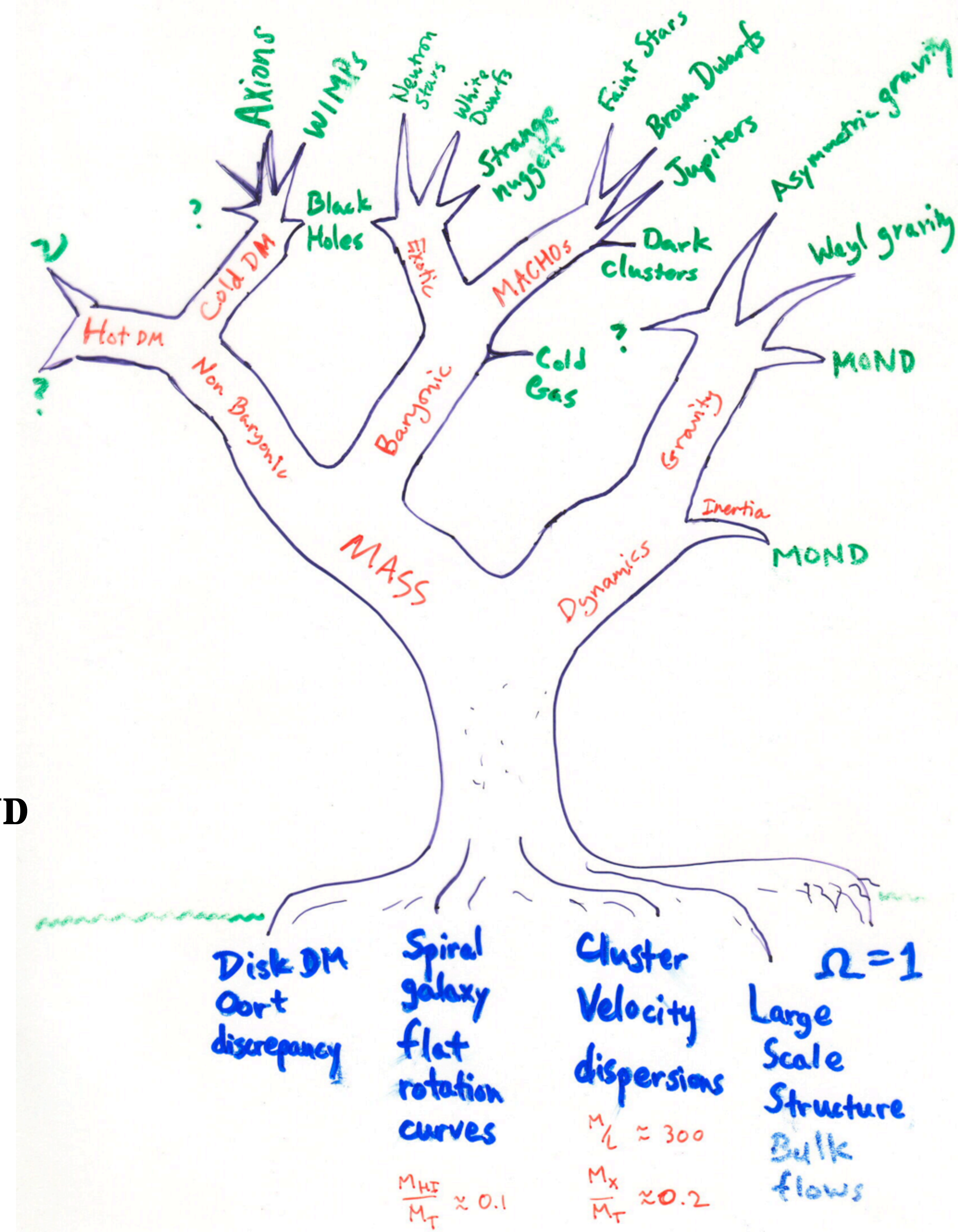
Dark Matter

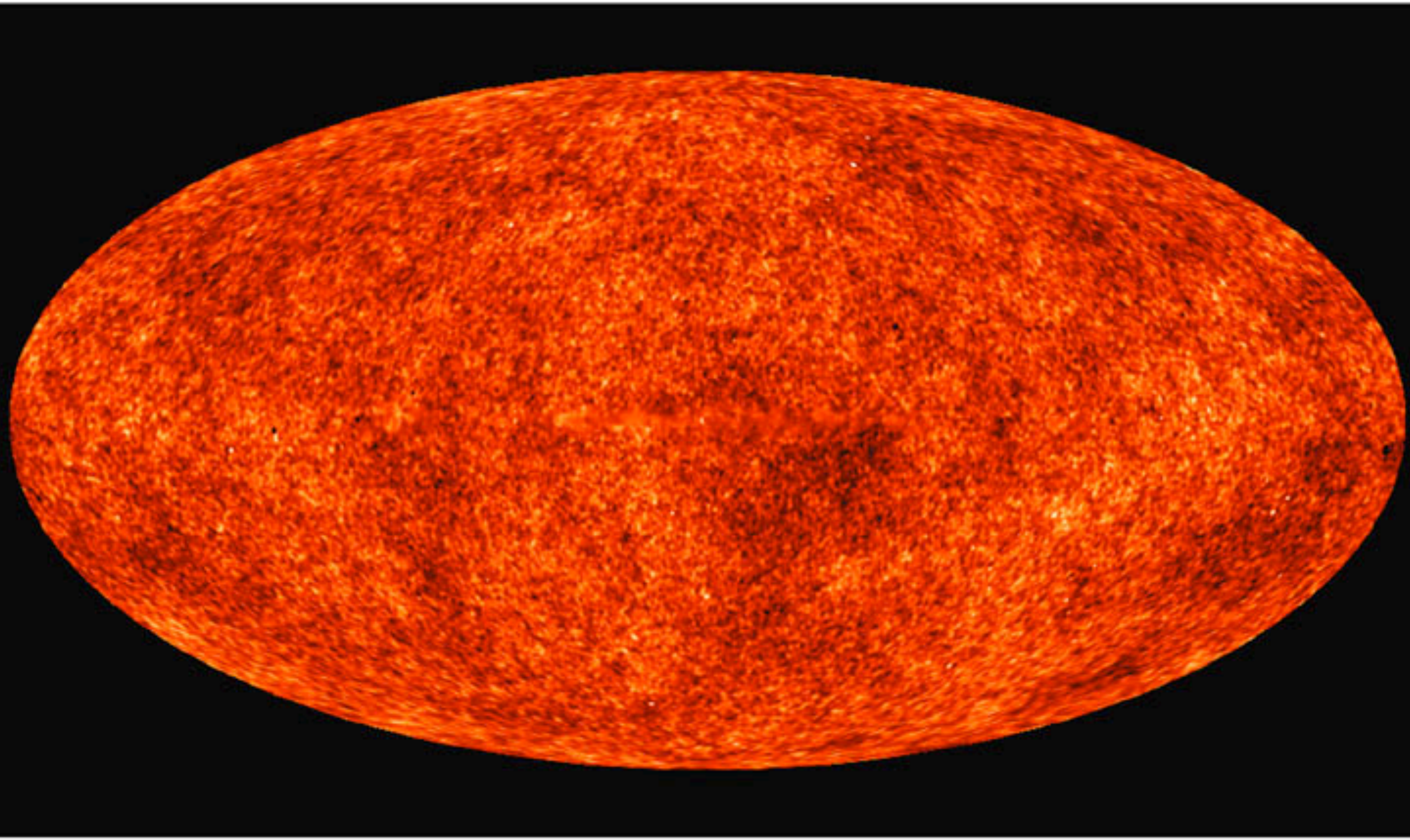
ASTR 333/433



TODAY

Cold Dark Matter in the Cosmic Microwave Background and the growth of Large Scale Structure

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.

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

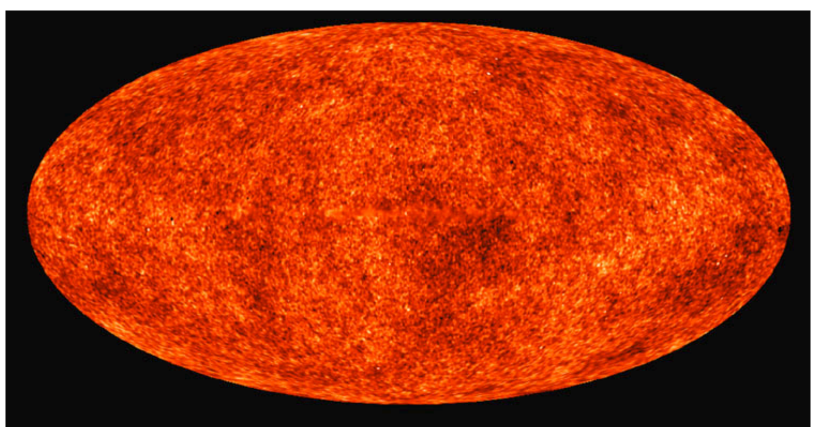
Gravity will grow the observed large scale structure, but it works slowly. Can't get here from there in a Hubble time: need a factor of 100,000 but only get 1,000. Cold dark matter speeds up the process while not overproducing the temperature fluctuations.

There isn't enough time for the observed large scale structure to grow from the smooth initial condition observed in the cosmic microwave background... unless there is a component of mass that does not couple to photons.

With CDM, you can get here from there

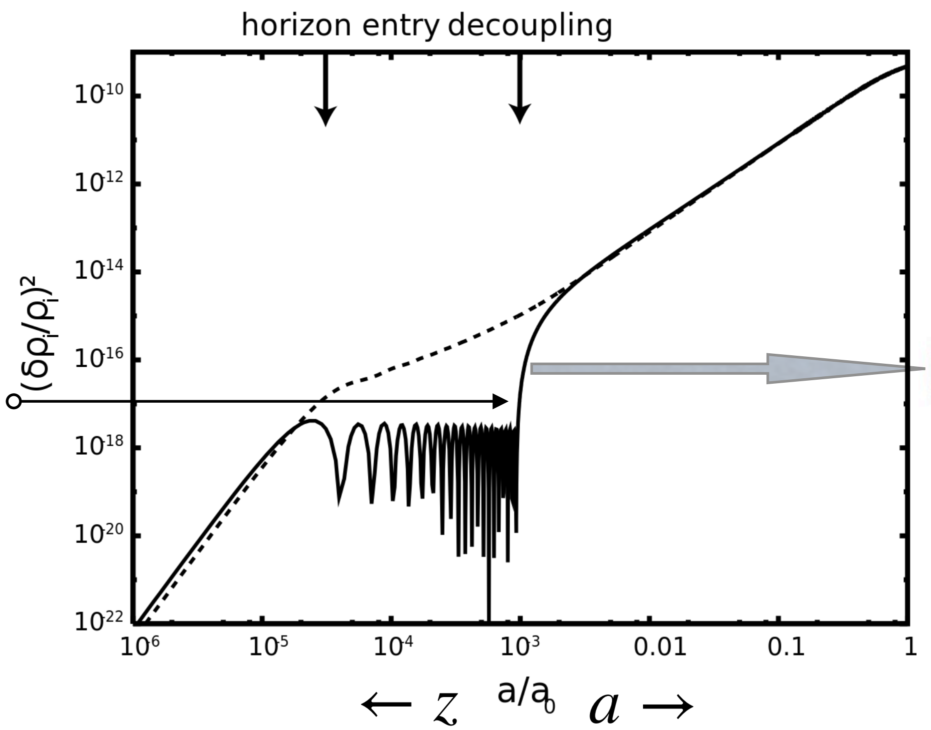
$\delta \propto a$

t = 3.8 x 10^5 yr



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

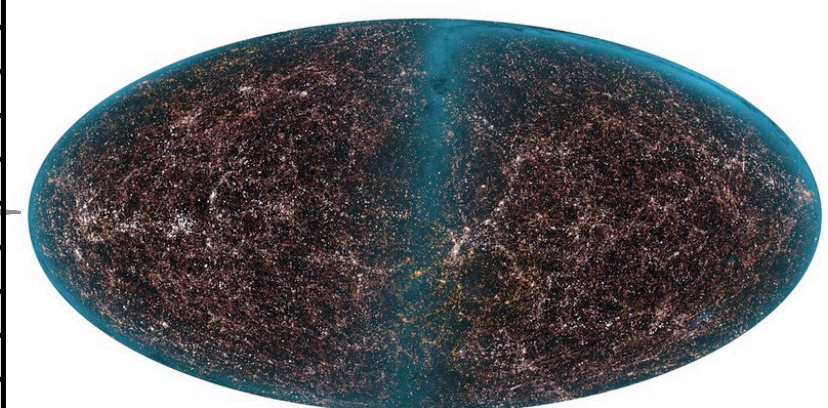
$z = 1090 \leftrightarrow a = 9 \times 10^{-4}$



$\leftarrow z$ $a \rightarrow$

$$a = \frac{1}{1+z}$$

t = 1.4 x 10^{10} yr



very lumpy: $\delta \sim 1$

$z = 0 \leftrightarrow a = 1$

Since perturbations grow at the same rate as the universe ($\delta \propto a$), the perturbations seen at $z = 1090$ should only have grown by that factor. Starting from the CMB observation $\delta = 10^{-5}$, that means structure now should have amplitude $\delta \approx 0.01$. Instead, it is 100 times larger! Non-baryonic CDM solves this problem by providing a component that can grow without imprinting large fluctuations on the CMB.

Non-baryonic Cold Dark Matter (CDM)

Some new particle, usually assumed to be a
WIMP (Weakly Interacting Massive Particle)
WIMPs don't interact electromagnetically, so are very dark.

Two big motivations:

1) total mass outweighs normal mass from BBN

$$\Omega_m > \Omega_b$$

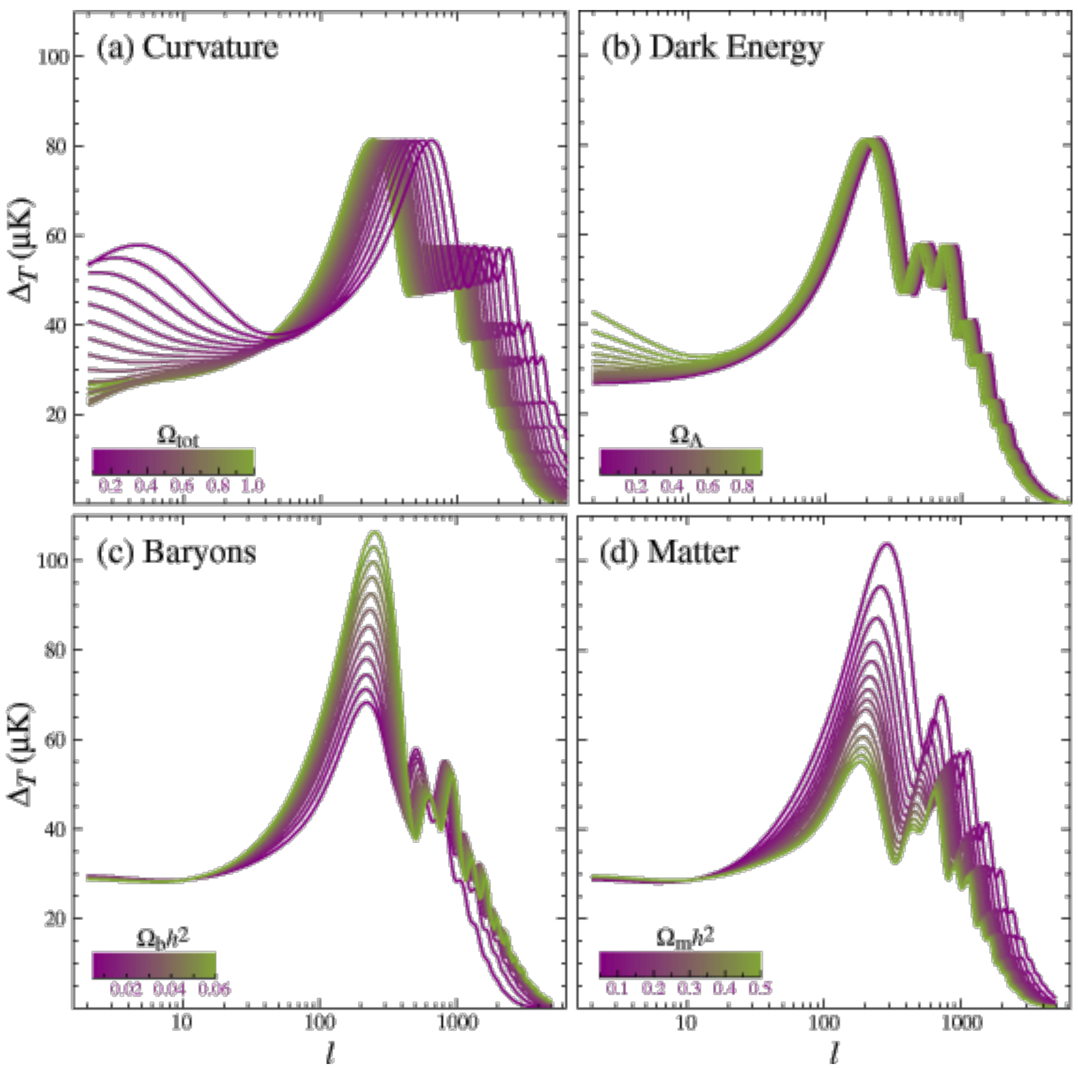
2) needed to grow cosmic structure

$$\delta_m \gg a$$

These two observations launched the CDM paradigm.
There is now additional evidence for CDM in the acoustic power spectrum of the CMB.

Acoustic power spectrum of the CMB

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

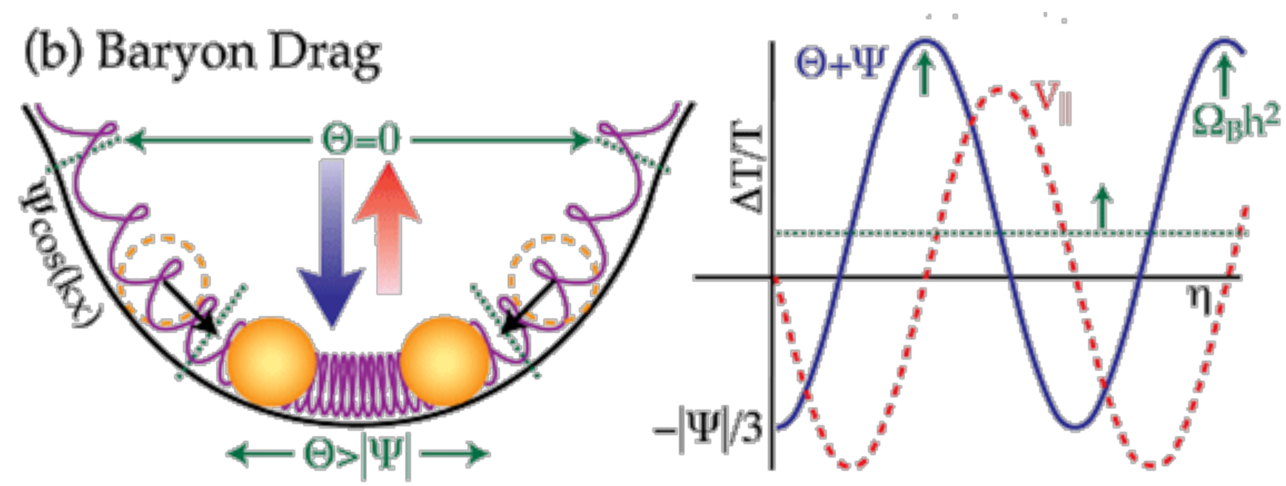
$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\rho}{\rho}$$

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.

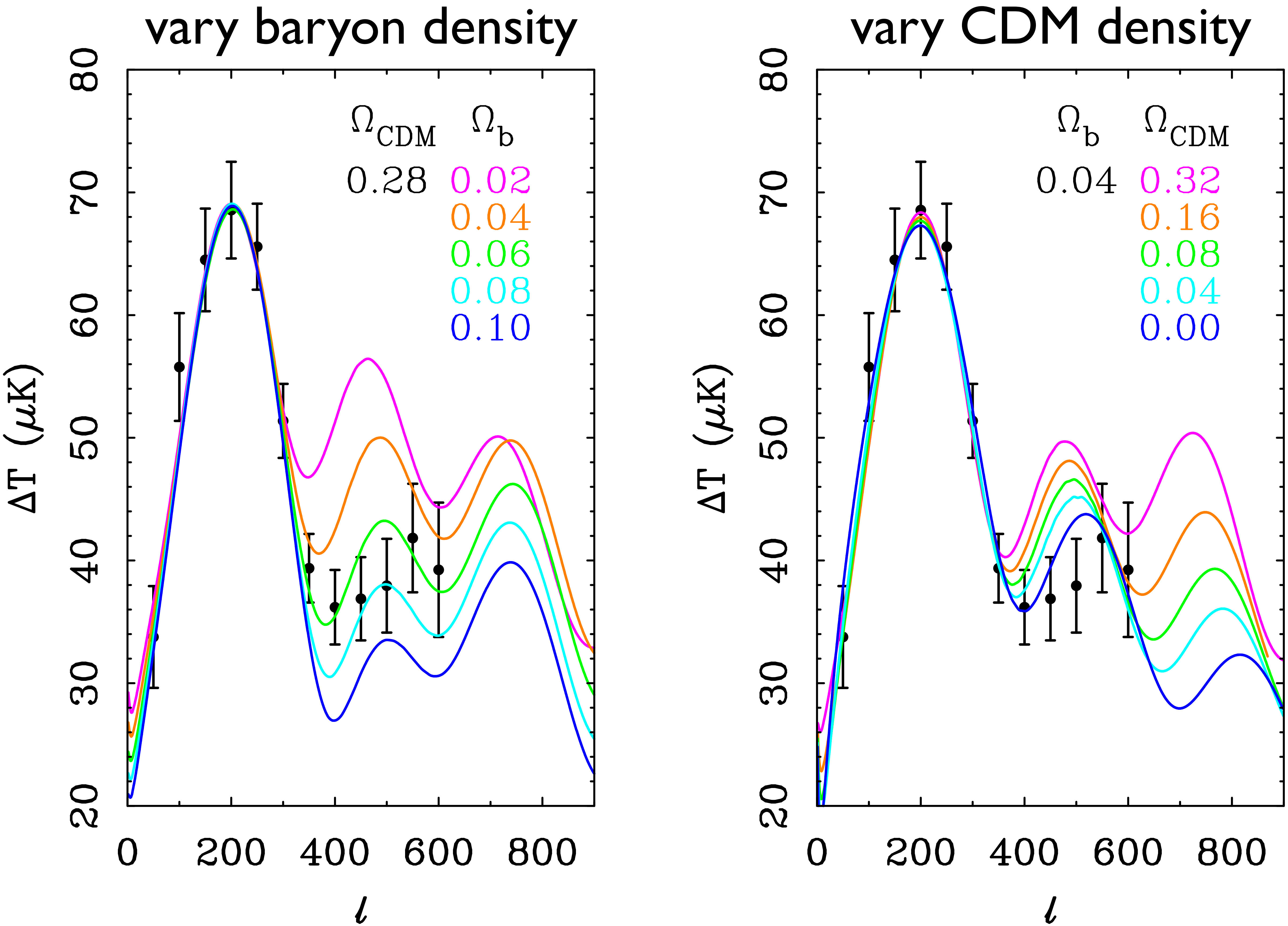


$$\nabla^2\Phi = 4\pi G(\rho_b\delta_b + \rho_\gamma\delta_\gamma + \rho_{CDM}\delta_{CDM})$$

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

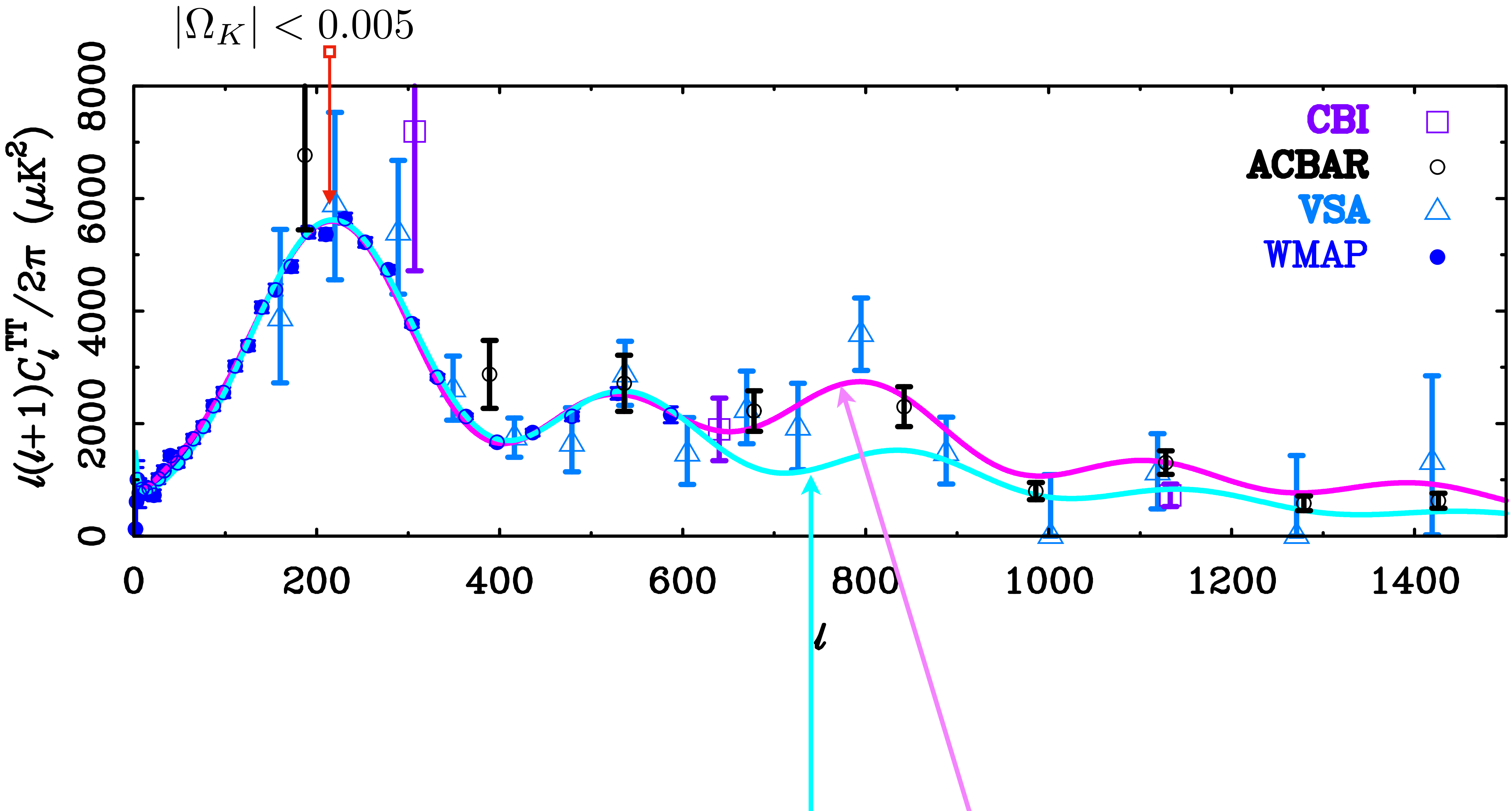
See also the movies of Max Tegmark at http://space.mit.edu/home/tegmark/movies.html

Acoustic power spectrum of the CMB



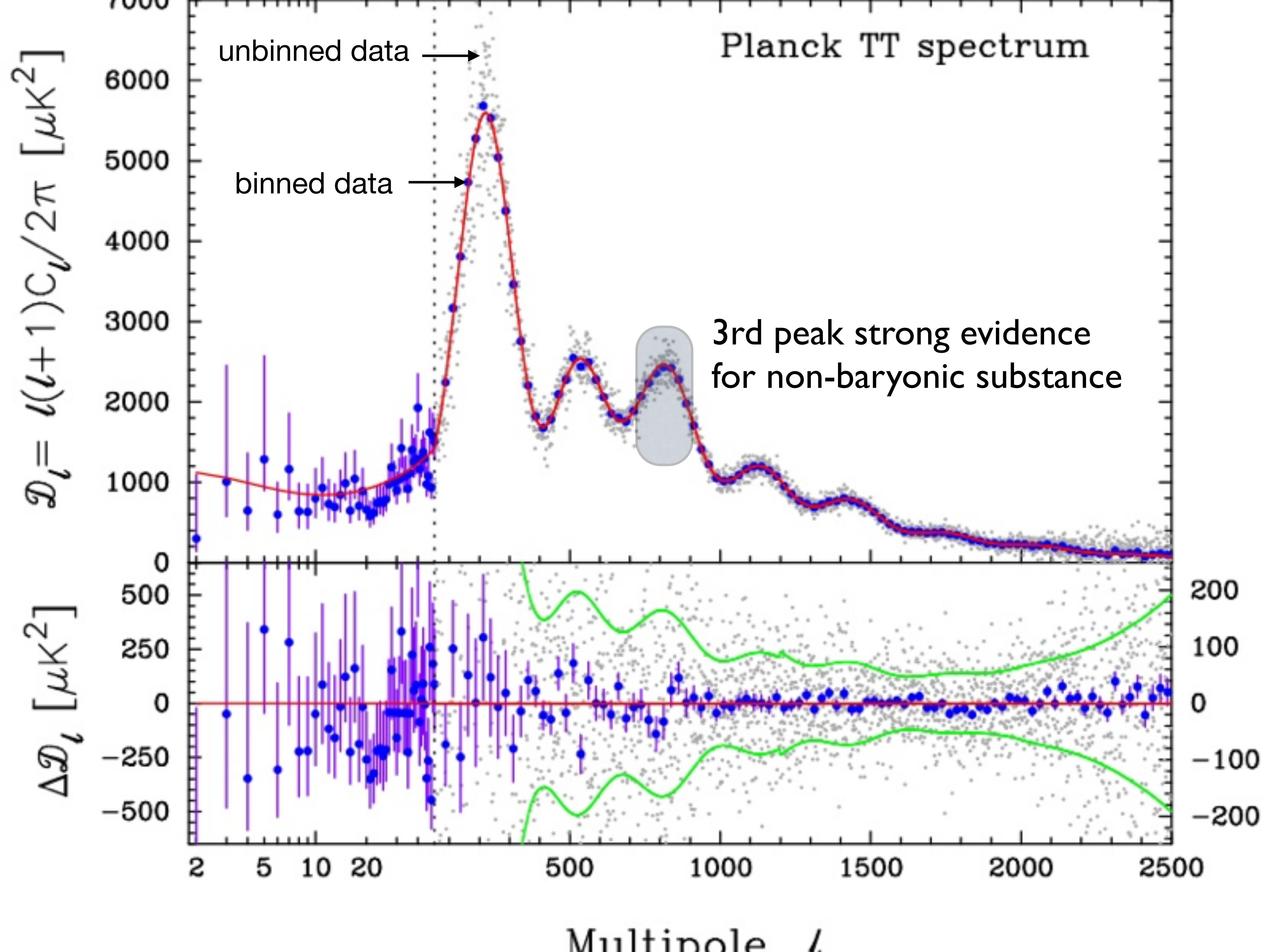
CMB power spectra

Acoustic power spectrum of the CMB



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

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



Planck TT spectrum
unbinned data
binned data
3rd peak strong evidence
for non-baryonic substance
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

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

(masses of ~ 10^5 $M_\odot$ conceivable, but most mass ranges have been excluded by gravitational lensing observations)

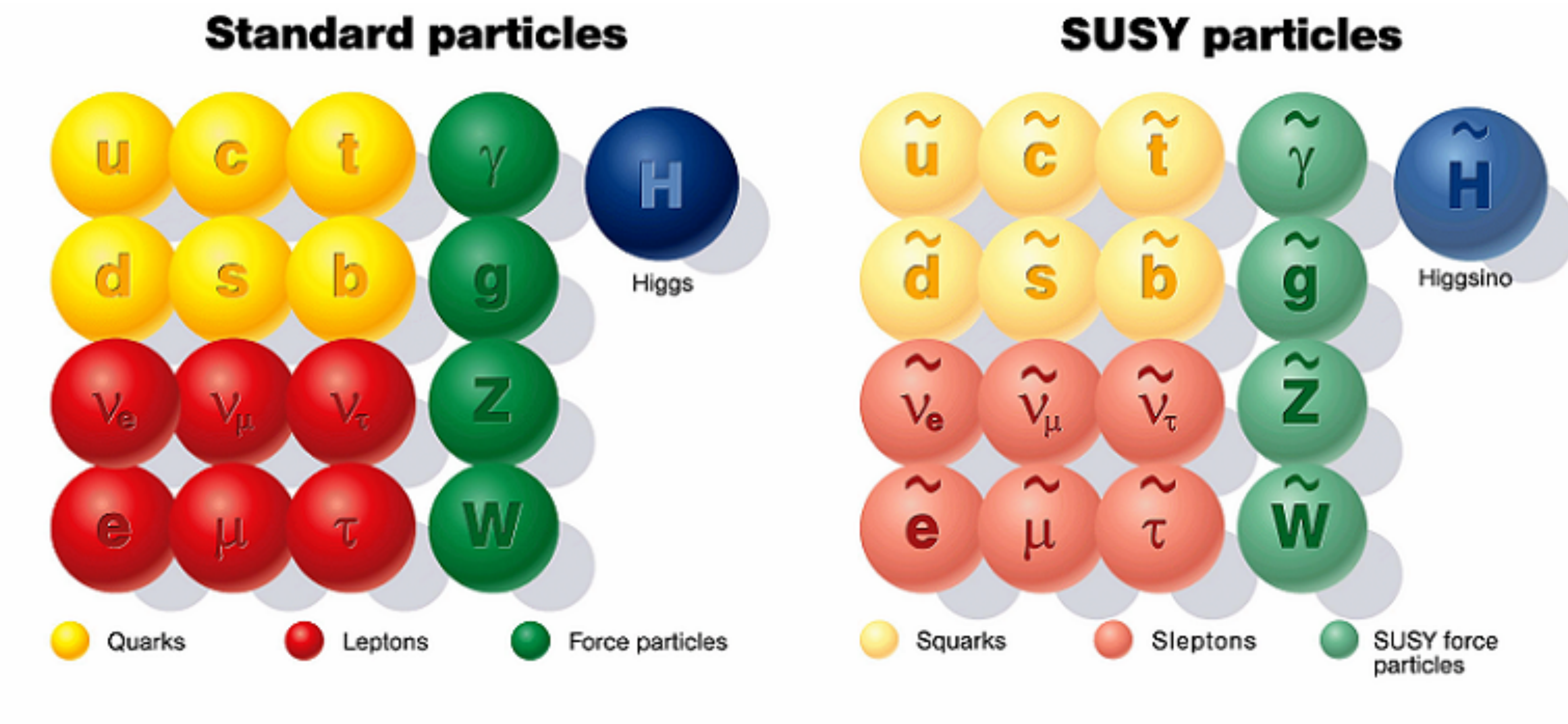
WIMPs are not just a new particle to discover. Their existence requires entirely new physics, something like SuperSymmetry.

STANDARD MODEL OF ELEMENTARY PARTICLES

proton:
up+up+down

neutron:
up+down+down

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

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93\ \mathrm{eV}}$$

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

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

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

$20 \lesssim x_{fo} < 50$
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: $m_X > 2\ \mathrm{GeV}$ to not over-produce cosmic mass density

THE WIMP MIRACLE

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

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

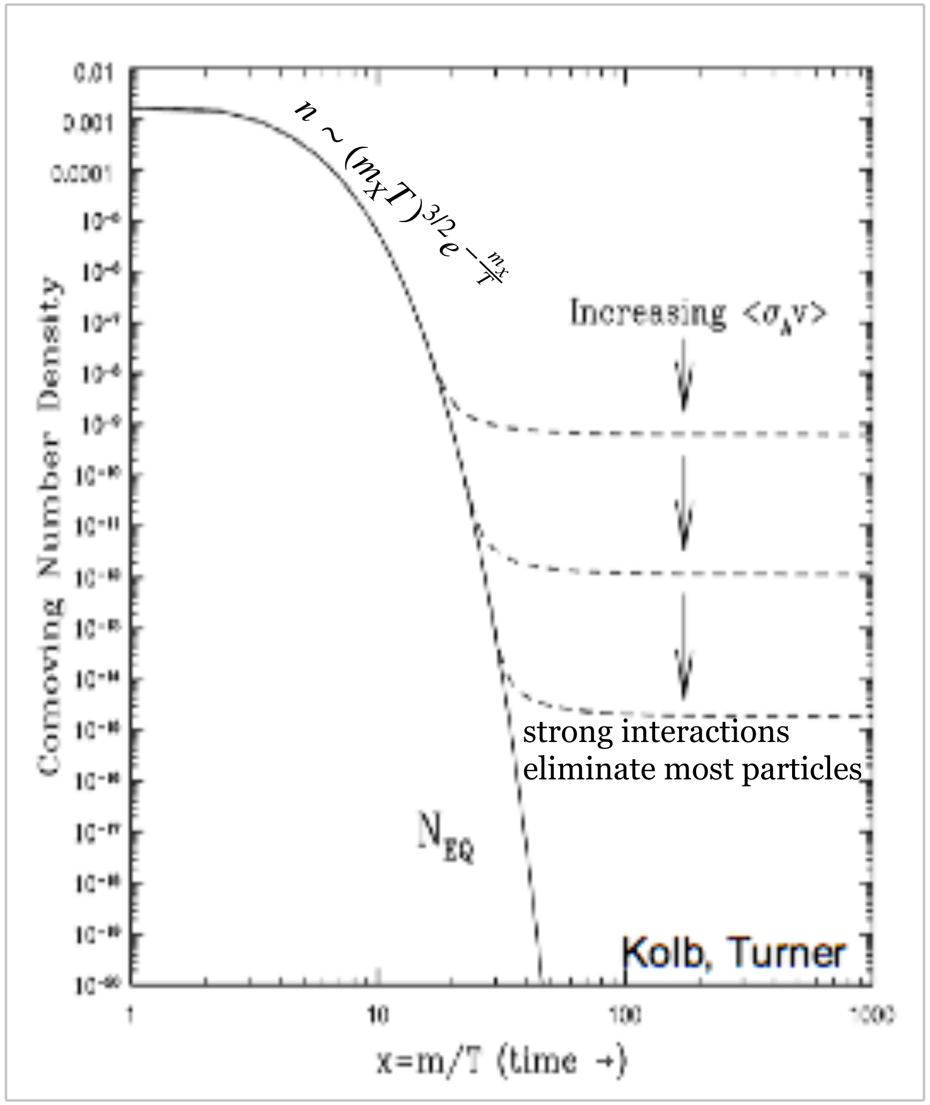
- $G_F \approx 1.1\ 10^5\ \text{GeV}^{-2} \rightarrow$ a new mass scale in nature

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

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

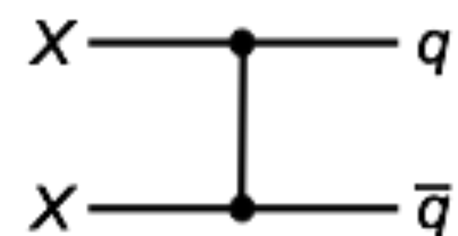
From review by Feng et al. linked from course review literature page.

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.



- 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, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

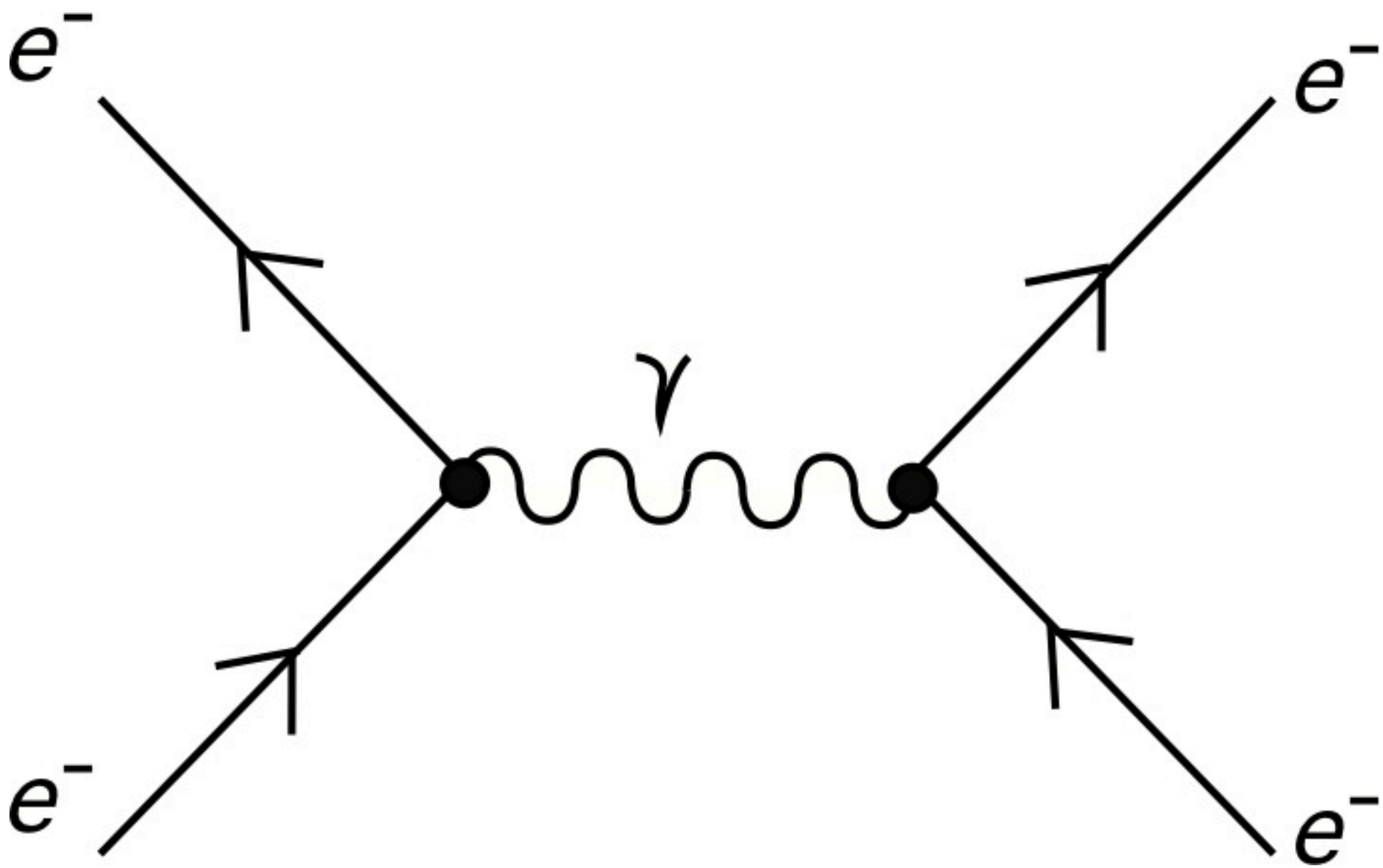
$\langle\sigma v\rangle$ "thermal cross-section"

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

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

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

Feynman diagram

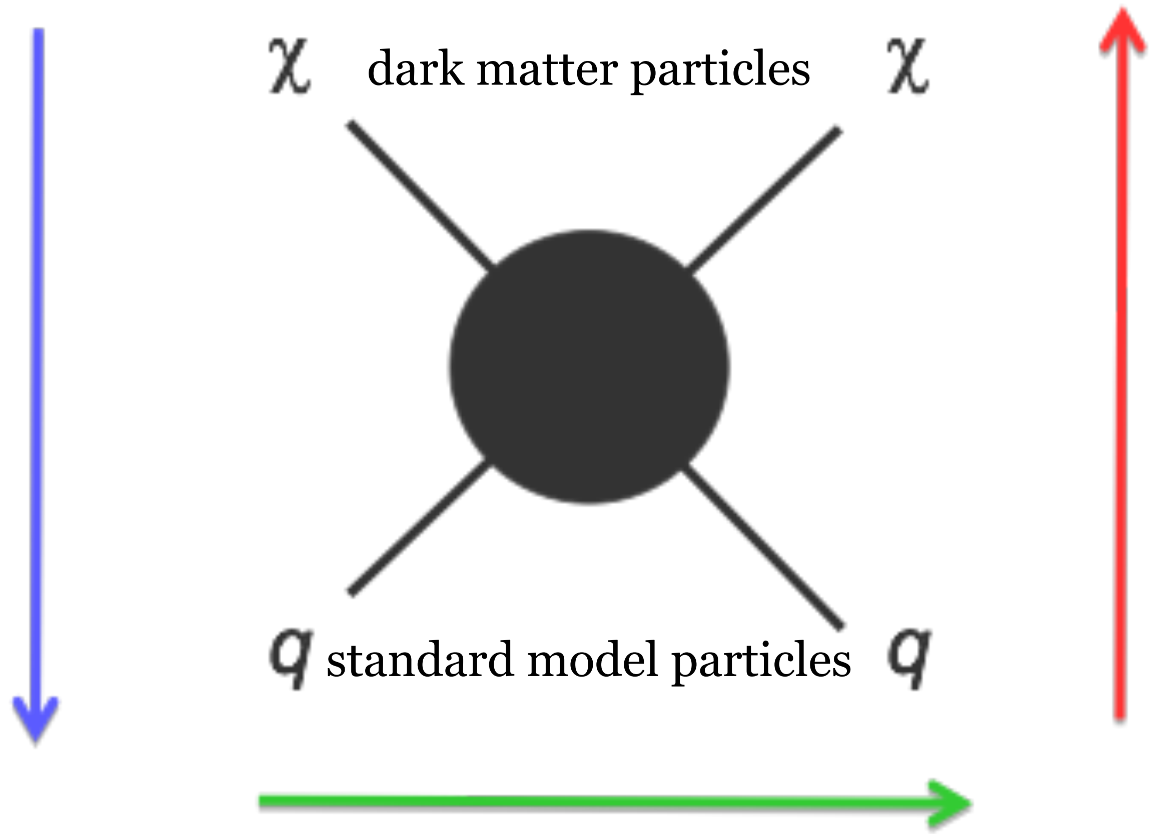


Illustrates the interaction of particles by the exchange of force carriers - in this case, electrons scatter by photon exchange

(electrostatic repulsion: two negatively charged particles repel each other)

WIMP DETECTION

Correct relic density → *Lower* bound on DM-SM interaction



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

Efficient annihilation now (Indirect detection)

Efficient production now (Particle colliders)

WIMPs created in particle colliders (like the LHC)

Efficient scattering now (Direct detection)

WIMPs scatter off nuclei in underground laboratory experiments