The domain of thermal dark matter, and a hot, dark history of the Universe

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Dark Matters, ULB, 1st December 2022

→ PRD **104** (2021) 5 (arXiv 2105.01263) with Thomas Hambye, Michel Tytgat and Laurent Vanderheyden

→ arXiv 2212.xyzab with Jean Kimus and Michel Tytgat

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Outline

1. Motivation
2. Constructing the domain
3. Looking into $T' > T$

Thermal dark matter

- Parameter space of DM is enormous, allowed mass spans dozens of orders of magnitude
- Can refine this by considering implications of production mechanism
- If DM thermalises with SM particles,
  - Cowsik-McClelland bound $\Rightarrow m_{\rm dm} \gtrsim 50$ eV Cowsik+McClelland, PRL '72
  - In almost all cases, BBN constrains $m_{\rm dm} \gtrsim 10$ MeV

    e.g. Sabti+, JCAP '20; Fields+, JCAP '20; exception in Berlin+Blinov, PRL '18
  - Unitarity bound $\Rightarrow m_{\rm dm} \lesssim 300$ TeV Griest+Kamionkowski, PRL '90

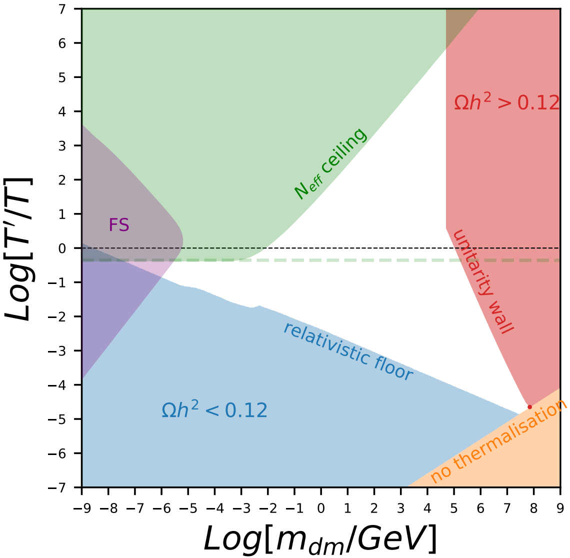
Thermal dark matter

- Suppose now that the dark sector has its own temperature, $\boldsymbol{T'}$
- This can be achieved in several ways, e.g. from inflationary physics
- As we vary the temperature ratio,

$$\xi \equiv \frac{\boldsymbol{T'}}{\boldsymbol{T}}\,, \tag{1}$$

how does the allowed range of $m_{\rm dm}$ change?

The domain



7
6
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2
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0
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−7
−9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6 7 8 9
Log[T′/T]
Log[m_dm/GeV]
N_eff ceiling
FS
Ωh² > 0.12
unitarity wall
relativistic floor
Ωh² < 0.12
no thermalisation

The boundaries of the domain

Here focus on the three most important model-independent constraints:

1. The relativistic floor
2. The unitarity wall
3. The $N_{\rm eff}$ ceiling

The relativistic floor

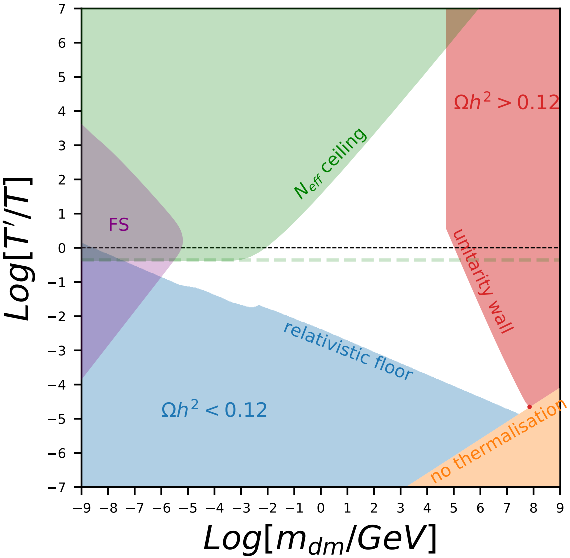
- Start with a very simple observation: the DM relic abundance depends on its **mass** and **yield**, $Y \equiv n/s$,

$$\Omega_{\rm dm} \propto m_{\rm dm} Y_{\rm dm} \qquad (2)$$

- Smallest possible mass is found by taking the largest possible yield, the relativistic one: for $\xi < 1$, $Y_{\rm dm} \approx T'^3/T^3 = \xi^3$

- Given $\Omega_{\rm dm} h^2 = 0.12$, this implies a fixed contour of $m_{\rm dm}\xi^3$, up to g_* effects Hambye+Vanderheyden, JCAP '20; Hambye+Lucca+Vanderheyden, PLB '20;

The domain



$\Omega h^2 > 0.12$
N_{eff} ceiling
FS
unitarity wall
relativistic floor
$\Omega h^2 < 0.12$
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$Log[T'/T]$
$Log[m_{dm}/GeV]$
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The unitarity wall

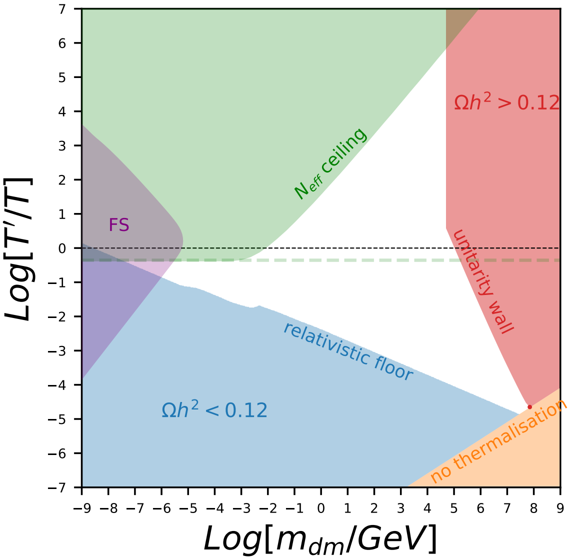
- Similarly, largest possible mass is found by taking the smallest possible number density: DM annihilates away as quickly as possible, with $\langle \sigma v \rangle$ at the **unitarity limit**
- Freeze-out calculation with $\xi \lesssim 1$ (hence $\rho \gg \rho'$) gives

$$\Omega_{\rm dm} h^2 \simeq 4.7 \times 10^8 \frac{g_{\rm dm} g_{*,\rm dec}^{1/2} x'_{\rm dec} \boldsymbol{\xi}}{g_{*s,\rm dec} m_{\rm Pl} \langle \boldsymbol{\sigma v} \rangle \mathrm{GeV}} \tag{3}$$

and $\langle \boldsymbol{\sigma v} \rangle \propto 1/m_{\rm dm}^2$, giving a contour of constant $m_{\rm dm}^2 \xi$

- When $\xi \gg 1$, freeze-out is independent of visible sector: the result is independent of T and hence of ξ, obtain $m_{\rm dm} \gtrsim 50 g_{\rm dm}^{1/4}$ TeV

The domain



$\Omega h^2 > 0.12$
N_{eff} ceiling
FS
unitarity wall
relativistic floor
$\Omega h^2 < 0.12$
no thermalisation
$Log[T'/T]$
$Log[m_{dm}/GeV]$

$N_{\rm eff}$ ceiling

- When the dark sector is relativistic, $\rho' \propto T'^4$, thus $\rho' < 0.3\rho_\nu$ at BBN if $\xi \lesssim 0.5$
- For larger ξ, DM must be non-relativistic by BBN, which corresponds roughly to the condition

$$m_{\rm dm} \gtrsim \xi\, T_{\rm BBN} \tag{4}$$

- Putting everything together gives the ranges for a Dirac fermion,

$$1 \text{ keV} \lesssim m_{\rm dm} \lesssim 52 \text{ PeV} \tag{5}$$

$$1.4 \times 10^{-5} \lesssim \xi \lesssim 6.9 \times 10^{5} \tag{6}$$

A hot dark sector

- Just saw that $\xi \gg 1$ can in principle be allowed
- Very little investigation in the literature: is it really possible?
- In particular, two things to worry about:
  1. Can we have dark-visible interactions which are weak enough to allow $\xi \gg 1$ but strong enough so that the dark mediator decays **before** BBN
  2. What is the effect of **entropy production**?
- Since the domain was model-independent, can a specific model even **extend** the allowed parameter space?

The model

- Dark QED, with dark matter χ and dark photon mediator γ', such that $m_{\gamma'} < m_\chi$, with kinetic mixing parameter ε
- The DM freezes out via $\chi\bar{\chi} \to \gamma'\gamma'$, then slow $\gamma' \to f\bar{f}$ decays
- Coupled differential equations after χ freeze-out,

$$a\frac{d\rho_t}{da} + 3(1+\omega_t)\rho_t = 0 \quad \text{(continuity)} \tag{7}$$

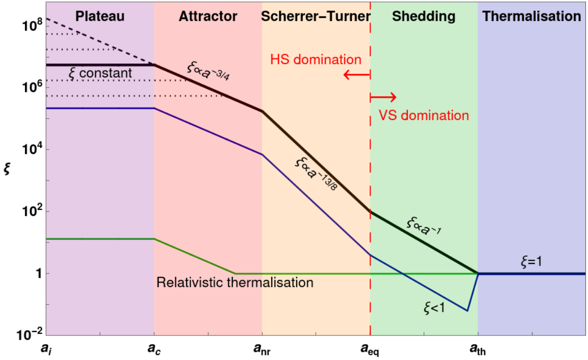
$$a\frac{d\rho'}{da} + 3(1+\omega')\rho' = \frac{m_{\gamma'}\Gamma_{\gamma'}}{H}\left[n'_{\rm eq}(T) - n'(T')\right] \quad \text{(E transfer)} \tag{8}$$

$$a\frac{dn'}{da} + 3n' = \frac{\Gamma_{\gamma'}}{H}\left[\frac{K_1(x)}{K_2(x)}n'_{\rm eq}(T) - \frac{K_1(x')}{K_2(x')}n'(T')\right] \quad \text{(n transfer)} \tag{9}$$

where $x^{(')} \equiv m_{\gamma'}/T^{(')}$

Evolution of the system

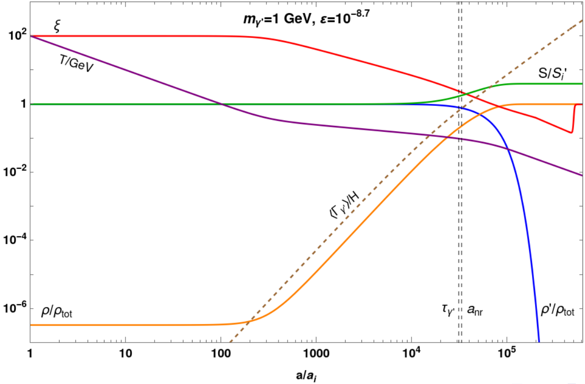
- Solution breaks into 3-5 regime, depending on whether many γ' decay **relativistically** or not



- At some point the γ' are no longer thermalised, T' is an **effective temperature**

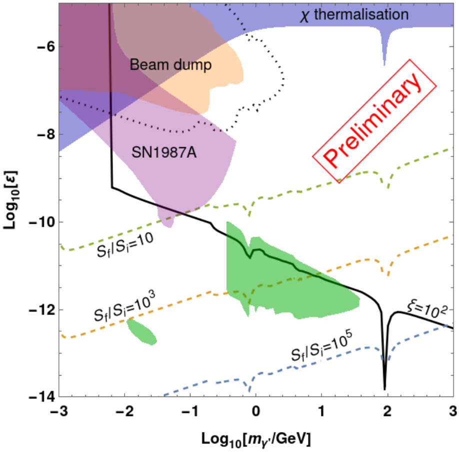
A specific example

- All five phases present in this case
- $\xi_i = 100$, but $\rho'/\rho_{\rm tot} \ll 1$ by $T \sim 30$ MeV
- Baryogenesis a challenge here since dilution of η by $\sim \xi^3$



Dark photon parameter space

- Bound corresponds to $\tau_{\gamma'} \lesssim 0.2$s, taking $\rho'/\rho < 0.04$ at BBN



Berger+Jedamzik+Walker, JCAP '16; Hardy+Lasenby, JHEP '17; Bauer+Foldenauer+Jaeckel, JHEP '18;...

Entropy production

- If the γ' decays while relativistic, entropy production is minimal: conservation of energy gives

$$\frac{S_f}{S_i} \approx (g_*/g_*')^{1/4} \tag{10}$$

- Greater entropy production if γ' decays non-relativistically, with

Scherrer+Turner, PRD '85

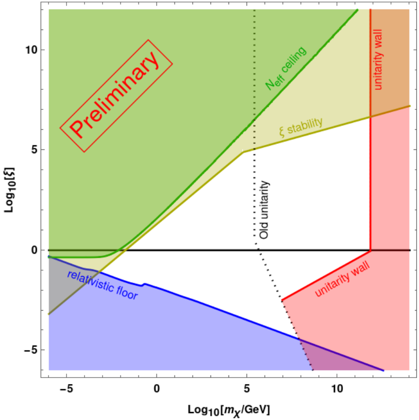
$$\frac{S_f}{S_i} \approx \frac{\tau_{\gamma'}}{t_{\mathrm{nr}}} \approx \frac{m_{\gamma'}}{\sqrt{\Gamma_{\gamma'} m_{\mathrm{Pl}}}} \tag{11}$$

- Entropy dilution allows one to go **beyond the unitarity limit**

see e.g. Berlin+Hooper+Krnjaic, PLB '16; PRD '16

Dark QED domain

- Accounted for entropy dilution, also imposed that ξ is **well-defined**, i.e. on plateau when DM freezes out



Conclusions

- Considered DM freeze-out for dark sector with temperature T'
- Found the allowed DM domain as a function of $m_{\rm dm}$ and T'/T, with $m_{\rm dm} \in [1.0 \text{ keV}, 52 \text{ PeV}]$ and $\xi \in [1.4 \times 10^{-5}, 6.9 \times 10^{5}]$
- Showed that $\xi \gg 1$ is indeed possible in dark QED
- Entropy dilution due to mediator decays stretches the domain, allowing $\xi \lesssim 10^{-6}$ and $m_\chi \lesssim 10^{12}$ GeV, but additional limit from stability of ξ
- Hot dark sectors are rare, rich and relevant

Back-up slides

The N_{eff} ceiling

- At BBN, $\Delta N_{\text{eff}} \lesssim 0.3$
- The DM contribution is

$$\Delta N_{\text{eff}} = \frac{60 g_{\text{dm}} \xi^4}{7\pi^4} \left(\frac{11}{4}\right)^{4/3} \int_{m_{\text{dm}}/T'_{\text{BBN}}}^{\infty} dz \frac{z^2 \sqrt{z^2 - m_{\text{dm}}^2/T'^2_{\text{BBN}}}}{e^z \pm 1} \quad (12)$$

- For $m_{\text{dm}} \ll T'_{\text{BBN}} = \xi T_{\text{BBN}}$, have $\Delta N_{\text{eff}} \sim \xi^4$, so require $\xi \lesssim 0.5$ independently of the DM mass
- Larger ξ is possible as long as the DM is non-relativistic, i.e. $m_{\text{dm}} \gtrsim T'_{\text{BBN}}$

Beyond canonical freeze-out

- We have in mind the simplest kind of FO, $\chi\overline{\chi} \to \psi\overline{\psi}$, but what else could happen?
  - Co-annihilation, $\chi\phi \to \psi\eta$, then unitarity limit will be on the heavier of χ, ϕ
  - DM is asymmetric, in which case a larger cross-section is required, and the unitarity bound on the DM mass is stronger
  - DM may be composite, conceivably with $\sigma \sim r_{\rm dm}^2 \gg 1/m_{\rm dm}^2$

  see e.g. Harigaya+, JHEP '16

- The first two cases are subject to the general bounds of the domain, the third is beyond our scope

The thermalisation constraint

- Assumed the DM sector thermalises—need to check this is true
- At some very high temperature above all relevant scales of the DM interaction, $\Gamma \sim \alpha'^2 T'$, and this entered into equilibrium at

$$T'_{\rm eq} \simeq \alpha'^2 \xi^2 \frac{M_{Pl}}{\sqrt{g_*}} \tag{13}$$

- The value of Γ/H typically peaks around $T' \sim m_{\rm dm}$: for larger T', $H \propto T^2$ grows faster than Γ, while for smaller T' the DM abundance is Boltzmann-suppressed
- DM barely equilibrates if $T'_{\rm eq} \simeq T'_{\rm FO} \sim m_{\rm dm}$

The thermalisation constraint

- Solving for $T'_{\rm eq} = m_{\rm dm}$ gives

$$\xi \simeq \sqrt{\frac{m_{\rm dm} g_*^{1/2}}{\alpha'^2 M_{Pl}}}\,. \tag{14}$$

- For smaller ξ, the DM does not equilibrate
- If there is some heavier mass involved, e.g. some other dark sector mass, m', then the bound is increased by $m_{\rm dm} \to m'$
- Doing this more carefully by solving $T'_{\rm eq} = T'_{\rm FO}$ for the unitarity cross-section gives a similar result
- Combining relativistic floor, thermalisation cellar and unitarity wall, find $m_{\rm dm} \leq 52$ PeV and $\xi \geq 1.4 \times 10^{-5}$ if DM is a Dirac fermion