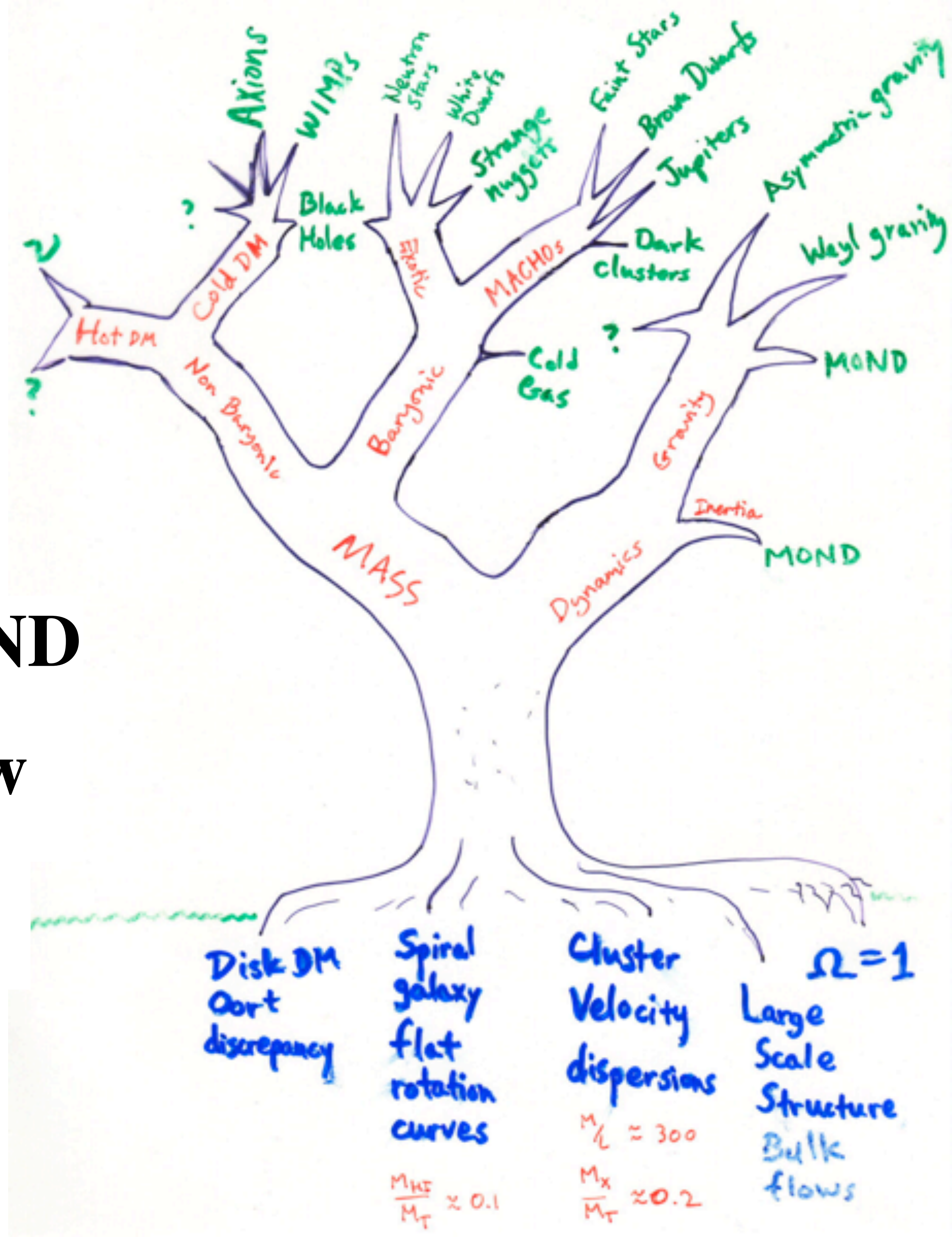
Today: **cosmology**

- CMB
- WIMPs

Tomorrow: **433, MOND**

4/19: **HW due, review**

4/21: **Exam**



CMB temperature fluctuations directly related to density fluctuations

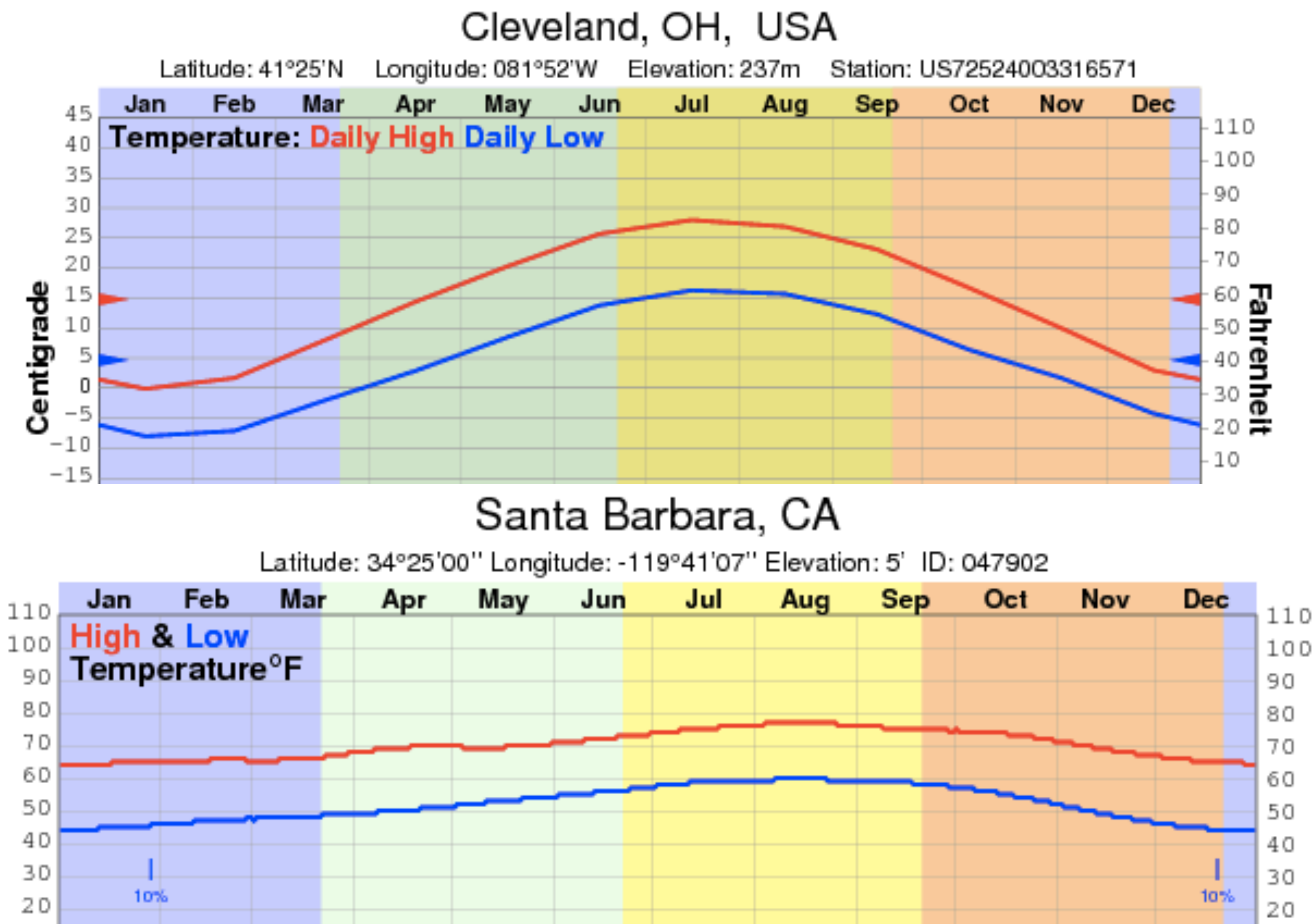
$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\rho}{\rho}$$

Fits to the acoustic power spectrum of the CMB strongly constrain cosmic parameters

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

Power Spectrum

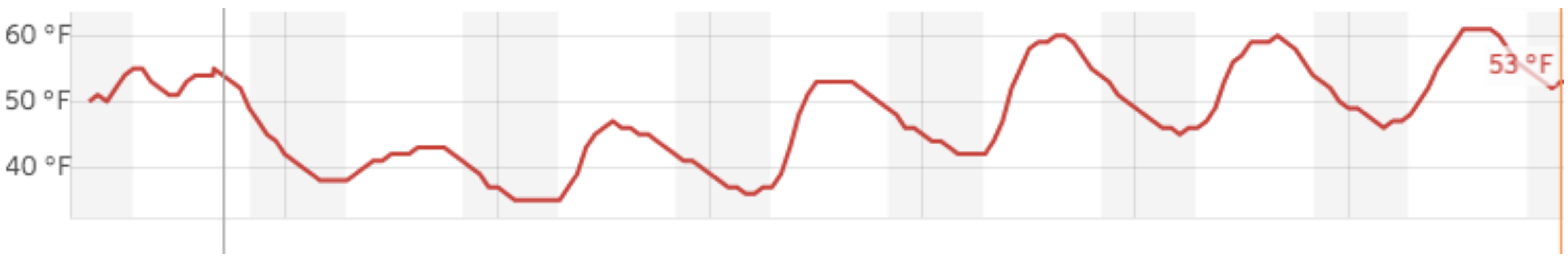
Example: weather in Cleveland and Santa Barbara
More power on long time scales in Cleveland (seasonal variation)



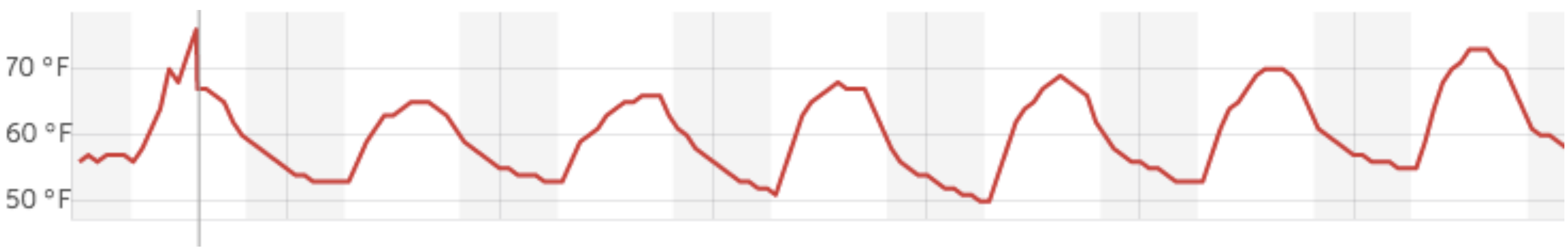
Power Spectrum

Example: weather in Cleveland and Santa Barbara
A little more power on short time scales in Santa Barbara
(diurnal variation)

Cleveland forecast

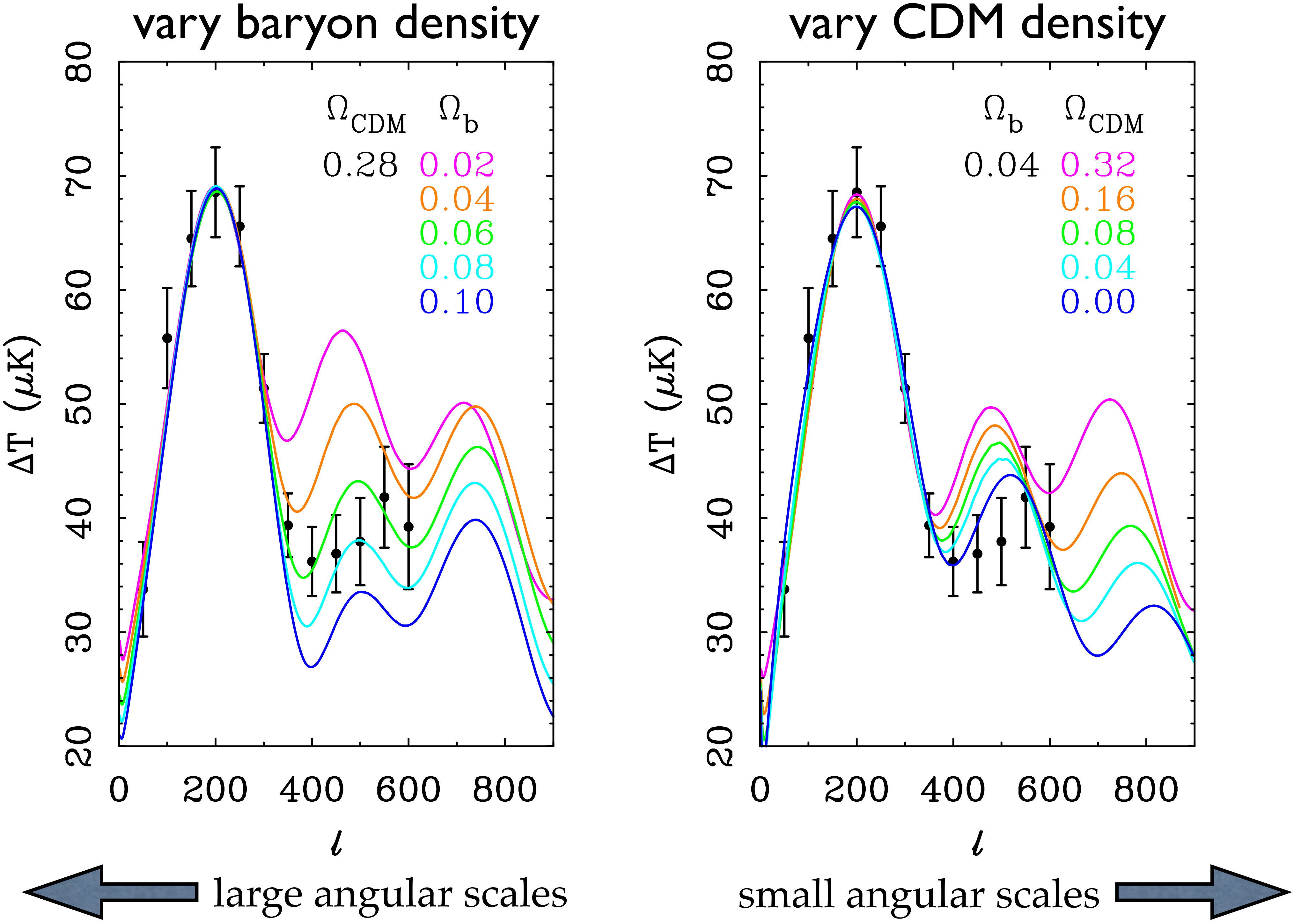


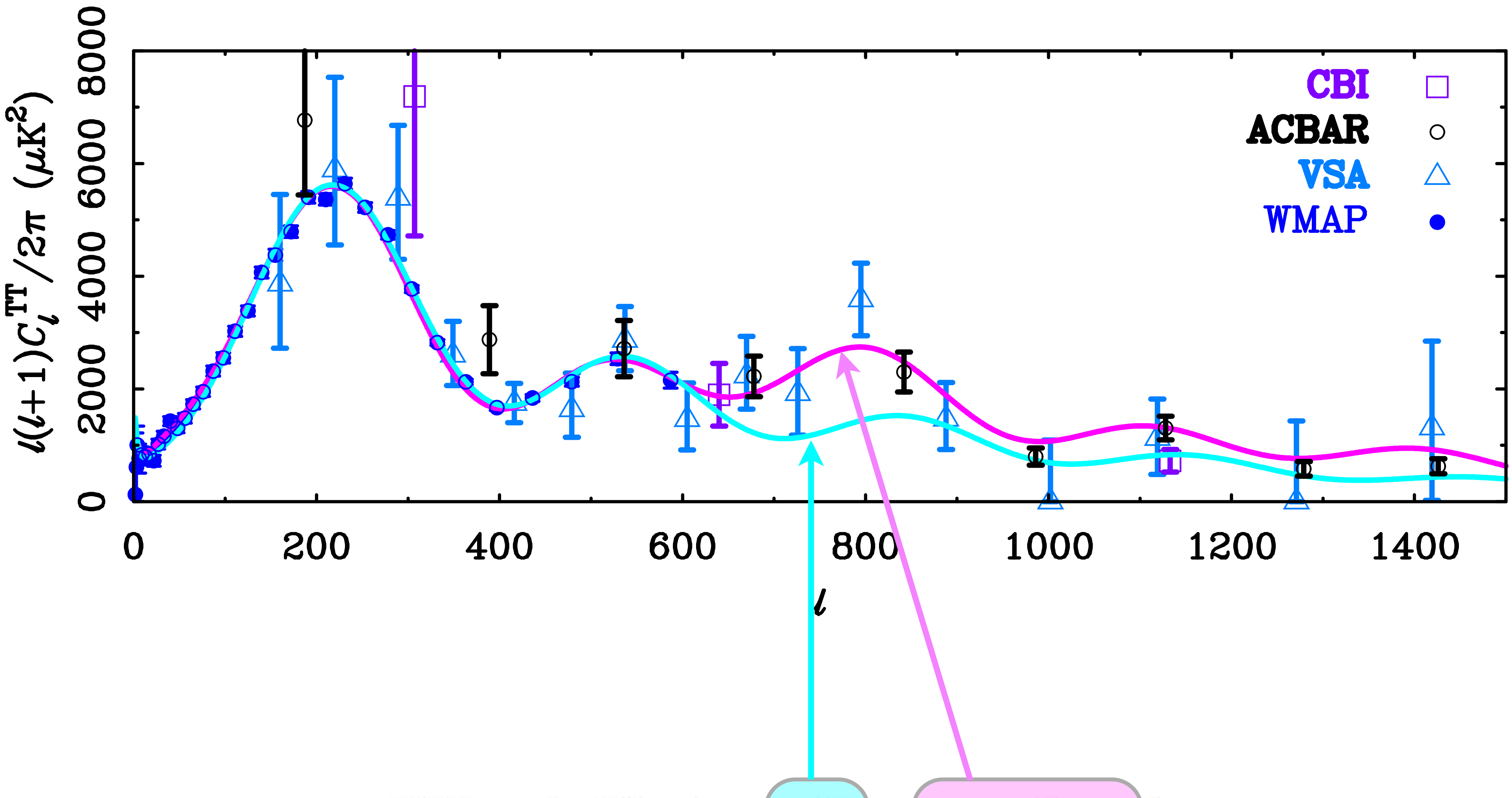
Santa Barbara forecast



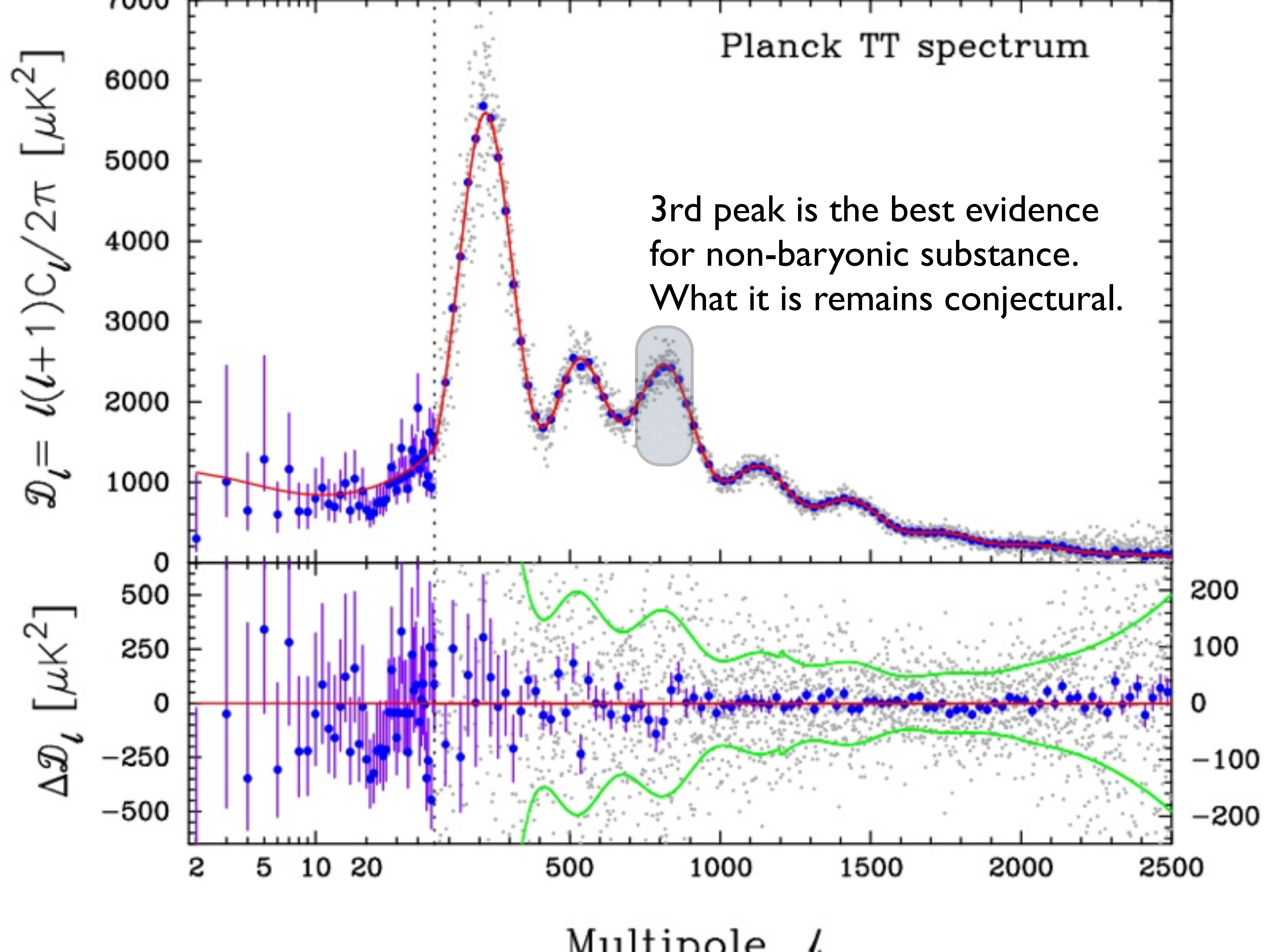
A power spectrum is a fourier transform that quantifies the relative variability on different scales

CMB power spectra



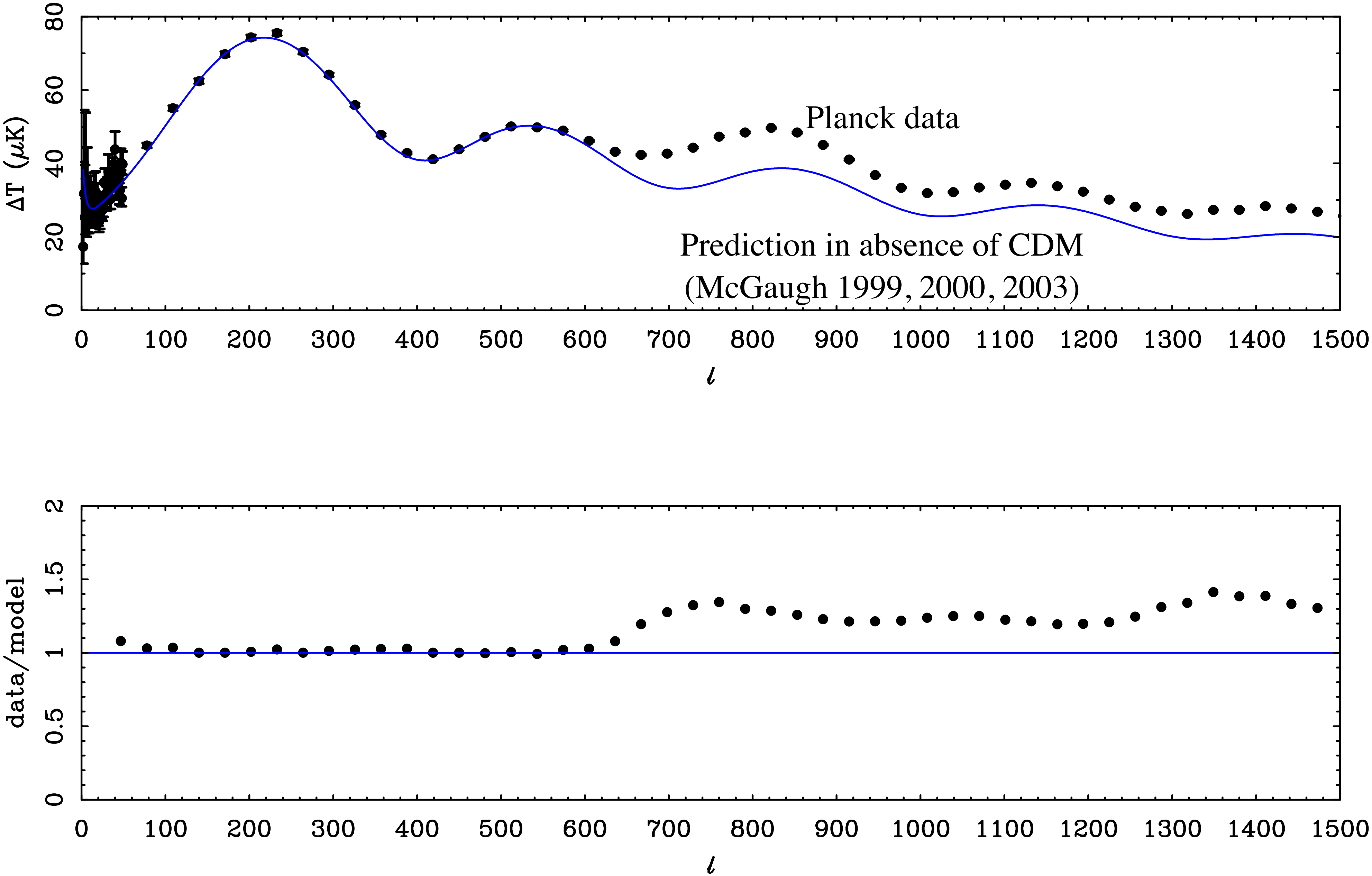


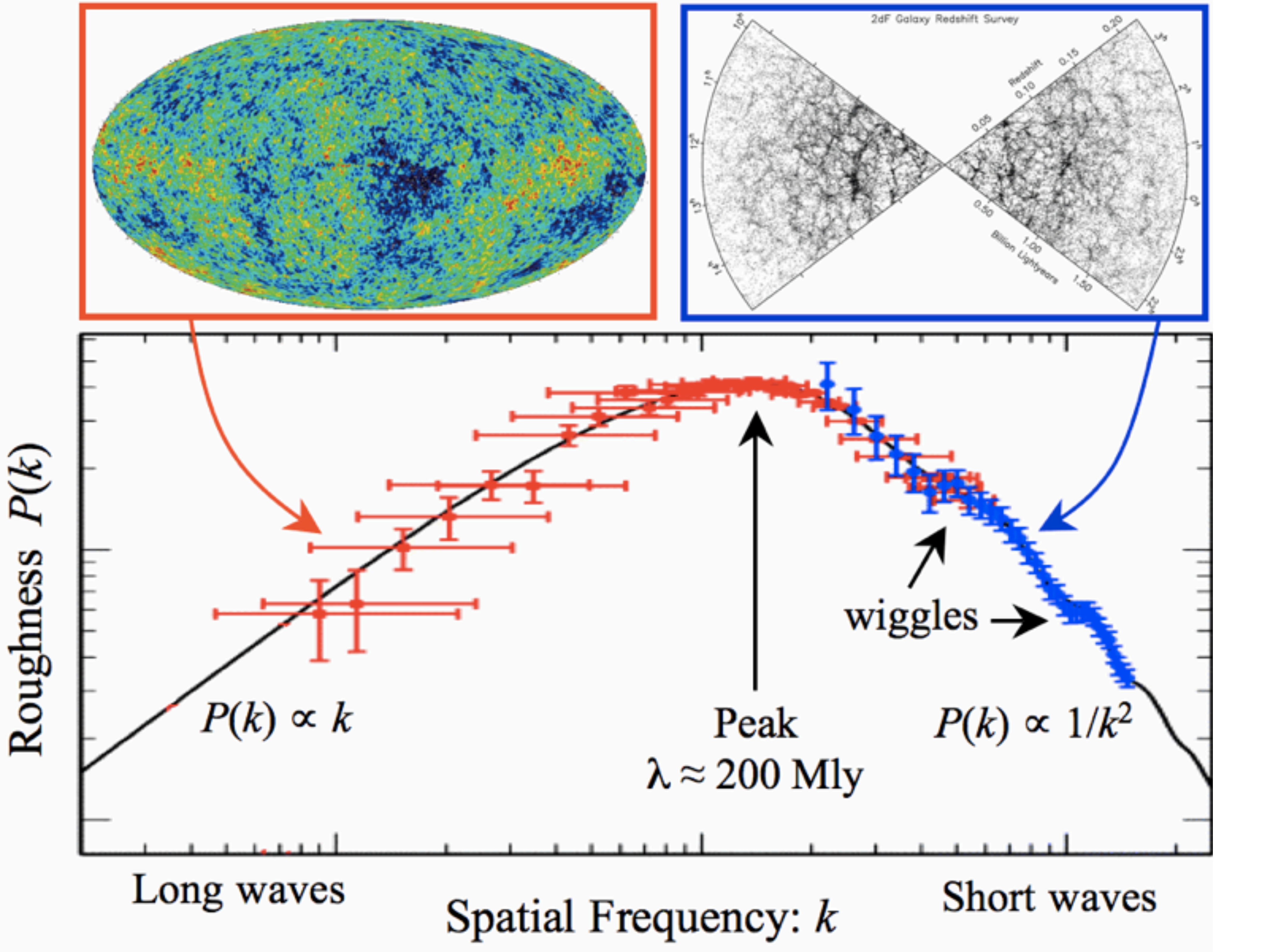
$$k^2\Phi = 4\pi G(\rho_b\delta_b + \rho_\gamma\delta_\gamma + \rho_{CDM}\delta_{CDM})$$



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

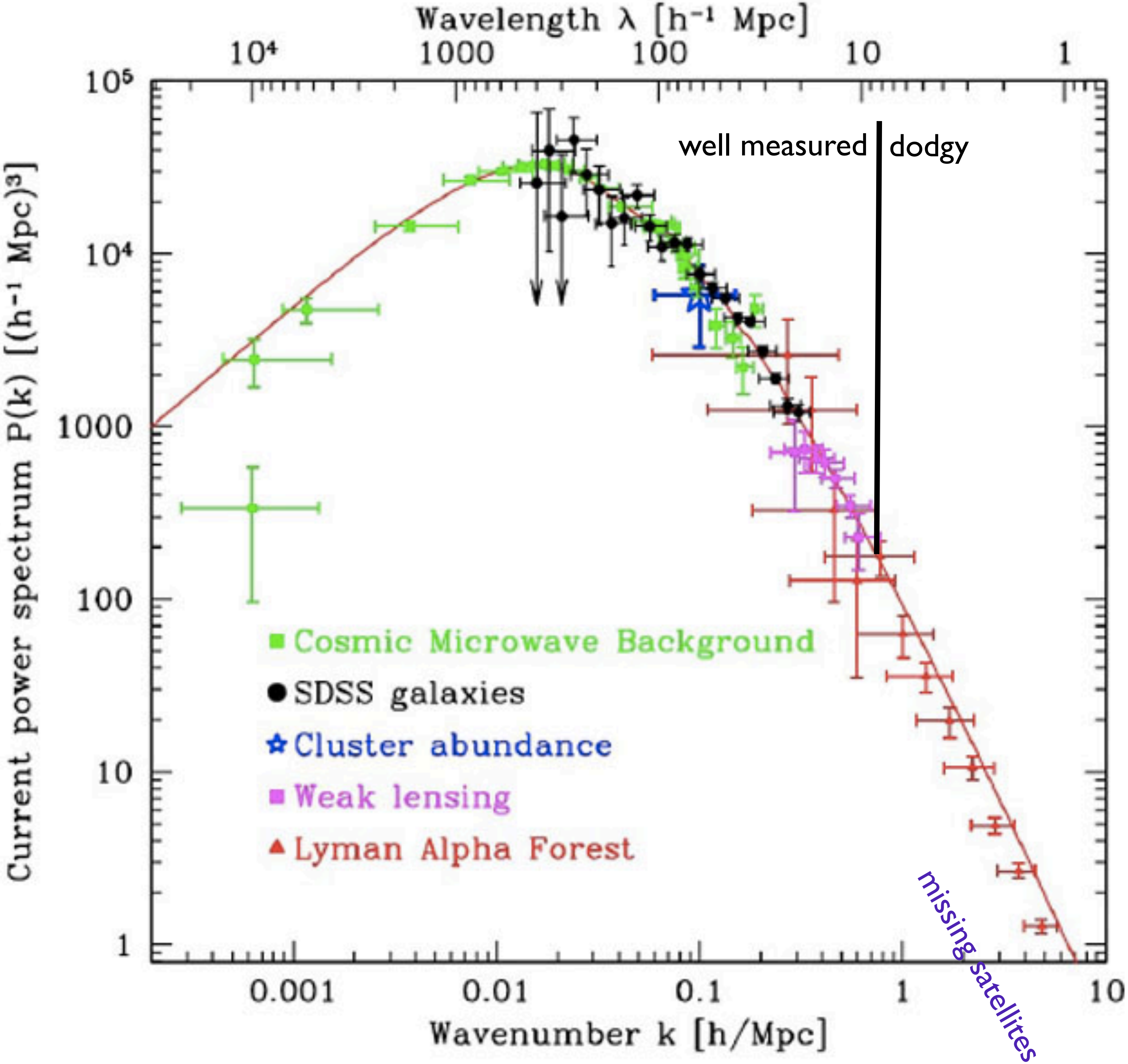
CMB power spectrum



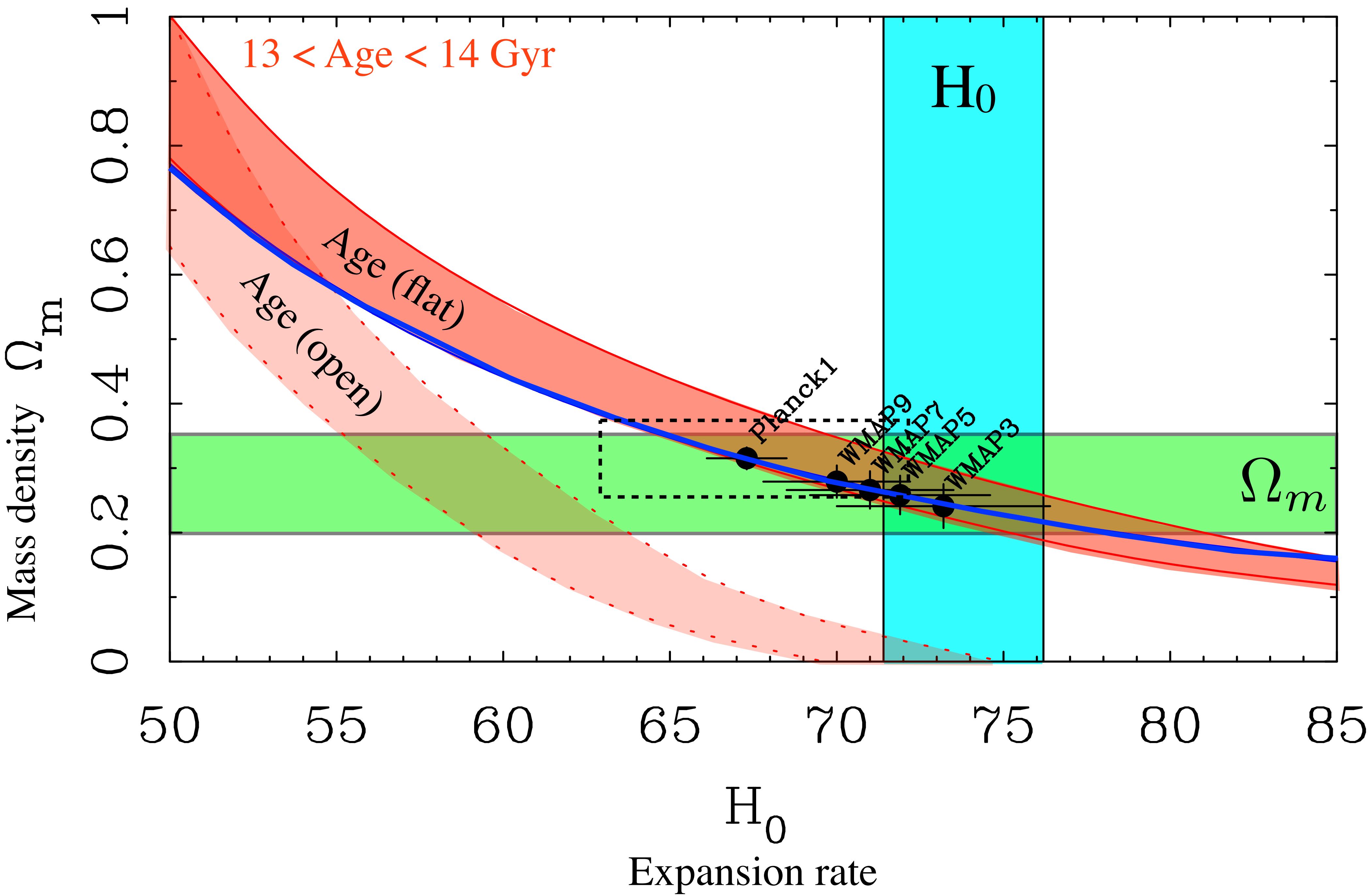


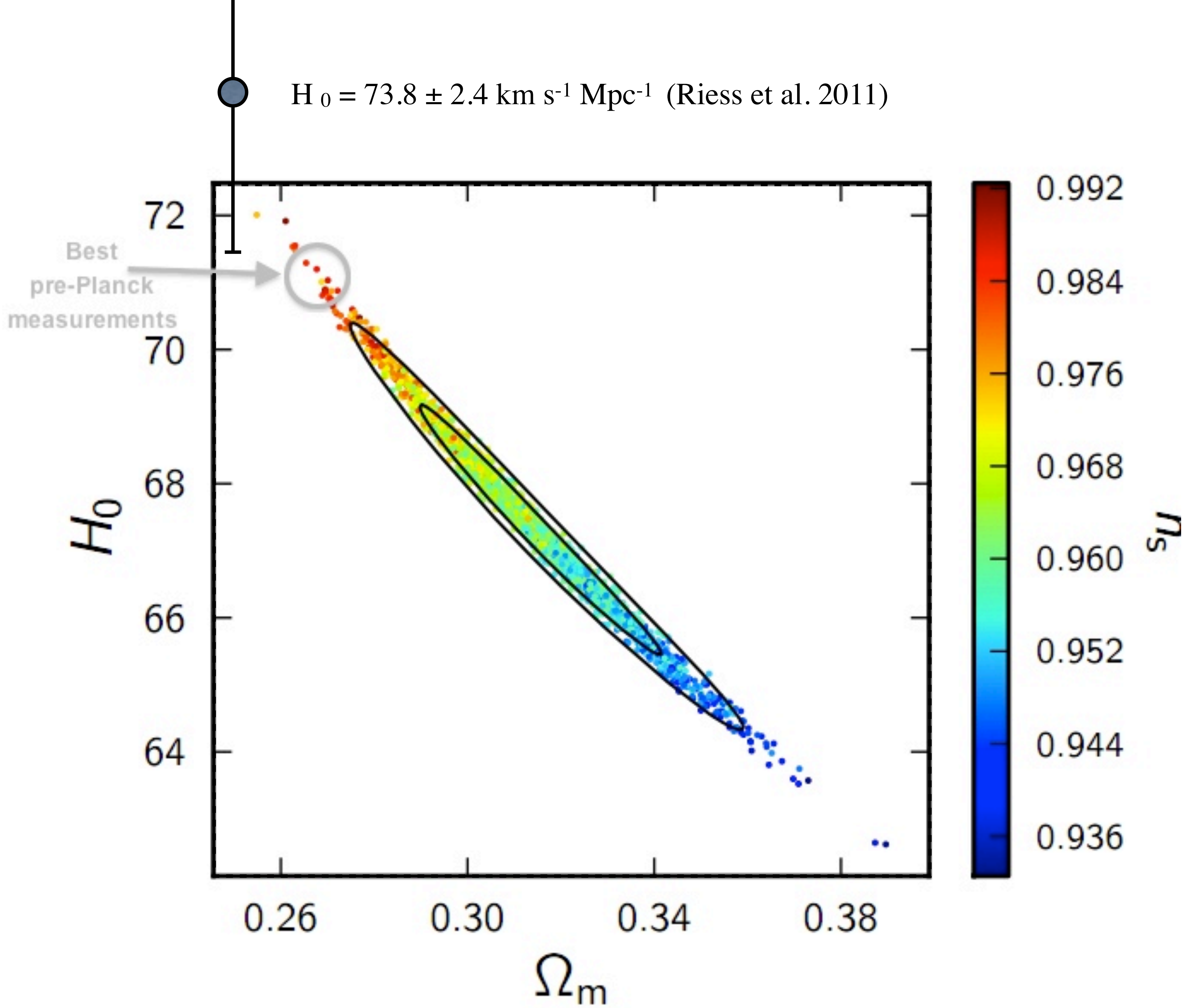
2dF Galaxy Redshift Survey
Redshift
Billion Lightyears
Roughness $P(k)$
$P(k) \propto k$
Peak
$\lambda \approx 200$ Mly
wiggles
$P(k) \propto 1/k^2$
Long waves
Spatial Frequency: k
Short waves

Power spectrum in 3D space (not 2D angle)



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





H $_0$ = 73.8 ± 2.4 km s^{-1} Mpc^{-1} (Riess et al. 2011)
Best
pre-Planck
measurements
72
70
68
66
64
H_0
0.26
0.30
0.34
0.38
Ω_m
0.992
0.984
0.976
0.968
0.960
0.952
0.944
0.936
n_s

"Cosmologists are often wrong, but never in doubt"

\- Lev Landau

Things we know for sure in cosmology:

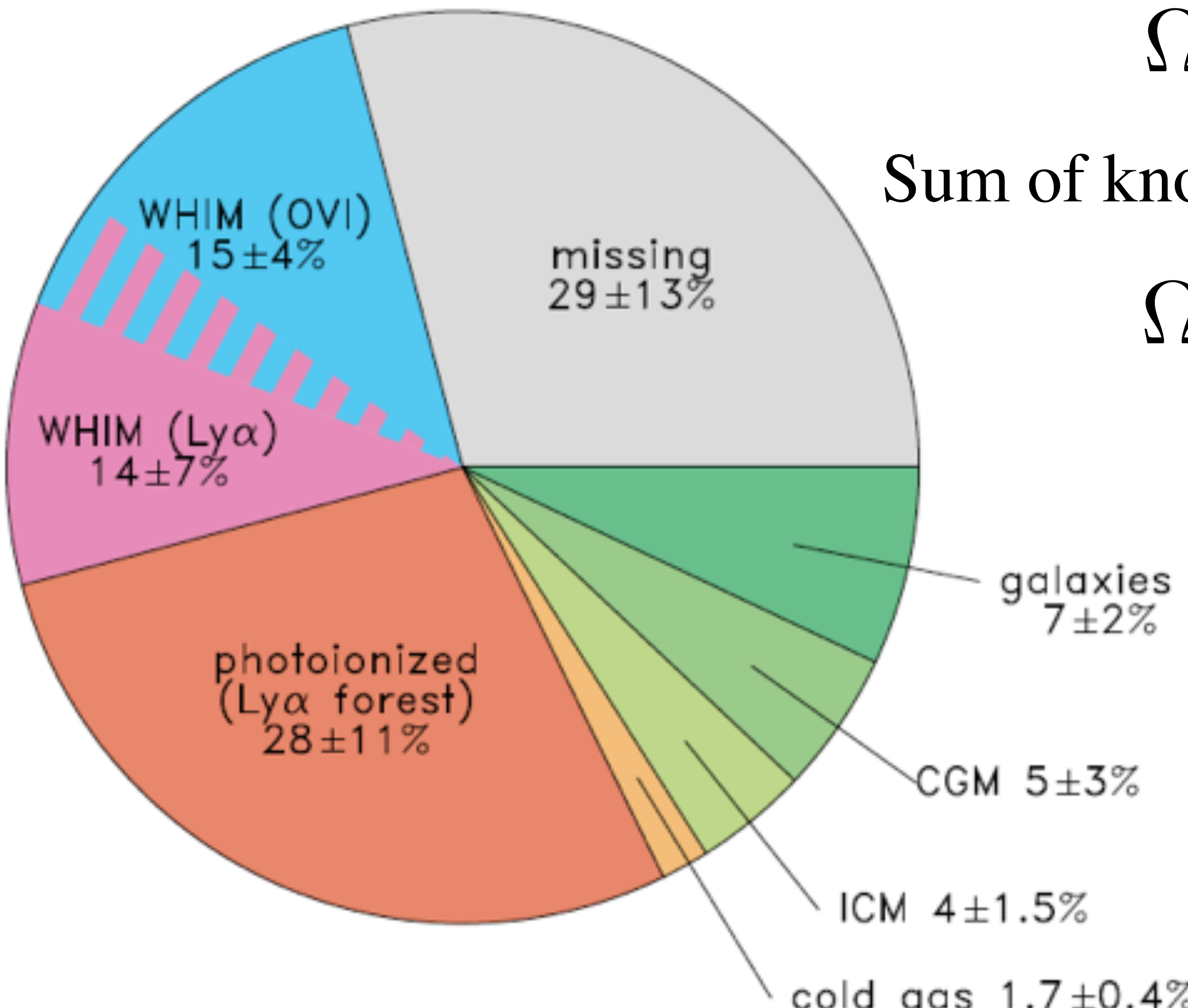
quantity	c. 1990	WMAP5 2008	Planck 2013
Ω_m	1.00	0.258±0.027	0.315±0.017
Ω_Λ	0.00	0.742	0.685
$\Omega_b h^2$	0.0125	0.02273 ±0.00062	0.02205 ±0.00028
$H_\circ$	50	71.9±2.7	67.3±1.2
dark matter	CDM	CDM	CDM

The global missing baryon problem

Cosmic baryon budget

(Shull et al arXiv:1112.2706)

@ $z = 0$



Big Bang Nucleosynthesis
CMB fits give

$$\Omega_b h^2 = 0.022$$

Sum of known baryons only

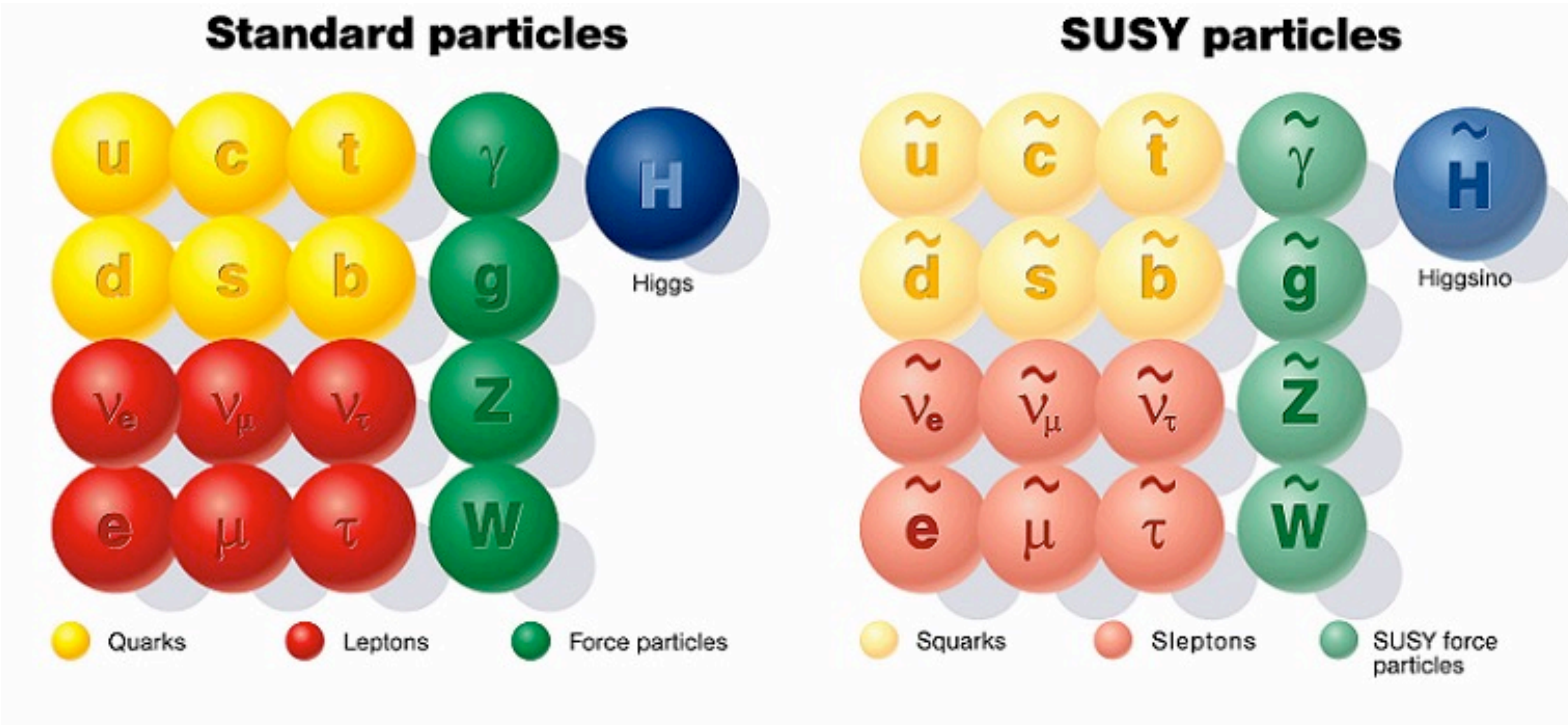
$$\Omega_b h^2 \approx 0.017$$

Total mass density

$$\Omega_m h^2 \approx 0.13$$

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).

THE WIMP MIRACLE

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

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

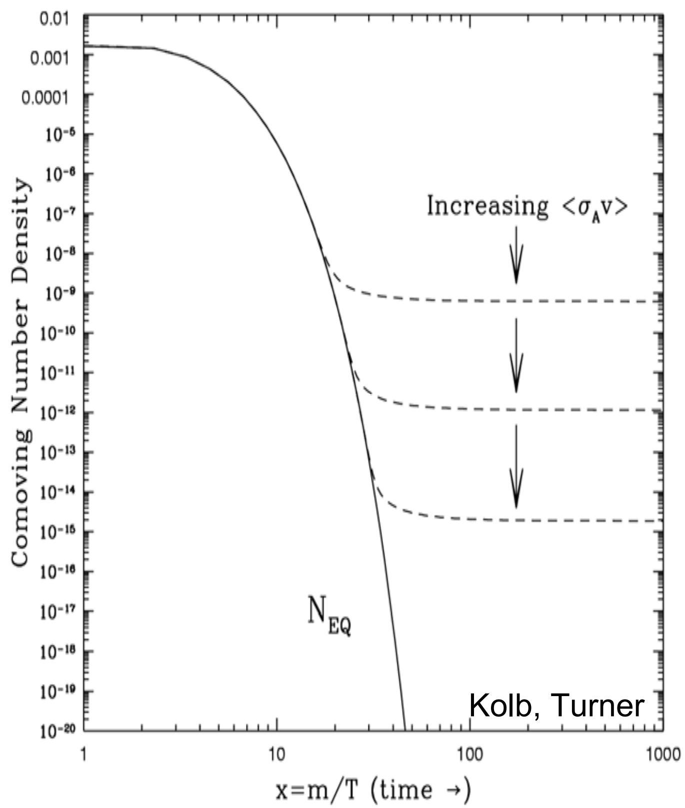
- $G_F \approx 1.1\ 10^5\ \text{GeV}^{-2} \rightarrow$ a new mass scale in nature

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

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

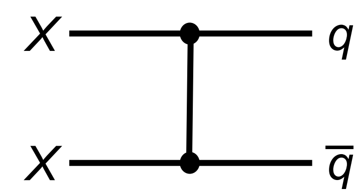
From review by Feng et al. linked off course review literature page.

THE WIMP MIRACLE



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

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



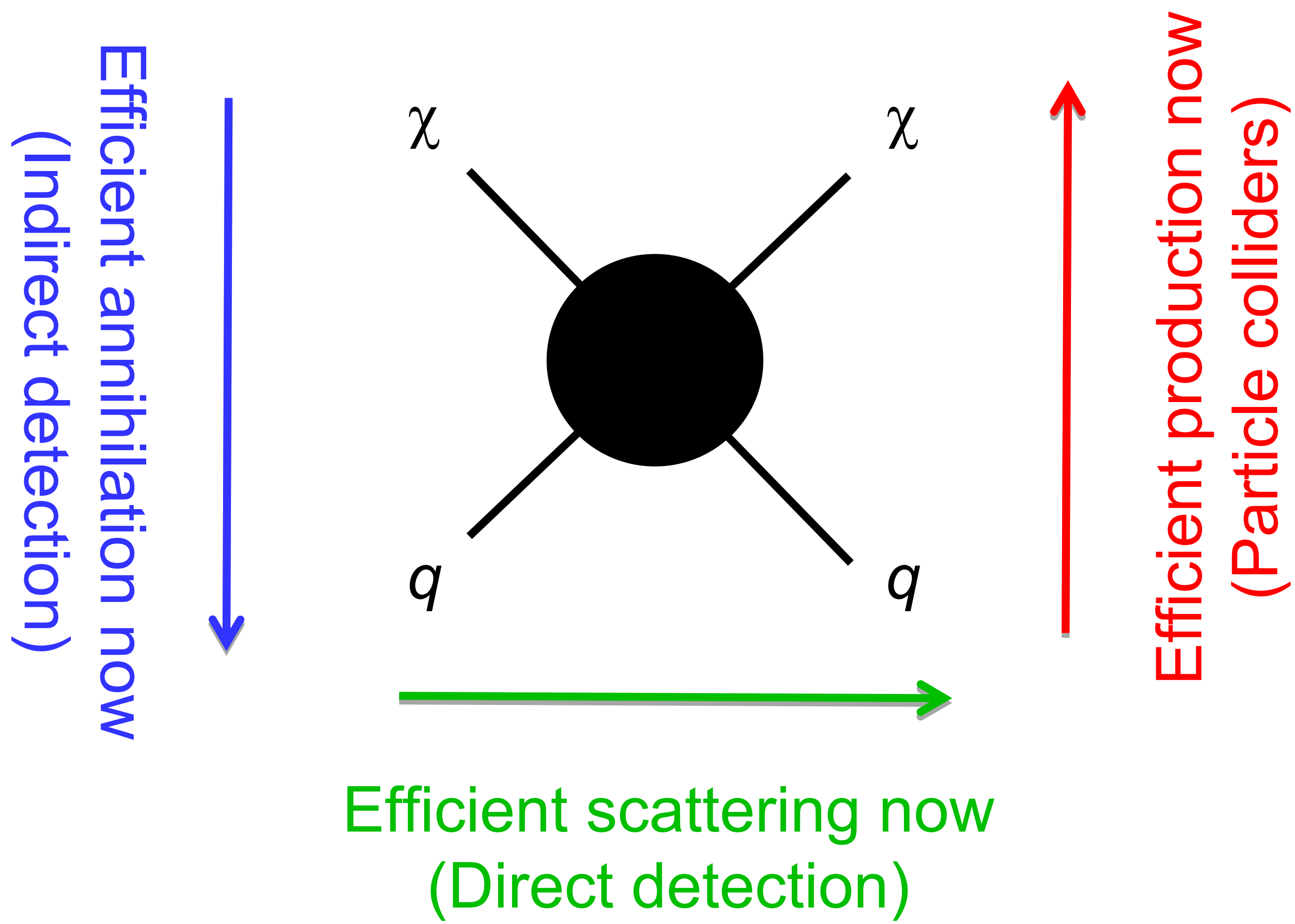
- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

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

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

WIMP DETECTION

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



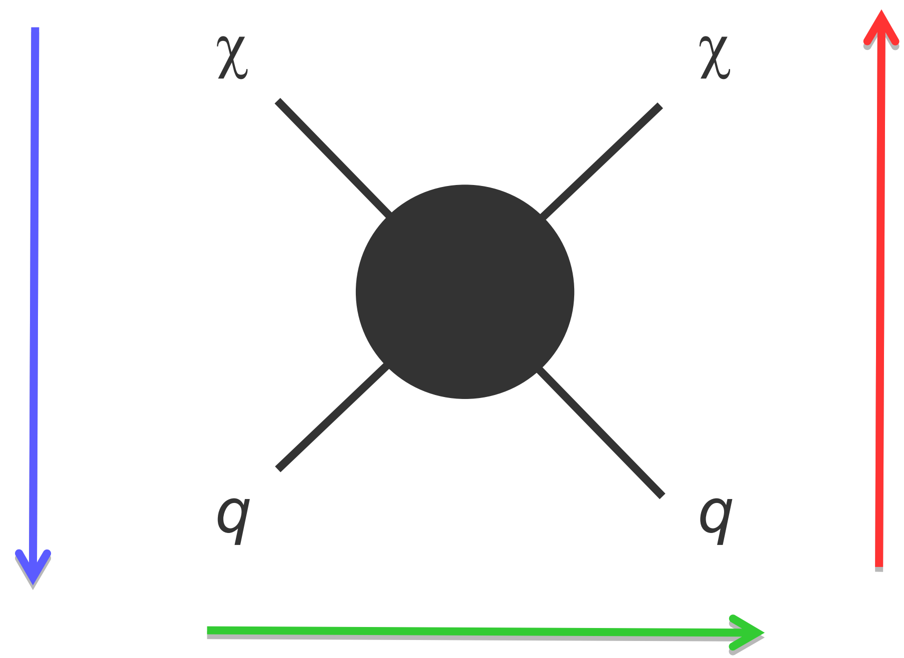
From review by Feng et al. linked off course review literature page.

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)

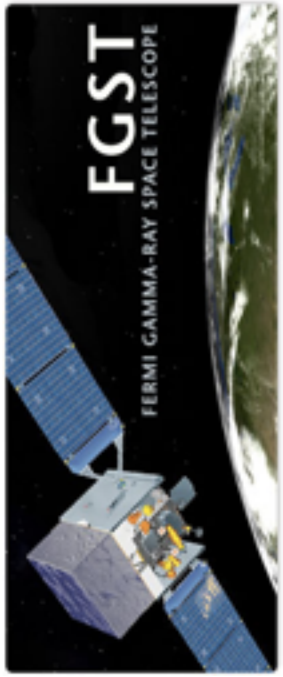


Efficient production now (Particle colliders)

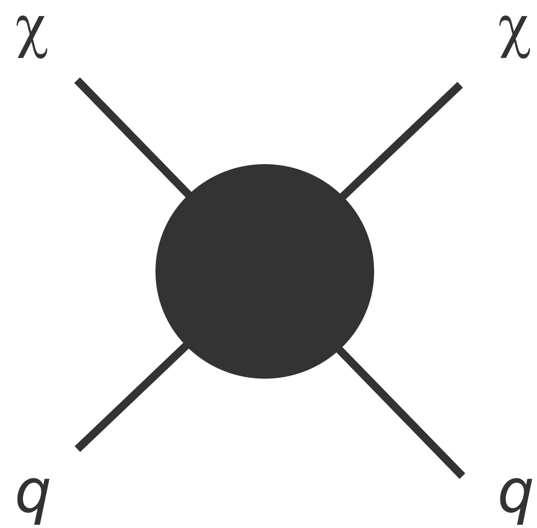
WIMPs created in particle colliders (like the LHC)

Efficient scattering now (Direct detection)

WIMPs scatter off nuclei in underground laboratory experiments



Efficient annihilation now
(Indirect detection)



Efficient production now
(Particle colliders)

Efficient scattering now
(Direct detection)

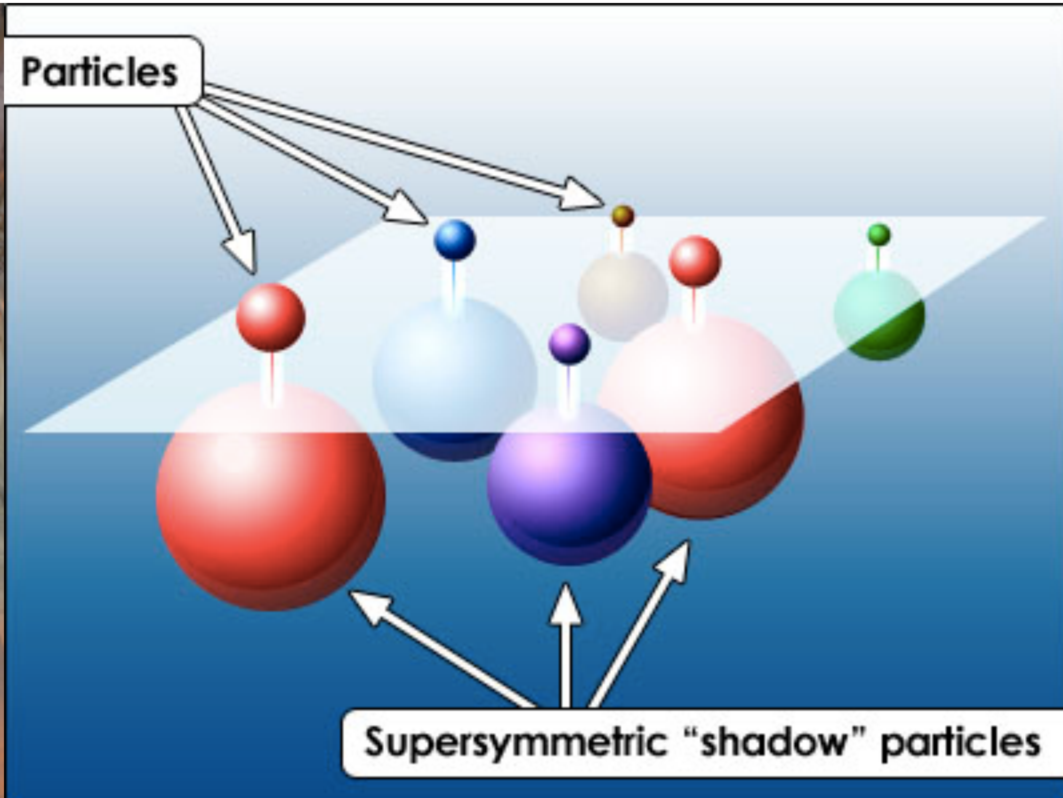
Experimental results to date (early 2016): nada

LHC: the LHC has discovered the Higgs

- a necessary ingredienty for SUSY
- too "normal" for MSSM (minimal SUSY)

the LHC has NOT observed excess Bs meson decay

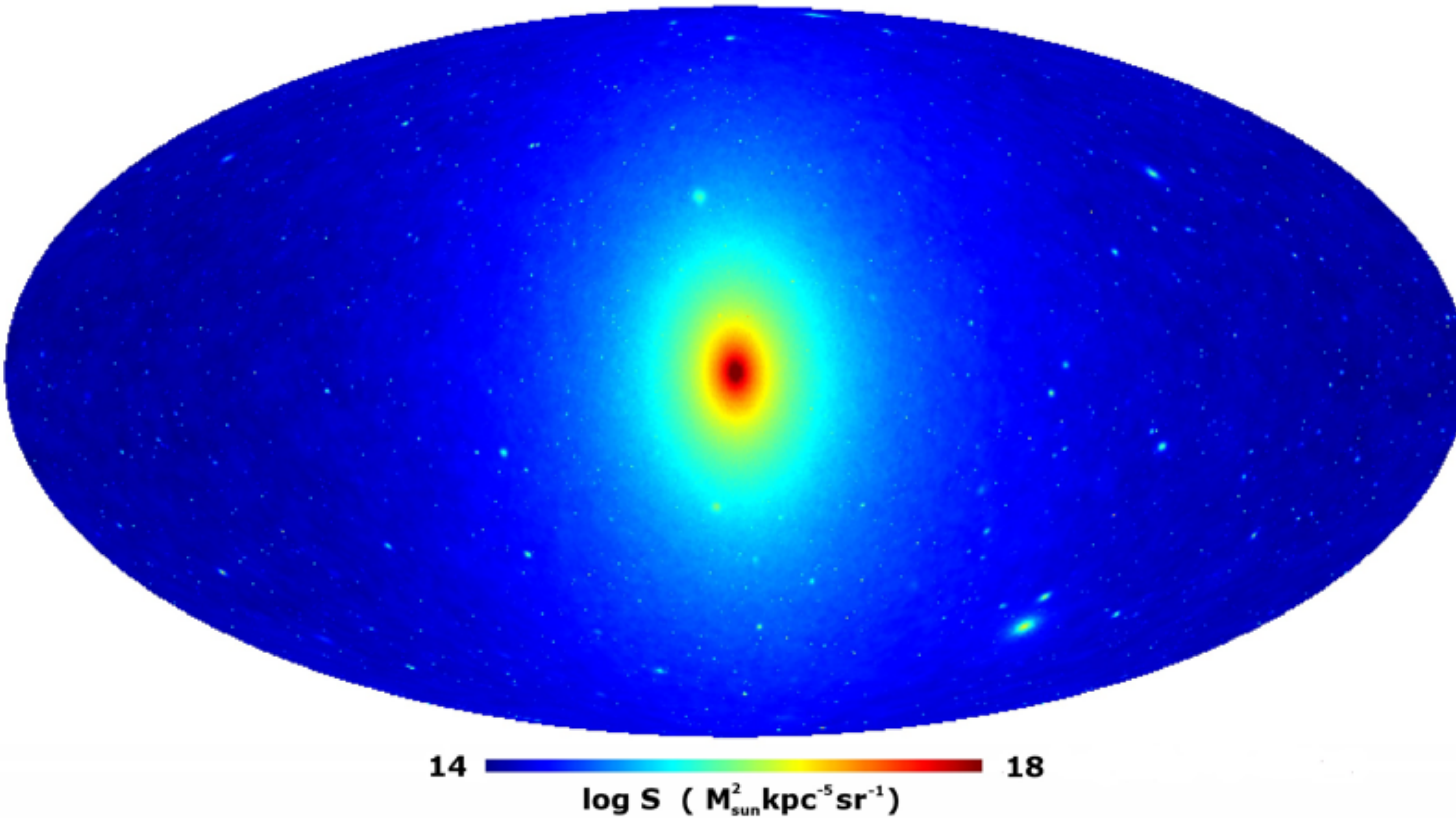
- the Golden Test for SUSY
- looking grim for MSSM, SUSY in general



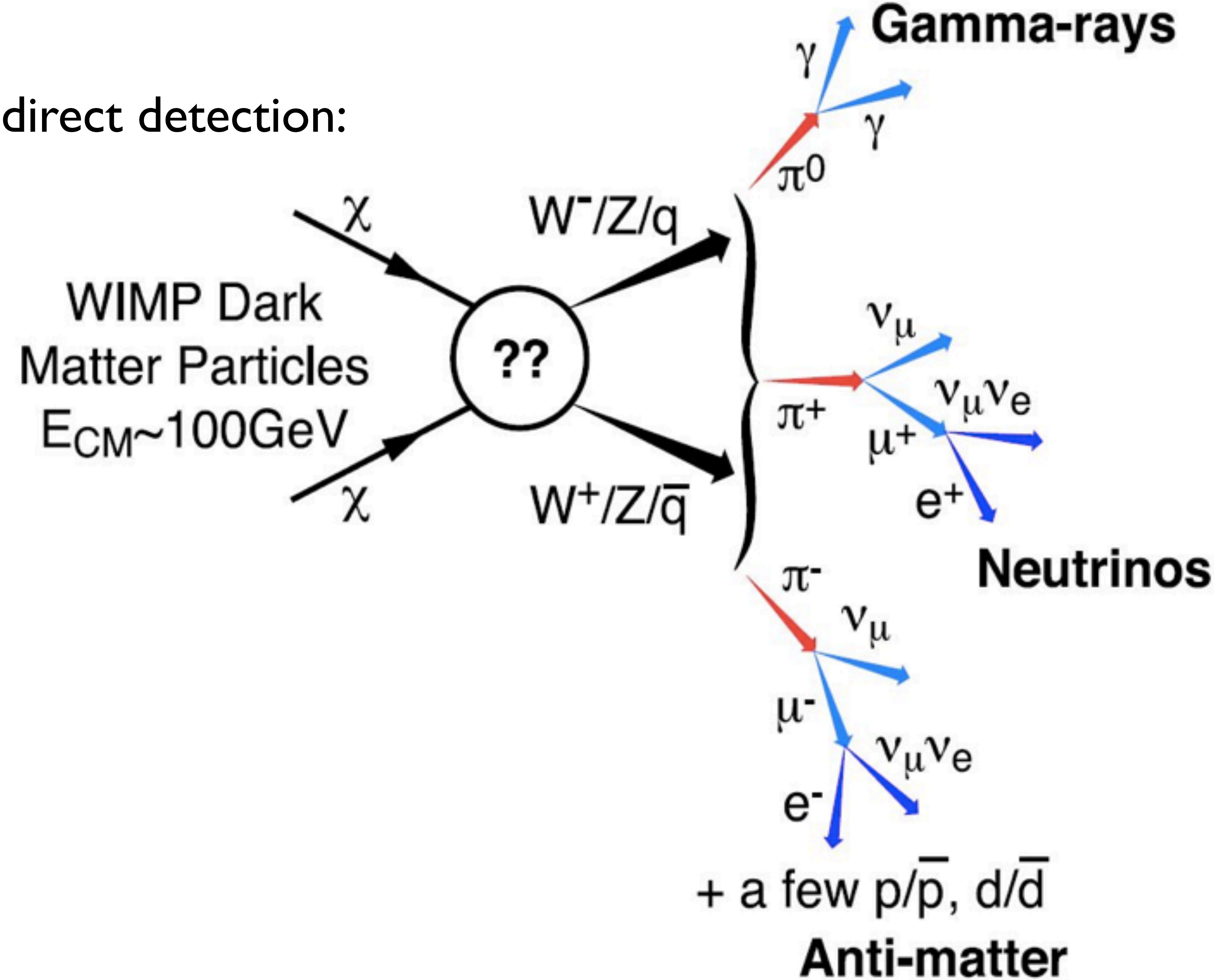
Experimental results to date (early 2016): nada

Indirect detection:

predicted gamma ray sky

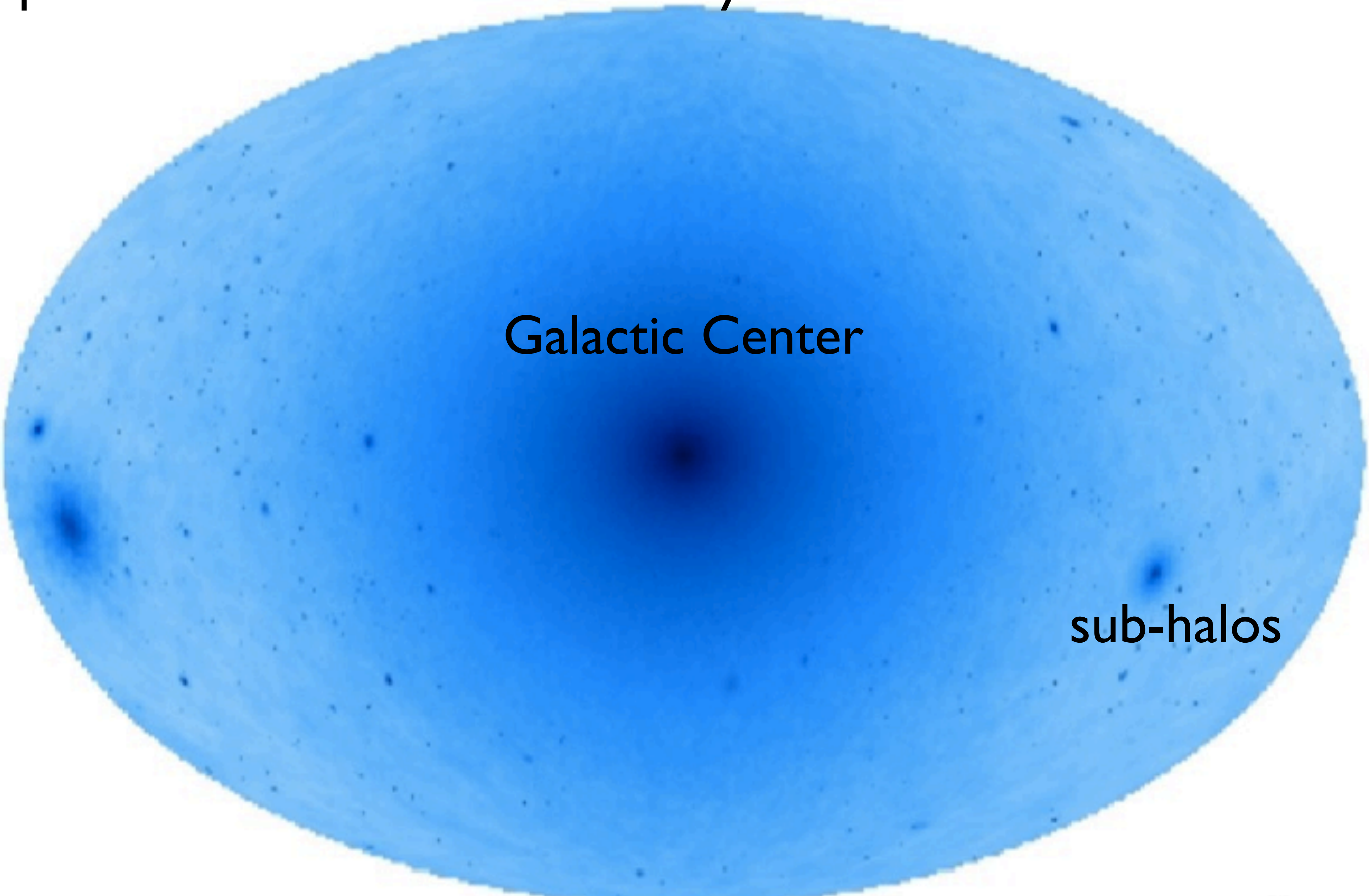


Indirect detection:



Experimental results to date (early 2016): nada

gamma ray flux from WIMP self-annihilation scales as the square of the dark matter density.



Low mass WIMPs excluded for various decay channels