Dark Matter

ASTR 333/433

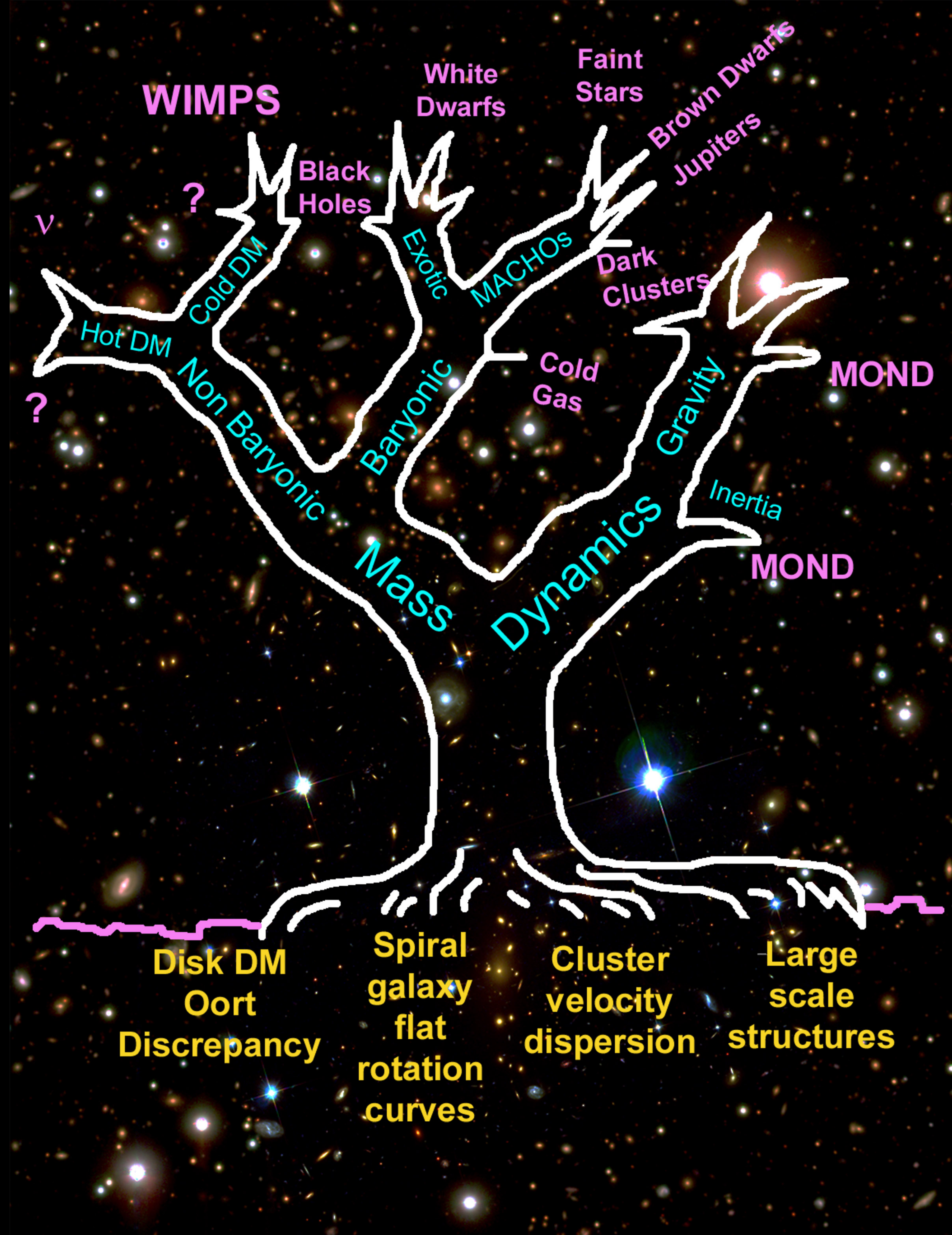
TODAY

WIMP dark matter

Power spectra

Homework 3

Due



CMB temperature fluctuations directly related to density fluctuations

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\rho}{\rho} \sim 10^{-5}$$

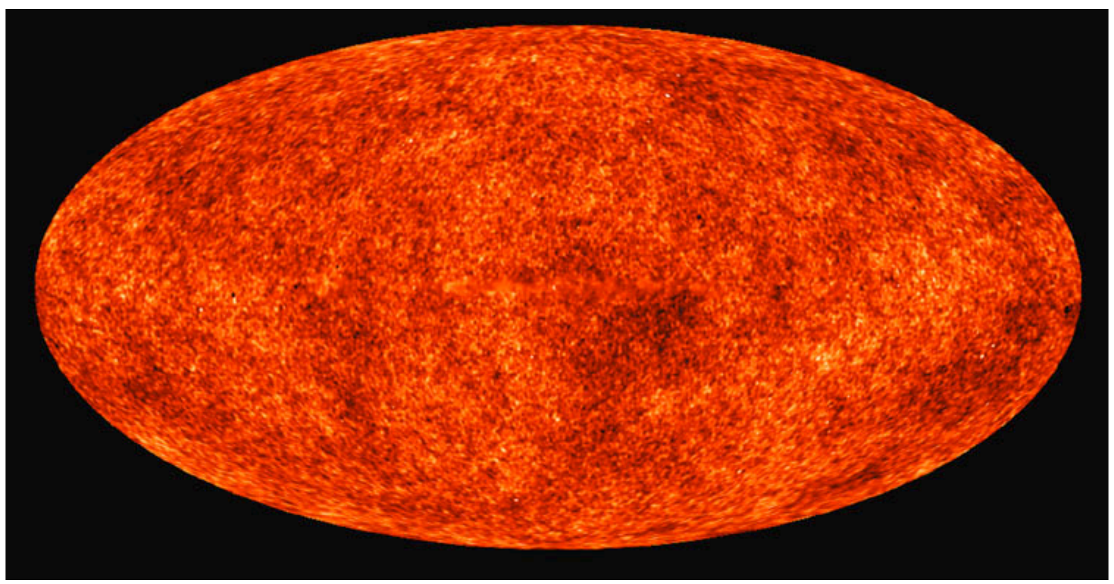
Basic problem:
not enough time for structure to grow.

$$\delta \propto a = 1091 \text{ since } z = 1090$$

Gravity will grow the observed large scale structure, but it works slowly. Can't get here from there in a Hubble time: need a factor of 100,000 but only get 1,000. Cold dark matter speeds up the process while not overproducing the temperature fluctuations.

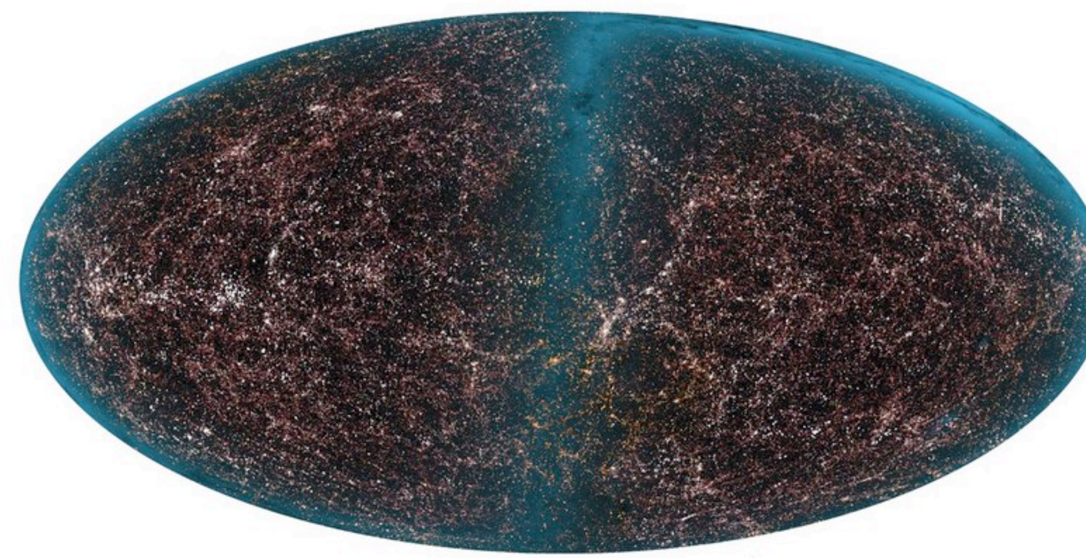
There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

$t = 3.8 \times 10^5$ yr



very smooth: $\delta\rho/\rho \sim 10^{-5}$

$t = 1.4 \times 10^{10}$ yr



very lumpy: $\delta\rho/\rho \sim 1$

$$\delta\rho/\rho \propto a \propto t^{2/3}$$

$a \propto t^{2/3}$ scale factor behaves like $\Omega_m = 1$ in the early universe

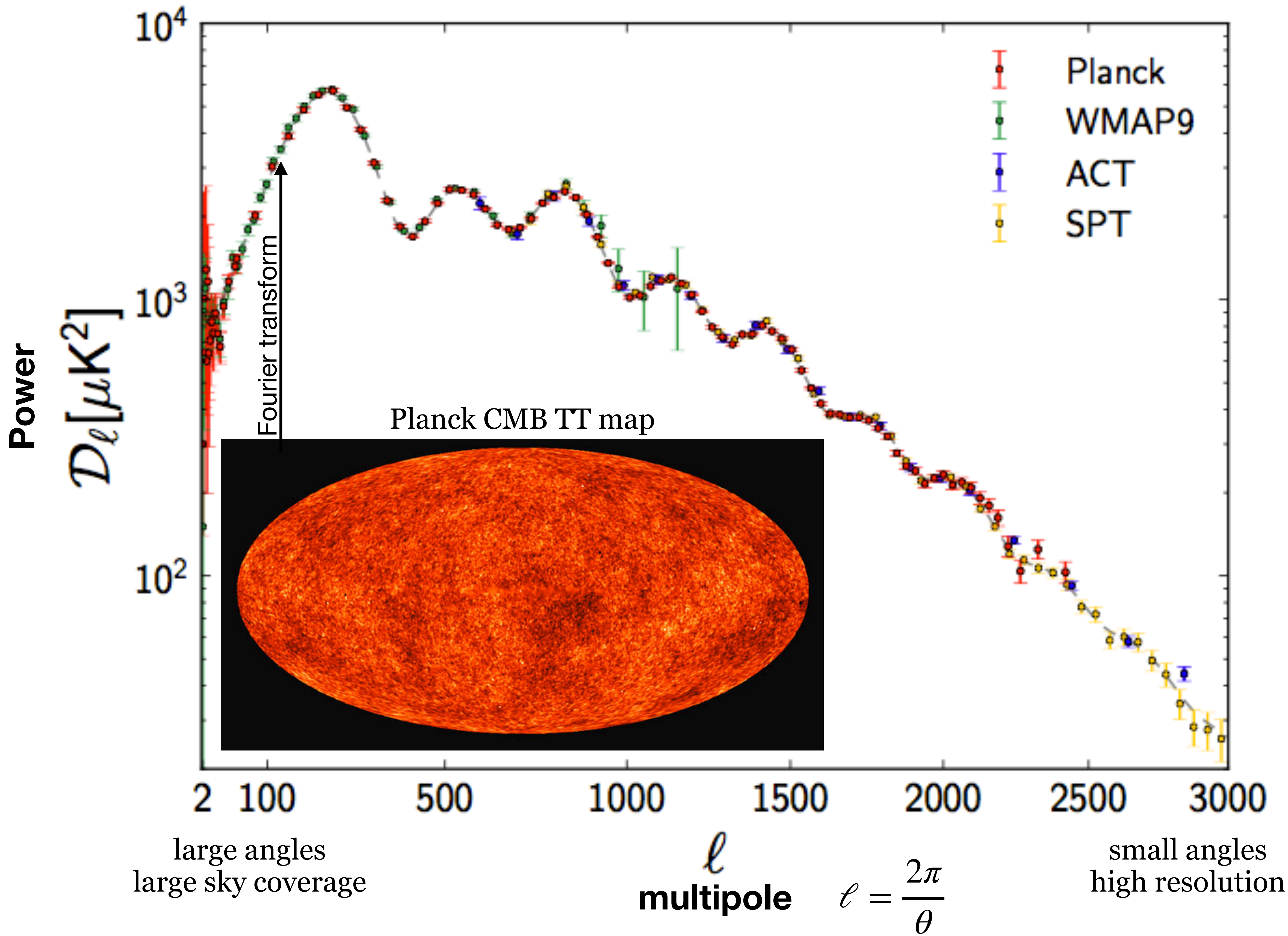
CMB temperature fluctuations directly related to density fluctuations

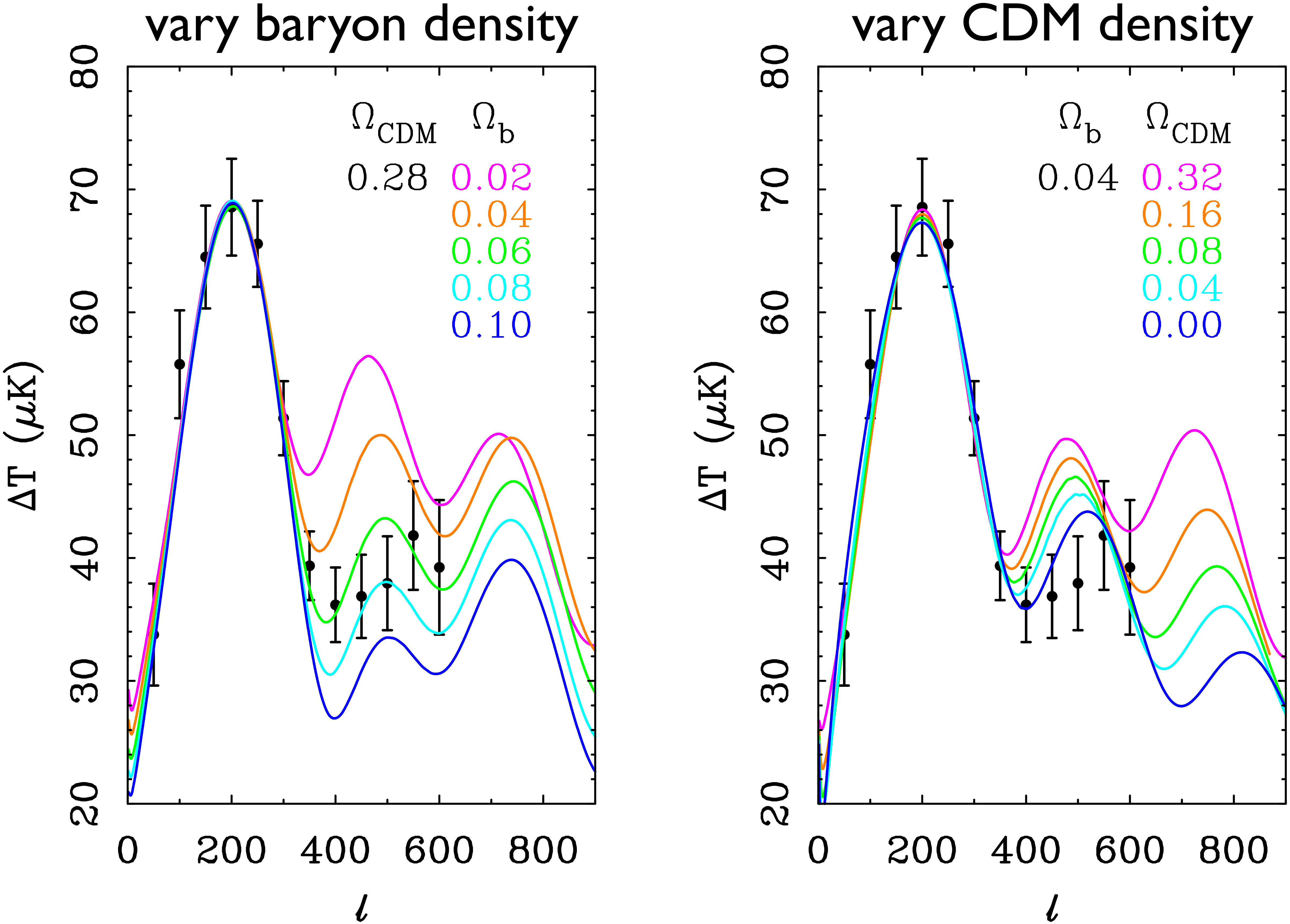
$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\rho}{\rho}$$

Fits to the acoustic power spectrum of the CMB strongly constrain cosmic parameters, assuming GR is adequate to describe the universe, which requires accepting the auxiliary hypotheses of dark matter and dark energy.

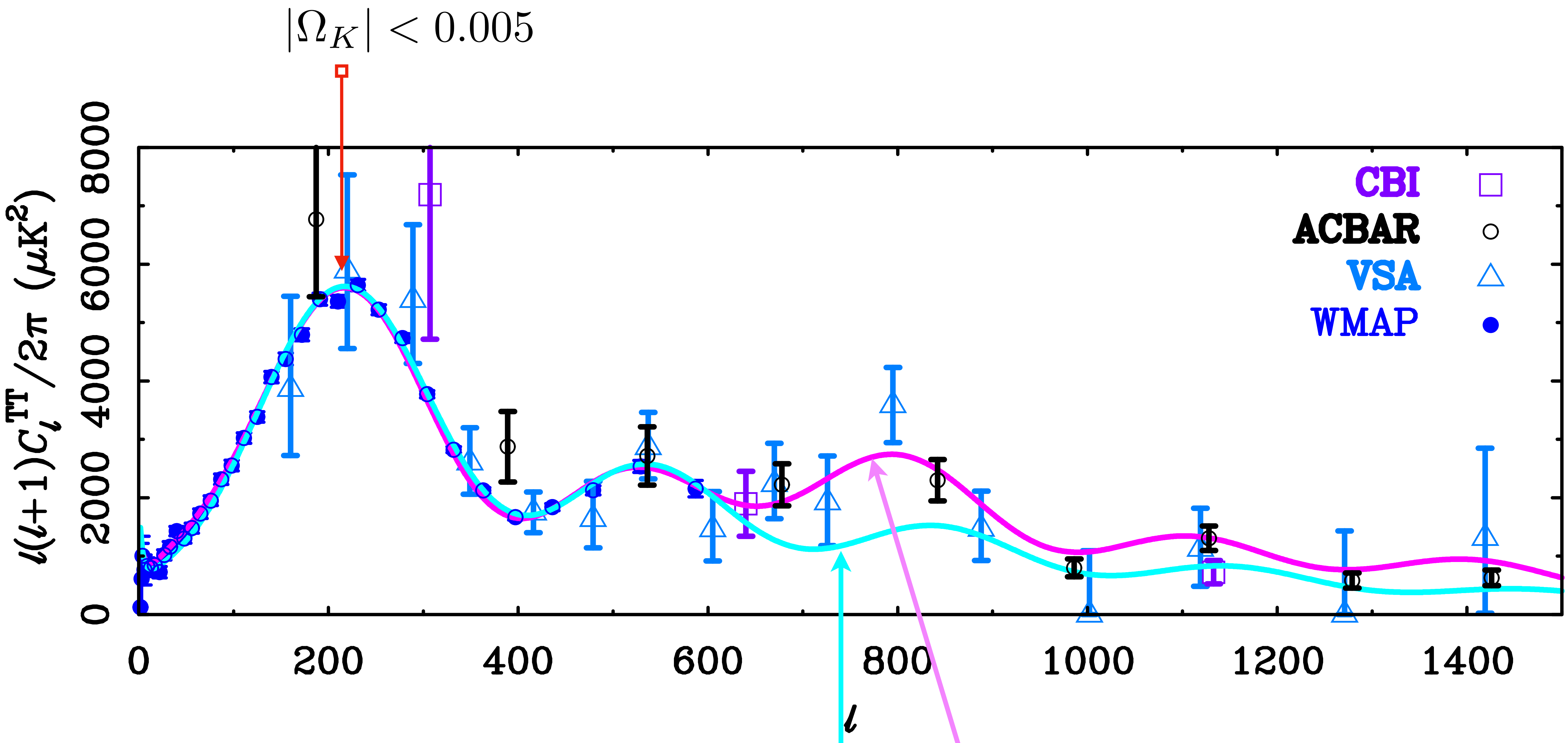
http://space.mit.edu/home/tegmark/movies.html

Acoustic power spectrum of the cosmic microwave background at z = 1090





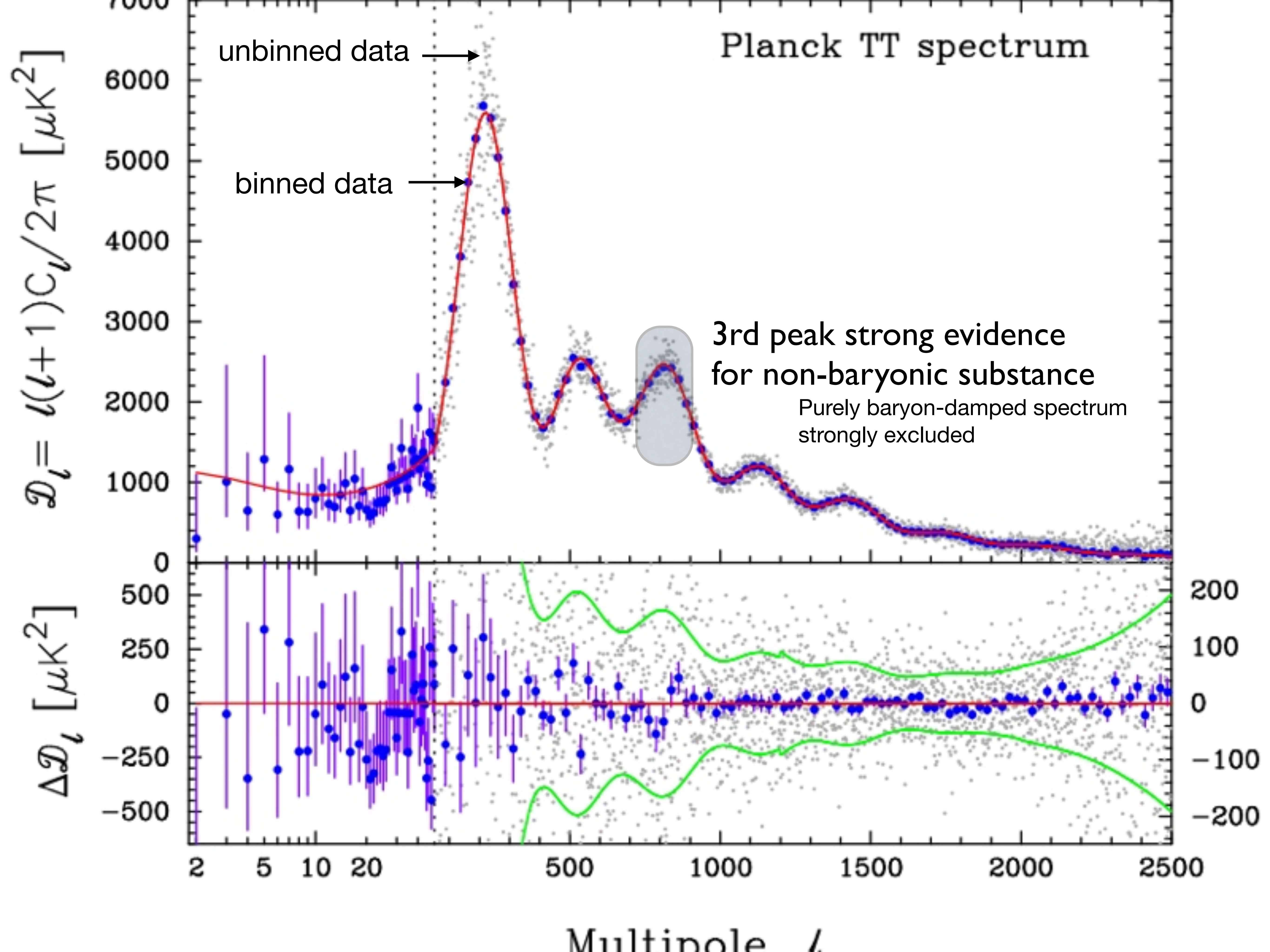
CMB power spectra



Poisson equation for acoustic oscillations in the early universe $(\delta_i \ll 1)$

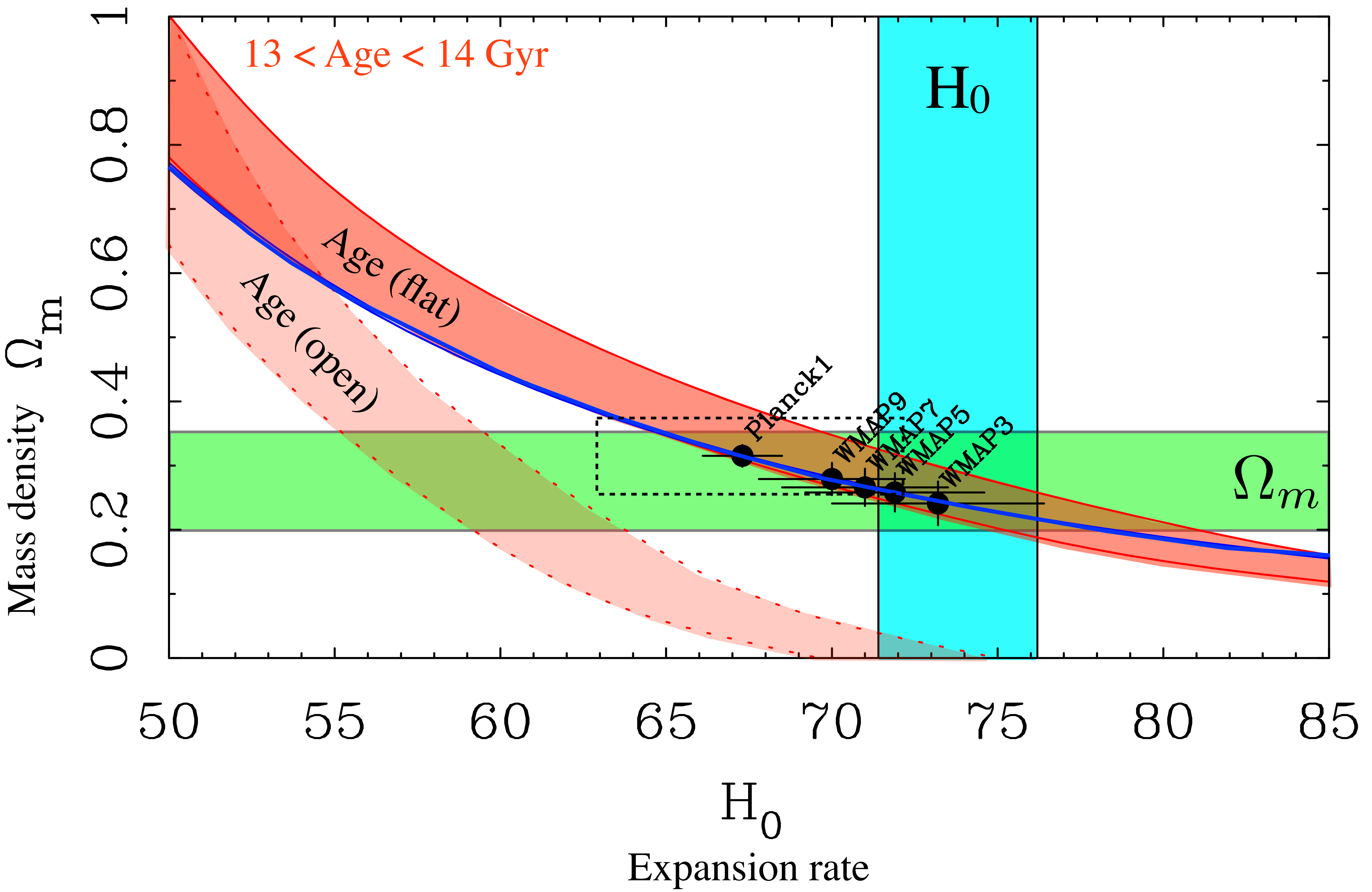
$$k^2\Phi = 4\pi G(\rho_\gamma\delta_\gamma + \rho_b\delta_b + \rho_{\rm CDM}\delta_{\rm CDM})$$

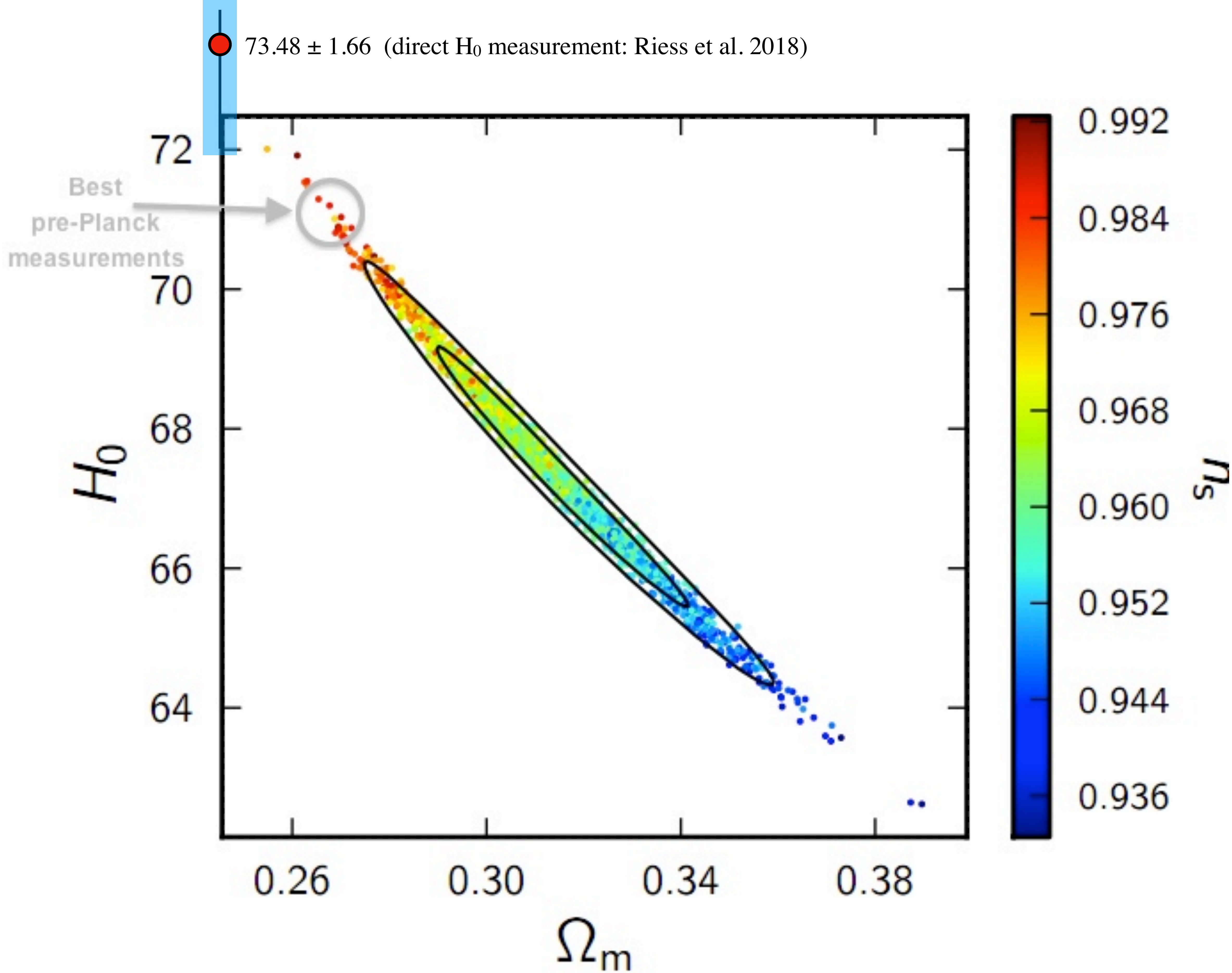
baryons a net drag **CDM a net forcing term**



Planck TT spectrum
unbinned data
binned data
3rd peak strong evidence
for non-baryonic substance
Purely baryon-damped spectrum
strongly excluded
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ

Planck constraint: $\Omega_m h^3 = 0.0959 \pm 0.0006$





73.48 ± 1.66 (direct H0 measurement: Riess et al. 2018)
Best
pre-Planck
measurements
72
70
68
66
64
H0
0.26
0.30
0.34
0.38
Ωm
0.992
0.984
0.976
0.968
0.960
0.952
0.944
0.936
ns

"Cosmologists are often wrong, but never in doubt"

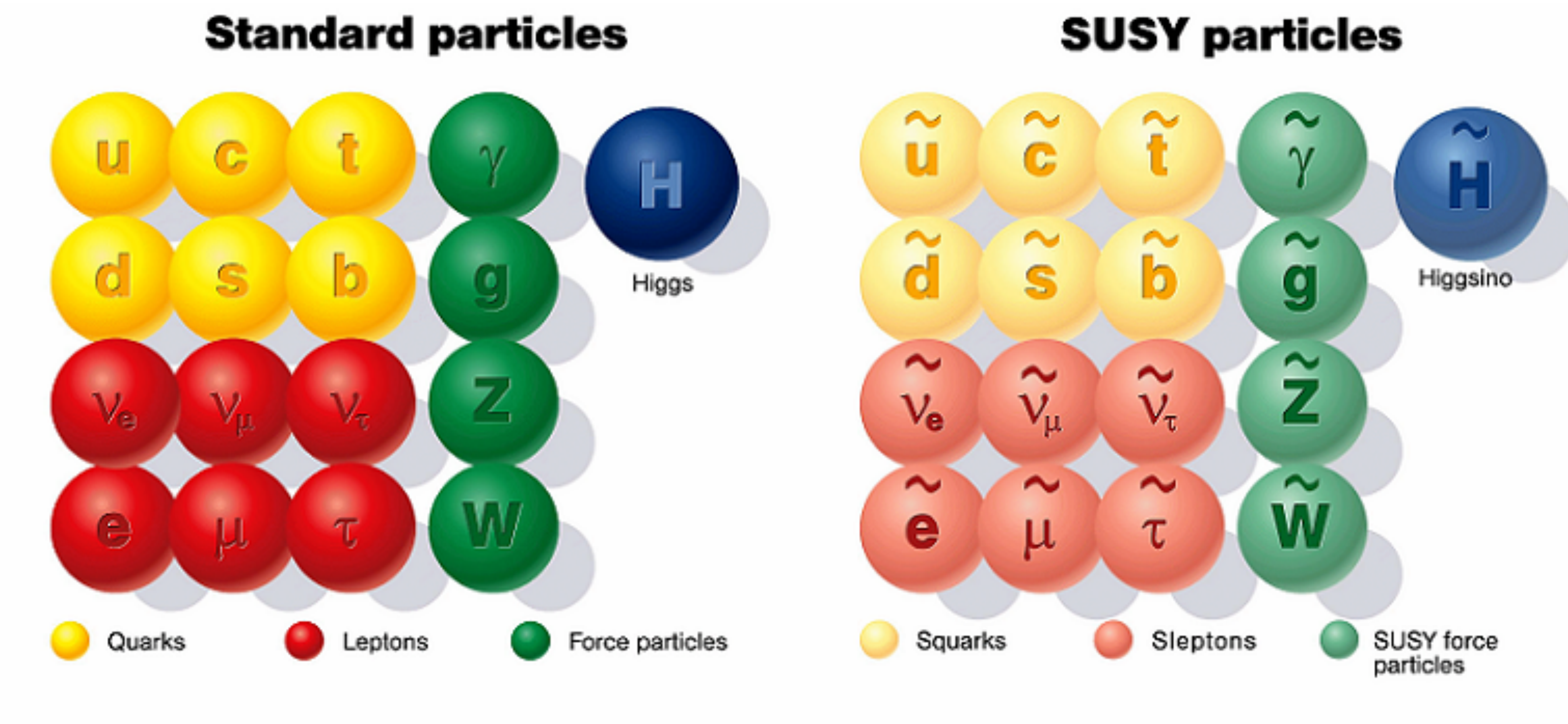
\- Lev Landau

Things we know for sure in cosmology:

quantity	c. 1990	WMAP5 2008	Planck 2018
Ω_m	1	0.258±0.027	0.315±0.007
Ω_Λ	0	0.742	0.685
$\Omega_b h^2$	0.0125	0.02273 ±0.00062	0.02237 ±0.00015
H_o	50	71.9±2.7	67.36±0.54
dark matter	CDM	CDM	CDM

STANDARD MODEL OF ELEMENTARY PARTICLES

Supersymmetry: a hypothetical new symmetry of nature



Every Standard Model particle has a superpartner.
The lightest stable massive superparticle is the most favored WIMP candidate. Usually the neutralino (theory dependent).

Relic density of particles determined by when they freeze out

number density x cross-section = expansion rate

Freeze out condition: $n\sigma \approx H$

HOT (relativistic)
e.g., neutrino

$T_\nu \gg m_\nu$ so number still around just depends on the photon density

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{91.5\ \text{eV}}$$

current limits

$$0.06 \leq \sum m_\nu \leq 0.12$$

neutrino oscillations — structure formation

COLD (non-relativistic)
e.g., WIMP

$T_X \ll m_X$ particle-antiparticle pairs have time to annihilate, so

$$n \sim (m_X T)^{3/2} e^{-\frac{m_X}{T}}$$

$$\frac{\Omega_X}{0.2} \approx \frac{x_{fo}}{20}\left(\frac{10^{-8}\ \text{GeV}^{-2}}{\sigma}\right)$$

$$20 \lesssim x_{fo} < 50$$

annoying quantum factor

$$\sigma \sim \frac{g^4}{m_X^2}$$

where **g** is the coupling strength
(e.g., the weak nuclear force)

Lee-Weinberg limit: $m_X > 2$ GeV to not over-produce cosmic mass density

THE WIMP MIRACLE

- Fermi's constant G_F introduced in 1930s to describe beta decay

$$n \rightarrow p\, e^- \bar{\nu}$$

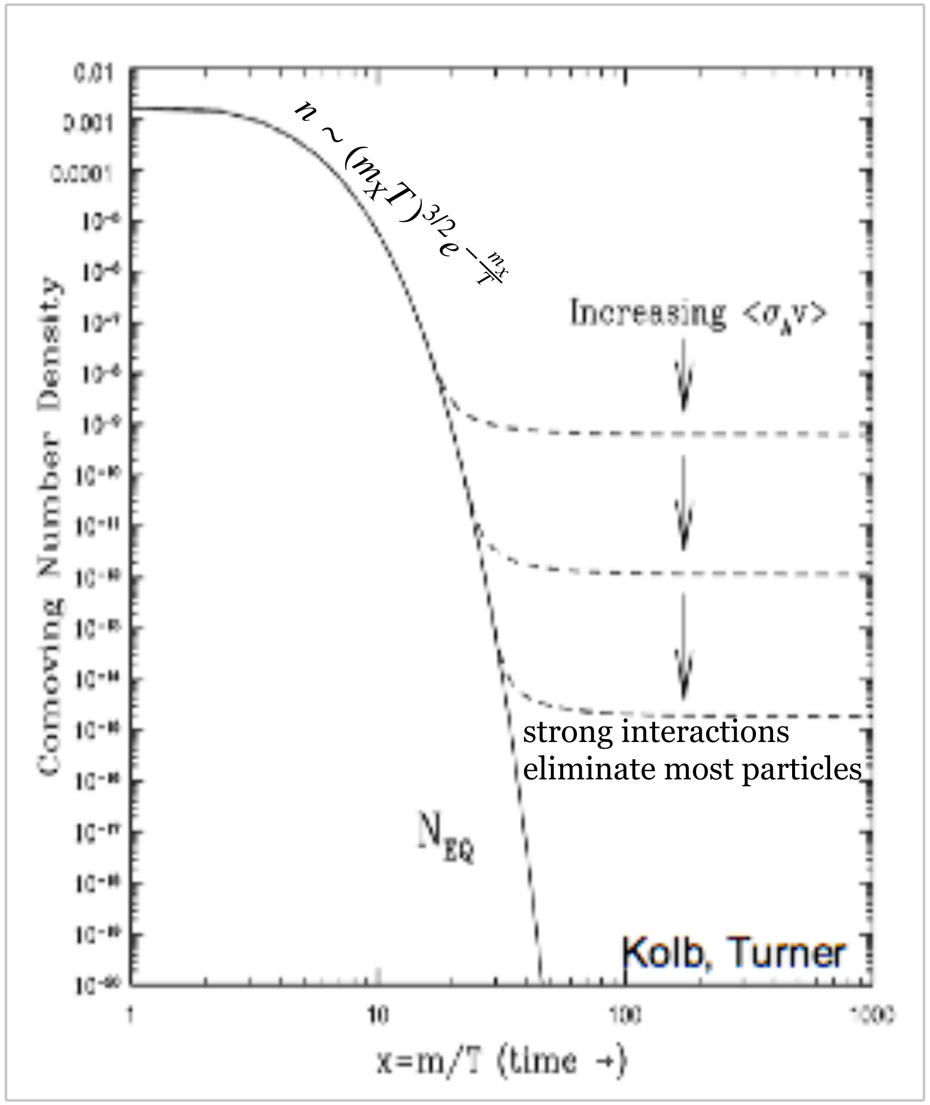
- $G_F \approx 1.1\ 10^5\ \mathrm{GeV}^{-2} \rightarrow$ a new mass scale in nature

$$m_{weak} \sim 100\ \mathrm{GeV}$$

- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

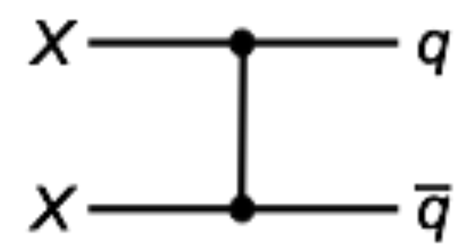
From review by Feng et al. linked from course review literature page.

THE WIMP MIRACLE



- Assume a new (heavy) particle X is initially in thermal equilibrium
- Its relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

$\langle \sigma v \rangle$ "thermal cross-section"

- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

From review by Feng et al. linked from course review literature page.