Particle Physics at Cosmic Dawn - Part III

Focus on Dark Matter imprint

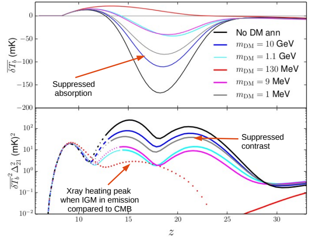
Laura Lopez Honorez

inspired by Phys.Rev.D 96 (2017) 10, JCAP 06 (2018) 007, Phys.Rev.D 99 (2019) 2, arXiv:2111.09321 in collaboration with Q. Decant, M. Escudero, J. Heisig, D. Hooper, O. Mena, S Palomares and P. Villanueva.

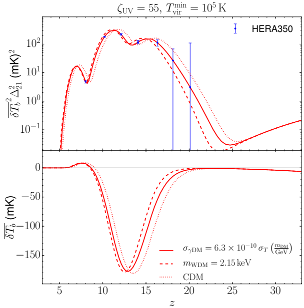
Frontiers of Astrophysics and Cosmology
Scuela Normale (Pisa, Italy)

In these seminar-lectures

- Extra energy injection
  - Annihilating DM
  - Energy injection affect e.g. CMB
  - further constraints from imprint at cosmic dawn?

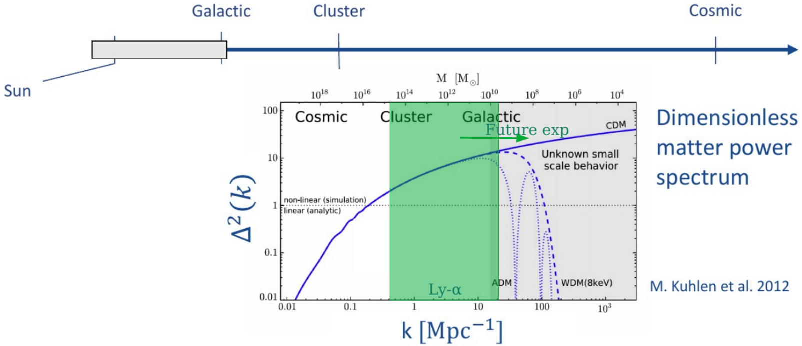


- Delay of structure formation
  - Non Cold Dark Matter: free-streeming, collisional damping
  - also delay in 21cm features
  - can help to disentangle NCDMs?



Non-Cold Dark Matter

Non-Cold Dark Matter

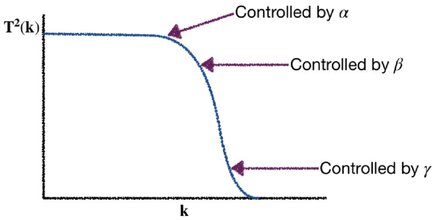


- Thermal WDM free-streaming from overdense to underdense regions $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int v/a dt$
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], includes NCDM free-streaming and collisional damping.

Non-Cold Dark Matter

$$T^2(k) = \frac{P(k)_{\rm nCDM}}{P(k)_{\rm CDM}} = \left[1 + (\alpha k)^\beta\right]^{2\gamma}$$

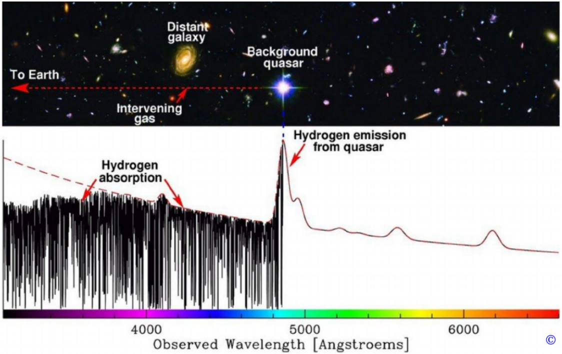
[Murgia'17]



[Courtesy DC Hooper]

- Thermal WDM free-streaming from overdense to underdense regions
$\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int v/a dt$
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], includes NCDM free-streaming and collisional damping.

Non-Cold Dark Matter



© M. Murphy

- Thermal WDM free-streaming from overdense to underdense regions $\rightsquigarrow$ Smooth out inhomegeneities for $\lambda \lesssim \lambda_{FS} \sim \int v/adt$
- Effects $P(k)$ and $T(k)$ generalized to Non-Cold DM see e.g. [Bode'00, Viel'05, Murgia'17], includes NCDM free-streaming and collisional damping.
- Thermal WDM against Lyman-α forest data: absorption lines along line of sights to distant quasars probe smallest structures $\rightsquigarrow$ $m_{\rm WDM}^{\rm thermal} > 1.9\text{-}5.3$ keV

see e.g. [Viel'05, Yeche'17, Palanque-Delabrouille'19,Garzilli'19]

NCDM is not necessarily thermal Warm Dark Matter

Cosmology

Particle Physics

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

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Cosmology

Particle Physics

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

Weak/strong coupling to SM

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

"Thermal" DM

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

NCDM is not necessarily thermal Warm Dark Matter

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Decouple still relativistic and freestream while struct. forms

Still coupled to light dof while struct. forms

"Thermal Warm" Dark Matter (WDM)

"Interacting" Dark Matter (IDM)

NCDM is not necessarily thermal Warm Dark Matter

Cosmology: $\dfrac{df_\chi(t,p)}{dt}$ = Particle Physics: $\mathcal{C}[f_\chi]$

Weak/strong coupling to SM

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

"Thermal" DM

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

- 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)

Feeble/No coupling to SM

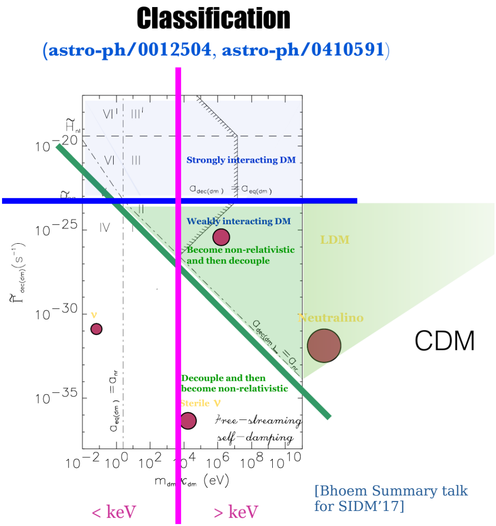
$\Gamma_{\chi\leftrightarrow\mathrm{SM}} < H$

"Non-Thermal" DM

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

- Produced through feeble interactions 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°

NCDM is not necessarily thermal Warm Dark Matter



[Bhoem Summary talk for SIDM'17]

Some NCDM candidates

Thermal WDM as Free-streaming DM

NCDM as thermal WDM

Cosmology

Particle Physics

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

Weak coupling
to SM

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

"Thermal" DM

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

Decouple still
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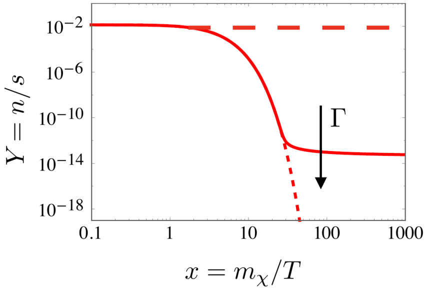
"Thermal Warm"
Dark Matter (WDM)

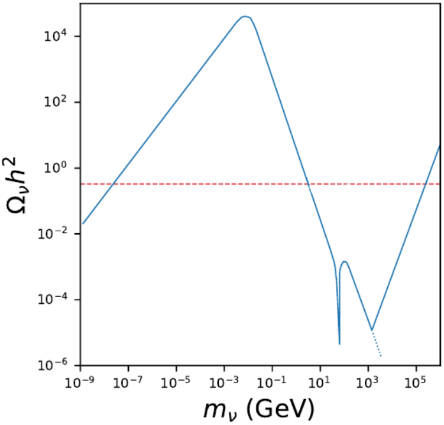
Thermal WDM freeze-out

$$\frac{df_\chi}{dt} = \mathcal{C}_{ann}[f_\chi] \quad \rightsquigarrow \quad n_\chi \propto \frac{g^0_{*,S}}{g_{*,S}(T_D)}$$



- DM annihilation driven freeze-out
- χ chem. & kin. equilibrium
- DM decouples while relativistic: $x_D = m_B/T_D$ and $x_D < 3$
- $\Omega_\chi h^2 = 0.12 \frac{g_\chi^{(n)} m_\chi}{6\,\text{eV}} \frac{g^0_{*,S}}{g_{*,S}(T_D)}$

Thermal WDM abundance



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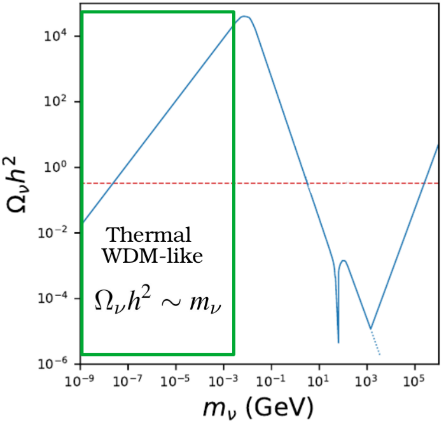
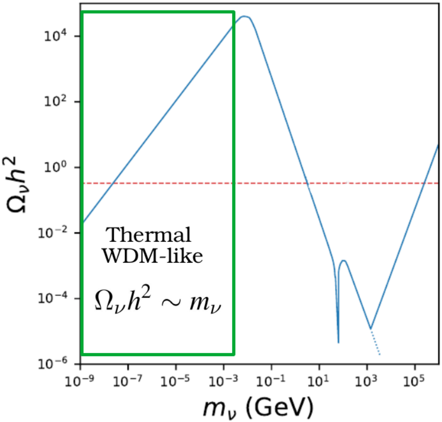


$$\Omega_\chi h^2 = 0.12 \frac{g_\chi^{(n)} m_\chi}{6\,\text{eV}} \frac{g^0_{*,S}}{g_{*,S}(T_D)}$$

- SM neutrinos (2 dof)
  $T_D \sim$ MeV, i.e. $g_{*,S}(T_D) = 10.75$
  $\rightsquigarrow \sum_\nu m_\nu \sim 10$ eV
  for all DM (Excluded!!)

Thermal WDM abundance



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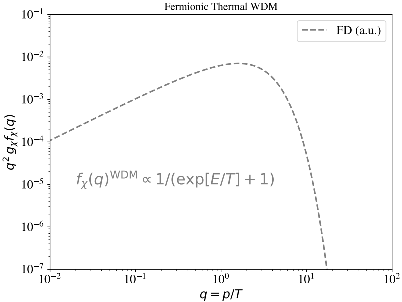
  $\rightsquigarrow \sum_\nu m_\nu \sim 10$ eV
  for all DM (Excluded!!)

- Thermal WDM (2 dof): needs $g_{*,S}(T_D) \sim 1000 \times (m_\chi/\text{keV})$ for all DM
  i.e. for few keV DM $g_{*,S}(T_D) \gg g^{tot}_{SM} \sim 100$

Thermal WDM: exponential cut in $P(k)$ at small scales

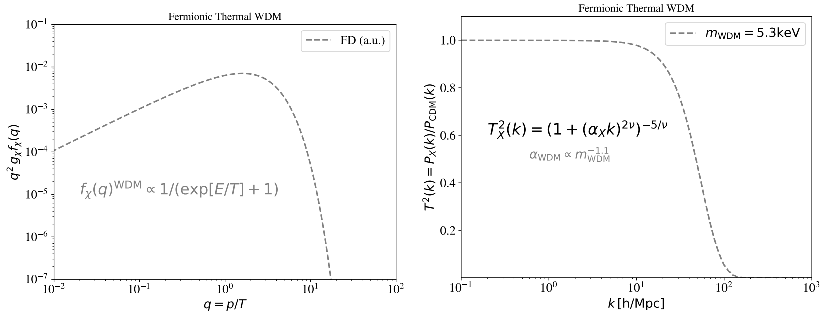
see also [Bode'00,Viel'05]



- Thermal WDM is in kinetic equilibrium thanks to fast elastic scatterings with thermal plasma: $\frac{d}{dt} f_\chi = \mathcal{C}_{el}[f_\chi] \rightsquigarrow f_\chi \propto f_\chi^{eq}(q)$

Thermal WDM: exponential cut in $P(k)$ at small scales

see also [Bode'00,Viel'05]



- Thermal WDM is in kinetic equilibrium thanks to fast elastic scatterings with thermal plasma: $\frac{d}{dt} f_\chi = \mathcal{C}_{el}[f_\chi] \rightsquigarrow f_\chi \propto f_\chi^{eq}(q)$
- Evolve f_χ up to 1st order pert. (w/ Boltzmann code as e.g. CLASS): Transfer function $T(k) = (1+(\alpha_{\rm WDM} k)^{2\nu})^{-5/\nu}$ with $\nu = 1.12$ [Viel'05]

Free-streaming scale: $\alpha_{\rm WDM} \sim 0.045\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-1.11}$ Mpc$/h$

FIMPs as Free-streaming DM

NCDM as a FIMP

Cosmology

Particle Physics

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

Feeble/No coupling to SM

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

"Non-Thermal" DM

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

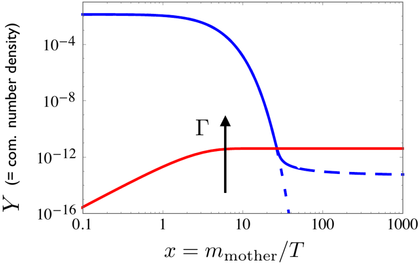
Produced through feeble interactions and freestream while struct. forms

"Feebly Interacting Massive Particles" (FIMPS)

Non-termal FIMP from Freeze-in

see also [McDonald '02; Covi'02; Choi'05; Asaka'06; Frère'06; Petraki'08; Hall'09; etc]

$$\frac{df_\chi}{dt} = \mathcal{C}_{B\to\chi}[f_\chi] \quad \rightsquigarrow \quad n_\chi \propto \Gamma_{B\to\chi}$$



- Freeze-in from B decays
- χ decoupled
- B in chem. & kin. equilibrium
- $\Omega_\chi h^2 \propto \Gamma_{B\to\chi} M_p/m_B^2 \sim R_\Gamma$
- $\Omega_\chi h^2 = 0.12 \rightsquigarrow \lambda_\chi \lesssim 10^{-8}$
- $x = m_B/T$ and $x_{\rm FI} \sim 3$

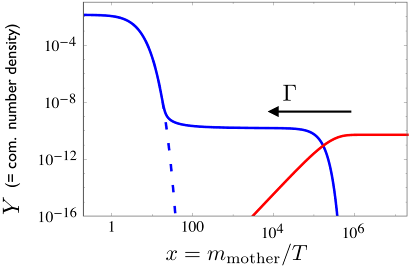
Careful: late decay (SW), production via scattering, early matter dominated era (T_R small), non renormalisable operators and thermal corrections for ultra-relativistic DM not taken into account.

Zero χ initial abundance assumed.

Non-termal FIMP from superWIMP

see also [Covi ’99 ;Feng ’03]

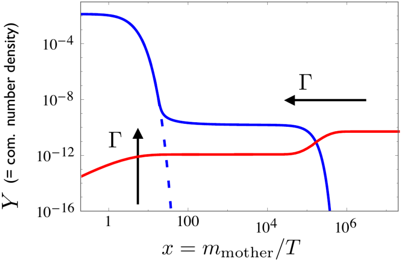
$$\frac{df_\chi}{dt} = \mathcal{C}_{B\to\chi}[f_\chi] \quad \rightsquigarrow \quad n_\chi \propto n_B^{\rm FO}$$



- superWIMP from late B decays
- χ decoupled
- B chem. decoupled
- $\Omega_\chi h^2 = m_\chi/m_B \times \Omega_B h^2|_{\rm FO}$
  if $B \to A_{\rm SM} A'_{SM}$ not open
- $x = m_B/T$ and $x_{\rm SW} \sim R_\Gamma^{-1/2} > 3$

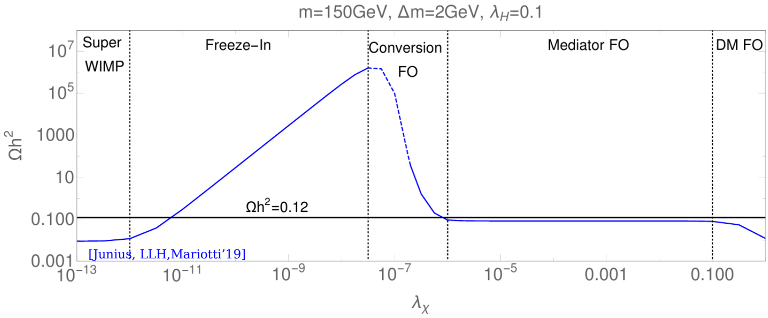
FIMPs from FI & superWIMP

Careful: both SW and FI contributions
are always present for production via B decays!!

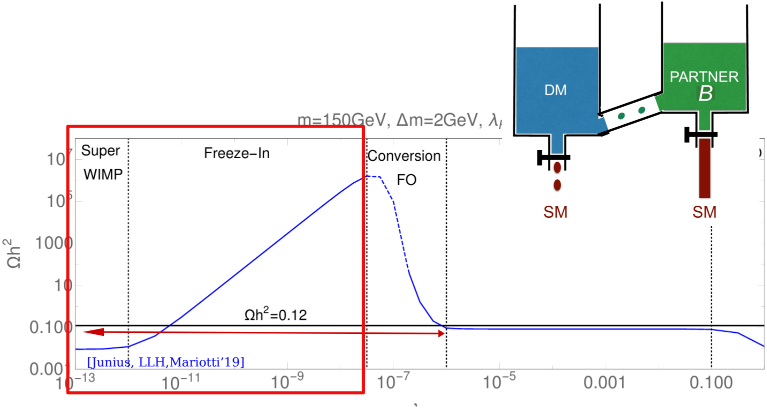


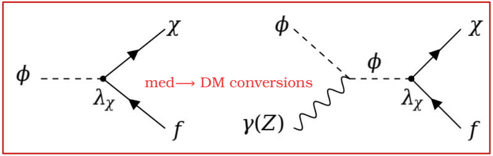
- χ decoupled
- χ population slowly builds up from B before and after FO.
- $\Omega_\chi h^2 = \Omega_\chi h^2|_{\rm FI} + \Omega_\chi h^2|_{\rm SW}$

Non thermal FIMP from FI and SW



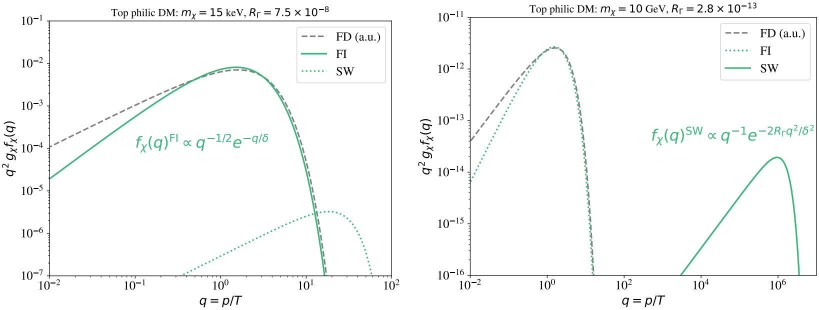
Non thermal FIMP from FI and SW





Pure FI & SW: WDM-like

see also [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.

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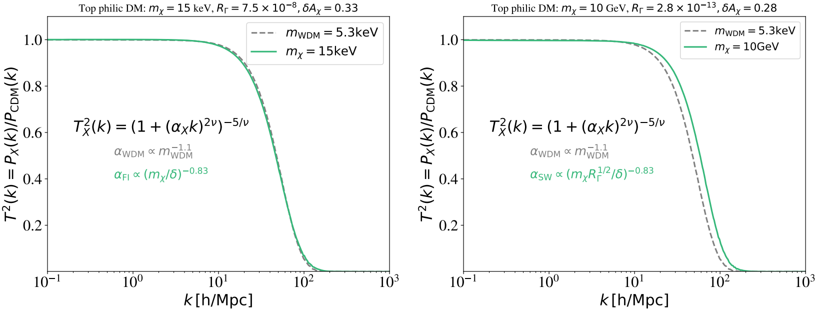

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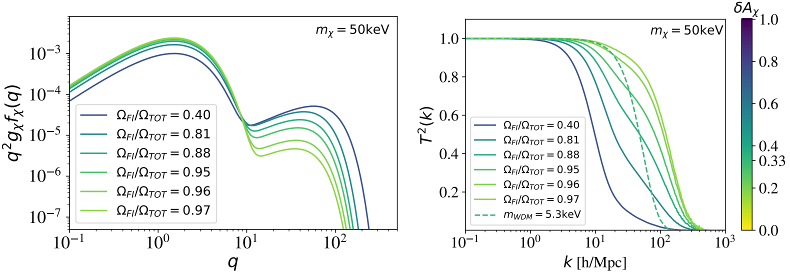
- Using CLASS: Pure FI/SW transfer functions similar to thermal WDM.
  $\rightsquigarrow$ Free-streaming scales [Decant, Heisig, Hooper,LLH'21]

$$\alpha_\chi \sim \begin{cases} 0.064 \times (m_\chi/\text{keV})^{-0.833}\ \text{Mpc}/h & \text{for FI,} \\ 0.021 \times (m_\chi/\text{keV} \times (R_\Gamma)^{-1/2})^{-0.833}\ \text{Mpc}/h & \text{for SW,} \end{cases}$$

Free-streaming scale vs Particle DM properties

- A measurement of the free-steaming scale could give an information on the DM fundamental properties (as its mass) iff we know its production mechanism in the early universe $\rightsquigarrow$ need complementary DM signatures/observations to conclude.
- There exist plethora of other (mixed) free-steaming DM scenarios which $T(k)$ features will differ from Thermal WDM. For example:

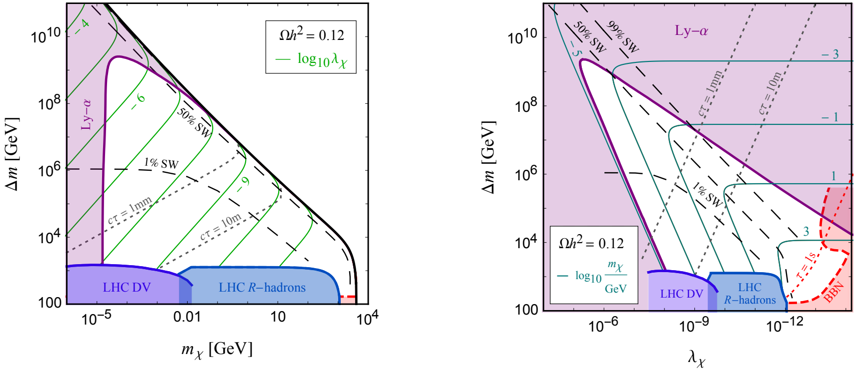
  Mixed FI-SM $q^2 f_\chi$ is multimodal $\rightsquigarrow T^2(k) = P_{\rm FIMP}(k)/P_{\rm CDM}(k)$ can significantly deviate from e.g. WDM, α, β, γ param. or CDM+WDM



Cosmo-Particles complementarity

see also e.g. [Hall'09; Co'15; Hessler'16; d'Eramo'17, Buchmueller'17; Brooijmans'18; Belanger'18; No'19; Garny'18; Calibbi'18,21; etc]

Topphilic FIMP : $\mathcal{L} \subset \mathcal{L}_K - \frac{m_\chi}{2}\bar{\chi}\chi - m_\phi \phi^\dagger \phi - \lambda_\chi \phi \bar{\chi} t_R + h.c.$



- Topphilic DM: Parameter space cornered by particle (DV + R-hadron searches at LHC - for top-philic) and cosmology (Lyman-α, BBN) probes.
- Lyman-α forest data probe DM over a large range of λ_χ, complementary to BBN for $m_\chi \sim$ few 100 GeV. What about 21cm?

Collisional damping

induced by DM scatterings off light dof

"Interacting DM (IDM) scenarios"

NCDM interacting with light degrees of freedom

Cosmology

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

Particle Physics

Weak/strong coupling to SM

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

"Thermal" DM

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

Still coupled to light dof while struct. forms

"Interacting" Dark Matter (IDM)

IDM linear regime: suppressed power at small scale

Considers CDM weakly interacting with γ, ν [Bhoem'01++,Schewtschenko'14++, Olivares-Del Campo'17, etc]

- f_χ for IDM evolved to 1st order:

without DM interactions

$$\begin{aligned}\dot\theta_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2\delta_b - R^{-1}\dot\kappa(\theta_b - \theta_\gamma)\\ \dot\theta_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot\kappa(\theta_\gamma - \theta_b)\,,\\ \dot\theta_{DM} &= k^2\psi - \mathcal{H}\theta_{DM}\,,\end{aligned}$$

with DM interactions

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$S = 3/4\rho_\chi/\rho_\gamma$, $\dot\mu = a\rho_\chi\sigma_{IDM}/m_\chi$

[Schewtschenko'14

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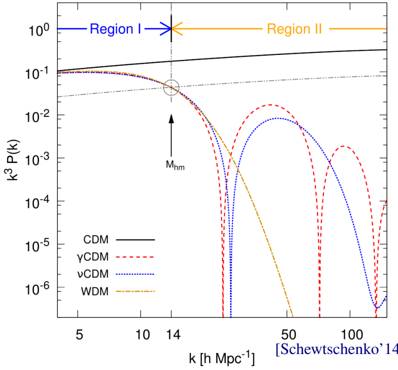
$S = 3/4\rho_\chi/\rho_\gamma$, $\dot\mu = a\rho_\chi\sigma_{IDM}/m_\chi$

- Collisional damping scale

$$T_X(k) = (1 + (\alpha_X k)^{2\nu})^{-5/\nu} \quad \nu = 1.2$$

$\alpha_{IDM} \propto (\sigma_{IDM}/m_{DM})^{0.48}$ [Bhoem'01]
for IDM with γ induced damping



[Schewtschenko'14

NCDM is not necessarily free-streaming see also [Bhoem'04,Murgia'17-18]

From linear $P(k)$ to halo mass function

NCDM non linear regime: less low mass haloes than CDM

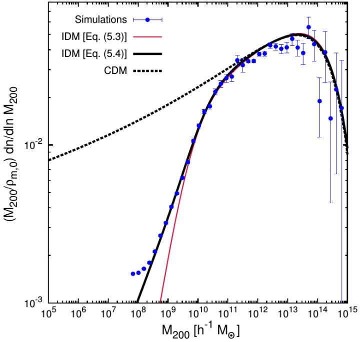
Default extended Press-Schechter (PS) [PS'74, Bond'91] approach:

$$\frac{dn(M,z)}{dM} = \frac{\rho_{m,0}}{M^2}\frac{d\ln\sigma^{-1}}{d\ln M}f(\sigma)$$

fails to capture the suppression at low halo masses for NCDM. Some solutions in the litterature:

- Consider top-hat (TH) for $W(kR)$ but correct by an extra NCDM dependent factor [Schneider'12, Bhoem'14, Moline'16]

$$\left.\frac{dn(M,z)}{dM}\right|_{\rm NCDM} = F_{\rm NCDM}(M_{hm}) \times \left.\frac{dn(M,z)}{dM}\right|_{\rm NCDM,TH}$$



IDM/WDM using $F_{\rm NCDM}(M_{hm})$ [Moline'16]

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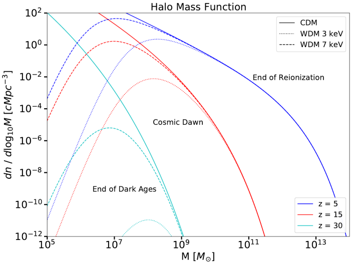
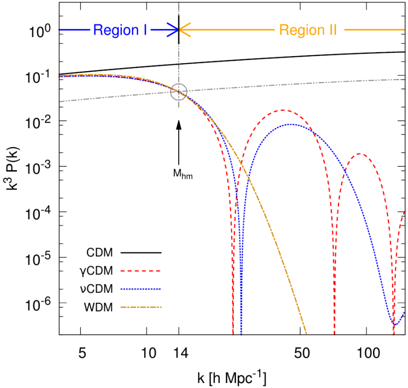
- Consider sharp-k (SK) cutoff for $W(kR)$ in $\sigma^2 = \sigma^2(P_{lin}(k), W(kR))$ [Schneider'13, Benson'13]

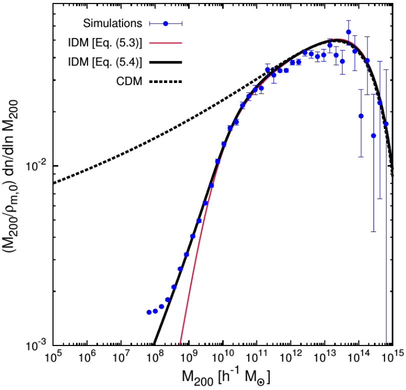
$$\left.\frac{dn(M,z)}{dM}\right|_{\rm NCDM} = \left.\frac{dn(M,z)}{dM}\right|_{\rm NCDM,SK}$$



WDM using $\sigma_{\rm SK}$ [Hibbard'22]

NB: IDM vs WDM: more low mass haloes in IDM



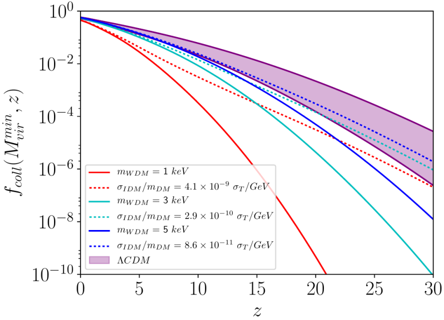


more low mass haloes in IDM than WDM at fixed α_X
due to extra power at small scales see also ETHOS IDMs [VogelsBerger'15, Muñoz'20]

Imprint of NCDM on 21cm signal

Suppressed NCDM $f_{coll}(M_{vir})$

Remember that Ionization, heating and excitation critically depend on the fraction of mass collapsed in halos: $f_{\rm coll}(> M_{\rm vir}) = \int_{M_{\rm vir}} \frac{M}{\rho_0} \frac{dn(M,z)}{dM}\, dM$



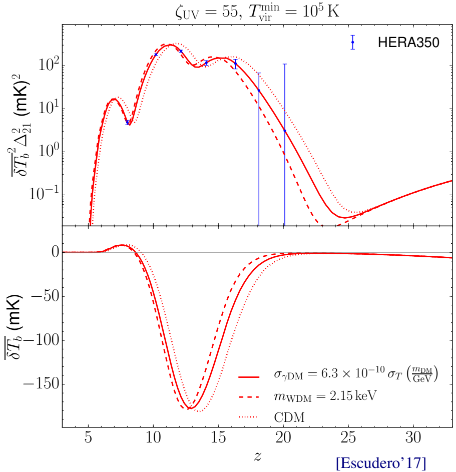
[LLH'17]

$\rightsquigarrow$ more severe suppression of f_{coll} at fixed z and fixed α_X in IDM than WDM.

Delayed 21cm features for Non-CDM

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

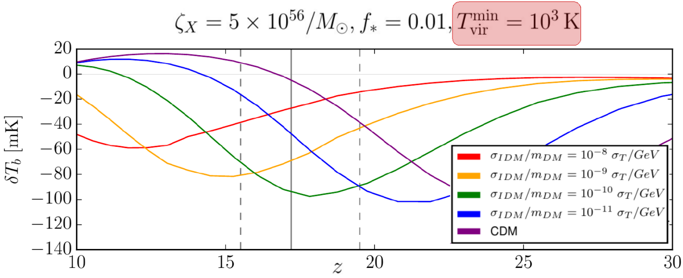
Halo suppression can lead to delayed astro processes giving rise to reionization or 21cm features. Stronger delay for WDM than IDM.



[Escudero'17]

Degeneracies between NCDM effects and astro

NCDM effect degenerate with T_{vir}^{min}, f_* and L_X [LLH'18]



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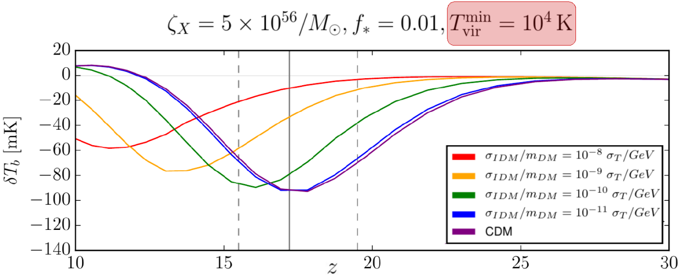
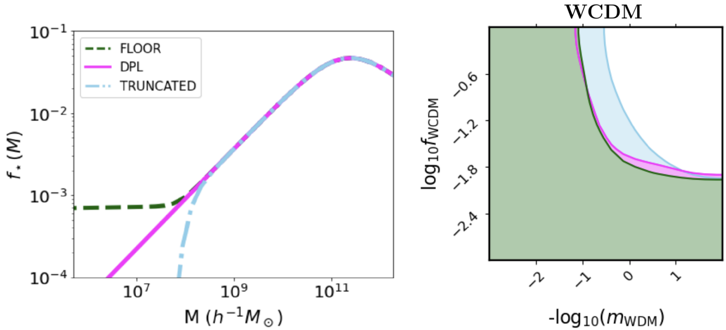


Forecast SKA constraints on WDM+CDM

[Giri'22] (MCMC analysis): For low minimum virial mass ($T_{vir}^{min} < 10^4$K) and in the case that minihaloes are populated with stars, stringent constraints can be obtained on e.g. 100% WDM: up to $m_{\rm WDM} < 15$ keV.

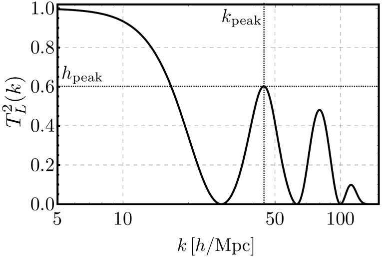


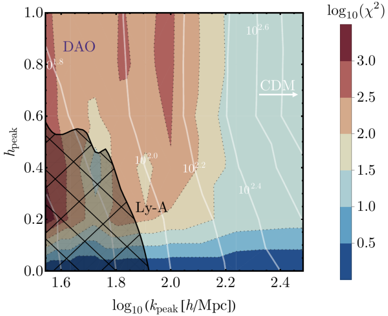
For $T_{vir}^{min} \sim 10^4$ K it will be difficult to distinguish between an inefficient source models and a universe filled with NCDM.

Forecast HERA constraints on IDM

[Muñoz'20] (χ^2 analysis): Even considering atomic cooling ($T_{vir}^{min} = 10^4$K), HERA shall be able to :

- distinguish CDM from models with $k_{peak} < 10^{2.3} h$/Mpc
- distinguish IDMs with $h_{peak} > 0.4$ from WDM ($h_{peak} \to 0$)





More enthousiastic conclusions than Giri'22?

Conclusion

Non CDM can either be free-steaming and/or experiencing collisional damping and give rise to suppressed stucture formation at small scales.

- NCDM is not nessaryly thermal WDM
- Multiple DM production mechanisms can give rise to the same/similar features in Cosmology observations. Complementary observations are necessary to pin point the DM nature.
- Overall NCDM is expected to delay 21cm features in global signal and power spectrum.
- Future telescopes such as HERA or SKA might put stringent constraints on NCDM and distinguish between NCDM scenarios (but this might depend on T_{vir}^{min} [Giri'22])

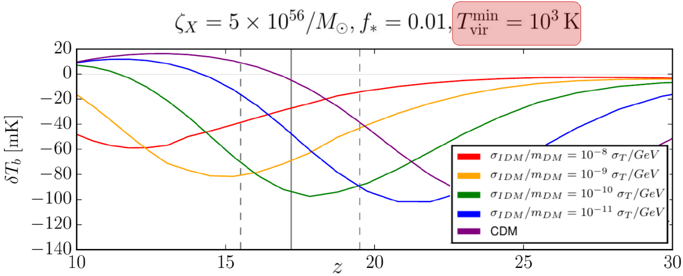
Thank you for the invitation
and for your attention!!

Backup

Imprint of NCDM on background 21cm signal

Halo suppression leads to delayed astro processes giving rise to 21cm features. Can be constrained by imposing early enough absorption [Schneider'18]

$$z(\delta T_b^{min}) > 17.2$$



Imprint of NCDM on background 21cm signal

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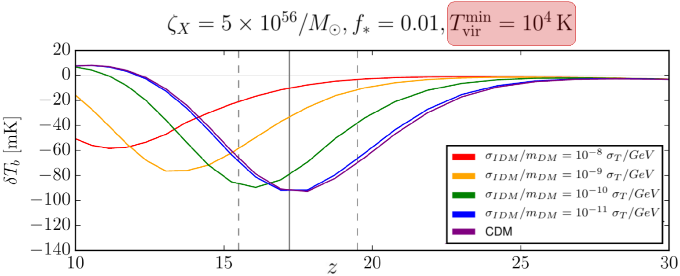
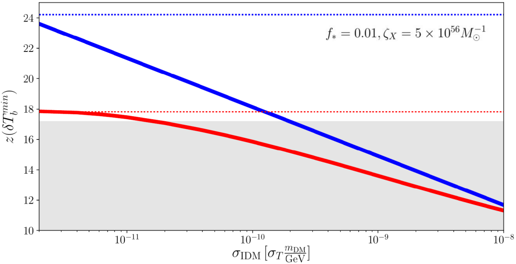


Beware important degeneracies with astrophysics (T_{vir}^{min}, f_* and ζ_X)

Constraints on NCDM from EDGES ?

- If the EDGES signal is confirmed for a fixed astro setup 21 cm can provide stringent constraints on NCDM [see also Safarzadeh'18, Lidz'18, Schneider'18]

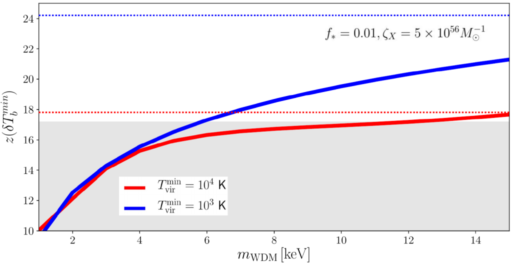


- To be compared with existing limits from Lyα forest [Yeche 17]

$$m_{WDM} > 5.3\,\text{keV}$$

and Satellite number count:

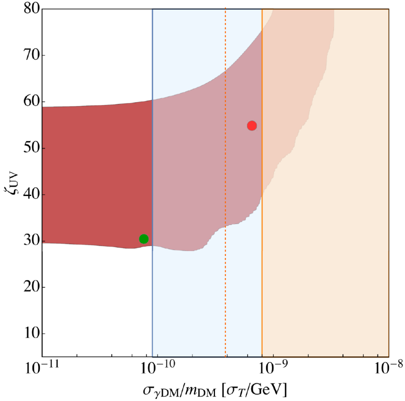
$$\sigma_{IDM} < 8 \times 10^{-10} (m_{DM}/GeV)$$



BEWARE: can easily be relaxed for larger f_* !

21cm could help to discriminate between Non-CDM

Halo suppression can lead to delayed astro processes giving rise to reionization or 21cm features. Stronger delay for IDM than WDM.



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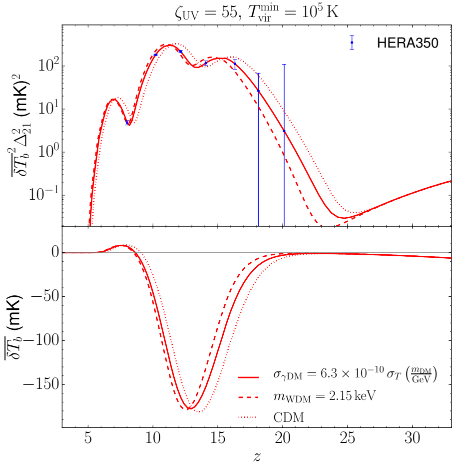

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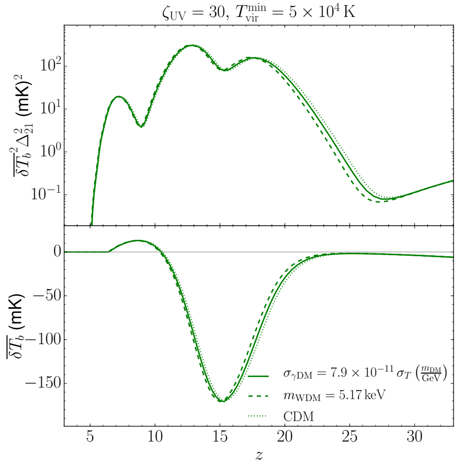


Particle physics models for DM-ν interactions

[Olivares-Del Campo'17]

Scenario	**Lagrangian** ($\mathcal{L}_{\rm int}$)	$\sigma \mathbf{v}_{\rm r}$	$\sigma_{\rm el}$
Complex DM Dirac Mediator	$-\,g\,\chi\,\overline{N_{\rm R}}\,\nu_{\rm L}\;+\;{\rm h.c.}$	$\frac{g^4}{12\,\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}\,v_{\rm CM}^2$	$\frac{g^4}{32\,\pi}\frac{m_{\rm DM}^2\,y^2}{(m_{\rm N}^2-m_{\rm DM}^2)^2}$
Real DM Dirac Mediator		$\frac{4\,g^4}{15\,\pi}\frac{m_{\rm DM}^6}{(m_{\rm DM}^2+m_{\rm N}^2)^4}\,v_{\rm CM}^4$	$\frac{g^4}{8\,\pi}\frac{m_{\rm DM}^6\,y^4}{(m_{\rm N}^2-m_{\rm DM}^2)^4}$
Complex DM Majorana Mediator		$\frac{g^4}{16\,\pi}\frac{m_{\rm N}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}$	$\frac{g^4}{32\,\pi}\frac{m_{\rm DM}^2\,y^2}{(m_{\rm N}^2-m_{\rm DM}^2)^2}$
Real DM Majorana Mediator		$\frac{g^4}{4\,\pi}\frac{m_{\rm N}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}$	$\frac{g^4}{8\,\pi}\frac{m_{\rm DM}^6\,y^4}{(m_{\rm N}^2-m_{\rm DM}^2)^4}$
Dirac DM Scalar Mediator	$-g\overline{\chi_{\rm R}}\nu_{\rm L}\phi\;+\;{\rm h.c.}$	$\frac{g^4}{32\,\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_\phi^2)^2}$	$\frac{g^4}{32\,\pi}\frac{m_{\rm DM}^2\,y^2}{(m_{\rm DM}^2-m_\phi^2)^2}$
Majorana DM Scalar Mediator		$\frac{g^4}{12\,\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_\phi^2)^2}\,v_{\rm CM}^2$	$\frac{g^4}{16\,\pi}\frac{m_{\rm DM}^2\,y^2}{(m_{\rm DM}^2-m_\phi^2)^2}$
Vector DM Dirac Mediator	$-\,g\overline{N_{\rm L}}\gamma^\mu\chi_\mu\nu_{\rm L}\;+\;{\rm h.c.}$	$\frac{2\,g^4}{9\,\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}$	$\frac{g^4}{4\,\pi}\frac{m_{\rm DM}^2\,y^2}{(m_{\rm DM}^2-m_{\rm N}^2)^2}$
Vector DM Majorana Mediator		$\frac{g^4}{6\,\pi}\frac{m_{\rm N}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}$	
Complex DM Vector mediator	$-\,g_\chi Z'^\mu((\partial_\mu\chi)\chi^\dagger-(\partial_\mu\chi)^\dagger\chi)$ $-\,g_\nu\overline{\nu_L}\gamma^\mu Z'_\mu\nu_{\rm L}$	$\frac{g_\chi^2\,g_\nu^2}{3\,\pi}\frac{m_{\rm DM}^2}{(4\,m_{\rm DM}^2-m_{Z'}^2)^2}\,v_{\rm CM}^2$	$\frac{g_\chi^2\,g_\nu^2}{8\,\pi}\frac{m_{\rm DM}^2\,y^2}{m_{Z'}^4}$
Dirac DM Vector Mediator	$-\,g_{\chi_{\rm L}}\overline{\chi_{\rm L}}\gamma^\mu Z'_\mu\chi_{\rm L}\;-\;g_{\chi_{\rm R}}\overline{\chi_{\rm R}}\gamma^\mu Z'_\mu\chi_{\rm R}$ $-\,g_\nu\overline{\nu_L}\gamma^\mu Z'_\mu\nu_{\rm L}$	$\frac{g_\chi^2\,g_\nu^2}{2\,\pi}\frac{m_{\rm DM}^2}{(4\,m_{\rm DM}^2-m_{Z'}^2)^2}$	$\frac{g_\chi^2\,g_\nu^2}{8\,\pi}\frac{m_{\rm DM}^2\,y^2}{m_{Z'}^4}$
Majorana DM Vector Mediator	$-\,\frac{g_\chi}{2}\bar\chi\gamma^\mu Z'_\mu\gamma^5\chi$ $-\,g_\nu\overline{\nu_L}\gamma^\mu Z'_\mu\nu_{\rm L}$	$\frac{g_\chi^2\,g_\nu^2}{12\,\pi}\frac{m_{\rm DM}^2}{(4\,m_{\rm DM}^2-m_{Z'}^2)^2}\,v_{\rm CM}^2$	$\frac{3\,g_\chi^2\,g_\nu^2}{32\,\pi}\frac{m_{\rm DM}^2\,y^2}{m_{Z'}^4}$
Vector DM Vector Mediator	$-\,g_\chi\frac{1}{2}\chi^\mu\partial_\mu\chi^\nu Z'_\nu\;+\;{\rm h.c.}$ $-\,g_\nu\overline{\nu_L}\gamma^\mu Z'_\mu\nu_{\rm L}$	$\frac{g_\chi^2\,g_\nu^2}{\pi}\frac{m_{\rm DM}^2}{(4\,m_{\rm DM}^2-m_{Z'}^2)^2}\,v_{\rm CM}^2$	$\frac{g_\chi^2\,g_\nu^2}{8\,\pi}\frac{m_{\rm DM}^2\,y^2}{m_{Z'}^4}$

TABLE I: This table presents the relevant terms in the Lagrangian, the approximate expressions for the annihilation cross section and the low-energy limit of the elastic scattering for all possible scenarios that involve DM-ν interactions (12 in total). Only the leading terms in $v_{\rm CM}$ and $y = (s - m_{\rm DM}^2)/m_{\rm DM}^2 \simeq 2\,E_\nu/m_{\rm DM}$ (with s the usual Mandelstam variable) are presented for the thermally averaged annihilation cross section and the elastic scattering cross section, respectively. We refer the reader to Appendix B for the full expressions of the elastic scattering cross sections.

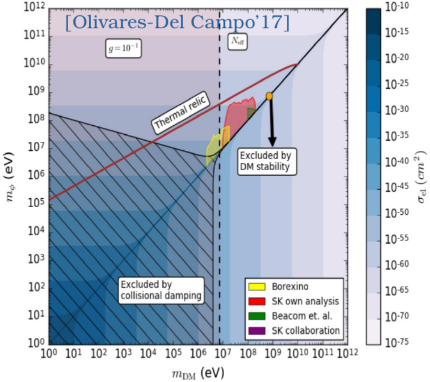
Particle physics models for DM-ν interactions

[Olivares-Del Campo'17]

Fermion DM coupled to a scalar mediator $-g\overline{\chi_R}\nu_L\phi + \text{h.c.}$

if the scalar mediator and the fermion DM candidate are degenerated

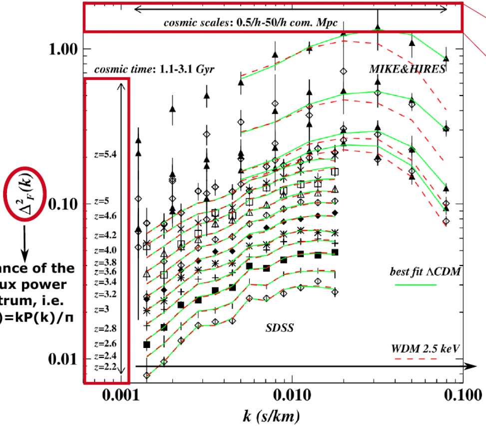
$\sigma_{el} = \frac{g^4}{32\,\pi\, m_{DM}^2}$ for Dirac DM and $\sigma_{el} = \frac{g^4}{16\,\pi\, m_{DM}^2}$ for Majorana DM



Lyman-α forest

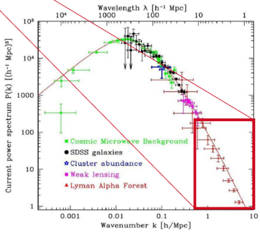
Absorption lines produced by the inhomogeneous IGM along different line of sights to distant quasars: a fraction of photons is absorbed at the Lyman-α wave- length (corresponding to $\lambda_\alpha \sim 121$ nm), resulting in a depletion of the observed spectrum at a given frequency ($\lambda_{abs} < \lambda_\alpha$).

- Allows us to trace neutal hydrogen clouds, i.e. smallest structures
- Provides a tracer of the matter power spectrum at high redshifts (2 <z < 6) and small scales ($0.5\ h/\text{Mpc} < k < 20\ h/\text{Mpc}$).
- IGM modelling requires nonlinear evolution: this needs N-body hydrodynamical simulations. Computational expensive and only available for few benchmark models.



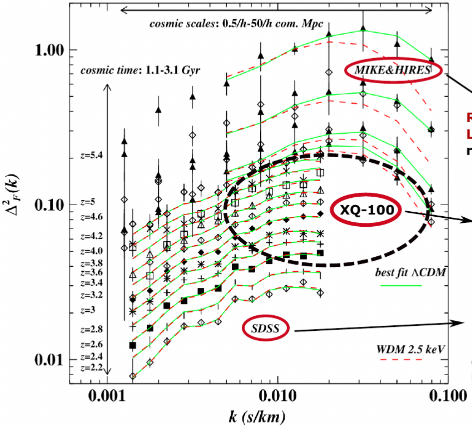
Variance of the 1D flux power spectrum, i.e. $\Delta^2(k)=kP(k)/\pi$

Adapted from Tegmark et al. 2004



The higher the z of the source,
1) the more absorbtion one gets,
2) the lower the mean transmission is,
3) the more the density fluctuations amplify,
4) the larger the amplitude of the spectrum

Adapted from Viel et al. 2013 4/25



Ref: Viel et al. 2013
Lkl: Publicly available and rather model-intependent

Ref: Irsic et al. 2017
Lkl: None publicly available yet

Ref: sdss.org (currently DR17)
Lkl: Publicly available but outdated (DR7, 2009) and halofit-dependent

Adapted from Viel et al. 2013 5/25

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

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

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

- Compute area under the curve

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

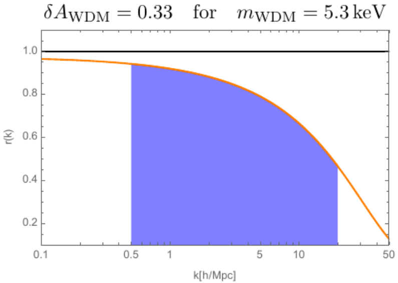
and

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

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

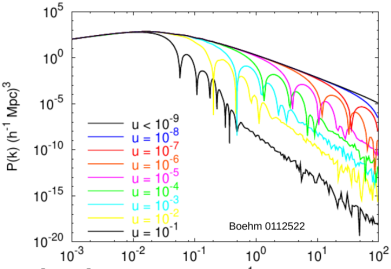
$$m_{\rm FI} > 15.3\,{\rm keV}$$

- Suitable for mixed scenario



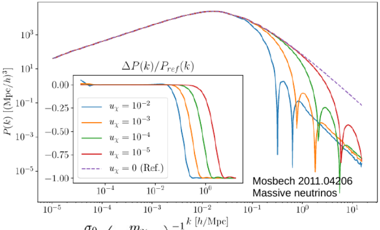
[see *also* D'Eramo, Lenoci, 2020; Egana-Ugrinovic, Essig, Gift, LoVerde 2021]

IDM $P(k)$



$$u \equiv \left[\frac{\sigma_{\gamma-\mathrm{DM}}}{\sigma_{\mathrm{Th}}}\right]\left[\frac{m_{\mathrm{DM}}}{100\,\mathrm{GeV}}\right]^{-1}$$

Planck sigma_{DM-photon} < 8 x 10^{-31} (m_DM/GeV) cm^2



$$u_{\nu\chi} = \frac{\sigma_0}{\sigma_{\mathrm{Th}}}\left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^{-1}$$

$u_\chi \leq 3.34 \cdot 10^{-4}$ Planck

NCDM from PBH evaporation

Cosmology

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

Particle Physics

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 gravitationnal interactions and freestream while struct. forms

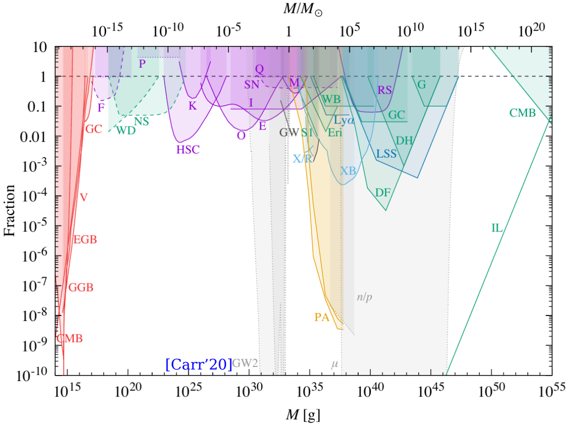
DM from Primordial Black Holes (PBH) evaporat°

PBH 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+]

PBH fully Evaporated Before BBN

PBH stable on Cosmological scales



PBH and Dark Matter

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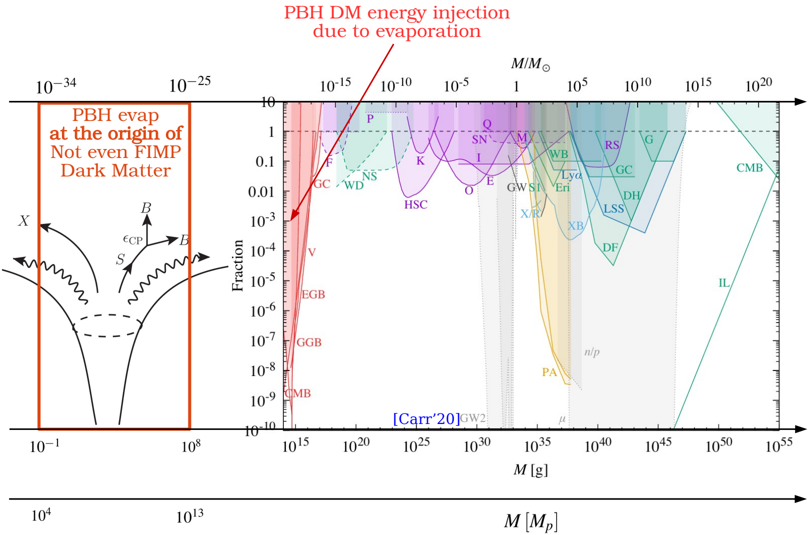

NCDM from PBH evaporation

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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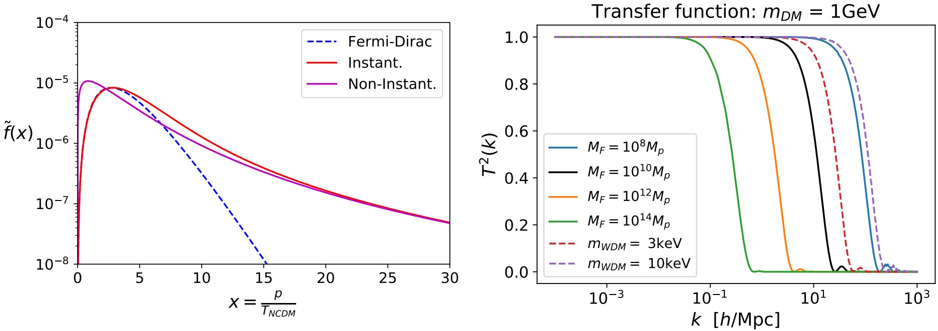

$$\Rightarrow m_{\rm DM}^{\rm PBH} \geq 2\,{\rm GeV} \times \left(M_F/(10^{10} M_p)\right)^{1/2}$$ [for $m^{{\rm Ly}-\alpha} > 3$ keV and $\beta > \beta_c$]

PBH evaporating after inflation and before BBN

PBH generation: during radiation domination (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]

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

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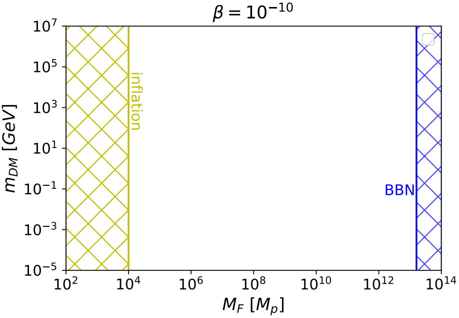

- PBH formed after inflation: $t_F > t_{\rm infl} \rightarrow M_F > 10^4 M_p$
- PBH evaporate before BBN: $t_{\rm ev} < t_{BBN} \rightarrow M_F < 2 \times 10^{13} M_p$

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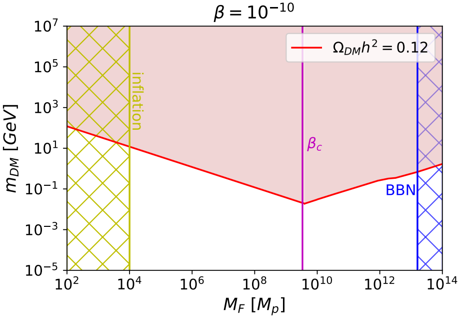

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- DM abundance depends on the initial BH fraction: $\beta \equiv \rho_{\rm PBH}/\rho_{\rm tot}|_{t_F} \leq 1$

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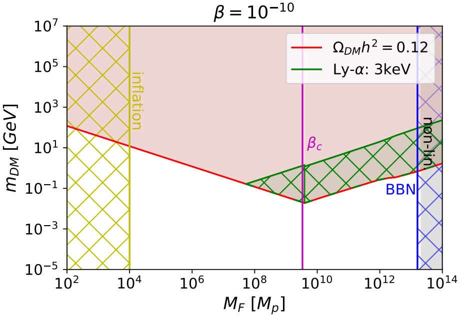

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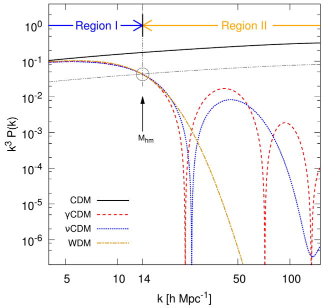
Lyman-α bound: NCDM account for all the DM if $\beta \lesssim 5 \times 10^{-7}$ and $m_{\rm DM} \gtrsim 2\,{\rm MeV}$.

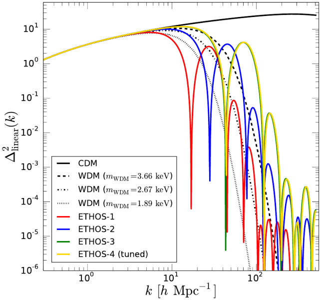
(S)IDM collisional Damping: linear regime

For dark matter interacting with (dark) relativistic degrees of freedom:

see also Zavala, Cyr-Racine, etc talks



[Schewtschenko'14]



[VogelsBerger'15]

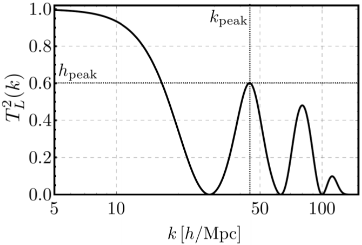
Towards generalized fit to non-CDM (SIDM included)? [Murgia'17]

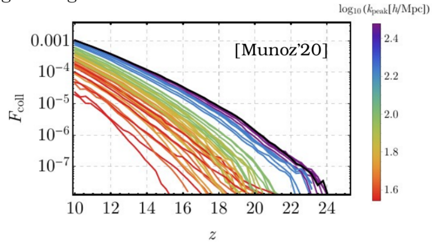
$T(k) = (1 + (\alpha k)^\beta)^\gamma$ → might be usefull enough to derive

Lyα forest and MW satelite count constraints

IDMs with ETHOS parametrisation

ETHOS parametrization of DM
interacting with light dof

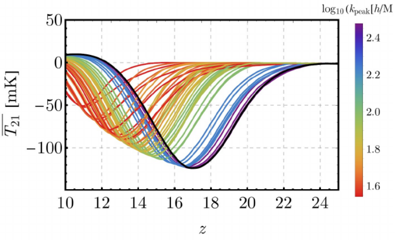




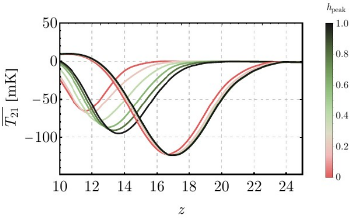
hpeak→ 0 corresponds to WDM

kpeak→ large values corresponds to CDM

IDMs with ETHOS parametrisation

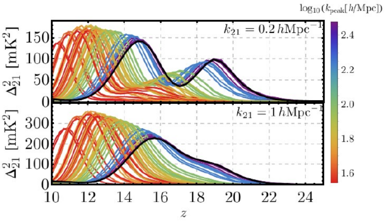


Cut at lower kpeak delay structure formation more

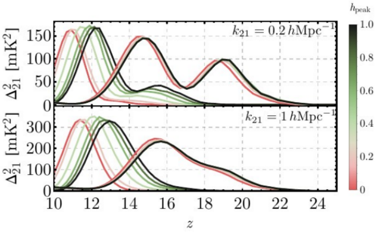


Higher values of hpeak gives more power at small scales and delay less structure formation

IDMs with ETHOS parametrisation



Cut at lower kpeak delay structure formation more



Higher values of hpeak gives more power at small scales and delay less structure formation

HMF details

$$f(\sigma) = A\sqrt{\frac{2q}{\pi}}\left(1+\left(\frac{\sigma^2}{q\,\delta_c^2}\right)^p\right)\left(\frac{\delta_c}{\sigma}\right)e^{-\frac{q\,\delta_c^2}{2\,\sigma^2}}$$ Sheth and Tormen (ST)

$$\sigma^2(M(R),z) = \left(\frac{D(z)}{D(0)}\right)^2\int\frac{d^3k}{(2\pi)^3}P(k)\,|W(kR)|^2$$

spherical top-hat (TH) function in real space, $W_{\rm TH}(kR) = \frac{3}{kR}\left(\sin(kR) - 3\cos(kR)\right)$ $R^3 = 3\,M/(4\pi\rho_{\rm m,0})$

sharp-k window $W_{\rm SK}(kR) = \Theta(1-kR)$ $M_{\rm SK} = \frac{4\pi}{3}\rho_m\,(c\,R_{\rm SK})^3$.

smooth-k filter $\mathcal{W}(k|R) = \frac{1}{1+(kR)^\beta}$

Top hat versus sharp k cutoff scale for γCDM

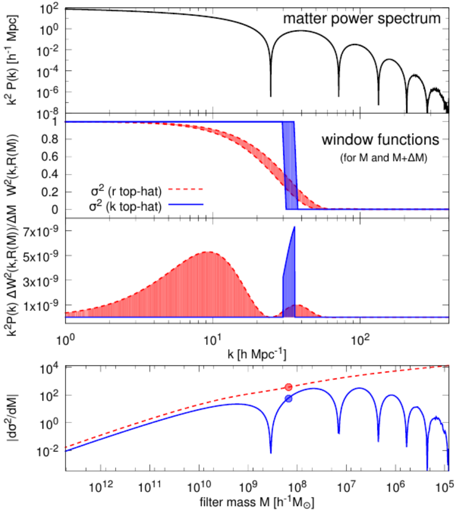


Figure 4. Real-space and k-space top-hat window functions in Press-Schechter HMF predictions for γCDM. The upper panel shows the matter power spectrum, while the second panel shows the Fourier transform of the two window functions (r top-hat and k top-hat). Each window function is evaluated for two filter masses, M and $M + \Delta M$. The difference between the two filter masses is highlighted by the shaded region in each case. The third panel shows the result of applying this differential filter to the matter distribution. Finally, the lower panel shows the integrated result for both window functions. The red and blue points are the results for the specific filter mass M used in the middle two panels.

$\rightsquigarrow$ with r-top hat filter (TH) a large number of un-suppressed small k scales contribute to $\sigma(M)$

$\rightsquigarrow$ not good to describe $\sigma(M)$ for suppressed $P(k)$ including WDM

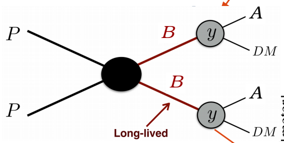
[Schewtschenko'14]

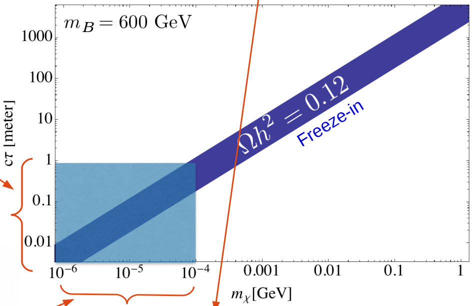
FIMPs: LLPs and NCDM

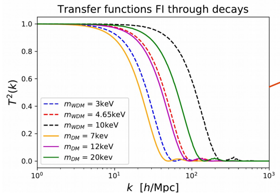
e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18, Calibbi'18, No'19, Belanger 18, etc]

$$\Omega h^2 \sim 0.12 \left(\frac{5\ \text{cm}}{c\tau_B}\right) \left(\frac{600\ \text{GeV}}{m_B}\right)^2 \left(\frac{m_\chi}{10\ \text{keV}}\right)$$

Mediator mass range reachable at colliders







Warm DM like signatures
Suppressing small scale structures

This is really the end