Data Learning on Manifolds and Future Challenges

DEDALE Tutorial Day

Deciphering Cosmological Parameters

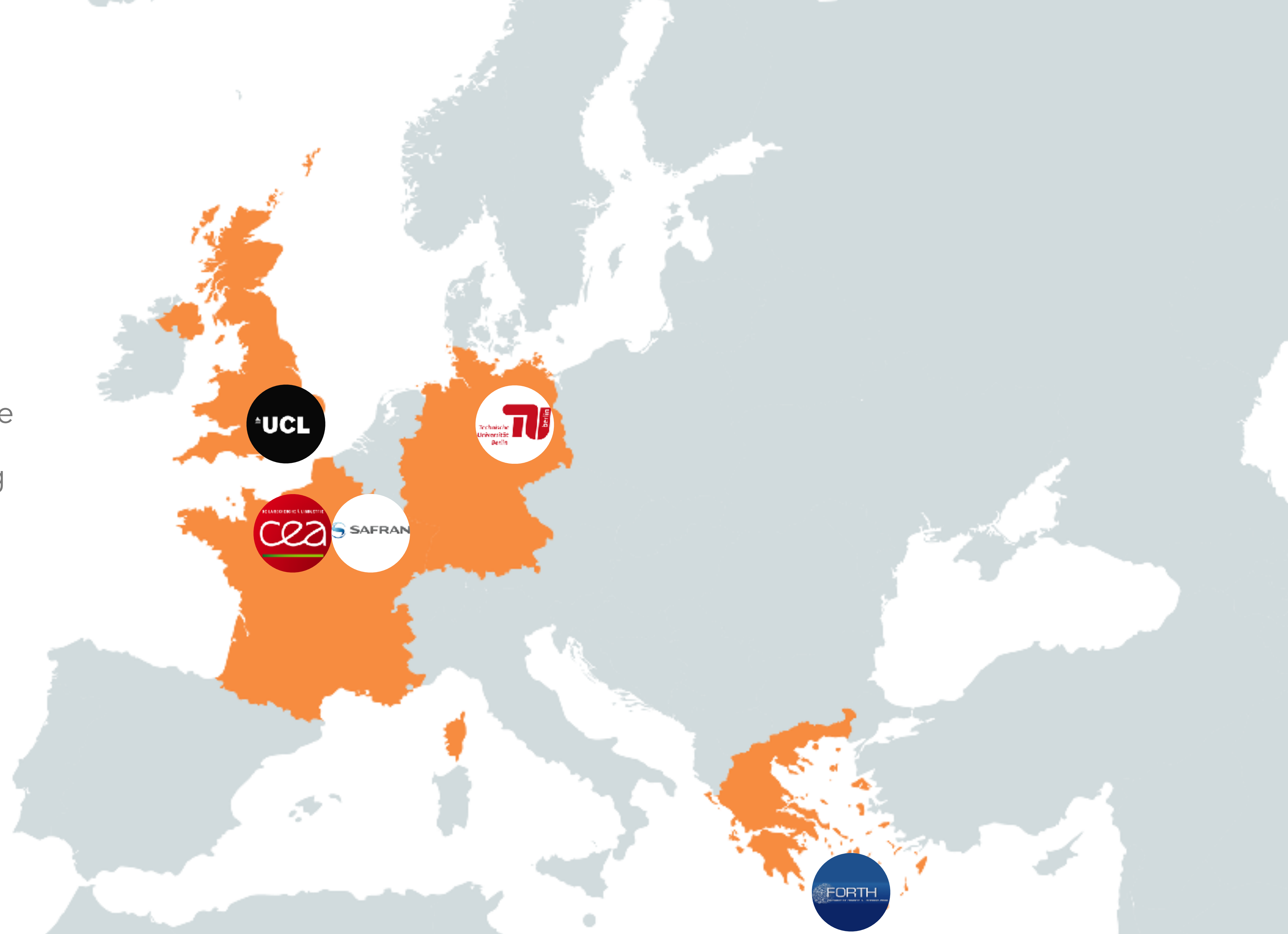
Samuel Farrens (CEA)

CEA - 16th November 2016

- **Introduction**

DEDALE

- Mathematics
- Signal Processing
- Computer Science
- Machine Learning
- Astrophysics
- Cosmology



DEDALE

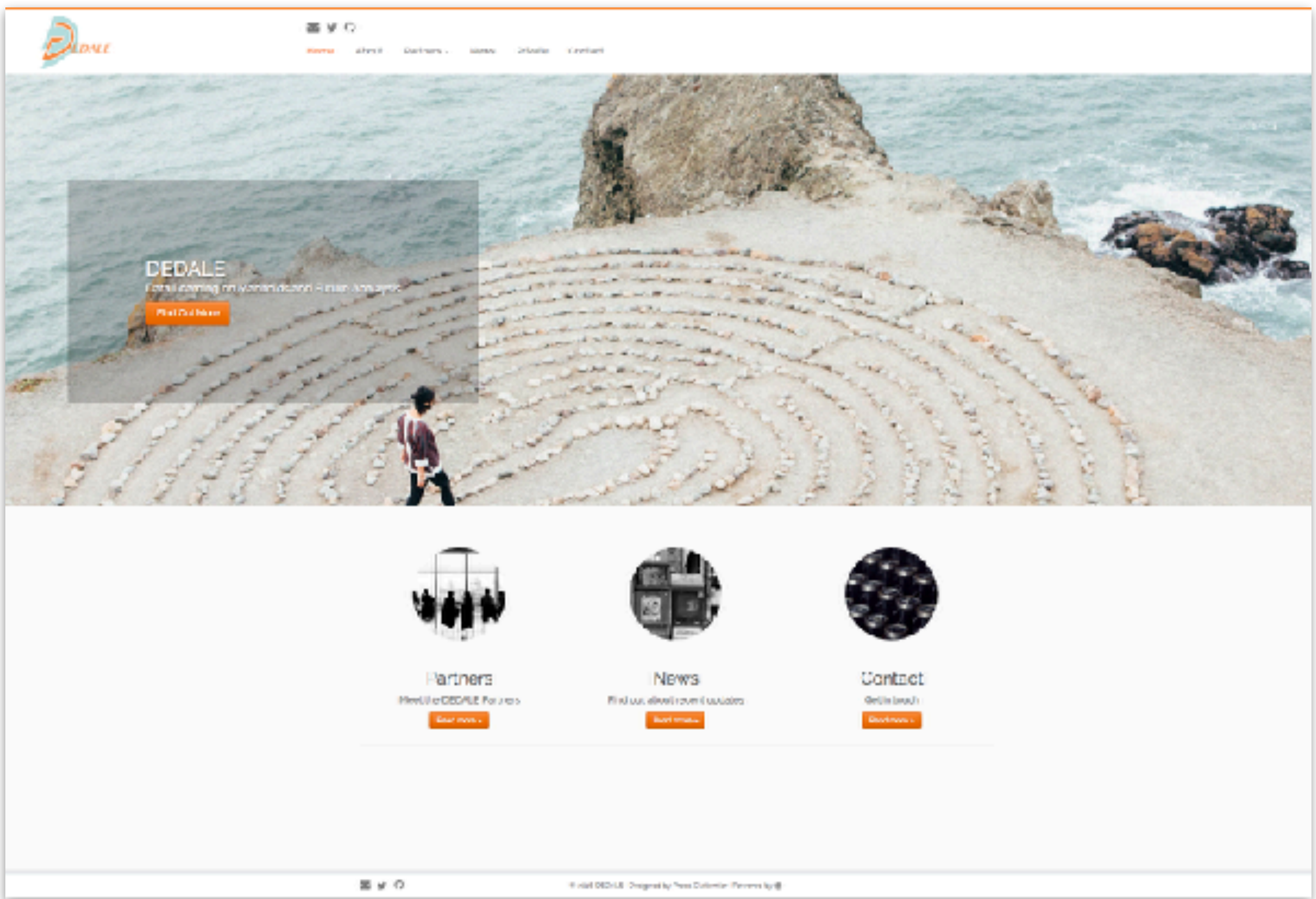
- DEDALE is an interdisciplinary project that intends to develop the next generation of data analysis methods for the new era of big data in astrophysics and compressed sensing.

- Our project have three main scientific directions:
  - i) Introduce new models and methods to analyse and restore complex, multivariate, manifold-based signals.
  - ii) Exploit the current knowledge in optimisation and operations research to build efficient numerical data processing algorithms in the large-scale settings.
  - iii) Show the reliability of the proposed methods in two different applications: one in cosmology and one in remote sensing.

DEDALE

Project Website

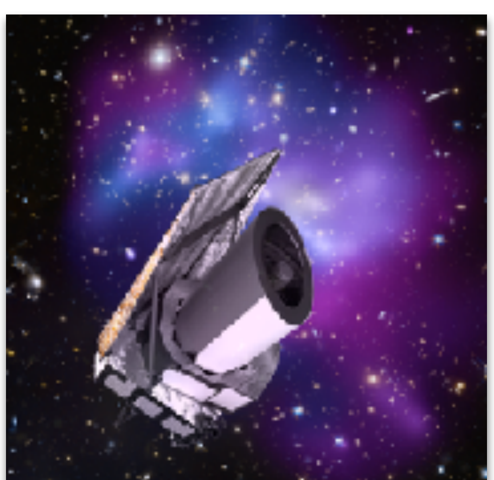
http://dedale.cosmostat.com



Euclid

- ESA funded space mission planned to launch in 2020
- 15,000 square degrees (H-band $\leq$ 24)
- Focused on weak lensing measurements

12,000 members in 15 countries



Satellite

http://www.euclid-ec.org/

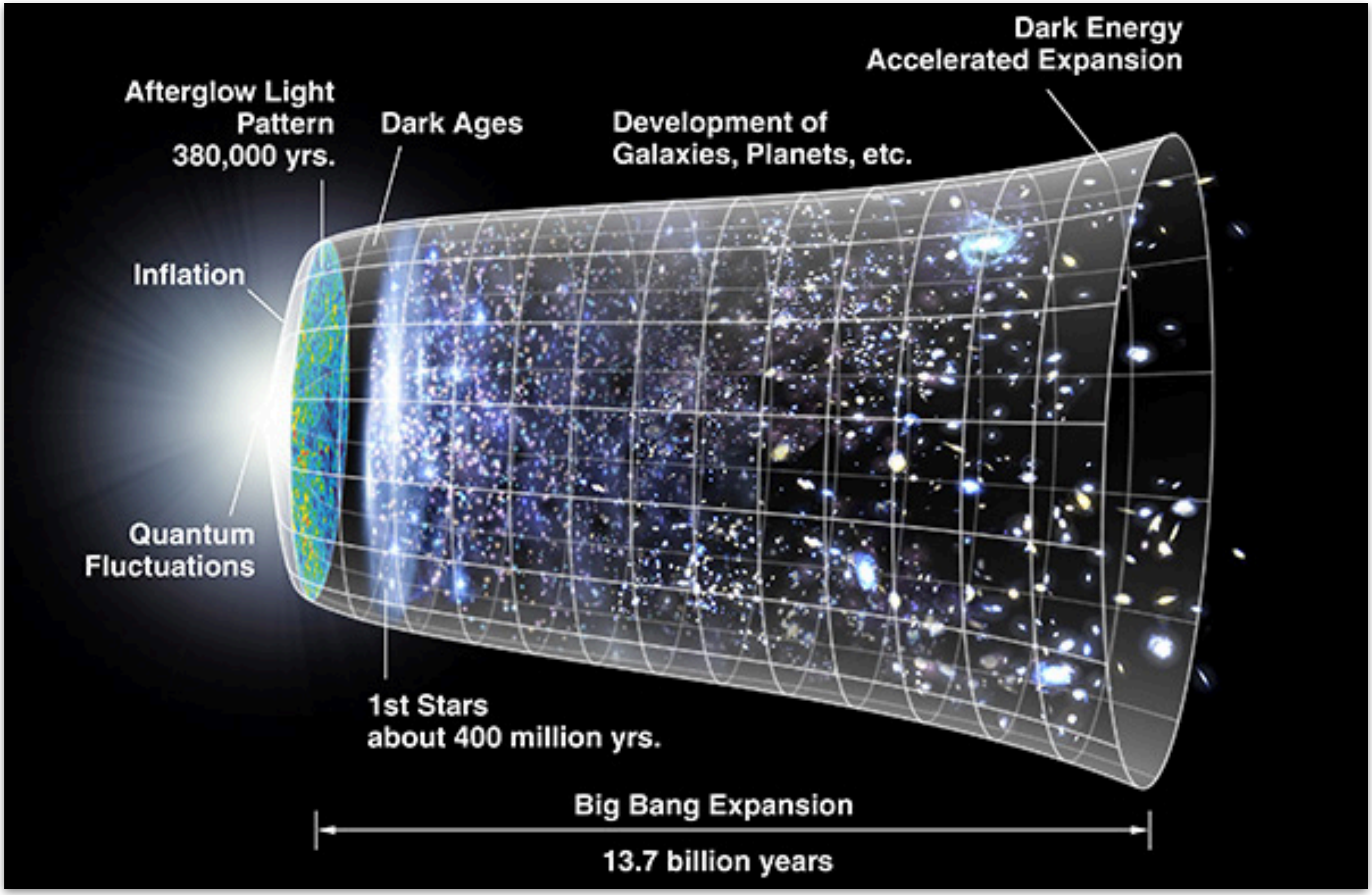
Agenda

Time	Tutorial Session	Presenter
10:00 - 11:00	Deciphering Cosmological Parameters	Samuel Farrens
11:00 - 12:00	The Redshift Problem in Cosmology	Bruno Moraes
12:00 - 13:00	**LUNCH**	
13:00 - 14:00	Systems for Sparse Representations: Fourier Analysis, Wavelets & Shearlets	Felix Voigtländer
14:00 - 15:00	Extended Sparse Dictionary Learning: Convolutional and Multiple Feature Spaces	Konstantina Fotiadou
15:00 - 16:00	Unsupervised Feature Learning: Denoising Autoencoders	Joana Frontera-Pons

- Cosmological Parameters

Cosmology

History of the Universe

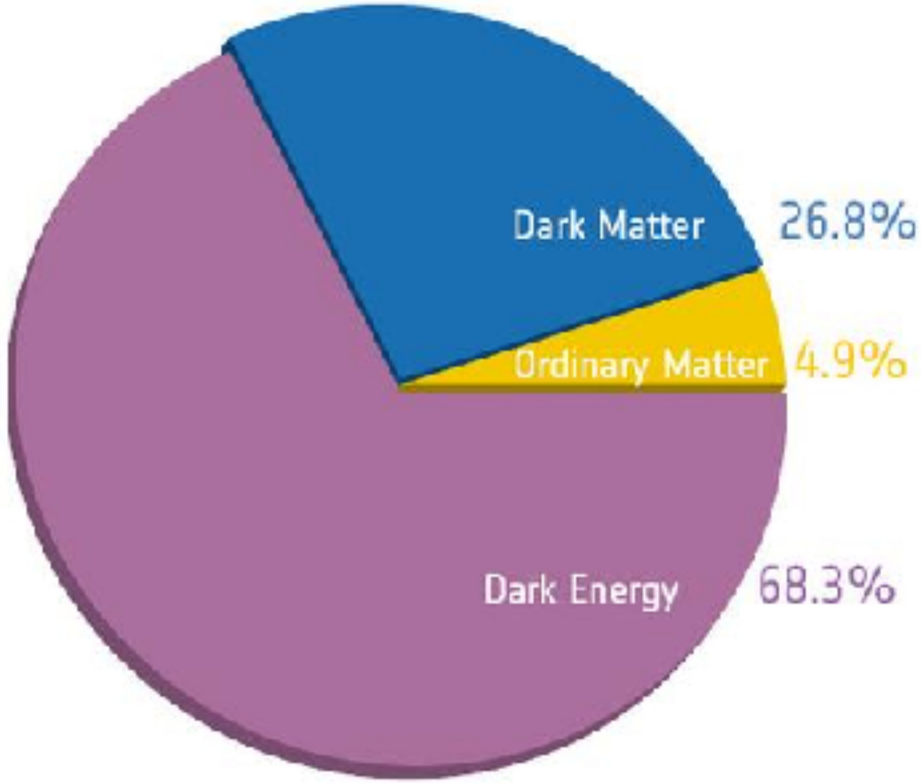


ΛCDM

Content of the Universe

ΛCDM = Dark Energy + Cold Dark Matter

- Dark energy accelerates the expansion of the Universe
- Cold means non-relativistic ($v \ll c$)
- Dark matter only interacts gravitationally (no light)



ΛCDM

Cosmological Parameters

Planck Collaboration: Cosmological parameters

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limits	*Planck*+lensing+WP+highL Best fit	*Planck*+lensing+WP+highL 68% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
A^{PS}_{100}	152	171 ± 60	209	212 ± 50	204	213 ± 50	204	212 ± 50
A^{PS}_{143}	63.3	54 ± 10	72.6	73 ± 8	72.2	72 ± 8	71.8	72.4 ± 8.0
A^{PS}_{217}	117.0	107^{+20}_{-10}	59.5	59 ± 10	60.2	58 ± 10	59.4	59 ± 10
A^{CIB}_{143}	0.0	< 10.7	3.57	3.24 ± 0.83	3.25	3.24 ± 0.83	3.30	3.25 ± 0.83
A^{CIB}_{217}	27.2	29^{+6}_{-9}	53.9	49.6 ± 5.0	52.3	50.0 ± 4.9	53.0	49.7 ± 5.0
A^{tSZ}_{143}	6.80	...	5.17	$2.54^{+1.1}_{-1.9}$	4.64	$2.51^{+1.2}_{-1.8}$	4.86	$2.54^{+1.2}_{-1.8}$
$r^{PS}_{143\times217}$	0.916	> 0.850	0.825	$0.823^{+0.069}_{-0.077}$	0.814	0.825 ± 0.071	0.824	0.823 ± 0.070
$r^{CIB}_{143\times217}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.928	1.0000	> 0.930
γ^{CIB}	0.601	$0.53^{+0.13}_{-0.12}$	0.674	0.638 ± 0.081	0.656	0.643 ± 0.080	0.667	0.639 ± 0.081
$\xi^{tSZ\times CIB}$	0.03	...	0.000	< 0.409	0.000	< 0.389	0.000	< 0.410
A^{kSZ}	0.9	...	0.89	$5.34^{+2.8}_{-1.9}$	1.14	$4.74^{+2.6}_{-2.1}$	1.58	$5.34^{+2.8}_{-2.0}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

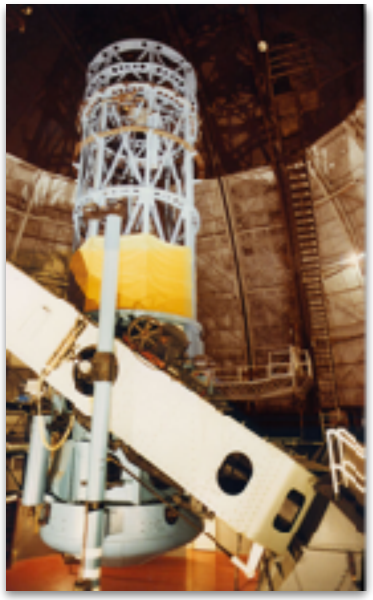
Table 5. Best-fit values and 68% confidence limits for the base ΛCDM model. Beam and calibration parameters, and additional nuisance parameters for "highL" data sets are not listed for brevity but may be found in the Explanatory Supplement (Planck Collaboration ES 2013).

Hubble Constant

$$H_0$$

Not really a constant!

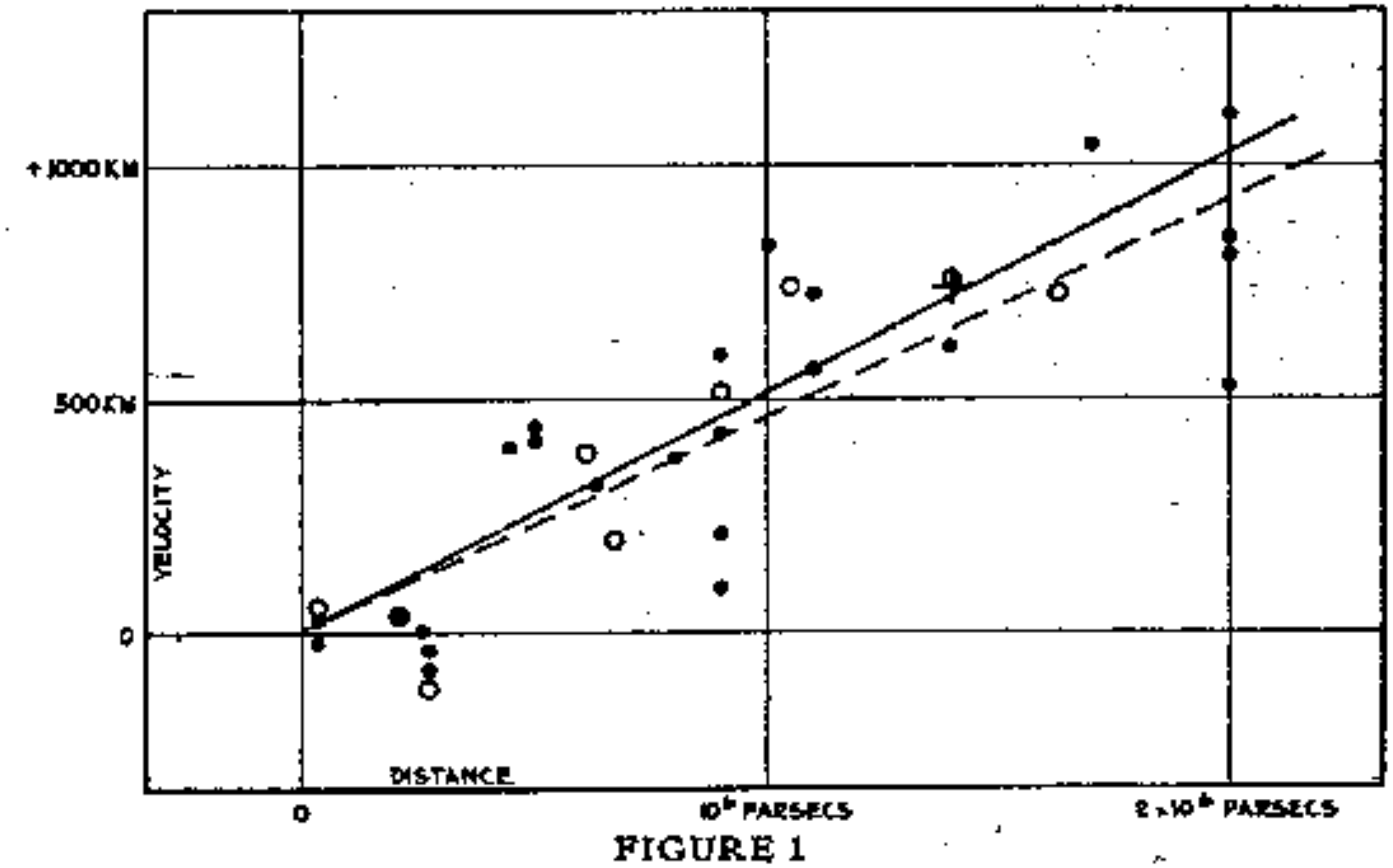
Edwin Hubble
(1889-1953)



Hooker telescope
(MWO)

$$v = H_0 d$$

(Hubble's Law)

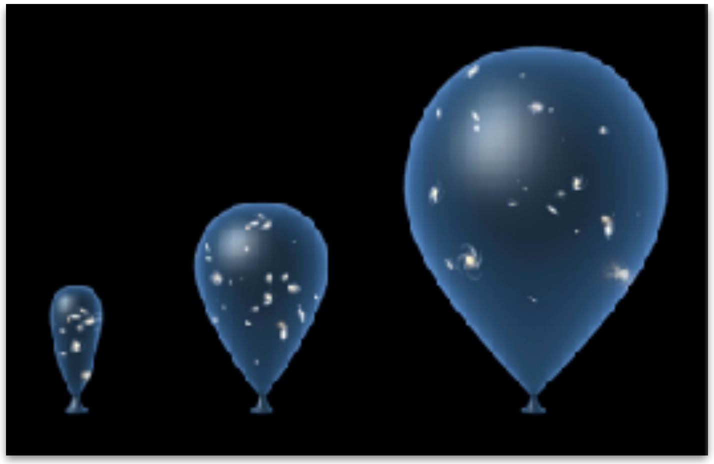


Hubble (1929)

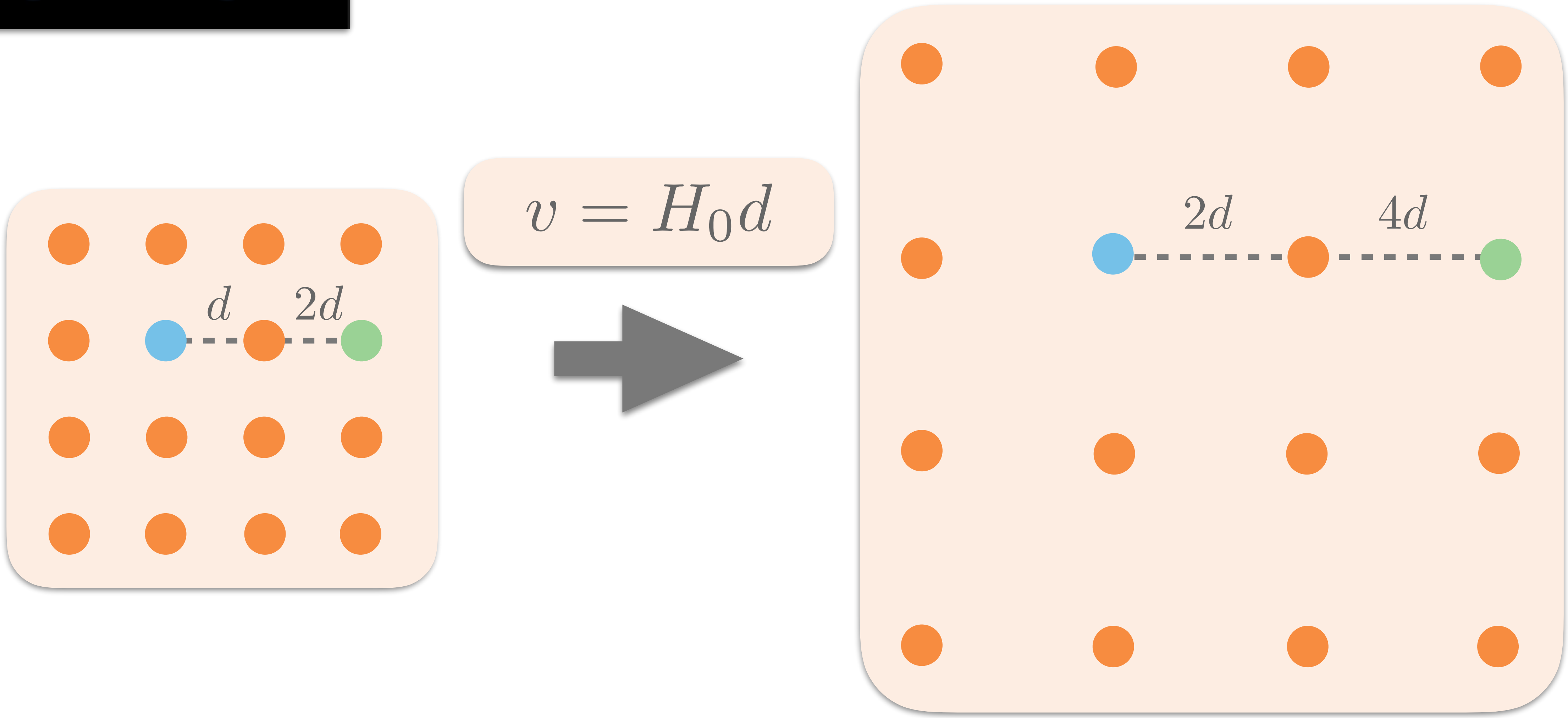
Hubble Space Telescope

Hubble Constant

$$H_0$$



Expansion of the Universe



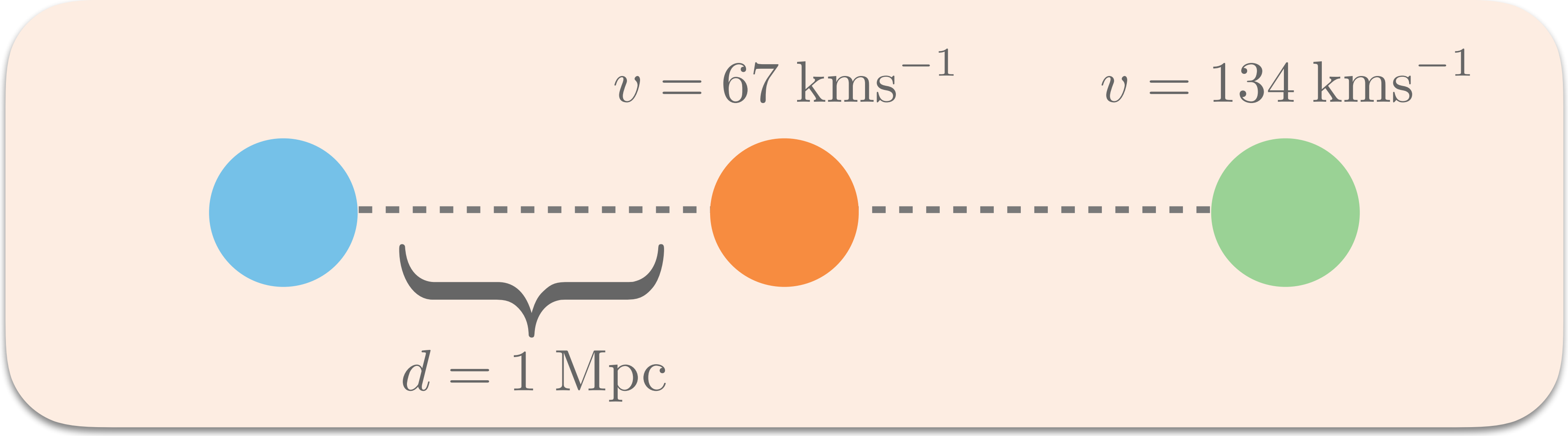
$$v = H_0 d$$

Hubble Constant

$$H_0$$

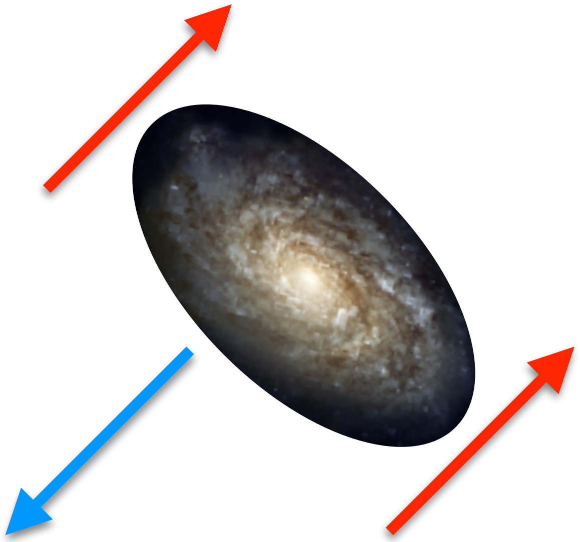
Current Estimate

$$H_0 \approx 67 \text{ kms}^{-1}\text{Mpc}^{-1}$$

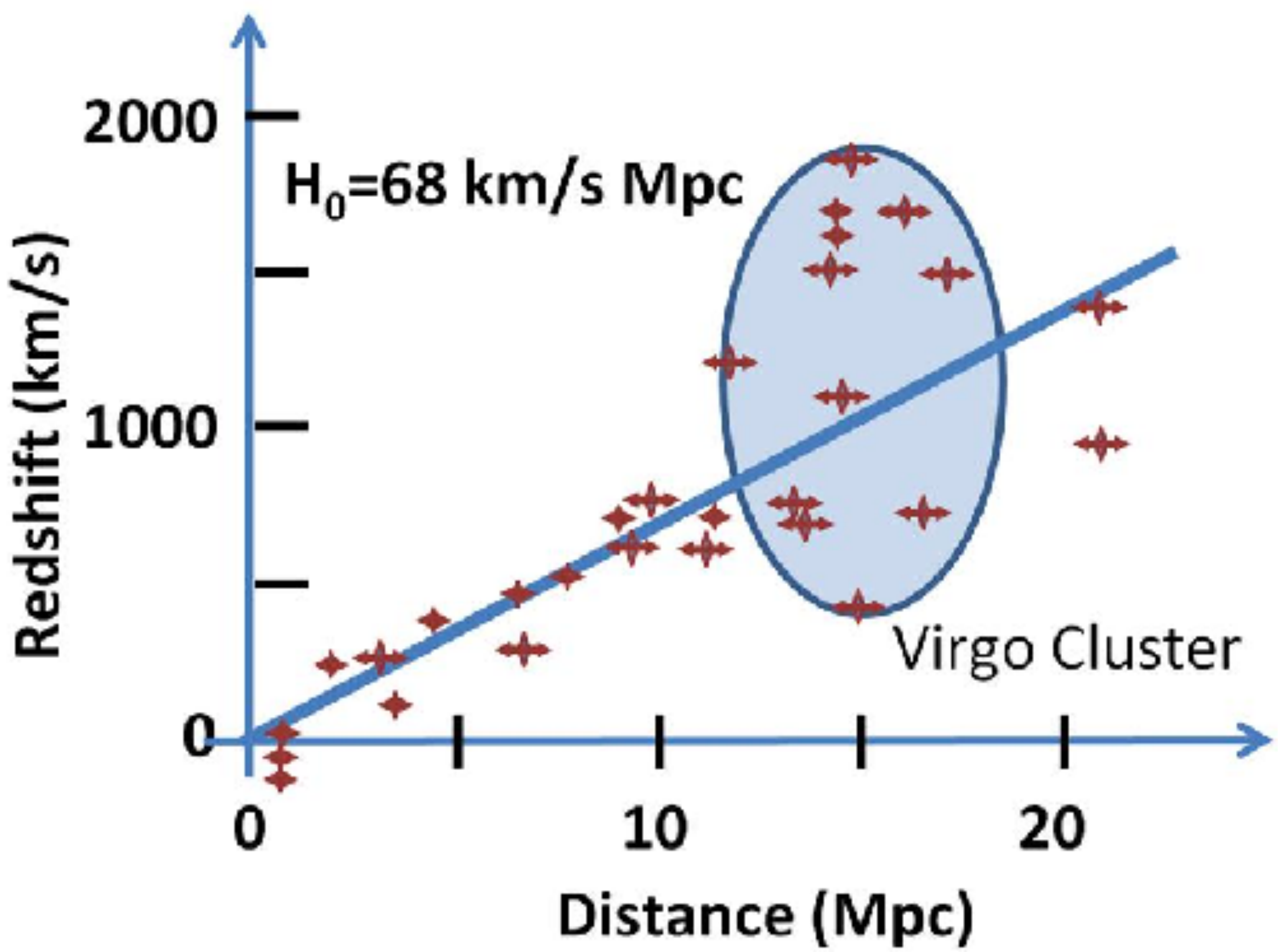


Hubble Constant

H_0



Peculiar Velocities



Hubble Constant

$$H_0$$

Units

$$\mathrm{kms^{-1}Mpc^{-1}} \rightarrow \mathrm{s^{-1}}$$

Hubble Time

$$\frac{1}{H_0} \approx 14.6\mathrm{Gyr}$$

Little **h**

$$H_0 = 100\ h\ \mathrm{kms^{-1}Mpc^{-1}}$$

e.g. Distance

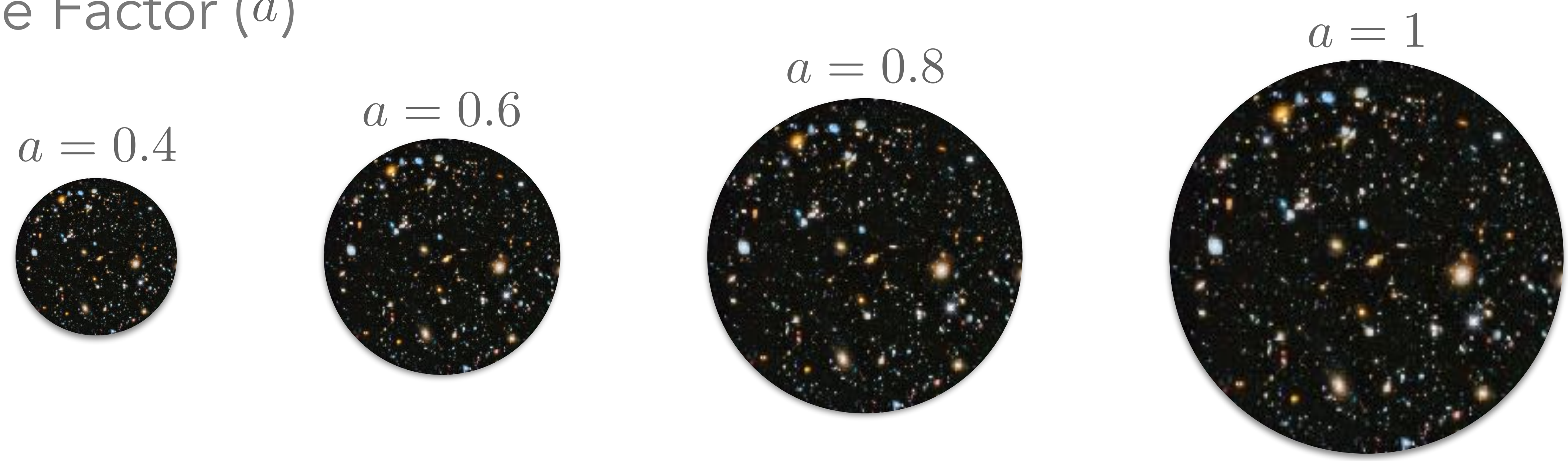
$$d = 1\ h^{-1}\ \mathrm{Mpc}$$

Hubble Parameter

$$H$$

$$H = \frac{\dot{a}}{a}$$

Scale Factor (a)



$$H^2(z) = H_0^2\left(\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right)$$

Density Parameter

$$\Omega$$

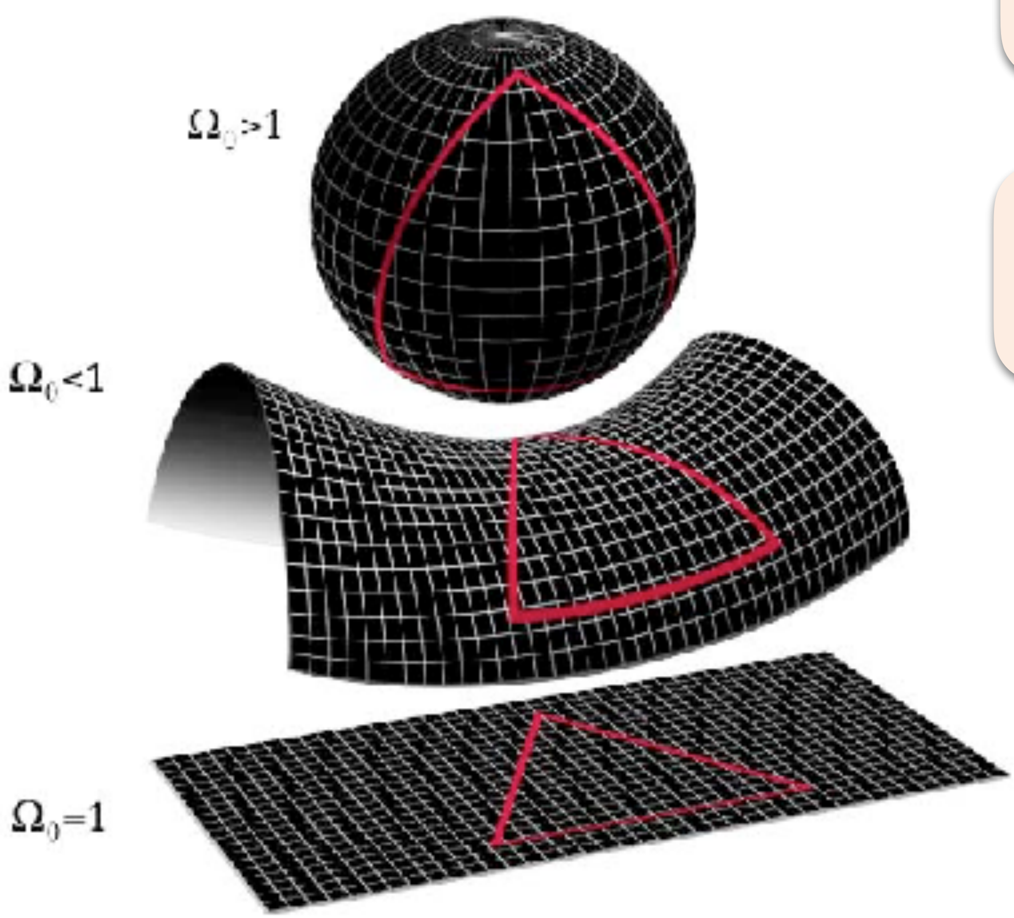
$$\Omega \equiv \frac{\rho}{\rho_c}$$

$$\Omega_0 \equiv \frac{\rho_0}{\rho_c}$$

$$\rho_c = \frac{3H^2}{8\pi G}$$

$$\Omega(t) = \Omega_R(t) + \Omega_M(t) + \Omega_k(t) + \Omega_\Lambda(t)$$

Spatial Geometry



- Ω_R Radiation density
- Ω_M Matter density
- Ω_k Spatial curvature
- Ω_Λ Dark energy density

Matter Density

$$\Omega_M$$

$$\Omega_M = \Omega_b + \Omega_c$$

Baryons Ω_b

Made of atoms

Stars

Galaxies

Dark Matter Ω_c

Fritz Zwicky
(1898-1974)

Coma Cluster

Matter Density

$$\Omega_M$$

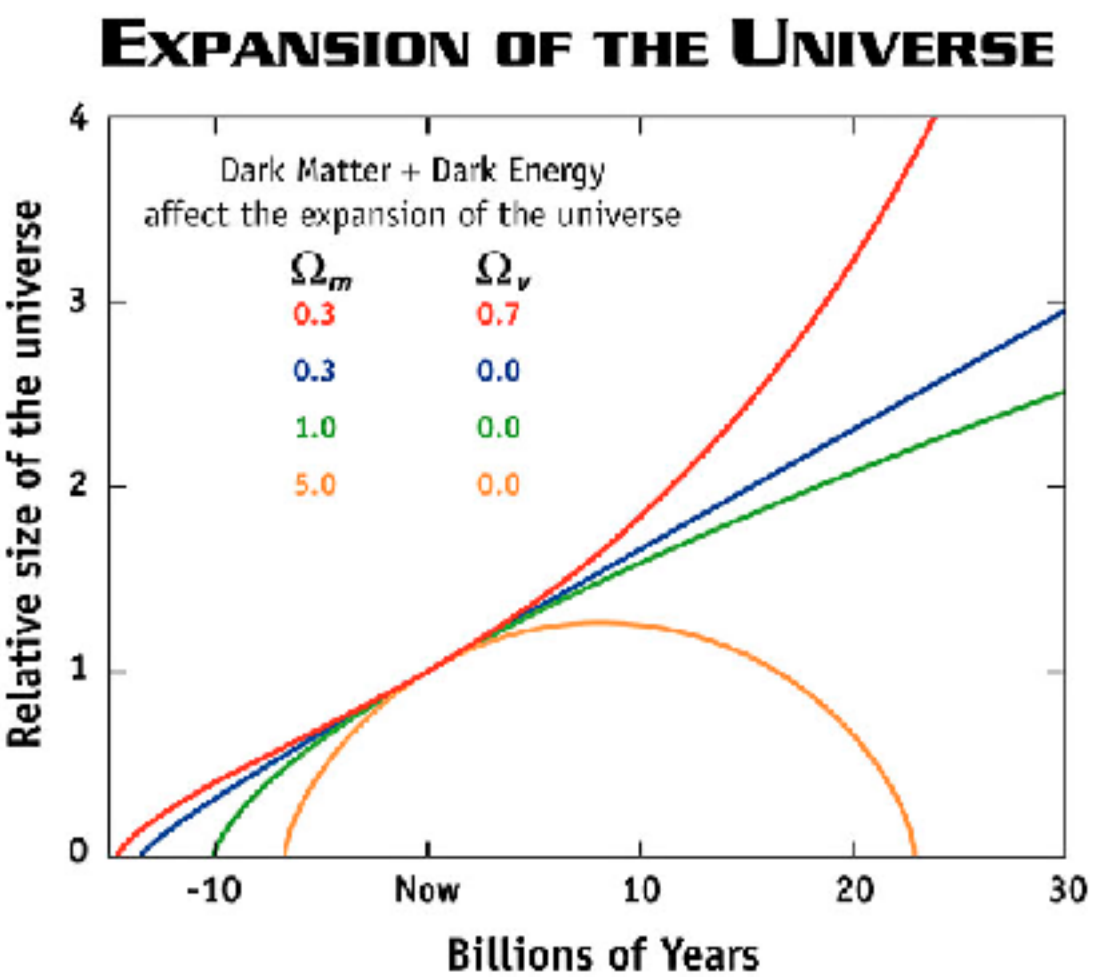
Current Estimate

$$\Omega_M \approx 0.3$$

$$\Omega_b \approx 0.05$$

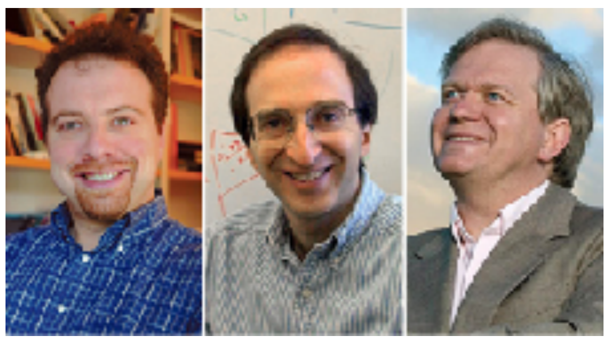
$$\Omega_c \approx 0.25$$

$$\Omega_b\, h^2,\ \Omega_c\, h^2$$



Dark Energy Density

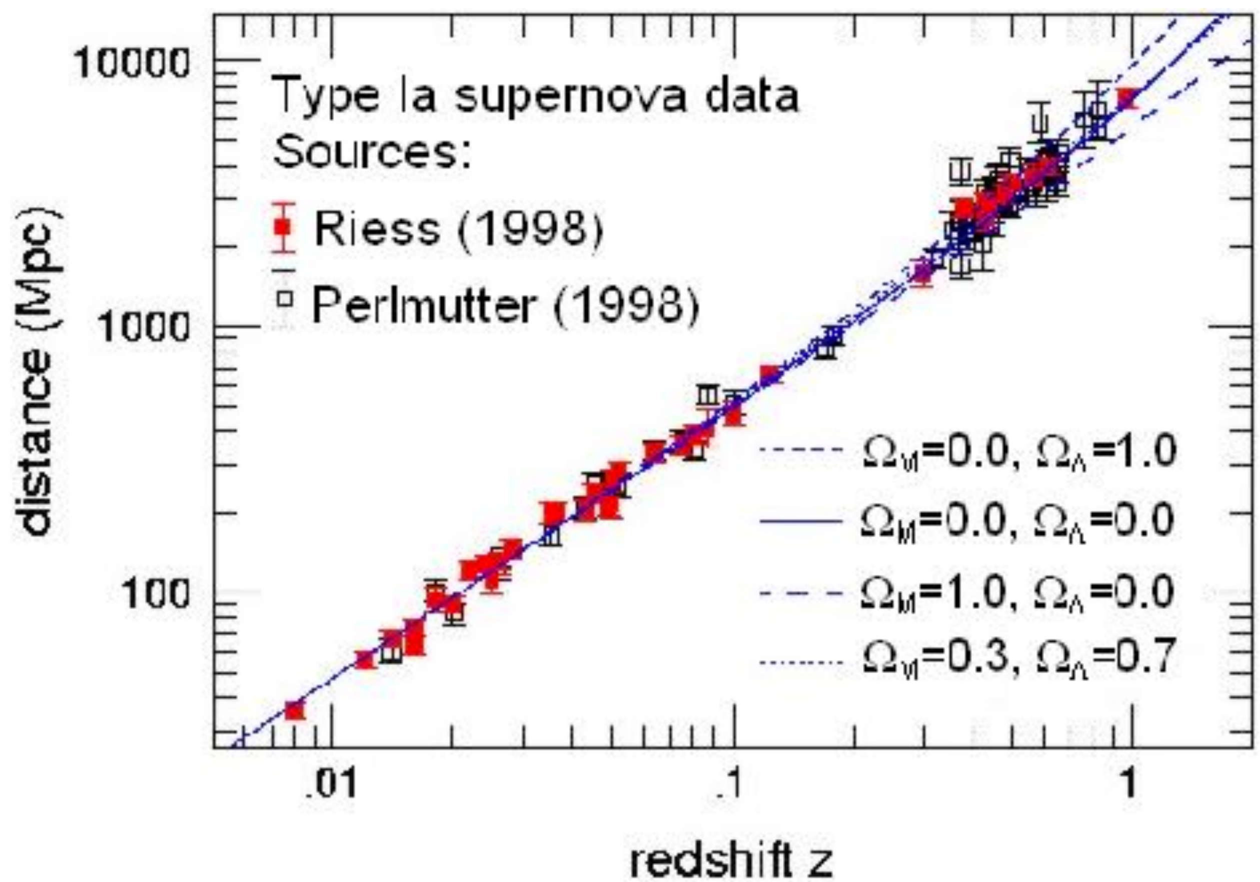
Ω_Λ



Adam Riess, Saul Perlmutter & Brian Schmidt

Type Ia Supernova

Accelerated Expansion



Riess et. al 1998 & Perlmutter et al. 1999

Dark Energy is the dominant source of energy in the present-day observable universe.

Dark Energy Density

Ω_Λ

Current Estimate

$\Omega_\Lambda \approx 0.7$

Age of the Universe

$$t_0$$

Cosmic Time

$$t_0 = \frac{2}{3H_0} \frac{1}{\sqrt{\Omega_\Lambda}} \ln\left(\frac{1+\sqrt{\Omega_\Lambda}}{\sqrt{\Omega_M}}\right)$$

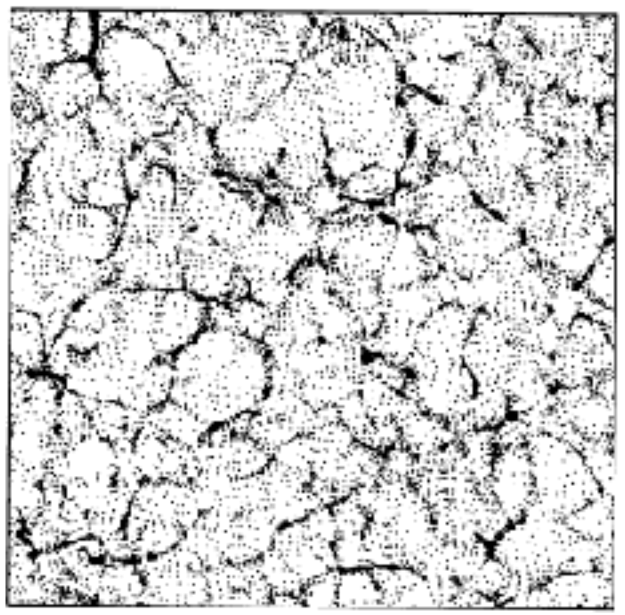
Current Estimate

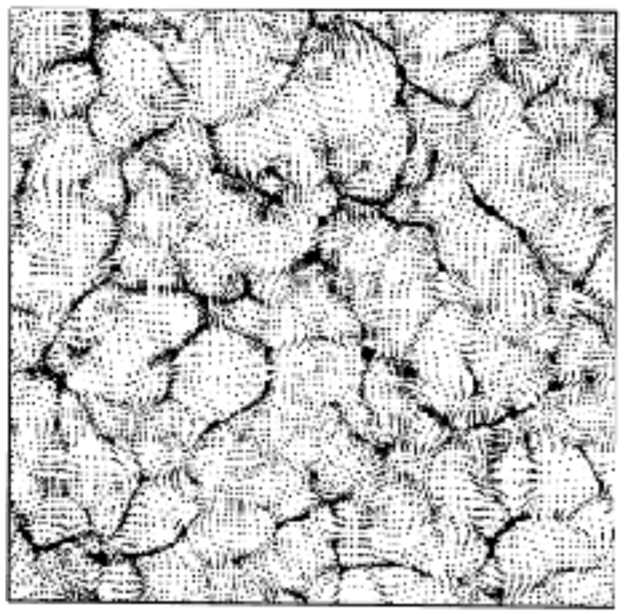
$$t_0 \approx 13.8 \text{ Gyr}$$

Fluctuation Amplitude

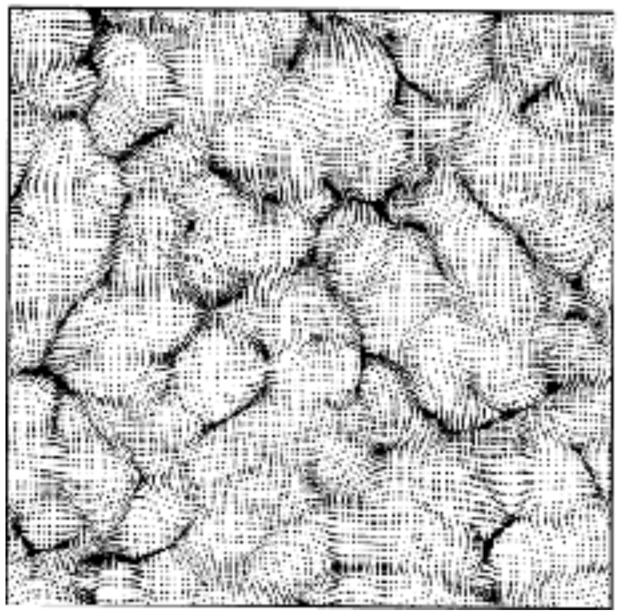
σ_8

High



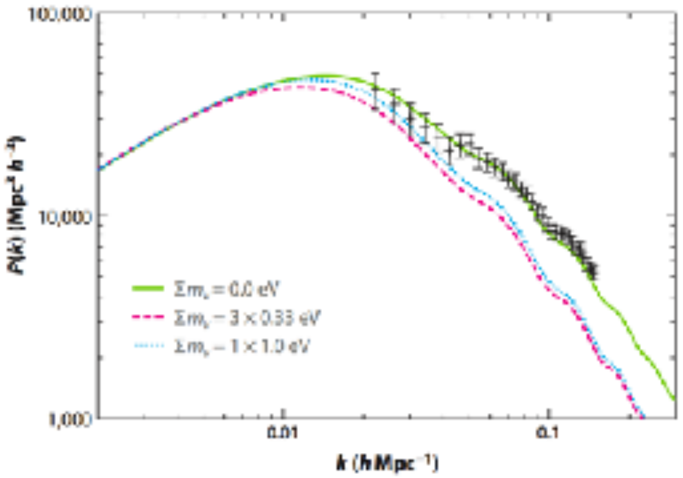


Low



Colombi et. al 1996

FFT →



Fluctuation Amplitude

σ_8

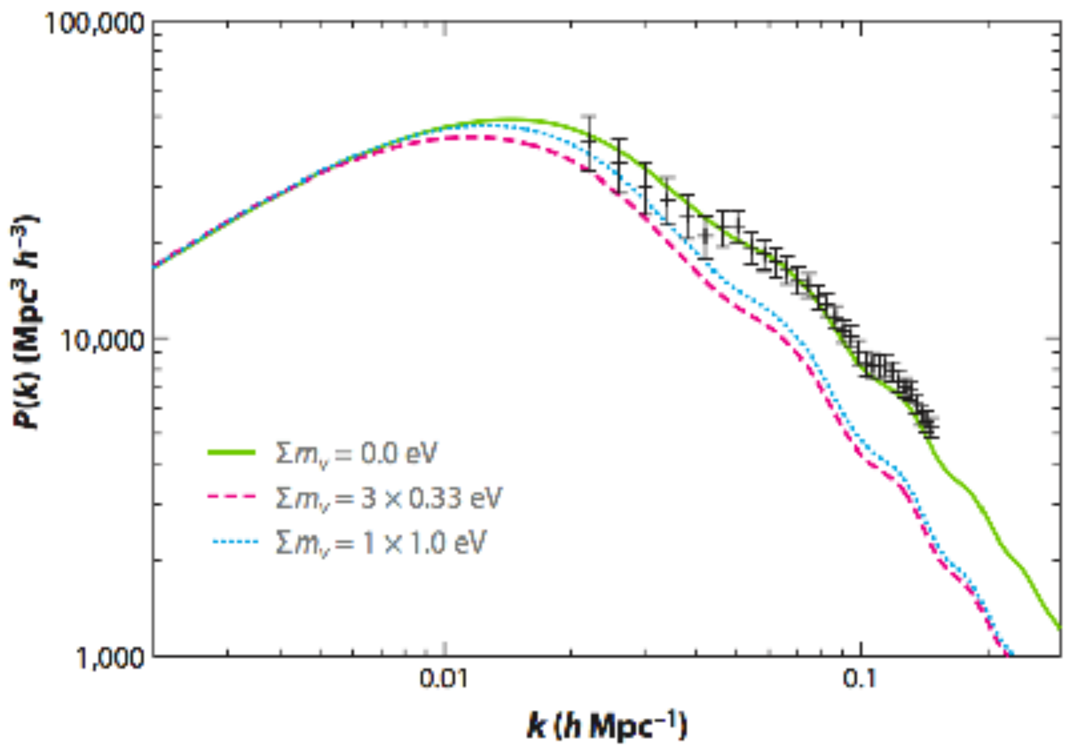
- Amplitude of fluctuations on a scale of $8\ h^{-1}\ \mathrm{Mpc}$
- Rate of growth of structures in the Universe
- Normalisation of the matter power spectrum

Current Estimate

$\sigma_8 \approx 0.83$

Amplitude →

Matter Power Spectrum



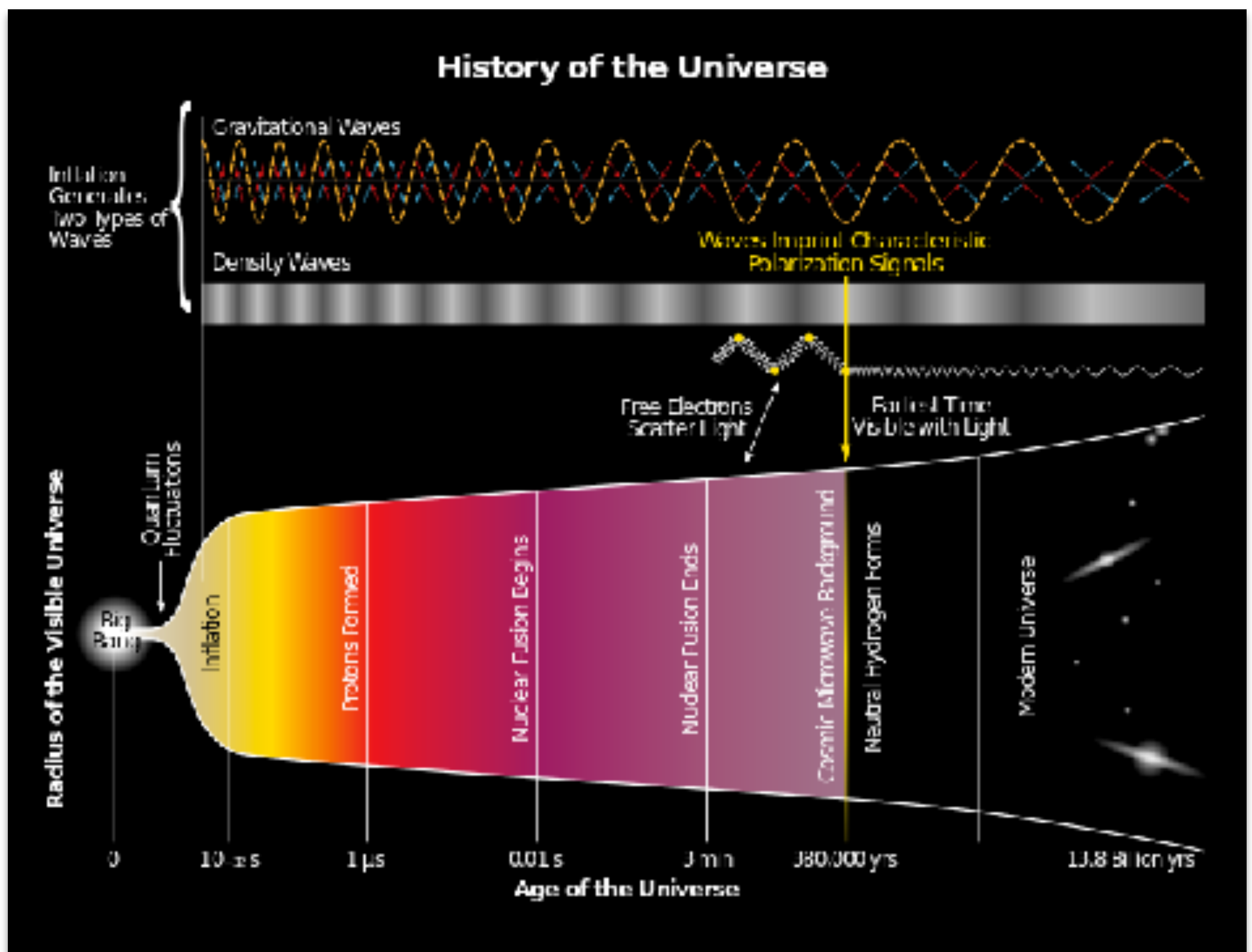
Cole et. al 2005

Spectral Index

n_s

Cosmic Inflation

Alan Guth



Period of accelerated expansion in which the scale factor of the Universe increased by a factor as much as 10^{50} in 10^{-36}s

Spectral Index

$$n_s$$

Scalar Spectral Index

$$n_s \equiv \frac{d \ln \mathcal{P}_\zeta}{d \ln k} + 1$$

Scale invariant fluctuations

$$n_s = 1$$

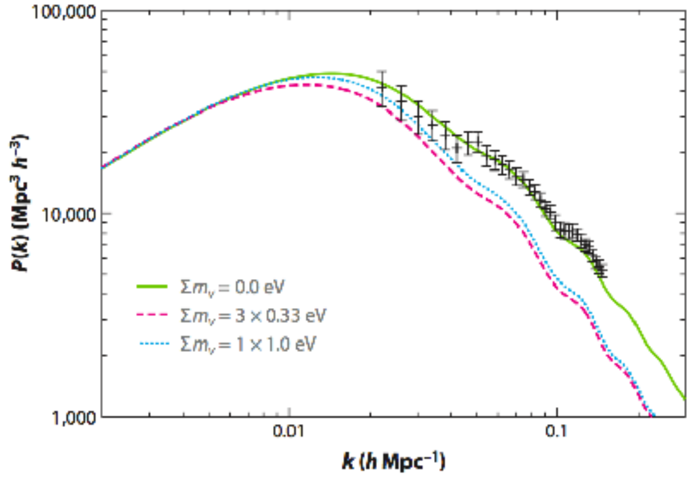
Current Estimate

Inflation predicts

$$n_s < 1$$

$$n_s \approx 0.96$$

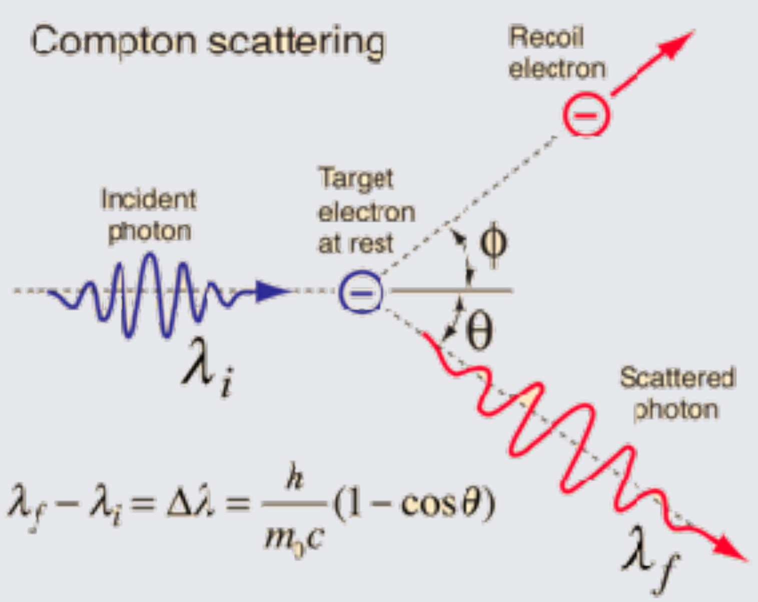
Slope →



Epoch of Reionization

τ

Reionization Optical Depth



Thomson Scattering
$\lambda_i = \lambda_f$

$$\tau(z) = \int_{t(z)}^{t_0} n_e \sigma_T c dt'$$

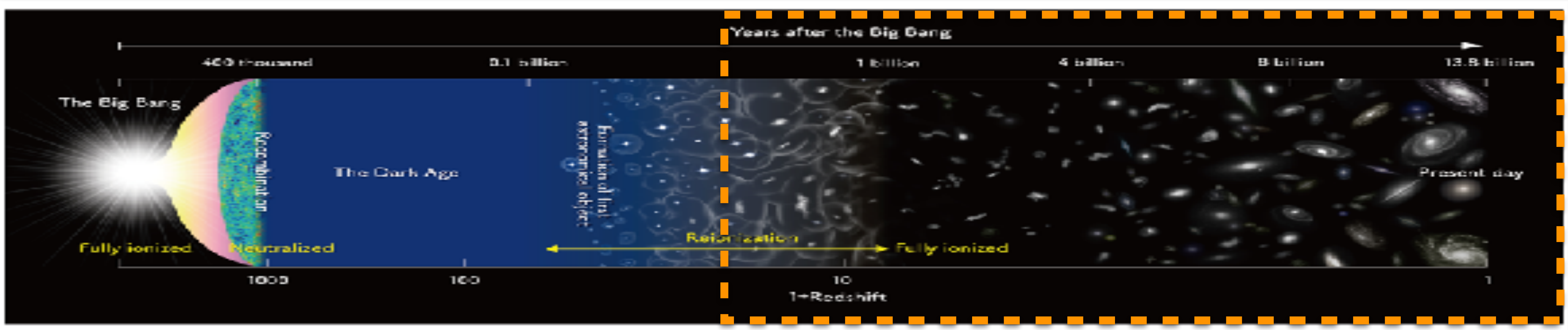
- n_e Number density of free electrons
- σ_T Thomson scattering cross-section

Epoch of Reionization

τ

Current Estimate

$$\tau \approx 0.07, \; z_{\rm re} \approx 8.5$$



Tutorial Day

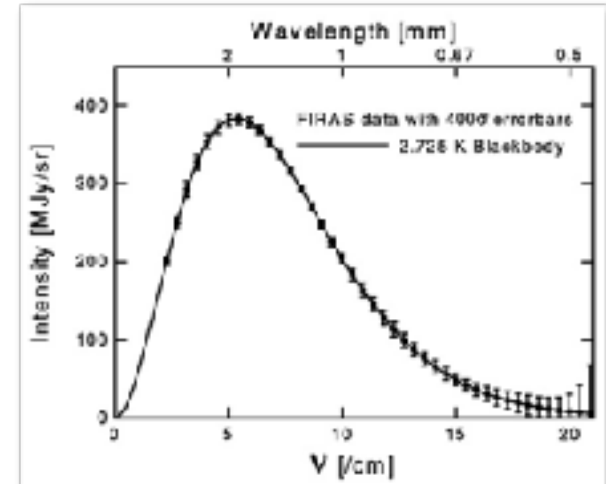
- Cosmological Probes

CMB

Cosmic Microwave Background

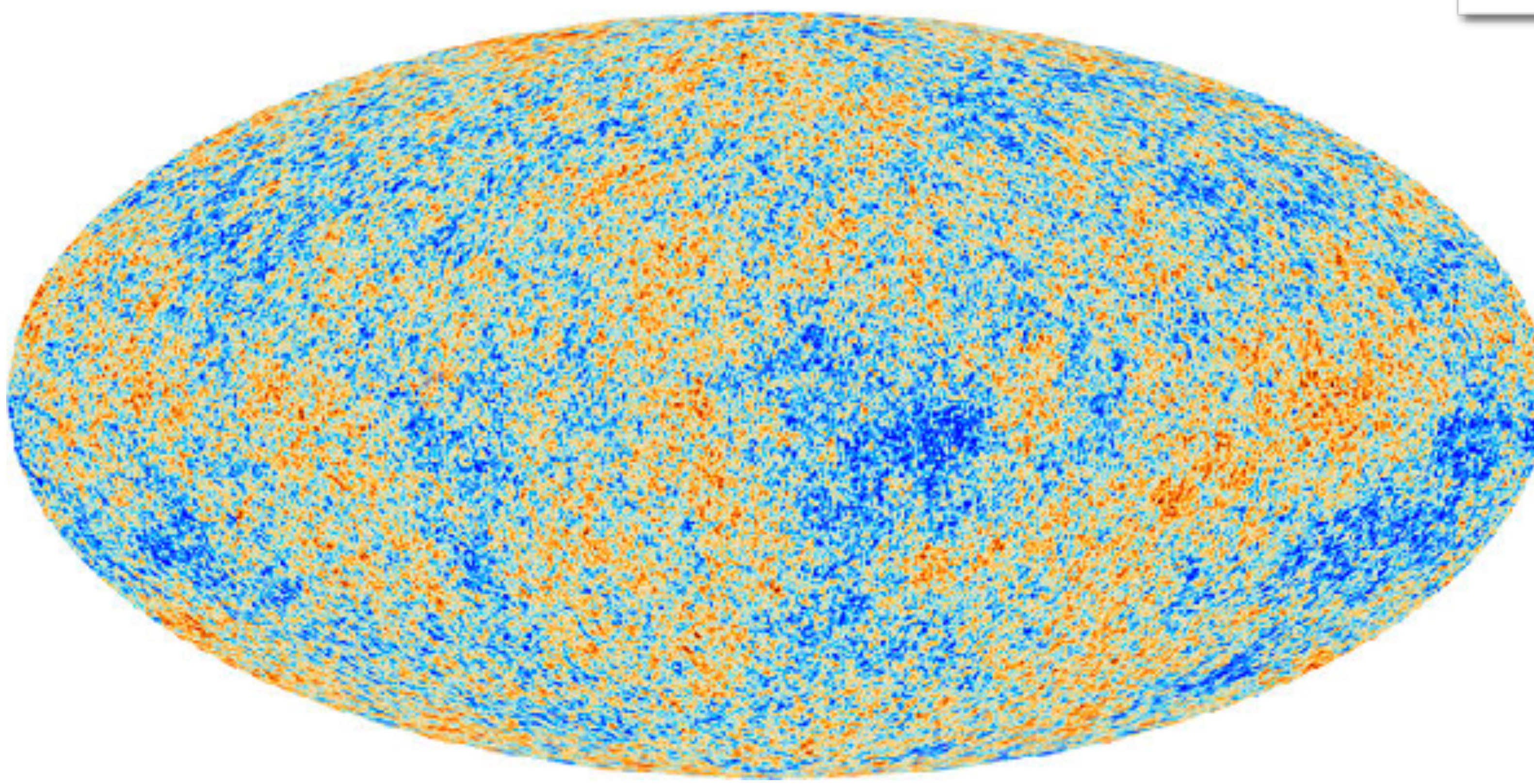
- Thermal radiation left over from recombination
- Oldest light in the Universe

Robert Wilson and Arno Penzias



Blackbody Spectrum

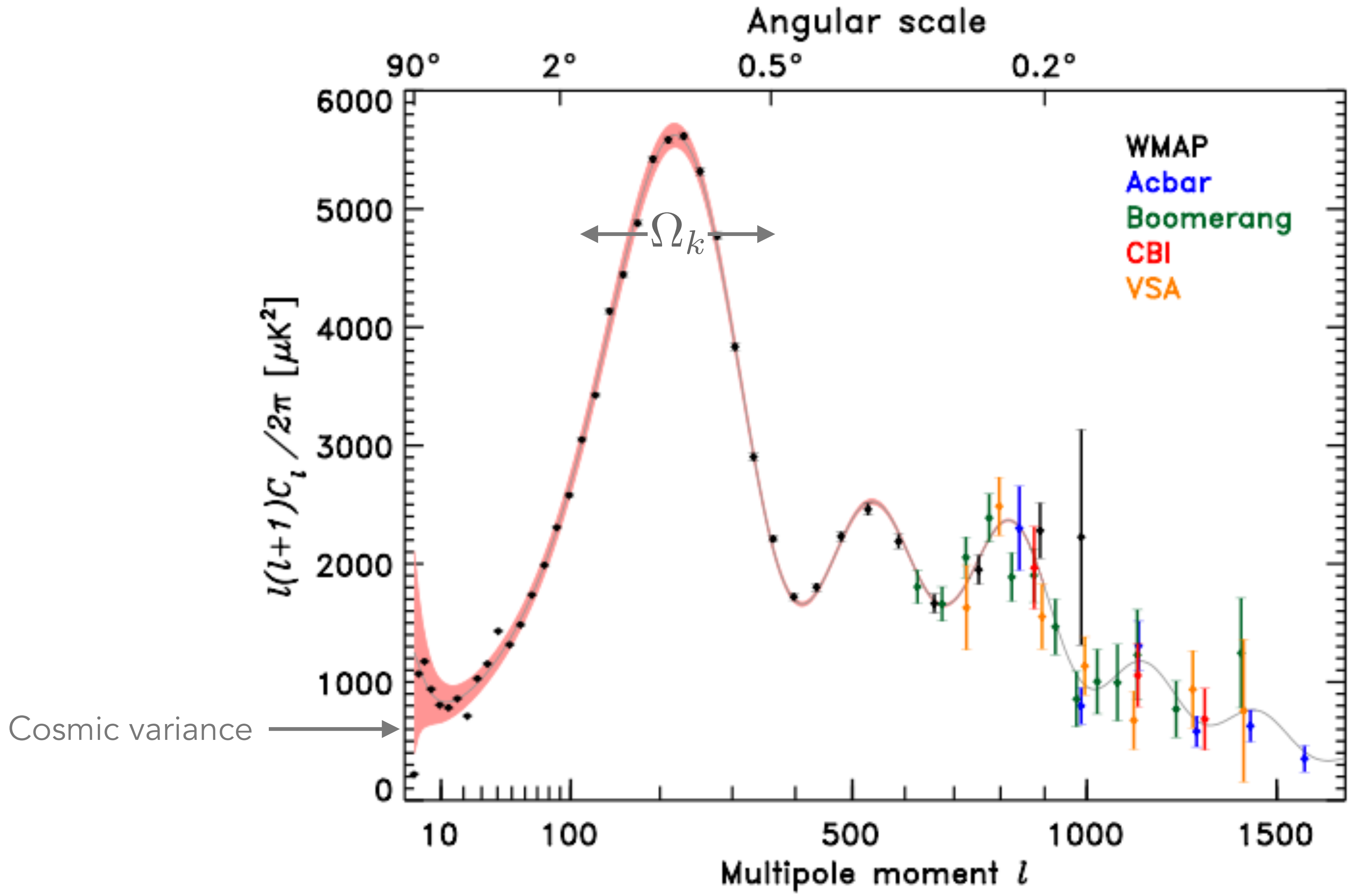
$T_{\text{eff}} = 2.725 \text{ K}$



Planck CMB Map

$z \approx 1100$

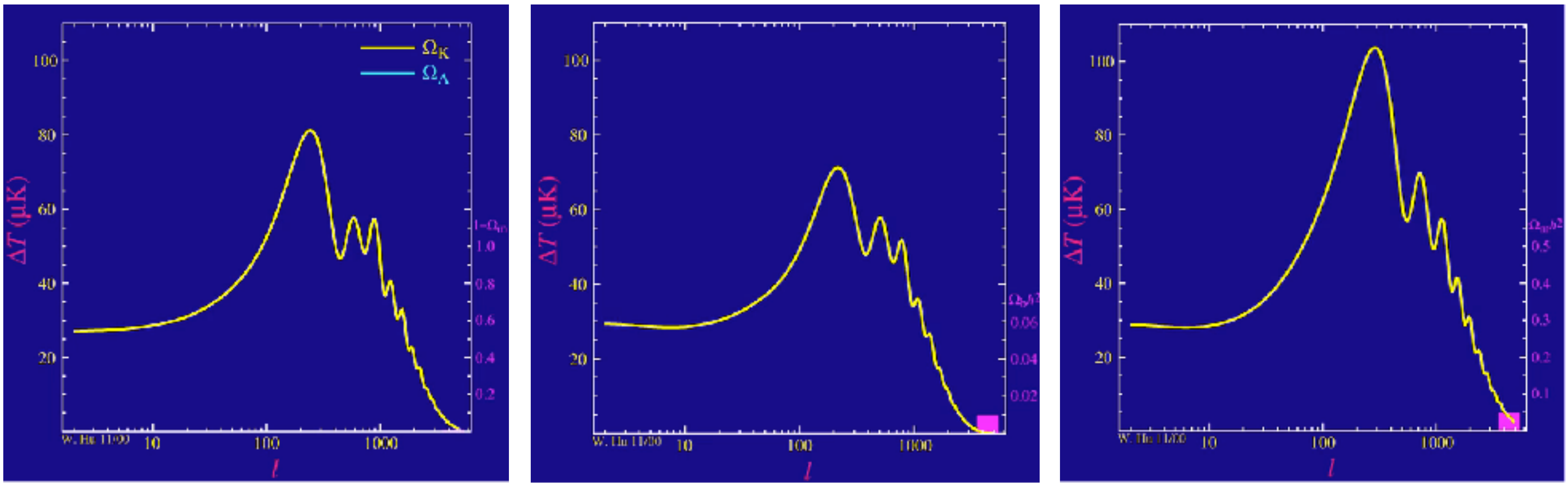
CMB Anisotropies



CMB Power Spectrum

CMB

CMB Anisotropies



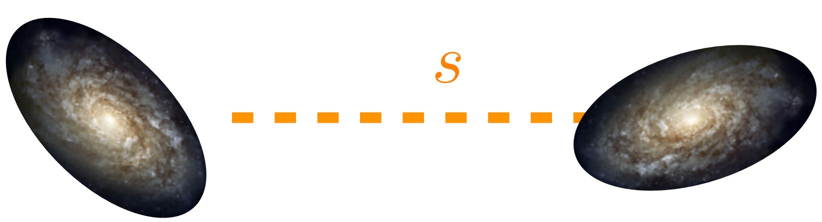
http://background.uchicago.edu/

Galaxies

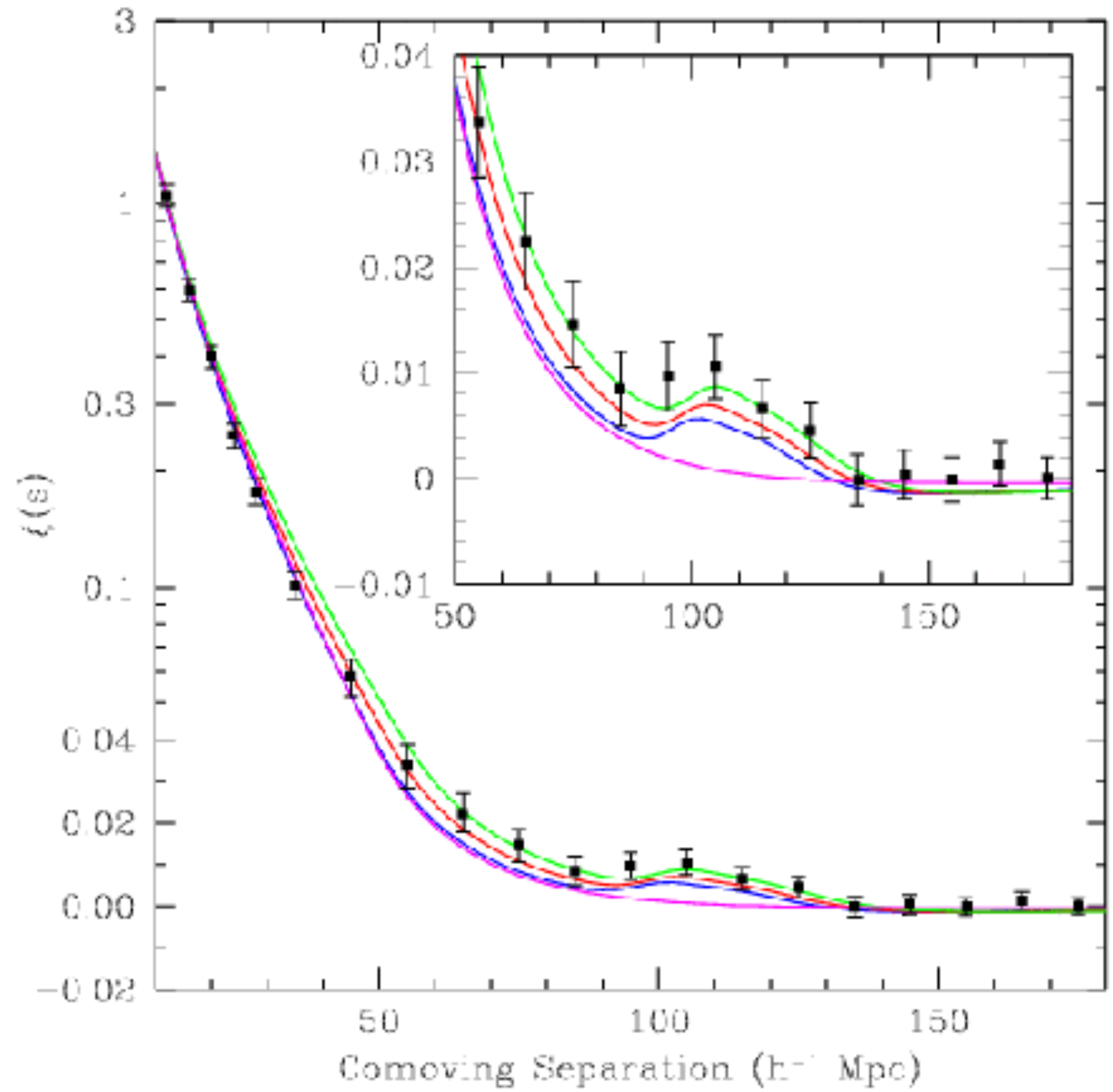
Galaxy Clustering

2-pt Correlation Function

$$\xi(s) = \frac{DD - 2DR + RR}{RR} - 1$$



Count pairs of galaxies at different separations

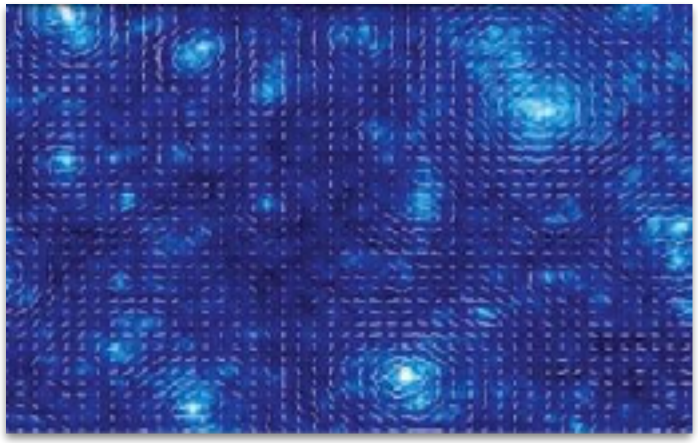


Galaxies

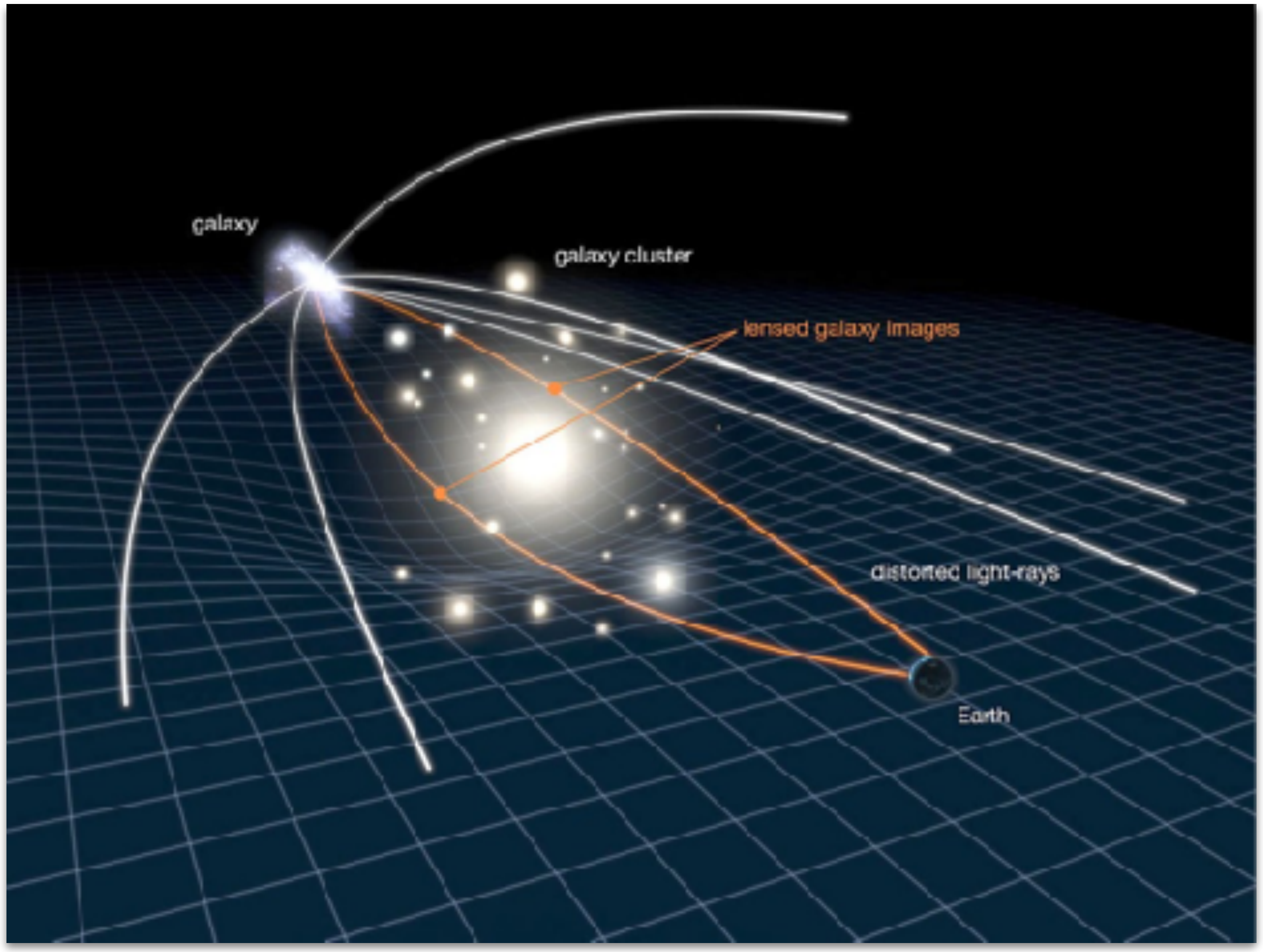
Gravitational Lensing

- Massive objects distort the path of light from background sources

Strongly lensed system



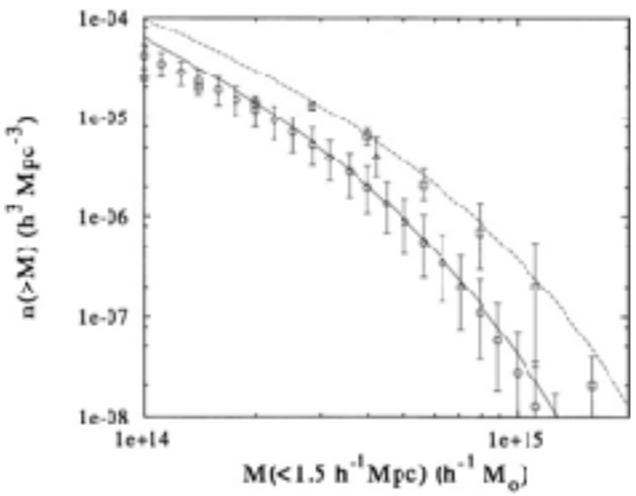
Weak lensing statistics



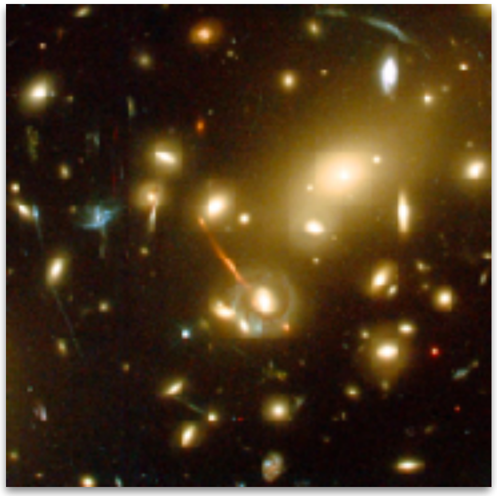
Galaxy Clusters

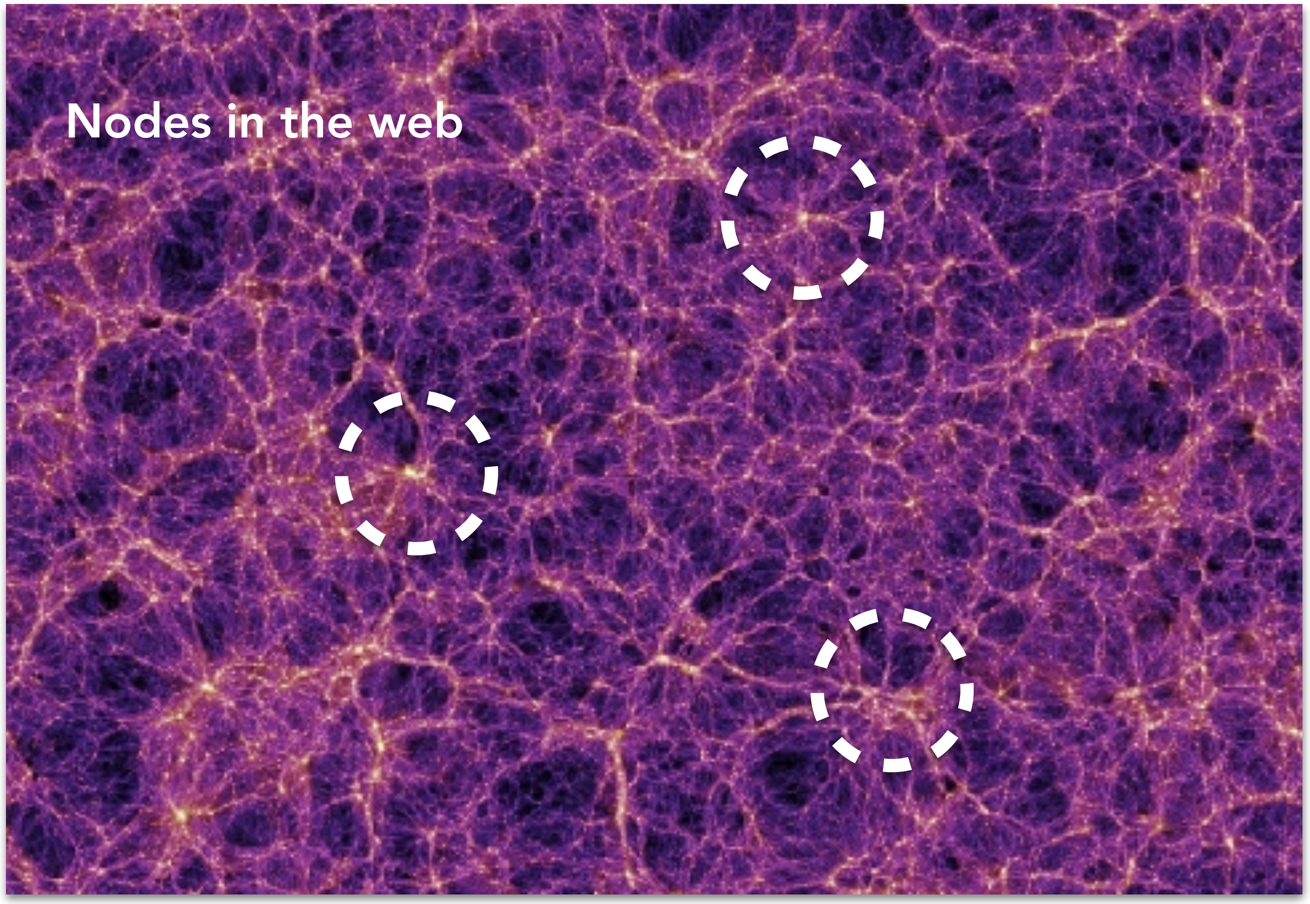
- Largest structures in the Universe

$$10^{13}\ \mathrm{M}_\odot \lesssim M \lesssim 10^{15}\ \mathrm{M}_\odot$$



Cluster mass function

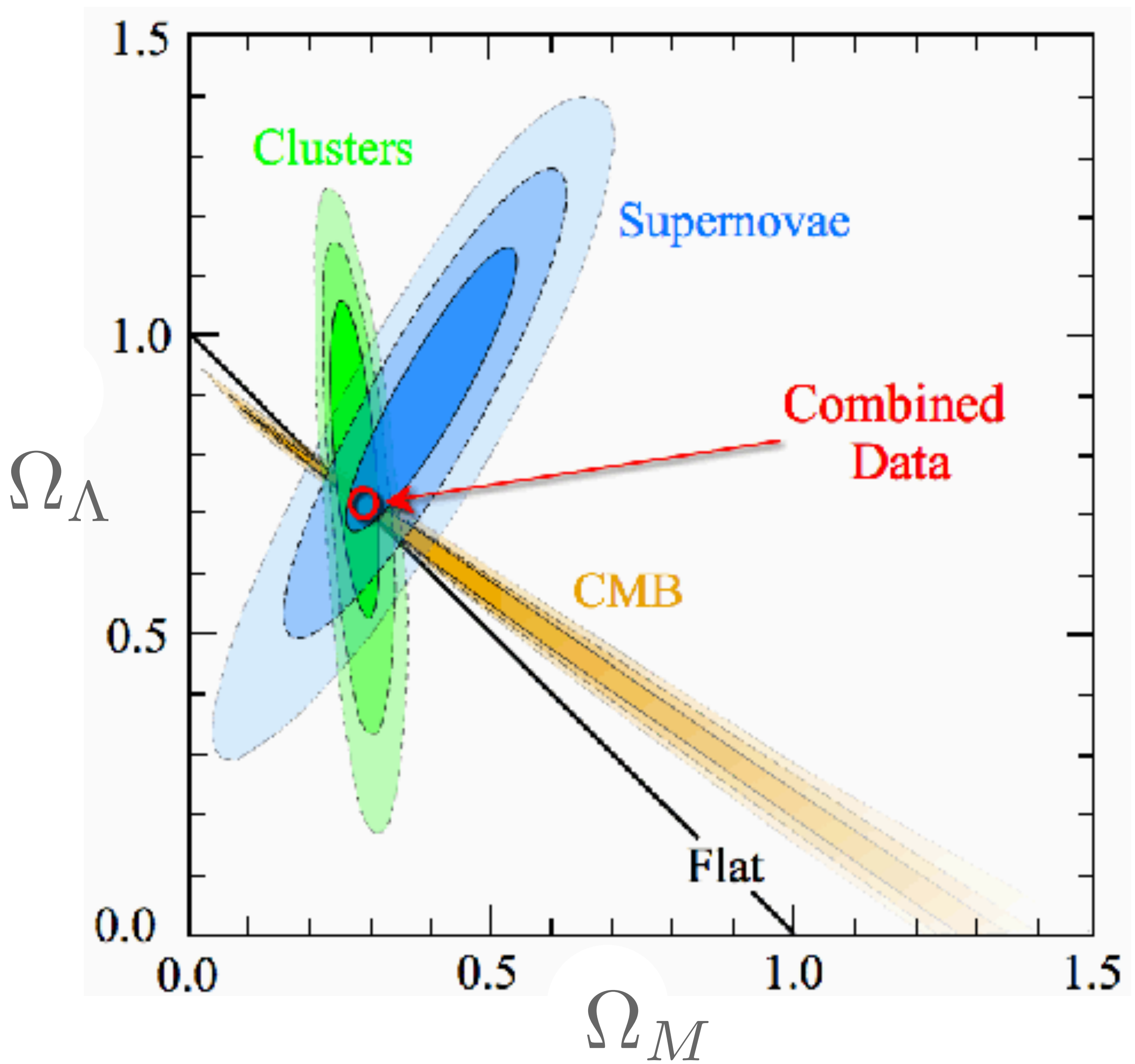




Simulated cosmic web

Combined Constraints

- Best constraining power obtained by combining various probes



Thank you!