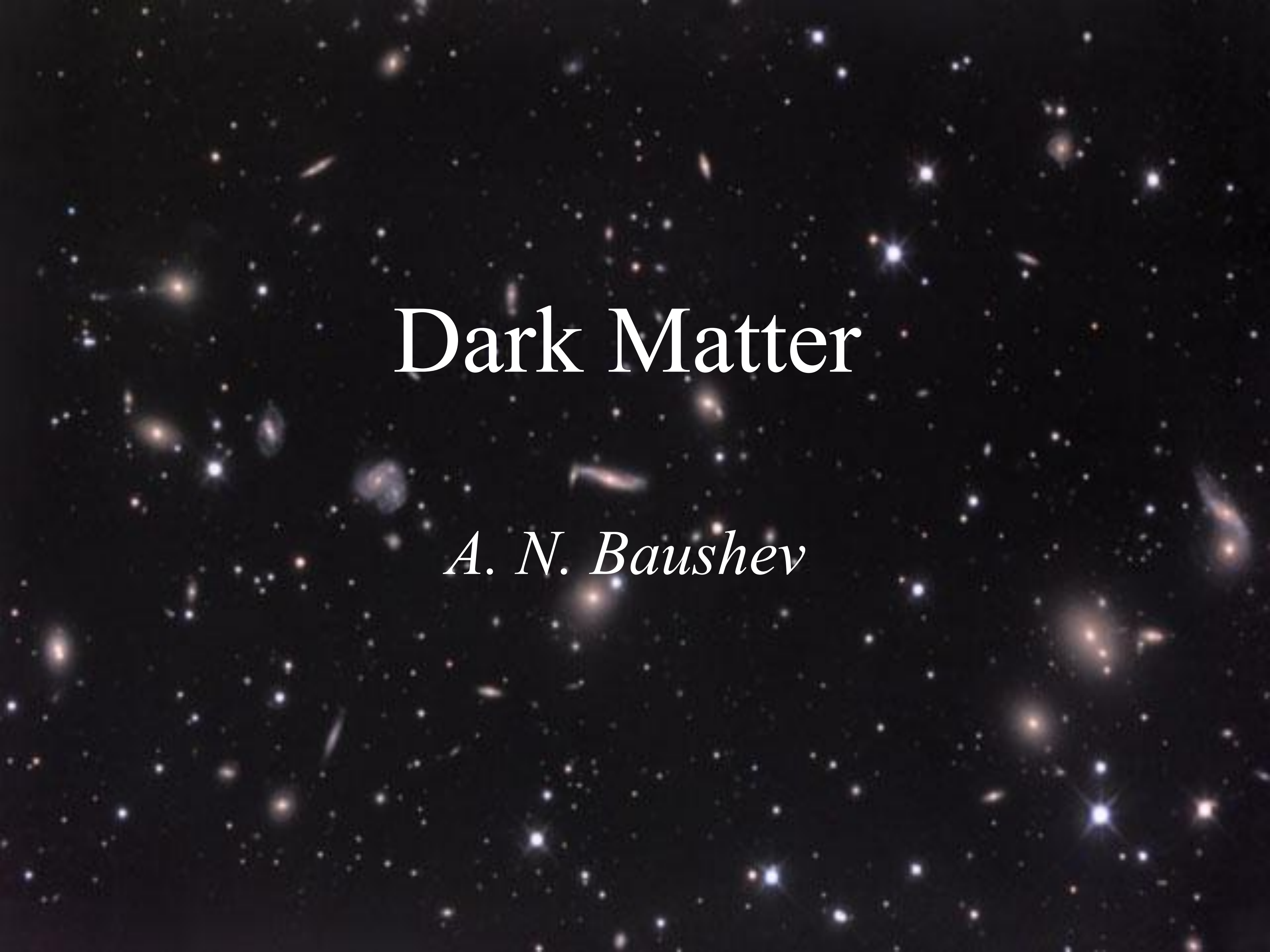


Dark Matter

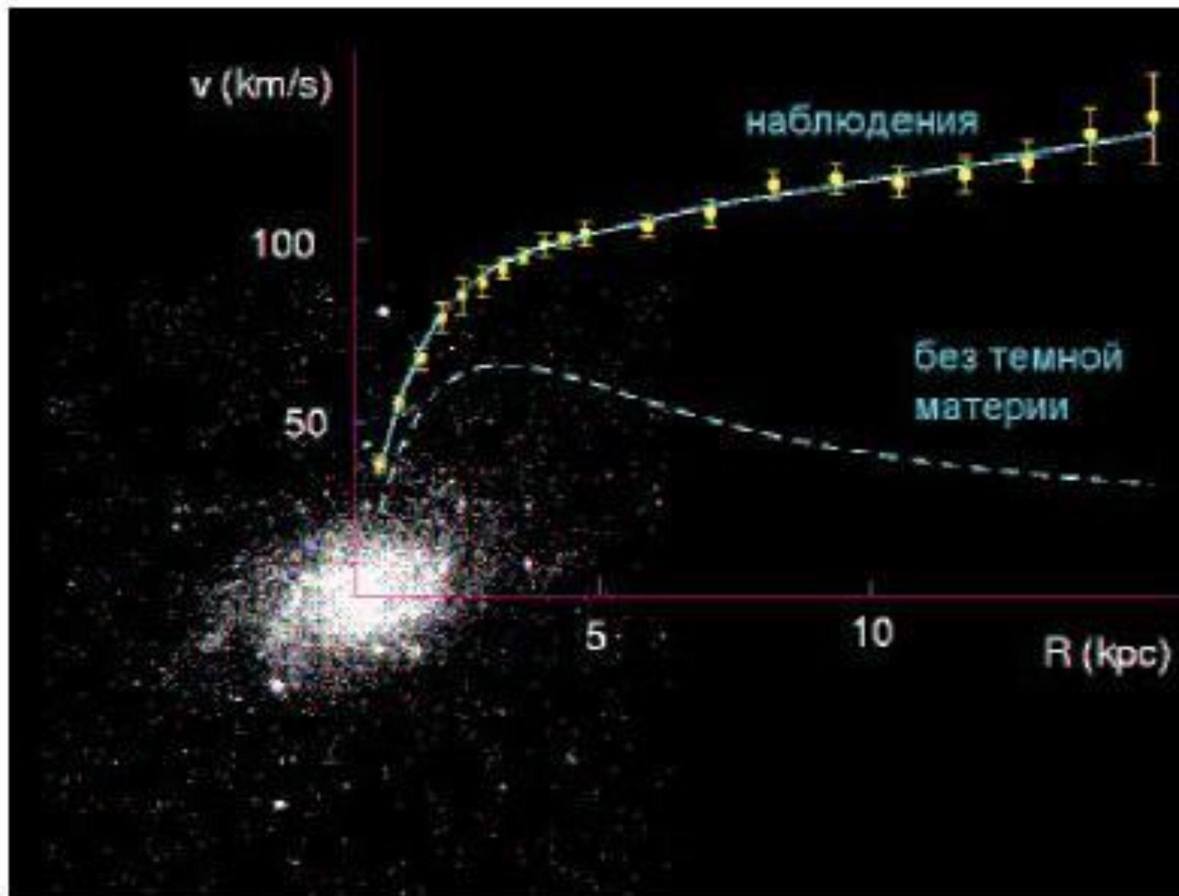
A. N. Baushev

- 1933, F.Zwicky

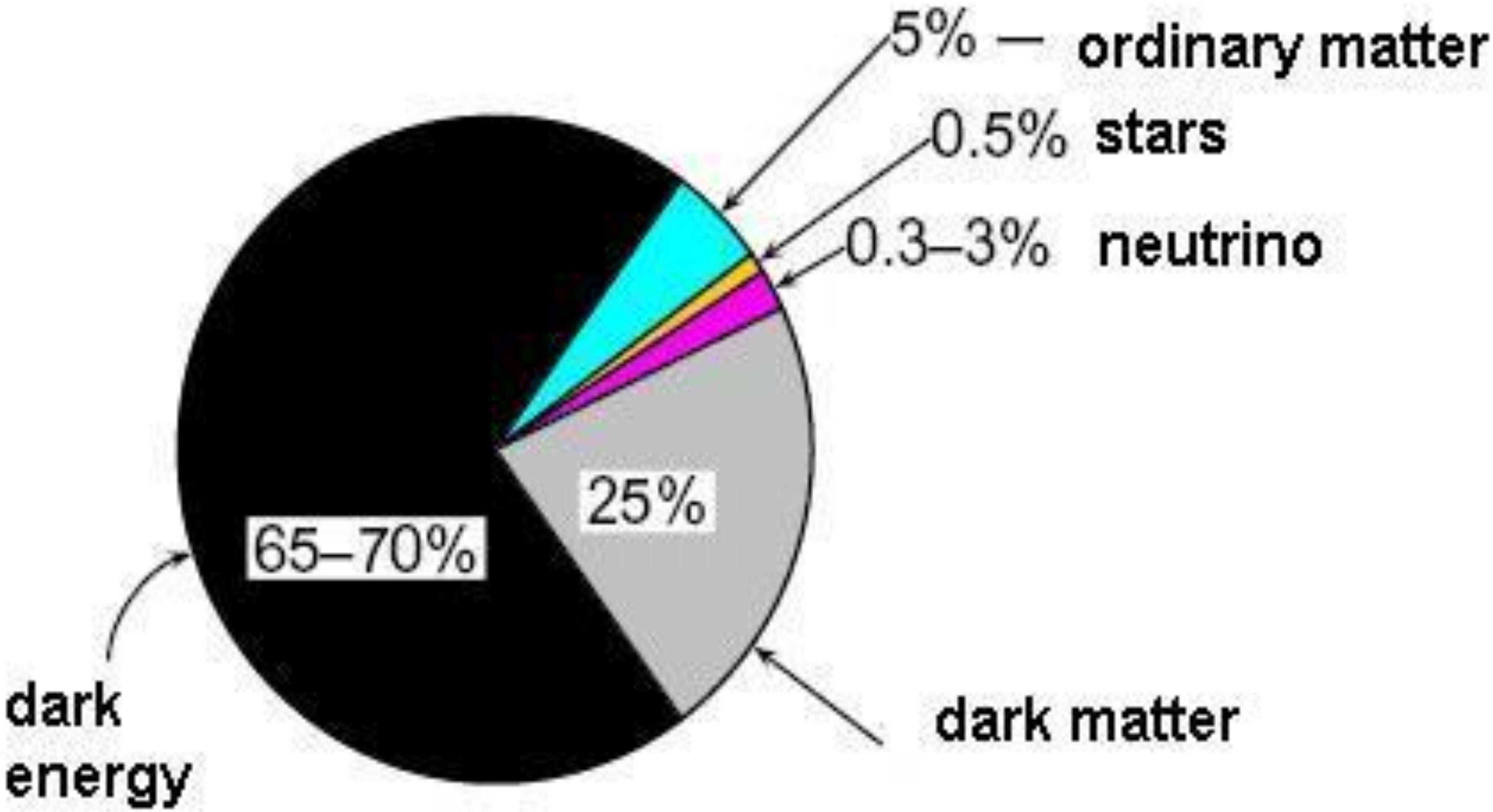
V.Rubin (optics)
A.Bosma (radio)

$$M(r) \approx \frac{r\,\upsilon_r^{\,2}(r)}{k}$$

$$\upsilon_r \propto r^{-1/2}$$



- Gas
- Star evolution remnants
- Jupiters
- Modified gravity



5% — ordinary matter
0.5% stars
0.3–3% neutrino
25%
65–70%
dark matter
dark
energy

Friedmann universes

$$ds^2 = dt^2 - a^2(t)\left[d\chi^2 + \chi^2(d\varsigma^2 + \sin^2\varsigma\, d\xi^2)\right]$$

$$ds^2 = dt^2 - a^2(t)\left[d\chi^2 + \sin^2\chi\,(d\varsigma^2 + \sin^2\varsigma\, d\xi^2)\right]$$

$$ds^2 = dt^2 - a^2(t)\left[d\chi^2 + \mathrm{sh}^2\chi\,(d\varsigma^2 + \sin^2\varsigma\, d\xi^2)\right]$$

$$ds^2 = dt^2 - a^2(t)\,dl^2 \qquad ds^2 = dt^2 - dl^2$$

Friedmann equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{a^2}$$

$$\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + p) = 0$$

Equation of state

$$p = \alpha\rho$$

1) Relativistic matter

$$T^{ik} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

$$p = \frac{1}{3}\rho \quad \rightarrow \quad \alpha = \frac{1}{3}$$

2) Non-relativistic matter

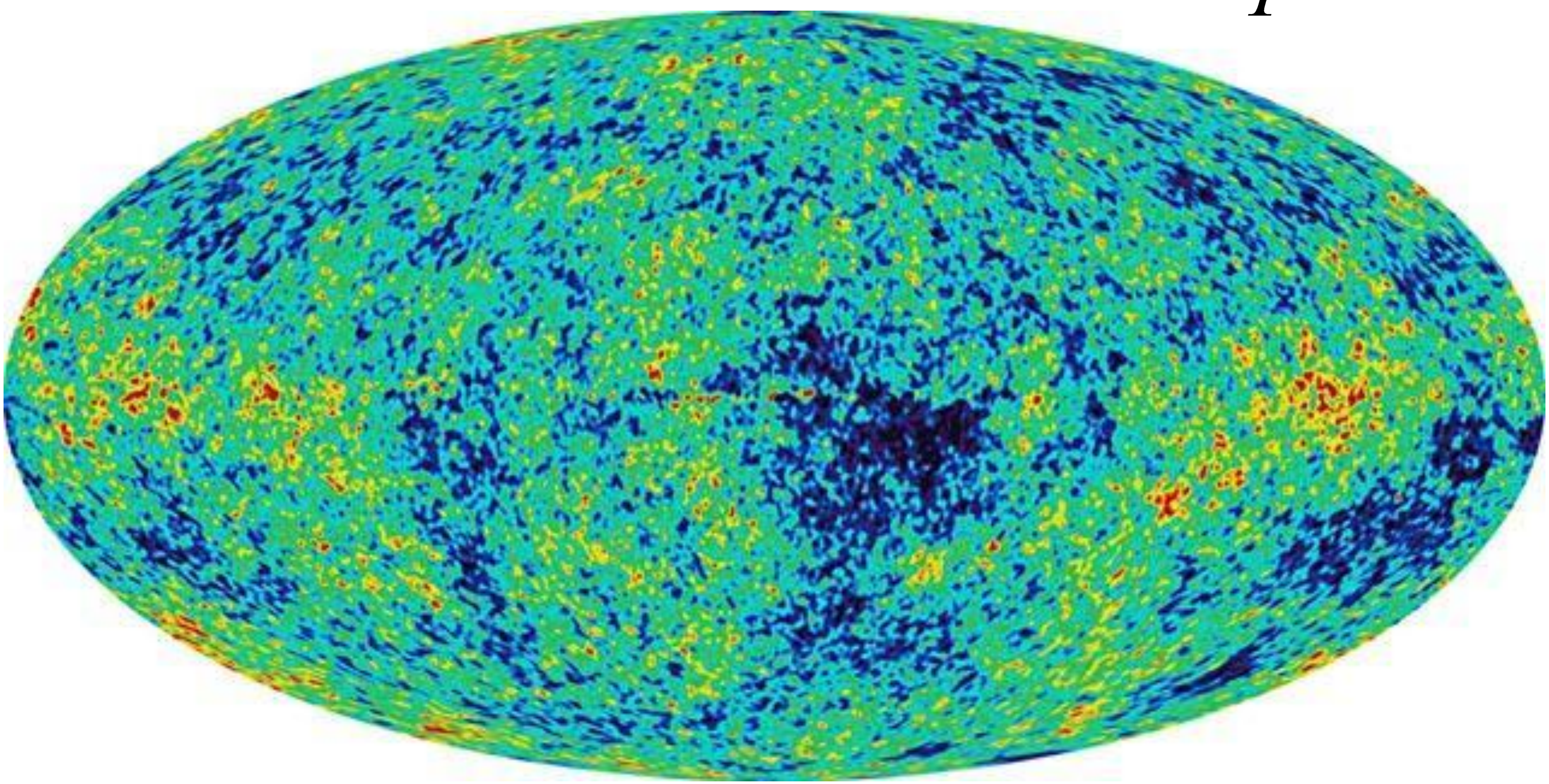
$$p = 0 \quad \rightarrow \quad \alpha = 0$$

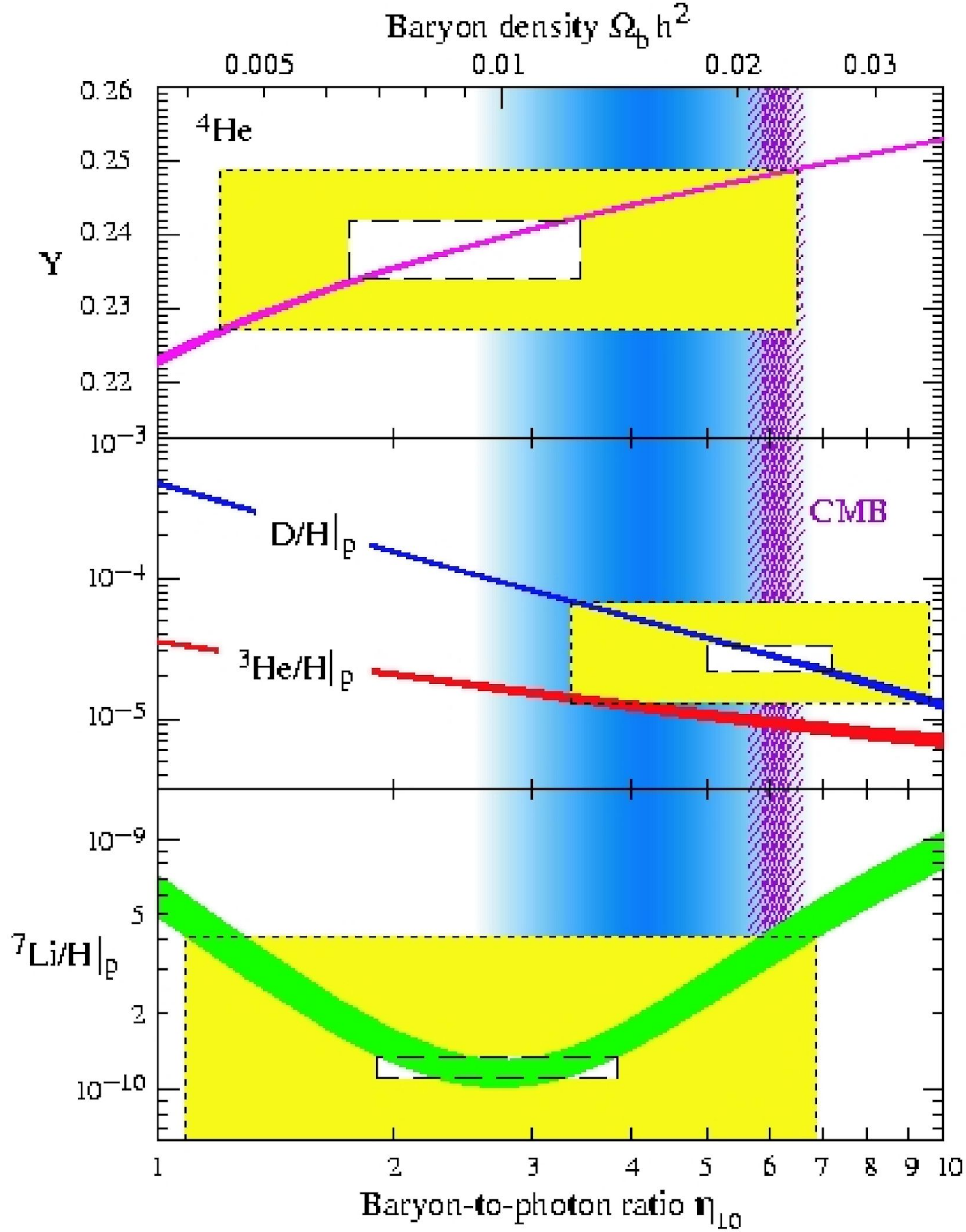
3) The cosmological constant

$$p = -\rho \quad \rightarrow \quad \alpha = -1$$

Relic radiation anisotropy

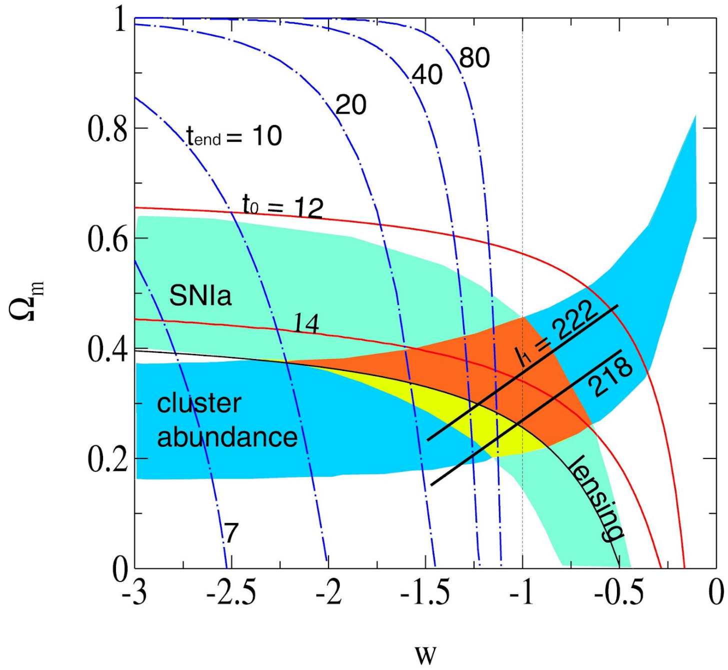
$$\frac{\delta T}{T} \sim 10^{-5}$$





Baryon density $\Omega_b h^2$
0.005
0.01
0.02
0.03
^{4}He
Y
0.26
0.25
0.24
0.23
0.22
10^{-3}
10^{-4}
10^{-5}
D/H|p
^{3}He/H|p
CMB
10^{-9}
5
^{7}Li/H|p
2
10^{-10}
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio η_{10}

Dark matter vs. Dark energy



$$p = \alpha\rho$$

$$p = -\rho$$

$$\frac{dp}{dr} = -\frac{(p+\rho)(m+4\pi r^3 p)}{r(r-2m)}$$

Candidates

$$\langle \sigma \upsilon \rangle \approx \frac{3\times10^{-27}\, cm^3 s^{-1}}{\Omega_\chi h^2} \qquad \Omega_\chi \simeq 0.25, \quad h \simeq 0.7$$

1) Weakly Interacting Massive Particles (WIMP)

2) Extremely weakly interacting particles (EWIP)

3) Low-massive black holes

4) Something else

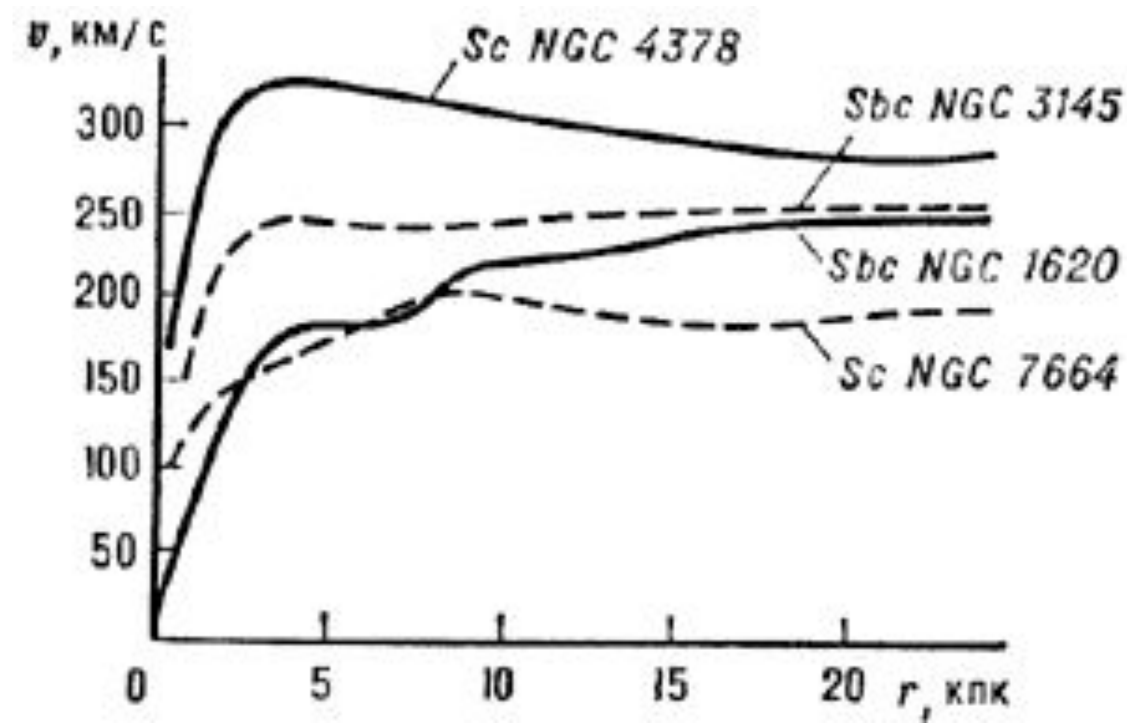
Dark matter structure

$$\square\ 0.3\,\frac{GeV}{cm^3}$$

$$60\,GeV$$

$$\square\ 0.005\,cm^{-3}$$

$$\upsilon_r \approx const$$



$$M(r) \propto r$$

$$n(r) \propto \rho(r) \propto r^{-2}$$

$$n(r) \propto \rho(r) \propto r^{-1.8}$$

$$M = \int \rho(r)\, 4\pi r^2 dr \propto \int r^{0.2} dr$$

$$N = \int \frac{1}{2} \langle \sigma \upsilon \rangle n^2\, 4\pi r^2 dr \propto \int r^{-1.6} dr$$

Relic radiation anisotropy

$$\frac{\delta T}{T} \sim 10^{-5}$$