Emergence of the Cosmic Web

Dick Bond @
CITA ICAT Canadian Institute for Theoretical Astrophysics / L'institut canadien d'astrophysique theorique
25 years cifar

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

Chicago hwc Spring82 Chandra stayed! Frenk thinks Aspen82 Moriond83

***Emergence of yDM**, y=h,w,c, isocCDM, isocB/BH, stringCDM, ...*

Emergence of xCDM

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

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

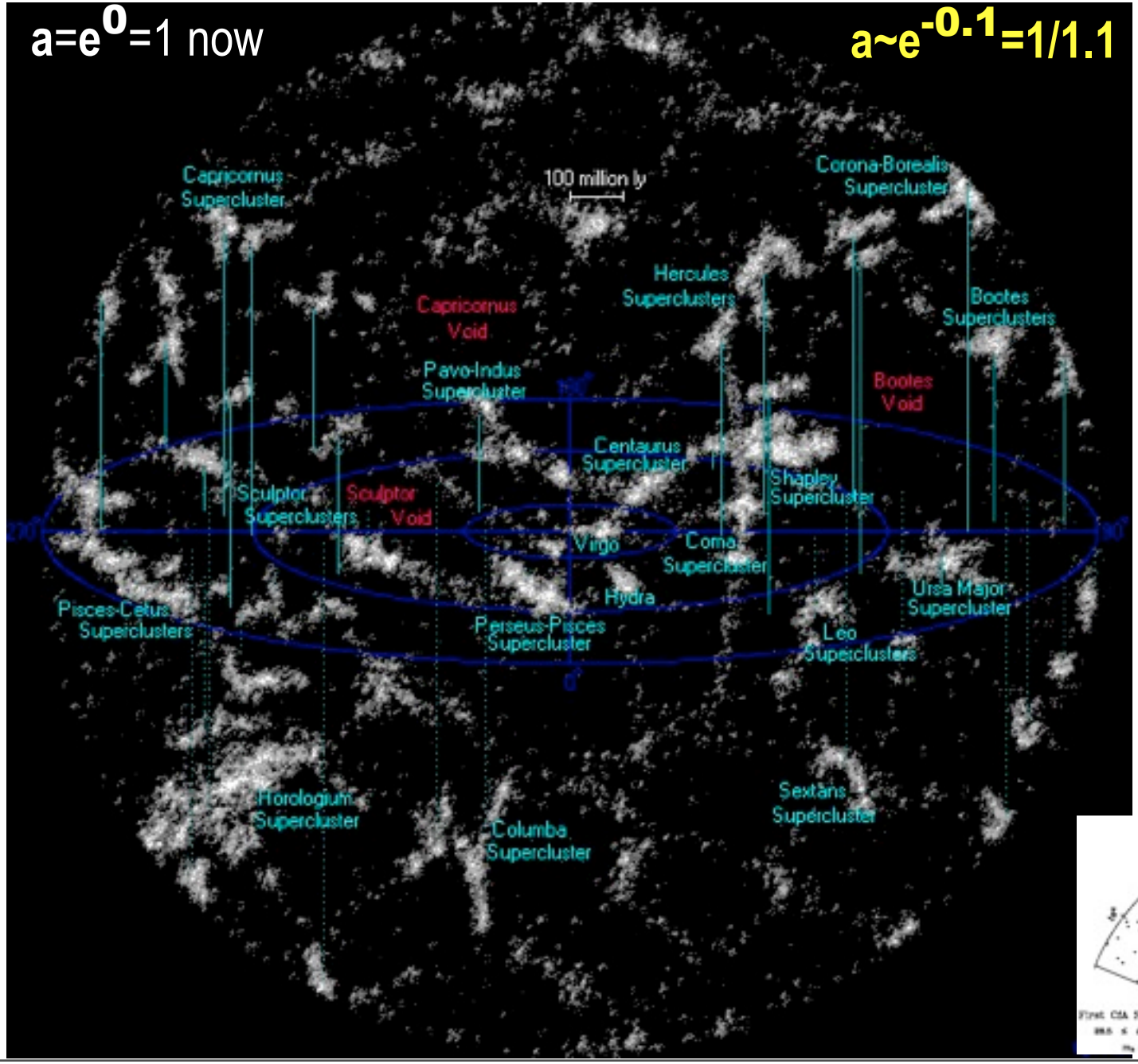
review articles

in ``A Pan-Chromatic View of Clusters of Galaxies and the Large-Scale Structure'', (Berlin/Heidelberg: Springer)

Clusters and the Theory of the Cosmic Web
Rien van der Weygaert & J.Richard Bond, 2008, Lecture Notes in Physics 740, 335-408
http://www.astro.rug.nl/~weygaert/tim1publication/weybondgh2005.paper1.pdf

Observations and Morphology of the Cosmic Web
Rien van der Weygaert & J.Richard Bond, 2008, Lecture Notes in Physics 740, 409-468
http://www.astro.rug.nl/~weygaert/tim1publication/weybondgh2005.paper2.pdf

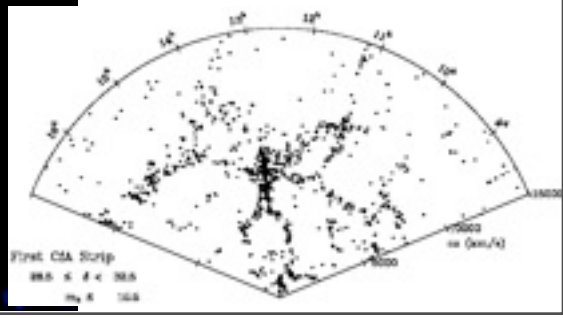
cosmic web of nearby superclusters < Giga*lyr*



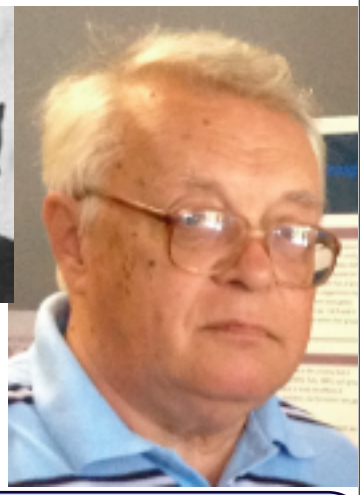
70s adiabatic pancake (physical filter)
Doroshkevich
cf.
70s isoc B/BH (power law CorrFn)
Basko

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

emergence of superclusters
Peebles vs. 70s Einasto+.. 80 + Oort +



the $\mathbf{e}_J^j$ *history*



На здоровье

Szalay: **Bond** one of two (BJones) in the west into **Doroshkevich 70 ++** *and with enthusiasm*

82 IAU Crete

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**

$$d\mathbf{X}^j/a = (\mathbf{V}^i - \mathbf{H}\mathbf{X}^i)/a\, dt + \mathbf{e}_J^j(r,t)d\mathbf{r}^J$$

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

ε=strain tensor $\mathbf{e}_J^j \equiv exp(\boldsymbol{\varepsilon})_J^j$ ⇒ *ln* $\rho/\langle\rho\rangle$ = -Trace ε

$\mathbf{X}(\mathbf{r},t) = a(t)\,(\mathbf{r} - \mathbf{s}(\mathbf{r},t))$ general map of a cold medium, onto multi-stream map

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

$d\varepsilon/dt$ = **shear** tensor, $\varepsilon \propto$ **tidal** tensor: velocity potential $\Psi_{v=}$=-$dD/dt\ \psi_s$

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

80s: M **scale space** $ln\mathbf{R_f}$ 3+1D => 4+1D our ADS to CRFT => 9+1D $\boldsymbol{\varepsilon}$

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,...

$ln\mathbf{R_f}$ => 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 $\boldsymbol{\varepsilon^j_J}(r_{pk},t,R_{pk})$ fundamental in evolution; ***accurate mass & spatial structure determination cf. SP-O gps***; shearing patch simulations BW96-99-02, BWKP99

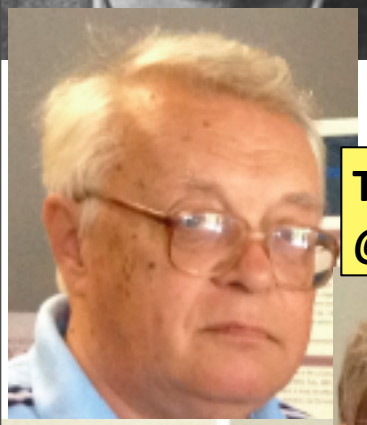
89: ***silicon graphics*** *visualization of ~32^3 SPH sims of Ly α forest with a super k-space realization =>* ***filaments are real*** *and dominate and where are the pancakes*

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

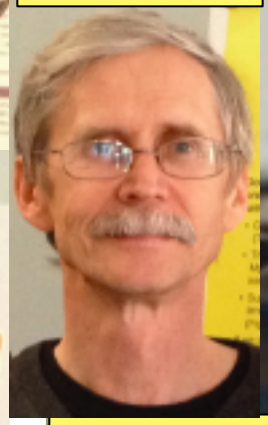
"molecular" picture of large scale structure

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

inner space outer space chicago apr 1984 from ITP84



Toyla
@sweet-60

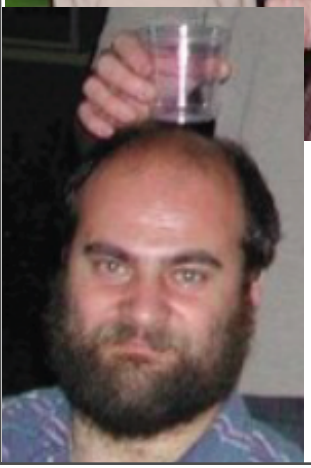


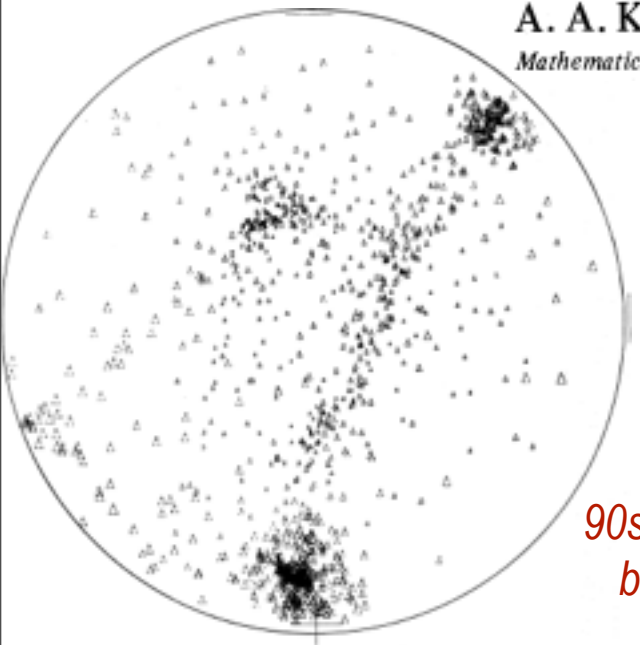
ambient SZ in pancake model SBS83; hdm ruled out by clusters FDW83; SZ from clusters, explosions, superconducting cosmic strings B88; ambient SZ pix B89 "**clustered shots**" (*aka* **halos** *aka* **bbks86-peaks**) ⇒ **peak patches BM91-96, SZ/CIB was the target**

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

inner space outer space chicago apr 1984 from ITP84

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





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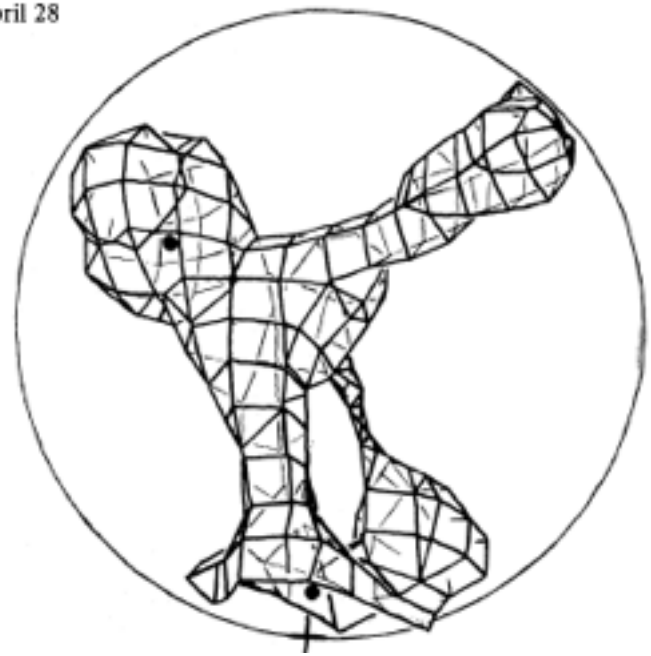
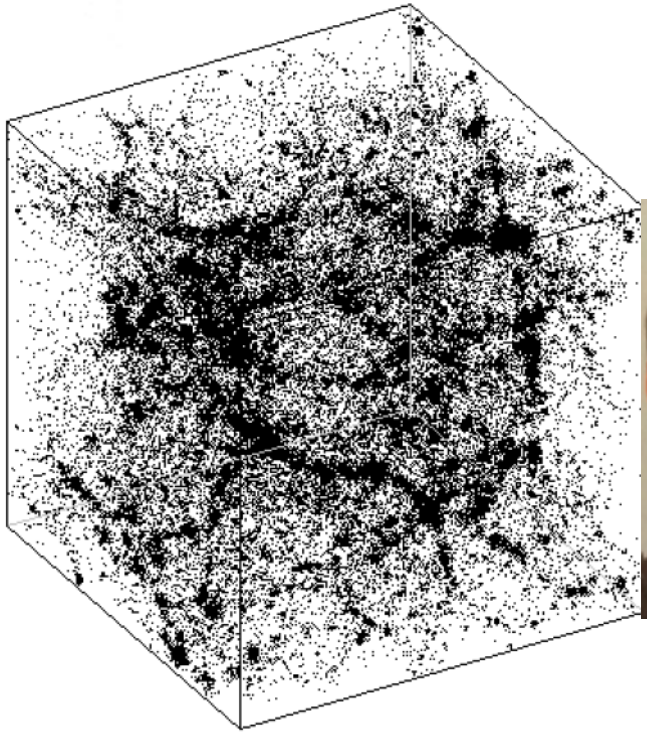
3D numerical model of the Universe

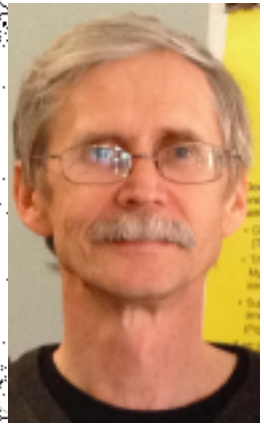


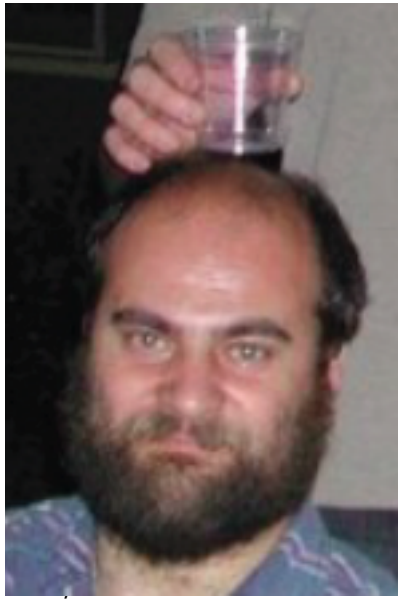
Klypin's vintage 82
160h^{-1}Mpc box 32^3 hDM

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

90s Klypin to CITA, 'the west is best', but New Mexico, IKI hates Bond



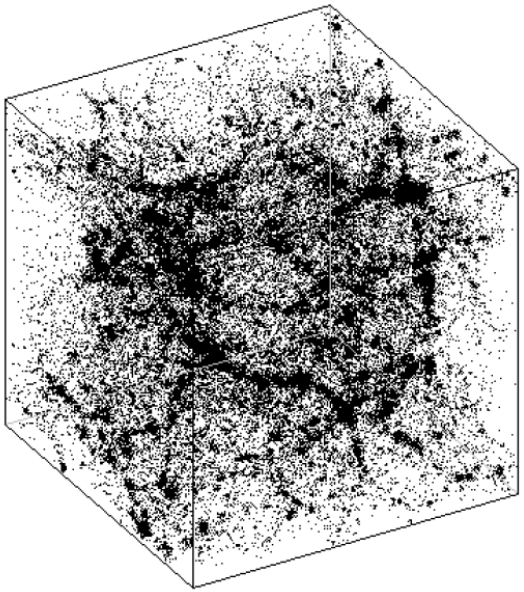




Klypin's vintage 93 50h^{-1}Mpc box 128^3 sCDM = BKP98 web workhorse

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,

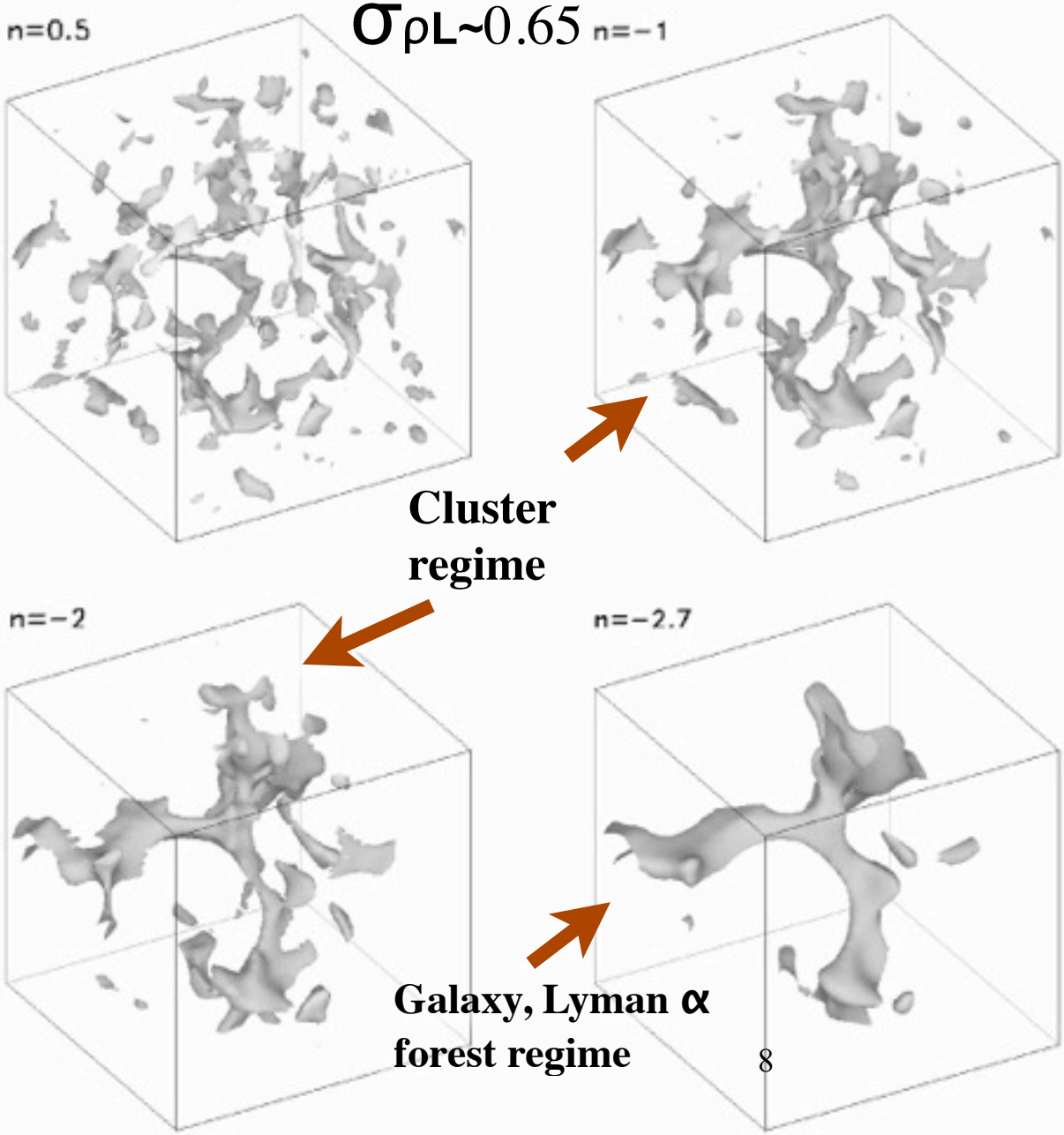
-2.3 galaxy scale,

-2.8 Lyman α scale

-3.04 large k, 1st star

percolation threshold contour

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



Cluster regime

Galaxy, Lyman α forest regime

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

peak-patches: Δ >100, *ln*ρ/<ρ> >5, clusters at z ~0-1

are the rare "events" in the medium ⇒ "intermittency"

the peak-patches give accurate mass, binding energy, & LSS. *BE / "DM" pressure patches*

initial tidal tensors of the patches orient the web

filaments: Δ ~5-10, *ln*ρ/<ρ> >2, bridge clusters, groups bead the bridges 2-peak constraint of nearly-aligned tidal tensors => **strong bridges**

membranes: Δ ~ 2, *ln*ρ/<ρ> >1/2, intra-filament webbing

3,4,...-peak constraint of "clustering patches' aka ***superclusters*** ~ *shear-patches*

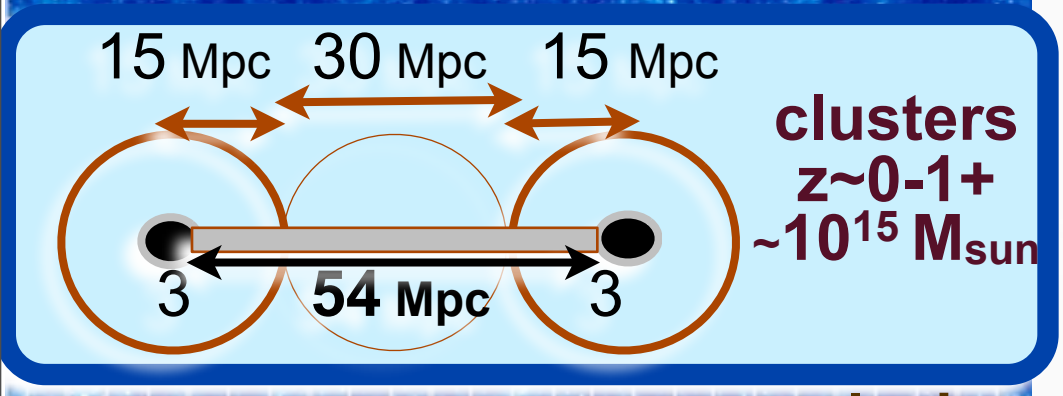
void-patches: Δ < 0.1 *ln*ρ/<ρ>-*minima*, exact obverse of peak-patches

The Cosmic Web

B+Kofman+Pogosyan 96-99

"Molecular" Picture of Filaments & Membranes in LSS

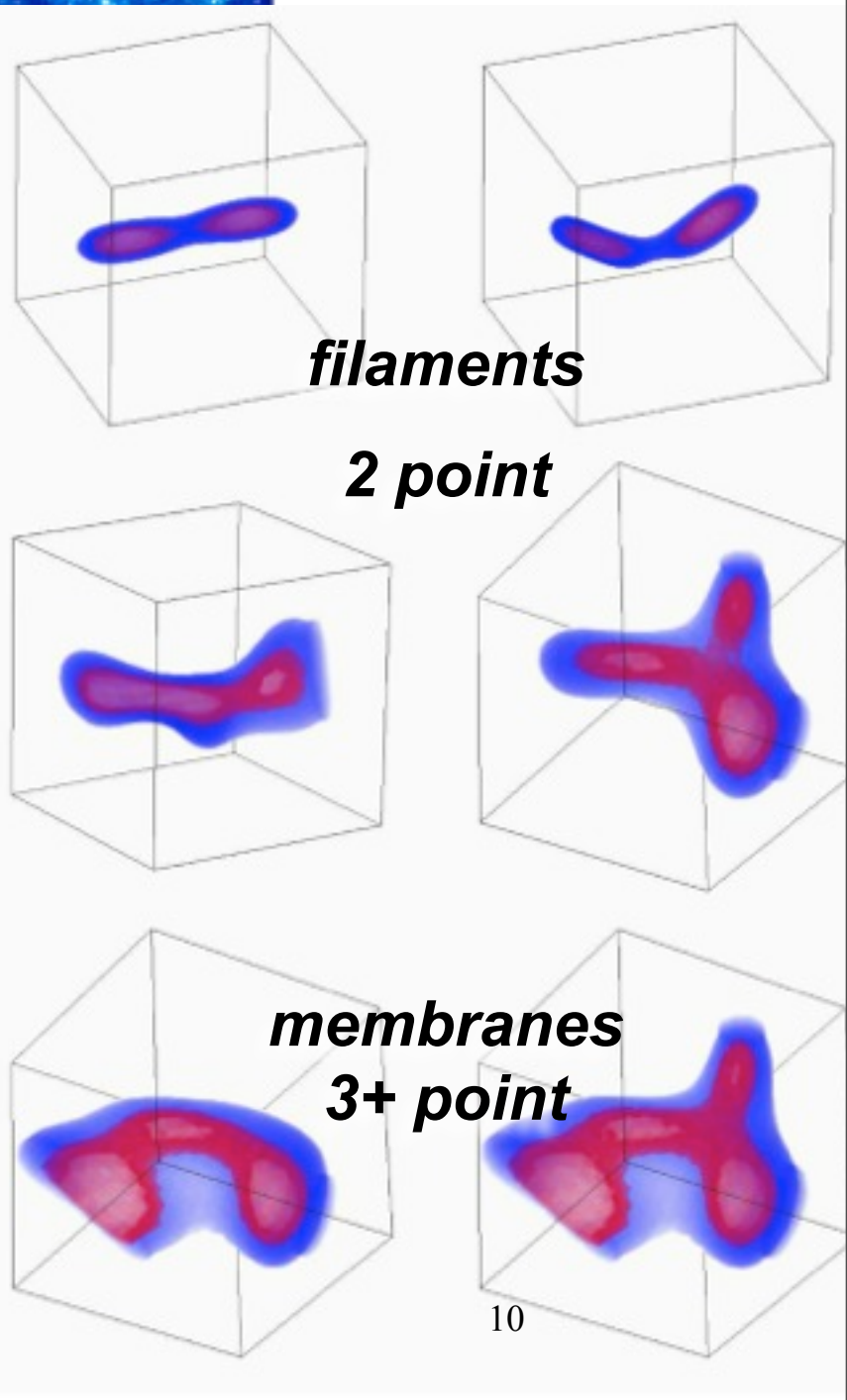
Constrained Correlation Functions



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

1 Mpc
2 Mpc
3.6 Mpc
1 Mpc

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



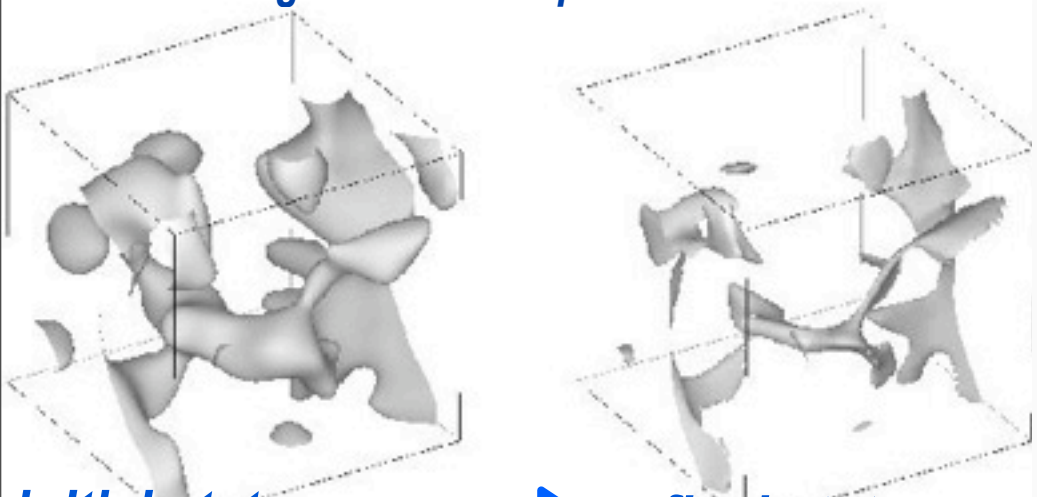
density field reconstruction of the filtered web

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

LSS convergence as N_{patch} increases

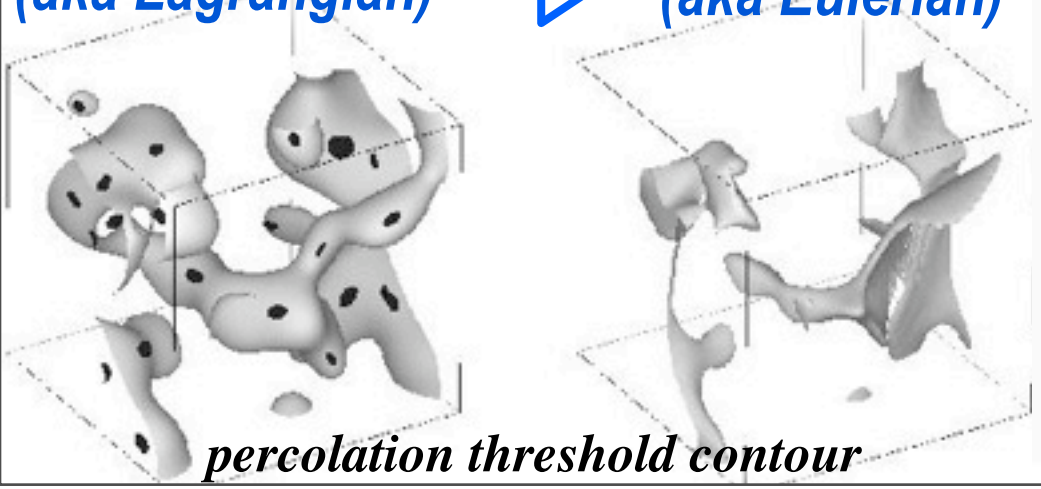
InformationQuality: clusters encode the web

interior and high resolution spatial detail <=> more info

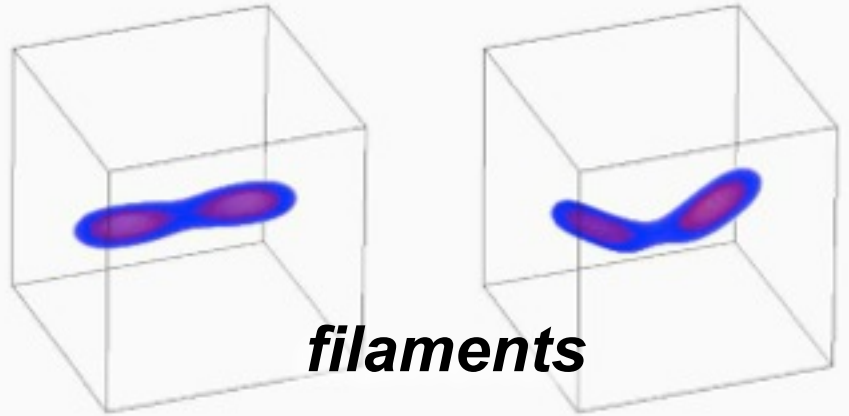


initial state space (aka Lagrangian)

final state space (aka Eulerian)

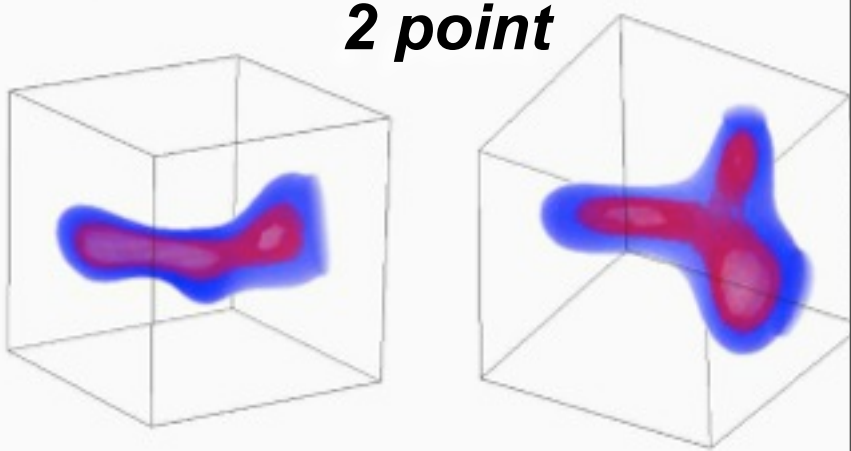


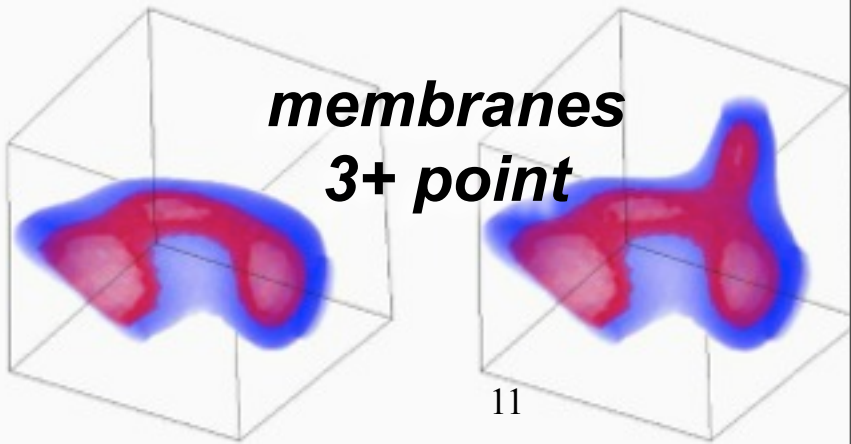
percolation threshold contour



filaments

2 point





membranes

3+ point

Some Applications of Peak-patch/web ideas *late 90s slide pre-gasoline, gadget*

clusters & superclusters at z~0-1.5: SZ, lens, X-rays (sph/treeP3M)
"reconstruct" initial conditions with "top N" peaks/voids
⇒*compression of essential LSS info* $\{r_{pk}, R_{pk}, \varepsilon_{pk,ij}, V_{pk}, \nabla\delta_L(r_{pk})=0\}$

importance sampling, control the rare event regions constrained-field gastrophysics simulations (via direct construction or select from large N-body simulation) for clusters, superclusters, Local Group, ... Shearing-Patch Sampling Applied to the Lyman-α Cloud/Intercloud Medium, astro-ph/01wwww, CITA-2001-62, J.W. Wadsley and J.R. Bond, http://www.cita.utoronto.ca/~bond/papers/lyapj/wbimptlya_Oct9.pdf

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 a forest** at z~2-5, filaments + dG's (sph/treePM)

"shearing patches", constrained by $\{\langle\varepsilon_{ij}\rangle_V\}$ ~ {n,e_V,p_V, eigen-orientations},
linear tidal field = linear strain field = linear shear field
First Objects: inhomogeneous reionization at z ~ 10-20
Stromgren spheres around 'dwarflet' peak-patch clusters. **flat P(*k*)-care**

then CMB BOOM B98,03 CBI, ACBAR, ACT, PLANCK, ABS, ACTpol, SPIDER...
sims for SZ feedback .. entropy/information in the web .. e.g., with neal dalal ..

Alverez, Bond, Hajian, Stein 13:* codes for larger tiling boxes cover ultralarge regions**, *e.g., hiz flat* ***non-G ICs
e.g., ***curvature = inflaton-Gaussian + spiky* F_{NL}(isocon-Gaussian)** *Bond, Braden, Frolov, Huang 13 "B^2FH"*

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

400 Mpc

ΛCDM

WMAP5

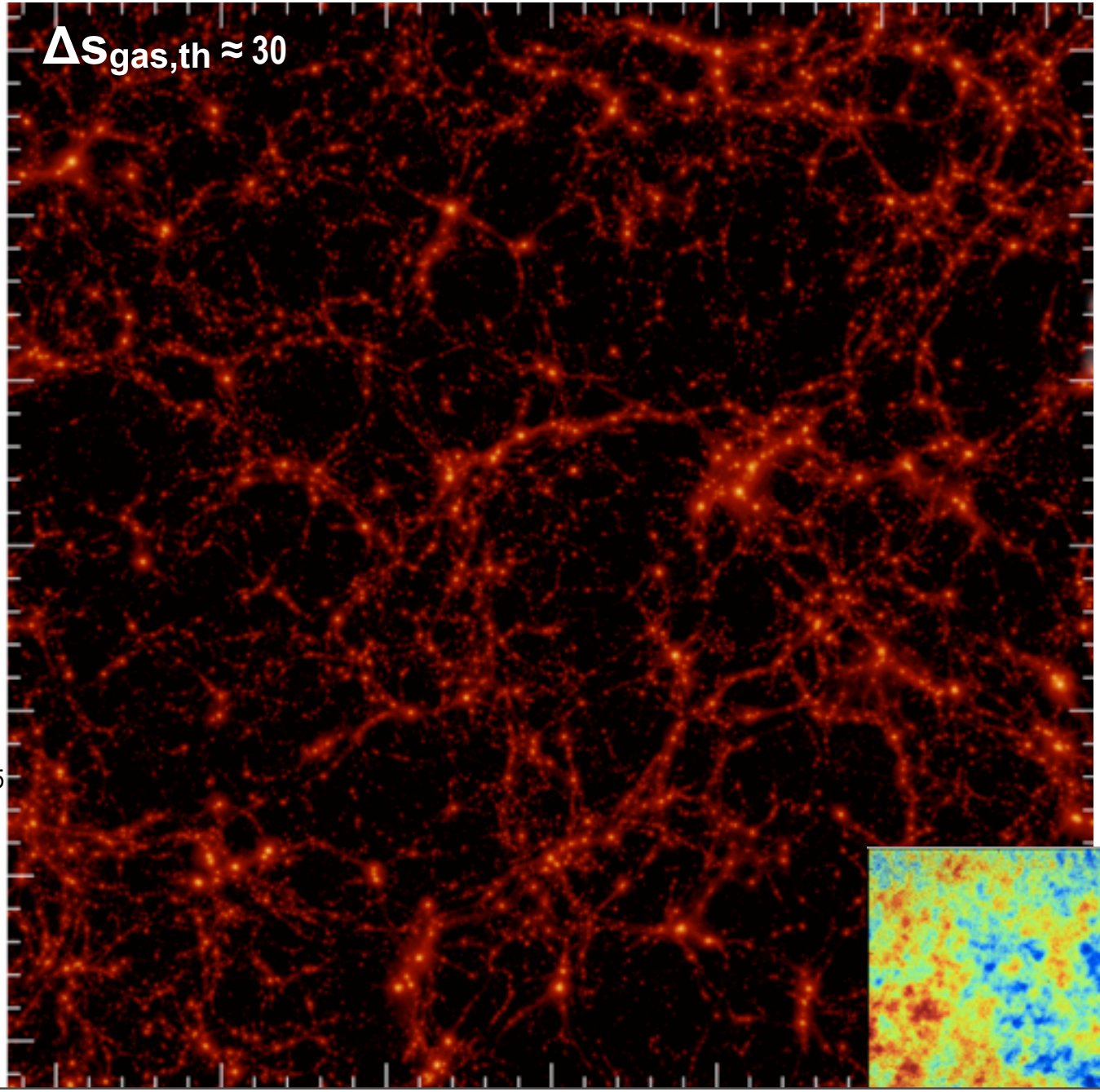
gas pressure

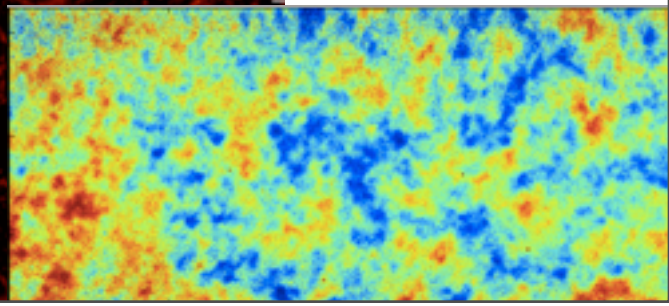
Gadget-3 SF+ SN E+ winds +CRs

512^3

BBPSS10

BBPS1,2,3,4,5





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

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

CMB gets entangled in the cosmic web

descending into the real gastrophysics of cosmic weather

the energetic, turbulent, dissipative, compressive

life of the IGM/ICM/ISM

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

400 Mpc

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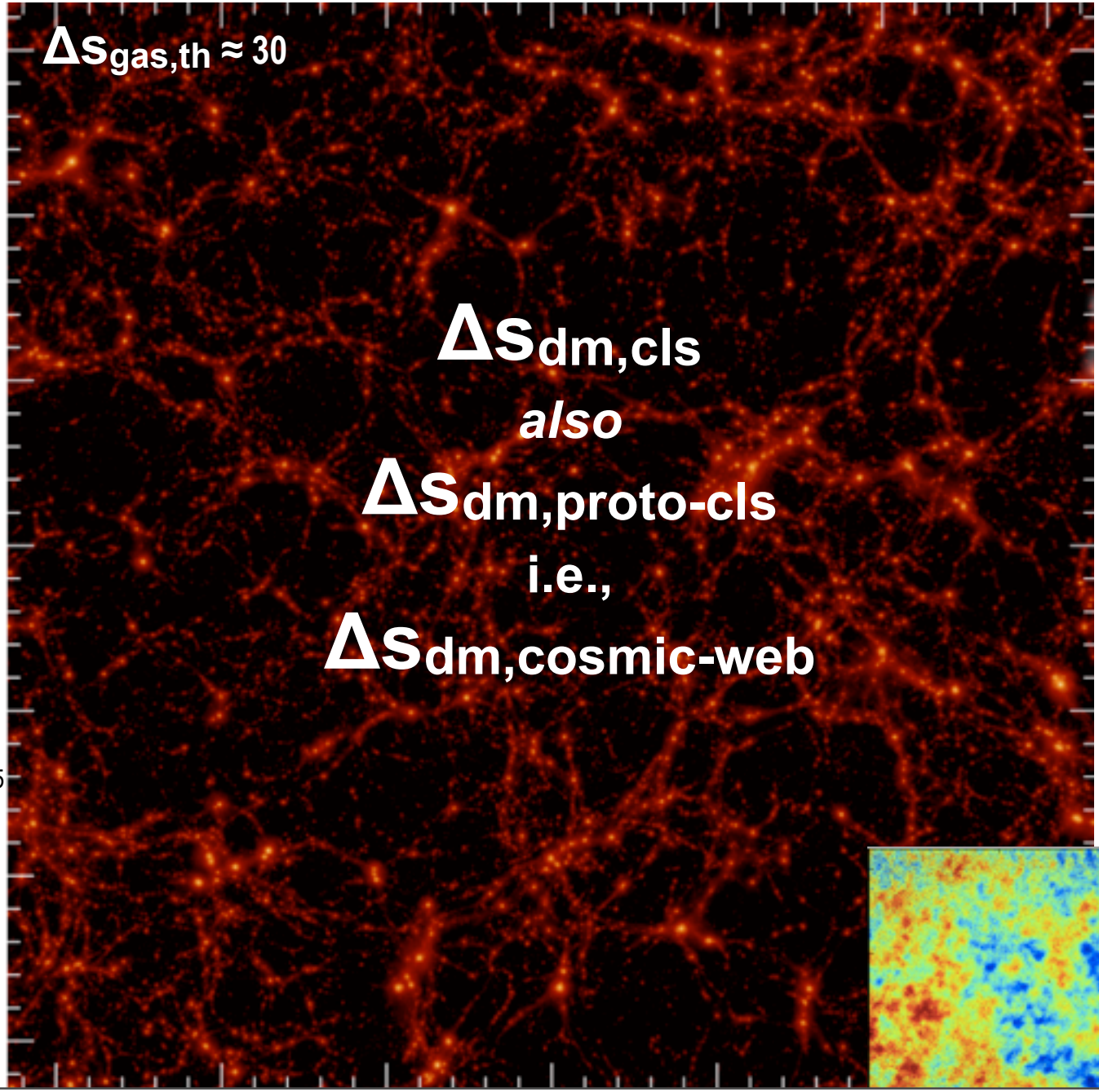
BBPS1,2,3,4,5



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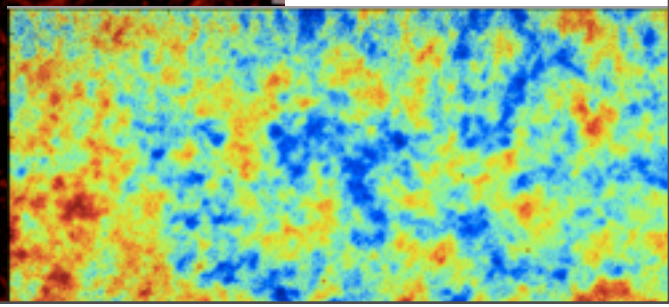

На здоровье


Galaxies in groups wi
supercluster – void n
Sergei
Shandarin