The Hubble Constant Troubled by Dark Matter

Simony Santos da Costa
simony.santosdacosta@pi.infn.it

in collaboration with: D.R da Silva, F.S. Queiroz, A. Santos

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Istituto Nazionale di Fisica Nucleare

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DarkCosmoGrav

Outline

- Introduction
- Dark Matter particles as the source of dark radiation
- Constraining the Hubble constant from non-thermal production of Dark Matter
  - LCDM
  - wCDM
- Discussion and perspectives

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The concordance model - ΛCDM: a set of assumptions

General Relativity + Cosmological Principle

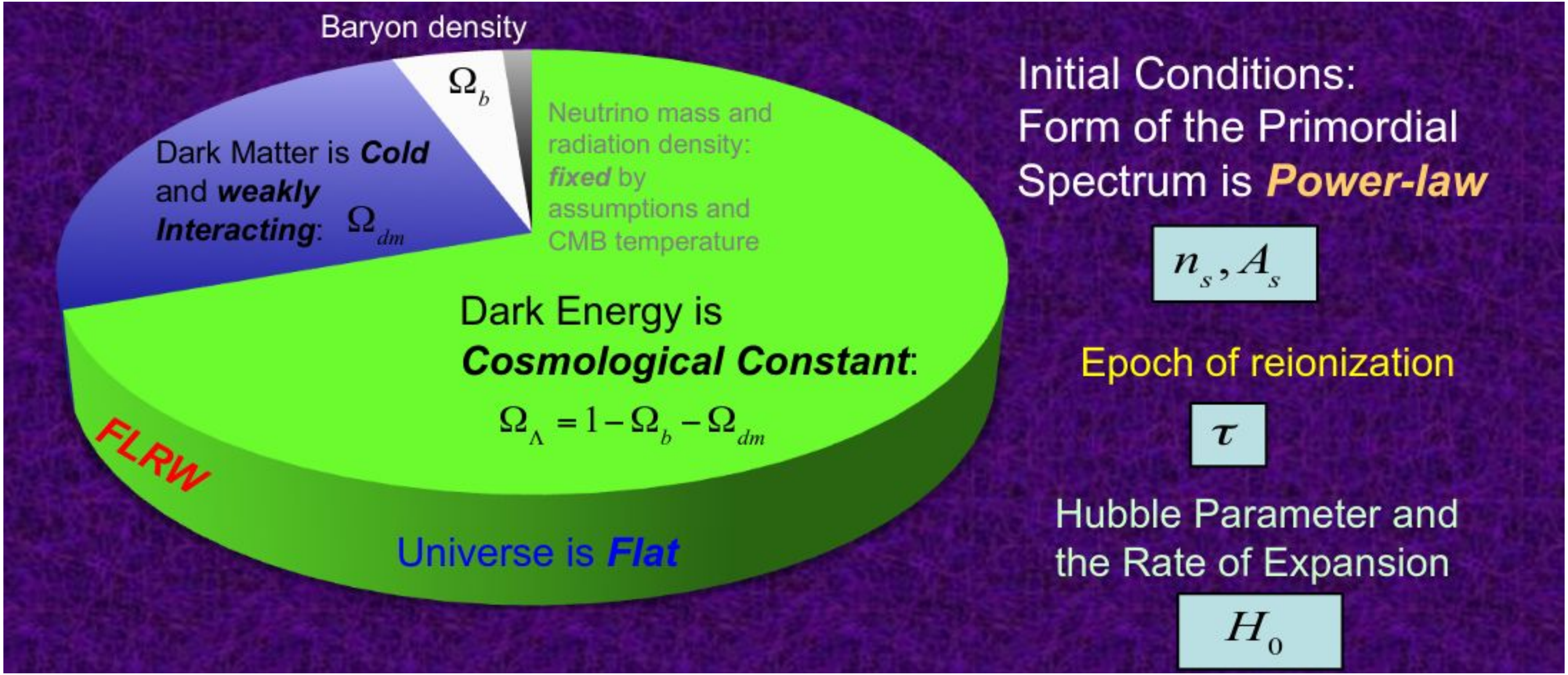
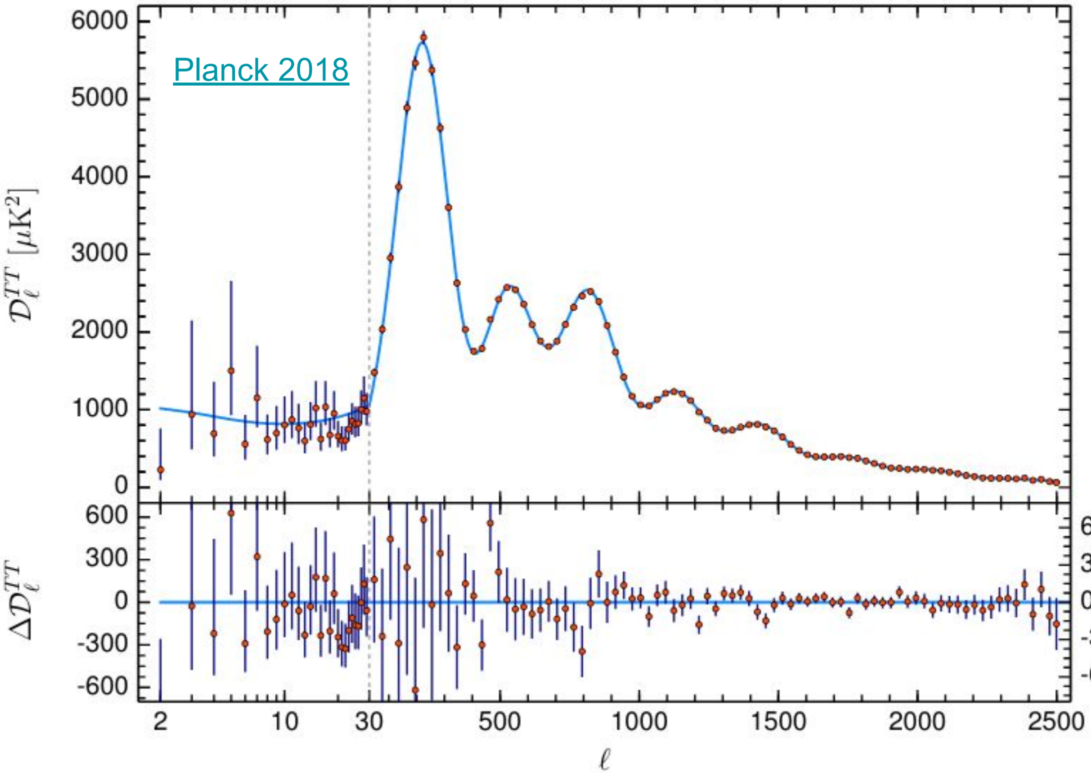


Figure from [A. Shafieloo]

The concordance model - ΛCDM: a set of assumptions confirmed by observational data



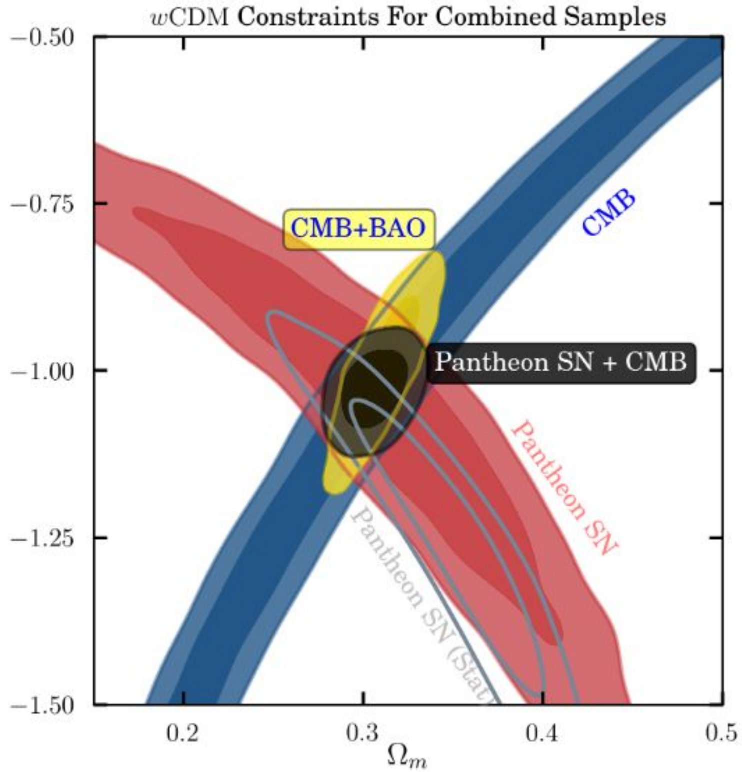


Figure from Scolnic et al. (2018)

The concordance model - ΛCDM

General Relativity + Cosmological Principle

Perfect fluid

$$g_{\mu\nu}dx^{\mu}dx^{\nu} = -dt^2 + a^2 d\chi^2$$

Scale factor

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

FRIEDMANN EQUATIONS

$$\frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho + \Lambda c^2}{3}$$

$$H^2 = H_0^2\left(\frac{\Omega_m}{a^3} + \frac{\Omega_r}{a^4} + \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

$$\rho_c = \frac{3H^2}{8\pi G} \qquad \Omega_M = \frac{\rho}{\rho_{crit}}$$

The concordance model - ΛCDM

How can we determine H0?

$$g_{\mu\nu}dx^{\mu}dx^{\nu} = -dt^2 + a^2 d\chi^2$$

$$ds^2 = 0$$

For a photon

$$dt = a(t)dr$$

$$a = \frac{1}{1+z} \qquad H(t) = \frac{1}{a(t)}\frac{da}{dt}$$

$$r = \int_{t_e}^{t_0} \frac{dt}{a(t)} = \int_0^z \frac{dz}{H(z)}$$

Distance measurements

- Luminosity distances from Cepheids and Supernovae
- Angular diameter distances from BAO, galaxy clustering

Using CMB observations

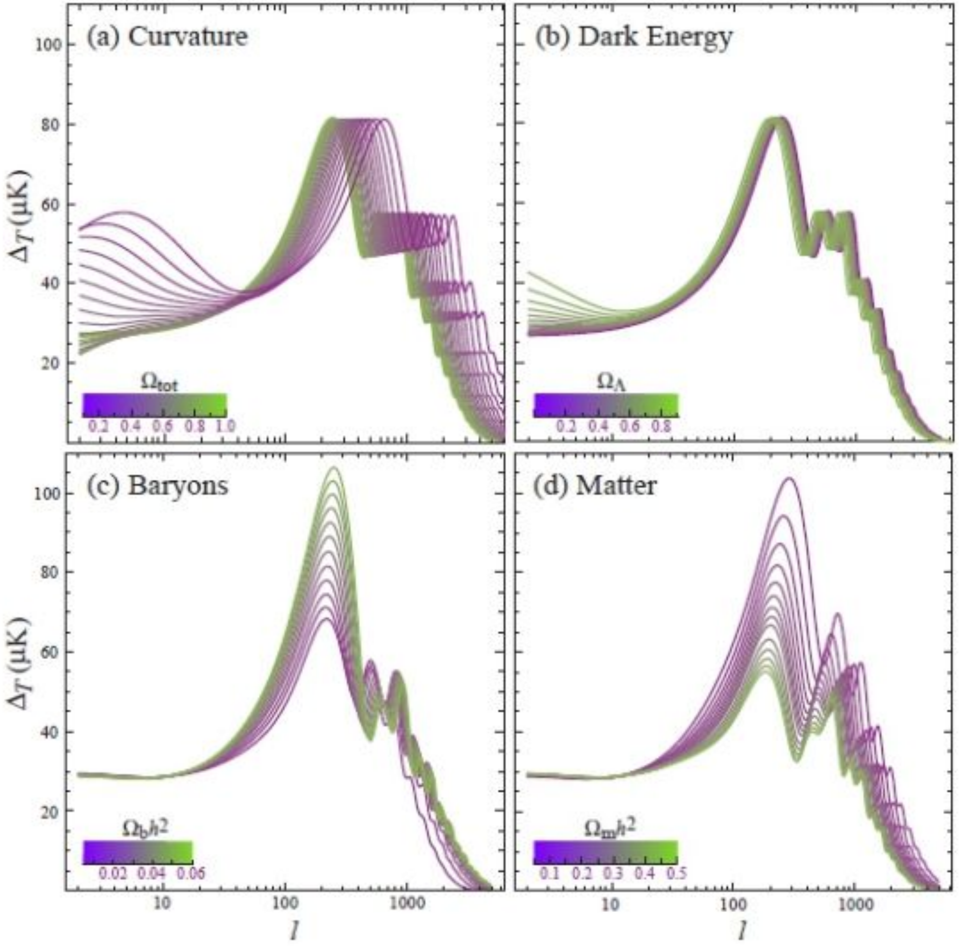
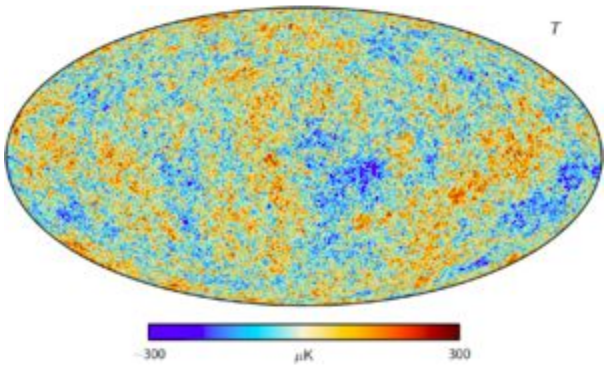
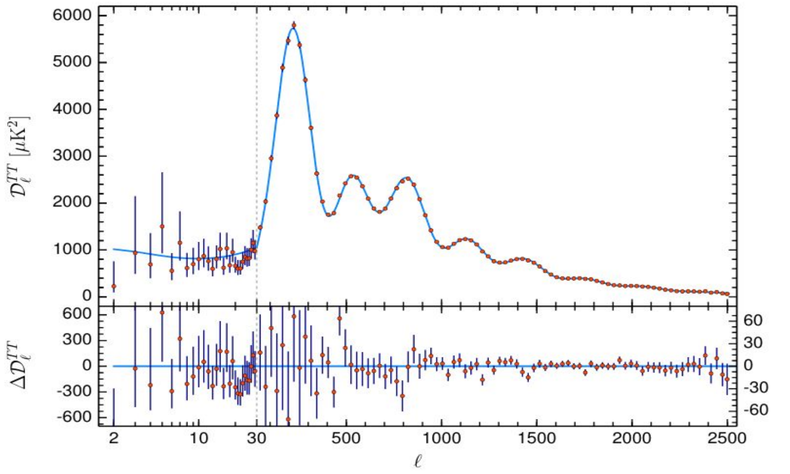


Figure from Hu and Dodelson (2001)

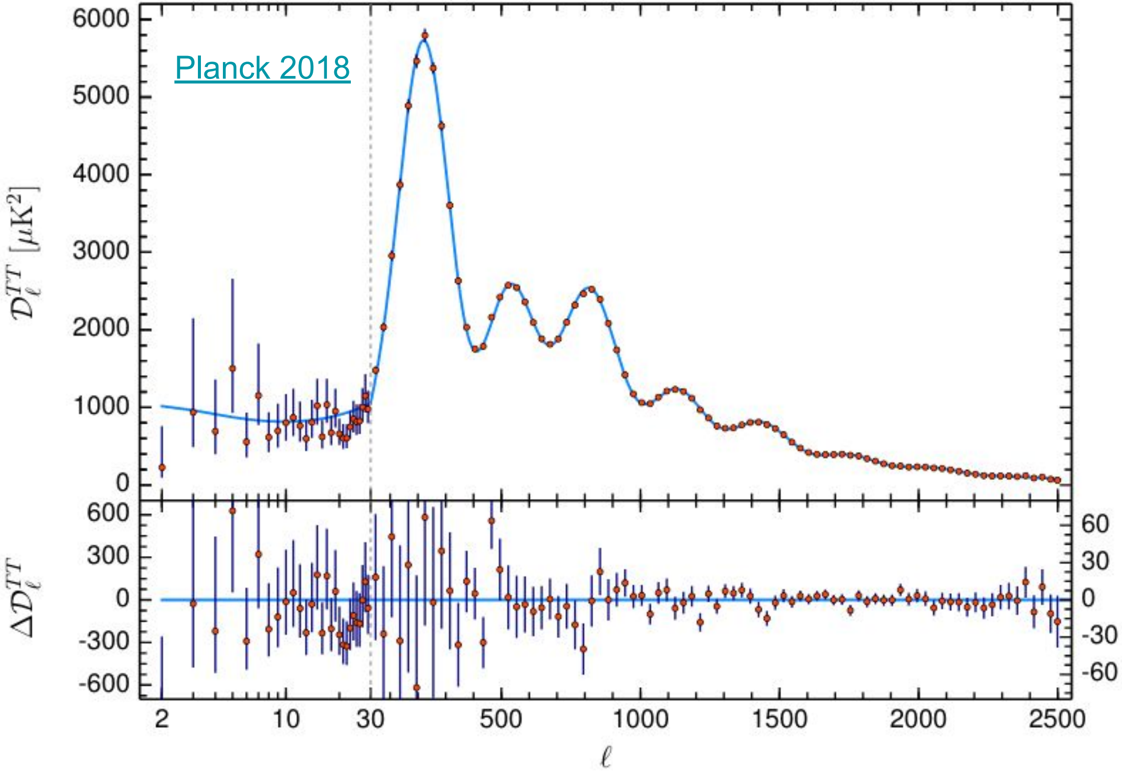


confront data and theory



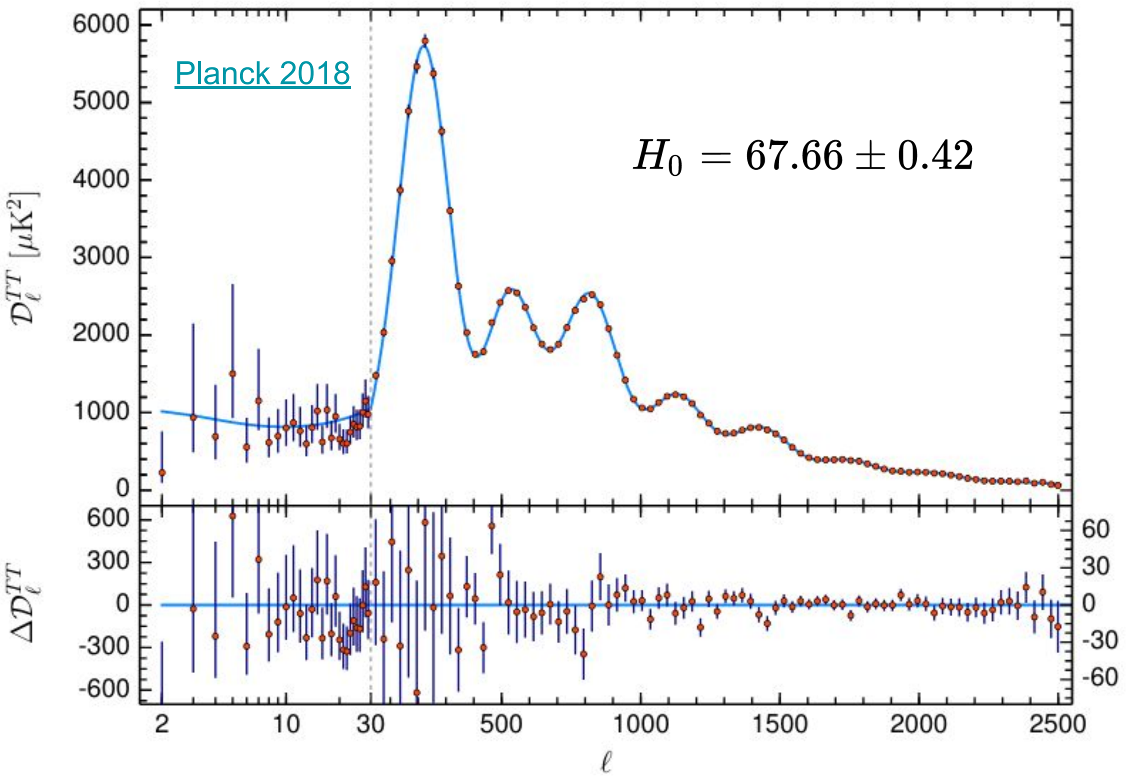
The concordance model - ΛCDM:

a set of assumptions confirmed by observational data



Parameter	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02242 ± 0.00014
$\Omega_c h^2$	0.11933 ± 0.00091
$100\theta_{MC}$	1.04101 ± 0.00029
τ	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.047 ± 0.014
n_s	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}]	67.66 ± 0.42
Ω_Λ	0.6889 ± 0.0056
Ω_m	0.3111 ± 0.0056

The concordance (??) model - ΛCDM: combination of reasonable assumptions



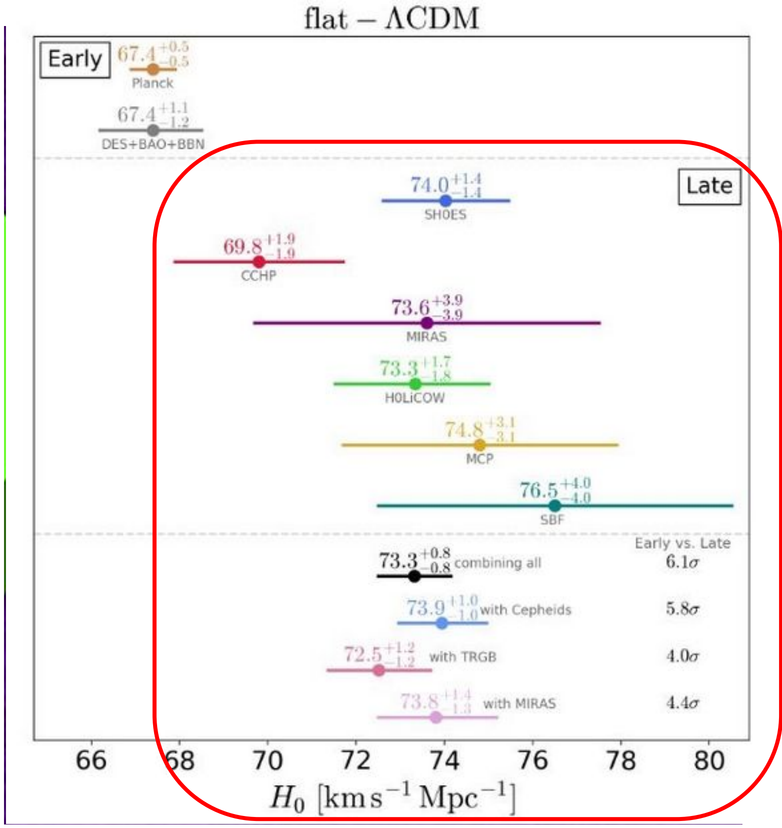


Figure from Verde et al. (2019)

The H0 tension

A huge discrepancy between the Hubble constant inferred from the CMB, fitting the standard LCDM model, and the one obtained from local measurements.

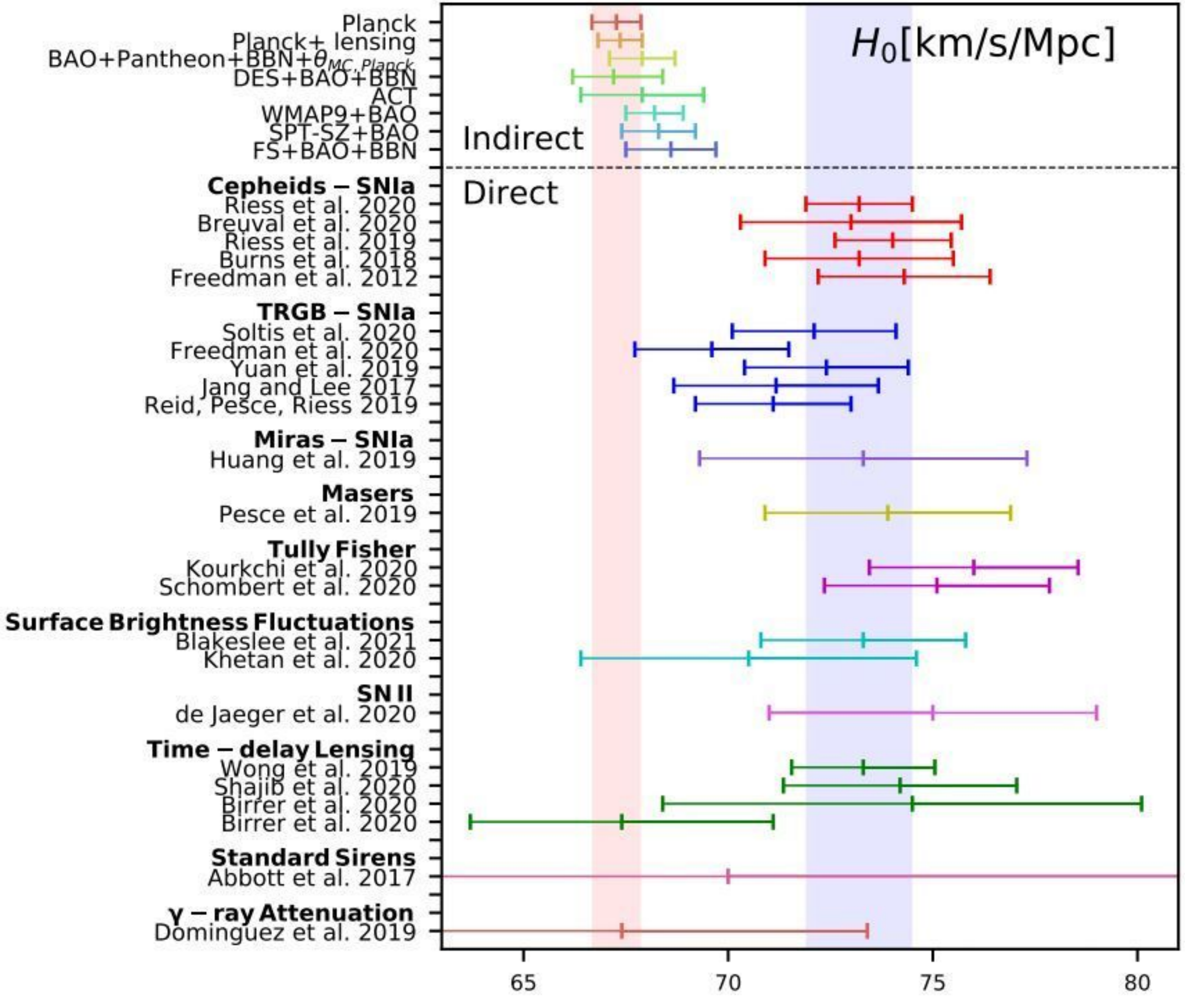


Figure from Di Valentino [2011.00246]

A lot of proposals to address the Hubble constant tension…

- The most famous attempts involve an **Early Dark Energy** component and **extra relativistic species at recombination**, but they can not increase the hubble constant enough to solve the tension with local measurements below 3σ.

- **Late time** modifications, such as **Phantom Dark Energy** and **Phenomenologically Emergent Dark Energy**, can completely solve the hubble tension within 1σ but leave the sound horizon unaltered introducing a tension with the BAO data.

- Last, another promising possibility is an **interaction between the dark matter and the dark energy models**, where the flux of energy between them allows for a lower matter density value and a larger $H0$ value.

See Di Valentino (2020) and references therein.

Dark Matter particles as the source of dark radiation

In the realm of particle physics, the majority of models that try to solve the H0 tension rely on new interactions involving the standard model neutrinos or decaying dark matter models [Abdalla, E. et al. (2022)].

Here, instead, we introduce a non-thermal production mechanism of dark matter to increase the relativistic degrees of freedom and consequently raise H0, via the decay

$$\chi' \rightarrow \chi + \nu \qquad\qquad m_{\chi'} \gg m_{\chi}$$

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mimic the effect of extra dark radiation, i.e. relativistic degrees of freedom N_{eff}

just a fraction of the dark matter abundance coming from this mechanism

Dark Matter particles as the source of dark radiation

Reminding that the radiation density (ρrad) is determined by the photon's temperature (T) and the relativistic degrees of freedom (g∗), i.e.,

$$\rho_{rad} = \frac{\pi^2}{30} g_* T^4. \qquad g_* = 2 + \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{eff}.$$

where Neff is the effective number of relativistic neutrino species, where in the LCDM is Neff = 3.

As we are trying to raise H0 by increasing Neff , Neff tell us how much extra radiation we are adding to the universe via our mechanism

$$\Delta N_{eff} = \frac{\rho_{extra}}{\rho_{1\nu}}.$$

Dark Matter particles as the source of dark radiation

In principle, we may reproduce the effect of an extra neutrino species by adding any other kind of radiation source. Calculating the ratio between one neutrino species density and cold dark matter density at the matter-radiation equality (t = teq) we get,

$$\left.\frac{\rho_{1\nu}}{\rho_{DM}}\right|_{t=t_{eq}} = \frac{\Omega_{\nu,0}\rho_c}{3a_{eq}^4} \times \left(\frac{\Omega_{DM,0}\rho_c}{a_{eq}^3}\right)^{-1} = 0.16.$$

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The 4-momentum conservation implies,

$$E_\chi(\tau) = m_\chi\left(\frac{m_{\chi'}}{2m_\chi} + \frac{m_\chi}{2m_{\chi'}}\right) \equiv m_\chi\gamma_\chi(\tau), \quad \Rightarrow \frac{E_\chi(t)}{m_\chi} = \left[1 + \left(\frac{a(\tau)}{a(t)}\right)^2\left(\gamma_\chi^2(\tau) - 1\right)\right]^{1/2} \equiv \gamma_\chi(t).$$

$$\gamma_\chi(t) = \sqrt{\frac{(m_\chi^2 - m_{\chi'}^2)^2}{4m_\chi^2 m_{\chi'}^2}\left(\frac{\tau}{t}\right) + 1}.$$

Dark Matter particles as the source of dark radiation

Let the dark matter energy be written as $$E_\chi = m_\chi(\gamma_\chi - 1) + m_\chi$$

In the ultra relativistic regime the first term dominates, such that we can rewritten the above equation as

$$E_{DM} = N_{HDM} m_\chi(\gamma_\chi - 1) + N_{CDM} m_\chi \qquad N_{HDM} \ll N_{CDM}$$

the total number of relativistic dark matter particles (hot particles) the total number of nonrelativistic DM (cold particles)

The ratio between relativistic and nonrelativistic dark matter density energy is,

$$\frac{\rho_{HDM}}{\rho_{CDM}} = \frac{N_{HDM} m_\chi(\gamma_\chi - 1)}{N_{CDM} m_\chi} \equiv f(\gamma_\chi - 1)$$

Dark Matter particles as the source of dark radiation

We find that the extra radiation produced via this mechanism is

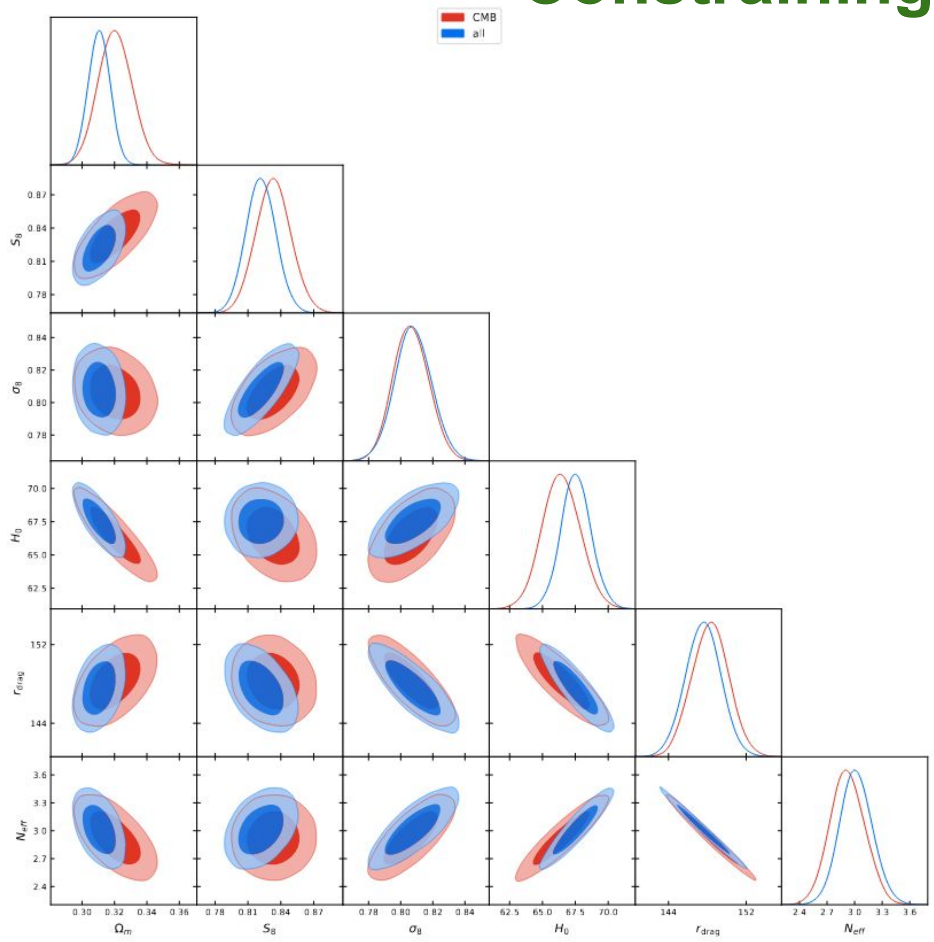
$$\Delta N_{eff} = \lim_{t \to t_{eq}} \frac{f\left(\gamma_\chi - 1\right)}{0.16},$$

In the regime $m_{\chi'} \gg m_\chi$

$$\Delta N_{eff} \approx 2.5 \times 10^{-3} \sqrt{\frac{\tau}{10^6 s}} \times f \frac{m_{\chi'}}{m_\chi}.$$

for teq ≈ 50,000 years ≈ $1.6 * 10^{12}$ s

Constraining the Hubble constant from varying Neff



The standard LCDM model with Neff free to vary already allow for higher values of H0.

Now, we are able to explore the origin of this increase on H0 through our expression for ΔN_{eff}

Figure from [Di Valentino (2021)]

How to constrain the Hubble constant from this non-thermal production of Dark Matter?

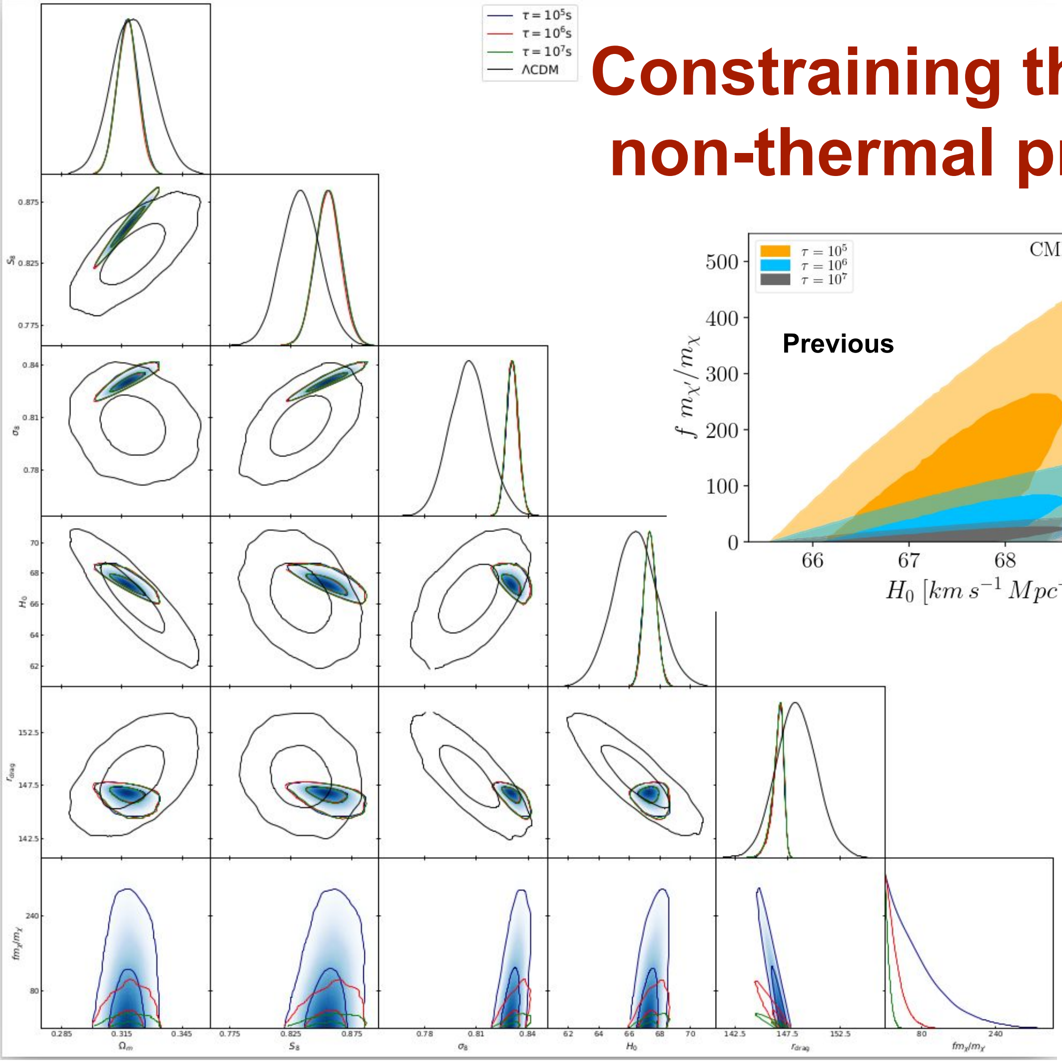
Embed ΔN_{eff} on a Boltzmann code: **CAMB**

Establish the priors on τ and $f\frac{m_{\chi'}}{m_\chi}$

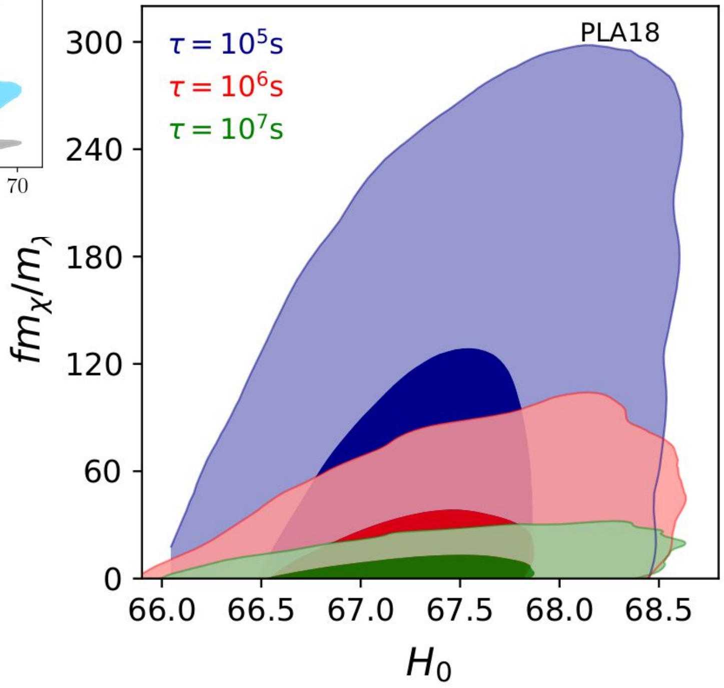
Perform an MCMC analysis: **CosmoMC**

τ	$f\frac{m_{\chi'}}{m_\chi}$	ΔN_{eff}
$10^5\,s$	$0-800$	$0-0.6$
$10^6\,s$	$0-300$	$0-0.6$
$10^7\,s$	$0-100$	$0-0.6$

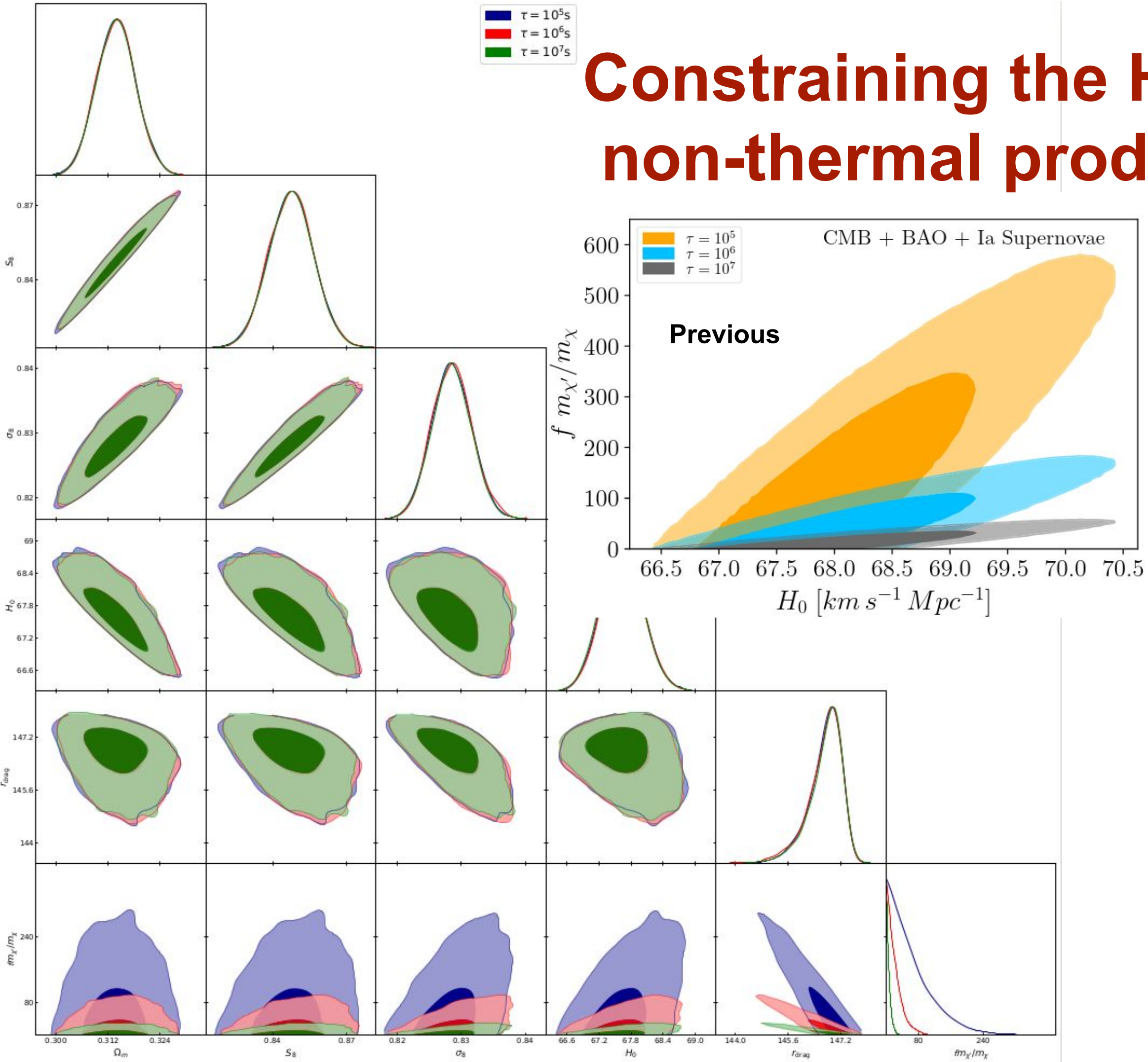
Constraining the Hubble constant from non-thermal production of Dark Matter



In the LCDM scenario



Constraining the Hubble constant from non-thermal production of Dark Matter



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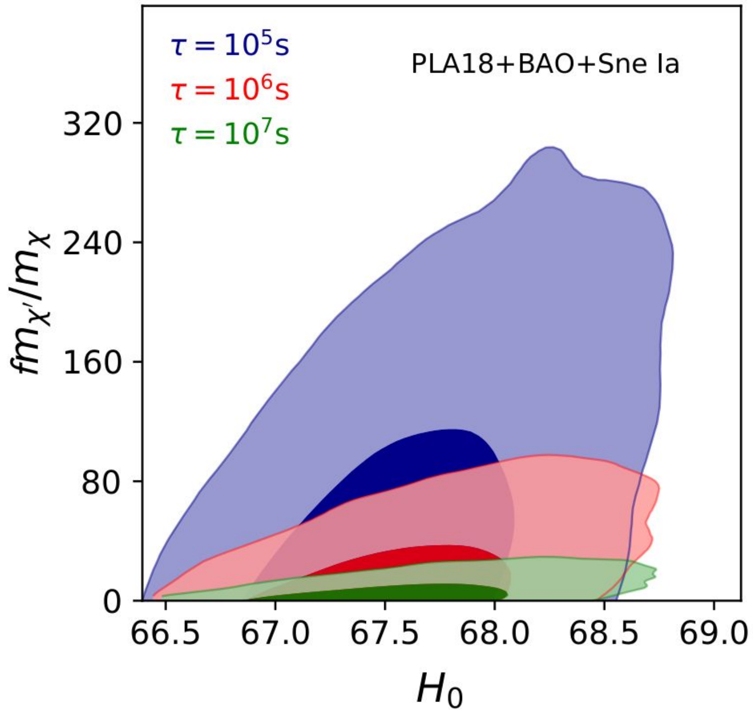

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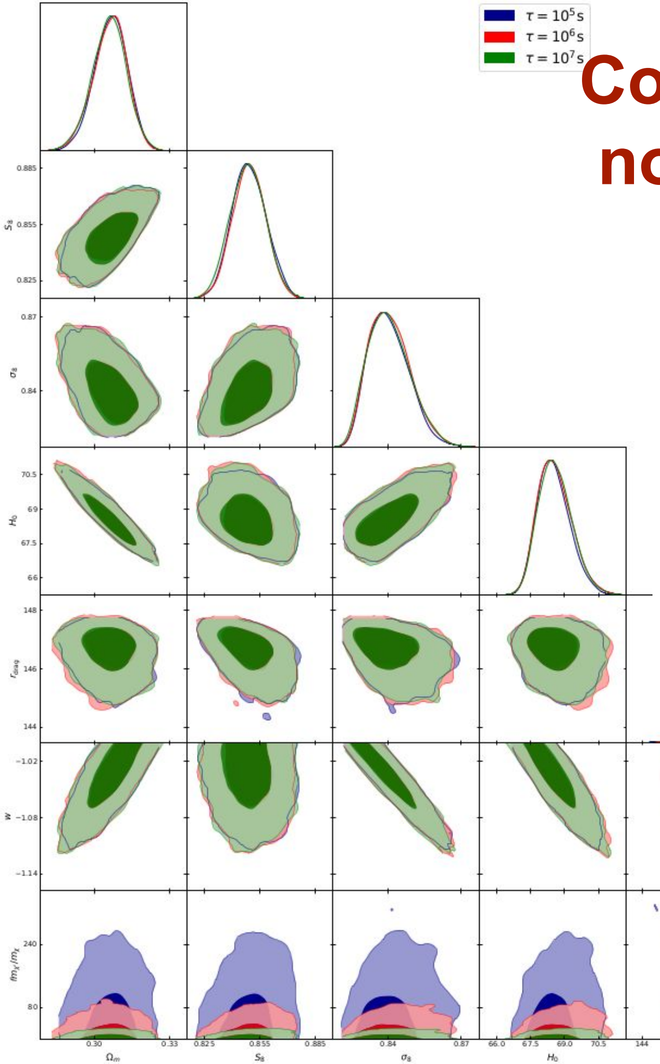
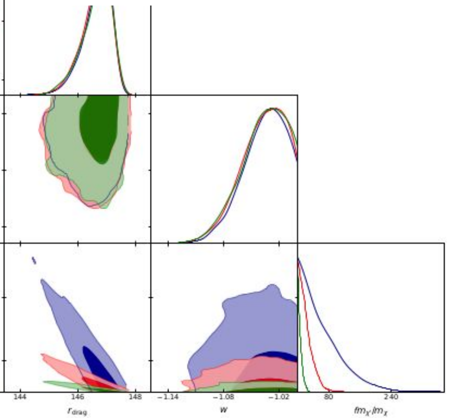
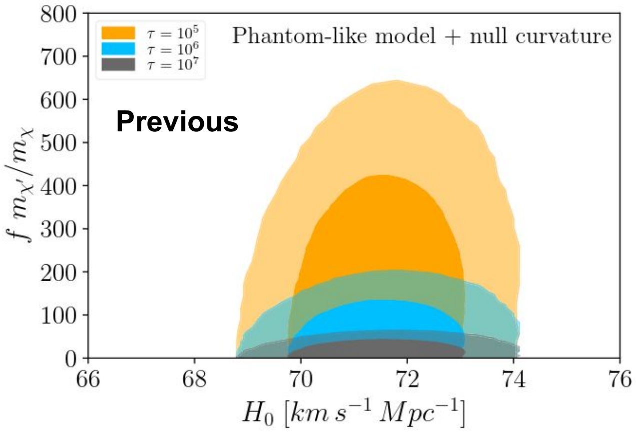
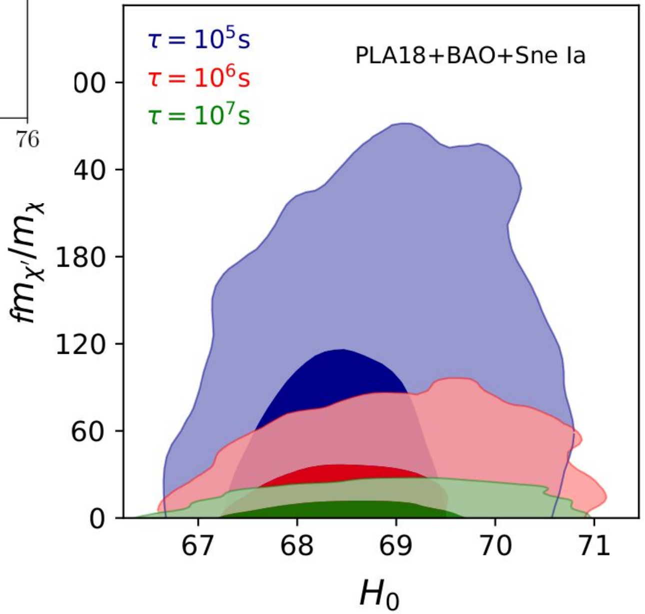
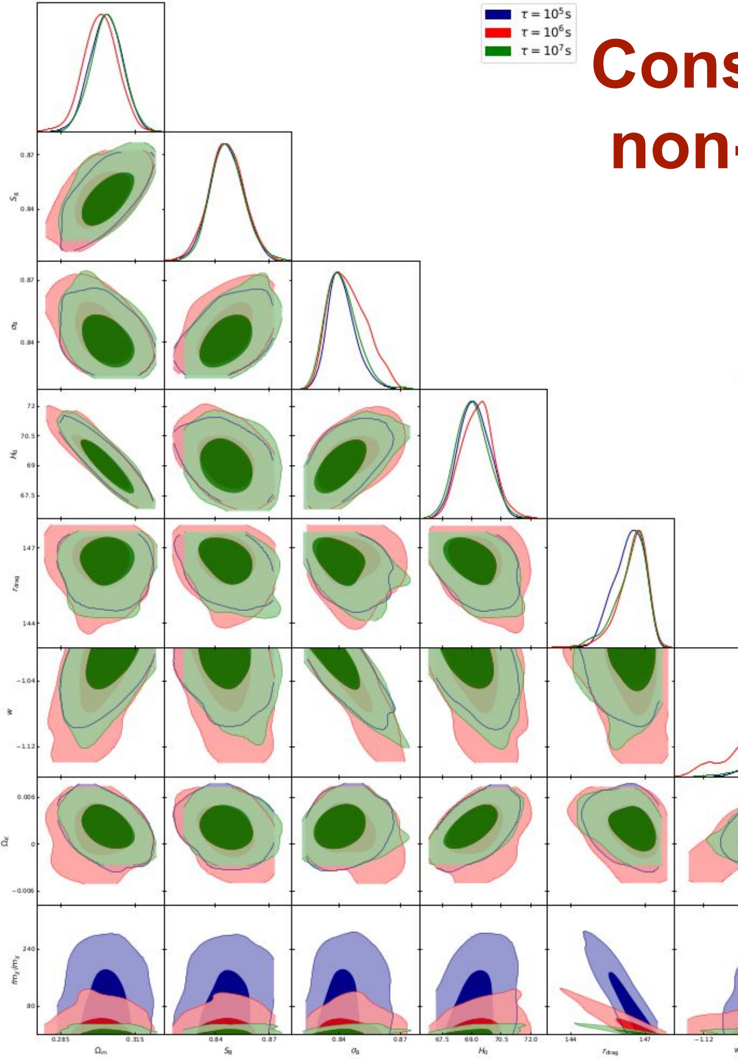



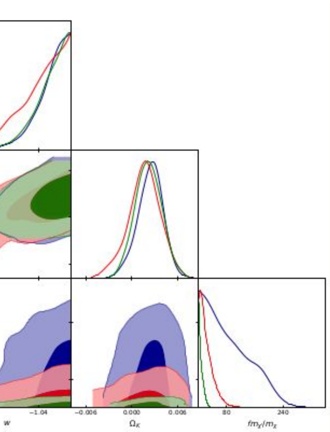


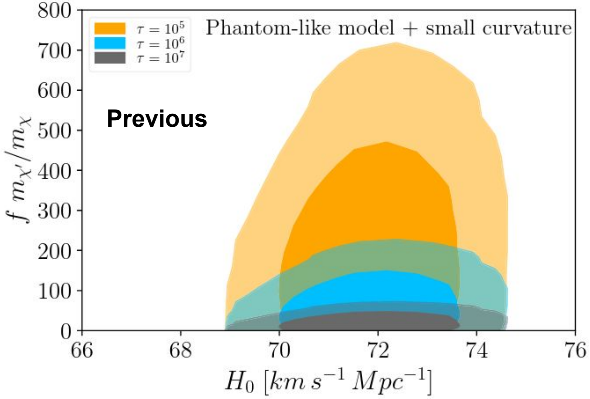
In the wCDM scenario



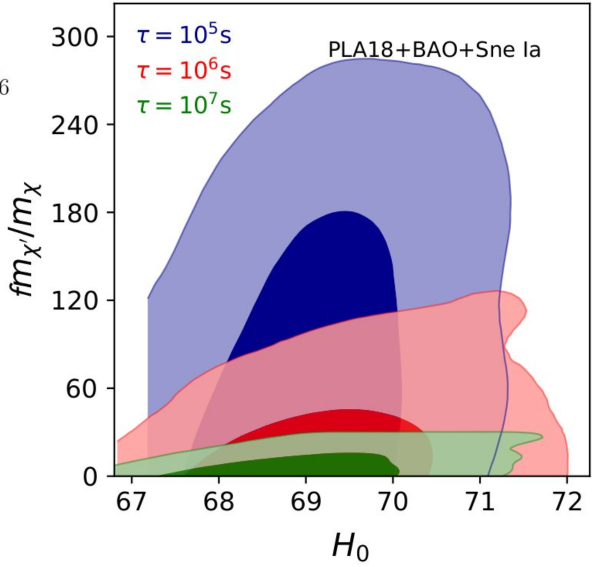
Constraining the Hubble constant from non-thermal production of Dark Matter







In the wCDM + curvature scenario



Perspectives

BBN bounds constraints the decay process to happen between

$$10^2\,s \leq \tau \leq 10^4\,s$$

So, we need to **consider this new prior on our analysis!**

Structure formation needs $f \leq 0.01$ to this non-thermal dark matter production be consistent with clustering data.

We can use this information to put constraints on the fraction $\dfrac{m_{\chi'}}{m_\chi}$


Grazie
Thank You
Merci
Kia Ora
Asante
Maake
Obrigado
Salamat
Arigato
Dyakuyu
Spasibo
Kiitos
Mamana
Terma Kasih
Juspaxar
Mochchakkeram
Dankon
Dank Je
Danke
Chokrane
Multumesc
Matur Nuwun
Cam on ban
Vinaka
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Ua Tsaug Rau Koj
Matondo
Welalin
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