16 December 2011

ASTROPHYSICAL PROPERTIES OF MIRROR DARK MATTER

Paolo Ciarcelluti

Motivation of this research

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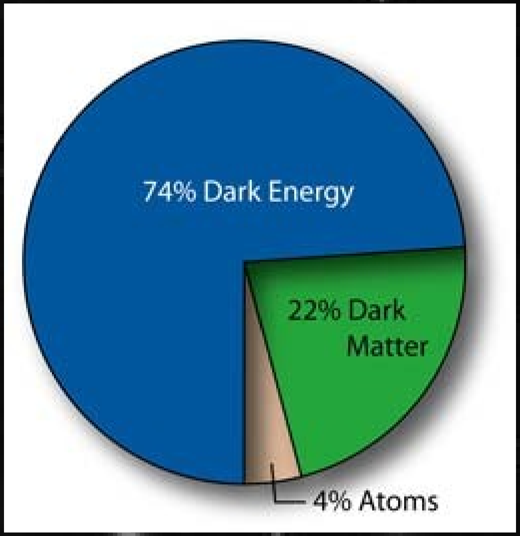
ERA OF PRECISION COSMOLOGY

and...



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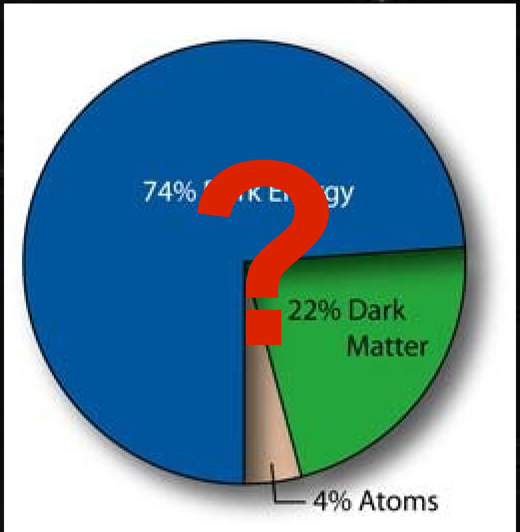

We <u>don't</u> know the nature of

MORE THAN 90% OF THE UNIVERSE!!

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search for dark matter candidates

Components of a flat Universe

in standard cosmology:

- radiation (relic γ and ν) $\rightarrow \Omega_R \sim 10^{-5} << \Omega_m$

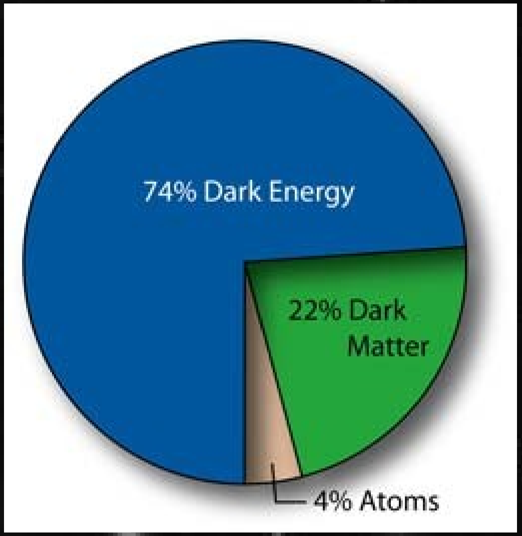
- matter $\rightarrow \Omega_m \approx 0.2\text{-}0.3$

  - 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) $\rightarrow \Omega_\Lambda = 1 - \Omega_m$



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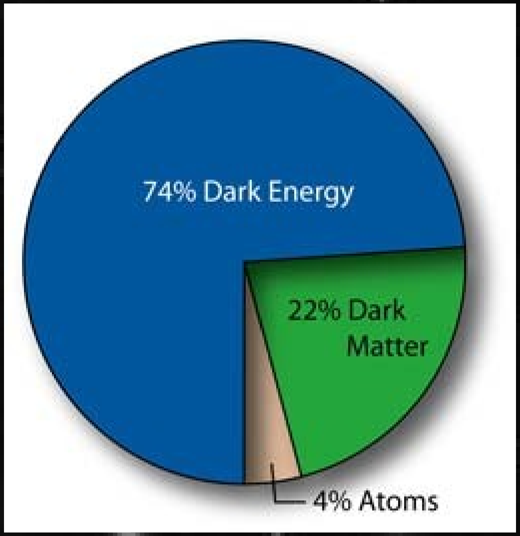

Every dark matter candidate has a **typical signature** in the Universe.

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

What is mirror matter ?

Lee & Yang, *Question of parity conservation in weak interactions*, 1956: “If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry.”

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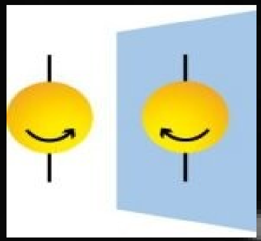

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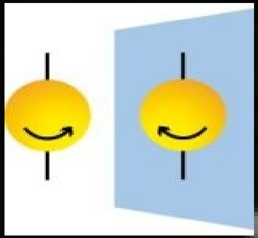

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Theory: product G×G′ of **two sectors with the identical particle contents**. Two sectors **communicate via gravity**. A symmetry P(G→G′), called **mirror parity**, implies that both sectors are described by the same Lagrangians. (Foot,Lew,Volkas,1991)

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

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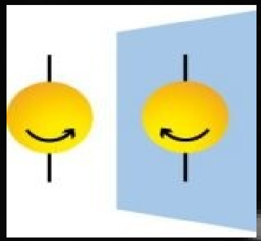

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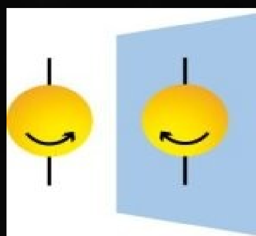

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Until now mirror particles can exist without violating any known experiment ⇒

⇒ we need to compare their astrophysical consequences with observations.

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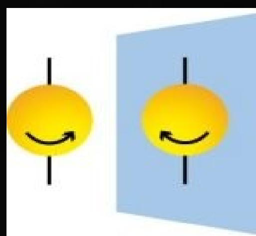

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Their microphysics is the same but… cosmology is not the same !!

Mirror baryons as dark matter

2 mirror parameters

$$x = \left(\frac{s'}{s} \right)^{1/3} \simeq \frac{T'}{T}$$

$$\beta = \frac{\Omega_b'}{\Omega_b}$$

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

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BBN bounds

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

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

Bound on effective number of extra-neutrinos: $\Delta N_\nu \lesssim 1 \Rightarrow x \lesssim 0.64(\Delta N_\nu)^{1/4} \simeq 0.64$

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The primordial abundance of 4He:
evidence for non-standard big bang nucleosynthesis
Y. I. Izotov, T. X. Thuan [arXiv:1001.4440]

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

Effects on neutron stars

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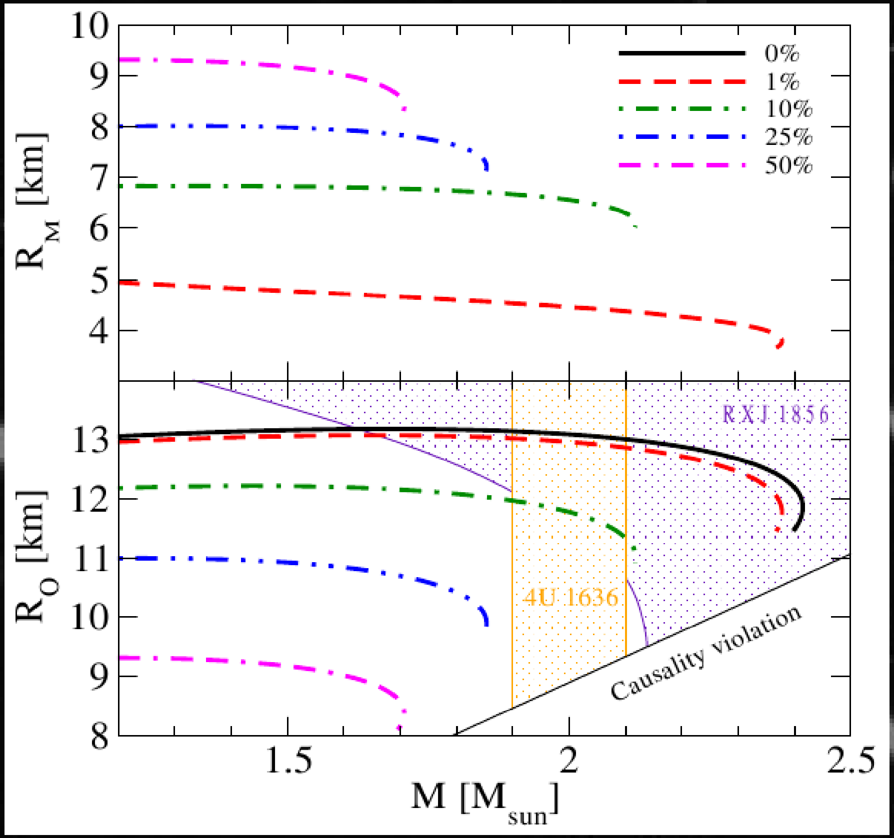

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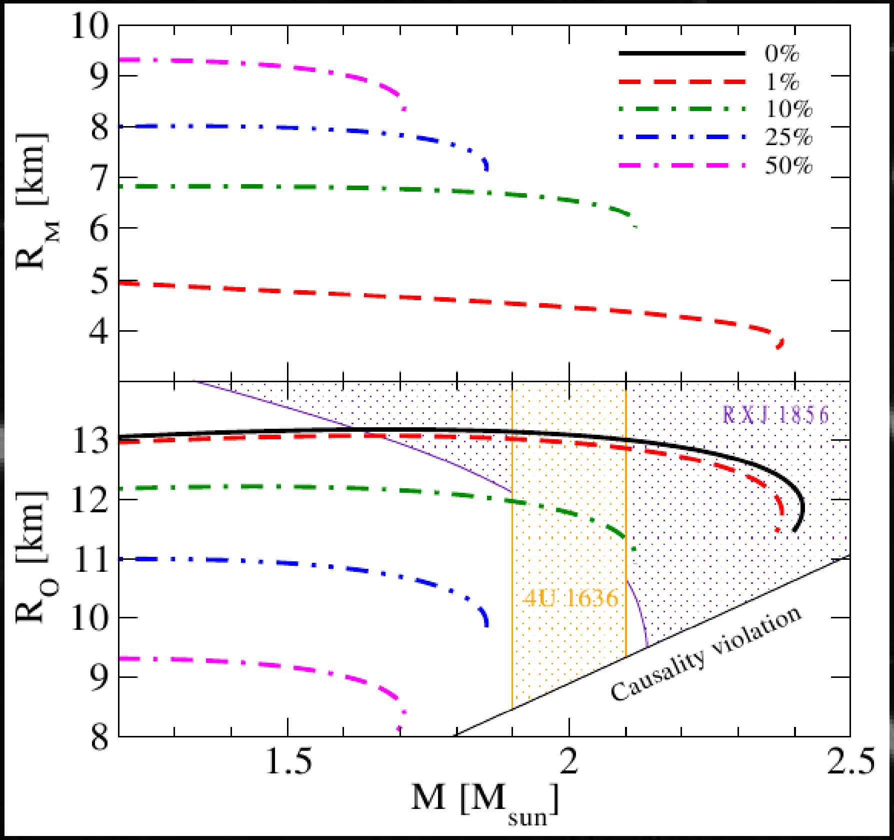

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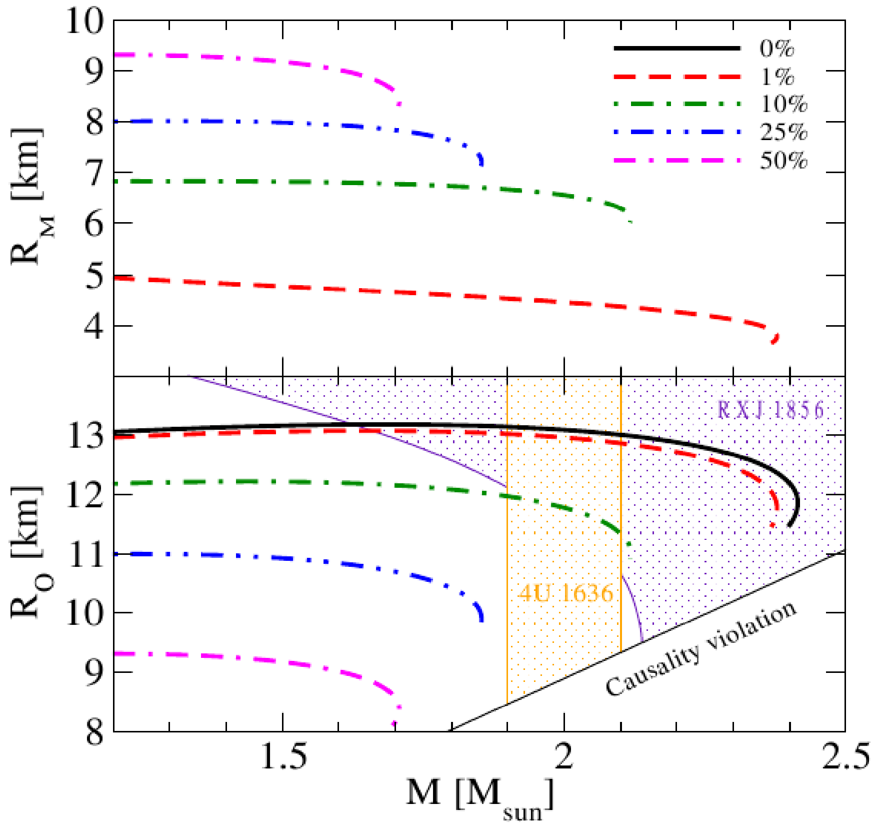

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The NS equilibrium sequence depends on the relative number of mirror baryons to ordinary baryons, i.e., it is ***history dependent***.

In contrast to the mass–radius relation of ordinary NS, it is not a one-parameter sequence:

non-uniqueness of the equilibrium sequence!

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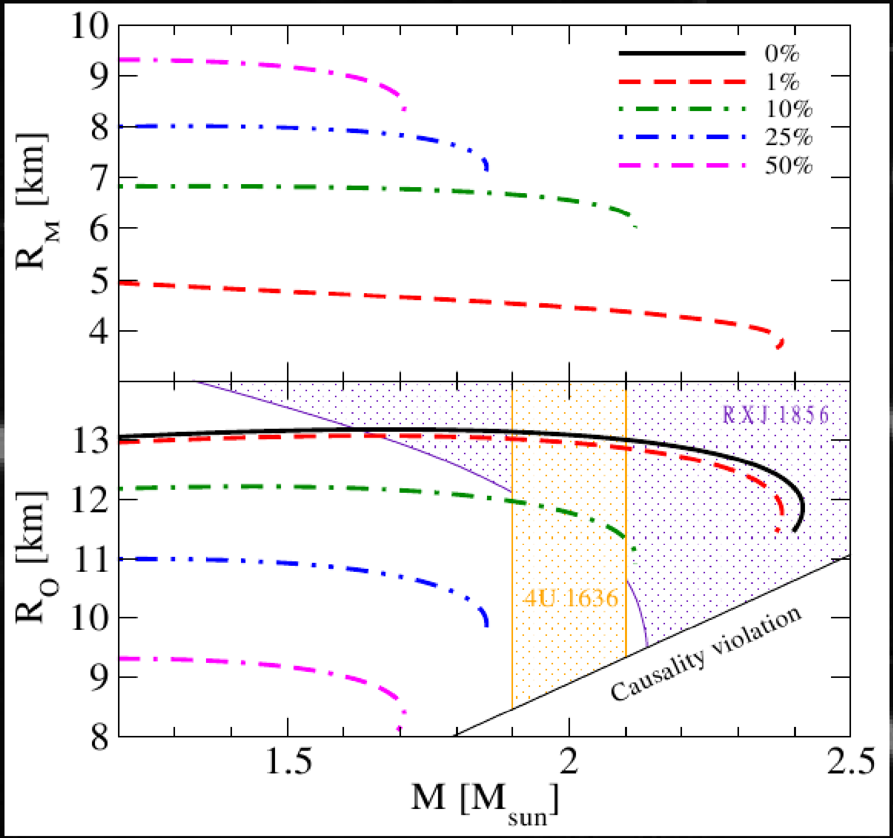
Key point: since mirror baryons are stable dark matter particles, they can accumulate into stars.



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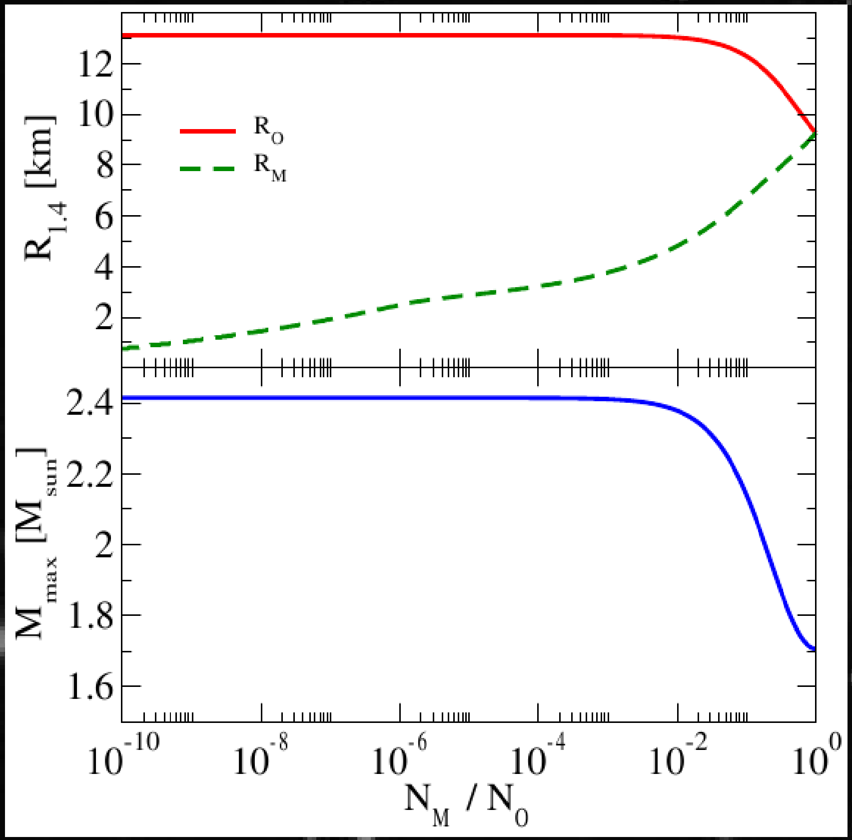
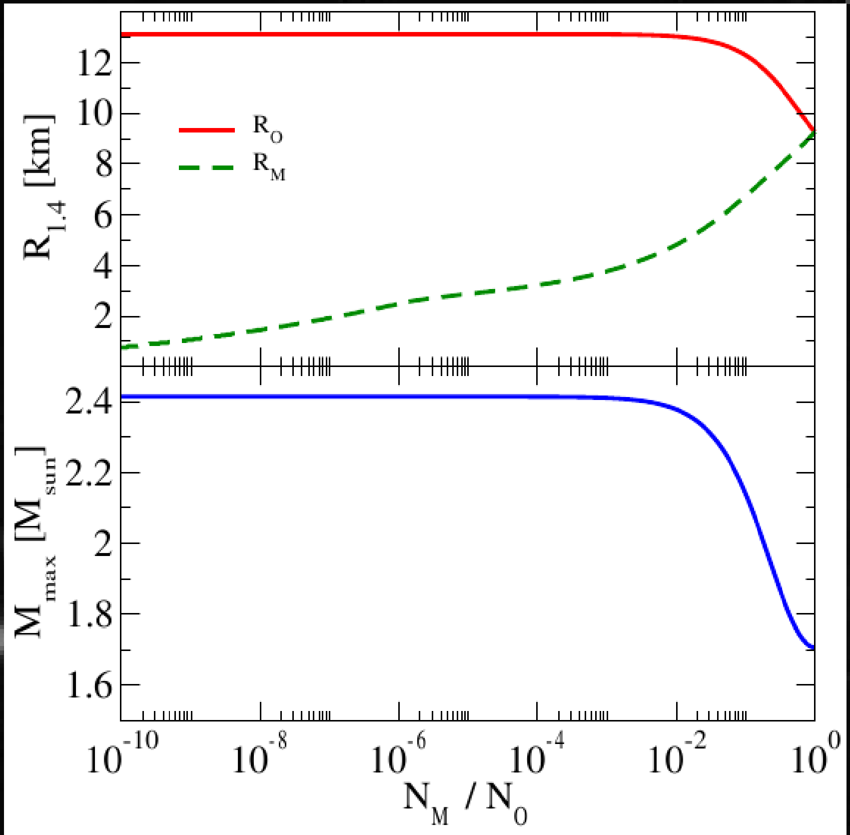


Effects on neutron stars

The distribution of mirror DM in galaxies is expected to be *non-homogeneous*, because mirror baryons should form complex structures in a similar way as ordinary baryons do.



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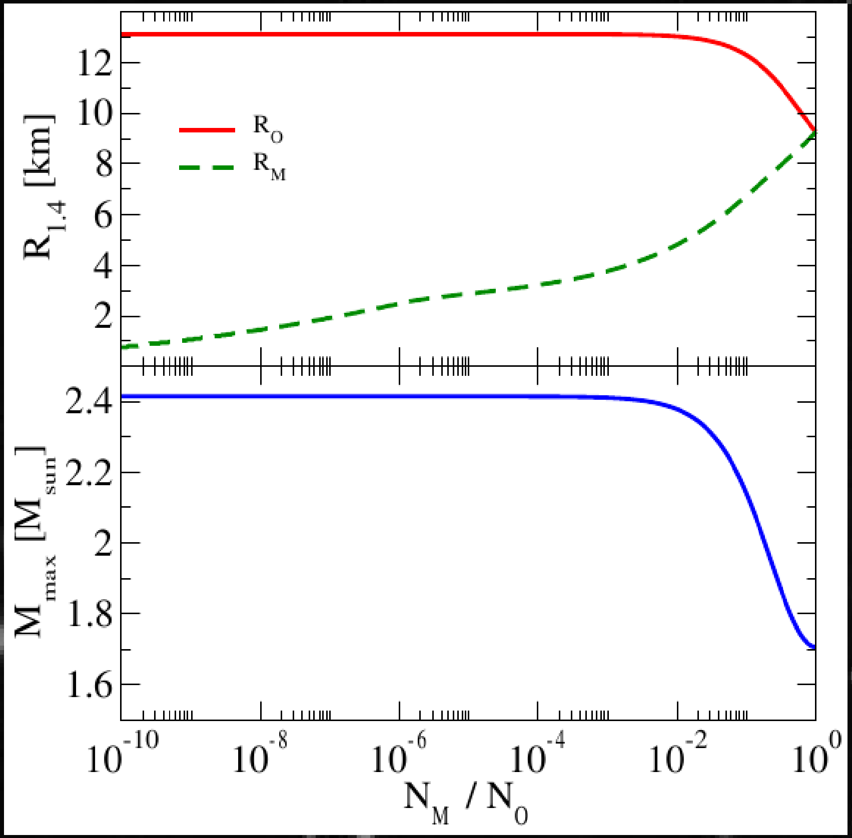

Besides the mirror matter already present at star formation, three possibilities for its capture by an ordinary NS (or the opposite):

- accretion of particles from the homogeneous mirror interstellar medium;
- enhanced accretion rate if a NS passes through a high-density region of space, e.g., a mirror molecular cloud or planetary nebula;
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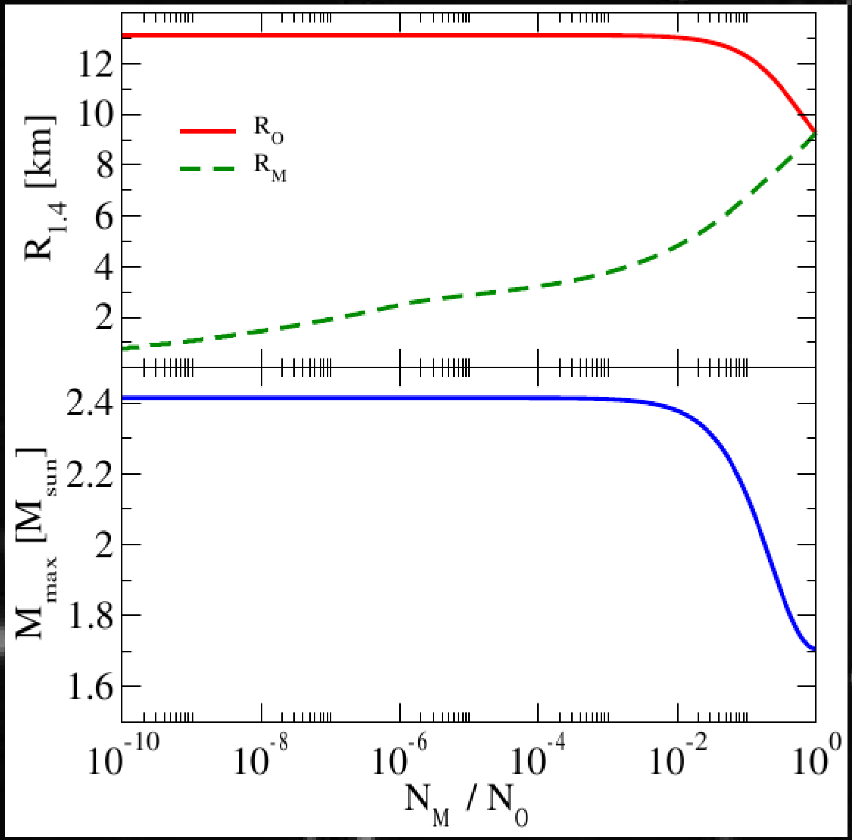

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The mass and radius are independent of the present DM accretion on the star, but depend on the whole DM capture process integrated over the stellar lifetime, i.e., ***the effects of mirror matter should depend on the location and history of each star.***

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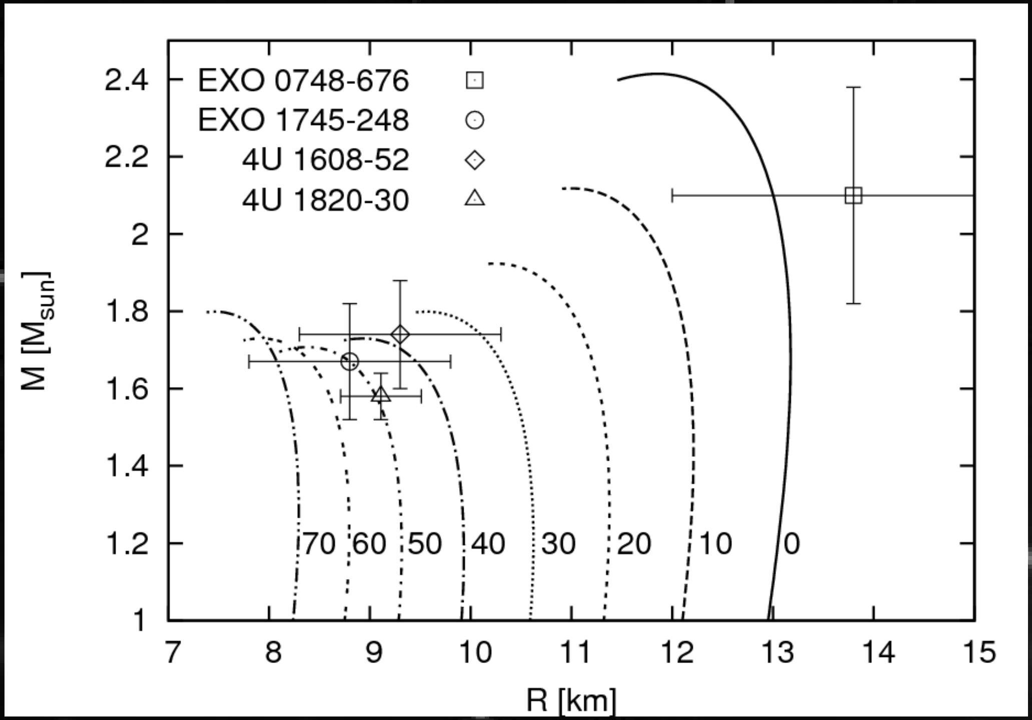

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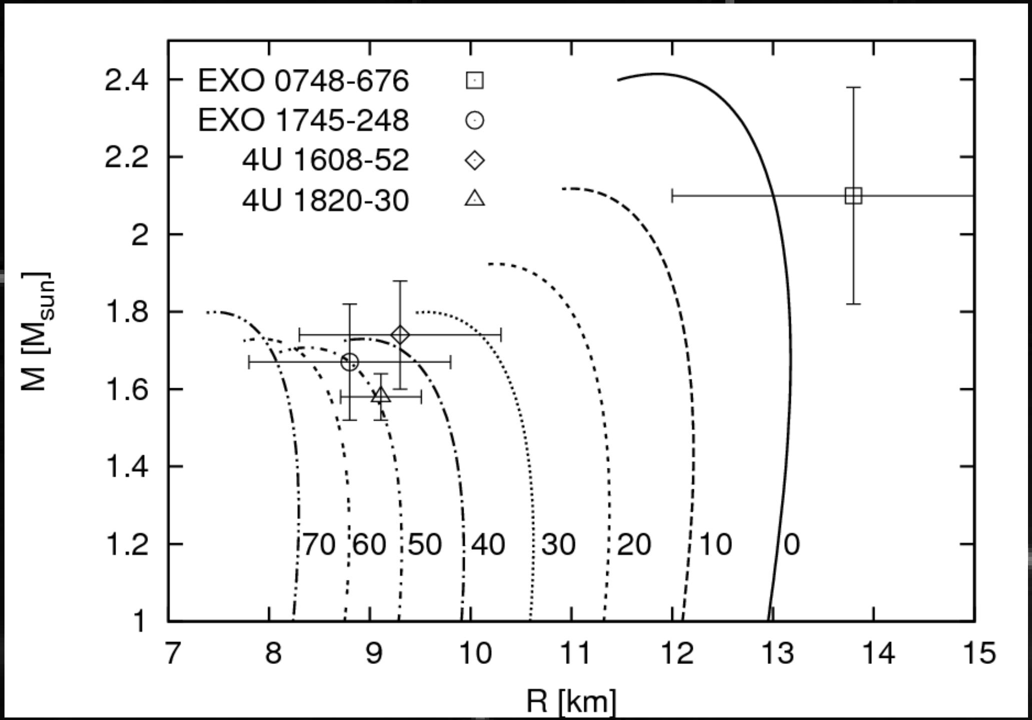

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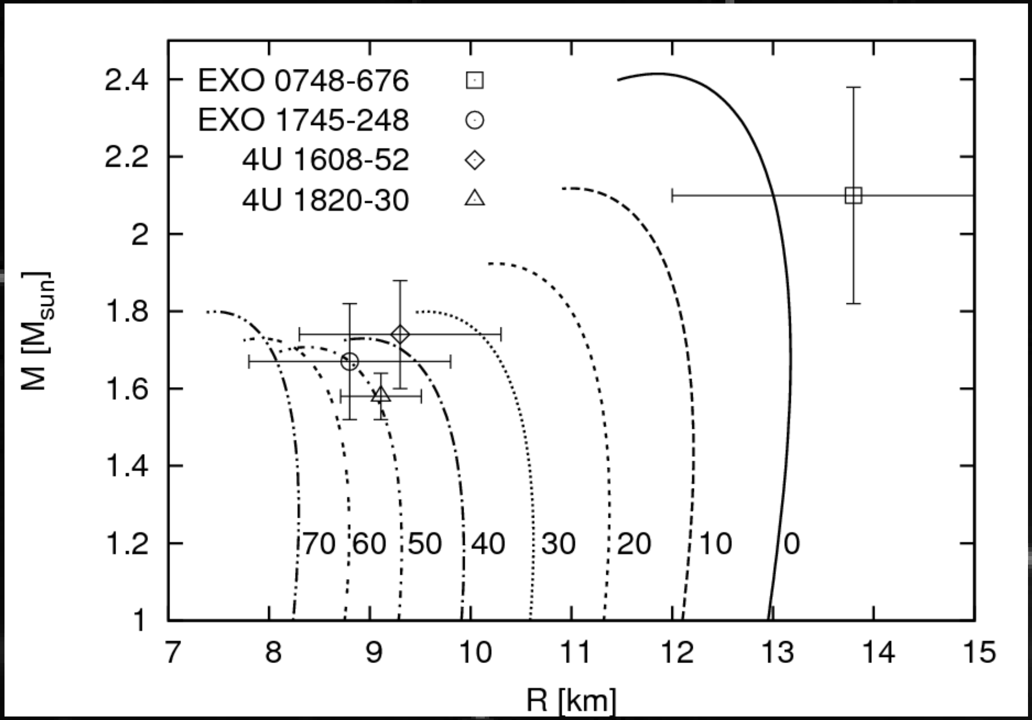

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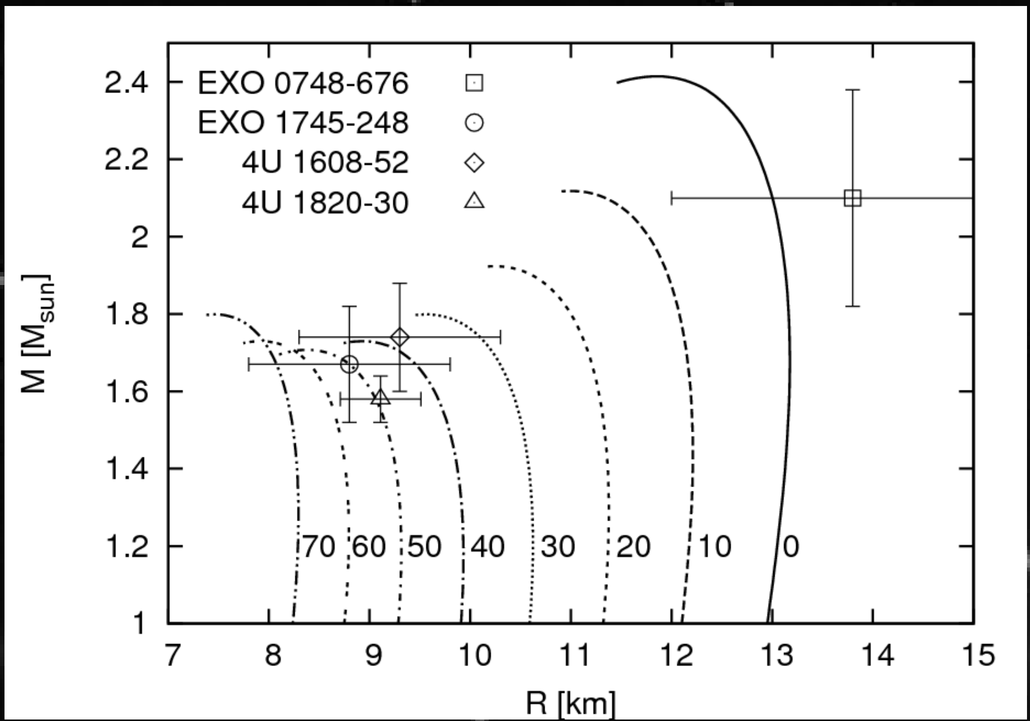

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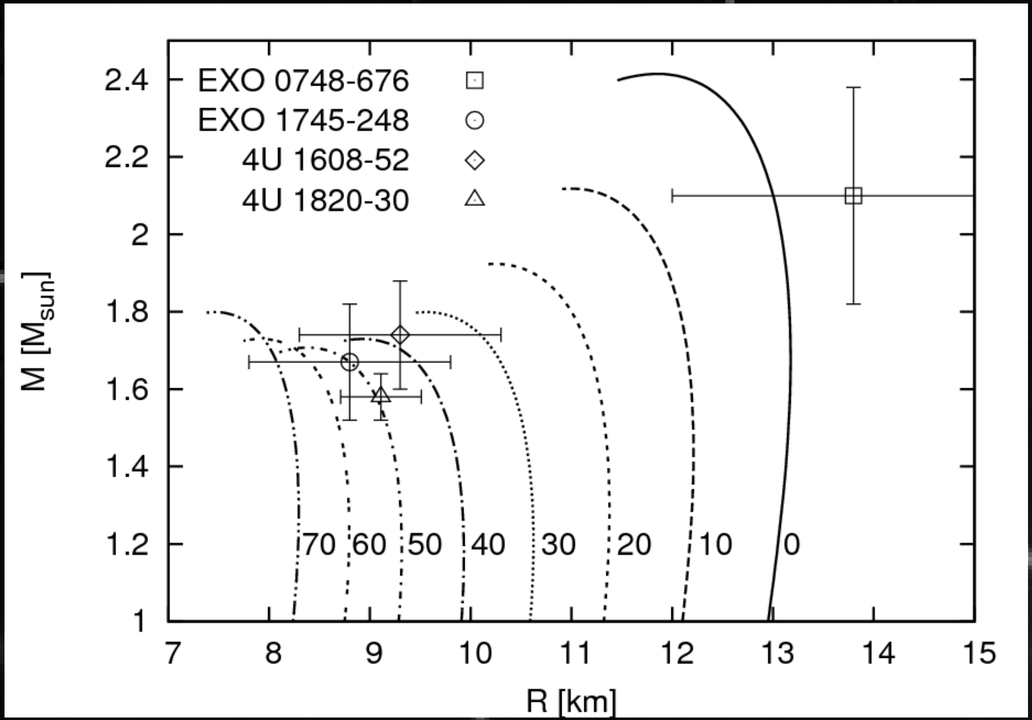

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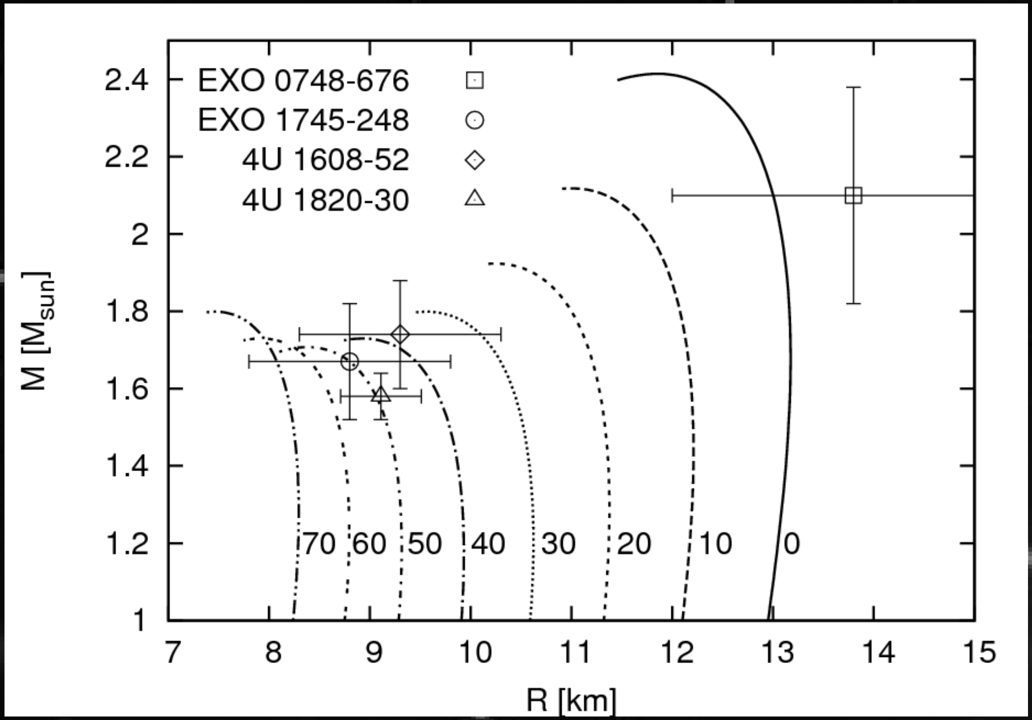

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With the estimated density for galactic DM, either the DM is present already during the star formation process, or the density distribution of DM is highly non-homogeneous, with events like mergers with compact astrophysical objects with stellar sizes made of DM.

Thermodynamics

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

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***x* free parameter**

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

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

Thermodynamics

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

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

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

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

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the contribution of the mirror species is negligible in view of the BBN constraint!
while the ordinary particles are crucial on the thermodynamics of the M ones!

Degrees of freedom in a Mirror Universe

During the expansion of the Universe:

- the two sectors evolve with separately conserved entropies;
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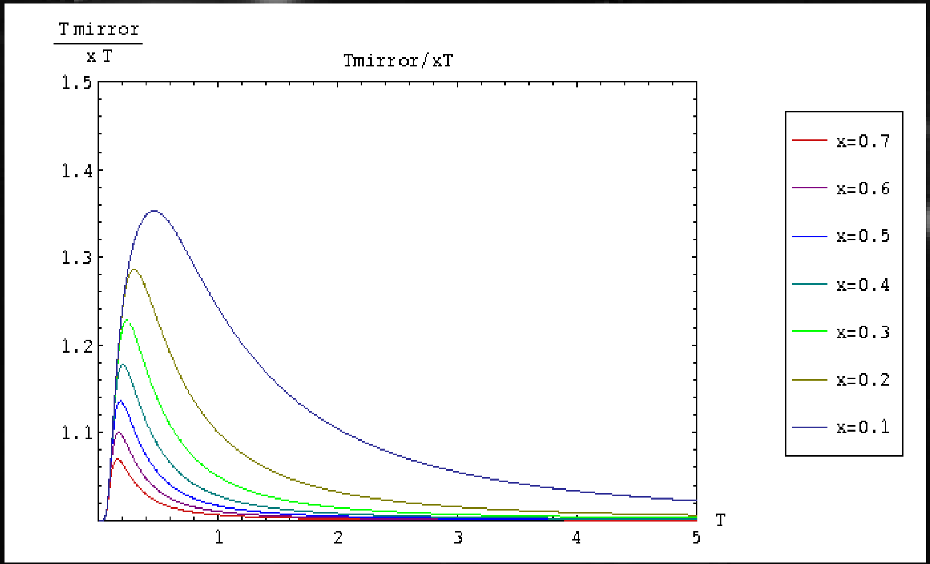

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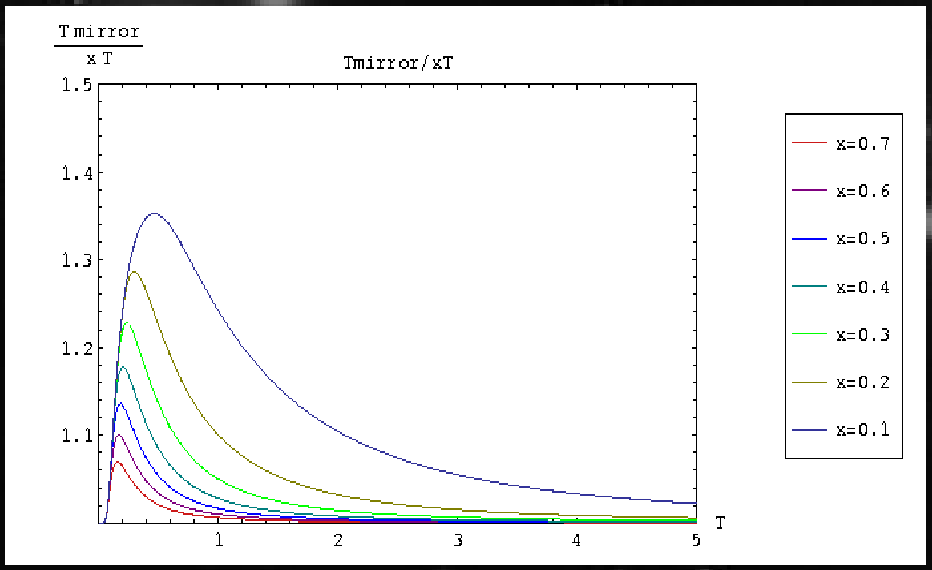

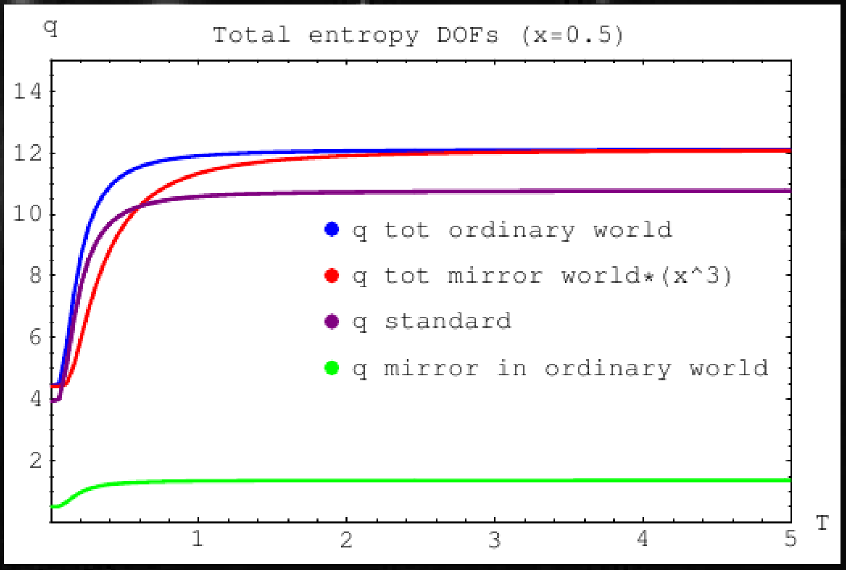

e^+-e^- annihilation epoch changes according with *x*

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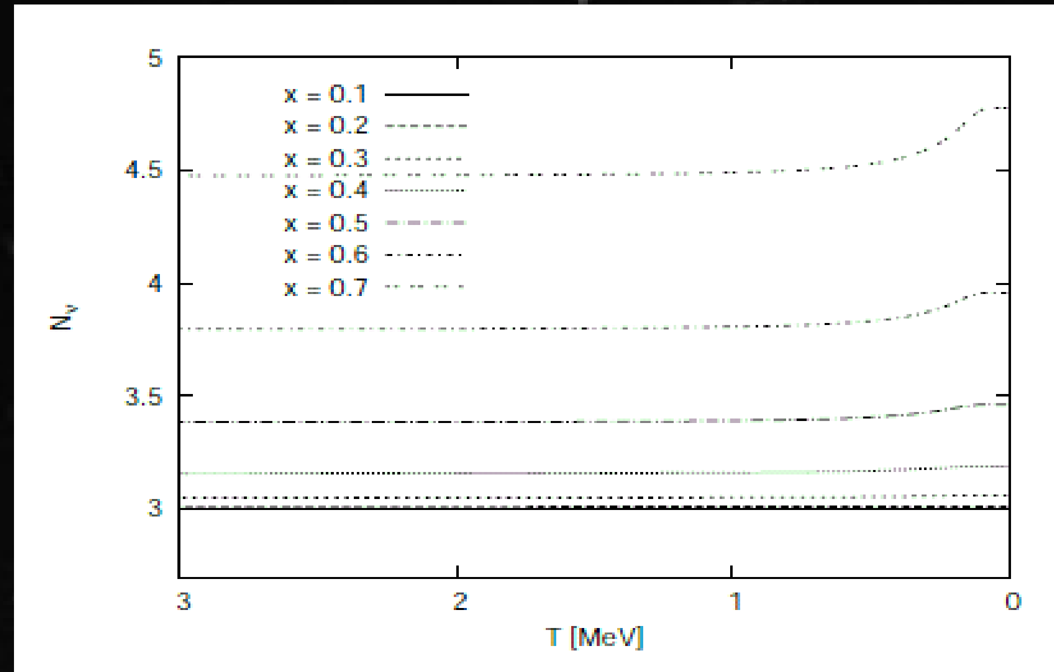

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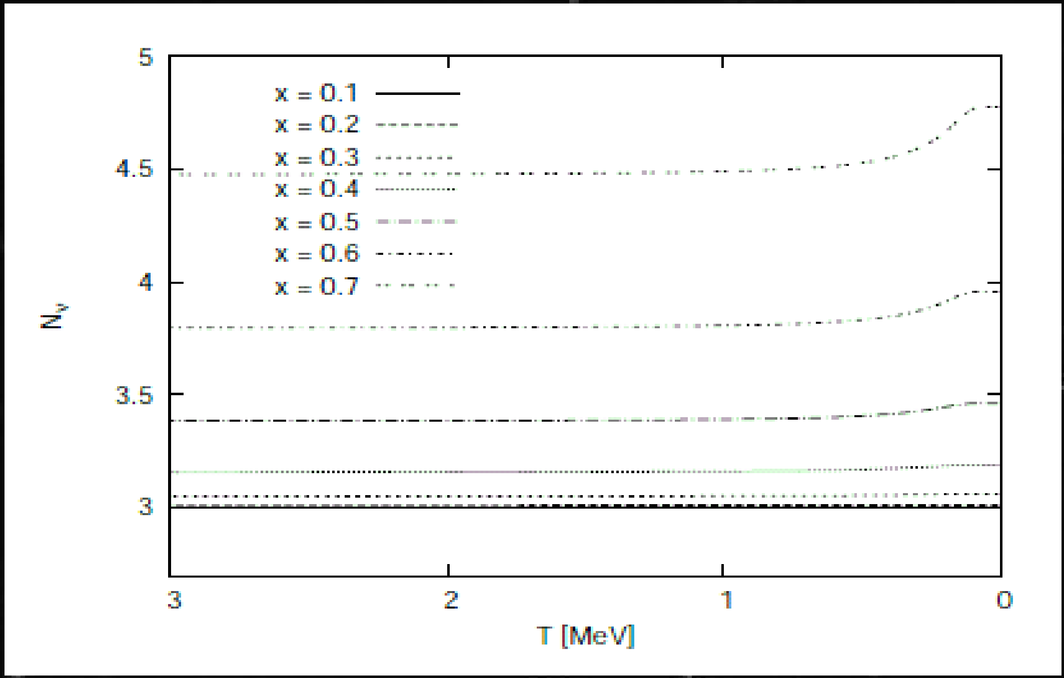

Mangano et al. (astro-ph/0612150) show some tension between degrees of freedom at different epochs.

standard model:	$N_\nu^{eff} = 3.046$
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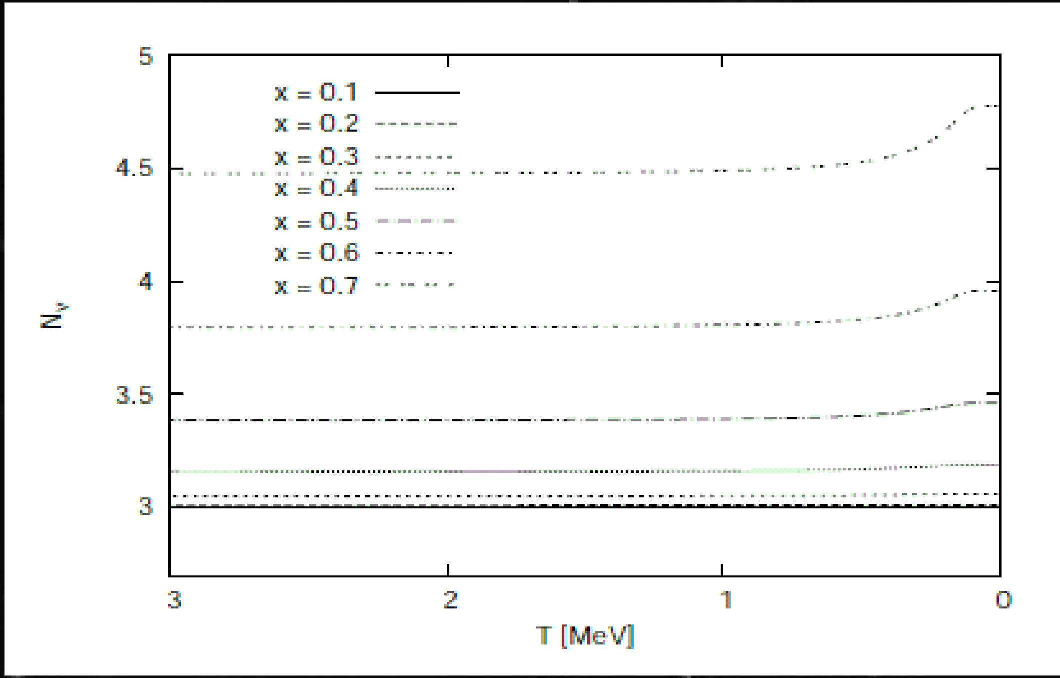

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Mirror matter naturally predicts different degrees of freedom at BBN (1 MeV) and recombination (1 eV) epochs!

$$N_\nu(T \ll T_{ann\, e^\pm}) - N_\nu(T \gg T_{D\nu}) = x^4 \cdot \frac{1}{\frac{7}{8} \cdot 2}\left[10.75 - 3.36\left(\frac{11}{4}\right)^{\frac{4}{3}}\right] \simeq 1.25 \cdot x^4$$

Big Bang nucleosynthesis

2 fundamental parameters:

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

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$D/H\,(10^{-5})$	2.554	2.555	2.575	2.709	3.144
$^3He/H\,(10^{-5})$	1.038	1.038	1.041	1.058	1.113
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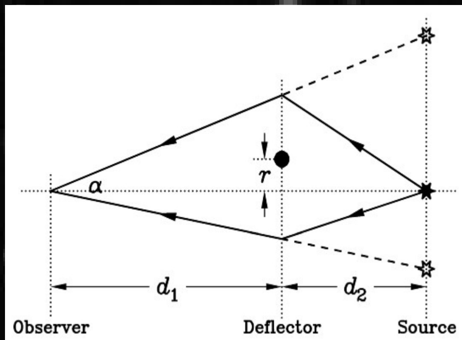
Mirror sector is a He-world!

Mirror dark stars (evolution)



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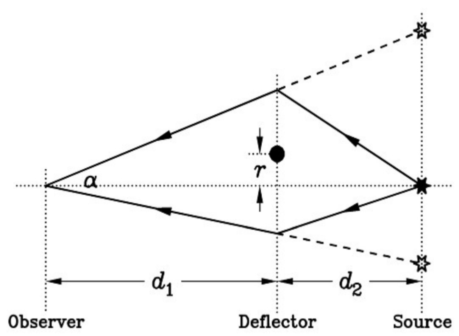

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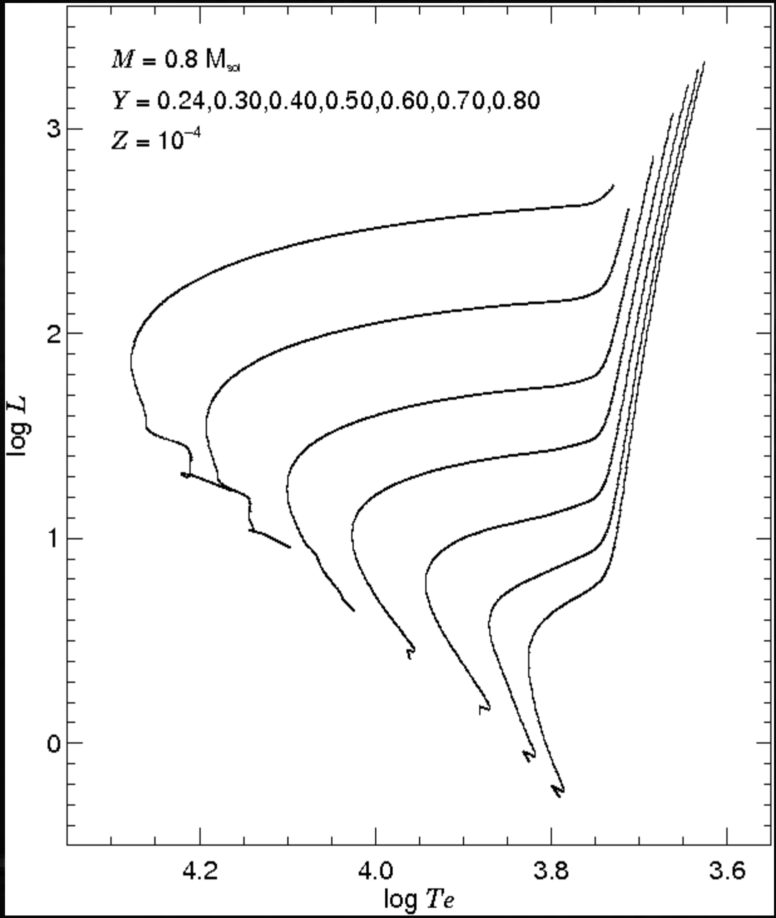
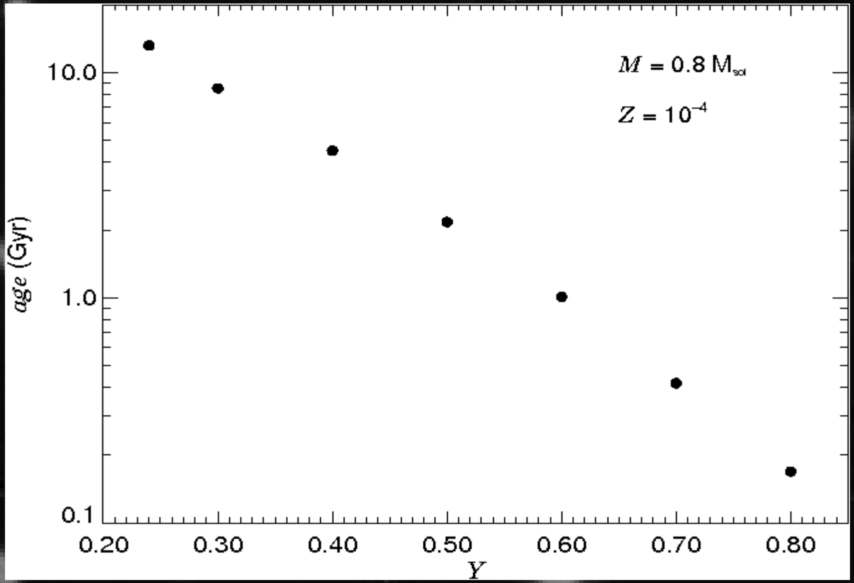
$$L \propto \mu^{7.5} M^{5.5} \qquad T_e^4 \propto \mu^{7.5} \qquad t_{MS} \propto \frac{X}{\mu^{1.4}}$$





faster evolutionary times!

Photon-mirror photon kinetic mixing and DAMA experiment

Besides gravity, mirror particles could interact with the ordinary ones via renormalizable ***photon-mirror photon kinetic mixing***, that enables mirror charged particles to couple to ordinary photons with charge εe.

$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

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This scenario requires that:

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Mirror baryons should constitute the dark halos of galaxies, primarily made of primordial He'. The high He' abundance induces fast stellar formation and evolution, that produce heavier nuclei, as O', ejected in SN explosions.

$\Rightarrow$ The dark halo is mainly constituted of He' and O'.

BBN with photon-mirror photon kinetic mixing

Assuming an effective initial condition T' << T, this mixing can populate the mirror sector in the early Universe, via the process $e^+e^- \to e^{+\prime}e^{-\prime}$, implying a generation of energy density in the mirror sector:

$$\frac{d\rho'}{dt}|_{generation} = \frac{dn_{e'}}{dt}\langle E\rangle \simeq 2\, n_{e^+}\sigma n_{e^-} \cdot 3.15\ T$$

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$$B = 0.74 \cdot 10^{15}\ \mathrm{MeV}$$

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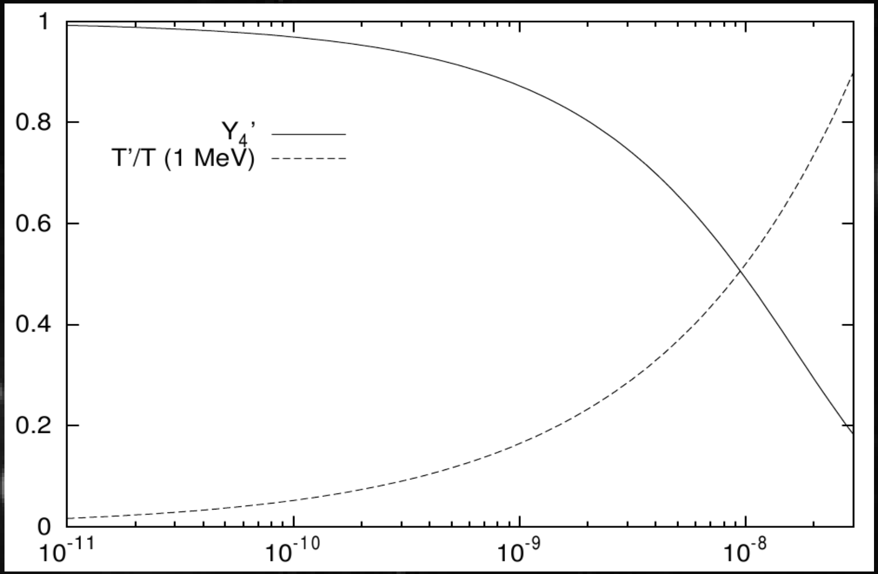

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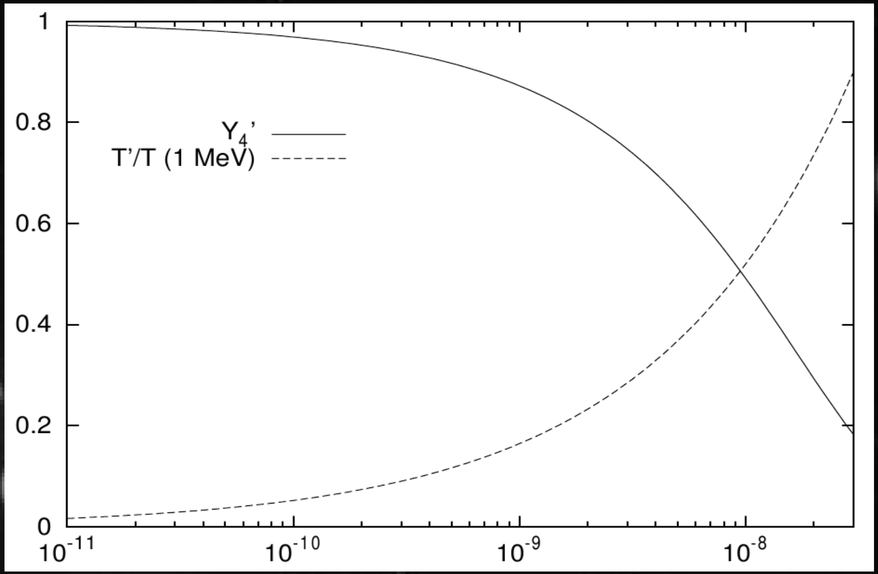

Constraint from ordinary BBN: $\delta N_\nu \leq 0.5 \Rightarrow$ T'/T < 0.6.

More stringent constraint from CMB and LSS: T'/T ≤ 0.3 ⇒ $\varepsilon \leq 3\ 10^{-9}$.

The photon-mirror photon mixing necessary to interpret dark matter detection experiments is consistent with constraints from ordinary BBN as well as the more stringent constraints from CMB and LSS.

A more accurate model

Using a more accurate model for energy transfer from ordinary to mirror sector, the generation of energy density in the mirror sector is: $\frac{\partial \rho'}{\partial t} = n_{e^+} n_{e^-} \langle \sigma v_{M\o l} \mathcal{E} \rangle$

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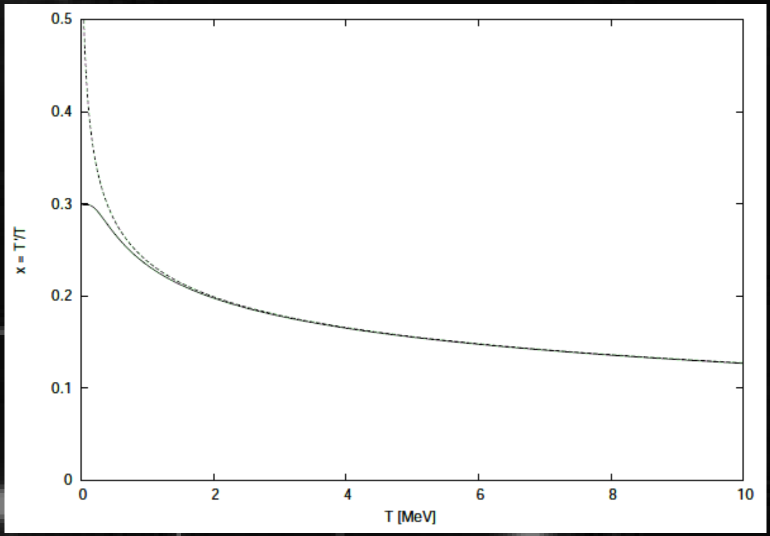

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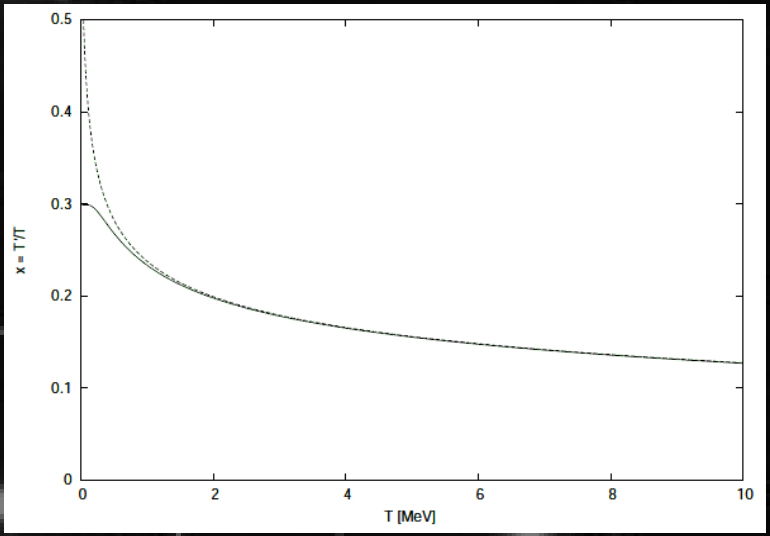

Mirror sector starts with T' much lower than T, and later the photon–mirror photon kinetic mixing increases only the temperature of mirror electron-positrons and photons, since neutrinos are decoupled.

$T_{\nu'} \ll T'$ $\quad T' = T_{\gamma'} \simeq T_{e'}$

$p' + e'^- \longrightarrow n' + \nu'$ $\quad n' + e'^+ \longrightarrow p' + \bar{\nu}'$

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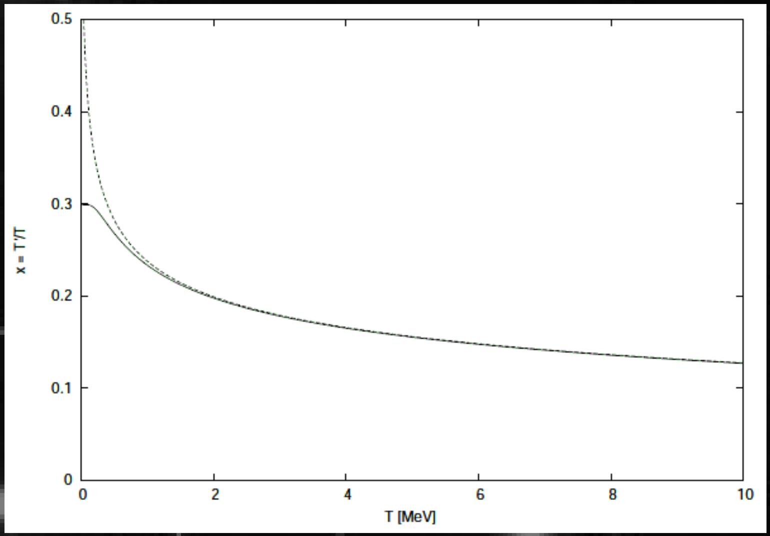

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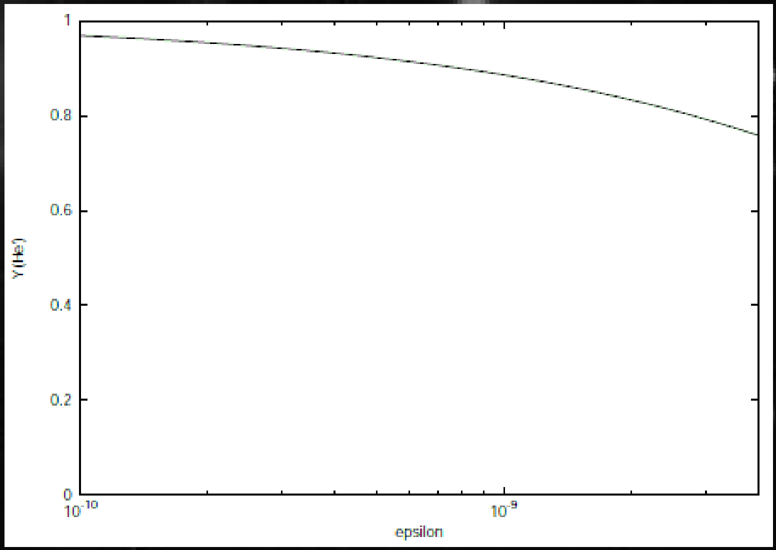
$$Y' \gtrsim 0.8 \text{ for } \epsilon \lesssim 3 \times 10^{-9}$$



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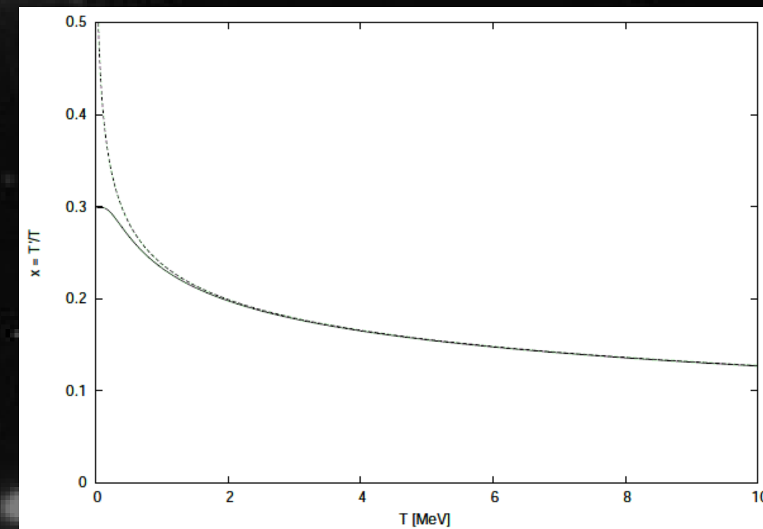
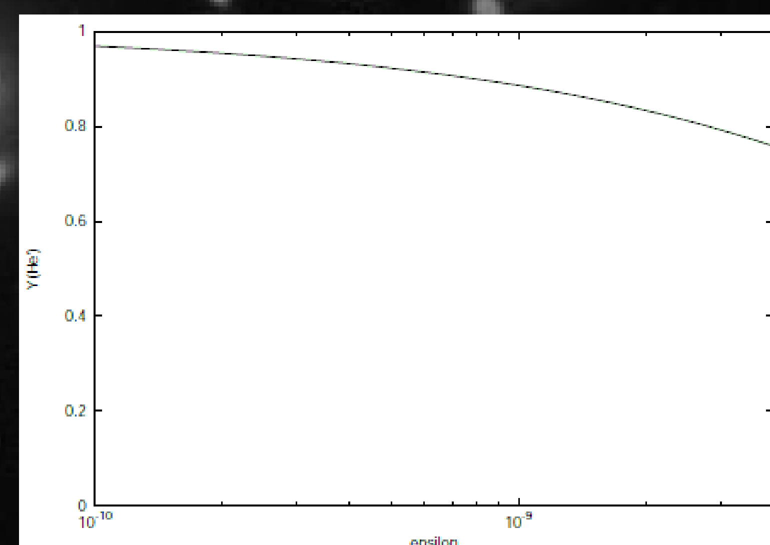


Mirror sector starts with T' much lower than T, and later the photon–mirror photon kinetic mixing increases only the temperature of mirror electron-positrons and photons, since neutrinos are decoupled.

$T_{\nu'} \ll T'$ $\quad T' = T_{\gamma'} \simeq T_{e'}$

$p' + e'^{-} \rightarrow n' + \nu'$ $\quad n' + e'^{+} \rightarrow p' + \bar{\nu}'$

$$\frac{dX_{n'}}{dt} = \lambda_{p' \to n'} (1 - X_{n'}) - \lambda_{n' \to p'} X_{n'}$$



Mirror nucleosynthesis is so fast that we may neglect neutron decay: $Y' \simeq 2X_{n'}$

$$Y' \gtrsim 0.8 \text{ for } \epsilon \lesssim 3 \times 10^{-9}$$

$${}^4He' + {}^4He' + {}^4He' \rightarrow {}^{12}C' + \gamma'$$

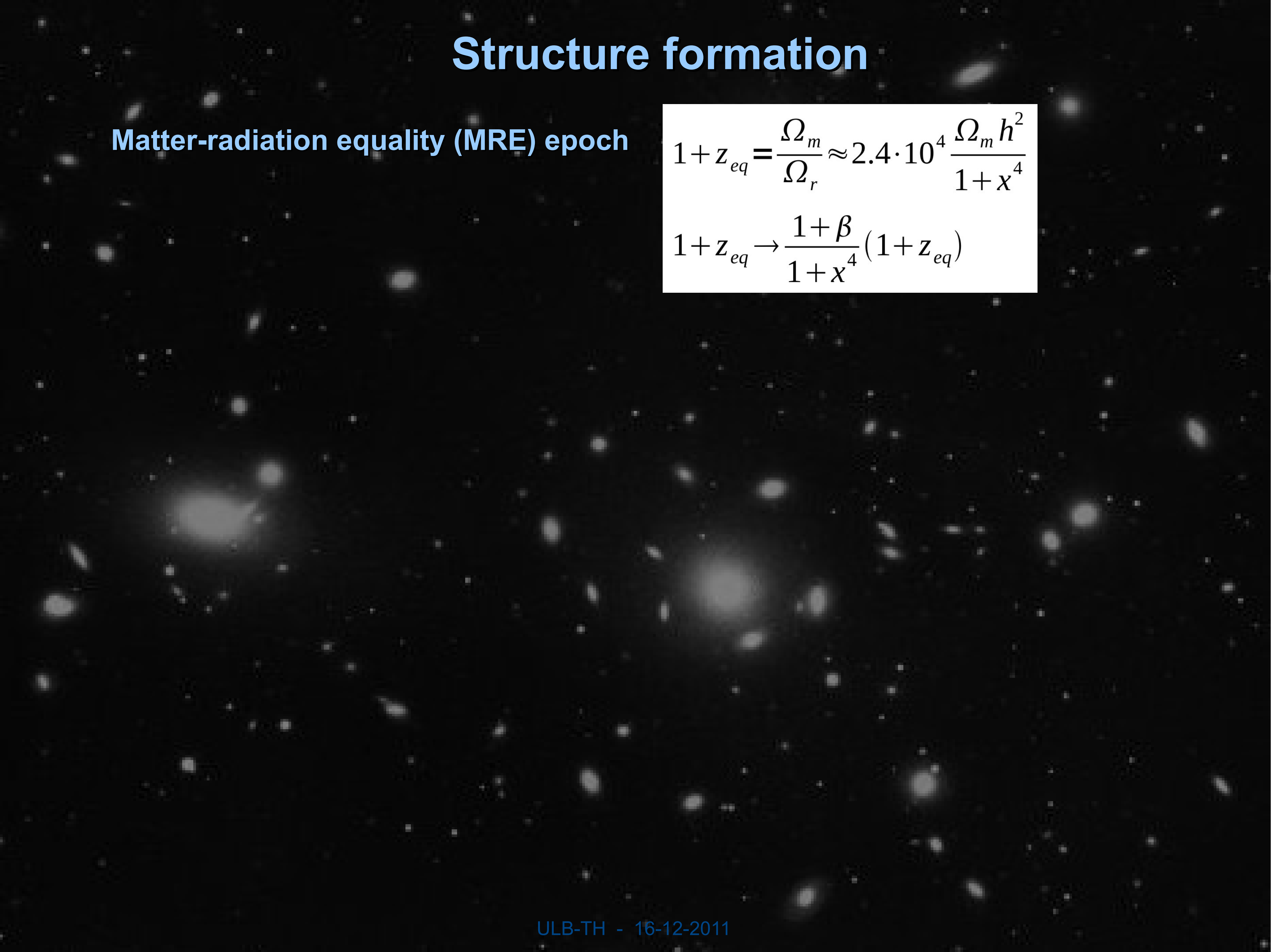
$$X_{C'} < 10^{-8}$$

Structure formation

Matter-radiation equality (MRE) epoch

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

$$1+z_{eq}\rightarrow\frac{1+\beta}{1+x^4}\left(1+z_{eq}\right)$$



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Baryon-photon decoupling (MRD) epoch

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

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

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 crucial differences at smaller scales which already went non-linear).

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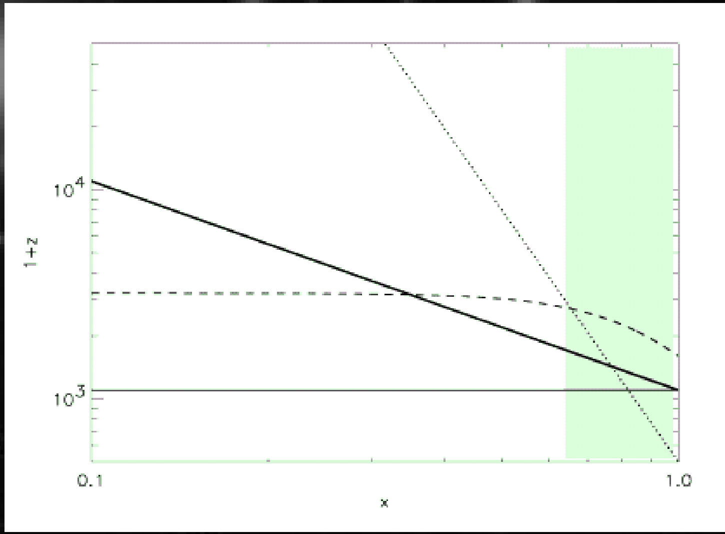


The Jeans mass

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

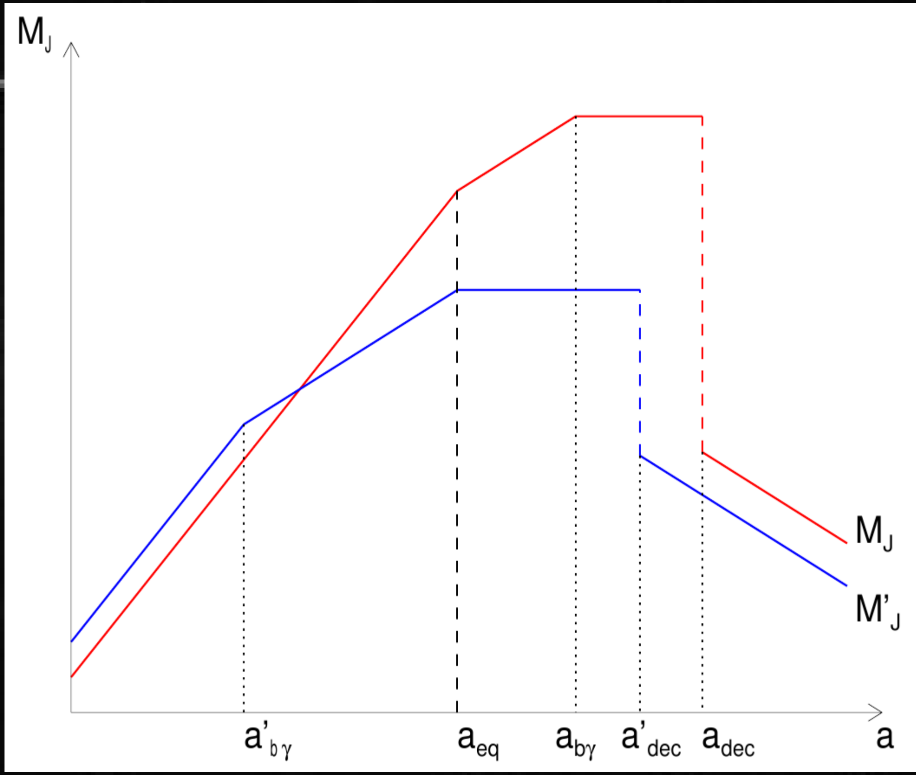
$$M_J'(a_{dec}') = 3.2\cdot 10^{14} M_\odot \beta^{-1/2}(1+\beta)^{-3/2}\left(\frac{x^4}{1+x^4}\right)^{3/2}(\Omega_b h^2)^{-2}$$

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

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

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

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



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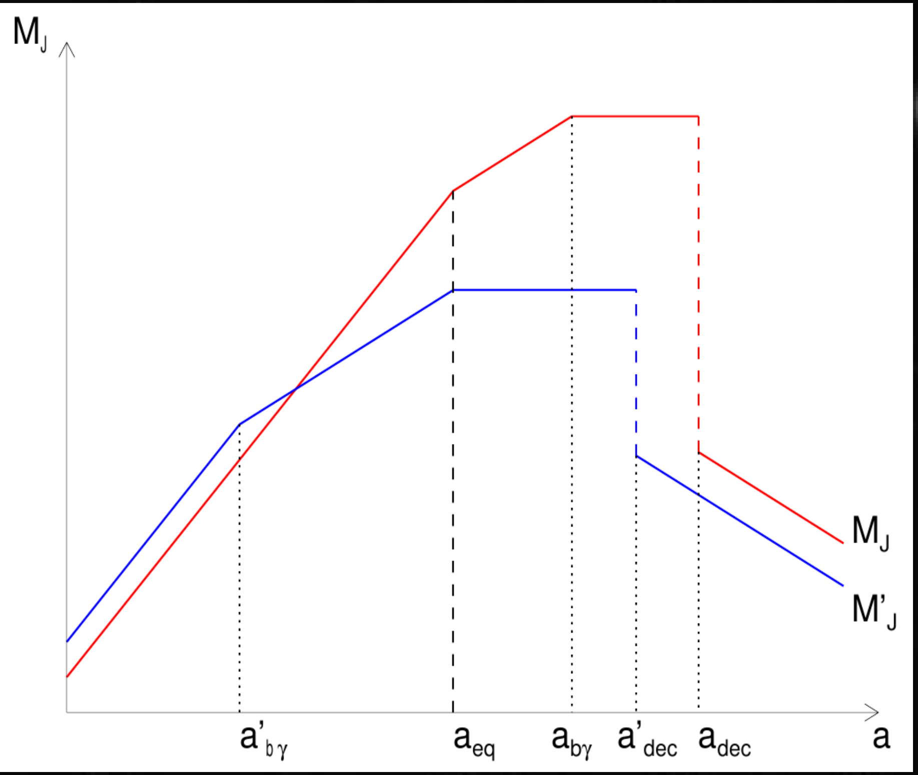

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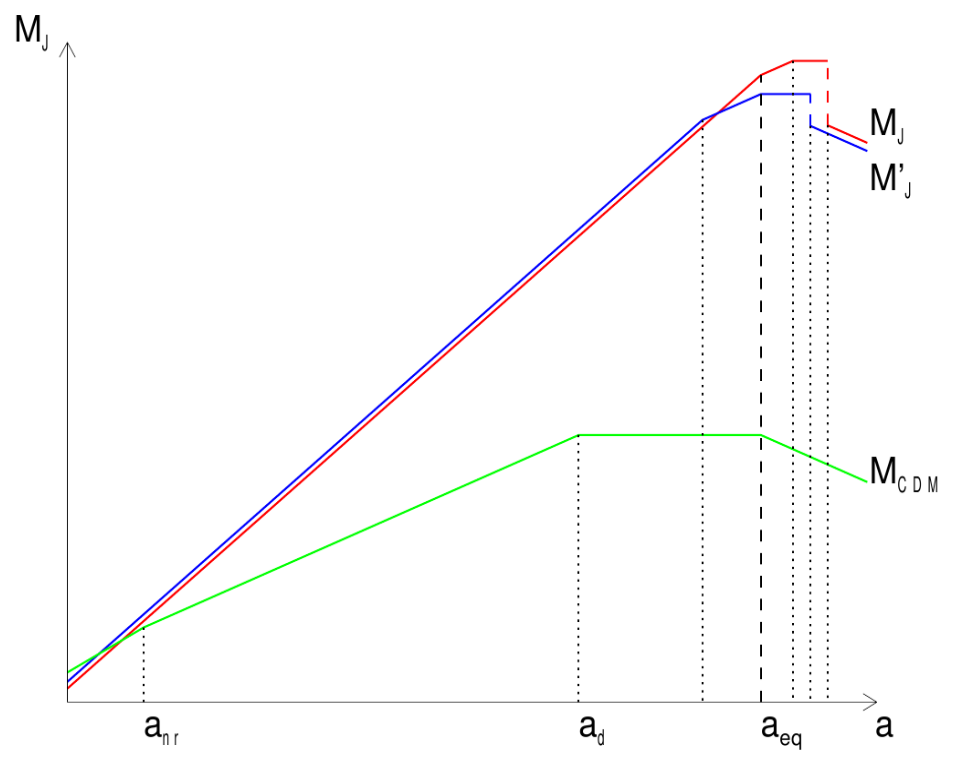


Dissipative effects

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**'**.

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

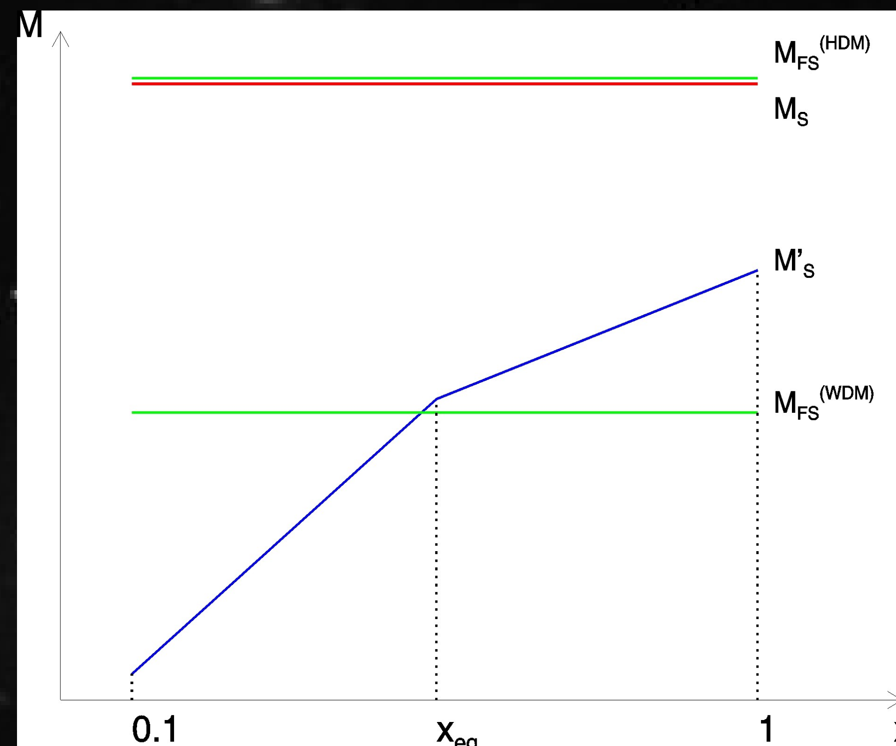
$$\Omega_b h^2 = 0.02 \quad \Rightarrow \quad M_S \approx 8 \cdot 10^{14} M_\odot$$

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

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

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

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



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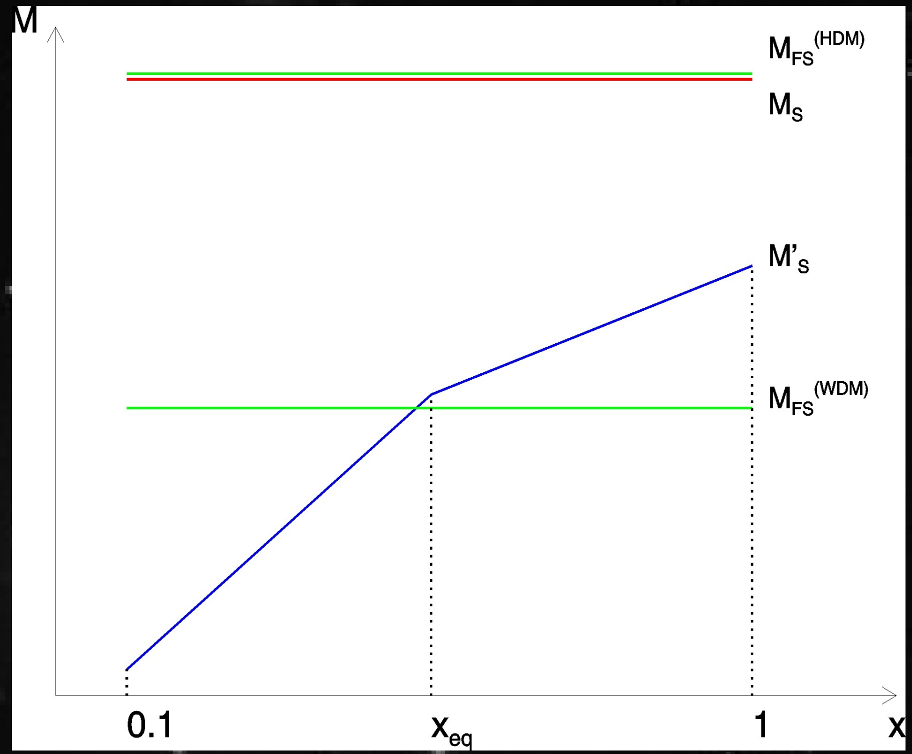


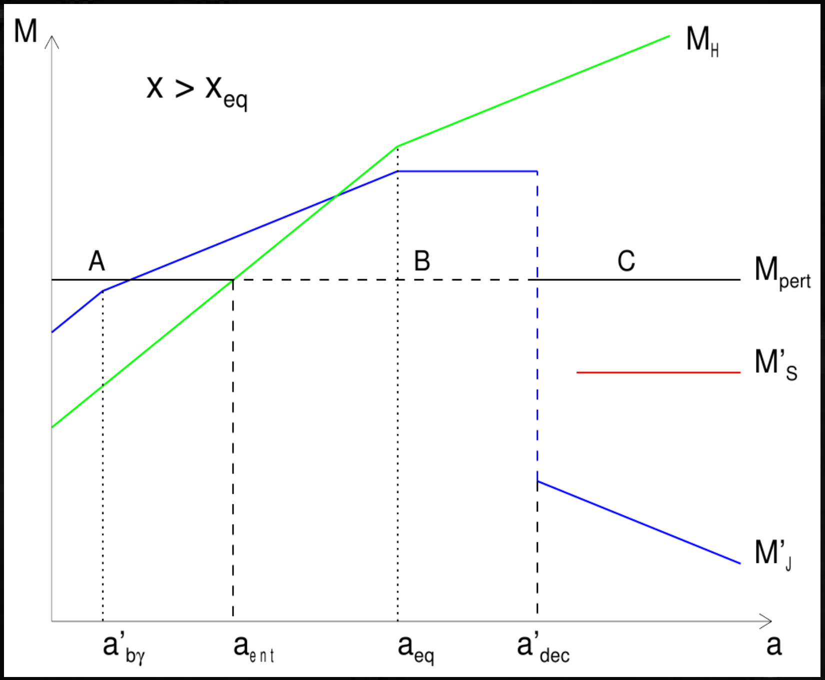
Differences with the WDM free streaming damping:

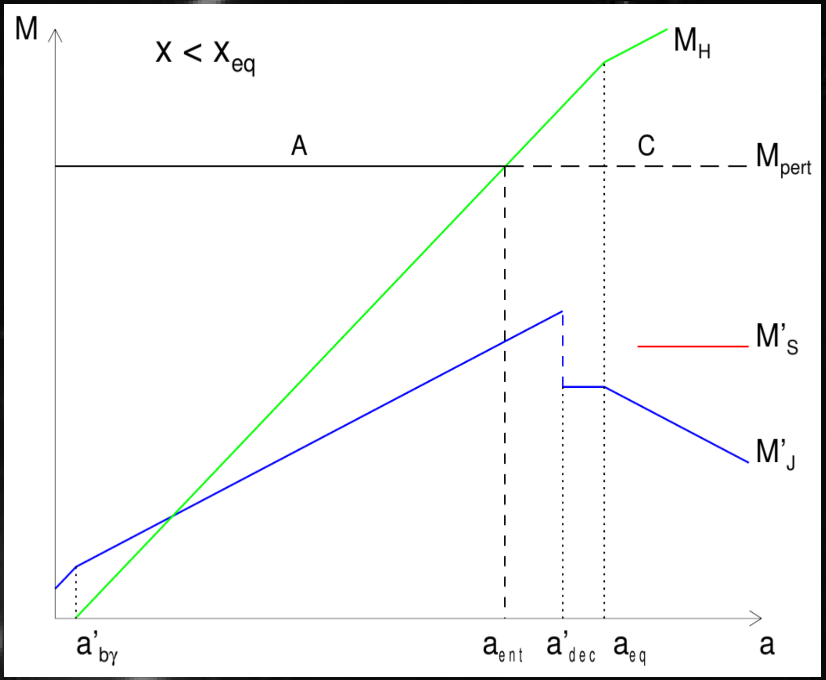
- the M baryons should show **acoustic oscillations in the LSS power spectrum**;
- such oscillations, transmitted via gravity to the O baryons, could cause observable **anomalies in the CMB power spectrum**.

Scenarios

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

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





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

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

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

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

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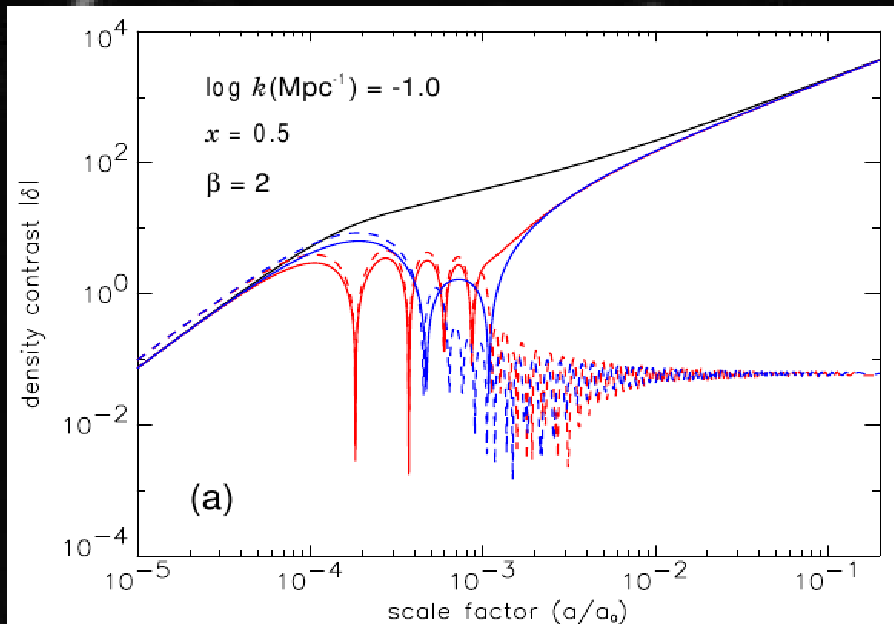
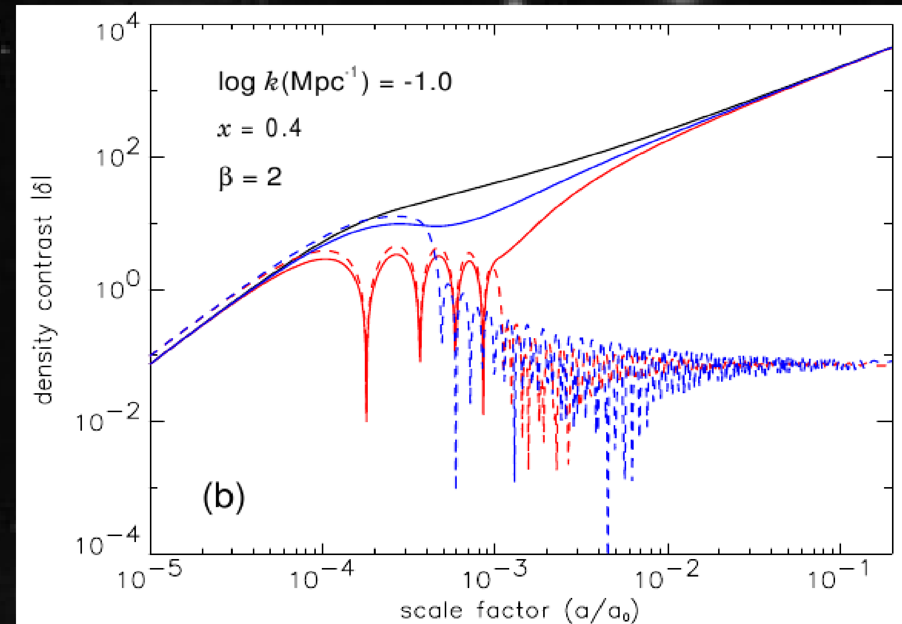
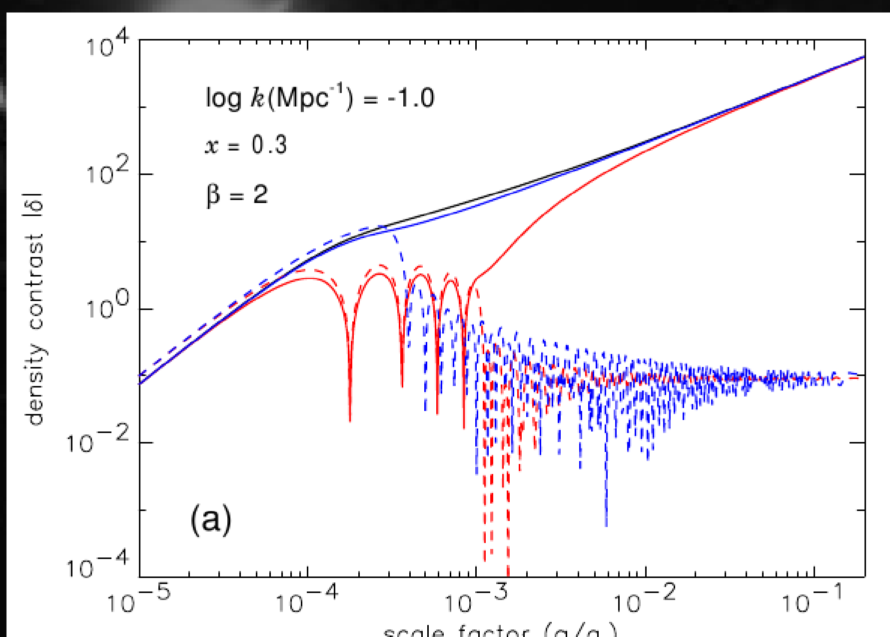
Temporal evolution of perturbations

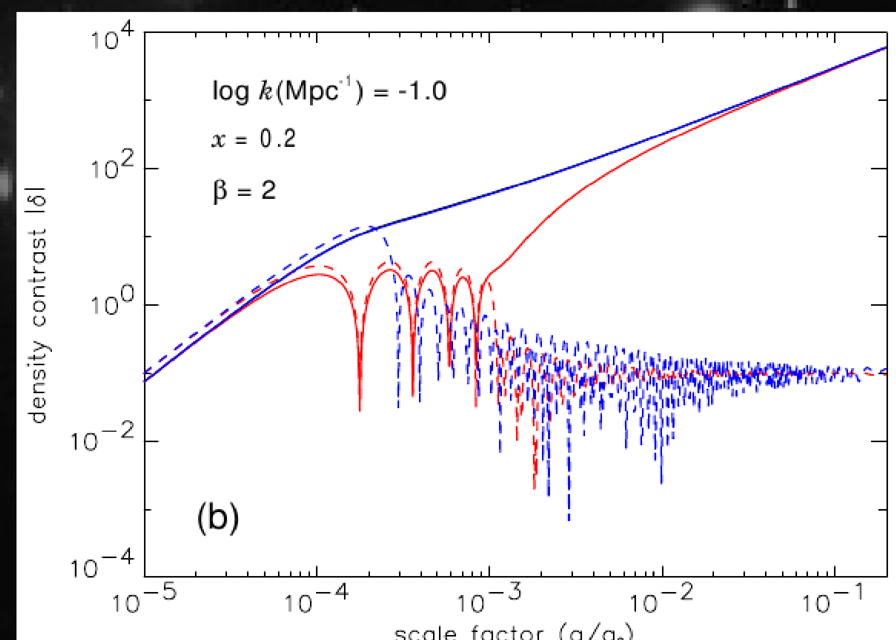
($\Omega_0 = 1$, $\Omega_m = 0.3$, $\omega_b = 0.02$, h = 0.7 ; $\lambda \approx 60$ Mpc)

x dependence









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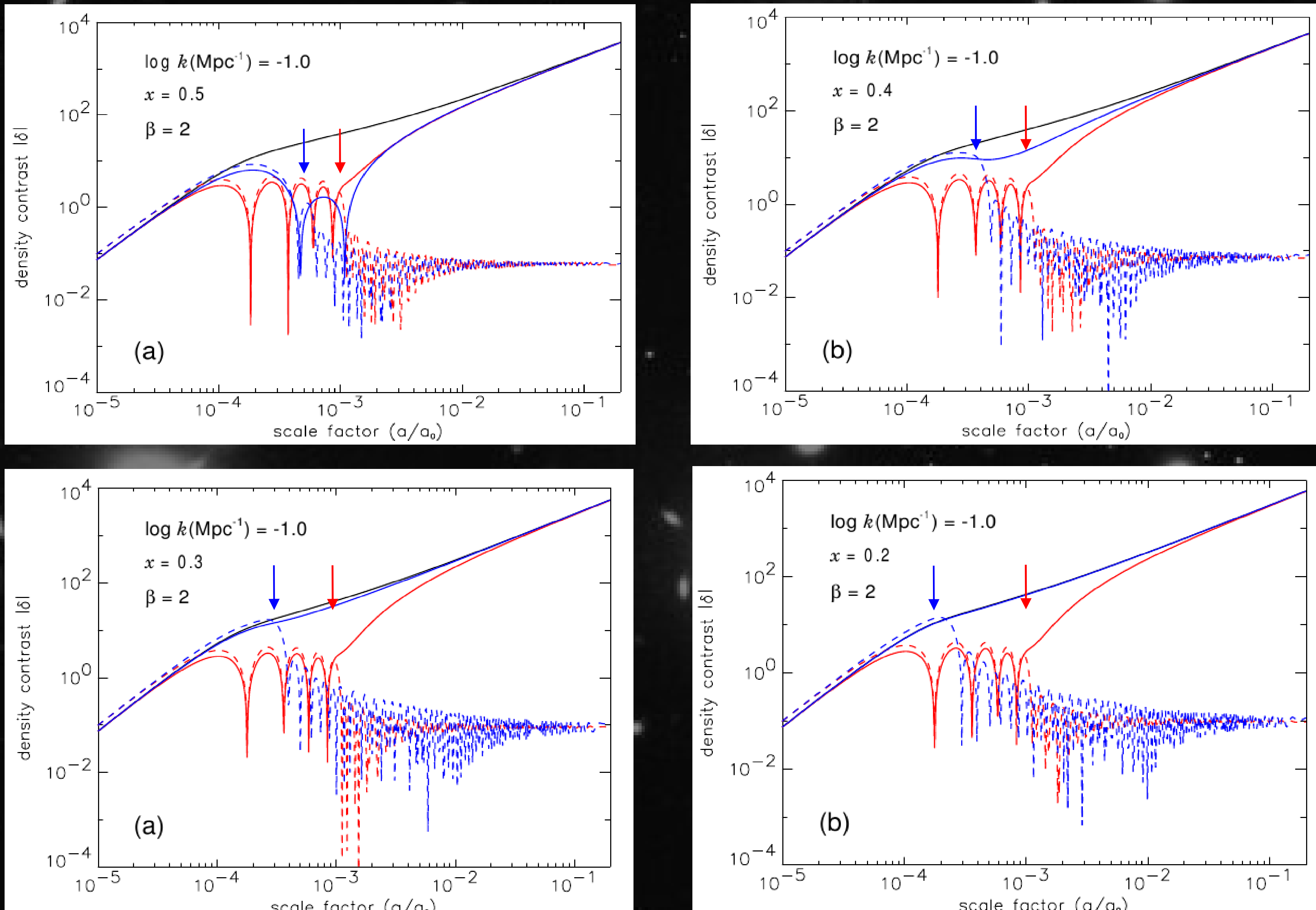
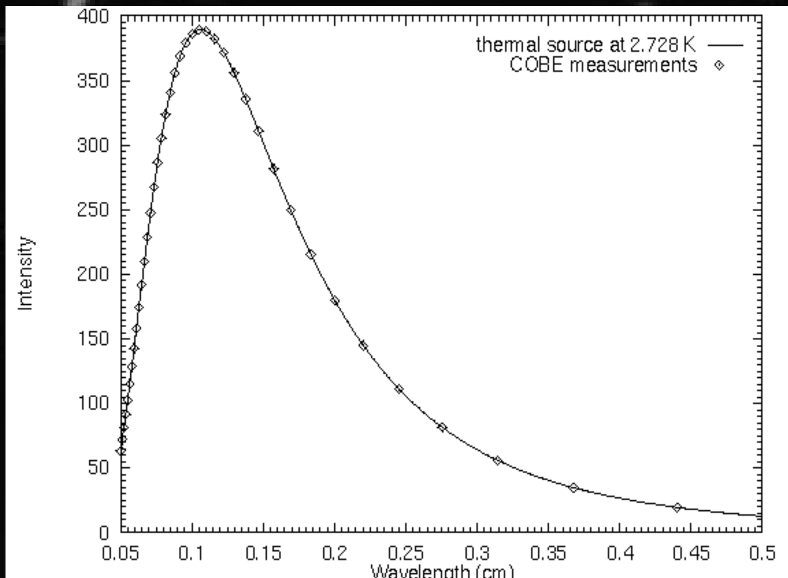
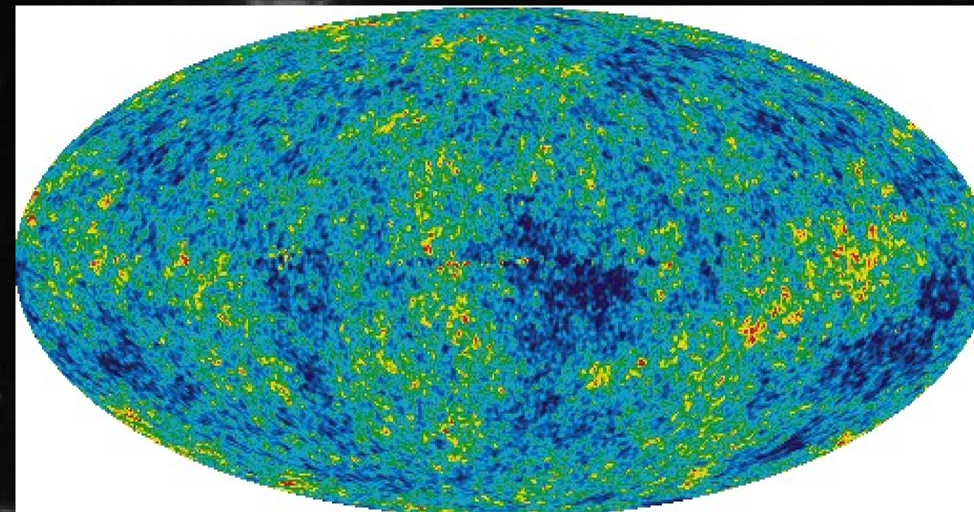
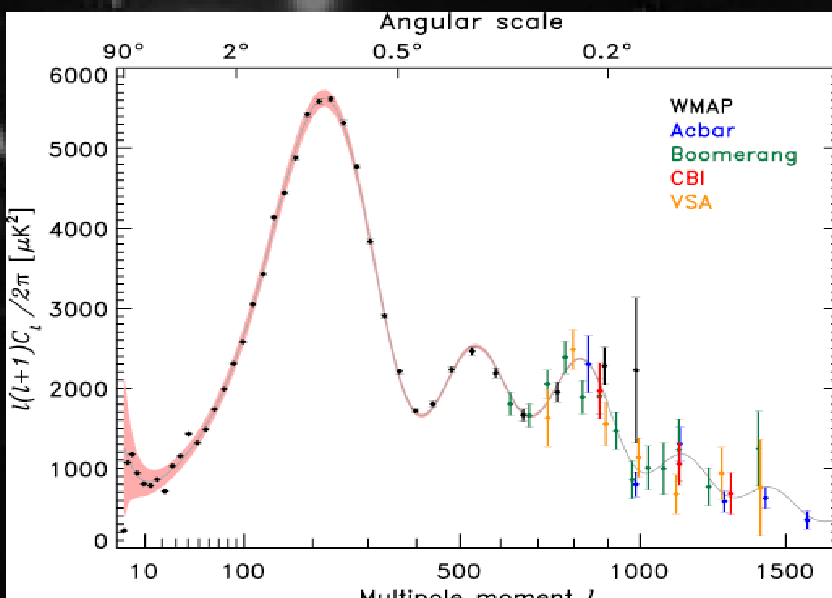


Cosmic Microwave Background







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

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

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

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

Cosmic Microwave Background

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…

⇒ $x=0.3,0.5,0.7$

⇒ $\Omega_b'=n\,\Omega_b\,(n=1,2,3,4,\ldots)$

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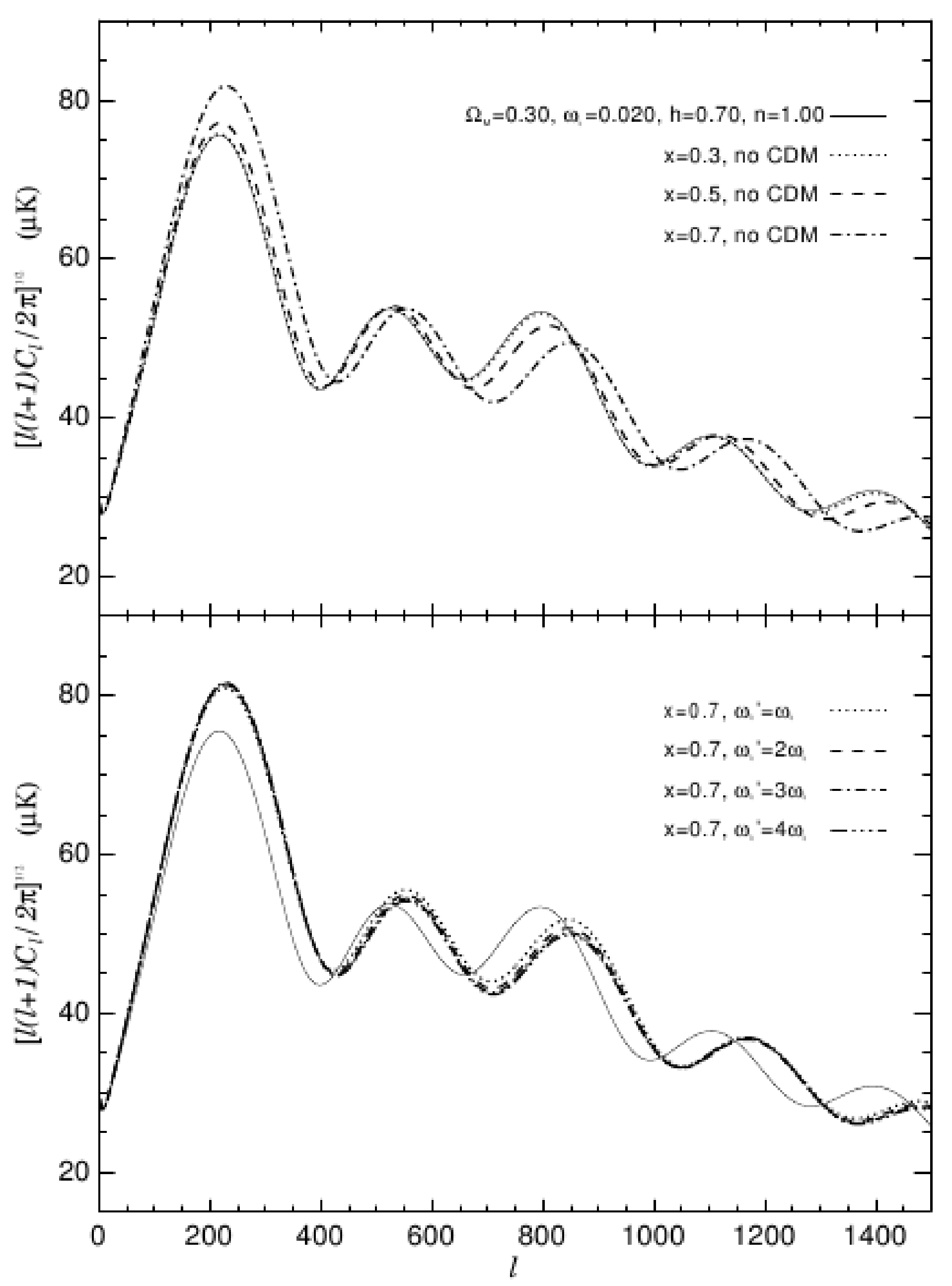

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⇨ $x=0.3, 0.5, 0.7$

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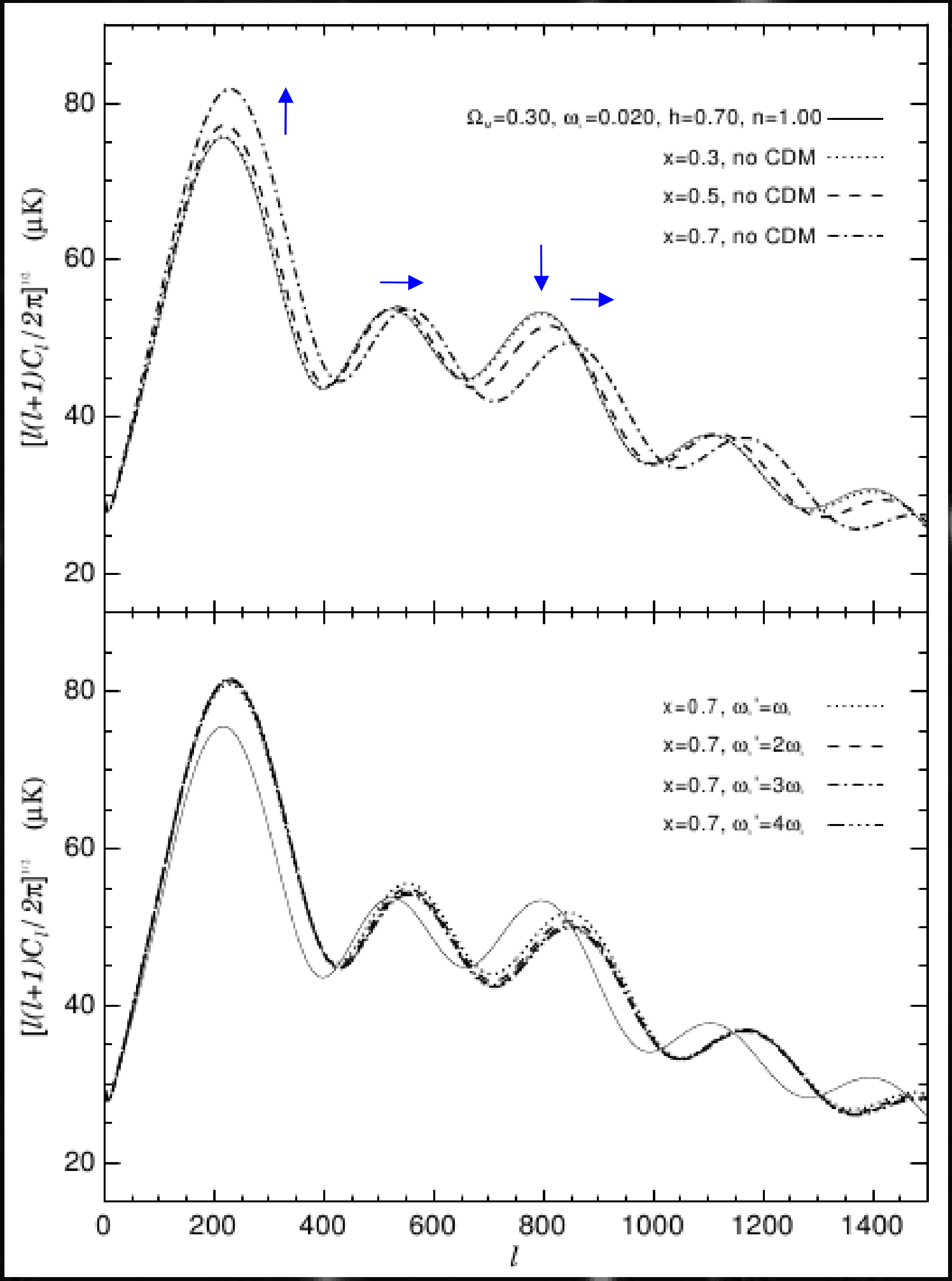
- **low x → similar to CDM**
- **low dependence on $\Omega_b{}'$**



Large Scale Structure

Field of density perturbations:

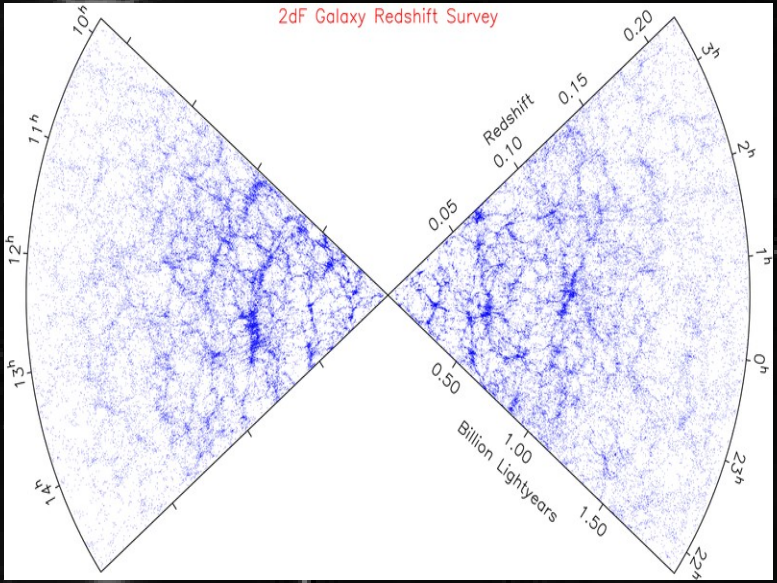
$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \rho_0}{\rho_0} \qquad \delta(\vec{x}) = \frac{1}{(2\pi)^3} \int \delta_k e^{-i\vec{k}\cdot\vec{x}} d^3k$$

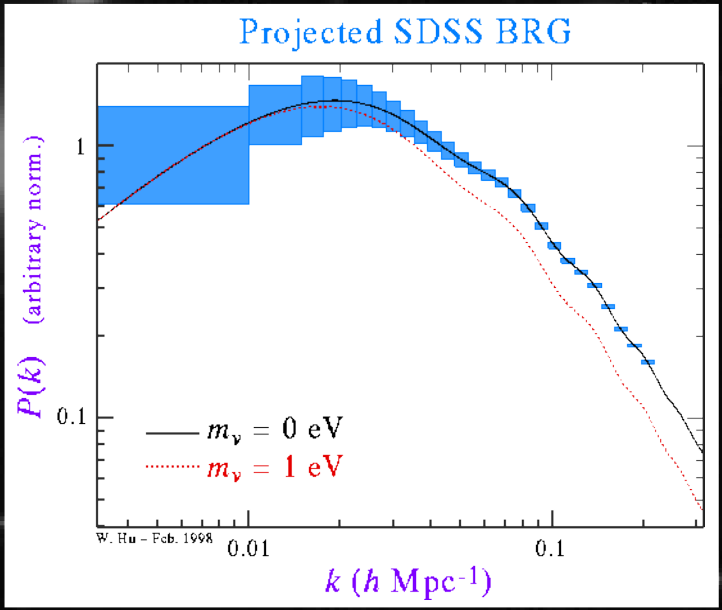
The power spectrum:

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

The transfer function: $T(k)$

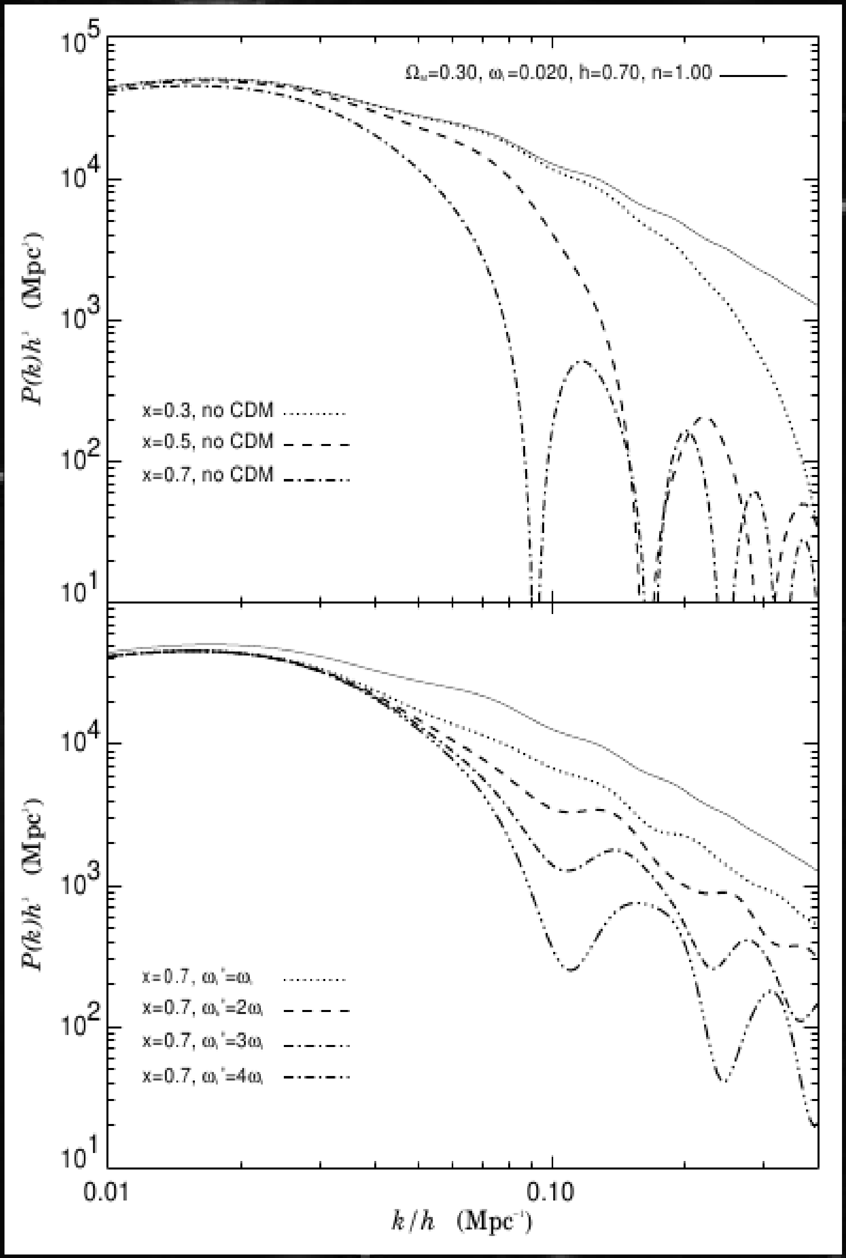
$$P(k;t_f) = \left[\frac{D(t_f)}{D(t_i)}\right]^2 T^2(k;t_f) P(k;t_i)$$





Large Scale Structure

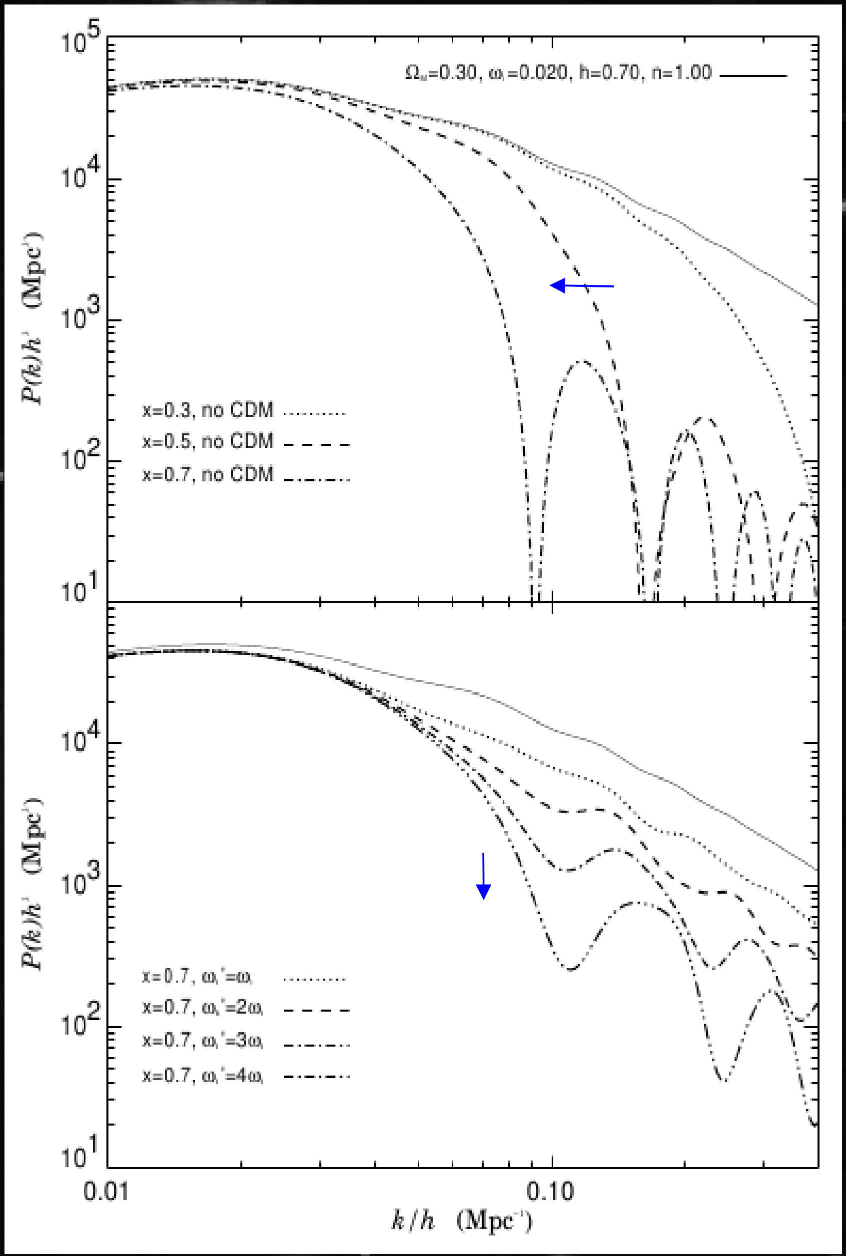
At linear scales…



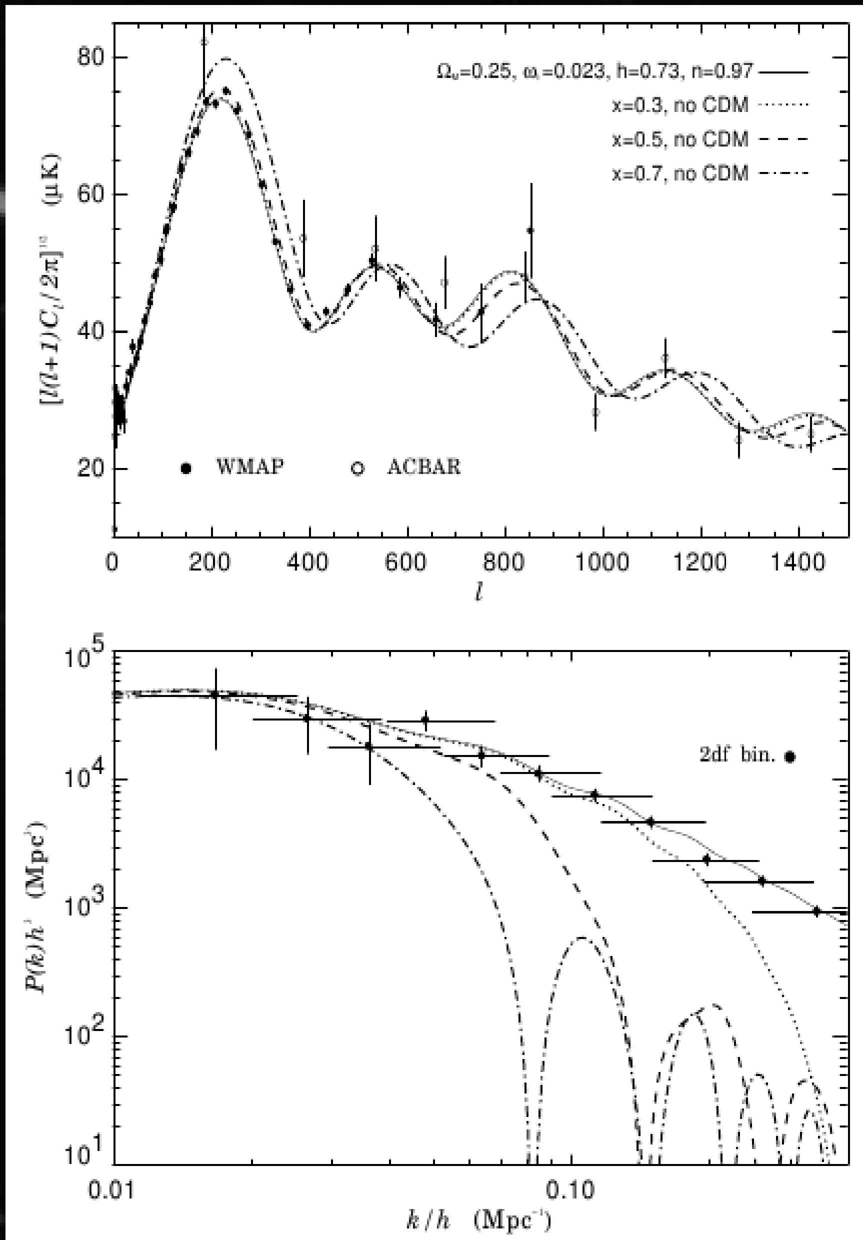
Large Scale Structure

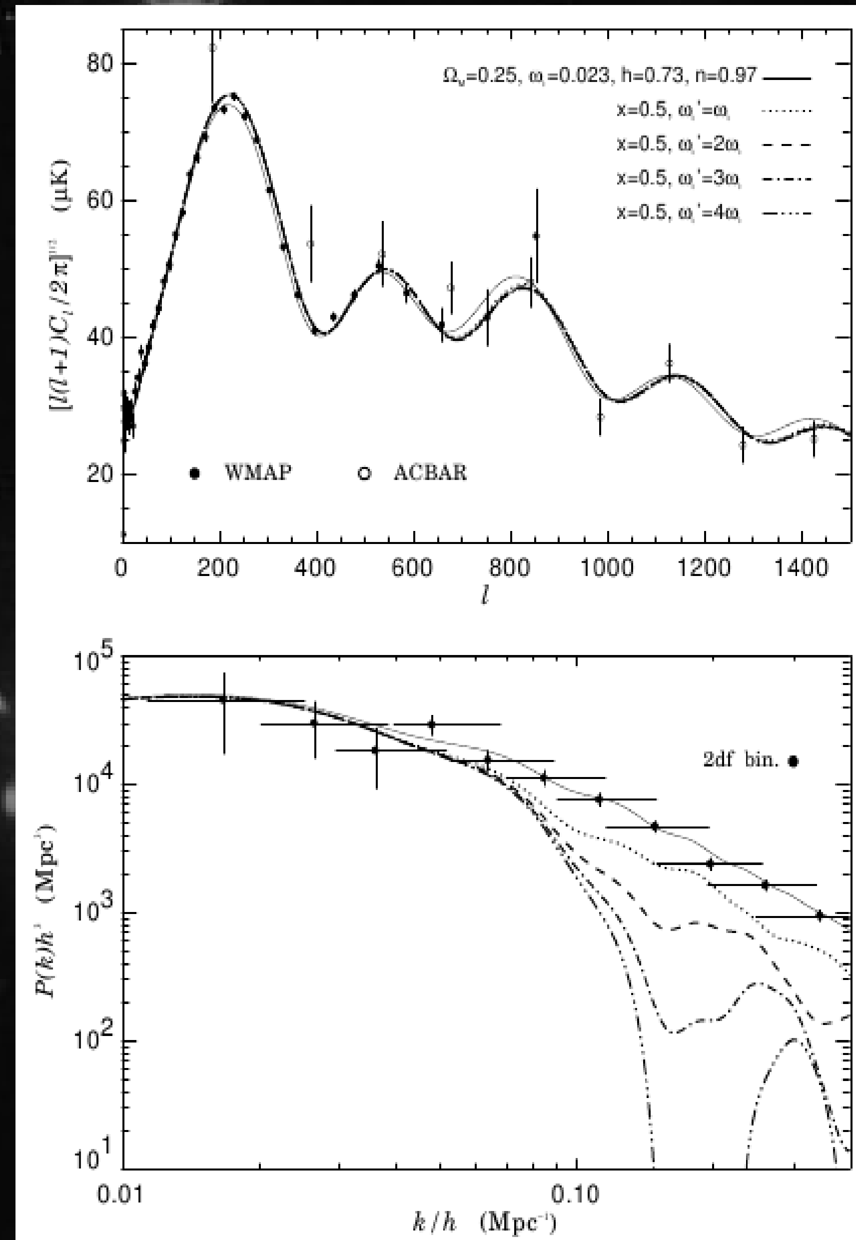
At linear scales…

- low x → similar to CDM
- high dependence on x
- high dependence on Ω_b'



Comparison with observations





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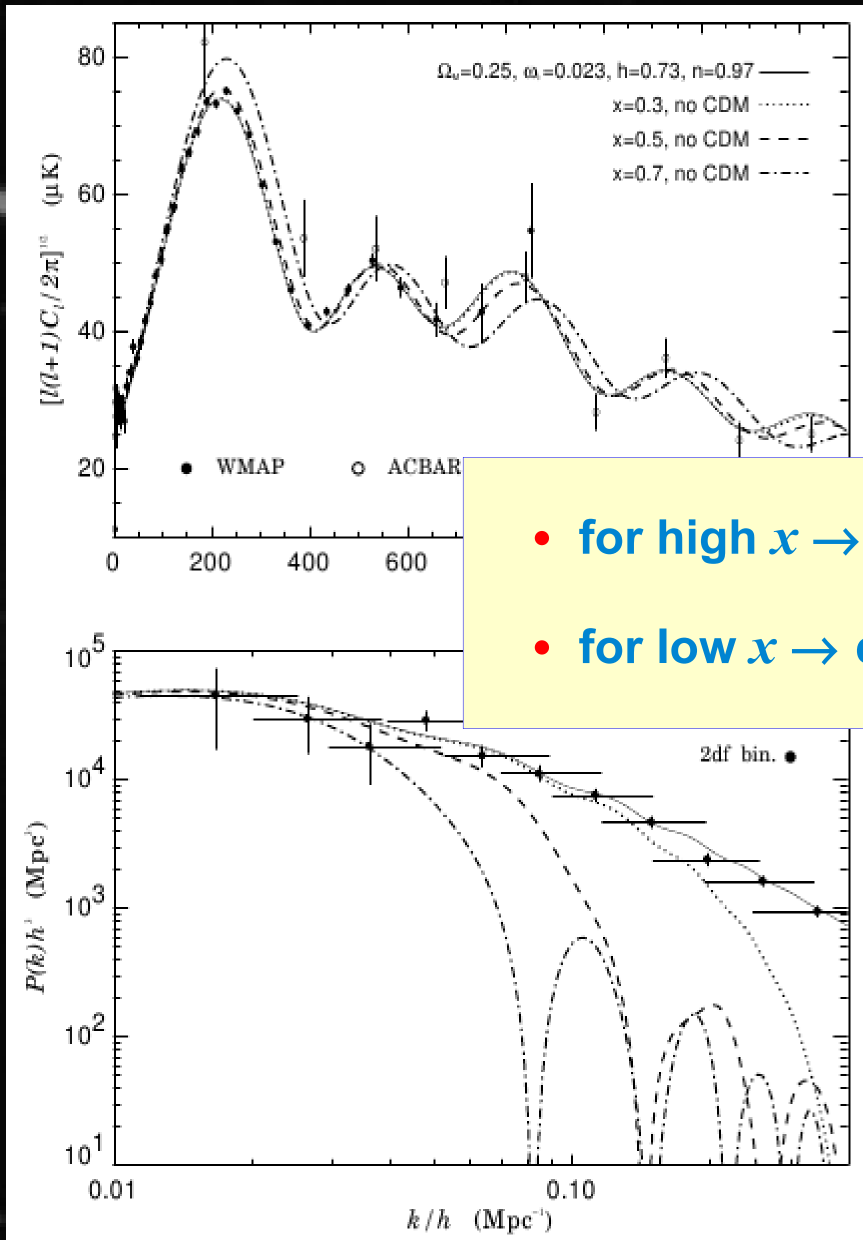
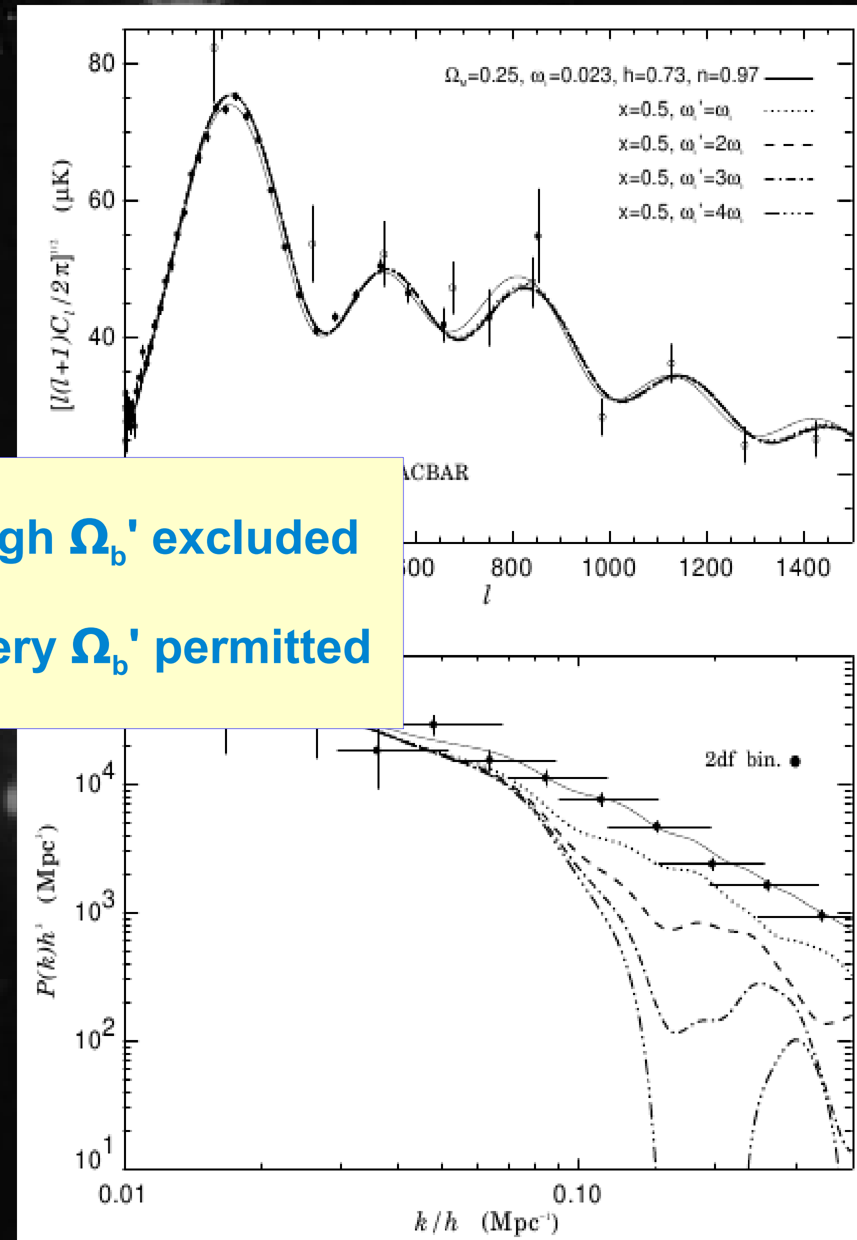
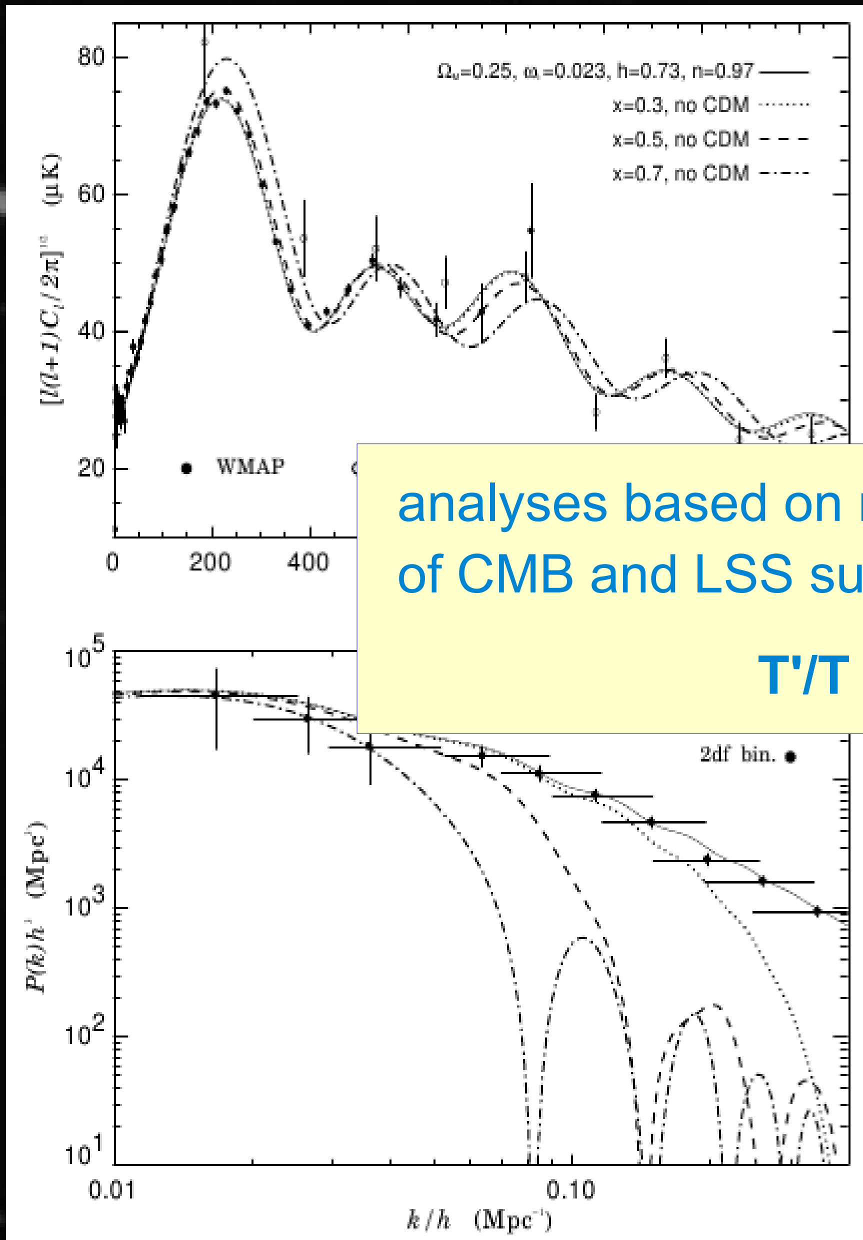
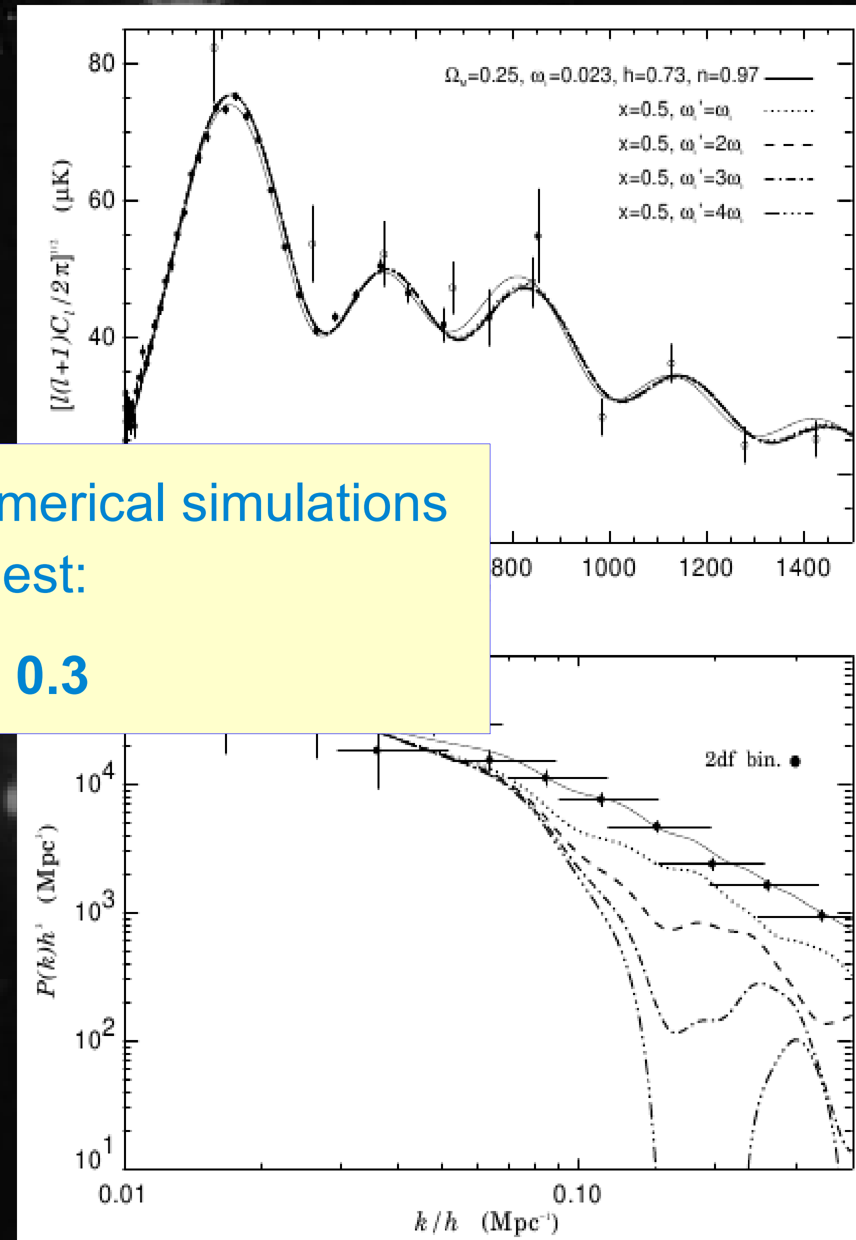




- **for high x → high Ω_b' excluded**
- **for low x → every Ω_b' permitted**

Comparison with observations





analyses based on numerical simulations of CMB and LSS suggest:

$T'/T \leq 0.3$

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

Primordial nuclear abundances

OBSERVATIONS

Mirror summary

THEORY

Thermodynamics of the early Universe

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Star formation

Star evolution

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OBSERVATIONS

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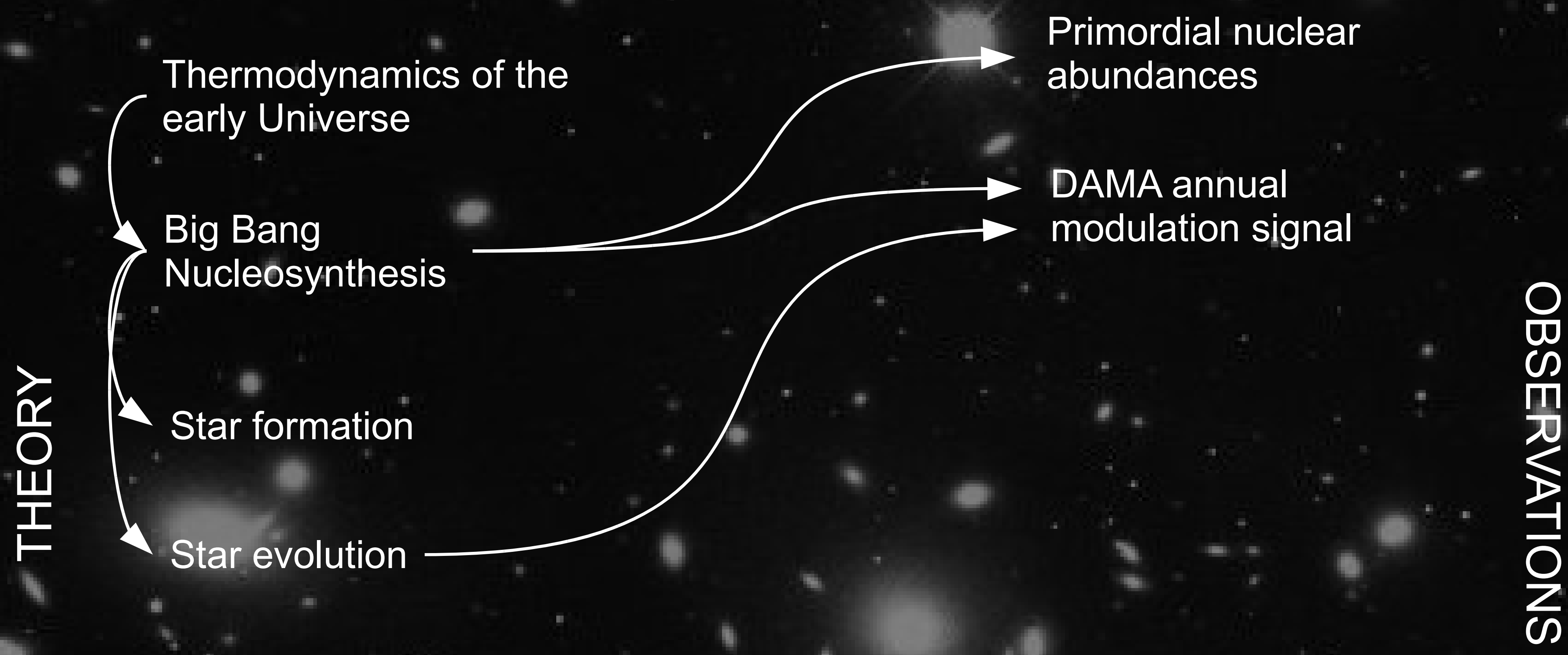

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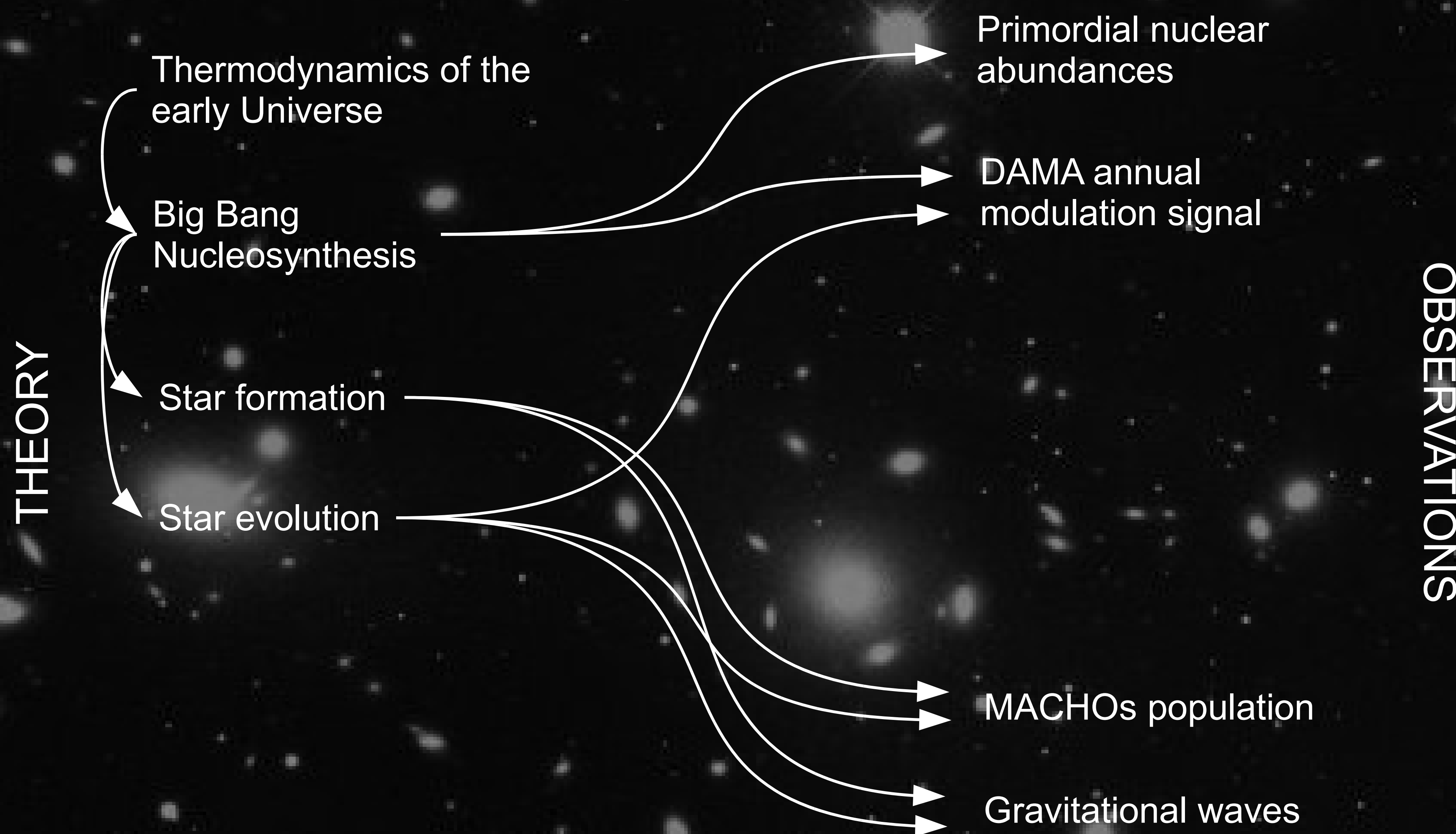

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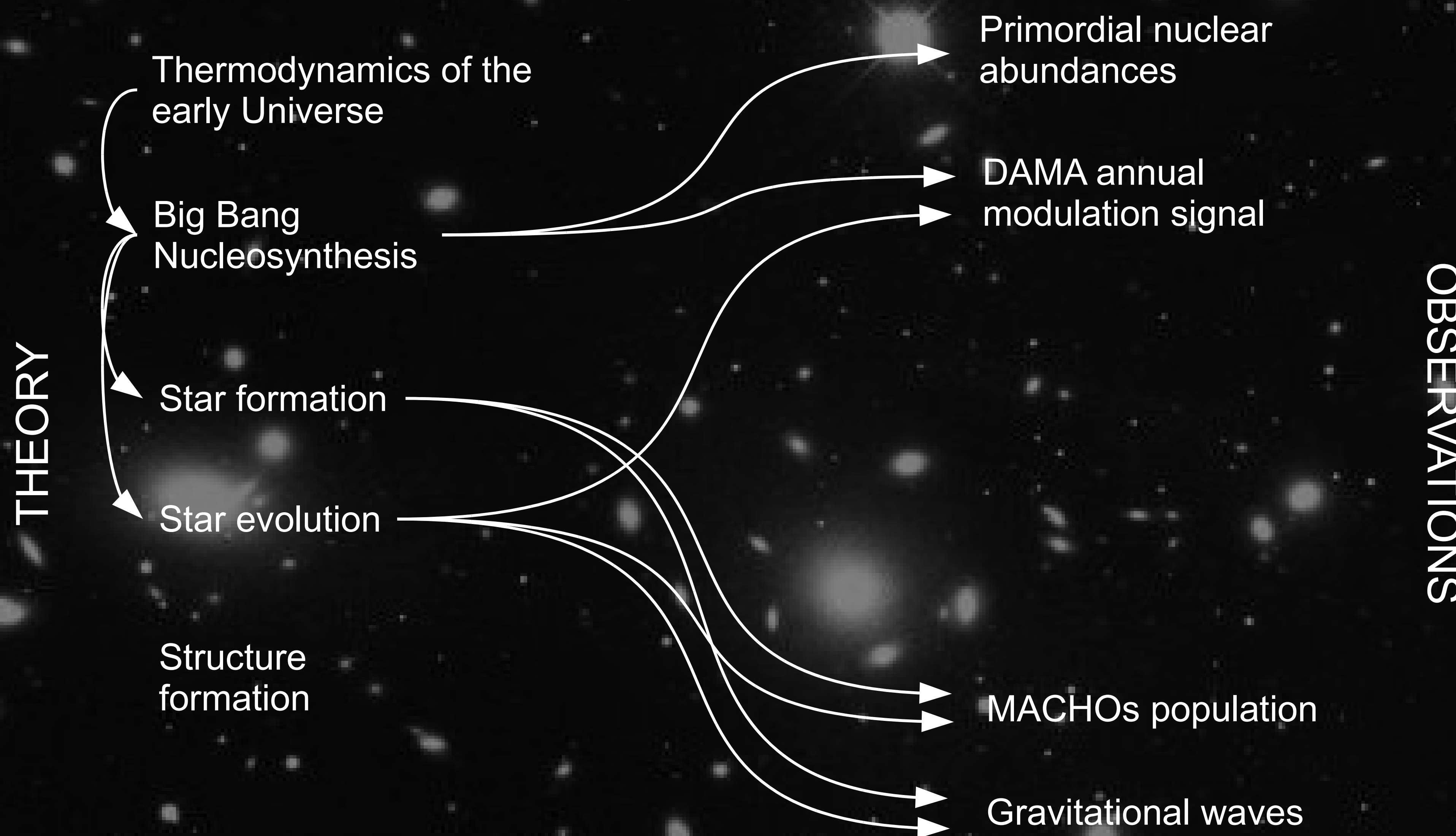

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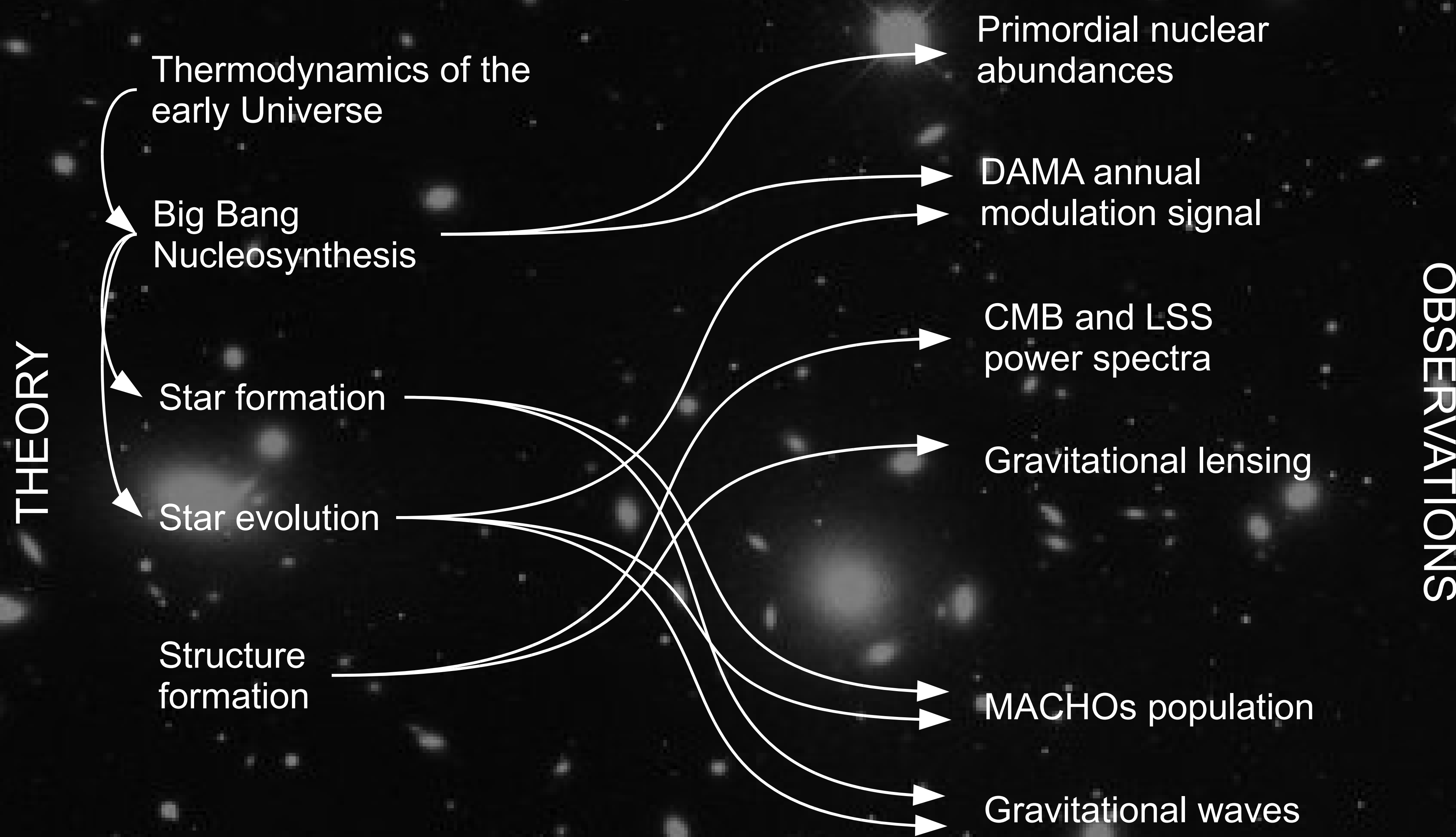

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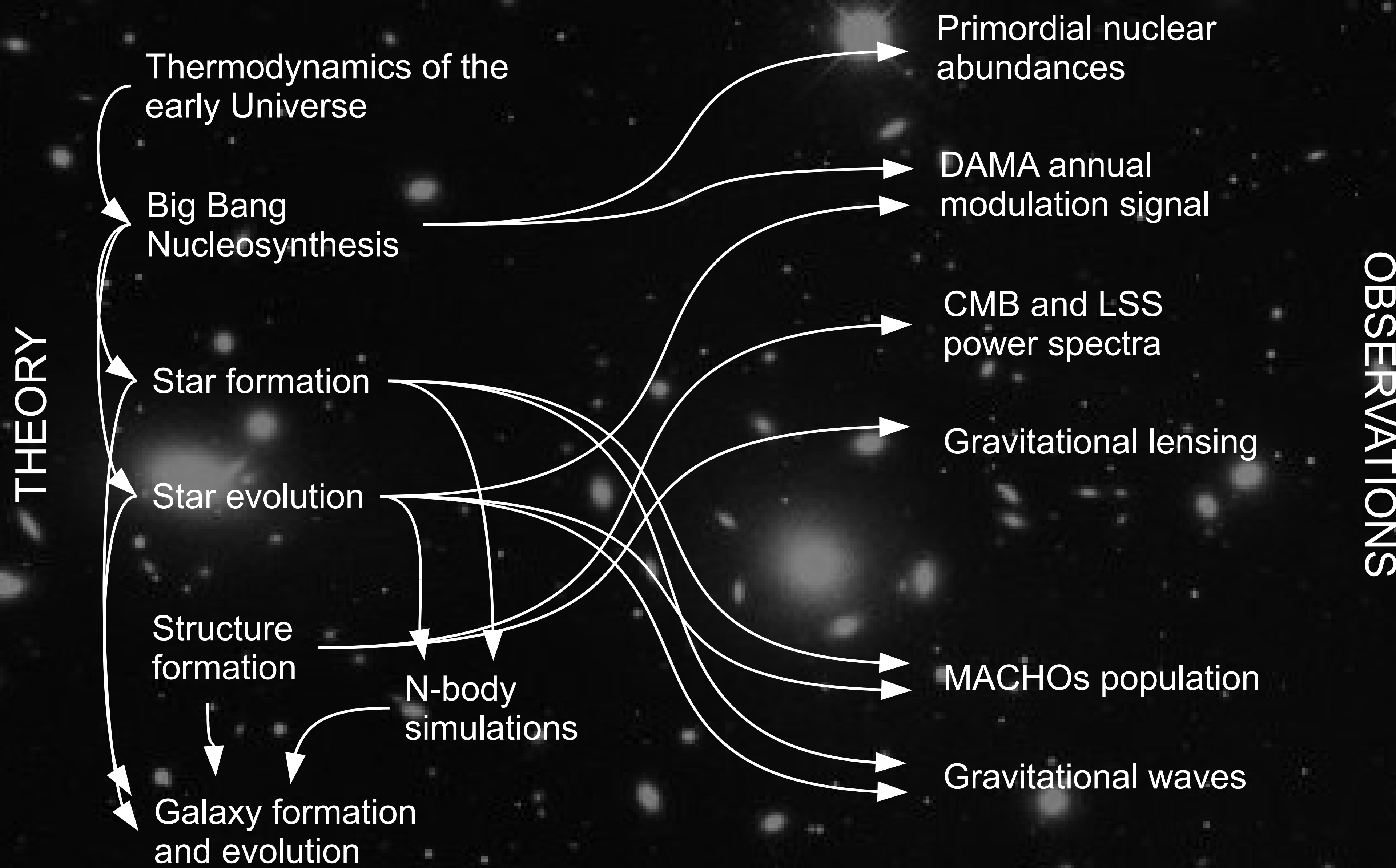

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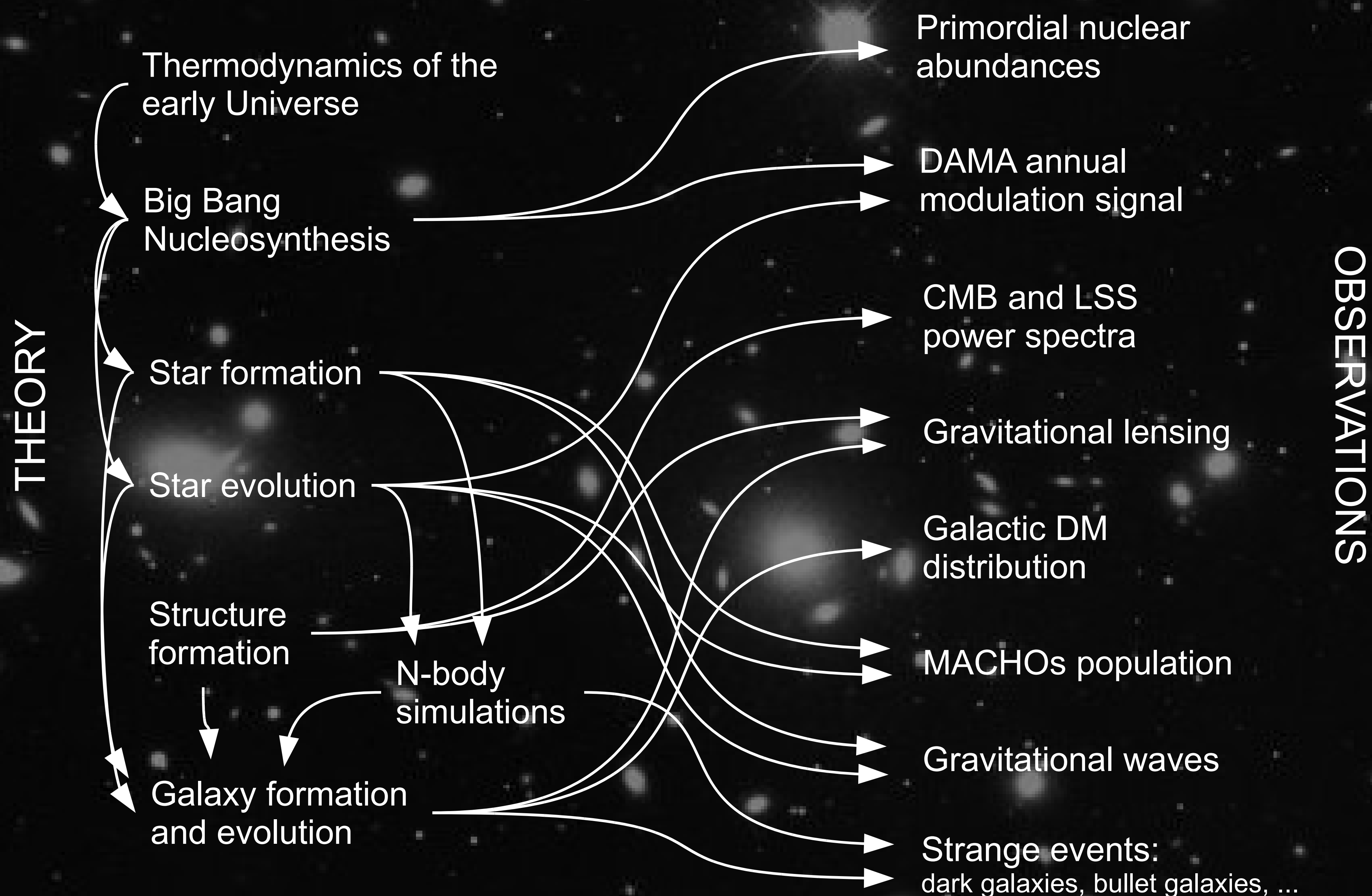

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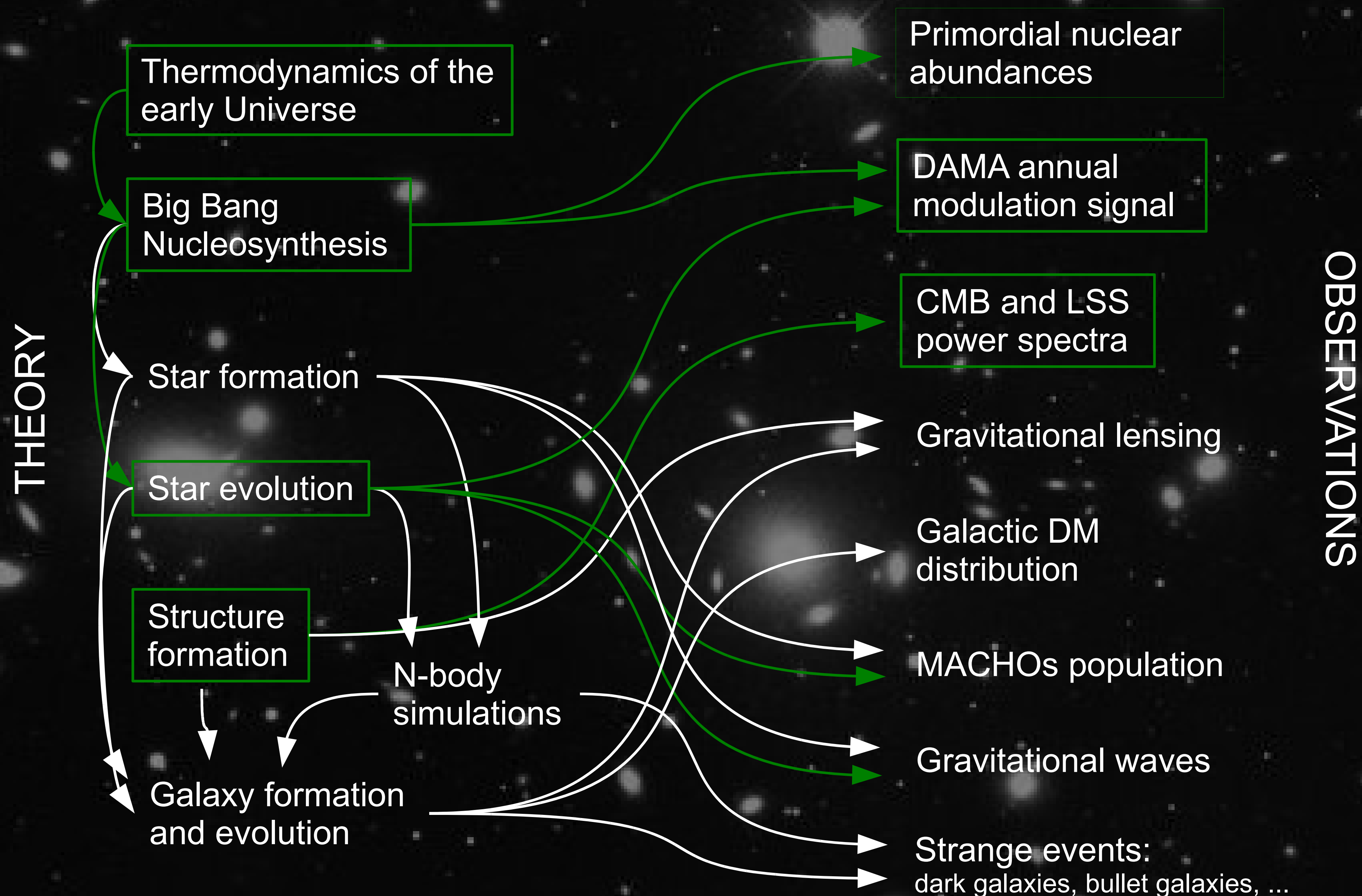
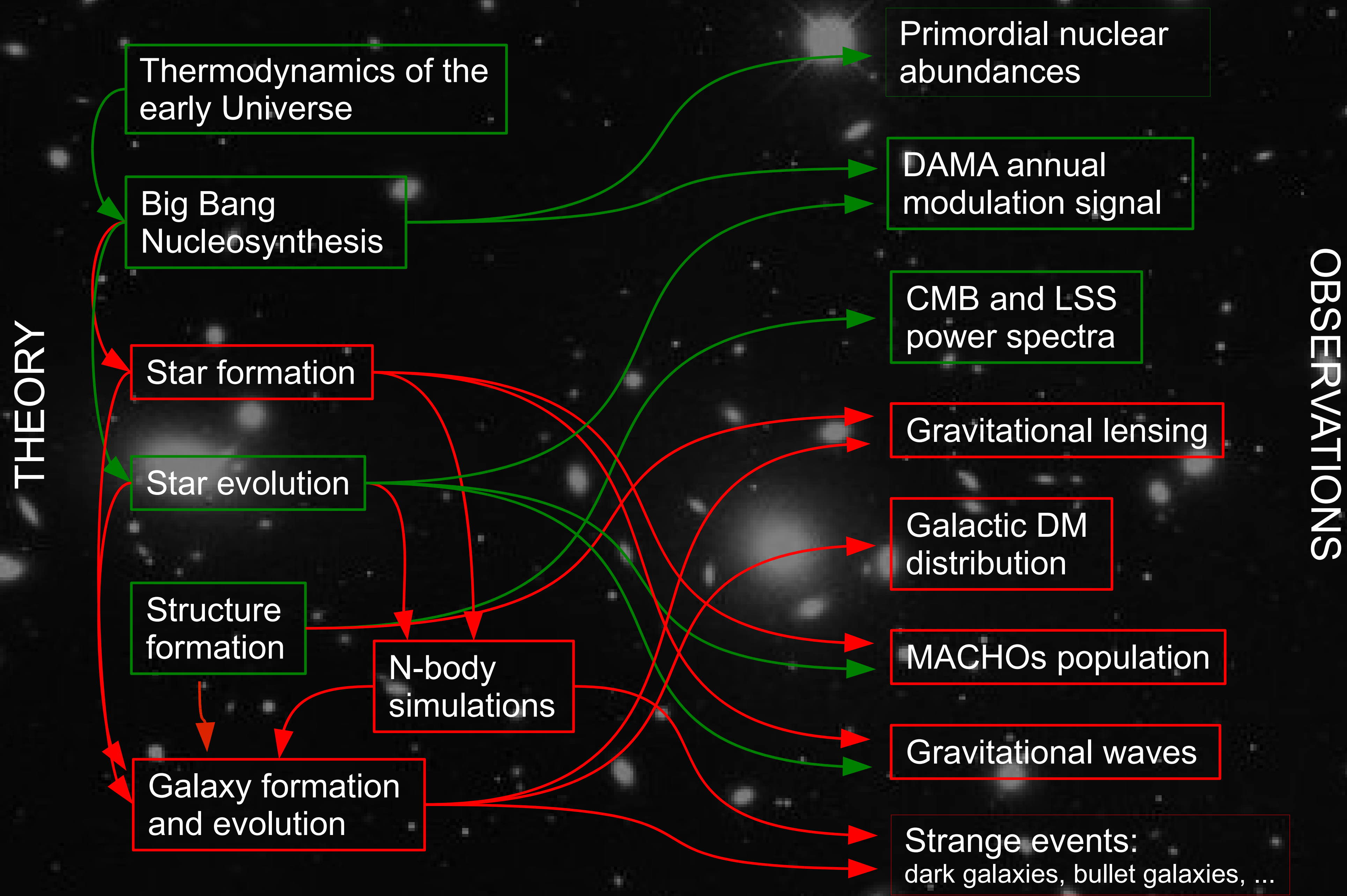


Mirror summary



And now your mirror feedback!

Comments?

Suggestions?

Collaborations?

Review: P. Ciarcelluti, Int. J. Mod. Phys. D 19, 2151-2230 (2010) [arXiv:1102.5530]

Publications related to this talk

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

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P. Ciarcelluti, A. Lepidi,
Phys. Rev. D 78, 123003 (2008) [arXiv:0809.0677]

P. Ciarcelluti,
AIP Conf. Proc. 1038, 202-210 (2008) [arXiv:0809.0668]

P. Ciarcelluti, R. Foot,
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Phys. Lett. B690, 462-465 (2010) [arXiv:1003.0880]

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

F. Sandin, P. Ciarcelluti,
Astropart. Phys. 32, 278-284 (2009), [arXiv:0809.2942]

P. Ciarcelluti, F. Sandin,
Phys. Lett. B 695, 19-21 (2011) [arXiv:1005.0857]

Structure formation

Cosmic Microwave Background
and Large Scale Structure

Thermodynamics
of the early Universe
and
Big Bang Nucleosynthesis

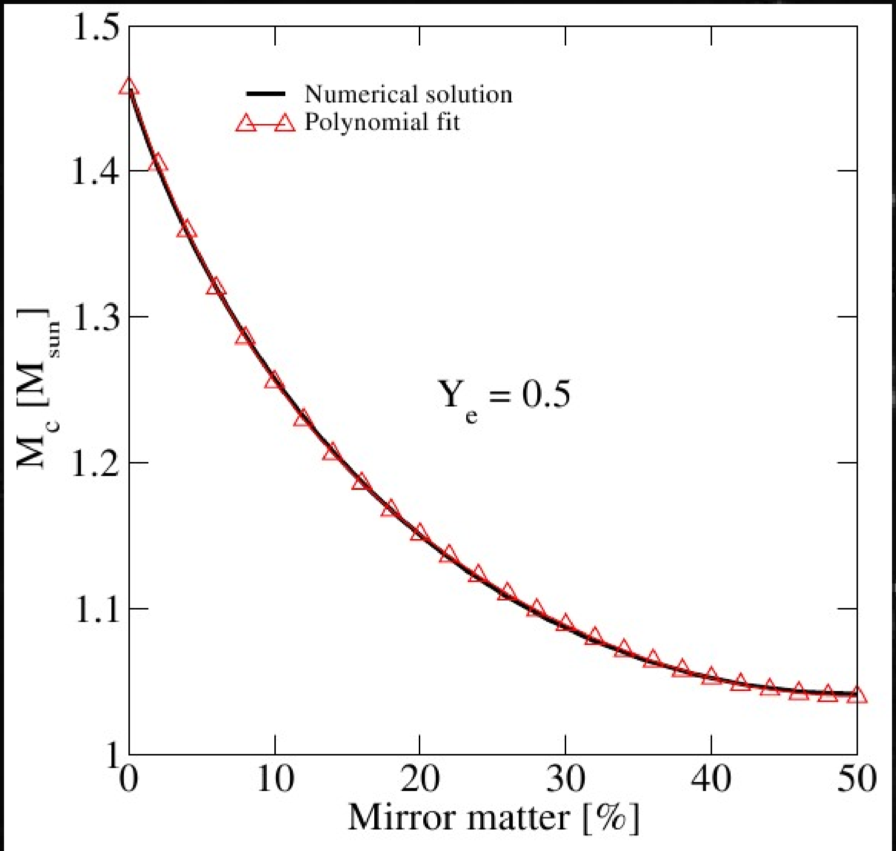
DAMA signal
compatibility

Mirror dark stars (MACHOs)
and neutron stars

Effects on neutron stars
the Chandrasekhar mass

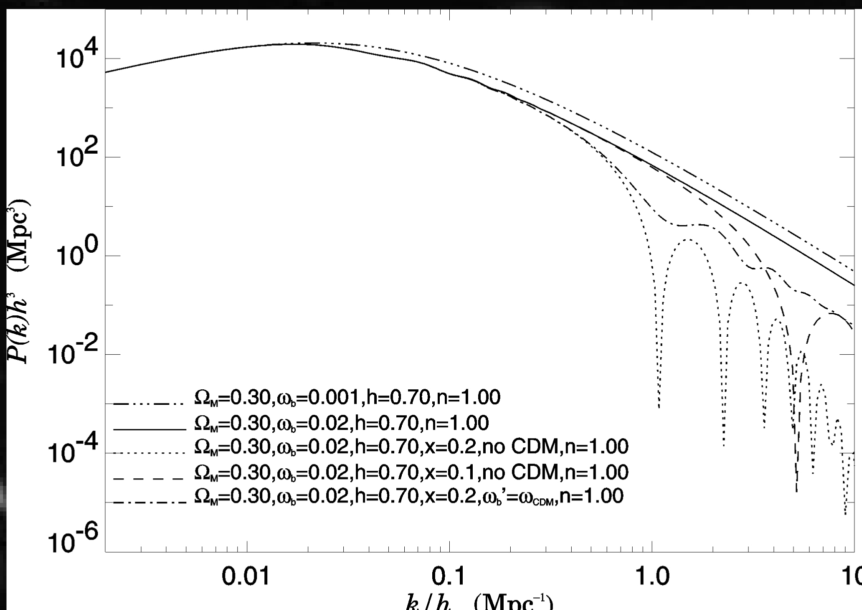
$$q = N_M/(N_O + N_M) - 0.5$$

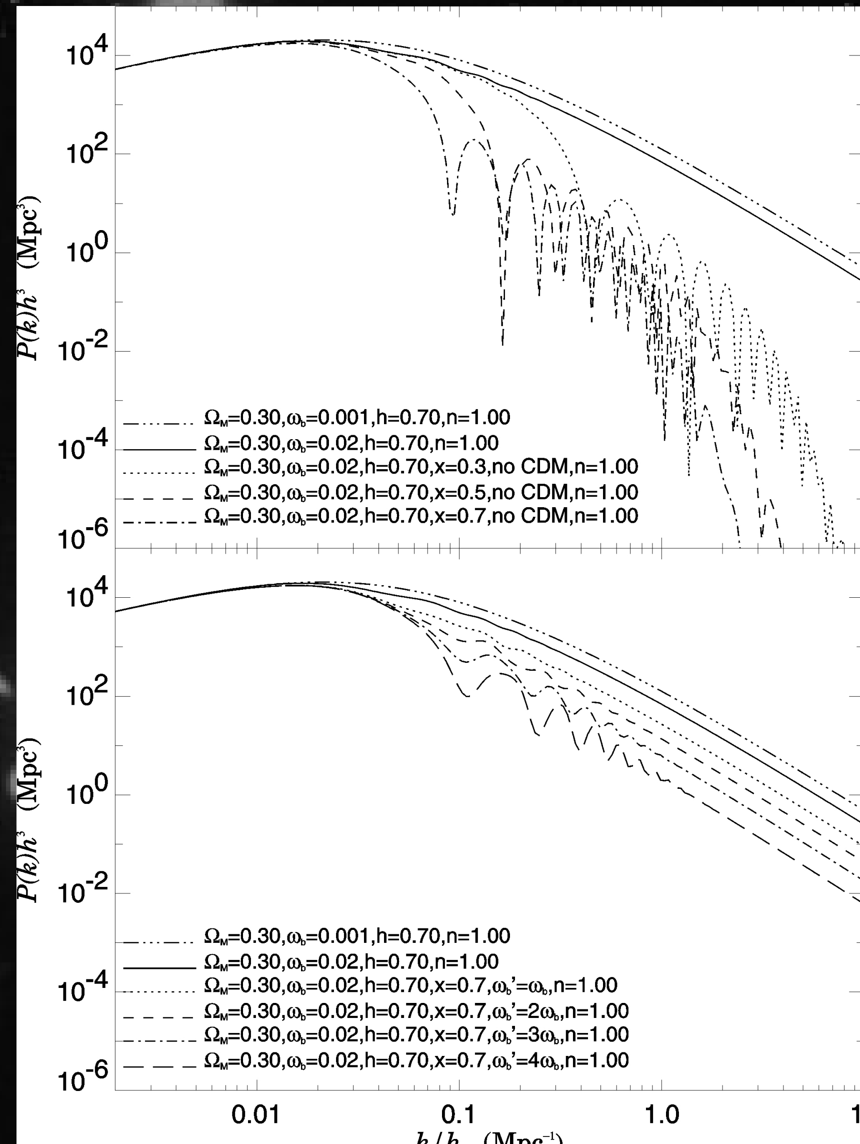
$$M_c \simeq (1.04 + 1.26q^2 - 1.36q^4 + 12.0q^6)\left(\frac{Y_e}{0.5}\right)^2 \mathrm{M}_\odot$$



Large Scale Structure

At smaller scales…





Cut-off scale dependent on x