SUSY2021

DM AND ASTROPARTICLE PHYSICS

23/08/2021

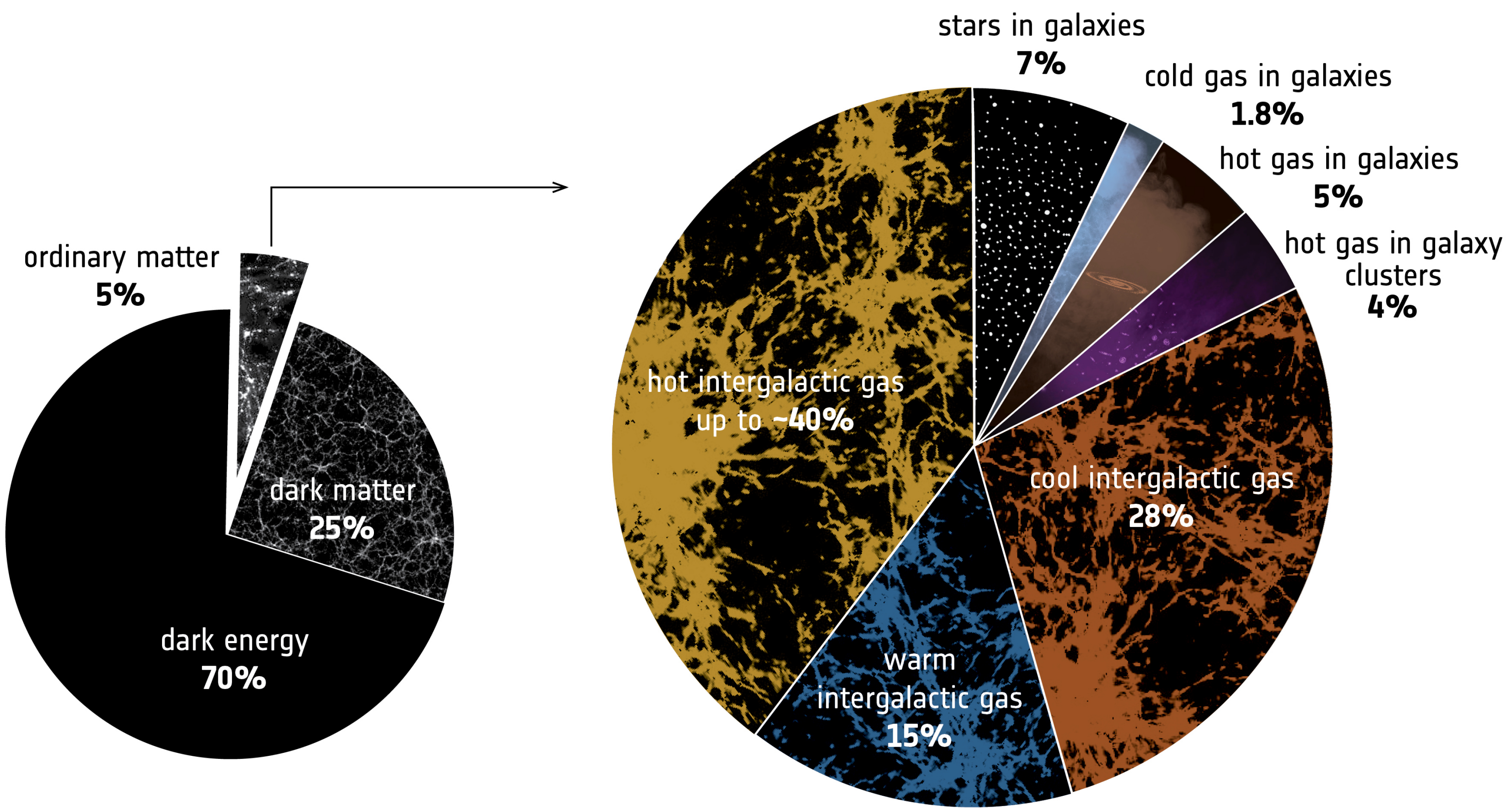
Lower Mass Bounds on FIMP Dark Matter.

Alessandro Lenoci

DESY

Francesco D'Eramo, Alessandro Lenoci
2012.01446

The cosmic pie: DM and Lyman-α forest.



$$\Omega_{\rm DM}(t_0)h^2 = 0.120 \pm 0.001$$ Planck CMB TT+EE+lensing

Thermal Warm Dark Matter Lyman-α constraints

$$m_{\rm WDM} > \begin{cases} 3.5 \text{ keV} \\ 5.3 \text{ keV} \end{cases}$$

M. Viel et al. 1702.01764

Our framework.

1. **Homogeneous** and **isotropic** FRW expanding Universe
2. **Standard model of particle physics** for $g_\star(T)$ and $g_{\star s}(T)$
3. DM is produced via **freeze-in** **IR dominated** at $T \sim M$
4. Single FIMP non-CDM particle χ
    - mass m_χ
    - g_χ internal degrees of freedom
    - **non-thermal** phase space distribution (PSD) $f_\chi(p)$
    - **Maxwell-Boltzmann (MB) statistics** (excellent approximation)
5. DM produced in **radiation-dominated era** $H(T) \propto \dfrac{M_{\rm Pl}}{T^2}$

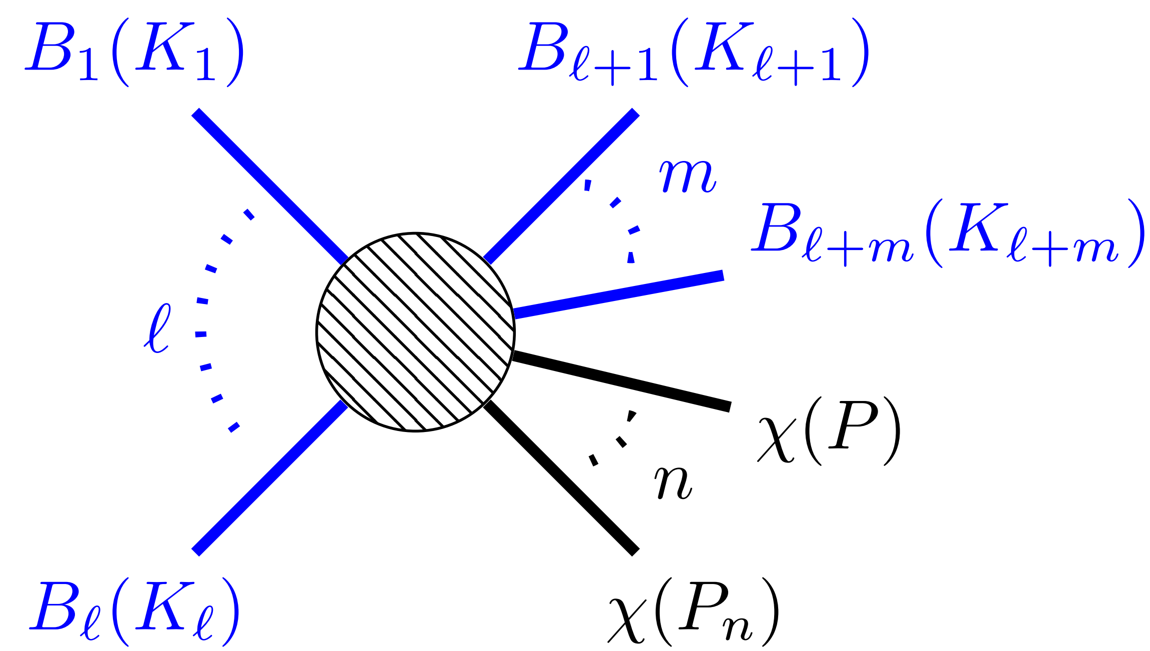
Boltzmann Equation for FIMPs.

$$x = \frac{M}{T}$$

$$q = \frac{p}{M}\frac{a(T)}{a(M)}$$

$$T_\chi = \frac{p}{q}$$

$$\boxed{\frac{df_\chi}{dt} = C[f_\chi]}$$

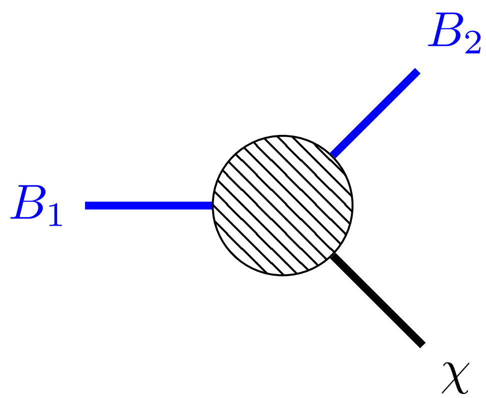
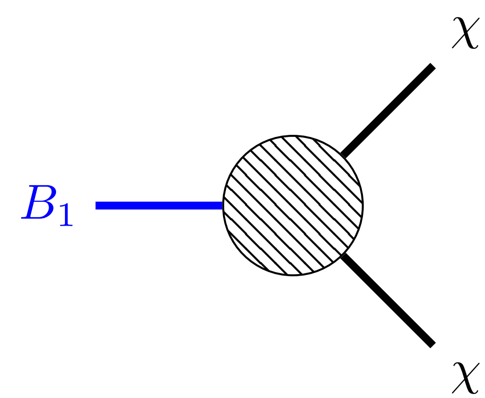
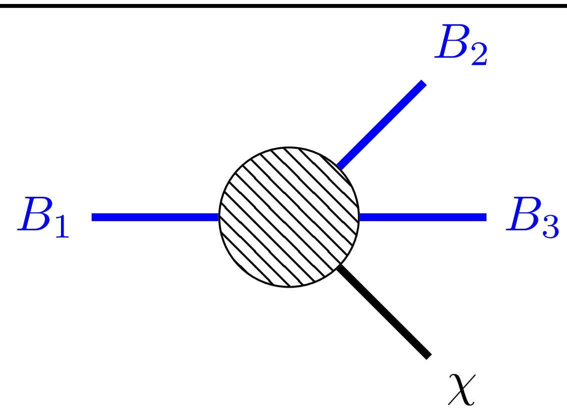
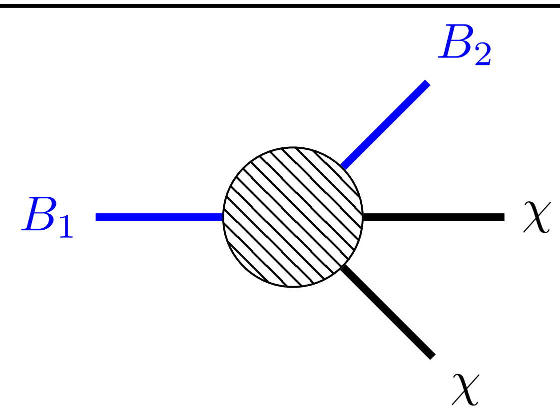
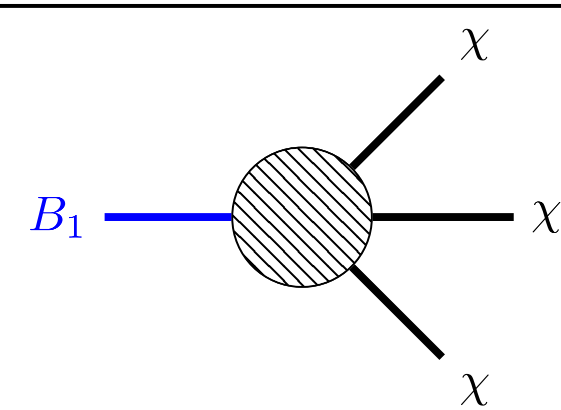
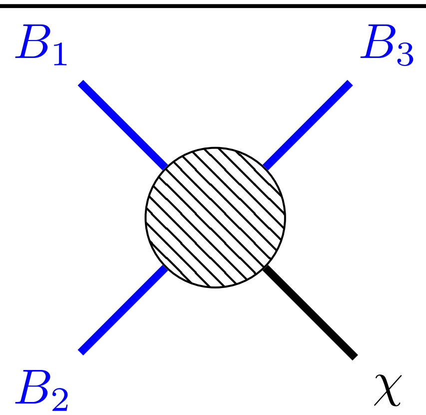
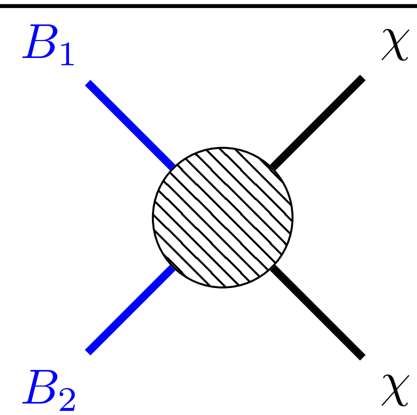


$$\boxed{g_\chi f_\chi(q) = \int_0^\infty d\log x \frac{1}{H(x)}\left(1 - \frac{1}{3}\frac{d\log g_\star}{d\log x}\right)\frac{\mathscr{C}(x,q)}{E}}$$

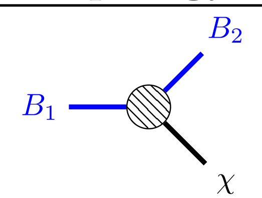
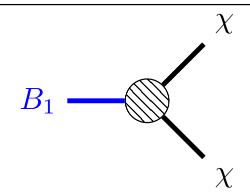
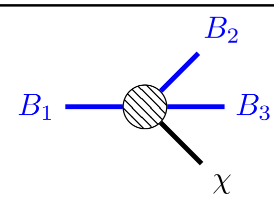
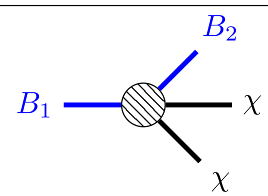
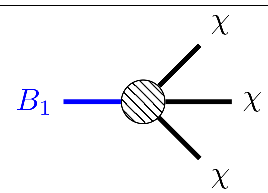
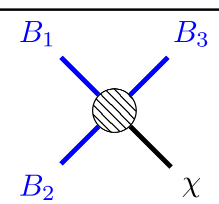
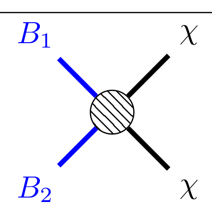
$$\mathscr{C}(T,p) \equiv \frac{n}{2}\int \prod_{i=1}^{\ell+m} d\mathscr{K}_i \prod_{i=2}^{n} d\Pi_i \,(2\pi)^4\,\delta^{(4)}(P_\mathrm{f} - P_\mathrm{i})\,|\mathscr{M}|^2 \prod_{i=1}^{\ell} f_i(k_i)$$

In our work we consider $|\mathscr{M}|^2 =$ const. since Freeze-in is IR dominated.
(Excellent approximation)

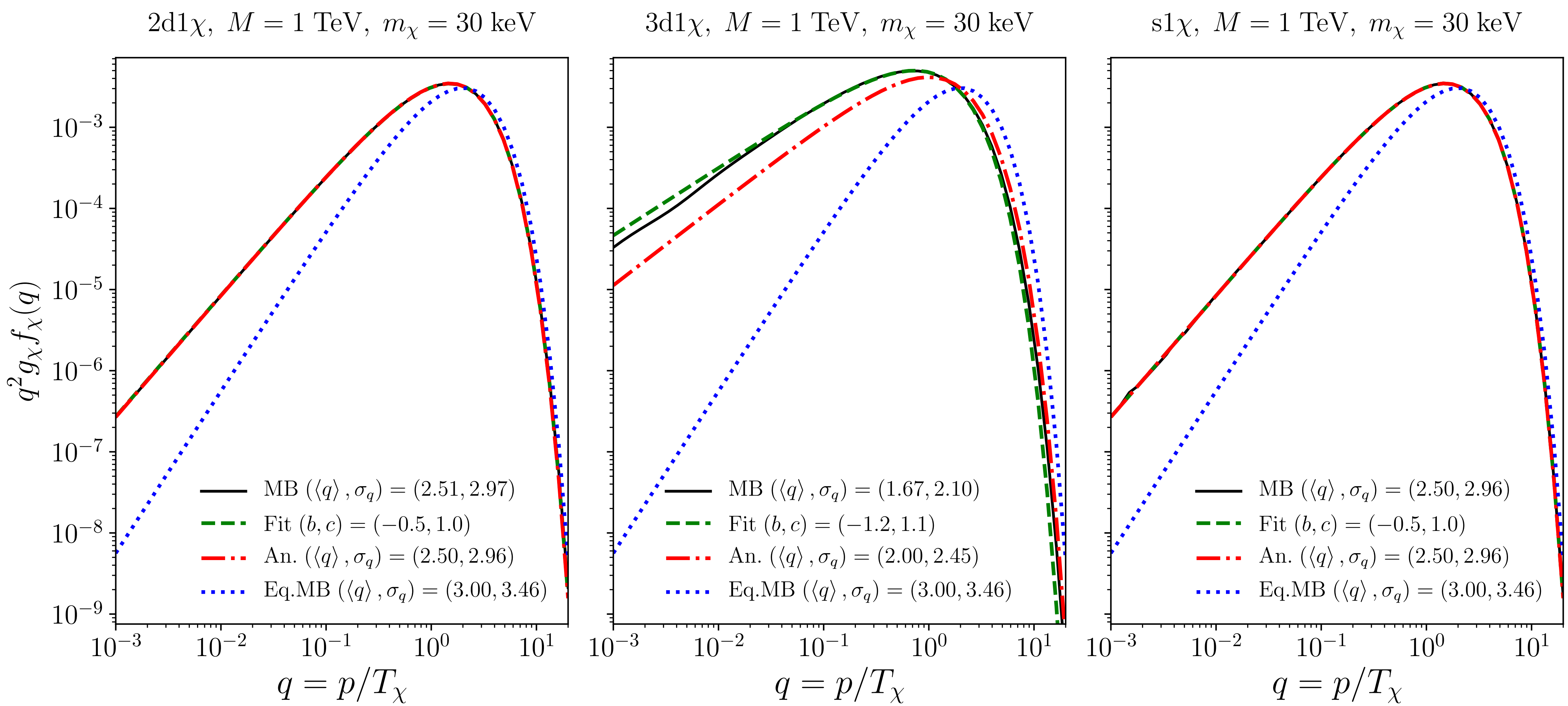
Our topologies.

	Single production	Pair production	Triple production
FIMP DM Two-body decays			
FIMP DM Three-body decays			
FIMP DM Scatterings			

Chosen benchmarks.

Benchmark	Topology	(m_1, m_2, m_3) [TeV]	Analytical $f_\chi(q)$
2d1χ		$(M, 0, -)$	$\propto \frac{\Gamma_1 M_{\rm Pl}}{M^2} \frac{1}{\sqrt{q}} e^{-q}$
2d2χ		$(M, -, -)$	
3d1χ		$(M, 0, 0)$	$\propto \frac{\Gamma_1 M_{\rm Pl}}{M^2} \frac{1}{q} e^{-q}$
3d2χ		$(M, 0, -)$	
3d3χ		$(M, -, -)$	
s1χ		$(M, 0, 0)$	$\propto \sigma^{\rm FI} M M_{\rm Pl} \frac{1}{\sqrt{q}} e^{-q}$
s2χ		$(M, M, -)$	

PSDs for benchmarks.



$$\boxed{g_\chi f_\chi(q) \propto q^b e^{-cq}}$$

$$\langle q \rangle = \frac{b+3}{c} \qquad \sigma_q = \sqrt{\langle q^2 \rangle} = \frac{\sqrt{(b+3)(b+4)}}{c}$$

Warmness constraints.

- **Free-streaming length**

$$\lambda_{\rm FS}(m_\chi, M, f_\chi) = \int_{t_{\rm prod}}^{t_{\rm equality}} dt \frac{\langle v(t)\rangle}{a(t)} < \lambda_{\rm WDM}(m_{\rm WDM})$$

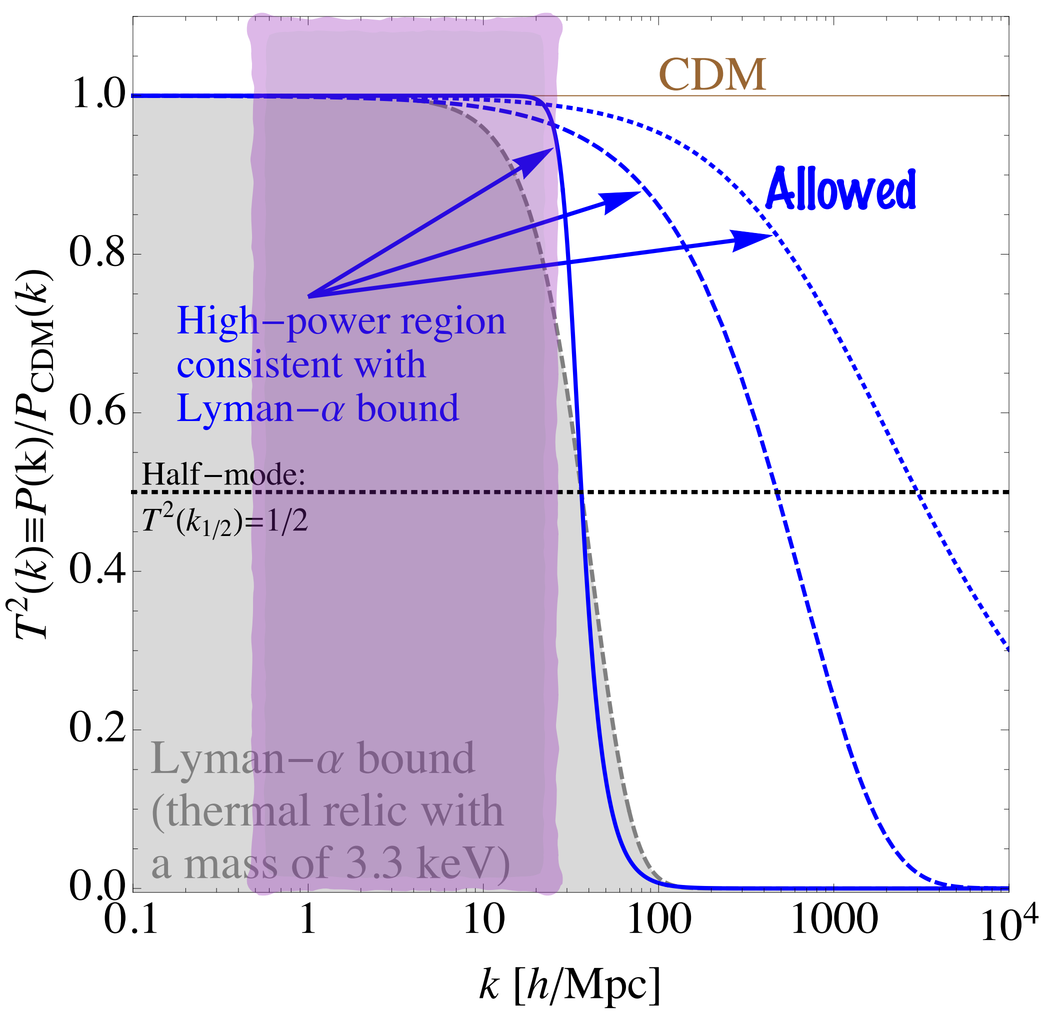
- **Momentum dispersion** $W_\chi = \sqrt{\langle p^2\rangle / m_\chi{}^2} < W_{\rm WDM}$ **Kamada, Yanagi - [1907.04558]**

$$\boxed{m_\chi > 19\ {\rm keV} \left(\frac{m_{\rm WDM}}{5.3\ {\rm keV}}\right)^{4/3} \left(\frac{\sigma_q}{3.6}\right) \left(\frac{106.75}{g_{\star s}(M)}\right)^{1/3}}$$

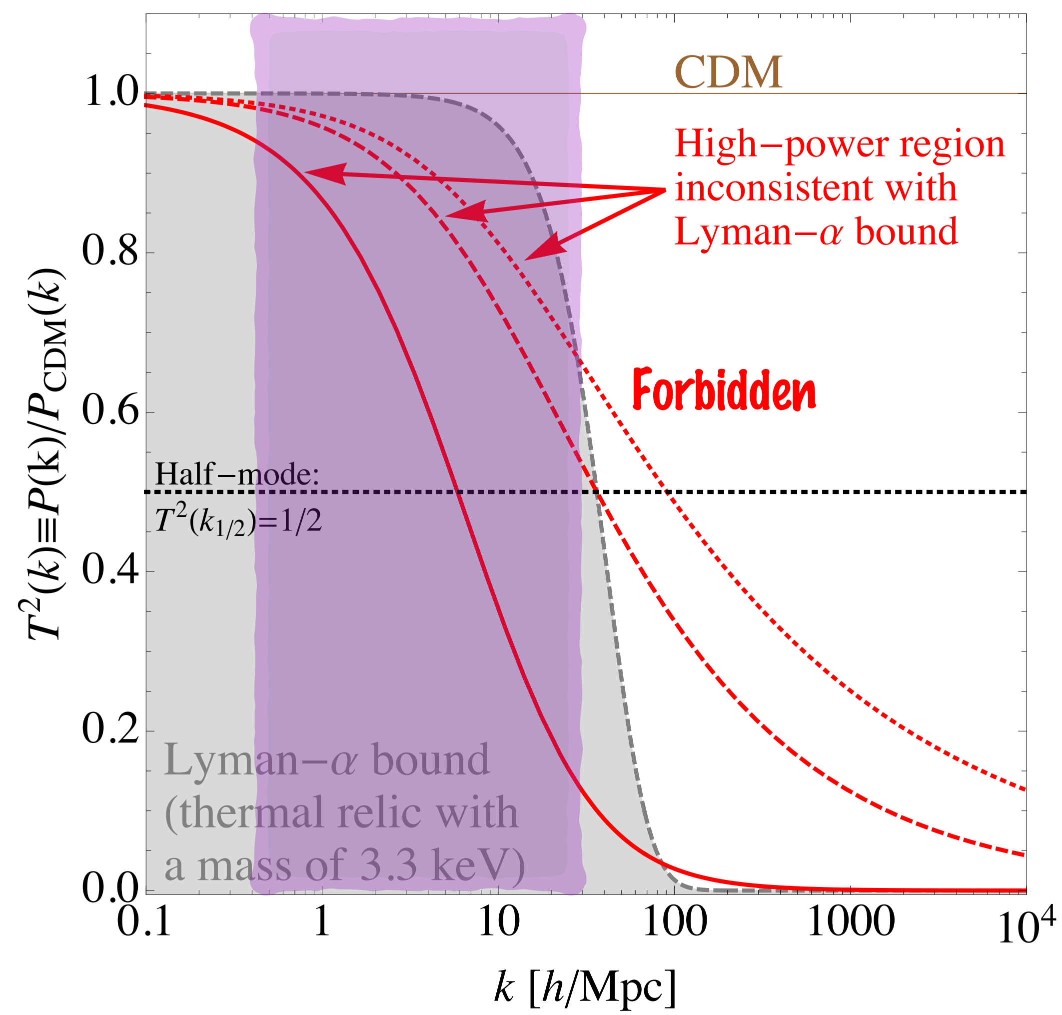
- **Linear matter power spectrum** $P(k)$ **computed with** CLASS

1. Relative transfer function $\mathcal{T}^2_{\rm 3D}(k) = P/P_{\rm CDM}$: $k_{1/2} > k_{1/2}^{\rm WDM}$
2. Relative 1D transfer function $\mathcal{T}^2_{\rm 1D}(k) = P^{\rm 1D}/P^{\rm 1D}_{\rm CDM}$: $\delta A < \delta A_{\rm WDM}$
3. Number of Milky way satellites $N_{\rm sat} \propto \int \frac{dM_{\rm sub}}{M^2_{\rm sub}} \frac{M_{\rm halo}}{R^3_{\rm sub}} \frac{P(1/R_{\rm sub})}{\sqrt{2\pi(S_{\rm sub} - S_{\rm halo})}} \gtrsim 57 - 63$

Relative transfer functions.



1609.01289



$$\boxed{k_{1/2} : \mathcal{T}^2_{3D}(k_{1/2}) = \frac{1}{2}}$$

$$\boxed{\delta A = 1 - \int_{k_{min}}^{k_{max}} dk' \frac{\mathcal{T}^2_{1D}(k')}{k_{max} - k_{min}}}$$

$$k_{1/2} > k_{1/2}^{\rm WDM}$$

$$\delta A < \delta A_{\rm WDM}$$

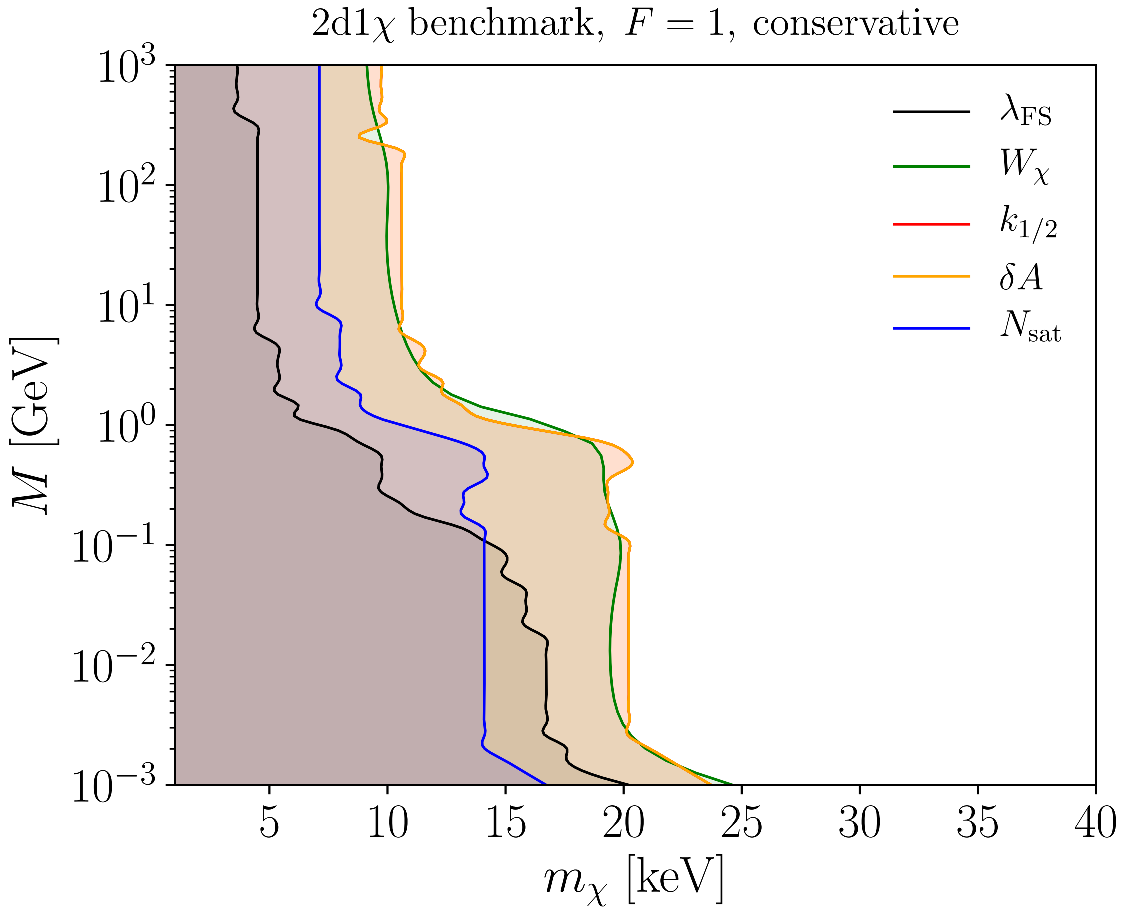
MIKE/HIRES+XQ-100

$$k_{max} = 20\ h/\mathrm{Mpc}$$
$$k_{min} = 0.5\ h/\mathrm{Mpc}$$

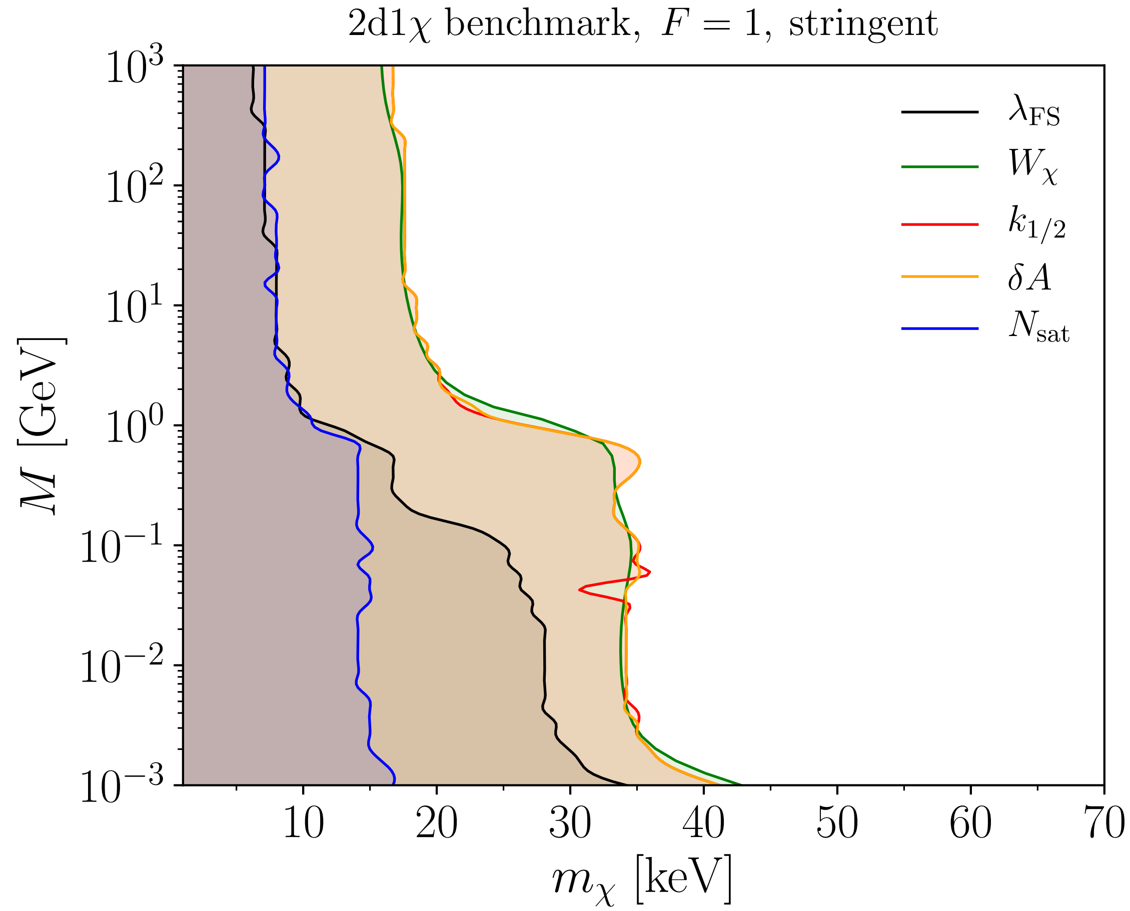
FIMP DM bounds: (m_χ, M) plane.

$$\left(m_1 = M, m_\chi, F = \frac{\Omega_\chi}{\Omega_{\rm DM}}, r_2 = \frac{m_2}{m_1}\right)$$

$m_{\rm WDM} = 3.5$ keV



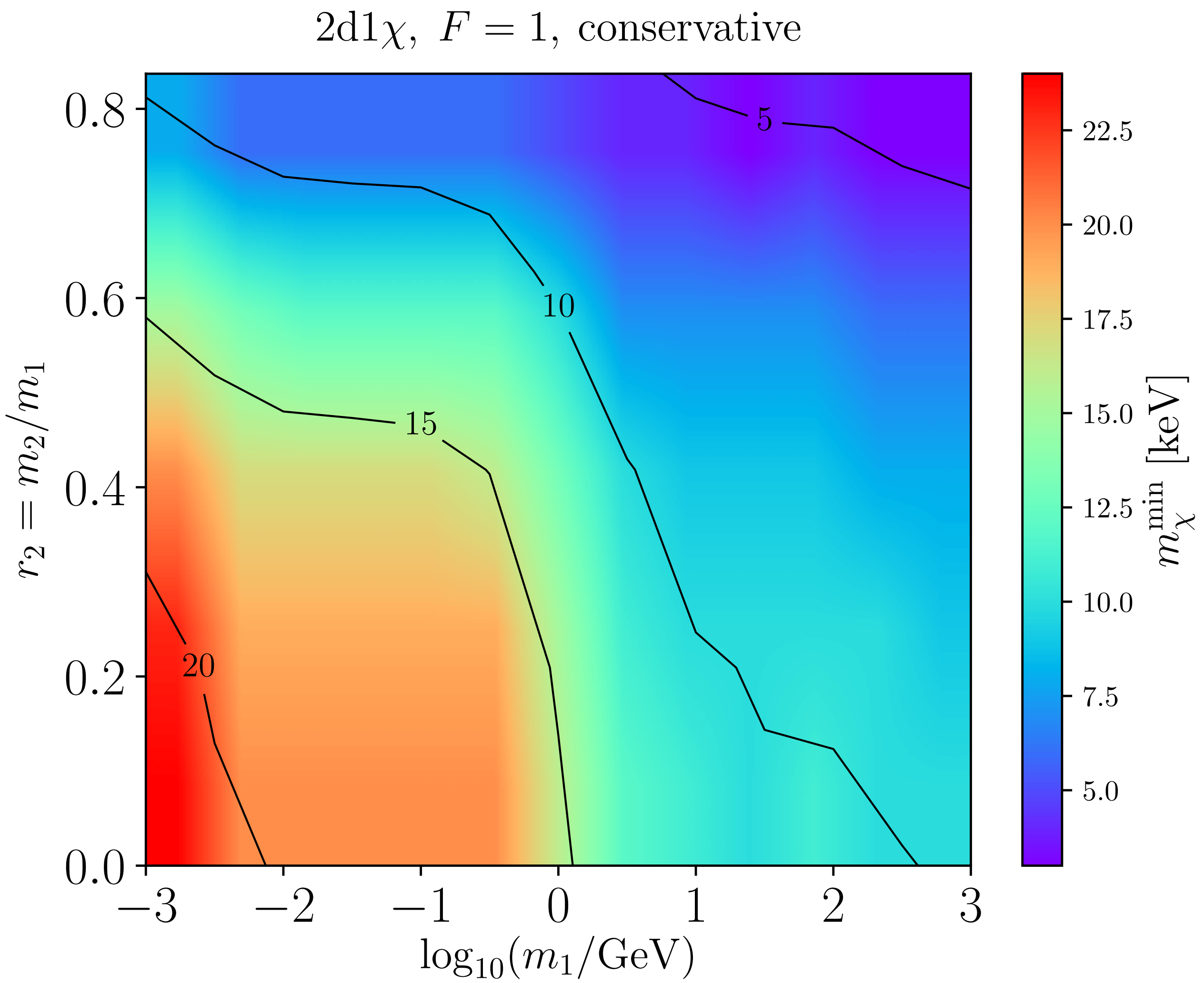
$m_{\rm WDM} = 5.3$ keV



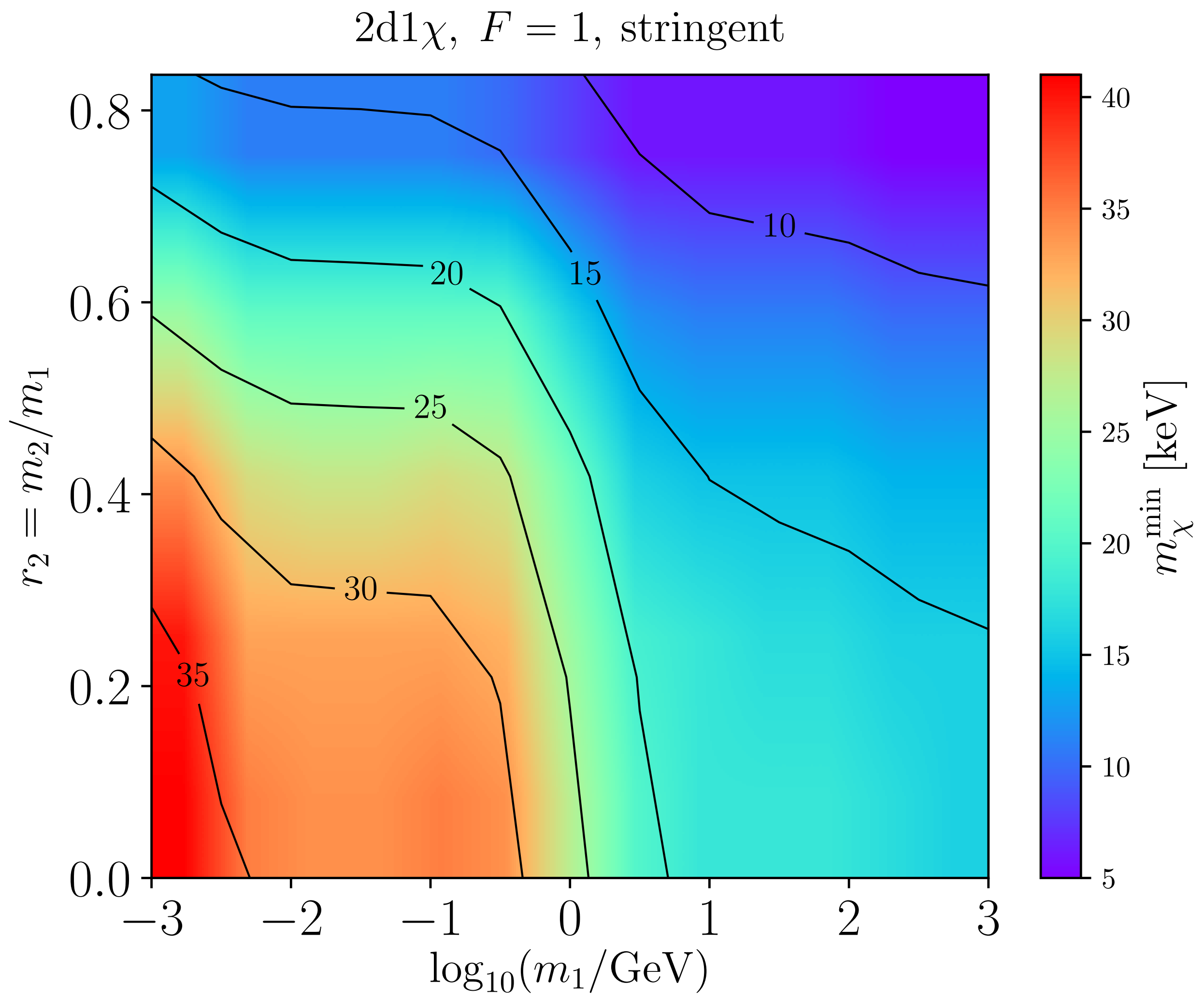
FIMP DM mass bounds: (m_1, r_2) plane.

$$\left(m_1 = M, m_\chi, F = \frac{\Omega_\chi}{\Omega_{\rm DM}}, r_2 = \frac{m_2}{m_1} \right)$$

$m_{\rm WDM} = 3.5$ keV



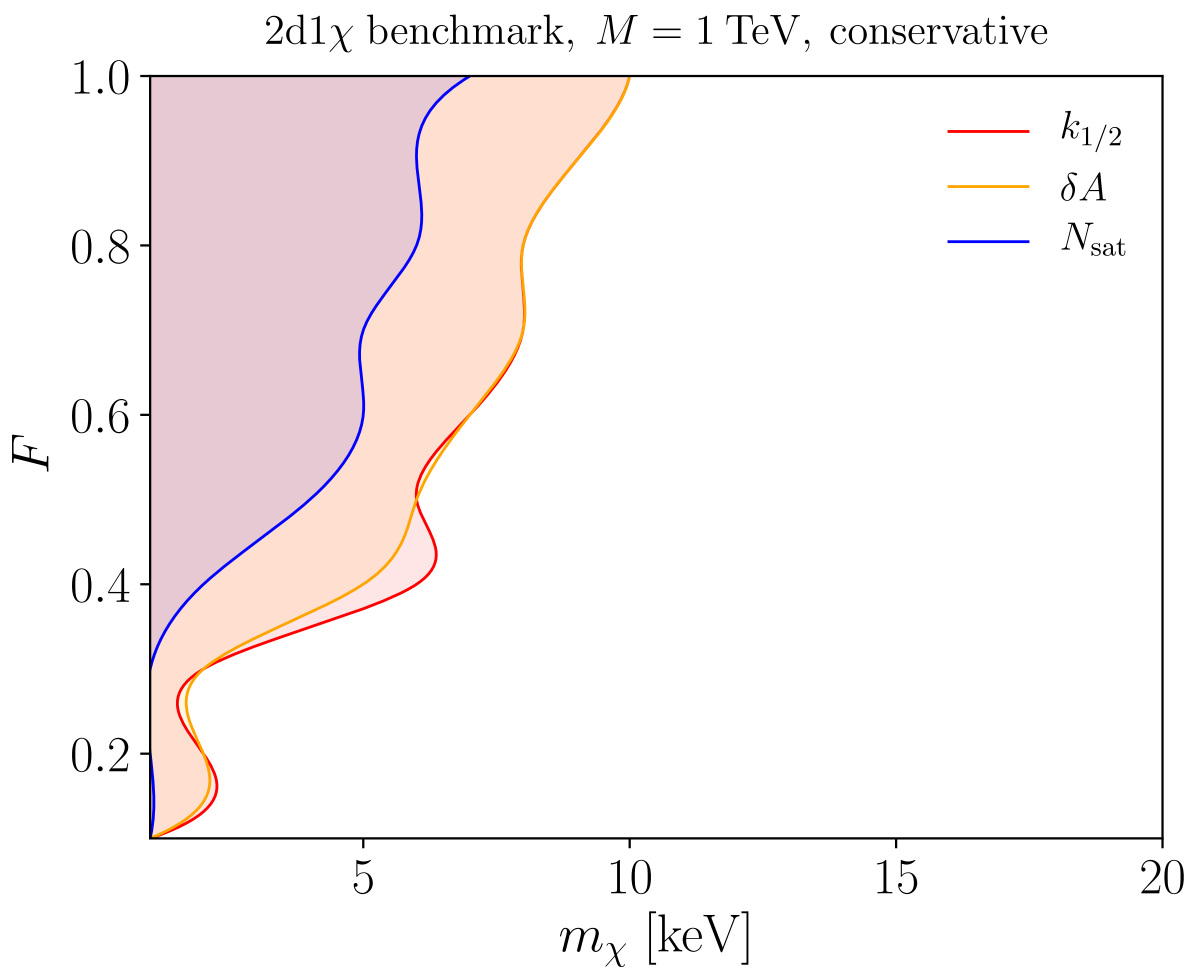
$m_{\rm WDM} = 5.3$ keV



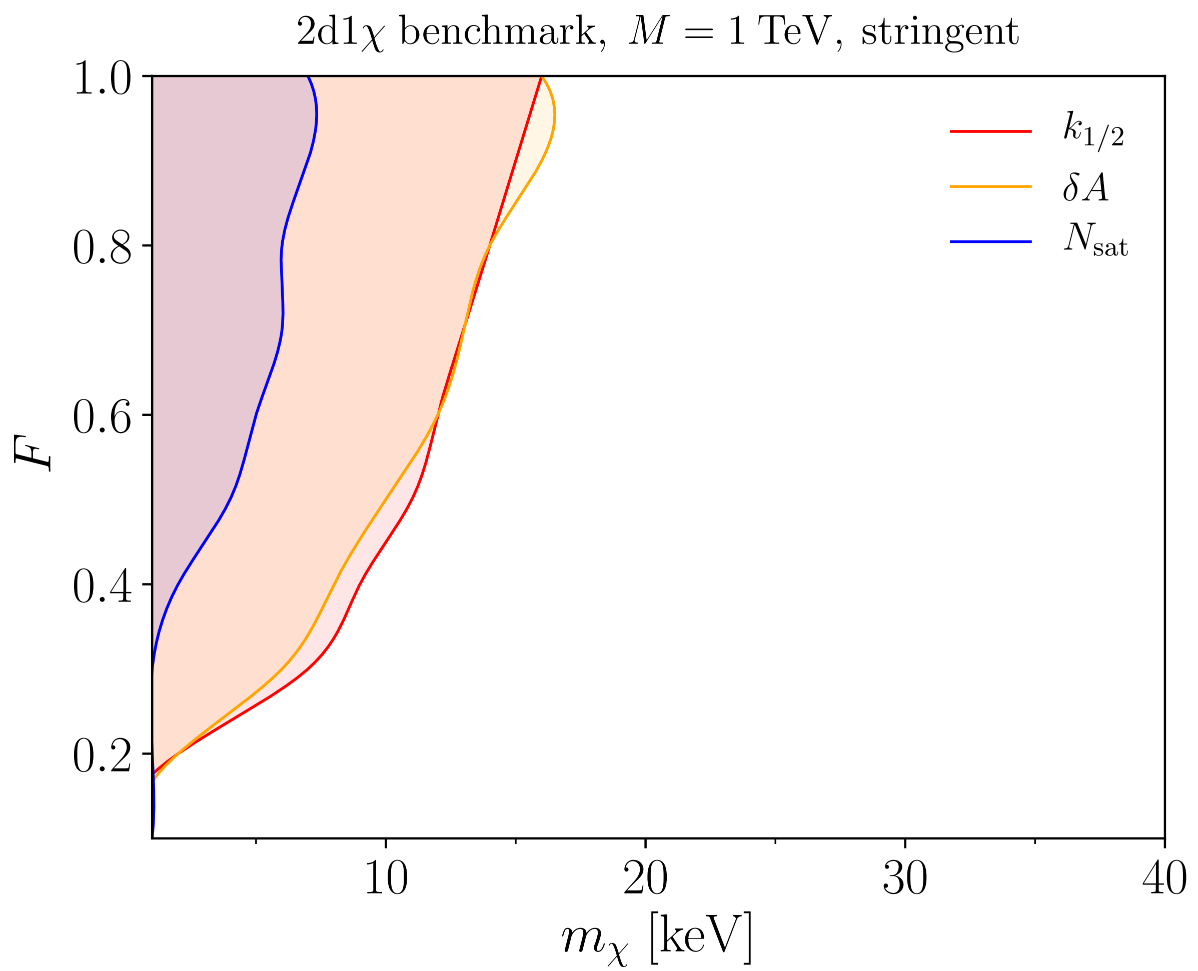
Subdominant FIMP DM bounds: (m_χ, F) plane.

$$\left(m_1 = M, m_\chi, F = \frac{\Omega_\chi}{\Omega_{\rm DM}}, r_2 = \frac{m_2}{m_1}\right)$$

$m_{\rm WDM} = 3.5$ keV



$m_{\rm WDM} = 5.3$ keV



Further developments.

1. We can change the **cosmological background up to BBN**
   - Early matter domination
   - Inflationary reheating (non adiabatic evolution)
   - Fast expanding universe: new species with $\rho \propto a^{-(4+n)}$

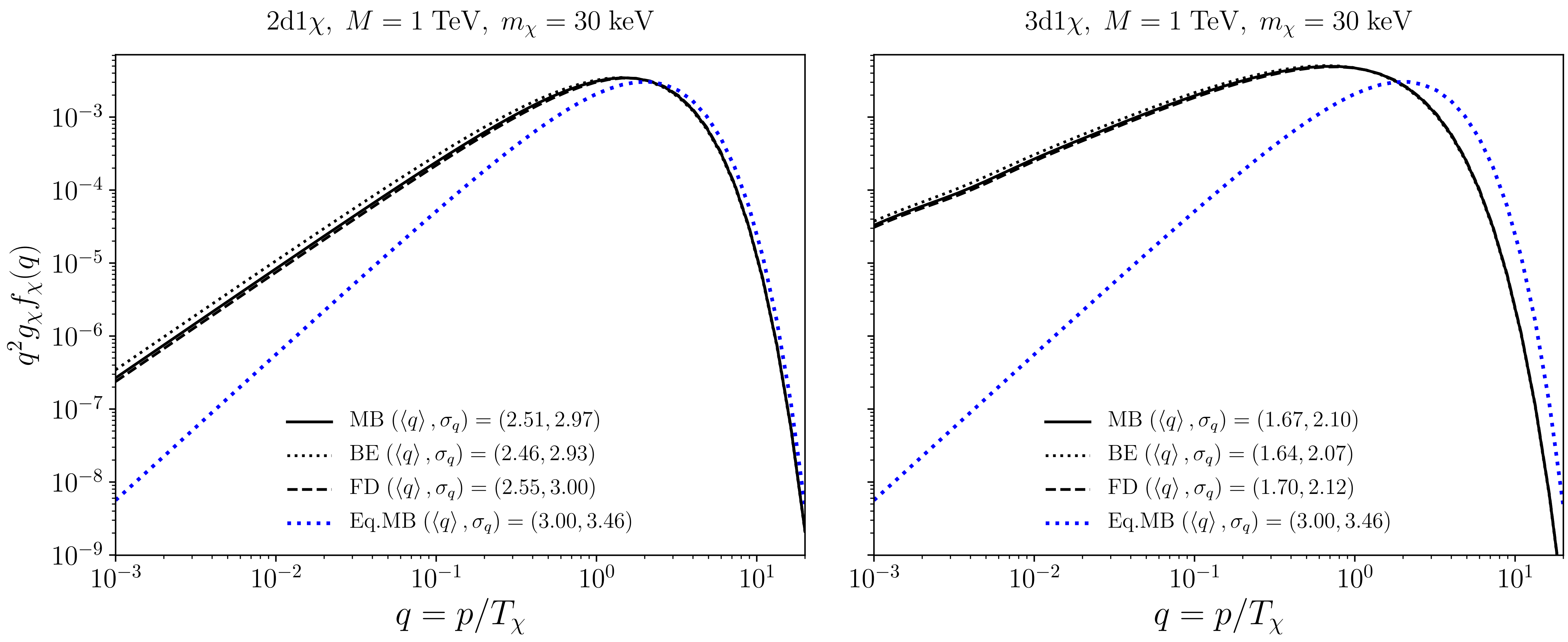
$$H(T) \propto \frac{M_{\rm Pl} M^{n/2}}{T^{2+n/2}}$$

2. Specific **microscopic realizations as portal models**
   - Portal models: dark photon, Higgs portal

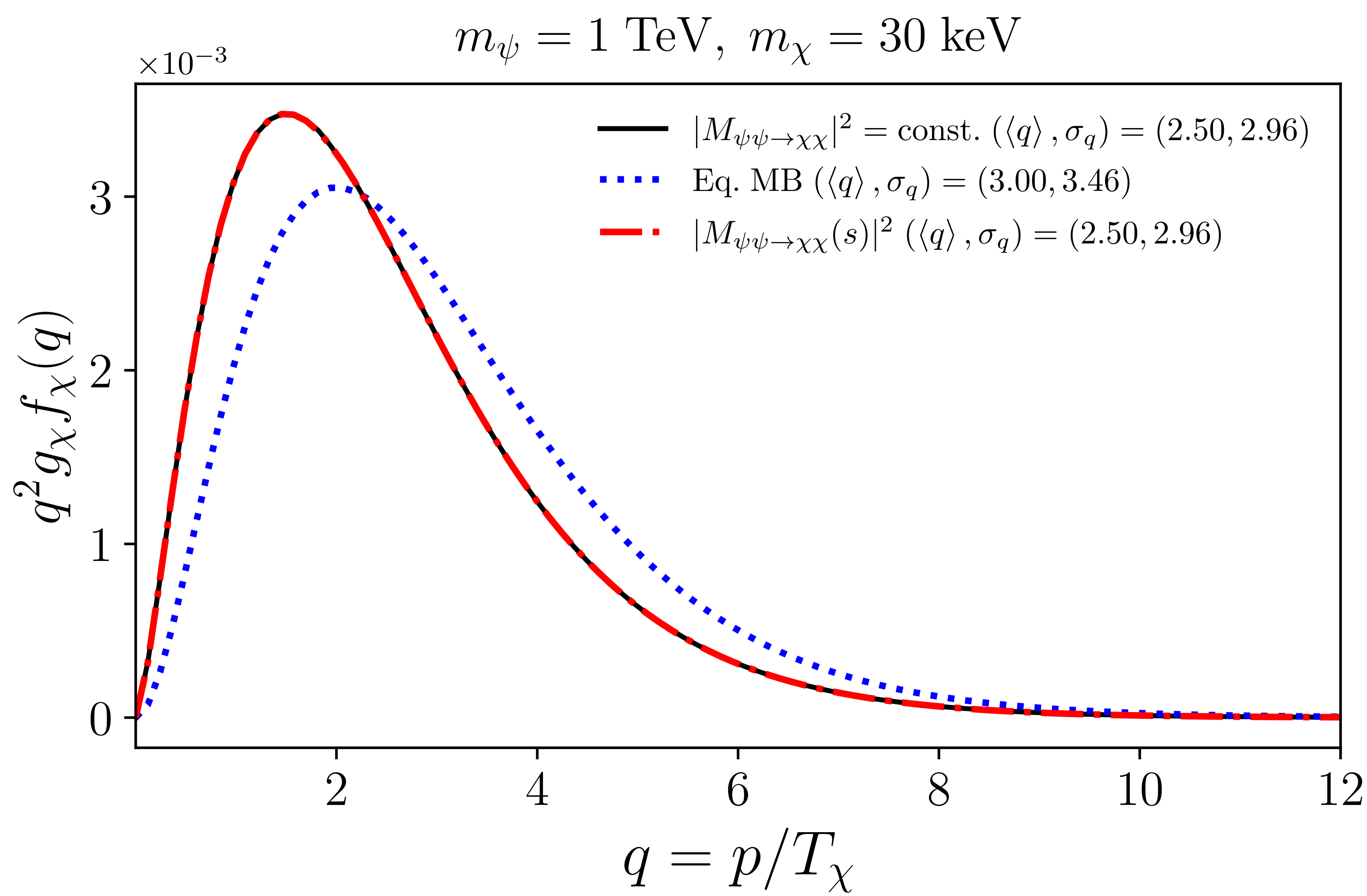
$\boxed{\textbf{FIMP model} \longrightarrow \textbf{our methodology + CLASS} \longrightarrow \textbf{constraints on FIMP parameters}}$

Thanks for listening!

The MB approximation.



The $|\mathscr{M}|^2$ = const. approximation.



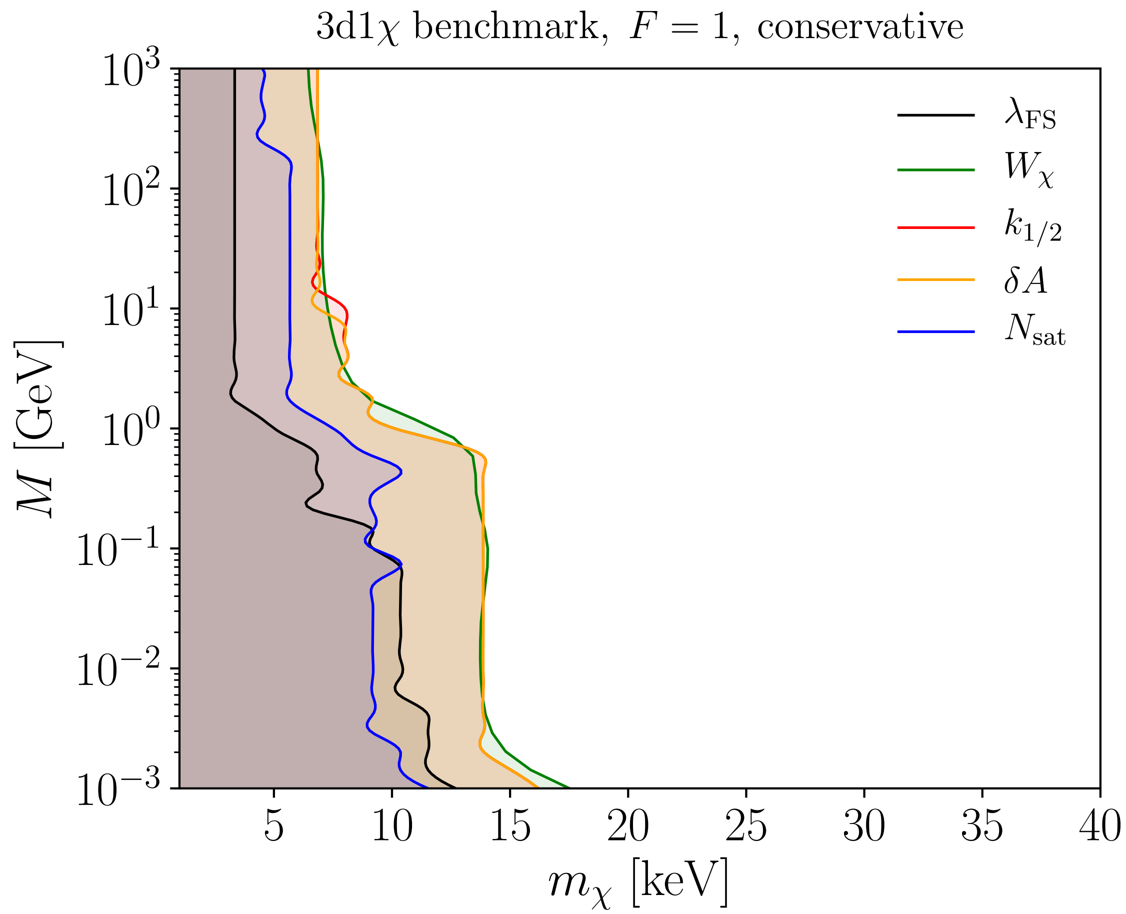
Specific simple model : fermion thermal bath ψ annihilation into χ DM through a scalar mediator ϕ

$$\mathscr{L} \supset y_\psi \phi \bar{\psi} \psi + y_\chi \phi \bar{\chi} \chi$$

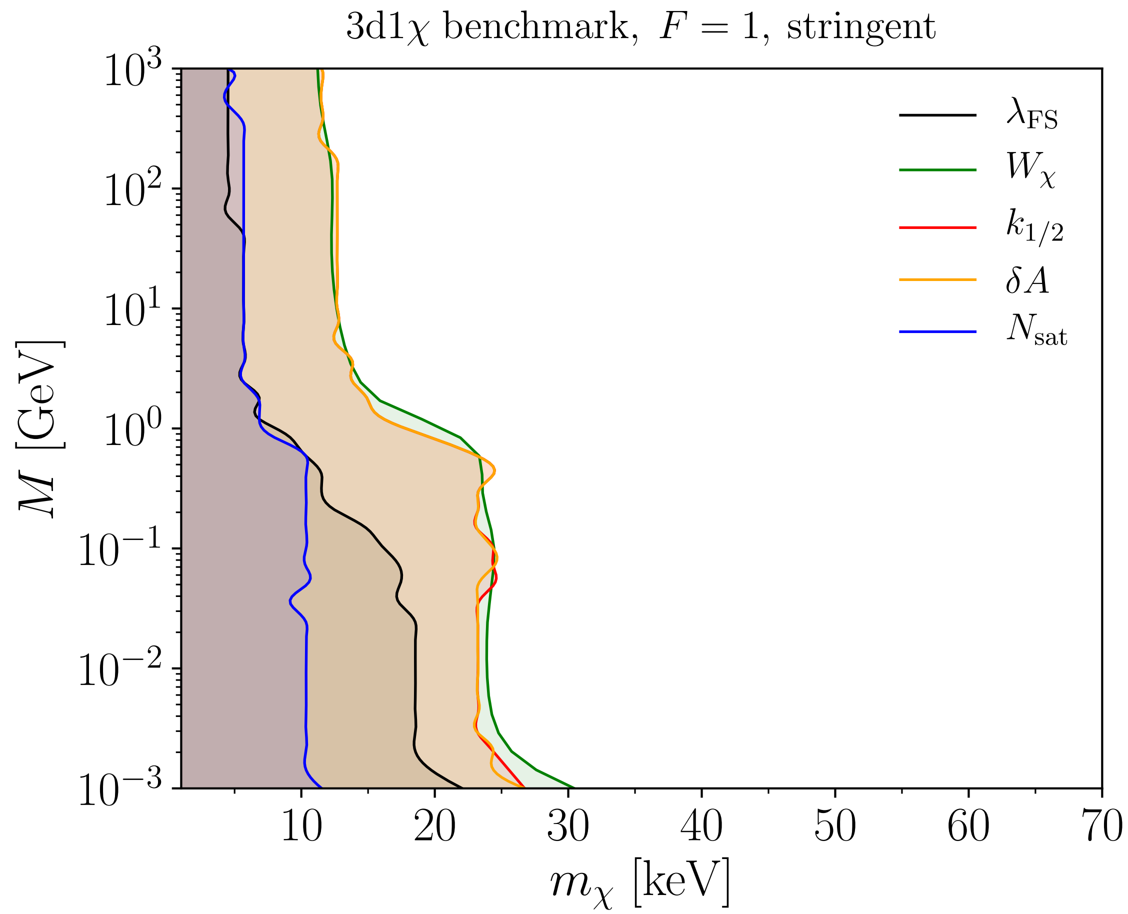
FIMP DM bounds: (m_χ, M) plane.

$$\left(m_1 = M, m_\chi, F = \frac{\Omega_\chi}{\Omega_{\rm DM}}, r_2 = \frac{m_2}{m_1} \right)$$

$m_{\rm WDM} = 3.5$ keV



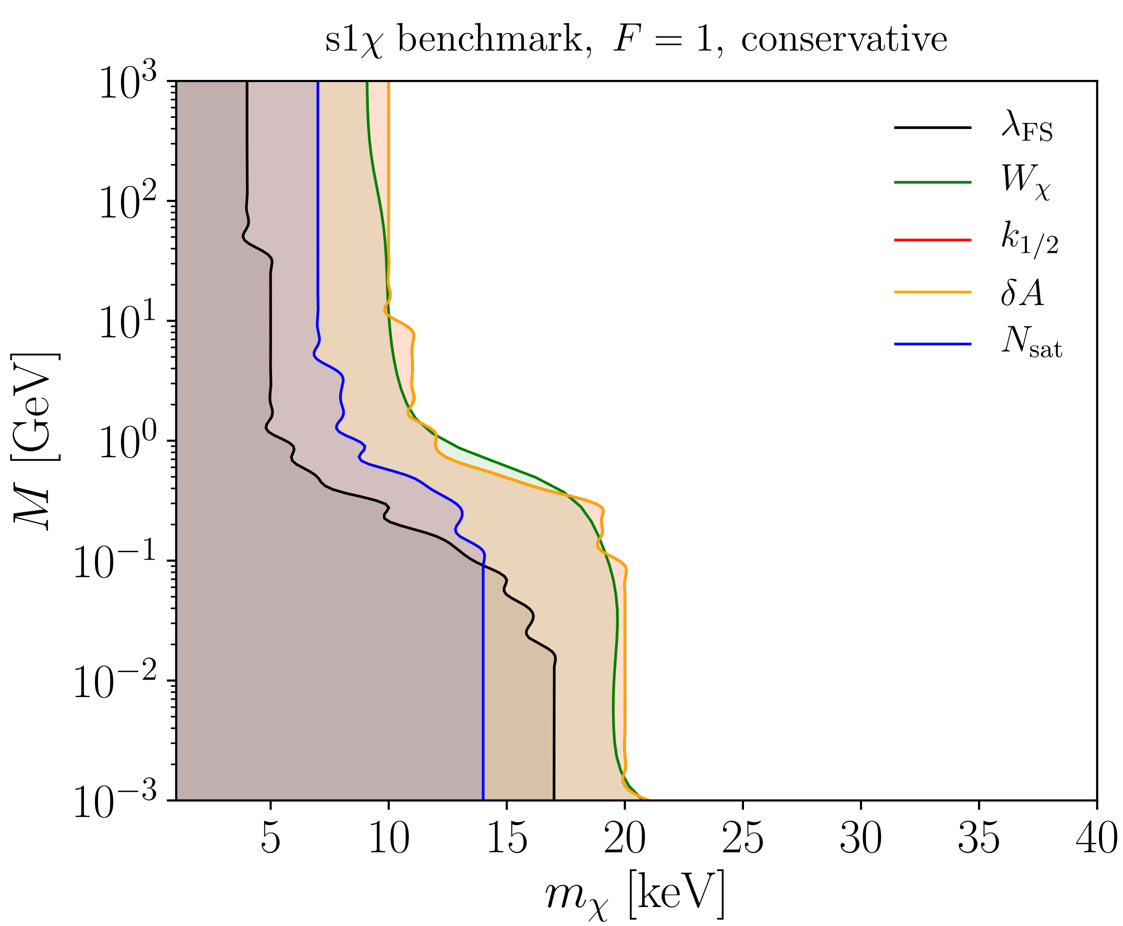
$m_{\rm WDM} = 5.3$ keV



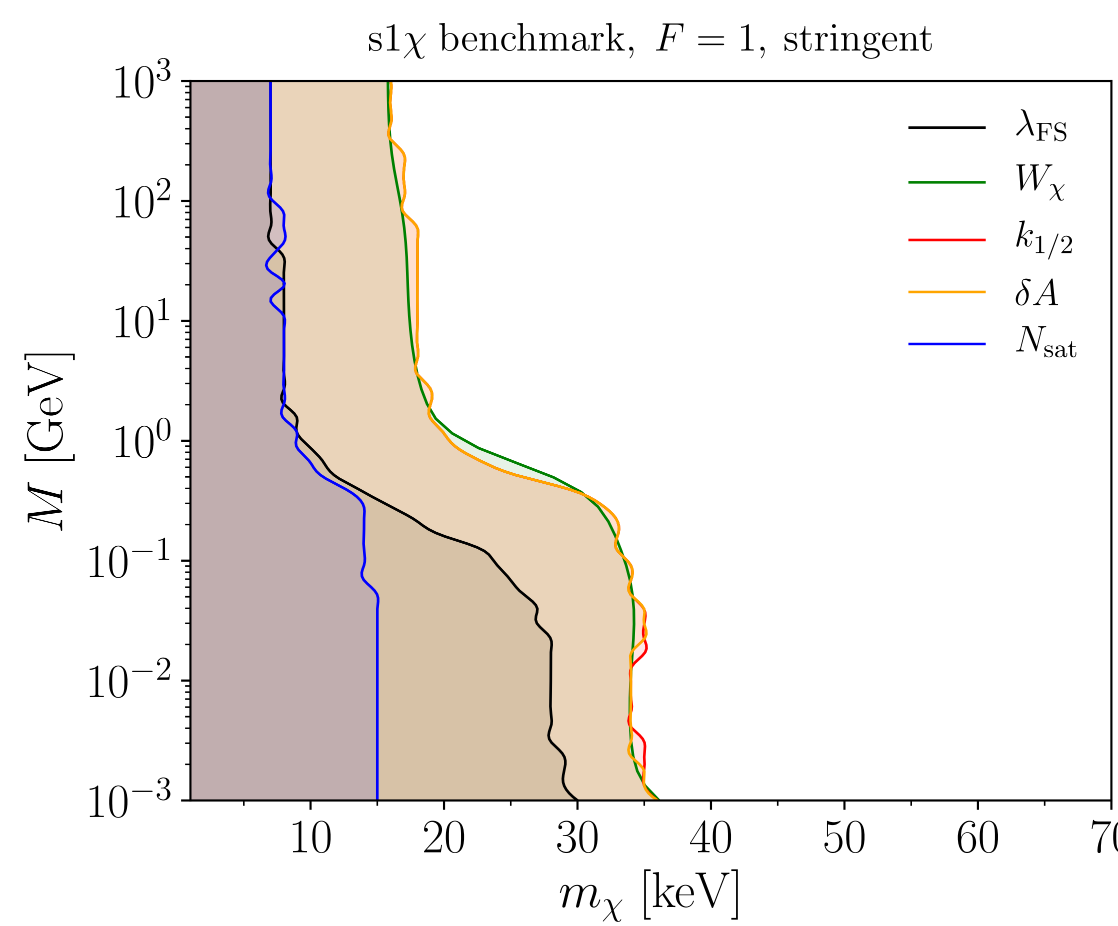
FIMP DM bounds: (m_χ, M) plane.

$$\boxed{\left(m_1 = M, m_\chi, F = \frac{\Omega_\chi}{\Omega_{\rm DM}}, r_2 = \frac{m_2}{m_1}\right)}$$

$m_{\rm WDM} = 3.5$ keV



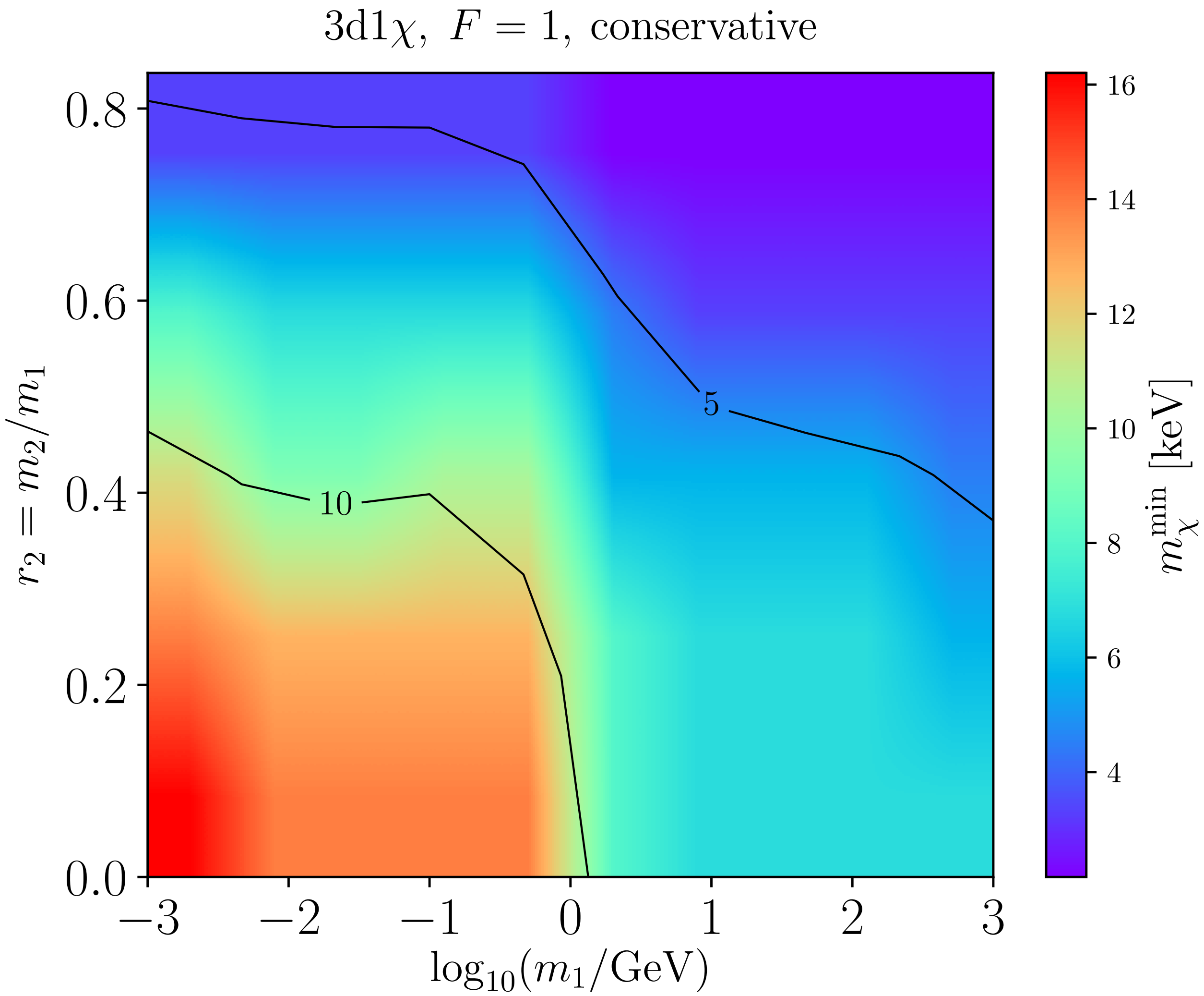
$m_{\rm WDM} = 5.3$ keV



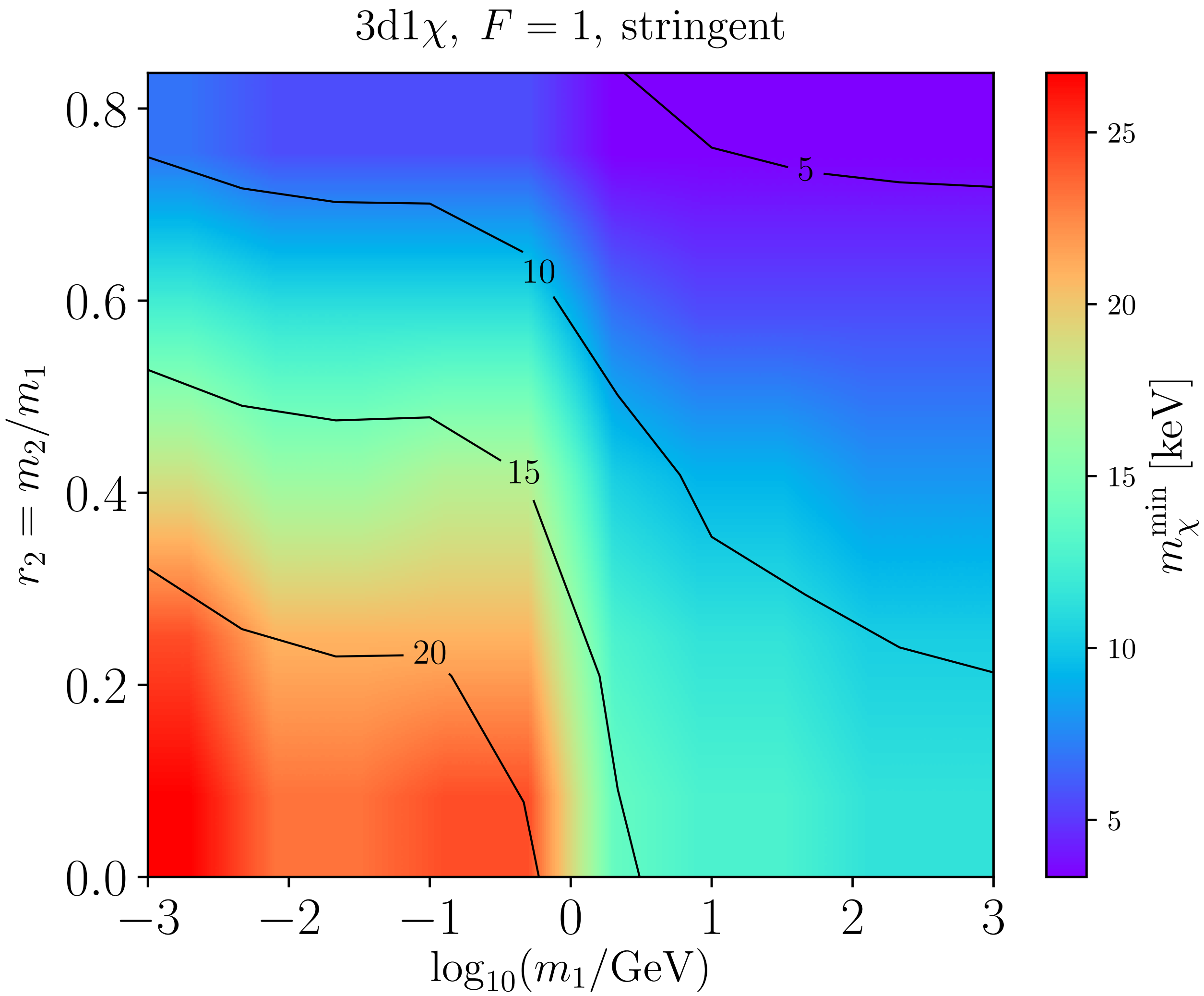
FIMP DM mass bounds: (m_1, r_2) plane.

$$\left(m_1 = M, m_\chi, F = \frac{\Omega_\chi}{\Omega_{\rm DM}}, r_2 = \frac{m_2}{m_1}\right)$$

$m_{\rm WDM} = 3.5$ keV



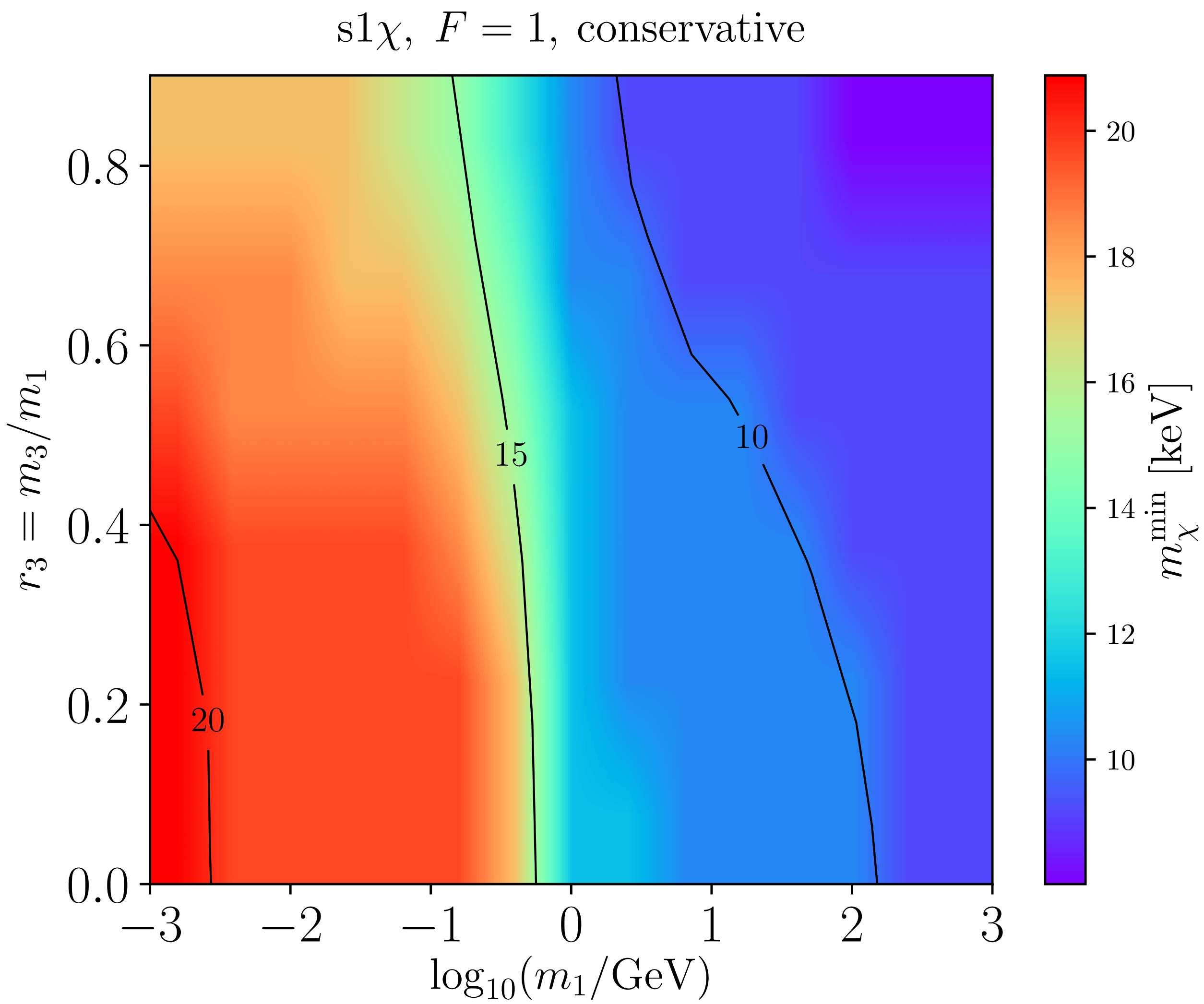
$m_{\rm WDM} = 5.3$ keV



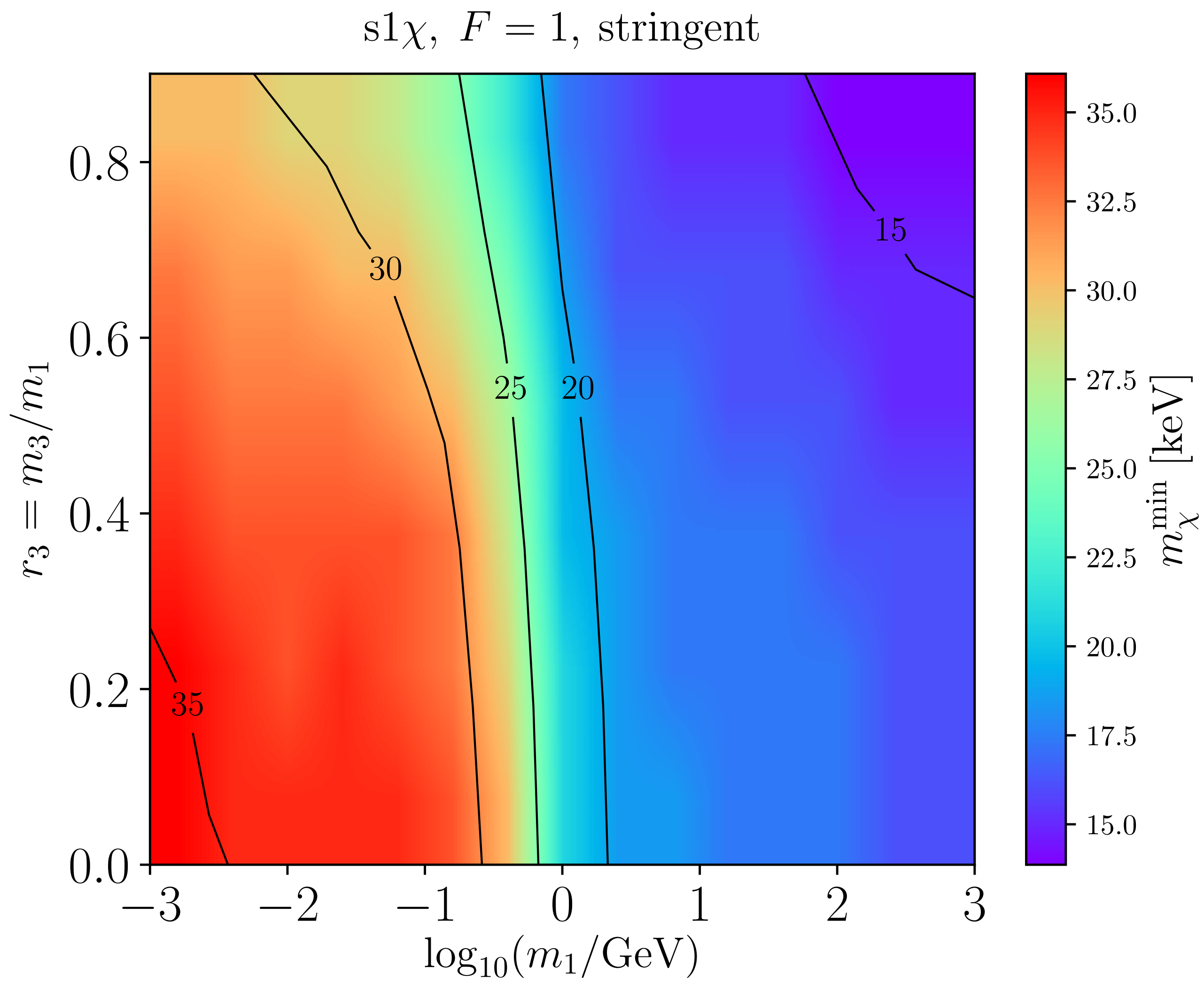
FIMP DM mass bounds: (m_1, r_2) plane.

$$\left(m_1 = M, m_\chi, F = \frac{\Omega_\chi}{\Omega_{\rm DM}}, r_2 = \frac{m_2}{m_1}\right)$$

$m_{\rm WDM} = 3.5$ keV



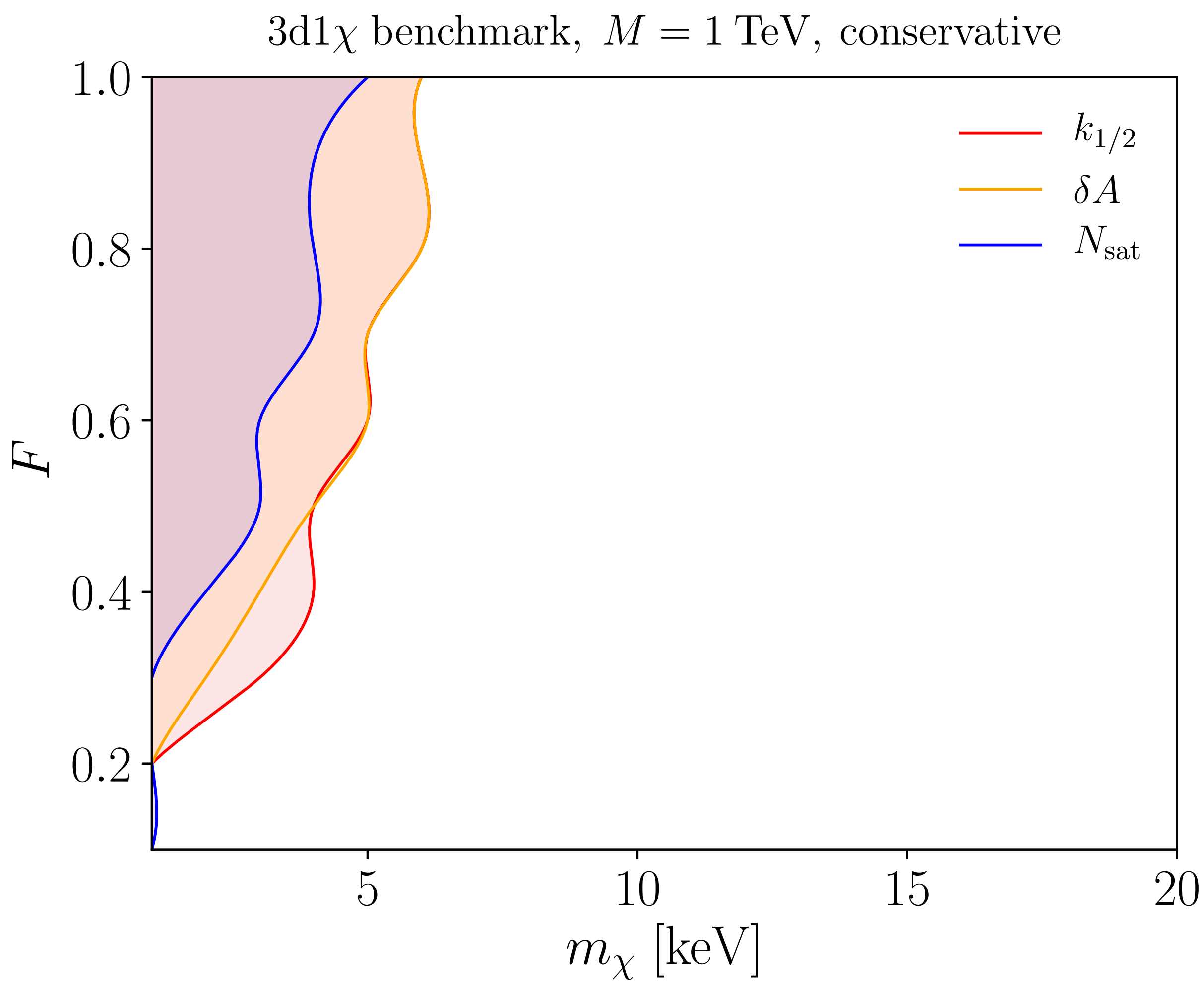
$m_{\rm WDM} = 5.3$ keV



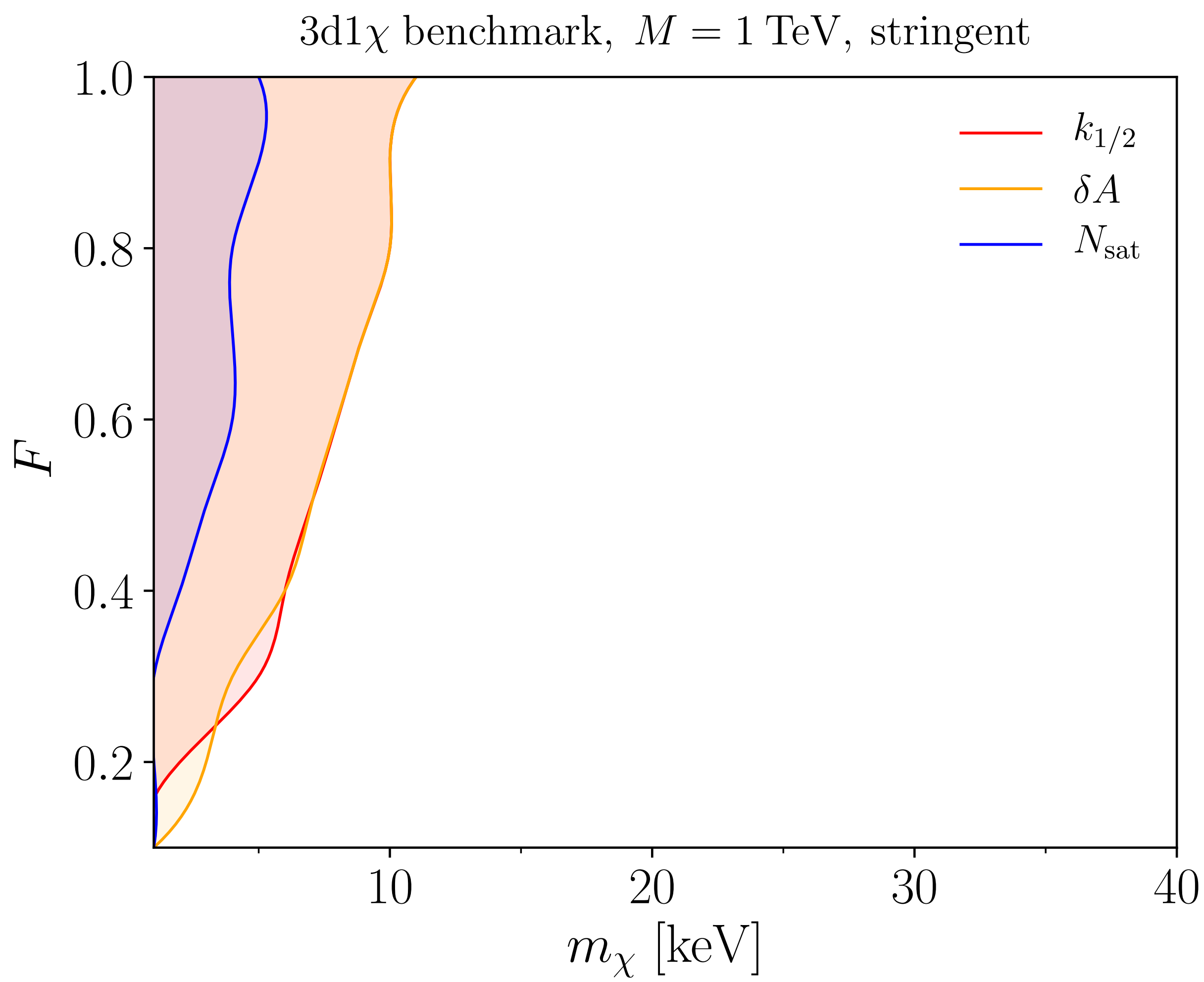
Subdominant FIMP DM bounds: (m_χ, F) plane.

$$\boxed{\left(m_1 = M, m_\chi, F = \frac{\Omega_\chi}{\Omega_{\rm DM}}, r_2 = \frac{m_2}{m_1}\right)}$$

$m_{\rm WDM} = 3.5$ keV



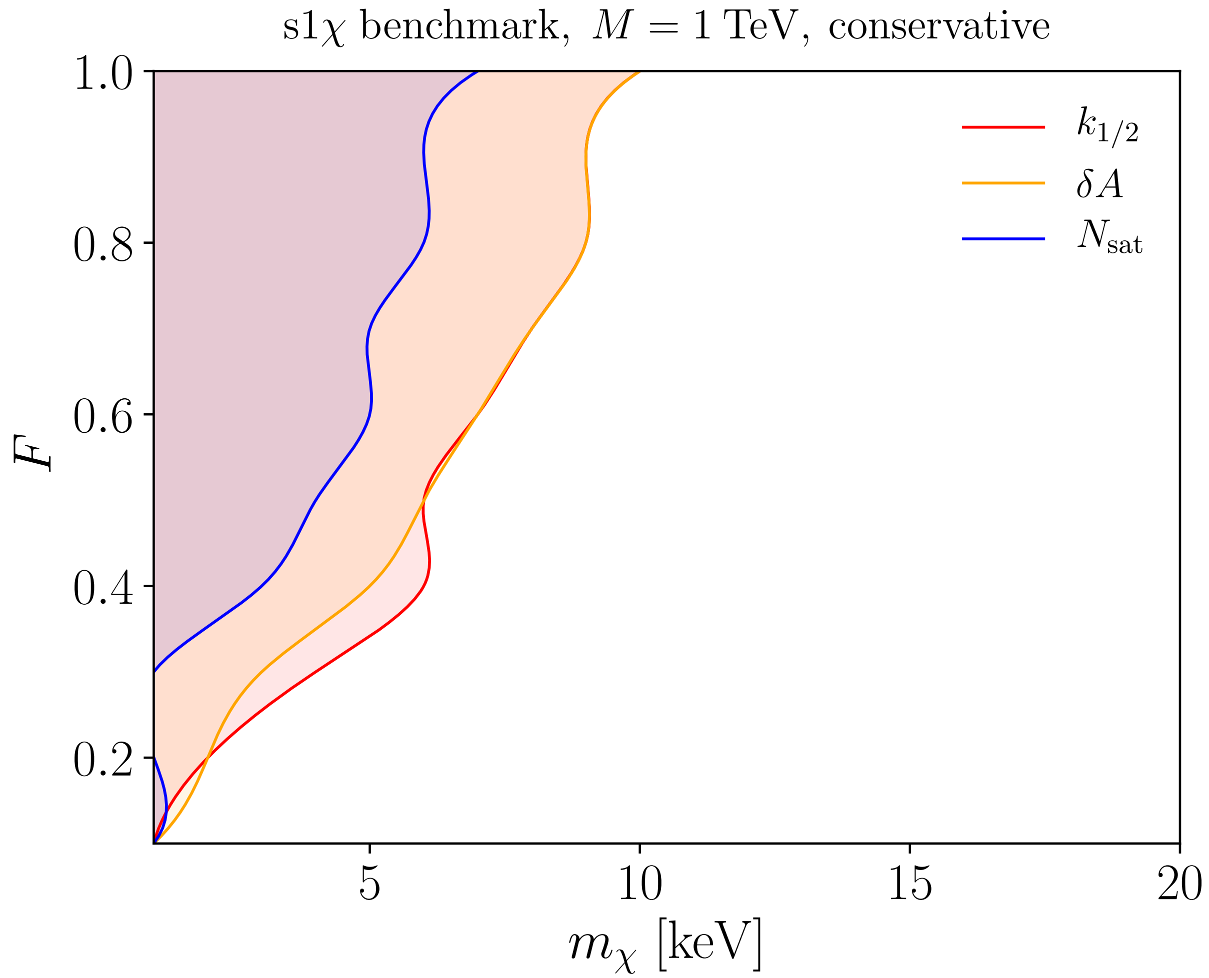
$m_{\rm WDM} = 5.3$ keV



Subdominant FIMP DM bounds: (m_χ, F) plane.

$$\boxed{\left(m_1 = M, m_\chi, F = \frac{\Omega_\chi}{\Omega_{\rm DM}}, r_2 = \frac{m_2}{m_1}\right)}$$

$m_{\rm WDM} = 3.5$ keV



$m_{\rm WDM} = 5.3$ keV