DARK SOLAR WIND

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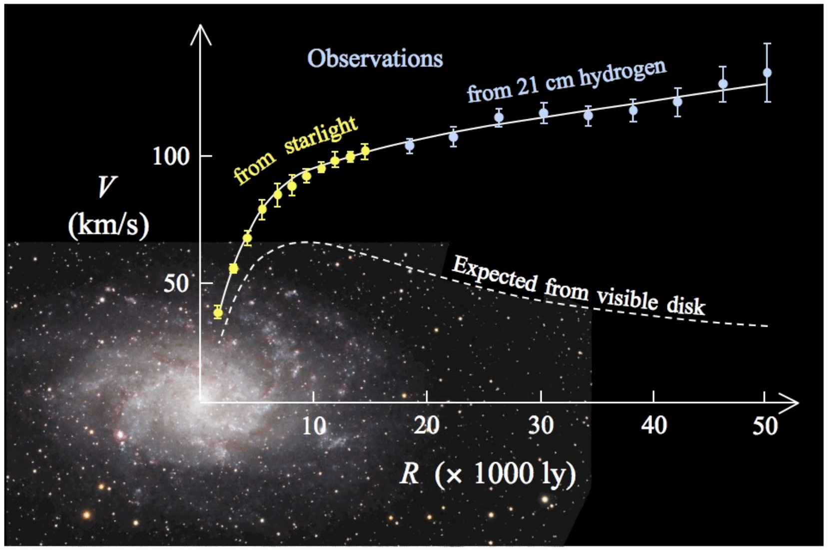
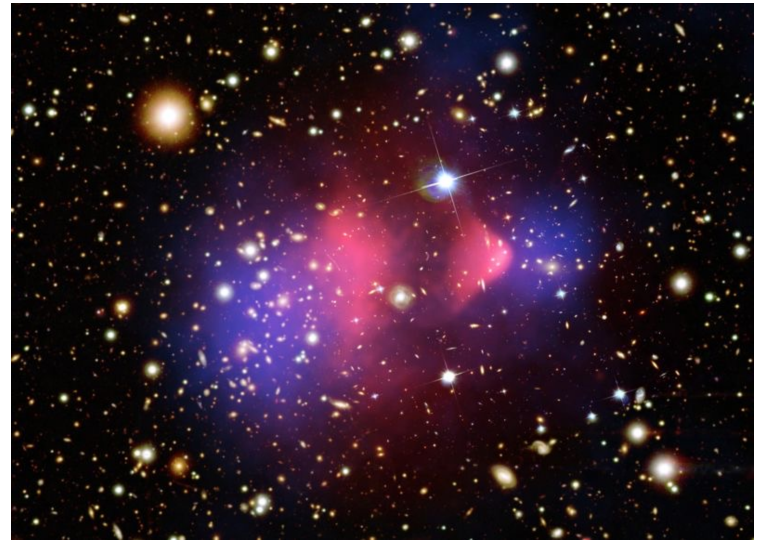
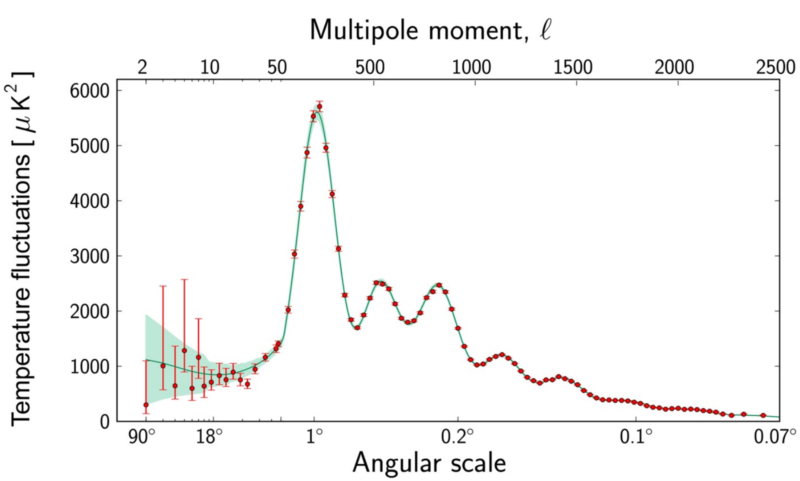
INTRODUCTION

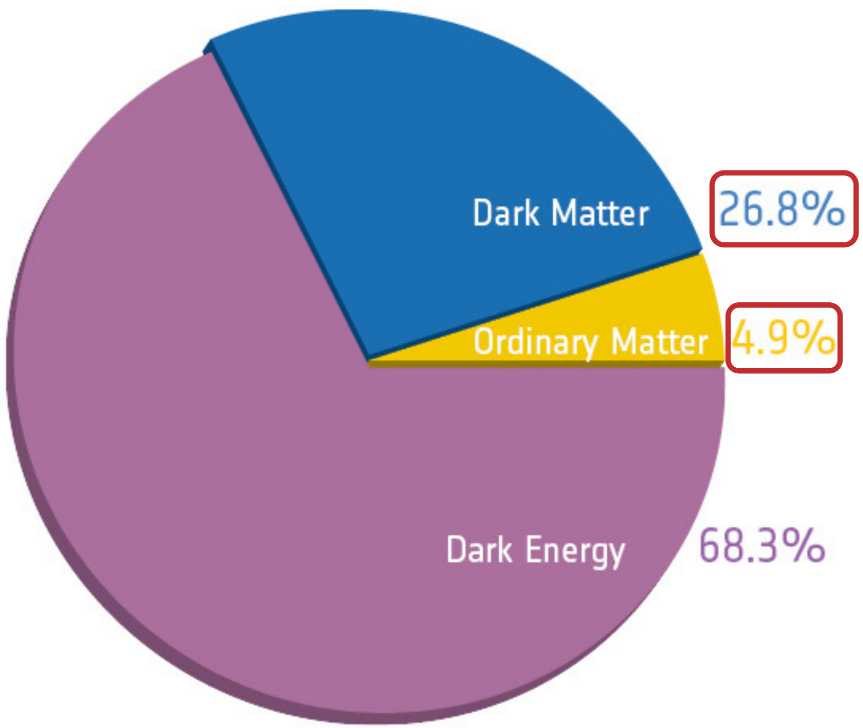
We all know Dark Matter exists







Dark Matter makes up 85% of matter



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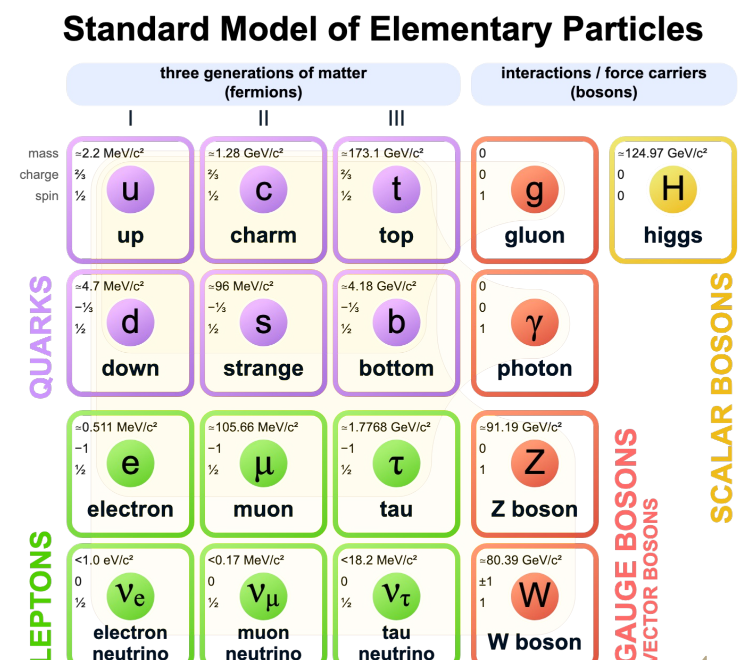
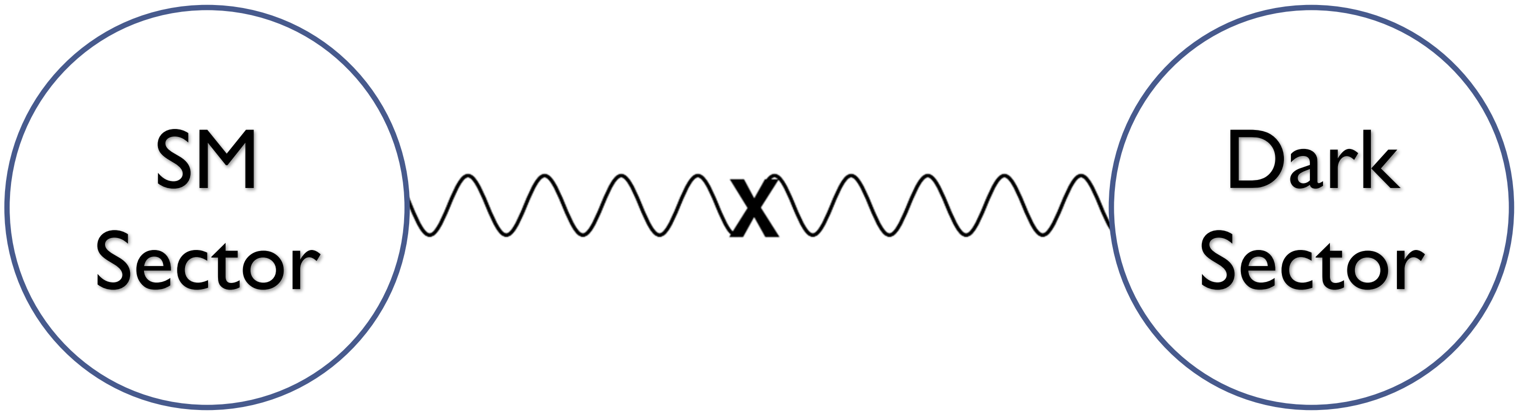


Dark Sectors



$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

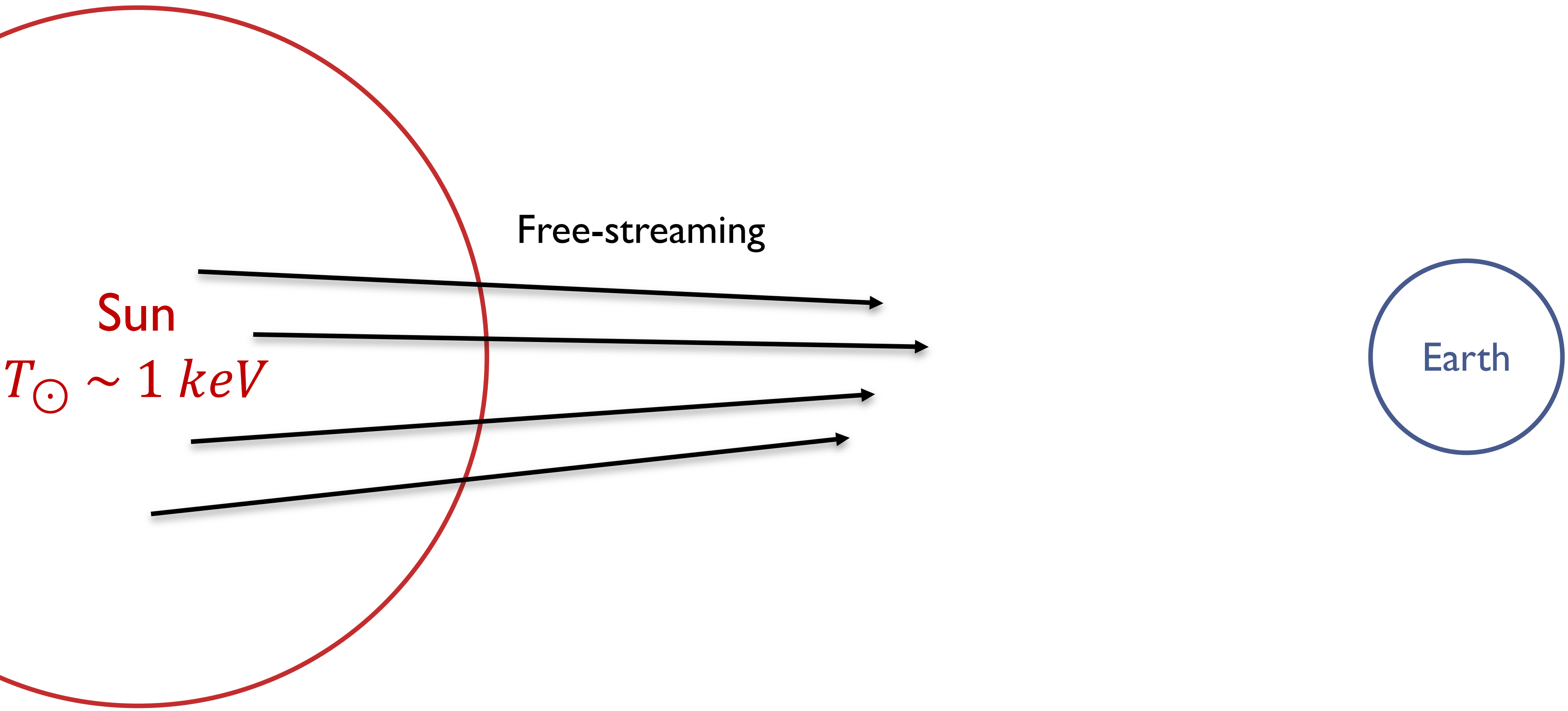
G_{Dark}

- Dark sector has its own gauge group
- Two sectors can be weakly connected through "portal"
- Vector Portal : $\epsilon B^{\mu\nu} F'_{\mu\nu}$

Light Dark Sector Searches

- Need high luminosity to probe
- For $MeV \lesssim m \lesssim GeV$: Beam dump experiments
- For $m \lesssim MeV$: Stellar objects
  - $m \lesssim 10\ MeV$: Supernova
  - $m \lesssim 1\ keV$: Red Giant, Sun

Particle Production from the Sun

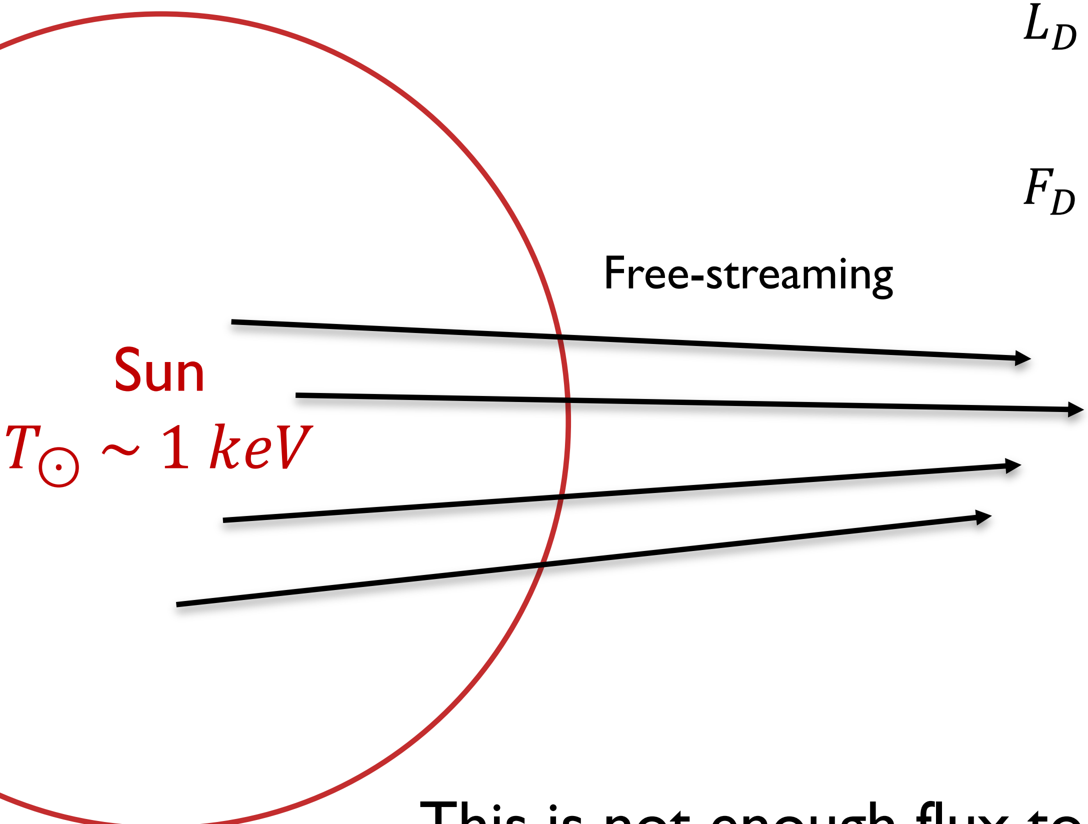


What's the maximum flux at Earth?

Luminosity of dark sector particles is limited by the cooling argument

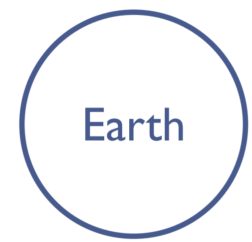
$$L_D < 0.01 L_\odot \sim 4\times 10^{31}\ erg\ s^{-1}$$

$$F_D = \frac{L_D}{4\pi D^2 \langle E \rangle}$$



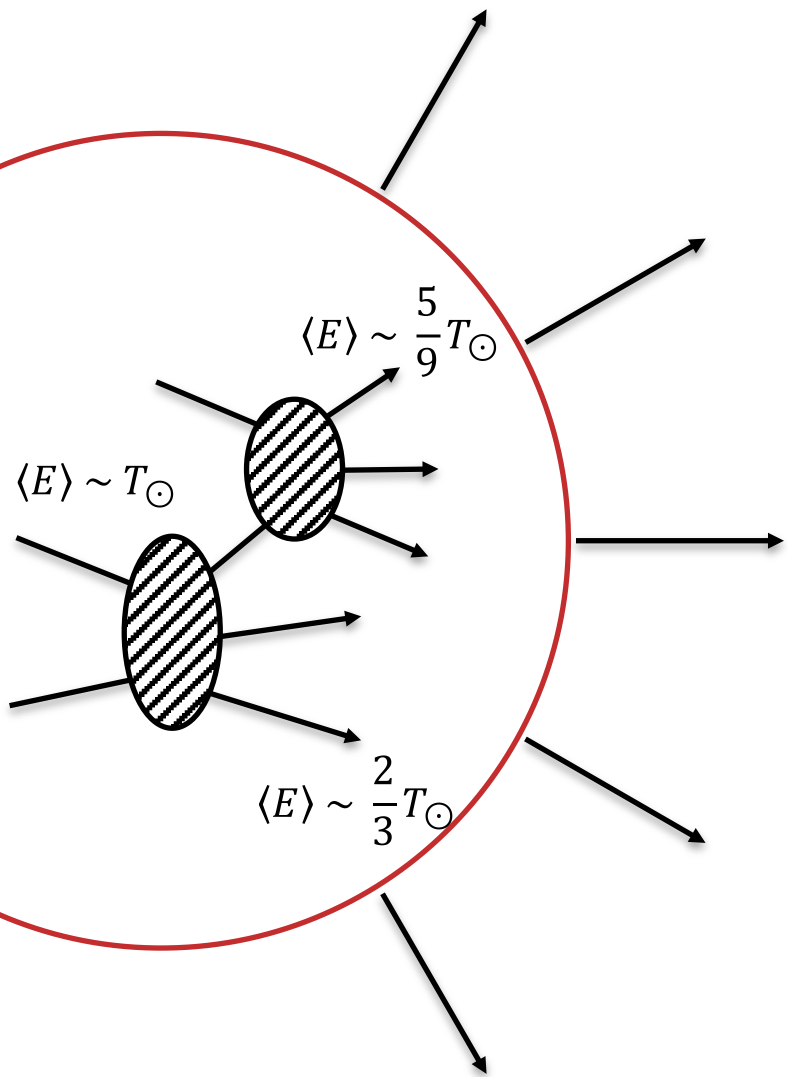
$D = 1\ AU$

$\langle E \rangle \sim T_\odot \sim 1\ keV$



This is not enough flux to detect dark sector particles!

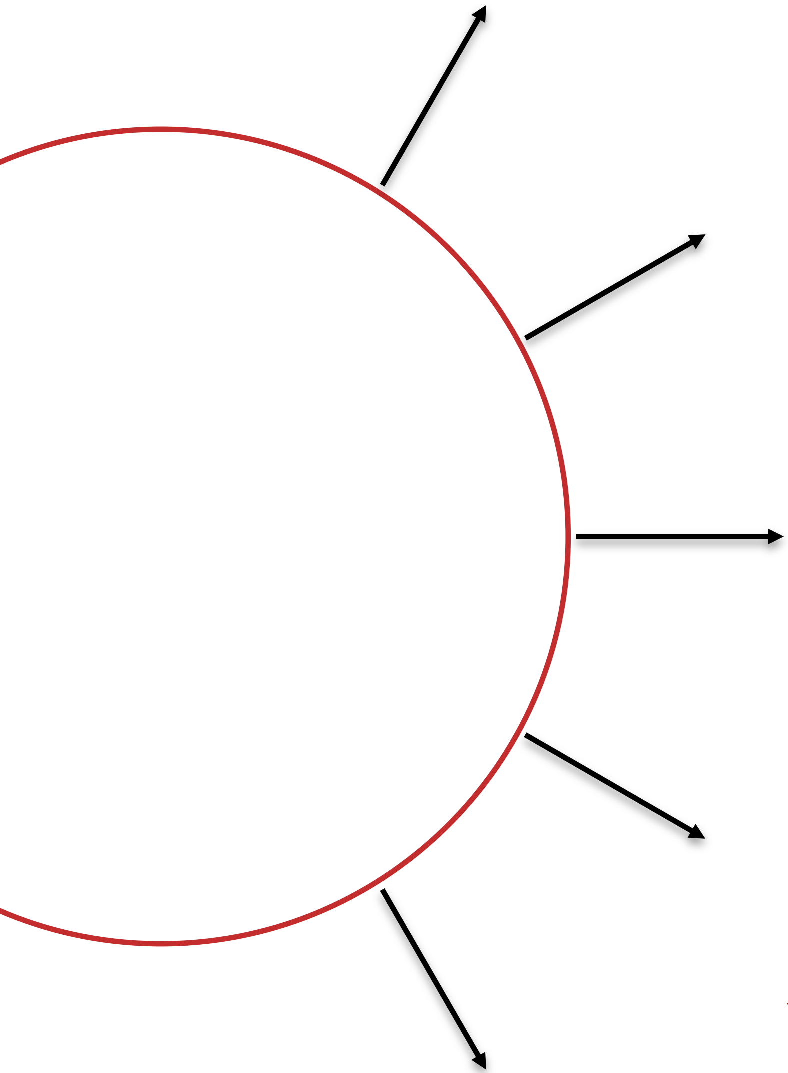
What if we add strong self-interactions?



- Self-thermalized plasma
- Boosted under its pressure
- Relativistic steady outflow

"Dark Solar Wind"

Flux of dark solar wind



$$L_D < 0.01 L_\odot \sim 4\times10^{31}\ erg\ s^{-1}$$

$$F_D = \frac{L_D}{4\pi D^2 \langle E\rangle} \lesssim 10^{13}\ cm^{-2}s^{-1}$$

$D = 1\ AU$

$\langle E\rangle \sim T_\odot \sim 1\ keV$

L_D and D are the same, but

$$\langle E\rangle \sim \left(\frac{L_D}{4\pi r_\odot^2}\right)^{1/4} \lesssim 0.1\ eV$$

$$F_D = \frac{L_D}{4\pi D^2 \langle E\rangle} \lesssim 10^{17}\ cm^{-2}s^{-1}$$

~4 orders of magnitude larger flux with ~4 orders of lower energies

Dark Solar Wind

- Dark sector particles can reach to the Earth in forms of boosted dark plasma

- This predicts 4 orders of magnitude larger flux compared to the free-streaming case

- It encourages new experimental directions

MODEL

Conditions for Dark Solar Wind

- Production from the Sun
  - Coupling between DS and SM exists
  - Should be smaller than the cooling bound
- Self-thermalization
  - Need a number changing process
  - Self-interaction is strong enough
- Relativistic fluid
  - They need to be relativistic even after thermalization
  - Mass should be light enough

A Millicharged Particle Model

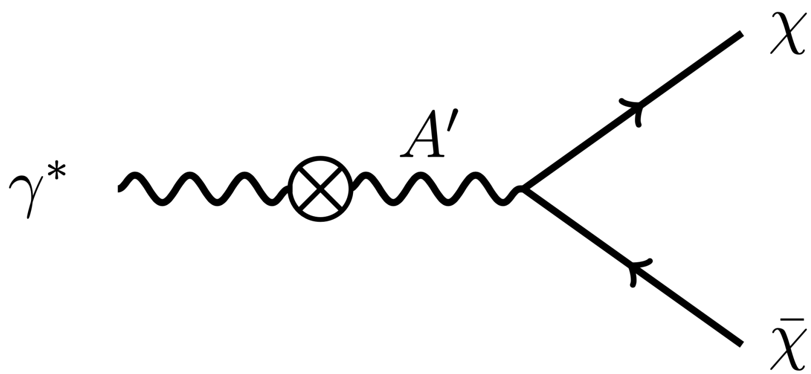
$$\mathcal{L}_D = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \bar{\chi}\left(i\gamma^\mu\partial_\mu + g_D\gamma^\mu A'_\mu - m_\chi\right)\chi$$

- Dark Photon A'_μ : A gauge boson of $U(1)_D$
- Millicharged Particle χ (MCP) : A fermion charged under $U(1)_D$
- Three model parameters : $m_\chi,\ \epsilon,\ \alpha_D = \frac{g_D^2}{4\pi}$

Relativistic Fluid

- We assume MCP is effectively massless
- We'll come back to massive cases later
- Remaining parameters are ϵ and α_D

Production from the Sun



- In the core of the Sun, photon gets a thermal mass

$$m_\gamma \sim \omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}}$$

- Plasmon decays to MCP, and this is the dominant production mechanism for small mass MCP

- Production rate $\Gamma_{\gamma^* \to \chi\bar{\chi}} = \epsilon^2 \alpha_D \frac{\omega_T^2 - k^2}{3\omega_T}$

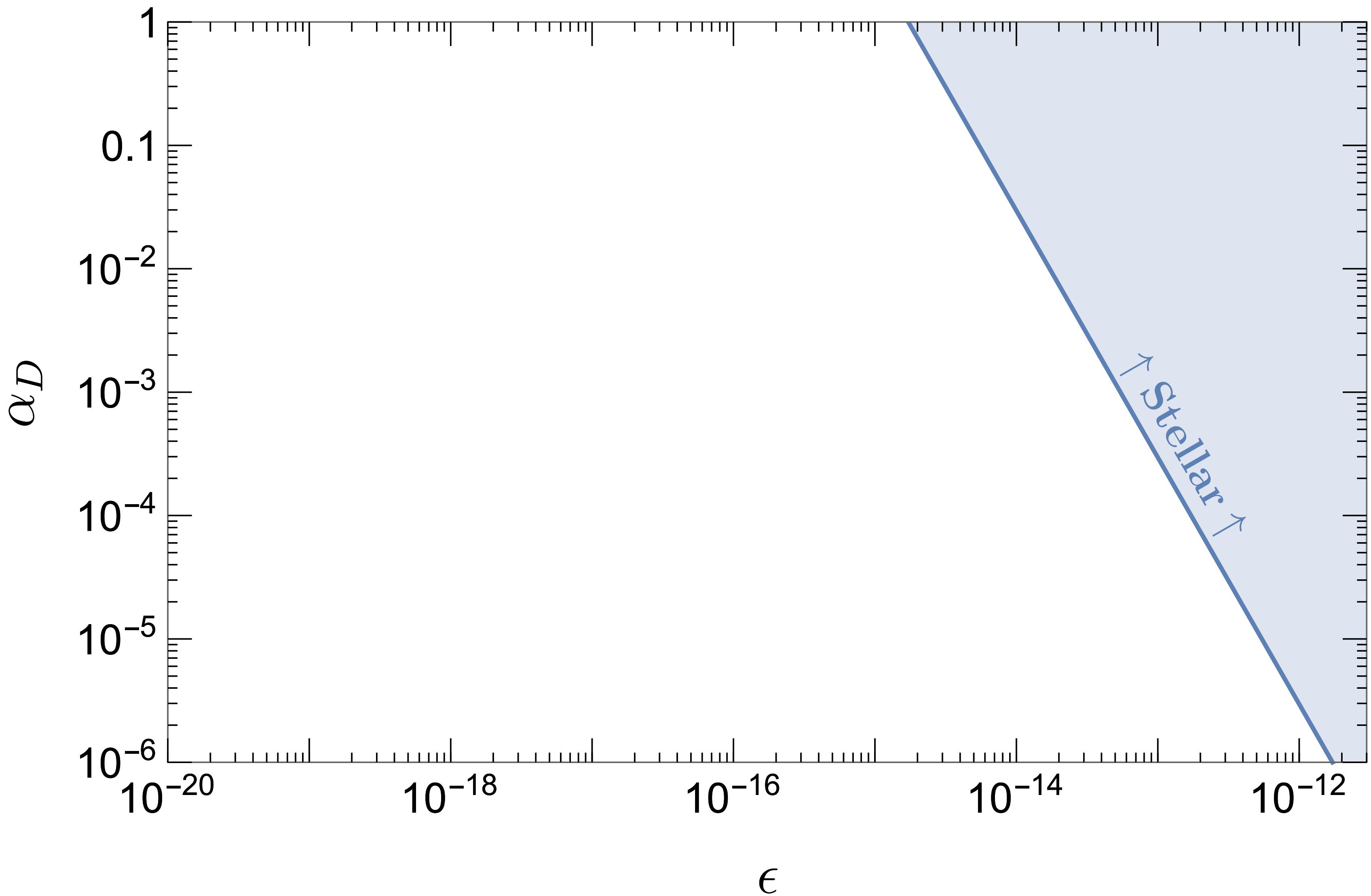
Stellar Cooling Bound

- Most stringent constraints for small mass MCP come from red giants

- Extra cooling delays helium ignition and makes red giants brighter than expected

- $\epsilon \alpha_D^{1/2} < 2 \times 10^{-15}$

Parameter Space



Self-thermalization

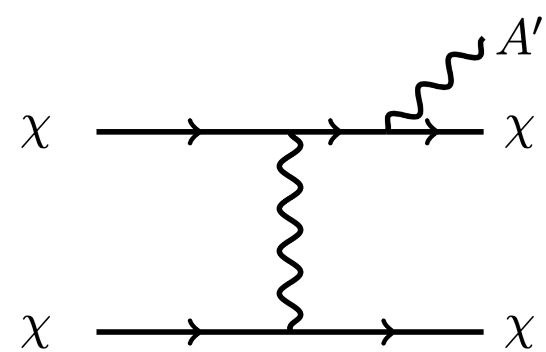
- Well-studied in reheating scenarios

- Number changing processes play most important role for thermalization

- In our case, soft bremsstrahlung of dark photon is most relevant process

- Need $\Gamma_{2\to3} > r_{\rm core}^{-1}$

- $\epsilon\alpha_D^{5/2} > 2\times10^{-26}$



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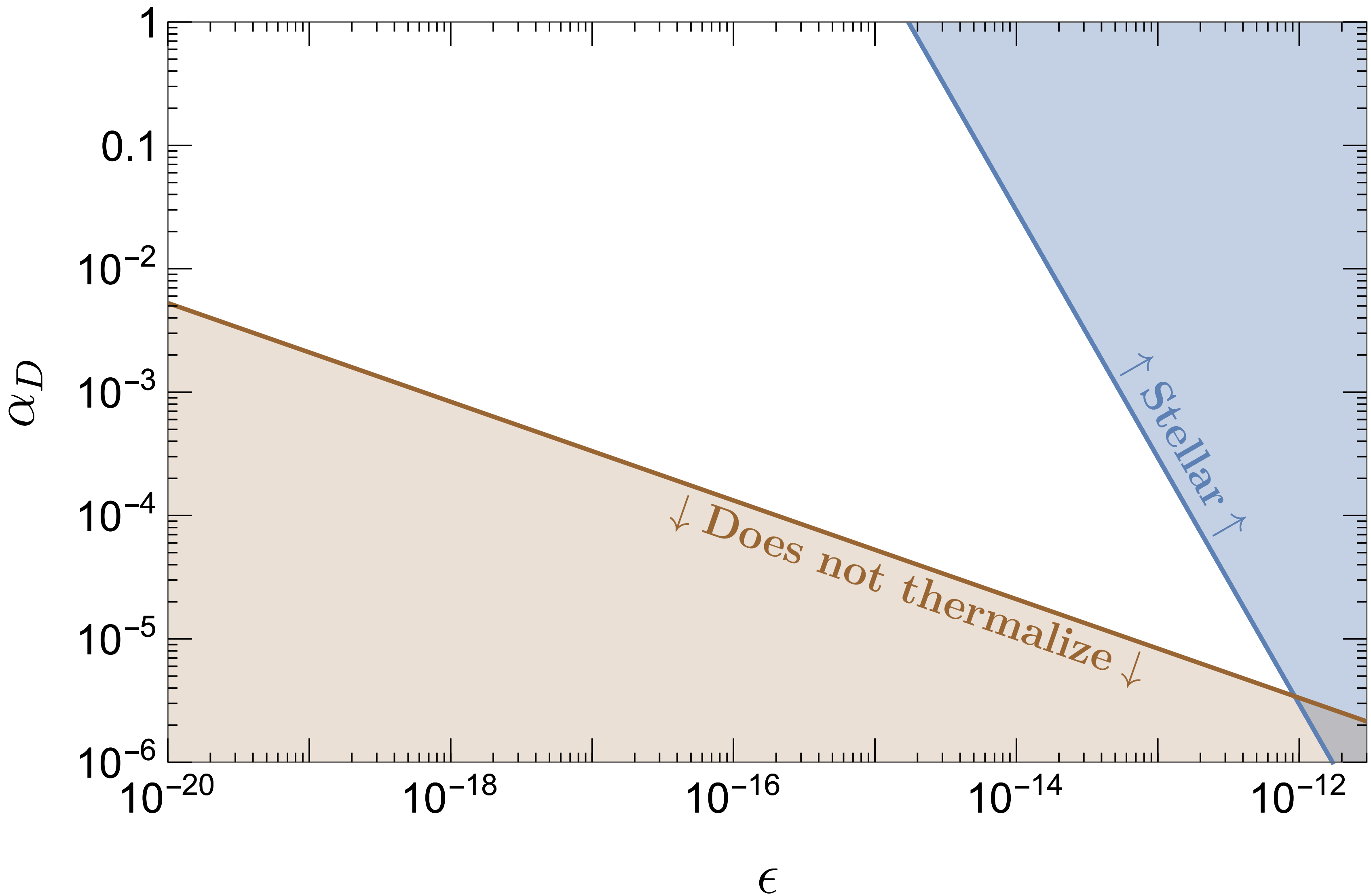


DARK SOLAR WIND

Perfect Dark Fluid

- MCPs and dark photons are fully thermalized

- Mean free path is small enough so we can assume a perfect fluid

$$T^{\mu\nu} = (\tilde{\rho} + \tilde{p})u^\mu u^\nu - \tilde{p} g^{\mu\nu}$$

  - $\tilde{\rho} = a\tilde{T}^4, \tilde{T}$ is the comoving temperature, $a = \frac{\pi^2}{30}\left(2 + \frac{7}{8} \times 4\right)$
  - $\tilde{p} = \frac{1}{3}\tilde{\rho}$
  - $u^\mu = \gamma(1, \vec{v}), \quad \gamma = (1 - v^2)^{-1/2}$
  - $g^{\mu\nu} = g_{\mu\nu} = \mathrm{diag}(1, -1, -r^2, -r^2 \sin^2\theta)$

- The properties of dark fluid are completely determined by two parameters, $\tilde{T}$ and v

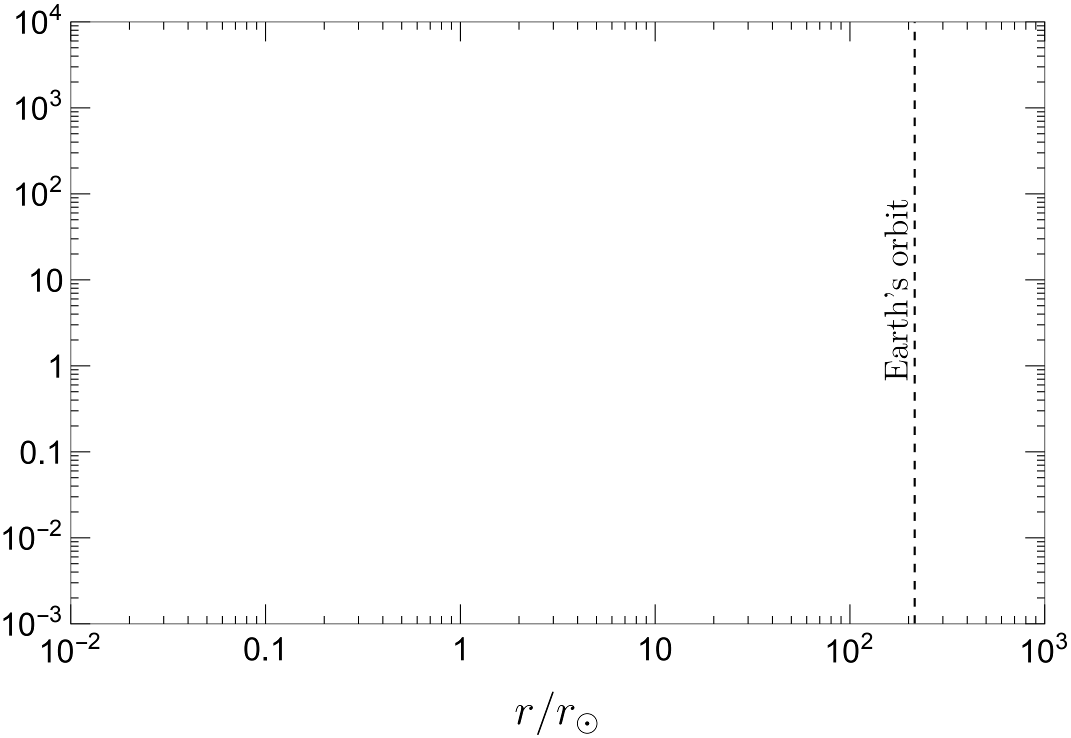
Continuity Equations

$$\partial_\mu T^{\mu\nu} = \sigma^\nu$$

- $\sigma^\nu = (\dot{Q}, 0,0,0)$, $\dot{Q} \propto \epsilon^2 \alpha_D$ is power per unit volume

- This gives 2 master equations:
  - $a\tilde{T}^4 = \frac{\int_0^r r'^2 \dot{Q}(r') dr'}{r^2 \gamma^2 v}$
  - $\frac{\partial \ln v}{\partial \ln r} = \frac{1/3 + v^2}{1/3 - v^2}\left(f(r) - \frac{2(1-v^2)}{1+3v^2} \right)$, $f(r) = \frac{r^3 \dot{Q}(r')}{\int_0^r r'^2 \dot{Q}(r') dr'}$

Dark Fluid Profiles



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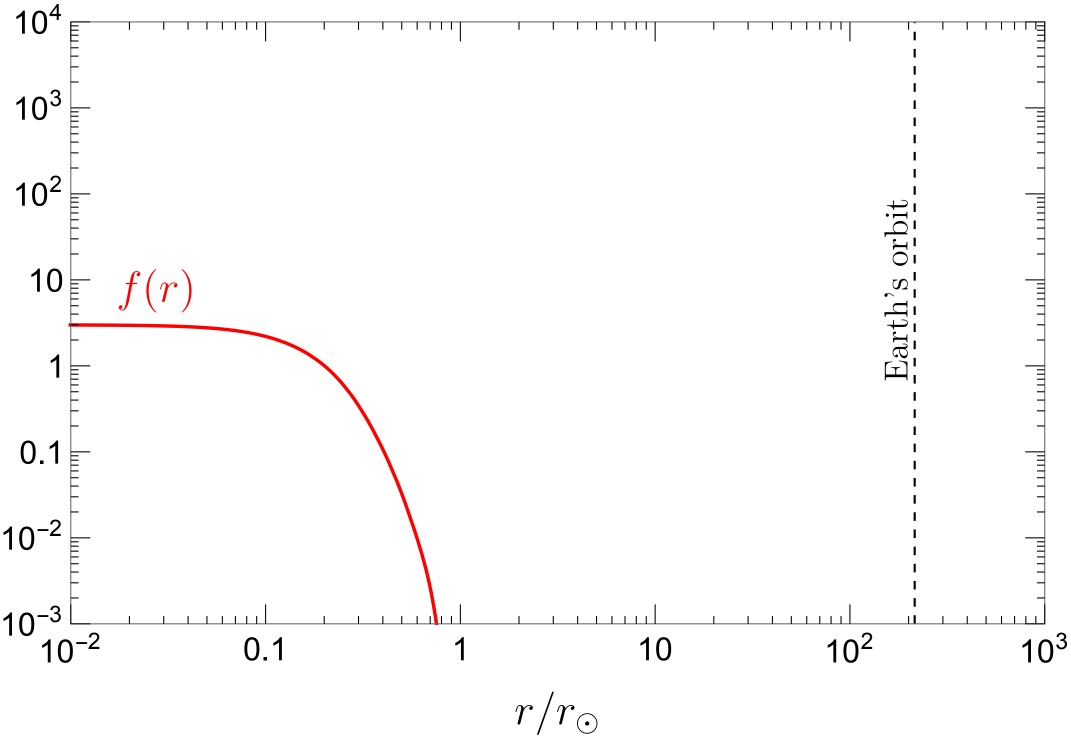

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- The equation blows up at $v = \sqrt{1/3}$
- At the sonic point, RHS needs to be 0 ($f(r) = 2/3$)

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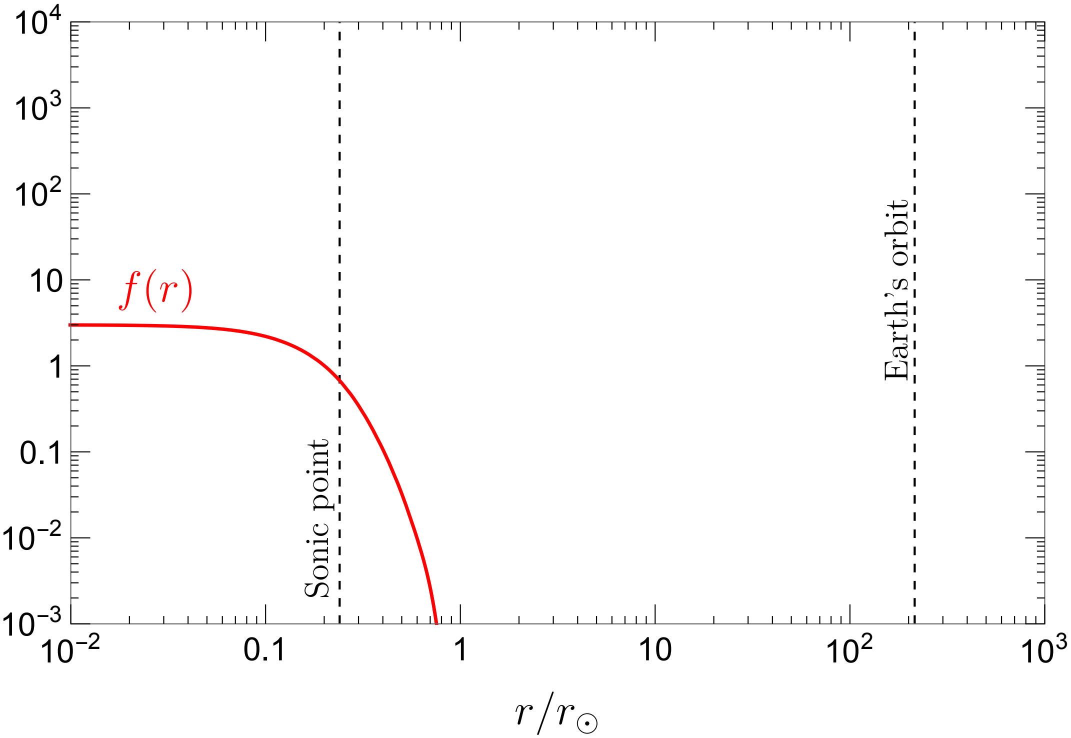

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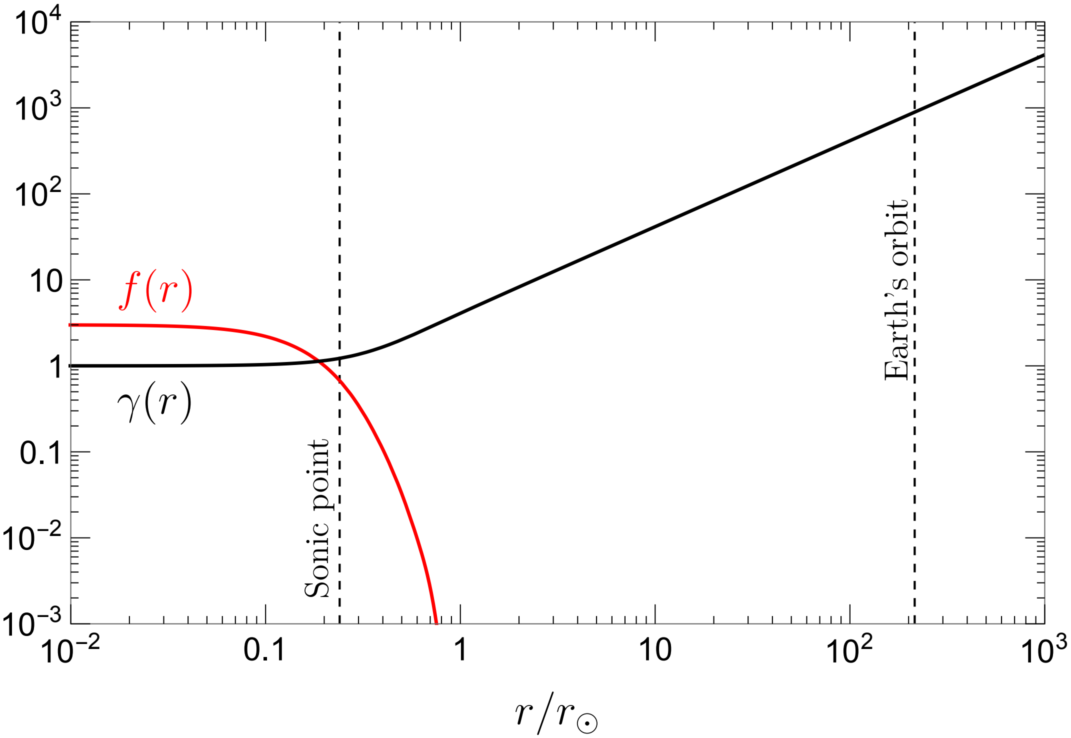

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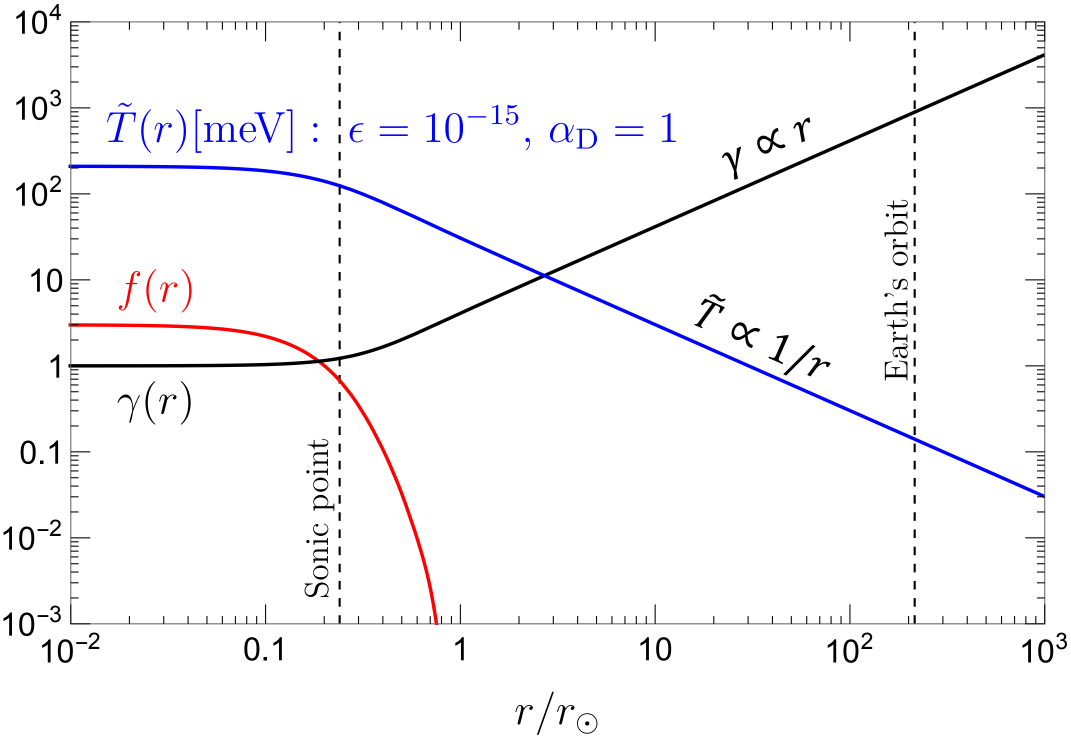
- We can get $\tilde{T}(r)$

Dark Fluid Profiles



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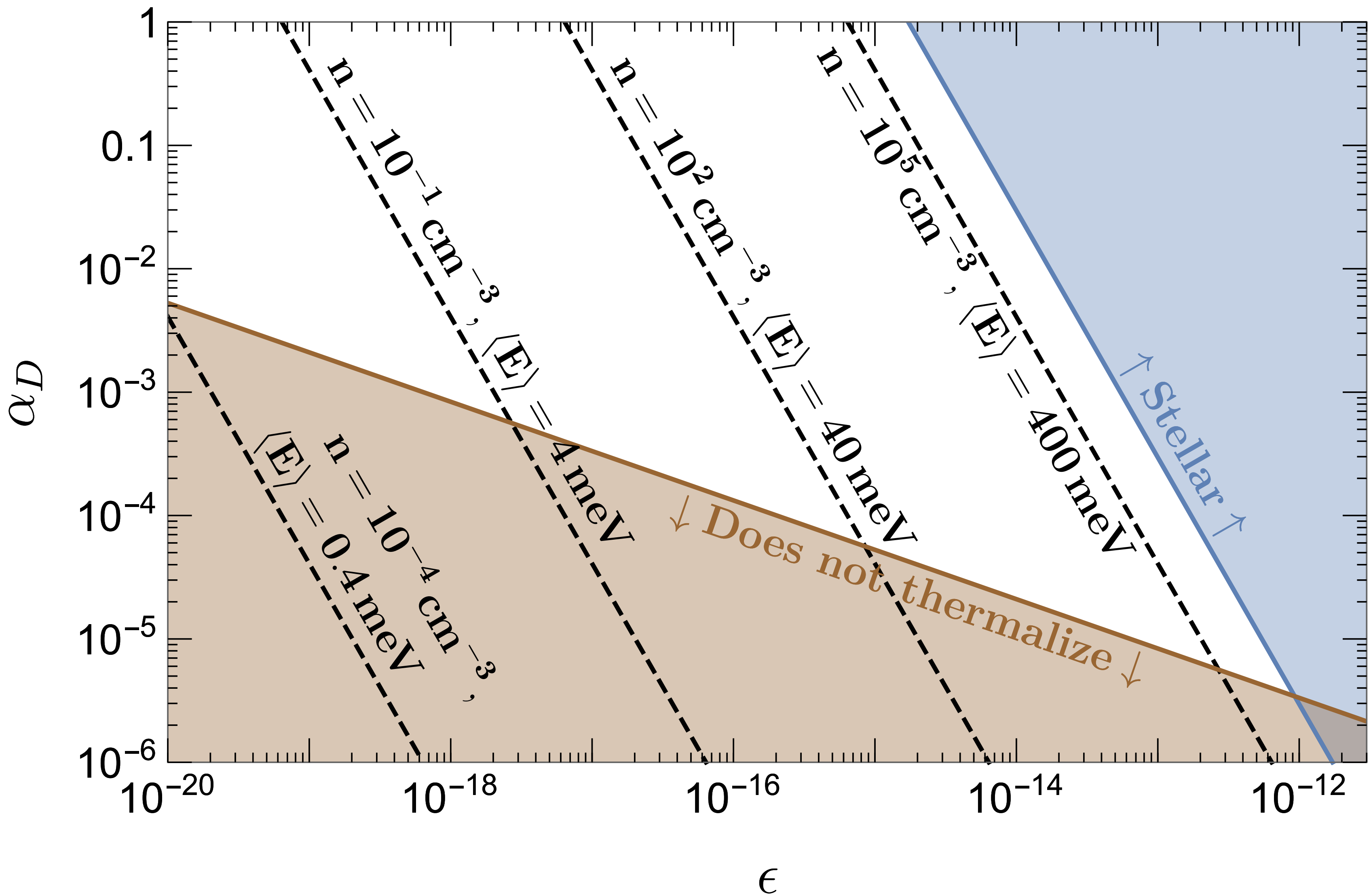
Similar to Parker's solar wind,
but asymptotes to the fireball solution

$$\langle E \rangle \sim \gamma \tilde{T} \sim \mathrm{const}$$
$$n \sim \gamma \tilde{T}^3 \sim 1/r^2$$

Dark Fluid Profiles near the Earth

- $\gamma \approx 893\left(\frac{r}{1\ \mathrm{AU}}\right)$
- $\tilde{T} \approx 0.14\ meV\ \left(\frac{\epsilon}{10^{-15}}\right)^{1/2}\left(\frac{\alpha_D}{1}\right)^{1/4}\left(\frac{1\ \mathrm{AU}}{r}\right)$
- $\langle E\rangle \sim \gamma\tilde{T} \sim 0.5\ eV\ \left(\frac{\epsilon}{10^{-15}}\right)^{1/2}\left(\frac{\alpha_D}{1}\right)^{1/4}$
- $n \sim \gamma\tilde{T}^3 \sim \frac{2\times10^5}{cm^3}\left(\frac{\epsilon}{10^{-15}}\right)^{3/2}\left(\frac{\alpha_D}{1}\right)^{3/4}\left(\frac{1\ \mathrm{AU}}{r}\right)^2$

Parameter Space



CONCLUSIONS

Conclusions

- Dark sector particles can be produced from the Sun
- If they have strong self-interactions, they thermalize and form dark solar wind
- Dark solar wind leads unique phenomenological signatures near the Earth
- Predicts higher flux but smaller energy compared to the free-streaming case
- Dark solar wind encourages new experimental directions

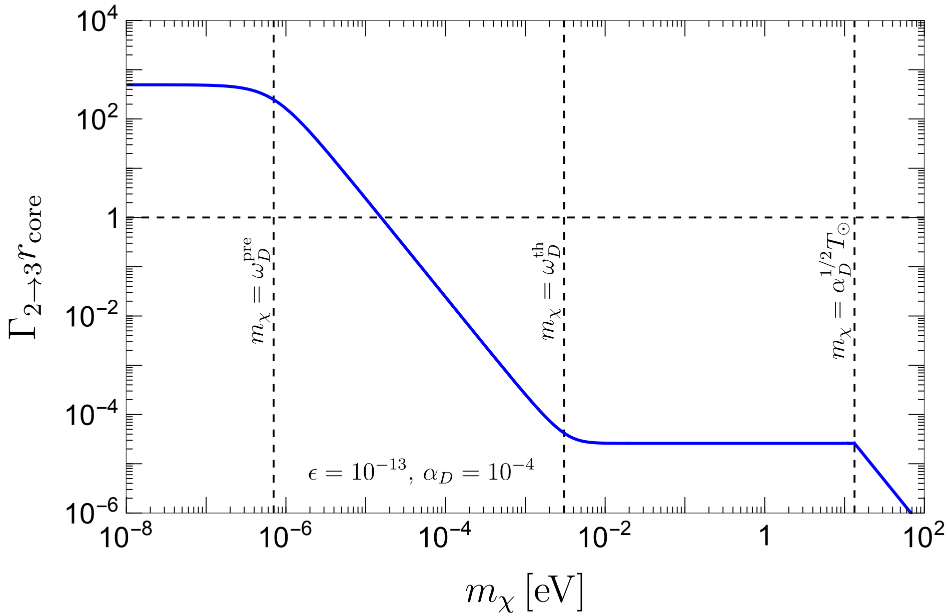
THANK YOU

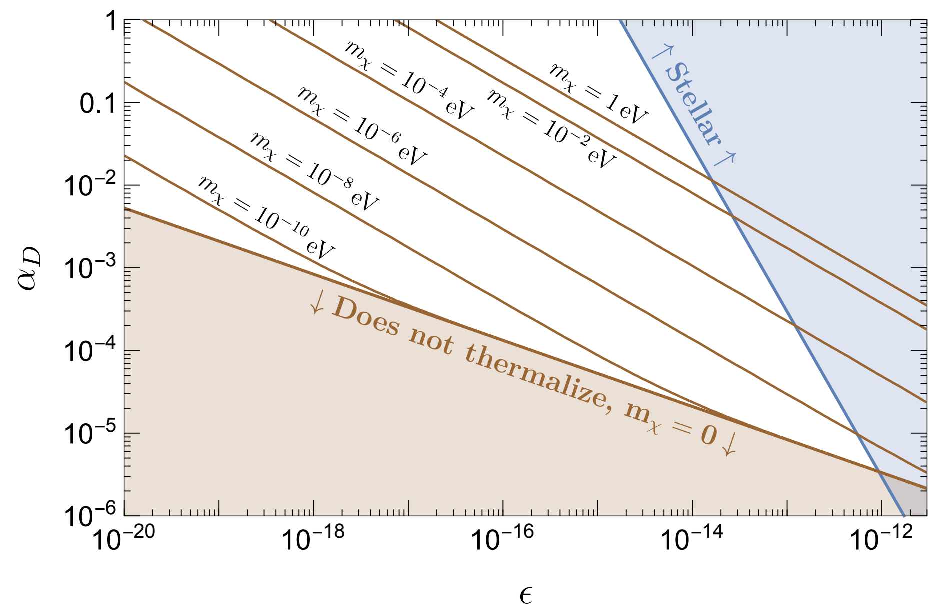
BACK UP

Future Works

- Detection Sensitivities
- Other models
- Other astrophysical objects

Massive Cases





- Thermalization condition changes
- Profiles remain the same as long as dark sector particles are fully thermalized inside the Sun ($m < \tilde{T}(r_\odot)$)

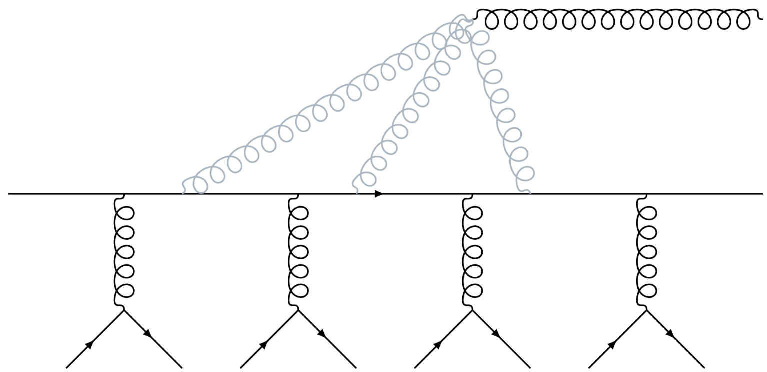
Self-thermalization

- MCP produced from plasmon decay has
  - $E_{\text{hard}} \sim T_{\odot} \sim 1\ keV$
  - $n_{\text{hard}} \sim \dot{n}_c r_{\text{core}}$
  - $\omega_D \sim \left(\frac{\alpha_D n_{\text{hard}}}{E_{\text{hard}}}\right)^{1/2}$

- Naïve expectation for $\Gamma_{2\to3}$

$$\Gamma_{2\to3} \sim \alpha_D \Gamma_{2\to2}^{\text{soft}} \sim \alpha_D n_{\text{hard}} \langle \sigma v \rangle \sim \frac{\alpha_D^3 n_{\text{hard}}}{\omega_D^2}$$

Landau–Pomeranchuk–Migdal (LPM) Effect



Garny et al, 1810.01428

- $\Gamma_{2\to3} \sim \alpha_D \min[\Gamma_{2\to2}^{\text{soft}}, t_{\text{form}}^{-1}]$
- $t_{\text{form}}^{-1} \sim \alpha_D^{1/2}\omega_D$, always smaller in our case
- $\Gamma_{2\to3} \sim \alpha_D^{3/2}\omega_D > r_{\text{core}}^{-1}$
- $\epsilon\alpha_D^{5/2} > 2\times10^{-26}$