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Thermal Transport of the Solar Captured Dark Matter and its Impact on the Indirect Dark Matter Search

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Outline

- Motivations
- How does thermal energy transport?
- Dark matter (DM) evolution and thermal transport
- Physical implications and its impact on indirect search
- Summary

Motivations

- Recent studies suggest that DM is not collisionless
- The DM temperature, T_χ, is not necessarily to be the same as the core temperature of the Sun, T_c
- Thermal energy can exchange between DM-DM and DM-nucleus or even dissipates through annihilation
- For much weaker $\sigma_{\chi p}$, the thermal energy exchange between DM-nucleus is less efficient
- In such case, T_χ can be distinct from T_c eventually
- As a consequence, it may alter the DM annihilation rate

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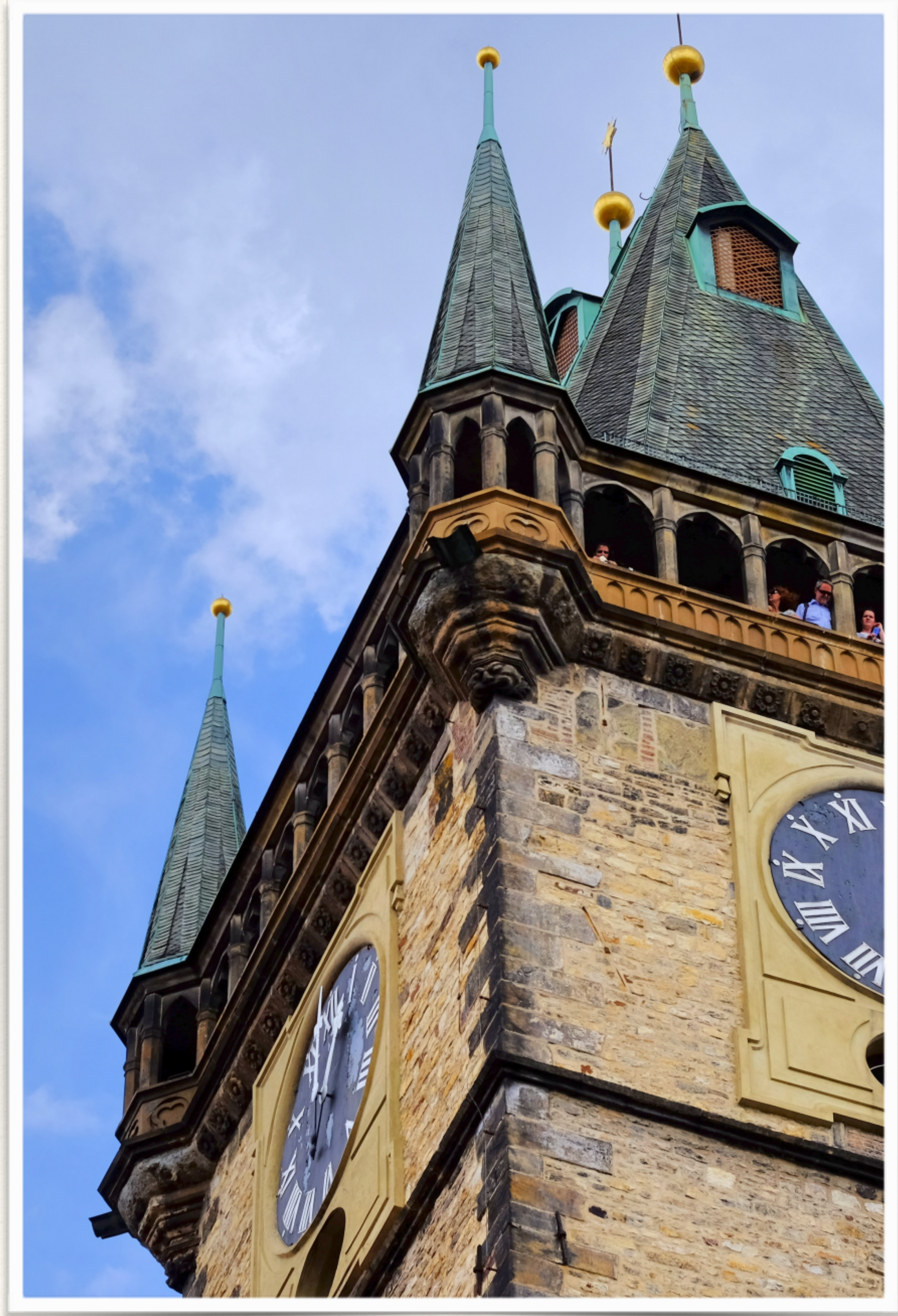
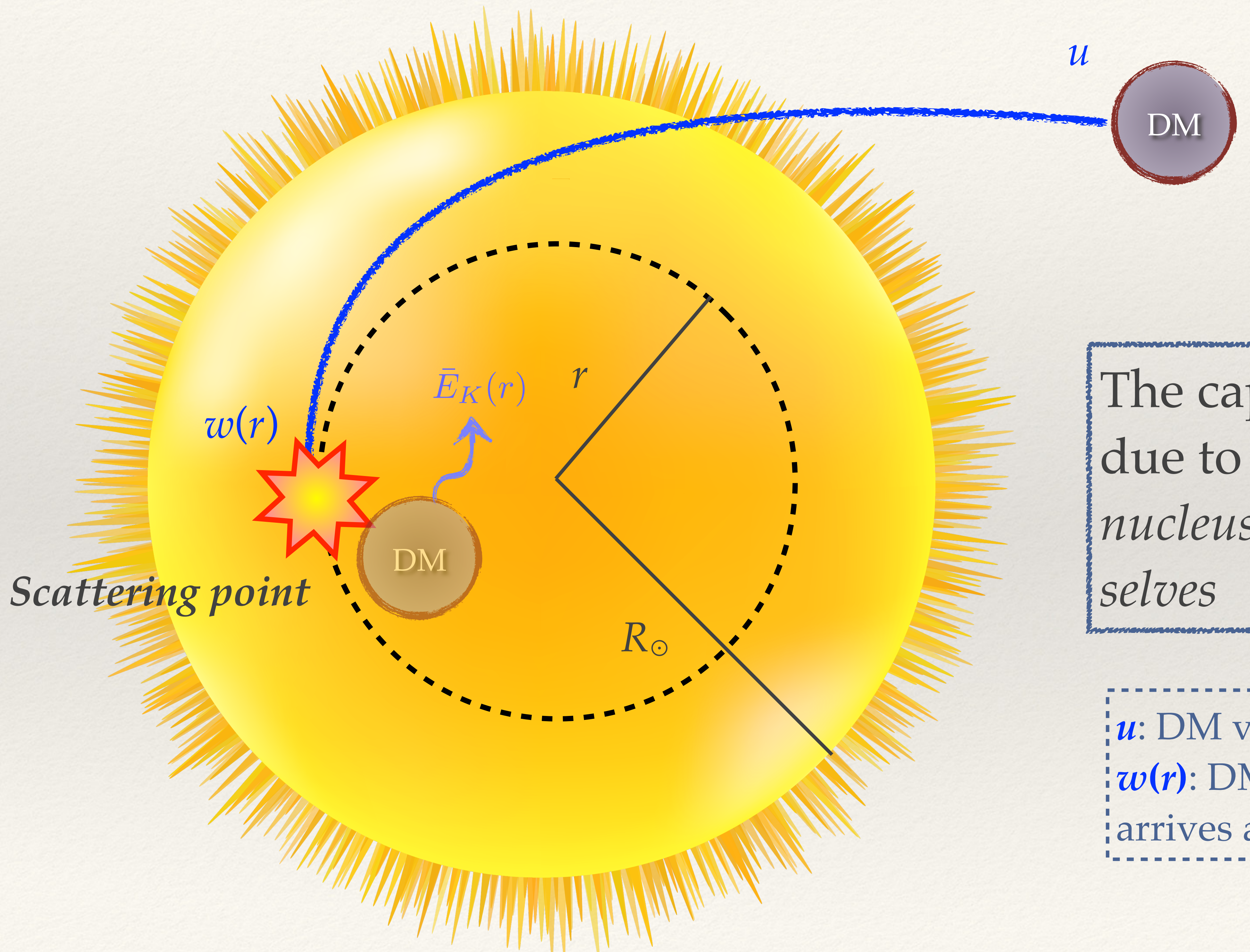
How does thermal energy transport?



Energy flow via capture



The capture could be due to scattering with *nucleus* or *DM themselves*

u: DM velocity in the halo
***w*(*r*)**: DM velocity when arrives at layer *r* in the Sun

DM kinetics after scattering

- When DM reaches layer r in the Sun, it carries velocity $w = \sqrt{u^2 + v_{\rm esc}^2(r)}$
- Thus, the average DM kinetic energy after scattering with nucleus is given by

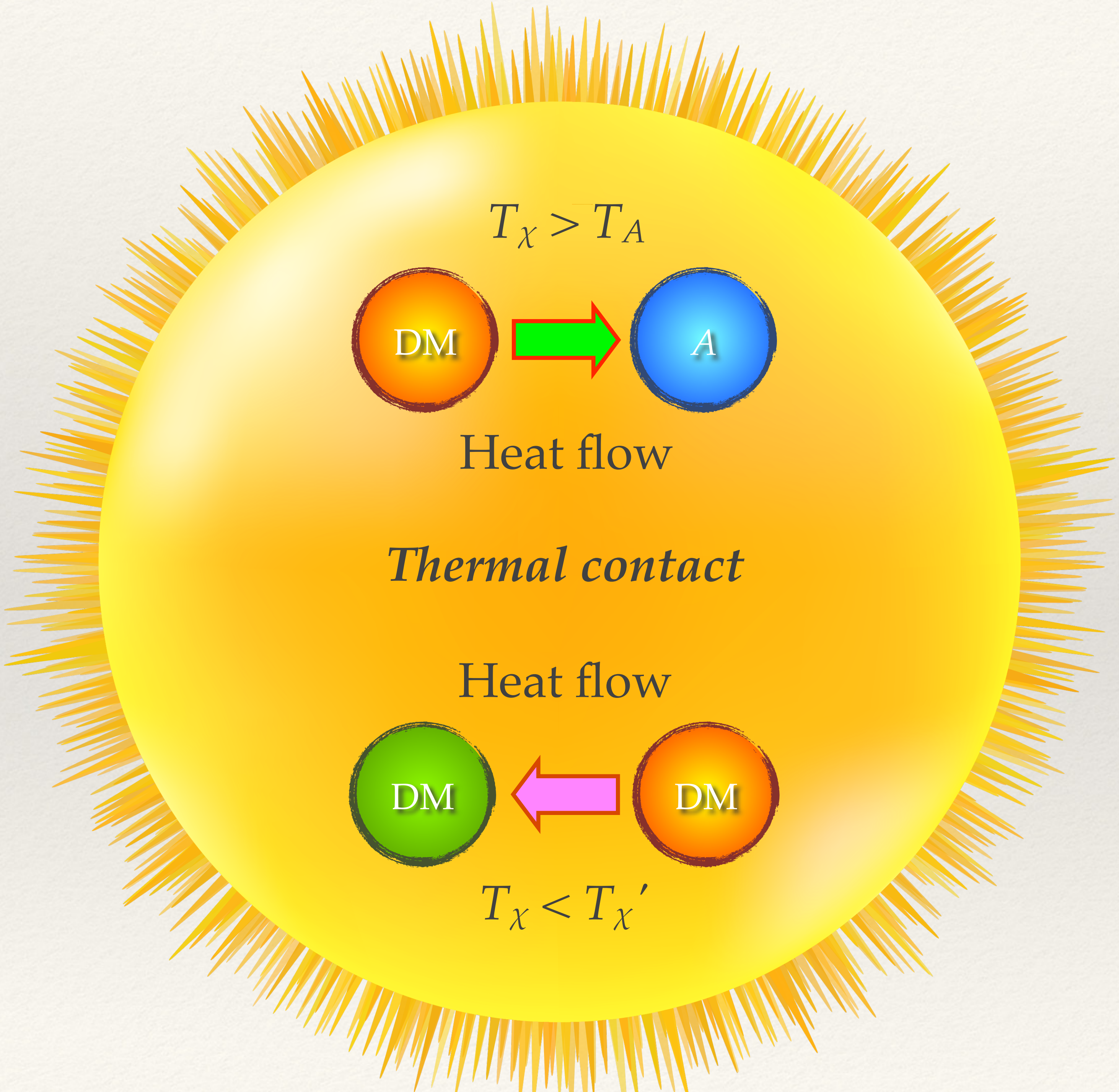
$$\bar{E}_K(r) = \frac{m_\chi}{4}\left(\frac{m_\chi - m_A}{m_\chi + m_A}\right)^2 u^2 + \frac{m_\chi}{2}\frac{m_\chi^2 + m_A^2}{(m_\chi + m_A)^2} v_{\rm esc}^2(r)$$

- However, the scattering among DM themselves gives

$$\bar{E}_K(r) = \frac{1}{4} m_\chi v_{\rm esc}^2(r)$$

- m_A is the nucleus mass of element A in the Sun

Energy flow via thermal contact



Thermal contact via *DM and nucleus A*

Thermal contact via *DM themselves*

[1] D. N. Spergel and W. H. Press, *Astrophys. J.* **294**, 663 (1985)

Mean collision time

- The mean collision time is used to determine which one reaches thermal equilibrium earlier, DM-DM or DM-nucleus
- Thereupon, by $\tau \sim 1/(n\sigma v)$ we have

$$\begin{cases} \tau_{\chi\chi}(t) \simeq \frac{V_\odot}{N_\chi(t)\sigma_{\chi\chi} v}, & \text{for DM-DM} \\ \tau_{\chi\odot} \simeq \frac{V_\odot}{\sum_i N_i \sigma_{\chi A_i} v}, & \text{for DM-nucleus} \end{cases}$$

- Suppose the time scale for DM to reach thermal equilibrium is $t = \tau_\chi^{\mathrm{eq}}$, we have

$$\tau_\chi^{\mathrm{eq}} \simeq \tau_{\chi\chi}(\tau_\chi^{\mathrm{eq}}) = \frac{V_\odot}{N_\chi(\tau_\chi^{\mathrm{eq}})\sigma_{\chi\chi} v}$$

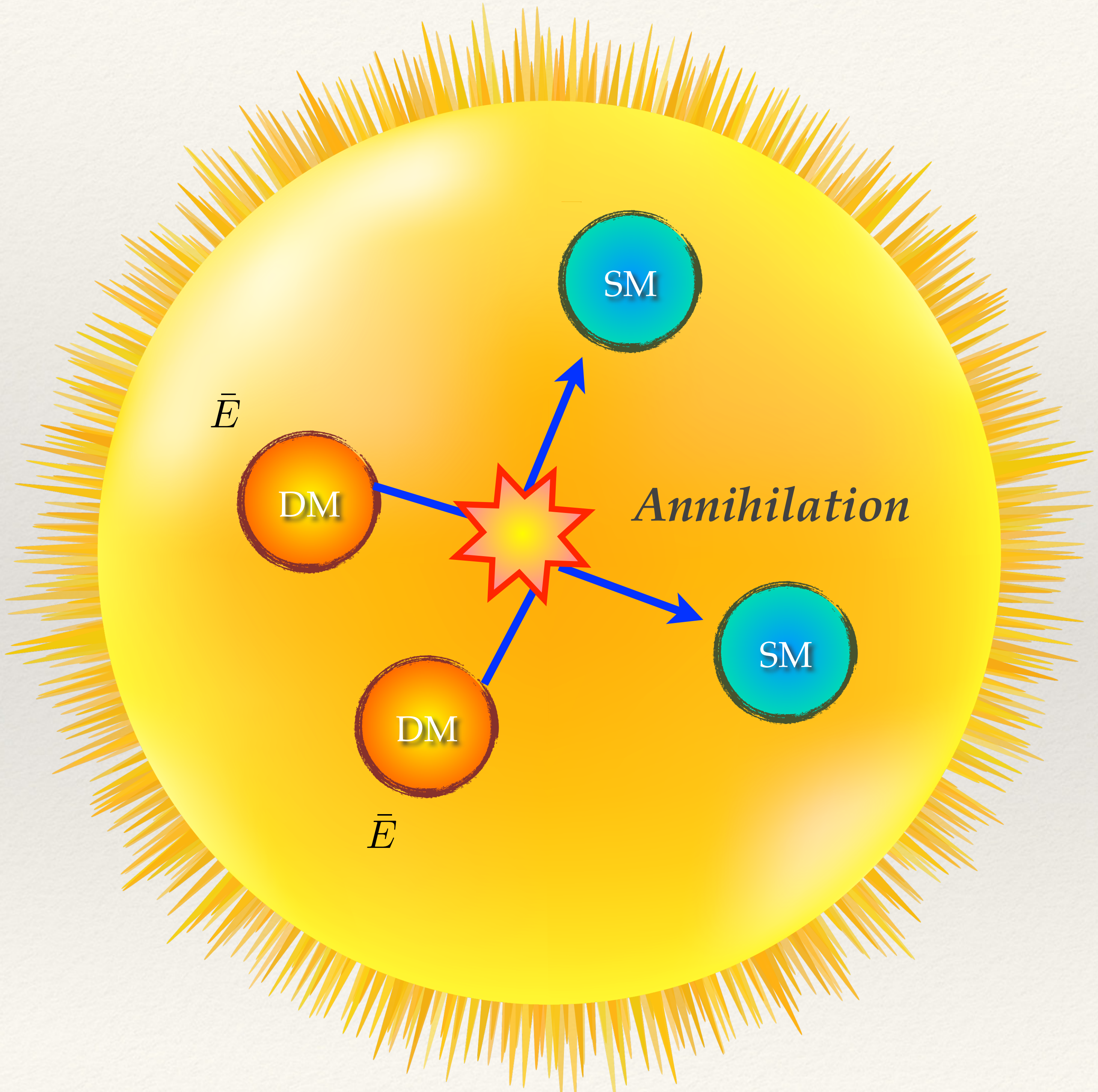
Thermal equilibrium time scale

- Assuming when DM reaches its own thermal equilibrium, N_χ is still its early stage of accumulation
- In other words, the capture by DM-nucleus scattering is dominant, $N_\chi \approx C_c t$
- By such assumption, we can define the ratio r

$$r \equiv \frac{\tau_\chi^{\rm eq}}{\tau_{\chi\odot}} \simeq 10^9 \sqrt{\frac{\sigma_{\chi p}}{\sigma_{\chi\chi}}}$$

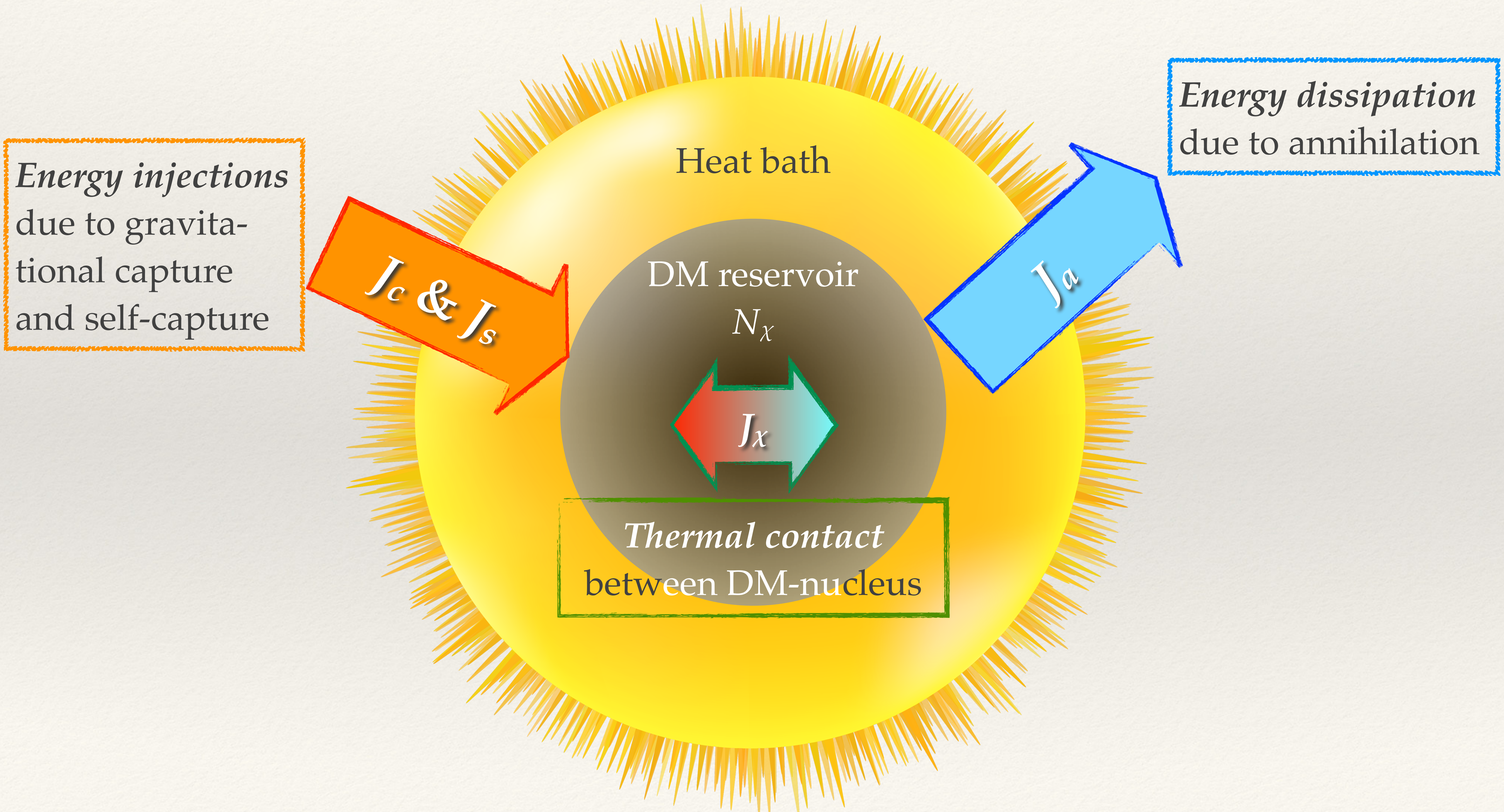
- For $r < 1$, DMs will reach their own thermal equilibrium quicker than with the solar medium
- Thus it is sufficient to just consider the thermal contact between DM and nucleus after $t = \tau_\chi^{\rm eq}$

Energy dissipation via annihilation



Annihilation takes DM away and transports them into the final SM products

Defining physical quantities



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DM evolution process and thermal exchange

DM evolution in the Sun

- The common DM evolution equation:

$$\frac{dN_\chi}{dt} = C_c + C_s N_\chi - C_a N_\chi^2$$

- Additionally, N_χ contributes to the total energy evolving as well. Thus, we have the energy evolution equation:

$$\frac{d(N_\chi \bar{E})}{dt} = J_c + (J_\chi + J_s) N_\chi - J_a N_\chi^2$$

$$\bar{E} = \frac{s}{2} k_B T_\chi(t)$$

- $T_\chi(t)$ is the average DM temperature and s denotes the d.o.f. of DM. We take $s = 3$ for subsequent discussions

T_χ-dependent quantity in dN_χ/dt

- The two differential equations are mutual dependent since C_a is T_χ-dependent[2]

$$C_a = \frac{\langle \sigma v \rangle V_2}{V_1^2} \qquad V_j \propto \left(\frac{T_\chi}{T_c} \frac{10 \text{ GeV}}{j m_\chi} \right)^{3/2} \qquad j = 1, 2$$

- How T_χ evolving will affect N_χ accumulation and then feedback to T_χ itself
- The factors $J_{c,s,\chi,a}$ are all T_χ-dependent

[2] K. Griest and D. Seckel, *Nucl. Phys. B* **283**, 681 (1987)

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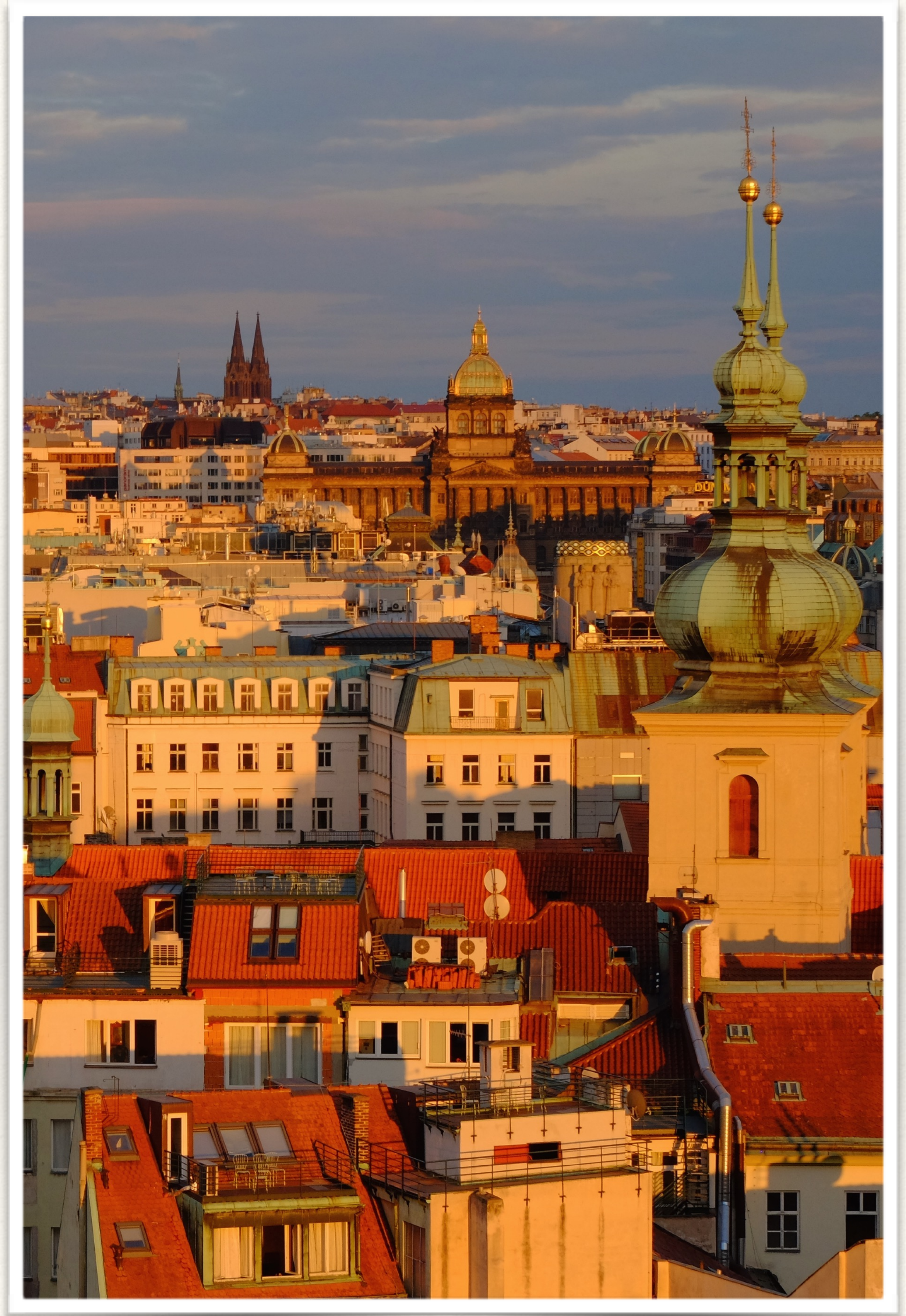
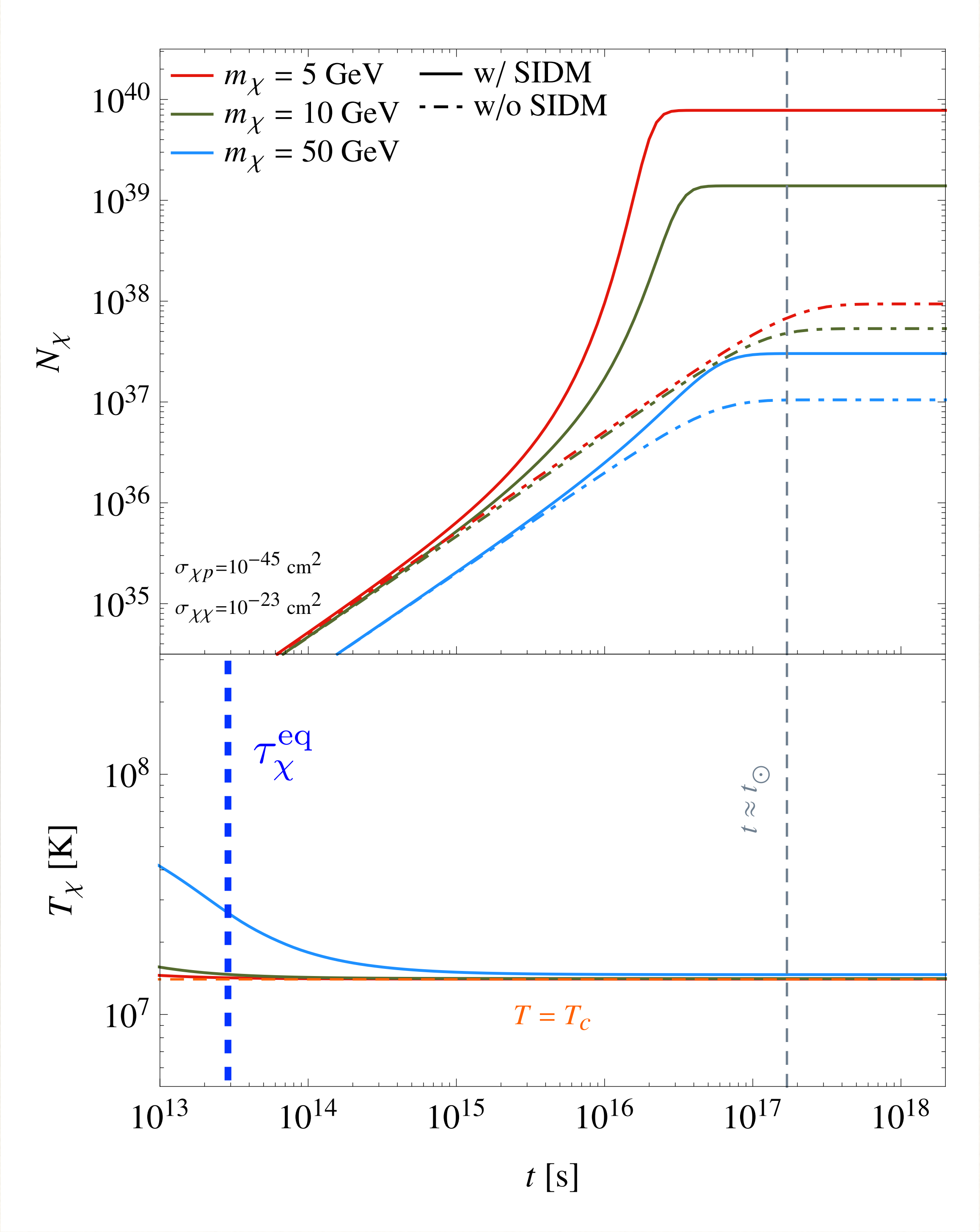
Physical implications



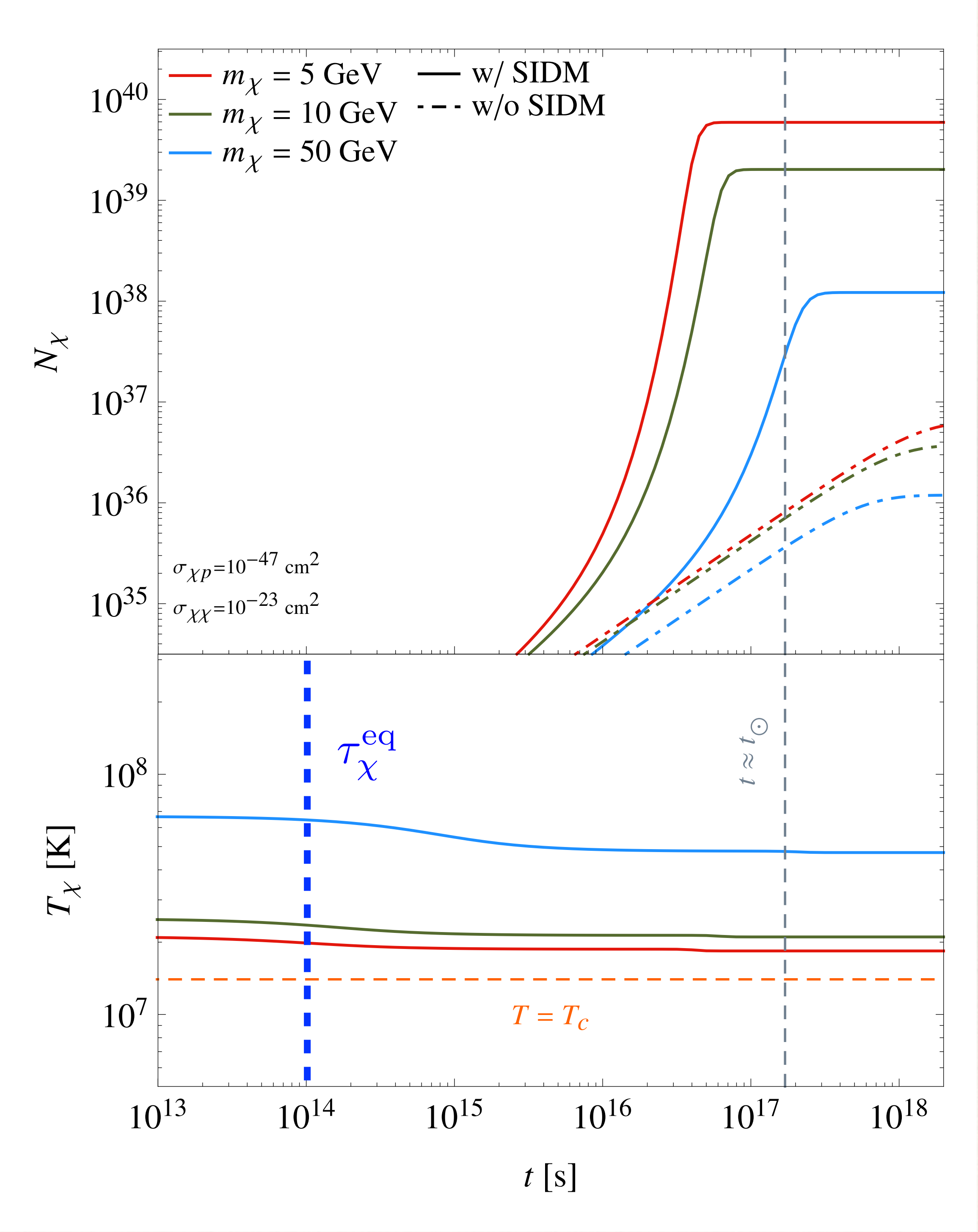
N_χ and T_χ evolutions: Stronger $\sigma_{\chi p}$

- $r \sim 0.01$ for $(\sigma_{\chi p}, \sigma_{\chi\chi})=(10^{-45}, 10^{-23})$ cm^2
- Although J_c and $J_s N_\chi$ transport energy into the DM reservoir, the thermal contact $J_\chi N_\chi$ makes the heat out of the reservoir due to larger $\sigma_{\chi p}$ as well as the $J_a N_\chi^2$
- Eventually T_χ will be balanced by the Sun with the core temperature T_c



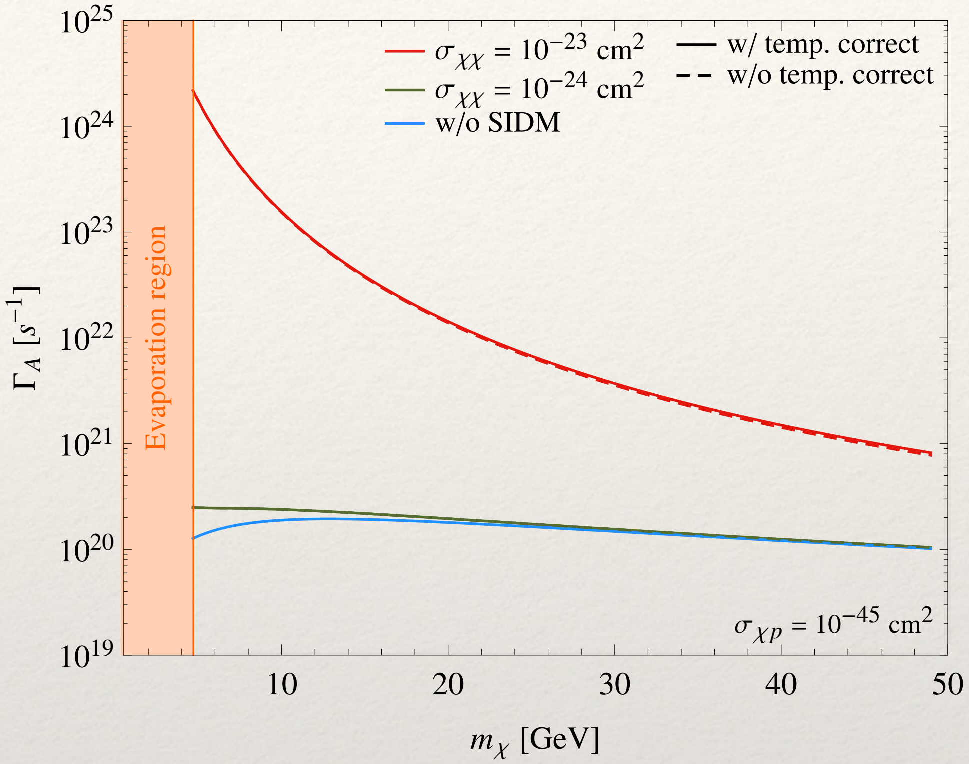
N_χ and T_χ evolutions: Weaker $\sigma_{\chi p}$

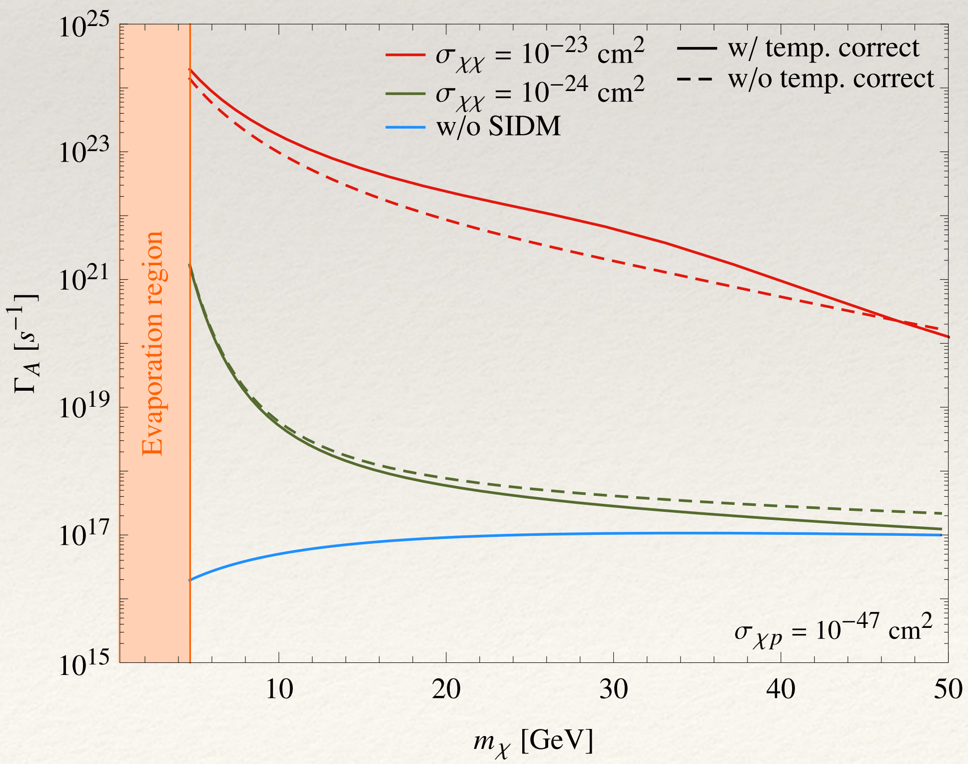
- $r \sim 10^{-4}$ for $(\sigma_{\chi p}, \sigma_{\chi\chi})=(10^{-47}, 10^{-23})$ cm^2
- In such case, the energy injection via J_c and J_s can overcome the dissipation due to J_χ and J_a
- Moreover, energy injects to the DM reservoir constantly and makes them form their own thermal system
- The T_χ is distinct from T_c in this case



The total annihilation rate Γ_A

- The total annihilation rate
$$\Gamma_A = \frac{1}{2} C_a N_\chi^2$$
- Since $C_a \propto T_\chi^{-1.5}$, larger T_χ makes smaller C_a.
- However, smaller C_a leads to more N_χ accumulation once $dN_\chi/dt = 0$ is attained[3]
- When N_χ^2 increment can overcome the C_a suppression, we have larger Γ_A compares to those without temperature correction
- For some cases, $dN_\chi/dt = 0$ does not attain at current epoch. It makes the correspon- ding Γ_A smaller than those without tempe- rature correction





[3] C.-S. Chen *et al.*, *JCAP* **10**, 049 (2014)

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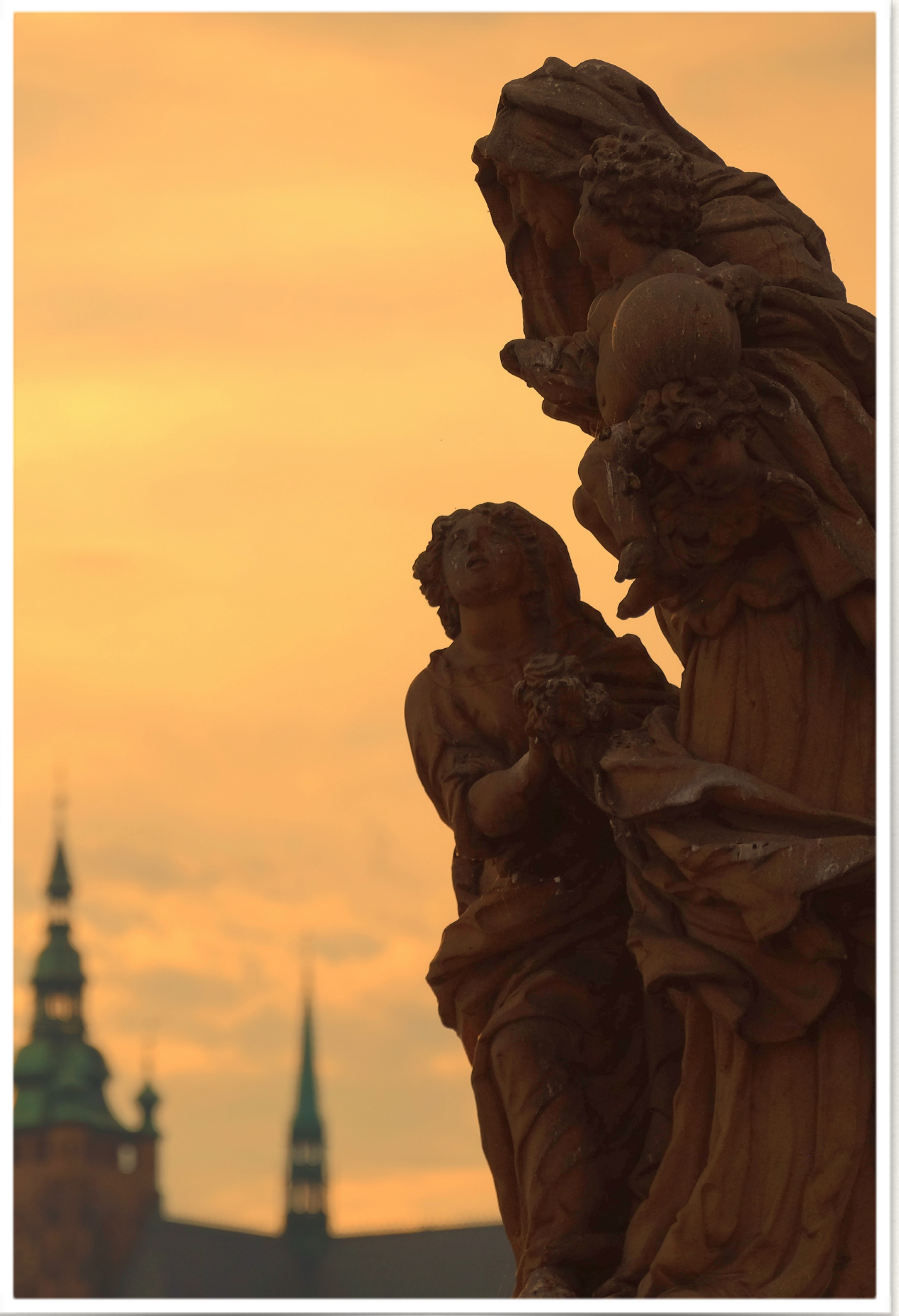
Summary



To summarize so far…

- The DM temperature does not necessarily equal to the Sun's core temperature for collisional DM
- As a consequence of $\tau_\chi^{\rm eq} < \tau_{\chi\odot}$, DM reaches thermal equilibrium before it starts thermal exchange with the solar nucleus efficiently
- If $\sigma_{\chi p}$ is small enough, eventually DM will have its own temperature inside the Sun regardless of T_c
- For more accurate prediction on the DM signal, the temperature correction factor should be considered