Model-independent cosmological constraints from the CMB.

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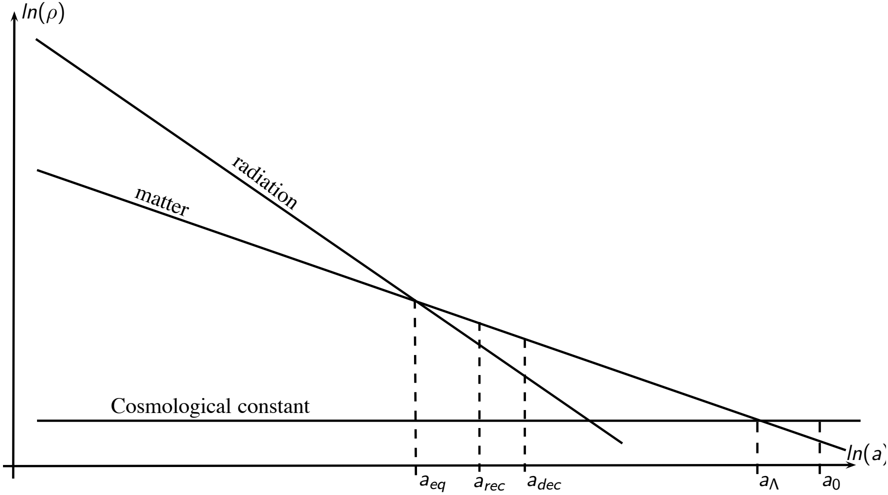
What we want to study and why it is interesting...

1. The standard model of cosmology in which $\Omega_m \sim 0.3$ and $\Omega_\Lambda \sim 0.7$ seems to fit an impressive variety of data.
2. However, Λ in $\Omega_\Lambda = \frac{\Lambda}{3H_0^2} = \frac{\rho_\Lambda}{\rho_c}$ faces many problems:
    - why is ρ_Λ so much smaller than we expect (120 order of magnitudes) ?
    - what is the origin of the small nonzero energy that comprises 70% of the universe today ?
    - why is the current value of the vacuum energy of the same order of magnitude as the matter density $\frac{\Omega_\Lambda}{\Omega_m} \sim a^3 \sim \mathcal{O}(1)$ today ?
3. Answers are model-dependent and uncertain, it is therefore worthwhile to study model-independently our universe.

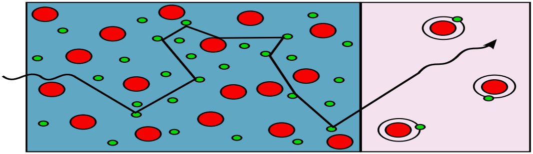
Dynamics of a Friedmann-Lemaître universe



Recombination and photon decoupling

- Before recombination ($T_{rec} = 3700K = 0.3eV$) , the cosmic fluid is in thermal equilibrium through the reaction

$$e^- + p \longleftrightarrow H + \gamma \quad (13.6\mathrm{eV})$$

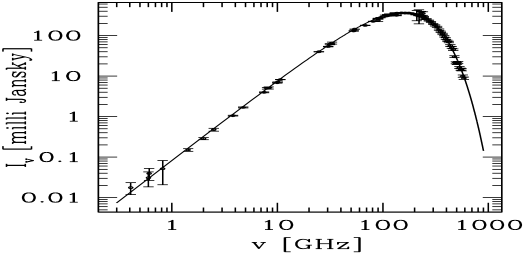


- After recombination, the free electrons density and photons interacting rate drop until the reaction stops (decoupling).
- Decoupling takes place at $T \sim 2970K = 0.26eV$ and redshift $z_{dec} \sim 1089$.

CMB spectrum

- After decoupling, photons propagate freely, remarkably isotropic spectrum following Planck's law with $T = 2.725K$:

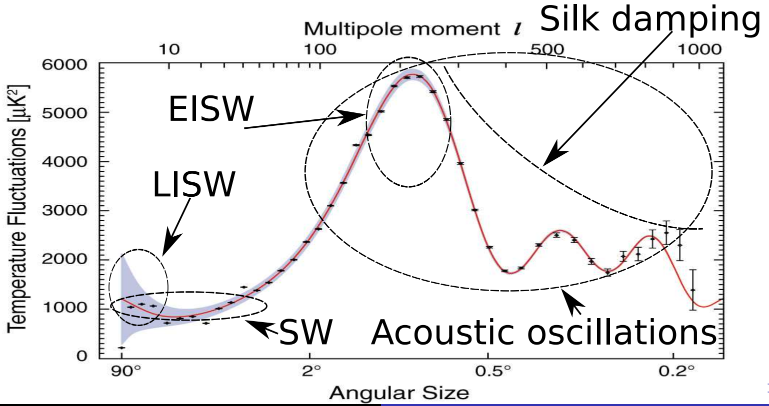
$$\frac{\Delta T}{T} \simeq 10^{-5}.$$



Durrer, The Cosmic Microwave Background (Cambridge, 2008)

CMB anisotropies

- CMB anisotropies have mostly been produced at the last scattering surface (LSS) at $z = z_{rec}$ via the coupling between matter and radiation.



Physics at decoupling (1)

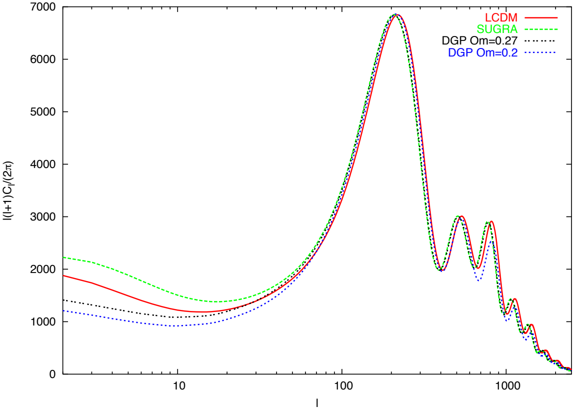
- We assume that the physics up to and including decoupling is completely standard :

1. normal 4-dimensional General Relativity
2. perturbed *FL* universe
3. standard Model particle physics and dark matter

Late time evolution (1)

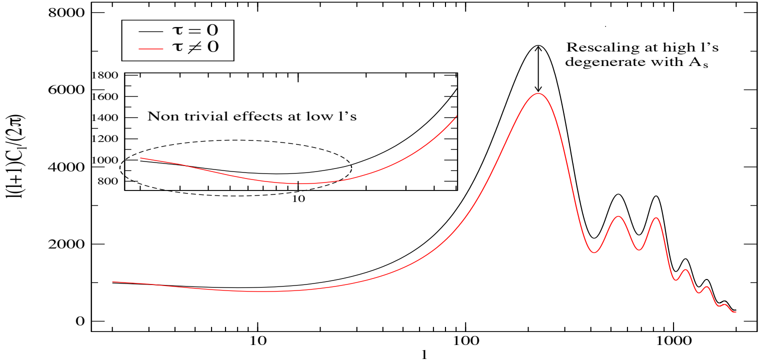
1. Badly understood, highly model-dependent:
   - deviation of gravity from *GR*
   - exotic matter component with negative pressure
   - breakdown of the homogeneous and isotropic approximation
2. reionization

Late time evolution (2)



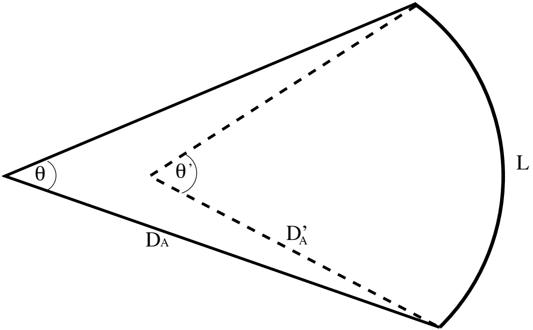
Ishak, Upadhye, Spergel (2006)

Late time evolution (3)



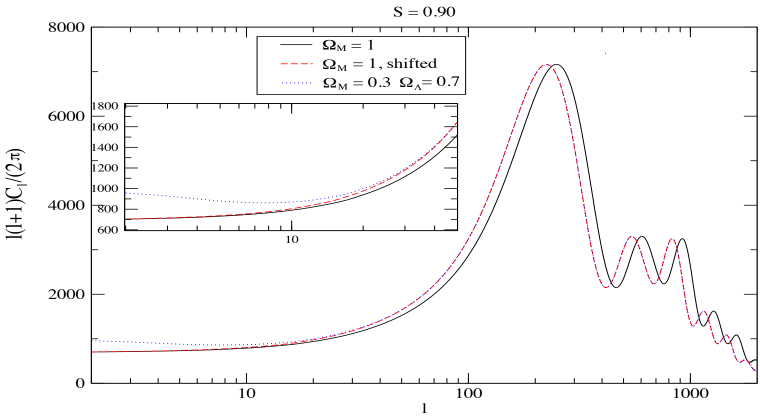
Rescaling (1)

- Rescaling of the angular scale has to be taken into account by adding a new parameter S.



$$D_A(z) = \frac{L}{\theta}, \qquad \theta' = \frac{D_A}{D'_A}\,\theta \equiv S\,\theta$$

Rescaling (2)


S = 0.90
$\Omega_M = 1$
$\Omega_M = 1$, shifted
$\Omega_M = 0.3$ $\Omega_\Lambda = 0.7$
$l(l+1)C_l/(2\pi)$
l
0
2000
4000
6000
8000
10
100
1000
600
800
1000
1200
1400
1600
1800
10

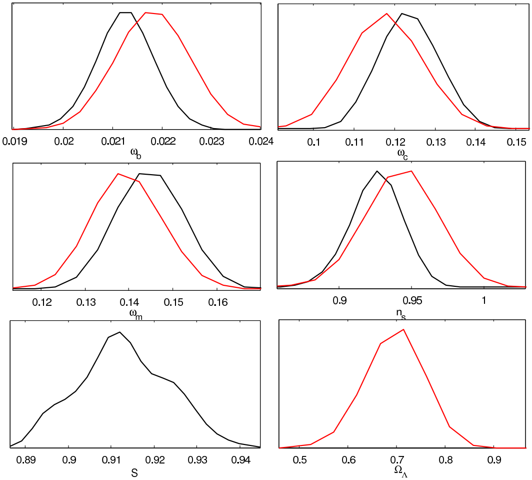
How to extract the model-independent informations of the CMB?

- Discard the low multipoles, up to $\ell = 40$.
- At high multipoles, the effect of reionization is absorbed in A_s. No pertinent constraints are therefore expected for A_s.
- We want to know the deviation of D_A from the simplest cosmological model, the Einstein-de Sitter model ($\Omega_m = 1$) by introducing the scale parameter S defined as

$$S \equiv \frac{D_A(z^*)}{D_{A,EdS}(z^*)}.$$

- Therefore, our new set of parameters (5) is $\mathcal{S}' = \{\omega_b, \omega_c, S, n_s, A_s\}$.
- Finally, modify and use CAMB code and Monte Carlo Markov Chain to obtain model-independent constraints on $\mathcal{S}'$.

Results (1)


0.019
0.02
0.021
0.022
0.023
0.024
ω_b
0.1
0.11
0.12
0.13
0.14
0.15
ω_c
0.12
0.13
0.14
0.15
0.16
ω_m
0.9
0.95
1
n_s
0.89
0.9
0.91
0.92
0.93
0.94
S
0.5
0.6
0.7
0.8
0.9
Ω_Λ

Results (2)

- Constraints on cosmological parameters including statistical and systematic errors :

$$
\begin{aligned}
100\omega_b &= 2.13^{+0.1}_{-0.06} & \omega_c &= 0.124^{+0.003}_{-0.006} \\
n_s &= 0.93^{+0.03}_{-0.02} & S &= 0.913^{+0.01}_{-0.01} .
\end{aligned}
$$

- $\Delta = 2\left(\log(\mathcal{L}_{\Lambda CDM}) - \log(\mathcal{L}_{\mathrm{shift}})\right) \simeq 1$

Conclusion

- We have analyzed the CMB data in a way which is independent of late time cosmology.
- An EdS model shifted by $S = 0.913$ is a good fit to the present CMB data, apart from the low multipoles.
- No significant improvement of our analyze is expected from Planck data because of lensing.
- Our results are valid for all models of late time dark energy (quintessence models, modified gravity and back-reaction).