

# Self-interacting dark matter with a stable vector mediator

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[1804.10385] : Michael Duerr, Kai Schmidt-Hoberg, SW

[1704.02149] : Felix Kahlhoefer, Kai Schmidt-Hoberg, SW



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Bonn



# Self-interacting dark matter (SIDM) with a light mediator: pros and problems

## SIDM with a stable vector mediator

Thermal history

Bounds from CMB and BBN

Viability of strong self-interactions

## Conclusions

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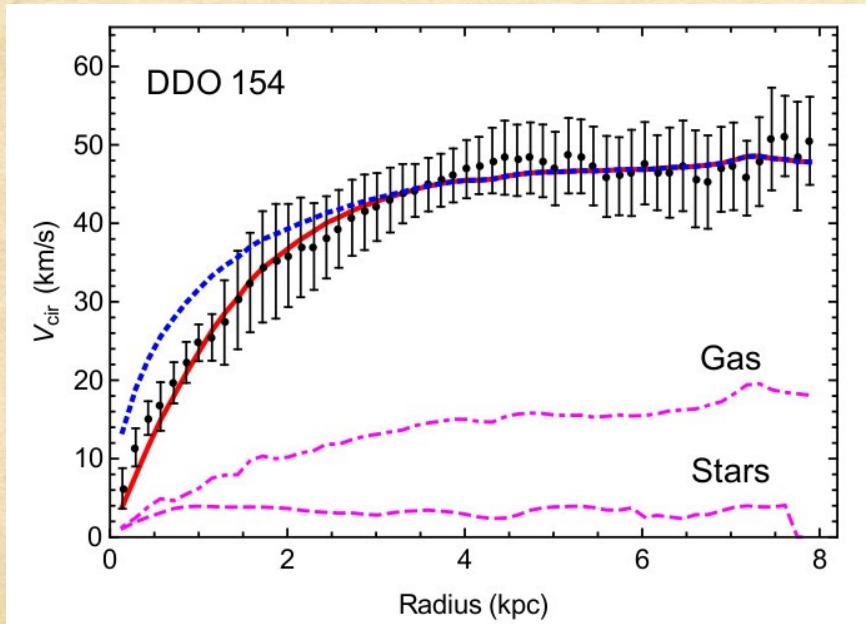
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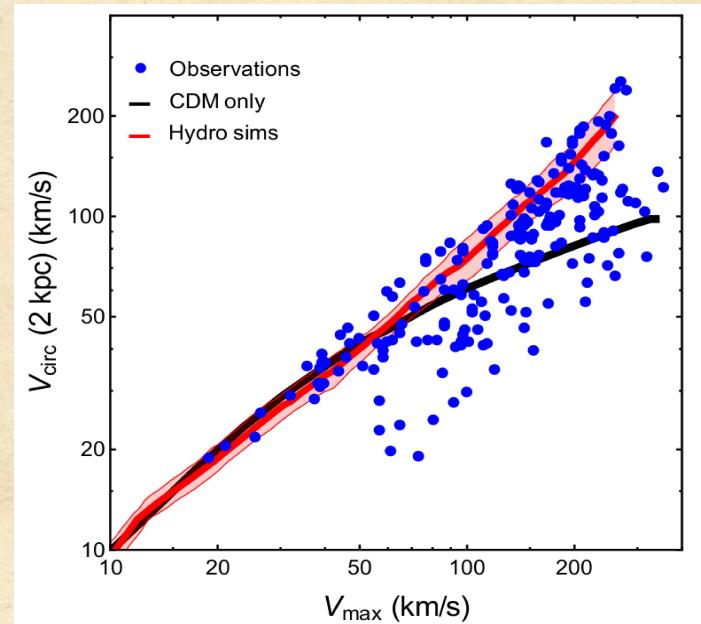
# A small-scale crisis for standard cold DM?

- Long-standing discrepancies between N-body simulations and observations on **small scales** (galaxies):

Recent review: Tulin+ [1705.02358]



Cusp-vs-core problem



Diversity problem

- Essentially two possible solutions:
  - (1) Baryonic feedback processes (star formation, supernovae, ...)
  - (2) “New” DM physics

# Self-interacting dark matter (SIDM)

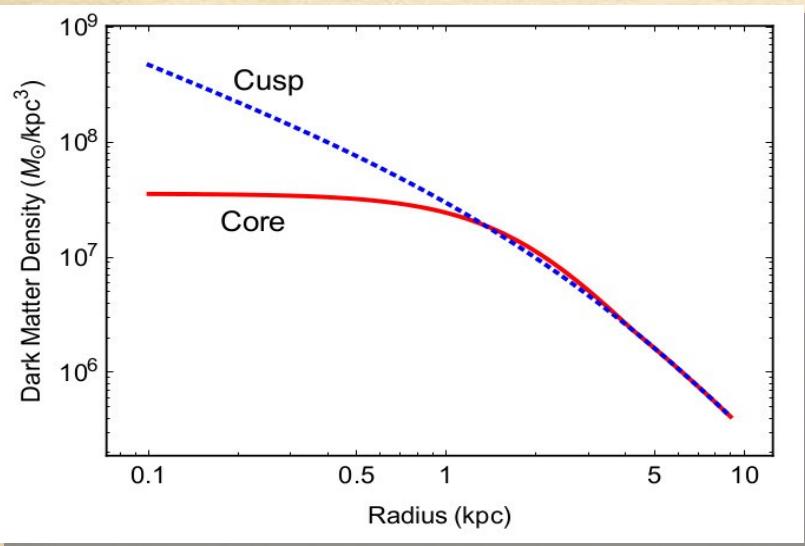
Strong self-interactions of DM can potentially cure the small-scale crisis of standard cold DM

Spergel+  
[astro-ph/  
9909386]

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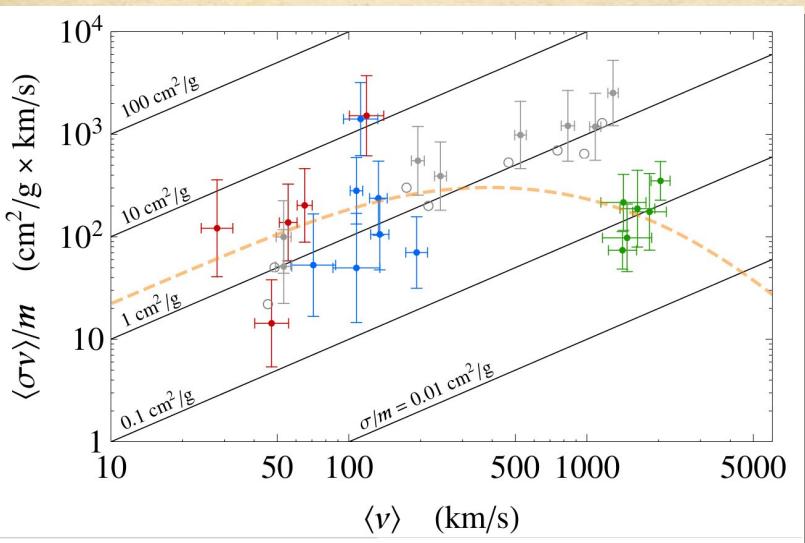
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- Self-interactions allow for efficient energy transfer between DM particles
- This heats up DM and creates an isothermal core
- Observational preference for **velocity-dependent SIDM:**

$$\sigma_T/m \sim 1 - 10 \text{ cm}^2/\text{g}$$
$$\sim 2 - 20 \text{ barn/GeV } (v \sim 30 \text{ km/s})$$

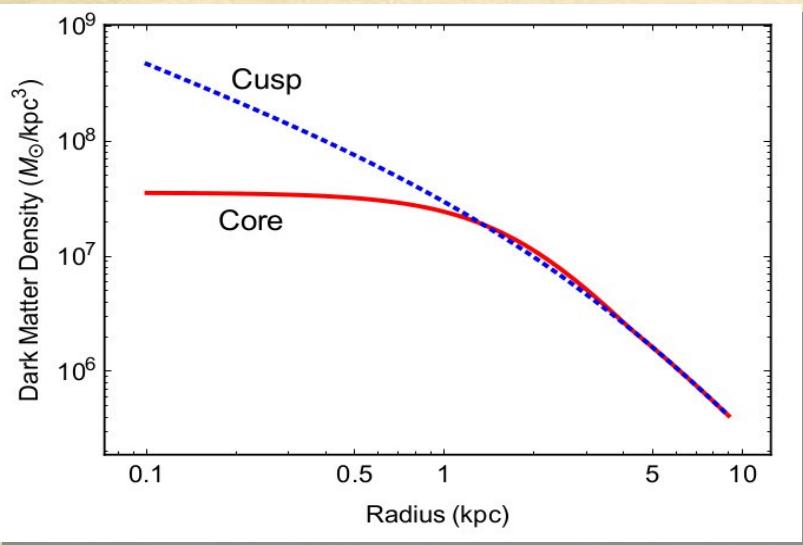
$$\sigma_T/m \lesssim 0.1 - 1 \text{ cm}^2/\text{g } (v \sim 1000 \text{ km/s})$$



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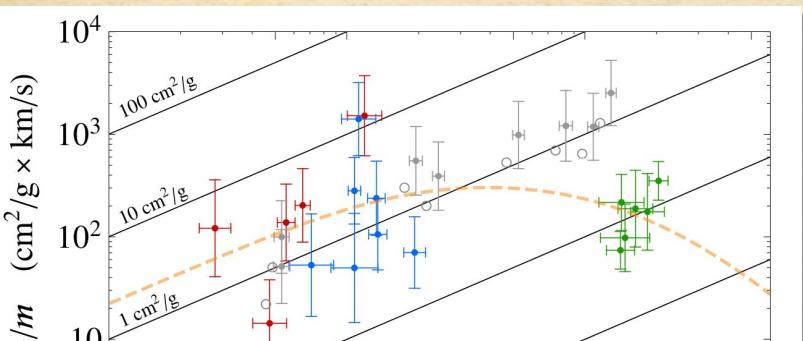
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Which models can provide a **large and velocity-dependent** self-interaction cross section of dark matter ?

# SIDM via a light mediator

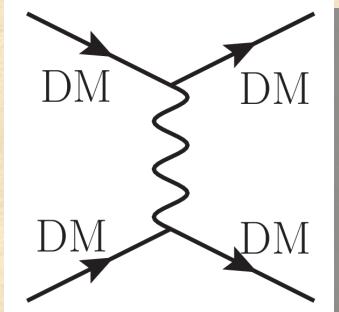
Feng+ [0905.3039]

Buckley+ [0911.3898]

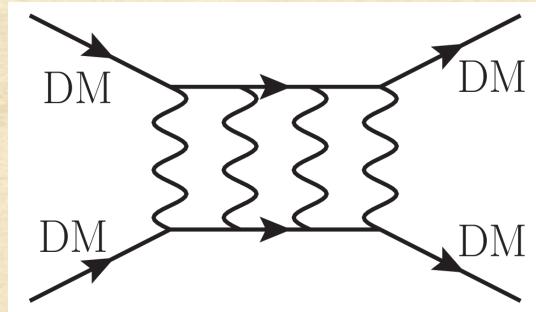
Tulin+ [1302.3898]

SW+ [1704.02149]

- WIMP  $(m_{\text{DM}} \simeq \text{GeV} - \text{TeV})$   
+ light mediator  $(m_{\text{med}} \simeq 1 \text{ MeV} - 100 \text{ MeV})$   
+ weak coupling  $(g \simeq 0.1)$



→ enhanced by  $1/q^4$  or  $1/m_{\text{med}}^4$



→ enhanced by non-perturbative effects  
(relevant if  $\alpha_g m_{\text{DM}} / m_{\text{med}} \gtrsim 1$ )

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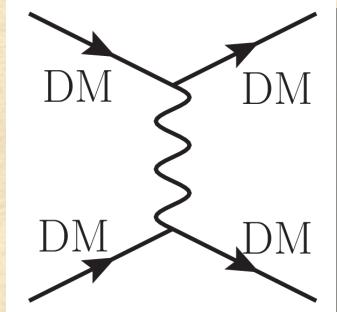
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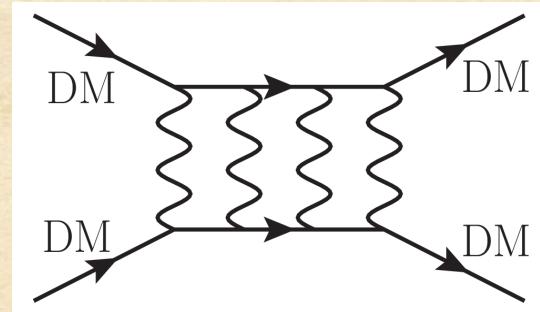
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(relevant if  $\alpha_g m_{\text{DM}} / m_{\text{med}} \gtrsim 1$ )

- Strong DM self-interactions with weak couplings! ✓
- Desired velocity-dependence comes for free:
  - large cross section at dwarf scales ✓
  - suppressed cross section at cluster scales ✓
- How can this be realized in a concrete particle physics model ?

# SIDM via a decaying vector mediator

$$\mathcal{L} = -y_\psi \bar{\psi} \gamma_\mu \psi Z_D^\mu - \sin \epsilon B_{\mu\nu} Z_D^{\mu\nu}$$

$m_\psi \sim 10 \text{ MeV} - 10 \text{ TeV}$

$m_{Z_D} \sim 0.1 \text{ MeV} - 100 \text{ MeV}$

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Feng/Kaplinghat/Tu/Yu [0905.3039]

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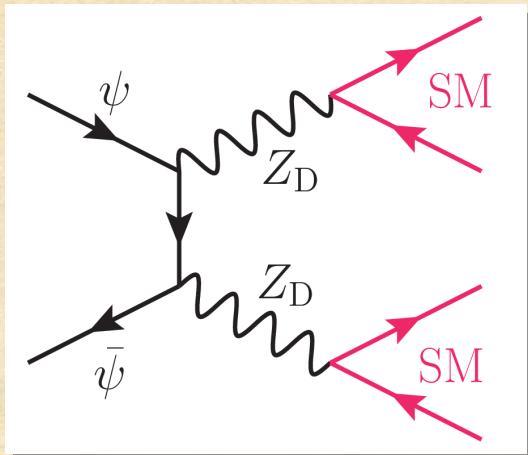
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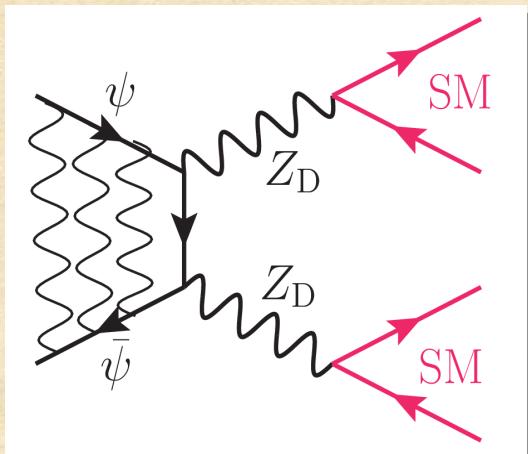
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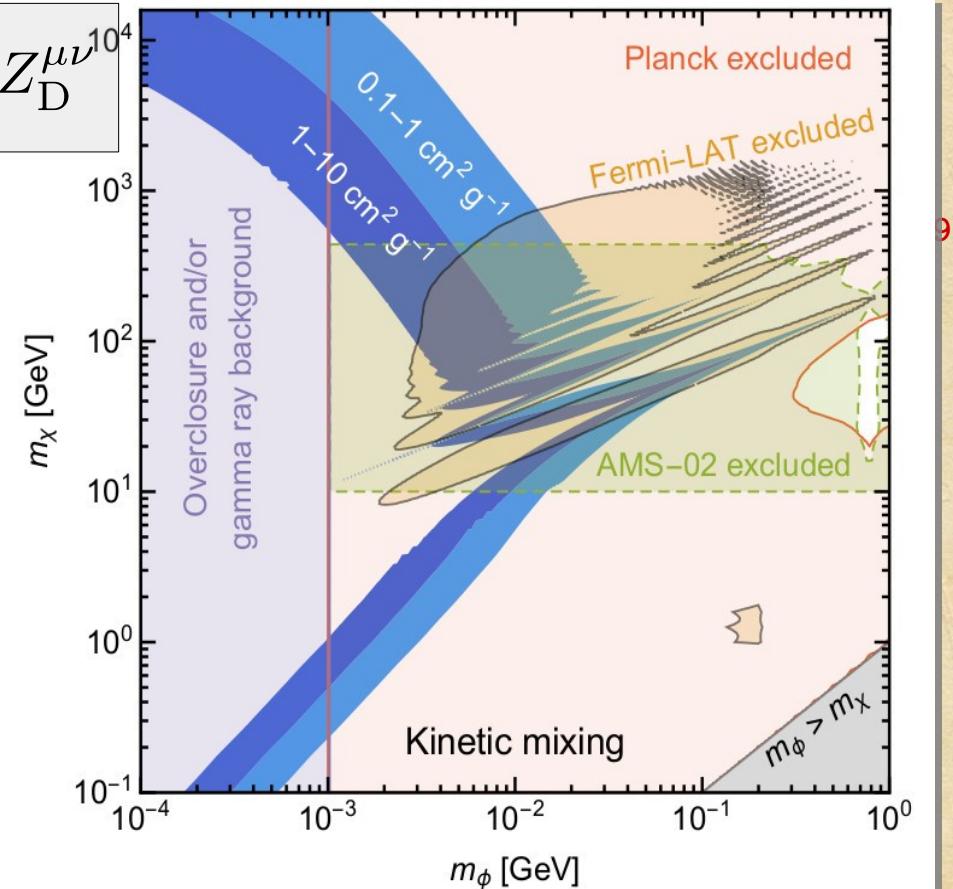
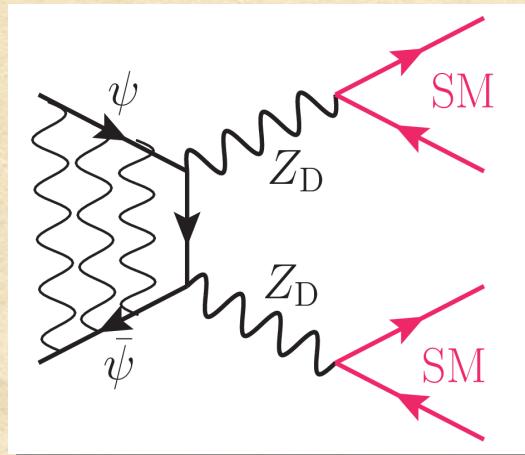
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Bringmann+ [1612.00845]

Simple model with a decaying vector mediator is excluded

Side remark: also the model with a scalar mediator is under strong pressure SW+ [1704.02149]

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# What if the vector mediator is stable?

- If  $Z_D^\mu$  is stable, the CMB constraints from  $\psi\bar{\psi} \rightarrow Z_D Z_D$  are avoided
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- Problem:  $Z_D^\mu$  would overclose the Universe
  - introduce a scalar field  $\sigma$  which breaks the  $U(1)_D$  associated to  $Z_D^\mu$
  - massive  $Z_D^\mu$  and a **dark Higgs**  $h_D$
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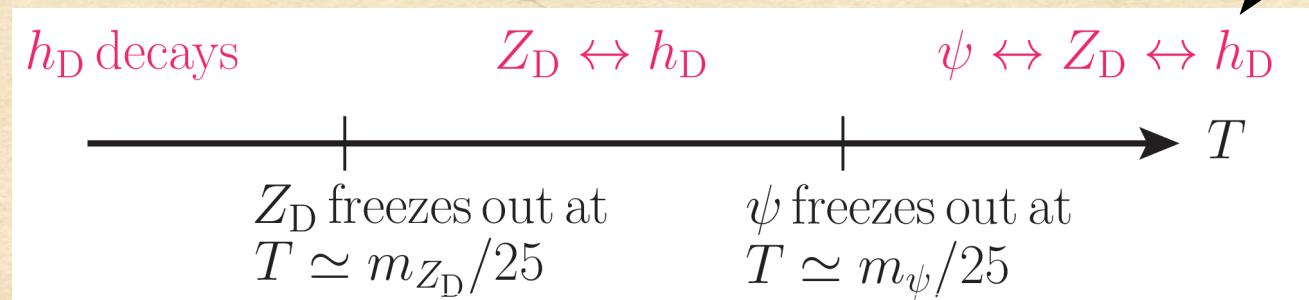
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- Model summary (after symmetry breaking):
  - Dirac fermion  $\psi$ ,  $m_\psi \sim \text{GeV-TeV}$ ,  $U(1)_D$  charge  $g_\psi$ 
    - dominant DM component
  - Gauge boson  $Z_D^\mu$ ,  $m_{Z_D} \sim (1-100) \text{ MeV}$ 
    - subdominant DM component
  - Dark higgs boson  $h_D$ ,  $m_{h_D} \sim 1 \text{ MeV} < m_{Z_D}$ 
    - associated to scalar field with  $U(1)_D$  charge  $g_D$
    - small mixing with SM Higgs  $\propto \lambda_{hD}$

# Thermal history

- Dark sector freeze-out of  $\psi$  and  $Z_D^\mu$  :

equilibration with SM at large  $T$   
via  $h_D - h$  mixing  $\propto \lambda_{hD}$

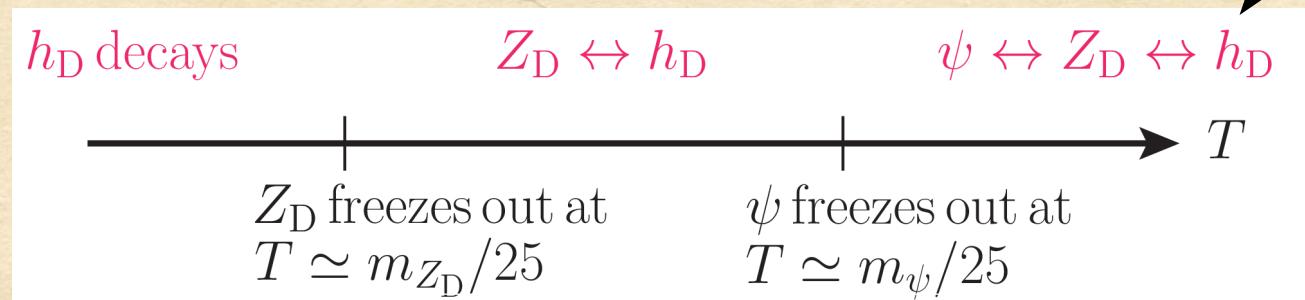


- Correct relic density for  $g_\psi, g_D \simeq 10^{-3} - 10^{-1}$ 
  - $\Omega_{Z_D}/\Omega_\psi \simeq 10^{-7} - 10^{-1}$
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(conversion processes, semi-annihilation, ...)

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(conversion processes, semi-annihilation, ...)
- BBN bounds?
  - For  $\lambda_{hD} \lesssim 4 \times 10^{-4}$ , dark and SM sectors decoupling prior to QCD phase transition, resulting in  $\Delta N_{\text{eff}} \lesssim 0.27$  ✓
  - For  $m_{h_D} \lesssim 2 \text{ MeV}$ , decay products of  $h_D$  are below the photo-disintegration threshold of deuterium ✓

More detailed BBN analysis of MeV-scale decaying particles:  
Ongoing work [Hufnagel, Schmidt-Hoberg, SW]

# CMB constraints strike back

Two types of CMB constraints:

- (1) **Spectral distortions** from late-time decays of  $h_D$  exclude  $\tau_{h_D} \gtrsim 10^5$  s
  - this (basically) excludes  $m_{h_D} < 2m_e$
  - we fix  $m_{h_D} = 1.5$  MeV (precise value irrelevant)

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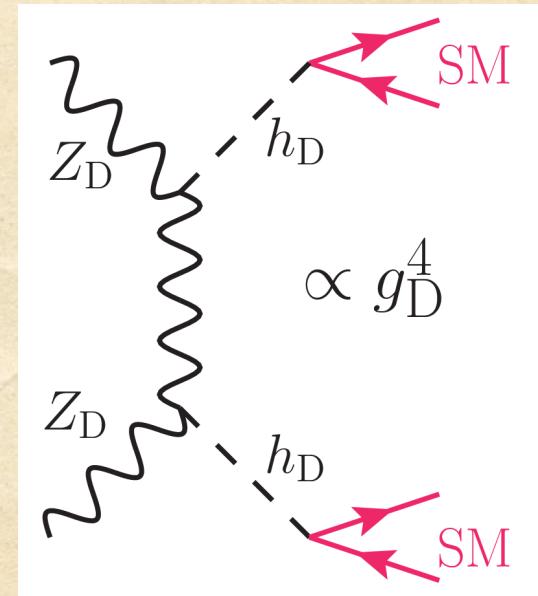
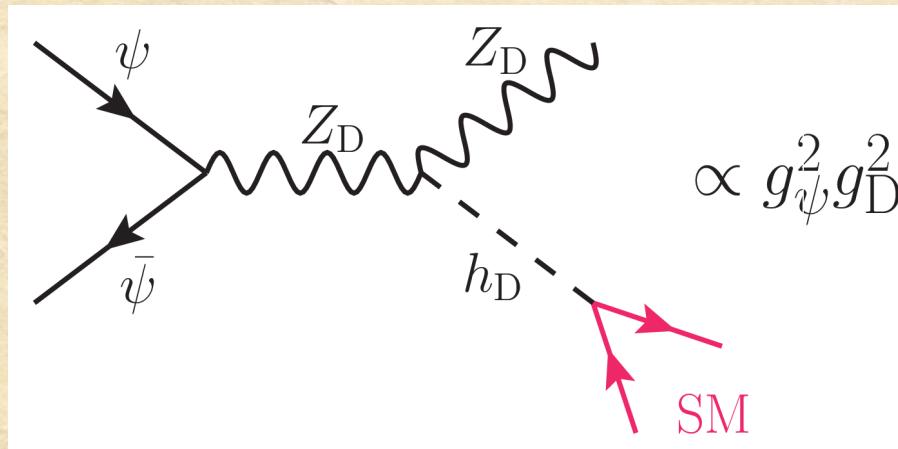
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(2) Energy injection from **late-time annihilations** of  $\psi$  and  $Z_D^\mu$  :

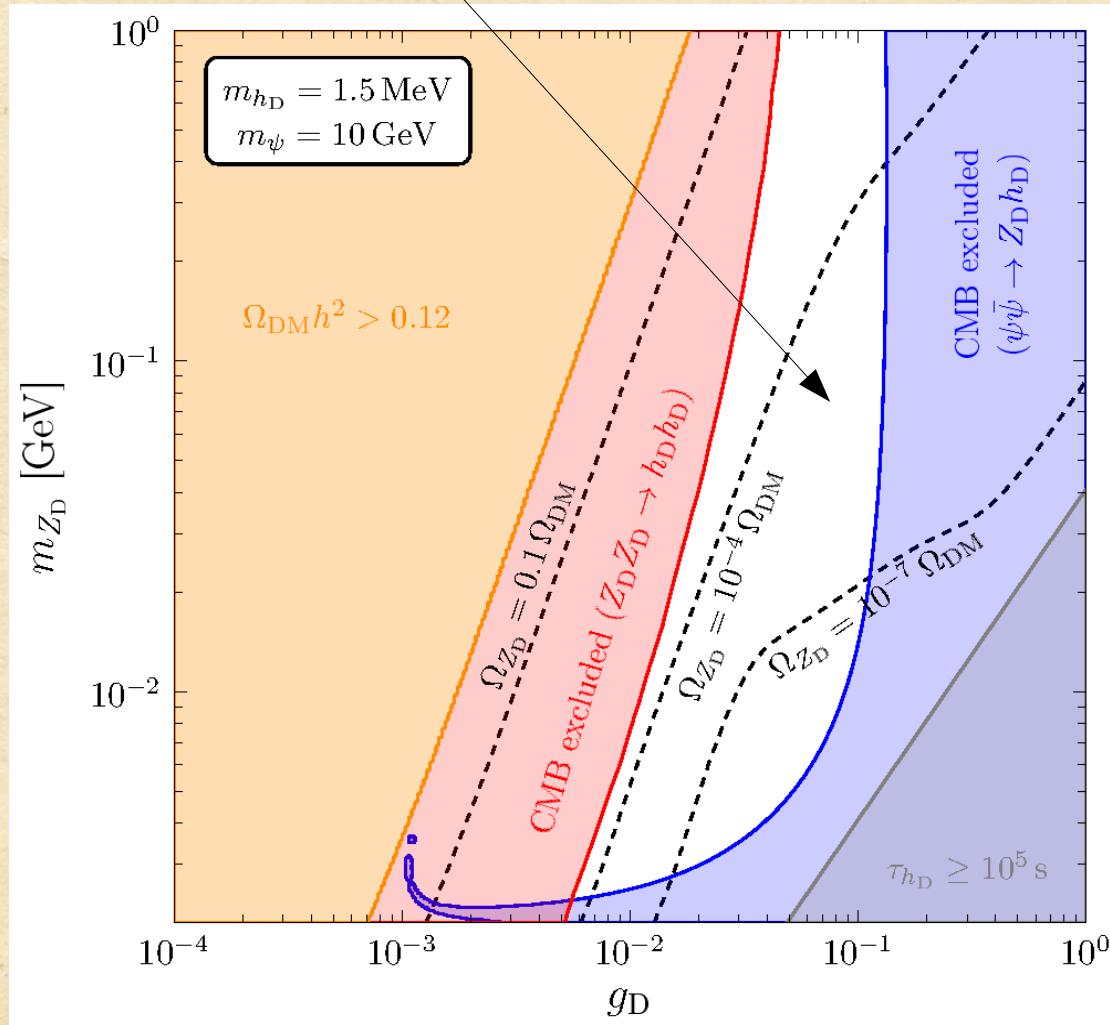


- $\psi\bar{\psi} \rightarrow Z_D h_D$  is Sommerfeld enhanced
- $Z_D Z_D \rightarrow h_D h_D$  can give important constraints even for  $\Omega_{Z_D} h^2 \ll 0.12$
- We employ the bounds on  $\langle \sigma v \rangle$  from **Slatyer [1506.03811]**

# Impact of CMB constraints

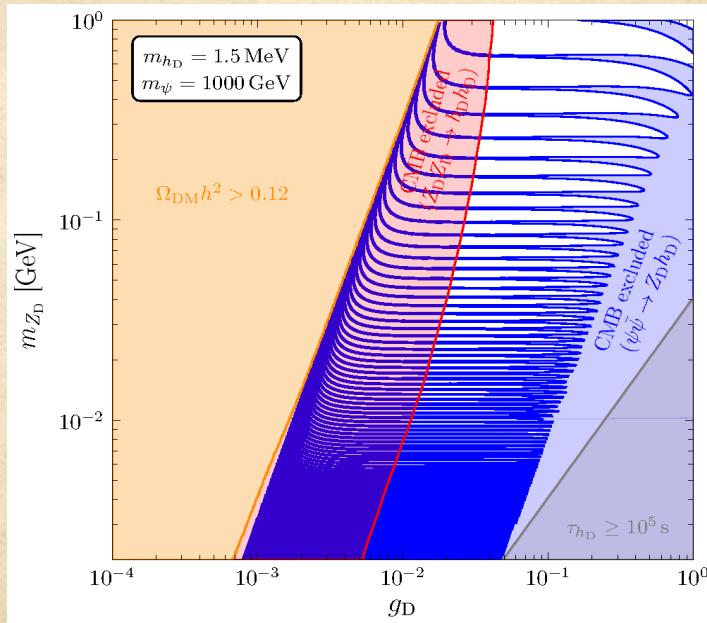
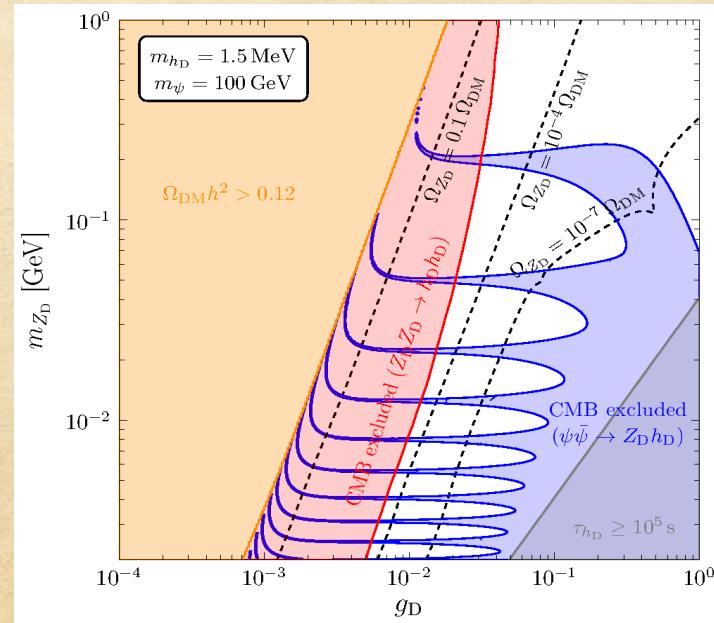
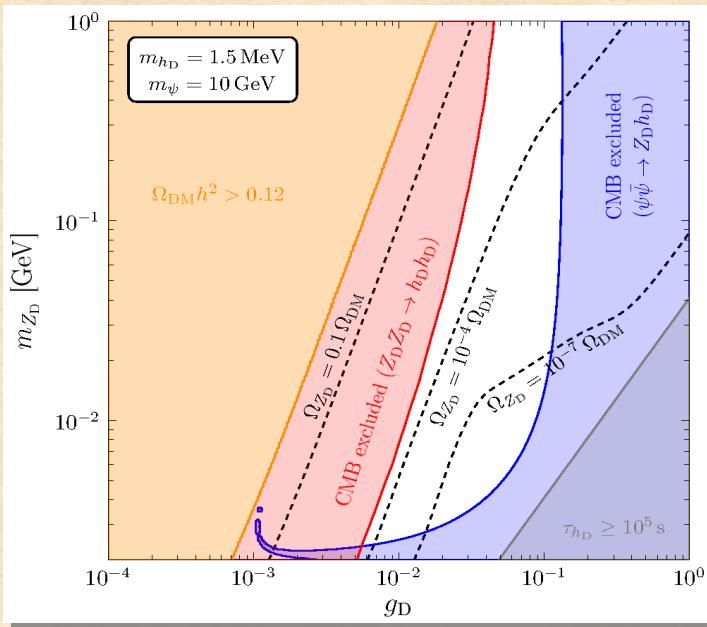
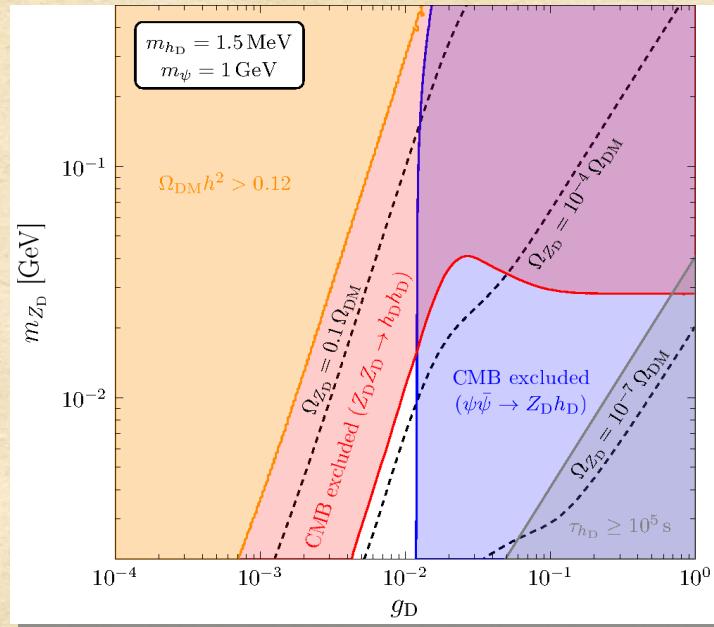
not excluded!

$\psi$  dominantly annihilates via  $\psi\bar{\psi} \rightarrow Z_D h_D$

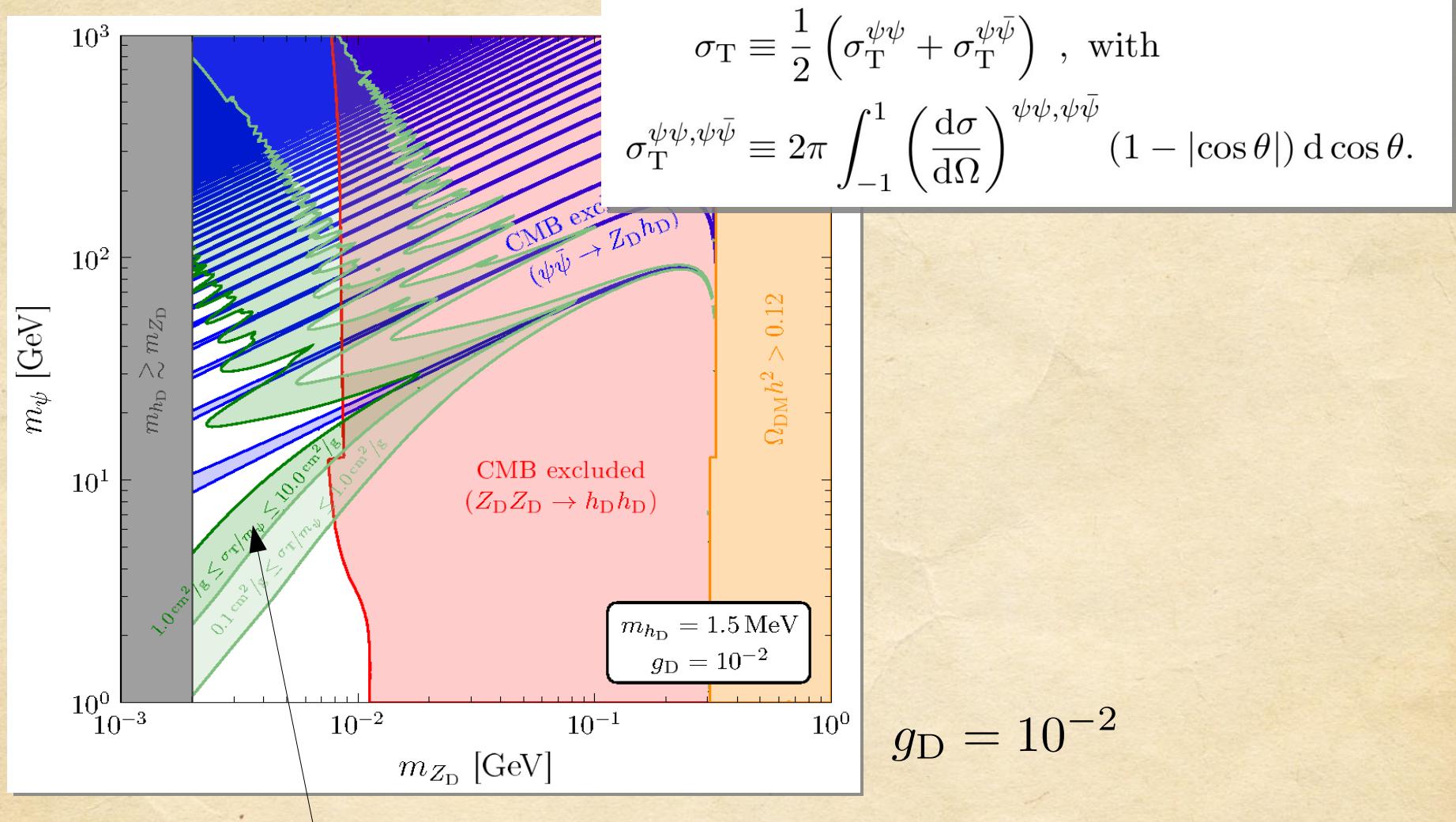


→  $Z_D$  abundance grows

# Impact of CMB constraints



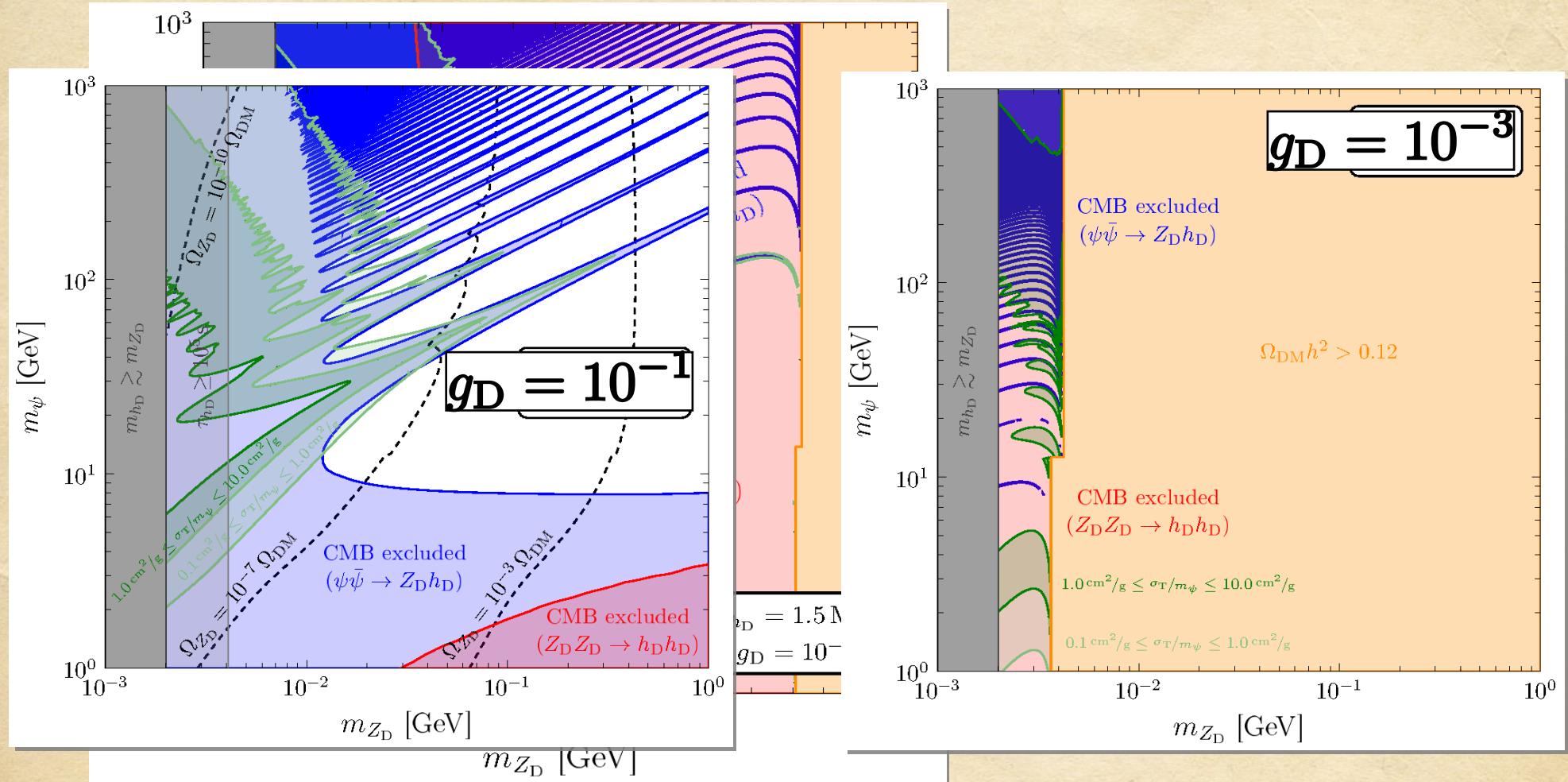
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There are regions in parameter space leading to the desired  $\sigma_T/m_\psi$ , without being excluded by CMB or BBN!

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- **Self-interacting dark matter** is an interesting solution to the small-scale problems appearing within the standard cold dark matter paradigm
- Model-building challenge: large and velocity-dependent cross sections
  - WIMP + MeV-scale mediator
  - most simple realizations are under strong pressure
- New idea:  
SIDM with a **stable vector mediator**  $Z_D^\mu$  and a dark Higgs  $h_D$ 
  - annihilations  $Z_D Z_D \rightarrow h_D h_D$  suppress abundance of  $Z_D^\mu$
  - Two DM particles:  $\psi$  (dominant, GeV-scale)  
 $Z_D^\mu$  (subdominant, MeV-scale)
- Most important constraints on this scenario:
  - (1) CMB constraints on spectral distortions from  $h_D$  decay
  - (2) CMB constraints on late-time annihilations of  $\psi$  and  $Z_D^\mu$

There are regions in parameter space leading to the desired self-interaction cross section, without being excluded by CMB or BBN!

Backup material

# SIDM with a scalar mediator

