Minimal self-interacting DM models

Thomas Hambye
Univ. of Brussels (ULB), Belgium

Work in collaboration with Laurent Vanderheyden: arXiv:1912.11708

Pollica 19/06/2023

Small scale anomalies

- Missing satellites

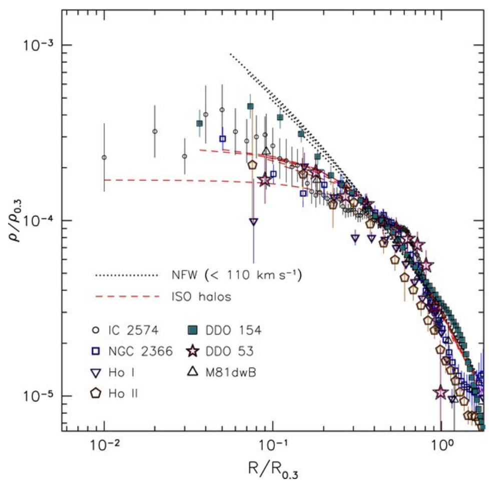
simulations predict ~100 times less small satellites galaxies than observed

Klypin et al 99', Moore et al 99', ...

- Core-Cusp problem

simulations predict dwarf galaxies very inner part profile more cuspy than observed

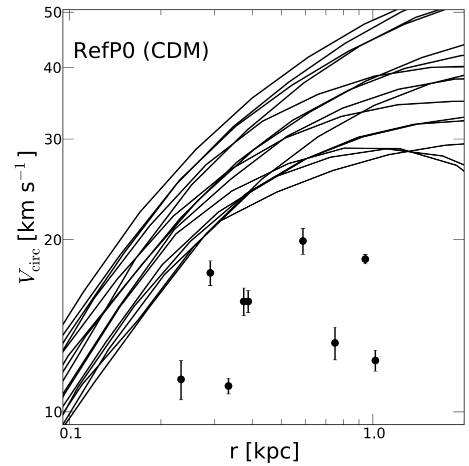
Spergel-Steinhardt 00'
De Block, McGaugh 97',
see e.g. Oh et al 11' ….



- Too big to fail problem

simulations predict massive satellite not observed (too big to be missed), potential observed candidates have too small rotation velocities

Boylan-Kolchin et al 11',
Vogelsberger et al 12' ….



- Diversity problem

Oman et al 15'
Kamada, Kaplinghat, Pace, Yu 16'
Tulin, Yu 18'
….

DM self-interactions hints (very briefly)

Core-cusp+ too big to fail: $\sigma_{SI}/m_{DM} \sim [0.1\text{–}10]\,\mathrm{cm}^2/\mathrm{gr}$ $\sim 10^{12}\mathrm{pb}$

for dwarf satellite velocities: $v \sim 10\,\mathrm{km/sec}$

$\vee$

$\wedge$

Spergel-Steinhardt 00'
Wandeelt et al 00'
Vogelsberger et al 12'
Rocha et al 13'
Kaplinghat, Tulin, Yu 15'

see the many contributions by Kaplinghat, Tulin, Yu, Feng, …

$\langle \sigma_{annih.} v \rangle \sim 1\,\mathrm{pb}$

thermal freezee-out

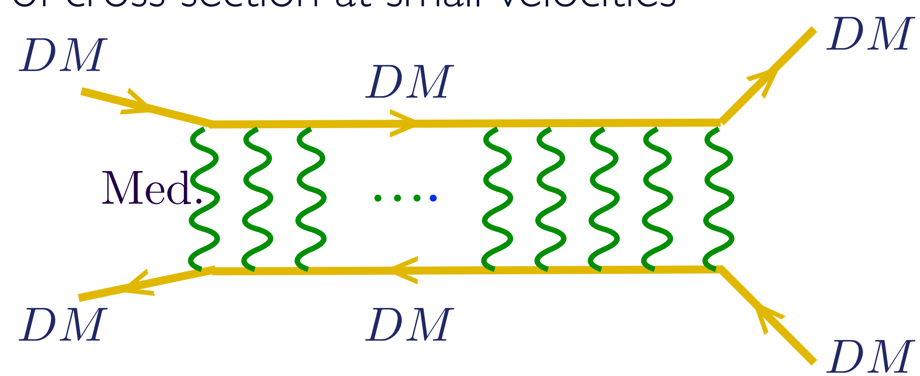
Clusters: $\sigma_{SI}/m_{DM} \lesssim 0.5\,\mathrm{cm}^2/\mathrm{gr}$

for cluster velocities: $v \sim 1000\,\mathrm{km/sec}$

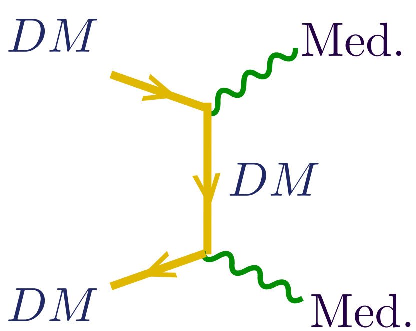
$\Rightarrow$ suggests a velocity dependent self interaction cross section

Light mediator self interaction scenario

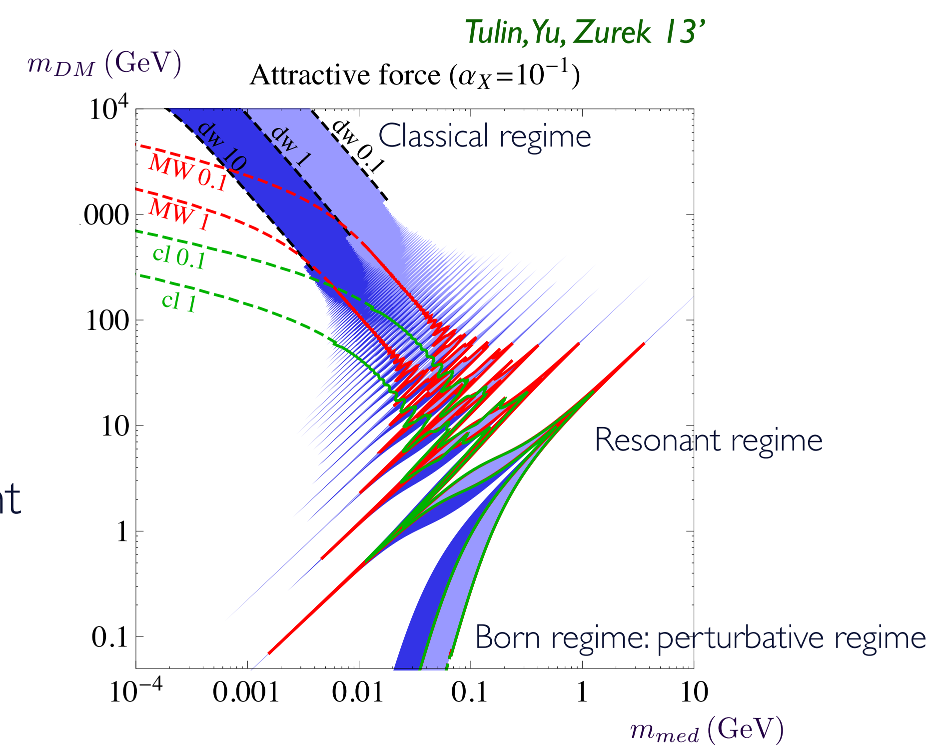
Non-relativistic Sommerfeld effet: enhancement of cross section at small velocities



Unavoidable $DM\ DM \to Med.\ Med.$ annihilation: much less Sommerfeld enhanced



Fixing DM-DM-Med coupling
from thermal freeze-out constraint



2 benchmark truly minimal models

Light dark photon mediator

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

DM-DM-Med interaction

kinetic mixing portal

s-wave annihilation

$$DMDM \to \gamma'\gamma'$$

Light scalar mediator

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

DM-DM-Med interaction

Higgs portal

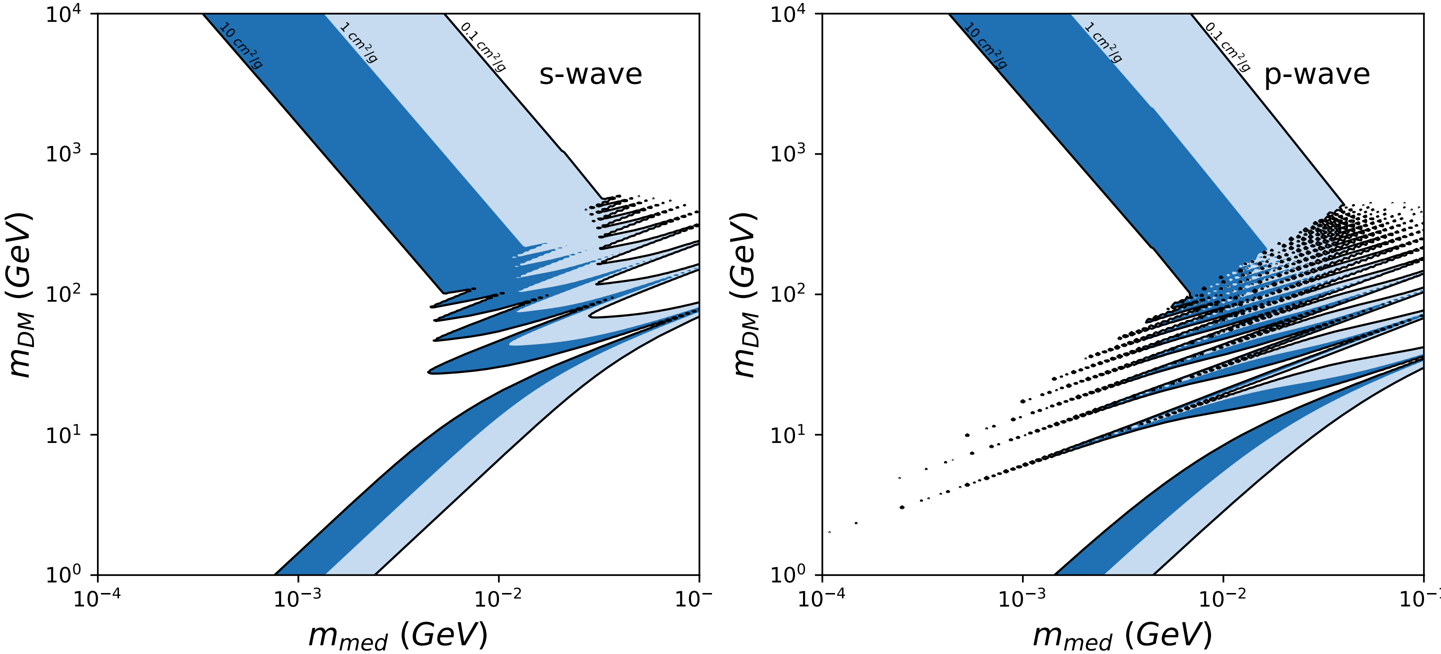
p-wave annihilation

$$DMDM \to \phi\phi$$

1. Relic density & 2. Self-interactions

Fixing DM-DM-Med coupling from thermal freeze-out constraint

dark photon model | light scalar model



TH, Vanderheyden 19'

3. Non-overclosure of Universe by light mediator

relativistic decoupling of light mediator at DM freeze-out $\Rightarrow$ many light mediator

$\Downarrow$

overcloses the universe

unless $m_{Med} \lesssim \text{few eV}$

or mediator number density

reduced after DM decoupling

(decay, extra annihilation…)

The many constraints on the light mediator scenario

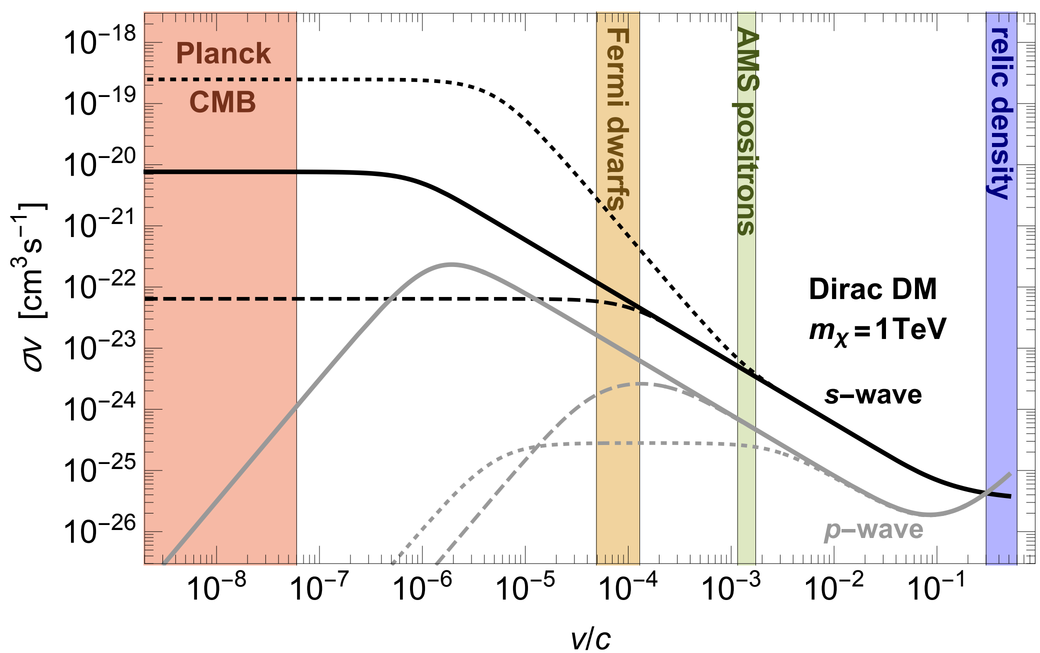
3.1 CMB constraints on annihilation

DM annihilations into e-m material at recombination time spoil CMB anisotropies

$$\langle \sigma v \rangle_{rec} \lesssim N_\chi \cdot 4 \times 10^{-25}\ \mathrm{cm}^3\mathrm{s}^{-1} \left(\frac{f_{eff}}{0.1}\right)^{-1} \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)$$

Slatyer 16'

$$f_{eff} = \text{ fraction of mediator energy into e-m material}$$



Bringmann, Kahlhoefer, Schmidt-Hoberg, Walia 16'

⇒ s-wave scenario excluded, p-wave scenario ok

3.2 CMB constraints on energy injection from light mediator decay
3.3 CMB $\Delta_{N_{eff}}$

decays after or before recombination also affects CMB

$$\tau_{med} = 10^{13,15,17,19,21,23,25}\,\mathrm{sec} \Rightarrow \Omega_{med}h^2 \lesssim 10^{-11.7,-10.9,-9,-7,-5,-3,-1}$$

Slatyer 12'

Poulin, Lesgougues, Serpico 16'

$$\Omega_{med}h^2 = 10^{0,-1,-2,-3,-4,-5} \Rightarrow \tau_{med} \lesssim 10^{5.7,6.2,6.8,8.2,10.2,12.2}\,\mathrm{sec}$$

extra radiation affects CMB anisotropies: $\Delta_{N_{eff}}$

τ_{med} upper bound for relativistic decoupling (sec)

$m_{\gamma'}$ (MeV)	0.01	0.03	0.1	0.3	1	3	10	30	100	300
N_{eff}	$10^{6.3}$	$10^{5.3}$	$10^{4.3}$	$10^{3.3}$	$10^{2.2}$	$10^{1.1}$	$10^{0.1}$	$10^{-0.4}$	$10^{-0.7}$	$10^{-0.9}$

m_{ϕ} (MeV)	0.01	0.03	0.1	0.3	1	3	10	30	100	300
N_{eff}	$10^{7.3}$	$10^{6.3}$	$10^{5.3}$	$10^{4.3}$	$10^{3.2}$	$10^{2.1}$	$10^{1.1}$	$10^{0.1}$	$10^{-0.5}$	$10^{-0.7}$

Hufnagel, Schmidt-Hoberg, Wild 18'

5. BBN constraints

4.1 Photodisintegration, 4.2 Entropy injection and ΔN_{eff}

photodisintegration of Deuterium if mediator decay products contain photon for $m_{med} > 4.4\,MeV$

mediator decay injects entropy and modifiers H modifying nuclei abundance

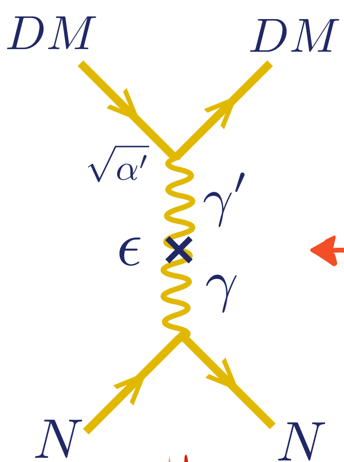
τ_{med} upper bound for relativistic decoupling (sec)

$m_{\gamma'}$ (MeV)	0.01	0.03	0.1	0.3	1	3	10	30	100	300
Photodis./Entropy inj.	$10^{5.9}$	$10^{4.9}$	$10^{3.9}$	$10^{3.1}$	$10^{2.4}$	$10^{2.0}$	$10^{1.0}$	$10^{0.0}$	$10^{-0.4}$	$10^{-0.5}$
m_{ϕ} (MeV)	0.01	0.03	0.1	0.3	1	3	10	30	100	300
Photodis./Entropy inj.	$10^{6.8}$	$10^{5.9}$	$10^{4.8}$	$10^{3.9}$	$10^{3.0}$	$10^{2.4}$	$10^{2.0}$	$10^{1.0}$	$10^{-0.1}$	$10^{-0.4}$

Hufnagel, Schmidt-Hoberg, Wild 18'

6. Direct detection

light mediator also boosts the direct detection cross section: t-channel exchange



$$\frac{1}{q^2} \rightarrow \frac{1}{E_r^2}$$

$E_r \sim$ few KeV

huge enhancement

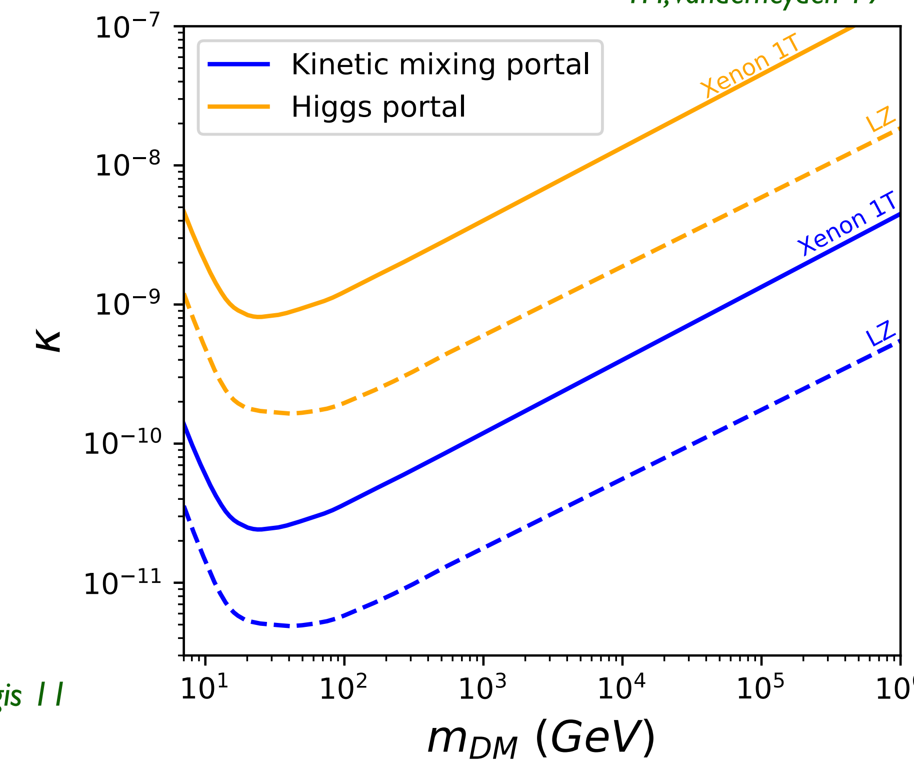
direct detection sensitive to very small connector values

$$\frac{d\sigma}{dE_r} = \frac{1}{E_r^2}\frac{1}{v^2}\frac{2\pi\kappa^2 Z^2\alpha^2}{m_A}F_A^2(q r_A)$$

Foot et al, ..., 11
Scwhetz, Zupan 11
Fornengo, Panci, Regis 11
Chu, T.H., Tytgat 11

$$\kappa_{KM} \equiv \sqrt{\alpha'/\alpha}\,\epsilon$$
$$\kappa_{HP} \equiv y_\phi \sin 2\theta/2$$

TH, Vanderheyden 19'



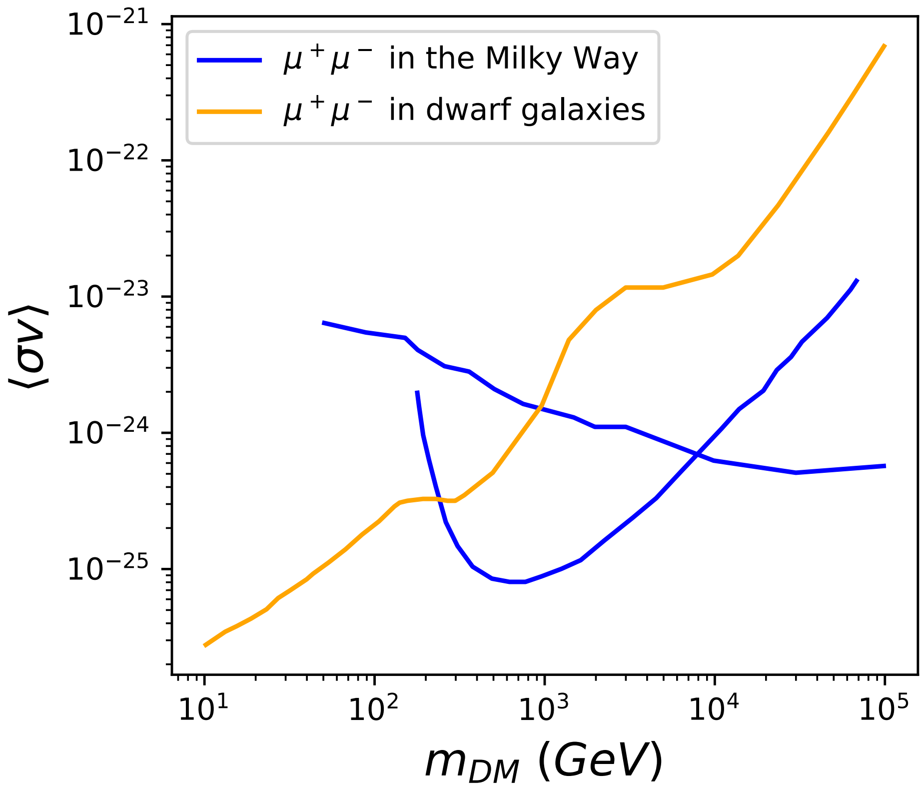
⇒ clash between upper bound on portal from direct detection and lower bound on portal from BBN

↪ excludes p-wave scalar mediator model

7. Indirect detection

light mediator also boosts the indirect detection cross section: Sommerfeld effect

example:



+ 8. X-rays + 9. Supernovae + 10. other constraints on size of kinetic mixing, Higgs portal…

2 preliminaries for ways out

Self-interactions can accommodate smaller annihilation cross sections

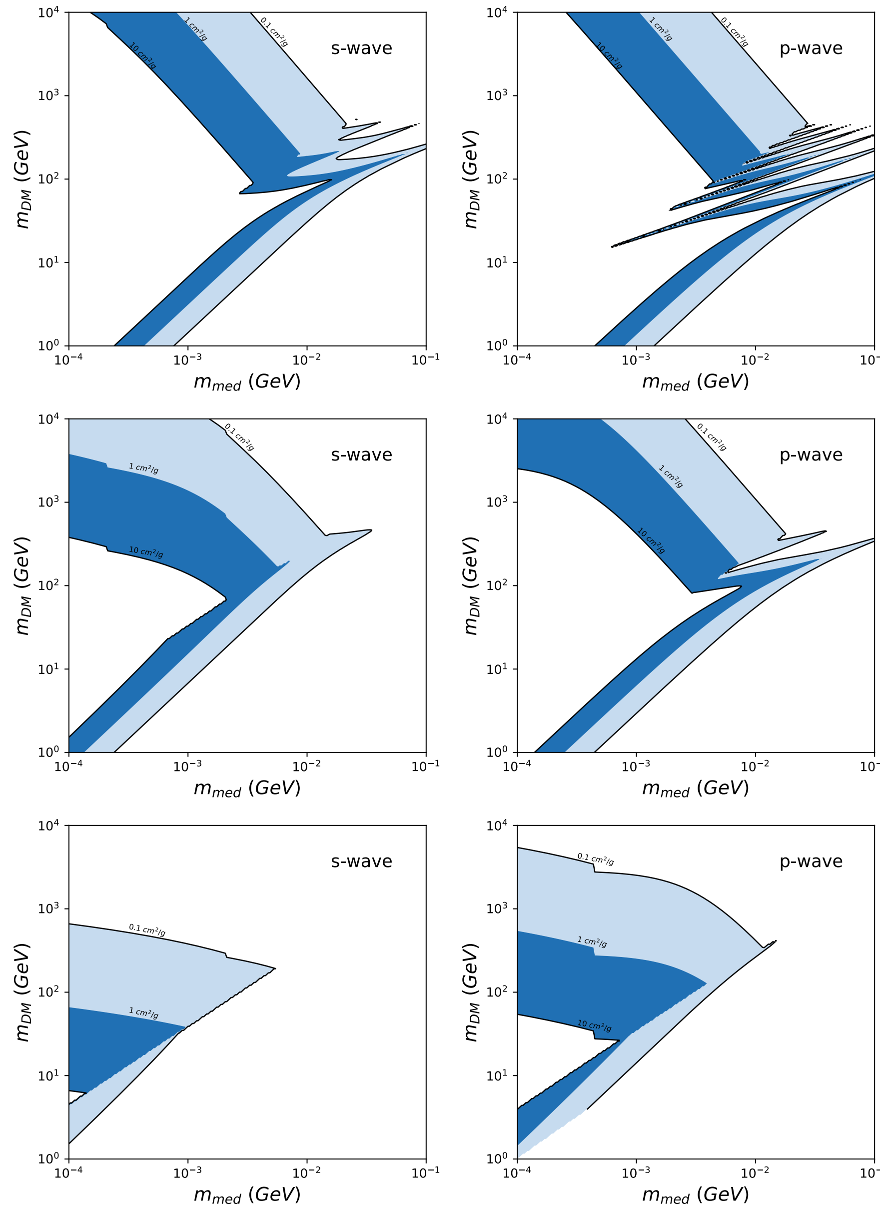
$$\frac{\langle \sigma_{annih} v \rangle}{\langle \sigma_{annih} v \rangle_{thermal}} = 10^{-2}$$

$$\frac{\langle \sigma_{annih} v \rangle}{\langle \sigma_{annih} v \rangle_{thermal}} = 10^{-4}$$

$$\frac{\langle \sigma_{annih} v \rangle}{\langle \sigma_{annih} v \rangle_{thermal}} = 10^{-6}$$

dark photon model

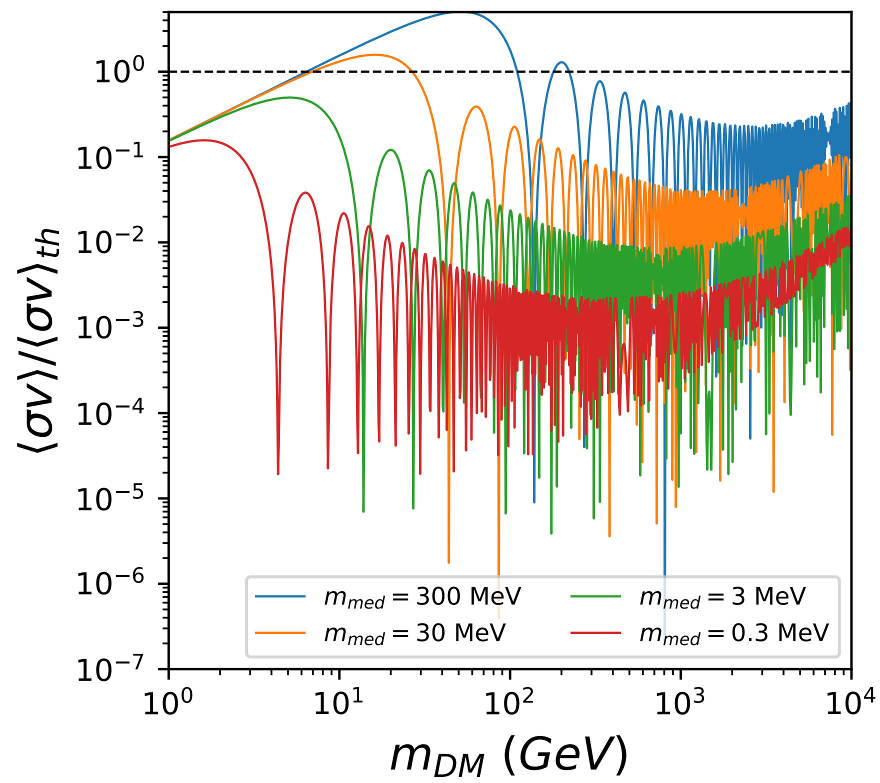
light scalar model



TH,Vanderheyden 19'

2 preliminaries for ways out

s-wave annihilation cross section should not be much smaller than thermal value to accommodate CMB annihilation cross section constraint



A straightforward way out: colder dark sector

TH, Vanderheyden 19'

keeping the model truly minimal

portal could be small enough fo dark sector not to thermalize with SM sector

(kinetic mixing constrained to be small...)

SM visible sector T $\longleftrightarrow$ Hidden sector T'

portal

if $T'/T < 1$ almost all constraints relax

less DM around $\Rightarrow$ less Boltzmann suppression needed

$\Downarrow$

smaller annihilation cross section

- OK for self-interact.
- OK for CMB s-wave annih.
- direct detection cross section reduced

less mediators around $\Rightarrow$ mediator overclosure and decay constraints relaxed

BBN, CMB

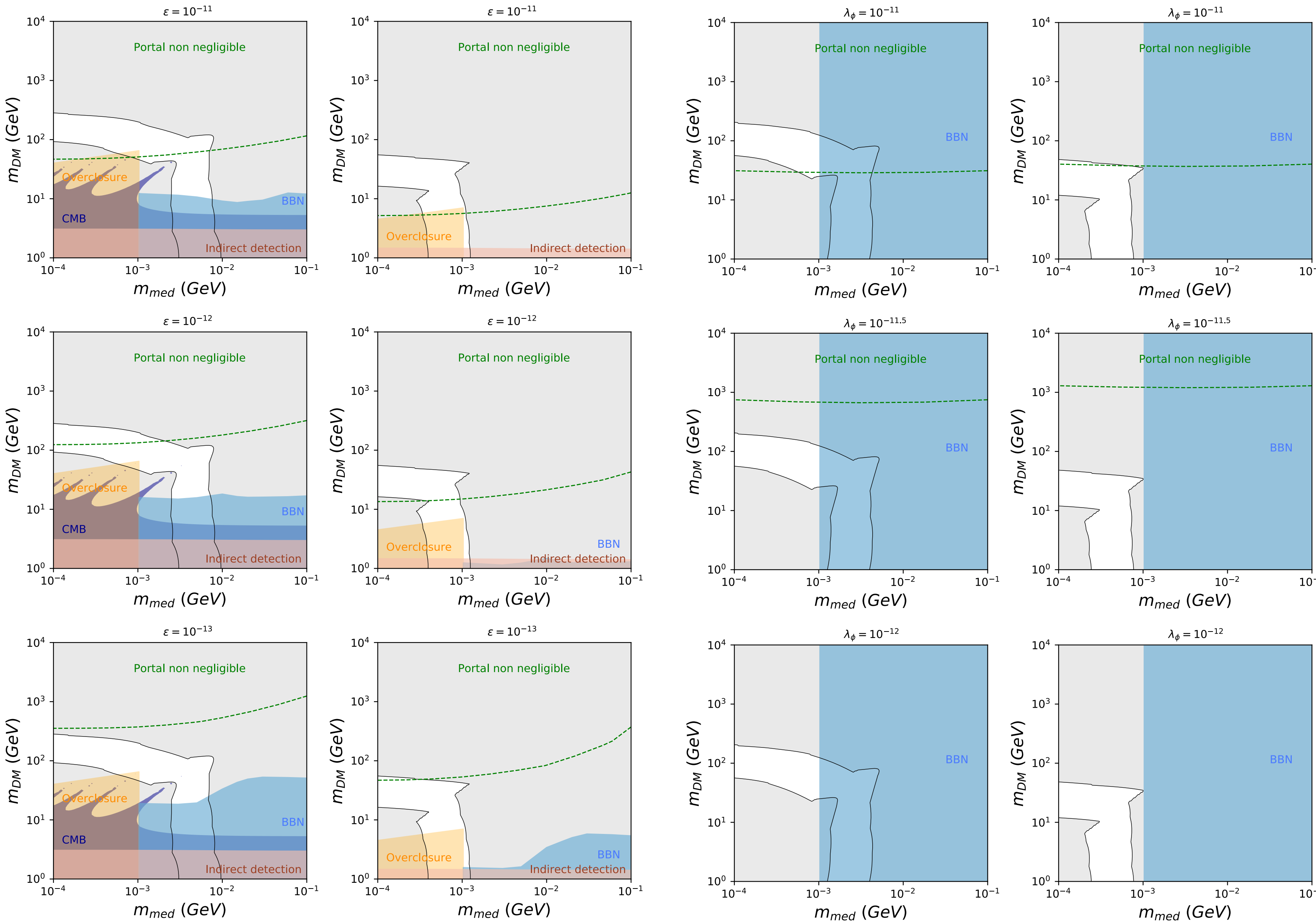
A straightforward way out: colder dark sector

TH, Vanderheyden 19'

for fixed couplings and fixing T'/T from relic density constraint

$$\alpha_\phi \equiv \frac{y_\phi^2}{4\pi}$$

$\alpha' = 10^{-4}$ $\alpha' = 10^{-5}$ $\alpha_\phi = 10^{-4}$ $\alpha_\phi = 10^{-5}$



A second simple way out: annihilation to mediators sub-dominant

TH, Vanderheyden 19'

if DM annihilates dominantly into an extra heavier particle "S"

$$\mathcal{L} \ni -g\gamma'_\mu J^\mu_{DM} - \frac{\epsilon}{2} F^Y_{\mu\nu} F'^{\mu\nu}$$
$$-y_S S\bar{\psi}\psi + \lambda_{HS} H^\dagger H S^2$$

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

$\Rightarrow$ smaller annihilation cross section into med.

OK for self-interact.

OK for CMB s-wave annih.

direct detection cross section reduced

BBN CMB med decay constraints not reduced but tension with direct detection reduced

CMB constraint on $DMDM \rightarrow SS$ OK : p-wave

CMB, BBN constraints on S decay: OK because S is heavier and decay fast enough

A second simple way out: annih. to mediators sub-dominant

TH, Vanderheyden 19'

m_{DM} (GeV)	$m_{\gamma'}$ (MeV)	m_S (GeV)	α'	y_S	σ_T/m_{DM} (cm^2/g)	$\frac{\sigma_{DMDM\to\gamma'\gamma'}}{\sigma_{thermal}}$	$\kappa_{\gamma'}$ $\left(\frac{\kappa_{\gamma'}}{\kappa_{KM}^{DD}}\right)$	κ_S $\left(\frac{\kappa_S}{\kappa_{HP}^{DD}}\right)$	$\tau_{\gamma'}$ (sec)	τ_S (sec)
83	18	31	1.7×10^{-4}	0.25	0.18	1.2×10^{-2}	1.8×10^{-11} (0.55)	1.1×10^{-10} $(\ll 1)$	0.30	0.089
326	12	62	6.5×10^{-5}	0.51	0.35	1.2×10^{-4}	2.3×10^{-11} (0.35)	1.8×10^{-10} $(\ll 1)$	0.12	0.006
617	11	12	3.8×10^{-4}	0.70	0.13	1.0×10^{-3}	4.4×10^{-11} (0.47)	4.4×10^{-10} $(\ll 1)$	0.22	0.020

m_{DM} (GeV)	m_{ϕ} (MeV)	m_S (GeV)	α_ϕ	y_S	σ_T/m_{DM} (cm^2/g)	$\frac{\sigma_{DMDM\to\phi\phi}}{\sigma_{thermal}}$	κ_{ϕ} $\left(\frac{\kappa_{\phi}}{\kappa_{HP}^{DD}}\right)$	κ_S $\left(\frac{\kappa_S}{\kappa_{HP}^{DD}}\right)$	τ_{ϕ} (sec)	τ_S (sec)
0.5	1.1	0.01	1.5×10^{-5}	0.02	0.19	0.23	6.8×10^{-7} (0.60)	9.4×10^{-8} (0.09)	27	1
2	3	0.01	4.5×10^{-5}	0.04	0.13	0.13	1.9×10^{-7} (0.99)	1.9×10^{-7} (0.99)	24	1
326	12	62	6.5×10^{-5}	0.51	0.35	1.0×10^{-5}	1.4×10^{-8} (6.17)	1.8×10^{-10} $(\ll 1)$	38	0.006

a third way: p-wave option with mediator decay into lighter hidden sector particle

TH,Vanderheyden 19'

$$
\begin{aligned}
\mathcal{L} \;=\; & -(y_\phi \phi \overline{\chi^c}\chi + h.c.) - \lambda_{\phi H}\phi^\dagger \phi H^\dagger H \\
& -\lambda_{\phi S}\phi^\dagger \phi S^2 - \lambda_{HS} H^\dagger H S^2
\end{aligned}
$$

p-wave annihilation: CMB annihilation OK

$\lambda_{\phi H}$ small : suppressed direct detection

$\lambda_{\phi S}$ sizeable : ϕ decays before BBN

λ_{HS} sizeable : S decays before BBN

indirect detection: testable even if p-wave: Sommerfeld compnsation

m_{DM} (GeV)	m_ϕ (MeV)	m_S (MeV)	v_ϕ (MeV)	v_S (MeV)	$\lambda_{\phi H}$	$\lambda_{\phi S}$	λ_{HS}	σ_T/m_{DM} (cm^2/g)	$\frac{\kappa_{HP}^{DD}}{\kappa_{HP}}$	τ_ϕ (sec)	τ_S (sec)	Γ_h^{inv} (MeV)	$\langle\sigma_{\phi\phi\to SS}v\rangle$ (GeV^{-2})	$\Omega^0_{med}h^2$
126	20	2	500	500	5.4×10^{-8}	6.2×10^{-12}	0.008	0.28	0.05	0.14	3.0	0.31	$\ll \sigma_{thermal}$	0
382	71	7	436	83	6.3×10^{-7}	3.2×10^{-11}	0.007	0.21	0.49	0.03	2.7	0.24	$\ll \sigma_{thermal}$	0

a fourth way: a stable mediator annihilating into lighter hidden sector particles

TH, Vanderheyden 19'

if mediator is stable: oveclosure constraint ?

modification of Hubble constant?

can be OK if mediator annihilation into lighter particles

example: $$\mathcal{L} = -(y_\phi \phi \overline{\chi^c} \chi + h.c.) - \lambda_{\phi H} \phi^\dagger \phi H^\dagger H - \lambda_{\phi S} \phi^\dagger \phi S^2 - \lambda_{HS} H^\dagger H S^2$$

$$\phi\phi \to SS$$

p-wave annihilation: CMB annihilation OK

$\lambda_{\phi H}$ small : suppressed direct detection

λ_{HS} sizeable : S decays before BBN

see also Duerr, Schmidt-Hoberg, Wild 18'

m_{DM} (GeV)	m_ϕ (MeV)	m_S (MeV)	v_ϕ (MeV)	v_S (MeV)	$\lambda_{\phi H}$	$\lambda_{\phi S}$	λ_{HS}	σ_T/m_{DM} (cm^2/g)	$\frac{\kappa_{HP}}{\kappa_{HP}^{DD}}$	τ_ϕ (sec)	τ_S (sec)	Γ_h^{inv} (MeV)	$\langle\sigma_{\phi\phi\to SS} v\rangle$ (GeV^{-2})	$\Omega^0_{med} h^2$
83	50	2	$\ll 1$	500	6.3×10^{-8}	0.010	0.008	0.11	$\ll 1$	$\gg 1$	3.0	0.31	2.5×10^{-5}	2.5×10^{-5}
173	300	10	$\ll 1$	50	1.0×10^{-6}	0.015	0.010	0.21	$\ll 1$	$\gg 1$	1.44	0.48	1.5×10^{-6}	4.0×10^{-4}

a fifth way: the neutrino option: mediator decay into neutrinos

Bringmann, Kahlhoefer, Schmidt-Hoberg, Walia 16'
TH, Vanderheyden 19'

a sixth way: giving up freeboot: freezein, annihilation,…

Benal, Garcia-Cely, TH, Zaldivar 15'

a seventh way: asymmetric DM (marginally)

Baldes et al 17'

……..

Outline

Many constraints apply on light mediator self-interacting DM scenario

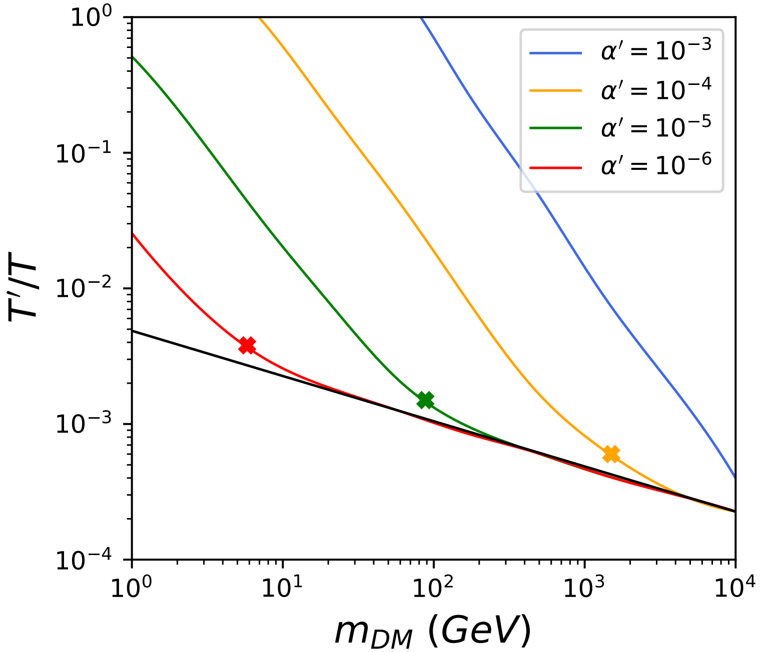
- DM relic density
- DM self interactions
- non Unverse overclosure byn light mediator
- CMB: DM annihilation, mediator decay, ΔN_{eff}
- BBN: mediator decay, ΔN_{eff}
- DM direct détection
- DM indirect détection
- X-rays, supernova, ….

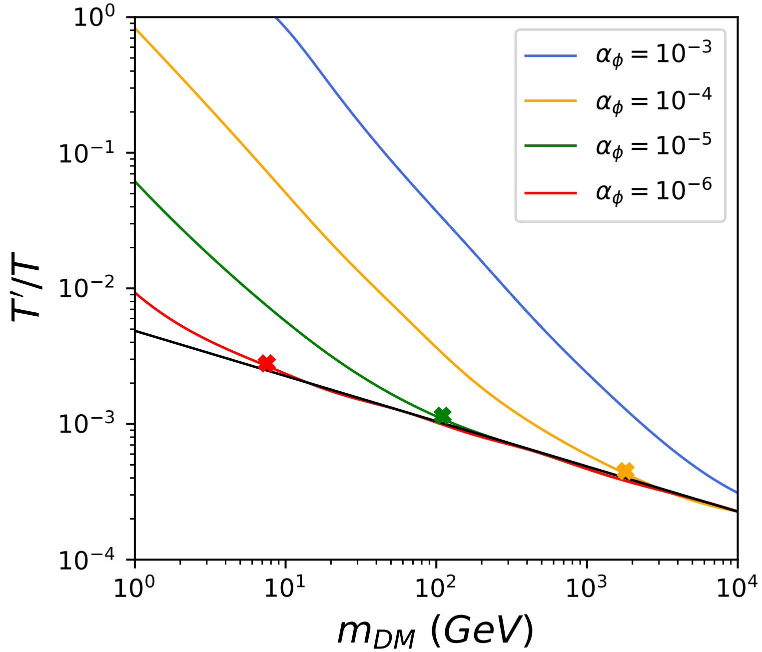
non-abelian case

γ

specific ways out:

- colder dark sector (keeping the model truly minimal)
- annihilation into mediators sub-dominant (dominant p-wave annih. into heavier particles)
- p-wave annihilation with mediator decay into lighter dark sector particle
- stable mediator annihilating into light dark sector particles
- neutrino option
- …





TH, Vanderheyden 19'

TH, Lucca, Vanderheyden 20'