Historical Perspective of Cosmology

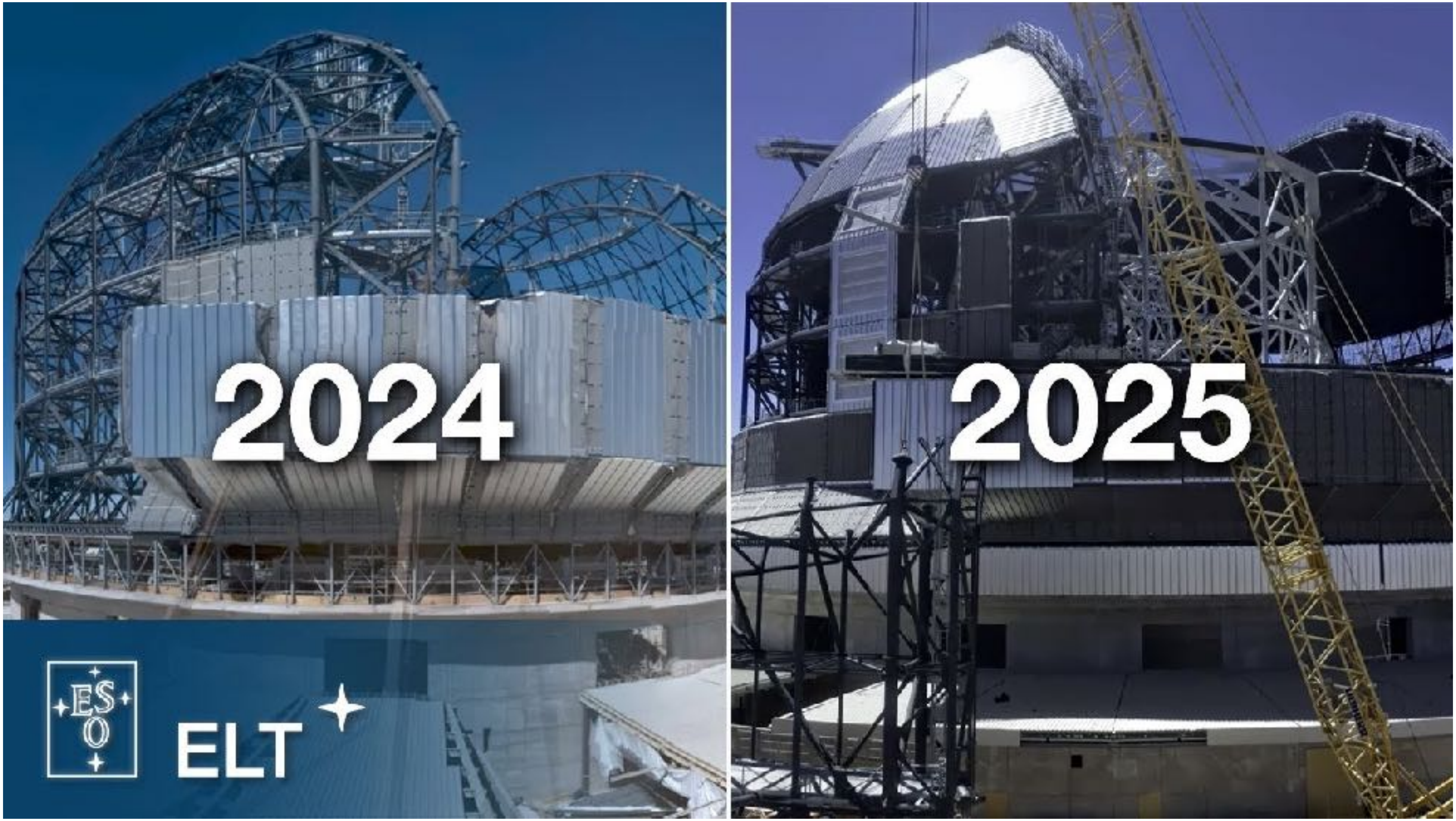
Contents and Properties of the Observable Universe-1

Jean-Paul KNEIB

Feb 25, 2025

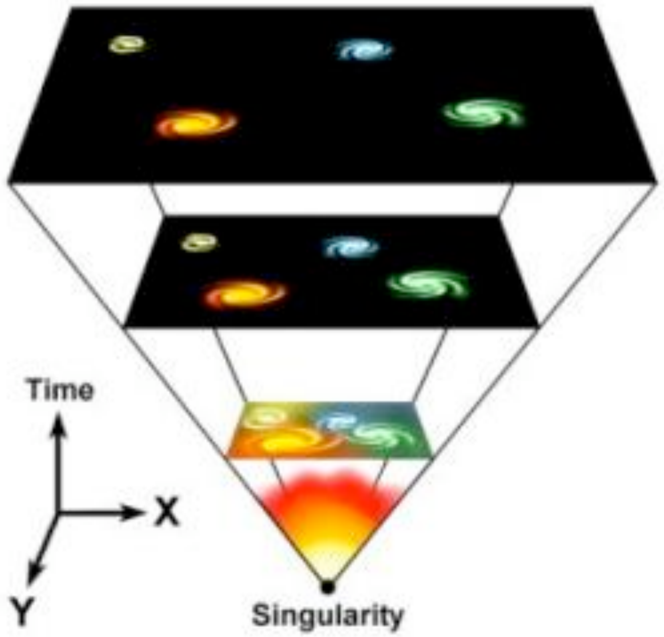
The Exciting Little Timelapse: A year in the life of the ELT

https://elt.eso.org/



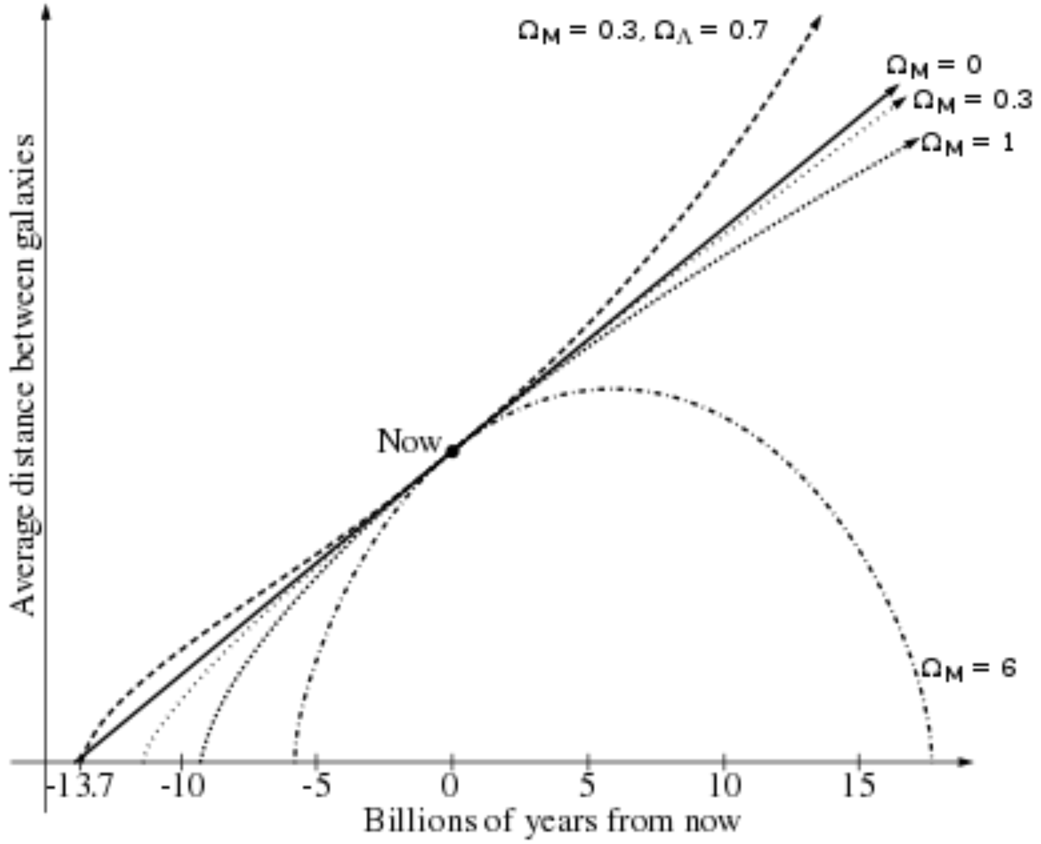
https://www.eso.org/public/videos/potw2508a/

The expanding Universe: => idea of an initial singularity



Going back in the past, the Universe was **smaller**, but also **denser**, and **hotter**.

Notion of a singularity:
The **Big-Bang model [1950]**

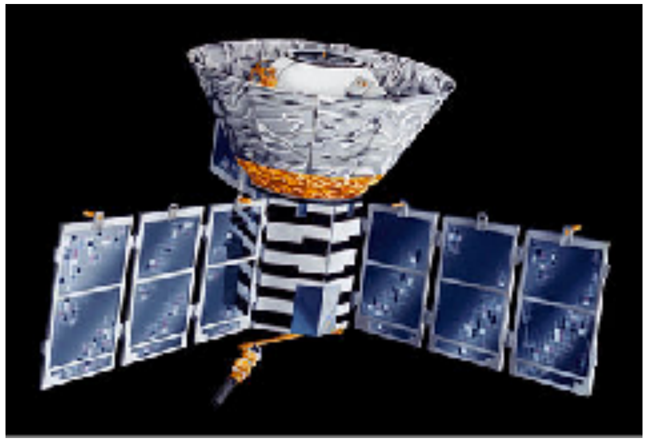


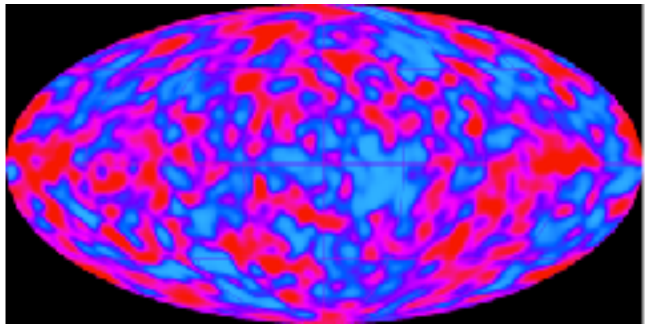
The thermal history and the cosmic microwave background

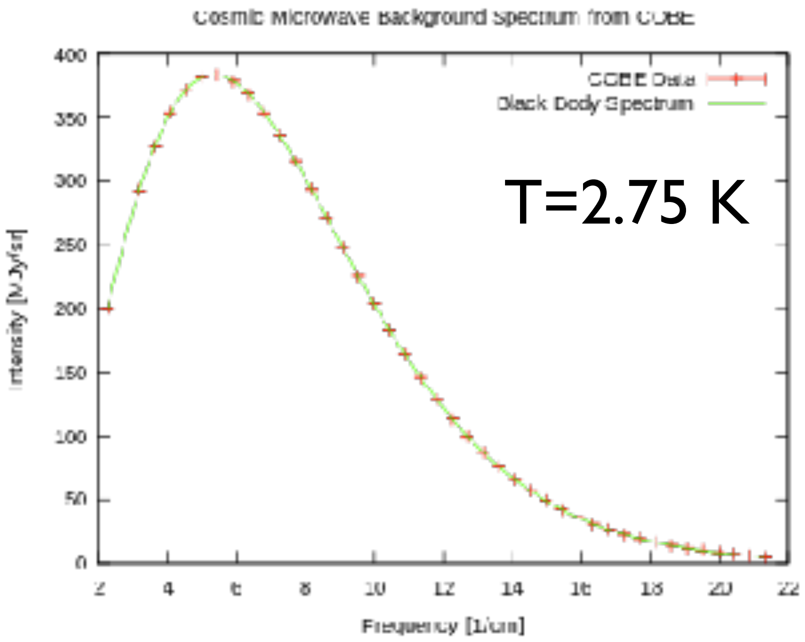
- **1946** Georges Gamow estimated a temperature of *50K* and presented a theory where all elements in the Universe are produced at the beginning.
- **1946** Robert Dicke predicted a microwave background radiation temperature of "less than *20K*" , but later revised to *45K*
- **1948** Ralph Alpher and Robert Herman re-estimated Gamow's estimate at 5K. After the nucleosynthesis, they mentioned that the universe then cooler had become "transparent" - photons can cross the Universe.
- **1949** Alpher and Herman re-re-estimated Gamow's estimate at *28K*.
- **1960s** Robert Dicke re-estimated an MBR (microwave background radiation) temperature of ~*10K*
- **1964** Arno Penzias and Robert W. Wilson measured the temperature to be approximately *3K* using a microwave telescope.
- Lemaître learned about these measurement just before his death in 1966

COBE and the measurement of the CMB

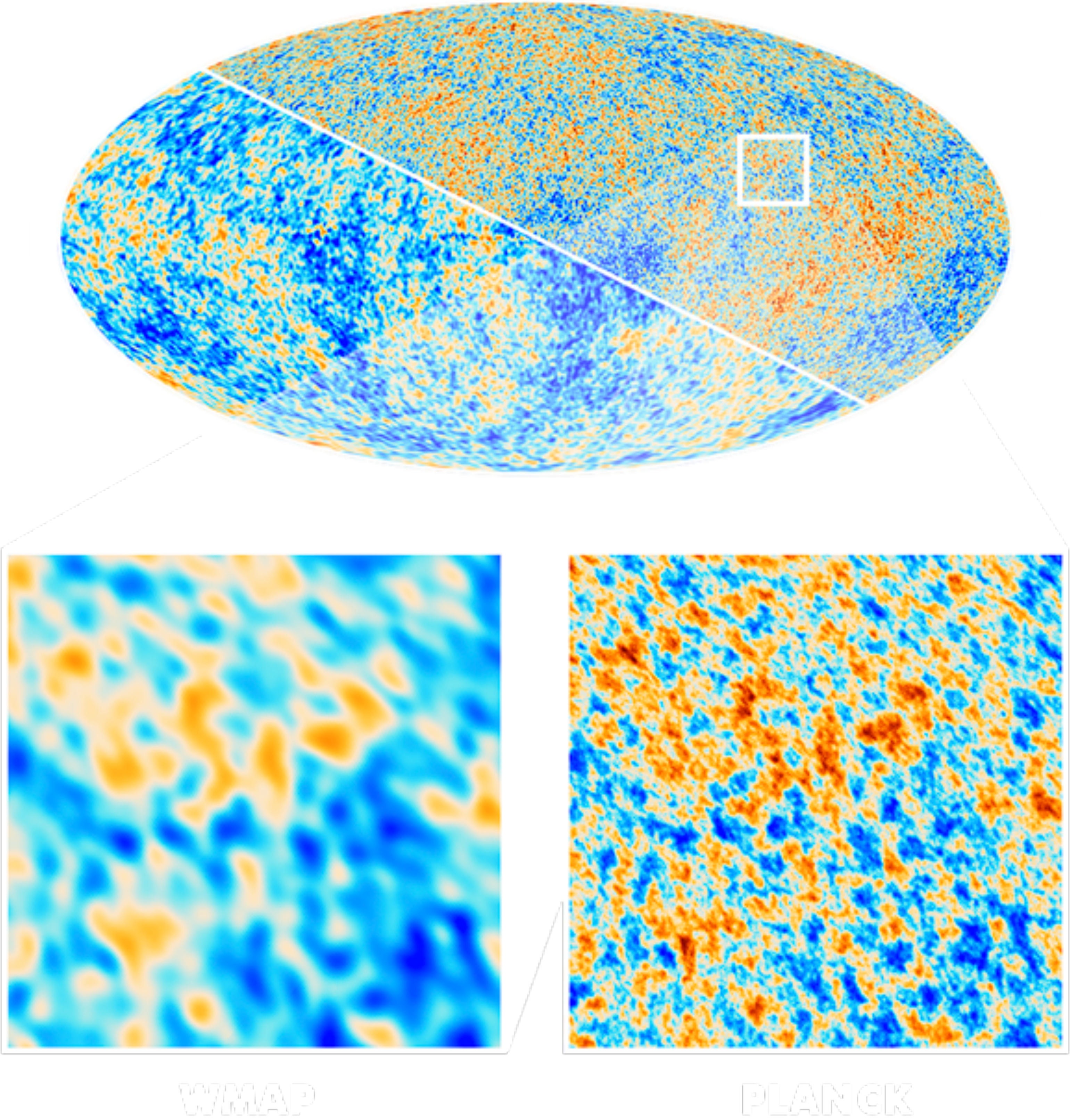
- In **1974**, NASA issued an Announcement of Opportunity for a small/medium missions.
- Out of the 121 proposals received, 3 dealt with studying the cosmological background radiation.
- These 3 proposals lost out to the Infrared Astronomical Satellite (IRAS).
- In **1976**, NASA formed a committee of members from each of 1974's 3 proposal teams to put together their ideas for such a satellite. A year later, COBE was born.
- In **1989**, COBE was launched.
- In **1992** the CMB anisotropy map was published. It displayed small variations of temperature across the sky: $\Delta T/T \sim 10^{-5}$. These variation are now known to be linked to matter density fluctuation in the early Universe, fluctuations that are the seeds of the structures in today's Universe.







T=2.75 K

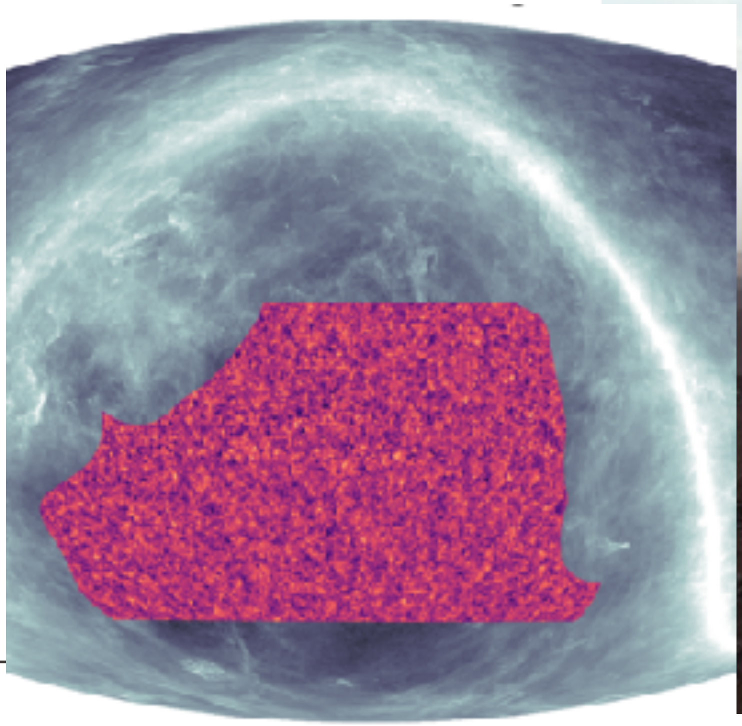


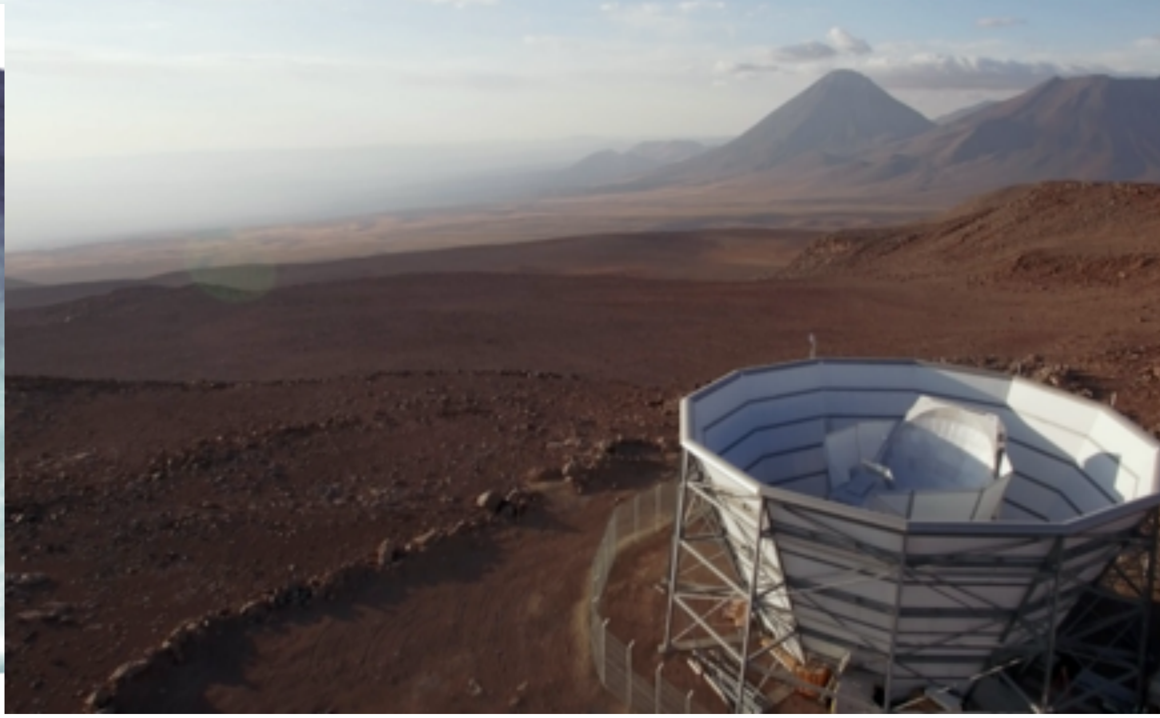
WMAP

Planck

Most recent measurement of the anisotropy with WMAP & Planck

WMAP, launched in 2001.
Planck, launched in 2009.

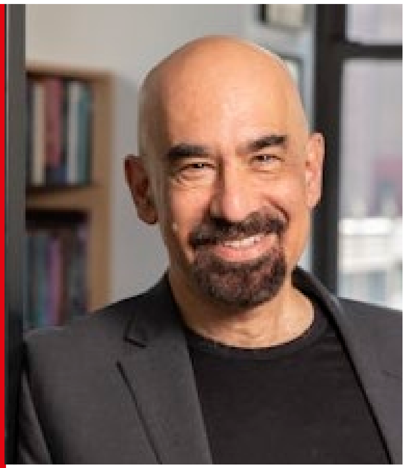




EPFL

PHYSICS COLLOQUIUM

Recent Results from the Atacama Cosmology Telescope



Prof. David Spergel
Princeton Univ.

President, Simons Foundation

Thursday
March 20th
12:15
CE1 4

The Atacama Cosmology Telescope has recently reported the most accurate measurements of temperature and polarization of the cosmic microwave background. I will highlight these results and their implications for our understanding of cosmology.

The new measurements constrain the number and mass of neutrinos, the presence of new light particles, the properties of dark matter and dark energy, and the physics of inflation.

APERO
after the
colloquium

or on zoom :
https://epfl.zoom.us/j/64905394203

Host: Prof. Jean-Paul Kneib

School
of Basic
Sciences

Organized by the Institute of Physics, EPFL

All good?

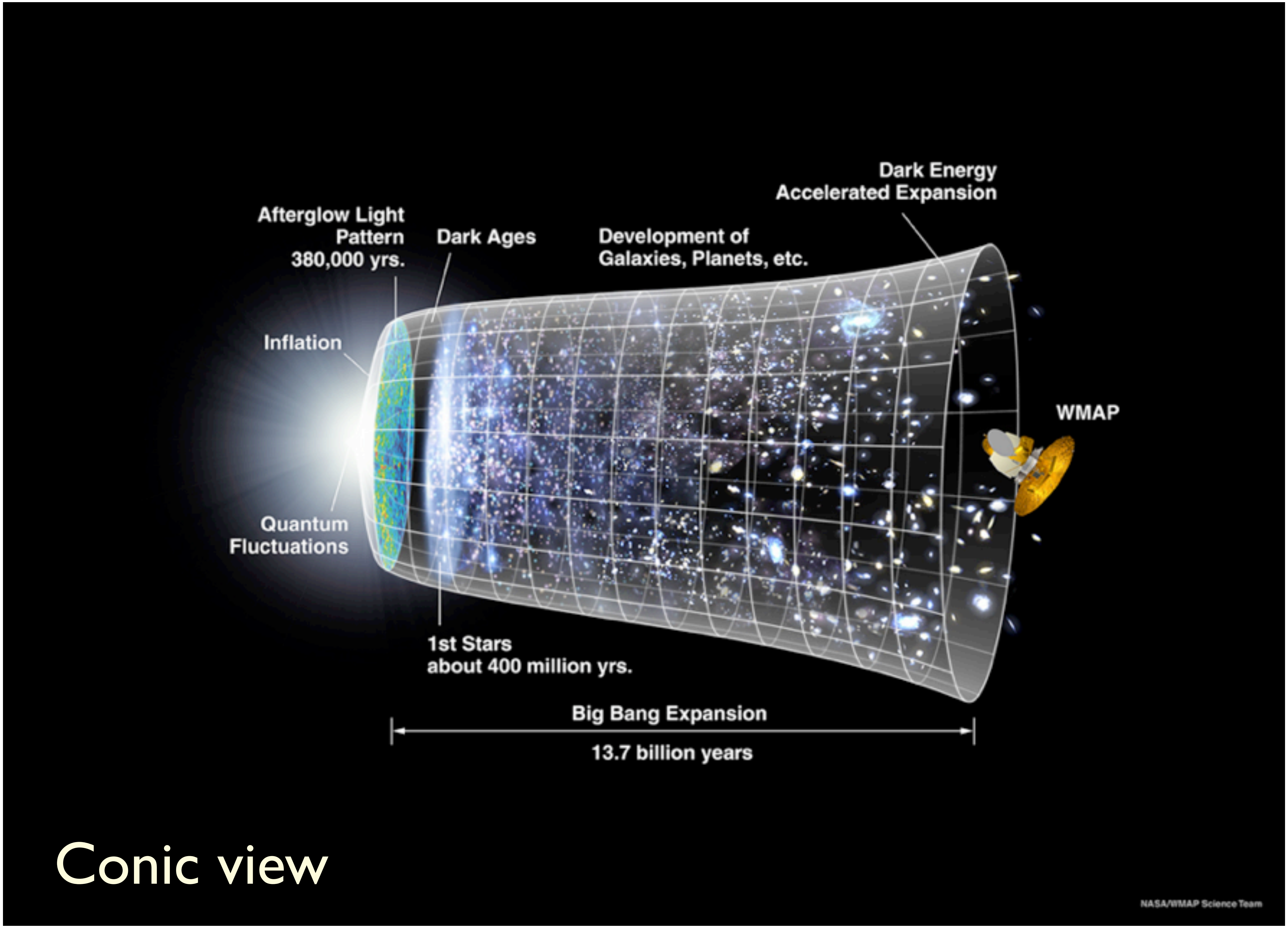
Quizz

- What is “General Relativity” ?
- How much is “One Parcsec”?
- What is the typical distance between 2 galaxies?
- How much is “One SolarMass” ? (in gram)
- What is the “redshift” ?
- What is “the Hubble Law” ? What it means ?
- What is “the age of the Universe” ?

AstroOne

- Access to a dedicated LLM focusing on Astronomy:
- **https://astroone.zero2x.org.cn/universal-login/new**
- Have you registered?

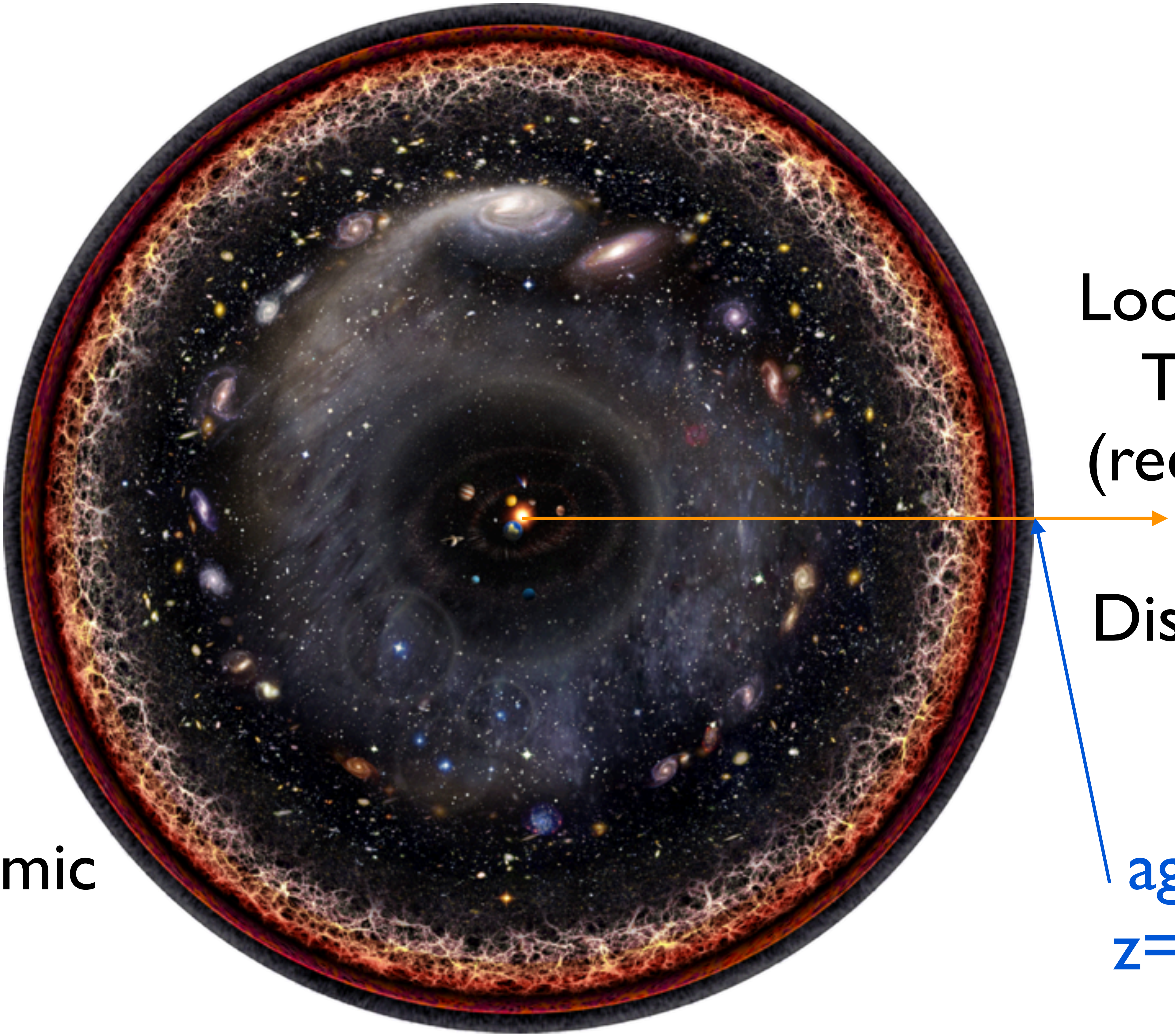
The Observable Universe



Conic view

NASA/WMAP Science Team

The Observable Universe



Lookback
Time
(redshift)

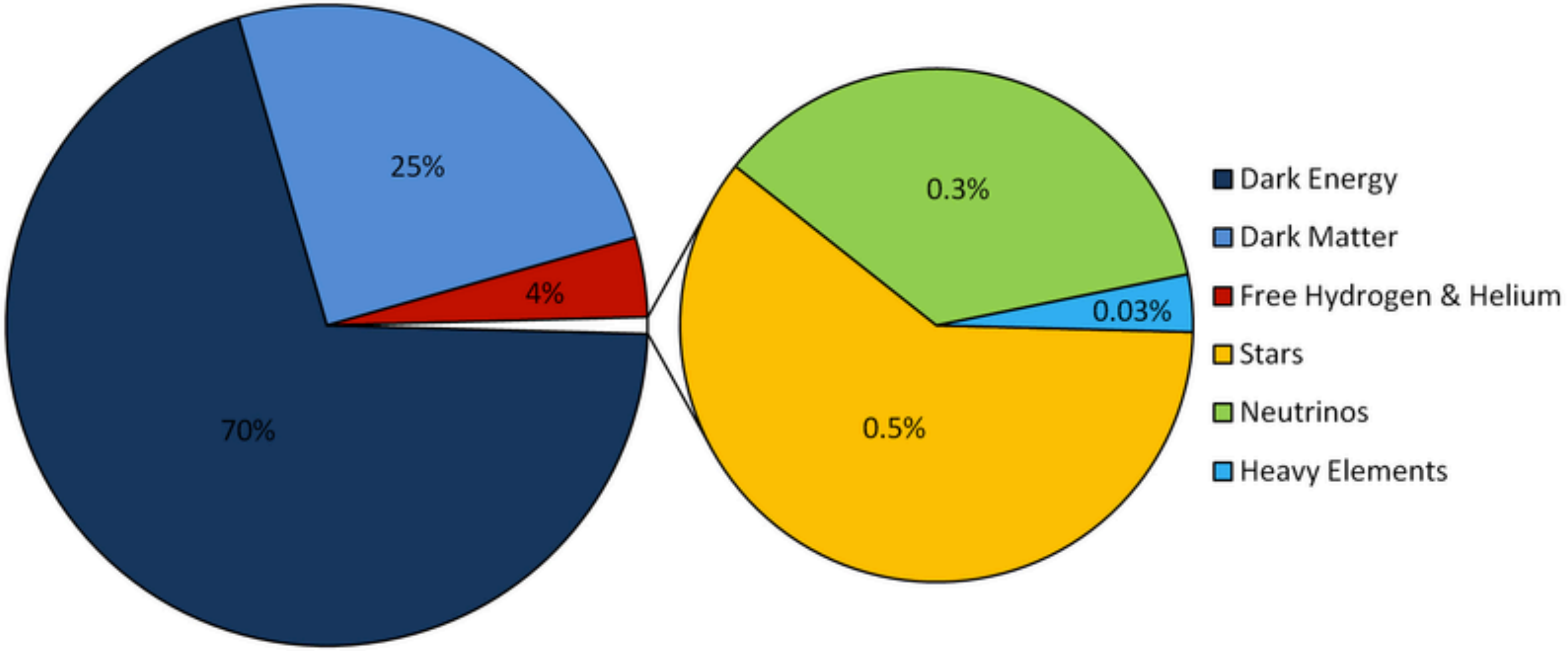
Distance

age=“0”
z=infinity

Logarithmic
view

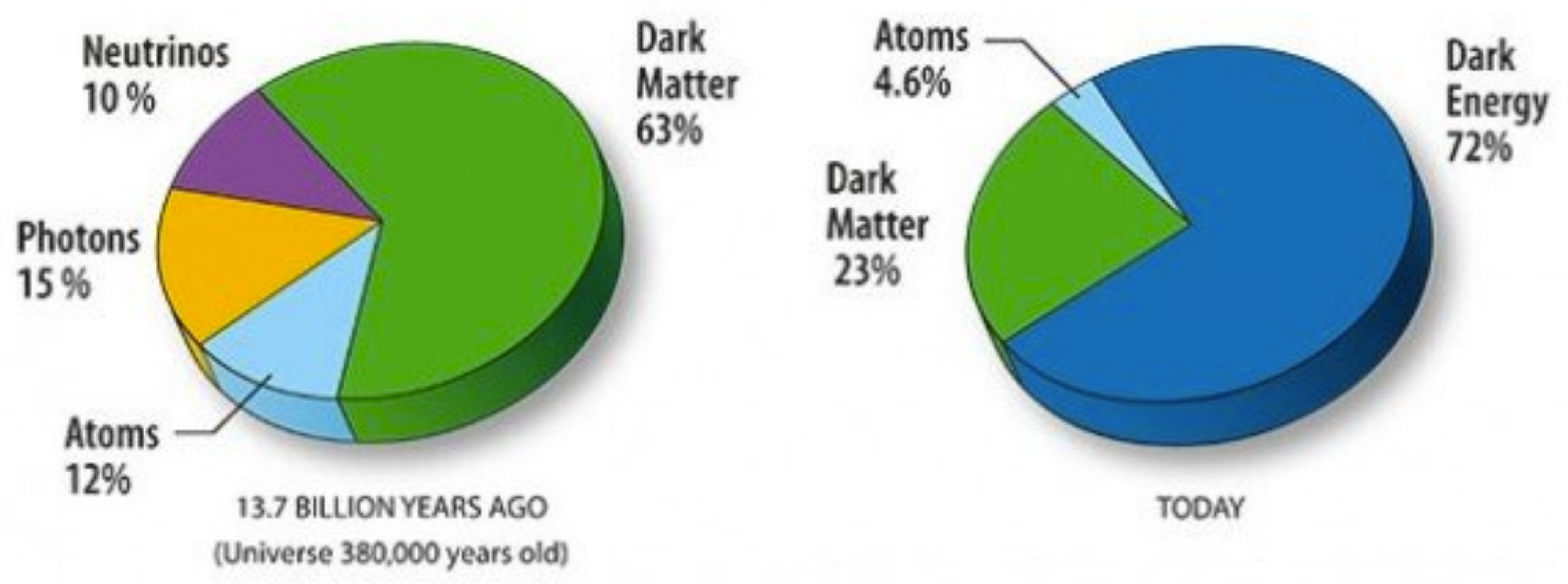
Content of the Universe

- **(Dark) Energy**
- **Mass (Dark / Baryonic)**



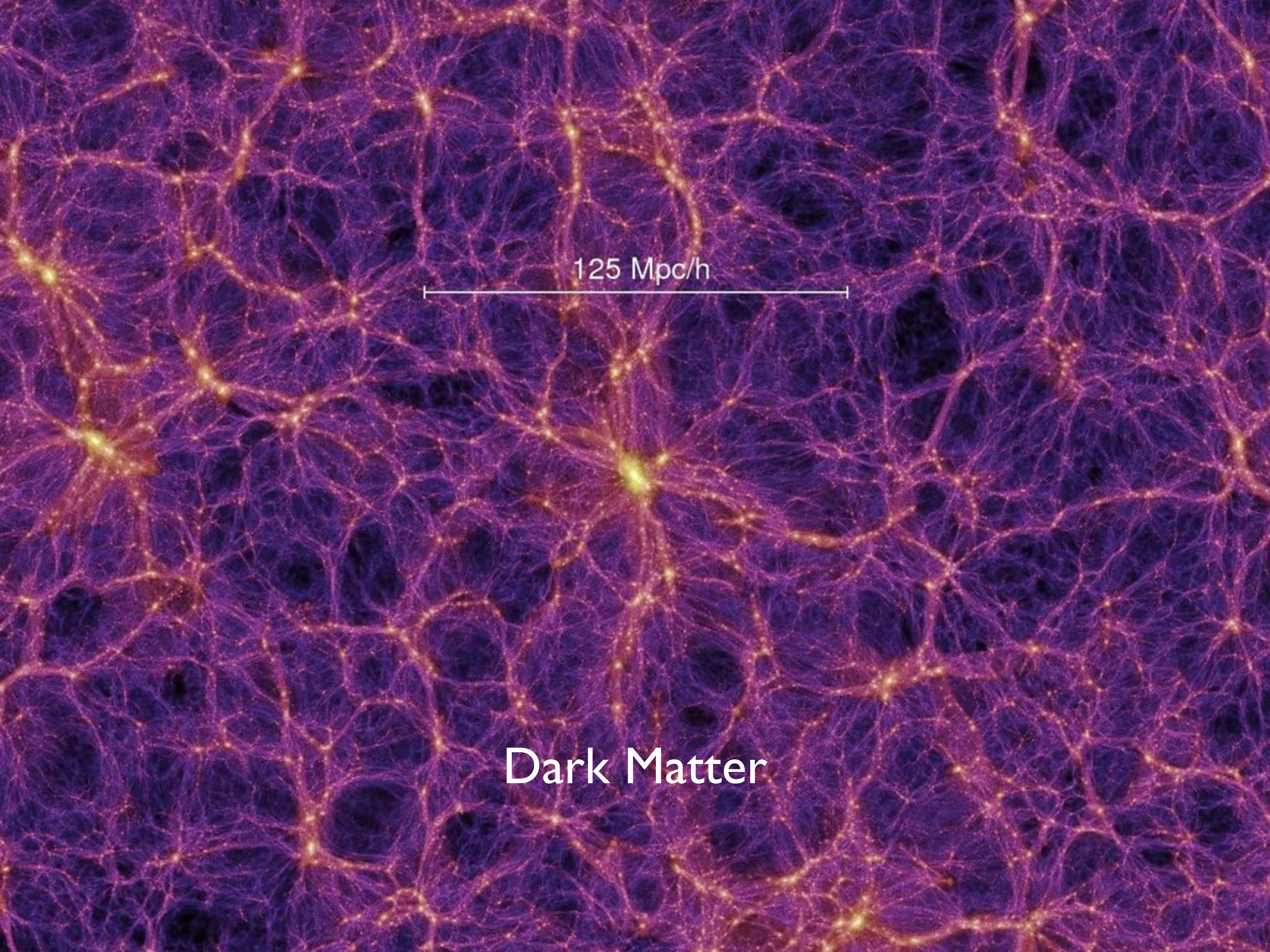
Content of the Universe

- **Content is varying with time:**
  - **Mass (# of particles) is constant**
  - **Density of (dark) energy ~constant**
  - **but geometry is expanding (mass & radiation densities are decreasing ...)**

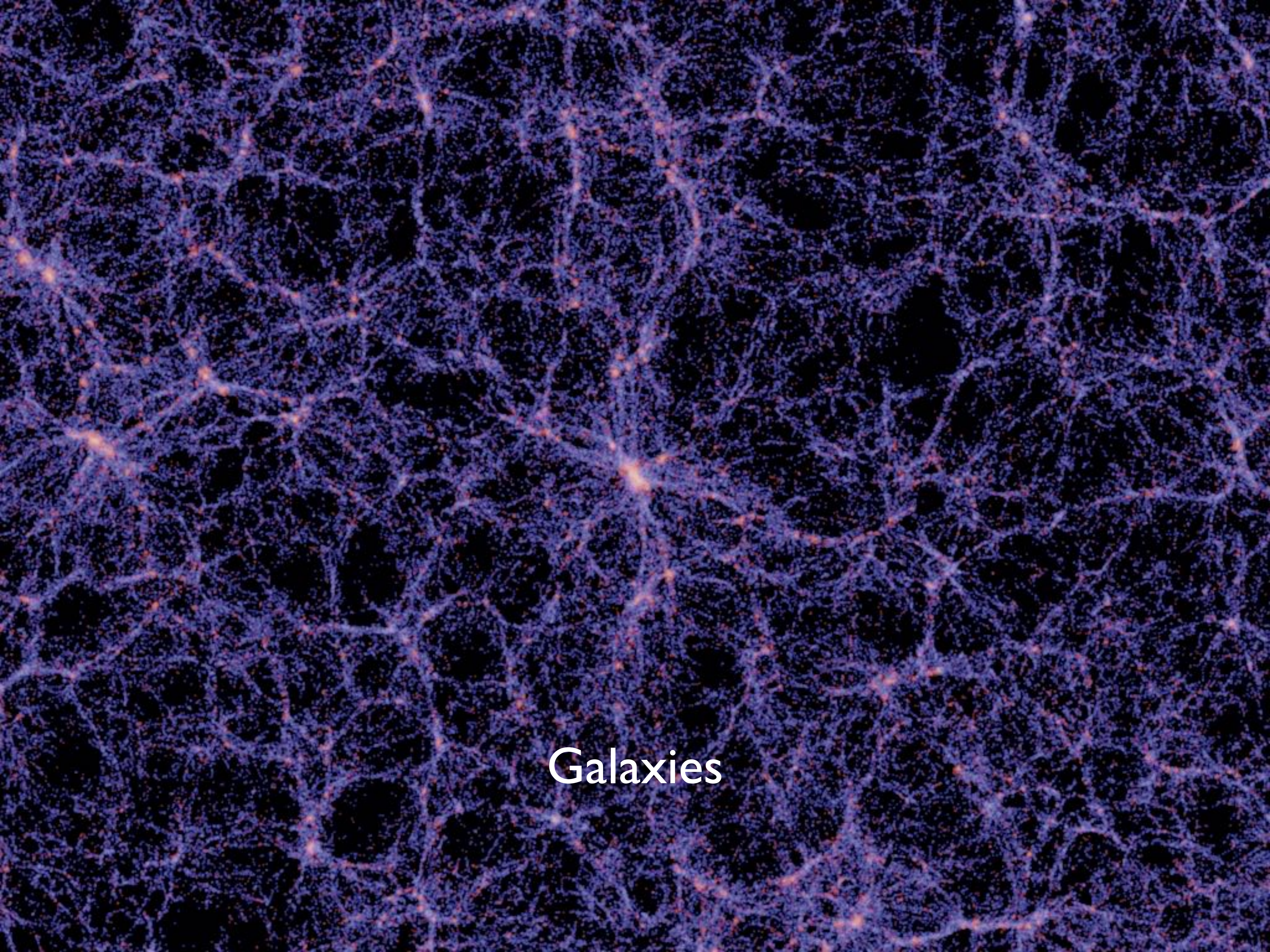


Content of the Universe

- Main baryonic tracers from a Cosmology standpoint:
  - **a few 10^{11} Galaxies** (~1000 per square.arcmin)
  - **~10^5 Cluster of Galaxies** (a few per square.degrees)
  - Large Scale Structures: Cosmic Web: Filaments & Voids: typical scale ~100 Mpc
  -



Dark Matter



Galaxies

Content of the Universe

- Main tracers from a Cosmology standpoint:
    - **a few 10^{11} Galaxies** (~1000 per square.arcmin)
    - **~10^5 Cluster of Galaxies** (a few per square.degrees)
    - Large Scale Structures: Cosmic Web: Filaments & Voids: typical scale ~100 Mpc
- *Warm gas*: Inter-Galactic Medium (neutral/ionized gas)
- *Hot gas* (ionized plasma in massive clusters of galaxies)
- *Black-Holes* (BH) revealed by Gravitational Waves
- *Quasars* - SMBH at the center of galaxies
- *Background Radiation* (e.g. Cosmic Microwave Background)

Galaxy Size and Mass

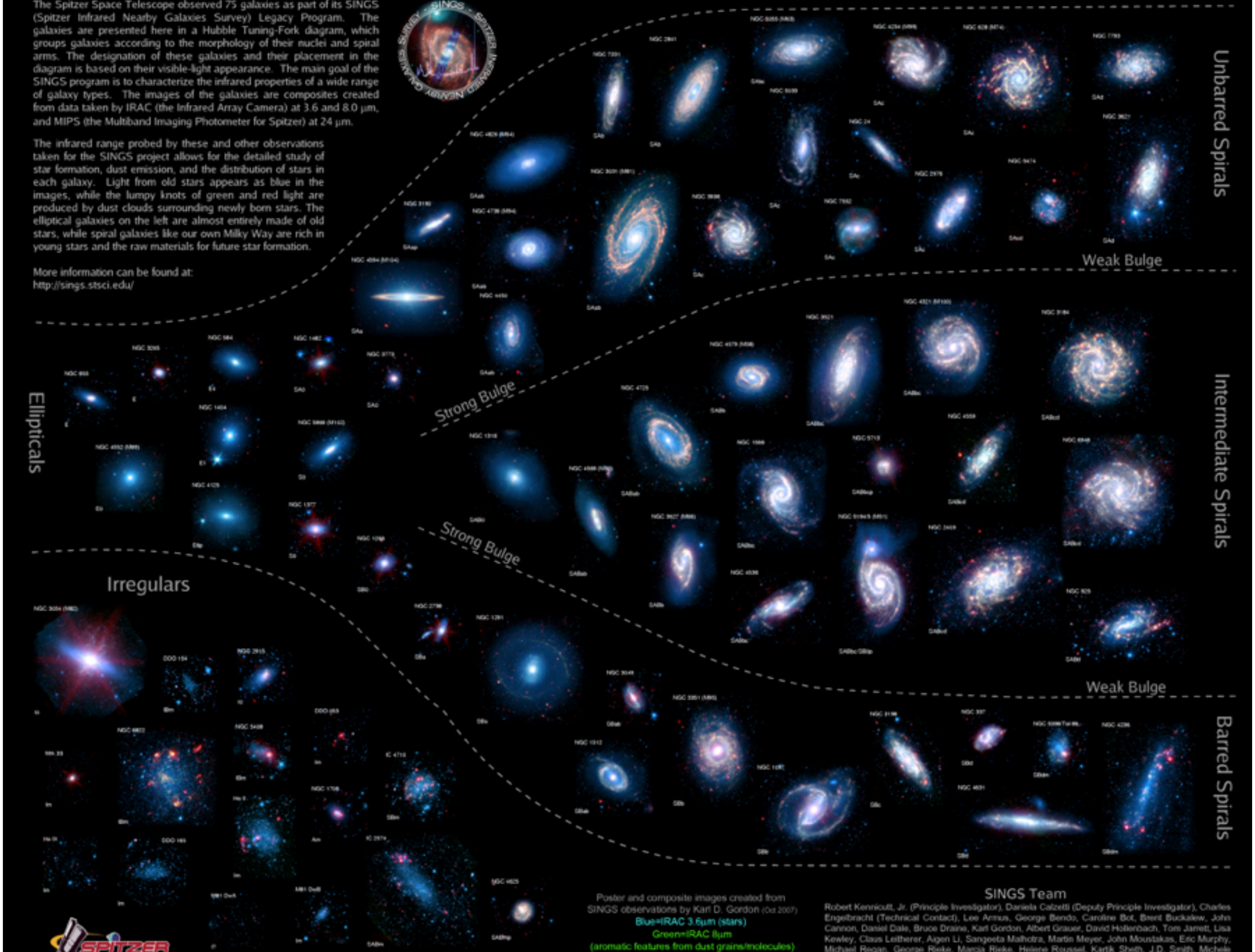
- Galaxy masses:
    - 10^6 Solar Mass for a Dwarf
    - 10^{13} Solar Mass for a Giant Elliptical
    - dominated by Dark Matter
- Galaxy sizes:
    - ~5 kpc radius
    - up to 100-500 kpc for Giant Elliptical
    - traced by the stellar distribution, cold gas (HI) can extend on larger scale (10x)
- Galaxy morphologies: Hubble Classification

The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork

The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm.

The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.

More information can be found at:
http://sings.stsci.edu/

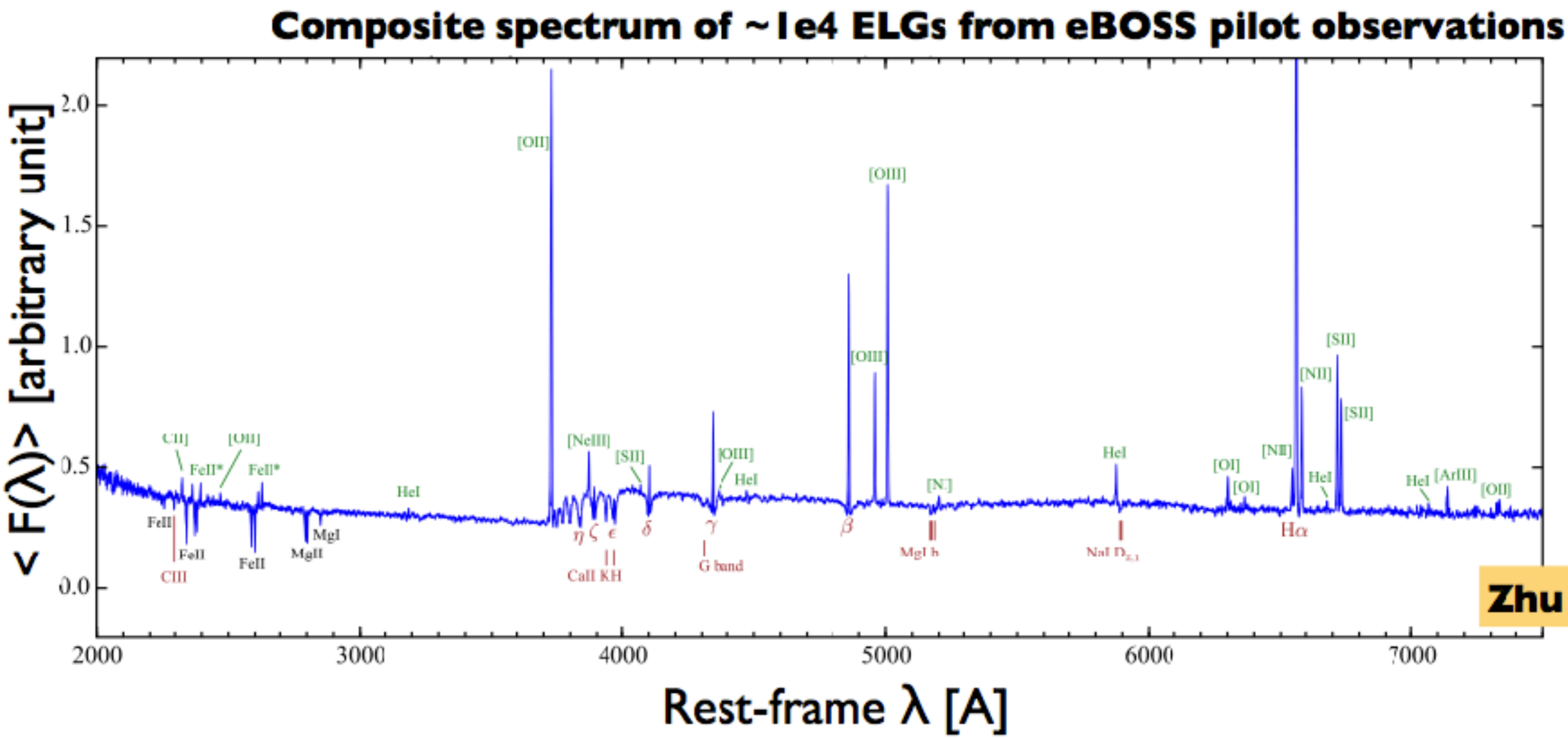


Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)

SINGS Team

Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou

Spectrum of Star Forming Galaxy



Composite spectrum of ~1e4 ELGs from eBOSS pilot observations

Zhu et al. 2015

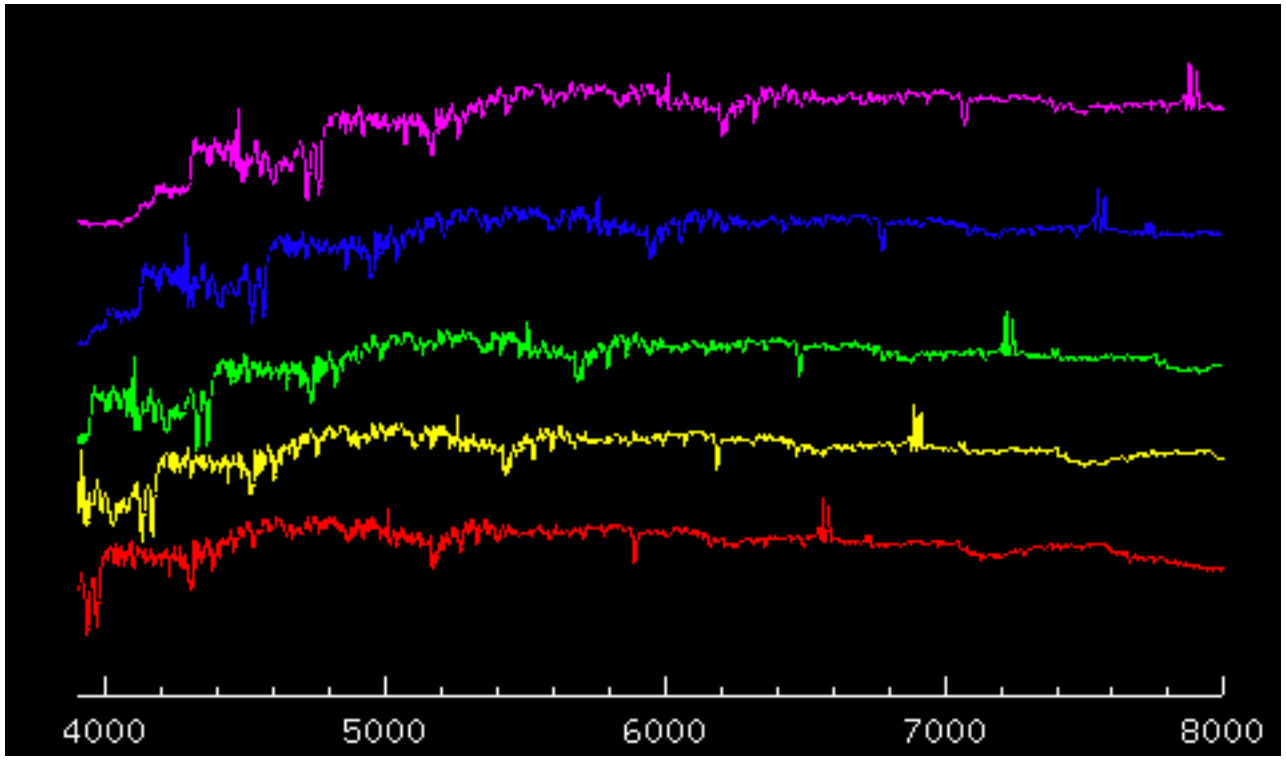
A spectrum of a distant
galaxy is “red-shifted”

Universe expansion & Redshift

- Redshift of a galaxy measured e.g. from an emission line:

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} \ ,$$

- Recession velocity: $v = cz \ ,$



A galaxy spectrum at 4 different redshifts (0.0, 0.05, 0.10, 0.15, 0.20)

Universe expansion

- Hubble Law: $v = H_0 \times D$

- Observed Flux (F) depending on Luminosity (L) and redshift:

$$F = \frac{L}{4\pi D^2} = \frac{L}{4\pi} \frac{H_0^2}{c^2 z^2},$$

- Observed magnitude:

$$m = -2.5 \log(F) + C, \qquad m = 5 \times \log[z] + C'.$$

Universe expansion

- Hubble Law: $v = H_0 \times D$

Formula Works
for Low Redshift
z<<1

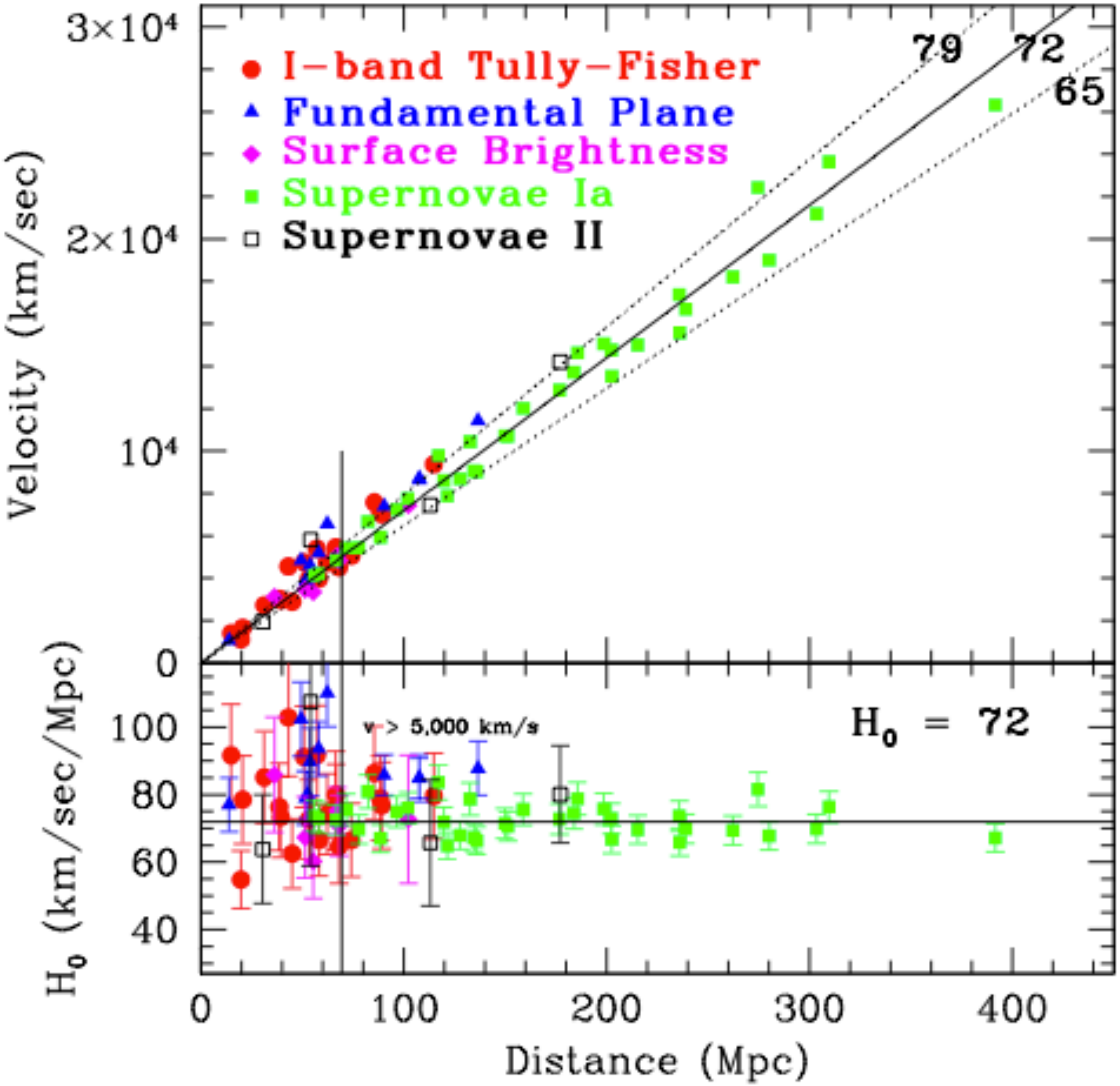
- Observed Flux (F) depending on Luminosity (L) and redshift:

$$F = \frac{L}{4\pi D^2} = \frac{L}{4\pi} \frac{H_0^2}{c^2 z^2},$$

- Observed magnitude:

$$m = -2.5\log\left(F\right) + C, \qquad m = 5 \times \log\left[z\right] + C'.$$

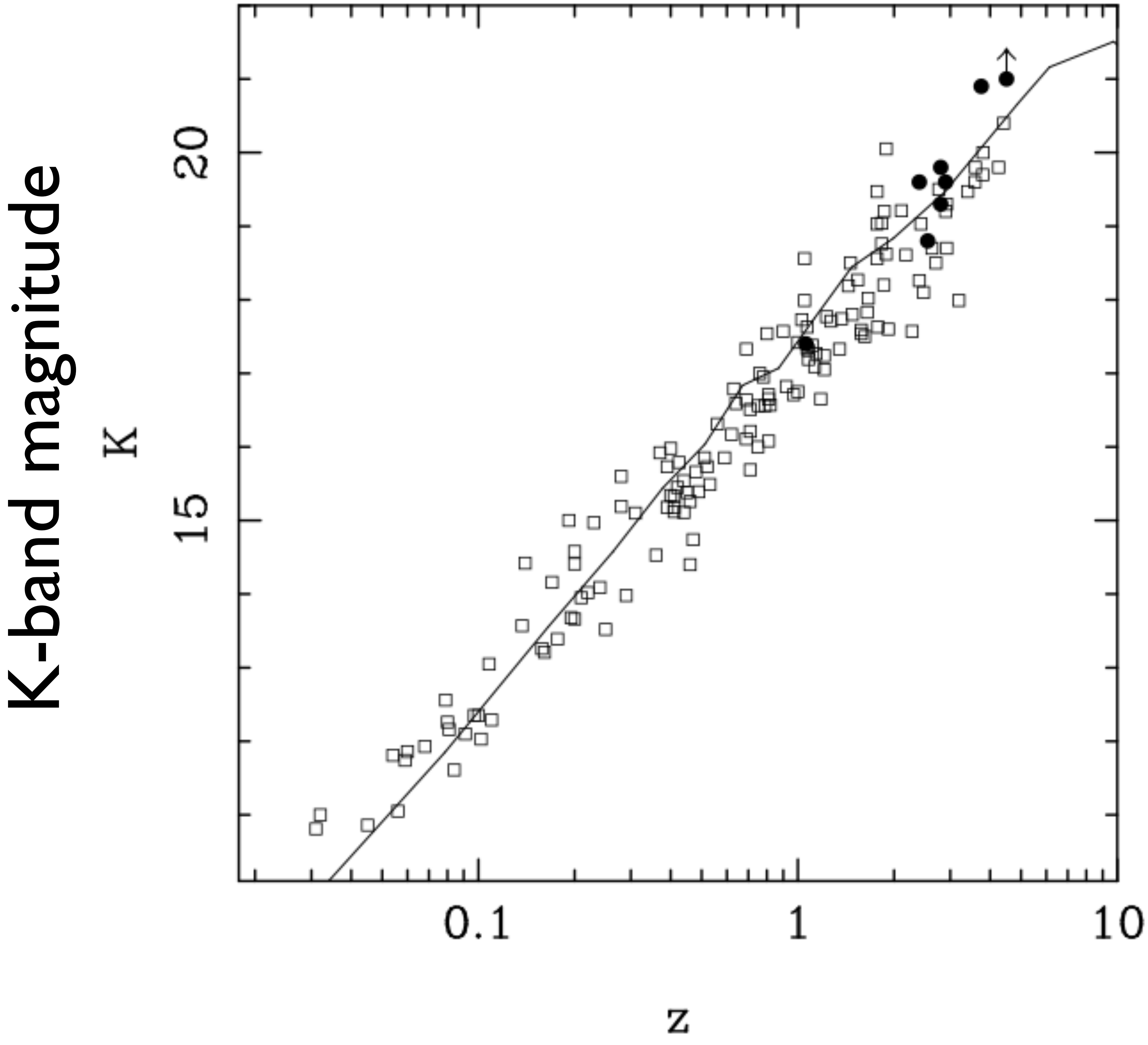
Universe expansion



$$v = H_0 \times D$$

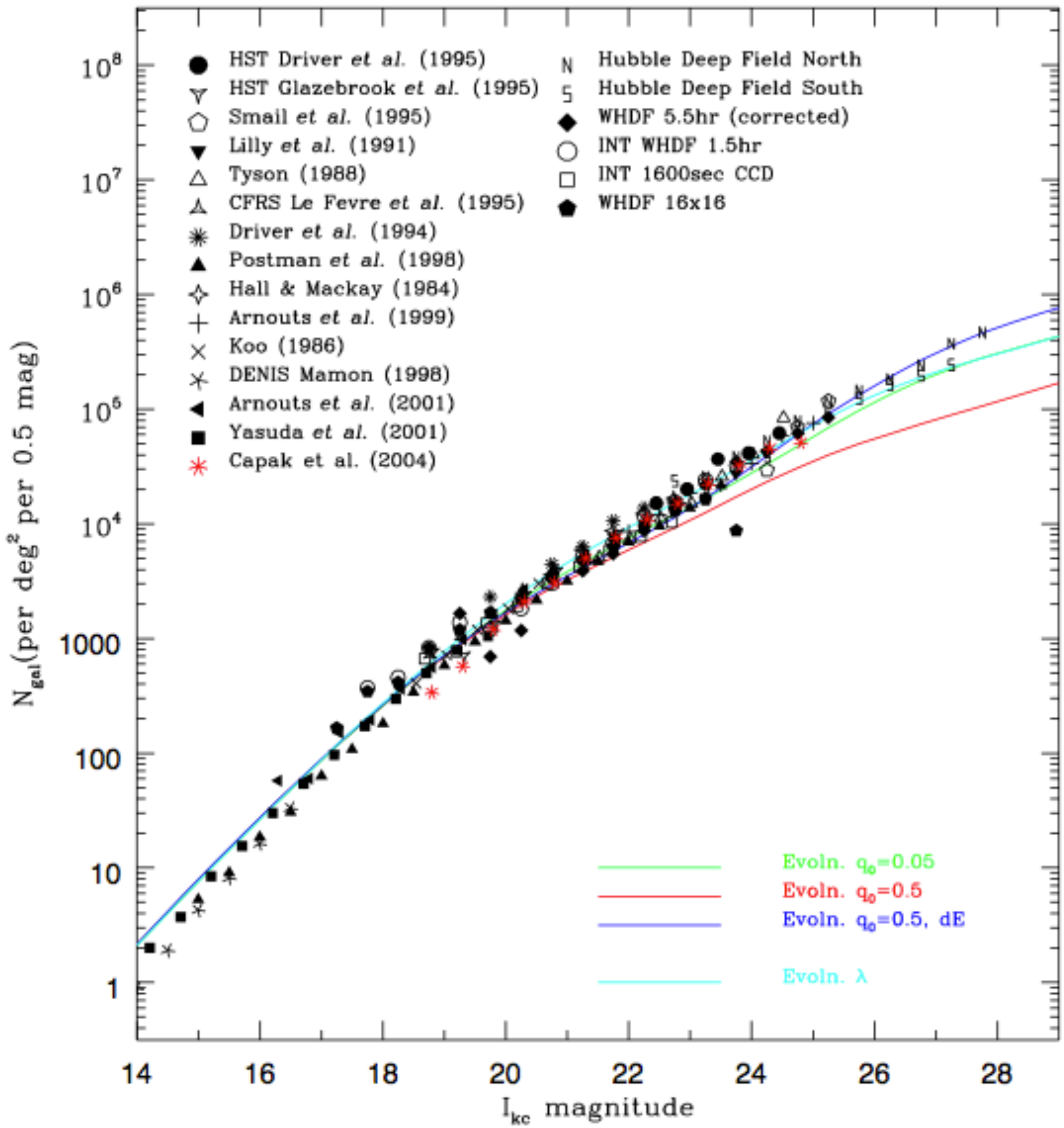
100 Mpc
=>
~7200 km/s
z~0.02

Universe expansion



Hubble Diagram
for 3CR and 6CR
radio galaxies
(these are galaxies
with similar
luminosity)

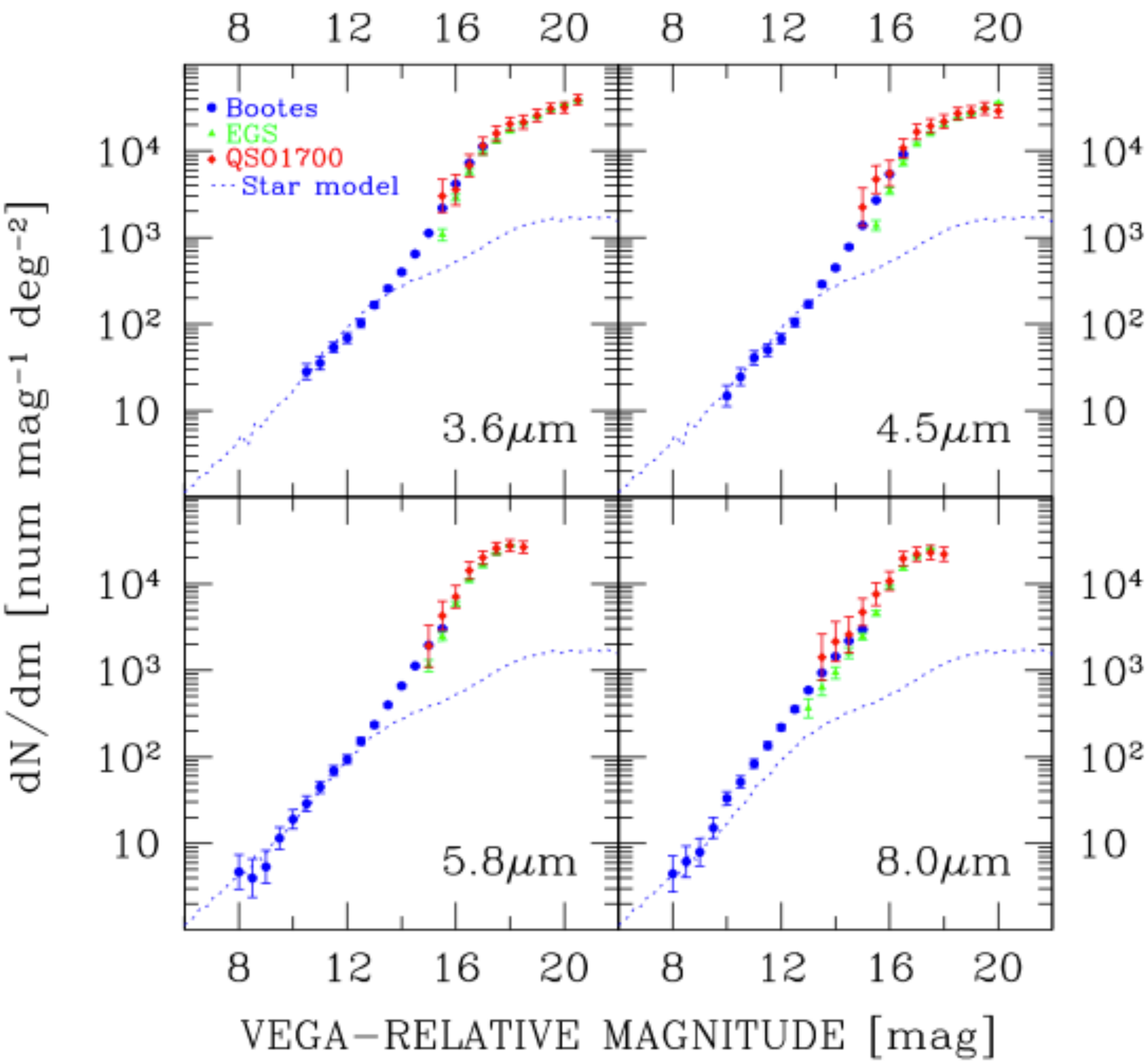
Galaxy Counts



Number of galaxies as a function of magnitude.
At faint limits we have more than 5.10^5 galaxies per square degrees of sky.

So about 100 billions of galaxies over the full sky.

Galaxy Counts in MIR



The diversity of Galaxies
How to quantify them?

Galaxy Luminosity Function

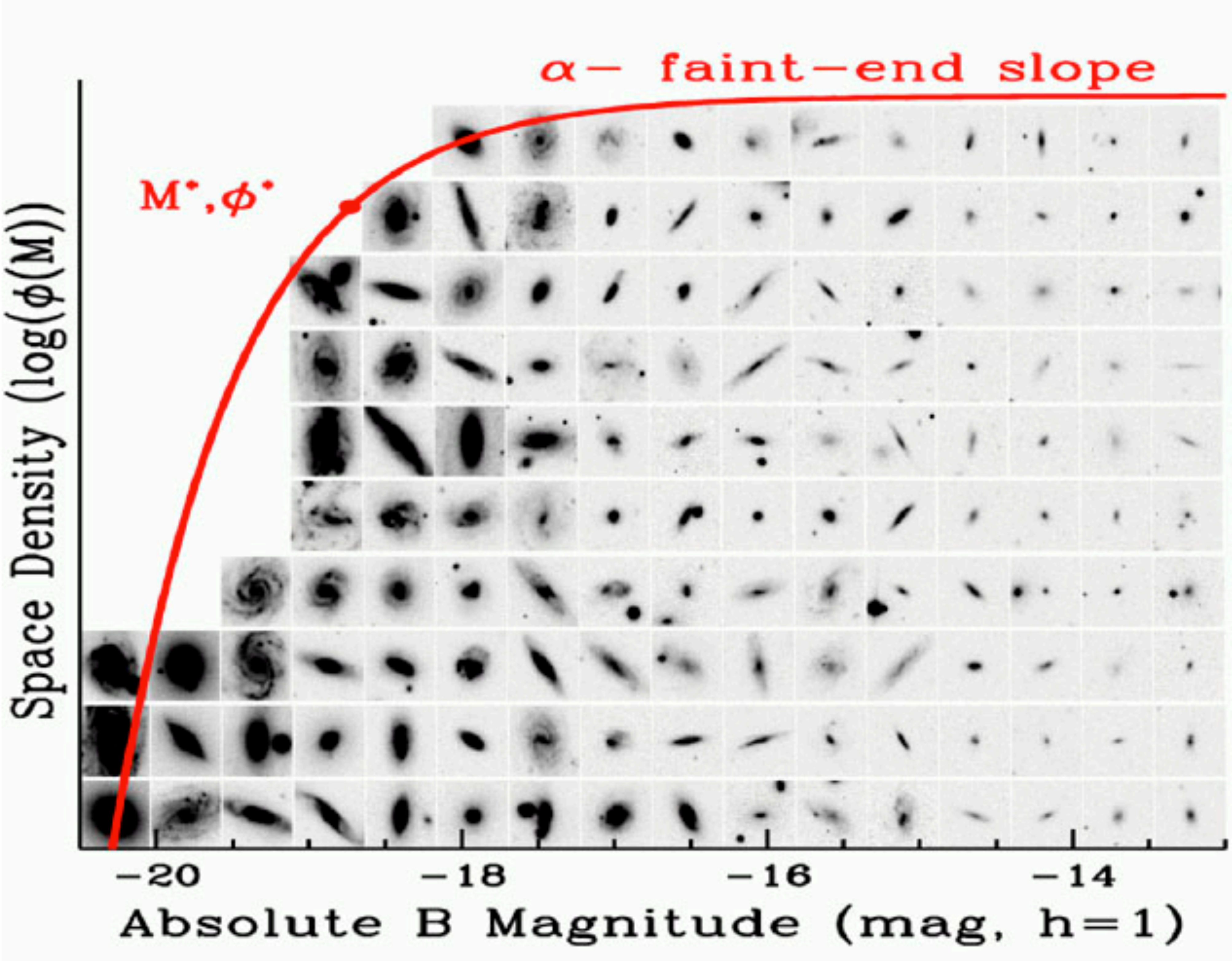
- The Luminosity of a galaxy is relatively simple to measure (quantity of light emitted): L
- The luminosity function Φ(L) of galaxies gives the number of galaxies with luminosity between L and L+dL.
- Observations show that the luminosity function follow an empirical function: **the *Schechter* function** (1976) :

$$\mathrm{d}n(L) = \Phi(L)\mathrm{d}L = \Phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \frac{\mathrm{d}L}{L^*},$$

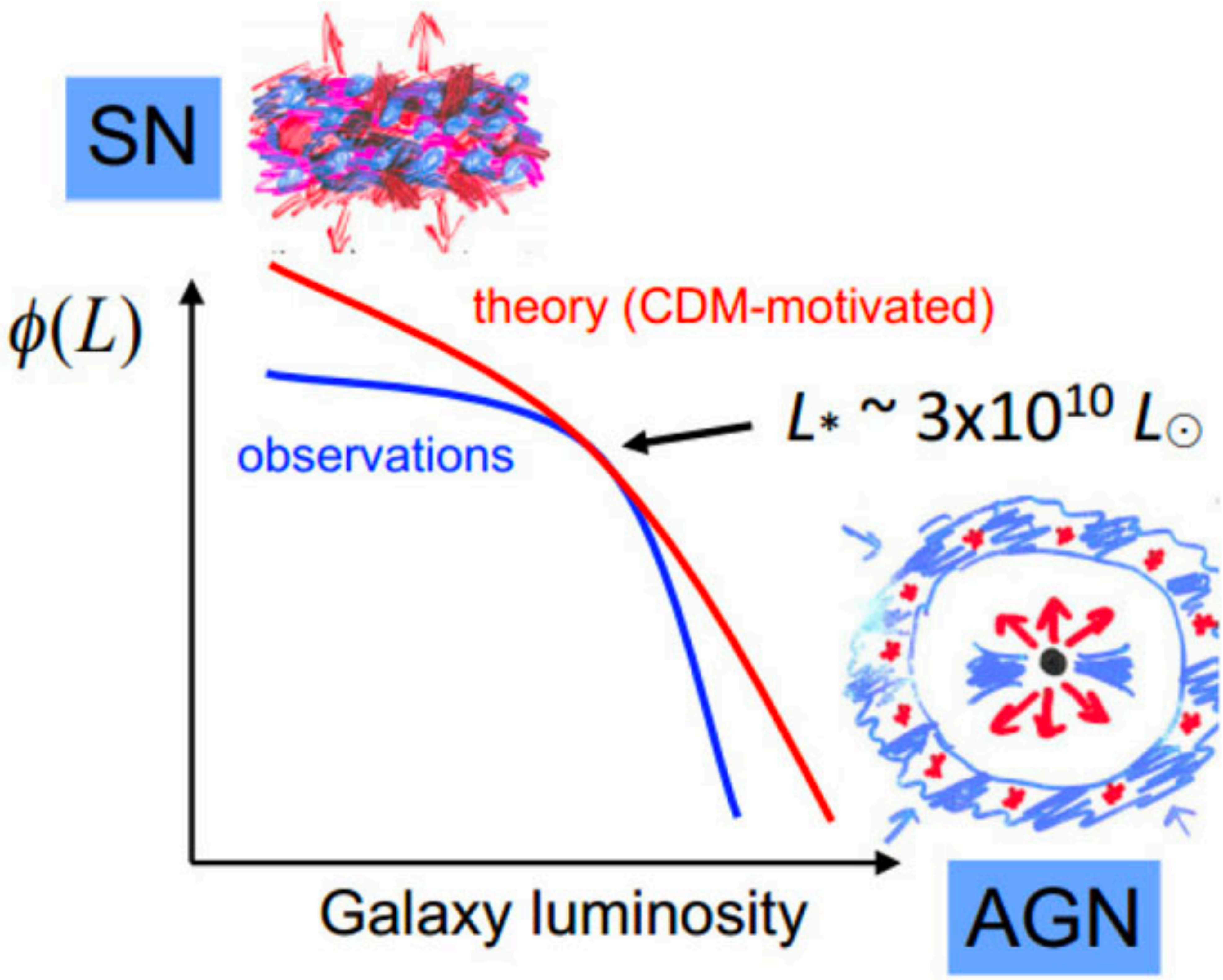
Can be expressed in terms of absolute magnitude

$$\frac{L}{L^*} = 10^{0.4(M^* - M)}$$

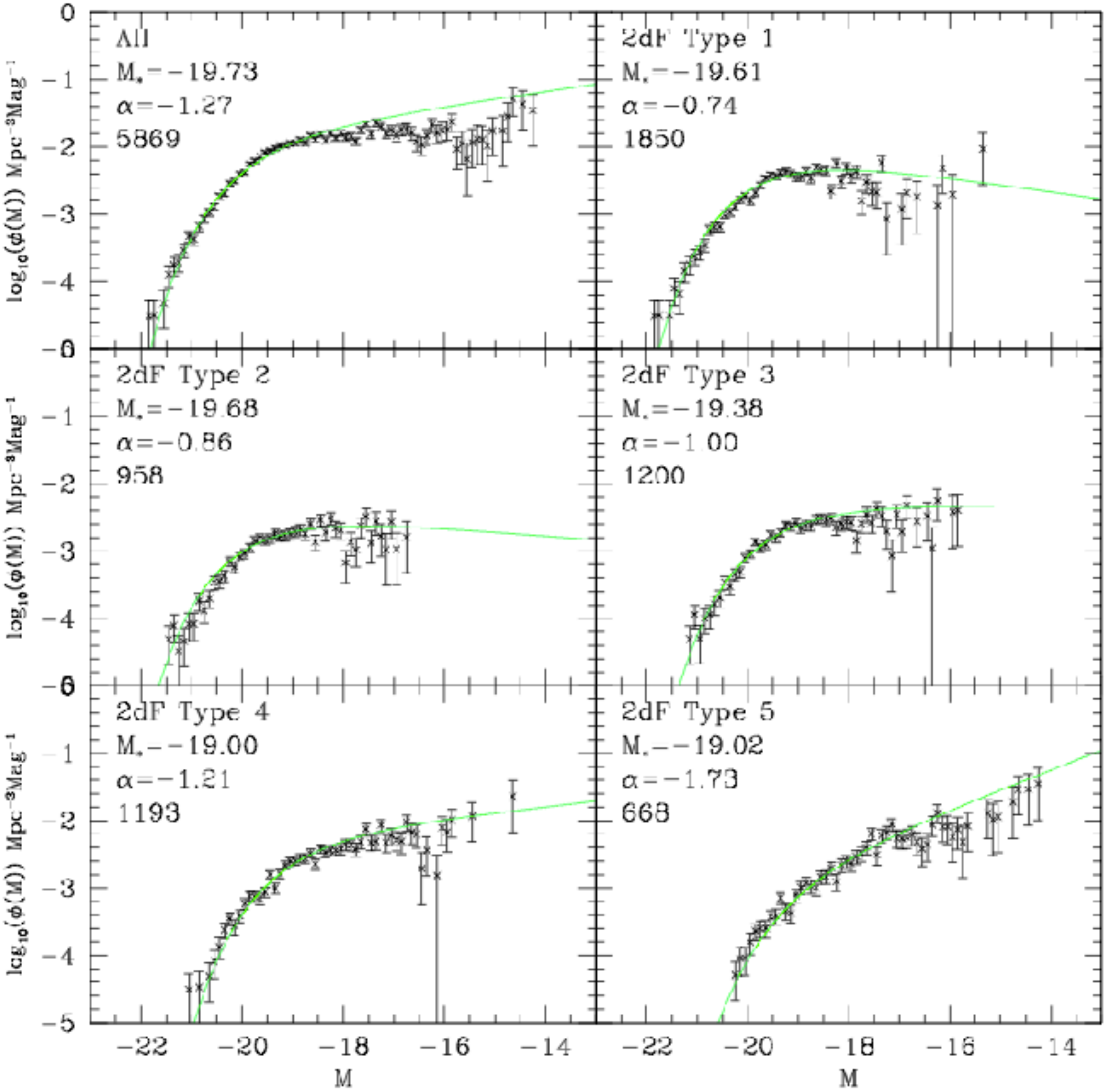
Galaxy Luminosity Function



Galaxy Luminosity Function

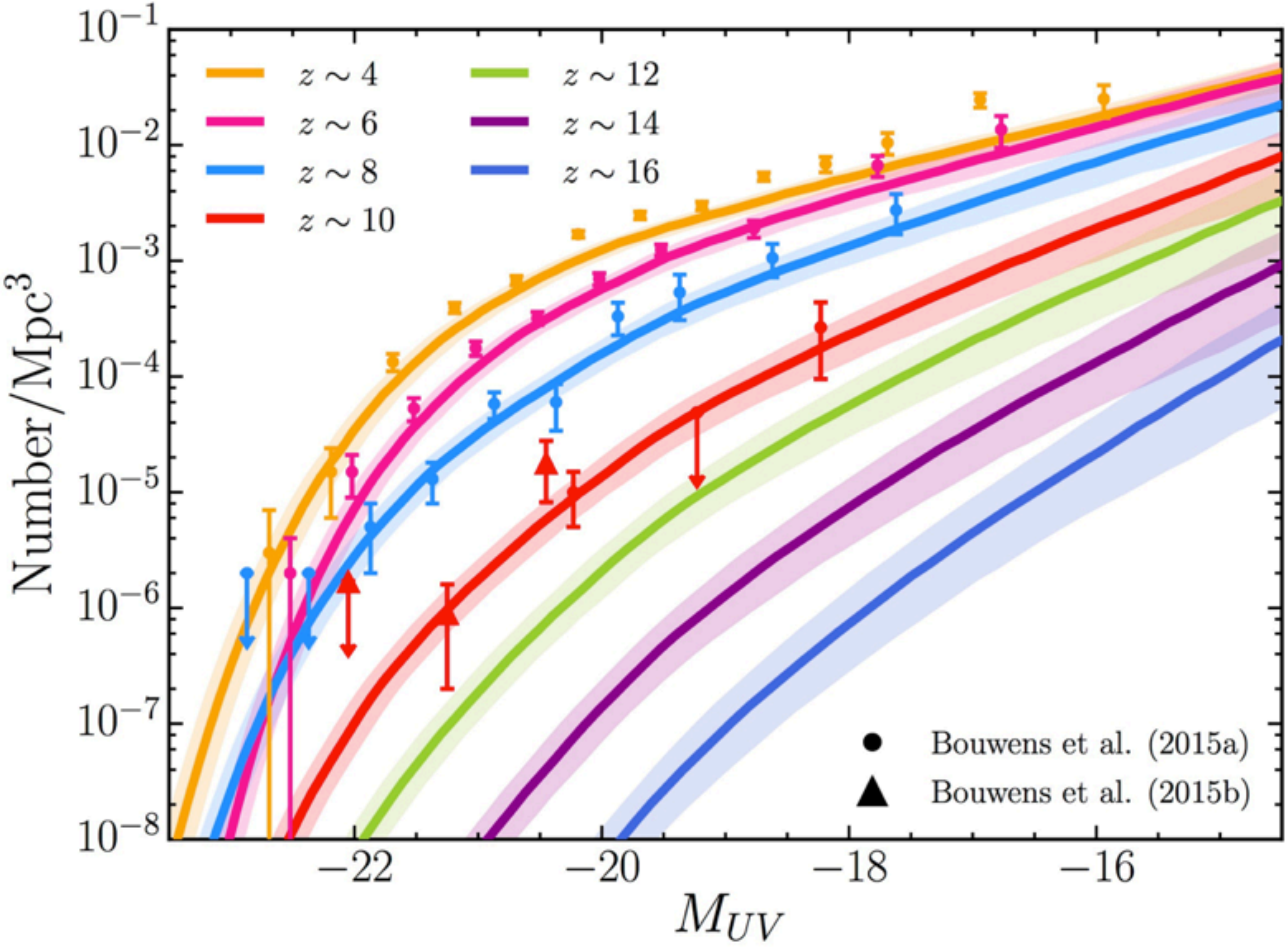


Luminosity Function of Nearby Galaxies



LF plots from the 2dF galaxy Redshift Survey

Luminosity Function of Galaxy at High Redshift



Comparison of observations and models.

Steeper faint end slope than measurement at low redshift

Integral of the Galaxy Luminosity Function

- Number of galaxies with luminosity larger than L_{min} :

$$\begin{aligned} N(L > L_{min}) &= \int_{L_{min}}^{\infty} \Phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \frac{\mathrm{d}L}{L^*} \\ &= \Phi^* \int_{y_{min}}^{\infty} y^{\alpha} \mathrm{e}^{-y} \mathrm{d}y \\ &= \Phi^* \Gamma\left(1+\alpha; \frac{L_{min}}{L^*}\right), \end{aligned}$$

$$n_{gal} = \Phi^* \Gamma\left(1+\alpha\right)$$

Luminosity Density of Galaxies

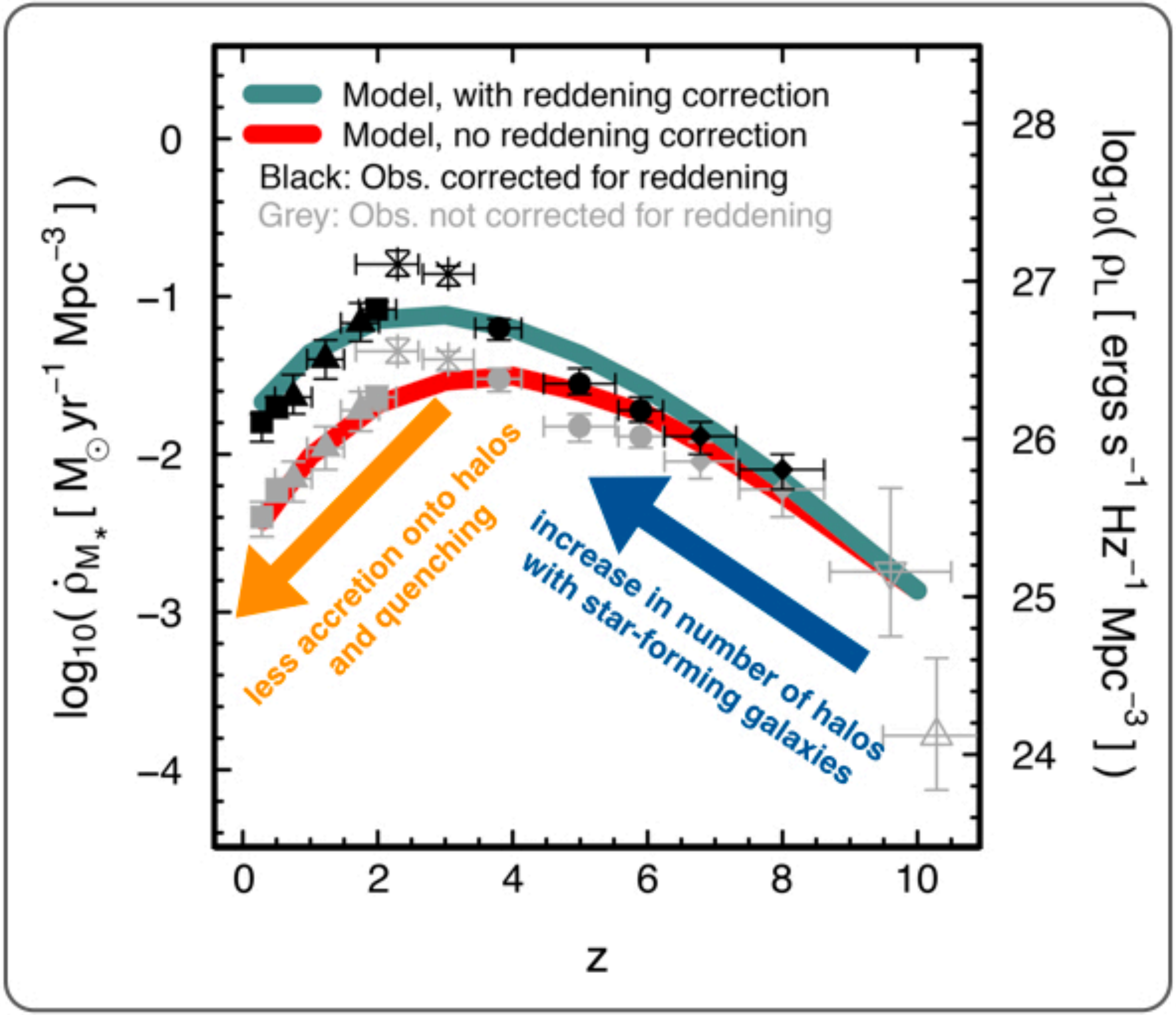
- Luminosity density of galaxies with luminosity larger than L_{min} :

$$\begin{aligned} \rho_L(L > L_{min}) &= \int_0^{\infty} n(L)\; L\; \mathrm{d}L \\ &= L^*\Phi^* \int_{L_{min}}^{\infty} \frac{L}{L^*} \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \frac{\mathrm{d}L}{L^*} \\ &= L^*\Phi^* \int_{y_{min}}^{\infty} y^{(1+\alpha)} \mathrm{e}^{-y} \mathrm{d}y \\ &= L^*\Phi^*\Gamma\left(2+\alpha; \frac{L_{min}}{L^*}\right). \end{aligned}$$

$\rho_L = L^*\Phi^*\Gamma\left(2+\alpha\right)$ total luminosity density

$\rho_L = 2.0 \pm 0.2 \times 10^8\ h\ L_{\odot}\ \mathrm{Mpc}^{-3}$ typical number

Galaxy Luminosity Density Evolution

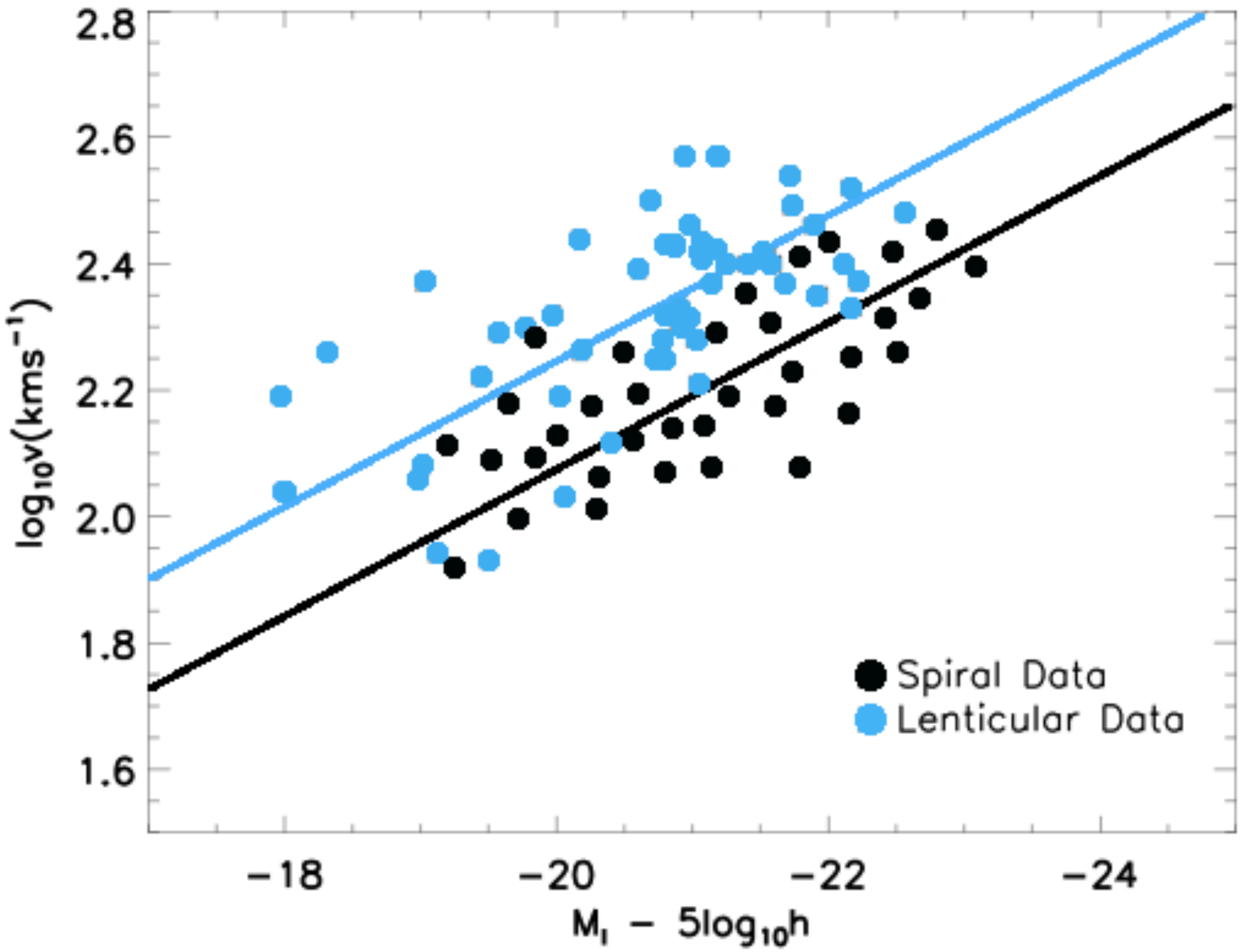


Link between
Luminosity & Mass ?

Dynamical properties of
galaxies ?

Tully-Fisher Relation

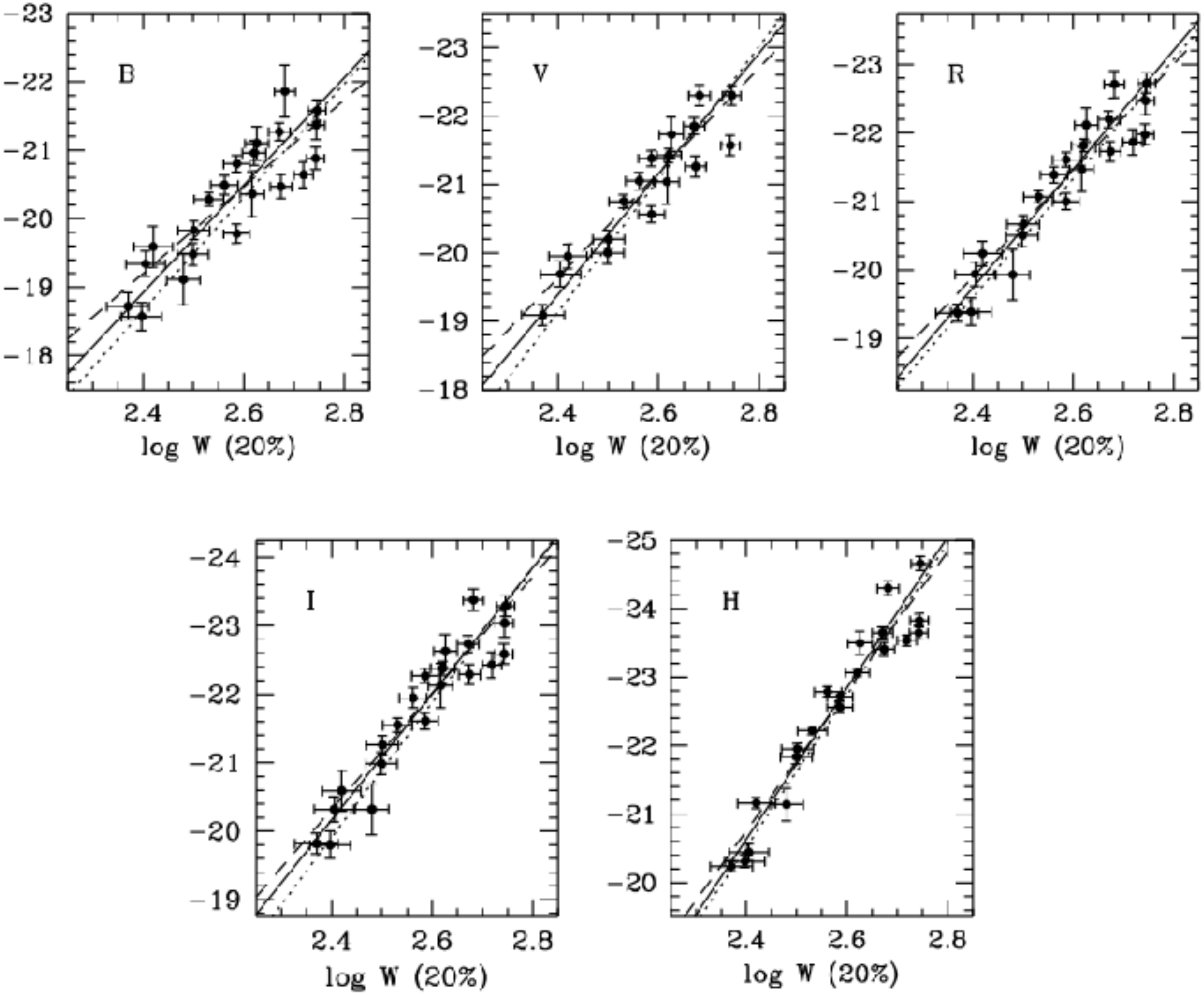
Need magnitude, redshift and rotational velocity



- For Spiral Galaxies
- Relation between the rotation velocity and the absolute magnitude/ luminosity
- α is between 3 and 4. Closer to 4 for IR luminosity
- Used as distance indicator

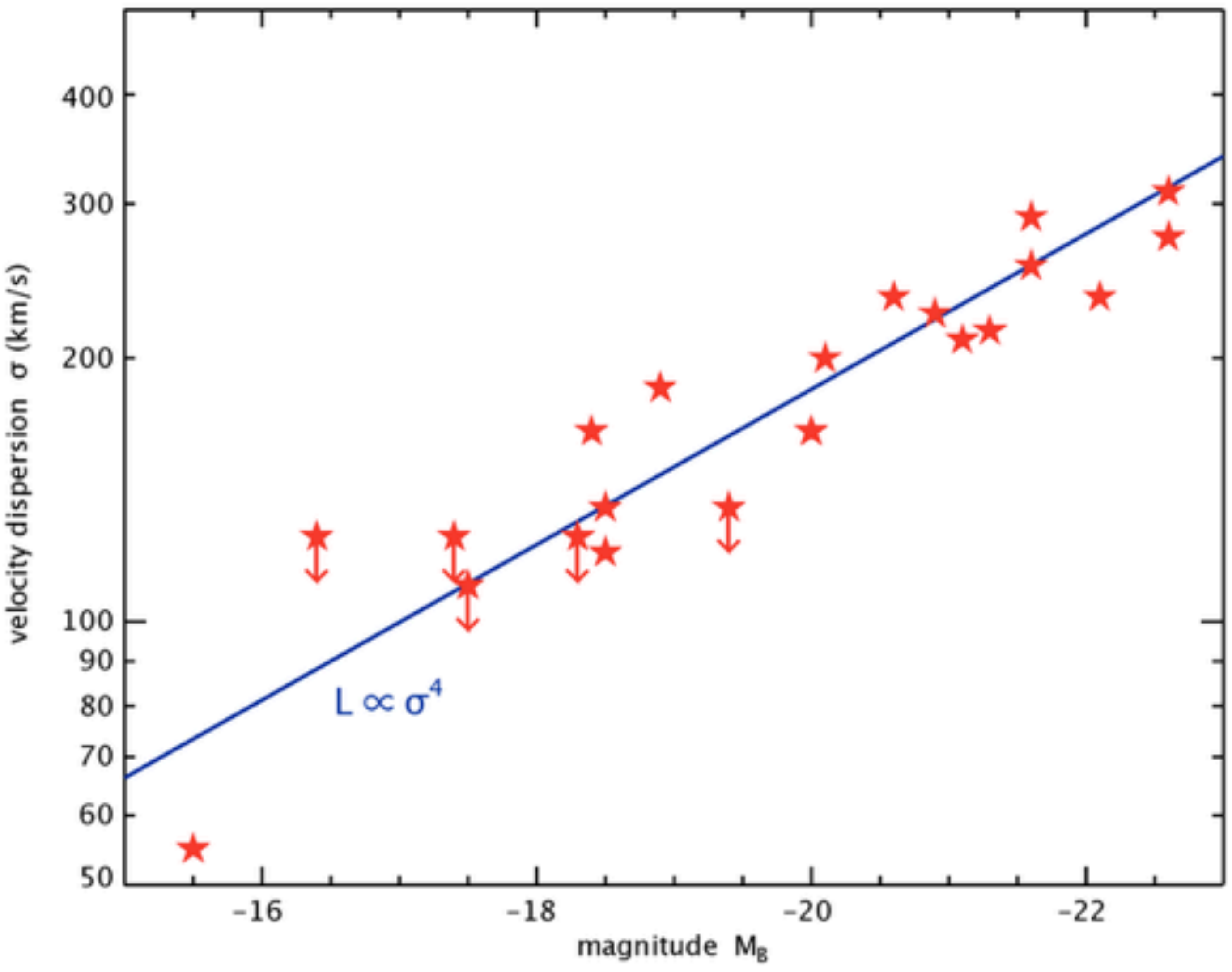
$$L \propto V_r^\alpha$$

Tully-Fisher Relation



Faber-Jackson Relation

Need magnitude, redshift and velocity dispersion



- For Elliptical Galaxies
- Relation between the velocity dispersion and the absolute magnitude/ luminosity

$$L \sim \sigma^{\gamma}$$

- The exponent is about 4.
- Used as a distance indicator

Fundamental Plane

Need magnitude, redshift, size and velocity dispersion

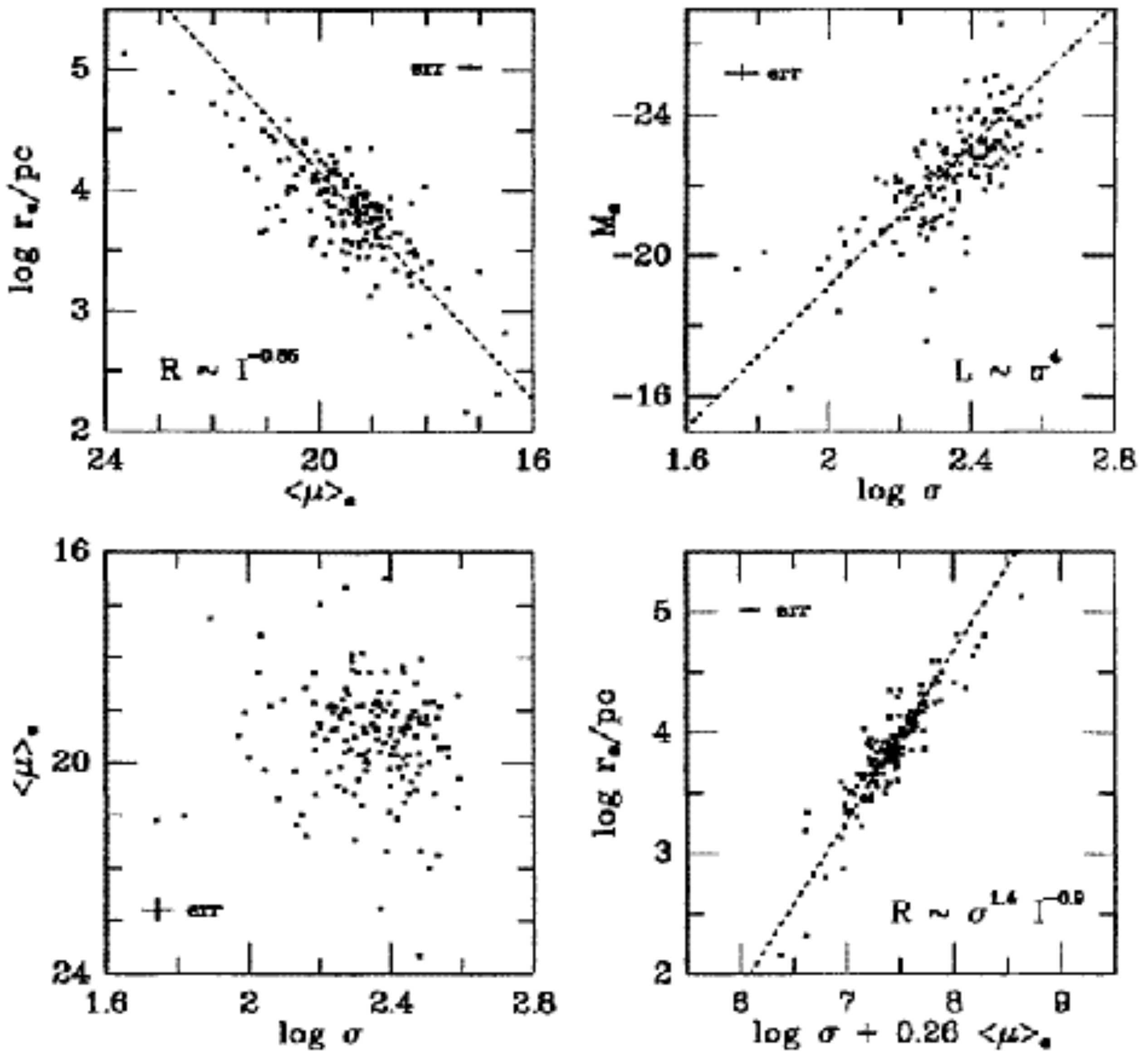


Figure 2 Projections of the fundamental parameter plane of elliptical galaxies. *Top panels:*

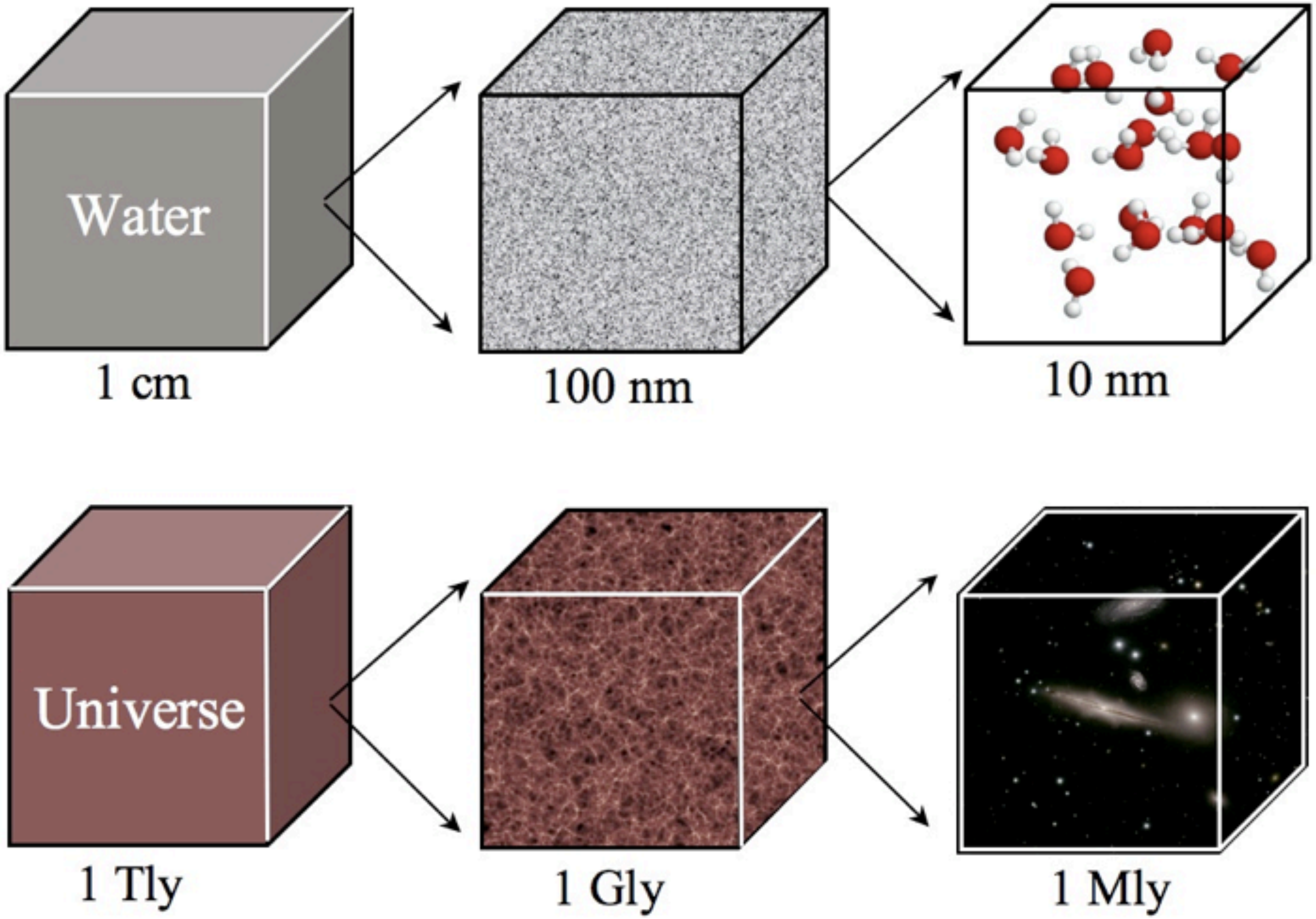
- For Elliptical Galaxies
- A more precise representation of the scaling relation between luminosity, velocity dispersion and galaxy size

$$\log R_e = 0.36\,(\langle I \rangle_e/\mu_B) + 1.4\,\log \sigma_o$$

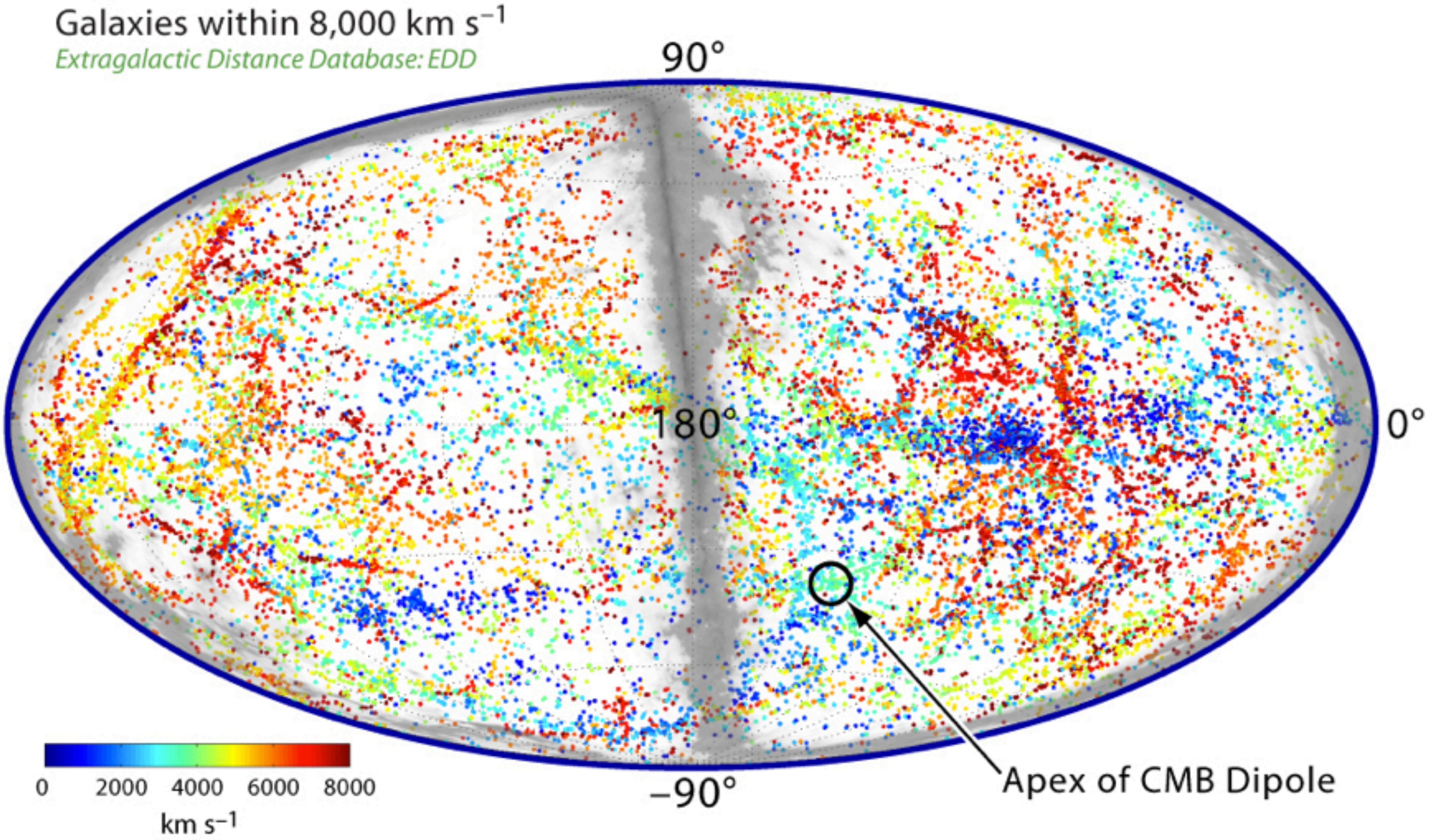
Observed distribution of galaxies ?

Galaxy distribution

- homogeneity and non-homogeneity - SCALE?

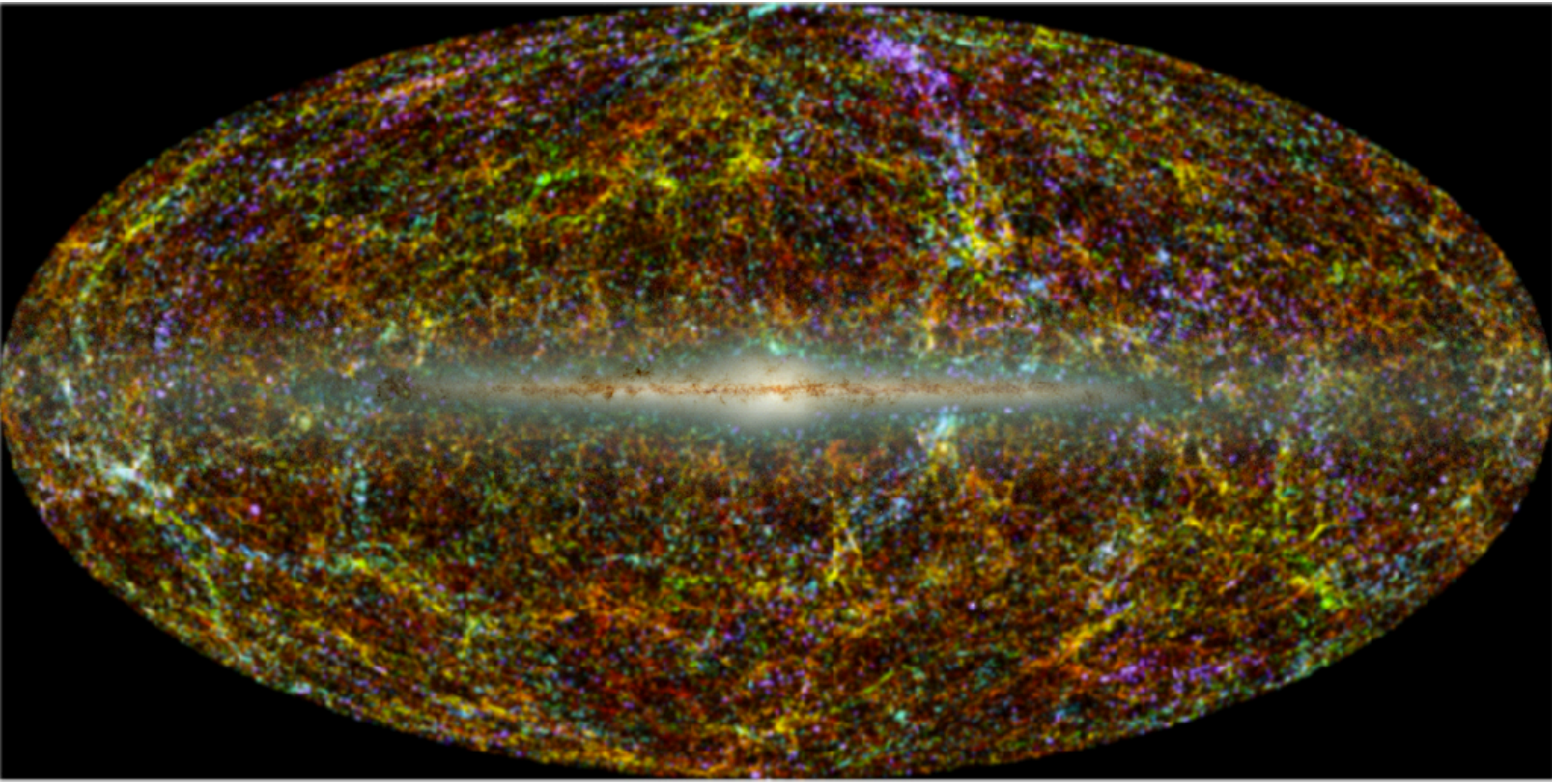


Galaxy distribution



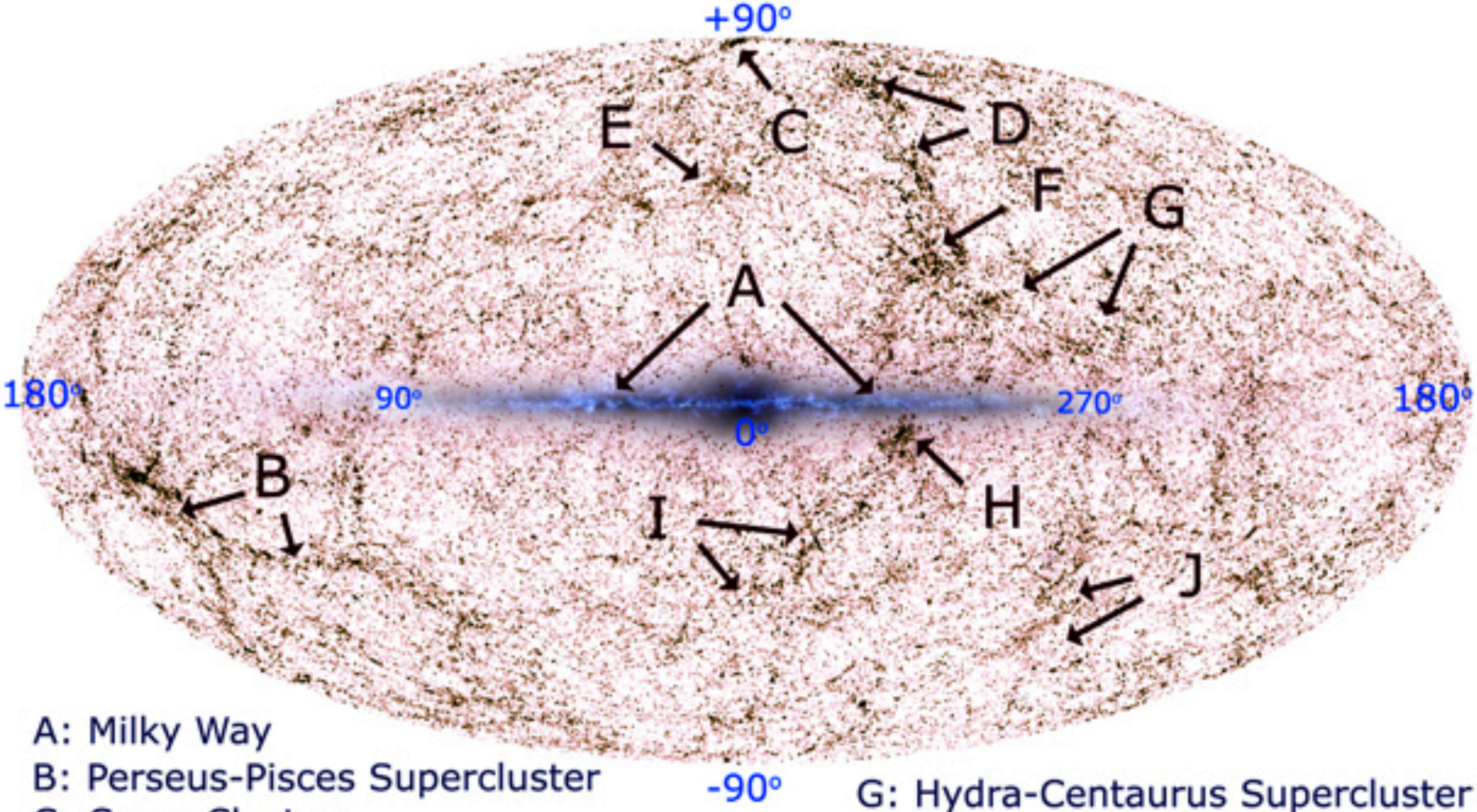
- local galaxy distribution is relatively inhomogeneous

Galaxy distribution



- 2MASS (infrared. Imaging survey) galaxies local distribution
- z<0.03 (or 115 Mpc) - use of colour coding for the distance

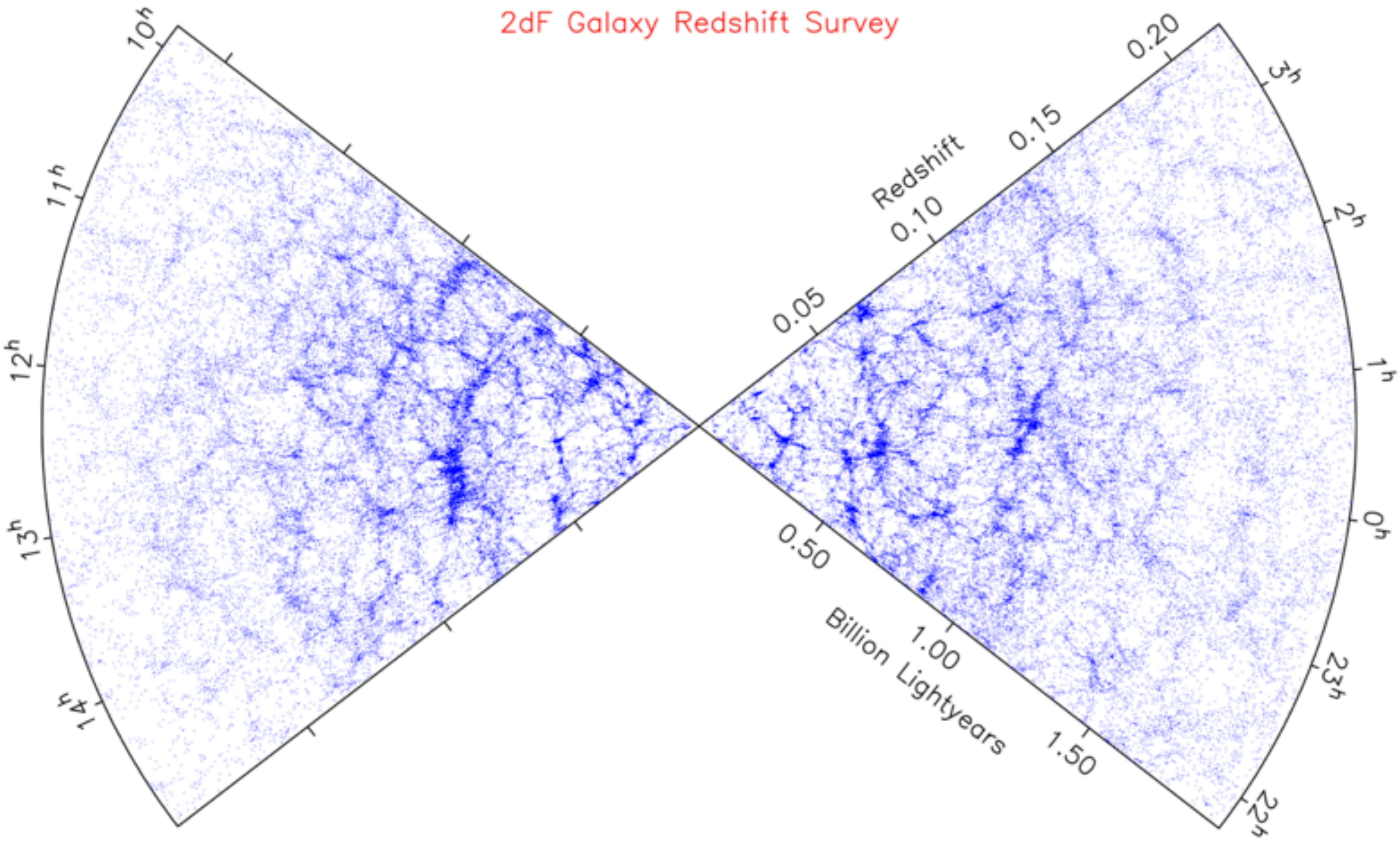
Galaxy distribution



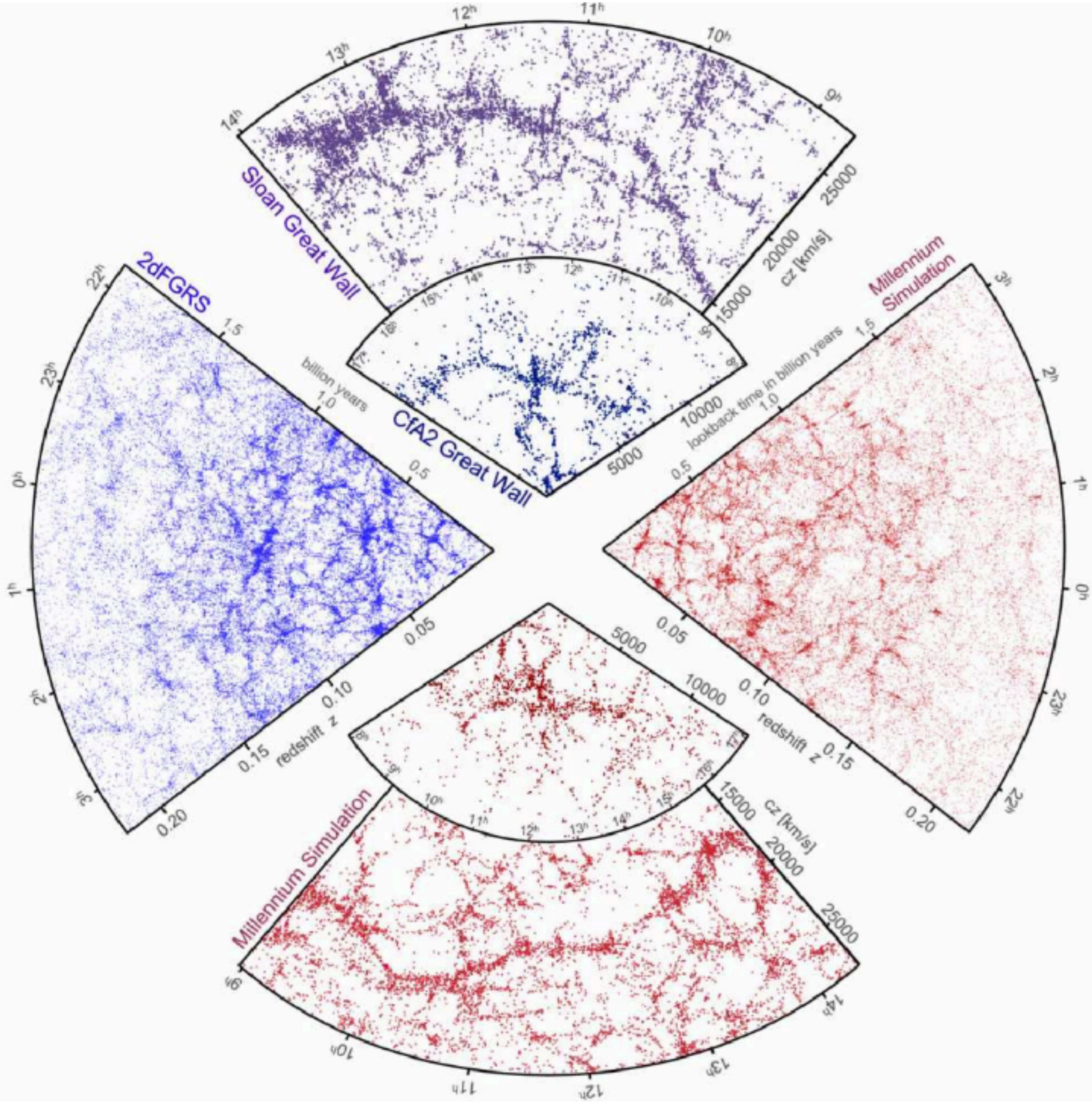
A: Milky Way
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster
E: Hercules Supercluster
F: Shapley Concentration/Abell 3558

G: Hydra-Centaurus Supercluster
H: "Great Attractor"/Abell 3627
I: Pavo-Indus Supercluster
J: Horologium-Reticulum Supercluster

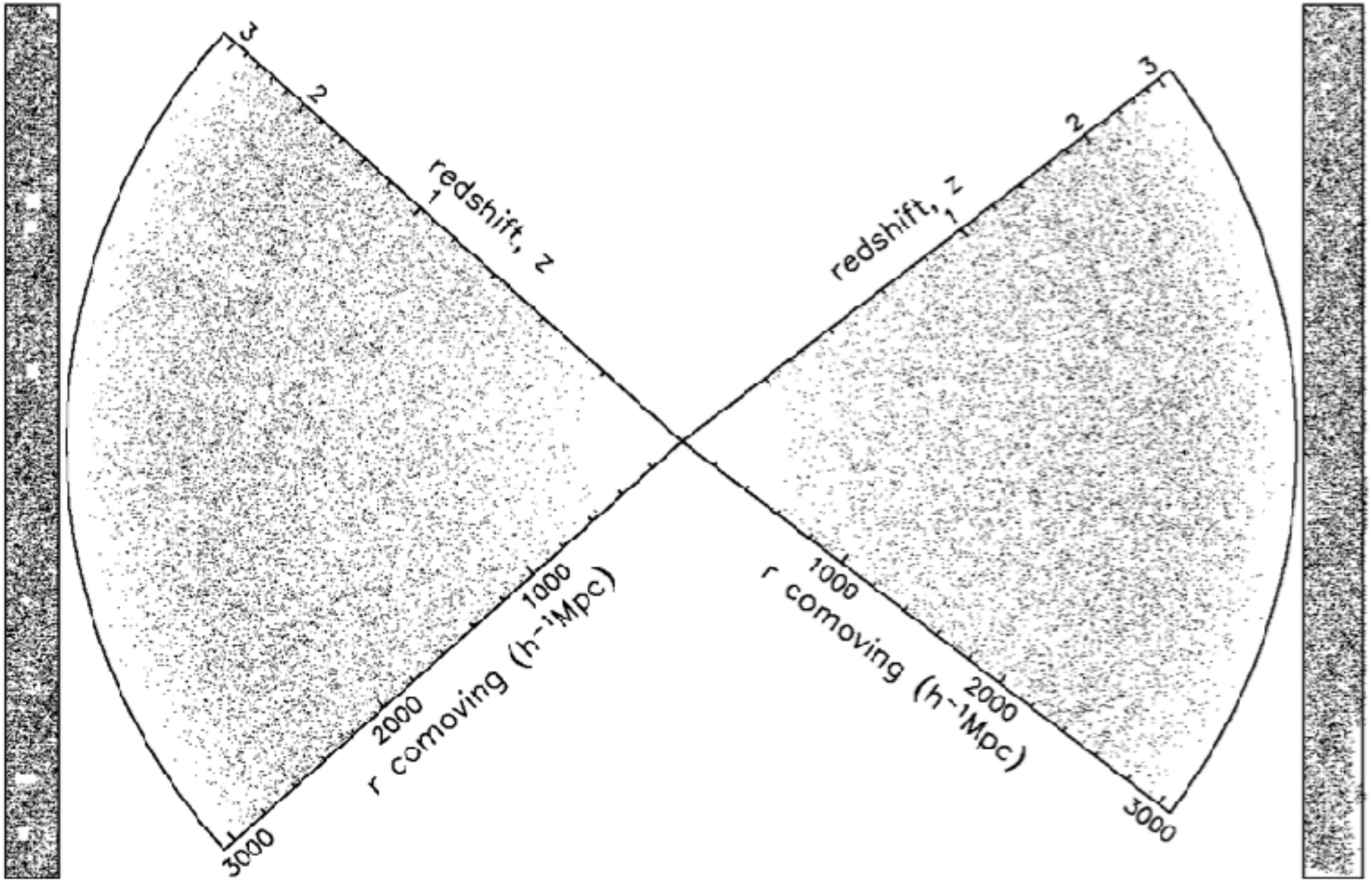
Galaxy redshift distribution



- 2DF galaxy Redshift survey extends to z~0.2
- Fly through SDSS: https://www.youtube.com/watch?v=08LBltePDZw
- LSS in the SDSS: https://www.youtube.com/watch?v=Bo9EQ6mIhRY

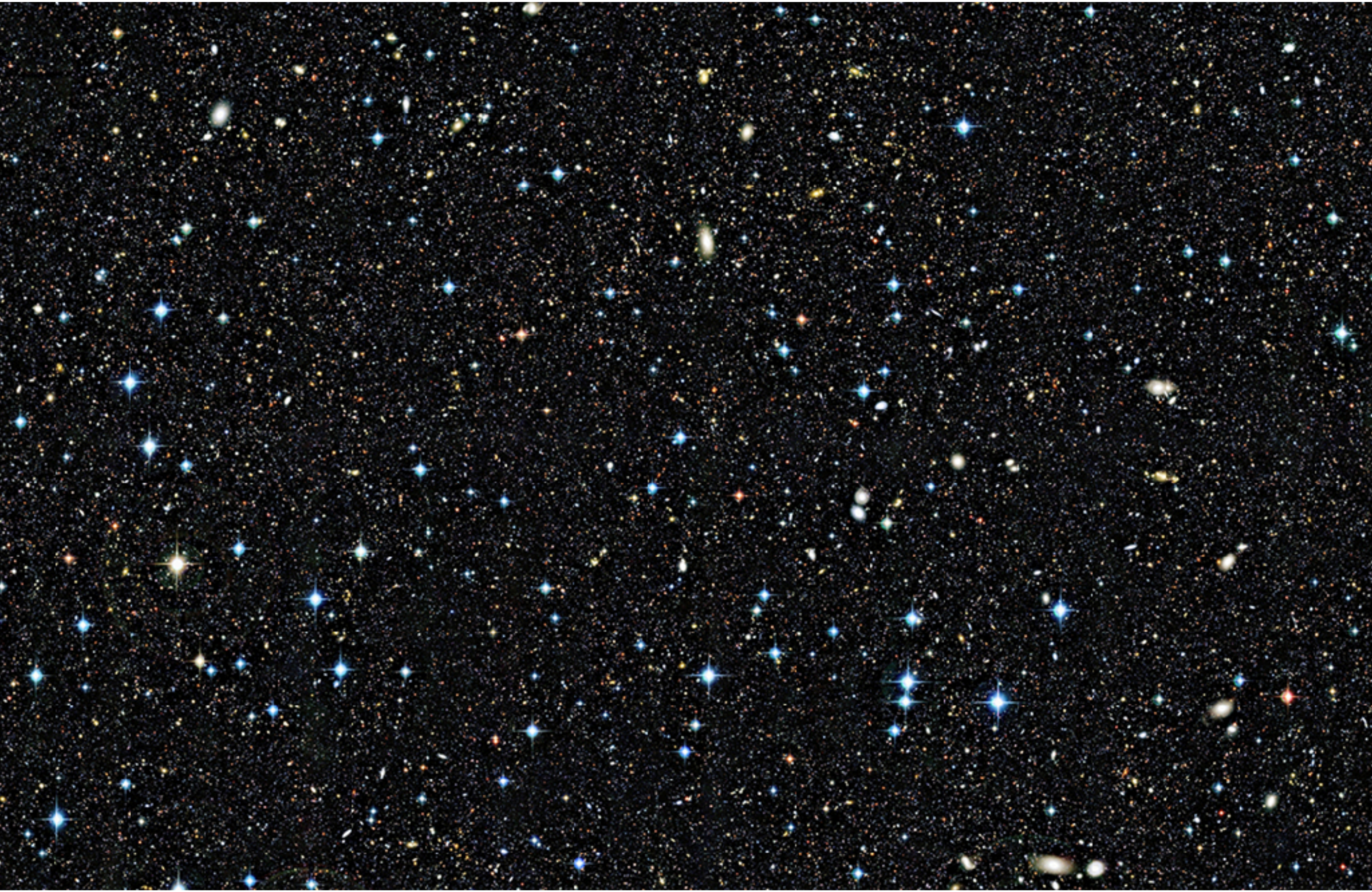

Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
Millennium Simulation
cz [km/s]
5000
10000
15000
20000
25000
billion years
lookback time in billion years
0.5
1.0
1.5
redshift z
0.05
0.10
0.15
0.20
9h
10h
11h
12h
13h
14h
15h
16h
17h
8h
22h
23h
0h
1h
2h
3h

Quasar redshift distribution

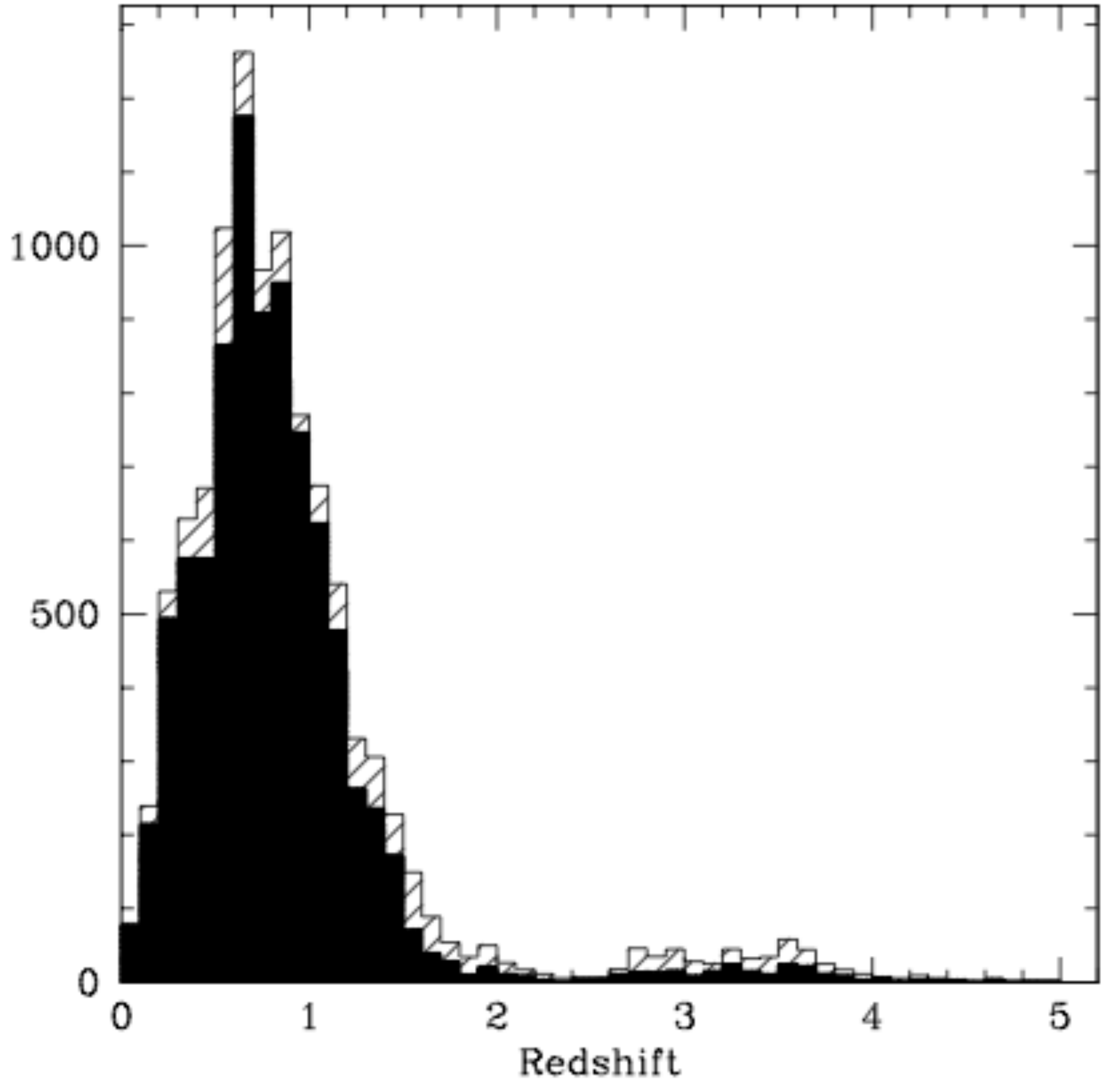


- 2DF QSO Redshift survey extends to z~3
- Density distribution is rather homogenous (but not dense enough to identify LSS on small scale)

Pencil beam surveys

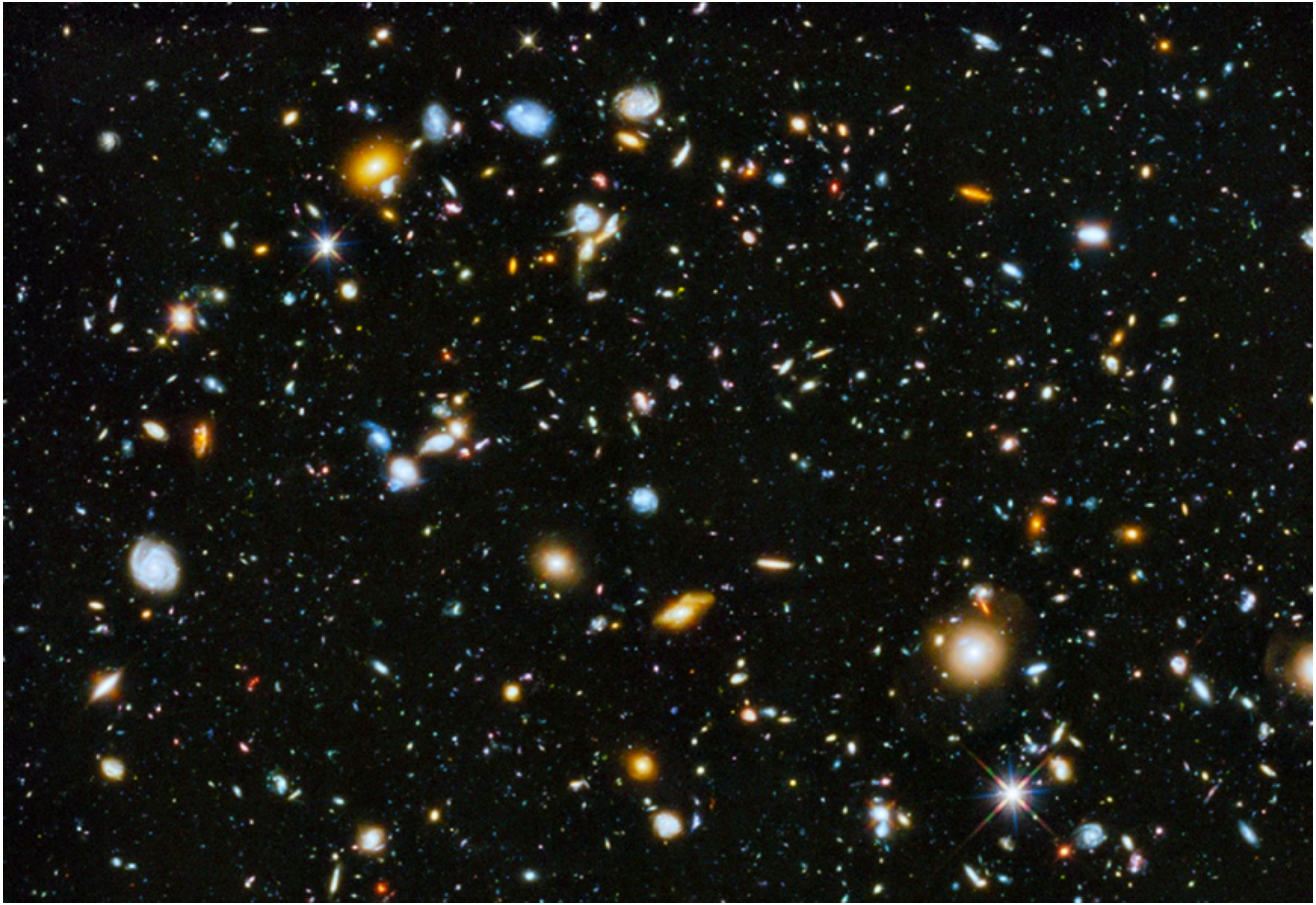


Pencil beam surveys



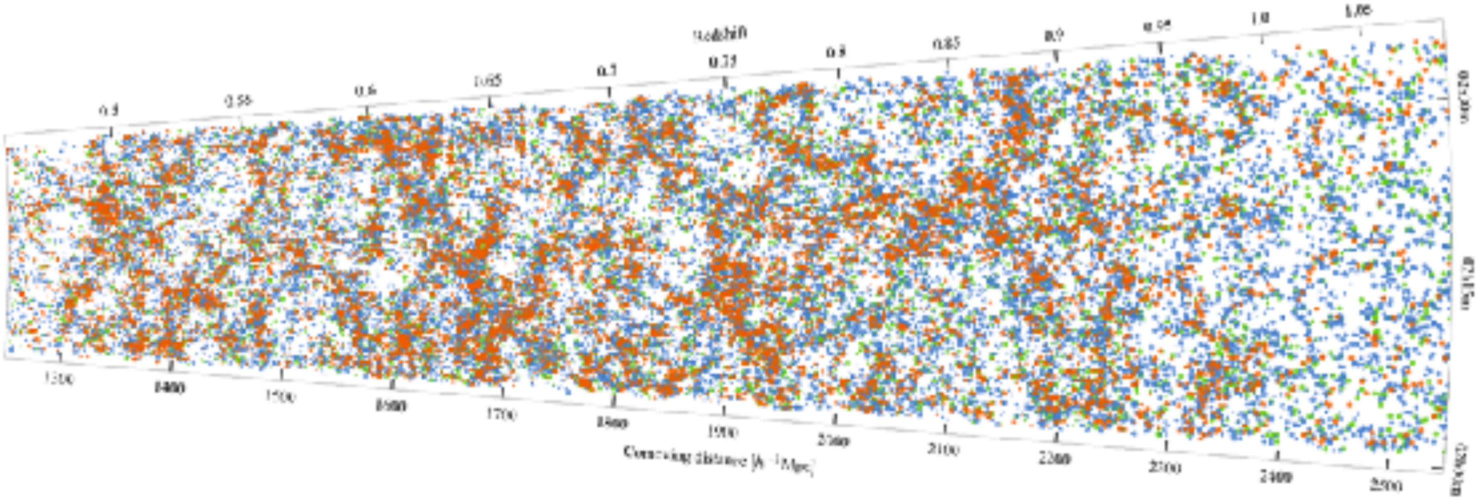
- Redshift distribution of I<24.5 galaxies using the optical VIMOS spectrograph (VVDS survey)

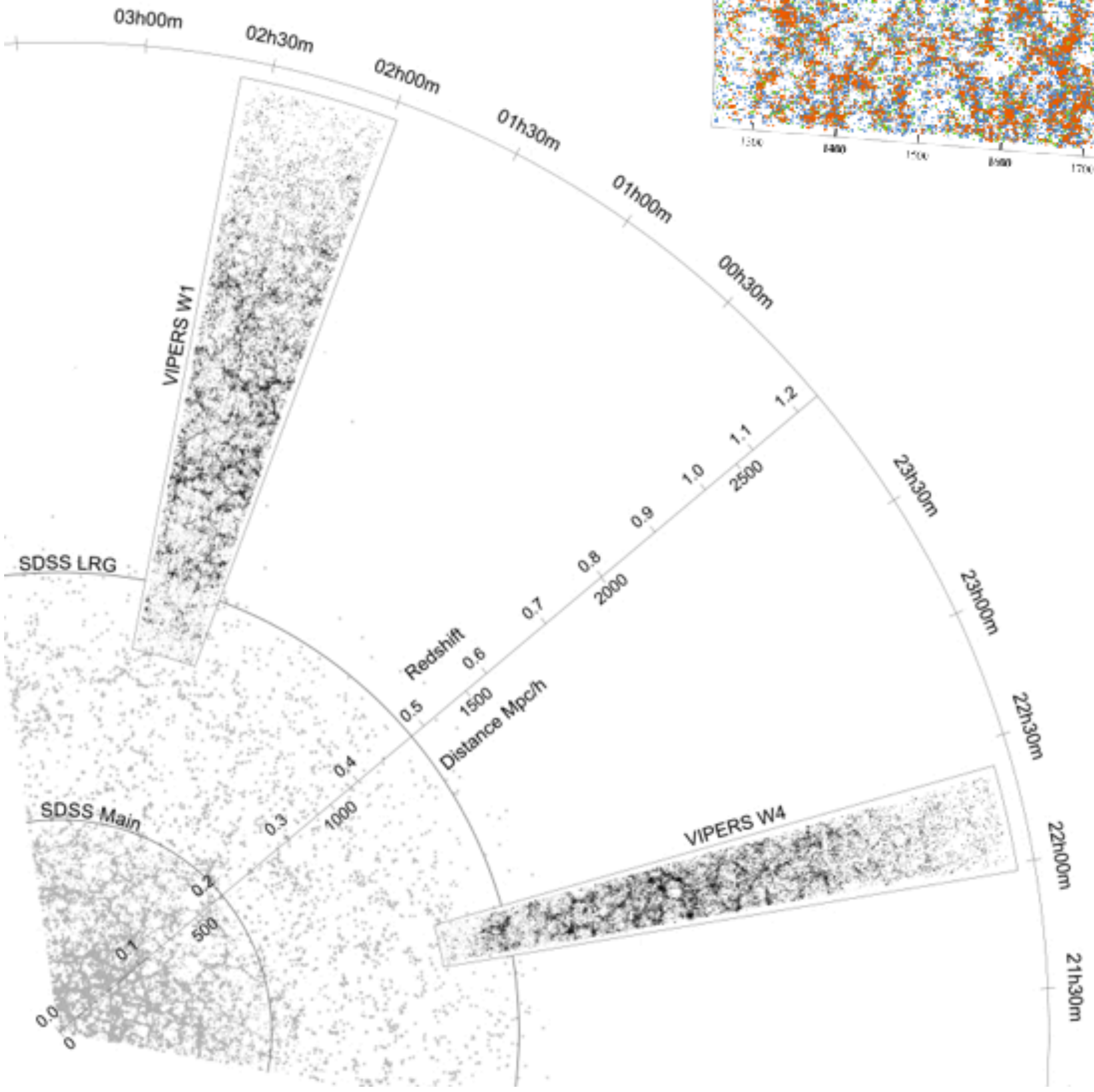
Hubble Deep Field



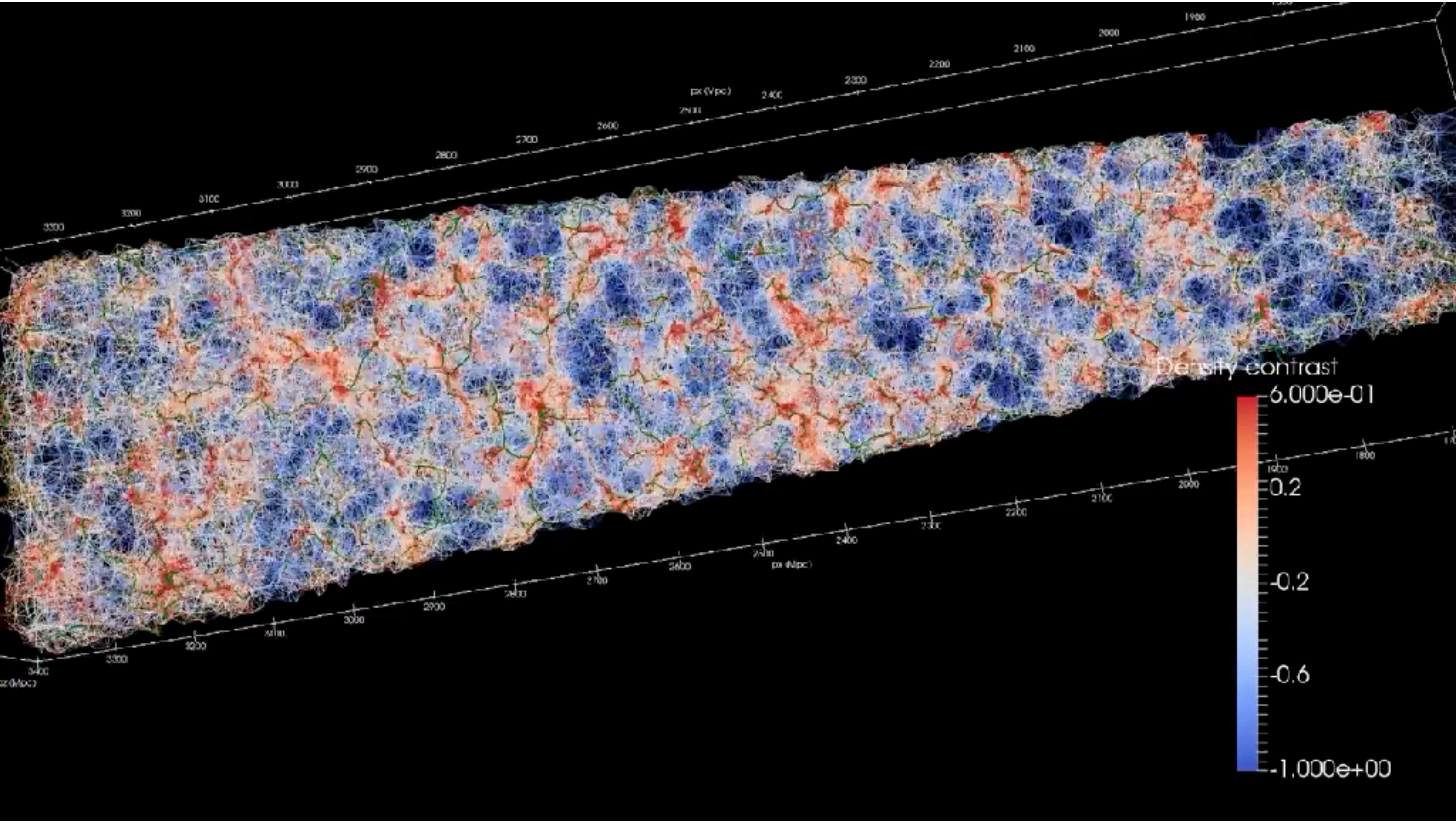
https://www.youtube.com/watch?v=PDMp8a-YNe0

Pencil beam surveys



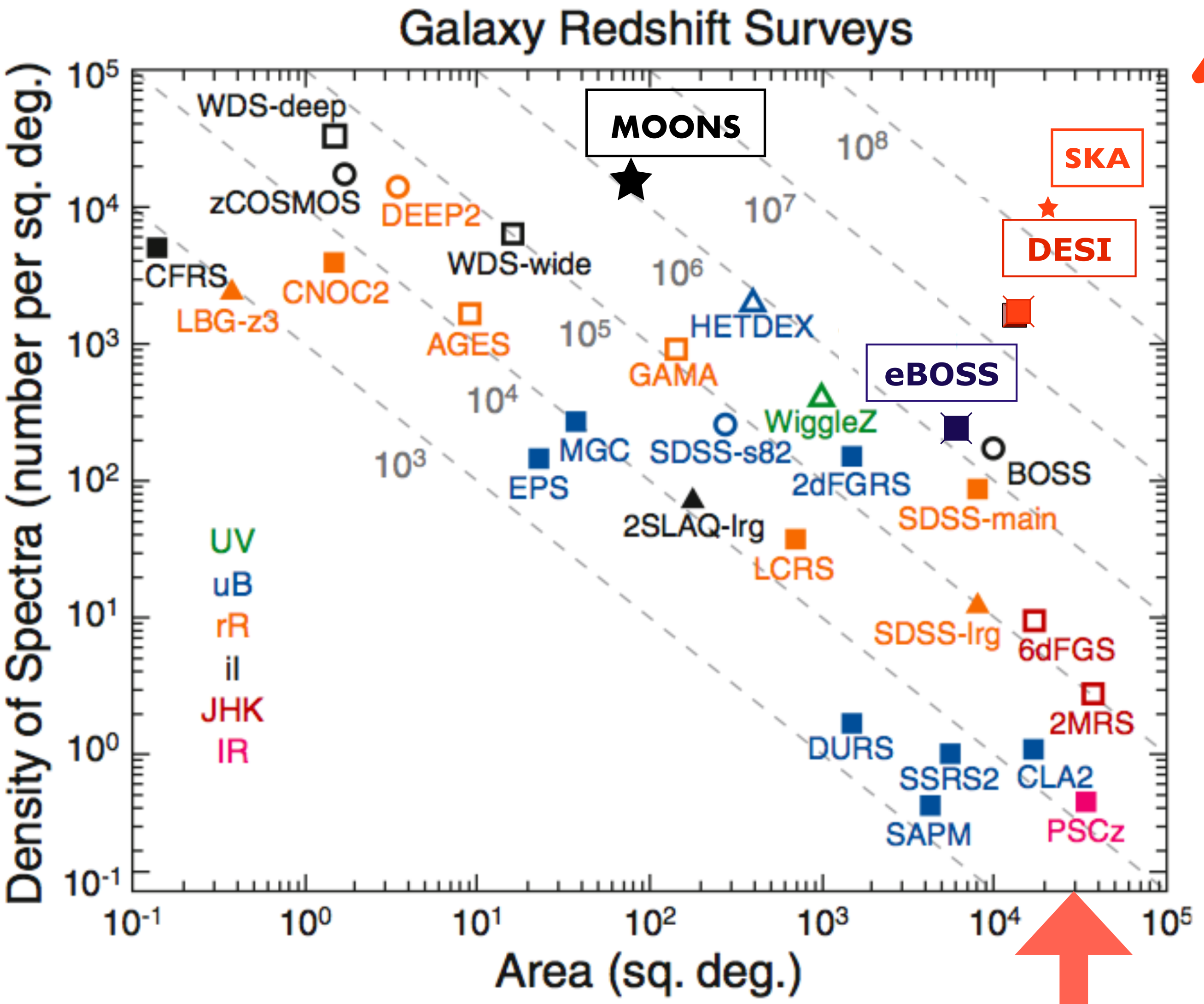


- VIPERS survey
- http://vipers.inaf.it/



https://www.youtube.com/watch?v=dmArPfz2ryg

3D mapping of galaxies



- **Hubble (1930):** Expansion of the Universe
- **CfA Redshift Survey (1985):** first large scale structures
- **2dF (~2000):** 1500 deg^2
- **SDSS-I-II (~2005):** 5700 deg^2
- **VVDS/DEEP2 (~2004):** Deep universe ~1 deg^2
- **WiggleZ (2011)**: 800 deg^2 BAO
- **VIPERS (2012):** 25 deg^2 RSD
- **SDSS-III/BOSS (2009-2014)**: 10,000 deg^2 BAO/LSS - 1.5 millions
- **e-BOSS** (2014-2020) - 1.1 millions
- **DESI** (2020-25) - 35 millions
- **EUCLID** (2023) - 50 millions
- **PFS** (2025) - 3 millions
- **4MOST** (2025) - 10 millions
- **SKA** (2030) ~100+ millions
- **MUST** (2030) 100+ millions?
- **Spec-S5** (2035)
- **WST** (2040)

How to quantify the 3D distribution of galaxies?

Clustering of galaxies

- Correlation function of 2 points - estimator of the excess probability to find an other galaxy at a distant r of a given galaxy
- P: probability, dV_i: volume element, n number density. For a Poisson distribution

$$\mathrm{d}P = \bar{n}^2 \mathrm{d}V_1 \mathrm{d}V_2$$

- in general, we have:

$$\mathrm{d}P = \bar{n}^2 \left[1 + \xi(\mathbf{r}_1, \mathbf{r}_2)\right] \mathrm{d}V_1 \mathrm{d}V_2$$

- $\xi > 0$ means correlation, $\xi < 0$ means anti-correlation

Clustering of galaxies

- For a homogeneous Universe:
  - $\xi(\mathbf{r}_1,\mathbf{r}_2)=\xi(\mathbf{r}_1-\mathbf{r}_2)$
- For an homogeneous and isotropic Universe (same in all direction)
  - $\xi(\mathbf{r}_1-\mathbf{r}_2)=\xi(|\mathbf{r}_1-\mathbf{r}_2|)=\xi(\mathrm{r})$
- For a density field described by $\varrho(\mathrm{r})$:

$$\xi(r) = \frac{\langle(\rho(\mathbf{u}) - \bar{\rho})\,(\rho(\mathbf{u}+\mathbf{r}) - \bar{\rho}\rangle}{\bar{\rho}^2}$$

Clustering of galaxies

- We can define the excess (mass) density field by:

$$\delta\left(\mathbf{x}\right) = \frac{\rho\left(\mathbf{x}\right) - \bar{\rho}}{\bar{\rho}}$$

- then the correlation function can be written:

$$\xi(\mathbf{r}) = \langle\delta\left(\mathbf{x}\right)\ \delta\left(\mathbf{x}+\mathbf{r}\right)\rangle$$

- The excess (mass) density field can be express in the Fourier space:

$$\begin{cases} \hat{\delta}\left(\mathbf{k}\right) & = \int \delta\left(\mathbf{r}\right) e^{i\mathbf{k}.\mathbf{r}} \mathrm{d}^3\mathbf{r} \\ \delta\left(\mathbf{r}\right) & = \frac{1}{(2\pi)^3} \int \hat{\delta}\left(\mathbf{k}\right) e^{-i\mathbf{k}.\mathbf{r}} \mathrm{d}^3\mathbf{k} \end{cases}$$

Clustering of galaxies

- And the correlation function can be expressed in terms of the excess density in Fourier space:

$$\xi_\delta(\mathbf{r}) = \langle\left(\frac{1}{(2\pi)^3}\int \hat{\delta}^*\left(\mathbf{k}\right)e^{i\mathbf{k}.\mathbf{x}}\mathrm{d}^3\mathbf{k}\right)\cdot\left(\frac{1}{(2\pi)^3}\int \hat{\delta}\left(\mathbf{k}'\right)e^{-i\mathbf{k}'.(\mathbf{x}+\mathbf{r})}\mathrm{d}^3\mathbf{k}'\right)\rangle$$

- Which can be written in terms of the Power spectrum P_δ (k)

$$\xi_\delta\left(\mathbf{r}\right) = \frac{1}{(2\pi)^3}\int \mathrm{d}^3\mathbf{k}P_\delta\left(\mathbf{k}\right)e^{-i\mathbf{k}.\mathbf{r}}$$

Clustering of galaxies

- For an isotropic homogeneous universe:

$$\begin{cases} \xi_\delta(r) = & \dfrac{1}{(2\pi)^2} \displaystyle\int k^2 P_\delta(k) \frac{\sin(kr)}{kr} \mathrm{d}k \\ P_\delta(k) = & 4\pi \displaystyle\int r^2 \xi_\delta(r) \frac{\sin(kr)}{kr} \mathrm{d}r \end{cases}$$

- In practice, galaxy distribution do not exactly follow the mass density distribution in the Universe. There is a bias factor b (to be accounted for):

$$b = \left(\frac{\delta n}{\delta \rho}\right)$$

Clustering of galaxies

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Number density of galaxies

Matter density

Clustering measurement

- In practice the correlation function is computed in the following way:

$$\xi(r) = \frac{N_{obs}(r)}{N_{random}(r)} - 1$$

- N_i are the number of pairs of galaxies separated by a distant r.
- N_{obs} is the measurement in the observable catalogue. N_{random} is the measurement in a random catalog.
- More complex estimator exists, some of them are less biased.

Clustering measurement

- The first galaxy clustering measurement led to the following relation:

$$\xi(r)=({}^{r}/_{r_0})^{-\gamma}$$

- with $r<10\ h^{-1}$ Mpc, $\gamma = 1.8$ and $r_0 = 5h^{-1}$ Mpc
- Measuring $\xi(r)$ means with have the distribution in 3D (hence a redshift measurement for galaxies)
- The most available data is the information in position on the sky.

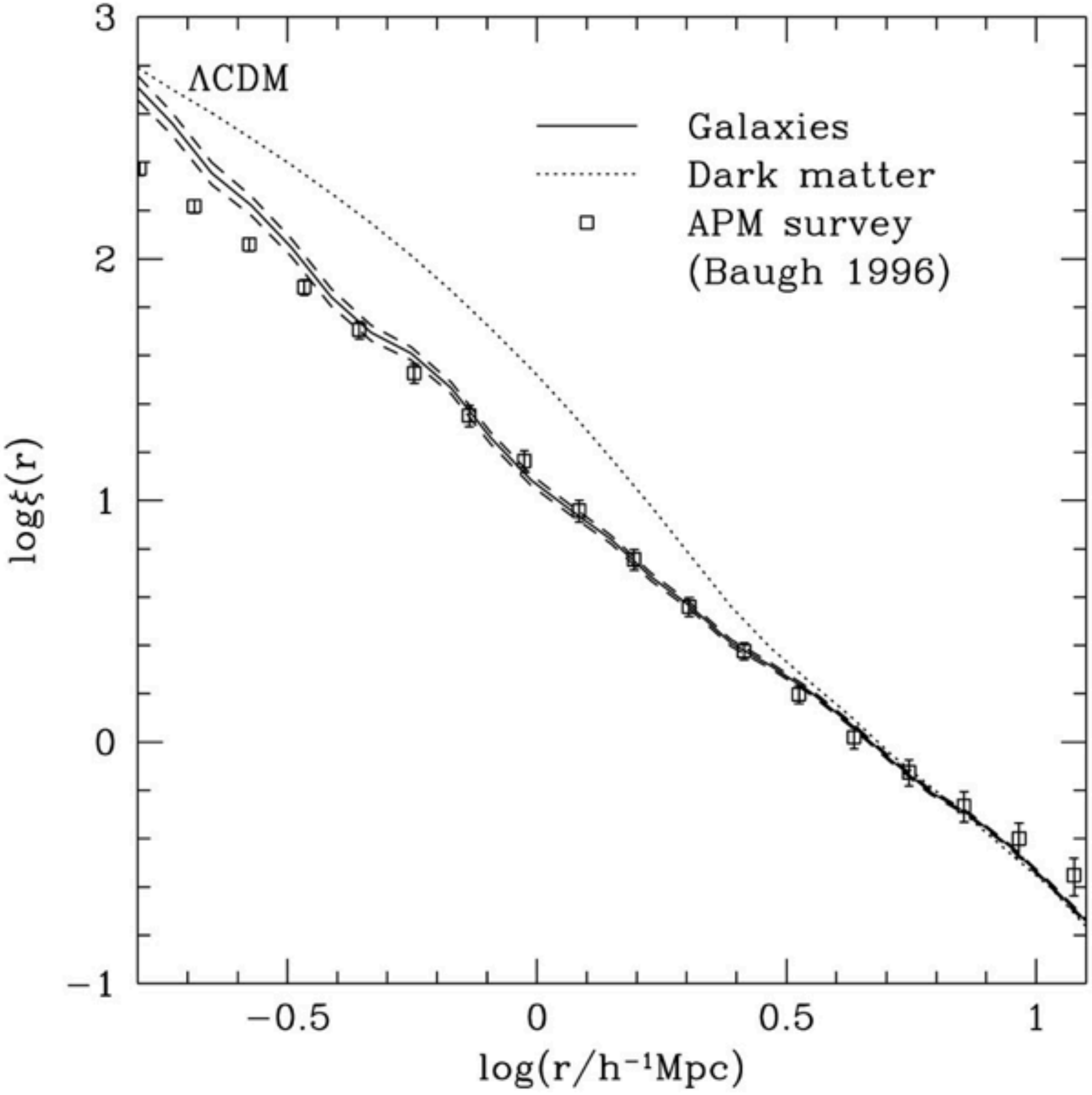
Clustering measurement

- Angular (2D) correlation function $\omega(\theta)$: this is similarly define as for the 3D correlation function $\xi(r)$:

$$dP = \overline{N}^{2} [1+\omega(\theta)] d\Omega_1 d\Omega_2$$

- one can show that if $\xi(r)$ is a power law with index $\gamma > 0$, then the angular correlation function is also a power law with an index $1 - \gamma$.

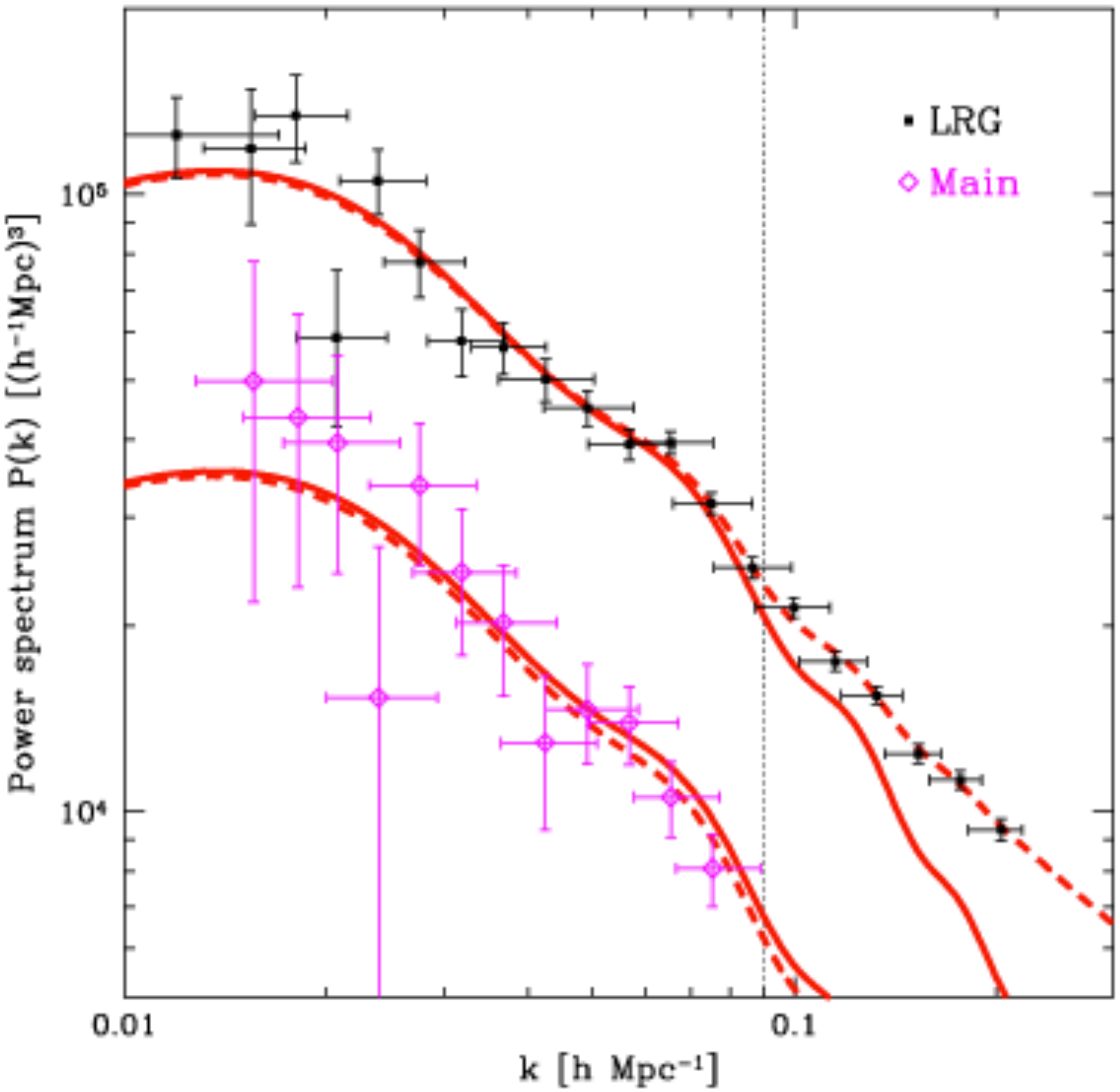
Clustering measurement



Correlation function of galaxies:

- observations
- model

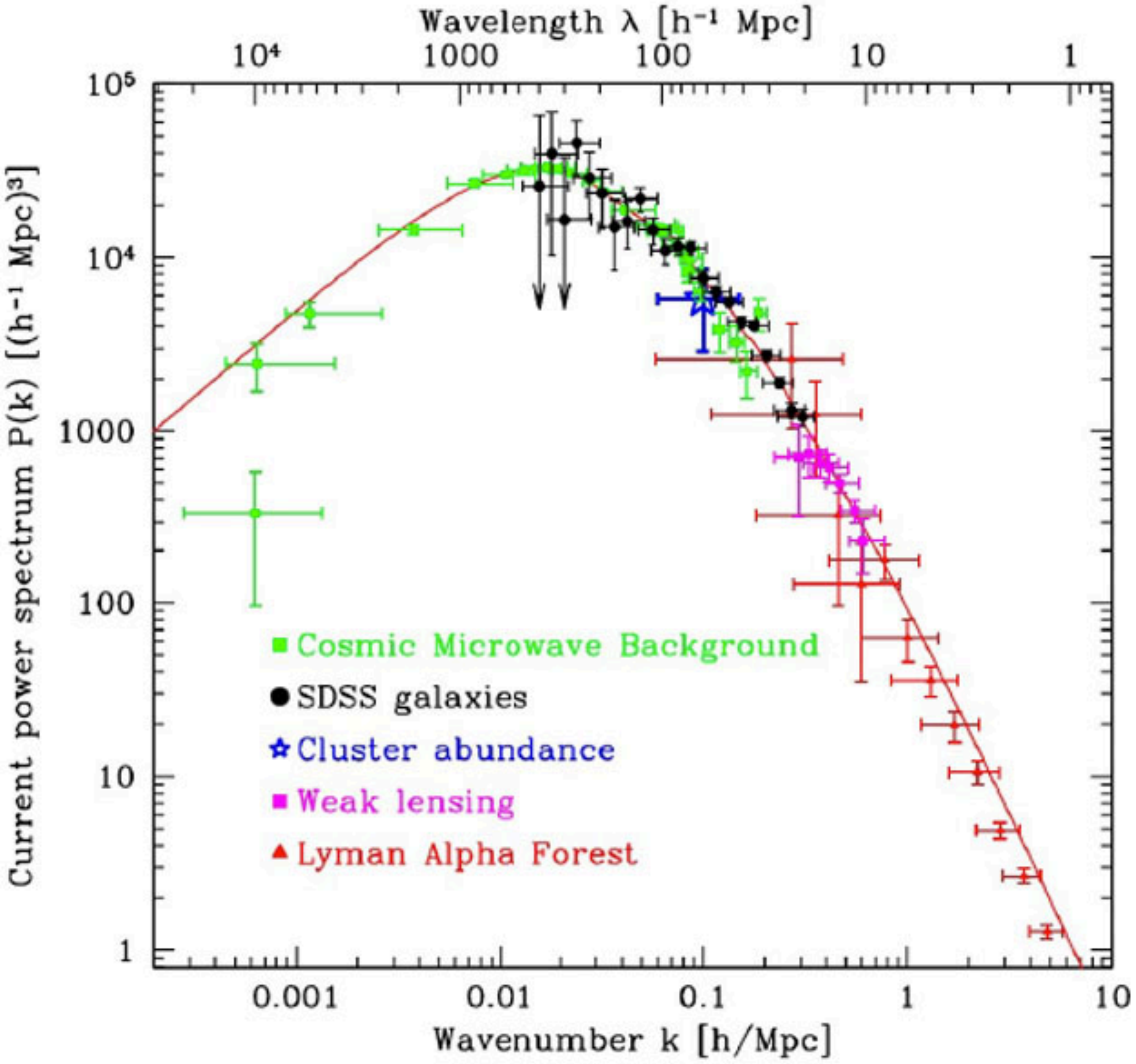
Clustering measurement



Galaxy Power Spectrum of SDSS galaxies

- main z~0.1
- LRG z~03

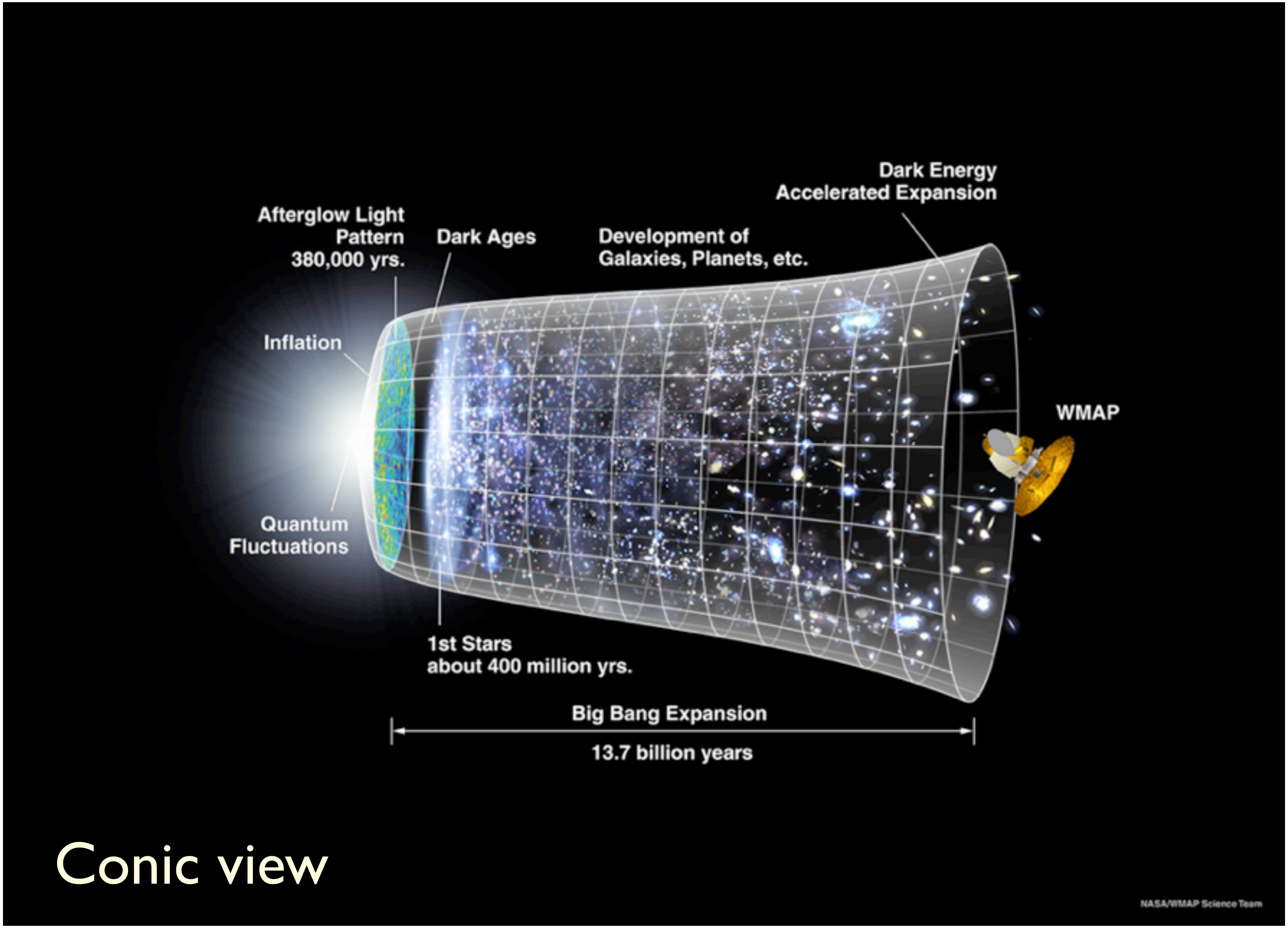
Clustering measurement



A global view of the matter power spectrum with data coming from different tracers

The Cosmological Microwave Background

The Observable Universe



Conic view

NASA/WMAP Science Team

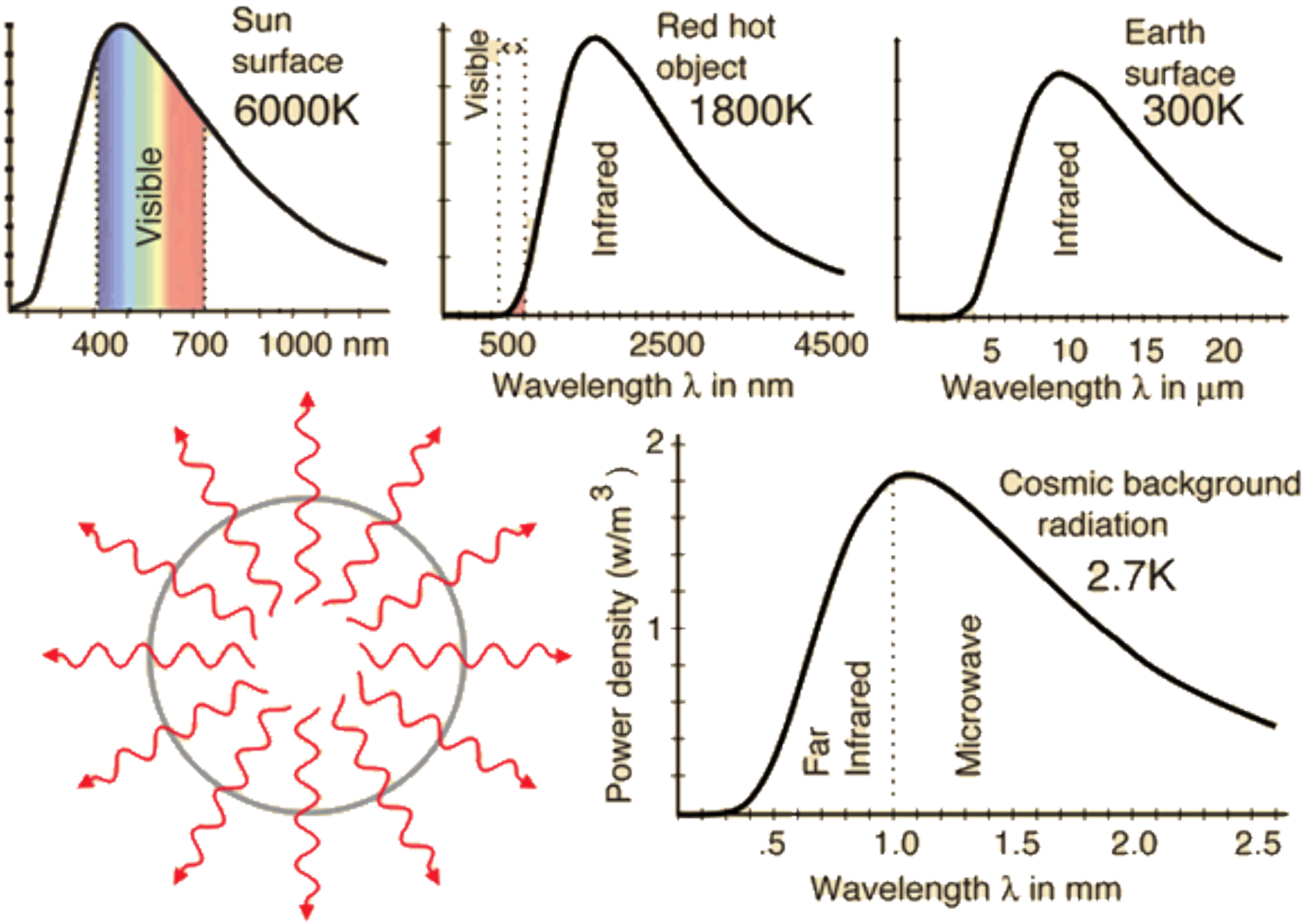
Cosmic Microwave Background

- The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380,000 years old (z~1100)
- It shows tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today.
- the CMB radiation is an emission of uniform, black body thermal energy coming from all parts of the sky.
- The radiation is isotropic to roughly 1 in 100,000: the root mean square variations are only 18 μK, after subtracting out a dipole anisotropy from the Doppler shift of the background radiation.
- The Doppler shift is caused by the peculiar velocity of the Earth relative to the comoving cosmic rest frame as the planet moves at some ~370 km/s towards the constellation Leo.

Cosmic Microwave Background

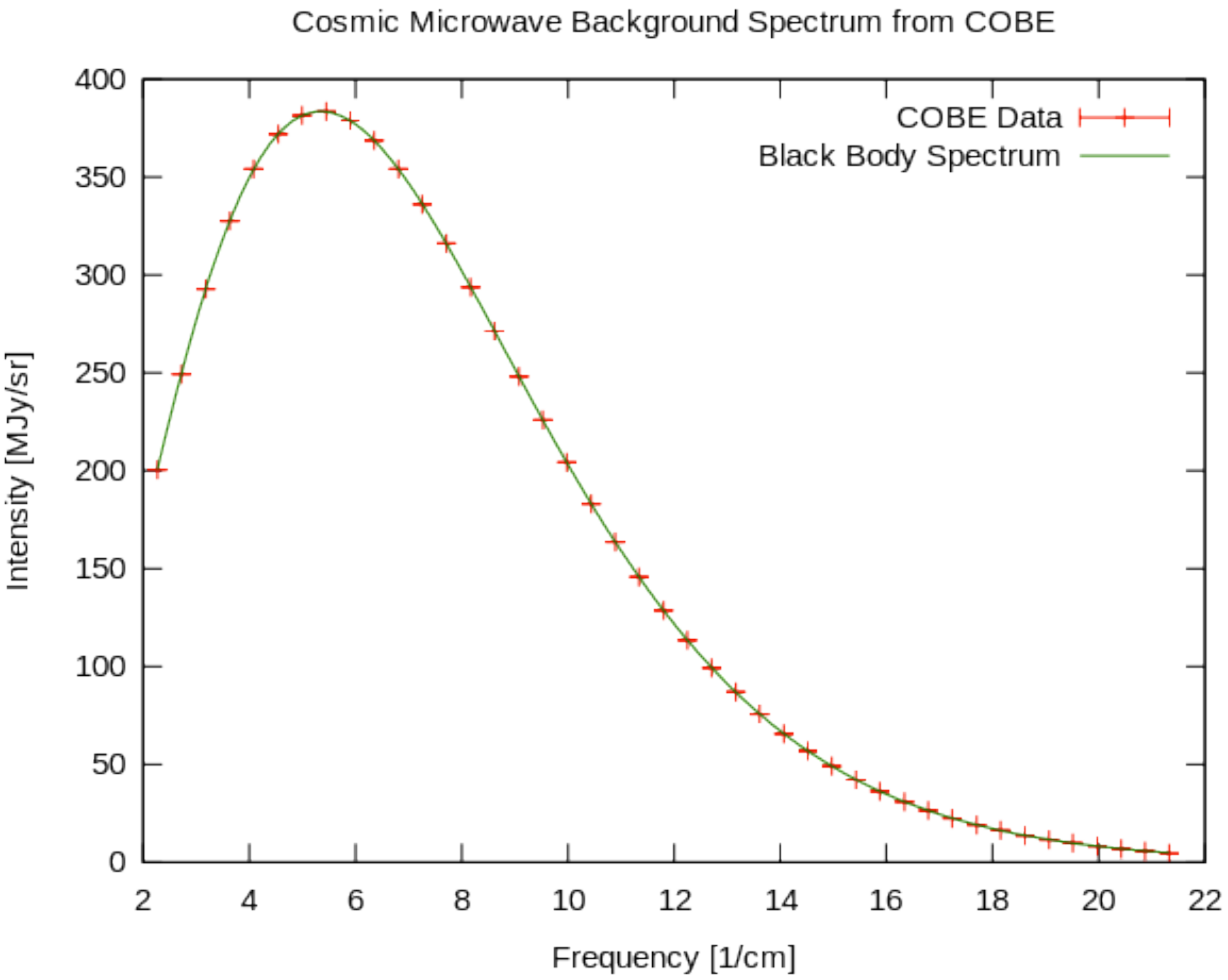
- Early on the density of mass is large enough that it has a form of a plasma (matter and radiation are in constant interaction => photons are not traveling far away).
- As the universe expanded, the energy density of the plasma decrease until it became favorable for electrons to combine with protons, forming hydrogen atoms.
- This recombination event happened when the temperature was ~3000 K or when the universe was approximately 379,000 years old.
- At this point, the photons no longer interacted with the now electrically neutral atoms and began to travel freely through space, resulting in the decoupling of matter and radiation => the CMB map.

Cosmic Microwave Background



- Black-body curves as a function of temperature

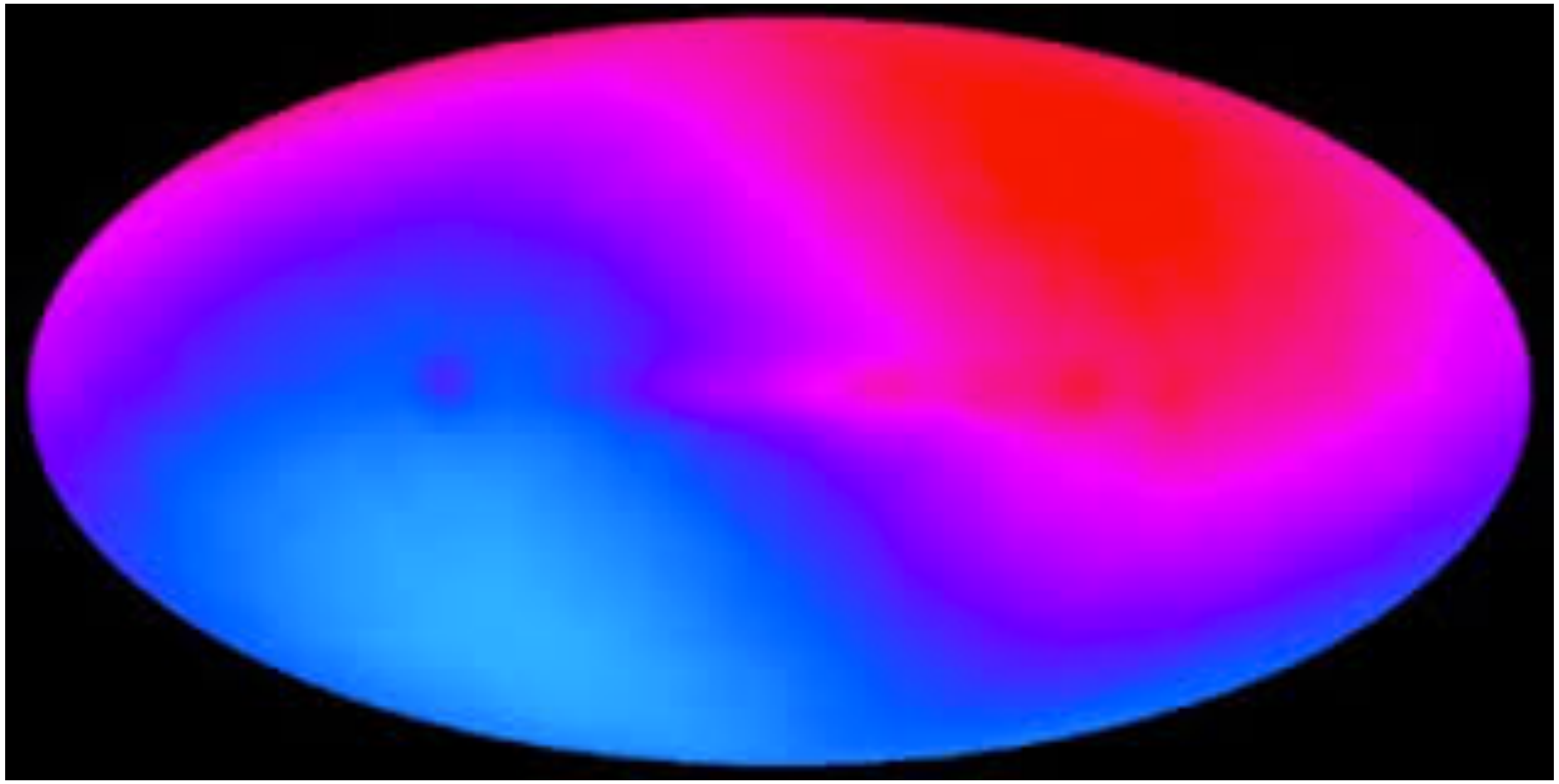
Cosmic Microwave Background



Black Body temperature of 2.7260±0.0013 K

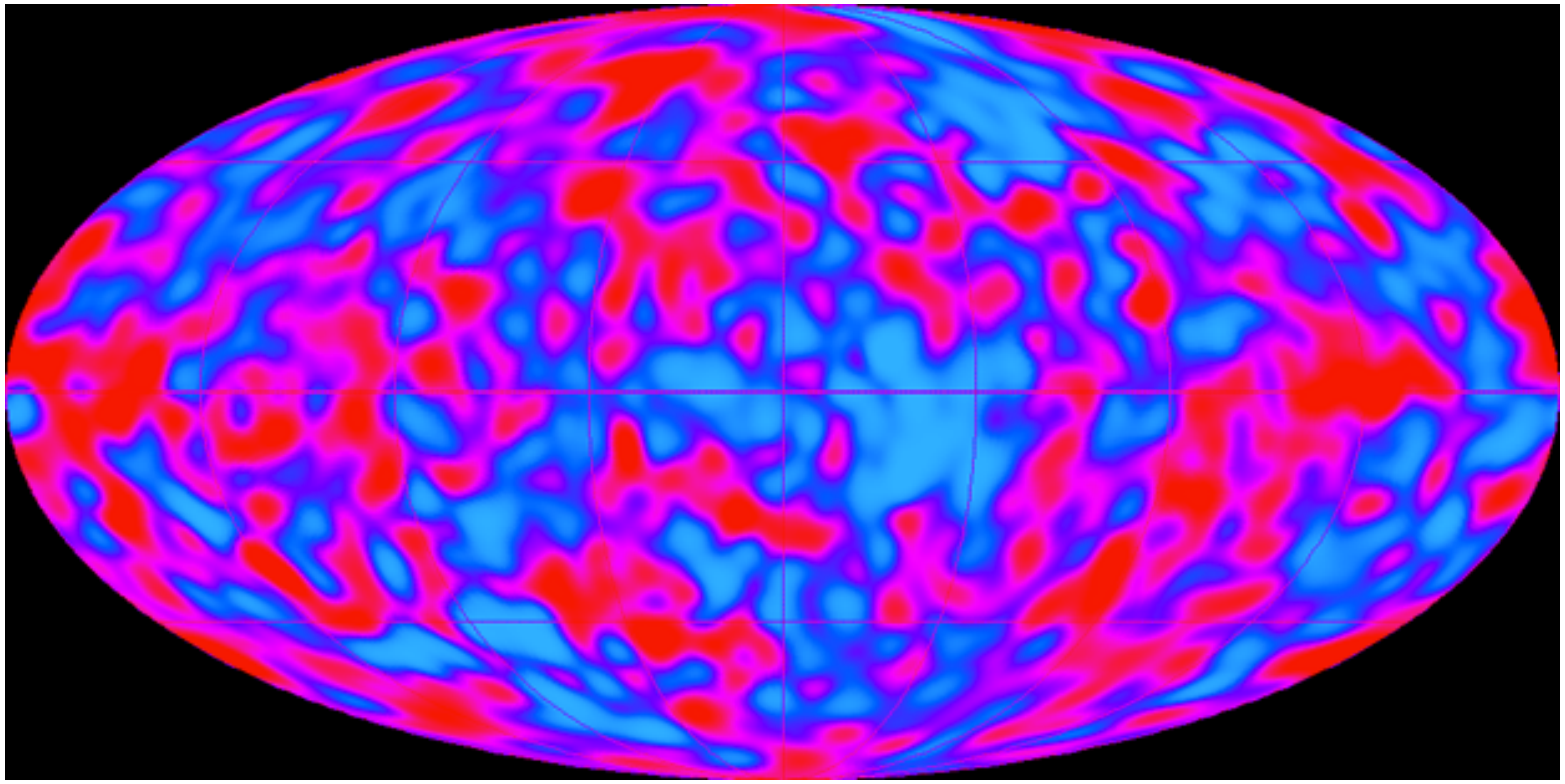
- The CMB spectrum measured with COBE

Cosmic Microwave Background



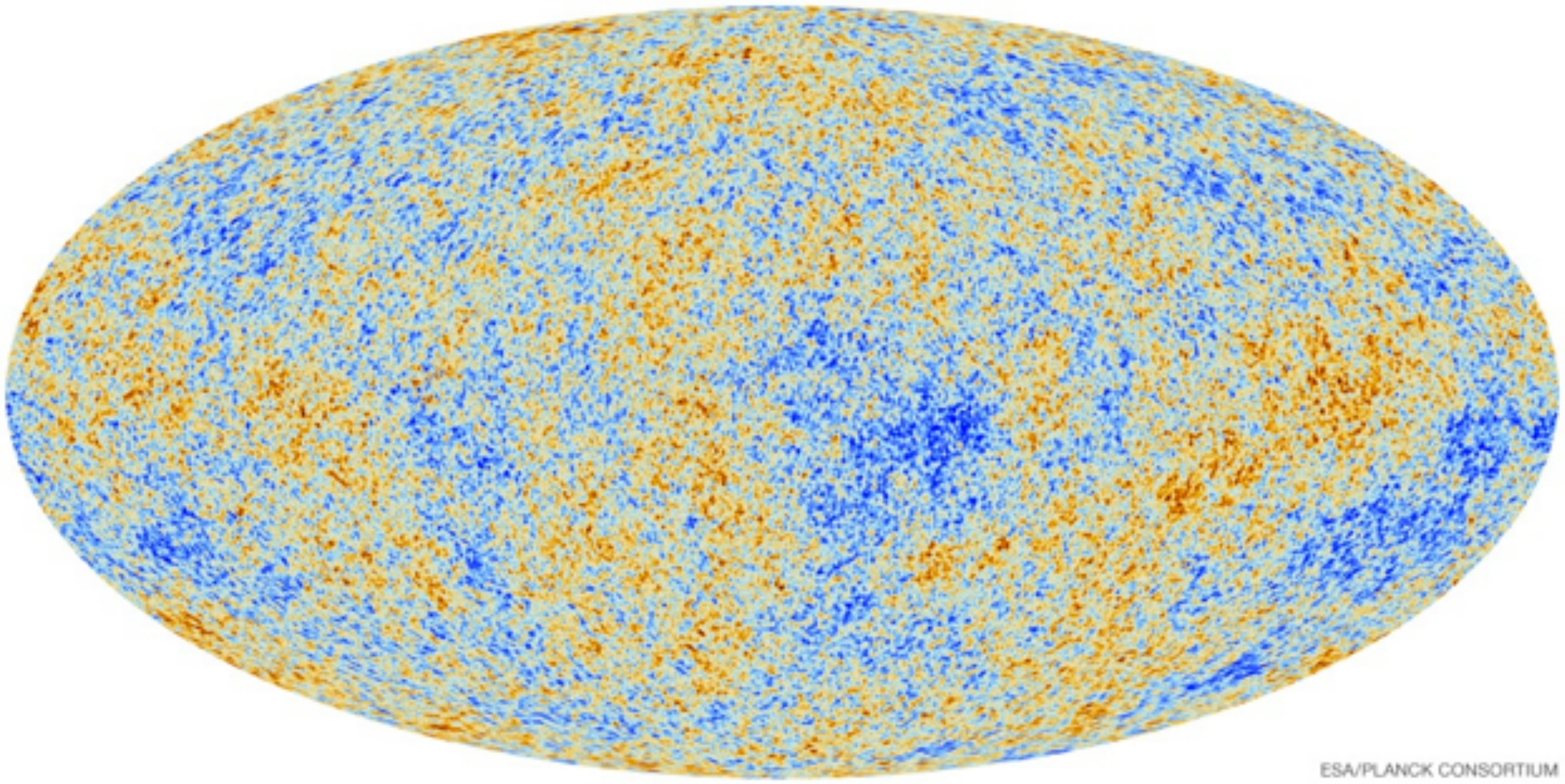
- The CMB dipole shift measured with COBE

Cosmic Microwave Background



- The CMB fluctuations measured with COBE

Cosmic Microwave Background



ESA/PLANCK CONSORTIUM

- The CMB fluctuations measured with Planck

Cosmic Microwave Background

- energy density of the CMB (black-body law):

$$\rho_{CMB}c^2 = c^2 \int_0^\infty u_r(\nu)\mathrm{d}\nu = c^2 \int_0^\infty \frac{8\pi h\nu^3}{\exp\left(\frac{h\nu}{k_B T_\nu}\right) - 1}\mathrm{d}\nu \ = \ \sigma T^4$$

$$\rho_{CMB}(t_0) = \frac{\sigma T_0^4}{c^2} = 4.8 \times 10^{-34}\ \mathrm{g\ cm^{-3}}$$

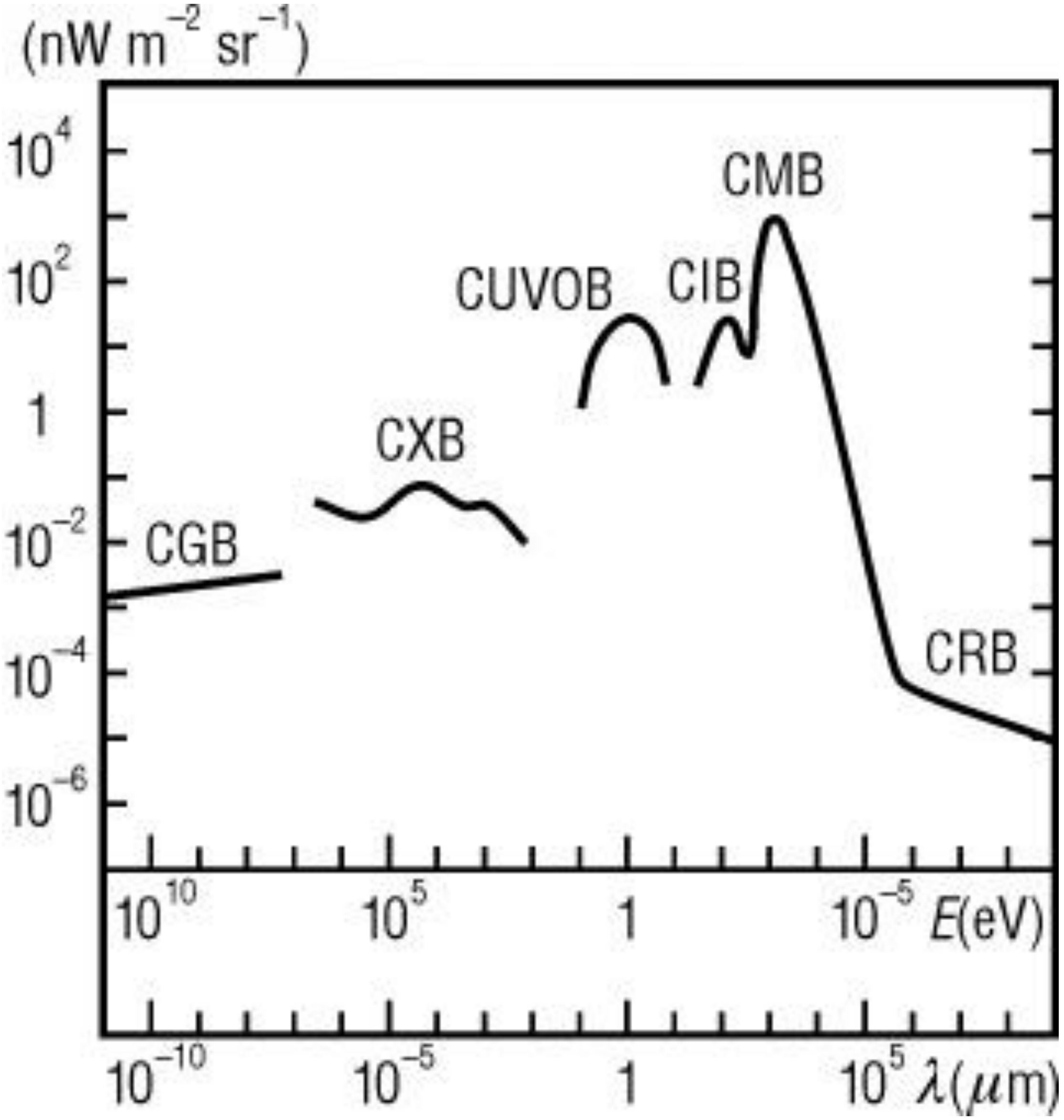
Cosmic Microwave Background

- number density of photons:

$$n_{CMB} = \int \frac{\rho_\gamma(\nu)}{h\nu} \mathrm{d}\nu \approx 0.4 \frac{\sigma}{k_B} T^3 = 20.4\ T^3$$

$$n_{CMB}(t_0) = 413 \text{ photons cm}^{-3}$$

Cosmic Background Radiation



- Diffuse photon field from extragalactic origin that fill our Universe. It contains photons over ~ 20 decades of energy from ~10^{-7} eV to ~100 GeV