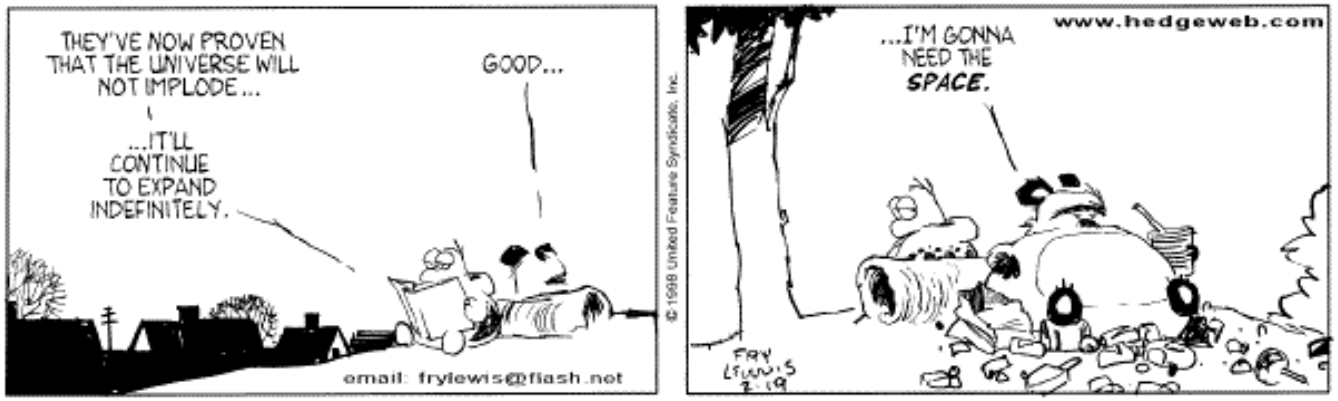
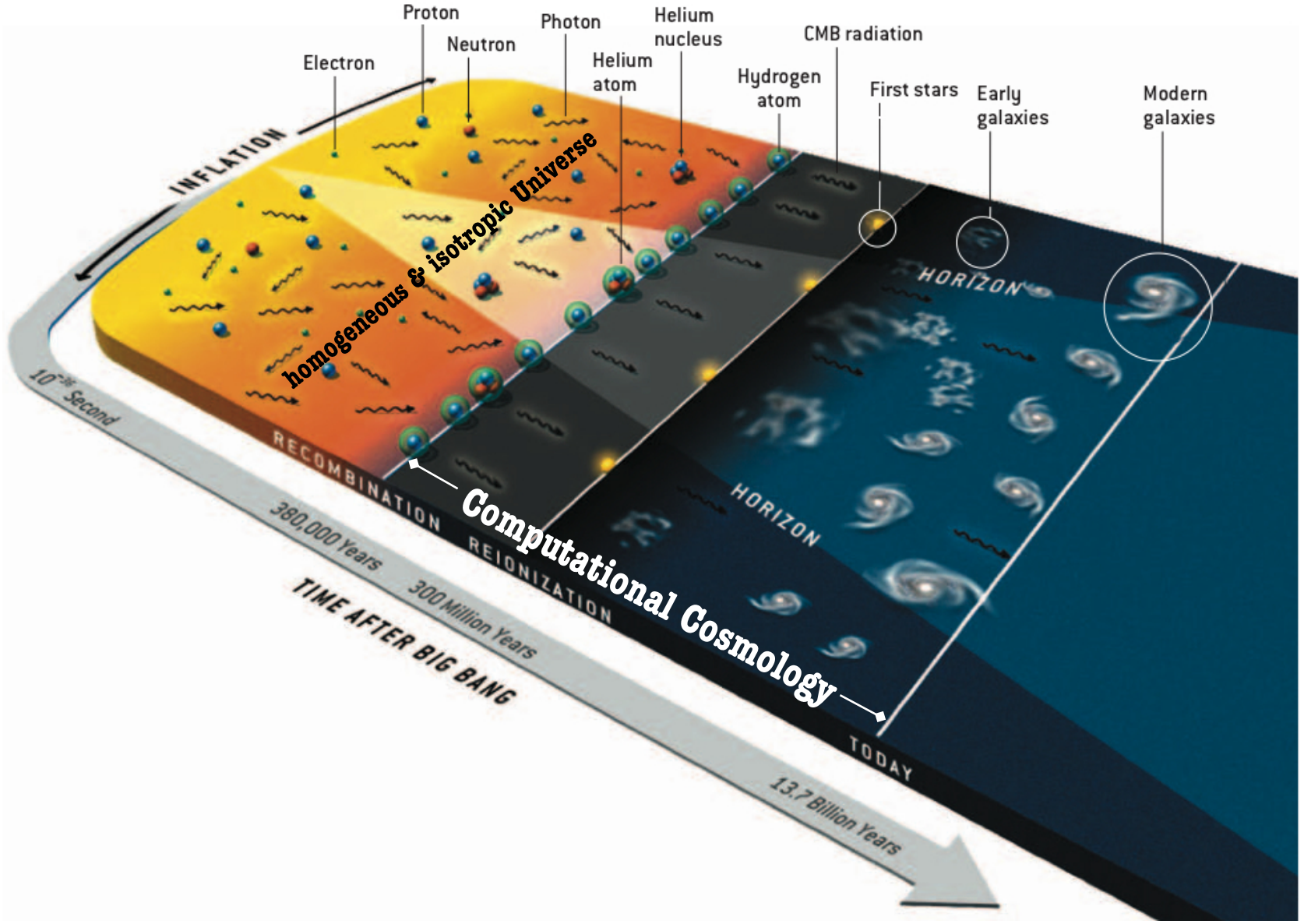
Alexander Knebe, *Universidad Autonoma de Madrid*

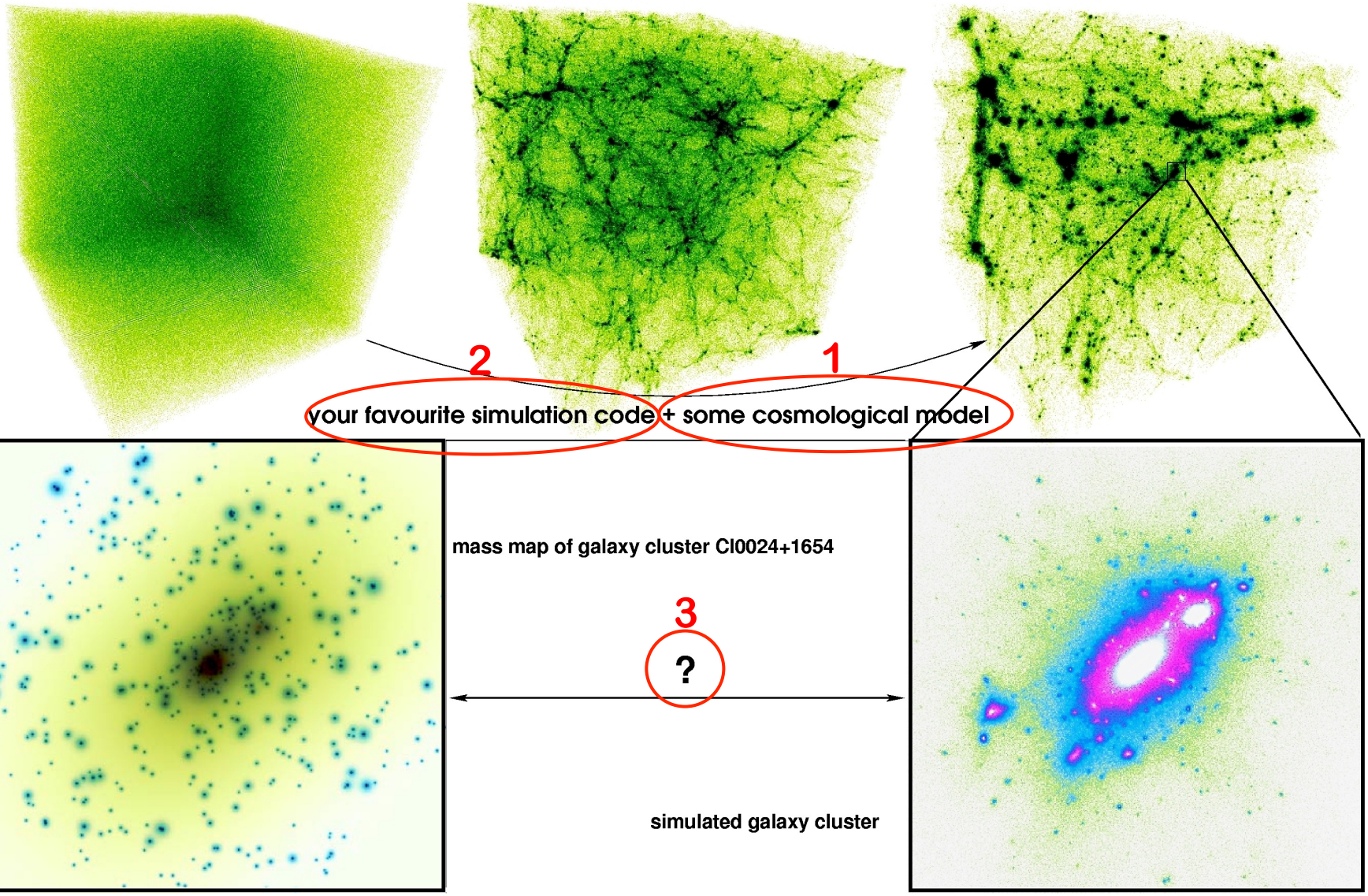


Cosmology is the study

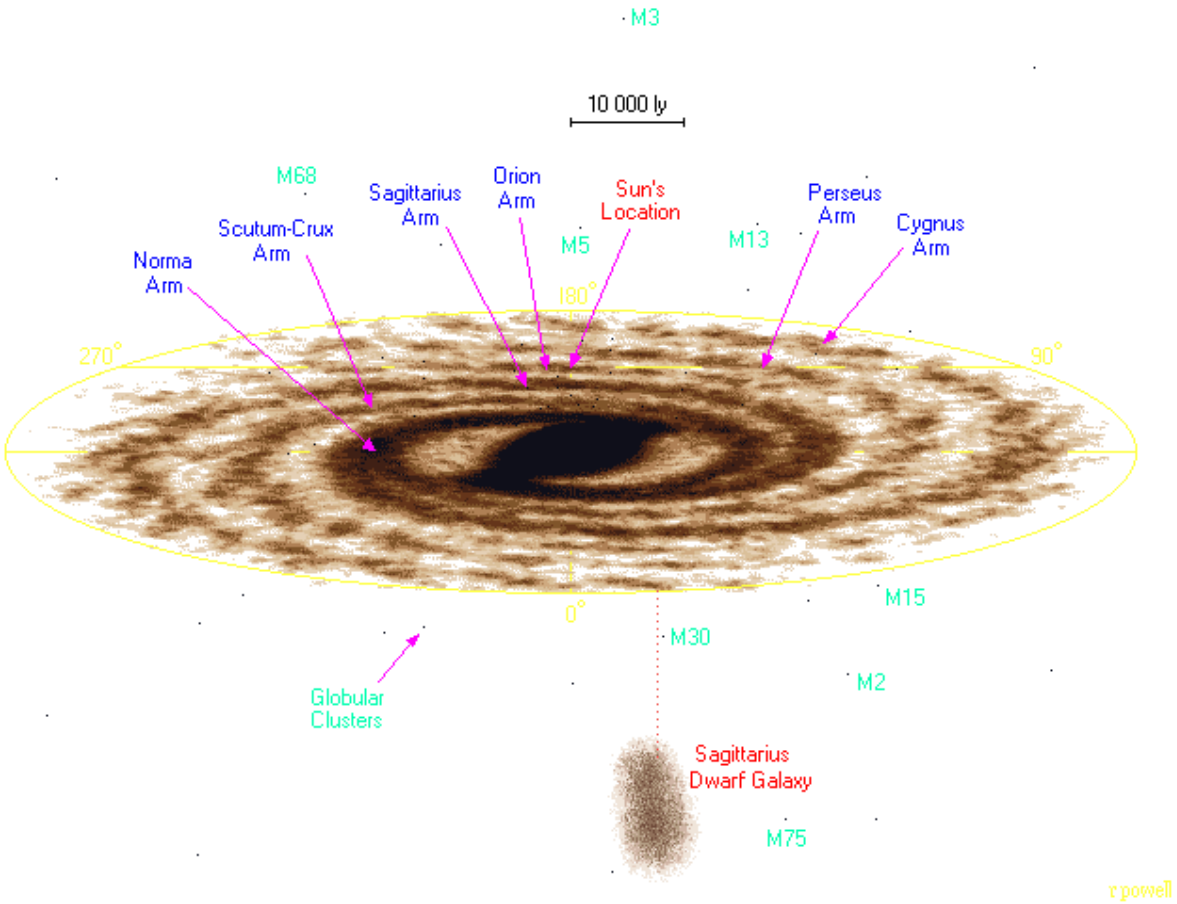
of the origin, evolution, and future

of our Universe


Proton
Neutron
Photon
Helium nucleus
CMB radiation
Electron
Helium atom
Hydrogen atom
First stars
Early galaxies
Modern galaxies
INFLATION
homogeneous & isotropic Universe
HORIZON
HORIZON
RECOMBINATION
REIONIZATION
Computational Cosmology
TODAY
10⁻³⁶ Second
380,000 Years
300 Million Years
13.7 Billion Years
TIME AFTER BIG BANG

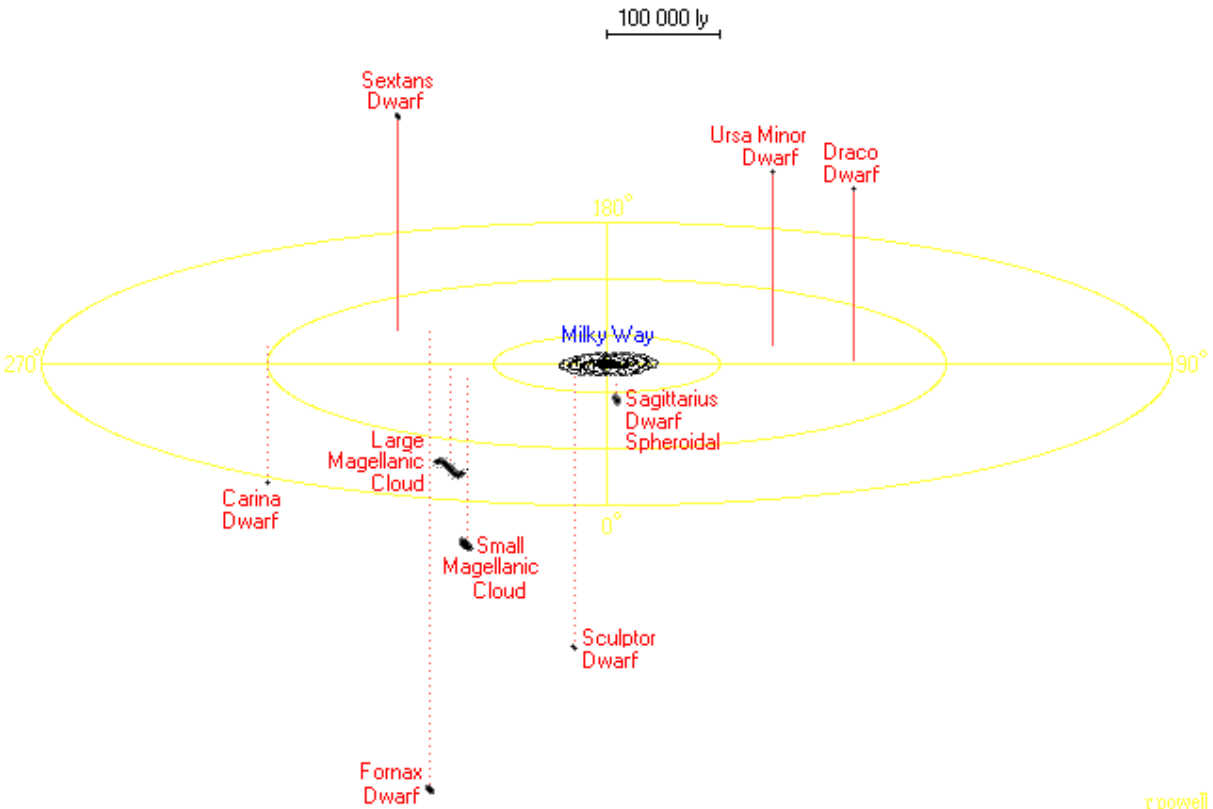

2
1
your favourite simulation code + some cosmological model
mass map of galaxy cluster Cl0024+1654
3
?
simulated galaxy cluster

- orders of ten



http://hometown.aol.com/nlpjp/cosmo.htm

- orders of ten



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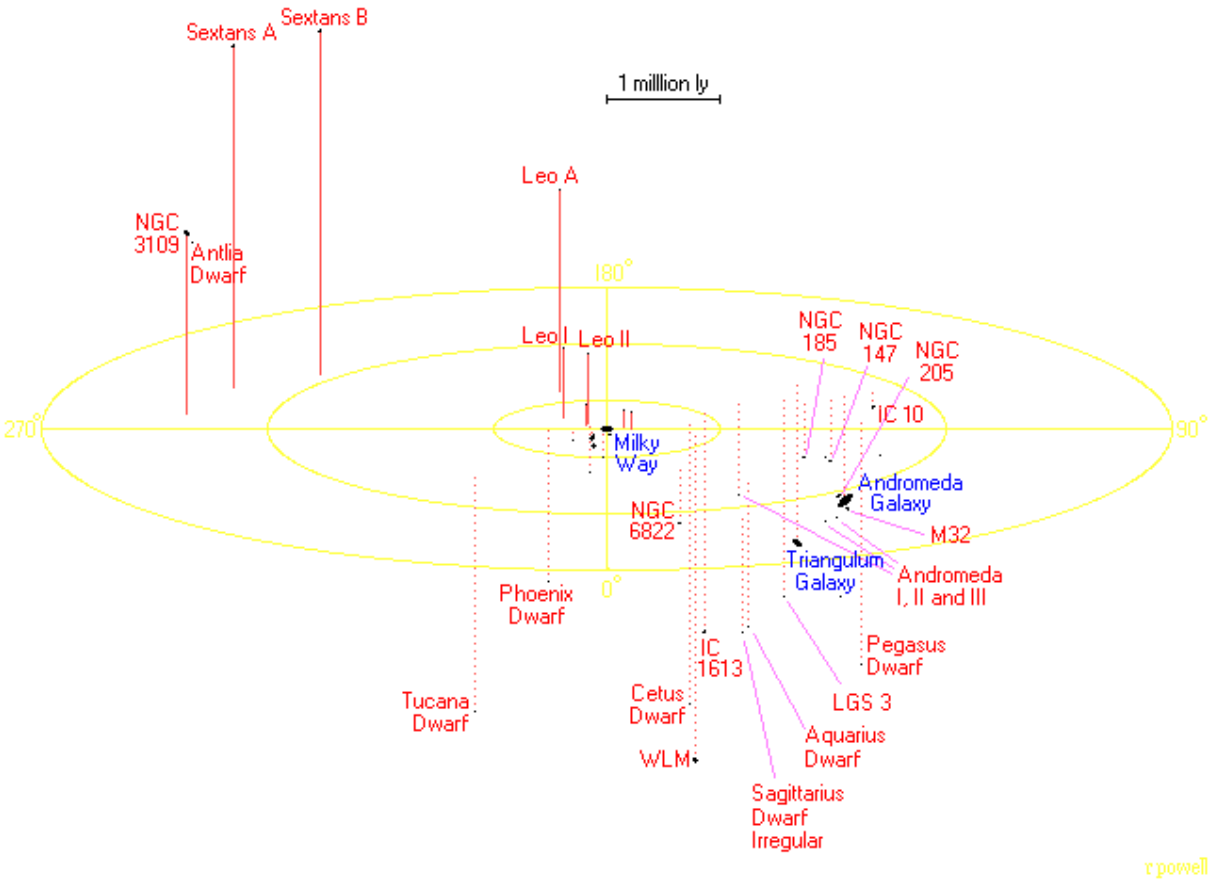

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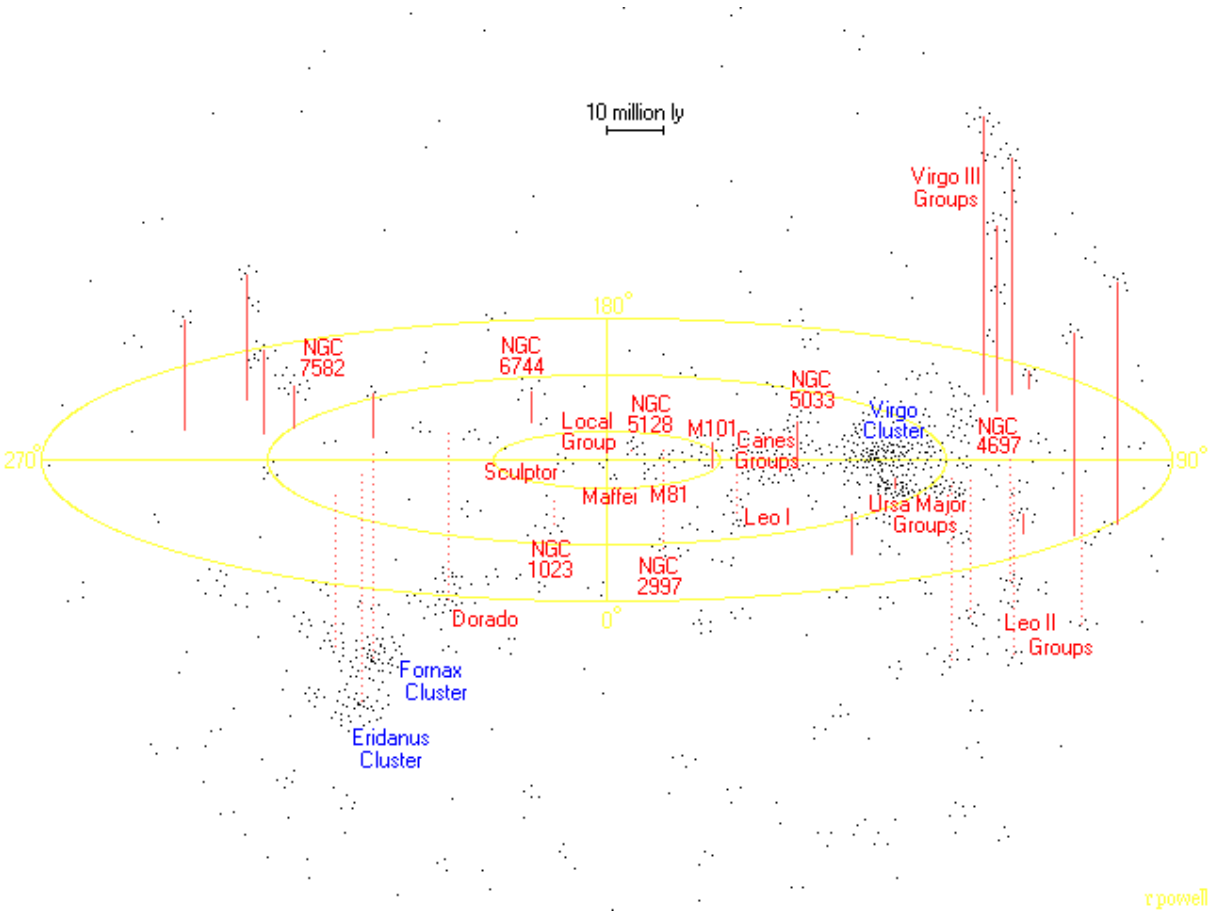

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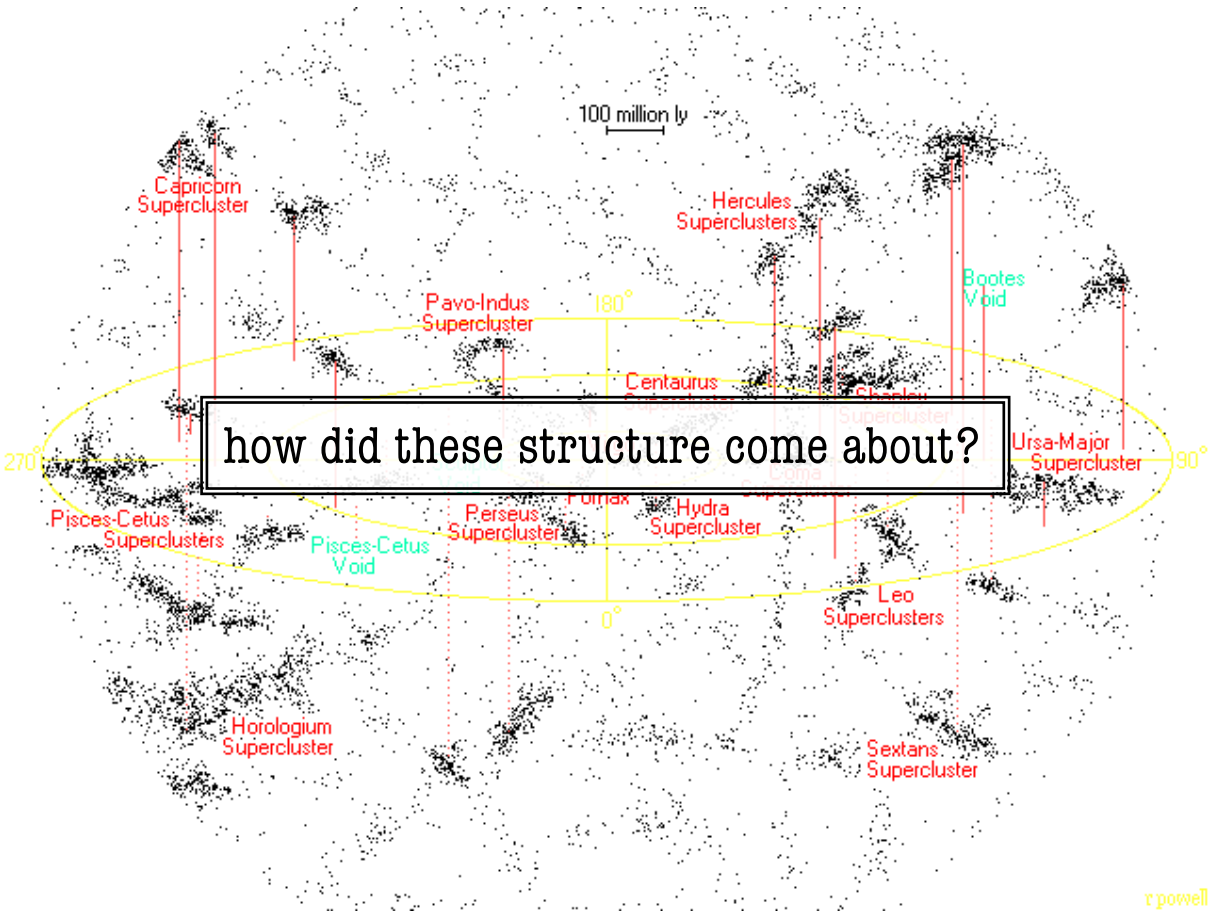
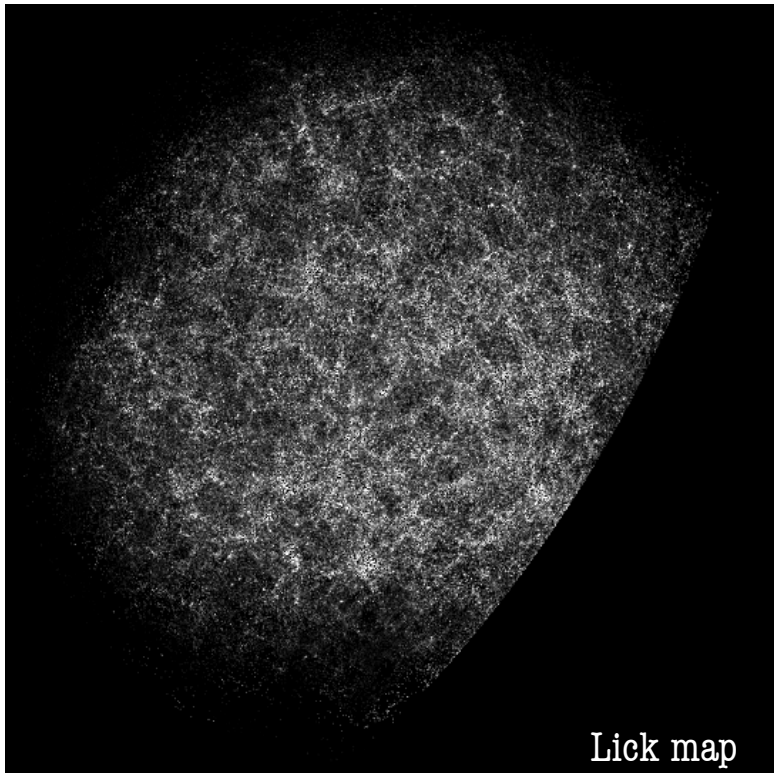
- orders of ten

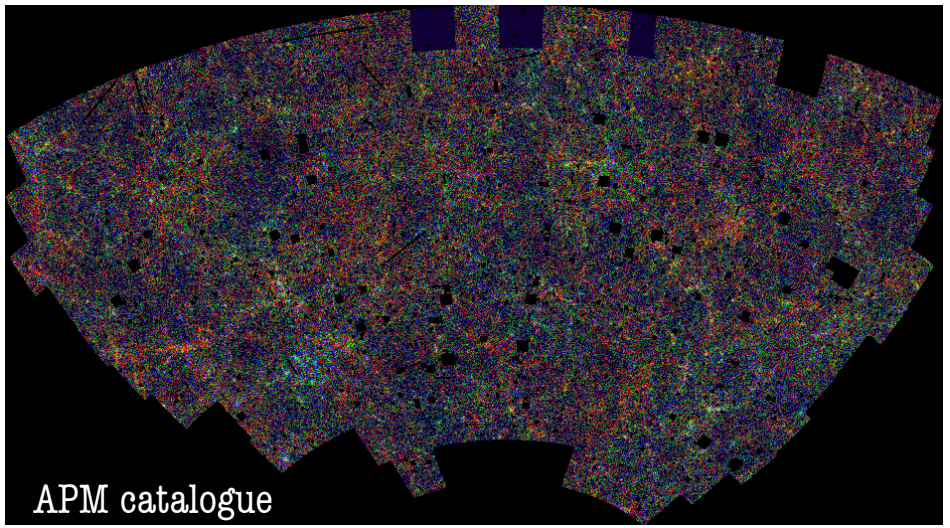


http://hometown.aol.com/nlpjp/cosmo.htm

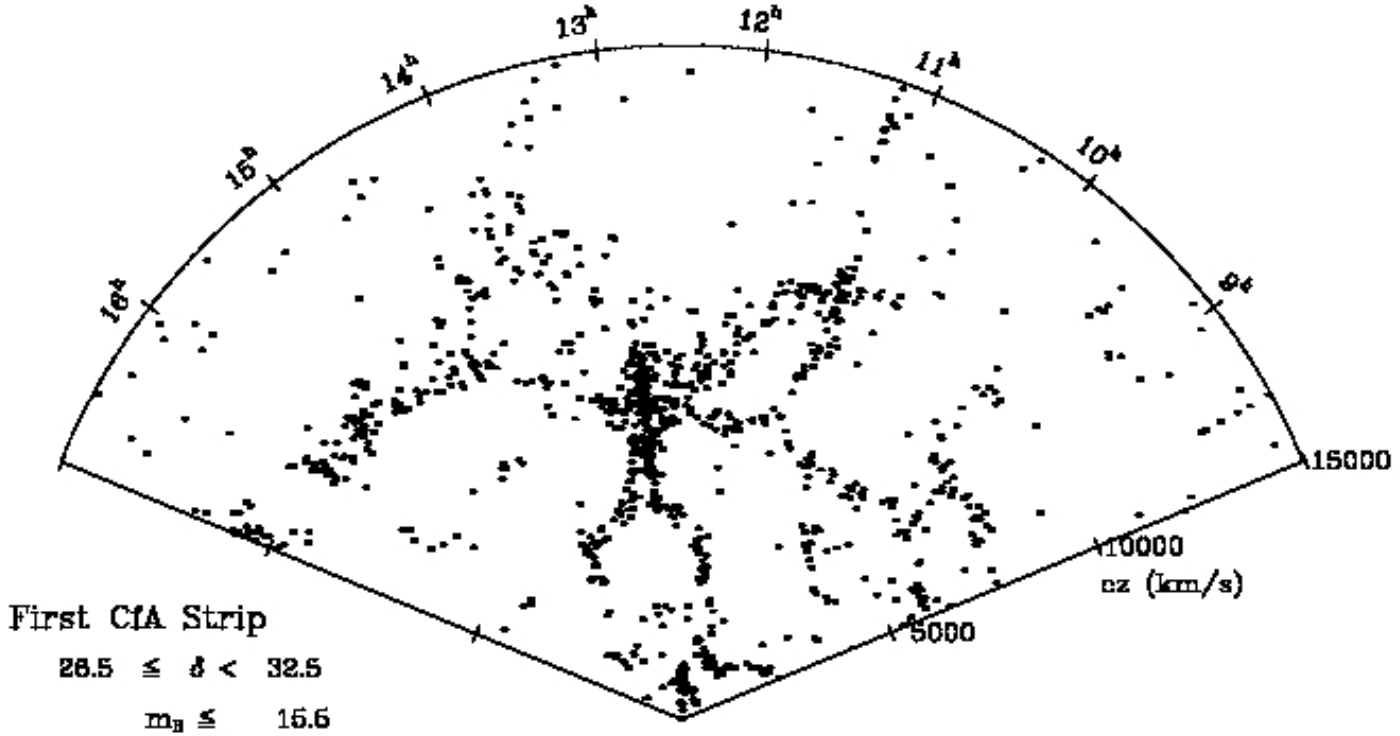
- galaxy catalogues (2D)

• Shapley & Ames (1932)	1,250 galaxies
• Palomar Sky Survey (1950)	~5,000 galaxies
• Lick Survey (1967)	~1,000,000 galaxies
• APM catalogue (1990)	~2,000,000 galaxies


Lick map


APM catalogue

- galaxy catalogues (3D)
  - CfA (1986) ~1,000 galaxies



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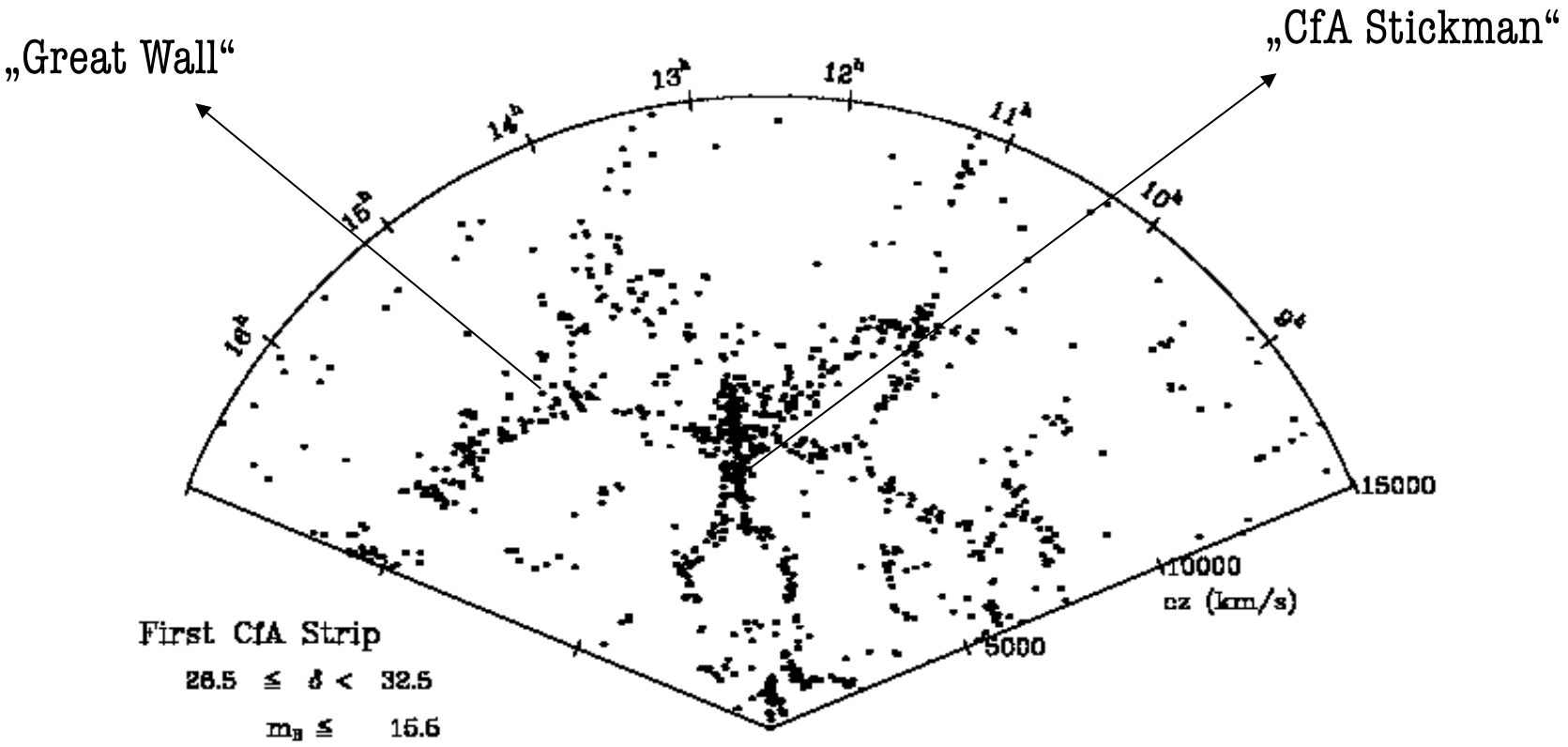
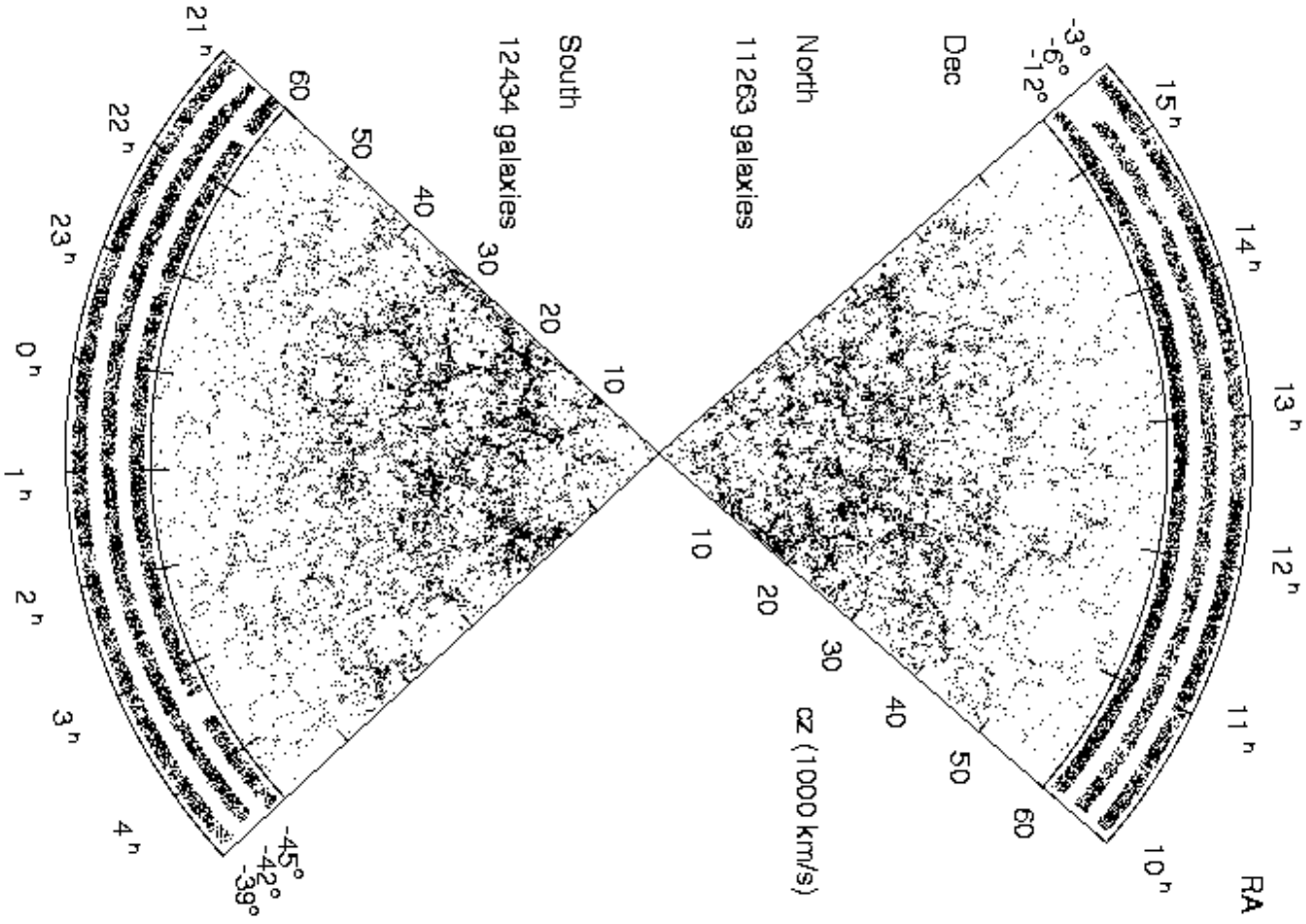
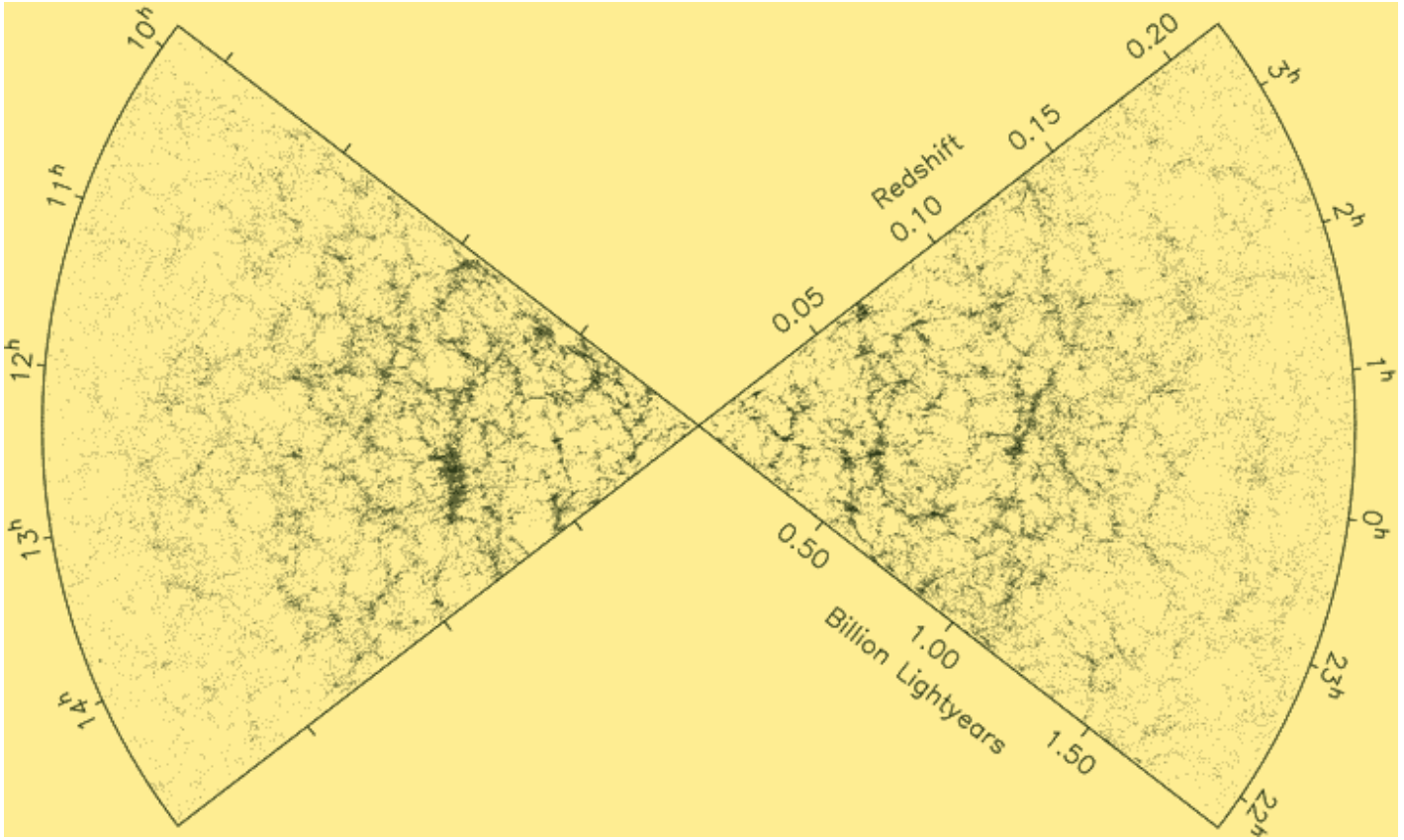


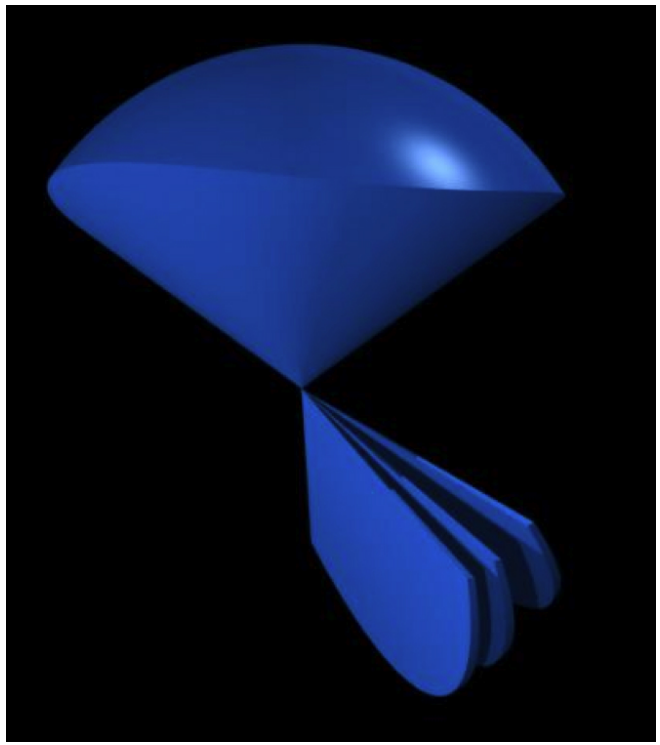
- galaxy catalogues (3D)
  - Las Campanas Redshift Survey (1998) ~20,000 galaxies

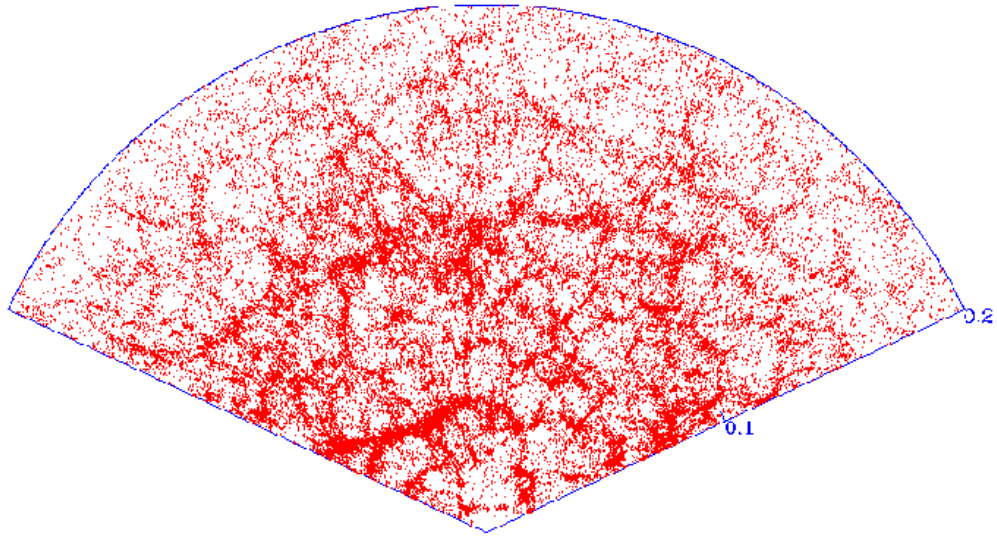


- galaxy catalogues (3D)
  - 2dF Survey (2003) ~200,000 galaxies



- galaxy catalogues (3D)
    - Sloan Digital Sky Survey (2003) ~1,000,000 galaxies





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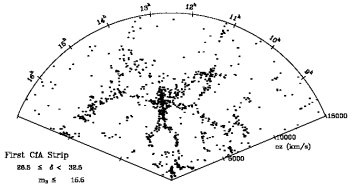
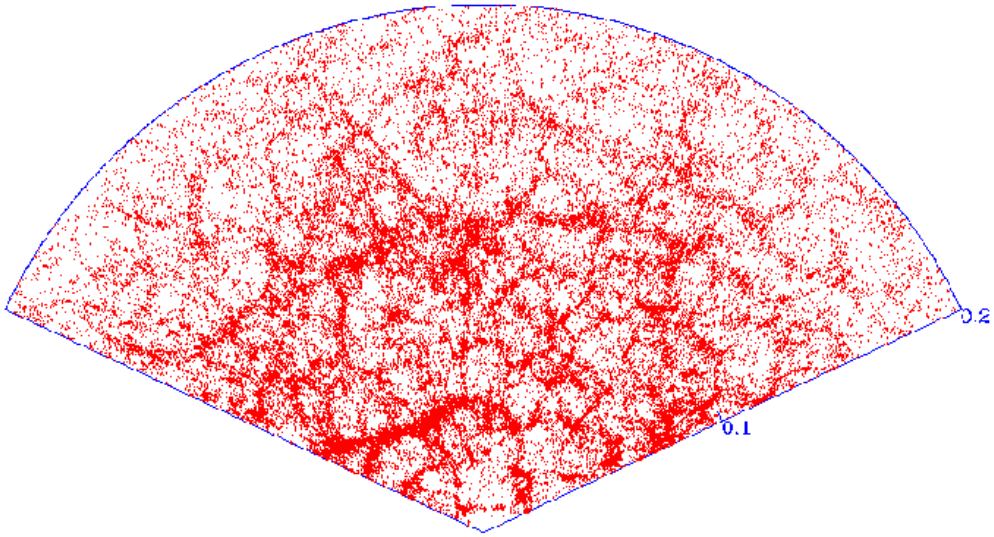
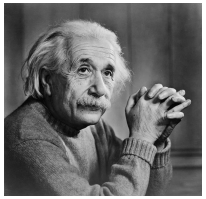


CfA (1986)



SDSS (2003)

GRT $\xrightarrow[\text{homogeneity}]{\text{isotropy}}$ Friedmann Equations



Albert Einstein

Alexander Friedmann

GRT $\xrightarrow[\text{homogeneity}]{\text{isotropy}}$ Friedmann Equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = .H_0^2(\Omega_0^r a^{-4} + \Omega_0^m a^{-3} + \Omega_0^k a^{-2} + \Omega_0^\Lambda)$$

$$q = .\frac{1}{2}\Omega_m - \Omega_\Lambda - \Omega_r$$

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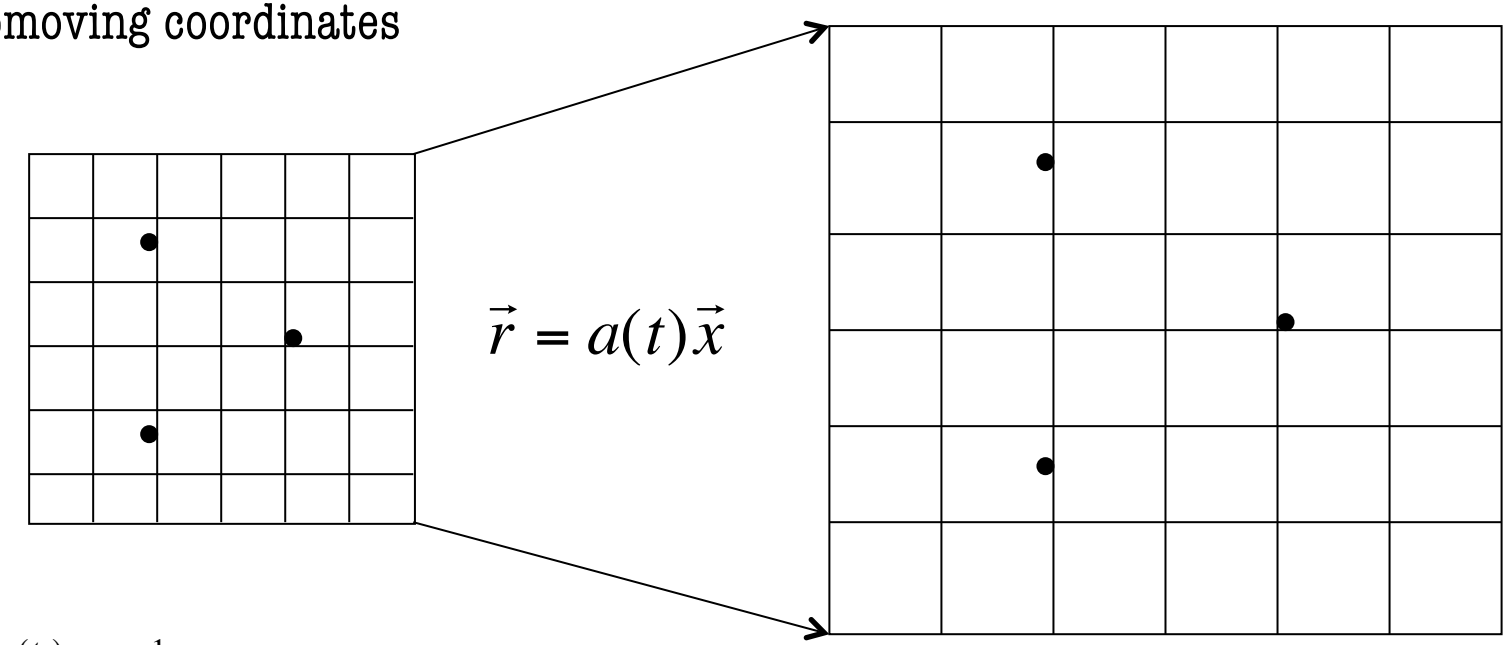
- comoving coordinates



$a(t_0) = a_0 = 1$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = .H_0^2(\Omega_0^r a^{-4} + \Omega_0^m a^{-3} + \Omega_0^k a^{-2} + \Omega_0^\Lambda)$$

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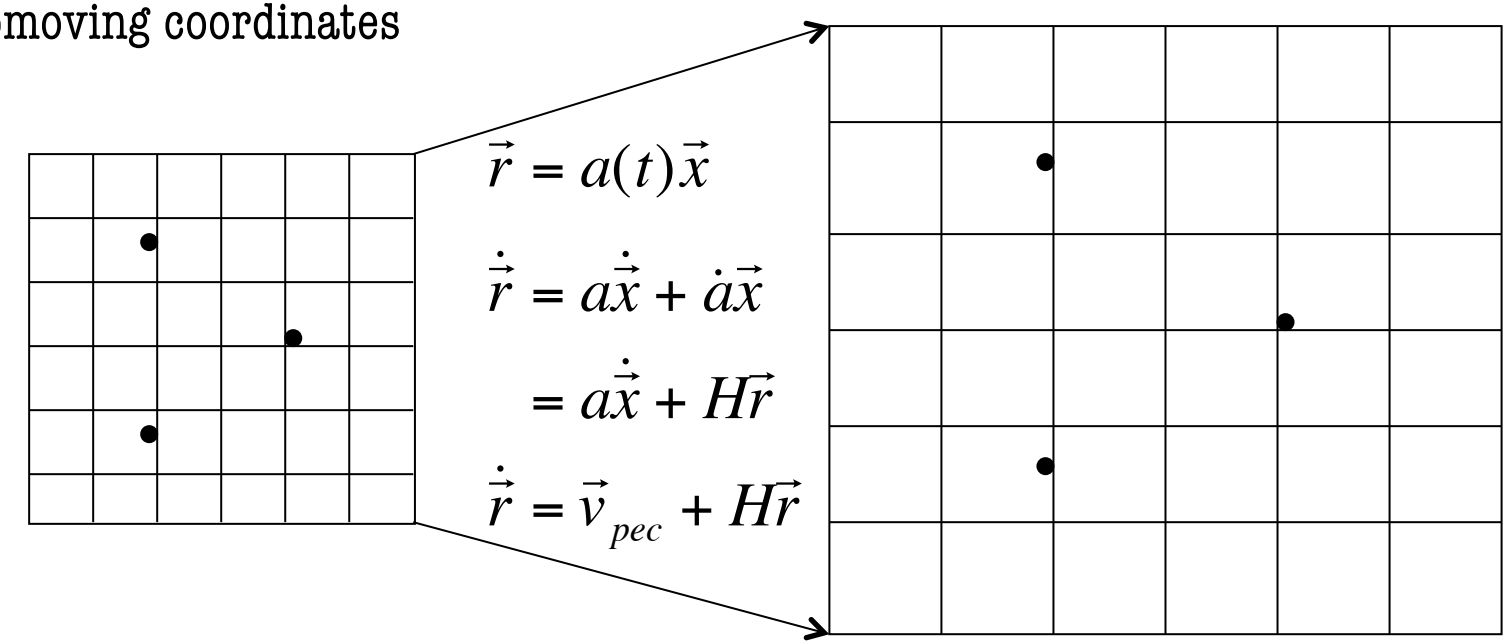

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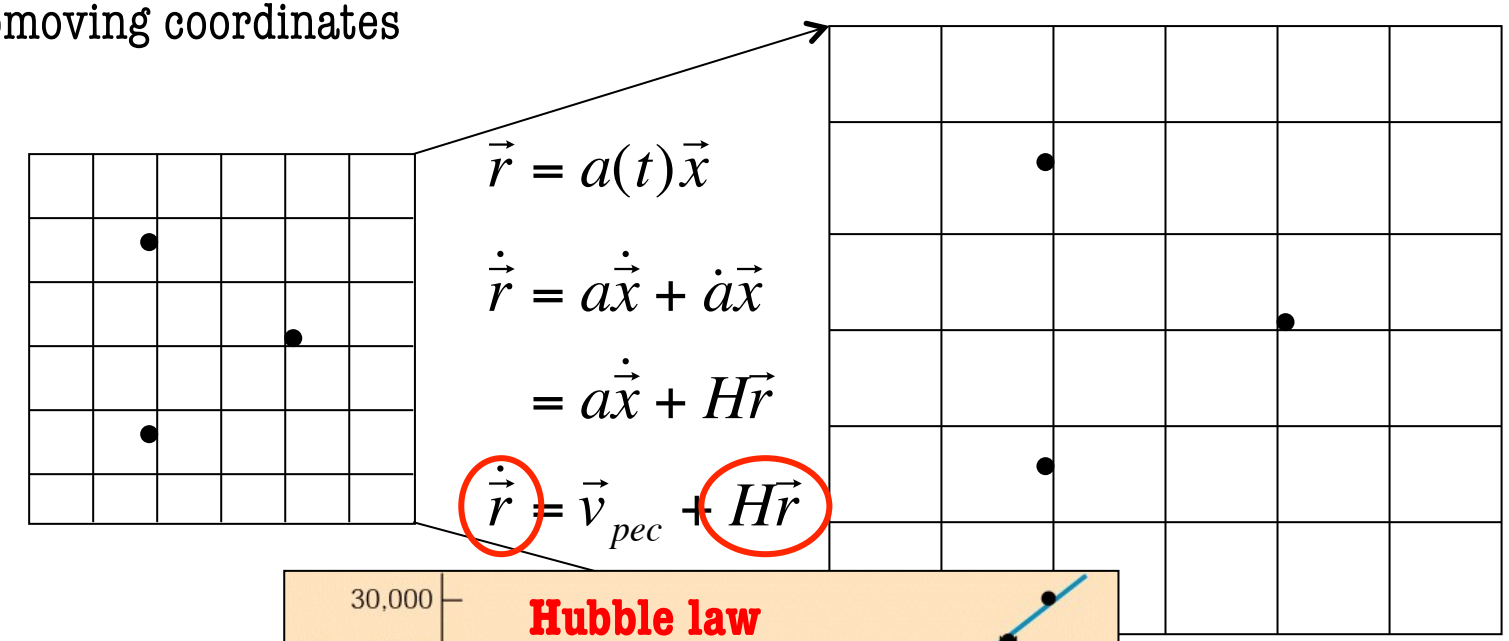
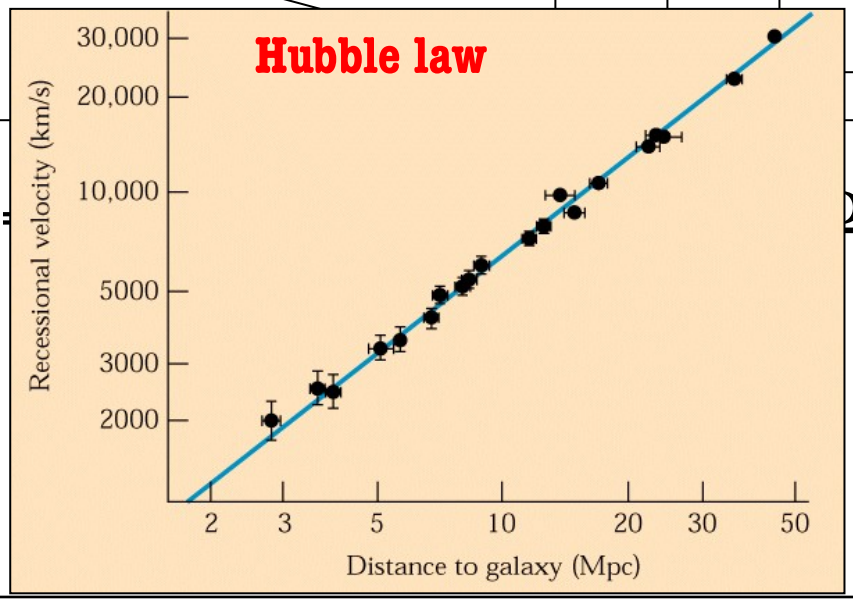


$$\vec{r} = a(t)\vec{x}$$

$$\dot{\vec{r}} = a\dot{\vec{x}} + \dot{a}\vec{x}$$

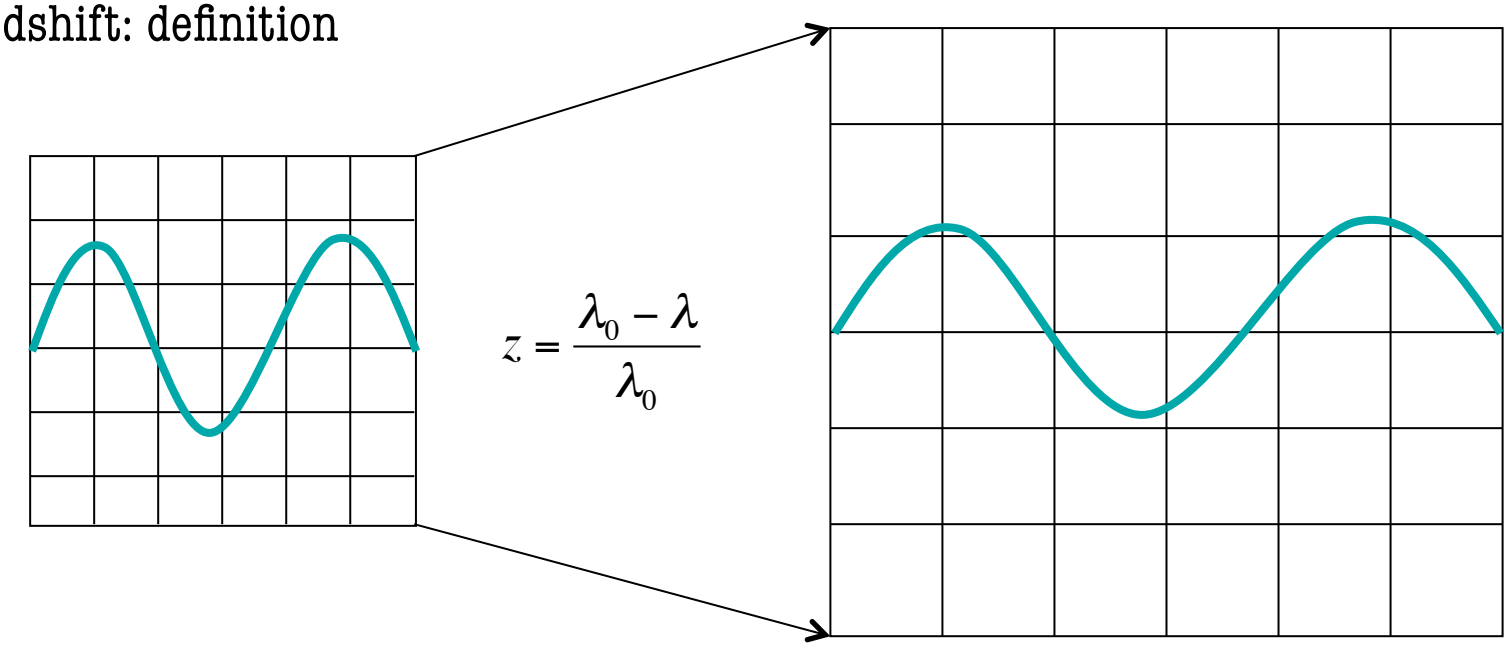
$$= a\dot{\vec{x}} + H\vec{r}$$

$$\dot{\vec{r}} = \vec{v}_{pec} + H\vec{r}$$



$$H^2 = \quad \Omega_0^k a^{-2} + \Omega_0^\Lambda)$$

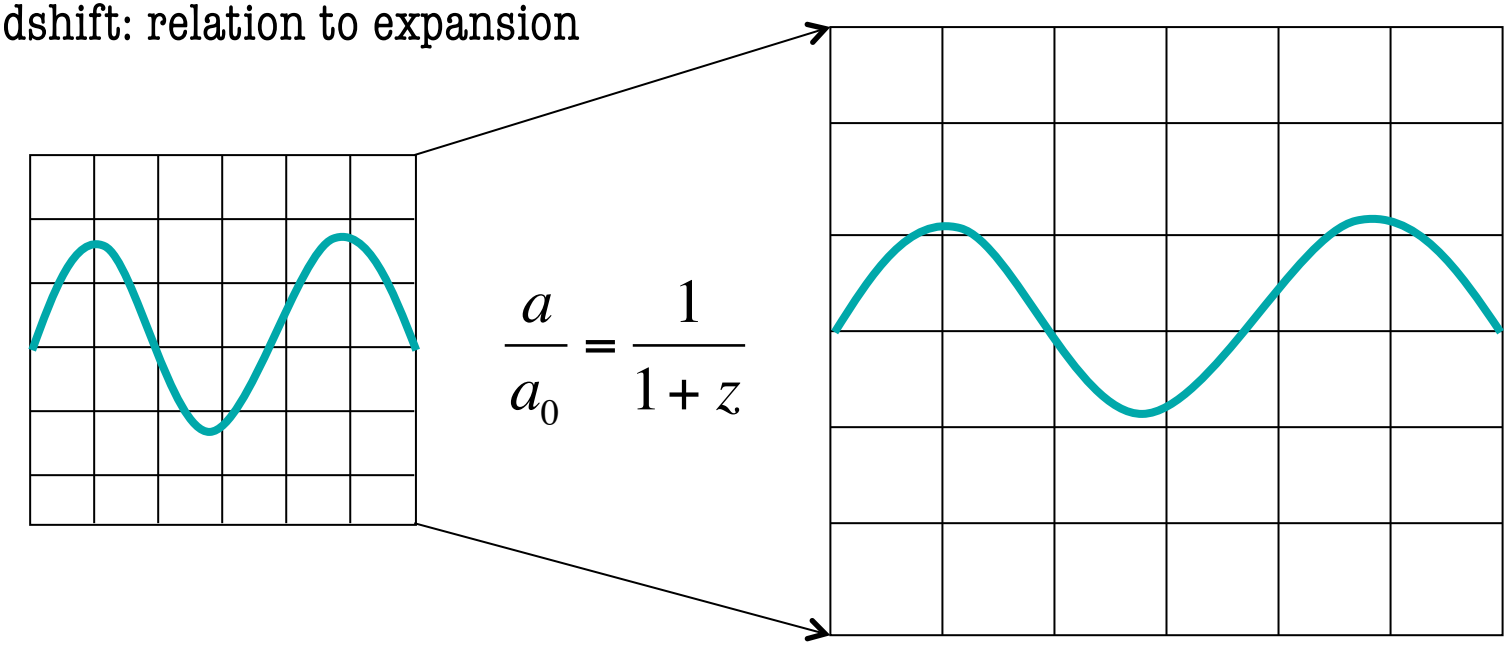
- redshift: definition



$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = .H_0^2(\Omega_0^r a^{-4} + \Omega_0^m a^{-3} + \Omega_0^k a^{-2} + \Omega_0^\Lambda)$$

$$q = .\frac{1}{2}\Omega_m - \Omega_\Lambda - \Omega_r$$

- redshift: relation to expansion

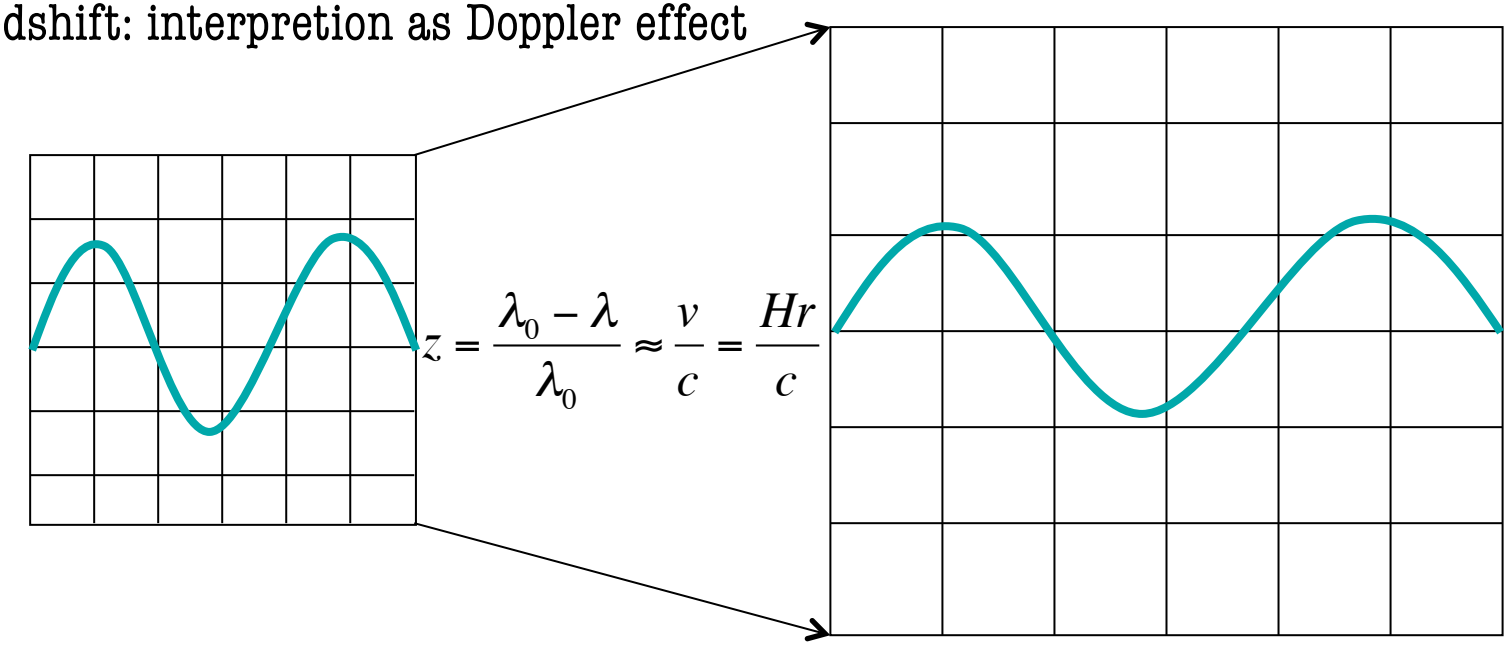


$$\frac{a}{a_0} = \frac{1}{1+z}$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = .H_0^2(\Omega_0^r a^{-4} + \Omega_0^m a^{-3} + \Omega_0^k a^{-2} + \Omega_0^\Lambda)$$

$$q = .\frac{1}{2}\Omega_m - \Omega_\Lambda - \Omega_r$$

- redshift: interpretion as Doppler effect



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$$q = .\frac{1}{2}\Omega_m - \Omega_\Lambda - \Omega_r$$

$a(t)$ expansion factor of the Universe

$H(t) = \frac{\dot{a}}{a}$ Hubble parameter

$q(t) = -\frac{\ddot{a}a}{\dot{a}^2}$ deceleration parameter

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = .H_0^2(\Omega_0^r a^{-4} + \Omega_0^m a^{-3} + \Omega_0^k a^{-2} + \Omega_0^\Lambda)$$

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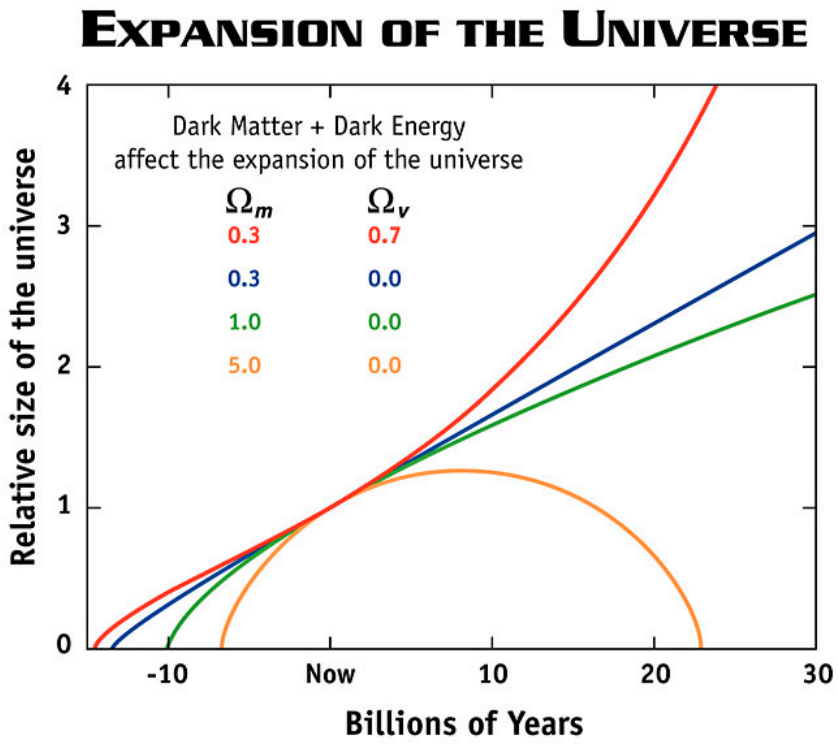

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$$q = .\frac{1}{2}\Omega_m - \Omega_\Lambda - \Omega_r$$

$$\Omega_m = \frac{8\pi G}{3H^2}\rho_m$$ matter energy density

$$\Omega_r = \frac{8\pi G}{3H^2}\rho_r$$ radiation energy density

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H^2}$$ cosmological constant

$$\Omega_k = -\frac{kc^2}{H^2}$$ curvature of the Universe

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = .H_0^2(\Omega_0^r a^{-4} + \Omega_0^m a^{-3} + \Omega_0^k a^{-2} + \Omega_0^\Lambda)$$

$$q = .\frac{1}{2}\Omega_m - \Omega_\Lambda - \Omega_r$$

$$\Omega_m = \frac{8\pi G}{3H^2}\rho_m$$ matter energy density

$3H^2/8\pi G$ = critical density to "close" the Universe
(ca. 1 H-atom per m^3)

$$\Omega_r = \frac{8\pi G}{3H^2}\rho_r$$ radiation energy density

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H^2}$$ cosmological constant

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- ΛCDM - Λ Cold Dark Matter

$$\Omega_m^0 \approx 0.3$$
$$\Omega_\Lambda^0 \approx 0.7$$
$$\Omega_r^0 \approx 2.3 \times 10^{-5} h^{-2}$$
$$\Omega_k^0 \approx 0$$

- ΛCDM - Λ Cold Dark Matter

$$\Omega_m^0 \approx 0.3$$
$$\Omega_\Lambda^0 \approx 0.7$$

- the Universe is spatially flat
- ca. 30% of the total energy density comes from matter
- ca. 70% of the total energy density is vacuum energy

- ΛCDM - Λ Cold Dark Matter

$$\Omega_m^0 \approx 0.3 = 0.26 + 0.04$$
$$\Omega_\Lambda^0 \approx 0.7$$

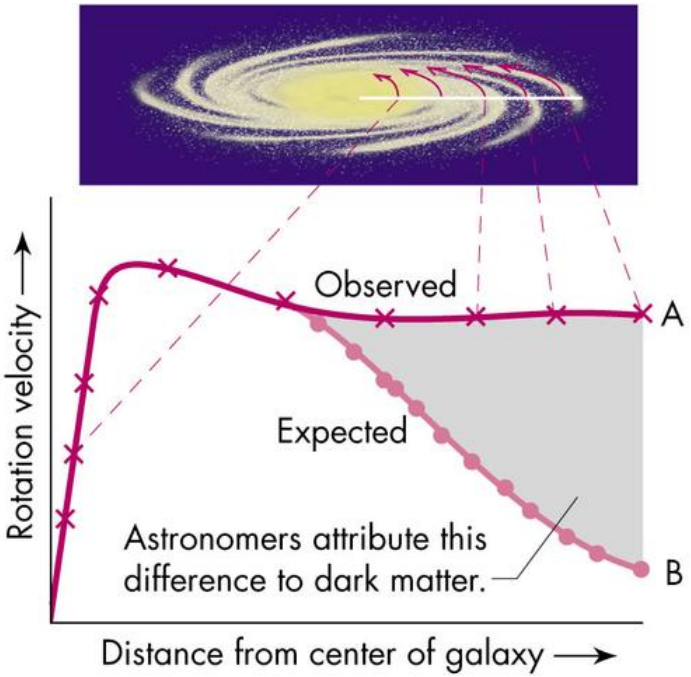
„dark matter“ luminous matter

- the Universe is spatially flat
- ca. 30% of the total energy density comes from matter
  - about 85% of that matter is “dark”
  - **only 15% of all matter in the Universe is luminous**
- ca. 70% of the total energy density is vacuum energy

- ΛCDM - Λ Cold Dark Matter

$$\Omega_m^0 \approx 0.3 = 0.26 + 0.04$$
$$\Omega_\Lambda^0 \approx 0.7$$

„dark matter“ luminous matter



- ΛCDM - Λ Cold Dark Matter

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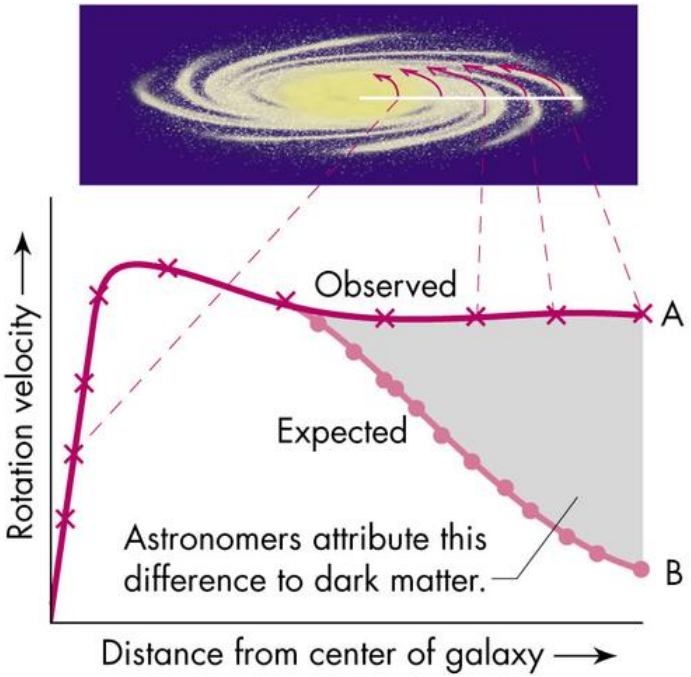


- ΛCDM - Λ Cold Dark Matter

(non-baryonic) Dark Matter Candidates

axion:	10^{-5} eV
neutrino:	10eV
WIMP:	1-10^{3} GeV
monopoles:	10^{16} GeV
Planck relics:	10^{19} GeV $(h^{\alpha}c^{\beta}G^{\gamma})$
primordial BHs:	>10^{15}g

???

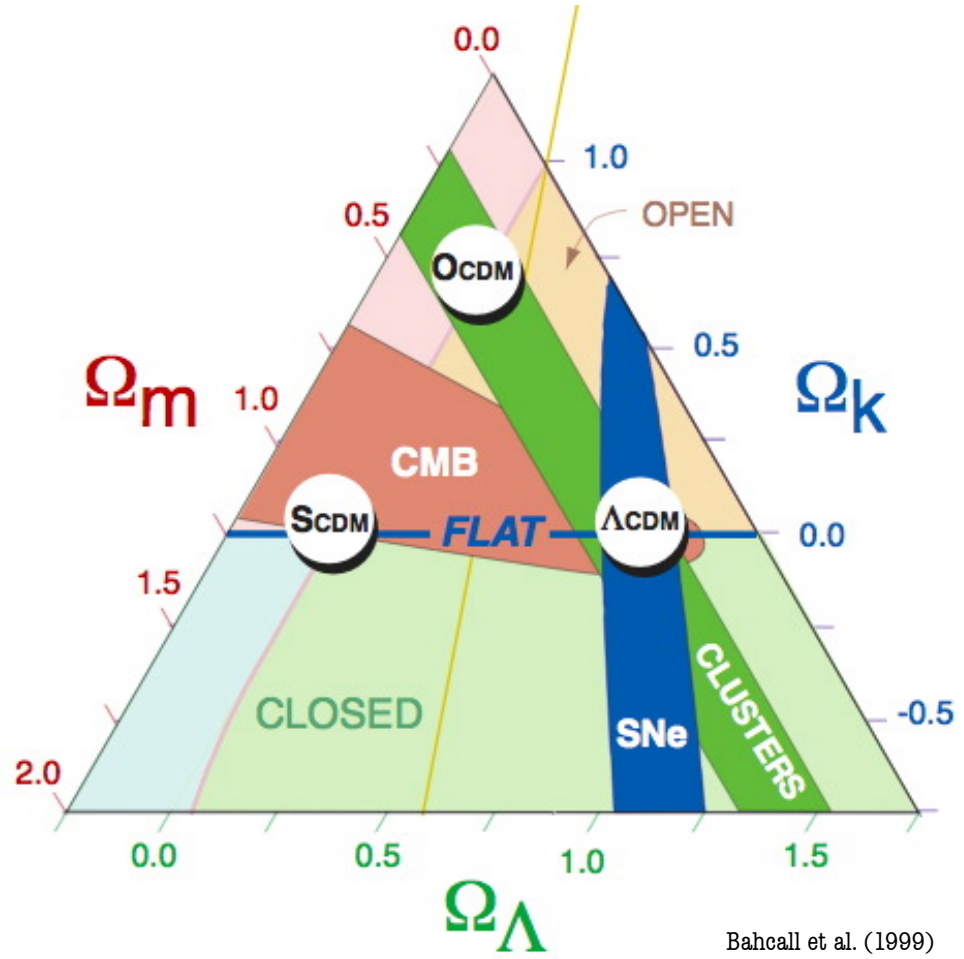
- ΛCDM - Λ Cold Dark Matter

(non-baryonic) Dark Matter Candidates

hot dark matter	axion:	10^{-5} eV
	neutrino:	10eV
warm dark matter		
cold dark matter	WIMP:	$1\text{-}10^{3}$ GeV
	monopoles:	10^{16} GeV
	Planck relics:	10^{19} GeV $(h^{\alpha}c^{\beta}G^{\gamma})$
	primordial BHs:	$>10^{15}$g

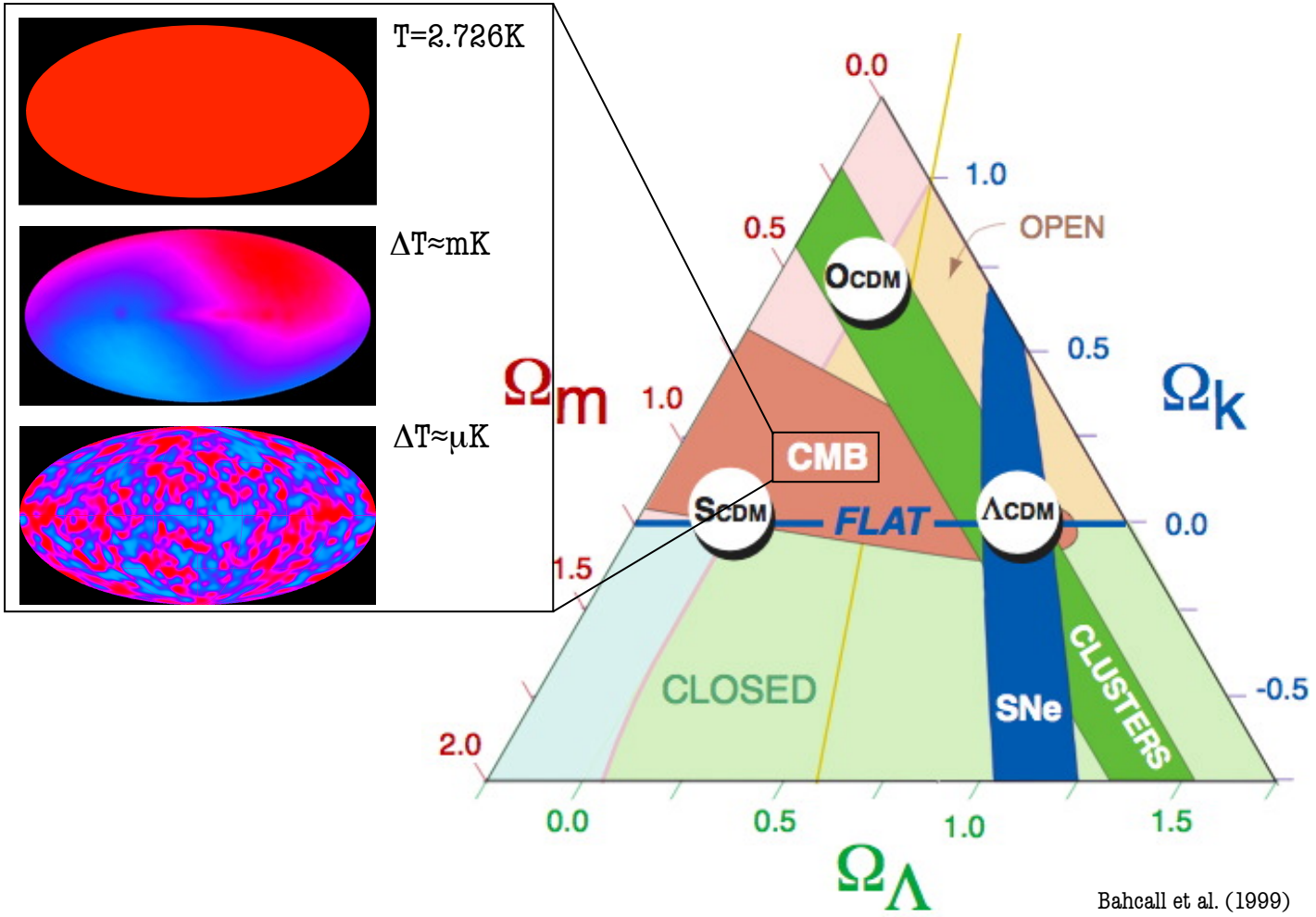
???

- ΛCDM - Λ Cold Dark Matter



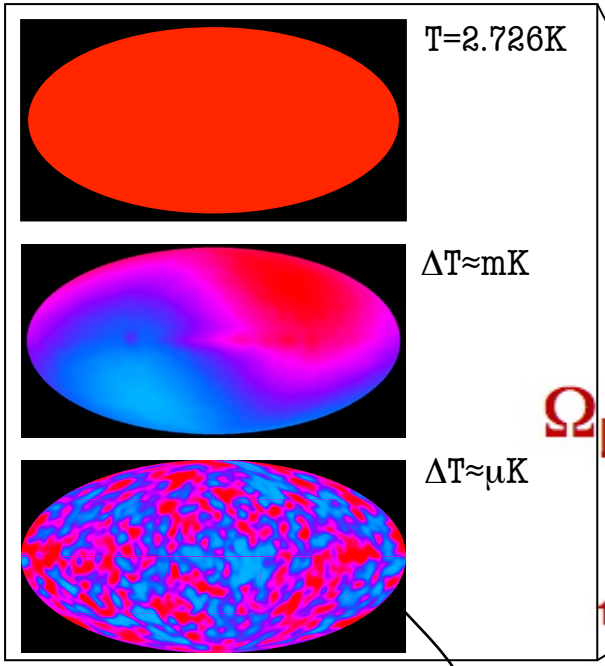
Bahcall et al. (1999)

- ΛCDM - Λ Cold Dark Matter

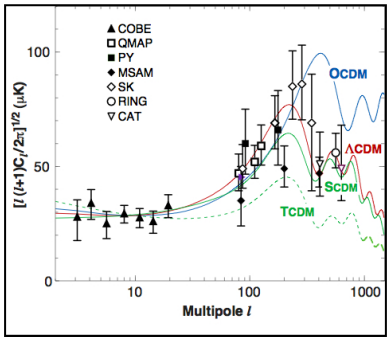


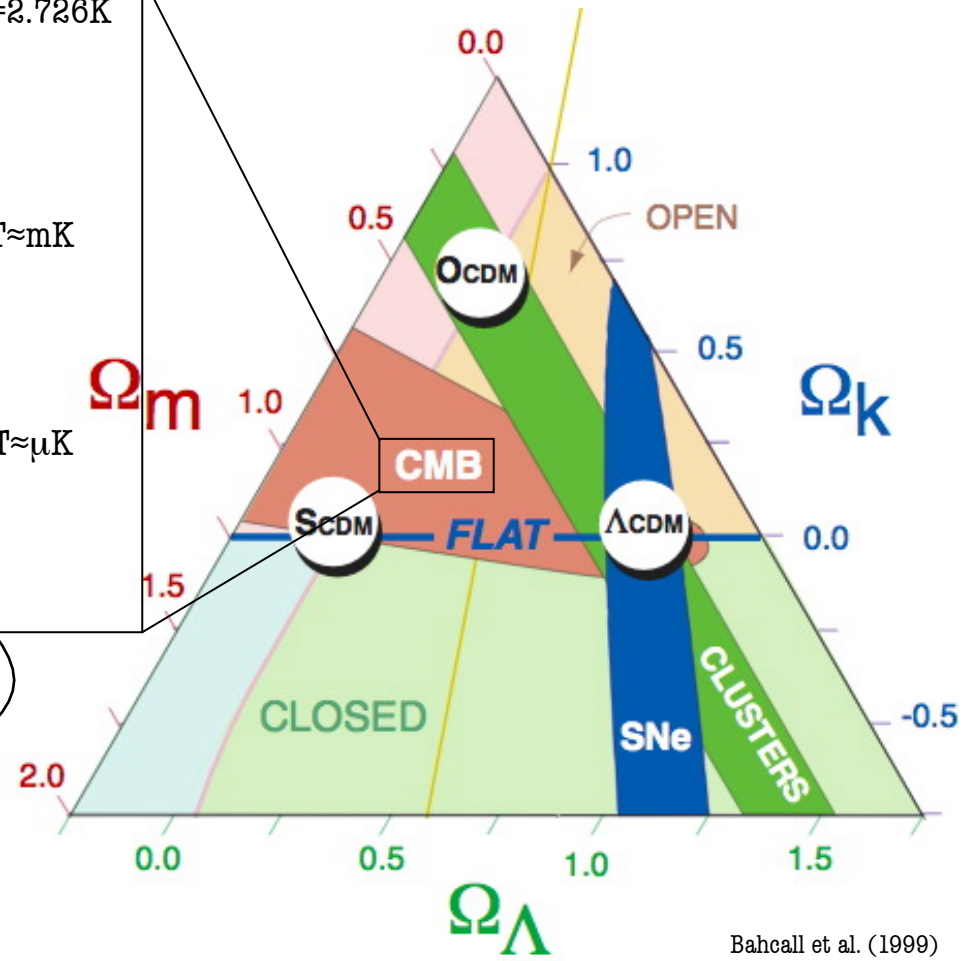
Bahcall et al. (1999)

- ΛCDM - Λ Cold Dark Matter



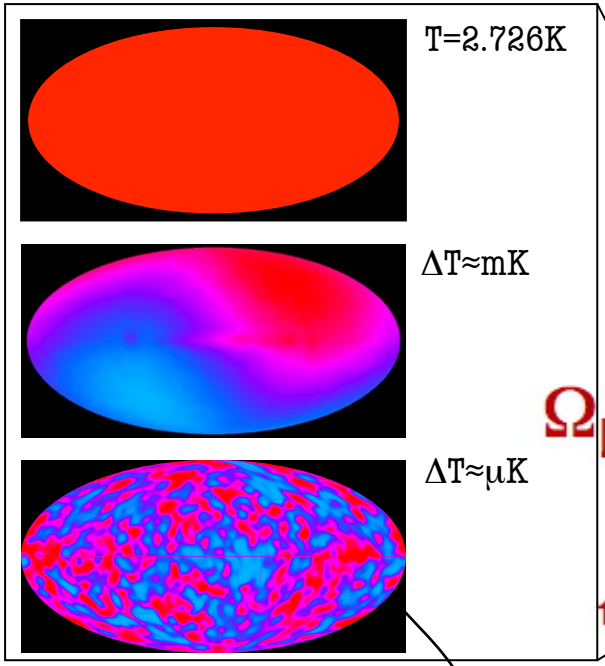
decomposition into spherical harmonics

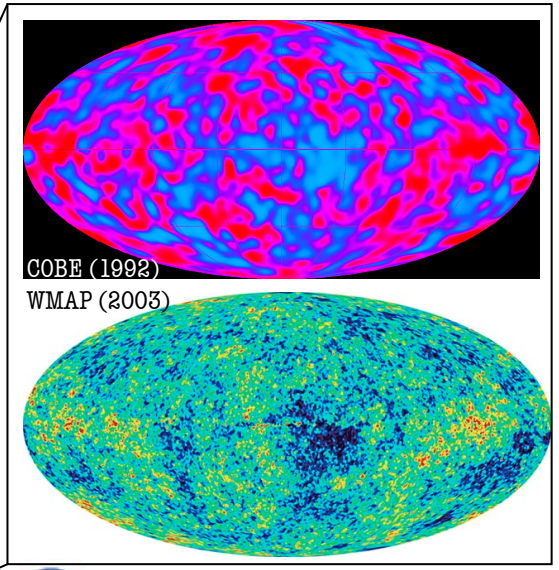


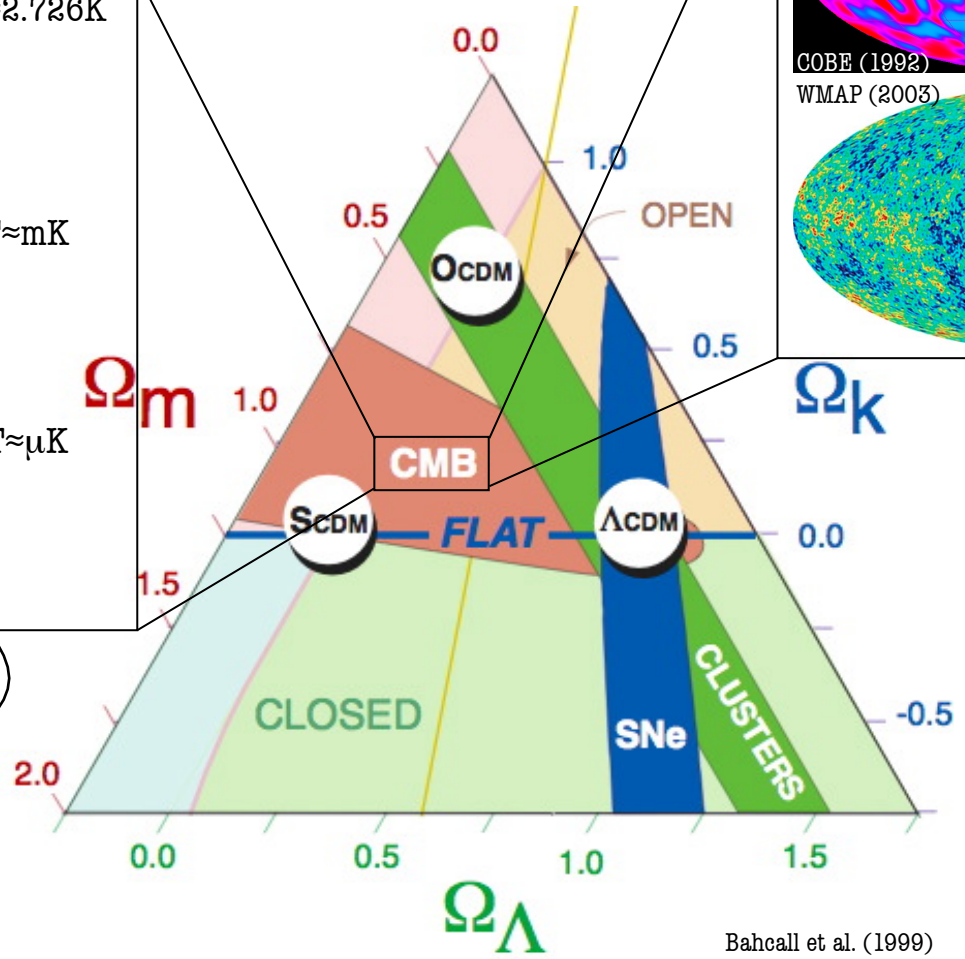


Bahcall et al. (1999)

- ΛCDM - Λ Cold Dark Matter

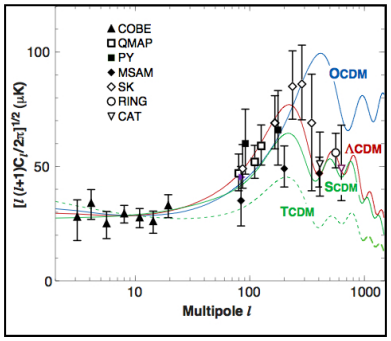




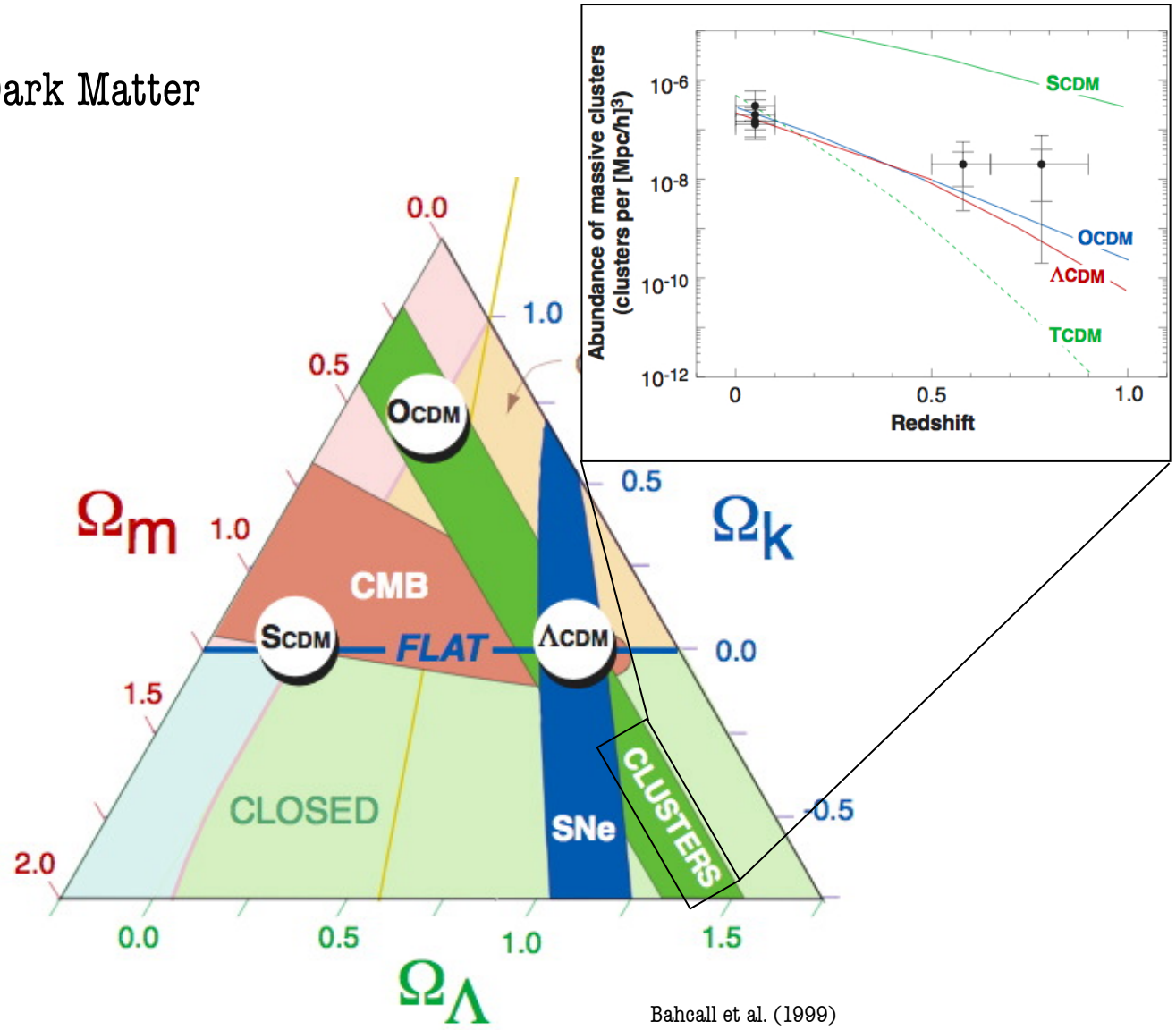


Bahcall et al. (1999)

decomposition into spherical harmonics

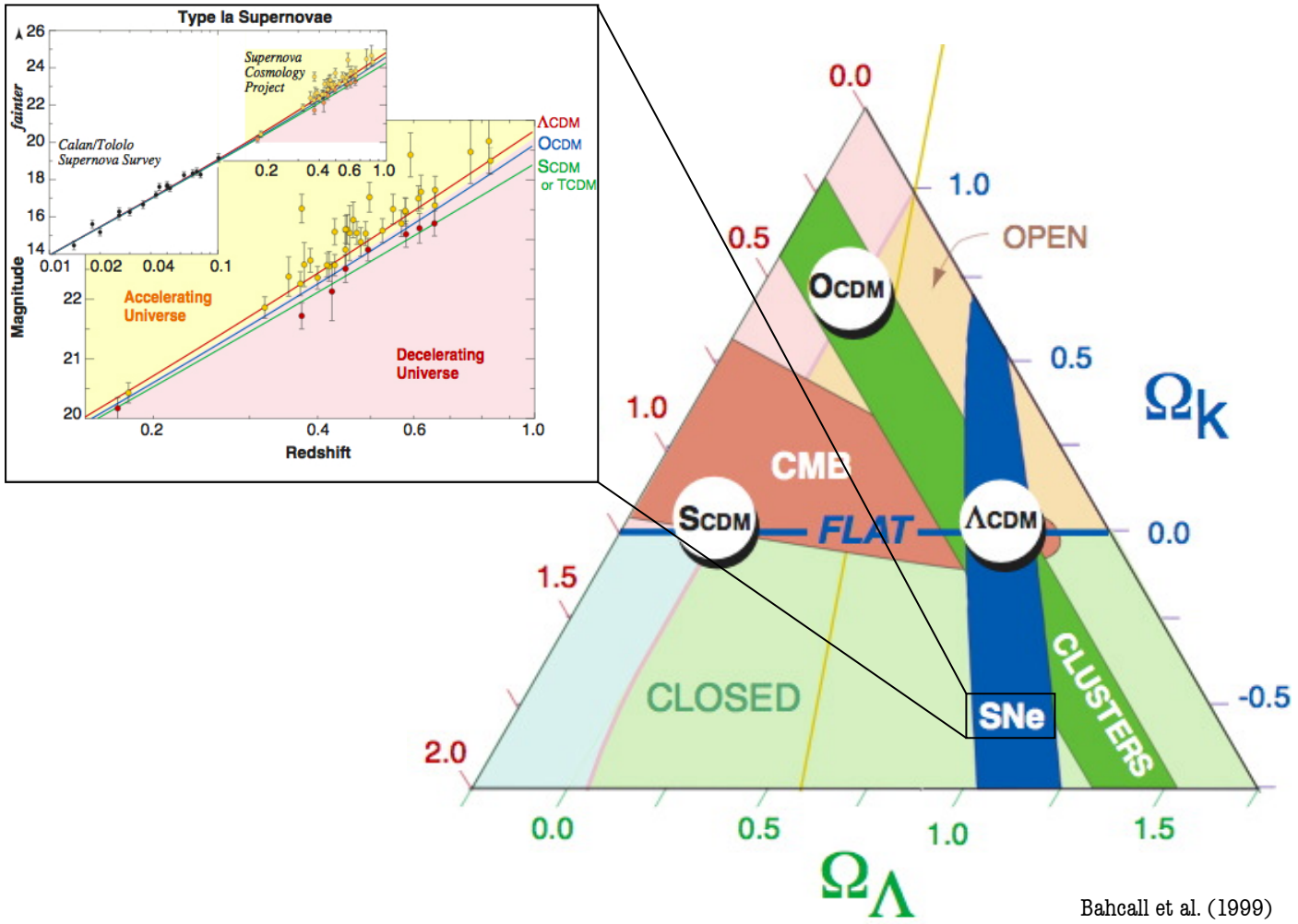


- ΛCDM - Λ Cold Dark Matter



Bahcall et al. (1999)

- ΛCDM - Λ Cold Dark Matter



Bahcall et al. (1999)

- background cosmology

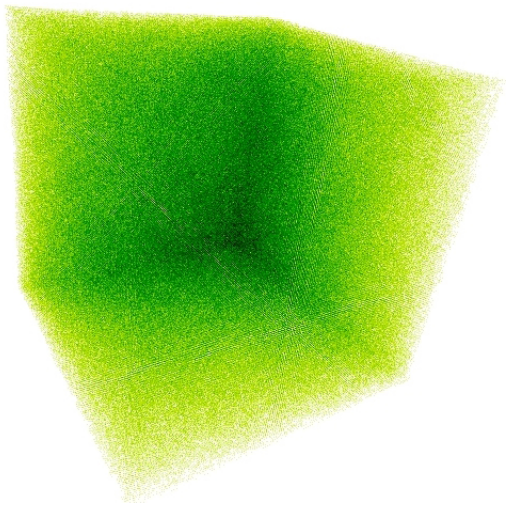
$$H^2 = H_0^2(\Omega_m^0 a^{-3} + \Omega_\Lambda^0)$$

$$q = \frac{1}{2}\Omega_m - \Omega_\Lambda$$

$$\Omega_m^0 \approx 0.3 = 0.26 + 0.04$$

$$\Omega_\Lambda^0 \approx 0.7$$

- the Universe is spatially flat
- ca. 30% of the total energy density comes from matter
  - about 85% of that matter is “dark”
  - **only 15% of all matter in the Universe is luminous**
- ca. 70% of the total energy density is vacuum energy



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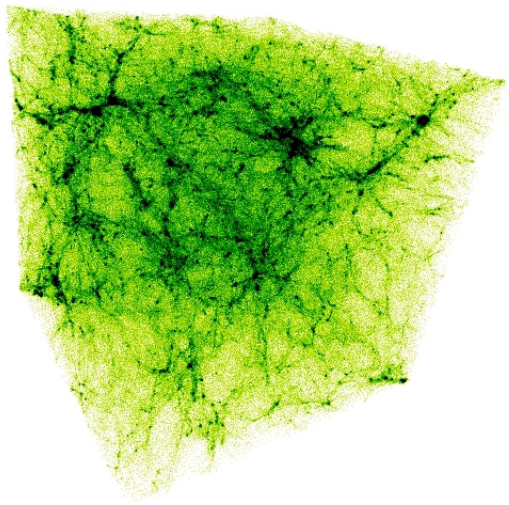
generating the initial conditions



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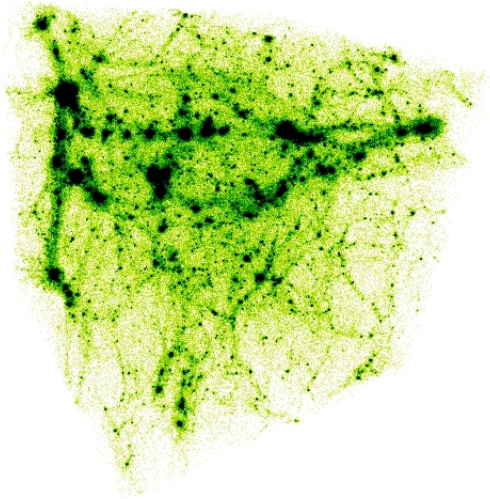
running the simulation



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analysing the data