Extra-Galactic Astronomy - I
Cosmology

IUCAA / NCRA Graduate School 2016-17

Aseem Paranjape

Part I - Lecture 6

Standard Model of Cosmology

- Radiation
- Baryons
- Cold Dark Matter
- Cosmological constant
- Spatial Curvature ≈ 0

$$E(z)^2 \equiv H(z)^2/H_0^2 = \Omega_{R0}(1+z)^4 + \Omega_{m0}(1+z)^3 + \Omega_{\Lambda 0} + \Omega_{k0}(1+z)^2$$

$$[\ \Omega_{m0} = \Omega_{b0} + \Omega_{cdm0}\ ]$$

$H_0 = 100h$ km s^{-1}Mpc^{-1}

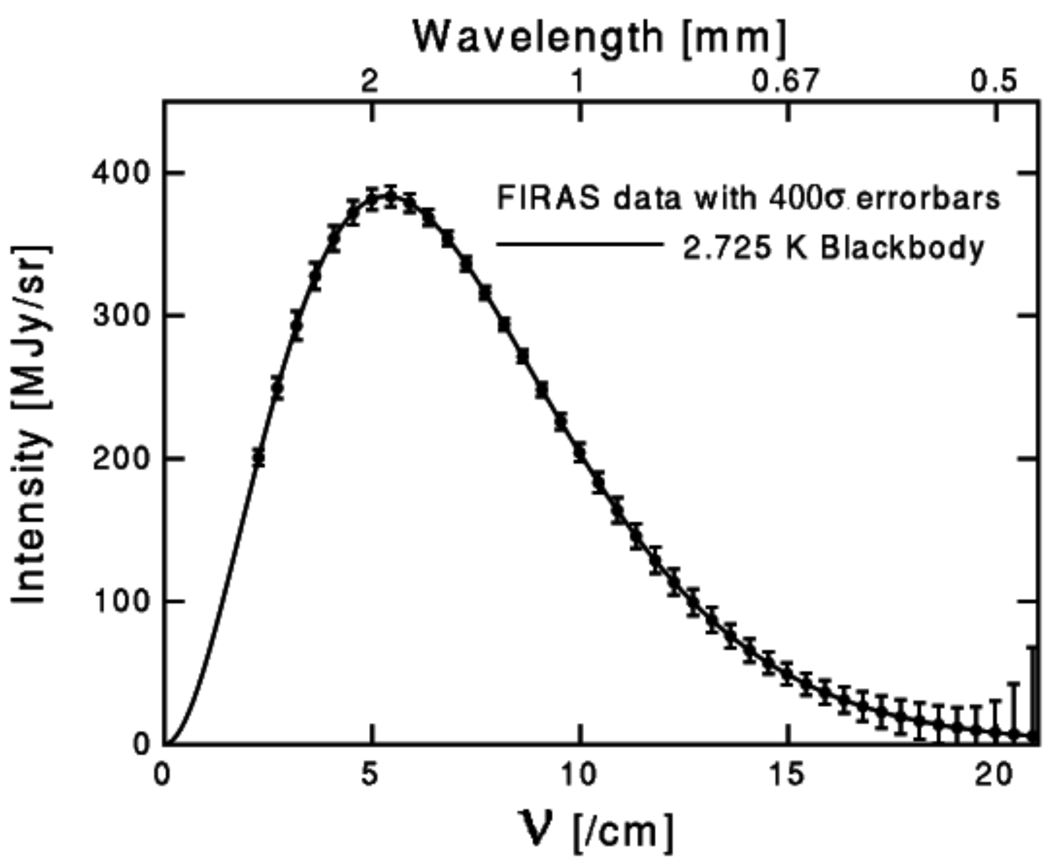
$\boldsymbol{h \approx 0.7}$ [depending on probe]

Radiation

$\rho_\gamma = (4\sigma/c)T^4$ where σ = Stefan-Boltzmann constant

CMB temperature today measured to be (Fixsen 2009)

$T_0 = 2.72548 \pm 0.00057$ K



So $\rho_{\gamma 0} = (4\sigma/c)T_0^4$

$= (4.175 \pm 0.004) \times 10^{-13}$ erg cm^{-3}

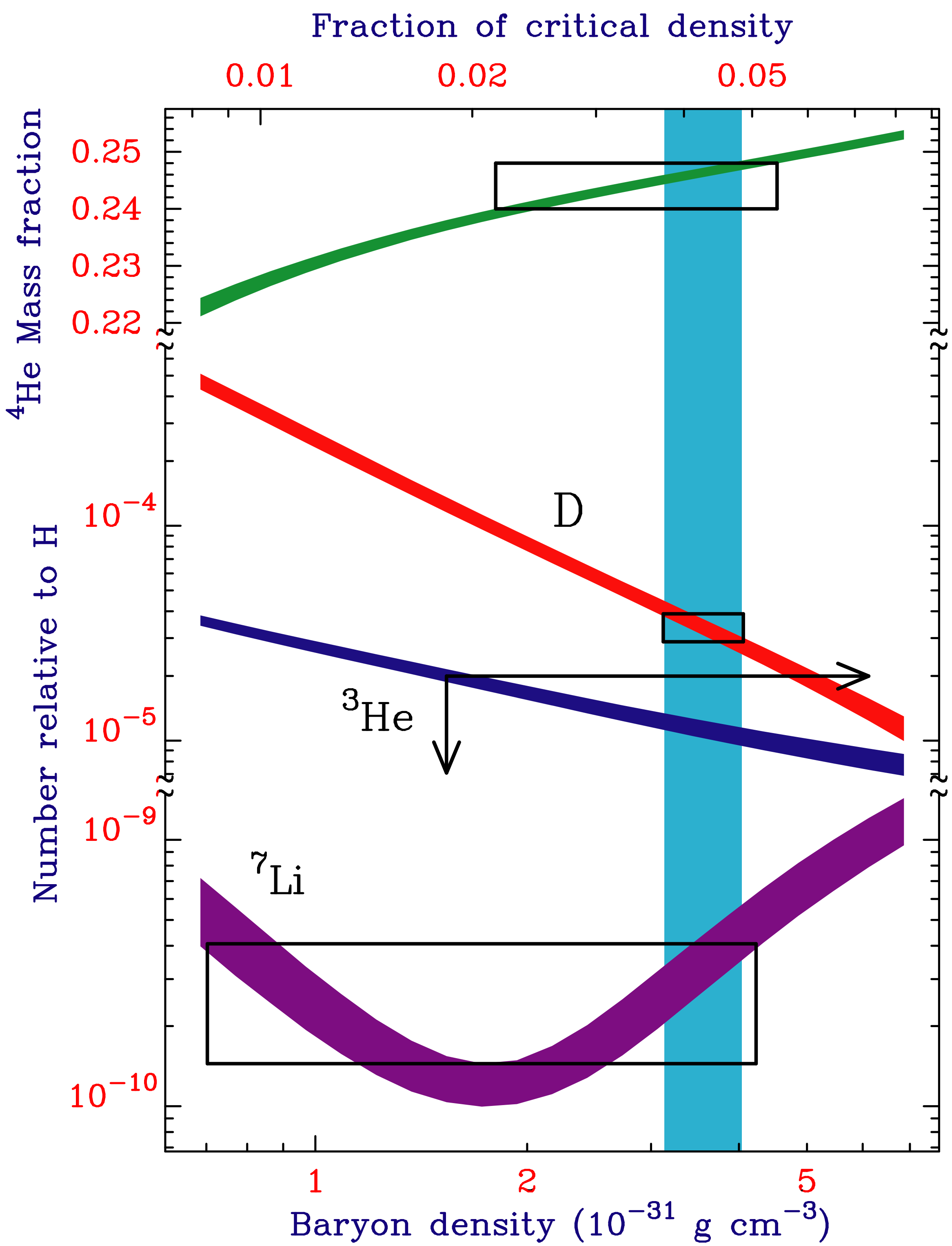
and $\rho_{crit0} = 1.688 \times 10^{-8}\, h^2$ erg cm^{-3}

$\therefore\ \Omega_{\gamma 0} h^2 = (2.473 \pm 0.002) \times 10^{-5}$

Including 3 relativistic neutrinos gives

$\Omega_{R0} h^2 = (4.158 \pm 0.003) \times 10^{-5}$

Baryons



[Plot by Wayne Hu]

Burles, Nollett, Turner (1999)

Constraint from BBN (95% C.L.)

$\rho_{b0} = (3.76 \pm 0.38) \times 10^{-31}$ g cm^{-3}

$\mathbf{\Omega_{b0} h^2 = 0.020 \pm 0.002}$

Constraint from CMB anisotropies (Planck-2015, 95% C.L.)

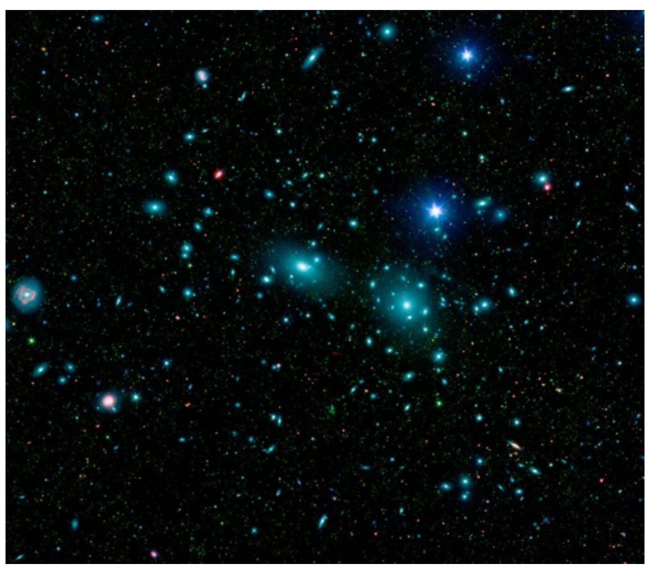
$\mathbf{\Omega_{b0} h^2 = 0.0222 \pm 0.0003}$

Cold Dark Matter

Non-baryonic component. Non-relativistic for most of cosmic history.
Dominant interaction with ordinary matter and radiation is through gravity.

Virial theorem

[Zwicky 1933;1937]



$$\langle V^2 \rangle = GM/R_{vir}$$

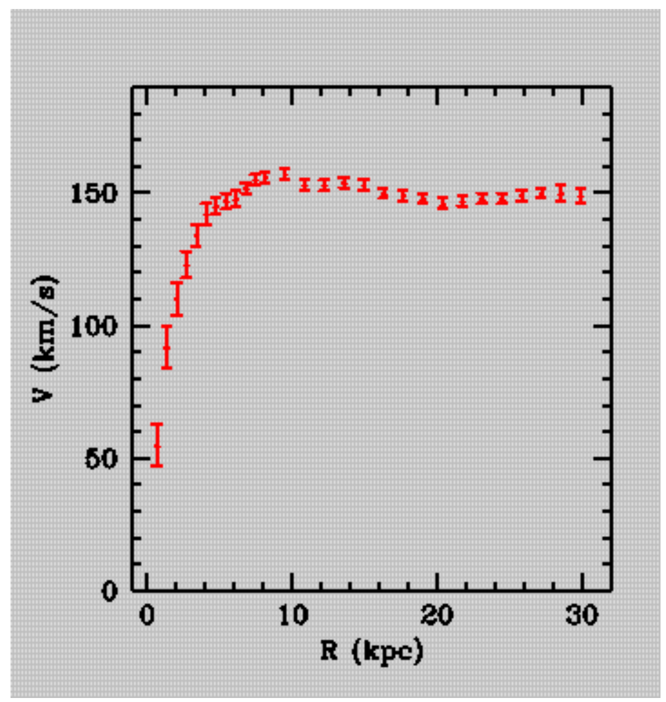
$\langle V^2 \rangle \rightarrow$ redshifts; $R_{vir} \rightarrow$ size

$M_{vir} \sim 10\ M_{gas} \sim 50\ M_{stars}$

→ Missing mass

Galaxy rotation curves

[Rubin+ 1978;1980]

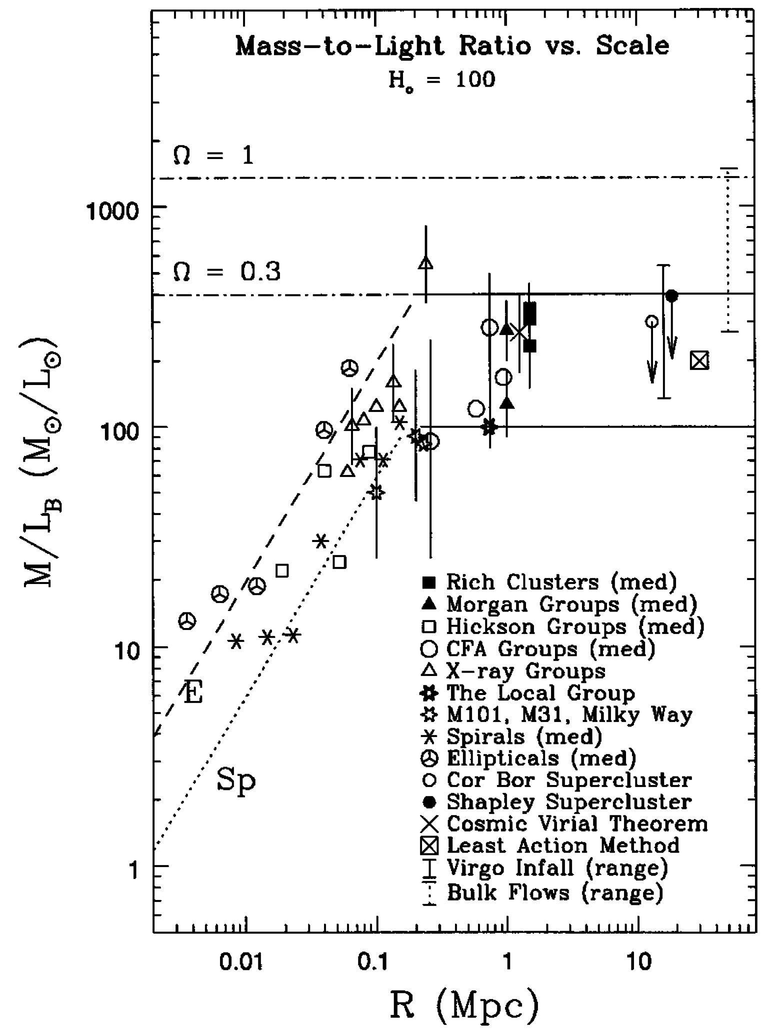


[Begeman+ 1989]

Expect $V \propto R^{-1/2}$ far from disk.
Need extra $\rho \propto R^{-2}$ to fit data.

Scale-dependent M/L

[Bahcall+ 1995;2000]



Ratio flattens at large scales.
Explained by $\Omega_{m0} \approx 0.2$-0.3

Consistent with latest CMB determination

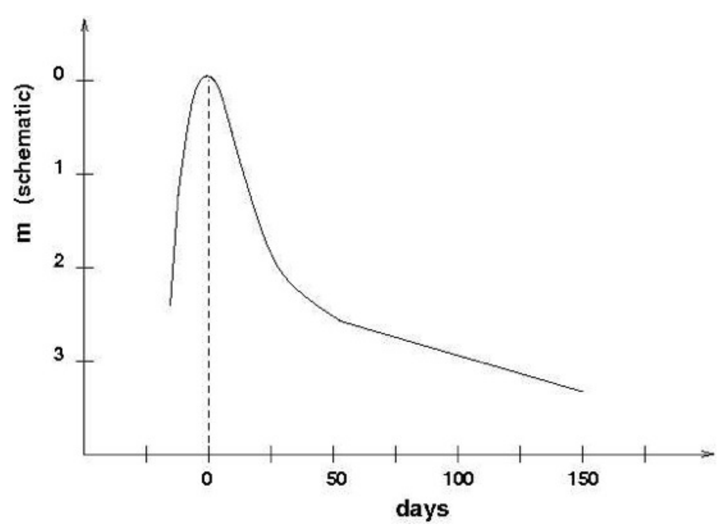
$$\Omega_{m0} = 0.316 \pm 0.009$$

Cosmological Constant Λ

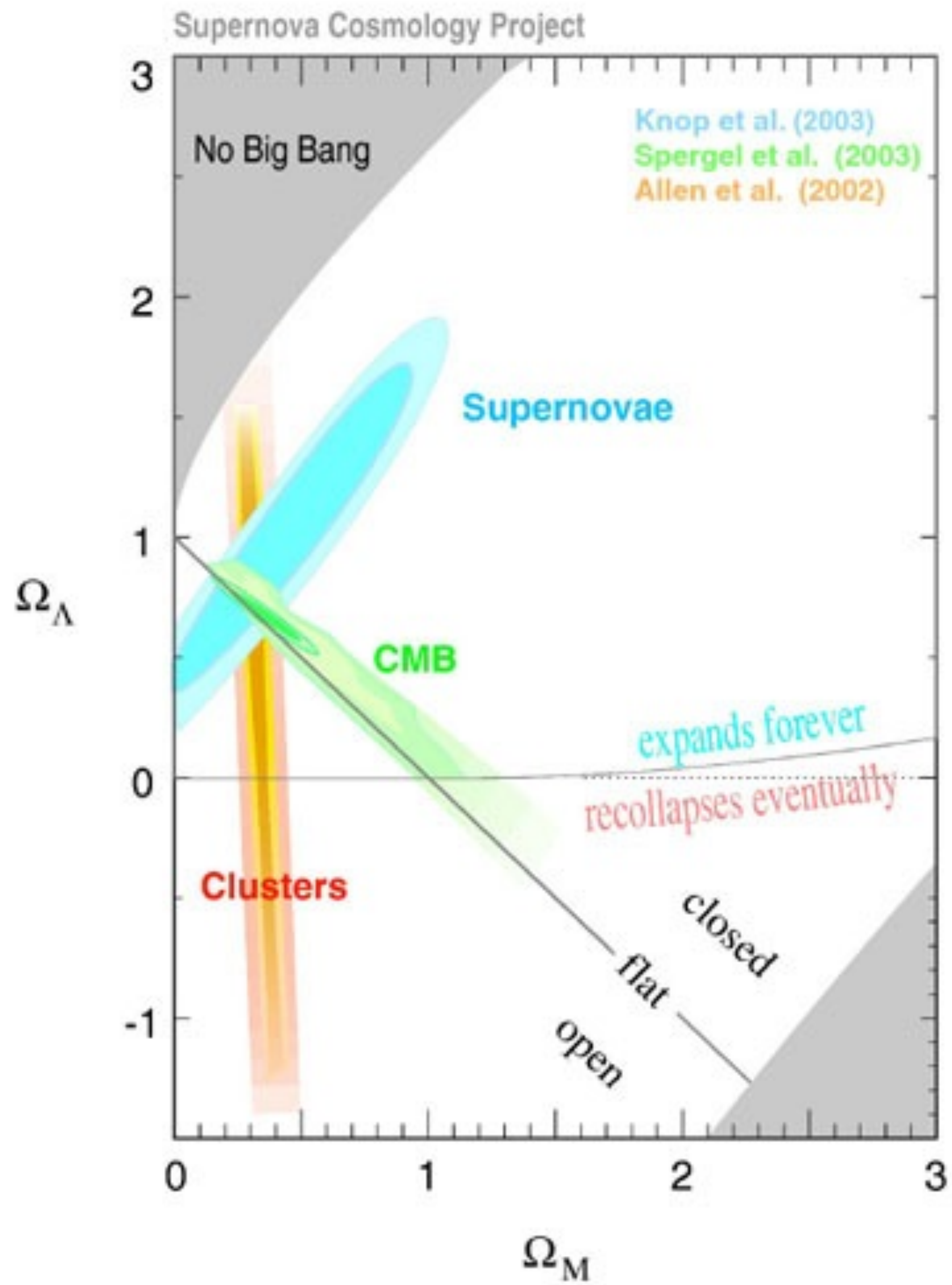
First introduced (and discarded) by Einstein, followed by a tortured history of epicycles.

Currently, cleanest evidence provided by SNe Ia cosmography which gives $q_0 \approx -0.55$ so that $d^2a/dt^2 > 0$, which requires $w < -1/3$ for at least one component.

Cosmological constant ($w = -1$) is the simplest choice consistent with data.



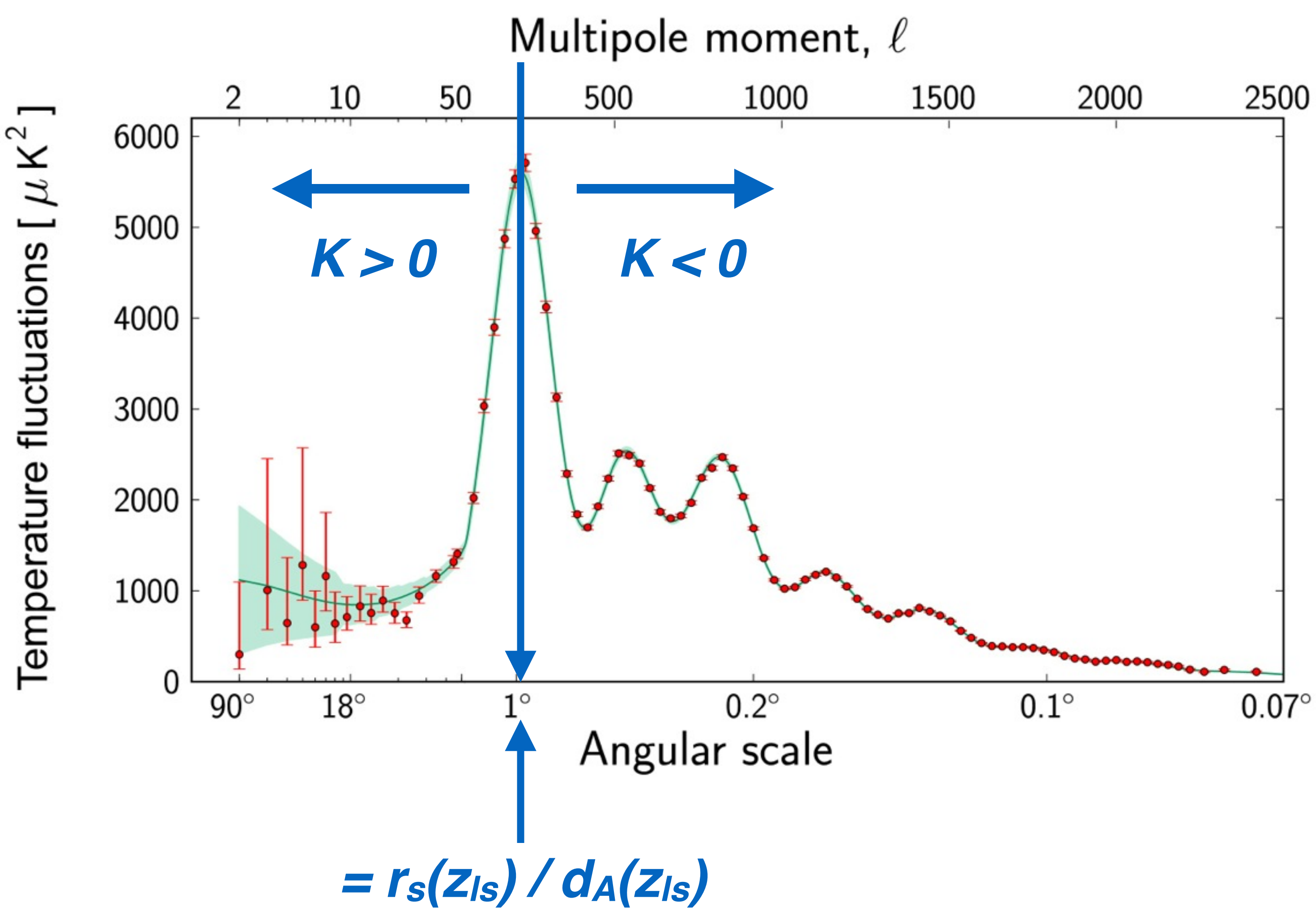
Empirical correlations between peak luminosity & light curve shape
⇒ ***standardisable*** candles



Spatial Curvature

Presence of curvature changes distances (recall expressions for $d_A(z)$ and $d_L(z)$ in terms of $S_k[\boldsymbol{\chi}(z)]$).

Longest lever arm provided by angular diameter distance to last scattering surface, best accessible via 1st peak of CMB power spectrum.

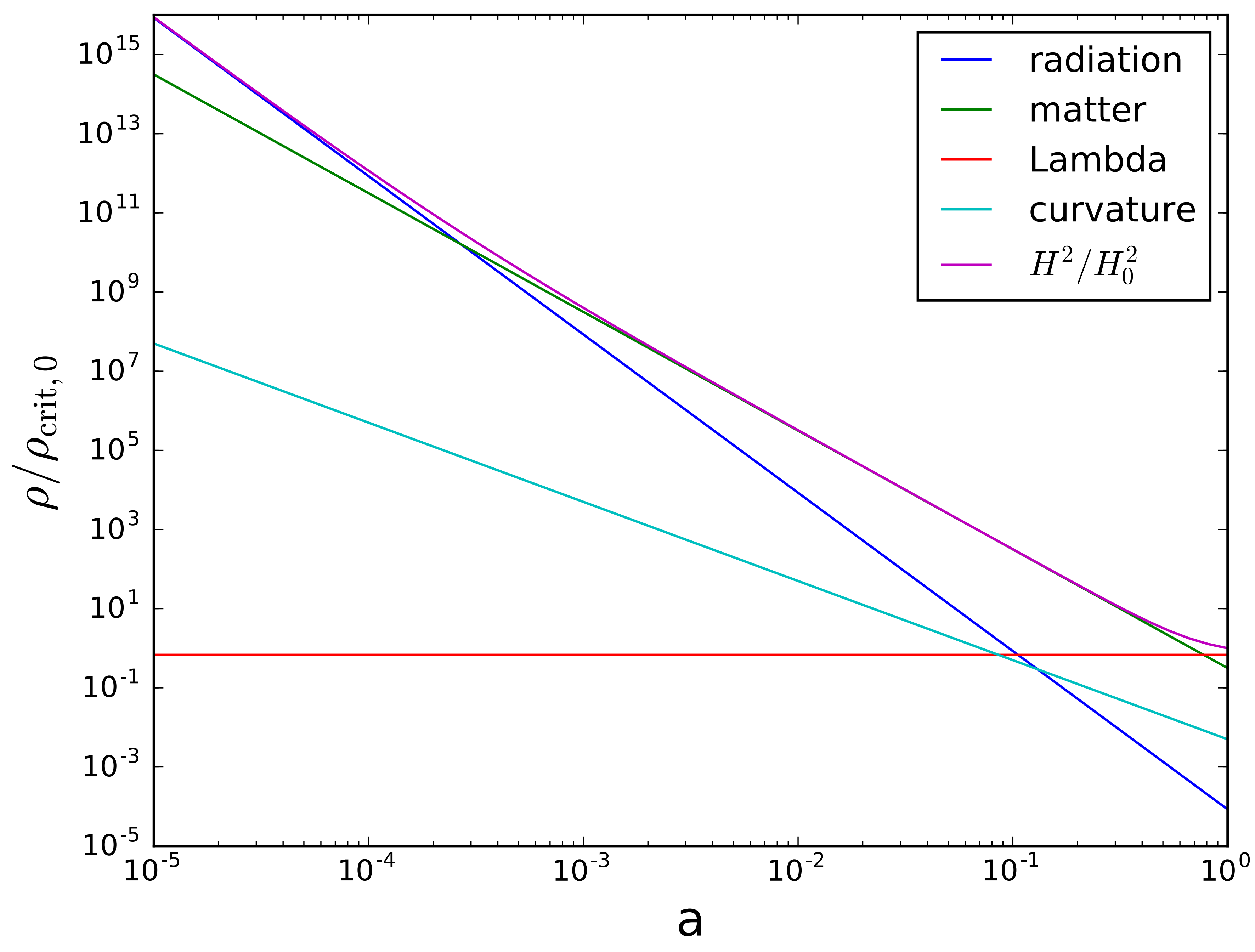


Can be strengthened by including BAO measurements [$\boldsymbol{r_s}$ at multiple $\boldsymbol{z}$].

Current constraint, assuming ΛCDM (95% C.L.)

$$\boldsymbol{\Omega_{k0} = 0.000 \pm 0.005}$$

Expansion History



Some human history…

Models for the evolving Universe

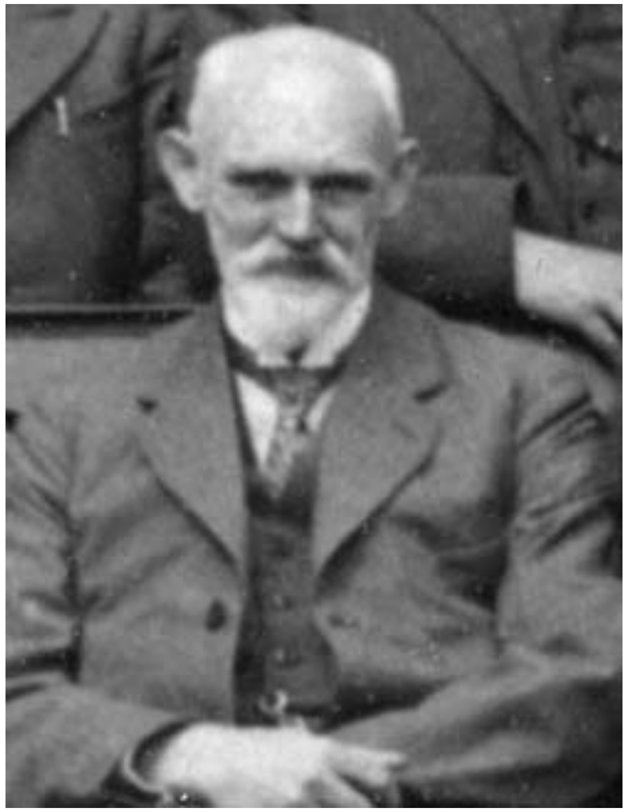
The cosmological constant Λ

1917

Matter without motion

Albert Einstein

Motion without matter



Willem deSitter

Models for the evolving Universe

Dynamical universes with matter

Alexander Friedmann

1922 Published ``closed universe" model, with and without **Λ**. Einstein claimed Friedmann's algebra was wrong, but later retracted (1923).

1924 Published ``open universe" model. Same year as Hubble's observations of Cepheids. Died 1925, aged 37.

Models for the evolving Universe

Dynamical universes with matter

Georges Lemaître

1924 - 1936

Lemaître's theoretical contributions

- In 1927 paper, constructed a solution of Friedmann's equation with nonzero Λ. Derived the linear distance-redshift relation. Explained observed redshifts in terms of an expanding Universe rather than as Doppler shifts.

- 1931: Constructed yet another solution, the coasting universe, with Λ tuned to give a long, nearly static phase, hence solving the age problem.

- Extrapolated this solution to early times, suggested notion of a beginning: seed of Big Bang cosmology. His views remained unfashionable well into the 1950's.

- 1934: Suggested notion of Λ as arising from vacuum fluctuations. Later rigorously calculated by Zel'dovich (1968) in QFT framework (but very sensitive to high-energy cutoff).