HLPW meeting – March 6-8, 2008

Astrophysical tests of mirror dark matter

Paolo Ciarcelluti

ULg IFPA

Fundamental Interactions in Physics and Astrophysics

University of Liège

Publications related to this talk

P. Ciarcelluti,
Ph.D. Thesis [astro-ph/0312607].

P. Ciarcelluti,
Int. J. Mod. Phys. D 14, 187-222 (2005)
[astro-ph/0409630].

P. Ciarcelluti,
Int. J. Mod. Phys. D 14, 223-256 (2005)
[astro-ph/0409633].

Z.Berezhiani, P.Ciarcelluti, D.Comelli, F.Villante,
Int. J. Mod. Phys. D 14, 107-120 (2005)
[astro-ph/0312605].

P. Ciarcelluti, A. Lepidi,
papers submitted and in preparation

P. Ciarcelluti,
paper in preparation

Z.Berezhiani, P.Ciarcelluti, S.Cassisi, A.Pietrinferni,
Astropart. Phys. 24, 495-510 (2006)
[astro-ph/0507153].

Structure formation

Cosmic Microwave Background and Large Scale Structure

Thermodynamics of the early Universe and Big Bang Nucleosynthesis

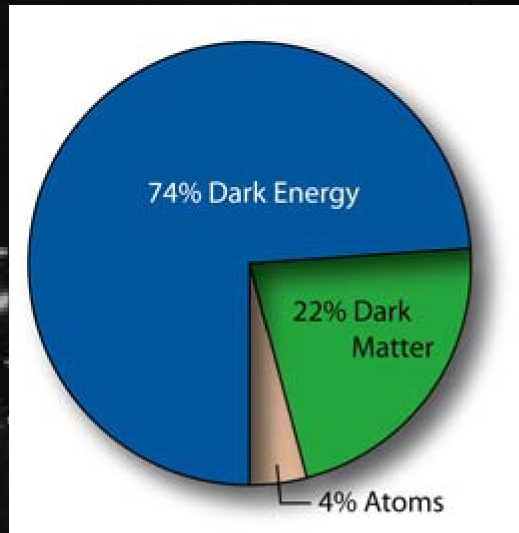
Mirror dark stars and MACHOs

Motivation of this research

search for dark matter candidates

Components of a flat Universe

in standard cosmology:



- radiation (relic γ and ν) $\rightarrow \Omega_R \sim 10^{-5} << \Omega_m$
- matter $\rightarrow \Omega_m \approx 0.2\text{-}0.3$
  - visible (baryonic) matter $\rightarrow \Omega_b \cong 0.02\ h^{-2}$
  - dark matter (CDM, WDM, some HDM)

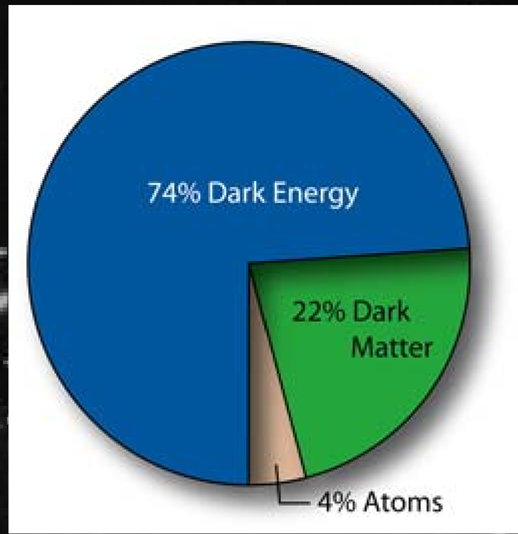
    $\rightarrow \Omega_{DM} = \Omega_m - \Omega_b$
- dark energy (cosmological constant or quintessence) $\rightarrow \Omega_\Lambda = 1 - \Omega_m$

Motivation of this research

search for dark matter candidates

Components of a flat Universe

in standard cosmology:



- radiation (relic γ and ν) $\rightarrow \Omega_R \sim 10^{-5} << \Omega_m$
- matter $\rightarrow \Omega_m \approx 0.2\text{-}0.3$
  - visible (baryonic) matter $\rightarrow \Omega_b \cong 0.02\, h^{-2}$
  - dark matter (CDM, WDM, some HDM)

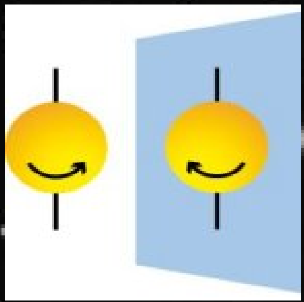
    $\rightarrow \Omega_{DM} = \Omega_m - \Omega_b$
- dark energy (cosmological constant or quintessence) $\rightarrow \Omega_\Lambda = 1 - \Omega_m$

Every dark matter candidate has a **typical signature** in the Universe.

The Universe itself is a **giant laboratory** for testing new physics.

What is mirror matter ?

Idea: there can exist a **hidden mirror sector** of particles and interactions which is the exact duplicate of our observable world. (Lee and Yang, 1956; Foot,Lew,Volkas,1991)



Theory: product G×G′ of **two sectors with the identical particle contents**. Two sectors **communicate via gravity**. A symmetry P(G→G′), called **mirror parity**, implies that both sectors are described by the same Lagrangians.

$G_{SM} = SU(3) \times SU(2) \times U(1)$ → standard model of observable particles

$G'_{SM} = [SU(3) \times SU(2) \times U(1)]'$ → mirror counterpart with analogous particles

Mirror photons cannot interact with ordinary baryons ⇒ dark matter !

Until now mirror particles can exist without violating any known experiment ⟹

⟹ we need to compare their astrophysical consequences with observations.

Their microphysics is the same but… cosmology is <u>not</u> the same !!

Mirror baryons as dark matter

$$\Omega_{TOT} = \Omega_m + \Omega_r + \Omega_\Lambda \approx 1$$

$$\Omega_m = \Omega_b + \Omega_b{}' + \Omega_{CDM} = \Omega_b(1+\beta) + \Omega_{CDM}$$

$$\Omega_r h^2 = 4.2 \cdot 10^{-5}(1 + x^4)$$

2 mirror parameters

$$x = \frac{T'}{T} \qquad \beta = \frac{\Omega_b{}'}{\Omega_b}$$

Mirror baryons as dark matter

$$\Omega_{TOT} = \Omega_m + \Omega_r + \Omega_\Lambda \approx 1$$

$$\Omega_m = \Omega_b + \Omega_b' + \Omega_{CDM} = \Omega_b(1+\beta) + \Omega_{CDM}$$

$$\Omega_r h^2 = 4.2 \cdot 10^{-5}(1+x^4)$$

2 mirror parameters

$$x = \frac{T'}{T} \qquad \beta = \frac{\Omega_b'}{\Omega_b}$$

BBN bounds

If particles in the two sectors O and M had the **same cosmological densities** ⇒ ⇒ **conflict with BBN** (T ~ 1MeV)!!

If T′=T , mirror photons, electrons and neutrinos → $\Delta N_\nu \approx 6.14$

Bound on the effective number of extra neutrinos: **$\Delta N_\nu < 1$ ⇒ T′/T < 0.64**

⇓

Due to the temperature difference, **in the M sector all key epochs proceed at somewhat different conditions than in the O sector!**

Thermodynamics

$$T'(t)\neq T(t)\quad\Rightarrow\quad \begin{array}{ll} \rho(t)=\dfrac{\pi^2}{30}g(T)T^4\neq\rho'(t)=\dfrac{\pi^2}{30}g'(T')T'^4 & g'\neq g \\ s(t)=\dfrac{2\pi^2}{45}q(T)T^3(t)\neq s'(t)=\dfrac{2\pi^2}{45}q'(T')T'^3(t) & q'\neq q \end{array}$$

During the Universe expansion, **the two sectors evolve with separately conserved entropies.**

$$x\equiv\left(\frac{s'}{s}\right)^{1/3}$$ is time independent

$$\frac{T'(t)}{T(t)}=x\left[\frac{q(T)}{q'(T')}\right]^{1/3}\quad\Rightarrow\quad \boxed{x=\frac{T'}{T}}$$

$$q'(T')\approx q(T)$$

***x* free parameter !**

$$H(t)=\frac{1}{2t}=1.66\sqrt{\bar{g}(T)}\frac{T^2}{M_{Pl}}=1.66\sqrt{\bar{g}'(T')}\frac{T'^2}{M_{Pl}}$$

$$\bar{g}(T)\approx g(T)(1+x^4)\qquad \bar{g}'(T)\approx g'(T')(1+x^{-4})$$

Thermodynamics

$$T'(t) \neq T(t) \quad \Rightarrow \quad \begin{aligned} &\rho(t) = \frac{\pi^2}{30} g(T) T^4 \neq \rho'(t) = \frac{\pi^2}{30} g'(T') T'^4 && g' \neq g \\ &s(t) = \frac{2\pi^2}{45} q(T) T^3(t) \neq s'(t) = \frac{2\pi^2}{45} q'(T') T'^3(t) && q' \neq q \end{aligned}$$

During the Universe expansion, **the two sectors evolve with separately conserved entropies.**

$$x \equiv \left(\frac{s'}{s}\right)^{1/3}$$

is time independent

$$\frac{T'(t)}{T(t)} = x \left[\frac{q(T)}{q'(T')}\right]^{1/3} \quad \Rightarrow \quad \boxed{x = \frac{T'}{T}}$$

$$q'(T') \approx q(T)$$

***x* free parameter !**

$$H(t) = \frac{1}{2t} = 1.66 \sqrt{\bar{g}(T)} \frac{T^2}{M_{Pl}} = 1.66 \sqrt{\bar{g}'(T')} \frac{T'^2}{M_{Pl}}$$

$$\bar{g}(T) \approx g(T)(1 + x^4) \qquad \bar{g}'(T) \approx g'(T')(1 + x^{-4})$$

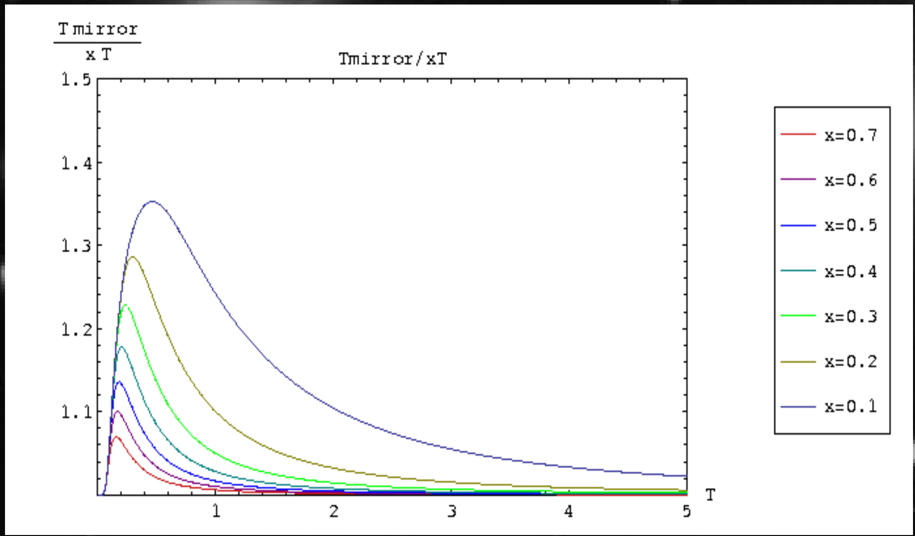
the contribution of the mirror species is negligible in view of the BBN constraint!

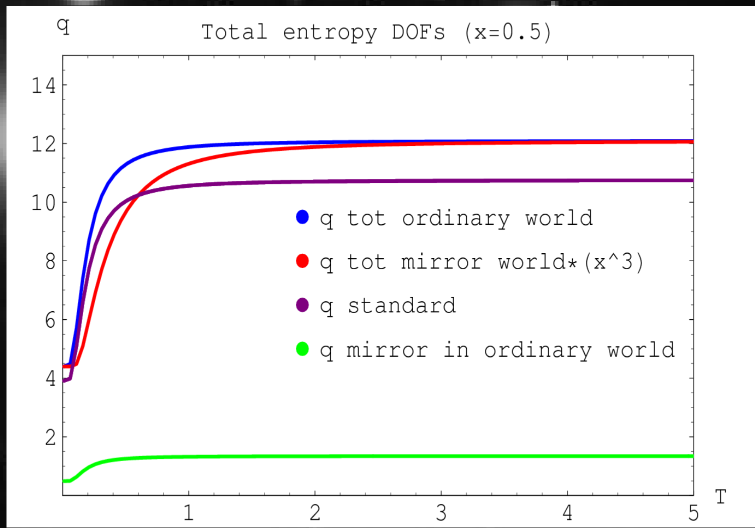
Degrees of freedom in a Mirror Universe

$$\frac{22}{21}=\frac{7/8\,q_e(T')+q_\gamma}{7/8\,q_\nu}\left(\frac{T'}{T_\nu'}\right)^3$$

$$\frac{22}{21}=\frac{7/8\,q_e(T)+q_\gamma}{7/8\,q_\nu}\left(\frac{T}{T_\nu}\right)^3$$

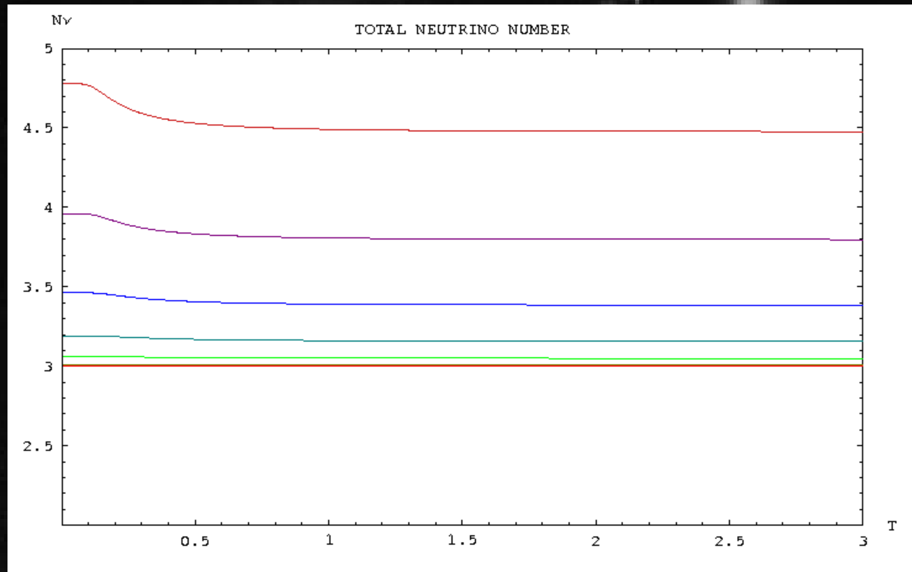
$$x^3=\frac{s'\cdot a^3}{s\cdot a^3}=\frac{\left[7/8\,q_e(T')+q_\gamma\right]T'^3+7/8\,q_\nu T_\nu'^3}{\left[7/8\,q_e(T)+q_\gamma\right]T^3+7/8\,q_\nu T_\nu^3}$$





e^+-e^- annihilation epoch changes according with x

$$N_\nu = \frac{\bar{g} - g_e(T) - g_\gamma}{7/8 \cdot 2} \cdot \left(\frac{T}{T_\nu} \right)^4$$



standard model:	$N_\nu^{eff} = 3.046$
BBN:	$N_\nu^{eff} = 3.1^{+1.4}_{-1.2}$
CMB+LSS+Lyα+BAO:	$N_\nu^{eff} = 4.6^{+1.6}_{-1.5}$

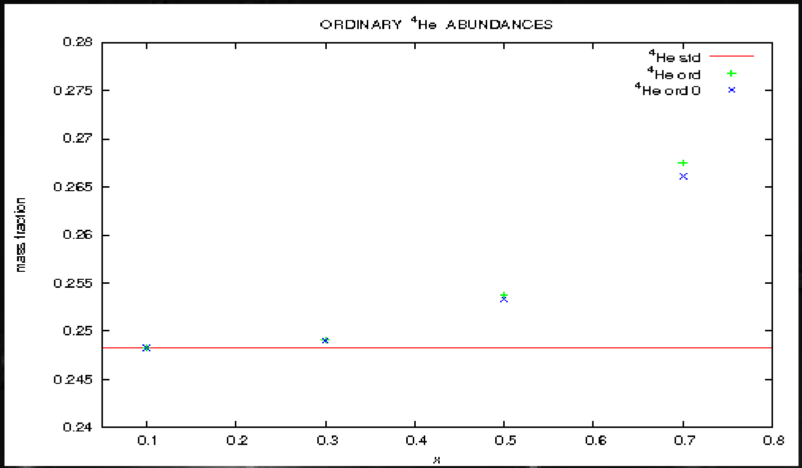
Mangano et al. (astro-ph/0612150) show some tension between degrees of freedom at different epochs.

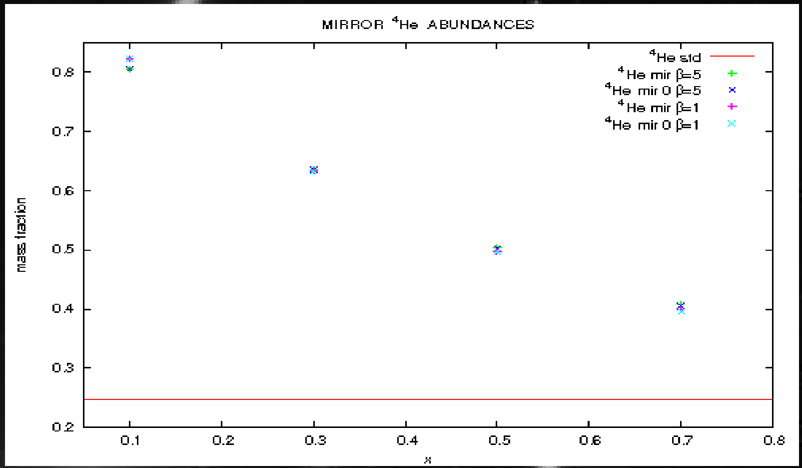
Mirror matter naturally predicts different degrees of freedom at BBN (1 MeV) and recombination (1 eV) epochs!

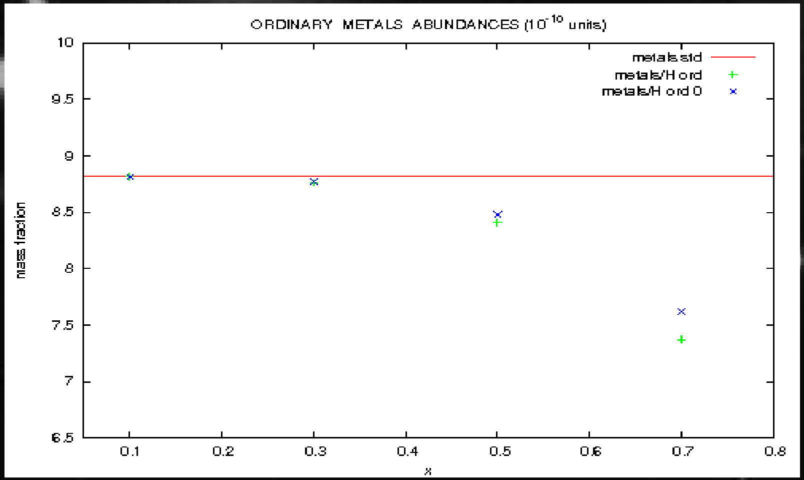
Big Bang nucleosynthesis

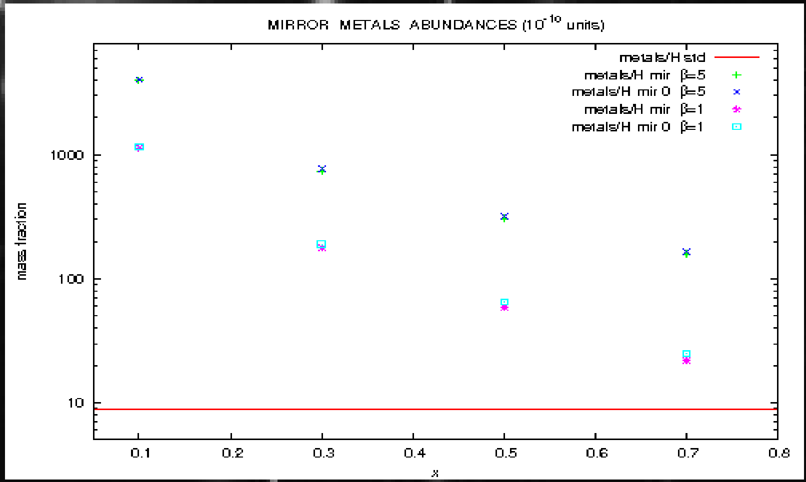
2 fundamental parameters:

degrees of freedom (extra-ν families), **baryon to photon ratio**: $\eta' = \beta x^{-3} \eta$







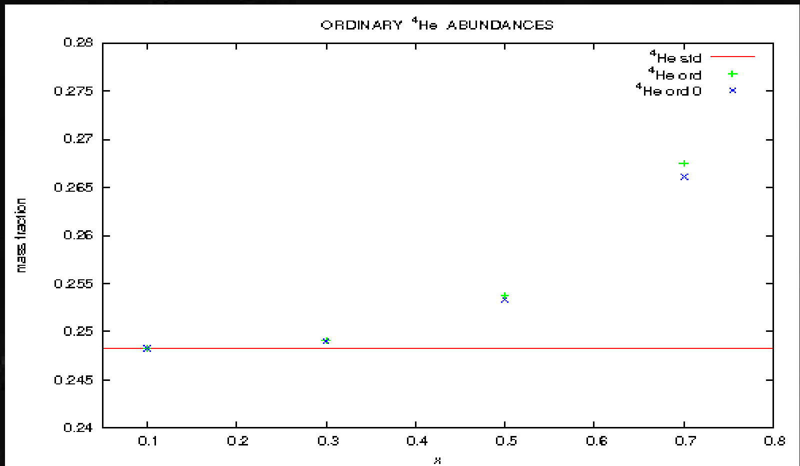


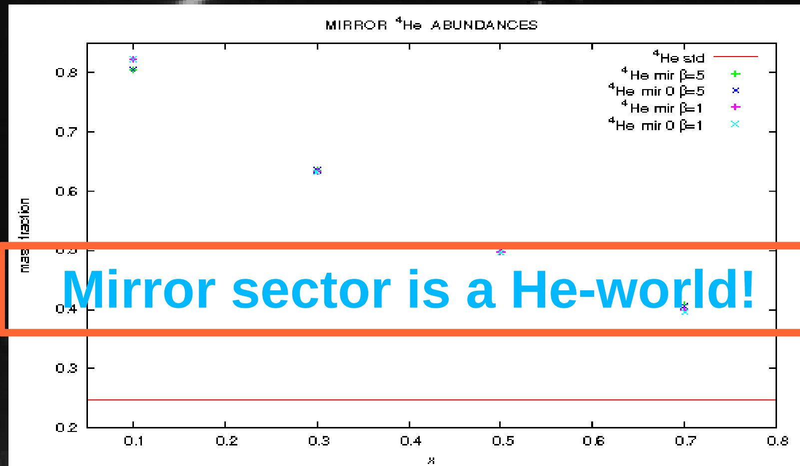
Big Bang nucleosynthesis

2 fundamental parameters:

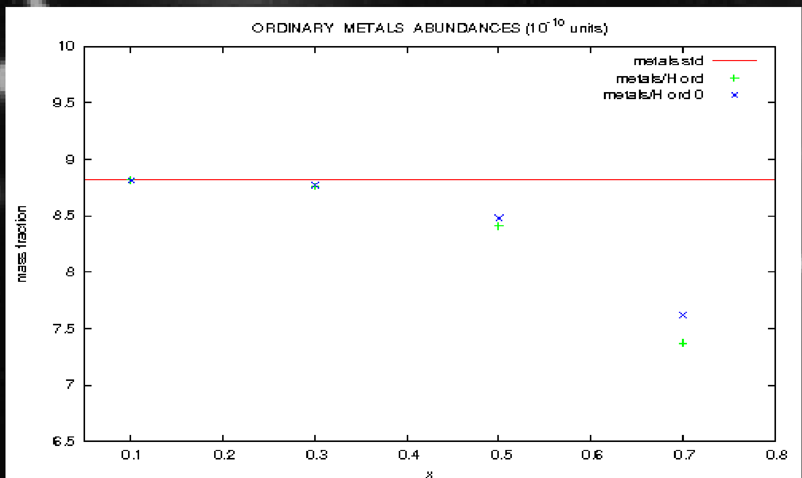
degrees of freedom (extra-ν families), **baryon to photon ratio**:

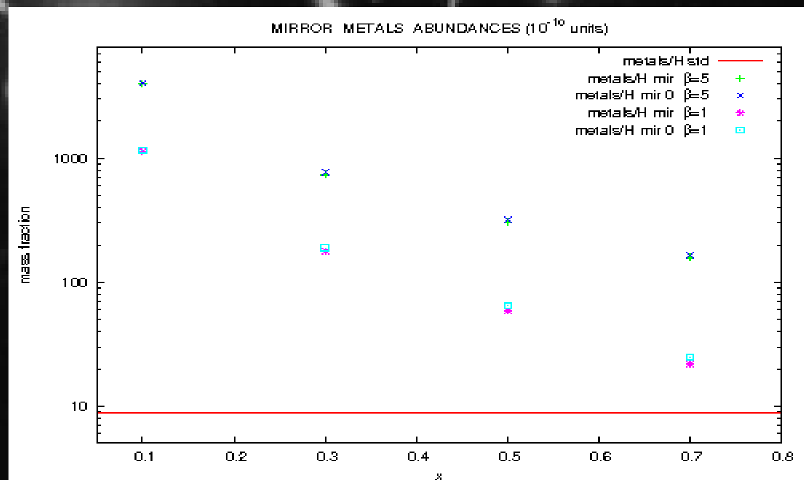
$$\eta' = \beta x^{-3} \eta$$





Mirror sector is a He-world!





Structure formation

Matter-radiation equality (MRE) epoch

$$1+z_{eq} = \frac{\Omega_m}{\Omega_r} \approx 2.4 \cdot 10^4 \frac{\Omega_m h^2}{1+x^4}$$

$$1+z'_{eq} = \frac{1+\beta}{1+x^4}\left(1+z_{eq}\right)$$

Baryon-photon decoupling (MRD) epoch

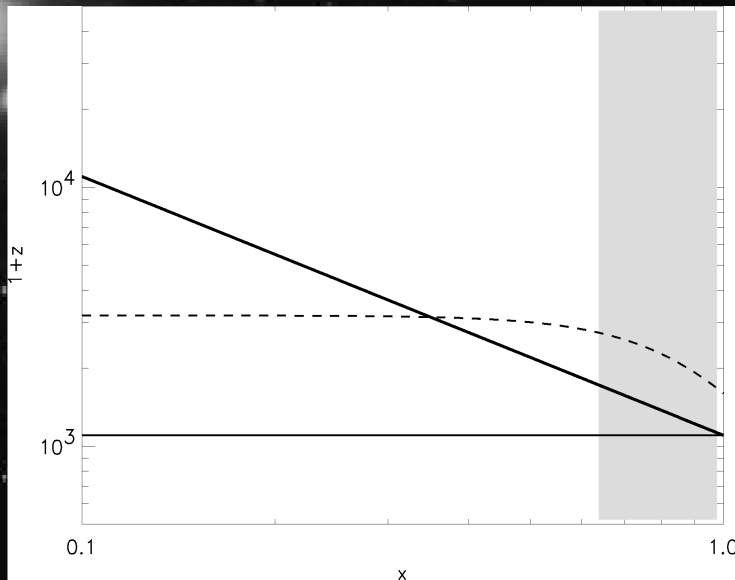
$$T_{dec} \approx 0.26\, eV \quad \Rightarrow \quad 1+z_{dec} = \frac{T_{dec}}{T_0} \approx 1100$$

$$T'_{dec} \approx T_{dec} \quad \Rightarrow \quad 1+z'_{dec} \approx x^{-1}\left(1+z_{dec}\right) \approx 1.1 \cdot 10^3\, x^{-1}$$

The MRD in the M sector occurs earlier than in the O one!

$$x < x_{eq} \approx 0.046 \left(\Omega_m h^2\right)^{-1}$$

For small *x* the M matter decouples before the MRE moment → it manifests as the CDM as far as the LSS is concerned (but there still can be a crucial difference at smaller scales which already went non-linear).



The Jeans mass

$$M_J' = \frac{4}{3}\pi\rho_b'\left(\frac{\lambda_J'}{2}\right)^3 \qquad \lambda_J' = v_S'\sqrt{\frac{\pi}{G\rho_{dom}}}$$

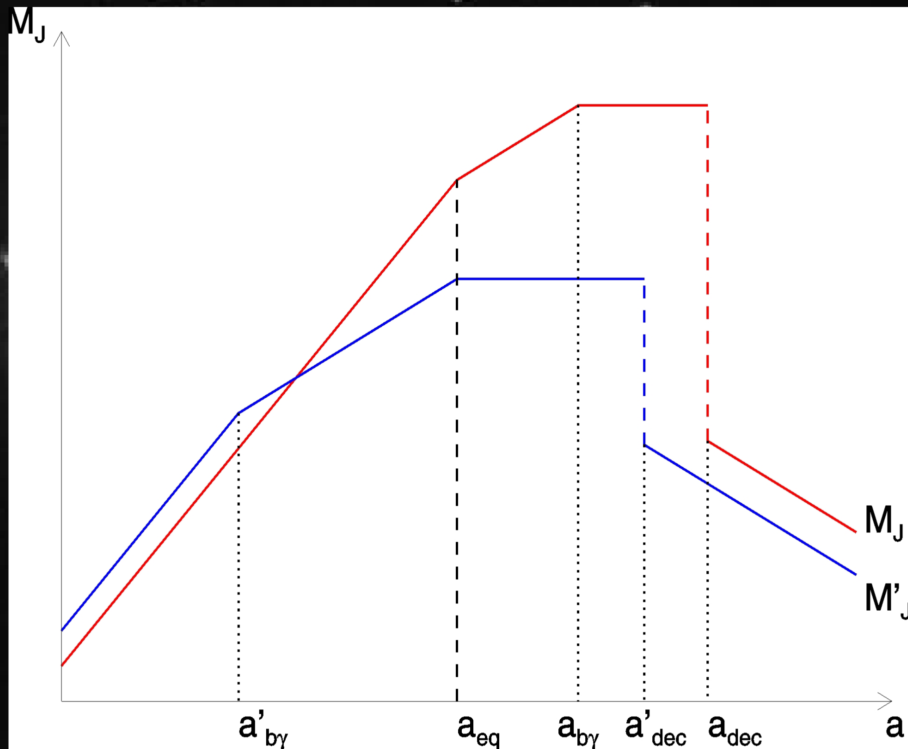
$$M_J'(a_{dec}') = 3.2\cdot10^{14} M_\odot \beta^{-1/2}(1+\beta)^{-3/2}\left(\frac{x^4}{1+x^4}\right)^{3/2}(\Omega_b h^2)^{-2}$$

$$M_J'(a_{dec}') \approx \beta^{-1/2}\left(\frac{x^4}{1+x^4}\right)^{3/2} M_J(a_{dec})$$

$$\begin{aligned} x &= 0.6 \\ \beta &= 2 \end{aligned} \quad \Rightarrow \quad M_J' \approx 0.03\, M_J \approx 10^{14} M_\odot$$

$$M_J'_{max}(x_{eq/2}) \approx 0.005 M_J'_{max}(x_{eq})$$

$$M_J'_{max}(2x_{eq}) \approx 64\, M_J'_{max}(x_{eq})$$



The Jeans mass

$$M_J' = \frac{4}{3}\pi\rho_b'\left(\frac{\lambda_J'}{2}\right)^3 \qquad \lambda_J' = v_S'\sqrt{\frac{\pi}{G\rho_{dom}}}$$

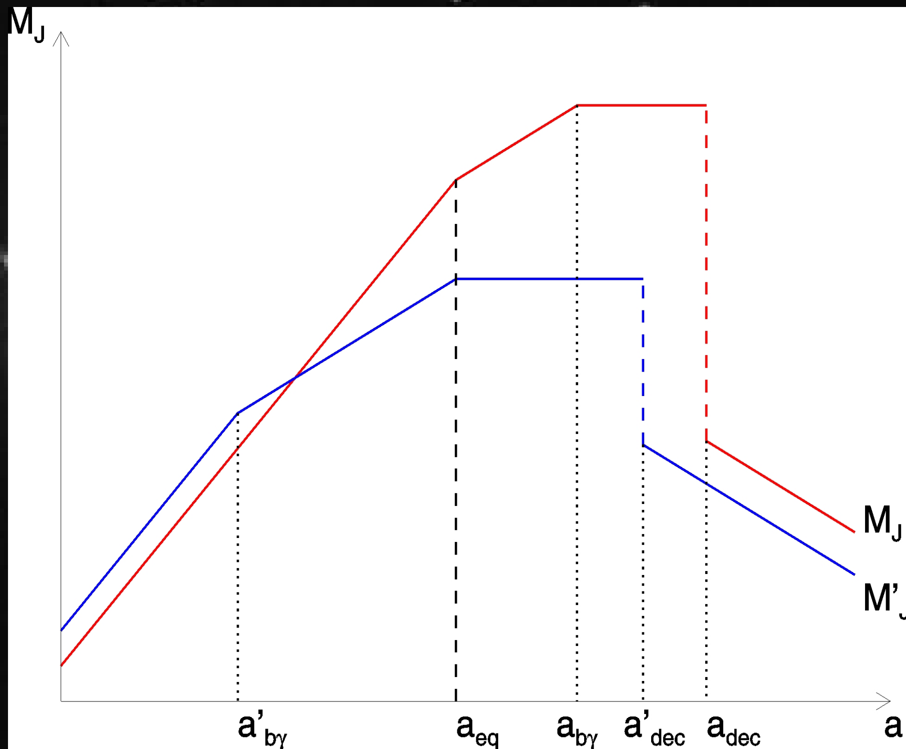
$$M_J'(a_{dec}') = 3.2\cdot 10^{14} M_\odot \beta^{-1/2}(1+\beta)^{-3/2}\left(\frac{x^4}{1+x^4}\right)^{3/2}(\Omega_b h^2)^{-2}$$

$$M_J'(a_{dec}') \approx \beta^{-1/2}\left(\frac{x^4}{1+x^4}\right)^{3/2} M_J(a_{dec})$$

$$\begin{array}{l} x = 0.6 \\ \beta = 2 \end{array} \Rightarrow M_J' \approx 0.03\, M_J \approx 10^{14} M_\odot$$

$$M_J'_{max}(x_{eq/2}) \approx 0.005 \mathrm{M}_J'_{max}(x_{eq})$$

$$M_J'_{max}(2x_{eq}) \approx 64\, M_J'_{max}(x_{eq})$$



The Jeans mass

$$M_J' = \frac{4}{3}\pi\rho_b'\left(\frac{\lambda_J'}{2}\right)^3 \qquad \lambda_J' = v_S'\sqrt{\frac{\pi}{G\rho_{dom}}}$$

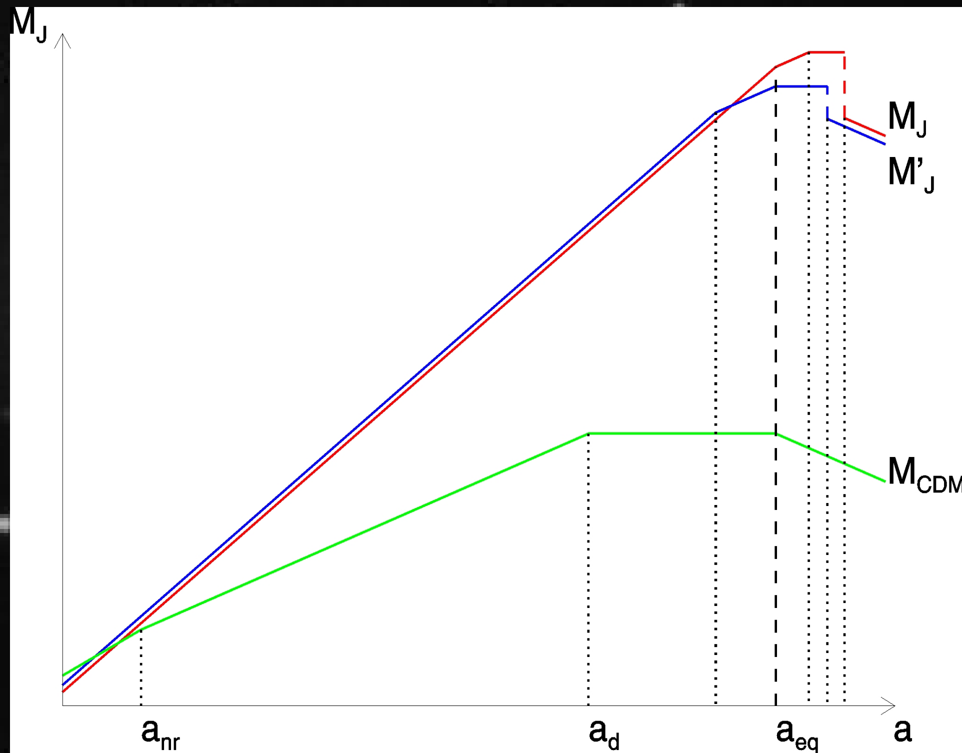
$$M_J'(a_{dec}') = 3.2\cdot 10^{14} M_\odot \beta^{-1/2}(1+\beta)^{-3/2}\left(\frac{x^4}{1+x^4}\right)^{3/2}(\Omega_b h^2)^{-2}$$

$$M_J'(a_{dec}') \approx \beta^{-1/2}\left(\frac{x^4}{1+x^4}\right)^{3/2} M_J(a_{dec})$$

$$x = 0.6 \quad \beta = 2 \quad \Rightarrow \quad M_J' \approx 0.03\, M_J \approx 10^{14} M_\odot$$

$$M_J'{}_{max}(x_{eq/2}) \approx 0.005 M_J'{}_{max}(x_{eq})$$

$$M_J'{}_{max}(2x_{eq}) \approx 64\, M_J'{}_{max}(x_{eq})$$



Dissipative effects

The M **baryons density fluctuations should undergo the strong *collisional damping* around the time of** M **recombination** due to photon diffusion, which washes out the perturbations at scales smaller than the M **Silk scale** M_S'.

$$M_S \approx 6.2 \cdot 10^{12} (\Omega_b h^2)^{-5/4} M_\odot$$

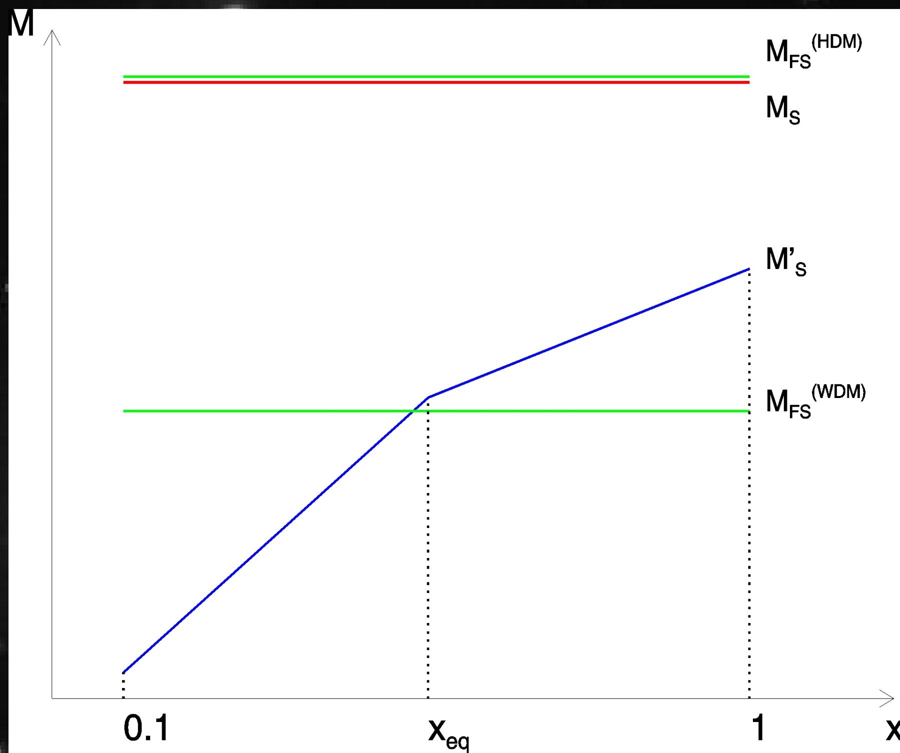
$$\Omega_b h^2 = 0.02 \quad \Rightarrow \quad M_S \approx 8 \cdot 10^{14} M_\odot$$

$$M_S' \approx [f(x)/2]^3 (\Omega_b' h^2)^{-5/4} \cdot 10^{12} M_\odot$$

$$f(x) = x^{5/4} \qquad x > x_{eq}$$

$$f(x) = (x/x_{eq})^{3/2} x_{eq}^{5/4} \qquad x < x_{eq}$$

$$M_S'(x_{eq}) \approx 10^7 (\Omega_b h^2)^{-5} M_\odot \approx 3 \cdot 10^{10} M_\odot$$



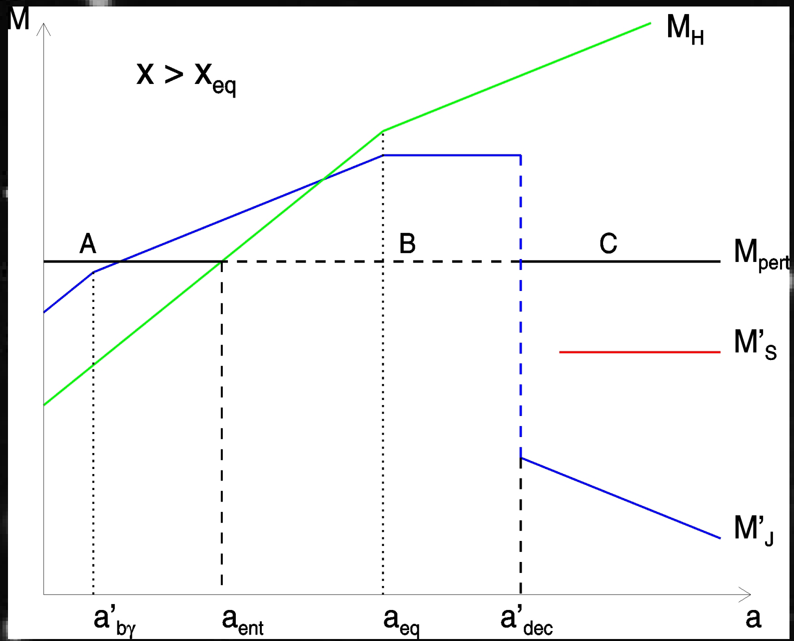
Differences with the WDM free streaming damping:

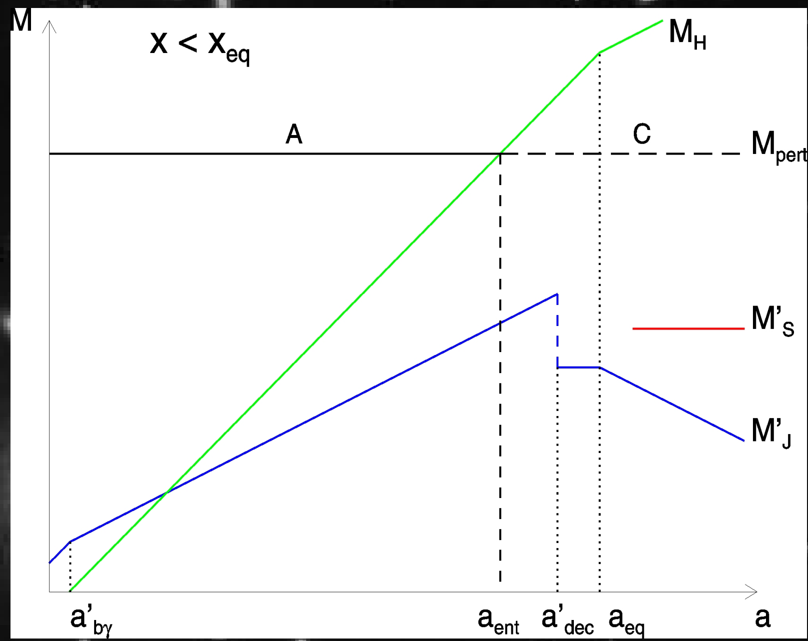
- the M baryons should show **acustic oscillations in the LSS power spectrum**;
- such oscillations, transmitted via gravity to the O baryons, could cause observable **anomalies in the CMB power spectrum**.

Scenarios

$$x > x_{eq} \quad \Rightarrow \quad a_{dec}' > a_{dec}$$

$$x < x_{eq} \quad \Rightarrow \quad a_{dec}' < a_{dec}$$





$$M_{pert} > M_J'(a_{eq}) \quad \Rightarrow \quad growth$$

$$M_S' < M_{pert} < M_J'(a_{eq}) \quad \Rightarrow \quad grow. + oscill. + grow.$$

$$M_{pert} < M_S' \quad \Rightarrow \quad dissipation$$

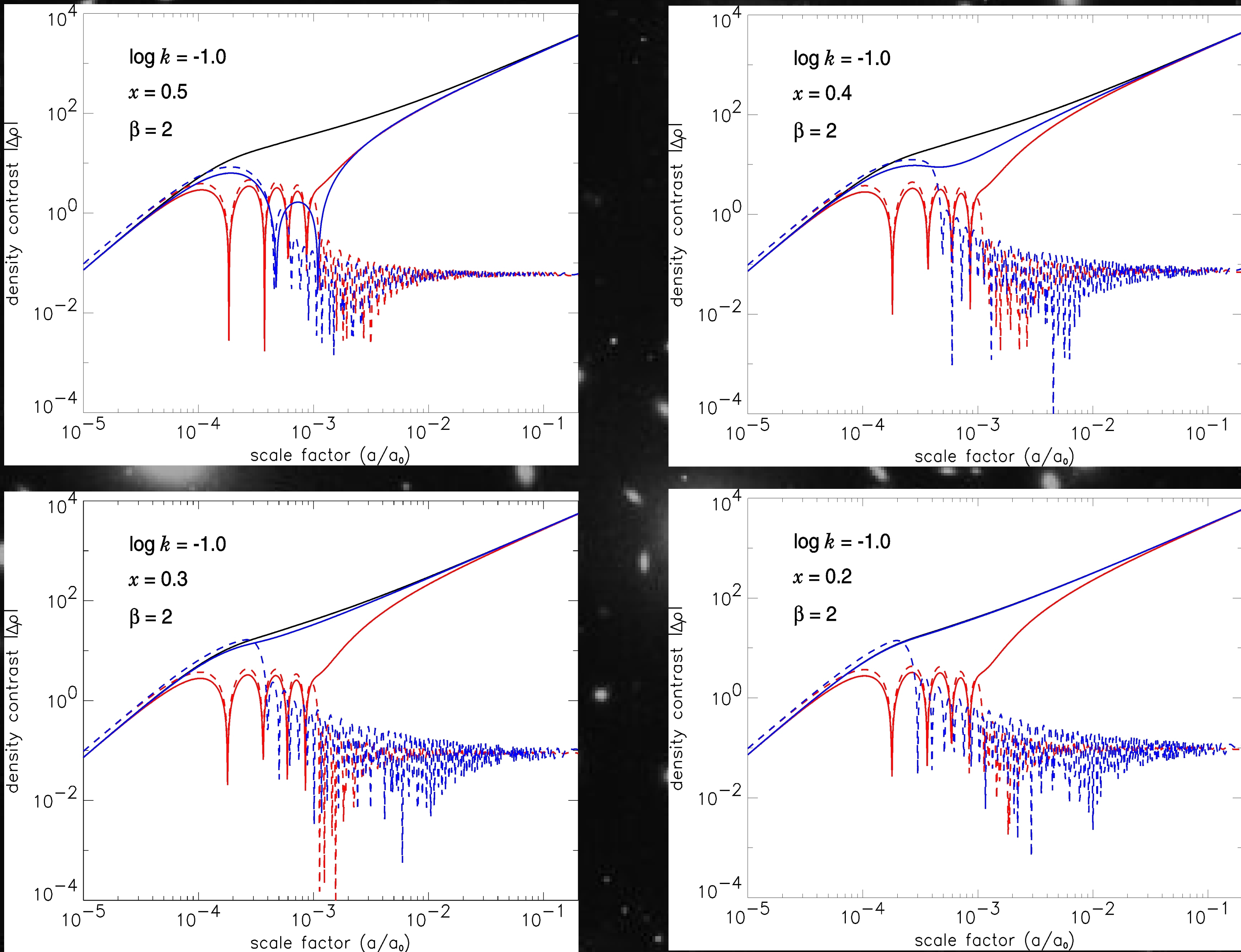
$$M_{pert} > M_J'(a_{dec}') \quad \Rightarrow \quad growth$$

$$M_{pert} < M_S' \quad \Rightarrow \quad dissipation$$

Temporal evolution of perturbations

($\Omega_0 = 1$, $\Omega_m = 0.3$, $\omega_b = 0.02$, $h = 0.7$; $\lambda \approx 60$ Mpc)

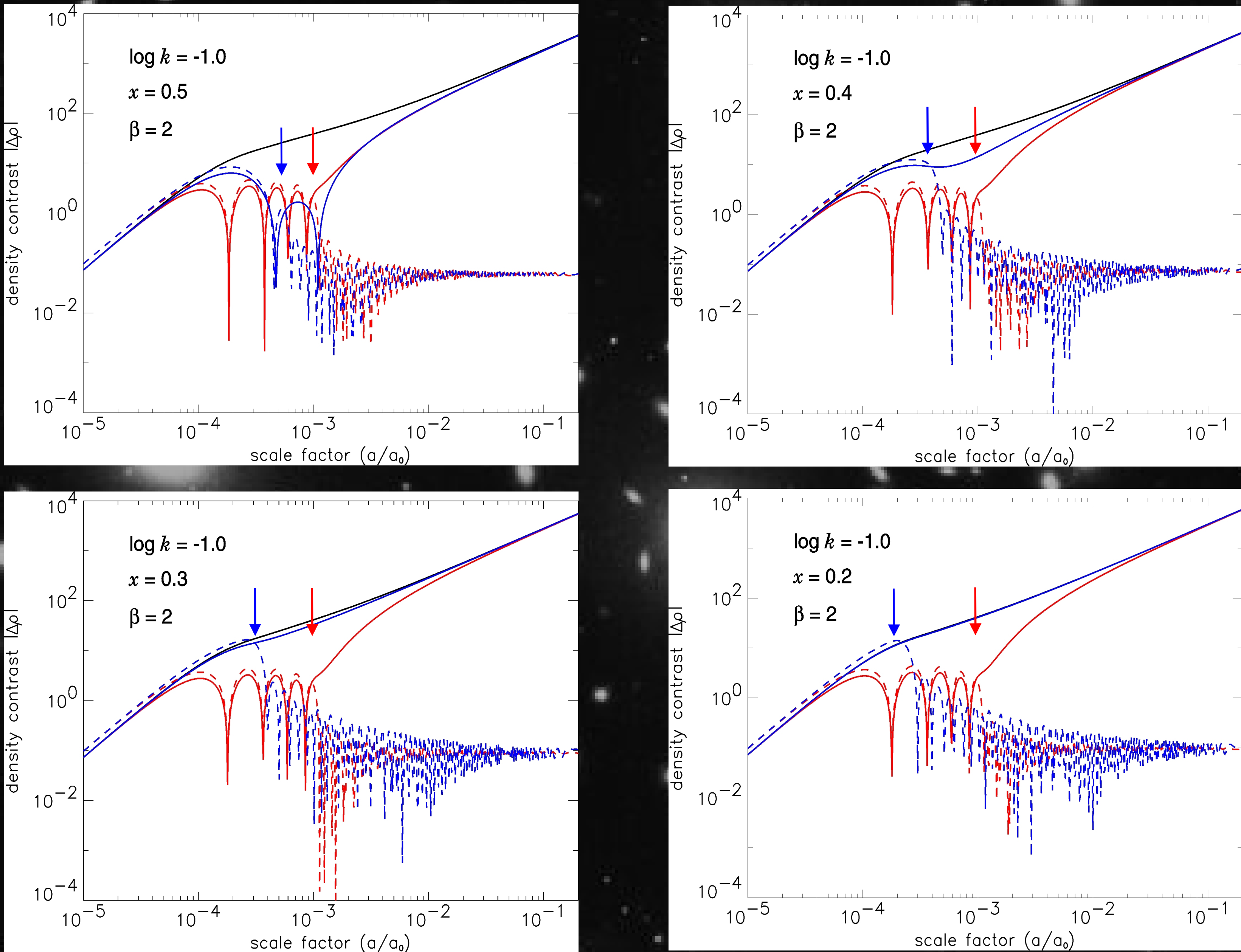
x dependence



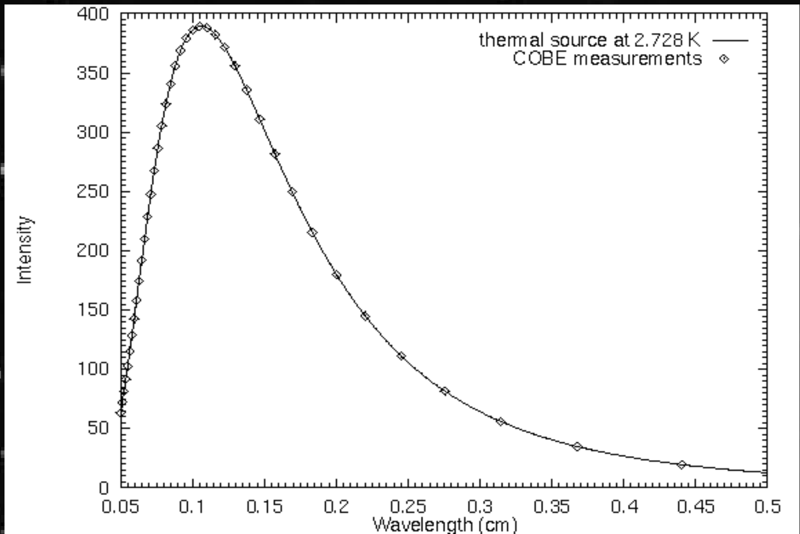
Temporal evolution of perturbations

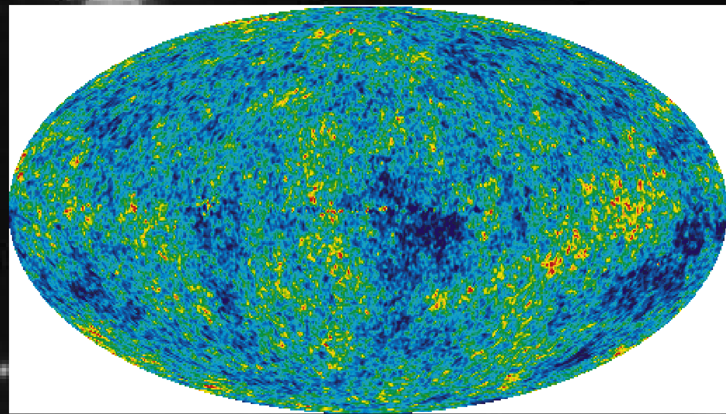
($\Omega_0 = 1$, $\Omega_m = 0.3$, $\omega_b = 0.02$, $h = 0.7$; $\lambda \approx 60$ Mpc)

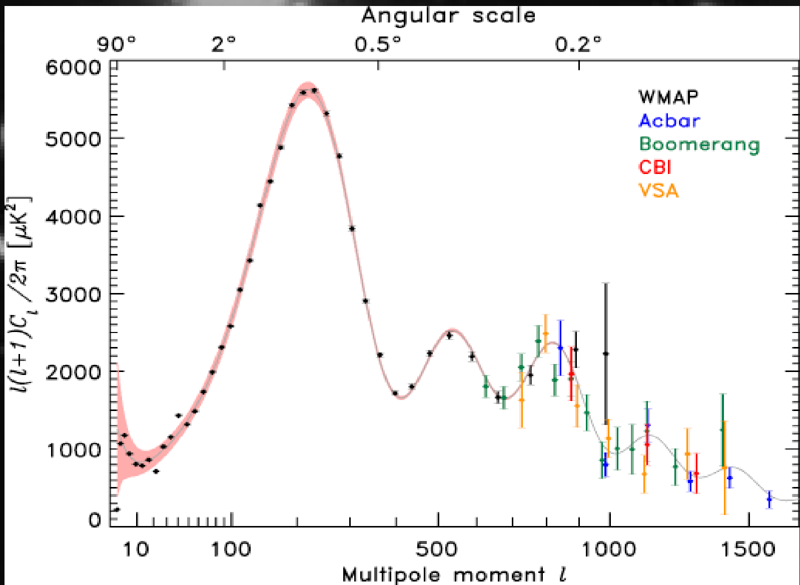
***x* dependence**



Cosmic Microwave Background







$$T = (2.725 \pm 0.001)\,K \qquad \frac{\Delta T}{T} \approx 10^{-5}$$

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

$$C_l = a_l^2 \equiv \frac{1}{2l+1} \sum_{m=-l}^{+l} |a_{lm}|^2 = \langle |a_{lm}|^2 \rangle$$

$$\delta T_l^2 \equiv l(l+1) C_l / 2\pi$$

Mirror CMB

We start from a *reference* model

$$\Omega_{tot}=1$$

$$\Omega_m=0.30$$

$$\Omega_{CDM}=\Omega_m-\Omega_b{}'$$

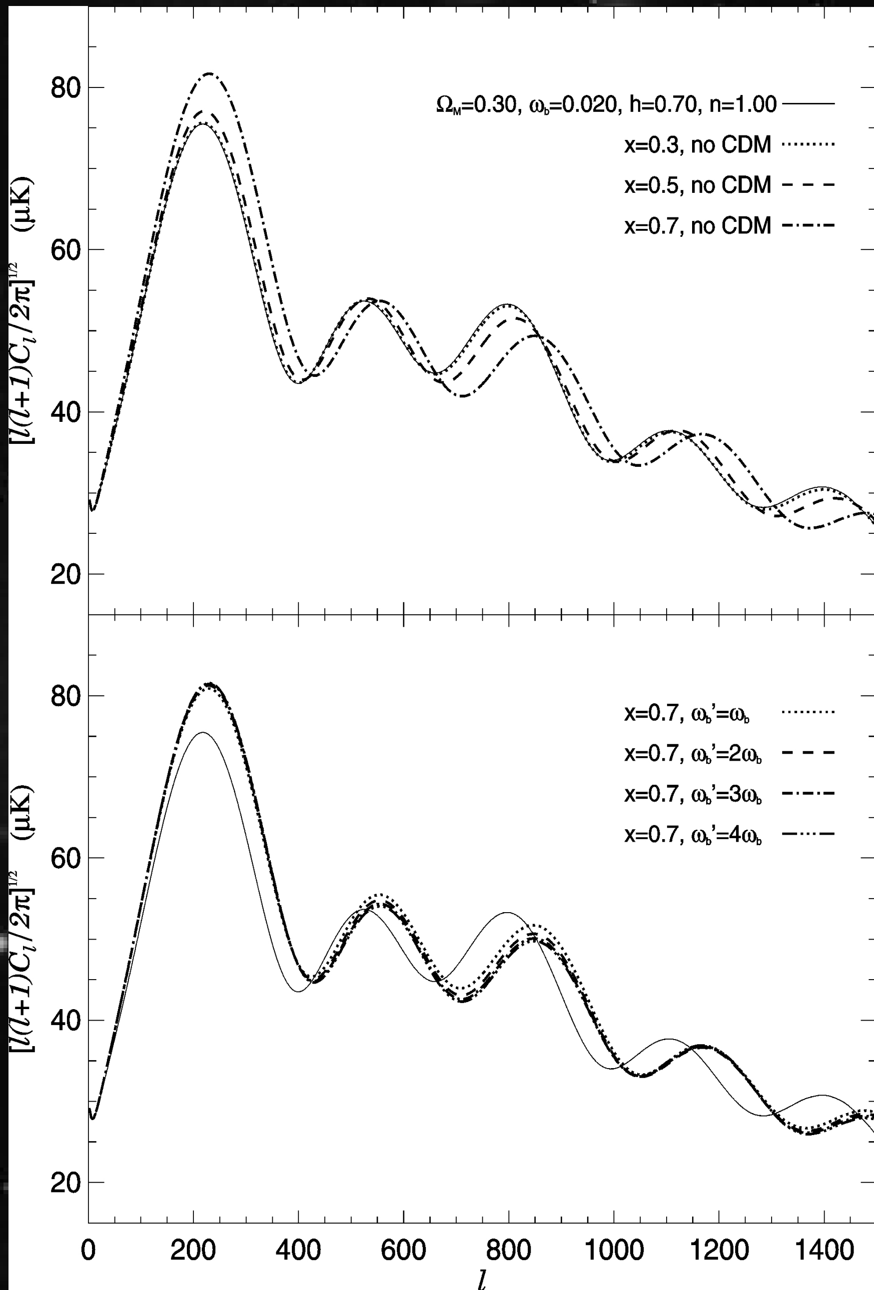
$$\Omega_b h^2=0.02$$

$$h=0.70$$

$$n_s=1.00$$

and we replace CDM…

- $x=0.3\,,0.5\,,0.7$
- $\Omega_b{}'=n\,\Omega_b\,(n=1,2,3,4,\ldots)$



Mirror CMB

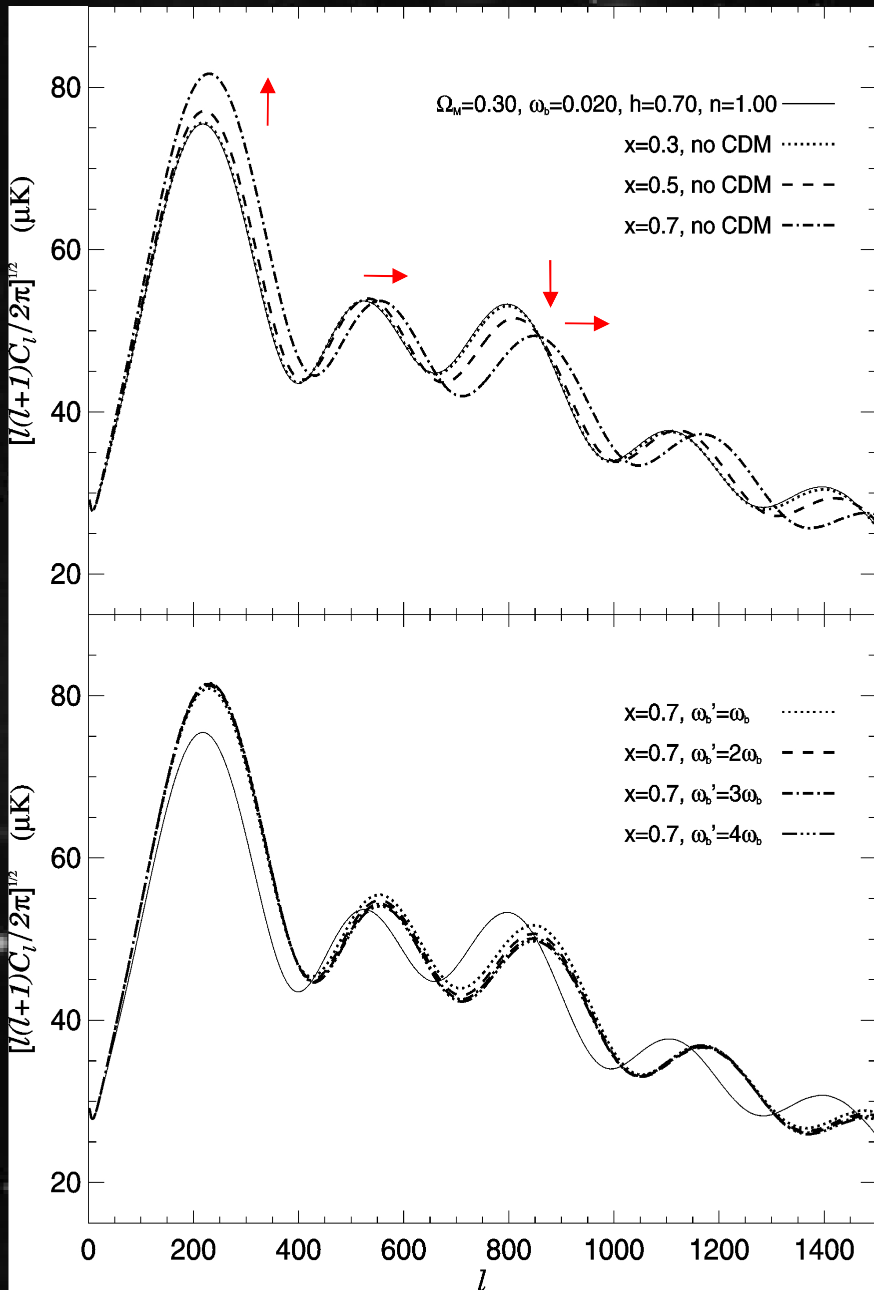
We start from a *reference* model

$$\Omega_{tot}=1$$
$$\Omega_m=0.30$$
$$\Omega_{CDM}=\Omega_m-\Omega_b'$$
$$\Omega_b h^2=0.02$$
$$h=0.70$$
$$n_s=1.00$$

and we replace CDM…

- $x=0.3\,,0.5\,,0.7$
- $\Omega_b'=n\,\Omega_b\,(n=1,2,3,4,\ldots)$

- **low x $\rightarrow$ CDM**
- **small dependence on Ω_b'**



Large Scale Structure

Field of density perturbations:

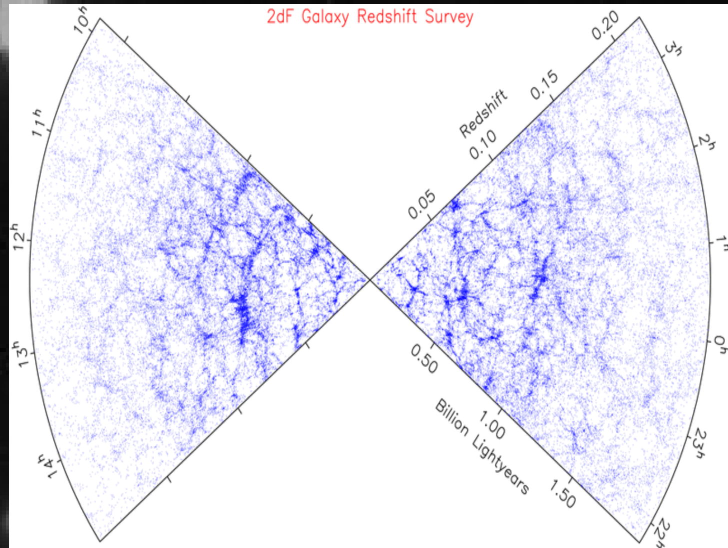
$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \rho_0}{\rho_0} \qquad \delta(\vec{x}) = \frac{1}{(2\pi)^3} \int \delta_k e^{-i\vec{k}\cdot\vec{x}} d^3k$$

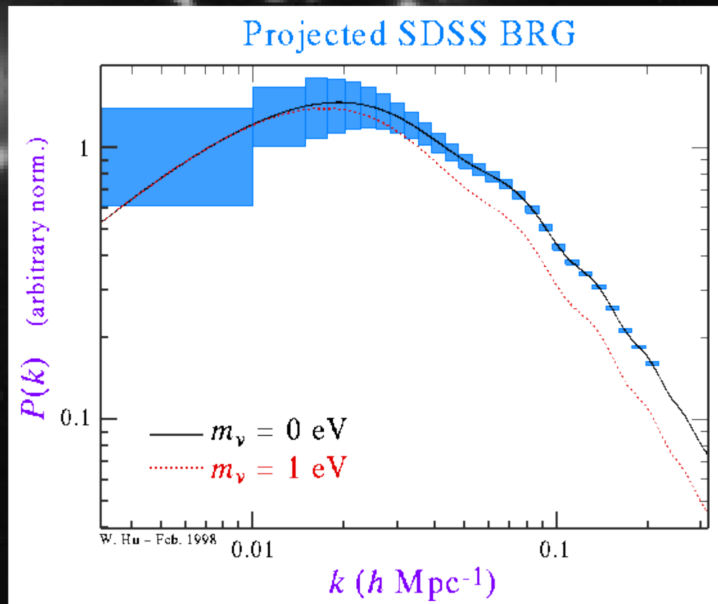
The power spectrum:

$$P(k) \equiv \langle |\delta_k|^2 \rangle = A k^n$$

The transfer function: $T(k)$

$$P(k;t_f) = \left[\frac{D(t_f)}{D(t_i)}\right]^2 T^2(k;t_f)\, P(k;t_i)$$

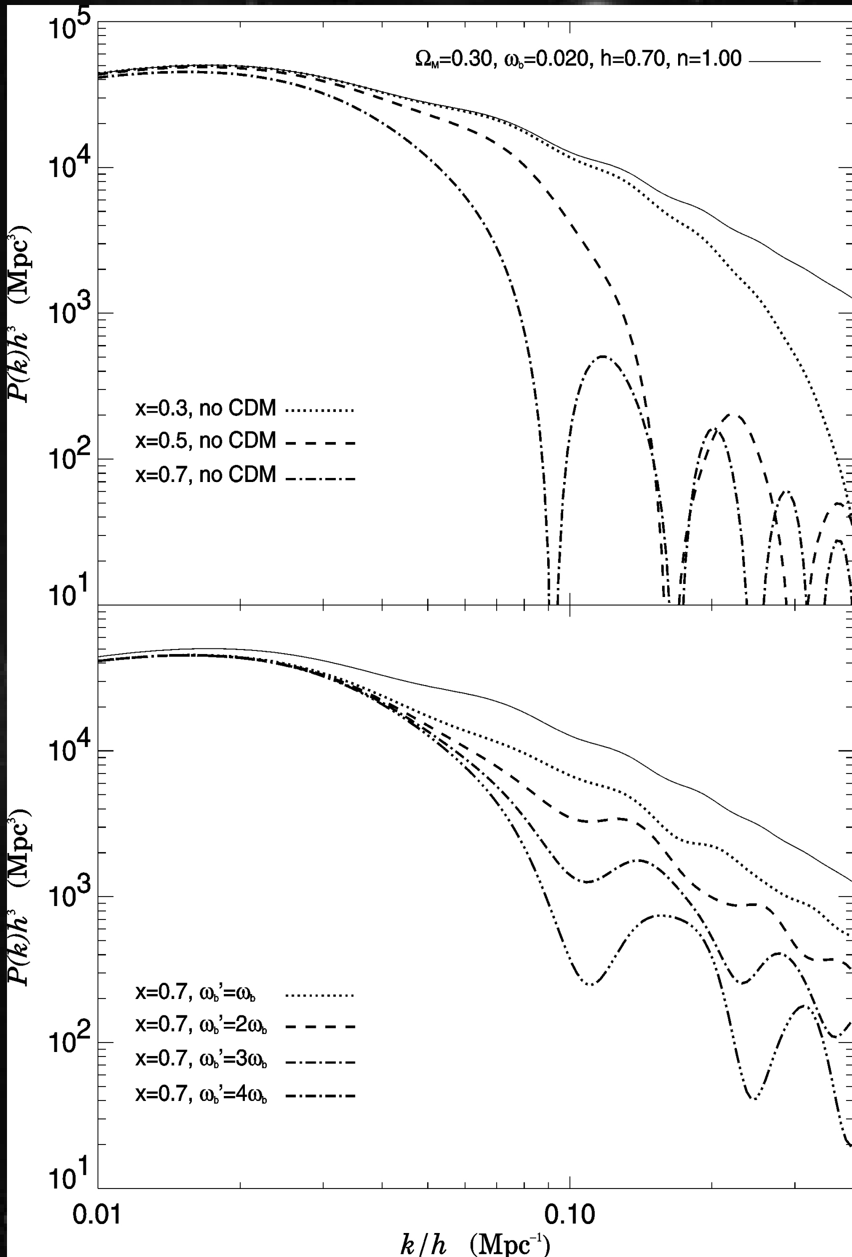




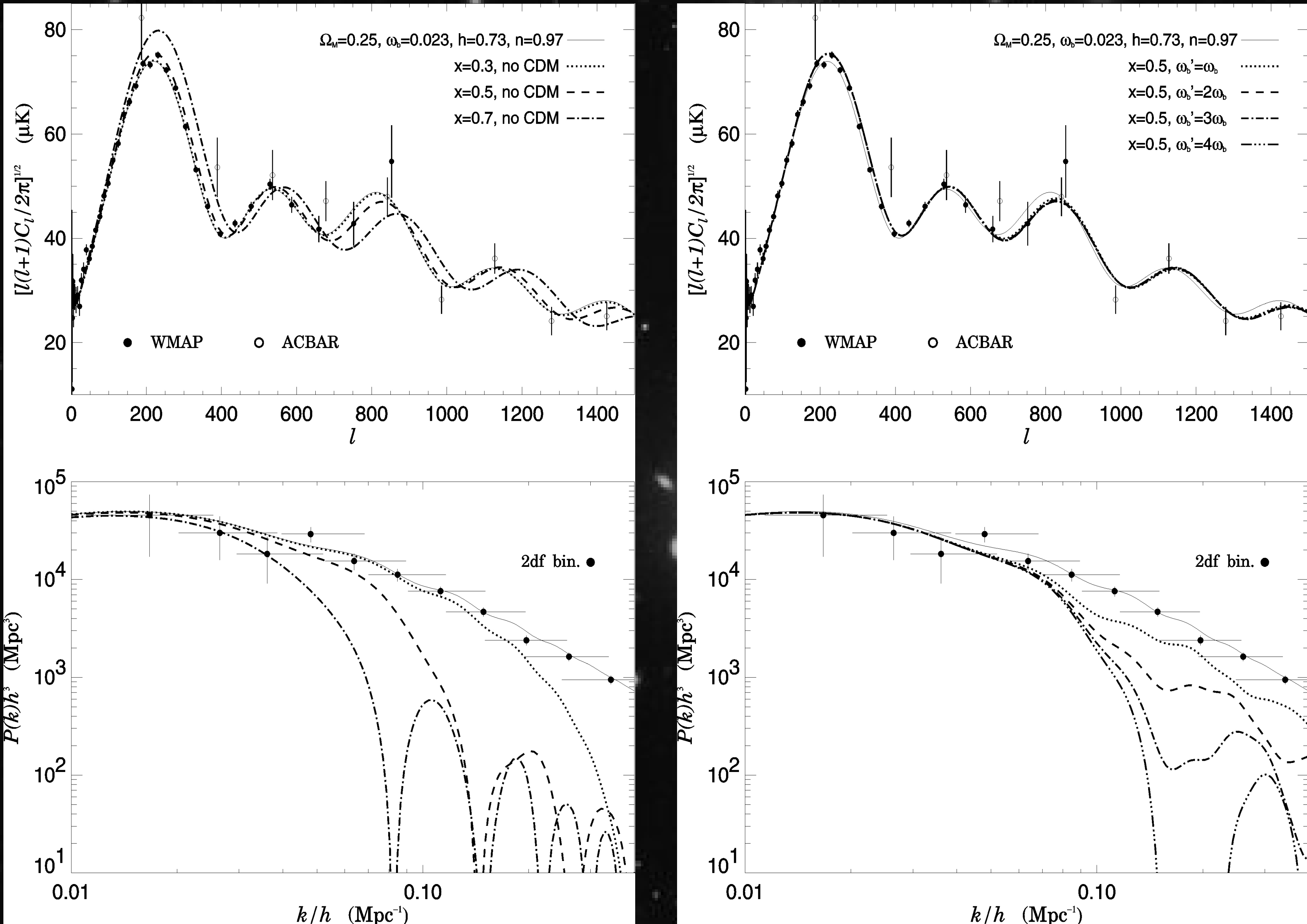
Mirror LSS

At linear scales…

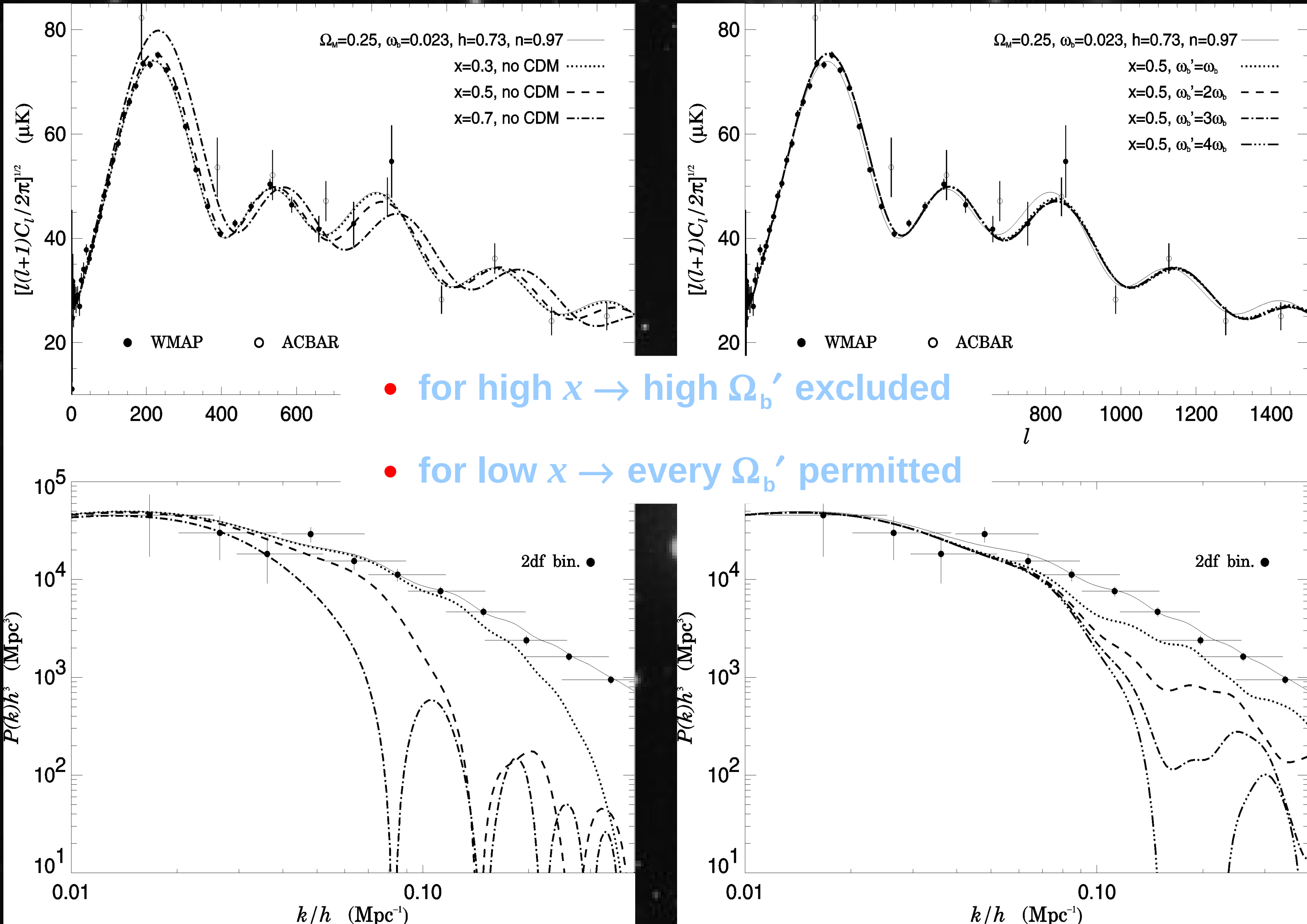
- low $x \rightarrow$ CDM
- high dependence on x
- high dependence on Ω_b'
- higher $\Omega_b' \rightarrow$ deeper oscillations



Comparison with observations

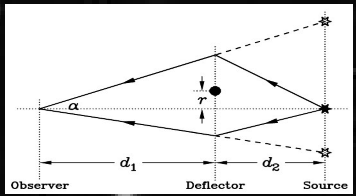


Comparison with observations

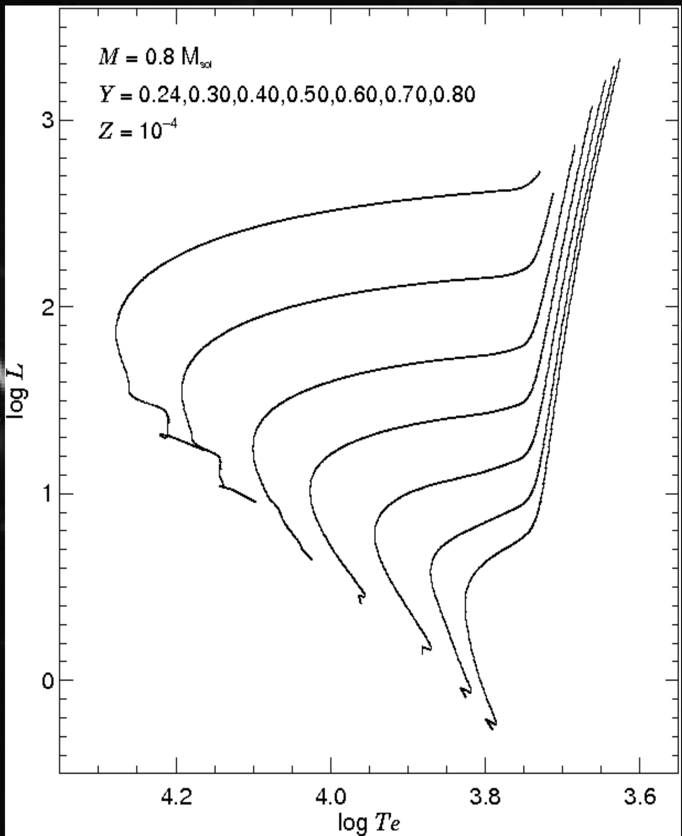


- for high $x \rightarrow$ high Ω_b' excluded
- for low $x \rightarrow$ every Ω_b' permitted

Mirror dark stars (evolution)



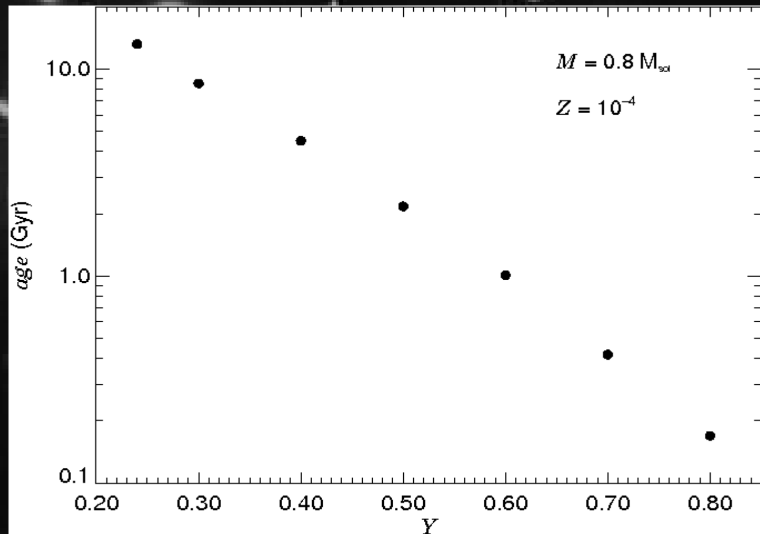
microlensing events ⇒ Massive Astrophysical Compact Halo Objects (MACHOs)



$$L \propto \mu^{7.5} M^{5.5}$$

$$T_e^4 \propto \mu^{7.5}$$

$$t_{MS} \propto \frac{X}{\mu^{1.4}}$$



faster evolutionary times!

Mirror summary

Mirror summary

Thermodynamics of
the early Universe

THEORY

OBSERVATIONS

Mirror summary

THEORY

Thermodynamics of the early Universe

Big Bang Nucleosynthesis

OBSERVATIONS

Mirror summary

THEORY

Thermodynamics of the early Universe

Big Bang Nucleosynthesis

Star formation

Star evolution

Primordial nuclear abundances

OBSERVATIONS

Mirror summary

THEORY

Thermodynamics of the early Universe

Big Bang Nucleosynthesis

Star formation

Star evolution

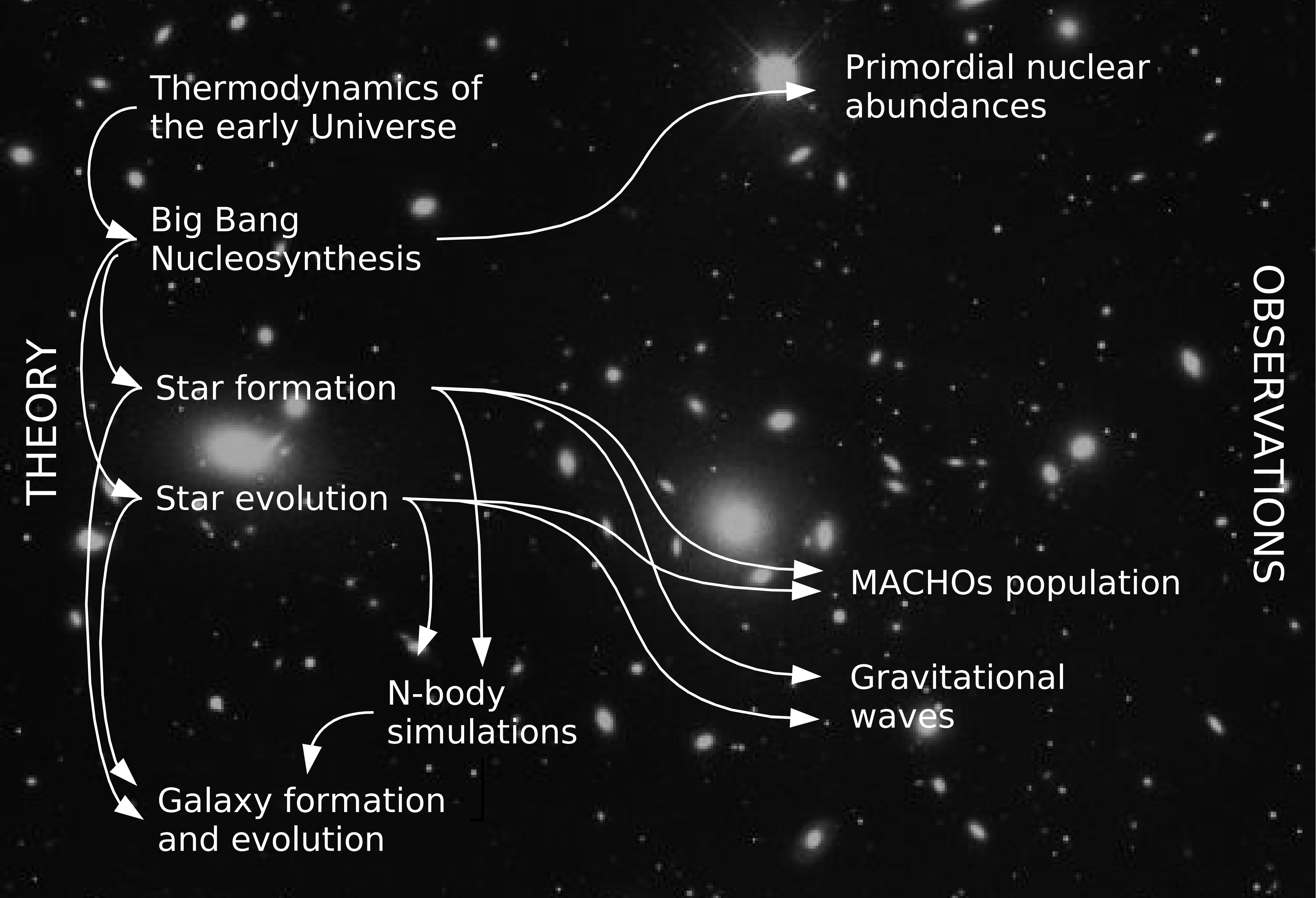
OBSERVATIONS

Primordial nuclear abundances

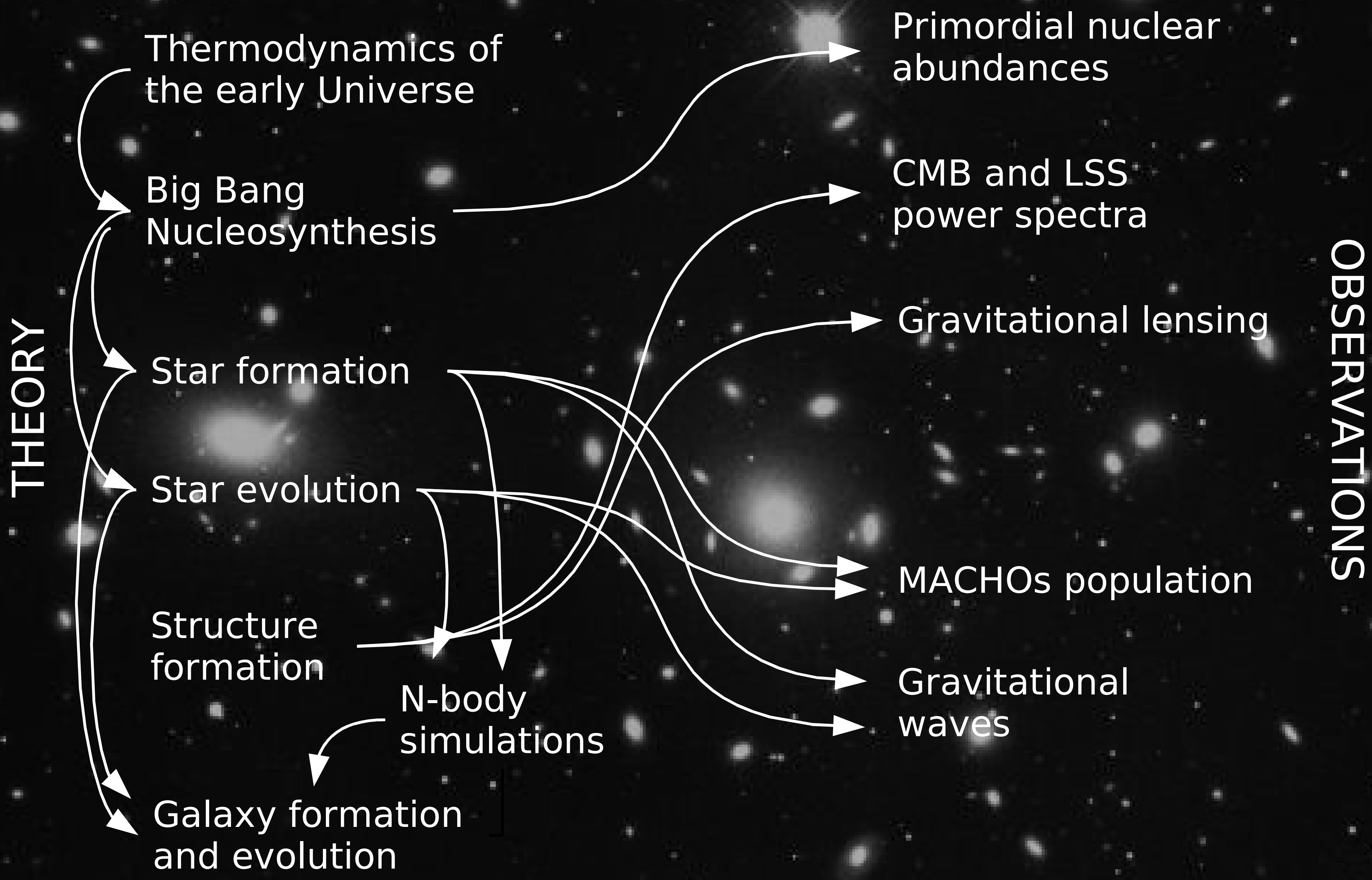
MACHOs population

Gravitational waves

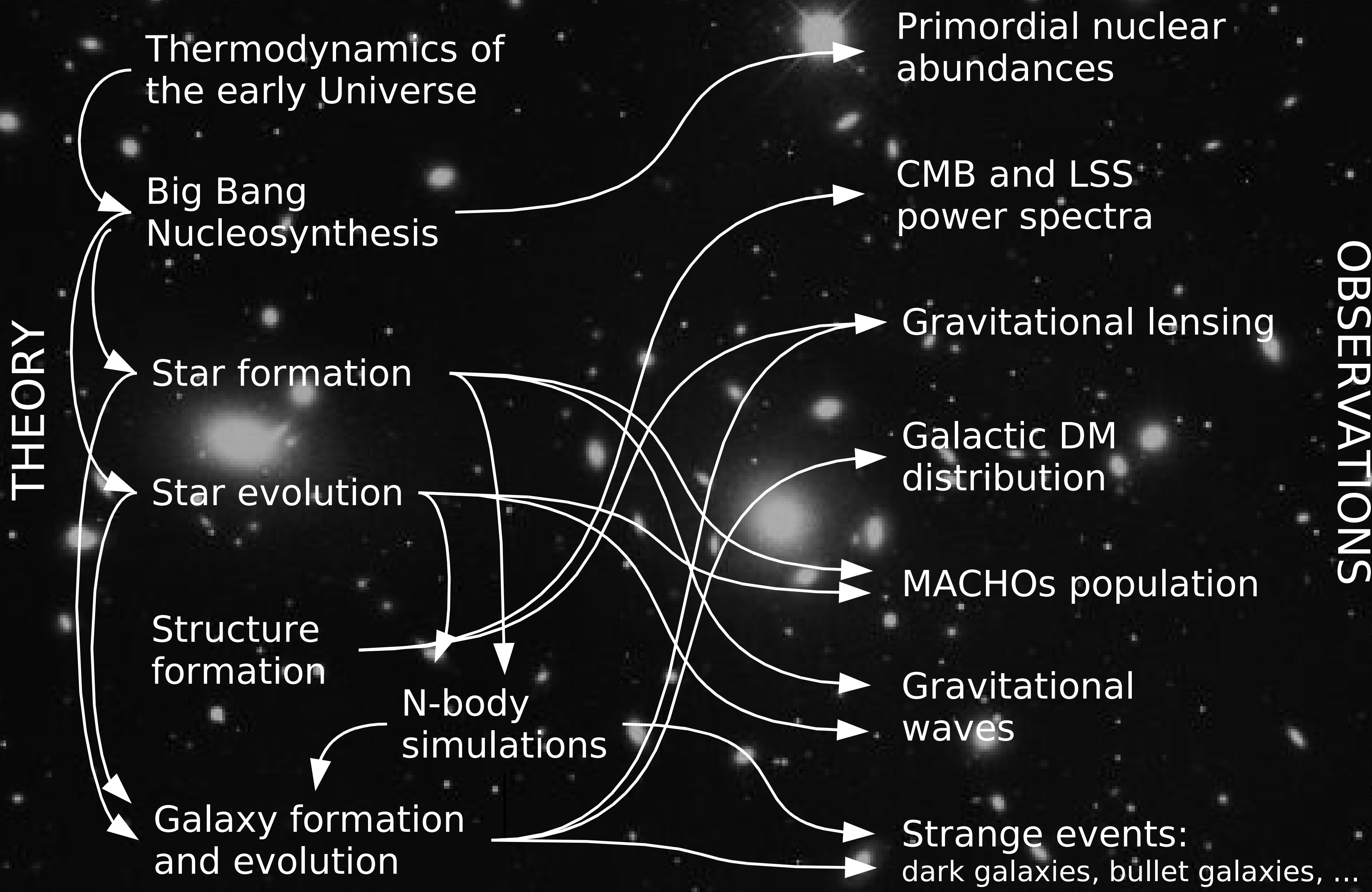
Mirror summary



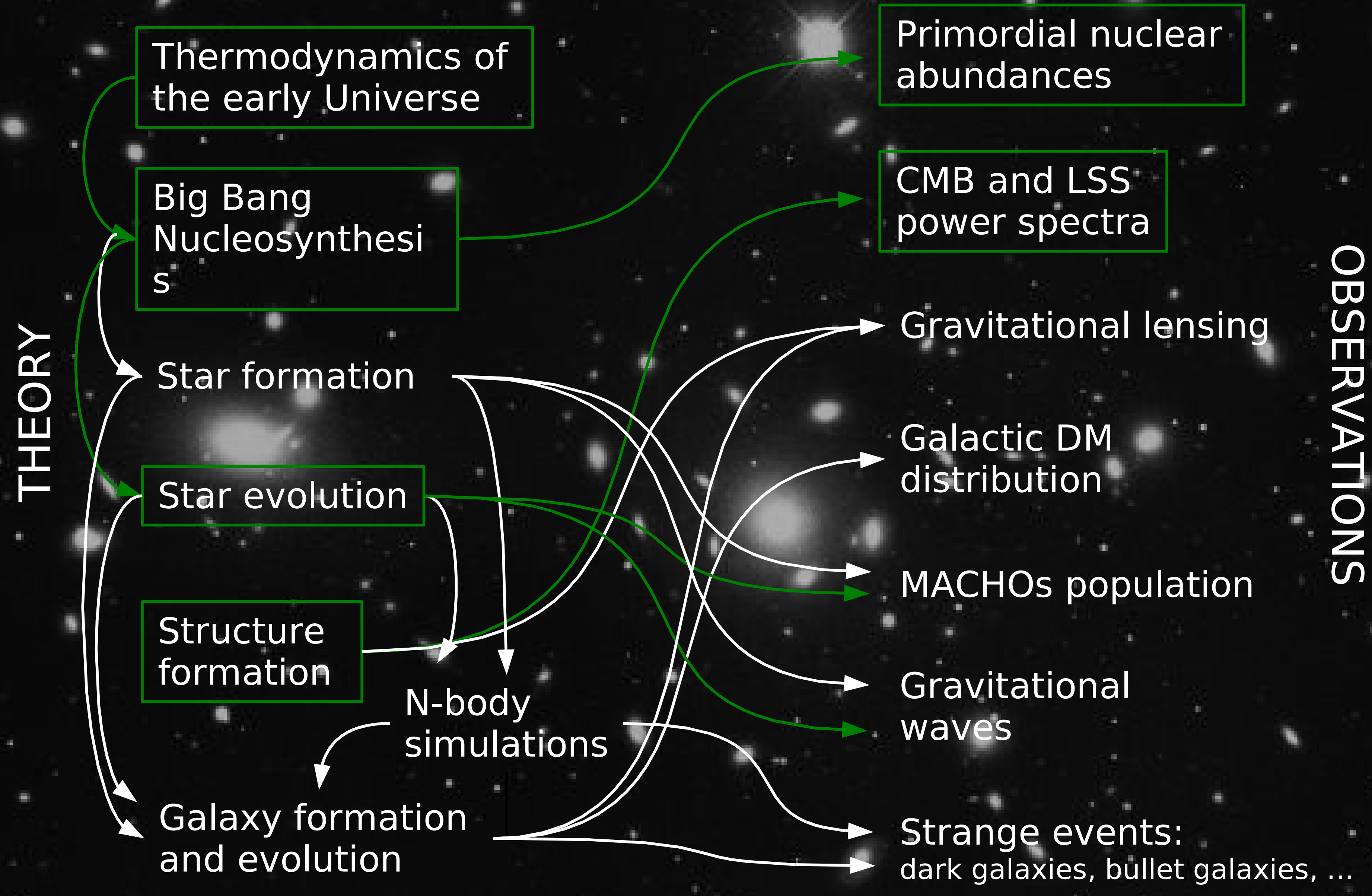
Mirror summary



Mirror summary



Mirror summary



Mirror summary