Cosmology

ETH Alexandre Refregier
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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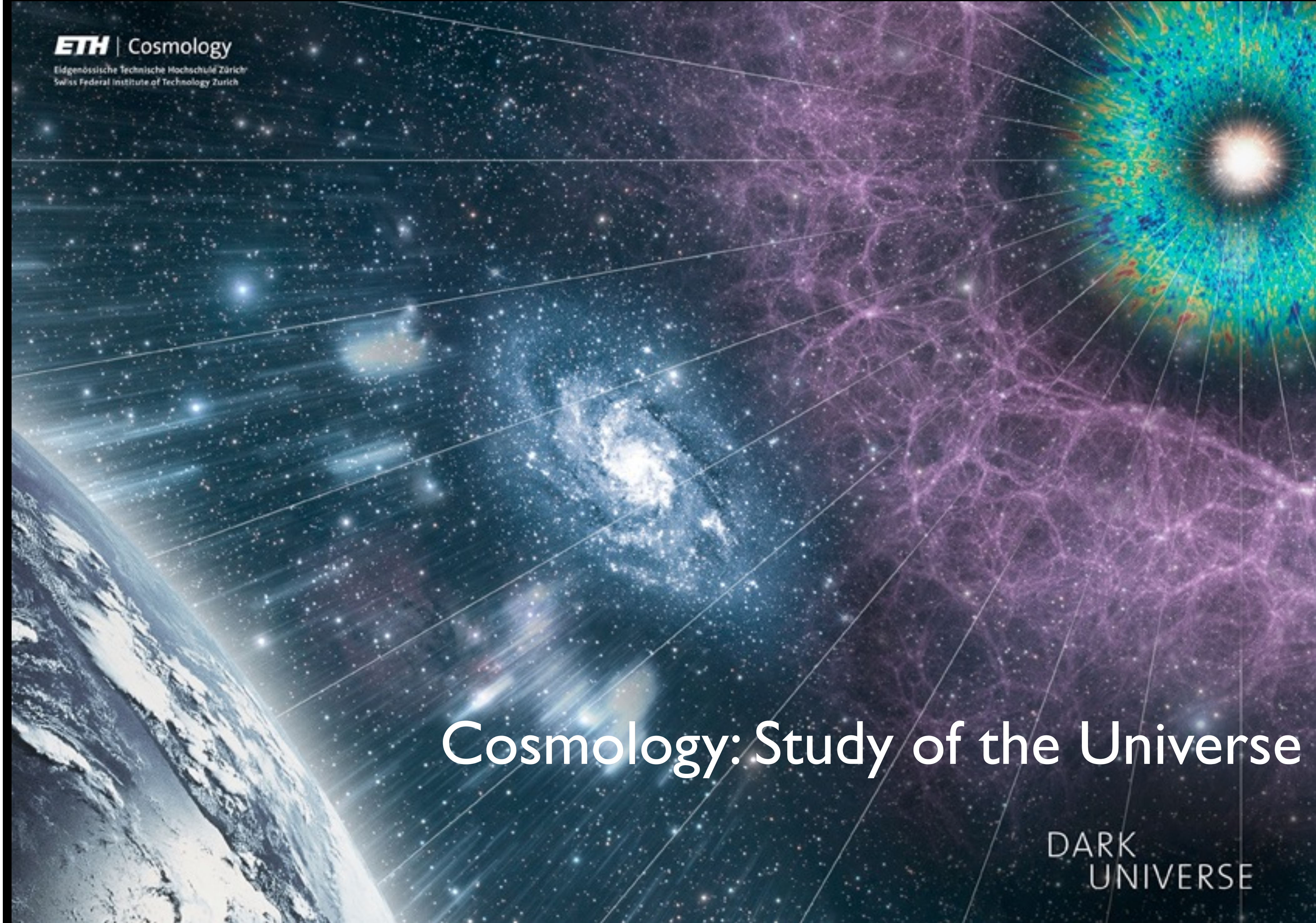
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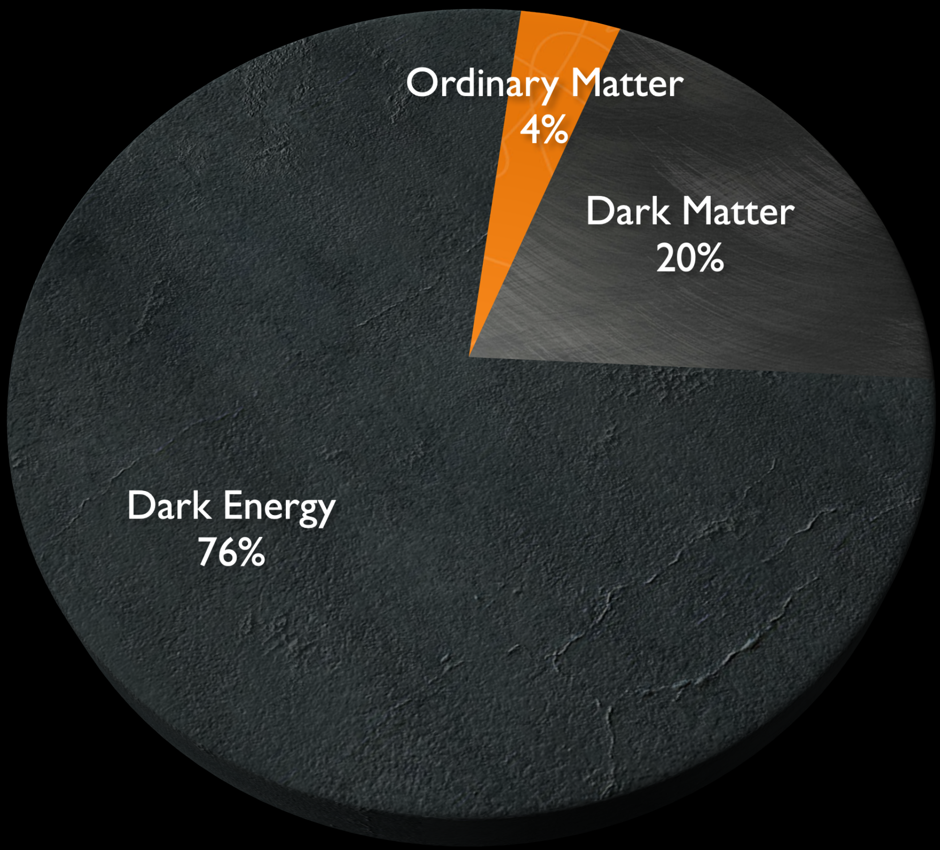
Cosmology: Study of the Universe
DARK
UNIVERSE

The Dark Universe



Gravity

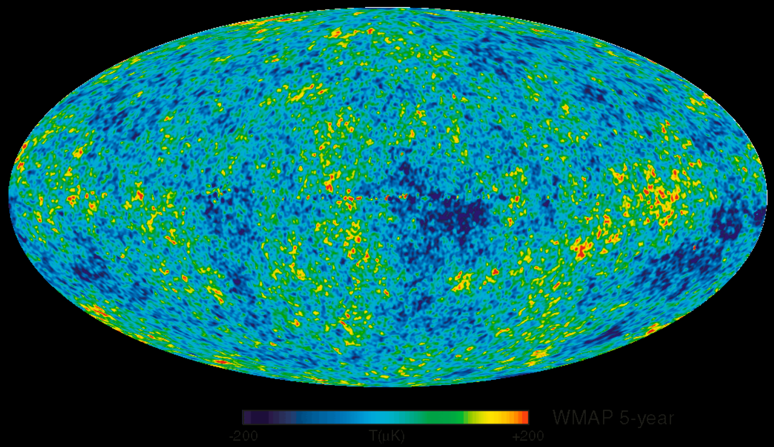
Cosmology

- Can look back in time
- Only one sky: cosmic variance
- Cosmological principle: $\langle \ldots \rangle_{\mathrm{sky}} = \langle \ldots \rangle_{\mathrm{stat}}$
- No controlled experiments

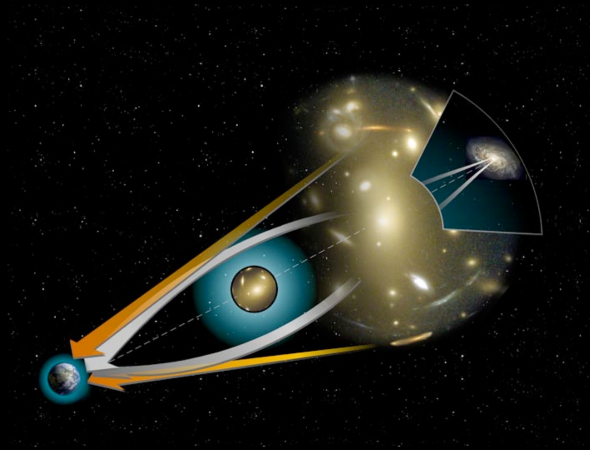
$\rightarrow$ Use combination of cosmological probes

Cosmological Probes

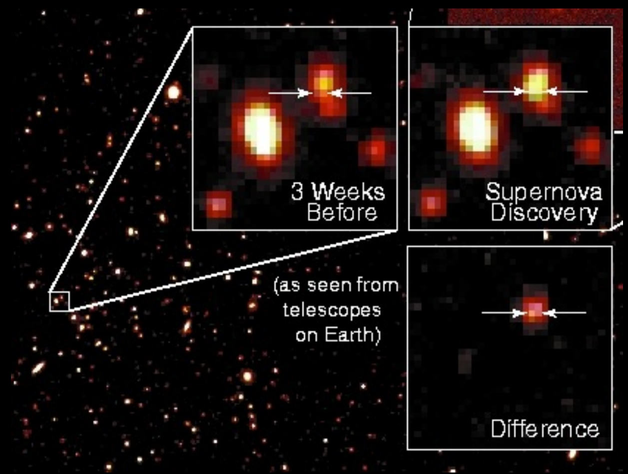
Cosmic Microwave Background



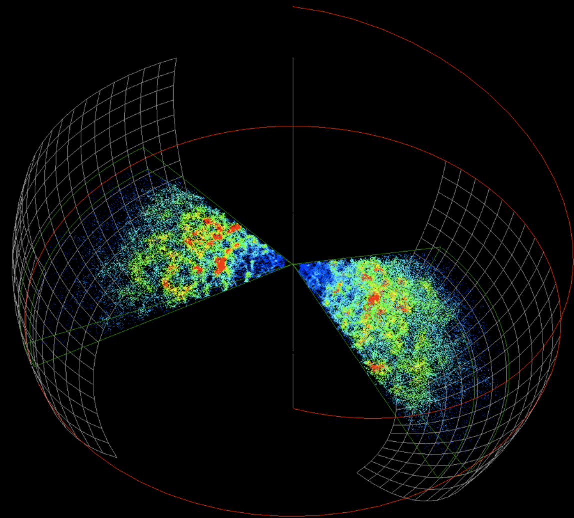
Gravitational Lensing



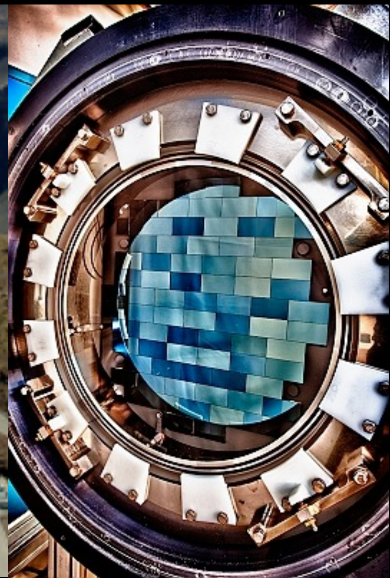
Supernovae



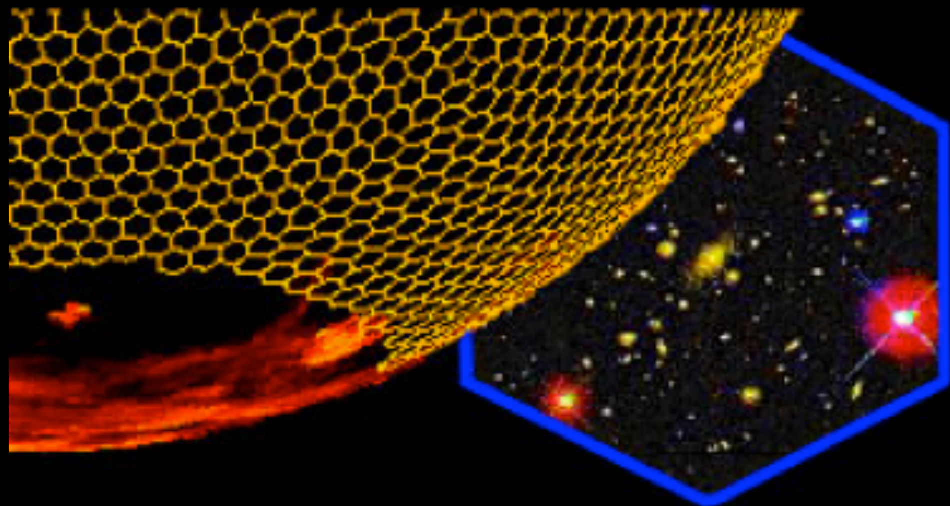
Galaxy Clustering



Dark Energy Survey



Blanco 4m at CTIO
74 2k×4k CCDs, 0.27”/pix
2.2 deg² FOV
5000 deg² survey (+SNe survey)
g,r,i,z,y to mag 24
200M galaxies



Outline

0 Introduction

I Cosmological Model

II Smooth Universe

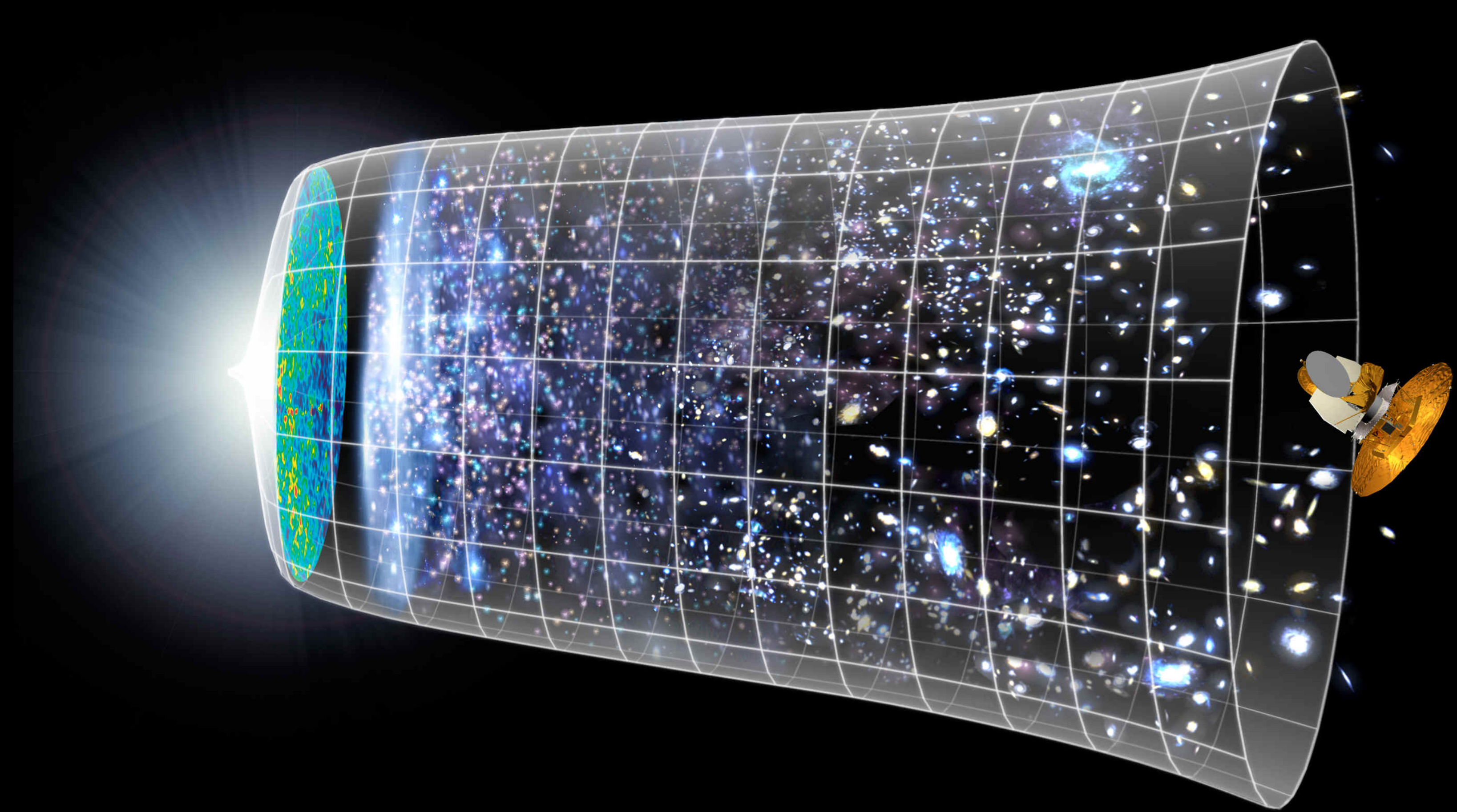
III Structure Formation

IV Cosmological Probes

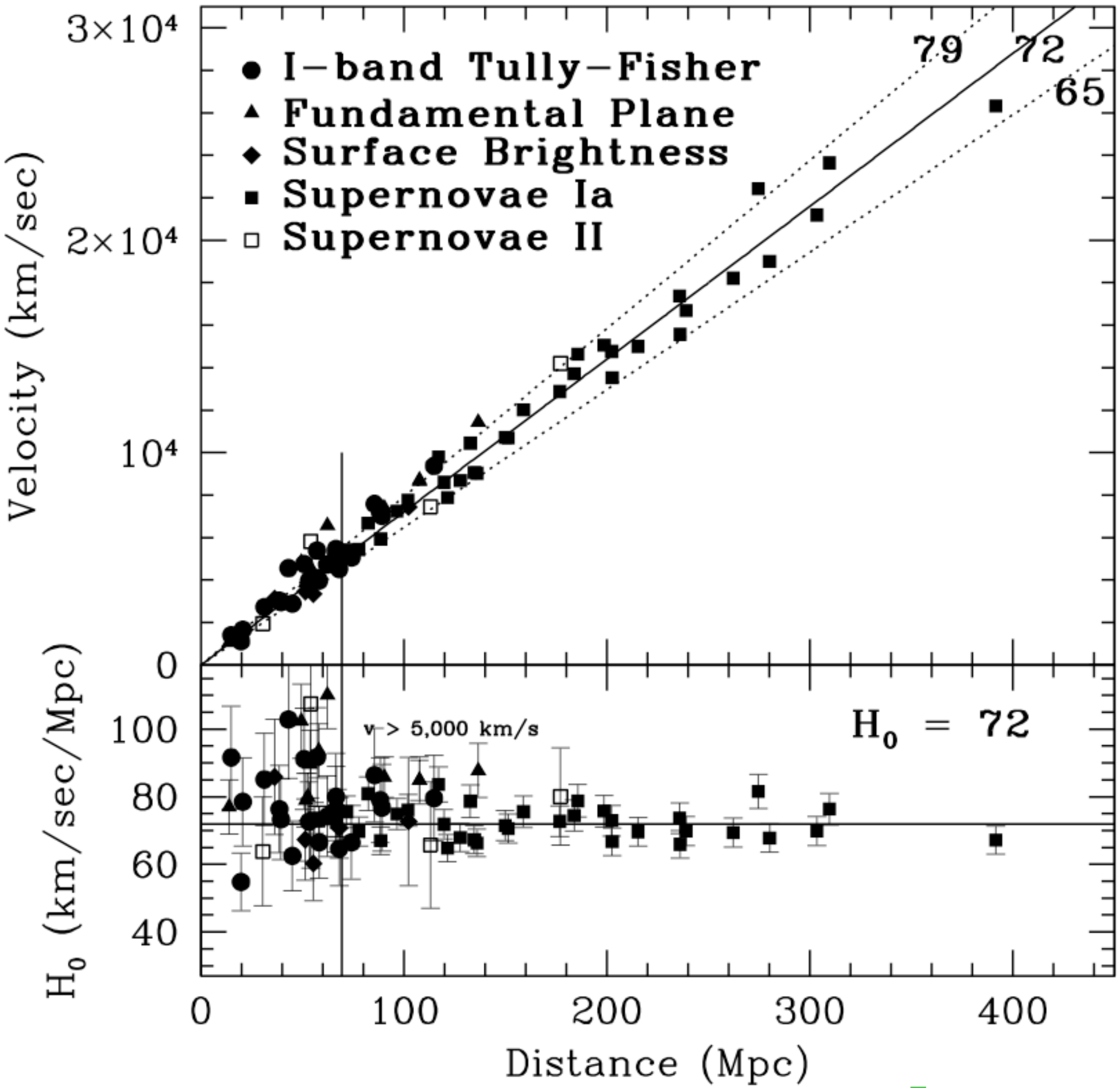
V Current Status and Future Prospects

I Cosmological Model

Big Bang Model

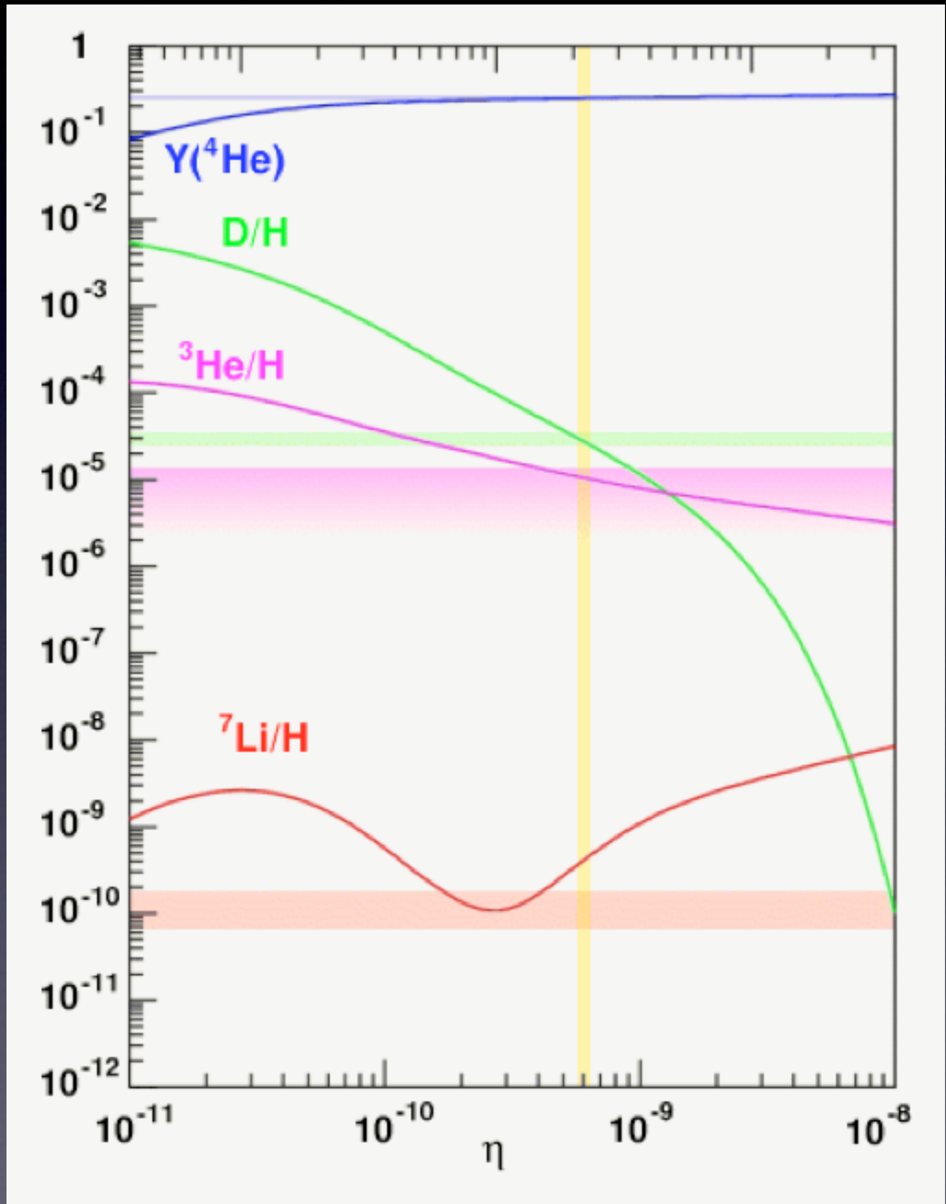


Hubble Diagramme



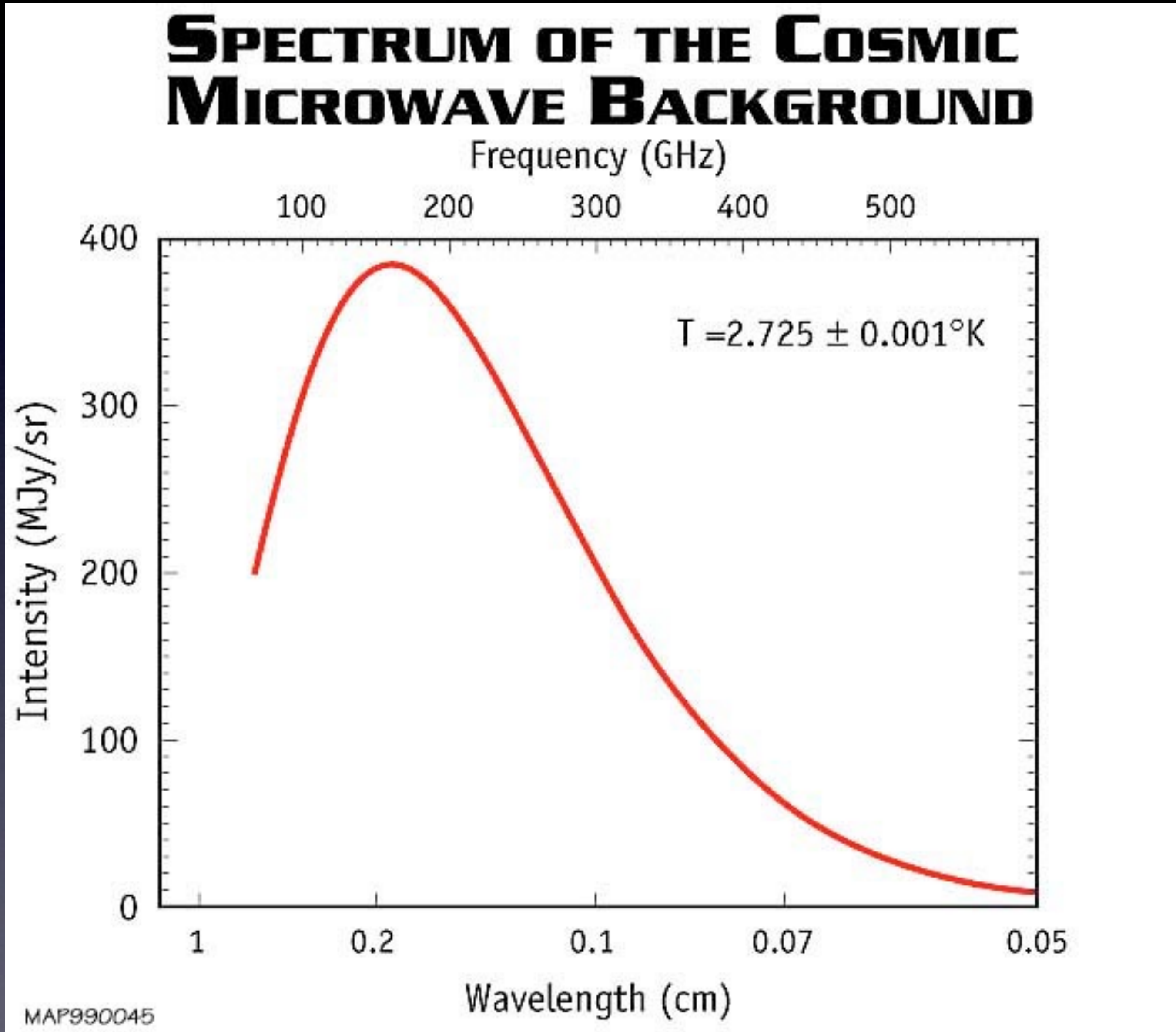
Freeman et al 2000

Big Bang Nucleosynthesis



Weiss 2006

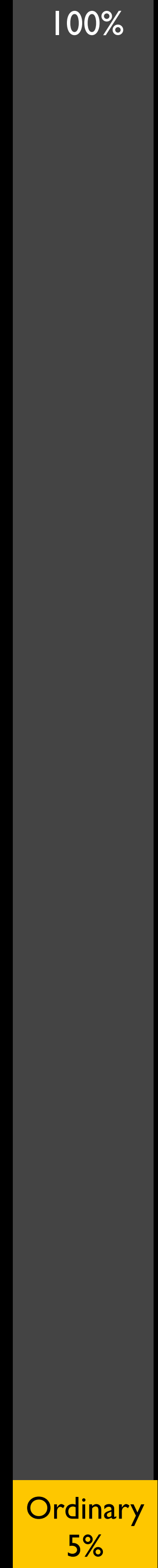
Cosmic Microwave Background



COBE/FIRAS, Mather et al. 1999

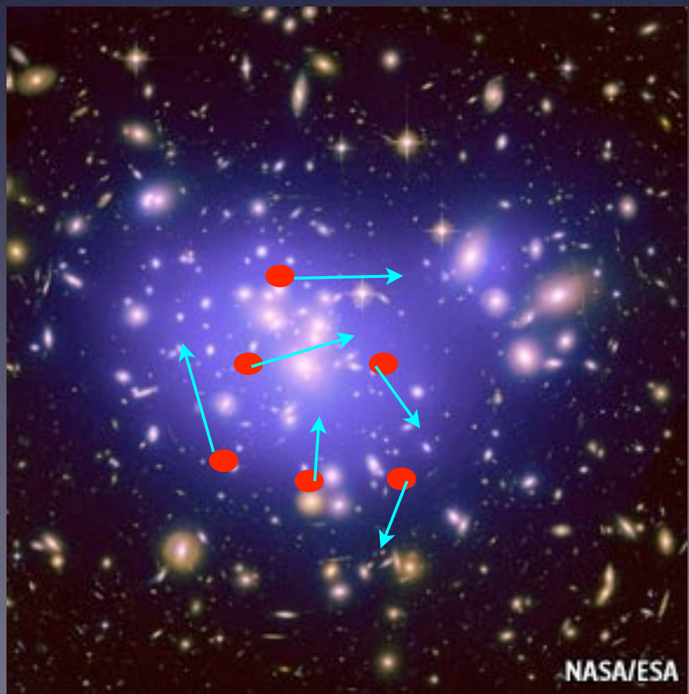
ΛCDM Model


Ordinary Matter


100%
Ordinary
5%

Dark Matter

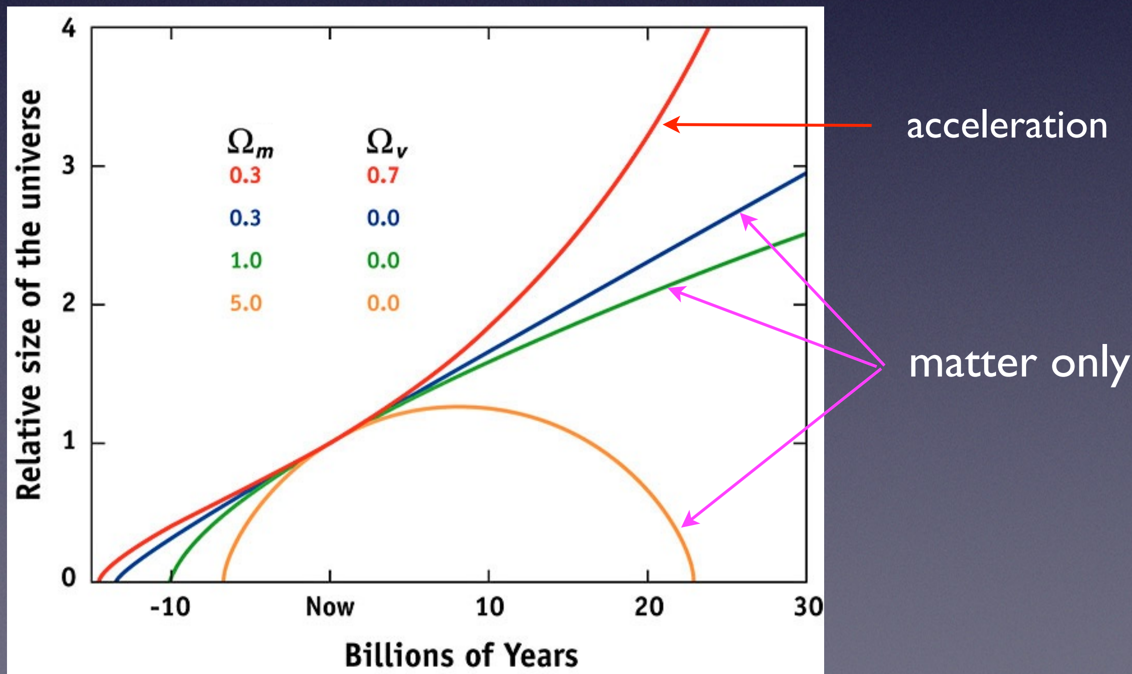
- Initially postulated by Zwicky (1933)
- Does not emit light: evidence via its gravitational effect
- Properties: weakly interacting, cold, non-baryonic, smooth
- Candidate: Unknown Particles beyond standard model



Dark Energy

- Describes recent acceleration of the expansion
- Fluid with equation of state parameter $w=p/\rho<0$
- Cosmological constant Λ: $w=-1$ *at all times*

→ difficult to reconcile with quantum mechanics of vacuum

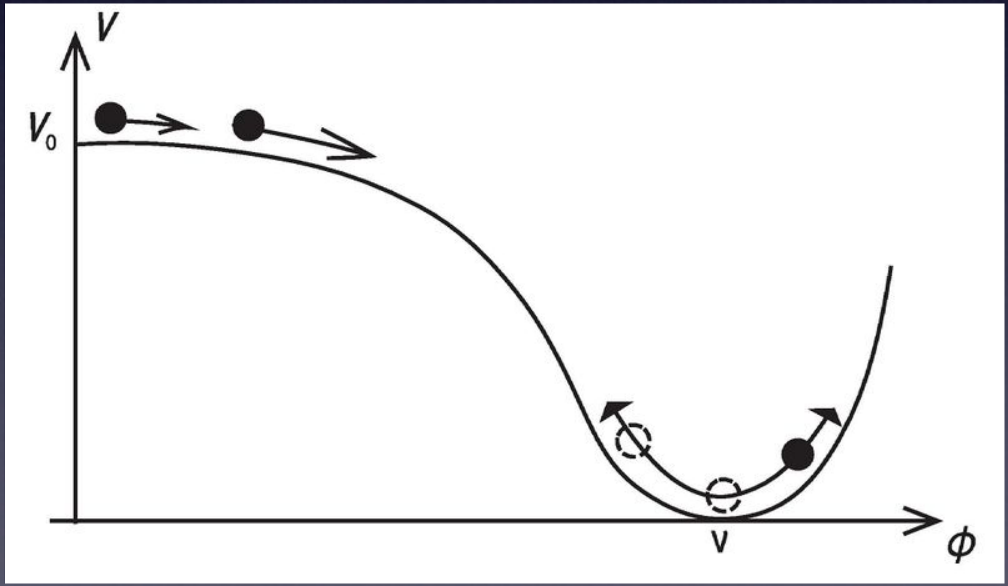


Inflation

Inflation introduced to solve:

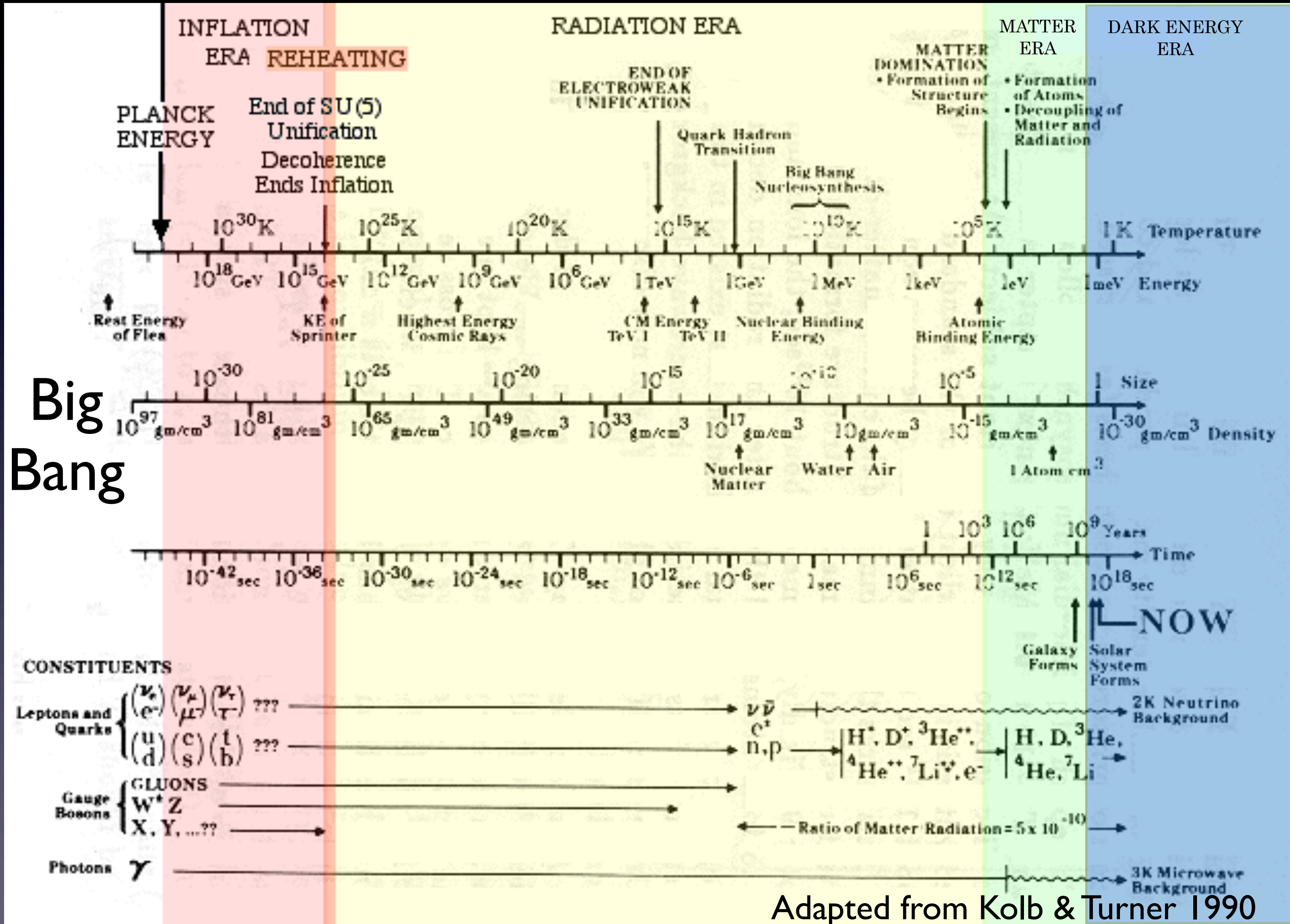
- Flatness problem
- Horizon problem
- Origin of structures problem

Exponential expansion driven by inflaton field



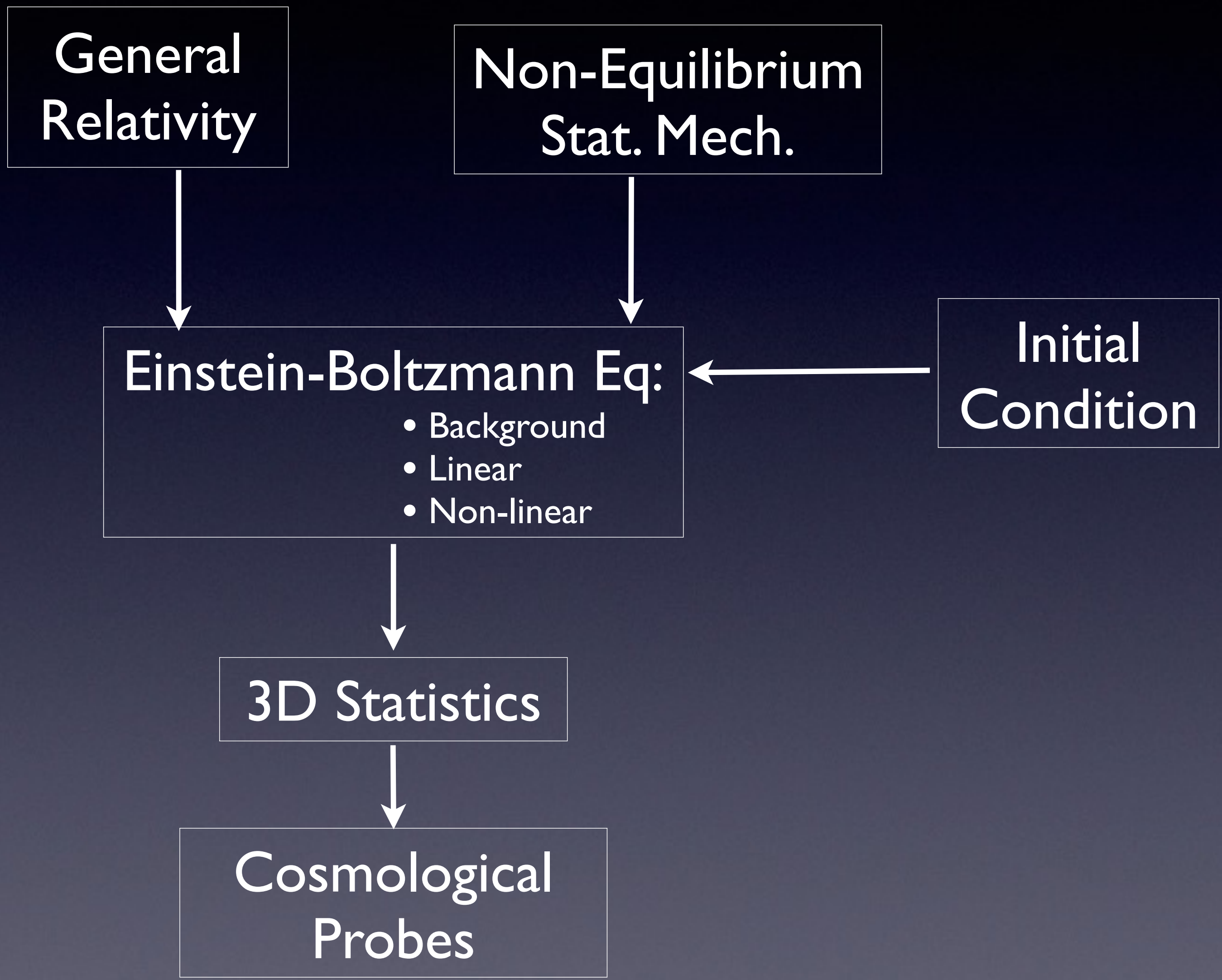
Quantum fluctuations yield large scale classical perturbations after inflation with $P_\Phi(k) \sim k^{n-4}$ and $n \simeq 1$

Thermal History of the Universe



Adapted from Kolb & Turner 1990

Theoretical Predictions



II Smooth Universe

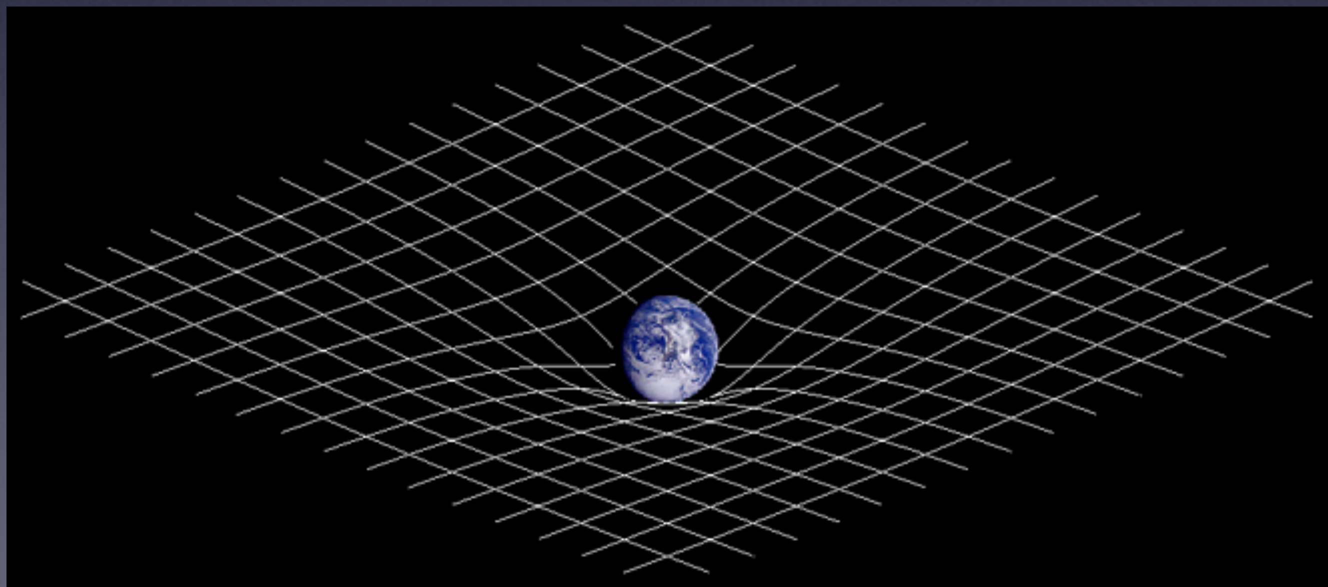
General Relativity

In GR, physical distances in 4D space-time are given by a metric with Lorenz signature (-+++)

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

The metric determines the curvature of space time which is related to the matter content by Einstein's Equation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



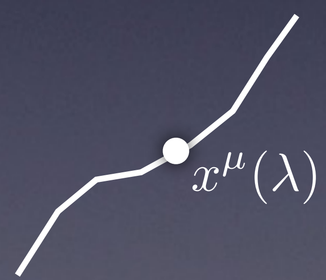
Photon Trajectories

Geodesic equation

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\lambda}\frac{dx^\beta}{d\lambda} = 0$$

Photon 4-momentum

$$p^\mu = \frac{dx^\mu}{d\lambda}$$

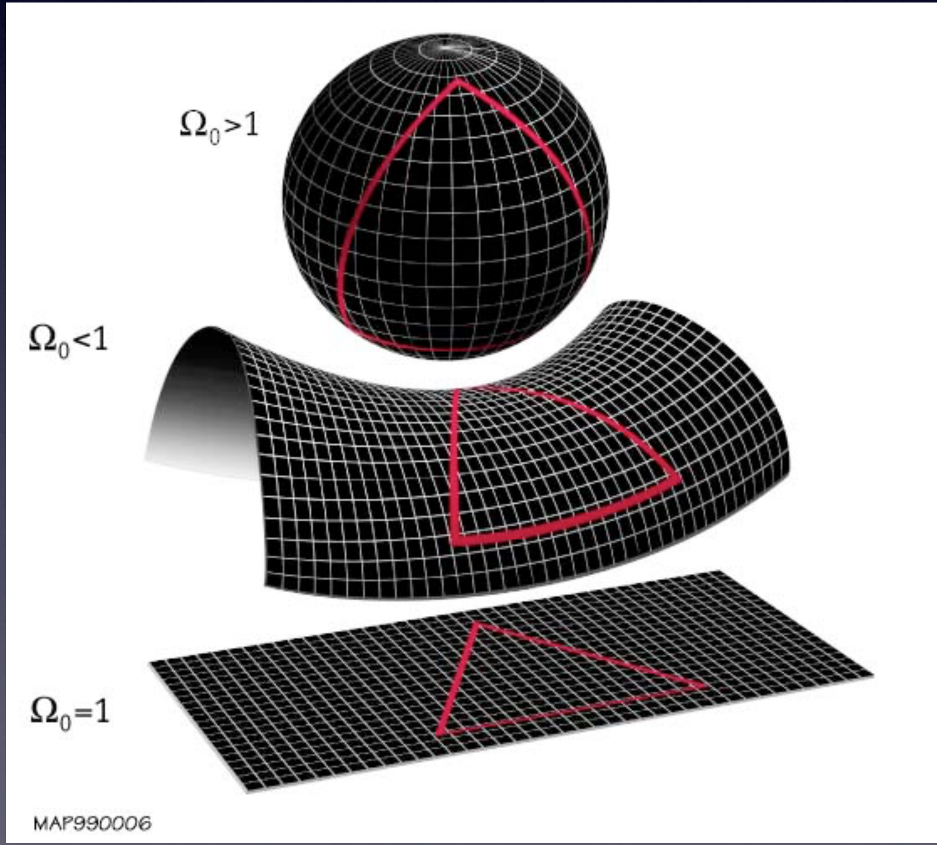


FRW Solution

For homogeneous and isotropic universe

$$ds^2 = -dt^2 + a^2(t)\left[d\chi^2 + r^2(\chi)d\Omega)\right]$$

$$r = \begin{cases} R_0 \sin(\frac{\chi}{R_0}), & \text{closed} \\ R_0 \sinh(\frac{\chi}{R_0}), & \text{open} \\ \chi, & \text{flat} \end{cases}$$



Friedmann Equation

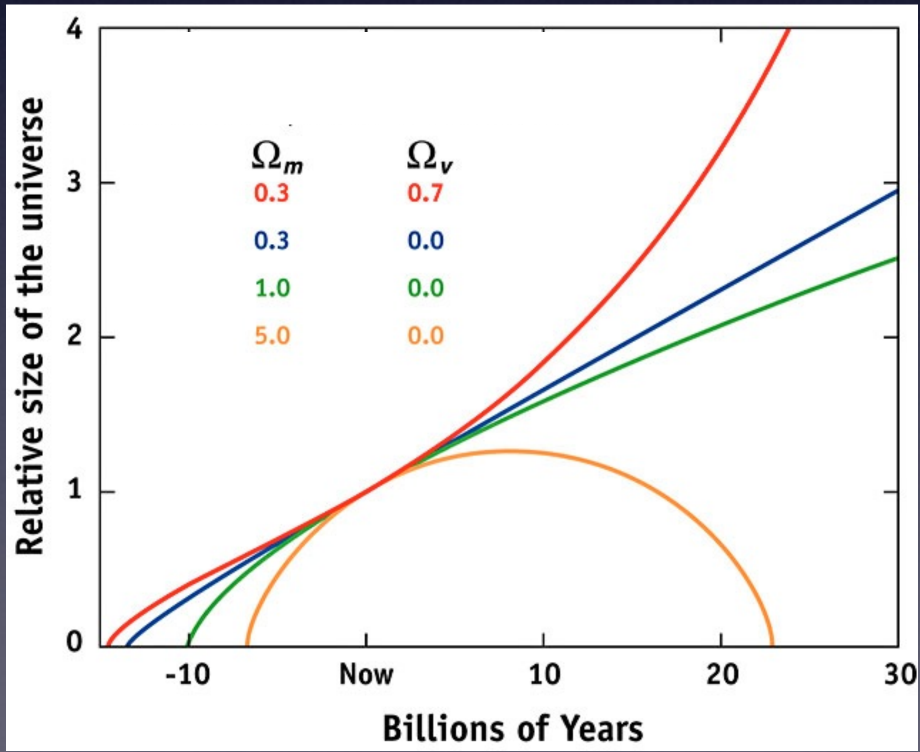
Time-time component of the Einstein Equation for the FRW metric yields:

$$\frac{H}{H_0} = \left[\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_\kappa a^{-2} + \Omega_\Lambda\right]^{\frac{1}{2}}$$

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

$$\Omega_i = \rho_i/\rho_{\rm crit}$$

$$\rho_{\rm crit} = 3H_0^2/8\pi G$$



Distances

Redshift: $$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} = \frac{1}{a_{\rm emit}}$$

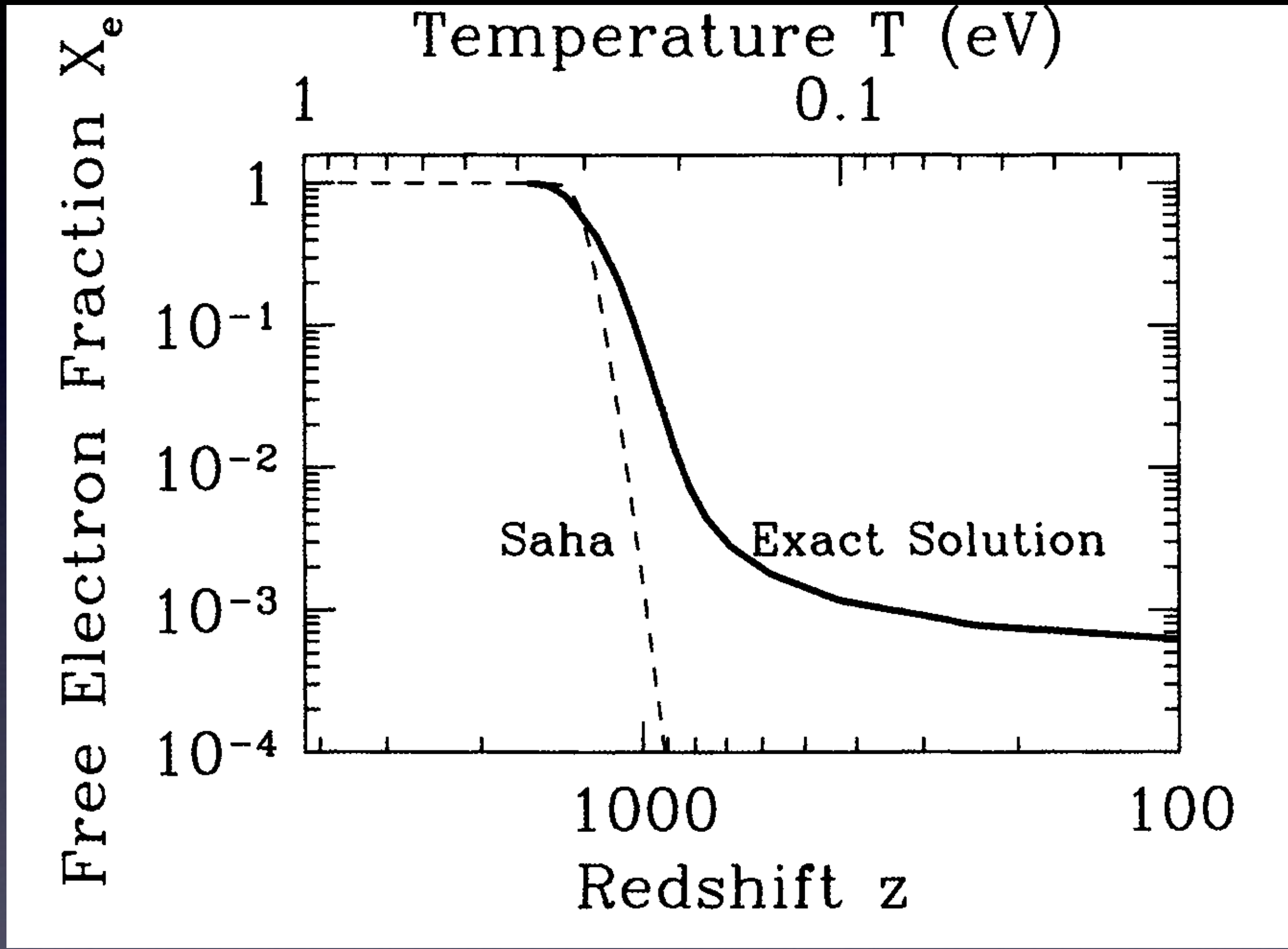
Angular-Diameter distance: $$D_A = R_{\rm phys}/\Delta\theta$$

Luminosity distance: $$F = L/4\pi D_L^2$$

$$D_L = D_A a^{-2} = r(\chi) a^{-1}$$

Comoving Horizon (conformal time) $$\eta = \int_0^a \frac{da'}{a' H(a')}$$

Recombination



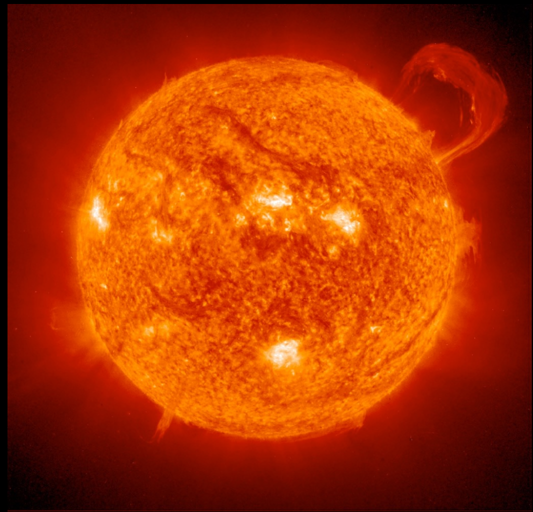
Dodelson 2003

Similar beyond equilibrium processes for:
Big Bang Nucleosynthesis and Dark Matter relics

III Structure Formation

Cosmic Structures

$10^{-6}\ M_\odot$



$1\ M_\odot$

$10^{5}\ M_\odot$

$10^{11}\ M_\odot$

$10^{14}\ M_\odot$

Cosmological Perturbations

Perturbed metric:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

Decomposition theorem:

- scalar perturbations
- vector perturbations
- tensor perturbations

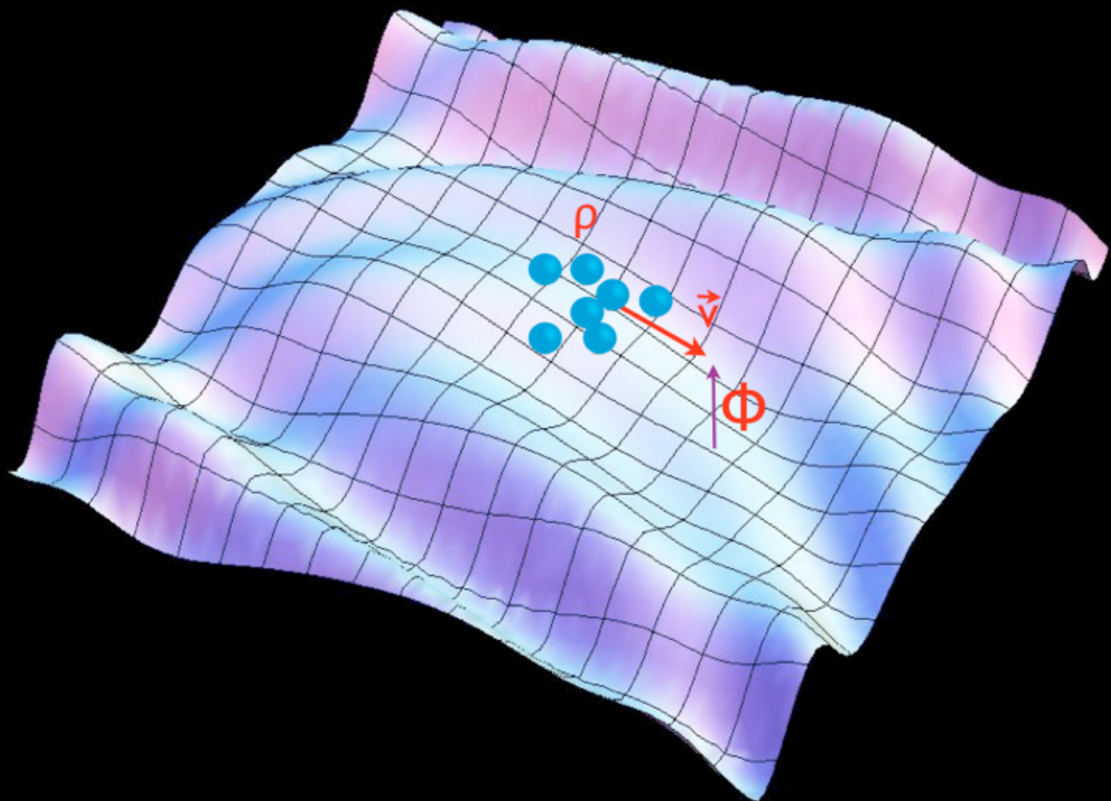
Perturbed Einstein Equation:

$$\bar{G}_{\mu\nu} + \Delta G_{\mu\nu} = 8(\bar{T}_{\mu\nu} + \Delta T_{\mu\nu})$$

Perturbed FRW Model

Flat FRW model in Newtonian gauge with scalar perturbations:

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)\delta_{ij}dx^i dx^j$$



Boltzmann Equation

Distribution function: $f(t, x^i, p^i)$

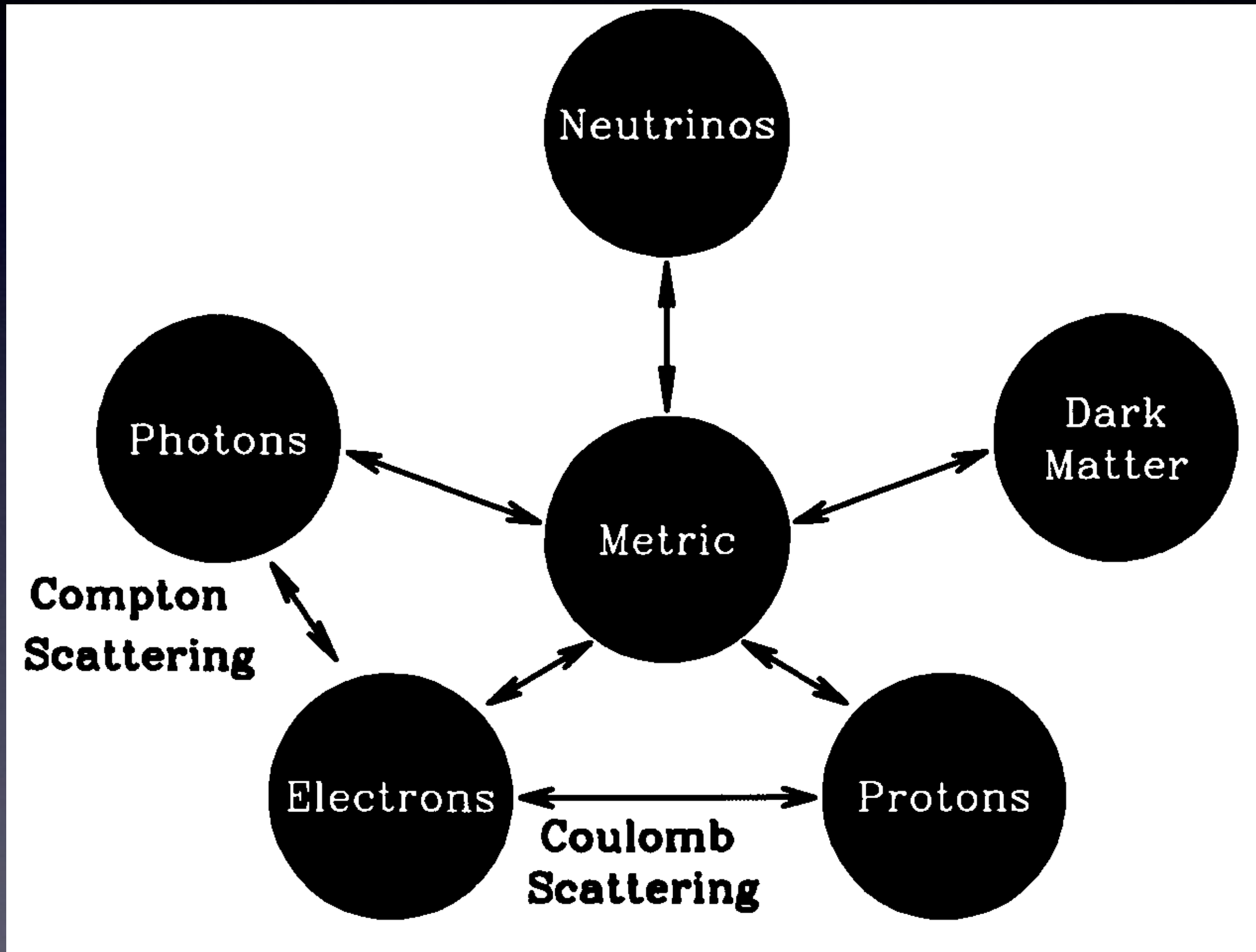
Time evolution:

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial x^i}\frac{dx^i}{dt} + \frac{\partial f}{\partial p^i}\frac{dp^i}{dt} = C[f]$$

Stress-Energy Tensor:

$$T^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3 E} p^\mu p^\nu f(t, x^i, p^i)$$

Species and Interactions



Dodelson 2003

Einstein-Boltzmann Equations

Linear evolution

$$\dot{\Theta} + ik\mu\Theta = -\dot{\Phi} - ik\mu\Psi - \dot{\tau}\left[\Theta_0 - \Theta + \mu v_b - \frac{1}{2}\mathcal{P}_2(\mu)\Pi\right]$$

$$\Pi = \Theta_2 + \Theta_{P2} + \Theta_{P0}$$

$$\dot{\Theta}_P + ik\mu\Theta_P = -\dot{\tau}\left[-\Theta_P + \frac{1}{2}(1 - \mathcal{P}_2(\mu))\Pi\right]$$

$$\dot{\delta} + ikv = -3\dot{\Phi}$$

$$\dot{v} + \frac{\dot{a}}{a}v = -ik\Psi$$

$$\dot{\delta}_b + ikv_b = -3\dot{\Phi}$$

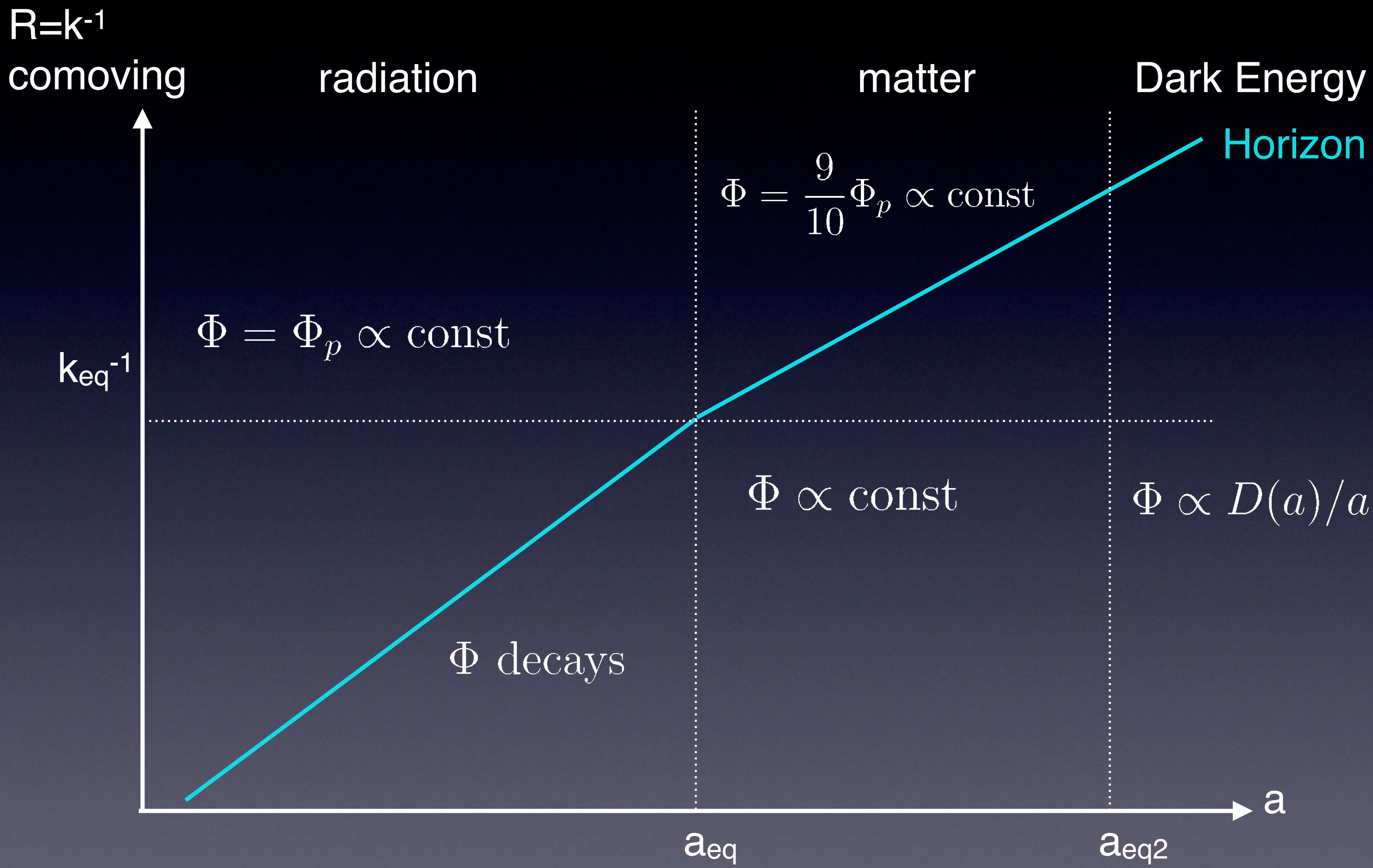
$$\dot{v}_b + \frac{\dot{a}}{a}v_b = -ik\Psi + \frac{\dot{\tau}}{R}\left[v_b + 3i\Theta_1\right]$$

$$\dot{\mathcal{N}} + ik\mu\mathcal{N} = -\dot{\Phi} - ik\mu\Psi.$$

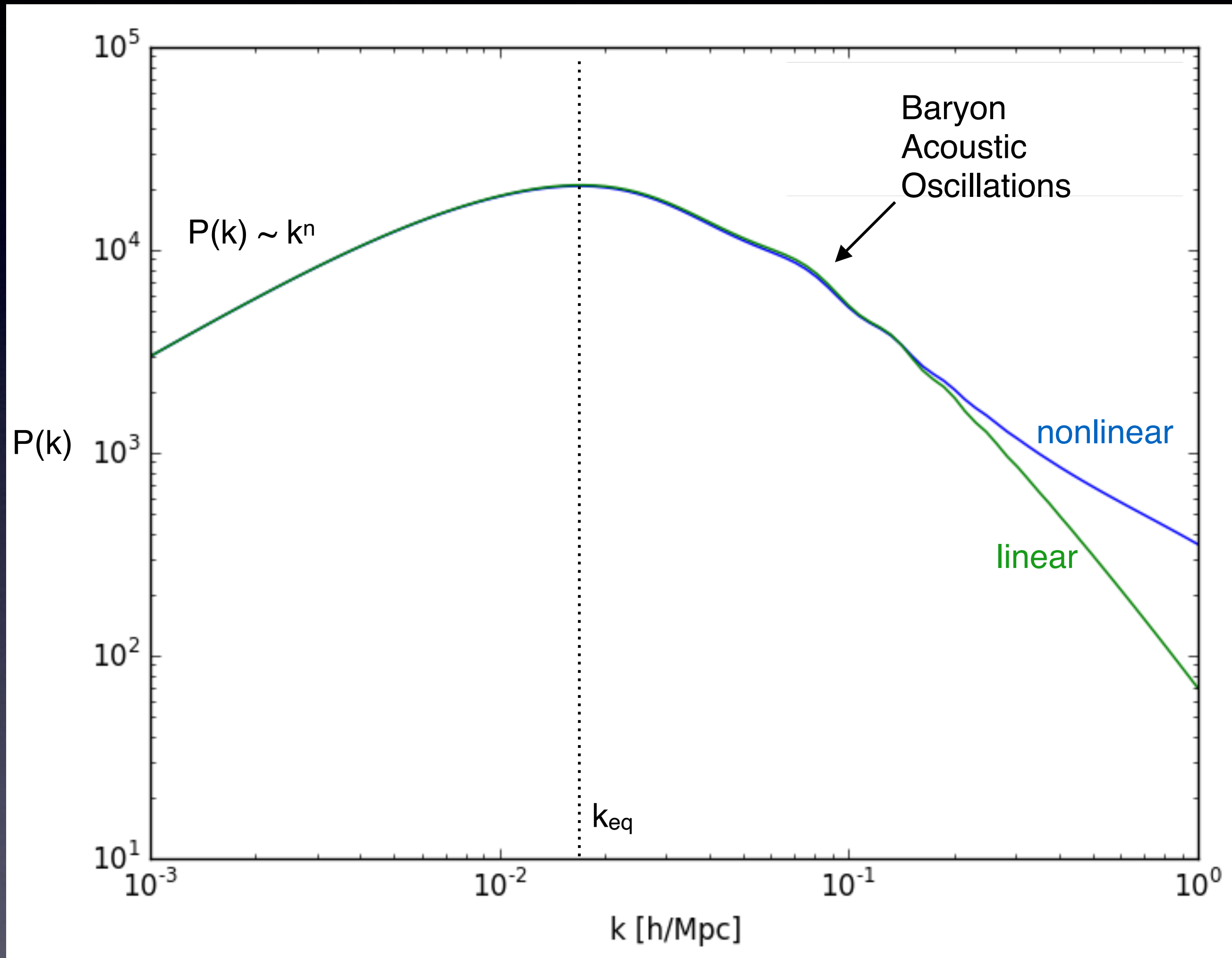
$$k^2\Phi + 3\frac{\dot{a}}{a}\left(\dot{\Phi} - \Psi\frac{\dot{a}}{a}\right) = 4\pi G a^2\left[\rho_m\delta_m + 4\rho_r\Theta_{r,0}\right]$$

$$k^2(\Phi + \Psi) = -32\pi G a^2\rho_r\Theta_{r,2}.$$

Evolution of the Perturbations



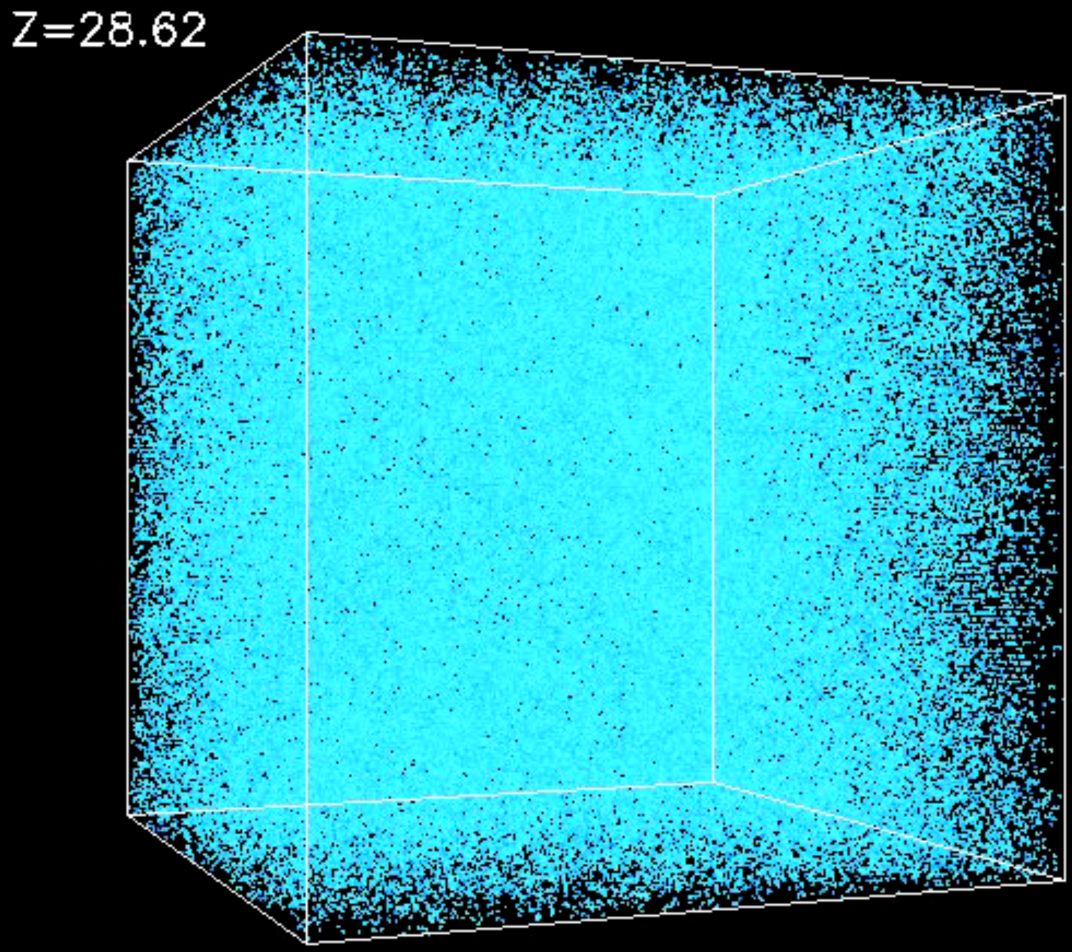
Matter Power Spectrum



adapted from Lannus et al. 2014

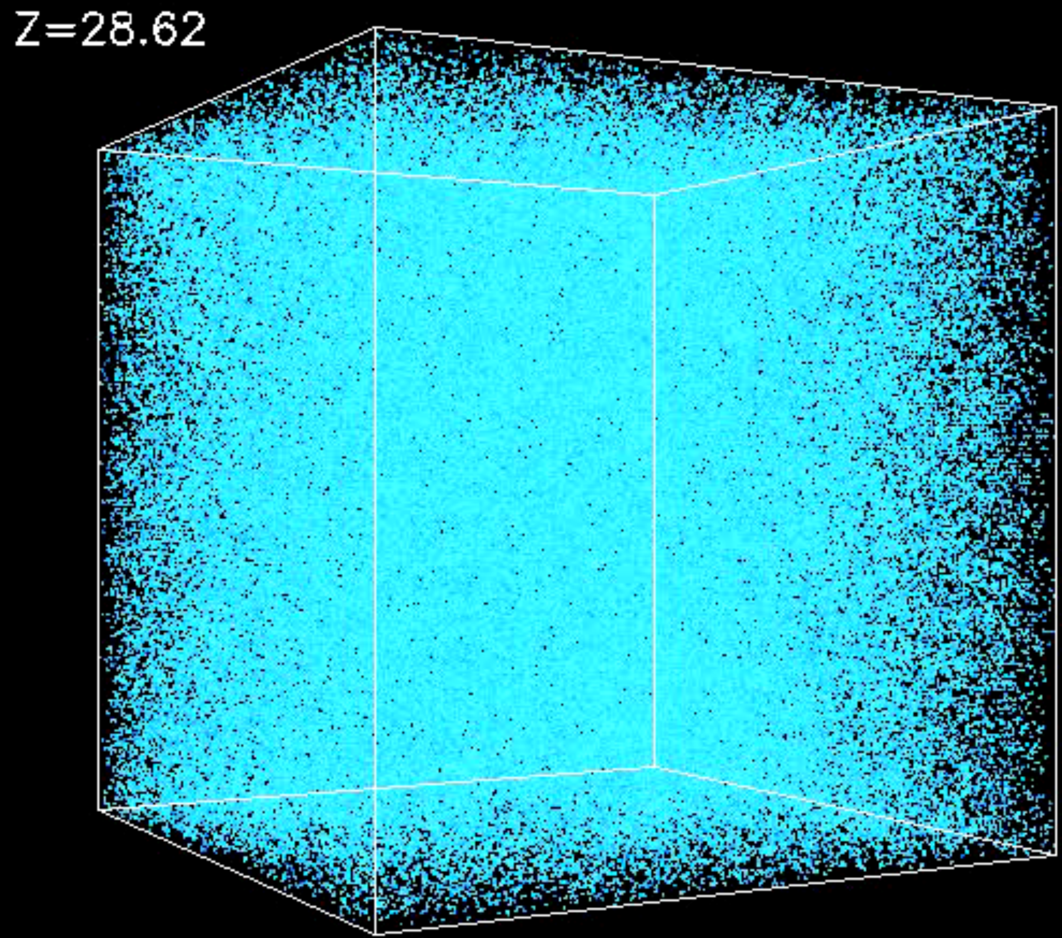
Late times: $P(k,a) \sim k^n T^2(k) D^2(a)$

Nonlinear Evolution



Kravstov et al. 2005

Nonlinear Evolution



Kravstov et al. 2005