3rd General Meeting of COST Action COSMIC WISPers (CA21106), Sofia, Bulgaria
09/09/2025

Dark Matter Freeze-in and Small-Scale Observables: Bounds and Viable Models

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Based on
F. D'Eramo, **AL**, A. Dekker (2506.13864)

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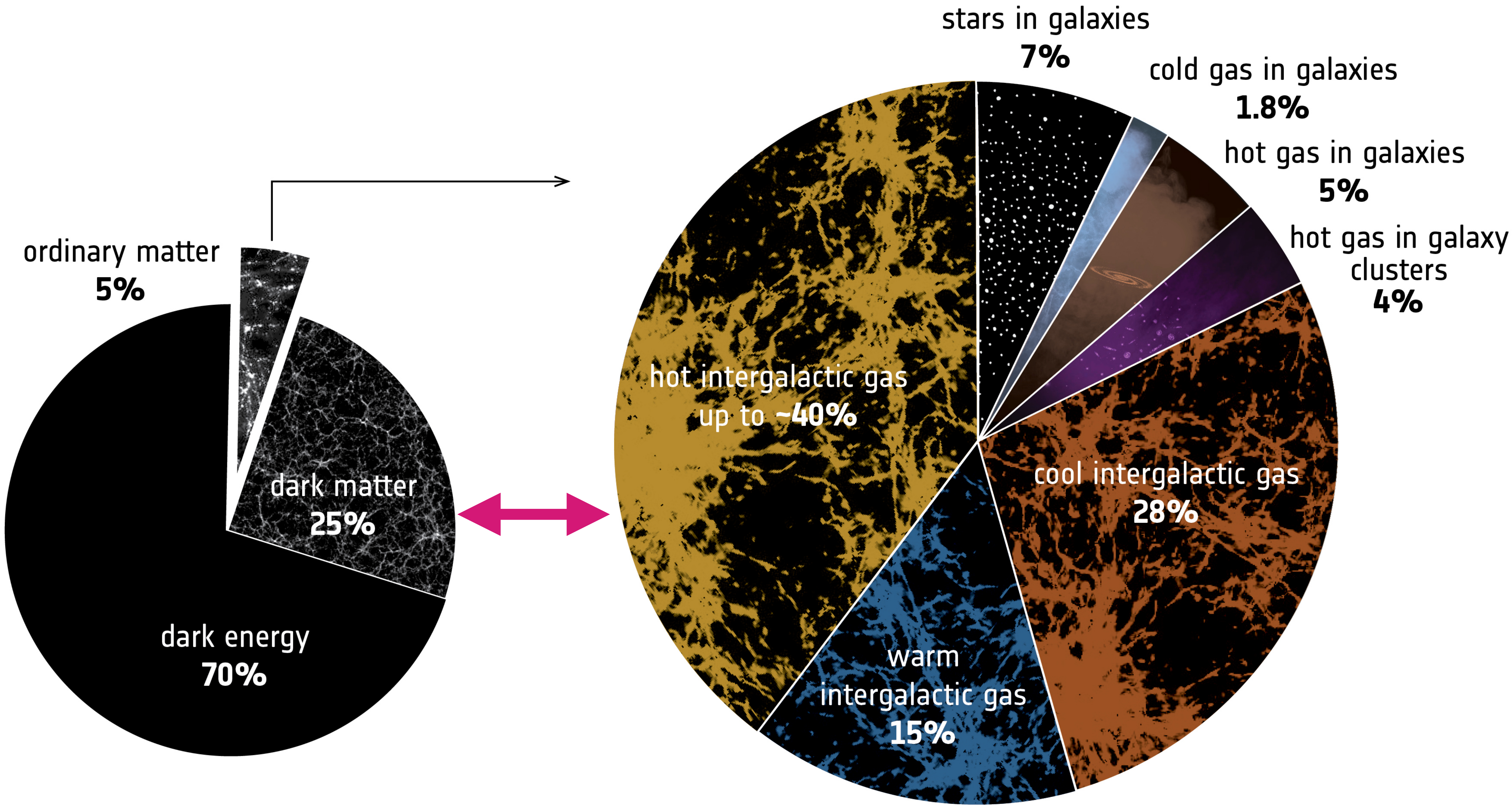
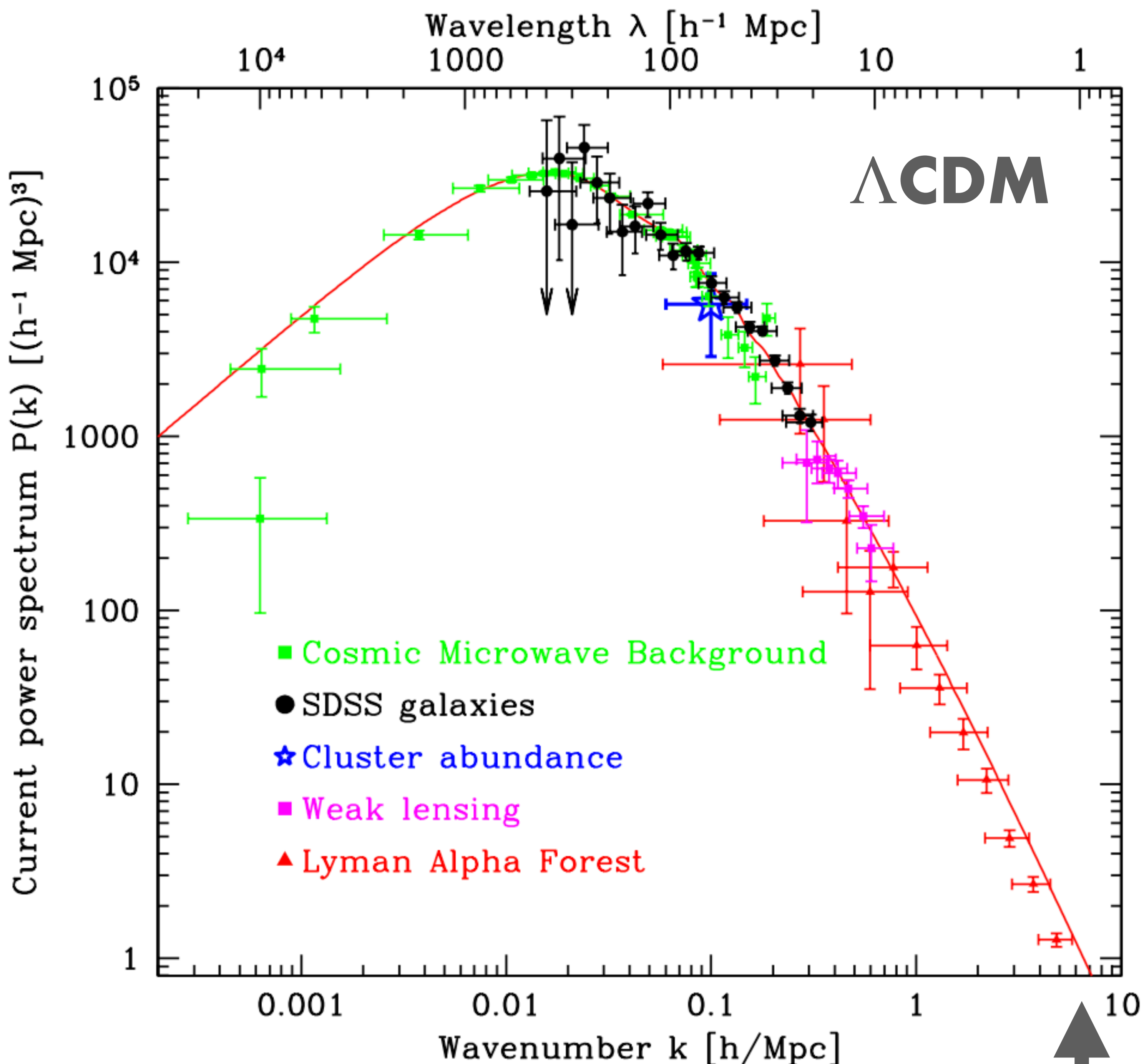
Dark and Visible Matter



[ESA 2018]

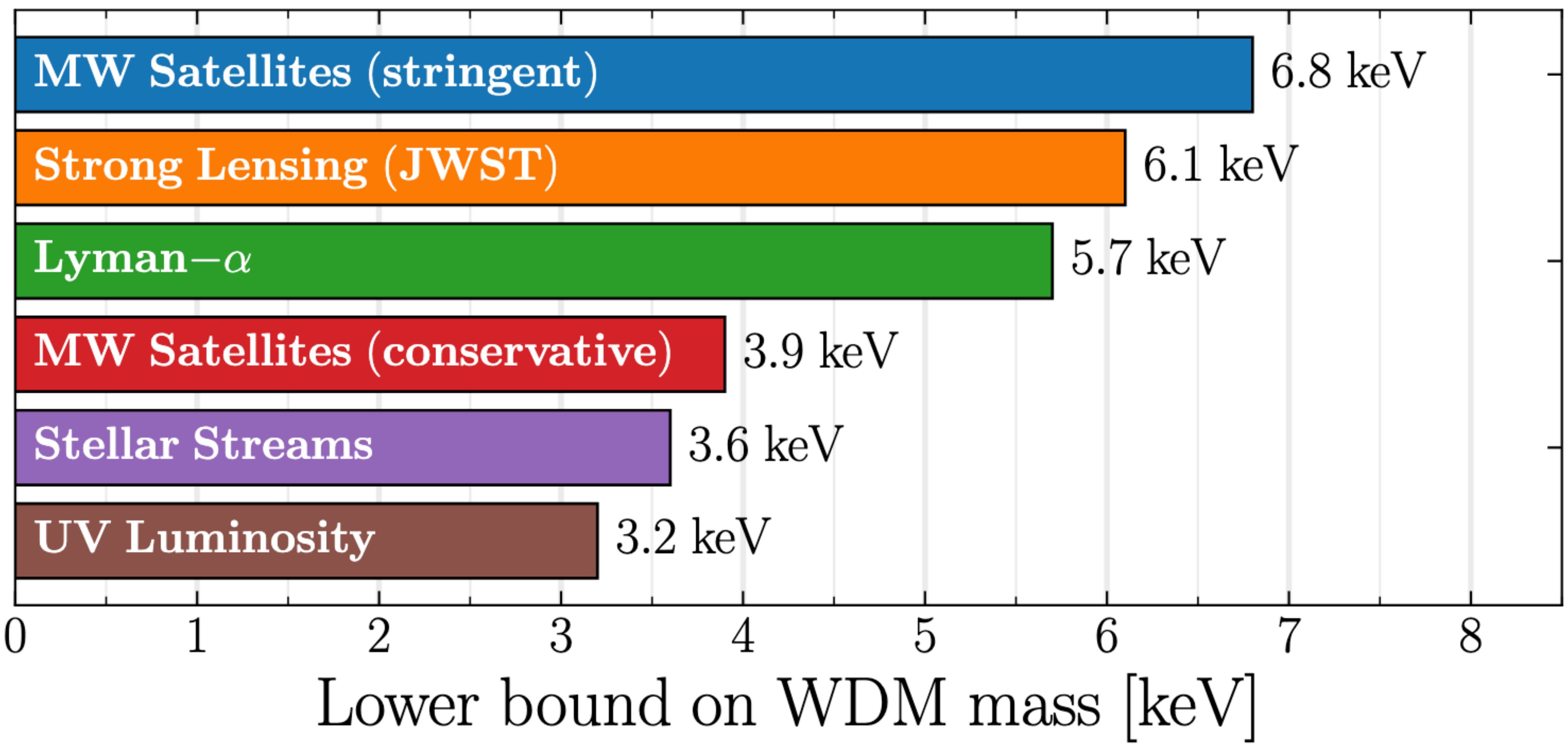
Dark Matter Power Spectrum



[SDSS Collaboration, APJ, 702 (2004), astro-ph/0310725]

Warmness cutoff?

WDM constraints from observations

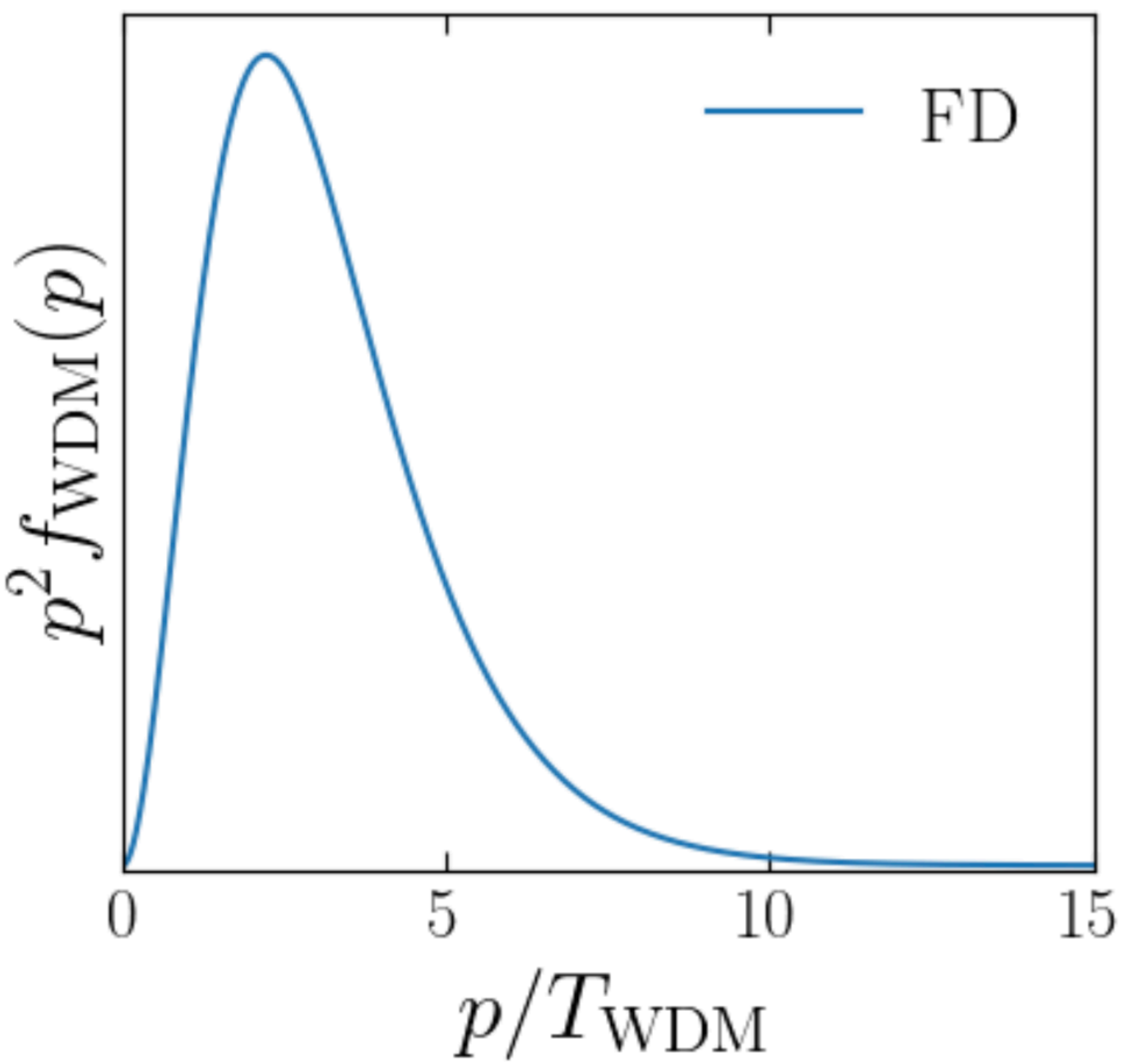


[R. E. Keeley+, MRAS 535, 1652 (2024), 2405.01620]
[V. Irsic+, PRD 109, 043511 (2024), 2309.04533]

[N. Banik+, MNRAS, 502, 2364 (2021), 1911.02662]
[B. Liu+, APJ 968, 79 (2024), 2404.13596]

Warm Dark Matter

The PSD is assumed to be thermal, e.g. with FD statistics $\sim \nu$



$$f_{\rm WDM} \propto \frac{1}{\exp(p/T_{\rm WDM}) + 1}$$

$T_{\rm WDM}$ **set by the DM relic density**

$$\rho_{\rm WDM} \propto m_{\rm WDM} T^3_{\rm WDM}$$

RMS velocity

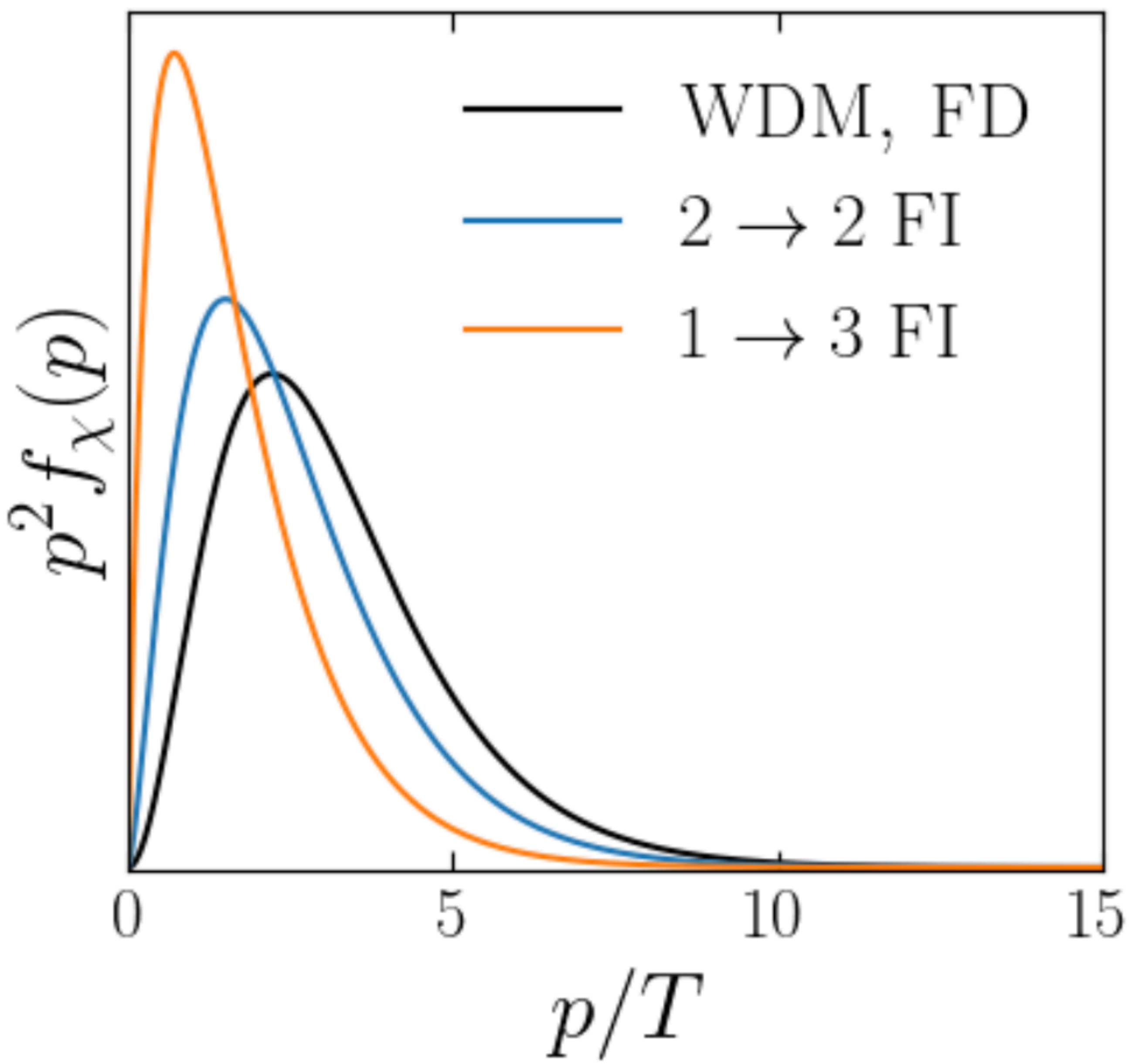
$$W_\chi = \frac{1}{m_{\rm WDM}} \sqrt{\langle p^2 \rangle} = \sigma_{\rm WDM} \frac{T_{\rm WDM}}{m_{\rm WDM}}$$

$\sigma_{\rm WDM} \simeq 3.6$

$m_{\rm WDM}$ **only parameter**

Quasi-thermal DM

Physical properties approximated by the very first few moments of the PSD



$$n = \int \frac{d^3p}{(2\pi)^3} \, f_\chi(p)$$

$$\langle p \rangle = \int \frac{d^3p}{(2\pi)^3} \, p \, f_\chi(p)$$

$$\sqrt{\langle p^2 \rangle} = \sqrt{\int \frac{d^3p}{(2\pi)^3} \, p^2 \, f_\chi(p)}$$

Rms velocity

$$W_\chi = \frac{1}{m_\chi} \sqrt{\langle p^2 \rangle}$$

The general strategy

DM production mechanism

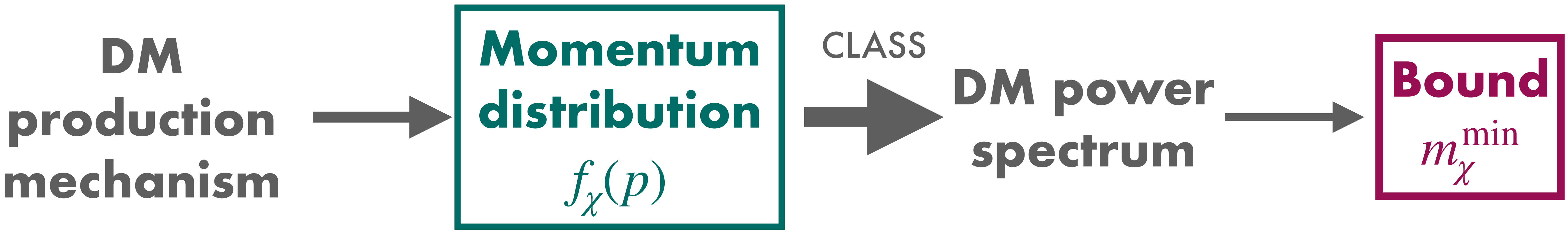
WDM power spectrum → **Bound** $m_{\rm WDM}^{\rm min}$

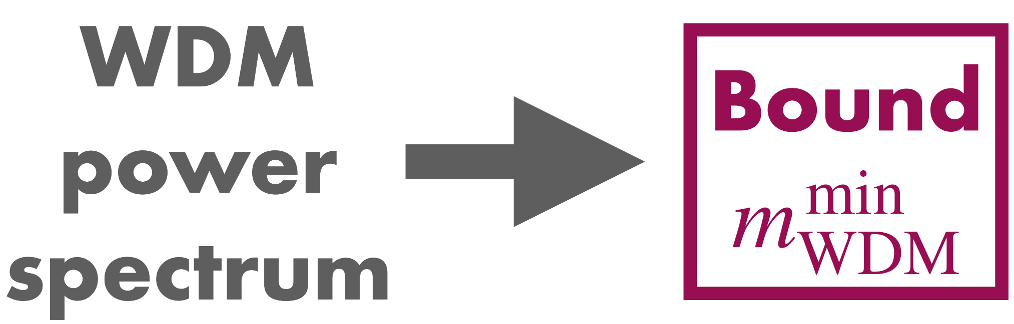
The general strategy

DM production mechanism → **Momentum distribution** $f_\chi(p)$

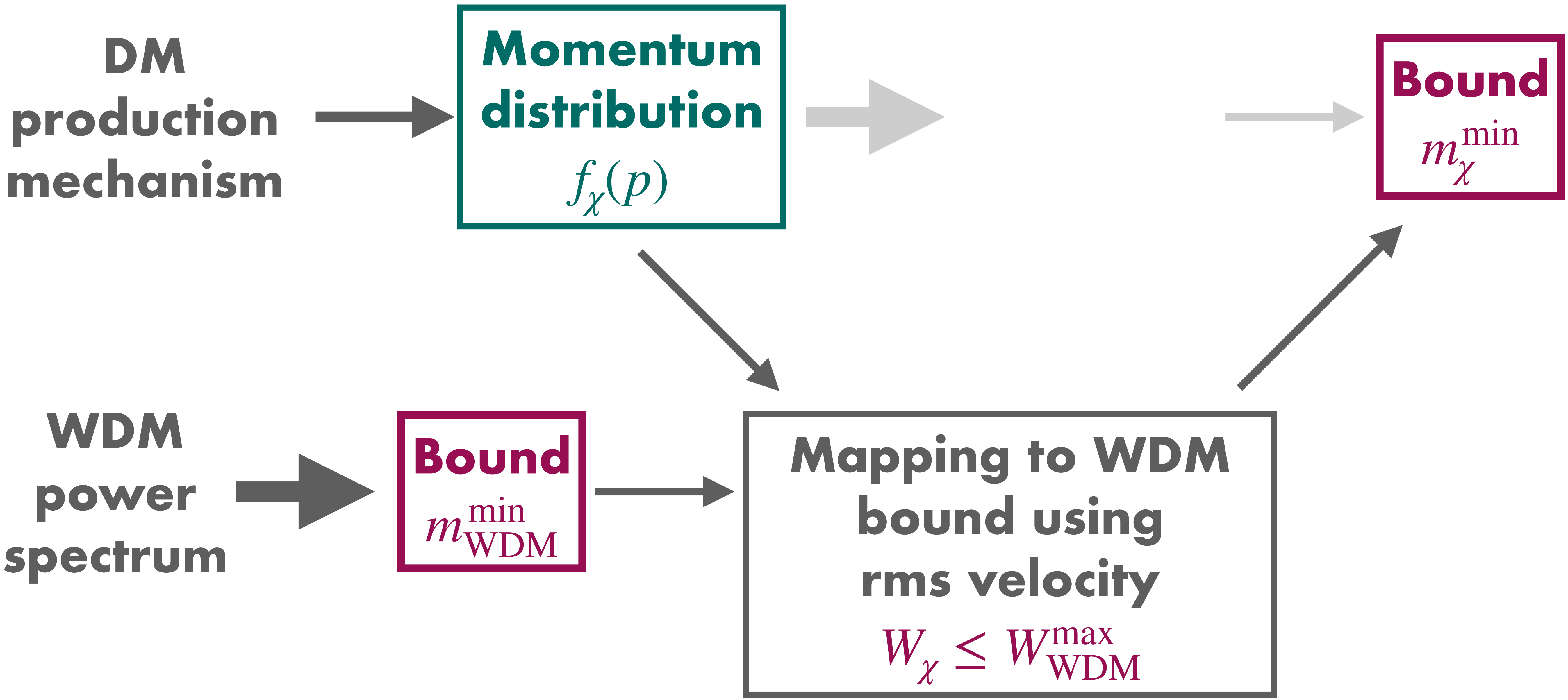
WDM power spectrum → **Bound** $m_{\rm WDM}^{\rm min}$

The general strategy





The general strategy



[F. D'Eramo, **AL** JCAP 10 (2021) 045, 2012.01446]

The map to WDM

$p \propto a^{-1}$

After production, PSD is "frozen" and the DM free-streams

$$q = \frac{p}{T_P} \frac{a}{a(t_P)}$$

comoving momentum

The mapping requires

$$W_\chi \leq W_{\rm WDM}(m_{\rm WDM}^{\rm min})$$

$$m_\chi^{\rm min} = 22 \text{ keV} \left(\frac{m_{\rm WDM}^{\rm min}}{6 \text{ keV}}\right)^{4/3} \left(\frac{\sigma_q}{3.6}\right) \left(\frac{106.75}{g_{\star s}(T_P)}\right)^{1/3}$$

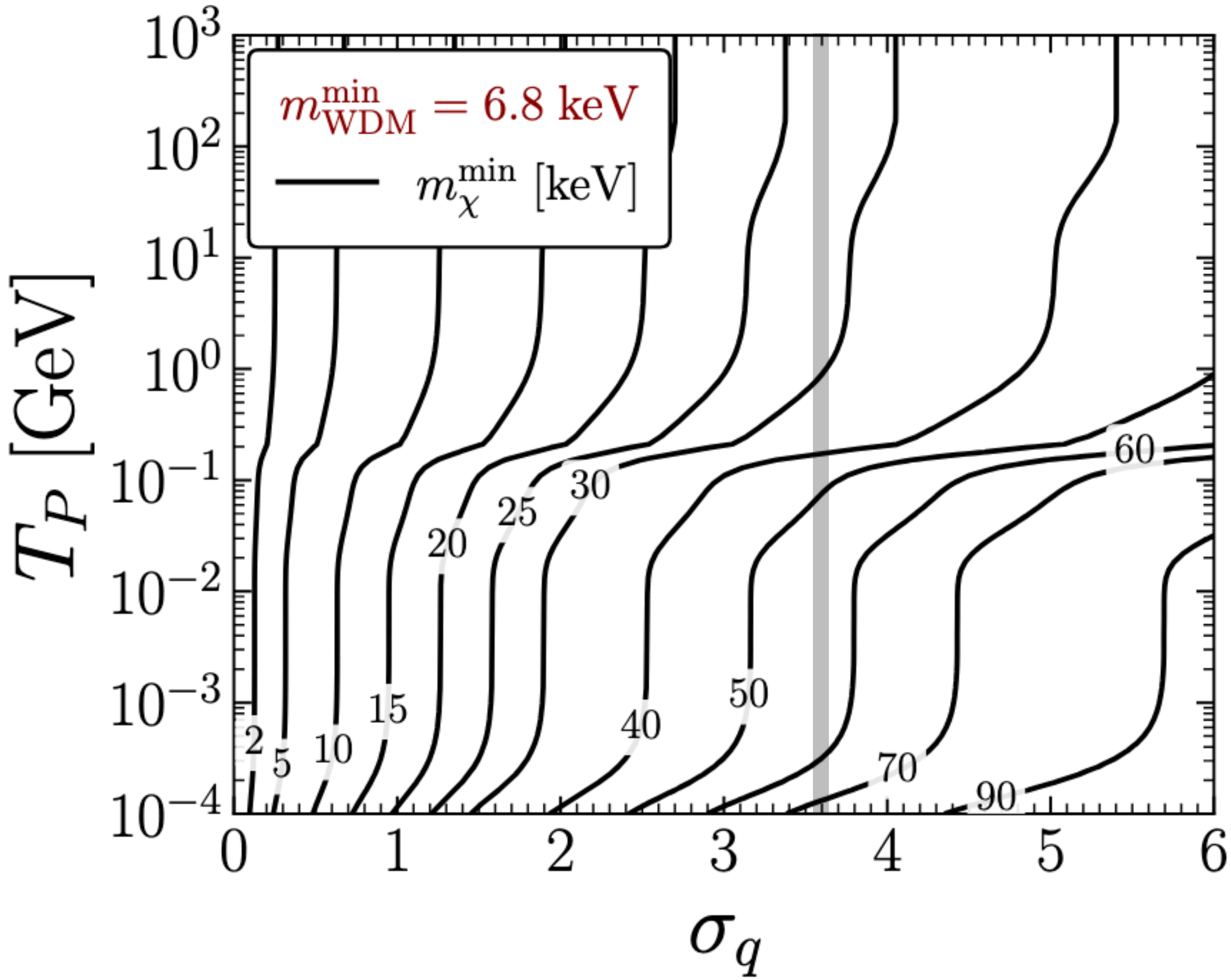
Reference WDM bound from observables

$$\sigma_q^2 = \frac{\int dq\, q^4 f_\chi}{\int dq\, q^2 f_\chi}$$

Reference temperature, determines definition of σ_q

Mass bounds on quasi-thermal DM

Reference temperature, can be associated to the production energy scale



PSD width, depends on the production mechanism (PSD shape)

Quasi-thermal DM via freeze-in

$$\frac{df_\chi}{dt} = \frac{C(p,t)}{E}$$

Quasi-thermal DM via freeze-in

$$\frac{df_\chi}{dt} = \frac{C(p,t)}{E}$$

Two-body decays $\sigma_q \simeq 2.96\sqrt{1-(m_2/m_1)^2}$

$$C_{1\to 2\chi} = \frac{\ell}{2}\int d\Pi_1 d\Pi_2 (2\pi)^4 \delta^{(4)}(P_1 - P_2 - P)\,|\mathcal{M}|^2 f_1^{\rm eq}\,.$$

$$f_\chi \propto \frac{1}{\sqrt{q}} e^{-q(1-m_2^2/m_1^2)^{-1}}$$

Binary scatterings $\sigma_q \simeq 2.96$

$$C_{12\to 3\chi} = \frac{\ell}{2}\int \prod_{i=1}^{3} d\Pi_i (2\pi)^4 \delta^{(4)}(P_{\rm i} - P_{\rm f})\,|\mathcal{M}|^2 f_1^{\rm eq} f_2^{\rm eq}\,.$$

$$f_\chi \propto \frac{1}{\sqrt{q}} e^{-q}$$

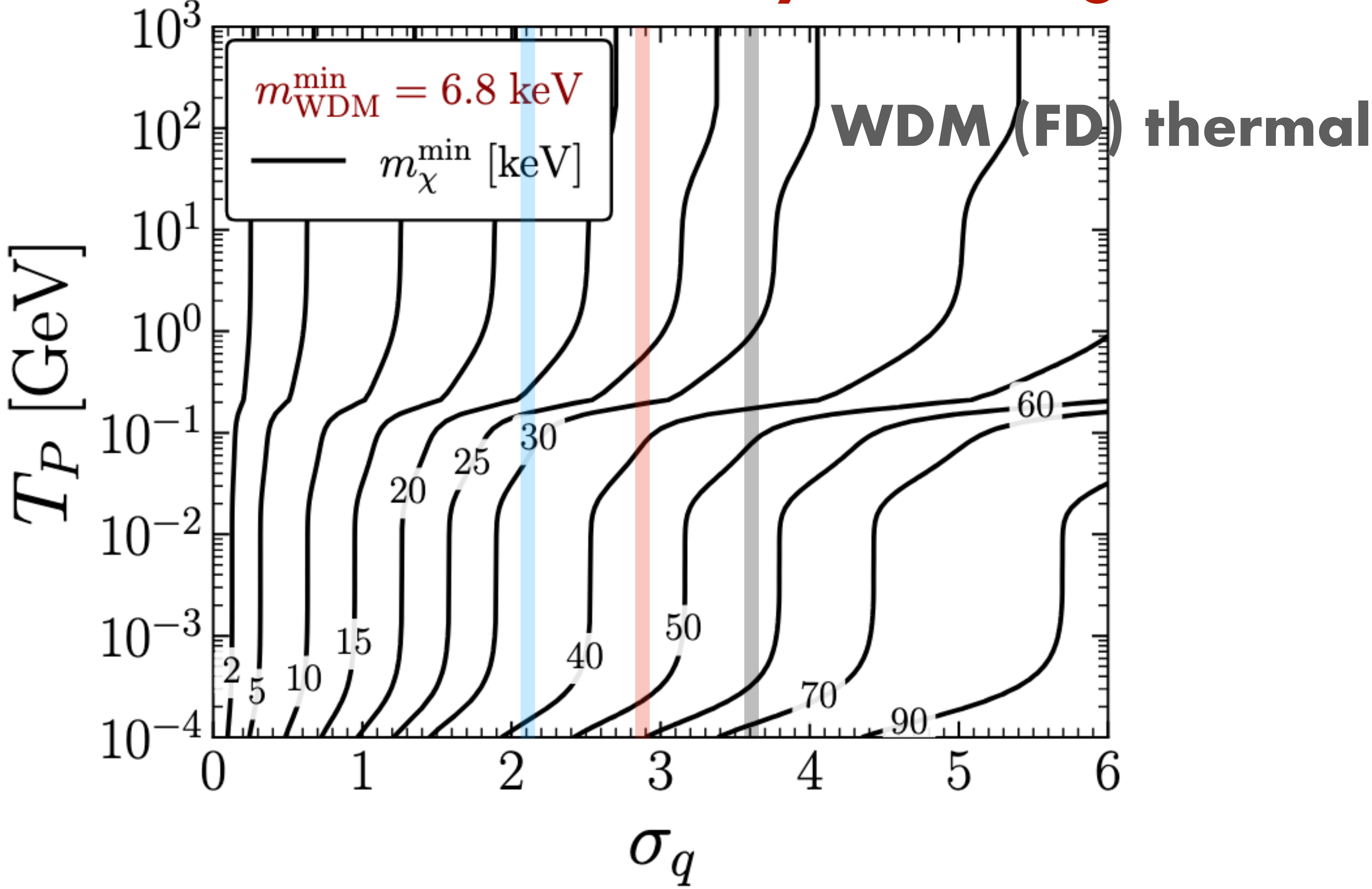
Three-body decays $\sigma_q \simeq 2.09\sqrt{1-(m_2/m_1)^2}$

$$C_{1\to 23\chi} = \frac{\ell}{2}\int \prod_{i=1}^{3} d\Pi_i (2\pi)^4 \delta^{(4)}(P_{\rm i} - P_{\rm f})\,|\mathcal{M}|^2 f_1^{\rm eq}\,.$$

$$f_\chi \propto \frac{1}{q}\,\mathrm{erfc}\left(\sqrt{\frac{q}{1-m_2^2/m_1^2}}\right)$$

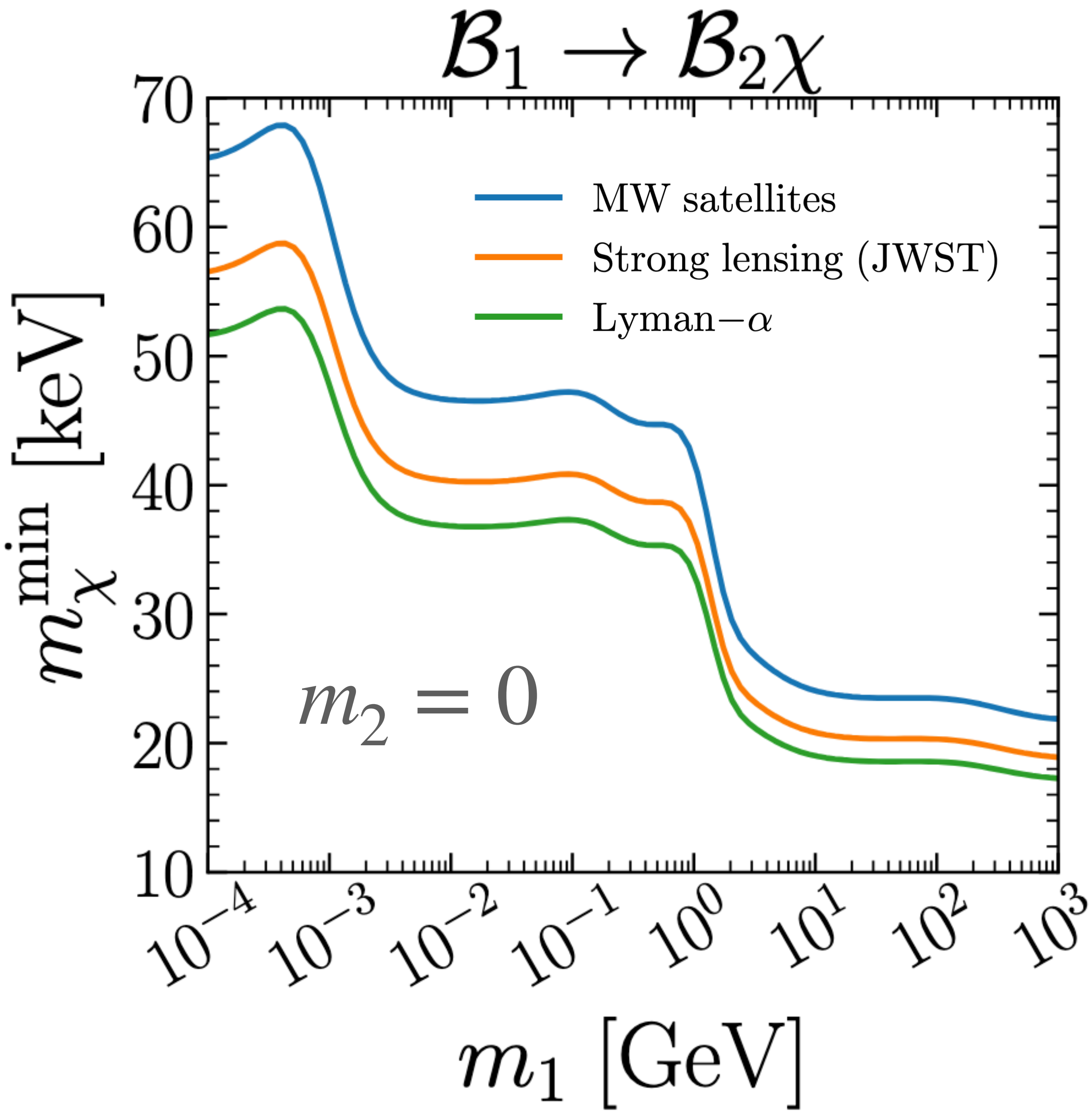
Two-body decays $m_2 = 0$
Binary scatterings

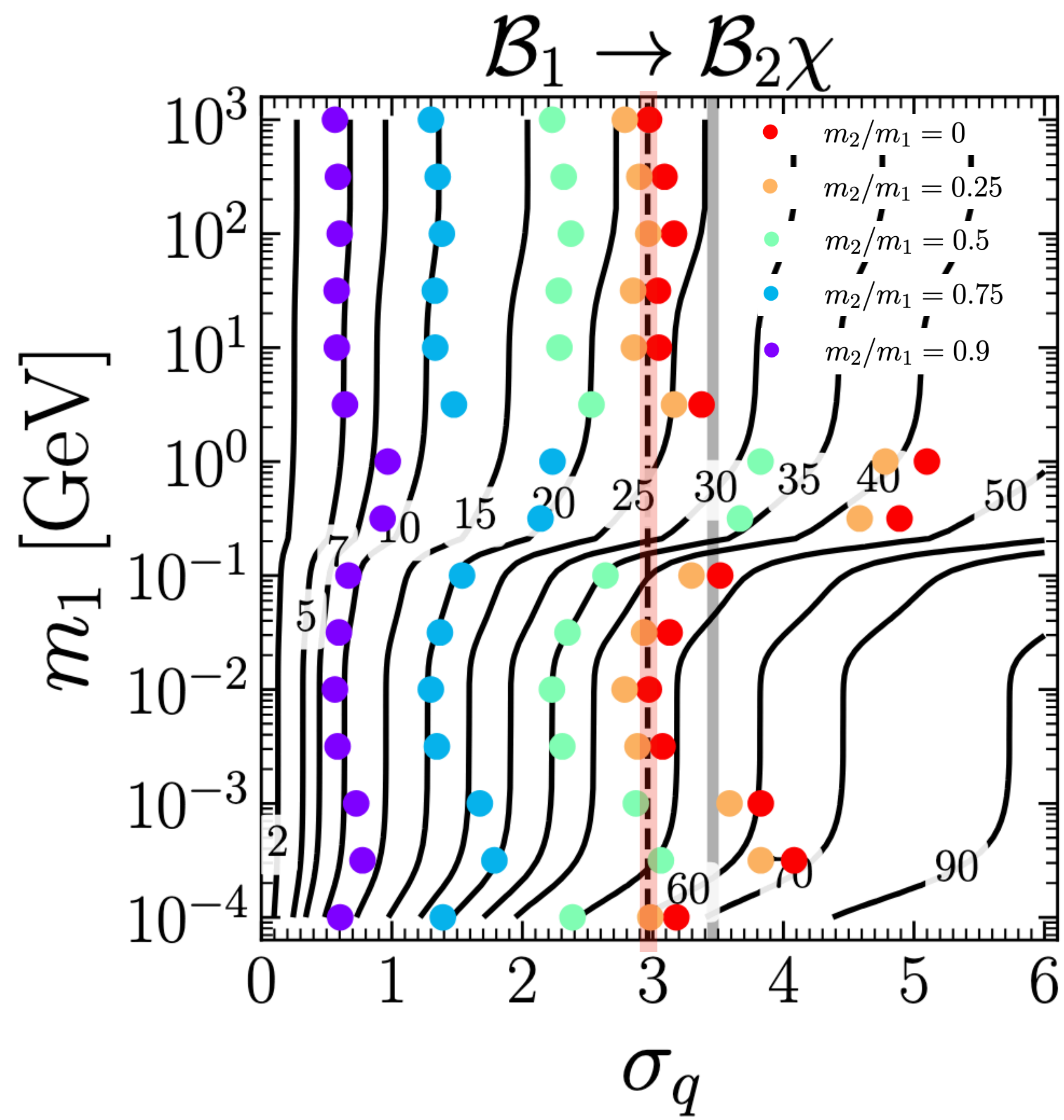
$m_1 = T_P$



Three-body decays $m_2 = m_3 = 0$

Freeze-in general bounds, decays

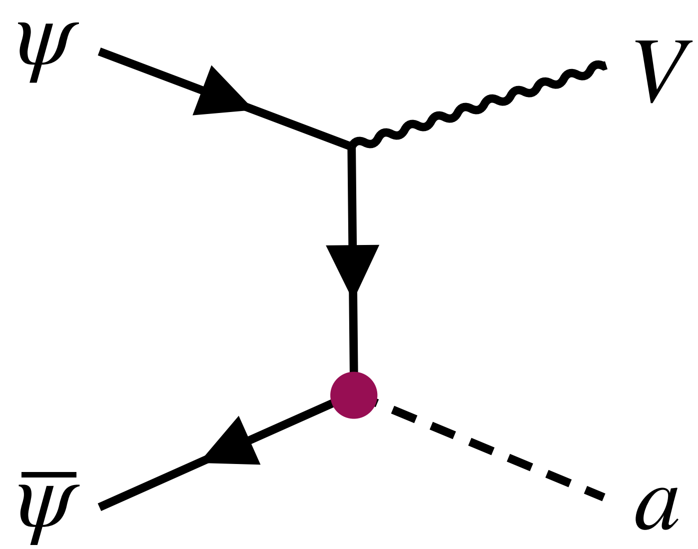


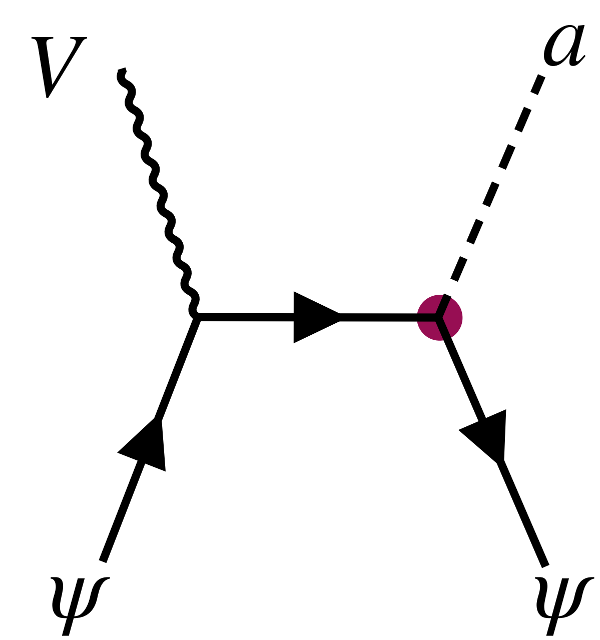


Axions coupled to SM fermions

$$\mathcal{L}_a = -\frac{\partial_\mu a}{2\Lambda_\psi} \sum_\psi c_\psi \overline{\psi} \gamma^\mu \gamma^5 \psi$$

ψ **is a lepton or a quark**
V **is a photon or gluon**





IR-dominated freeze-in via binary scatterings

We work in the limit $m_a \ll m_\psi$ and $T < v_{\rm EW}$

Lower mass bounds on quasi-thermal axion

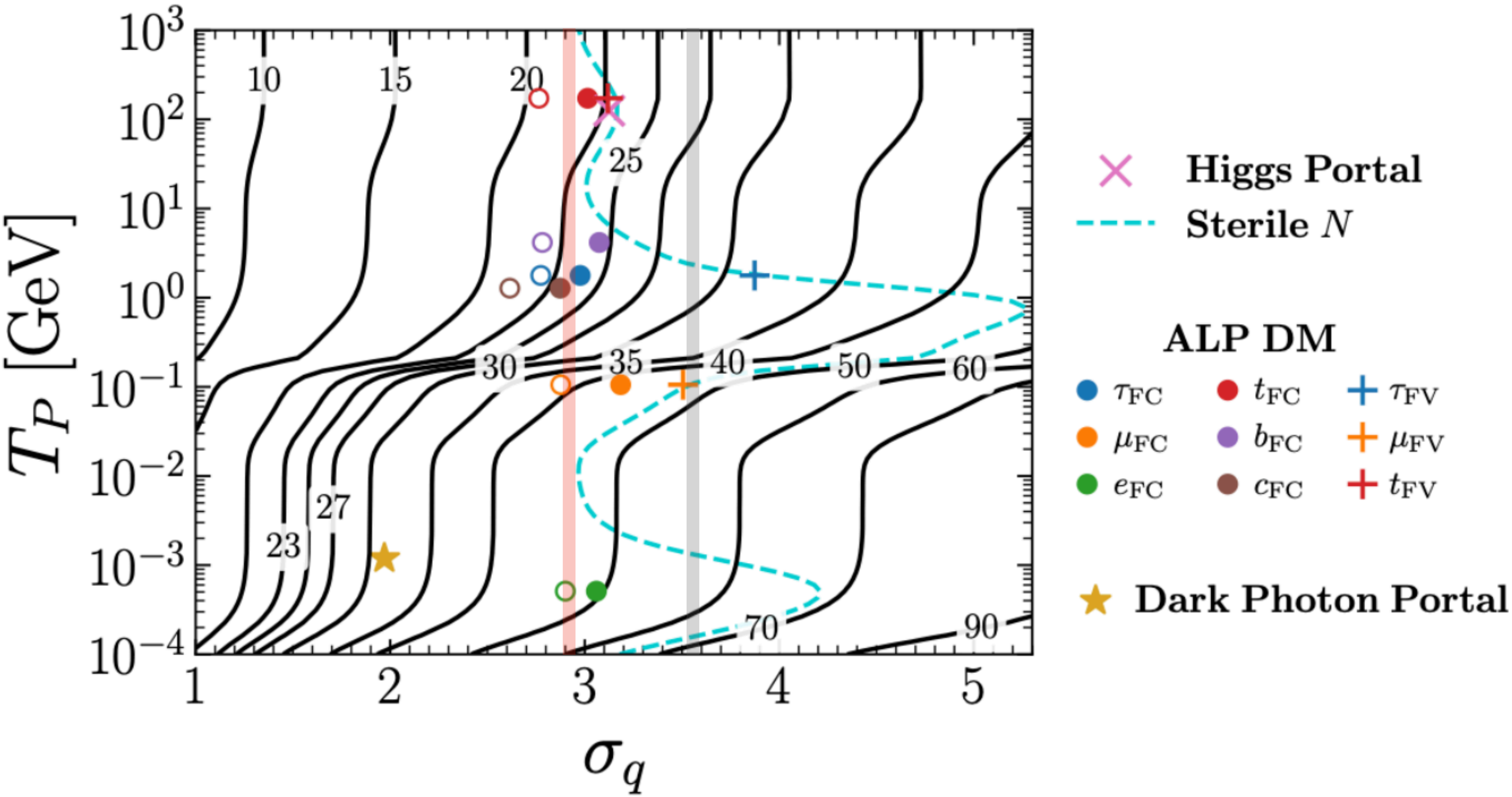
	$m_a^{\min}$(keV)			Relic density requirement and X-ray constraints			
ψ	Lyα	JWST	Satellite	$\Lambda_\psi^{\rm relic}$(GeV)	$-\Delta g_{a\gamma\gamma}$ (GeV^{-1})	$\tau_{a\to\gamma\gamma}$(sec)	Allowed?
electron	39	43	49	5.7×10^7	3.1×10^{-14}	1.2×10^{18}	✗
muon	33	37	43	3.6×10^8	5.6×10^{-20}	1.1×10^{30}	✓
tau	19	21	24	4.9×10^8	7.3×10^{-23}	1.8×10^{36}	✓
charm	19	20	23	4.5×10^9	1.8×10^{-23}	3.1×10^{37}	✓
bottom	19	21	24	7.3×10^9	3.2×10^{-25}	8.3×10^{40}	✓
top	18	19	22	2.8×10^{10}	1.5×10^{-28}	5.5×10^{47}	✓

Minimum ALP mass

Symmetry breaking scale (coupling) fixed by relic density

1-loop induced coupling to photons and ALP lifetime

Summary



10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
T_P [GeV]
1
2
3
4
5
σ_q
10
15
20
25
23
27
30
35
40
50
60
70
90
Higgs Portal
Sterile N
ALP DM
$\tau_{\rm FC}$
$t_{\rm FC}$
$\tau_{\rm FV}$
$\mu_{\rm FC}$
$b_{\rm FC}$
$\mu_{\rm FV}$
$e_{\rm FC}$
$c_{\rm FC}$
$t_{\rm FV}$
Dark Photon Portal

...and outlook

**Much to do, different cosmologies,
mixed CDM+WDM scenarios, different models,
all in phase space!**

Thank you!

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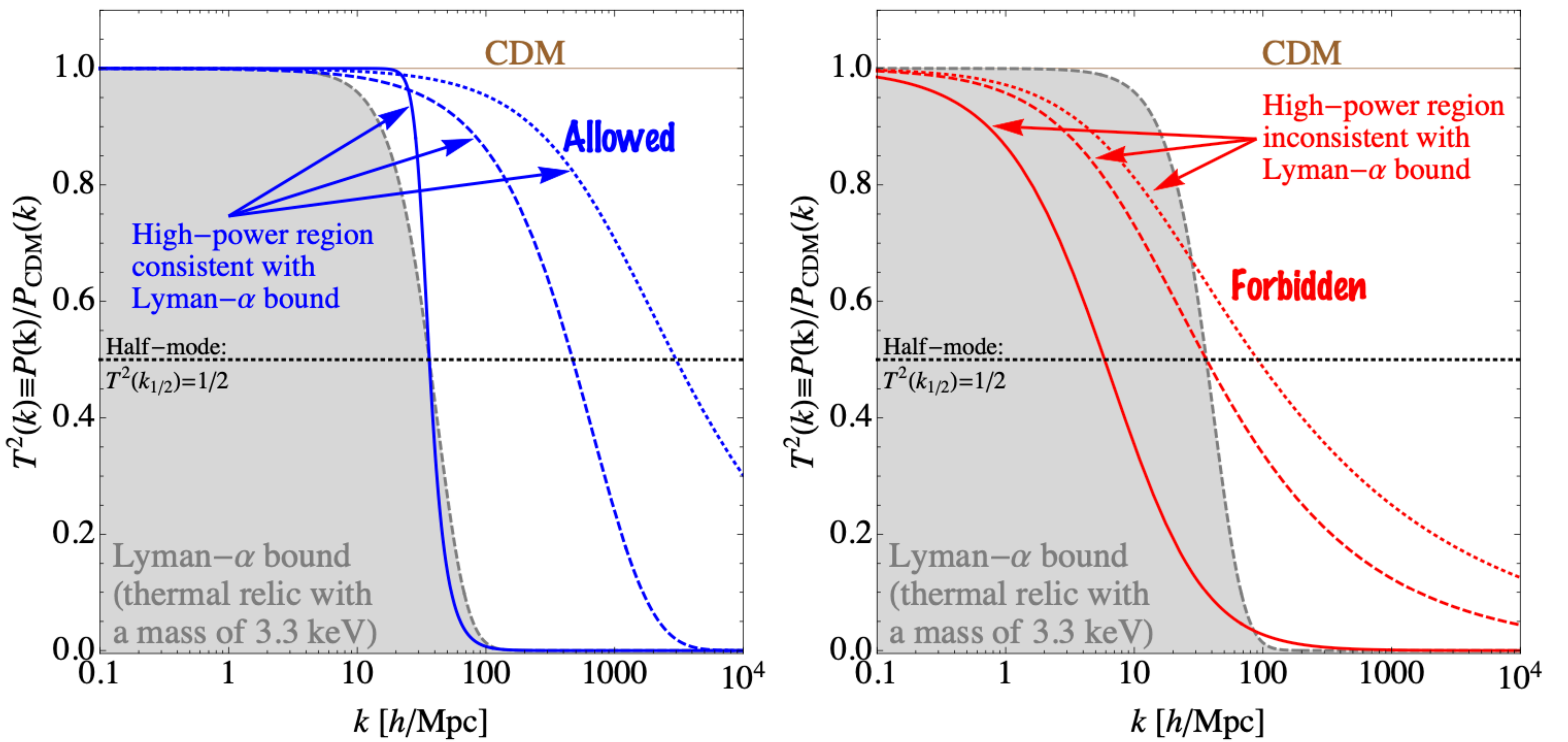
WDM power spectrum

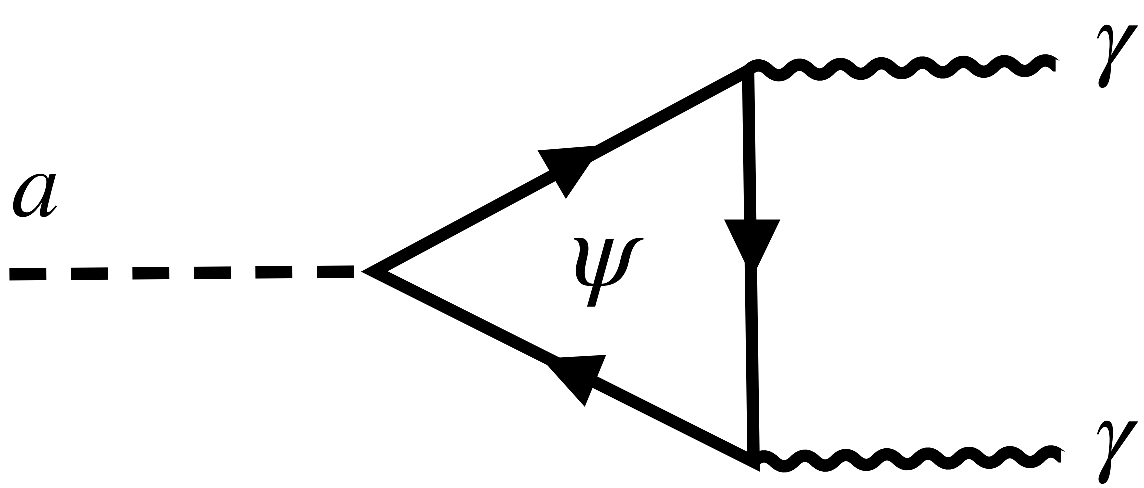


WDM power spectrum → **Bound** $m_{\rm WDM}^{\rm min}$

Constraints on keV axions

A coupling to photons is induced via a fermion loop

[Bauer et al 1708.00443]
[Bauer et al 2012.12272]



$$\Delta g_{a\gamma\gamma} \approx -\frac{\alpha_{\rm em} N^c_\psi Q^2_\psi}{12\pi f_a}\left(\frac{m_a}{m_\psi}\right)^2$$

X-ray, NuStar, INTEGRAL, constrain

[Calore et al 2209.06299]
[eg. Roach et al 2207.04572]

$$g_{a\gamma\gamma} < 10^{-19}\ \mathrm{GeV}^{-1}$$

for axions in the 10 keV - 100 keV range.
We check for $(m_a^{\rm min}, f_a^{\rm relic})$ if the bound is respected or not

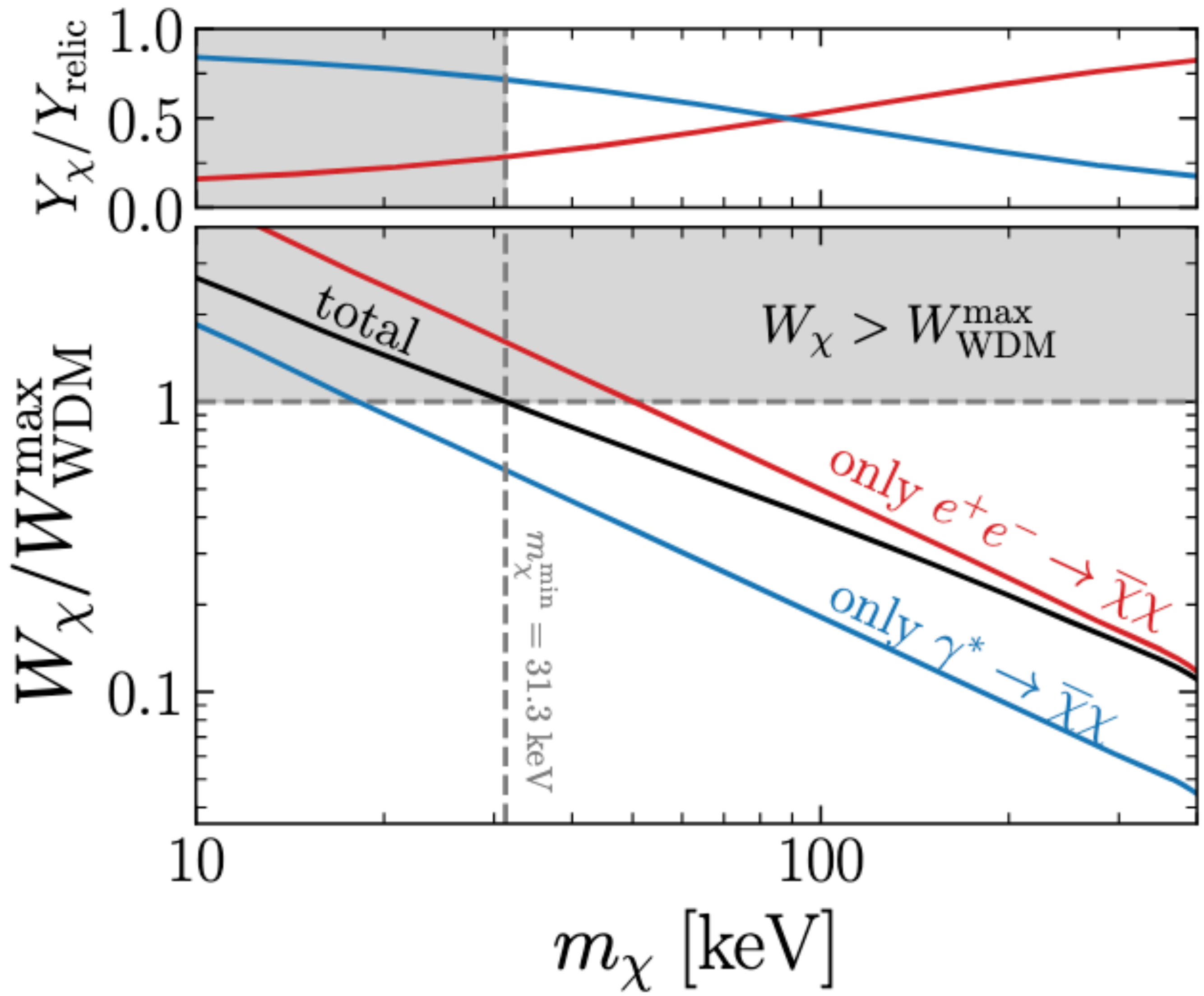
Dark photon portal DM

$$\mathscr{L}_{\rm DP} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\kappa}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$
$$+ eJ^\mu_{\rm EM}A_\mu + \bar{\chi}\gamma^\mu(i\partial_\mu + e_D A'_\mu)\chi\,.$$

Two processes:

1) Pair annihilation

2) Plasmon decays



Dark photon portal DM

$$\mathscr{L}_{\rm DP} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\kappa}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu$$
$$+eJ^\mu_{\rm EM}A_\mu + \bar{\chi}\gamma^\mu(i\partial_\mu + e_D A'_\mu)\chi\,.$$