Progress on Old and New Themes in cosmology 2017

Split Light Dark Matter

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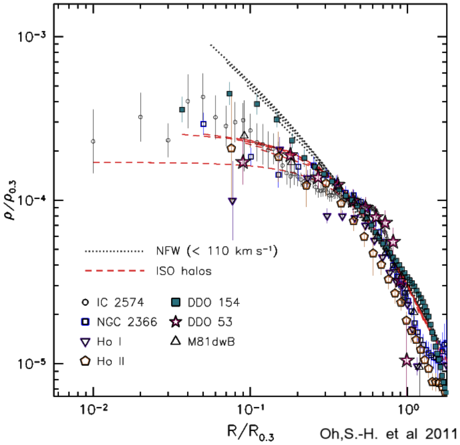
Work with Nicolás Bernal and Josef Pradler (1702.04906 and on-going study)

Outline:

1. Self-Interacting Dark Matter (SIDM)
2. Split DM model
3. DM self-interaction in astrophysics
4. More and Summary

Motivations

- Core/cusp problem.–ΛCDM simulations predict inner region of DM haloes is cuspy (NFW-like) while observations from dwarf galaxies prefer a core (ISO-like). [Moore 1994, Flores et al. 1994, Naray et al. 2011, Ferrero et al. 2011, Boylan-Kolchin et al. 2011/2012, Papastergis et al. 2014...]



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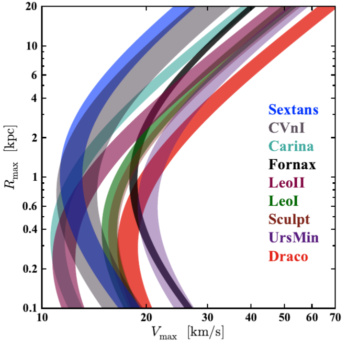
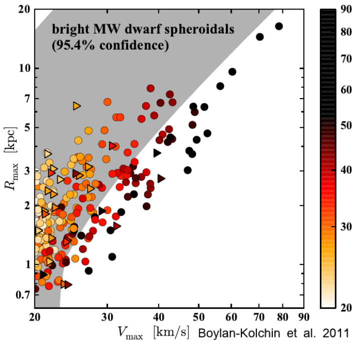
· "Too-big-to-fail" problem.-ΛCDM simulations also produce heavier/denser DM subhalos, whose characteristic dwarfs are not observed. [Boylan-Kolchin et al. 2011, Ferrero et al. 2011, Boylan-Kolchin et al. 2012, Papastergis et al. 2014...]





Boylan-Kolchin et al. 2011

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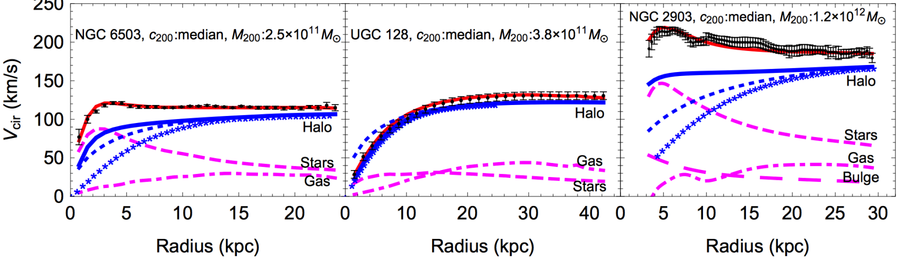
- Diversity in galactic rotation curves?–Interplay between baryonic and SIDM effects. [Kaplinghat et al. 2013, Kamada et al. 2016, ...]



A. Kamada et al. 2016

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- Diversity in galactic rotation curves?–Interplay between baryonic and SIDM effects. [Kaplinghat et al. 2013, Kamada et al. 2016, ...]

- Possible hints in colliding clusters?–Offset in mass distributions of DM and gas in colliding clusters [Massey et al. 2015, Kahlhoefer et al. 2015, Robertson et al. 2016, ...]

Self-interacting DM (SIDM) solution:

Self-scattering cross section per mass, $\sigma_{\mathsf{SI}}/m_{\rm DM} \gtrsim 0.1\,\mathrm{cm}^2/\mathrm{g}\,(\sim 0.2\,\mathrm{barn}/\mathrm{GeV})$, flattening central regions of dark halos. [Rocha et al. 2012, Peter et al. 2012, ...]

More signatures from SIDM?

· Velocity-dependent self-interaction: a light mediator [Spergel & Steinhardt 1999]

· (Partially) dissipative dark matter: unbroken dark U(1) [Fan et al. 2013, ...]

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- Split light dark matter: two nearly-degenerate states.

  A new way to regularize DM self-interaction, leading to rich phenomena.

Outline

Split DM Model

Start with a pseudo-Dirac fermion, Ψ, with a U'(1) gauge boson V:

$$\mathcal{L}_\Psi = \bar{\Psi}\left(i\not{D} - m\right)\Psi - \frac{\Delta m}{2}\left(\bar{\Psi}^c\Psi + h.c.\right),$$

in which $\Delta m \ll m$.

Inelastic/excited dark matter to explain DAMA/3.5 keV [L. J. Hall et al. 1997, D.Smith et al. 2001, ...].

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in which $\Delta m \ll m$.

Symmetry breaking $(\Delta m \neq 0)$ ⇒ two nearly-degenerate mass eigenstates:

lighter, stable dominant DM: $\chi_1 \simeq \frac{i}{\sqrt{2}}(\Psi - \Psi^c)$,

(meta-)stable subleading DM: $\chi_2 \simeq \frac{1}{\sqrt{2}}(\Psi + \Psi^c)$,

which interact (assuming a heavier V) mainly via

$$ig_V\left(\bar{\chi_1}\gamma^\mu\chi_2\right)V_\mu, \quad \cancel{\left(\bar{\chi_1}\gamma^\mu\chi_1\right)V_\mu}.$$

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Assuming a decoupled dark sector and $m_V > 2m + \Delta m$:

Freeze-out via 4-body annihilation (e.g. $\chi_1\chi_1\chi_1\chi_2 \to \chi_1\chi_2$) decides

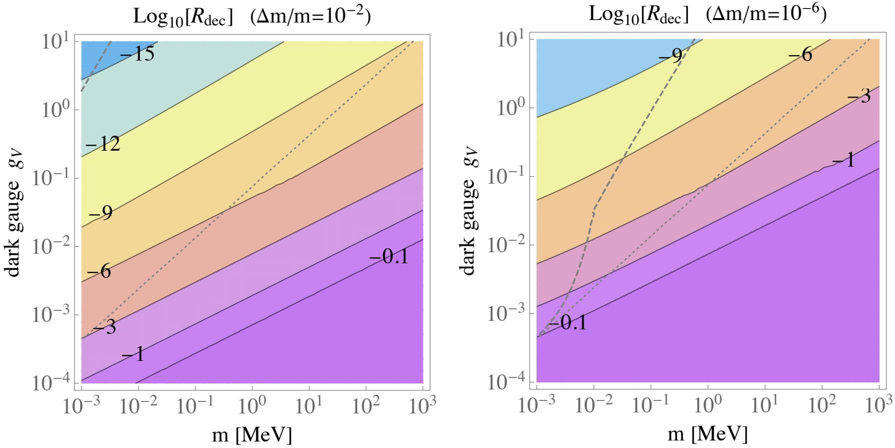
$$\Omega_{\rm DM} = \Omega_{\chi_1} + \Omega_{\chi_2}\,,$$

Two-body annihilation $\chi_2\chi_2 \to \chi_1\chi_1$ (depending on $\Delta m/m$) decides

the relative abundance ratio: $R_0 = \frac{\Omega_{\chi_2}}{\Omega_{\chi_1}} \ll 1$

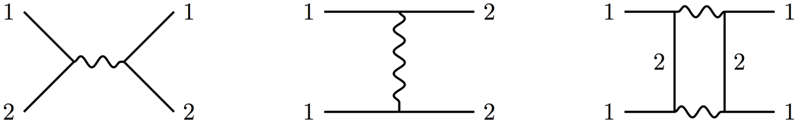
at present.

Assuming a decoupled dark sector and $m_V > 2m + \Delta m$:



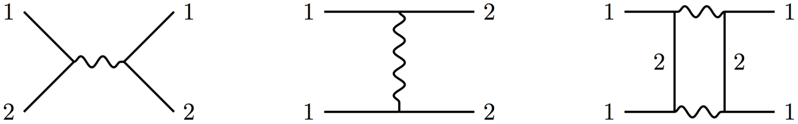
Outline

Self-scattering diagrams



- Two-state scattering: $12 \rightarrow 12$;
  - depending on the relative abundance of χ_2, i.e. R_0.
- Endothermic scattering: $11 \rightarrow 22$;
  - kinetically suppressed due to $\Delta m/m$.
- Loop-induced scattering: $11 \rightarrow 11$.
  - loop suppressed by $\mathcal{O}(g_V^4/\pi^2)$.

Self-scattering diagrams



Subleading component χ_2 plays an important role!

- Two-state scattering: $12 \to 12$;
  - depending on the relative abundance of χ_2, i.e. R_0.

(being dominant for light DM and $\Delta m/m \gg 10^{-5}$)

SIDM effective cross section

Effectively leading DM χ_1 only scatters with χ_2 :

$$\frac{\sigma_{\rm eff}^{\rm SI}}{m} \simeq R_0 \frac{\sigma_{12}}{m} \sim 0.1 - 1\,{\rm cm}^2/{\rm g}\,.$$

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Recall some of the strongest constraints (most likely over-estimated)

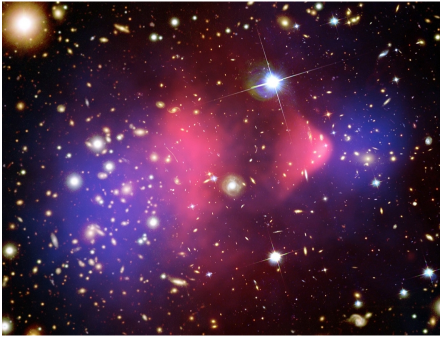
- Displacement of stellar and DM mass in colliding clusters: $\sigma_{SI}/m_{DM} \lesssim 0.47\,\mathrm{cm}^2/\mathrm{g}$ [D.Harvey et al. 2015, ...],

  Mass loss in Bullet cluster: $\sigma_{SI}/m_{DM} \lesssim 0.6\,\mathrm{cm}^2/\mathrm{g}$ [S.W.Randall et al. 2007, ...],
- Ellipticities of cluster/galaxy halos: $\sigma_{SI}/m_{DM} \lesssim 0.02 - 1\,\mathrm{cm}^2/\mathrm{g}$ [Miralda-Escudé 2002, Buote et al. 2002, A.Peter et al. 2012, ...],
- Sub-halo evaporation (much weaker).

Examining bounds on σ^{SI}/m for split DM

- Colliding cluster bounds do not apply.

  χ_1 only scatters with χ_2 $\Rightarrow$ most of χ_2 may get scattered away.



Bullet Cluster:

mass loss $\leq$ 23% at 68% C.L.

[S.W.Randall et al. 2007]

Distorted Profile:

scattering fraction $\leq$ 10% at 3σ C.L. (projected) [D.Harvey et al. 2016]

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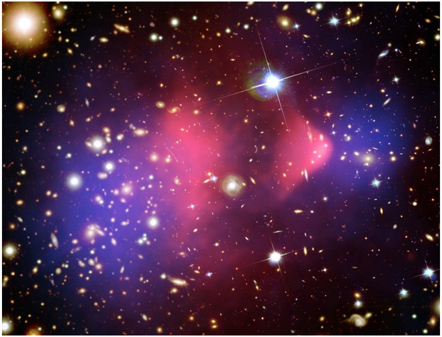

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Neither significant mass loss nor offset between mass distributions of DM and gas during halo collision if $R_0 \leq 5\% - 10\%$.

Examining bounds on σ^{SI}/m for split DM

- Ellipticity bounds do not necessarily apply.

  Core-collapse of collisional DM: when inner halo heats up, it shrinks.

  $$2\mathrm{E}_{\mathrm{kin}} + \mathrm{V} \simeq 0 \quad \Rightarrow \quad \mathrm{E}_{\mathrm{tot}} = \mathrm{E}_{\mathrm{kin}} + \mathrm{V} \simeq -\mathrm{E}_{\mathrm{kin}}.$$

  DM $\chi_{1,2}$ only collide with each other & $\Omega_{\chi_1} \gg \Omega_{\chi_2}$,

  χ_2 in halos has much shorter relaxation time.

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χ_2 in halos has much shorter relaxation time.

$\Rightarrow$ It is plausible that χ_2 is more sensitive to core-collapse/assembly of SIDM/baryons.

Examining bounds on σ^{SI}/m for split DM

If $R_0(r) \uparrow$ with $r \downarrow$, it enhances DM scatterings at small radii, to avoid ellipticity bounds (at large radii) .

also seed supermassive black holes(?) (for partially strongly SIDM [J. Pollack et al. 2015]).

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Detailed investigation is required:

- Semi-analytical model of two-component gravitating fluid (for self-gravitating system of light/heavy stars [A.P.Lightman et al. 1978]),
- N-body cosmological simulation.

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More generally:

· Actual abundance of χ_2 depends on merger history of halos.

R_0 may be smaller in more massive halos.

Outline

Direct detection

V-portal: Introducing gauge mixing between $U'(1)$ and $U_Y(1)$:.

$$\mathcal{L}_{\rm portal} = \kappa e \cdot V_\mu (\bar{f}_{\rm SM} \gamma^\mu f_{\rm SM}).$$

Exothermic scattering on electrons: $\chi_2 + e \to \chi_1 + e$.

It leads to large energy deposit (assuming negligible DM velocity):

$$E_{\rm recoil} \sim \Delta m \times \frac{\mu_{\chi e}}{m_e}\,.$$

DM mass $\sim$ MeV, $\Delta m/m \sim 10^{-2} \Rightarrow E_{\rm recoil} \sim 10\,\text{keV}$ (although $m v_0^2 \sim \text{eV}$) .

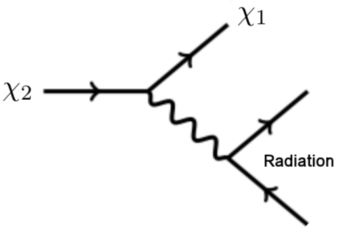
Other relevant searches for V-portal:

- CMB spectrum:

  Electromagnetic energy injection in

  $\chi_2 \to \chi_1 + V^\star$, $V^\star \to 3\gamma/2e$:

  $$\frac{\tau_2}{10^{24}\ \mathrm{sec}} \gtrsim \mathrm{Br_{em}} \times R_{\rm dec} \times \frac{\Delta m}{m}\,.$$



- X-ray observations:

  current bound (from diffused X-ray observations) is relatively weaker.

- Dark photon absorption in SM targets;

- Known constraints from astrophysics (stars and supernovae, ...).

Summary

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- Remaining issues:

  Fine-tuned to have $R_0 \sim \mathcal{O}(0.1 - 0.01)$ given a decoupled sector.

  (extensions, e.g.,$3\chi \to \chi V$?)

  Semi-analytic modeling / N-body simulation needed.

Thanks for Your Attention!

Backups

Relative abundance ratio

A decoupled dark sector with T'/T, where the parameters

$$m,\ \Delta m,\ g_V,\ m_V,$$

determine the DM relic density:

$$\Omega_{\rm DM} \propto m_{\rm DM}\, n_{\rm DM} \simeq m(n_1 + n_2)$$

and the relative abundance ratio

at present: $R_0 \equiv n_2/n_1.$

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$$\text{at decoupling of } 22{\to}11: \quad R_{\rm dec} \propto e^{-\Delta m/T'_{\rm dec}}.$$

Parameter choice:

1) $m_V = 5m/2$ and $\Delta m/m = 10^{-2}$, 10^{-6};
2) T'/T fixed by the observed $\Omega_{\rm DM}$.
3) scan m, g_V to determine $R_{\rm dec}$;

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   - as required by strong self-interaction.

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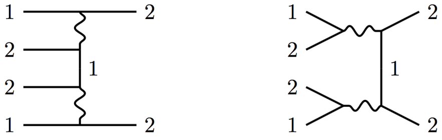
   - entropy conserved before decoupling.
   - $4 \to 2$ freeze-out, fixing $\Omega_{\rm DM}$.
   - $\chi_1\chi_1\chi_2 \leftrightarrow V\chi_1$ is sub-leading due to heavy V. [J. Cline et al. 2017]



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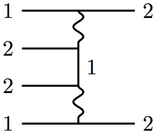

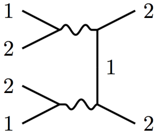

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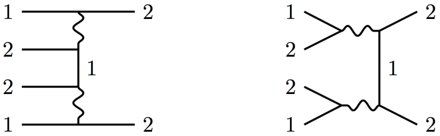

3. Annihilation $22 \to 11$ process decouples at $T_{\rm dec}$.
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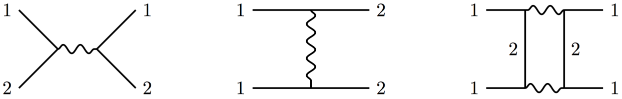
4. DM self-scattering processes stop.
   - χ_1 starts to free stream.



Solving the Boltzmann equations:

$$\frac{dY}{dx} = -\frac{s^3 \, \langle \sigma v^3 \rangle_{4\to 2}}{x\, H} \left(Y^4 - Y^2\, Y_{\rm eq}^2 \right), \ldots$$

where $x = m/T$, $Y = (n_1 + n_2)/s$, and s the entropy density.

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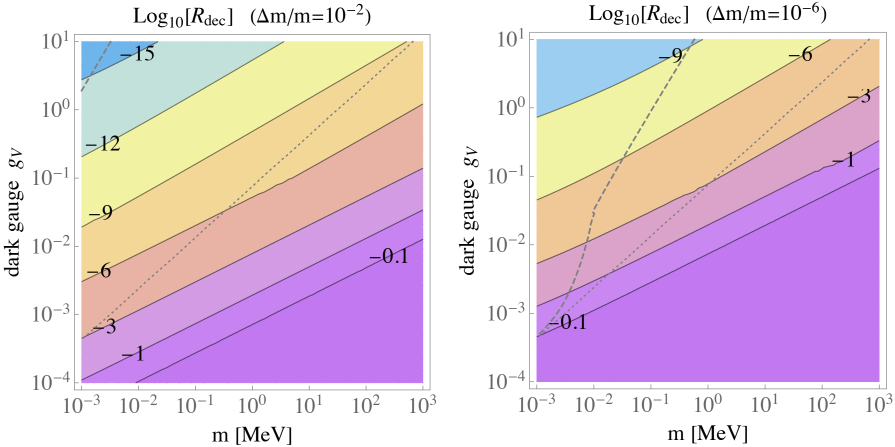
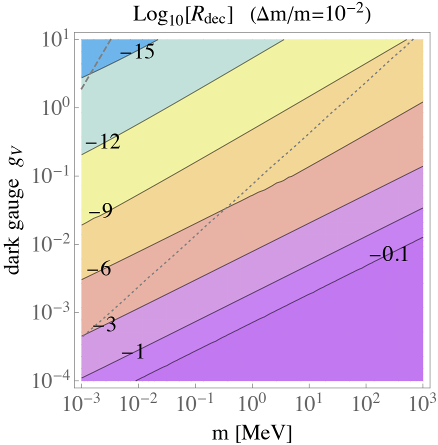
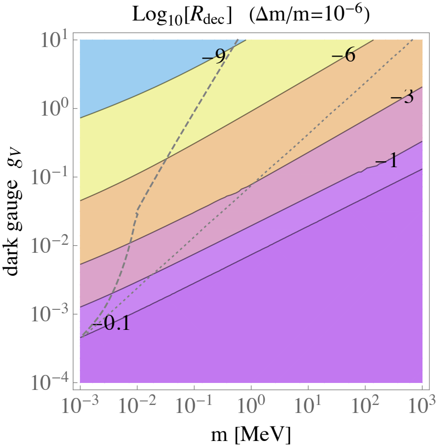


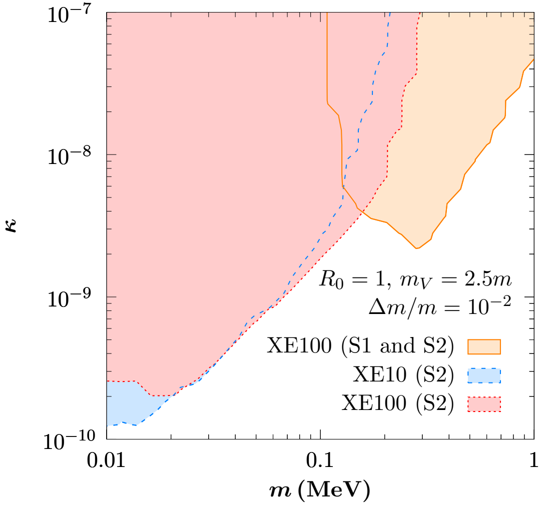
Decreasing $\Delta m/m \Rightarrow$ larger $R_{\rm dec}$:

- $\sigma_{12\to12}/m = 1\,{\rm cm}^2/{\rm g}$ (dotted) & $R_{\rm dec}\sigma_{12\to12}/m = 1\,{\rm cm}^2/{\rm g}$ (dashed) .
- $\mathcal{O}(10^{-2})$ $R_{\rm dec}$ is possible for lighter SIDM and smaller $\Delta m/m$.





Assuming the relative abundance $R_0 = 1$ ($\Omega_{\chi_1} = \Omega_{\chi_2}$):



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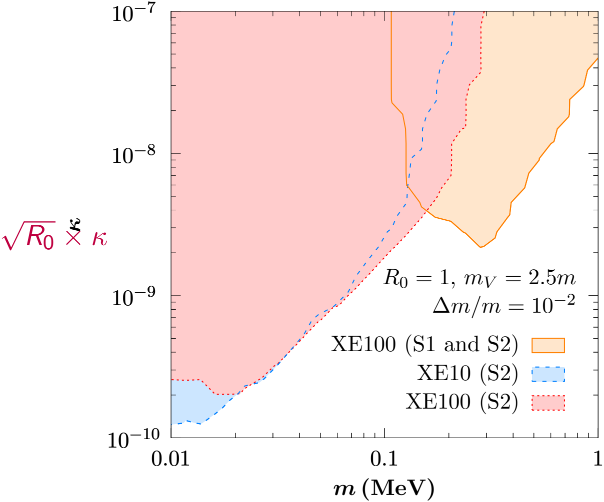
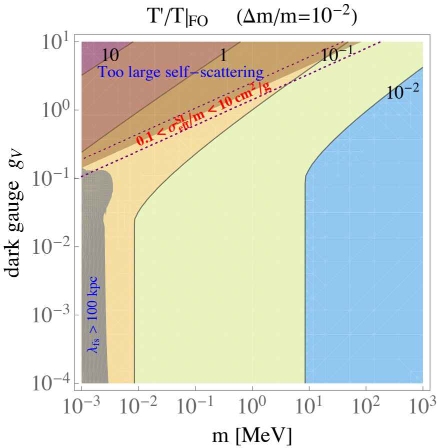
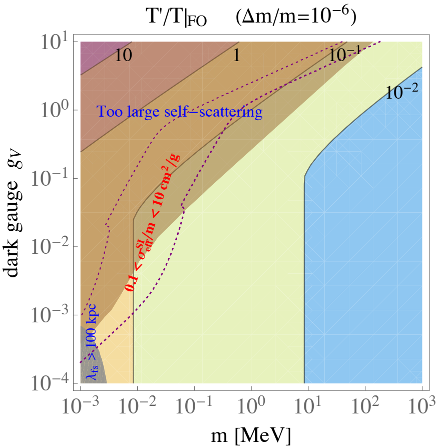


Astrophysical bounds





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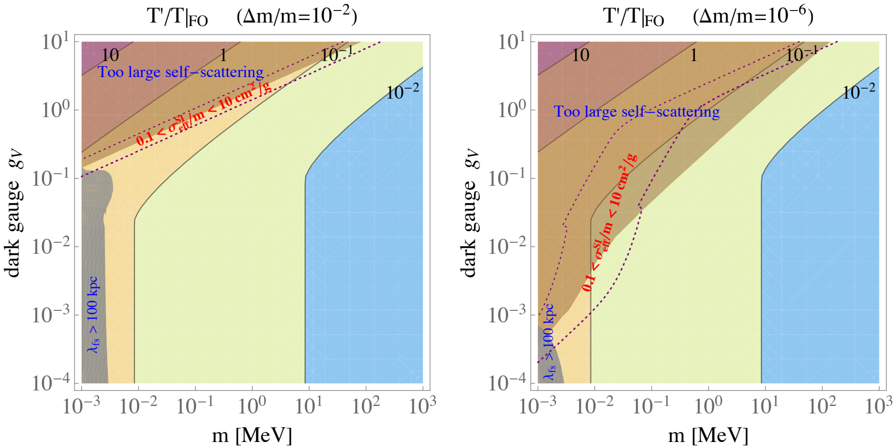
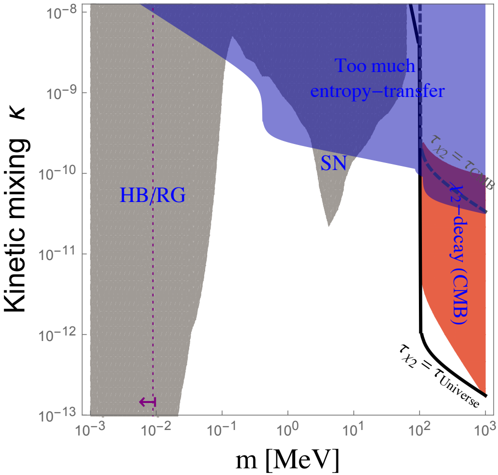


- For larger mass splitting, 12 → 12 scattering dominates $\sigma_{\rm eff}^{\rm SI}$.
- For small mass splitting, 11 → 22 scattering dominates for $m \geq 30\,\text{keV}$.
  - larger $v_0 \Rightarrow$ larger self-scattering (opposite to case of light mediator).

Current bounds on the portal

One example with $g_V = e, \;\; \Delta m/m = 10^{-2}$, and $m_V = 2.5\,m$:



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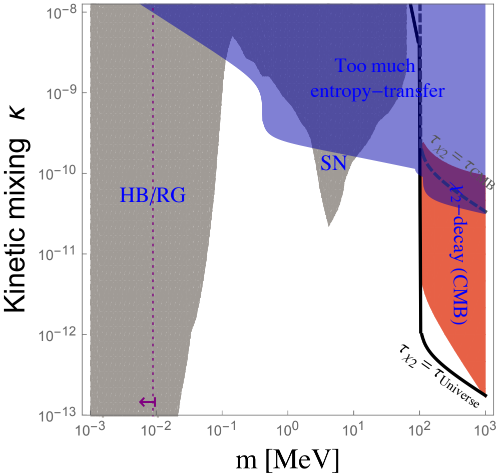

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Bounds can be re-scaled for other values of g_V.