Light dark matter vis-à-vis resonance and its possible probes

[arXiv:2205.10149 [hep-ph]]

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LAPTh, Annecy
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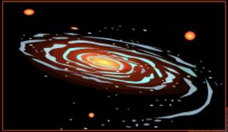
Evidence for Dark Matter



Rotation of galaxies

Velocities of galaxies in clusters

Velocities of stars in dwarf galaxies

Hot gas in galaxy clusters

Galaxy interactions

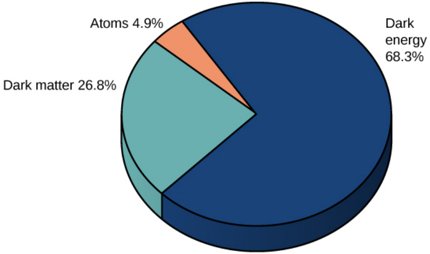
Collisions of galaxy clusters

Gravitational lensing

credit : Caty Pilachowski

Some known facts

Cold:	moves much slower than c
Pressureless:	gravitational attractive, clusters
Dark :	no/weakly electromagnetic interaction
Collisionless:	no/weakly self-interaction or interaction with baryons
Abundance:	amount of dark matter today known



Some unknown facts

What is DM? What is its nature?

~~Cold~~ → How cold it is? WDM

~~Pressureless~~ → Cluster on all scales?

~~Dark (transparent)~~ → Non-gravitational interaction? Milicharged DM

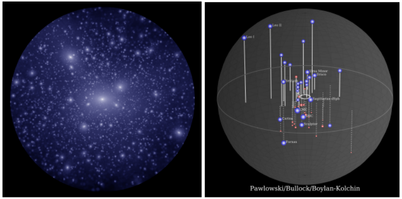
~~Collisionless~~ → How small self-interaction SIDM

Although still behaves
like CDM on large scales

Small scale behaviour: still weakly constrained
and small scale challenges

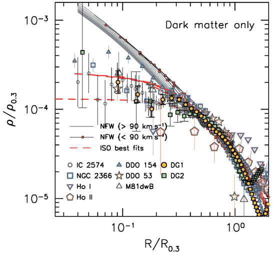
Small scale crisis

Missing Satellites


Pawlowski/Bullock/Boylan-Kolchin

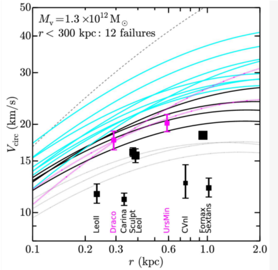
Discrepancy between the # of satellites
predicted by ΛCDM
and the # observed satellites

Core-cusp problem

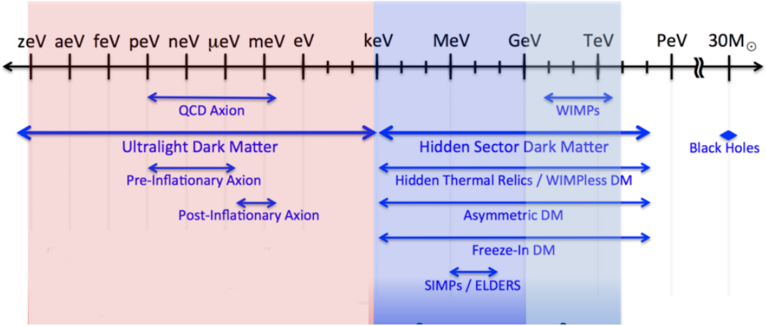


N-body simulations (CDM) show cuspy density profiles (NFW), whereas observations indicate a cored structure.

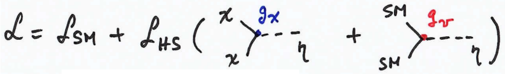
Too big to fail



Particle nature of dark matter

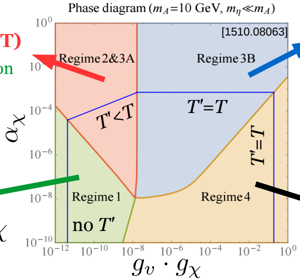


Different thermal histories of DM

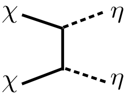


Dark Freeze-out (T' < T)

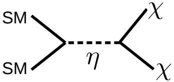
- Freeze-in production
+ dark annihilation



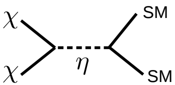
Dark Freeze-out (T' = T)



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

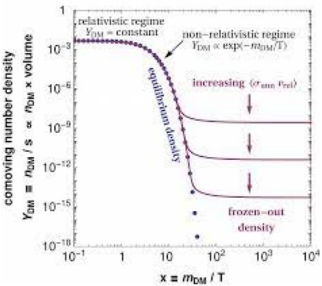
Electroweak mediators ⇒ Lee – Weinberg window

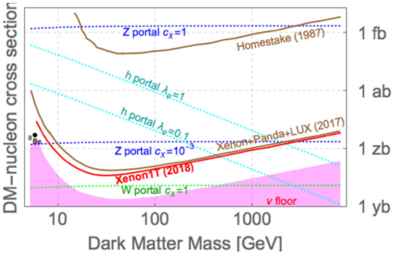
$$\sigma(v/c) \propto \begin{cases} G_F^2\, m_{DM}^2 & \text{for } m_{DM} \ll m_W \\ 1/m_{DM}^2 & \text{for } m_{DM} \gg m_W \end{cases} \quad \Rightarrow \quad \text{few GeV} < m_{DM} < \text{few TeV}$$

It modeled decades of direct search experiment designs

WIMP miracle

But.....



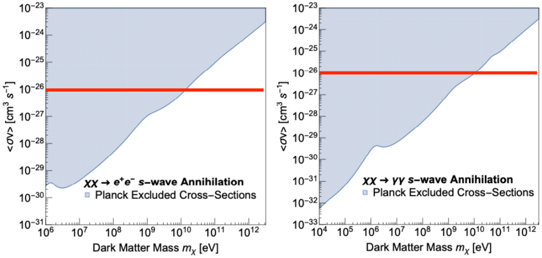


Maybe lighter dark sectors?

Status of Light thermal DM

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*

Let’s take an example....

The model

New particles

scalar 1 : χ, Z_2 odd → **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

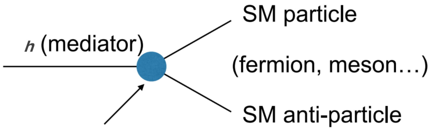
$$H = (0, v_H + h')^T/\sqrt{2},\ v_H \simeq 246\,\mathrm{GeV}$$
$$\Phi = v_\Phi + \phi',\ v_\Phi = 0$$

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

Interactions

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

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



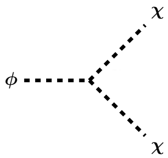
h (mediator)

SM particle

(fermion, meson…)

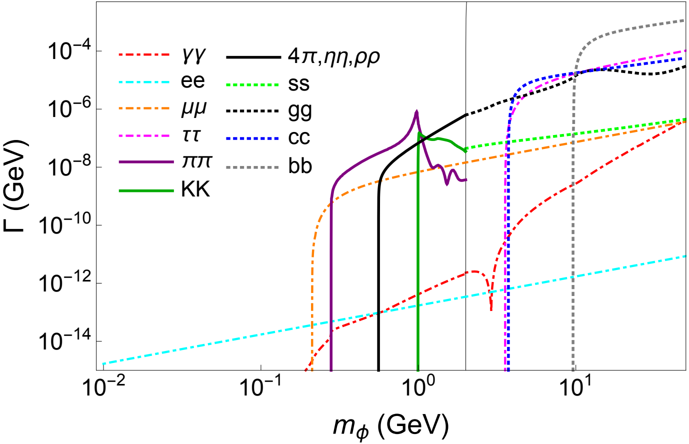
SM anti-particle

suppressed by mixing angle



not suppressed by mixing angle

Decay of the mediator



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

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

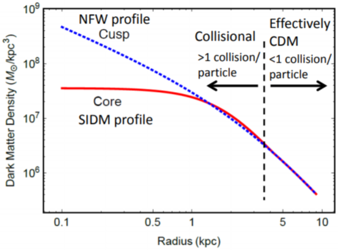
Parameters

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

Self-interactions

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?

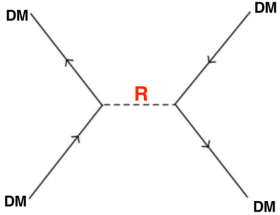
Possibilities : a light mediator

Spergel & Steinhardt 1999, Bringmann, et al. 2016

OR..

SIDM via a resonance

[XC, C. Garcia-Cely, H. Murayama, 1810.04709]



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

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

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

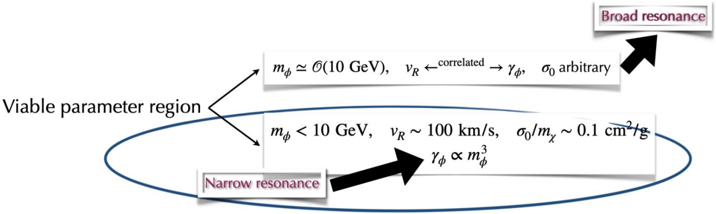
$$\Gamma(v) = m_R \gamma v^{2L+1}$$

L — partial wave

γ — couplings

v_R — **near resonance**

Xiaoyong Chu, Humboldt Kolleg 2019



Viable parameter region

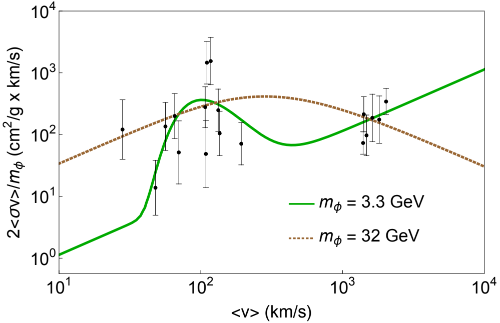
$m_\phi \simeq \mathcal{O}(10\text{ GeV}),\quad v_R \xleftrightarrow{\text{correlated}} \gamma_\phi,\quad \sigma_0$ arbitrary

Broad resonance

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

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

Narrow resonance



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

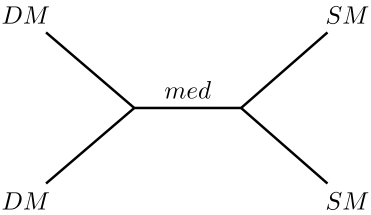
$(5035\,\text{km/s},\ 0,\ 10^{-1.1},\ 32\,\text{GeV})$

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

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

Relic density

- 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

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

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

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

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

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

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

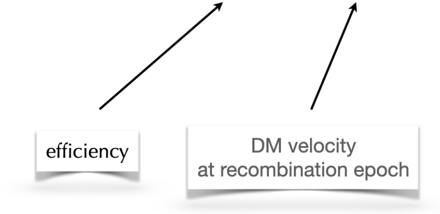
$$\boxed{10^{-6} \lesssim \sin\theta \lesssim 10^{-3}}$$

CMB

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

The velocity is estimated to be

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

$T_\gamma = 0.235\ {\rm eV}$

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

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

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

- PLANCK

$$f_{\rm eff}(m_\chi)\,\langle\sigma v\rangle_{v_{\rm DM}}/m_\chi \leq 4.1\times10^{-28}\,\text{cm}^3/\text{s}/\text{GeV at 95\% C.L.}$$

Mediator mass above ~ 4 GeV is excluded

But… $500\ \text{MeV} \leq m_\phi \leq 4\ \text{GeV}$

No robust way to calculate fragmentation function for hadronic final states

Another limit from CMB

ΔN_{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 (ΔN_{eff})
- Assuming the instantaneous neutrino decoupling and no heating of the neutrinos from electrons and positrons

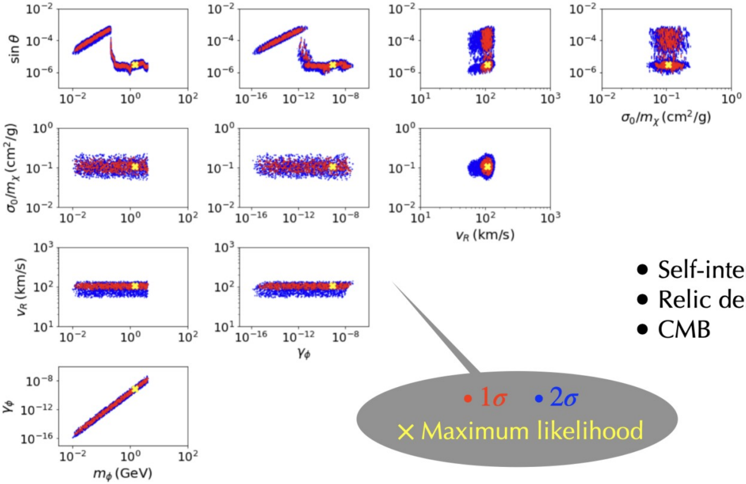
$$N_{\mathrm{eff}} \simeq 3 \left\{ 1 + \frac{45}{11\pi^2 T_D^3} \left[s_\chi(T_D) + s_\phi(T_D) \right] \right\}^{-4/3}, \qquad s_i(T_D) = h_i(T_D) \frac{2\pi^2}{45} T_D^3,$$

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

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

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

Likelihood



• 1σ • 2σ

× Maximum likelihood

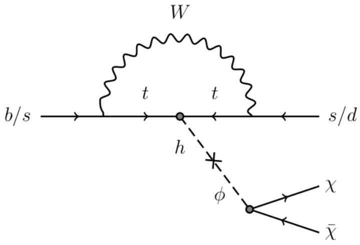
- Self-interaction
- Relic density
- CMB

How to probe this model ???

Collider searches

the light mediator can be probed in the searches for

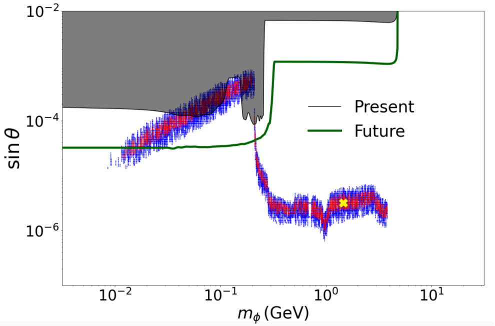
invisible decays of rare mesons



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

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

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

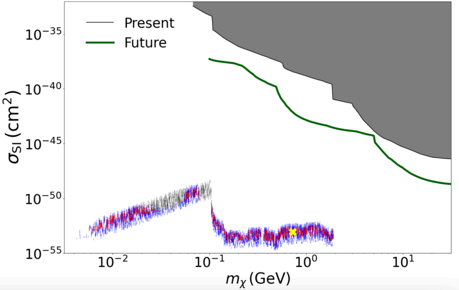


- **Current limits** : Belle, BaBar, E949, NA62, and KOTO at 90% C.L

- **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

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

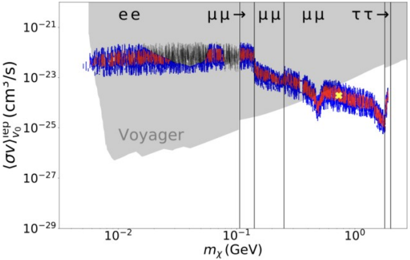
- DM annihilation into leptons contributes to cosmic ray flux
- Signal flux ∝
  - (DM density)^2
  - $\langle \sigma v \rangle_{v_0}$

Uncertainties

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

$\rho_{\rm DM}(r_\odot) = 0.25 \pm 0.11\ \mathrm{GeV/cm^3}$ [*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 $\leq m_\chi \leq$ 2 GeV

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

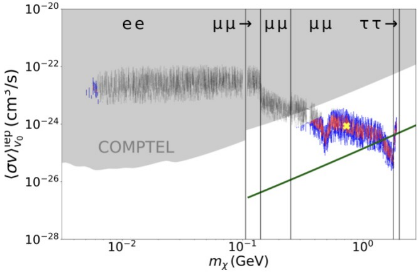
- $v_0 = 400$ km/s

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

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

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