

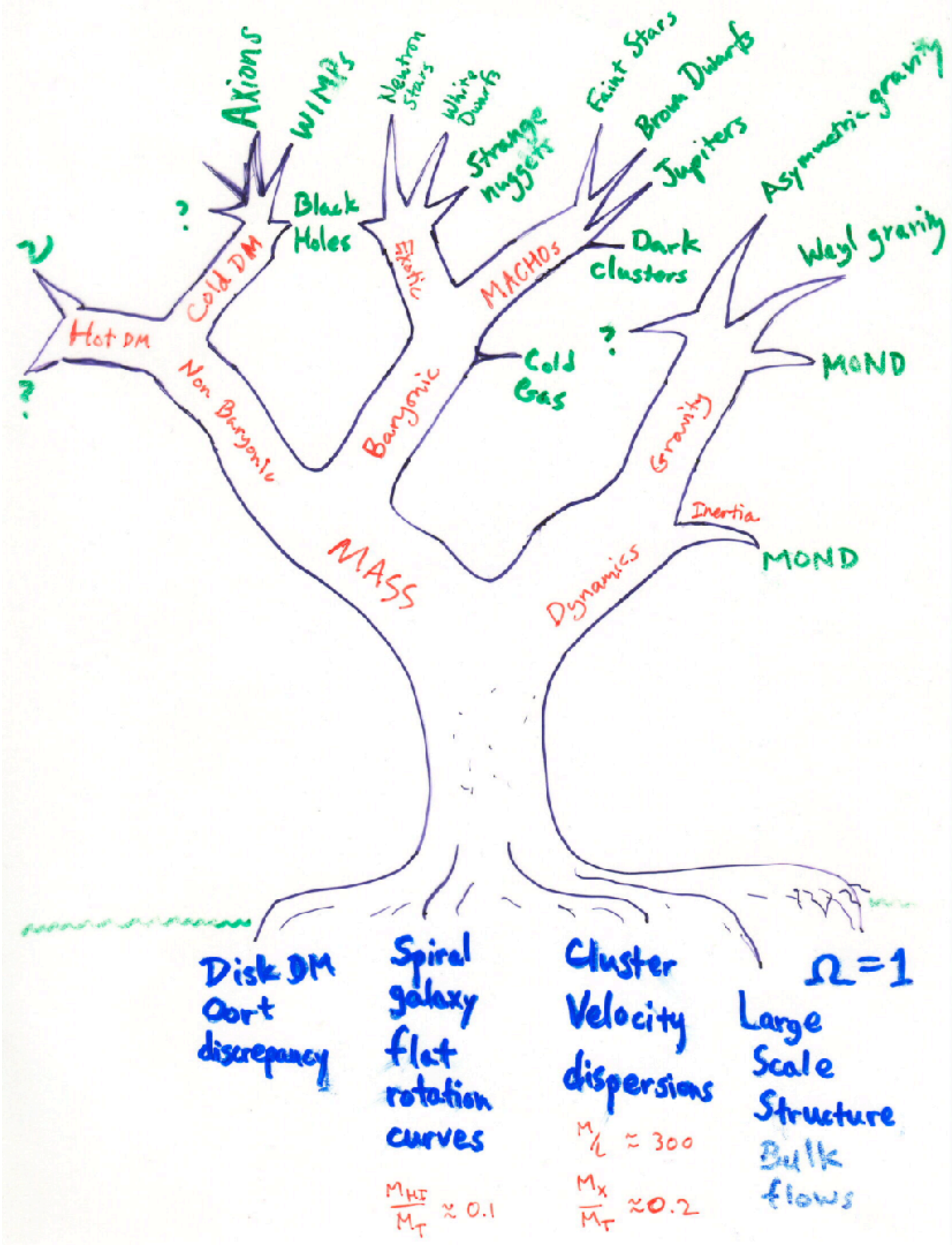
DARK MATTER

ASTR 333/433
SPRING 2026
TR 11:30AM-12:45PM
SEARS 552

<http://astroweb.case.edu/ssm/ASTR333/>

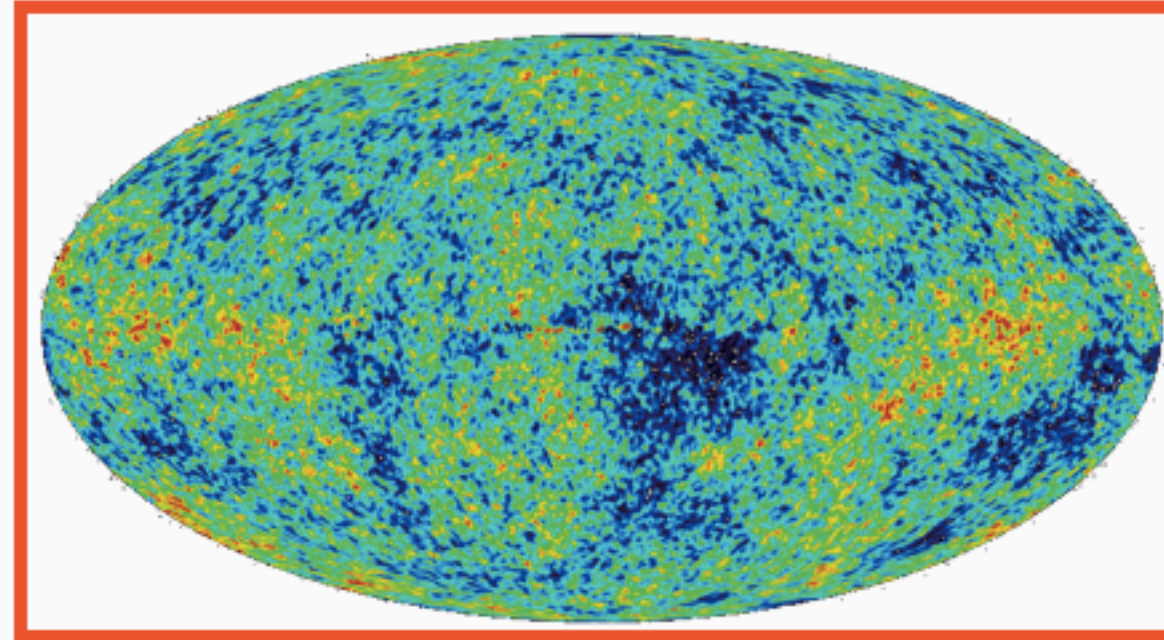
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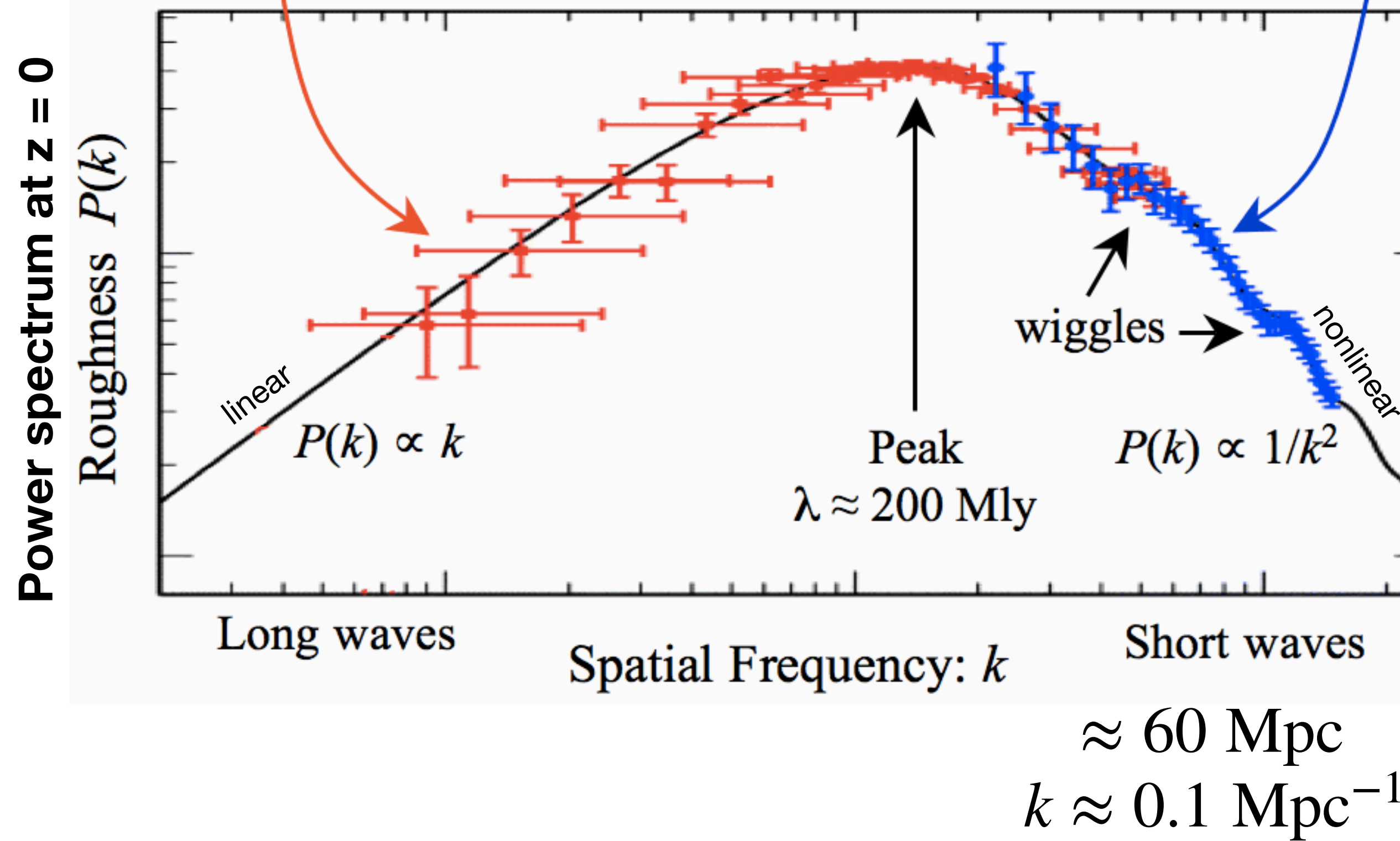
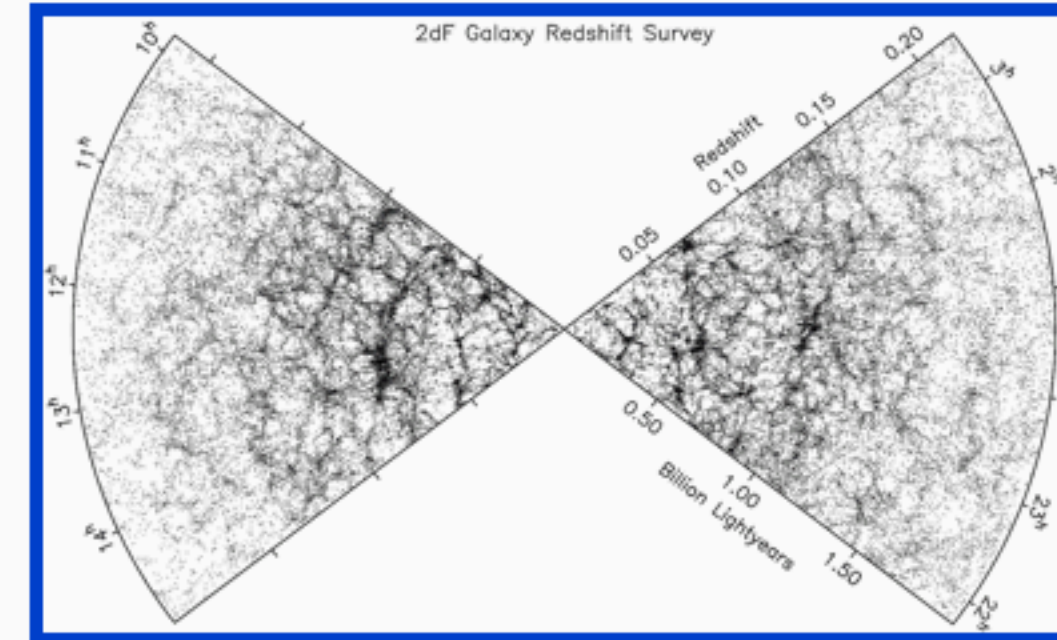


Power spectrum at $z = 1090$
 extrapolated to $z = 0$
 assuming linear growth
 $\frac{\delta\rho}{\rho} \propto a = \frac{1}{1+z}$.

Observations at $z = 1090$



Observations at $z = 0$



$$\delta\rho = \rho_{local} - \rho_{average}$$

SO

$$\frac{\delta\rho}{\rho} = \frac{\rho_{local}}{\rho_{average}} - 1$$

also gets called

$$\delta = \frac{\delta\rho}{\rho}$$

or

$$\Delta$$

usually δ is used for small (linear) perturbations ($\delta < 1$) and Δ for large (nonlinear) overdensities (like $\Delta = 200$ for a dark matter halo).

Cosmology in the 1990s was like an accident report in the *Boston Driver's Handbook*:
“The guy was all over the road. I had to swerve several times before I hit him.”

The standard cosmological model that emerged with the advent of cold dark matter in the 1980s was Standard Cold Dark Matter (SCDM)

The power spectrum of SCDM missed badly:
 too much power on small scales;
 too little power on large scales.

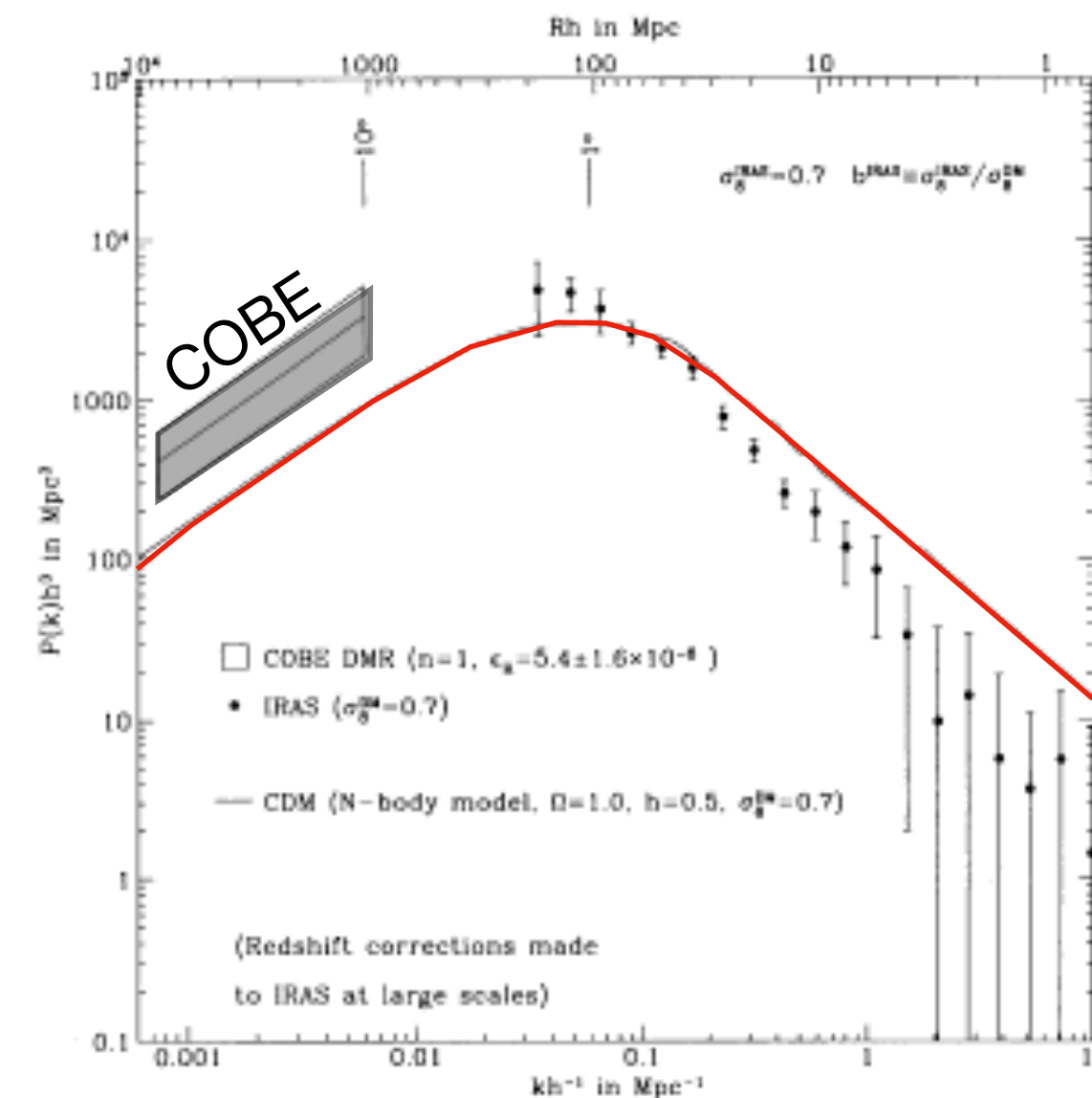
SCDM (“Standard” CDM)

$$\Omega_m = 1$$

$$H_0 = 50$$

$\Omega_m h = 0.5$ expected
 (worse if $h > 0.5$)

$\Omega_m h \approx 0.2$ observed



SCDM
 $\Omega_m h = 0.5$
 $\sigma_8 = 0.7$

FIG. 10.—Solid curve is the real space power spectrum of the full nonlinear CDM N -body simulation (as in Fig. 3) normalized to the real space variance of *IRAS* galaxies ($\sigma_8 = 0.7$). The points are the *IRAS* redshift space $\bar{P}(k)$ from Fig. 4, rescaled by eq. (17) with $\Omega = 1$ and $b = 1$; this is then, apart from the effects of the convolution in eq. (14), an approximation to the power spectrum of *IRAS* galaxies in *real* space on large scales if the *IRAS* galaxies are unbiased. The box indicates the power spectrum inferred from the *COBE* DMR measurements, assuming a $n = 1$ spectral index and $\epsilon_H = (5.4 \pm 1.6) \times 10^{-6}$ (Smoot et al. 1992; Wright et al. 1992). Note that when the CDM model is normalized to the *IRAS* variance, it produces excessive power on small scales while simultaneously failing to produce sufficient power on large scales to match the *COBE* results.

Fisher et al. (1993) ApJ, 402, 42

The power spectrum gives

$$\Omega_m h = 0.21$$

$$\sigma_8 = 0.83$$

$$n_s = 0.965$$

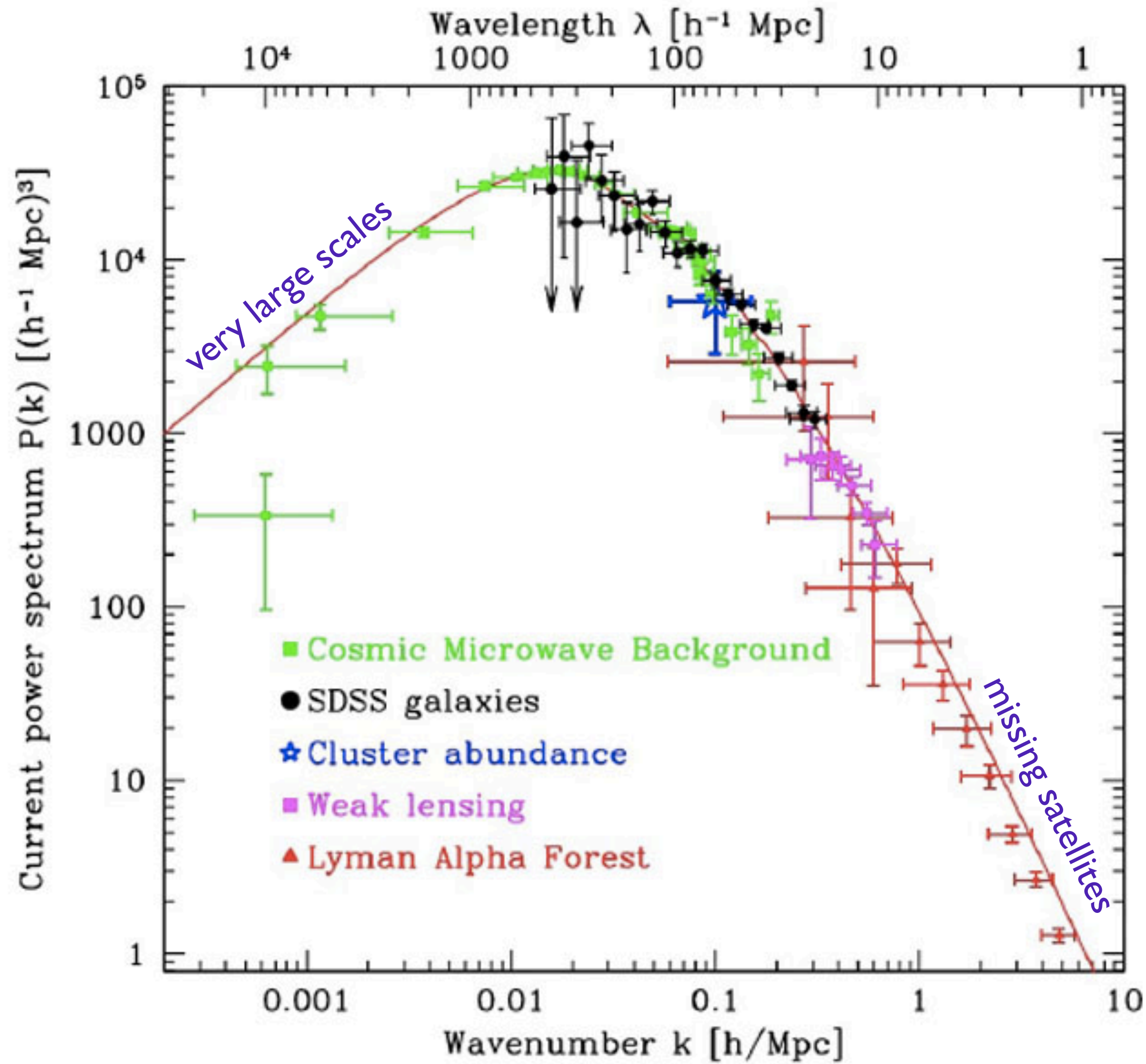
LCDM

$$\Omega_m = 0.3$$

$$H_0 = 70$$

$$\Omega_\Lambda = 0.7$$

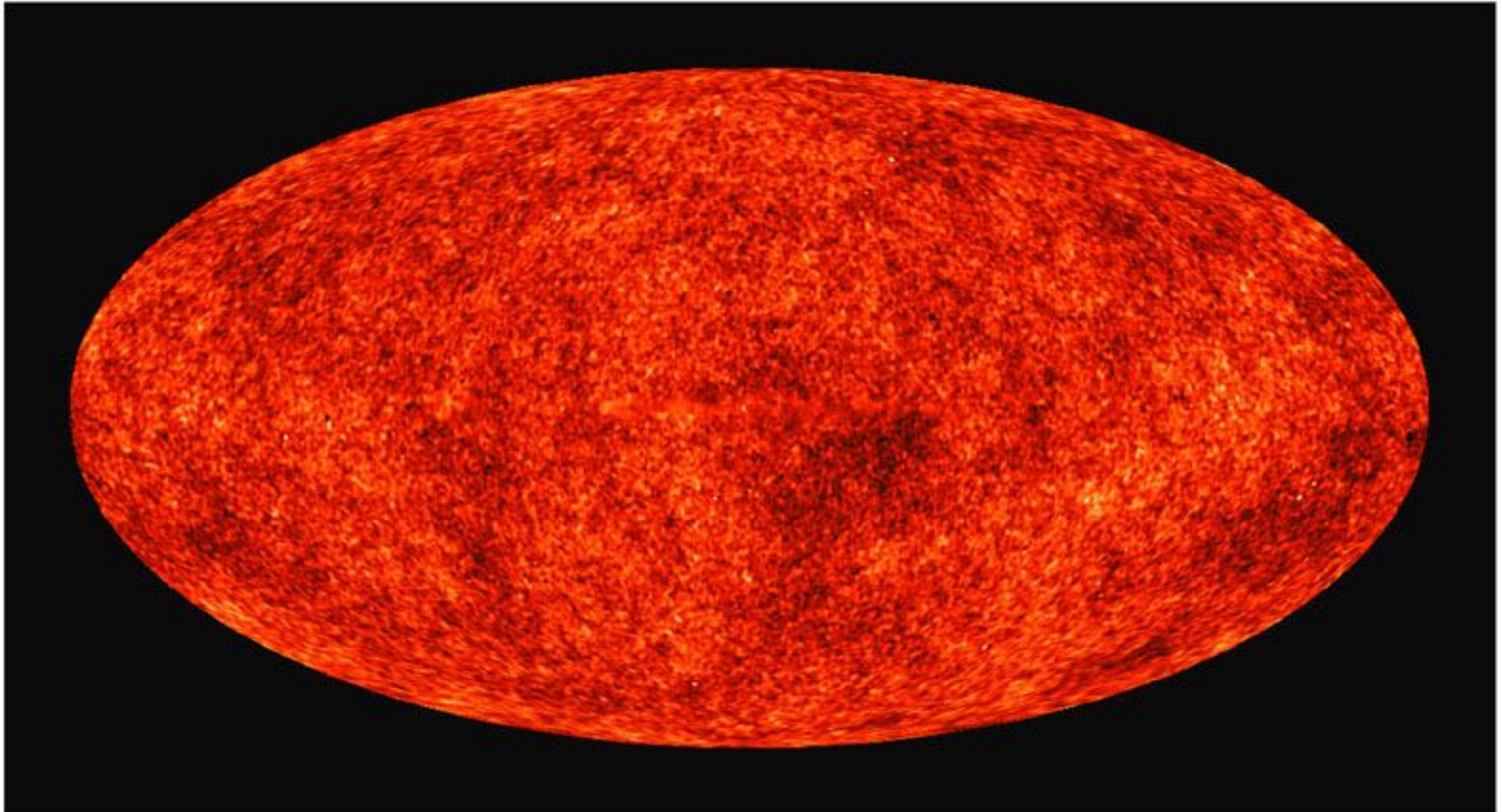
This specific set of parameters is sometimes called "vanilla LCDM"



LCDM replaced SCDM by the end of the 1990s because many observations required $\Omega_m \approx 0.3$, which is less than one.

(Inflation predicted $\Omega_m = 1$ but is sorta OK with $\Omega_m + \Omega_\Lambda = 1$.)

CMB: Baby picture of the universe (370,000 years old)



Universe very uniform at $z = 1090$ (370,000 years old)

CMB temperature fluctuations directly related to density fluctuations

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

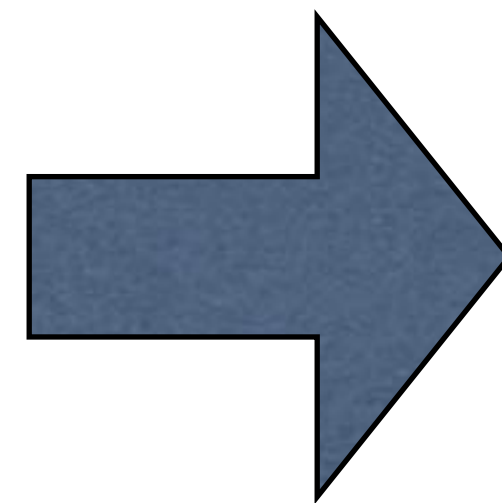
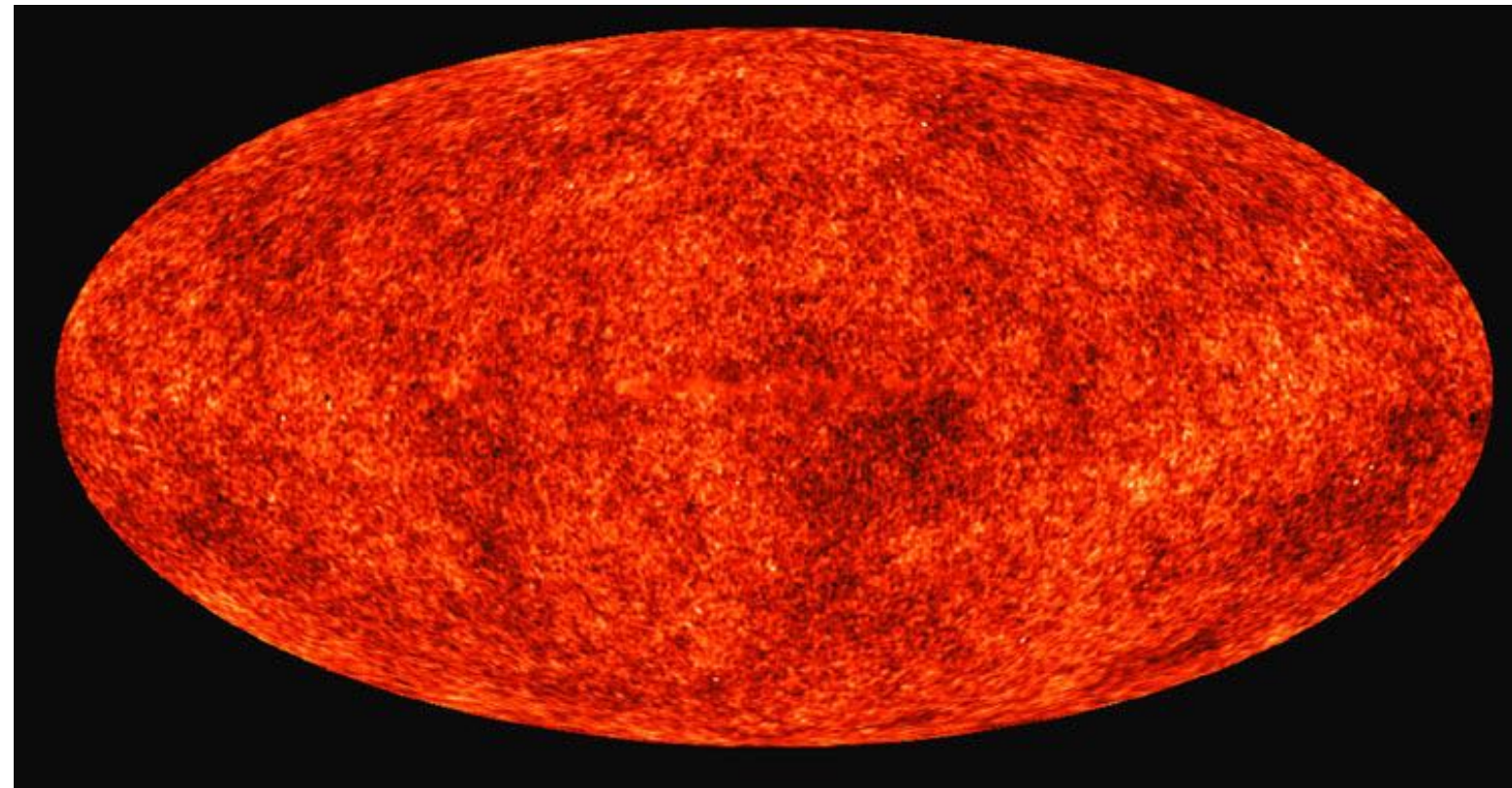
Basic problem:
not enough time for structure to grow.

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

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.

$t = 3.8 \times 10^5 \text{ yr}$



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



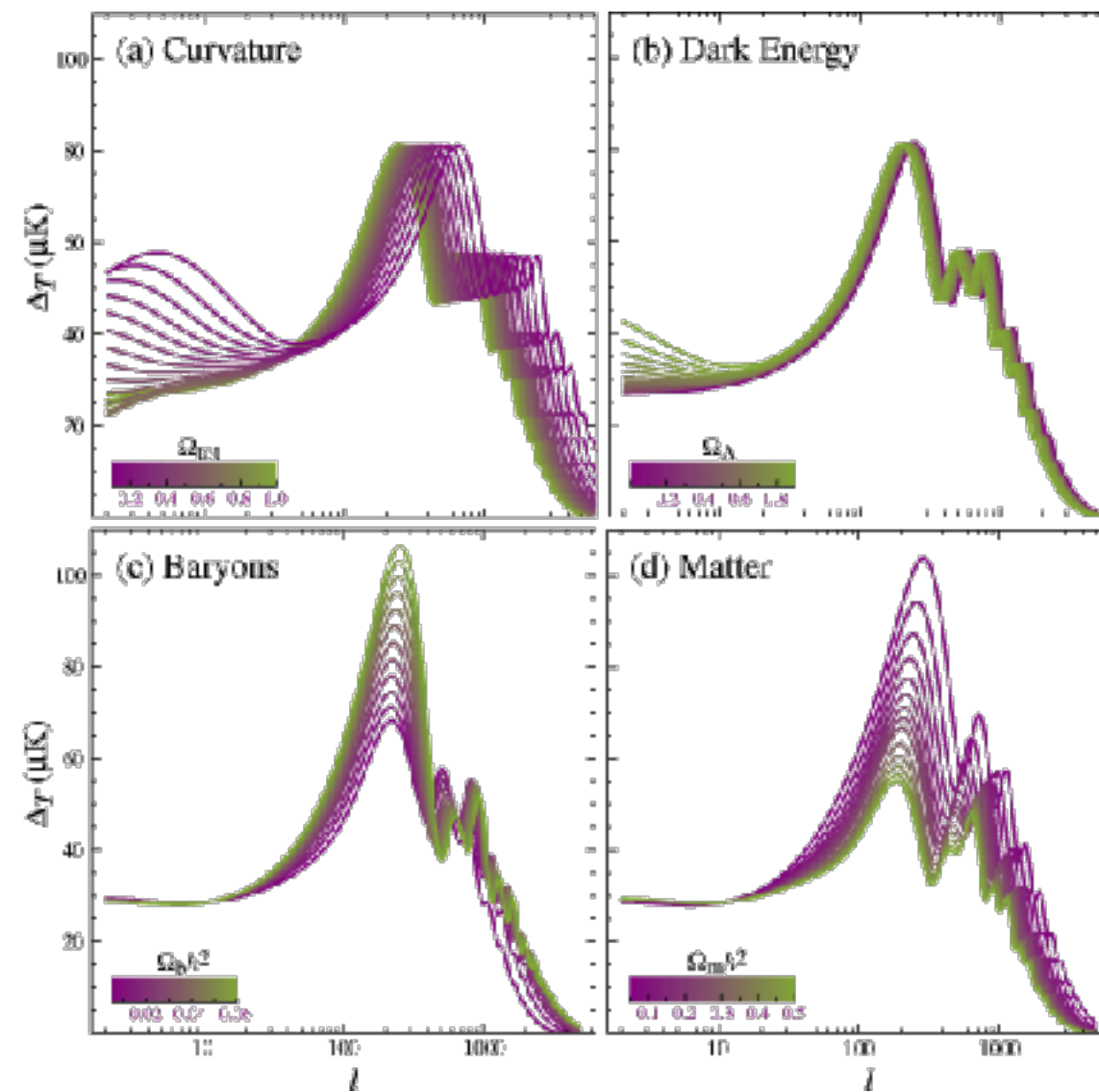
Early universe very smooth: $\delta \sim 10^{-5}$

Current universe very lumpy: $\delta \sim 1$

$$\delta \propto a$$

$$a \propto t^{2/3} \text{ at early times}$$

Detailed shape of the acoustic power spectrum depends sensitively on cosmic parameters.



Best-fit cosmology obtained from multi-parameter fit. Well constrained, but not unique - lots of parameter degeneracy.

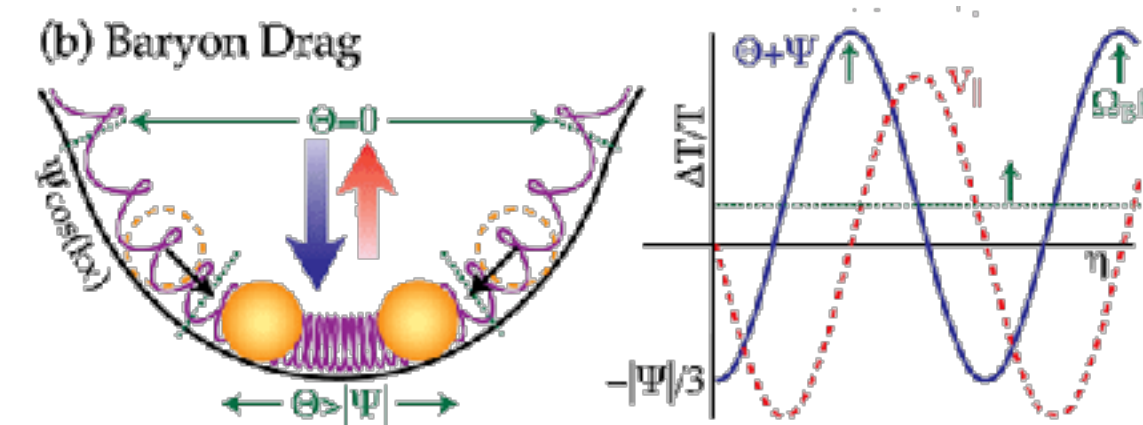
Compression and rarefaction nearly cancel out, but don't quite. Left with

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

Damped and driven oscillator

Baryons damp oscillations, like a kid dragging his feet on a swing.
pure damping spectrum in limit of all baryons

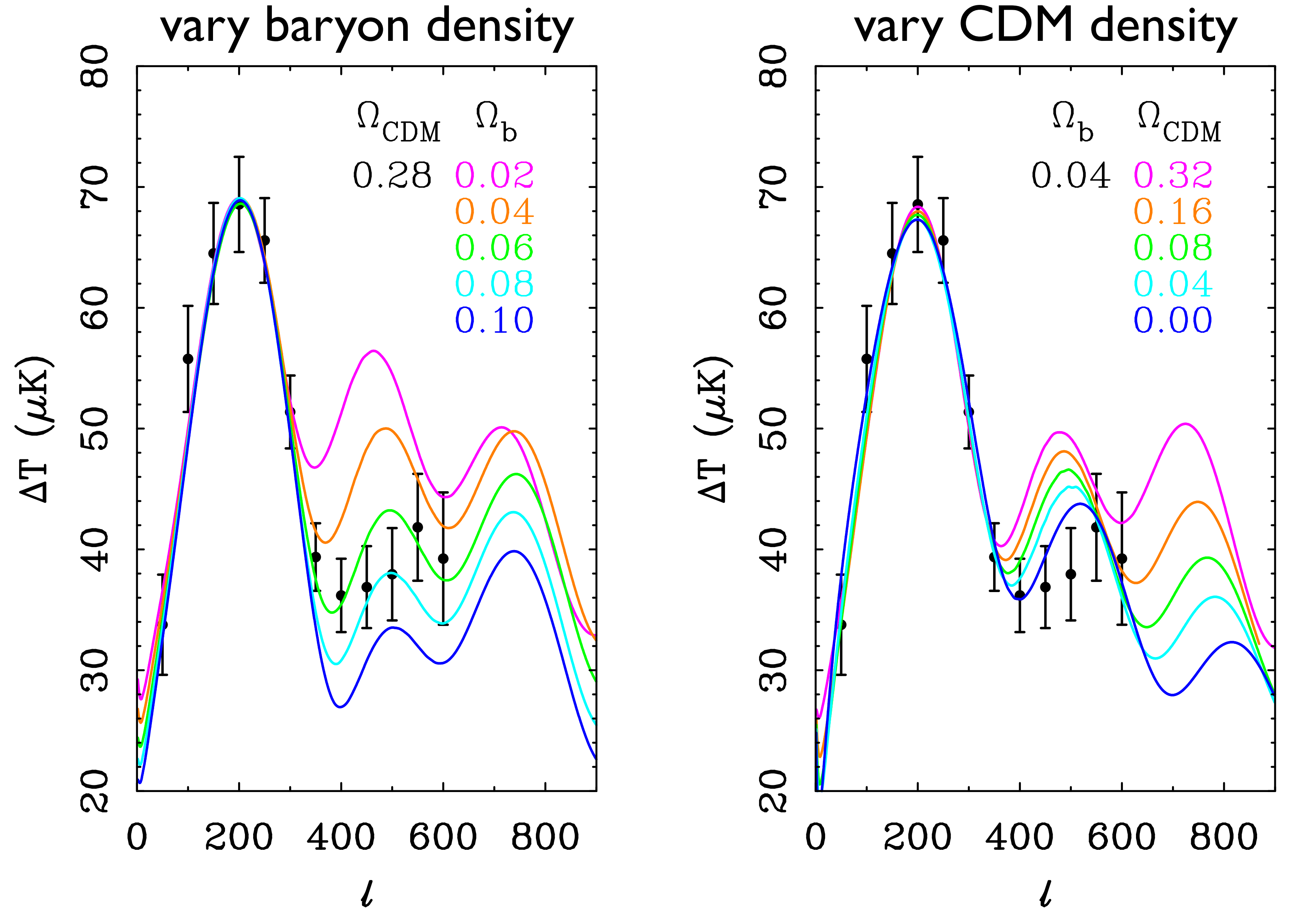
Dark matter helps drive oscillations, like a parent pushing the kid.



Wayne Hu provides a nice CMB tutorial at <http://background.uchicago.edu/index.html>

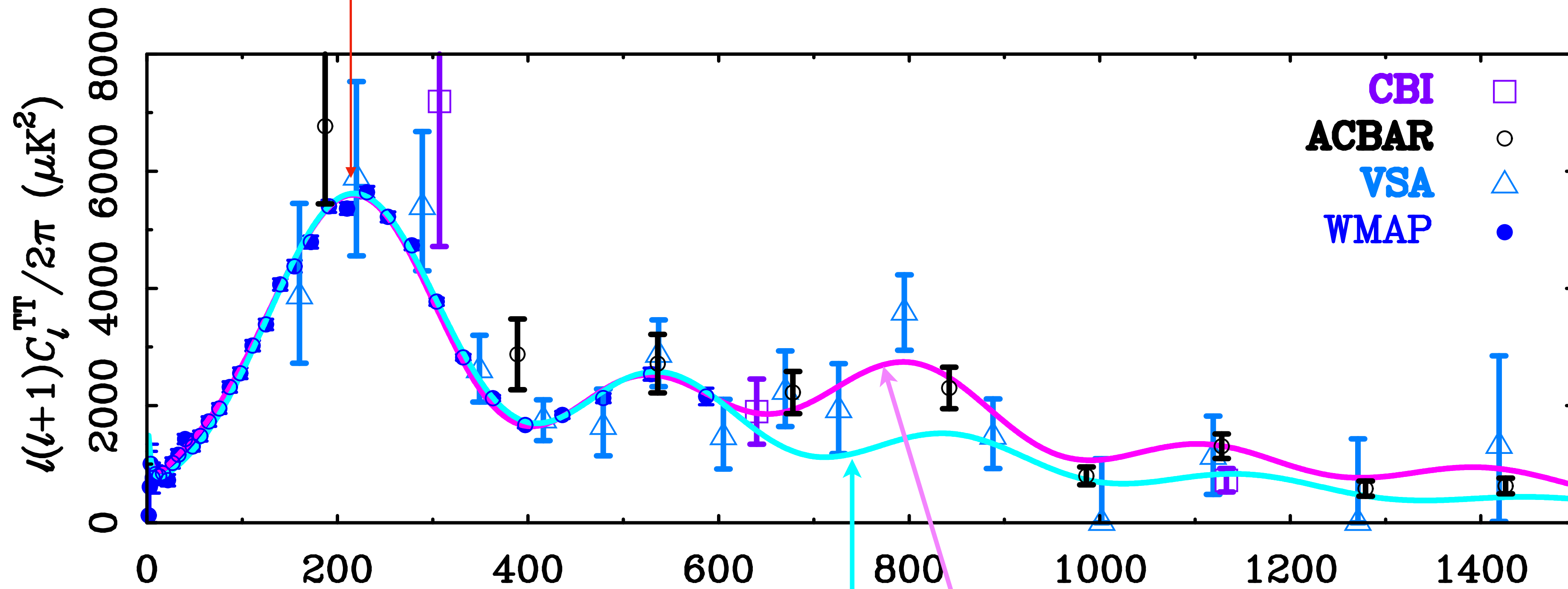
See also the movies of Max Tegmark at <http://space.mit.edu/home/tegmark/movies.html>

CMB power spectra



artificially normalize first peak to show variation in shape

The location of the first peak constrains the curvature to be small ($|\Omega_k| < 0.005$) so the universe is flat and $\Omega_m + \Omega_\Lambda = 1$



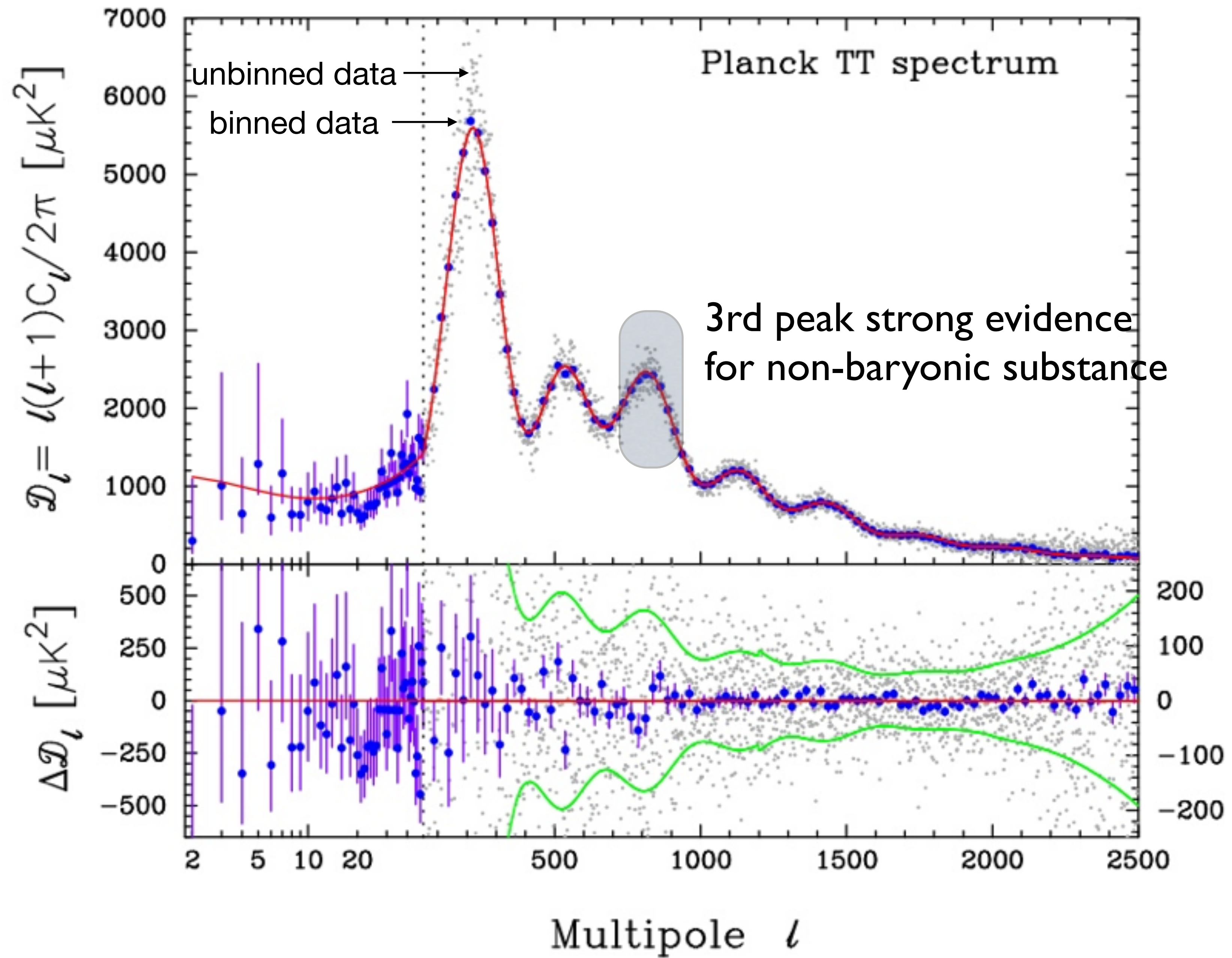
Effective Poisson eqn for mode k

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

Assume modes are independent - a good assumption in linear regime

baryons a net drag

CDM a net forcing term
out of phase with baryons



Measurements of the gravitating mass density

- Cluster M/L $\Omega_m \approx 0.25$ Bahcall et al. (1995) White et al. (1993, cluster baryon fractions)
 - measure M/L of a cluster, combine with measured luminosity density of universe.
 - Weak lensing $\Omega_m \approx 0.18 \pm 0.04$ Dark Energy Survey arxiv:2002.11124
 - measure shear over large scales
 - Peculiar Velocity Field $\Omega_m = 0.25 \pm 0.05$ Tonry & Davis (1980)
 - measure deviations from Hubble flow
 - Power spectrum of galaxies
 - CMB fits $\Omega_m h = 0.213 \pm 0.023$
 $\Omega_m = 0.3$ for $h = 0.71$ Tegmark et al. (2004)
- $\Omega_m = 0.315 \pm 0.007$ Planck Collaboration (2018)
also gives $h = 0.674 \pm 0.005$

73.48 ± 1.66 (direct H_0 measurement: Riess et al. 2018)

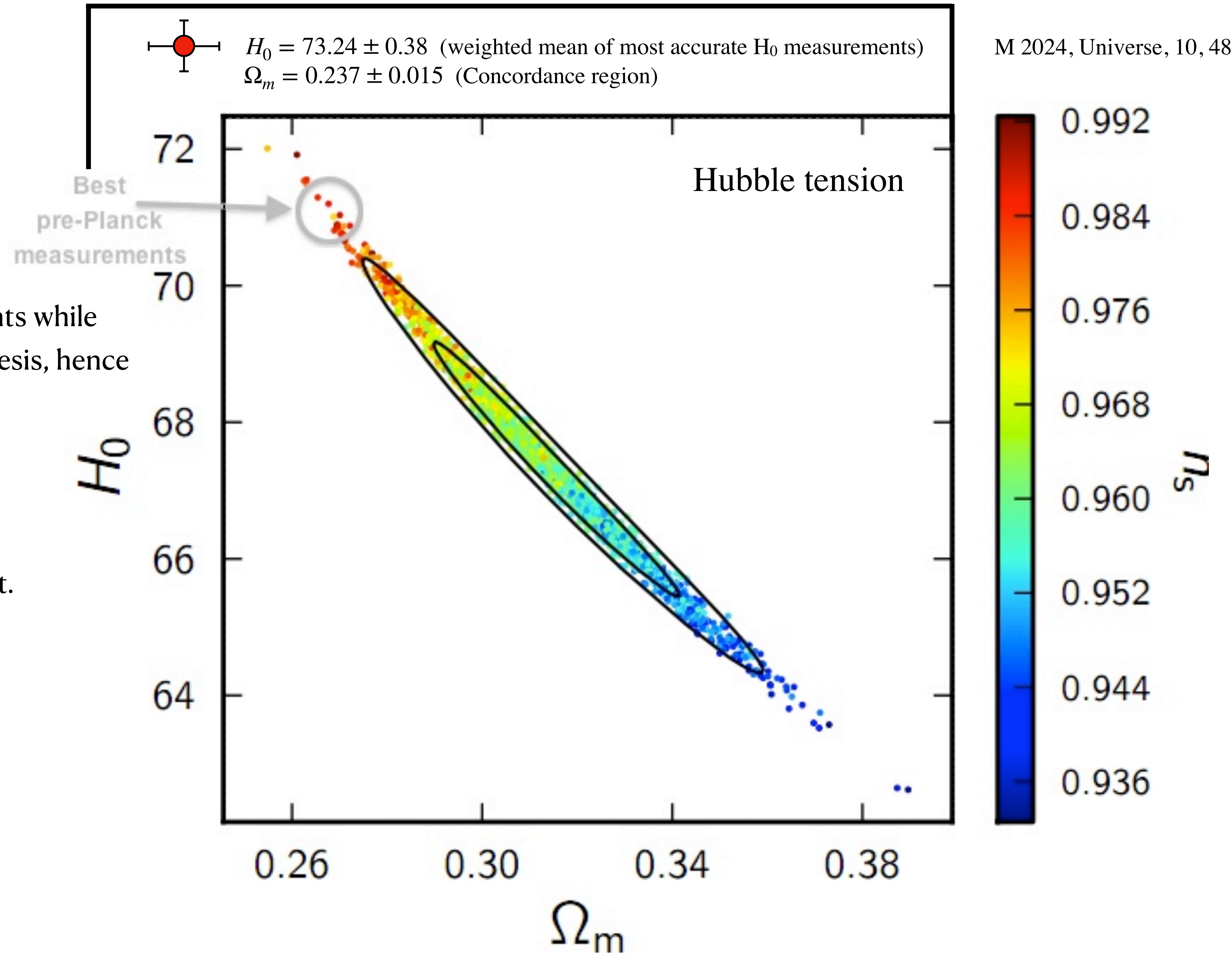
2026 updates: 73.50 ± 0.81 (2510.23823); 76.0 ± 2.5 (Duey et al., real soon)

M 2024, Universe, 10, 48

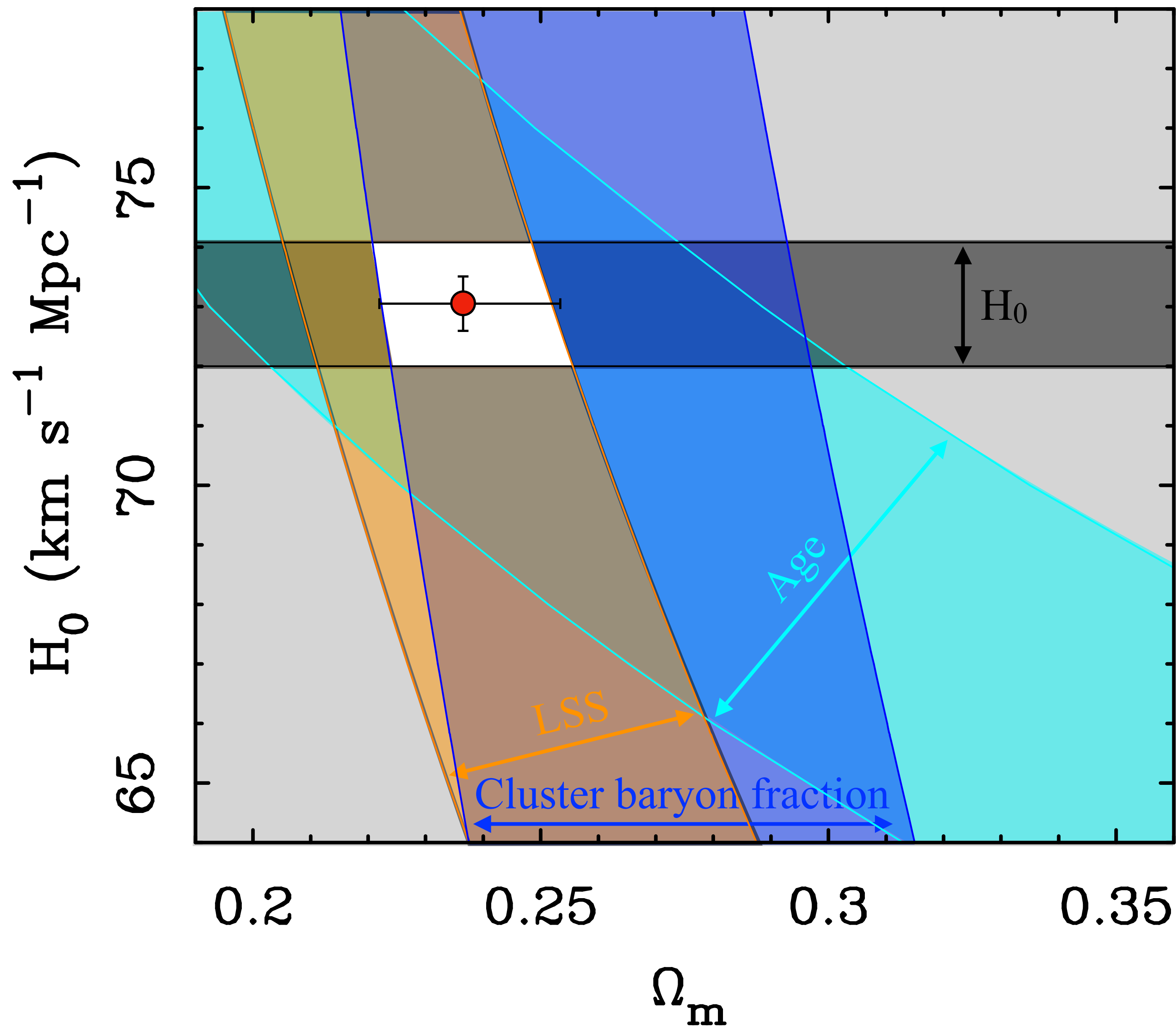
So:

$\Omega_m \approx 0.30$ from dynamical measurements while
 $\Omega_b \approx 0.05$ from primordial nucleosynthesis, hence
 $\Omega_m > \Omega_b$ for sure and we need
non-baryonic dark matter...

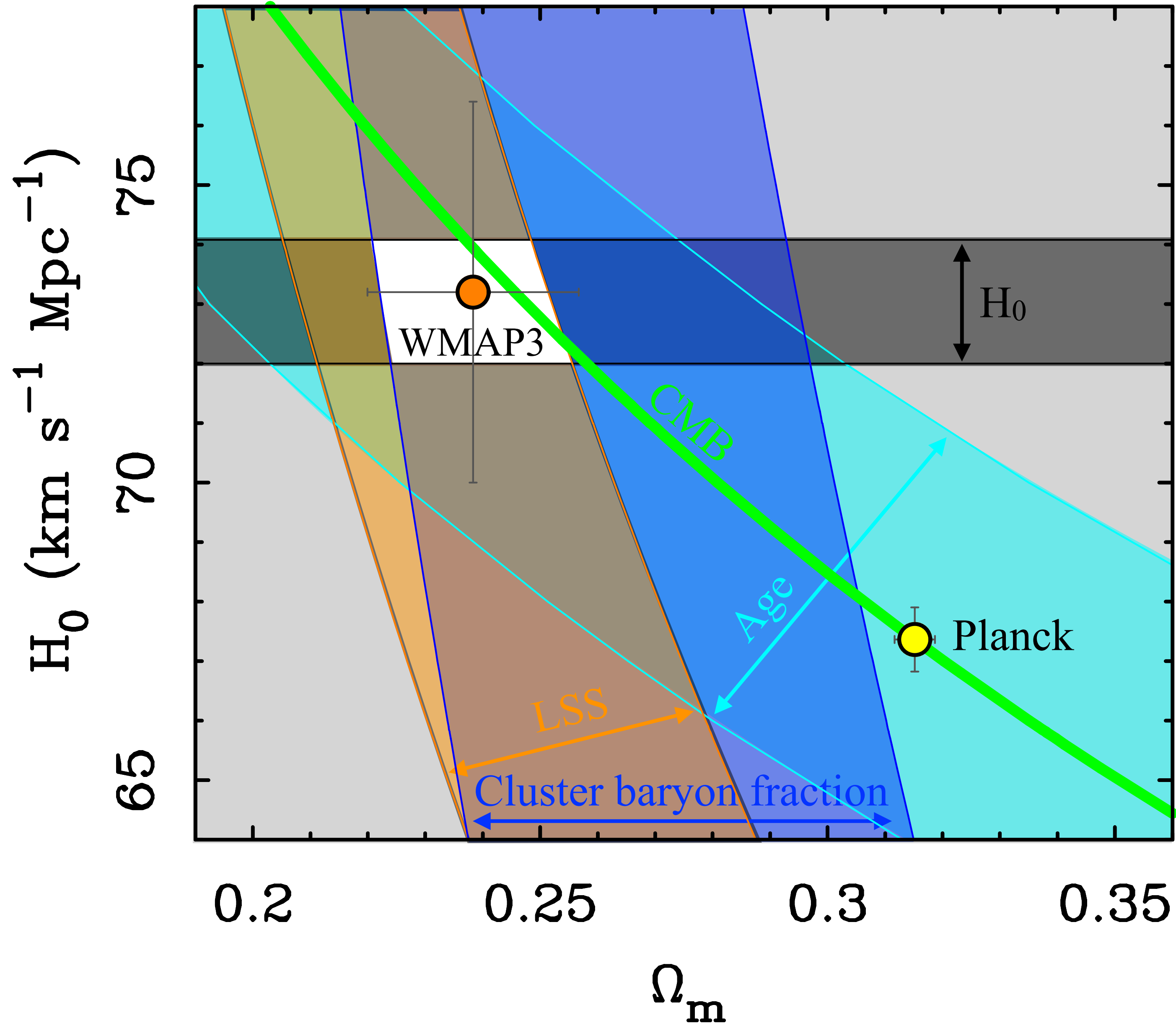
assuming the FLRW cosmology is correct.



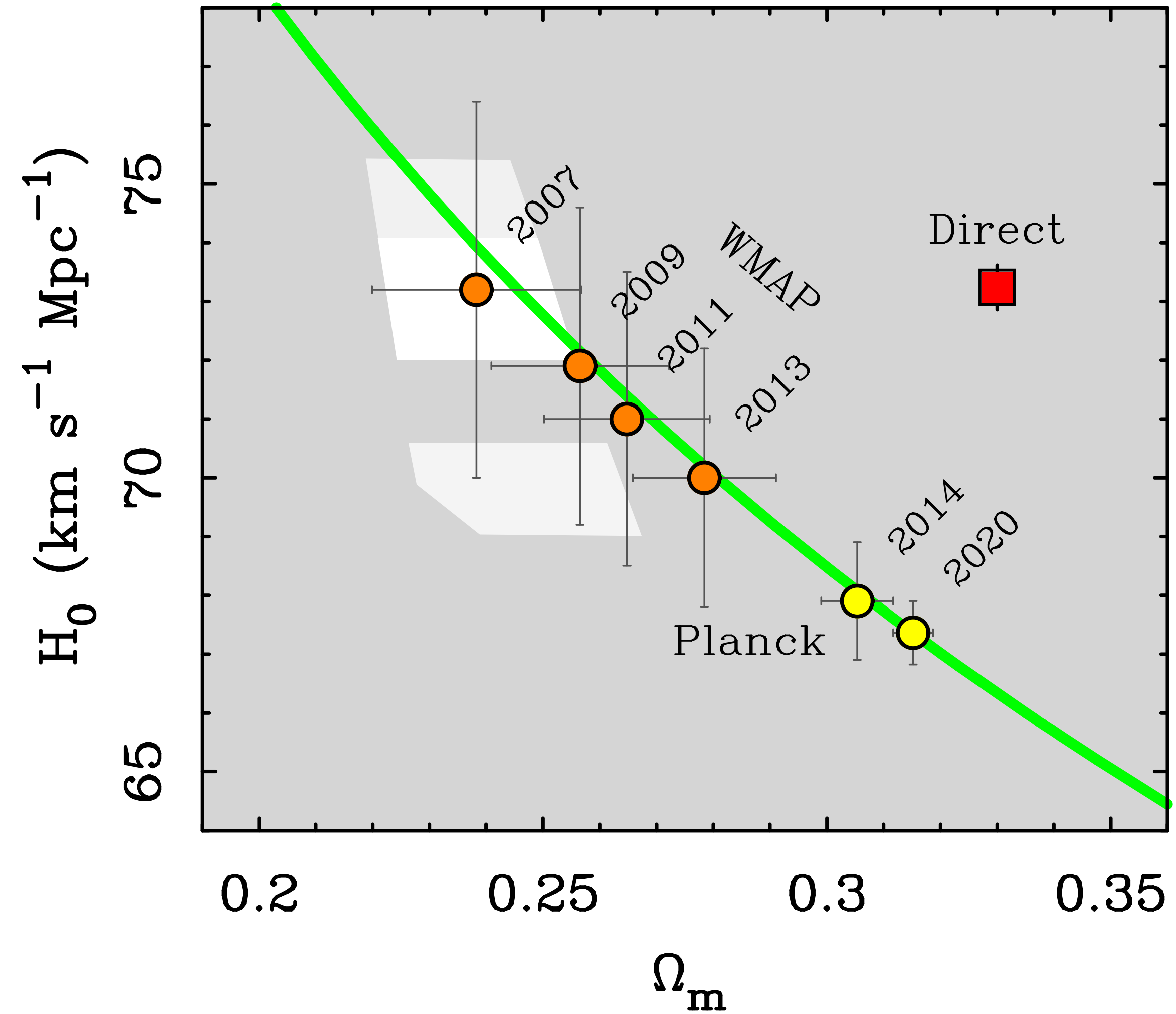
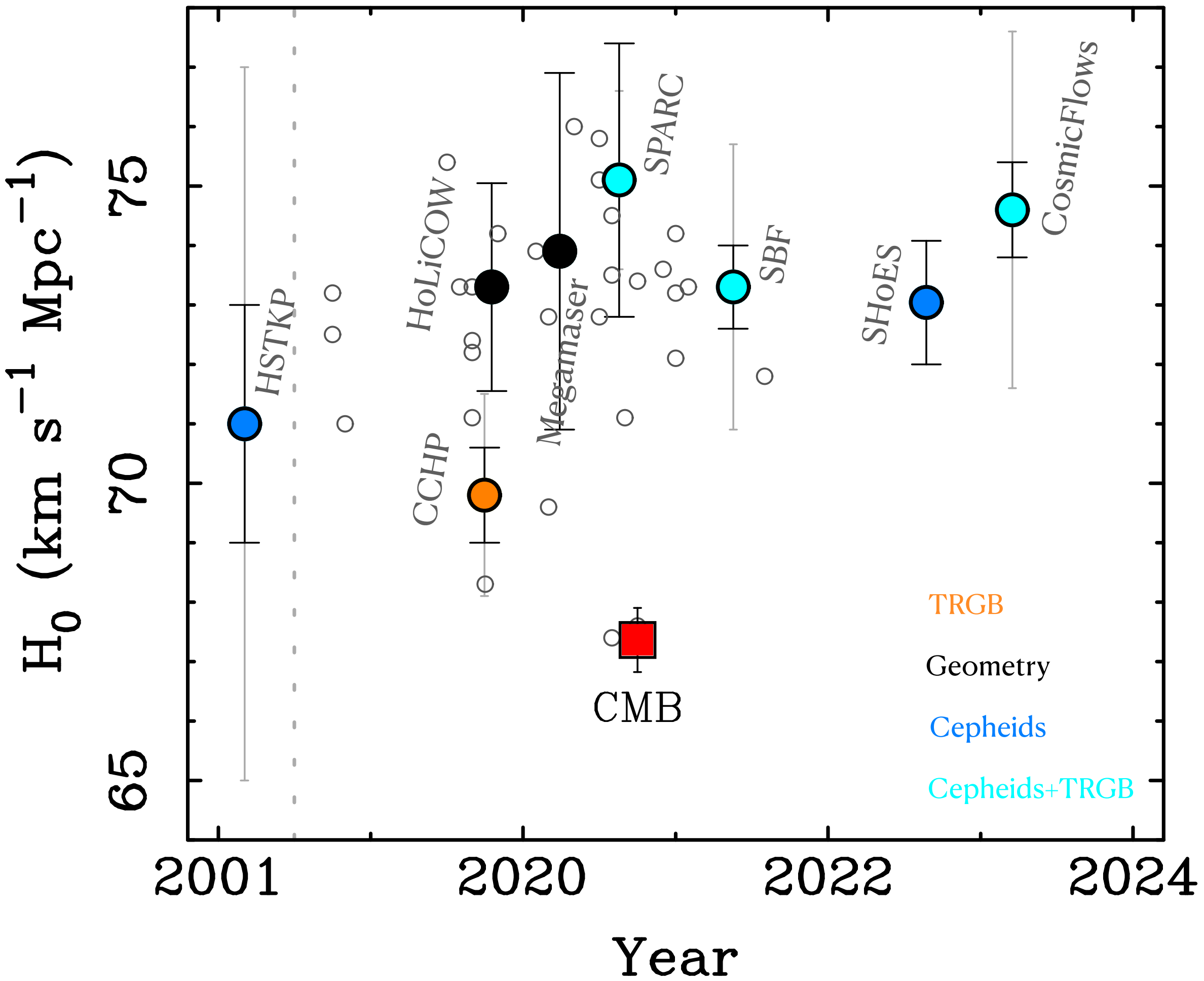
Concordance LCDM without CMB



Concordance(?) LCDM with CMB



The Hubble tension appears to be real, and a result of time variation in the CMB best fit.



FLRW cosmology works if and only if there is non-baryonic cold dark matter (and dark energy).

Things we know **for sure** in cosmology:

“Cosmologists are often wrong, but never in doubt”
- Lev Landau

Cosmological parameters over time

Quantity	circa 1990	circa 2000	WMAP5 2008	Planck 2018
Ω_m	1	0.3	0.274 ± 0.013	0.315 ± 0.007
Ω_Λ	0	0.7	0.726	0.685
$\Omega_b h^2$	0.0125 ± 0.0025	0.019 ± 0.001	0.02247 ± 0.00075	0.02237 ± 0.00015
H_0	50	72 ± 8	70.5 ± 1.3	67.4 ± 0.5
dark matter	CDM	CDM	CDM	CDM

Cosmologically, the only requirement to be CDM is

- dynamically cold (slow moving)
- non-baryonic (no E&M interactions)

could be
WIMPS

(or some other particle, but there are lots of extra particle-physics constraints on new particles)

or

Black Holes

(primordial BHs with masses of $\sim 30 M_{\odot}$ are conceivable, but most mass ranges have been excluded by gravitational lensing observations)

WIMPs are considered the odds-on favorite CDM candidate because of the so-called 'WIMP miracle': the relic density of a new weakly interacting particle is about right to explain the mass density.

Cosmologically, the only requirement to be CDM is

- dynamically cold (slow moving)
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could be
WIMPS







(or some other particle, but there are lots of extra particle-physics constraints on new particles)

WIMPS, or whatever it is, represent new physics beyond the Standard Model of particle physics.



WIMPs are not just a new particle to discover. Their existence requires entirely new physics outside the Standard Model of particle physics; e.g., something like SuperSymmetry.

STANDARD MODEL OF ELEMENTARY PARTICLES


QUARKS


UP mass $2,3 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ 	CHARM mass $1,275 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ 	TOP mass $173,07 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ 
DOWN mass $4,8 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ 	STRANGE mass $95 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ 	BOTTOM mass $4,18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ 


LEPTONS

ELECTRON mass $0,511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ 	MUON mass $105,7 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ 	TAU mass $1,777 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ 
ELECTRON NEUTRINO mass $<2,2 \text{ eV}/c^2$ charge 0 spin $\frac{1}{2}$ 	MUON NEUTRINO mass $<0,17 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ 	TAU NEUTRINO mass $<15,5 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ 

GLUON
 mass 0
 charge 0
 spin 1


PHOTON
 mass 0
 charge 0
 spin 1


Z BOSON
 mass $91,2 \text{ GeV}/c^2$
 charge 0
 spin 1


W BOSON
 mass $80,4 \text{ GeV}/c^2$
 charge ± 1
 spin 1


HIGGS BOSON
 mass $126 \text{ GeV}/c^2$
 charge 0
 spin 0

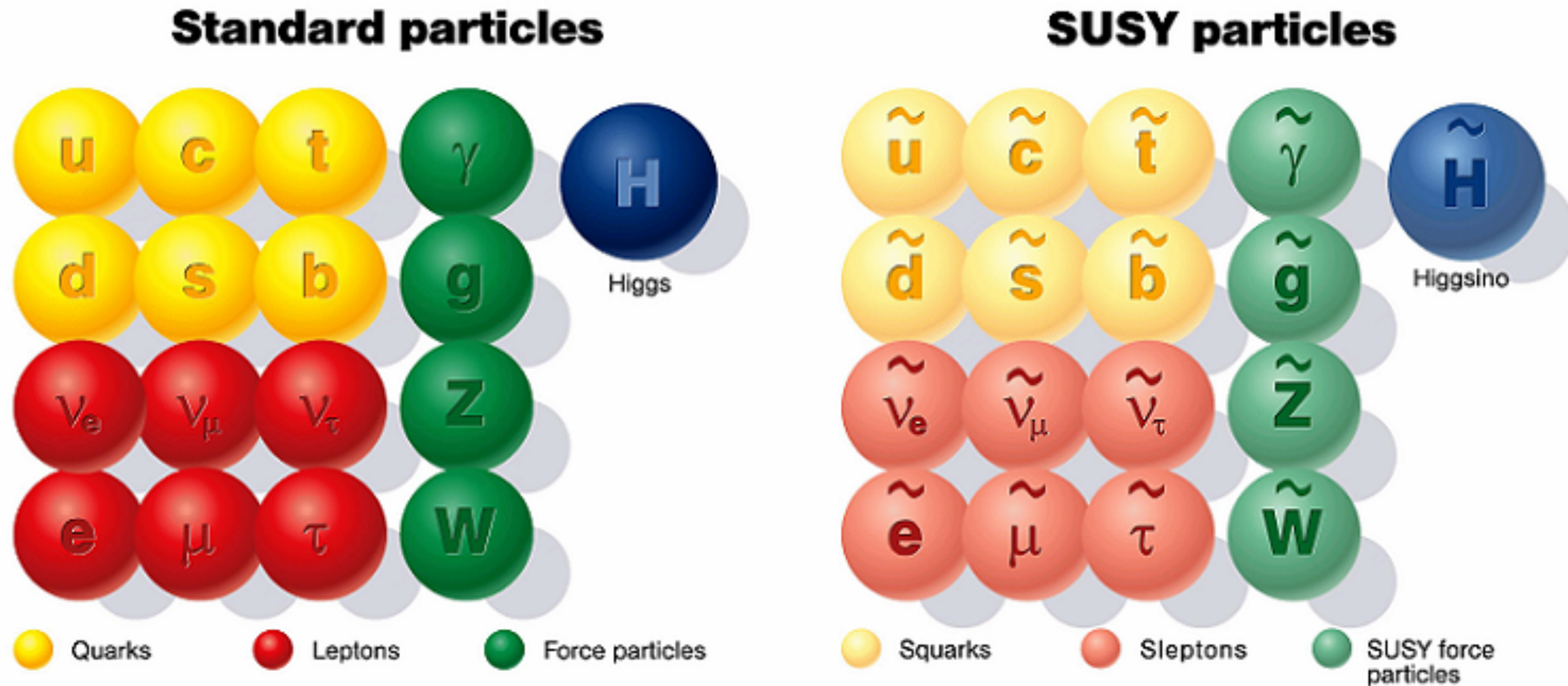

GAUGE BOSONS

proton:
up+up+down

neutron:
up+down+down

Supersymmetry: a hypothetical new symmetry of nature

arxiv.org/abs/hep-ph/9606414



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 \times 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 \mathbf{g} is the coupling strength
(e.g., the weak nuclear force)

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

THE WIMP MIRACLE

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



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

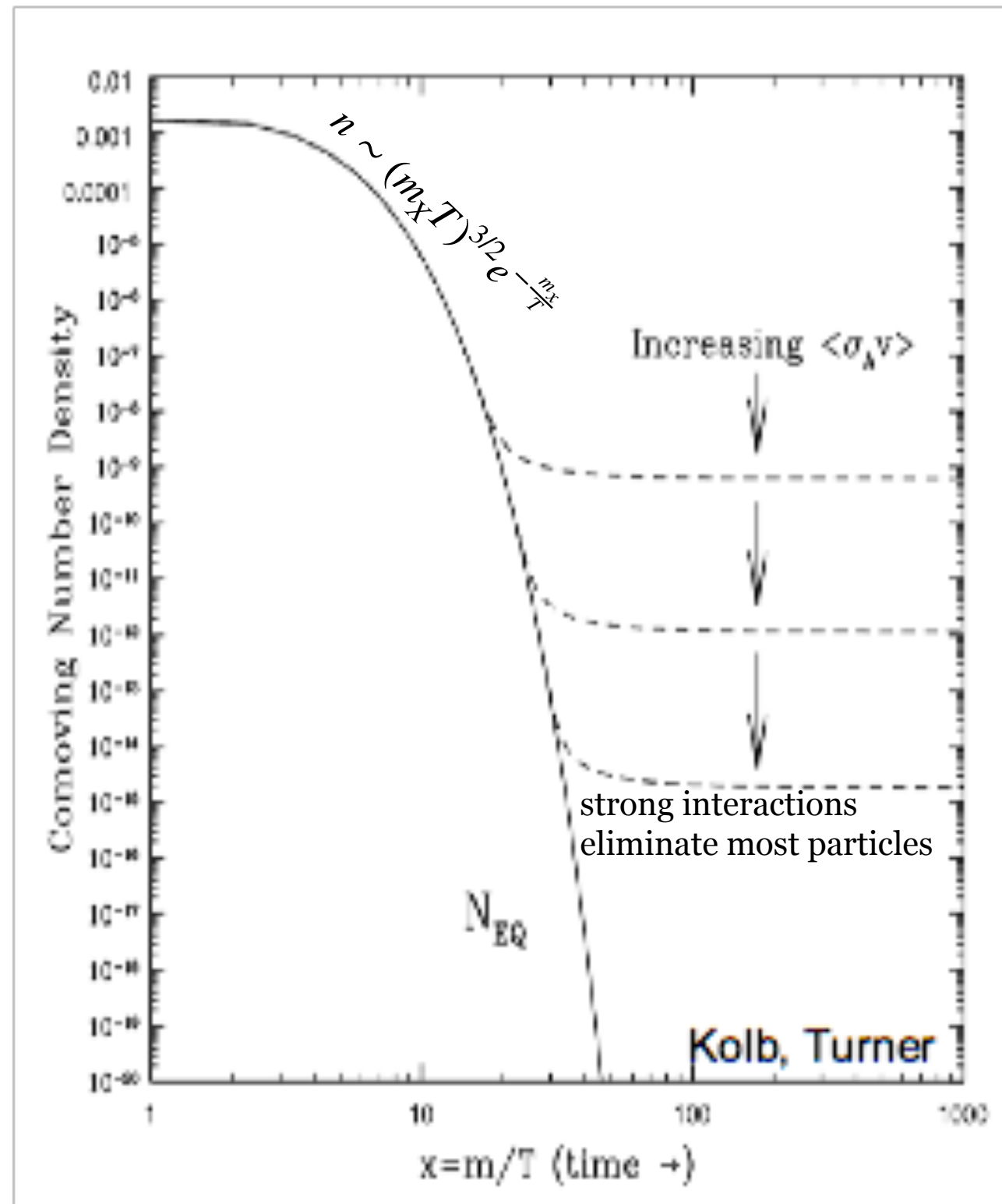
$$m_{\text{weak}} \sim 100 \text{ GeV}$$

- 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.
Original idea goes back to Peebles (1984) & Steigmann & Turner (1985).
See also the cosmology textbook by Kolb & Turner.

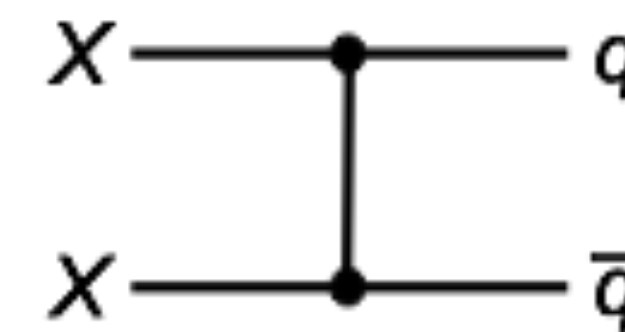
THE WIMP MIRACLE



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

- Its relic density is

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



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

$\langle \sigma v \rangle$ “thermal cross-section”

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

Originally expected $\sigma \sim 10^{-39} \text{ cm}^{-2}$, but only the thermal cross-section $\langle \sigma v \rangle$ matters here.

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

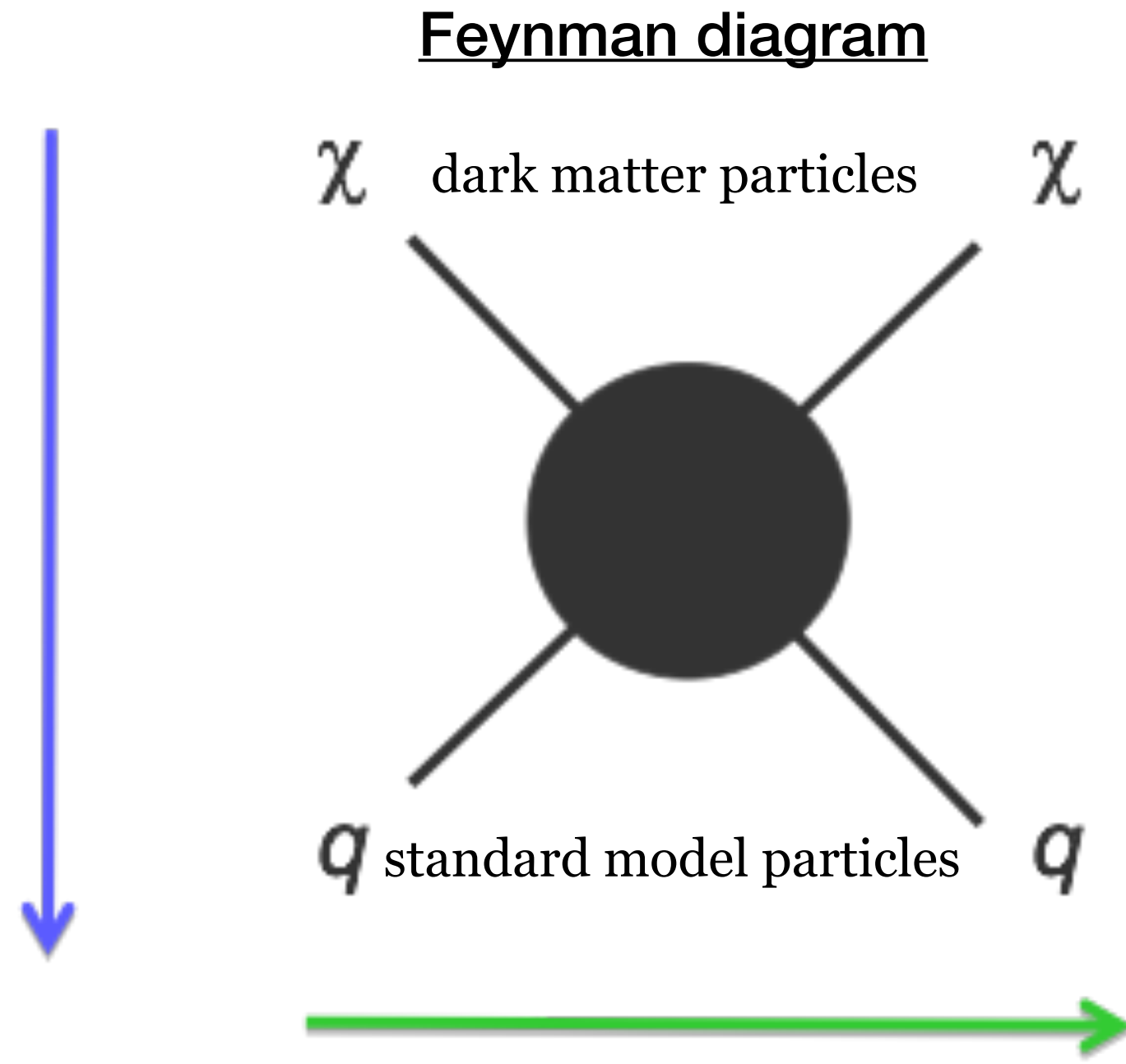
WIMP DETECTION

Correct relic density \rightarrow Lower bound on DM-SM interaction

WIMPs decay into
standard model particles
(gamma rays, cosmic rays)

11 Dec 09

Efficient annihilation now
(Indirect detection)



Efficient scattering now
(Direct detection)

WIMPs scatter off nuclei in
underground laboratory
experiments

Efficient production now
(Particle colliders)

WIMPs created in particle
colliders (like the LHC)

Feng 5