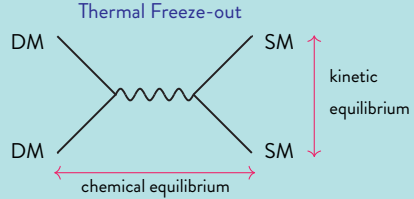
Dark Matter from Reheating

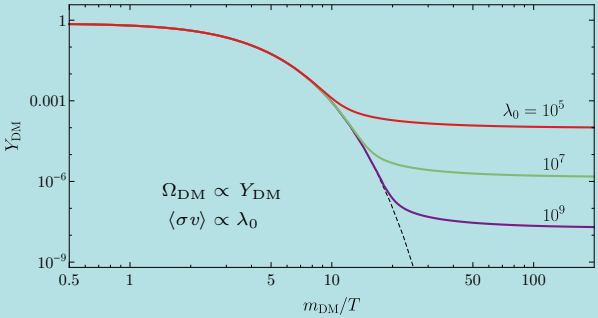
Marcos A. G. García

10/09/2021

1222·2022 800 ANNI
UNIVERSITÀ DEGLI STUDI DI PADOVA
INFN PADOVA

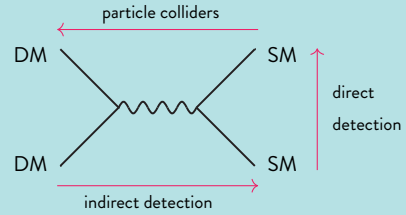
The many virtues of the WIMP

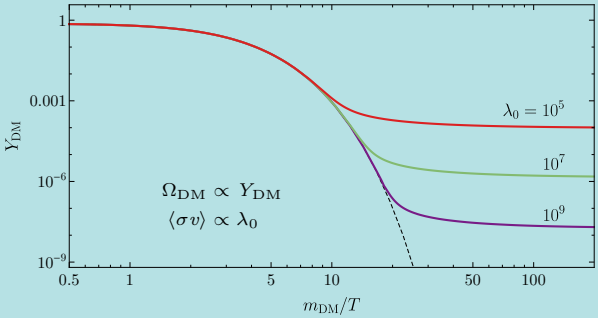




$$\Omega_{\rm DM}h^2 \equiv \frac{\rho_{\rm DM}}{\rho_{\rm tot}}h^2 \sim \frac{0.1\,{\rm pb}}{\langle\sigma v\rangle}$$
$$\sim 0.1\left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)^2$$

The many virtues of the WIMP





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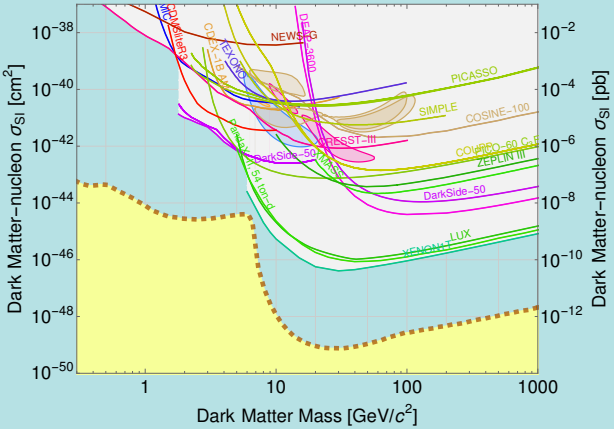
Beyond the WIMP

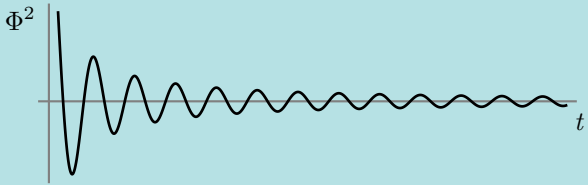


- [x] GRAVITY
- [x] ELECTROMAGNETISM
- [x] WEAK FORCE
- [x] STRONG FORCE

Feeble interactions = dependence on initial conditions

(Re)populating the Universe after inflation

During reheating, the inflaton provides an oscillating background



$$\mathcal{L}_\psi = y\,\Phi\bar{\psi}\psi \equiv m_\psi(t)\bar{\psi}\psi$$

$$\mathcal{L}_\chi = \frac{1}{2}\sigma\,\Phi^2\chi^2 \equiv \frac{1}{2}m_\chi^2(t)\chi^2$$

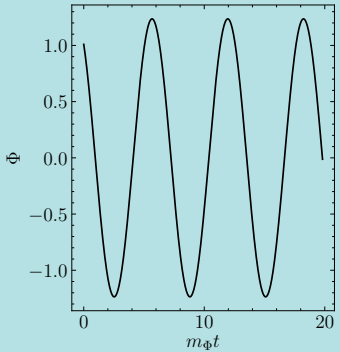
Mixing of +/- frequency modes $\rightarrow$ particle production!

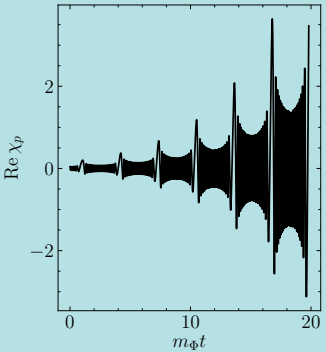
Scalar (p)reheating

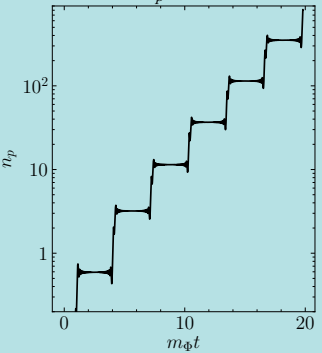
$$\ddot{\chi}_p + 3H\dot{\chi}_p + \left[\frac{p^2}{a^2} + m_\chi^2(t)\right]\chi_p \;=\; 0\,, \qquad m_\chi^2(t) = \sigma\Phi^2 + m_{\chi,0}^2$$

Neglecting expansion,

$$n_p = \frac{1}{2\omega_p}|\omega_p\chi_p - i\dot{\chi}|^2$$







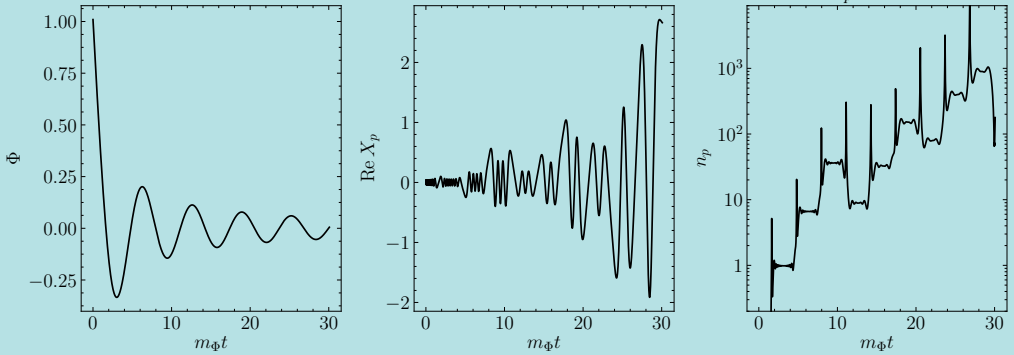
Scalar (p)reheating

$$\ddot{\chi}_p + 3H\dot{\chi}_p + \left[\frac{p^2}{a^2} + m_\chi^2(t)\right]\chi_p \;=\; 0\,, \qquad m_\chi^2(t) = \sigma\Phi^2 + m_{\chi,0}^2$$

With expansion,

$X = a\chi$

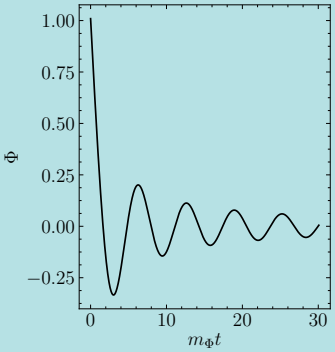
$$n_p = \frac{1}{2\omega_p}|\omega_p\chi_p - i\chi'|^2$$

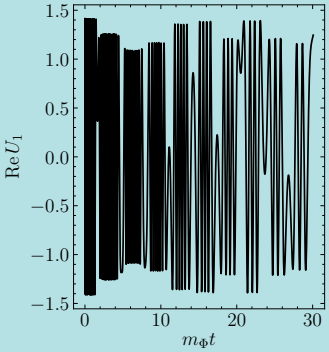


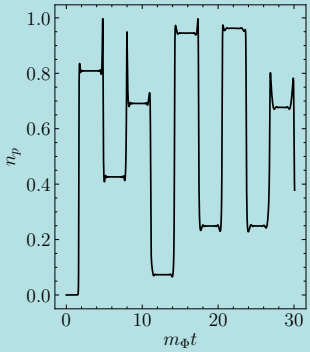
Fermion (p)reheating

$$\left[i\gamma^\mu\partial_\mu + i\frac{3a'}{2a}\gamma^0 - a m_\psi(\tau)\right]\psi \;=\; 0\,, \qquad m_\psi^2(\tau) = \left(y\Phi + m_{\psi,0}\right)^2$$

With expansion,



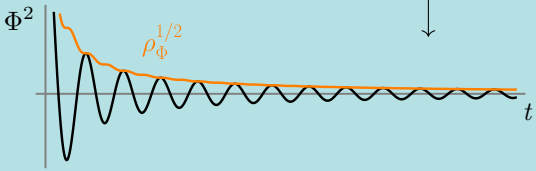




The perturbative (dissipative) picture

Reheating as the exchange of energy between two ideal fluids

$$T^{\mu\nu} = T^{\mu\nu}_{\Phi} + T^{\mu\nu}_{R} = \begin{pmatrix} \rho_\Phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + \frac{1}{3}\begin{pmatrix} 3\rho_R & 0 & 0 & 0 \\ 0 & \rho_R & 0 & 0 \\ 0 & 0 & \rho_R & 0 \\ 0 & 0 & 0 & \rho_R \end{pmatrix}$$



$$\langle p_\Phi \rangle = \tfrac{1}{2}\langle \dot{\Phi}^2 + m_\Phi^2 \Phi^2 \rangle \simeq 0$$

(matter)

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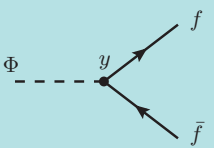
Conservation $\nabla_\mu T^{\mu\nu} = 0$,

$$\dot{\rho}_R + 4H\rho_R = -(\dot{\rho}_\Phi + 3H\rho_\Phi) \equiv \Gamma_\Phi \rho_\Phi$$



$$\Gamma_\Phi = \frac{y^2}{8\pi} m_\Phi$$

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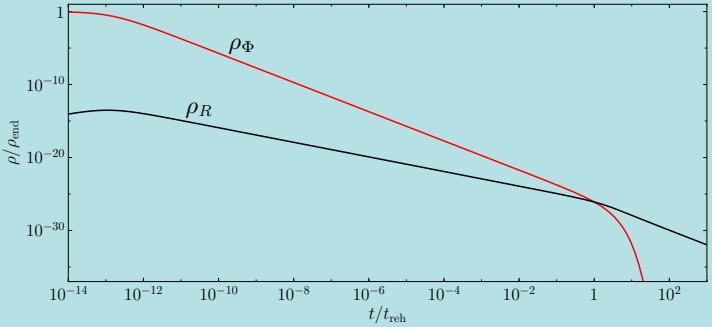
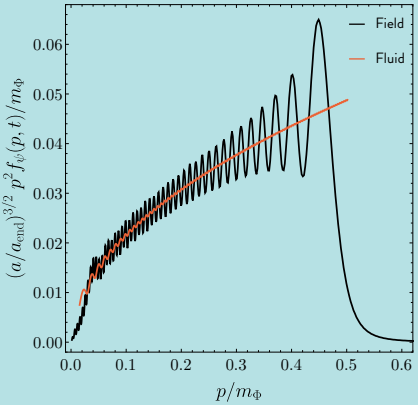


The phase space distribution

$$n_\psi \;=\; \int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\, f_\psi(p,t)$$



$$\frac{\partial f_\psi}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_\psi}{\partial |\boldsymbol{p}|} = \frac{1}{2p_0}\int d\Pi\, |\mathcal{M}|^2_{\Phi\to\bar\psi\psi} n_\Phi \delta^{(3)}(\boldsymbol{P}) \;+\; \mathcal{C}^{\rm int}[f_\psi]$$

The phase space distribution

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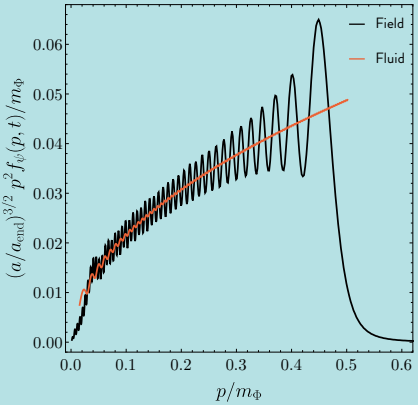

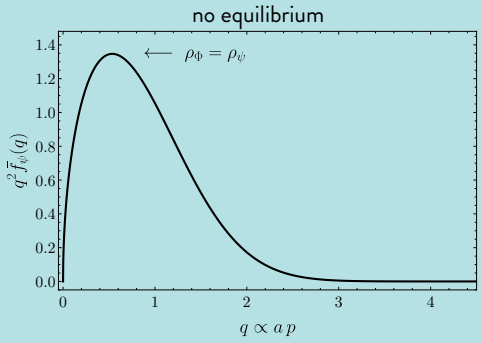

G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

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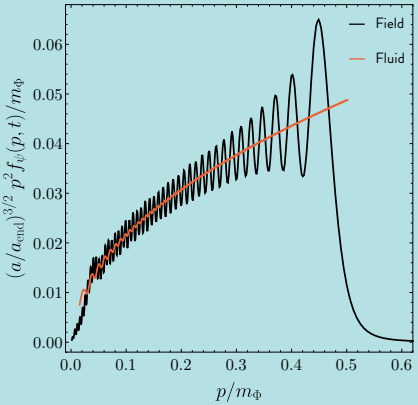
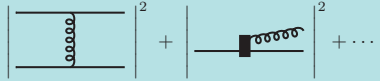


$$\mathcal{C}^{\rm int}[f_\psi] =$$



$$+ \cdots$$

K. Harigaya, K. Mukaida, JHEP 05 (2014), 006

The phase space distribution

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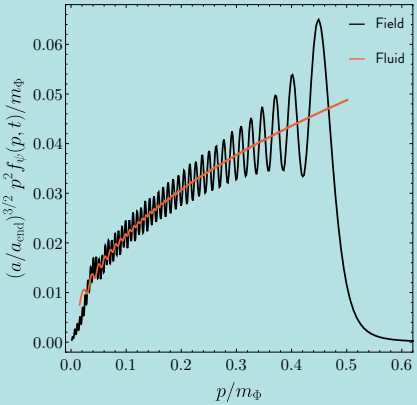

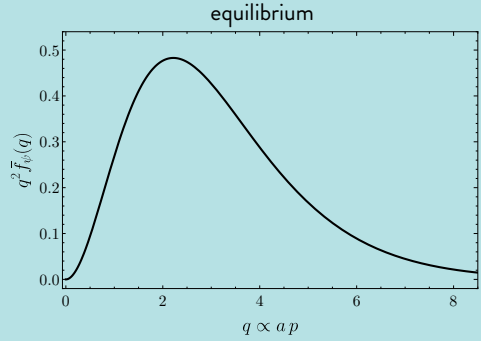

Is a spin-$\frac{3}{2}$ dark matter particle the missing piece in the puzzle?

	spin 0	spin 1/2	spin 1	spin 3/2	spin 2
SM:	H	u_L	W^0		G

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	spin 0	spin 1/2	spin 1	spin 3/2	spin 2
SM+DM:	H	u_L	W^0	Ψ	G
				raritron	

$$\mathcal{L} \;=\; -\tfrac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu$$

(Rarita-Schwinger)

For gravitinos see e.g. J. Ellis, MG, D. Nanopoulos, K. Olive and M. Peloso, JCAP 03 (2016), 008;
E. Dudas, MG, Y. Mambrini, K. Olive, M. Peloso and S. Verner, PRD 103 (2021), 123519

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	spin 0	spin 1/2	spin 1	spin 3/2	spin 2
SM+DM:	H	u_L	W^0	Ψ	G
	Φ	ν_R			
	inflaton	R-neutrino		*raritron*	

$$\mathcal{L} = -\tfrac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]}\right)\Psi_\nu$$
$$+ yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}_R^c\nu_R \qquad (\nu \text{ masses through see-saw})$$
$$+ y_\nu\Phi\bar{\nu}_R\nu_R \qquad (\text{reheating})$$

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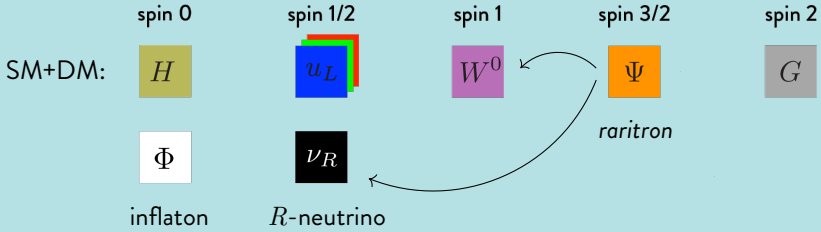
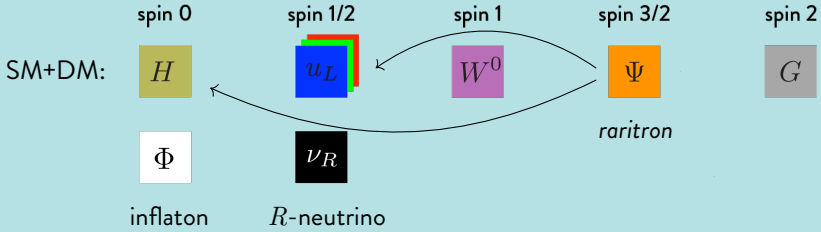


$$
\begin{aligned}
\mathcal{L} \;=\; & -\tfrac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu \\
& + yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}_R^c\nu_R \\
& + y_\nu \Phi \bar{\nu}_R \nu_R \\
& + i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma}
\end{aligned}
$$

Is a spin-$\frac{3}{2}$ dark matter particle the missing piece in the puzzle?

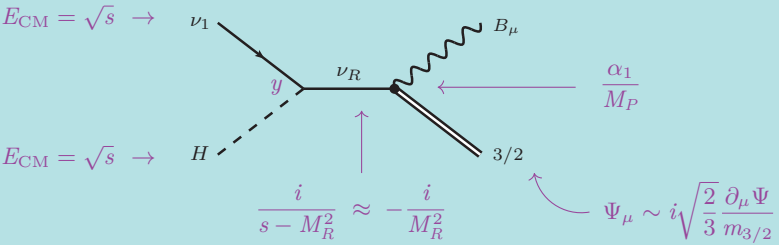


$$
\begin{aligned}
\mathcal{L} \;=\; & -\tfrac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu \\
& + yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}_R^c\nu_R \\
& + y_\nu \Phi \bar{\nu}_R \nu_R \\
& + i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma} + i\frac{\alpha_2}{2M_P} i\sigma_2 (D^\mu H)^* \bar{L}\Psi_\mu + \cdots
\end{aligned}
$$

MG, Y. Mambrini, K. A. Olive and S. Verner, PRD 102 (2020), 083533

Scatterings and decays

$$\mathcal{L}_{3/2} = \boxed{i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma}} + i\frac{\alpha_2}{2M_P}i\sigma_2(D^\mu H)^*\bar{L}\Psi_\mu + \text{h.c.}$$

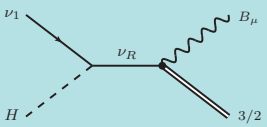


$$\Rightarrow \quad \sigma(s) \propto \frac{\alpha_1^2 y^2 s^2}{m_{3/2}^2 M_R^2 M_P^2}$$

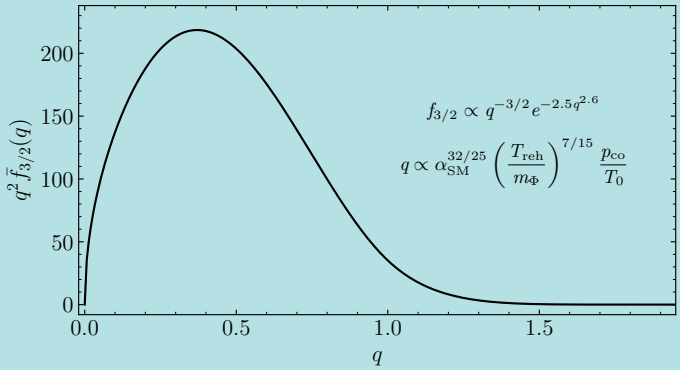
- Production peaked at high energies → reheating
- Ψ is never in thermal equilibrium (*freeze-in*)

Scatterings and decays

not equilibrated

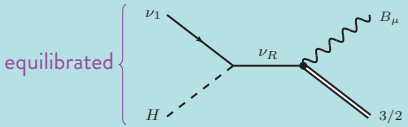


$$\Omega_{3/2} \propto \alpha_1 \frac{m_\nu m_\Phi^2 T_{\rm reh}^3}{m_{3/2} M_R t_{\rm therm}}$$

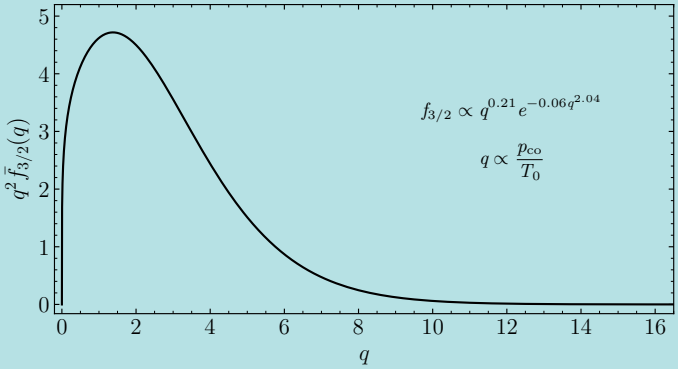


MG and M. A. Amin, PRD 98 (2018), 103504; G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

Scatterings and decays

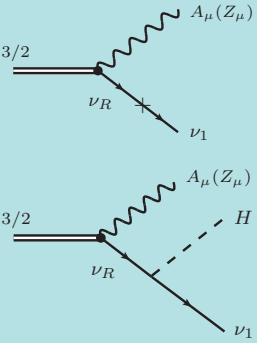


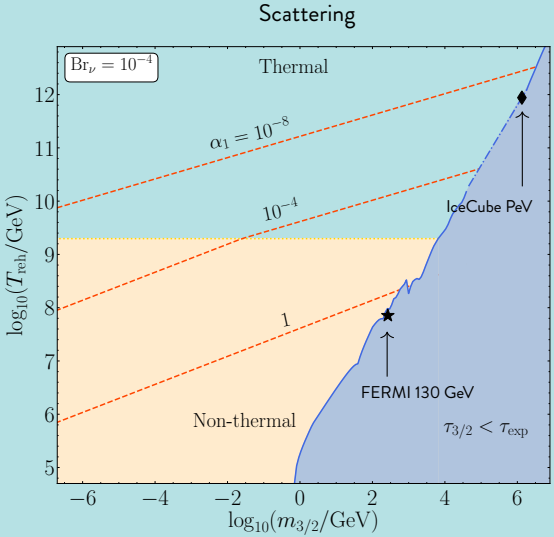
$$\Omega_{3/2} \propto \alpha_1 \frac{m_\nu T_{\rm reh}^5}{m_{3/2} M_R}$$



G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

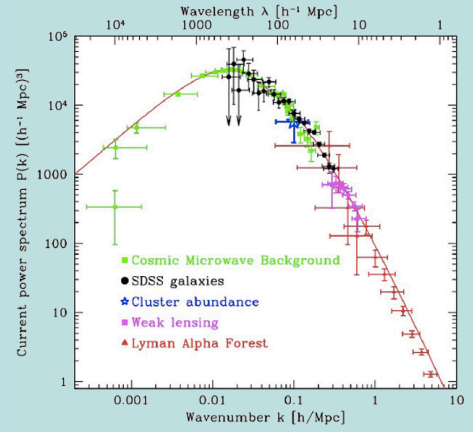
Scatterings and decays

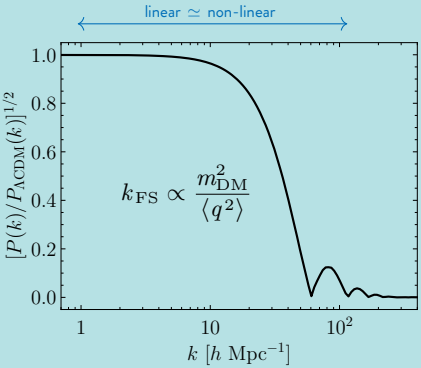




How warm is out-of-equilibrium dark matter?

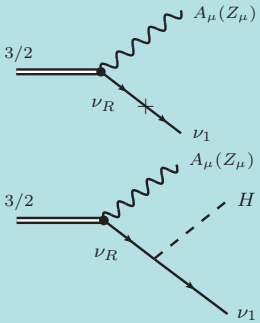
R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540

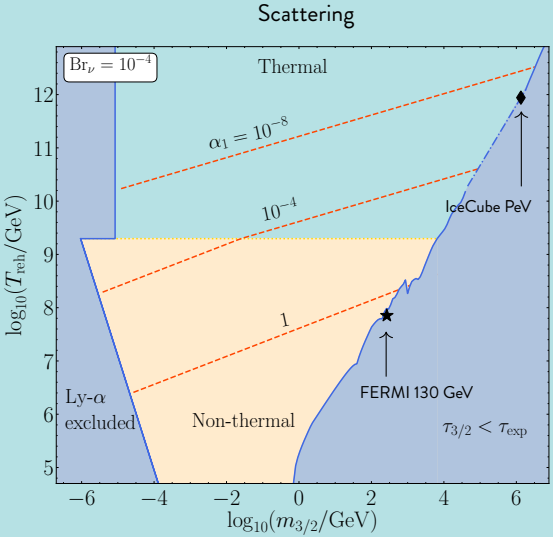




G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

Constraints: $\Omega_{\rm DM} + \gamma + \nu +$ Lyman-α

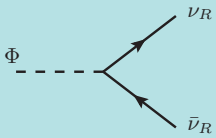


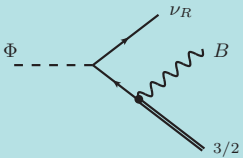


Production (via inflaton decay)

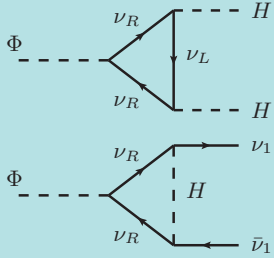
Via α_1,

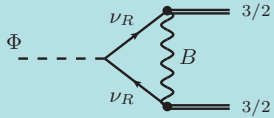
$M_R \ll m_\Phi$:





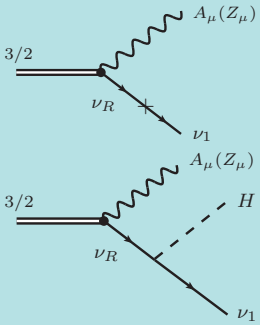
$M_R \gg m_\Phi$:



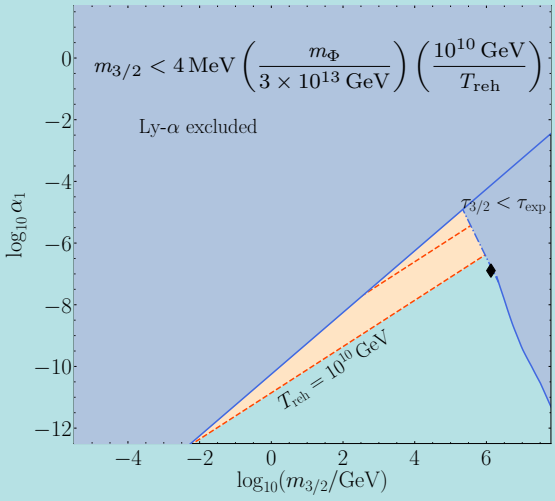


(via α_2 are 2-loop suppressed)

Constraints: $\Omega_{\rm DM} + \gamma + \nu +$ Lyman-α

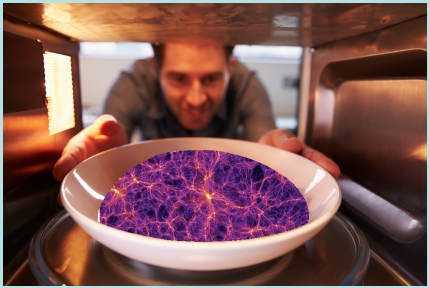


Inflaton decay



Conclusion

- The light beyond the WIMP: the Big Bang itself?
- Dark matter as a probe of early dynamics
- Beyond weak coupling: large effective masses, (WIMPzillas), metric preheating (PBHs), fragmentation (soliton DM)
- Not in this talk: Dark Matter production *during* inflation



Thank You