Light dark matter and its possible probes

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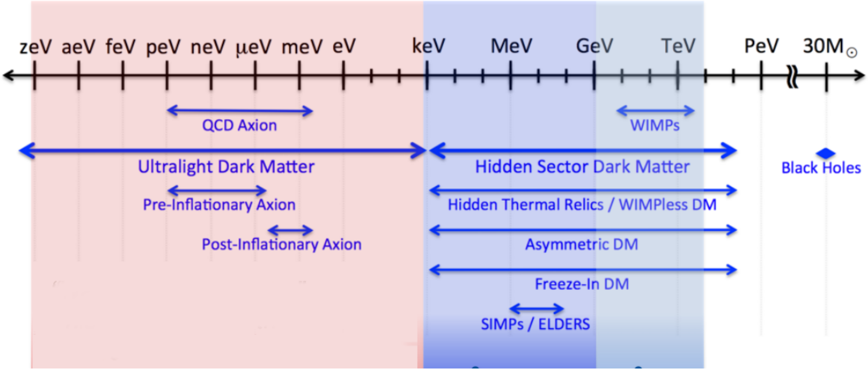
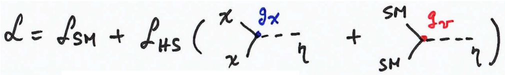
Dark matter candidates

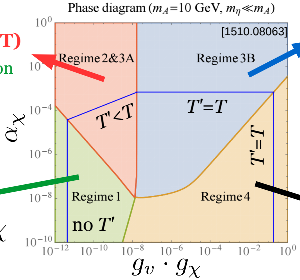


Different thermal histories of DM

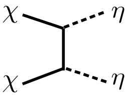


Dark Freeze-out (T' < T)

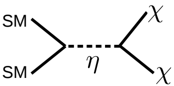
- Freeze-in production
+ dark annihilation



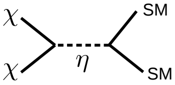
Dark Freeze-out (T' = T)



Freeze-in



usual Freeze-out



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

WIMPs. . .

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

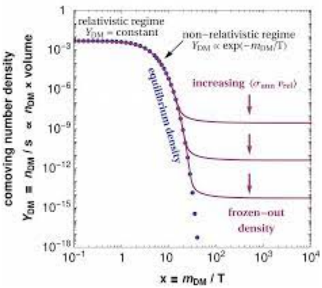
Electroweak mediators $\Rightarrow$ Lee – Weinberg window

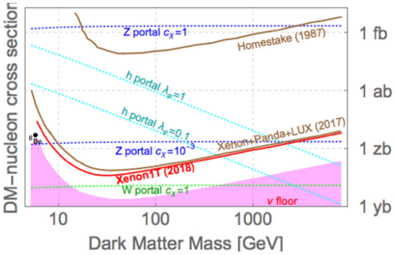
$$\sigma(v/c) \propto \begin{cases} G_F^2\, m_{DM}^2 & \text{for } m_{DM} \ll m_W \\ 1/m_{DM}^2 & \text{for } m_{DM} \gg m_W \end{cases} \Rightarrow \text{few GeV} < m_{DM} < \text{few TeV}$$

WIMP miracle

It modeled decades of direct search experiment designs

But.....

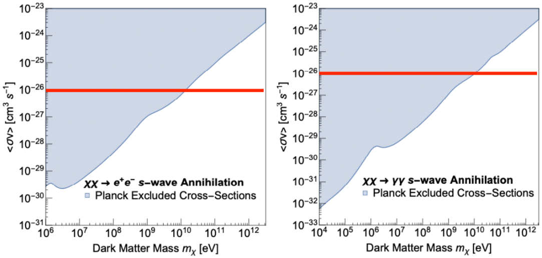




Maybe lighter dark sectors?

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

The 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

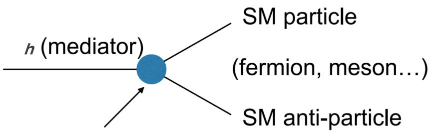
$$H = (0, v_H + h')^T/\sqrt{2},\ v_H \simeq 246\,\mathrm{GeV}$$
$$\Phi = v_\Phi + \phi',\ v_\Phi = 0$$

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

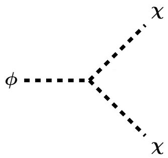
Interactions

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

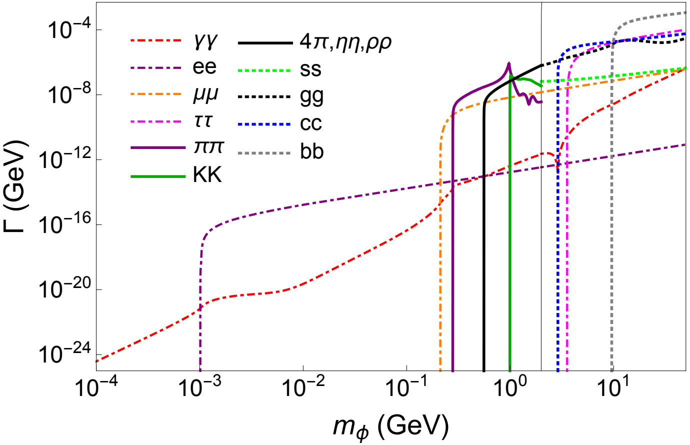
$$C_{h\chi\chi} = \lambda_{H\chi} v_H c_\theta - \mu_{\Phi\chi} s_\theta,$$
$$C_{\phi\chi\chi} = \lambda_{H\chi} v_H s_\theta + \mu_{\Phi\chi} c_\theta,$$
$$C_{hh\chi\chi} = \lambda_{H\chi} c_\theta^2 + \lambda_{\Phi\chi} s_\theta^2,$$
$$C_{\phi h\chi\chi} = \lambda_{H\chi} c_\theta s_\theta - \lambda_{\Phi\chi}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



suppressed by mixing angle



not suppressed by mixing angle



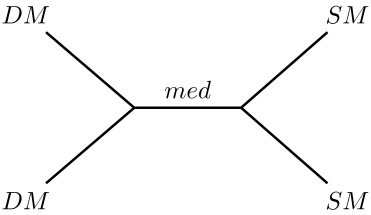
$$\Gamma\left(\phi \to \mathrm{SMs}\right) = \sin^2\theta \;\; \Gamma(h_{\mathrm{SM}} \to \mathrm{SMs})|_{m^2_{h_{\mathrm{SM}}} \to m^2_\phi}$$

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

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

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

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

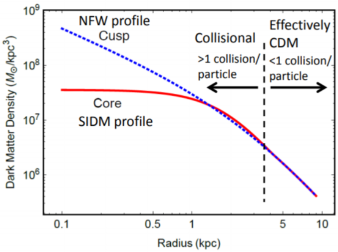
$$s \simeq m^2_\phi (1 + v^2/4)/(1 + v_R^2/8)^2$$

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

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

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

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

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

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

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

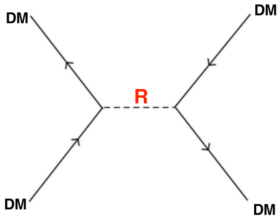
A velocity-dependence in DM self-scattering

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

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

t/u - channel

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

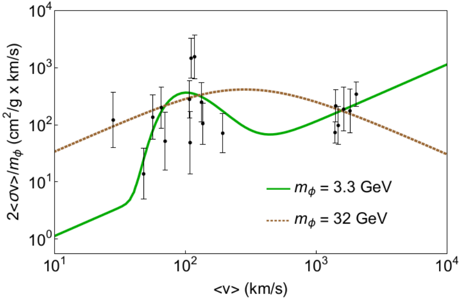
$$E(v) = \frac{1}{2}\frac{m}{2}v^2 \quad \text{and} \quad S = \frac{2J_R + 1}{(2J_{\rm DM}+1)^2}$$

L — partial wave

γ — couplings

v_R — **near resonance**

Resonant self-interaction



Viable parameter region

$m_\phi \simeq \mathcal{O}(10\text{ GeV}),\quad v_R \xleftarrow{\text{correlated}}\!\!\rightarrow \gamma_\phi,\quad \sigma_0$ arbitrary → **Broad resonance**

$m_\phi < 10\text{ GeV},\quad v_R \sim 100\text{ km/s},\quad \sigma_0/m_\chi \sim 0.1\text{ cm}^2/\text{g}$

$\gamma_\phi \propto m_\phi^3$

Narrow resonance

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

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

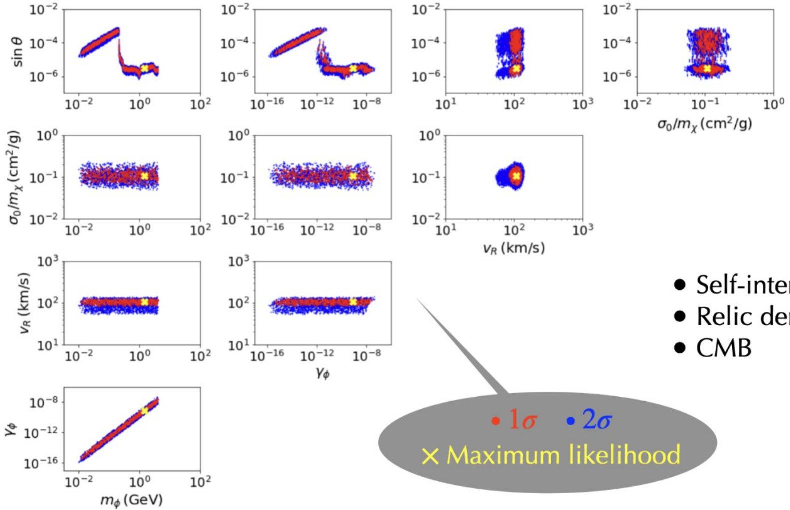
- We estimate the efficiency $f_{\rm eff}(m_\chi)$ taking only leptonic final states into account

- PLANCK ➡ $f_{\rm eff}(m_\chi)\,\langle\sigma v\rangle_{v_{\rm DM}}/m_\chi \leq 4.1\times10^{-28}$ cm³/s/GeV at 95% C.L.

⬇

Mediator mass above ~ 4 GeV is excluded

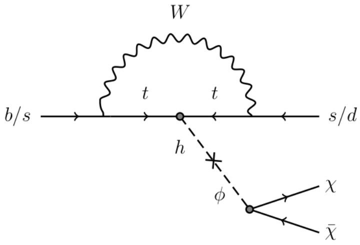
Parameter space



- Self-interaction
- Relic density
- CMB

How to probe this model ???

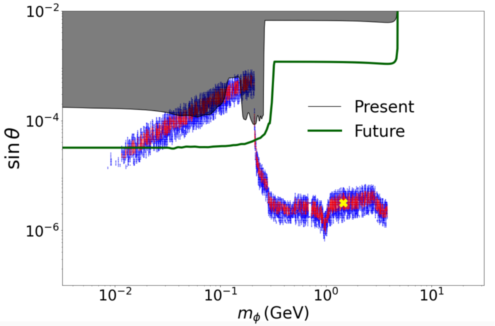
the light mediator can be probed in the searches for
invisible decays of rare mesons



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

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

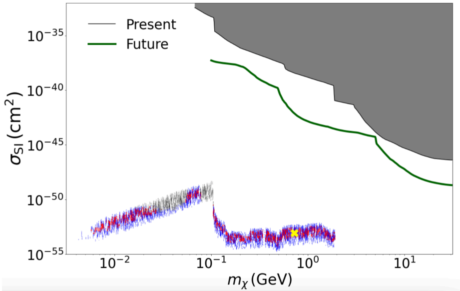
$$\Gamma(K_L \to \pi^0 \phi) = \frac{|C_{sd}|^2}{64\pi m_{K_L}^3} \left(\frac{m_{K_L}^2 - m_{\pi^0}^2}{m_s - m_d}\right)^2 \sqrt{(m_{K_L}^2 - m_{\pi^0}^2 - m_\phi^2)^2 - 4 m_{\pi^0}^2 m_\phi^2}$$



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

Direct detection

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



- **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

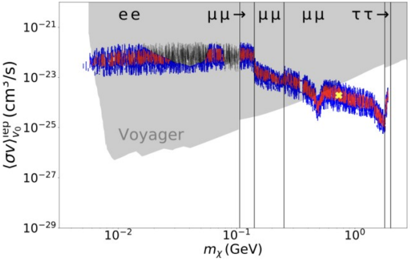
Cosmic ray observations

- 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*]

$\rho_{DM}(r_\odot) = 0.25 \pm 0.11$ 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

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

- $v_0 = 400$ km/s

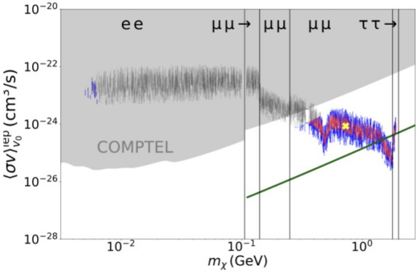
$$\frac{d\Phi_\gamma}{dE_\gamma} \simeq \left[\frac{\langle\sigma v\rangle_{v_0}}{8\pi m_\chi^2}\sum_{f_{\rm SM}} {\rm Br}\,(\chi\chi\to f_{\rm SM})\,\frac{dN_\gamma}{dE_\gamma}\bigg|_{f_{\rm SM}}\right]\times\left[\int_{\Delta\Omega} d\Omega\int_{\rm l.o.s} ds\,\rho_{\rm DM}^2\right]$$

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

- 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

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
- $\sin\theta$
- $C_{h\chi\chi}$
- $C_{\phi\phi h}$
- $C_{\phi\phi\phi}$
- $C_{\phi\phi\chi\chi}$
- $C_{\phi\phi\phi\phi}$

SIDM

II. SIDM halo model. Scattering between DM particles is more prevalent in the halo center where the DM density is largest. It is useful to divide the halo into two regions, separated by a characteristic radius r_1 where the average scattering rate per particle times the halo age ($t_{\rm age}$) is equal to unity. Thus,

$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1)\, t_{\rm age} \approx 1\,, \tag{1}$$

where σ is the scattering cross section, m is the DM particle mass, v is the relative velocity between DM particles and $\langle \ldots \rangle$ denotes ensemble averaging. Since we do not assume σ to be constant in velocity, we find it more convenient to quote $\langle \sigma v \rangle / m$ rather than σ/m. We set $t_{\rm age} = 5$ and 10 Gyr for clusters and galaxies, respectively. Although Eq. (1) is a dramatic simplification for time integration over the assembly history of a halo, we show by comparing to numerical simulations that it works remarkably well.

$$\nabla^2 \ln \rho_{\rm DM}(r) = -\frac{4\pi}{\sigma_{v0}^2} G \left[\rho_{\rm DM}(r) + \rho_{\rm baryon}(r)\right]$$

Phys. Rev. Lett. 116, 041302 (2016)

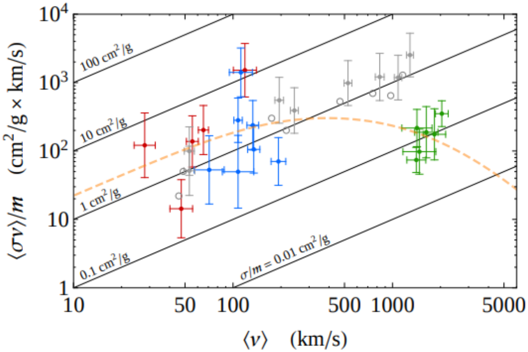
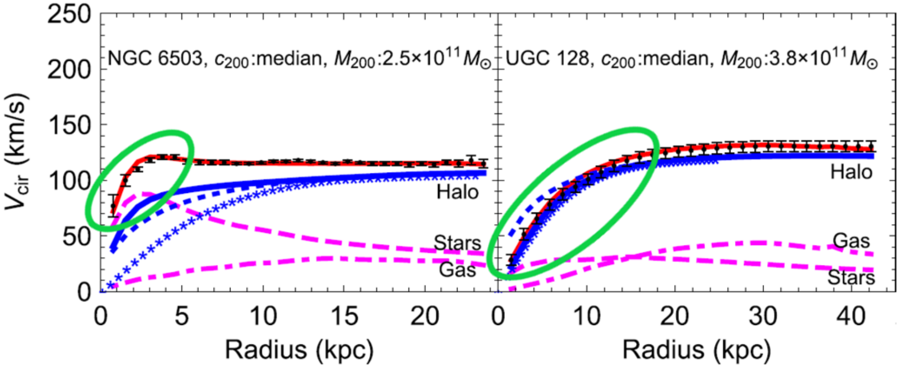


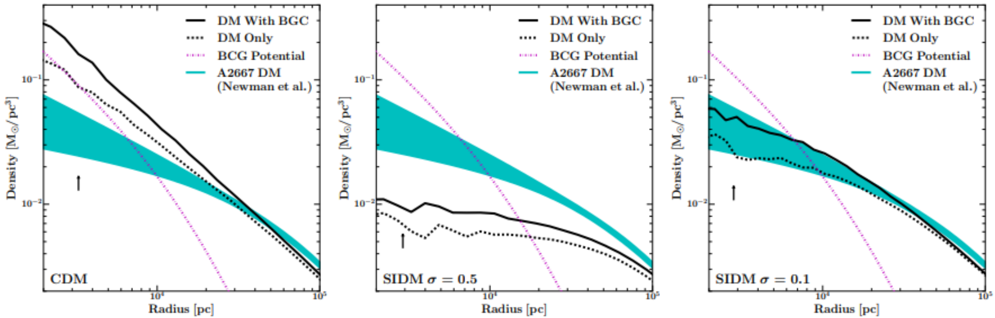
FIG. 1: Self-interaction cross section measured from astrophysical data, given as the velocity-weighted cross section per unit mass as a function of mean collision velocity. Data includes dwarfs (red), LSBs (blue) and clusters (green), as well as halos from SIDM N-body simulations with $\sigma/m = 1$ cm^2/g (gray). Diagonal lines are contours of constant σ/m and the dashed curve is the velocity-dependent cross section from our best-fit dark photon model

Diversity problem



Kamada et. al, PhysRevLett.119.111102

Diversity problem



Kamada et. al, PhysRevLett.119.111102

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

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

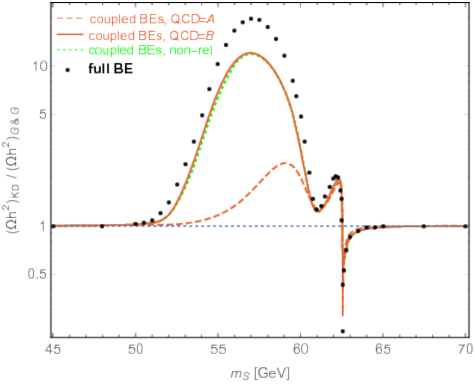
$$h_i(T_D) = (15x_i^4)/(4\pi^4) \int_1^\infty dy\, (4y^2-1)\sqrt{y^2-1}/(e^{x_i y}-1) \qquad x_i \equiv m_i/T_D$$

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

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

Early Kinetic Decoupling

- Small SM-mediator coupling reduces scattering rate between DM and SM particles in the thermal bath
- Suppressed scattering rate causes DM to kinetically decouple **much earlier** than the standard freeze-out case
- Phase space distribution differs from standard WIMP scenario.
- Drastic drop in relic density around resonance than standard case ⇒ smaller DM-SM coupling for EKD to maintain right relic



Binder et. al, 2017

- The uncertainty on the "the relativistic degrees of freedom" leads to 10% ambiguity in the relic abundance when the freeze-out temperature is around the QCD phase transition
- The relic abundance calculated by taking all relevant scattering processes into account is the same as the one computed assuming no scattering between DM and SM particles at around 10 % level.
- 20 % of $\Omega_{\rm DM} h^2$ adopted as the standard deviation to take the ambiguities into account conservatively

We use **DRAKE** code to compute relic density with EKD

- Relic abundance including EKD effect becomes $\sim$ 10 times smaller than that without the effect, leading to the favored mixing angle evaluated including the effect being $\sim$ 6 times smaller than that without it.

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

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

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, $T_{kd} \sim \mathcal{O}(T_{\text{freeze-out}})$

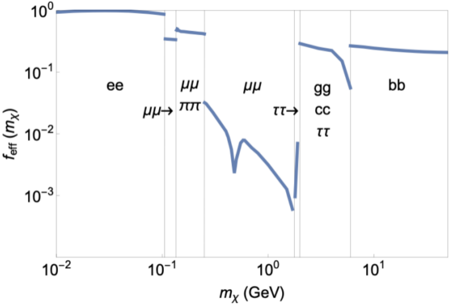
Since $v_{\rm DM} \ll v_R$ ➡ **only s-wave component contributes to annihilation at recombination**

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

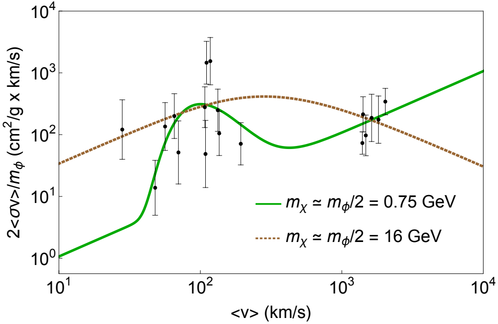
Fragmentation functions



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

But… 500 MeV $\le m_\phi \le$ 4 GeV

No robust way to calculate fragmentation function for hadronic final states



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

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

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

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