DARK SOLAR WIND

Based on arXiv:2205.11527 with:

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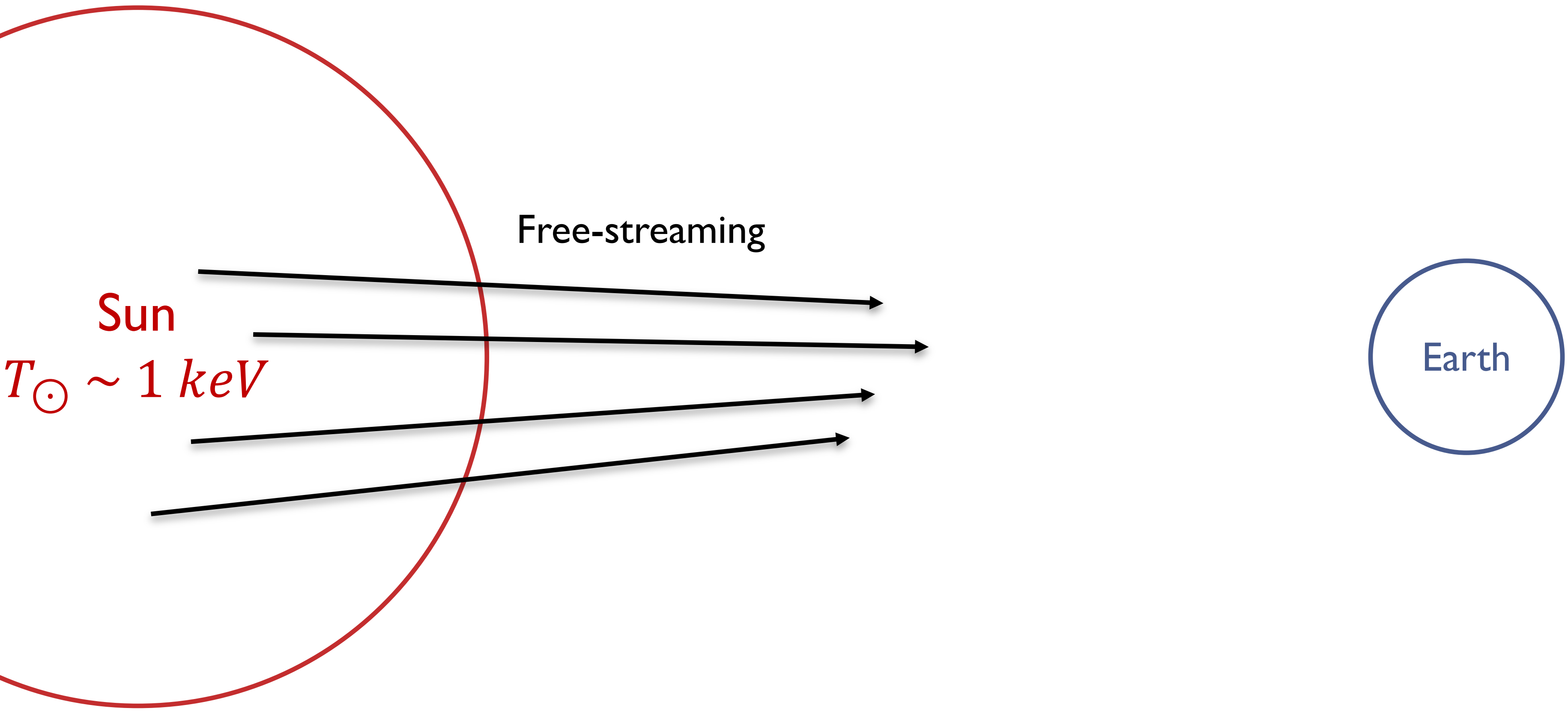
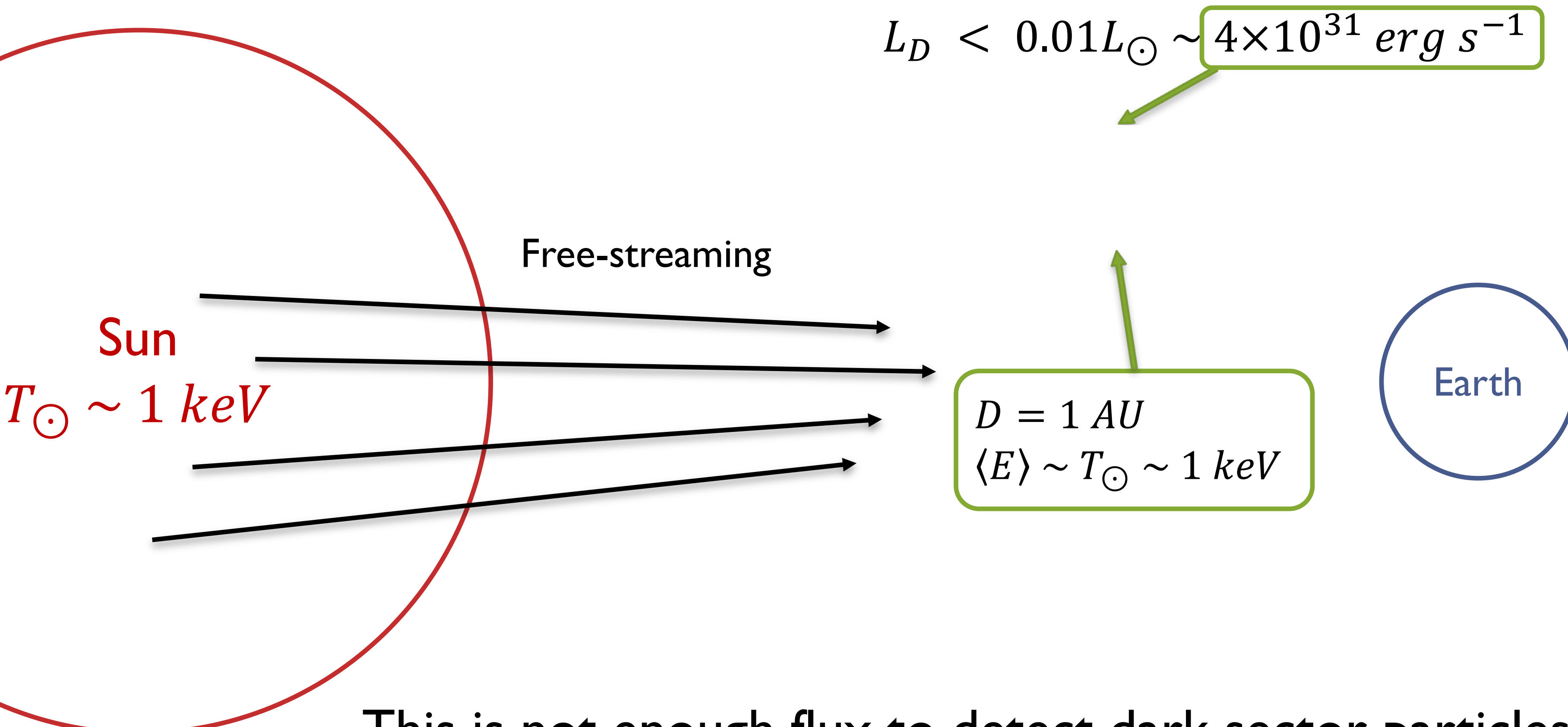
08/19/2022 Dark Matter in Compact Objects, Stars, and in Low Energy Experiments

Particle Production from the Sun



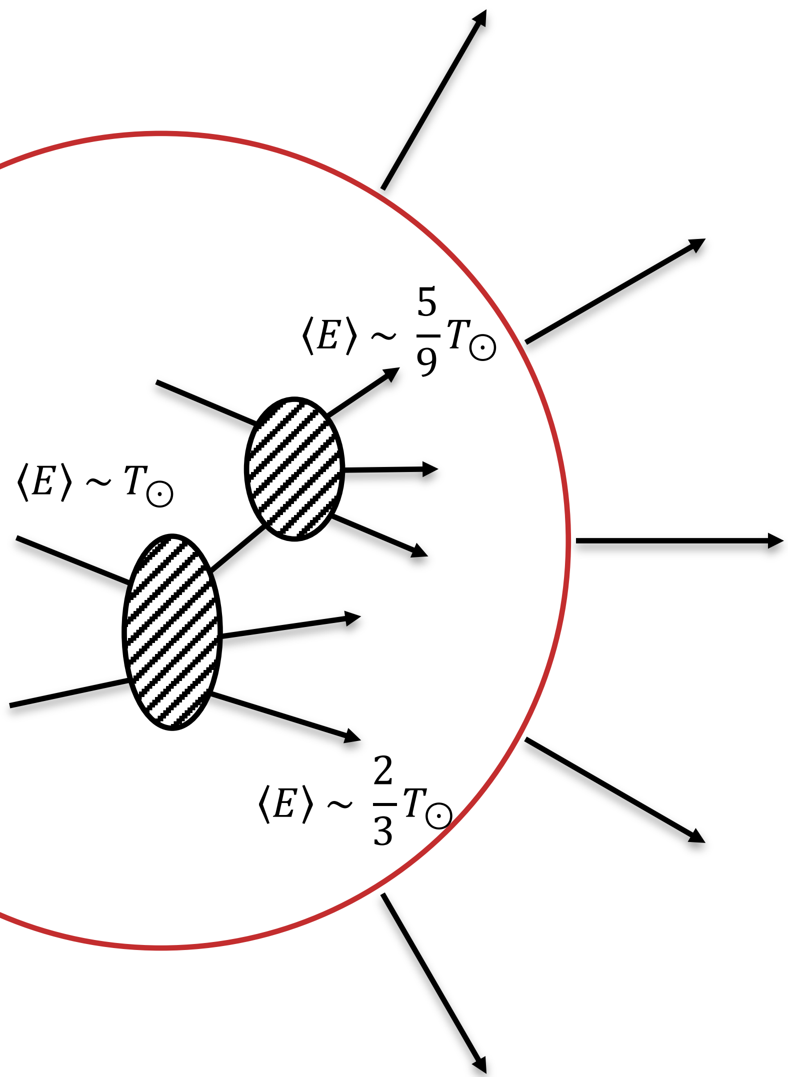
What's the maximum flux at Earth?

Luminosity of dark sector particles is limited by the cooling argument



This is not enough flux to detect dark sector particles!

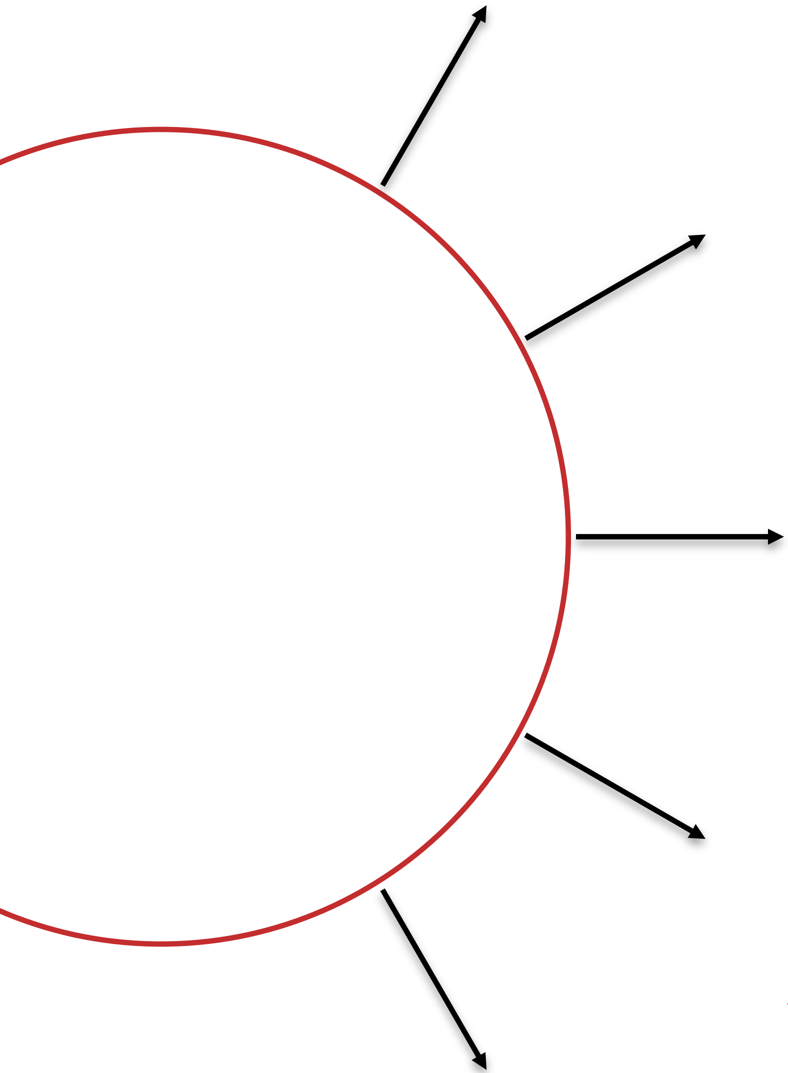
What if we add strong self-interactions?



- 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

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

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

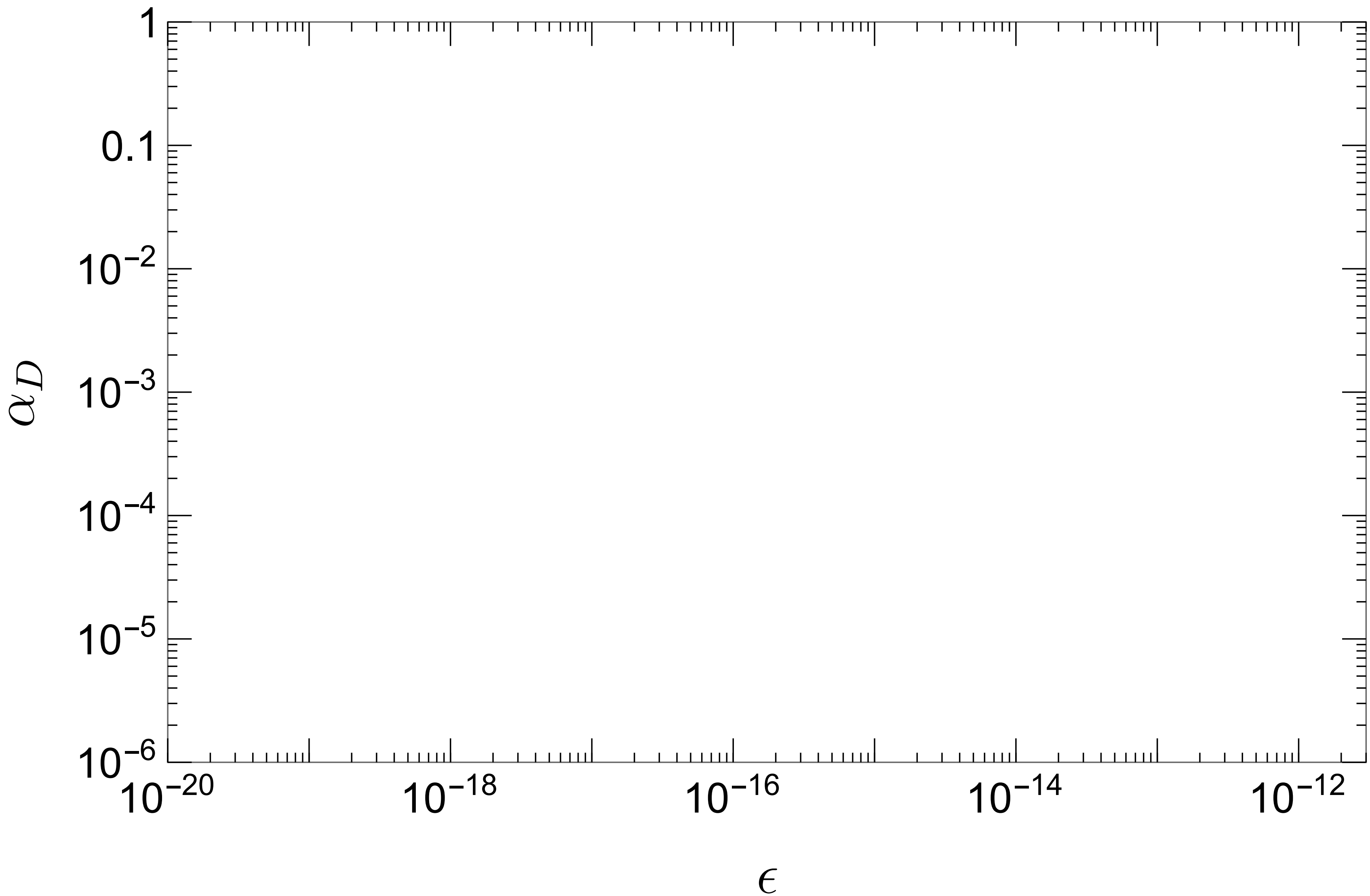
~4 orders of magnitude larger flux with ~4 orders of lower energies

Model : Millicharged particles

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

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

Parameter Space



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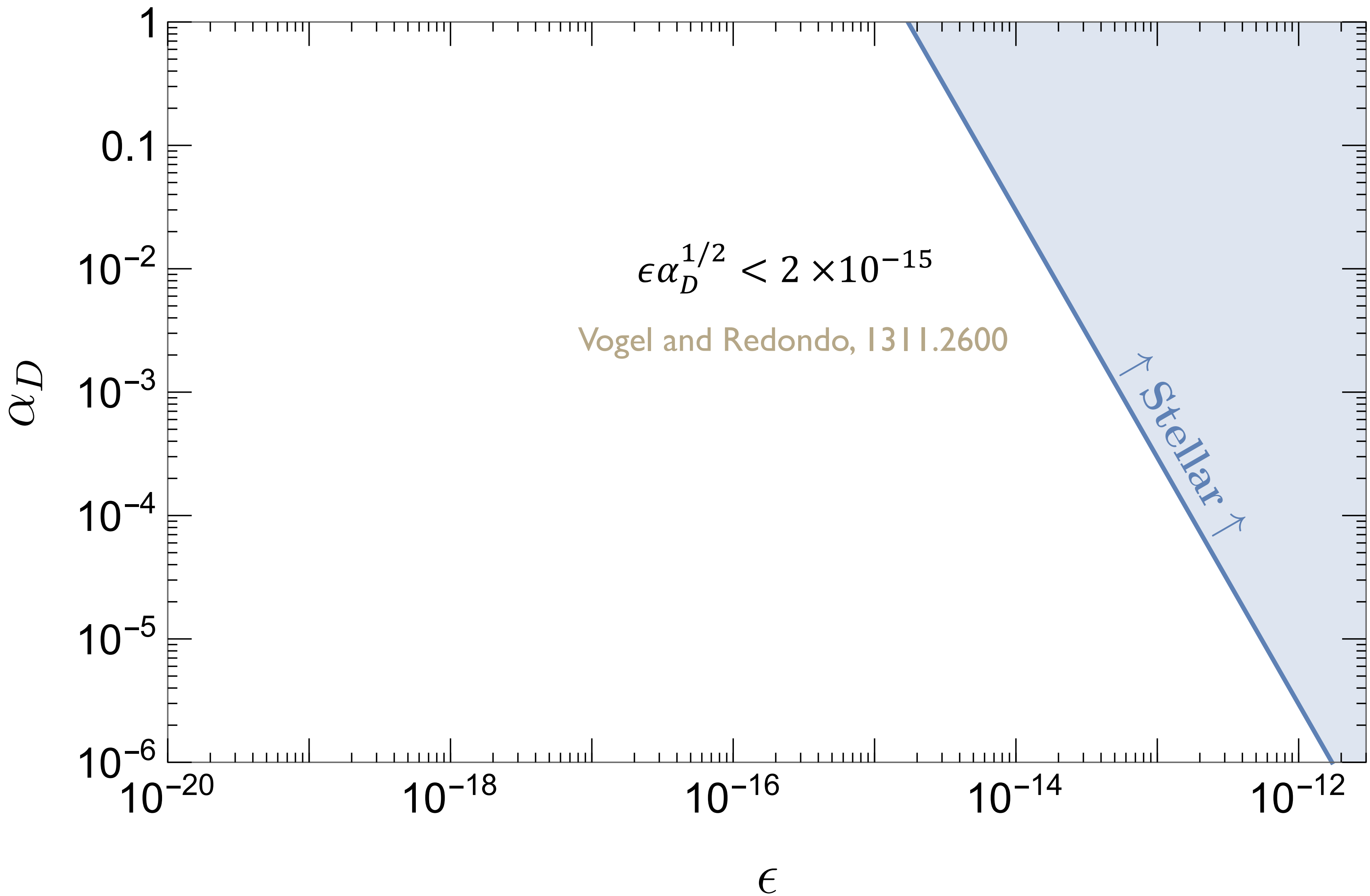

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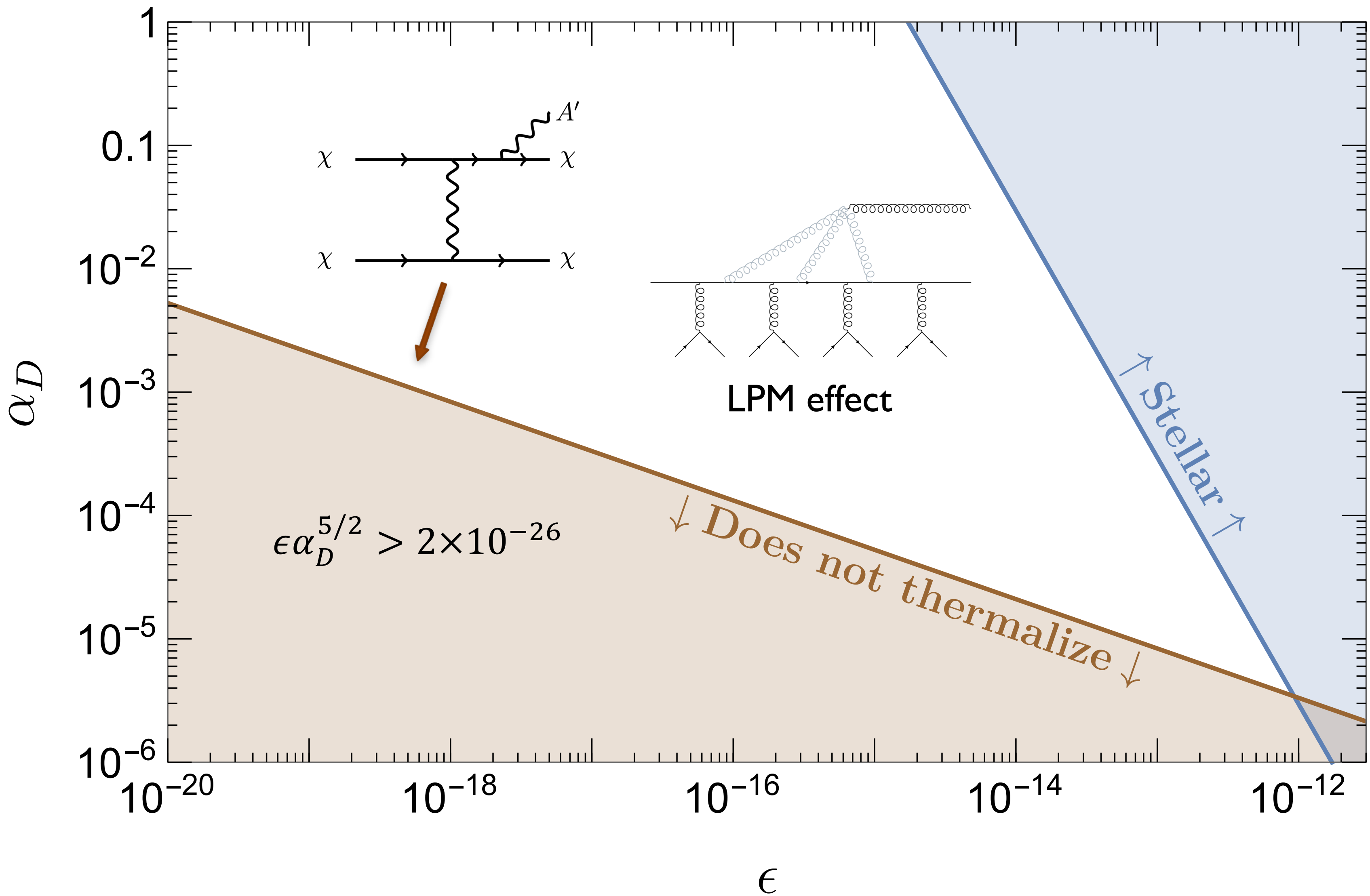

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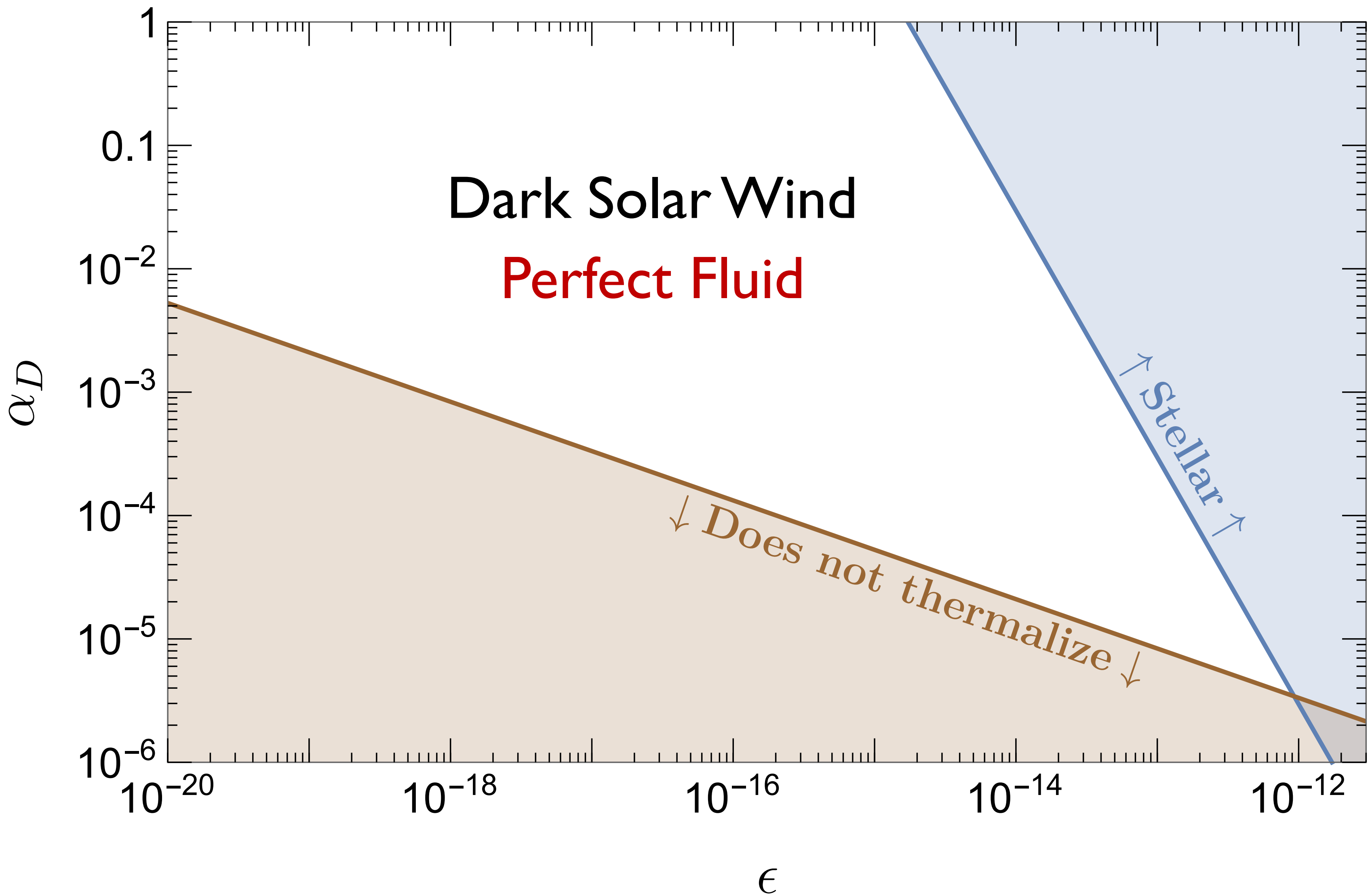


Fluid Dynamics

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

$$\partial_\mu T^{\mu\nu} = \sigma^\nu = (\dot{Q}, 0,0,0)$$

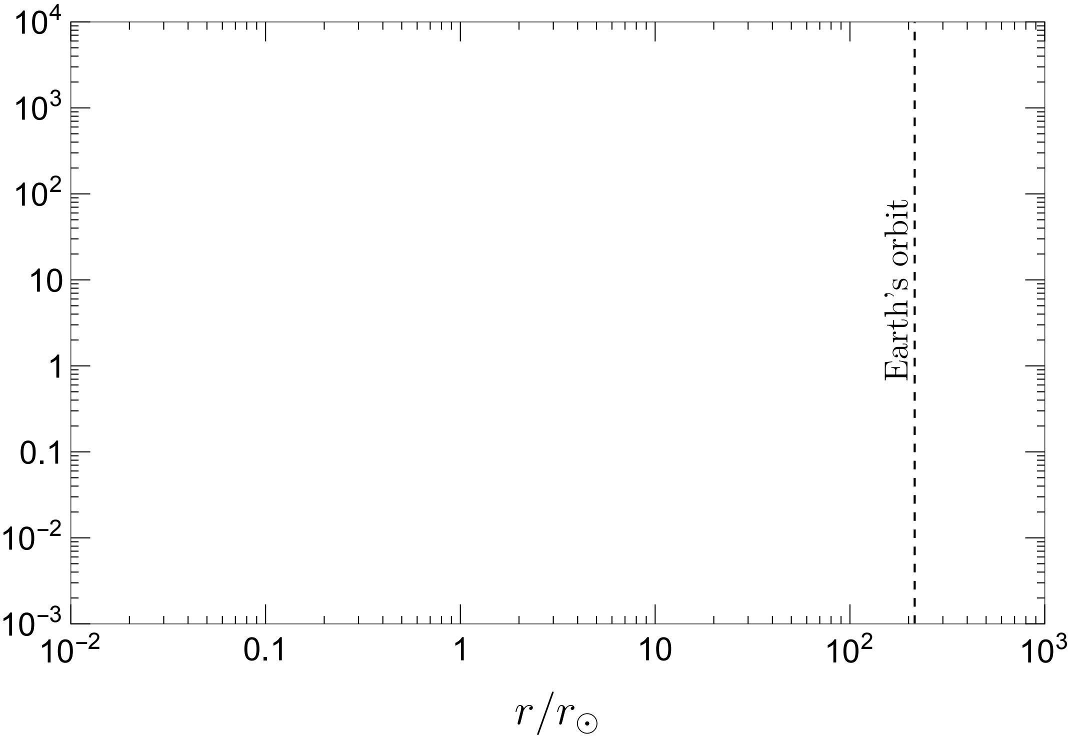
$\dot{Q} \propto \epsilon^2 \alpha_D$ is power per unit volume

$$a\tilde{T}^4 = \frac{\int_0^r r'^2 \dot{Q}(r') dr'}{r^2 \gamma^2 v}$$

$$\frac{\partial \ln v}{\partial \ln r} = \frac{1/3 + v^2}{1/3 - v^2}\left(f(r) - \frac{2(1 - v^2)}{1 + 3v^2}\right)$$

$$f(r) = \frac{r^3 \dot{Q}(r')}{\int_0^r r'^2 \dot{Q}(r') dr'}$$

Dark Fluid Profiles



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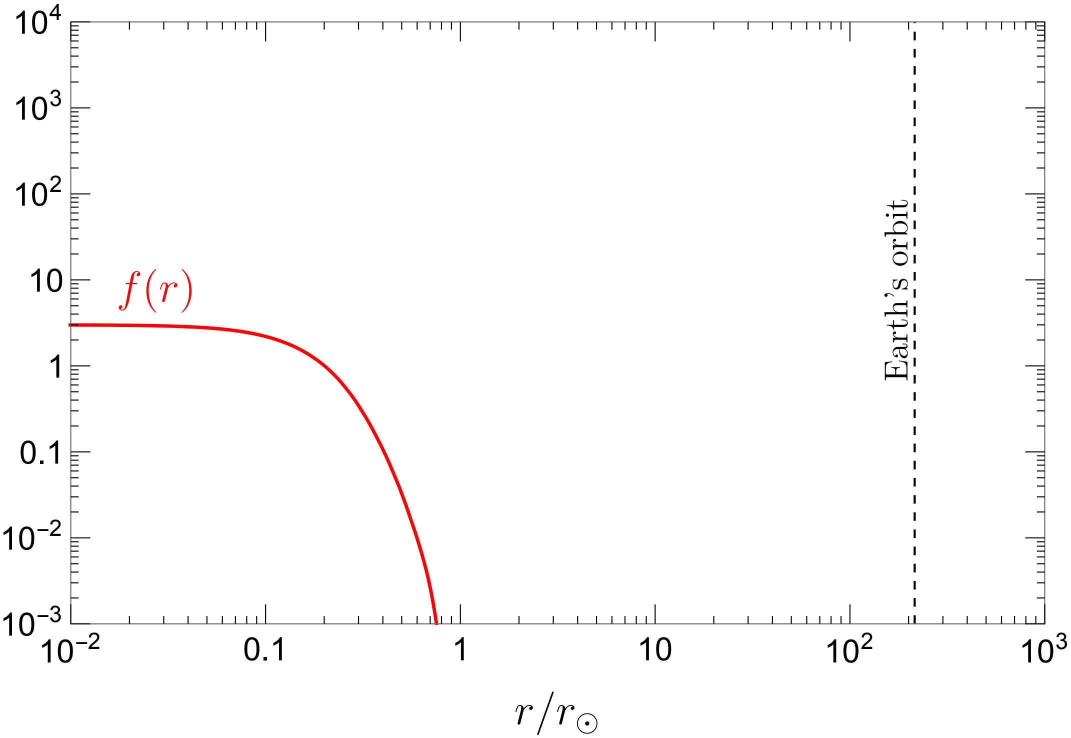

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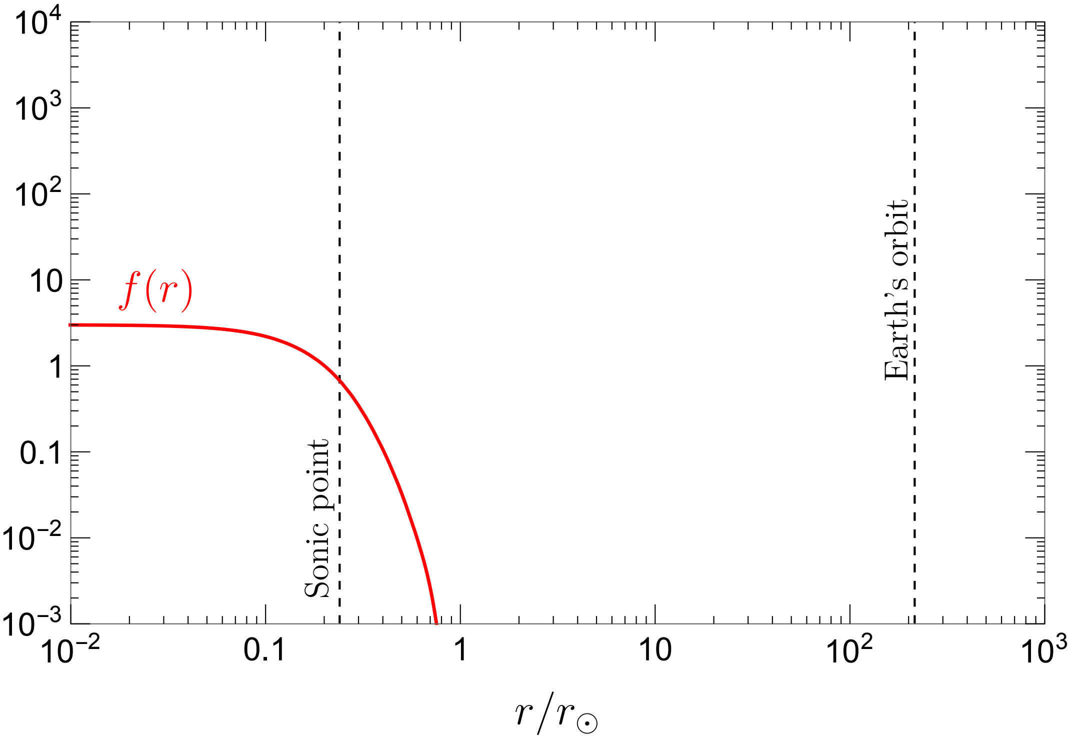

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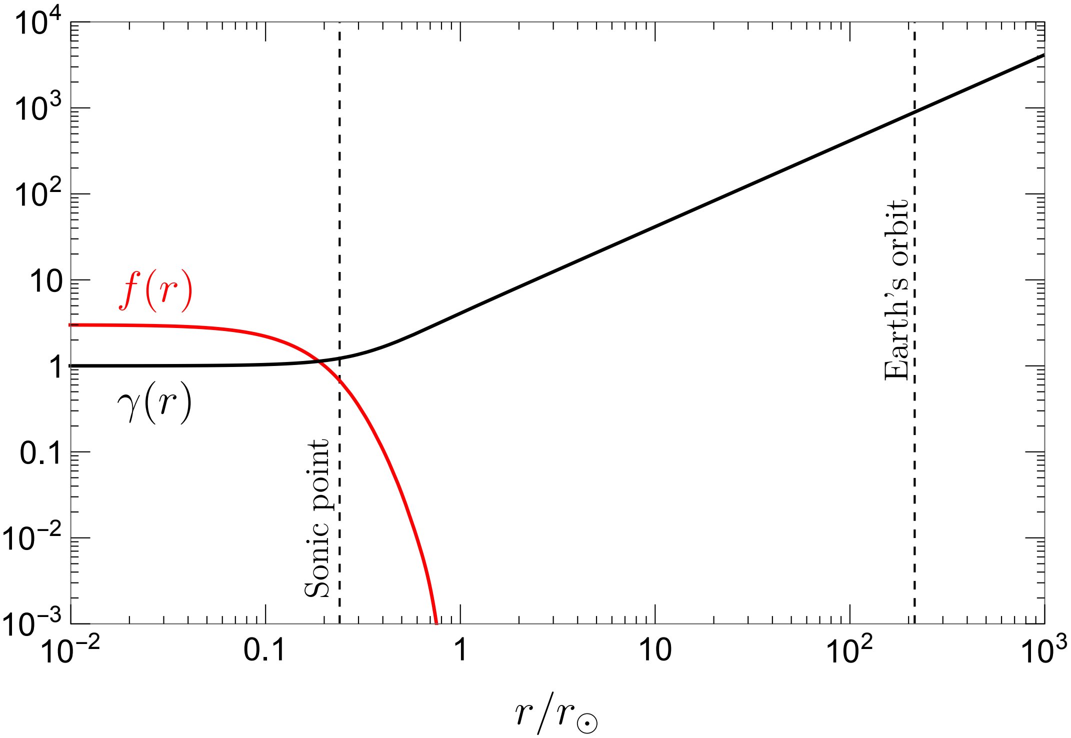

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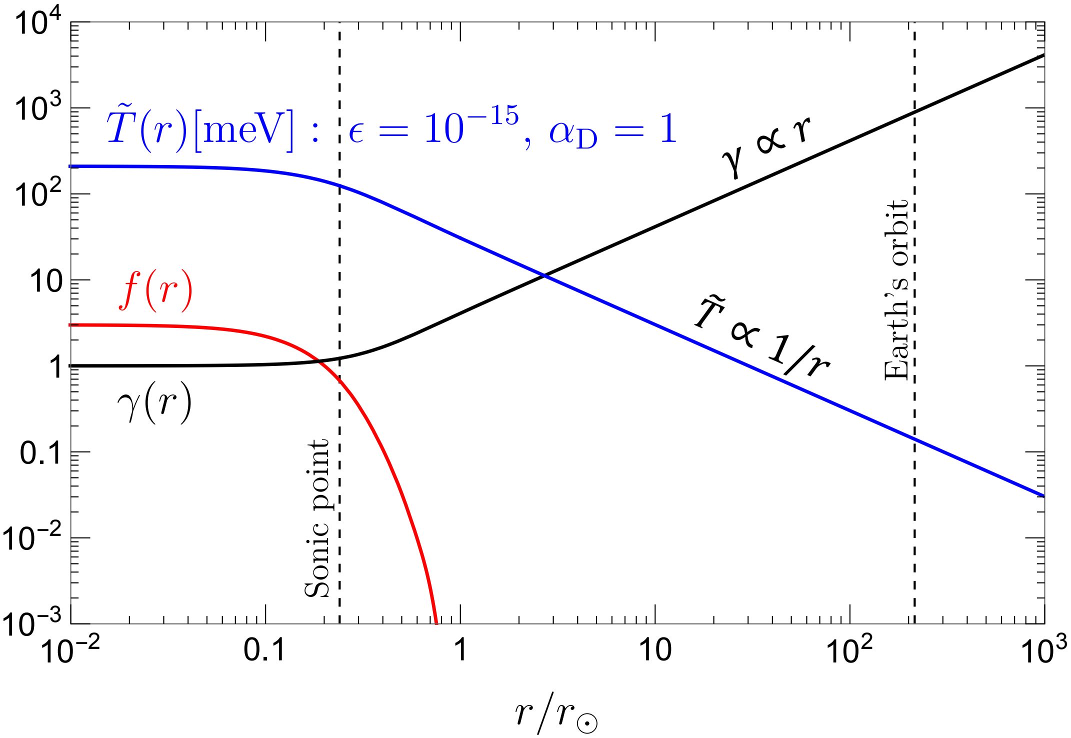

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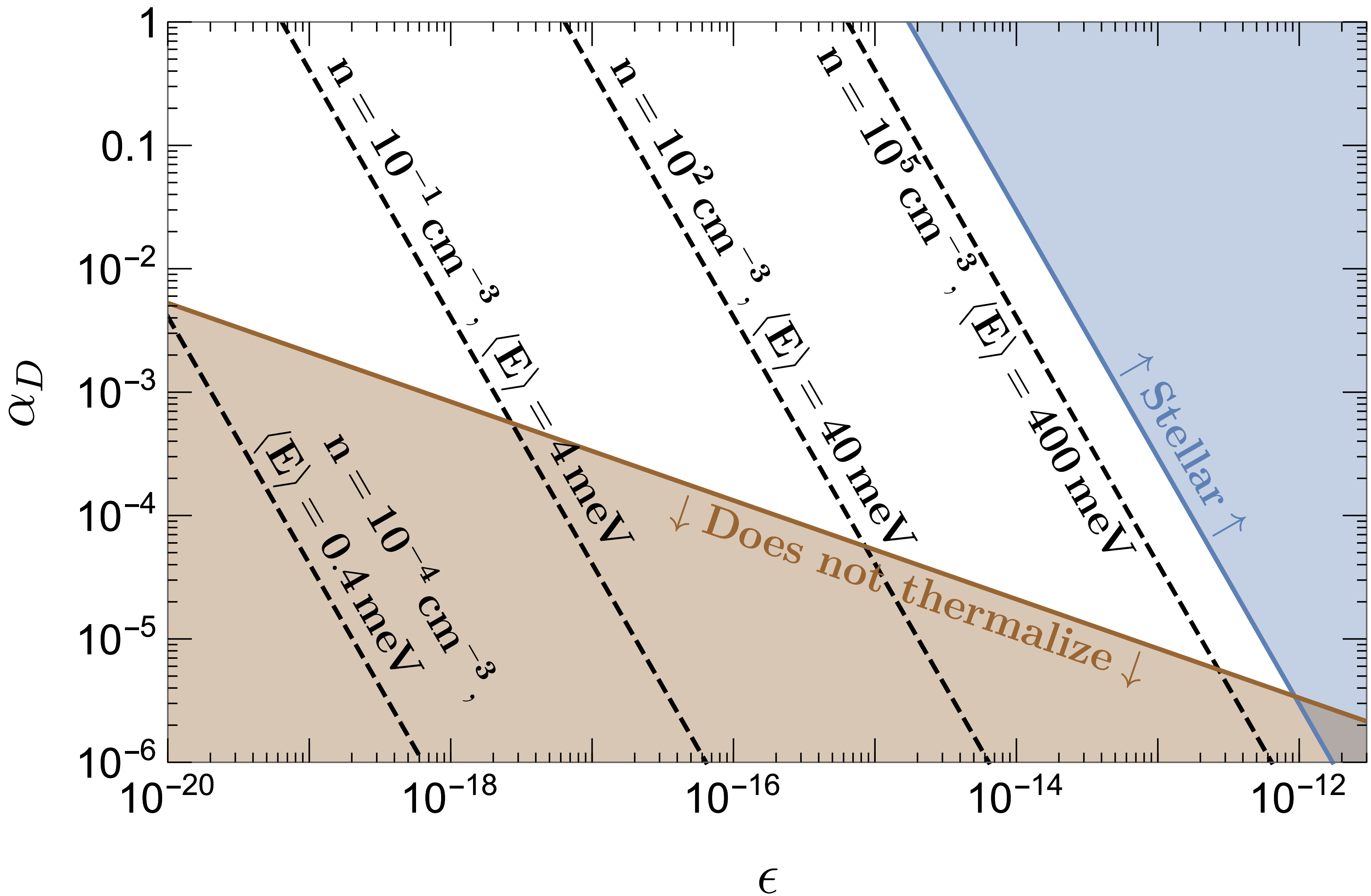
Similar to Parker's solar wind,
but asymptotes to the fireball solution

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

Parameter Space



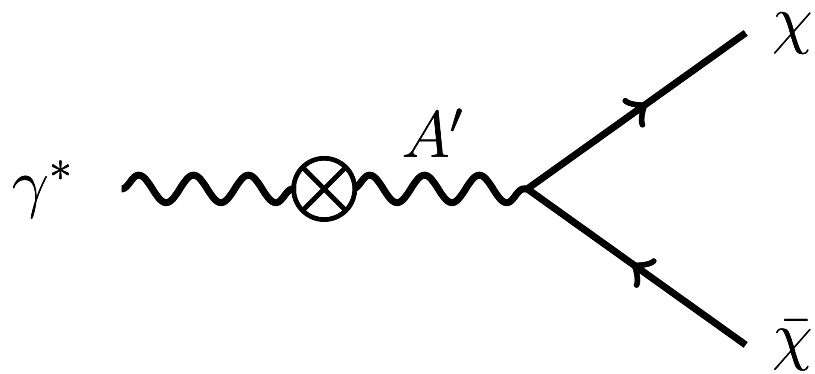
Conclusions

- 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

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 $\Gamma_{\gamma^* \to \chi\bar{\chi}} \propto \epsilon^2 \alpha_D$

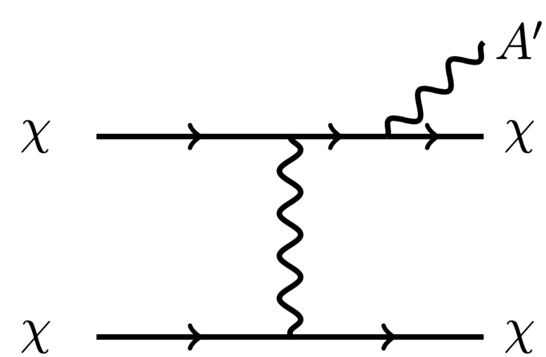
Self-thermalization

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



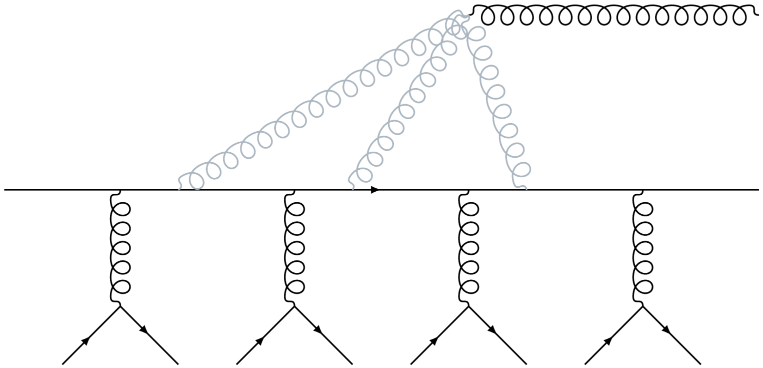
Self-thermalization

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

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

$$\Gamma_{2\to3} \sim \alpha_D \Gamma_{2\to2}^{\rm soft} \sim \frac{\alpha_D^3 n_{\rm hard}}{\omega_D^2}$$

Landau–Pomeranchuk–Migdal (LPM) Effect



- $\Gamma_{2\to 3} \sim \alpha_D \min[\Gamma_{2\to 2}^{\text{soft}}, t_{\text{form}}^{-1}]$
- $t_{\text{form}}^{-1} \sim \alpha_D^{1/2} \omega_D$, always smaller in our case
- $\Gamma_{2\to 3} \sim \alpha_D^{3/2} \omega_D > r_{\text{core}}^{-1}$
- $\epsilon \alpha_D^{5/2} > 2\times 10^{-26}$

Fluid Dynamics

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

Continuity Equations

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

- $\nu = 0$ term gives an energy equation
- $\nu = 1,2,3$ terms give momentum equations
- $\nu = 2, 3$ terms vanish assuming spherical symmetry
- $\sigma^\nu = (\dot{Q}, 0,0,0)$, $\dot{Q}$ is power per unit volume

Continuity Equations

$$\frac{1}{r^2}\partial_r[r^2\gamma^2 v(\tilde{\rho}+\tilde{p})] = \dot{Q}(r)$$
$$\frac{1}{r^2}\partial_r[r^2\gamma^2 v^2(\tilde{\rho}+\tilde{p})] = -\partial_r\tilde{p}$$

- Integrating the energy equation gives

$$a\tilde{T}^4 = \frac{\int_0^r r'^2\dot{Q}(r')dr'}{r^2\gamma^2 v}$$

- Substituting this to momentum equation gives

$$\left(\frac{\frac{1}{3}-v^2}{\frac{1}{3}+v^2}\right)\frac{\partial \ln v}{\partial \ln r} = f(r) - \frac{2(1-v^2)}{1+3v^2}, \qquad f(r) = \frac{r^3\dot{Q}(r')}{\int_0^r r'^2\dot{Q}(r')dr'}$$

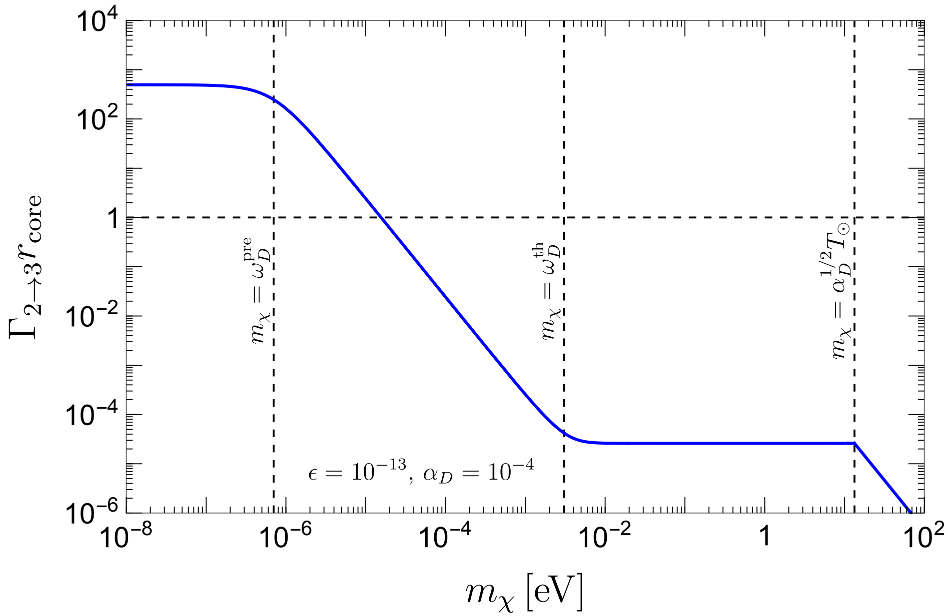
Velocity Equation

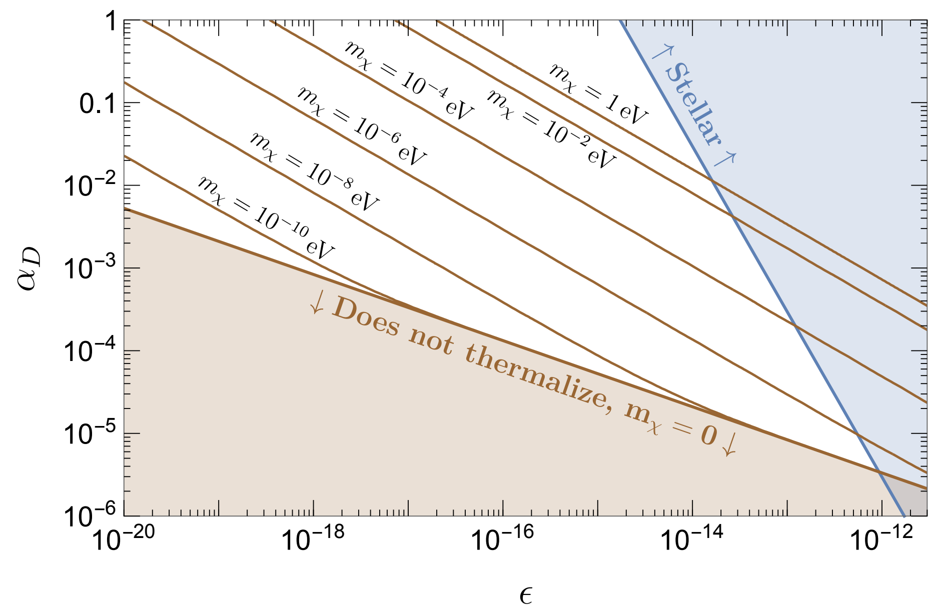
$$\left(\frac{\frac{1}{3}-v^2}{\frac{1}{3}+v^2}\right)\frac{\partial \ln v}{\partial \ln r} = f(r) - \frac{2(1-v^2)}{1+3v^2}, \qquad a\tilde{T}^4 = \frac{\int_0^r r'^2 \dot{Q}(r')dr'}{r^2\gamma^2 v}$$

- We set a boundary condition $v = 0$ at $r = 0$

- There are two solutions
  - Subsonic solution : $v < \sqrt{1/3}$ at all r
    - $v \propto r^{-2}$ at large radius
    - Need finite $\tilde{T}$ at $r \to \infty$
  - Transonic solution : $v > \sqrt{1/3}$ at large r
    - $\gamma \propto r$ at large radius
    - $\tilde{T} \propto r^{-1}$ at large radius
    - Asymptotes to the fireball solution

Massive Cases





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