Common Origin of Warm Dark Matter & Dark Radiation

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arXiv: 1911.13267

BROWN

24 Aug - 04 Sep 2020

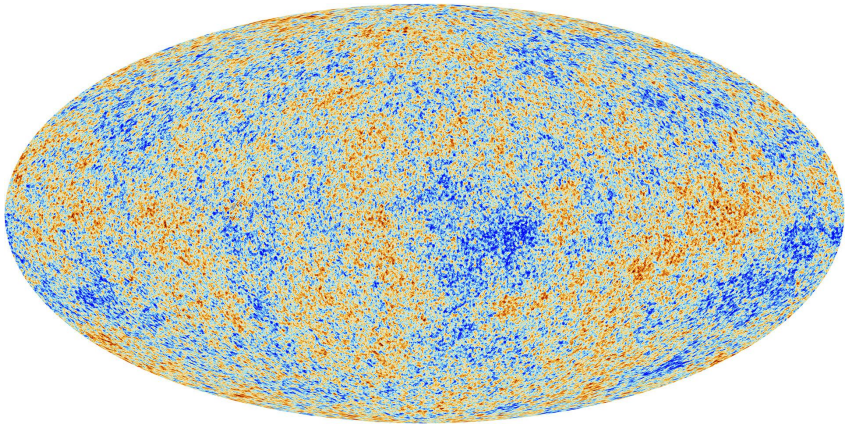
Outline

I. Motivation
II. Model
III. Results
IV. Outlook and Conclusions

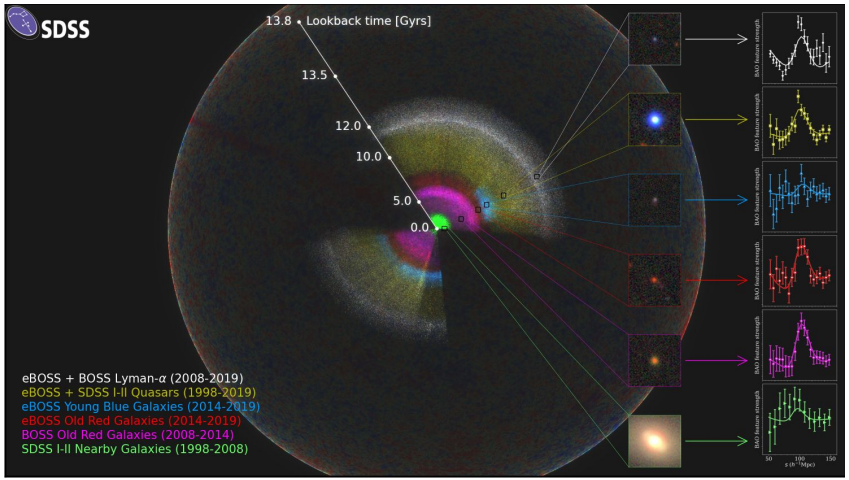
I. Motivation

Precision Cosmology

e.g.:



CMB - Planck



MPS - SDSS

Standard Framework

However...

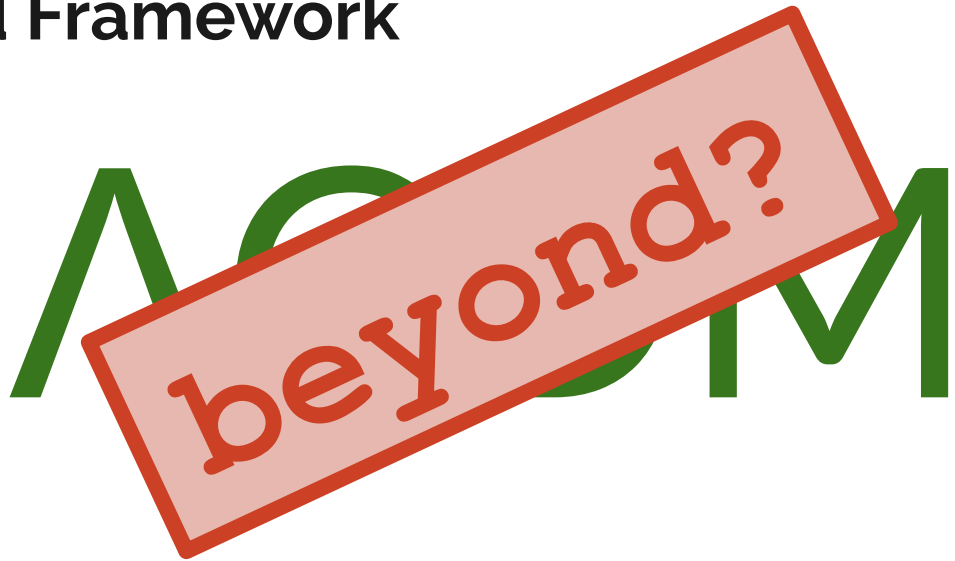
Experimental Tensions, *e.g:*

- H_0 **crisis:** Direct > Indirect
  - SH0ES etc. v. Planck
  - recent reviews: 1907.10625 2001.03624
- σ_8**:** Direct < Indirect
  - KiDS etc. v. Planck
  - recent results: 2007.15632

Theoretical Motivations, *e.g.:*

- DM origin ⇒ rich DS
- Particle Physics Problems:
  - Hierarchy: SUSY & WIMPs
  - Strong CP: axions
  - ν Masses: sterile neutrinos

Standard Framework



Dark Sectors

- Dark Matter...
- … Dark Radiation...
- … also Dark Energy

Beyond ΛCDM: common paths

Dark Radiation (DR): ΔN_{eff}

$$\Delta N_{\rm eff} \frac{\pi^2}{30} \frac{7}{4} \left(\frac{4}{11}\right)^{\frac{4}{3}} T^4$$

- CMB: peaks, damping, equality…
- MPS: increase structure & σ_8 [maintain equality]

Warm Dark Matter (WDM): f_{wdm}, a_{nr} ($\propto 1/T_{nr}$)

$$\lambda_{\rm FS} \simeq 4\ {\rm Mpc} \left(\frac{100\ {\rm eV}}{T_{\rm nr}}\right) \left(\frac{\ln(T_{\rm nr}/T_{\rm eq})}{5}\right)$$

- MPS: Free-streams ⇒ suppresses structure

II. Model

Common Origin of Warm and Relativistic Decay particles

Common
Origin of
Warm
and
Relativistic
Decay particles

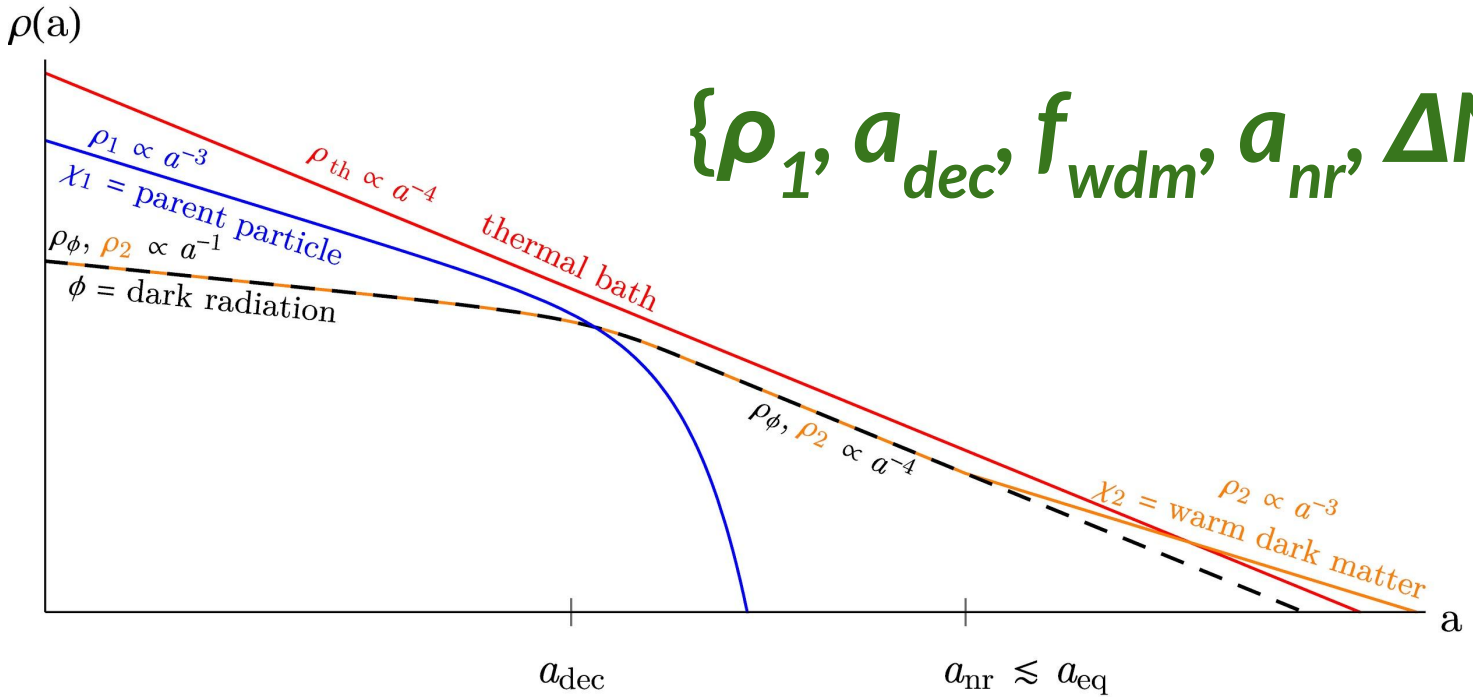
COWaRD:

$$X_1 \longrightarrow X_2 + \varphi$$

COWaRD: $\chi_1 \longrightarrow \chi_2 + \varphi$

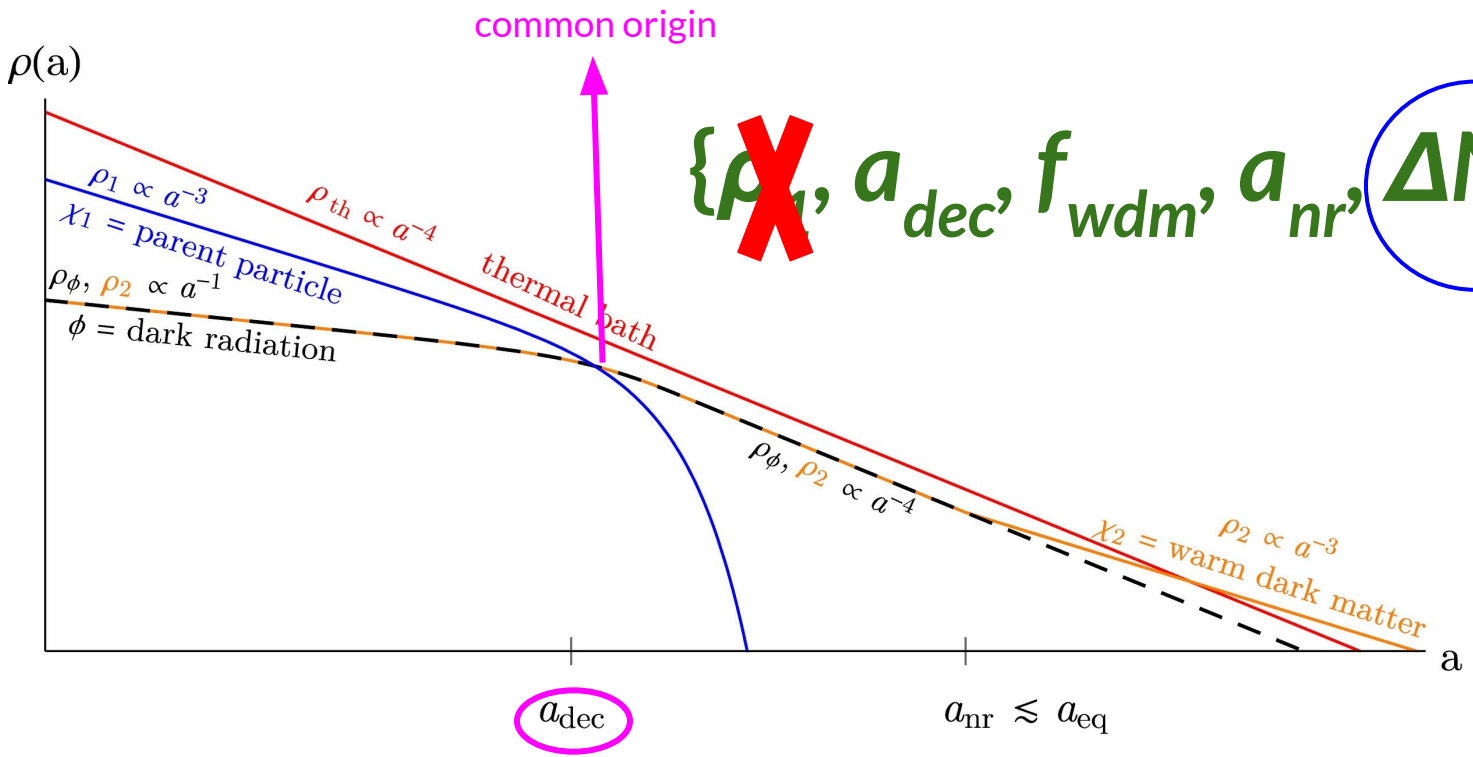
- χ_1: Decaying DM
  - Unstable massive parent
  - $\rho_1, \Gamma \Rightarrow a_{dec}$
- χ_2 : WDM
  - Stable massive daughter
  - f_{wdm}, a_{nr}
- φ: DR
  - Lightest/massless daughter
  - ΔN_{eff}

$$\{\rho_1, a_{dec}, f_{wdm}, a_{nr}, \Delta N_{eff}\}$$



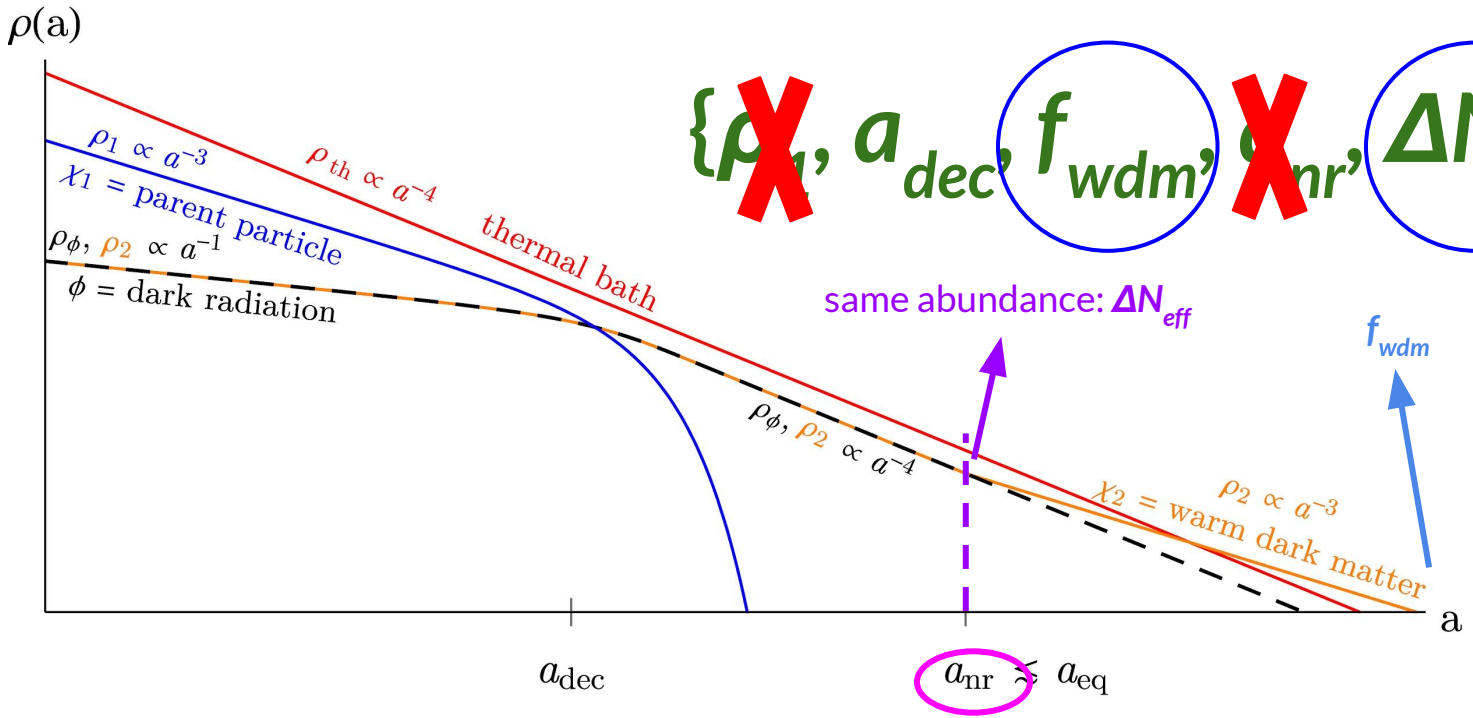
$\{\rho_1, a_{dec}, f_{wdm}, a_{nr}, \Delta N_{eff}\}$

COWaRD Thermal History

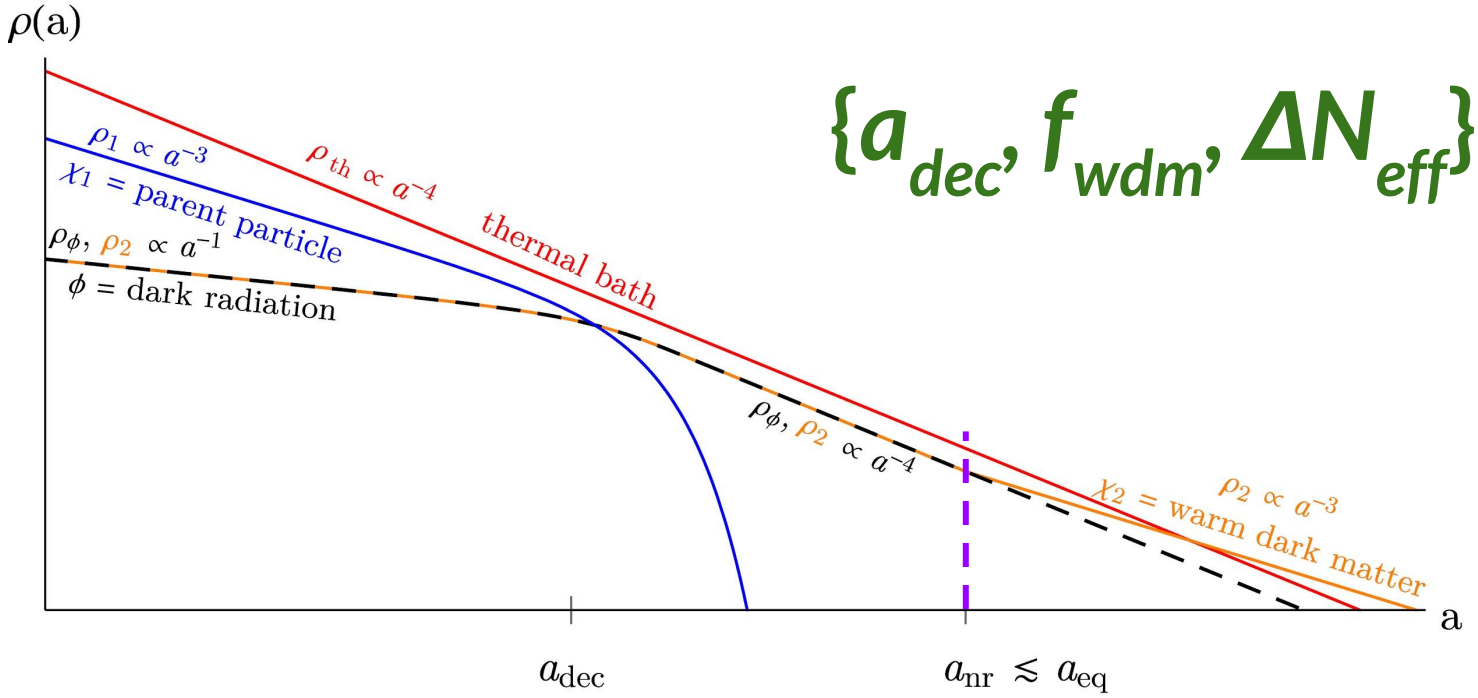


$\{\rho_1, a_{dec}, f_{wdm}, a_{nr}, \Delta N_{eff}\}$

COWaRD Thermal History



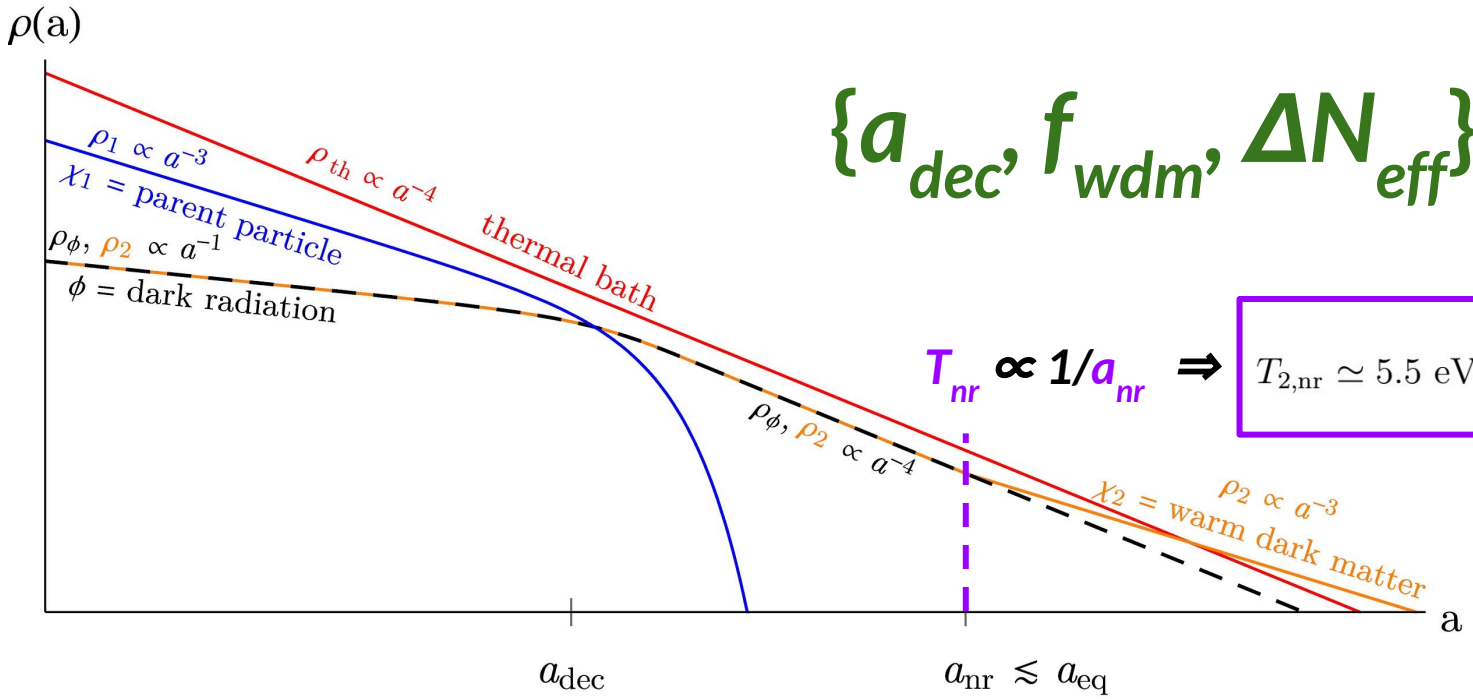
COWaRD Thermal History



$\{a_{dec}, f_{wdm}, \Delta N_{eff}\}$

$a_{nr} \propto \Delta N_{eff} / f_{wdm}$

COWaRD Thermal History



$\{a_{dec}, f_{wdm}, \Delta N_{eff}\}$

$T_{nr} \propto 1/a_{nr} \Rightarrow$

$$T_{2,\mathrm{nr}} \simeq 5.5\ \mathrm{eV} \left(\frac{f_{\mathrm{wdm}}}{\Delta N_{\mathrm{eff}}}\right)$$

$$a_{nr} \propto \Delta N_{eff} / f_{wdm}$$

COWaRD Thermal History

$$\lambda_{\rm FS} \simeq 4\ {\rm Mpc} \left(\frac{100\ {\rm eV}}{T_{\rm nr}}\right) \left(\frac{\ln(T_{\rm nr}/T_{\rm eq})}{5}\right)$$

WDM

$$T_{2,{\rm nr}} \simeq 5.5\ {\rm eV} \left(\frac{f_{\rm wdm}}{\Delta N_{\rm eff}}\right)$$

COWaRD

$$\lambda_{\rm FS} \simeq 4\ {\rm Mpc} \left(\frac{100\ {\rm eV}}{T_{\rm nr}}\right) \left(\frac{\ln(T_{\rm nr}/T_{\rm eq})}{5}\right)$$

WDM

$$\lambda_{FS} \sim \Delta N_{eff}/f_{wdm}$$

$$T_{2,{\rm nr}} \simeq 5.5\ {\rm eV} \left(\frac{f_{\rm wdm}}{\Delta N_{\rm eff}}\right)$$

COWaRD

$$\lambda_{\rm FS} \simeq 4\ {\rm Mpc} \left(\frac{100\ {\rm eV}}{T_{\rm nr}}\right) \left(\frac{\ln(T_{\rm nr}/T_{\rm eq})}{5}\right)$$

WDM

$$T_{2,\rm nr} \simeq 5.5\ {\rm eV} \left(\frac{f_{\rm wdm}}{\Delta N_{\rm eff}}\right)$$

COWaRD

$$\lambda_{FS} \sim \Delta N_{eff}/f_{wdm}$$

$\sigma_8 \leftrightarrow \Delta N_{eff}$

COWaRD: ***anti***-correlated
(naive DR: correlated)

BSM COWaRD examples

$\chi_1 \rightarrow \chi_2 + \varphi$: SUSY+ axions

- axino ⟶ gravitino + axion
- gravitino ⟶ axino + axion

$\{m_1, m_2, N_{1,ini}\}$ ⇒ $\{a_{dec}, f_{wdm}, \Delta N_{eff}\}$

particle physics | cosmology

III. Results

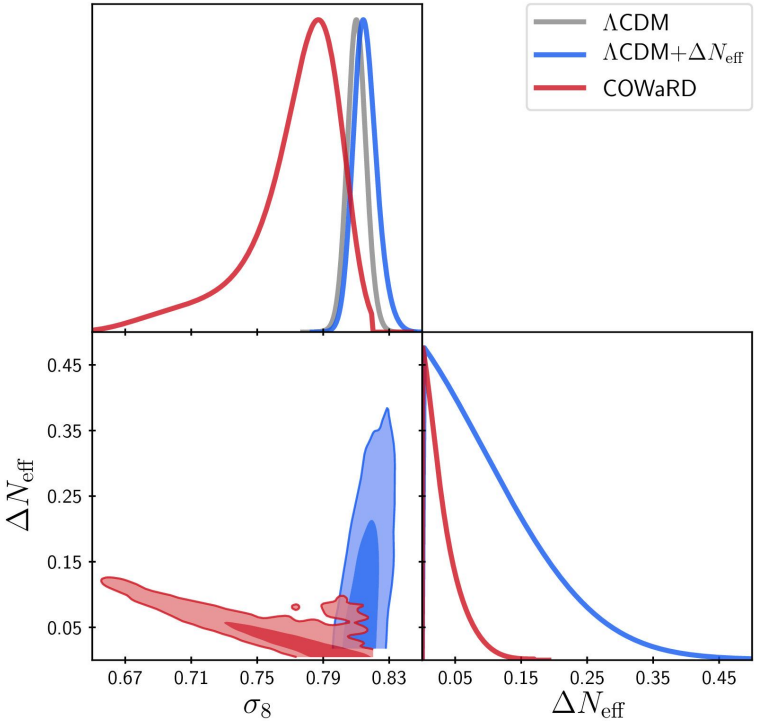
Implementation

Numerics

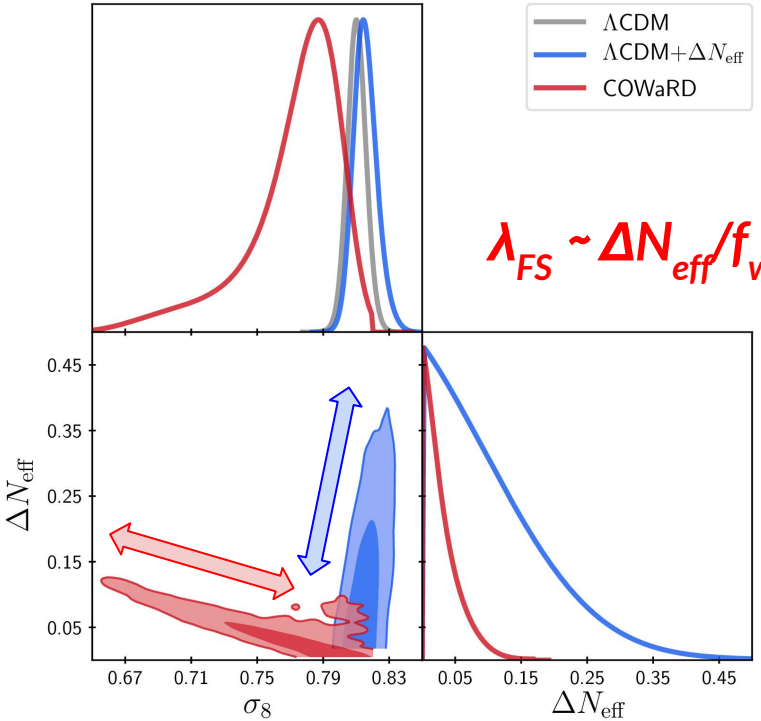
- CLASS Boltzmann solver
- MontePython MCMC
  - Small a_{dec} no effect on fit ⇒ assumed χ_1 already decayed (fixed $a_{dec}=10^{-7}$)
  - ⇒ Fit only $\{\Delta N_{eff}, f_{wdm}\}$

Data

- CMB: Pl18 TT+TE+EE+lens
- BAO: 6dFGS+SDSS+BOSS
- **No σ_8 data**



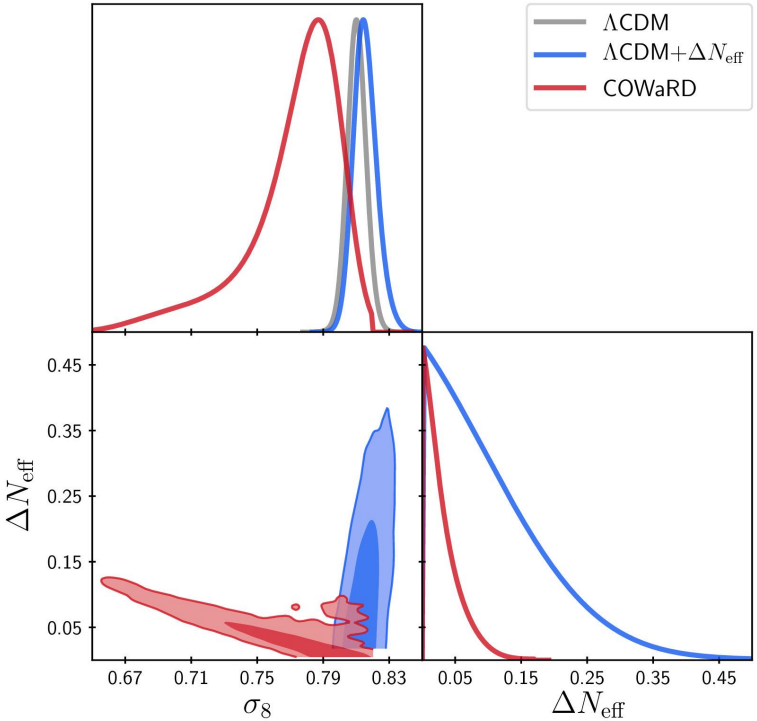
Numerical Results

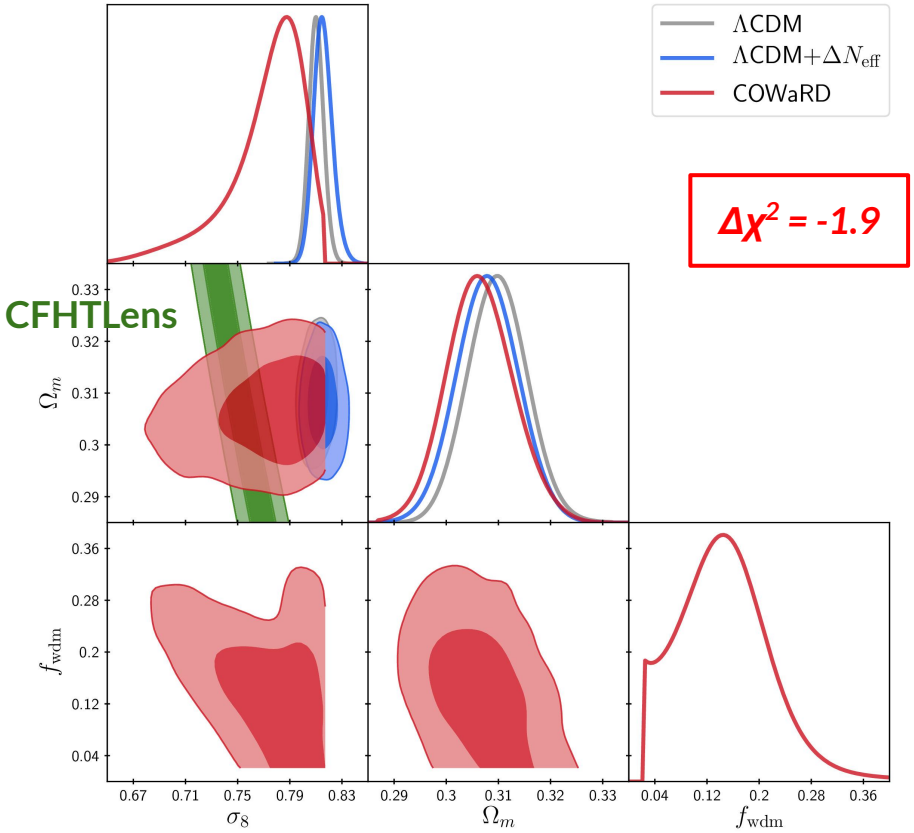


$\lambda_{FS} \sim \Delta N_{eff}/f_{wdm}$

correlated: usual DR (ΔN_{eff}) behavior
anti-correlated: COWaRD

Numerical Results





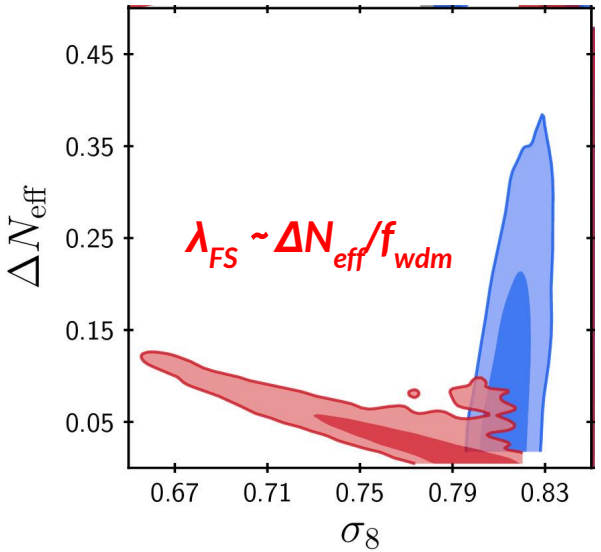
$\Delta\chi^2 = -1.9$

Numerical Results

IV. Outlook & Conclusions

Outlook

- CMB-S4: $\Delta N_{eff} \geq 0.03$
  - COWaRD fit to CMB: predicts $\sigma_8(\Delta N_{eff})$
- Future work:
  - Full decay implementation (solve psd function)



Conclusions

Particular: **COWaRD**

- Theoretically motivated model
- Solves σ_8 tension w/o degrading CMB fit, *and w/o asking it to!*
- Combines DR & WDM
  - Interesting effects
  - Few parameters

General: moral

- **Naive ΛCDM extensions ≠ their actual model realization!!!**
  - Within pheno models:
    - parameters can act differently...
    - … and be related!
  - Actual realizations can give surprising cosmology!

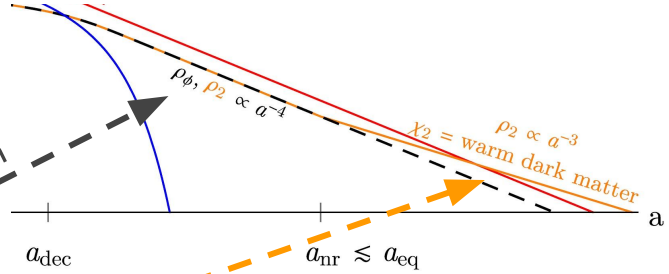
¡Gracias!

Back-up slides

COWaRD: a_{nr}

$$\rho_{2,nr}(a_{nr})^4 \sim \rho_{\varphi,nr}(a_{nr})^4 \propto \Delta N_{eff}$$

$$\rho_{2,nr}(a_{nr})^3 \approx \rho_{2,0} \propto f_{wdm}$$



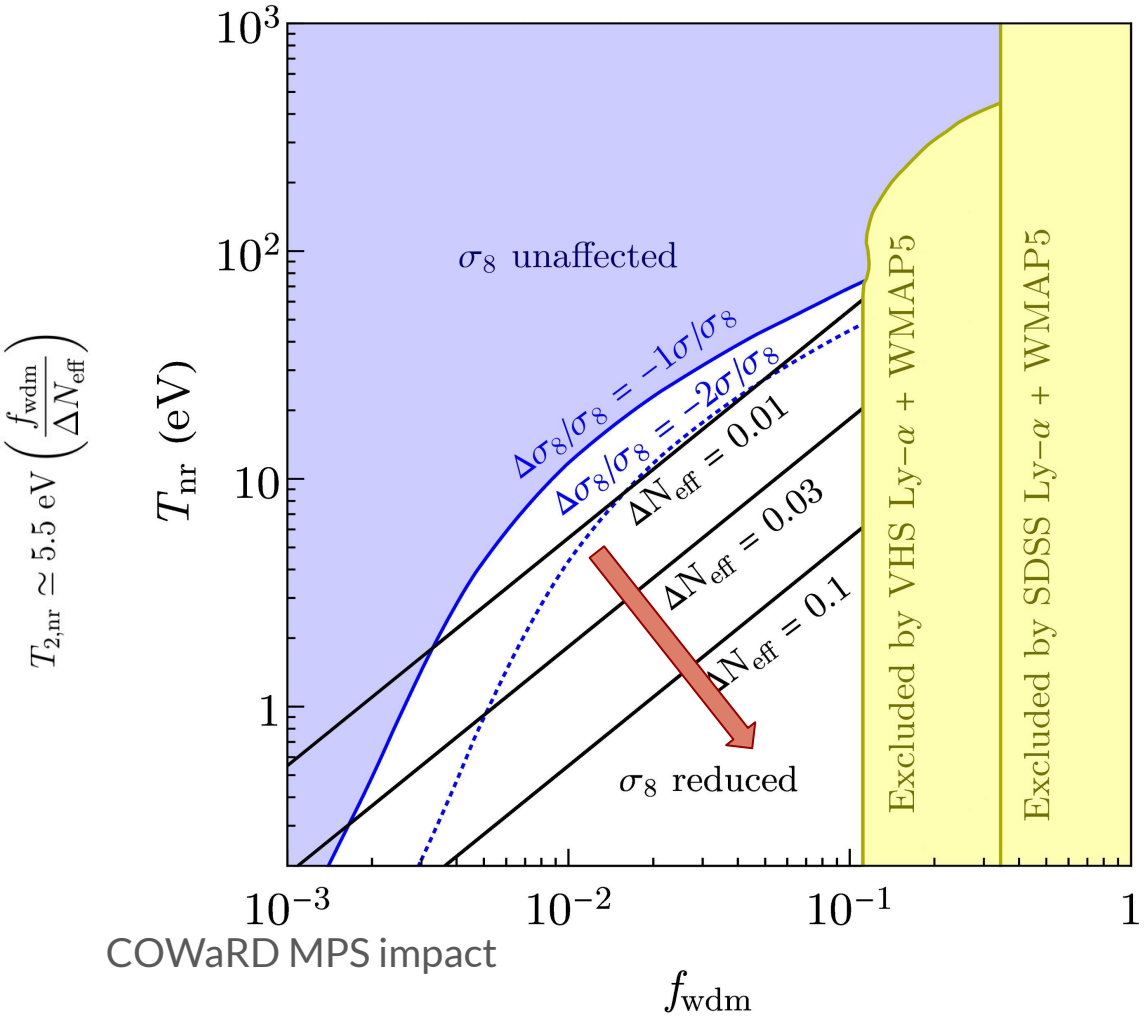
COWaRD: a_{nr}

$$\rho_{2,nr}(a_{nr})^4 \sim \rho_{\varphi,nr}(a_{nr})^4 \propto \Delta N_{eff}$$

$$\rho_{2,nr}(a_{nr})^3 \approx \rho_{2,0} \propto f_{wdm}$$

$$\Rightarrow f_{wdm} a_{nr} \propto \Delta N_{eff}$$

$$T_{nr} \propto 1/a_{nr} \Rightarrow T_{2,\mathrm{nr}} \simeq 5.5\ \mathrm{eV} \left(\frac{f_{\mathrm{wdm}}}{\Delta N_{\mathrm{eff}}} \right)$$



COWaRD MPS impact

$\lambda_{FS} \sim \Delta N_{eff}/f_{wdm}$

$\sigma_8 \leftrightarrow \Delta N_{eff}$

Naive DR: correlated

COWaRD: ***anti***-correlated

BSM COWaRD examples

$\chi_1 \rightarrow \chi_2 + \varphi$: SUSY+ axions

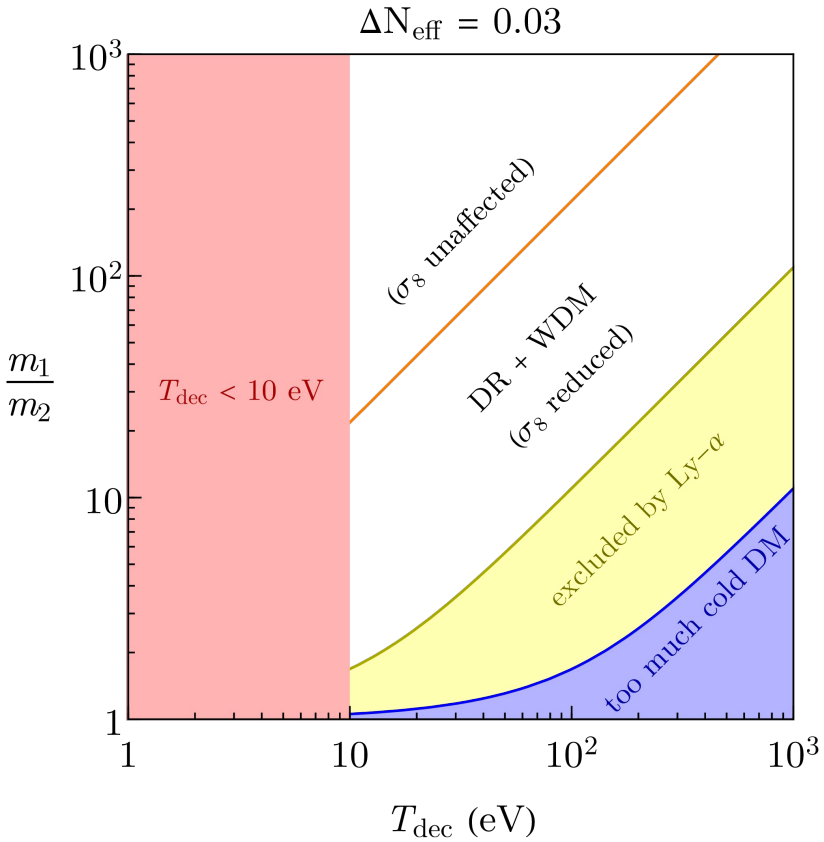
- **axino ⟶ gravitino + axion**
- gravitino ⟶ axino + axion

$$\Gamma_{\tilde{a}\to\tilde{G}a} = \frac{m_{\tilde{a}}^5}{96\pi m_{3/2}^2 M_{\rm Pl}^2}\left(1-\frac{m_{3/2}}{m_{\tilde{a}}}\right)^2\left(1-\left(\frac{m_{3/2}}{m_{\tilde{a}}}\right)^2\right)^3$$

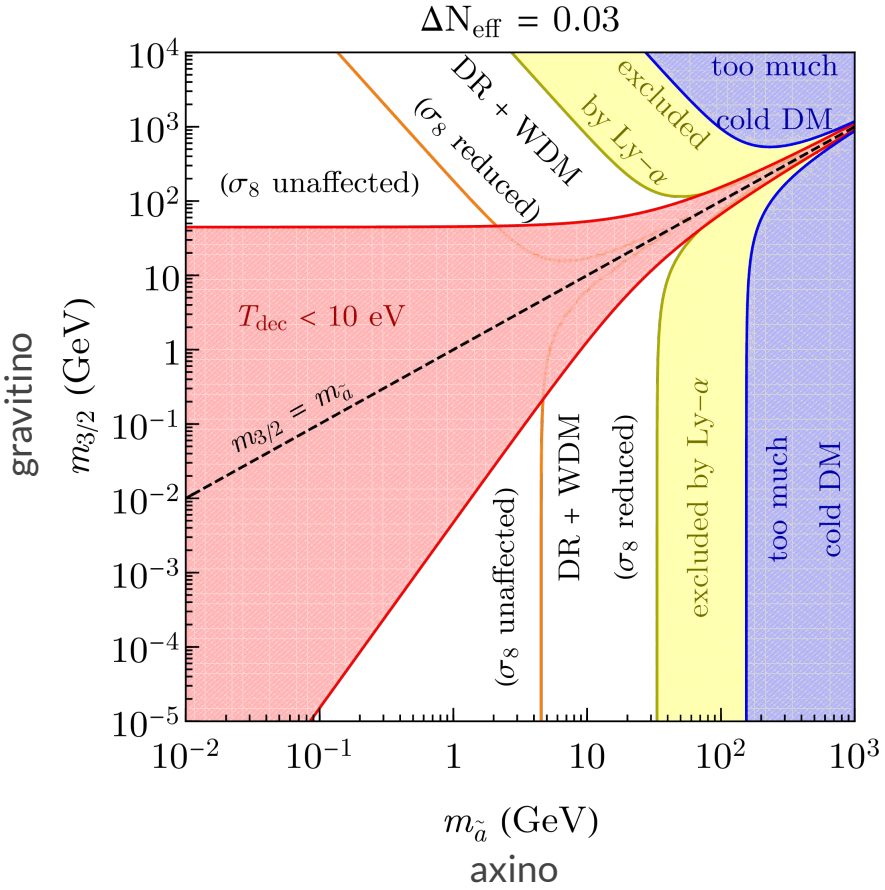
$\{m_1, m_2, N_{1,ini}\}$ ⇒ $\{a_{dec}, f_{wdm}, \Delta N_{eff}\}$

particle physics

cosmology



Other parameters: T_{dec} & m_1/m_2


$\Delta N_{eff} = 0.03$
too much
cold DM
excluded
by Ly−α
DR + WDM
(σ_8 reduced)
(σ_8 unaffected)
$T_{dec} < 10$ eV
$m_{3/2} = m_{\tilde{a}}$
gravitino
$m_{3/2}$ (GeV)
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
(σ_8 unaffected)
DR + WDM
(σ_8 reduced)
excluded by Ly−α
too much
cold DM
10^{-2}
10^{-1}
1
10
10^2
10^3
$m_{\tilde{a}}$ (GeV)
axino

m_1 & m_2

Best-fit χ^2					
Data Sets	ΛCDM	ΛCDM+$\Delta N_{\rm eff}$	ΛCDM+$\Delta N_{\rm eff}$ (= 0.06)	COWaRD	COWaRD ($\Delta N_{\rm eff}$ = 0.03)
high-ℓ TTTEEE	2347.56	2348.03	2349.39	2345.94	2346.38
low-ℓ EE	396.37	396.72	396.35	395.95	395.96
low-ℓ TT	22.86	22.96	22.27	22.47	22.25
lensing	8.87	8.79	9.06	10.11	10.45
Pantheon	1027.49	1027.08	1027.05	1027.06	1027.02
BAO	5.57	5.35	5.32	5.29	5.24
TOTAL	3808.72	3808.92	3809.44	3806.82	3807.28
$\Delta\chi^2_{\rm eff}$	—	+0.2	+0.72	−1.9	−1.44

TABLE I. Minimum *effective chi square* $\chi^2_{\rm eff} = -2\ln\mathcal{L}$ of the ΛCDM and COWaRD models.

Best Fit χ^2

Parameter values					
Parameter	ΛCDM	ΛCDM+$\Delta N_{\rm eff}$	ΛCDM+$\Delta N_{\rm eff}$ (= 0.06)	COWaRD	COWaRD ($\Delta N_{\rm eff}$ = 0.03)
$100\ \omega_b$	$2.245^{+0.014}_{-0.014}$	$2.252^{+0.015}_{-0.015}$	$2.249^{+0.013}_{-0.014}$	$2.254^{+0.015}_{-0.015}$	$2.254^{+0.014}_{-0.015}$
n_s	$0.968^{+0.004}_{-0.004}$	$0.971^{+0.004}_{-0.005}$	$0.970^{+0.004}_{-0.004}$	$0.970^{+0.004}_{-0.004}$	$0.970^{+0.004}_{-0.004}$
$\tau_{\rm reio}$	$0.056^{+0.007}_{-0.008}$	$0.057^{+0.007}_{-0.008}$	$0.057^{+0.007}_{-0.007}$	$0.052^{+0.008}_{-0.008}$	$0.052^{+0.008}_{-0.009}$
$100\ \theta_s$	$1.0420^{+0.00029}_{-0.00029}$	$1.0417^{+0.00037}_{-0.00033}$	$1.0418^{+0.00028}_{-0.00029}$	$1.0419^{+0.00032}_{-0.00031}$	$1.0419^{+0.00030}_{-0.00030}$
$\ln 10^{10} A_s$	$3.048^{+0.014}_{-0.015}$	$3.053^{+0.014}_{-0.016}$	$3.051^{+0.015}_{-0.014}$	$3.037^{+0.016}_{-0.017}$	$3.037^{+0.017}_{-0.018}$
$\omega_{\rm cdm}$	$0.1192^{+0.0009}_{-0.0009}$	$0.1210^{+0.0012}_{-0.0020}$	$0.1202^{+0.0009}_{-0.0010}$	$0.1029^{+0.0096}_{-0.0097}$	$0.1038^{+0.0056}_{-0.0087}$
$\Delta N_{\rm eff}$	—	$0.110^{+0.028}_{-0.110}$	0.06	$0.031^{+0.007}_{-0.031}$	0.03
$f_{\rm wdm}$	—	—	—	$0.138^{+0.074}_{-0.082}$	$0.130^{+0.067}_{-0.044}$
H_0	$67.77^{+0.43}_{-0.43}$	$68.43^{+0.55}_{-0.77}$	$68.13^{+0.42}_{-0.41}$	$68.19^{+0.47}_{-0.53}$	$68.21^{+0.46}_{-0.48}$
σ_8	$0.801^{+0.006}_{-0.006}$	$0.816^{+0.007}_{-0.008}$	$0.813^{+0.006}_{-0.006}$	$0.773^{+0.038}_{-0.014}$	$0.770^{+0.006}_{-0.010}$
Ω_m	$0.310^{+0.006}_{-0.006}$	$0.308^{+0.006}_{-0.006}$	$0.309^{+0.005}_{-0.006}$	$0.307^{+0.006}_{-0.007}$	$0.306^{+0.006}_{-0.006}$

TABLE II. Mean values and 68% C.L. intervals of the parameters of the ΛCDM and COWaRD models.

Parameter values

Contour Plots