Searching for the dark side of the universe with the help from the Sun

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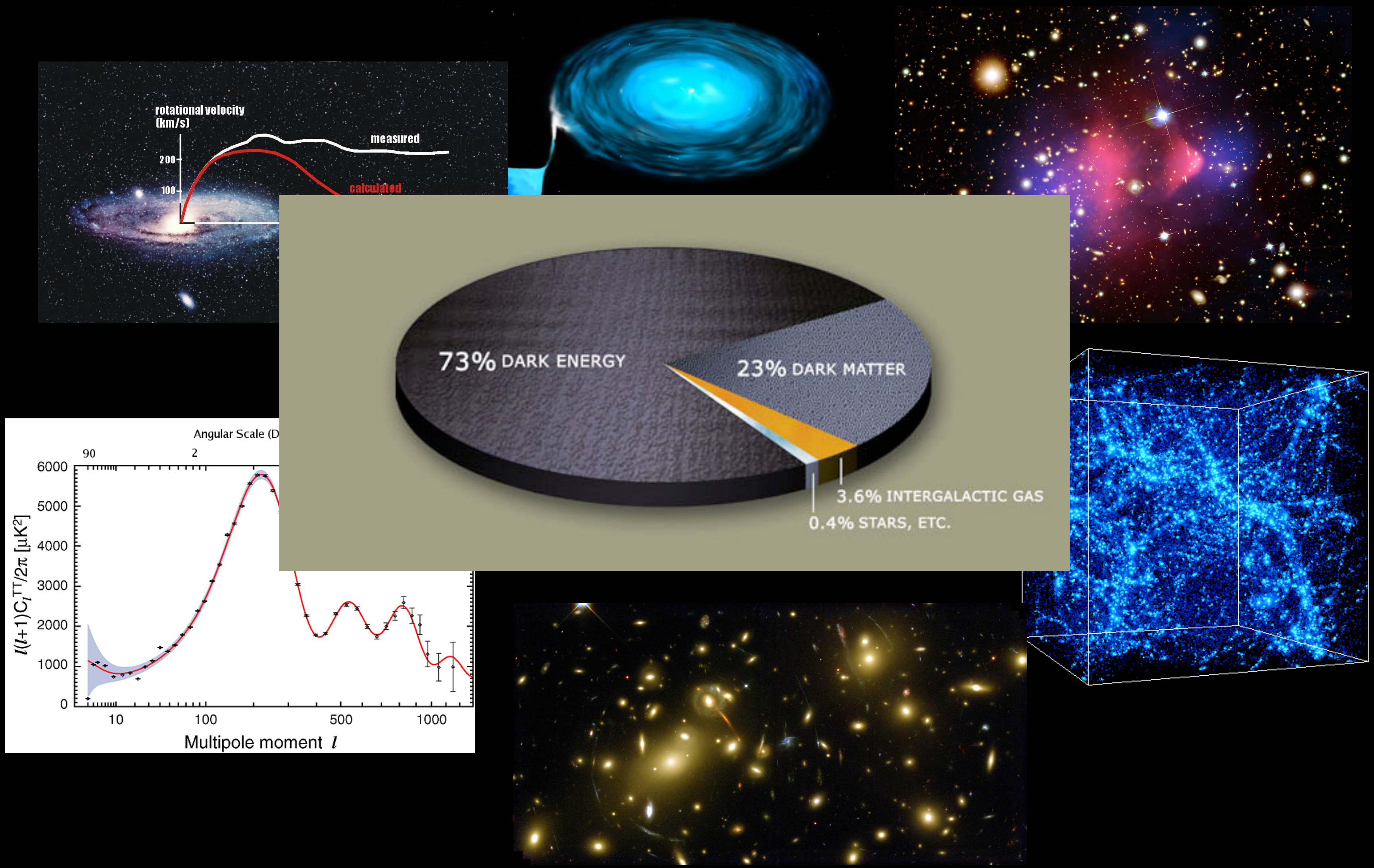
NCTS Annual Theory Meeting, Dec. 9-11, 2020

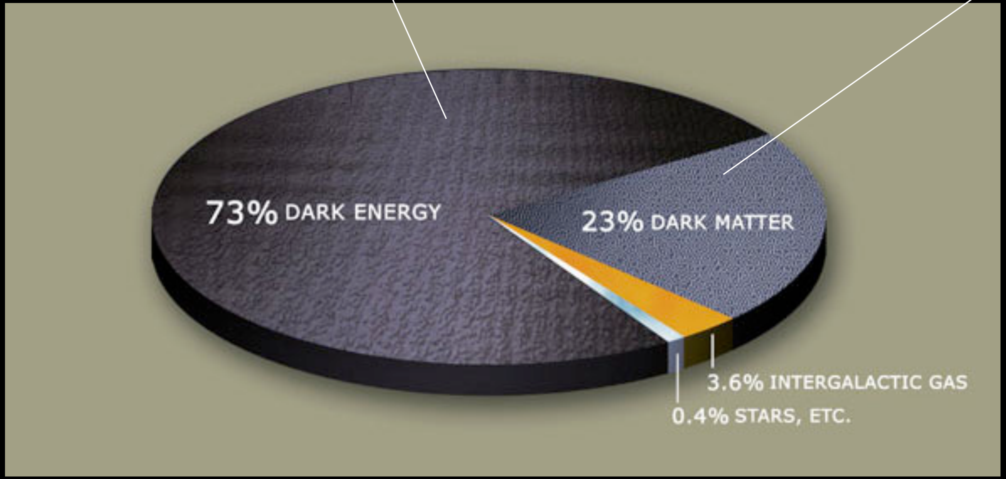
Concordant universe



What we know already

$p = -\rho$

$p \approx 0 \; (\rho \gg p)$



Non relativistic ideal gas model:

$p \sim nmv^2, \rho \sim nm$

$v \ll 1$

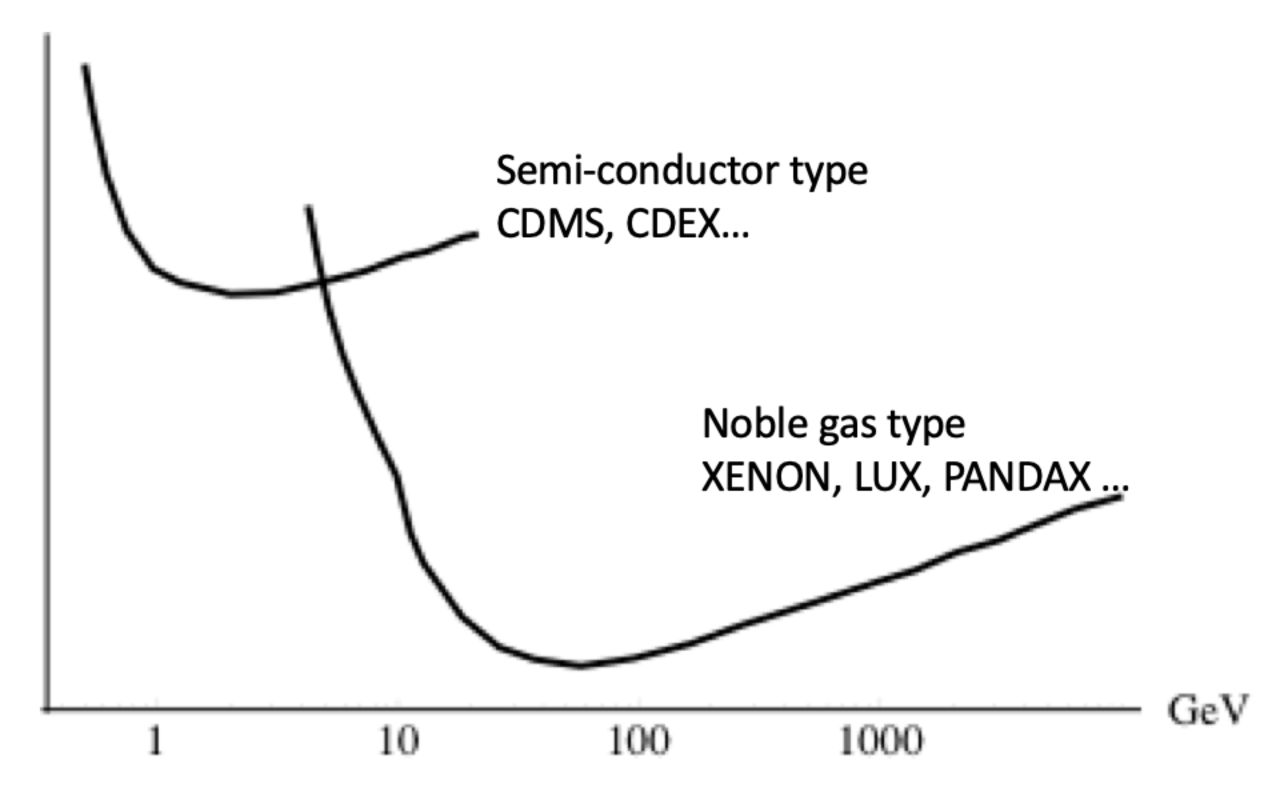
Dark matter is composed of non-relativistic particles.

Searching for dark matter

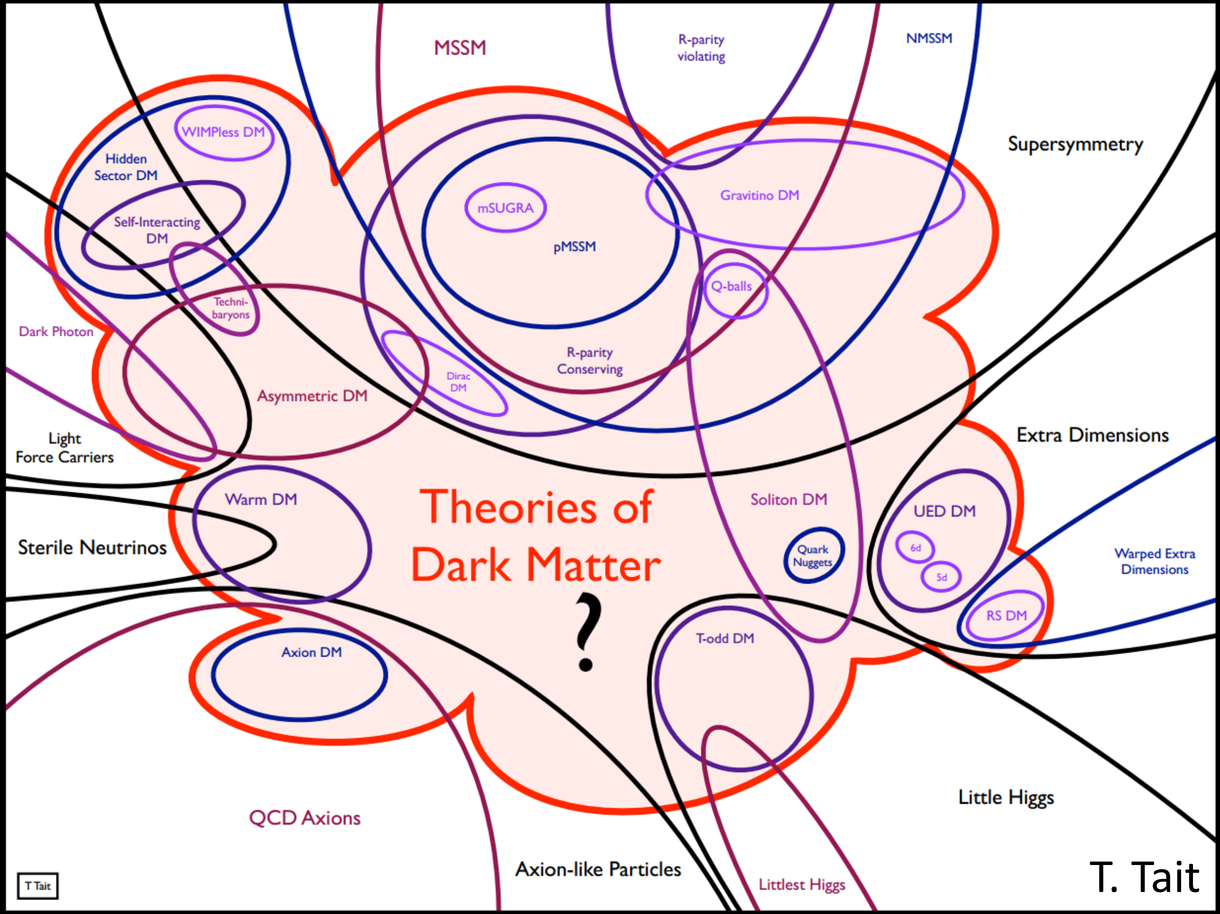
- All the evidences of dark matter are from gravitational effects.

- We want to understand its particle nature:
  - Mass
  - Spin
  - Size
  - Inner structure if any
  - Interactions with Standard Model particles
  - Its self-interaction
  - …

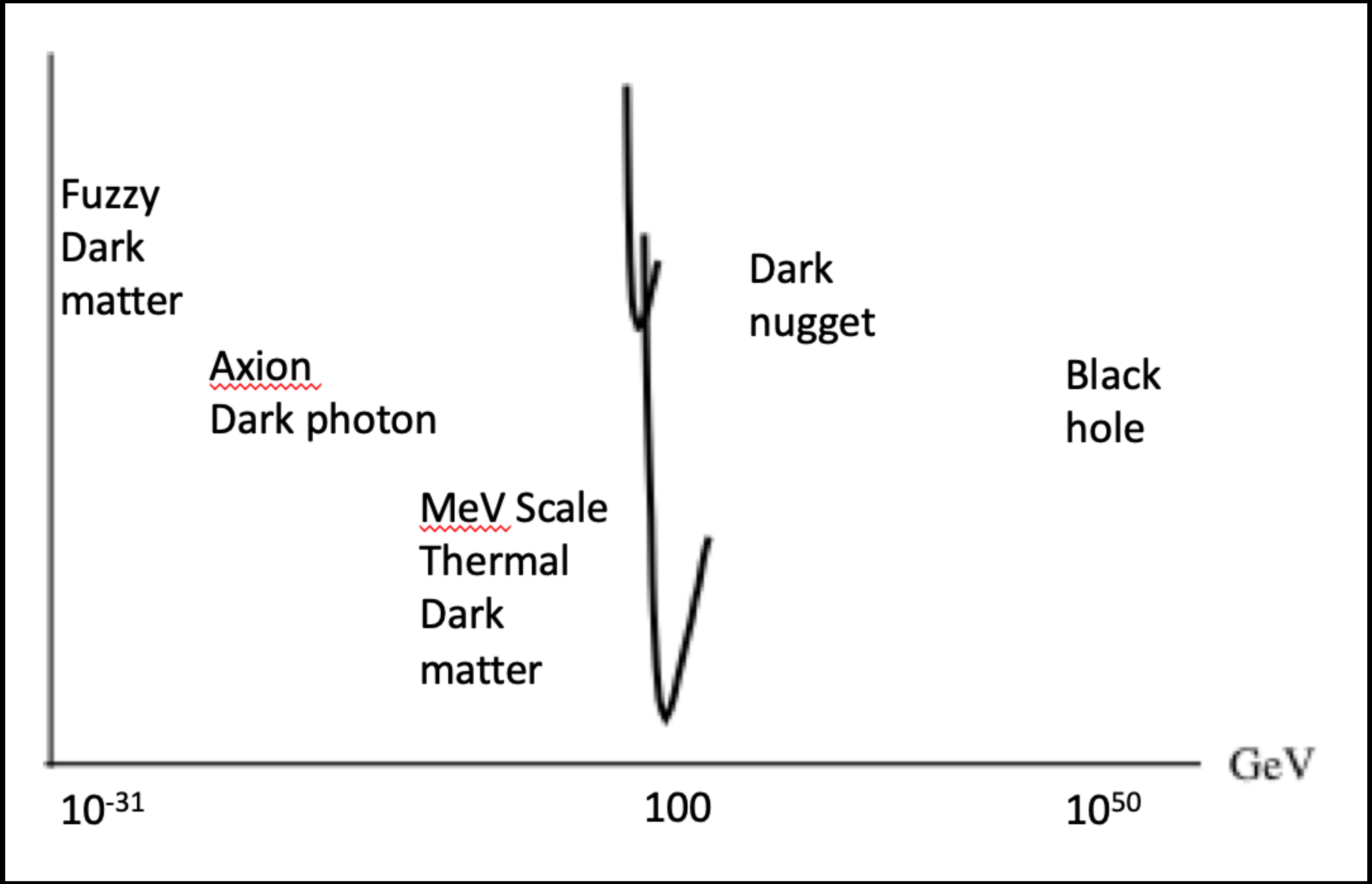
Searching for WIMPs



Theories of dark matter

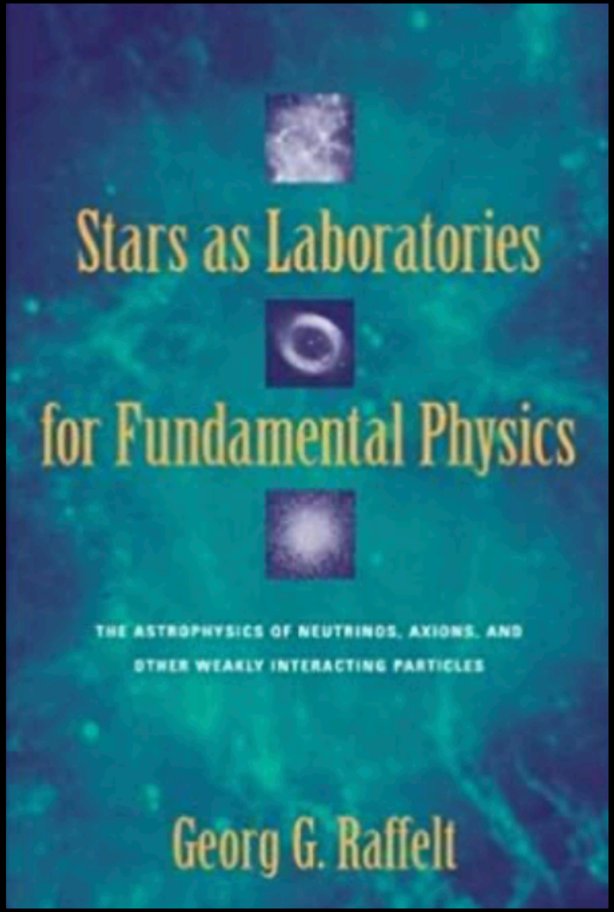


Possible mass range



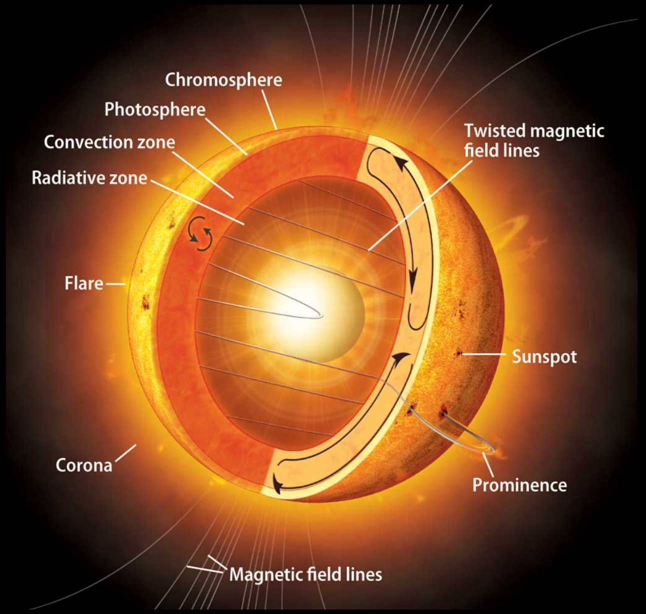
Stars as Laboratories for Fundamental Physics

- Sun
  - closest to us
- Red Giants and horizontal branch stars
  - $T_{core} \sim 10 - 100\ \mathrm{keV}$
- Neutron stars
  - large magnetic field
- Supernova
  - $T \sim 20 - 30\ \mathrm{MeV}$
- Black holes
  - Superradiance



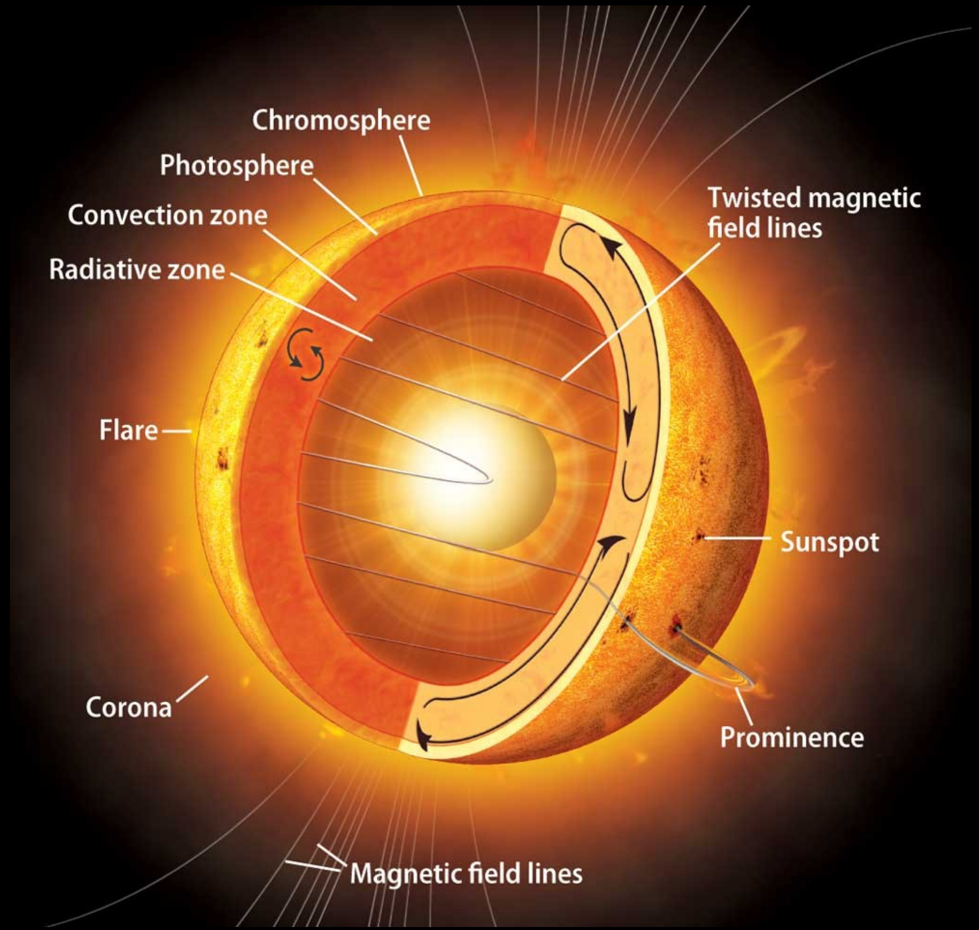
Outline

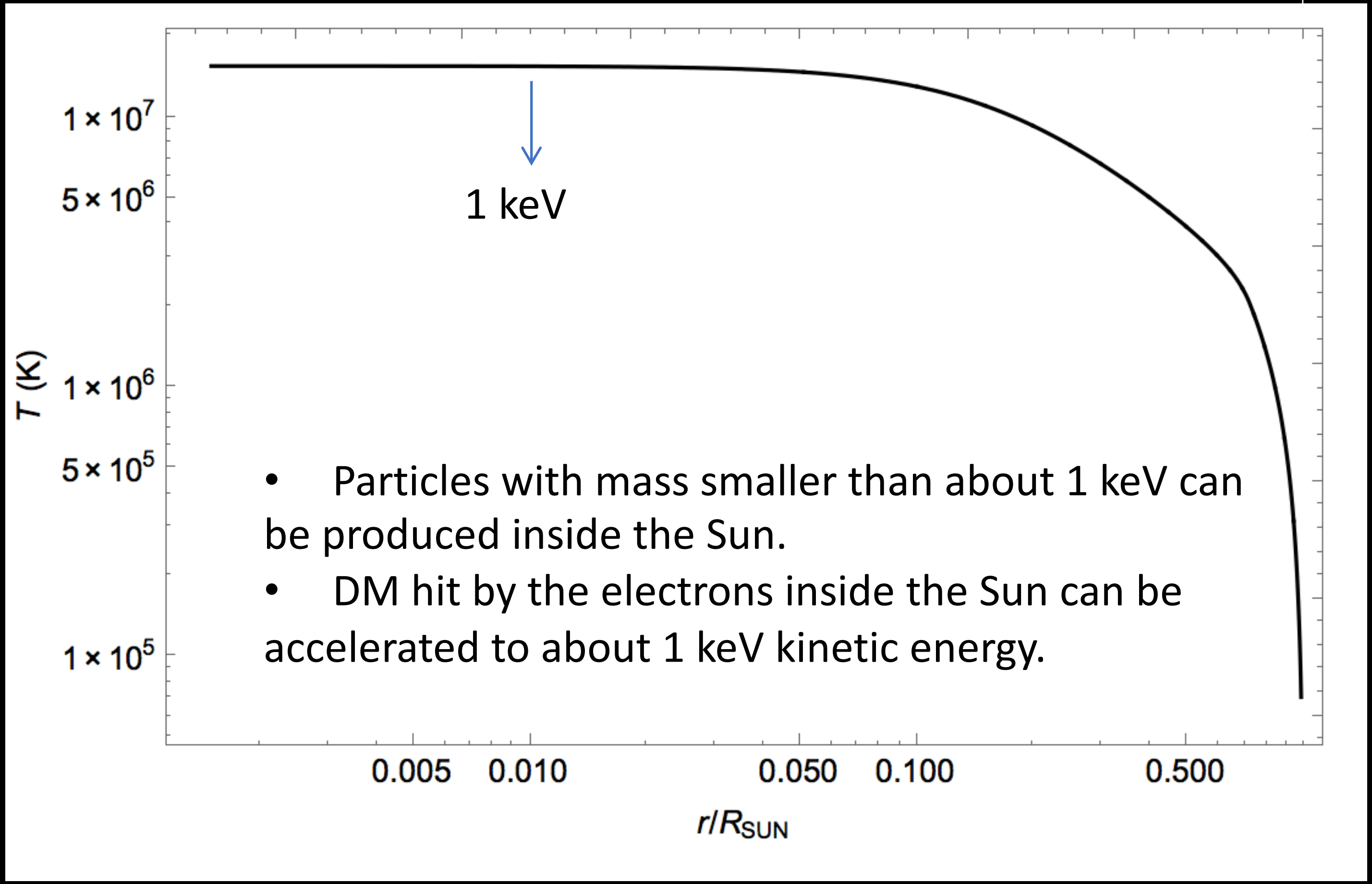
- Basic structure of the Sun
- MeV scale thermal dark matter (accelerated inside the Sun)
- Dark Photons
  - Produced inside the Sun
  - Converted at the Sun's corona
- Summary



Temperature distribution inside the Sun

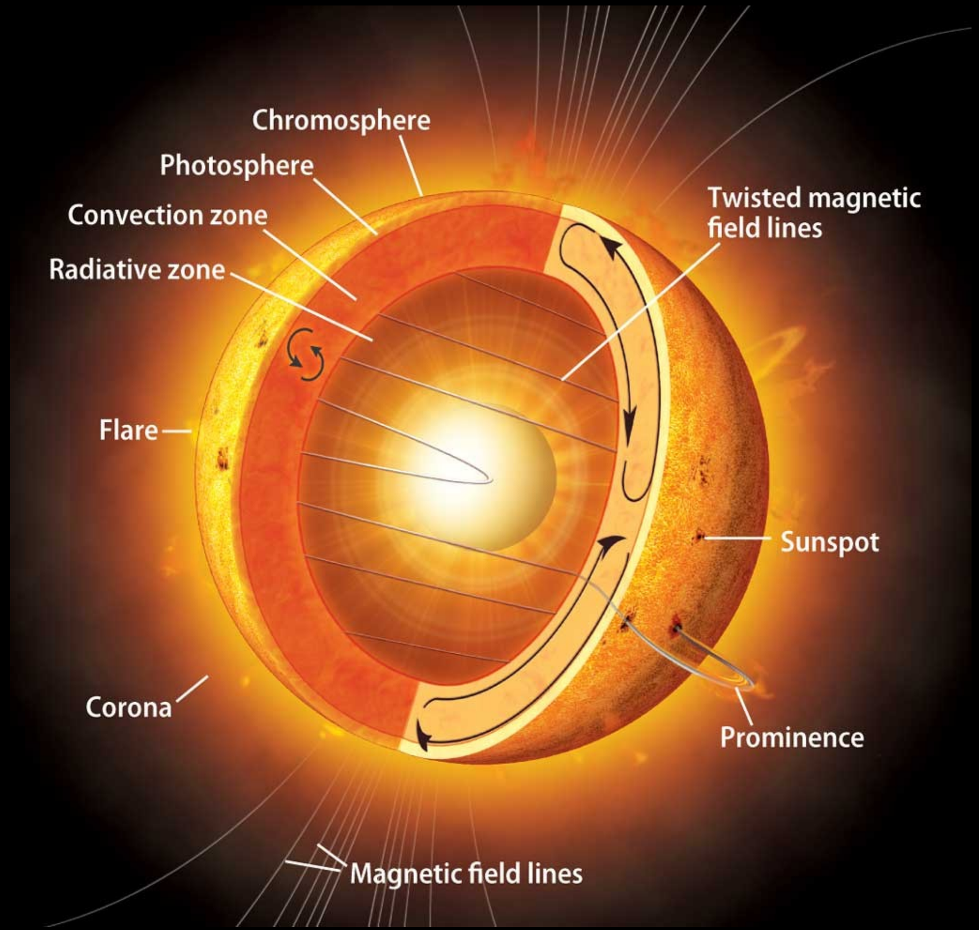
Photosphere

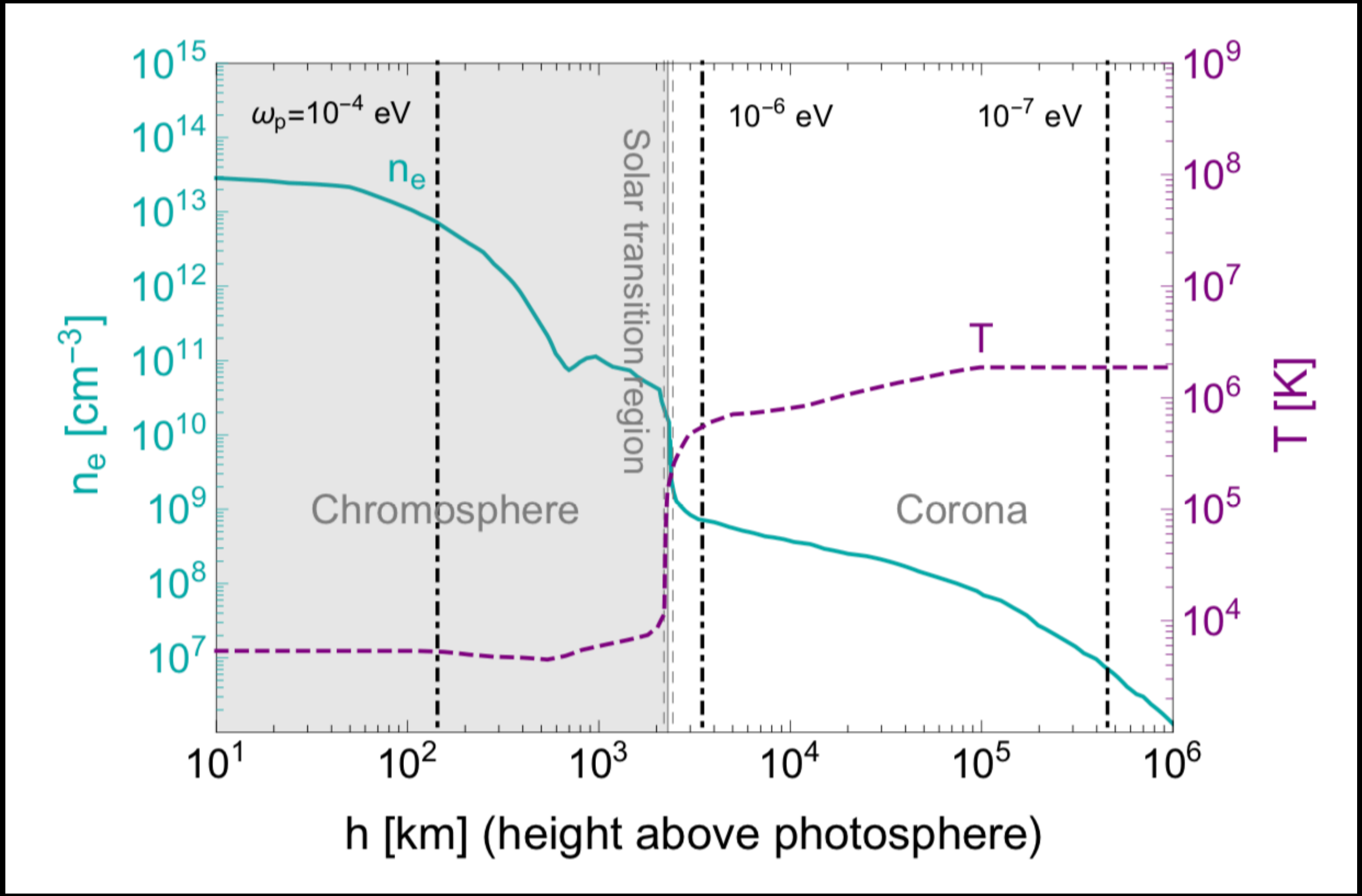




- Particles with mass smaller than about 1 keV can be produced inside the Sun.
- DM hit by the electrons inside the Sun can be accelerated to about 1 keV kinetic energy.

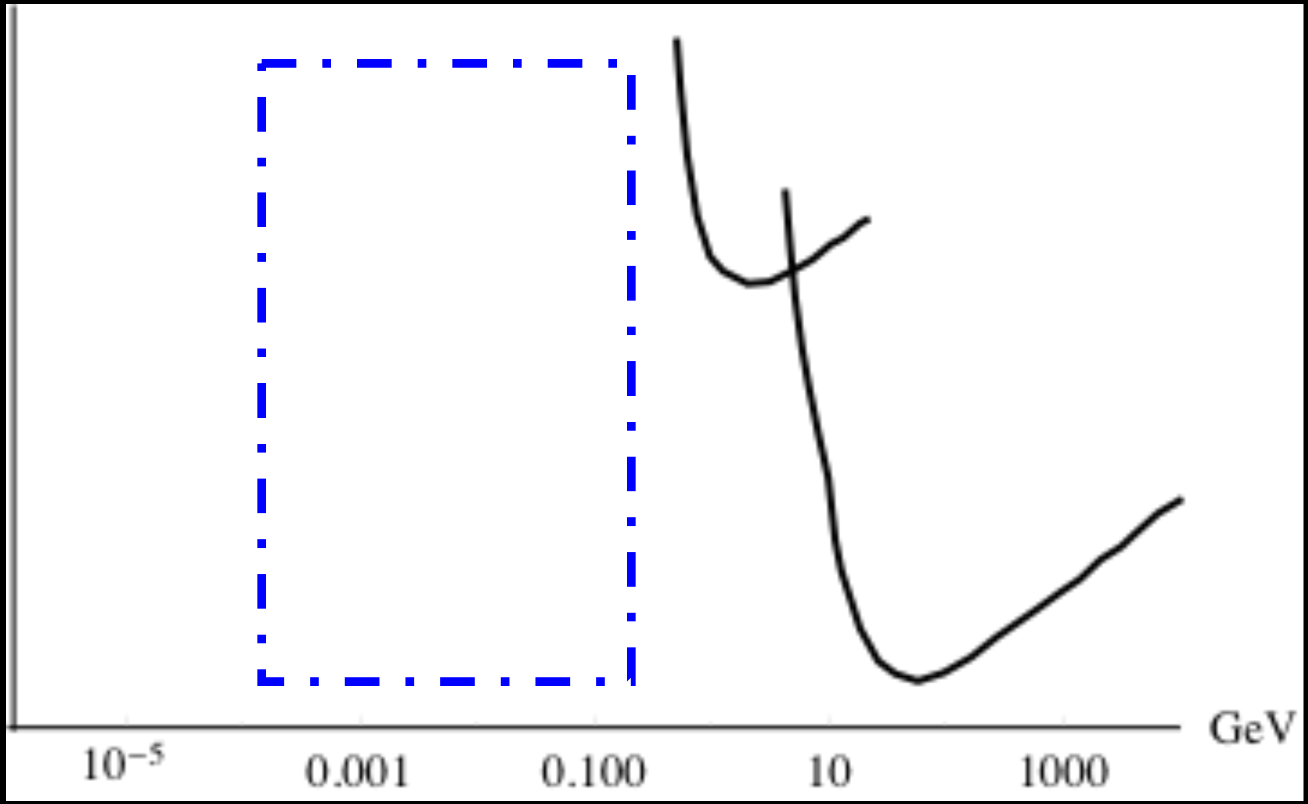
Temperature distribution outside the Sun





From GeV to MeV

- What if the DM is lighter than GeV scale?

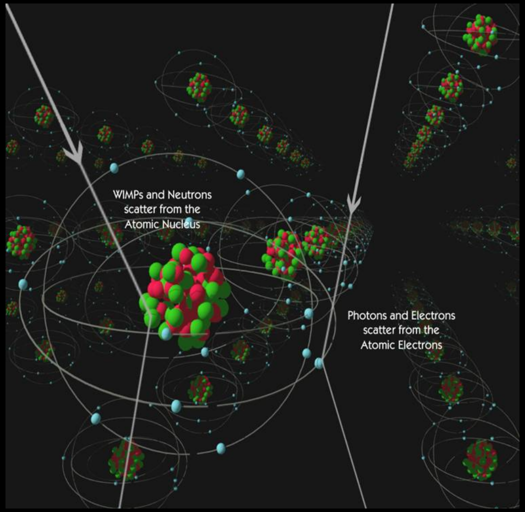


Use electron recoil for light DM

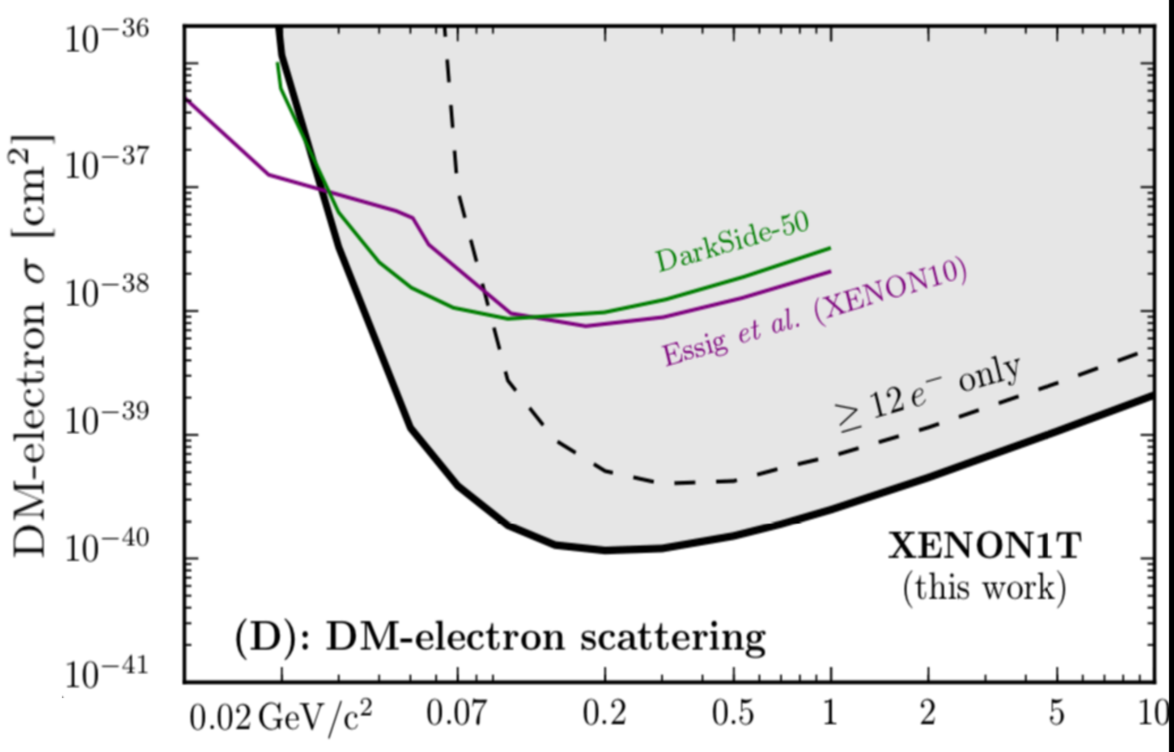
- For elastic scattering

$$E_{\text{recoil}} \sim \frac{m_{\text{DM}} m_T}{(m_{\text{DM}} + m_T)^2} E_{\text{DM}}$$

Use light targets



XENON1T 1907.11485



m_D> 10 MeV

Motivations

- How to search for DM if m_D < 10 MeV?
  - Lower the threshold (Using semi-conductor, superconductor, or skipper CCD technology, nano tubes …)
  - Accelerate the DM particles (Sun, cosmic rays)

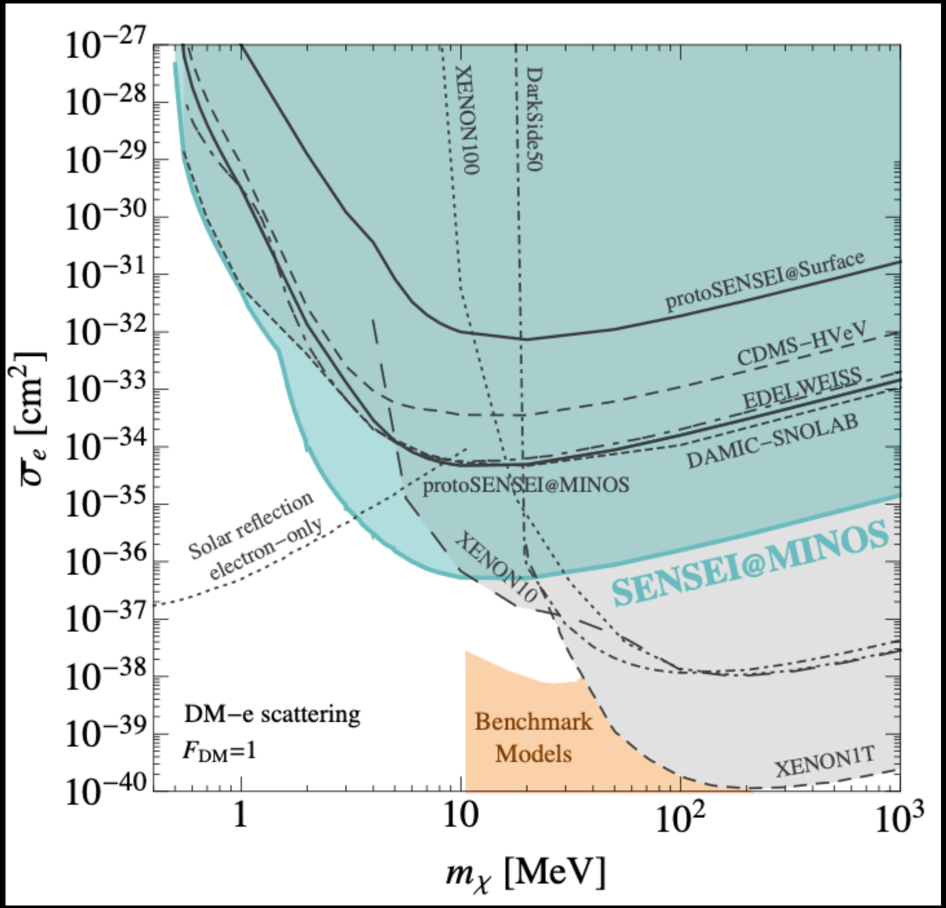
Sensei Experiment

- Skipper CCD technology

Electron recoild threshold ~ 1.2 eV

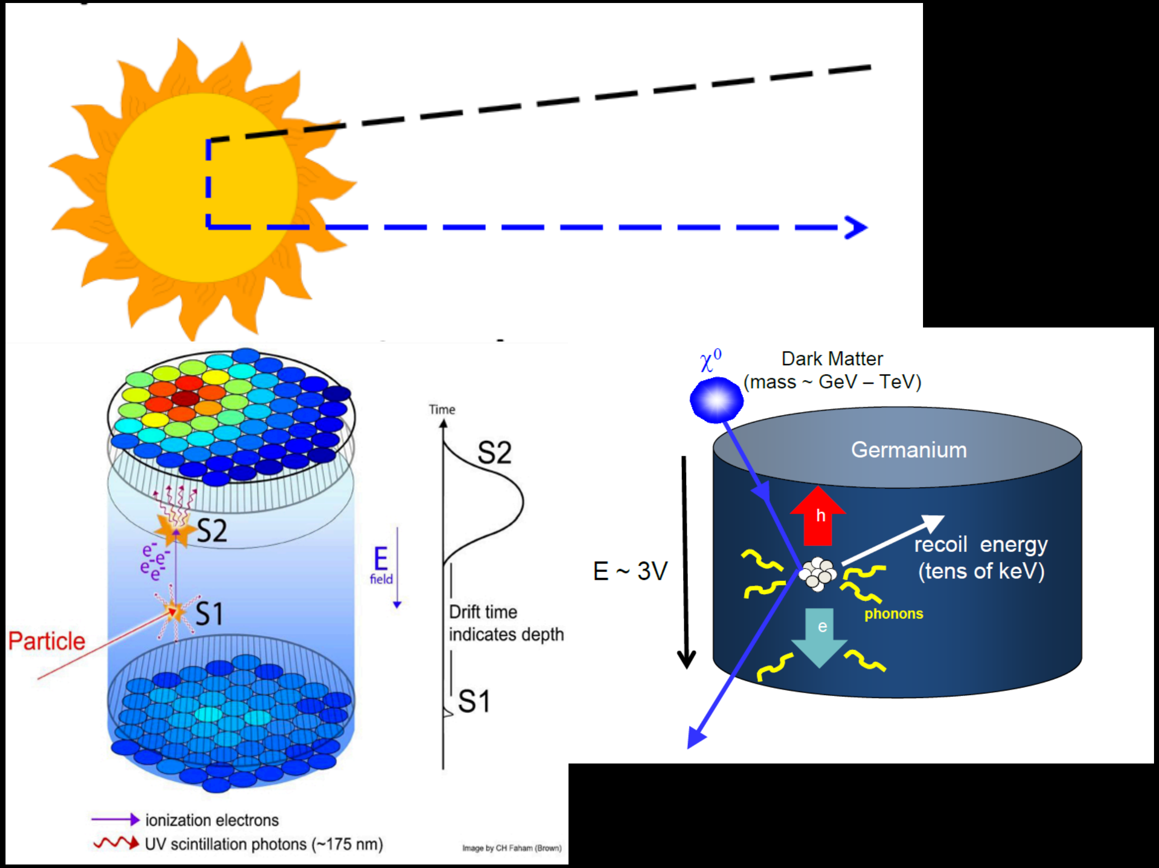
$m_D \sim$ 0.5 MeV for scattering
$m_D \sim$ 1.2 eV for absorption

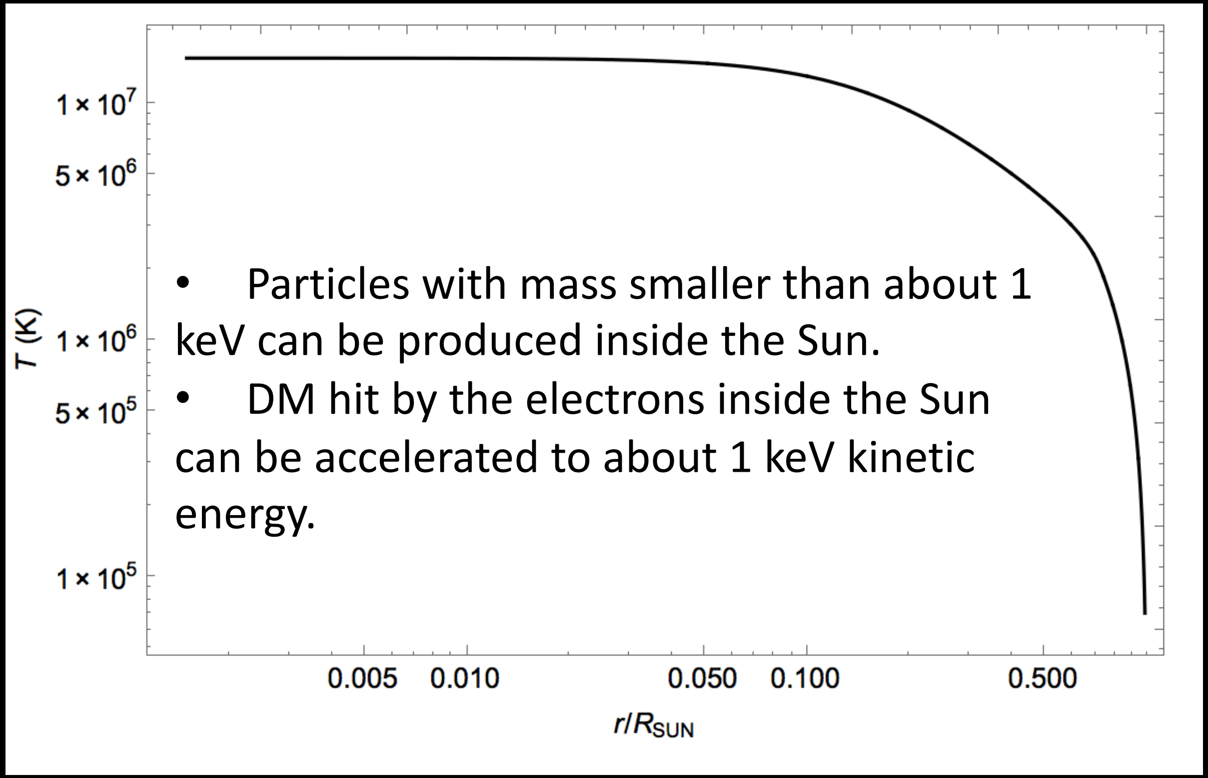
SENSEI 2004.11378, 48 gram-days



Solar accelerated DM particles

- The Sun can help us.





- Particles with mass smaller than about 1 keV can be produced inside the Sun.
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Solar accelerated DM particles

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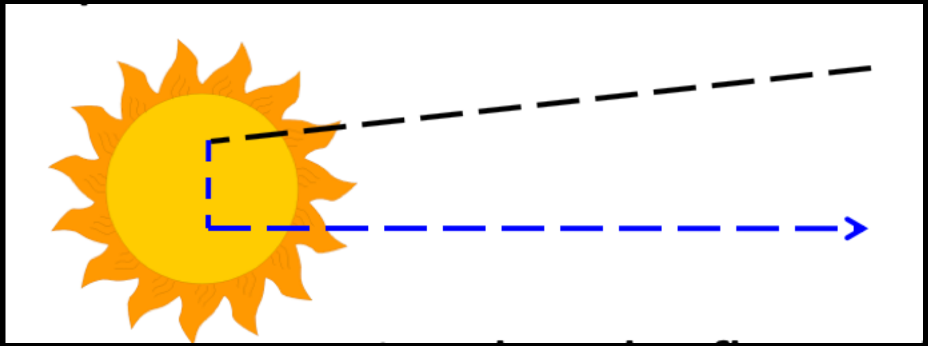


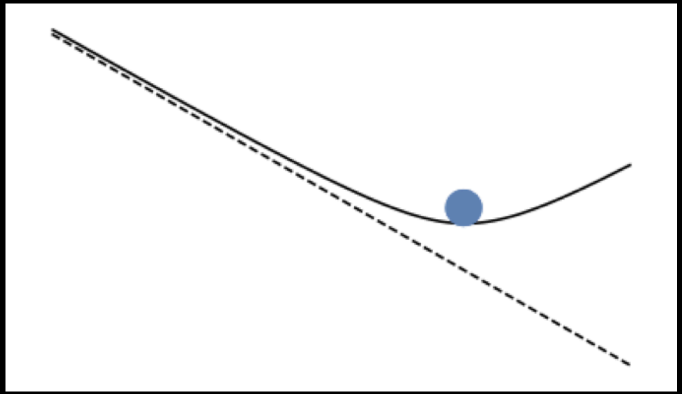
$T_{sun} \sim 1$ keV
well above the
thresholds of most
experiments!

- We pay the price that the flux at the earth surface is suppressed.

$$\Phi_{\text{Earth}} = \Phi_{\text{Sun}} \times \underbrace{\frac{\pi R^2_{\text{Sun}}}{4\pi d^2_{\text{Sun-Earth}}}}_{10^{-5}}$$

Solar accelerated DM particles

- Gravitational focusing effect



$$\frac{1}{2}v_{\rm DM}^2 = -\frac{G_N M_\odot}{R_\odot} + \frac{1}{2}v_{\rm DM}'^2$$

$$v_{\rm DM} R_0 = v'_{\rm DM} R_\odot$$

$$\Longrightarrow \frac{R_0^2}{R_\odot^2} = 1 + \frac{2G_N M_\odot}{R_\odot v_{\rm DM}^2}$$

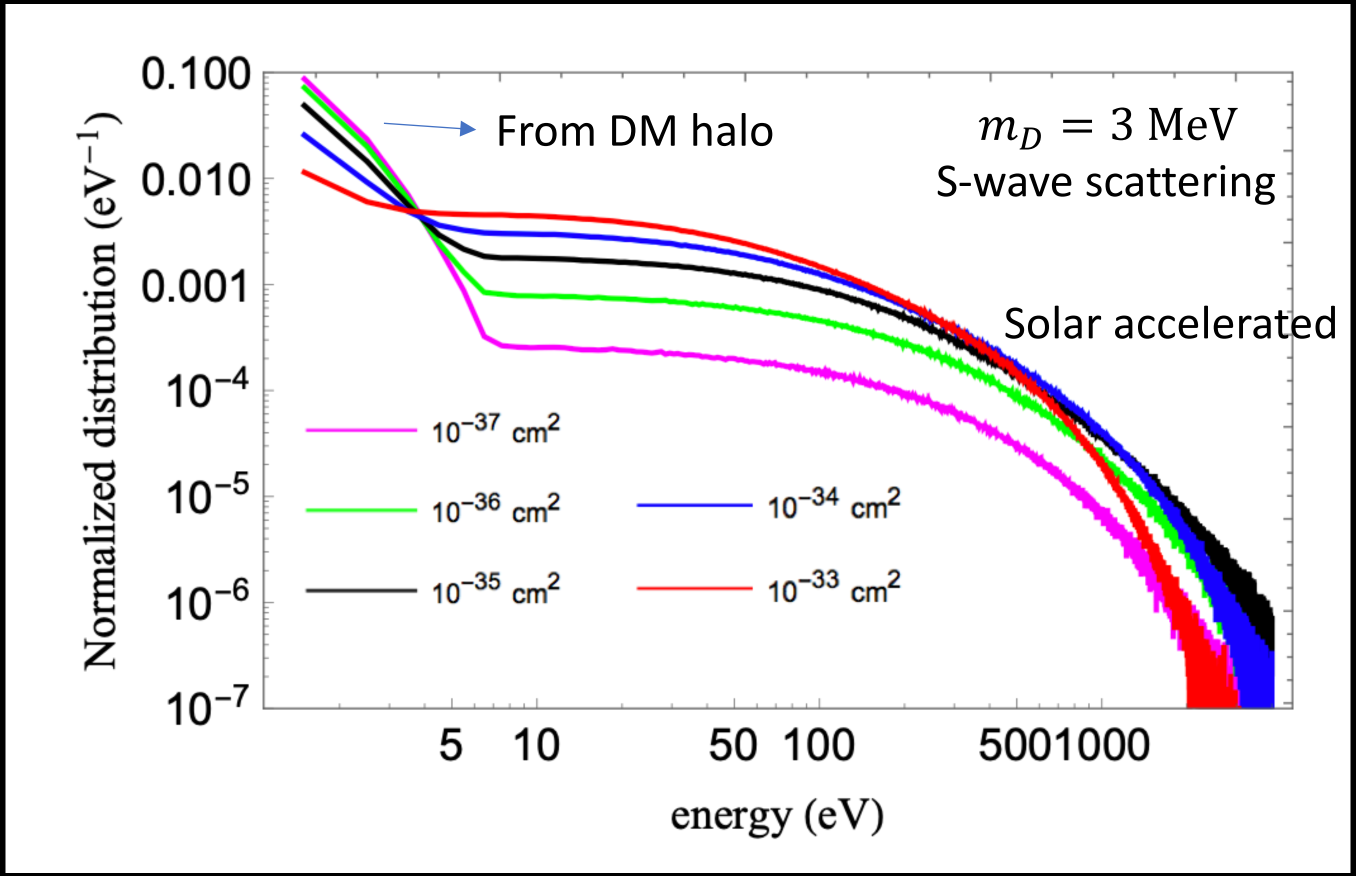
$$\frac{2G_N M_\odot}{R_\odot} = v_{\rm esc}^2 \approx (620\ {\rm km/sec})^2$$

$$v_{\rm DM} \approx 220\ {\rm km/sec}$$

$$\Longrightarrow \frac{R_0^2}{R_\odot^2} \approx 10$$

Solar accelerated DM particles

HA, M. Pospelov, J. Pradler, A. Ritz, PRL 120 (2018) 141801



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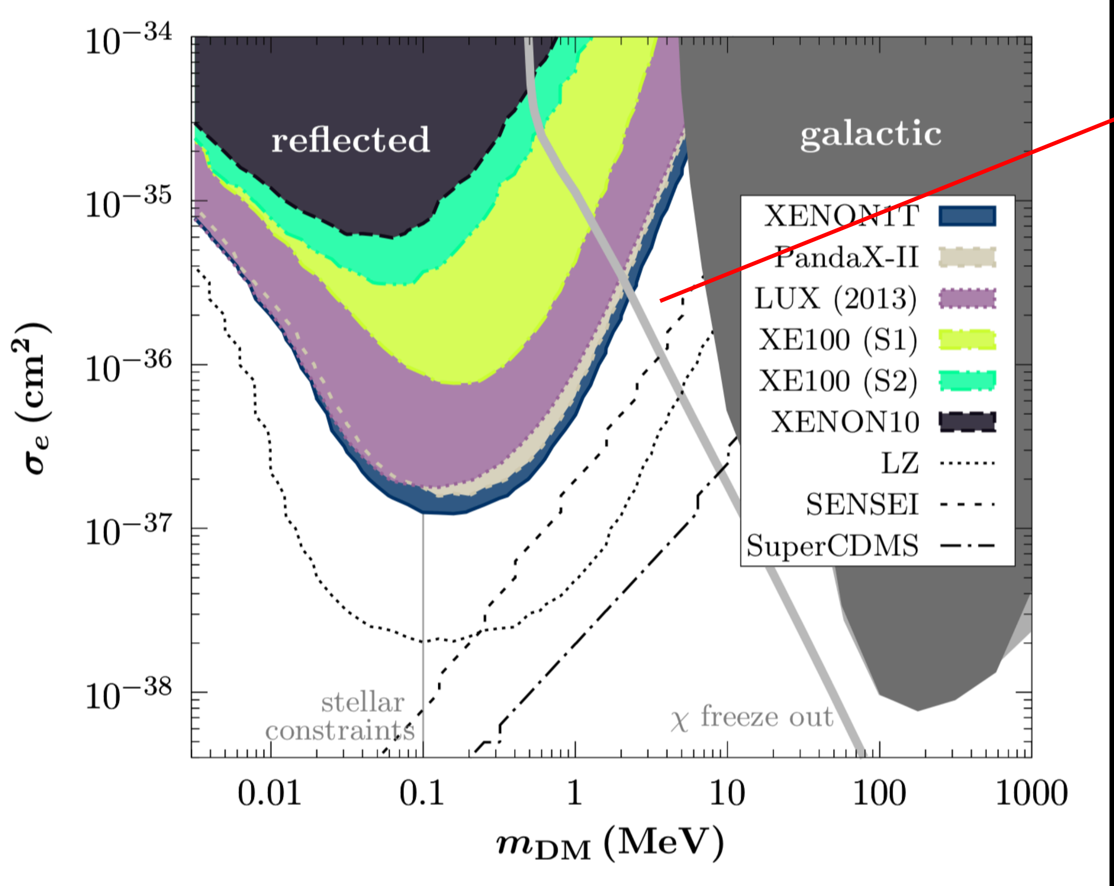
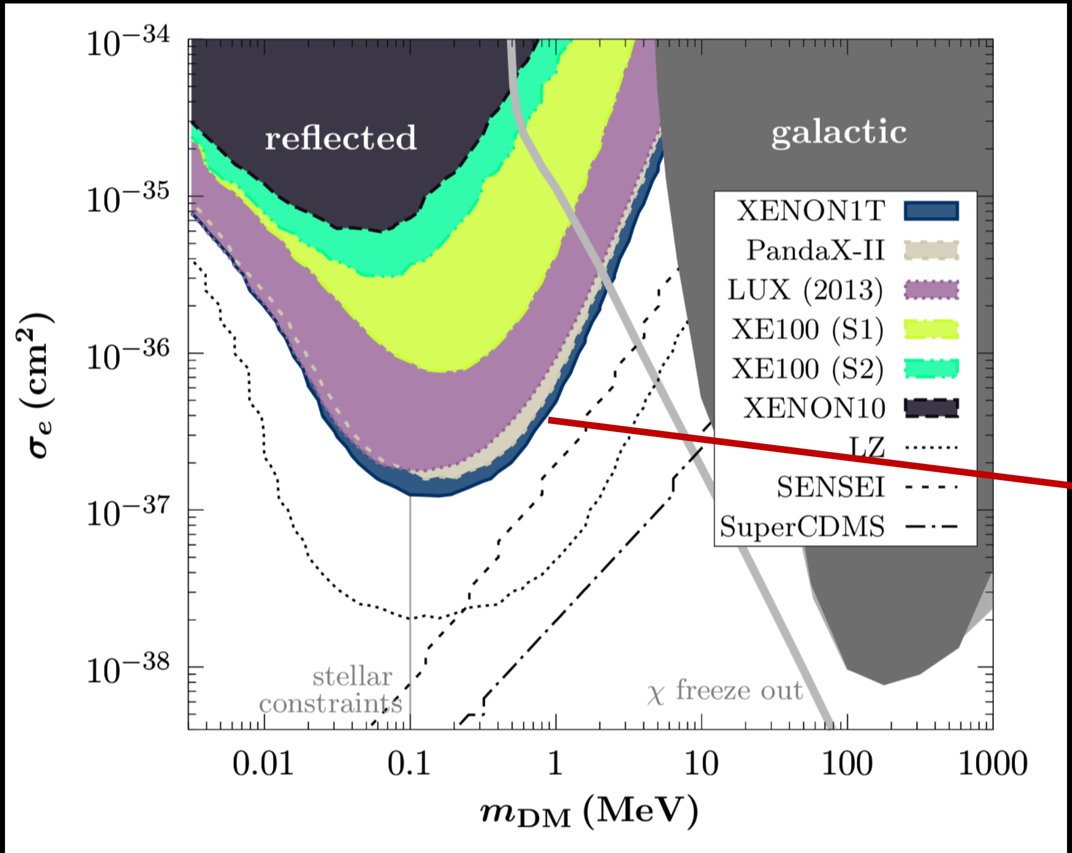
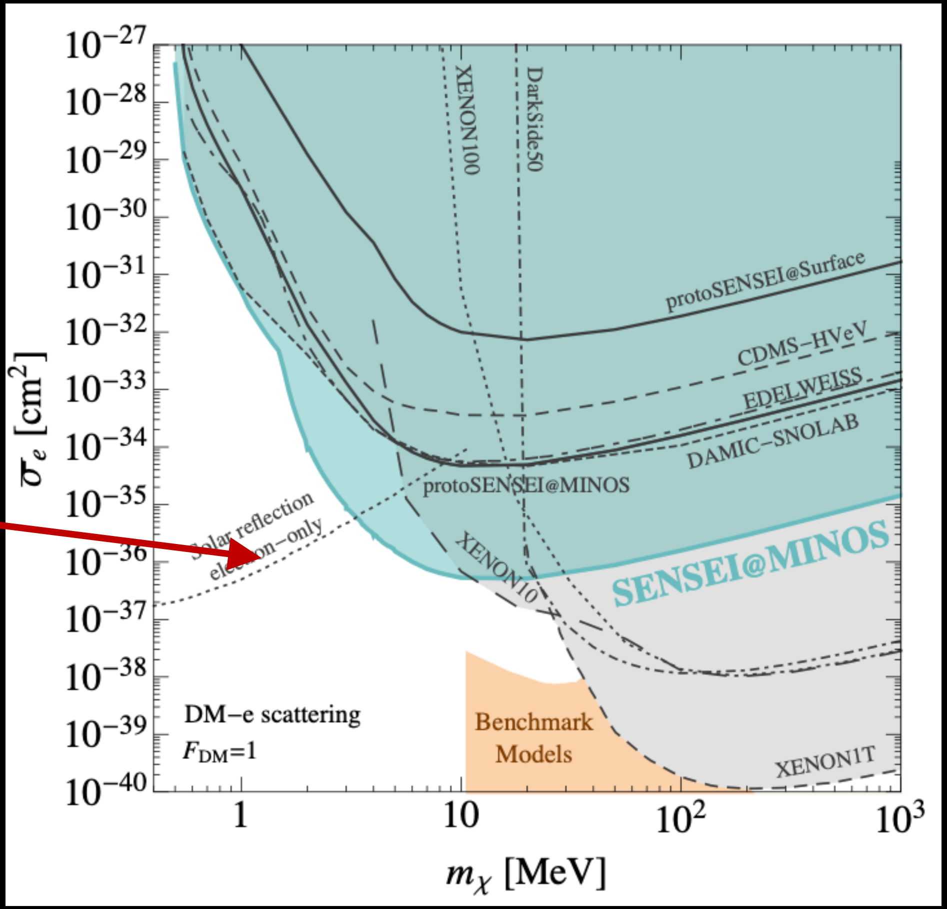


Observed relic abundance through thermal annihilation

Solar accelerated DM particles

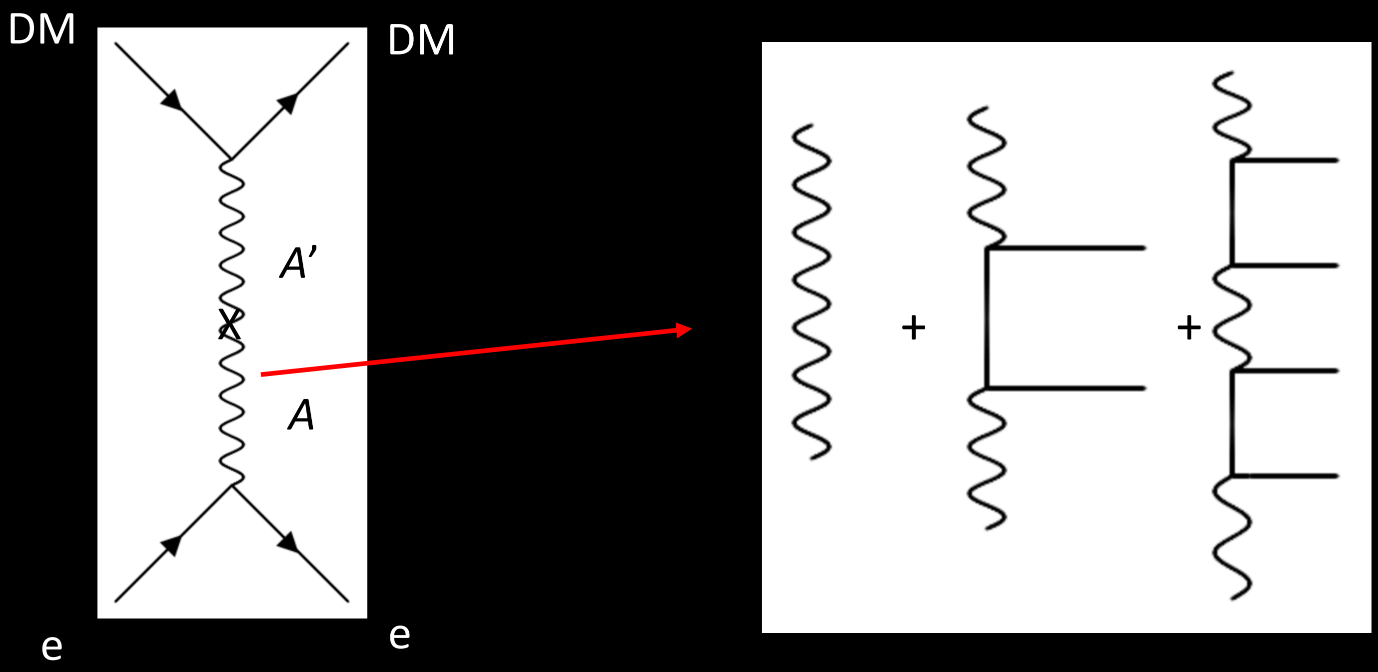


SENSEI 2004.11378, 48 gram-days



Beyond contact interaction (work in progress)

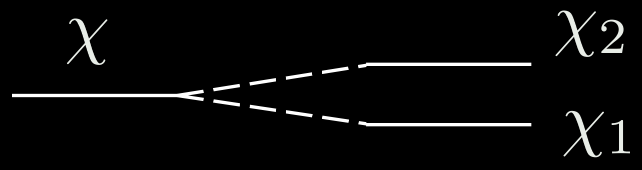
- Very light mediator case
  - Freeze-in scenario (no N_{eff} constraint)
  - Kinetic mixing model (no constraint if the dark photon is very light)



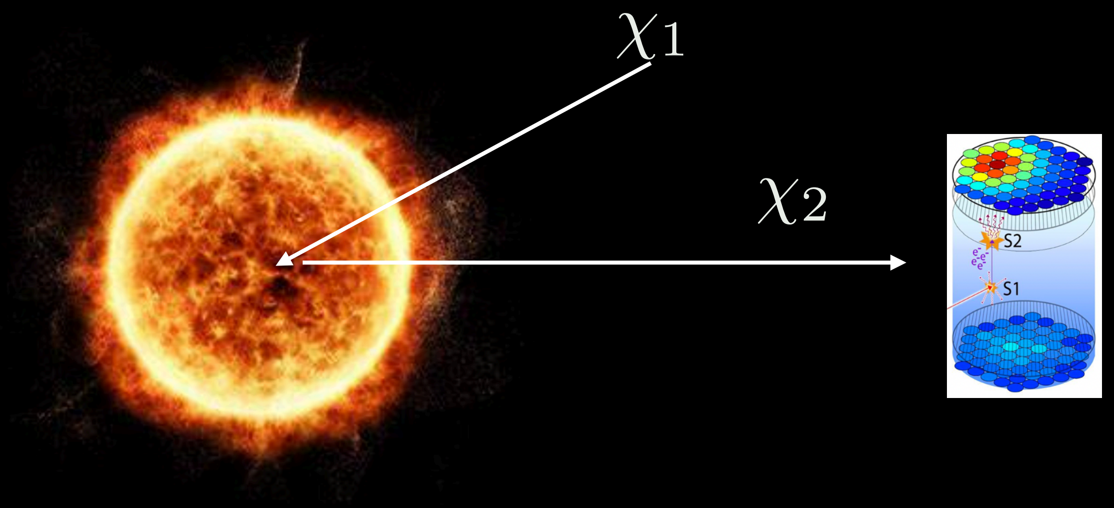
Momentum dependent
Debye screening effect

Beyond contact interaction (work in progress)

- Inelastic dark matter excited inside the Sun



$$\Delta m_D \sim 1 \text{ keV} \ll m_D$$



Baryakhar, Berlin, Liu, Weiner, 2006.13918 in light of XENON1T excess.

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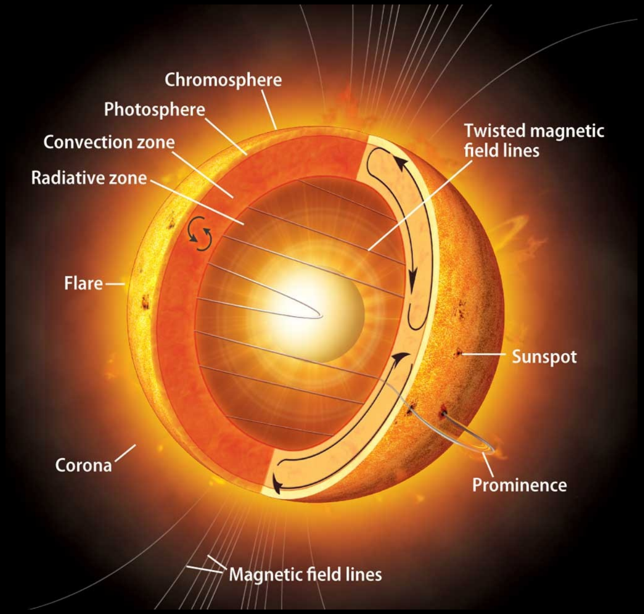


What is dark photon?

- It is a vector field coupled to SM particles only through kinetic mixing with the EM field.
- It is massive.

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

Stueckelberg

$$\frac{1}{2}m'^2_A A'_\mu A'^\mu$$

Higgsed

$$\frac{1}{2}m'^2_A A'_\mu A'^\mu + \underline{e_D m'_A h_D A'_\mu A'^\mu} + \frac{1}{2}e_D^2 h_D^2 A'_\mu A'^\mu$$

Crucial for the production inside plasma

How to produce dark photon DM?

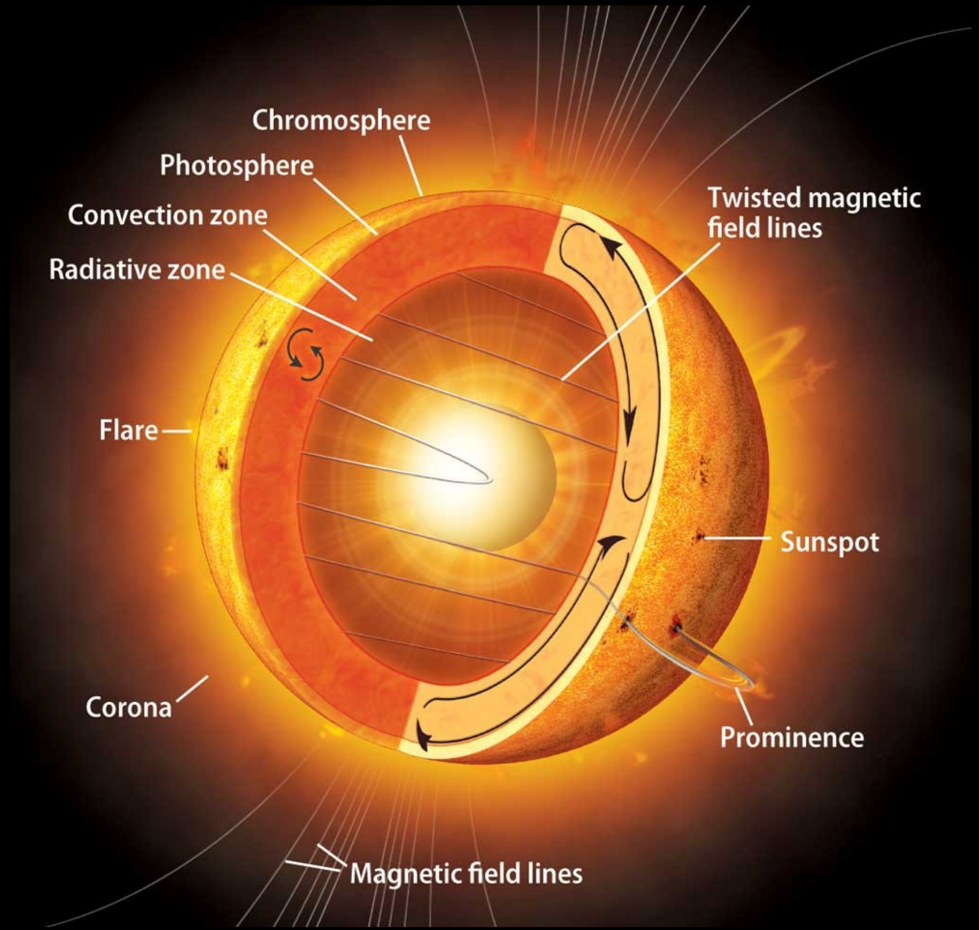
- The longitudinal mode of dark photon dark matter can be produced during inflation. *P.W.Graham, J.Mardon, S.Rajendran, 1504.02102*
- Parametric resonance production from scalar field oscillation.

R.T.Co, A.Pierce, Z.Zhang,Y.Zhao, 1810.07196
J.A.Dror, K.Harigaya, V.Narayan, 1810.07195
M.Bastero-Gil, J.Santiago, L.Ubaldi, R.Vega-Morales, 1810.07208
P.Agrawal, N.Kitajima, M.Reece, T.Sekiguchi, F.Takahashi, 1810.07188

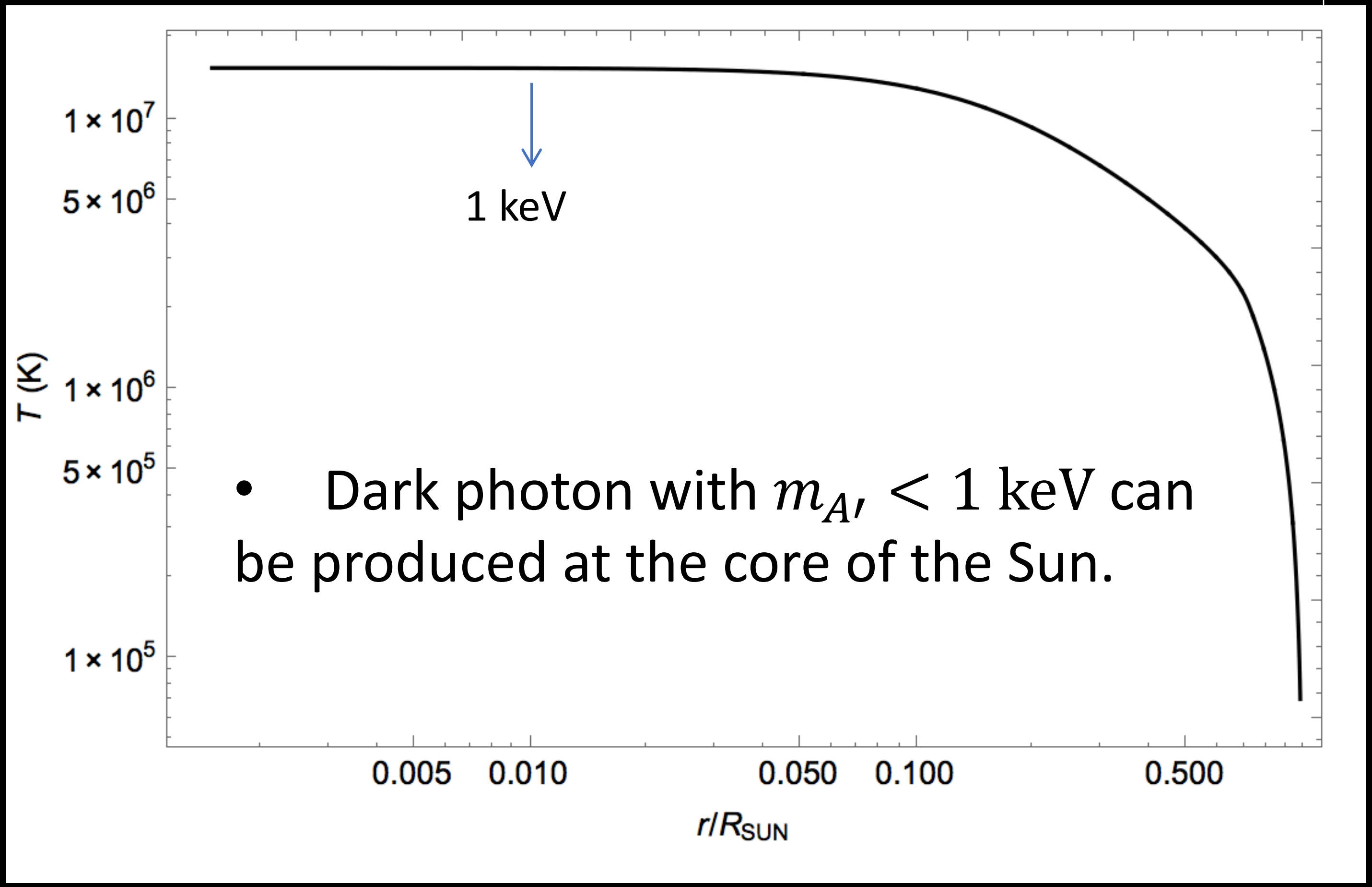
- Misalignment with non-minimal coupling to gravity

G.Alonso-Alvarez, T.Hugle, J.Jaeckel, 1905.09836

Produce dark photon inside the Sun



Photosphere

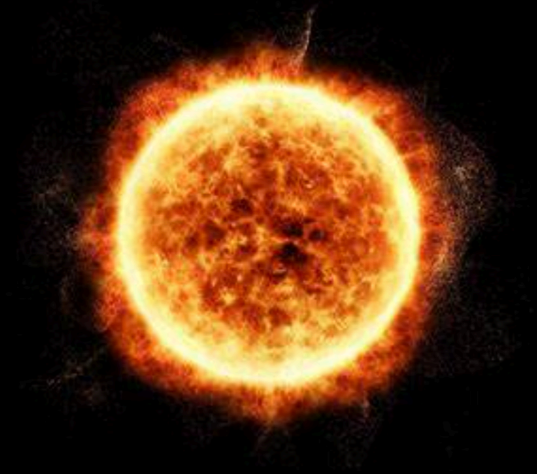


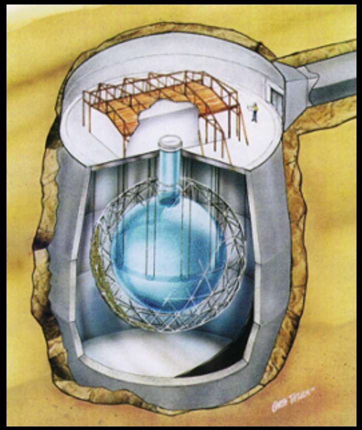
- Dark photon with $m_{A'} < 1\,\mathrm{keV}$ can be produced at the core of the Sun.

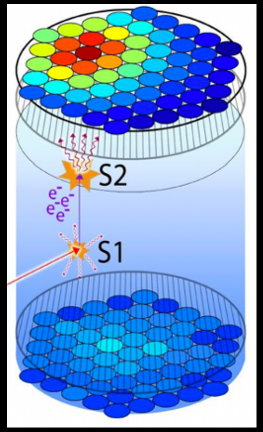
Searching for dark photon DM

- Produced inside the Sun

  - It will take more energy and accelerate the burning of the Sun.
  - It will change the temperature at the Sun's core and thus change the solar neutrino flux.
  - The keV scale dark photon can be directly detected by dark matter direct detection detectors.







Resonant production of dark photon inside the Sun

$$-\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

- Dispersion relations in the vacuum
  - For photon: $\omega^2 - k^2 = 0$
  - For dark photon: $\omega^2 - k^2 = m_{A'}^2$
  - Photons cannot convert into dark photon in the vacuum.

Resonant production of dark photon inside the Sun

- Dispersion relations in plasma

$$-\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

  - For photon: $\omega^2 - k^2 = \omega_p^2$ $\qquad \omega_p^2 = \frac{4\pi\alpha_{EM}n_e}{m_e}$
  - For dark photon: $\omega^2 - k^2 = m_{A'}^2$
  - Photons can convert into dark photon in the plasma if $\omega_p = m_{A'}$

Resonant production of dark photon inside the Sun

$$-\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

- Dispersion relations in plasma
  - For photon: $\omega^2 - k^2 = \omega_p^2$ $\qquad \omega_p^2 = \frac{4\pi\alpha_{EM}n_e}{m_e}$
  - For dark photon: $\omega^2 - k^2 = m_{A'}^2$
  - Photons can convert into dark photon in the plasma if $\omega_p = m_{A'}$
  - This is only true for transverse photon.

Resonant production of Longitudinal dark photon

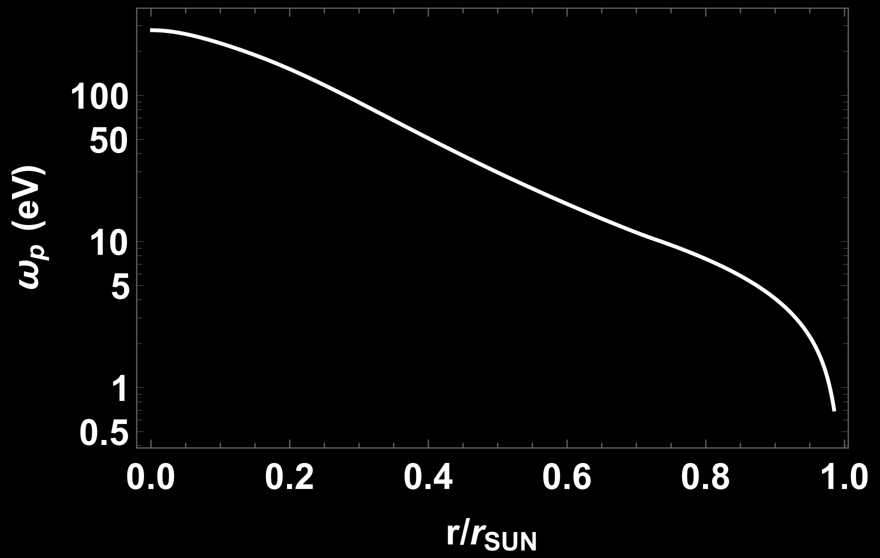
- What is longitudinal photon in a plasma?
  - It is a collective oscillation of the elections with dispersion relation:
  - For longitudinal dark photon we still have

$$\omega = \omega_p \qquad\qquad \omega^2 - k^2 = m_{A'}^2$$

  - To match the four-momentum, we have

$$\omega = \omega_p$$
$$\omega > m_{A'}$$

Resonant production of dark photon inside the Sun



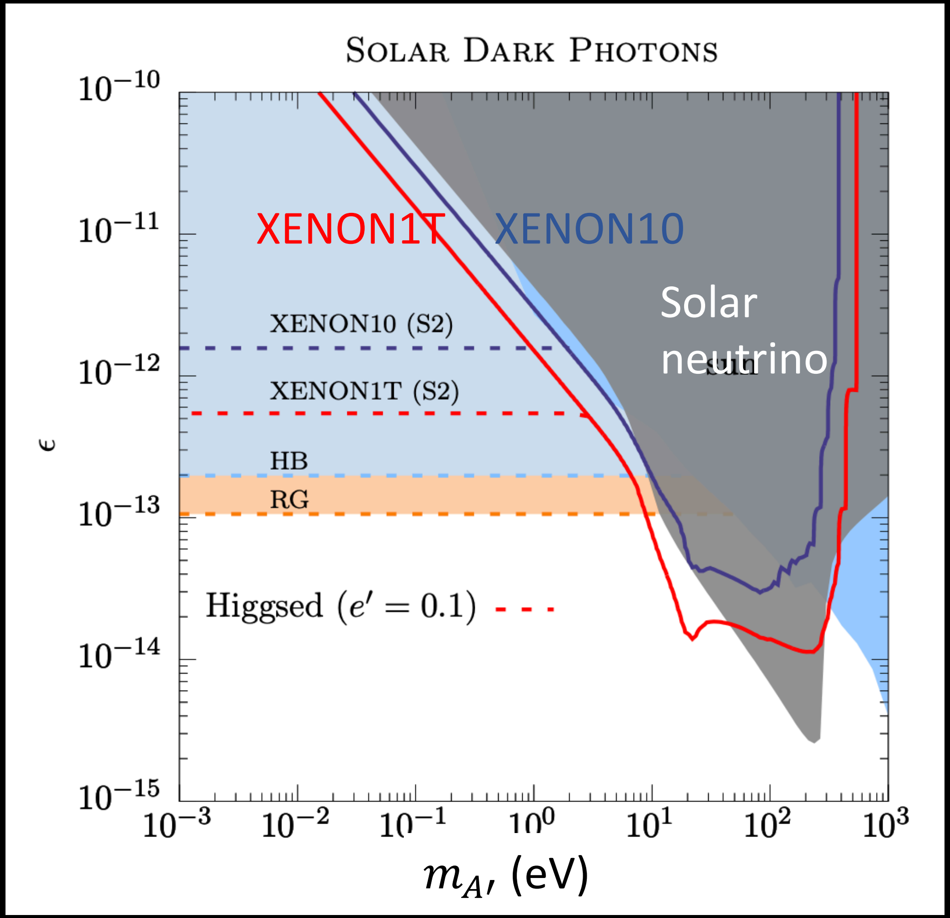
- Inside the Sun
  - $1 \text{ eV} < \omega_p < 300 \text{ eV}$

    surface center

  - For $1 \text{ eV} < m_{A'} < 300 \text{ eV}$, both longitudinal and transverse models can be resonantly produced.
  - For $m_{A'} < 1 \text{ eV}$ only longitudinal modes can be resonantly produced.
  - For $m_{A'} > 300 \text{ eV}$, no resonant production.

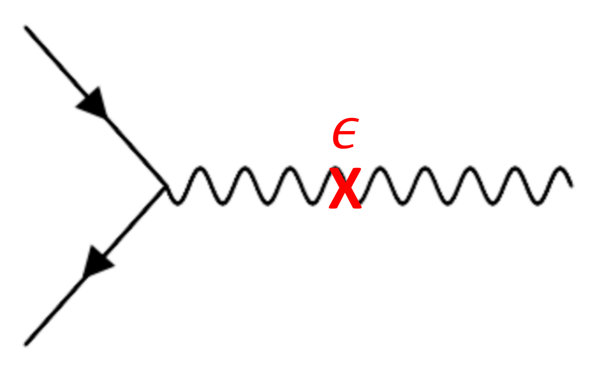
Searching for dark photon DM

- Produced inside the Sun
  - Hidden Luminosity < 10% solar luminosity (solar neutrino flux)
    HA, M.Pospelov, J.Pradler, PLB 725 (2013) 190
  - Direct detection of solar dark photon by XENON experiments
    HA, M.Pospelov, J.Pradler, PRL 111 (2013) 041302



HA, Pospelov, Pradler, A.Ritz, 2006.13929

Stueckelberg case vs Higgsed case



$$-\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} \longrightarrow \epsilon A_\nu \partial_\mu F'^{\mu\nu} \longrightarrow \epsilon m_{A'}^2 A_\mu A'^\mu$$

In vacuum $\mathcal{M} = \frac{\epsilon m_{A'}^2}{k^2}\langle f | J^\mu_{\rm EM} | i \rangle \varepsilon_\mu$

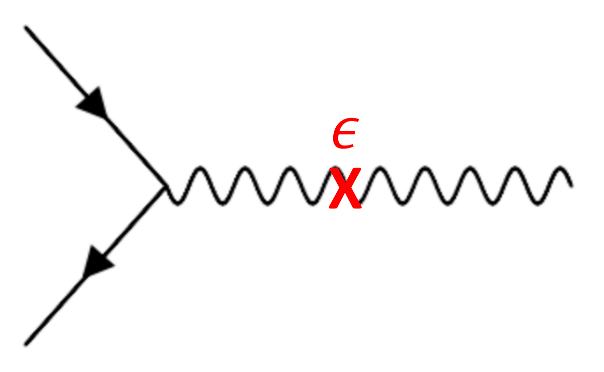
In plasma $\mathcal{M} = \frac{\epsilon m_{A'}^2}{m_{A'}^2 - \Pi}\langle f | J^\mu_{\rm EM} | i \rangle \varepsilon_\mu$

Transverse modes: $\Pi_T = \Pi_{\mu\nu}\varepsilon^\mu_T \varepsilon^\nu_T = \omega_p^2$ $\Pi^{\mu\nu} = \langle T J^\mu_{\rm EM} J^\nu_{\rm EM} \rangle$

$\longrightarrow$ For $m_{A'} \ll \omega_p$, $\mathcal{M}_T \propto \epsilon m_{A'}^2/\omega_p^2$

$\Gamma_T \propto \epsilon^2 m_A'^4/\omega_p^4$

Stueckelberg case vs Higgsed case



$$-\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} \longrightarrow \epsilon A_\nu \partial_\mu F'^{\mu\nu} \longrightarrow \epsilon m_{A'}^2 A_\mu A'^\mu$$

In vacuum $\quad \mathcal{M} = \frac{\epsilon m_{A'}^2}{k^2}\langle f|J_{\rm EM}^\mu|i\rangle \varepsilon_\mu$

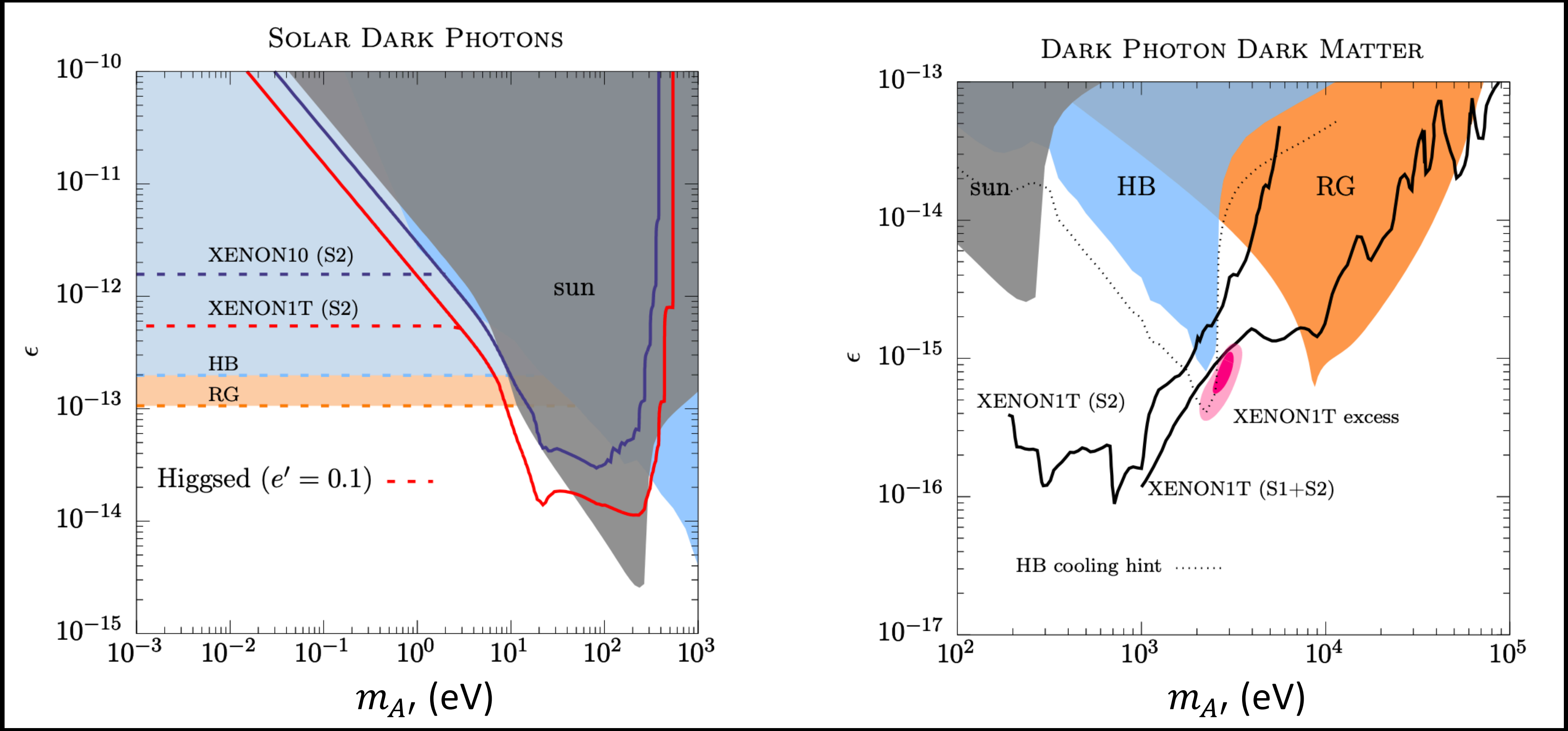
In plasma $\quad \mathcal{M} = \frac{\epsilon m_{A'}^2}{m_{A'}^2 - \Pi}\langle f|J_{\rm EM}^\mu|i\rangle \varepsilon_\mu$

Logitudinal mode: $\quad \Pi_L = \Pi_{\mu\nu}\varepsilon_L^\mu \varepsilon_L^\nu \propto m_{A'}^2 \qquad \Pi^{\mu\nu} = \langle T J_{\rm EM}^\mu J_{\rm EM}^\nu \rangle$

$\longrightarrow$ For $m_{A'} \ll \omega_p$, $\quad \mathcal{M}_L \propto \epsilon m_{A'}/\omega_p$

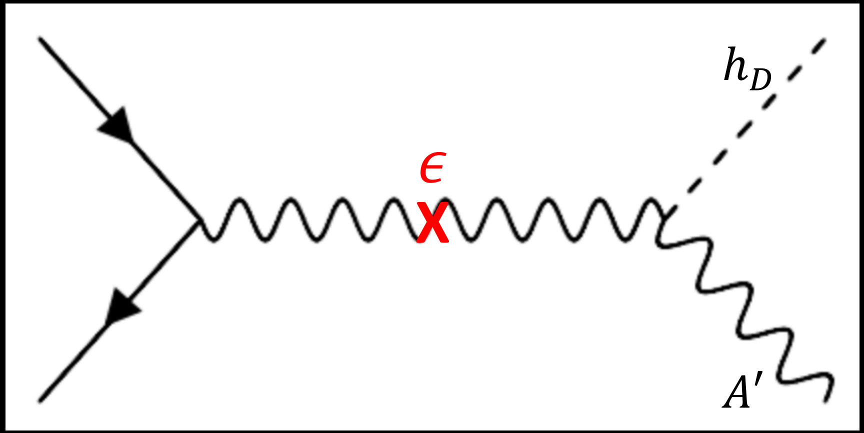
$\Gamma_L \propto \epsilon^2 m_A'^2/\omega_p^2$

Comparison with the direct search for halo dark matter

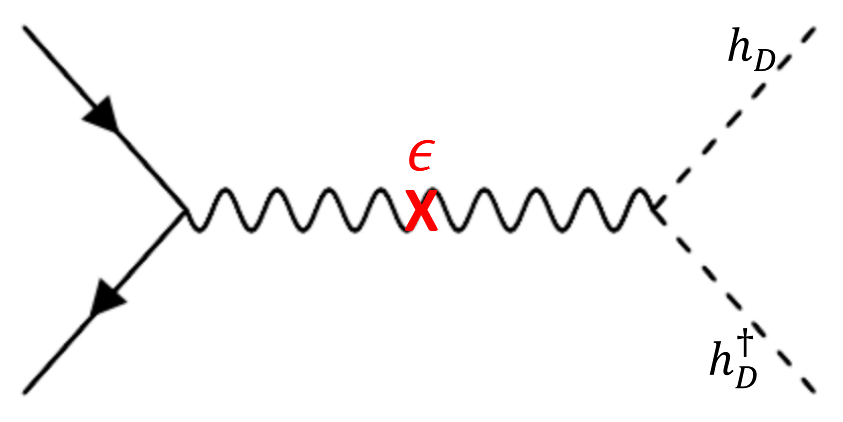


Stueckelberg case vs Higgsed case

- Higgsed case $$\frac{1}{2}m'^2_A A'_\mu A'^\mu + e_D m'_A h_D A'_\mu A'^\mu + \frac{1}{2}e_D^2 h_D^2 A'_\mu A'^\mu$$



$m_{A'} \ll \omega_p$

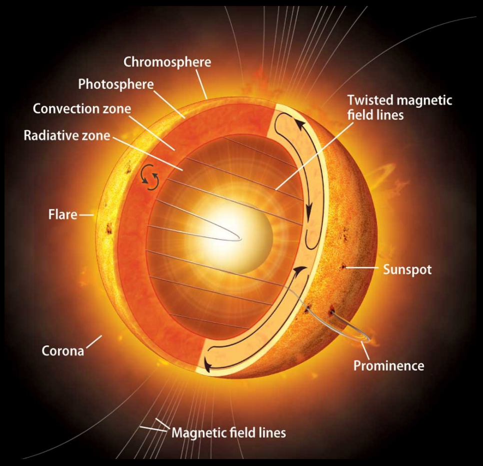


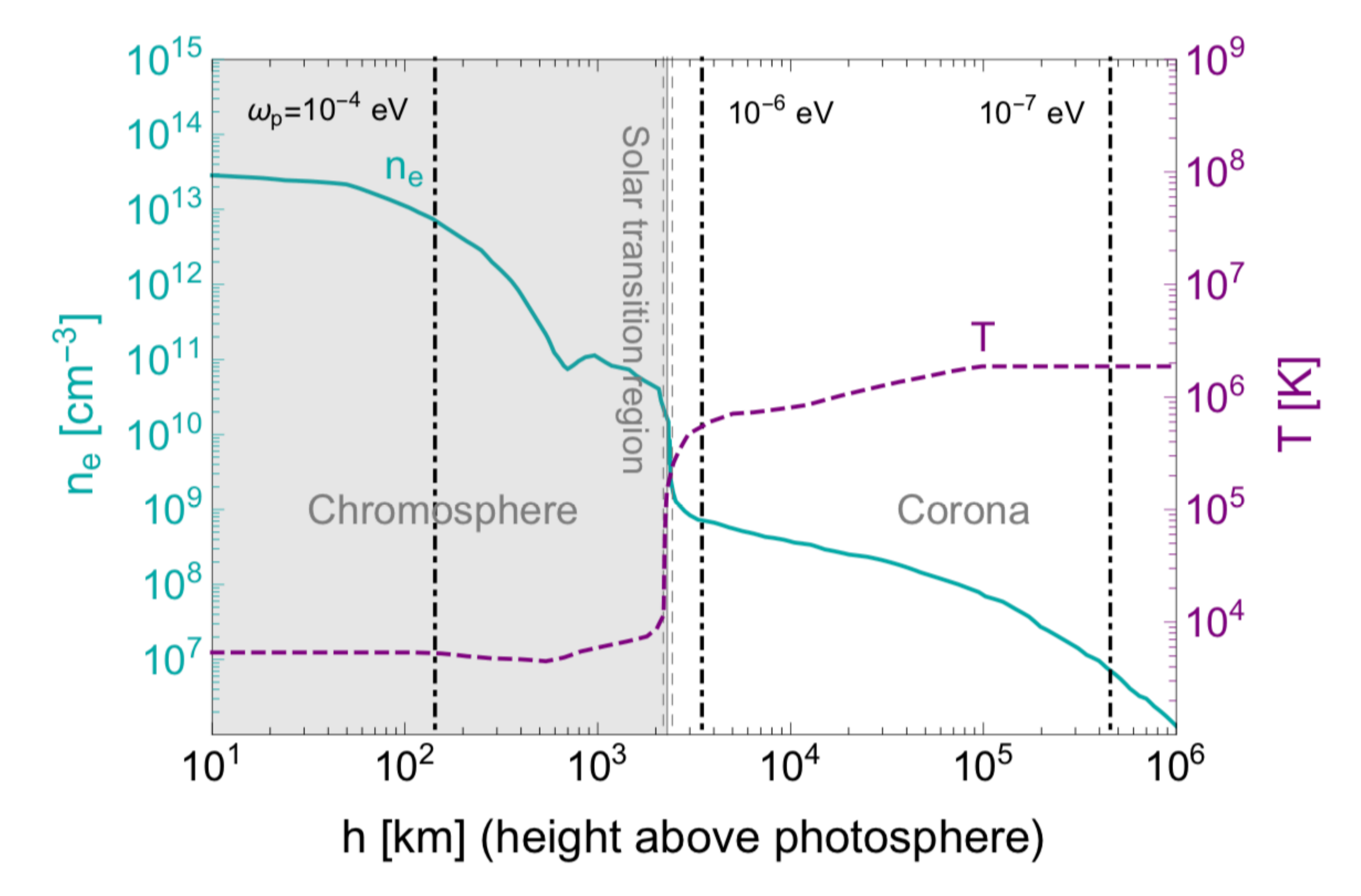
- It is equivalent to the case of producing light milli-charged particle through massive photon decay. No suppression from $m_{A'}$.

Searching for dark photon dark matter with thermal plasma

- Dispersion relations in plasma
  - For photon: $\omega^2 - k^2 = \omega_p^2$ $\qquad$ $\omega_p^2 = \frac{4\pi\alpha_{EM} n_e}{m_e}$
  - For dark photon: $\omega^2 - k^2 = m_{A'}^2$
  - Dark photons can convert into photon in the plasma if $\omega_p = m_{A'}$.
- The Sun's atmosphere is a vast source of plasma and may be transparent.

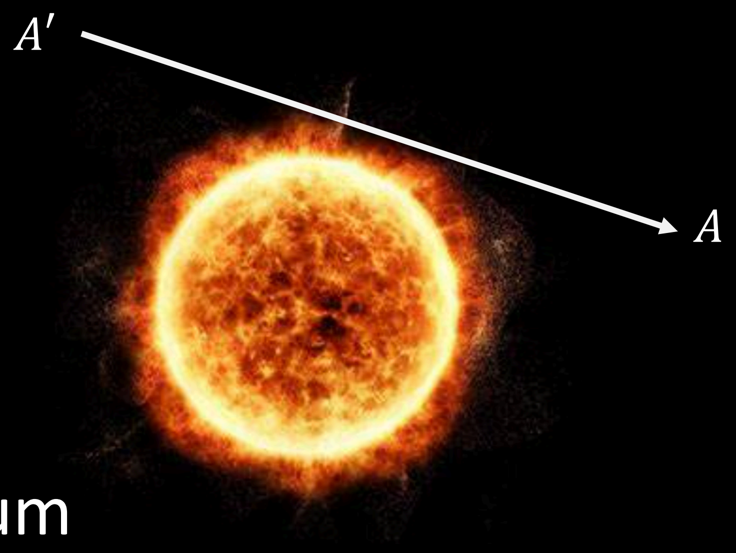
Dark photon dark matter converted at the Sun's atmosphere





Dark photon dark matter converted at the Sun’s atmosphere

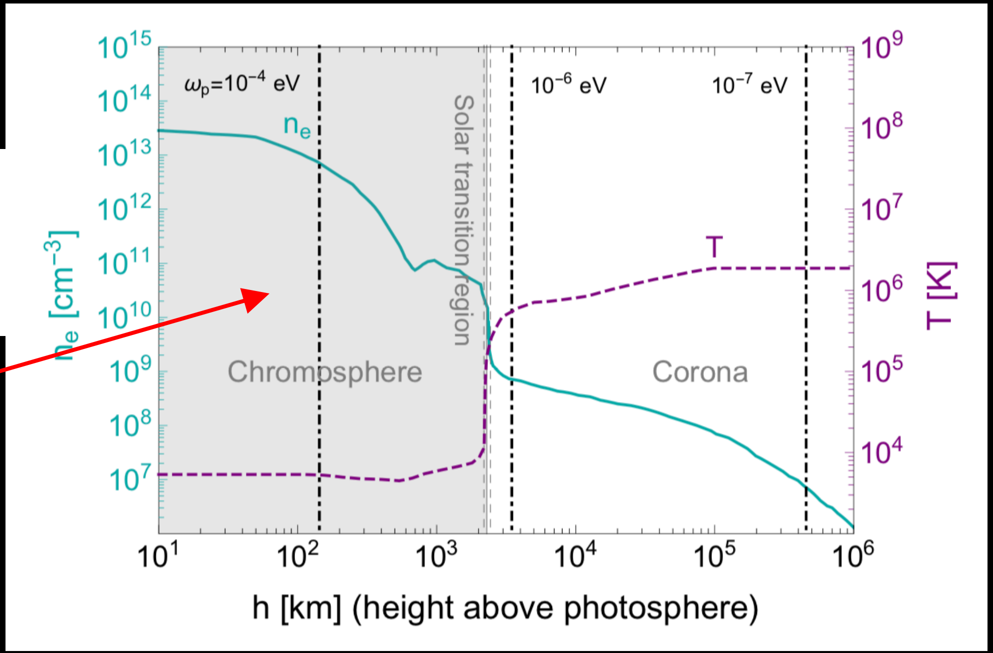
- Resonant conversion
  - $\omega_p = m_{A'}$
- Inside the dark matter halo
  - $v_{A'} \sim 10^{-3}$
- The frequency of the converted photon
  - $\omega \approx m_{A'}$, with the dispersion $\sim 10^{-6}$.
- The signal is a sharp peak in the solar spectrum



Absorption of the converted photon during propagation

- Inverse bremsstrahlung absorption

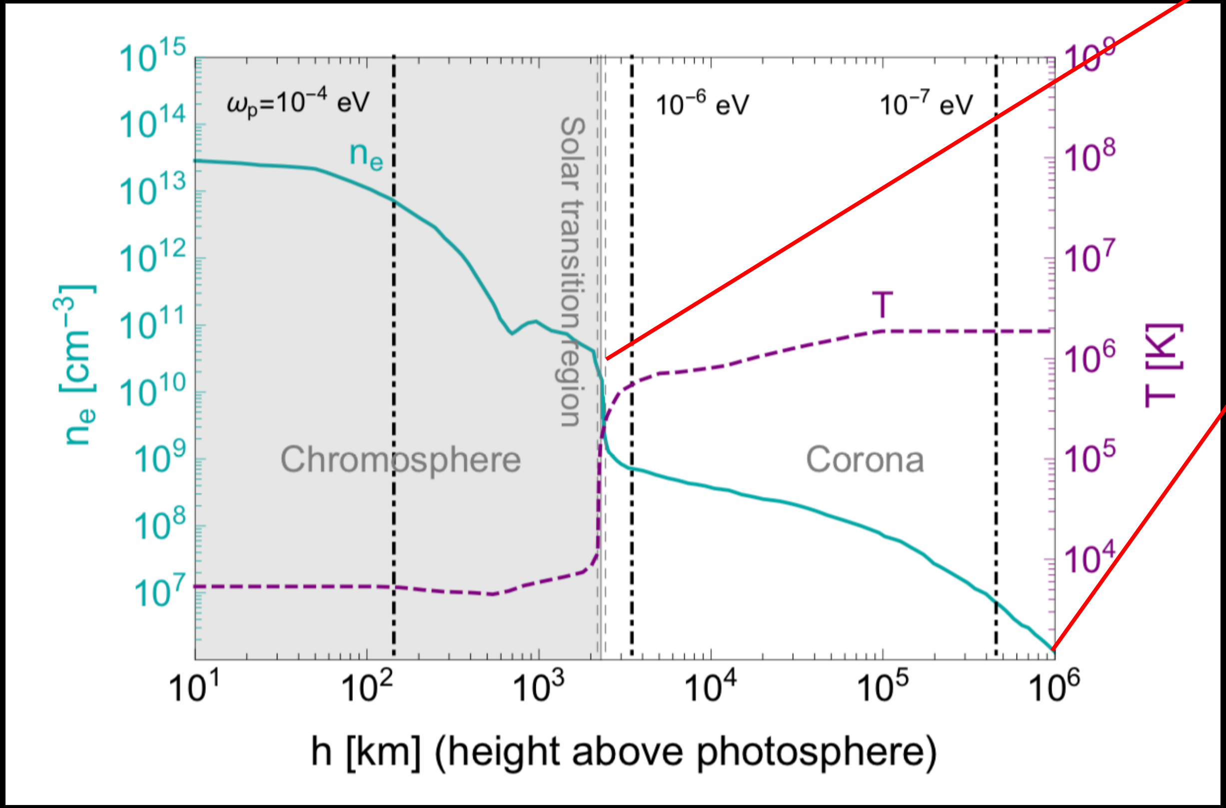
$$\Gamma_{\text{inv}} \approx \frac{8\pi n_e n_N \alpha^3}{3\omega^3 m_e^2} \left(\frac{2\pi m_e}{T}\right)^{1/2} \log\left(\frac{2T^2}{\omega_p^2}\right) \left(1 - e^{-\omega/T}\right)$$



Photon converted in chromosphere cannot fly out.

- Compton scattering
  - Compton scattering can shift the frequency of the converted photon.
- $\Gamma_{att} = \Gamma_{inv} + \Gamma_{com}$

Searching for the converted photon with radio telescopes



$f = 1\ \mathrm{GHz}$

$f = 10\ \mathrm{MHz}$

Searching for the converted photon with radio telescopes

- The minimal detectable flux $S_{\min} = \dfrac{\mathrm{SEFD}}{\eta_s \sqrt{n_{\mathrm{pol}} \mathcal{B} t_{\mathrm{obs}}}}$ $\quad \mathrm{SEFD} = 2k_B \dfrac{T_{\mathrm{sys}} + T_{\odot}^{\mathrm{nos}}}{A_{\mathrm{eff}}}$

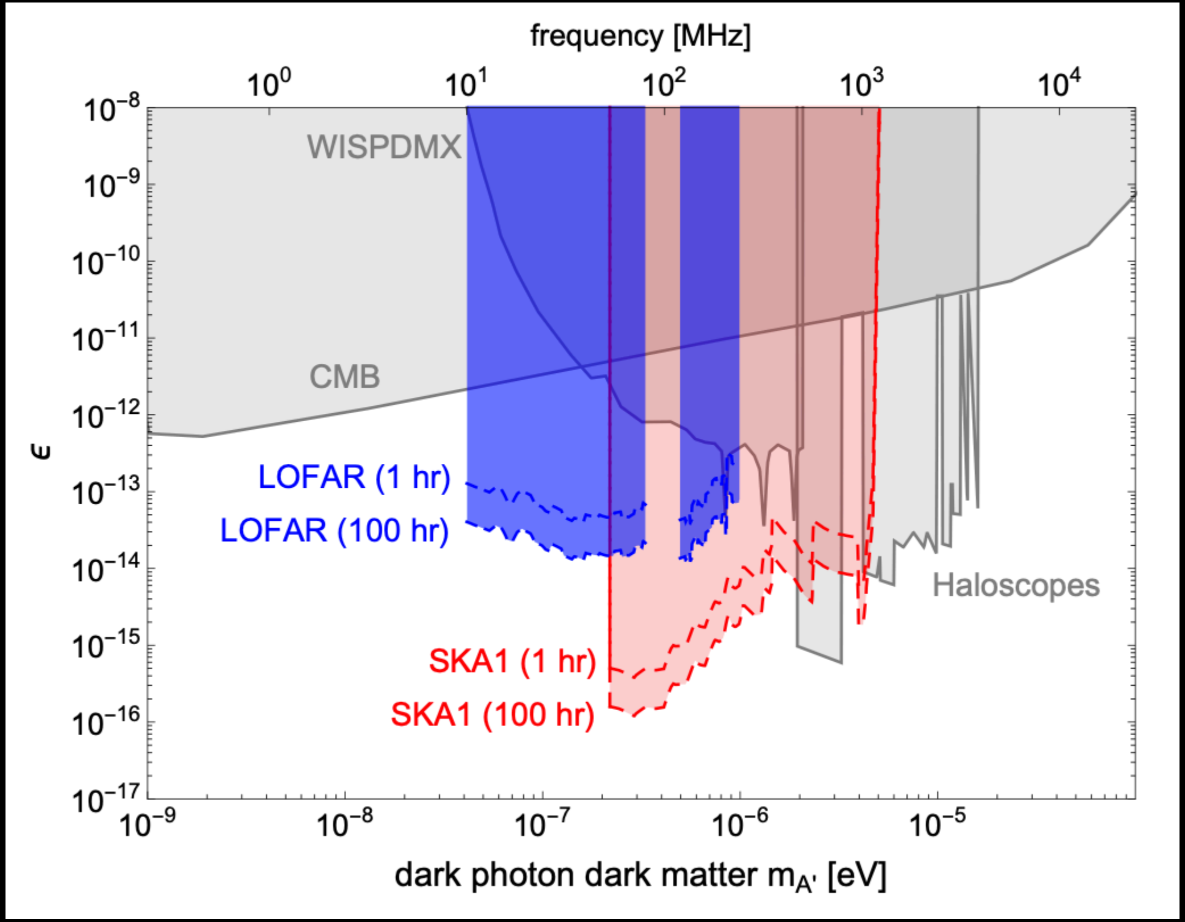
Name	f [MHz]	B_{res} [kHz]	$\langle T_{\mathrm{sys}} \rangle$ [K]	$\langle A_{\mathrm{eff}} \rangle$ [m^2]
SKA1-Low	(50, 350)	1	680	2.2×10^5
SKA1-Mid B1	(350, 1050)	3.9	28	2.7×10^4
SKA1-Mid B2	(950, 1760)	3.9	20	3.5×10^4
LOFAR	(10, 80)	195	28,110	1,830
LOFAR	(120, 240)	195	1,770	1,530

West Australia

Netherland

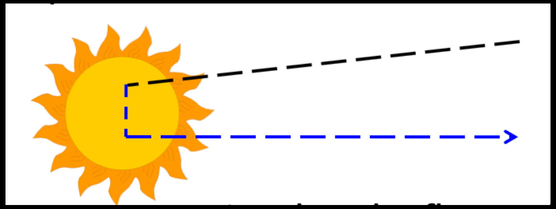
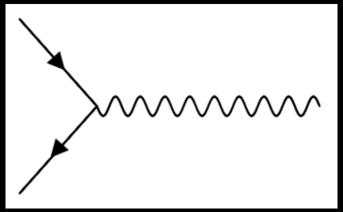
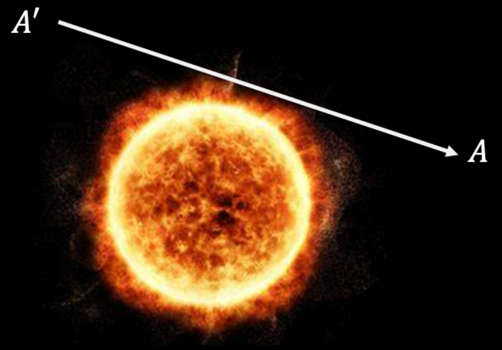
Radiofrequency Dark Photon DM

HA, F.P. Huang, J.Liu, W.Xue, arXiv:2010.15836



Summary and outlook

- Dark matters exist and we are eager to search for their particle natures.
- The Sun as own star may help us to search for them if they are light.

- We still don't fully understand the internal structure of the Sun. The magnetic field ($< 10^7$ Gauss). If it is saturated the Sun can give a very stringent constraint on axions (Gurarini, Carenza, Galan, Giannotti, Mirizzi, 2010.06601).
- Can we use the plasma in the earth's ionosphere to search for dark photon?