Formation of dark matter solar halos

DESY Summer Student programme 2024

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HELMHOLTZ

Content

Introduction

What is Dark Matter?

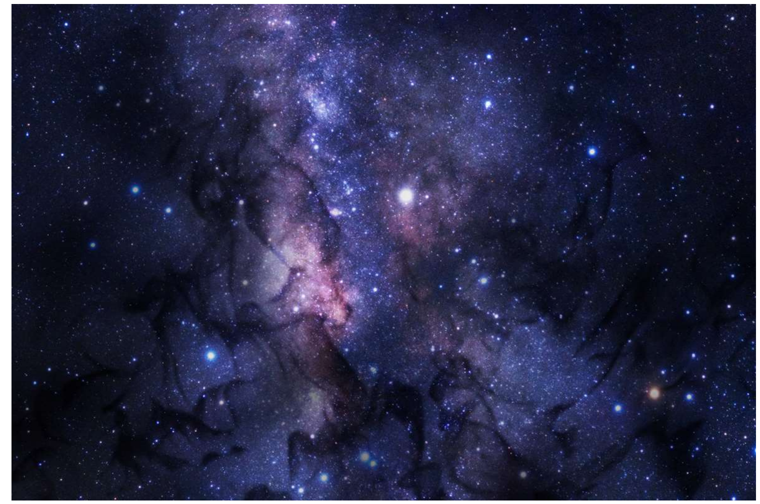
Evidence of dark matter in the Universe

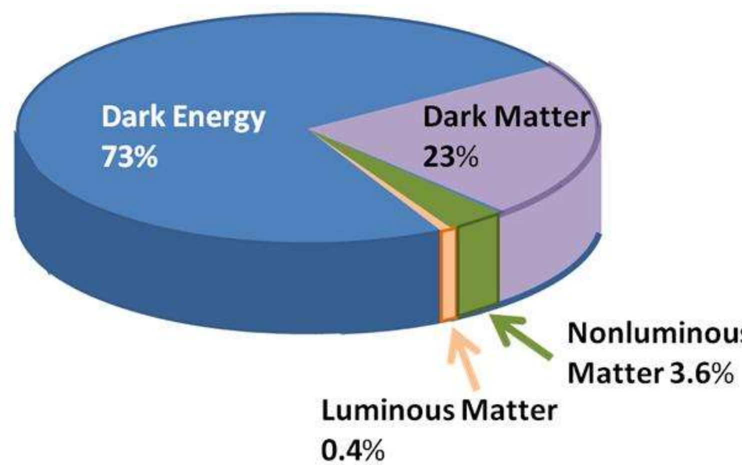
- Rotation velocity of the stars in the galaxies;
- High-speed, gravitationally bound clusters of galaxies;
- Gravitational Lensing;
- Observations from cluster collisions;

A lot of different candidates! See Dark Matter Lecture

Why dark matter?

- Predicted production during Early Universe
- Axions could explain other problems, such as in QCD





Spin-0 bosons

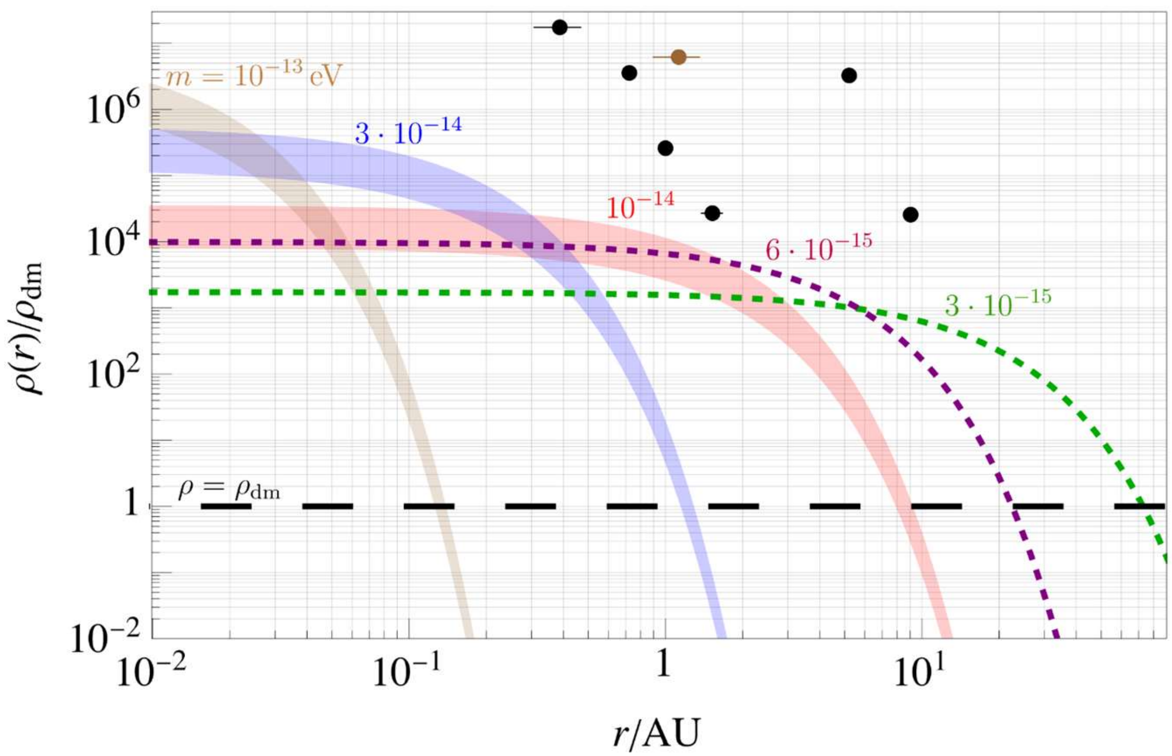
How much DM is in our Solar System?

DM density in our galaxy averaged on scales much bigger than the Solar System

$$\rho_{\mathrm{dm}} = 0.4\ \mathrm{GeV}/\mathrm{cm}^3$$

Loose upper bounds from Solar System ephemerides from:

- planets (arXiv: 0903.4849)
- asteroids (arXiv: 2210.03749)

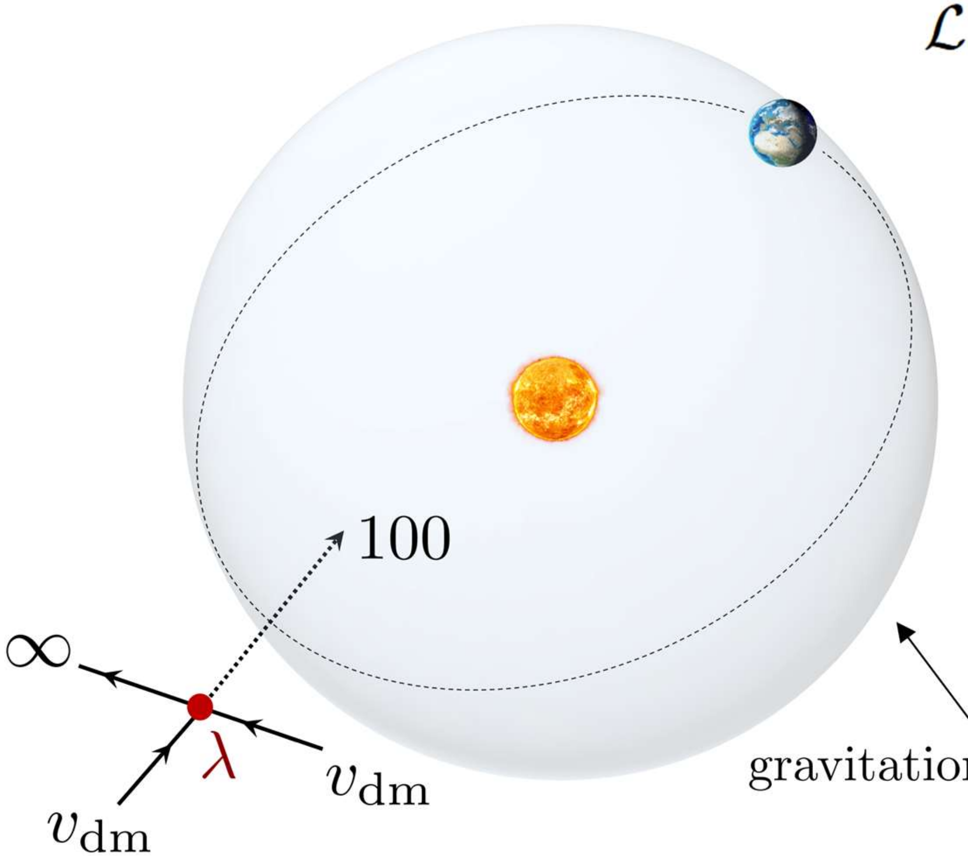


From arXiv: 2306.12477 [hep-ph]

Spin-0 bosons

Can the Sun gravitationally capture DM?

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \, \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \underbrace{\frac{\lambda}{4!}\phi^4}_{\text{self-interaction}}$$



gravitational atom (‘solar halo’)

$$v_\odot = 240 \text{ km/s} \overset{!}{=} v_{\rm dm}$$

Spin-0 bosons

Can the Sun gravitationally capture DM?

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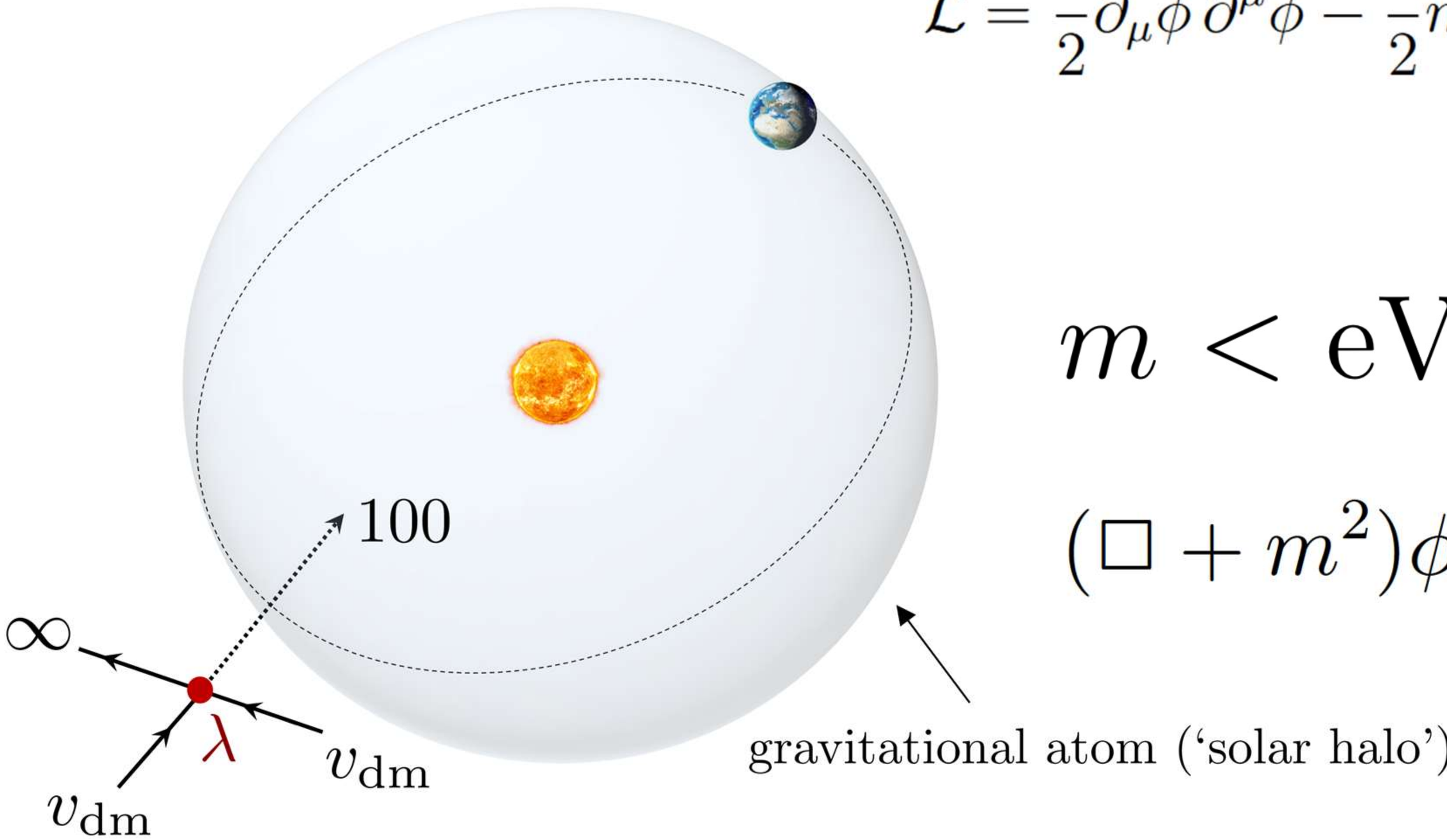

$$m < \mathrm{eV} \quad \text{(ULDM)}$$

$$(\Box + m^2)\phi = -\frac{\lambda}{6}\phi^3$$

Spin-0 bosons

Can the Sun gravitationally capture DM?

Non-relativistic approximation

$$\phi = \frac{1}{\sqrt{2m}}\left(\psi e^{-imt} + \mathrm{c.c.}\right) \quad \text{with } \dot{\psi} \ll m\psi$$

+ gravitational potential

$$\Phi = -\frac{GM}{r}$$

→ Schroedinger-Poisson equation

$$\left(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r}\right)\psi = g|\psi|^2\psi$$

$$\alpha = GMm$$

$$\alpha_{em} = \frac{e^2}{4\pi\epsilon_0}$$

From arXiv: 2306.12477 [hep-ph]

Spin-0 bosons

Can the Sun gravitationally capture DM?

Analogy with Hydrogen atom ($g = 0$) → expansion in its eigenfunctions

$$\psi(\boldsymbol{x},t) = \sum_{nlm} c_{nlm}(t) e^{-i\omega_{nlm}t}\psi_{nlm}(\boldsymbol{x}) + \int [dk] c_{\boldsymbol{k}}(t) e^{-i\omega_{\boldsymbol{k}}t}\psi_{\boldsymbol{k}}(\boldsymbol{x})$$

and a lot of calculations (and sweat)…

ULDM: coherence time $\tau_{\mathrm{dm}} = \frac{2\pi}{m v_{\mathrm{dm}}^2}$ after which uncorrelated waves:

$$\langle a^*(\boldsymbol{k}) a(\boldsymbol{k}')\rangle \equiv (2\pi)^3 f(\boldsymbol{k})\delta(\boldsymbol{k}-\boldsymbol{k}')$$

use $\langle \cdot \rangle$ over times much larger than τ_{dm}

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Spin-0 bosons

Can the Sun gravitationally capture DM?

Analogy with Hydrogen atom ($g = 0$) → expansion in its eigenfunctions

$$\psi(\boldsymbol{x}, t) = \sum_{nlm} c_{nlm}(t) e^{-i\omega_{nlm} t} \psi_{nlm}(\boldsymbol{x}) + \int [dk] c_{\boldsymbol{k}}(t) e^{-i\omega_{\boldsymbol{k}} t} \psi_{\boldsymbol{k}}(\boldsymbol{x})$$

and a lot of calculations (and sweat)…

$$i\dot{c}^{(1)}_{nlm}(t) + \sqrt{N^{(0)}_{nlm}} \omega^{(1)}_{nlm} = g e^{i\omega_n t} \int d^3x \boxed{\left|\psi^{(0)}\right|^2 \psi^{(0)} \psi^*_{nlm}}$$

2→2 scattering processes

From arXiv: 2306.12477 [hep-ph]

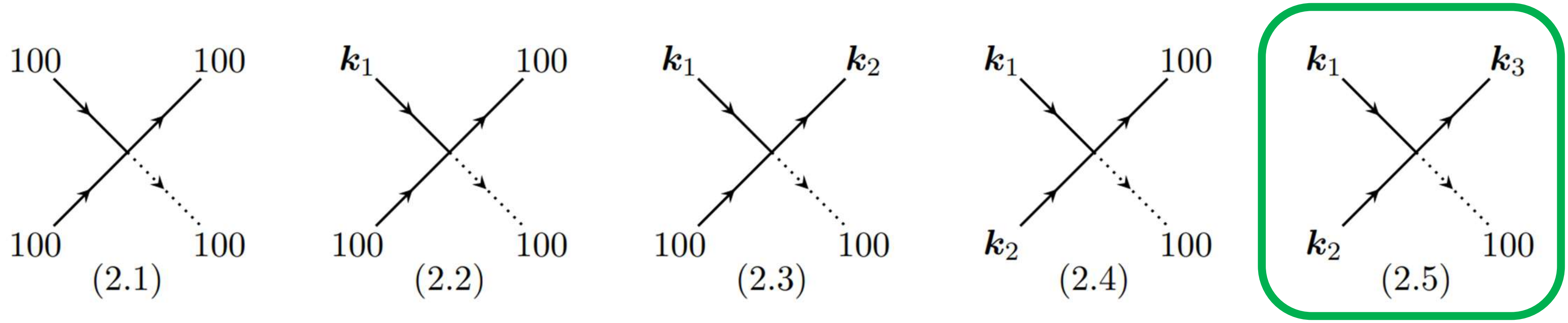
Spin-0 bosons

Can the Sun gravitationally capture DM?

Initial state: waves + ground state 100

$$\psi^{(0)} = \sqrt{N_{100}^{(0)}} e^{-i\omega_1 t}\psi_{100} + \int [dk] a(\boldsymbol{k}) e^{-i\omega_k t}\psi_{\boldsymbol{k}}$$

1st order: 2→2 scattering processes. 5 possible diagrams:



From arXiv: 2306.12477 [hep-ph]

Spin-0 bosons

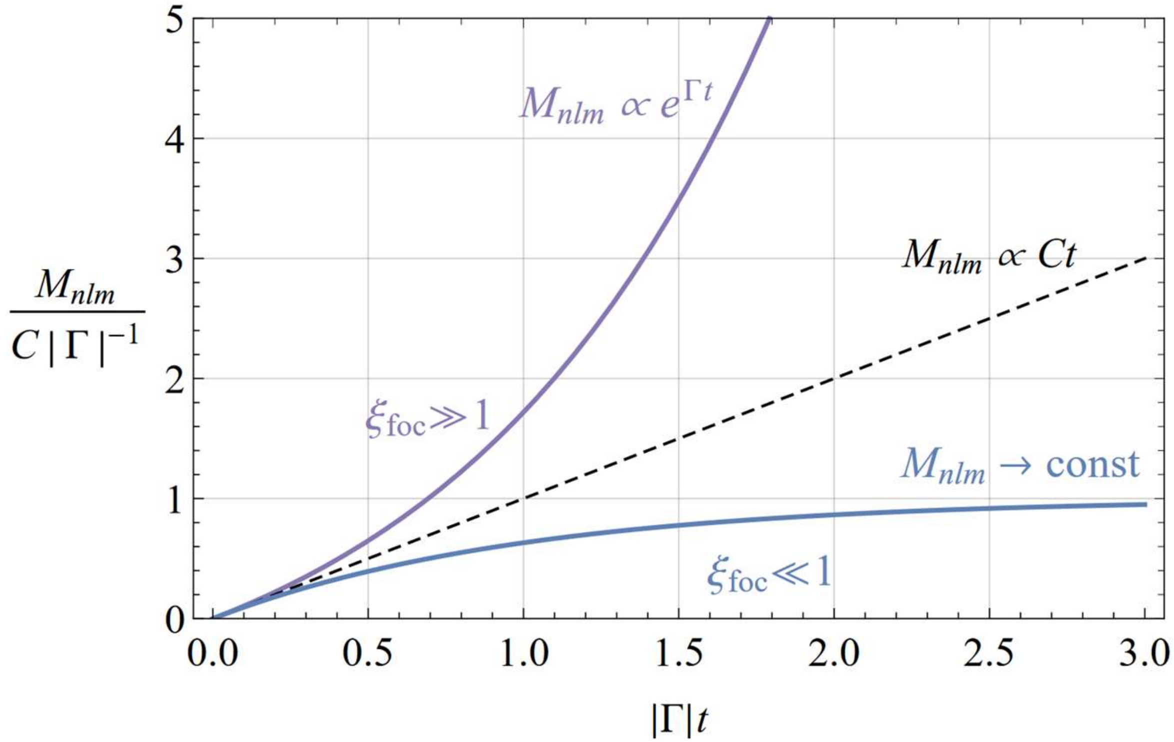
Can the Sun gravitationally capture DM?

gravitational focusing $\xi_{\text{foc}}(k) \stackrel{\text{def}}{=} \frac{\lambda_{\text{dB}}}{R_\star} = \frac{2\pi}{kR_\star} = \frac{2\pi\alpha}{v}$

In conclusion $$\dot{M}_{100} = m\dot{N}_{100} = C + \Gamma M_{100} + \ldots$$

2 regimes:

- $\Gamma < 0$ (blue)
  - asymptotically constant
  - usually not overdensity
- $\Gamma > 0$ (violet)
  - exponential increase
  - likely Bosenova



From arXiv: 2306.12477 [hep-ph]

Dark photons (spin-1 bosons)

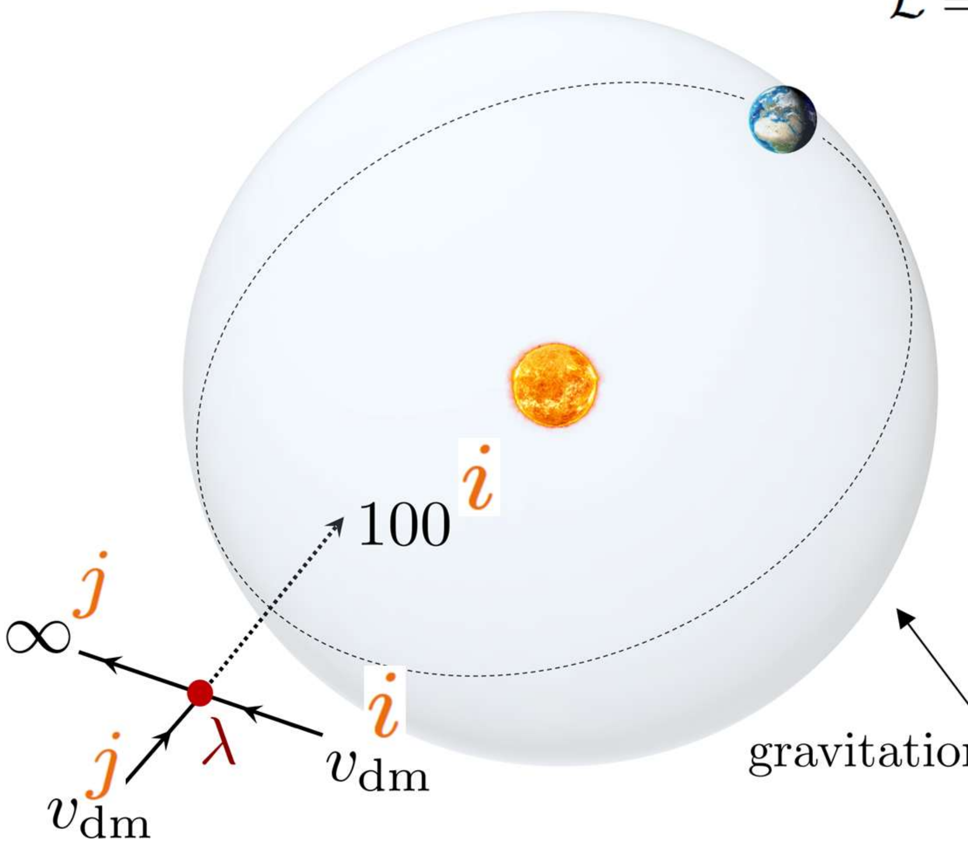
Can the Sun gravitationally capture DP?

$$\mathcal{L} = -\frac{1}{4}F_{\rho\sigma}F^{\rho\sigma} - \frac{1}{2}m^2 A_\rho A^\rho + \underbrace{\frac{1}{\Lambda^4}(F_{\rho\sigma}F^{\rho\sigma})^2}_{\text{self-interaction}}$$

$$F^{\mu\nu} = \partial_\mu A^\nu - \partial_\nu A^\mu$$

$$A^i = \frac{1}{\sqrt{2m}}\left(\psi^i e^{-imt} + \text{c.c.}\right)$$

with $\partial_\nu \psi^i \ll m\psi^i$



gravitational atom ('solar halo')

Dark photons (spin-1 bosons)

Can the Sun gravitationally capture DP?

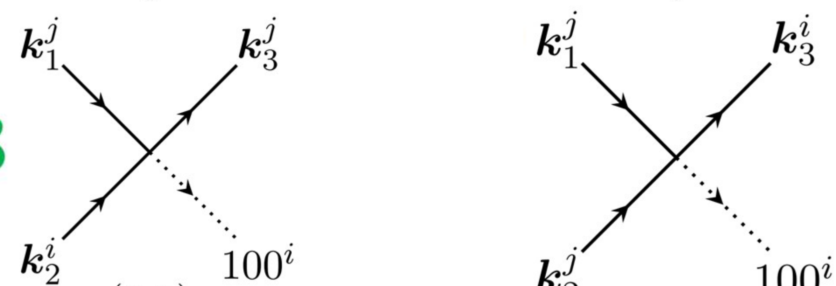
Non-relativistic limit + gravitational potential →

$$\rightarrow \left(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r} \right) \psi^i = g \sum_j \left(-2|\psi^j|^2 \psi^i - (\psi^j)^2 \psi^{i*} \right)$$

Same as for spin-0 bosons (but more sweat)… and finally

$$i\dot{c}_{100}^{i(1)}(t) = g e^{i\omega_1 t} \boxed{\sum_j} \int d^3x \left(-2 \underbrace{|\psi^{j(0)}|^2 \psi^{i(0)} \psi^{i*}_{100}} - \underbrace{(\psi^{j(0)})^2 \psi^{i(0)*} \psi^{i*}_{100}} \right)$$

$$j = 1, 2, 3$$



(3.1) (3.2)

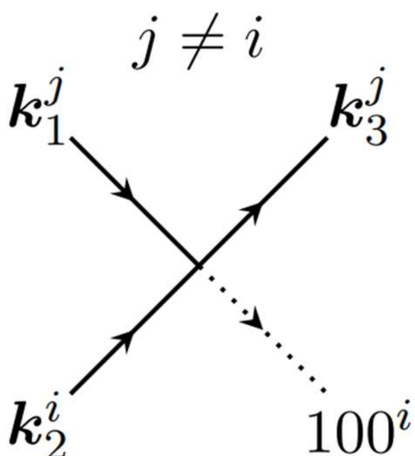
Dark photons (spin-1 bosons)

Can the Sun gravitationally capture DP?

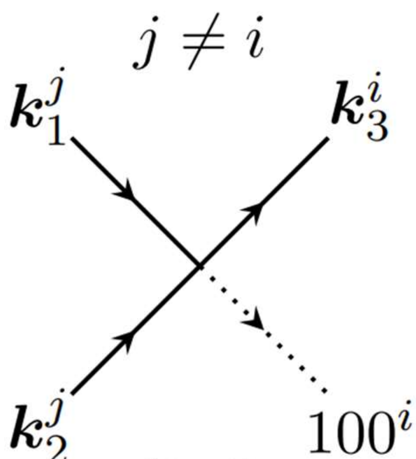
But… problem! Non-zero interference (3.1)x(3.2)* complicates calculation

Solution: interference from equal diagrams → separate the culprit $(j = i)$

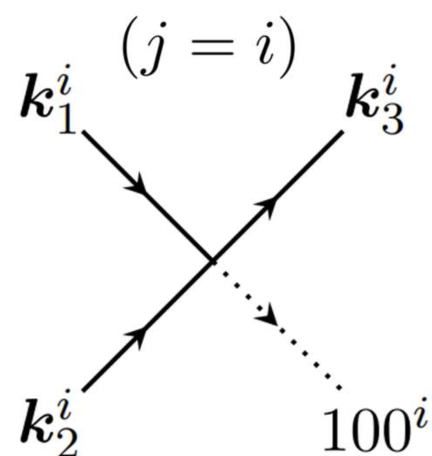
→ 3 new diagrams → Bose enhancement method ✓



(3.3)



(3.4)



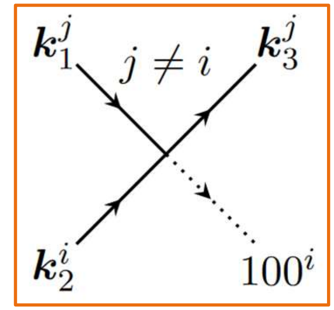
(3.5)

Dark photons (spin-1 bosons)

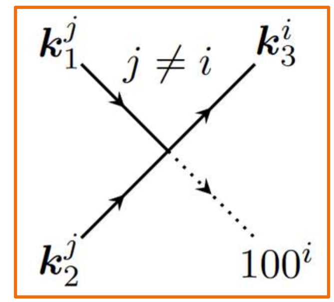
Can the Sun gravitationally capture DP?

$$\dot{N}^{i}_{100} = \dot{N}^{i(3.3)}_{100} + \dot{N}^{i(3.4)}_{100} + \dot{N}^{i(3.5)}_{100}$$

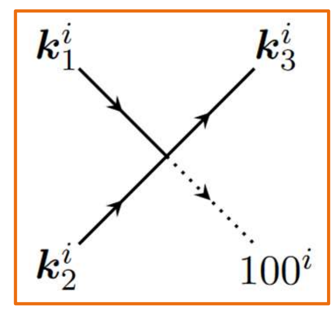
$$\begin{aligned}\dot{N}^{i(3.3)}_{100} = \frac{4}{27}\sum_{j\neq i} g^2 \int &[dk_1][dk_2][dk_3](2\pi)\delta(\Delta\omega)|\mathcal{M}|^2\times \\ &\times\Big\{ f^j(\boldsymbol{k}_1)f^i(\boldsymbol{k}_2)f^j(\boldsymbol{k}_3) \\ &\quad + N^i_{100}\big[f^j(\boldsymbol{k}_1)f^i(\boldsymbol{k}_2) - \big(f^j(\boldsymbol{k}_1)+f^i(\boldsymbol{k}_2)\big)f^j(\boldsymbol{k}_3)\big]\Big\}\end{aligned}$$



$$\begin{aligned}\dot{N}^{i(3.4)}_{100} = \frac{2}{27}\sum_{j\neq i} g^2 \int &[dk_1][dk_2][dk_3](2\pi)\delta(\Delta\omega)|\mathcal{M}|^2\times \\ &\times\Big\{ f^j(\boldsymbol{k}_1)f^j(\boldsymbol{k}_2)f^i(\boldsymbol{k}_3) \\ &\quad + N^i_{100}\big[f^j(\boldsymbol{k}_1)f^j(\boldsymbol{k}_2) - \big(f^j(\boldsymbol{k}_1)+f^j(\boldsymbol{k}_2)\big)f^i(\boldsymbol{k}_3)\big]\Big\}\end{aligned}$$



$$\begin{aligned}\dot{N}^{i(3.5)}_{100} = \frac{18}{27} g^2 \int &[dk_1][dk_2][dk_3](2\pi)\delta(\Delta\omega)|\mathcal{M}|^2\times \\ &\times\Big\{ f^i(\boldsymbol{k}_1)f^i(\boldsymbol{k}_2)f^i(\boldsymbol{k}_3) \\ &\quad + N^i_{100}\big[f^i(\boldsymbol{k}_1)f^i(\boldsymbol{k}_2) - \big(f^i(\boldsymbol{k}_1)+f^i(\boldsymbol{k}_2)\big)f^i(\boldsymbol{k}_3)\big]\Big\}\end{aligned}$$



What's next?

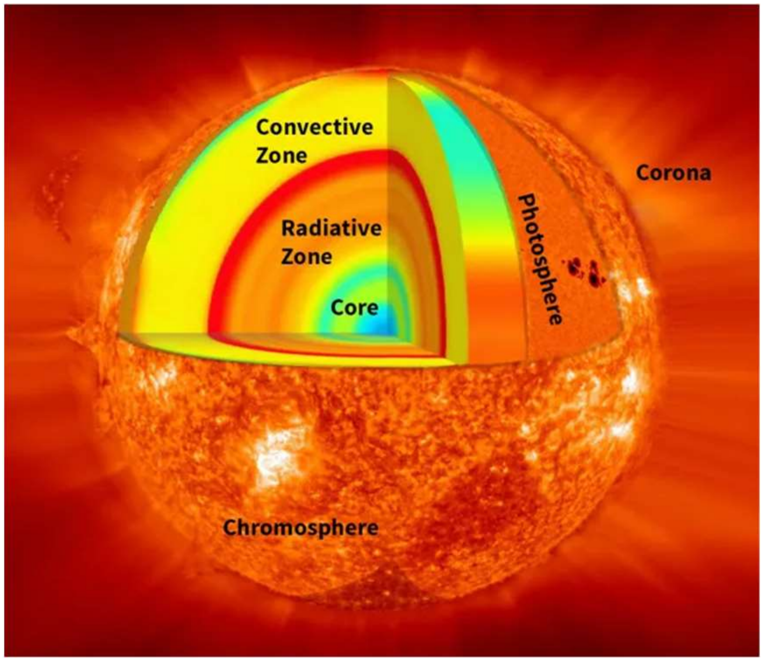
- Typical regimes for DP solar halo formation

  2 possibilities:
  - symmetric initial condition
  - asymmetric initial condition

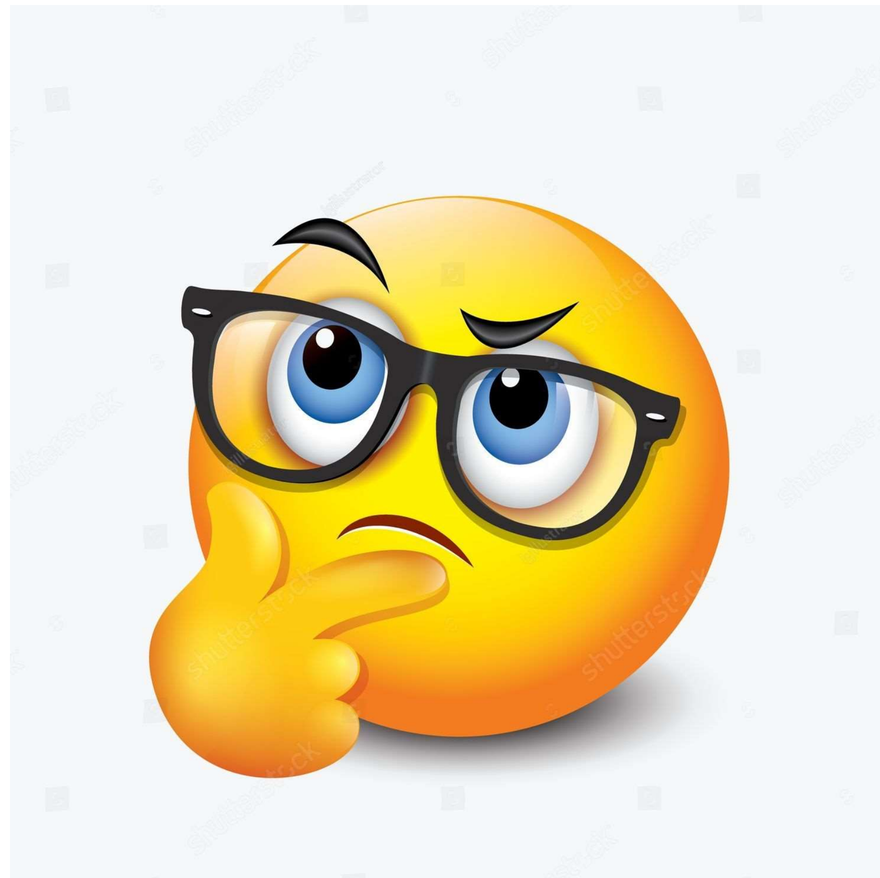
- DM solar halo *inside* the Sun
  (or other massive object)

  → gravitational potential $\Phi \not\propto \frac{1}{r}$

  depending on mass distribution $\rho_M(r)$
  inside the Sun (massive object)



Thank you.
Questions?



Thank you.

Contact

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Dark photons (spin-1 bosons)

Can the Sun gravitationally capture DP?

$$\langle a^{i*}(\boldsymbol{k}) a^j(\boldsymbol{k}')\rangle \equiv (2\pi)^3 f^i(\boldsymbol{k})\delta(\boldsymbol{k}-\boldsymbol{k}')\frac{\delta_{ij}}{3}$$

$$\mathcal{L} = -\frac{1}{4}F_{\rho\sigma}F^{\rho\sigma} - \frac{1}{2}m^2 A_\rho A^\rho + \underbrace{\frac{1}{\Lambda^4}(F_{\rho\sigma}F^{\rho\sigma})^2}_{\text{self-interaction}}$$

$$F^{\mu\nu} = \partial_\mu A^\nu - \partial_\nu A^\mu$$

$\partial_\mu A^\mu = 0$ (Lorentz condition)

$$(-\Box + m^2)A^i + \frac{8}{\Lambda^4}(\partial_\mu F^2)F^{\mu i} + \frac{8}{\Lambda^4}F^2 \Box A^i = 0$$

$$A^i = \frac{1}{\sqrt{2m}}\left(\psi^i e^{-imt} + \text{c.c.}\right) \quad \text{with } \partial_\nu \psi^i \ll m\psi^i$$

$$\left(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r}\right)\psi^i = g\sum_j \left(-2|\psi^j|^2\psi^i - (\psi^j)^2\psi^{i*}\right)$$