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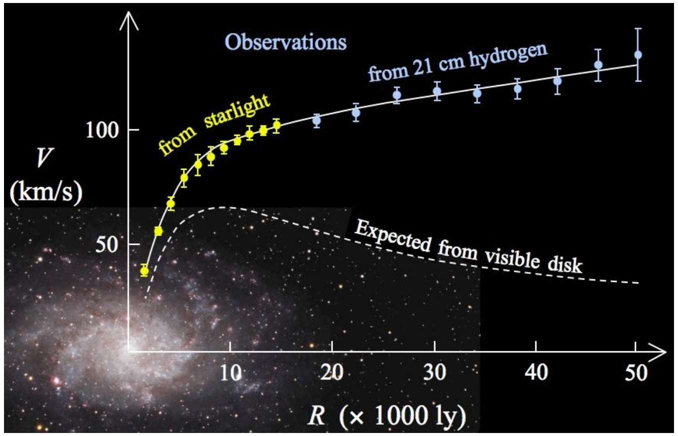
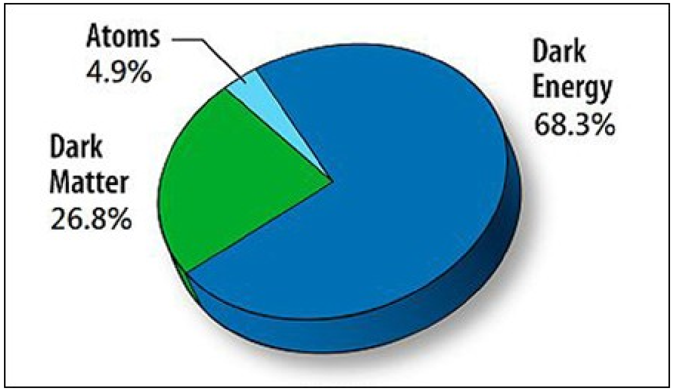
Self-interacting dark matter with a stable scalar mediator

TMEX2020
ICISE, Quy Nhon,
8 January 2020

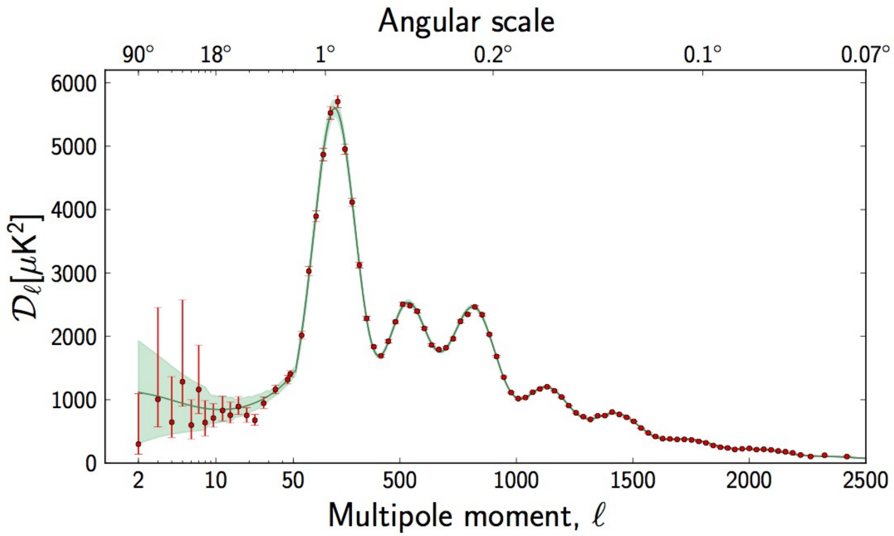
MD, Bohdan Grzadkowski, Da Huang, [1910.01238]

Dark matter – motivation





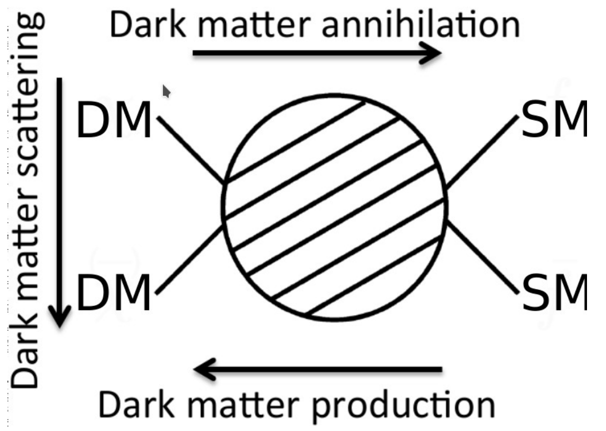
Convincing evidence on various astrophysical and cosmological scales



leading hypothesis → new, unknown particle

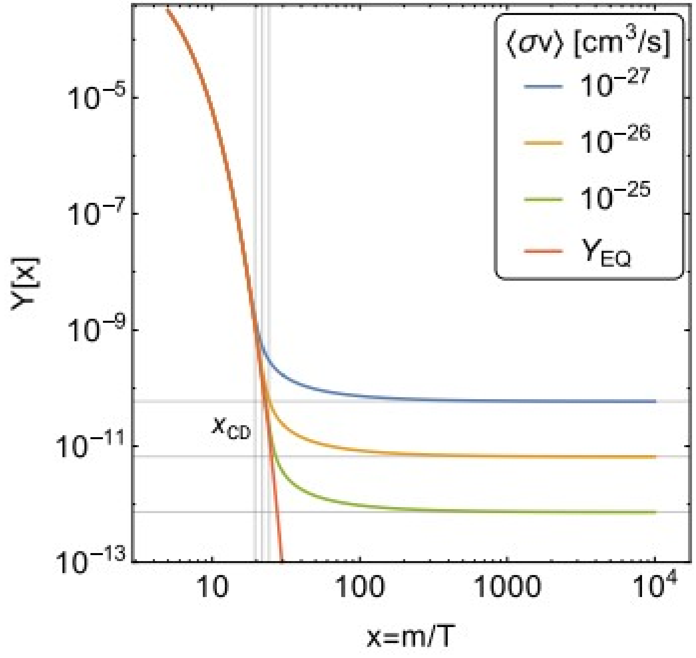
Weakly-interacting massive particle (WIMP)

Properties of dark matter:
- electrically neutral (non-luminous)
- stable or long-lived
- weakly interacting with ordinary matter
  - ✓ production mechanisms
  - ✓ experimental probes
- collisionless or self-interacting?



DM chemical decoupling

$$n_{EQ}\langle\sigma v_{\rm rel}\rangle \sim H(x)$$

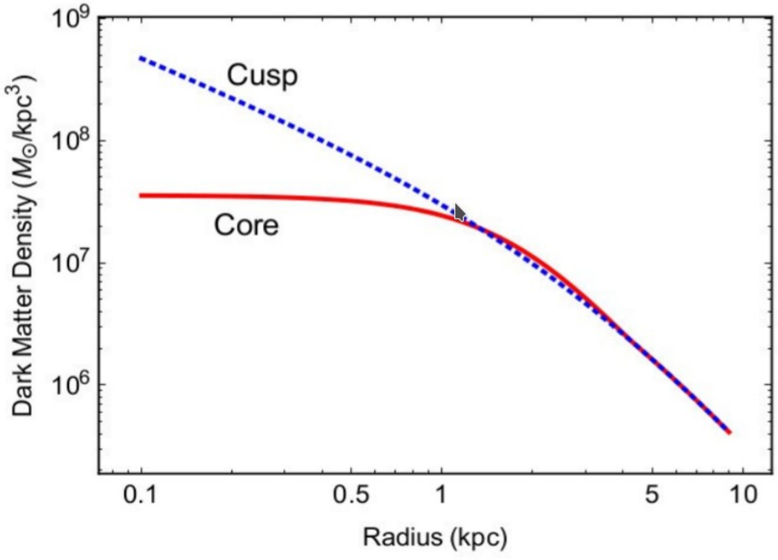


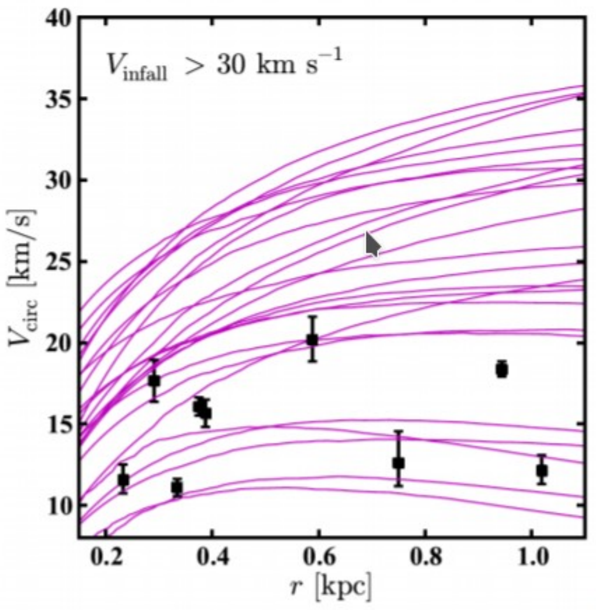
Small scale structure problems

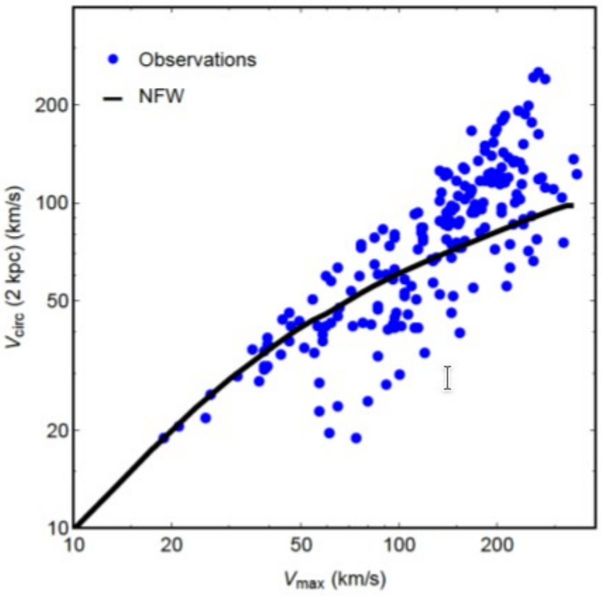
core-cusp problem

missing satellite problem

diversity problem





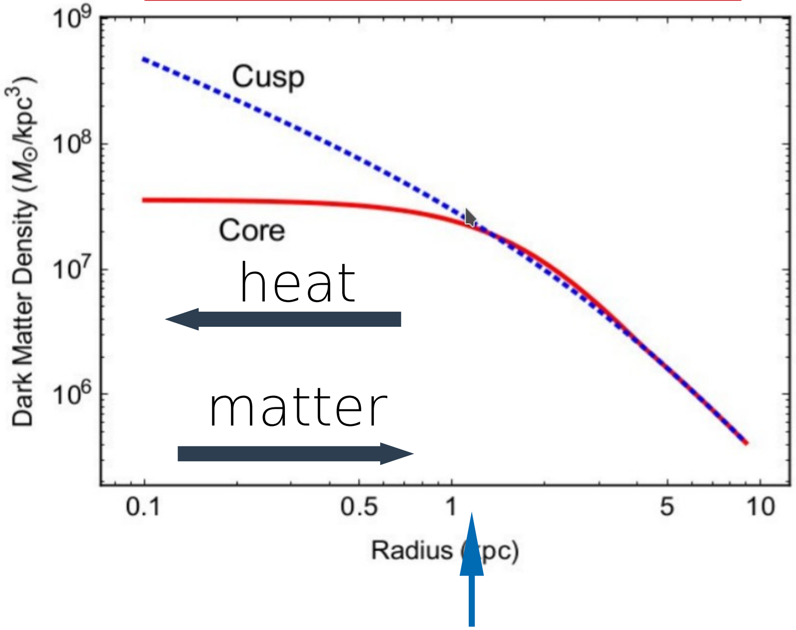


Tulin, Yu 2017

Small scale structure problems

Possible solutions:
- observational problems
  → no real problem
- baryonic feedback processes
  (star formation, supernovae, …)
- new DM properties
  (self-interactions)

core-cusp problem



Self-interactions thermalize inner part of halo and reduce central DM density

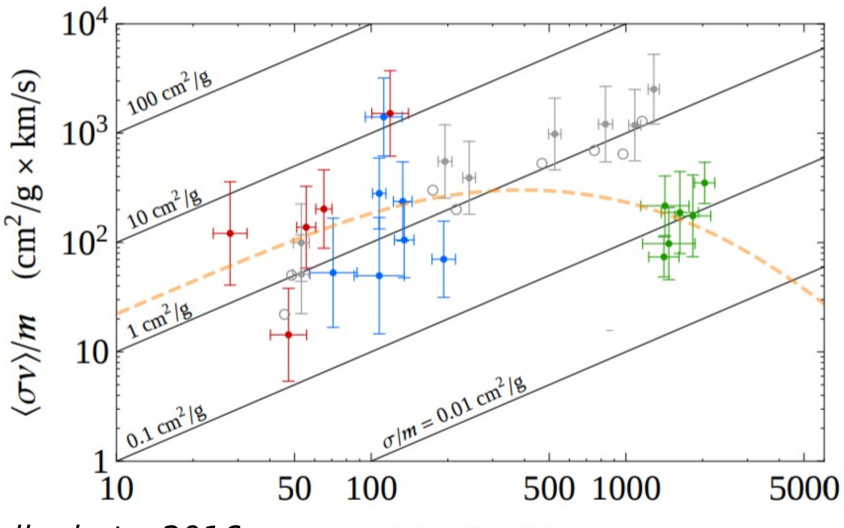
single interaction during halo lifetime

$$R_{\rm scat} = \sigma v \frac{\rho_{\rm DM}}{m_{\rm DM}} \approx 0.1 {\rm Gyr}^{-1} \times \left(\frac{\rho_{\rm DM}}{0.1\ M_{\rm Sun}/{\rm pc}^3}\right)\left(\frac{v}{50\ {\rm km/s}}\right)\left(\frac{\sigma/m_{\rm DM}}{1\ {\rm cm}^2/{\rm g}}\right)$$

Self-interacting dark matter (SIDM)

Velocity dependent self-scattering cross-section is preferred by data

$$\sigma/m \approx \begin{cases} 2\ \mathrm{cm^2/g} & v \sim 50\ \mathrm{km/s}\ \text{(dwarf galaxies)} \\ 0.1\ \mathrm{cm^2/g} & v \sim 1500\ \mathrm{km/s}\ \text{(clusters)} \end{cases}$$



Kaplinghat+ 2016

Nuclear size cross-section → much stronger than the weak scale cross-section

$$0.1\,\frac{\mathrm{cm}^2}{\mathrm{g}} \lesssim \frac{\sigma_{\rm self}}{M_{DM}} \lesssim 2\,\frac{\mathrm{cm}^2}{\mathrm{g}} \sim \frac{\mathrm{barn}}{\mathrm{GeV}} \gg \frac{\mathrm{pb}}{\mathrm{GeV}}$$

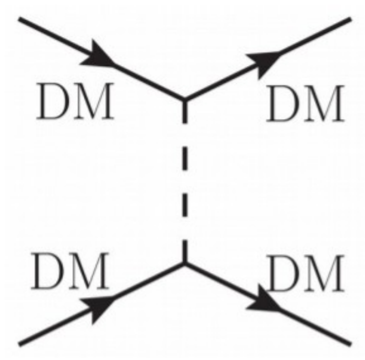
Bullet cluster bound

$$\sigma/m < 1.25\,\mathrm{cm}^2/\mathrm{g}\ (68\%\ \mathrm{CL})$$

SIDM from light mediator

Feng+ 2009, Buckley+ 2009, Loeb+2011, Tulin+ 2012

DM (GeV – TeV mass) + light mediator (1 – 100 MeV) + weak coupling



cross-sectior $\propto g^4 \frac{m_{\rm DM}^2}{m_{\rm med}^4}$

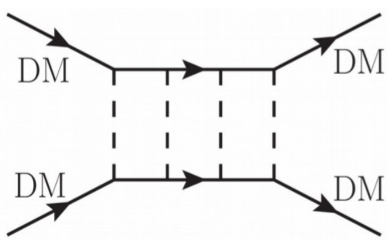
<u>velocity dependence:</u>

- hard-sphere like scattering (constant cross-section)

$$m_{\rm med} \gg m_{\rm DM} v_{\rm rel}$$

- Rutherford-like scattering ($1/v^4$)

$$m_{\rm med} \ll m_{\rm DM} v_{\rm rel}$$



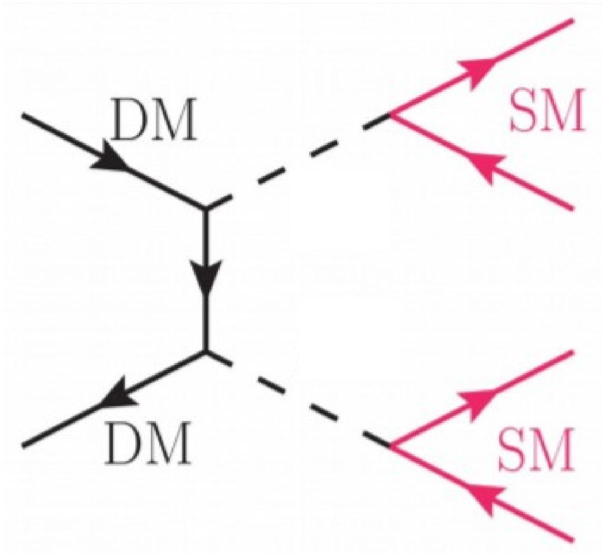
enhanced further by non-perturbative effects

$$\alpha_g m_{\rm DM}/m_{\rm med} > 1 \qquad V = \frac{\alpha_g}{r} e^{-m_{\rm med} r}$$

Alternative scenarios: strongly-interacting DM (QCD-like theory, dark hadrons, dark nuclei), massless mediators (dark atoms, DM with dark radiation), heavy mediator in a Breit-Wigner resonance

MD+ 2017, Chu+ 2018, 2019

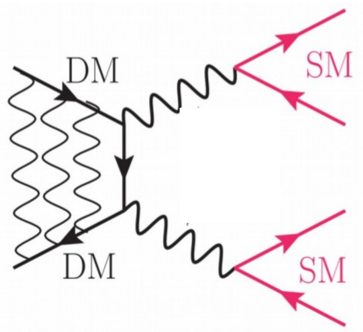
SIDM from light mediator – bounds

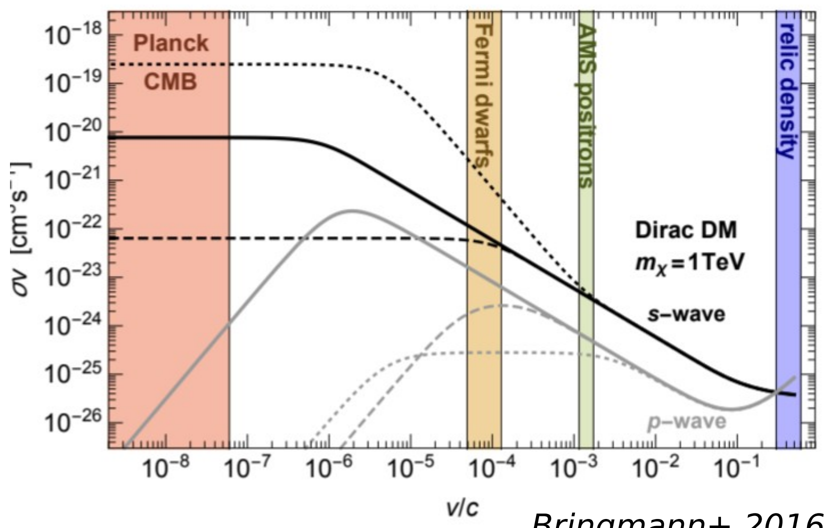


Generically present indirect detection bounds on 1-step cascade DM annihilation

Large Sommerfeld enhancement possible

$$(\sigma v)_{\rm CMB} \gg 2 \times 10^{-26}{\rm cm}^3/{\rm s}$$

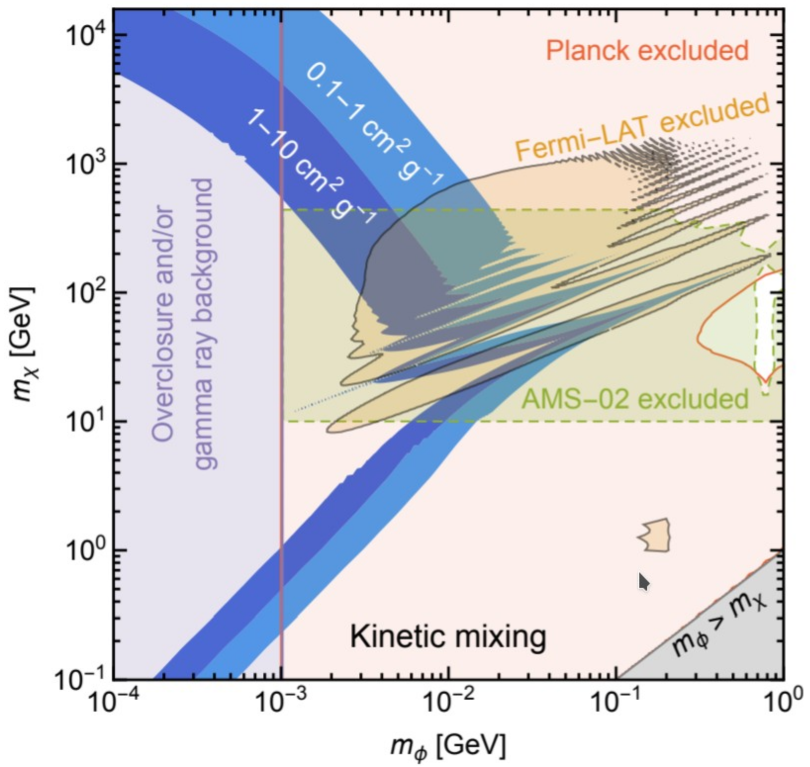




Bringmann+ 2016

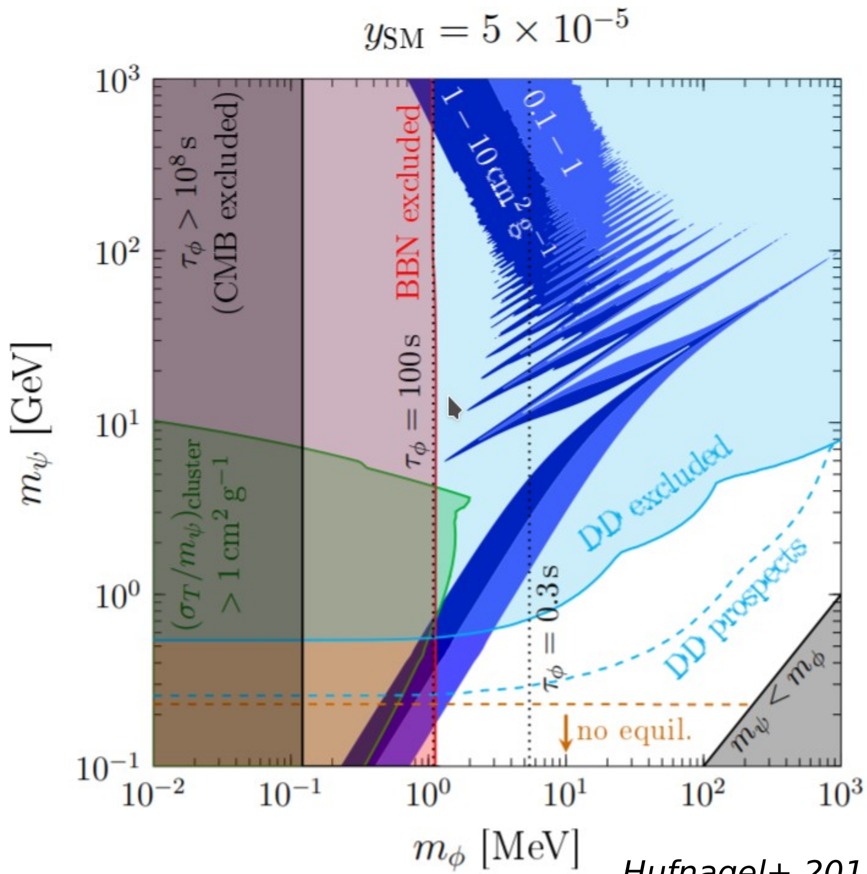
SIDM from light mediator – bounds

vector mediator



Bringmann+ 2016

scalar mediator



Hufnagel+ 2018

- s-wave DM annihilation cross-section
- excluded by the Planck constraint on DM annihilation rate at recombination

- p-wave annihilation
- nearly excluded by the combination of direct detection and BBN bounds

How to evade constraints?

- mediator decaying into sterile neutrinos

Aarsen+ 2012, Bringmann+ 2014

- mixed scalar/pseudoscalar couplings with CP violation

Kahlhoefer+ 2017

- non-thermal DM production (eg. by freeze-in mechanism)

Bernal+ 2015, MD+ 2017

- DM mass splitting (inelastic scattering)

Blennow+ 2016, MD+ 2017

- stable mediator

Ma+ 2017, MD+ 2017, Duerr+ 2018, MD+2019

Fermionic DM with stable scalar mediator

SM extension:

- Dirac fermion χ with GeV mass that is dominant DM component
- light scalar mediator S (1-100 MeV)

Both stable due to the symmetry

$$\chi \to i\chi \,, \qquad S \to -S \qquad V_{\chi S} = m_\chi \bar{\chi}\chi + \frac{g_Y}{2} S(\bar{\chi^c}\chi + \bar{\chi}\chi^c)$$

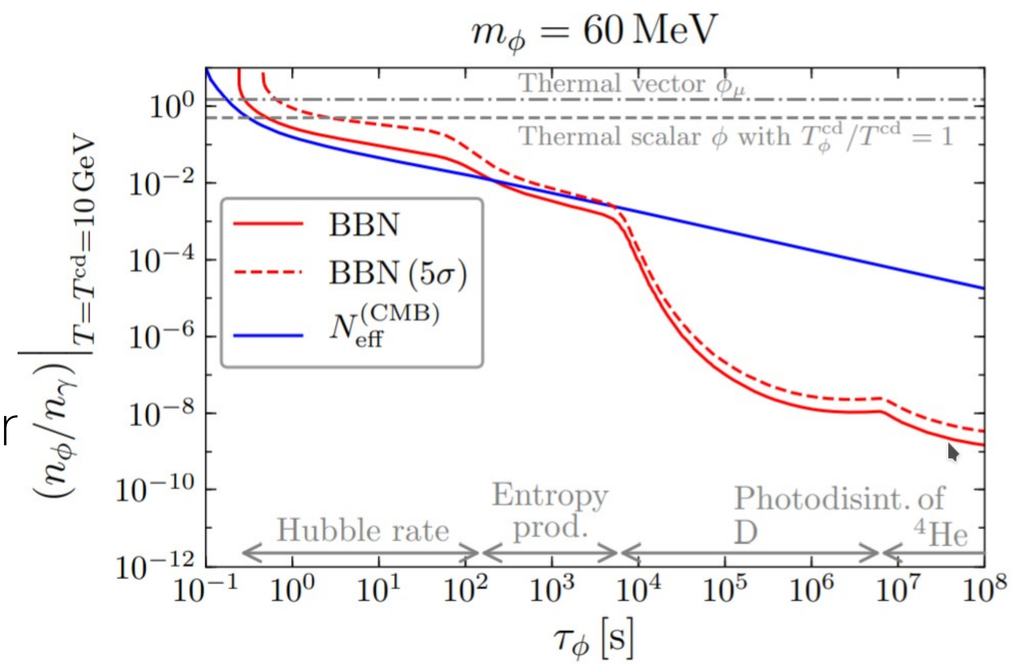
Extra light scalar h_2 (dark Higgs) required to allow for effective annihilation of subdominant DM component

$$m_{h_2} < m_S$$

BBN bounds

Extra light states may modify the successful predictions of BBN

- Hubble rate increase
- entropy production from light state decays and modification of baryon-to-photon ratio
- photodistingration of deuteriur



Hufnagel+ 2018

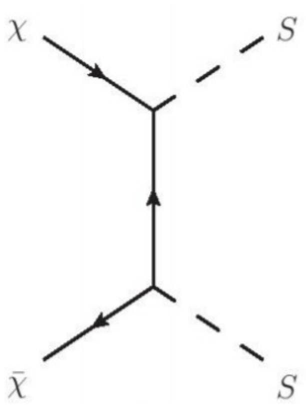
$$m_{h_2} > E_{\mathrm{dis}} = 2.2\mathrm{MeV}$$

Density of S and h_2 with respect to photons may be substantially supressed, when the dark sector decouples before QCD phase transition

Lifetime of h_2 should be below 10s $\rightarrow$ problem for the stable vector mediator scenario *Duerr+ 2018*

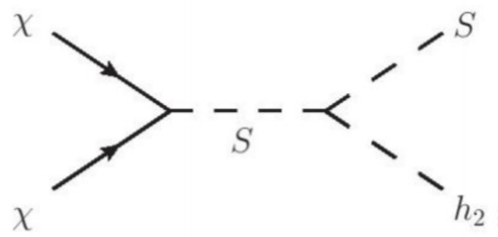
Indirect detection

conversion



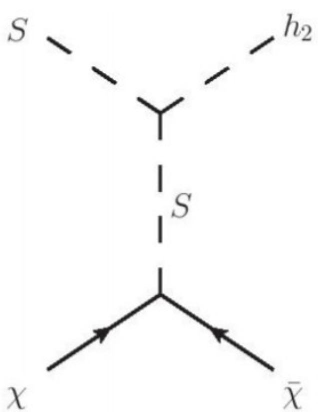
S is stable → no visible indirect detection signal

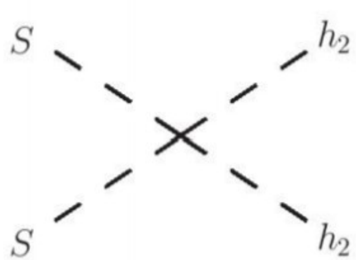
semi-annihilation



p-wave cross-section → highly suppressed by the small velocity of annihilating DM

visible signal from the dark Higgs decay





1-step cascade decay into e^+e^-

Slatyer+ 2015

$$\frac{1}{2}\langle\sigma v\rangle_{\chi S\to\bar{\chi}h_2}\left(\frac{\Omega_S h^2}{\Omega_{\rm DM}h^2}\right)\left(\frac{\Omega_\chi h^2}{\Omega_{\rm DM}h^2}\right) < \langle\sigma v_{\rm rel}\rangle^{4e^\pm}_{\rm CMB}(m_S)$$

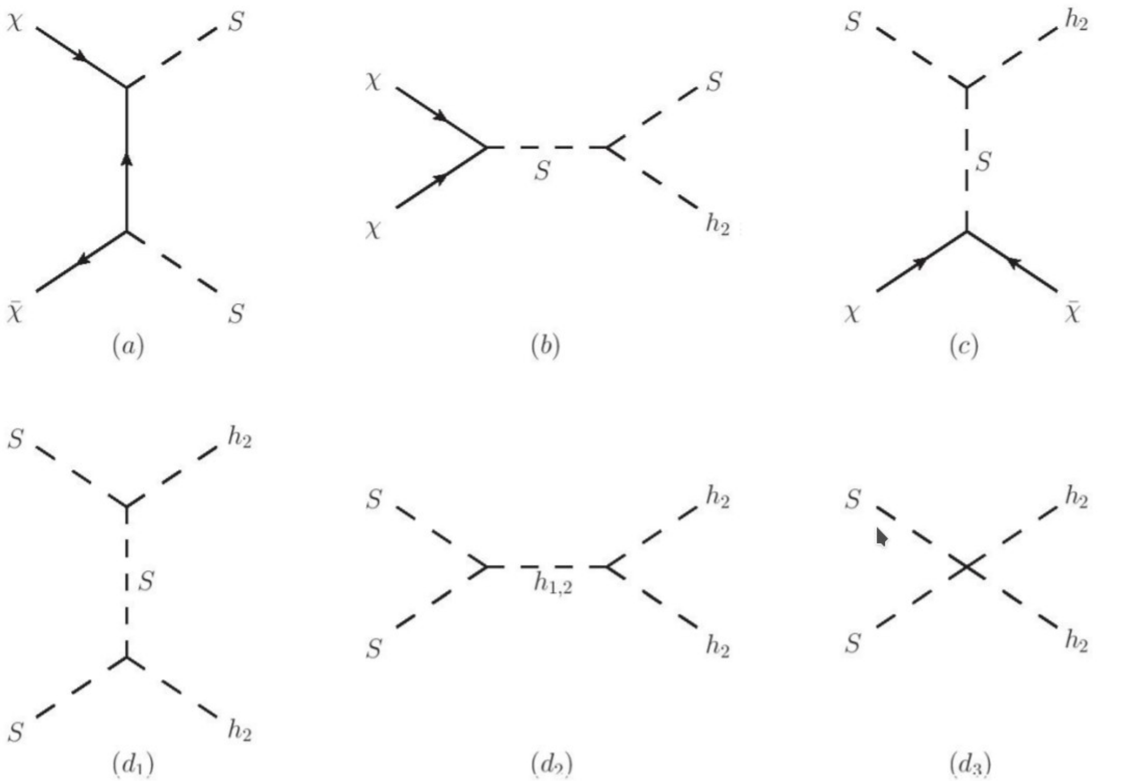
$$\langle\sigma v\rangle_{SS\to h_2h_2}\left(\frac{\Omega_S h^2}{\Omega_{\rm DM}h^2}\right)^2 < \langle\sigma v_{\rm rel}\rangle^{4e^\pm}_{\rm CMB}(m_S)$$

Relic abundance

Two-component DM scenario

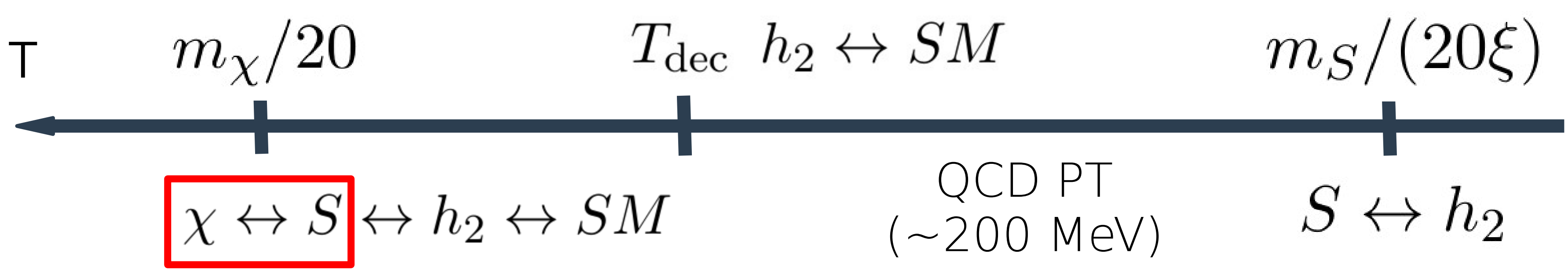
Various processes relevant in the determination of relic abundance

- annihilation,
- semi-annihilation,
- conversion



dark sector decoupling before QCD phase transition → dark freeze-out

$$\xi(T) \equiv \frac{T_D(T)}{T} = \left(\frac{g_{*S}(T)}{g_{*S}(T_{\rm dec})} \frac{g^D_{*S}(T_{\rm dec})}{g^D_{*S}(T_D)} \right)^{1/3}$$

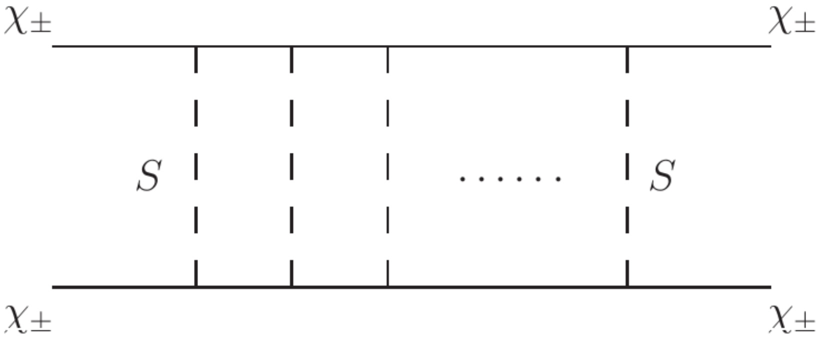


Self-interactions

Convenient basis to analyze DM self-interactions

two Majorana states

$$\chi_+ = \frac{1}{\sqrt{2}}(\chi + \chi^c)\,, \qquad \chi_- = \frac{i}{\sqrt{2}}(\chi - \chi^c)$$



$\chi_+\chi_+$ and $\chi_-\chi_-$ scatterings are attractive $V_a = -\frac{g^2}{4\pi r}e^{-m_S r}$

$\chi_+\chi_-$ scatterings are repulsive $V_r = +\frac{g^2}{4\pi r}e^{-m_S r}$

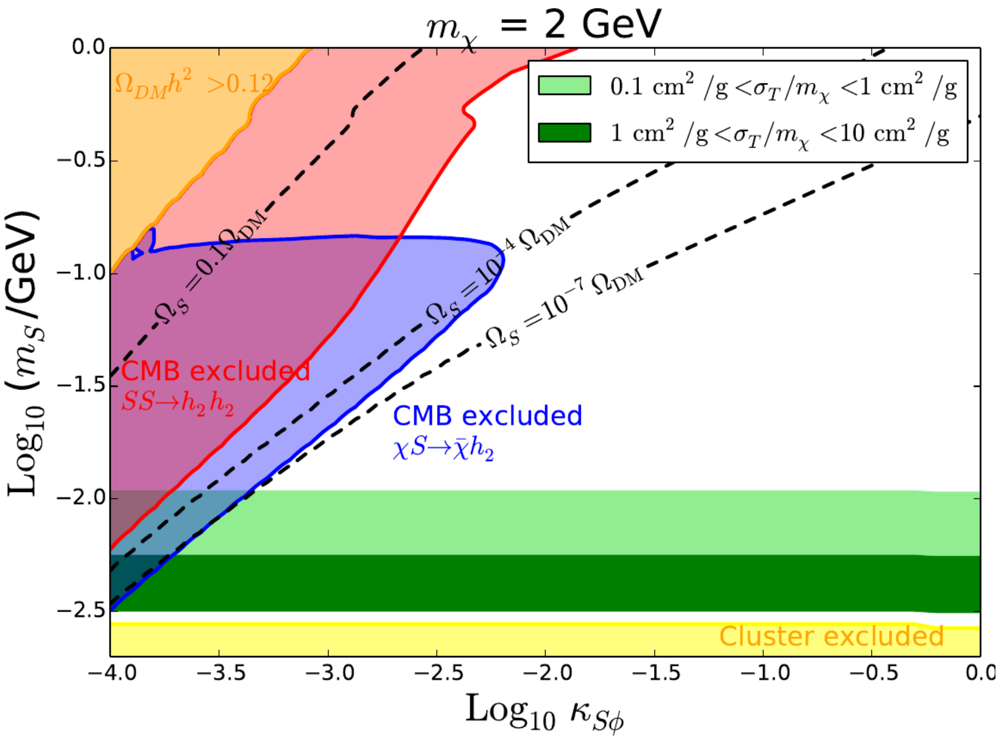
Cross section obtained from the numerical solution of Schroedinger equation with Yukawa potential $\frac{d\sigma}{d\Omega} \propto |f(\theta)|^2$

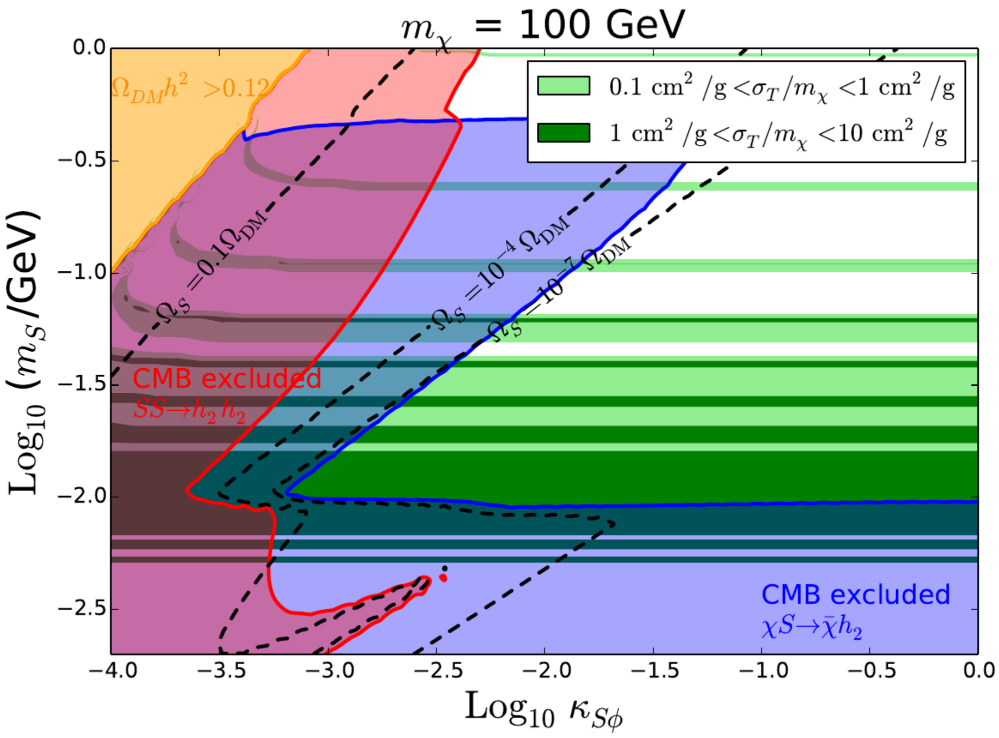
Zurek+ 2013

Proper averaging $\sigma_T \equiv \frac{1}{4}\left(\sigma_T^{++} + \sigma_T^{--} + \sigma_T^{+-} + \sigma_T^{-+}\right) = \frac{1}{2}\left(\sigma_T^a + \sigma_T^r\right)$

Kahlhoefer+ 2017

CMB bounds in the parameter space

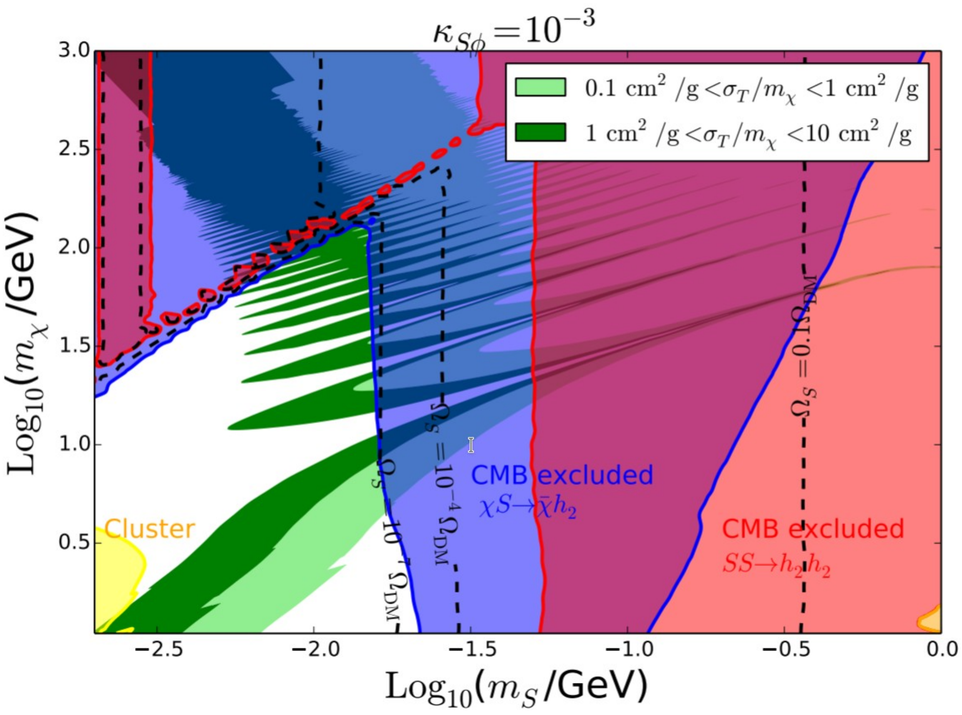


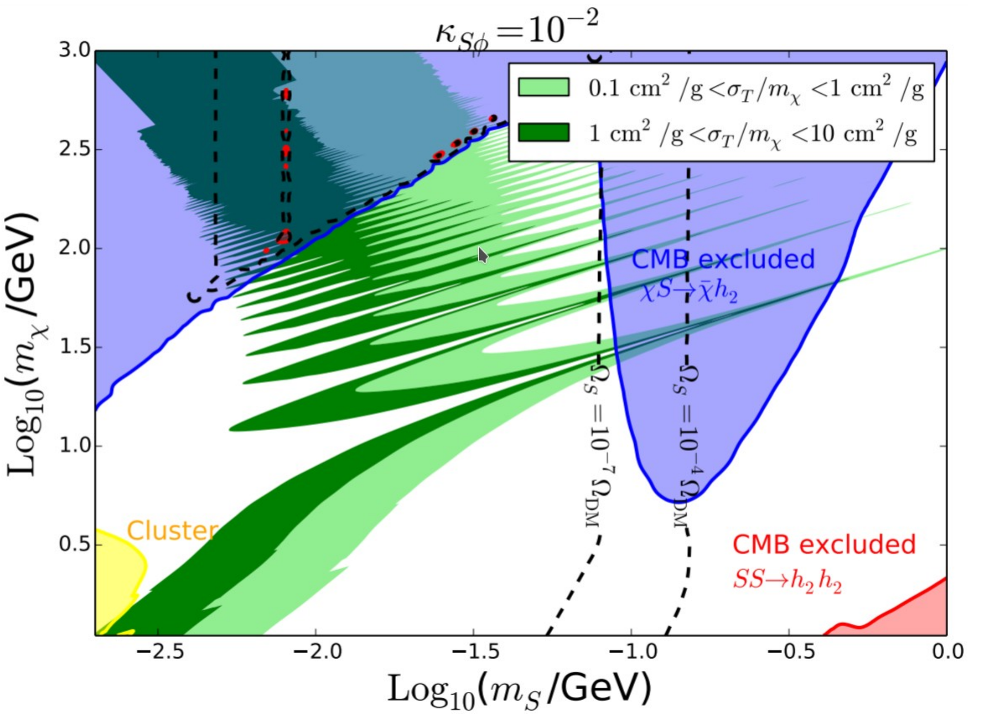


Regions of larger h_2 and S coupling are allowed

Bounds on the p-wave DM annihilation are absent, but DM semi-annihilation and mediator annihilations are constrained by CMB

Allowed regions in the parameter space





Viable regions with the desired value of the self-scattering DM cross-section

Conclusions

- self-interacting dark matter (SIDM) provides a possible solution to small scale structure problems
- strong DM self-interactions may naturally arise when light mediator is present, but simple scenarios are strongly constrained by indirect, direct detection, CMB or BBN
- model with stable scalar mediator evades existing CMB and BBN bounds