Self-interacting dark matter with light mediators: direct detection, BBN and the CMB

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(1) Introduction to (self-interacting) dark matter

(2) BBN constraints on decaying particles at the MeV scale

(3) SIDM from a stable vector mediator?

(4) Conclusions

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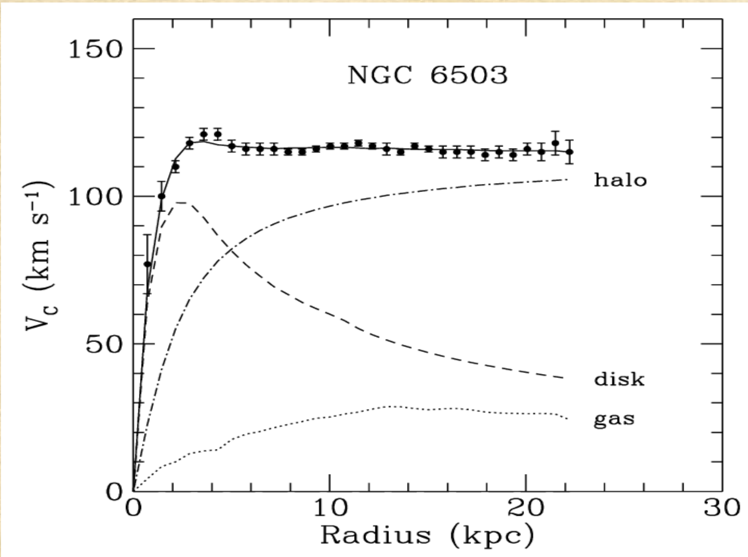
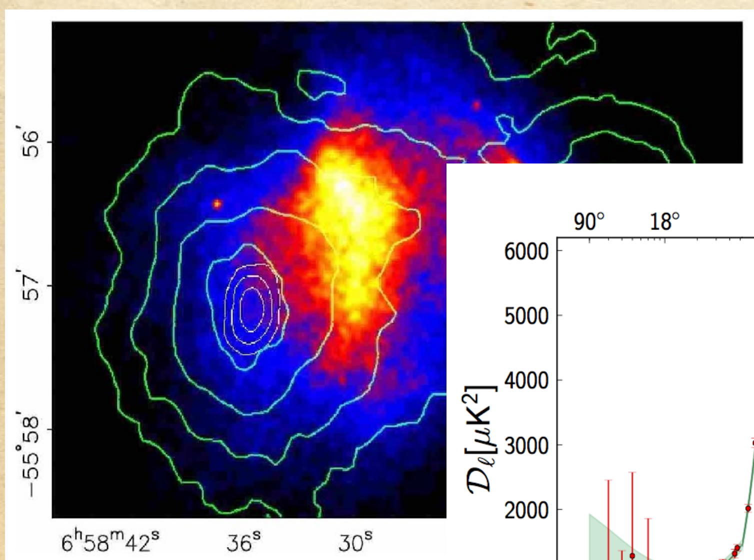
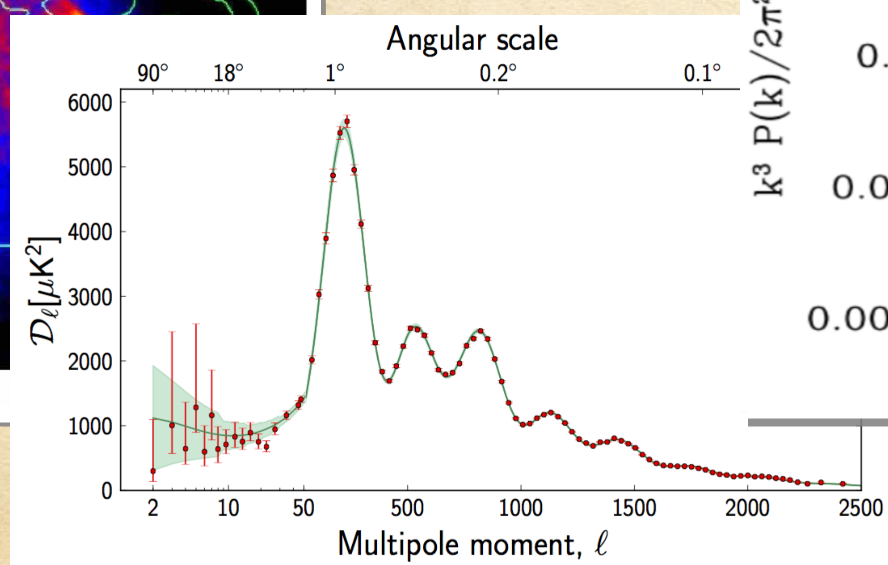
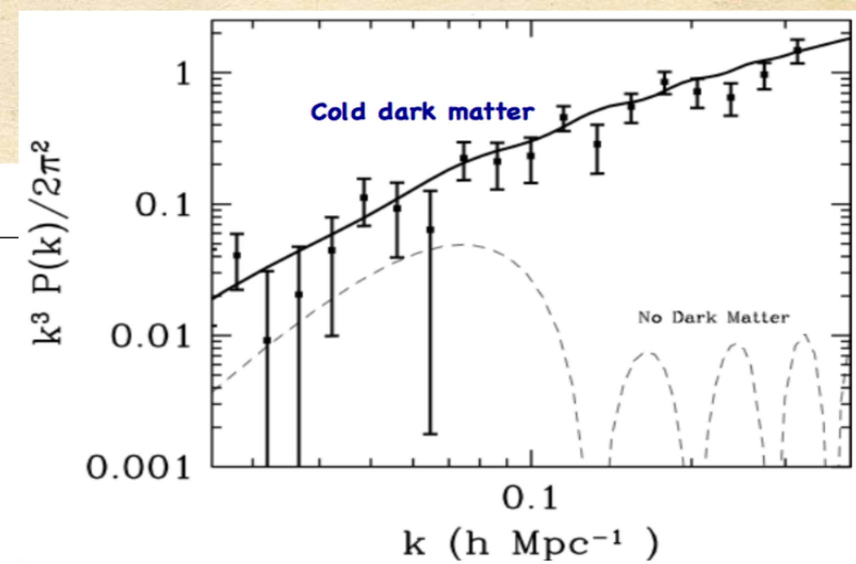
(4) Conclusions

Evidence for dark matter



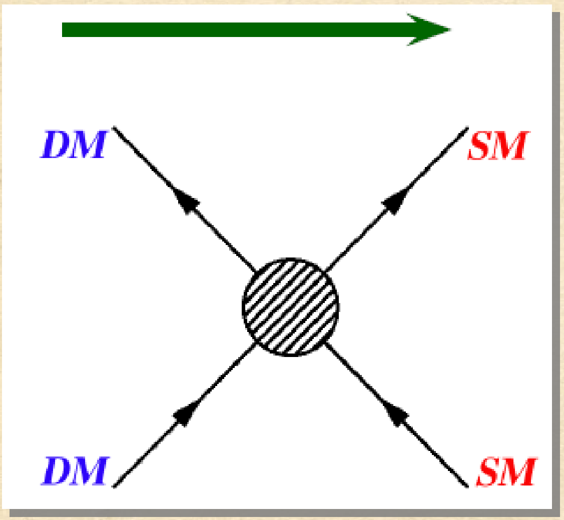


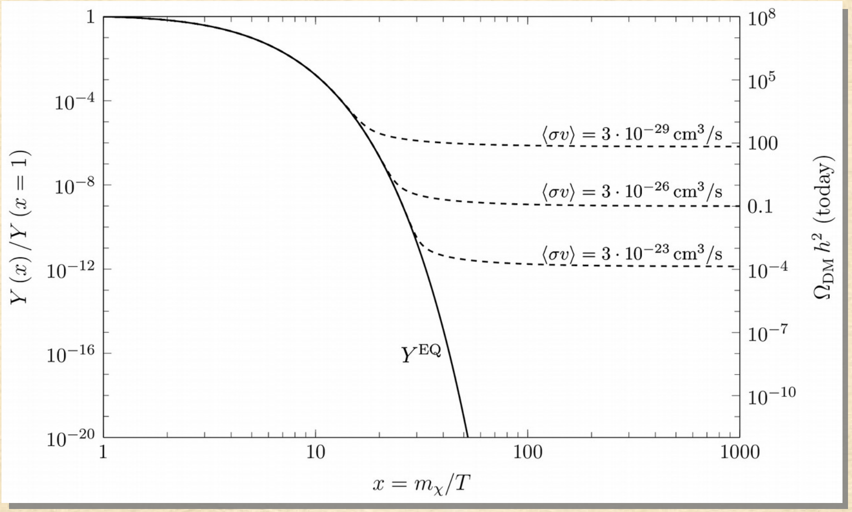




Motivation of WIMPs

Hypothesis: 1) $m_{\mathrm{DM}} \simeq 100\,\mathrm{MeV} \ldots 100\,\mathrm{TeV}$
2) DM has weak-scale interactions with its annihilation products





$$\Omega_{\mathrm{DM}}h^2 \simeq 0.12 \cdot \frac{2.2\cdot 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \longrightarrow$$ **"WIMP miracle"**

Variation of the WIMP idea:

DM annihilates only into other **dark states** $\mathrm{DM\,DM} \leftrightarrow \phi\phi$

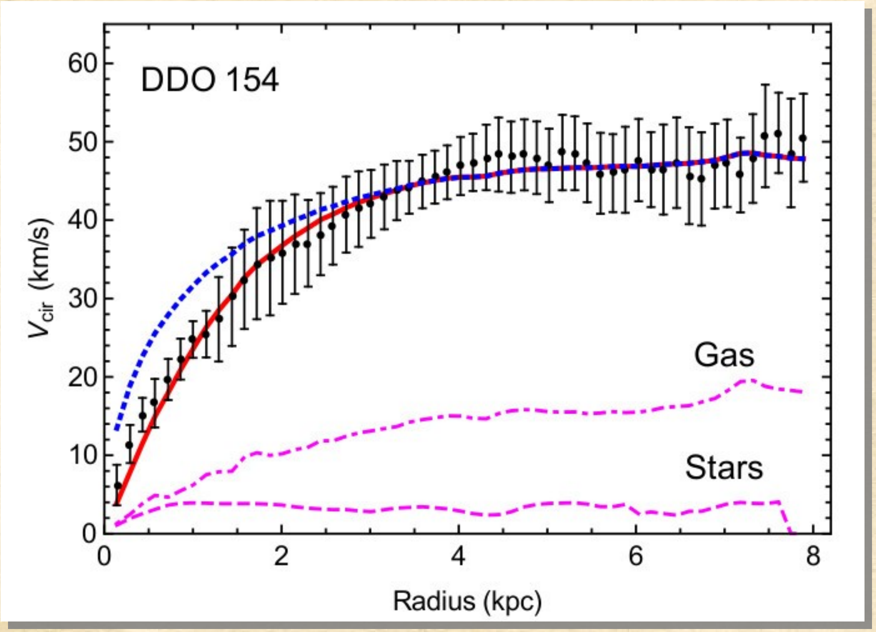
→ "hidden sector freeze-out"

→ The visible and dark sector are potentially only **very** weakly coupled

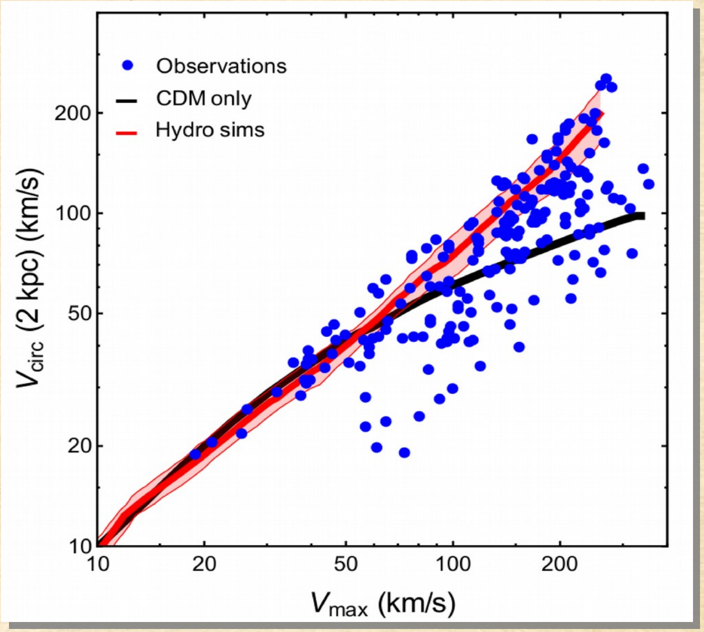
A small-scale crisis for standard cold DM?

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

Recent review: Tulin+ [1705.02358]



Cusp-vs-core problem
→ especially relevant in DM-rich dwarf galaxies
→ difficult to solve with baryonic physics



Diversity problem

Solving the small-scale crisis

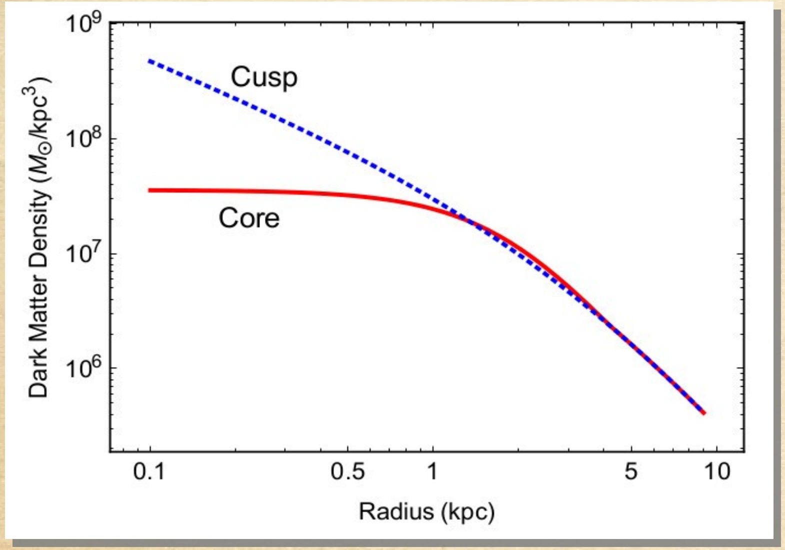
Essentially three possible solutions:

(1) Observational problems → no solution required

(2) Baryonic feedback processes (star formation, supernovae, ...)

(3) "**New**" **DM physics** Spergel+ [astro-ph/9909386]

→ Ongoing debate in the field. Stay tuned...



Basic idea for solution (3):

- Self-interactions allow for efficient energy transfer between DM particles
- This heats up DM and creates an isothermal core
- Similarly, subhalos can heat up and evaporate (→ missing satellites)

What are the required cross sections?

$$R_{\mathrm{scattering}} \simeq \sigma v_{\mathrm{rel}} \rho_{\mathrm{DM}} / m_{\mathrm{DM}} \simeq 0.1\,\mathrm{Gyr}^{-1} \times \left(\frac{\rho_{\mathrm{DM}}}{0.1\,M_\odot/\mathrm{pc}^3} \right) \left(\frac{v_{\mathrm{rel}}}{50\,\mathrm{km/s}} \right) \left(\frac{\sigma / m_{\mathrm{DM}}}{1\,\mathrm{cm}^2/\mathrm{g}} \right)$$

→ This is a **large cross section**:
$\sigma / m_{\mathrm{DM}} \sim 1\,\mathrm{cm}^2/\mathrm{g} \sim 2\,\mathrm{barn}/\mathrm{GeV} \quad \gg \quad (\sigma / m_{\mathrm{DM}})_{\mathrm{naive\ WIMP}}$

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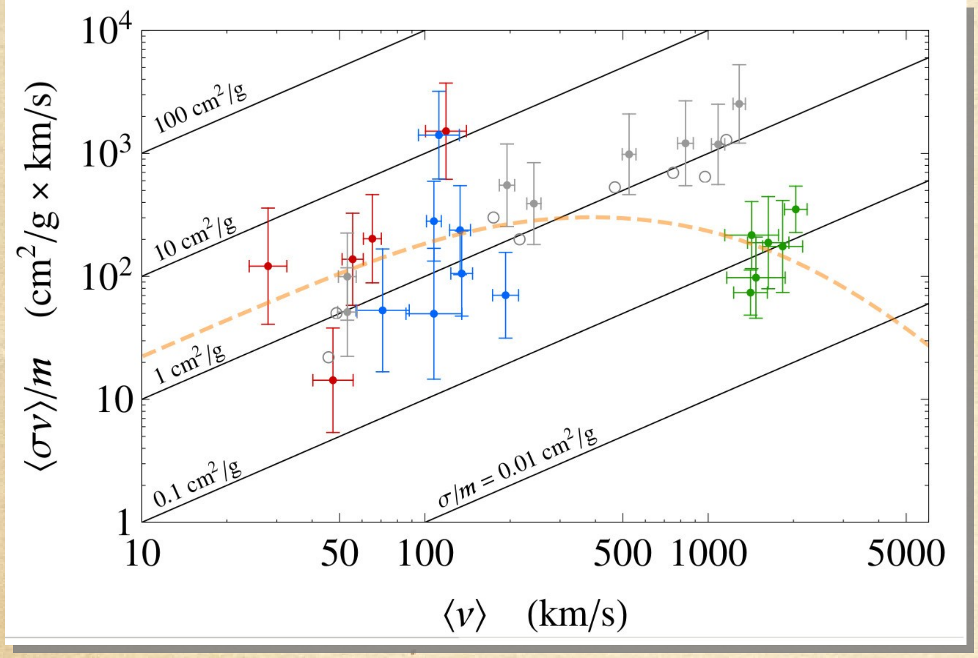
Kaplinghat+ [1508.03339]



- Observational preference for **velocity-dependent** SIDM:

  $\sigma/m \sim 1 - 10\,{\rm cm}^2/{\rm g}$
  at dwarf scales ($v \sim 30$ km/s)

  $\sigma/m \lesssim 0.1 - 1\,{\rm cm}^2/{\rm g}$
  at cluster scales ($v \sim 1000$ km/s)

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

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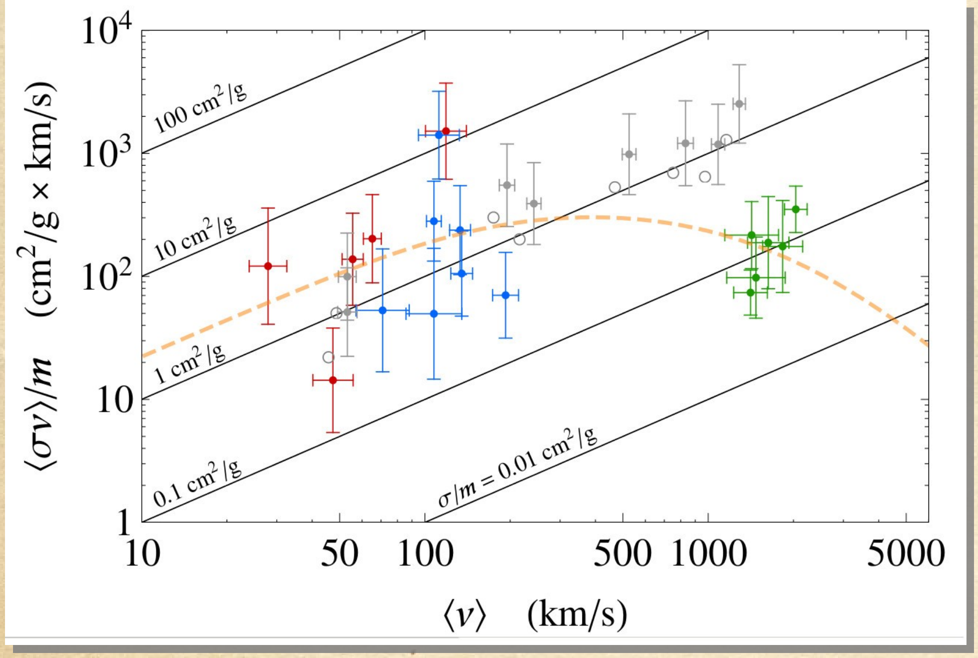

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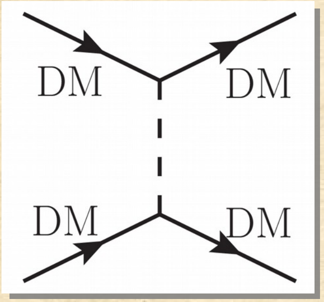
Which WIMP models can provide a **large** and **velocity-dependent** self-interaction cross section of dark matter ?

→ most can't! → Confirmation of SIDM would exclude neutralinos, axions, PBHs, ...

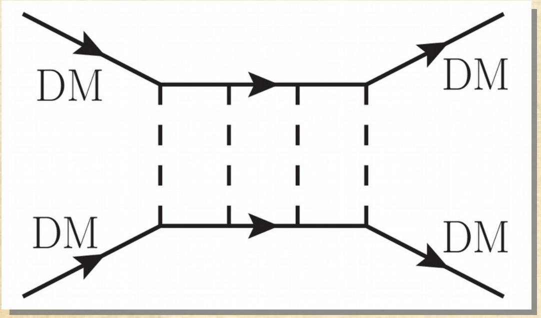
SIDM via a light mediator

Feng+ [0905.3039]
Buckley+ [0911.3898]

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



… enhanced by $1/q^4$ or $1/m_{\rm med}^4$



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

$$V(r) \propto \frac{e^{-m_\phi r}}{r} \longrightarrow \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = |f(\theta)|^2$$

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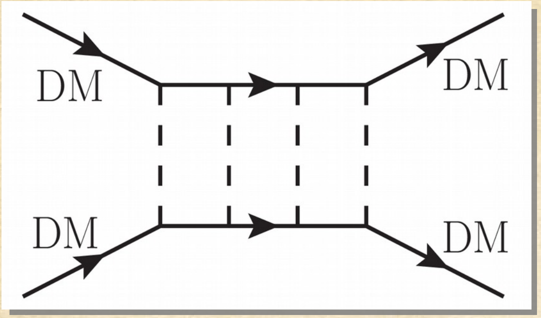

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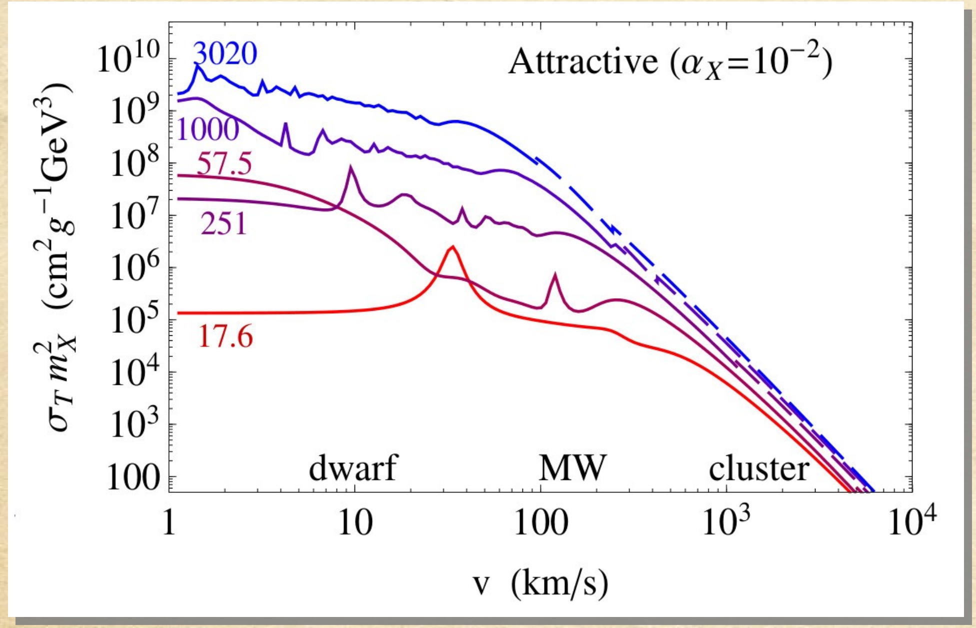
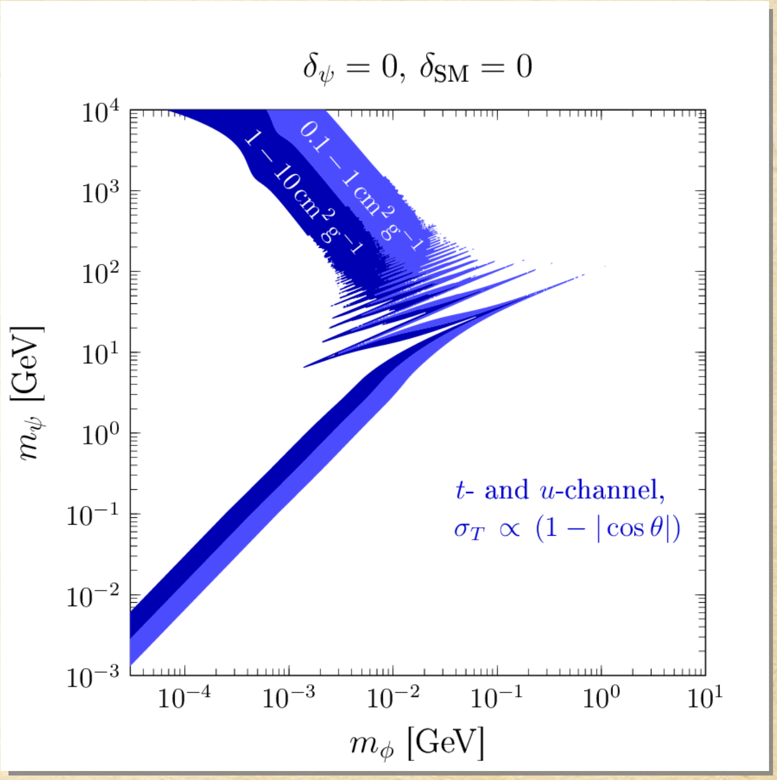
Kahlhoefer/Schmidt-Hoberg/SW [1704.02149]

Tulin/Yu/Zurek [1302.3898]





Strong DM self-interactions with **weak** couplings!

→ Required velocity dependence of self-interaction cross section comes for free!

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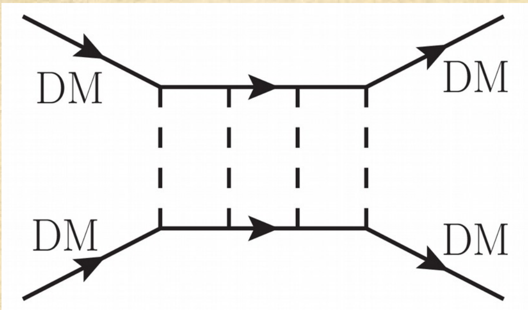

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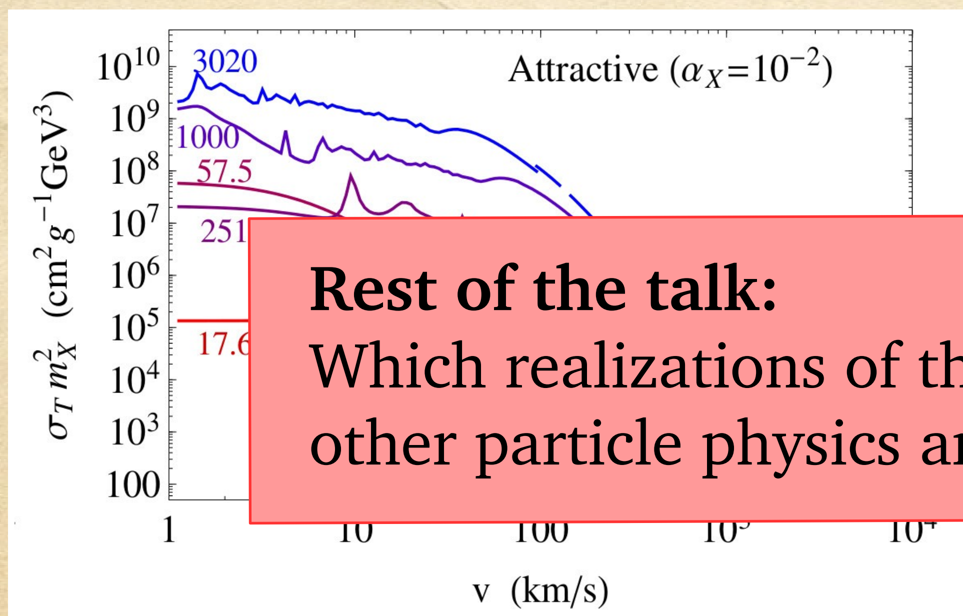

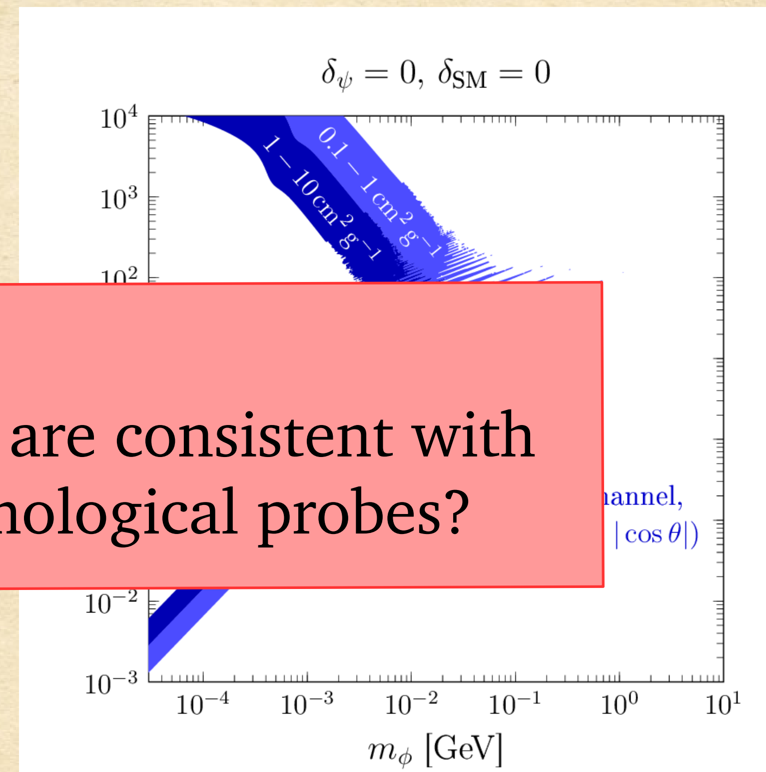

Rest of the talk:
Which realizations of this idea are consistent with other particle physics and cosmological probes?

Strong DM self-interactions with **weak** couplings!

→ Required velocity dependence of self-interaction cross section comes for free!

Simple model (I): light scalar mediator

$$\mathcal{L} = -y_\psi \bar{\psi}\psi\phi - y_{\rm SM} \sum_f \frac{m_f}{v_{\rm EW}} \bar{f} f \phi$$

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

$m_\phi \sim 0.1\,\text{MeV} - 100\,\text{MeV}$

Buckley/Fox [0911.3898]
Feng/Kaplinghat/Tu/Yu [0905.3039]
Tulin/Yu/Zurek [1302.3898]
Matsumoto/Sming Tsai/Tseng [1811.03292]

- $y_{\rm SM} \lesssim 10^{-4}$ (constrained e.g. by rare Kaon decays)
  - → freeze-out via $\psi\bar{\psi} \to \phi\phi$
  - → $y_\psi \sim 0.01 - 1$

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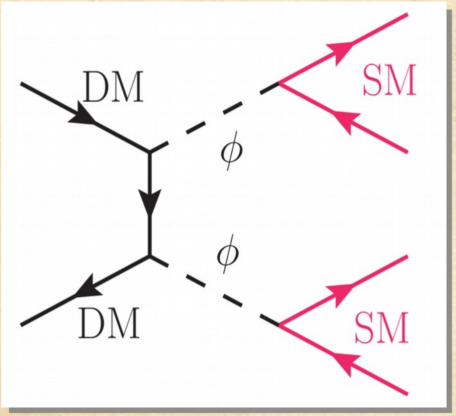

$$\propto v^2 \begin{cases} \simeq 0.3 & \text{during DM freeze-out} \\ \simeq 10^{-6} & \text{in present-day DM halos} \\ \simeq 10^{-18} & \text{at } T \simeq T_{\rm CMB} \end{cases}$$

Annihilation is p-waved suppressed
→ **no relevant constraints from indirect detection/CMB**

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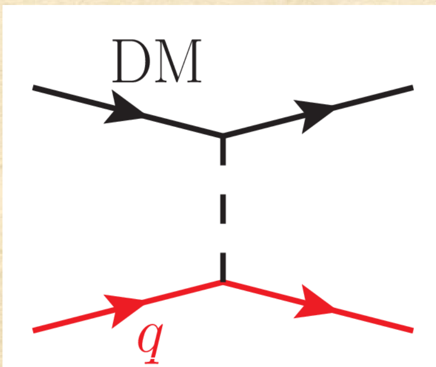
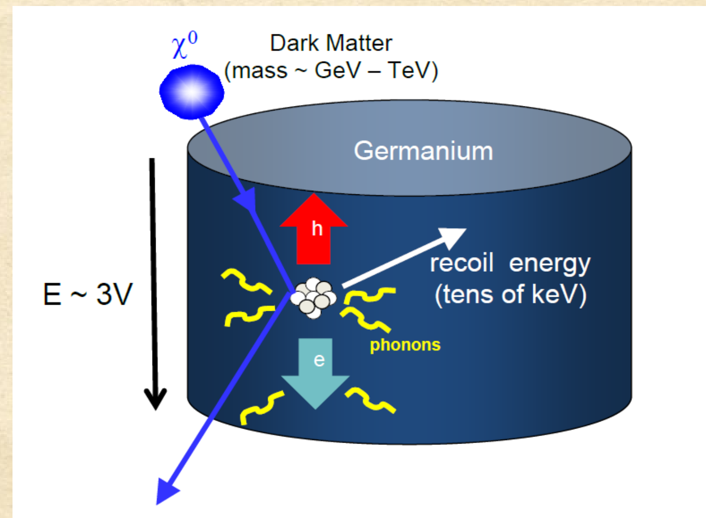
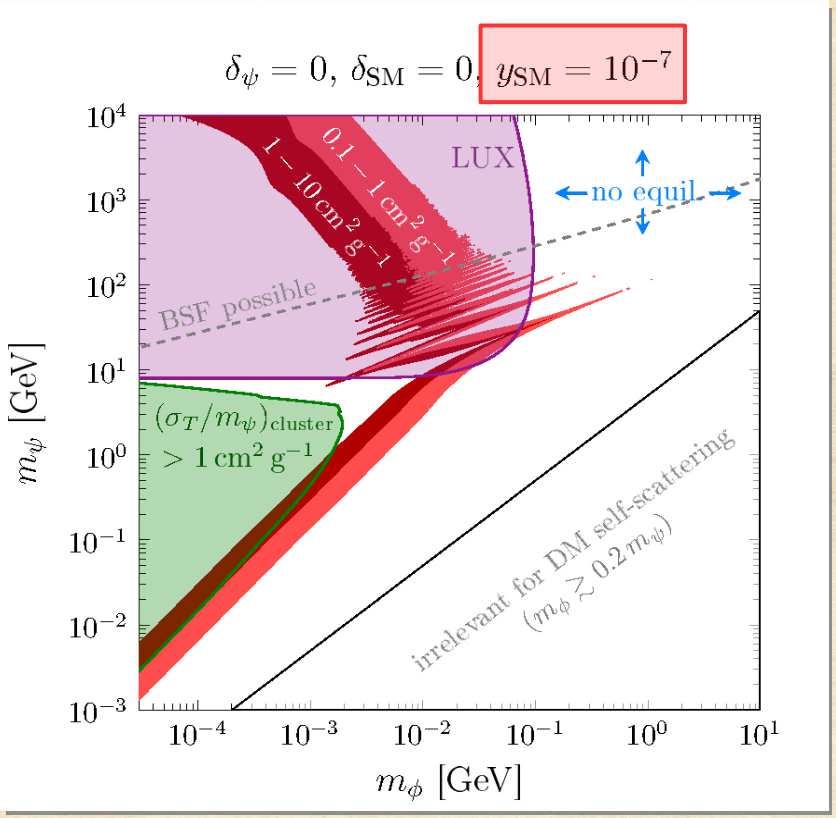




Direct detection of dark matter:
Strong enhancement $\sim m_h^4/m_{\rm med}^4$ compared to heavy mediator
→ relevant even down to very small values of $y_{\rm SM} \gtrsim 10^{-7}$

Simple model (I): light scalar mediator

Kahlhoefer/Schmidt-Hoberg/SW [1704.02149]



- This model faces **strong direct detection constraints**, even for very small y_{SM} see also DelNobile/Kaplinghat/Yu [1507.04007]
- Direct detection pushes the model to $\tau_\phi \gtrsim 0.1\,\mathrm{s}$
  → **BBN constraints** become highly relevant!

(1) Introduction to (self-interacting) dark matter

(2) BBN constraints on decaying particles at the MeV scale

(3) SIDM from pseudo-scalar exchange?

(4) SIDM from a stable vector mediator?

(5) Future direct detection prospects:
measuring the mediator mass?

(6) Conclusions

BBN constraints on MeV-scale mediators

- BBN bounds on (unstable) relics are well-known for
  (a) particles which are non-relativistic during BBN ($T \simeq (0.1 - 10)\,\mathrm{MeV}$)
  (b) ultra-relativistic particles, i.e. extra radiation (ΔN_{eff})

→ The scenario $m_\phi \simeq T_{\mathrm{BBN}} \simeq 1\,\mathrm{MeV}$ requires a dedicated study!

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- Further complication:
  spectrum of photons originating from the decay does not follow the usual universal spectrum for $m_{\mathrm{DM}} \lesssim 100\,\mathrm{MeV}$

- We have derived model-independent results for MeV-scale particles decaying with $10^{-2}\,\mathrm{s} \lesssim \tau_\phi \lesssim 10^8\,\mathrm{s}$ into $e^+e^-, \gamma\gamma$ or sterile states

  Part 1 (sterile decays): [1712.03972]
  Part 2 (electromagnetic decays): [1808.09324]

Cosmological evolution

- Assumption: particle ϕ is fully decoupled during BBN, subject only to redshift and decay
  → this is the case e.g. for hidden sector freeze-out $\mathrm{DM}\,\mathrm{DM} \leftrightarrow \phi\phi$

$$E\frac{\partial f_\phi(t,E)}{\partial t} - H(t)(E^2 - m_\phi^2)\frac{\partial f_\phi(t,E)}{\partial E} = -\frac{m_\phi}{\tau_\phi} f_\phi(t,E)$$

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- We solve the **full** Boltzmann equation for f_ϕ , and thus obtain $n_\phi(t)$
  → Friedman equation gives

$$\dot{\rho}_{\mathrm{SM}} + 3H\left(\rho_{\mathrm{SM}} + p_{\mathrm{SM}}\right) = \frac{m_\phi}{\tau_\phi} n_\phi$$

Injection of entropy into the thermal bath

  → Modified $H(T)$, $T_\gamma(t)$, $T_\nu(t)$
  → **Reduced** N_{eff} at recombination, as the photon bath is heated with respect to the neutrinos
  → modified time evolution of $\eta = n_B/n_\gamma$ (SM entropy is not conserved!)

- We haved implemented this modified cosmology in `AlterBBN`, which solves the evolution equations of light nuclei Arbey [1106.1363]

Photodisintegration

- BBN terminates at $t \simeq 10^4\,\mathrm{s}$. If $\tau_\phi \gtrsim 10^4\,\mathrm{s}$, non-thermal photons produced in the decay of ϕ can further modify light element abundances: **photodisintegration**

$$d + \gamma \to p + n, \;\; {}^4\mathrm{He} + \gamma \to n + {}^3\mathrm{He}, \;\; \ldots$$

- Decay products of ϕ induce an **electromagnetic cascade** on background photons, electrons and nuclei. For $m_\phi \gg 100\,\mathrm{MeV}$, the spectrum is **universal**:

$$f_\gamma^{(\mathrm{uni.})}(E) \sim \begin{cases} K_0 \left(\frac{E}{E_X}\right)^{-3/2} & \text{for } E < E_X \\ K_0 \left(\frac{E}{E_X}\right)^{-2} & \text{for } E_X \leq E \leq E_C \\ 0 & \text{for } E > E_C \end{cases}$$

Electromagentic cascade

- In large parts of our parameter space, the universal spectrum is not valid
- Instead, we solve the coupled cascade equations from scratch:

$$f_X(E) = \frac{1}{\Gamma_X(E)} \left(S_X(E) + \int_E^\infty \mathrm{d}E' \sum_{X'} \left[K_{X' \to X}(E, E') f_{X'}(E') \right] \right)$$

spectrum of $X \in \{\gamma, e^-, e^+\}$

source term $\propto n_\phi / \tau_\phi$

interaction rate for scattering of $X'(E') \to X(E)$

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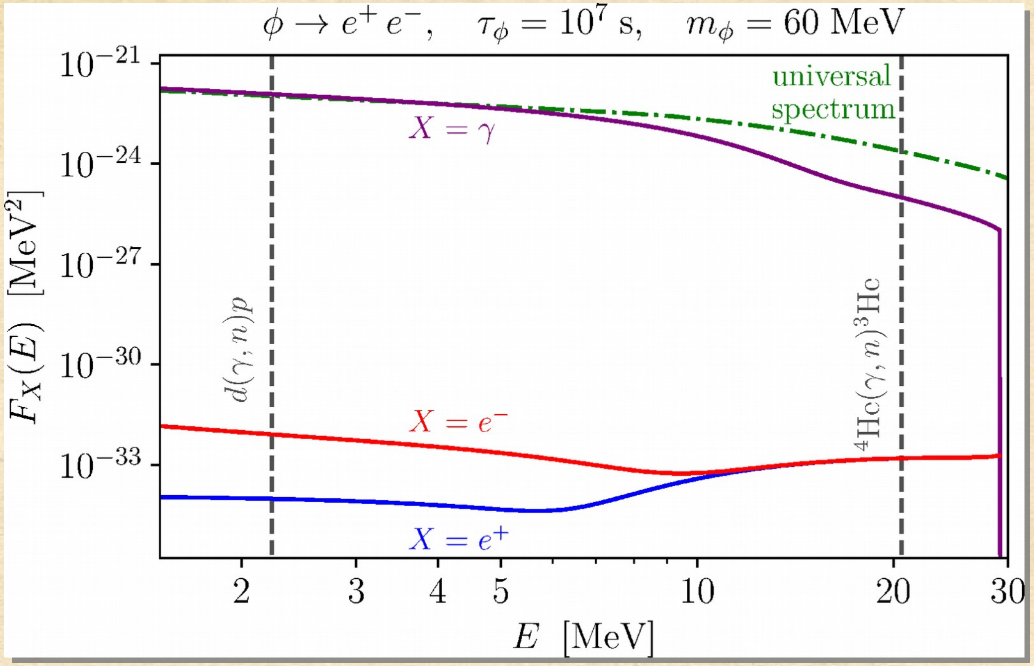
- Relevant scattering processes:
  - Photon pair creation $\gamma\gamma \to e^- e^+$
  - Photon-photon scattering $\gamma\gamma \to \gamma\gamma$
  - Bethe-Heitler pair creation $\gamma N \to \gamma e^- e^+$
  - Compton scattering $\gamma e^- \to \gamma e^-$
  - Inverse Compton scattering $e^\pm \gamma \to e^\pm \gamma$

- We numerically solve this integro-differential equatinos for $f_X(E)$ using an appropriate discretization method

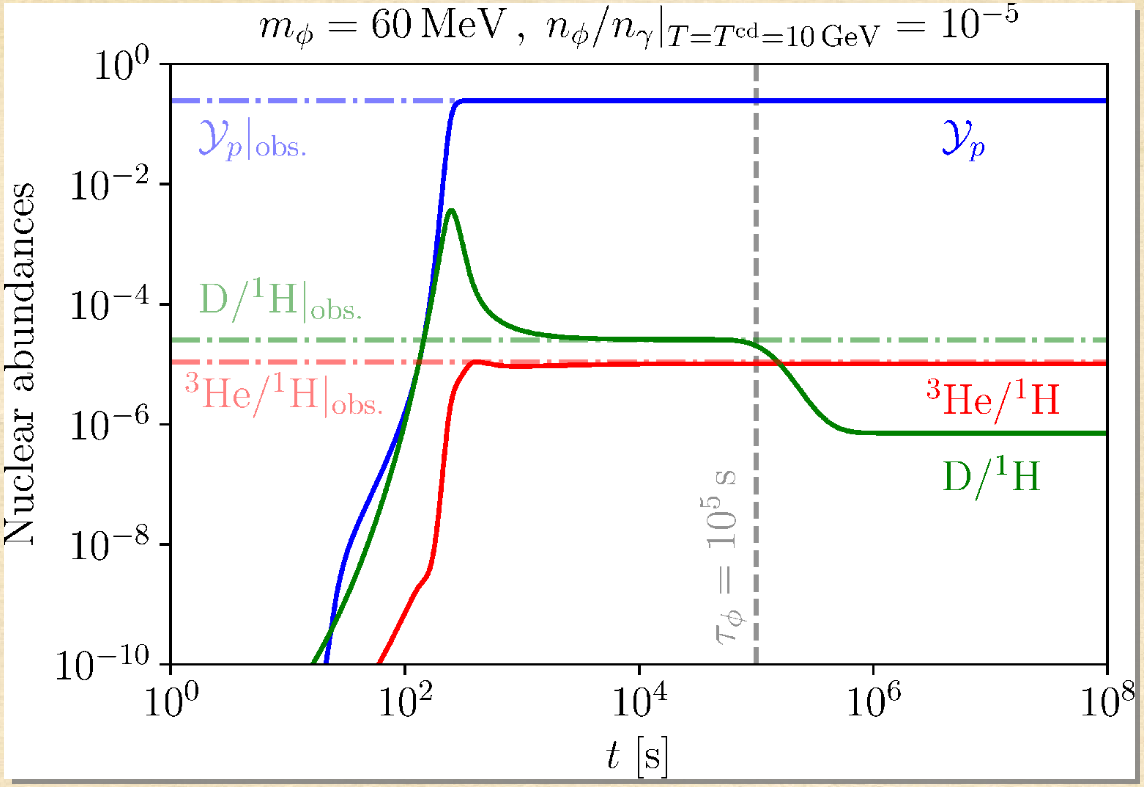
Electromagentic cascade



- For a given photon spectrum, we obtain the temperature evolution of the abundances of light elements by solving

$$\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right)\frac{\mathrm{d}Y_X}{\mathrm{d}T} = \sum_{N_i} Y_{N_i} \int_0^\infty \mathrm{d}E\, f_\gamma(E)\sigma_{\gamma+N_i\to X}(E) - Y_X \sum_{N_f} \int_0^\infty \mathrm{d}E\, f_\gamma(E)\sigma_{\gamma+X\to N_f}(E)$$

Evolution of nuclear abundances: example

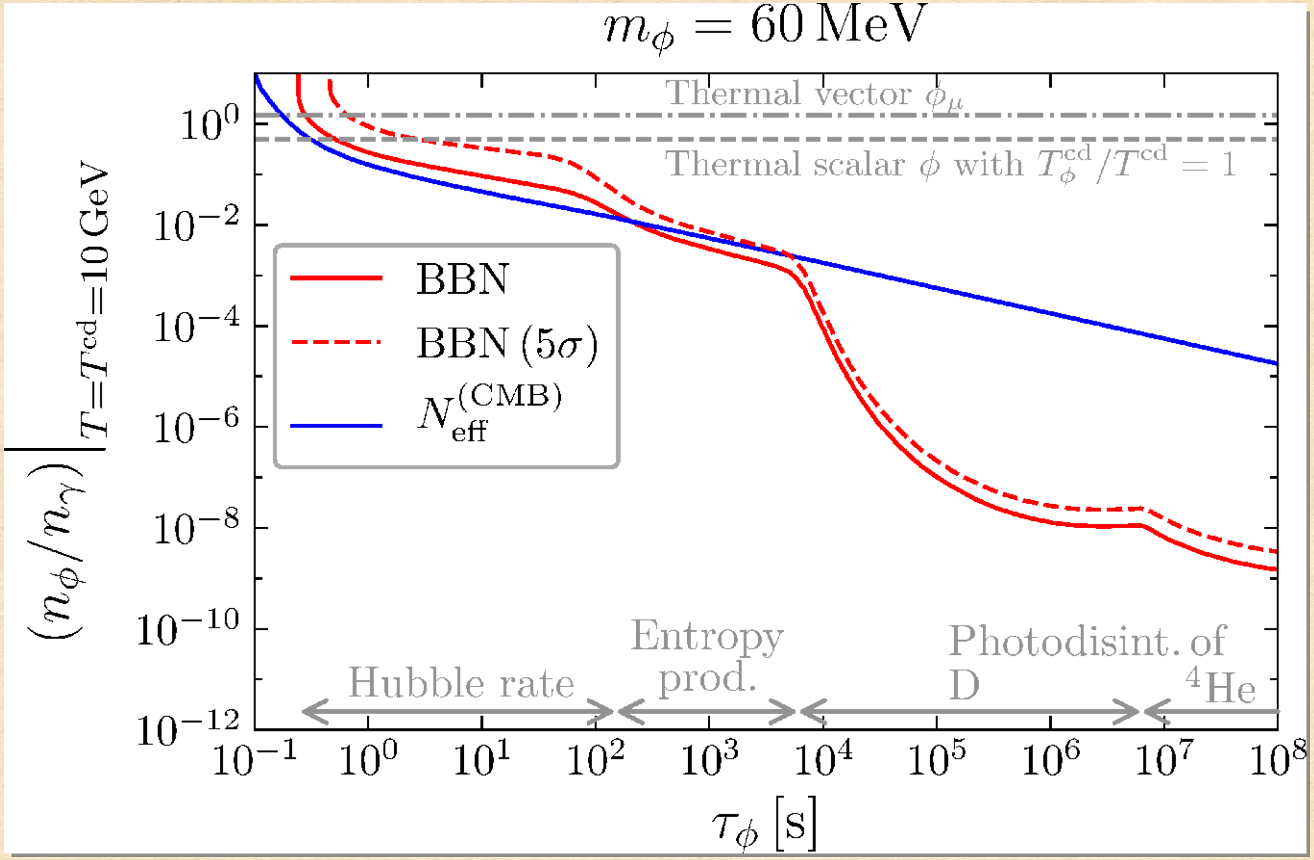


- We derive constraints by comparing to the observed values:

$\mathcal{Y}_\mathrm{p}$	$(2.45 \pm 0.04) \times 10^{-1}$,
$\mathrm{D}/^1\mathrm{H}$	$(2.53 \pm 0.04) \times 10^{-5}$,
$^3\mathrm{He}/^1\mathrm{H}$	$(1.1 \pm 0.2) \times 10^{-5}$.

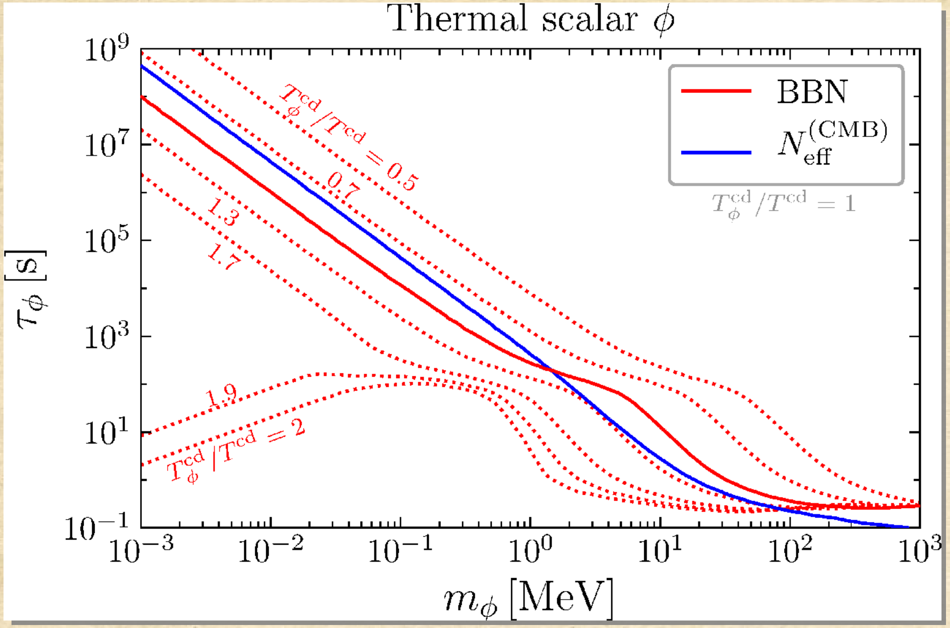
- We take into account both observational as well as systematic (i.e. nuclear) uncertainties

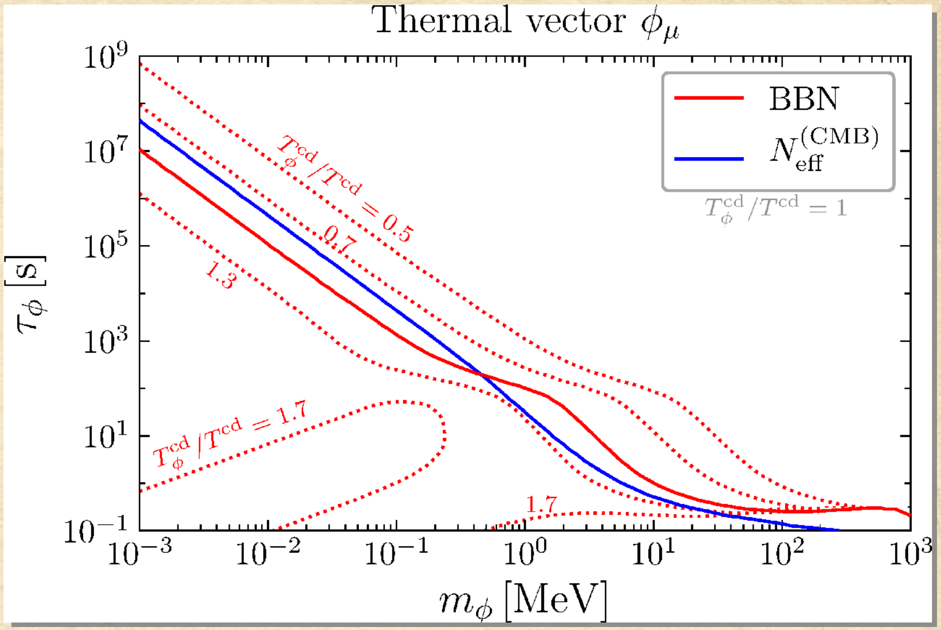
Model-independent bounds from BBN



- We provide upper limits on the initial abundance of ϕ , as a function of τ_ϕ for various values of m_ϕ
  → easy to re-use for a given model!
- Depending on τ_ϕ, different effects provide the most stringent constraint

Bounds for thermally produced particles

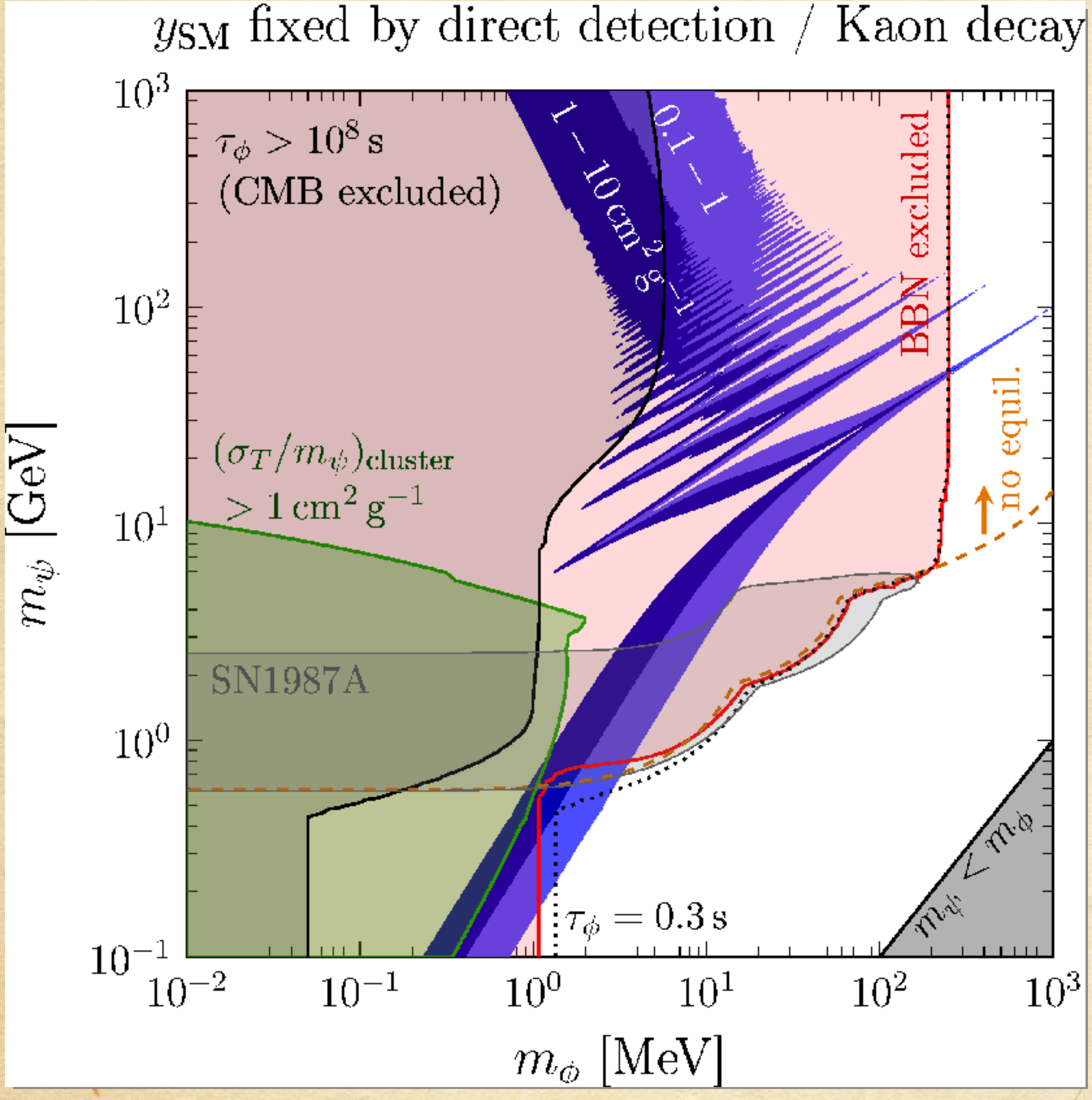




- For thermally produced particles, the initial abundance is fixed
  → it still depends on $T_\phi^{\rm cd}/T^{\rm cd}$
- Bound on τ_ϕ strongly depends on m_ϕ :
  → $\tau_\phi \lesssim 0.3\,{\rm s}$ for $m_\phi \gtrsim 100\,{\rm MeV}$
  → $\tau_\phi \lesssim 100\,{\rm s}$ for $m_\phi \simeq 1\,{\rm MeV}$
  → Even less stringent bounds for $m_\phi \ll 1\,{\rm MeV}$!

→ The naive bound $\tau_\phi \lesssim 1\,{\rm s}$ can be quite misleading!

Implications for SIDM via a scalar mediator



- We fix y_{SM} to the largest value allowed by direct detection & rare Kaon decays
- **BBN + DD excludes almost all of the parameter space!**
- Remaining viable parameters:

  $m_\psi \simeq 0.5\,\text{GeV}$

  $m_\phi \simeq 1.1\,\text{MeV}$

  $y_{SM} \simeq 5 \times 10^{-5}$

  $(\rightarrow \tau_\phi \simeq 30\,\text{s})$

  → interesting for future low-threshold experiments such as CRESST-III ddcalc.hepforge.org

Interlude: DDCalc

- Public code for **accurate direct detection likelihoods**
  - → 20 present and future experiments
  - → including latest Xenon1T results from 2018
  - → including experimental analyses with multiple signal-regions
- Support for:
  - → standard SI/SD interactions
  - → full set of non-relavistic scattering operators
  - → interface with `DirectDM` (running & matching of Wilson coefficients)
- Interfaces (incl. many examples) in Python, C, Fortran90

```python
import DDCalc

detector = DDCalc.InitExperiment('Xenon1T_2018')

halo = DDCalc.InitHalo()
DDCalc.SetSHM(halo, 0.4, 240.0, 240.0, 533.0)

wimp = DDCalc.InitWIMP()
mDM = 100.0
sigman_SD = 8.0e-5
DDCalc.SetWIMP_msigma(wimp, mDM, 0.0, 0.0, 0.0, sigman_SD)

DDCalc.CalcRates(detector, wimp, halo)
LogLikelihood = DDCalc.LogLikelihood(detector)
```

(1) Introduction to (self-interacting) dark matter

(2) BBN constraints on decaying particles at the MeV scale

(3) SIDM from a stable vector mediator?

(4) Conclusions

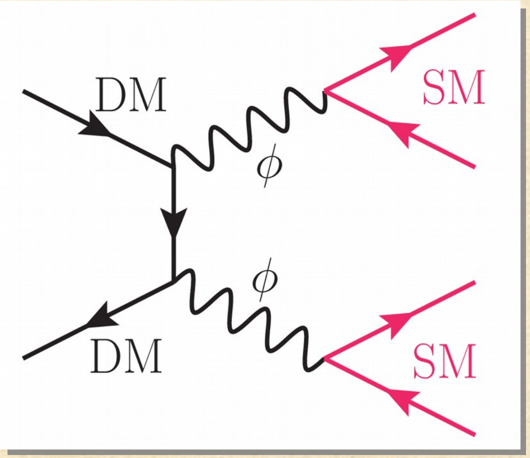
Simple model (II): light vector mediator

$$\mathcal{L} = -y_\psi \bar{\psi}\gamma^\mu \psi \phi_\mu - \sin\epsilon\, B^{\mu\nu}\phi_{\mu\nu}$$

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

$m_\phi \sim 0.1\,\text{MeV} - 100\,\text{MeV}$

Buckley/Fox [0911.3898]
Feng/Kaplinghat/Tu/Yu [0905.3039]
Tulin/Yu/Zurek [1302.3898]



- In contrast to the scalar case, this annihilation process is **s-wave**
  → At $T_{\text{CMB}} \sim \text{eV}$, DM still can annihilate
  → injection of energetic electrons and photons

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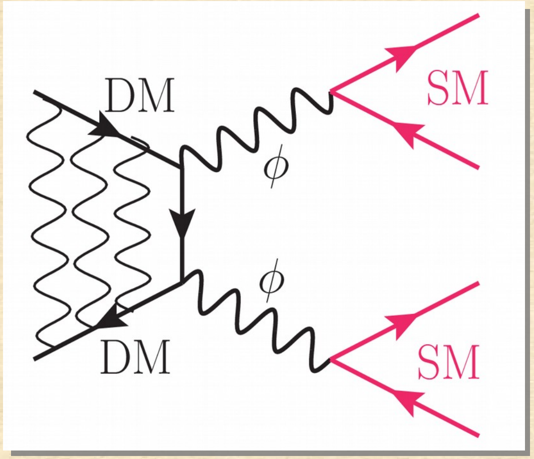

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  → $(\sigma v)_{\mathrm{CMB}} \gg 3 \cdot 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$

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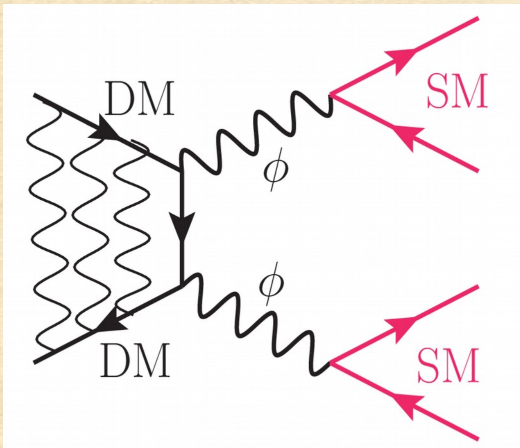
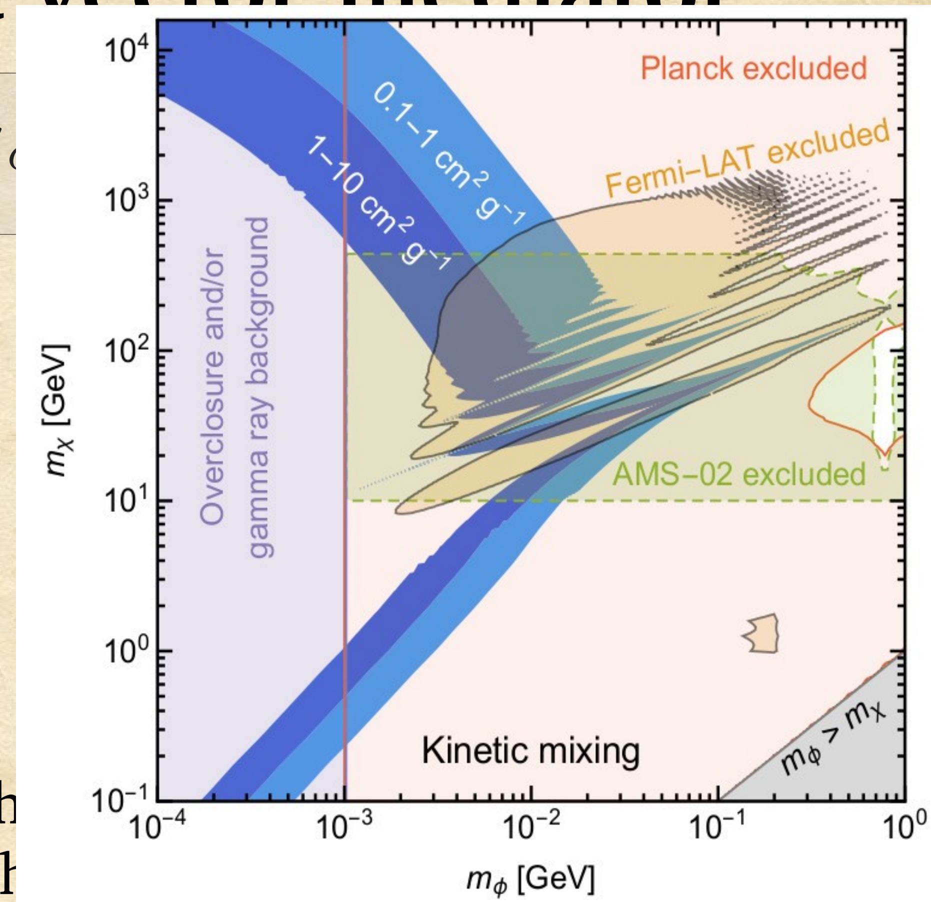
9]





- In contrast to the scalar case, this annih
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Bringmann+ [1612.00845]

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  → $(\sigma v)_{\rm CMB} \gg 3 \cdot 10^{-26}\, \text{cm}^3/\text{s}$

Simple vector mediator model is excluded

See Kamada/Kaneta/Yanagi/Yu [1805.00651] for a possible way out

What if the vector mediator is stable?

- If Z_{D}^{μ} is stable, the CMB constraints from $\psi\bar{\psi} \to Z_{\mathrm{D}} Z_{\mathrm{D}}$ are avoided
  → sufficiently small kinetic mixing parameter
  → or: **dark charge conjugation symmetry** Ma [1704.04666]

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- Problem: $Z_{\rm D}^\mu$ would overclose the Universe
  → introduce a scalar field σ which breaks the $U(1)_{\rm D}$ associated to $Z_{\rm D}^\mu$
  → massive $Z_{\rm D}^\mu$ and a **dark Higgs** $h_{\rm D}$
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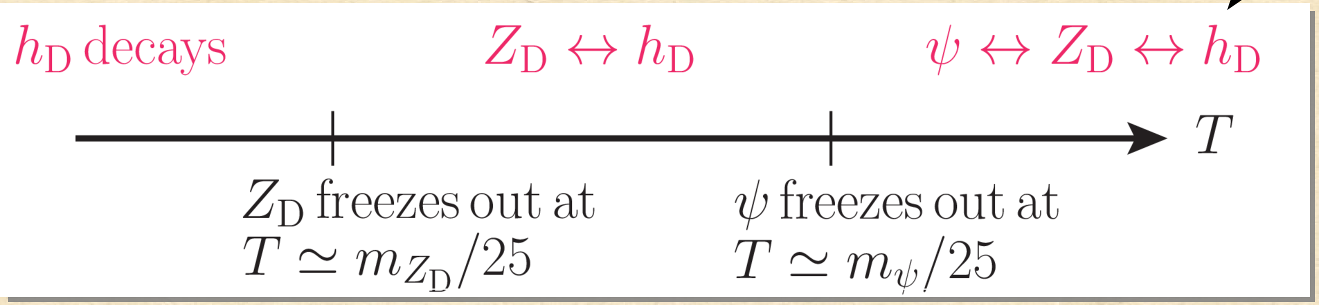
- Model summary (after symmetry breaking):
  - Dirac fermion ψ , $m_\psi \sim \mathrm{GeV–TeV}$, $U(1)_\mathrm{D}$ charge g_ψ
    → dominant DM component
  - Gauge boson Z_D^μ , $m_{Z_\mathrm{D}} \sim (1–100)\ \mathrm{MeV}$
    → subdominant DM component
  - Dark higgs boson h_D , $m_{h_\mathrm{D}} \sim 1\ \mathrm{MeV} < m_{Z_\mathrm{D}}$
    associated to scalar field with $U(1)_\mathrm{D}$ charge g_D
    → small mixing with SM Higgs $\propto \lambda_{h\mathrm{D}}$

Thermal history

- **Dark sector freeze-out** of ψ and Z^μ_{D} :

equilibration with SM at large T
via $h_{\mathrm{D}} - h$ mixing $\propto \lambda_{h\mathrm{D}}$



- Correct relic density for $g_\psi, g_{\mathrm{D}} \simeq 10^{-3} - 10^{-1}$
  → $\Omega_{Z_{\mathrm{D}}}/\Omega_\psi \simeq 10^{-7} - 10^{-1}$
  → numerical treatment using `micromegas v4.3.5`
  (conversion processes, semi-annihilation, …)

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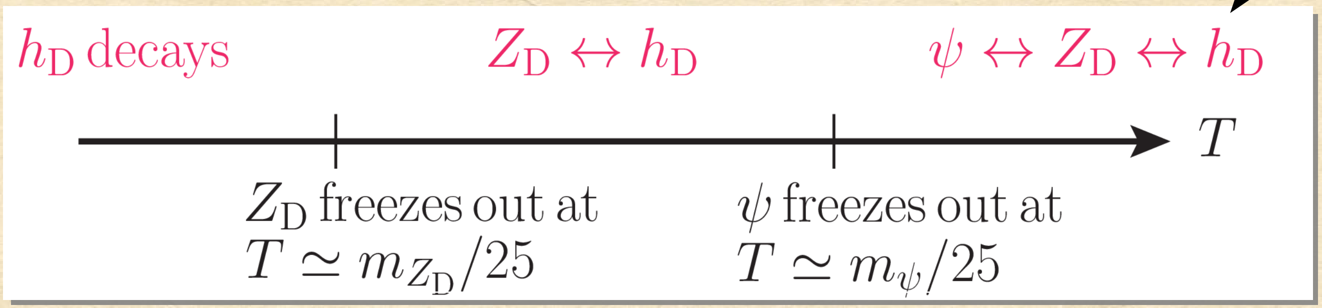

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- **BBN bounds?**
  → For $\lambda_{h\mathrm{D}} \lesssim 4 \times 10^{-4}$, dark and SM sectors decouple prior to QCD phase transition, resulting in $\Delta N_\mathrm{eff} \lesssim 0.27$ ✓
  → For $m_{\mathrm{h_D}} \lesssim 2\,\mathrm{MeV}$, decay products of h_D are below the photo-disintegration threshold of deuterium ✓

CMB constraints strike back

Two types of CMB constraints:

(1) **Spectral distortions** from late-time decays of h_D exclude $\tau_{h_\mathrm{D}} \gtrsim 10^5\,\mathrm{s}$

→ this (basically) excludes $m_{h_\mathrm{D}} < 2m_e$

→ we fix $m_{h_\mathrm{D}} = 1.5\,\mathrm{MeV}$ (precise value irrelevant)

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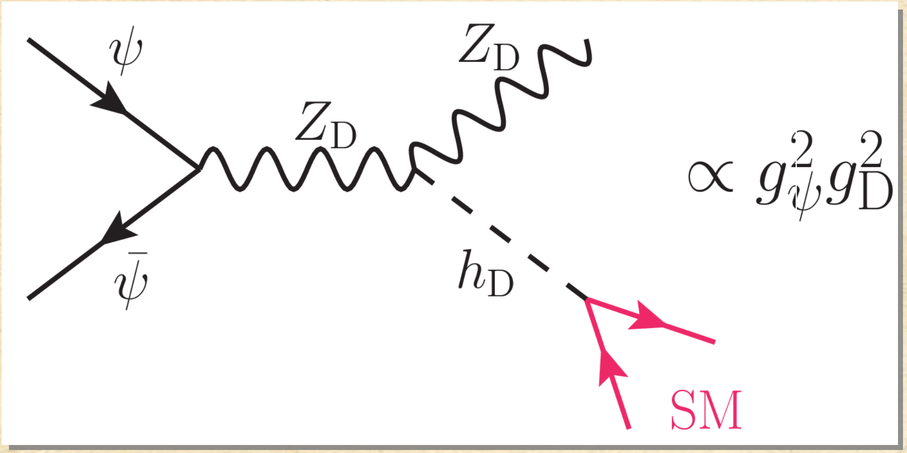
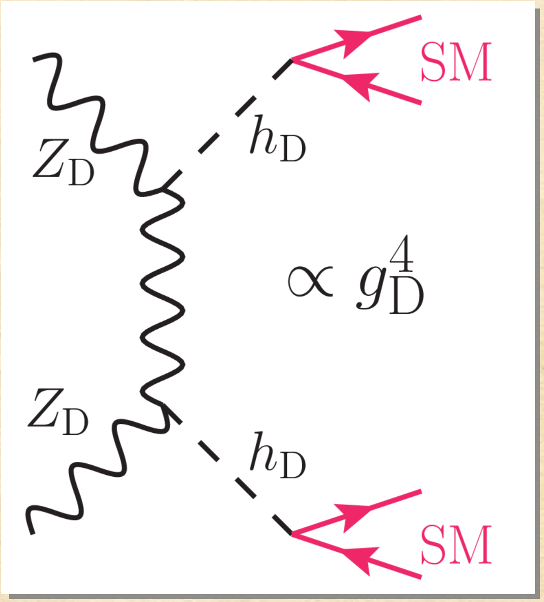
(2) Energy injection from **late-time annihilations** of ψ and Z^μ_D :



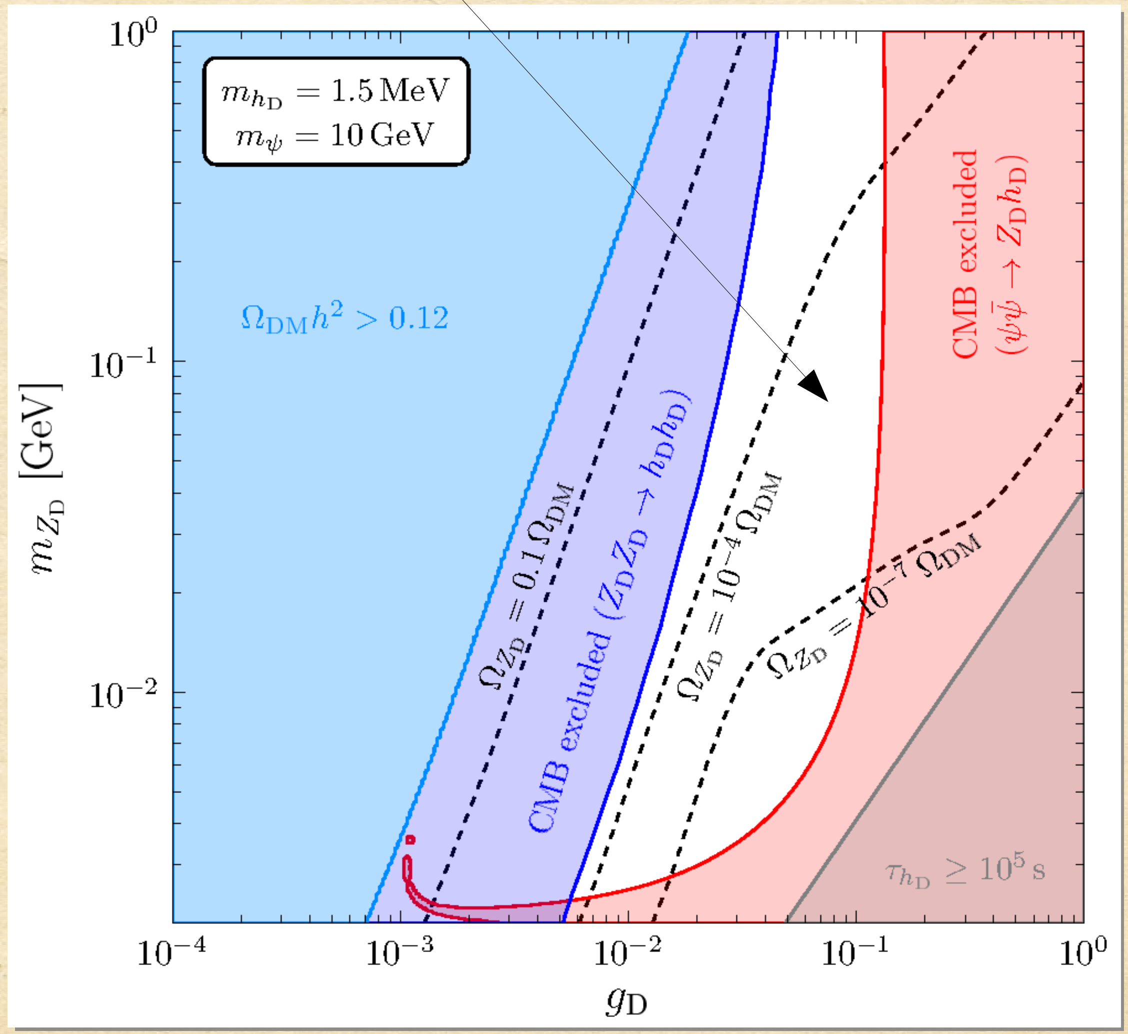


- $\psi\bar{\psi} \to Z_\mathrm{D} h_\mathrm{D}$ is Sommerfeld enhanced
- $Z_\mathrm{D} Z_\mathrm{D} \to h_\mathrm{D} h_\mathrm{D}$ can give important constraints even for $\Omega_{Z_\mathrm{D}} h^2 \ll 0.12$
- We employ the bounds on $\langle \sigma v \rangle$ from Slatyer [1506.03811]

Impact of CMB constraints

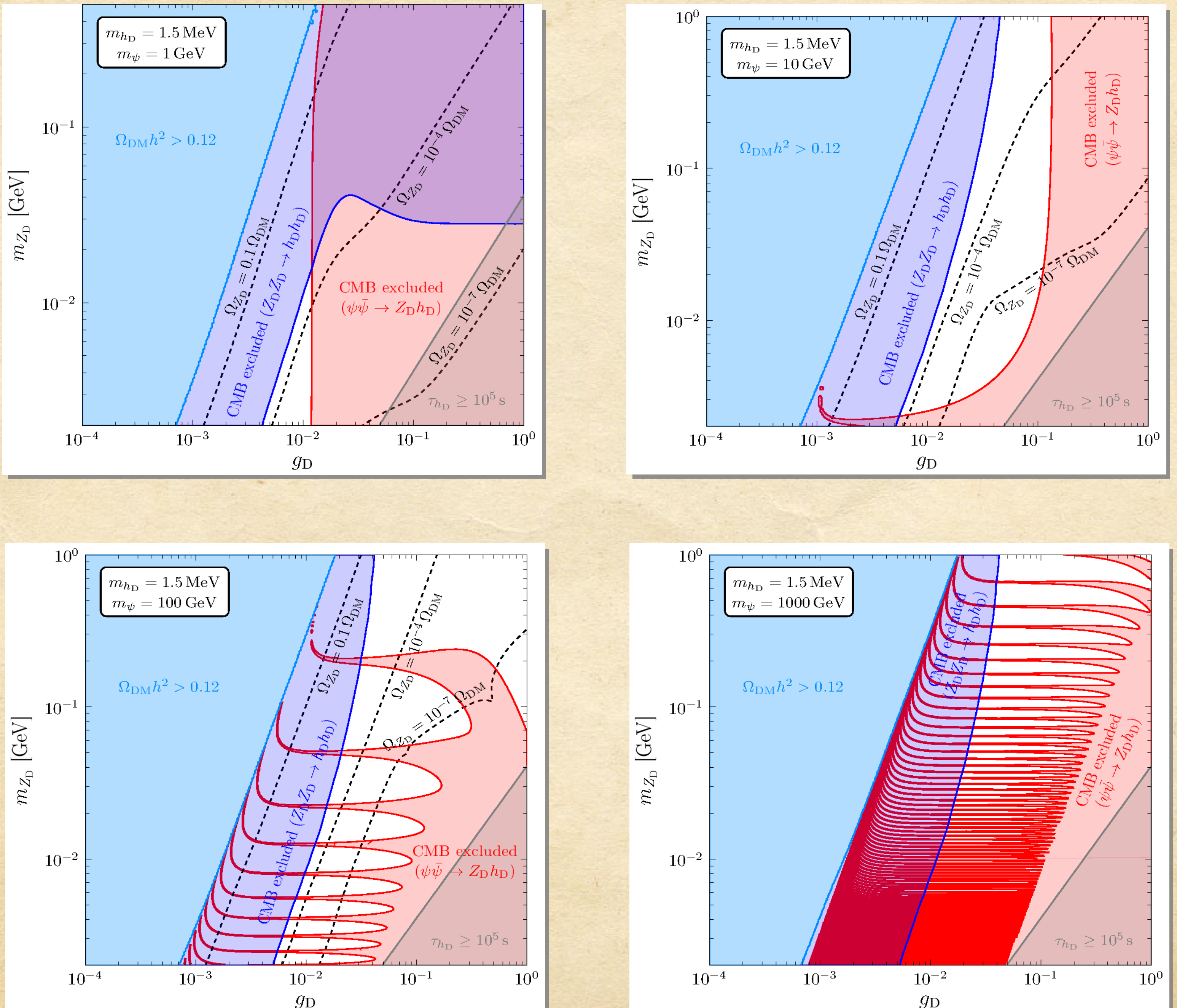
not excluded!

ψ dominantly annihilates via $\psi\bar{\psi} \to Z_\mathrm{D} h_\mathrm{D}$



Z_D abundance grows

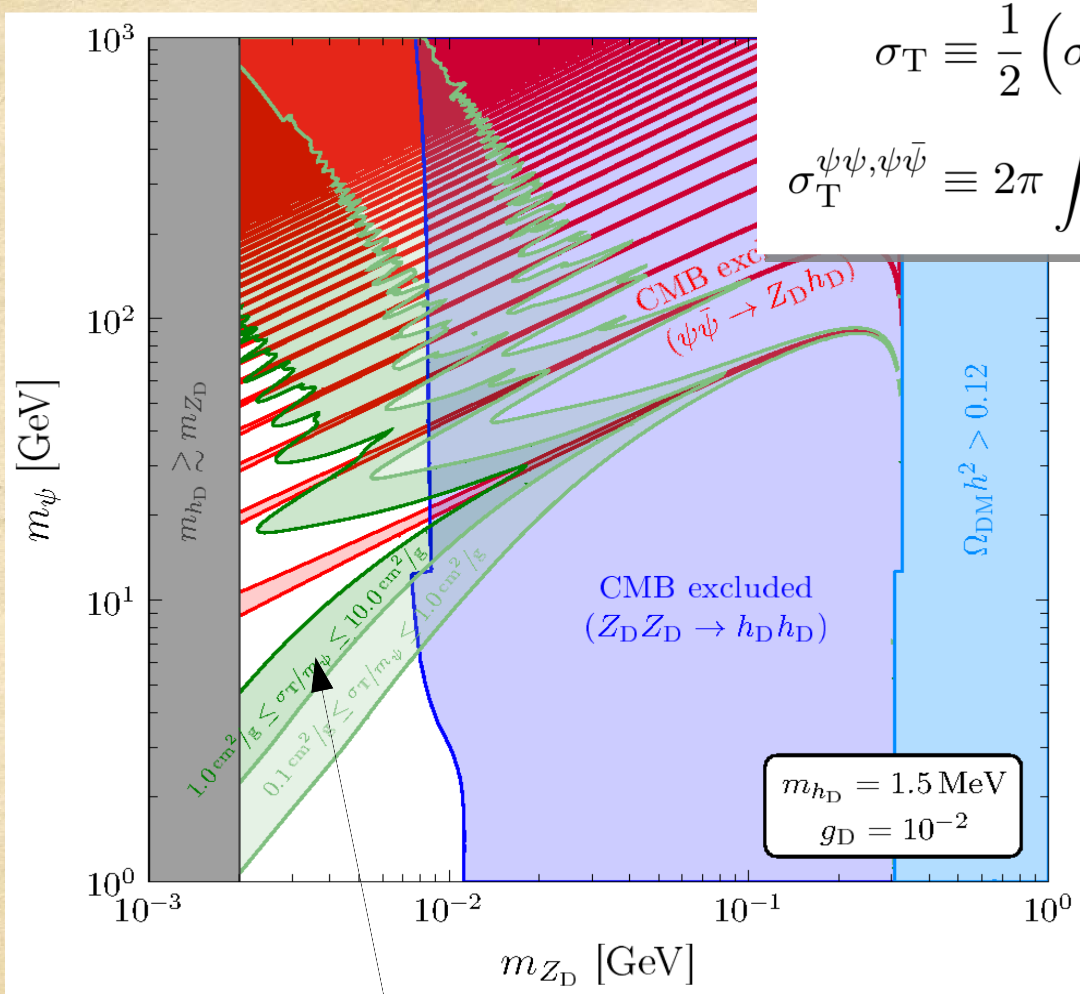
Impact of CMB constraints



Viability of self-interacting DM?

$$\sigma_{\mathrm{T}} \equiv \frac{1}{2}\left(\sigma_{\mathrm{T}}^{\psi\psi} + \sigma_{\mathrm{T}}^{\psi\bar{\psi}}\right) \;, \text{ with}$$

$$\sigma_{\mathrm{T}}^{\psi\psi,\psi\bar{\psi}} \equiv 2\pi \int_{-1}^{1} \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\psi\psi,\psi\bar{\psi}} (1 - |\cos\theta|)\, \mathrm{d}\cos\theta .$$



$g_\mathrm{D} = 10^{-2}$

There are regions in parameter space leading to the desired σ_T/m_ψ, without being excluded by CMB or BBN!

(upper bound on σ_T/m_ψ on cluster scales is satisfied)

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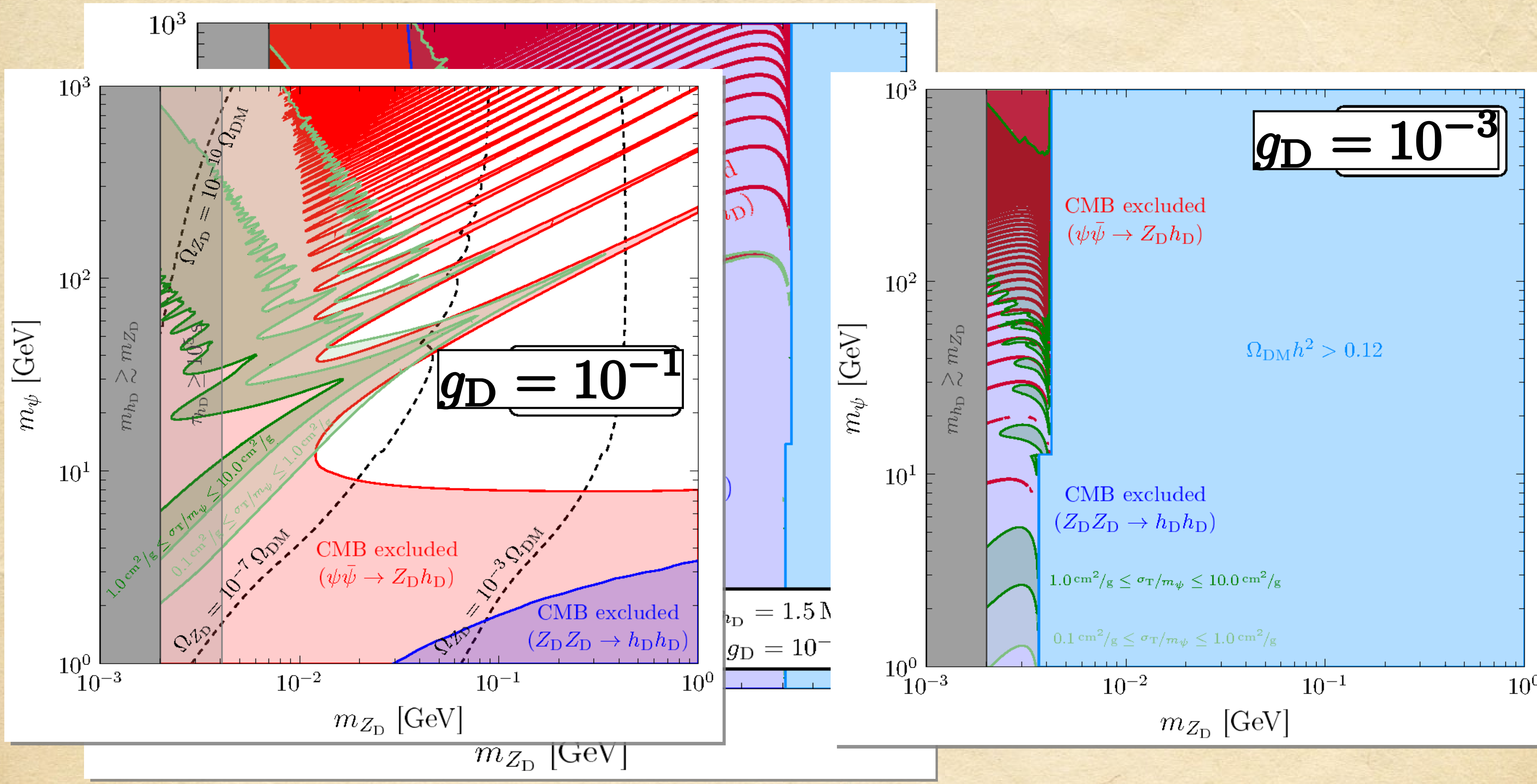

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Conclusions

- **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**

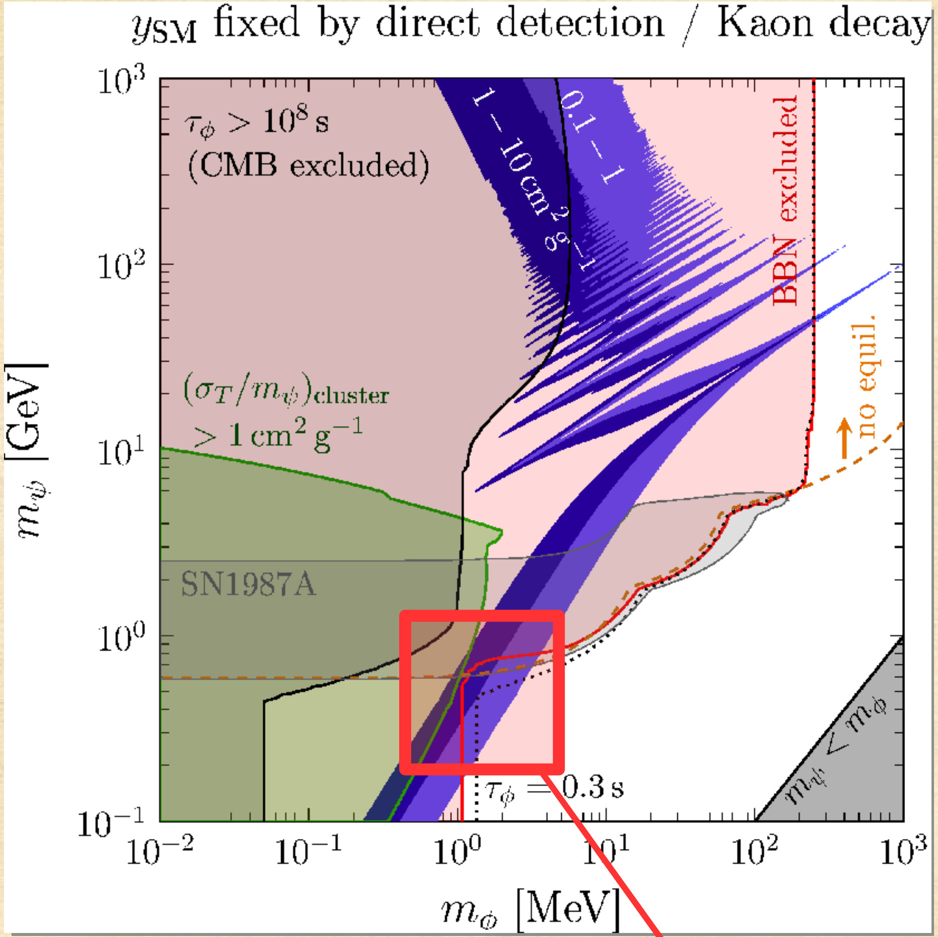
- We obtained the first dedicated BBN bounds on decaying MeV-scale particles
  → combined with direct detection constraints, this puts **strong constraints** on the simplest SIDM model with a scalar mediator

.

- SIDM with a decaying vector mediator is excluded by CMB constraints (Sommerfeld-enhanced s-wave annihilation)
  → this can be circumvented for a **stable vector mediator**, at the price of introducing one more dark sector particle
  → non-trivial interplay of various CMB constraints

Backup material

Future prospects for direct detection



Potentially remaining parameter space: $m_{\mathrm{DM}} \sim \mathrm{GeV}\,,\; m_\phi \sim 1 - 10\ \mathrm{MeV}$

→ what can we learn from **future direct detection experiments**?

Direct detection with light mediators

- Rate $\propto \left(q^2 + m_\phi^2\right)^{-2}$
  $q \equiv \sqrt{2 m_T E_T} \sim (1 - 100)\,\mathrm{MeV}$

  (1) Low threshold is even more important for light mediators (steeply falling spectrum)

  (2) spectrum depends sensitively on m_ϕ if $m_\phi \sim (1 - 100)\,\mathrm{MeV}$ SIDM!

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- Future low-threshold experiments (CRESST-III, SuperCDMS@Snolab) will improve their sensitivity by **3-4 orders of magnitude** within the next ~10 years
  → **strong discovery potential** in particular for low-mass DM
  → Measuring **mediator masses** and **self-interaction cross section** with direct detection?

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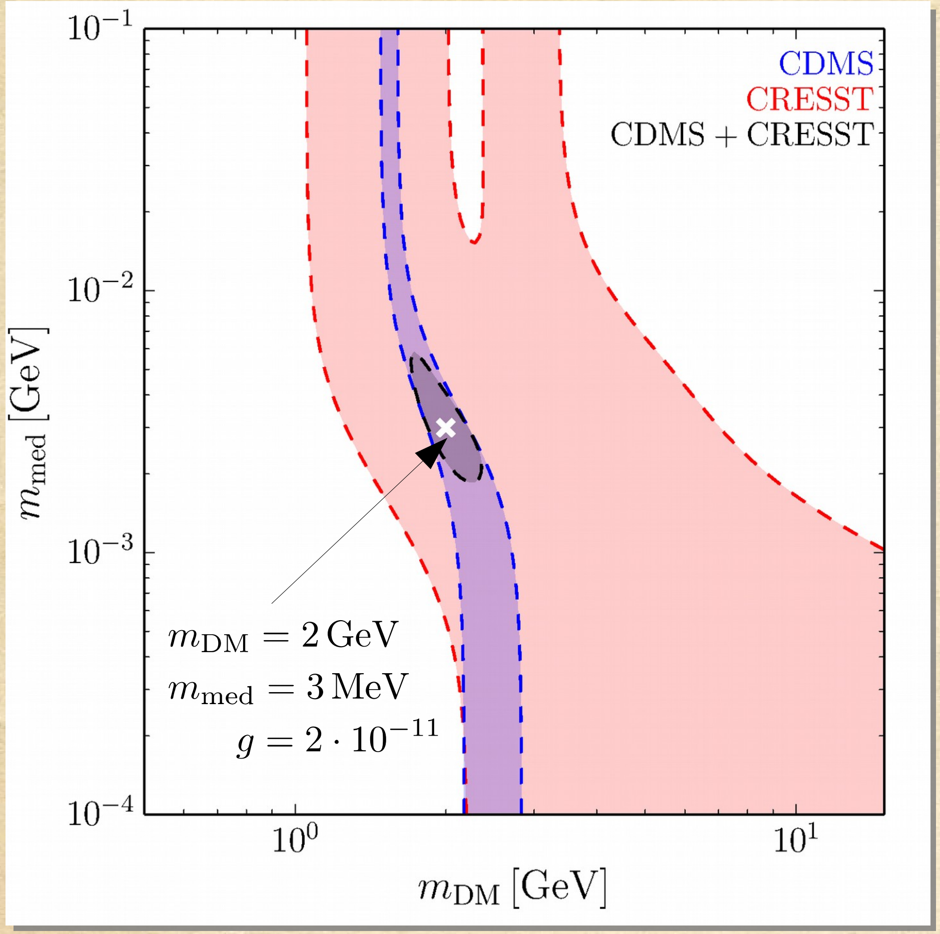
- We have simulated the outcome of future experiments, assuming given values for $m_{\mathrm{DM}}, m_\phi, g$

  → **Parameter reconstruction** based on realistic experimental setups

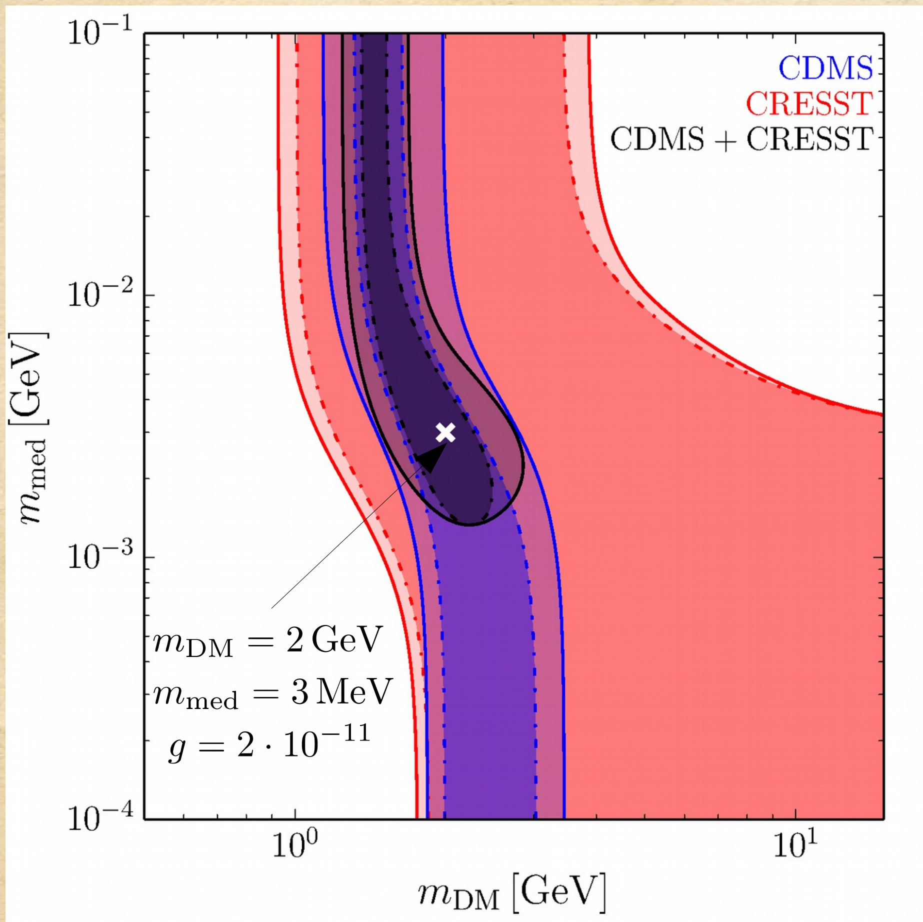
Parameter reconstruction: an example

Kahlhoefer, Kulkarni, SW [1707.08571]



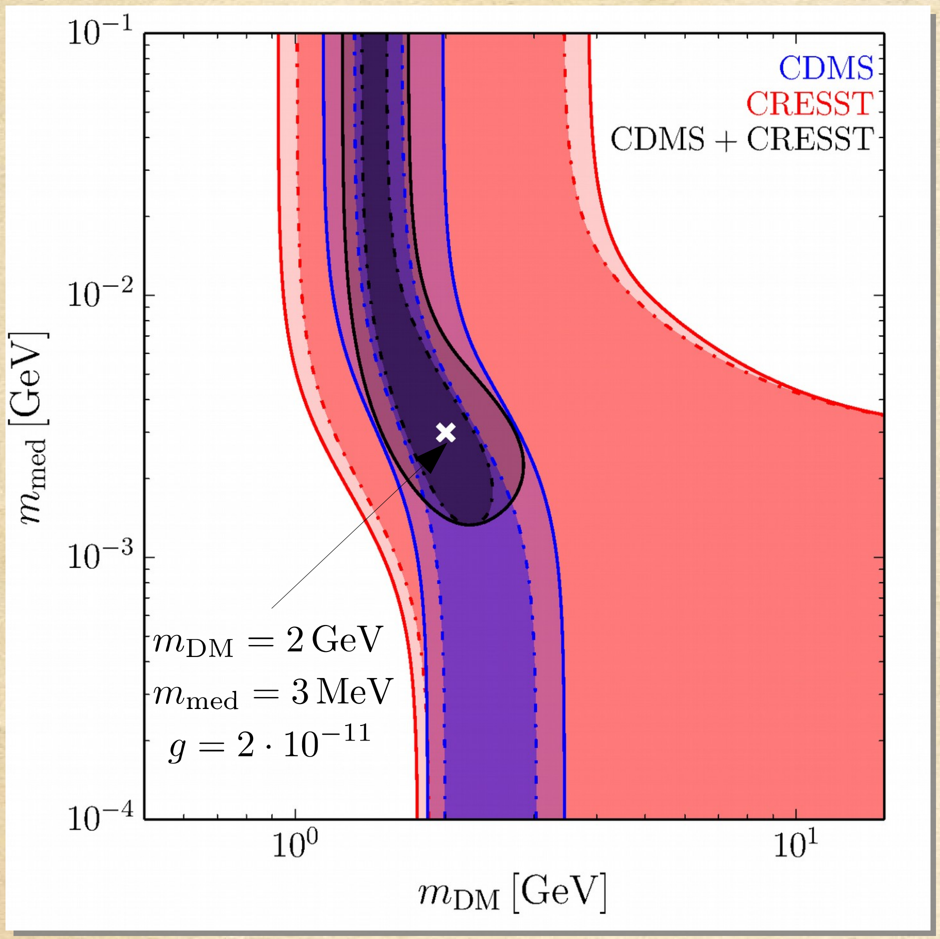
- For this benchmark point:
  $N_{\mathrm{CDMS}} \simeq 700,\ N_{\mathrm{CRESST}} \simeq 200$
- In this plot:
  no additional nuisance parameters
- Two branches for CRESST:
  scattering of Ca/O vs. W
- Smaller m_{DM} can be (partially) compensated by larger m_{med}
- **Strong complementarity** of CDMS and CRESST!

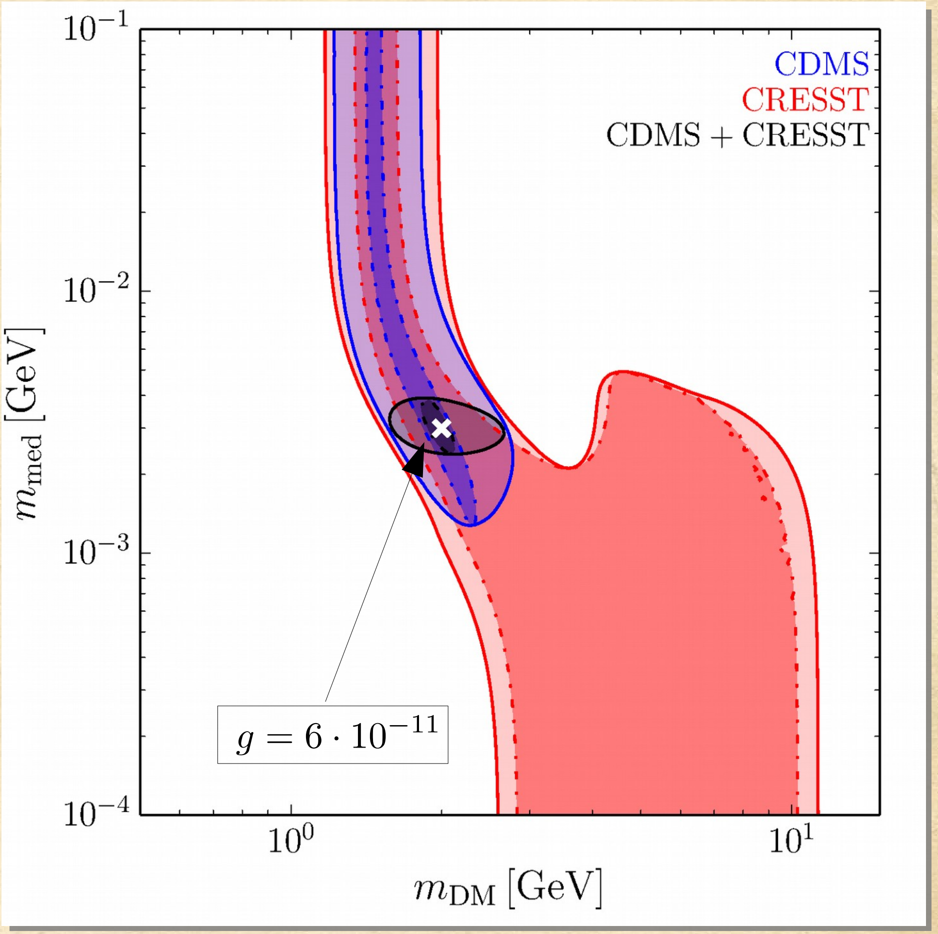
Parameter reconstruction: an example



- We also take into account various nuisance parameters affecting the parameter reconstruction:
  - background uncertainties
  - astrophysical uncertainties
  - different coupling to protons and neutrons

Parameter reconstruction: an example





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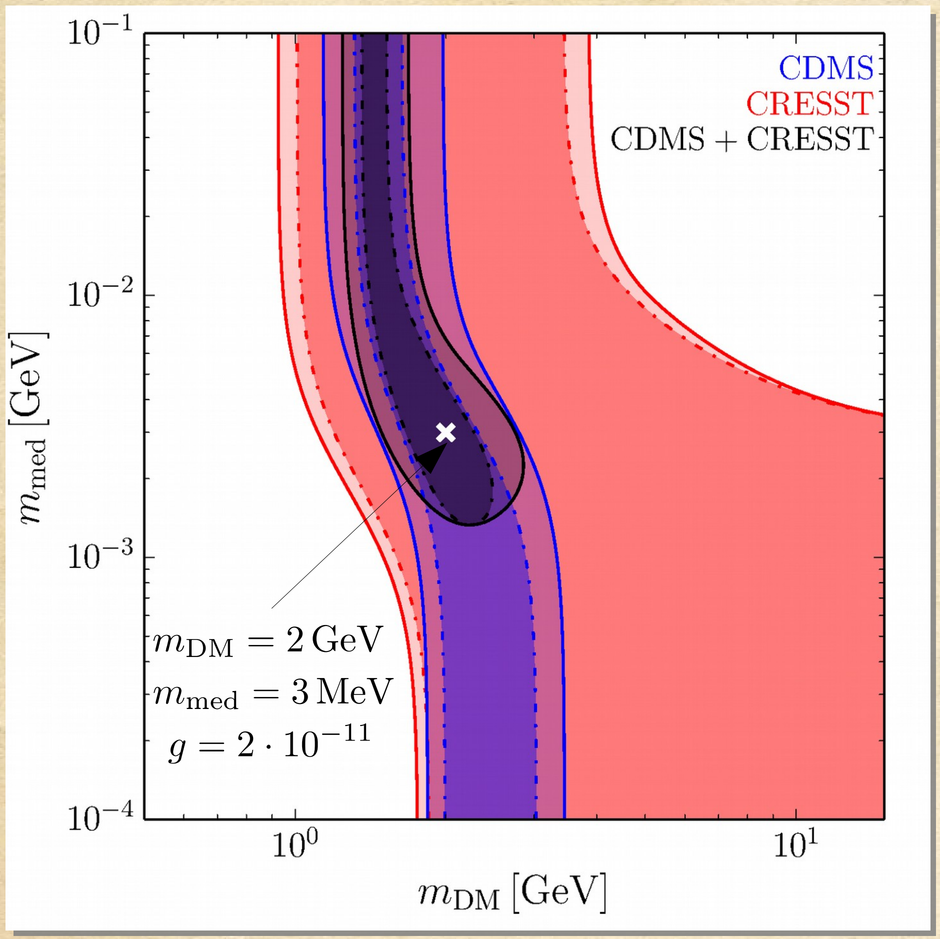
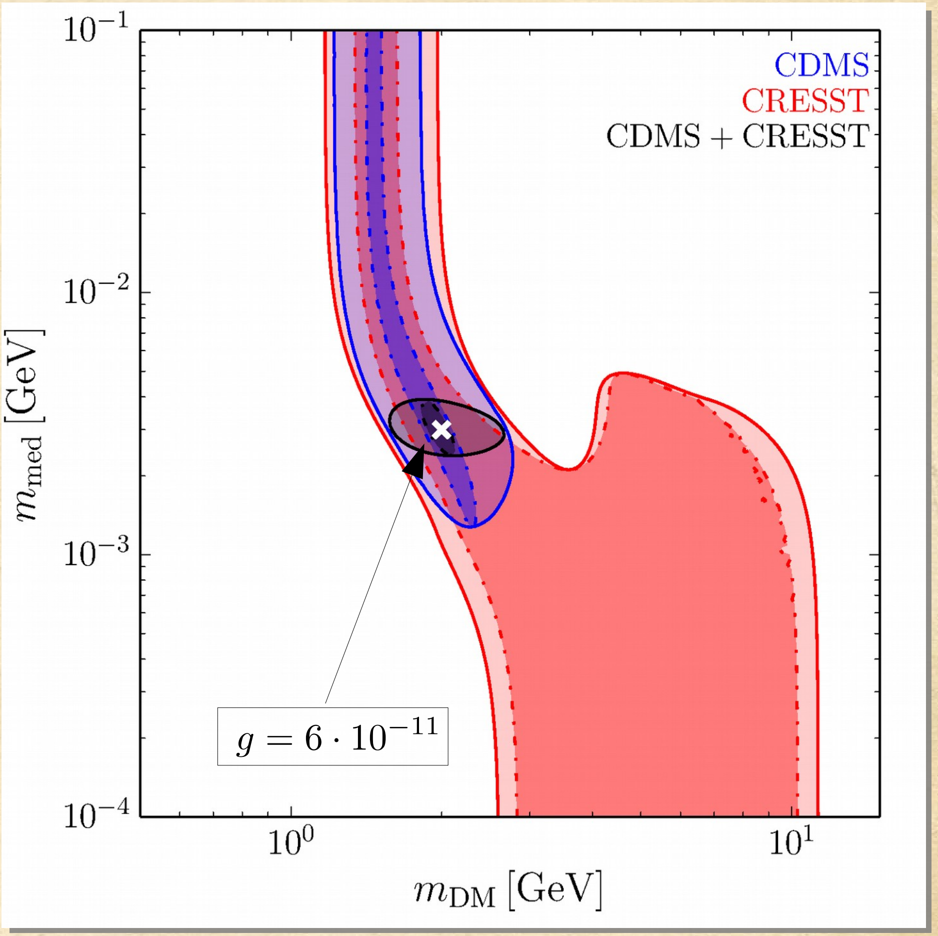




Using the combined information from two experiments, it is feasible to **measure simultaneously** m_{DM} and m_{med} !

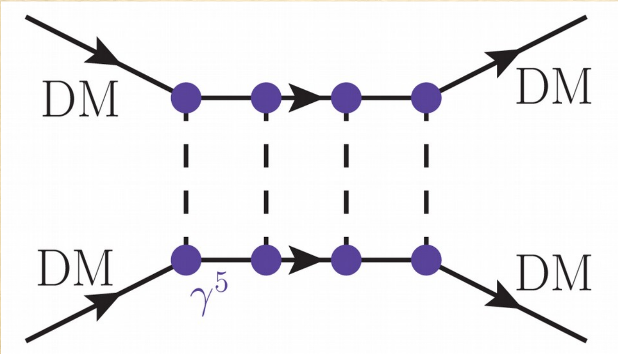
→ for realistic exposures and not-yet-excluded scenarios

→ even after taking into account various nuisance parameters

SIDM via pseudoscalar exchange?

$$\mathcal{L} = -iy_\psi \bar{\psi}\gamma^5\psi\phi - iy_{\rm SM}\sum_f \frac{m_f}{v_{\rm EW}}\bar{f}\gamma^5 f\phi$$

→ DD constraints are easily evaded ($\sigma \propto q^4$)



$$V_{\rm PS}(r) = \frac{y_\psi^2}{48\pi}\frac{m_\phi^2}{m_\psi^2}\left(\frac{e^{-m_\phi r}}{r} - \frac{4\pi}{m_\phi^2}\delta^{(3)}(\vec{r})\right)\vec{\sigma}_1\cdot\vec{\sigma}_2 + \frac{y_\psi^2}{48\pi}\frac{m_\phi^2}{m_\psi^2}\left(1+\frac{3}{m_\phi r}+\frac{3}{m_\phi^2 r^2}\right)\frac{e^{-m_\phi r}}{r}S_{12}(\vec{r})$$

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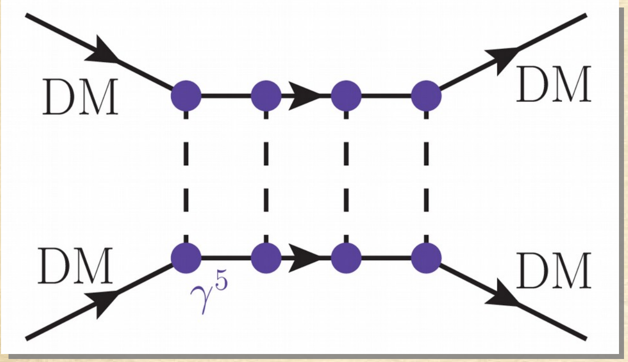

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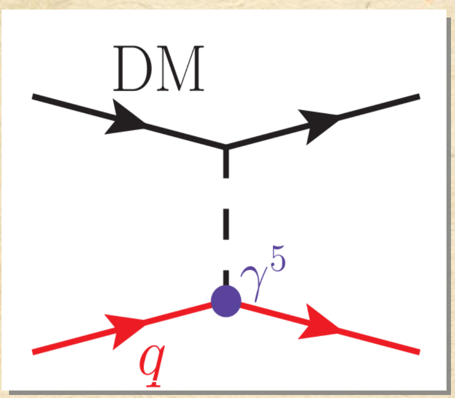
- Yukawa term $\propto e^{-m_\phi r}/r$ is suppressed by m_ϕ^2/m_ψ^2 Bellazzini+ [1307.1129]
- $1/r^3$ term leads to singular solutions of Schrödinger equation
  - → renormalization techniques do not give predictive results
  - → notice: same problem (in principle) appears already for standard vector/scalar exchange: $V_{LS} \propto L \cdot S/r^3$

→ No significant self-interactions expected from pseudoscalar exchange

Maximally CP-violating DM interactions

$$\mathcal{L} = -y_\psi \bar{\psi}\psi\phi - i y_{\rm SM} \sum_f \frac{m_f}{v_{\rm EW}} \bar{f}\gamma^5 f\phi$$

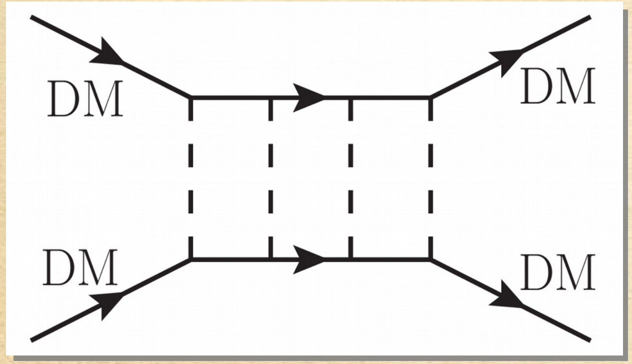
Direct detection:



$\propto q^2$ for a mixed scalar/pseudoscalar mediator

→ direct detection constraints are still evaded

Self-interactions:



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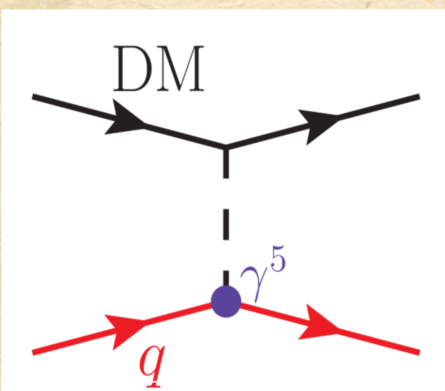

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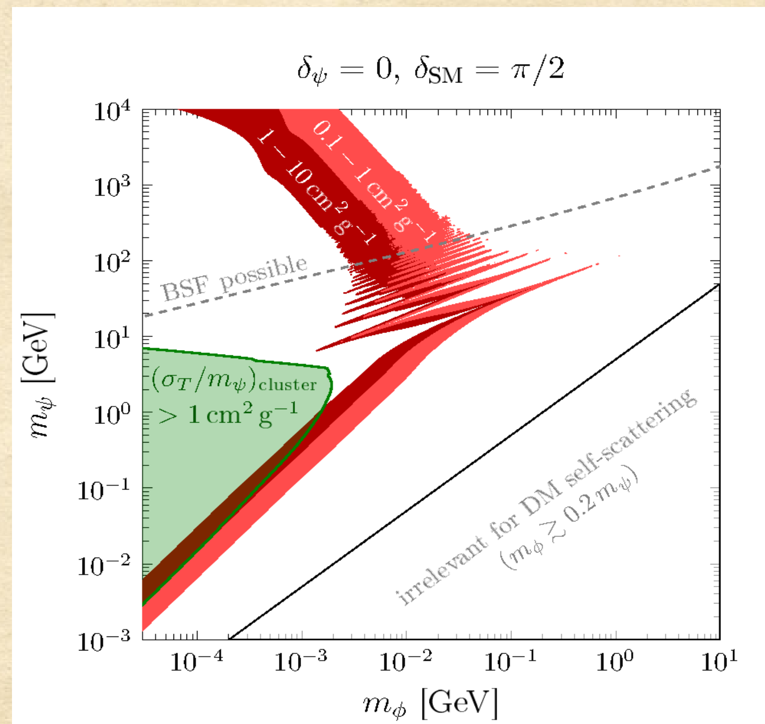

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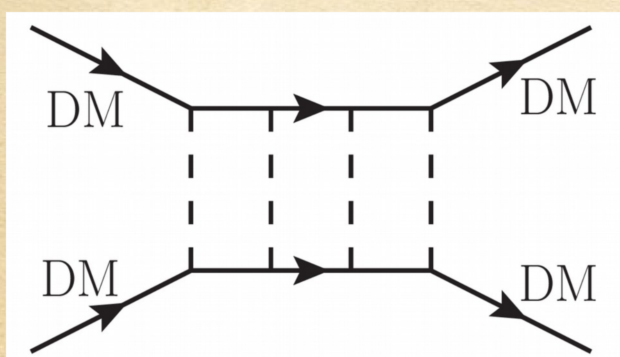

$$V(r) \propto \frac{e^{-m_\phi r}}{r}$$

Phenomenologically viable also for large $m_{\rm DM}$!

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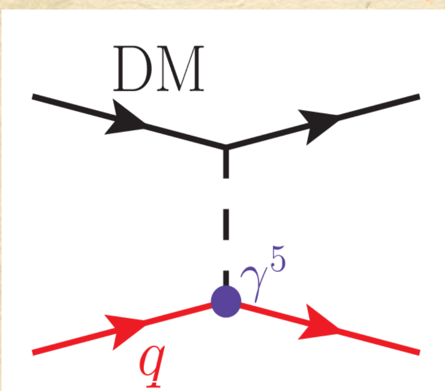
Unmotivated/tuned

Direct detection:



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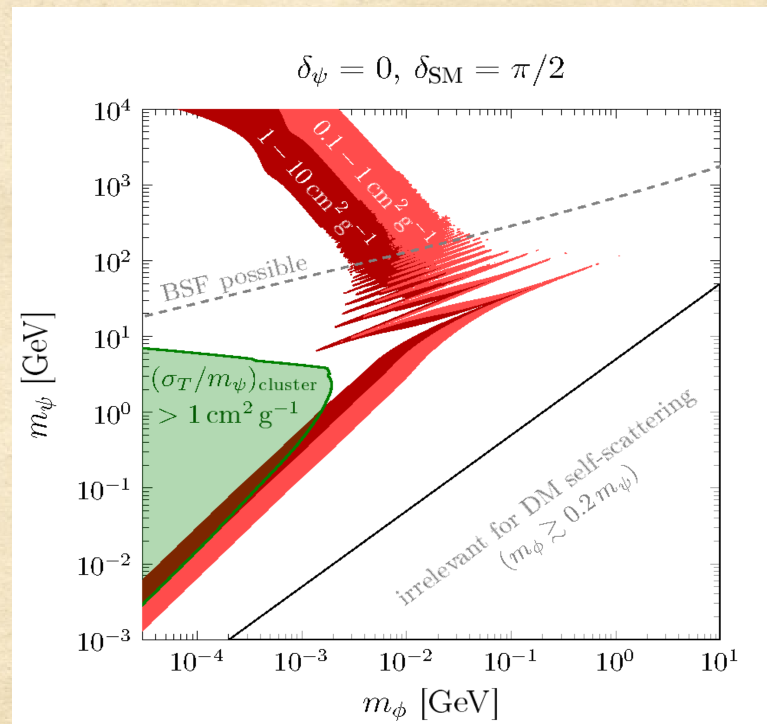

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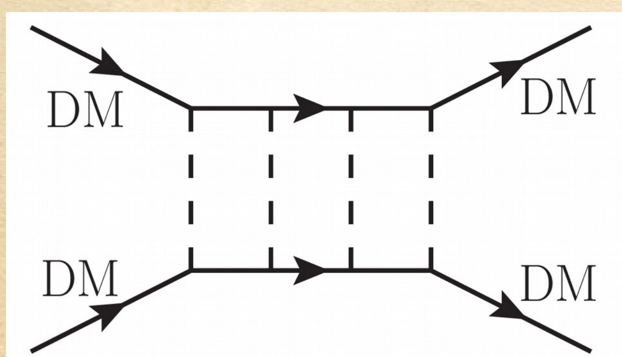

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CP violating SIDM: general case

$$\mathcal{L} = -y_\psi \cos\delta_\psi \bar{\psi}\psi\phi - i y_\psi \sin\delta_\psi \bar{\psi}\gamma^5\psi\phi$$
$$-y_{\rm SM}\sum_f \left[\frac{m_f}{v_{\rm EW}}\cos\delta_{\rm SM}\bar{f}f\phi + i\frac{m_f}{v_{\rm EW}}\sin\delta_{\rm SM}\bar{f}\gamma^5 f\phi\right]$$

- No a priori reason for CP conservation in the dark sector
  → in fact, such a general setup can arise from **spontaneous CP violation**, starting from a CP conserving coupling to a pseudoscalar
  → we treat δ_ψ and $\delta_{\rm SM}$ as free parameters

CP violating SIDM: general case

$$\mathcal{L} = -y_\psi \cos\delta_\psi \bar{\psi}\psi\phi - i y_\psi \sin\delta_\psi \bar{\psi}\gamma^5\psi\phi$$
$$-y_{\rm SM}\sum_f \left[\frac{m_f}{v_{\rm EW}}\cos\delta_{\rm SM}\bar{f}f\phi + i\frac{m_f}{v_{\rm EW}}\sin\delta_{\rm SM}\bar{f}\gamma^5 f\phi\right]$$

- No a priori reason for CP conservation in the dark sector
  → in fact, such a general setup can arise from **spontaneous CP violation**, starting from a CP conserving coupling to a pseudoscalar
  → we treat δ_ψ and $\delta_{\rm SM}$ as free parameters

- s-wave contribution to lowest order DM annihilation process:

$$(\sigma v)_{\psi\bar{\psi}\to\phi\phi} \simeq \frac{y_\psi^4\sin^2(2\delta_\psi)}{32\pi m_\psi^2} \neq 0 \quad \text{for } \delta_\psi \neq 0, \pi/2$$

  → unsuppressed annihilation $\psi\bar{\psi}\to\phi\phi$ for CP-violating couplings!
  → for $m_\phi \ll m_\psi$ this annihilation channel is strongly **Sommerfeld enhanced** during CMB

→ Strong CMB constraints on CP-violating phase δ_ψ

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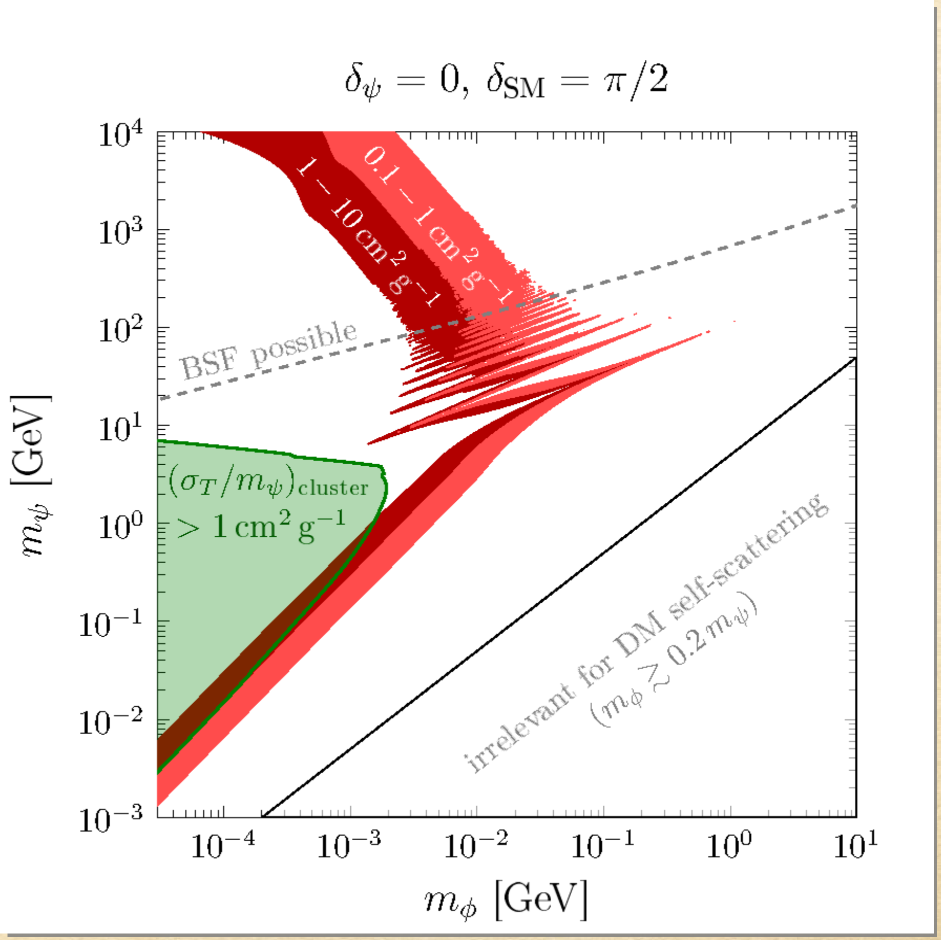

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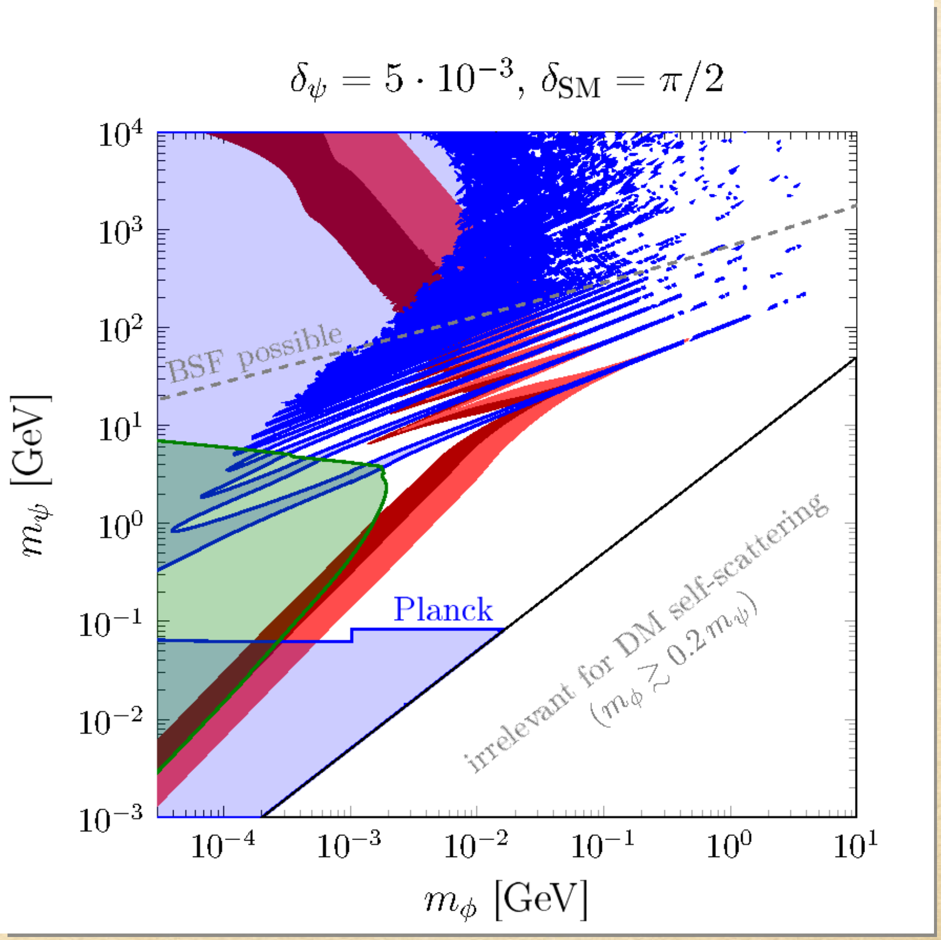

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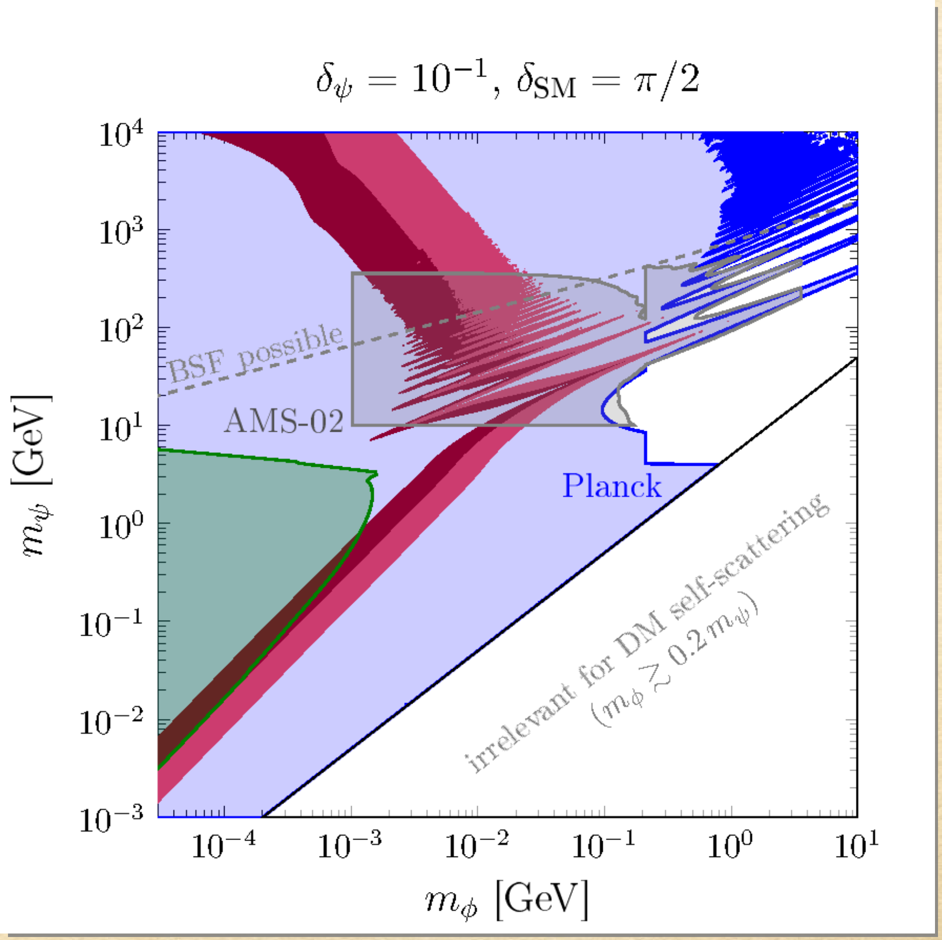

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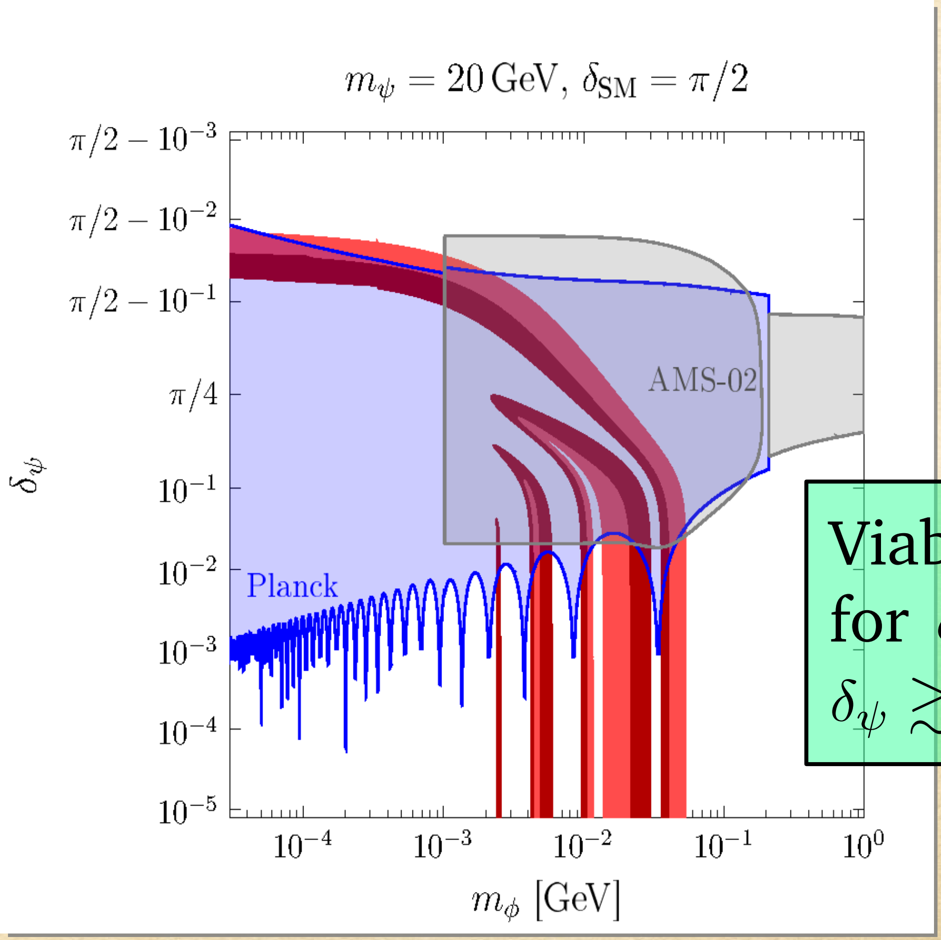
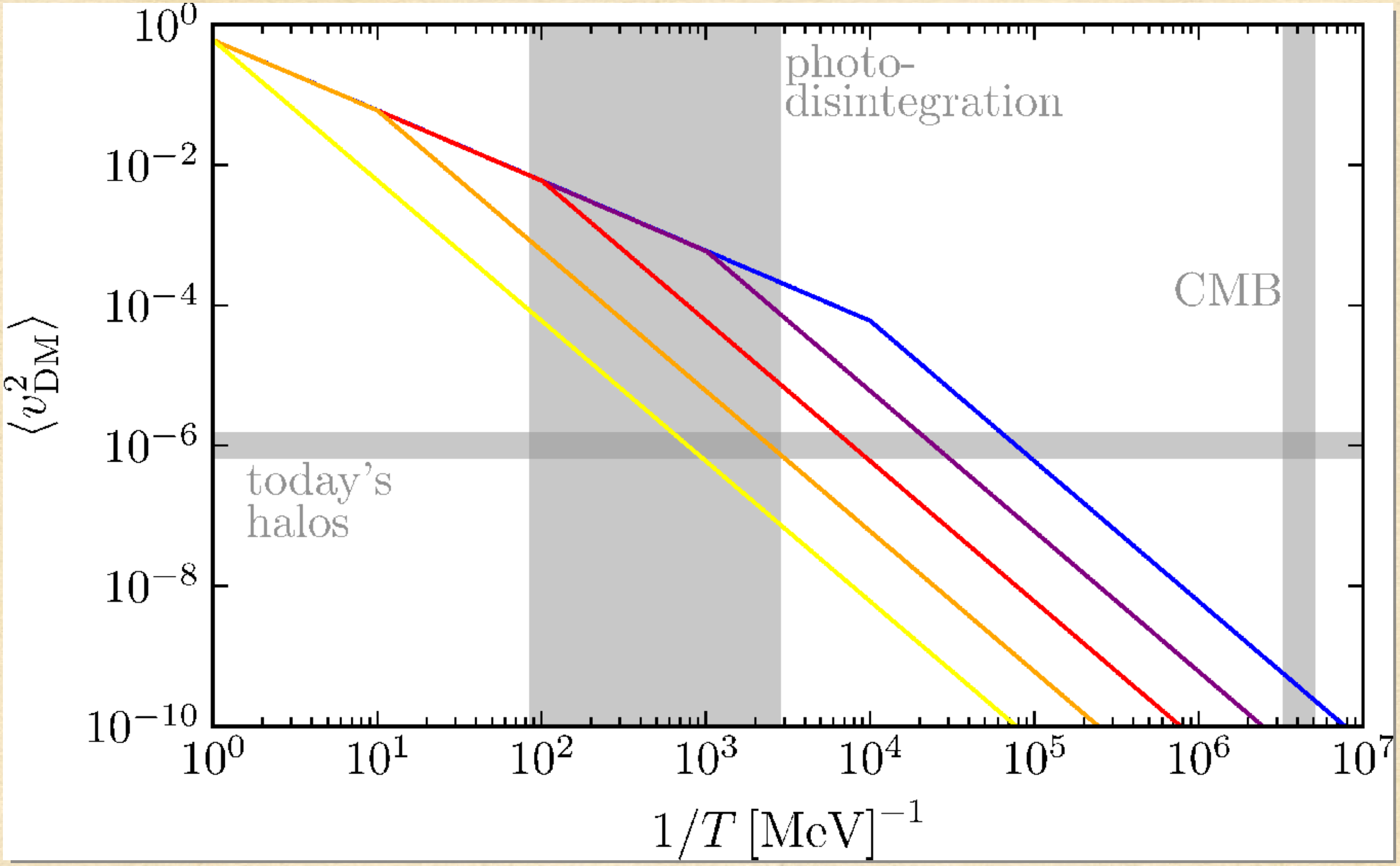


Viable SIDM scenario for $\delta_\psi \lesssim 10^{-2}$ or $\delta_\psi \gtrsim \pi/2 - 0.1$

MeV-scale annihilating DM



- $v_{\rm DM}(T = T_{\rm BBN}) \gg v(T = T_{\rm CMB})$
  → Use BBN as a probe for p-wave annihilating DM?
- Region of MeV-masses has to be treated with care:
  non-universal spectrum, photodisintegration thresholds

MeV-scale annihilating DM