Bose Einstein Condensation as Dark Energy and Dark Matter [1]

--- Quantum Structure in the Universe ---

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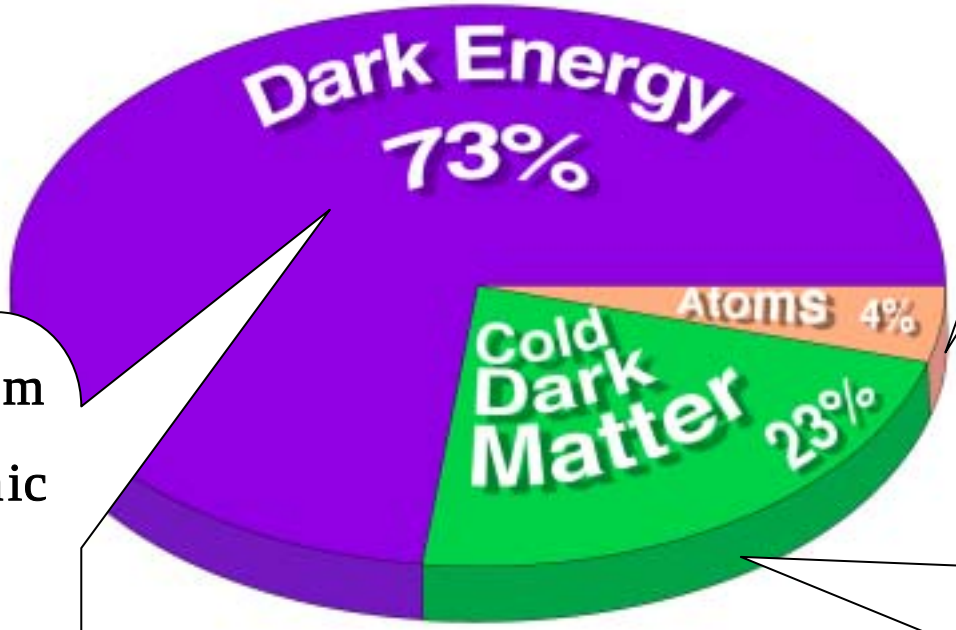
Dark Matter, Dark Energy, Non-linear evolution,…

1. Introduction

Matter contents of the universe: [2] [3]

We do not know 96% of the total matter in the universe!

luminous
directly
observable



mostly uniform
promotes cosmic
acceleration
$w \equiv p / \rho < -0.78$

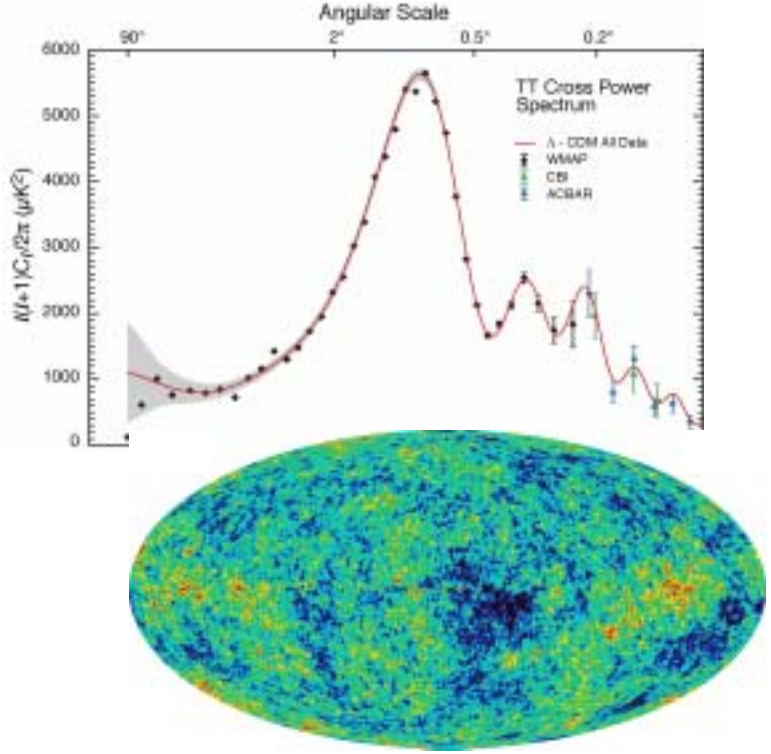
localized
promotes
galaxy
formation
$p = 0$

Success of the standard ΛCDM model … mostly in the linear stage

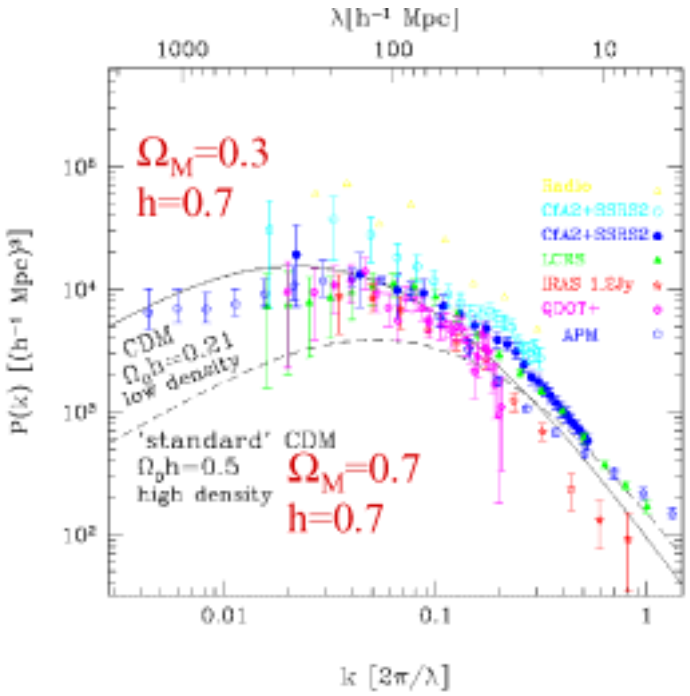
Dark Energy (DE) = cosmological constant Λ of unknown/fine-tuned origin

Dark Matter (DM) = unknown dust particles/objects form cluster by gravity

Baryon → forms stars/galaxies in the potential well of **DM**.



Temperature fluctuations δT **in the sky (WMAP)**



Power spectrum $P(k)$ **of density fluctuations**

What are missing in standard ΛCDM model

1. Dark Energy (DE) & Dark Matter (DM) : what are these components?

2. Non-linear stage:

very early formation of objects(re-ionization$z \approx 20$?)

biasing mechanism?

how the first ★ formed?

Requirements:

A. DE has negative pressure: $p < 0$ to promote accelerated expansion

$$\ddot{a}(t) = -\frac{4\pi G}{3}(\rho + 3p)a(t), \qquad \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

B. DE and DM are almost the same amount. → about 3:1

⇒ Known matter which shows negative pressure (independently of volume):

coherent classical field (V-dominated)

This may be the macroscopic wave function of Bose Einstein condensation (BEC) with attractive interaction.

We propose a model

DE = Bose-Einstein condensation[4]

DM ≈ Normal boson gas

Cf) For the ideal BEC,

$$p = \frac{m^{3/2}}{\hbar^3} T^{5/2} \rightarrow$$ **volume independent.**

An Introduction of the attractive interaction would naturally yield $p < 0$**.**

2. Cosmic BEC mechanism

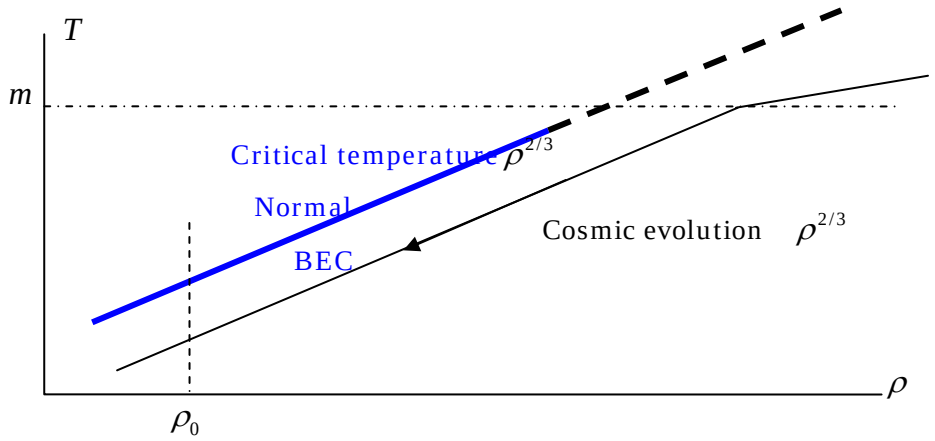
BEC if (thermal de Broglie length) > (mean separation of particles):

$$\lambda_{dB} \equiv \left(\frac{2\pi\hbar^2}{mkT}\right)^{1/2} > r \equiv n^{-1/3} \quad \textbf{i.e.} \quad kT < \frac{2\pi\hbar^2 n^{2/3}}{m} \quad \textbf{and}$$

Cosmic evolution: $n = n_0\left(\frac{m}{2\pi\hbar^2}\frac{T}{T_0}\right)^{3/2}$ **has the same temperature dependence!**

⇒ **if the boson temperature=radiation temperature at** $z = 3000$**.**

$T_{cr} = 0.0027K, \rho = \rho_{now} = 9.44\ 10^{-30}\mathrm{g/cm}^3$, **then** $m < 1.96\mathrm{eV}$.



$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}(\rho_{Cond} + \rho_{Gas} + \rho_{Baryon})$$

Matter dominant, $\rho \propto a^{-3} \propto T^{3/2}$

Radiation dominant, $\rho \propto a^{-4} \propto T^{4}$

Figure 1. T_c and cosmic density evolution

3. Quantum liquid model of cosmic BEC

BEC: mean-field analysis based on Gross-Pitaevskii equation

(non-linear Schrödinger equation)

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\Delta\psi + V\psi + g|\psi|^2\psi, \qquad \textbf{(1)}$$

$\psi(\vec{x},t)$**: condensate wave function,** $V(\vec{x})$**: potential,**

$g = 4\pi\hbar^2 a / m$**, and** a **is the s-wave scattering length.**

Decomposition $\psi = \sqrt{n}e^{iS}$ **yields** ($\vec{v} = \hbar\vec{\nabla}S / m$)

$$\frac{\partial n}{\partial t} + \vec{\nabla}\cdot\vec{j} = 0 \qquad \textbf{(continuity equation)} \qquad \text{and} \qquad (2)$$

$$m\frac{\partial \vec{v}}{\partial t} + \vec{\nabla}\left(\frac{mv^2}{2} + V + gn - \frac{\hbar^2}{2m\sqrt{n}}\Delta\sqrt{n}\right) = 0 \quad \textbf{(hydrodynamic equation)} \qquad \textbf{(3)}$$

★ $\hbar^2$ **(quantum pressure) term is neglected if** $k^2 < k_c^2 \equiv 2mgn / \hbar^2$

★ **attractive interaction** $g < 0$

⇒ **general fluid with EOS** $p = -A\rho^{\alpha}$

We introduce the simplest quantum liquid model:

We suppose

◆ **BEC=DE has eq. of state** $p = -\rho$

◆ **DM** $p = 0$

◆ **Sedimentation of BEC gradually proceeds with time scale** Γ^{-1}

In the Linear stage

For $\rho_c > \rho_g$, linear perturbation equation for the gauge invariant quantity:

$$\delta_k'' + 5\delta_k' = -\left(6 - \left(\frac{k}{aH}\right)^2\right)\delta_k$$

where $(\cdots)' \equiv \frac{d(\cdots)}{d\ln a}$, $c_s^2 \equiv \frac{\partial p}{\partial \rho} = -1$ **(no sound wave).**

Then,

small scale mode $\tilde{k}^2 > 6H^2$ **is unstable: grows very rapidly,** $\delta \propto a(t)^{\tilde{k}/H}$

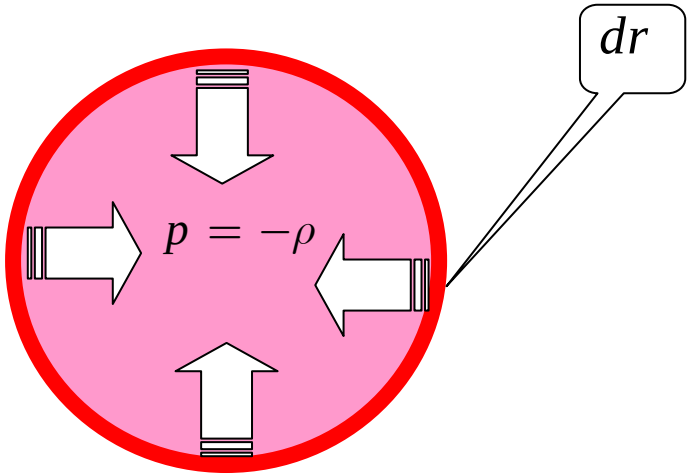
$\Rightarrow$ **the development of the potential will attract Baryons to form astronomical objects.**

large scale mode $\tilde{k}^2 < 6H^2$ **is stable: decays slowly,** $\delta \propto a(t)^{-5/2}$

where the comoving wave number $\tilde{k} \equiv k/a$

In the non-linear stage

$p = 0$



Skin(widthdr) acquires energy $4\pi r^2 dr\,(-p) = 4\pi r^2 dr\,\rho$

$$\frac{d\,(m_t \gamma \dot{r}\,)}{dt} = -4\pi r_t^2 \rho \qquad \textbf{(4)}$$

where $m_t = \frac{4\pi}{3}\left(r_0^3 - r_t^3\right)\rho$ **: time dependent mass of the skin**

Solutions of Eq.(4) approach to the constant velocity solution: Almost the light velocity

$$\gamma = \sqrt{2},\ \dot{r} = \frac{1}{\sqrt{2}} \qquad \textbf{(5)}$$

Negative pressure, as well as, gravity promote clustering!

Therefore many compact clumps (BS, BH) are rapidly formed after t_C **at the smallest scale (∼galaxy scale)!** t_C **: the first collapse time of BEC**

4. Gradual sedimentation of the condensation

$\rho_g(t)$ **is diluted by the cosmic expansion.**

$\rho_c(t)$**is not diluted: energy gained** $-pdV = \rho dV$ **by the adiabatic cosmic expansion produces new BEC in the new region** dV **.**

For $t_{dec} < t_C$**, does not affect the WMAP observations. Evolution of** $a(t)$**is accelerated after** t_C

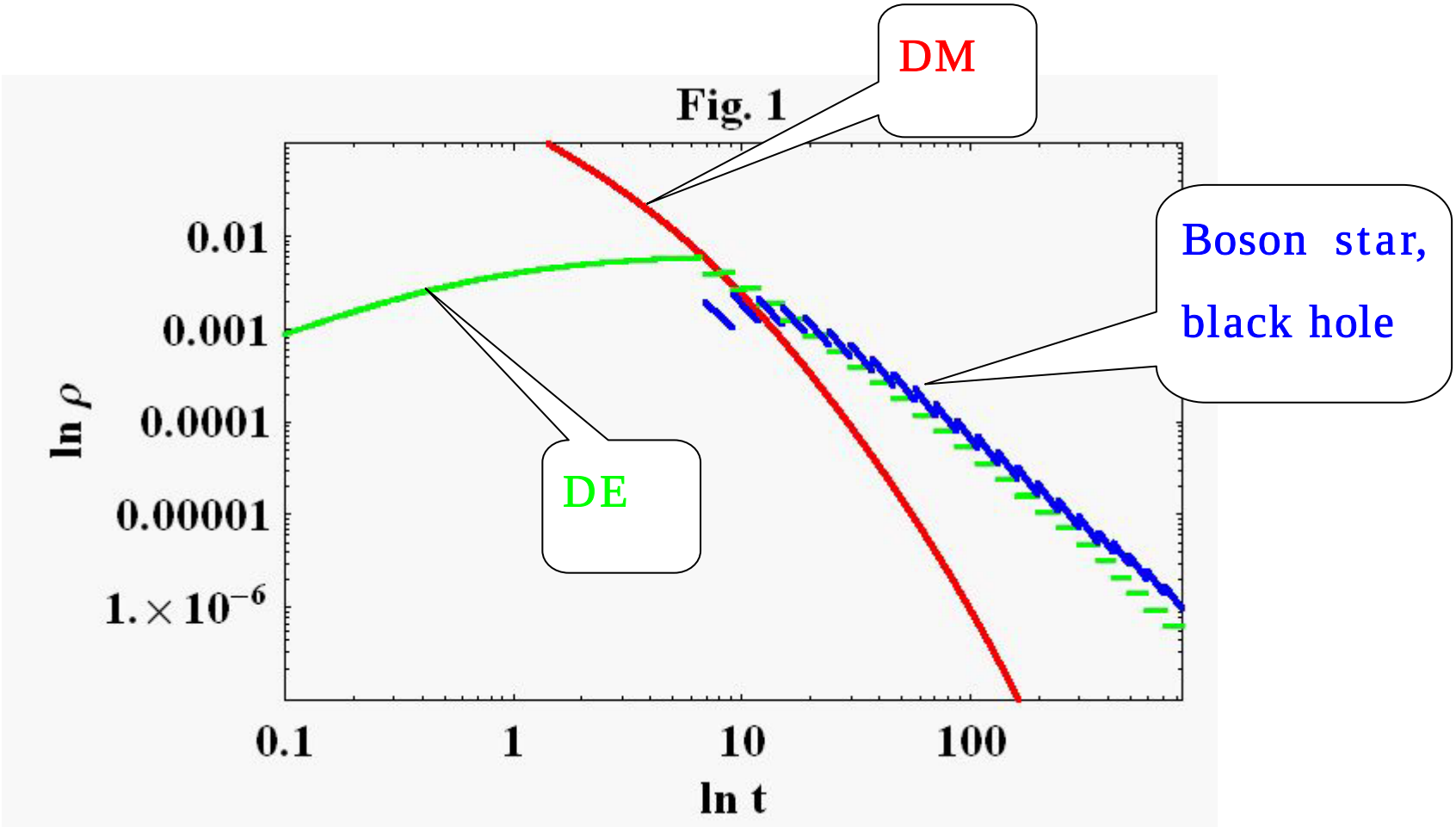
$$\rho = \rho_c + \rho_g + \rho_l$$

$$\dot{\rho}_c = \Gamma \rho_g$$

$$\dot{\rho}_g = -3H\rho_g - \Gamma\rho_g$$

$$\dot{\rho}_l = -3H\rho_l$$

$$H \equiv \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G\rho}{3}} \qquad \textbf{(1)}$$



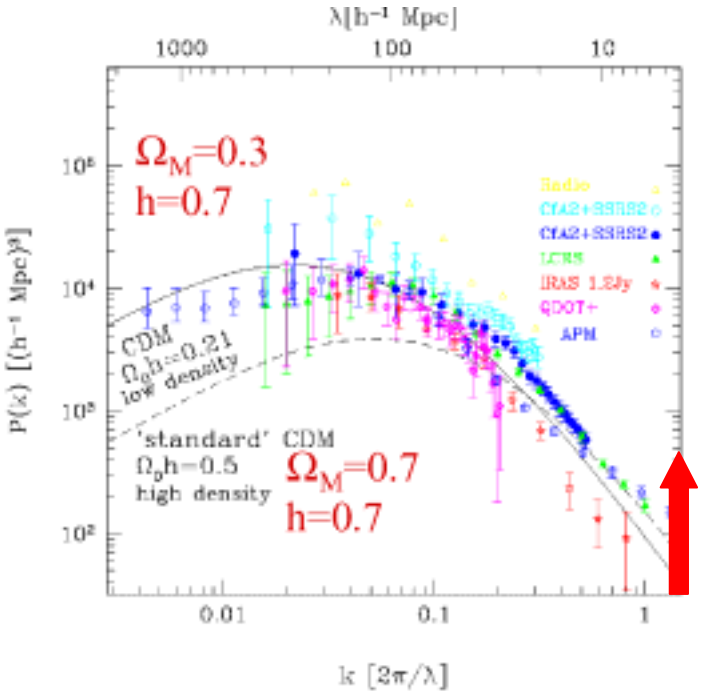
Evolution of densities ρ_c, ρ_g, ρ_l. We set $\Gamma = 0.1$ with the unit $8\pi G/3 = 1$. The transition rate from ρ_c to ρ_l is set $1/3$. After 22cycles, the scale factor grows 200 times. The ration of DE(ρ_c) and DM($\rho_g + \rho_l$) autonomously approaches to one. SOC[5]

5. Predictions and observational tests

5.1 *Large scale structure*

The collapse of the condensate proceeds in the smallest scale.

⇒ BEC model does not affect the power spectrum in the linear (large scale) regime however it extremely enhances the smaller non-linear regime.

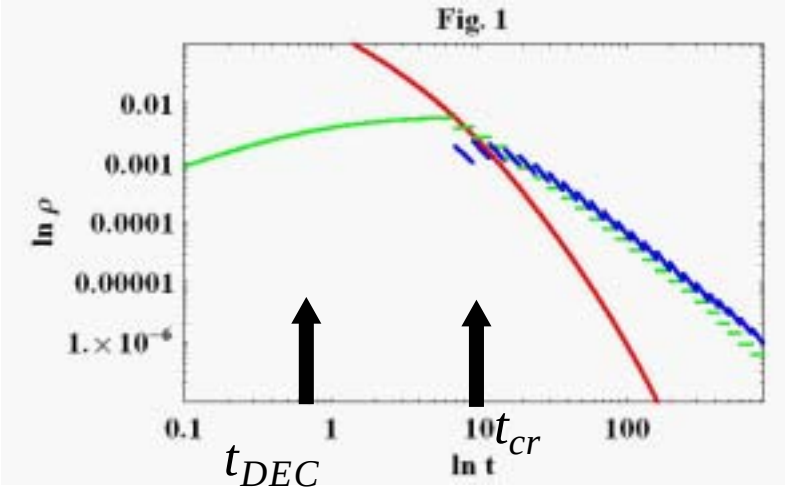


Power spectrum $P(k)$ of density fluctuations

5.2 *Microwave Background Radiation*

The condensation is supposed to dominate well after the decoupling time.

⇒ temperature inhomogeneity generated within the decoupling era would not be changed from the standard ΛCDM model. However the integrated Sacks-Wolfe effect has a chance to modify the spectrum.

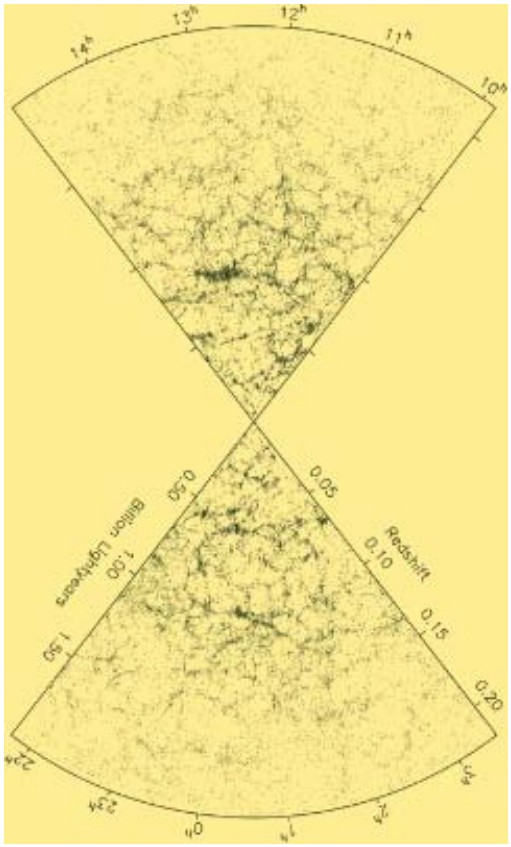


5.3 *Void-wall structure formed by DE component.*

In the later phase of BEC collapse,
irregular fluctuations would dominantly collapse

⇒ non-linearity: two-dimensional sheet.

⇒ Great Wall structure ?



5.4 *A first star harbors a boson star*

For bosons, there is no degenerate pressure like fermions. Only the Heisenberg uncertainty principle (quantum pressure) can support the star against the collapse.

$\lambda_{comton} = \frac{2\pi\hbar}{mc} \approx R$ **radius of the clustered object must larger than**

$R_S = 3\left(\frac{2GM}{c^2}\right)$ **Black Hole radius.**

$\Rightarrow \quad M_{critical} \approx m_{pl}^2 / m \equiv M_{KAUP}$ **This is the boson star[6].**

For $m = 10^{-5}$ eV, $M_{critical} = 10^{-5} M_{\odot} = M_{\oplus}$.

The collapse of condensed boson into these boson stars will induce that of Baryon.

5.5 *A first galaxy harbors a giant black hole*

If $M > M_{critical}$, then the quantum pressure cannot prevent the collapse.

$\Rightarrow$ BH is inevitably formed. It can be a seed of a proto -galaxy.

The collapse of condensed boson into these BHs induces that of Baryon.

Gravitational energy released: $NT \approx \frac{GM^2}{R} \approx Nm$

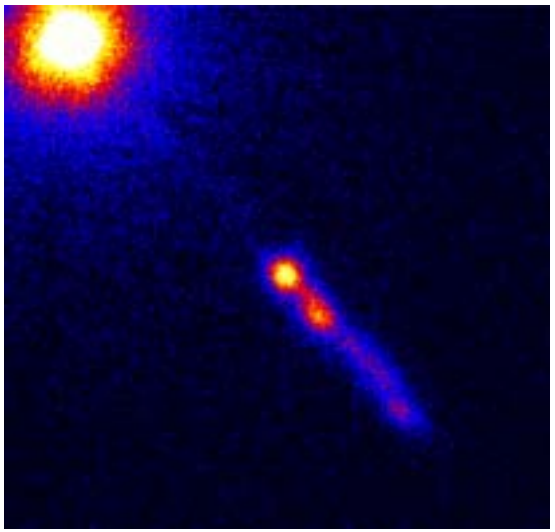
$\rightarrow$ the boson gas becomes relativistic and the condensation melts to form Hot Dark Matter.

This melted boson gas acquires positive pressure, and therefore violently expand.

$\Rightarrow$ Galaxy formation at very early stage $\Rightarrow$ early reionization ($z \approx 20$)

5.6 *Ejection of matter*

The collapsing condensate eventually becomes relativistic and bounces many times. At each bounce, some amount of condensate would be energetically ejected towards the direction of the angular moment. This process would be observed as discrete jets.



3C273: Quasar Jet

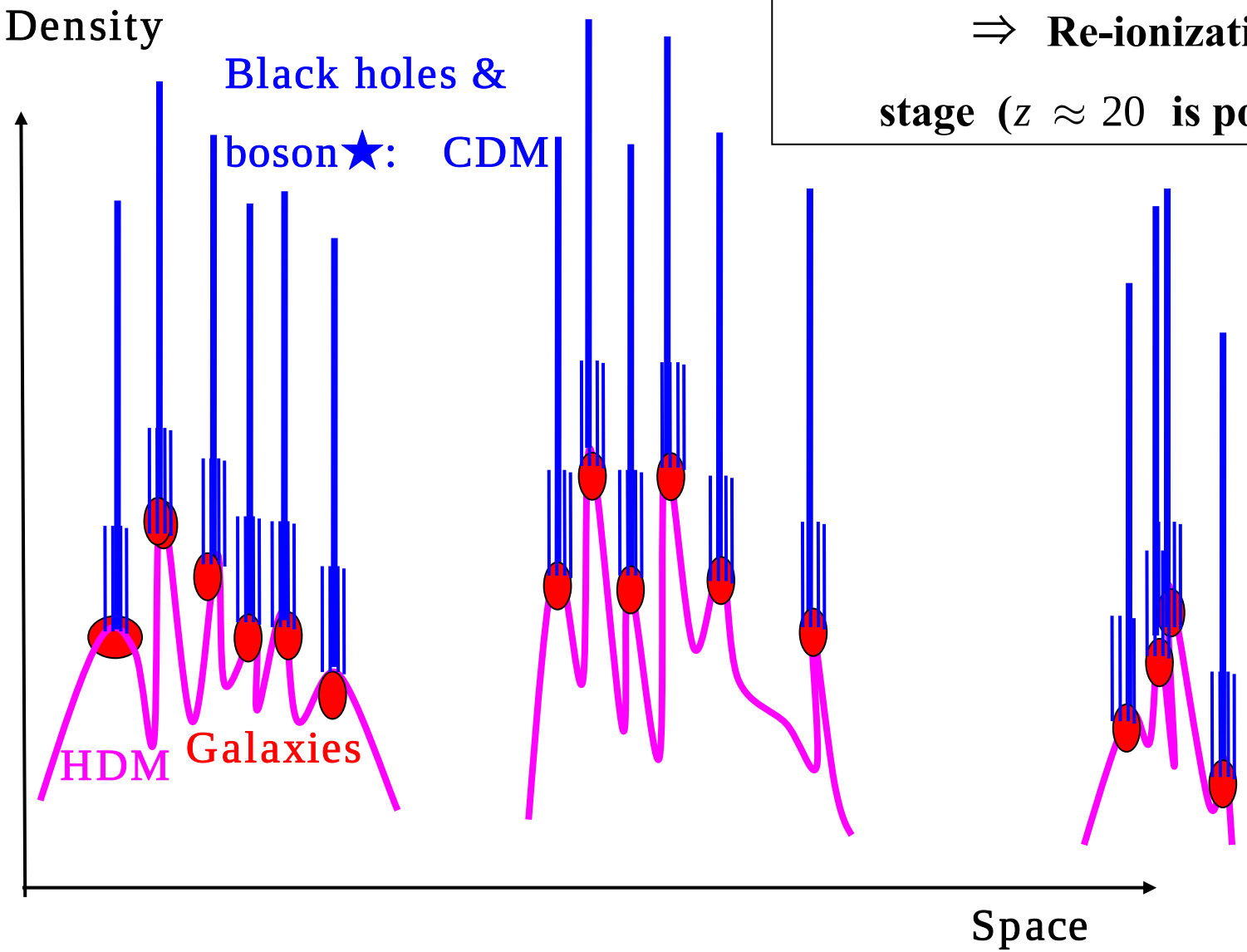
(Chandra)

M87's Jet (Chandra)

Are jets discreet ?

All stars and galaxies form very early

$\Rightarrow$ Re-ionization in the early stage ($z \approx 20$ is possible)



6. Summary and further developments

Summary **BEC scenario:**

(a) Bose gas is introduced as DM which initially dominates the energy density and the condensate of the boson (BEC) is identified as DE.

(b) The condensate has negative pressure due to its potential which reflects the attractive interaction. For the spatially uniform component of BEC, this negative pressure works as a cosmological constant and guarantees the accelerated expansion.

(c) The sedimentation of the condensate slowly proceeds in the cosmic evolution.

(d) When the energy density of BEC exceeds some critical value, it collapses to compact boson stars or black holes, which work as the standard cold dark matter and become the seeds of galaxies. Simultaneously a new sedimentation begins. This cycle of sedimentation-collapse repeats many times. $\Rightarrow$ Self organized critical Universe

(e) These rapid collapses take place well after the photon-decoupling stage, and therefore the large scale structure predicted by the ΛCDM model and actually observed pattern in CMB fluctuations would not strongly be violated.

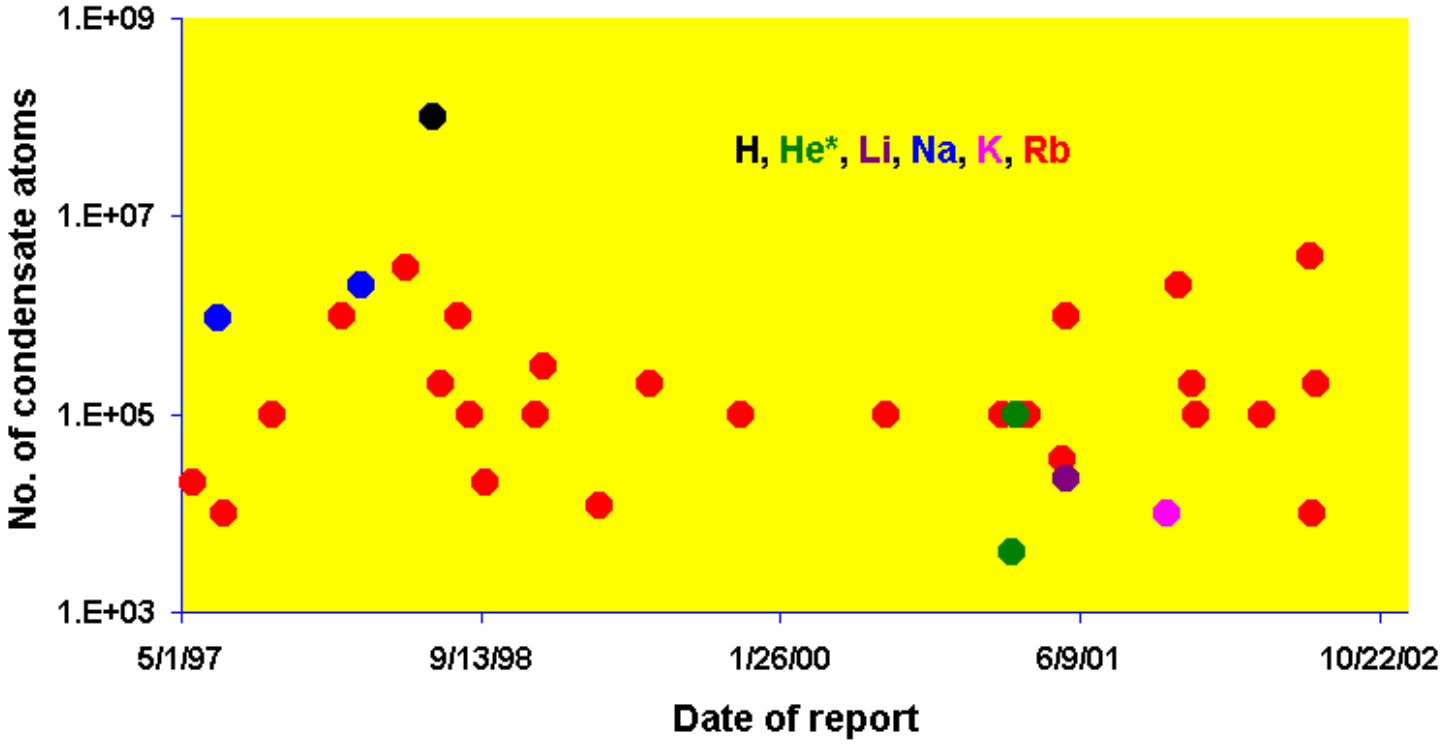
Further developments:

★ **Detailed comparison with ΛCDM model.**

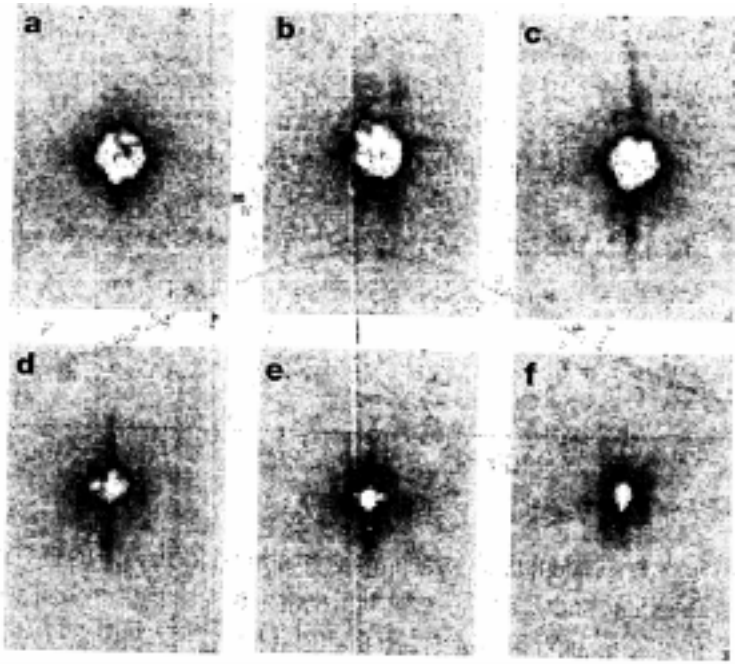
★ **Complete model building**

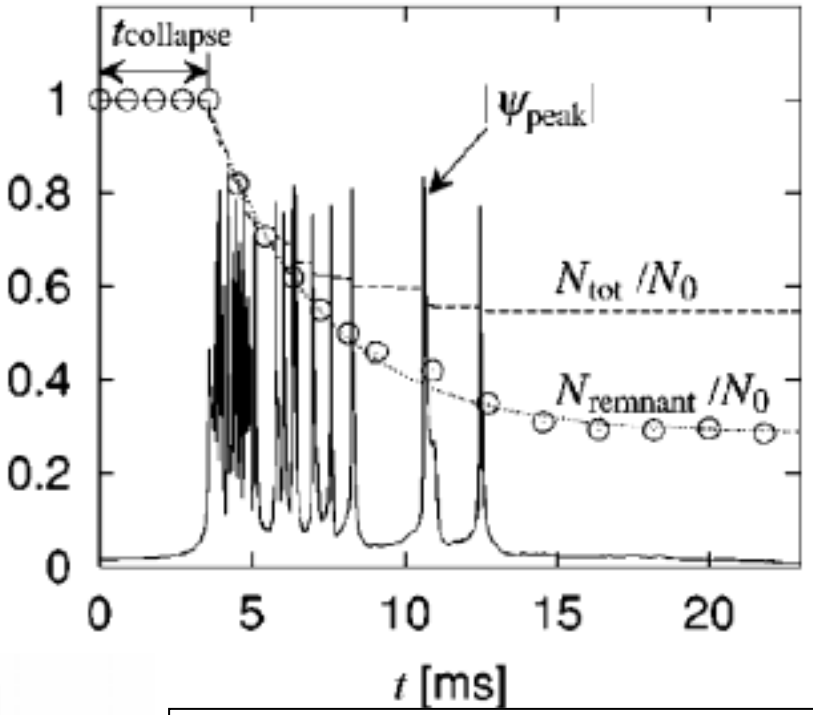
★ **Experimentally found BEC in dilute gases of alkali atoms:**

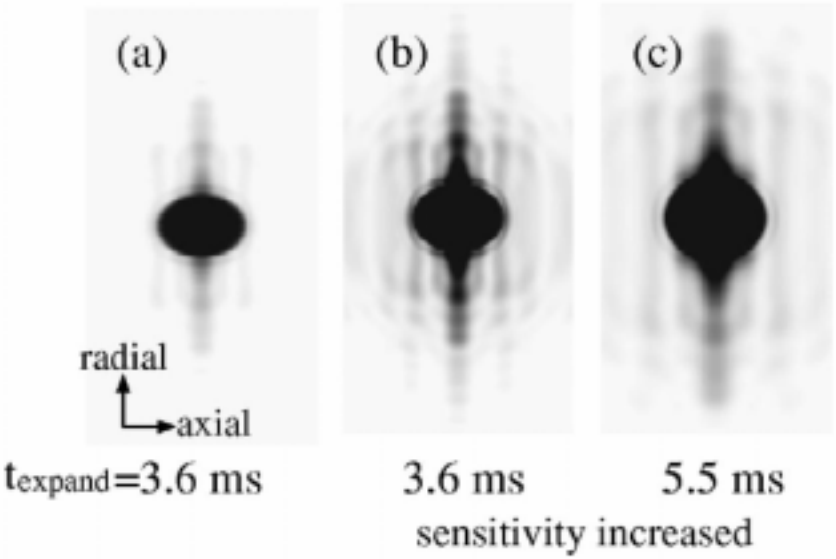
http://amo.phy.gasou.edu/bec.html/



boson-nova in BEC experiments: Wieman et.al.[7] [8]







BEC: Pressure $+ \Rightarrow -$

decay jet formation

collapse-explosion repeats many times

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