Cosmological bound on the neutrino masses

Jordi Salvado

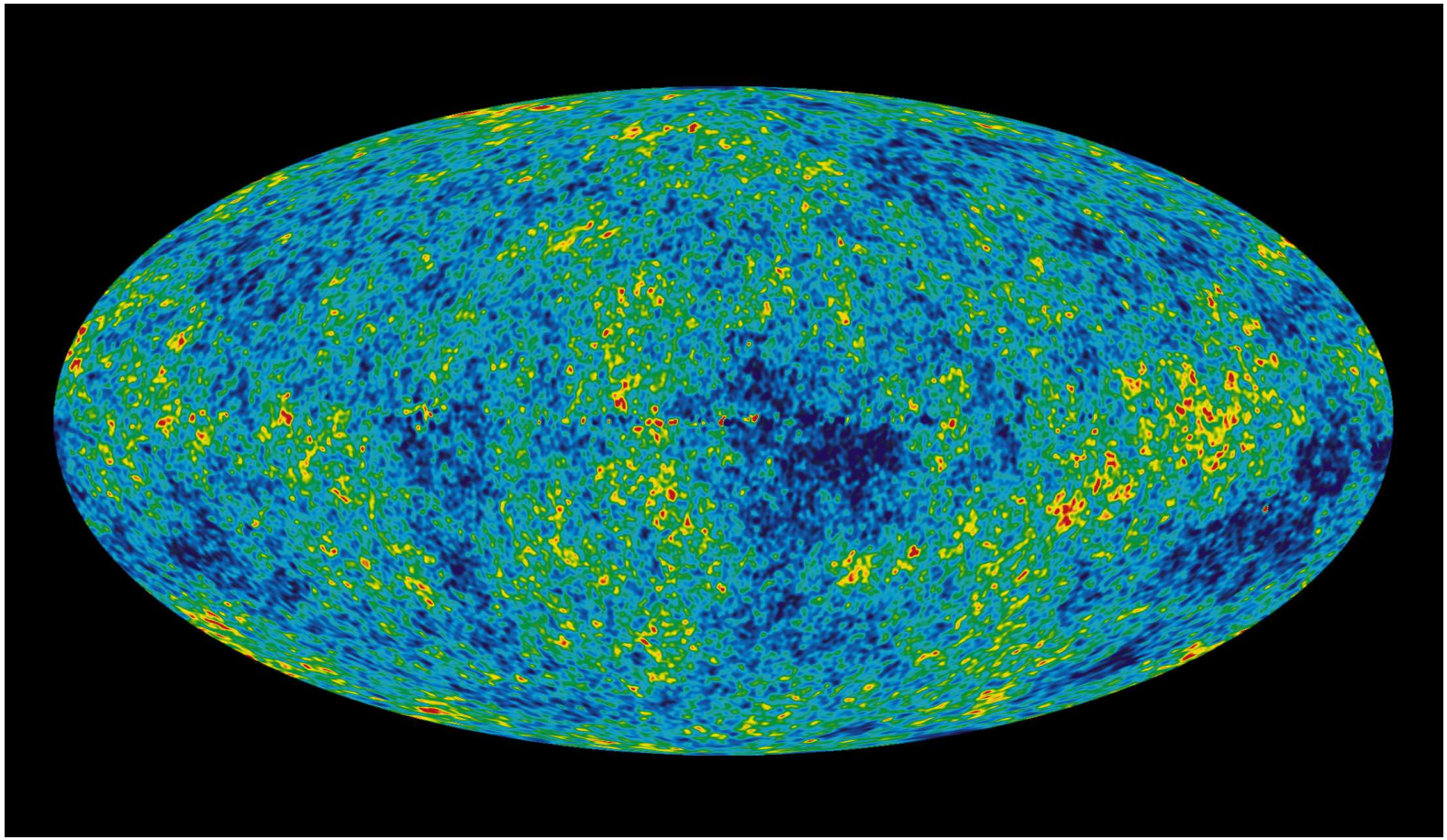
jsalvado@ecm.ub.es

Universitat de Barcelona & Institut de Ciencies del Cosmos

Content

- How is the Universe?
- Geometry
- Particle content
- Physics of the perturbations
- Cosmological observations
- Data analysis and parameter estimation

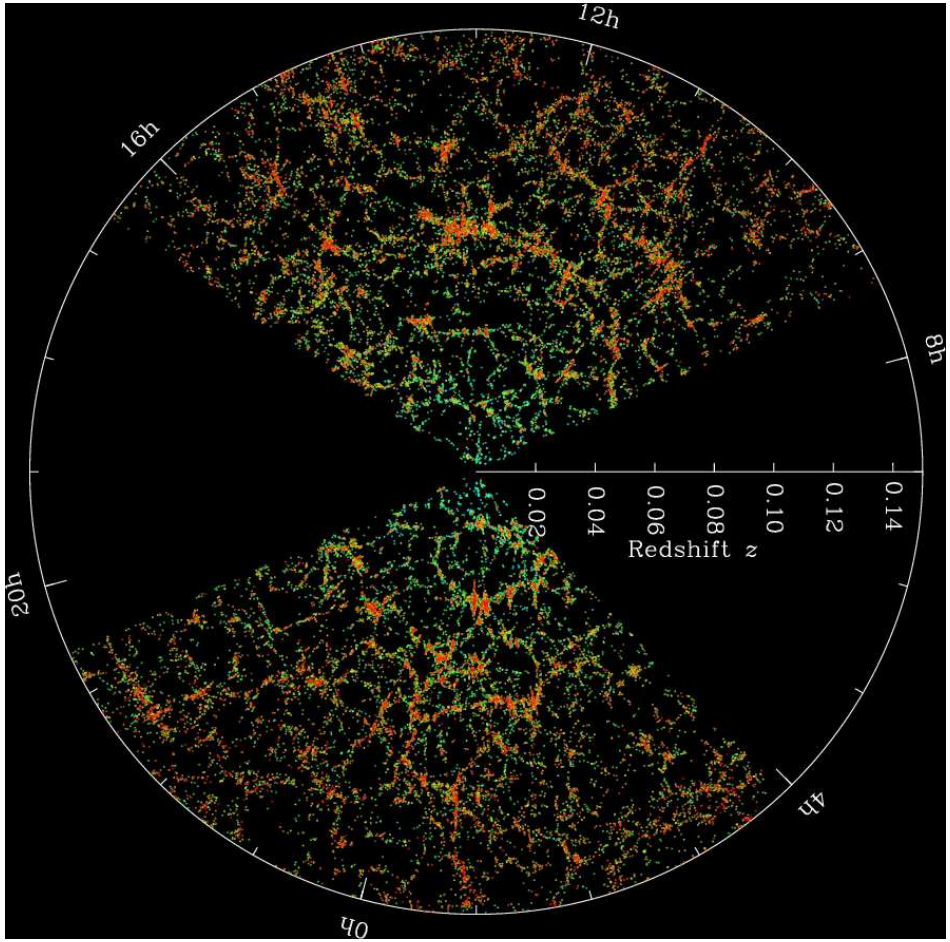
How is the Universe



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

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

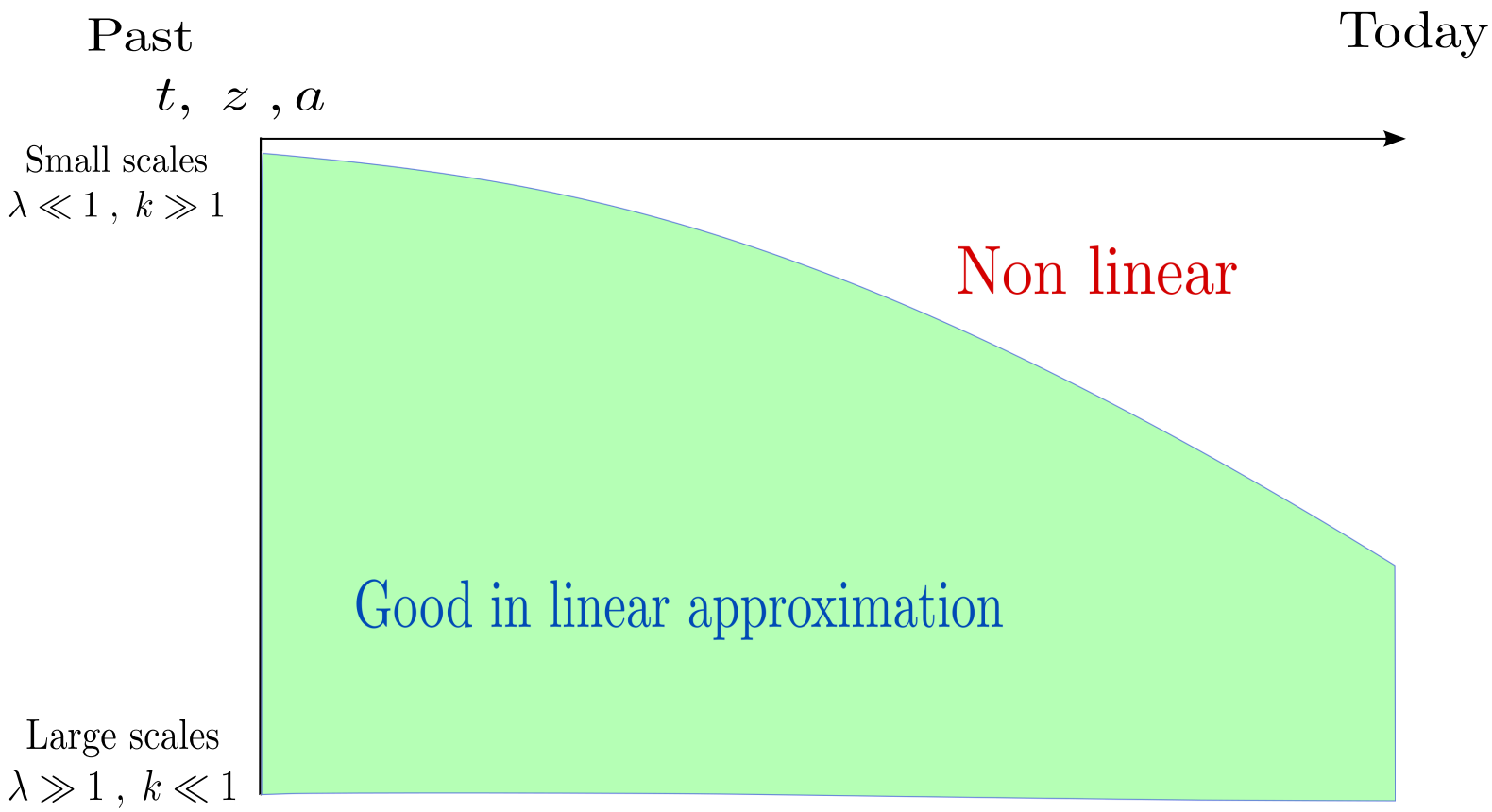
How is the Universe



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

$P_b(k,z) = \langle |\frac{\delta\rho(k_i,z)}{\rho}|^2 \rangle$ where $\delta\rho(k_i,z)$ is the F.T. of the density fluctuations.

Scales


Past
Today
$t, \ z \ , a$
Small scales
$\lambda \ll 1 \ , \ k \gg 1$
Non linear
Good in linear approximation
Large scales
$\lambda \gg 1 \ , \ k \ll 1$

Geometry of the Universe

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

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

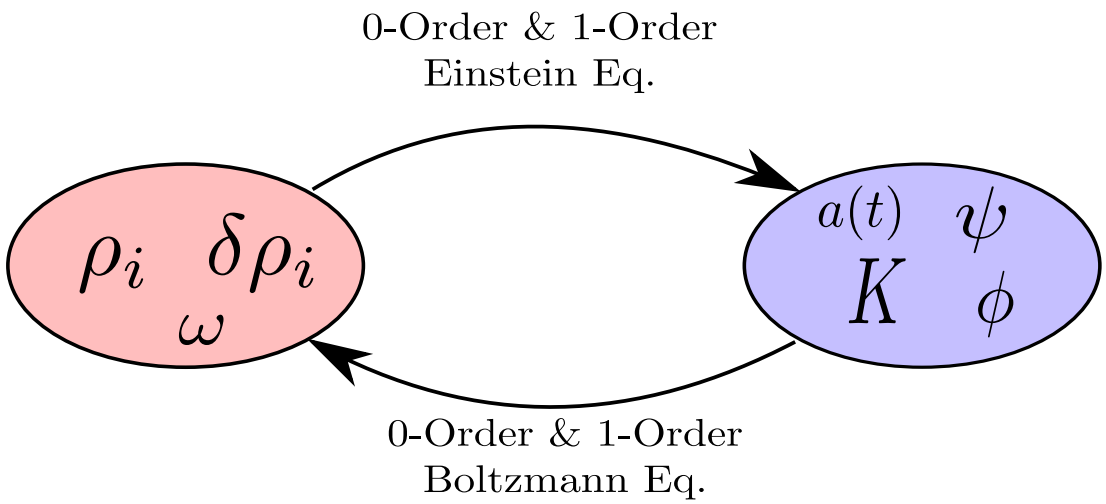
all the dynamics is in the function $a(t)$, $a(t)$ and K are determined by the particle content.

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

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

Particle Content

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



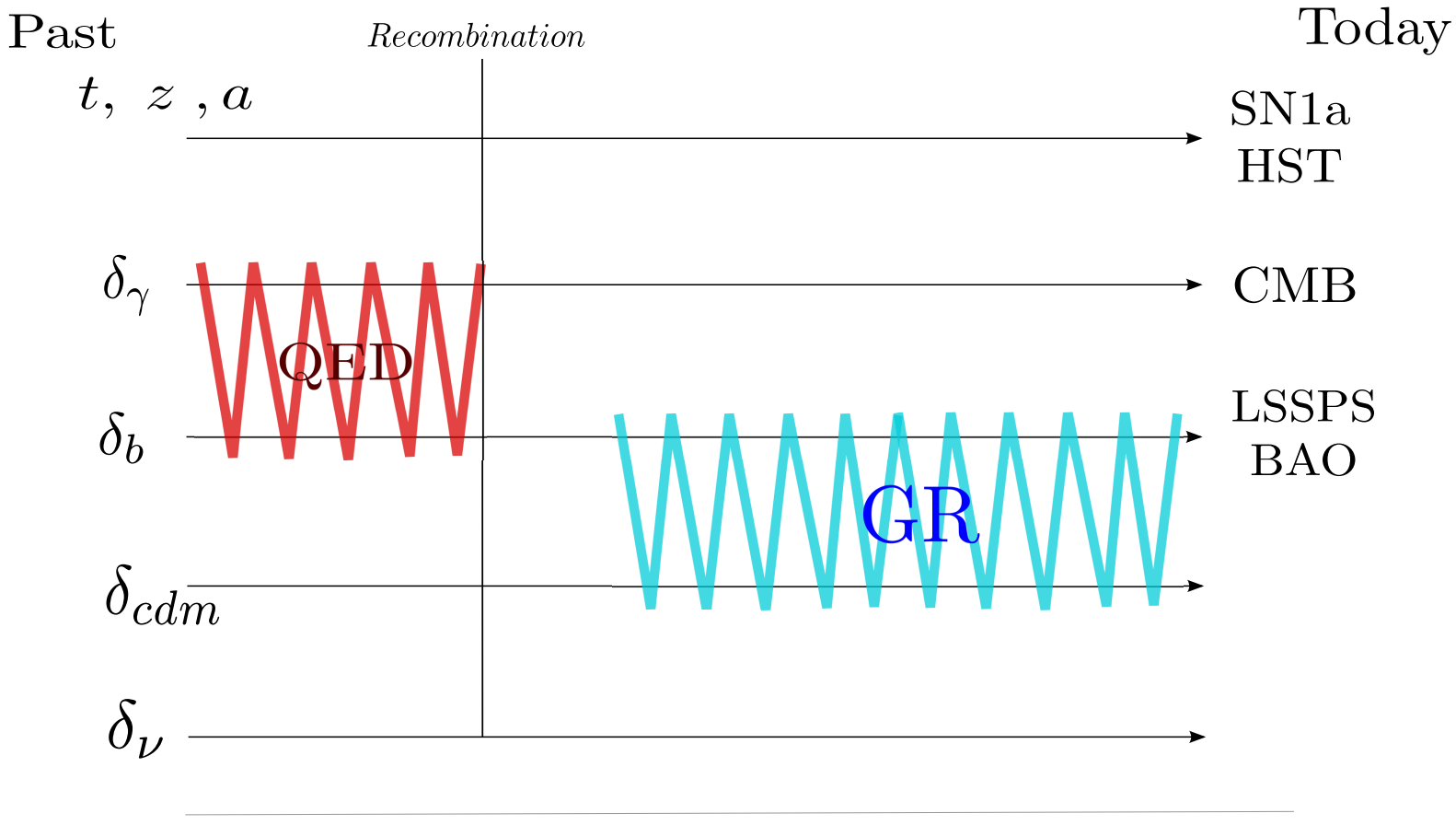
- Matter evolution is given solving Boltzmann equations up to first order in $\delta\rho_i/\rho_i$.

Cosmological Parameters

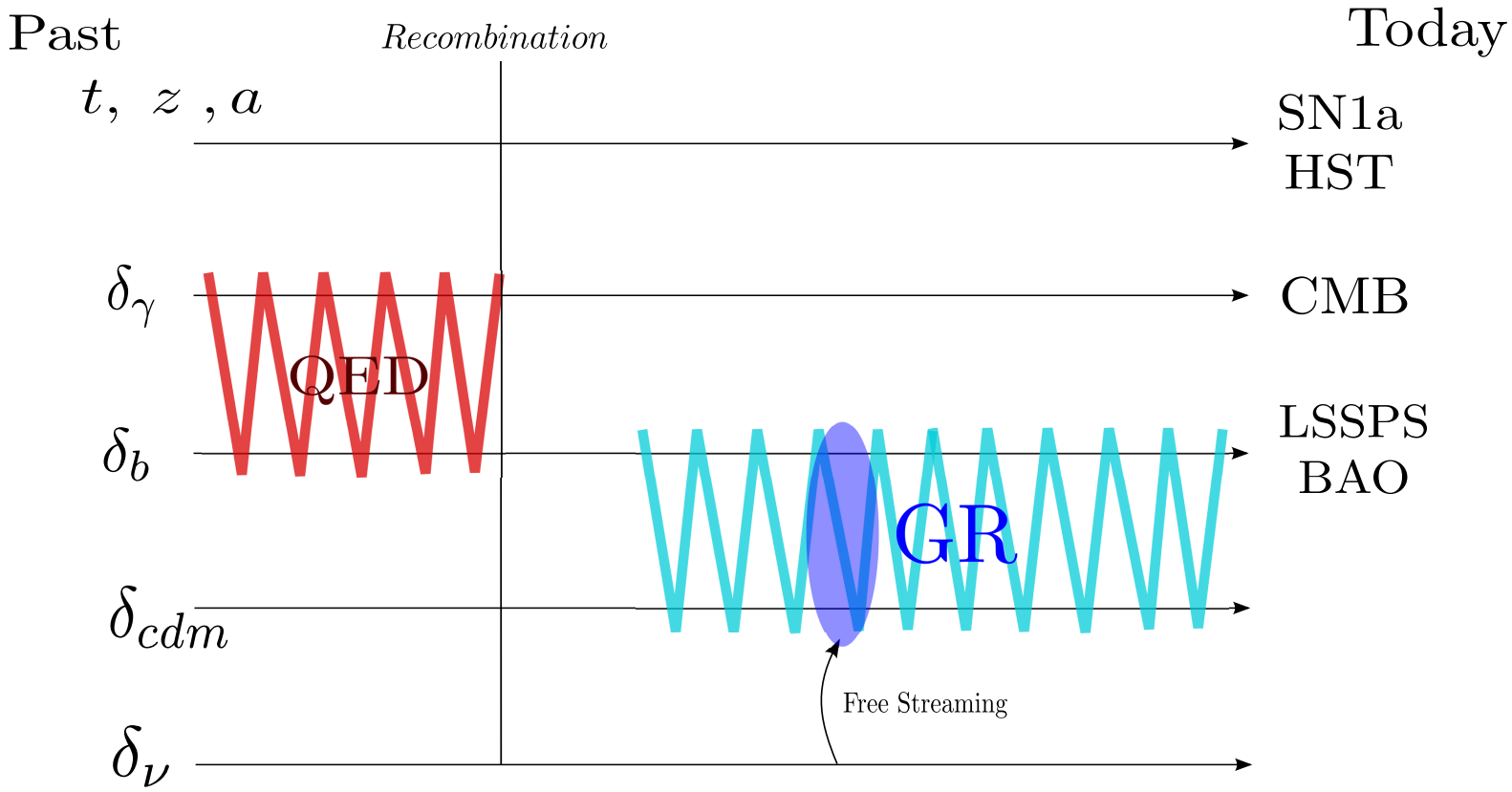
- 0-order(homogeneous and isotropic),
  - Matter $\rightarrow \Omega_m \rightarrow \Omega_{cdm},\ \Omega_b,\ \Omega_\nu$
  - Radiation $\rightarrow \Omega_r \rightarrow \Omega_\gamma$ (fixed by T_{CMB}), $\Delta N_{rel} = N_\nu - 3$
  - Dark energy $\rightarrow \Omega_K$ (instead of Ω_Λ), ω
  - Reionization optical depth $\rightarrow \tau$
  - Hubble parameter today $\rightarrow H_0$
- 1-order, initial conditions for $\delta\rho/\rho$ are determined by the primordial power spectrum from inflation,
  - Primordial spectrum amplitude $\rightarrow A_s$ (we use σ_8)
  - Spectral index($n_s = 1 \Rightarrow$ flat spectra) $\rightarrow n_s$

where $\Omega_i \equiv \rho_i/\rho_{crit}$.

Physics of the perturbations



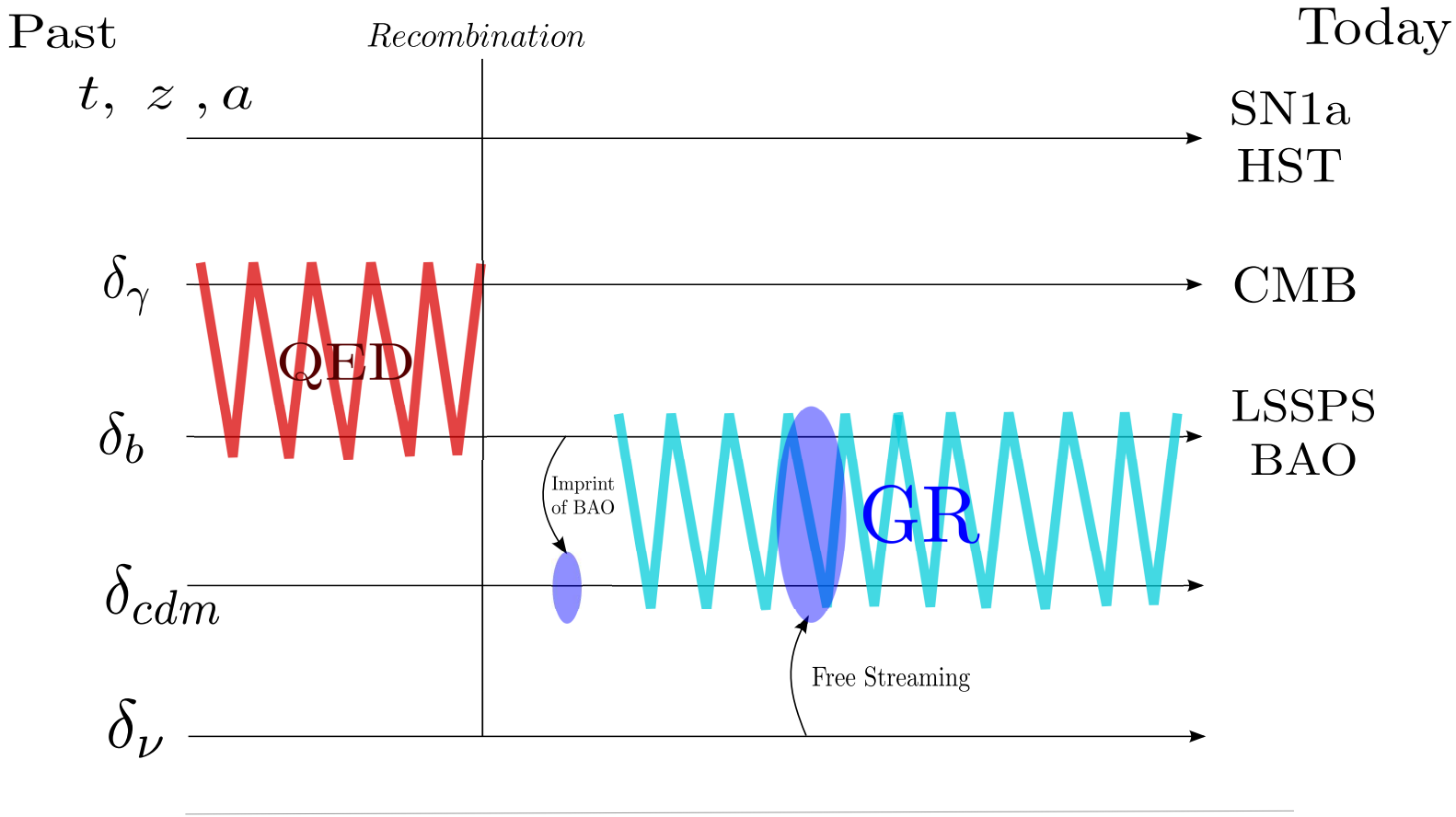
Physics of the perturbations



FS is an effect of the thermal dispersion velocity

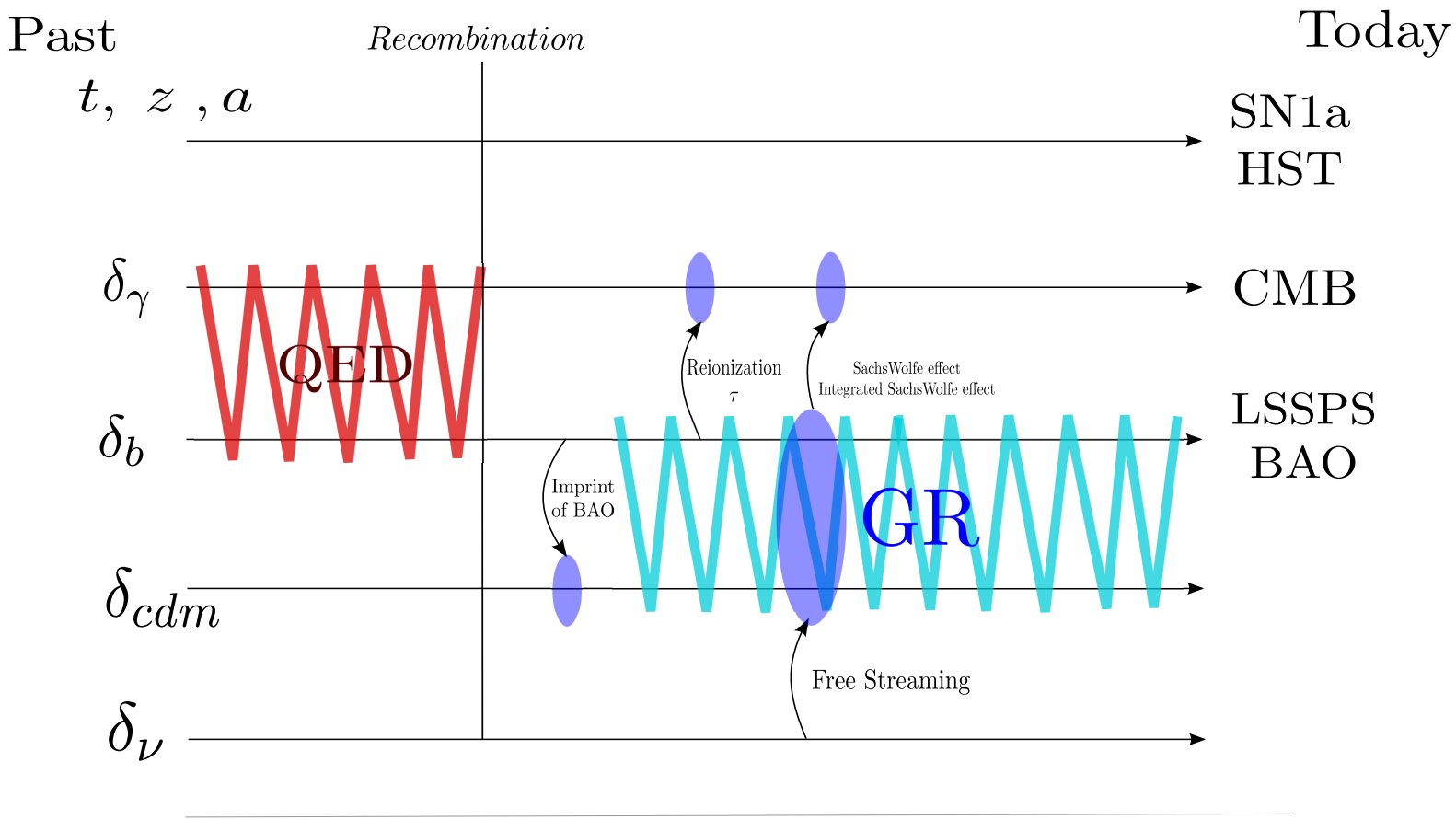
$v_{th} \simeq \frac{T_\nu}{m_\nu}$ and $\lambda_{FS} \propto \frac{T_\nu}{m_\nu}$.

Physics of the perturbations



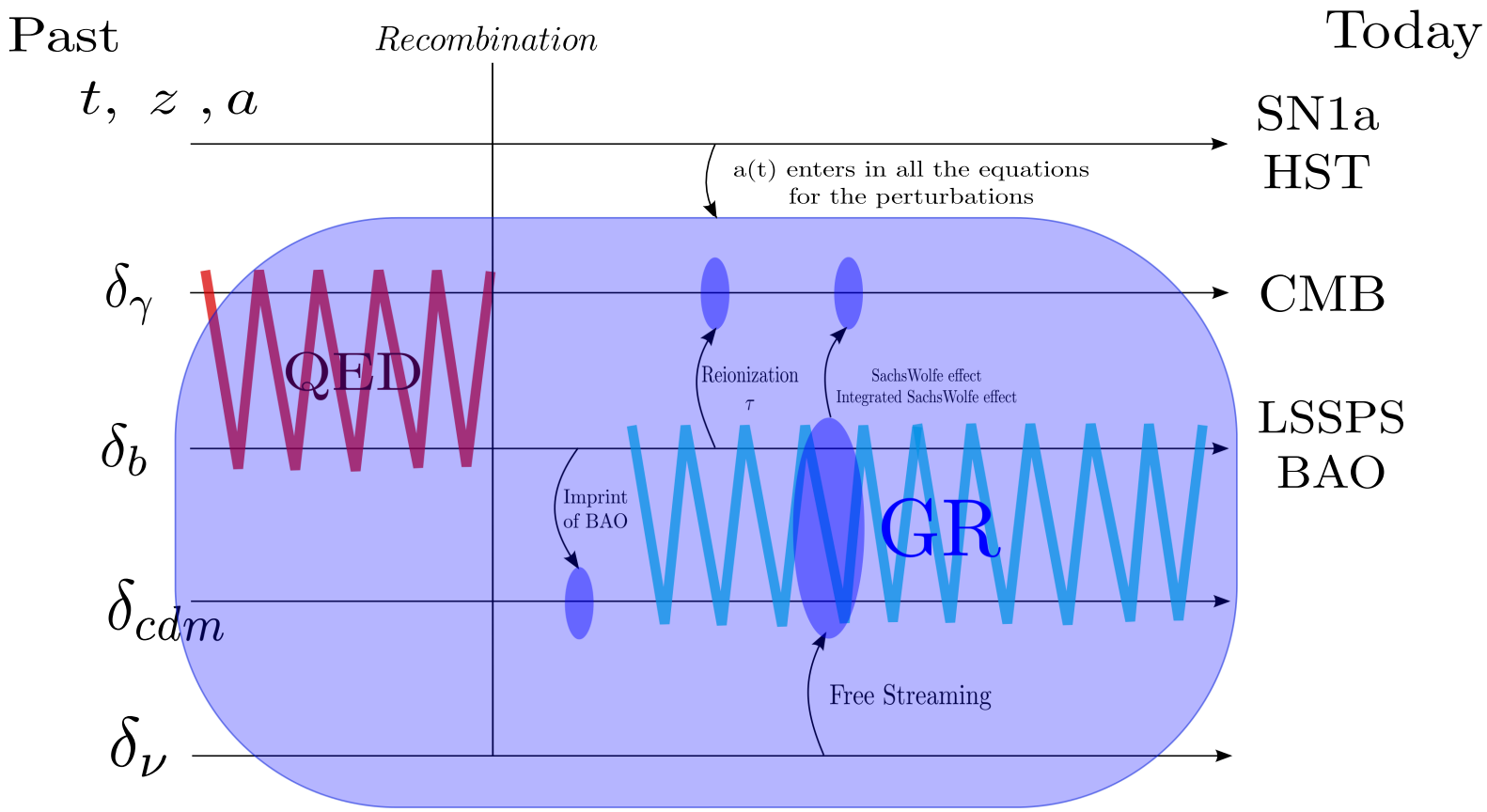
The BAO oscillations in the δ_b have an effect on the full matter PS.

Physics of the perturbations



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

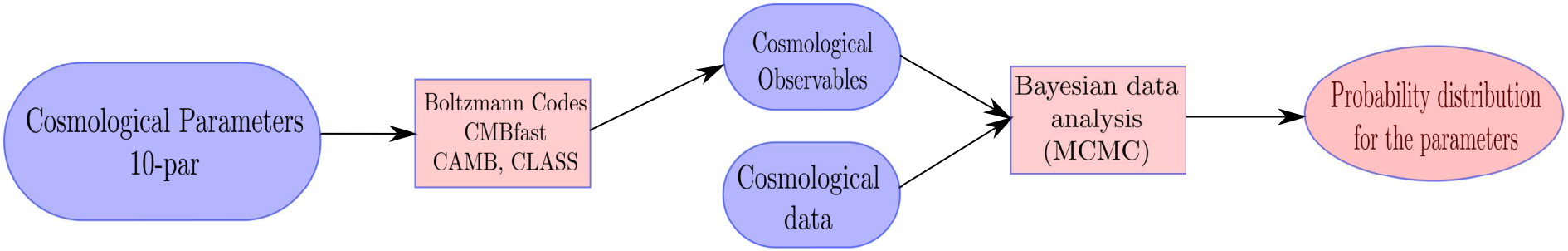
Physics of the perturbations



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

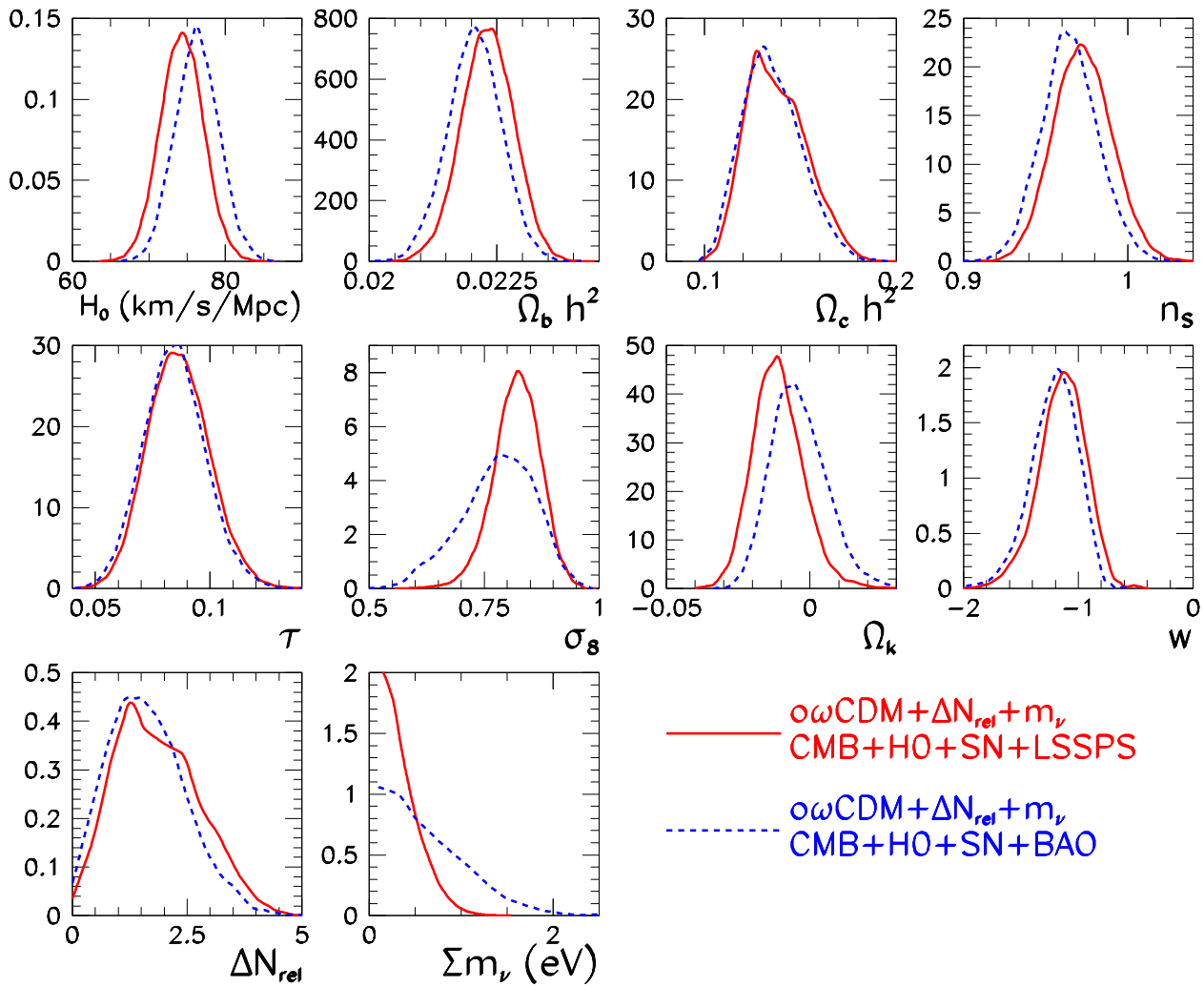
Cosmological Observations

HST	$\rightarrow$	low-z supernovae, HST, A. G. Riess *et al.* `0905.0695`
SN1a	$\rightarrow$	High-z supernovae, M. Hicken *et al.*, `0901.4804`
BAO	$\rightarrow$	BAO from SDSS & 2dFGRS, W. J. Percival *et al.*, `0907.1660`
CMB	$\rightarrow$	WMAP, E. Komatsu, *et al.*,`1001.4538`
LSSPS	$\rightarrow$	SDSS, B. A. Reid *et al.* `0907.1659`

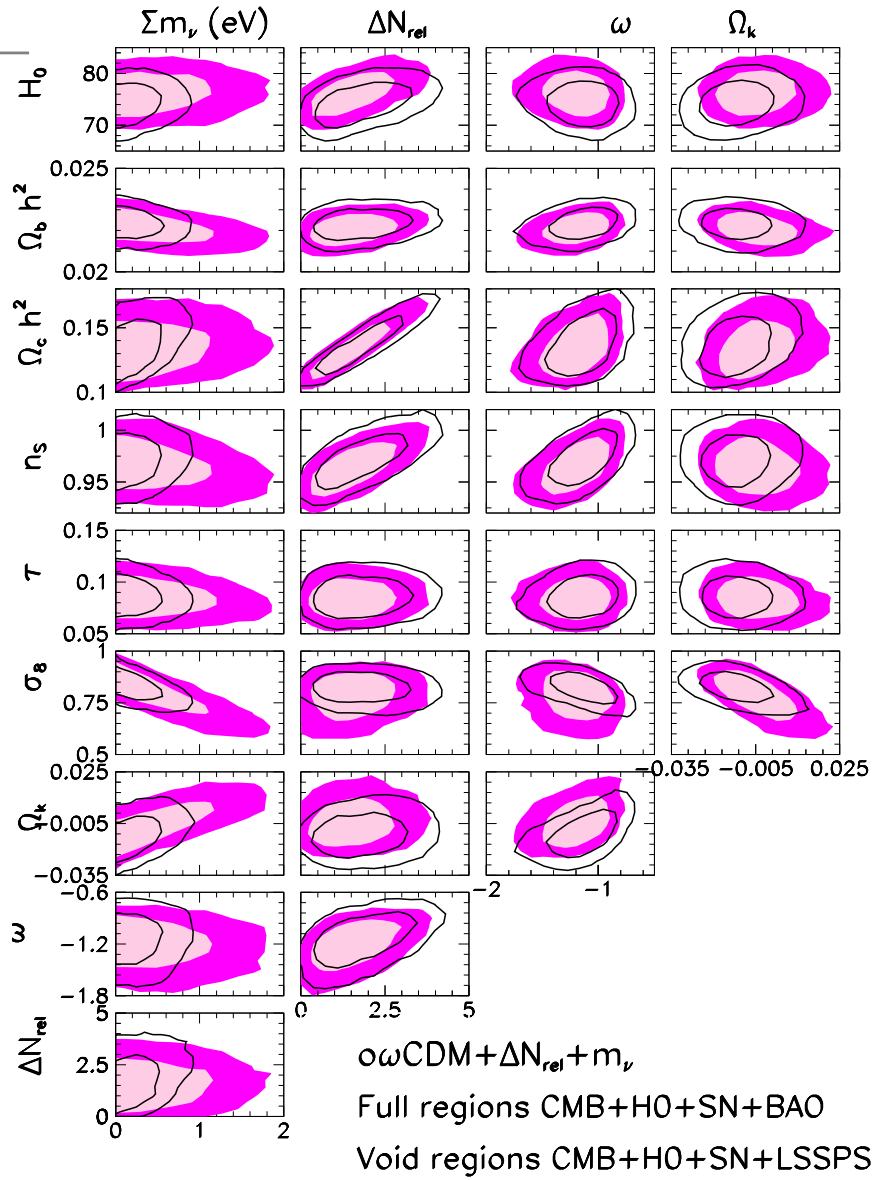


We develop a code implementing a Markov Chain Monte Carlo (MCMC) algorithm for parameter sampling and to determine the posterior probability distribution for the cosmological parameters.

1D-Results


H₀ (km/s/Mpc)
Ω_b h²
Ω_c h²
n_s
τ
σ_8
Ω_k
w
ΔN_rel
Σm_ν (eV)
oωCDM+ΔN_rel+m_ν
CMB+H0+SN+LSSPS
oωCDM+ΔN_rel+m_ν
CMB+H0+SN+BAO

2D-Results



- Correlation between the σ_8 and $\sum m_\nu$.
- Correlation between the ΔN_{rel} and $h^2\Omega_c$ due to their effect on the matter-radiation equality.
- Main difference between using LSSPS or BAO is on the neutrino masses parameter $\sum m_\nu$.

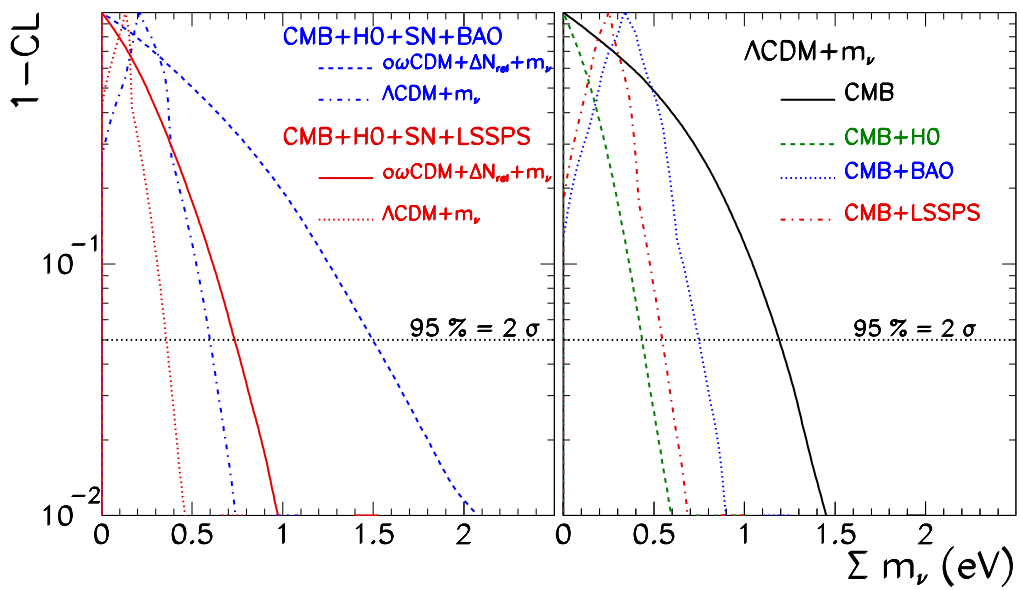
Results

	CMB+HO+SN+BAO			CMB+HO+SN+LSS-PS		
	best	1σ	95% CL	best	1σ	95% CL
H_0 km/s/Mpc	76.2	$^{+3.0}_{-2.8}$	$^{+5.7}_{-5.6}$	74.4	$^{+2.8}_{-2.9}$	$^{+5.6}_{-5.6}$
$\Omega_b h^2 \times 100$	2.205	$^{+0.057}_{-0.050}$	$^{+0.103}_{-0.105}$	2.239	$^{+0.059}_{-0.046}$	$^{+0.095}_{-0.108}$
$\Omega_c h^2$	0.131	$^{+0.018}_{-0.013}$	$^{+0.036}_{-0.023}$	0.128	$^{+0.024}_{-0.009}$	$^{+0.042}_{-0.018}$
n_S	0.961	$^{+0.021}_{-0.015}$	$^{+0.040}_{-0.030}$	0.971	$^{+0.019}_{-0.017}$	$^{+0.037}_{-0.033}$
τ	0.086	$^{+0.011}_{-0.015}$	$^{+0.026}_{-0.028}$	0.083	$^{+0.016}_{-0.011}$	$^{+0.030}_{-0.023}$
σ_8	0.787	$^{+0.091}_{-0.073}$	$^{+0.135}_{-0.179}$	0.824	$^{+0.051}_{-0.048}$	$^{+0.097}_{-0.105}$
Ω_k	-0.006	$^{+0.010}_{-0.009}$	$-0.022 \leq \Omega_k \leq 0.016$	-0.011	$^{+0.008}_{-0.009}$	$-0.028 \leq \Omega_k \leq 0.007$
ω	-1.17	$^{+0.19}_{-0.21}$	$-0.62 \leq \omega + 1 \leq 0.18$	-1.12	$^{+0.21}_{-0.20}$	$-0.57 \leq \omega + 1 \leq 0.26$
$\Delta N_{\rm rel}$	1.2	$^{+1.1}_{-0.61}$	$0.08 \leq \Delta N_{\rm rel} \leq 3.2$	1.3	$^{+1.4}_{-0.54}$	$0.21 \leq \Delta N_{\rm rel} \leq 3.6$
$\sum m_\nu$ (eV)		≤ 0.77	≤ 1.5		≤ 0.37	≤ 0.76

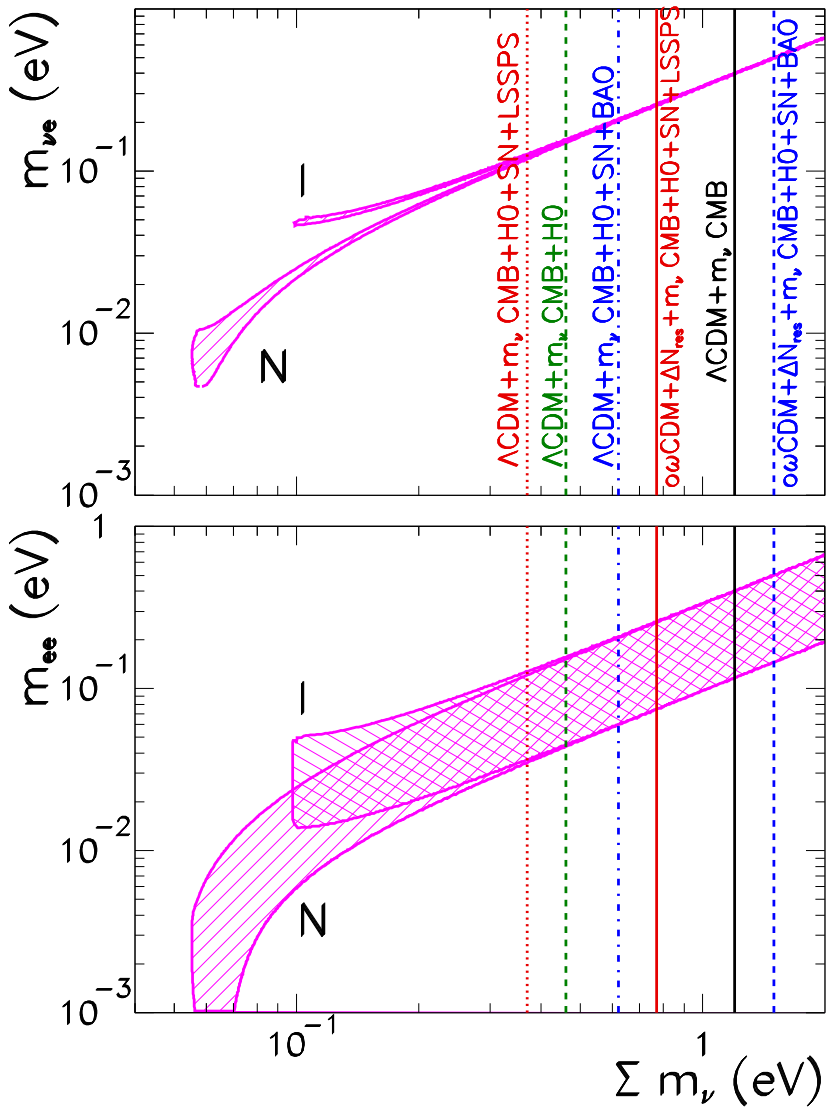
1σ (68%) and 2σ (95%).

Neutrino Masses

Model	Observables	Σm_ν (eV) 95% Bound
$o\omega\mathrm{CDM} + \Delta N_{\mathrm{rel}} + m_\nu$	CMB+HO+SN+BAO	≤ 1.5
$o\omega\mathrm{CDM} + \Delta N_{\mathrm{rel}} + m_\nu$	CMB+HO+SN+LSSPS	≤ 0.76
$\Lambda\mathrm{CDM} + m_\nu$	CMB+H0+SN+BAO	≤ 0.61
$\Lambda\mathrm{CDM} + m_\nu$	CMB+H0+SN+LSSPS	≤ 0.36
$\Lambda\mathrm{CDM} + m_\nu$	CMB (+SN)	≤ 1.2
$\Lambda\mathrm{CDM} + m_\nu$	CMB+BAO	≤ 0.75
$\Lambda\mathrm{CDM} + m_\nu$	CMB+LSSPS	≤ 0.55
$\Lambda\mathrm{CDM} + m_\nu$	CMB+H0	≤ 0.45



Neutrino Masses



Cosmological bound on the neutrino masses

Conclusions

- Structure formation is strongly affected by neutrino masses.
- But bound depends on cosmological model assumed and on data used in the analysis.
  - In a general cosmological model (allowing curvature, DE equation of state, and extraradiation) :
    - Using the LSSPS we get $\sum m_\nu \leq 0.76$ (95% CL) we need to have in to account non linear corrections.
    - Using BAO which is more conservative we get $\sum m_\nu \leq 1.5$ (95% CL).
  - To be compared to bounds in ΛCDM cosmology:
    - Using the LSSPS we get $\sum m_\nu \leq 0.36$ (95% CL)
    - Using BAO $\sum m_\nu \leq 0.61$ (95% CL).
- The cosmological data gives also evidences for $N_{rel} > 3$
  - $\Delta N_{\rm rel} = 1.2^{+1.1}_{-0.61}$, (95% CL) $0.21 \leq \Delta N_{\rm rel} \leq 3.6$ for LSSPS.
  - $\Delta N_{\rm rel} = 1.3^{+1.4}_{-0.54}$ (95% CL) $0.08 \leq \Delta N_{\rm rel} \leq 3.2$ for BAO.