

Minimal self-interacting dark matter models with light mediator

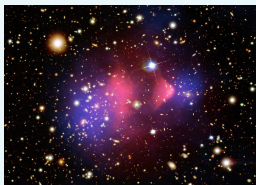
Laurent Vanderheyden
Université Libre de Bruxelles

Based on
JCAP 05 (2020) 001 - [1912.11708]
T. Hambye and LV



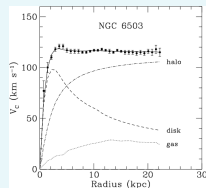
Why do we study DM?

Galaxies collisions



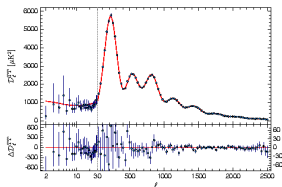
[M.Markevitch et al., 2006]

Rotations curves



[K.G. Begeman et al., 1991]

CMB anisotropies

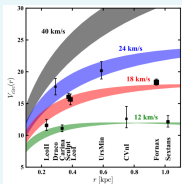


CMB anisotropies show
that $\Omega_{DM} h^2 \simeq 0.1188$

[Planck Collaboration, 2015]

Small scale crisis

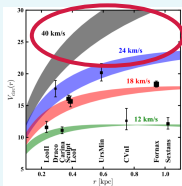
Too-big-to-fail



[M. Baylan et al., 2011]

Small scale crisis

Too-big-to-fail

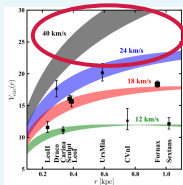


Missing massive
subhaloes

[M. Baylan et al., 2011]

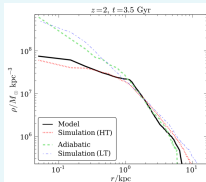
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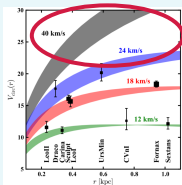
Core-vs-cusp



[A. Pontzen and F. Governato., 2011]

Small scale crisis

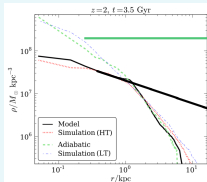
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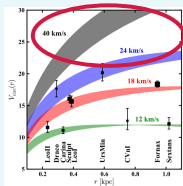
Collisionless DM

Observation

[A. Pontzen and F. Governato., 2011]

Small scale crisis

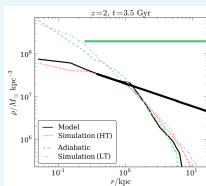
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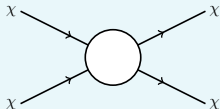


Collisionless DM

Observation

[A. Pontzen and F. Governato., 2011]

Self-interacting DM

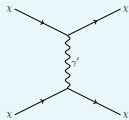


$$\Rightarrow \sigma_T/m_{DM} \sim \text{cm}^2/\text{g}$$

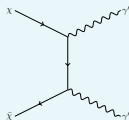
Simple models with a light mediator

Kinetic mixing

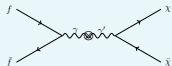
$$\mathcal{L} \ni -g_{\gamma'} \bar{\chi} \gamma^\mu \chi A'_\mu + h.c. \\ -\frac{\epsilon}{2} F_{\mu\nu}^Y F'^{\mu\nu}$$



FO process

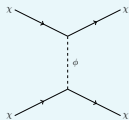


Portal

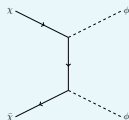


Scalar mixing

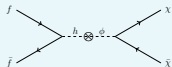
$$\mathcal{L} \ni -y_\phi \phi \bar{\chi} \chi + h.c. \\ -\lambda \phi^\dagger \phi H^\dagger H$$



FO process

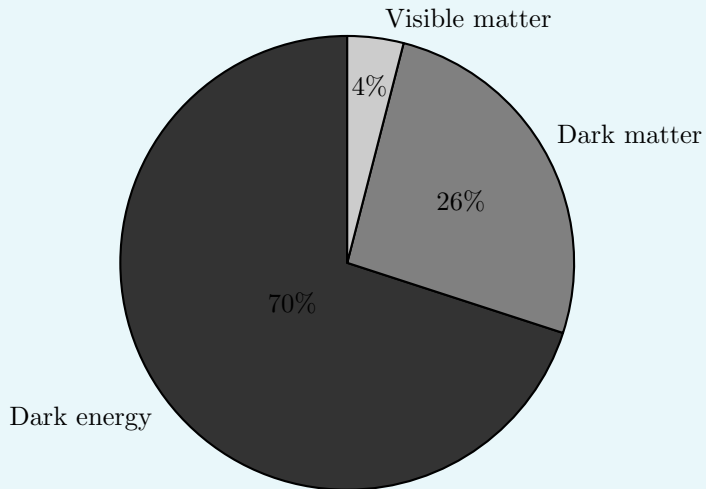


Portal



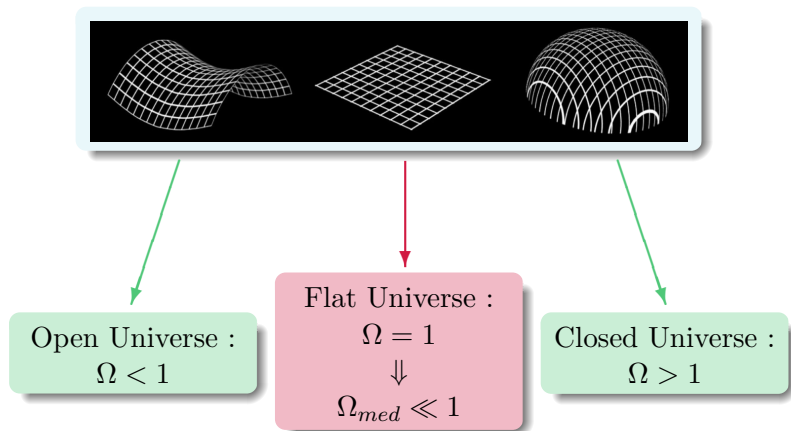
Constraints on SIDM with light mediator

DM relic density



$$\Omega_{DM} = 0.2645 \pm 0.0050$$

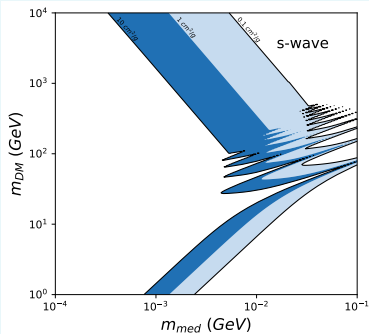
Non overclosure of the Universe by the light mediator



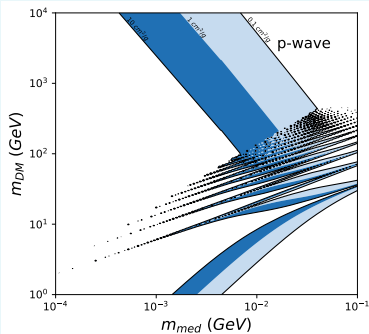
Small scale structure

$$0.10 \text{ cm}^2/\text{g} < \sigma_T/m_{DM} < 0.47 \text{ cm}^2/\text{g}$$

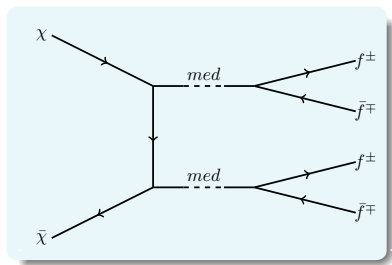
Kinetic mixing portal



Higgs portal

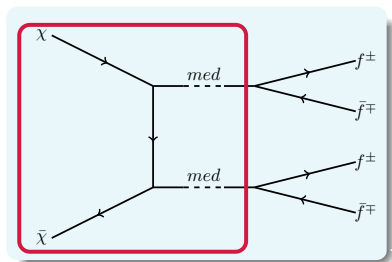


CMB (1) : constraint on DM annihilation rate

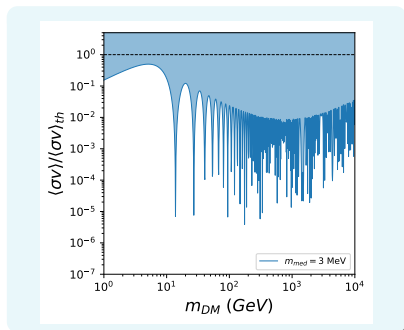


Production of
charged particles

CMB (1) : constraint on DM annihilation rate

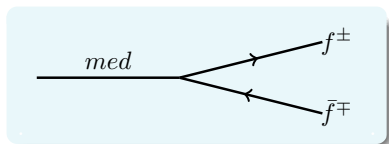


Production of
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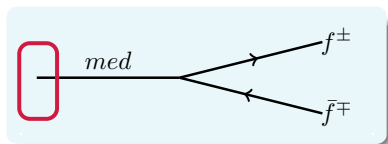
[N. Bernal et al., 2015] [T. Bringmann et al., 2016]

CMB (2) : constraints on mediator decay

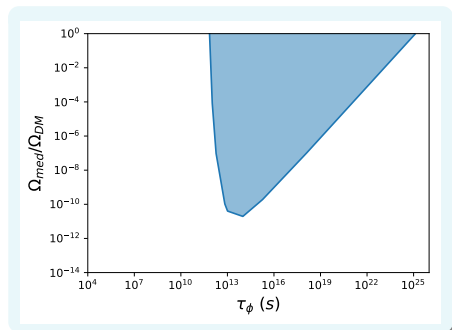


Production of
charged particles

CMB (2) : constraints on mediator decay



Production of
charged particles



[V. Poulin et al., 2016]

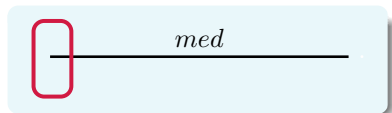
CMB (3) : constraint on N_{eff}

med

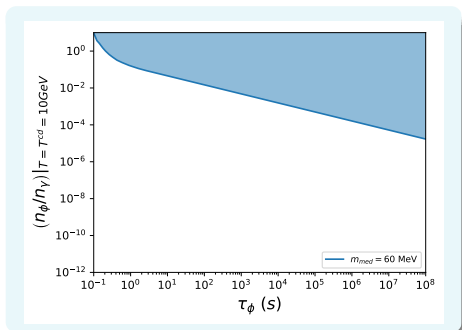


Additional
relativistic d.o.f.

CMB (3) : constraint on N_{eff}

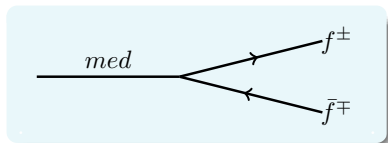


Additional
relativistic d.o.f.



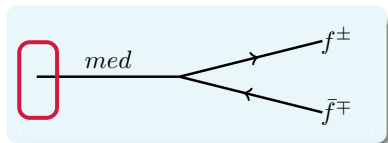
[M. Hufnagel et al., 2018]

BBN (1) : Photodisintegration

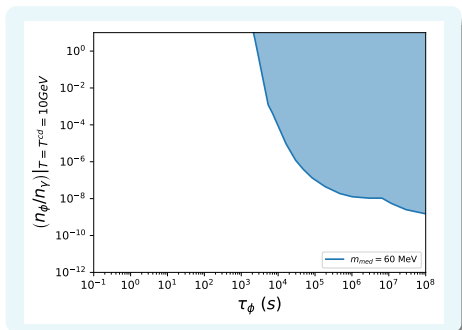


Production of
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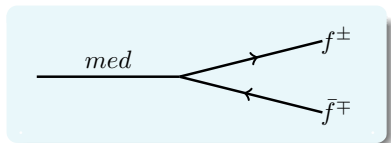


Production of
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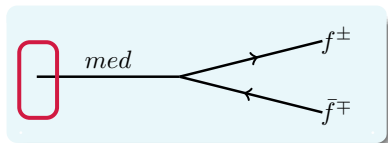
[M. Hufnagel et al., 2018]

BBN (2) : Hubble constant and entropy injection

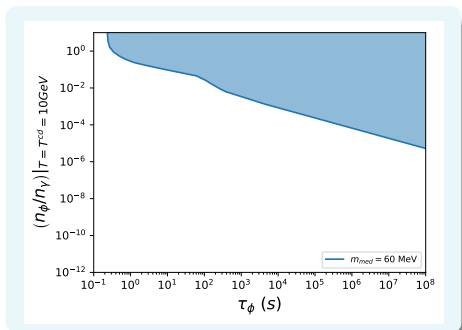


Modification of $H(t)$
and
Entropy injection

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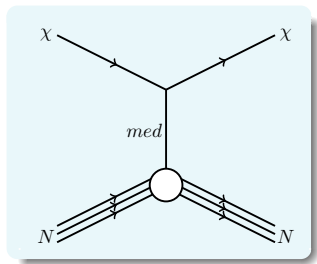


Modification of $H(t)$
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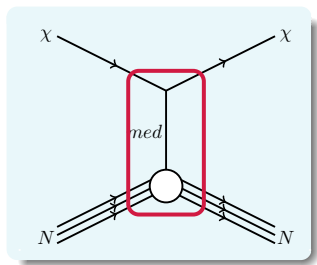
[M. Hufnagel et al., 2018]

Direct detection

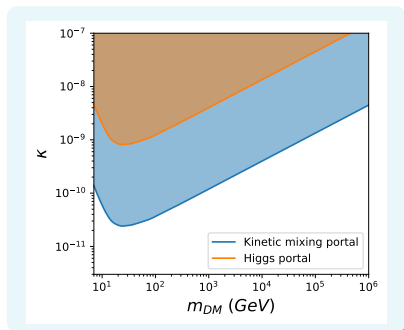


DM scatters on nucleon

Direct detection

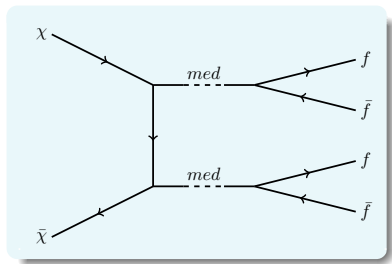


DM scatters on nucleon



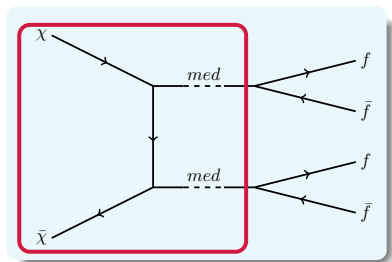
[T. Hambye et al., 2018] [T. Hambye and LV, 2019]

Indirect detection

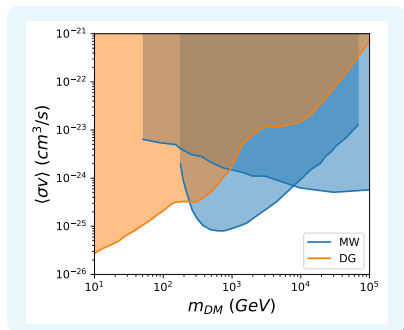


Production of
SM particles

Indirect detection



Production of
SM particles



[MAGIC, FERMI-LAT collaborations, 2016]

[H.E.S.S collaboration, 2016] [ANTARES collaboration, 2016]

Highly constrained scenario

Small scale structures :

$$\alpha' \nearrow$$
$$DM \leftrightarrow med$$

Particle physics :

$$\alpha' \epsilon^2 \searrow$$
$$DM \leftrightarrow SM$$

Cosmology :

$$\epsilon \nearrow$$
$$SM \leftrightarrow med$$

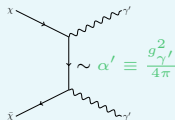
Minimal ways out

SM and HS not thermally connected : $T' < T$

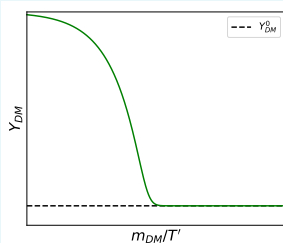
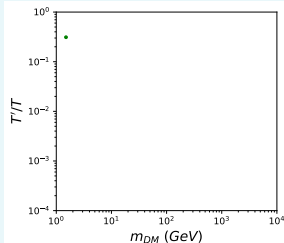
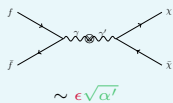
Kinetic mixing portal

$$\mathcal{L} \ni -g_{\gamma'} \bar{\chi} \gamma^\mu \chi A'_\mu + h.c. - \frac{\epsilon}{2} F_{\mu\nu}^Y F'^{\mu\nu}$$

FO process



Portal



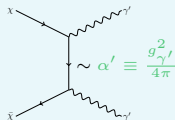
Fixing $\alpha' = 10^{-5}$ (and $\epsilon = 10^{-12}$)

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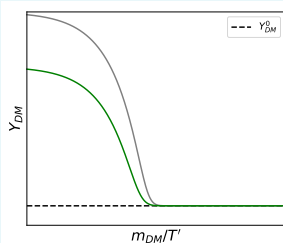
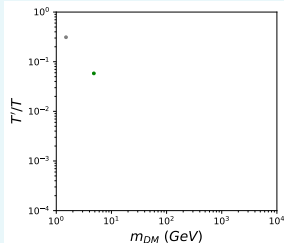
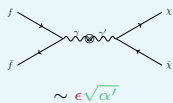
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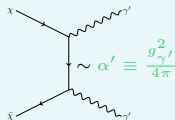
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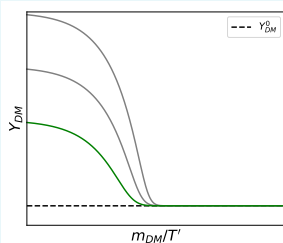
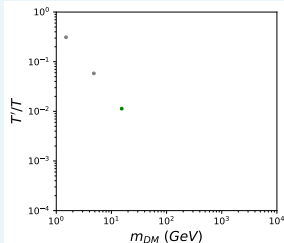
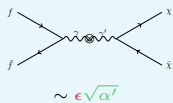
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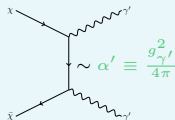
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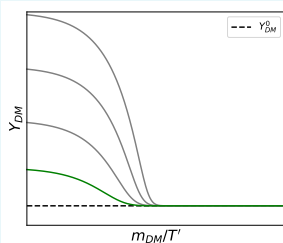
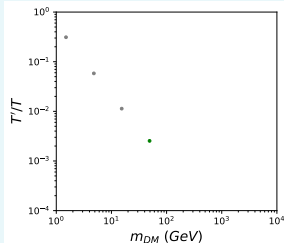
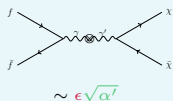
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FO process



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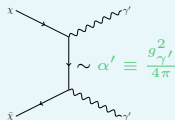
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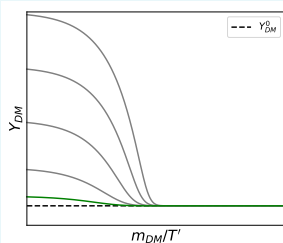
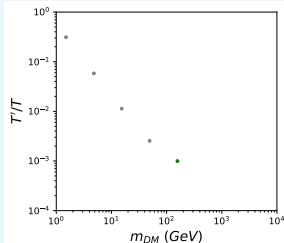
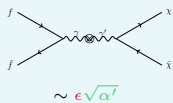
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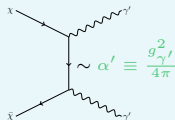
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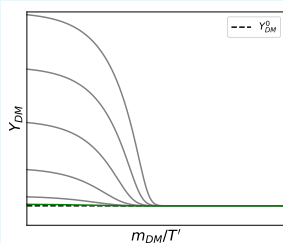
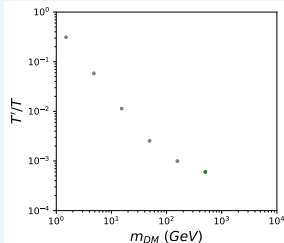
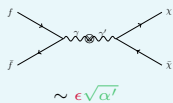
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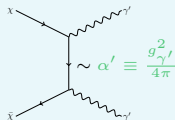
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SM and HS not thermally connected : $T' < T$

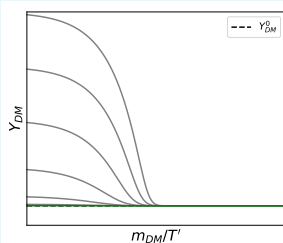
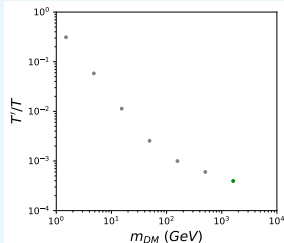
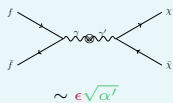
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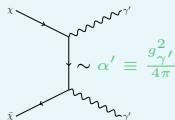
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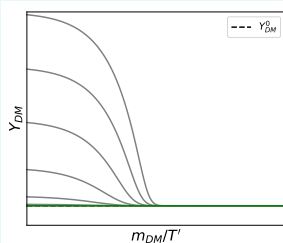
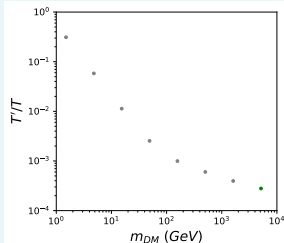
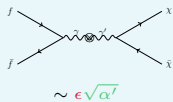
Kinetic mixing portal

$$\mathcal{L} \ni -g_{\gamma'} \bar{\chi} \gamma^\mu \chi A'_\mu + h.c. - \frac{\epsilon}{2} F_{\mu\nu}^Y F'^{\mu\nu}$$

FO process

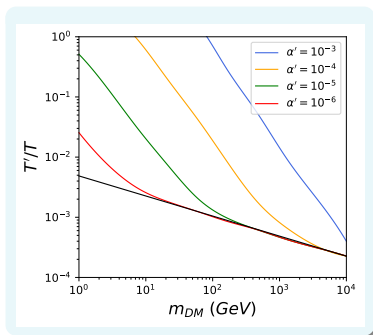


Portal



Fixing $\alpha' = 10^{-5}$ (and $\epsilon = 10^{-12}$)

SM and HS not thermally connected : $T' < T$



[T. Hambye and LV, 2019]

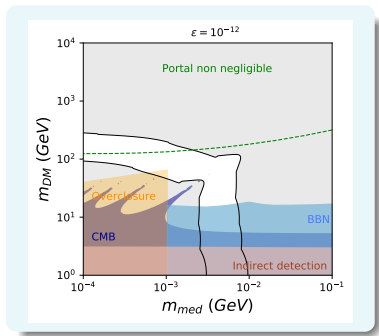
Relativistic decoupling :

$$n_{DM} \sim T'^3 \text{ and } \Omega_{DM} \sim \left(\frac{T'_{dec}}{T_{dec}} \right)^3 \left(\frac{m_{DM}}{1 \text{ TeV}} \right)$$

\Downarrow

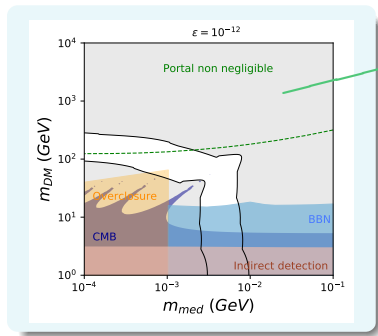
$$\frac{T'}{T} \geq 2.46 \times 10^{-4} \cdot \left(\frac{100 \text{ GeV}}{m_{DM}} \right)^{1/3} \cdot \left(\frac{g_*^S(T_{dec})}{g_{DM}} \right)^{1/3}$$

SM and HS not thermally connected : $T' < T$



[T. Hambye and LV, 2019]

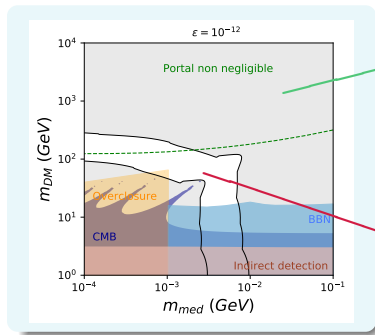
SM and HS not thermally connected : $T' < T$



(Sequential) Freeze-In
non negligible

[T. Hambye and LV, 2019]

SM and HS not thermally connected : $T' < T$



[T. Hambye and LV, 2019]

(Sequential) Freeze-In
non negligible

SIDM with light
mediator allowed for a
large region of the
parameter space!

Highly constrained scenario

Small scale structures :

$$\alpha' \nearrow$$
$$DM \leftrightarrow med$$

Particle physics :

$$\alpha' \epsilon^2 \searrow$$
$$DM \leftrightarrow SM$$

Cosmology :

$$\epsilon \nearrow$$
$$SM \leftrightarrow med$$

Minimal ways out with one extra particle

Subleading DM annihilation into light mediators

$$\mathcal{L} \ni -g_{\gamma'} \bar{\chi} \gamma^\mu \chi A'_\mu + h.c. - \frac{\epsilon}{2} F_{\mu\nu}^Y F'^{\mu\nu} - y_S S \bar{\chi} \chi + \lambda_{HS} H^\dagger H S^2$$

with $m_{\gamma'} \ll m_S < m_{DM}$

- Light mediator γ' responsible for SI \Rightarrow Alleviate tensions in the small scale crisis
- Heavy mediator S responsible for the FO process then decays quickly into SM particles

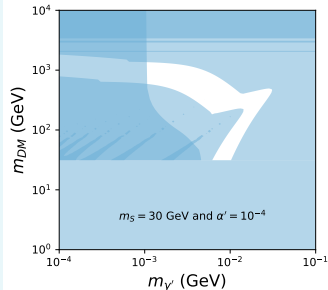
Minimal ways out with one extra particle

Subleading DM annihilation into light mediators

$$\mathcal{L} \ni -g_{\gamma'} \bar{\chi} \gamma^\mu \chi A'_\mu + h.c. - \frac{\epsilon}{2} F_{\mu\nu}^Y F'^{\mu\nu} - y_S S \bar{\chi} \chi + \lambda_{HS} H^\dagger H S^2$$

with $m_{\gamma'} \ll m_S < m_{DM}$

- Light mediator γ' responsible for SI \Rightarrow Alleviate tensions in the small scale crisis
- Heavy mediator S responsible for the FO process then decays quickly into SM particles



[T. Hambye and LV, 2019]

Minimal ways out with one extra particle

P-wave annihilation and decay of the light mediator into extra hidden sector particles

$$\mathcal{L} \ni -y_\phi \phi \bar{\chi}^c \chi + h.c. - \lambda_{\phi H} \phi^\dagger \phi H^\dagger H - \lambda_{\phi S} \phi^\dagger \phi S^2 - \lambda_{HS} H^\dagger H S^2$$

with $m_S < m_\phi \ll m_{DM}$

- "Heavy" mediator ϕ responsible for SI \Rightarrow Alleviate tensions in the small scale crisis
- "Heavy" mediator ϕ decays into Light mediator S which decay quickly into SM particles

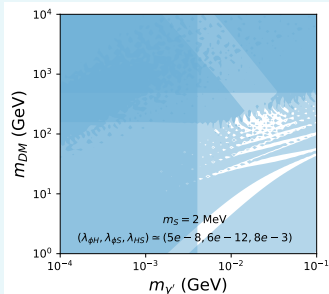
Minimal ways out with one extra particle

P-wave annihilation and decay of the light mediator into extra hidden sector particles

$$\mathcal{L} \ni -y_\phi \phi \bar{\chi}^c \chi + h.c. - \lambda_{\phi H} \phi^\dagger \phi H^\dagger H - \lambda_{\phi S} \phi^\dagger \phi S^2 - \lambda_{HS} H^\dagger H S^2$$

with $m_S < m_\phi \ll m_{DM}$

- "Heavy" mediator ϕ responsible for SI \Rightarrow Alleviate tensions in the small scale crisis
- "Heavy" mediator ϕ decays into Light mediator S which decay quickly into SM particles



[T. Hambye and LV, 2019]

Other minimal ways out

- Stable mediator with annihilation into hidden sector particles
- Neutrino option
- ...

Conclusion

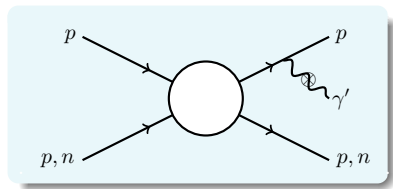
Self-interacting Dark Matter with a light mediator is an attractive possible answer to the small scale crisis. Even if this scenario seems to be highly constrained by Cosmology, Astrophysics and Particle Physics, several very simple ways out can be built in order to alleviate the various tensions.

- DM annihilation into light mediator in a hidden sector with $T' < T$
- Subleading DM annihilation into light mediators
- P-wave annihilation and decay of the light mediator into extra hidden sector particles

Thank you!

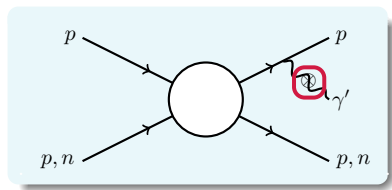
Backup slides

Supernovae - SN1987A

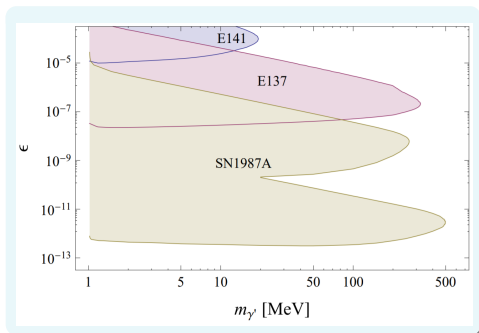


Luminosity argument,
Blow-away arguments
and
MeV γ -rays observations

Supernovae - SN1987A

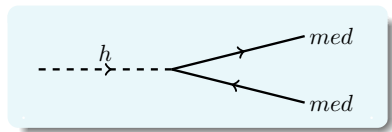


Luminosity argument,
Blow-away arguments
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MeV γ -rays observations



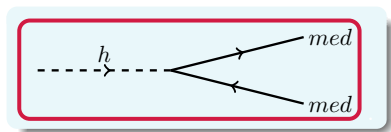
[D. Kazanas et al., 2014]

Direct limits on the size of the portals

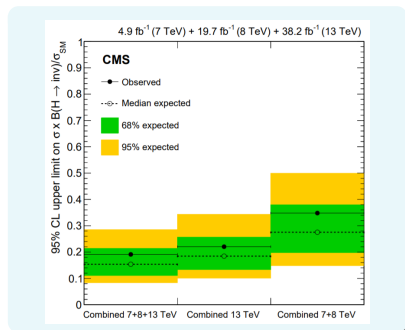


Invisible Higgs
decay width

Direct limits on the size of the portals



Invisible Higgs
decay width



[CMS collaboration, 2018]

