WORKSHOP ON MULTI-HIGGS MODELS 2024

Dark matter dynamics with light scalars

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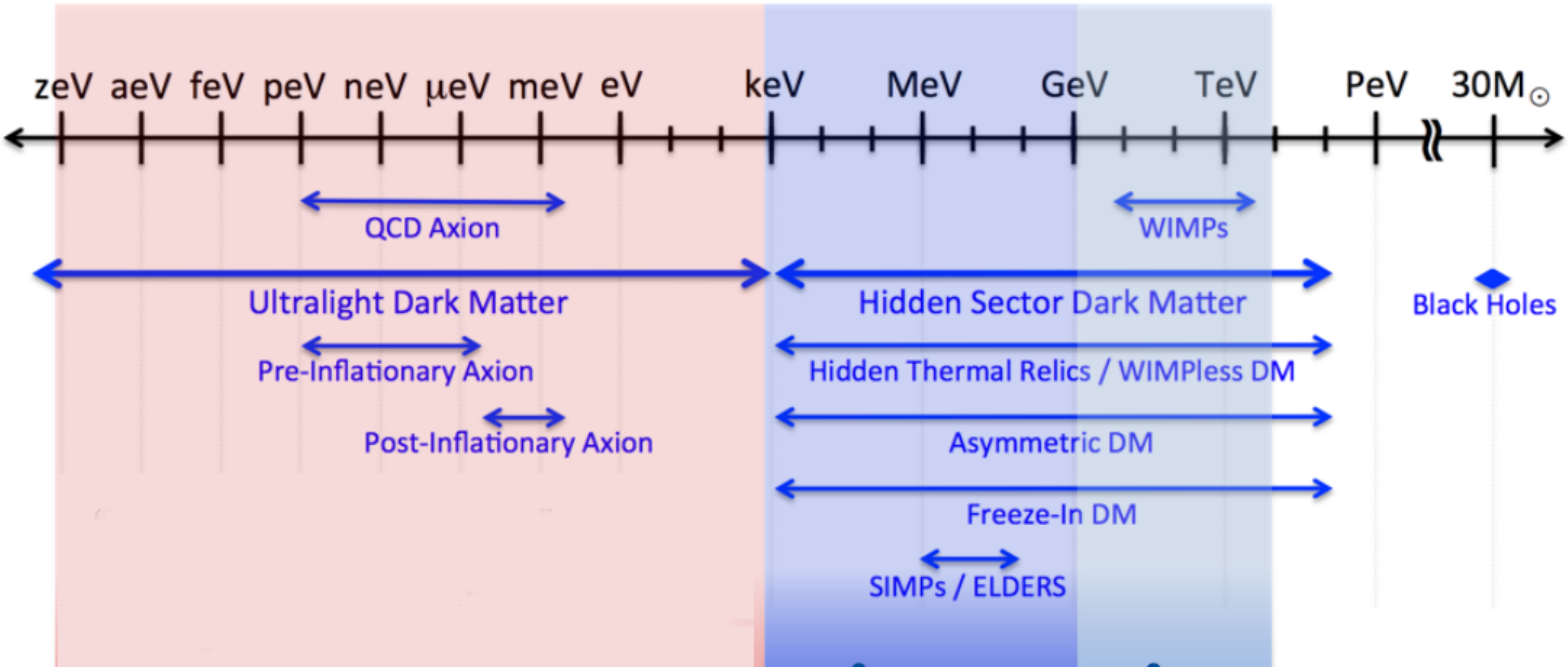
T. Binder, SC, S. Matsumoto and Y. Watanabe, JHEP 01 (2023) 106



zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS

WIMPs..

WIMP paradigm: $\sigma_{ann}(v/c) \approx 1$ pb $\Rightarrow \Omega_{DM} \approx 0.12$

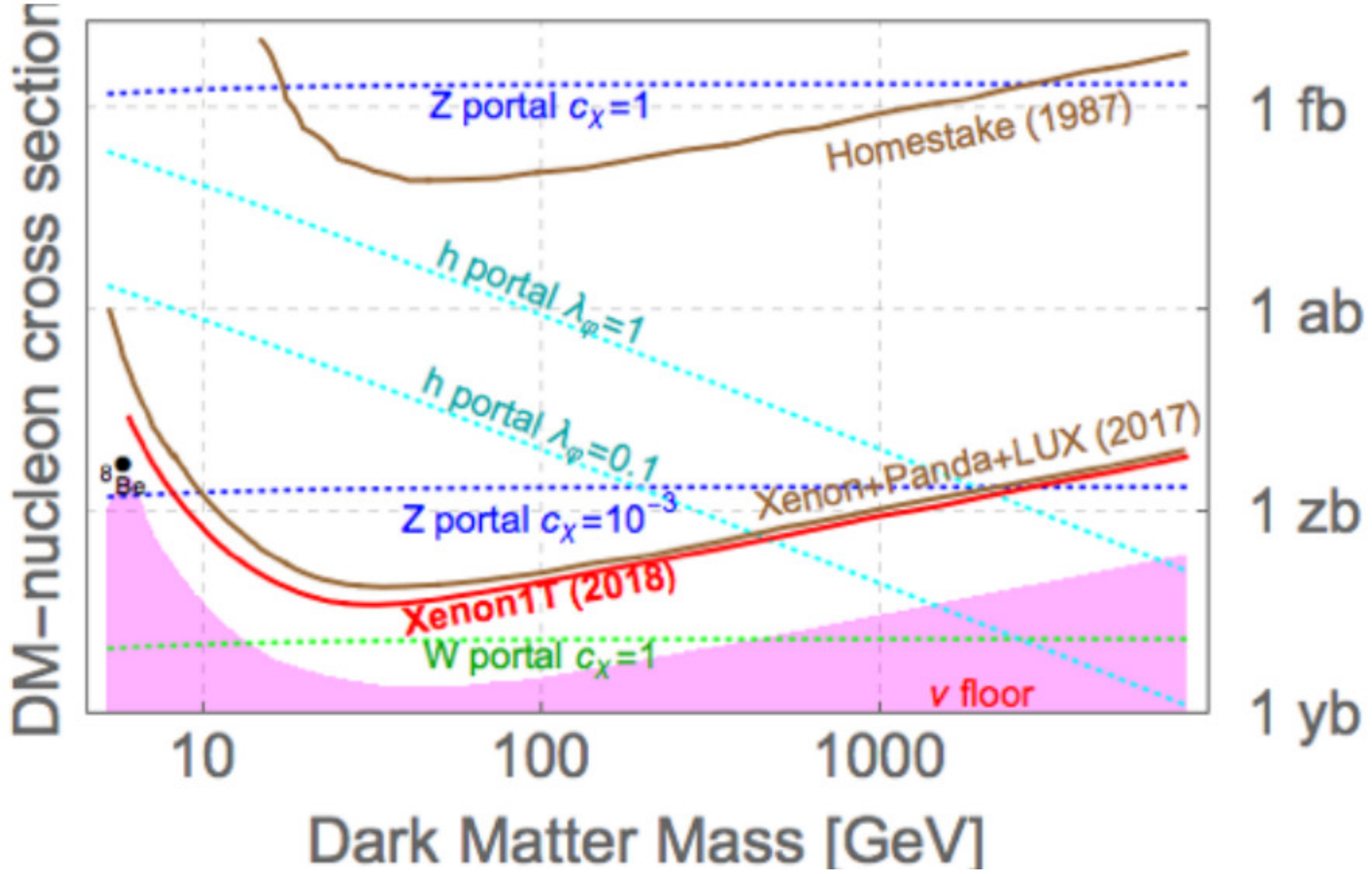
Electroweak mediators $\Rightarrow$ Lee – Weinberg window

$$\sigma(v/c) \propto \begin{cases} G_F^2\, m_{DM}^2 & \text{for } m_{DM} \ll m_W \\ 1/m_{DM}^2 & \text{for } m_{DM} \gg m_W \end{cases} \Rightarrow \text{few GeV} < m_{DM} < \text{few TeV}$$

It modeled decades of direct search experiment designs

WIMP miracle

But…



Maybe lighter dark sectors?

There is a large, potentially interesting part of thermal DM parameter space that is not so sensitive to DM-nuclear scattering, but is potentially within reach of other probes

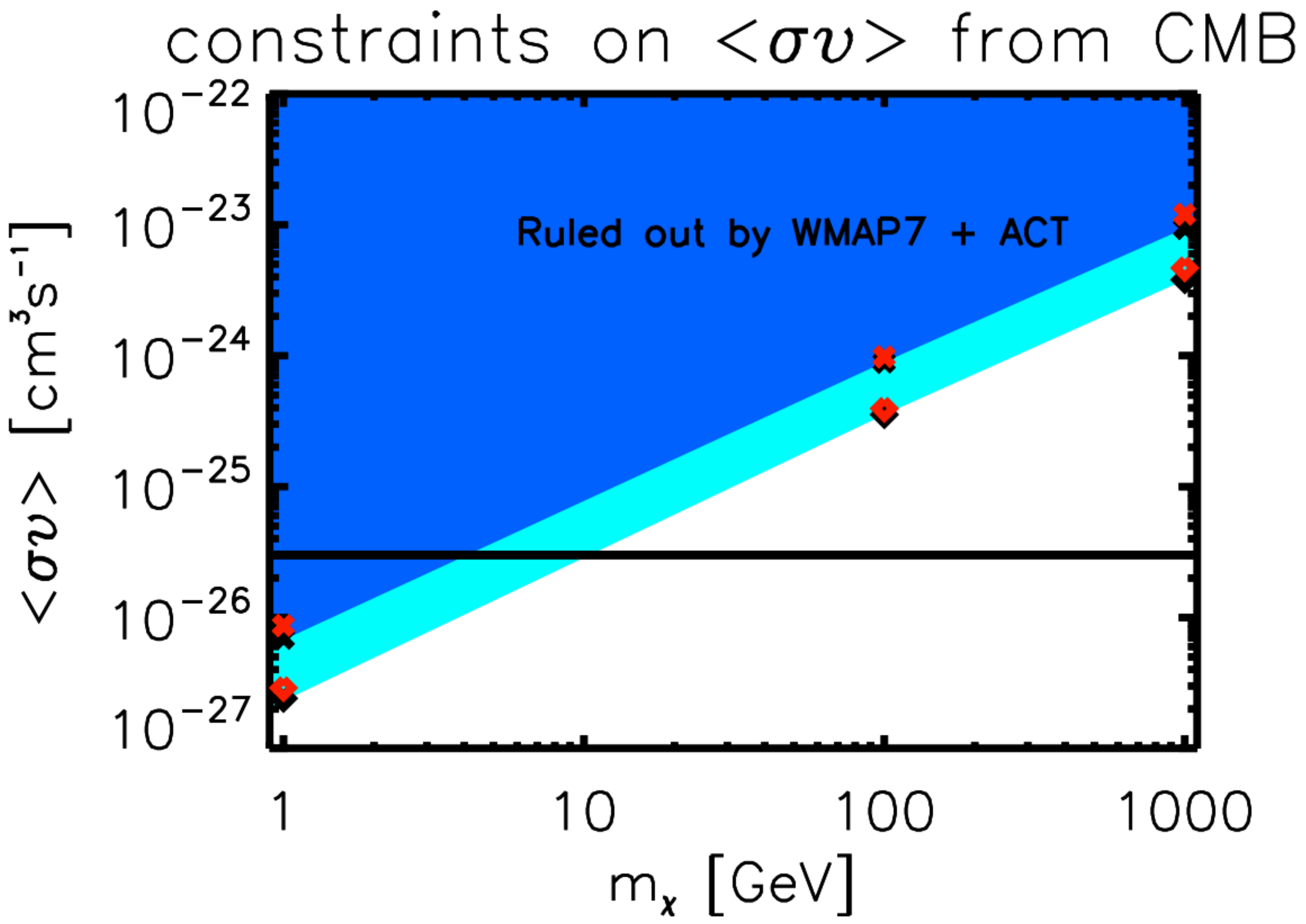
How to have Light DM?

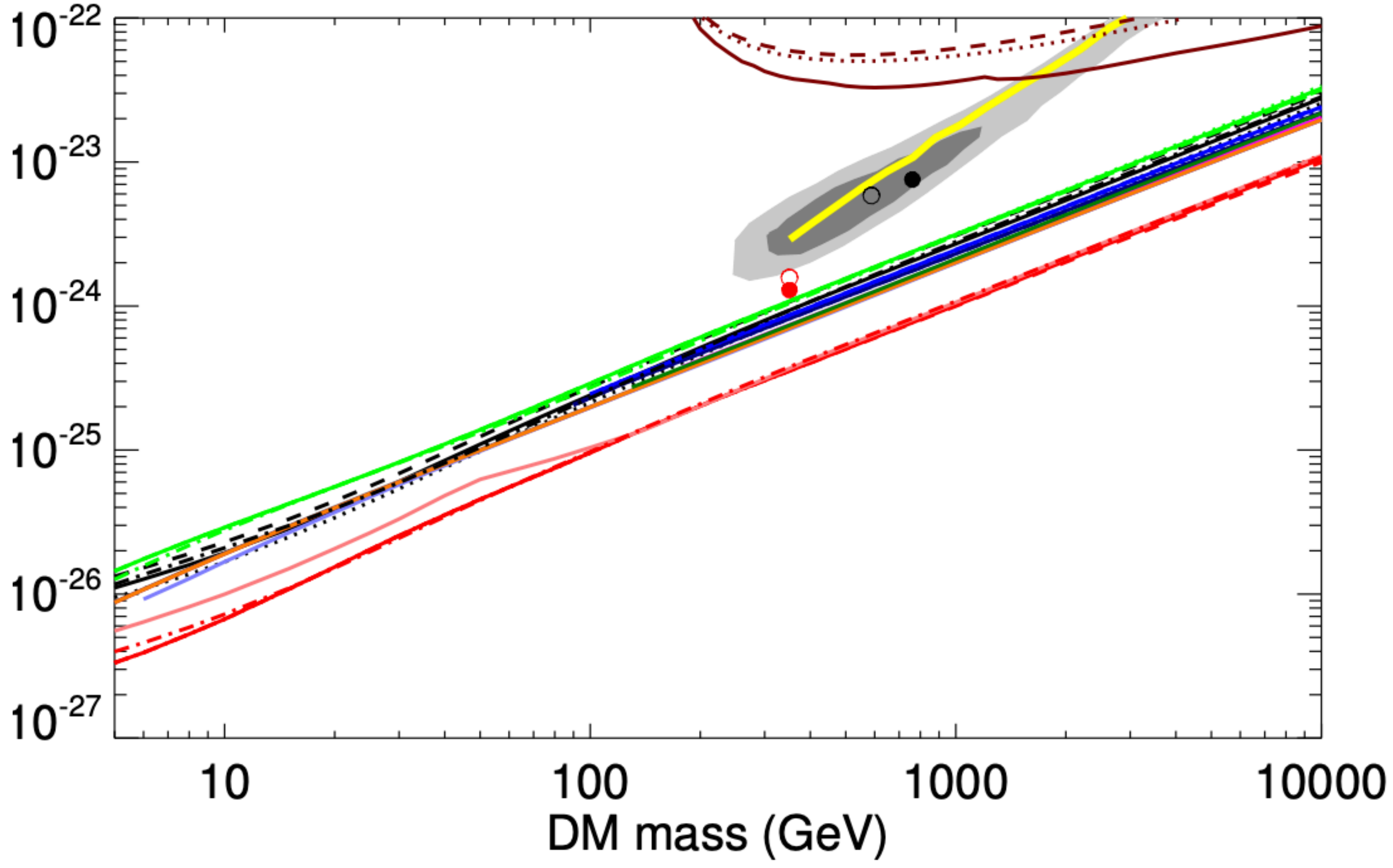
Freeze-out scenario with **light dark matter** requires a **light mediator** to explain the relic density, or dark matter is overproduced.

Challenges

DM of mass range 100 MeV-a few GeV → stringent CMB limits !!!

PHYSICAL REVIEW D **84,** 027302 (2011)





T. Slatyer, Phys. Rev. D 93, 023527 (2016)

Ways around

Velocity-dependent annihilation cross-section ??

- *p*-wave annihilation
- *BW* resonance
- Sommerfeld enhancement

Ways around

Velocity-dependent annihilation cross-section ??

p-wave annihilation

BW resonance

Sommerfeld enhancement

Model

New particles

- Scalar 1 : χ, Z_2 odd $\rightarrow$ **DM**
- Scalar 2 : φ', charge neutral

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \chi)^2 - \frac{\mu_\chi^2}{2}\chi^2 - \frac{\lambda_{H\chi}}{2}|H|^2\chi^2 - \frac{\lambda_\chi}{4!}\chi^4 + \frac{1}{2}(\partial_\mu \Phi)^2 - \frac{\mu_{\Phi\chi}}{2}\Phi\chi^2 - \frac{\lambda_{\Phi\chi}}{4}\Phi^2\chi^2 - V(\Phi, H),$$

$$V(\Phi, H) = \mu_{\Phi H}\Phi|H|^2 + \frac{\lambda_{\Phi H}}{2}\Phi^2|H|^2 + \mu_1^3\Phi + \frac{\mu_\Phi^2}{2}\Phi^2 + \frac{\mu_3}{3!}\Phi^3 + \frac{\lambda_\Phi}{4!}\Phi^4,$$

After the electroweak symmetry breaking

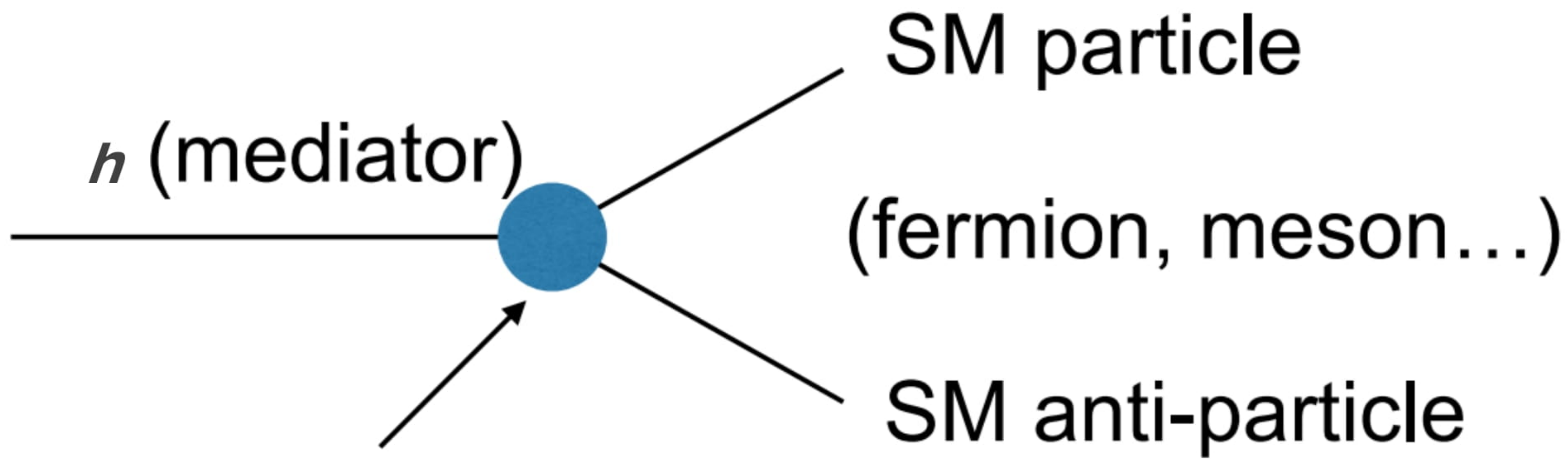
$$H = (0, v_H + h')^T/\sqrt{2}, \; v_H \simeq 246\,\mathrm{GeV}$$

$$\Phi = v_\Phi + \varphi', \; v_\Phi = 0$$

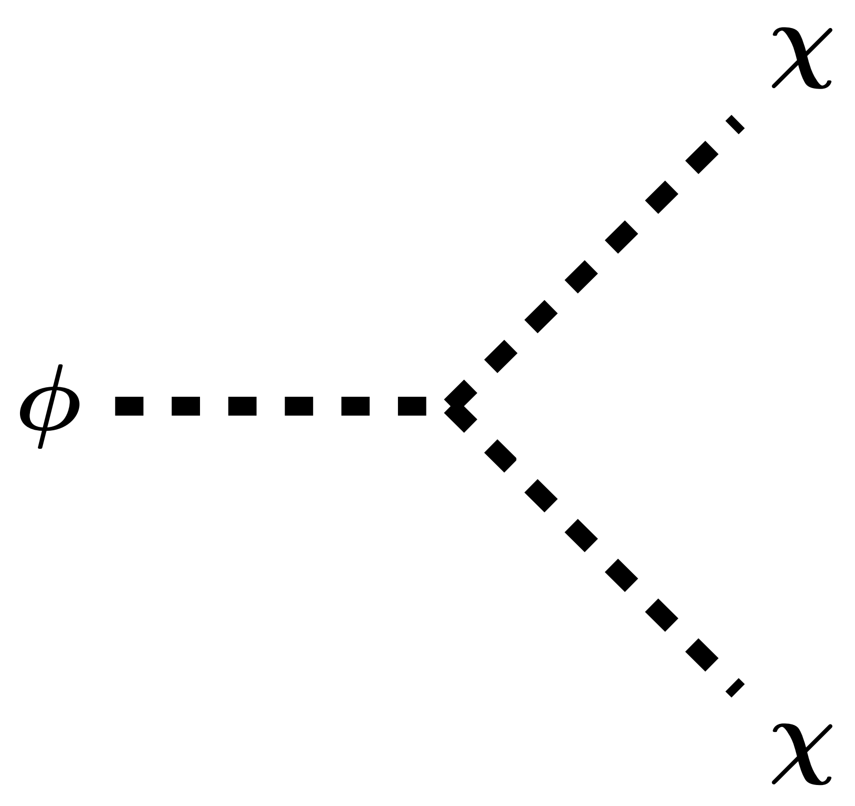
$$\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h' \\ \phi' \end{pmatrix}$$

$$\mathscr{L}_{\text{int}} = -\frac{C_{h\chi\chi}}{2} h\chi^2 - \frac{C_{\phi\chi\chi}}{2}\phi\chi^2 - \frac{C_{hh\chi\chi}}{4} h^2\chi^2 - \frac{C_{\phi h\chi\chi}}{2}\phi h\chi^2 - \frac{C_{\phi\phi\chi\chi}}{4}\phi^2\chi^2 - \frac{\lambda_\chi}{4!}\chi^4$$
$$- \frac{s_\theta\phi + c_\theta h}{v_H}\sum_f m_f \bar{f} f + \left[\frac{s_\theta\phi + c_\theta h}{v_H} + \frac{(s_\theta\phi + c_\theta h)^2}{2v_H^2}\right]\left(2m_W^2 W_\mu^\dagger W^\mu + m_Z^2 Z_\mu Z^\mu\right)$$
$$- \frac{C_{hhh}}{3!}h^3 - \frac{C_{\phi hh}}{2}\phi h^2 - \frac{C_{\phi\phi h}}{2}\phi^2 h - \frac{C_{\phi\phi\phi}}{3!}\phi^3$$
$$- \frac{C_{hhhh}}{4!}h^4 - \frac{C_{\phi hhh}}{3!}\phi h^3 - \frac{C_{\phi\phi hh}}{4}\phi^2 h^2 - \frac{C_{\phi\phi\phi h}}{3!}\phi^3 h - \frac{C_{\phi\phi\phi\phi}}{4!}\phi^4 + \cdots$$

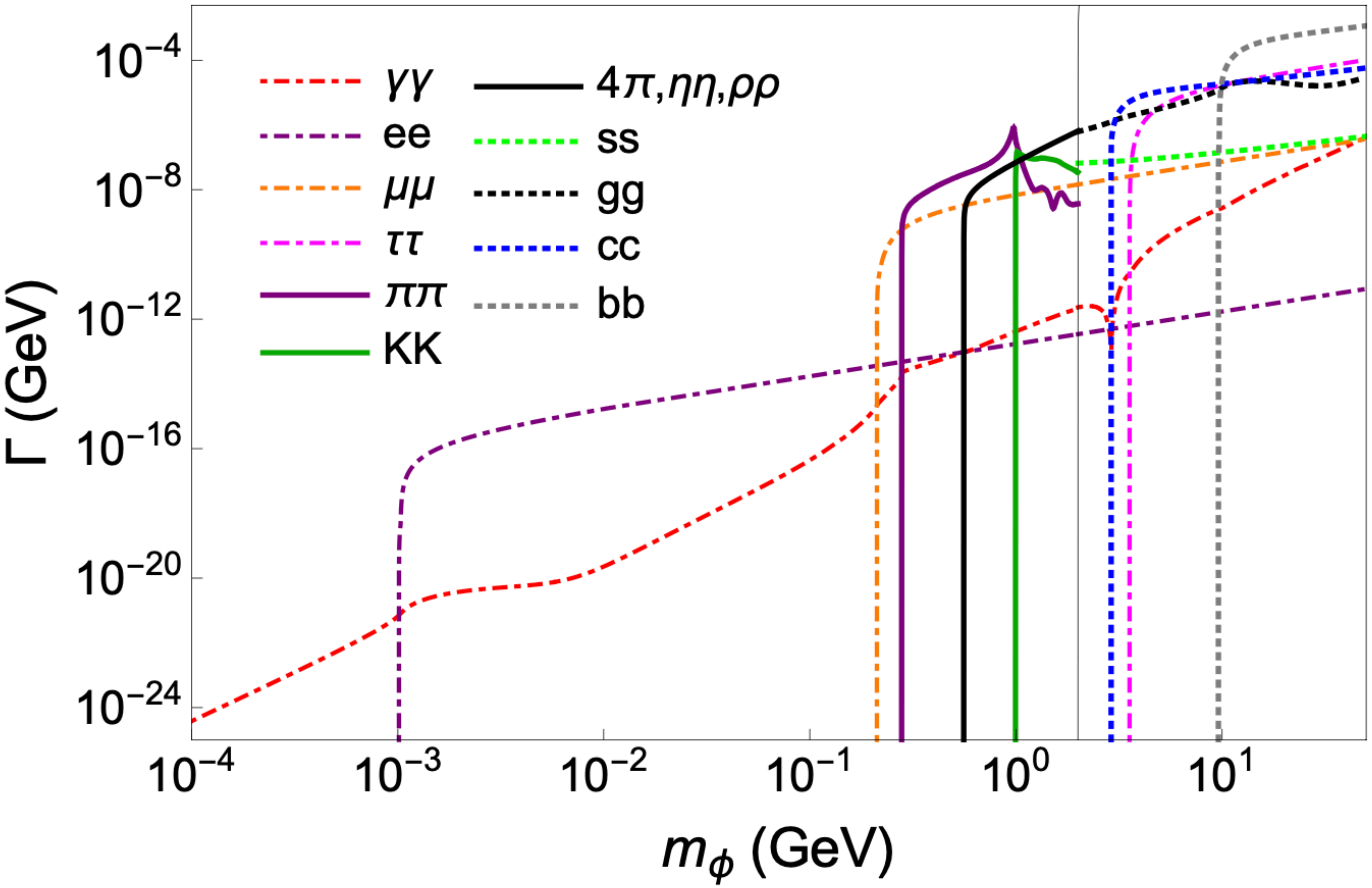
$$\begin{aligned}
C_{h\chi\chi} &= \lambda_{H\chi} v_H c_\theta - \mu_{\Phi\chi} s_\theta, \\
C_{\phi\chi\chi} &= \lambda_{H\chi} v_H s_\theta + \mu_{\Phi\chi} c_\theta, \\
C_{hh\chi\chi} &= \lambda_{H\chi} c_\theta^2 + \lambda_{\Phi\chi} s_\theta^2, \\
C_{\phi h\chi\chi} &= \lambda_{H\chi} c_\theta s_\theta - \lambda_{\Phi\chi} s_\theta c_\theta, \\
C_{\phi\phi\chi\chi} &= \lambda_{H\chi} s_\theta^2 + \lambda_{\Phi\chi} c_\theta^2.
\end{aligned}$$



suppressed by mixing angle



not suppressed by mixing angle



$$\Gamma\left(\phi \to \mathrm{SMs}\right) = \sin^2\theta\ \ \Gamma(h_{\mathrm{SM}} \to \mathrm{SMs})\big|_{m^2_{h_{\mathrm{SM}}} \to m^2_{\phi}}$$

If $m_\phi > 2m_\chi$, mediator decays almost entirely into DM

Parameters

- $v_R \equiv 2\left(\frac{m_\varphi}{m_\chi} - 2\right)^{1/2}$

$m_\varphi > 2m_\chi$

- $\gamma_\varphi = \frac{1}{64\pi}\left(\frac{C_{\varphi\chi\chi}}{m_\varphi}\right)^2$

- $C_{h\chi\chi}$
- $C_{\varphi\varphi\chi\chi}$
- $C_{\varphi\varphi h}$
- $C_{\varphi\varphi\varphi\varphi}$
- m_φ
- $C_{\varphi\varphi\varphi}$
- $\sin\theta$

CMB anisotropy

CMB puts a bound on electromagnetic energy injection into primordial plasma

An upper limit on $f_{\rm eff}(m_\chi)\langle \sigma v \rangle_{v_{\rm DM}}/m_\chi$

Slayter et al. 2016

efficiency

DM velocity
at recombination epoch

To suppress annihilation at recombination maximally,

one needs only the *s*-wave part of $\langle \sigma v \rangle_{\rm ann}$ $\Longrightarrow$ $v_R >> v_{\rm DM}$

Relic density

$$\sigma v\,(\chi\chi \to f_{\rm SM}) \simeq \frac{32C_{\phi\chi\chi}^2}{m_\phi^5}\frac{[\Gamma\,(\phi \to f_{\rm SM})]_{m_\phi^2\to s}}{(v^2 - v_R^2)^2 + 16\Gamma_\phi^2(s)/m_\phi^2}$$

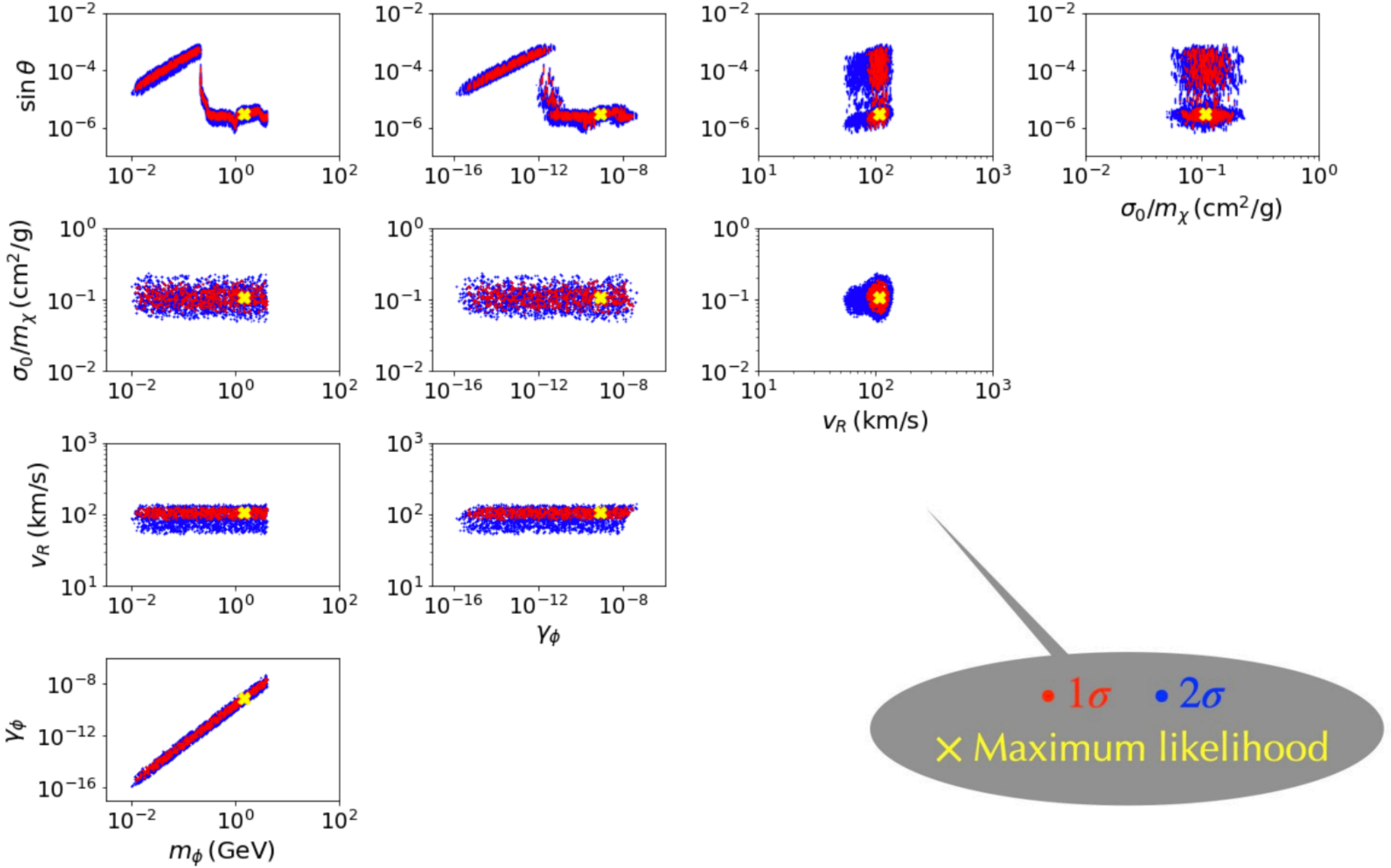
$$\Gamma_\phi(s) \equiv [\Gamma\,(\phi \to \chi\chi) + \sum_{f_{\rm SM}} \Gamma\,(\phi \to f_{\rm SM})]_{m_\phi^2\to s}$$

$$\langle \sigma v\,(\chi\chi \to f_{\rm SM})\rangle_{v_0} \simeq \int_0^\infty dv\,\sigma v\,(\chi\chi \to f_{\rm SM}) f(v, v_0)$$

$$s \simeq m_\phi^2(1 + v^2/4)/(1 + v_R^2/8)^2$$

$$v_R^2 \equiv 4(m_\phi/m_\chi - 2), \gamma \equiv \Gamma_\phi^2(s)/m_\phi^2$$

- At freeze-out, v_R is closer to v_{FO} compared to that of CMB, so BW enhancement is significant.
- The enhanced cross-section must go with suppressed couplings to match with the observed relic density
- Suppressed coupling with SM particles lead to insignificant energy exchange with thermal bath through scatterings , DM kinetically decouples from the thermal bath much earlier than usual freeze out : **early kinetic decoupling**
- The effect is maximal when $T_{kd} \sim \mathcal{O}(T_{\text{freeze-out}})$



sin θ
σ₀/m_χ (cm²/g)
v_R (km/s)
γ_φ
m_φ (GeV)
• 1σ • 2σ
× Maximum likelihood

- For DM mass below 10 GeV, observed relic density fixes the mixing angle in the range

$$10^{-6} \lesssim \sin\theta \lesssim 10^{-3}$$

- $v_R \sim 100$ km/s $\sim 10^{-3}$

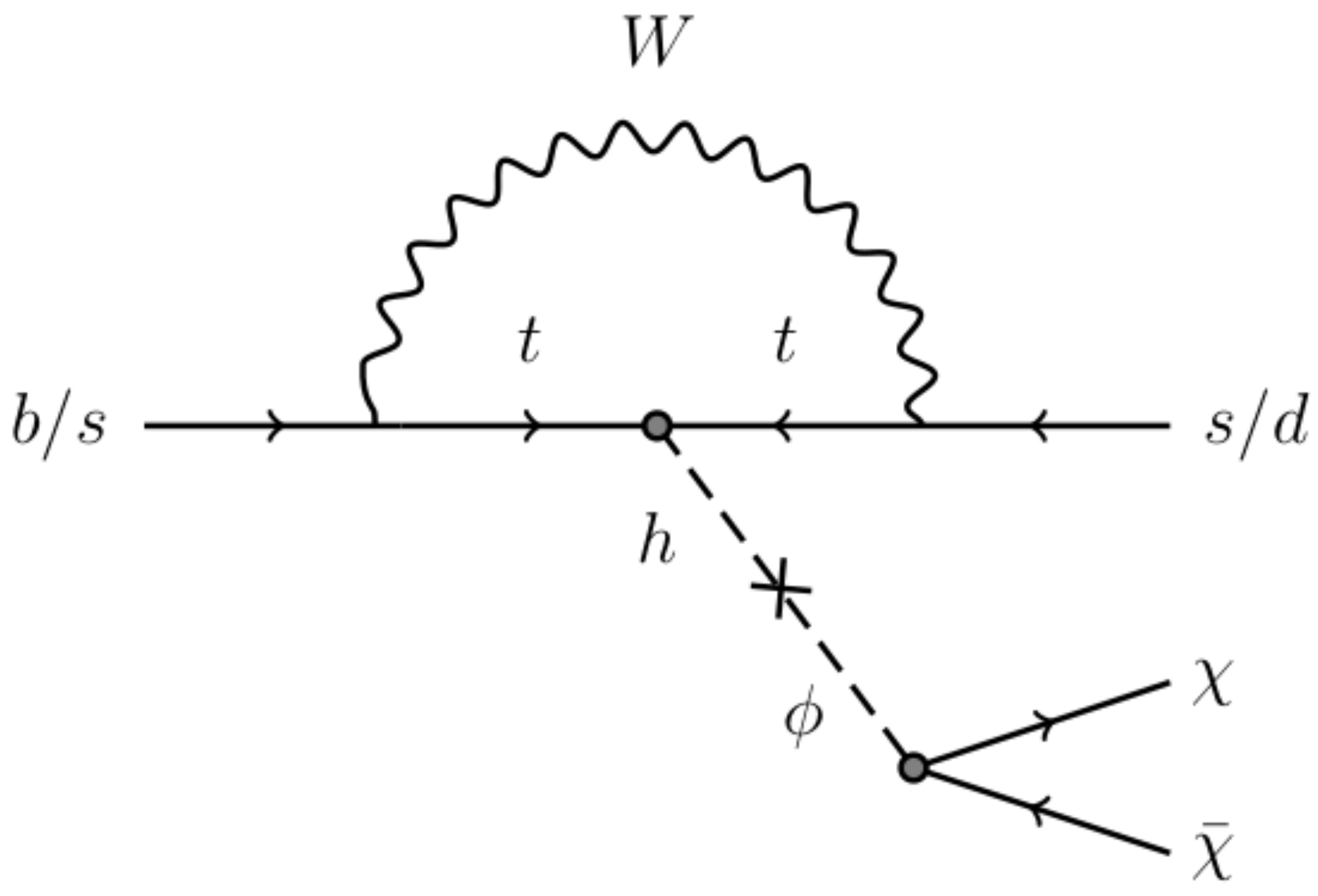
- PLANCK ➡ $f_{\rm eff}(m_\chi)\,\langle\sigma v\rangle_{v_{\rm DM}}/m_\chi \leq 4.1\times 10^{-28}$ cm³/s/GeV at 95% C.L.

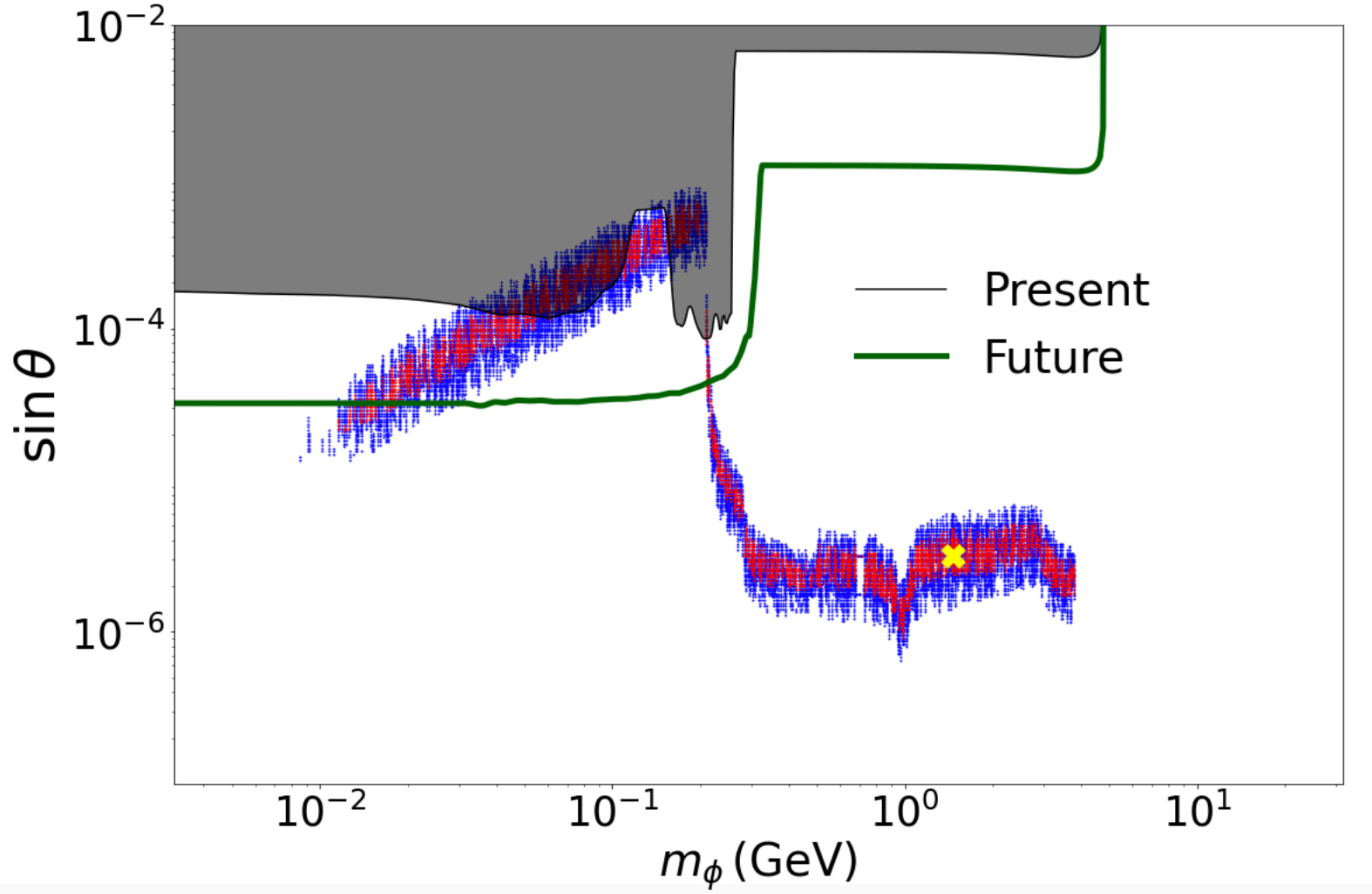
⬇

Mediator mass above ~ 4 GeV is excluded

Collider searches

the light mediator can be probed in the searches for
invisible rare decays of mesons



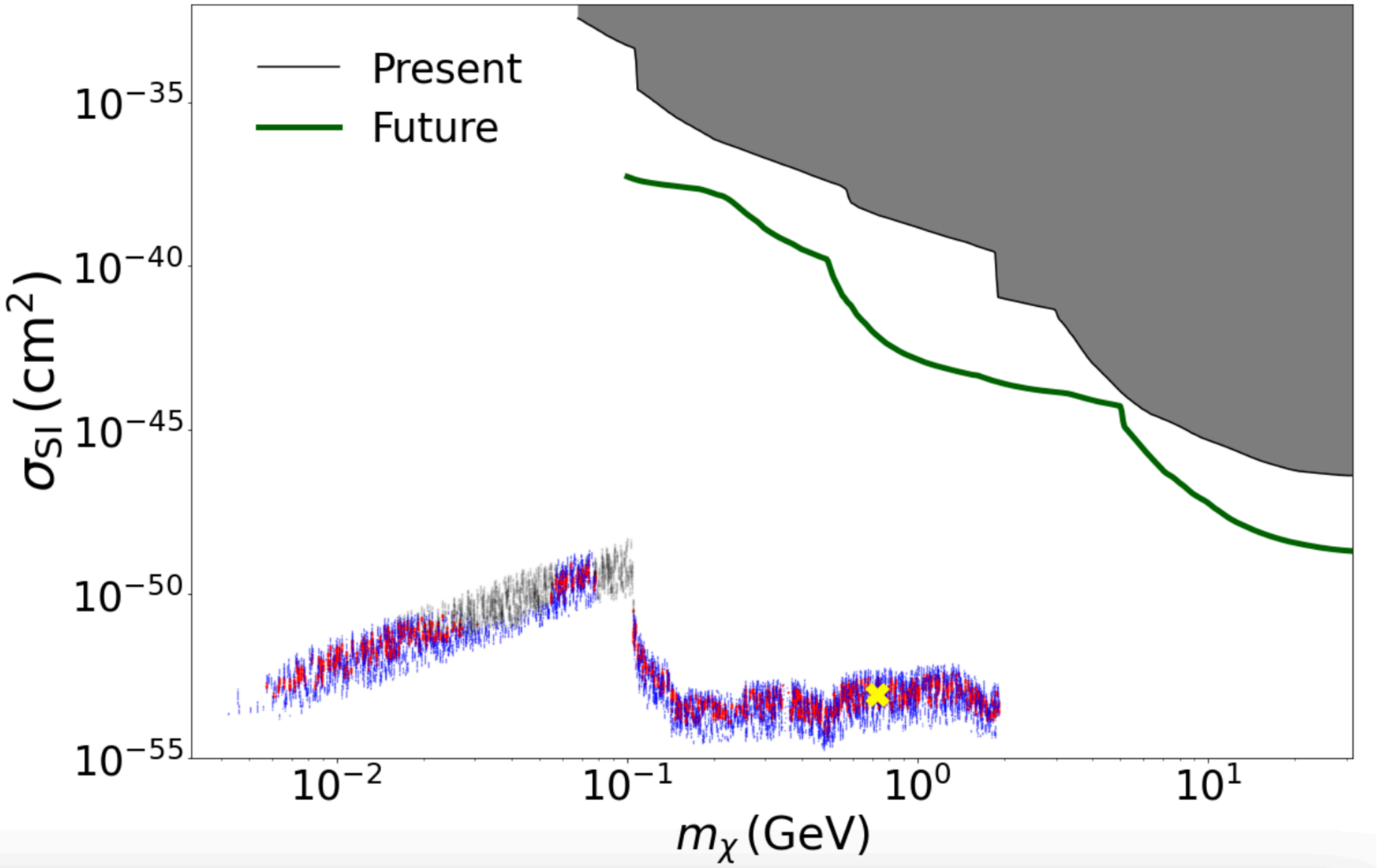


Current limits : Belle, BaBar, E949, NA62, and KOTO at 90% C.L.
Future projections : Belle II and KLEVER

Direct detection

$$\sigma_{\rm SI}(\chi N \to \chi N) = \frac{f_N^2 m_N^4}{4\pi v_H^2 (m_\chi + m_N)^2} \left(\sin\theta \frac{C_{\phi\chi\chi}}{m_\phi^2} + \cos\theta \frac{C_{h\chi\chi}}{m_h^2} \right)^2$$

$\sigma_{\rm SI}$ is minuscule due to tiny $\sin\theta$ and γ_ϕ throughout the analysis



- **Current limits** : CDEX, DarkSide-50 and XENON1T(M) at 90% C.L.

- **Future projections** : NEWS-G, SuperCDMS, CYGNUS, and DARWIN

Indirect detection

Indirect detection can constrain DM annihilation into electromagnetically charged particles

For our analysis

$$\boxed{v_R \sim 10^{-3} \sim v_{\rm DM} \text{ at present epoch}}$$

DM annihilation cross-section at present epoch has the maximal contribution from the higher partial waves

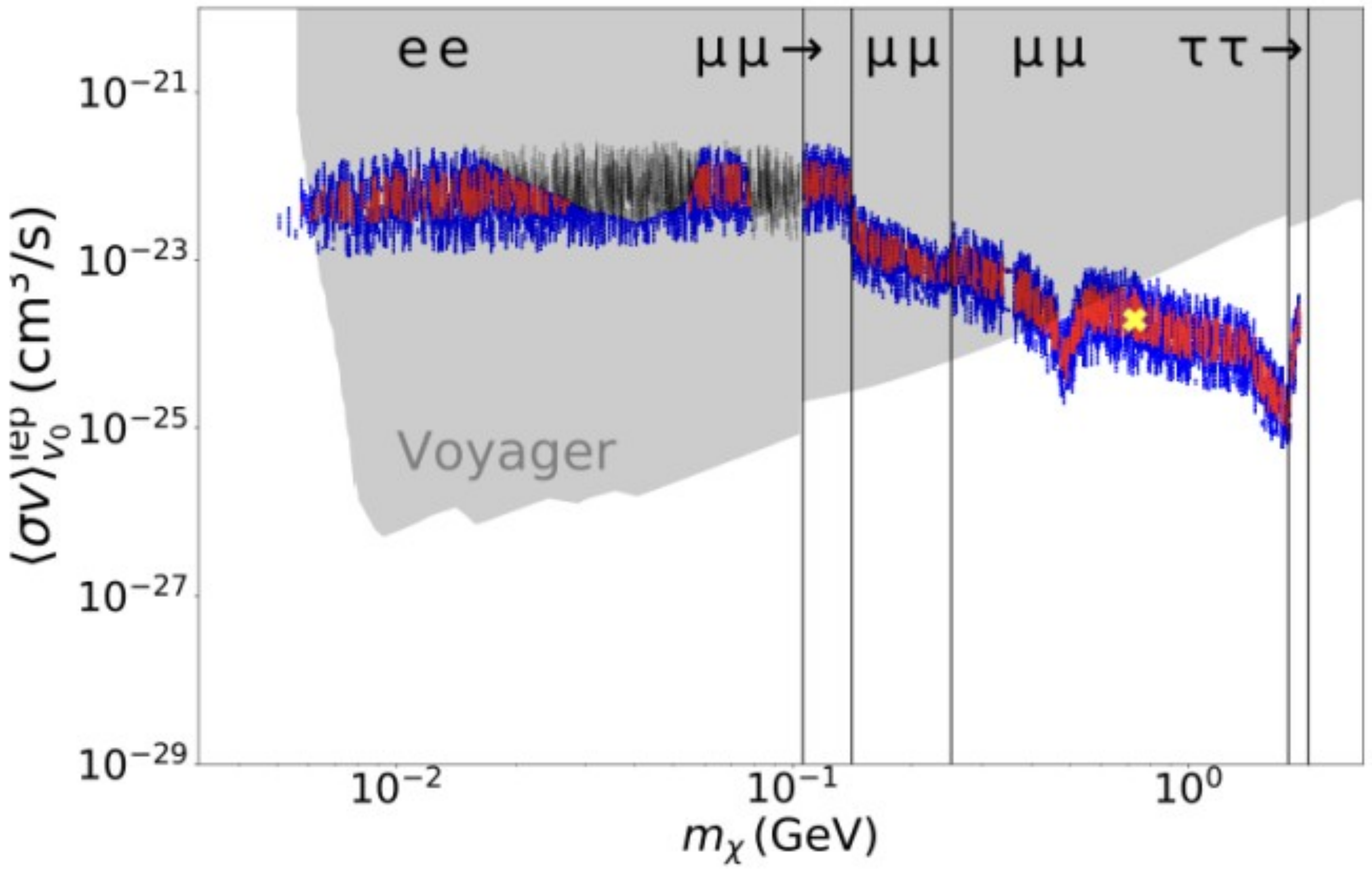
Cosmic ray observations

- DM annihilation into leptons contributes to cosmic ray flux
- Signal flux ∝ (DM density)^2, $\langle \sigma v \rangle_{v_0}$ → **Uncertainties**

Propagation B [*Boudaud et al. 2017, Kappl et al. 2015*]

$\rho_{\rm DM}(r_\odot) = 0.25 \pm 0.11$ GeV/cm^3 [*Read et. al 2014*]
$v_0(r_\odot) \simeq 300$ km/s [*Lacroix et. al 2020*]

Limits available from Voyager I, being the only cosmic ray detector located outside the heliosphere



- Annihilation considered only into lepton pairs
- Grey area excluded by Voyager I at 90% C.L.

Several parameter sets survive within
250 MeV ≤ m_χ ≤ 2 GeV

γ-ray observations

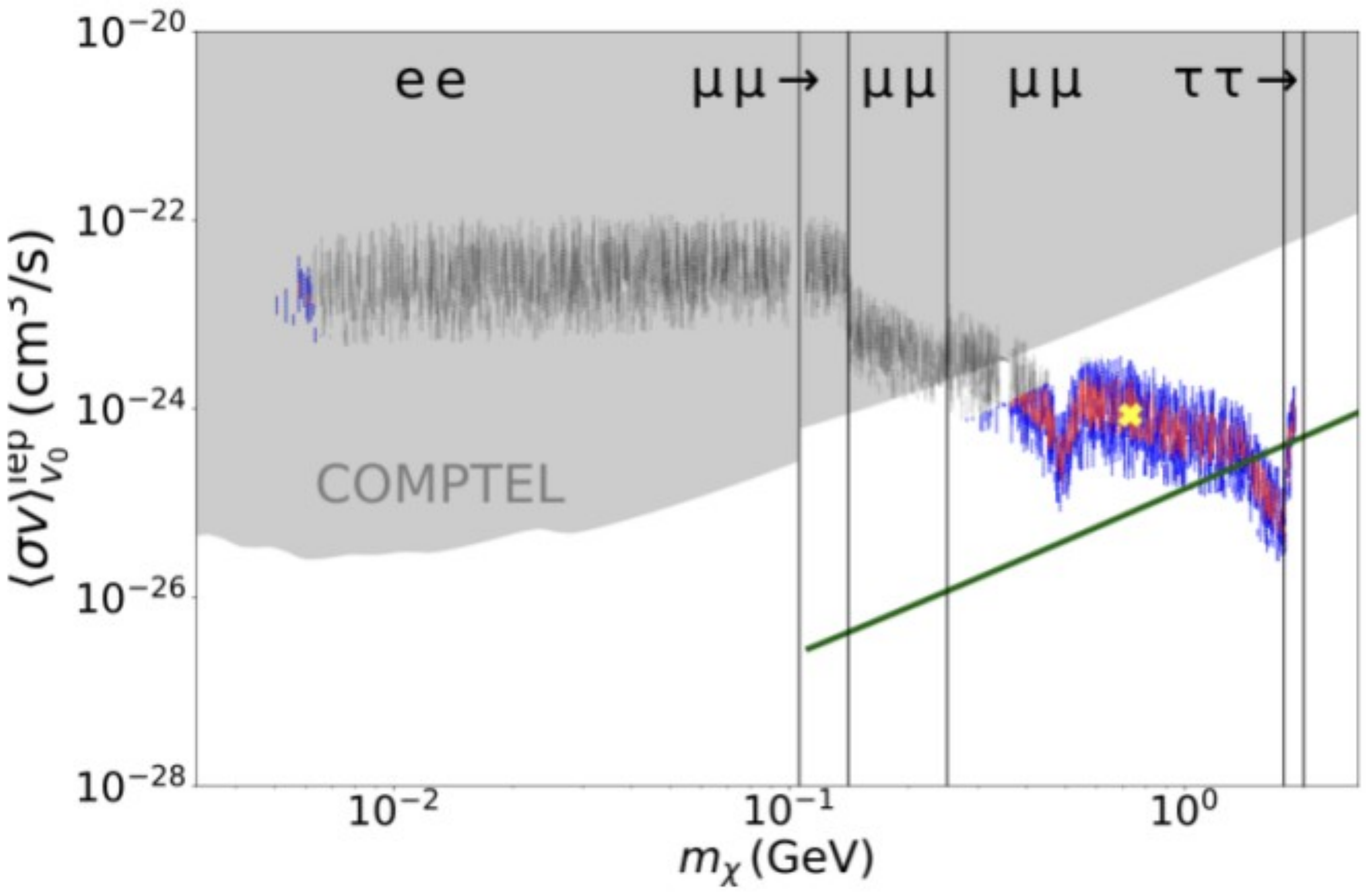
gamma-ray flux from the dark matter annihilation at the galactic center

- $v_0 = 400$ km/s

$$\frac{d\Phi_\gamma}{dE_\gamma} \simeq \left[\frac{\langle\sigma v\rangle_{v_0}}{8\pi m_\chi^2}\sum_{f_{\rm SM}} {\rm Br}\,(\chi\chi \to f_{\rm SM})\frac{dN_\gamma}{dE_\gamma}\bigg|_{f_{\rm SM}}\right] \times \left[\int_{\Delta\Omega} d\Omega \int_{\rm l.o.s} ds\, \rho_{\rm DM}^2\right]$$

J-factor

Produced photons typically have **MeV energies** ⇒ experimentally difficult to probe → COMPTEL (Current) / GECCO, COSI (Future)



- DM annihilation cross section into SM lepton pairs
- Grey area excluded by COMPTEL at 90% C.L.
- GECCO projection in green

Near future observation almost covers surviving parameter region for 250 MeV $\leq m_\chi \leq$ 2 GeV

Take home

- ✓ We have considered a GeV-scale dark matter model with two singlet scalars, one acting as DM while the other is the mediator
- ✓ DM annihilation is essentially *s*-wave
- ✓ Strong CMB-constraints are evaded by tuning the resonance parameters
- ✓ Focussing on the BW resonance region makes way for interesting probes through indirect searches
- ✓ Low-energy direct detection and accelerator searches (proton and electron beam-dumps, searches through rare meson decays etc) give complementary probes

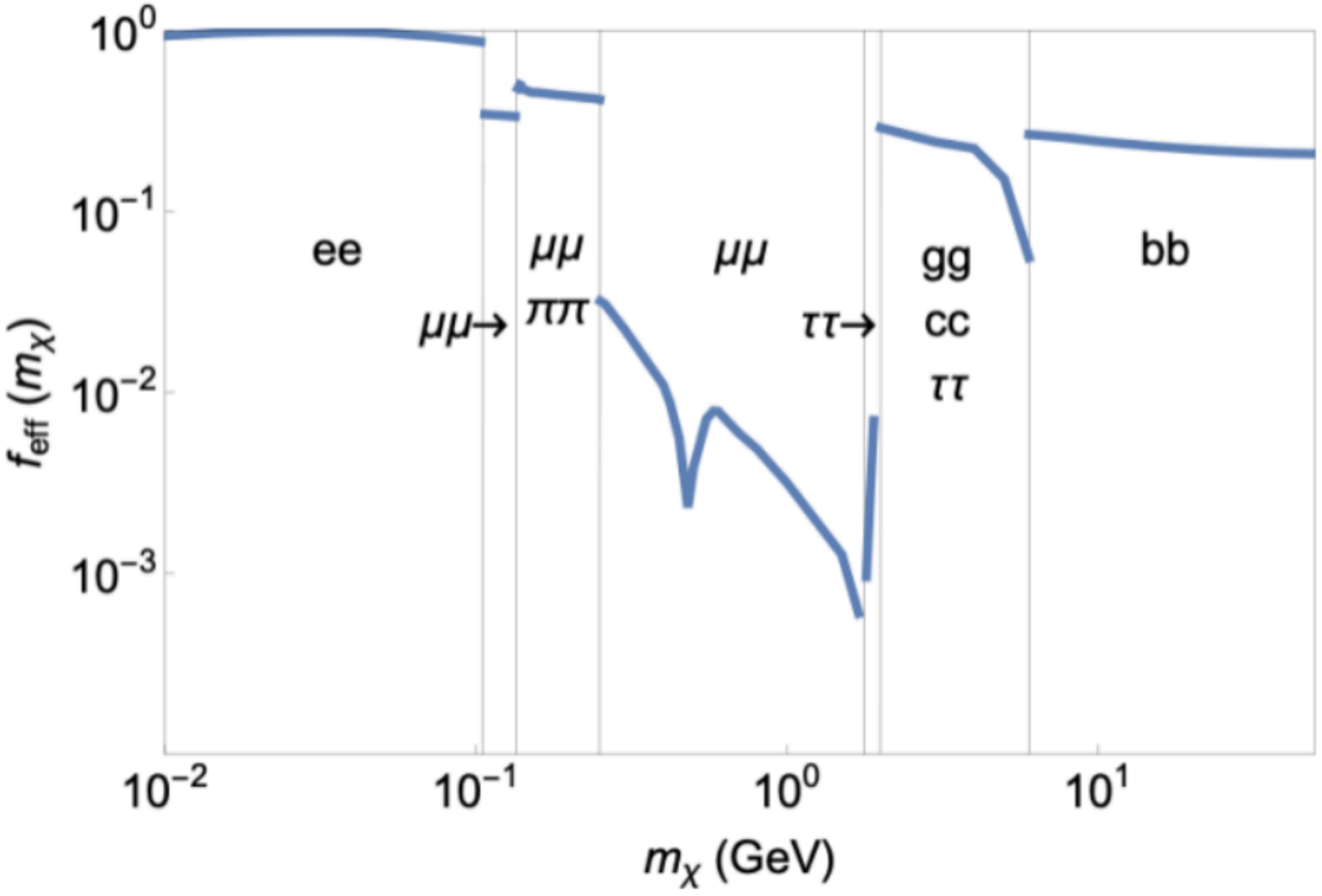
Backup

$$f_{\rm eff}(m_\chi) = \int_0^{m_\chi} dE \frac{E}{2m_\chi} \sum_{f_{\rm SM}} {\rm Br}(\chi\chi \to f_{\rm SM}) \left[2 f_{\rm eff}^{(e)}(E) \left.\frac{dN_e}{dE}\right|_{f_{\rm SM}} + f_{\rm eff}^{(\gamma)}(E) \left.\frac{dN_\gamma}{dE}\right|_{f_{\rm SM}} \right]$$

Efficiencies

Fragmentation functions

Problem !!



- $m_\phi \leq 2m_\mu$, $2m_\mu \leq m_\phi \leq 2m_\pi$, and $2m_\pi \leq m_\phi \leq 500$ MeV → **HAZMA**
- 4 GeV $\leq m_\phi \leq 2m_b$, and $m_\phi \geq 2m_b$ → **micrOMEGAs**

But… 500 MeV $\leq m_\phi \leq$ 4 GeV

No robust way to calculate fragmentation function for hadronic final states

Kinetic decoupling

- Thermalization of DM occurs primarily through an exchange of energy due to collisions with the SM plasma
- For small couplings, kinetic equilibrium is not always maintained, and DM can decouple from the thermal bath earlier than usual
- We assume that χ has significant self interactions and after kinetic decoupling has occurred, reaches equilibrium at a temperature T_χ which is different from the plasma temperature T.
- When DM decouples thermally from the primordial plasma, its temperature drops faster than usual. T_χ decreases as a^{-2}, while T scales approximately like a^{-1}. As DM cools down, the annihilation cross-section $\langle \sigma v_{ann} \rangle$ increases, and hence relic density drops.