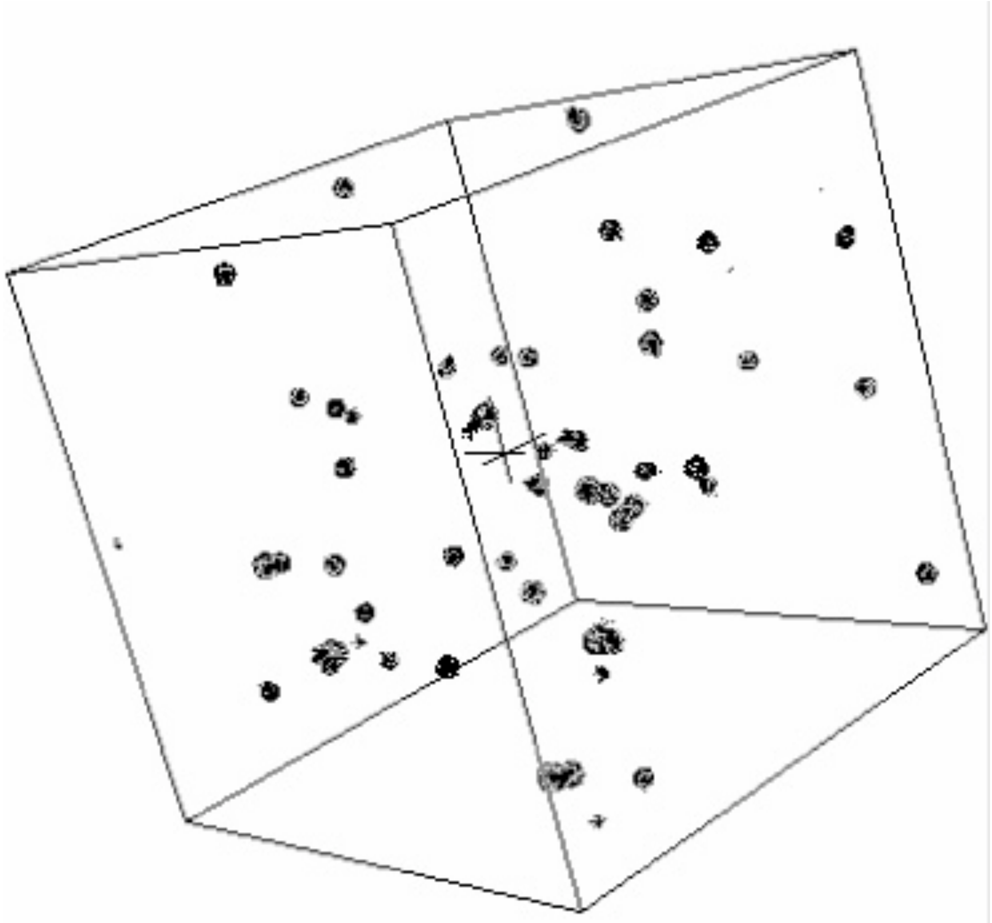
N-body groups in Final State Space

(Eulerian)



(400 Mpc)^3 simulation

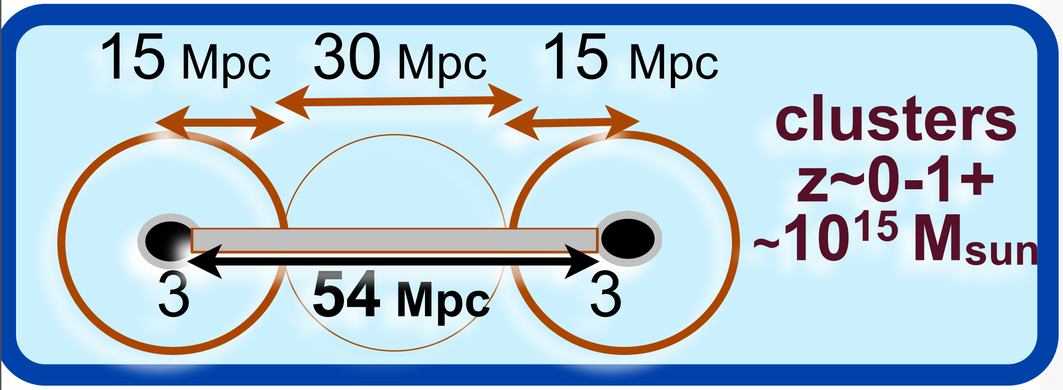
Cluster peak patches & N-body groups overlapped



$(400\ \mathrm{Mpc})^3$ simulation

“Molecular” Picture of Filaments & Membranes in LSS

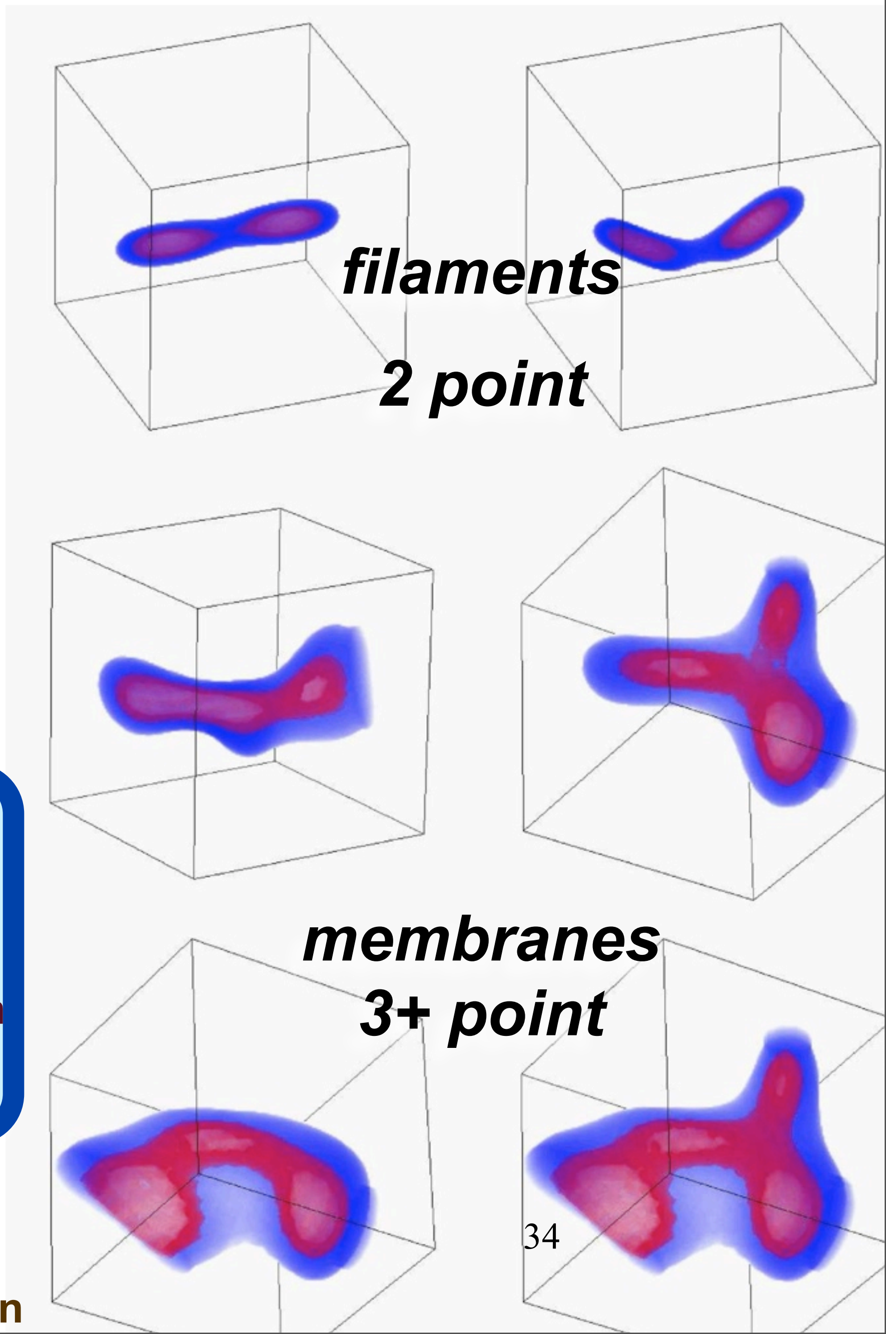
B+Kofman+Pogosyan 96-99



1 Mpc 2 Mpc 1 Mpc

3.6 Mpc

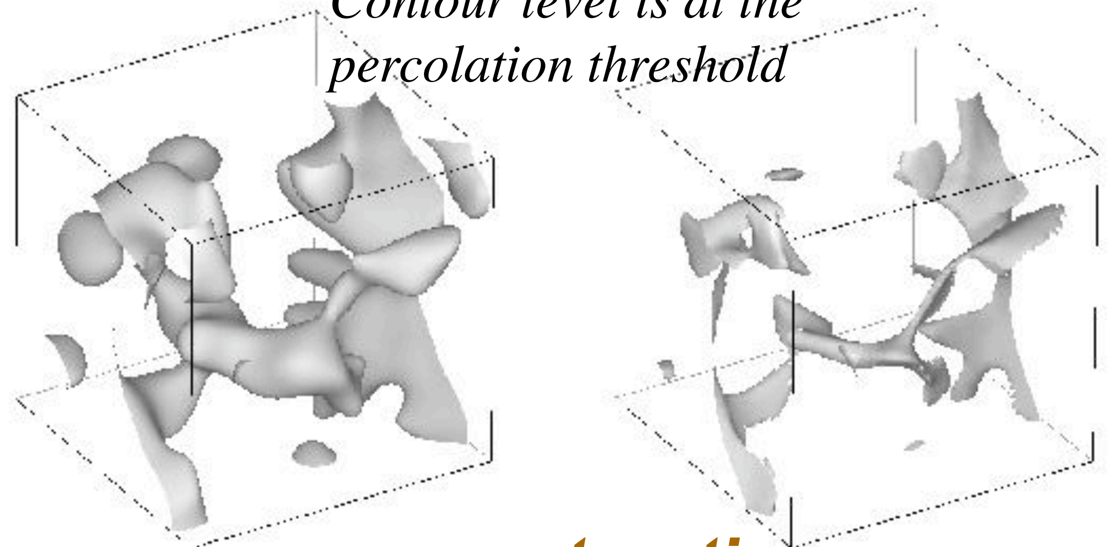
galaxies
z~2-5
$\sim 10^{11.5}\,M_{sun}$



sample density field reconstruction from the most massive peak-patch clusters

Lagrangian space (initial condition) Eulerian space (final state)

Contour level is at the percolation threshold



initial density spectrum $d\sigma_{\rho L}^2/d\ln k$

smoothing

$\sigma_{\rho L}$ **(k)~0.65**

cf. $\sigma_{\rho L}$ **(k_{NL})=1**

cf. halo $\delta_L \equiv$ $\nu\sigma_{\rho L}$ **(k) ~1.6-2.7**

$n_{halo}(\sigma_{\rho L}^2$,...)

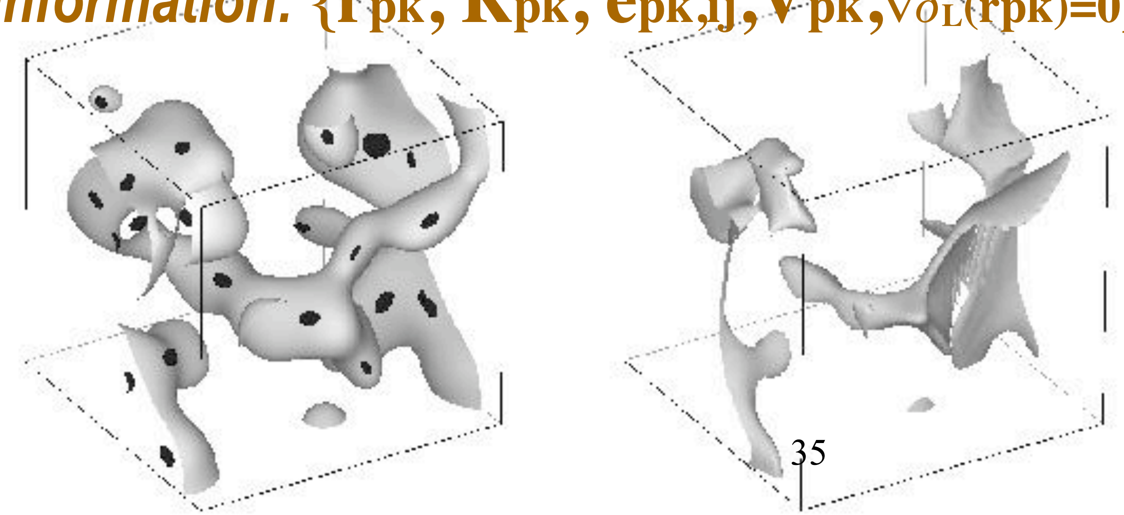
~ n_{halo} (M,...)

bias(M,...) ~ $\delta n_{halo} / \delta\rho_m$

P(*subhalo|halo)*

cf. ***reconstructions***

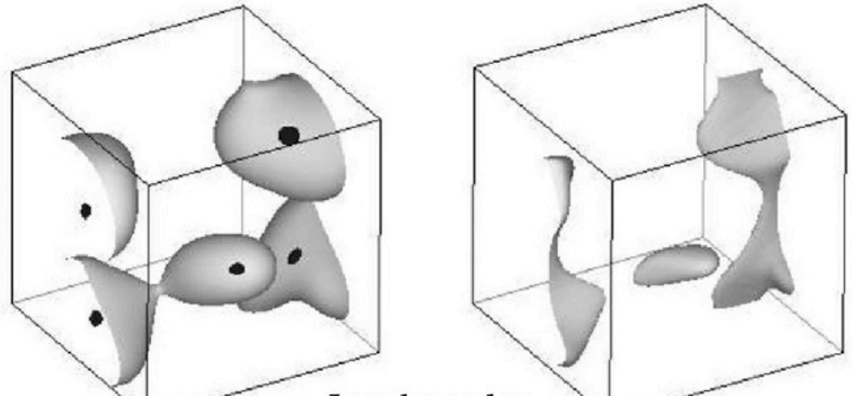
compressed information: **$\{r_{pk}, R_{pk}, e_{pk,ij}, V_{pk}, \nabla\delta_L(r_{pk})=0\}$**



Eulerian space *reconstructions: convergence as compressed information increases*

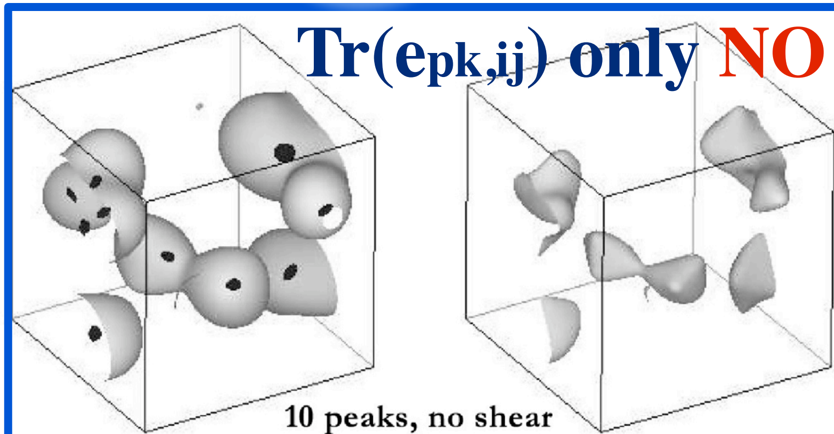
compressed information without anisotropic strain:

$\{\mathbf{r}_{pk},\ \mathbf{R}_{pk},\ \mathbf{e}_{pk,ij},\ \mathbf{V}_{pk},\ \nabla\delta_L(\mathbf{r}_{pk})=0\}$

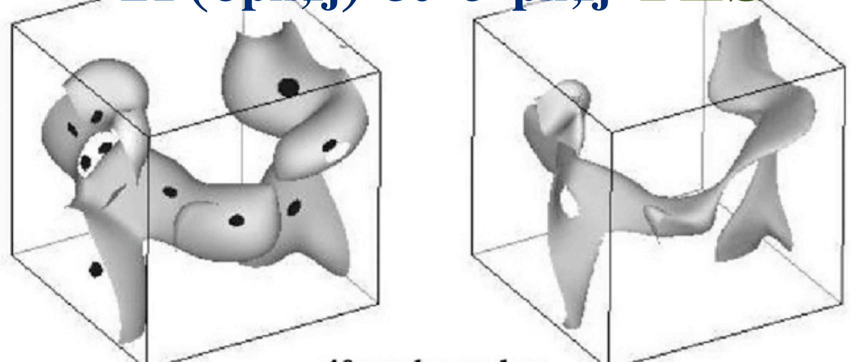


5 peak patches

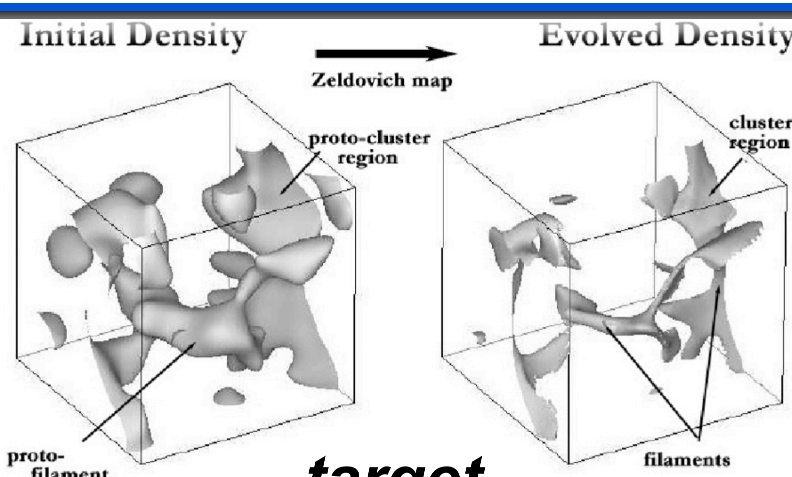
$\mathrm{Tr}(e_{pk,ij})$ only NO cf. **$\mathrm{Tr}(e_{pk,ij})$ & $e'_{pk,ij}$ YES**



10 peaks, no shear

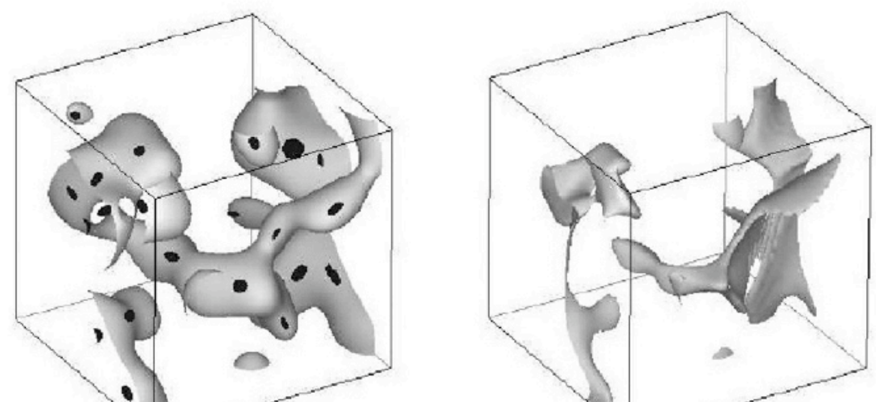


10 peak patches



target

cf.



20 peak patches

Cosmic Web

varies with

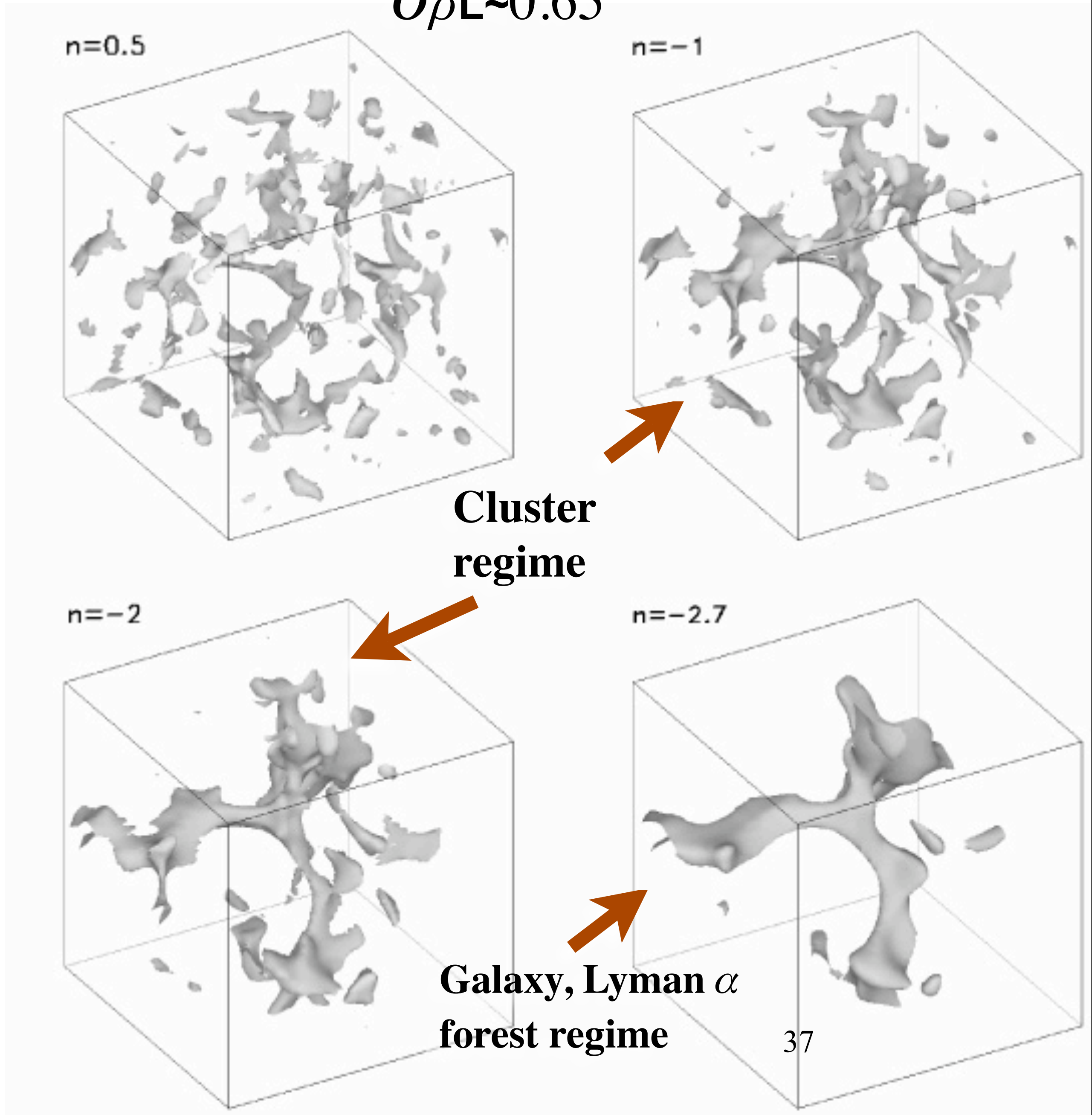
initial density

spectrum tilt

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

smoothing

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



neff (k) *varies for 'standard' tilted* Λ*CDM model:*

neff (k) ~

.962 ± .013 small k,

-1.3 cluster scale,

-2.3 galaxy scale,

-2.8 Lyman α *scale*

-3.04 large k

Applications of Peak-patch/web ideas

clusters & superclusters at z~0-1.5: SZ, lens, X-rays (sph/treeP_3M)
"reconstruct" initial conditions with "top N" peaks/voids
⇒compression of essential LSS info $\{r_{pk}, R_{pk}, e_{pk,ij}, V_{pk}, \nabla\delta_L(r_{pk})=0\}$
constrained-field gastrophysics simulations (via direct construction or select from large N-body simulation) for clusters, superclusters, Local Group, ...

galaxy bias & likelihood of rare super-patches at z ~ 2-5
peak-patch clustering via multi-box tiling of large regions with phase-coherent ultra-long waves as well as short ones

starbursting galaxies at z ~ 2-5, seen in submm merging peak-patches
Intergalactic medium **Lyman** α **forest** at z~2-5, filaments + dG's (sph/treePM)

"shearing patches", constrained by $\{<e_{ij}>_V\} \sim \{\nu, e_v, p_v$, eigen-orientations$\}$,
linear tidal field = linear strain field = linear shear field

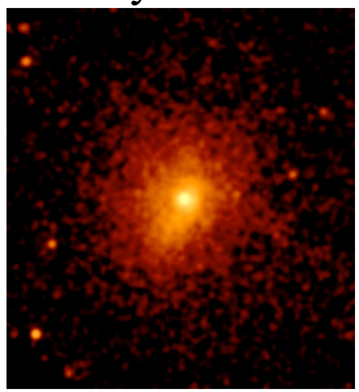
First Objects: inhomogeneous reionization at z ~ 10-20
Strorngren spheres around 'dwarflet' peak-patch clusters

galaxy clusters: *intermittency in cosmic random fields* of mass, pressure, X-ray & optical luminosity, tides/shear (lensing) …

- The most massive, collapsed structures in the universe, probed through galaxies, hot, ionized gas ($10^{7\text{-}8}$K) and dark matter, and maybe cosmic rays and magnetic fields. They are good probes because they are massive and "easy" to detect, but they have complex cores.

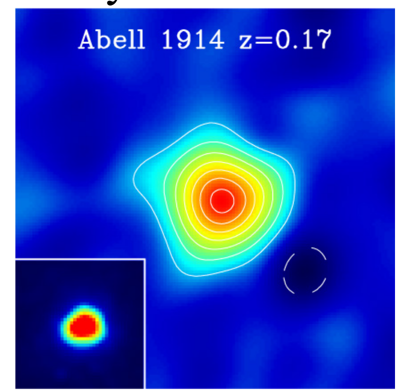
Light from galaxies

X-ray emission

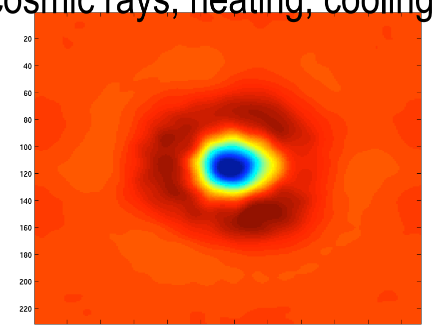


Gravitational lensing

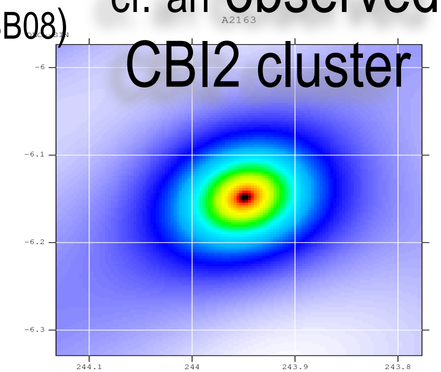
Sunyaev-Zel'dovich effect



Sample **constrained Virgo-like cluster** as CBI1 would see it (treePM-SPH sim includes CMB, cosmic rays, heating, cooling PSSB08)



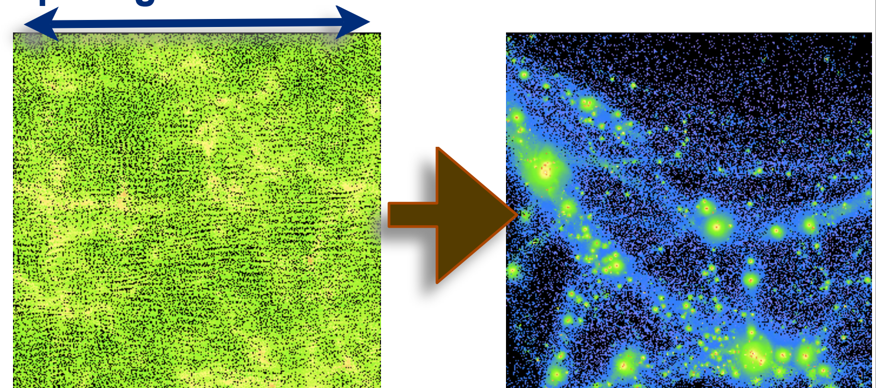
cf. an observed CBI2 cluster

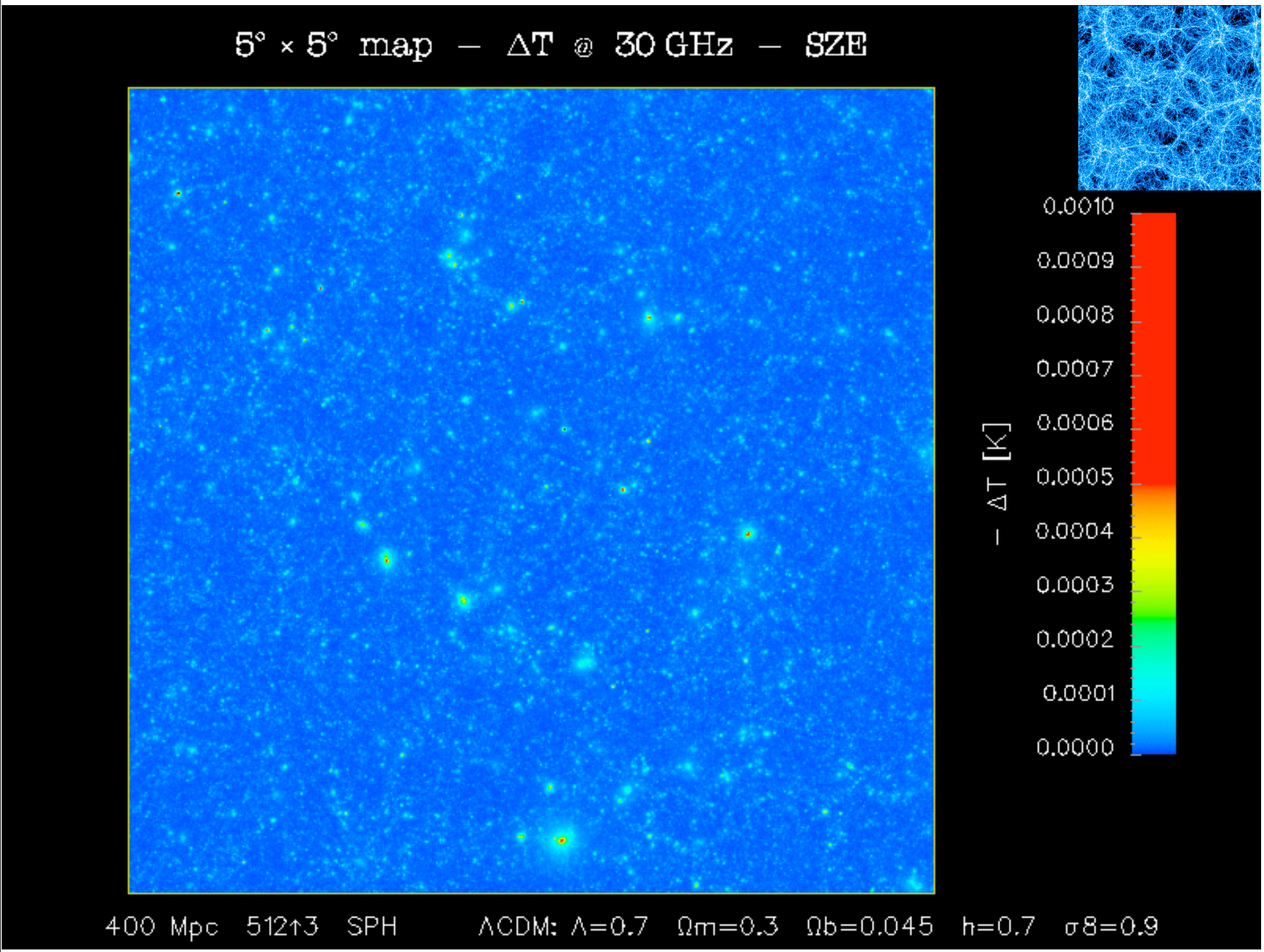


constrained supercluster sim treePM-SPH

BKPW97/99 **largest k-range of its time** (>> Virgo sim)

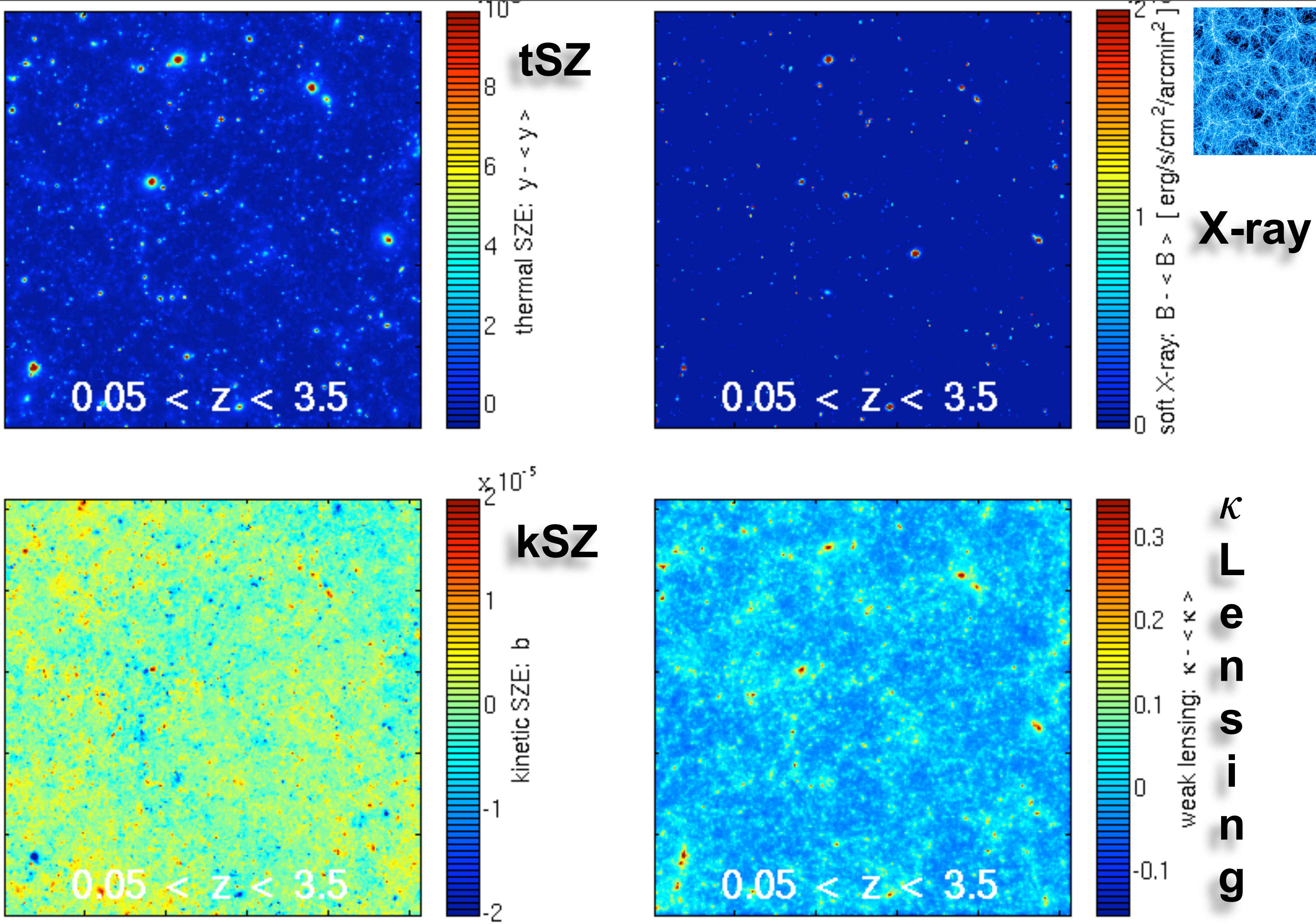
104 Mpc HighResolution +166 MedRes +266 LoRes





pass the CMB thru the cosmic web; CBI extra power??

512^3 LCDM sim tSZ maps: rotate & translate copies(z) of 400 Mpc box



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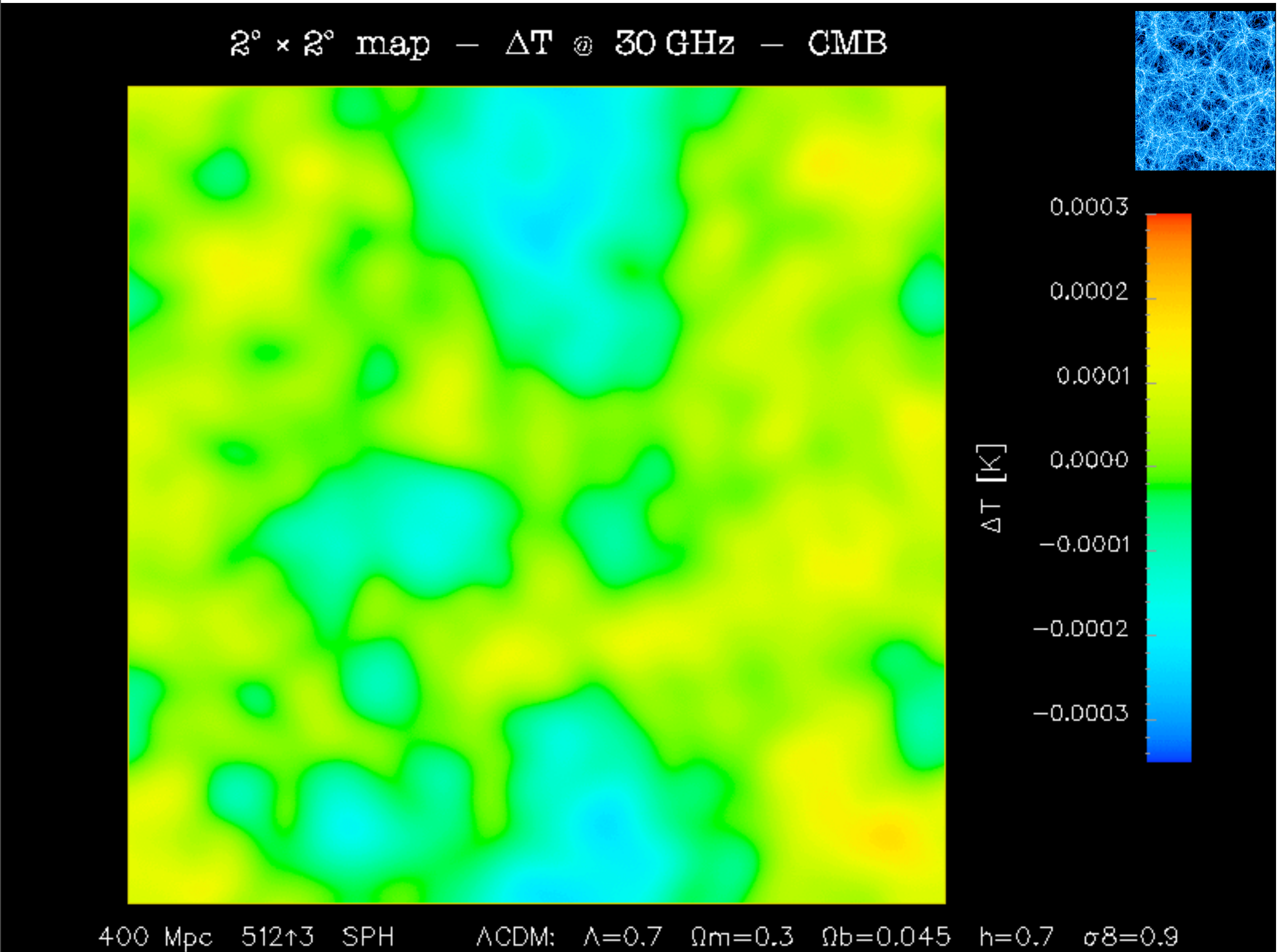
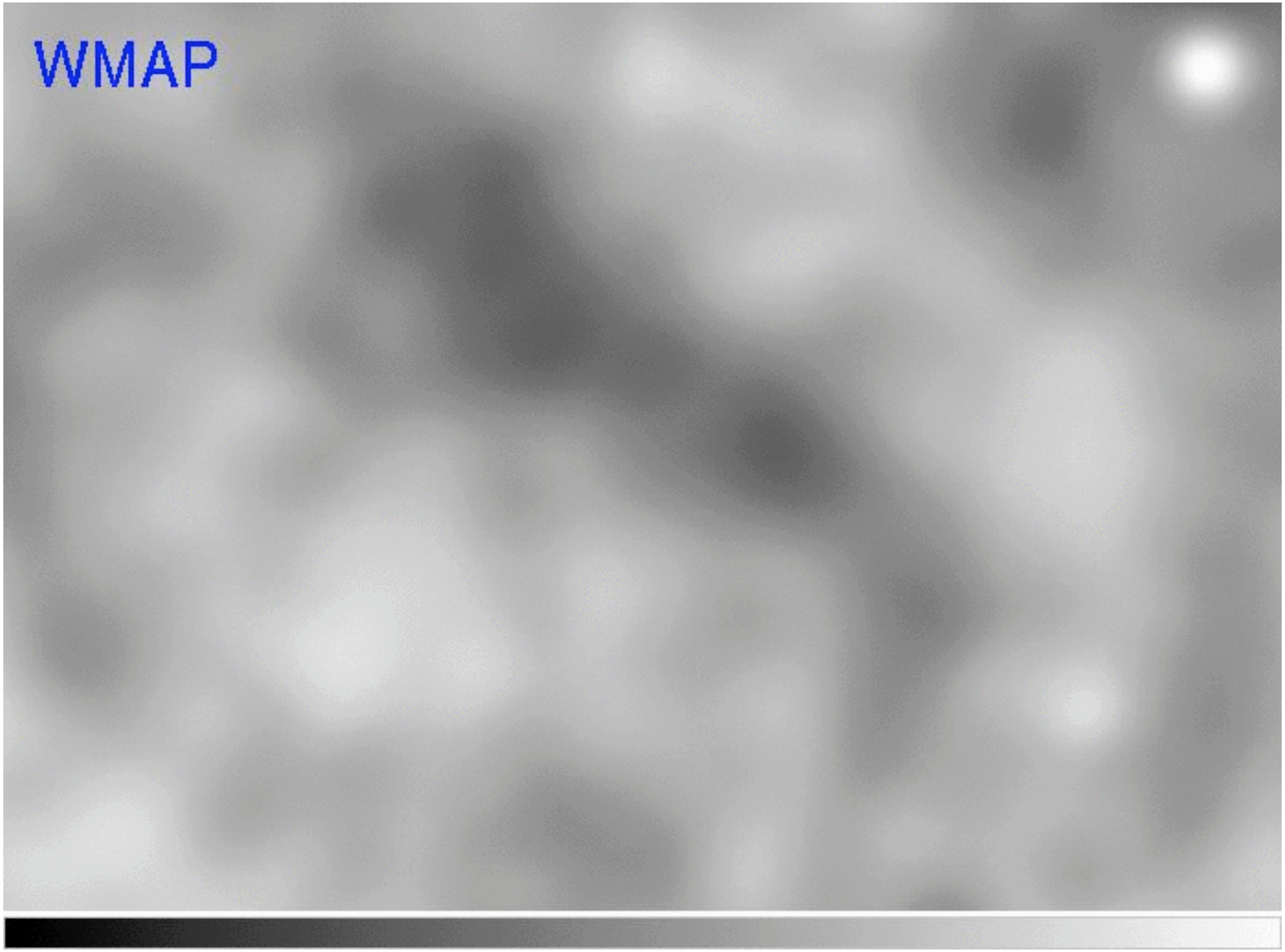


pass the CMB thru the cosmic web; CBI extra power??

WMAP⇒BOOM⇒ACBAR⇒ACT
the high resolution CMB frontier



Toby Marriage

ACT@5170m

why Atacama? driest desert in the world. thus: cbi, toco, apex, asti, act, alma, quiet, clover

CBI2@5040m

end