N_{eff} from Decaying Matter

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arXiv:1212.1472 M. C. Gonzalez-Garcia, V. Niro, J.S.

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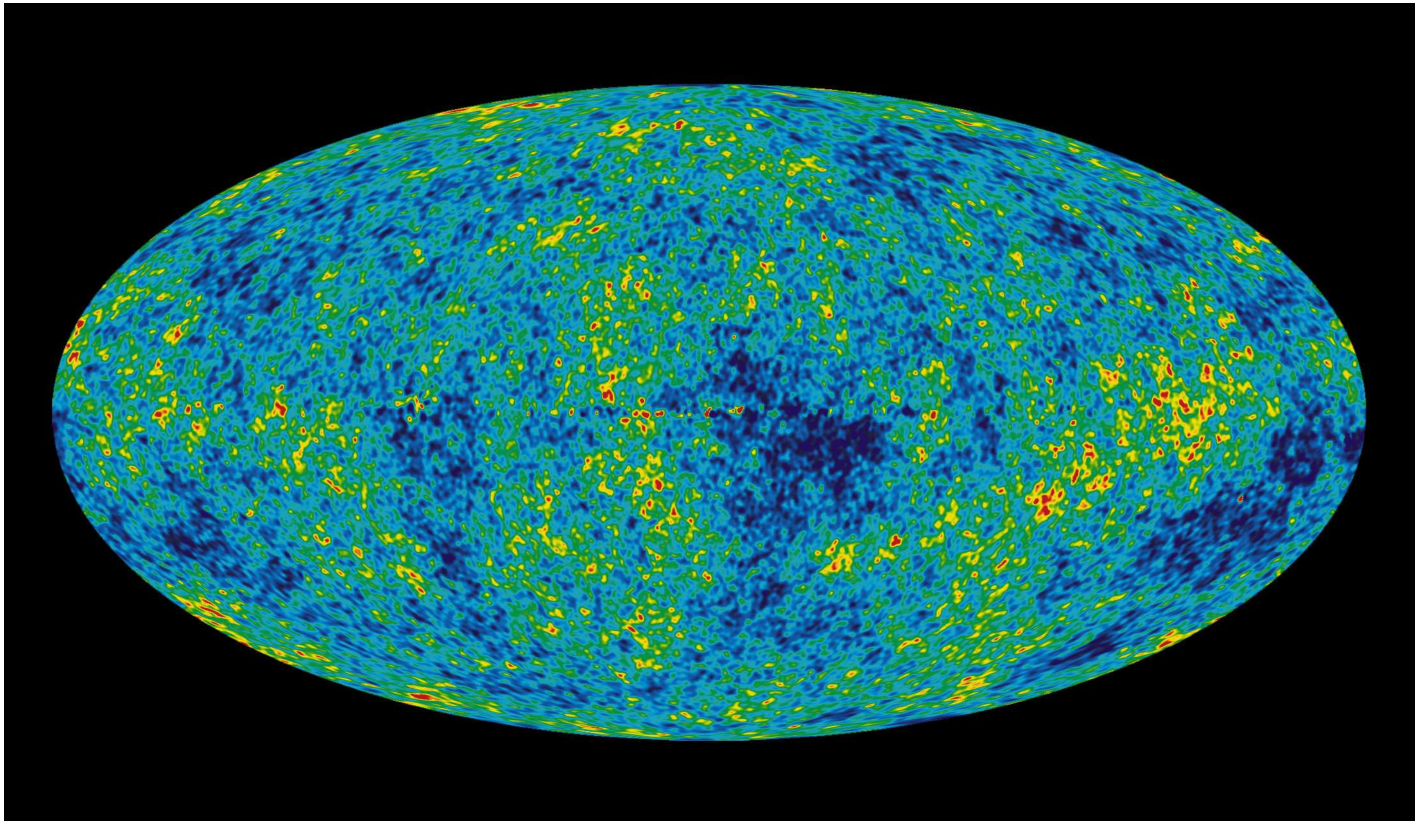
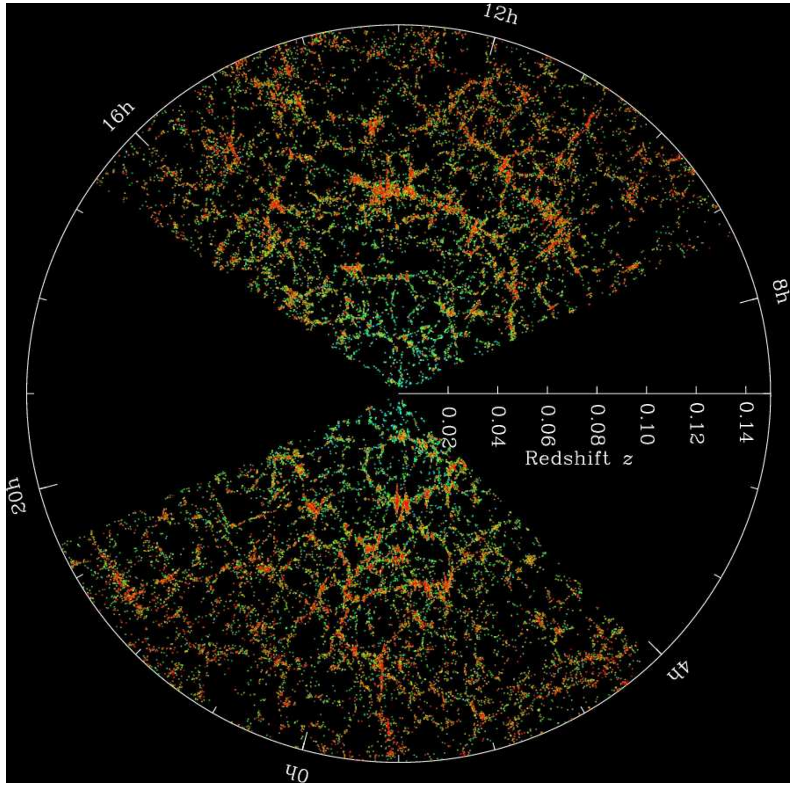
Cosmological Observations



WMAP and SPT $z \approx 1100$ $\frac{\delta T}{T} \approx 10^{-5}$

$$\left\langle \frac{\delta T}{\bar{T}}(\hat{n}) \frac{\delta T}{\bar{T}}(\hat{n}') \right\rangle = \sum_{l=0}^{\infty} \frac{2l+1}{4\pi} C_l P_l(\hat{n} \cdot \hat{n}')$$

Cosmological Observations



SDSS $z \approx 0.1$ $\frac{\delta\rho}{\rho}$ is small only at large scales.

$$P_{gal}(k,z) = \langle | \frac{\delta\rho(k_i,z)}{\rho} |^2 \rangle$$

$\delta\rho(k_i,z)$ is the F.T. of the density fluctuations.

Cosmological Observations

- HST $\rightarrow$ low-z supernovae, HST, A. G. Riess *et al.* `0905.0695`
- SN1a $\rightarrow$ High-z supernovae, M. Hicken *et al.*, `0901.4804`
- BBN $\rightarrow$ primordial abundances for the elements are affected by the expansion rate of the Universe at the BBN time (Mangano *et al.* `1103.1261`).

CosmoTh: Geometry of the Universe

- The metric for a general homogeneous and isotropic Universe is,

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-Kr^2} + r^2 d\Omega^2\right) ,$$

  all the dynamics is in the function $a(t)$, $a(t)$ and K are determined by the content of the Universe

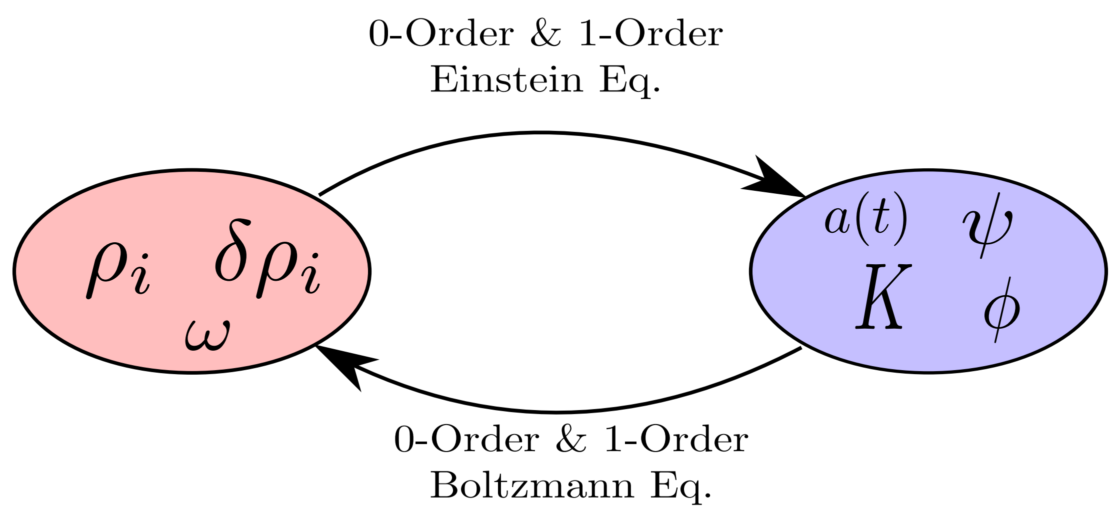
- To take into account the small deviations we need to go beyond the homogeneous and isotropic solution. F.e for scalar perturbations

$$ds^2 = (1-2\psi(t,x))dt^2 - (1+2\phi(t,x))a^2(t)\left(\frac{dr^2}{1-Kr^2} + r^2 d\Omega^2\right) .$$

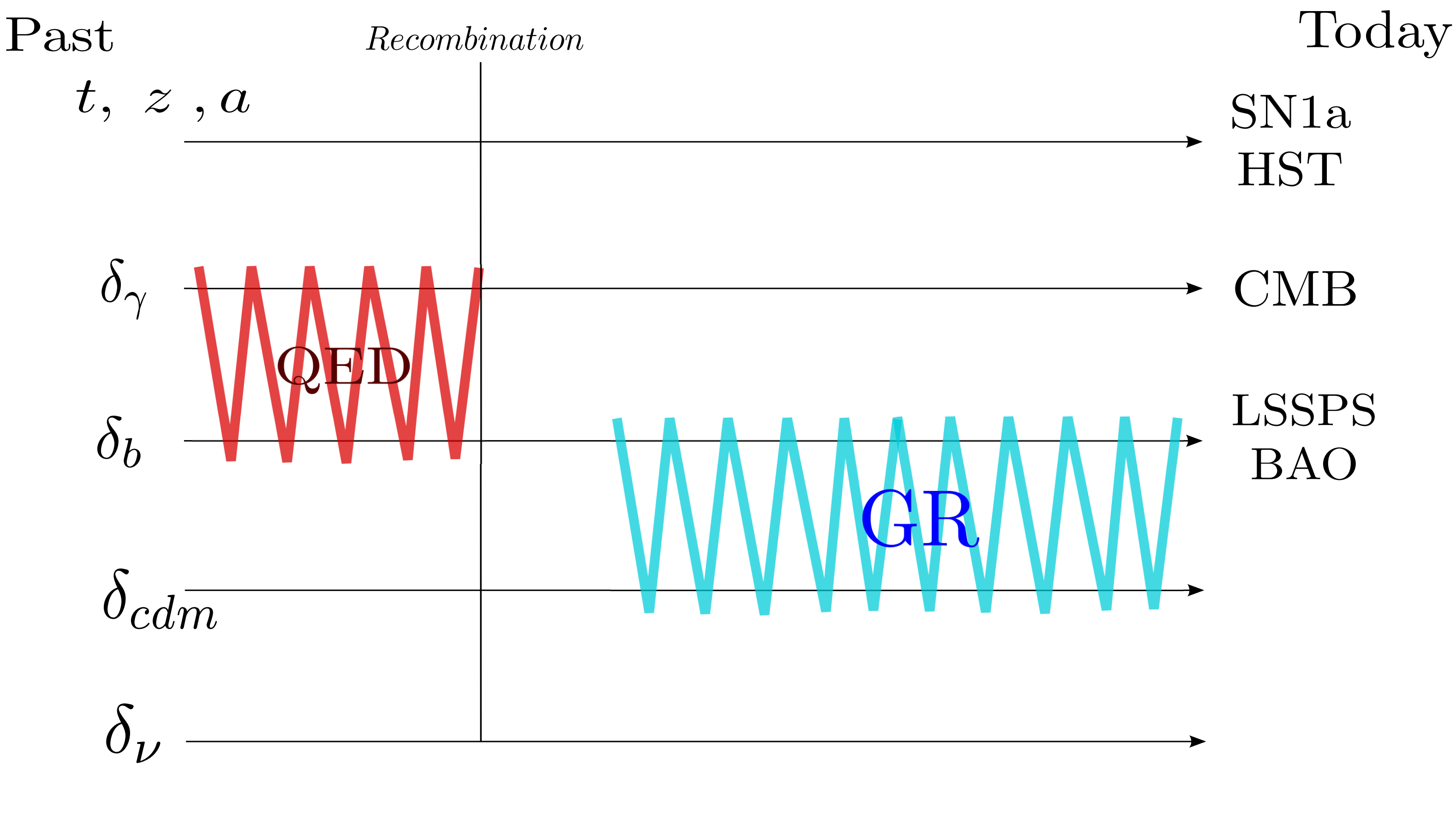
CosmoTh: ΛCDM $+N_{eff}$ Model

Type	0-order	1-order
Matter	$\rho_{cdm}(t),\ \rho_b(t)$	$\delta\rho_{cdm}(t,x),\ \delta\rho_b(t,x)$
Radiation	$\rho_\gamma(t),\ \rho_{N_{rel}}(t)$	$\delta\rho_\gamma(t,x),\ \delta\rho_\nu(t,x)$
Dark energy	$\rho_\Lambda(t),\ \omega$	

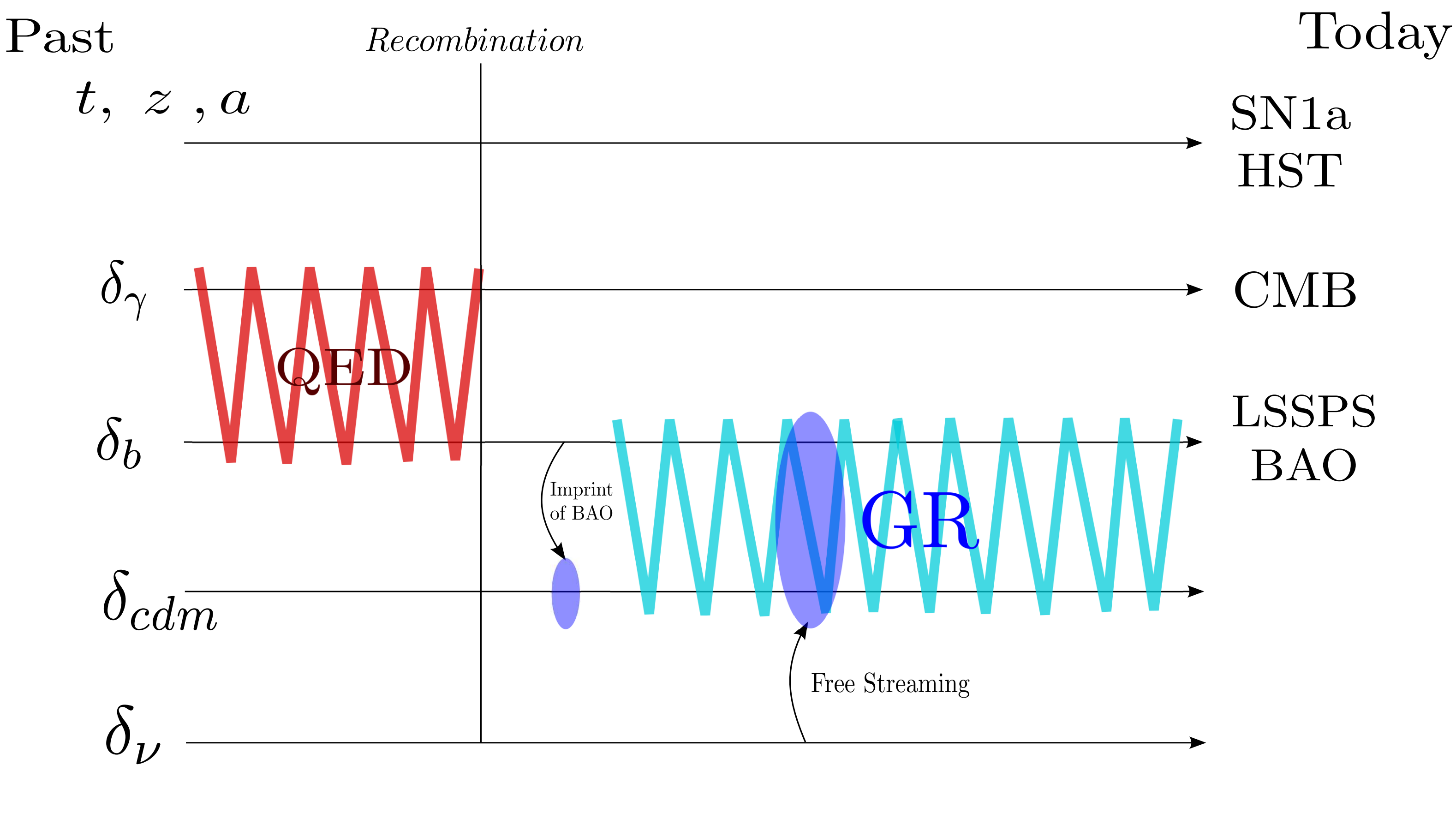
- Matter and radiation evolution is determined by Boltzmann equations up to first order in $\delta\rho_i/\rho_i$.
- Geometry is determined by Einstein equations $H(z) = \sqrt{\sum_i \rho_i(z)}$
- Both sets of eqs are coupled



CosmoTh: Physics of the Perturbations

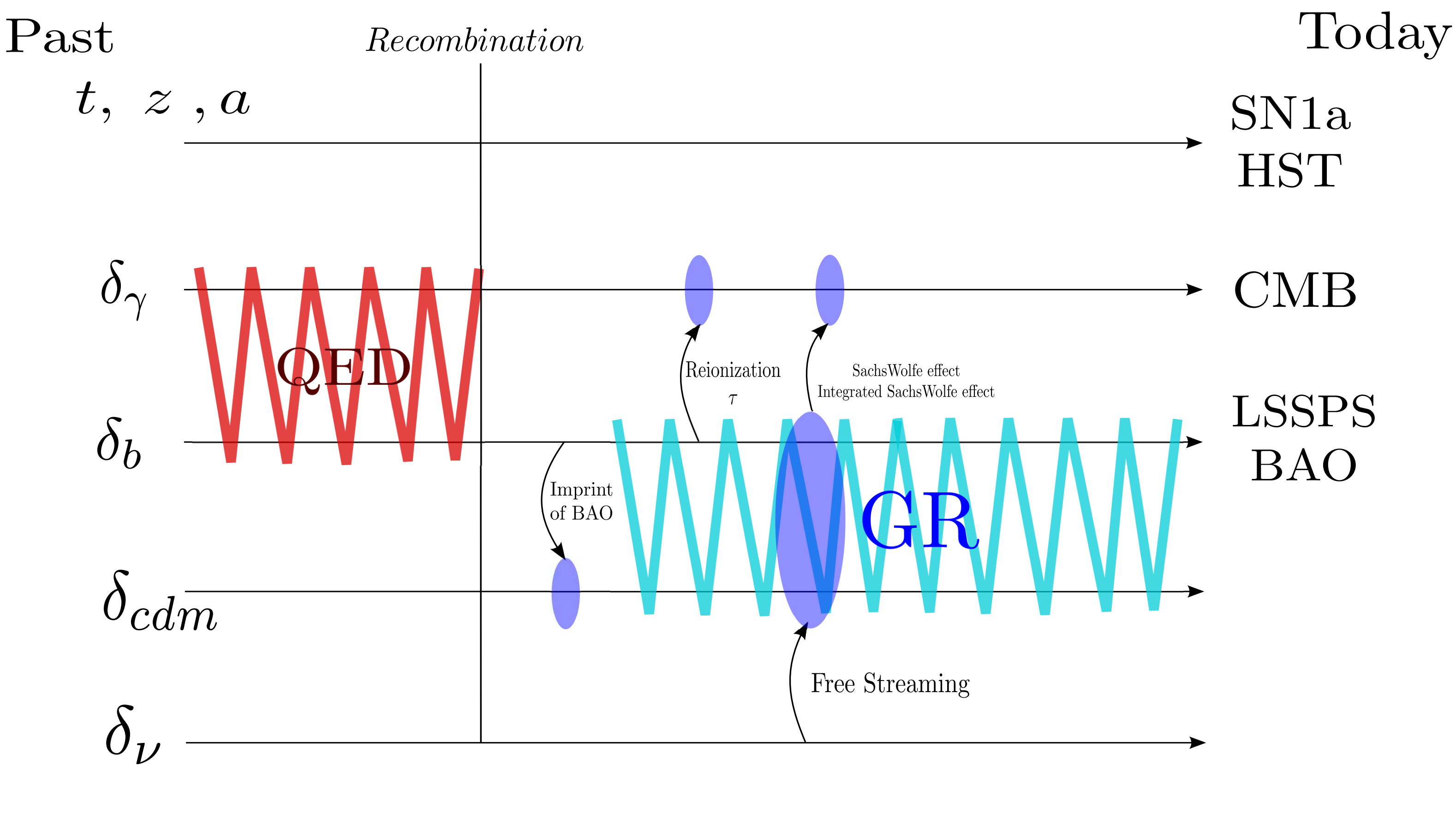


CosmoTh: Physics of the Perturbations



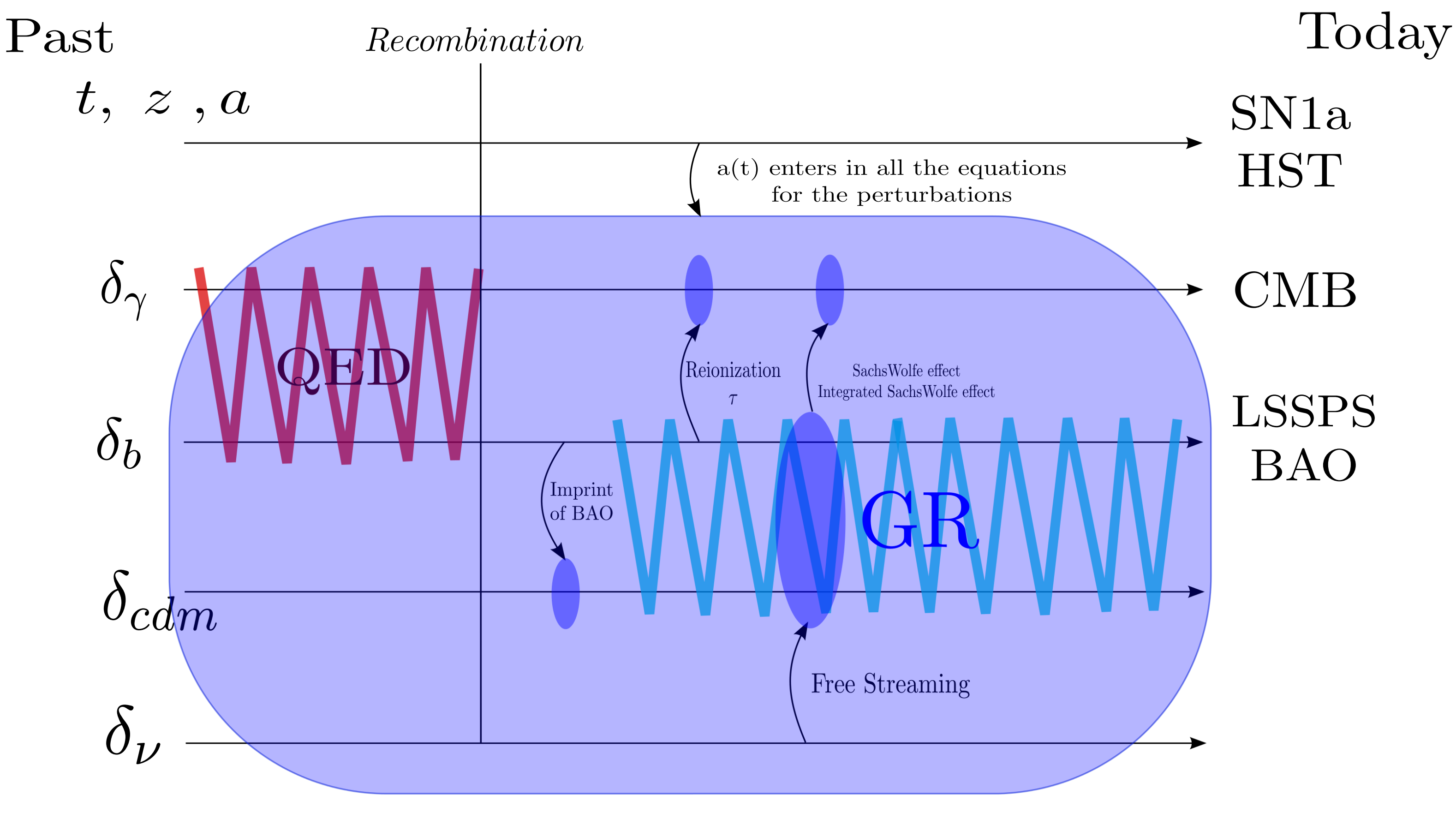
The BAO oscillations in the δ_b have an effect on the full matter PS.

CosmoTh: Physics of the Perturbations



We parametrize the reionization by unknown parameter τ
SW and ISW effects are included in the Boltzmann codes.

CosmoTh: Physics of the Perturbations



The background evolution enters in all the 1-order equations, therefore the perturbations contain information about all the parameters.

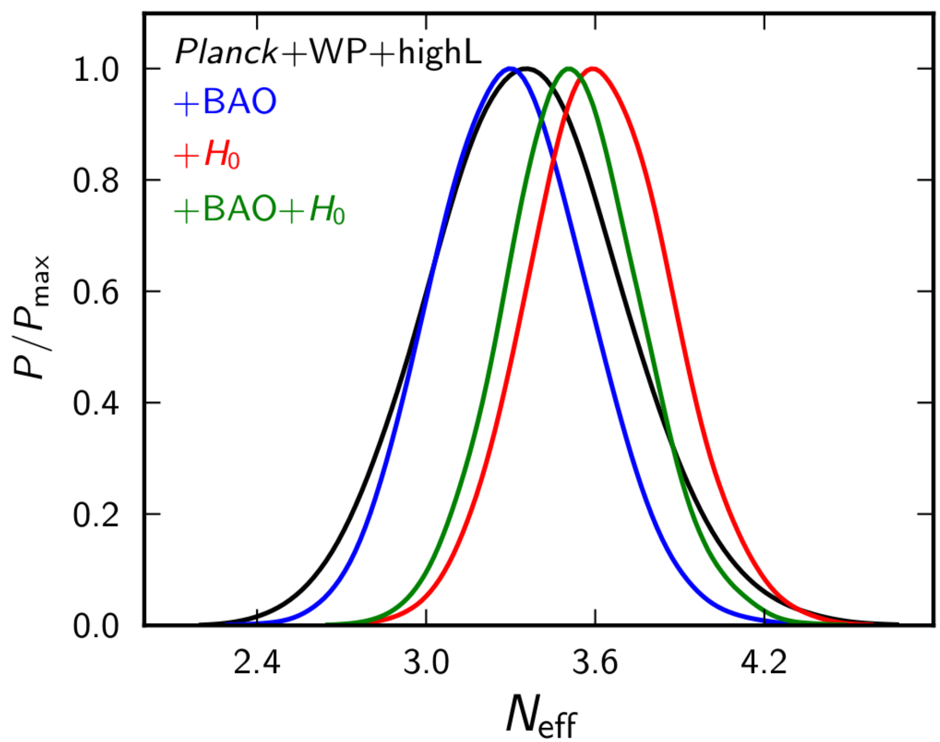
ΛCDM $+N_{eff}$ Parameters

- 0-order(homogeneous and isotropic),($\Omega_i \equiv \rho_i/\rho_{crit}, \quad \rho_{crit} = \frac{3H^2}{8\pi G}$)
  - Matter $\rightarrow \Omega_m \rightarrow \Omega_{cdm}, \ \Omega_b$
  - Radiation $\rightarrow \Omega_r \rightarrow \Omega_\gamma$ (fixed by T_{CMB}), N_{rel}
  - Reionization optical depth $\rightarrow \tau$
  - Hubble parameter today $\rightarrow H_0 \rightarrow \Omega_\Lambda$
- 1-order, initial conditions for $\delta\rho/\rho$ are determined by the primordial power spectrum from inflation,
  - Primordial spectrum amplitude $\rightarrow A_s$
  - Spectral index($n_s = 1 \Rightarrow$ flat spectra) $\rightarrow n_s$

$$P(k) = A_s \frac{k^{1-n_s}}{k^3} \quad \rightarrow \quad C_l, P_{gal}(k)$$

Is ΔN_{eff} bigger than zero?

- ΛCDM+N_{eff} with WMAP9 + spt + act $N_{eff} = 3.89 \pm 0.67 (68\% CL)$.
- ΛCDM+$m_\nu + N_{eff}$ with Planck + WP +spt + act
  $\sum m_\nu < 0.6 eV \quad N_{eff} = 3.29^{+0.67}_{-0.64} (95\% CL)$



Planck 2013 results. XVI

Does $N_{eff} > 0$ imply new light DOF?

IF (Thermal eq.) Then

$$T, N_{dof} \rightarrow \rho_{rad}$$

Else

$$\rho_{rad} = \rho_{th} + \rho_{nonth} = N_{dof} F(T) + \rho_{nonth} = N_{eff} F(T)$$

- Only near to the equilibrium N_{eff} and N_{dof} are similar.
  - Can the extra radiation be explained by non thermal contribution in to non standard neutrinos? arXiv:1212.1472
  - We study the possibility of include new cold matter that decays in to standard neutrinos to explain the extra radiation

Decaying Matter

- In order to include the new decaying matter we should extend the matter content.

Type	0-order	1-order
Matter	$\rho_{cdm}(t),\ \rho_b(t),\ \rho_{dec}(t)$	$\delta\rho_{cdm}(t,x),\ \delta\rho_b(t,x)$
Radiation	$\rho_\gamma(t),\ \rho_\nu(t)$	$\delta\rho_\gamma(t,x),\ \delta\rho_\nu(t,x)$
Dark energy	$\rho_\Lambda(t),\ \omega$	

- 0-order Boltzmann equations:

$$\dot{\rho}_{dec} = -3aH\rho_{dec} - a\Gamma_{dec}\,\rho_{dec}$$

$$\dot{\rho}_\nu = -4aH\rho_\nu + a\Gamma_{dec}\,\rho_{dec}$$

Decaying Matter Parameters

- 0-order(homogeneous and isotropic),($\Omega_i \equiv \rho_i/\rho_{crit}, \quad \rho_{crit} = \frac{3H^2}{8\pi G}$)
  - Matter $\rightarrow \Omega_m \rightarrow \Omega_{cdm}, \ \Omega_b, \Omega_{dec}, \Gamma_{dec}$
  - Radiation $\rightarrow \Omega_r \rightarrow \Omega_\gamma$ (fixed by T_{CMB}),$N_{eff} = 3$
  - Reionization optical depth $\rightarrow \tau$
  - Hubble parameter today $\rightarrow H_0 \rightarrow \Omega_\Lambda$
- 1-order, initial conditions for $\delta\rho/\rho$ are determined by the primordial power spectrum from inflation,
  - Primordial spectrum amplitude $\rightarrow A_s$
  - Spectral index($n_s = 1 \Rightarrow$ flat spectra) $\rightarrow n_s$

$$P(k) = A_s \frac{k^{1-n_s}}{k^3} \quad \rightarrow \quad C_l, P_{gal}(k)$$

Data Analysis

HST → low-z supernovae, HST, A. G. Riess *et al.* `0905.0695`

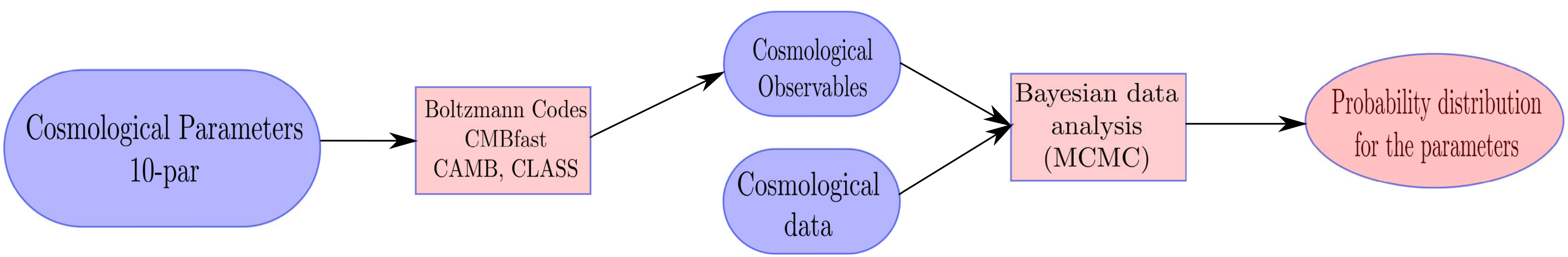
SN1a → High-z supernovae, M. Hicken *et al.*, `0901.4804`

BAO → BAO from SDSS & 2dFGRS, W. J. Percival *et al.*, `0907.1660`

CMB → WMAP, E. Komatsu, *et al.*,`1001.4538`

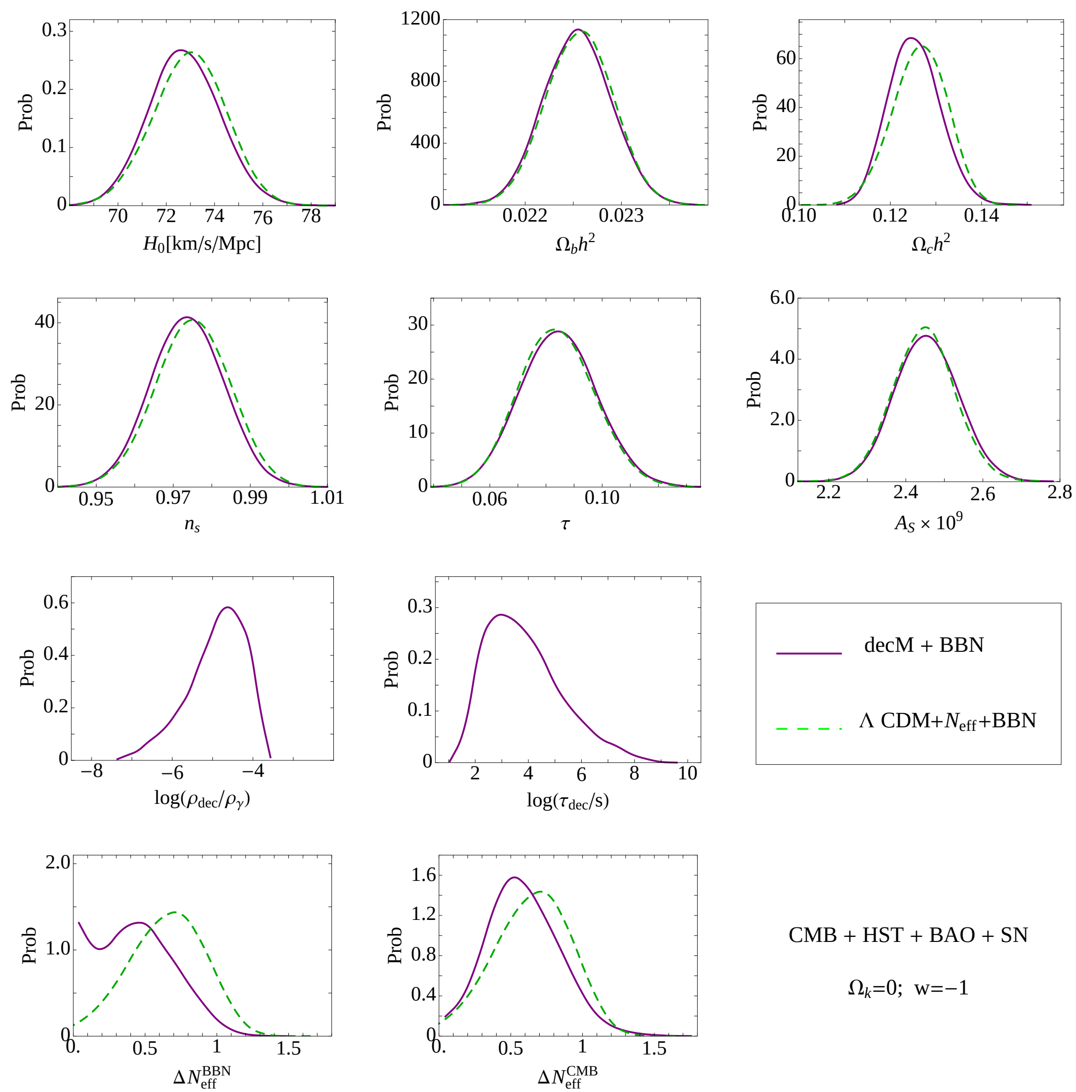
CMB → SPT, Keisler, R, *et al.*, `1105.3182`

BBN → primordial abundances, Mangano *et al.* `1103.1261`



We develop a code implementing a Markov Chain Monte Carlo (MCMC) algorithm for parameter sampling and to determine the posterior probability distribution for the cosmological parameters.

decM data analysis results



CMB + HST + BAO + SN

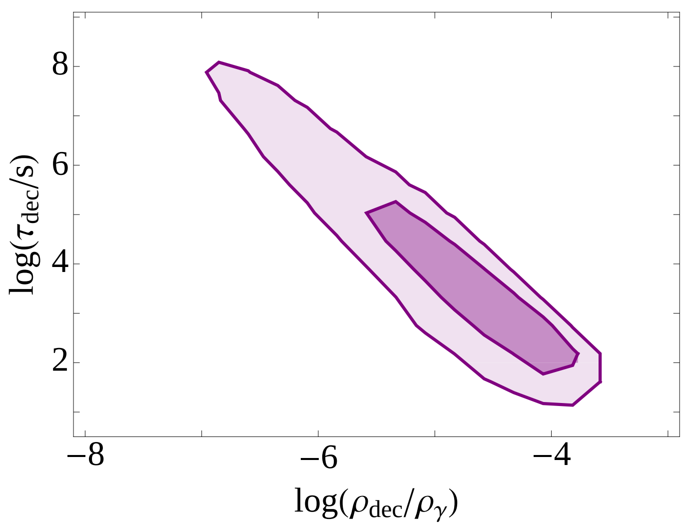
Ω_k=0; w=−1

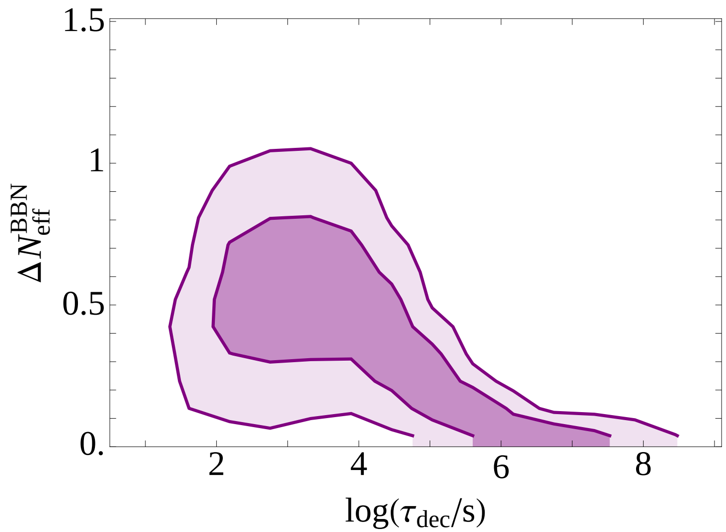
decM data analysis

	*dec*M+BBN			ΛCDM+$N_{\rm eff}$+BBN		
Parameter	best	1σ	95%	best	1σ	95%
H_0 [km/s/Mpc]	72.6	$^{+1.5}_{-1.4}$	$^{+3.0}_{-2.8}$	73.0	$^{+1.5}_{-1.5}$	$^{+2.8}_{-3.0}$
$\Omega_b h^2 \times 100$	2.254	$^{+0.034}_{-0.037}$	$^{+0.069}_{-0.068}$	2.258	$^{+0.032}_{-0.037}$	$^{+0.065}_{-0.070}$
$\Omega_c h^2$	0.125	$^{+0.005}_{-0.005}$	$^{+0.012}_{-0.010}$	0.127	$^{+0.006}_{-0.006}$	$^{+0.011}_{-0.012}$
$\log(\rho_{dec}/\rho_\gamma)$ at $t = 10^{-4}$ s	-4.61	$^{+0.61}_{-0.73}$	$^{+0.92}_{-1.7}$	–	–	–
n_s	0.973	$^{+0.009}_{-0.009}$	$^{+0.018}_{-0.018}$	0.975	$^{+0.010}_{-0.010}$	$^{+0.019}_{-0.019}$
τ	0.084	$^{+0.013}_{-0.015}$	$^{+0.026}_{-0.026}$	0.083	$^{+0.013}_{-0.013}$	$^{+0.027}_{-0.024}$
$A_s \times 10^9$	2.452	$^{+0.082}_{-0.083}$	$^{+0.164}_{-0.157}$	2.449	$^{+0.075}_{-0.083}$	$^{+0.155}_{-0.159}$
$\log(\tau_{dec}/{\rm s})$	2.9	$^{+1.7}_{-1.0}$	$^{+3.7}_{-1.5}$	–	–	–
$\Delta N_{\rm eff}^{\rm CMB}$	0.50	$^{+0.30}_{-0.19}$	$^{+0.58}_{-0.42}$	0.70	$^{+0.25}_{-0.30}$	$^{+0.44}_{-0.59}$
$\Delta N_{\rm eff}^{\rm BBN}$	–	–	≤ 0.90	0.70	$^{+0.25}_{-0.30}$	$^{+0.44}_{-0.59}$

decM data analysis results

- 2D contour plots





- In radiation dominated universe $\Delta N_{eff} \propto \rho_{dec}\sqrt{\tau_{dec}}$

Motivations for $N_{eff} > 0$

- Many extensions of the SM contain extra light particles, axions, light sterile neutrinos ...
- Sterile Neutrino Experimental Motivation:
  - LSND excess of $\bar{\nu}_\mu \to \bar{\nu}_e$ with $\Delta m^2 \sim 1eV^2$
  - MiniBoone $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance
  - Gallium Anomaly, SAGE and GALLEX event rates lower than expected, can be explained by ν_e disappearance with $\Delta m^2 \geq 1eV^2$
  - New reactor flux calculation (Mueller et al., 1101.2663, P. Huber, 1106.0687) 3% higher, tension in short-baseline ($L \leq 100m$) experiments, can be explained by ν_e disappearance with oscillation with $\Delta m^2 \sim 1eV^2$.
- Work in progress: Sterile Neutrino Analysis in IceCube using IC-79 and IC-86 data

decM data analysis results

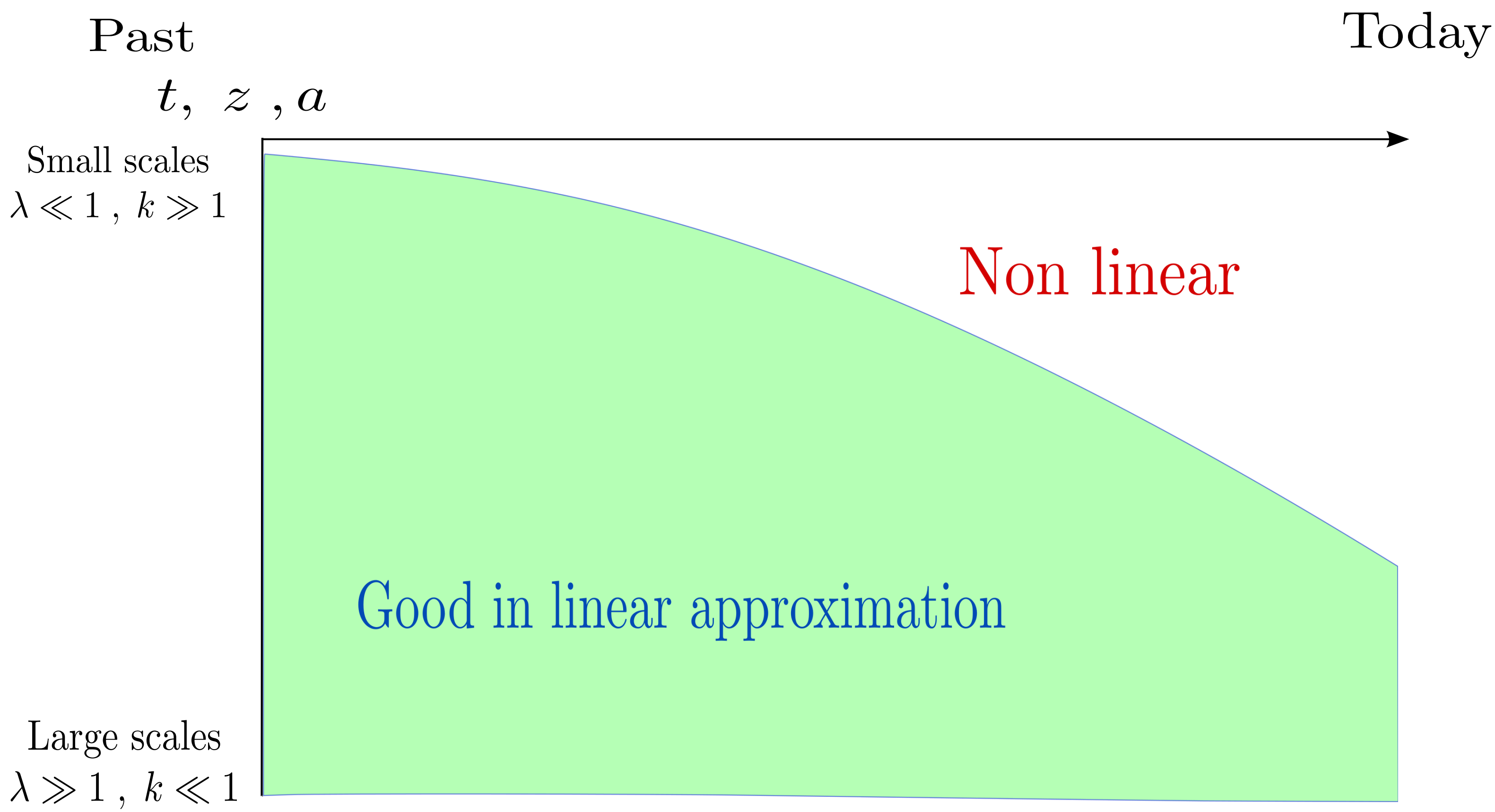
- The bump at $\Delta N_{eff}^{BBN} = 0$ can be understood by the prior.
- We use a flat prior in $\tilde{\Omega}_{\rm dec}$ and $\Gamma_{\rm dec}$

$$\mathcal{P}(\tilde{\Omega}_{\rm dec}, \Gamma_{\rm dec}) = cnt$$

- Using the approximate analytic solution in radiation dominated universe and $\mathcal{P}(\tilde{\Omega}_{\rm dec}, \Gamma_{\rm dec}) d\tilde{\Omega}_{\rm dec} d\Gamma_{\rm dec} = \tilde{\mathcal{P}}(N_{\rm eff}, Z) dN_{\rm eff} dZ$

$$\tilde{\mathcal{P}}(N_{\rm eff}, Z) \propto 1/N_{\rm eff}$$

CosmoTh: Scales



N_{eff} in the CMB

- N_{eff} gives a contribution to the energy density therefore affects the expansion rate H at the CMB time.
- The CMB physics is determines by the length scales:

$$d_s(t_{CMB}) \propto 1/H \quad \lambda_d(t_{CMB}) \propto 1/\sqrt{H} \quad d_A(t_{CMB}) \propto 1/H$$

- The position of the peaks depends on:

$$\frac{d_s(t_{CMB})}{d_A(t_{CMB})}$$

therefore is not affected by the expansion rate.

- The damping effect ant high-l is determined by:

$$\frac{\lambda_d(t_{CMB})}{d_A(t_{CMB})} = \frac{1}{\sqrt{H}}$$

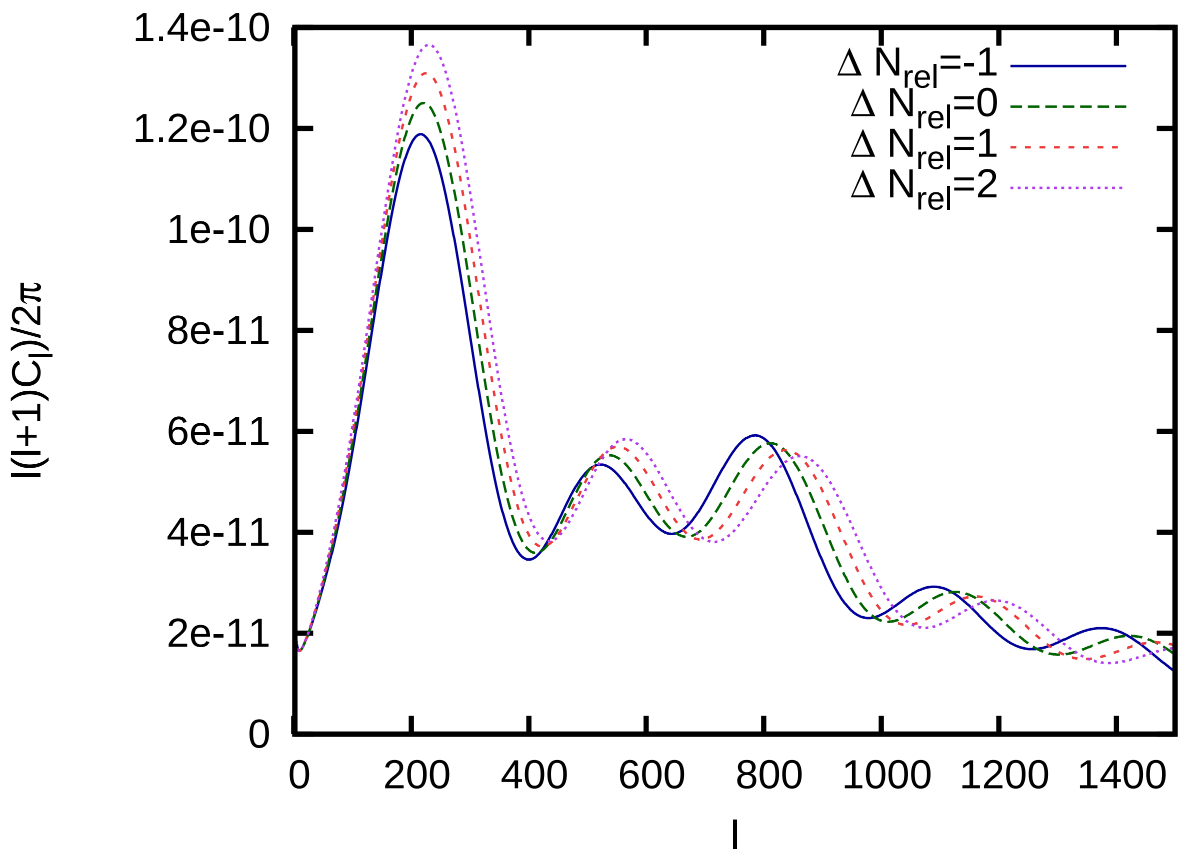
The effect on the CMB at high-l is affected by H and can give information about N_eff

Cosmological Observations

	ΛCDM+$N_{\rm eff}$		
Parameter	best	1σ	95%
H_0 [km/s/Mpc]	73.0	$^{+1.5}_{-1.5}$	$^{+2.8}_{-3.0}$
$\Omega_b h^2 \times 100$	2.258	$^{+0.032}_{-0.037}$	$^{+0.065}_{-0.070}$
$\Omega_c h^2$	0.127	$^{+0.006}_{-0.006}$	$^{+0.011}_{-0.012}$
n_s	0.975	$^{+0.010}_{-0.010}$	$^{+0.019}_{-0.019}$
τ	0.083	$^{+0.013}_{-0.013}$	$^{+0.027}_{-0.024}$
$A_s \times 10^9$	2.449	$^{+0.075}_{-0.083}$	$^{+0.155}_{-0.159}$
$\Delta N_{\rm eff}$	0.70	$^{+0.25}_{-0.30}$	$^{+0.44}_{-0.59}$

- BBN, $N_{eff} < 4$ at 95% C.L.(Mangano *et al.* 1103.1261)
- Without BBN $N_{eff} = 3.87 \pm 0.42$ (Joudaki, Shahab. 1202.0005)
- Before SPT and without BBN in extended cosmological models $N_{eff} = 4.2^{+1.1}_{-0.61}$ (Gonzalez-Garcia, M.C, *et al.* 1006.3795)

N_{eff} in the CMB



- Effect in the CMB of the extra relativistic radiation ΔN_{rel} in the Universe.

Bayesian Data Analysis

- For a given values of the theory parameters θ the probability of measuring a data sample $\bar{d}$ is the likelihood function $\mathcal{L}(\bar{d};\theta)$.
- In Bayesian Interpretation the probability is associated with the knowledge, therefore we can summarize our knowledge of the theoretical parameters θ as a probability distribution $p(\theta|\bar{d})$.
- Using the Bayesian theorem we can relate this probability with the likelihood:

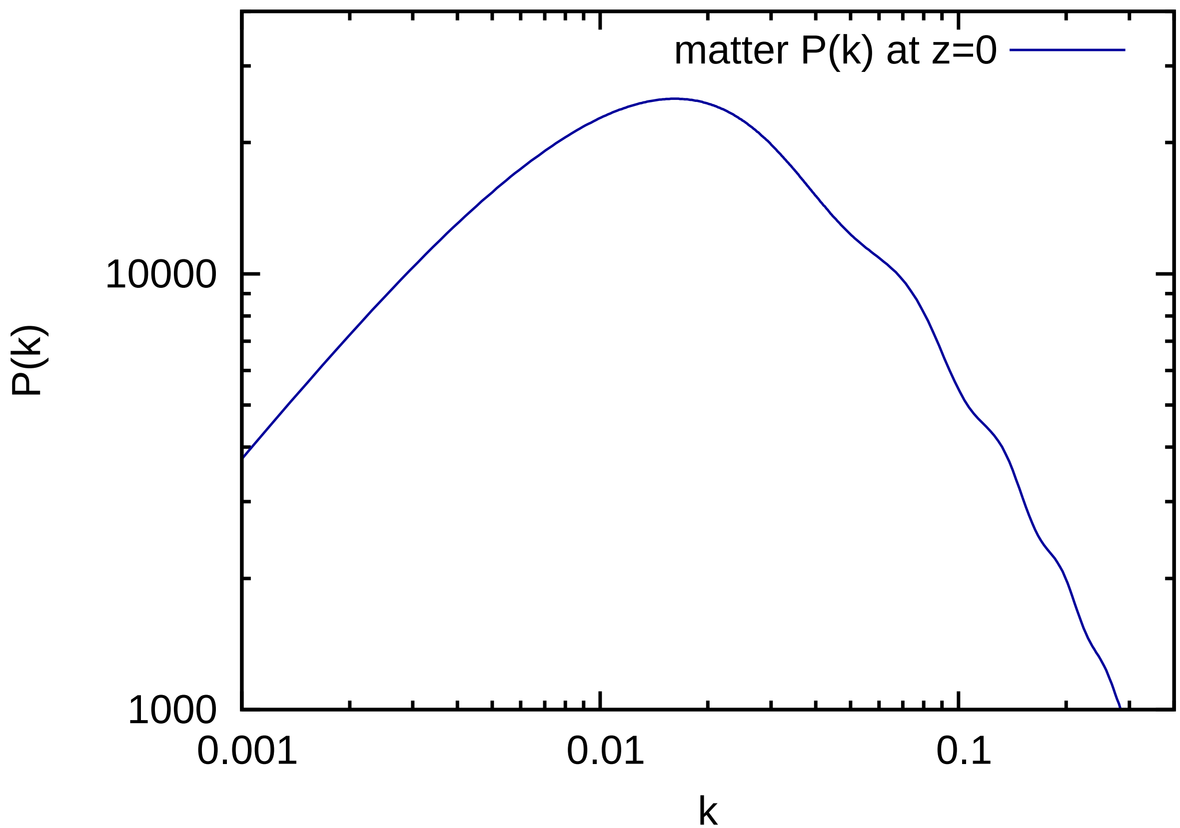
$$p(\theta|\bar{d}) = \frac{\mathcal{L}(\bar{d}|\theta)\pi(\theta)}{\sum_{\theta'} \mathcal{L}(\bar{d}|\theta')\pi(\theta')}$$

Decaying Matter

- 1-order Botzmann equations:

$$
\begin{aligned}
\dot{\delta}_{DM} &= -\frac{1}{2}\dot{h}\,, \\
\dot{\delta}_{R} &= -\frac{2}{3}\dot{h} - \frac{4}{3}\theta_{R} + a\Gamma_{dec}\frac{\rho_{dec}}{\rho_{R}}\left(\delta_{DM} - \delta_{R}\right)\,, \\
\dot{\theta}_{R} &= k^2\left(\frac{1}{4}\delta_{R} - \sigma_{R}\right) - a\Gamma_{dec}\frac{\rho_{dec}}{\rho_{R}}\theta_{R}\,, \\
\dot{\sigma}_{R} &= \frac{1}{2}\left(\frac{8}{15}\theta_{R} - \frac{3}{5}kF_3 + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta}\right) - a\Gamma_{dec}\frac{\rho_{dec}}{\rho_{R}}\sigma_{R}\,, \\
\dot{F}_l &= \frac{k}{2l+1}\left[lF_{l-1} - (l+1)\,F_{l+1}\right] - a\Gamma_{dec}\frac{\rho_{dec}}{\rho_{R}}F_l\,,
\end{aligned}
$$

Cosmological Observations



- From the matter power spectrum we use the scale associated with the Baryonic Acoustic Oscillations (BAO).