Spontaneous Freeze-Out from Thermal Phase Transition of Heavy Dark-Matter

Lucien HEURTIER

In collaboration with

Hervé Partouche (CPHT, École Polytechnique, Palaiseau)

Based on 1910.XXXX

IRN Terascale
Bruxelles

THE UNIVERSITY OF ARIZONA

October 2019

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However we know that this is not the case for most of the particles in cosmology !

- Presence of a high temperature
- Thermal effects $\longrightarrow \langle h \rangle = 0$
- All particles massless at large T

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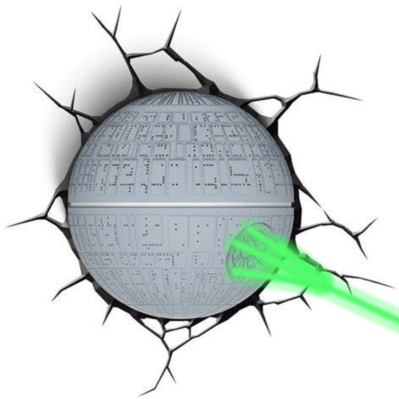

- Interactions between the dark sector and the thermal bath $\longrightarrow$ thermal effects
- Mass terms in the dark sector might vary with T

However we know that this is not the case for most of the particles in cosmology !

- Presence of a high temperature
- Thermal effects $\longrightarrow$ $\langle h \rangle = 0$
- All particles massless at large T

An educational toy model :

$$\mathcal{L}_{\text{tree}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{dark}} + \mathcal{L}_{\text{int}} \, ,$$

$\mathcal{L}_{\text{int}}$: Interaction between DM particles ψ and SM particles

$$\mathcal{L}_{\text{dark}} = i\bar{\psi}\partial\!\!\!/\psi + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - y\phi\bar{\psi}\psi - \mathcal{V}_{\text{tree}}(\phi) + \mathcal{L}_{\text{dark}}^{\text{c.t.}} \, ,$$

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$$m_\psi(\langle\phi\rangle) = y\langle\phi\rangle \longleftarrow \mathcal{V}_{\rm tree}(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4!}\phi^4 \, ,$$

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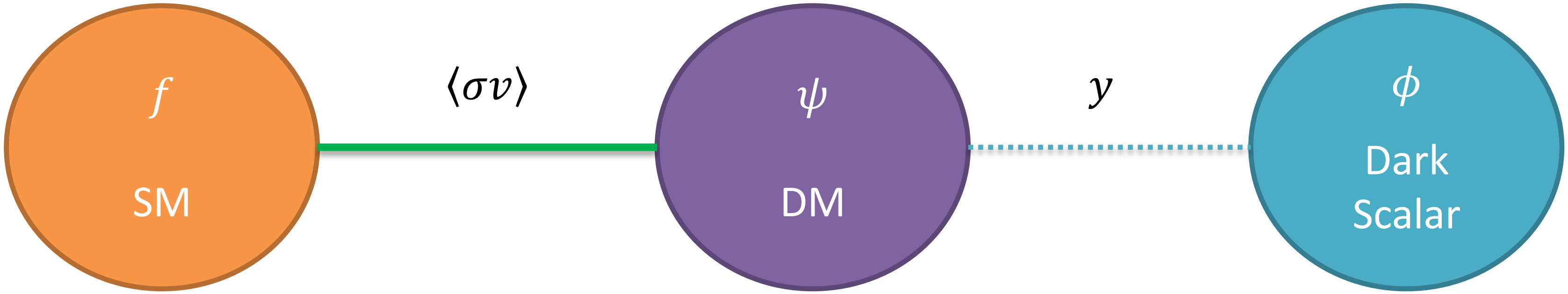
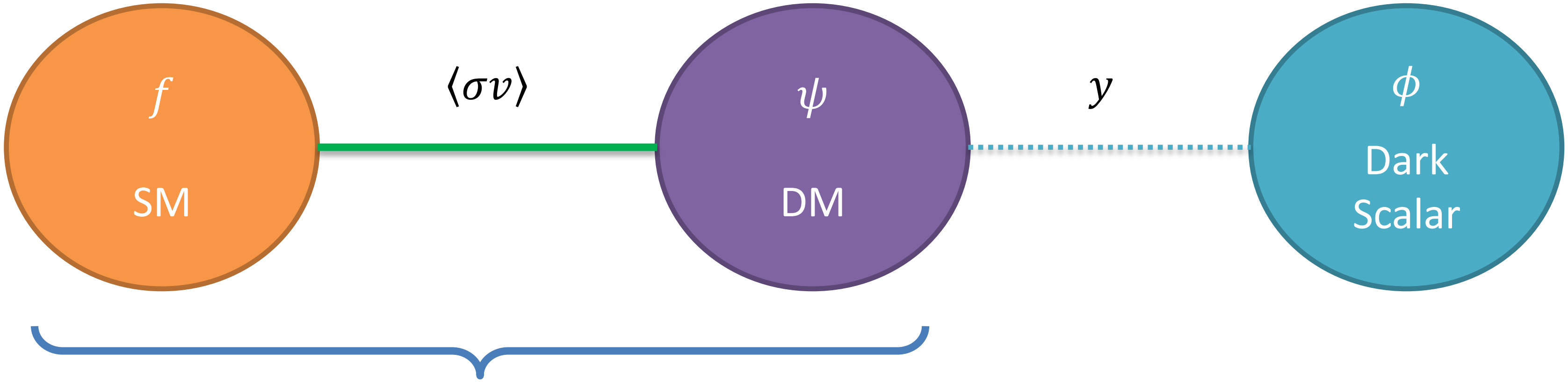
But this is in the vacuum, at $T = 0$ ...



f
SM
$\langle \sigma v \rangle$
ψ
DM
y
ϕ
Dark
Scalar



Thermal equilibrium : $T \longrightarrow \mathcal{V}_{\rm eff}^{\rm th}(T,\phi)$

$$\boxed{\mathcal{V}_{\rm eff}^{\rm th}(T,\phi) = \mathcal{V}_{\rm tree}(\phi) + \mathcal{V}_{\rm CW}(\phi) + \mathcal{V}_{\rm dark}^{\rm c.t.}(\phi) + \mathcal{F}(T,\phi)}$$

Zero Temperature CW

1-loop correction to the free energy

Only ψ is assumed to be thermalized...

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$$\mathcal{V}_{\rm CW}(\phi) + \mathcal{V}_{\rm dark}^{\rm c.t.}(\phi) = -n_F \frac{m_\psi(\phi)^4}{64\pi^2}\left[\log\left(\frac{m_\psi(\phi)^2}{Q^2}\right) - \frac{3}{2}\right]$$

$$\mathcal{F}(T,\phi) = -n_F \frac{T^4}{2\pi^2} J_F\left(\frac{m_\psi(\phi)^2}{T^2}\right)$$

$$J_F\left(\frac{m^2}{T^2}\right) = \int_0^{+\infty} du\, u^2 \log\left(1 + e^{-\sqrt{u^2+m^2/T^2}}\right)$$

$$= \frac{7\pi^4}{360} - \frac{\pi^2}{24}\frac{m^2}{T^2} - \frac{1}{32}\frac{m^4}{T^4}\log\frac{m^2}{\alpha T^2} + \mathcal{O}\left(\frac{m^6}{T^6}\right)$$

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$$\mathcal{V}_{\mathrm{eff}}^{\mathrm{th}}(T,\phi) = -n_F \frac{7\pi^2}{720} T^4 - \frac{\mu_{\mathrm{eff}}(T)^2}{2}\phi^2 + \frac{\lambda_{\mathrm{eff}}(T)}{4!}\phi^4$$

$$\mu_{\mathrm{eff}}(T)^2 = \mu^2 - \frac{n_F}{24} y^2 T^2 \,,$$

$$\lambda_{\mathrm{eff}}(T) = \lambda + \frac{3n_F}{8\pi^2} y^4 \log\left(\frac{Q^2}{\pi^2 e^{-2\gamma_E} T^2}\right)$$

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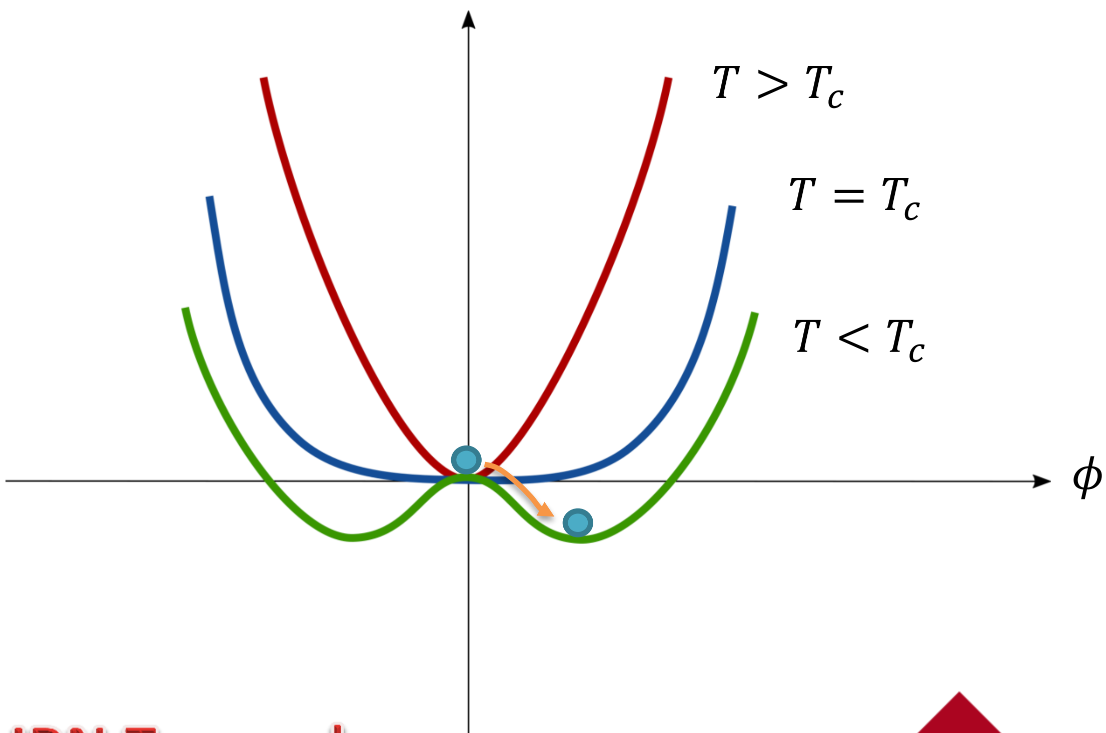


2nd order phase transition

$T > T_c$ DM massless

$T < T_c$ DM acquires mass

Spontaneous Freeze Out

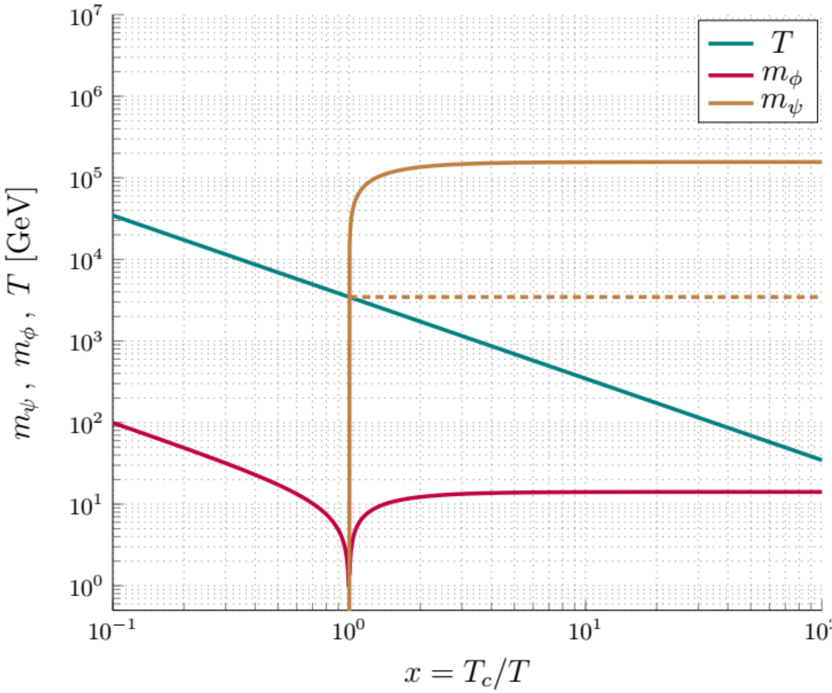
$$Q = \pi e^{-\gamma_E} T_c \,, \qquad x = \frac{T_c}{T} \,.$$

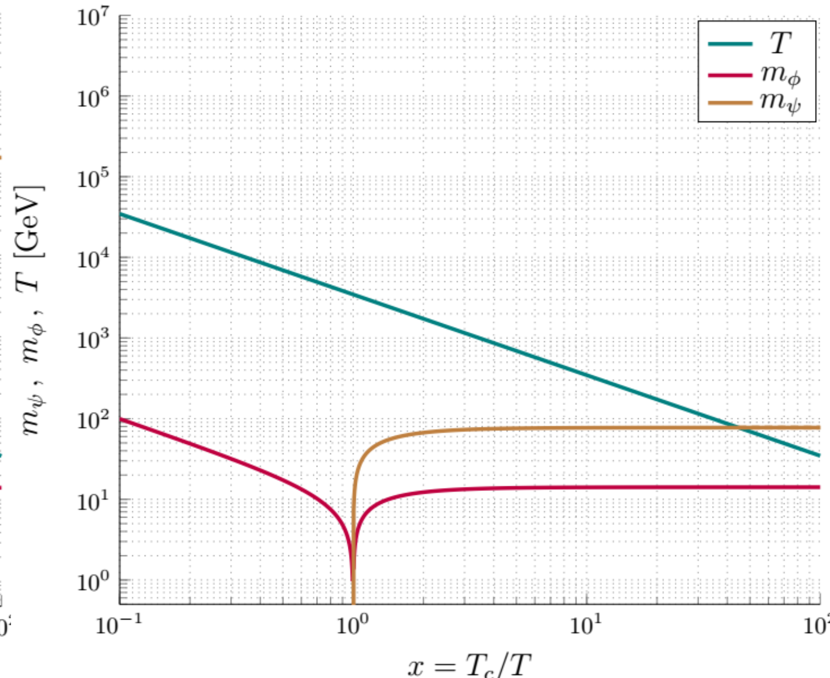
$$x \leq 1 : \quad \langle \phi \rangle = 0 \,,$$

$$1 \leq x \leq x_f : \quad \langle \phi \rangle = \mu_{\text{eff}}(x) \sqrt{\frac{6}{\lambda_{\text{eff}}(x)}} \,,$$

$$m_\psi(x) = 0 \,,$$

$$m_\psi(x) = y \sqrt{\frac{3}{\lambda_{\text{eff}}(x)}} \, m_\phi(x) \,.$$





$$x_f \equiv \frac{T_c}{T_f} = \sqrt{1 + u(x_f)}\,, \quad \text{where}$$

$$u(x) = \frac{4\kappa^2 \lambda_{\text{eff}}(x)}{n_F y^4} = \kappa^2 \left(\frac{4}{n_F} \frac{\lambda}{y^4} + \frac{3}{\pi^2} \log x \right)$$

$$T_f = m_\psi(x_f)/\kappa$$

$$u(x_f) \gg 1$$

$$1 \ll x \le x_f: \quad m_\phi(x) \simeq m_\phi^{\text{tree}}\,,$$

$$m_\psi(x) \simeq y \sqrt{\frac{3}{\lambda_{\text{eff}}(x)}}\, m_\phi^{\text{tree}}\,.$$

FO

$$u(x_f) = \mathcal{O}(1)$$

$$1 \lesssim x \lesssim x_f: \quad m_\phi(x) \simeq 2\mu\sqrt{x - 1}\,,$$

$$m_\psi(x) \simeq 2\mu y \sqrt{\frac{3(x-1)}{\lambda_{\text{eff}}(x)}}\,.$$

Spont. FO

Decoupling of Dark Matter And Scalar Potential

After Dark Matter freezes out

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{d\mathcal{V}_{\rm eff}}{d\phi} - \frac{d\mathcal{V}_{\rm dust}}{d\phi}$$

$$\mathcal{V}_{\rm eff}(\phi) = \mathcal{V}_{\rm tree}(\phi) + \mathcal{V}_{\rm CW}(\phi) + \mathcal{V}^{\rm c.t.}_{\rm dark}(\phi)$$

$$S_{\rm dust} = -\sum_i \int d\tau_i \, y\phi(X_i) \sqrt{g_{\mu\nu}(X_i)\,\frac{dX_i^\mu}{d\tau_i}\frac{dX_i^\nu}{d\tau_i}}$$

$$\rho_{\rm dust} = n_\psi y\phi\,, \qquad P_{\rm dust} = 0\,. \qquad \frac{d\mathcal{V}_{\rm dust}}{d\phi} = yn_\psi$$

Interactions with the Standard Model

To compute the relic abundance : need to specify $\mathcal{L}_{\rm int}$

Consider SI interactions : $\mathcal{O}_V = \bar{\psi}\gamma_\mu\psi\bar{f}\gamma^\mu f$ and $\mathcal{O}_S = \bar{\psi}\psi\bar{f}f$

$$\langle\sigma v\rangle_V \simeq \frac{G_V^2}{2\pi}\left(1+\frac{x^{-1}T_c}{m_\psi(x)}\right)m_\psi^2(x)\,,$$
$$\langle\sigma v\rangle_S \simeq \frac{3G_S^2}{8\pi}\,x^{-1}T_c m_\psi(x)\,.$$

$$\boxed{\Omega h^2 = n_F\frac{m_\psi(x_0)s_0}{6H_0^2M_p^2}\,Y_\psi^0}$$

$$Y_\psi = n_\psi/s$$
$$\frac{\mathrm{d}Y_\psi}{dx} = \frac{\langle\sigma v\rangle s}{xH}(Y_{\psi,\rm eq}^2 - Y_\psi^2)$$

Interactions with the Standard Model

After Spontaneous Freeze Out

For a given $\langle \sigma v \rangle$ if $m_\psi(x) \nearrow$ then $\Omega h^2 \nearrow$

→ In order to have Ωh^2 = *0.12* one needs a larger annihilation cross section

→ Models more accessible to detection

→ Unitarity limit modified as compared to the usual WIMP scenario

Unitarity Bound

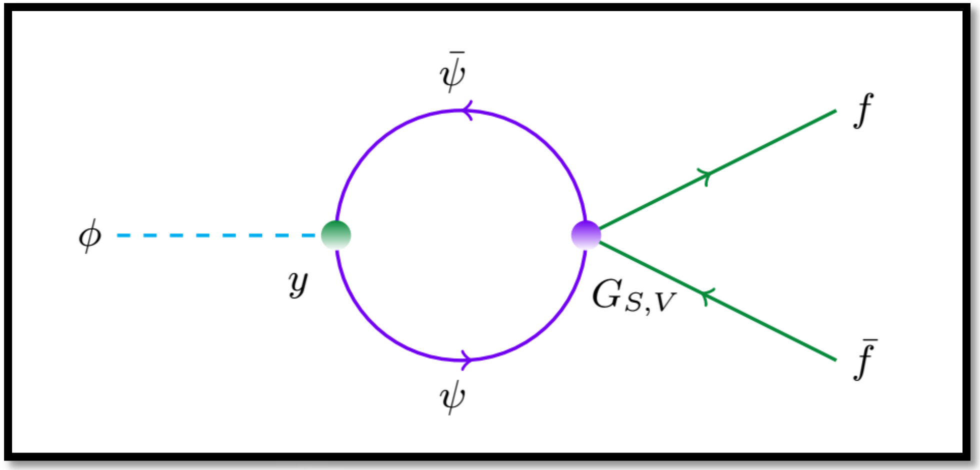
In the usual WIMP scenario, unitarity imposes that

$$\sigma_J v_{rel} < \frac{4\pi(2J+1)}{{m_\psi}^2 v_{rel}}$$

In our scenario, for a given dark-matter mass today, the DM mass at freeze-out was smaller

$$(\sigma_J v_{rel})^{FO}{}_{max} < (\sigma_J v_{rel})^{SFO}{}_{max}$$

Stability of the dark scalar ?



$$\mathcal{O}_S^{\text{eff}} = \left(y \frac{G_S m_\psi^2}{2\pi^2} \right) \phi \bar f f \,,$$

$$\mathcal{O}_V^{\text{eff}} = \left(y \frac{G_V m_\psi}{4\pi^2} \right) \partial_\mu \phi \bar f \gamma^\mu f \,,$$

$$(\tau_\phi^S)^{-1} = \Gamma_\phi^S = \frac{m_\phi}{8\pi} \left(\frac{y\, G_S m_\psi^2}{2\pi^2} \right)^2 \left(1 - \frac{4m_f^2}{m_\phi^2} \right)^{3/2} ,$$

$$(\tau_\phi^V)^{-1} = \Gamma_\phi^V = \frac{m_\phi^3}{8\pi} \left(\frac{y\, G_V m_\psi}{4\pi^2} \right)^2 \left(1 - \frac{4m_f^2}{m_\phi^2} \right)^{3/2} .$$

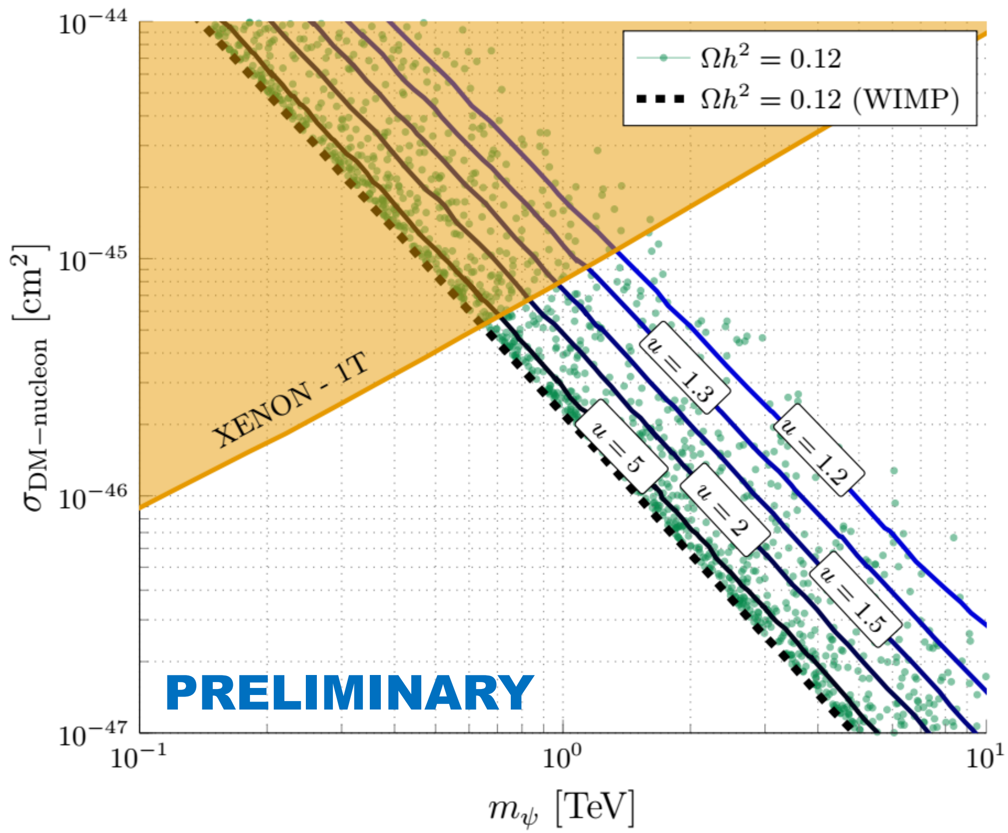
- ϕ could be produced through a Freeze-In mechanism and participate to the relic abundance…
- Could decay after BBN…

Direct Detection constraints

$$\mathcal{O}_S = \bar{\psi}\psi\bar{f}f$$

- Velocity suppressed
- No constraints from indirect detection
- Might be detectable through direct detection…

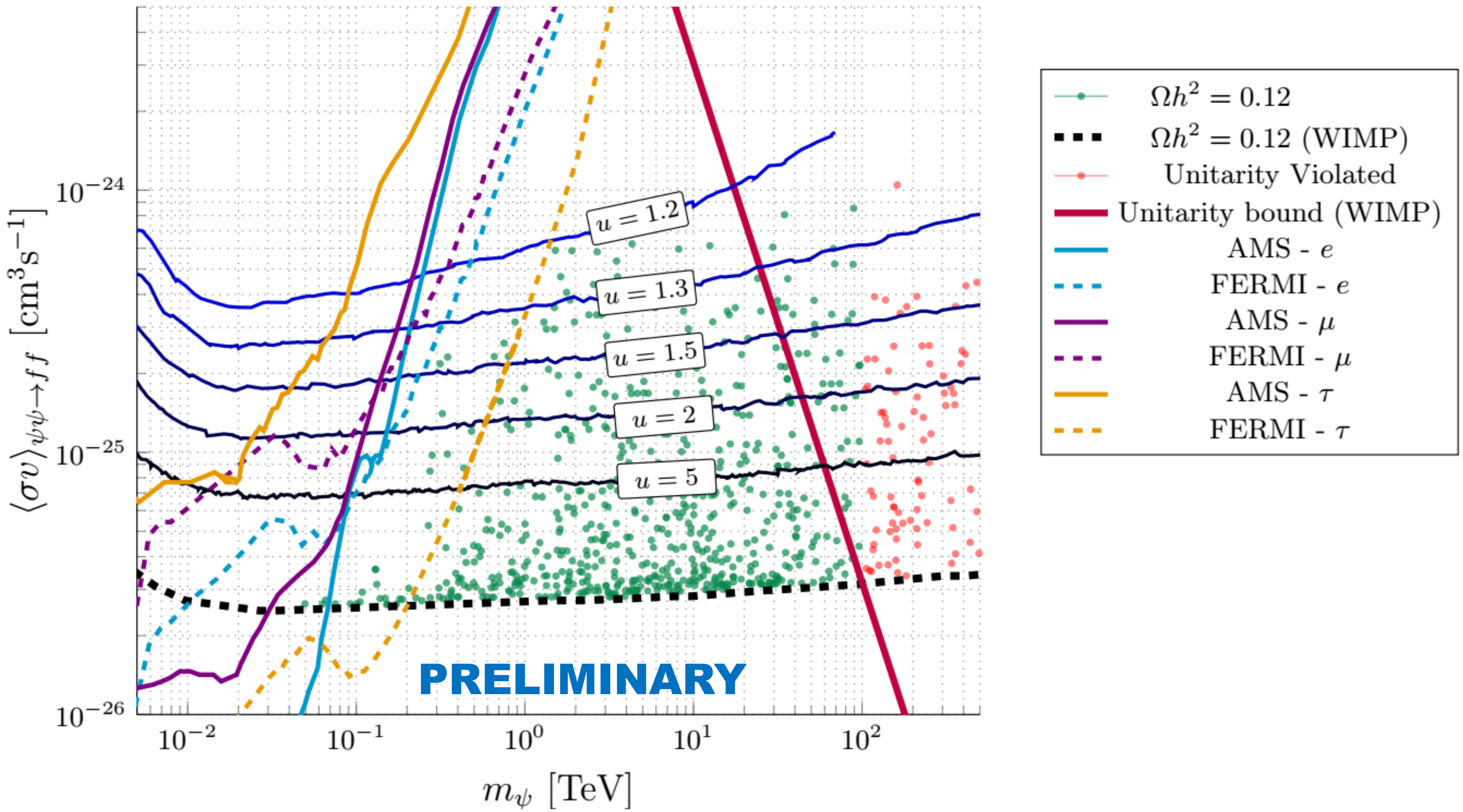
$$f = \{q\}_{q=u,d,s,c,b,t}$$



Indirect Detection constraints

$f = \{l\}_{l=e,\tau,\mu}$

$$\mathcal{O}_V = \bar{\psi}\gamma_\mu\psi\bar{f}\gamma^\mu f$$



Conclusion

- Masses in the dark sector might be generated by the spontaneous breaking of some global symmetry
- While DM particles are in thermal equilibrium, thermal corrections to the scalar potential associated with such SSB might be significant and restore the symetry above some critical temperature
- The sudden 2nd order phase transition taking place at $T = T_c$ might provoke the Spontaneous Freeze Out of dark matter particles before their mass reached their asymptotic value
- The cross section necessary to generate the correct DM relic abundance is typically larger than in the usual WIMP scenario
- The model might involve the presence of long lived scalars which might be detectable in future experiments
- Unitarity bounds on the WIMP mass might be overshot thanks to the dynamical evolution of the dark matter mass

Thank you very much!