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Abstract:

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Impeding and Enabling Light Thermal Relic Dark Matter

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New Directions in Dark Matter and Neutrino Physics
Perimeter Institute
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JHEP12(2016)033
with Joachim Kopp, Jia Liu, Xiao-Ping Wang & Wei Xue
arxiv:1702.07716, submitted to PRD
with James Cline, Hongwan Liu & Wei Xue

Light dark matter

~MeV ~GeV ~TeV ~100 TeV

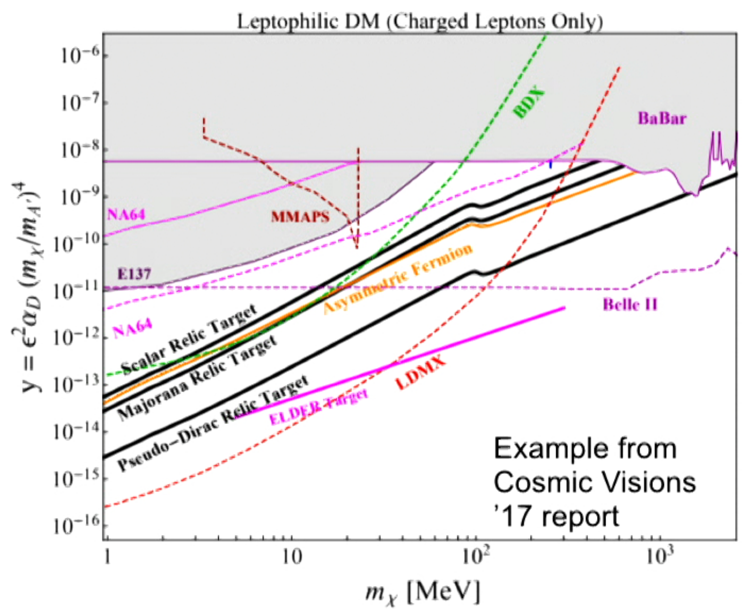
nonthermal (with some caveats)

Traditional WIMP window

not pointlike (also with caveats)

new thermal target?

- Thermal dark matter: was once in thermal equilibrium with Standard Model.
- Thermal relic: abundance determined by annihilation rate.
- If annihilation is to SM particles, implies lower bound on DM-SM couplings - highly predictive.

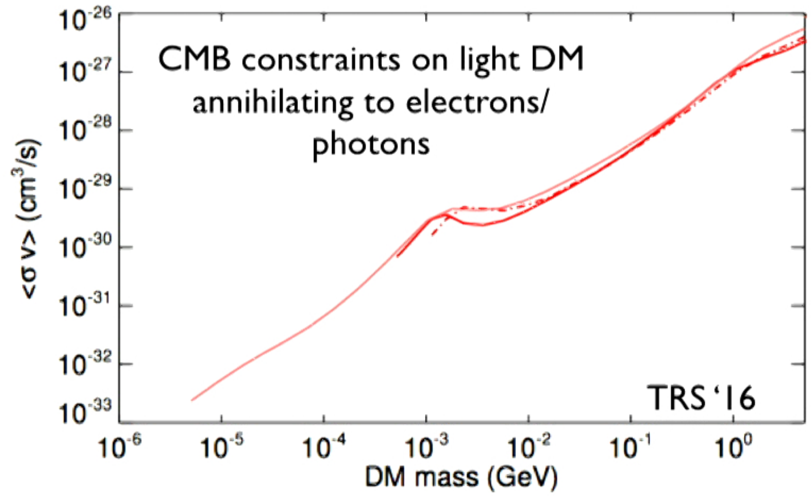


Example from Cosmic Visions '17 report

Challenges for sub-GeV thermal relic dark matter

- Obtaining correct relic density (with purely light dark sector) requires small couplings or suppressed annihilation:

$$\langle \sigma v \rangle \sim \alpha_D^2 / m_\chi^2 \sim 1/M_{\rm Pl} T_{\rm eq}$$
$$\alpha_D \sim 10^{-5} (m_\chi / 1{\rm GeV})$$



- Alternatively, for light DM coupled to weak-scale or heavier mediators, requires large couplings (Lee-Weinberg):

$$\langle \sigma v \rangle \sim \alpha_D^2 m_\chi^2 / m_M^4$$
$$\alpha_D \sim 10^{-1} (m_M / 100{\rm GeV})^2 (m_\chi / 1{\rm GeV})^{-1}$$

- Avoiding late-time constraints, e.g. from cosmic microwave background, requires further suppressed cross section: $\langle \sigma v \rangle \lesssim (m_\chi / 1{\rm GeV}) \times 10^{-27} {\rm cm}^3/{\rm s}$
- Possible solutions: p-wave suppression, asymmetric DM, SIMPs, forbidden DM…

This talk

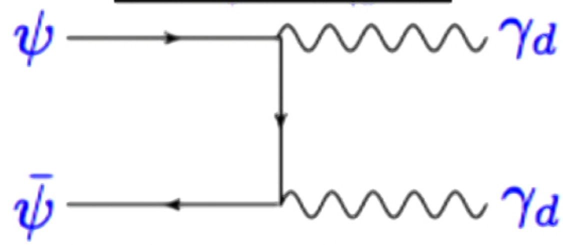
- Introduce two parameter regimes that naturally yield light thermal relic dark matter for O(0.01-1) couplings in single-scale dark sectors, while evading indirect detection limits.
- “Not forbidden DM”: 3-body annihilations dominate freezeout.
- “Impeded DM”: Phase-space-suppressed DM annihilation from small mass splittings.

Dark photons

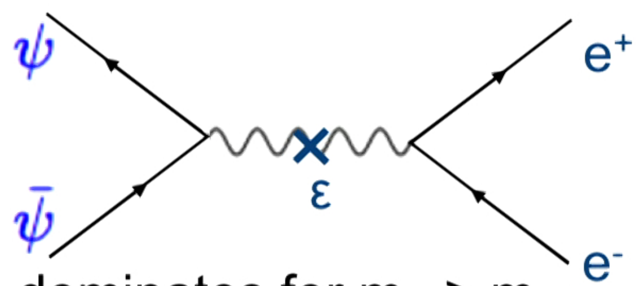
- Dark photon = gauge boson of dark U(1) gauge symmetry.
- Dark matter is charged under dark U(1).
- Simple "vector portal" for dark sector-visible sector interactions, via dim-4 kinetic mixing term between dark and visible photons.

$$\mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F^{\mu\nu} F^{D}_{\mu\nu}$$

<u>Standard lore:</u>



dominates for $m_\psi < m_{\gamma D}$



dominates for $m_\psi > m_{\gamma D}$

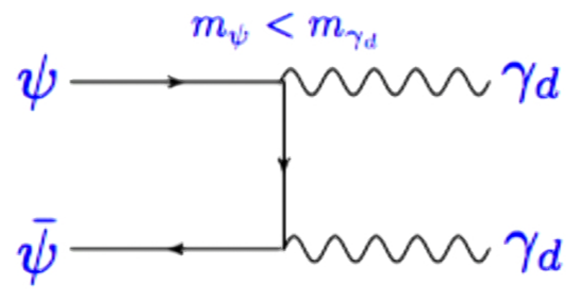
Forbidden dark matter

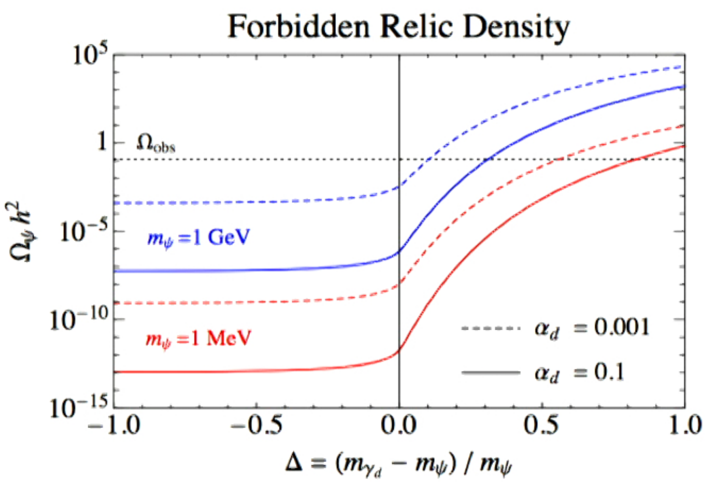
d'Agnolo & Ruderman, Phys. Rev. Lett. 115, 061301 (2015)

- Dominant annihilation channel during freezeout is DM DM → $\gamma_D\gamma_D$, where:

$$m_{\rm DM} < m_{\gamma_D} < m_{\rm DM} + {\rm KE}$$

- Requires DM on tail of the Boltzmann distribution: exponential suppression allows light DM with moderate-to-large couplings.
- At late times: forbidden channel is negligible, indirect signals dominated by direct annihilation to SM particles, controlled by small mixings.
- Requires a dark-sector particle with mass comparable to the DM, but slightly heavier.



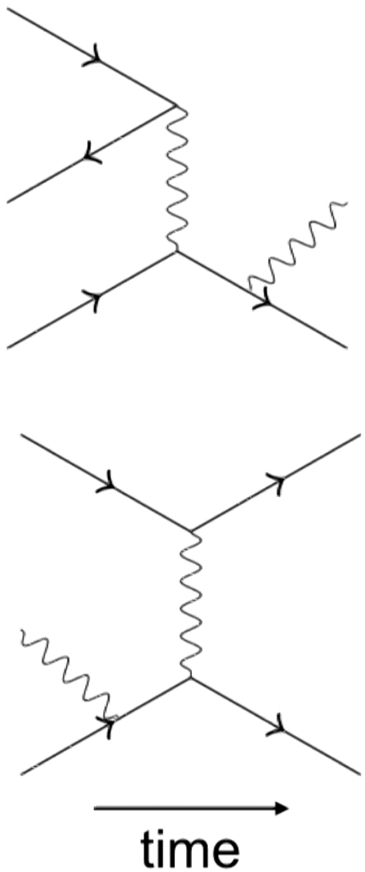


Beyond forbidden channels

- However, as 2→2 annihilations become increasingly suppressed, other channels can play key roles.
- Simple example: consider model where DM is a Dirac fermion charged under a dark U(1).
- If the dark U(1) is broken such that the dark photon has mass satisfying:

$$2m_{\mathrm{DM}} > m_{\gamma_D} > m_{\mathrm{DM}}$$

- Then 3-body annihilations can dominate freezeout (also seen e.g. in SIMP models).



~~Forbidden~~ DM cosmology

- Need to solve coupled Boltzmann equations for DM and dark photon populations, including 2- and 3-body annihilation processes, and dark photon decays.

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\frac{1}{4}\langle\sigma v^2\rangle_{\substack{\chi\chi\bar{\chi}\\ \to\chi A'}} \left(n_\chi^3 - n_{\chi,0}^2 n_\chi \frac{n_{A'}}{n_{A',0}}\right) + \langle\sigma v\rangle_{\substack{A'A'\\ \to\bar{\chi}\chi}} \left(n_{A'}^2 - n_{A',0}^2 \frac{n_\chi^2}{n_{\chi,0}^2}\right)$$

$$\frac{dn_{A'}}{dt} + 3Hn_{A'} = \frac{1}{8}\langle\sigma v^2\rangle_{\substack{\chi\chi\bar{\chi}\\ \to\chi A'}} \left(n_\chi^3 - n_{\chi,0}^2 n_\chi \frac{n_{A'}}{n_{A',0}}\right) - \frac{1}{4}\left(\langle\sigma v^2\rangle_{\substack{\chi\bar{\chi}A'\\ \to\chi\bar{\chi}}} + \langle\sigma v^2\rangle_{\substack{\chi\chi A'\\ \to\chi\chi}}\right)\left(n_\chi^2 n_{A'} - n_\chi^2 n_{A',0}\right)$$
$$-\langle\sigma v\rangle_{\substack{A'A'\\ \to\bar{\chi}\chi}} \left(n_{A'}^2 - n_{A',0}^2 \frac{n_\chi^2}{n_{\chi,0}^2}\right) - \Gamma_{A'\to f\bar{f}}\left(n_{A'} - n_{A',0}\right)$$

- In general: two functions to solve for, n_χ and $n_{A'}$. Two fastest processes dominate evolution equations: fastest process gives one constraint on n_χ and $n_{A'}$, second-fastest maintains both n_χ and $n_{A'}$ at equilibrium values if it is faster than Hubble.

- Thus freezeout begins when second-fastest process rate becomes comparable to H; interplay between fastest and second-fastest processes controls freezeout.

~~Forbidden~~ DM cosmology

- Classic freezeout: decay of A' is fastest process, fast enough to keep $n_{A'}$ in equilibrium. Freezeout of n_χ set by second-fastest process, annihilation $\chi\chi \longleftrightarrow A'A'$.
- Not-forbidden DM: either decay + 3→2 annihilation, or 2→2 + 3→2 annihilation, can also control freezeout - wide range of possible scenarios.
- When should 3→2 annihilation dominate?

$n_{i,0} \sim \exp(-m_i/T)$, in equilibrium

$$\Gamma_{\substack{\chi\chi\bar{\chi} \\ \to \chi A'}} \sim \langle \sigma v^2 \rangle_{\substack{\chi\chi\bar{\chi} \\ \to \chi A'}} n_{\chi,0}^2 \sim \exp(-2m_\chi/T)$$

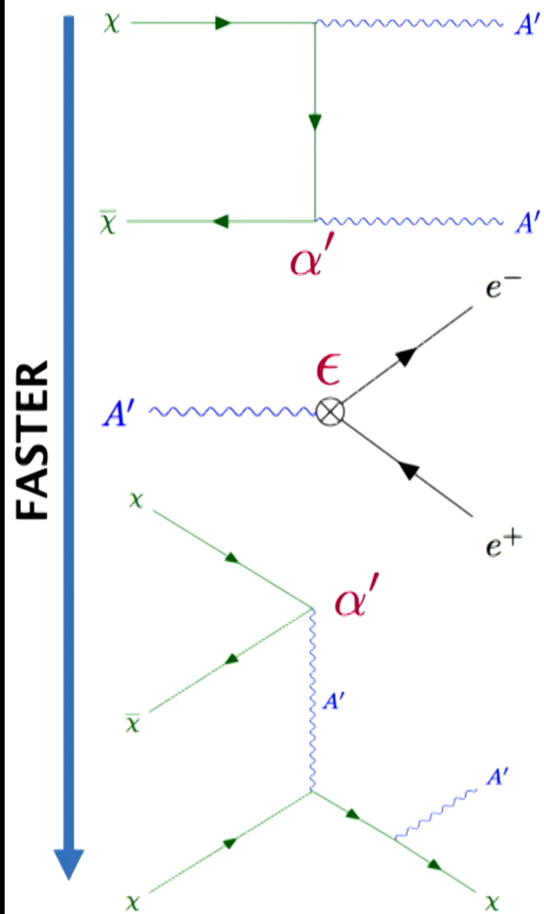
$$\begin{aligned} \Gamma_{\bar{\chi}\chi \to A'A'} &\sim \langle \sigma v \rangle_{\bar{\chi}\chi \to A'A'} n_{\chi,0} \\ &\sim \langle \sigma v \rangle_{A'A' \to \bar{\chi}\chi} n_{A',0}^2 / n_{\chi,0} \\ &\sim \exp(-(2m_{A'} - m_\chi)/T) \end{aligned}$$

3→2 annihilation exponentially enhanced (suppressed) relative to 2→2 for:

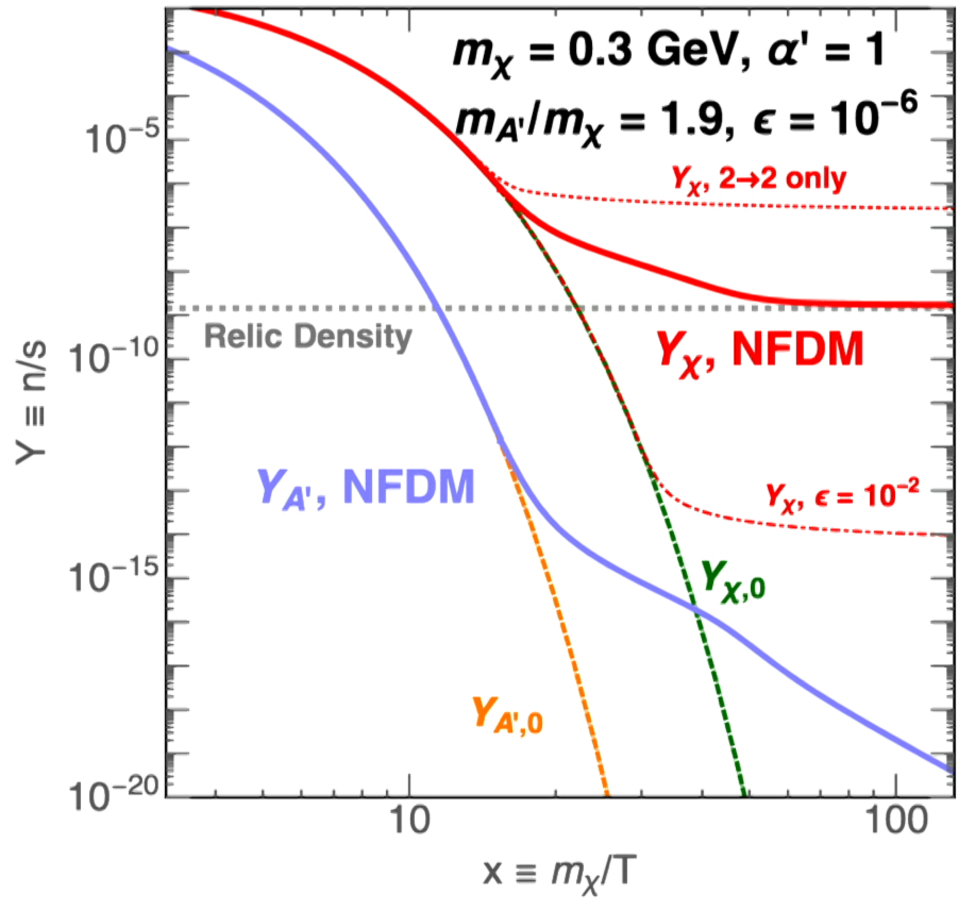
$$m_{A'} \gtrsim (\lesssim) \frac{3}{2} m_\chi$$

Not-forbidden DM region

Freezeout



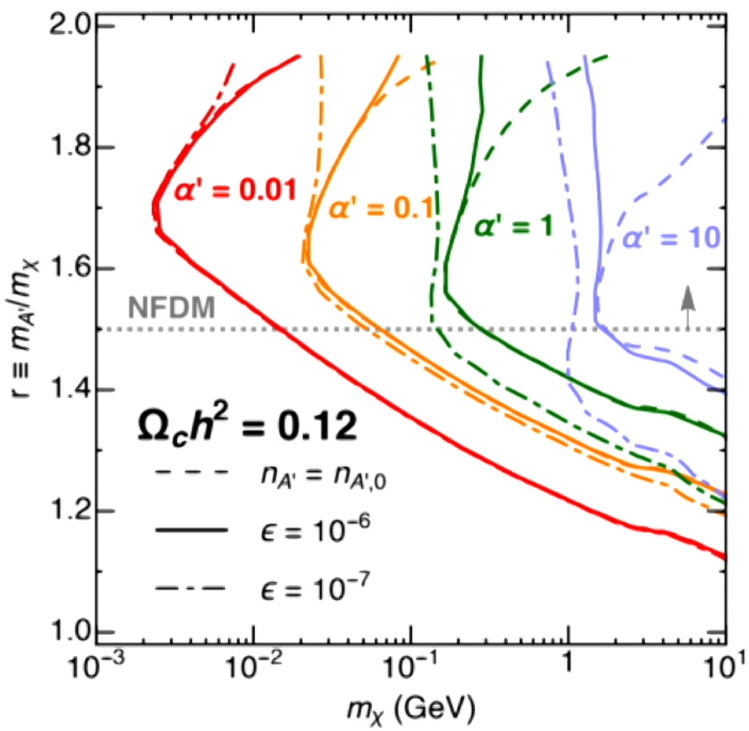
FASTER
χ
A′
χ̄
A′
α′
e⁻
ϵ
A′
e⁺
χ
α′
χ̄
A′
A′
χ
χ



m_χ = 0.3 GeV, α' = 1
$m_{A'}/m_\chi$ = 1.9, ϵ = 10^{-6}
Y_χ, 2→2 only
Relic Density
Y_χ, NFDM
$Y_{A'}$, NFDM
Y_χ, ϵ = 10^{-2}
$Y_{\chi,0}$
$Y_{A',0}$
Y ≡ n/s
x ≡ m_χ/T
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10
100

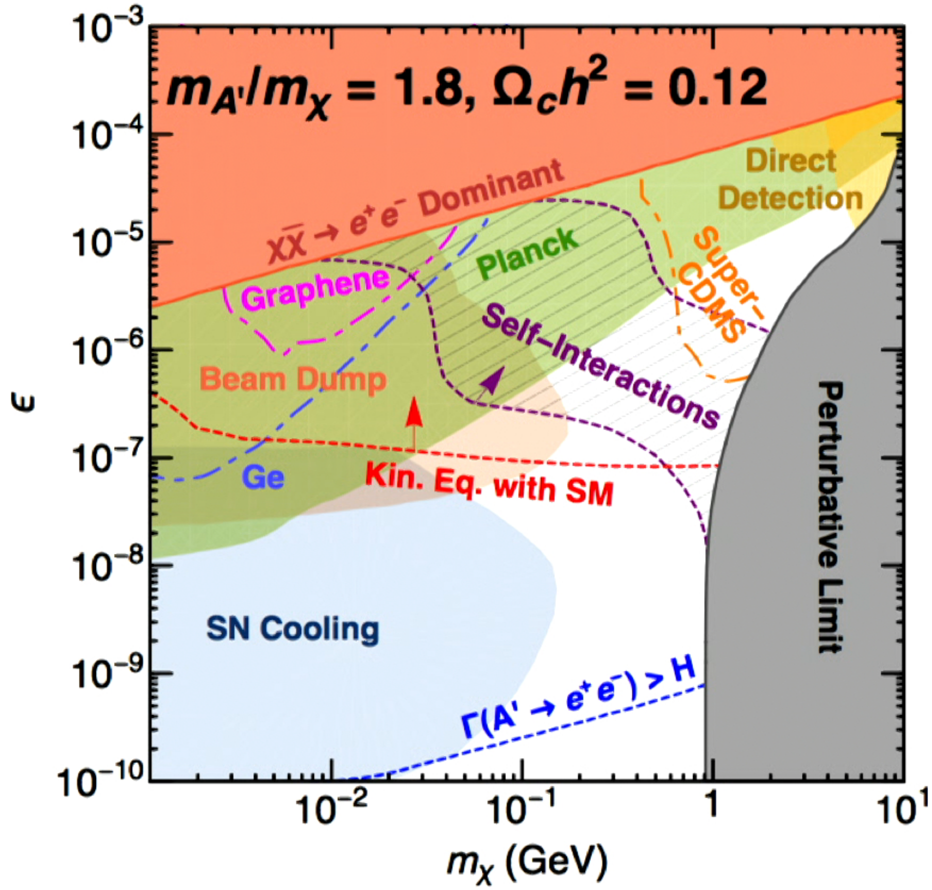
Relic density

- Lower half of plot: “forbidden DM” region, forbidden 2→2 process dominates, strong dependence on mass ratio r.
- Upper half of plot: NFDM region, kinematically allowed 3→2 process dominates.
- Coupling needed to yield correct relic density no longer highly sensitive to $m_{A'}$
- Similar to standard WIMP, but without requiring very small/large couplings for MeV-GeV DM.

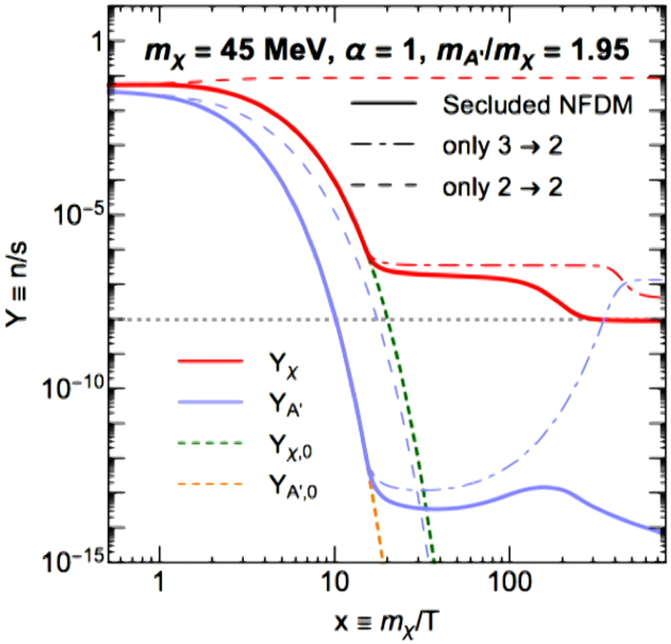


Constraints on NFDM

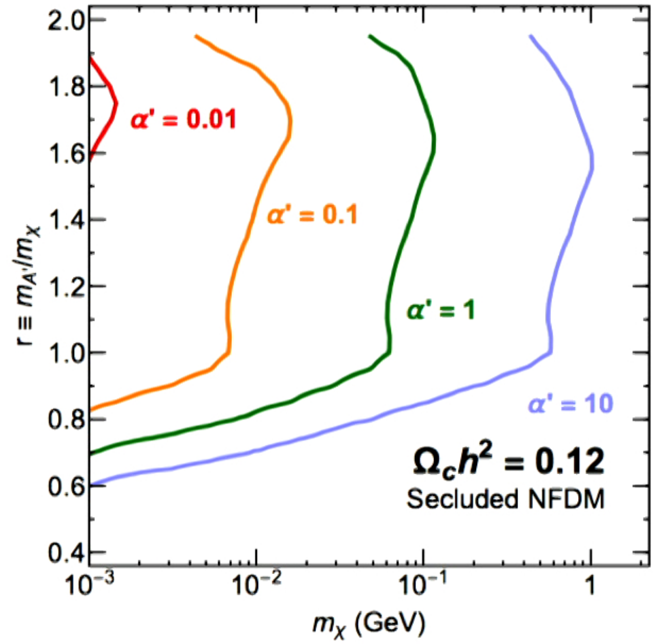
- Coupling chosen to produce correct relic density.
- CMB limits on annihilation through s-channel A' to e^+e^- (3-body annihilation negligible due to low DM density).
- Beam dump, SN cooling limits bound dark photon directly.
- Allowed region naturally predicts self-interaction of correct size to explain small-scale structure issues.



Secluded enabled DM



(a)



(b)

- Switch off decays of A'; freezeout determined by interplay of 3→2 and 2→2 processes.
- Note: need to add more ingredients to dark sector in this case, to avoid an overly high DM temperature (as dark sector cannot dissipate entropy into the Standard Model).

Impeded dark matter

- Similar to (not) forbidden DM, but mass splittings between DM and annihilation products (denoted X) are much smaller - do not cause exponential suppression during freezeout.
- Define $\Delta = m_{DM} - m_X$. Δ can be either positive or negative.
  - Δ negative: similar to forbidden case. Annihilation exponentially suppressed below a characteristic velocity scale. For small Δ, this scale is usually far below freezeout, but can be relevant for indirect detection.
  - Δ positive: annihilation never forbidden, but phase space suppresses rate.

Phase space suppression

- For s-wave processes, matrix element for scattering/annihilation is momentum-independent.
- Consequently, cross section for any 2→2 process scales as (COM frame): $\sigma \propto \frac{1}{s} \frac{|\vec{p}_{\rm out}|}{|\vec{p}_{\rm in}|}$
- For non-relativistic DM, approximate s = (2 m_{DM})^2, initial momentum m_{DM} v_{rel}/2, so we have: $\sigma v_{\rm rel} \propto |\vec{p}_{\rm out}|$
- For typical DM annihilation to much lighter species, p_{out} ~ m_{DM}, so σv_{rel} is momentum-independent.
- For DM-DM scattering, p_{out} ~ m_{DM} v_{rel}, so σ is momentum-independent.
- For DM-DM annihilation to XX, with mass m_X:

$$
\begin{aligned}
p_{\rm out} &= \sqrt{E_{\rm DM}^2 - m_X^2} \\
&\approx \sqrt{(m_{\rm DM} + \frac{1}{2} m_{\rm DM} v_{\rm rel}^2/4 + m_X)(m_{\rm DM} + \frac{1}{2} m_{\rm DM} v_{\rm rel}^2/4 - m_X)} \\
&\approx 2 m_{\rm DM} \sqrt{\frac{2\Delta}{m_{\rm DM}} + \frac{1}{4} v_{\rm rel}^2}
\end{aligned}
$$

assuming non-relativistic DM

approximating $\Delta = m_{DM} - m_X << m_{DM}$

Impeded dark matter

- For $1 >> v_{rel}^2 >> 8 |\Delta| / m_{DM}$, behavior is the same independent of sign of Δ; σv_{rel} scales as v_{rel}, similar to scattering rather than s-wave annihilation.
- More mild velocity suppression than p-wave annihilation ($\sigma v_{rel} \propto v_{rel}^2$), but similar qualitative impact: suppresses indirect signals in objects/regions/epochs with small velocity dispersions, e.g. the epoch of recombination (no bound DM structures $\Rightarrow$ very small velocity dispersion) or dwarf galaxies.
- For $v_{rel}^2 < 8 |\Delta| / m_{DM}$, behavior depends on sign of Δ; for Δ negative, the annihilation becomes kinematically forbidden, for Δ positive, σv_{rel} becomes constant but with a phase-space suppression factor of order $(\Delta/m_{DM})^{1/2}$.

Example models

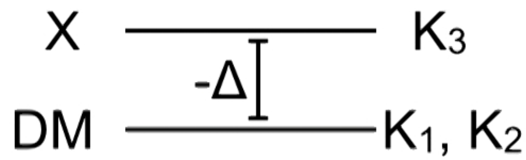
- Adapt examples of states with similar mass from Standard Model
  - Gauge bosons with masses connected by residual symmetry after breaking
  - Charged and neutral pions

Model	$SU(2)_d$ dark gauge boson		dark pion
mass splitting	$\Delta \simeq -\frac{1}{2}\varepsilon^2 m_{\rm DM}$, eq. (10)		$\Delta \simeq g'^2 f_\pi^2/(2m_\pi)$, eq. (28)
	$10^{-7} \lesssim \varepsilon \lesssim 10^{-3}$ $\Delta < 0$ small	$\varepsilon \gtrsim 10^{-3}$ $\Delta < 0$ large	$g' \gtrsim 0.05$ $\Delta > 0$
freeze-out	$\sigma v_{\rm rel} \propto v_{\rm rel}$		
CMB	$\sigma v_{\rm rel} \simeq 0$	$\sigma v_{\rm rel} \simeq 0$	$\sigma v_{\rm rel} \propto \sqrt{\frac{2\Delta}{m_{\rm DM}}}$
Galaxies	$\sigma v_{\rm rel} \propto v_{\rm rel}$		
Clusters			$\sigma v_{\rm rel} \propto \mathbf{BF} \times \sqrt{\frac{2\Delta}{m_{\rm DM}}}$

Example model: Δ < 0

- Dark sector consists of a dark SU(2) + dark scalar doublet Φ to break symmetry.

- DM is lightest SU(2) gauge boson(s); undergoes impeded annihilation to heavier SU(2) gauge bosons.

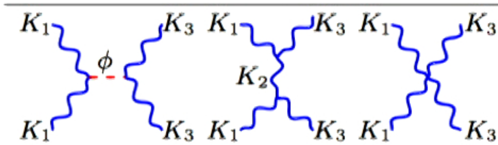
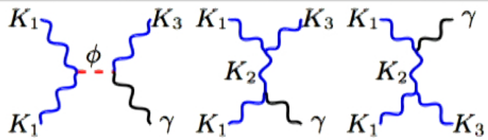
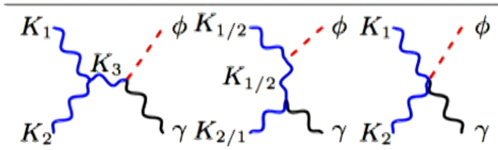
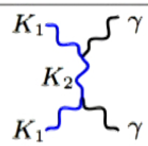
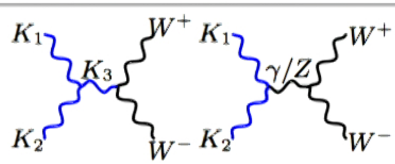
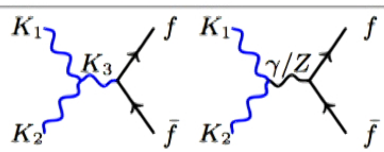


- Dark SU(2) coupled to SM through dimension-6 non-Abelian kinetic mixing term:

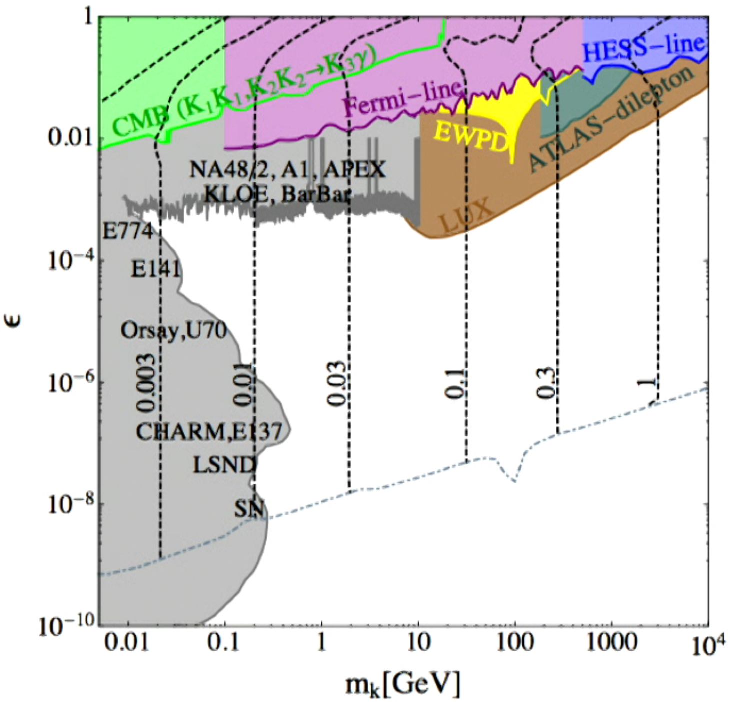
$$\mathcal{L}_{\rm mix} = \frac{1}{\Lambda^2}(\Phi^\dagger T^a \Phi) K^a_{\mu\nu} B_{\mu\nu}$$

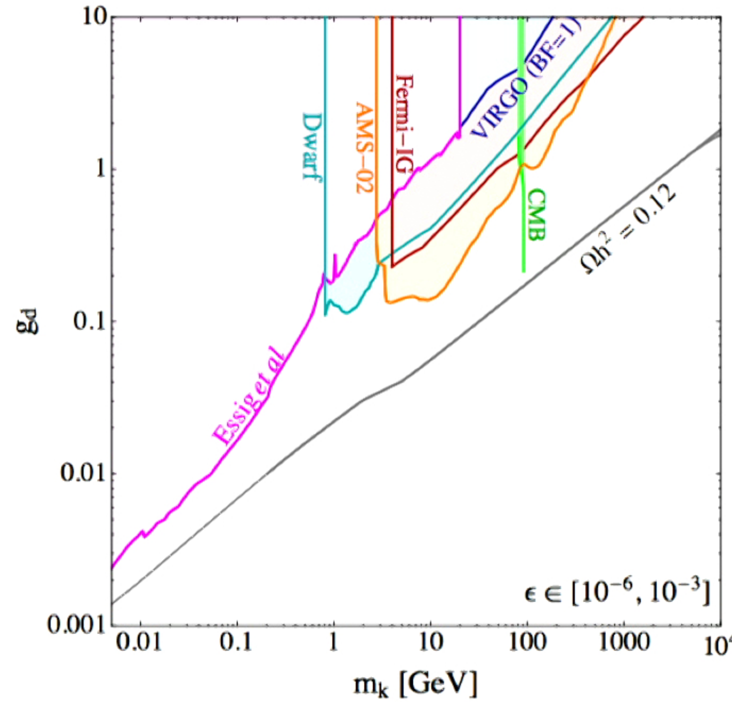
- After SU(2) breaking, only K_3^μ (denoting gauge bosons by K_a^μ) mixes with SM Z and photon fields - induces a mass splitting between K_3^μ (functions as unstable X) and K_1^μ , K_2^μ (constitute the DM).

$$\Delta \equiv m_k - m_{K_3} \simeq -\frac{m_k}{2}\frac{\varepsilon^2}{\cos^2\theta_w}\frac{(m_k^2 - \cos^2\theta_w m_{Z,\rm SM}^2)}{m_k^2 - m_{Z,\rm SM}^2} \qquad \varepsilon \equiv -v_d^2 \cos\theta_w/(2\Lambda^2)$$

process	$v_{\rm rel}$-dependence	ε-dependence	freeze-out	CMB	Indirect Detection
	$\sqrt{\frac{v_{\rm rel}^2}{4}+\frac{2\Delta}{m_{\rm DM}}}$	1	dominant	negligible	✓
	1	ε^2	subdominant	dominant	✓ (γ line)
	1	ε^2	subdominant (requires $m_\phi < 2m_k$)	dominant (requires $m_\phi < 2m_k$)	✓ (γ line if $m_\phi < 2m_k$)
	1	ε^4	negligible	negligible	negligible
	$v_{\rm rel}^2$	ε^2	subdominant	negligible	negligible
	$v_{\rm rel}^2$	ε^2	subdominant	negligible	negligible

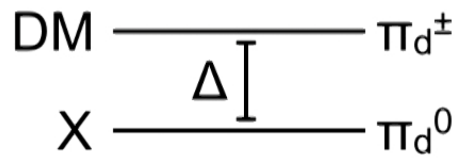
Constraints on dark SU(2) $\Delta < 0$ model



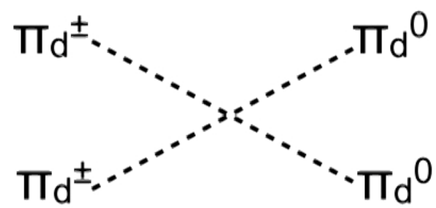


Example model: Δ > 0

- Dark sector has a SU(N) x U(1) gauge symmetry, based on SM strong+electromagnetic interactions. Contains two light "dark quarks", and a dark scalar field with U(1)-charge 2, which breaks the dark U(1) symmetry.



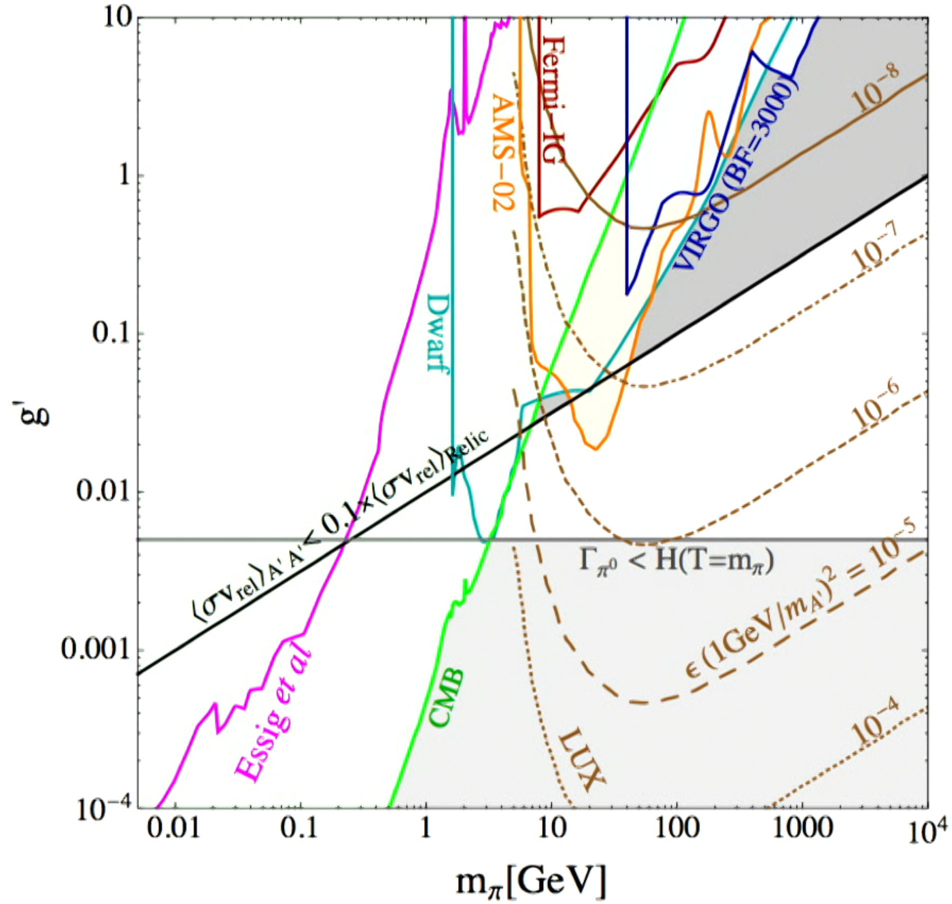
- Dark matter = dark "charged pions", stabilized by residual Z_2 symmetry after U(1) breaking.
- Freezeout dominated by impeded annihilation of DM to neutral pions.



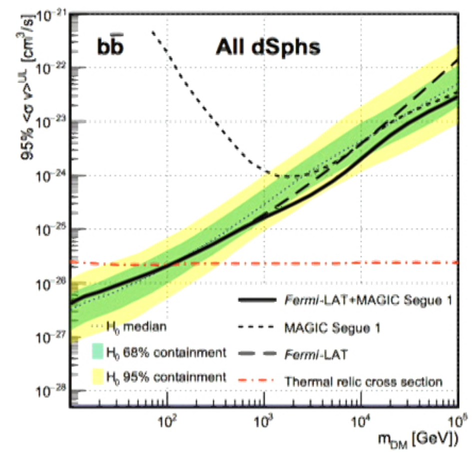
- Dark "neutral pion" decays to dark photons (through chiral anomaly), in analogy to SM.
- Dark photons kinetically mix with SM photon.
- Radiative mass splitting: $\Delta \equiv m_{\pi_d^\pm} - m_{\pi_d^0} \approx \frac{g'^2}{16\pi^2}\frac{\Lambda_N^2}{2m_\pi}$ $\Lambda_N = 4\pi f_\pi$

set by relic density

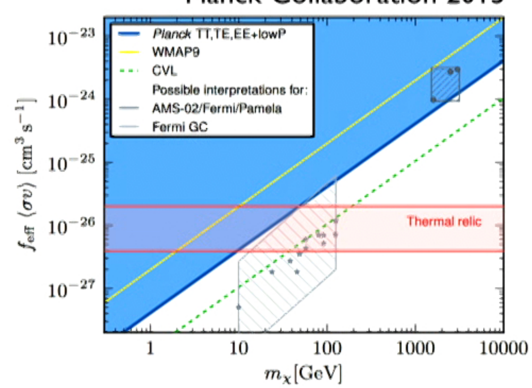
Constraints on the dark pion model



Ahnen et al '16



Planck Collaboration 2015



Summary

- The suppression of annihilation in forbidden dark matter models can be partially lifted by the presence of many$\rightarrow$2 channels. Freezeout dominated by 3$\rightarrow$2 annihilation can be natural for simple dark sectors where the particles share a similar mass scale, even when the couplings are small.
- Such models prefer lower DM masses for given couplings, strongly alleviate limits from indirect detection, and can naturally possess interesting scattering cross sections.
- Near-degeneracy between the DM and its annihilation products can lead to novel velocity-dependent annihilation signals, and suppress or remove late-time indirect detection bounds on light dark matter.