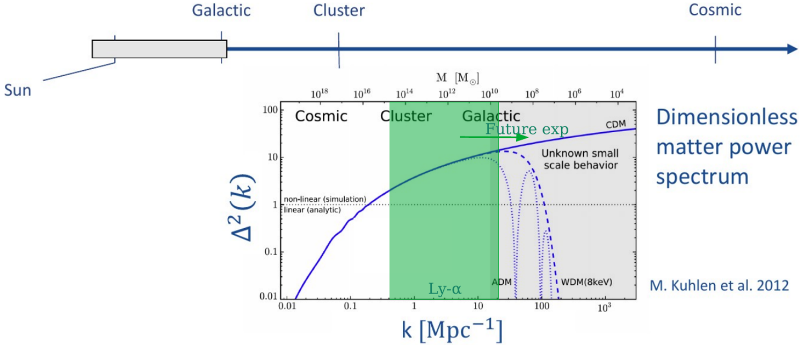
Non Cold Dark Matter
from Burdened Primordial Black Holes

Laura Lopez Honorez

based on 2604.00090 and JCAP 08 (2020) 045 in collaboration with
V. Thoss, M. Hufnagel & F. Kühnel and I. Baldes, Q. Decant & D.C. Hooper

IDM, Zaragoza, 1-5/06/2026

Non-Cold Dark Matter erases small scale structures



- WDM free-streaming from overdense to underdense regions
  $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int v/adt$
- Effects $P(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], including non-thermal FIMPs [see talk O. Lebedev] or e.g. DM from PBH evap [this talk].

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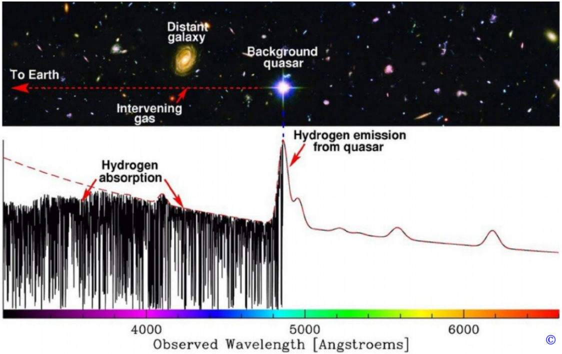

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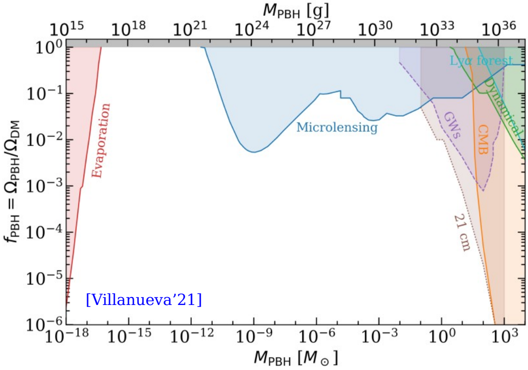
- Tested against Lyman-α: absorption lines along line of sights to distant quasars probe smallest structures $\rightsquigarrow$ $m_{\rm WDM}^{\rm thermal} > 5.3\text{-}5.7$ keV
  see e.g. [Viel'05, Yeche'17, Palanque-Delabrouille'19,Garzilli'19,Isric'23]

PBH evaporation and Dark Matter

see also e.g. [Bauman'07,Fujita'14,Allahverdi'17, Lennon'17,Morrison'17, Hooper'19+, Masina'20,Keith'20, Gondolo'20,Bernal'20+,..,

Barman'24, Haque'24] + talks P. De la Torre Luque, F. Kühnel

PBH stable on
Cosmological scales



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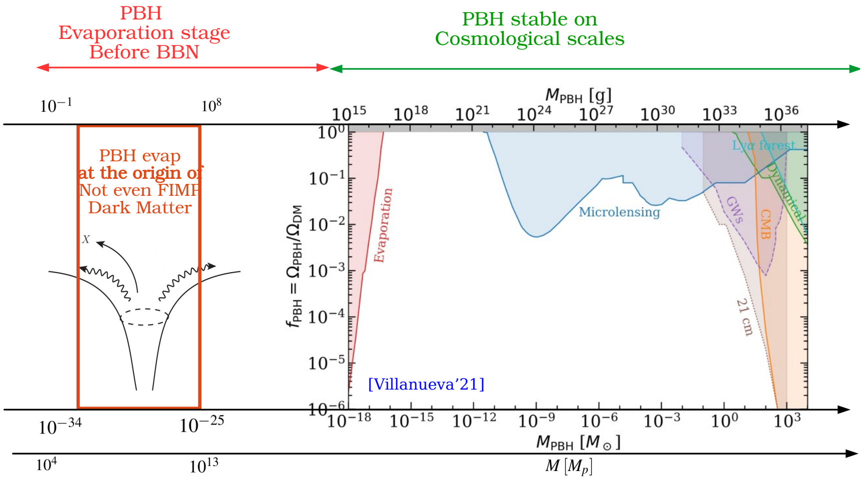

Burdened PBH evaporation

Memory Burden: Slow down of PBH evaporation

PBHs must be light enough to decay via **Hawking radiation** at an early enough epoch to avoid constraints.

- $T = \frac{M_{\rm P}^2}{8\pi M}$ and $S = 4\pi\,\frac{M^2}{M_{\rm P}^2}$

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- $T = \frac{M_\mathrm{P}^2}{8\pi M}$ and $S = 4\pi\,\frac{M^2}{M_\mathrm{P}^2}$
- Semi-classical: evap self similar evaporation from M_F to $M = 0$:

$$\frac{\mathrm{d}N_j^{\mathrm{sc}}}{\mathrm{d}E\,\mathrm{d}t} = \frac{g_j}{2\pi}\,\frac{\Gamma(E, M, s_j)}{e^{E/T} - (-1)^{2s_j}} \quad \text{and} \quad t_{\mathrm{sc}} \sim \frac{M_\mathrm{F}^3}{M_\mathrm{P}^4}$$

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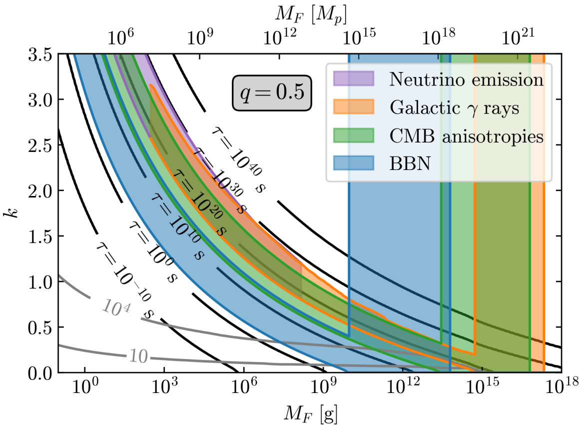
- Memory Burden: evap drops drastically from $M = qM_\mathrm{F}$ [Dvali'20]

$$\frac{\mathrm{d}N_j^{\mathrm{mb}}}{\mathrm{d}E\,\mathrm{d}t} = \frac{1}{S^k} \times \frac{\mathrm{d}N_j^{\mathrm{sc}}}{\mathrm{d}E\,\mathrm{d}t} \quad \text{and} \quad t_{\mathrm{mb}} \propto 3\, q^3\, S(q\, M_\mathrm{F})^k\, t_{\mathrm{sc}}\,.$$

Burdened PBH parameter space

see also e.g. [Thoss'24, Chianese'24, Chaudhuri'25, Haque'24, Barman'24, etc]

Constraints from BBN, CMB anisotropies, γ-rays and neutrino observations, assuming instantaneous transition SC$\rightarrow$ MB:



*Also for MB setting at very early stage $q \ll 1$ a few % evaporated particle DM could add up to PBH DM.

- upper right: PBH makes all DM iff very suppressed initial abundance ($\beta < 10^{-21}$)*
  Considering a smooth transition excludes this region. [Montefacone'25, Dvali'25]
- lower left: PBH fully evaporated and potential source of DM
  Focus of this talk

(Not even FIMP) DM production from Burdened PBH

NCDM from PBH evaporation

see also earlier works from [Bell'98, Dolgov'00, Baumann'07, Dai'09, Fujita'14, Lenon'17,Morisson'18, Hooper'19++, Gondolo'20, Masina'20, Baldes'20, Bernal'20, Auffinger'20, etc]

- DM particles (and SM) will be produced from PBH evaporation given **gravitational interactions** (not even FIMPs needed).
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$$\Omega_{\rm DM}^{(0)} \sim \begin{cases} \beta \left(\dfrac{M_{\rm F}}{M_{\rm P}}\right)^{1/2} & \text{RD } (\beta < \beta_{\rm c})\,, \\ q^{-2} \left(\dfrac{M_{\rm P}}{qM_{\rm F}}\right)^{k+1/2} & \text{MD } (\beta > \beta_{\rm c})\,. \end{cases}$$

MB only influences $\Omega_{\rm DM}^{(0)}$ in MD.

see also [Haque'24, Barman'24]

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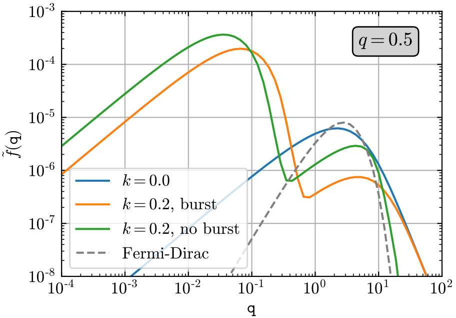

- In general: two populations DM (NCDM+CDM); if MB and SC near in time $\rightsquigarrow$ two populations NCDM

Translating WDM bound to NCDM?

see also [Kamada'19, Baumholzer'19, Ballesteros'20, d'Eramo'20, Decant'21]

Naive estimate for "similar velocity distributions" :

$$\langle v_\chi \rangle|_{t_0}^{\rm NCDM} \geq \langle v_\chi \rangle|_{t_0}^{\rm WDM\,lim}$$

$$\text{with} \quad \langle v_\chi \rangle|_{t_0} = \left.\frac{\sqrt{\langle p_\chi^2 \rangle}}{m_\chi}\right|_{t_0} = \left.\frac{\sqrt{\langle p_\chi^2 \rangle}}{T_\star}\right|_{t_{\rm prod}} \times \frac{T_{\star\rm prod}\, a_{\rm prod}}{T_0} \times \frac{T_0}{m_\chi}$$

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- WDM: $T_{\star \rm prod} a_{\rm prod} = \left(\frac{g_{*S}(t_0)}{g_{*S}(t_{\rm D})}\right)^{1/3} T_0$ and
  $\Omega_\chi h^2 = 0.12 \rightsquigarrow g_{*,S}(T_D) \simeq 10^3 \times \frac{m_\chi}{\rm keV} \Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm WDM} \propto m_{\rm WDM}^{-4/3}$
- PBH: $T_{\star \rm prod} a_{\rm prod} \sim T_F \times a_{\rm ev}^{mb} \sim M_F^{-1} \times M_F^{3/2} S^{k/2}$
  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm PBH} \propto m_\chi^{-1} \times M_{\rm PBH}^{1/2+k}$

$$m_\chi \gtrsim \# M_{\rm PBH}^{1/2+k} \times m_{\rm WDM\,lim}^{4/3}$$

$\rightsquigarrow$ the NCDM lower bound on the DM mass increases for larger k values

PBH evaporating after inflation and before BBN

see also [Barman'24, Haque'24]

PBH generation: after inflation an initially large density perturbation at sufficiently small scale can collapse to form a PBH with mass of order the horizon mass.
[Zeldovich & Novikov; Hawking; Carr & Hawking]

$$M_{BH}^{init} \equiv M_F = M_{\rm horiz} = \gamma \rho_{\rm tot} \times 4\pi/(3H_F^3)$$

- PBH formed after inflation: $t_F > t_{\rm infl} \to M_F > 10^4 M_p$
- PBH evaporate before BBN: $t_{\rm ev} < t_{BBN} \to M_F < M_{\rm max}^{\rm ev}$
- DM abundance depends on the initial BH fraction: $\beta \equiv \rho_{\rm PBH}/\rho_{\rm tot}|_{t_F} \leq 1$

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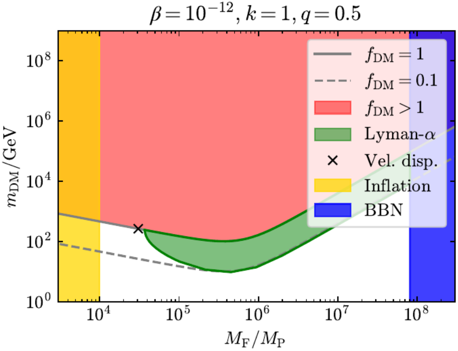

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Lyman-α bound using area estimator [Schneider'16, Murgia'17] : can exclude NCDM with $m_{\rm DM} \gg$ keV. NCDM always excluded in MD (=PBH dominated) era ($\beta > \beta_c$)

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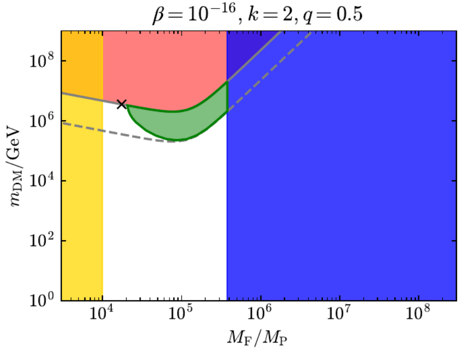

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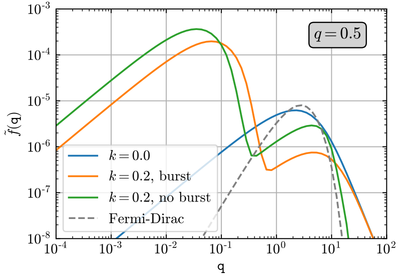
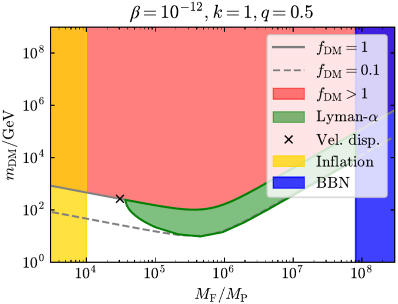
Take home message





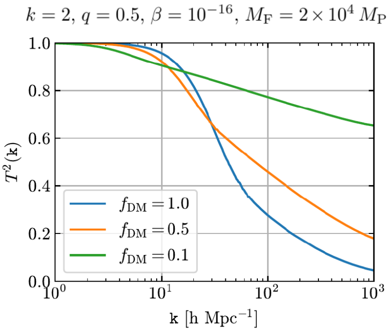
- Not even feebly coupled NCDM can be produced from PBH evaporation
- Memory burden naturally leads to two populations of DM
  CDM + NCDM or 2 NCDM populations
- Lyman-α observations exclude all DM from PBH evaporation in a PBH dominated universe and can exclude NCDM with masses $\gg$ few keV

Thank you for your attention!!

Bonus

Reinterpretation of WDM bounds

Introduce exact velocity distribution in `CLASS` to extract $T^2_X(\mathtt{k}) = P(\mathtt{k})/P_{\rm CDM}(\mathtt{k})$



Use the area estimator: $\delta A_X = \frac{A_{\rm CDM} - A_X}{A_{\rm CDM}}$ with $A_X = \int_{\mathtt{k}_{\rm min}}^{\mathtt{k}_{\rm max}} d\mathtt{k}' \, \frac{P^X_{1D}(\mathtt{k}')}{P^{\rm CDM}_{1D}(\mathtt{k}')}$, to extract CDM+NCDM bounds corresponding to $m^{\rm lim}_{\rm WDM} = 5.3$ keV for 100% WDM ($\delta A_{\rm WDM} = 0.32$).

Area criterium [Schneider 2016, Murgia, Merle, Viel, Totzauer, Schneider 2017]

- Consider ratio of 1D power spectra, computed with CLASS

$$r(k) = \frac{P_{1D}^{X}(k)}{P_{1D}^{\rm CDM}(k)} \quad \text{with} \quad P_{1D}^{X}(k) = \int_k^\infty dk'\, k'\, P_X(k')\,,$$

- Compute area under the curve

$$A_X = \int_{\rm k_{min}}^{k_{\rm max}} dk'\, r(k')$$

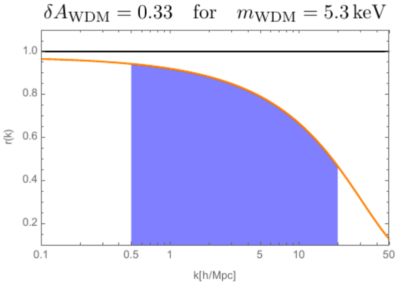
and

$$\delta A_X = \frac{A_{\rm CDM} - A_X}{A_{\rm CDM}}$$

- For freeze-in ($\delta = 1$):

$$m_{\rm FI} > 15.3\,{\rm keV}$$

- Suitable for mixed scenario



[*see also* D'Eramo, Lenoci, 2020; Egana-Ugrinovic, Essig, Gift, LoVerde 2021]

DM Production: Model and Cosmology Dependent

Cosmology

Particle Physics

$$\boxed{L[f_\chi(t,p)]} = \boxed{\mathcal{C}[f_\chi]}$$

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Weak/strong coupling to SM

$\Gamma_{\chi\leftrightarrow \mathrm{SM}} > H$

Feeble/No coupling to SM

$\Gamma_{\chi\leftrightarrow \mathrm{SM}} < H$

“Thermal” DM

$f_\chi(t,p) = f_\chi(t,p)^{fD,BE}$

“Non-Thermal” DM

$f_\chi(t,p) \neq f_\chi(t,p)^{fD,BE}$

Decouple still relativistic and freestream while struct. forms

“Thermal Warm” Dark Matter (WDM)

Still coupled to light dof while struct. forms

“Interacting” Dark Matter (IDM)

Produced through feeble interactions and freestream while struct. forms

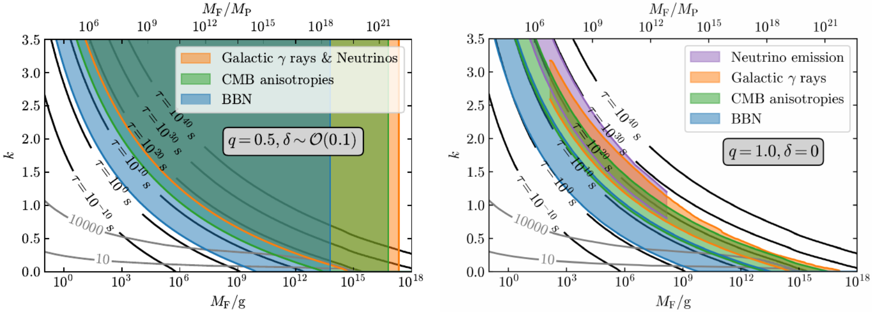
“Feebly Interacting Massive Particles” (FIMPS)

Produced through gravitationnal interactions and freestream while struct. forms

DM from Primordial Black Holes (PBH) evaporat°

PBH and memory burden

see also [Barman'24, Haque'24, Dvali'25, Montefalcone'25]



- Smoother transition SC$\rightarrow$ MB ($\delta = 0.1$)
  $\rightsquigarrow$ close the viable PBH parameter space with masses $M_F < 10^{15}$g.
- $q = 1$ moves to MB from the start of evaporation
  $\rightsquigarrow$ SC vertical exclusion bands disappear.

PBH lifetime and Lyman-α bound estimate

Memory Burden implies a delayed evaporation

$$\tau_{\rm sc} = \frac{1}{3e_T}\frac{M_{\rm F}^3}{M_{\rm P}^4} \simeq 1.1\times 10^{-14}\,s\left(\frac{M_{\rm F}}{3\times 10^4\,{\rm g}}\right)^3 . \qquad \tau_{\rm mb} = \zeta_{\rm burst}\, q^{3+2k} S(M_{\rm F})^k \times \tau_{\rm sc} .$$

$$t_{q=0.5} \simeq 4.2\times 10^{-17}\,s\left(\frac{M_{\rm F}}{4.9\times 10^3{\rm g}}\right)^3 \quad \text{and} \quad \tau_{\rm mb} = 4.6\times 10^{17}\,s\left(\frac{M_{\rm F}}{4.9\times 10^3{\rm g}}\right)^7$$

$q = 0.5$ and $k = 2$

The delayed evaporation easily play the major rôle in Lyman-alpha bound

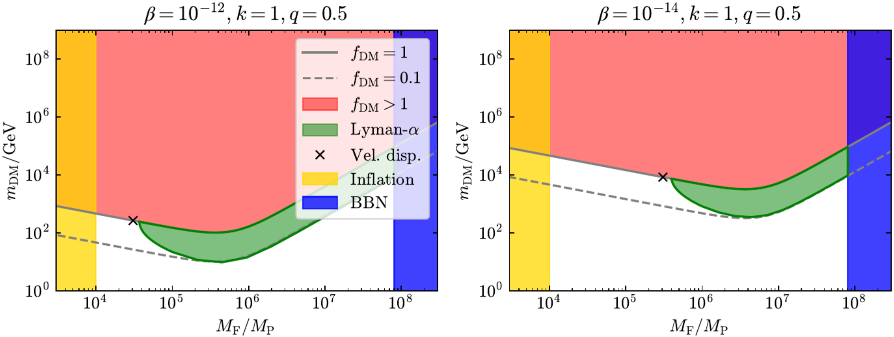
$$m_{\rm DM} \gtrsim 1.74\,{\rm keV}\times\sqrt{\langle \mathsf{q}_\star^2\rangle}\,\mathrm{T}_{\rm NCDM}\times\left(\frac{m_{\rm WDM}^{\rm ly\alpha}}{\rm keV}\right)^{4/3}$$

$$m_{\rm DM} \gtrsim 1.2\,{\rm keV}\times\left(\frac{m_{\rm WDM}^{\rm ly\alpha}}{\rm keV}\right)^{4/3}\sqrt{\frac{M_F}{M_p}}\frac{1}{\sqrt{1+(\xi-1)q^2}} \tag{4.10}$$

$$\times\left[(1-q^2)(1-q^3)\langle\mathsf{q}_{\rm DM}^2\rangle_{\rm sc} + \left(\xi(1-q^3)+\xi(4\pi)^k q^{3+2k}\zeta_{\rm burst}\left(\frac{M_F}{M_p}\right)^{2k}\right)\langle\mathsf{q}_{\rm DM}^2\rangle_{\rm mb}\right]^{1/2} .$$

PBH parameter space

see also [Barman'24, Haque'24]



- relic DM abundance depend on β in RD era and on k in MD era
- Increasing k supresses more evaporation in the memory burden phase making BBN constraints more stringent (for $k > 4$ no viable parameter space left).
- Ly-α constrains $\beta \lesssim 0.015\beta_c$ as in SC case [Decant'21].
- Larger $\beta \rightsquigarrow$ less viable parameter space as it moves the RD-MD to lower M_F.

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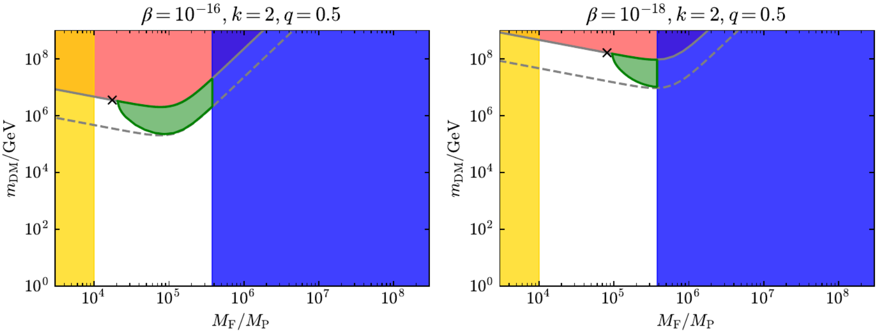

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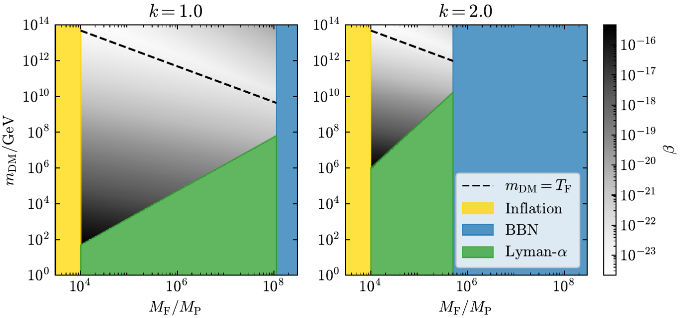

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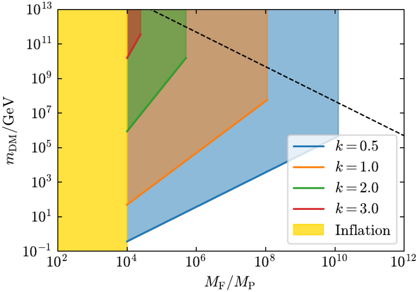

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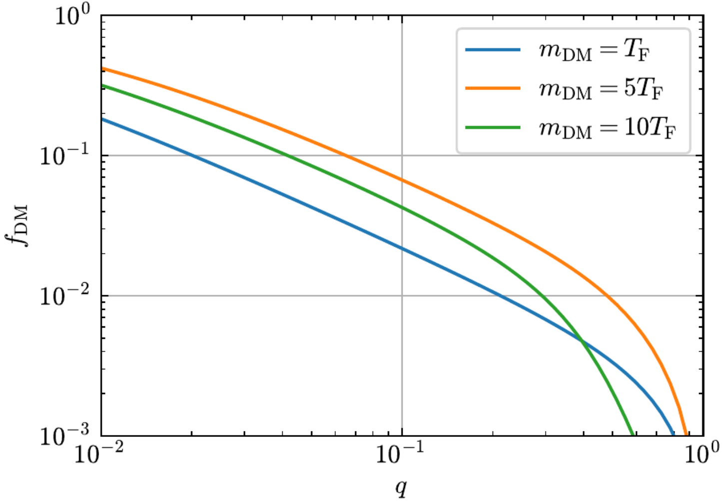
- For DM fraction lower than 10%, no Ly-α constraints.

Long MB with stable PBH



Ly-α for fraction of NCDM

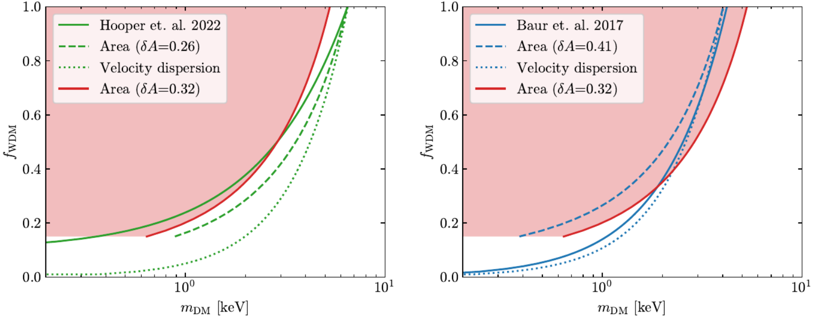


Figure 11. Comparison of the Lyman-α bound derived in Refs. [79, 89] for W+CDM to the ones described in Secs. 4.2.2 and 4.2.3. The left figure shows a comparison to the bound at 95%CL from Ref. [79], whereas the 2σ bound from [89] is shown on the right. Their results are compared to the velocity dispersion estimate (dotted line) and the area criterion (dashed line) matched to [79, 89] for $f_{\rm WDM} = 1$. In addition, we show as a red line the results from the area criterion for $m_{\rm WDM}^{\rm Ly\text{-}\alpha} = 5.3$ keV at $f_{\rm WDM} = 1$ (in agreement with the findings of Ref. [74]), that are being used in this work.

This is really the end