Beyond WIMP Dark Matter

Laura Lopez Honorez

TeVPA, Valencia, 3-7/11/2025

84% of the matter content is made of Dark Matter

DM Partice: Wide range of mass

see also [M. Taoso talk]

Some a priori benchmarks:

- Bosonic DM: $m_{DM} > 10^{-22}$ eV for $\lambda_{DB} <$ kpc
  in addition: m_{DM} <few tens of eV wave-like behaviour $\lambda_{DB} > n_{DM}^{-1/3}$
  [see J. Redondo talk]
- Fermionic DM: m_{DM} >few tens of eV
  from Pauli exclusion in astro objects.
- $m_{DM} \sim 100$ TeV: unitary limit for annihilating DM
  non-perturbative physics shall be accounted for [von Harling & Petraki '14, Smirnov & Beacom'19]+ non-termal DM, non-standard cosmo can go beyond e.g. [Asasi'21]
- $m_{DM} > 10^{19}$ GeV $\sim 10^{-38} M_{\odot}$: macroscopic objects (PBH) e.g. [Byrnes talk]
  $\rightsquigarrow$ can also source DM particle production with e.g. Non Cold signatures

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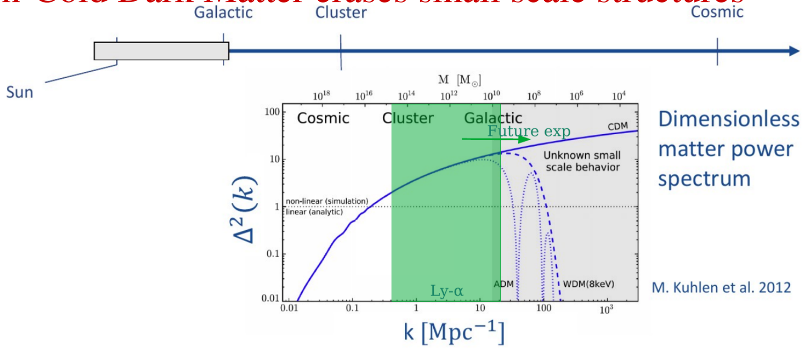
In the talk we focus on *some* particle DM candidates (bosons or fermions) beyond WIMPs giving rise to specific non-cold signatures in Cosmology.

Non-Cold Dark Matter erases small scale structures



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

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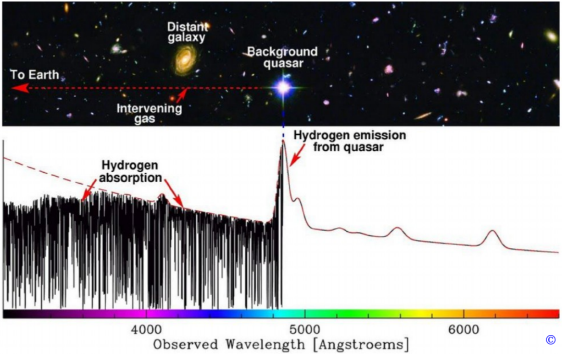

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  [or e.g. free-streeming ALPs, see also R. Impavido talk]
- Tested against Lyman-α: absorption lines along line of sights to distant quasars probe smallest structures $\rightsquigarrow m_{\rm WDM}^{\rm thermal} > 5.3$-$5.7$ keV
  see e.g. [Viel'05,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

DM Production: Model and Cosmology Dependent

Cosmology

Particle Physics ?

$$\frac{df_\chi(t,p)}{dt} = \mathcal{S}[f_\chi]$$

DM Production: Model and Cosmology Dependent

Cosmology

$$\frac{df_\chi(t,p)}{dt} = \mathcal{S}[f_\chi]$$

Weak/strong coupling to SM

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

"Thermal" DM

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

Feeble/No coupling to SM

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

"Non-Thermal" DM

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

Produced through feeble interactions

Produced through gravitational interactions

WIMP is under pressure ...
but not dead

WIMP Dark Matter

Weakly Interacting Massive particles coined in 1985 [Steigman & Turner] originally for CDM particles (heavy ν, SUSY, axions).

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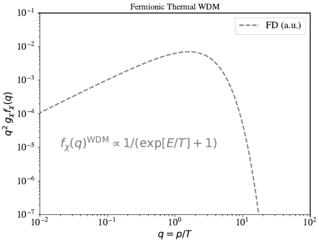
Cosmology   Particle Physics

$$\frac{df_\chi(t,p)}{dt} = \mathcal{C}[f_\chi]$$



- WIMP assumptions
  - $\sim$ Weak interactions
  - In thermal and chemical equilibrium with SM initially

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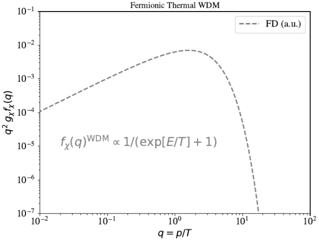
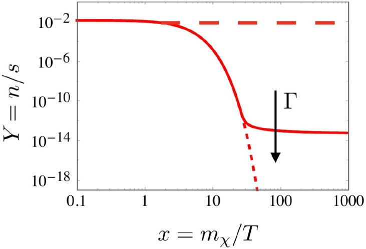
Cosmology

$$\frac{df_\chi(t,p)}{dt} = \mathcal{C}[f_\chi]$$

Particle Physics

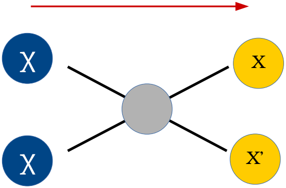
- WIMP assumptions
  - $\sim$ Weak interactions
  - In thermal and chemical equilibrium with SM initially
  - Non relativistic DM
  - Radiation dom. era





Large mass range: WIMP (testable!?) Paradigm

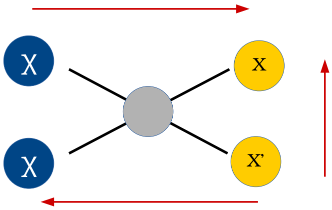
WIMP paradigm
Non-relativistic thermal
DM Freeze-out



Large mass range: WIMP (testable!?) Paradigm

eV keV MeV GeV TeV 100 TeV

WIMP paradigm
Non-relativistic thermal
DM Freeze-out



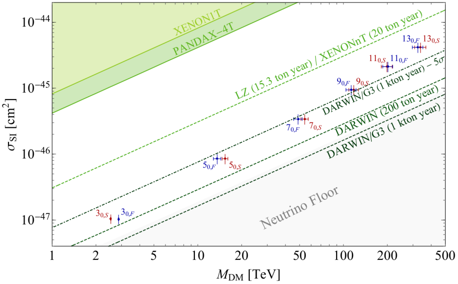
Particle phys DM searches :
Indirect : DM annihilates to SM
Direct : strong threat
Colliders : prompt searches

Cosmology
DM energy injection:
CMB, Ly-alpha, 21cm probes

WIMP: Strong threat from direct DM searches

Predictive WIMP benchmark: Minimal DM [Cirelli'05]
DM = EW multiplet $n > 1$, including $\chi_{Q=0}$
& need Z_2 stabilizing symmetry for $n < 5$

- Very predictive: $SU(2)_L$ interactions
- Connecting dots? H-portal between n and $n+1$ [Oncala'21,LLH'17]



[Bottaro'22]

WIMP: Strong threat from direct DM searches

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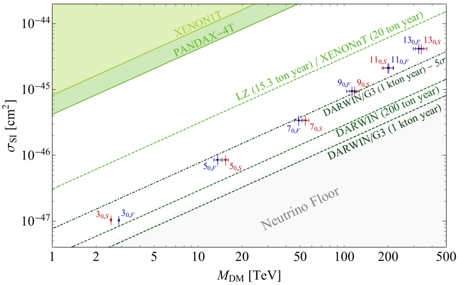
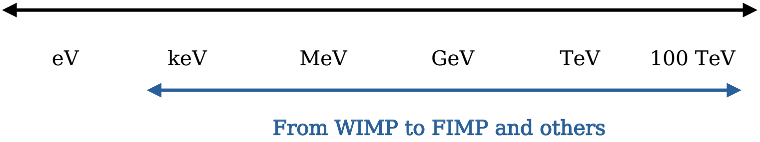
- Theory Challenge
  Accurate DM relic and Indirect signatures (γ lines) needs Sommerfeld, bound state treatment [Oncala'21,Beacom'19, Mitridate'17,]
- Exp. Challenge: go deeper
  Direct Detection & Indirect detection
  [M. Taoso, D. Cerdeño + Mon-Thur talks]
- $n = 3$ ruled out by Fermi (even for large core) [Safdi & Xu'25]



[Bottaro'22]

Beyond WIMP
with feeble interactions

From WIMP to FIMP: thermal and non-thermal candidates



From WIMP to FIMP: thermal and non-thermal candidates

eV keV MeV GeV TeV 100 TeV

From WIMP to FIMP and others

Thermal to non thermal DM production :
Mediator annihilation/Conversion/Semi-annihilation driven Freeze-out ; Freeze-in – Super-WIMP ; + +SIMPs ; asymmetric DM ; etc

Particle physics searches :[see talks D. Cerdeño, M. Taoso, S. Lowette]
Direct DM searches: sub-GeV challenge
Colliders : Displaced vertex searches
Beam-dump experiments

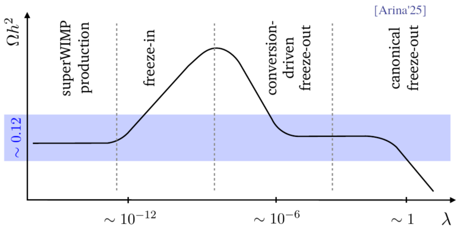
Cosmology : [see e.g. A. Mesinger, D. Agius talks]
BBN (~MeV), Lyman-alpha (non-cold), **Δ**Neff, energy injection, 21cm probes

From WIMP to FIMP: t-channel as illustrative framework

t-channel models requiere 2 dark sector particles X = DM, Y = mediator

$$\mathcal{L} = \lambda\, X\, Y\, SM + h.c.$$

- Relic Abundance: Can continuously go from thermal relics with DM Freeze-out ($XX \to$ SMSM) to non-thermal relics from Freeze-in and Super-WIMP (set by $Y \to X$) by decreasing the coupling λ.



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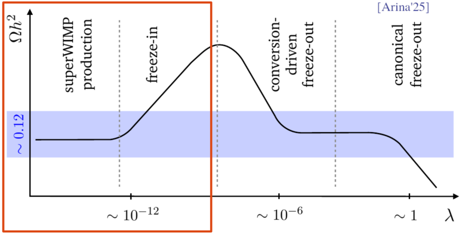
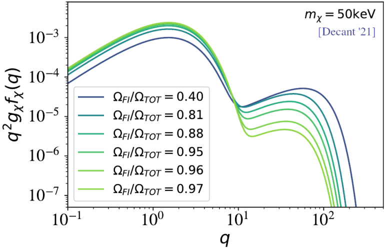
- Relic Abundance: Can continuously go from thermal relics with DM Freeze-out ($XX \to$ SMSM) to non-thermal relics from Freeze-in and Super-WIMP (set by $Y \to X$) by decreasing the coupling λ.
- FIMPs characteristics
  - feeble interactions ($\lambda \ll 1$)
  - non thermal distribution
  - imprint sensitive to early universe Cosmo





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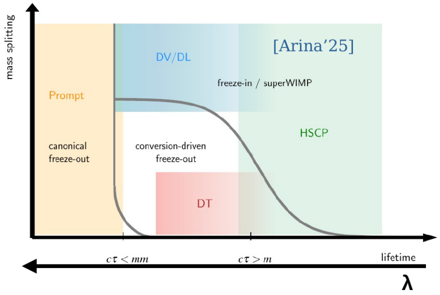

- Colliders may help to probe each regimes see also [S. Lowette talk]

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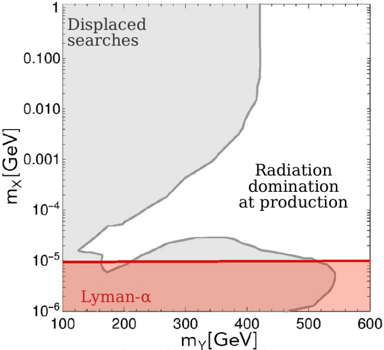
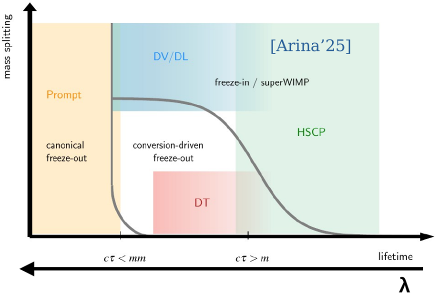


[adapted from Calibbi'21]



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- Complementarity with Cosmo probes for FIMPs (Ly-α, BBN, etc)

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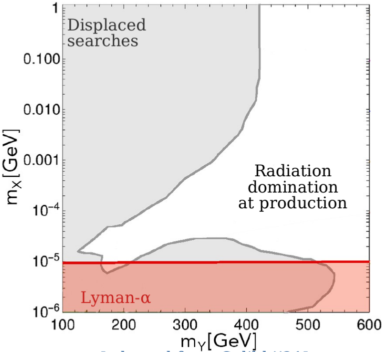

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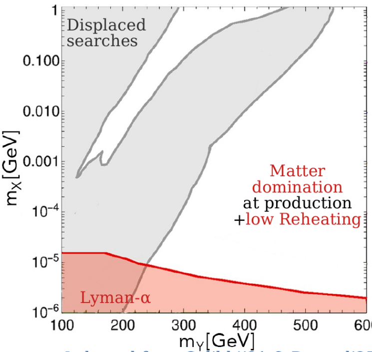


[adapted from Calibbi'21 & Deread'25]

- Colliders may help to probe each regimes see also [S. Lowette talk]
- Complementarity with Cosmo probes for FIMPs (Ly-α, BBN, etc)
- Modified early Cosmology with late Reheating see also [N. Barbieri talk]: can improve collider reach and suppress Cosmology bound

Challenge: Large parts of the parameter space are still to be reached

need complementary Astro-Particle-Cosmo exp. efforts to constrain or validate key signatures.

Beyond WIMP
Gravitational production (not even feeble interactions)

Production of not even feebly coupled DM

- Cosmological gravitational particle production (CGPP)

  particle production from vacuum due to time evol. of the bgd grav. field due to the expansion of the Universe.

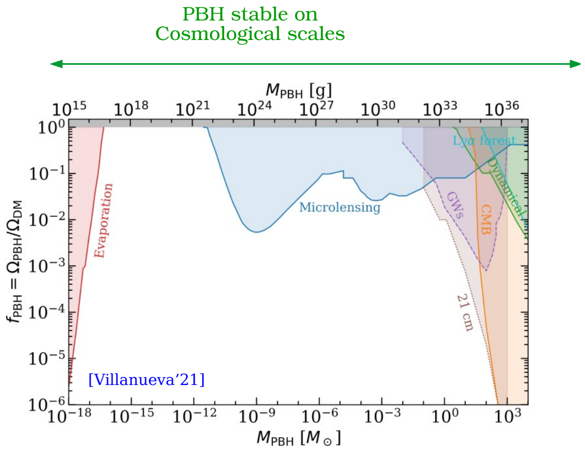
  [see e.g. Kolb'23 review, Garcia'23 for NCDM]

- DM production from evaporating PBH

  Discussed here

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 and C. Byrnes talk]



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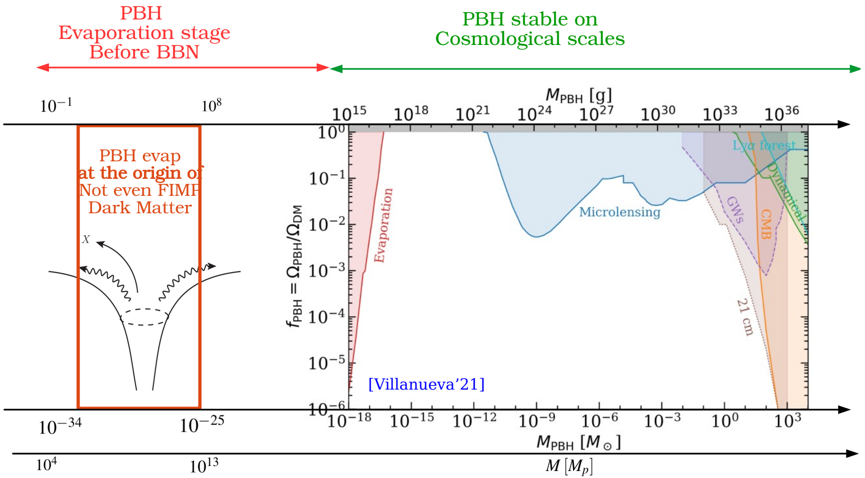

NCDM from PBH evaporation

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

- DM particles (and SM) will be produced from PBH evaporation given **gravitational interactions** (not even FIMPs needed).
- For $m_{DM} < T_{BH}^{init} = M_p^2/(8\pi M_{BH}^{init})$, behave as non-thermal NCDM.

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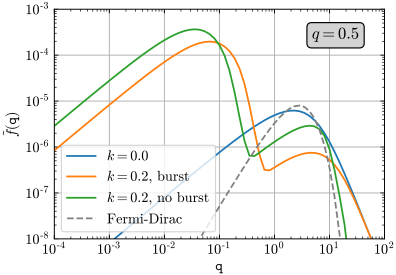

DM production/NCDM properties depends on the initial PBH abund. β, memory burden [Dvali'18] k and q (starting for $M_{\rm BH} = q M_{\rm BH}^{ini}$ and evap. slow down as $dN_{\rm DM}/dt \propto S^{-k}$), DM and PBH mass, etc see also e.g. Barman'24, Haque'24.

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

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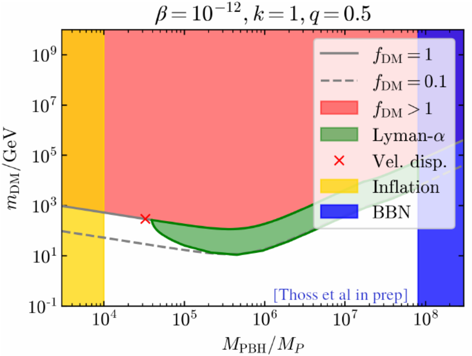

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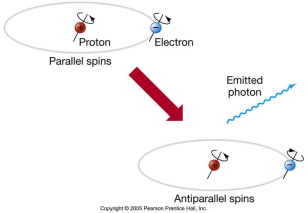
Lyman-α bound: can exclude NCDM with $m_{\text{DM}} \gg keV$.
NCDM always excluded in MD era ($\beta > \beta_c$)

21cm Cosmology future NCDM probe?

Cosmic Dawn and 21 cm Cosmology?

see also Andrei Mesinger talk

The most powerful probe of the Cosmic Dawn ($\equiv$ period where first galaxies started to shine) up until reionization (EoR) is 21 cm spin flip line of HI :



- Transitions between the two ground state energy levels of neutral hydrogen HI $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)

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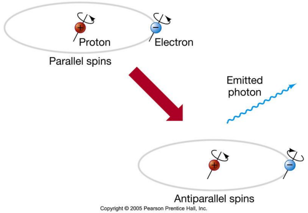
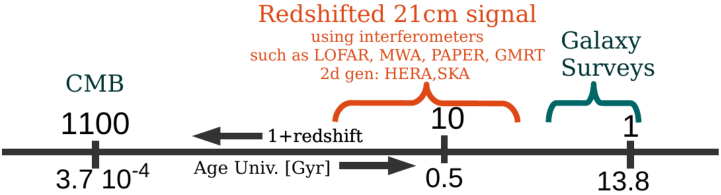
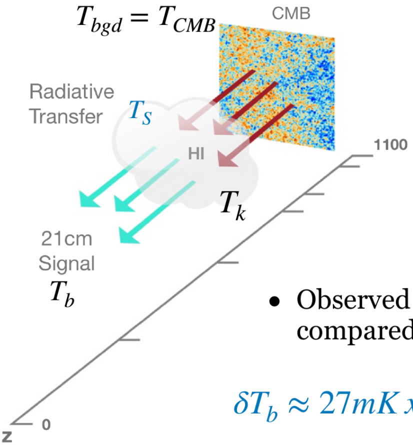


- Transitions between the two ground state energy levels of neutral hydrogen HI
  $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)
- 21 cm photon from HI clouds during Cosmic Dawn & EoR redshifted to $\nu \sim 100$ MHz
  $\rightsquigarrow$ new cosmology probe



21 cm Cosmology in practice



credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions
- The spin temperature (= excitation T of HI) charaterises the relative occupancy of HI gnd state

$$n_1/n_0 = 3\exp(-h\nu_0/k_B T_S)$$

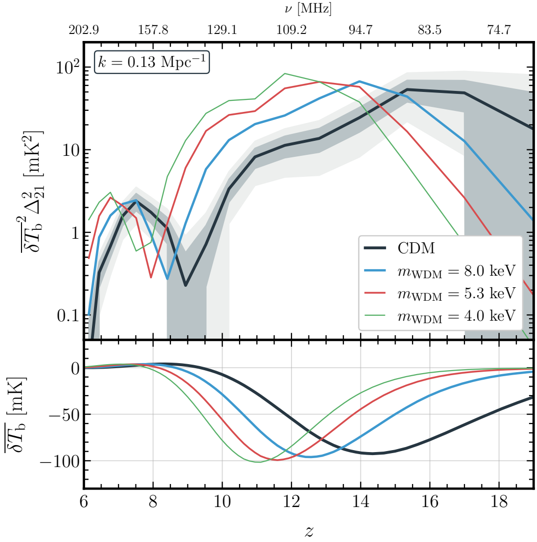
- Observed brightness of a patch of HI compared to CMB at $\nu = \nu_0/(1+z)$

$$\delta T_b \approx 27mK\, x_{HI}(1+\delta)\sqrt{\frac{1+z}{10}}\left(1 - \frac{T_{CMB}}{T_S}\right)$$

Delayed 21cm features for NCDM

see also [Sitwell'13,Escudero'18, Schneider'18,Safarzadeh'18,Lidz'18, LLH'18, Muñoz'20,Schneider'22, Giri'22, Schosser'24, Decant'24]

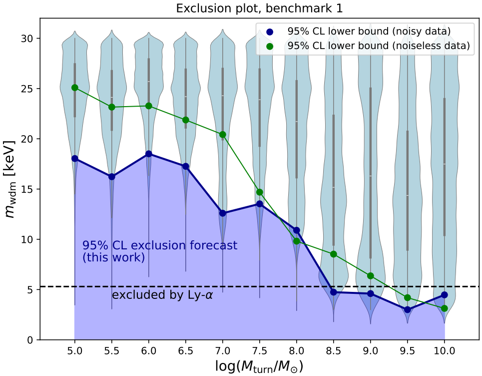
NCDM low mass halo suppression can lead to delayed ion, exc, heat.



21cm Cosmology might improve WDM bound

see also [Giri'22, Kovetz'22, Schosser'24, Decant'24]

Considering one single population of galaxies of fixed $M_{\rm turn}$



Lower $M_{\rm turn}$ allow to probe higher $m_{\rm WDM}$ $\equiv$ colder NCDM

To improve on existing bounds, we need $M_{\rm turn} < 10^8 M_\odot$. [Decant'21]
For the lowest $M_{\rm turn} = 10^5 M_\odot$, the improvement on the lower bound on $m_{\rm WDM}$ reached by HERA will depend on the CD galaxies properties.

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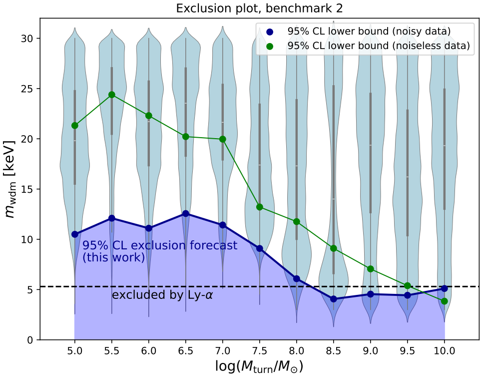

Lower $M_{\rm turn}$ allow to probe higher $m_{\rm WDM}$

$\equiv$ colder NCDM

Increasing X-ray params

$\rightsquigarrow$ suppressed contrast

$\rightsquigarrow$ more challenging.

see also D. Agius talk

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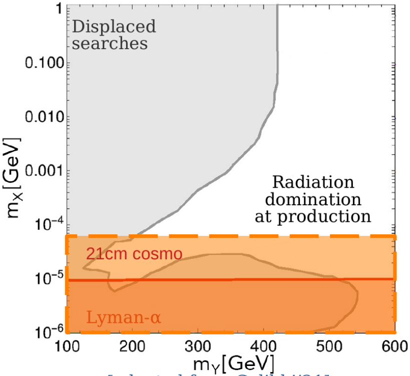
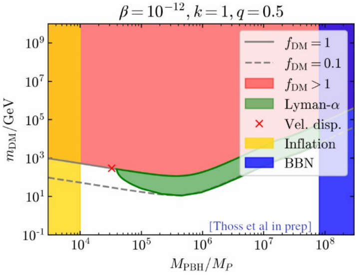
see also [Giri'22, Kovetz'22, Schosser'24, Decant'21,Ballesteros'20]

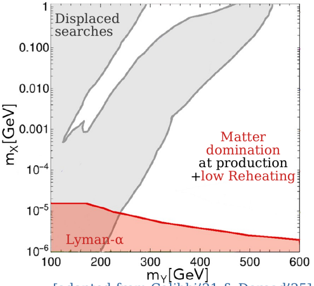


[adapted from Calibbi'21]

assuming that the bound on $m_{\rm DM}^{\rm FI} \propto (m_{\rm WDM}^{\rm 21cm})^{4/3}$
and $m_{\rm WDM}^{\rm 21cm} < 15$ keV, which would be the best case scenario.

Take home message





- WIMP DM is under pressure but not dead
- Yet there is a wide range of possibilities to be explored beyond WIMP.
- If (not even) feebly coupled DM, the challenge will be to use all probes to charaterize DM.
- Complementarity between astro-cosmo-particle is an asset.

Thank you for the invitation
and for your attention!!

Backup

Translating WDM bound to NCDM?

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

Naive estimate for "similar velocity distributions" :

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

$$\text{with} \quad \langle v_\chi \rangle|_{t_0} = \left.\frac{\langle p_\chi \rangle}{m_\chi}\right|_{t_0} = \left.\frac{\langle p_\chi \rangle}{T}\right|_{t_{\rm prod}} \times \left(\frac{g_{*S}(t_0)}{g_{*S}(t_{\rm prod})}\right)^{1/3} \times \frac{T_0}{m_\chi}$$

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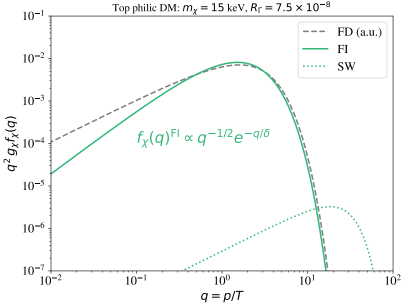
- WDM: $\Omega_\chi h^2 = 0.12 \rightsquigarrow g_{*,S}(T_D) \simeq 10^3 \times \frac{m_\chi}{\rm keV}$
  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm WDM} \propto m_{\rm WDM}^{-4/3}$
- FI: $T_{\rm prod} \sim m_B/3$ and $\langle p_\chi \rangle|_{t_{\rm prod}} \sim m_B/2$
  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm FI} \propto m_\chi^{-1}$
- SW: $T_{\rm prod} \sim \sqrt{\Gamma_B M_{Pl}}$ and $\langle p_\chi \rangle|_{t_{\rm prod}} \sim m_B/2$, with $R_\Gamma = \Gamma_B M_{Pl}/m_B^2$
  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm SW} \propto m_\chi^{-1} \times R_\Gamma^{-1/2}$
- PBH: $T_{\rm prod} \sim M_{\rm PBH}^{-3/2}$ and $\langle p_\chi \rangle|_{t_{\rm prod}} \sim 6.3/M_{\rm PBH}$
  $\Rightarrow \langle v_\chi \rangle|_{t_0}^{\rm PBH} \propto m_\chi^{-1} \times M_{\rm PBH}^{1/2+k}$

“Pure” FI & SW: WDM-like

see also [Petraki’16,Heeck’17, Boulebnane’17, Kamada’19, Baumholzer’19, Ballesteros’20, d’Eramo’20]



- Contrarily to “usual” WDM, FIMPs are non-thermaly produced. Distribution $f_\chi \propto q_\star^{-\alpha} \exp(-q_\star^\beta)$ with $\alpha = \frac{1}{2}, 1$ and $\beta = 1, 2$ for FI, SW.

[Decant, Heisig, Hooper,LLH’21]

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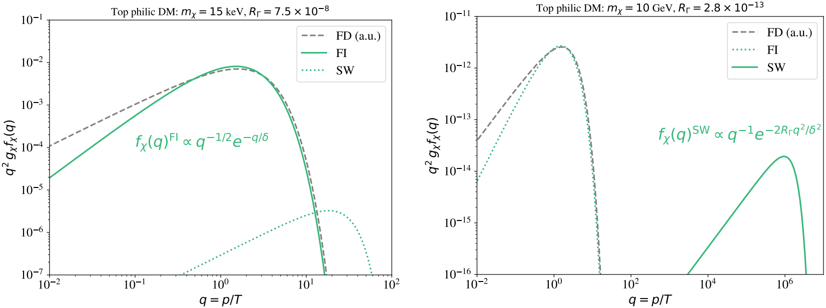

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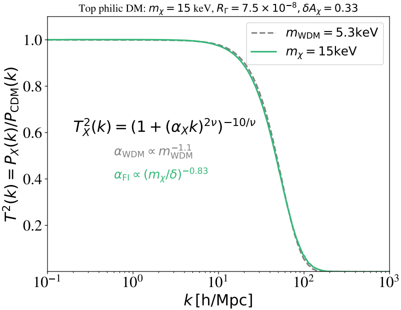

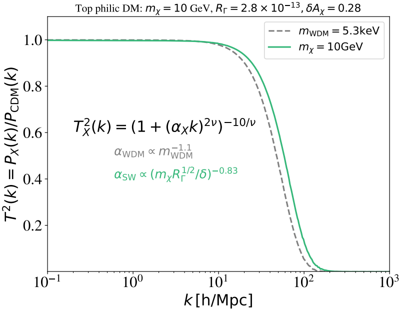

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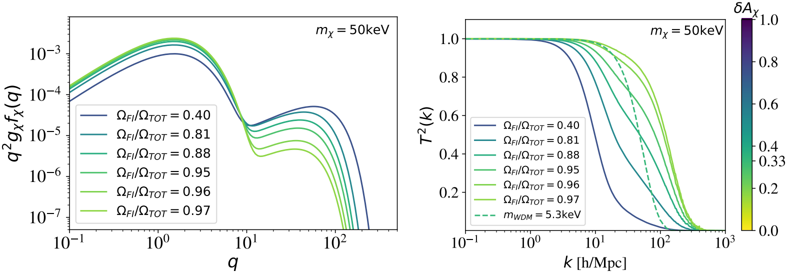
- Modified CLASS: Pure FI/SW transfer functions similar to thermal WDM. $\rightsquigarrow$ Lower mass bound from Lyman-α $(m_B \ll m_A,\, T_{\rm prod} > T_{\rm EW})$:

$$m_\chi \gtrsim \begin{cases} 15\,\text{keV} & \text{for FI,} \\ 3.8\,\text{GeV} \times \sqrt{10^{-12}/R_\Gamma} & \text{for SW,} \end{cases} \quad \text{for } m_{\rm WDM}^{\rm Ly-\alpha} > 5.3\,\text{keV}$$

[Decant, Heisig, Hooper,LLH'21]

Mixed FI & SW: significant deviations from WDM



- Mixed FI-SM $q^2 f_\chi$ is multimodal $\rightsquigarrow T^2(k) = P_{\rm FIMP}(k)/P_{\rm CDM}(k)$ can significantly deviate from e.g. WDM, α, β, γ param. or CDM+WDM

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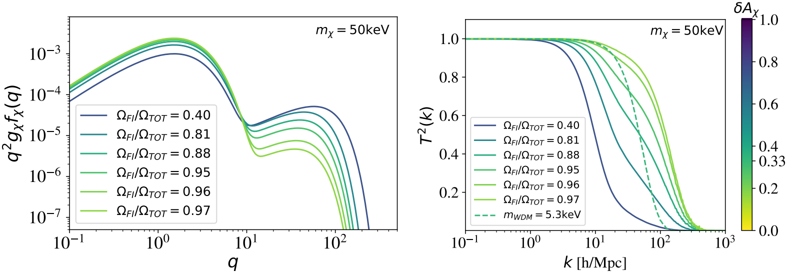

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- We use the area criterion [Murgia'17] measuring the relative $P_{1D}(k)$ deviation over $0.5h/{\rm Mpc} < k < 20h/{\rm Mpc}$: $\delta A_\chi < \delta A^{ly-\alpha}_{\rm WDM} = 0.33$ for $m^{\rm Ly-\alpha}_{\rm WDM} > 5.3$ keV

see also [Schneider'16] and e.g. [D'Eramo'20, Egana-Ugrinovic'21]

Modified early cosmology

see also e.g. [Co'15; d'Eramo'17, Calibbi'21, A. G. Garcia'21, Becker'23 etc]

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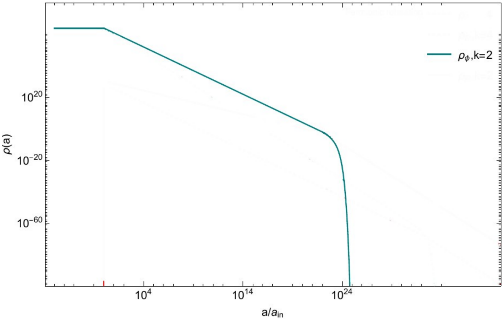
During RH [see Garci'21]:

- $w_\phi = \frac{k-2}{k+2}$
- ϕ decays to e.g. fermionic species F: $\Gamma_\phi \sim y_F^2 m_\phi(t)$

$\rightsquigarrow$ sets $T(t) \propto a^{-\frac{3k-3}{2k+4}}$ durin the RH period and $T_{RH}(\lambda, y_F, k)$



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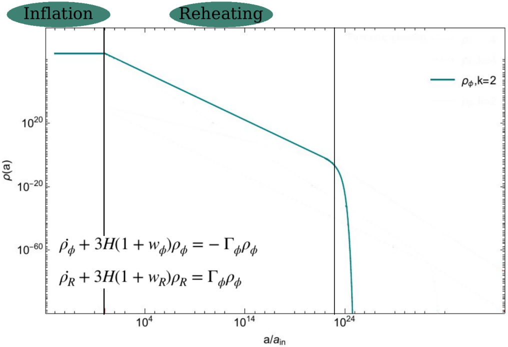

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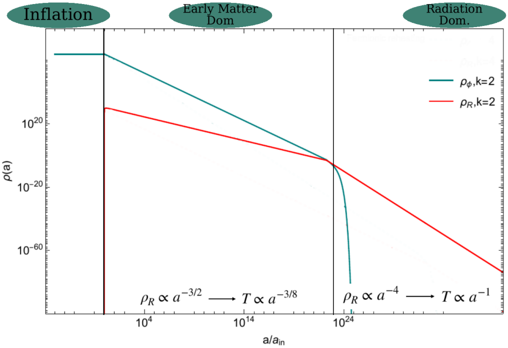

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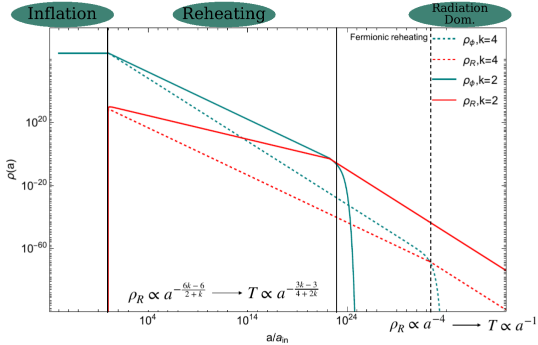

DM production during RH while entropy is being injected ($T > T_{RH}$)

$\rightsquigarrow D(T) = S(T)/S(T_{\rm RH}) \simeq (T_{RH}/T)^{\frac{7-k}{k-1}}$ dilution of $Y_{\rm DM}$ and $\langle p_{\rm DM}\rangle$

Modified History affects the momentum distribution

Cosmology

$$\frac{df_\chi(t,p)}{dt} = \mathcal{C}[f_\chi]$$

Particle Physics : FIMP
from B decays

"Standard" Cosmo

$$H = \frac{\sqrt{\rho_R}}{\sqrt{3}M_{pl}} = \frac{T^2}{M_0}$$

$$f(q)\,|_{RD} \propto q^{-1/2}e^{-q}$$

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Early "k-dominated"

$$H = \frac{\sqrt{\rho_\phi}}{\sqrt{3}M_{pl}} = \frac{1}{M_0}\frac{T^{\frac{2k}{k-1}}}{T_R^{\frac{2k}{k-1}-2}}$$

$$f(q)|_{RD} \propto q^{-1/2}e^{-q} \qquad f(q)|_{FR} \propto \left(\frac{T_R}{m_B}\right)^{\frac{2k}{k-1}-2} q^{\frac{3k-5}{2k-2}}e^{-q}$$

low momentum $f_\chi(q)$ is k dependent

due to Liouville op. k dependence (through H)

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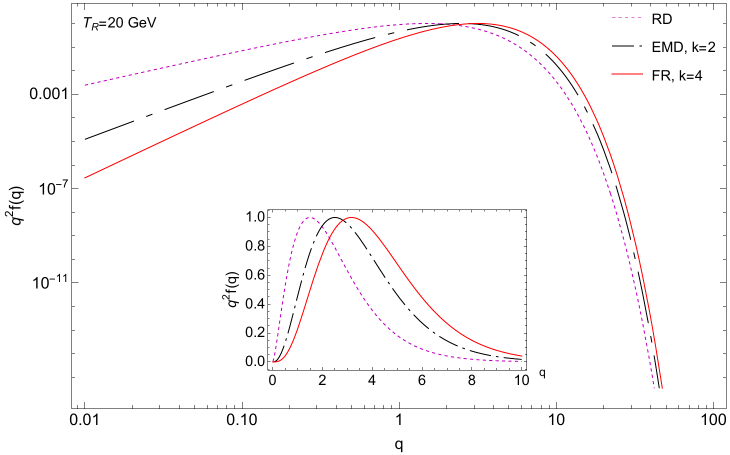


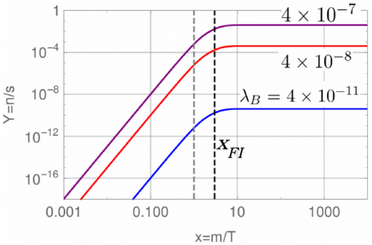
low momentum $f_\chi(q)$ is k dependent

due to Liouville op. k dependence (through H) $\rightsquigarrow$ variations in $\langle p/T \rangle|_{t_{\rm prod}}$

Higher FIMP couplings and shorter partner life times

Freeze-in DM production (m_{DM}=10 GeV and m_B=1 TeV)

in Radiation Dominated (RD) era



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Freeze-in DM production (m_{DM}=10 GeV and m_B=1 TeV)

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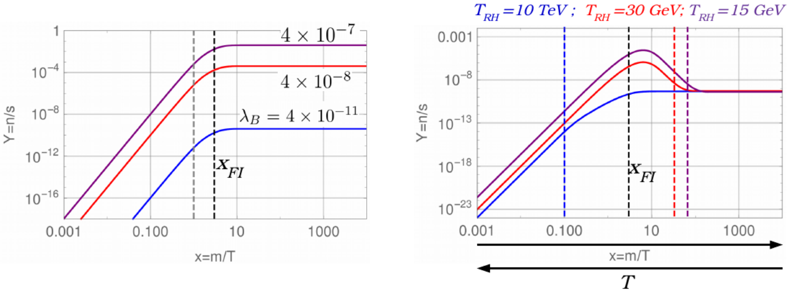

DM yield is diluted due to extra entropy production from inflaton decay:

$$Y_\chi^\infty / Y_\chi(T_{FI}) \propto D(T_{FI}) \sim (T_{RH}/T_{FI})^{\frac{7-k}{k-1}} \,,$$

$\rightsquigarrow$ The lower T_{RH}, the smaller is $D(T)$, and the lower is Y_χ^∞ compared to $Y_\chi(T_{FI})$, the higher is λ_χ to account for DM abundance and the shorter is $c\tau_B$.

Lower FIMP velocities today

Naive estimate for "similar velocity distributions" :

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

$$\text{with} \quad \langle v_\chi \rangle|_{t_0} = \left.\frac{\langle p_\chi \rangle}{m_\chi}\right|_{t_0} = \left.\frac{\langle p_\chi \rangle}{T}\right|_{t_{\text{prod}}} \times \left(\frac{g_{*S}(t_0)}{g_{*S}(t_{\text{prod}})}\right)^{1/3} \times \frac{T_0}{m_\chi}$$

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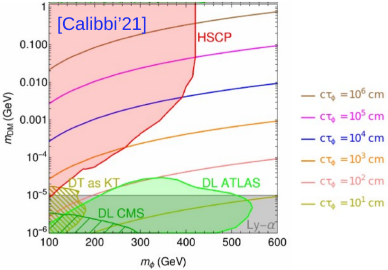
Lyman-α constraints can relax for $T_{RH} < T_{FI}$

Exemplary case of Leptophilic DM

Case of an early matter dominated era (k=2) with $T_{RH} = 20$ GeV:

$$L \supset \frac{1}{2}\bar{\chi}\gamma^\mu\partial_\mu\chi - \frac{m_\chi}{2}\bar{\chi}\chi + (D_\mu\phi_B)^\dagger D^\mu\phi_B \; - m_{\phi_B}^2|\phi_B|^2 - \kappa\phi_B\bar{\chi}\mu_R + h.c$$



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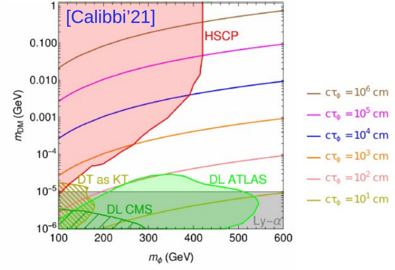

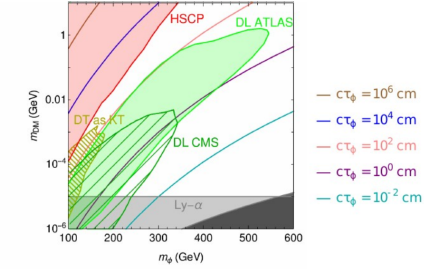

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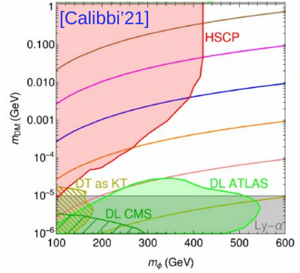
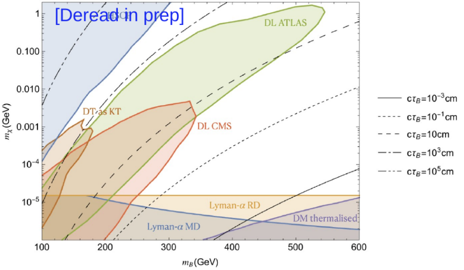
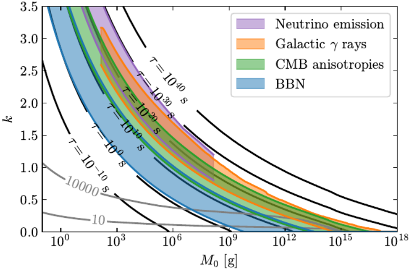


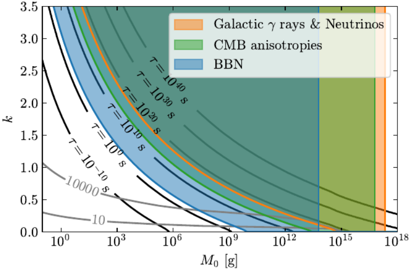


- Dilution of Y_{χ} $\rightsquigarrow$ larger couplings and shorter $c\tau_B$
  $\rightsquigarrow$ diplaced signatures can be probed at colliders in different points of the parameter space
- Lower velocities $\rightsquigarrow$ relaxed Lyman-α constraints for $T_{FI} > T_{RH}$

PBH and memory burden

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





Memory Burden : entropy prevents efficient evaporation from M=q M_{ini}

$$\frac{dN^{mb}}{dEdt} = \frac{1}{S^k}\frac{dN^{sc}}{dEdt} \qquad S = 4\pi\frac{M^2}{M_P^2}.$$

[Dvali'18+]

Transition from Semi-Classical to Memory Burden can be smooth (non drastic Slowdown and close the « new window » for PBH to account all DM at large M and k values [Dvali'25, Montefalcone'25]

DM relic abundance

See [Haque'24]

$$m_j < T_{\rm BH}^{\rm in}$$

$$\frac{\Omega_j h^2}{0.12} = 2.85 \times 10^6 \, \frac{\xi \, g_j}{q^2} \, \left(2^k (3+2k)\right)^{1/2} \left(\frac{M_P}{q \, M_{\rm in}}\right)^{\frac{2k+1}{2}} \, \frac{m_j}{\rm GeV} \, . \qquad \beta > \beta_{\rm c}$$

In MD, strong k dependence but also q (MB params),

$$\frac{\Omega_j h^2}{0.12} = 2.54 \times 10^6 \, \beta \, \xi \, g_j \, \left(\frac{M_{\rm in}}{M_P}\right)^{\frac{1}{2}} \, \frac{m_j}{\rm GeV} \simeq \xi \, g_j \left(\frac{\beta}{10^{-20}}\right) \left(\frac{M_{\rm in}}{1\,{\rm g}}\right)^{\frac{1}{2}} \left(\frac{m_j}{8.2 \times 10^{10}\,{\rm GeV}}\right) \qquad \beta < \beta_{\rm c}$$

In RD, no k dependence (MB), but beta dependence

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

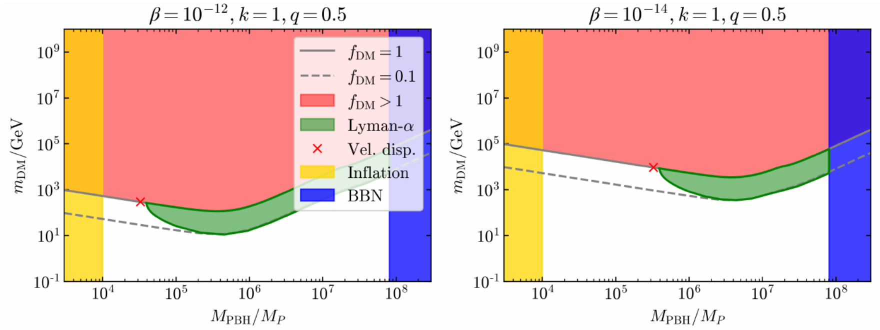
$$m_{\rm DM} \gtrsim 1.74\,{\rm keV} \times \sqrt{\langle \mathrm{q}_\star^2\rangle}\, \mathrm{T}_{\rm NCDM} \times \left(\frac{m_{\rm WDM}^{\rm ly\alpha}}{\rm keV}\right)^{4/3}$$

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

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

PBH parameter space

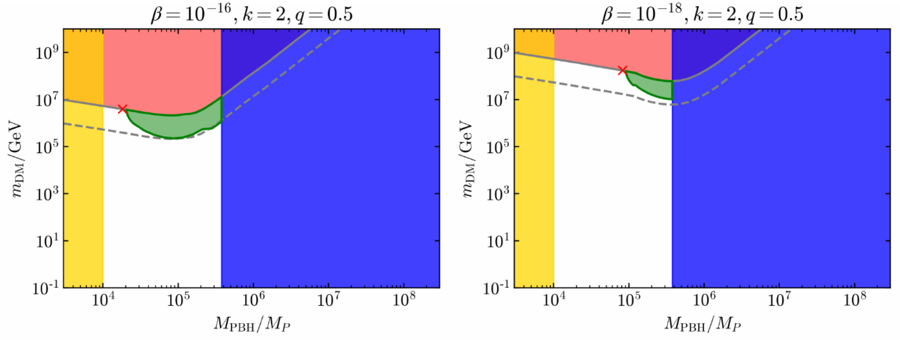
see also [Barman'24, Haque'24]



- relic DM abundance depend on β in RD era and on k in MD era
- Larger $\beta \rightsquigarrow$ less viable parameter space.
- Increasing k supresses more evaporation in the memory burden phase making BBN constraints more stringent (for $k > 4$ no viable parameter space left).
- For DM fraction lower than 10%, no Ly-α constraints.

PBH parameter space

see also [Barman'24, Haque'24]



- relic DM abundance depend on β in RD era and on k in MD era
- Larger $\beta \rightsquigarrow$ less viable parameter space.
- Increasing k supresses more evaporation in the memory burden phase making BBN constraints more stringent (for $k > 4$ no viable parameter space left).
- For DM fraction lower than 10%, no Ly-α constraints.

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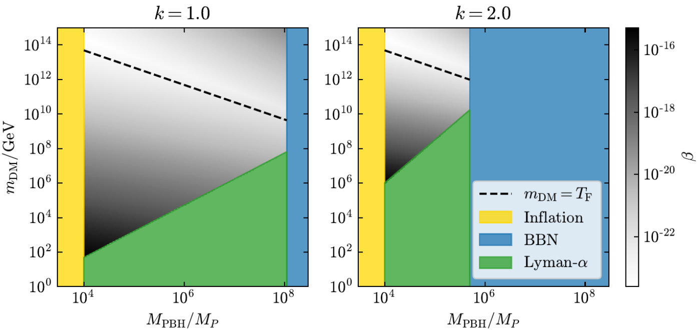

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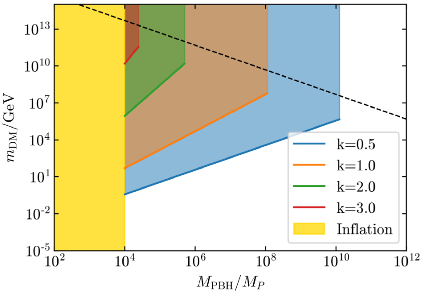

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Intermediate mass-range: Hidden sectors

Hidden sector: new particles and new forces

$\rightsquigarrow$ allows to populate wider mass range with multiple mechanisms (freeze-in, freeze-out, SIMP, asymmetric, DM etc). Example dark vector portal A'_μ.

Challenge: Experiments to look for those new forces
$\rightsquigarrow$ viable DM in sub-GeV range.

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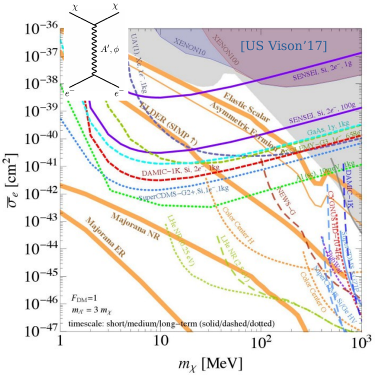
Challenge: Experiments to look for those new forces
⇝ viable DM in sub-GeV range.

- Direct detection experiments: with electrons scatterings/excitations, making use of different materials (ferromagnets, superfluid He, etc) .
  ⇝ Diversity of new proposed experiments for low momentum transfer

[see talks Tue& Thu, see also blazar boosted DM of Laura Manenti.]



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Challenge: Experiments to look for those new forces
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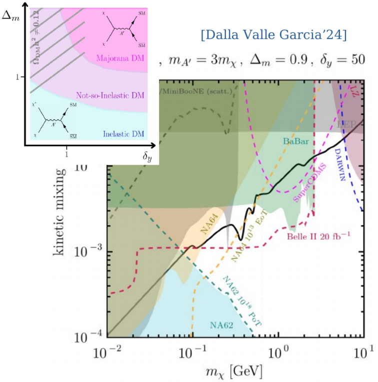
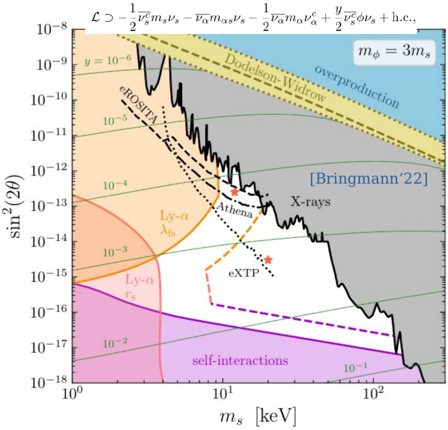
- beam dump exp. & LLP detectors:
    - Inelastic DM or not so: gives displaced decays $A' \to \chi\chi^* \to \chi\chi\bar{l}l$
      [G. Dalla Valle Garcia talk]
    - SIMP: Dark pion from confined dark sectors: $3\pi_D \to \pi_D\rho_D$ populates $m > 100$ MeVlong lived ρ_D can give rise to DV at Beam dump exp. [N. Hemme talk]



Intermediate mass-range: Sterile Neutrino

Connection between SM neutrinos and keV DM

- Minimal sterile neutrino DM: Majorana ν_s mixing with SM ν and light scalar ϕ.
  Challenge: strong constraints from X-rays and Ly-α and self interactions.
  [e.g. Bringmann'22]



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Connection between SM neutrinos and keV DM

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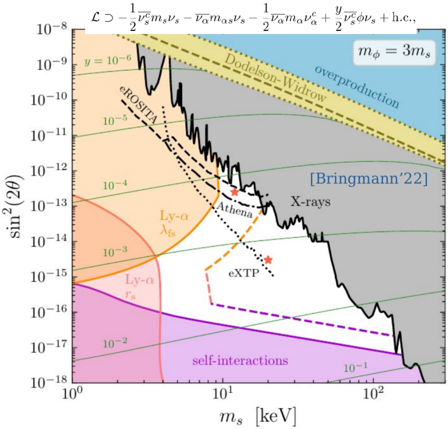
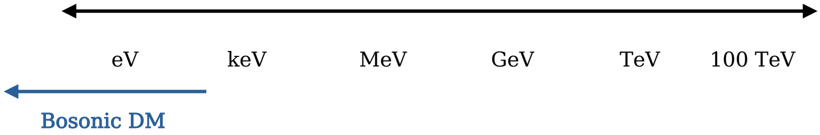
- Adding gauge interactions Z'_μ and light dark fermions χ, Ψ with Ψ =DM:
  Evade X-ray constraints and relax tension between neutrino mass from Cosmo and particle phys.
  [see talk Cristina Benso]



Lower mass-range: Bosonic DM



Lower mass-range: Bosonic DM

Bosonic DM

Typically non-thermal :
Axions, ALP, Dark photon

Cosmology :
Lyman-alpha (ULDM),
ΔNeff, energy injection.

Lower mass-range: Bosonic DM

eV keV MeV GeV TeV 100 TeV

Bosonic DM

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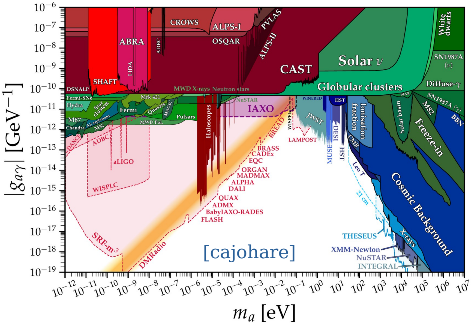

Lower mass-range: Bosonic DM

eV keV MeV GeV TeV 100 TeV

Bosonic DM

Typically non-thermal :
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Cosmology :
Lyman-alpha (ULDM),
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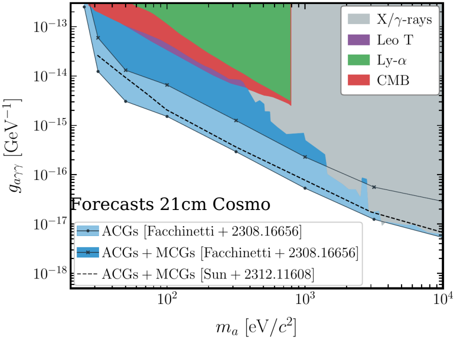
strong lensing

$a \to \gamma\gamma$



This is really the end