COSMOLOGICAL AND ASTROPHYSICAL CONSTRAINTS ON MAJORON DARK MATTER

Massimiliano Lattanzi

Dipartimento di Fisica e Scienze della Terra, Università di Ferrara,
and INFN, sezione di Ferrara

based on work in collaboration with
Federica Bazzocchi, Signe Riemer-Sørensen,
Mariam Tórtola, and José Valle

22/5/2013

RICAP 2013 – Università di Roma “Sapienza”

NEUTRINO MASSES

We know from oscilaltion experiments that neutrinos have a mass. In the standard model, however, neutrinos have zero mass due to the absence of right-handed neutrinos ν_R .
These would give rise to a Dirac mass term in the Lagrangian

$$\mathcal{L}^D \sim Y_\nu \, \bar{\nu}_L \, \Phi \, \nu_R + h.c. \longrightarrow m_D \; (\bar{\nu}_L \, \nu_R + \nu_L \, \bar{\nu}_R) \, .$$

where Φ is the Higgs doublet, and $m_D = Y_\nu \langle \Phi \rangle$

Another possibility would be to add a Majorana mass term for the LH neutrinos:

$$\mathcal{L}^M \sim Y_3 \, \bar{\nu}_L \, \Delta \, \nu_L \longrightarrow m_L^M \, \bar{\nu}_L \, \nu_L \, .$$

where Δ is a Higgs triplet (not present in the SM) and $m_L^M = Y_3 \langle \Delta \rangle$
This mass term violates lepton number by 2 units.
(one could also introduce a term of the kind $(\nu\Phi)^T(\nu\Phi)$ but that would spoil renormalizability)

NEUTRINO MASSES

Extending the SM to have RH neutrinos ν_R, one can also have a majorana term for the RH neutrinos:

$$\mathcal{L}^M \sim Y_1\, \bar{\nu}_R\, \sigma\, \nu_R \longrightarrow m_R^M\, \bar{\nu}_R\, \nu_R.$$

where σ is a Higgs singlet, and $m_R^M = Y_1 \langle \sigma \rangle$.

Thus the more general neutrino mass term is:

$$\mathcal{L}^{D+M} \sim (\nu_L \quad \bar{\nu}_R) \begin{pmatrix} m_L^M & m^D \\ m^D & m_R^M \end{pmatrix} \begin{pmatrix} \bar{\nu}_L \\ \nu_R \end{pmatrix}$$

$$= (\nu_L \quad \bar{\nu}_R) \begin{pmatrix} Y_3 v_3 & Y_\nu v_2 \\ Y_\nu v_2 & Y_1 v_1 \end{pmatrix} \begin{pmatrix} \bar{\nu}_L \\ \nu_R \end{pmatrix}$$

THE SEESAW MECHANISM

In the limit $m^M{}_L = 0$ and $m^M{}_R >> m^D$, diagonalization of the mass matrix yields eigenvalues

$$m_{\text{light}} \simeq \frac{\left(m^D\right)^2}{m_R^M} \qquad \ll \qquad m_{\text{heavy}} \simeq m_R^M$$

The Dirac mass m^D is expected to be of the same order as the other fermion masses, but the Majorana mass is not constrained by the gauge simmetry and thus can be arbitrarily large.

This is the (type I) **see-saw mechanism** that naturally explains the smallness of neutrino masses with respect to the other SM fermions.

THE MAJORON MODEL

Thus a natural way to understand the smallness of neutrino masses with respect to the charged leptons involves neutrinos to be Majorana particles, and consequently the violation of lepton number L.

There are three possibilities:

- L is explicitly broken in the lagrangian;
- L is spontaneously broken locally;
- L is spontaneously broken globally;

In the latter case, a (massless) Nambu-Goldstone boson appears in the theory – the **majoron** (Chikashige, Mohapatra, Peccei, 1981).

THE MAJORON MODEL

In a bit more detail, recall the Majorana mass term for the RH nu's:

$$\mathcal{L}^M \sim Y_1\, \bar{\nu}_R\, \sigma\, \nu_R \longrightarrow m_R^M\, \bar{\nu}_R\, \nu_R .$$

σ is the parent field of the majoron – in fact after symmetry breaking it develops a non-zero vacuum expectation value and

$$\sigma = \frac{1}{\sqrt{2}}\left(\langle\sigma\rangle + \rho + iJ\right)$$

J is the majoron.

THE MAJORON MODEL

In the following I shall consider a more complicated model, with a full seesaw structure (i.e. including also a Higgs triplet and a majorana mass term for the LH neutrinos). The full Yukawa lagrangian is:

$$\mathcal{L}_Y = Y_u \bar{Q}_L \Phi^* u_L^c + Y_d \bar{Q}_L \Phi d_L^c + Y_e \bar{L}_L \Phi e_L^c + \\ + Y_\nu \bar{L}_L \Phi^* \nu_L^c + \tilde{Y}_\nu L_L^T \Delta L_L + \frac{Y_R}{2} \nu_L^c \nu_L^c \sigma + H.c. \,,$$

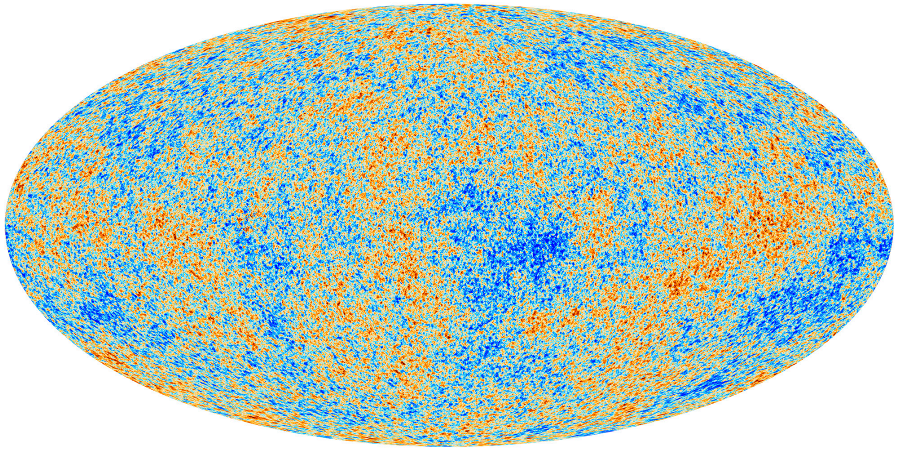
The vev's of the singlet, doublet and triplet Higgs scalar obey the (type-II) seesaw relation $v_3 << v_2 << v_1$.

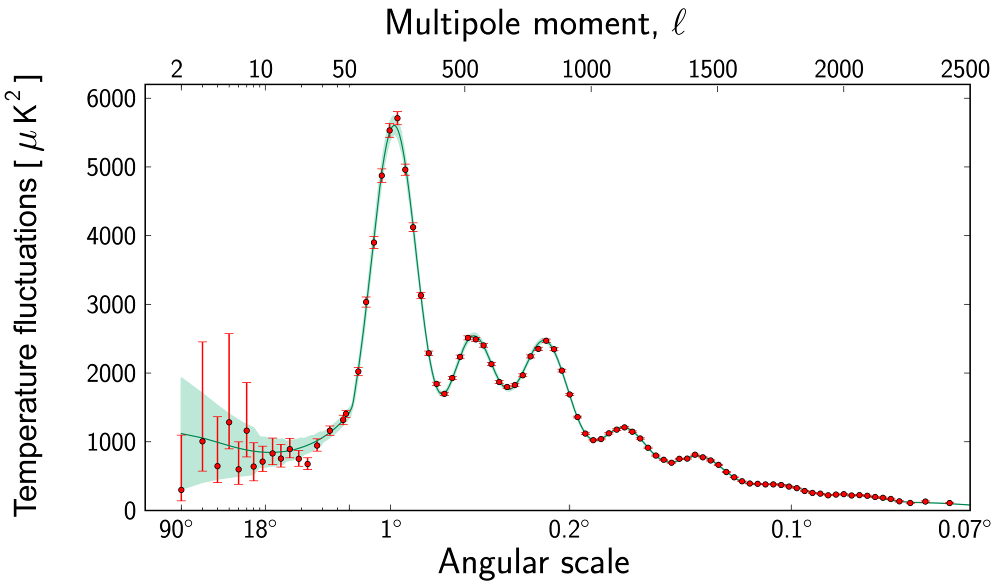
In this approximation the majoron is the following combination of the Higgs fields:

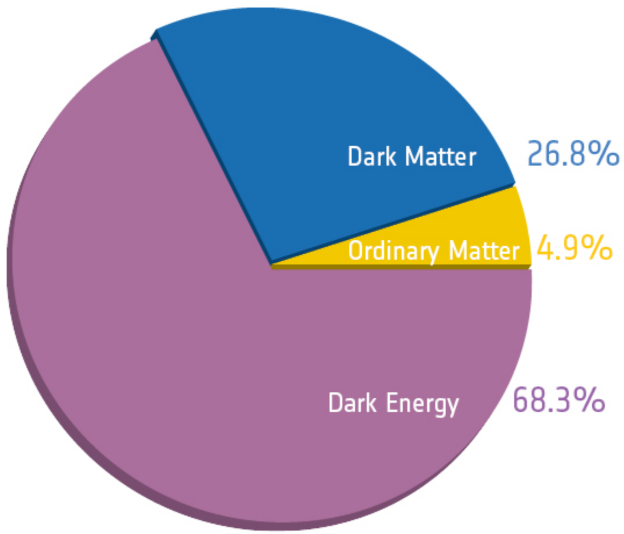
$$J \propto v_3 {v_2}^2 \Im(\Delta^0) - 2 v_2 {v_3}^2 \Im(\Phi^0) + v_1 ({v_2}^2 + 4{v_3}^2) \Im(\sigma)$$

THE SM OF COSMOLOGY

The standard cosmological model can consistently explain current observations, in particular the temperature anisotropies of the CMB… but still leaves many open questions about the nature of dark matter and dark energy

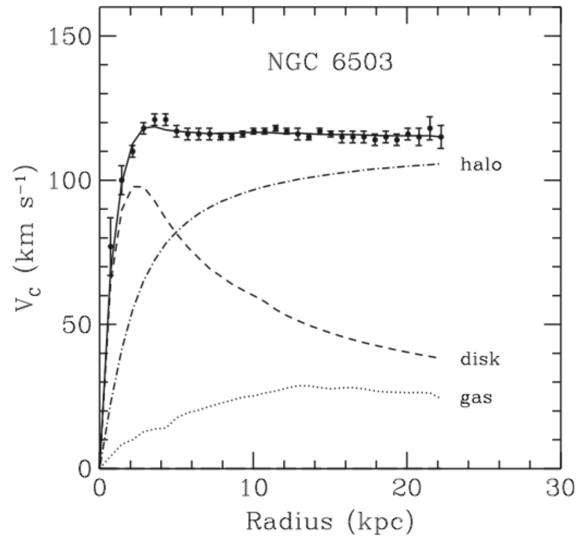


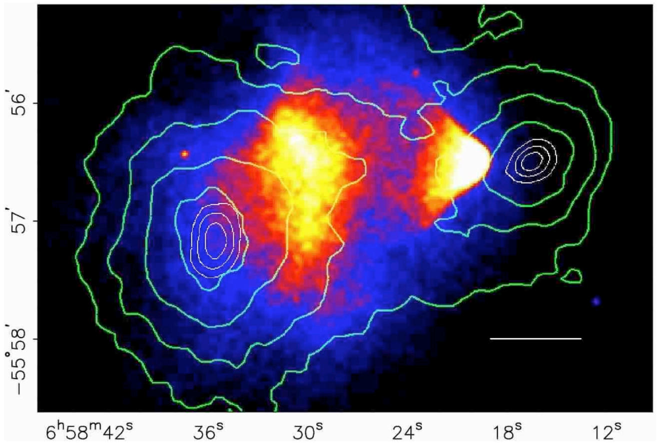




A COSMIC PUZZLE: DARK MATTER

- On galactic scales:
  - **Rotation curves of galaxies;**
  - **Weak gravitational lensing;**
  - **Velocity dispersion of dwarf spheroidal galaxies;**
  - **Velocity dispersion of spiral galaxy saltellites;**
- On the scale of galaxy clusters:
  - **Distribution of radial velocities;**
  - **Weak gravitational lensing;**
  - **X-ray emission;**
- On cosmological scales:
  - **CMB anisotropy spectrum;**
  - **Matter power spectrum.**





Majoron Dark Matter

Could the dark matter be related to the origin of neutrino masses? More precisely, could the majoron be the DM?
The idea was first put forward by Berezinsky & Valle (1993).

A viable DM candidate should be massive, stable (or long-lived enough) and neutral.

As a Goldstone boson, the majoron is massless, but it could can acquire a mass from non-perturbative gravitational effects that explicitly break global symmetries (Akhmedov et al. 1993).

The majoron can decay to neutrinos but it can be long lived enough.

This "majoron DM" hypothesis can be tested through cosmological and astrophysical observations.

MAJORON DARK MATTER

Majorons could be produced in the early Universe either thermally or through a non-thermal mechanism (e.g. a phase transition)

However, the majoron couples to neutrinos and decays with a rate

$$\Gamma_{J\to\nu\nu} = \frac{m_J}{32\pi}\frac{\sum_i (m_i^\nu)^2}{2v_1^2} .$$

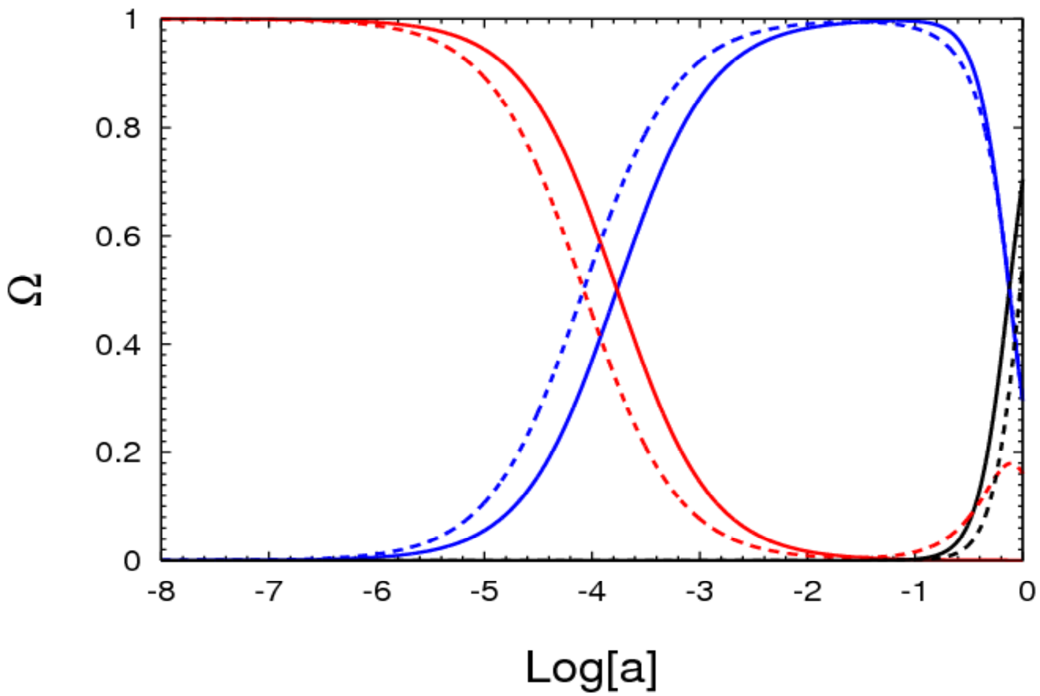
The present cosmological density of majorons will be

$$\Omega_J h^2 = \beta \frac{m_J}{1.25\,\mathrm{keV}} e^{-t_0/\tau}$$

where $\beta = 1$ is for the thermal production mechanism.
The observable signature of majoron decay on the CMB anisotropies has been first studied in Lattanzi & Valle (2007).

MAJORON PHENOMENOLOGY

If the majoron has a finite lifetime, then for a fixed Ω_J there will be more DM at early times and matter-radiation equality will be anticipated:



Ω_J=0.25

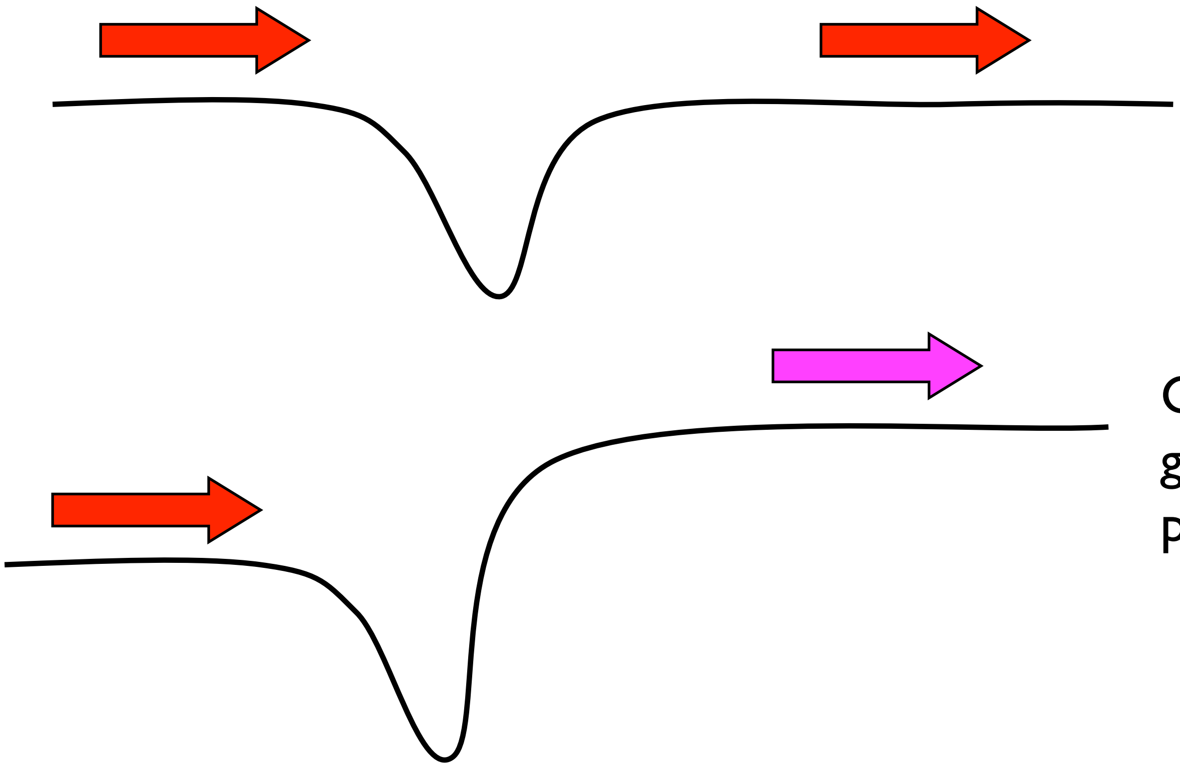
τ_J = 14 Gyr

Smaller early ISW and decreased first peak in the CMB anisotropy spectrum

MAJORON PHENOMENOLOGY

On the other hand, late majoron decays will make the gravitational potentials vary during the recent stages of cosmological evolution.

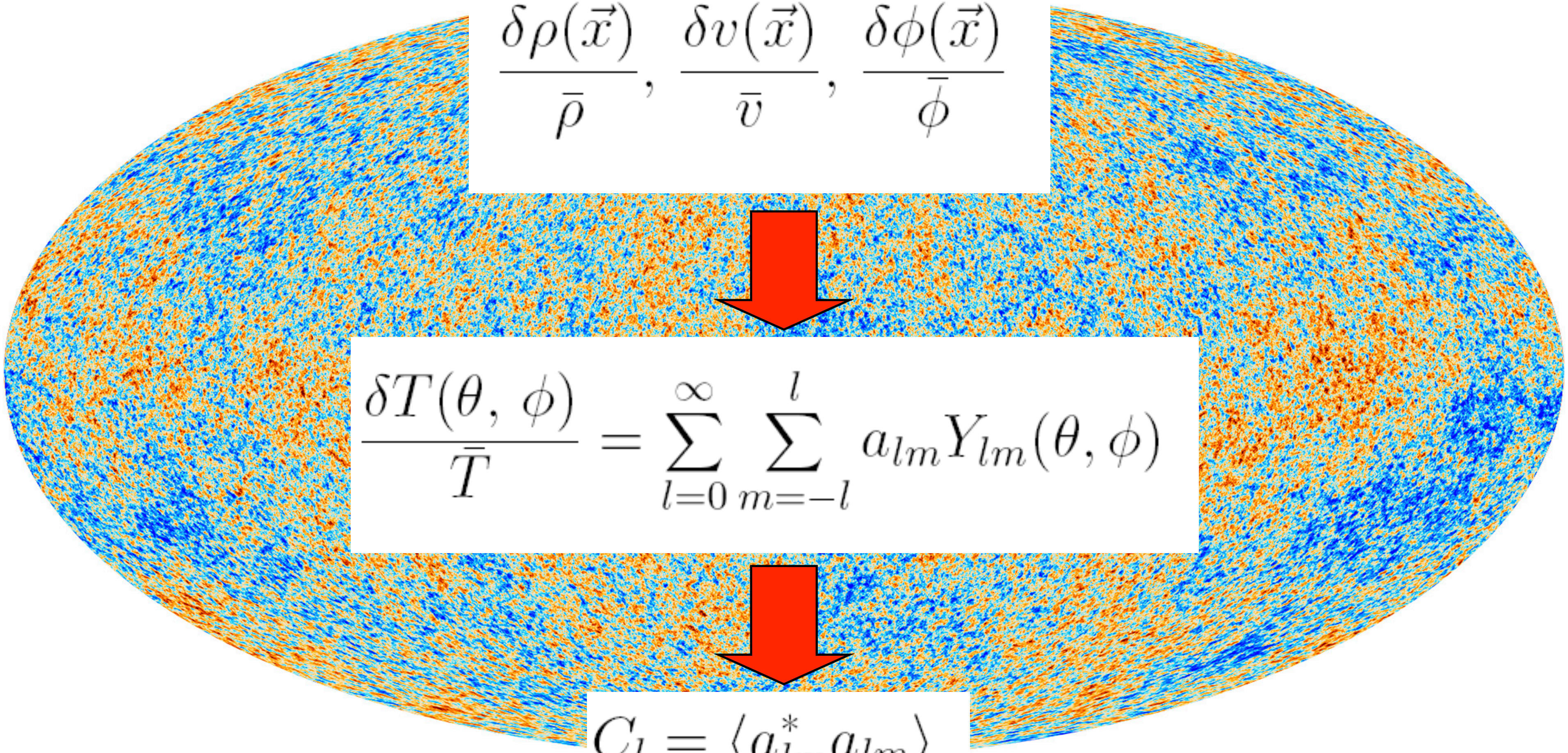
This a source for the late-time integrated Sachs-Wolfe (LISW) effect, that causes an excess of power at small multipoles.



Constant gravitational potential

Growing gravitational potential

CMB ANISOTROPIES

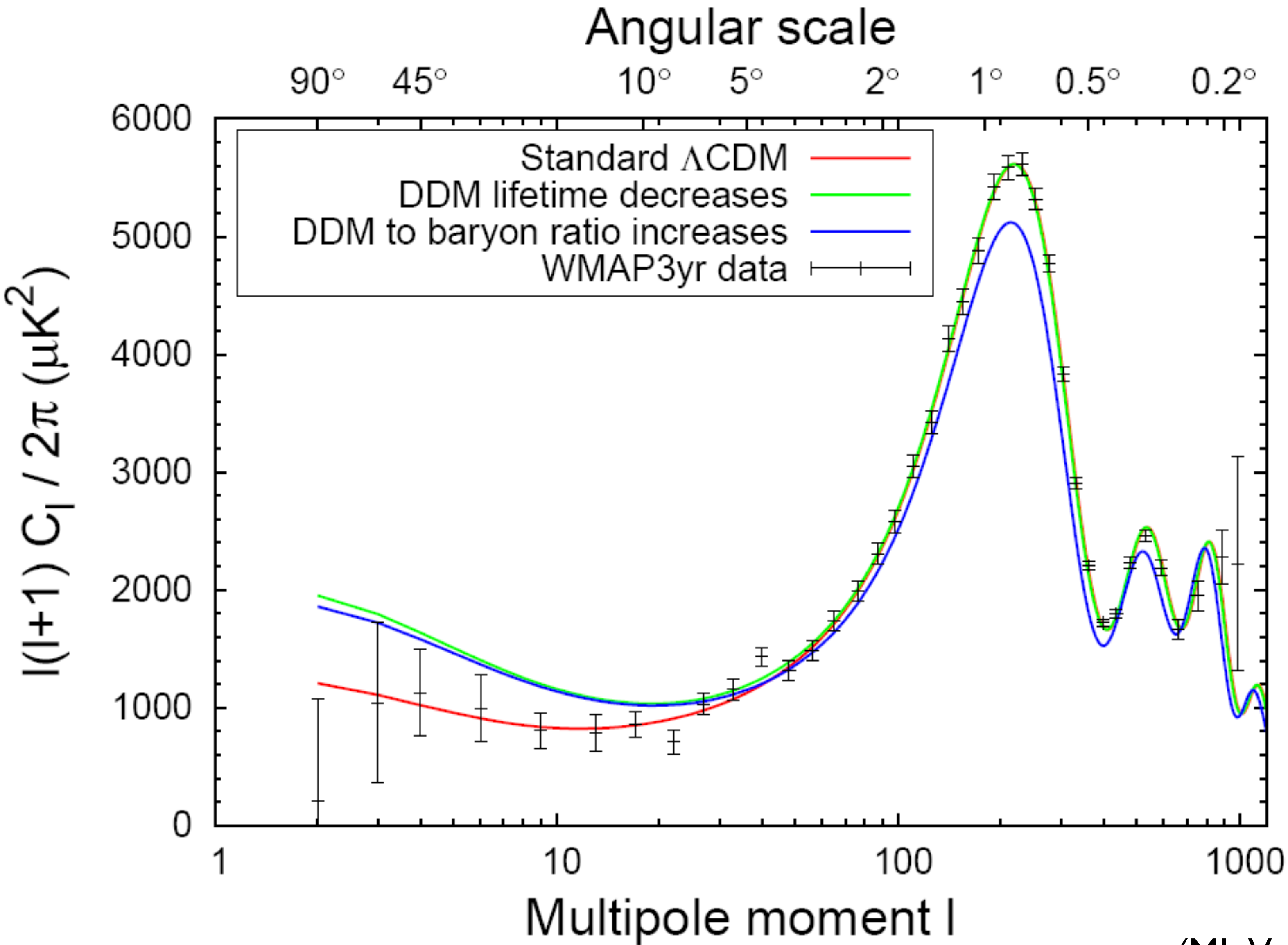


$$\frac{\delta\rho(\vec{x})}{\bar{\rho}},\ \frac{\delta v(\vec{x})}{\bar{v}},\ \frac{\delta\phi(\vec{x})}{\bar{\phi}}$$

$$\frac{\delta T(\theta,\,\phi)}{\bar{T}} = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

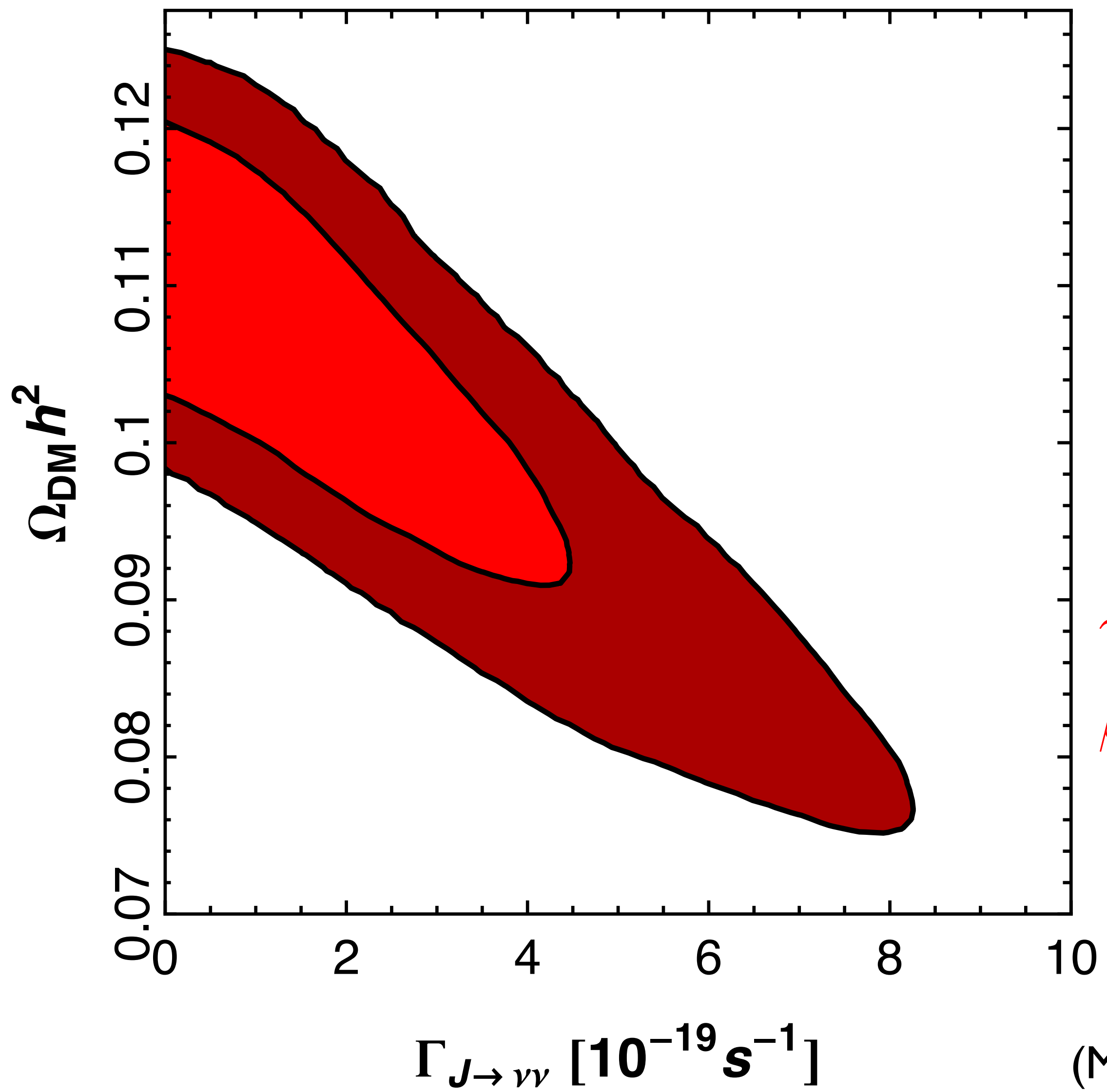
$$C_l = \langle a^*_{lm} a_{lm} \rangle$$

MAJORON CMB PHENOMENOLOGY



(ML, Valle, 2007)

CMB CONSTRAINTS



From a MCMC analysis of WMAP9 temperature and polarization data we get (@95% CL):

$$\Gamma_{J\to\nu\bar{\nu}} \leq 6.4\times 10^{-19}\mathrm{s}^{-1}$$

$$\Omega_J h^2 = 0.102 \pm 0.021$$

$$\tau_J \geq 50\mathrm{Gyr}$$

$$\beta m_J = (0.141 \pm 0.012)\mathrm{keV}$$

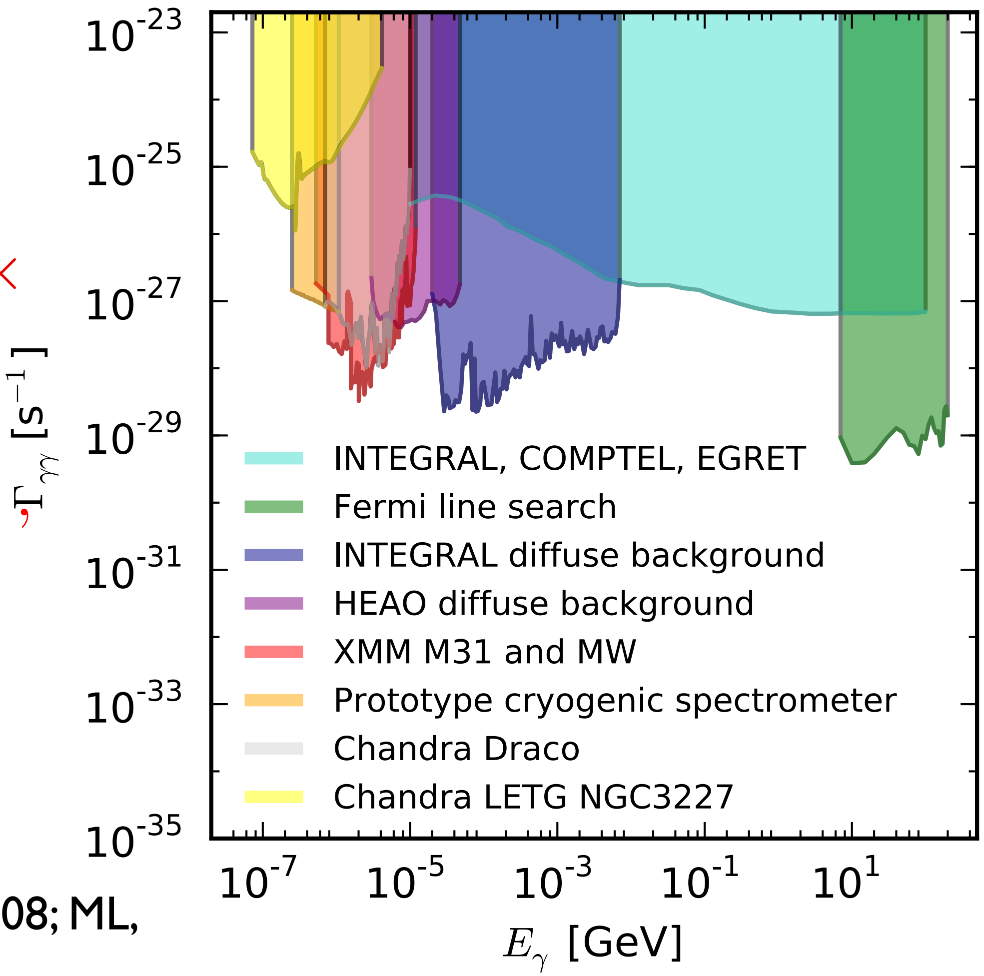
$$v_1 \gtrsim 3\times 10^6\,\beta^{-1/2}\,\mathrm{GeV}$$

(ML, Riemer-Sørensen, Tortola, Valle, 2013)

TWO-PHOTON DECAY MODE

The neutrino decay mode of the majoron is accompanied by a sub-dominant two-photon mode

$$\Gamma_{J\to\gamma\gamma} = \frac{\alpha^2 m_J^3}{64\pi^3}\left|\sum_f N_f Q_f^2 \frac{2v_3^2}{v_2^2 v_1}\times (-2T_3^f)\ \frac{m_J^2}{12m_f^2}\right|^2$$



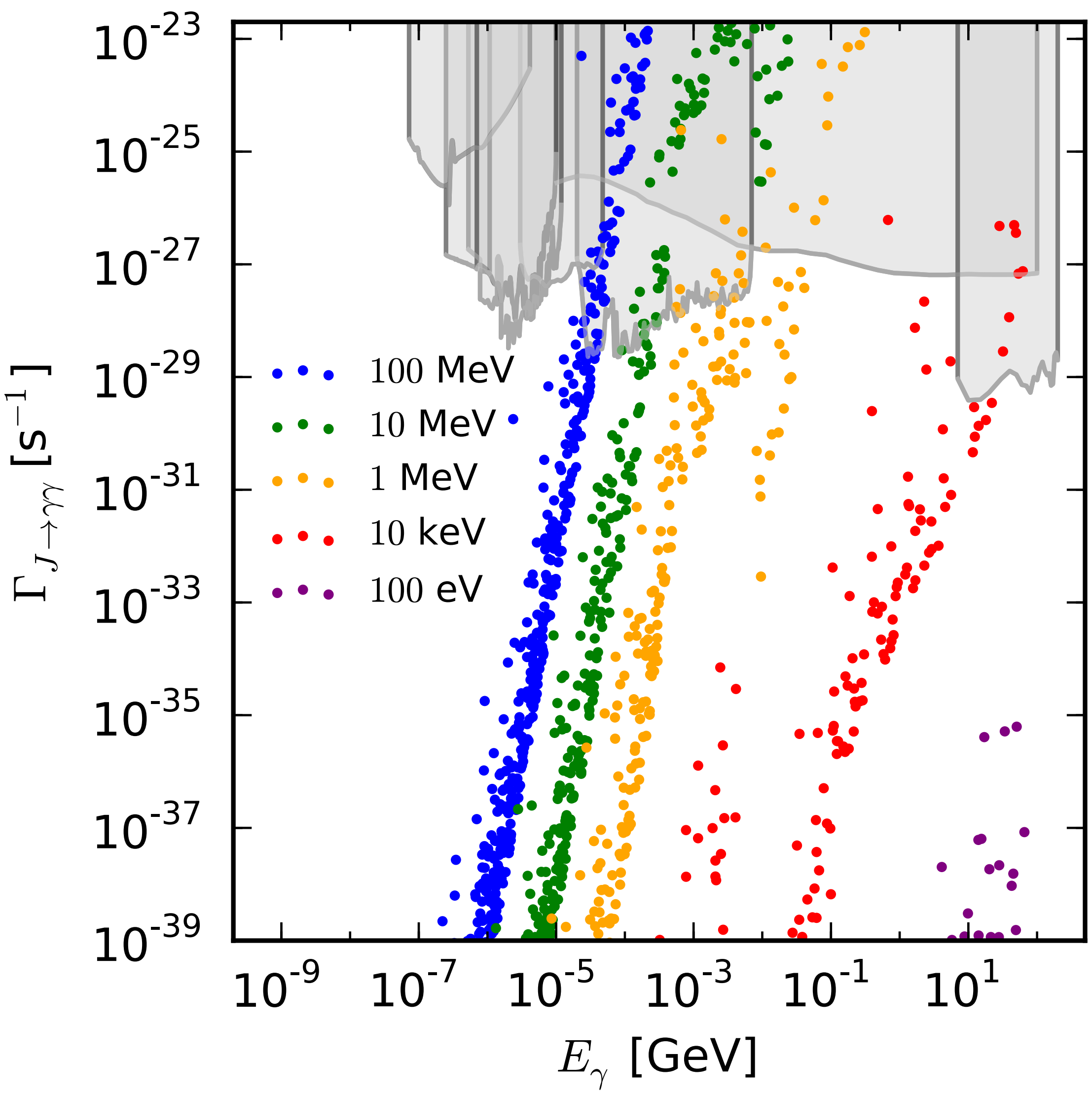
This can be constrained by a number of astrophysical observations

(Bazzocchi, ML, Riemer-Sørensen, Valle, 2008; ML, Riemer-Sorensen, Tortola, Valle, 2013)

TWO-PHOTON DECAY MODE

We have performed a random scan over the Yukawa matrices and vevs.
For each point in parameter space we compute the light nu mass matrix and the decay rate and exclude models that do not agree with current nu oscillation data and with the CMB bound on the majoron lifetime.
Finally we compute the two-photon decay rate.

The line emission constraints start to cut realistic models, especially for v_3 > a few MeVs



(ML, Riemer-Sørensen, Tortola, Valle, 2013)

SUMMARY

• An elegant way to give mass to the neutrinos (and to explain the smallness of such a mass) involves them being Majorana particles and thus the violation of lepton number

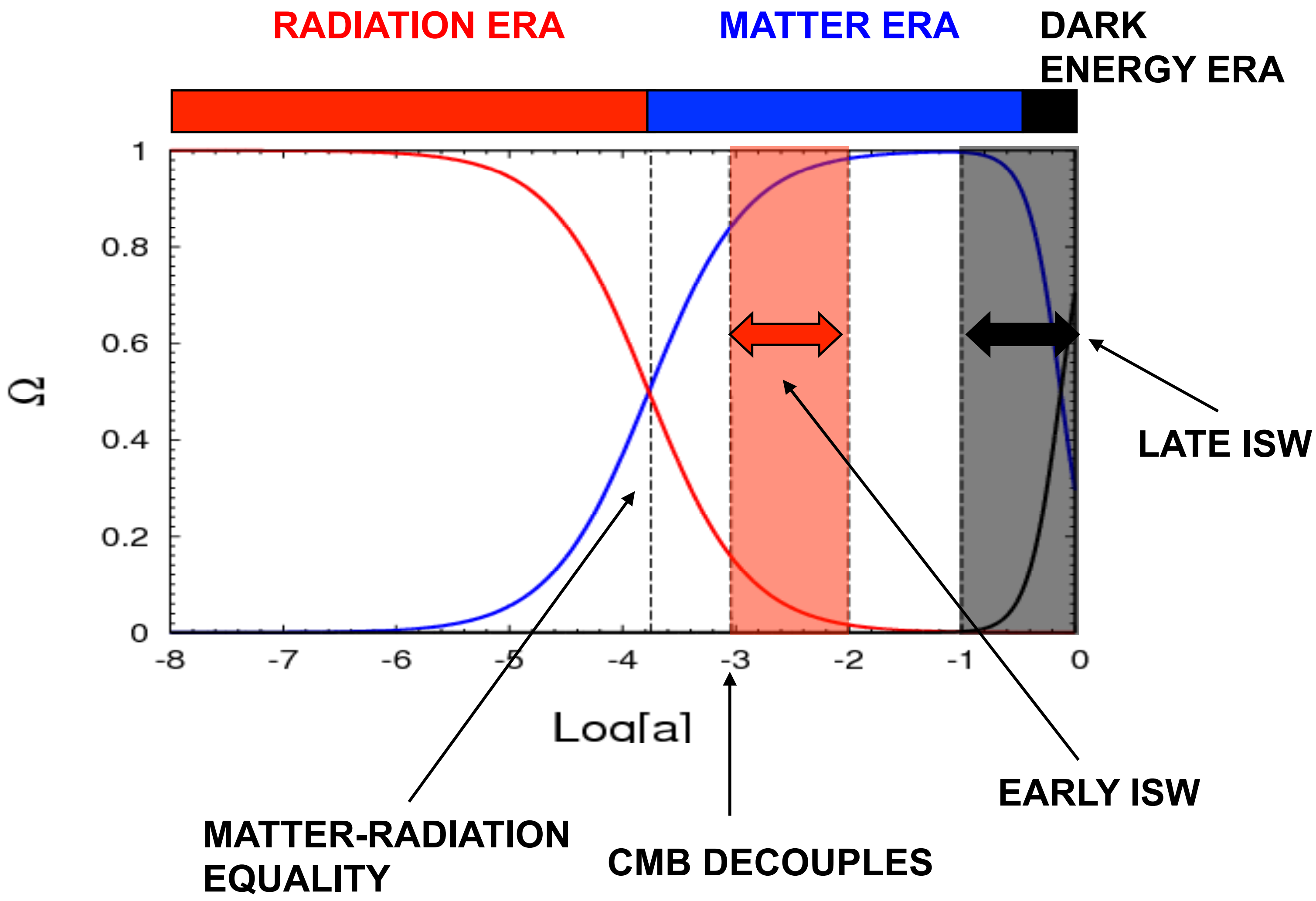
• In the framework where lepton number is broken globally, a Nambu-Goldstone boson – the majoron – appears, and can acquire a mass due to non-perturbative gravitational effects

• The majoron is massive, long-lived and neutral – it could be a viable dark matter candidate

• The majoron dark matter hypothesis can be tested by a number of cosmological and astrophysical observations

• CMB anisotropies can be used to constraint its density and lifetime

• X- and gamma- line searches can be used to constraint its coupling to photons


RADIATION ERA
MATTER ERA
DARK ENERGY ERA
1
0.8
0.6
0.4
0.2
0
Ω
-8
-7
-6
-5
-4
-3
-2
-1
0
Log[a]
LATE ISW
EARLY ISW
MATTER-RADIATION EQUALITY
CMB DECOUPLES