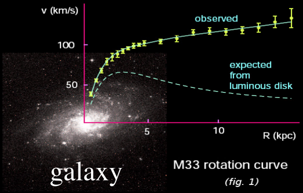
(Non Cold) Dark Matter: at the interface between Particle physics & Cosmology

Laura Lopez Honorez

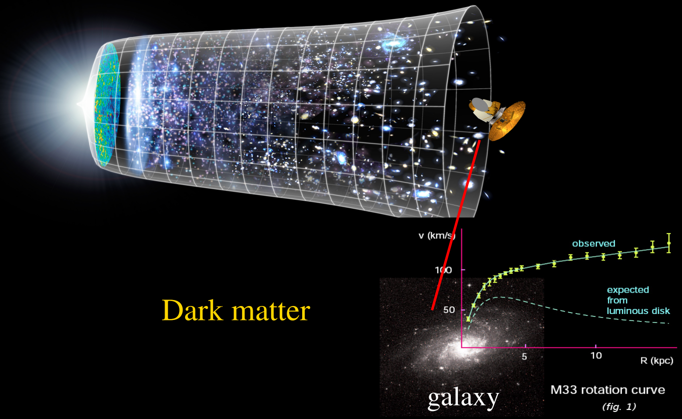
partially inspired by JCAP 03 (2022) 041

in collaboration with Q. Decant, J. Heisig, & D.C. Hooper

PRISMA+ Colloquium, Johannes Gutenberg University Mainz



The Quest to determine the Composition of our Universe



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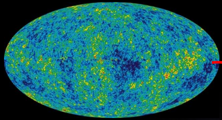
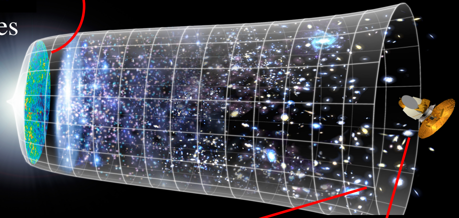
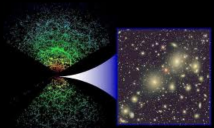


CMB anisotropies

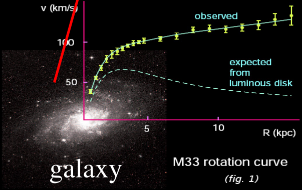


Large Scale Structures (LSS)



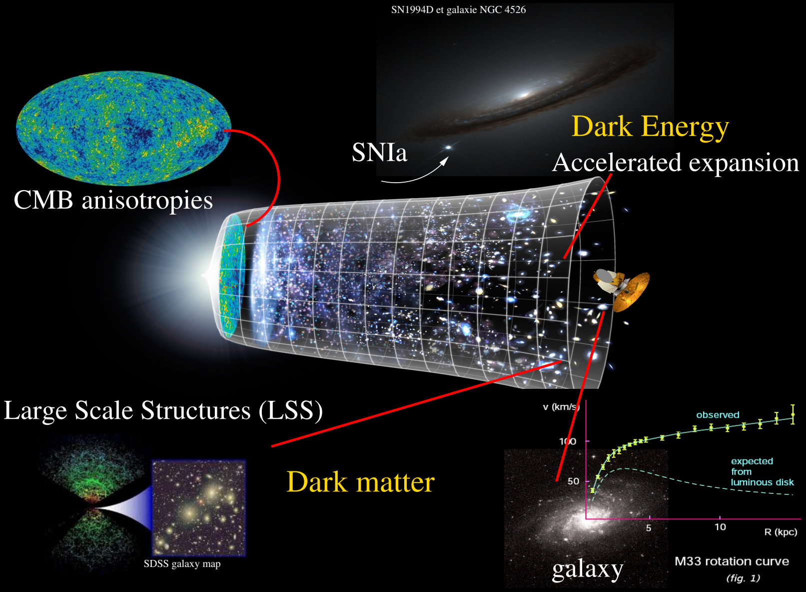
SDSS galaxy map

Dark matter



M33 rotation curve
(fig. 1)

The Quest to determine the Composition of our Universe



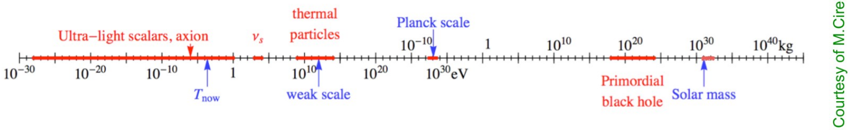
The Quest to determine the Composition of our Universe

80% of the matter content is made of Dark Matter

What is the Nature of Dark Matter?

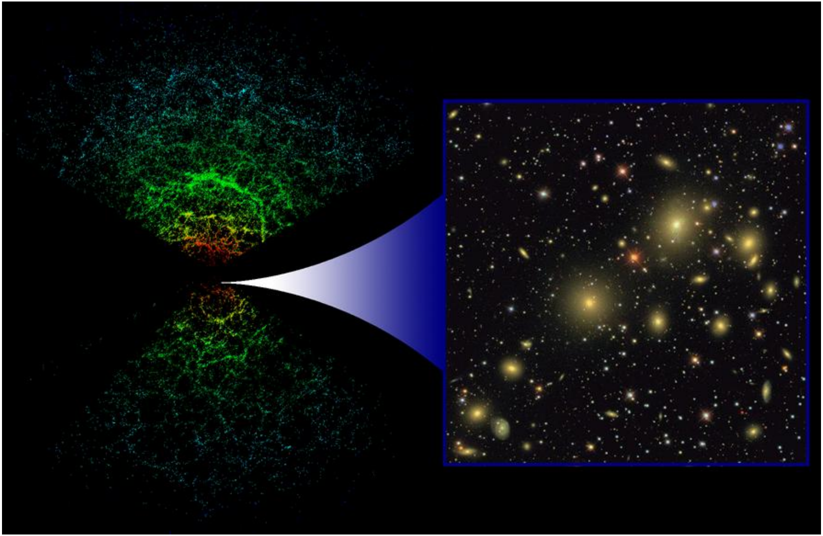
Dark Matter should be essentially:

- Neutral
- Massive
- Beyond the Standard Model (non baryonic)



Non-Cold Dark Matter

Inhomogeneities



The power spectrum measures clumpiness

- Some tracers measure
  Inhomogeneities
  $\delta(\vec{x}) = \frac{n(\vec{x})}{\bar{n}(\vec{x})} - 1$
- Fourrier transform:
  $\delta(\vec{x}) \leftrightarrow \delta(\vec{k})$ with $k = 2\pi/x$.

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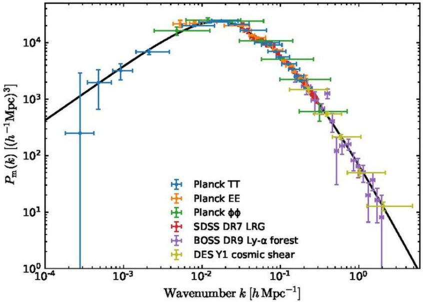
- Fourrier transform: $\delta(\vec{x}) \leftrightarrow \delta(\vec{k})$ with $k = 2\pi/x$.
- Characterized by two point-correlation functions: $\langle \delta(\vec{x}_1)\delta(\vec{x}_2) \rangle$ $\leftrightarrow P(k) \sim \langle |\delta(\vec{k})|^2 \rangle$ $k = 2\pi/r$ with $r = |\vec{x}_1 - \vec{x}_2|$



The power spectrum measures clumpiness

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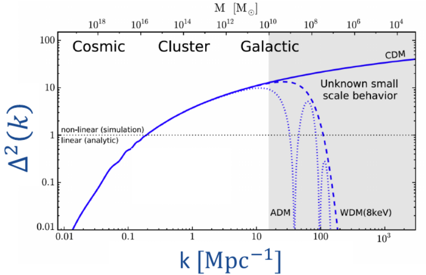


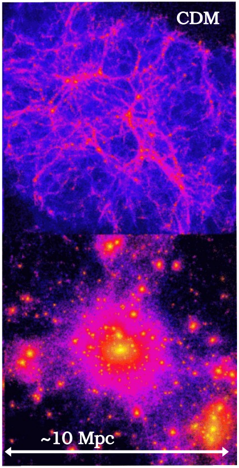
$\Delta^2(k) = k^3 P(k)$ = dimensionless Power Spectrum

measures clumpiness at $k \sim 1/r$

lots of over/under dense regions $\rightsquigarrow$ larger $\Delta^2(k)$

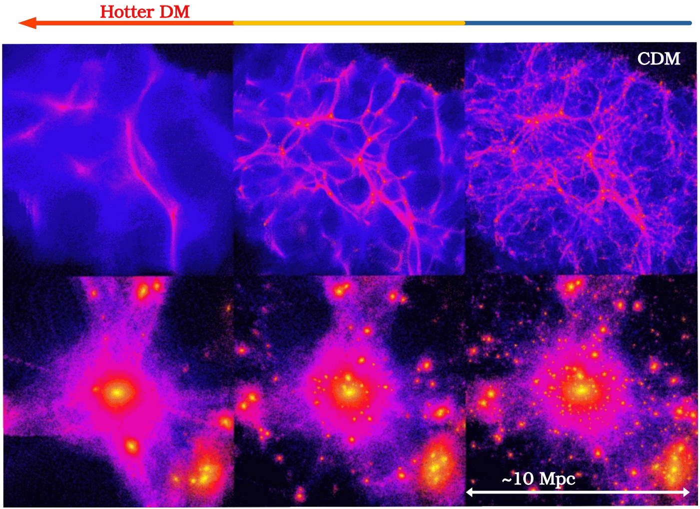
smooth distribution $\rightsquigarrow$ smaller $\Delta^2(k)$

Cold and Non-Cold Dark Matter



Simus [B. Moore]

Cold and Non-Cold Dark Matter



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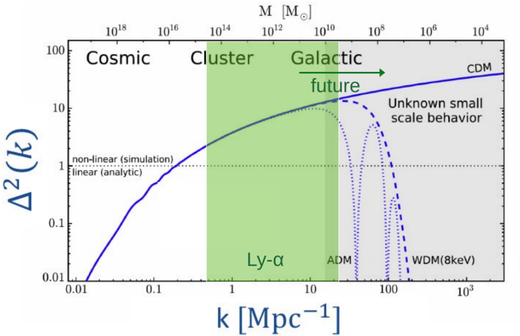


Dimensionless matter power spectrum

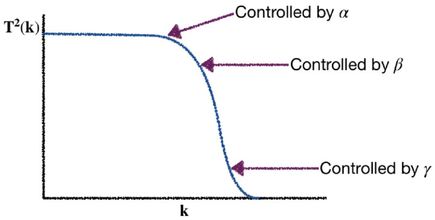
M. Kuhlen et al. 2012

- 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
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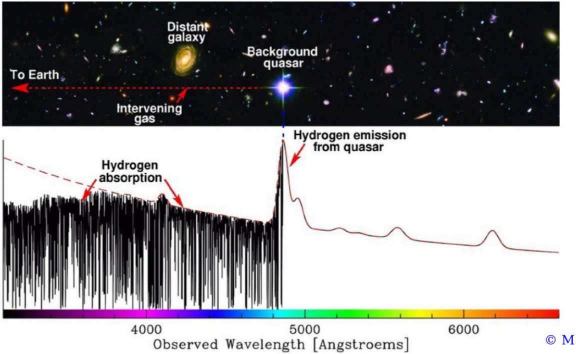
Non-Cold Dark Matter



© 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

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

NCDM is not necessarily thermal Warm Dark Matter

Cosmology

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

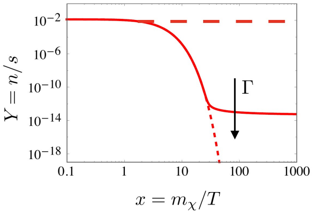
Particle Physics

Weak coupling
to SM

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

"Thermal DM" (incl. WIMP)

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



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Weak coupling to SM

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Feeble coupling to SM

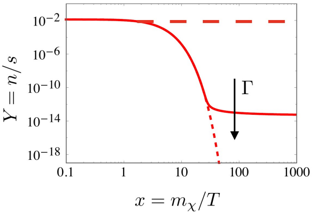
$\Gamma_{\chi\leftrightarrow \mathrm{SM}} < H$

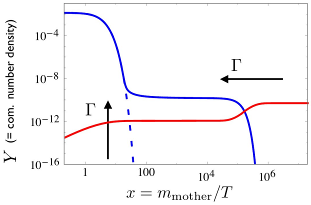
"Thermal DM" (incl. WIMP)

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

"Non-Thermal" FIMP

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





NCDM is not necessarily thermal Warm Dark Matter

Cosmology

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

Particle Physics

Weak/strong coupling to SM

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

“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

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

“Non-Thermal” DM

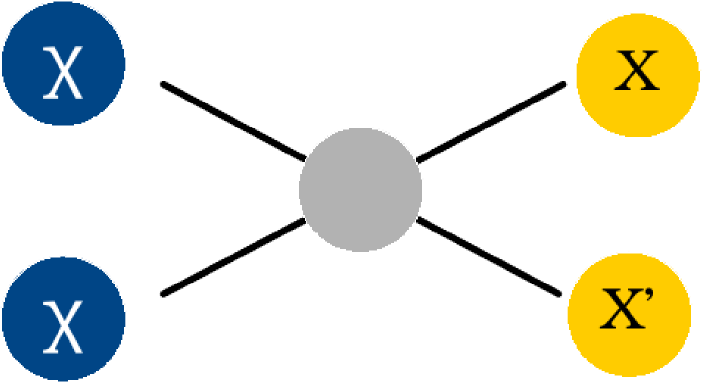
$f_\chi(t,p) \neq f_\chi(t,p)^{fD,BE}$

- Produced through feeble interactions and freestream while struct. forms → “Feebly Interacting Massive Particles” (FIMPS)
- Produced through gravitationnal interactions and freestream while struct. forms → DM from Primordial Black Holes (PBH) evaporat°

Usual NCDM suspect:
Thermal WDM

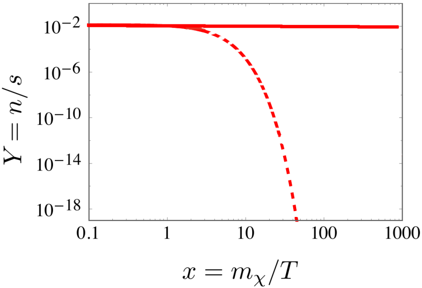
Thermal WDM relic: annihilation driven freeze-out

$$\mathcal{C}[f_\chi] \to \mathcal{C}_{ann}[f_\chi]$$



Thermal WDM freeze-out

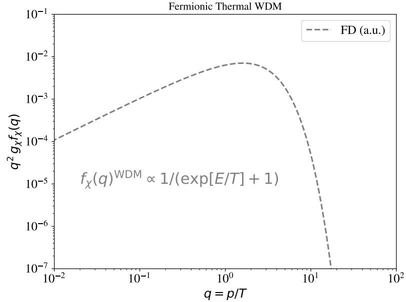
$$\frac{df_\chi}{dt} = \mathcal{C}_{ann}[f_\chi] \quad \rightsquigarrow \quad n_\chi \propto \frac{g^0_{*,S}}{g_{*,S}(T_D)}$$



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

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

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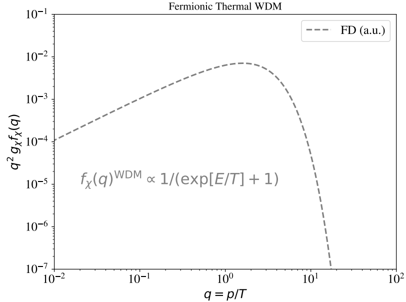
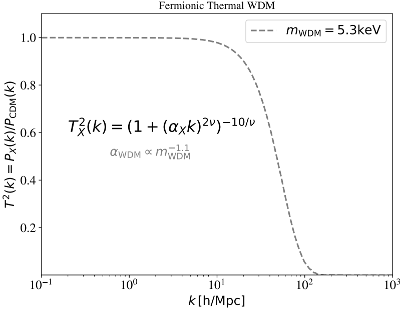




- Thermal WDM is in kinetic equilibrium thanks to fast elastic scatterings with thermal plasma: $\frac{d}{dt} f_\chi = \mathcal{C}_{el}[f_\chi] \rightsquigarrow f_\chi \propto f_\chi^{eq}(q)$
- Rule of Thumb: $\langle v_{\rm WDM}\rangle|_{t_0}^{\rm WDM} \propto m_{\rm WDM}^{-4/3}$
  Evolve f_χ up to 1st order pert. (w/ Boltzmann code):

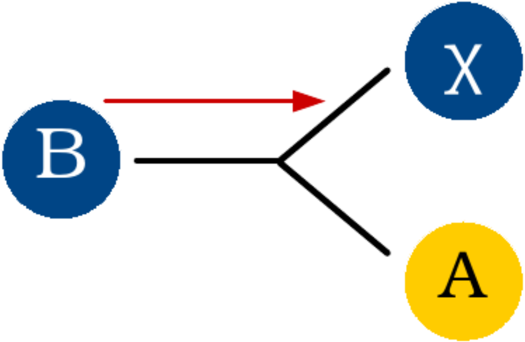
Free-streaming scale: $\alpha_{\rm WDM} \sim 0.045\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-1.11}$ Mpc$/h$

FIMPs from freeze-in and SuperWIMP

see arXiv:2111.09321

Non-Thermal FIMP from *B* decays

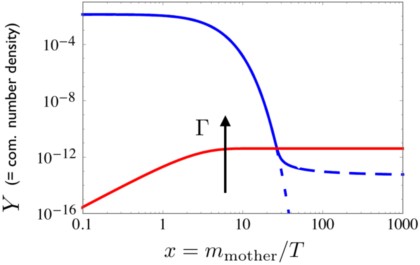
$$\mathcal{C}[f_\chi] \to \mathcal{C}_{B\to A\chi}[f_\chi]$$



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 $x_{\text{FI}} \sim 3$

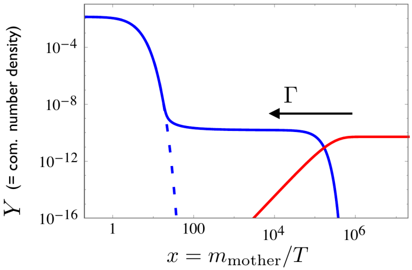
Careful: late decay (SW), production via scattering, early matter dominated era (T_R small), non renormalisable operators and thermal corrections for ultra-relativistic DM not taken into account.

Zero χ initial abundance assumed.

Non-termal FIMP from superWIMP

see also [Covi ’99 ;Feng ’03]

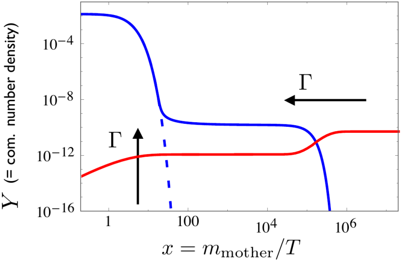
$$\frac{df_\chi}{dt} = \mathcal{C}_{B\to\chi}[f_\chi] \quad \rightsquigarrow \quad n_\chi \propto n_B^{\rm FO}$$



- 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

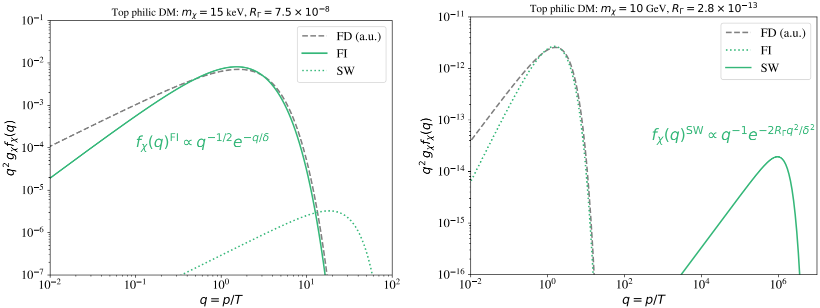
Careful: both SW and FI contributions
are always present for production via B decays!!



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

Pure FI & SW: WDM-like

see also [Jedamzik'05, Heeck'17, Boulebnane'17, Kamada'19, Baumholzer'19, Ballesteros'20, d'Eramo'20, etc]



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

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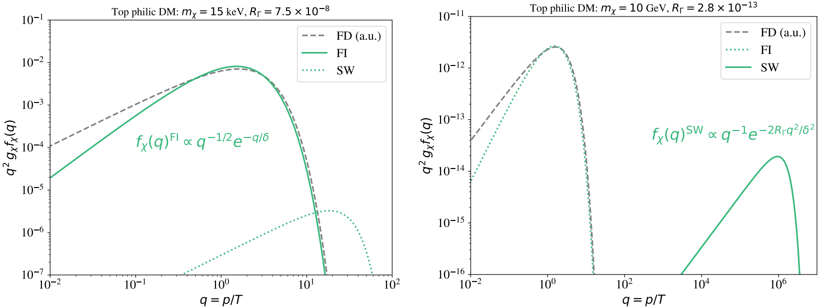

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- Rule of Thumb: $\langle v_\chi \rangle|_{t_0}^{\rm FI} \propto m_\chi^{-1}$ and $\langle v_\chi \rangle|_{t_0}^{\rm SW} \propto m_\chi^{-1} \times R_\Gamma^{-1/2}$.

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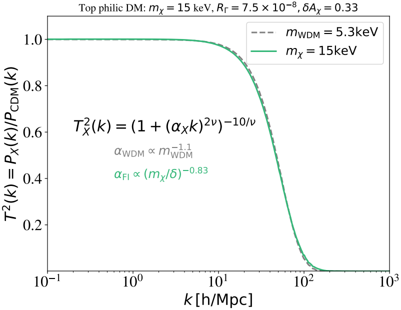

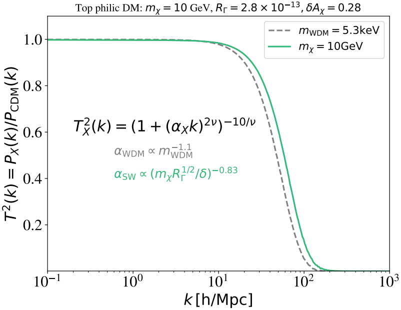

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- Rule of Thumb: $\langle v_\chi \rangle|_{t_0}^{FI} \propto m_\chi^{-1}$ and $\langle v_\chi \rangle|_{t_0}^{SW} \propto m_\chi^{-1} \times R_\Gamma^{-1/2}$. Pure FI/SW $T(k)$ similar to thermal WDM $\rightsquigarrow$ Ly-α Lower bound :

$$m_\chi \gtrsim \begin{cases} 15\,\text{keV} & \text{for FI,} \\ 3.8\,\text{GeV} \times \left(R_\Gamma^{SW}/10^{-12}\right)^{-1/2} & \text{for SW,} \end{cases} \quad \text{for } m_{WDM}^{Ly-\alpha} > 5.3\,\text{keV}$$

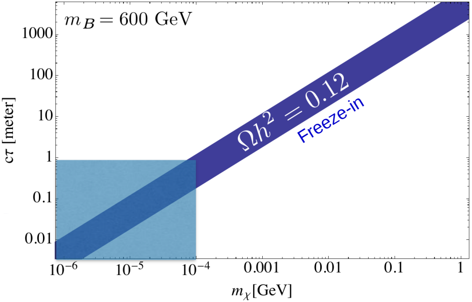
Cosmo-Particle Interplay

FIMPs: NCDM and Long Lived Particles

e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18, Calibbi'18&21, No'19, Belanger'18, Decant'22,Becker'23, 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



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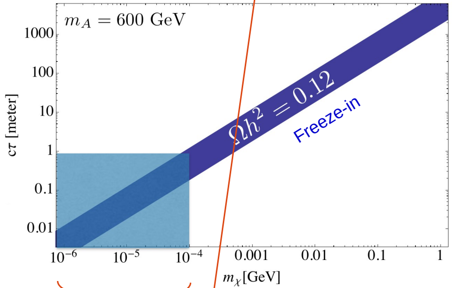
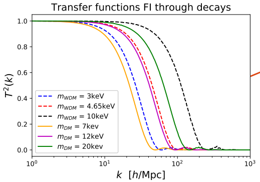
$$\Omega h^2 \sim 0.12 \left(\frac{5\text{ cm}}{c\tau_A}\right)\left(\frac{600\text{ GeV}}{m_A}\right)^2 \left(\frac{m_\chi}{10\text{ keV}}\right)$$

Mediator mass range reachable at colliders





Warm DM like signatures
Suppressing small scale structures

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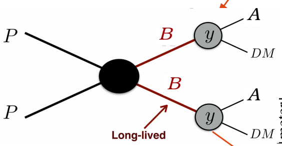
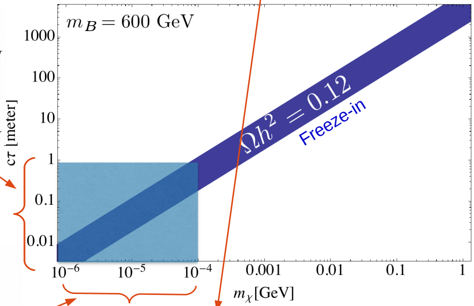
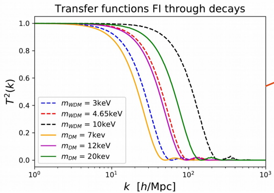
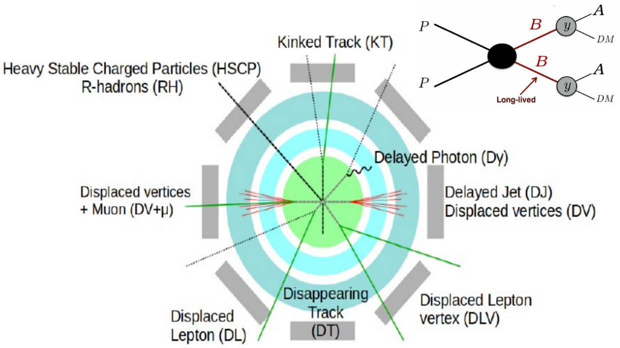






Warm DM like signatures
Suppressing small scale structures

FIMPs and Long lived Mediators



- FIMP= feebly interacting massive particle, i.e. $\lambda_\chi \ll 1$
- $\lambda_\chi \ll 1 \rightsquigarrow$ possibly $c\tau_B \gtrsim$ collider detector size.
- B long lived particle (LLP), heavy stable particle and displaced events

Illustrative frameworks

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Illustrative framework: minimal FIMP models

Dark matter χ coupled to dark B and SM A through Yukawa-like interactions

$$\mathcal{L} \subset \lambda_\chi \, \chi \, A_{SM} B$$

- Dark sector (Z_2 odd): $m_B > m_\chi$
- B is $SU(3) \times SU(2) \times U(1)$ charged
  - fast $B^\dagger B \leftrightarrow$ SM SM through gauge interactions at early time
  - B is produced at colliders today

Illustrative framework: minimal FIMP models

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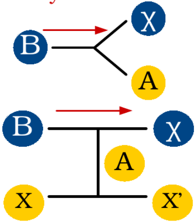
- Minimal scenarios:

$A_{\rm SM}$	Spin DM	Spin B	Interaction	Label
$\psi_{\rm SM}$	0	1/2	$\bar{\psi}_{\rm SM}\Psi_B\phi$	$\mathcal{F}_{\psi_{\rm SM}\phi}$
	1/2	0	$\bar{\psi}_{\rm SM}\chi\Phi_B$	$\mathcal{S}_{\psi_{\rm SM}\chi}$
$F^{\mu\nu}$	1/2	1/2	$\bar{\Psi}_B\sigma_{\mu\nu}\chi F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0	$H^\dagger\Phi_B\phi$	$\mathcal{S}_{H\phi}$
	1/2	1/2	$\bar{\Psi}_B\chi H$	$\mathcal{F}_{H\chi}$

[Calibbi, D'Eramo, Junius, LLH,Mariotti 21]

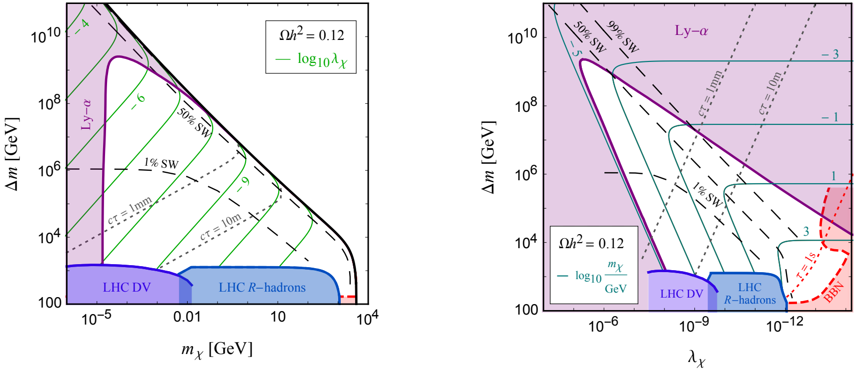
Production in the early universe



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.

Conclusion

Even if dark matter would be (not even) very feebly interacting with the SM if can leave distinctive cosmology signature in the form of NCDM. Non CDM can be free-steaming (focus of today's talk) and/or experiencing collisional damping and give rise to suppressed stucture formation at small scales.

- NCDM is not necessarily thermal WDM and can have a mass much larger than few keV.
- Multiple NCDM production mechanisms can give rise to the same/similar features in Cosmology observations. Lyman-α forest data can probe a large parts of the DM parameter space.
- Complementary observations are necessary to pin point the DM nature.
- Future radio telescopes (21cm Cosmology) 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

Translating WDM bound to NCDM?

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

Naive estimate for "similar velocity distributions" :

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

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

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- 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 $\langle p_\chi \rangle|_{t_{\rm prod}} \sim m_B/2$
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- SW: $T_{\rm prod} \sim \sqrt{\Gamma_B M_{Pl}}$ and $\langle p_\chi \rangle|_{t_{\rm prod}} \sim m_B/2$
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- PBH: $T_{\rm prod} \sim M_{\rm PBH}^{-3/2}$ and $\langle p_\chi \rangle|_{t_{\rm prod}} \sim 6.3/M_{\rm PBH}$
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$$m_\chi \gtrsim \left(m_{\text{WDM}}^{\text{lim}}\right)^{4/3} \begin{cases} \#_{\text{FI}} & \text{for FI,} \\ \#_{\text{SW}} \times (R_\Gamma)^{-1/2} & \text{for SW,} \end{cases}$$

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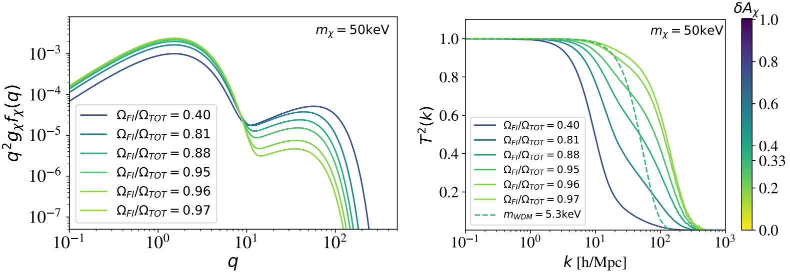
$$m_\chi \gtrsim \begin{cases} 16\,\text{keV} & \text{for FI,} \\ 3.8\,\text{keV} \times (R_\Gamma)^{-1/2} & \text{for SW,} \end{cases} \quad \text{for } m_{\text{WDM}}^{\text{Ly}-\alpha} > 5.3\,\text{keV}$$

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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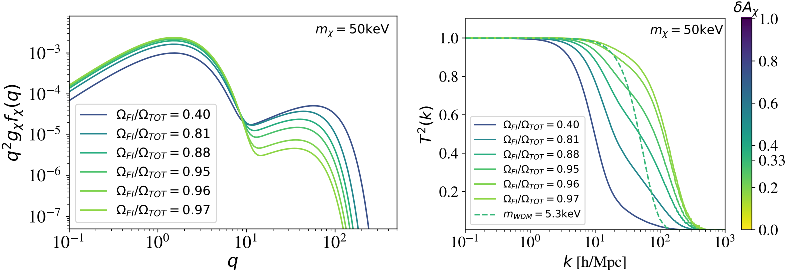

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- We use the area criterion [Murgia'17] measuring the relative $P_{1D}(k)$ deviation over $0.5h/{\rm Mpc} < k < 20h/{\rm Mpc}$: $\delta A_\chi < \delta A^{ly-\alpha}_{\rm WDM} = 0.33$ for $m^{\rm Ly-\alpha}_{\rm WDM} > 5.3$ keV

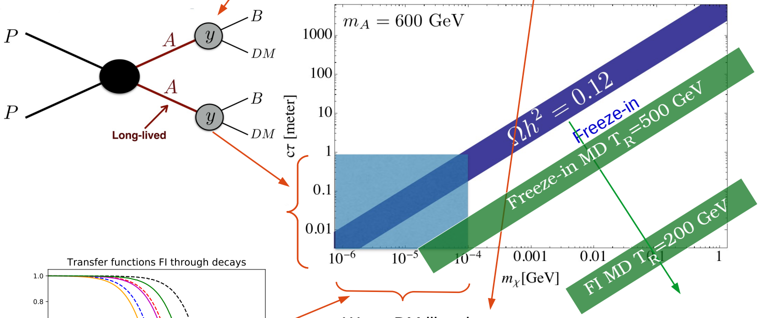
see also [Schneider'16] and e.g. [D'Eramo'20, Egana-Ugrinovic'21,Dienes'21]

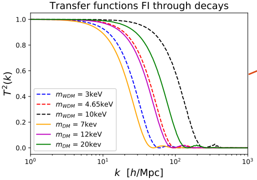
FIMPs: NCDM and Long Lived Particles

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]

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

Mediator mass range reachable at colliders

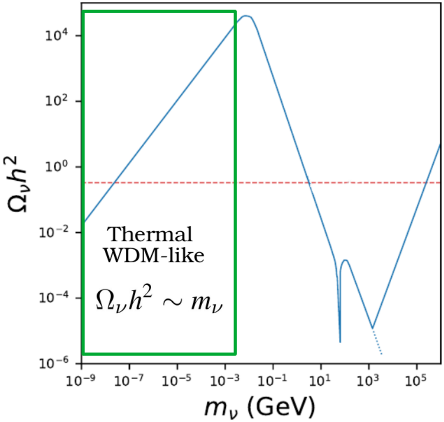




Warm DM like signatures
Suppressing small scale structures

Thermal WDM abundance

see [Coy'21, Kanulainen'02]



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

- Illustrative case of 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!!)

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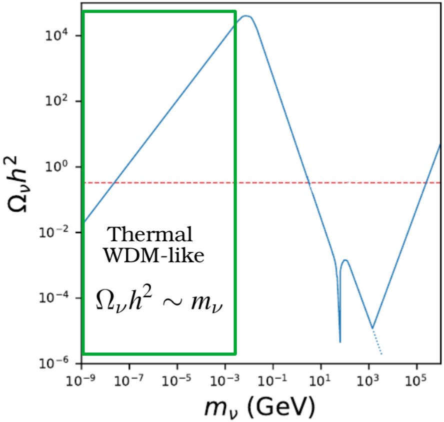

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- Thermal WDM candidate (fermion w/ 2 dof) needs $g_{*,S}(T_D) \sim 1000 \times (m_\chi/\mathrm{keV})$ for all DM i.e. for few keV DM $g_{*,S}(T_D) \gg g_{SM}^{tot} \sim 100$

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 ($0.5\ h/\mathrm{Mpc} < k < 20\ h/\mathrm{Mpc}$).
- IGM modelling requires nonlinear evolution: this needs N-body hydrodynamical simulations. Computational expensive and only available for few benchmark models.

DM from evaporating PBH as free streaming DM

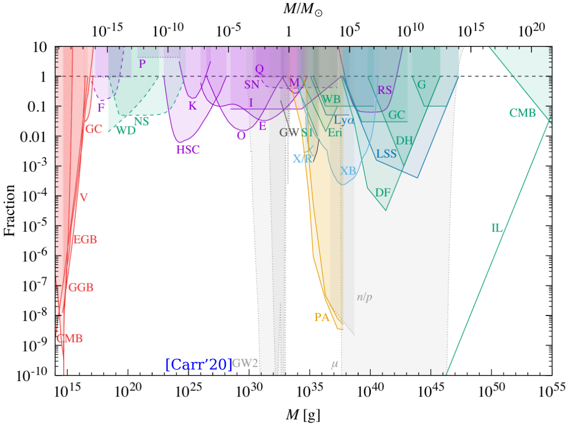
see JCAP 08 (2020) 045

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



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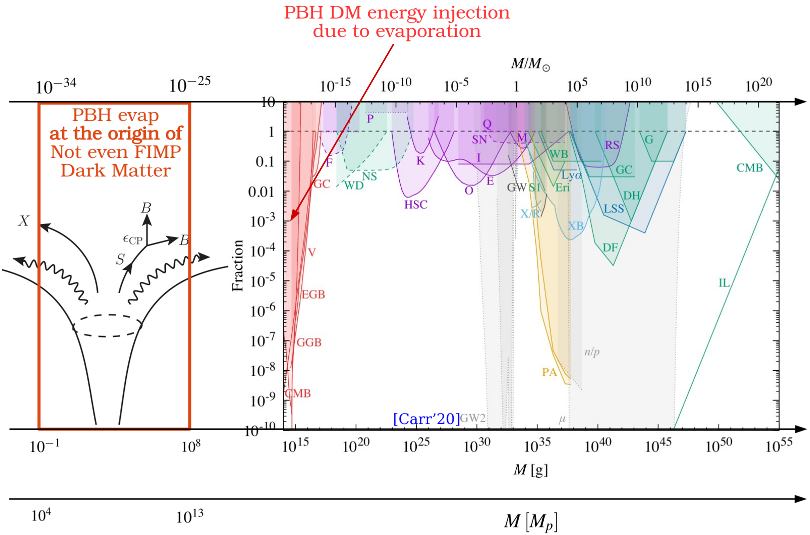

NCDM from PBH evaporation

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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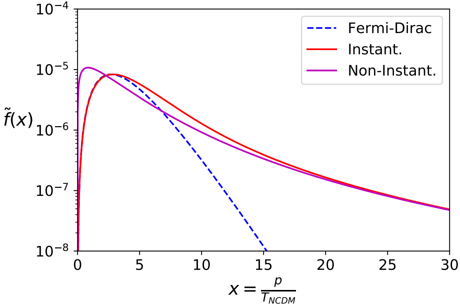

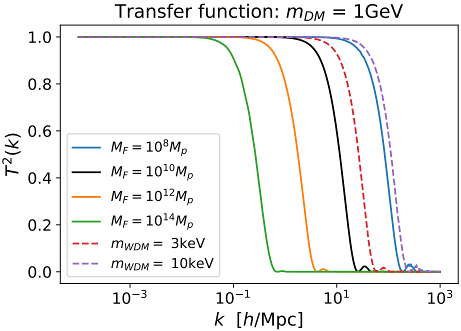

For $T(k) = (1 + (\alpha_{\rm PBH} k)^{2\nu})^{-5/\nu}$ we get $\alpha_{\rm PBH} \propto m_{\rm DM}^{-0.83} \times (M_{BH}^{init})^{0.42}$

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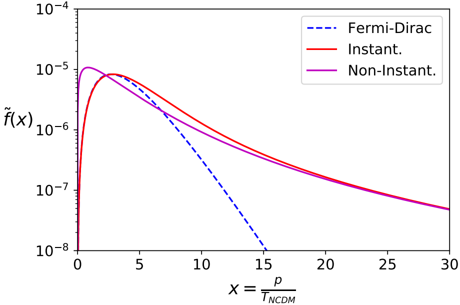

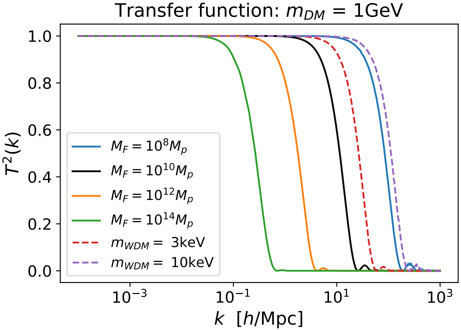

Lyman-α bound: $m_{\rm DM}^{\rm PBH} \geq 2\,{\rm GeV} \times \left(M_{\rm BH}^{init}/(10^{10} M_p)\right)^{1/2}$ [for $m^{\rm Ly-\alpha} > 3$ keV and $\beta > \beta_c$]

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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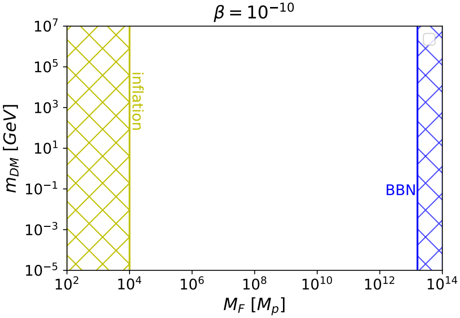

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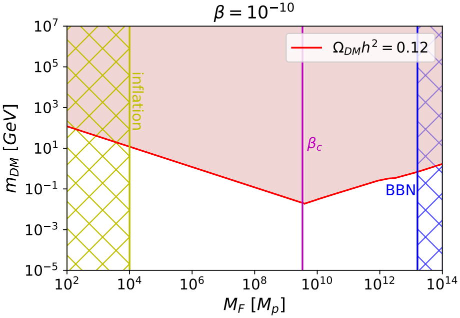

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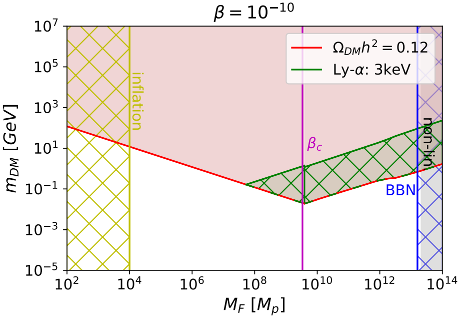
- DM abundance depends on the initial BH fraction: $\beta \equiv \rho_{\rm PBH}/\rho_{\rm tot}|_{t_F} \leq 1$

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]

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

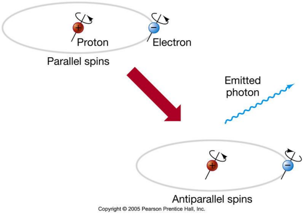


- PBH formed after inflation: $t_F > t_{\rm infl} \to M_F > 10^4 M_p$
- PBH evaporate before BBN: $t_{\rm ev} < t_{BBN} \to M_F < 2 \times 10^{13} M_p$
- DM abundance depends on the initial BH fraction: $\beta \equiv \rho_{\rm PBH}/\rho_{\rm tot}|_{t_F} \leq 1$

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

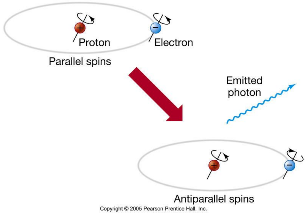
Future constraints on Non-Cold Dark Matter?

21 cm Cosmology

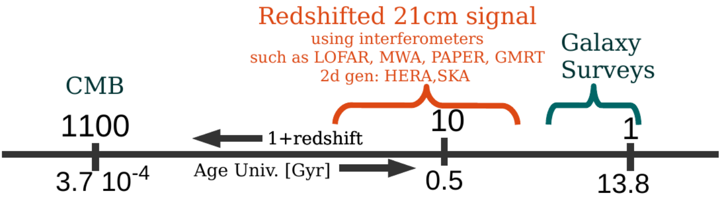


- Transitions between the two ground state energy levels of neutral hydrogen HI $\rightsquigarrow$ 21 cm photon ($\nu_0 = 1420$ MHz)

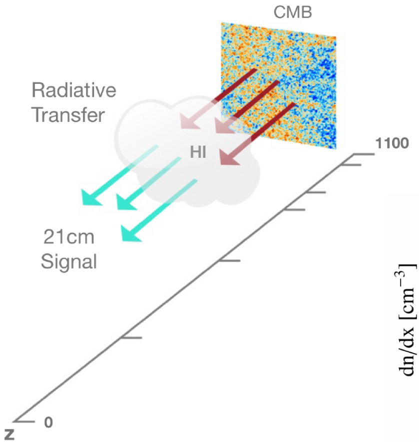
21 cm Cosmology



- 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 dark ages & EoR redshifted to $\nu \sim 100$ MHz $\rightsquigarrow$ new cosmology probe



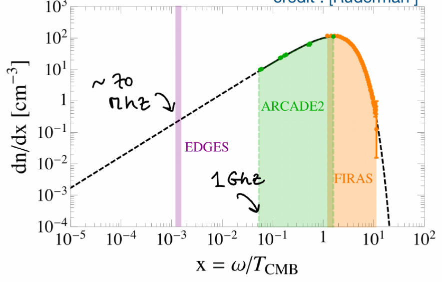
21 cm in practice



credit : [Kovetz]

- 21cm signal observed as CMB spectral distortions

credit : [Ruderman]



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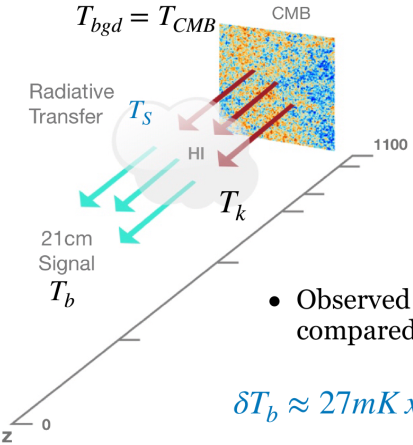


credit : [Kovetz]

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

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

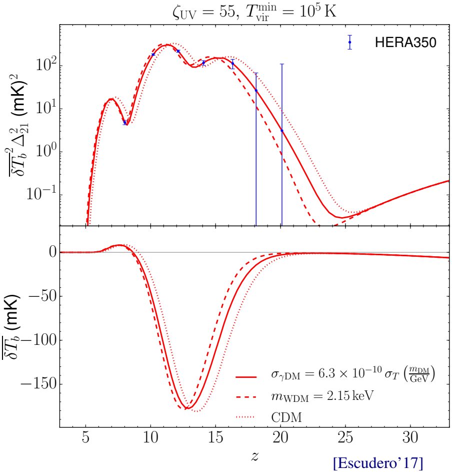
- Observed brightness of a patch of HI compared to CMB at $\nu = \nu_0/(1+z)$

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

Delayed 21cm features for Non-CDM

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

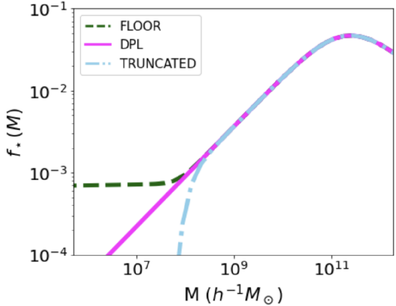
Halo suppression can lead to delayed astro processes giving rise to reionization or 21cm features. Stronger delay for WDM than IDM.

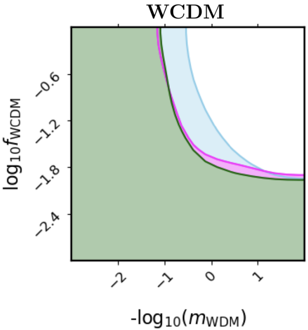


[Escudero'17]

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.

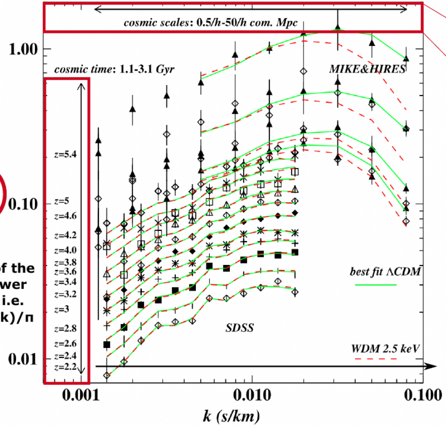




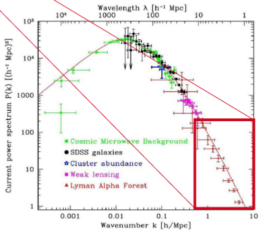
For $T_{vir}^{min} \sim 10^4$ K it will be difficult to distinguish between an inefficient source models and a universe filled with NCDM.

$\Delta^2_F(k)$

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

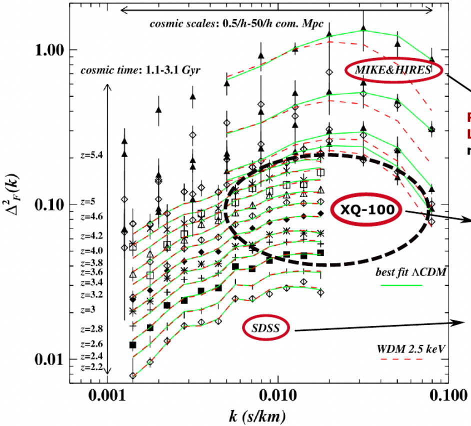


Adapted from Tegmark et al. 2004



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



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

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

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

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

- Compute area under the curve

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

and

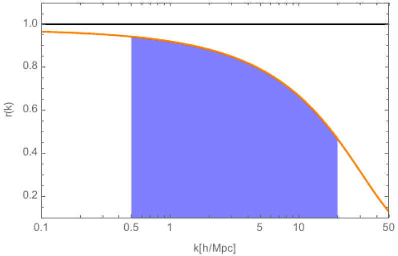
$$\delta A_X = \frac{A_{\rm CDM} - A_X}{A_{\rm CDM}}$$

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

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

- Suitable for mixed scenario

$\delta A_{\rm WDM} = 0.33 \quad \text{for} \quad m_{\rm WDM} = 5.3\,\mathrm{keV}$



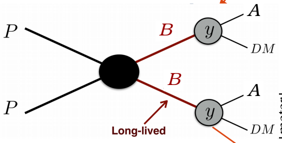
[see *also* D'Eramo, Lenoci, 2020; Egana-Ugrinovic, Essig, Gift, LoVerde 2021]

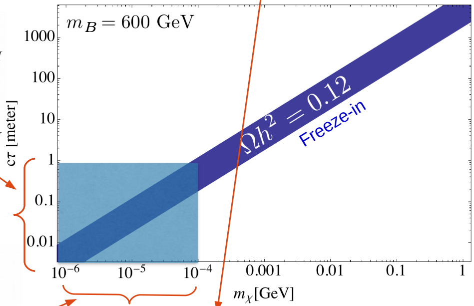
FIMPs: LLPs and NCDM

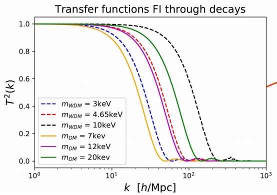
e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18, Calibbi'18, No'19, Belanger 18, etc]

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

Mediator mass range reachable at colliders

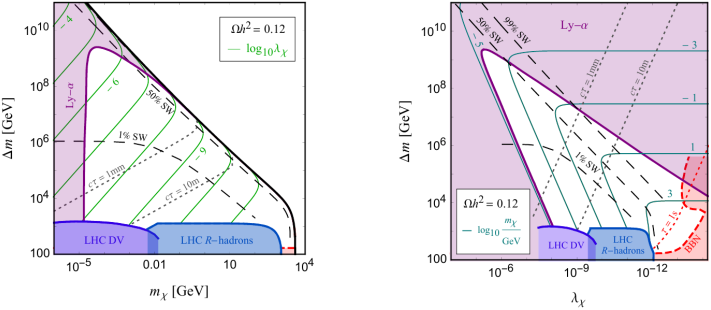






Warm DM like signatures
Suppressing small scale structures

Exemplary case of top-philic DM



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

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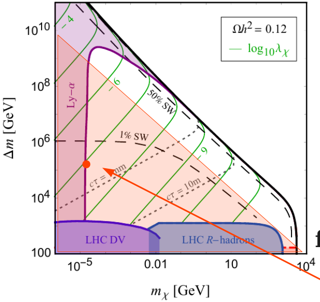
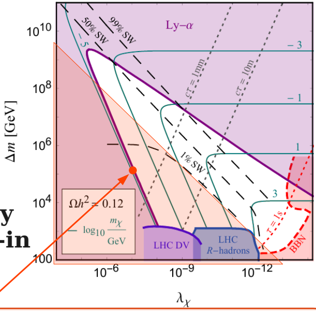
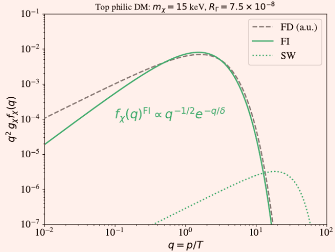
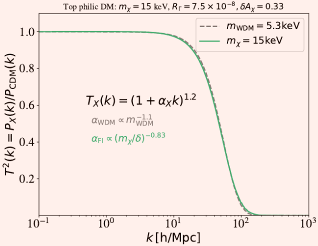




Mostly freeze-in





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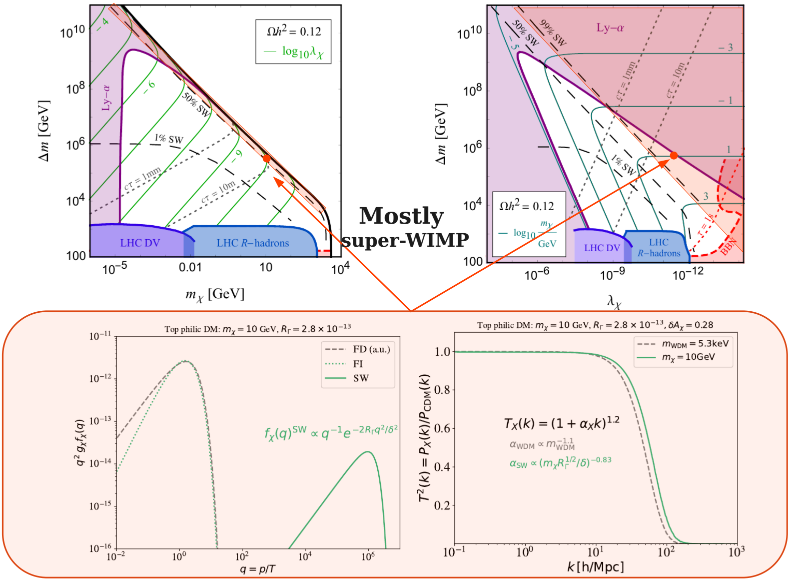

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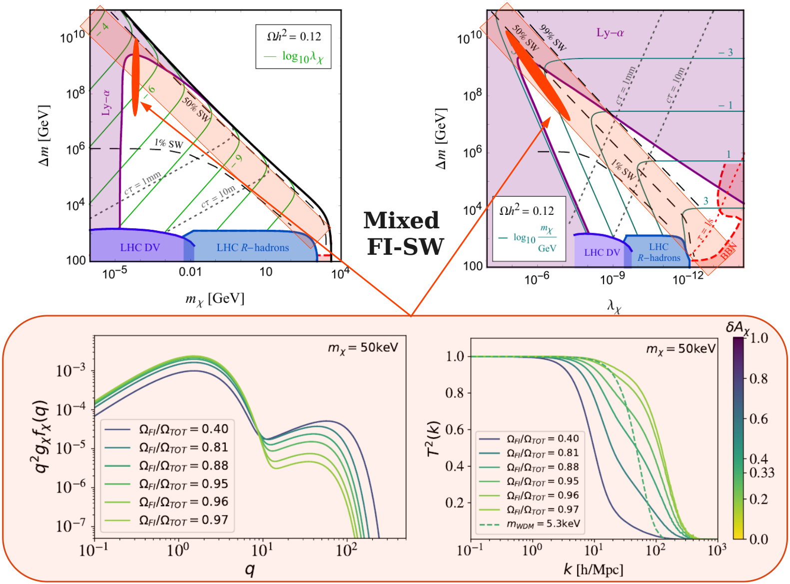

PBH evaporation and Greybody factors

BH temperature and Evaporation see [Hawking 74-75, Bardeen 1973,Page 1976 & Mc Gibbon1990]

$$T_{\rm BH} = \frac{M_p^2}{8\pi M_{\rm BH}} \quad \text{and} \quad \frac{dN_j}{dtdE} = \frac{g_j}{2\pi}\frac{\Gamma_j(E, M_{\rm BH})}{\exp\left(E/T_{\rm BH}\right) \pm 1},$$

where $\Gamma_j(E, M_{\rm BH})$ are spin and energy dependent greybody factors. We use the high energy limit $\Gamma_j \to 27E^2M_{\rm BH}^2/M_p^4$.

$$\frac{dM_{\rm BH}}{dt} = -\sum_j \int_0^\infty E\frac{dN_j}{dtdE}dE = -e_T\frac{M_p^4}{M_{\rm BH}^2},$$
$$N_j = -\int_{t_F}^{\tau} dt \int_0^\infty dEE\frac{dN_j}{dtdE} = g_j\frac{81\zeta(3)}{4096\pi^4 e_T}\frac{M_F^2}{M_p^2}$$

with a lifetime $\tau = \frac{1}{3e_T}\frac{M_F^3}{M_p^4}$.

Including the full treatment of the greybody factors [Mc Gibbon1990] , our e_T is approximatively twice as large as the correct $\tilde{e}_T$ for dM/dt. This implies that we underestimated τ by a factor of 2. The corrected $\tilde{\Omega}_{\rm DM}(t_0)$ to differ from $\Omega_{\rm DM}(t_0)$ by a factor $1.8 \times X'_{\rm DM}$ for $\beta < \beta_c$ and a factor $1.3 \times X'_{\rm DM}$ for $\beta > \beta_c$. It would also imply a strengthening of the Ly-α bounds obtained by $\sim 25\,\%$ aside from the shift in the peak velocity to higher velocities that would strengthen this bound even further.

NCDM from PBH: Lyman-α & $\Delta N_{\rm eff}$

- Suppressed power at small scales:

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

with $\nu = 1.12$ and WDM and PBH breaking scale are given by:

$\alpha_{\rm WDM} = 0.049 \left(\frac{m_{\rm WDM}}{1\,{\rm keV}}\right)^{-1.11} \left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}{\rm Mpc}$ [Viel'05]

$\alpha_{\rm PBH} = 53.2 \left(\frac{m_{\rm DM}}{1\,{\rm eV}}\right)^{-0.83} \left(\frac{M_{\rm F}}{M_p}\right)^{0.42} h^{-1}{\rm Mpc}$ [our result for $\beta > \beta_c$ using CLASS]

$$\rightsquigarrow m_{\rm DM} \geq 4.4\,{\rm keV} \times \left(\frac{m_{\rm WDM}^{{\rm Ly}-\alpha}}{\rm keV}\right)^{4/3} \left(\frac{M_F}{M_p}\right)^{1/2}$$

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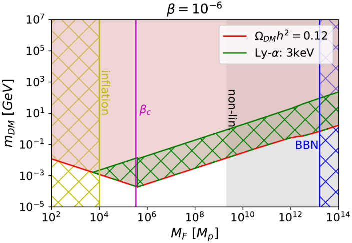
- Extra relativistic dof at recombination or BBN [Merle '15]:

$$\Delta N_{\rm eff}(T) = \frac{\rho_{\rm DM}(T) - m_{\rm DM} n_{\rm DM}(T)}{\rho_{rel\,\nu}(T)/N_{\rm eff}^{\nu}(T)}$$

$\rightsquigarrow \Delta N_{\rm eff} < 4.1 \times 10^{-2}$ (independently of M_F)
too small to be detected by CMB experiments (for $g_{\rm DM} = 2$)

($\Delta N_{\rm eff}(T_{\rm CMB}) < 0.28$ at 95 % C.L. [Planck'18] and ~ 0.06 for CMB Stage IV [Abazajian'19])

PBH: summary



$$M_{\rm BH}(t) = M_F \left(1 - \frac{(t - t_F)}{\tau}\right)^{1/3} \qquad \tau = \frac{1}{3e_T}\frac{M_F^3}{M_p^4}\,.$$

$$\beta_c = \sqrt{\frac{3e_T}{\gamma}\frac{M_p}{M_F}}\,.$$

This is really the end