Co-Interacting Dark matter: the dark atom laser emission

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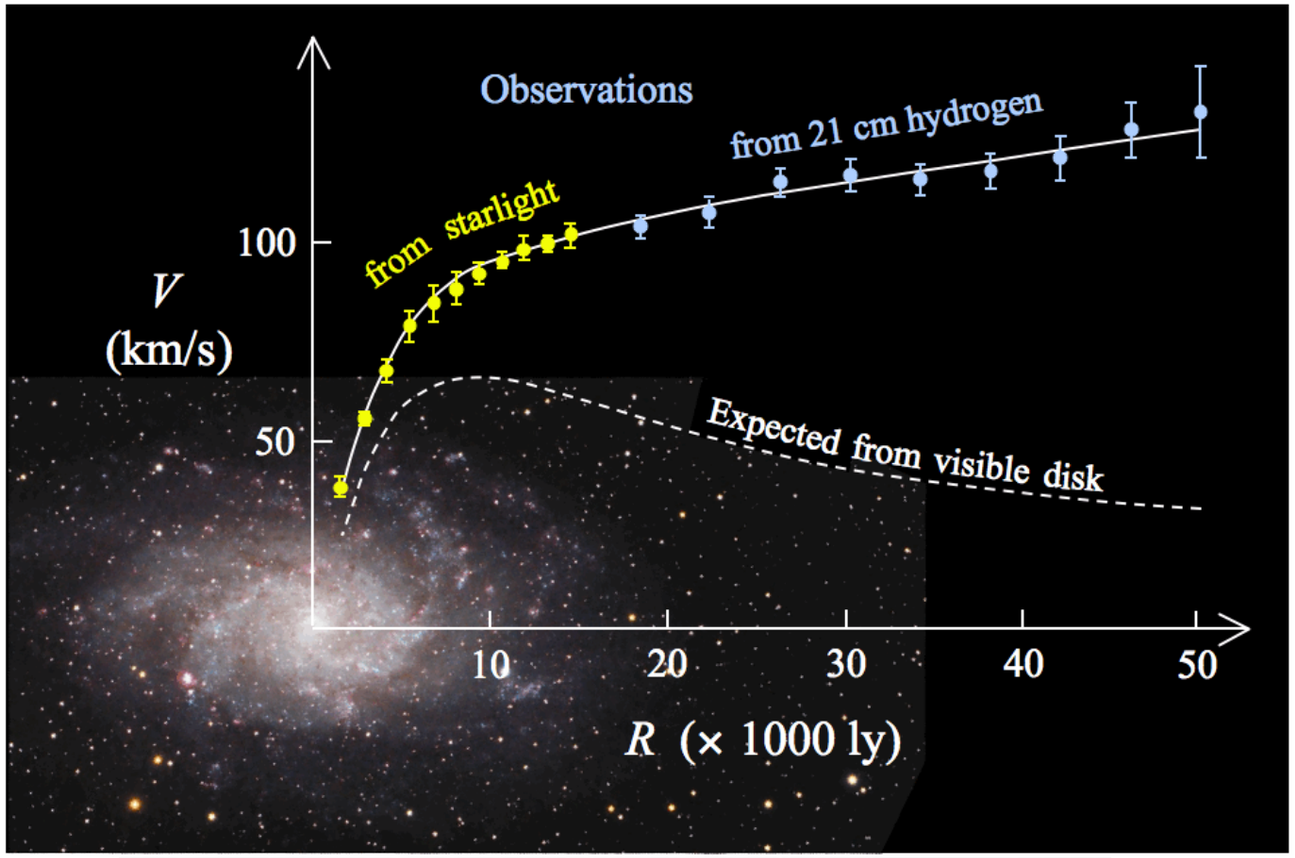
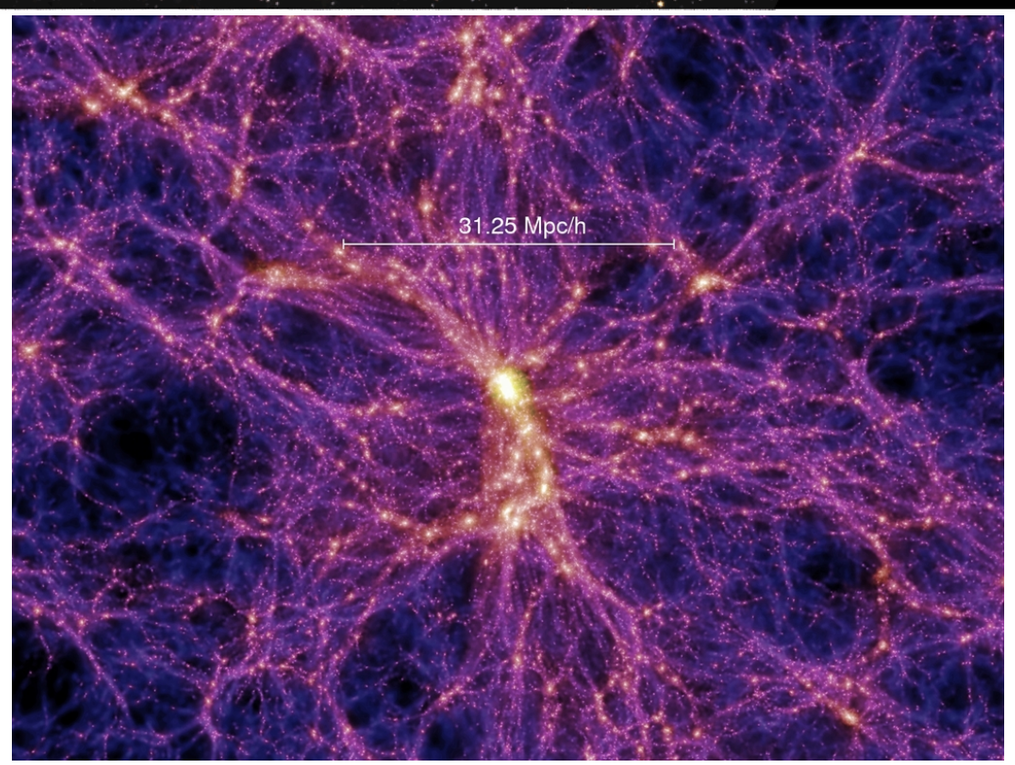
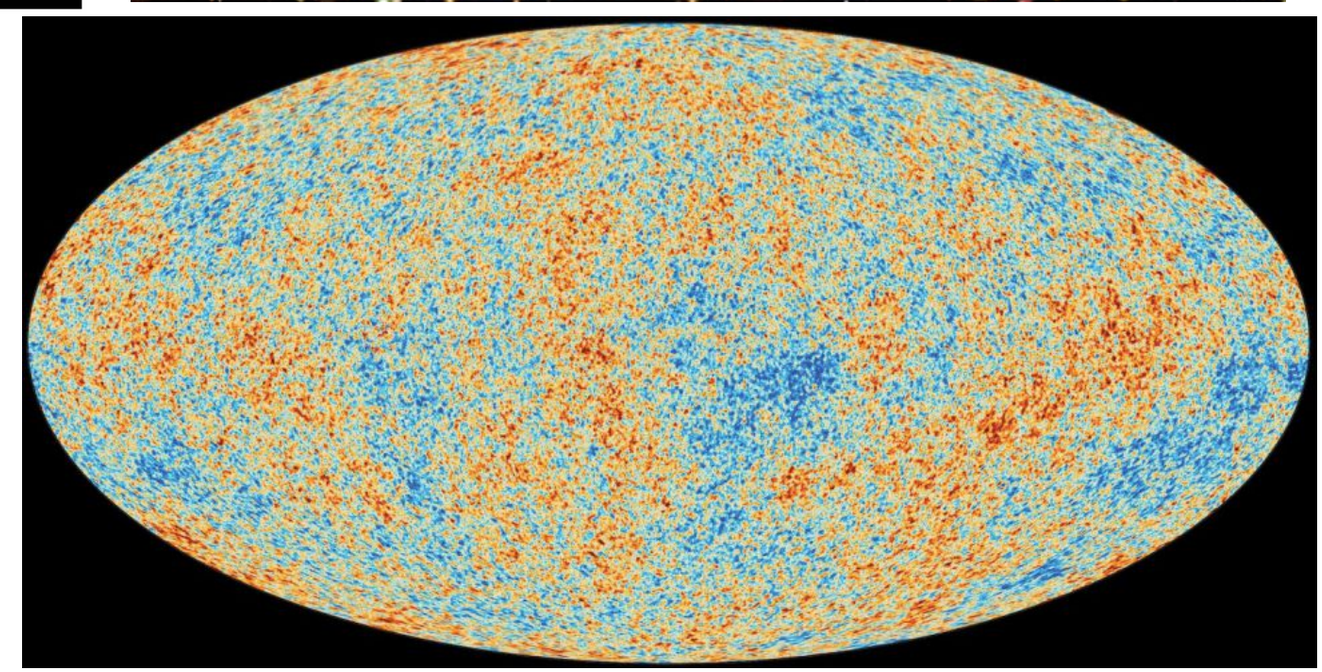
Cold Dark Matter







Cold Dark Matter: the small-scale challenges

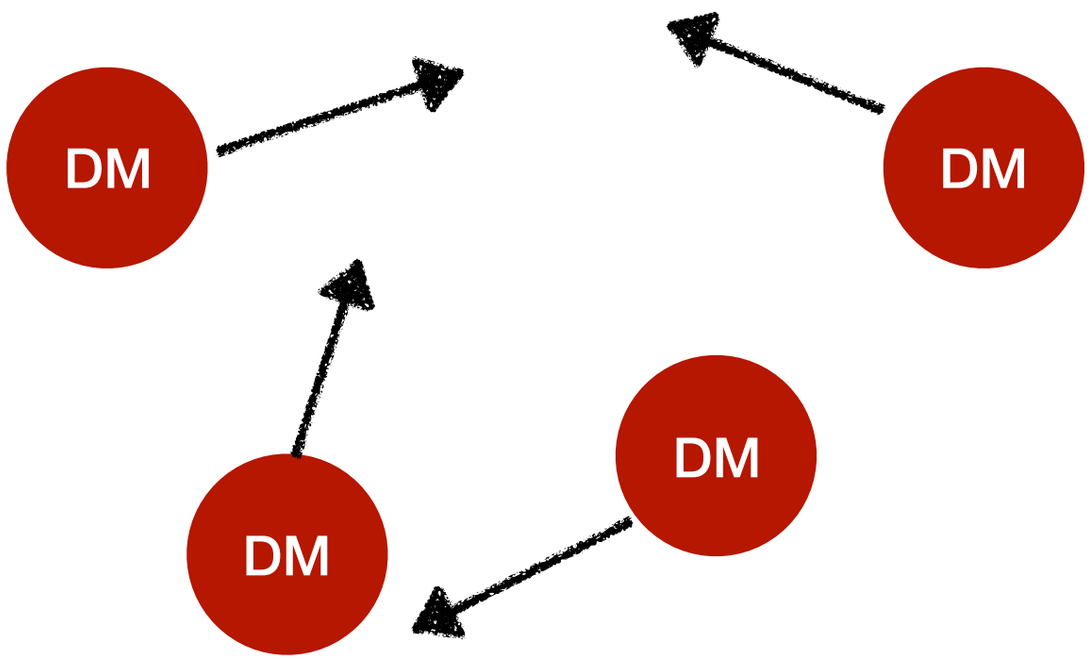
- The small-scale problems
  - Core-cusp
  - Missing satellite
  - Too big to fail
- The possible solutions
  - Better understanding of baryonic physics
  - Self-interacting dark matter (SIDM): self-interaction kinematically thermalize the inner halo
  - Fuzzy dark matter: de Broglie wavelength ~ kpc scale

Motivation of Co-Interacting dark matter

- Demonstrating that any interactions can finally make the system equilibrium and solve the core-cusp problem, not necessarily constrained to SIDM.

SIDM v.s. Co-Interacting DM

- SIDM picture:
  self-collisions can cause heat (kinetic energy) transfer



SIDM v.s. Co-Interacting DM

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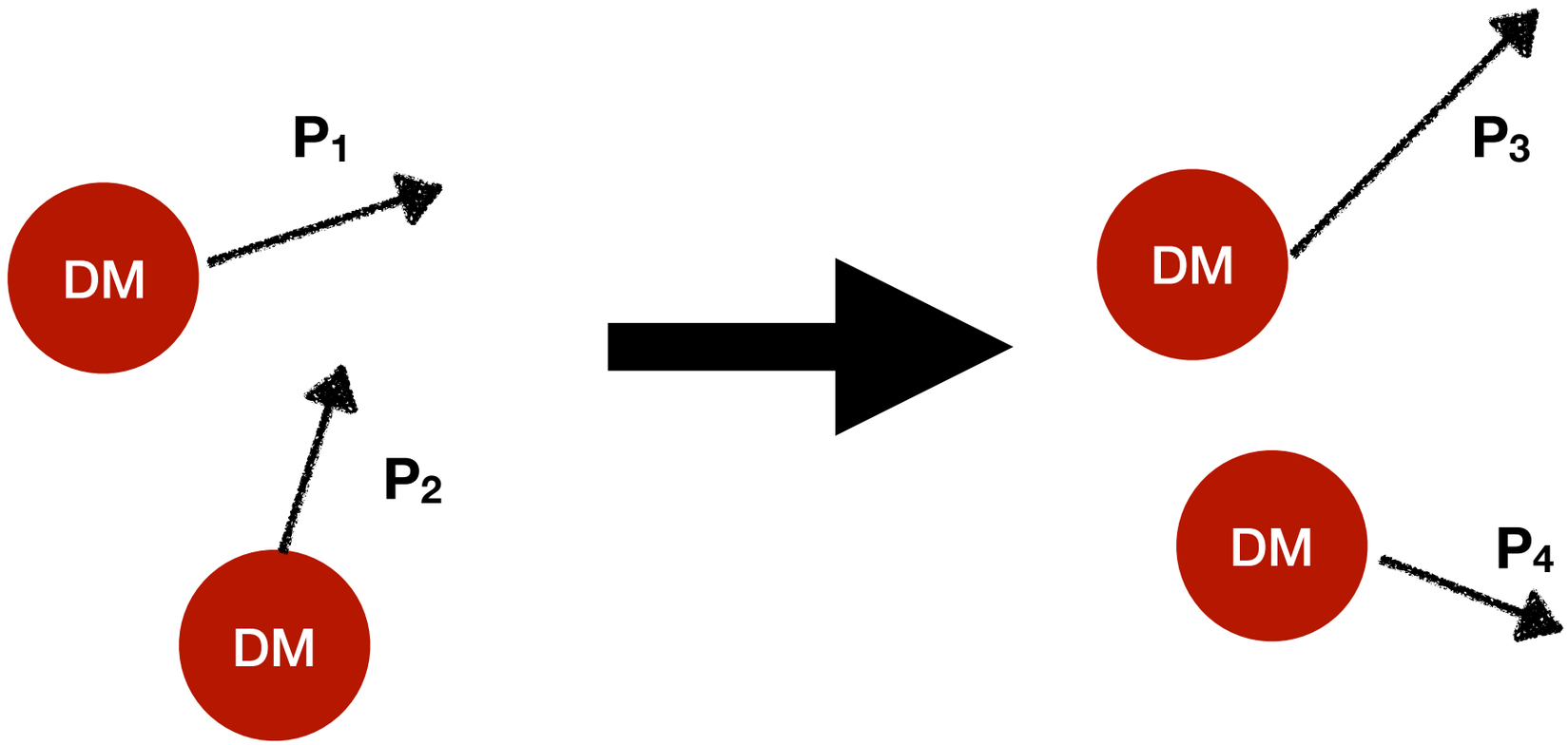

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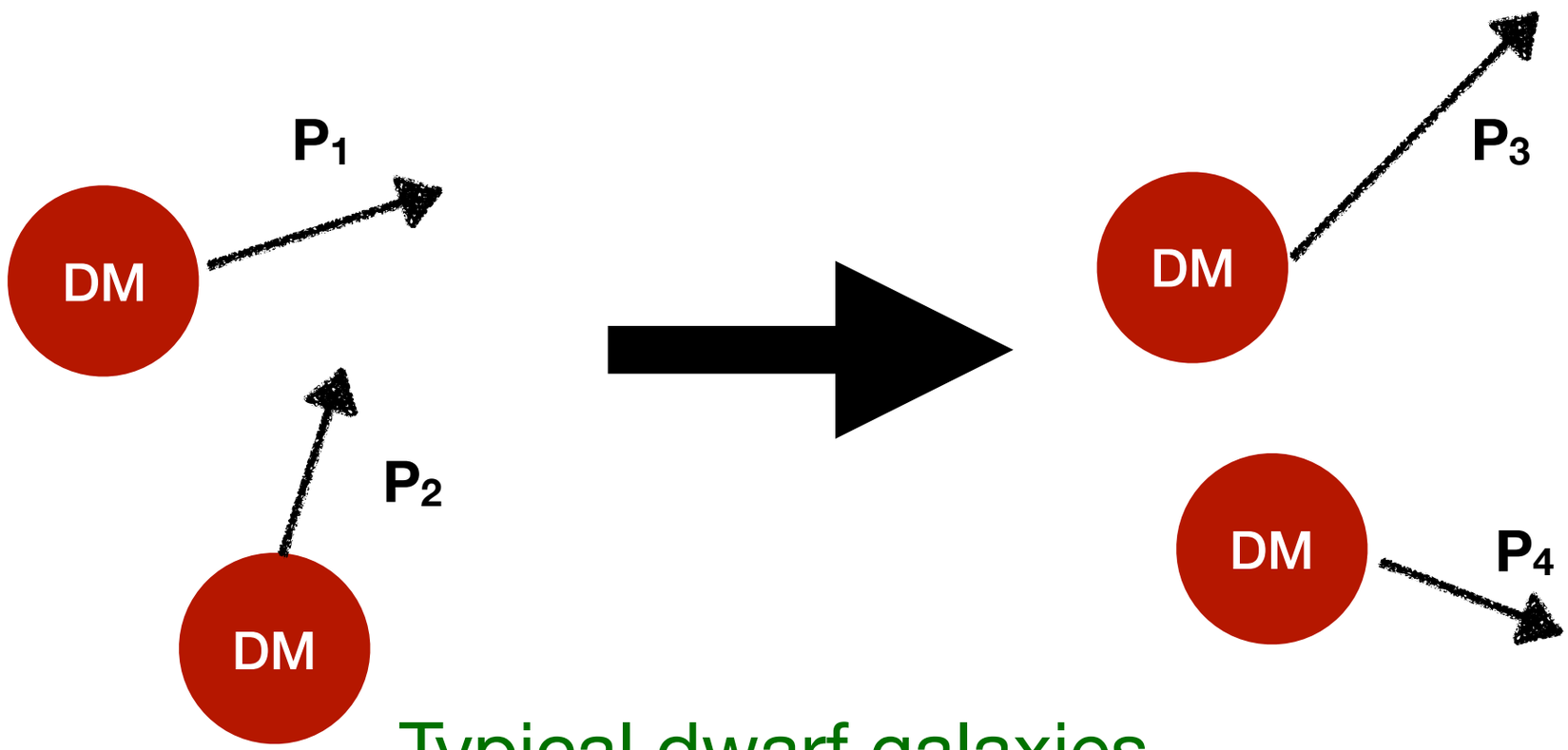


Typical dwarf galaxies

$$\rho_{\rm DM} \sim 0.1 {\rm M}_\odot/{\rm pc}^3, v_{\rm rel} \sim 50 {\rm km/s}$$

Solution from SIDM

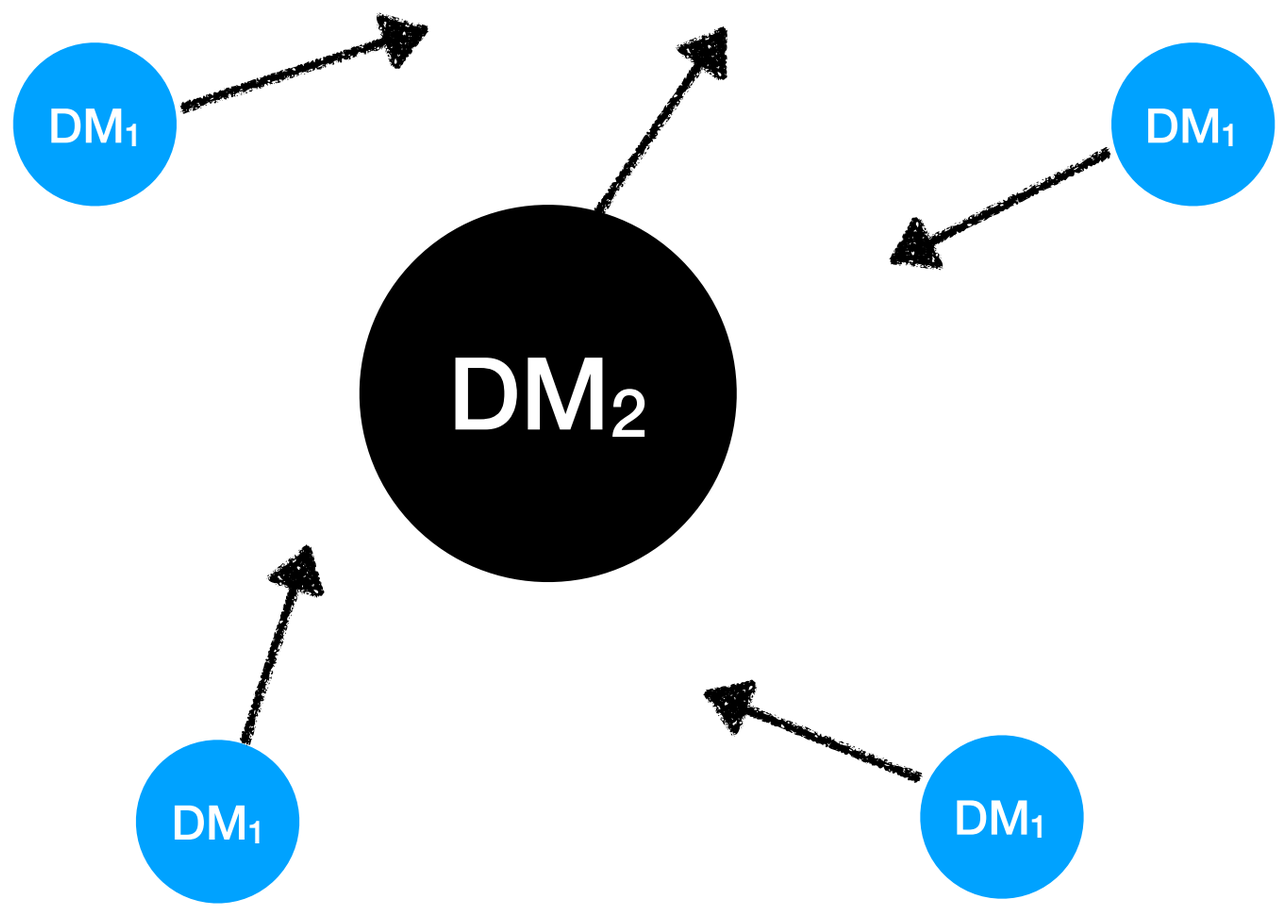
$$\frac{\sigma}{m} \sim \frac{{\rm cm}^2}{\rm g}$$

$$R = \sigma v_{\rm rel} \rho_{\rm DM}/m \sim 0.1 {\rm Gyr}^{-1}$$

For individual DM_1 , one collision per 10 Gyr is enough.
Due to equal mass, one collision is **effective**.

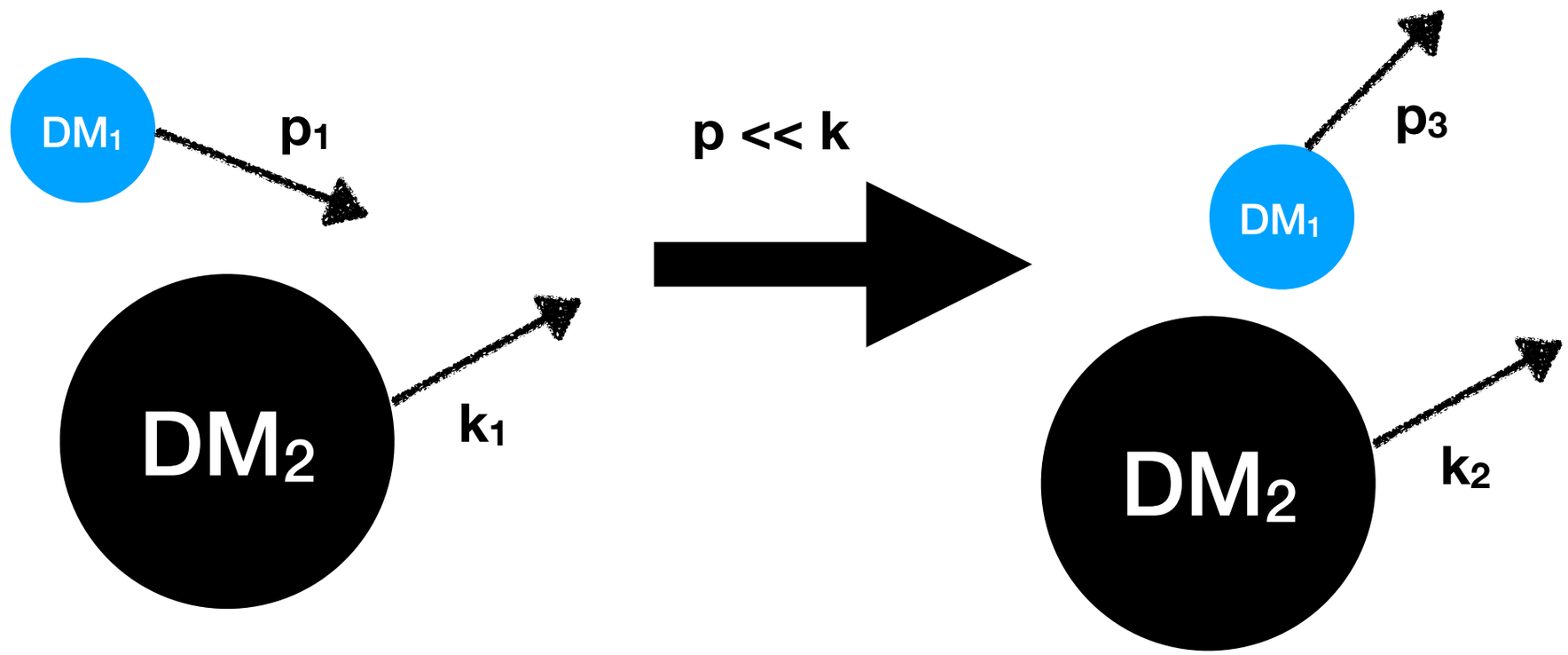
SIDM v.s. Co-Interacting DM

- Co-IDM picture:
  1. two DM component DM_1 and DM_2 (two WIMPs example)
  2. **m_1 (1GeV) << m_2 (1TeV)**, relic density fraction **f_1 >> f_2**
  3. **1-2 interaction cross-section** >> 1-1 and 2-2 interactions



SIDM v.s. Co-Interacting DM

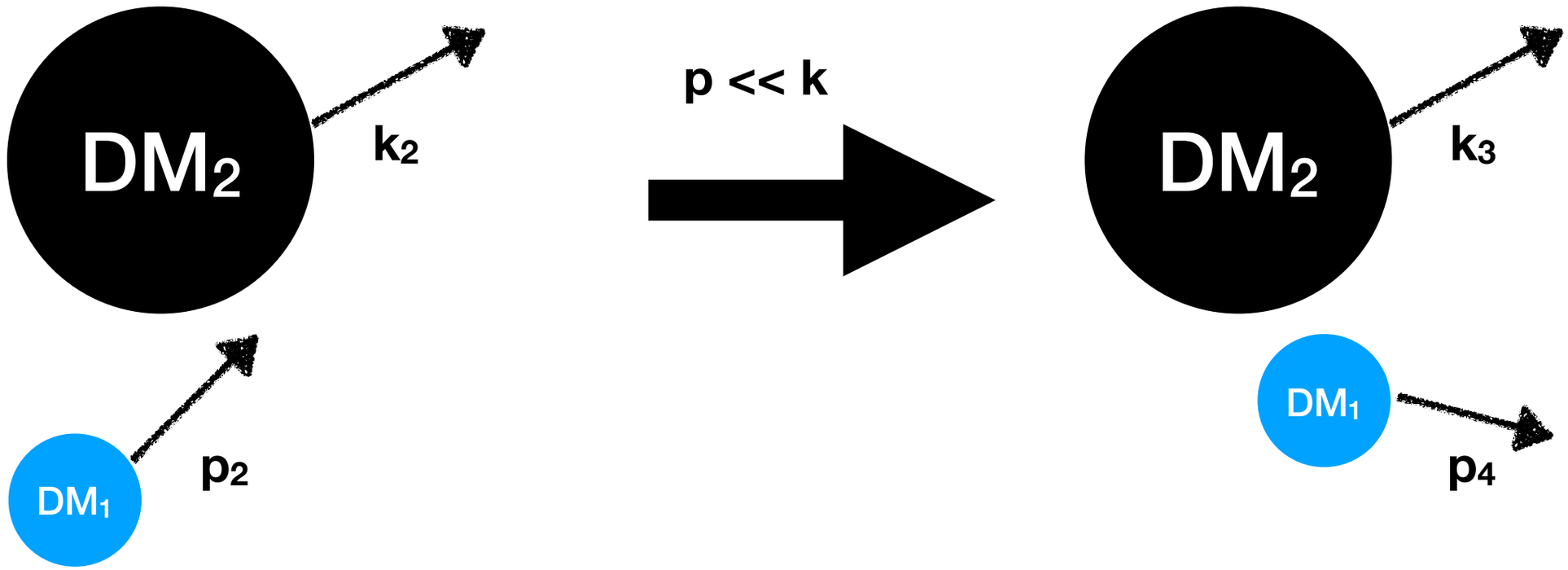
- Co-IDM picture:
  DM_1 kinetic energy can be transferred through collision with DM_2



- Both DM_1 and DM_2 have similar initial velocity dispersion from gravitational falling

SIDM v.s. Co-Interacting DM

- Co-IDM picture:
  DM_1 kinetic energy can be transferred through collision with DM_2

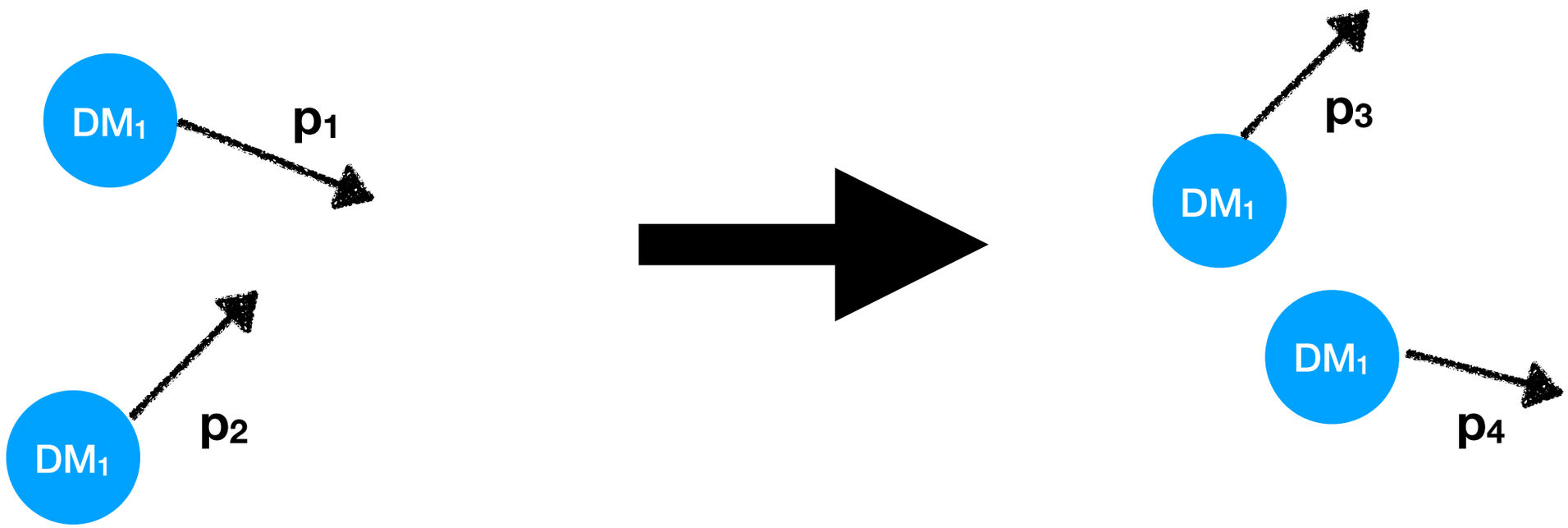


- After the first collision, another DM_1 collides with DM_2

- $m_1 << m_2$: DM_1 significantly change momentum by one collision, while DM_2 needs $(DM_2/DM_1)^2$ times of scattering (the random walk penalty)

SIDM v.s. Co-Interacting DM

- Co-IDM picture:
  DM_1 kinetic energy transferred between different DM_1

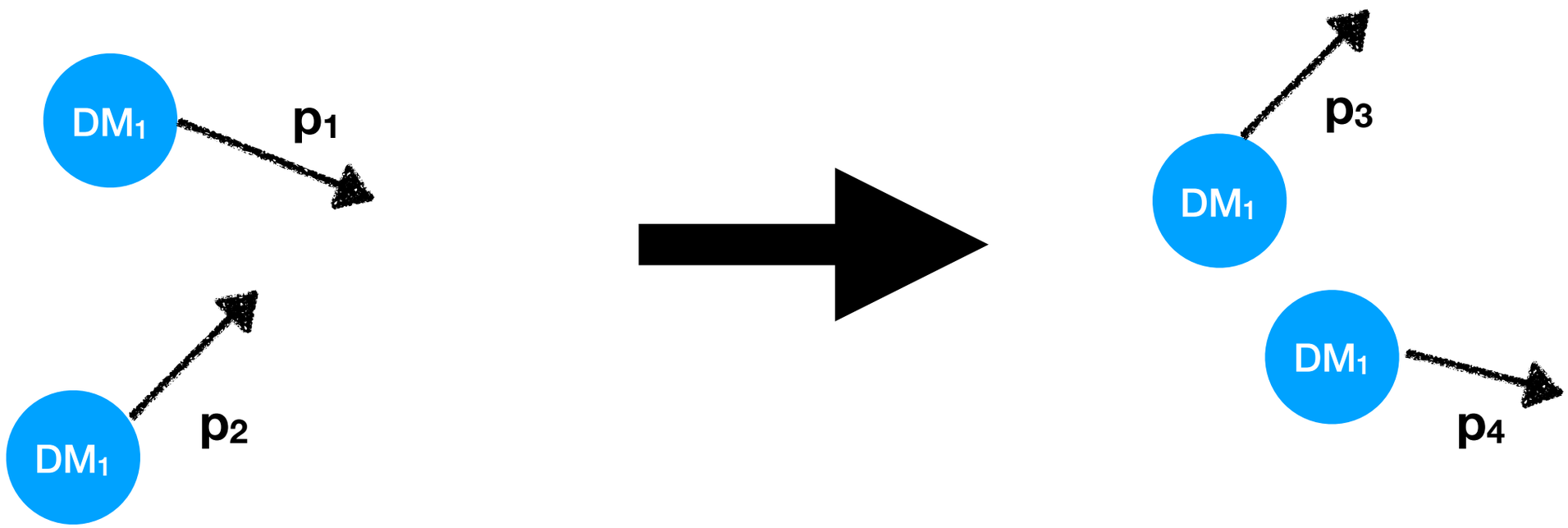


- Neglecting DM_2 momentum/energy changes (small f_2 = small total kinetic energy)

- **The Net effect**: DM_1 particles has kinetic energy transfer between themselves

SIDM v.s. Co-Interacting DM

- Co-IDM picture:
  DM_1 kinetic energy transferred between different DM_1



Typical dwarf galaxies

$$\rho_{\rm DM} \sim 0.1 {\rm M}_\odot/{\rm pc}^3, v_{\rm rel} \sim 50 {\rm km/s}$$

Solution from Co-Interaction DM

$$R_1 = (\sigma_{12} v_{\rm rel}) \rho_{{\rm DM}_2}/m_2$$
$$= f_2 (\sigma_{12} v_{\rm rel}) \rho_{\rm DM}/m_2 \sim 0.1 {\rm Gyr}^{-1}$$

1. For each DM_1, one collision with DM_2 per 10 Gyr is enough.
2. Due to small mass, one collision for DM_1 is **effective**.
3. For each DM_2, it has many collisions with DM_1 per 10 Gyr, but its momentum change is suppressed by random walk factors.

Co-Interacting dark matter

- Example model: two component DM, A' and dark fermion ψ with U(1) interaction

$$\mathscr{L} \supset g' \bar{\psi} \gamma_\mu \psi A'^\mu$$

Co-Interacting dark matter

- Example model: two component DM, A' and dark fermion ψ with U(1) interaction

$$\mathscr{L} \supset g'\bar{\psi}\gamma_\mu\psi A'^\mu$$

  - Novelty:
    1. A' (DM_1) dominant component, $m_1 << eV$
    2. ψ (DM_2) dark fermion subdominant, $m_2 \sim$ weak scale

  - Unusual features:
    1. A' has large occupation number
    2. two components has huge mass difference

  - Other assumptions:
    1. similar initial velocity dispersion
    2. $f_1 + f_2 = 1$

A' and ψ scattering

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

- Boltzmann equation

$$(\partial_t + v_i \partial_{x_i} + \dot{v}_i \partial_{v_i}) \mathcal{N}(\mathbf{x}, \mathbf{p}, \mathbf{t}) = \mathcal{C}(\mathbf{x}, \mathbf{p}, \mathbf{t})$$

Collisional kernels in the limit of large occupation number $\mathcal{N}^{A'} \gg 1$

$$C_\psi \simeq \sum_{spin} \int \frac{d^3\mathbf{p_1} d^3\mathbf{k_2}}{(2\pi)^5 8 m_{A'}^2 m_\psi^2} |\mathbf{M}\left(\mathbf{k_1}, \mathbf{p_1}, \mathbf{k_2}, \mathbf{p_2}\right)|^2 \times \delta(E_{k_1} + E_{p_1} - E_{k_2} - E_{p_2}) \underline{\mathcal{N}_{p_1}^{A'} \mathcal{N}_{p_2}^{A'} \left(\mathcal{N}_{k_2}^{\psi} - \mathcal{N}_{k_1}^{\psi}\right)}$$

$$C_{A'} \simeq \sum_{spin} \int \frac{d^3\mathbf{k_1} d^3\mathbf{k_2}}{(2\pi)^5 8 m_{A'}^2 m_\psi^2} |\mathbf{M}\left(\mathbf{k_1}, \mathbf{p_1}, \mathbf{k_2}, \mathbf{p_2}\right)|^2 \times \delta(E_{k_1} + E_{p_1} - E_{k_2} - E_{p_2}) \underline{\mathcal{N}_{p_1}^{A'} \mathcal{N}_{p_2}^{A'} \left(\mathcal{N}_{k_2}^{\psi} - \mathcal{N}_{k_1}^{\psi}\right)}$$

Recall normally it is

$$\underline{\mathcal{N}_1 \mathcal{N}_2 \left(1 \pm \mathcal{N}_3\right) \left(1 \pm \mathcal{N}_4\right) - \mathcal{N}_3 \mathcal{N}_4 \left(1 \pm \mathcal{N}_1\right) \left(1 \pm \mathcal{N}_2\right) \approx \left(\mathcal{N}_1 \mathcal{N}_2 - \mathcal{N}_3 \mathcal{N}_4\right)}$$

Novel features

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

1. Large occupation number of A'

$$\langle \mathcal{N}^{A'} \rangle \sim \frac{\rho_{A'}/m_{A'}}{m_{A'}^3 v_0^3} \sim 3 \times 10^{76} \times \left(\frac{\rho_{A'}}{0.1 \mathrm{M}_\odot/\mathrm{pc}^3} \right) \left(\frac{m_{A'}}{10^{-18}\mathrm{eV}} \right)^{-4} \left(\frac{v_0}{10^{-3}} \right)^{-3}$$

2. Suppression from the forward-backward scattering cancellation

$$p \ll k \to \left(\mathcal{N}^{\psi}_{k_2} - \mathcal{N}^{\psi}_{k_1} \right) \sim \mathcal{N}^{\psi} \times \frac{m_{A'}}{m_\psi}$$

3. Random walk suppression from multiple scattering for ψ

$$\Gamma_\psi \equiv \frac{C_\psi}{\mathcal{N}_\psi}, \quad \Gamma_\psi^{\mathrm{eff}} \simeq \Gamma_\psi \frac{m_{A'}^2}{m_\psi^2}$$

"effective" = collision rate with significant momentum change

A' and ψ effective scattering rate

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

- A' dominates relic abundance

$$\Gamma^{\rm eff}_{A'} \simeq \Gamma_{A'} \equiv \frac{C_{A'}}{\mathcal{N}_{A'}} \simeq n_\psi \langle \sigma v \rangle_{\psi A'} \langle \mathcal{N}^{A'} \rangle \left(\frac{m_{A'}}{m_\psi} \right)$$

Small A' mass

Final state Bose enhancement

Scattering cross-section

$$\langle \sigma v \rangle_{\psi A'} \simeq \frac{g'^4 v_{\rm rel}}{4\pi m_\psi^2}$$

Forward-backward cancellation

The dark atom laser emission

$$\psi(k_1) + A'(p_1) \to \psi^* \to \psi(k_2) + A'(p_2)$$

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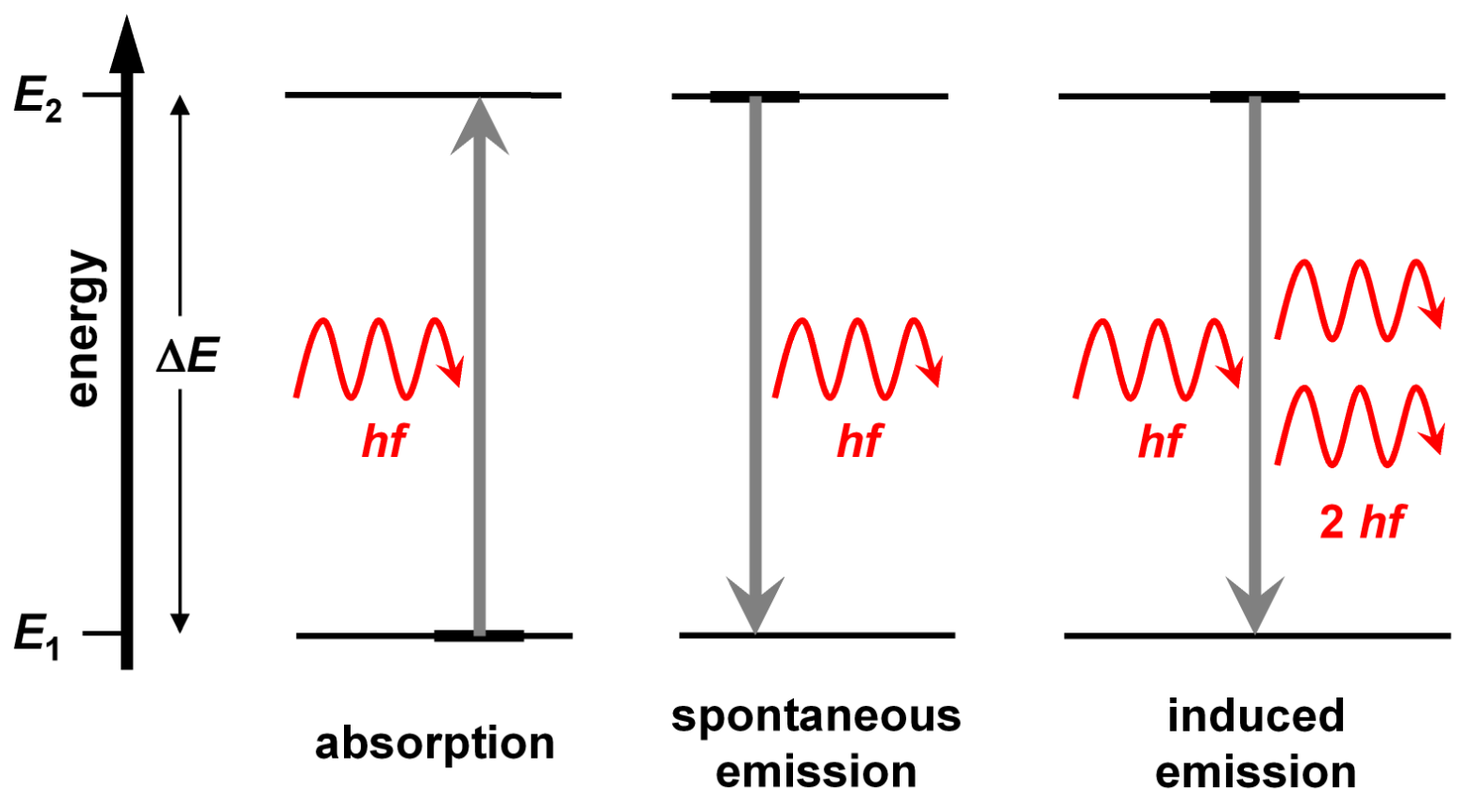
Laser emission



The dark atom laser emission

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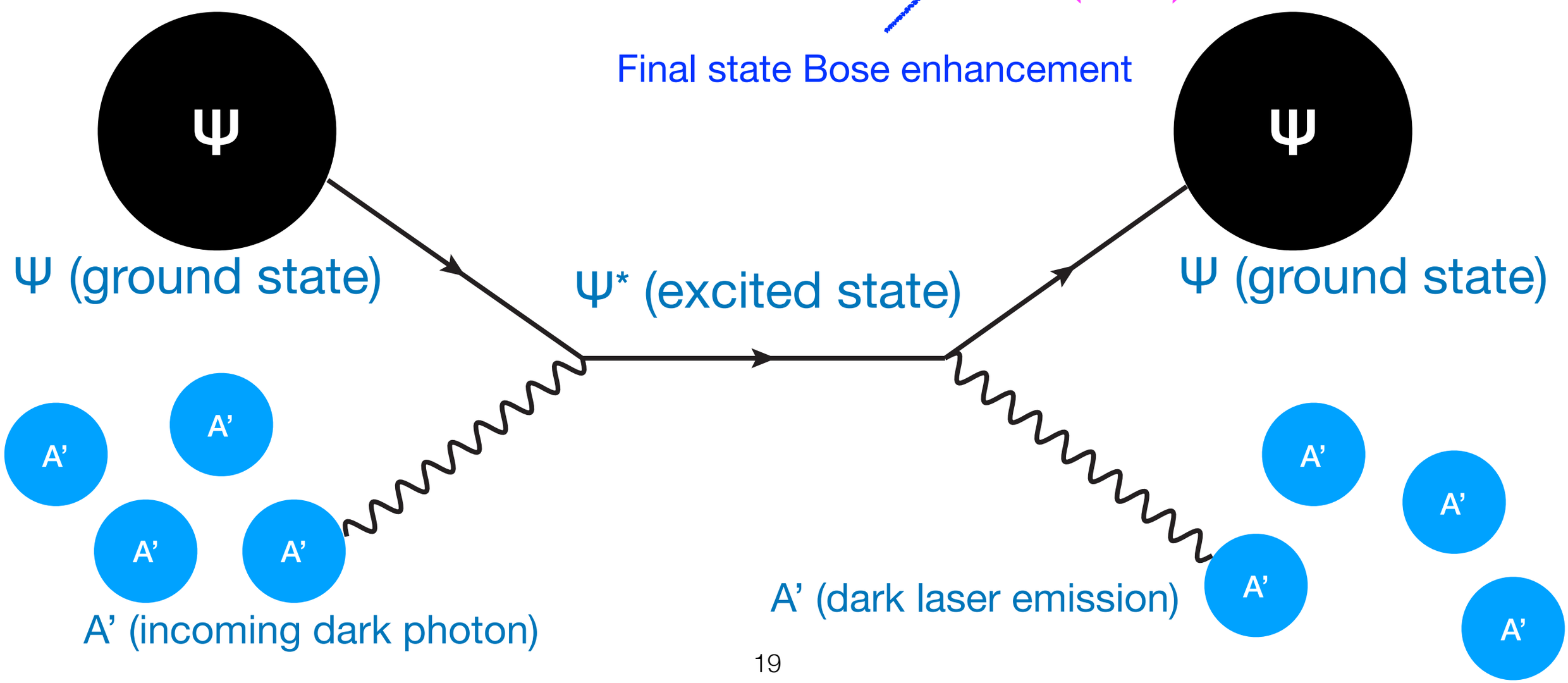
Final state Bose enhancement

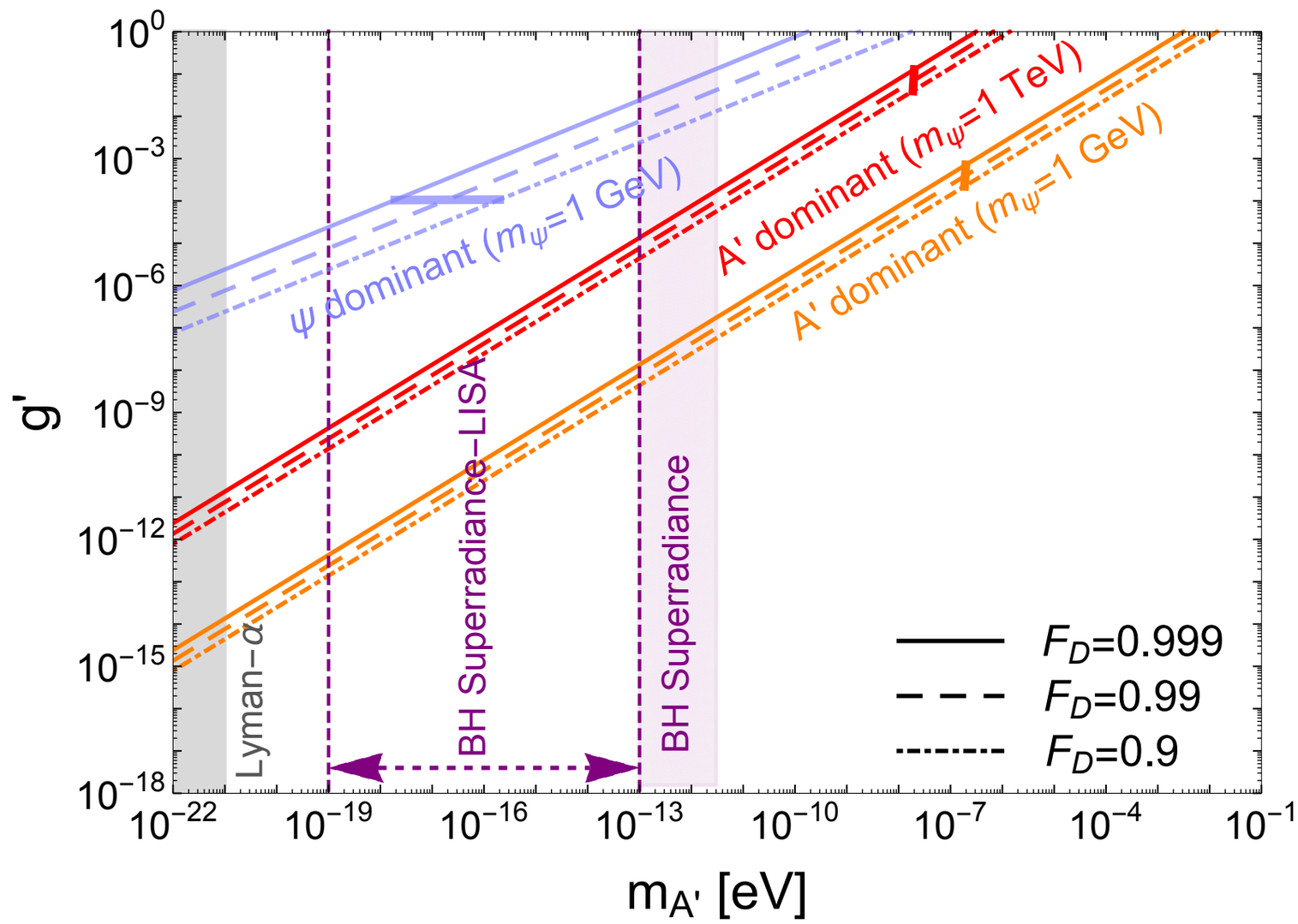


A' and ψ effective scattering rate

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

- In typical dwarf galaxies

$$\Gamma^{\rm eff}_{A'} \approx 0.14{\rm Gyr}^{-1}\frac{F_\psi}{0.05}\left(\frac{g'}{10^{-12}}\right)^4\left(\frac{m_{A'}}{10^{-18}{\rm eV}}\right)^{-3}\left(\frac{m_\psi}{1{\rm GeV}}\right)^{-4}\times\left(\frac{v_{\rm rel}}{10{\rm km/s}}\right)\left(\frac{v_0}{10{\rm km/s}}\right)^{-3}\left(\frac{\rho_{\rm DM}}{0.1{\rm M}_\odot/{\rm pc}^3}\right)^2$$



Summary

- We discussed a two component DM model as an example, that a system can be kinetically thermalized via interaction with others

- Specific DM model: ultralight A' + ψ with U(1) interactions

  - 1. Large occupation number of A'

  - 2. Forward-backward scattering cancellation

  - 3. Random walk suppression for ψ

- Dark atom laser emission solves the core-cusp problem for ultralight A' DM in [10^{-19}, 10^{-7}] eV mass range.

$$\psi(k_1) + A'(p_1) \to \psi^* \to \psi(k_2) + A'(p_2)$$

Thank you!

Backup slides

A' and ψ effective scattering rate

$$\psi(k_1) + A'(p_1) \to \psi(k_2) + A'(p_2)$$

- A' dominates relic abundance

$$\Gamma^{\rm eff}_{A'} \simeq \Gamma_{A'} \equiv \frac{C_{A'}}{\mathcal{N}_{A'}} \simeq n_\psi \langle \sigma v \rangle_{\psi A'} \langle \mathcal{N}^{A'} \rangle \left(\frac{m_{A'}}{m_\psi} \right)$$

Small A' mass

Final state Bose enhancement

Scattering cross-section

Forward-backward cancellation

$$\langle \sigma v \rangle_{\psi A'} \simeq \frac{g'^4 v_{\rm rel}}{4\pi m_\psi^2}$$

- Rate for ψ

$$\Gamma^{\rm eff}_{\psi} \simeq n_{A'} \langle \sigma v \rangle_{\psi A'} \langle \mathcal{N}^{A'} \rangle \frac{m_{A'}}{m_\psi} \frac{m_{A'}^2}{m_\psi^2}$$

Large ψ mass
Random walk factor

$$\Gamma^{\rm eff}_{\psi} \ll \Gamma^{\rm eff}_{A'}$$