Light thermal dark matter and its possible probes

[arXiv:2205.10149 [hep-ph]]

EDSU2022
Nov 7–11, 2022
La Réunion, France

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Nov 09, 2022

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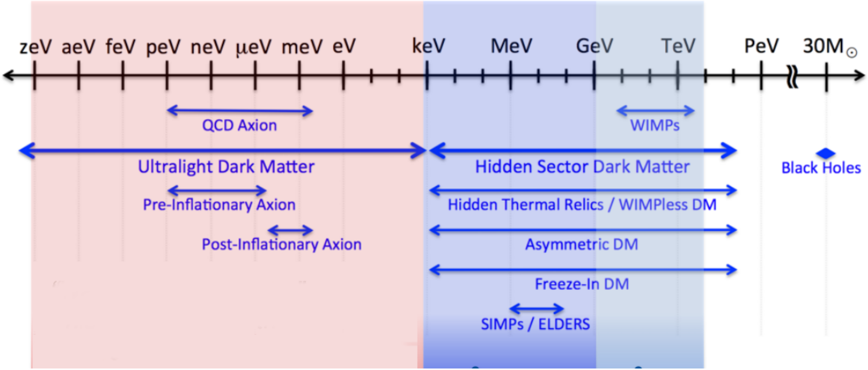
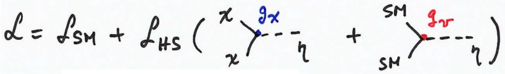
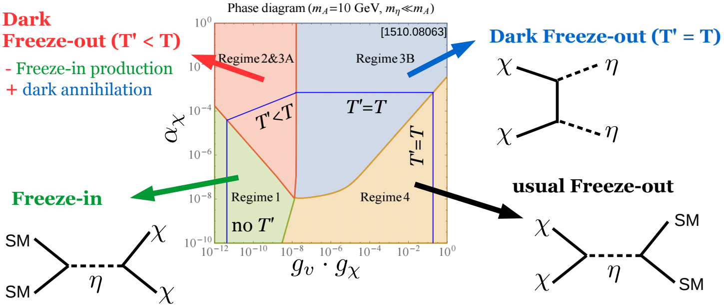
Dark matter candidates



Different thermal histories of DM





Chu, Hambye & Tytgat, 1112.0493
Bernal, Chu, García-Cely, Hambye & Zaldivar, 1510.08063

T': temperature of dark sector
T: temperature of visible sector

credit : Bryan Zaldivar

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

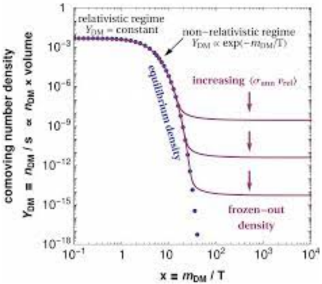
Electroweak mediators $\Rightarrow$ Lee – Weinberg window

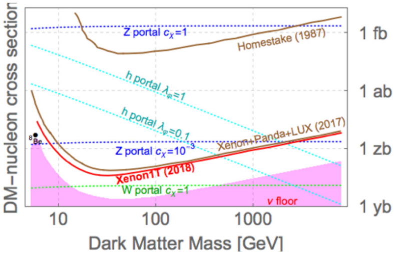
$$\sigma(v/c) \propto \begin{cases} G_F^2\, m_{DM}^2 & \text{for } m_{DM} \ll m_W \\ 1/m_{DM}^2 & \text{for } m_{DM} \gg m_W \end{cases} \Rightarrow \text{few GeV} < m_{DM} < \text{few TeV}$$

It modeled decades of direct search experiment designs

WIMP miracle

But.....

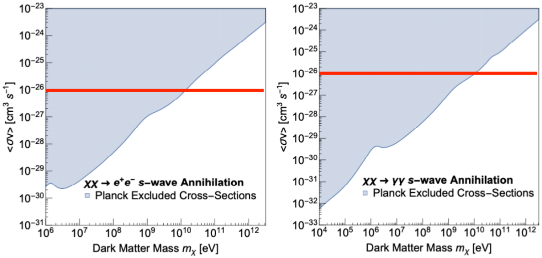




Maybe lighter dark sectors?

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

But.....



Liu et. al, 2016

- Light DM below 10 GeV is excluded by CMB if DM annihilation into SM is *s*-wave.
- The constraint is much weaker if other partial waves are dominant in the annihilation cross-section

Forbidden DM
Resonant DM *Katayose et. al, 2021*

A velocity dependence is needed

New particles

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

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

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

After the electroweak symmetry breaking

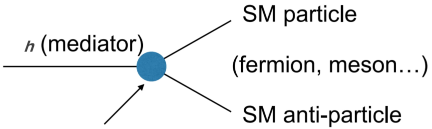
$$H = (0, v_H + h')^T/\sqrt{2},\ v_H \simeq 246\,\mathrm{GeV}$$
$$\Phi = v_\Phi + \phi',\ v_\Phi = 0$$

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

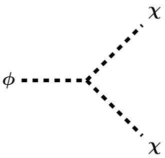
Interactions

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

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



suppressed by mixing angle



not suppressed by mixing angle

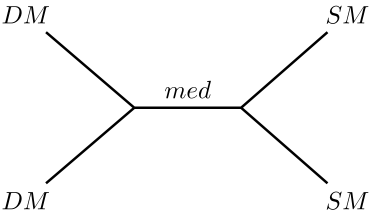
we focus on

the **Resonant annihilation region**

$$\boxed{m_\phi \simeq 2m_\chi}$$

Mediator is a little heavier than twice of DM mass

- Dark matter annihilates into SM particles through s-channel resonance from ϕ mediation.



- Enhanced cross-section keeps the dark sector coupling down in order to match with the observed relic density

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

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

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

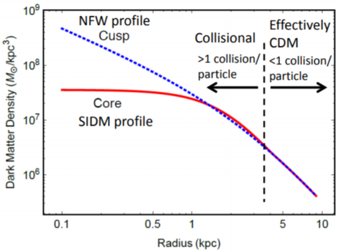
$$s \simeq m^2_\phi (1 + v^2/4)/(1 + v_R^2/8)^2$$

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

The mixing angle, ie, $\sin\theta$ is constrained to very low values

Why self-interaction?

A solution to small-scale structure problem



Direct detection of SIDM, S. Tulin

- Stronger self-scattering needed for (dwarf-sized) halos

$\frac{\sigma_{SI}}{m_{\rm DM}} \sim 0.5 - 10\ {\rm cm}^2/{\rm g}$ at dwarf scales of DM velocity ~ 10 km/s

O. D. Elbert et al. 2016, K. Bondarenko 2016,....

- Weaker self-scattering favoured by cluster merging/halo profiles etc

$\frac{\sigma_{SI}}{m_{\rm DM}} \sim 0.2 - 1\ {\rm cm}^2/{\rm g}$ at cluster scales of DM velocity ~ 1000 km/s

O. D. Elbert et al. 2016, K. Bondarenko 2016,....

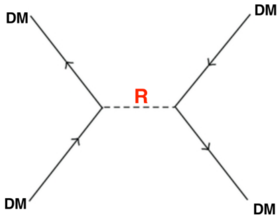
A velocity-dependence in DM self-scattering

Possibilities : a light mediator

Spergel & Steinhardt 1999, Bringmann, et al. 2016

OR..

SIDM via a resonance [XC, C. Garcia-Cely, H. Murayama, 1810.04709]



If $v_R^2 \equiv \frac{m_R - 2m_{\rm DM}}{m_{\rm DM}} \ll 1$

An enhancement
&
a velocity-dependence

$$\sigma = \sigma_0 + \frac{4\pi\, S}{m E(v)} \cdot \frac{\Gamma(v)^2/4}{(E(v) - E(v_R))^2 + \Gamma(v)^2/4}$$

t/u - channel

$$E(v) = \frac{1}{2}\frac{m}{2}v^2 \quad \text{and} \quad S = \frac{2J_R + 1}{(2J_{\rm DM}+1)^2}$$

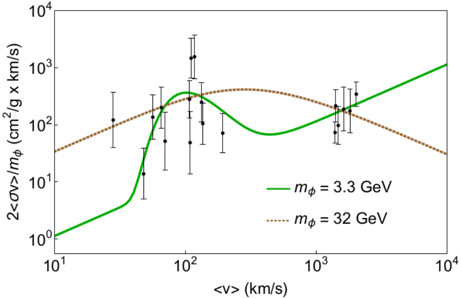
$$\Gamma(v) = m_R \gamma v^{2L+1}$$

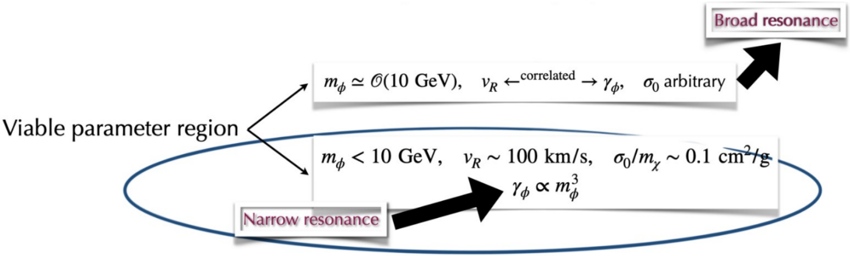
L — partial wave

γ — couplings

v_R — **near resonance**

Resonant self-interaction





CMB puts a bound on electromagnetic energy injection into primordial plasma

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

Slayter et al. 2016

efficiency

DM velocity
at recombination epoch

Since $v_{\text{DM}} \ll v_R$ ➡ **only s-wave component contributes to annihilation at recombination**

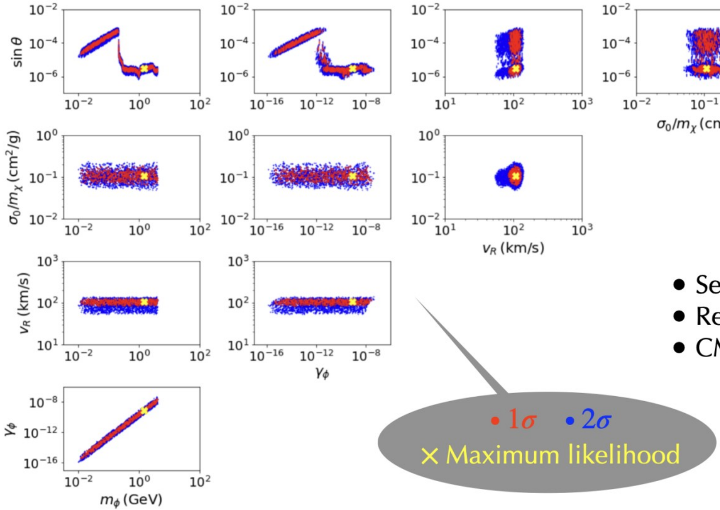
- We estimate the efficiency $f_{\rm eff}(m_\chi)$ taking only leptonic final states into account

- PLANCK ➡ $f_{\rm eff}(m_\chi)\,\langle\sigma v\rangle_{v_{\rm DM}}/m_\chi \leq 4.1 \times 10^{-28}$ cm^3/s/GeV at 95% C.L.

⬇

Mediator mass above ~ 4 GeV is excluded

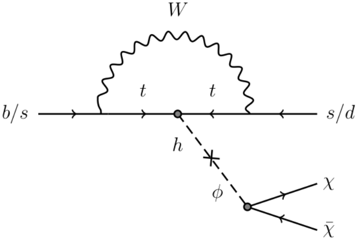
Parameter space



- Self-interaction
- Relic density
- CMB

How to probe this model ???

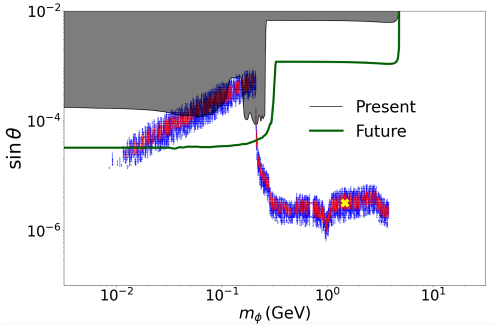
the light mediator can be probed in the searches for
invisible decays of rare mesons



$$\Gamma(B^\pm \to K^\pm \phi) = \frac{|C_{sb}|^2 F_K^2(m_\phi)}{64\pi m_B^3}\left(\frac{m_B^2 - m_K^2}{m_b - m_s}\right)^2 \sqrt{(m_B^2 - m_K^2 - m_\phi^2)^2 - 4m_K^2 m_\phi^2}$$

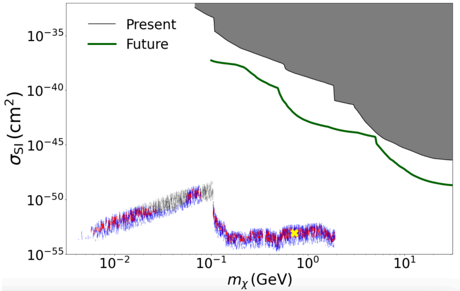
$$\Gamma(K^\pm \to \pi^\pm \phi) = \frac{|C_{sd}|^2}{64\pi m_{K^\pm}^3}\left(\frac{m_{K^\pm}^2 - m_{\pi^\pm}^2}{m_s - m_d}\right)^2 \sqrt{(m_{K^\pm}^2 - m_{\pi^\pm}^2 - m_\phi^2)^2 - 4m_{\pi^\pm}^2 m_\phi^2}$$

$$\Gamma(K_L \to \pi^0 \phi) = \frac{|C_{sd}|^2}{64\pi m_{K_L}^3}\left(\frac{m_{K_L}^2 - m_{\pi^0}^2}{m_s - m_d}\right)^2 \sqrt{(m_{K_L}^2 - m_{\pi^0}^2 - m_\phi^2)^2 - 4m_{\pi^0}^2 m_\phi^2}$$



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

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



- **Current limits** : CDEX, DarkSide-50 and XENON1T(M) at 90% C.L
- **Future projections** : NEWS-G, SuperCDMS, CYGNUS, and DARWIN

Indirect detection can constrain DM annihilation into electromagnetically charged particles

For our analysis

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

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

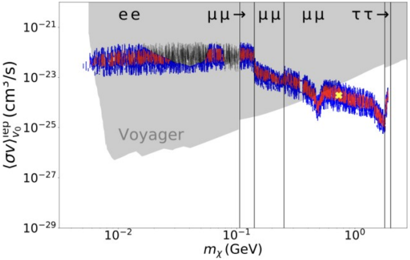
Cosmic ray observations

- 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*]

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

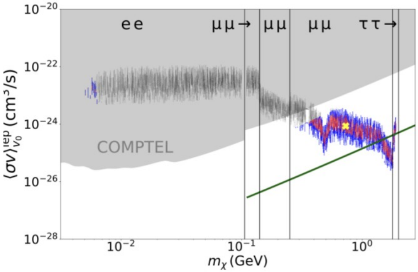
gamma-ray flux from the dark matter annihilation at the galactic center

- $v_0 = 400$ 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 consider a minimal thermal light DM model that resolves the core-cusp problem of the universe if the dark matter self-scattering occurs via the Breit-Wigner resonance caused by exchanging the mediator particle in the s-channel.

- The model is compatible with self-interaction, relic density and CMB constraints in the dark matter mass range of $10\,\text{MeV} \leqslant m_\phi \leqslant 4\,\text{GeV}$.

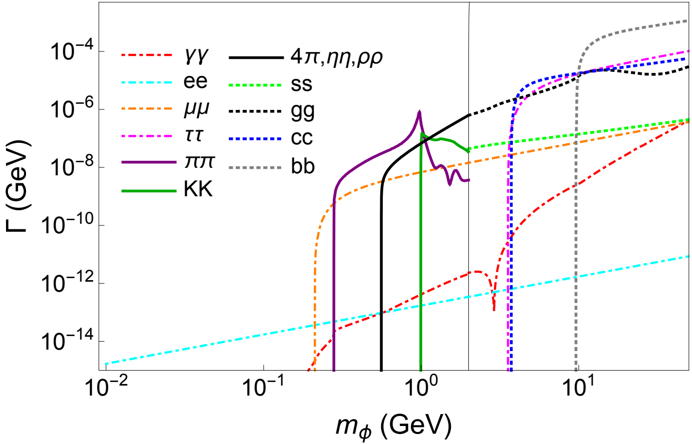
- There are strong constraints from collider searches due to the extensive search for rare K-meson decays. Moreover, future K-meson experiments can explore most of the parameter sets with $m_\phi \leqslant 100\,\text{MeV}$

- A lighter dark matter region, $m_\chi \lesssim 300\,\text{MeV}$, is excluded by the indirect dark matter detection using cosmic-ray and gamma-ray observations, for the signal strength is boosted by the s-channel resonance.

- Only the parameter sets with $300\,\text{MeV} \lesssim m_\chi \lesssim 2\,\text{GeV}$ avoid the severe constraints, although upcoming experiments in the near future is expected to probe this region.

BACKUP

Decay of the mediator



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

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

Parameters

- m_ϕ
- $v_R \equiv 2\left(\frac{m_\phi}{m_\chi} - 2\right)^{1/2}$
- $\gamma_\phi = \frac{1}{64\pi}\left(\frac{C_{\phi\chi\chi}}{m_\phi}\right)^2$
- σ_0
- $\sin\theta$
- $C_{h\chi\chi}$
- $C_{\phi\phi h}$
- $C_{\phi\phi\phi}$
- $C_{\phi\phi\chi\chi}$
- $C_{\phi\phi\phi\phi}$

Another limit from CMB

$\Delta N_{\rm eff}$

- Adding new particles with mass close to the neutrino decoupling temperature $T_D \sim 2$ MeV to the dark sector affects expansion rate of the Universe at the recombination epoch
- CMB set a **lower limit** on the light mediator not to alter the effective # of relativistic d.o.f ($\Delta N_{\rm eff}$)
- Assuming the instantaneous neutrino decoupling and no heating of the neutrinos from electrons and positrons

$$N_{\rm eff} \simeq 3\left\{1+\frac{45}{11\pi^2 T_D^3}\left[s_\chi(T_D)+s_\phi(T_D)\right]\right\}^{-4/3}, \qquad s_i(T_D)=h_i(T_D)\frac{2\pi^2}{45}T_D^3,$$

$$h_i(T_D) = (15x_i^4)/(4\pi^4)\int_1^\infty dy\,(4y^2-1)\sqrt{y^2-1}/(e^{x_i y}-1) \qquad x_i \equiv m_i/T_D$$

$$N_{\rm eff} = 2.99 \pm 0.17$$

PLANCK excludes mediator mass below 11 MeV at 95% C.L

The velocity is estimated to be

$$v_{\rm DM} \simeq 2 \times 10^{-7}(T_\gamma/1\ {\rm eV})(1\ {\rm GeV}/m_\chi)(10^{-4}/x_{kd})^{1/2}$$

$T_\gamma = 0.235$ eV

$x_{kd} = T_{kd}/m_\chi$

In the early kinematical decoupling scenario, $T_{kd} \sim \mathcal{O}(T_{\text{freeze-out}})$

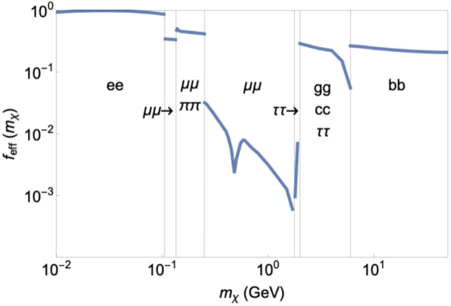
Since $v_{\rm DM} \ll v_R$ ➡ **only s-wave component contributes to annihilation at recombination**

But at freeze-out velocity is not so suppressed ➡ so higher momenta also contribute to relic density

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

Efficiencies

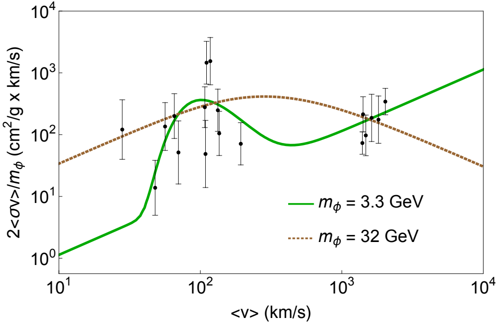
Fragmentation functions



- $m_\phi \leq 2m_\mu$, $2m_\mu \leq m_\phi \leq 2m_\pi$, 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



$(v_R, \sigma_0/m_\phi, \gamma_\phi, m_\phi)$: $(110\,\mathrm{km/s},\ 0.06\,\mathrm{cm}^2/\mathrm{g},\ 10^{-7.9},\ 3.3\,\mathrm{GeV})$

$(5035\,\mathrm{km/s},\ 0,\ 10^{-1.1},\ 32\,\mathrm{GeV})$

$$\langle \sigma v(\chi\chi \to \chi\chi)\rangle_{v_0} \simeq \frac{2v_0}{\sqrt{\pi}}\sigma_0 + \frac{1}{2\pi m_\phi^6}\int_0^\infty dv \frac{v\, C_{\phi\chi\chi}^4 f(v, v_0)}{(v^2 - v_R^2)^2 + 16\Gamma_\phi^2(s)/m_\phi^2}$$

$$\sigma_0 \equiv (\lambda_\chi - 2C_{\phi\chi\chi}^2/m_\phi^2 - 3C_{h\chi\chi}^2/m_h^2)^2/(32\pi m_\phi^2)$$