XIV International Workshop on Interconnections between Particle Physics and Cosmology

Hints for decaying dark matter from S_8 measurements

Guillermo Franco Abellán

Based on:
GFA, Murgia, Poulin, Lavalle, arXiv:2008.09615
GFA, Murgia, Poulin, arXiv:2102.12498

20/05/21

The S_8 tension

$\boxed{\boldsymbol{S_8 = \sigma_8\sqrt{\frac{\Omega_m}{0.3}}}}$ where $\sigma_8 = \int \frac{k^3}{2\pi} P_m(k) W_R^2(k) d\ln k$ at $R = 8\ \mathrm{Mpc}/h$

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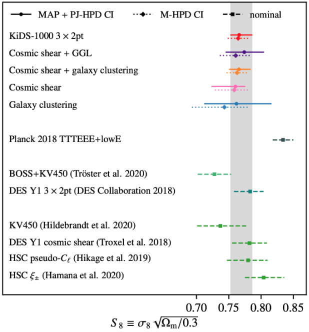
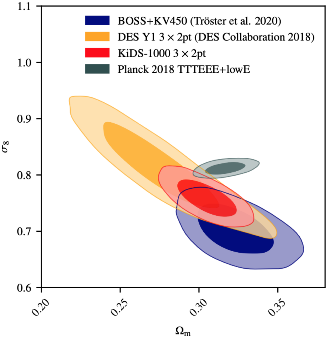
2−3σ tension between Weak Lensing and Planck (assuming flat ΛCDM)





From 2008.11285

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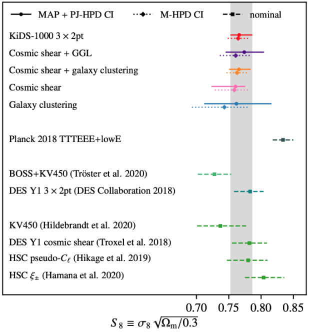

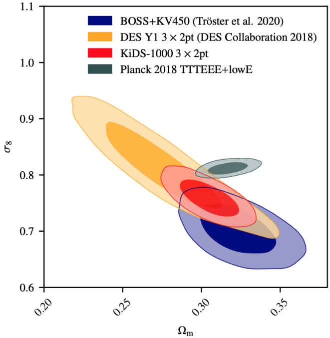

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BOSS+KIDS+2dfLenS analysis revealed tension is mainly **driven by σ_8**

The stability of dark matter

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- Could the S_8 tension be explained by **DM decays** ?

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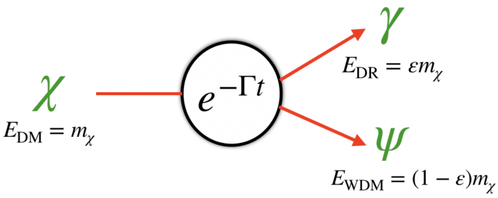
- We explore DM decays to massless (**Dark Radiation**) and massive (**Warm Dark Matter**) particles, $\chi(\mathrm{DM}) \to \gamma(\mathrm{DR}) + \psi(\mathrm{WDM})$



Two extra parameters:
Γ and ***ε***

$$\varepsilon = \frac{1}{2}\left(1 - \frac{m_\psi^2}{m_\chi^2}\right) \in \left[0, \frac{1}{2}\right]$$

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Evolution of perturbations: full description

- Effects on $P(k)$ and C_ℓ? $\rightarrow$ Track **linear perturbations** for the daughter particles: δ_i, θ_i and σ_i (for $i = \mathrm{dr}, \mathrm{wdm}$)

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- Boltzmann hierarchy of eqs. dictate the evolution of the **p.s.d. multipoles** $\delta f_\ell(q, k, \tau)$

  - ◇ **DR treatment is easy**, momentum d.o.f. are integrated out

  - ◇ **For WDM**, one needs to follow the evolution of the full p.s.d. Computationally expensive $\rightarrow$ $\mathcal{O}(\mathbf{10^8})$ **ODEs to solve !**

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Based on a **fluid** description for massive neutrinos (1104.2935)

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$$\dot{\theta}_{\rm wdm} = -\mathcal{H}(1-3c_a^2)\theta_{\rm wdm} + \frac{c^2_{\rm syn}}{1+w}k^2\delta_{\rm wdm} - k^2\sigma_{\rm wdm} - a\Gamma(1-\varepsilon)\frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{1+c_a^2}{1+w}\theta_{\rm wdm}$$

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where

$$c_a^2(\tau) = w\left(5 - \frac{\mathfrak{p}_{\rm wdm}}{\bar{P}_{\rm wdm}} - \frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{a\Gamma}{3w\mathcal{H}}\frac{\varepsilon^2}{1-\varepsilon}\right)\left[3(1+w) - \frac{\bar{\rho}_{\rm dm}}{\bar{\rho}_{\rm wdm}}\frac{a\Gamma}{\mathcal{H}}(1-\varepsilon)\right]^{-1}$$

and

$$c_{\rm syn}^2(k,\tau) = c_a^2(\tau)\left[1 + (1-2\varepsilon)T(k/k_{\rm fs})\right]$$

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Accurate at the $\mathcal{O}(0.1\%)$ level in C_ℓ, and at $\mathcal{O}(1\%)$ level in $P(k)$

CPU time reduced from ~ 1 day to ~ 1 minute!

Impact on the linear matter power spectrum

The WDM daughter leads to a **power suppression** in $P_m(k)$

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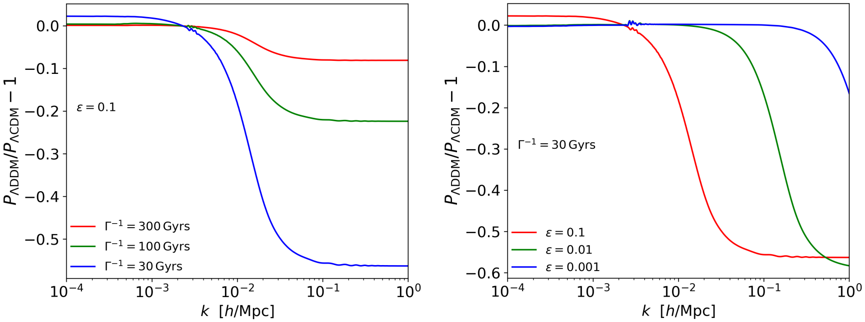
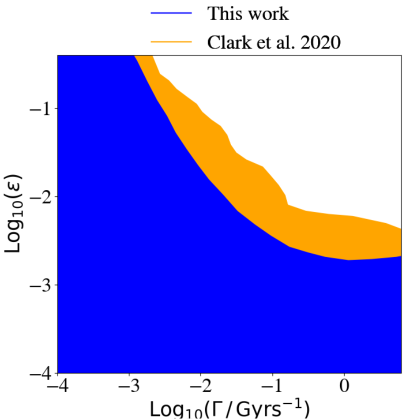
The WDM daughter leads to a **power suppression** in $P_m(k)$ at small scales, $\boldsymbol{k} > \boldsymbol{k}_{\rm fs}$, where $k_{\rm fs} \sim \mathcal{H}/c_a$

- $\boldsymbol{\Gamma}$ controls the **depth** of the power suppression
- ε controls the **cut-off** scale $(k_{\rm fs})$



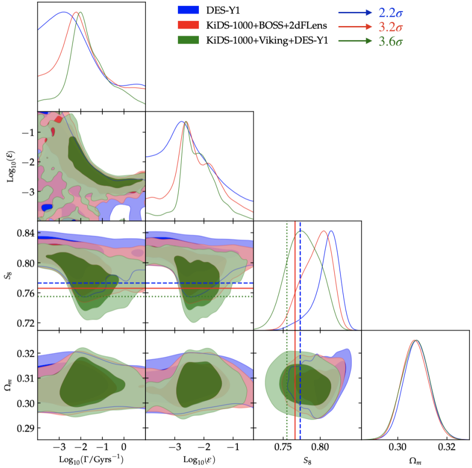
Results: General constraints

Modified version of public Boltzmann solver `CLASS`
Run MCMC against latest **BAO**,**SNIa** and **Planck** data



Constraints are up to **1 order of magnitude stronger** than previous literature (due to the inclusion of WDM perturbations)

Results: resolving the S_8 tension



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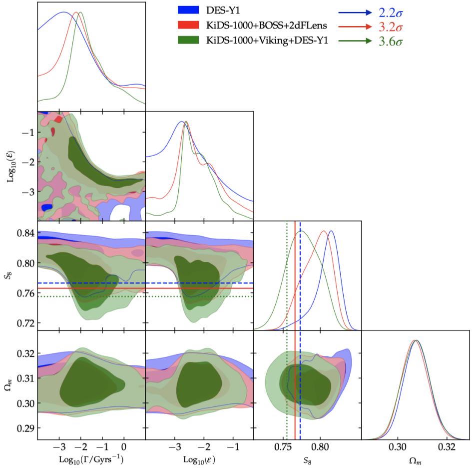

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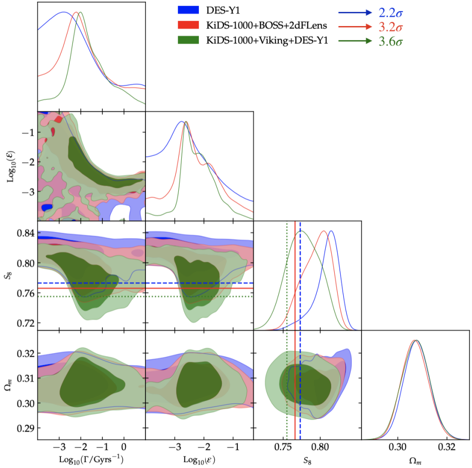

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- Due to the $\Delta\chi^2_{\rm min} < 0$ the DM decay is detected at $\mathbf{\Gamma^{-1} \simeq 55\ (\varepsilon/0.007)^{1.4}}$ **Gyrs**
- The level of detection depends on the level of tension with ΛCDM

N.B.: Simpler solutions, like **massive neutrinos**, *don't work*. The 2-body decay gives a *better fit* due to the **time-dependence of the suppression**

Interesting implications

- **Model building**: Why $\varepsilon \ll 1/2$, i.e., $m_{\rm wdm} \sim m_{\rm dm}$?
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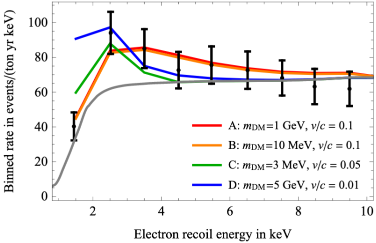
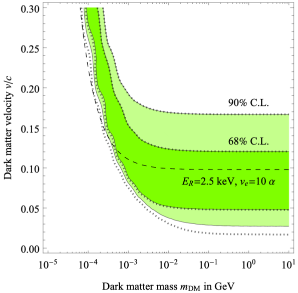
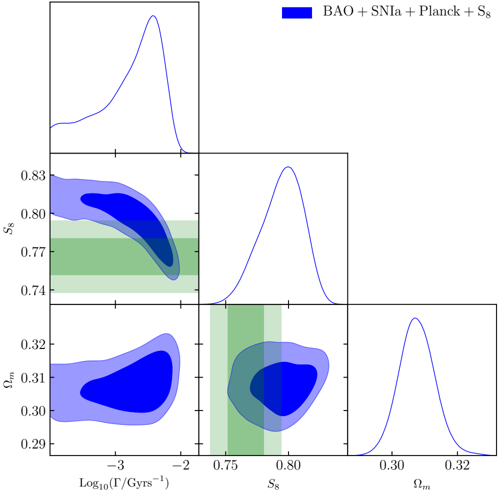
- **Small-scale crisis of ΛCDM**: Reduction in the abundance of subhalos and their concentrations (1309.7354, 1406.0527)

- **Xenon-1T excess:** It could be explained by a fast DM component, such as the WDM, with $v/c \simeq \varepsilon$ (2006.10735)



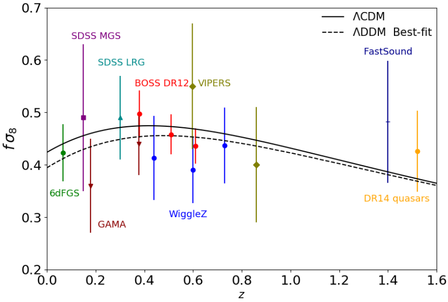


Redo the **BAO+SNIa+Planck+S$_8$** analysis, but fixing $\varepsilon = \mathbf{0.05}$ as a proxy for the Xenon-1T detection



The S_8 tension can still be resolved if DM decays with $\boldsymbol{\Gamma^{-1} \simeq 275}$ **Gyrs** !

Prospects



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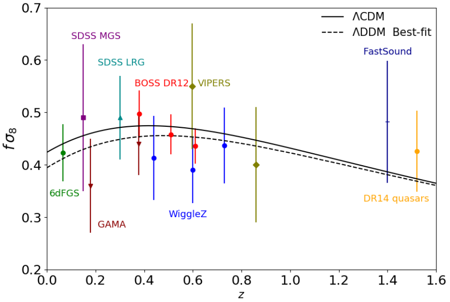

Accurate measurements of $f\sigma_8$ at $0 \lesssim z \lesssim 1$ will further test the 2-body decay

- Predict **non-linear matter spectrum** (using either N-body simulations or EFT of LSS)
- Investigate further decaying models that could explain the Xenon-1T excess and survive cosmic constraints

Conclusions

- First thorough cosmological analysis of the 2-body DM decay scenario and **strongest model-independent** constraints up to date
- It can **resolve the S_8 tension** (as opposed to massive neutrinos) but the level of detection depends on the chosen S_8 data
- It could have interesting implications for model building, the small-scale crisis, and the recent **Xenon-1T excess**
- **Future growth factor** measurements can further test this scenario

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THANKS FOR YOUR ATTENTION

$$f(q,k,\mu,\tau) = \bar{f}(q,\tau) + \delta f(q,k,\mu,\tau)$$

Expand δf in multipoles. The Boltzmann eq. leads to the following **hierarchy** (*in synchronous gauge comoving with the mother*)

$$\begin{aligned}
\frac{\partial}{\partial\tau}(\delta f_0) &= -\frac{\mathbf{q}k}{\boldsymbol{\mathcal{E}}}\delta f_1 + q\frac{\partial\bar{f}}{\partial q}\frac{\dot{h}}{6} + a\frac{\Gamma\bar{N}_{\rm dm}(\tau)}{4\pi q^3\mathcal{H}}\delta(\tau-\tau_q)\delta_{\rm dm},\\
\frac{\partial}{\partial\tau}(\delta f_1) &= \frac{\mathbf{q}k}{3\boldsymbol{\mathcal{E}}}\left[\delta f_0 - 2\delta f_2\right],\\
\frac{\partial}{\partial\tau}(\delta f_2) &= \frac{\mathbf{q}k}{5\boldsymbol{\mathcal{E}}}\left[2\delta f_1 - 3\delta f_3\right] - q\frac{\partial\bar{f}}{\partial q}\frac{(\dot{h}+6\dot{\eta})}{15},\\
\frac{\partial}{\partial\tau}(\delta f_\ell) &= \frac{\mathbf{q}k}{(2\ell+1)\boldsymbol{\mathcal{E}}}\left[\ell\delta f_{\ell-1} - (\ell+1)\delta f_{\ell+1}\right] \qquad (\text{for } \ell\geq 3).
\end{aligned}$$

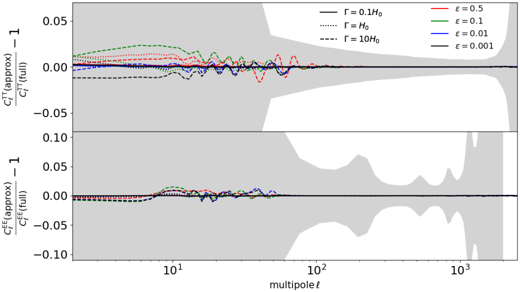
where $q = a(\tau_q)p_{\rm max}$. In the relat. limit $\mathbf{q}/\boldsymbol{\mathcal{E}} = 1$, so we can take

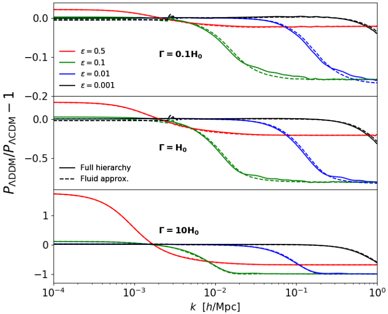
$F_\ell \equiv \frac{4\pi}{\rho_c}\int dq\; q^3\delta f_\ell$ and **integrate out the dependency on** q

Bonus II: Checking the accuracy of the WDM fluid approximation

We compare two configurations

- **Full**: Solve Boltzmann hierarchy with $N_q = 10^4$
- **Approx**: Solve Boltzmann hierarchy with $N_q = 300$ and switch-on fluid eqs. at $k\tau > 25$



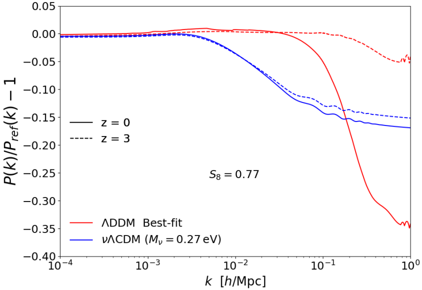


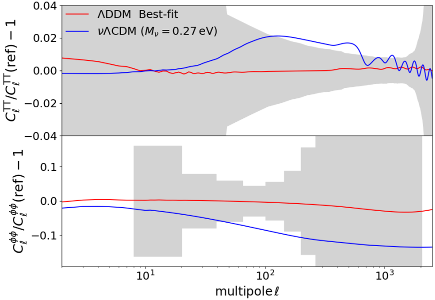
The residual error on S_8 is $\sim 0.65\%$, smaller than the $\sim 1.8\%$ error of the measurement from BOSS+KIDS+2dfLenS

Bonus III: Comparison with massive neutrinos

- The WDM leads to the same $S_8 \simeq 0.77$ value as massive neutrinos with $\boldsymbol{M_\nu = 0.27}$ eV [2] (**ruled out by CMB**)

- The 2-body decay gives a better fit thanks to the **time-dependence of the power suppression** and the cut-off scale

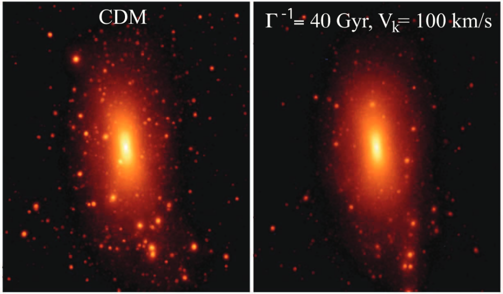


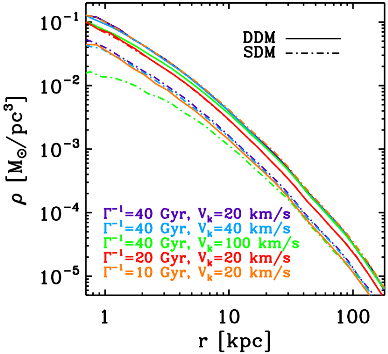


[2] And a smaller $\omega_{\rm cdm}$, to keep $\Omega_{\rm m}$ fixed.

Bonus IV: Implications for small-scale crisis

Results of N-body simulations from 1406.0527

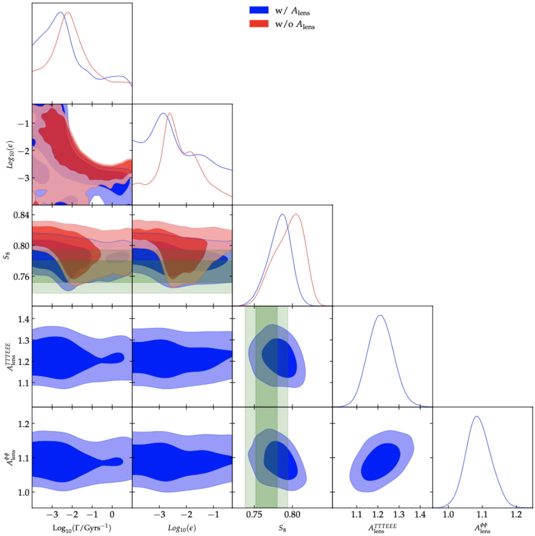




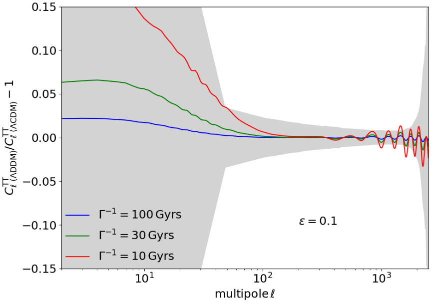
Recoil kick velocity received by WDM given by $V_{\rm k} \sim \varepsilon c$

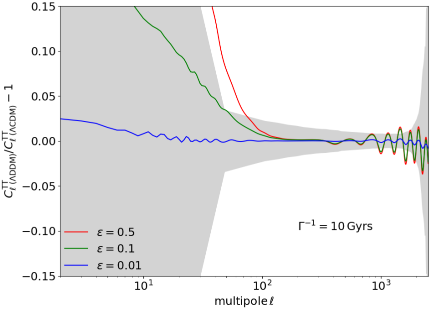
Bonus V: Relation to the $A_{\rm lens}$ anomaly

Redo the **BAO+SNIa+Planck+S$_8$** analysis,
but *marginalising over lensing information* ($A_{\rm lens}^{\phi\phi}$ and $A_{\rm lens}^{\rm TTTEEE}$)



Low-ℓ: **enhanced** Late Integrated Sachs-Wolfe (**LISW**) effect
High-ℓ: **suppressed lensing** (higher contrast between peaks)





Similar signatures for large Γ and small ε or vice-versa