Exoplanets: New Targets for Exploring Dark Matter

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Based on ongoing works with Hai-Bo Yu (UCR)

Outline

- How Exoplanets …
- Capture Rates
- Bounds on Parameter Space

Astrophysical Objects Can Capture Dark Matter

- As astrophysical objects move in the DM halo, they sweep DM particles on their way.
- Gravitational forces accelerate DM particles to the objects.
- If they lose enough kinetic energy, they get captured.
- The capture is studied for the sun, earth, solar system planets, neutron stars, and white dwarfs.
- The captured DM particles can contribute to neutrino emission, forming black holes inside the objects, and increasing their temperatures.
- The temperature increase happens by depositing DM kinetic energy to the objects, and through DM annihilation.
- In Exoplanets, DM annihilation is the major mechanism.

Why Exoplanets Are Good Candidates

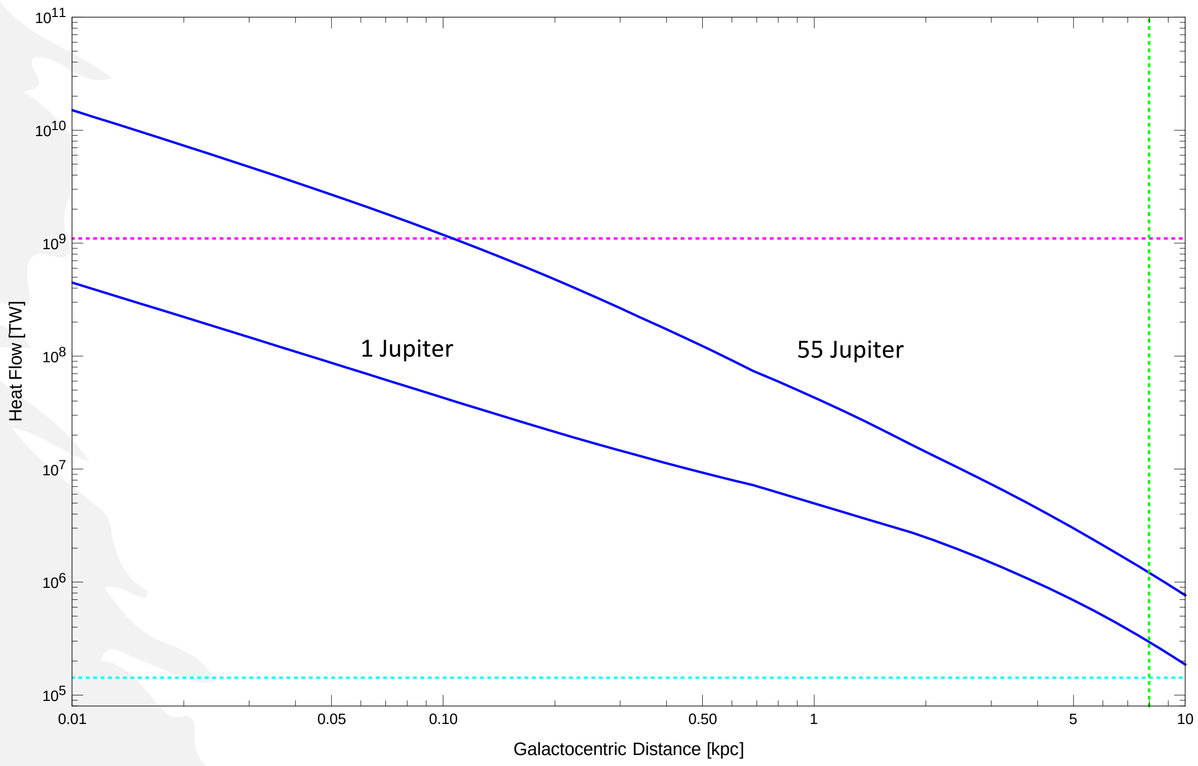
- A rapidly accelerating research program
- The enormous number of expected exoplanets
- Much larger surface area than neutron stars
- Easier to find than neutron stars
- Low temperatures

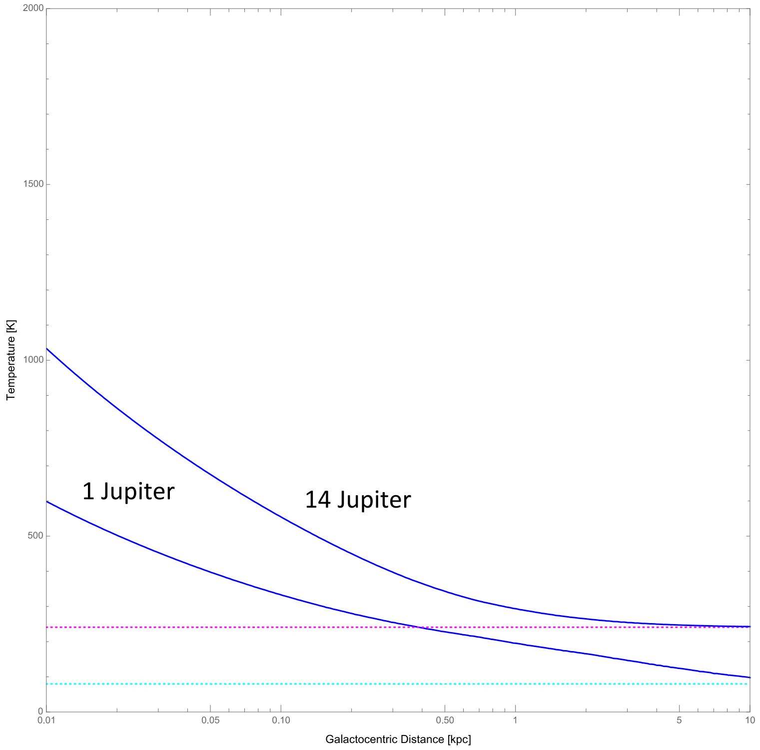
Temperature of Exoplanets

Benchmark point of T Jupiter 87 and T brown dwarfs 750

$$\Gamma_{\rm heat}^{\rm tot} = \Gamma_{\rm heat}^{\rm ext} + \Gamma_{\rm heat}^{\rm int} + \Gamma_{\rm heat}^{\rm DM} = 4\pi R^2 \, \sigma_{\rm SB} \, T^4 \, \epsilon$$

$$\Gamma_{\rm heat}^{\rm DM} = m_\chi \, f \, C_{\rm max}$$



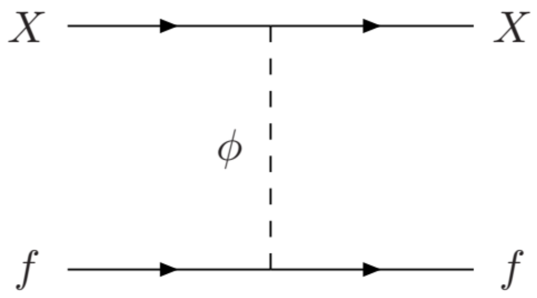


Captured Dark Matter Number Evolution

$$\begin{cases} \dfrac{dN_\chi}{dt} = C_\mathrm{c} + C_\mathrm{s} N_\chi - C_\mathrm{a} N_\chi^2 \\[2ex] \zeta = \dfrac{1}{\sqrt{C_\mathrm{c} C_\mathrm{a} + C_s^2/4}} \\[2ex] N_\chi = \dfrac{C_\mathrm{c} \tanh\left(t/\zeta\right)}{\zeta^{-1} - \tanh\left(t/\zeta\right)/2} \end{cases} \xrightarrow{\tau_\odot \gg \zeta} N_\chi^{eq} = \frac{C_\mathrm{s}}{2C_\mathrm{a}} + \sqrt{\frac{C_\mathrm{s}^2}{4C_\mathrm{a}^2} + \frac{C_\mathrm{c}}{C_\mathrm{a}}}.$$

$$f = \frac{C_\mathrm{c}}{C_\mathrm{max}} + \frac{C_\mathrm{s}^2}{2C_\mathrm{a} C_\mathrm{max}} \left(1 + \sqrt{1 + \frac{4C_\mathrm{a} C_\mathrm{c}}{C_\mathrm{s}^2}}\right)$$

Capture Rate



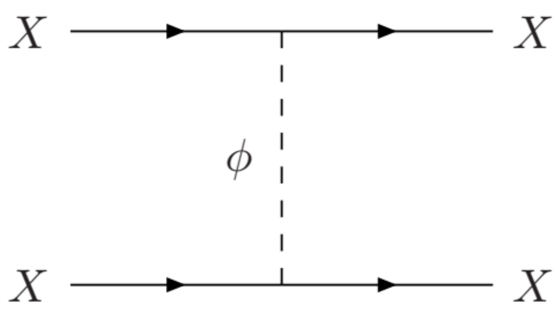
- DM Particles should lose enough energy to get captured.
- Multiple time scattering
- Heavy mass DM particles need more scattering
- Captured DM particles occupy a small region in the core
- Thermalization and evaporation
- High core temperatures $\longrightarrow$ Higher masses evaporation
- Exoplanets' core temperature is low $\longrightarrow$ Explore lower DM masses

$$C_c = \sum_{i=1}^{N} p_N(\tau)\, \pi R^2 \left(\frac{6}{\pi}\right)^{\frac{1}{2}} n_\chi^h(d)\, \bar{v}(d)\, \frac{v_{\mathrm{esc}}(R)^2}{\bar{v}(d)^2} \left(\left(1 + \frac{2\bar{v}(d)^2}{3v_{\mathrm{esc}}(R)^2}\right) - \left(\frac{2v_{\mathrm{N}}^2}{3v_{\mathrm{esc}}(R)^2} + \frac{2\bar{v}(d)^2}{3v_{\mathrm{esc}}(R)^2}\right) \mathrm{e}^{-\frac{3}{2}\frac{\left(v_{\mathrm{N}}^2 - v_{\mathrm{esc}}(R)^2\right)}{\bar{v}(d)^2}} \right)$$

Self-Capture Rate

- The captured DM can capture new DM particles.
- This capture is kinematically more efficient.
- However, the new DM can kick the older one outside of the planet.

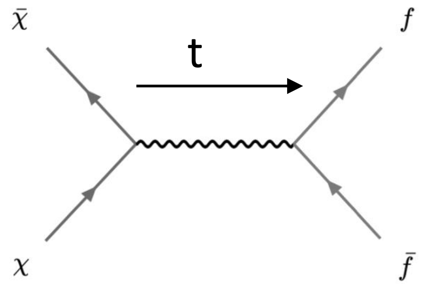
$$
\begin{aligned}
C_{\mathrm{s}} &= \sigma_{\chi\chi} \int g(w)\, w^2 \frac{f(u)}{u} du \,\Big|_{r=0} \\
&= \sigma_{\chi\chi} \left(\frac{6}{\pi}\right)^{\frac{1}{2}} n_\chi^h(d)\, \bar{v}(d) \frac{v_{\mathrm{esc}}(0)^2}{\bar{v}(d)^2} \left(1 - \frac{1 - \mathrm{e}^{-\frac{3}{2}\frac{v_{\mathrm{esc}}(0)^2}{\bar{v}(d)^2}}}{\frac{3}{2}\frac{v_{\mathrm{esc}}(0)^2}{\bar{v}(d)^2}}\right)
\end{aligned}
$$



DM self-interactions

Annihilation Rate

- Captured DM particles occupy a small region inside the planet.
- Isothermal Sphere
- A balance between capture and annihilation
- Sommerfeld enhancement



$$n_\chi(r) = N_\chi \frac{e^{-\frac{m_\chi \Phi(r)}{kT_\chi}}}{\int_0^R 4\pi r^2 e^{-\frac{m_\chi \Phi(r)}{kT_\chi}}}$$

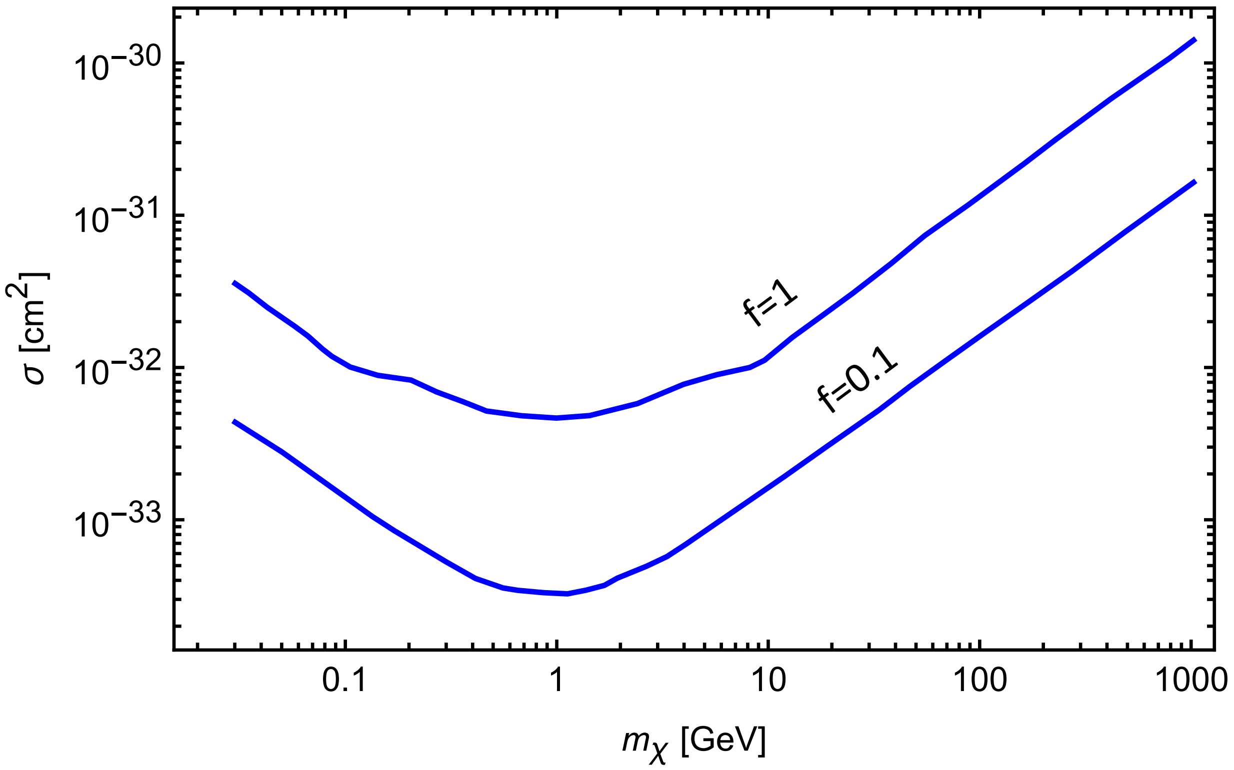
$$C_a = \frac{\int_0^R r^2 e^{-2\frac{m_\chi \Phi(r)}{kT(0)}} \langle \sigma v \rangle}{\left(\int_0^R r^2 e^{-\frac{m_\chi \Phi(r)}{kT(0)}}\right)^2}$$

Constraints on cross-section

$$f = \frac{C_c}{C_{max}} + \frac{C_s^2}{2C_a C_{max}}\left(1 + \sqrt{1 + \frac{4C_a C_c}{C_s^2}}\right)$$

$$\frac{\sigma_s}{m_\chi} = 1 - 10$$

$$\sigma v = 3 \times 10^{-26}$$



Summary

- Exoplanets are good candidates to study the phenomenology of dark matter.
- Dark matter can heat up the exoplanets and increase their temperature.
- The observation of the temperature of exoplanets will put bounds on our benchmark model.

Thank You