Constraining atomic dark matter with white dwarfs

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arXiv:2005.?????, ...

with David Curtin

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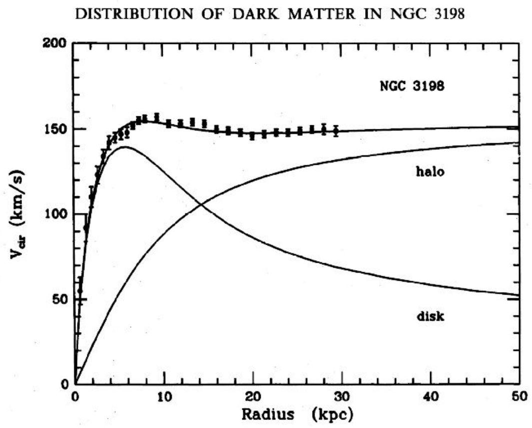
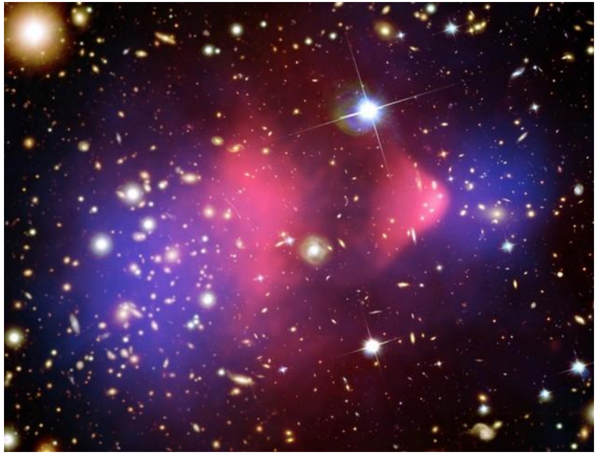
Dark matter exists...

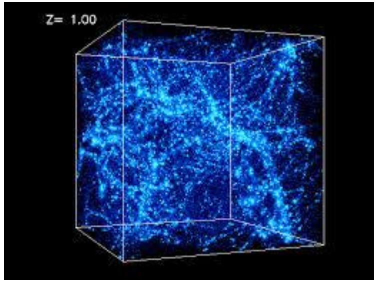
Evidence for dark matter
is overwhelming.



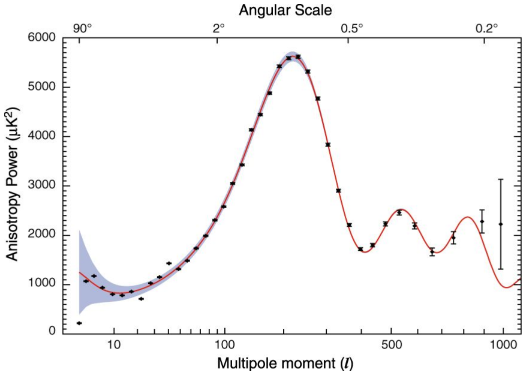
Galactic rotation curves



Bullet cluster



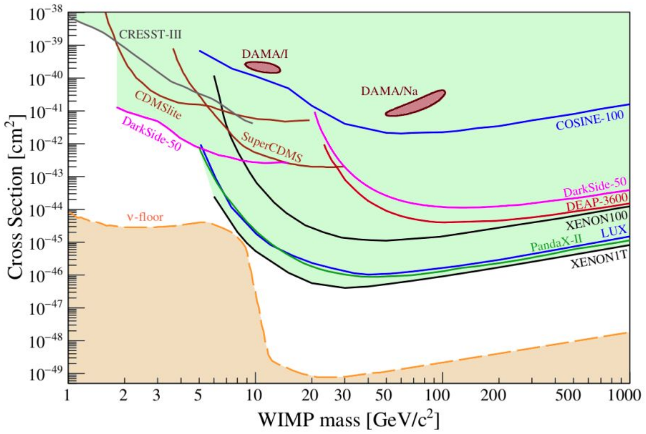
Structure formation



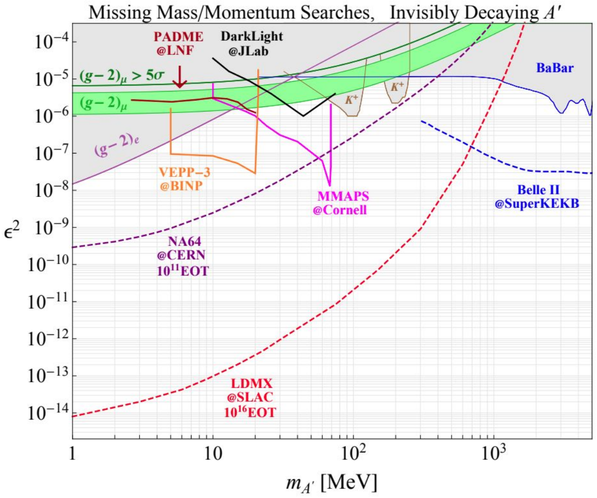
CMB power spectrum

…but we haven't found it yet

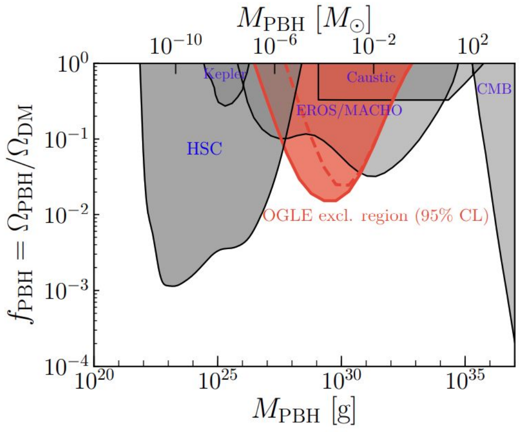
Ongoing searches for WIMPs, axion-like particles, dark photons, millicharged particles, primordial black holes, the list goes on…



`[arXiv:1903.03026]`



`[arXiv:1608.08632]`



`[arXiv:1901.07120]`

Dark sector could be non-minimal

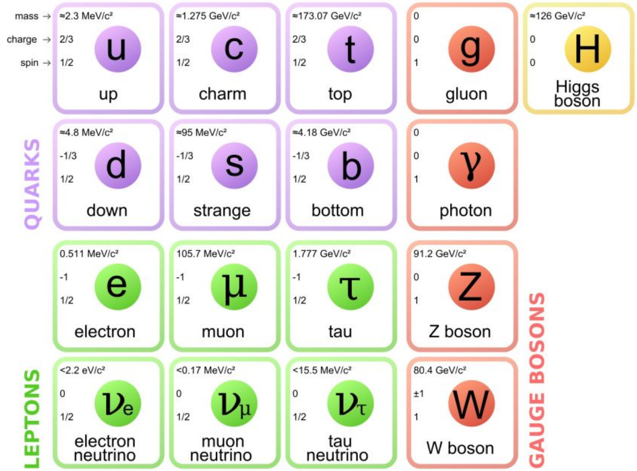
The Standard Model is a very non-minimal model:

- Bound states, confinement,
- Multiple interactions.

Should we expect the dark sector to be any simpler?

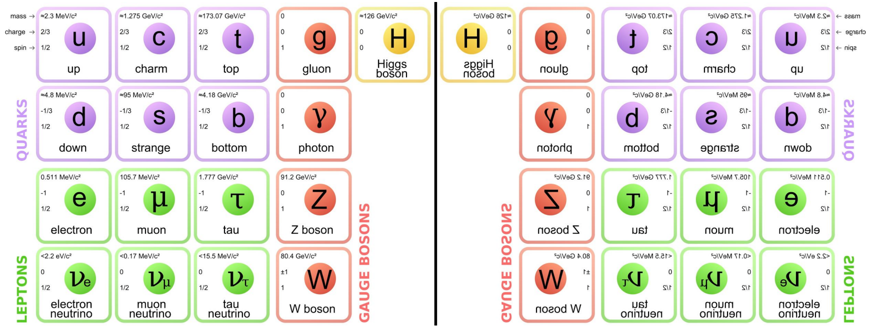
Dark sector could be composite with multiple stable relics: confinement, and/or atomic dark matter.

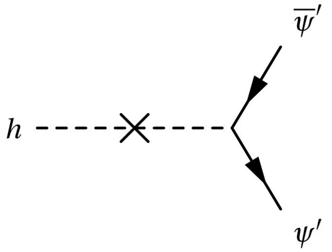
New physics could be related to Standard Model via symmetry, e.g. supersymmetry, Twin Higgs.



Mirror Twin Higgs

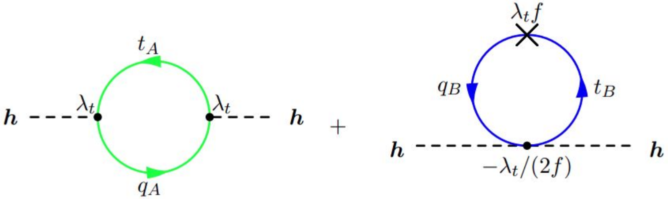
Raise twin Higgs VEV by a factor of a few to get around collider / cosmological constraints…





$$v_B/v_A \gtrsim 3$$

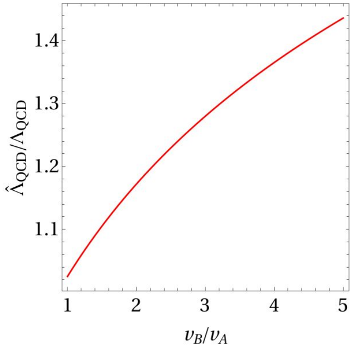
- Raises the masses of the fundamental mirror sector particles by a factor of a few.



[arXiv:0506256, arXiv:0510273, image from arXiv:1411.3310]

- Proton, neutron masses

$$\propto \Lambda'_{QCD}$$

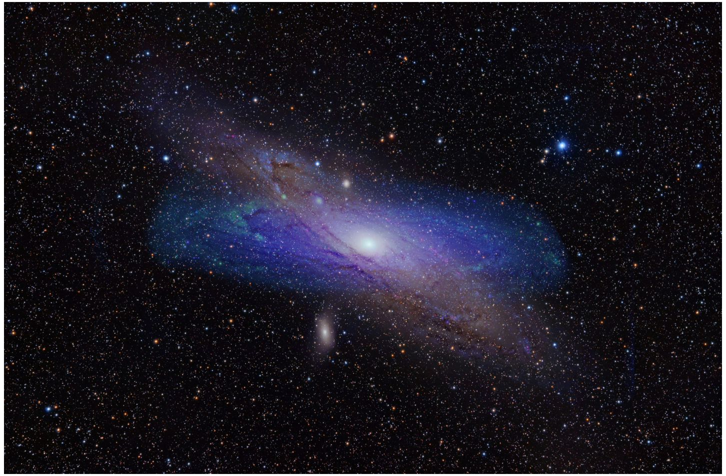


Complex = interesting!

Complex dark matter can behave in radically different ways.

Atomic dark matter can form complex structures, cooling from a halo into a dark disk structure

Constraints on self-interactions (structure formation and others) < around 5-10% of total dark matter abundance.



[Fan, Katz, Randall, Reece:
arXiv:1303.1521, arXiv:3271]

(Mirror) stellar probes

Ways to probe this kind of dark sector?

- Direct detection
- Look for mirror stars!
- Other constraints from stellar physics.

Stars would *accumulate* atomic dark matter, which can radiate to produce a signature.

Can lead deviations from known physics.

[David Curtin & JS, arXiv:1909.04071, arXiv:1909.04072]

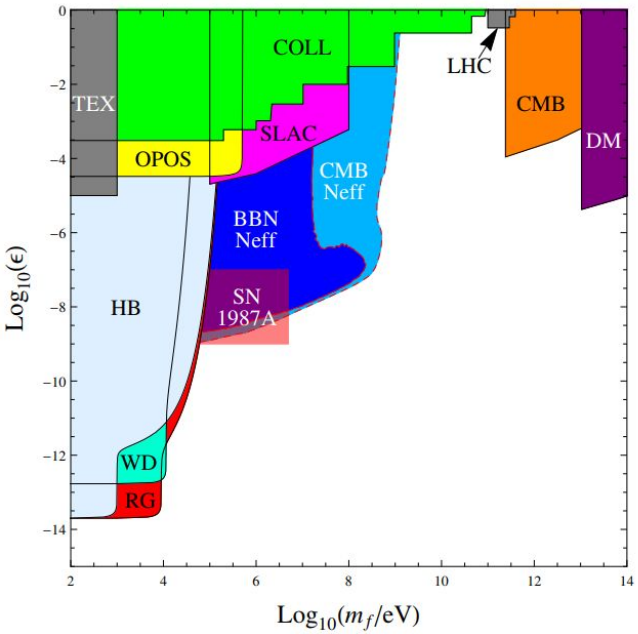
Kinetic mixing

Parameter constrained to be very small. Very small cross sections.

All these probes are in spite of very tiny interactions.

In MTH, kinetic mixing not generated at up to 3-loop — small values can be obtained naturally.

$\Delta\epsilon \sim 10^{-13}$ contribution from *graviton* loops. [Gherghetta, Pospelov, et al. arXiv:1909.00696]



[Vogel, Redondo, arXiv:1311.2600]

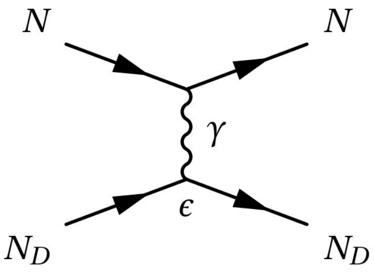
$$\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} \longrightarrow$$

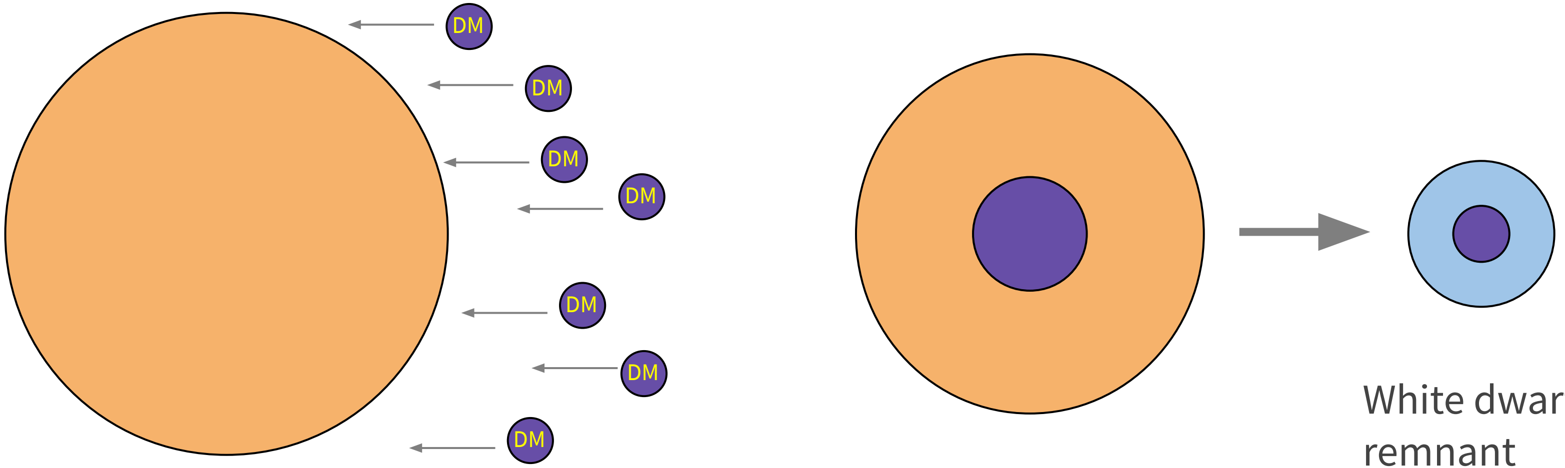
	$U(1)_{SM}$	$U(1)_{mirror}$
SM	1	ϵ
Mirror	0	1

	$U(1)_{SM}$	$U(1)_{mirror}$
SM	1	0
Mirror	ϵ	1

Dark matter capture

Ordinary stars will accumulate atomic dark matter.





White dwarf remnant

Capture calculation

Standard capture calculation:

$$\Omega_+(w,r) = \sum_i n_i(r) w(r)\, \Theta(E_R^{max} - E_R^{min}) \int_{E_R^{min}}^{E_R^{max}} dE_R \frac{d\sigma_i}{dE_R}$$

Integrate over velocity distribution of incoming matter/dark matter and volume of the star.

Incoming particles scatter off *both* the stellar material, and the already-captured material.

Capture cross section cannot exceed GEOMETRIC LIMIT:

$\sigma_{cap} \sim \pi R^2$ where $R = R_{star}$ or R_{nugget}

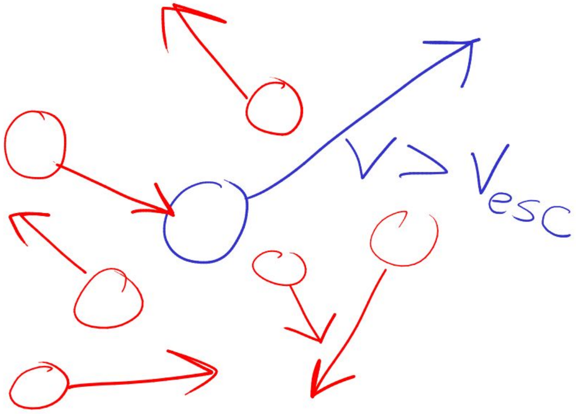
Evaporation

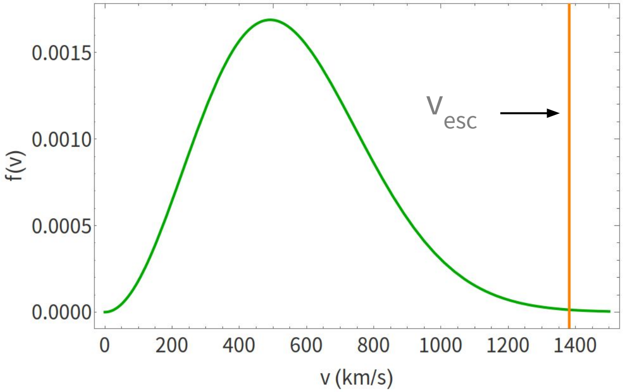
Depending on mass and cross section, captured matter/dark matter can be ejected via evaporation.

Define local evaporation rate $\Omega_{-}(v_{esc}, r)$, has a very sensitive (exponential) dependence on captured mass.

True rate is suppressed by the mean free path of "evaporated" particles through the nugget:

$$\int_{v_{esc}(r)}^{\infty} dv\, n_{cap}(r)\, P_{esc}(v,r)\, \Omega_{-}(v,r)$$

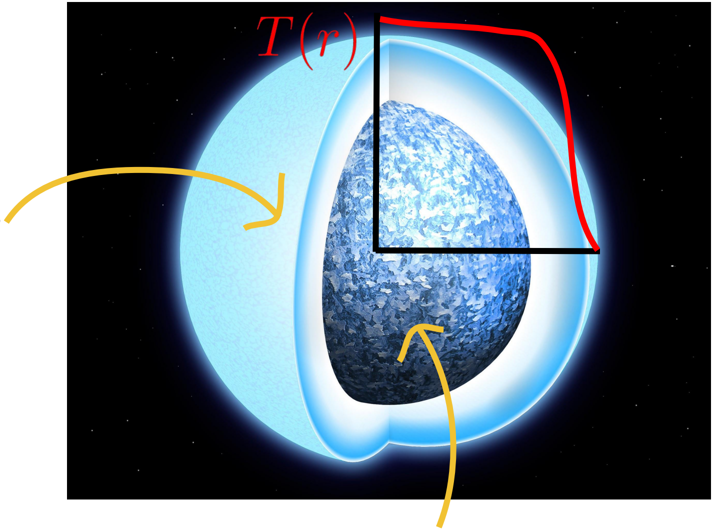




White dwarf cooling

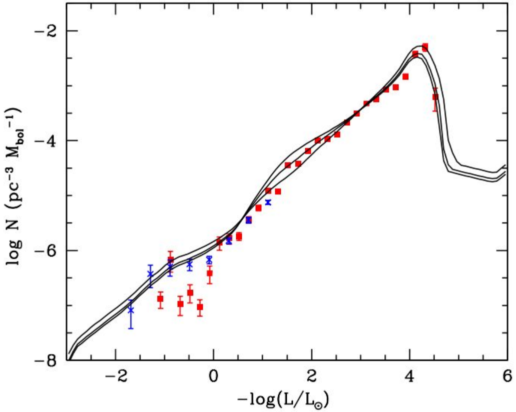
Compared to main sequence stars, white dwarfs are relatively simple astronomical objects.

- No nuclear fusion.
- Slowly radiates away internal thermal energy.
- Cooling rate slows over time.



Insulating “blanket”, high temperature gradient

Degenerate, nearly isothermal core



White dwarf cooling

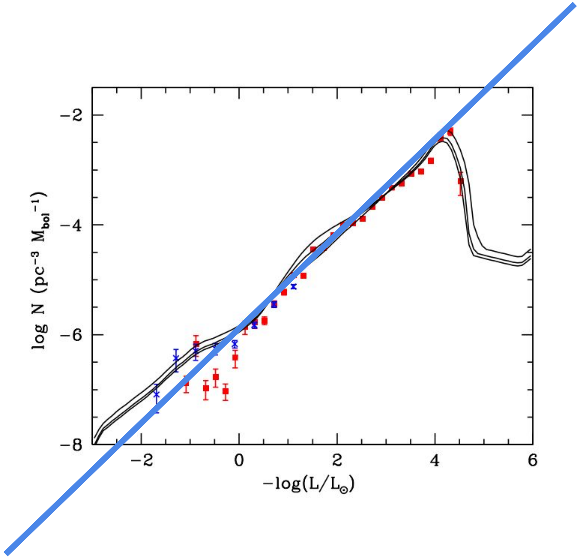
Approximate power-law luminosity function given by Mestel’s law.

$$\frac{dN}{dL} \propto \frac{dt}{dL} = \frac{dt}{dU}\frac{dU}{dL} = -C_{WD}\frac{1}{L}\frac{dT}{dL}$$

$$L \propto T^m \rightarrow \frac{dT}{dL} \propto L^{\frac{1-m}{m}}$$

$$\rightarrow \frac{dN}{dL} \propto -L^{\frac{1-2m}{m}}$$

For white dwarfs,
m = 7/2



Mestel’s law

White dwarf cooling

Approximate power-law luminosity function given by Mestel’s law.

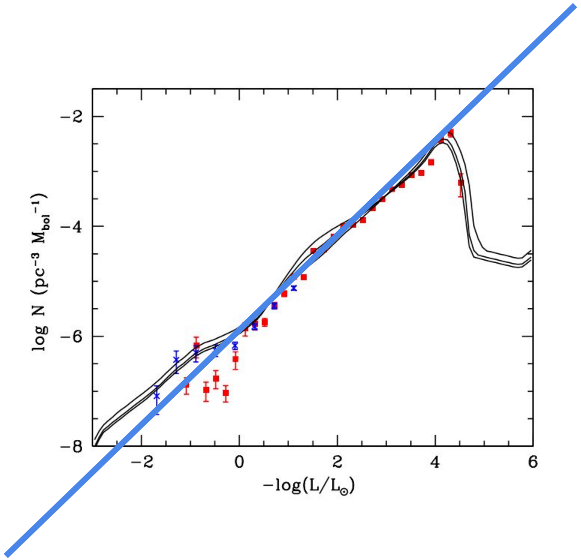
$$\log_{10}\left(\frac{dN}{dM_{\mathrm{bol}}}\right) = A + \frac{2}{7}M_{\mathrm{bol}}$$

$$\downarrow$$

$$\log_{10}\left(\frac{dN}{dM_{\mathrm{bol}}}\right) = A + \frac{2}{7}M_{\mathrm{bol}} + \log_{10}\left(\frac{L_\gamma}{L_\gamma + L_{dark}}\right)$$

White dwarfs also used to constrain e.g. axions, 5th force...

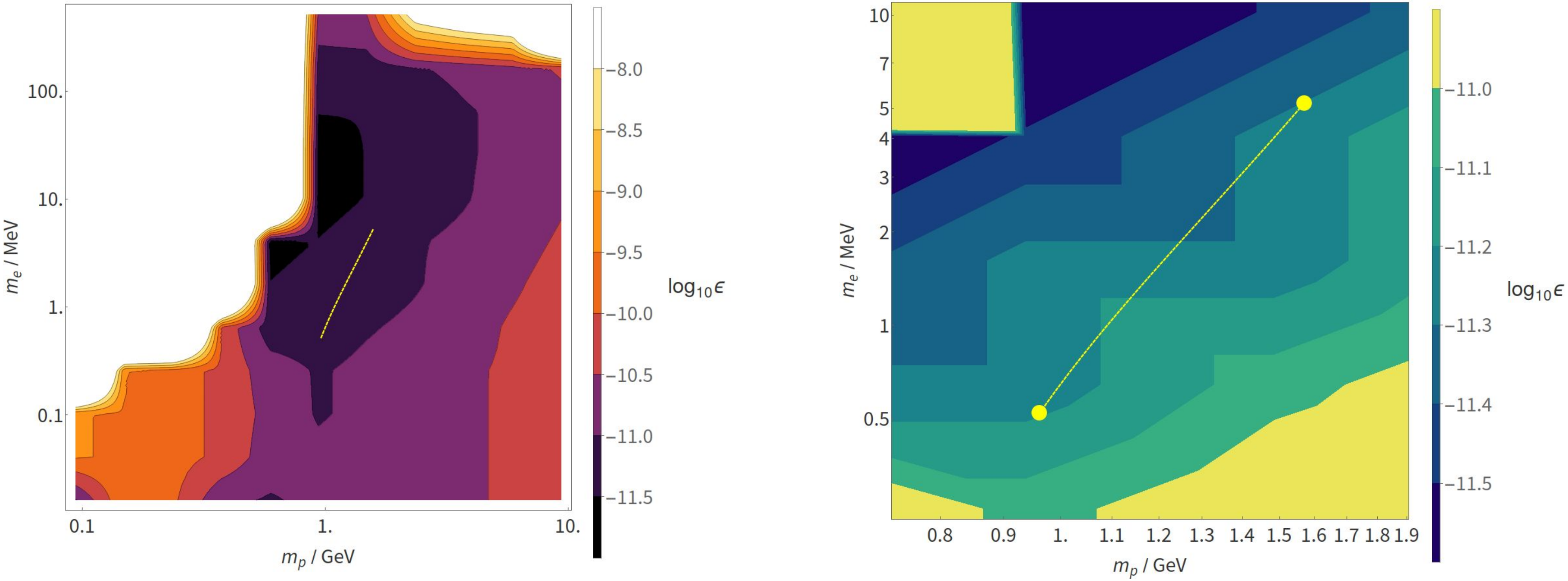
Assume that we can exclude $L_{dark} = L_\gamma$ at low-luminosity tail of the distribution.



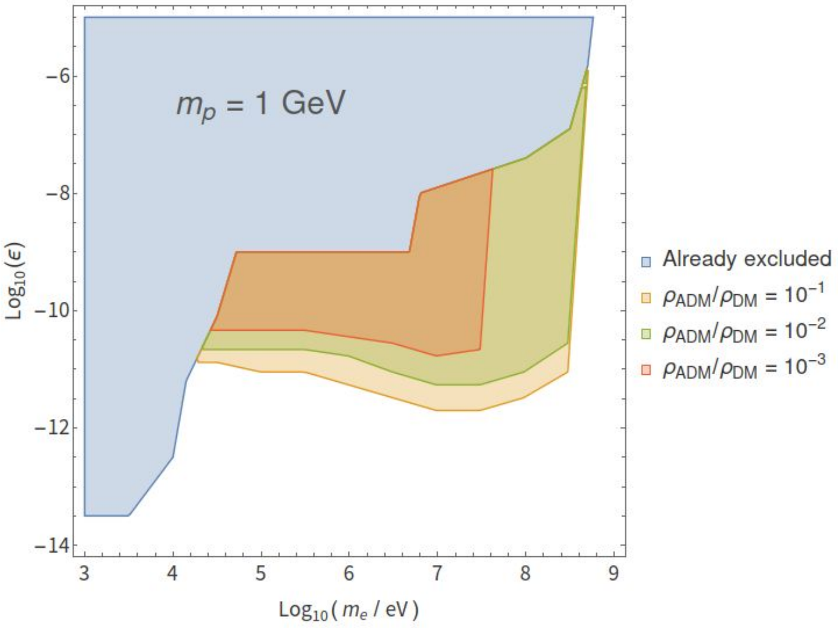
Mestel’s law

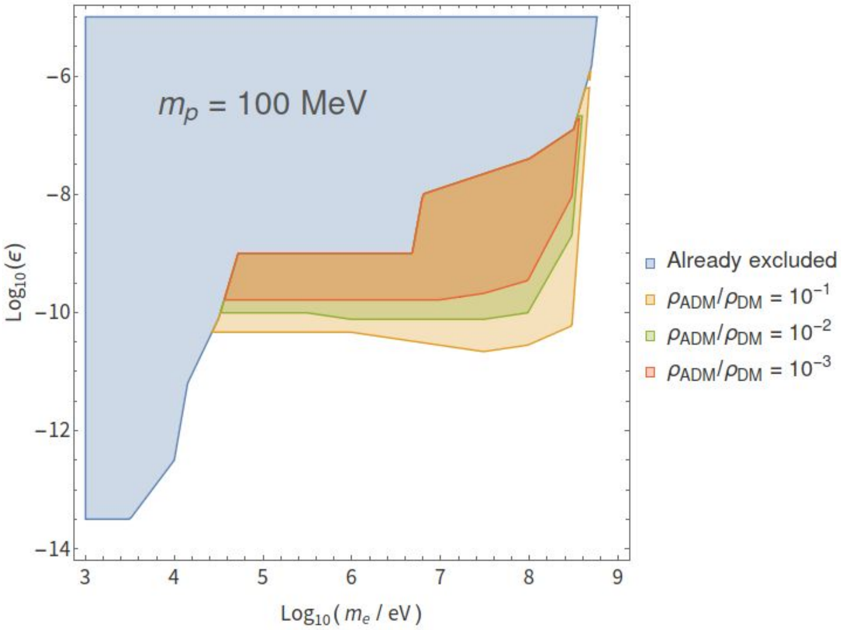
White dwarf constraints

Assuming $\rho_{ADM}/\rho_{DM} = 0.1$, average velocity ~ 220 km/s



White dwarf constraints





Conclusion

- Non-minimal dark sectors well motivated.
- Atomic dark matter interesting possibility — predicted in various models of neutral naturalness.
- Stars capture dissipative / atomic dark matter, which could lead to deviations from predicted stellar physics.
- We use the white dwarf luminosity function to constrain accumulation -> current best constraints on atomic dark matter!