The axion-photon interaction and gamma ray signals of dark matter

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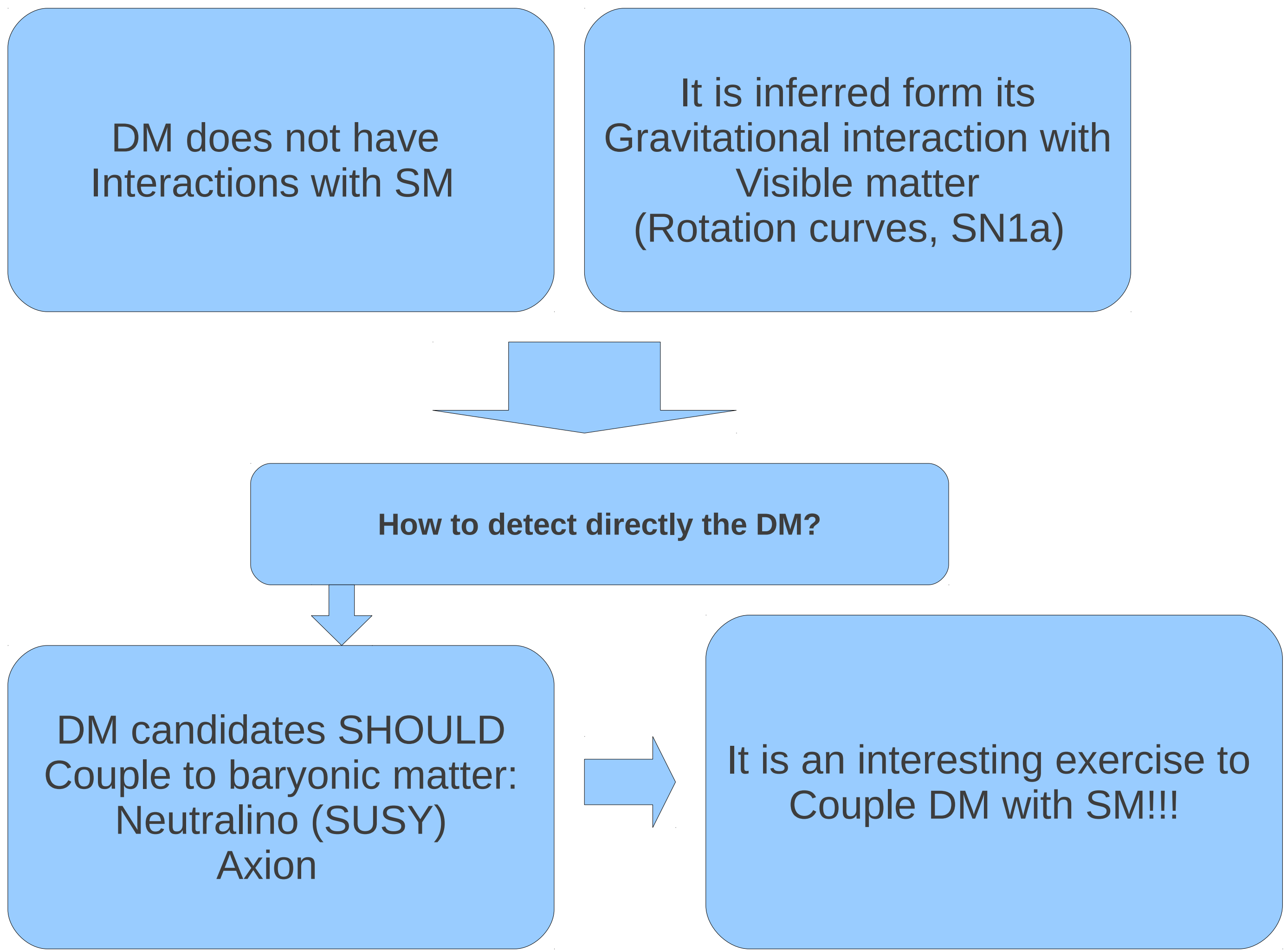
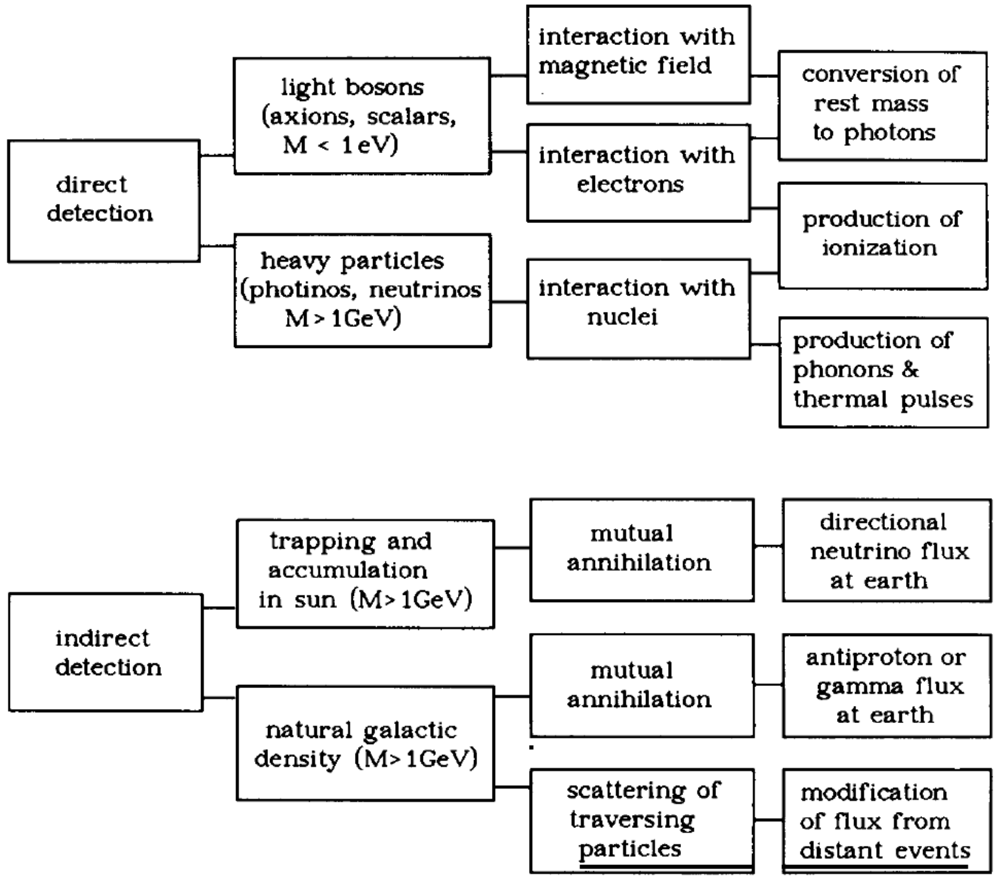
Outline

- Dark matter detection
- A couple of new proposal for indirect dark matter detection
  - UHE neutrino flux suppression
  - Gamma rays and the axion-photon mixing
    1. A galactic halo made of collisionless ensemble of axion stars?
    2. A possible flux of high energy photons from the Sun?
- Conclusions

Motivation


DM does not have
Interactions with SM
It is inferred form its
Gravitational interaction with
Visible matter
(Rotation curves, SN1a)
How to detect directly the DM?
DM candidates SHOULD
Couple to baryonic matter:
Neutralino (SUSY)
Axion
It is an interesting exercise to
Couple DM with SM!!!

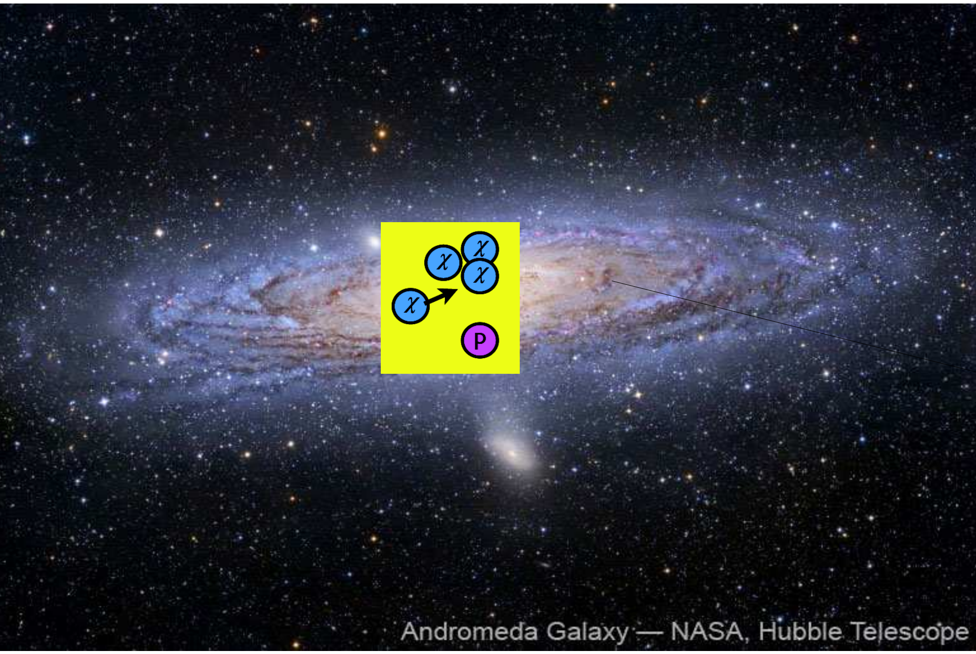
Dark matter detection

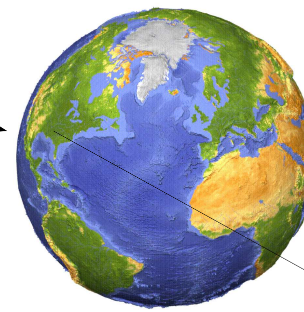


No Dark matter candidate has been detected so far (?)

Indirect DM searches

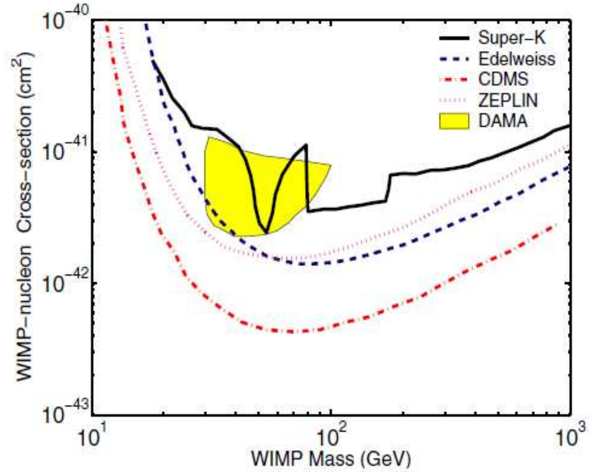
$$\chi\chi \to \gamma\gamma$$

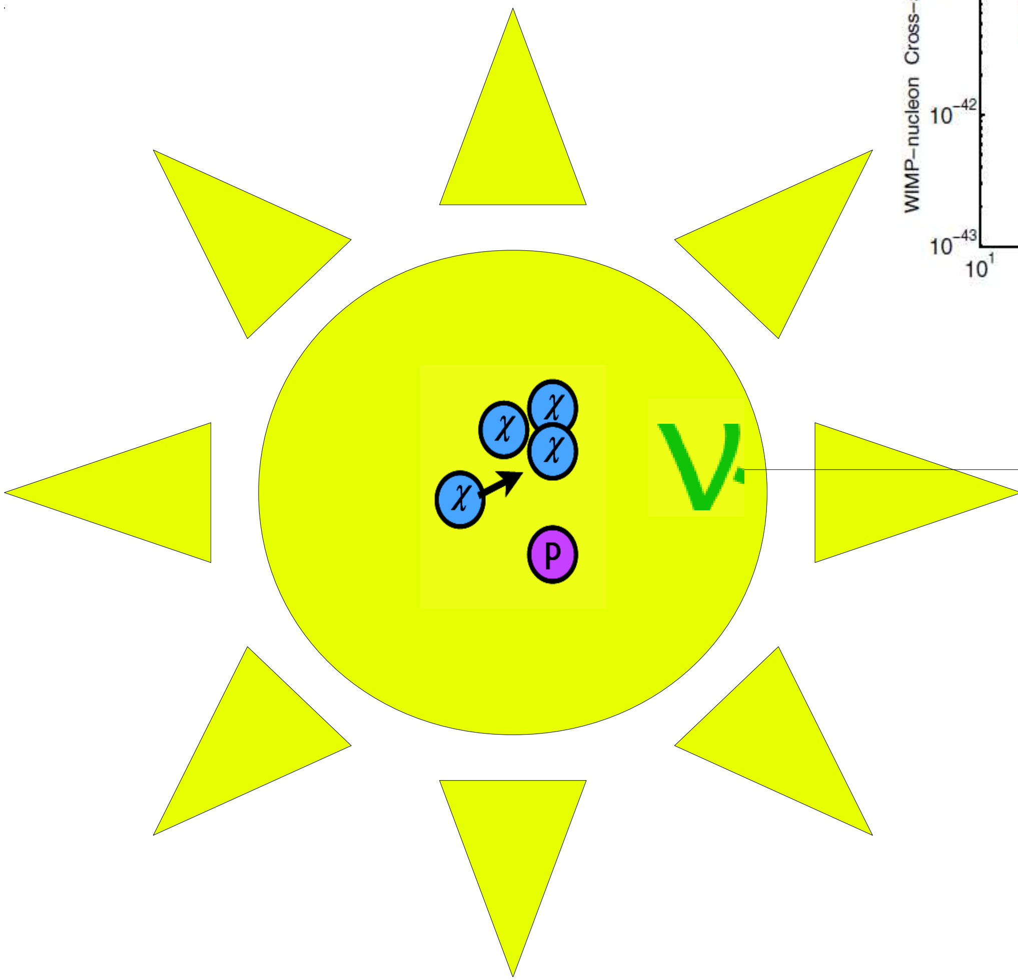


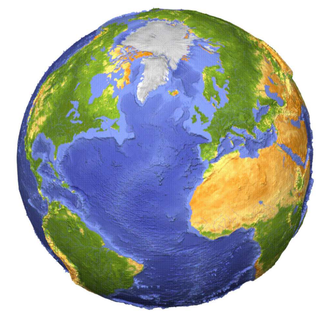


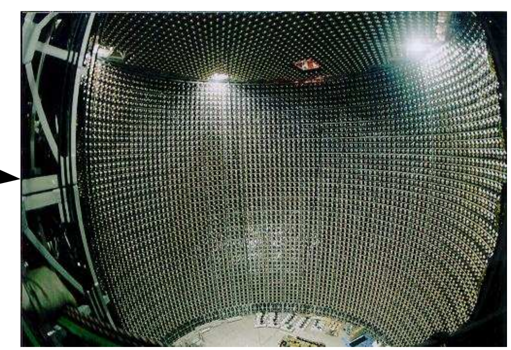
$$\frac{dN}{dt} = C - C_A N^2 \quad \begin{cases} C \propto \sigma_{SD}\, \rho_{DM} \\ C_A \propto \langle \sigma v \rangle \end{cases}$$

Indirect DM searches









$$\frac{dN}{dt} = C - C_A N^2 \begin{cases} C \propto \sigma_{SD}\,\rho_{DM} \\ C_A \propto \langle \sigma v \rangle \end{cases}$$

Does it exist alternative ways?

Does it exist alternative ways?

- If cosmic rays (i.e. ν's or photons) interact with DM there could be some effect

Possible suppression

- The mean free path

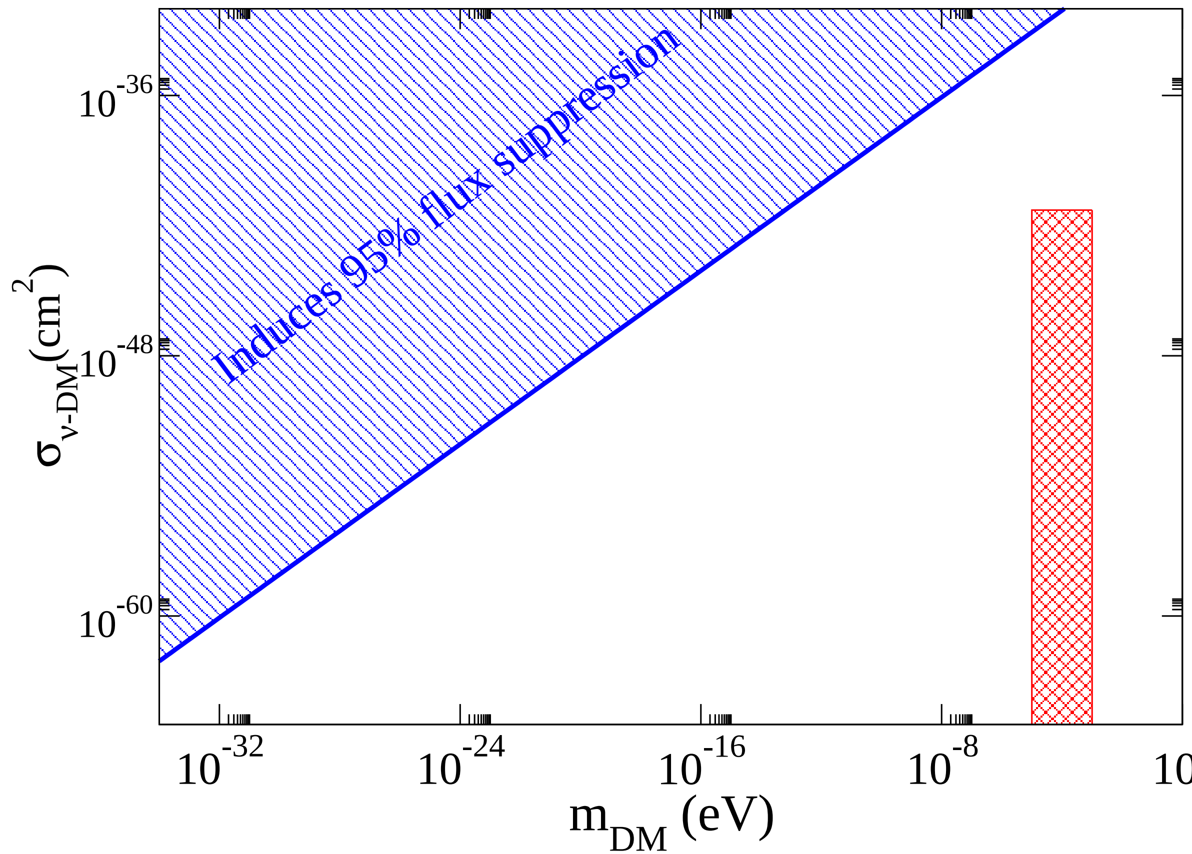
$$\lambda^{mfp} = (n\sigma)^{-1} \; = \frac{m_{DM}}{\rho_{DM}\sigma},$$

where n is the DM density and σ is the elastic cross section ν-DM, and m_{DM} is the mass of the DM particle.

- There will be a ν's UHE flux suppression given by

$$F(L) = F_0 e^{-L/\lambda^{mfp}} \; ,$$

where $F(L)$ is the suppressed flux and F_0 is the flux at the source.

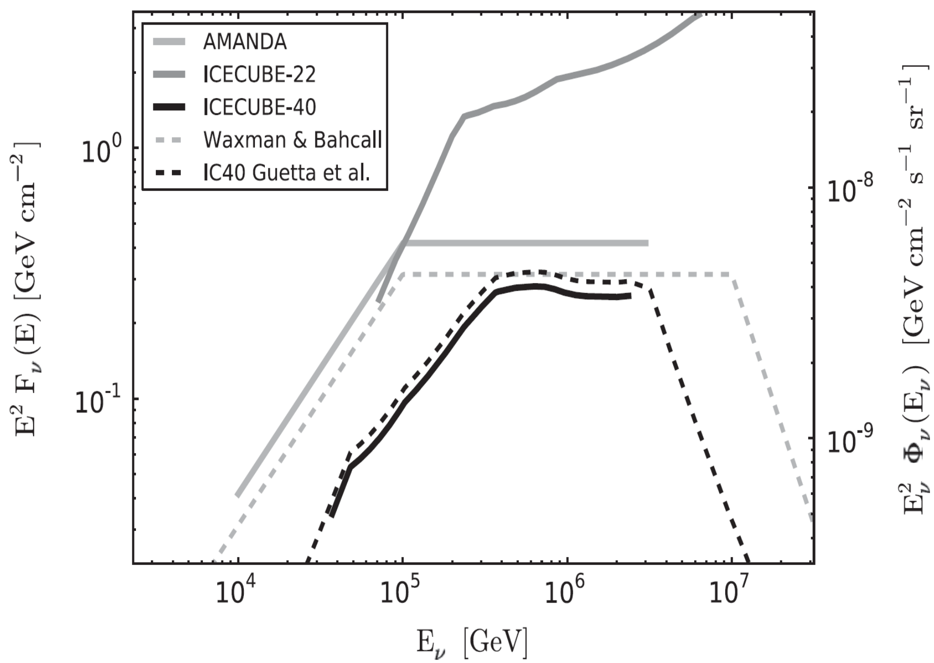


SFDM as a viable model for DM

- The Scalar Field Dark Matter model (SFDM)
  The Dark Matter is modeled by a scalar field with a ultra-light associated particle. ($m \sim 10^{-23}$eV)
  - At cosmological scales it behaves as cold dark matter
    T. Matos, L.A. Urena-Lopez, Class. Quant. Grav. **17** L75 (2000),
    V. Sahni and L.M. Wang, Phys. Rev D **62**, 103517 (2000).
  - At galactic scales, it does not have its problems: neither a cuspy profile, nor a over-density of satellite galaxies.
    A. Bernal, T. Matos, D. Nuñez, Rev. Mex. A.A. 44, 149 (2008)
    T. Matos, L.A. Urena-Lopez, Phys. Rev. D **63**, 063506 (2001)

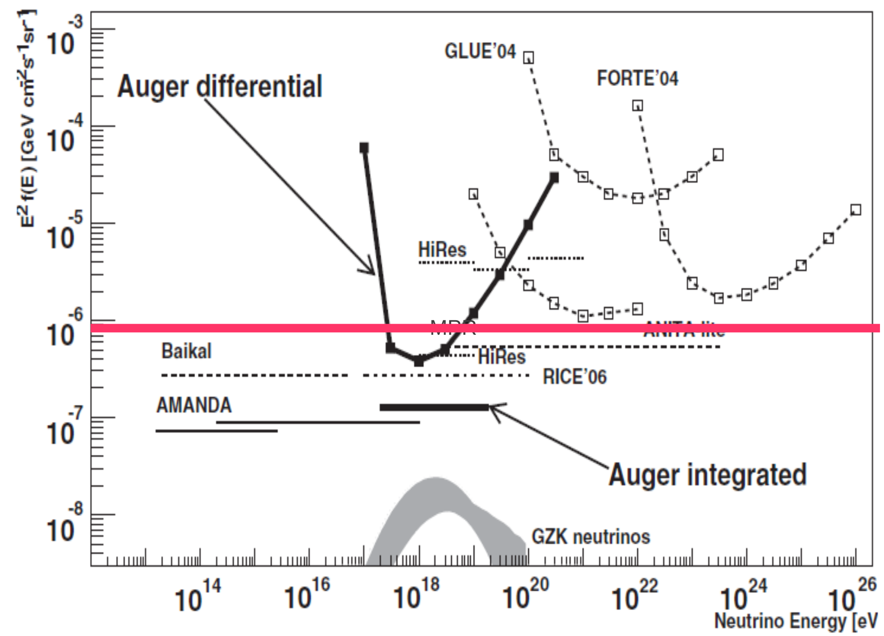
Could it be possible that we have already observed this interaction?

ICECUBE limit on ν's from GRBs



[PRL 106 (2011) 141101]

Auger limit



[PRL **100** (2008) 211101]

The cross section

- Assume $\nu - \phi$ interaction as in [D. Hooper *et al.* PRL **93** (2004) 161302, C. Boehm *et al.* PRL **92** (2004) 101301 C. Boehm and P. Fayet NPB **683** (2004) 219]
- If $m_\nu \sim 1$eV and $E_\nu \sim 10^{18}$ eV, the cross section is valid for $m_\phi >> \mathcal{O}\left(10^{-18}\right)$ eV. Furthermore, in the limit $s, u \ll M_I$ and integrating over solid angle

$$\sigma \simeq \left(\frac{g_{\nu\phi}}{M_I}\right)^4 \frac{m_\nu^2}{16\pi} \, .$$

useful limit for ultra-high-energetic neutrinos

-

$$\begin{aligned} \lambda &= 16\pi \times 10^{-6} \left(\frac{M_I/g_{\nu\phi}}{\mathrm{GeV}}\right)^4 \left(\frac{\mathrm{eV}}{m_\nu}\right)^2 \left(\frac{\mathrm{GeV}/\mathrm{cm}^3}{\rho_\phi}\right) \left(\frac{m_\phi}{10^{-15}\mathrm{eV}}\right) \mathrm{GeV}^2\mathrm{cm}^3 \\ &\simeq L_0 \left(\frac{M_I/g_{\nu\phi}}{\mathrm{GeV}}\right)^4 \left(\frac{\mathrm{eV}}{m_\nu}\right)^2 \left(\frac{\mathrm{GeV}/\mathrm{cm}^3}{\rho_\phi}\right) \left(\frac{m_\phi}{10^{-18}\mathrm{eV}}\right) \, , \end{aligned}$$

where $L_0 \simeq 42$ pc.

Possible suppression

$$F(L) = F_0 e^{-L/\lambda^{mfp}} ,$$

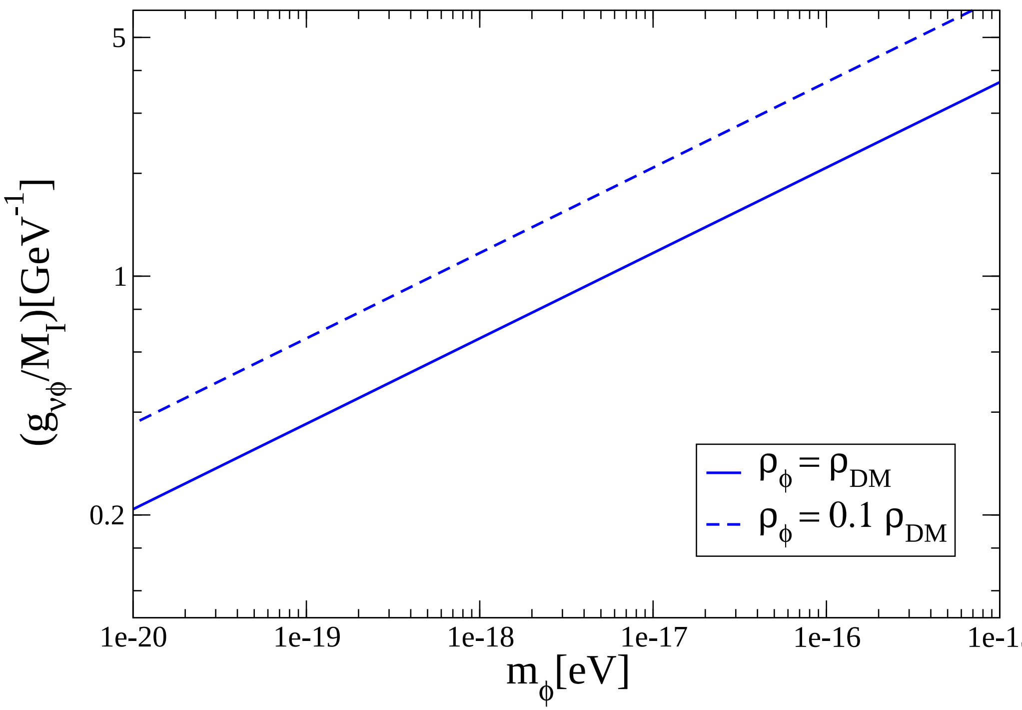
$$\frac{g_{\nu\phi}}{M_I} \gtrsim \left[\ln\left(\frac{F_0}{F}\right) \frac{L_0 m_\phi}{\rho_\phi m_\nu^2 L} \right]^{\frac{1}{4}} .$$

$L = 5 \times 10^2$ Mpc, $m_\nu \sim 1$ eV and $\rho_{\rm DM} = 1{,}2 \times 10^{-6}$ GeV/cm^3

J. Barranco, O. G. Miranda, C. A. Moura, T. I. Rashba, F. Rossi-Torres

JCAP 1110 (2011) 007

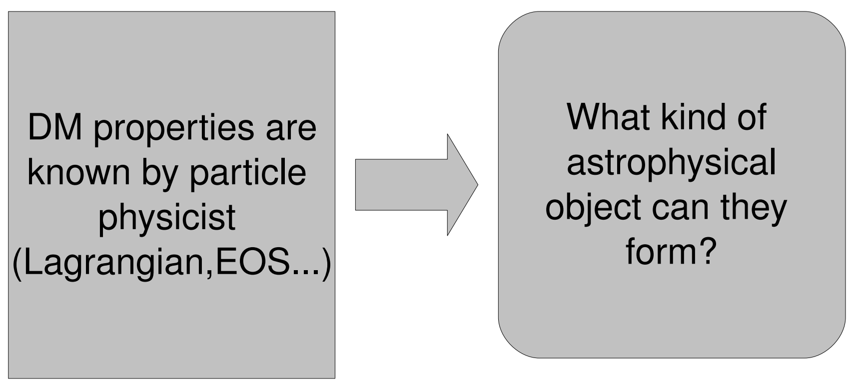
arXiv:1012.2476 [astro-ph.CO].



Axion

- Axion was originally proposed to solve strong CP problem
- There is a remnant $\gamma - a$ interaction

$$\mathcal{L} = \frac{1}{2}(\partial^\mu \phi \partial_\mu \phi - m^2 \phi^2) - \frac{1}{4}\frac{\phi}{M} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4} F_{\mu\nu}F^{\mu\nu}$$



Self-gravitating axion

Axion properties

$$10^{10}\text{GeV} \leq f_a \leq 10^{12}\text{GeV}$$

$$10^{-5}\text{eV} \leq m \leq 10^{-3}\text{eV}$$

At late times in the evolution of the universe, the energy density potential of the axion is

$$V(\phi) = m^2 f_a^2 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right],,$$

which can be expanded as

$$V(\phi) \sim \frac{1}{2} m^2 \phi^2 - \frac{1}{4!} m^2 \frac{\phi^4}{f_a^2} + \frac{1}{6!} m^2 \frac{\phi^6}{f_a^4} - \ldots$$

with the identification $\lambda = m^2/6f_a^2$: Hence, we can estimate (incorrectly)

$$M_{max} \sim 10^{27} \sqrt{\lambda} M_\odot \approx 10^4 M_\odot!$$

F.E. Shunck and W. Mielke. Class. Quantum Grav. **20** (2003)

Axion stars

$$V(\phi) = m^2 f_a^2 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right]$$

$$V(\phi) \sim \frac{1}{2} m^2 \phi^2 - \frac{1}{4!}\left(\frac{m}{f_a}\right)\phi^4 + \frac{1}{6!}\frac{m^2}{f_a^4}\phi^6 - \ldots$$

$$V(\phi) \to \langle Q|V(\hat{\phi})|Q\rangle$$

$$\hat{\phi} = \mu^+ R(r) e^{-iE_1 t} + \mu^- R(r) e^{+iE_1 t}$$

$$\mu|Q\rangle = 0$$

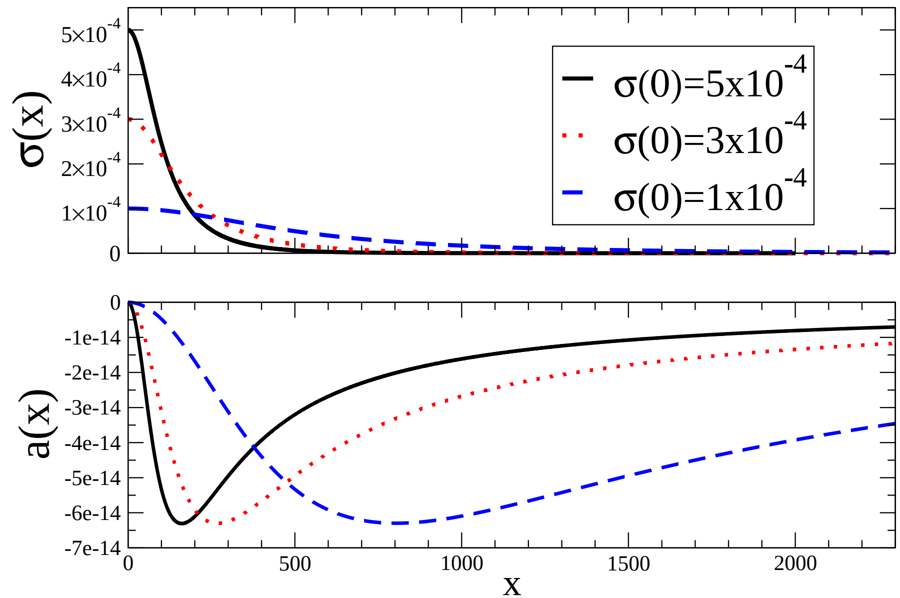
$$\begin{aligned} \langle Q|\hat{\phi}^2|Q\rangle &= R^2 \\ \langle Q|\hat{\phi}^4|Q\rangle &= 2R^4 \\ \langle Q|\hat{\phi}^6|Q\rangle &= 5R^6 \end{aligned}$$

Axion star

$$R = \frac{f_a}{\sqrt{m}}\sigma\,, \quad r = \frac{m_p}{f_a}\sqrt{\frac{m}{4\pi}}x\,, \quad \alpha = \frac{4\pi f_a^2}{m_p^2 m}$$

$$A(x) = 1 - a(x)$$

$$\begin{aligned}
a' + \frac{a(1+a)}{x} + (1-a)^2 x\left[\left(\frac{1}{B}+1\right)m^2\sigma^2 - \frac{m\sigma^4}{4} + \alpha\frac{\sigma'^2}{(1-a)} + \frac{\sigma^6}{72}\right] &= 0\,, \\
B' + \frac{aB}{x} - (1-a)Bx\left[\left(\frac{1}{B}-1\right)m^2\sigma^2 + \frac{m\sigma^4}{4} + \alpha\frac{\sigma'^2}{(1-a)} - \frac{\sigma^6}{72}\right] &= 0\,, \\
\sigma'' + \left(\frac{2}{x} + \frac{B'}{2B} + \frac{a'}{2(1-a)}\right)\sigma' + (1-a)\left[\left(\frac{1}{B}-1\right)m^2\sigma + \frac{m\sigma^3}{3} - \frac{\sigma^5}{24}\right] &= 0
\end{aligned}$$

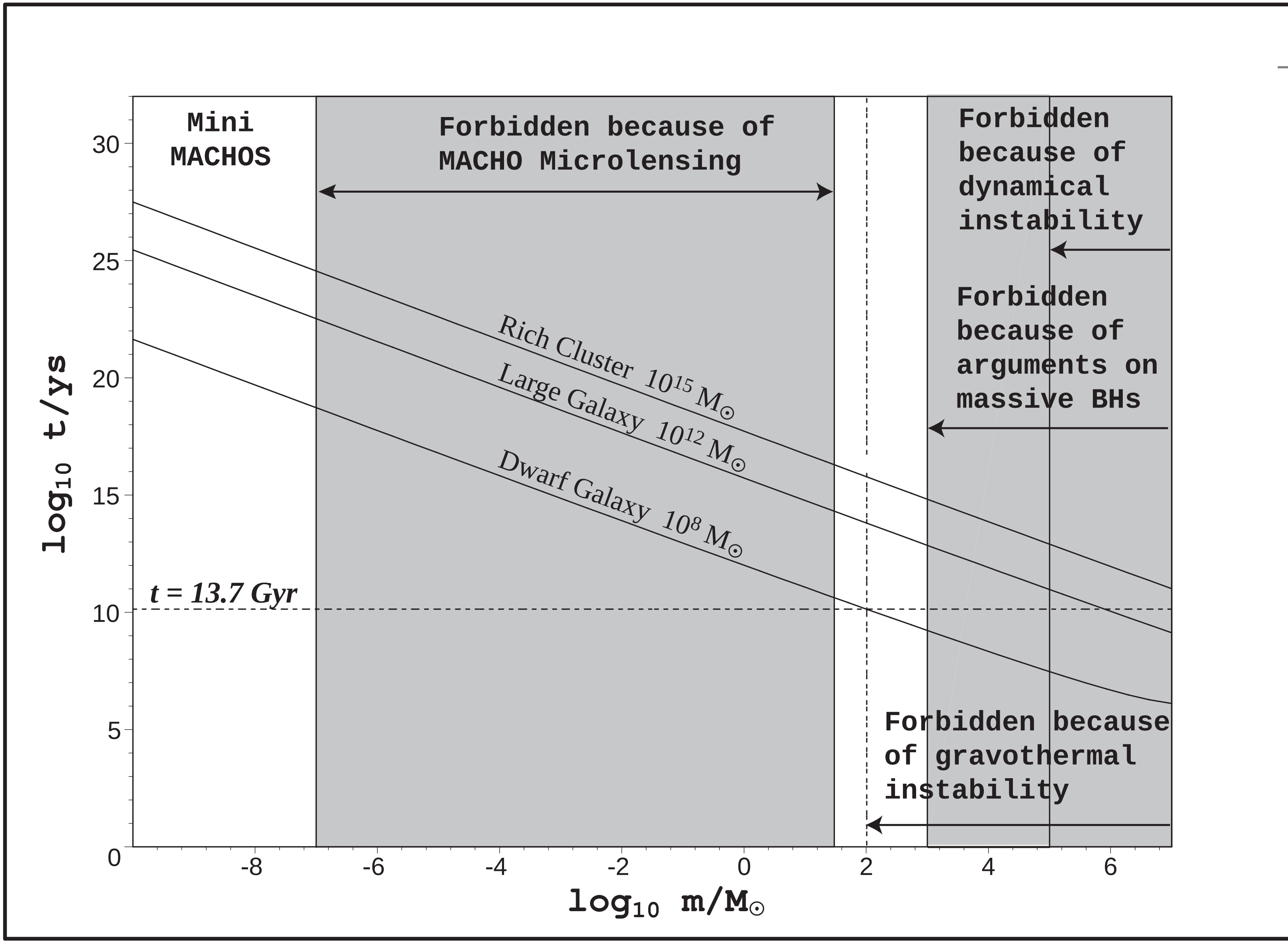


$$r = \frac{m_p}{f_a}\sqrt{\frac{m}{4\pi}}x$$

$\sigma(0)$	Mass (Kg)	R_{99} (meters)	density ρ (Kg/m^3)
5×10^{-4}	$3{,}90 \times 10^{13}$	$1{,}83$	$6{,}3 \times 10^{12}$
3×10^{-4}	$6{,}48 \times 10^{13}$	$2{,}86$	$2{,}7 \times 10^{12}$
1×10^{-4}	$1{,}94 \times 10^{14}$	$8{,}54$	$3{,}1 \times 10^{11}$

[J. Barranco, A. Bernal, PRD**83**, 043525 (2011)]

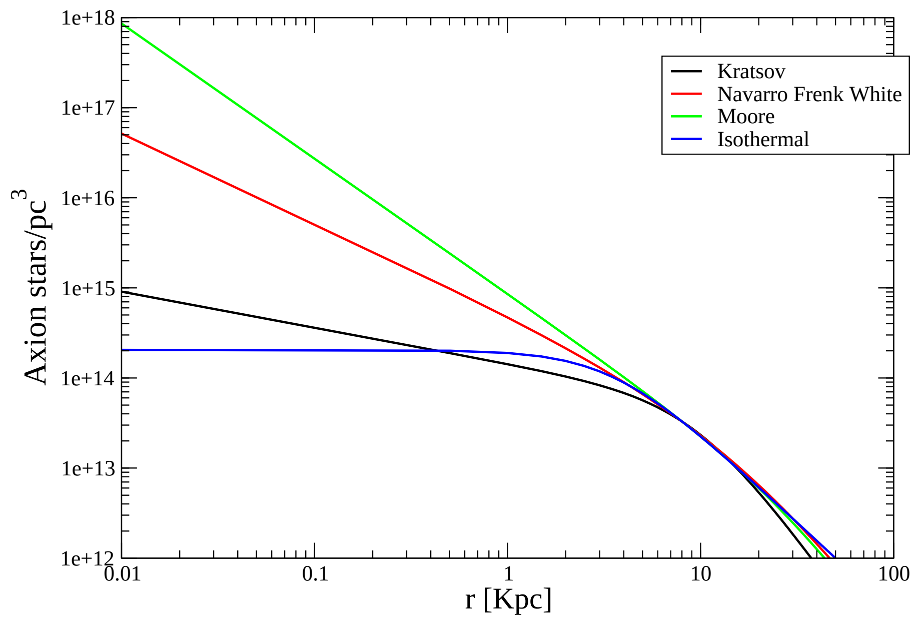
Galactic halo as a collisionless ensemble of DM machos



X. Hernandez, T. Matos, R. A. Sussman and Y. Verbin,
Phys. Rev. D **70**, 043537 (2004)

Possible γ signal?

- Consider the gal



- Remember

$$\mathcal{L} = \frac{1}{2}(\partial^\mu a \partial_\mu a - m^2 a^2) - \frac{1}{4}\frac{a}{M} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

- It is possible axion transform to photons in presence of an external magnetic field!

Possible γ signal?

- Strong magnetic fields $\rightarrow$ NS $> 10^8$ Gauss.
- $\sim 10^9$ NS in the galaxy
- Does axion stars collision with Neutron Stars produce a visible effect?
  - Start with

$$\mathcal{L}_{a\gamma\gamma} = \frac{c\alpha}{f_{PQ}\pi} a\vec{E} \cdot \vec{B}$$

  - Obtain “modified” Gauss law:

$$\partial \vec{E} = \frac{-c\alpha}{f_{PQ}\pi} \vec{\partial} \cdot (a\vec{B})$$

  - Energy dissipated in the magnetized conducting media, with averange σ electric conductivity (Ohm’s law)

$$W = \int_{ABS} \sigma E_a^2 d^3x = 4c^2 \times 10^{54} \mathrm{erg/s} \frac{\sigma}{10^{26/s}} \times \frac{M}{10^{-4} M_\odot} \frac{B^2}{(10^8 G)^2}$$

- YES! there could be a signal

HE Gamma rays from the Sun?

- Remember the Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial^\mu \phi \partial_\mu \phi - m^2\phi^2) - \frac{1}{4}\frac{\phi}{M}F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

- If the magnetic field changes on length scales larger than the wavelength of the particles, the equation of motion will be

$$\begin{aligned}
i\partial_z \Psi &= -(\omega + \mathcal{M})\Psi\,; \quad \Psi = (A_x, A_y, \phi) \\
\mathcal{M} &= \begin{pmatrix} \Delta_p & 0 & \Delta_{M_x} \\ 0 & \Delta_p & \Delta_{M_y} \\ \Delta_{M_x} & \Delta_{M_y} & \Delta_m \end{pmatrix}. \\
\Delta_{M_i} &= \frac{B_i}{2M} = 1{,}755 \times 10^{-11} \left(\frac{B_i}{1\mathrm{G}}\right)\left(\frac{10^5\mathrm{GeV}}{M}\right) \mathrm{cm}^{-1} \\
\Delta_m &= \frac{m^2}{2\omega} = 2{,}534 \times 10^{-11} \left(\frac{m}{10^{-3}\mathrm{eV}}\right)\left(\frac{1\mathrm{GeV}}{\omega}\right) \mathrm{cm}^{-1} \\
\Delta_p &= \frac{\omega_p^2}{2\omega} = 3{,}494 \times 10^{-11} \left(\frac{n_e}{10^{15}\mathrm{cm}^{-3}}\right)\left(\frac{1\mathrm{GeV}}{\omega}\right) \mathrm{cm}^{-1}
\end{aligned}$$

(1)

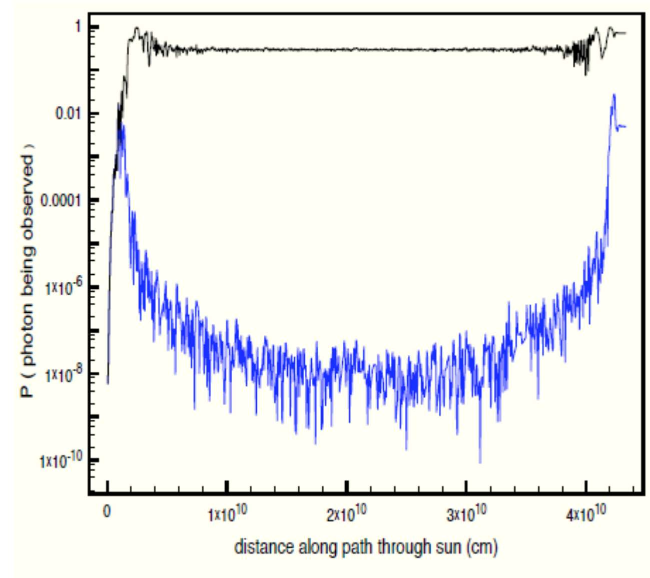
HE Gamma rays from the sun?

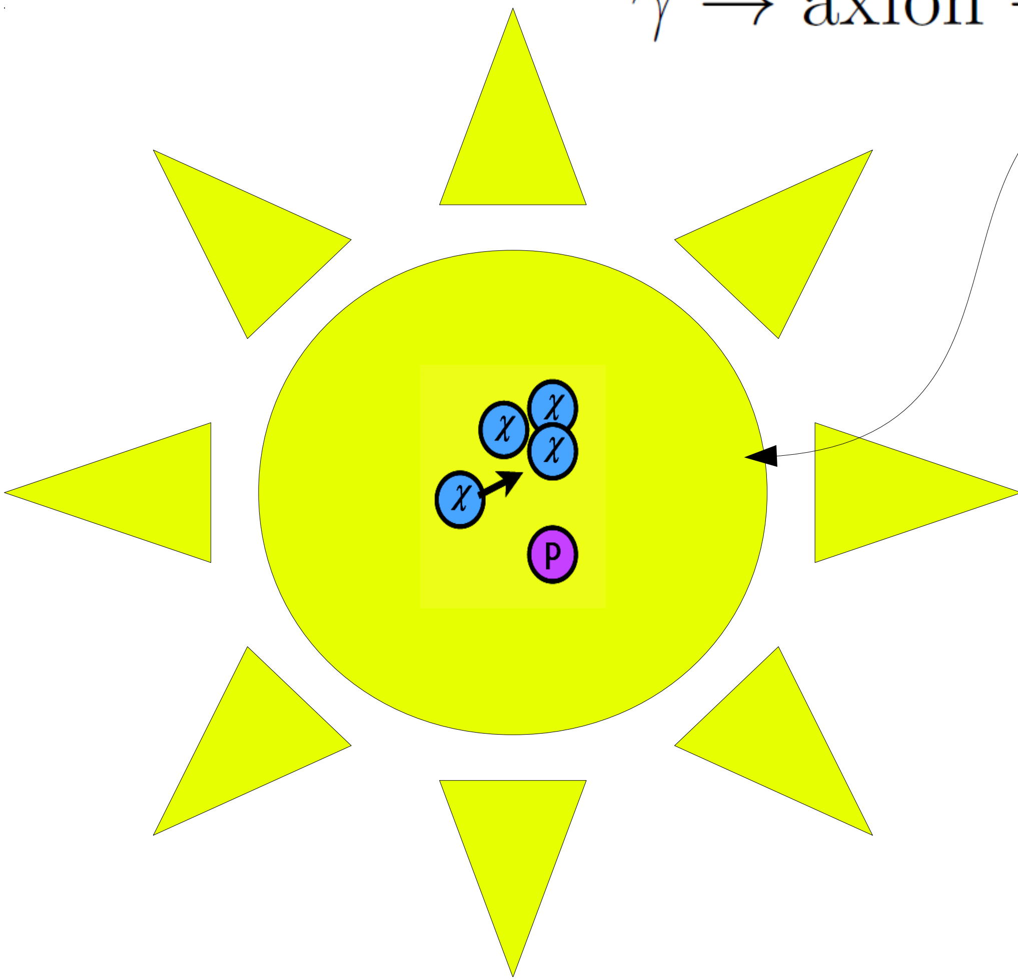
$$P = \frac{4B^2\omega^2}{M^2(\omega_p^2 - m^2)^2 + 4B^2\omega^2} \sin^2\left(\pi \frac{z}{l_{osc}}\right)$$

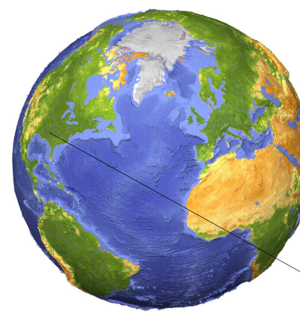
$$l_{osc} = \frac{4\pi\omega M}{\sqrt{M^2(\omega_p^2 - m^2)^2 + 4B^2\omega^2}}$$

HE Gamma rays from the sun?

$$\gamma \rightarrow \text{axion} \rightarrow \gamma$$







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Conclusions

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