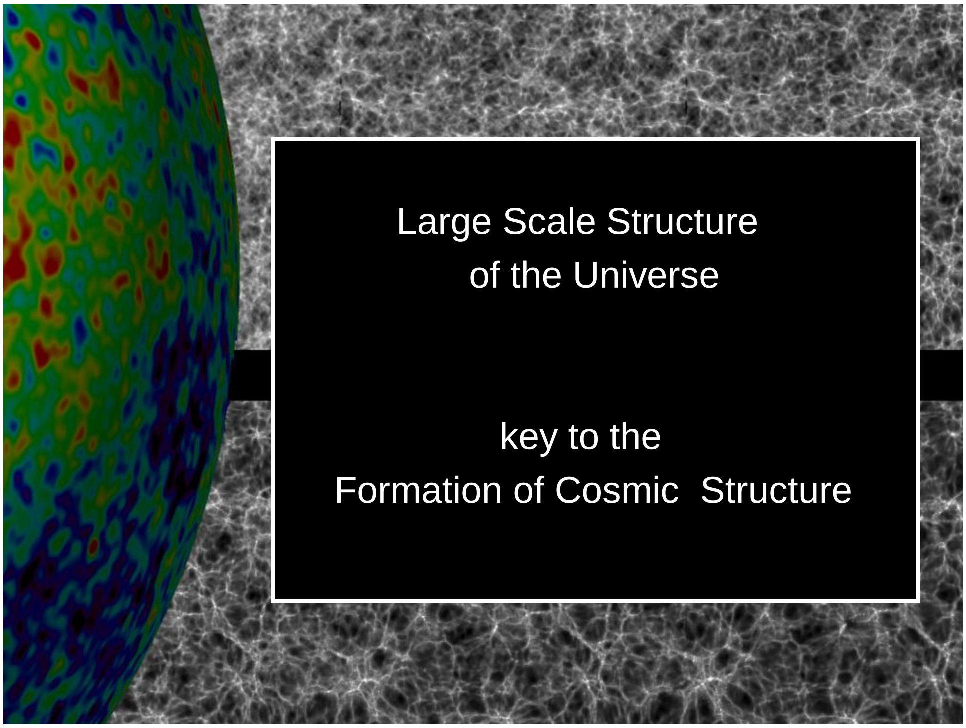
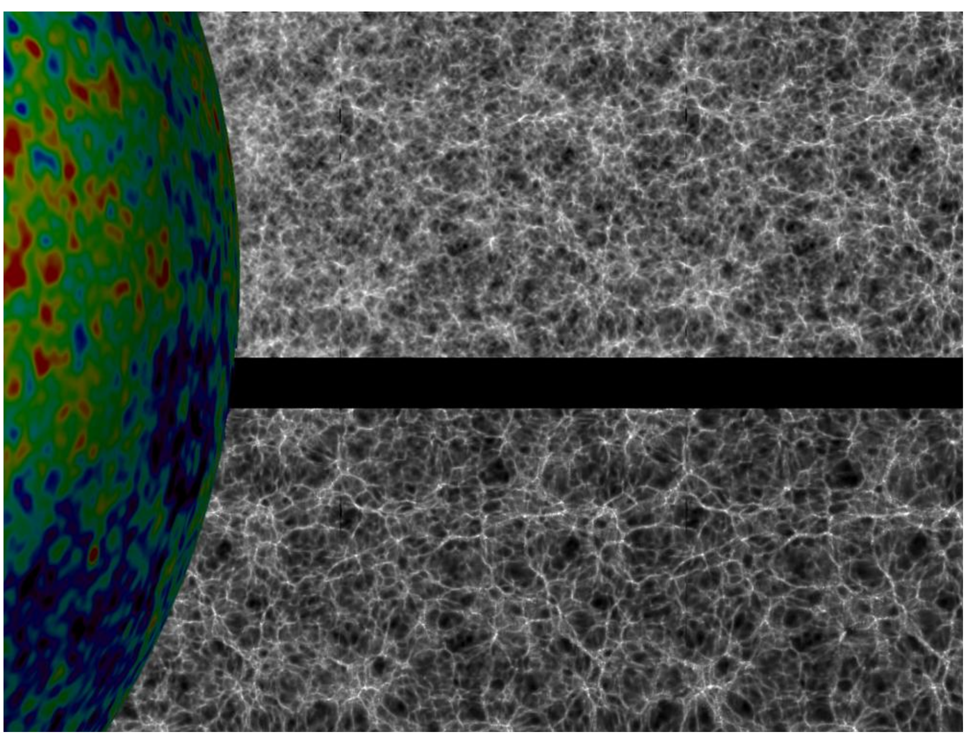

Large Scale Structure
of the Universe
key to the
Formation of Cosmic Structure



Structure in the Universe

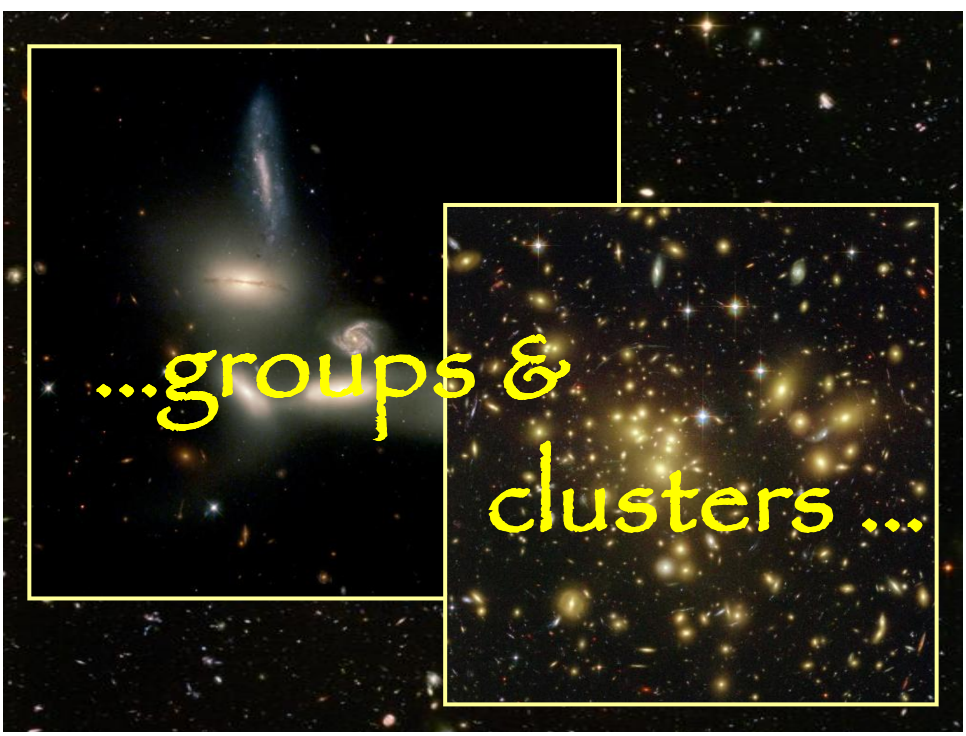

... and their cradles ...


... forming stars
in multitudes ...


… the Galaxy …

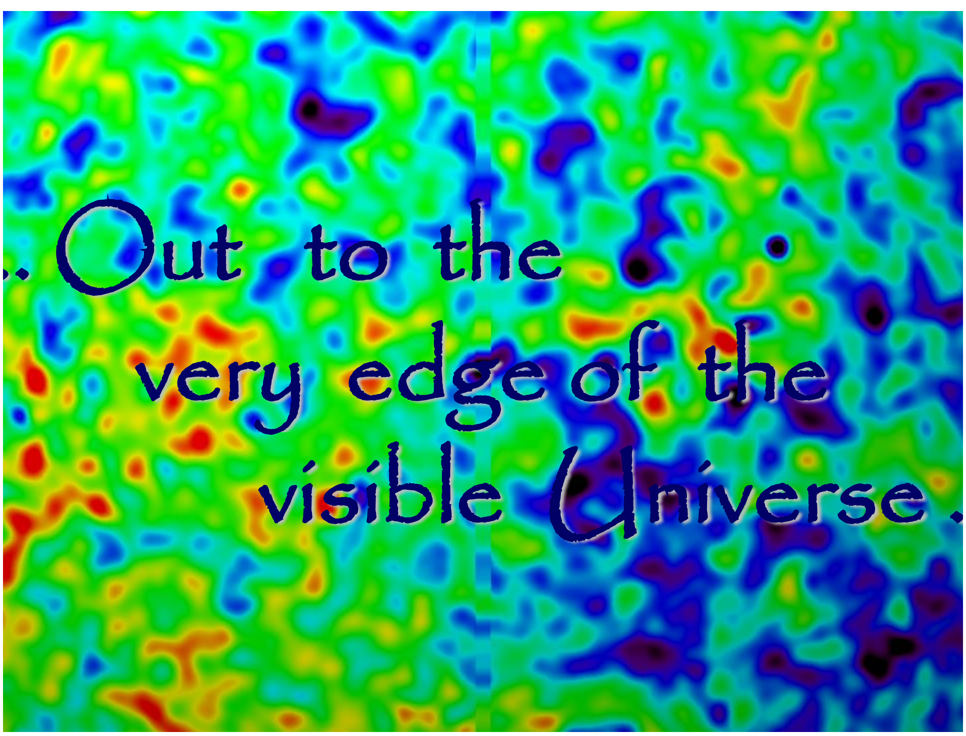

… galaxies …

Sociology of Galaxies: Interaction



Sociology of Galaxies: Clusters


... into the regions
with the First Stars
setting ablaze
the skies ...


.. Out to the
very edge of the
visible Universe .

Central Theme:

Cosmic Enigma

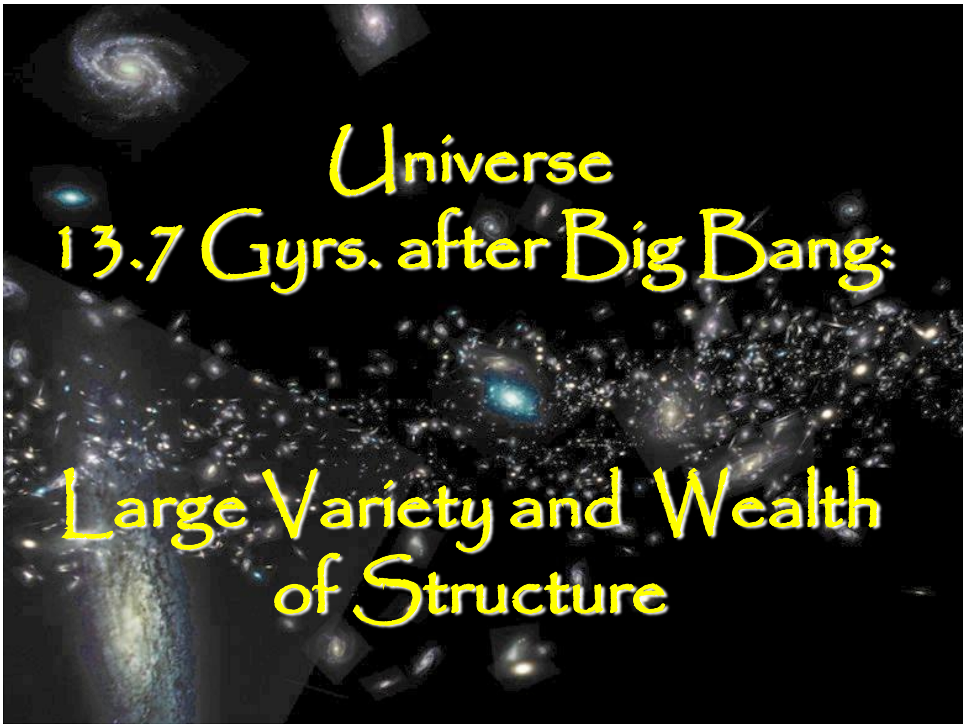
Universe

379,000 years after Big Bang

almost perfectly smooth

Microwave Background Radiation, surface of last scattering of cosmic photons is almost perfectly isotropic, all around the same temperature:

T=2.725 K



The Early Universe:

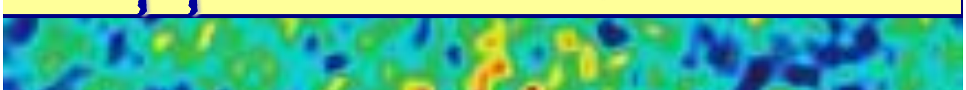
Almost perfectly homogeneous and isotropic, without any discernable structure ...

How did the present wealth and variety of structure emerge out of an almost featureless, pristine early Universe ?????

Cosmic Paradigm:

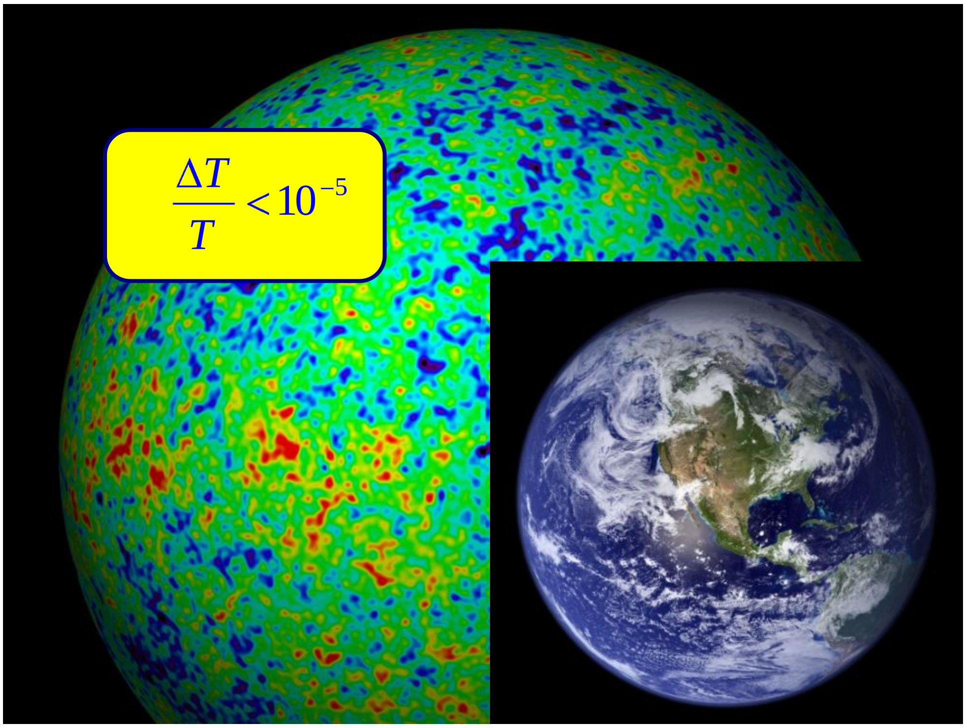
Gravitational Instability

Ripples in the Universe

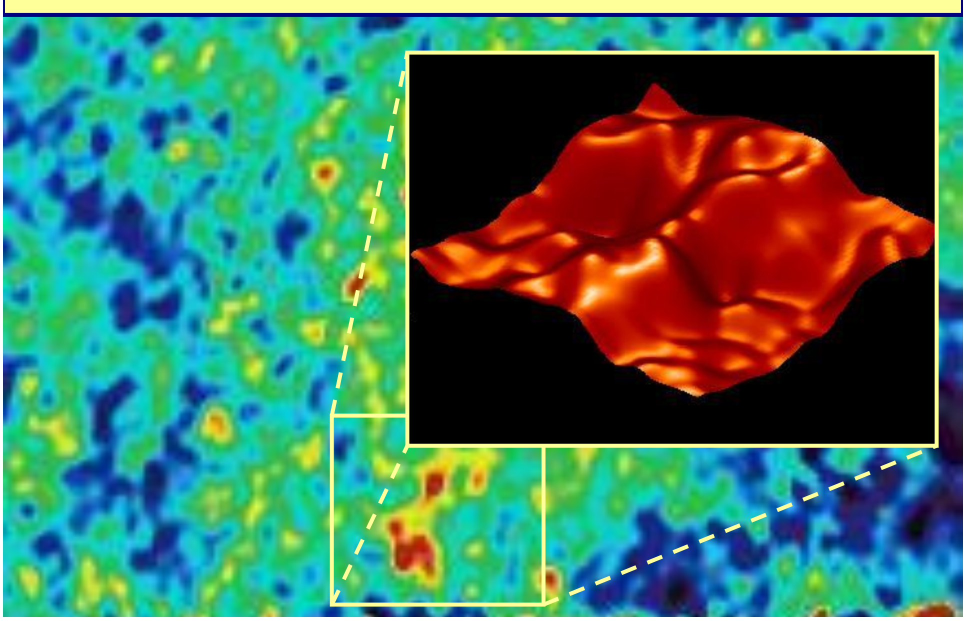


Tiny density perturbations in Early Universe:

- Origin: Quantum Fluctuations expanded to superhorizon scale during Inflation
- Gaussian Noise !!!
- Primordial Gaussian Density & Velocity Perturbations visible as corresponding Radiation Temperature Perturbations in Cosmic Microwave Background Radiation (CMB) Radiation



Primordial Gaussian Perturbations



Cosmic Structure Formation

After decoupling, density perturbations in the matter distribution gradually develop into forming structures by means of the "gravitational instability" mechanism. The origin of these density perturbations is still an unsettled issue. Their presence, however, has been proven beyond doubt: their imprint in the CMB beautifully confirmed by COBE and WMAP.

Hidden in the depths of the very first instances of the early universe, at present the most viable suggestion is that it concerns quantum fluctuations blown up to macroscopic proportions in an inflationary phase of cosmic expansion.

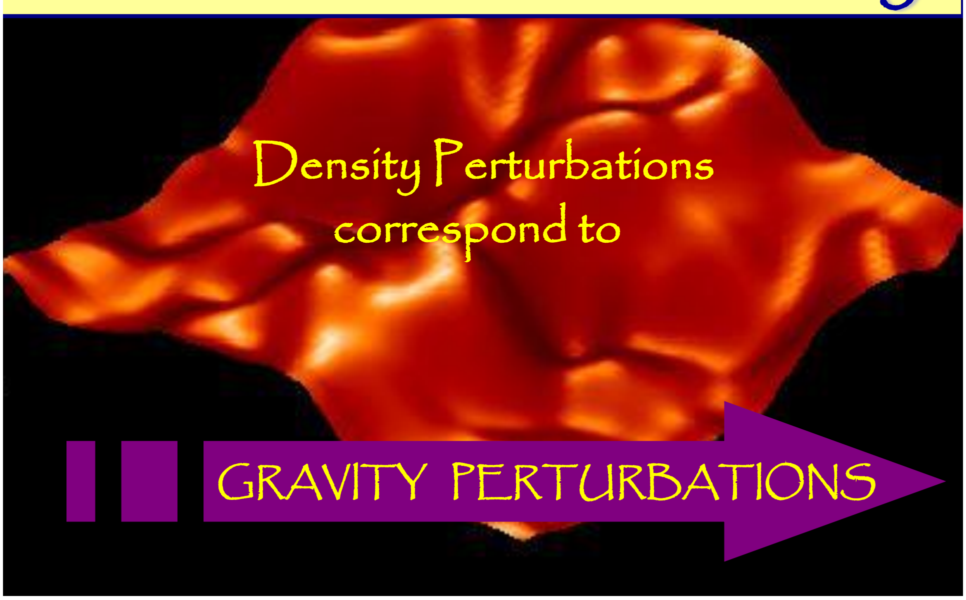
In the later phases of more "quiescent" cosmic expansion, density fluctuations, frozen while they have the superhorizon scale assumed in inflation, gradually enter the horizon (i.e they are overtaken).

From that instant on they can start growing!

$$\delta(\mathbf{x},t) \equiv \frac{\rho(\mathbf{x},t) - \bar{\rho}(t)}{\bar{\rho}(t)}$$

$$\delta(\mathbf{x}) = \int \frac{\mathrm{d}\mathbf{k}}{(2\pi)^3}\, \hat{\delta}(\mathbf{k})\, \mathrm{e}^{-\mathrm{i}\mathbf{k}\cdot\mathbf{x}}$$

Gravitational Instability



Gravitational Instability

$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

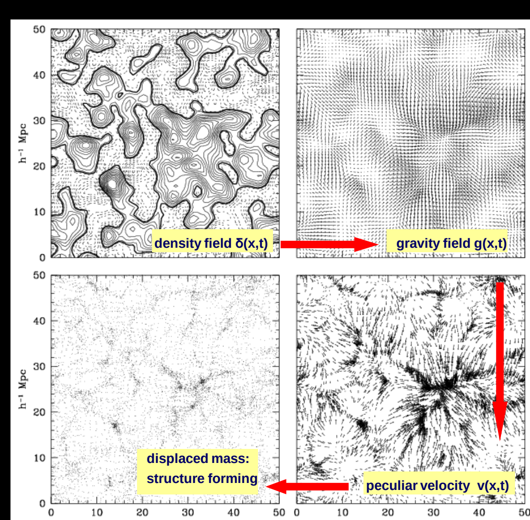
Cosmic Structure Formation

The gravity perturbations induce cosmic flows of matter. High density regions start to contract and finally collapse, assembling more and more matter from their surroundings.

By contrast, as matter is moving out of them, low density regions turn into empty void regions.

Gradually, dependent on scale, we see the emergence of cosmic structures.

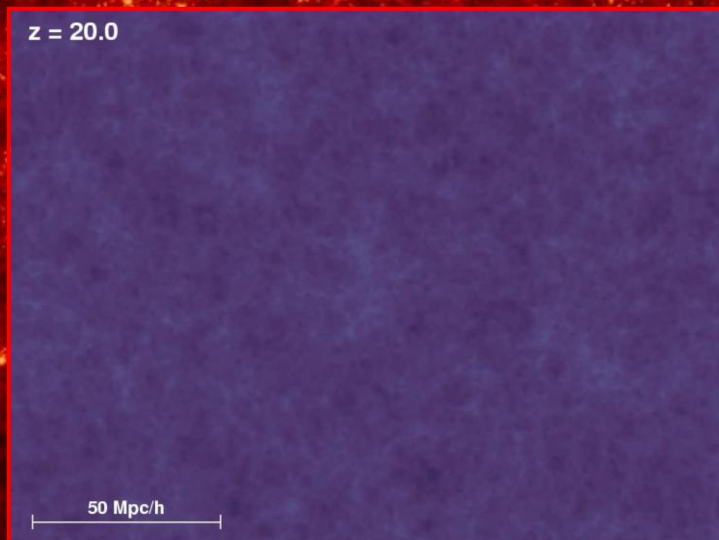
These days we can simulate the characteristics of the process through large computer simulations. Succesfull confrontation with the observational reality has given confidence in our understanding.



Cosmic Structure Formation

The formation of the cosmic web is tellingly illustrated in the simulation sequence shown to the right.

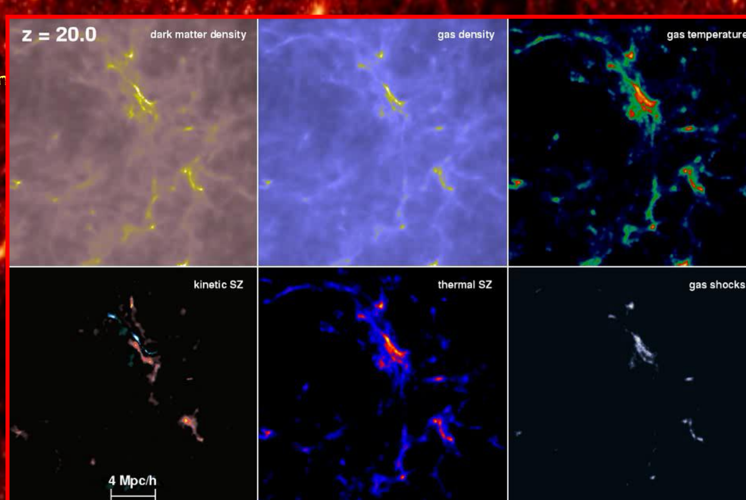
(courtesy: Virgo/V. Springel).



Cosmic Structure Formation

The formation of a cluster in the Cosmic Web

(courtesy: Virgo/V. Springel)

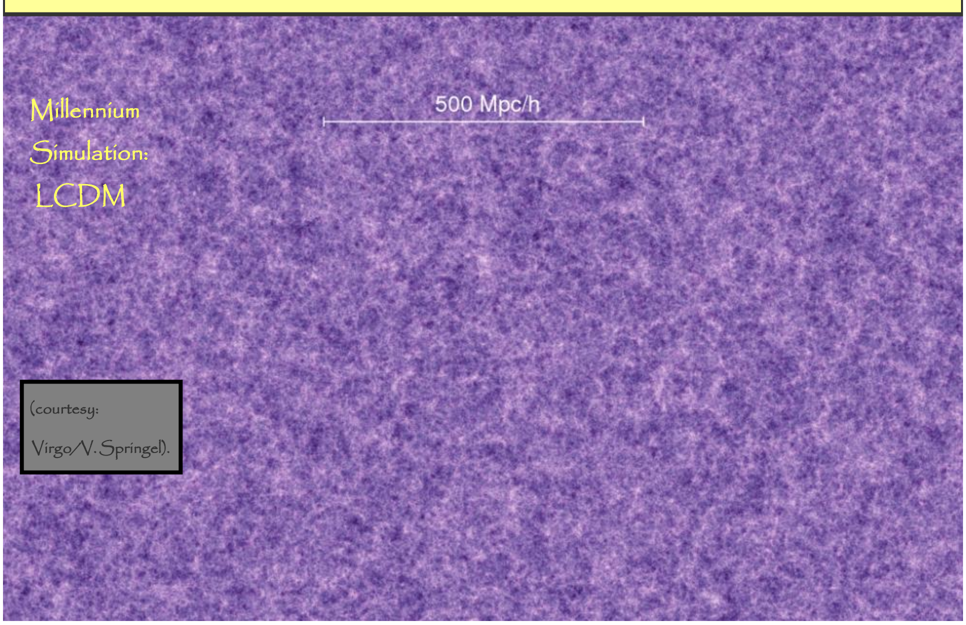


Gravitational Instability

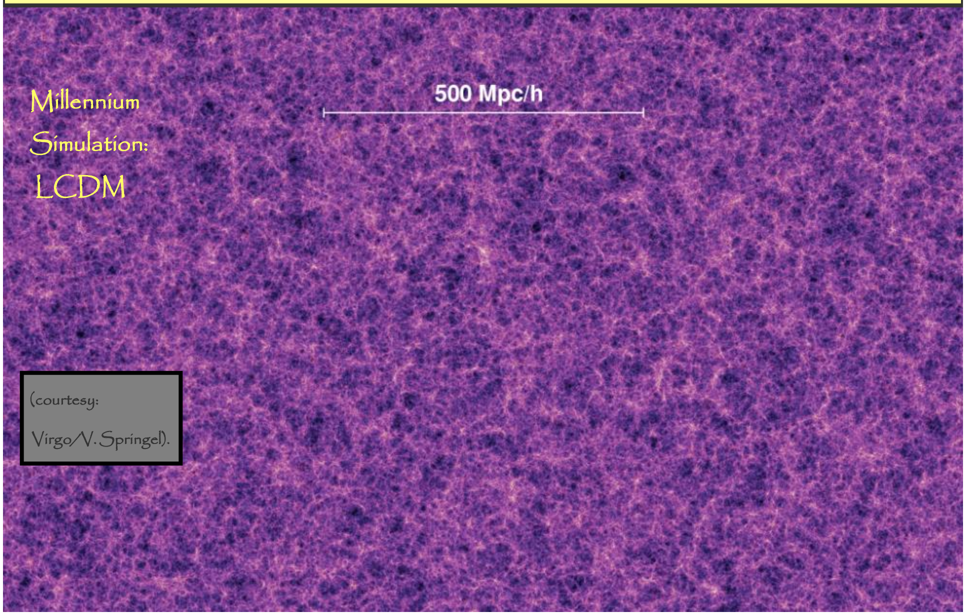
Perturbation Development:

- Generation: – .... Inflationary Phase ?
  – Gaussian Quantum Noise inflated to Cosmic Scale
- Superhorizon: – As long as perturbations superhorizon, no evolution
- Linear Growth: – Density & Velocity perturbations tiny
  Can be described analytically !
- Nonlinear Growth: – Interaction between fluctuations over range of scales
  – Emergence complex patterns & formation objects
  – Only analytical approximations,
  Computer (N-body) simulations necessary

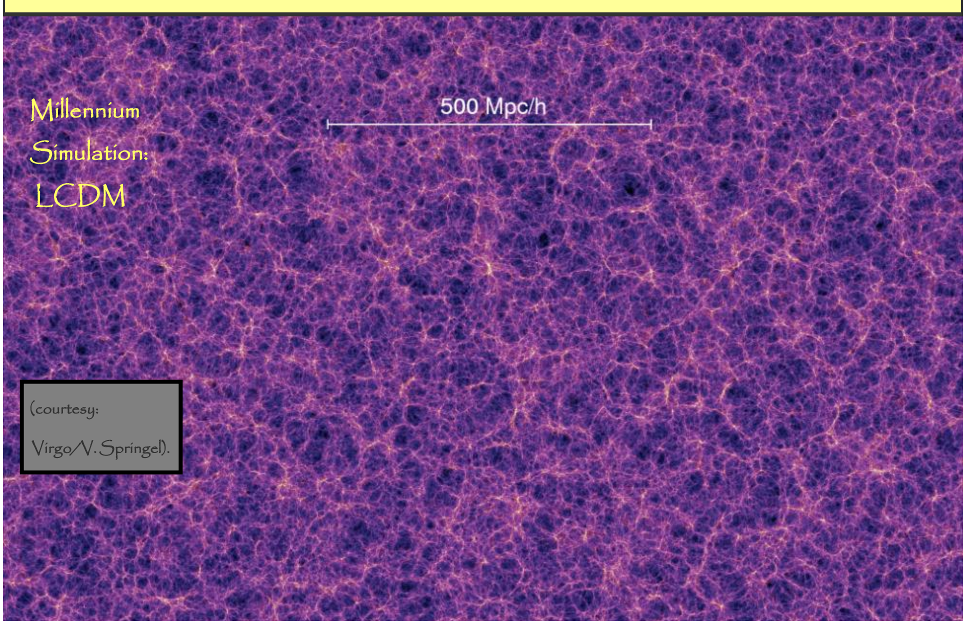
Millennium Simulation



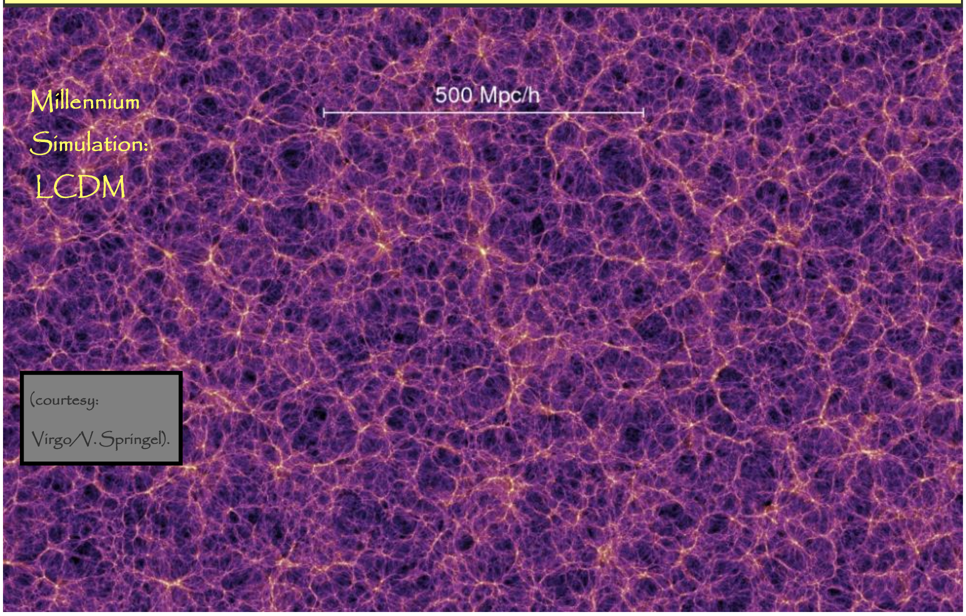
Millennium Simulation



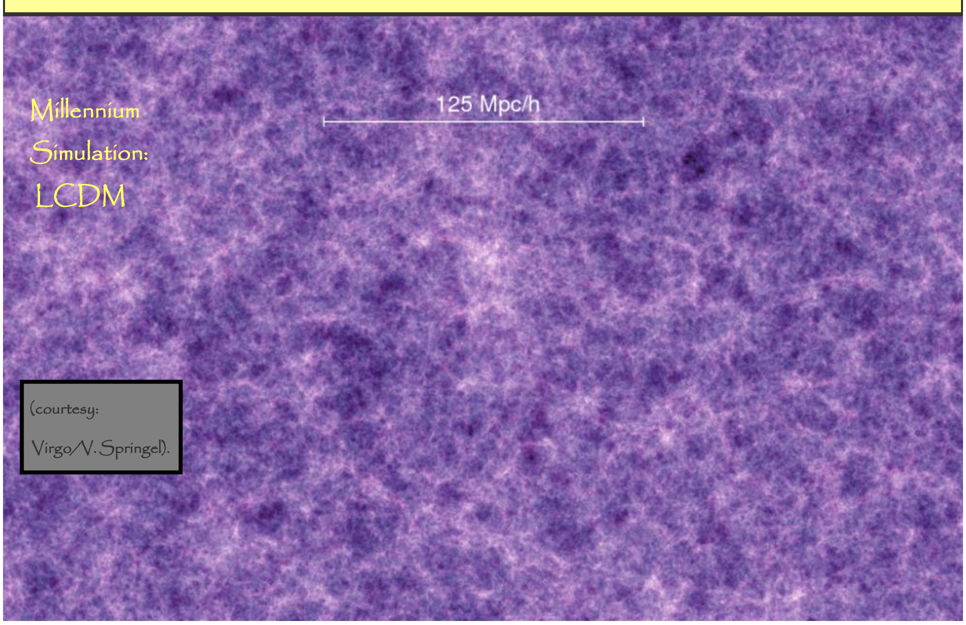
Millennium Simulation



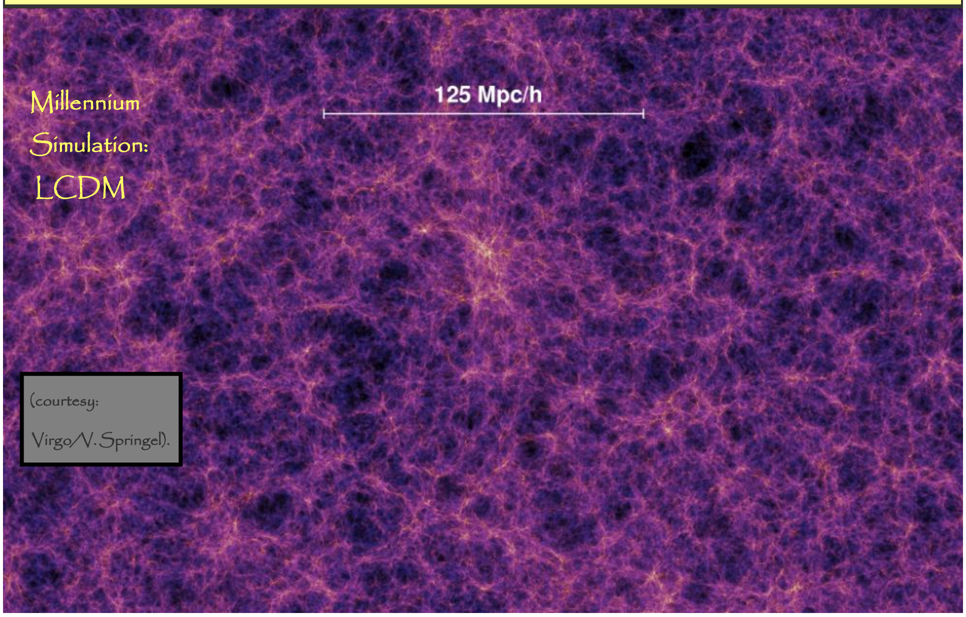
Millennium Simulation



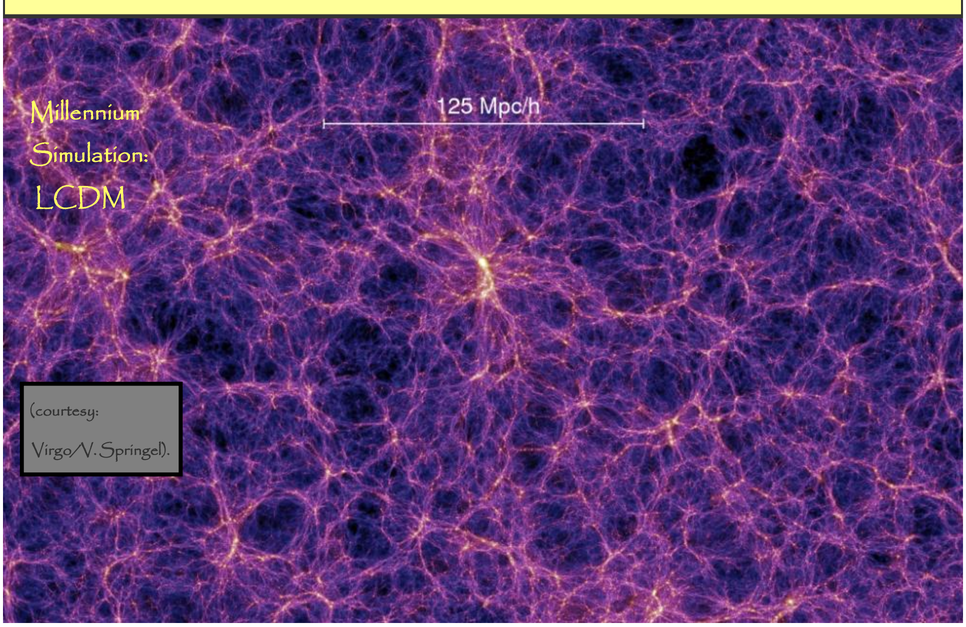
Millennium Simulation



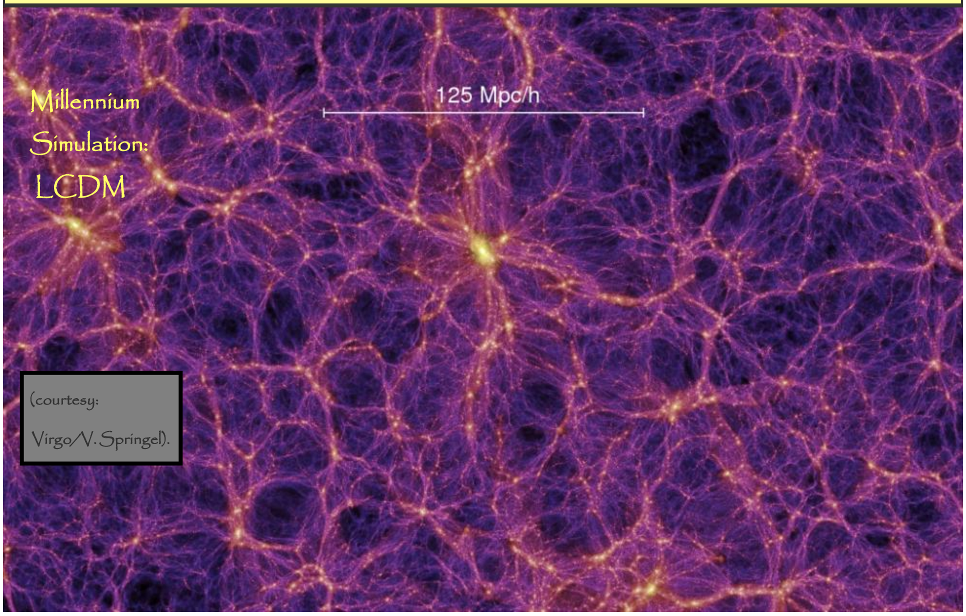
Millennium Simulation



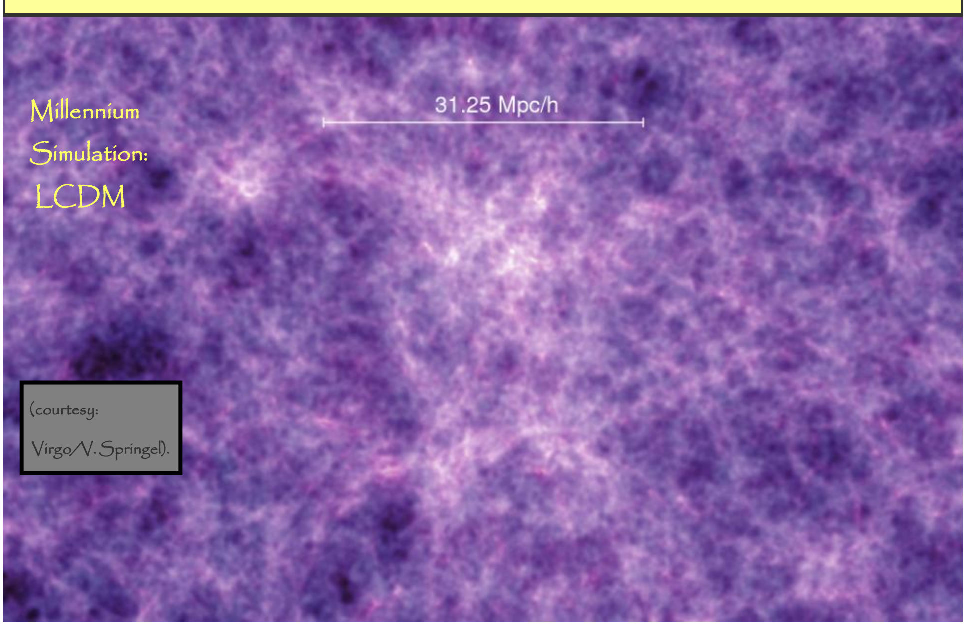
Millennium Simulation



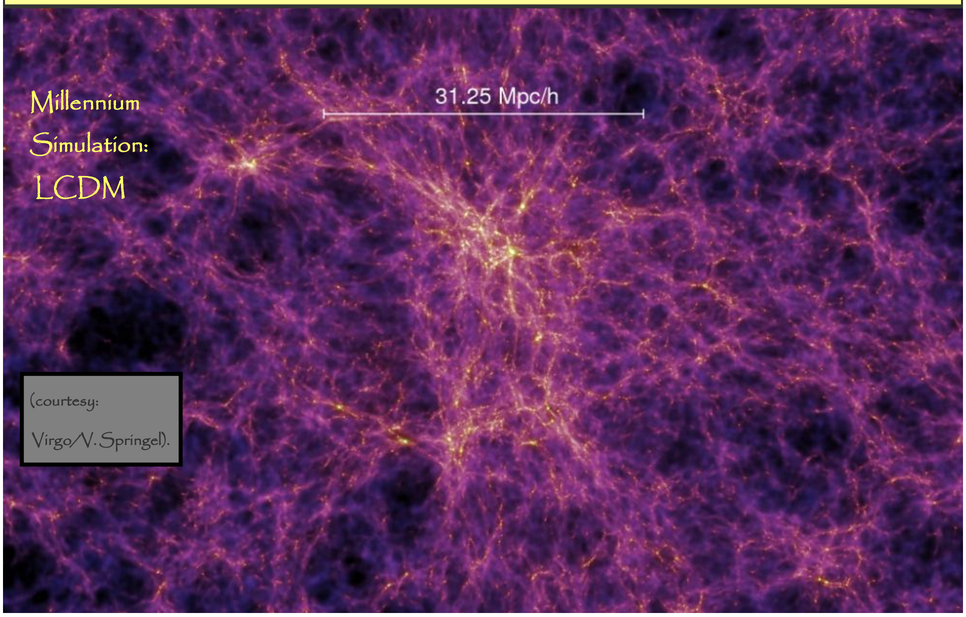
Millennium Simulation



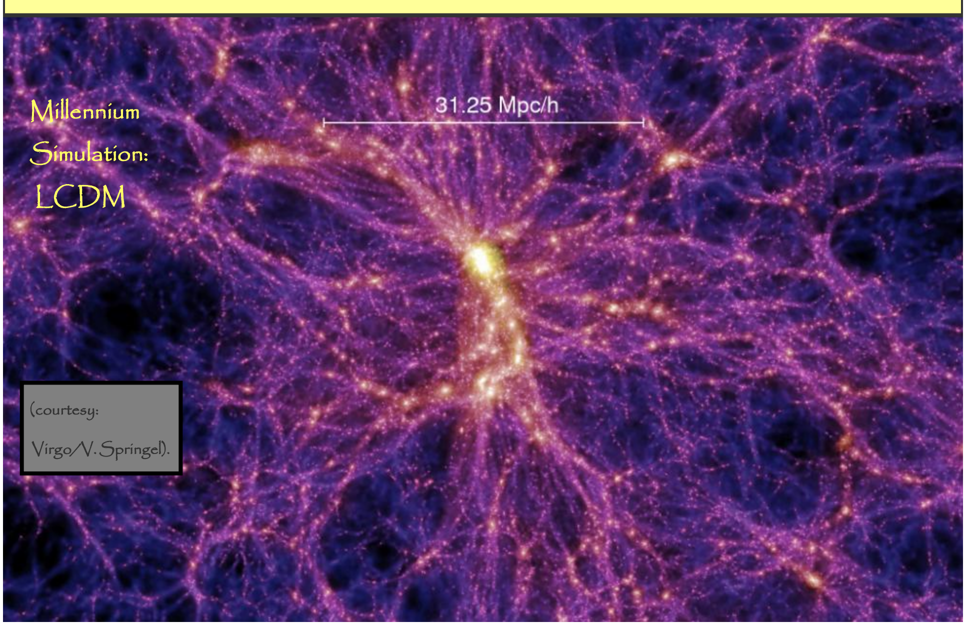
Millennium Simulation



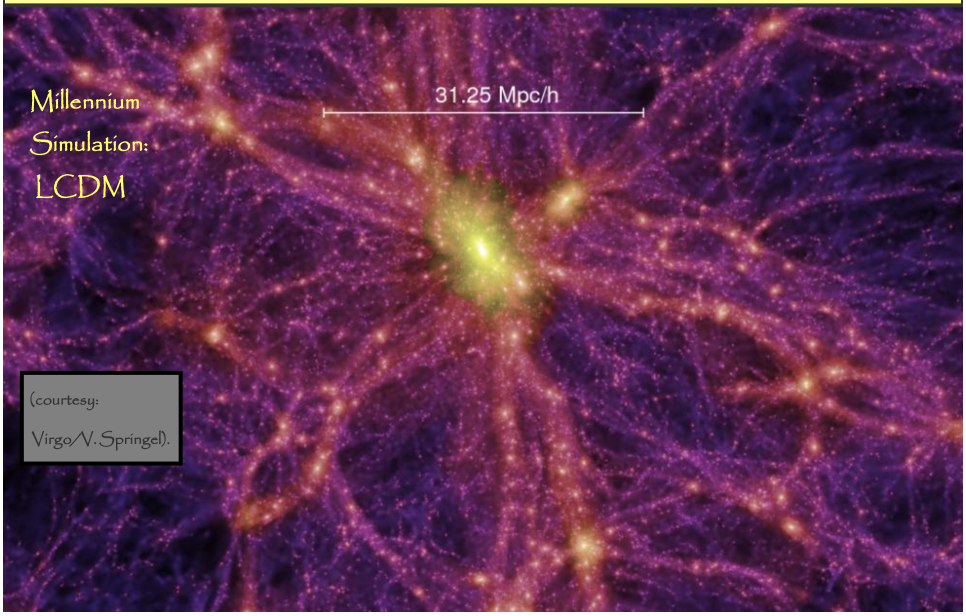
Millennium Simulation



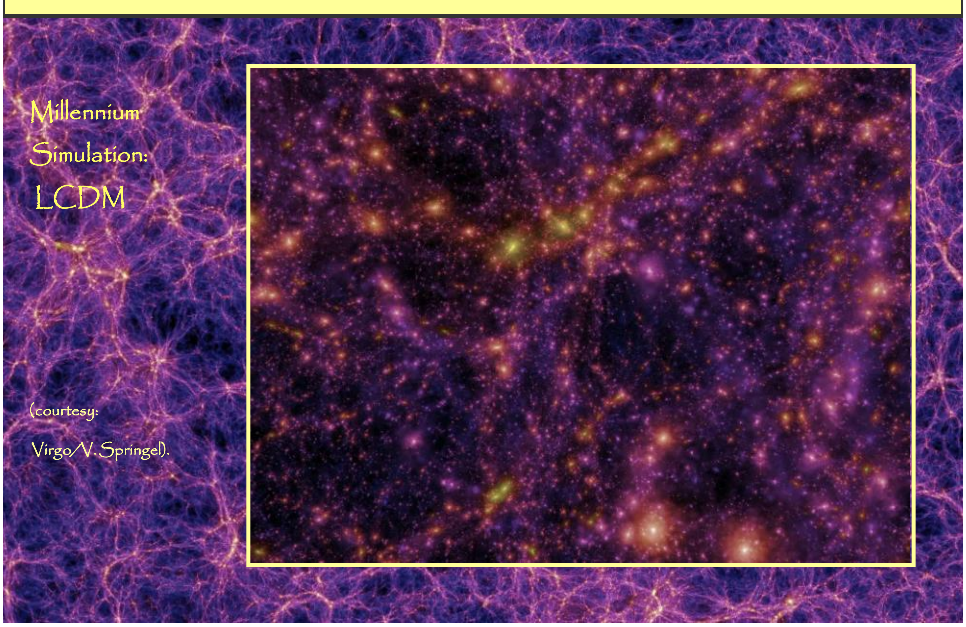
Millennium Simulation



Millennium Simulation



Millennium Simulation



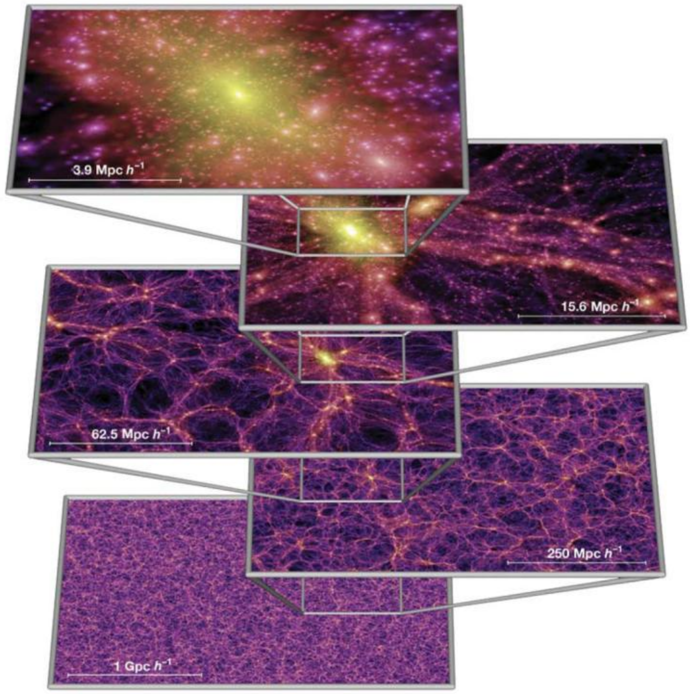
Cosmic Structure Formation

Once the first linear phase of structure formation has passed, we start to recognize the emergence of genuine cosmic structures. Three generic properties nonlinear structure formation:

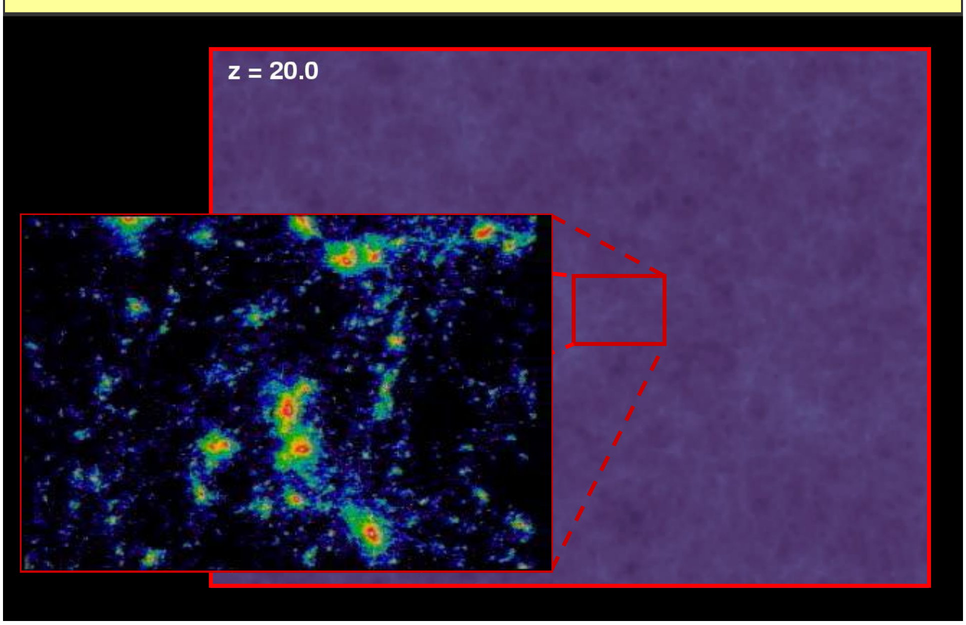
- hierarchical structure formation
- anisotropic collapse
- void formation:
  asymmetry
  overdense vs. underdense

Hierarchical Structure Formation

Small structures form first, then merge into larger and larger features.



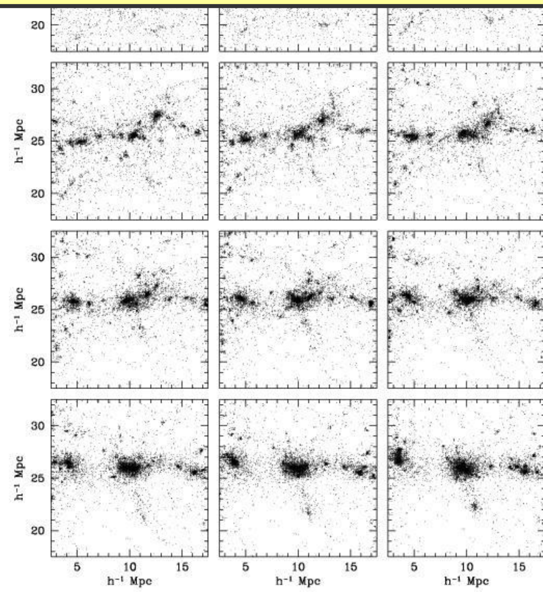
I. Hierarchical Structure Formation

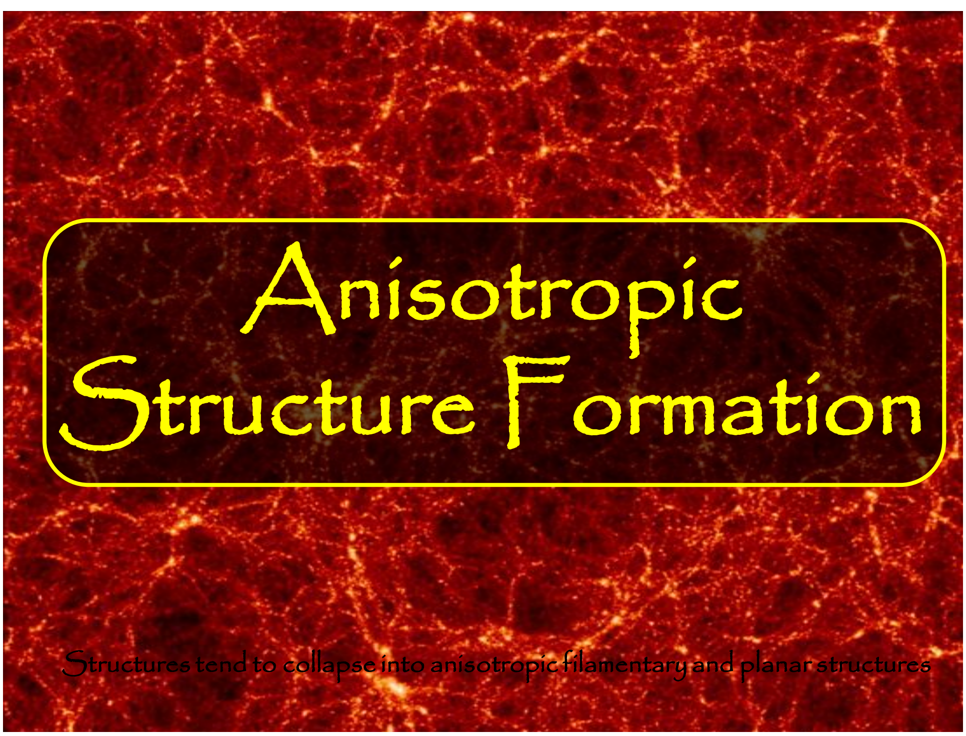


I. Hierarchical Structure Formation

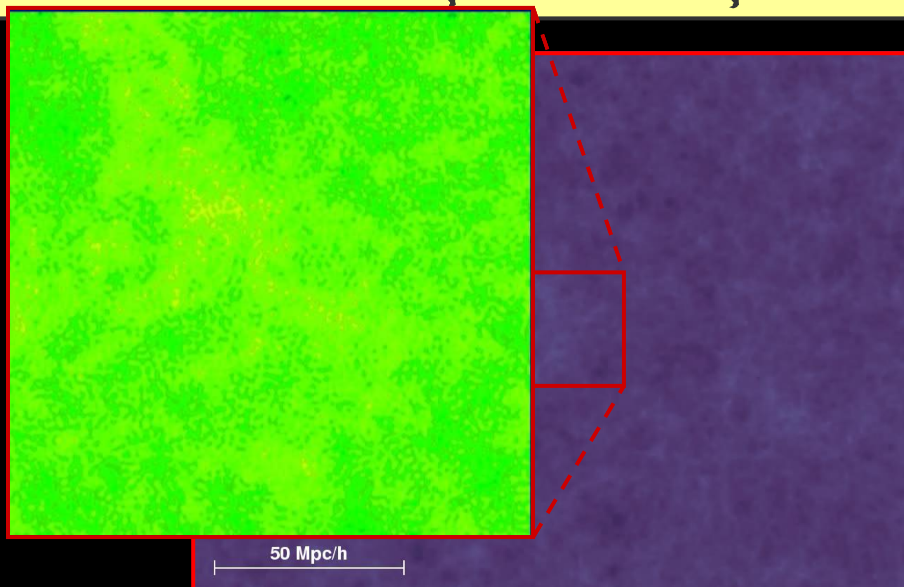
Structures in the Universe form
by
gradual hierarchical assembly:

- small objects emerge & collapse first
- merge with other clumps while forming larger object in hierarchy





II. Anisotropic Collapse



II. Anisotropic Collapse

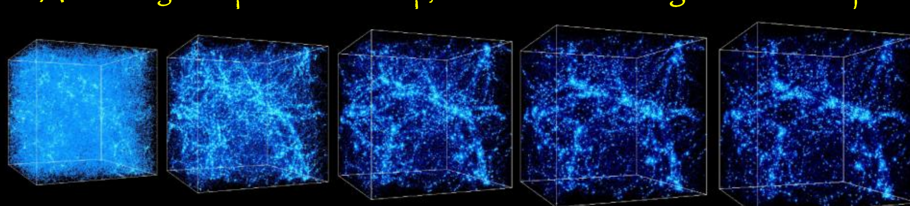
- Gravitational Instability:

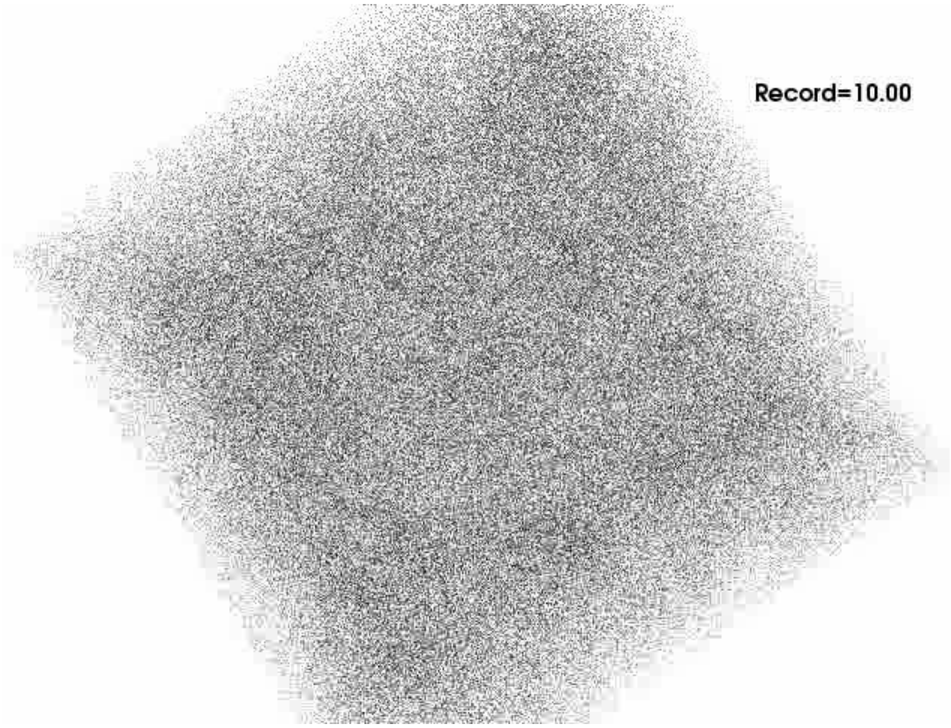
  - any small initial deviation from sphericity of a collapsing cloud gets magnified

  - gravitational collapse proceeds along sequence:

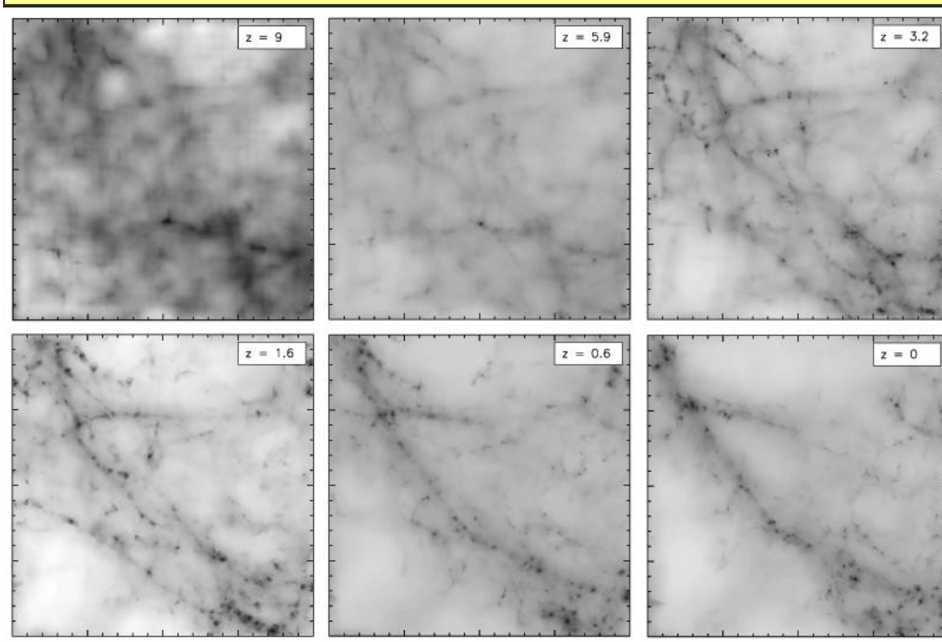
• collapse along smallest axis	→	planar geometry	↔	wall
• collapse medium axis	→	elongated	↔	filament
• full 3-D collapse	→	clump	↔	clump/halo

- After having collapsed into a clump, virialization and emergence cosmic object





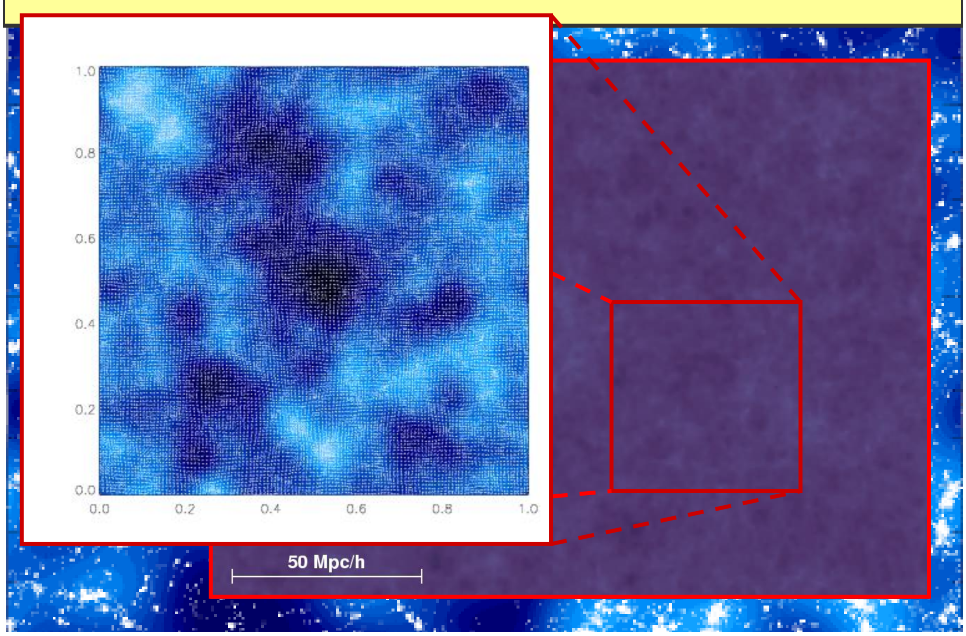
Hierarchical Filament Formation



Asymmetric Structure Formation: Void Dominance

While matter aggregates into ever denser and compacter structures, underdense void regions assume dominance in terms of occupied space.

III. Void Formation



III. Void Formation

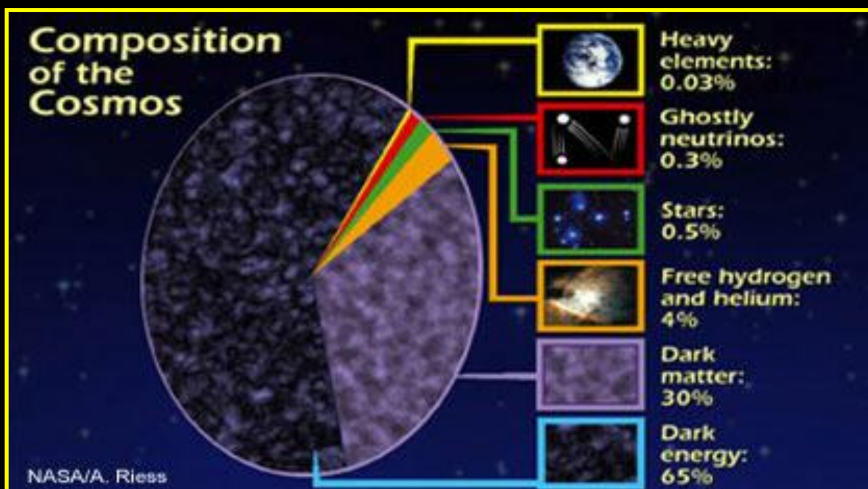
Origin of Voids:

- Voids natural product gravitational instability
- Voids evolve out of primordial underdensities:
  - Underdensity →
  - Gravity Deficit →
  - Matter Emigration
- Primordial Density Troughs → Present-Day voids

Structure Formation:

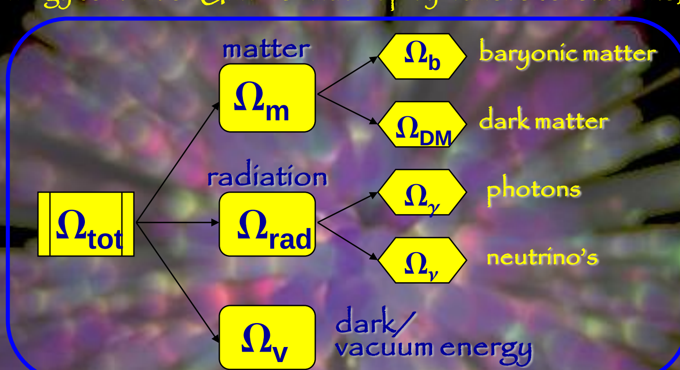
Cosmic Constituents

The Universe; What it consists of



Constituents of the Universe

The total energy content of Universe made up by various constituents, main ones:



In addition to the constituents mentioned in the diagram, there are contributions by e.g. gravitational waves, magnetic fields, etc. However, given the poor constraints on their contribution henceforth we will not take them into consideration.

Cosmic Energy Inventory

1	dark sector				0.954 ± 0.003
1.1	dark energy			0.72 ± 0.03	
1.2	dark matter			0.23 ± 0.03	
1.3	primeval gravitational waves			$\lesssim 10^{-10}$	
2	primeval thermal remnants				0.0010 ± 0.0005
2.1	electromagnetic radiation			$10^{-4.3\pm0.0}$	
2.2	neutrinos			$10^{-2.9\pm0.1}$	
2.3	prestellar nuclear binding energy			$-10^{-4.1\pm0.0}$	
3	baryon rest mass				0.045 ± 0.003
3.1	warm intergalactic plasma			0.040 ± 0.003	
3.1a	virialized regions of galaxies	0.024 ± 0.005			
3.1b	intergalactic	0.016 ± 0.005			
3.2	intracluster plasma			0.0018 ± 0.0007	
3.3	main sequence stars		spheroids and bulges	0.0015 ± 0.0004	
3.4			disks and irregulars	0.00055 ± 0.00014	
3.5	white dwarfs			0.00036 ± 0.00008	
3.6	neutron stars			0.00005 ± 0.00002	
3.7	black holes			0.00007 ± 0.00002	
3.8	substellar objects			0.00014 ± 0.00007	
3.9	HI + HeI			0.00062 ± 0.00010	
3.10	molecular gas			0.00016 ± 0.00006	
3.11	planets			10^{-6}	
3.12	condensed matter			$10^{-5.6\pm0.3}$	
3.13	sequestered in massive black holes			$10^{-5.4}(1+\epsilon_n)$	
4	primeval gravitational binding energy				$-10^{-6.1\pm0.1}$
4.1	virialized halos of galaxies			$-10^{-7.2}$	
4.2	clusters			$-10^{-6.9}$	
4.3	large-scale structure			$-10^{-6.2}$	

Fukugita & Peebles 2004

Cosmic Constituents: Equation of State

The energy content of the Universe may be broadly divided into various classes, dependent on how their (approximate) equation of state.

The equations of state for the three classes of cosmologically relevant constituents:

$$\begin{array}{llllll}
\text{radiation} & p(\rho) = \frac{1}{3}\rho c^2 & \Rightarrow & w = \frac{1}{3} & \\
\text{matter} & p(\rho) = 0 & \Rightarrow & w = 0 & \\
\text{dark energy} & p(\rho) = -\rho c^2 & \Rightarrow & w = -1 & (\Lambda) \\
 & \quad\;\;\; = w\,\rho c^2 & \Rightarrow & -1 < w < -1/3 & (general) \\
 & \quad\;\;\; = w\,\rho c^2 & \Rightarrow & w < -1 & (phantom)
\end{array}$$

Cosmic Constituents

The energy content of the Universe may be broadly divided into various classes, dependent on how their energy density evolves in time. The three most important ones are:

- Matter: $\rho_m \propto a(t)^{-3}$
- Radiation: $\rho_{rad} \propto a(t)^{-4}$
- Dark Energy:

$$\rho_v = a(t)^{-3(1+w)} \quad \Longleftarrow \quad p = w\,\rho_v$$
$$\Downarrow \quad w = -1$$
$$\rho_\Lambda = cst.$$

Inventory for a Flat Universe

$$\Omega_{rad} \approx 10^{-5}$$
$$\Omega_{matter} \approx 0.3$$
$$\Rightarrow \quad \Omega_\Lambda \approx 0.7 \quad \Leftarrow$$

Inventory for a Flat Universe

$$\Omega_{tot} = \Omega_{matter} + \Omega_{rad} + \Omega_{\Lambda} = 1$$

Precisely Enough Energy to Close Universe !!!!

→ $k = 0$

Constituents & Structure Formation

What is the role of Radiation in structure formation:

• Radiation: - Presently, minor energy component ($\Omega_{rad} \sim 10^{-5}$)
- But, by far, most abundant species in the Universe ($\eta \sim 10^9$)
- by good approximation, nearly all photons in the Universe Cosmic Microwave Background (stellar photons negligible)

Cosmic Microwave Background: Some Facts

Radiation Field of the Universe:

0) Discovered in 1965 (serendipitously) by Penzias & Wilson,

Nobelprize 1978 !!!!!

- Thermal radiation pervading throughout the whole Universe
- As yet it has a temperature of

T_γ=2.725 K

1) By far CMB photons represent the most abundant species in the Universe:

$n_\gamma \sim 415\ \mathrm{cm}^{-3}$

- For comparison: $n_\gamma/n_B \sim 1.9 \times 10^9$!!!! (second: cosmic neutrino's)
- Stellar photons: negligible !!!! (integrated over all stars at all times !)

Cosmic Microwave Background: Some Facts

7) CMB highly (impressively) Isotropic:

- in each direction on the sky the radiation has almost exactly the same temperature/intensity
- temperature anisotropies VERY SMALL, in the order of

$$\frac{\Delta T}{T} < 10^{-5}$$

- for comparison:

Planet Earth's highest mountain would be in the order 10-25 m !!!!!!

8) The electromagnetic spectrum of the CMB PERFECTLY Thermal Blackbody (most accurately measured BB spectrum ever):

$$I_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

Cosmic Microwave Background: Some Facts

6) CMB photons Last Scattered

379,000 yrs. after Big Bang

at a redshift z=1089 (ie. expansion factor a(t)=1/1089)

7) Following the - Decoupling of Radiation and (Baryonic) Matter

- Recombination Hydrogen Atoms

(as protons and electrons combine)

8) At recombination T ~ 3000 K: the (CMB) sky would look red

Since then, gradual cooling of radiation through expansion Universe:

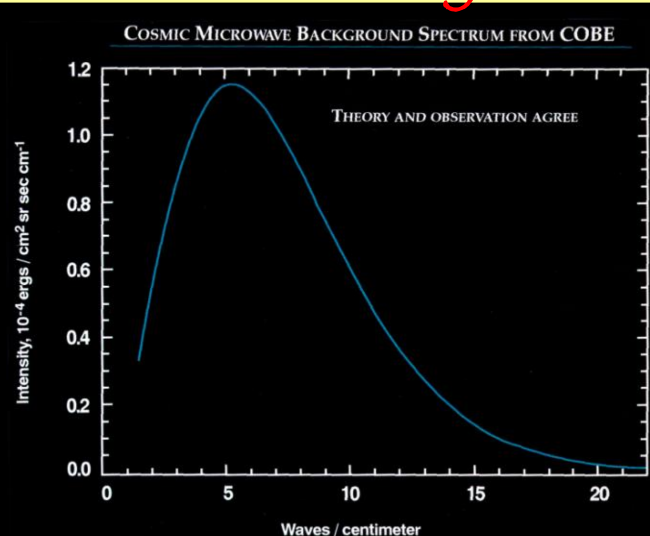
- cosmic redshift photons

9) The CMB photons created at much earlier epoch !!!

Last surge: positron-electron annihilation,

1 min. after Big Bang, redshift z ~ 10^9

Spectrum Blackbody Radiation



- John Mather
- COBE-DIRBE: temperature, blackbody
- Most accurately measured Black Body Spectrum Ever!!!!!

Key to the Universe

CMB Radiation, the cosmic radiation field of the Universe,

Cosmic Treasure Trove:

1) Direct probe of Thermal State of the early primordial Universe, the Universe before Decoupling:
   Ultimate Proof Reality of Hot Big Bang
2) Direct reflection of Primordial Structure of the Universe,
   the Embryonic State
   of all Structure in today's Universe
3) Through its simplicity (linearity) the ultimate diagnostic tool for measuring the Universe:
   Cosmic Parameters
4) Link on early decisive hypothetical/theoretical ($t \approx 10^{-36} - 10^{-34}$ sec)
   Inflationary Epoch

Constituents & Structure Formation

What is the role of Radiation in structure formation:

•Before Equivalence (z_{eq}~10^4) :

- Dynamically dominant

•Until Recombination:

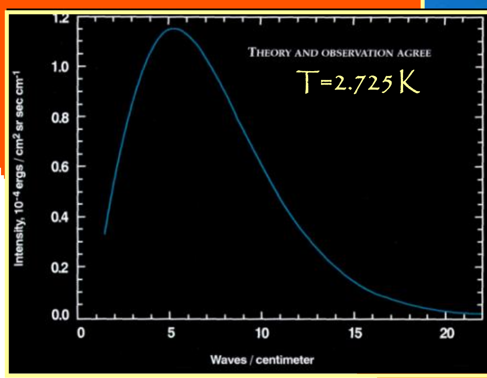
- still major physical constituent of the Universe
- important as main pressure source
- couples intimately to baryonic matter

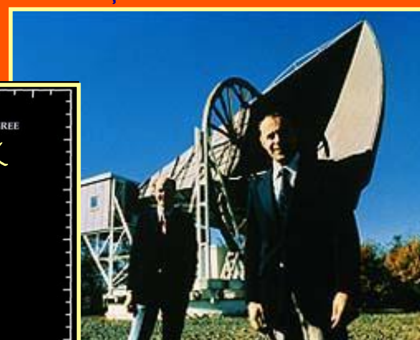
• After Recombination:

- plays modulating role in gas processes in early galaxy formation

Cosmic Microwave Background

Big Bang: The CMB photons produced at z~10⁹ visible as a perfectly thermal and isotropic radiation blanket





Discovered in 1965 by Penzias & Wilson (Nobelprize 1978)

Constituents & Structure Formation

What is the role of Matter in structure formation:

- Matter:
  - Baryonic Matter
  - Dark (nonbaryonic) Matter
- Dark Matter:
  - THE major component for cosmic structure formation:
    - gravitationally dominant for structure growth
    - dominant for shaping spectrum perturbations
- Baryonic Matter:
  - Gravitationally far less important than DM
  - Yet, its dissipative nature allows the formation of stars, galaxies, etc.

Baryonic Matter

Note:

- STARS are but a fraction of the total amount of baryonic matter
- There is still a large amount of undetected baryonic matter:
  - hiding as warm Intergalactic Gas (WHIM) ?

3	baryon rest mass				0.045 ± 0.003
3.1	warm intergalactic plasma			0.040 ± 0.003	
3.1a	virialized regions of galaxies		0.024 ± 0.005		
3.1b	intergalactic		0.016 ± 0.005		
3.2	intracluster plasma			0.0018 ± 0.0007	
3.3	main sequence stars	spheroids and bulges		0.0015 ± 0.0004	
3.4		disks and irregulars		0.00055 ± 0.00014	
3.5	white dwarfs			0.00036 ± 0.00008	
3.6	neutron stars			0.00005 ± 0.00002	
3.7	black holes			0.00007 ± 0.00002	
3.8	substellar objects			0.00014 ± 0.00007	
3.9	HI + HeI			0.00062 ± 0.00010	
3.10	molecular gas			0.00016 ± 0.00006	
3.11	planets			10^{-6}	
3.12	condensed matter			$10^{-5.6 \pm 0.3}$	
3.13	sequestered in massive black holes			$10^{-5.4}(1 + \epsilon_n)$	

Cosmic Structure Formation

It is important to realize the distinct difference between the evolution of the dark matter perturbations and those in baryonic matter.

Dark Matter:

- Dark matter is the dominant gravitational component of the universe, and thus also drives the structure formation process.
- The perturbations in the gravitationally dominant (collisionless) dark matter component started growing after matter came to dominate cosmic dynamics, i.e. after radiation-matter equivalence.

Baryonic Matter:

- Fluctuations in baryonic matter were enabled to grow only once radiation pressure disappeared, i.e. after decoupling epoch.
- Baryonic matter fluctuations start to grow strongly through infall into the gravitational potential wells defined by the developing dark matter perturbations.

Constituents & Structure Formation

What is the role of Dark Energy in structure formation:

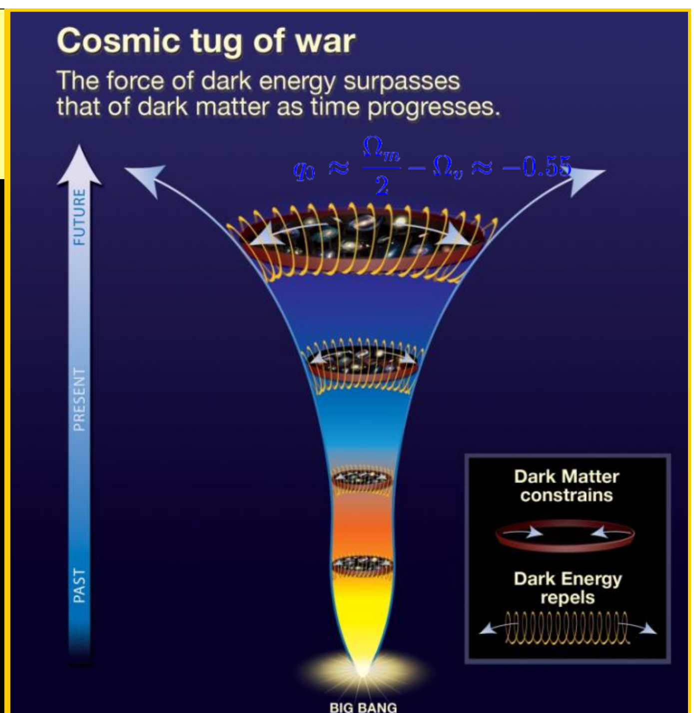
- Dark Energy
  - Perturbations in dark energy cannot grow
  - Minor dynamic role on Megaparsec scales
  - Major influence concerns that of determining the timescales available for structure growth
  - Minor factor in shaping power spectrum

Cosmic Acceleration

Our Universe

Present:
ACCELERATES

Past:
DECELERATED



Structure Formation:

Inflationary Origins

Inflationary Origins

Inflationary Origin of Cosmic Structure:

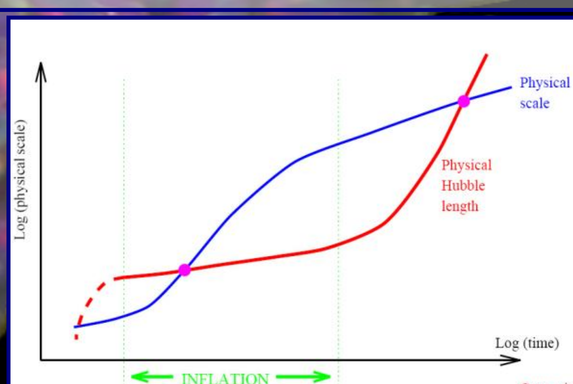
- Primordial Quantum Noise (due to uncertainty principle)
- becomes seeds for structure today
- at inflation the fluct's expanded to superhorizon size

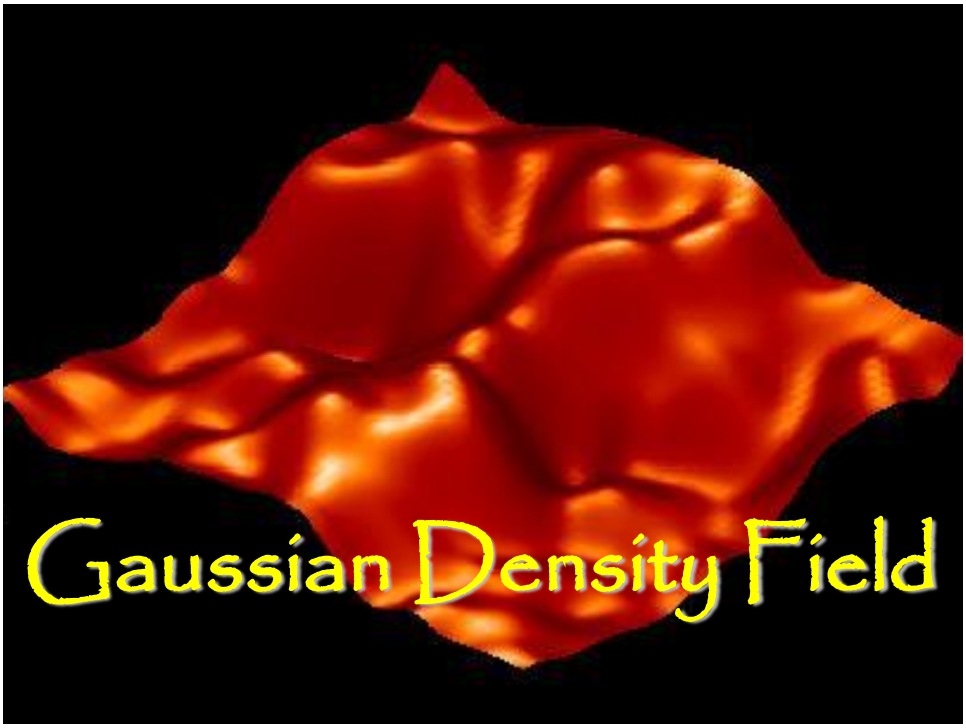
Predictions:

- Gaussian fluctuations
- Adiabatic fluctuations (radiation & matter equally perturbed)
- Near scale-free potential perturbations:

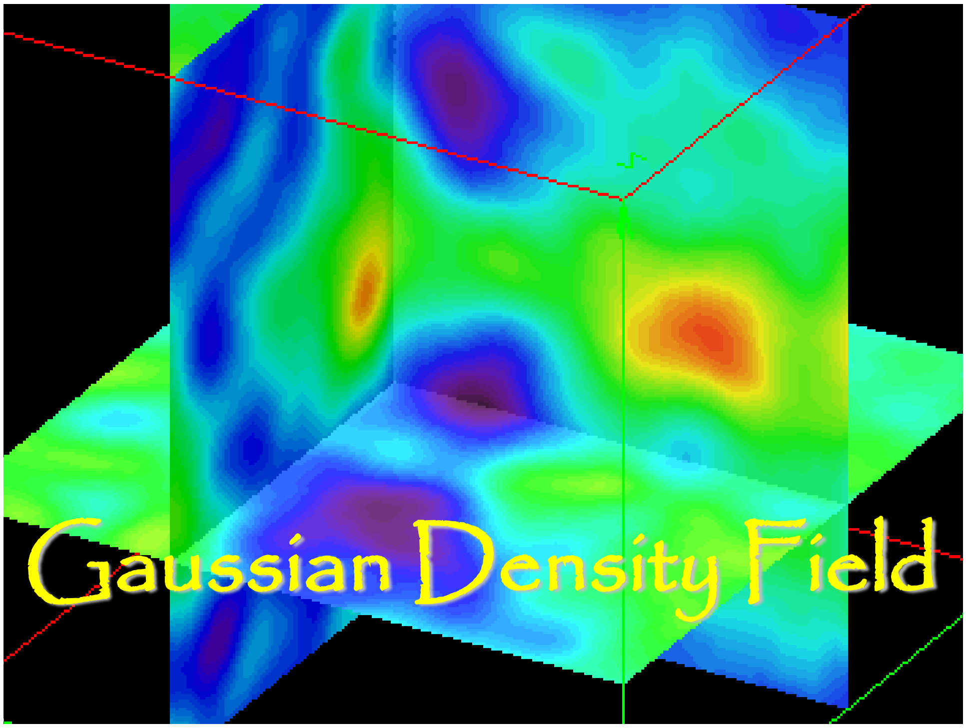
$P(k) \sim k^n$

$n \approx 0.96$




Gaussian Density Field


Gaussian Density Field



Structure Formation:

Power Spectrum

Primordial Perturbation Growth

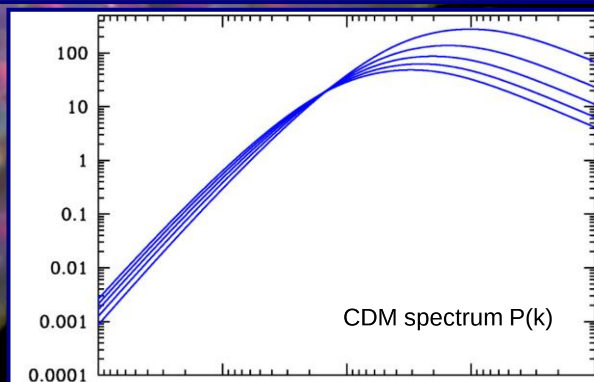
Once fluctuations "entered" the cosmic horizon,
they can start growing ...

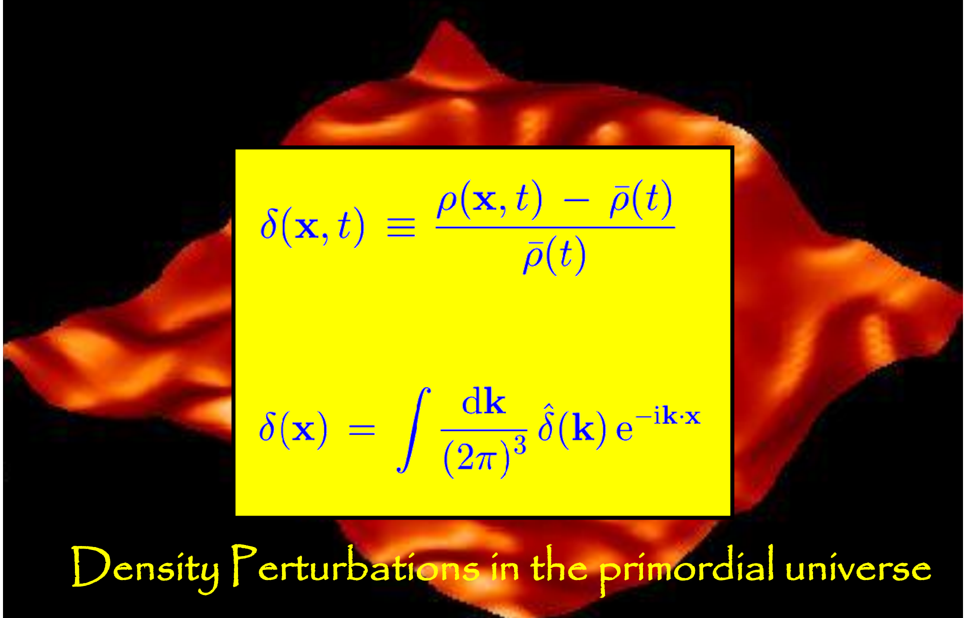
Growth dependent on a series of modulating processes, eg.:

Baryon perturbations
held up by pressure (Jeans!)

Dark Matter:
- starts growth at horizon entrance
- damps below free-streaming:
CDM vs. HDM

Cosmic Expansion regime:
- radiation dominance: no growth DM pert.
- matter dominance





$$\delta(\mathbf{x},t) \equiv \frac{\rho(\mathbf{x},t) - \bar{\rho}(t)}{\bar{\rho}(t)}$$

$$\delta(\mathbf{x}) = \int \frac{\mathrm{d}\mathbf{k}}{(2\pi)^3}\, \hat{\delta}(\mathbf{k})\, \mathrm{e}^{-\mathrm{i}\mathbf{k}\cdot\mathbf{x}}$$

Density Perturbations in the primordial universe

Gaussian Perturbations

$$\mathcal{P}_N = \frac{\exp\left[-\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} f_i\,(\mathsf{M}^{-1})_{ij}\,f_j\right]}{\left[(2\pi)^N\,(\det \mathsf{M})\right]^{1/2}}\prod_{i=1}^{N}\mathrm{d}f_i$$

$$\Uparrow$$

$$M_{ij} \equiv \langle f(\mathbf{x}_i)\,f(\mathbf{x}_j)\rangle = \xi(\mathbf{x}_i - \mathbf{x}_j) = \xi(|\mathbf{x}_i - \mathbf{x}_j|)$$

Gaussian perturbations represent the simplest stochastic field of fluctuations imaginable. It is fully and completely characterized by its second-order moment, the autocorrelation function ξ(r).

In fact, by concentrating on the contributions of the various scales and describing the field in terms of its Fourier components, we directly see that the FUNDAMENTAL function fully characterizing the Gaussian field

Power Spectrum P(k)

$$(2\pi)^3 P(k_1)\,\delta_{\mathrm{D}}(\mathbf{k}_1 - \mathbf{k}_2) = \langle \hat{f}(\mathbf{k}_1)\,\hat{f}^*(\mathbf{k}_2)\rangle$$

Arguably, the power spectrum is the single most important function for our understanding of the cosmic structure formation process.

Power Spectrum

- Direct Characterization of contribution on different scales to inhomogeneous matter distribution
- First direct measure of inhomogeneities in spatial matter distribution
- Along with its Fourier transform, the autocorrelation function ξ(r)
- For Gaussian primordial field, full characterization of density field
- Directly related to potential and velocity perturbations
- Encapsulates all relevant physical processes in early Universe affecting the primordial evolution density/potential/velocity perturbations
- Highly sensitive to constituency of Universe (nature dark matter, etc.)
- This is what the early (inflationary) Universe gives us !!!

Cosmic Power Spectrum

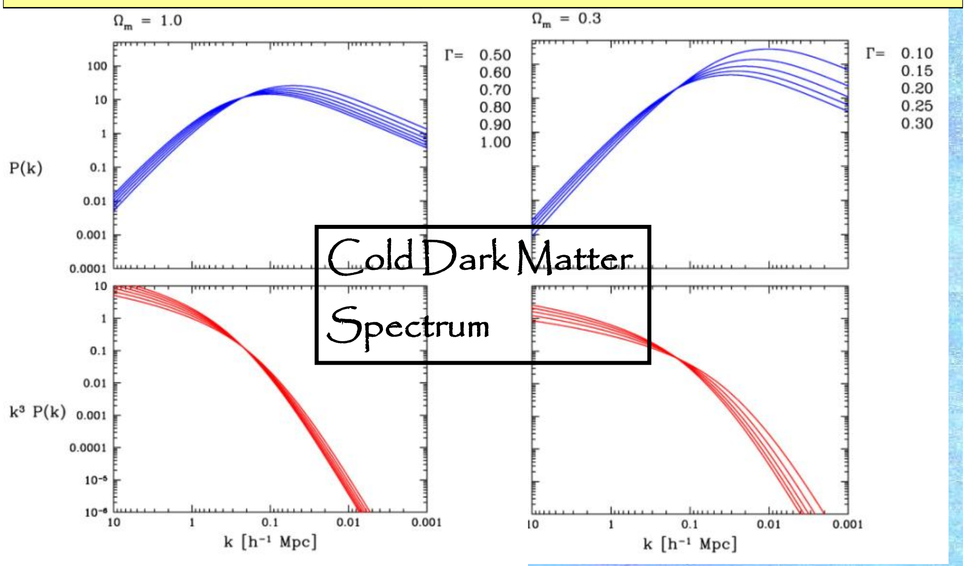
$$P(k) \propto \frac{k^n}{\left[1 + 3.89q + (16.1q)^2 + (5.46q)^3 + (6.71q)^4\right]^{1/2}} \times \frac{\left[\ln(1 + 2.34q)\right]^2}{(2.34q)^2},$$

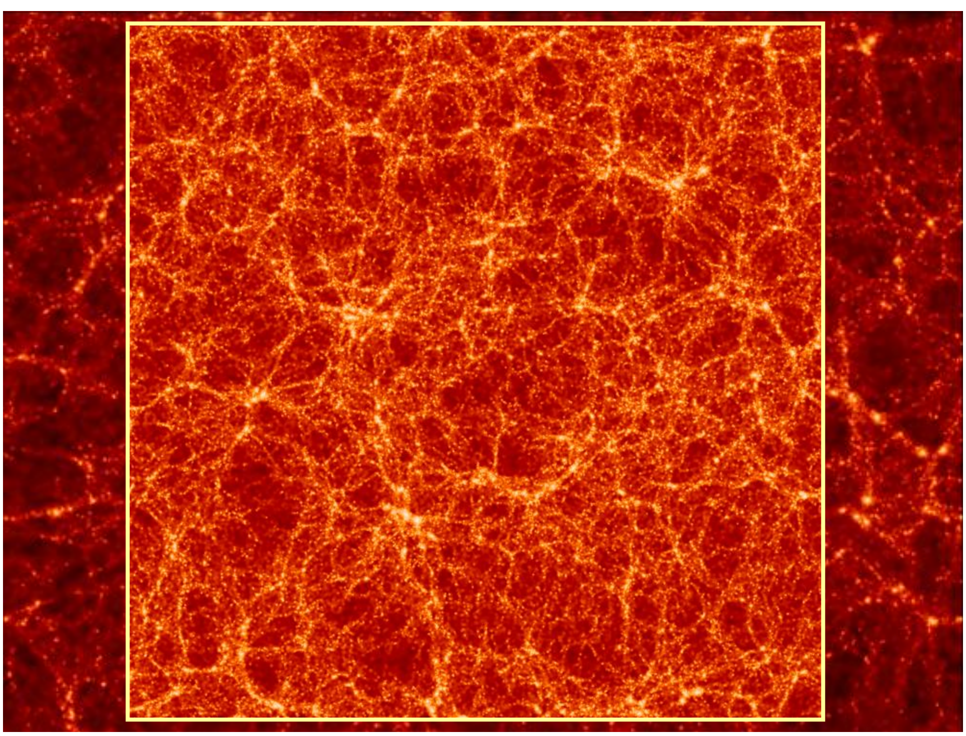
$$q = k/\Gamma$$

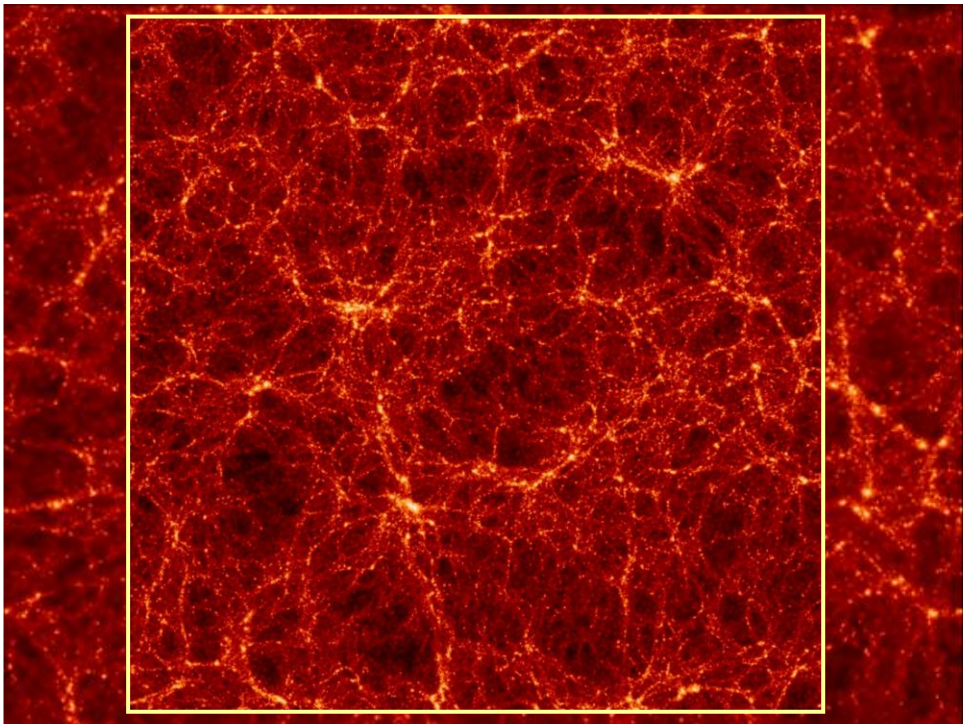
$$\Gamma = \Omega_0 h \, \exp(-\Omega_b - \Omega_b/\Omega_0)$$

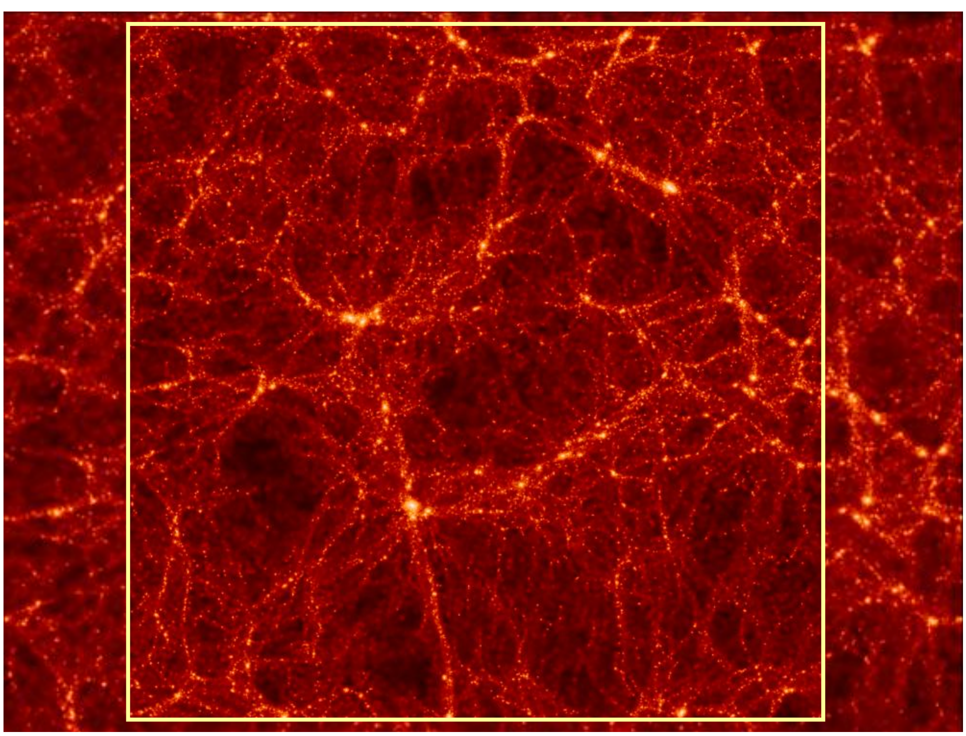
Cold Dark Matter Spectrum

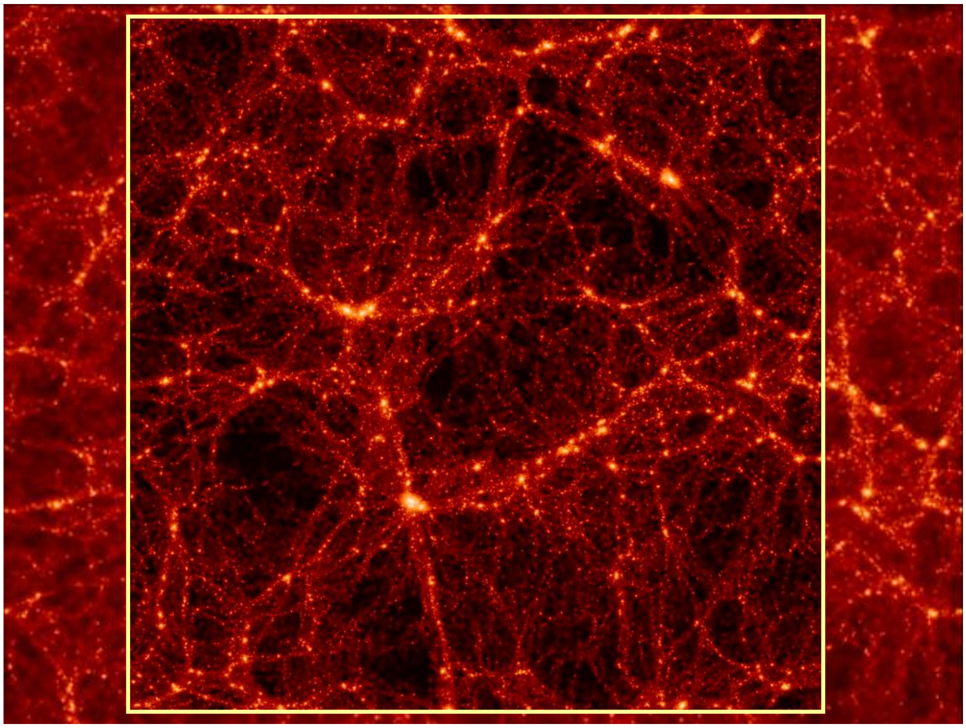
Cosmic Power Spectrum



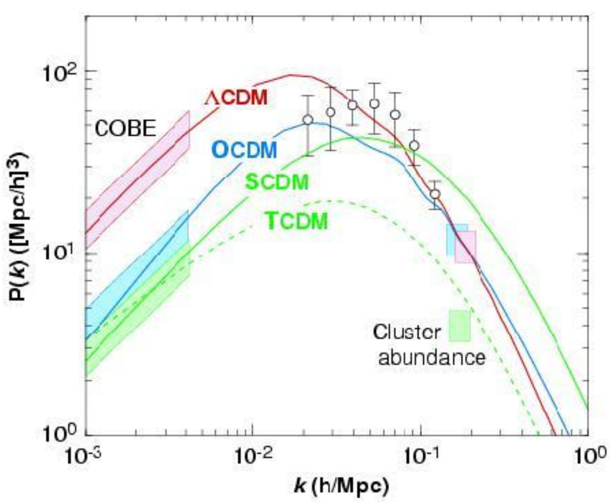




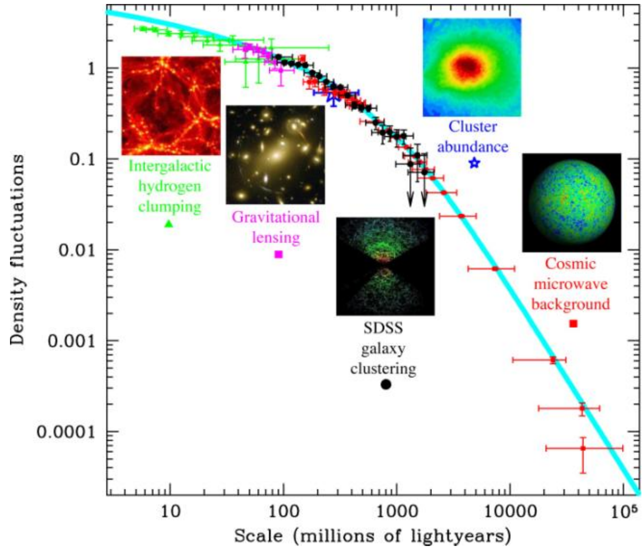




Cosmic Power Spectrum



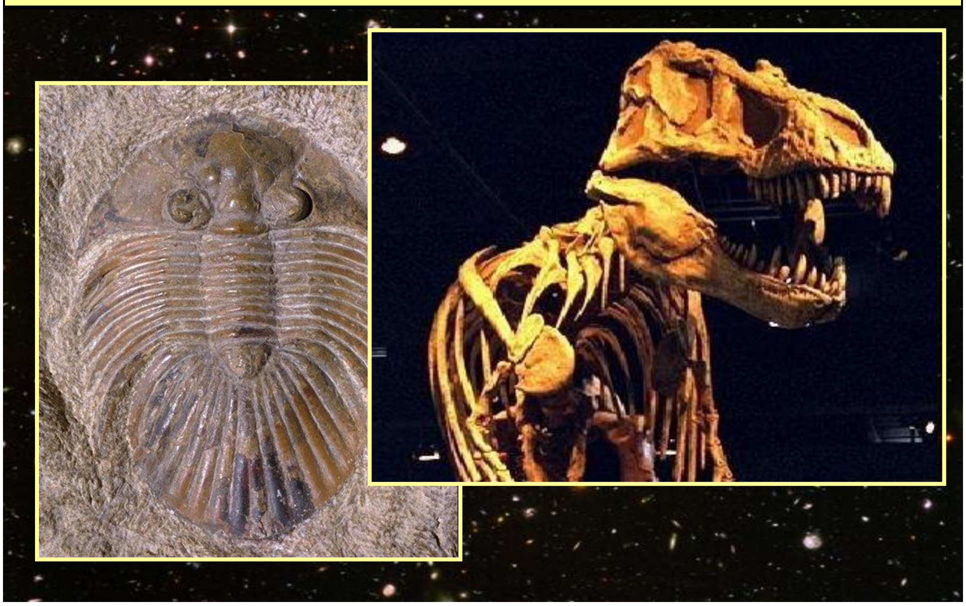
Cosmic Power Spectrum



Cosmic

Fossils

Cosmic Fossils ?



Cosmic Fossils

Which cosmic object contain direct information
on emergence and growth
of structure in the Universe ?

Wanted:

- Structures in youthful evolutionary phase
- Direct link with their initial conditions
- On scales of Megaparsecs, and larger, gravitational collapse only just started

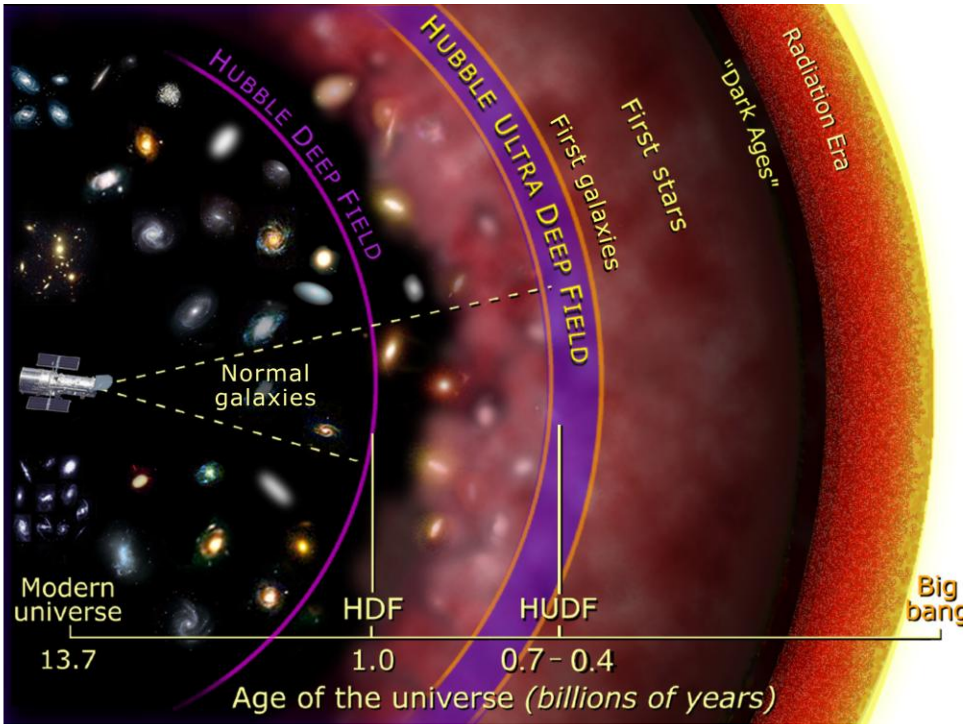
Recall:

- visible (baryonic) matter but a fraction of total energy content Universe

$$\Omega_{rad} \approx 10^{-5}$$

$$\Omega_{matter} \approx 0.3$$

$$\Rightarrow \quad \Omega_{\Lambda} \approx 0.7 \quad \Leftarrow$$



- <u>Primordial Conditions:</u>
  - temperature fluctuations in microwave background radiation
  - polarization Cosmic Microwave Background
  - treasure trove cosmological information
- <u>Dynamics:</u>
  - cosmic velocity flows
  - very difficult in practice, due to large uncertainties in distance estimate/measurements of galaxies, and hence the estimated deviations from Hubble expansion.
- <u>Mass Distribution:</u>
  - gravitational lensing of light by cosmic matter distribution
  - very promising, just started to yield significant results …

- Galaxy Distribution:
  - galaxies supposed to be a fair reflection of underlying cosmic matter distribution
  - most detailed and investigated impression of cosmic matter distribution
    - nonlinear scales: tracing the Cosmic Web
    - Megaparsec linear scales: measuring the Power Spectrum
    - Gigaparsec linear scales: Baryonic Oscillations, Primordial Power Spectrum
    - High redshift galaxies: tracing young Universe, early stages galaxy formation

  But: formation and evolution of galaxies still a notoriously ununderstood problem, so that the relation between matter and galaxy distribution is as yet not unequivocally clear

- Quasars & AGN
  - tracing the large scale matter distribution on scales of hundreds Mpc
  - but: largely unknown how they relate to the matter/galaxy distribution

- Clusters of Galaxies
  - spatial distribution tracer Cosmic Web
  - internal structure dictated by primordial perturbations
  - Hot intracluster gas (10^{7-8} K) - accurate tracer potential cluster
    - easily observable via X-rays

- Gaseous Cosmic Web
  - Baryonic gas traces the Cosmic Web:
    - Lyα forest: neutral hydrogen gas, mostly at high z
    - WHIM: shock-heated gas settled in cosmic web

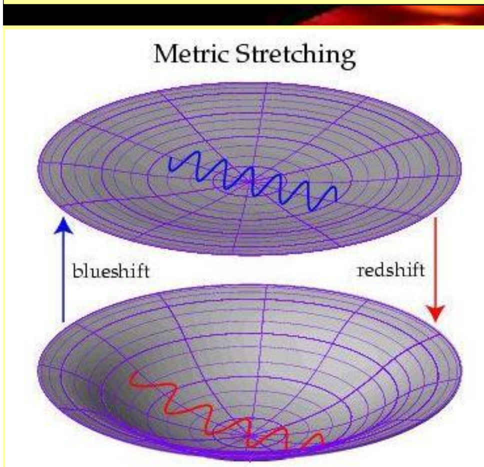
- Distribution & Physical State Gas @ Dark Ages
  - First Stars & Galaxies
  - Reionization of baryonic gas: very sensitive measure cosmology

- Structure of Galaxies
  - Mass distribution galaxies
  - Internal phase-space structure galaxy haloes

Embryonic Structure:

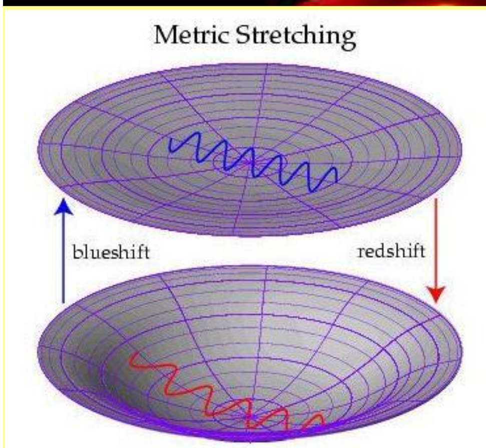
CMB:
Rippling the Photons

CMB Perturbations



- As a result of perturbations in
  Gravitational potential
  photons experience frequency shift
- While travelling through perturbation:
  - Gravitational Redshift +
  - (Relativistic) Time Dilation
- Combined effect:
  Sachs-Wolfe Effect

Sachs-Wolfe Effect



Sachs-Wolfe Effect

$$\frac{\Delta T}{T} \sim \frac{1}{3}\frac{\Delta \Phi}{c^2}$$

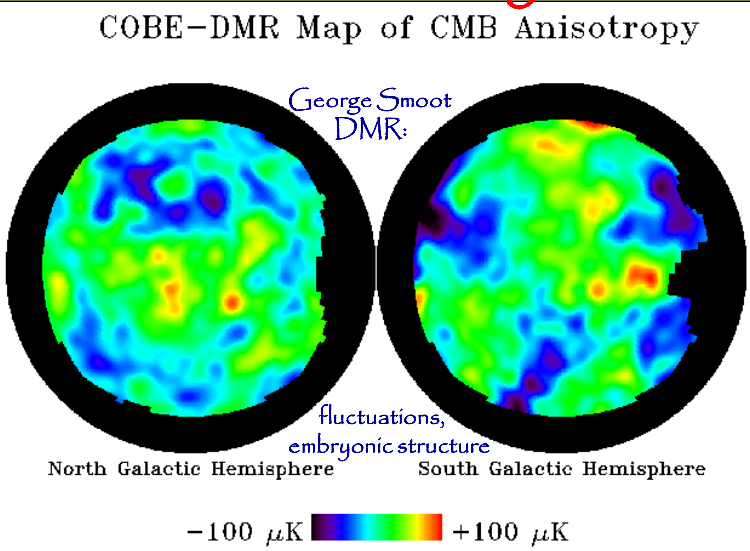
Cosmic Microwave Background

COBE (1992):

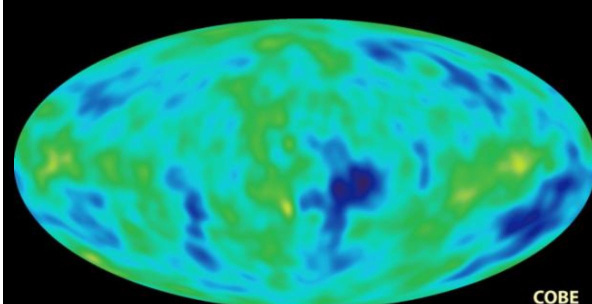
Accurate measurement Planck spectrum CMB

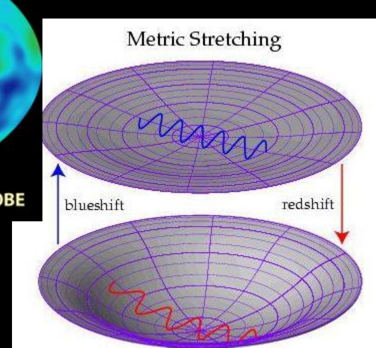
First detection angular temperature perturbations ($\theta \sim 7^o$): Sachs-Wolfe effect

Primordial Anisotropies CMB sky



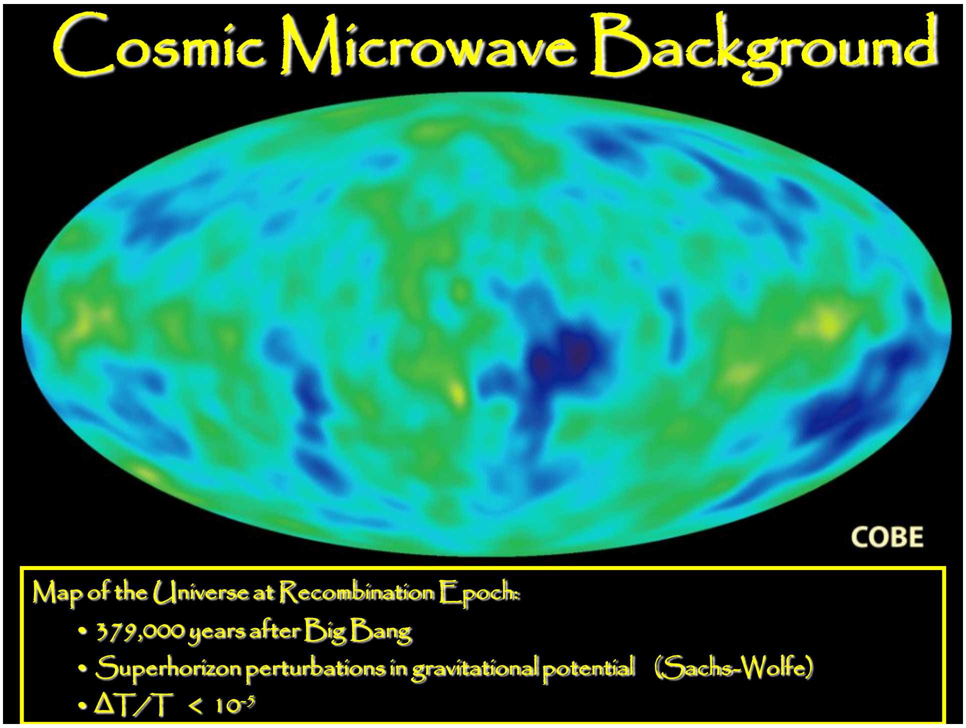
Cosmic Microwave Background





Map of the Universe at Recombination Epoch:

- 379,000 years after Big Bang
- Superhorizon perturbations in gravitational potential (Sachs-Wolfe)
- $\Delta T/T < 10^{-5}$


Cosmic Microwave Background
COBE
Map of the Universe at Recombination Epoch:
• 379,000 years after Big Bang
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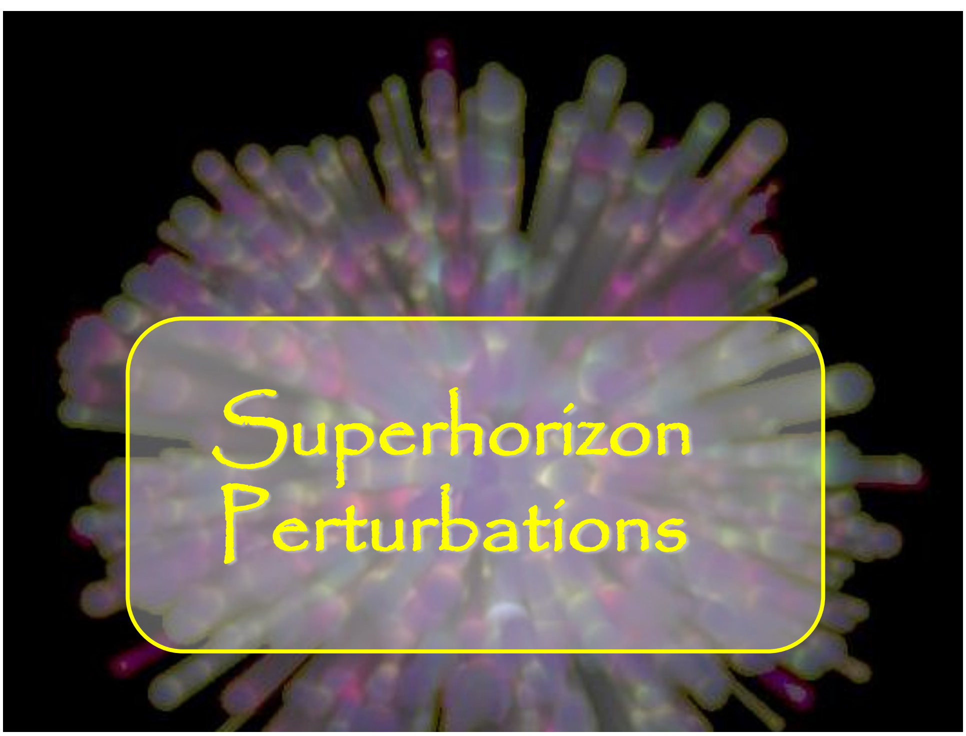
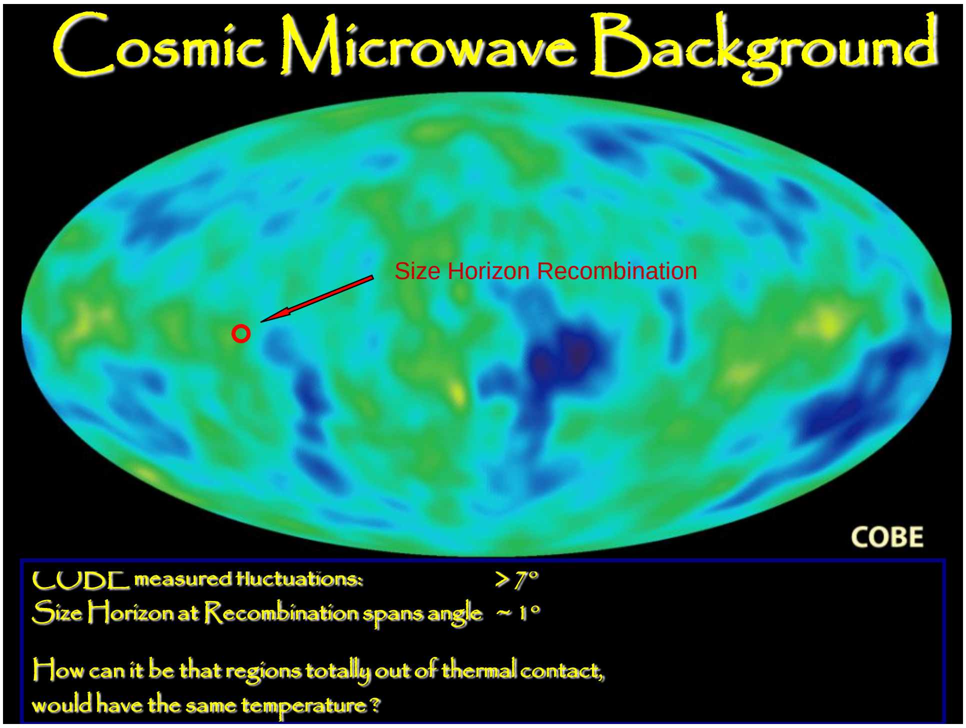
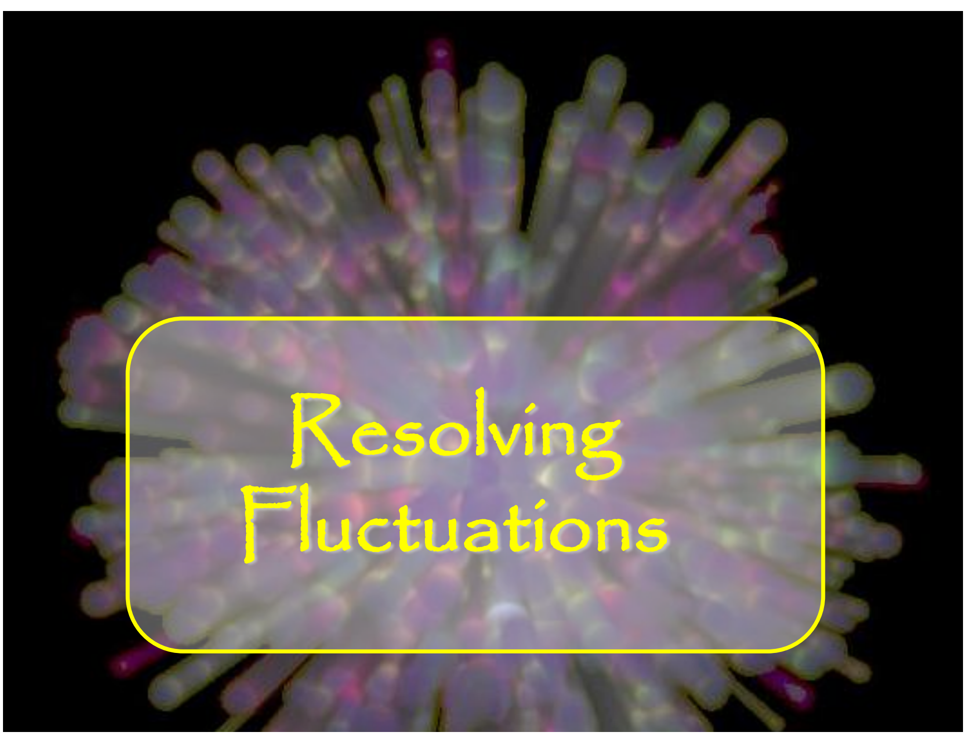
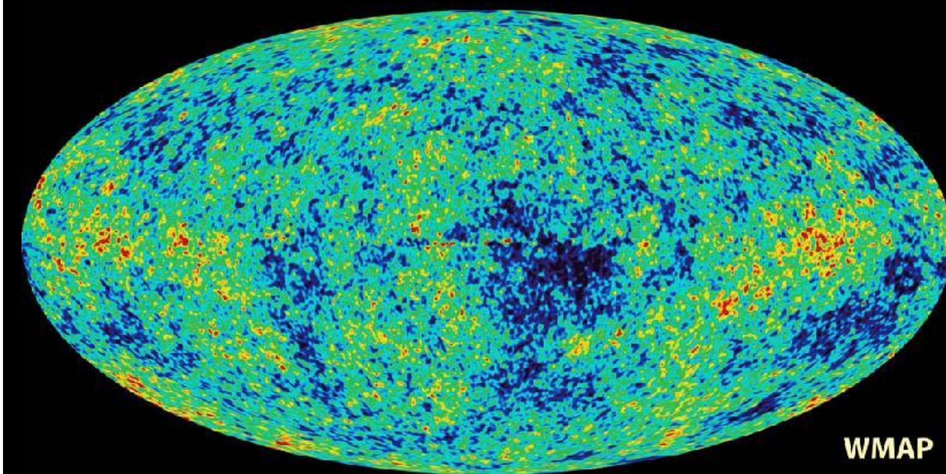
• ΔT/T < 10-5


Superhorizon Perturbations


Cosmic Microwave Background
Size Horizon Recombination
COBE
COBE measured fluctuations: > 7°
Size Horizon at Recombination spans angle ~ 1°
How can it be that regions totally out of thermal contact,
would have the same temperature ?


Resolving Fluctuations

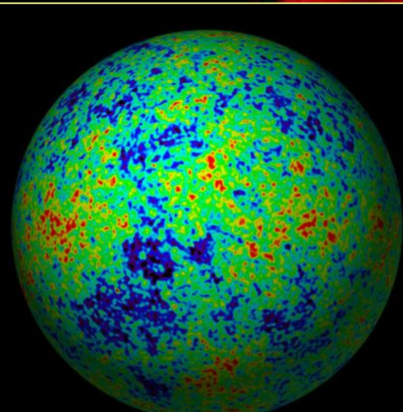
Cosmic Microwave Background



Map of the Universe at Recombination Epoch:

- 379,000 years after Big Bang
- Subhorizon perturbations: primordial sound waves
- $\Delta T/T < 10^{-5}$

Temperature Anisotropies

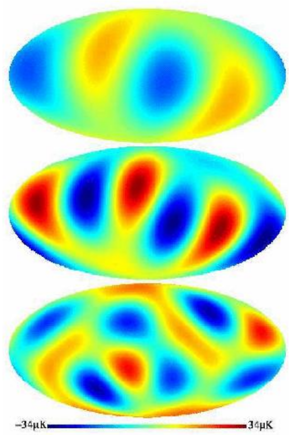


Temperature Perturbations in terms of Spherical Harmonics:

$$T(\theta,\phi) = \sum_{l,m} a_{lm} Y_l^m(\theta,\phi)$$

$$\phi \sim \frac{\pi}{l} \sim \frac{180^\circ}{l}$$

Temperature Anisotropies



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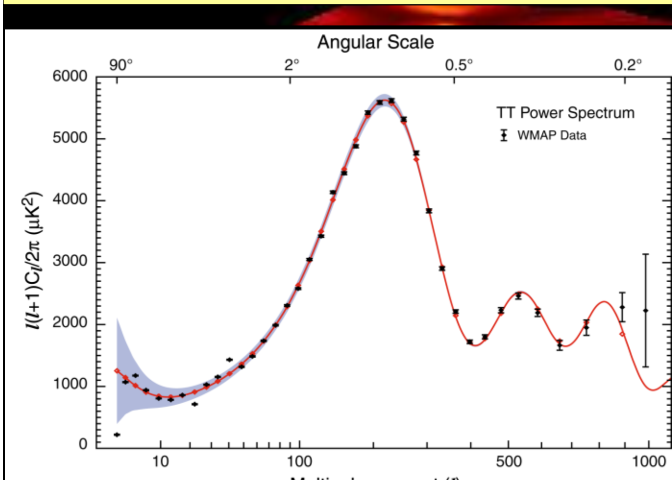
CMB Power Spectrum



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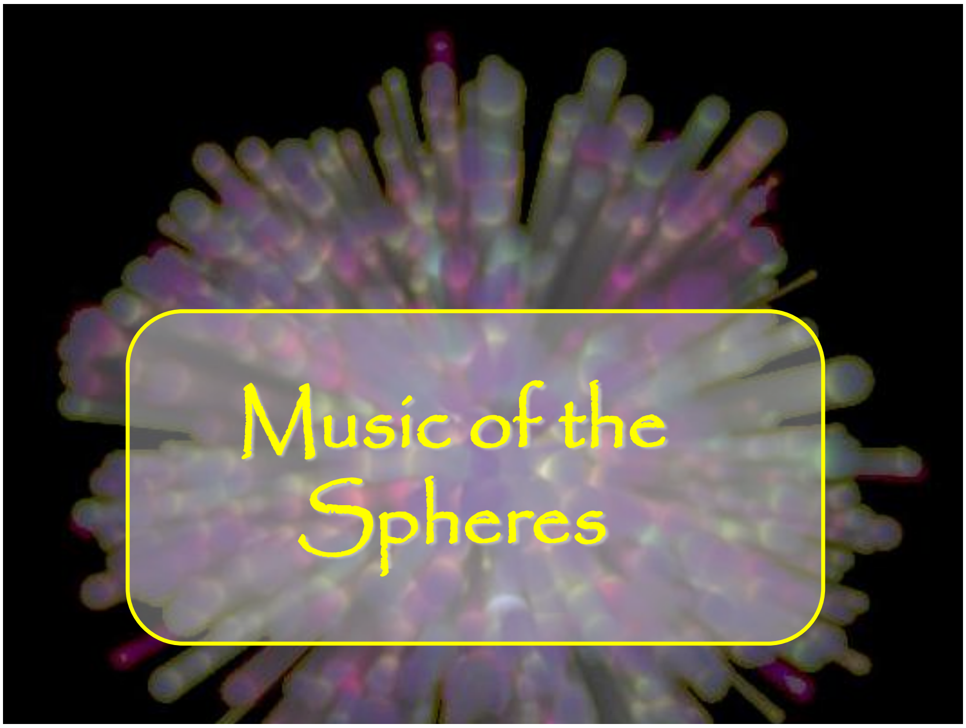
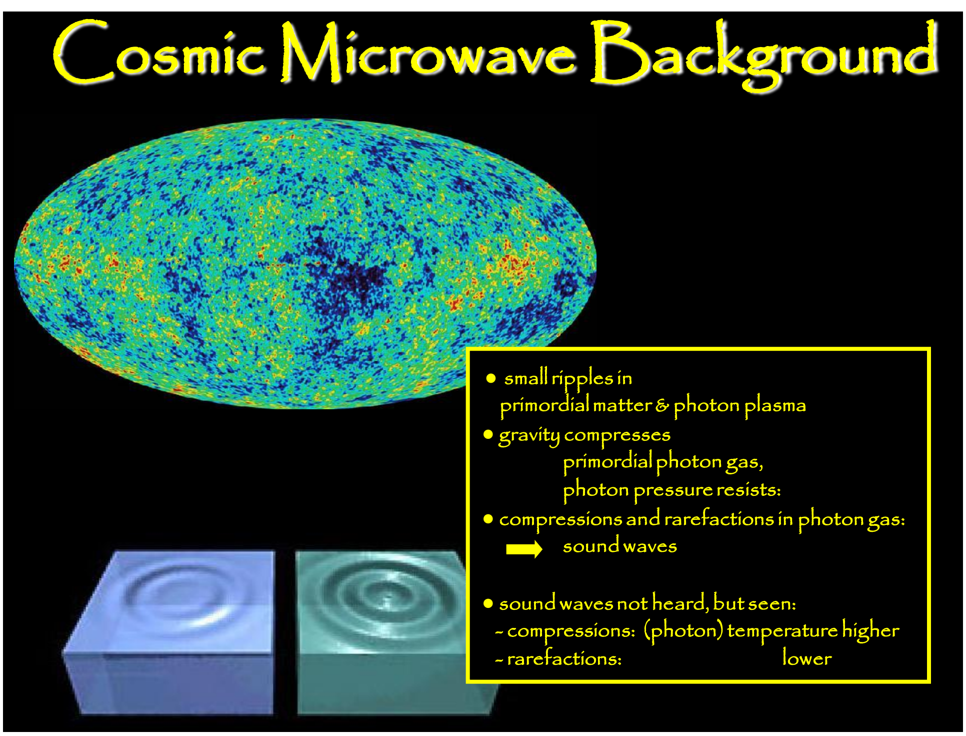

Music of the
Spheres


Cosmic Microwave Background
• small ripples in
primordial matter & photon plasma
• gravity compresses
primordial photon gas,
photon pressure resists:
• compressions and rarefactions in photon gas:
sound waves
• sound waves not heard, but seen:
- compressions: (photon) temperature higher
- rarefactions: lower

Seeing Sound

For graphics & science see website Wayne Hu

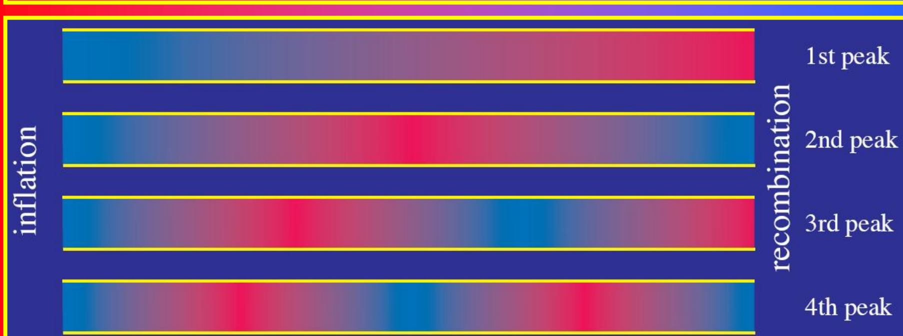
- Colliding electrons, protons and photons forms a plasma
- Acts like a gas
- Compressional disturbance propagates in the plasma through collisions

- Unlike sound in the air:
  - air molecules travel ≈ 10^{-5} cm before colliding
  - in primordial plasma, photons travel 10^{4} pc
- Unlike sound in the air:
  - we do not hear it but see it in the CMB
  - compression heats the gas resulting in a hot spot in the CMB

Piper at the Gates of Dawn

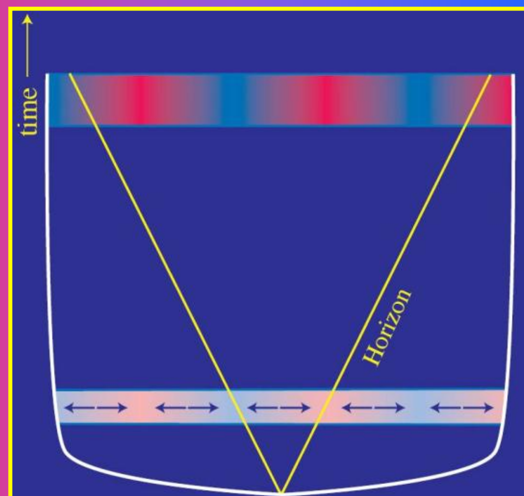
- Like blowing into a flute or an open pipe
- Spectrum of sound contains a

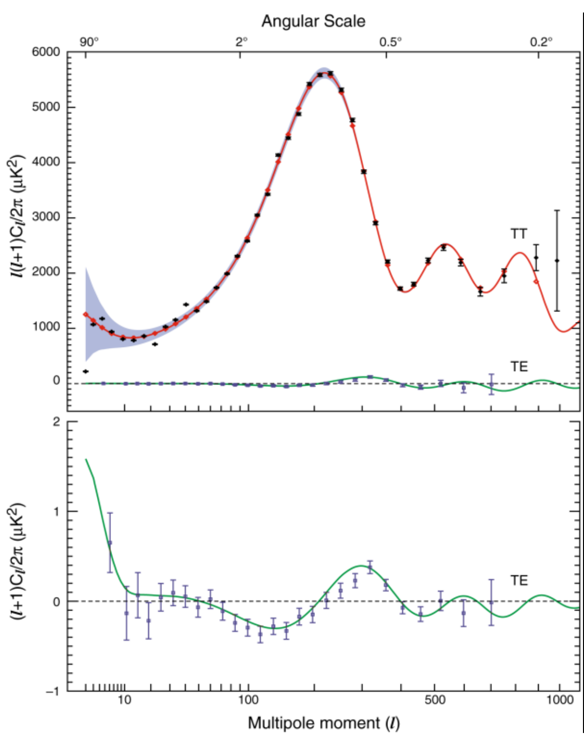
Fundamental frequency & Harmonic overtones



Piper at the Gates of Dawn

- Inflation is the source of sound waves at the beginning of time
- Sound waves are frozen at recombination, yielding a harmonic spectrum of frequencies that reach maximum displacement





CMB

Angular power spectrum

WMAP3

Temperature fluctuations

Temperature-Polarization

$$C_l \propto \langle a_{lm} a^*_{lm} \rangle$$

$$C_l \propto l(l+1)$$

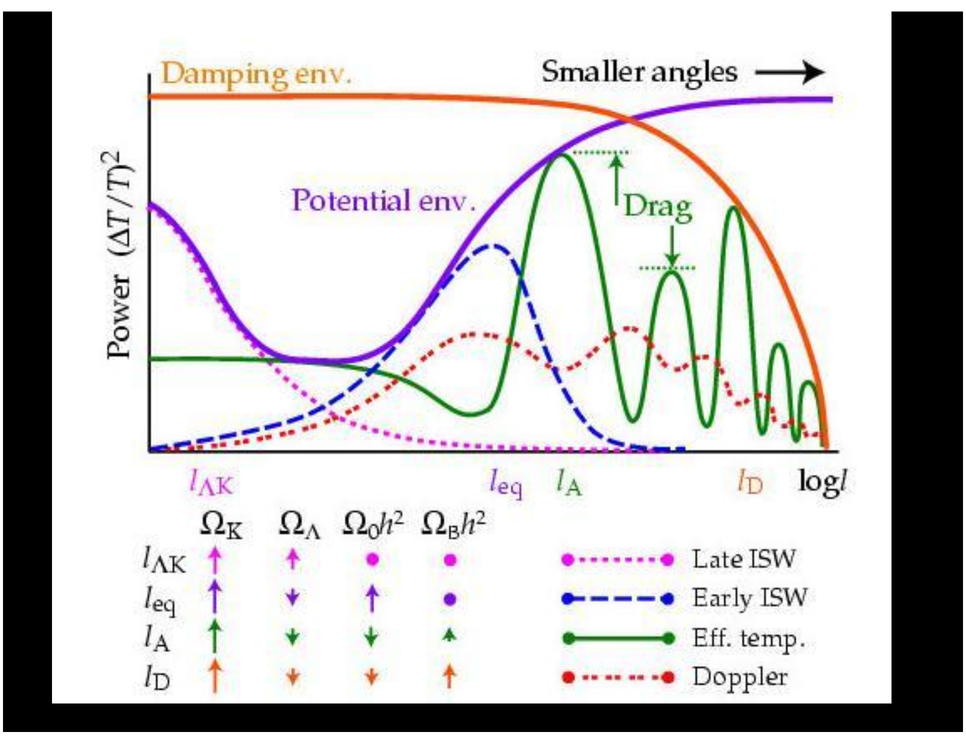
$$P(k) \propto k$$

Harmonic Signature

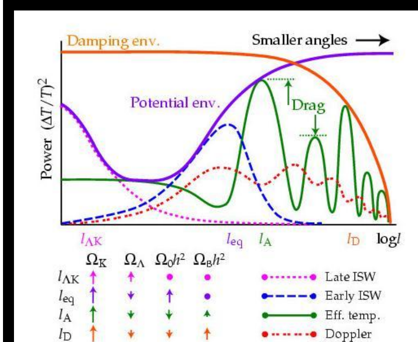
- Identify structure and composition of the Universe
  - through detailed examination of the pattern of overtones on the fundamental frequency
  - much like using them for a music instrument

- Observed frequency spectrum consistent with inflationary origin:
  - spectrum of cosmic sound has harmonics at integer ratios of fundamental

- Without inflation, fluctuations should have been generated at intermediate times
- This would have destroyed the harmonic structure of the peaks (like drilling holes in an organ pipe)



Music of the Spheres



Total Angular CMB Spectrum
modulated by combination of several effects,
the Primary Perturbations

1) Sachs-Wolfe potential fluctuations,
2) Acoustic perturbations
   as the corresponding potential fluct. enter horizon and start to collapse
3) Integrated Sachs-Wolfe potential perturbations:
   - Early ISW: matter/radiation at recomb.
   - Late ISW: expansion influence curvature & cosmological constant
4) Doppler perturbations
   velocity fluct. accompanying potential pert.
5) Silk Damping
   radiation damping of fluctuations

Modulating Influences

- Silk Damping:
  - photons diffuse out of matter perturbations
  - fluctuations with size < photon free-streaming length get suppressed
  - harmonic structure beyond third peak seriously damped

- Integrated Sachs-Wolfe effect:
  - damping/boosting temperature fluctuations due to decay/growth potential perturbations:
    * Early ISW: while still radiation-dominated, potential DM fluct's grow less, suppression of temp. fluct.
    * Late ISW: as Dark Energy takes over universe, potential wells decay (due to accelerated expansion)

The Cosmic Web:

Patterns Across the Universe

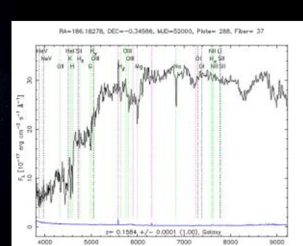
A Universe of Galaxies

Used as point tracers of underlying cosmic density field.

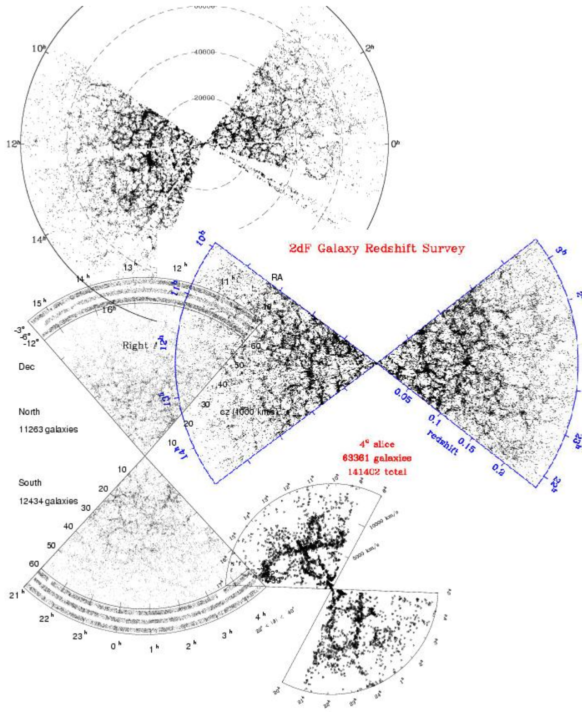
Intention is to map this cosmic matter field on Megaparsec scales.

"LSS" still reflects conditions primordial Universe:

Cosmic Fossil



galaxy spectrum: redshift-distance



Over the past two decades we have witnessed a paradigm shift in our perception of the Megaparsec scale structure in the Universe. As increasing elaborate galaxy redshift surveys charted ever larger regions in the nearby Universe, an intriguingly complex and salient foamlike network came to unfold and establish itself as the quintessential characteristic of the cosmic matter and galaxy distribution.

In a great many physical systems, the spatial organization of matter is one of the most readily observable manifestations of the forces and processes forming and moulding them. Richly structured morphologies are usually the consequence of the complex and nonlinear collective action of basic physical processes.

The vast Megaparsec cosmic web is undoubtedly one of the most striking examples of complex geometric patterns found in nature. In its own right, the vast dimensions and intricate composition of the cosmic foam make it one of the most imposing and intriguing patterns existing in the Universe. Its wide-ranging Importance stems from its status as a cosmic fossil. On a scale of tens up to a few hundred Megaparsecs It is still relatively straightforward to relate the configuration at the present cosmic epoch to that of the primordial matter distribution from which it emerged. With the cosmic foam seemingly representing this phase, it assumes a fundamental role in the quest for understanding the origin of all structures in the Universe.

While its complex cellular morphology involves one of the most outstanding and evident aspects of the Cosmic foam, it has also remained one defying simple definitions which may be the cause of it having Remained one of the least addressed aspects. The geometry of the cosmic foam may be described as a nontrivial stochastic assembly of various anisotropic and asymmetric elements. A major deficiency in the vast majority of studies on the large scale distribution of galaxies has been the lack of suitable quantitative and statistical characterizations of the truly fundamental aspects of the comsic foam geometry.

The Cosmic Web

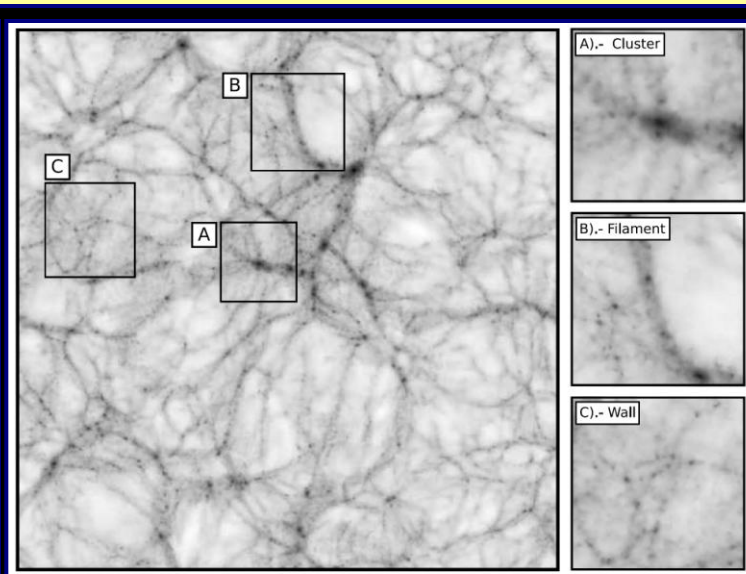
Stochastic Spatial Pattern of

- Clusters,
- Filaments &
- Walls

around

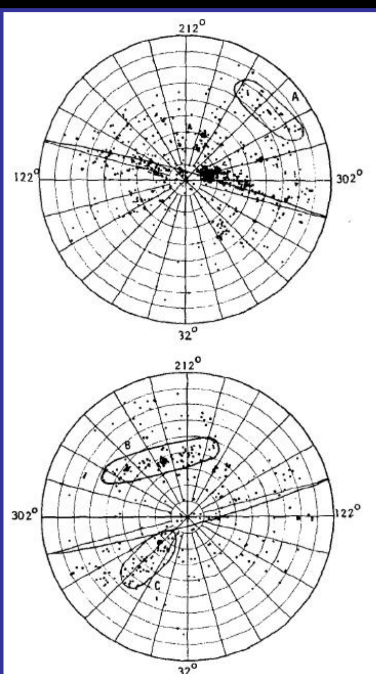
- Voids

in which matter, (DM, gas, gal's) has agglomerated



The Cosmic Web: A Census

Sky Maps:
world all around us



Early Views

Shapley-Ames catalog (1932) of nearby galaxies:

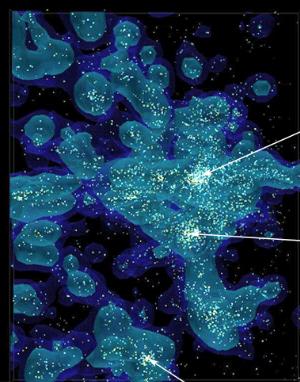
All-sky survey of galaxies to m=18.3

$\delta > -23^o$

- numerous concentrations:
  groups and clusters (incl. Virgo cluster)
- asymmetry between north and south:
  many more galaxies on northern sky
- conspicuous concentration along a line running through richest nearby cluster, the Virgo cluster:
- The Supergalactic Plane
  (first identified by de Vaucouleurs:
  the plane of our own Local Supercluster)

The Local Supercluster

End-on View of the Local Supercluster:



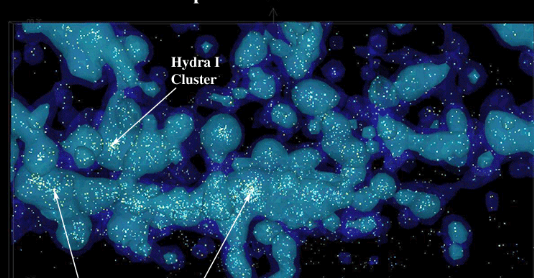
Courtesy: B. Tully

Our Local Group finds itself located at the outer region of a large supercluster region,

- the "Local Supercluster",
- a large flattened mass concentration ~ 10 h^{-1} Mpc in size,
- centered on one rich cluster, the Virgo cluster

The Local Supercluster

Polar View of Local Supercluster:

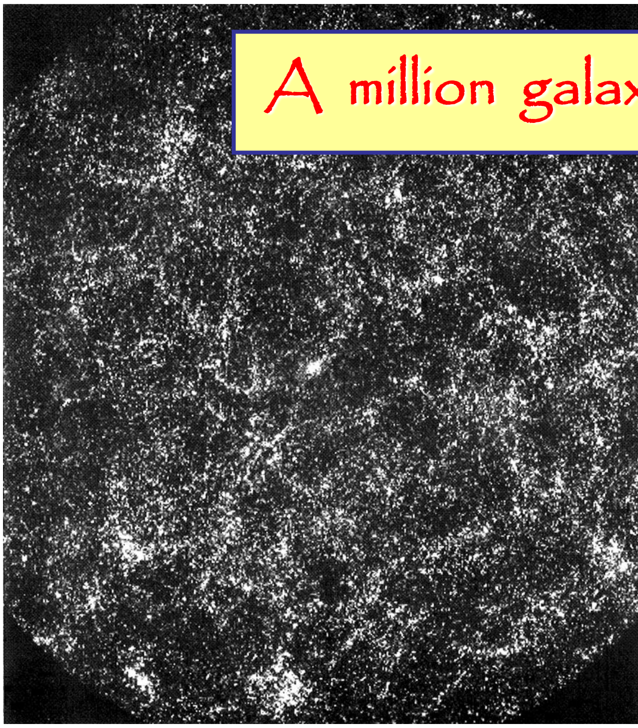


Courtesy: B. Tully

Our Local Group finds itself located at the outer region of a large supercluster region,

- the "Local Supercluster",
- a large flattened mass concentration ~ 10 h^{-1} Mpc in size,
- centered on one rich cluster, the Virgo cluster

A million galaxies



Shane-Wirtanen map:

On the basis of the Shane-Wirtanen counts, P.J.E. Peebles produced a map of the sky distribution of 1 million galaxies on the sky:

- Clearly visible are clusters
- hint of filamentary LSS features, embedding clusters

APM survey

- Sky map:

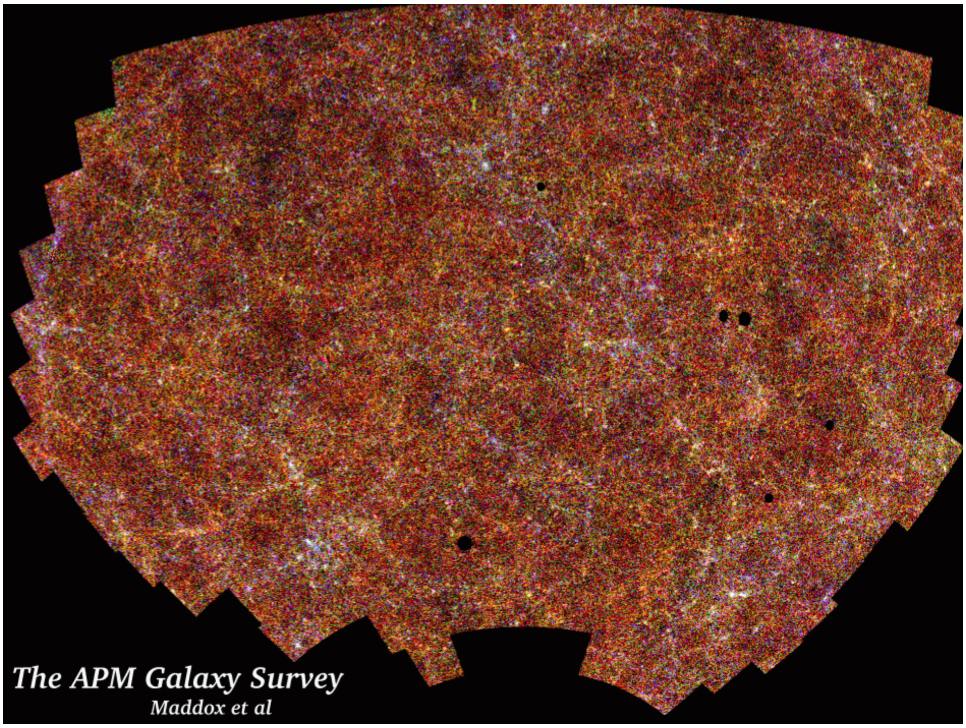
  2×10^6 galaxies

  $17 < m < 20.5$
- Uniformly defined
- Sky region: 4300 sq. deg.

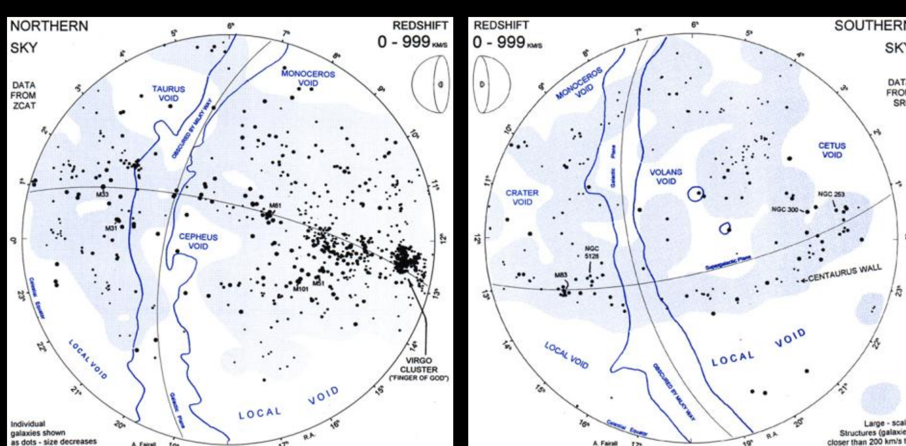
  185 UK Schmidt plates, $6^\circ \times 6^\circ$

- Large inhomogeneities, hints of weblike patterns, with clusters at densest regions.

courtesy: S. Maddox, G. Efstathiou, W. Sutherland, D. Loveday

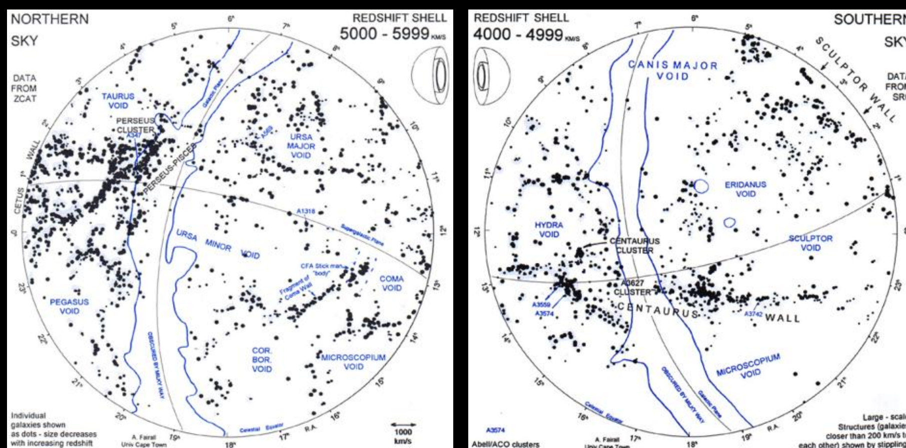


Local Views



Tony Fairall's nearby LSS map: Local Supercluster clearly visible at $v < 999$ km/s

Local Views: Moving into Foam

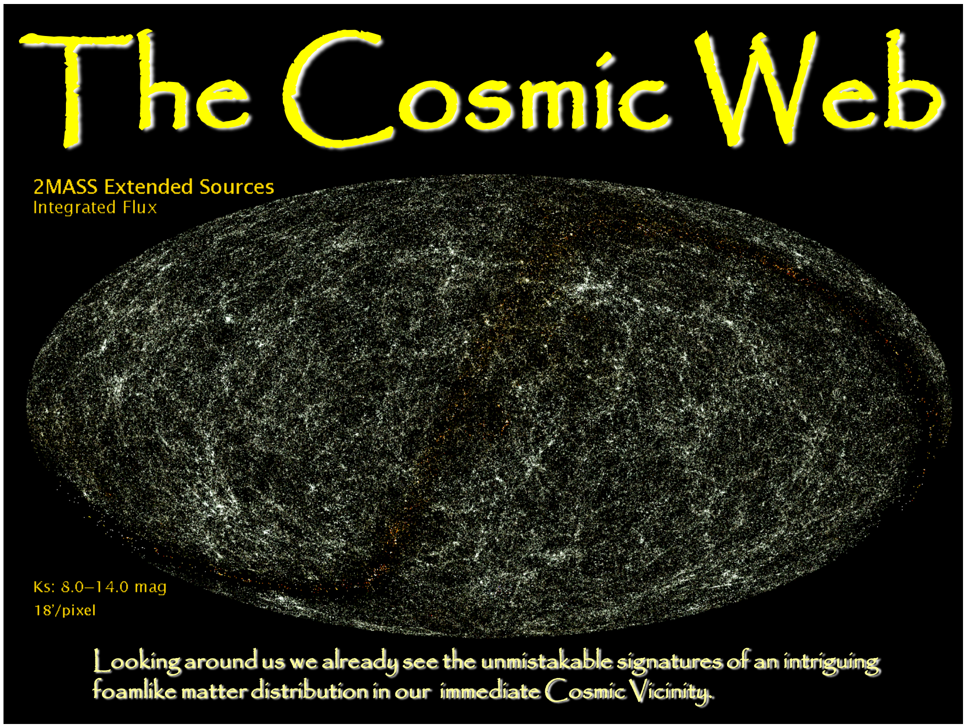


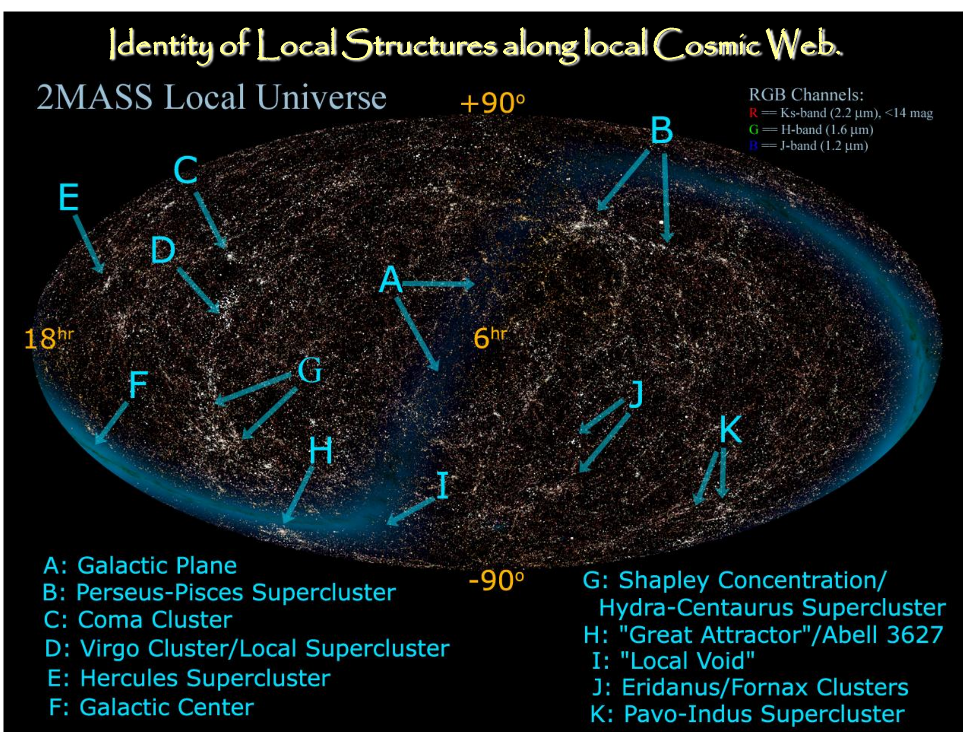
Tony Fairall's nearby LSS map: at cz=5000-5999 km/s clear views of local cosmic web

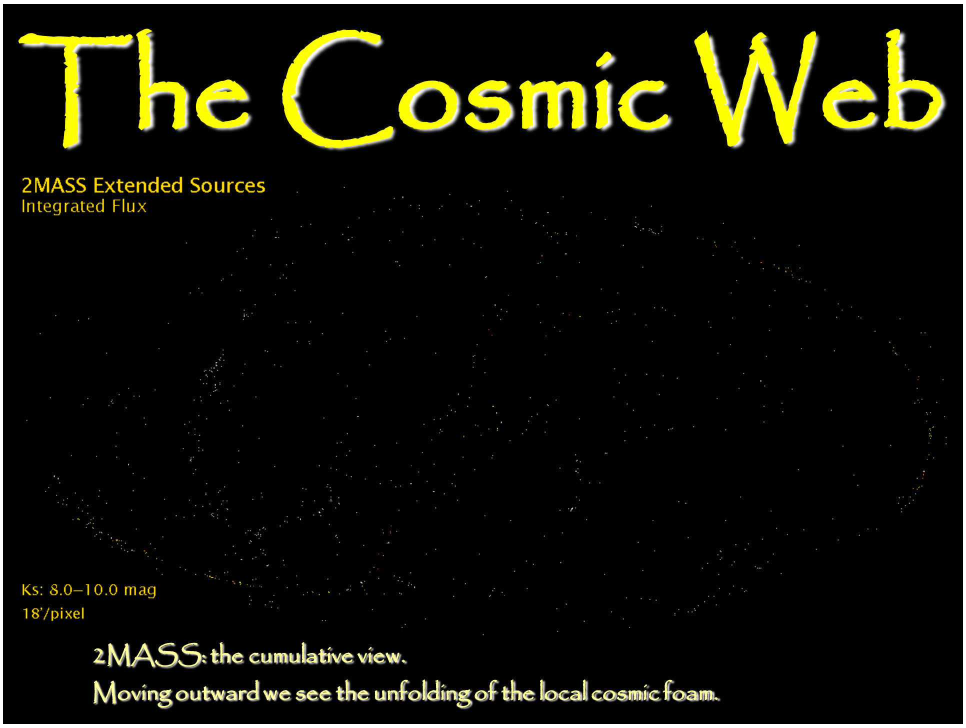
2MASS survey

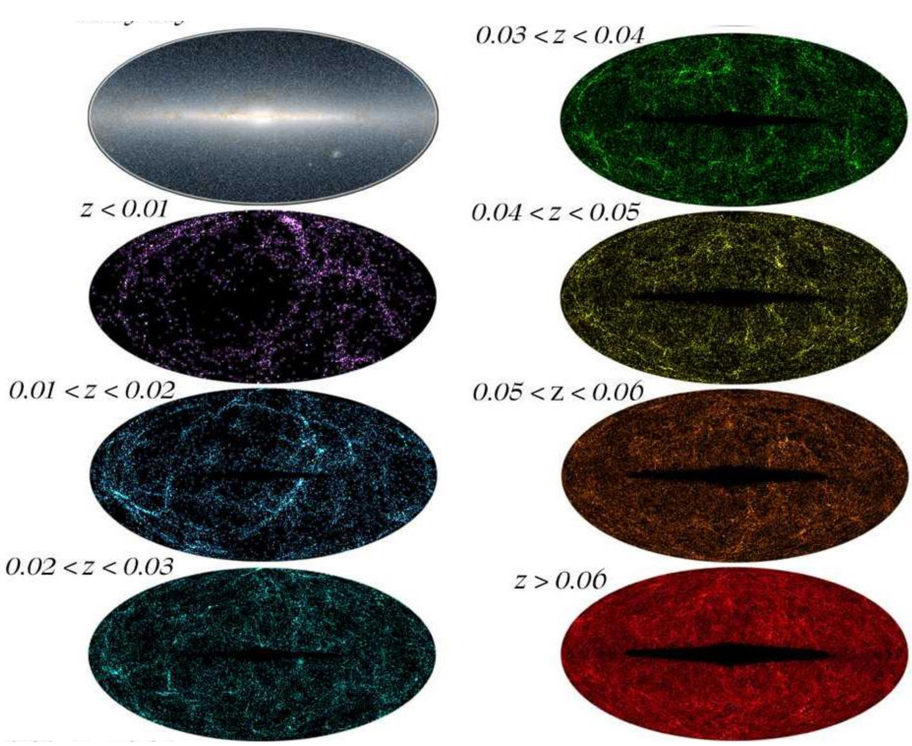
- 2MASS all-sky survey:
  ground-based near-infrared survey whole sky,
  J(1.2 μm), H(1.6 μm), K(2.2 μm)
- 2MASS extended source catalog (XSC):
  1.5 million galaxies
- unbiased sample nearby galaxies
- photometric redshifts: depth in 2MASS maps,
  "cosmic web" of (nearby) superclusters spanning the entire sky.

courtesy: T. Jarrett

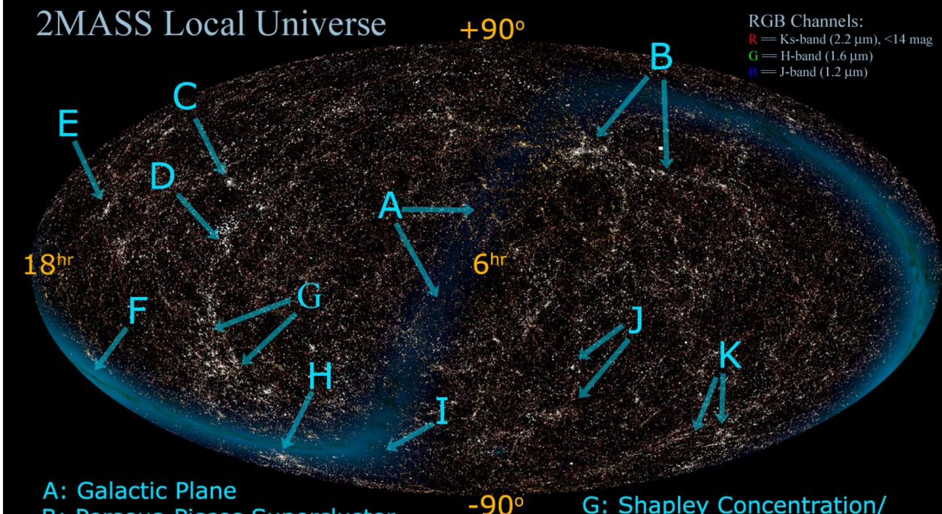

The Cosmic Web
2MASS Extended Sources
Integrated Flux
Ks: 8.0–14.0 mag
18′/pixel
Looking around us we already see the unmistakable signatures of an intriguing foamlike matter distribution in our immediate Cosmic Vicinity.


Identity of Local Structures along local Cosmic Web.
2MASS Local Universe
+90°
-90°
18hr
6hr
RGB Channels:
R == Ks-band (2.2 µm), <14 mag
G == H-band (1.6 µm)
B == J-band (1.2 µm)
A B C D E F G H I J K
A: Galactic Plane
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster
E: Hercules Supercluster
F: Galactic Center
G: Shapley Concentration/ Hydra-Centaurus Supercluster
H: "Great Attractor"/Abell 3627
I: "Local Void"
J: Eridanus/Fornax Clusters
K: Pavo-Indus Supercluster


The Cosmic Web
2MASS Extended Sources
Integrated Flux
Ks: 8.0–10.0 mag
18'/pixel
2MASS: the cumulative view.
Moving outward we see the unfolding of the local cosmic foam.


z < 0.01
0.01 < z < 0.02
0.02 < z < 0.03
0.03 < z < 0.04
0.04 < z < 0.05
0.05 < z < 0.06
z > 0.06

Identity of Local Structures along local Cosmic Web.



A: Galactic Plane
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster
E: Hercules Supercluster
F: Galactic Center
G: Shapley Concentration/ Hydra-Centaurus Supercluster
H: "Great Attractor"/Abell 3627
I: "Local Void"
J: Eridanus/Fornax Clusters
K: Pavo-Indus Supercluster

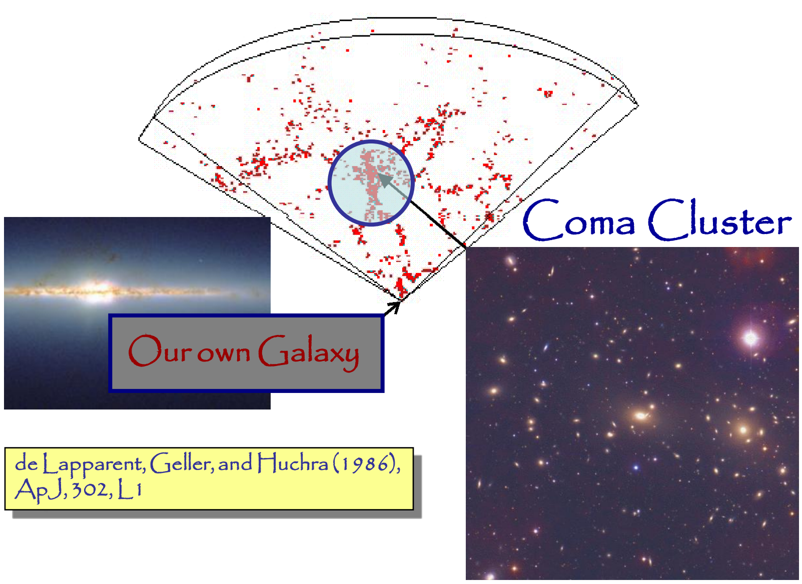
Maps of the Local Universe

The Cosmic Web Revealed:

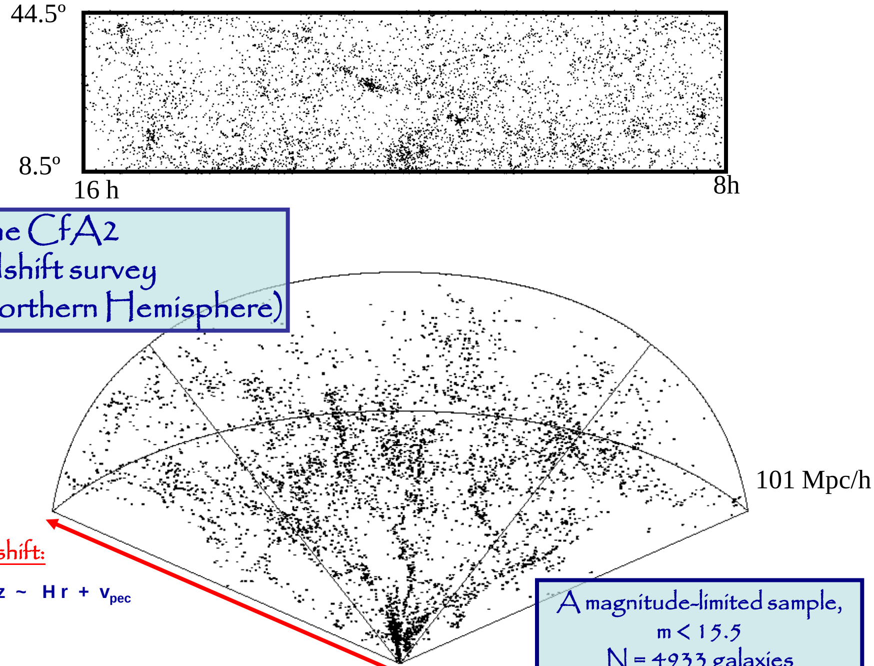
The CfA2 and SDSS survey slices

(de Lapparent, Geller, Huchra, … 1986, …)

Mapping the Universe



de Lapparent, Geller, and Huchra (1986), ApJ, 302, L1



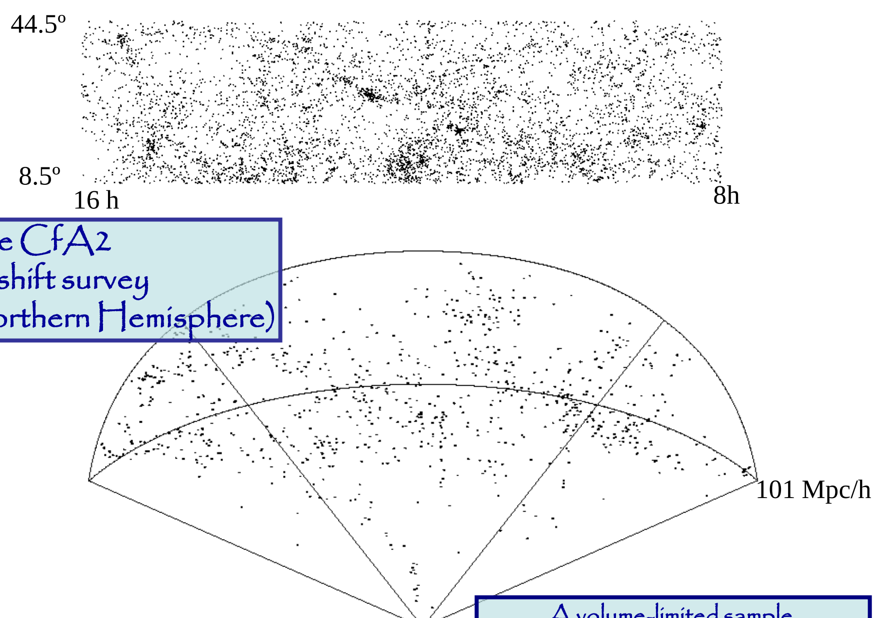
The CfA2
redshift survey
(Northern Hemisphere)

Redshift:

$v = cz \sim Hr + v_{pec}$

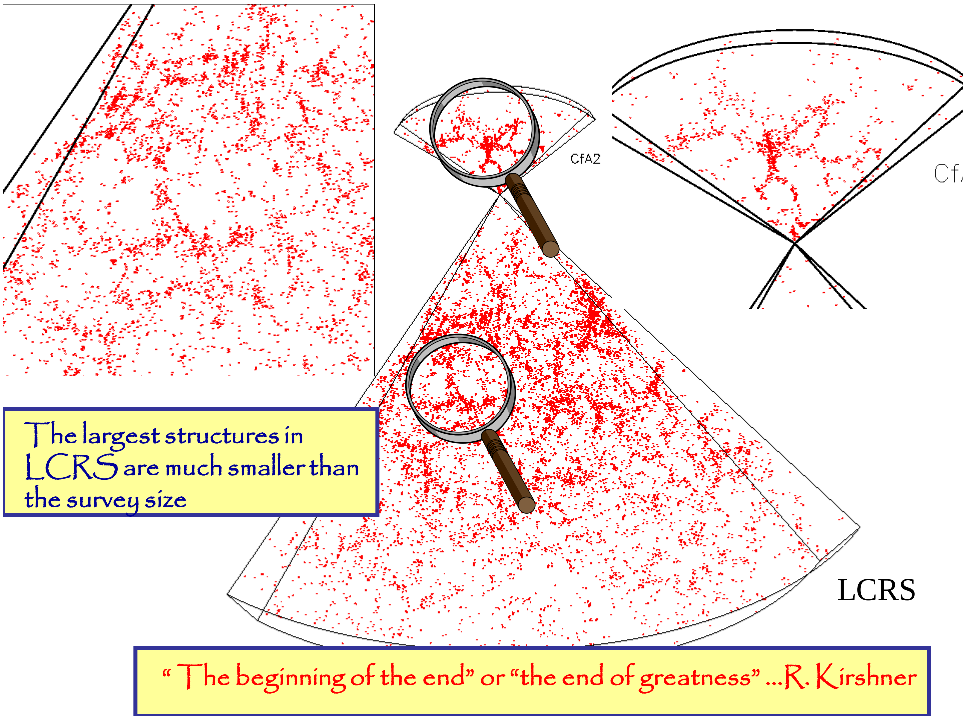
A magnitude-limited sample,
$m < 15.5$
N = 4933 galaxies

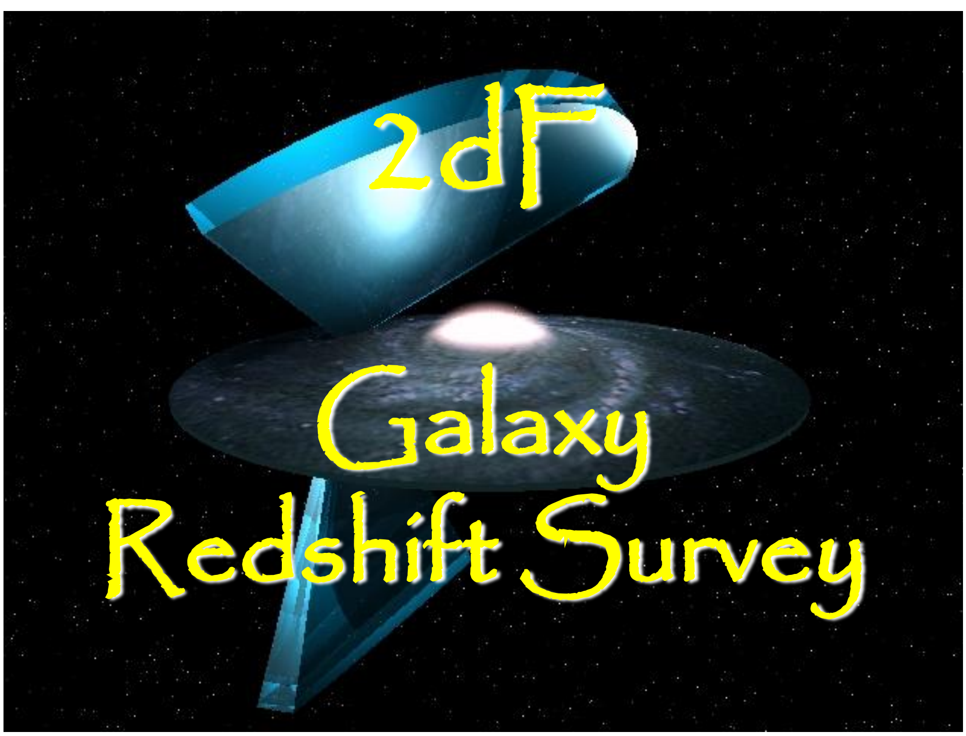
Figure courtesy: V. Martinez

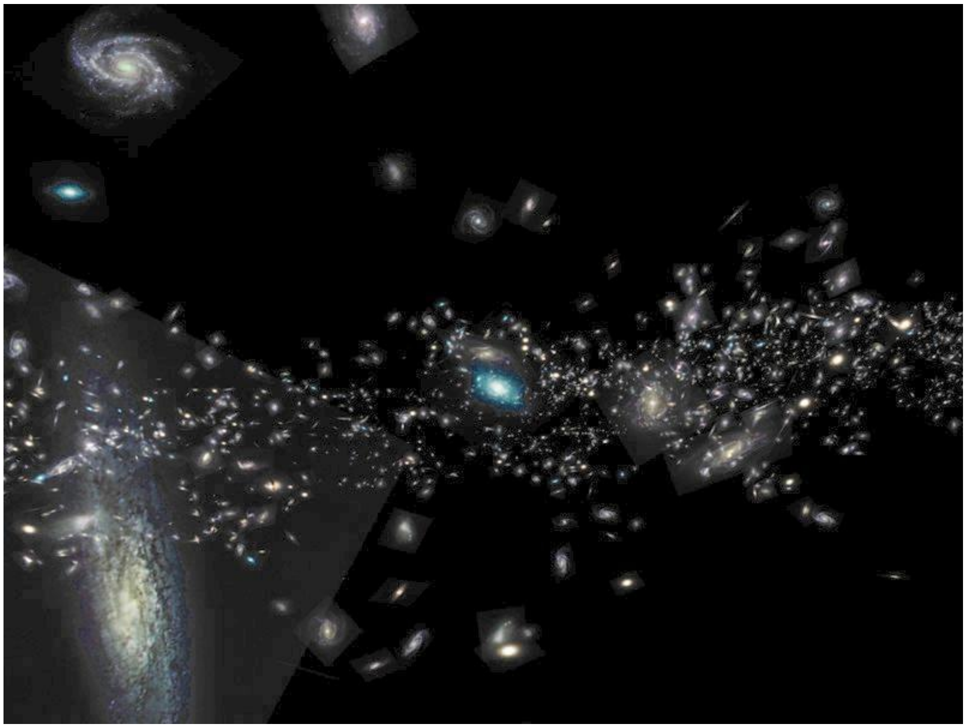


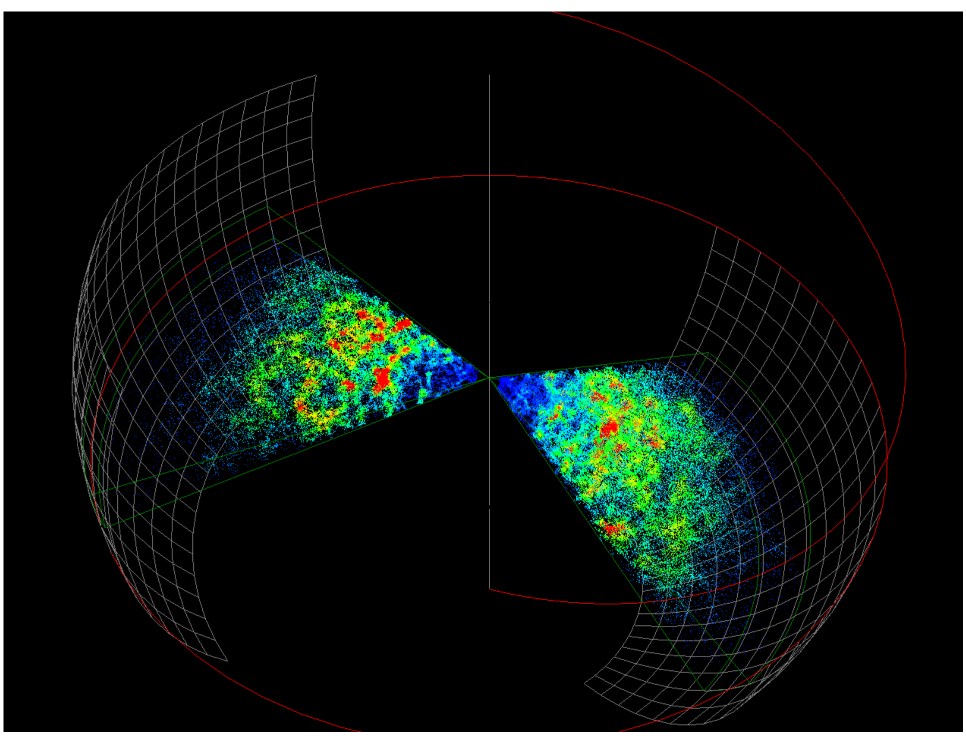
The CfA2
redshift survey
(Northern Hemisphere)

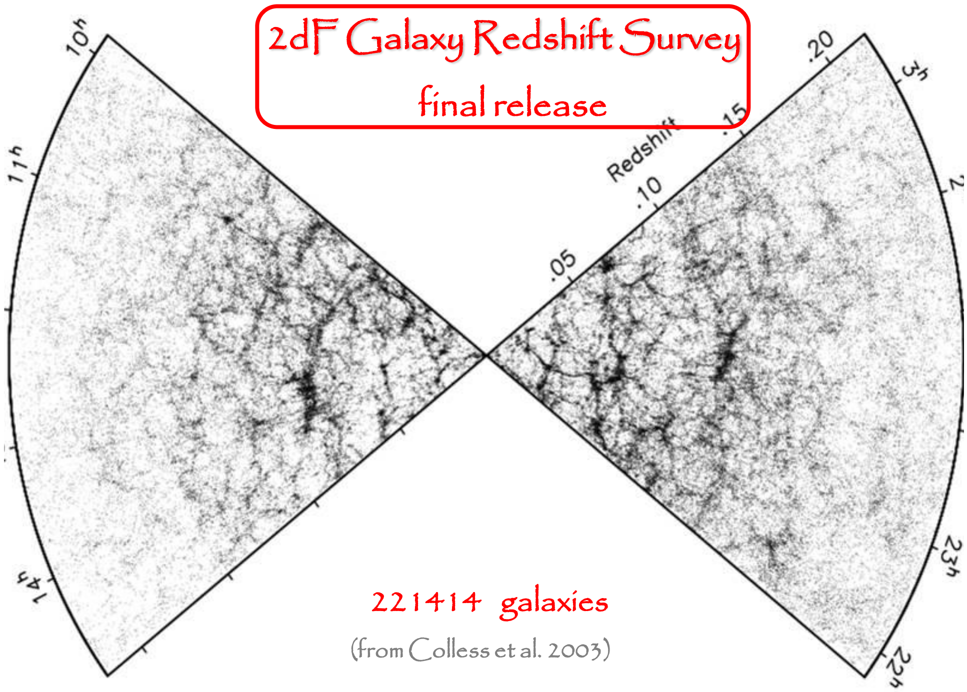
A volume-limited sample,
$M < 15.5 - 5\log(D(z)) - 25 - Kz$
N = 905 galaxies

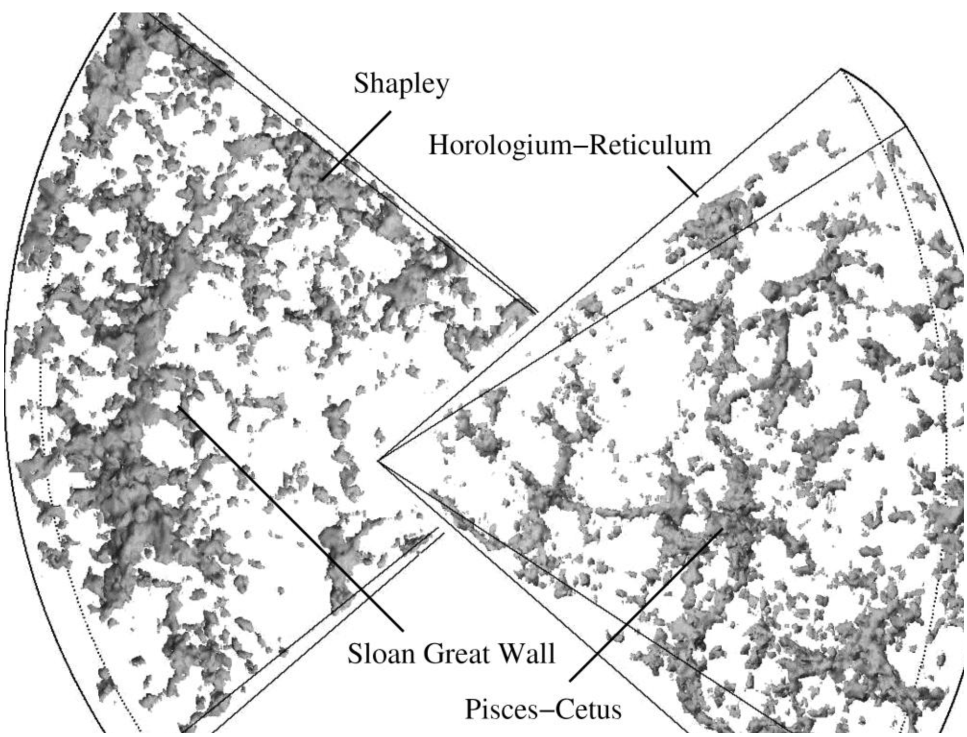

CfA2
Cf
LCRS
The largest structures in LCRS are much smaller than the survey size
" The beginning of the end" or "the end of greatness" ...R. Kirshner


2dF
Galaxy
Redshift Survey





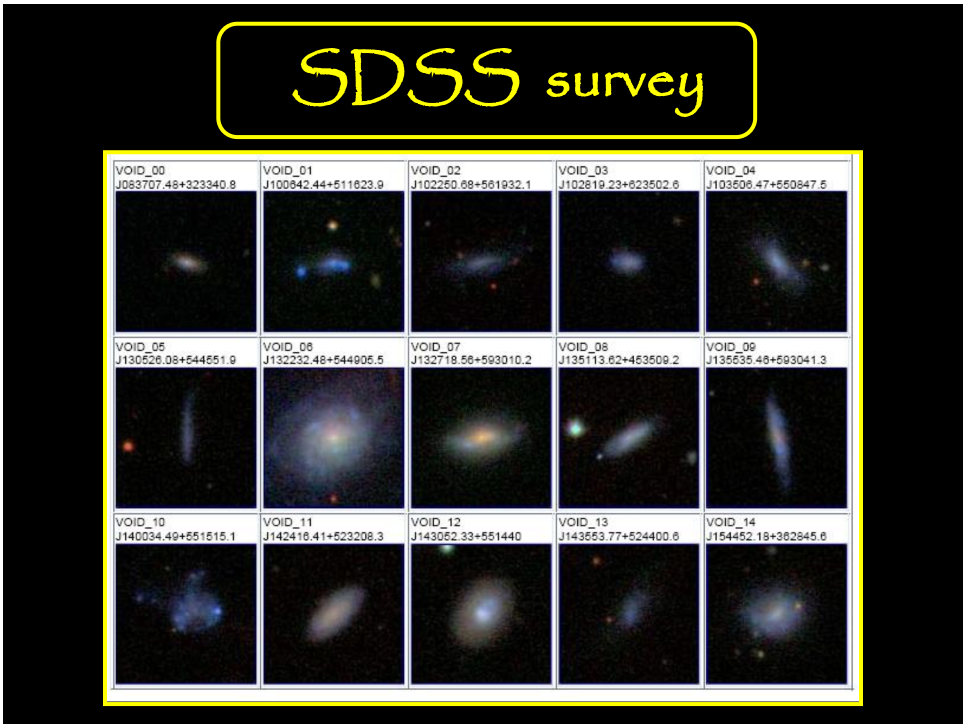

2dF Galaxy Redshift Survey
final release
10h
11h
14h
Redshift
.05
.10
.15
.20
3h
23h
22h
221414 galaxies
(from Colless et al. 2003)

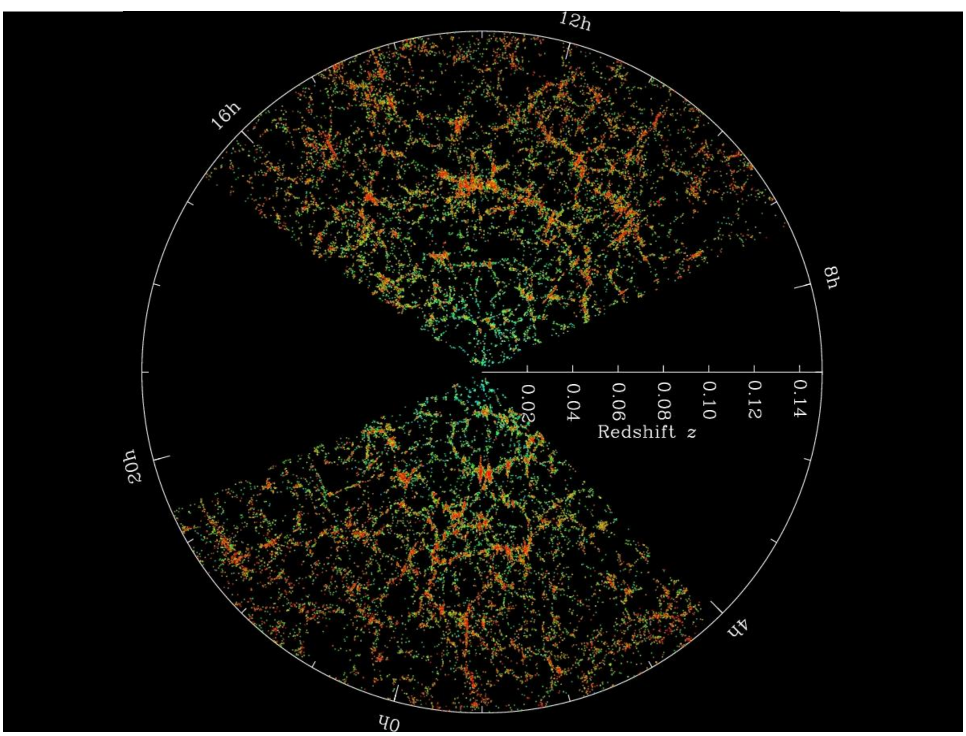

Shapley
Horologium–Reticulum
Sloan Great Wall
Pisces–Cetus

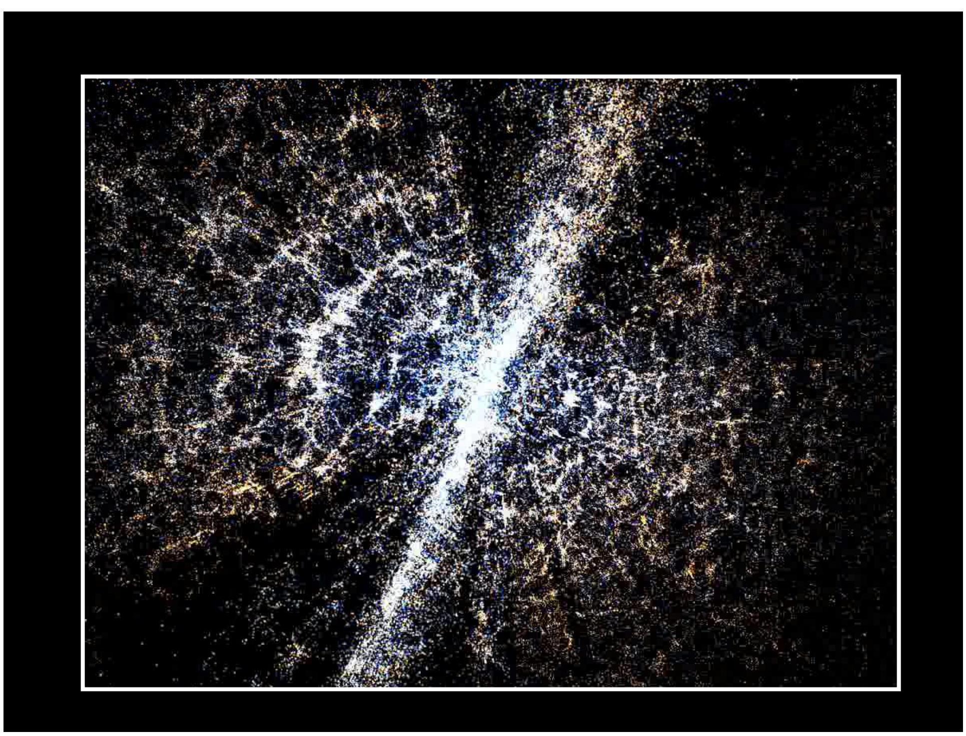
SDSS survey

- Largest and most systematic (digital !) sky survey in history of astronomy.
- Images sky in 5 photometric bands !!!!
  Down to apparent magnitude r~23.1
- Covers ~ 25% of the sky: 8452 sq. deg.
- With 2dFGRS, the SDSS will produce the most extensive map of the
  spatial structure of our cosmic neighbourhood.
- Million galaxies subsequently selected for measuring redshift z: electromagnetic spectrum

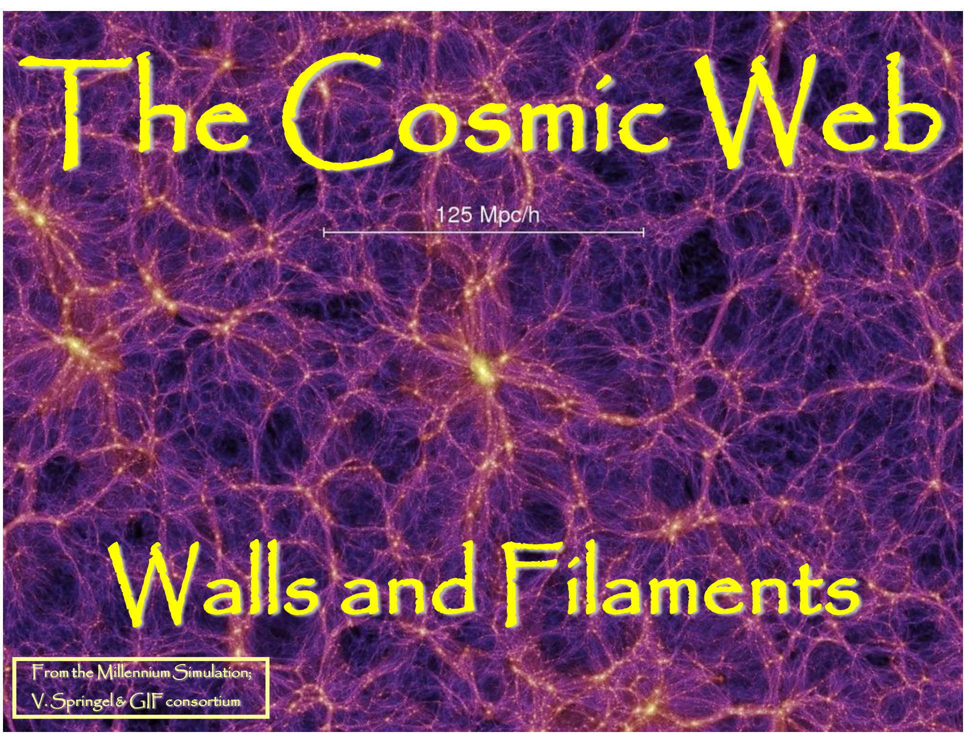
- Total:
  - sky survey: 10^8 stars, 10^8 galaxies, 10^5 quasars
  - spectroscopy: 10^6 galaxies, 10^5 quasars, 10^5 stars

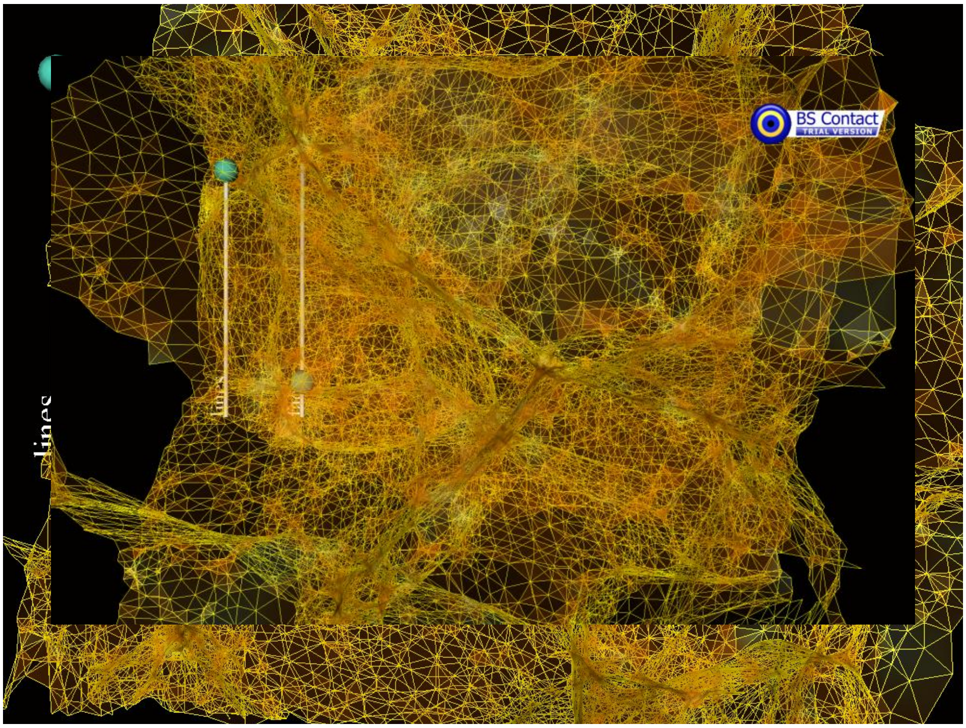

SDSS survey
VOID_00
J083707.48+323340.8
VOID_01
J100642.44+511623.9
VOID_02
J102250.68+561932.1
VOID_03
J102819.23+623502.6
VOID_04
J103506.47+550847.5
VOID_05
J130526.08+544551.9
VOID_06
J132232.48+544905.5
VOID_07
J132718.56+593010.2
VOID_08
J135113.62+453509.2
VOID_09
J135535.46+593041.3
VOID_10
J140034.49+551515.1
VOID_11
J142416.41+523208.3
VOID_12
J143052.33+551440
VOID_13
J143553.77+524400.6
VOID_14
J154452.18+362845.6

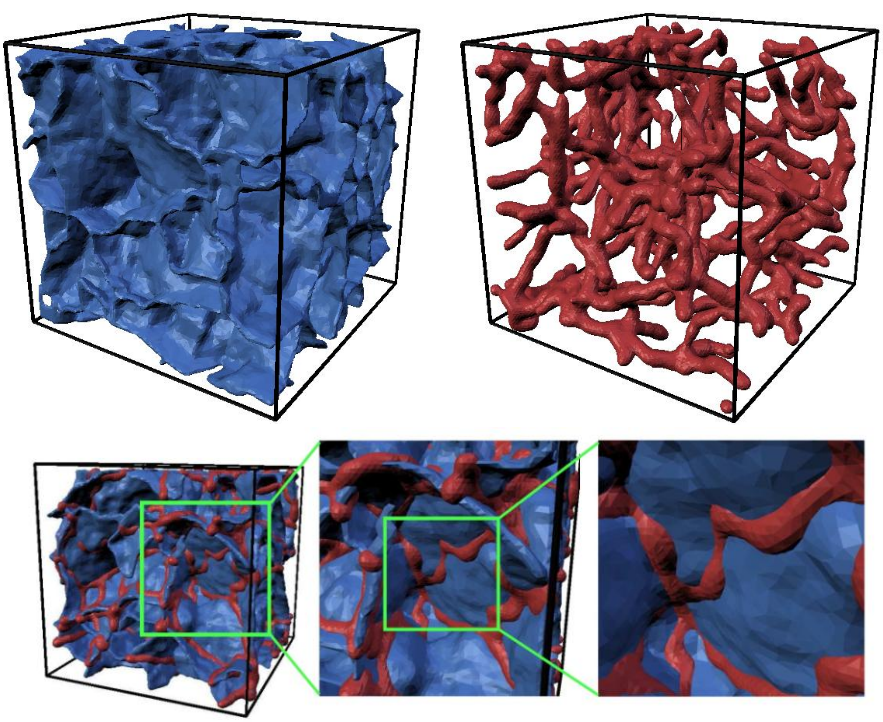

12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z



The Elements

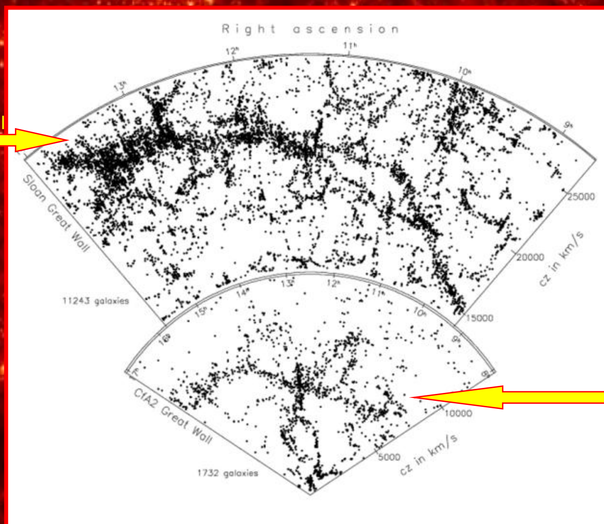



BS Contact
TRIAL VERSION



Walls and Filaments

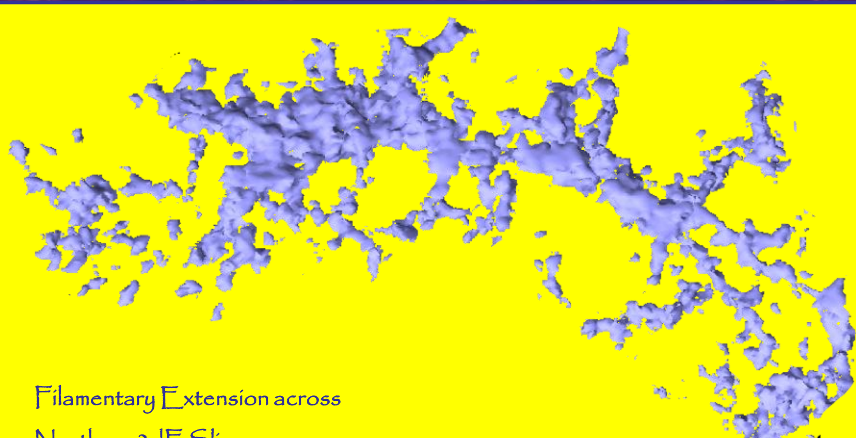
Sloan Great Wall



The ``Great Wall''

(Geller & Huchra 1989)

Walls and Filaments



Filamentary Extension across
Northern 2dF Slice

DTFE rendering: W. Schaap

Walls and Filaments

Pisces-Perseus Supercluster

Canonic example of a strongly flattened supercluster consisting of

- sheet-like central region, dense filamentary boundary ridge
- Relative proximity (d ~ 55h^{-1} Mpc),
- Characteristic & salient filamentary morphology,
- Favourable orientation.

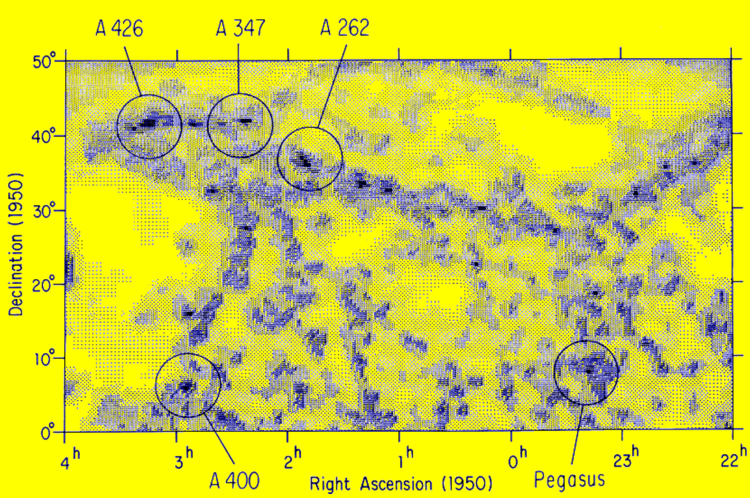
Northern boundary: ridge south-westward of Perseus cluster (A426)

Dimensions Ridge: 5h^{-1} Mpc wide

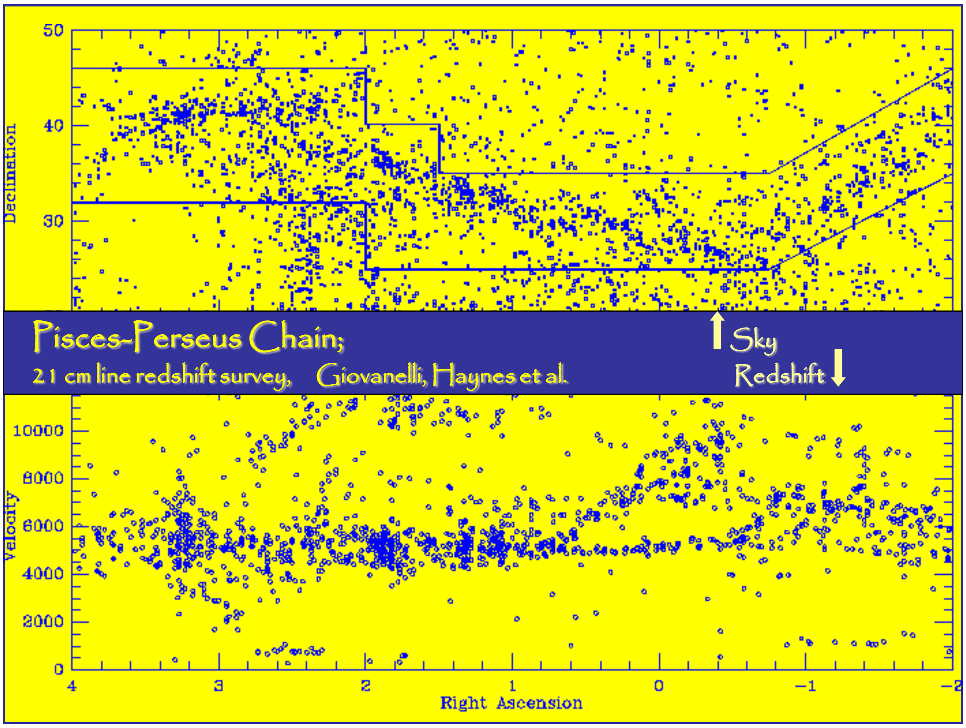
50h^{-1} Mpc length; possible 140h^{-1} Mpc extension

Along Ridge: high density clusters, incl. A462, A347, A262

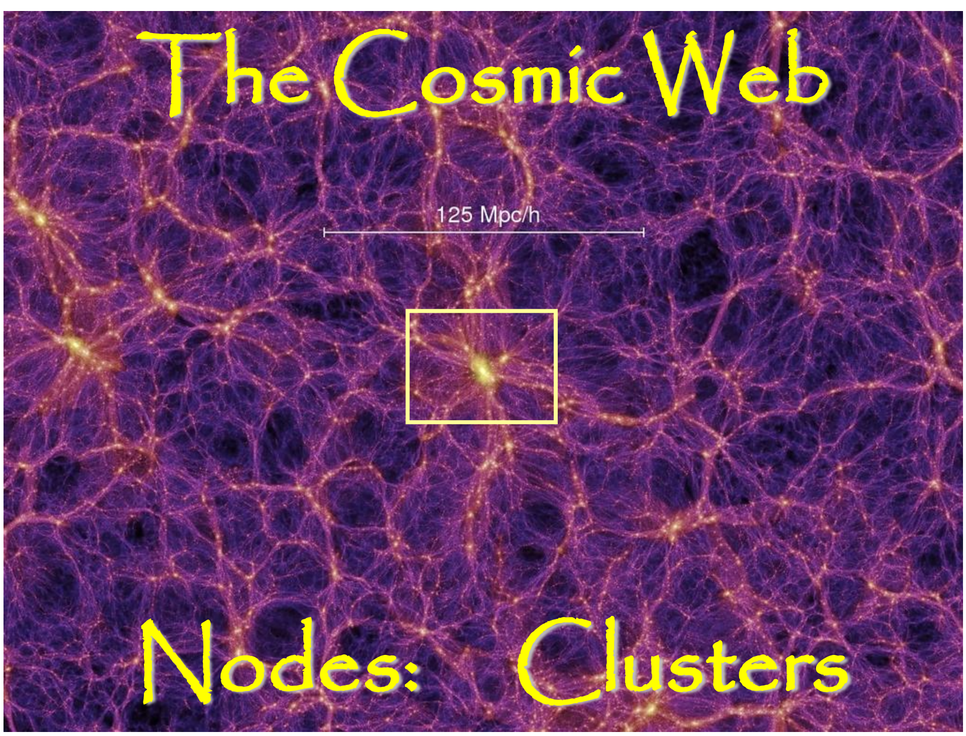
Walls and Filaments



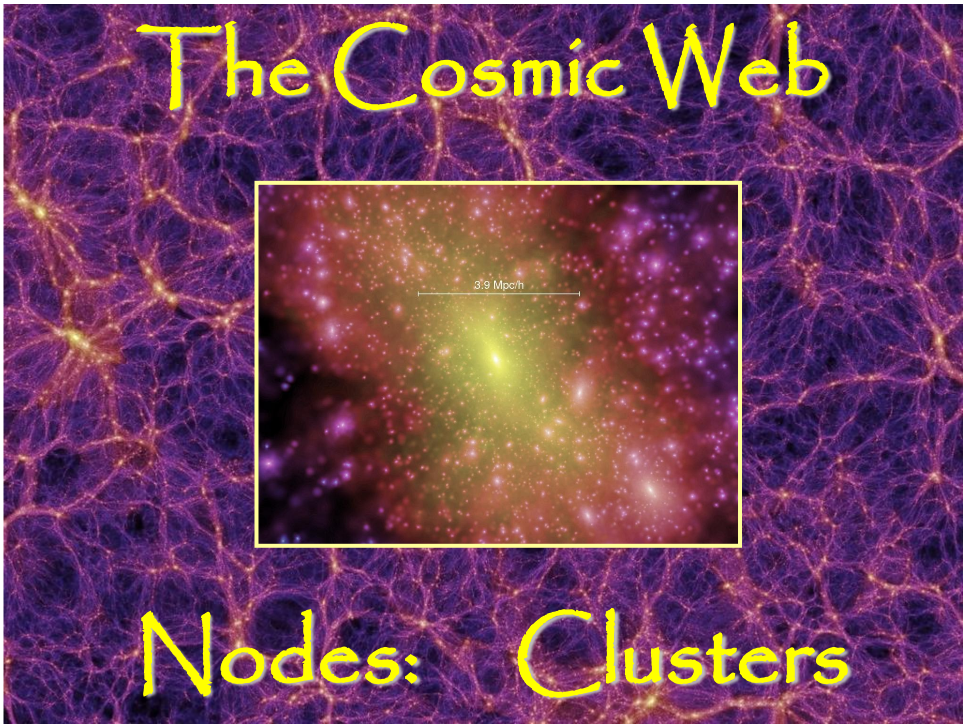
Pisces-Perseus Chain; 21 cm line redshift survey, Giovanelli & Haynes

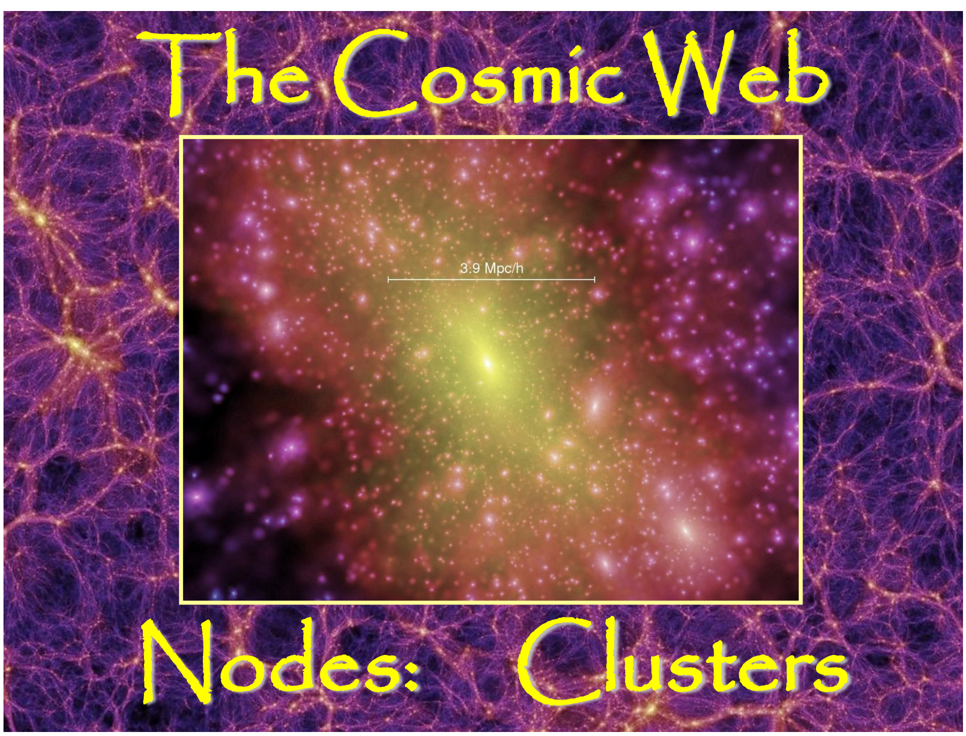


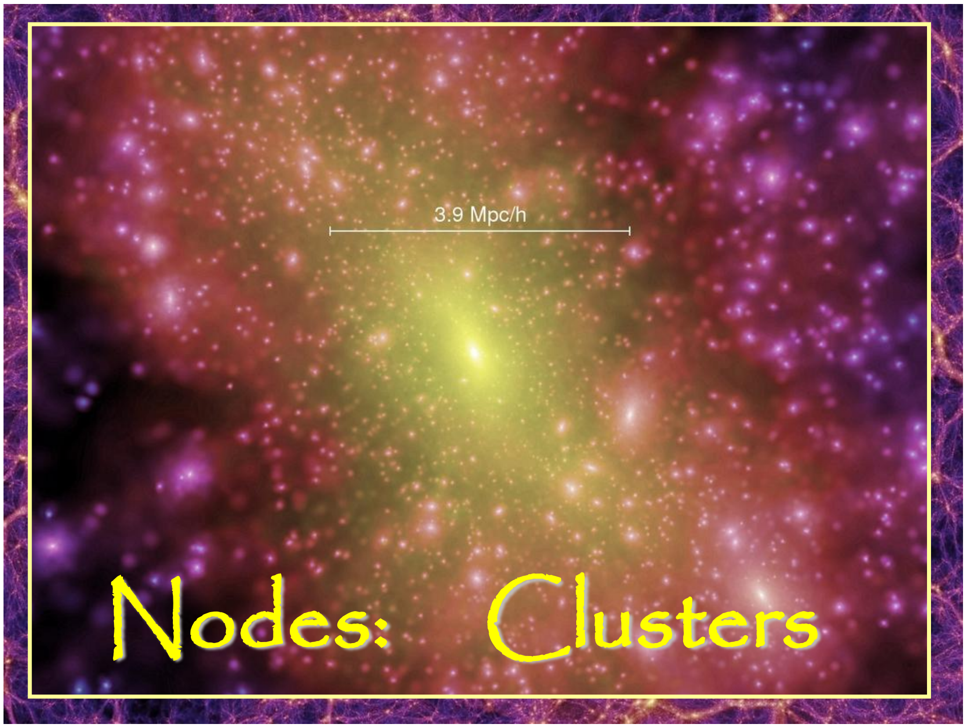
Pisces-Perseus Chain;
21 cm line redshift survey, Giovanelli, Haynes et al.
Sky
Redshift
Declination
Velocity
Right Ascension



The Cosmic Web
125 Mpc/h
Nodes: Clusters


The Cosmic Web
3.9 Mpc/h
Nodes: Clusters


The Cosmic Web
3.9 Mpc/h
Nodes: Clusters



Clusters of Galaxies

- Assemblies of up to 1000s of galaxies within a radius of only 1.5-2h^{-1} Mpc,
- Representing overdensities of $\delta \sim 1000$
- Galaxy move around with velocities ~ 1000 km/s
- They are the most massive, and most recently, fully collapsed structures in our Universe.

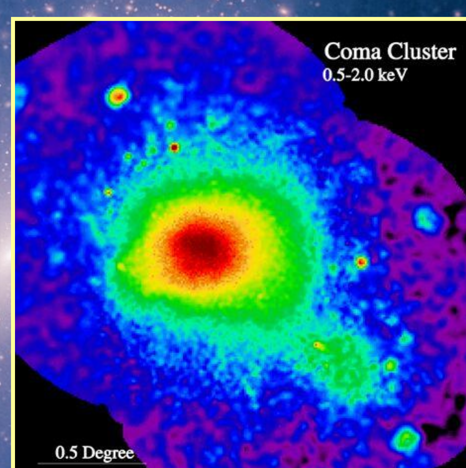
Clusters of Galaxies

Courtesy:
O. Lopez-Cruz

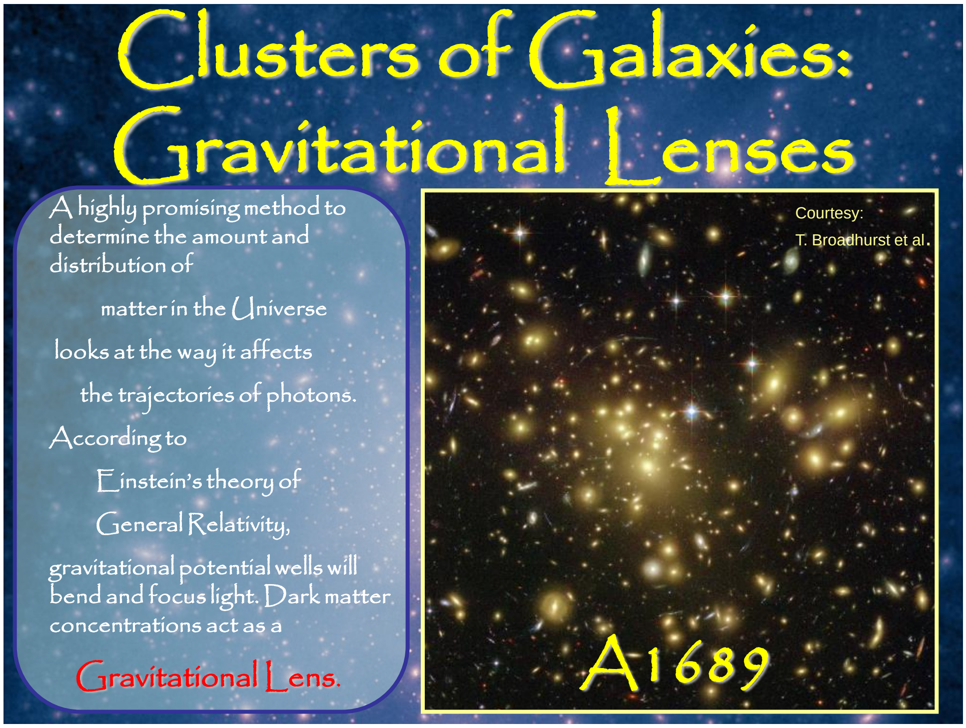
Coma Cluster

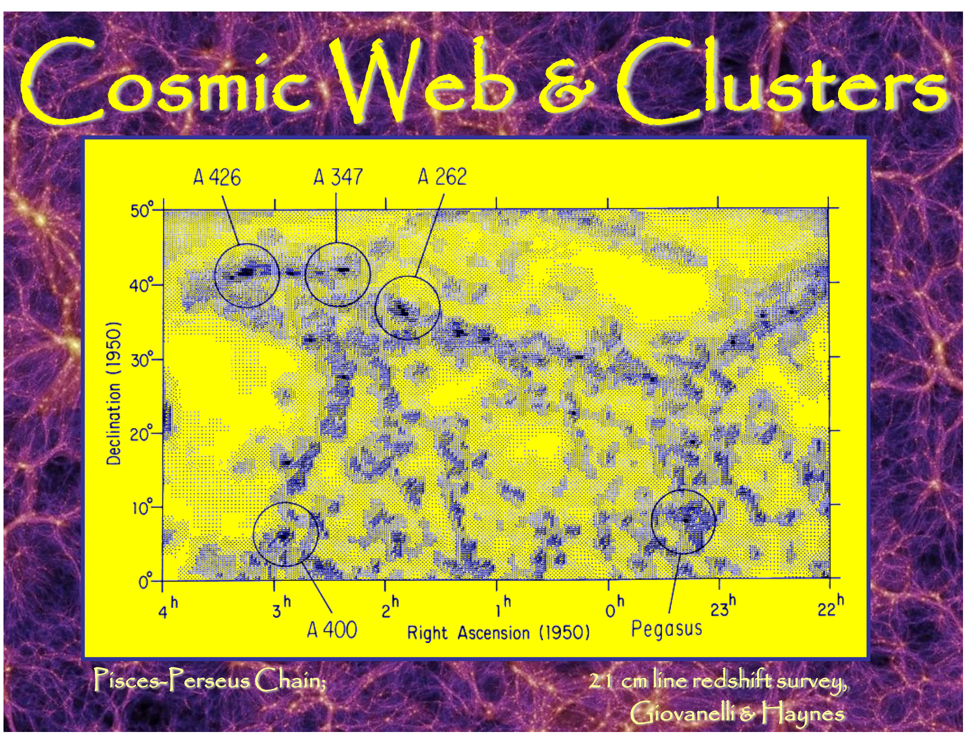
Clusters of Galaxies
X-ray intracluster gas

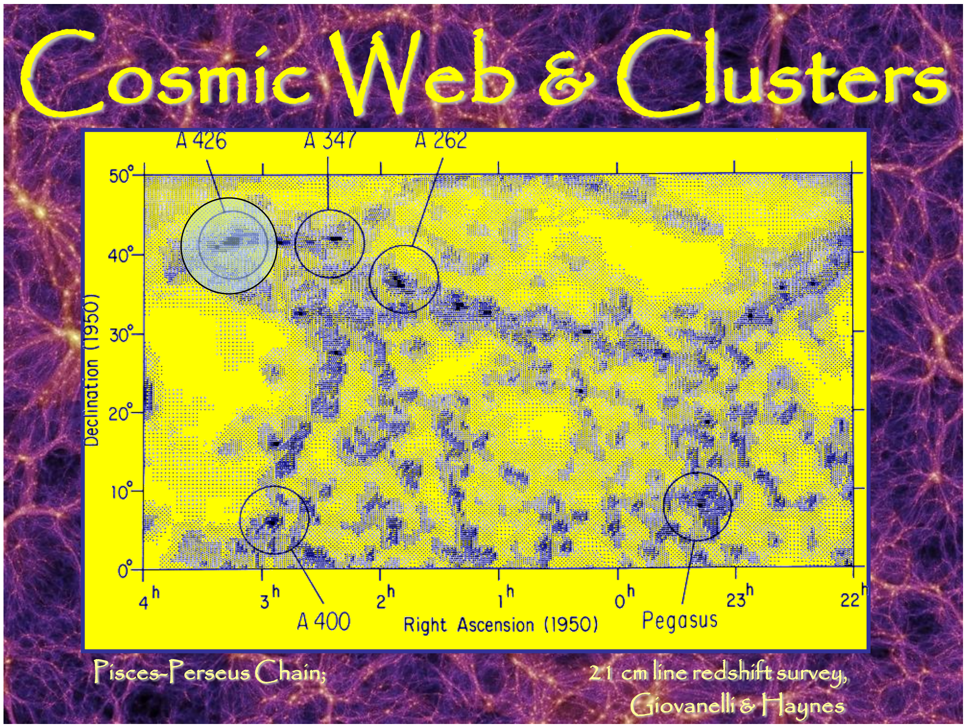
Baryonic matter in clusters is not only confined to galaxies. On the contrary, about 2 to 5 times more baryonic mass is in the form of a diffuse hot X-ray emitting intracluster gas, trapped and heated to a temperature of the order of 10^8 K by the gravitational potential of the cluster. At such high temperatures, this gas is a fully ionized plasma, producing powerful X-ray emission, bremsstrahlung radiation induced by the electron-ion interactions.

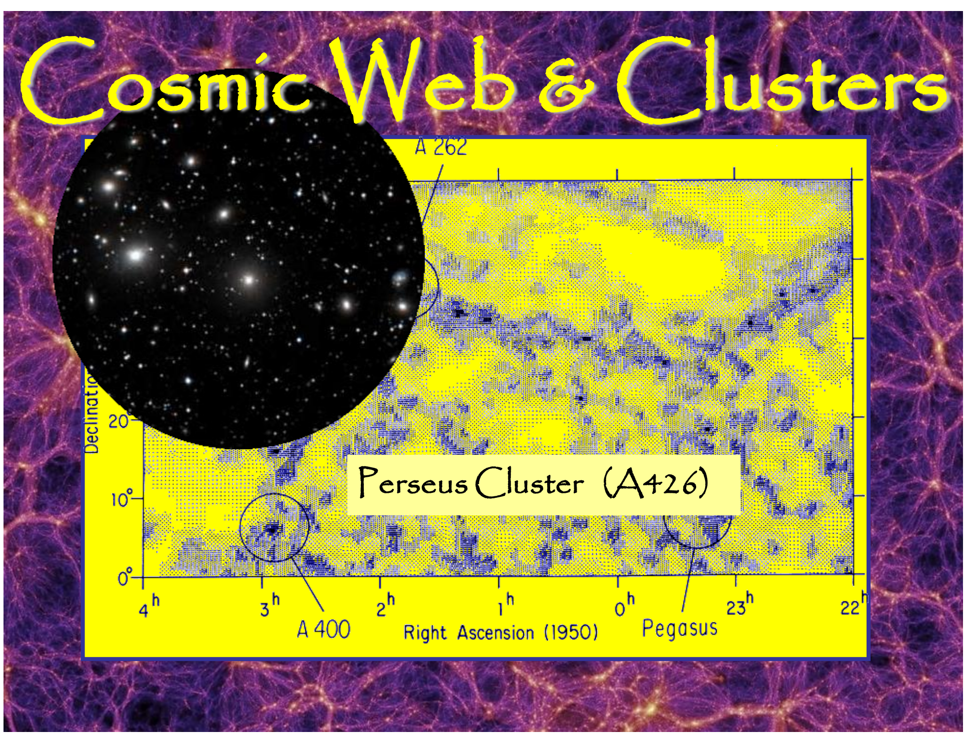


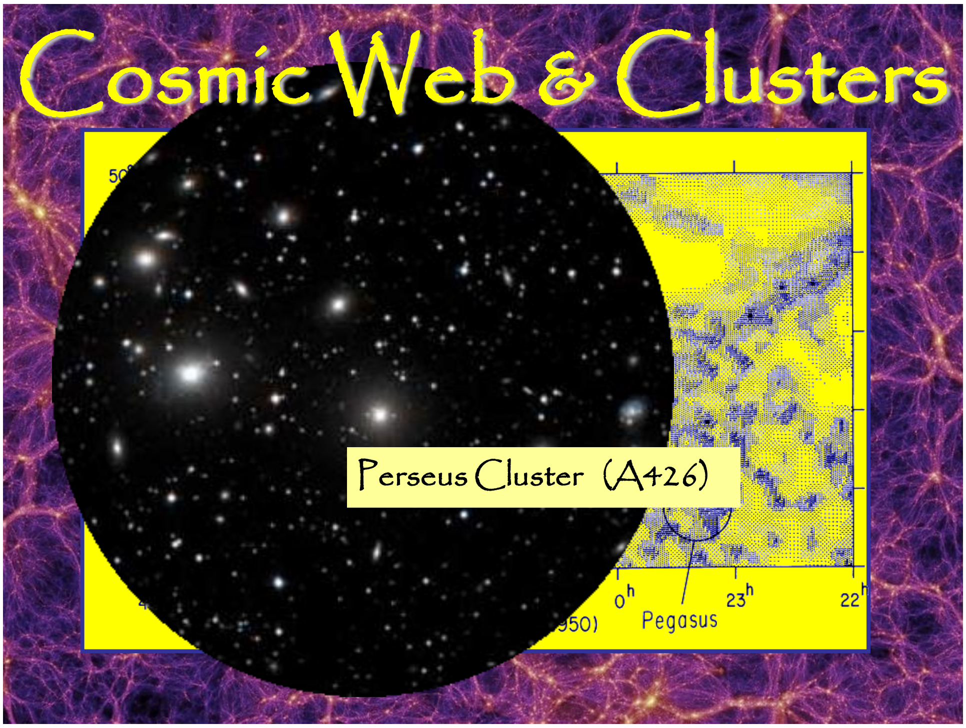
ROSAT X-ray image Coma Cluster


Clusters of Galaxies: Gravitational Lenses
A highly promising method to determine the amount and distribution of
matter in the Universe
looks at the way it affects
the trajectories of photons.
According to
Einstein's theory of
General Relativity,
gravitational potential wells will bend and focus light. Dark matter concentrations act as a
Gravitational Lens.
Courtesy:
T. Broadhurst et al.
A1689

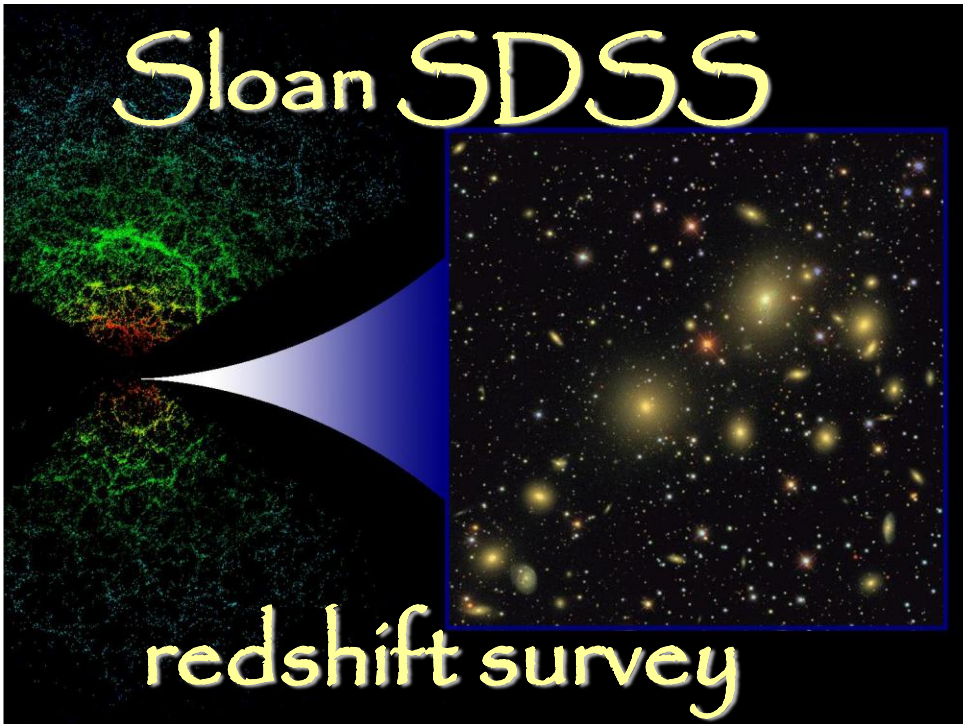

Cosmic Web & Clusters
A 426
A 347
A 262
50°
40°
30°
20°
10°
0°
Declination (1950)
4h
3h
2h
1h
0h
23h
22h
A 400
Right Ascension (1950)
Pegasus
Pisces-Perseus Chain;
21 cm line redshift survey,
Giovanelli & Haynes

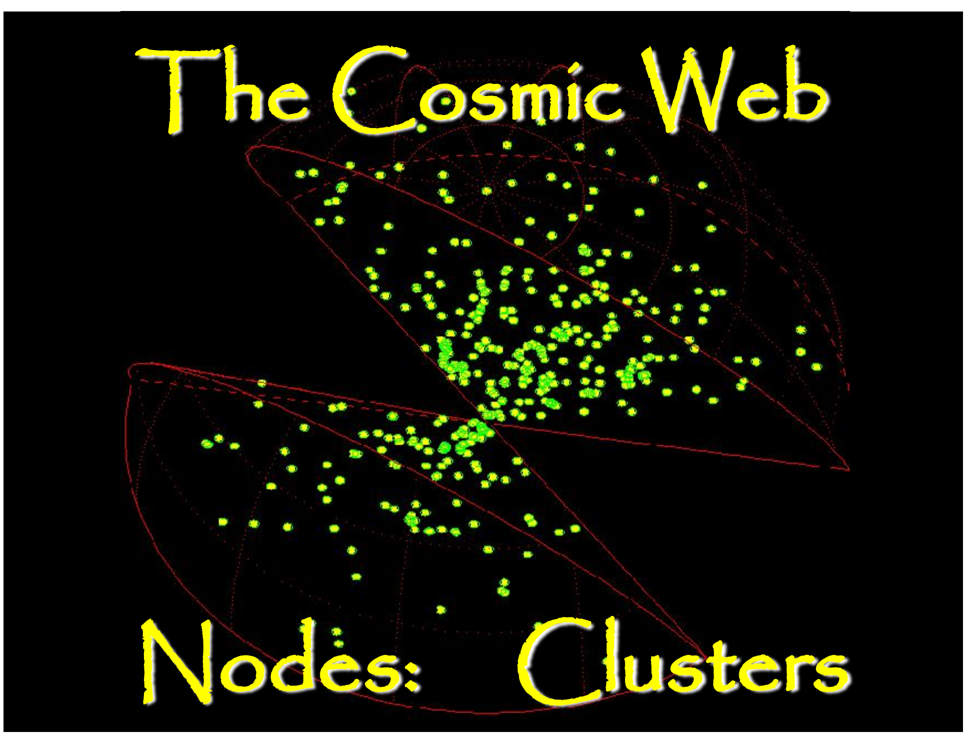

Cosmic Web & Clusters
A 426
A 347
A 262
50°
40°
30°
20°
10°
0°
Declination (1950)
4h
3h
2h
1h
0h
23h
22h
A 400
Right Ascension (1950)
Pegasus
Pisces-Perseus Chain;
21 cm line redshift survey,
Giovanelli & Haynes


Cosmic Web & Clusters
A 262
Perseus Cluster (A426)
20°
10°
0°
4h
3h
2h
1h
0h
23h
22h
A 400
Right Ascension (1950)
Pegasus

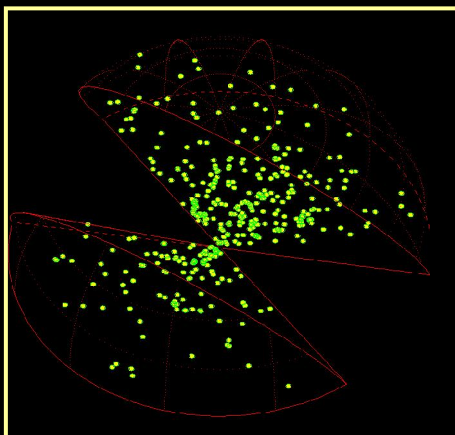

Cosmic Web & Clusters
Perseus Cluster (A426)
0h
23h
22h
Pegasus


Cosmic Web & Clusters
Perseus Cluster (A426)


Sloan SDSS
redshift survey


The Cosmic Web
Nodes: Clusters

The Cosmic Web



The spatial cluster distribution.

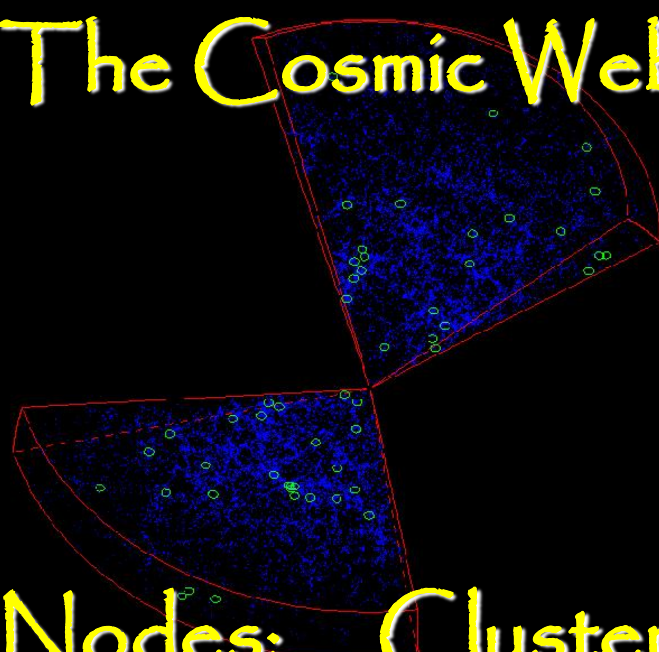
The full volume of the X-ray cluster REFLEX cluster survey within a distance of 600h^{-1} Mpc. The REFLEX galaxy cluster catalogue contains all clusters brighter than an X-ray flux of 3x10 ergs cm^{-2} over a large part of the in the southern sky. The missing part of hemisphere delineates the region highly obscured by the Galaxy.

REFLEX: Boehringer et al. (2001)

Courtesy: Borgani & Guzzo (2001)

Nodes: Clusters

The Cosmic Web



Nodes: Clusters

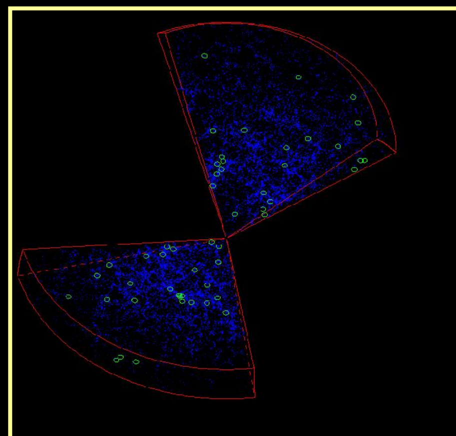
The Cosmic Web

The spatial cluster distribution and relation to Cosmic Web.

The green circles mark the positions of REFLEX X-ray clusters in the northern and southern slices of the Las Campanas redshift survey (LCRS, Shectman et al. 1996), out to a maximum distance of $600h^{-1}$ Mpc. Underlying, in blue, the galaxies in the LCRS delineate a foamlike distribution of filaments, walls and voids.

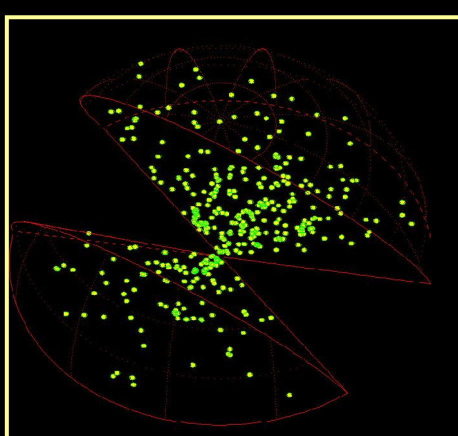
REFLEX: Boehringer et al. (2001)

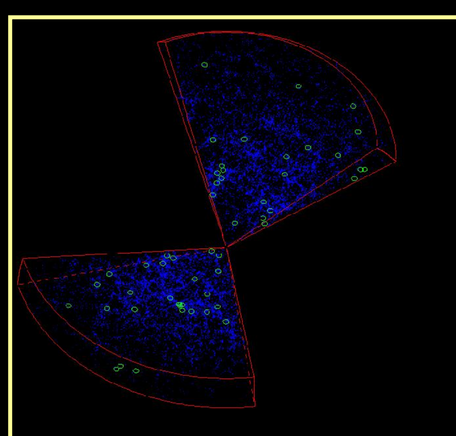
Courtesy: Borgani & Guzzo (2001)



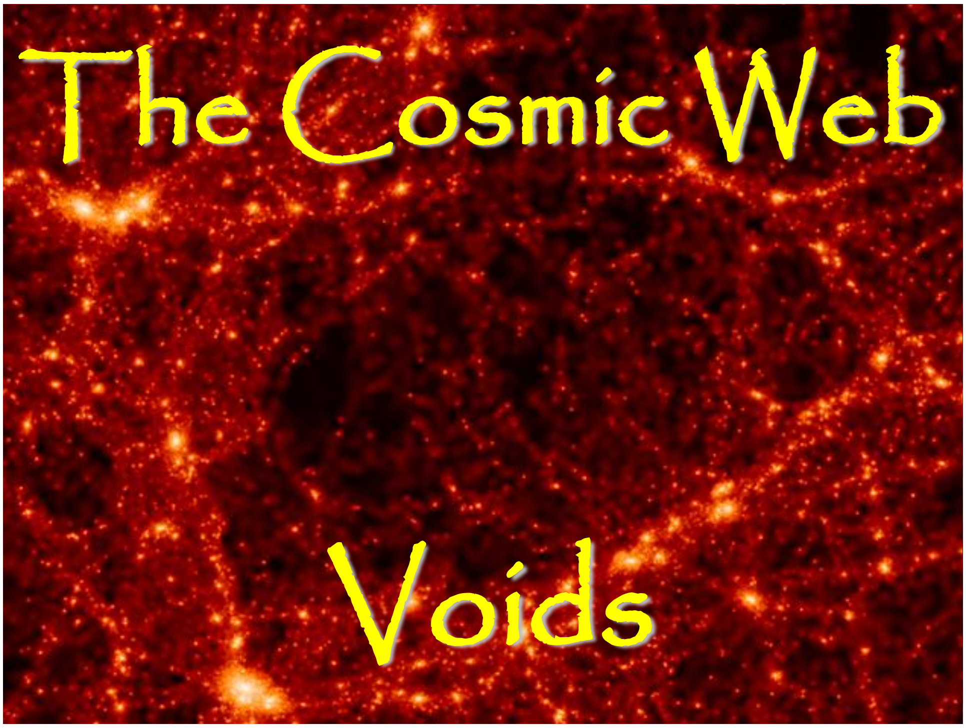
Nodes: Clusters

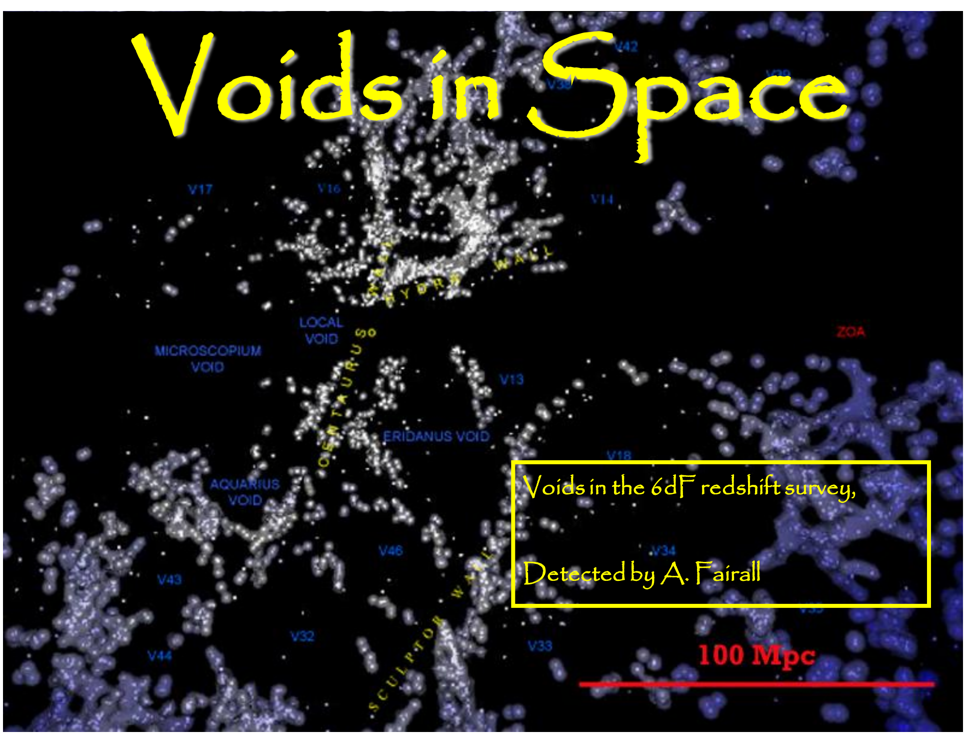
The Cosmic Web

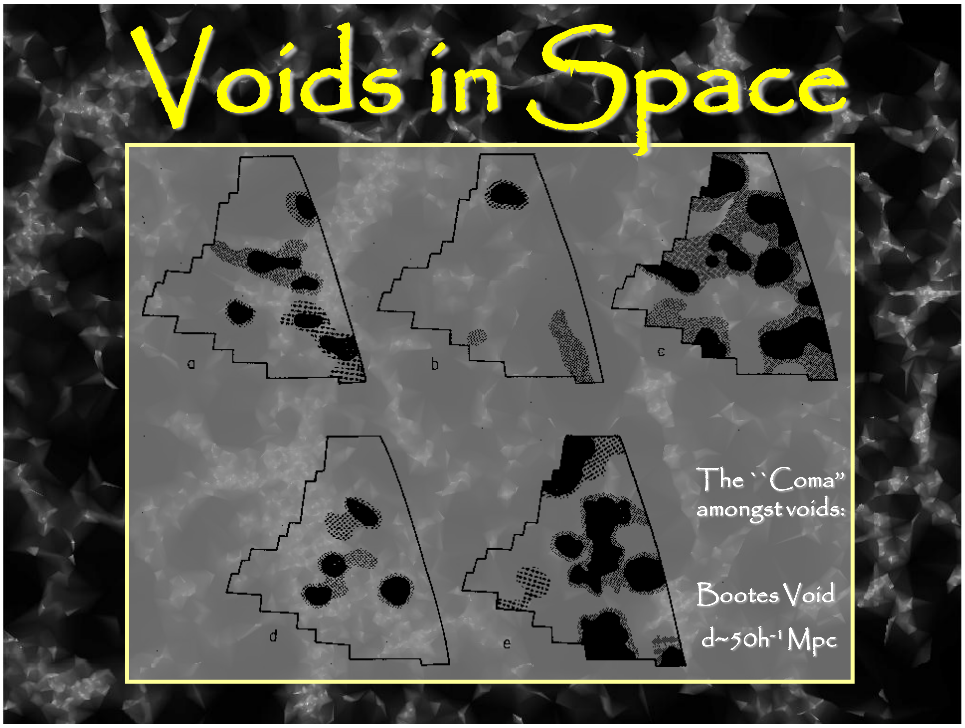


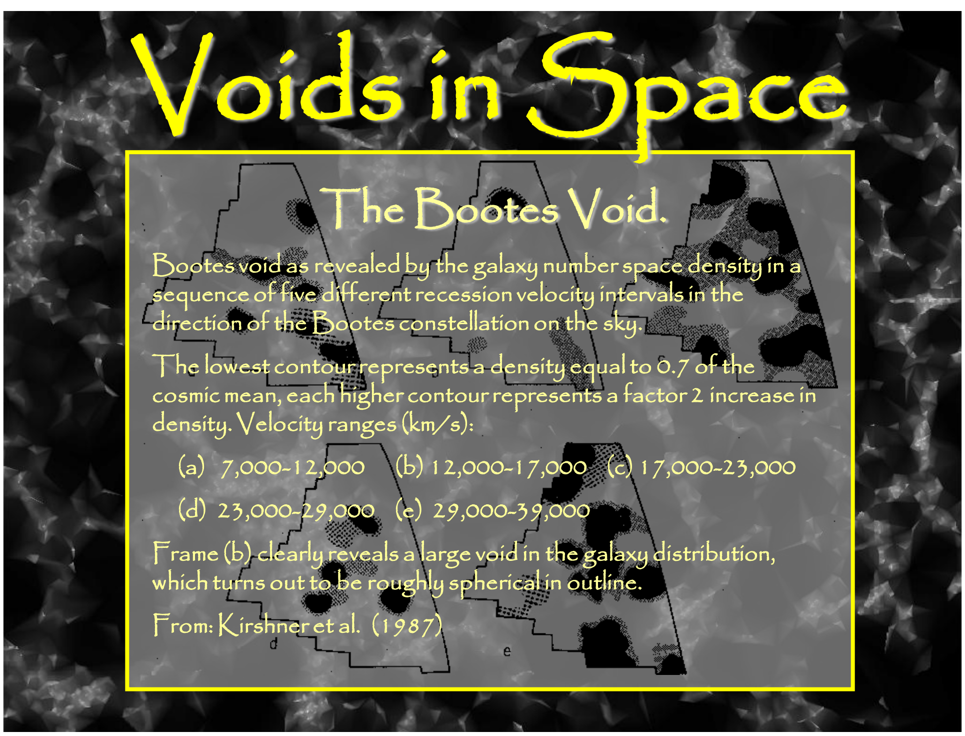


Nodes: Clusters

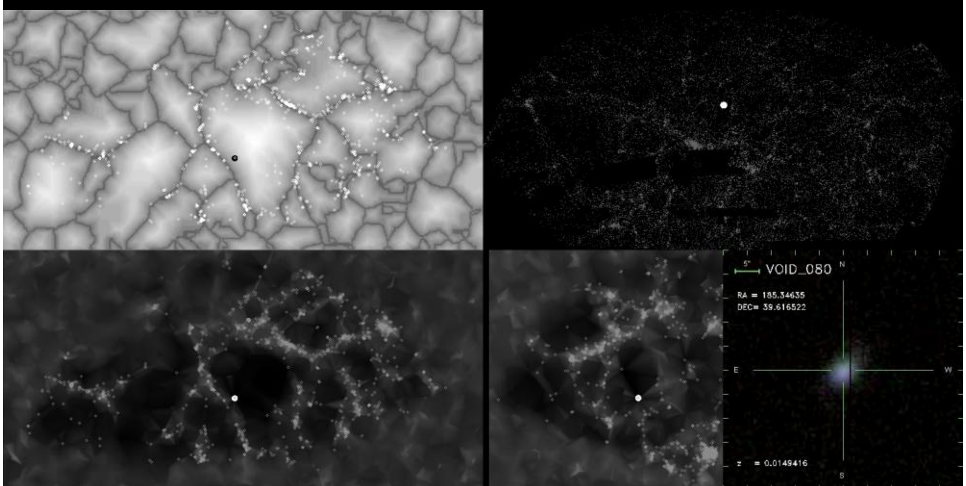

The Cosmic Web
Voids


Voids in Space
V17
V16
V14
LOCAL VOID
MICROSCOPIUM VOID
ZOA
V13
ERIDANUS VOID
AQUARIUS VOID
V46
V43
V32
V44
V33
Voids in the 6dF redshift survey,
Detected by A. Fairall
100 Mpc


Voids in Space
a
b
c
d
e
The ``Coma" amongst voids:
Bootes Void
d~50h^{-1} Mpc

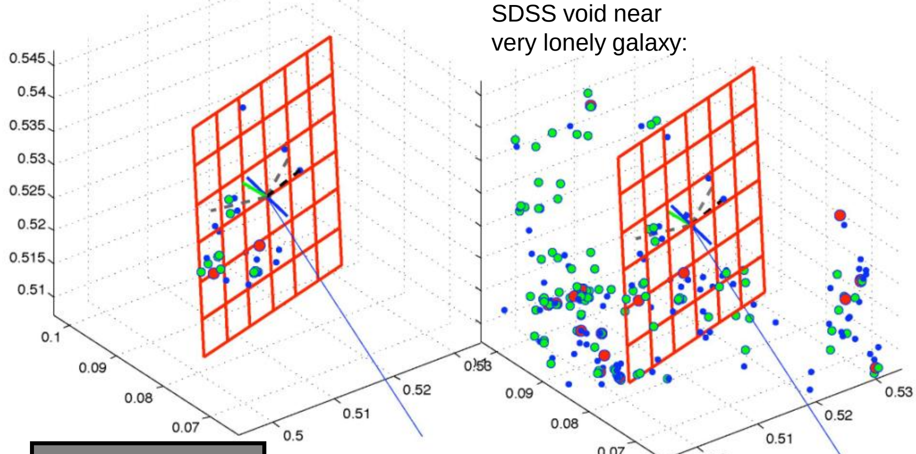

Voids in Space
The Bootes Void.
Bootes void as revealed by the galaxy number space density in a sequence of five different recession velocity intervals in the direction of the Bootes constellation on the sky.
The lowest contour represents a density equal to 0.7 of the cosmic mean, each higher contour represents a factor 2 increase in density. Velocity ranges (km/s):
(a) 7,000-12,000 (b) 12,000-17,000 (c) 17,000-23,000
(d) 23,000-29,000 (e) 29,000-39,000
Frame (b) clearly reveals a large void in the galaxy distribution, which turns out to be roughly spherical in outline.
From: Kirshner et al. (1987)

SDSS Voids



SDSS Voids

SDSS void near
very lonely galaxy:



sampled by
galaxies different brightness:
no difference

(courtesy:
P.J.E. Peebles & E. Platen)

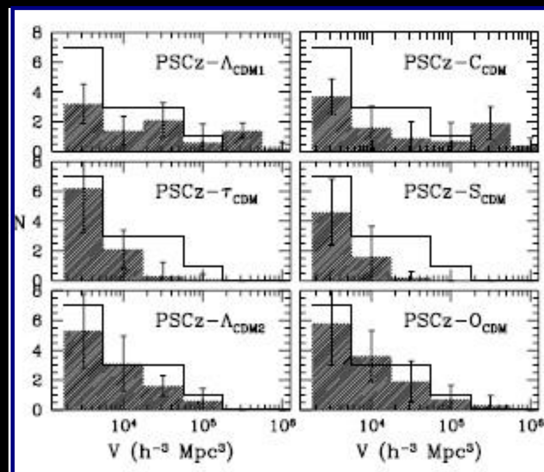
Void Size & Volume

Void Size

Void size distribution dependent on cosmology:

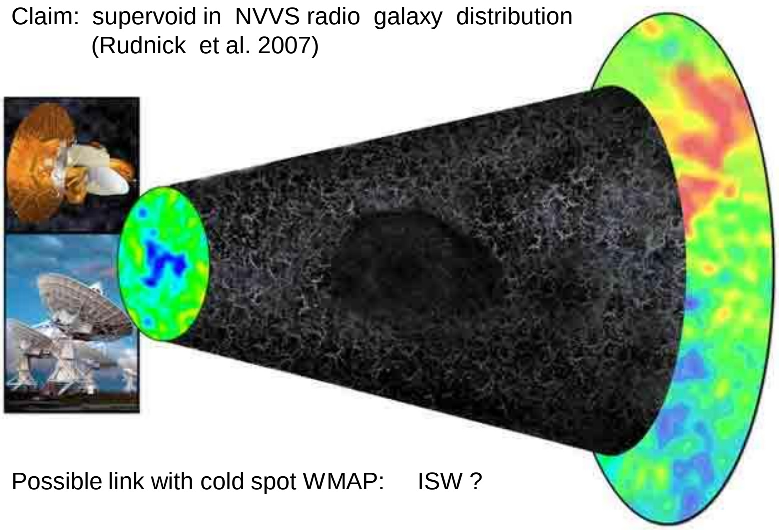
Comparison PSCz & models:

Plionis & Basilakos 2002

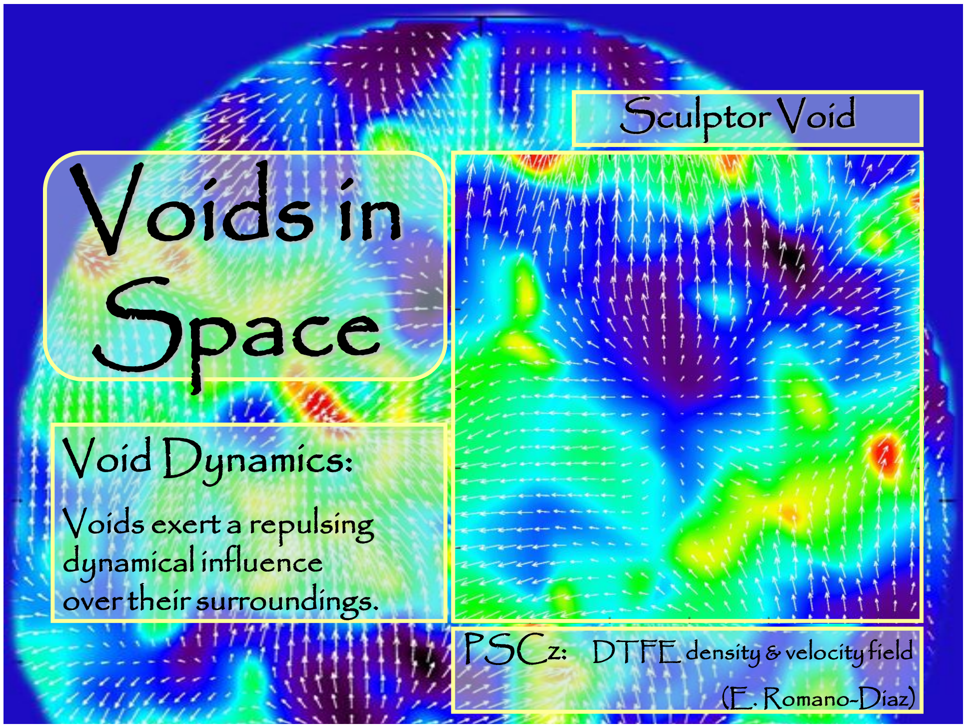


Supervoids ???

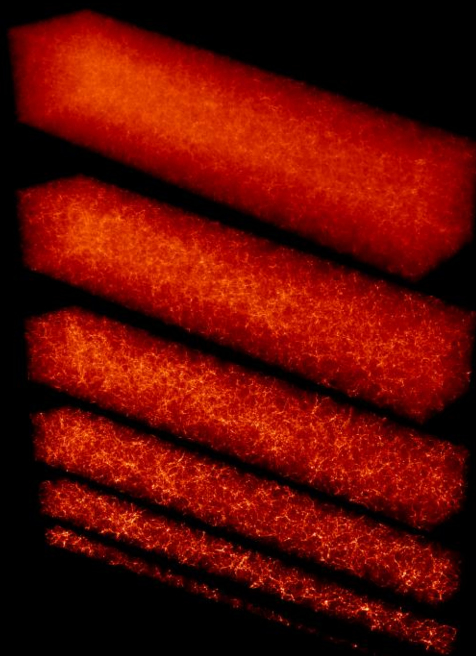
Claim: supervoid in NVVS radio galaxy distribution (Rudnick et al. 2007)



Possible link with cold spot WMAP: ISW ?


Voids in Space
Sculptor Void
Void Dynamics:
Voids exert a repulsing dynamical influence over their surroundings.
PSCz: DTFE density & velocity field
(E. Romano-Diaz)

Web in Depth



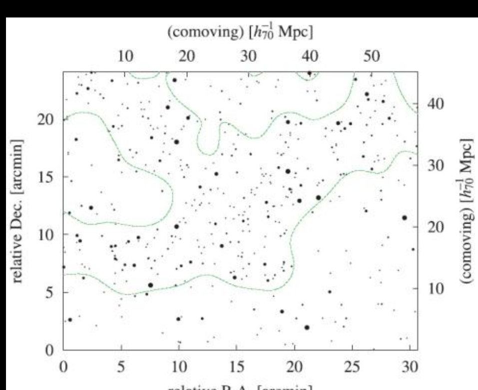
Far Away, Long Ago

Various surveys are attempting to trace the large scale structure out to large cosmic depths/redshifts.

- Is cosmic web truly universal
- What about the scales of the web (characteristic, largest structures, ...)
- Evolution of Megaparsec scale matter distribution.

Simulation of VIRMOS redshift survey, web out to large redshift

Far Away, Long Ago



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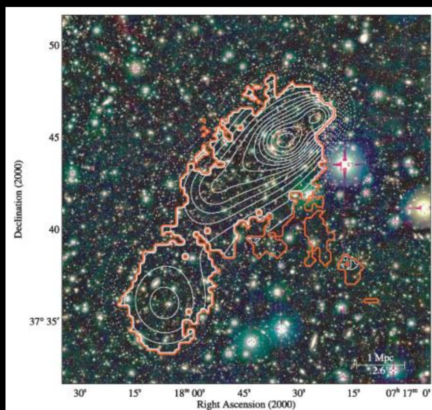
- Is cosmic web truly universal
- What about the scales of the web (characteristic, largest structures, ...)
- Evolution of Megaparsec scale matter distribution.

Subaru Survey: Amazing prominent large scale distribution of Lyα emitting galaxies.
A filament at redshift z~3 ?

Far Away, Long Ago



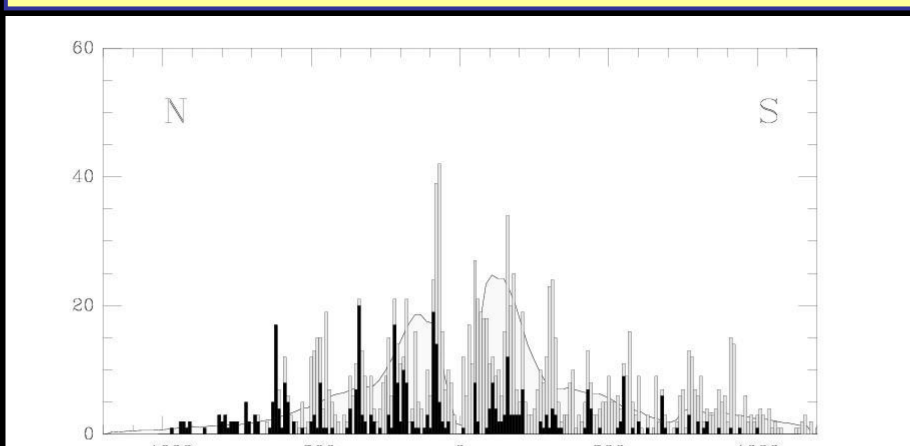
Various surveys are attempting to trace the large scale structure out to large cosmic depths/redshifts.

- Is cosmic web truly universal ?
- What about the scales of the web (characteristic, largest structures, ...)
- Evolution of Megaparsec scale matter distribution.

Ebeling et al. (2004):

A filamentary structure in between two rich clusters.

Far Away, Long Ago

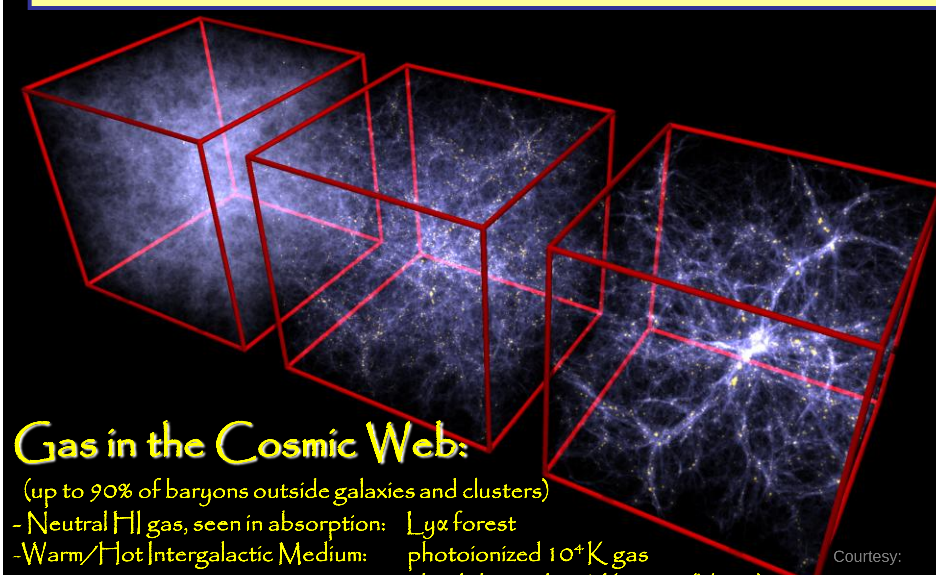


Deep pencil beam survey (Broadhurst et al):

A semi-regular pattern of redshift spikes along line of sight, indicating the passage of l.o.s. through sheets, filaments and clusters. Suggestions for a characteristic scale of ~120h^{-1} Mpc should be ascribed to the 1-D character of the redshift skewer through 3-D structure.

The Gastrophysical Web

The Gastrophysical Web



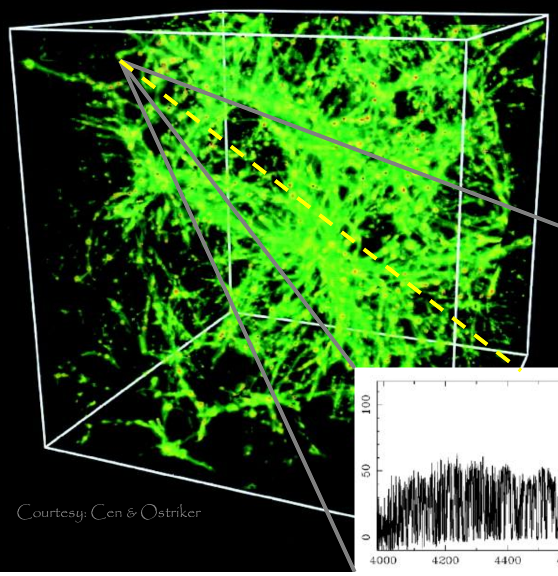
Gas in the Cosmic Web:

(up to 90% of baryons outside galaxies and clusters)

- Neutral HI gas, seen in absorption: Lyα forest
- Warm/Hot Intergalactic Medium: photoionized 10^4 K gas
  shock-heated 10^6 K gas (X-ray)

Courtesy: Virgo/V. Springel

The Gastrophysical Web

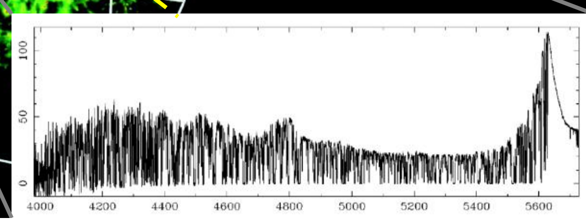


The Lyα forest:

HI gas in the intergalactic medium closely traces the density fluctuations in the dark matter distribution.

QSO absorption lines arise due to the line of sight intersection by the neutral hydrogen component

Low column density absorption lines associated with sheets and filaments in the "Cosmic Web"



Web Dynamics

Cosmic Migration Flows

CMB Dipole:

We move wrt Universe: v ~ 620 km/s

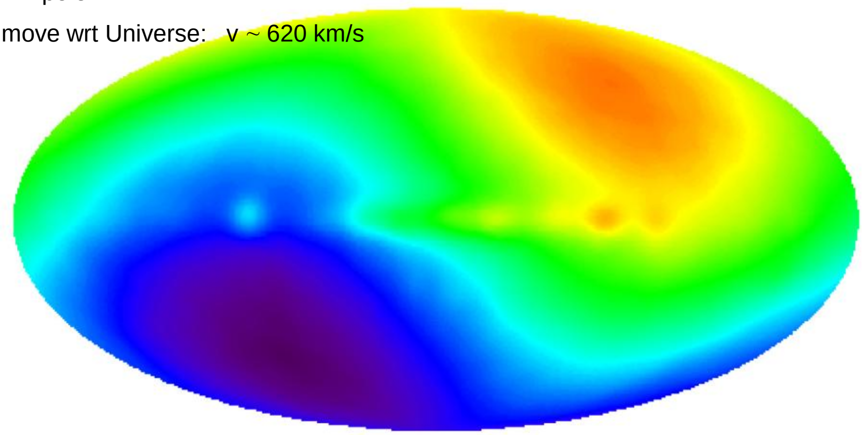
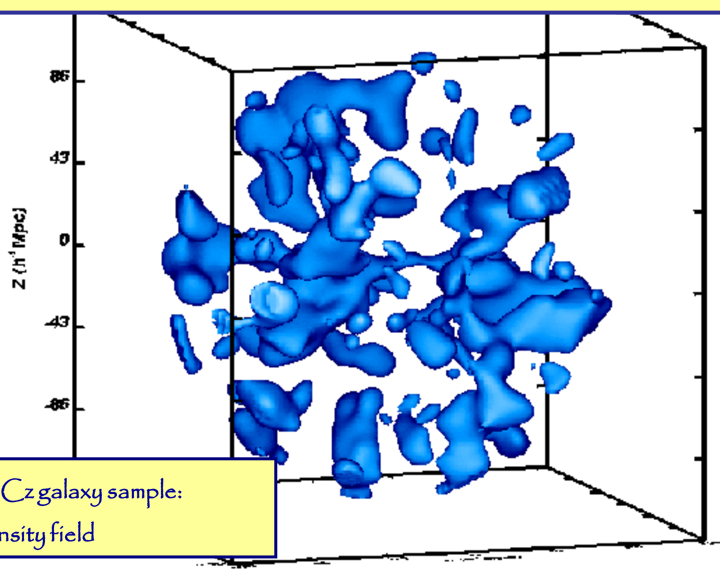


Figure 11. The Cosmic Microwave Background dipole as measured by the DMR instrument of the COBE microwave background satellite (see also Kogut et al. 1993)

Cosmic Migration Flows



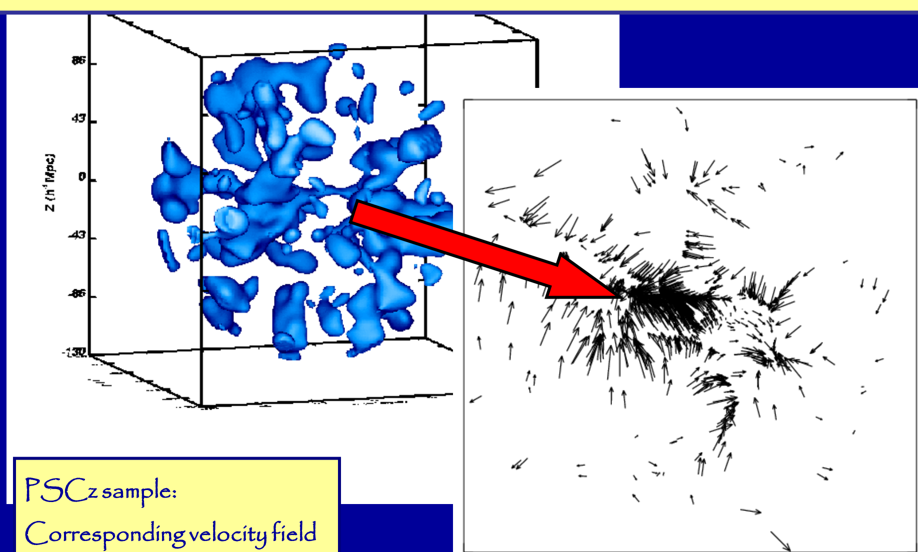
PSCz galaxy sample:
Density field

Cosmic Migration Flows

$$\mathbf{v} = \frac{H\,f}{4\pi G\,\rho_u}\,\mathbf{g} = \frac{2\,f}{3H\Omega}\,\mathbf{g}$$

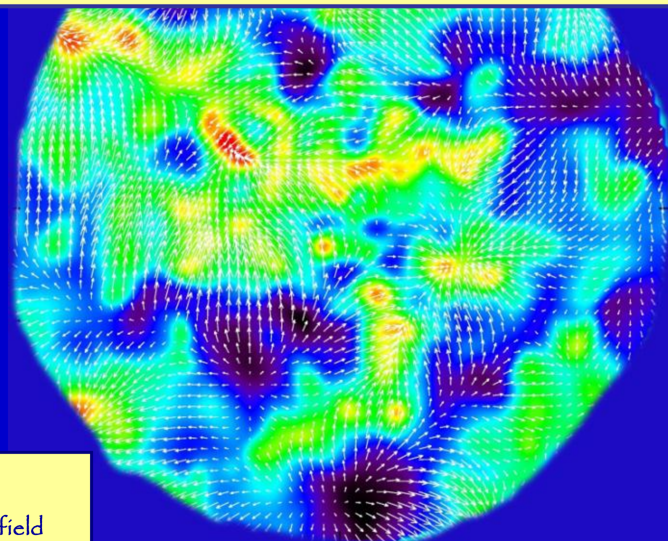
$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\,\frac{f(\Omega_m)}{b}\,a \int d\mathbf{x}'\;\delta_{gal}(\mathbf{x}',t)\;\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3} \qquad (158)$$

Cosmic Migration Flows



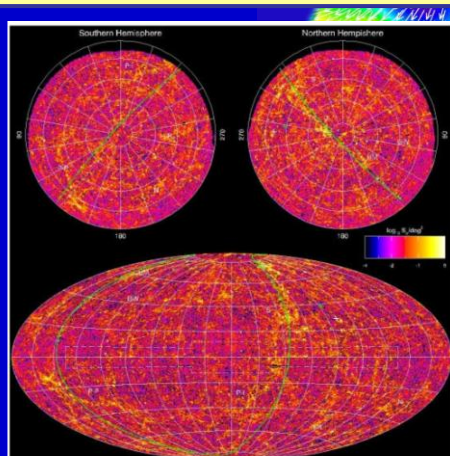
PSCz sample:
Corresponding velocity field

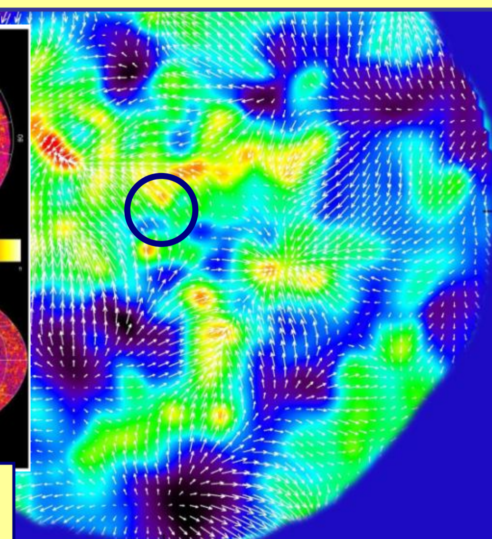
Cosmic Migration Flows



PSCz sample,
Map Density & Flow field

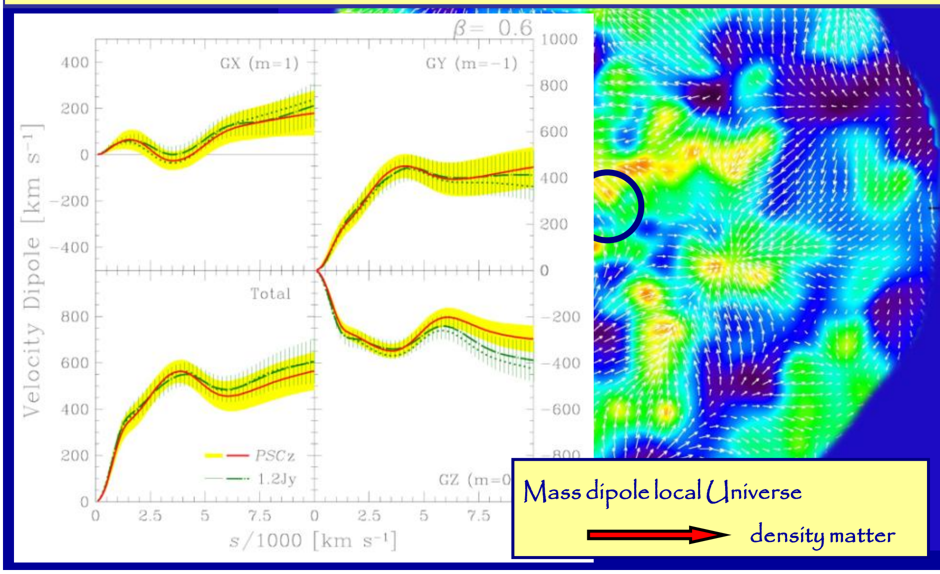
Cosmic Migration Flows



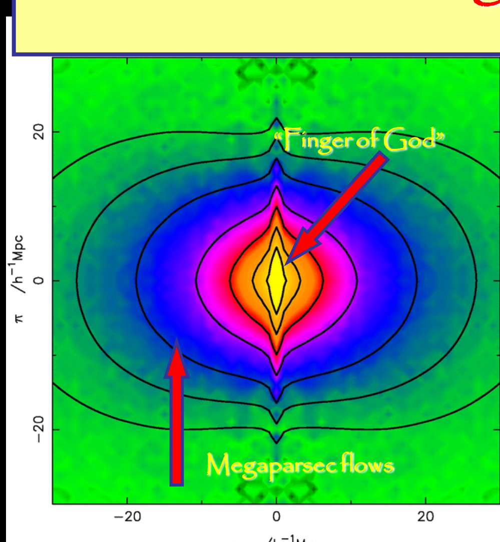


PSCz sample & 2MASS sky
Flow around Local Group

Cosmic Migration Flows



the Web: Migration Flows



Large scale flows lead to redshift distortions:

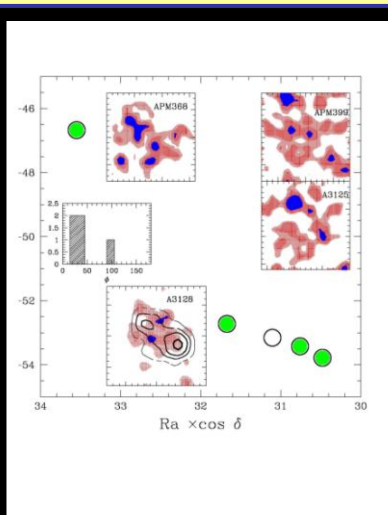
$$cz = Hr + v_{pec}$$

These flows are part of the assembly of large scale structures, and reach largest values as matter is transported along the filaments into the clusters.

When mapping the galaxy distribution in redshift space, this induces a distortion:

- Flattening along z as matter flows into Megaparsec features (v < 600 km/s).
- Extension due to thermal motions inside cluster (v ~ 1000 km/s): "Fingers of God"

Web Dynamics: Alignments



Plionis 2005

Of outmost importance for understanding the dynamical origin of the cosmic web is that of alignments between and around clusters of galaxies.

The presence of such alignments is an indication for the tidal origin of the cosmic web with the clusters as the dominant tidal agents.

This forms an essential ingredient of the "Cosmic Web" theory of Bond et al.

Work by various groups, most notably Plionis and collaborators, indicate that indeed clusters, and galaxies around them, reveal significant alignments.

Cosmic Shear & Gravitational Lensing

Gravitational Lensing

A highly promising method to determine the amount and distribution of matter in the Universe does not concentrate on the way in which Dark Matter affects

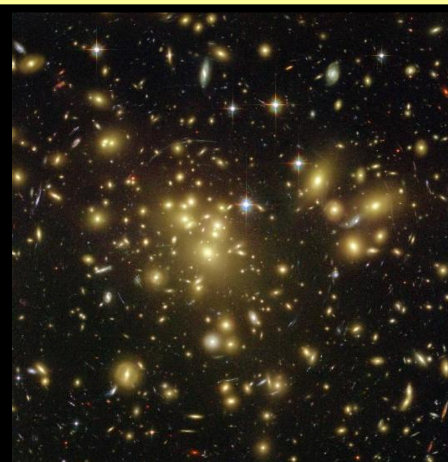
- the motions of galaxies and the intracluster gas,

but instead looks at the way it affects

- the trajectories of photons.

According to Einstein's theory of general relativity, gravitational potential wells will bend and focus light. Dark matter concentrations will therefore act

Gravitational Lens



A1689, HST, Broadhurst et al.

Gravitational Lensing

Illustration:

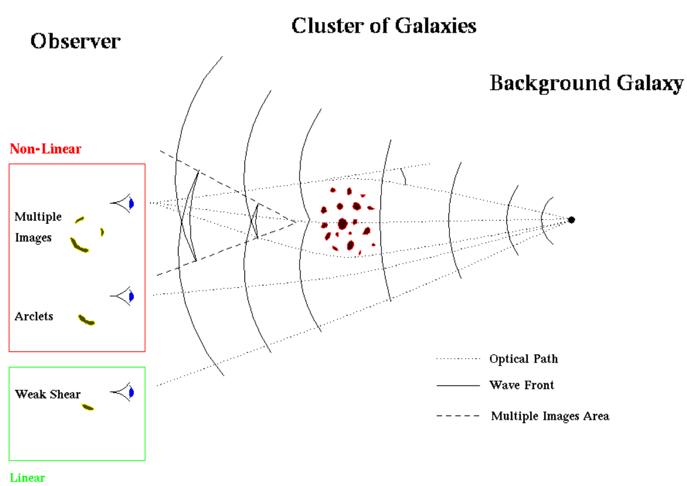
Mass passing in front of background of galaxies, distorting their received images.

Clusters: Gravitational Lensing

Illustration:

Dependent on whether the light passes within Einstein radius or outside, we deal with:

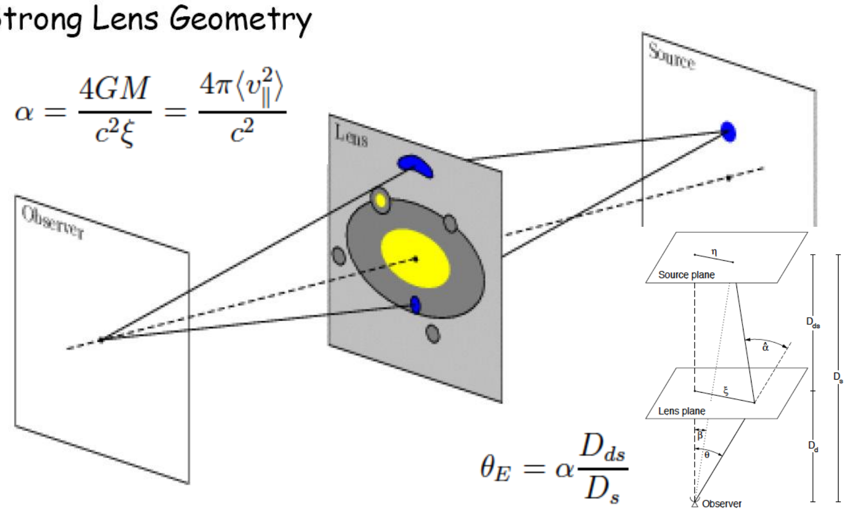
- Strong Lensing:
  nonlinear distortions
- Weak Lensing:
  linear distortions



Gravitational Strong Lensing

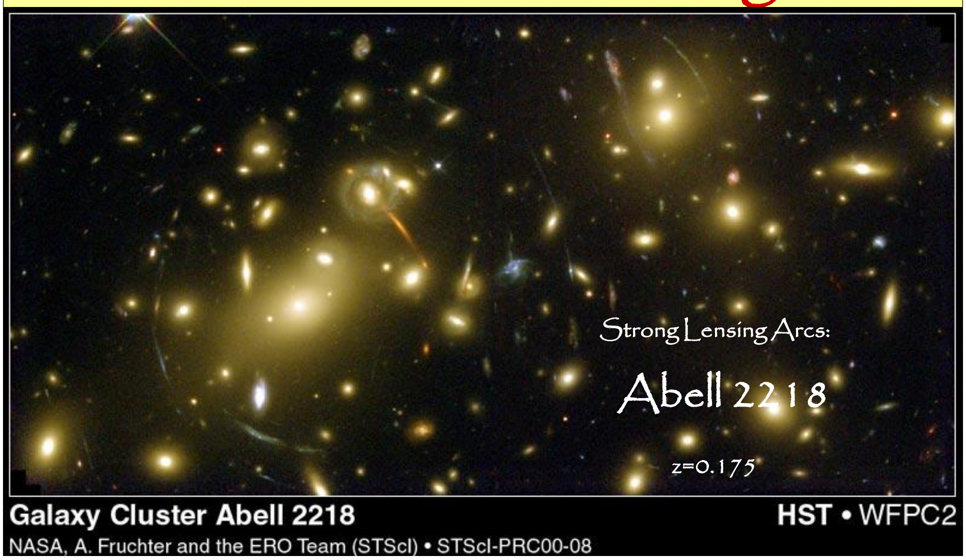
Strong Lens Geometry

$$\alpha = \frac{4GM}{c^2\xi} = \frac{4\pi\langle v_{\parallel}^2\rangle}{c^2}$$



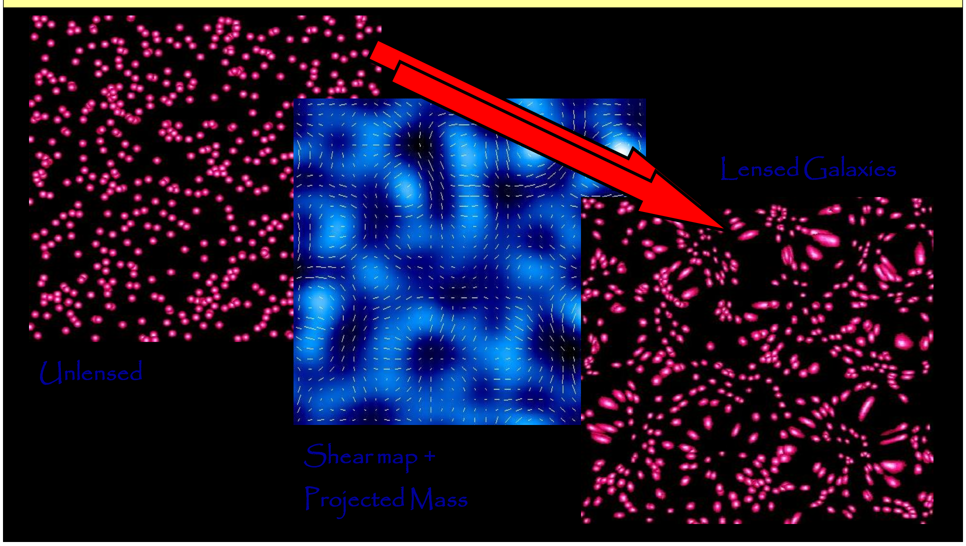
$$\theta_E = \alpha\frac{D_{ds}}{D_s}$$

Clusters: Gravitational Lensing



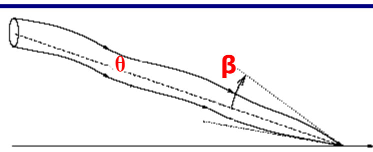
Clusters: Gravitational Weak Lensing

Gravitational Weak Lensing



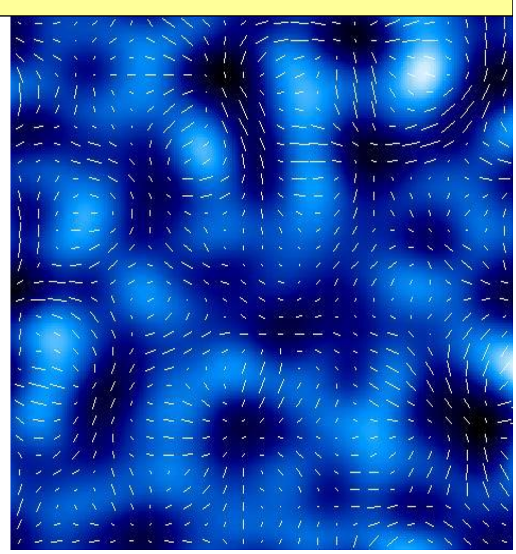
Gravitational Lensing

$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \underbrace{\begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix}}_{\text{Magnification}} + \underbrace{\begin{pmatrix} -\gamma_1 & \gamma_2 \\ \gamma_2 & \gamma_1 \end{pmatrix}}_{\text{Shear}}$$



$$\begin{aligned} \kappa &= \frac{1}{2}\left(\phi_{,11} + \phi_{,22}\right) \\ \gamma_1 &= \frac{1}{2}\left(\phi_{,11} - \phi_{,22}\right) \\ \gamma_2 &= \phi_{,12} \end{aligned}$$

$$\phi_{,ij} = \frac{\partial^2 \phi}{\partial \theta_i \partial \theta_j}$$

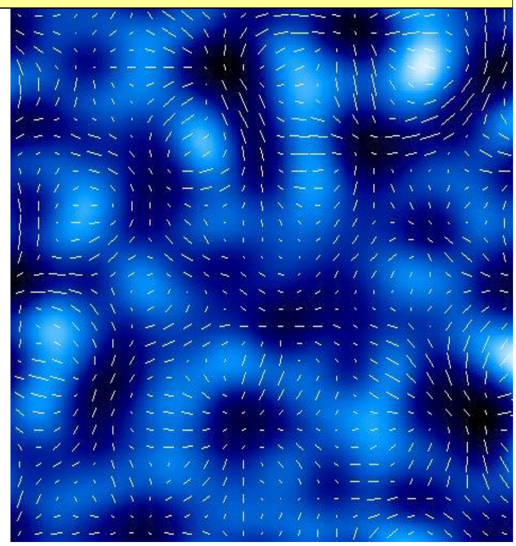


Gravitational Lensing

$$\kappa = \frac{1}{2}(\phi_{,11} + \phi_{,22})$$
$$\gamma_1 = \frac{1}{2}(\phi_{,11} - \phi_{,22})$$
$$\gamma_2 = \phi_{,12}$$
$$\phi_{,ij} = \frac{\partial^2 \phi}{\partial\theta_i \partial\theta_j}$$

Lensing Potential
related to
Peculiar Gravitational Potential

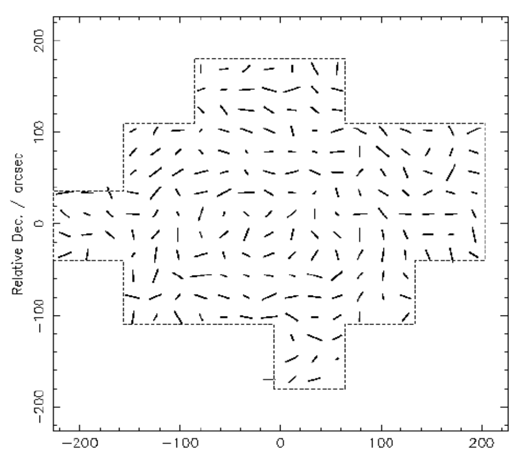
$$\phi(\mathbf{r}) = \frac{2}{c^2}\int_0^r dr' \, \Phi(\mathbf{r}') \left(\frac{1}{r} - \frac{1}{r'}\right)$$



Clusters: Gravitational Lensing

MS1054

- z=0.83 one of the highest z clusters
- Studied by
  - Clowe et al. Keck
  - Hoekstra et al. HST



Shear map

Clusters: Gravitational Lensing

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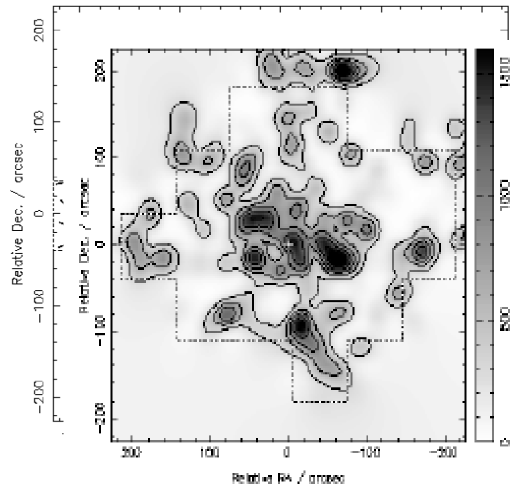
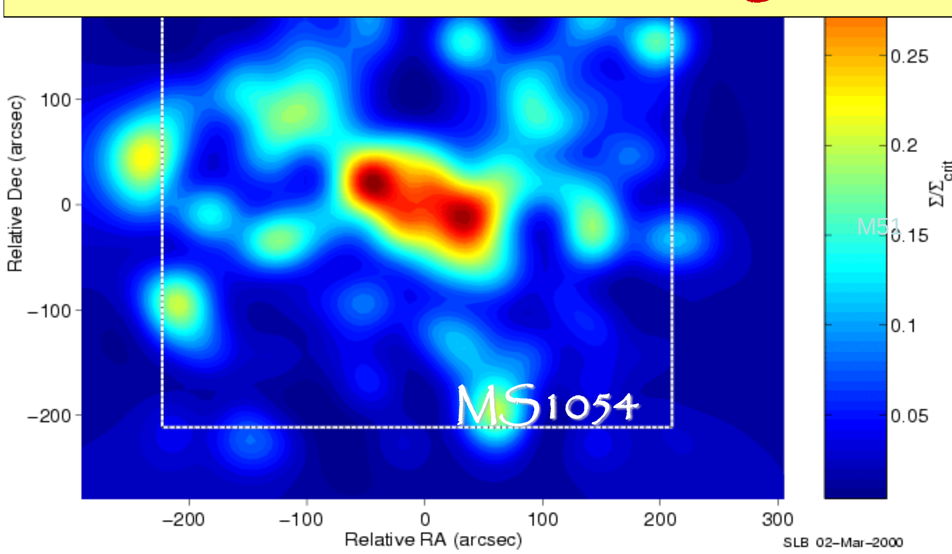
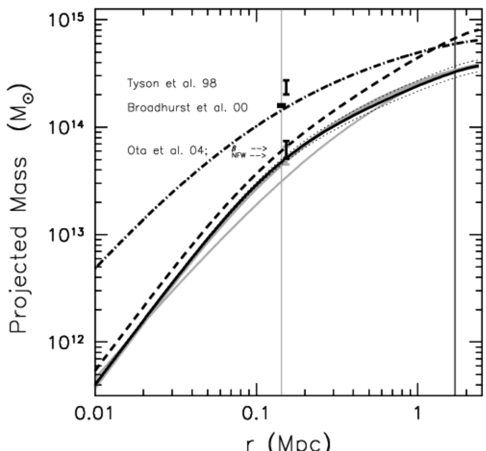


Clusters: Gravitational Lensing

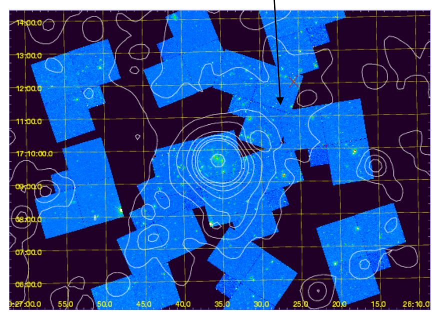


Clusters: Comparison Lensing & X-ray



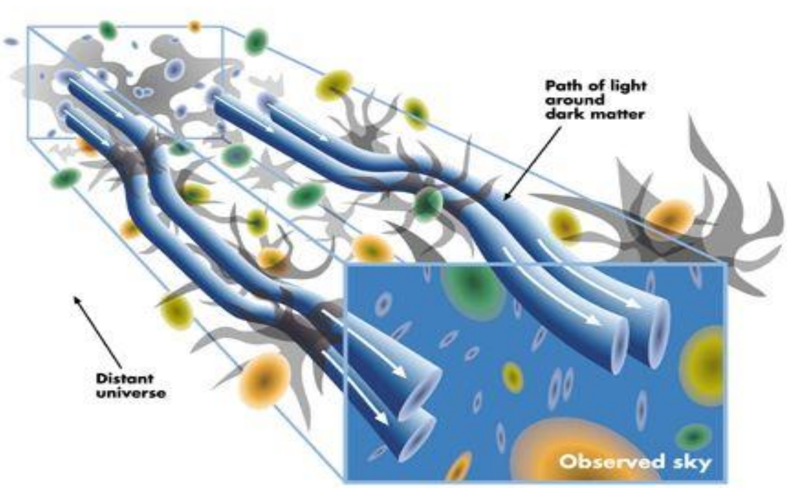
CL0024+17

Same substructure seen in weak lensing and X-rays

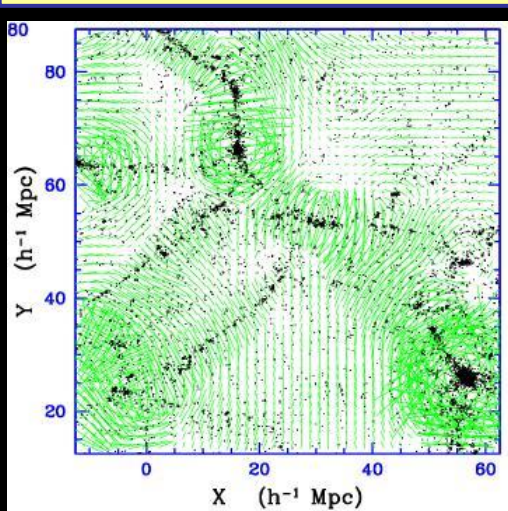


X-ray overlay on HST image

Cosmic Shear



the Web: Shear Distortions & Lensing



Large scale tidal shear distorts the paths of photons as they travel from their source to the observer.

This effect is known as "gravitational lensing". For moderate distortions, outside the Einstein radius ("weak lensing"),

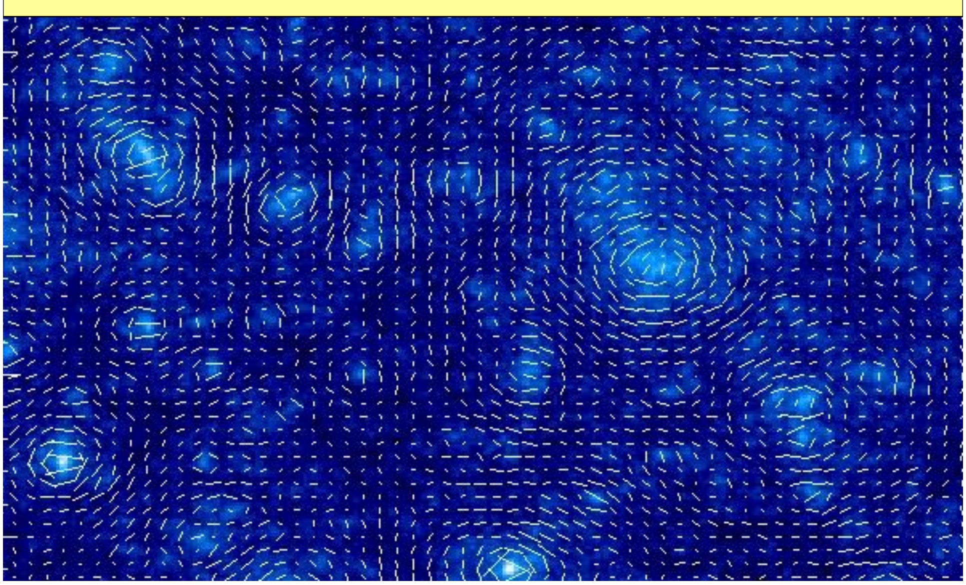
the distortions of galaxy shapes can be measured and inverted to yield the (projected) distorting mass distribution.

Clusters are outstanding, representing major potential wells.

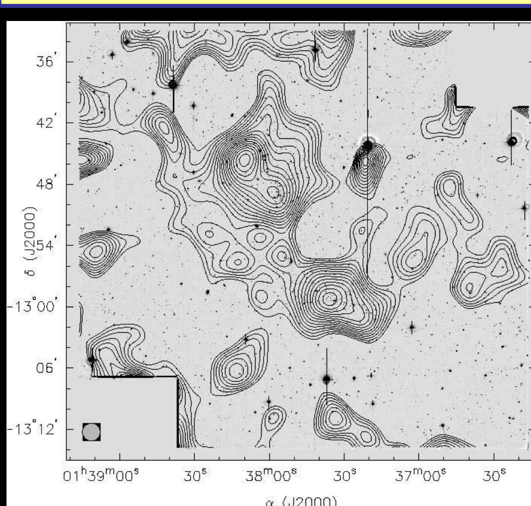
But also the generic Megaparsec matter distribution "lenses":

Cosmic Shear

Cosmic Shear



the Web: Shear Distortions & Lensing



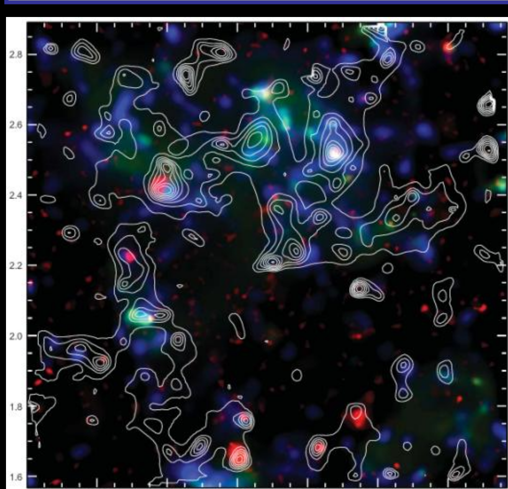
Although the cosmic shear due to a filament is considerably weaker than that of the clusters, recently

Dietrich, Schneider & Romano-Diaz (2004)

succeeded in mapping the filament between A222 and A333 on the basis of the measured lensing.

This shows that filaments are shown to be genuine dynamical entities.

the Web: Shear Distortions & Lensing



First genuine map

Large Scale

Cosmic Dark Matter distribution

by means of weak lensing:

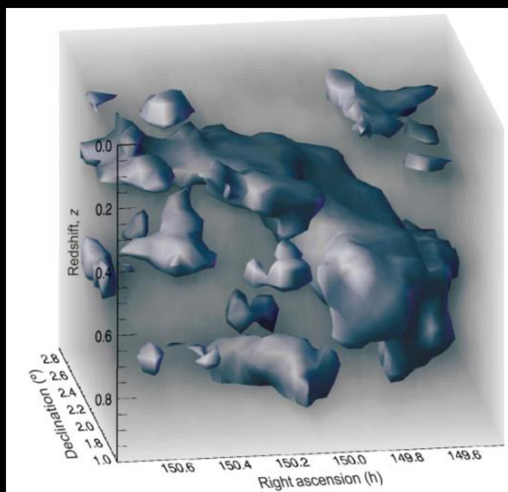
Clearly visible is the filamentary

Weblike nature of the mass

Distribution.

Massey et al. 2007

the Web: Shear Distortions & Lensing



First genuine map
Large Scale
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