# Growth of Nonbaryonic DM Theory Summary (Nature)

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## 1 Stem of Thought

- Additional matter: For spiral galaxies' stability, mass cannot be only in a disk supported by circular motion $\Rightarrow$ mass in disk subdominant to mass in a spherical dark halo.
- Nonbaryonic:
  (a) Problem: growing clumpy distribution of mass vs. still smooth CMB radiation
  (b) Solution: sCDM cosmology- Baryonic matter subdominant to non-baryonic dark matter (NBDM).
  (c) Reason: Mass density of CMB neutrinos $<$ cosmic mean density $\Rightarrow$ new class of neutrinos with large mass (WIMP) for annihilation of neutrino pairs $\Rightarrow$ remnant mass density reduction $\Rightarrow$ close the Universe.
    - Candidates: lightest stable supersymmetric partner, axions (cluster into galaxy halo).

## 2 $\Omega$ and $H$

Einstein-de Sitter (EdeS) model: require zero curvature ($\rho = \rho_c$) $\Rightarrow$ add $\Lambda$

## 2.1 Rate of Expansion of Homogeneous Universe:

$$H(t)^2=\left(\frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t}\right)^2=H_0^2\left[\Omega_{\mathrm{m}}\left(\frac{a\left(t_0\right)}{a(t)}\right)^3+\Omega_{\mathrm{k}}\left(\frac{a\left(t_0\right)}{a(t)}\right)^2+\Omega_\Lambda\right] \tag{1}$$

with,

$$\Omega_{\mathrm{m}}+\Omega_{\mathrm{k}}+\Omega_\Lambda=1 \tag{2}$$

Paramters:

- $\mathbf{H_0}$- current value of expansion rate H(t) ($[H(t)]=[T]^{-1}$);
- $\mathbf{\Omega_i}$- relative contributions to expansion: matter ($i=m$), space curvature ($i=k$), cosmological constant ($i=\Lambda$);
- $\mathbf{a}(\mathbf{t})$- cosmic scale factor (often used to relate proper distances at different reference times $l(t)=l_0a(t)$); Friedman equations;
- **t** - ideal clock moving with matter; $\mathbf{t_0}$ - present time.

**Hubble's law**- mean rate of separation:

$$v=\frac{\mathrm{d}l}{\mathrm{d}t}=\frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t}l=Hl, \quad H_0=100h\mathrm{kms}^{-1}\mathrm{Mpc}^{-1} \tag{3}$$

where $l(t)$- physical separation.

**Redshift of radiation emitted at $\mathbf{t_e}$, detected at $\mathbf{t_0}$:**

$$\frac{\lambda_0}{\lambda_{\mathrm{e}}}=\frac{a\left(t_0\right)}{a\left(t_{\mathrm{e}}\right)}\equiv 1+z \tag{4}$$

where **z**- cosmological redshift; at small $z$, $v=cz$.

## 2.2 Speculations of the 1980s and 1990s

- EdeS Universe: $\Omega_m\approx 1$,$\Omega_k=0$ (due to inflation), and $\Omega_\Lambda$ close to zero.
- NBDM could reconcile *EdeS* $\Omega_m$ with baryon density $\Omega_b$ (derived from theory of light element formation Big Bang nucleosynthesis)
  - If $\Omega_b=1$, abundant helium and most deuterium converted to helium

  - If $\Omega_b \approx 0.1$, less helium, and remnant deuterium visible.
  - Experimental: $\Omega_b < 0.3 \Rightarrow \Omega_m < 0.3$, a need of NBDM for $\Omega_m \approx 1$?

- Another observation: lower density from measures on smaller scales.

  - Reconciling the EdeS mass by "biasing": bulk of DM distributed with galaxies on large scales (globally larger $\Omega_m$); small fraction clusters with galaxies on small scales (locally smaller $\Omega_m$)
  - Other interpretations: space sections flat with a $\Lambda$, space sections open with $\Lambda = 0$, constraints on $\Lambda$, etc.

### 2.3 Developments of the 2000s

- Measurements of redshift-magnitude ($z-m$) relation ($z$ defined in Eq.4, $m$ the logarithmic measurement of observed energy flux density), and CMB anisotropy spectrum $\Rightarrow \Lambda CDM$ cosmology.

  - Fit to $z-m$ relation require if $\Omega_m \geq 0.1$, then $\Lambda > 0$
  - CMB temperature could be modelled as a function with bases $\langle |a_l^m|^2 \rangle$ (angular spectrum). In CDM cosmology, anistropy spectrum peaks at $l_{peak}$ and this requires small space curvature.
  - Cosmological constant $\Lambda$ added for small $\Omega_m \Rightarrow$ no space curvature.

- Present case- $\Lambda CDM$: from theory of structure formation $< 30Mpc$, and tests on scales of Hubble Length $c/H_0 = 4000Mpc$.

  - Flat space sections, and some free parameters (e.g.present matter densities in baryon and NBDM)

## 3 To Conclude..

Many a' efforts(measurements of CMB, redshift, abundance of deteurium/helium) $\Rightarrow$ nonbaryonic dark matter. What took so long?