ENERGY DENSITIES IN THE UNIVERSE

Research Team

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Self-Interacting Dark Matter

Evidence for Dark Matter

- Oort's discrepancy, Zwicky's observations of Coma cluster, ...
- Flatness of the rotation curves of Spiral Galaxies
- Large Scale Structure of the Universe (Cold Dark Matter Model)
- $\Omega_{Total} = 1 \quad \times \quad \Omega_{Baryons}\, h^2 \sim 0.004 - 0.023$

  $H_0 = 100\, h\; km\; s^{-1}\; Mpc^{-1}$

  Observations: $0.4 \lesssim h \lesssim 0.7$

Cold Dark Matter Model (CDM)

CDM Model premises:

- DM consists of weakly interacting "cold" elementary particles.
- Seed fluctuations from which large-scale structure grew are of the type predicted by inflation.
- Distribution of galaxies is related to the distribution of mass via a simple statistical prescription, i.e. linear biasing model.
- $\Omega_{DM} \lesssim 0.30$, $\Omega_{Baryons} \lesssim 0.05$ and $\Omega_V \gtrsim 0.65$ (ΛCDM) which is consistent with inflation ($\Omega_k = 0$), Big-Bang nucleosynthesis, cluster density, Cosmic Microwave Background (CMB) and SNe Ia observations.

CDM's inconsistencies with observations:

- Collisionless DM particles do not have any associated length scale and therefore dark halos of galaxies should have negligible core radius. However, most dwarf spiral galaxies, that are almost completely dominated by DM, have core radii of about $3 - 7\ kpc$.

- CDM models overestimate the mass within the central few kpc of the halos by a factor 4.

[Moore 1994]

- CDM models yield dispersion velocities in the Hubble flow within a sphere of $5\ h^{-1}\ Mpc$ between $150 - 300\ kms^{-1}$ for $\Omega_{DM} \sim 0.3$. The observed value is about $60\ kms^{-1}$.

[Governato et al. 1997]

Self-Interacting Dark Matter (SIDM)

- Letting DM particles, ϕ, to self-interact with a large scattering cross-section ($\sigma_{\phi\phi}$) and negligible dissipation seems to be an interesting way to circumvent the abovementioned difficulties.

[Spergel and Steinhardt 1999]

- Interaction introduces a mean free path, λ_ϕ, so that for DM particles with mass m_ϕ and a typical galaxy ($\rho_{Gal} \simeq 0.4\ GeV cm^{-3}$):

$$\frac{\sigma_{\phi\phi}}{m_\phi} = 8.1 \times 10^{-25} \left(\frac{\lambda_\phi}{Mpc}\right)^{-1} \frac{cm^2}{GeV}$$

Proposal

[Bento, Bertolami, Rosenfeld, Teodoro 2000]

- DM particle is a new scalar gauge singlet, ϕ, coupled to the Standard Model Higgs boson, h, with a Lagrangian density:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{g}{4}\phi^4 + g' v \phi^2 h$$

  where g is the field ϕ self-coupling constant, $v = 246$ GeV is the Higgs v.e.v. and g' is the coupling between the singlet ϕ and h.

- Since DM particles are non-relativistic, with $v \simeq 200$ km s^{-1}, there is no dissipation of energy. Only the elastic channel is kinetically accessible and near threshold ($s \simeq 4m_\phi^2$):

$$\sigma(\phi\phi \to \phi\phi) \equiv \sigma_{\phi\phi} = \frac{g^2}{16\pi s} \simeq \frac{g^2}{64\pi m_\phi^2}$$

  Hence

$$m_\phi = 13\, g^{2/3} \left(\frac{\lambda_\phi}{Mpc}\right)^{1/3} MeV$$

- Abundance of ϕ particles
  - ⋆ We assume that ϕ particles were produced during reheating after the end of inflation and the former takes place in the context of $\mathcal{N} = 1$ supergravity models where the inflaton couples to the gauge sector only through gravity.
  - ⋆ The number of ϕ particles expressed in terms of the ratio $Y_\phi \equiv \frac{n_\phi}{s_\gamma}$, where s_γ is the photonic entropy density, is related with the inflaton (χ) abundance after its decay by

$$Y_\phi = \frac{1}{N} Y_\chi \ ,$$

    where N is the number of degrees of freedom ($N \simeq 150$ in $\mathcal{N} = 1$ supergravity models).

⋆ In $\mathcal{N} = 1$ supergravity, in order to avoid the gravitino problem, Y_χ is given by the ratio of the reheating temperature and the inflaton mass, and for typical models

$$Y_\chi = \frac{T_{RH}}{m_\chi} = \epsilon \; 10^{-4}$$

where ϵ is an order one constant.

[Bento and Bertolami 1996]

⋆ Above assumptions allow estimating the energy density contribution of ϕ particles in terms of the baryonic density parameter:

$$\Omega_\phi \simeq 18.5 \; \epsilon \; g^{2/3} \left(\frac{\lambda_\phi}{Mpc} \right)^{1/3} \Omega_B$$

Hence, ϕ is a realistic cosmological dark matter candidate, as for $\epsilon \sim 0.5$, g of order one and λ_ϕ of about 1 **Mpc**, $\Omega_\phi \simeq \Omega_{DM} \lesssim 0.3$.

Outlook and Objectives

- Our gauge singlet candidate for DM particle does not couple to fermions and interacts only to the Higgs field and to itself. This fact has the following implications:

  ⋆ Searches for this candidate necessarily have to be carried out in accelerators.

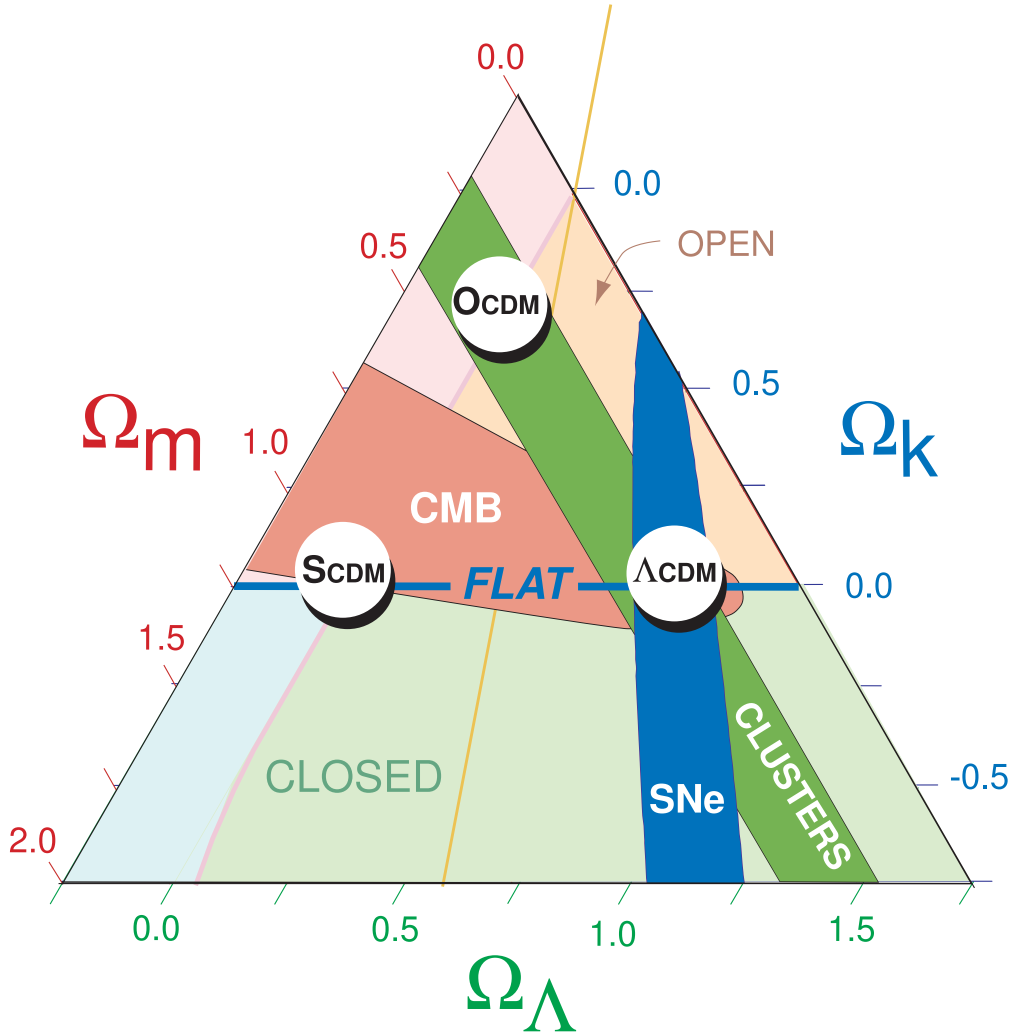
  ⋆ The ϕ field may lead to an "invisible" Higgs depending on the value of the coupling constant g'.

Further astrophysical and cosmological tests of our proposal should be worked out. These involve studies of the rotation curves of low brightness dwarf galaxies. Comparison between numerical simulations and observations may turn out to be crucial

Dark Energy and the CMB

Motivation

- A number of recent observations suggest that $\Omega_m \simeq 0.3$.
- Recent SNe Ia results suggest that the expansion of the Universe is accelerating.
- The location of the first peak in the CMB indicates that $\Omega_{Total} \simeq 1$, consistent with the inflationary prediction of a flat Universe.



These trends can be reconciled if there is another contribution to the energy density of the universe besides matter, namely a negative pressure dark energy

Nature of Dark Energy

- Cosmological Constant

  The simplest and most obvious candidate for the missing energy is a vacuum density or cosmological constant that contributes a fraction $\Omega_\Lambda \simeq 0.7$ of closure density. However: "cosmic coincidence" or "initial conditions" problem.

- Quintessence

  Quintessence, is a slowly varying component with a negative pressure. Tracker fields are a form of quintessence in which the scalar field rolls down a potential according to an attractor-like solution to the equations of motion, regardless of the initial conditions, thus resolving the "initial conditions problem".

  [Zlatev, Wang, Steinhardt 1998]

  [Caldwell, Dave, Steinhardt 1998]

- Decaying cosmological constant, extra dimensions ...

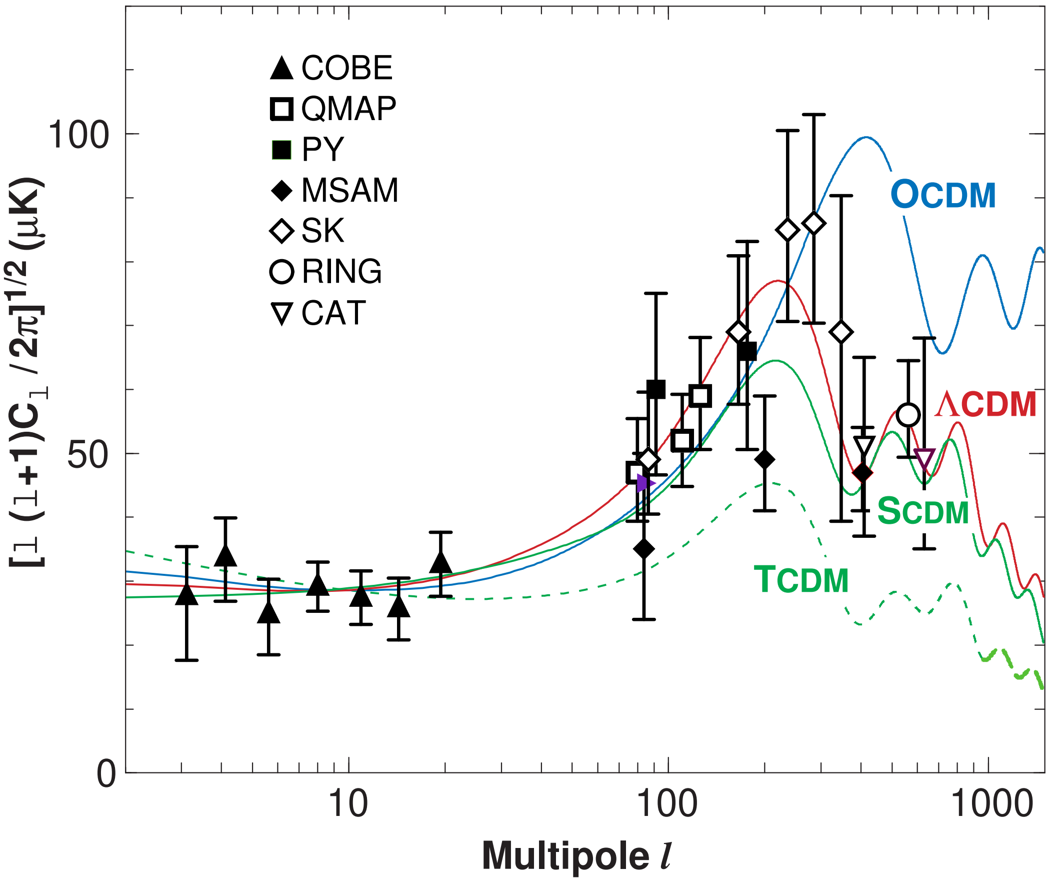
  [Bertolami 1986]

  [Bento and Bertolami 1999]

Dark energy has important implications for the evolution of large-scale structure in the Universe, for particle theory, and possibly for quantum gravity ➠ it is crucial to test for a non-zero dark energy as thoroughly as possible

Objectives

- We aim to study the nature and properties of dark energy mainly via its effect on CMB anisotropy
  - ⋆ Determining the distance to the last-scattering surface
  - ⋆ Peak location in CMB power spectrum
  - ⋆ Late-time ISW effect



We aim to analyse these issues both in the context of specific models and for general parametrizations of the dark energy sector

Reheating

Motivation

- Inflation brings major insights into modern theories of structure formation as it predicts that:
  - ⋆ Fluctuations in the matter fields which give rise to the observed large scale structure are due to the quantum fluctuations of the inflaton field.
  - ⋆ The exponential expansion of the Universe during inflation implies that quantum fluctuations of the inflaton were pushed outside the horizon, giving rise to a scale invariant spectrum as observed by COBE.
- However attractive, this scenario implies that by the end of inflation, all the contents of the Universe have been diluted and the Universe ended up empty and cold.

  Thus, the creation of matter must have occured after the end of inflation while the inflaton, χ, oscillated around the minimum of its potential, $V(\chi)$, and transferred its energy into matter fields. This stage is known as reheating

- In the perturbative context, reheating has been studied via a phenomenological decay width, Γ_χ, introduced into the inflaton equation of motion

$$\ddot{\chi} + (3\ H + \Gamma_\chi)\dot{\chi} + \frac{\partial V(\chi)}{\partial \chi} = 0$$

  so that the radiation energy density, ρ_γ, evolved as

$$\dot{\rho}_\gamma - \Gamma_\chi \dot{\chi}^2 + 4\ H\ \rho_\gamma = 0\ \ ,$$

  where H is the Hubble parameter

$$H^2 = \frac{8\pi G}{3}\left[\frac{1}{2}\dot{\chi}^2 + \rho_\gamma + V(\chi)\right]$$

[Albrecht, Steinhardt, Turner, Wilczek 1982]

[Ovrut and Steinhardt 1984]

[Bertolami and Ross 1986]

- However, it is only recently that the non-perturbative regime where resonant particle production occurs, the so-called preheating, has been analysed. In this phenomenon, large amounts of particles are produced.

[Kofman, Linde, Starobinsky 1994, 1997]

[Shtanov, Traschen, Brandenberger 1995]

- Mathematically, such an efficient particle production stems from the fact that the equation describing the production of particles, φ, coupled to the inflaton via a term, $-\frac{1}{2}g^2\chi^2\ \varphi^2$ can be cast in the form of a Mathieu equation

$$\frac{d^2\varphi}{dz^2} + [A(k) - 2q\cos(2\ z)]\varphi = 0$$

where for the momentum $k = |\vec{k}|$, $A(k) = k^2/m_\chi^2\ a^2 + 2q$, $q = g^2\chi_0^2/m_\chi^2$, $z = m_\chi t$, χ_0 being the amplitude of the inflaton field and a the scale factor.

Depending on the value of parameters, the Mathieu equation has solutions which grow exponentially in time. Preheating corresponds to solutions leading to an exponential increase in the number of particles produced

Objectives

- Recent studies show that the production of gravitational waves during preheating should be negligible. However, these studies do not include back reaction or the production of fields which create anisotropic stresses.

> It is our aim to include back reaction effects in order to compute the gravitational wave production during preheating

- It is not clear what the observational consequences of preheating might be and, in particular, the kind of distortions it introduces in the CMB.

> It is also our goal to evaluate the level of CMB anisotropies created by preheating