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

Zeldovich 100th:
Moscow June 2014,
Tallin IAU 308 June 2014

the Russian school & how Arnold fits into the evolving cosmic story 79-82 (Arnold, Shandarin & Zeldovich 1982)

CIFAR CANADIAN INSTITUTE FOR ADVANCED RESEARCH

Dick Bond &
Sergei Shandarin, U of Kansas

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

our Hubble patch

Initial conditions: a Gaussian random field in energy density & spatial curvature

initial content: scalar fields (inflation) + gravity + ??

post-inflation heating content: the standard model of particle physics, quark/gluon plasma

content now: baryons in a gas, photons, neutrinos, (cold) dark matter, dark energy

linear evolution phase, to reheating 1/a ~10+ when nonlinearity => the 1st stars form

nonlinear SCALE grows, defining the evolving cosmic web

ingredients now: clusters/groups = halos of Dark Matter, filaments, membranes, voids; galaxies, stars

IN EVERY teaspoon of air ~5 cubic cm

Ordinary Matter ~amu /nm^3 4.8% O_2 N ; H,He

THE DARK

Dark Matter

~amu /m^3 26.0 ± 1% compressed in MilkyWay ~0.1 amu /cm^3 ;
for LHC@CERN-type relics ~ 1 every 10 cm

Dark Energy

~vacuum potential ~ 3 amu /m^3 69.2 ± 1.0%

THE LIGHT

cosmic radiation

the 1st light of the universe 412 /cm^3 0.005%
cosmic neutrinos ~cosmic photons > 0.47%
cosmic gravity waves << cosmic photons

THE VACUUM

Higgs@CERN vacuum origin of mass
vacuum fluctuations origin of all the cosmic structure we see

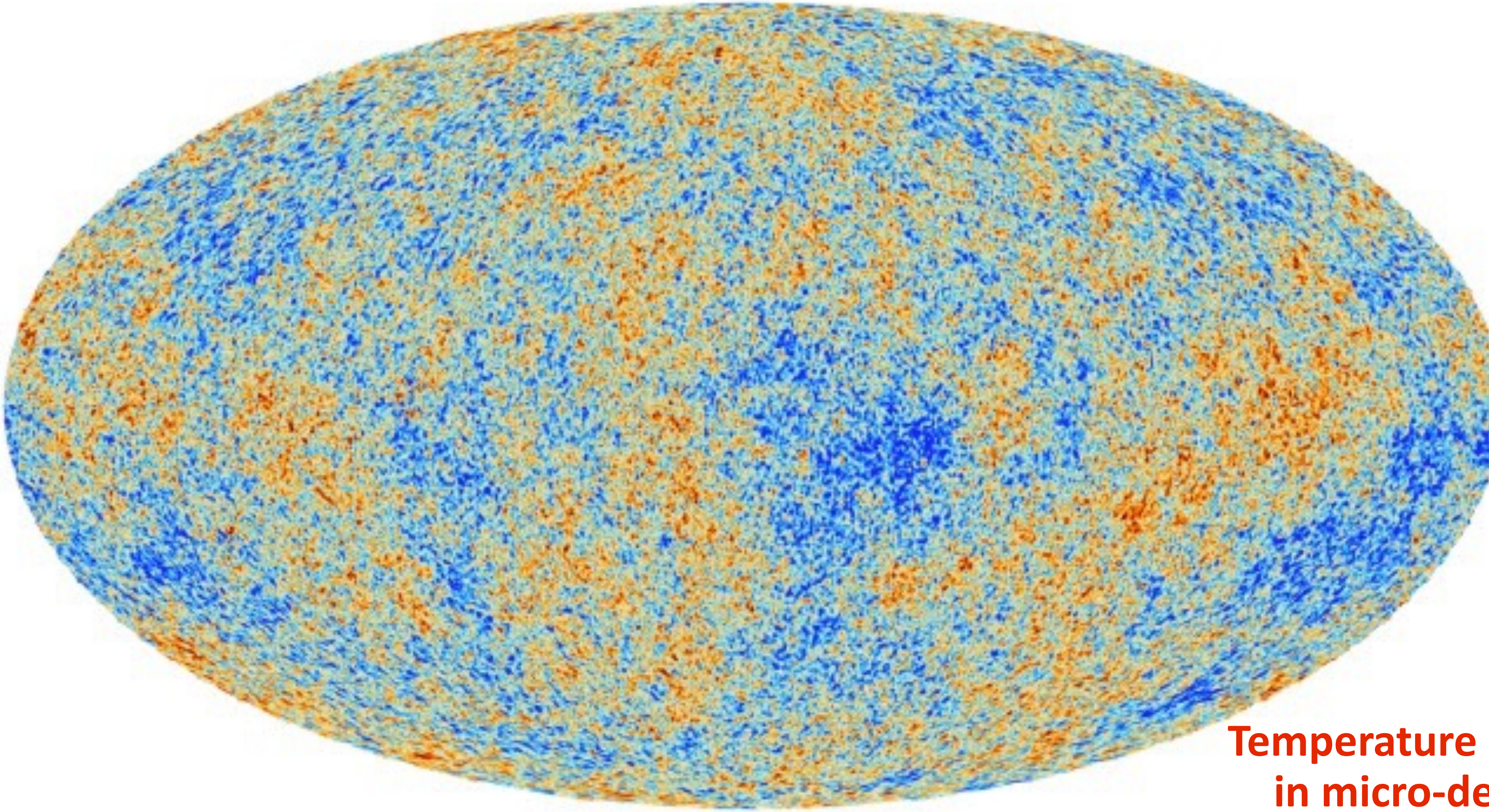
Planck's primordial light unveiled, March 21, 2013 (Dec. 1, 2014)

reveals the SIMPLICITY of primordial cosmic structure

in 7^+ numbers

=> learn **matter & energy content & structure** at $a \sim e^{-7}$ 380000 yr

=> infer structure **far far earlier** $a \sim e^{-127} \sim 1/10^{55}$ **in ~2 numbers**



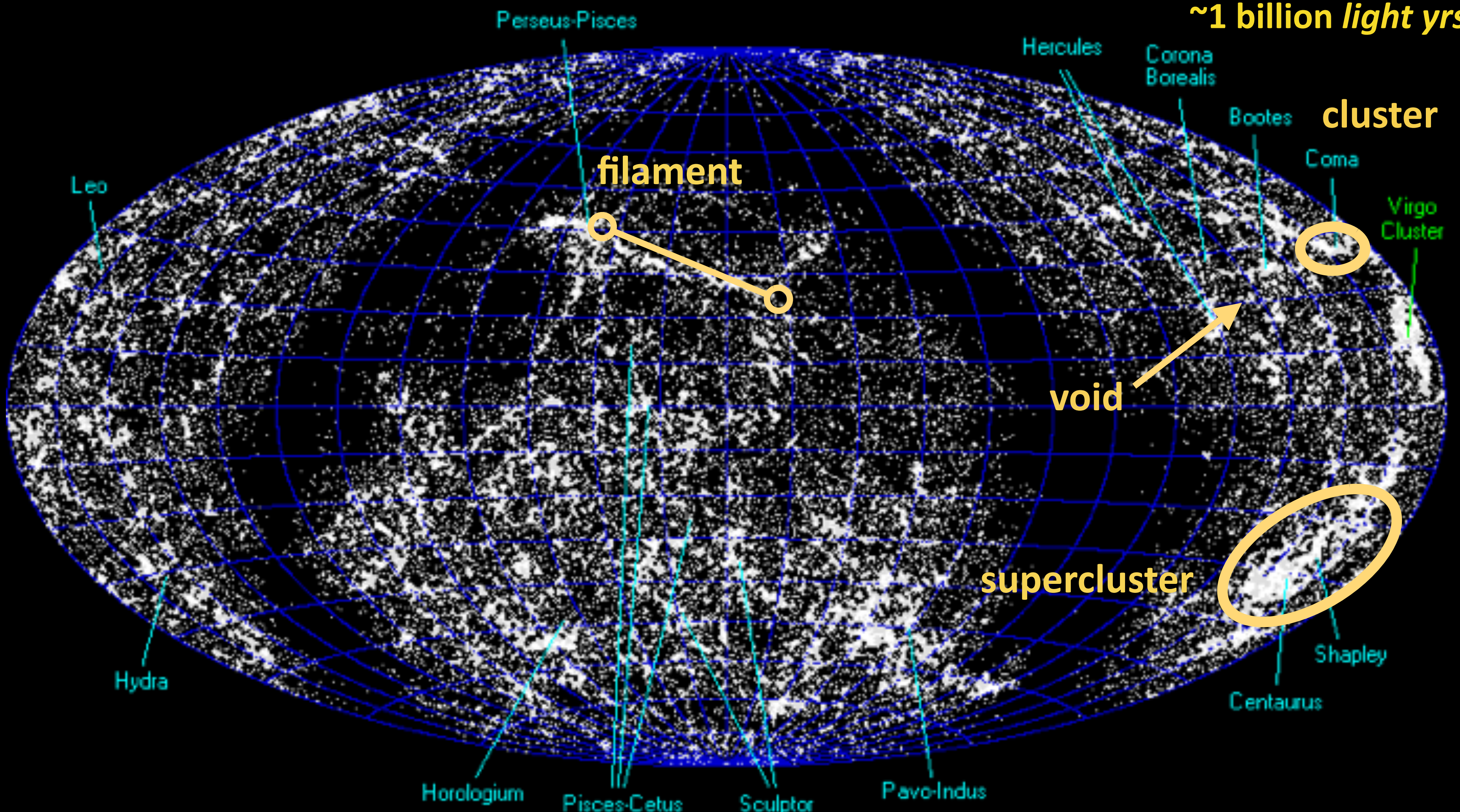
Temperature changes in micro-degrees

Gaussian 2D temperature field @ 370000 yrs => Gaussian random 3D density field from the ultra-early universe

Cosmic Web of 60,000 nearby galaxies: exhibits “local” **COMPLEXITY**

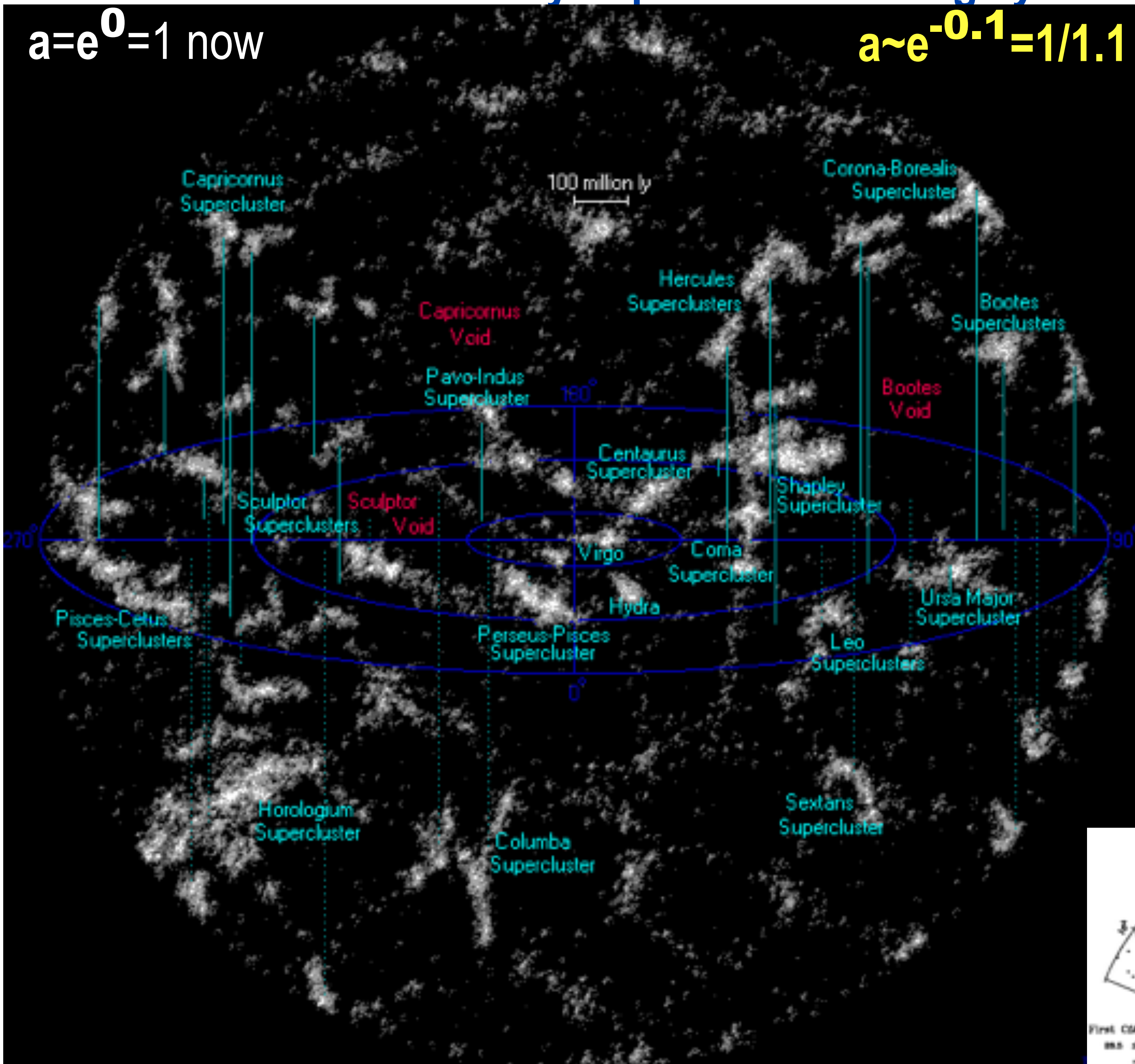
$a \sim e^{-0.1} = 1/1.1$

~1 billion *light yrs*



hard won observational emergence of the web. 79-81 sparse info, e.g., of Coma supercluster. So what Arnold, Shandarin and Zeldovich knew was very very much less, ie speculative theory to **a ~ 0.9 via 3D maps**

cosmic web *of* **nearby superclusters < Giga*lyr***



70s adiabatic pancake (physical filter)

Doroshkevich, Zeldovich

cf.

70s isoc B/BH (power law CorrFn)

Basko

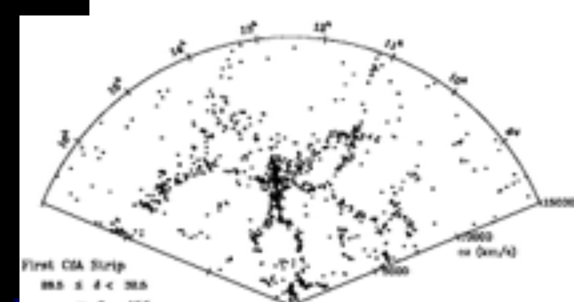
miracle of CDM = grand unification of east & west ideas with ~ HSZ spectrum

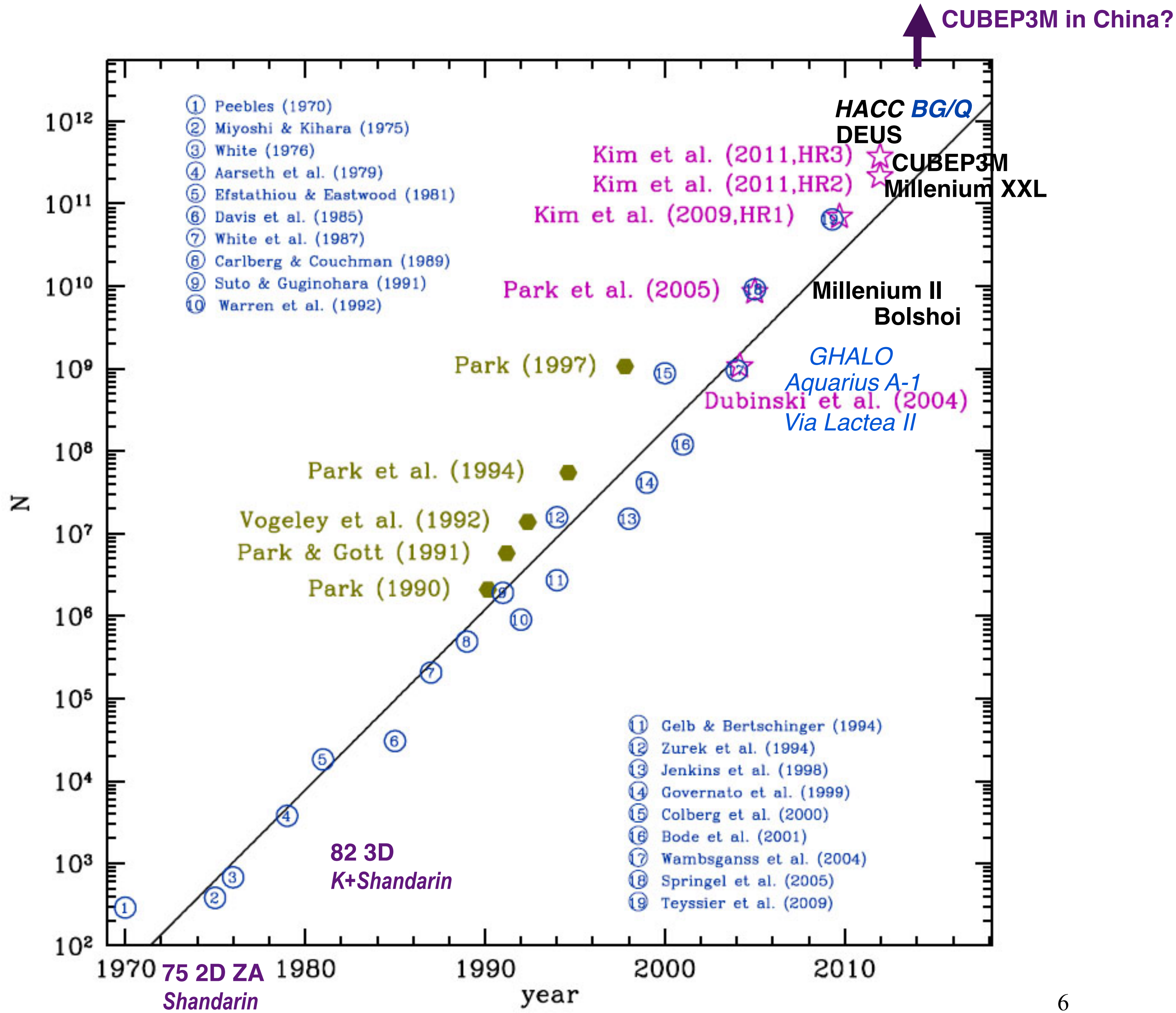
emergence of superclusters

Peebles vs.

70s Einasto+..

80 + Oort +

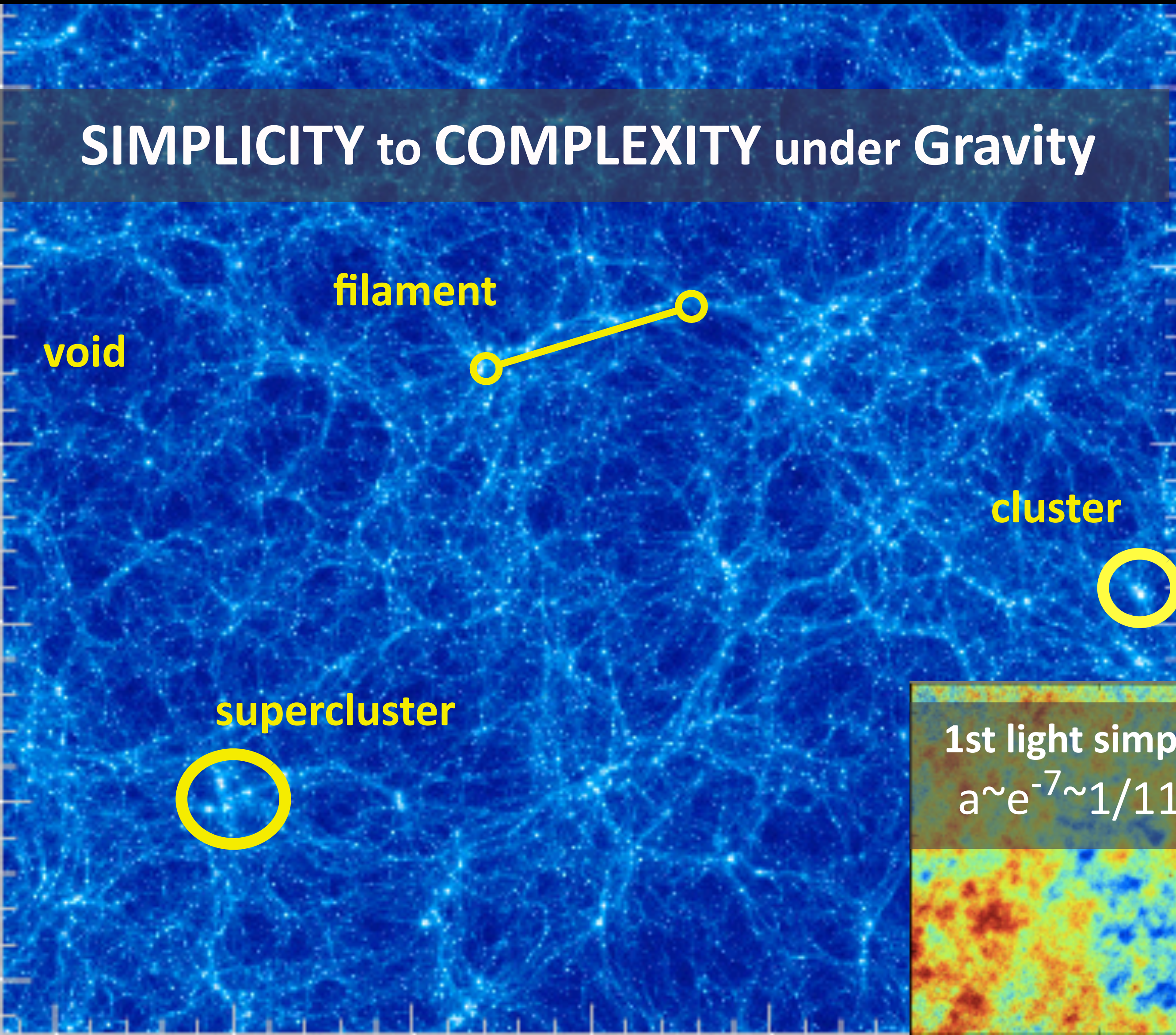


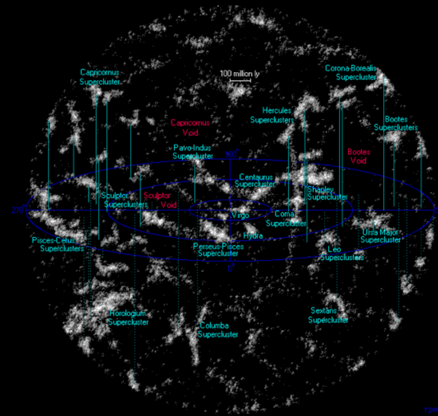


(Juhan Kim et al. 2011)

Simulation of the 7⁺ numbers

begets the **Cosmic Web** of clusters now a~1 & galaxies then a~1/4

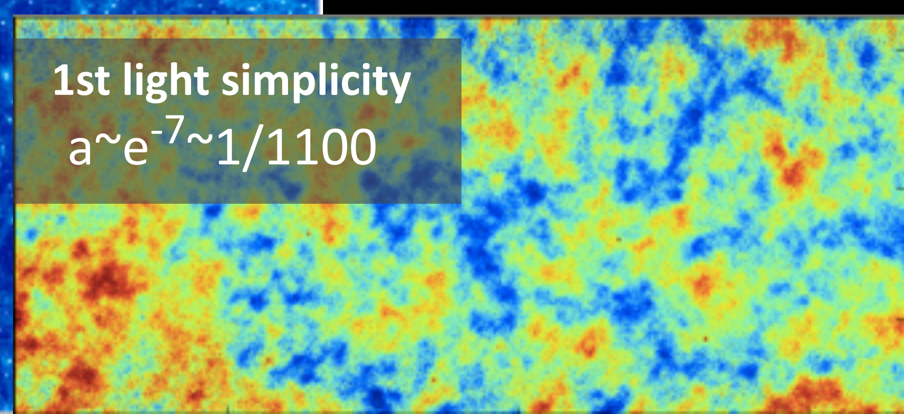




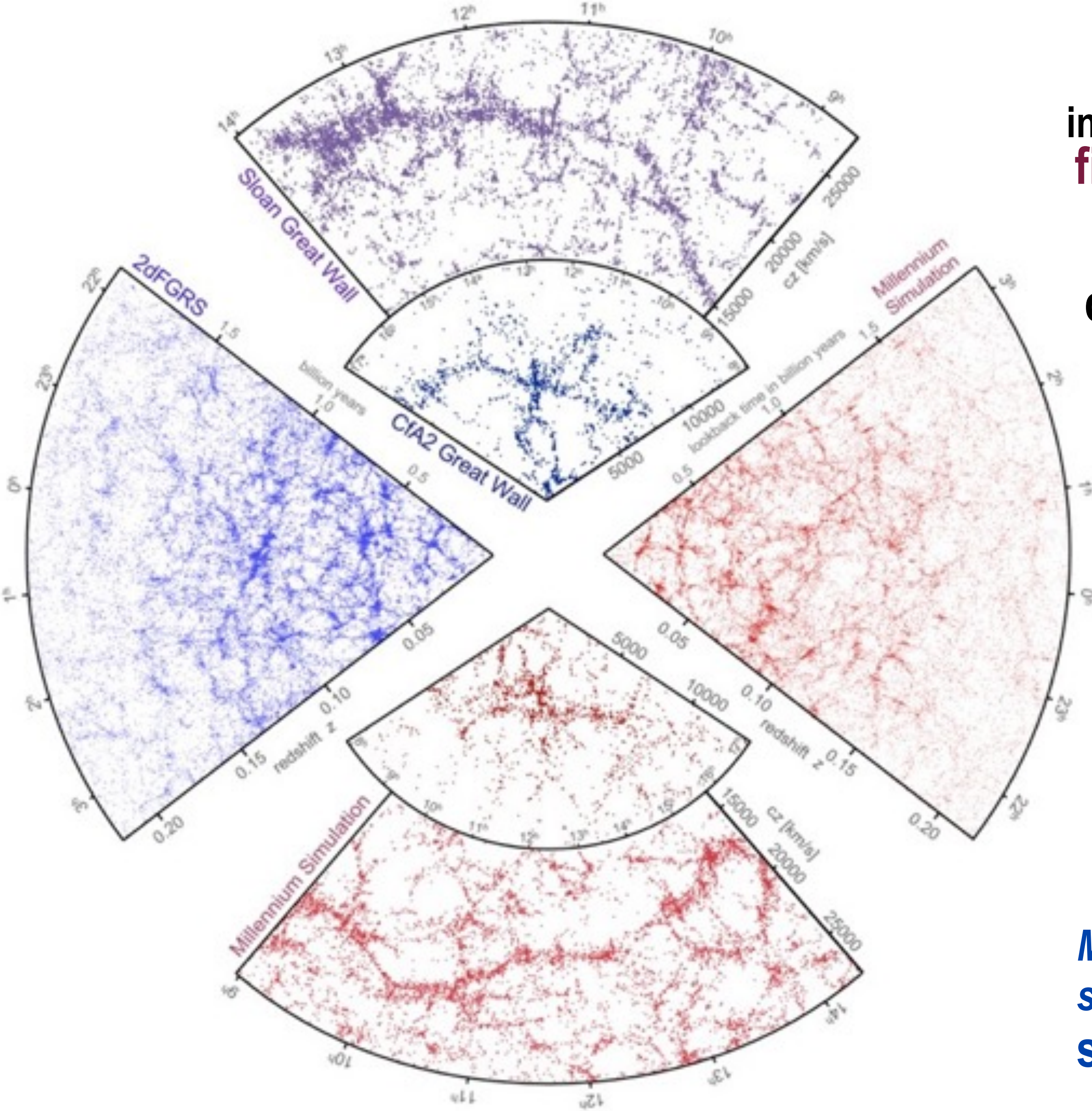
~ billion light years

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

ordinary matter
dark matter
dark energy



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

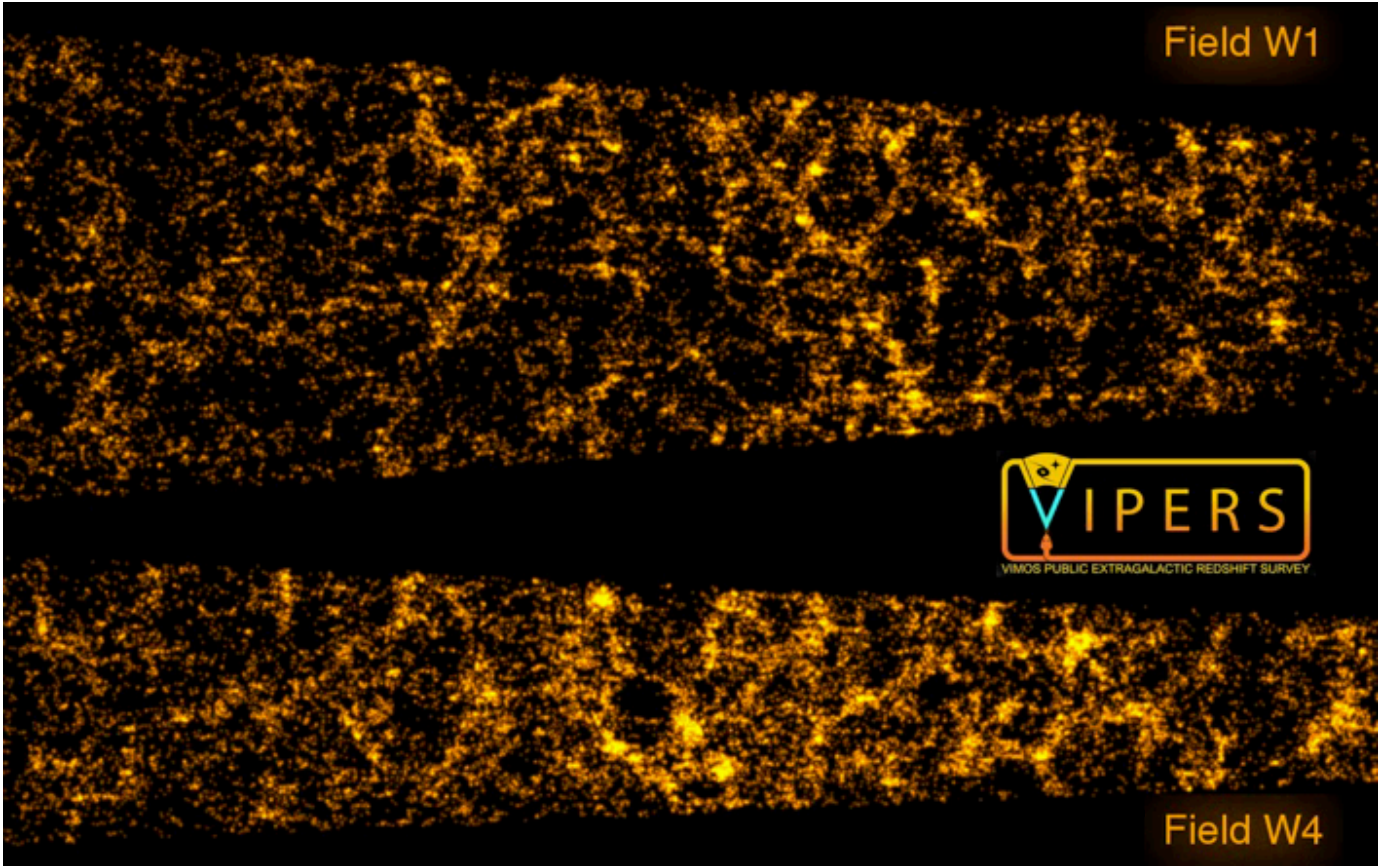


Collisionless matter **Simulation** of the initial **Gaussian random field** characterized by **7^+ numbers** does indeed beget the **Cosmic Web**

Millenium simulation web site "propaganda" on **sims** *cf.* **z-space data**

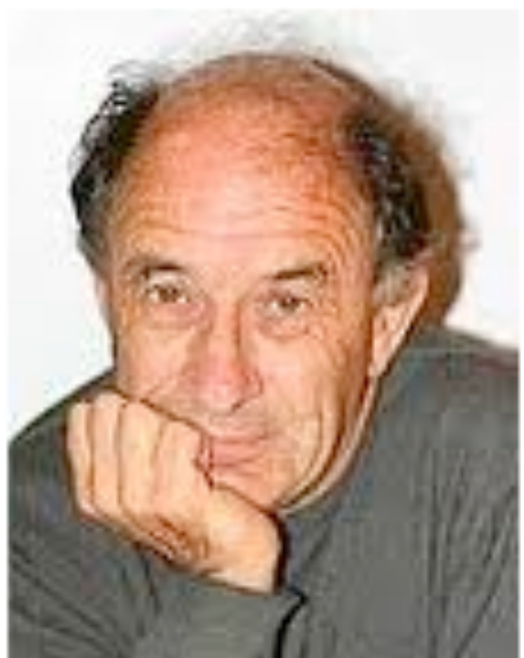
and to **a ~ 0.7 to 0.5 via 3D maps**

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



Yakov Borisovich
Zel’dovich
1914 - 1987

Vladimir Igorevich
Arnold
1937 - 2010



На здоровье

Terviseks

Z70,ZES82
AZS82
e_J^j

Zeldovich 1970 approximation $\mathbf{X}(\mathbf{r},t) = a(t)(\mathbf{r} + \mathbf{s}(\mathbf{r},t))$
general map of a cold medium, an onto multi-stream map

The first numerical simulation of the Zel'dovich Approximation in 2D

Shandarin 1975

published in review by Doroshkevich Zeldovich Sunyaev 1975 (in Russian)

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influential for Arnold, Shandarin Zeldovich 1982

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50s+ HALOS hierarchy, small round objects => large round objects

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

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

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

***87: x*= includes vacuum energy**

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

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

$dX^i/a = (V^i - HX^i)/a\,dt + \mathbf{e}^i{}_l(r,t)dr^l = v_{pec}{}^i dt + (\delta^i{}_l + \boldsymbol{\varepsilon}^i{}_l(r,t))dr^l$, where

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

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

the celebrated Zeldovich 1970 approximation, with caustics aka singularities ρ -> 0 when 1+ε -> 0 pancakes, but Lagrangian to Eulerian map in 3D => ASZ82 BUT nonlinear tidal corrections and “hot” regions of collapsed space, not good for halos

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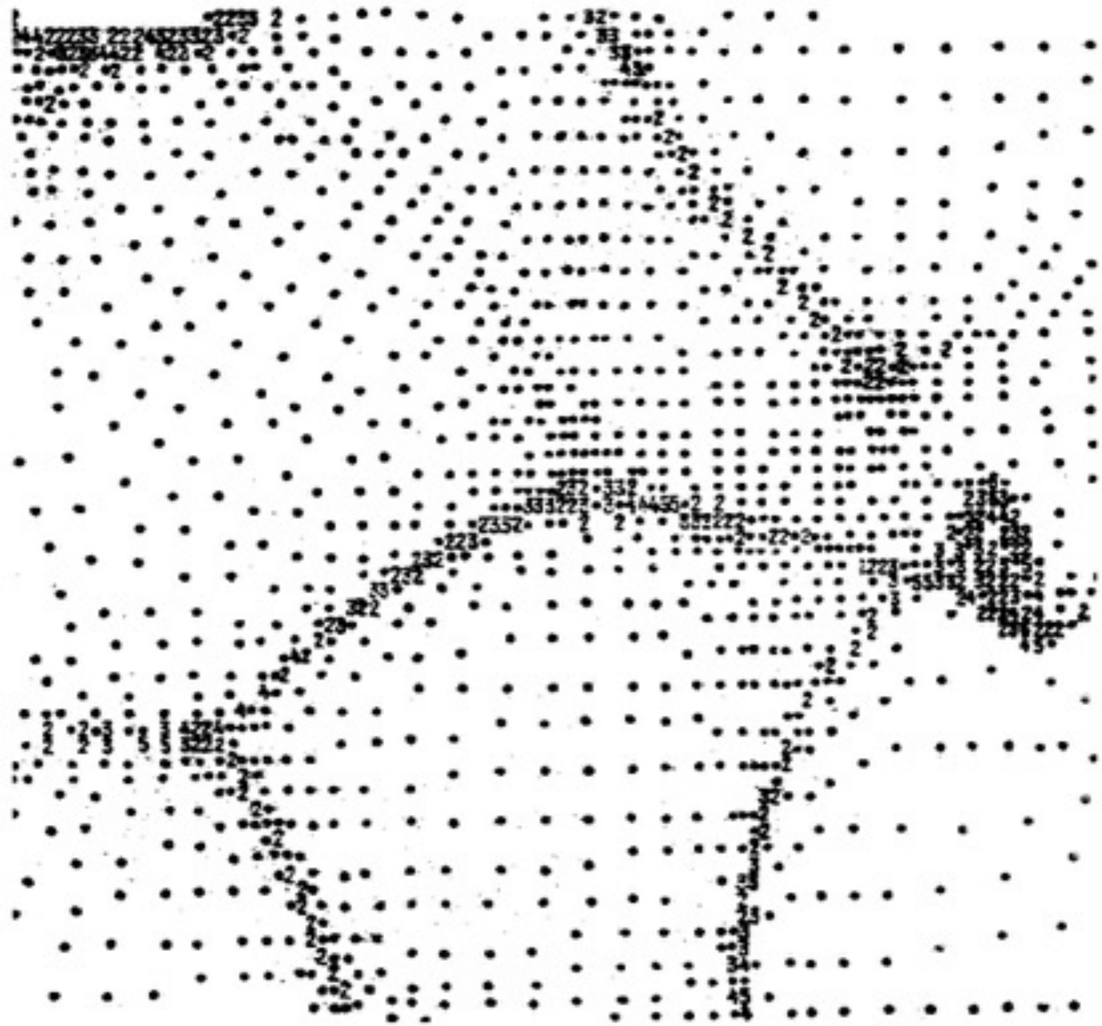

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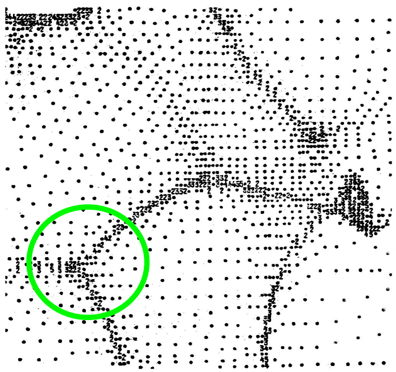
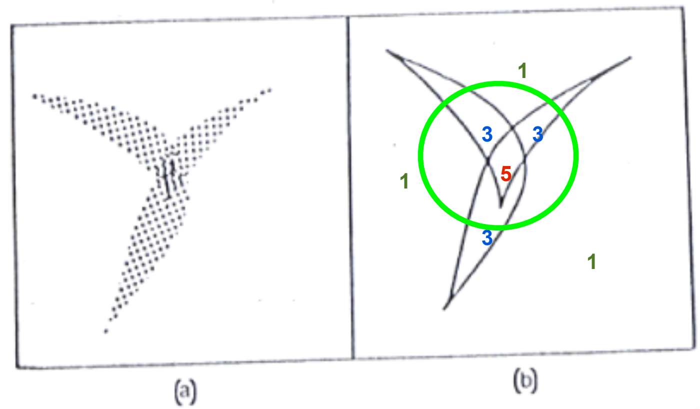
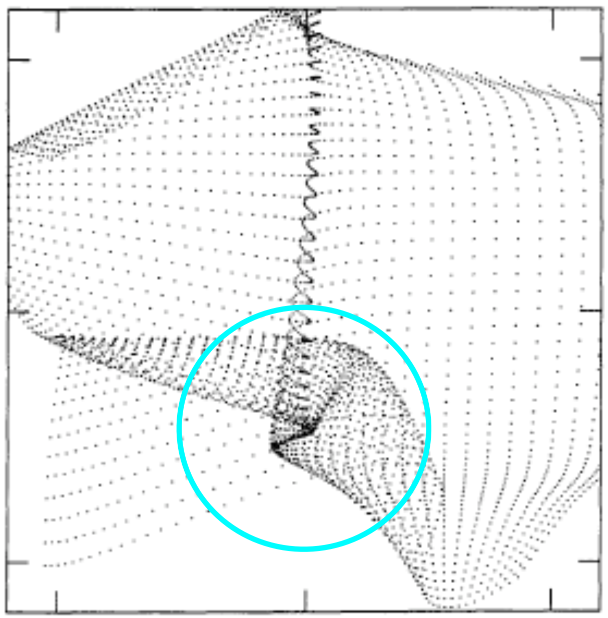
2D example: A4 (“swallow tail”) singularity



Shandarin 1975

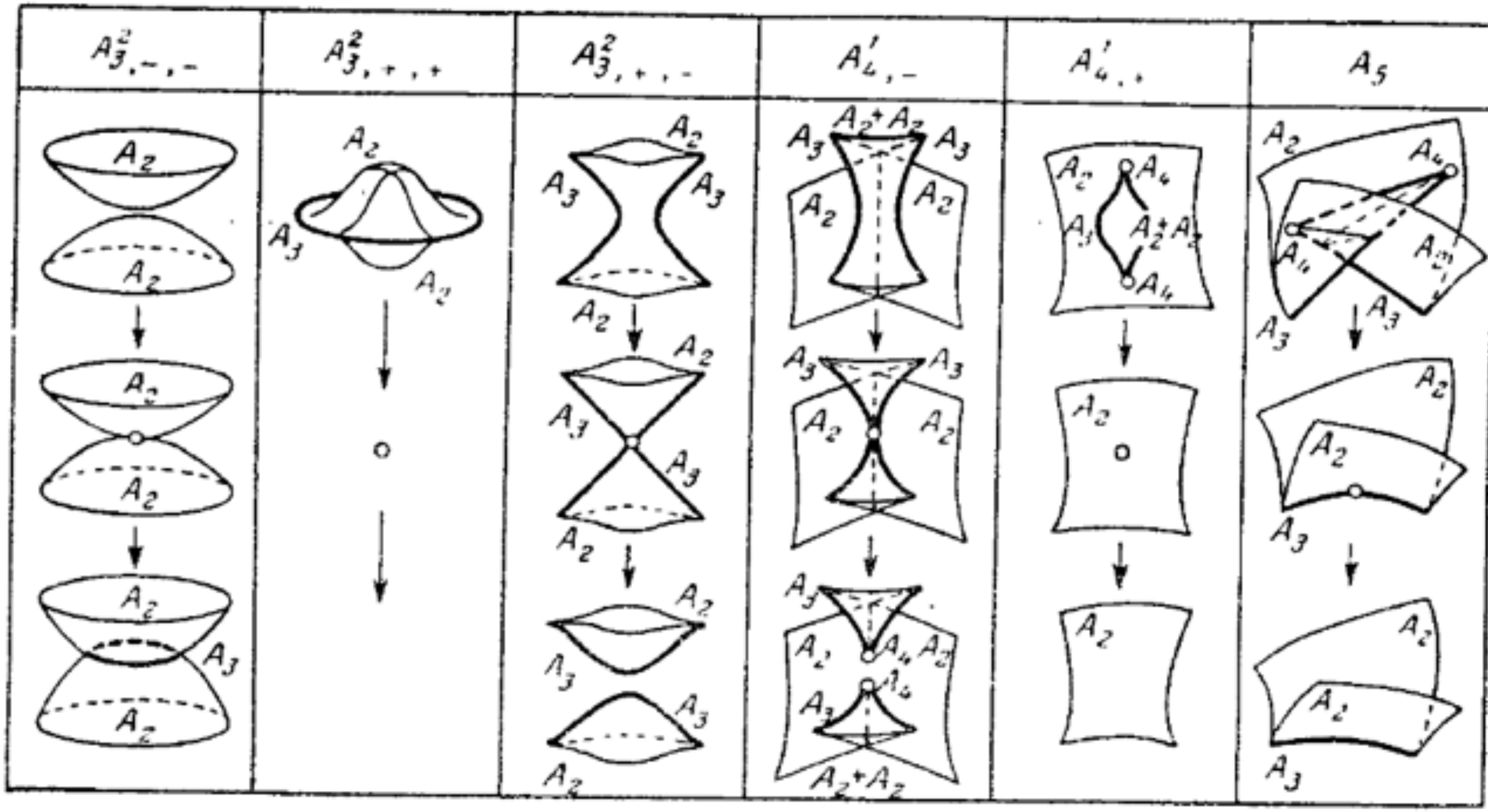


Arnold, Shandarin, Zel’dovich 1982



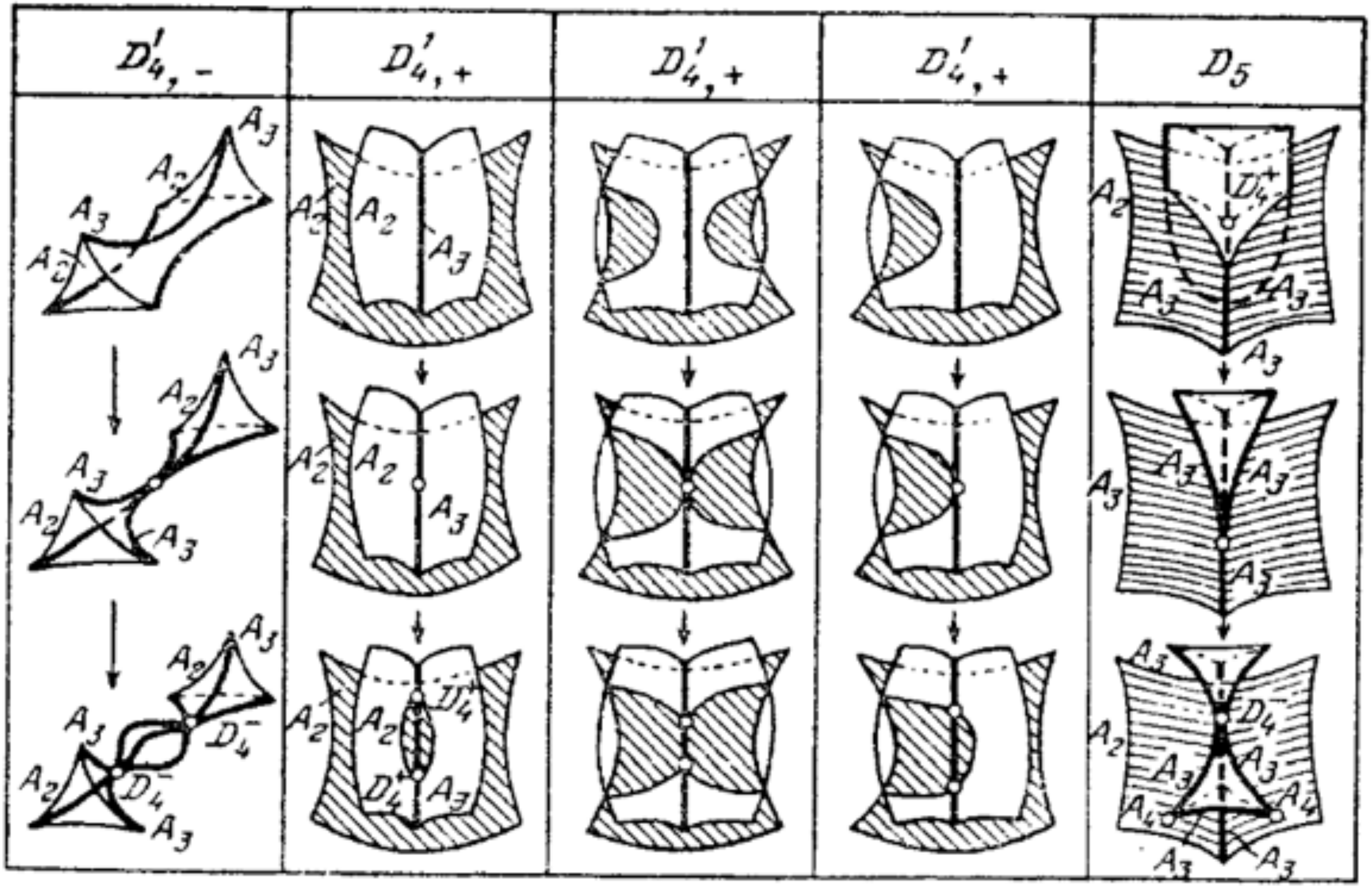
Nusser, Dekel 1990

A - caustics in 3D



Arnold, Shandarin & Zeldovich 1982

D - caustics in 3D



Arnold, Shandarin & Zeldovich 1982

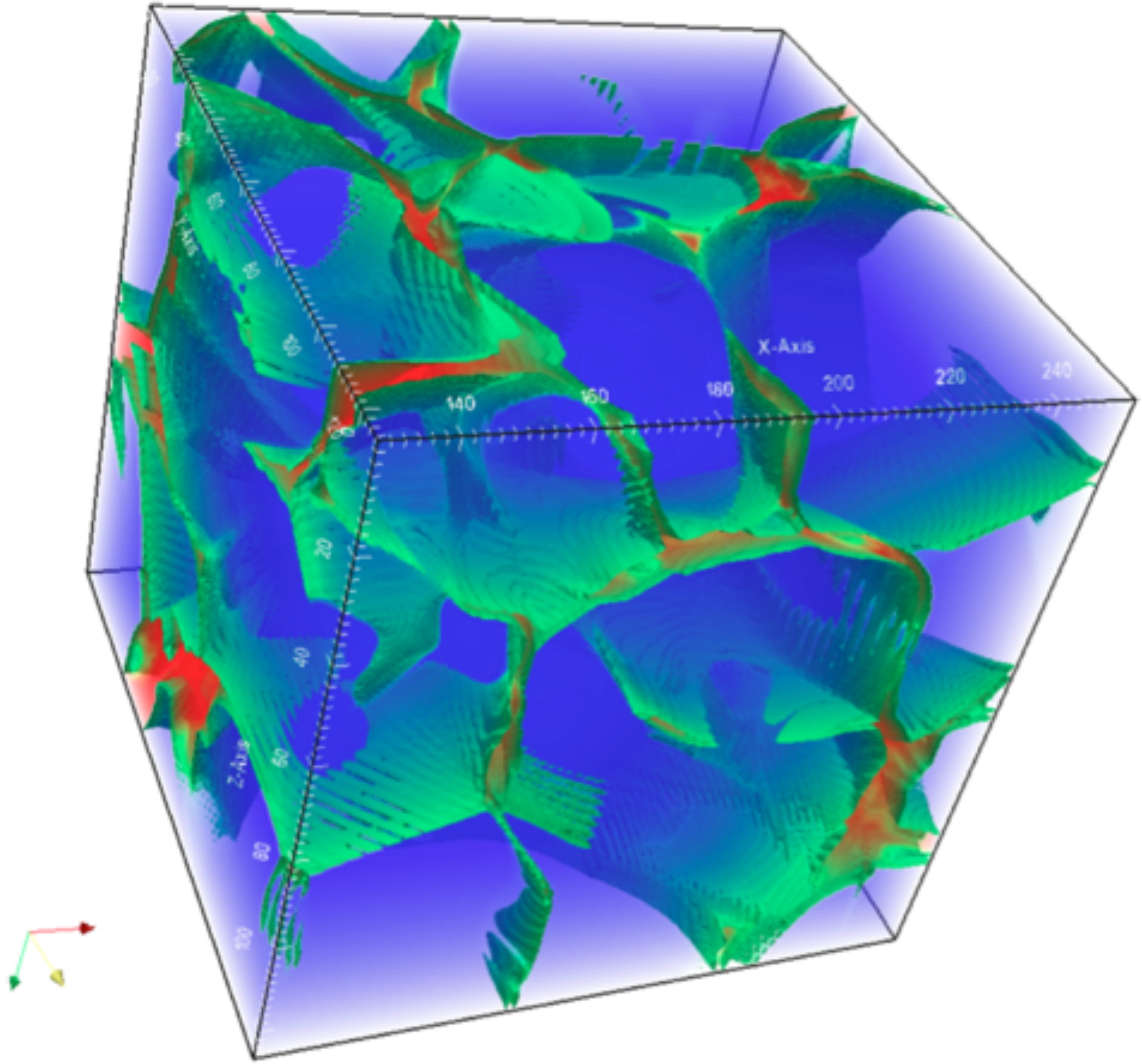
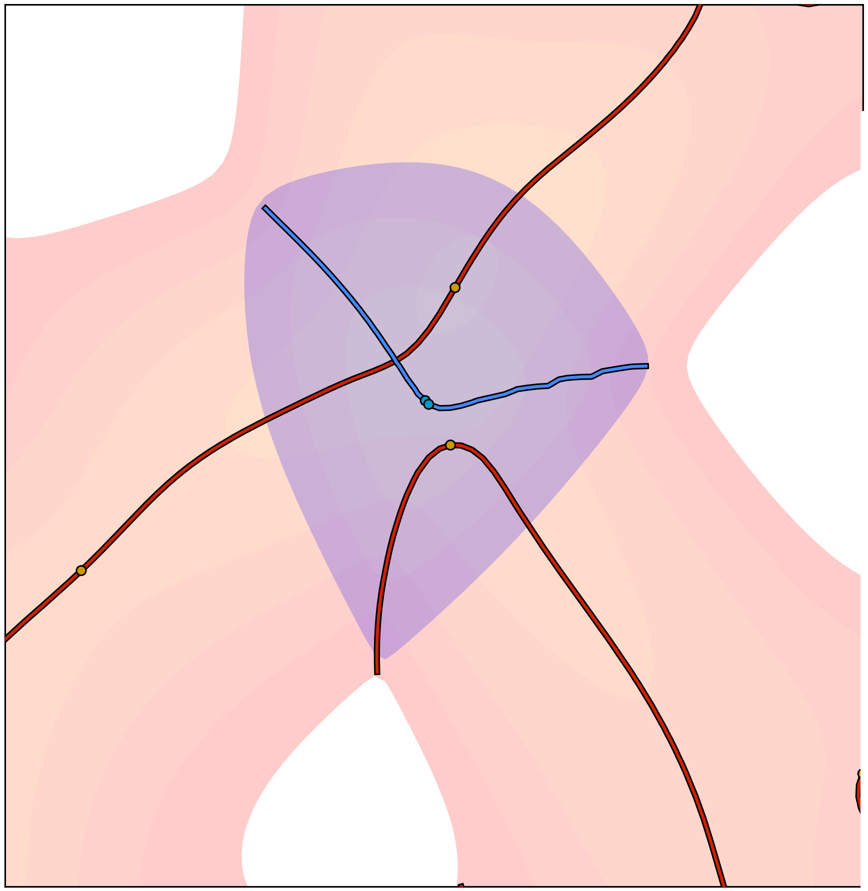


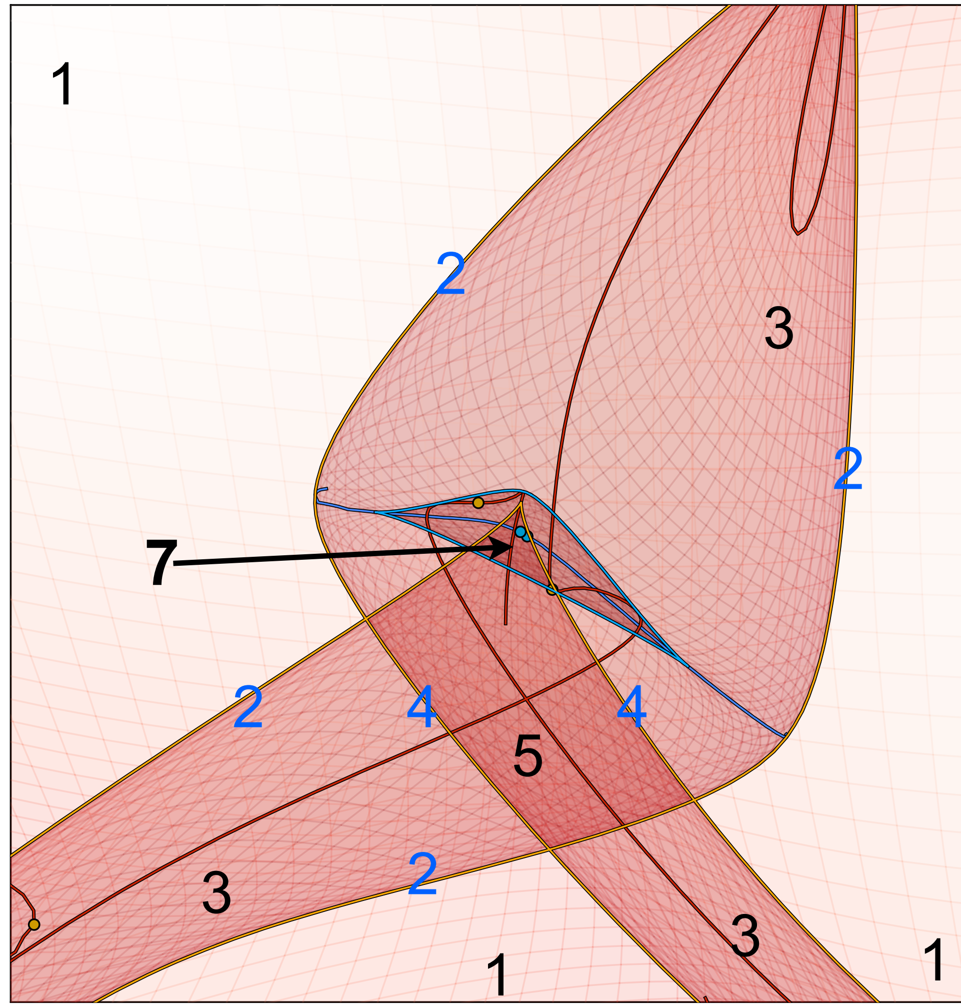
Figure 18. Caustic structure of ZA-evolved mass distribution in 3D. This is a three-dimensional analogy of the top right-panel in Fig. 1. The α-caustics are shown in green and β-caustics in red. The β-caustics are seen only through the openings in the surface of α-caustics by the box faces. This is the reason why one cannot see γ-caustics.

Complexity of caustics



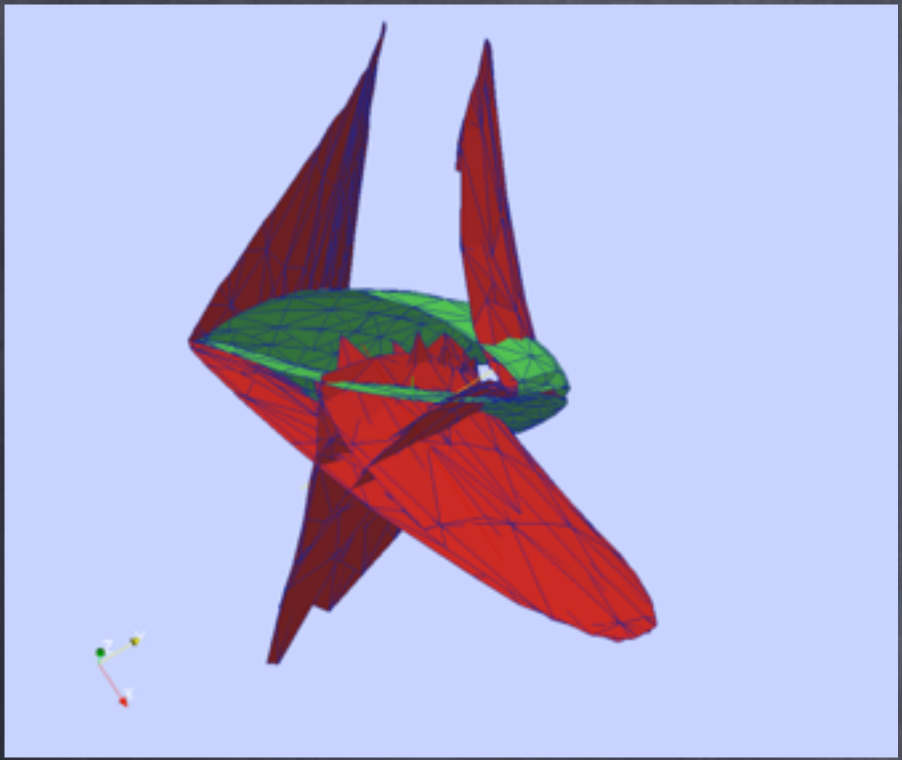
Lagrangian space

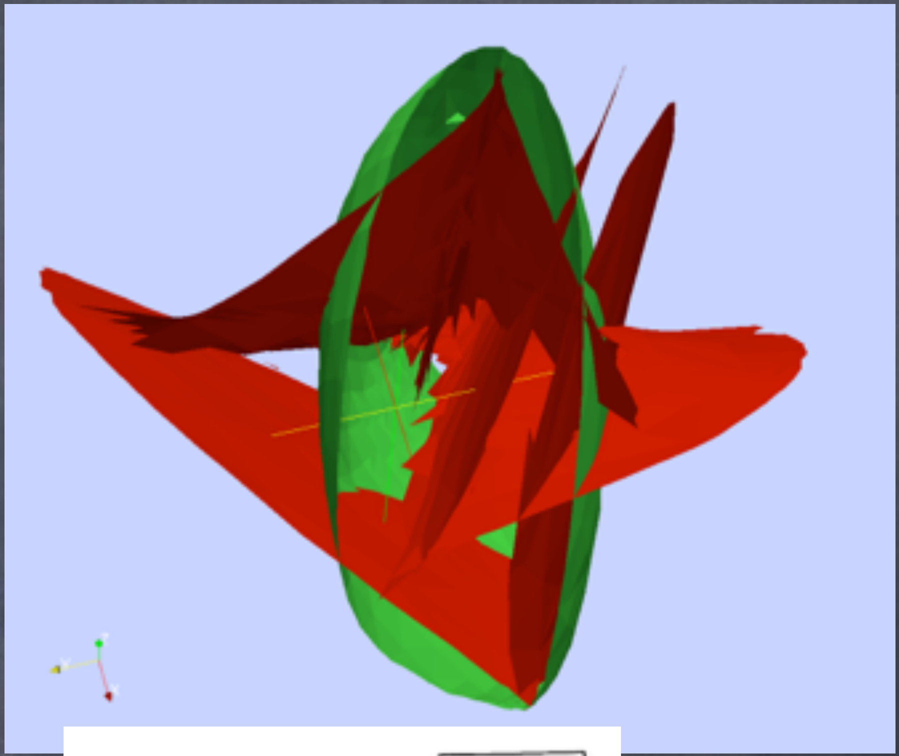
Number of streams in Eulerian space

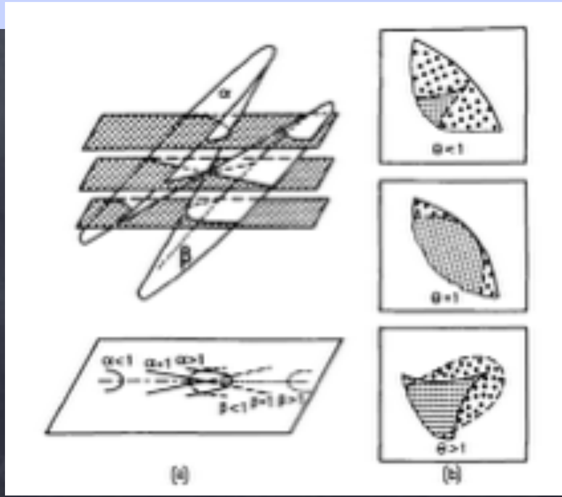


Hidding, Shandarin, van de Weygaert 2014

D_4 singularity in 3D space



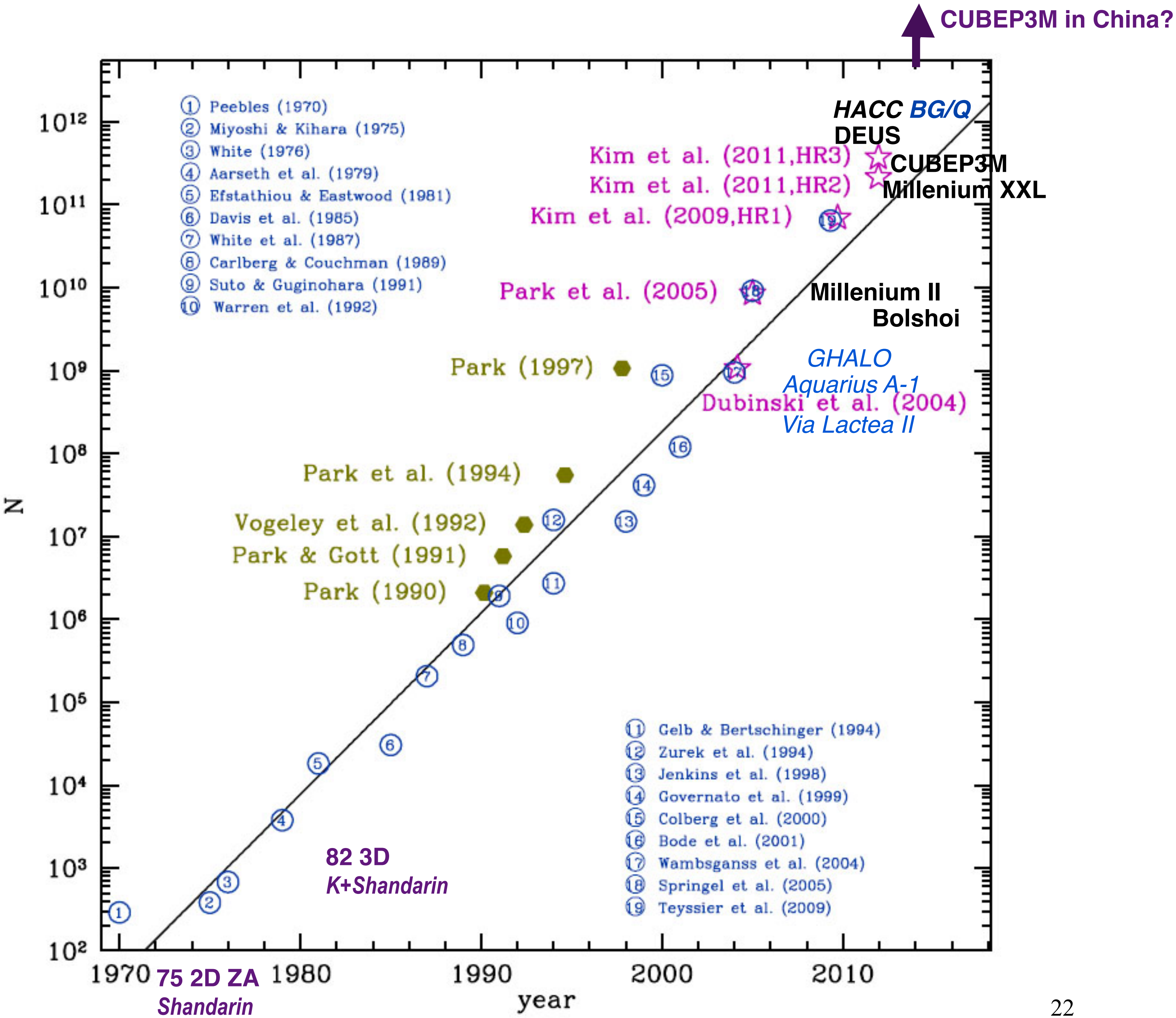




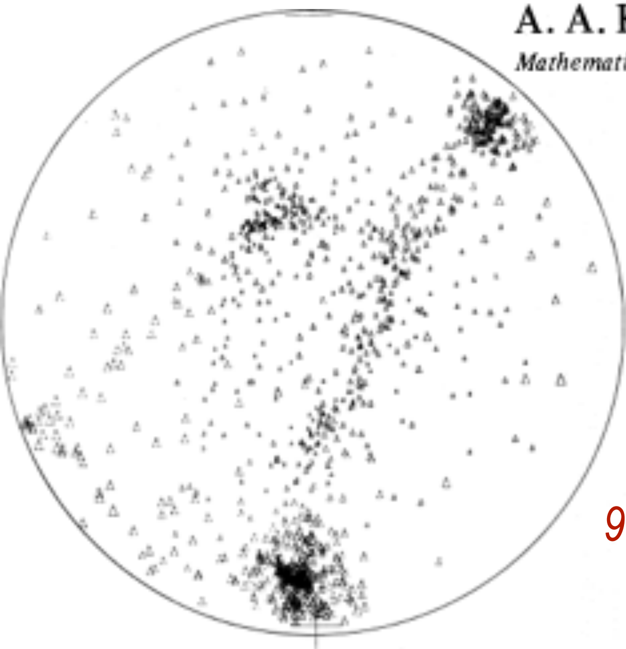
Hidding, Shandarin, van de Weygaert in preparation

Arnold, Shandarin, Zeldovich 1982

2D



(Juhan Kim et al. 2011)



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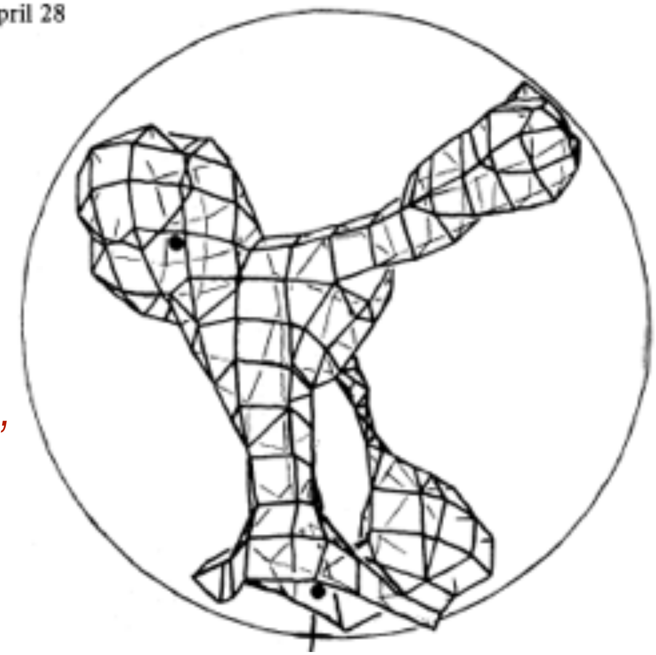
Received 1982 November 15; in original form 1982 April 28

3D numerical model of the Universe

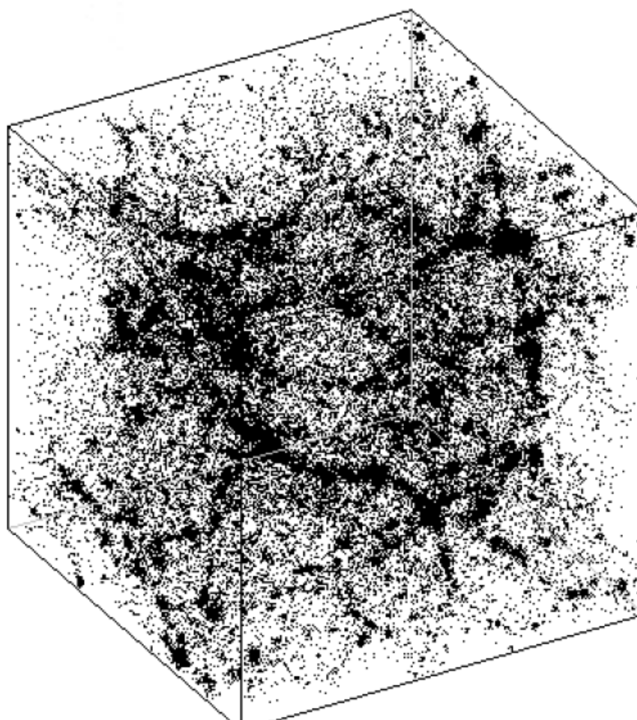


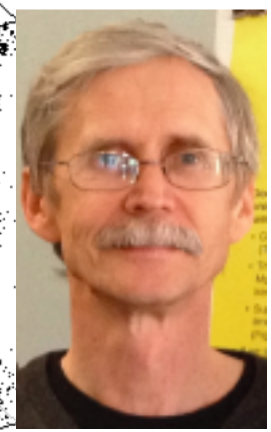
Klypin's vintage 82

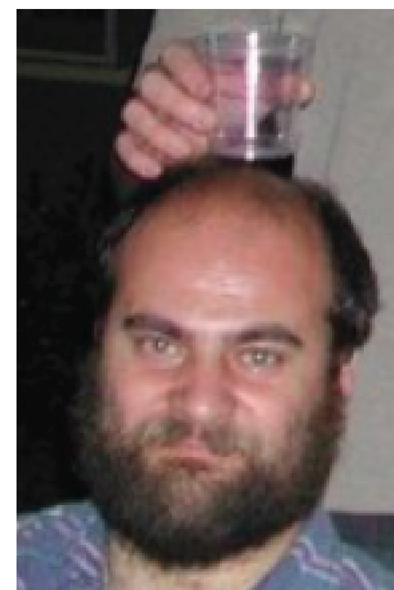
160h^{-1}Mpc box 32^3 hDM

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

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

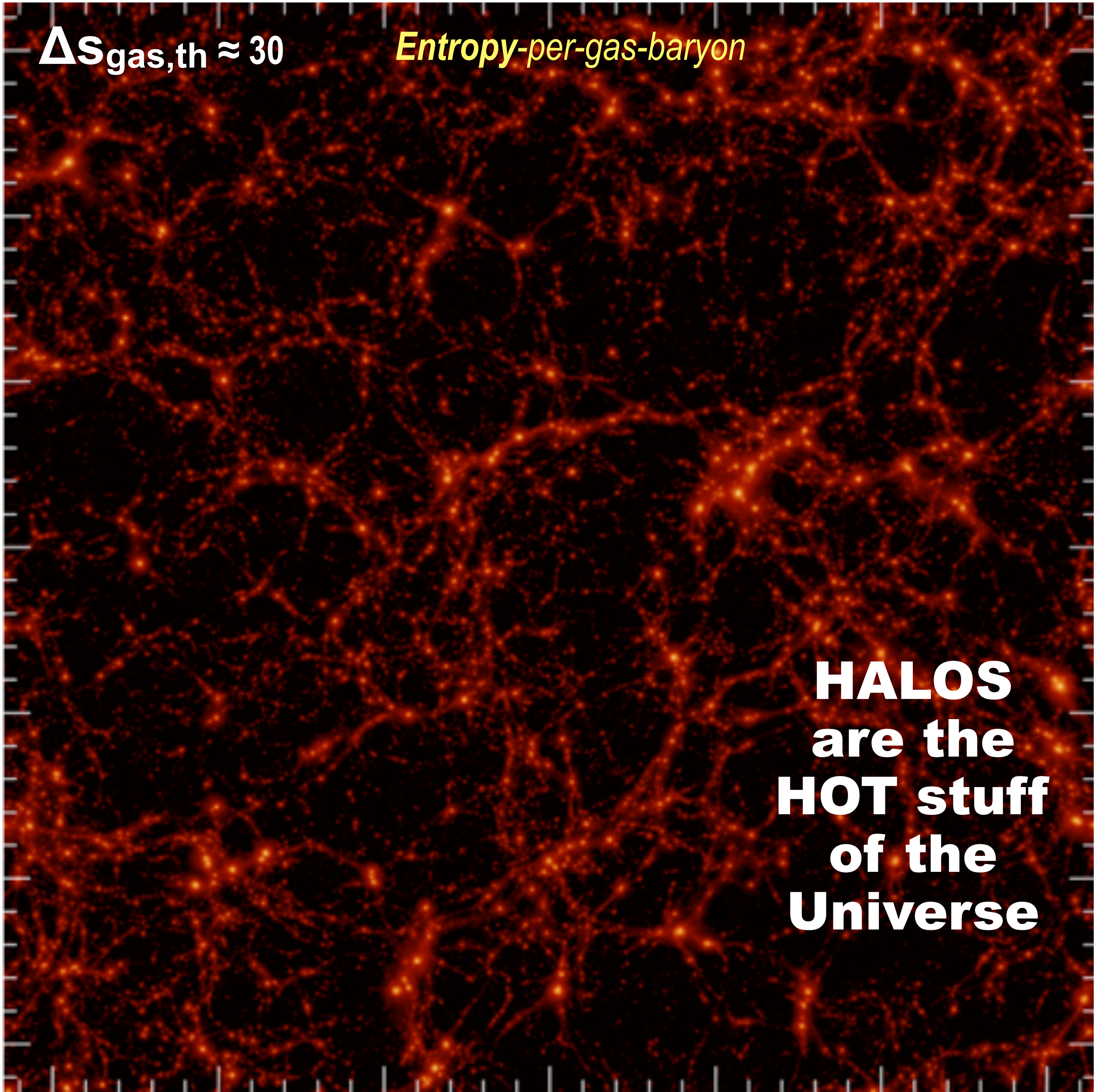
gas pressure

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

$\rho_g(x,t)$

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

$p_e(x,t)$

$I_\nu(x,t)$

$n_{dust}(x,t)$

non-Gaussian CDM entanglement

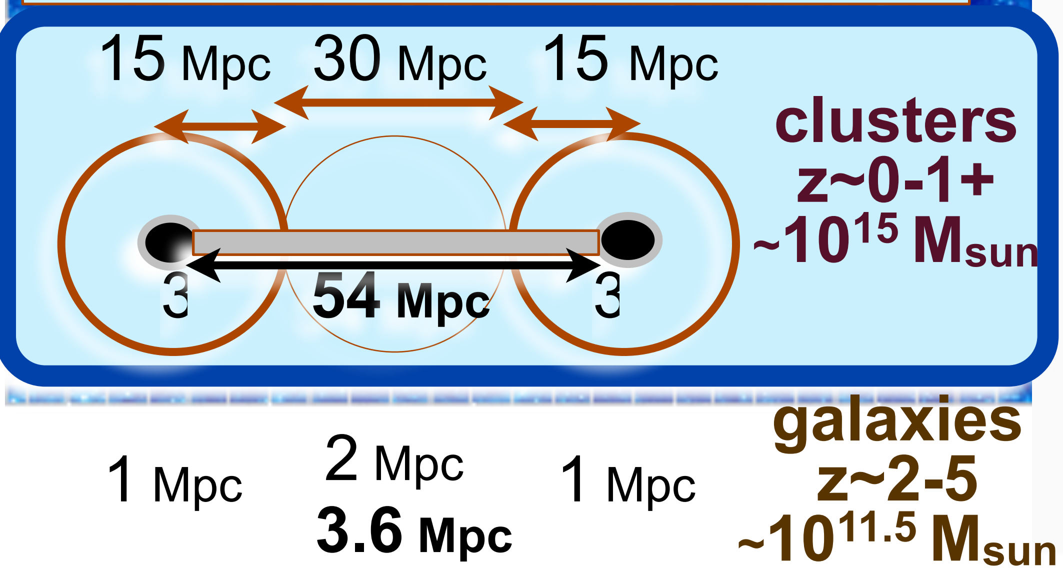
$\rho_{dm}(x,t)$

Peak-patches = "hot" halos
B+Myers 91-96; BBKS 83-86

The ***Cosmic Web***
B+Kofman+Pogosyan 96-99

"Molecular" Picture of LSS
Filaments & Membranes

HALOS are dynamically HOT, the hierarchical standard model, ΛCDM, => scale space (3+1D => 4+1D)
adaptive coarse-grain Zeldovich flows of Lagrangian peak-patches agree with N-body Eulerian halo simulations => fast mock surveys

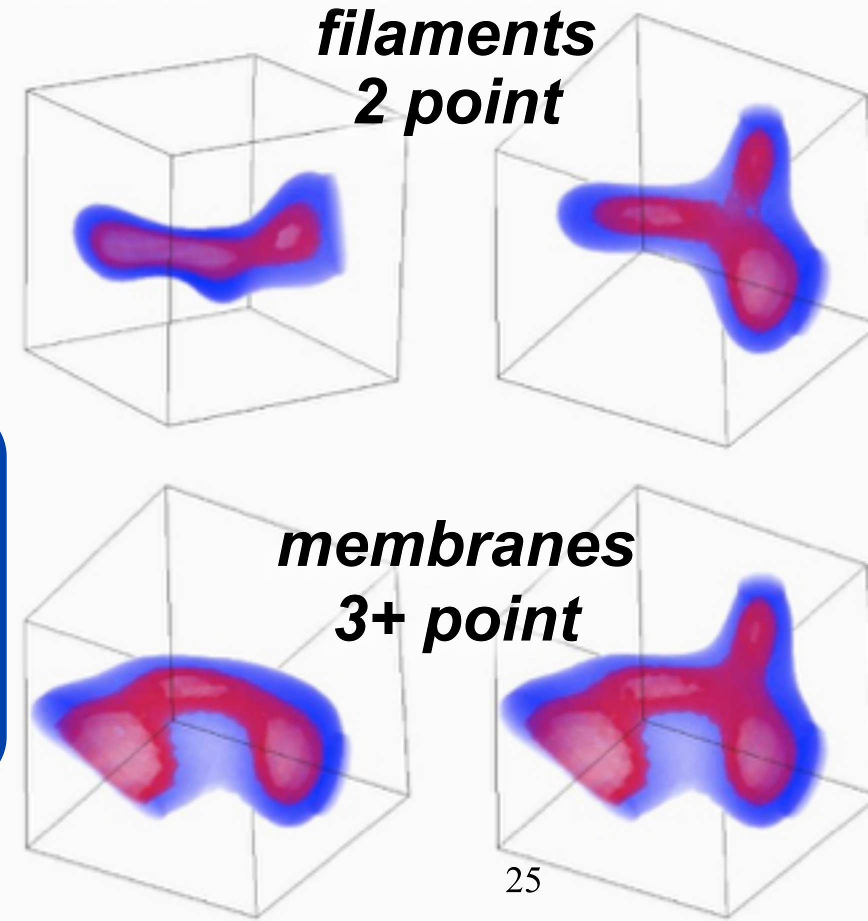


marriage of halos & Zeldovich

hot dynamics => $e^{i}_{J}(r_{pk},t,R_{pk})$

cool dynamics => $s^{i}(r_{pk},t,R_{pk})$

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



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

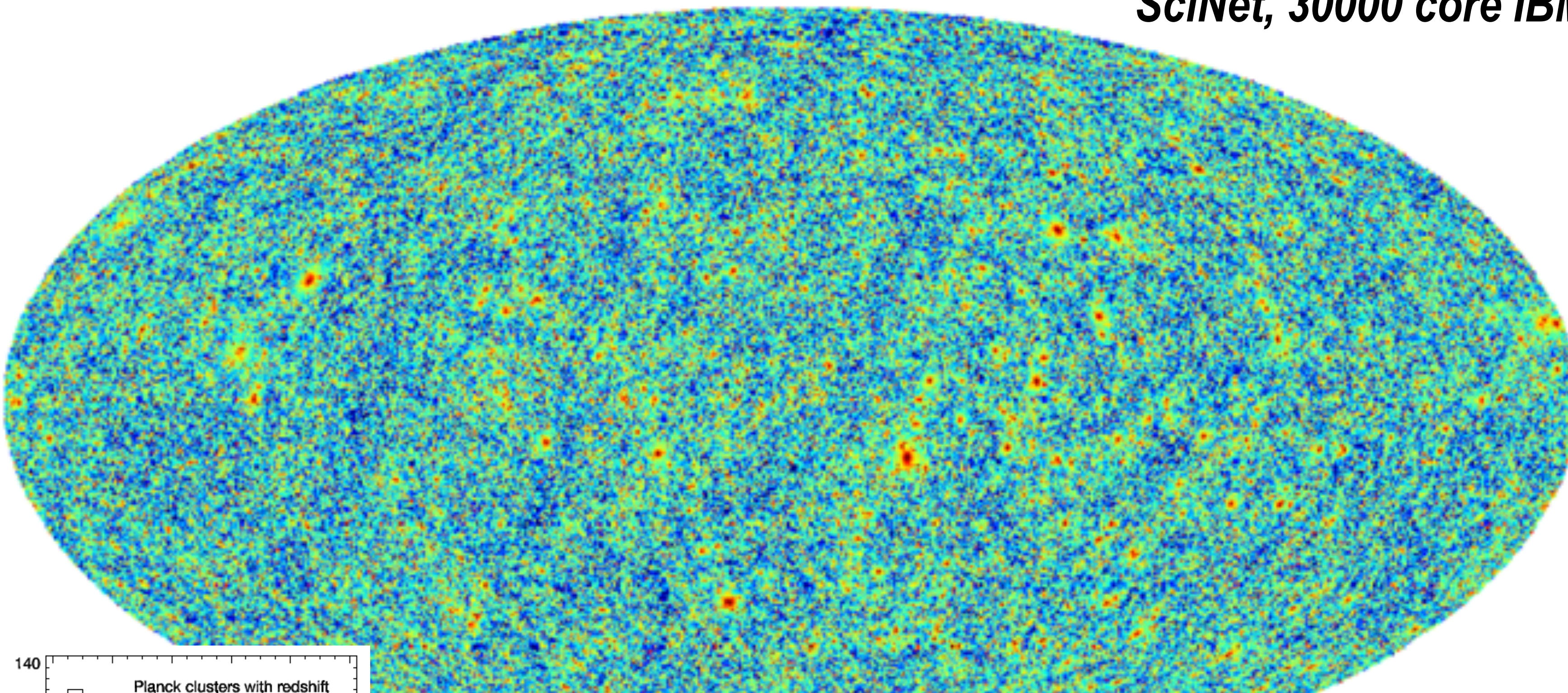
Compton cooling of high pressure electrons by the CMB

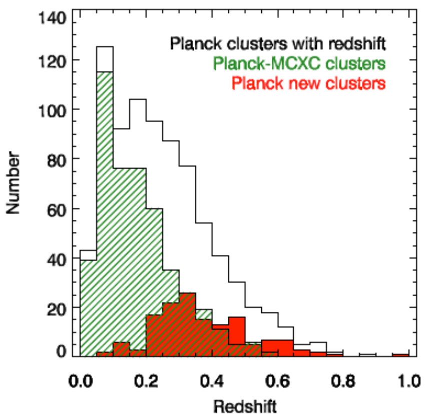
tSZ effect

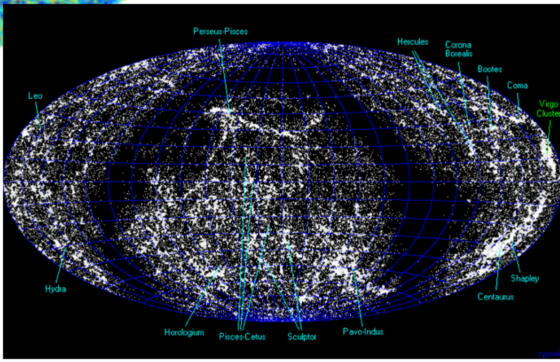
Lightcone Simulation of 35000 Clusters > 1.5×10^{13} M_{sun} to z=0.5 in projected pressure

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

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

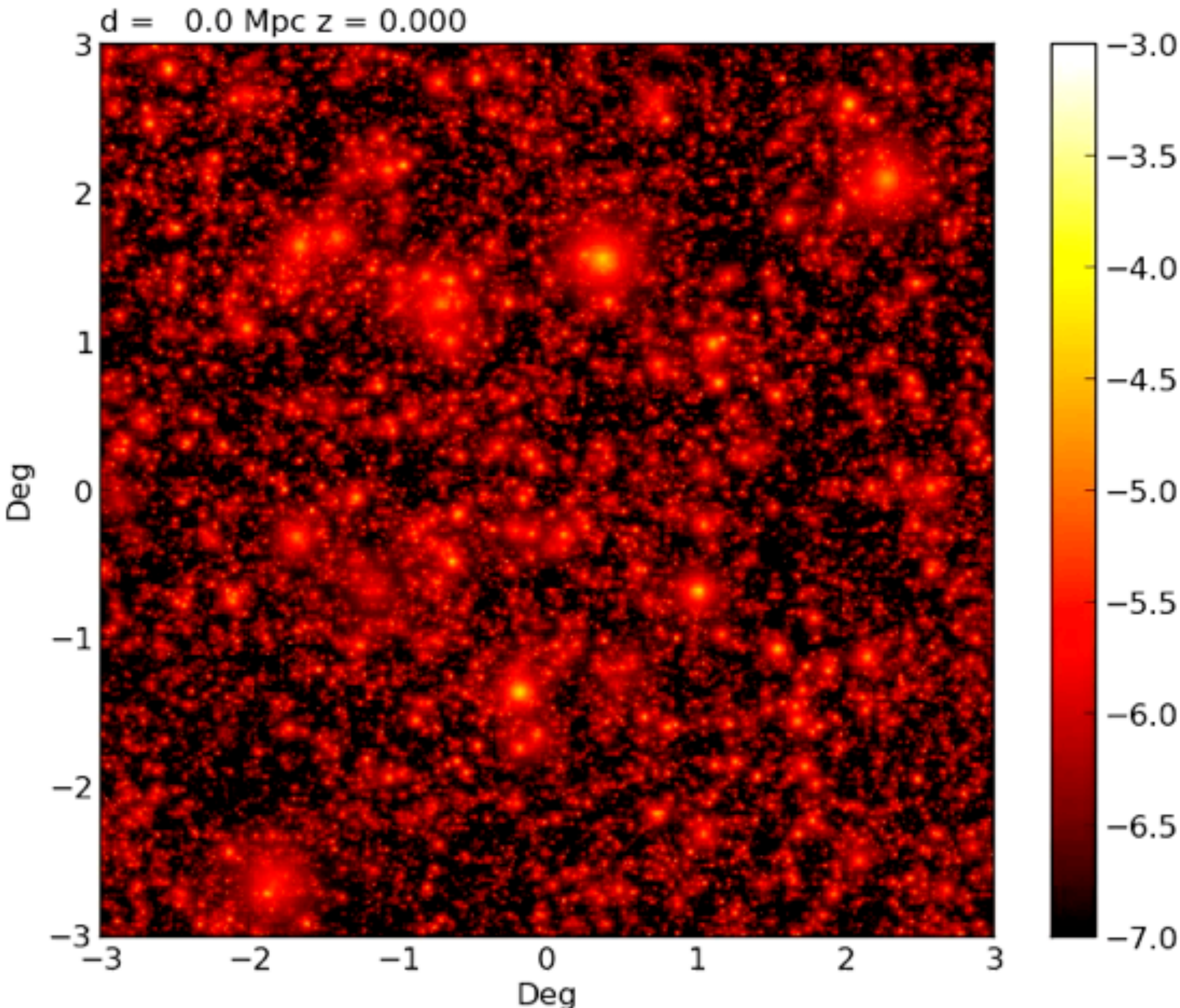






Mocking Heaven: lightcone simulation for ΛCDM 36 sq deg to z=2

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



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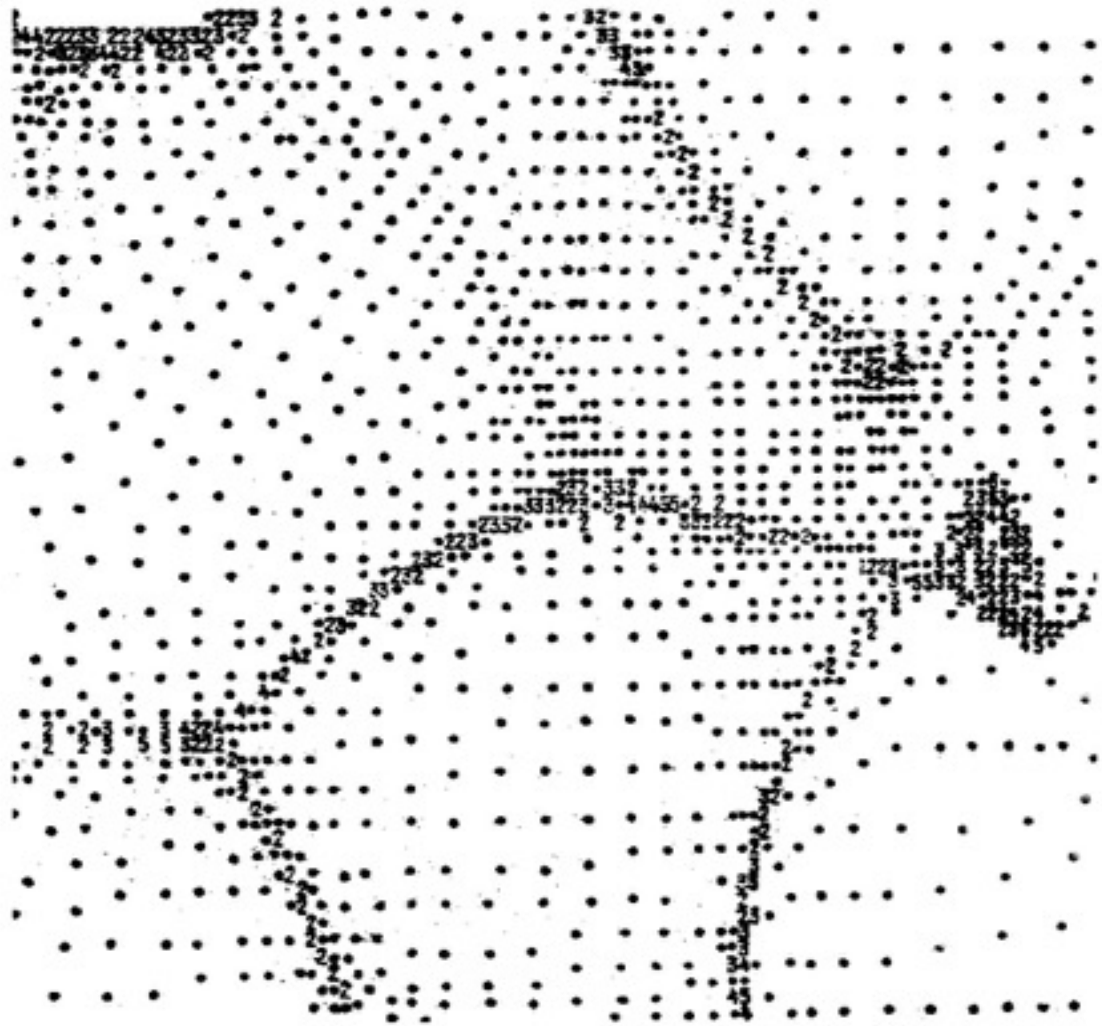

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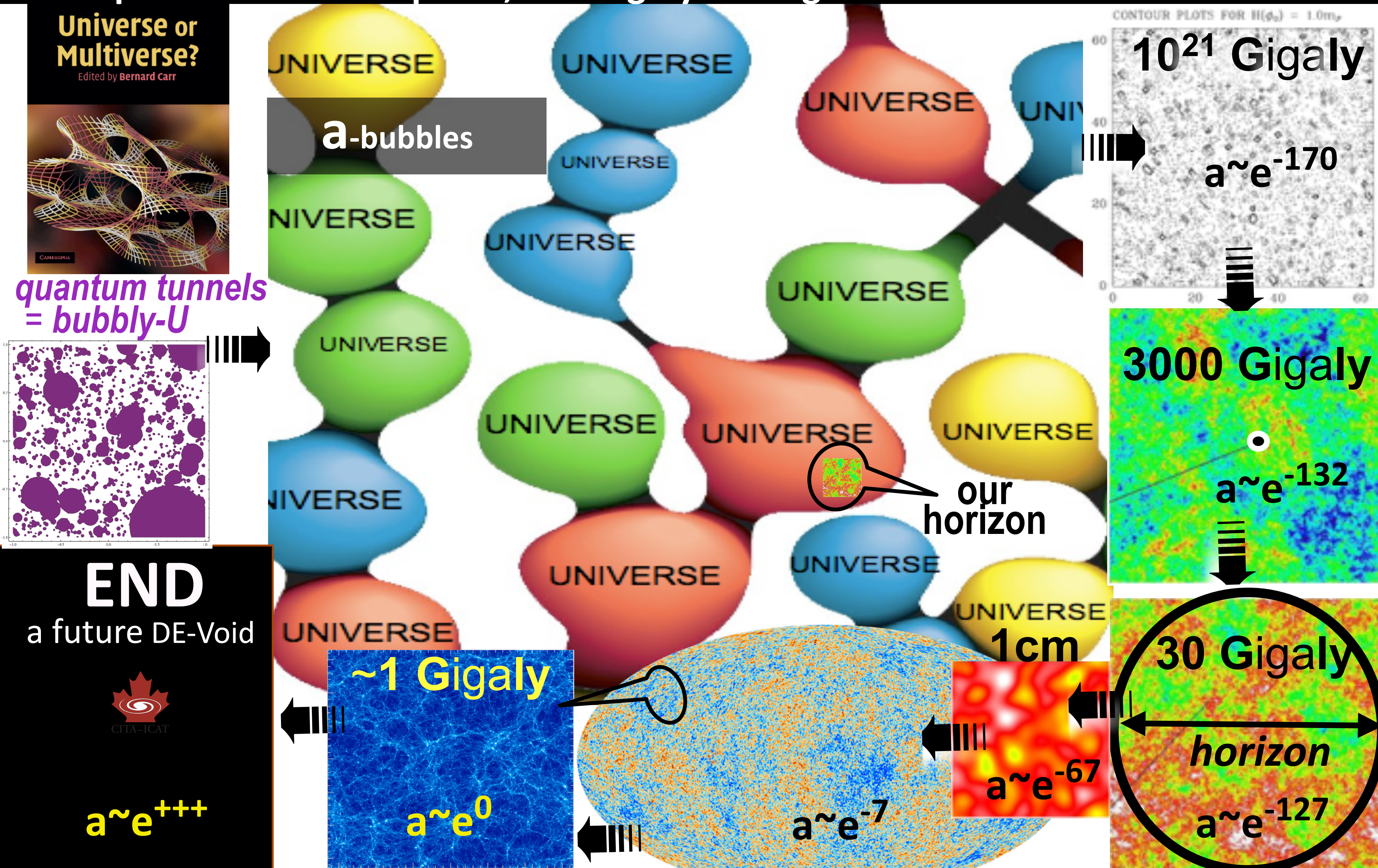
SuperWeb of ultra-Ultra Large Scale Structure of the Universe

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 on small to medium scales



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