A Biased Review on Dark Photon

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第十三届新物理研讨会

2024.9.5-10 @ 威海，山东

Outline

- Basic dark photon models
- Searches for dark photons
- Searches for dark photon dark matter
- Production of dark photon dark matter

Notations

- A'_μ and V_μ: dark photon vector field
- $F'_{\mu\nu}$ and $V_{\mu\nu}$: dark photon field strength
- ϵ and κ: kinetic mixing
- $m_{A'}$ and m_V: dark photon mass
- ω_p and f_p : Plasma frequency, $\omega_p = 2\pi f_p$
- e': dark gauge coupling

Dark photon models

- The simplest dark photon model

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

- It may also couple to current in the dark sector.

$$e' A'_\mu \bar{\chi}\gamma^\mu\chi$$

- It can also couple to the currents composed by Standard Model fields.

$$A'_\mu J^\mu_{B-L}\ , \ \ A'_\mu J^\mu_B\ , \ \ A'_\mu J^\mu_L\ , \ \ A'_\mu J^\mu_{\mu-\tau}\ , \ \ \cdots$$

Dark photon models

- It can be dark matter. Its lifetime is easily to be longer than the age of the universe.

$$\Gamma_{A'\to 3A} \sim \frac{\epsilon^2 m_{A'}^9}{m_e^8} \qquad \Gamma_{A'\to\nu\nu} \sim \frac{\epsilon^2 m_{A'}^5}{m_Z^4}$$

Origin of dark photon mass

- Massive U(1) theory

$$\mathcal{L}_{\mathrm{mass}} = \frac{1}{2} m_V^2 \left(V_\mu - \frac{\partial_\mu a}{m_V} \right)^2$$

Would-be Goldstone

- Should there be a dark Higgs?

No! (Naturalness)

Yes! A Higgs at weak scale has just been found.

Stueckelberg case

$$\mathcal{L}_{\mathrm{mass}} = \frac{1}{2} m_V^2 V_\mu^2$$

Higgsed case

$$\mathcal{L}_{\mathrm{mass}} = \frac{1}{2} m_V^2 V_\mu^2$$

$$\mathcal{L}_{\mathrm{int}} = e' m_V h' V_\mu^2 + \frac{1}{2} e'^2 h'^2 V_\mu^2$$

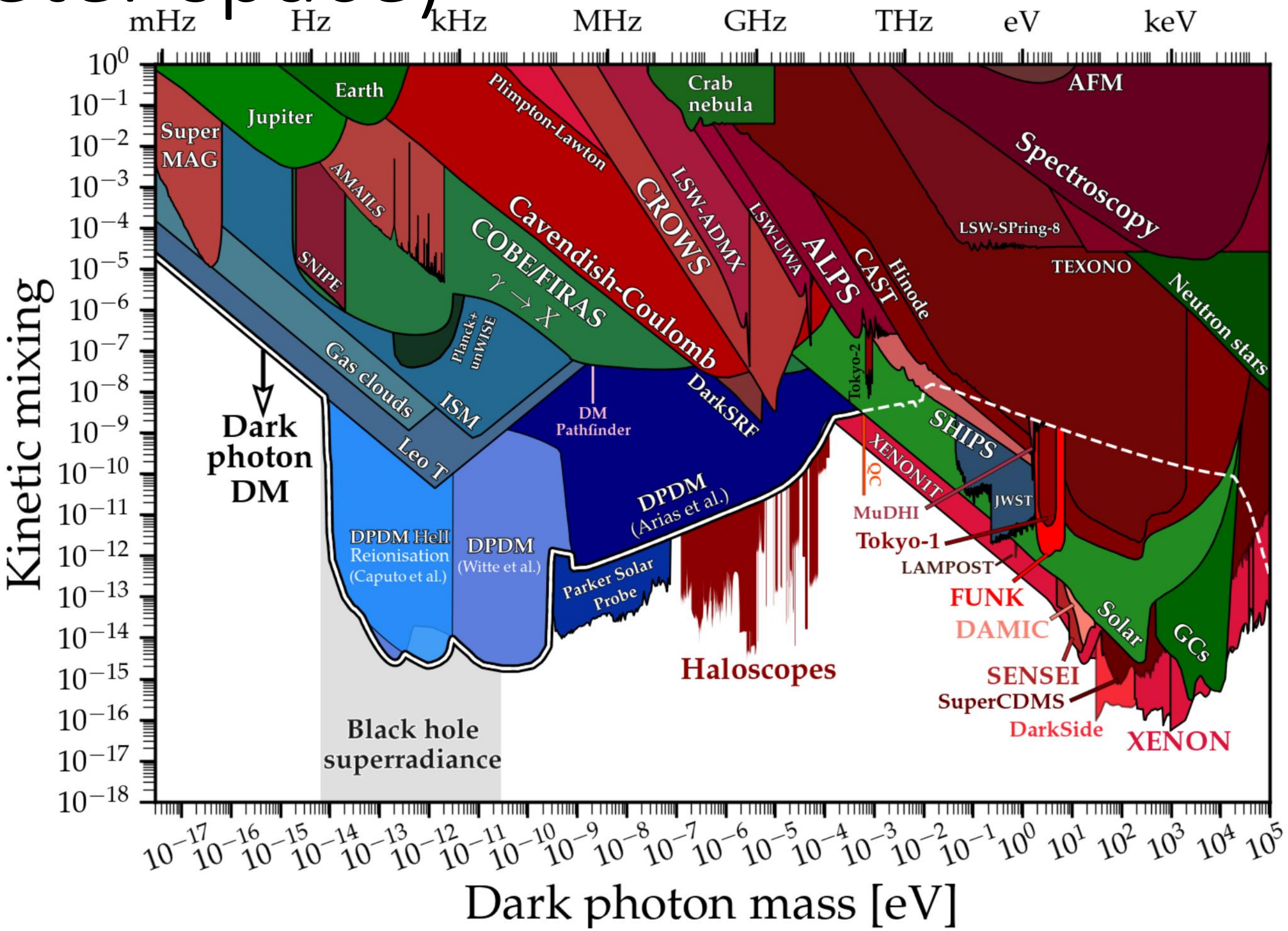
Diagonalization

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

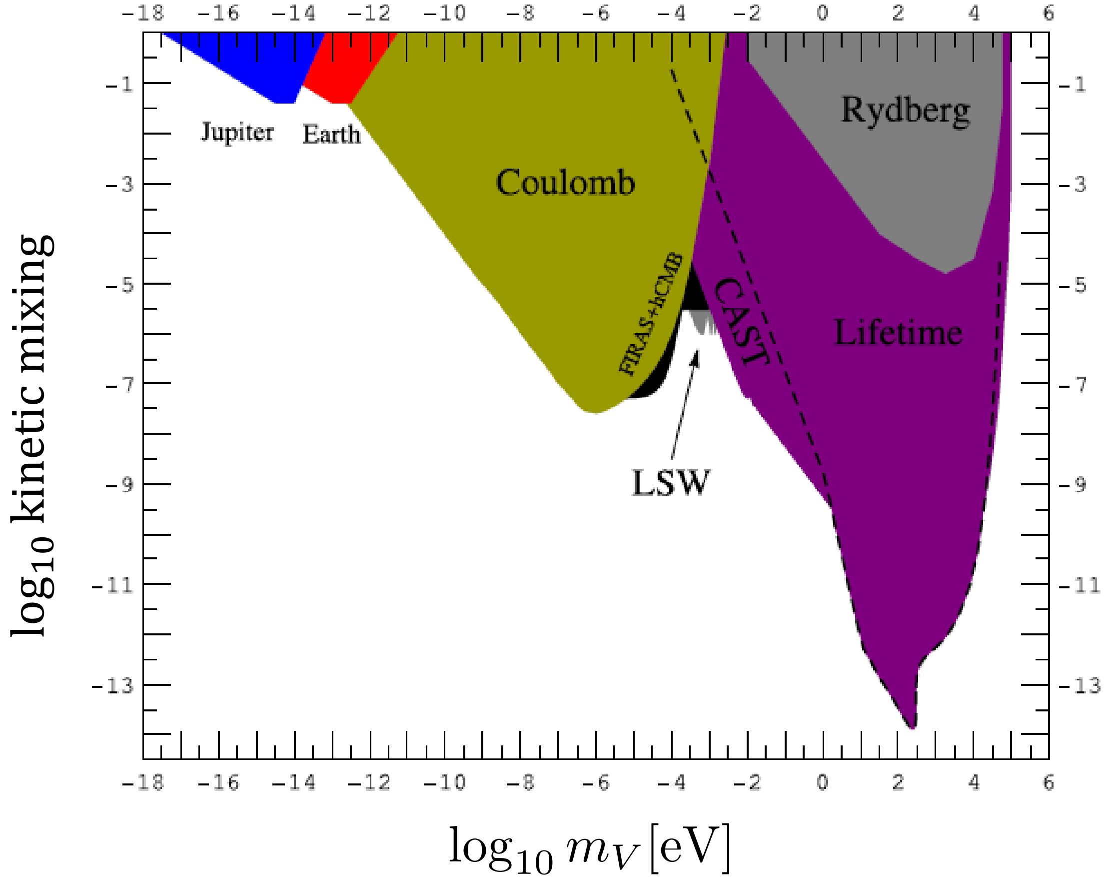
$$A_\mu \to A_\mu - \epsilon A'_\mu$$

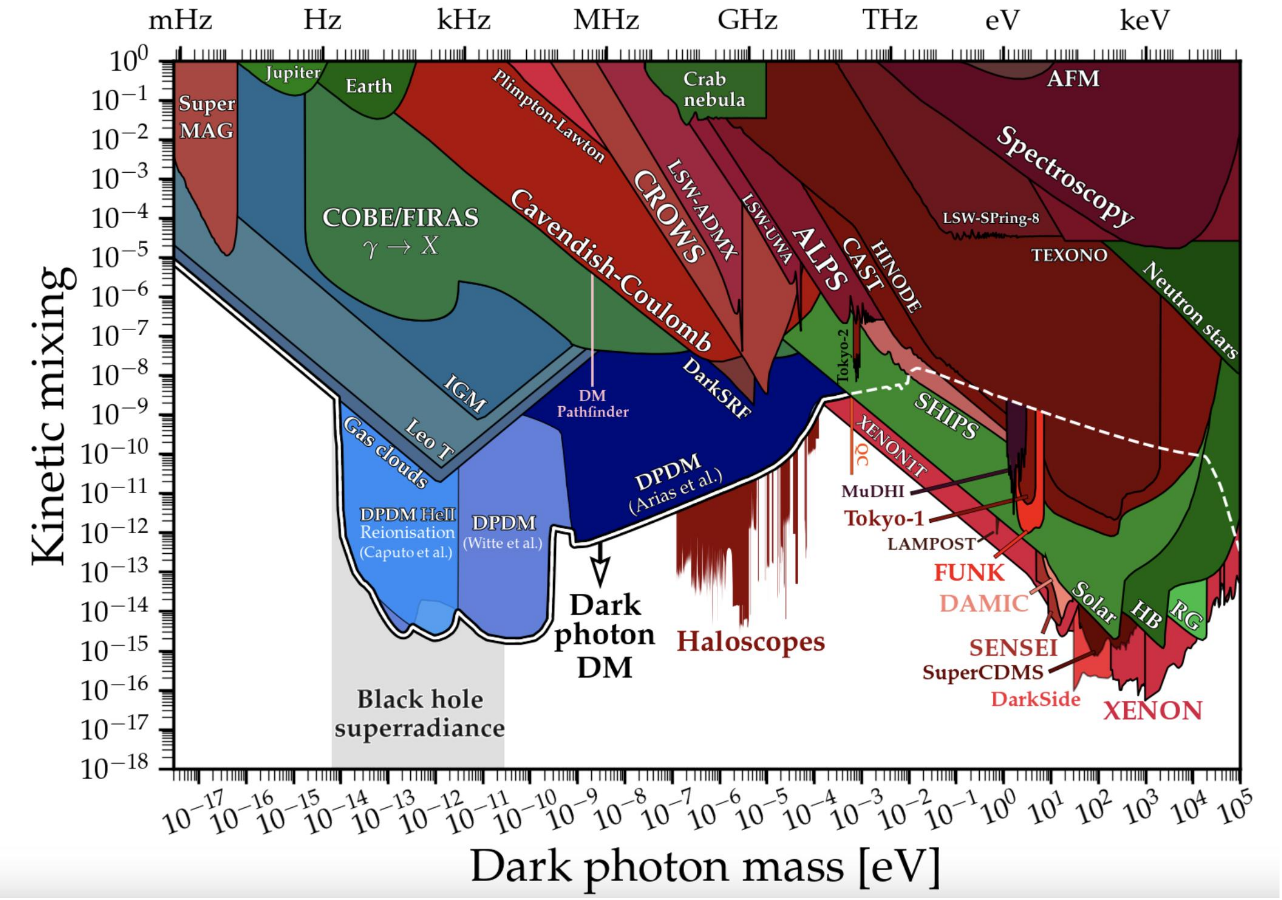
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + eA_\mu J^\mu - \epsilon e A'_\mu J^\mu$$

Searches for dark photon (Mining in the parameter space)



Stellar constraints





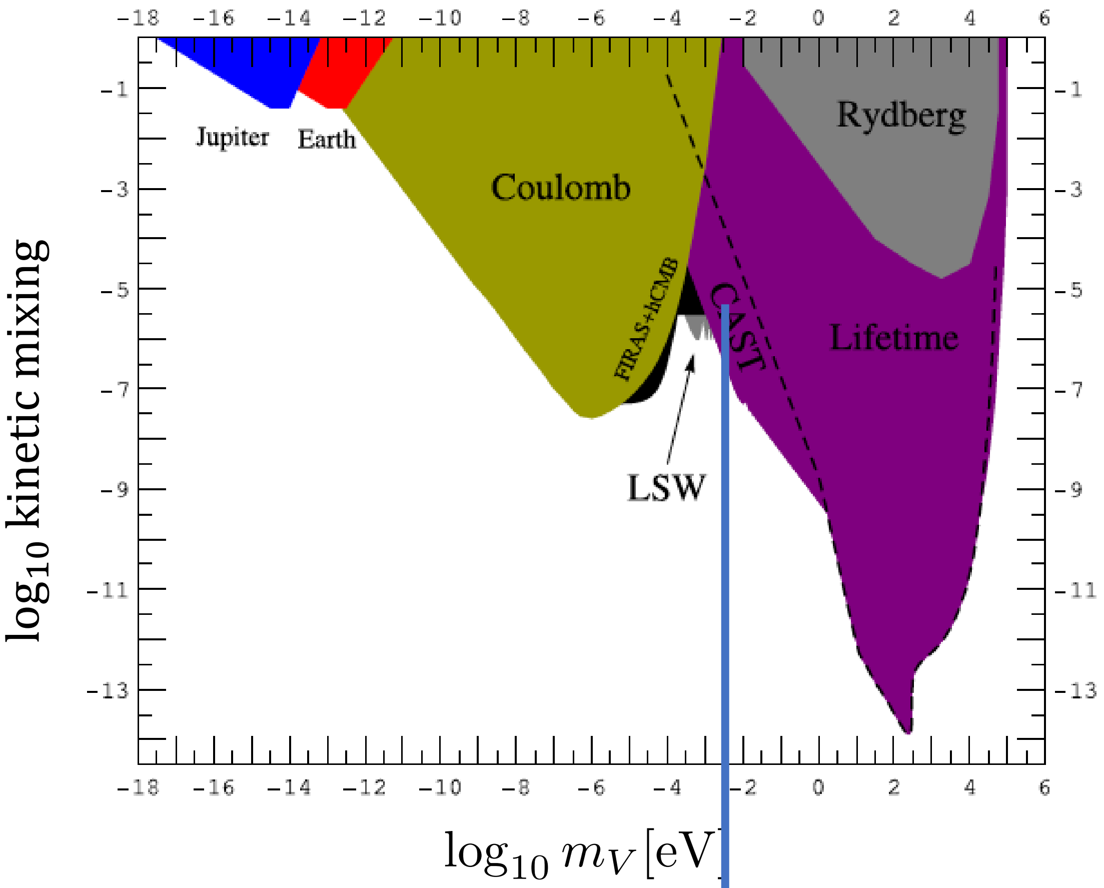
2008

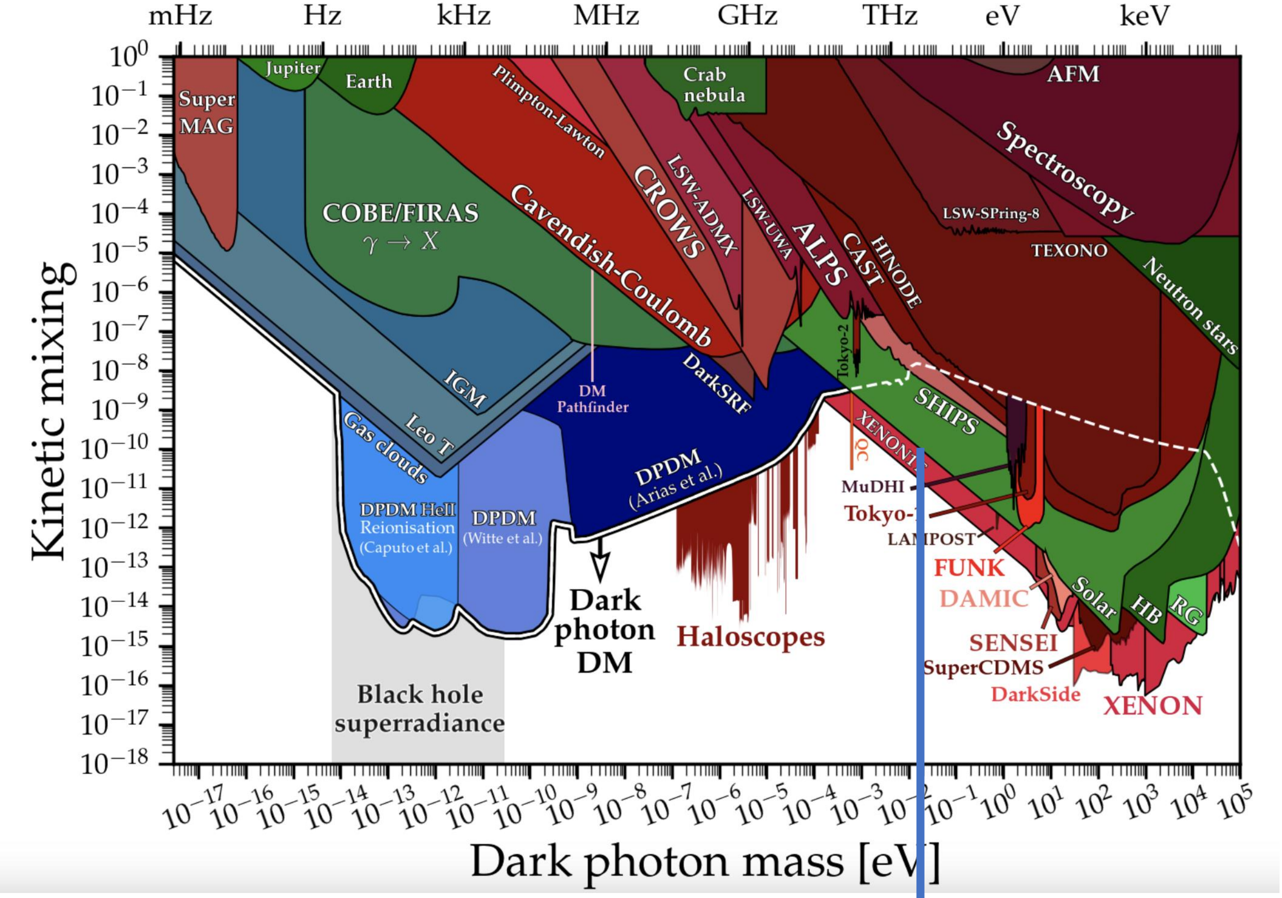
Redondo (JCAP 2008)

2023

https://cajohare.github.io/AxionLimits/

Stellar constraints

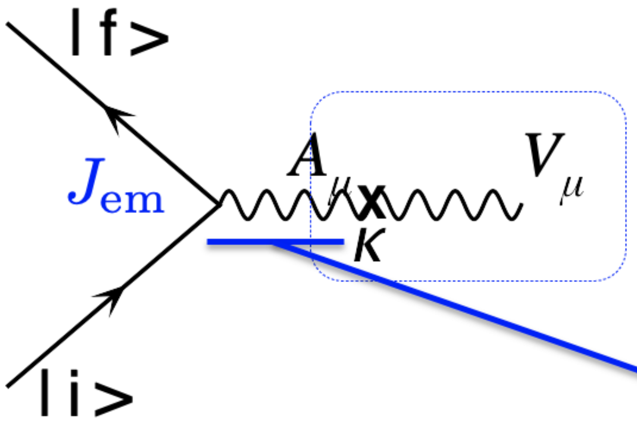




$\epsilon \sim m_{A'}^{-4}$? $\epsilon \sim m_{A'}^{-2}$

Stellar constraints

- Matrix element



$$-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} \to \kappa A_\nu \partial_\mu V^{\mu\nu}$$

E.O.M

$$\kappa m_V^2 A_\nu V^\nu$$

In the Feynman gauge:

$$\frac{1}{k^2} \to \frac{1}{k^2 - \Pi_{T,L}}$$

Plasma effect

$$\Pi^{\mu\nu} = e^2\langle J^\mu_{\rm em}, J^\nu_{\rm em}\rangle = \Pi_T \epsilon_i^{T\mu}\epsilon_i^{T\nu} + \Pi_L \epsilon^{L\mu}\epsilon^{L\nu}$$

$$\mathcal{M} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}}[eJ^\mu_{\rm em}]_{fi}\epsilon_\mu^{T,L}$$

Stellar constraints

- Inside a thermal plasma (with NR electrons)
  - For transverse modes

$$\mathrm{Re}\Pi_T = \omega_p^2 = \frac{4\pi\alpha_{\mathrm{em}} n_e}{m_e} \rightarrow \mathcal{M}_{i\to f+V_T} \sim \frac{m_V^2}{\omega_p^2}$$

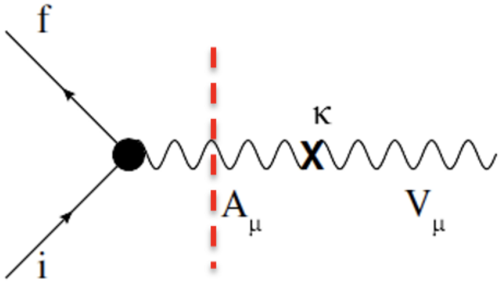
  - For longitudinal mode

$$J^{\mu}_{\mathrm{em}}\epsilon^{L}_{\mu} \sim m_V \rightarrow \Pi_L \sim m_V^2 \qquad \mathrm{Re}\,\Pi_L = \omega_p^2\left(1 - \frac{|\vec{k}|^2}{\omega^2}\right)$$

$$\rightarrow \mathcal{M}_{i\to f+V_L} \sim m_V$$

$$\Pi^{\mu\nu} = e^2\langle J^{\mu}_{\mathrm{em}}, J^{\nu}_{\mathrm{em}}\rangle = \Pi_T \epsilon_i^{T\mu}\epsilon_i^{T\nu} + \Pi_L \epsilon^{L\mu}\epsilon^{L\nu}$$

Transverse vs Longitudinal



On shell due to the thermal effect

$$k^\mu(A) = k^\mu(V)$$

$$m_V^2 = \mathrm{Re}\Pi_T = \omega_p^2$$

↓

$$m_V^2 = \omega_p^2$$

$$m_V^2 = \mathrm{Re}\Pi_L = \omega_p^2 m_V^2/\omega^2$$

↓

$$\omega^2 = \omega_p^2$$

Transverse vs Longitudinal (resonant conversion)

- Matching on shell conditions
  - Transverse photon

Dark photon

$$\omega^2 - |\vec{k}|^2 = \omega_p^2 \qquad \omega^2 - |\vec{k}|^2 = m_V^2$$

$$m_V^2 = \omega_p^2$$

  - Longitudinal photon (plasmon)

(collective motion of electrons)

$$\omega^2 = \omega_p^2 \qquad \omega^2 - |\vec{k}|^2 = m_V^2$$

$$\omega^2 = \omega_p^2$$

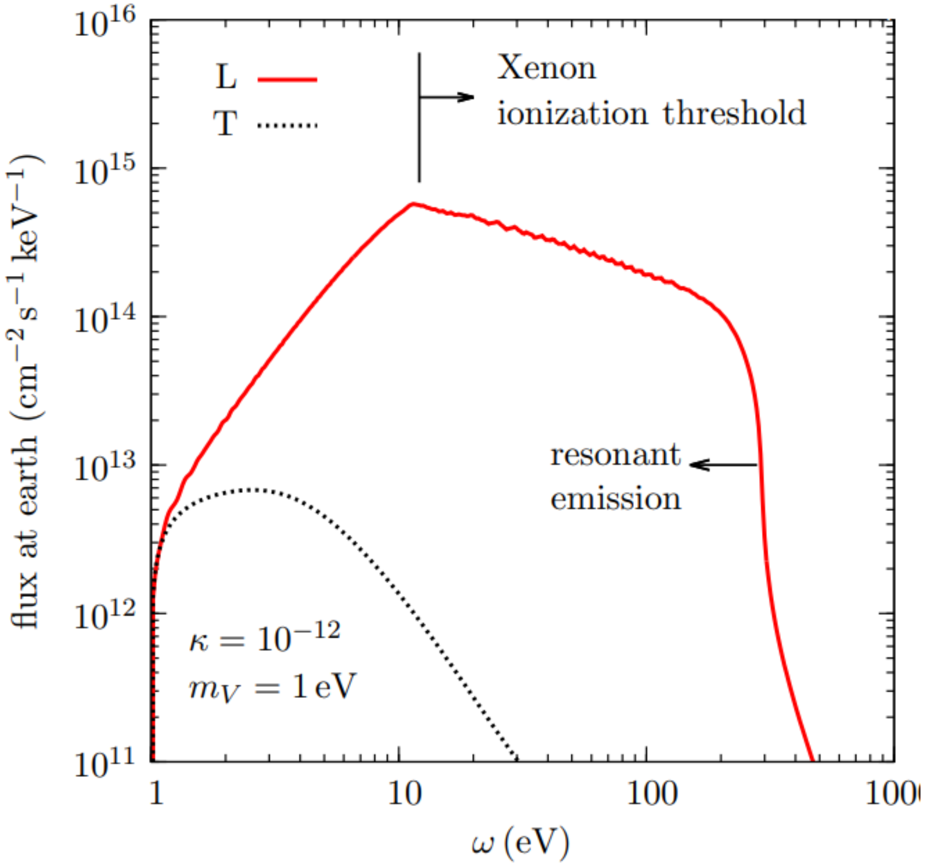
Transverse vs Longitudinal

$$\frac{dP_T}{dV\,d\omega} = \frac{\kappa^2 \omega_p^4 \sqrt{\omega^2 - \omega_p^2}}{2\pi(e^{\omega/T} - 1)} \delta(m_V - \omega_p)$$

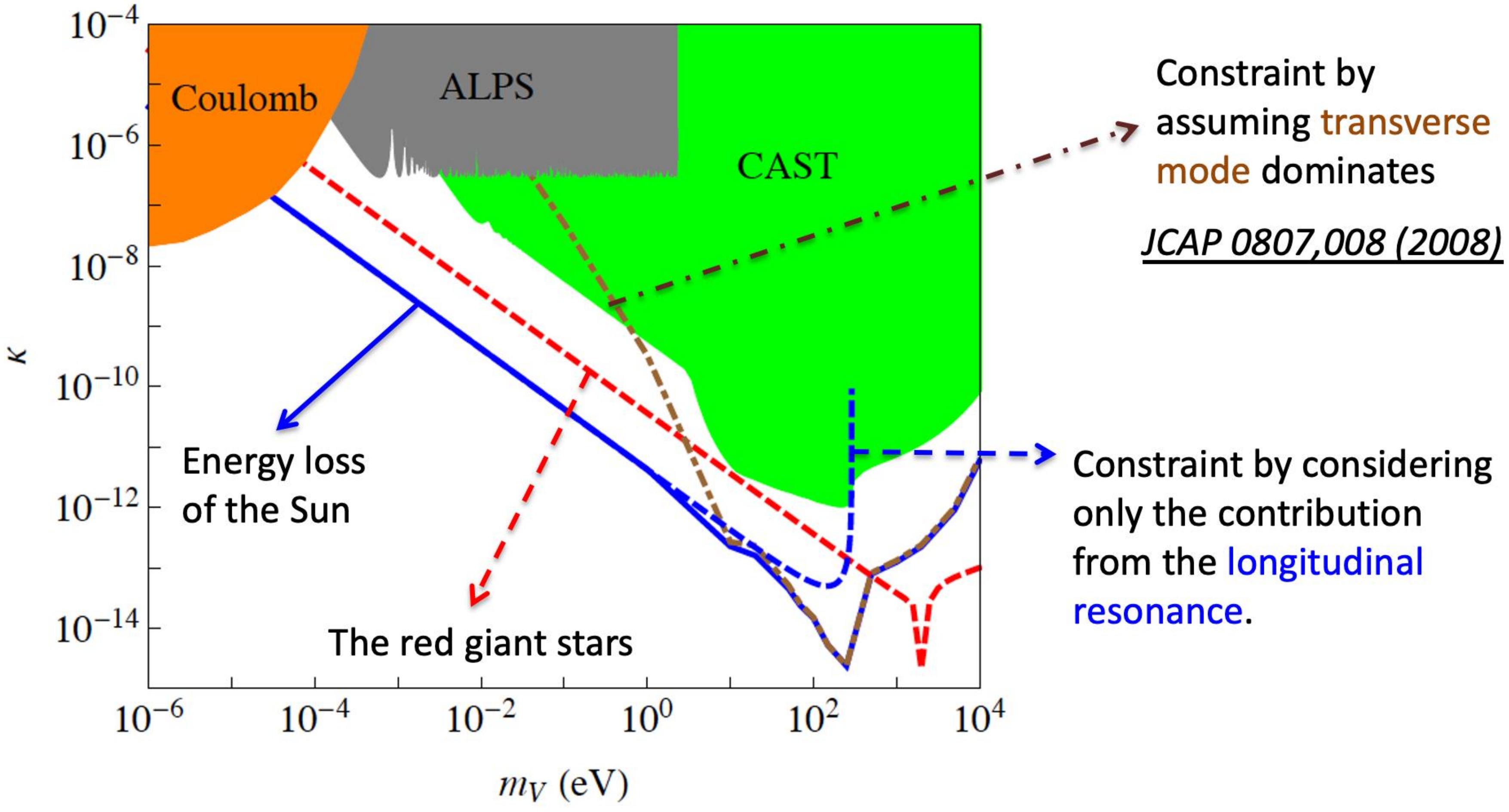
$$\frac{dP_L}{dV\,d\omega} = \frac{\kappa^2 m_V^2 \omega_p^2 \sqrt{\omega^2 - m_V^2}}{4\pi(e^{\omega/T} - 1)} \delta(\omega - \omega_p)$$

Inside the Sun, $1 \text{ eV} \lesssim \omega_p \lesssim 300 \text{ eV}$

$\text{T} - \text{mode dominates}\ ,\quad 1 \text{ eV} \lesssim m_V \lesssim 300 \text{ eV}$
$\text{L} - \text{mode dominates}\ ,\quad m_V \ll 1\ eV$



Stellar constraints



HA, Maxim Pospelov, Josef Pradler, PLB 725 (2013), 1302.3884

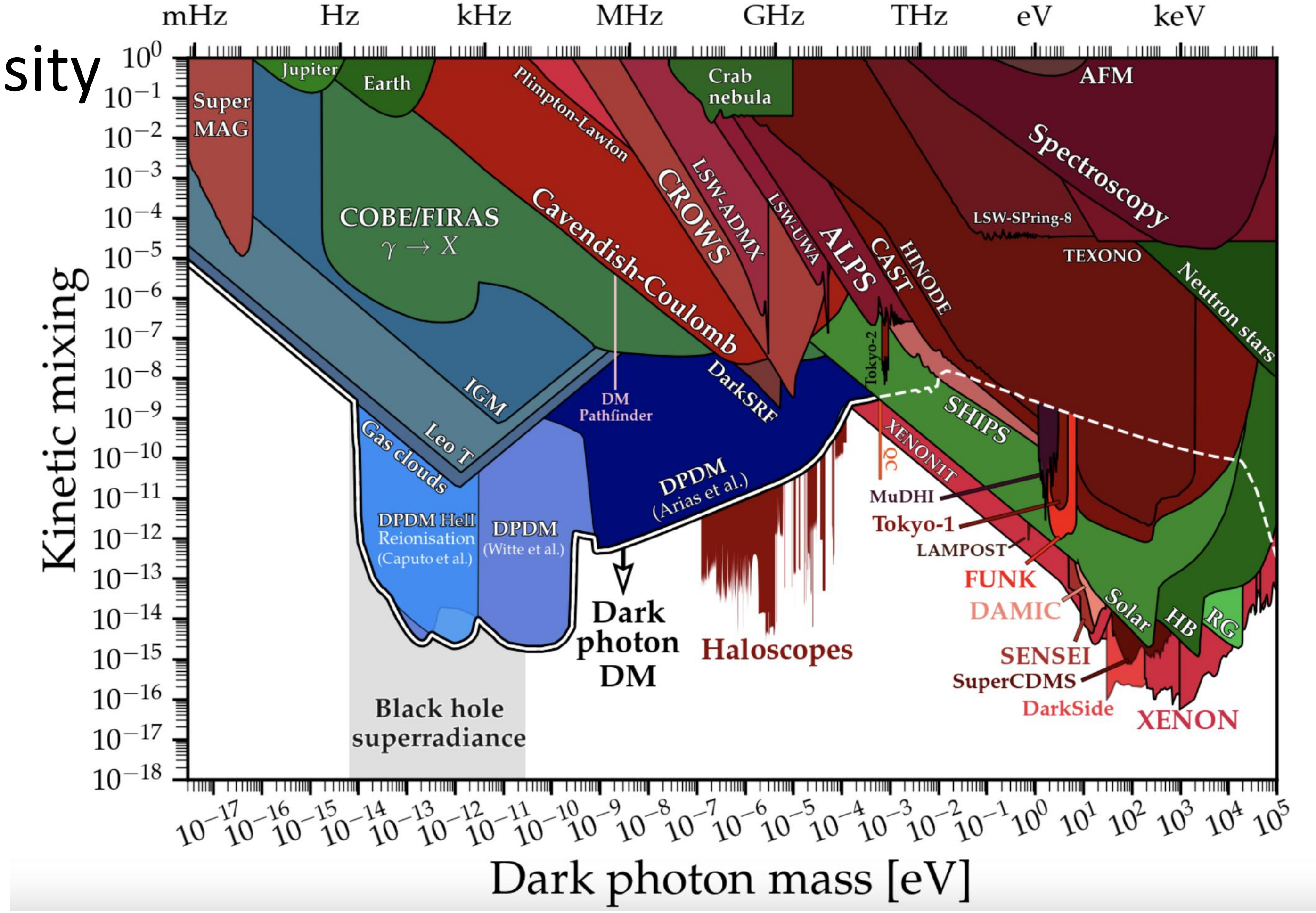
Stellar constraints

- Energy loss < 50% luminosity
- For the Sun, ^{8}B neutrino

  <10% luminosity.

$$\frac{dP_T}{dV\,d\omega} = \frac{\kappa^2\omega_p^4\sqrt{\omega^2-\omega_p^2}}{2\pi(e^{\omega/T}-1)}\delta(m_V-\omega_p)$$

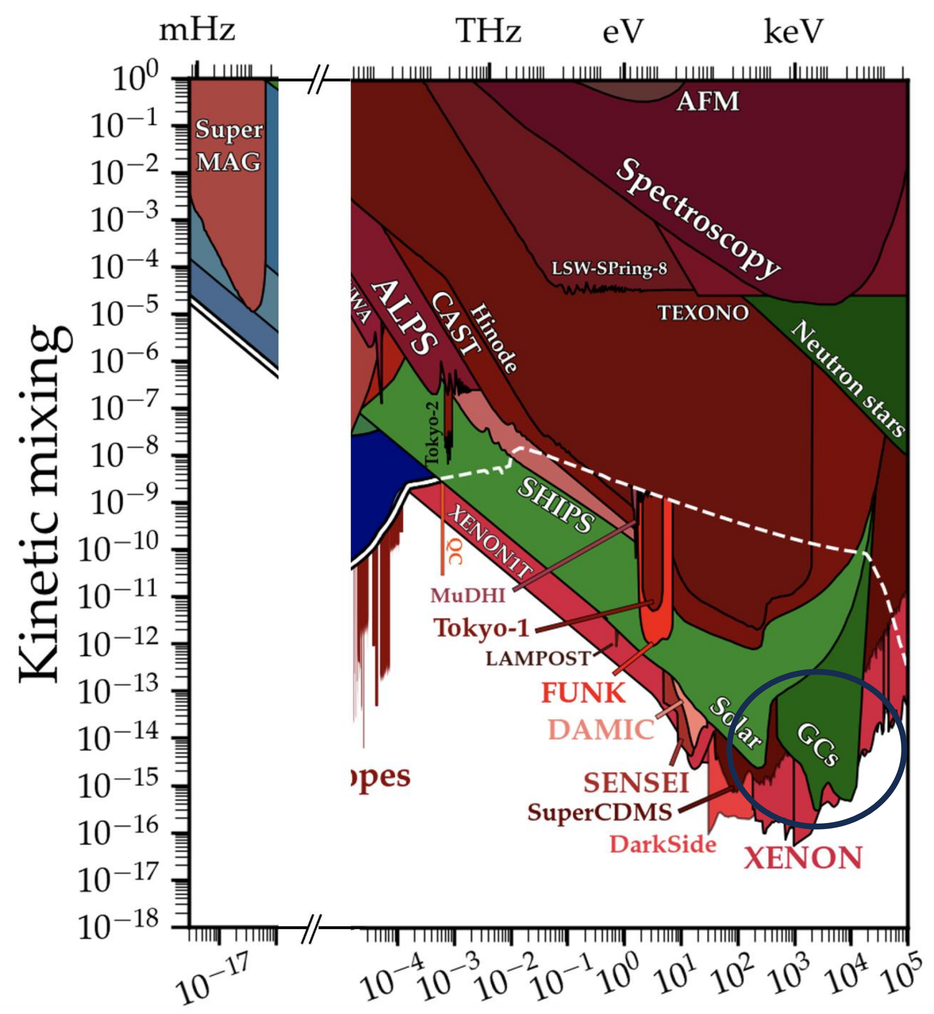
$$\frac{dP_L}{dV\,d\omega} = \frac{\kappa^2 m_V^2\omega_p^2\sqrt{\omega^2-m_V^2}}{4\pi(e^{\omega/T}-1)}\delta(\omega-\omega_p)$$



Searching for dark photon with globular cluster stars

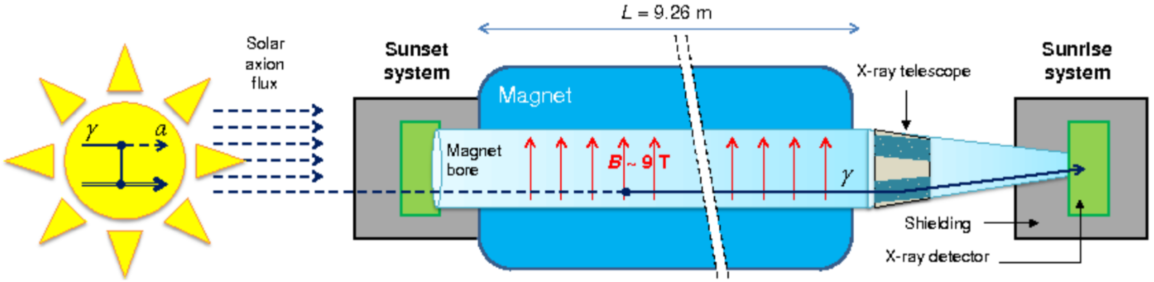
- Red giant branch stars ($T \sim 100\ \mathrm{keV}$)
- Red giant branch tips in globular clusters

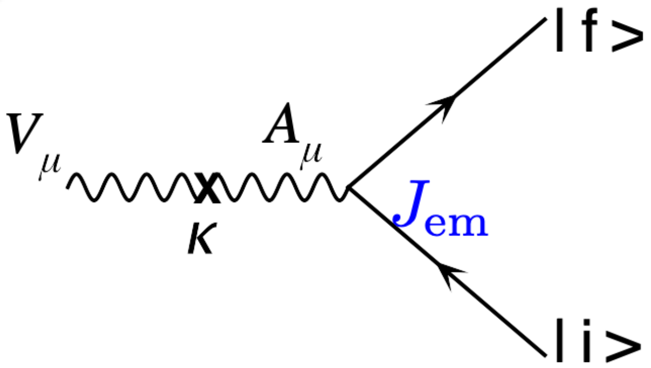
Dolan, Hiskens, Volkas, 2306.13335

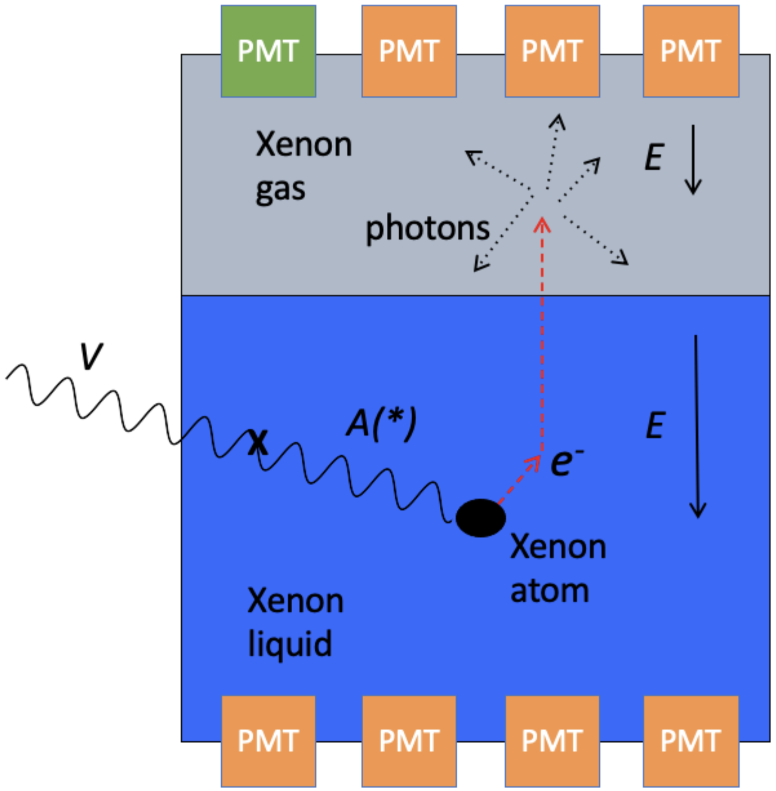


Dark Matter Detector as Dark Photon Helioscope

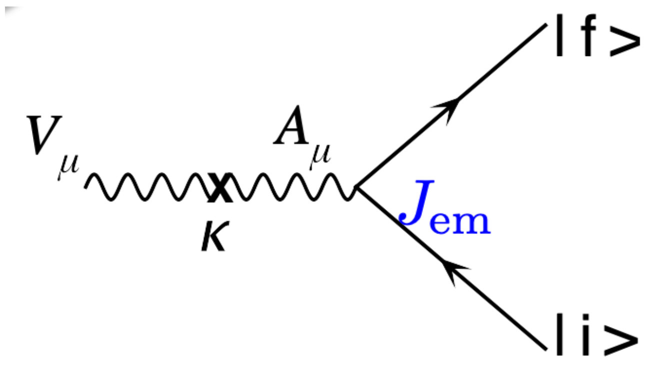
- CAST vs XENON







Dark photon absorption

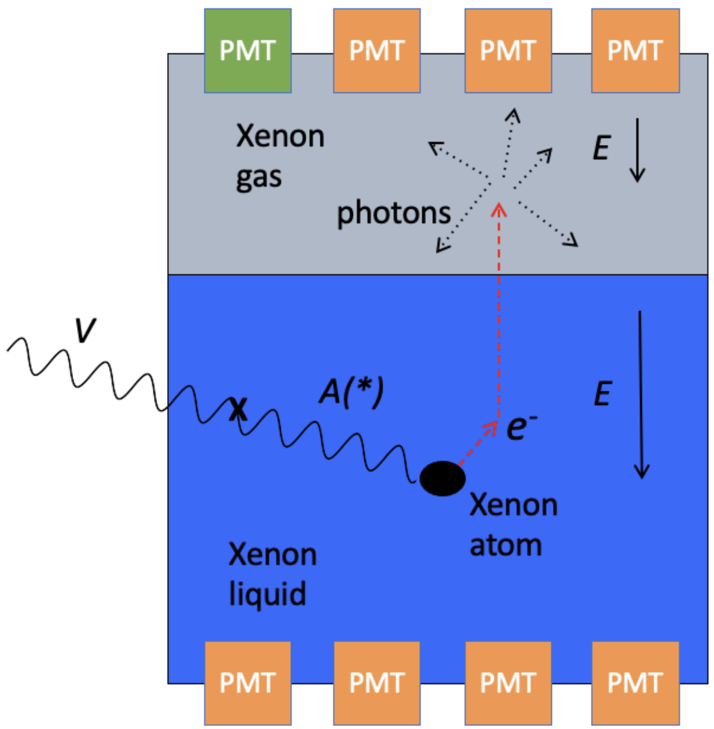


- Total absorption rate

$$\Gamma_T = \frac{\kappa^2\omega\left(\frac{m_V^2}{\omega^2|\Delta\epsilon_r|}\right)^2 \mathrm{Im}\varepsilon_r}{1+\frac{2m_V^2\omega^2\mathrm{Re}\Delta\varepsilon_r+m_V^4}{\omega^4|\Delta\varepsilon_r|^2}} \xrightarrow{m_V^2 \ll \omega^2|\Delta\varepsilon_r|} \kappa^2\omega\left(\frac{m_V^2}{\omega^2|\Delta\varepsilon_r|}\right)^2 \mathrm{Im}$$

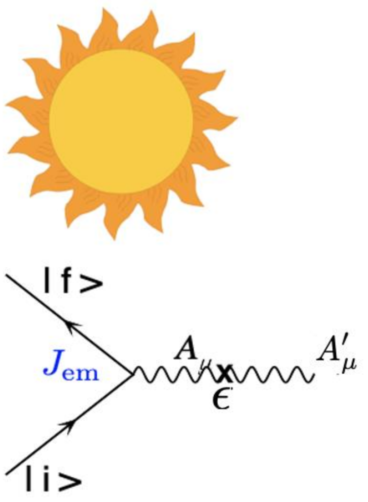
$$\xrightarrow{m_V^2 \gg \omega^2|\Delta\varepsilon_r|} \kappa^2\omega\mathrm{Im}\varepsilon_r$$

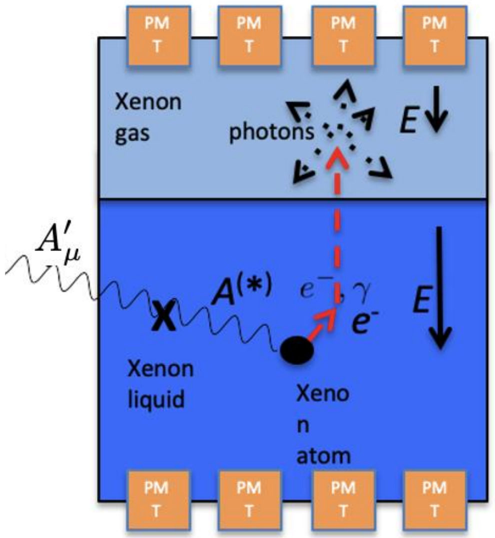
$$\Gamma_L = \frac{\kappa^2 m_V^2 \mathrm{Im}\varepsilon_r}{|\varepsilon_r|^2\omega}$$



- $\Delta\varepsilon_r \propto n_A,$ Atom number density
  - $m_V^2 \ll \omega^2|\Delta\varepsilon_r|$ $\quad \Gamma_T \propto n_A^{-1}$ $\quad \Gamma_L \propto n_A$
  - $m_V^2 \gg \omega^2|\Delta\varepsilon_r|$ $\quad \Gamma_T \propto n_A$ $\quad \Gamma_L \propto n_A$

Helioscopes for dark photon

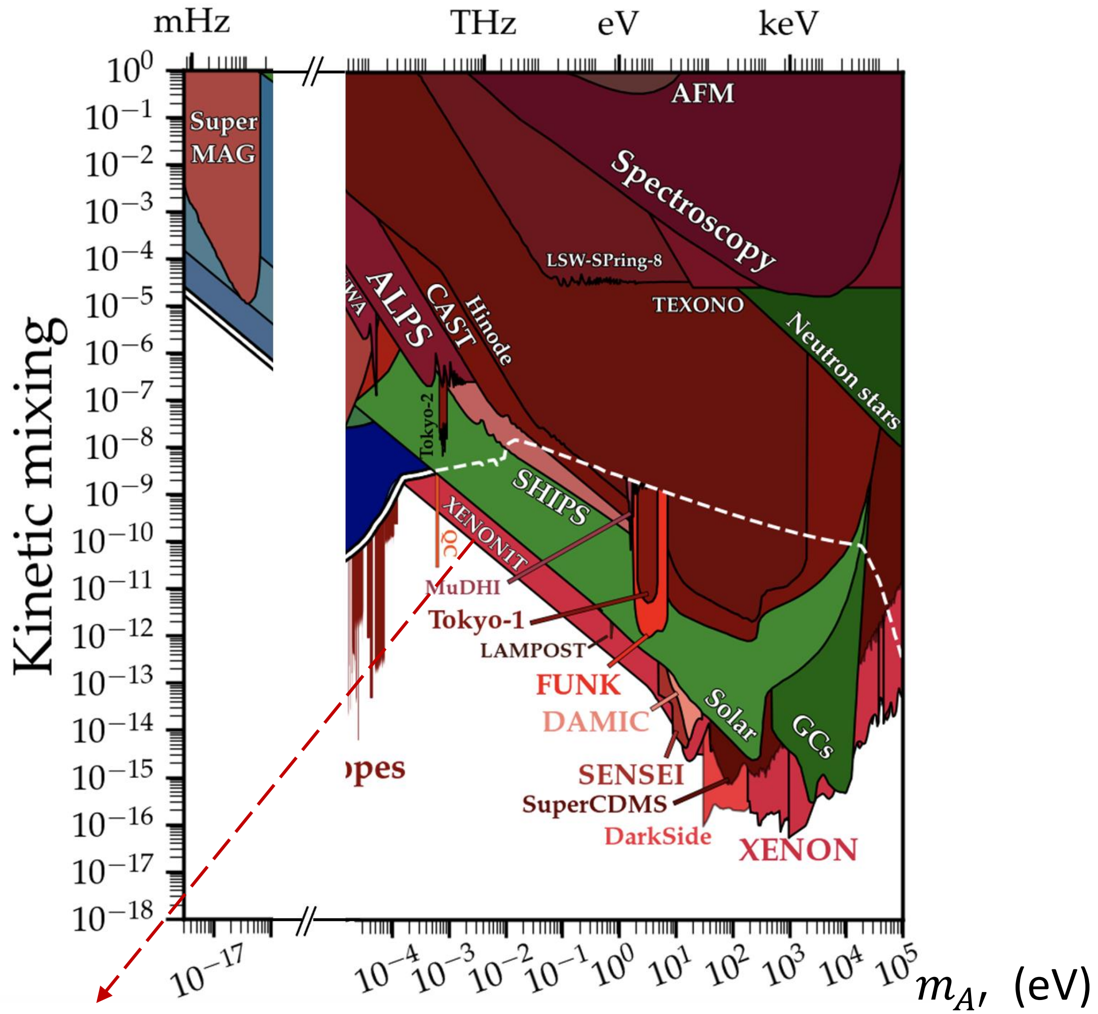




XENON experiment

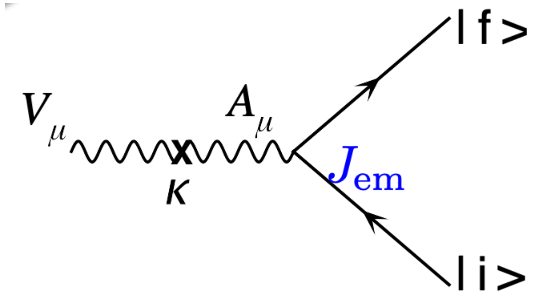
Sun, Horizontal branch starts, red giants …
Requirement: the energy loss by emitting dark photon should be smaller than 10% of the total normal flux.

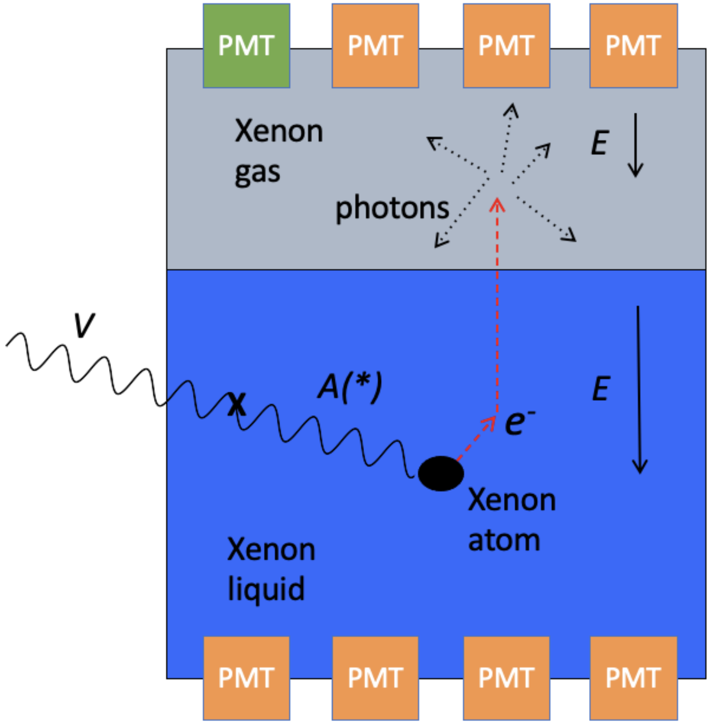
HA, Pospelov, Pradler, PLB 725 (2013) 190,
& PRL 111 (2013) 041302

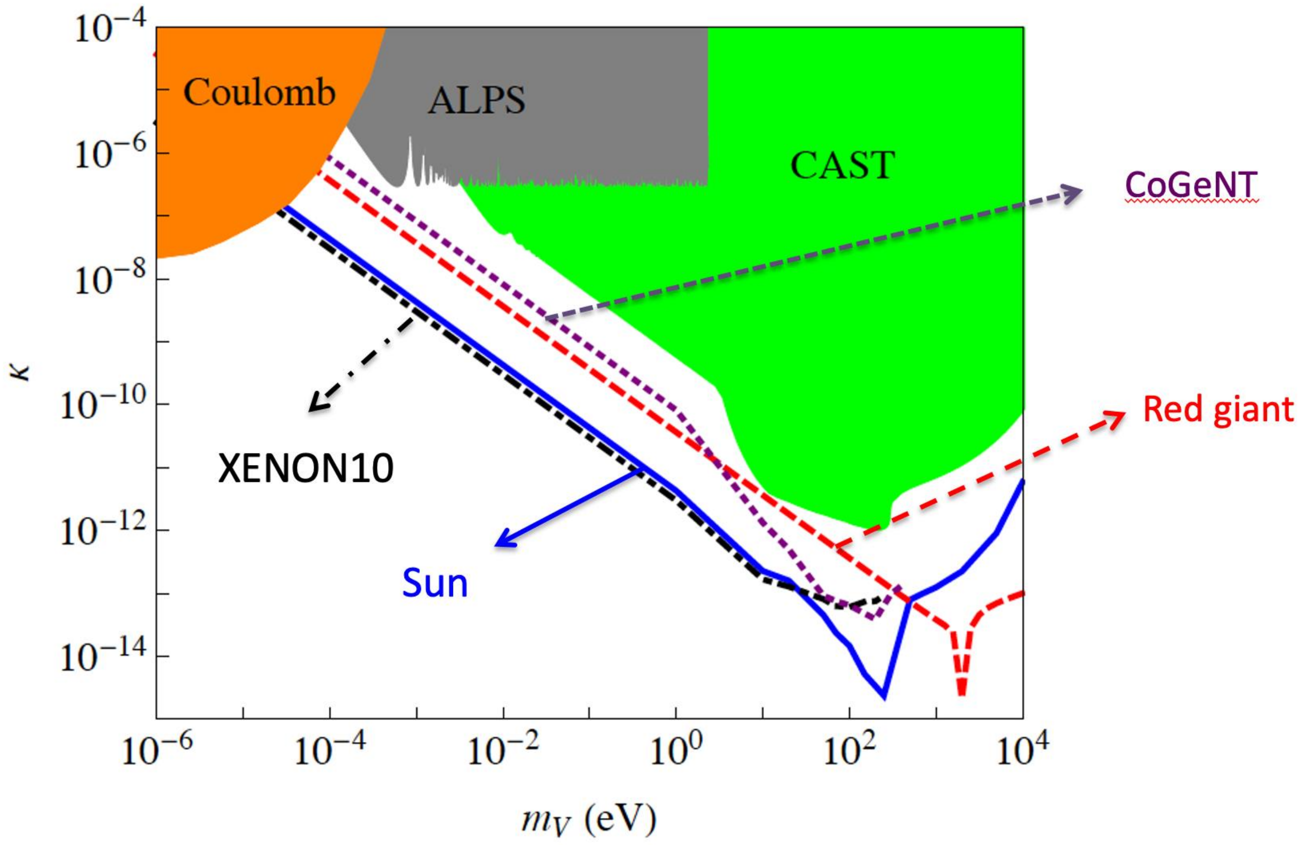


HA, Pospelov, Pradler, Ritz, PRD 102 (2020) 115022
XENON1T, PRD 106 (2021) 022001

Search for solar dark photon flux







HA, Maxim Pospelov, Josef Pradler, PRL 111 (2013) 041302, 1304.3461

Searching for dark photon with globular cluster stars

- Red giant branch stars ($T \sim 100$ keV)
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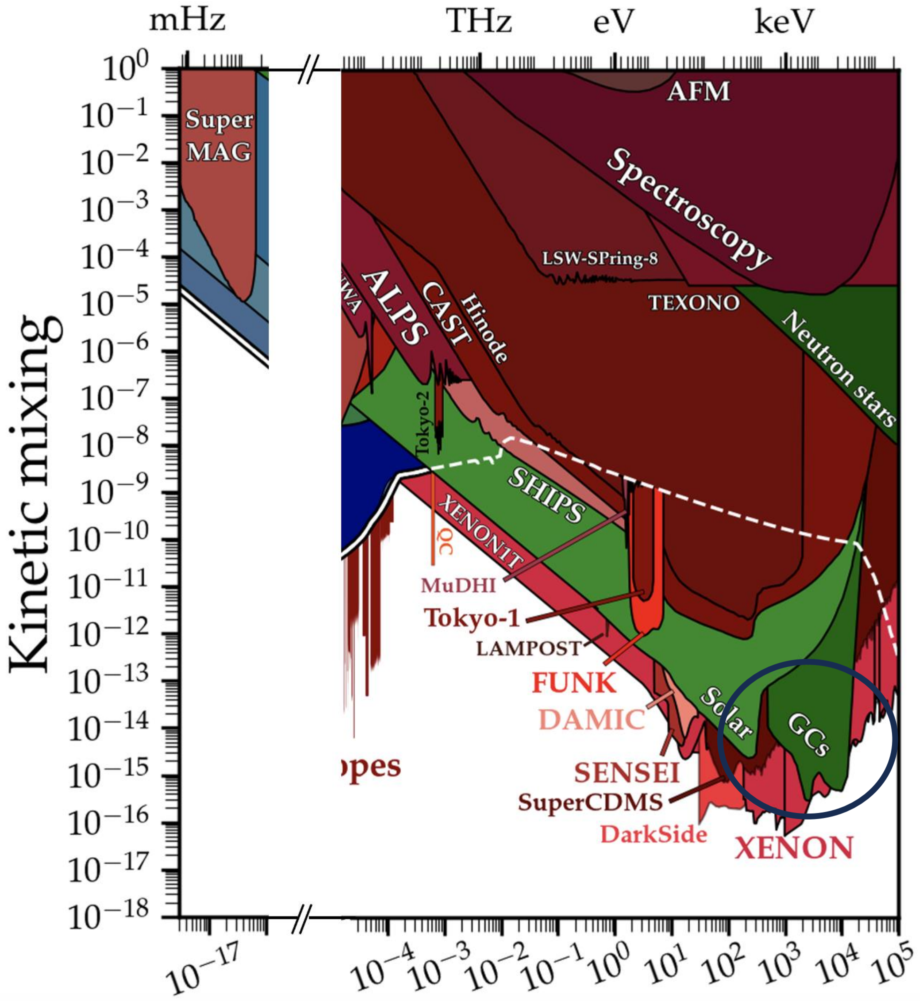
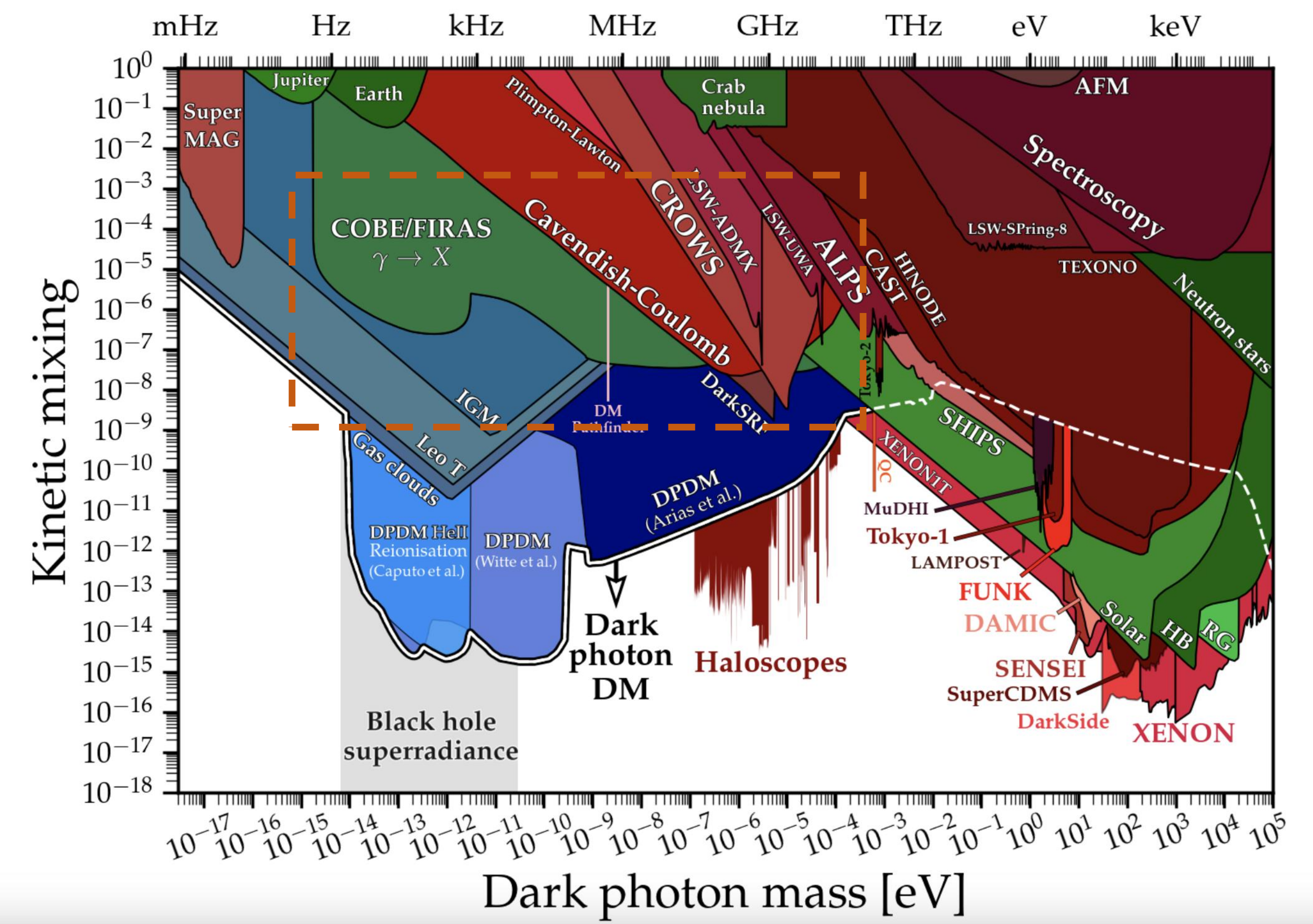
Dolan, Hiskens, Volkas, 2306.13335



Constraint from CMB distortion



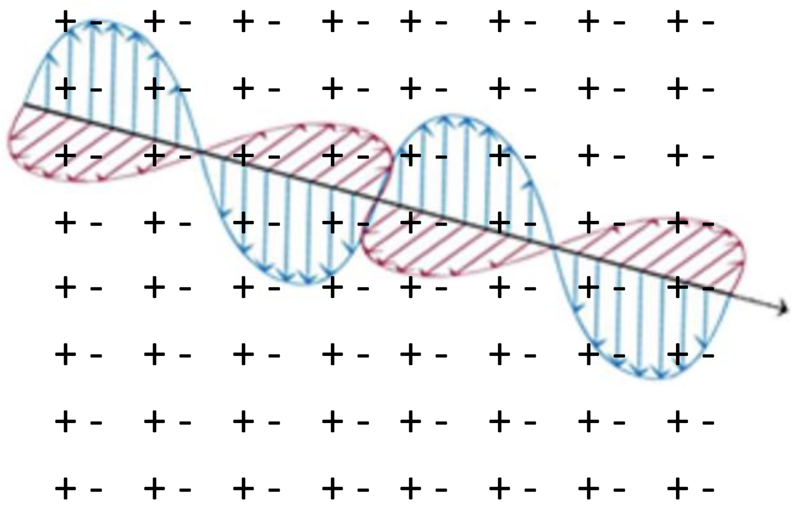
Photon Dark Photon Oscillation in plasma

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

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

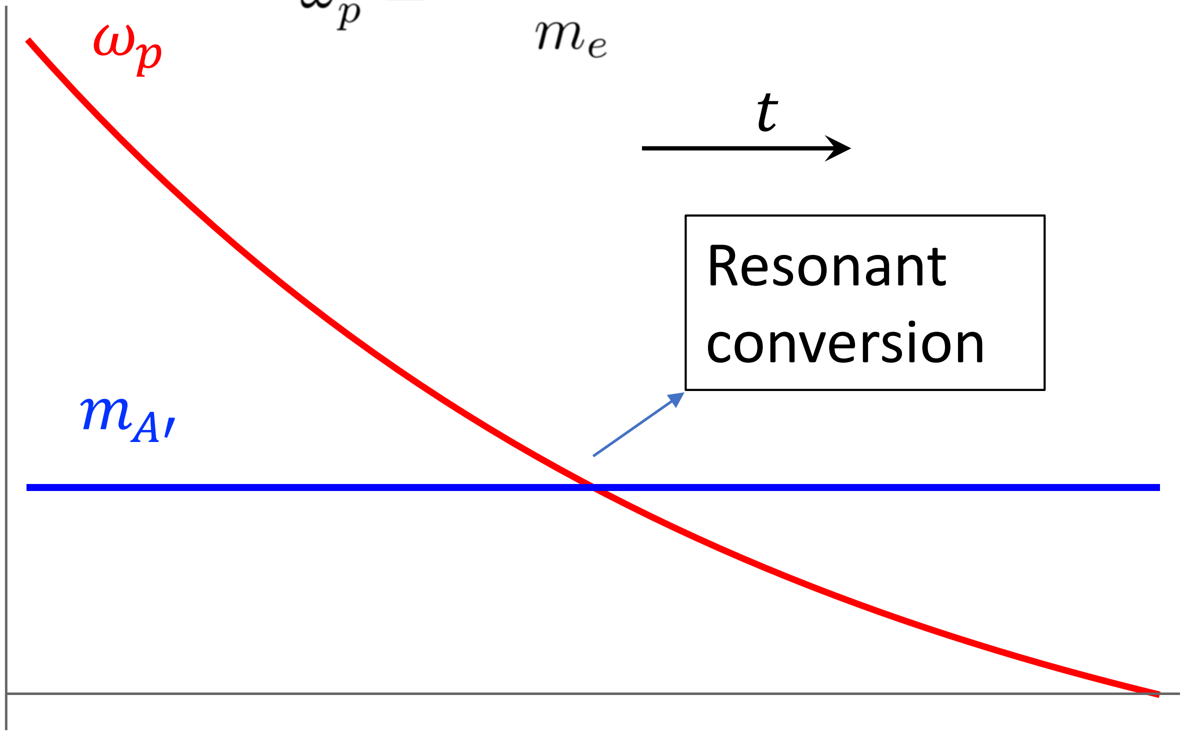
${A'}_\mu$ and A_μ are in mass eigenstate.

- In the vacuum, A' cannot be converted into A, no interaction
- In the plasma, (1) a mixing between A' and A is generated. (2) a mass for A is also generated.



CMB constraints from distortion

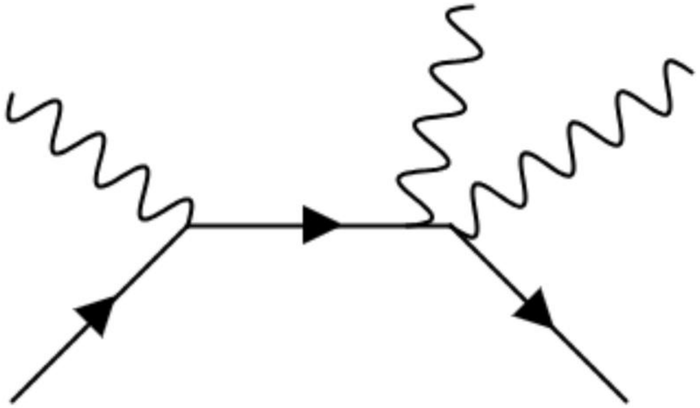
$$\omega_p^2 = \frac{4\pi\alpha_{\mathrm{EM}} n_e}{m_e}$$



- Distort the CMB black body spectrum.

  Jaeckel, Redondo, 0804.4157

When the temperature of the universe is lower than 1 kelvin, the double Compton scattering can no longer restore black body distribution of CMB.



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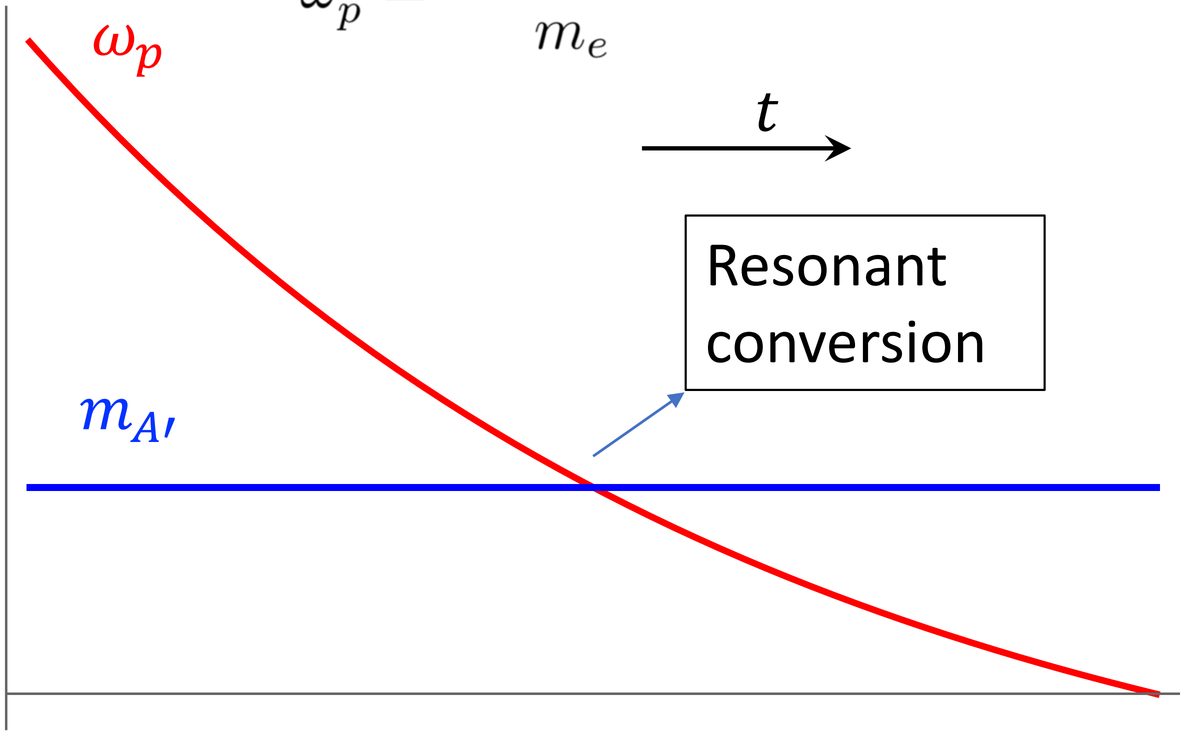


- Why the constraint is flat?

Jaeckel, Redondo, 0804.4157

$$\mathcal{M} = \epsilon m_{A'}^2 \varepsilon_\mu \epsilon_{A'}^\mu (2\pi)^4 \delta^4(k^\mu - k'^\mu)$$

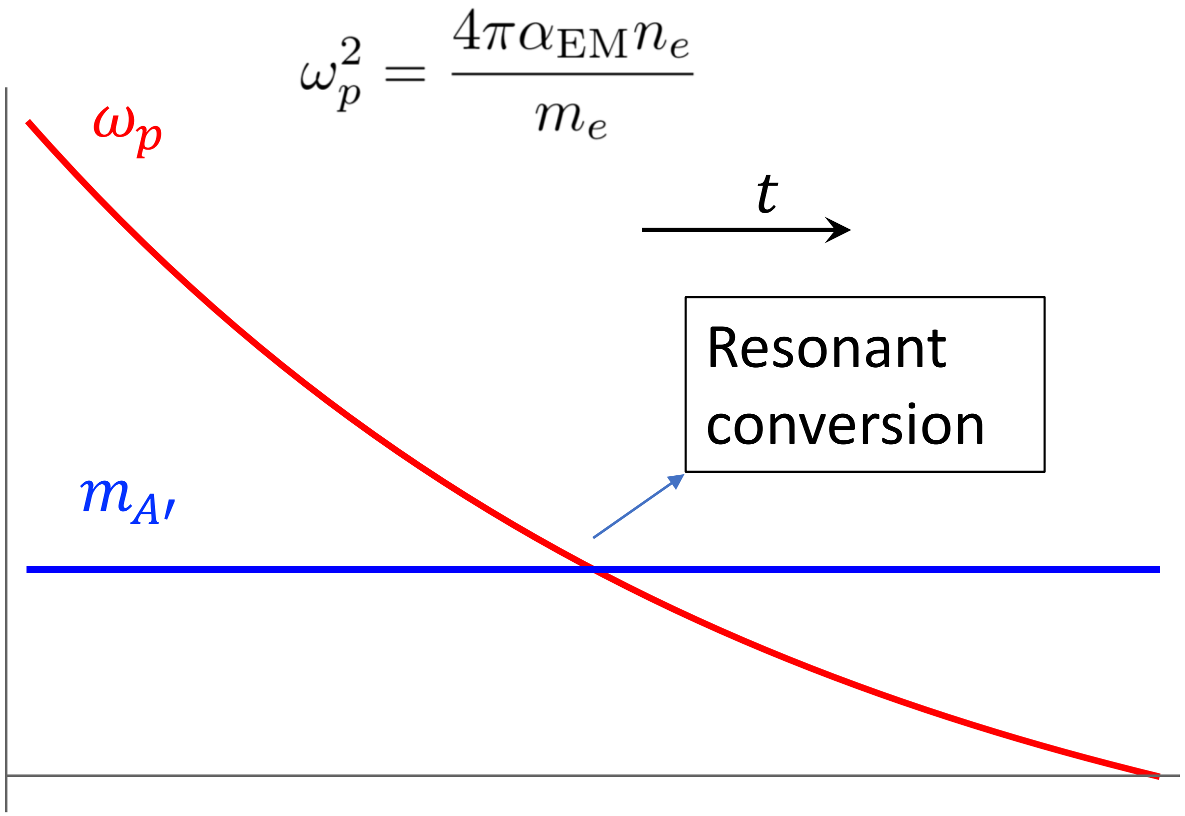
$$P_{A\to A'} \sim \int dt \epsilon^2 m_A'^2 \delta(\omega_p(t) - m_{A'})$$

$$\sim \epsilon^2 m_{A'}^2 \left[\frac{d\omega_p}{dt}\right]^{-1}_{m_{A'}=\omega_p}$$

$\sim Hubble^{-1}$

CMB constraints from anisotropy

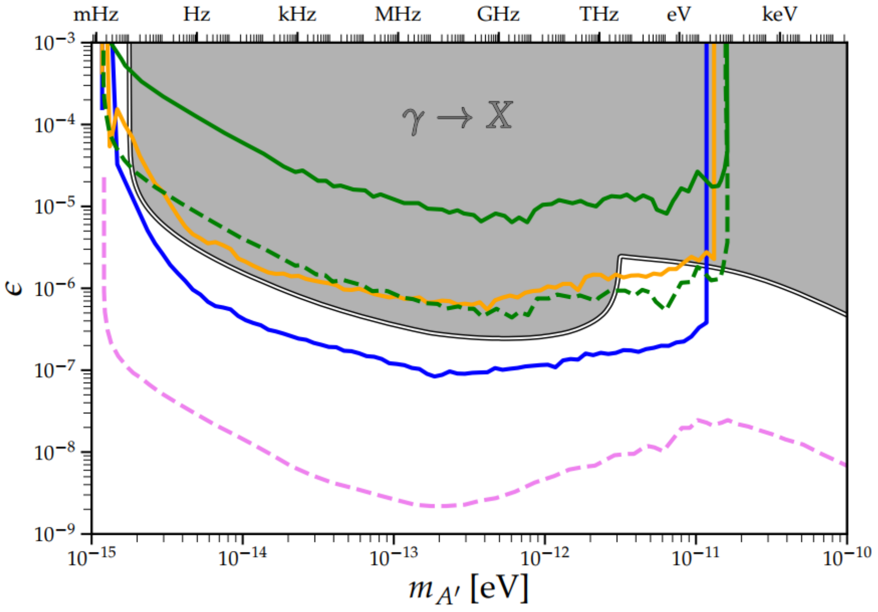
$$\omega_p^2 = \frac{4\pi\alpha_{\rm EM} n_e}{m_e}$$



- Enhance the CMB temperature anisotropy. Aramburo-Garcia et al, 2405.05104

Using the full power of numerical simulation and the CMB power spectrum

$$10^{-15}\text{eV} < m_{A'} < 10^{-11}\text{eV}$$



CMB constraints from anisotropy

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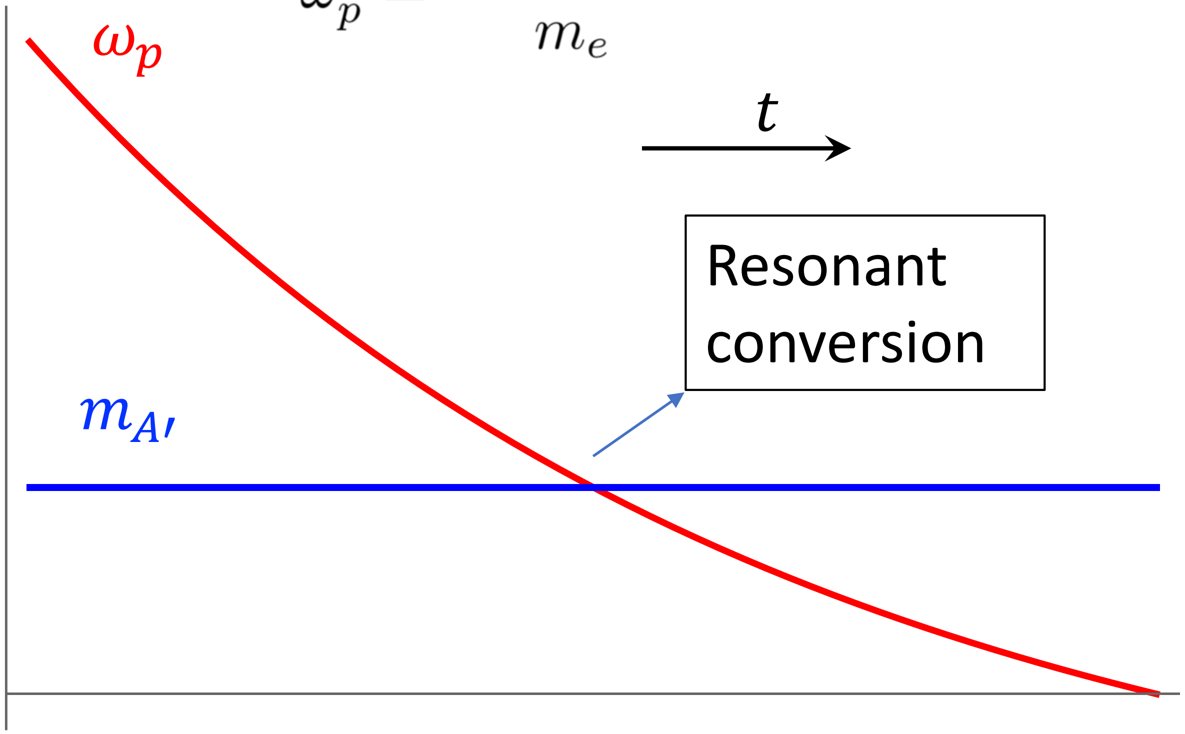


- Enhance the CMB temperature anisotropy.

  Pirvu, Huang, Johnson, 2405.05104

After reionization, resonant conversion occurs mainly in the ionized gas that occupies the virialized DM halos.

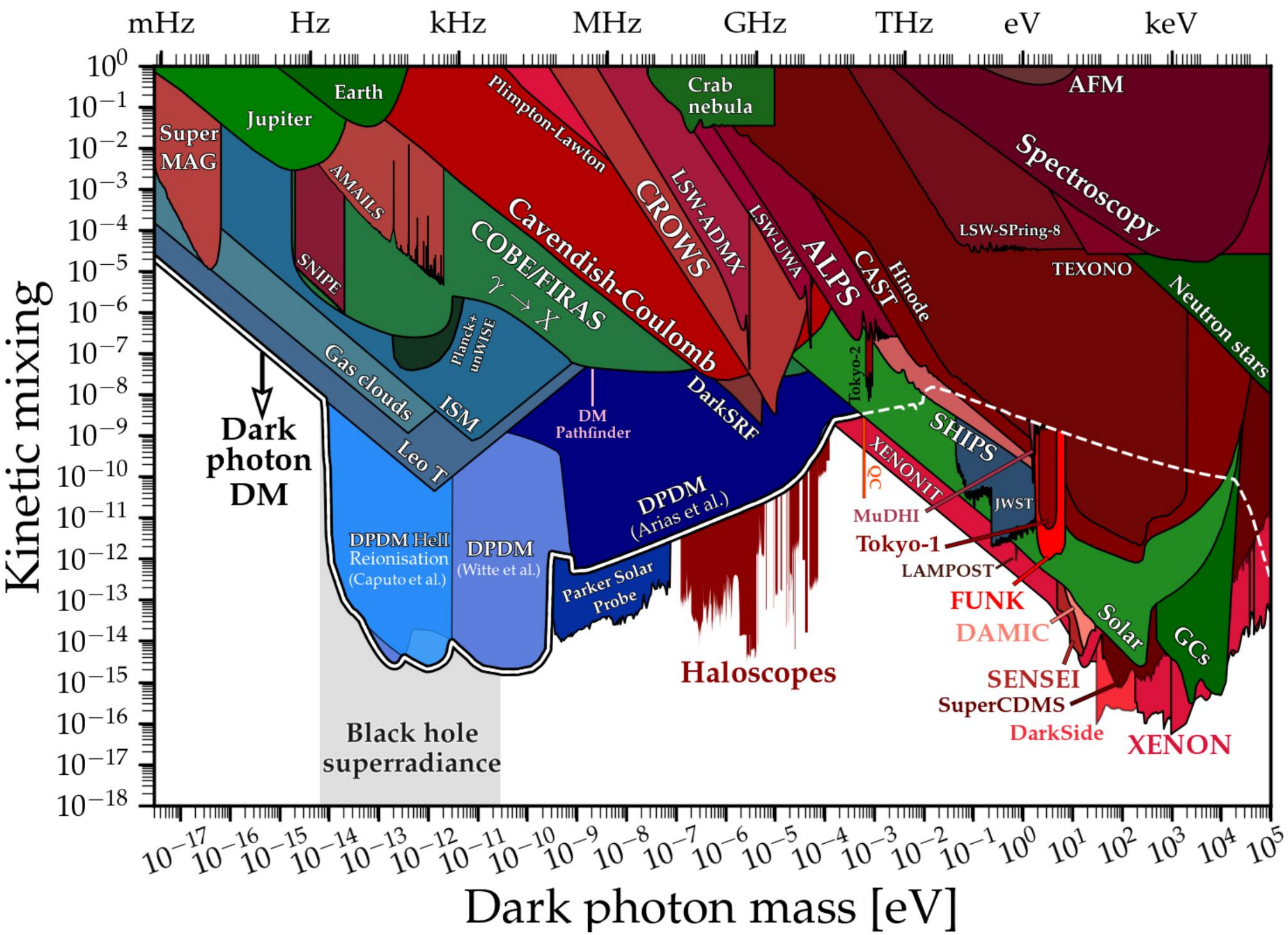
This leads to the correlation between the induced CMB anisotropy and the large scale structure.

Searching for dark photon dark matter

- It can be dark matter. Its lifetime is easily to be longer than the age of the universe.

$$\Gamma_{A'\to 3A} \sim \frac{\epsilon^2 m_{A'}^9}{m_e^8} \qquad \Gamma_{A'\to \nu\nu} \sim \frac{\epsilon^2 m_{A'}^5}{m_Z^4}$$

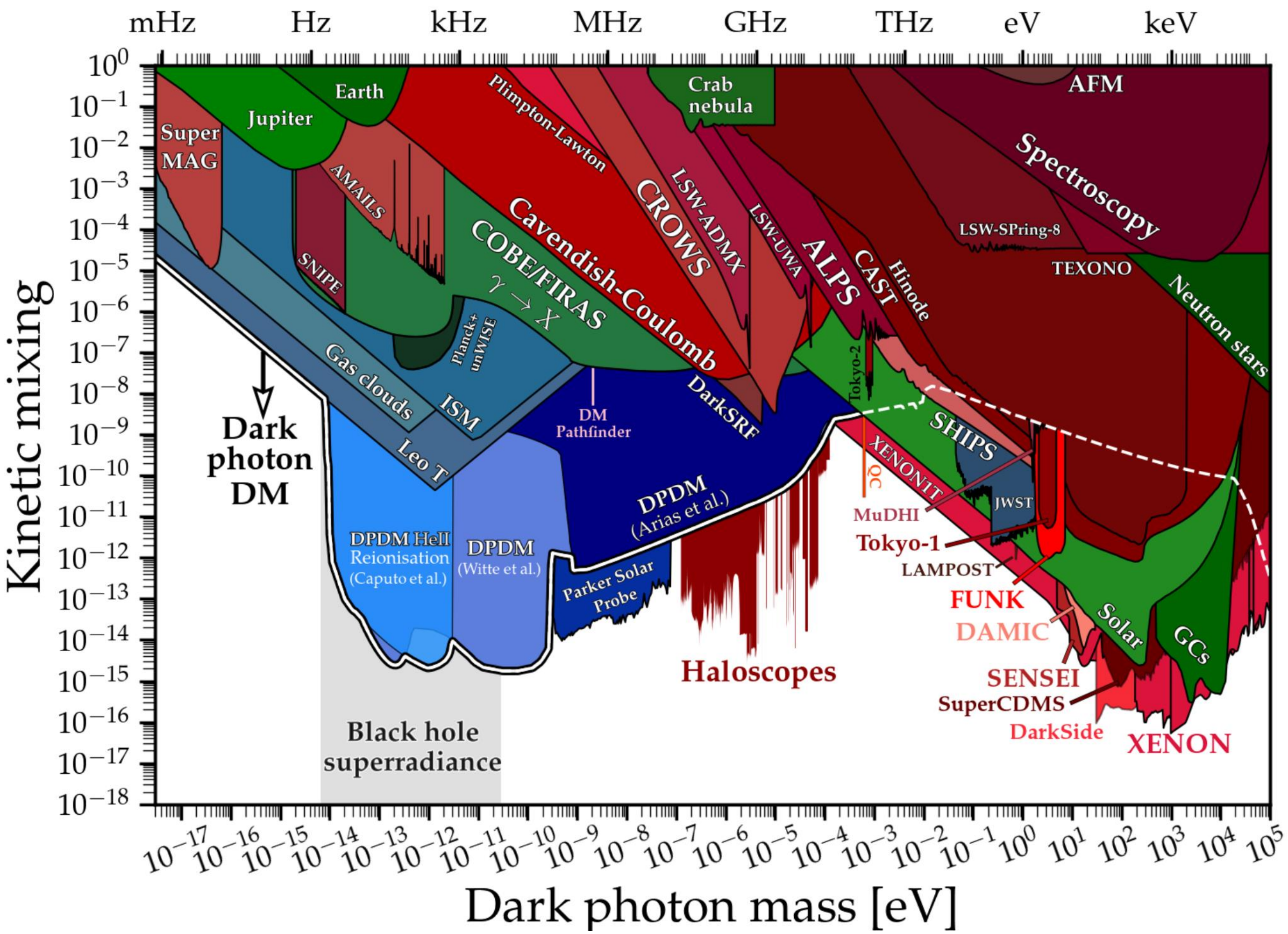
Searching for dark photon dark matter



longer than the age of

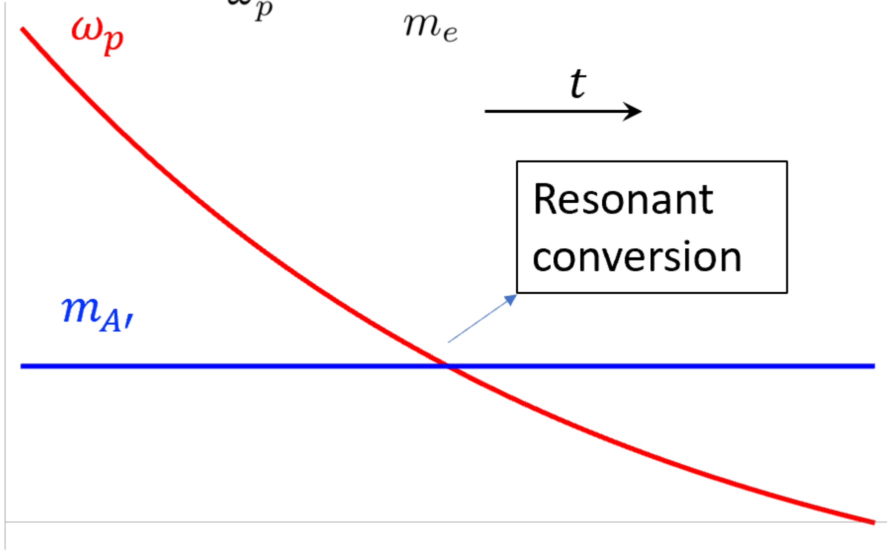
$$\frac{{}^2 m_{A'}^5}{m_Z^4}$$

CMB constraints on DPDM

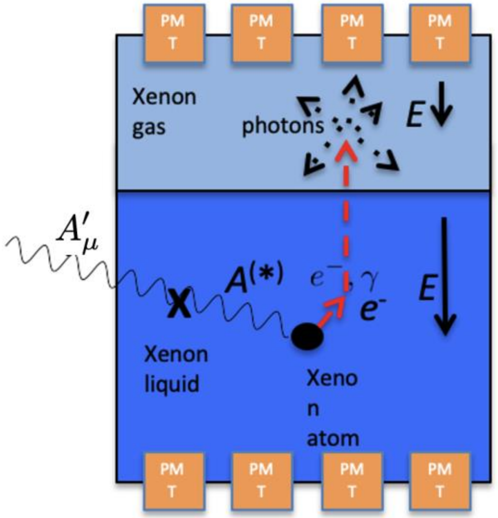


There are more particle in DPDM than in CMB.

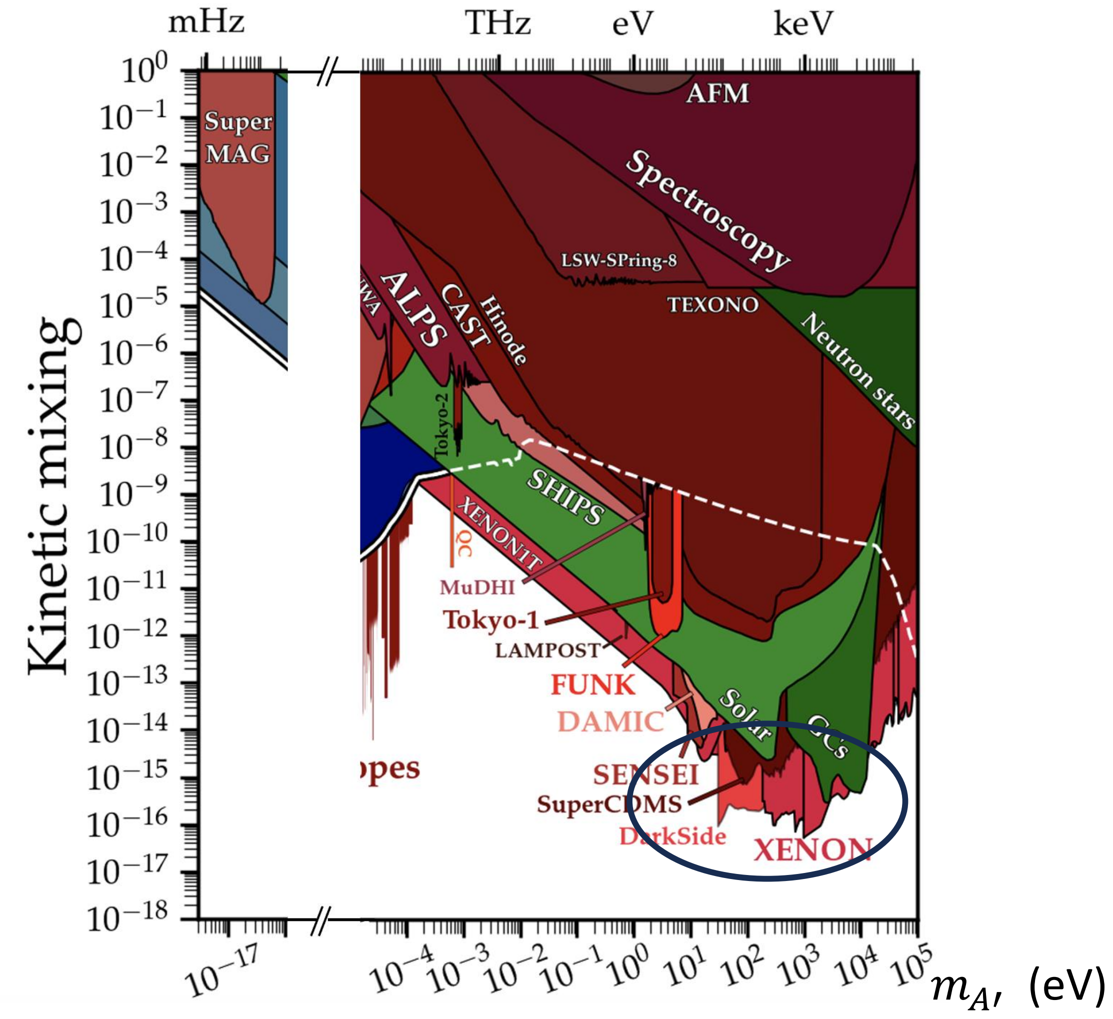
$$\omega_p^2 = \frac{4\pi\alpha_{\rm EM} n_e}{m_e}$$



Searching for ultralight dark matter directly with WIMP detectors



XENON experiment



HA, Pospelov, Pradler, Ritz, PLB 747 (2015) 190-195

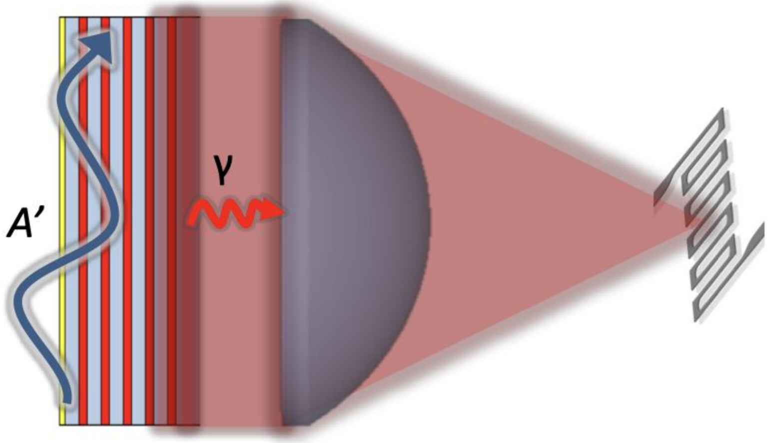
Resonant conversion from DPDM to photon

- DPDM are at rest, it can only resonantly convert into a photon at rest.
- To make the conversion happen, we must create a situation such that that photons are at rest. (the same for axion DM search)
- In resonant cavity: photons become standing waves.
- Inside plasma: photons are non-relativistic when $E \sim \omega_p$.

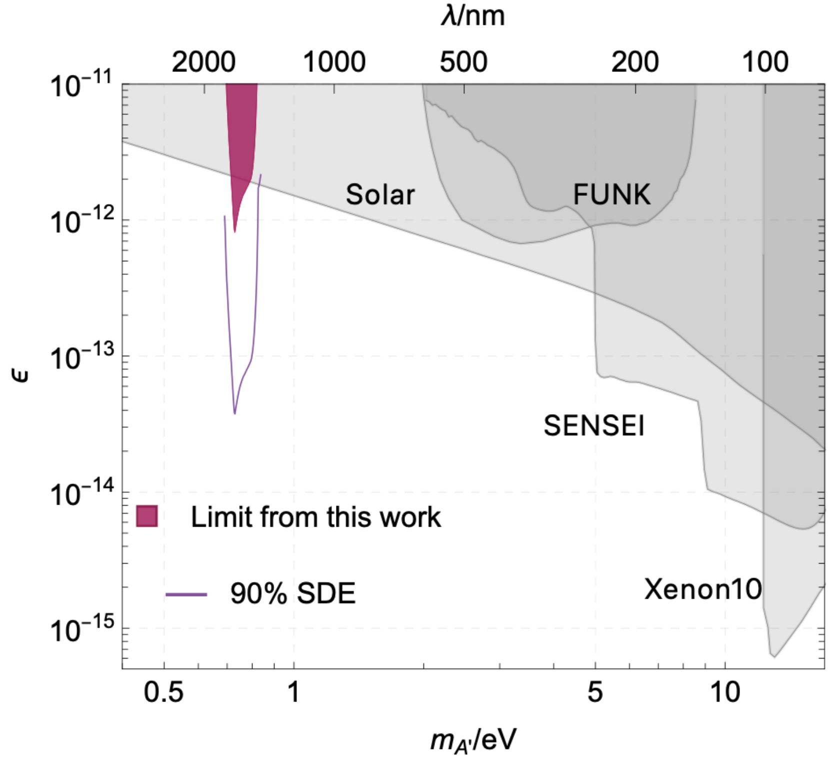
Searching for high frequency axions and dark photons with di-electric layers

- Dark photon dark matter oscillate to on-shell photons

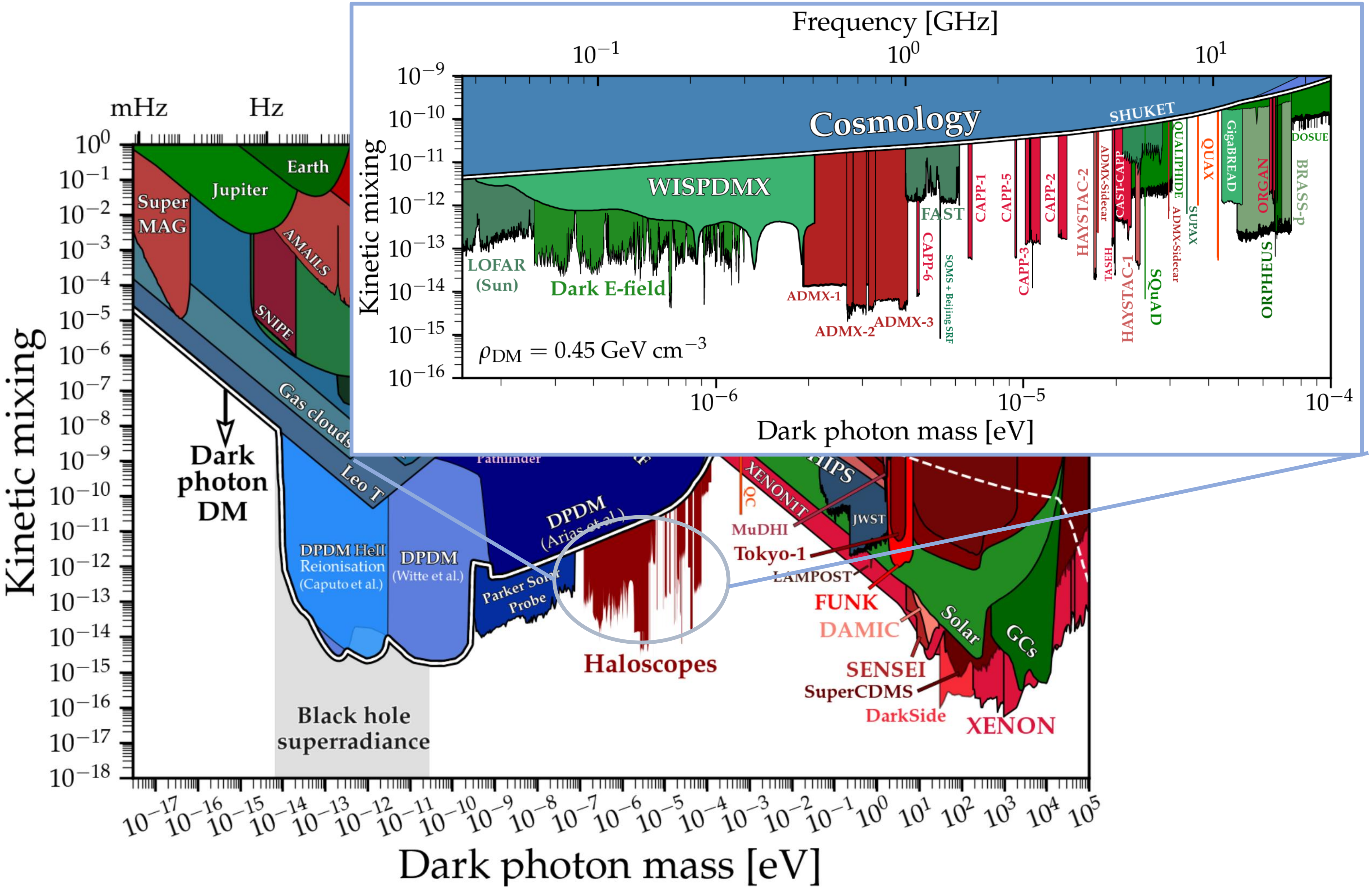
A stack of dielectric layers, with alternating indices of refraction, provide a non-zero momentum for the photon to propagate.



Baryakhar, Huang, Lasenby, PRD 98 (2018) 035006

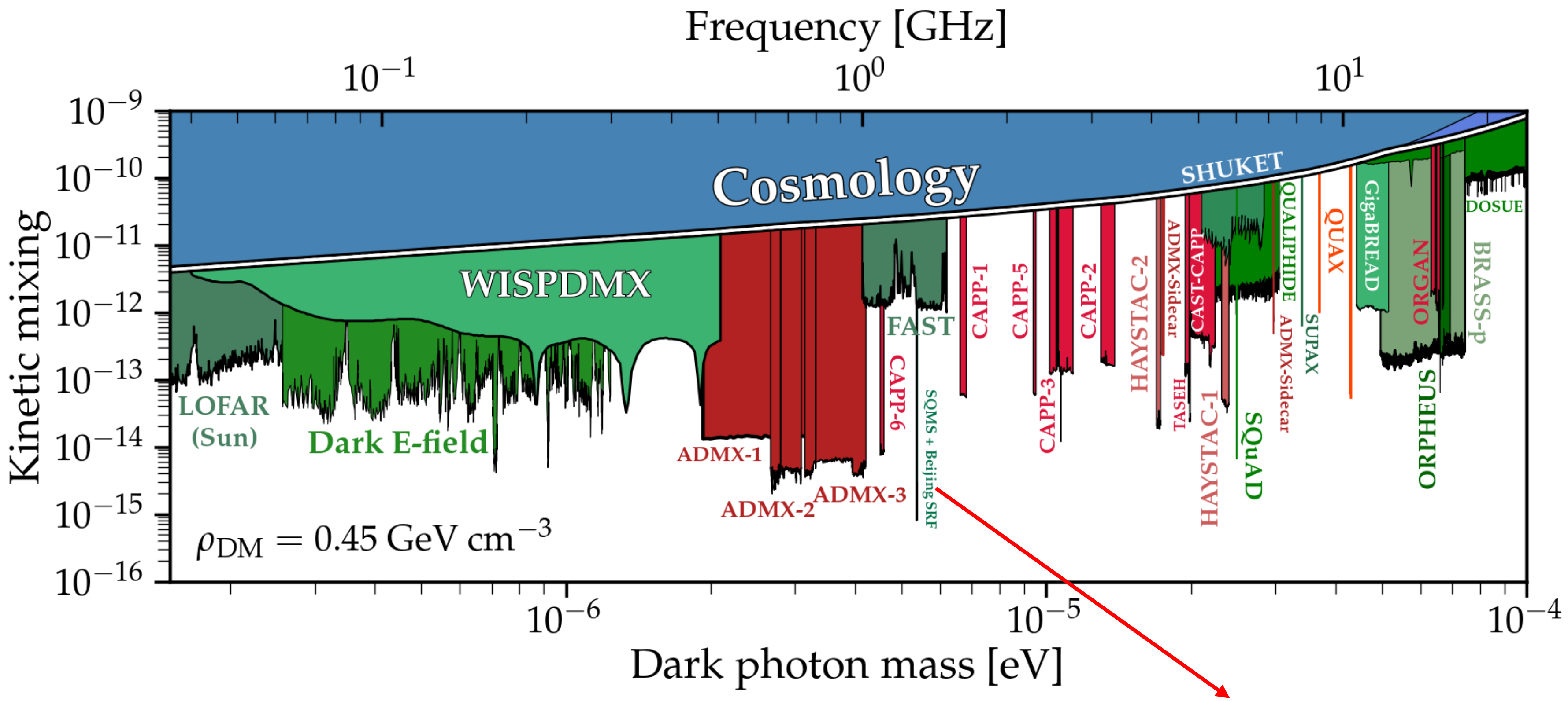


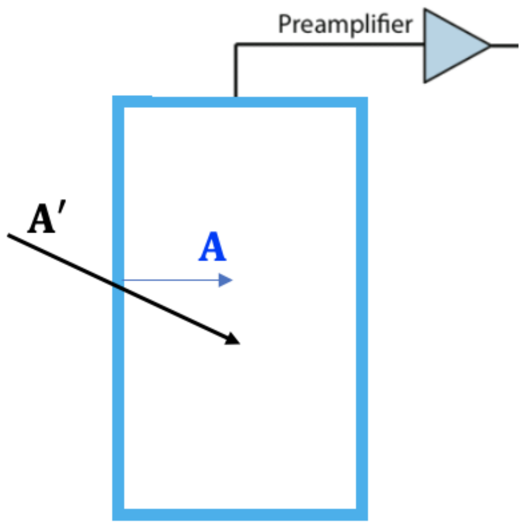
LAMPOST, PRL 128 (2022) 231802



Frequency [GHz]
Cosmology
WISPDMX
SHUKET
LOFAR (Sun)
Dark E-field
FAST
ADMX-1
ADMX-2
ADMX-3
CAPP-1
CAPP-2
CAPP-3
CAPP-5
CAPP-6
HAYSTAC-1
HAYSTAC-2
QUAX
GigaBREAD
ORGAN
BRASS-p
ORPHEUS
SQuAD
DOSUE
$\rho_{DM} = 0.45$ GeV cm^{-3}
Kinetic mixing
Dark photon mass [eV]
mHz
Hz
Earth
Jupiter
Super MAG
AMAILS
SNIPE
Gas clouds
Leo T
Dark photon DM
DPDM HeII Reionisation (Caputo et al.)
DPDM (Witte et al.)
Parker Solar Probe
DPDM (Arias et al.)
Haloscopes
Black hole superradiance
XENON1T
HIPS
JWST
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
DarkSide
XENON
Solar
GCs

Resonant cavities for dark photon dark matter





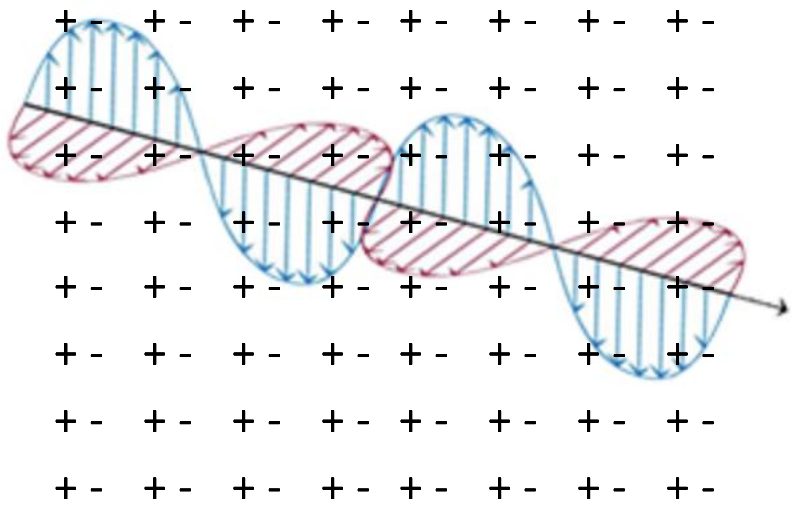
Jing Shu's experiment

Photon Dark Photon Oscillation

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu} + eA_{\mu}J^{\mu} - \epsilon e A'_{\mu}J^{\mu}$$

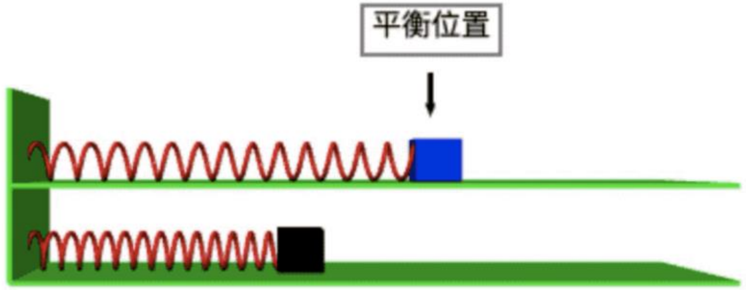
A'_{μ} and A_{μ} are in mass eigenstate.

- In the vacuum, A' cannot be converted into A, no interaction
- In the plasma, (1) a mixing between A' and A is generated. (2) a mass for A is also generated.



Photon Dark Photon Oscillation

$$\begin{pmatrix} A_T & V_T \end{pmatrix} \begin{pmatrix} \mathbf{k}^2 + \omega_p^2 & \kappa\omega_p^2 \\ 0 & \mathbf{k}^2 + m_V^2 \end{pmatrix} \begin{pmatrix} A_T \\ V_T \end{pmatrix}$$



$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$

- When $\omega_p = m_V$, photon and dark photon resonantly convert into each other.

Photon dark photon oscillation

- The transition probability

$$\omega_p^2 = m_V^2$$

$$P_{V\to A} = \int dt \Gamma_{V\to A} = \int \frac{dt}{2\omega} \frac{d^3p}{(2\pi)^3 2\omega} (2\pi)^4 \delta^4(p_V - p_A) \frac{1}{3} \sum_{\text{pol}} |\mathcal{M}|^2$$

$$= \frac{2}{3}\pi\kappa^2 m_V v_r^{-1} \left| \frac{\partial \log \omega_p^2}{\partial r} \right|_{r=r_c}^{-1}$$

Resonant region

Average of polarization

If v_r=0 the DM stays at the resonance region forever.

Searching for ultralight DM with radio telescopes

$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$$

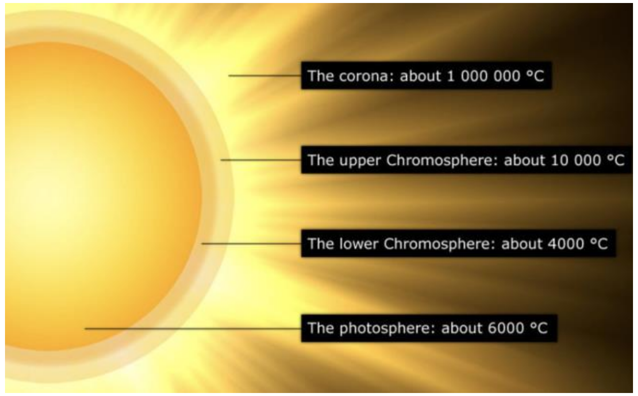
- For dark photon:

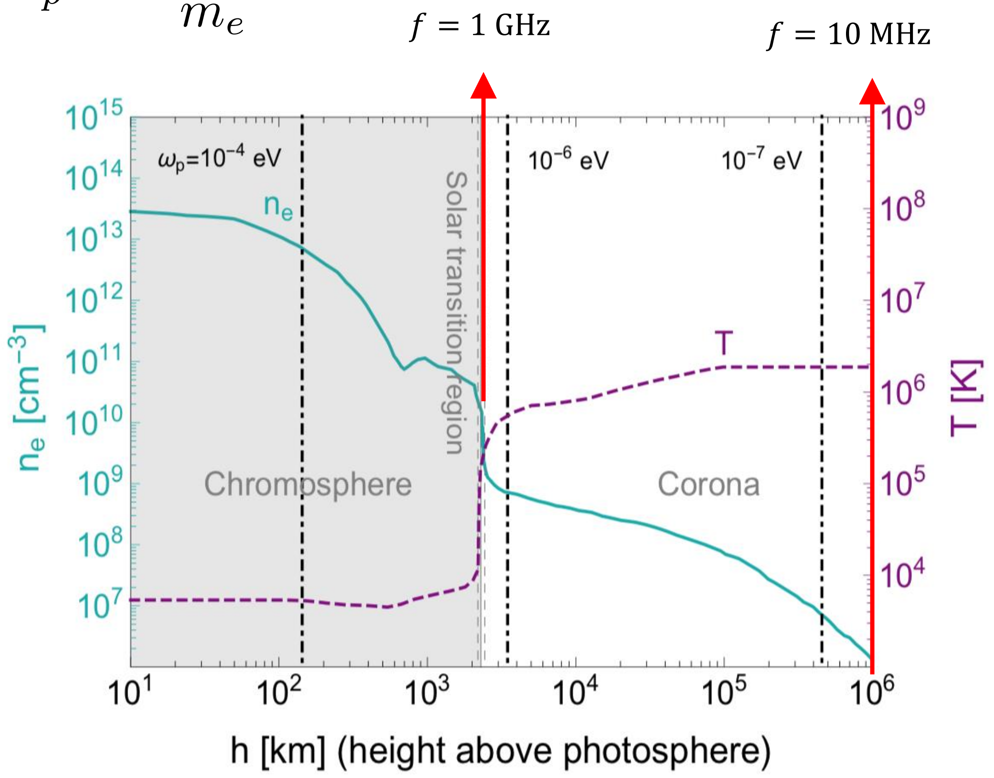
$$\omega^2 - k^2 = m_V^2$$

- For photon in plasma:

$$\omega^2 - k^2 = \omega_p^2$$

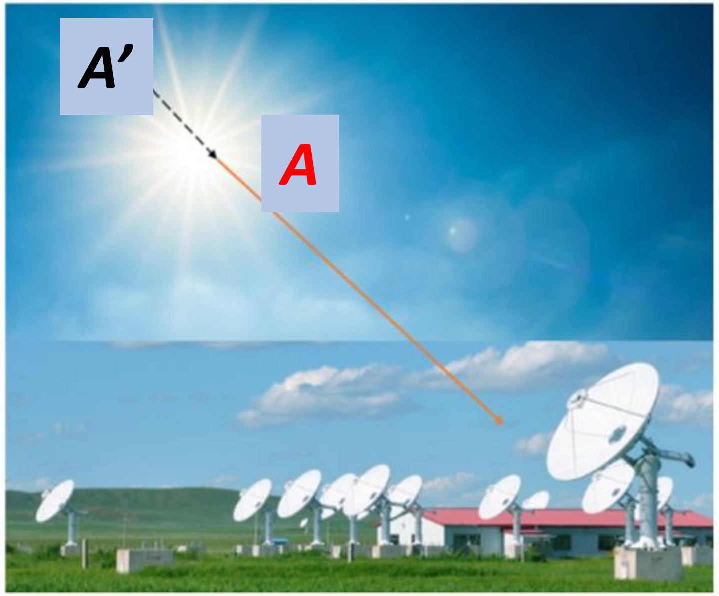
- We need plasma.





Dark photon dark matter converted at the Sun's atmosphere

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

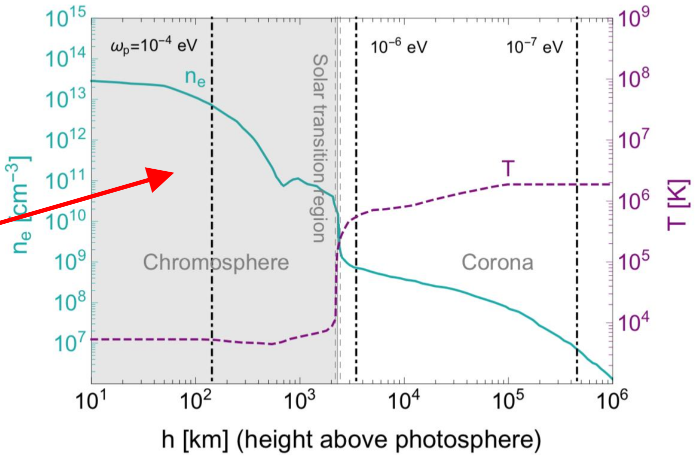


Absorption of the converted photon during propagation

- Inverse bremsstrahlung absorption

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

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

- The minimal detectable flux

$$S_{\rm min} = \frac{\rm SEFD}{\eta_s \sqrt{n_{\rm pol}\, \mathcal{B}\, t_{\rm obs}}}$$

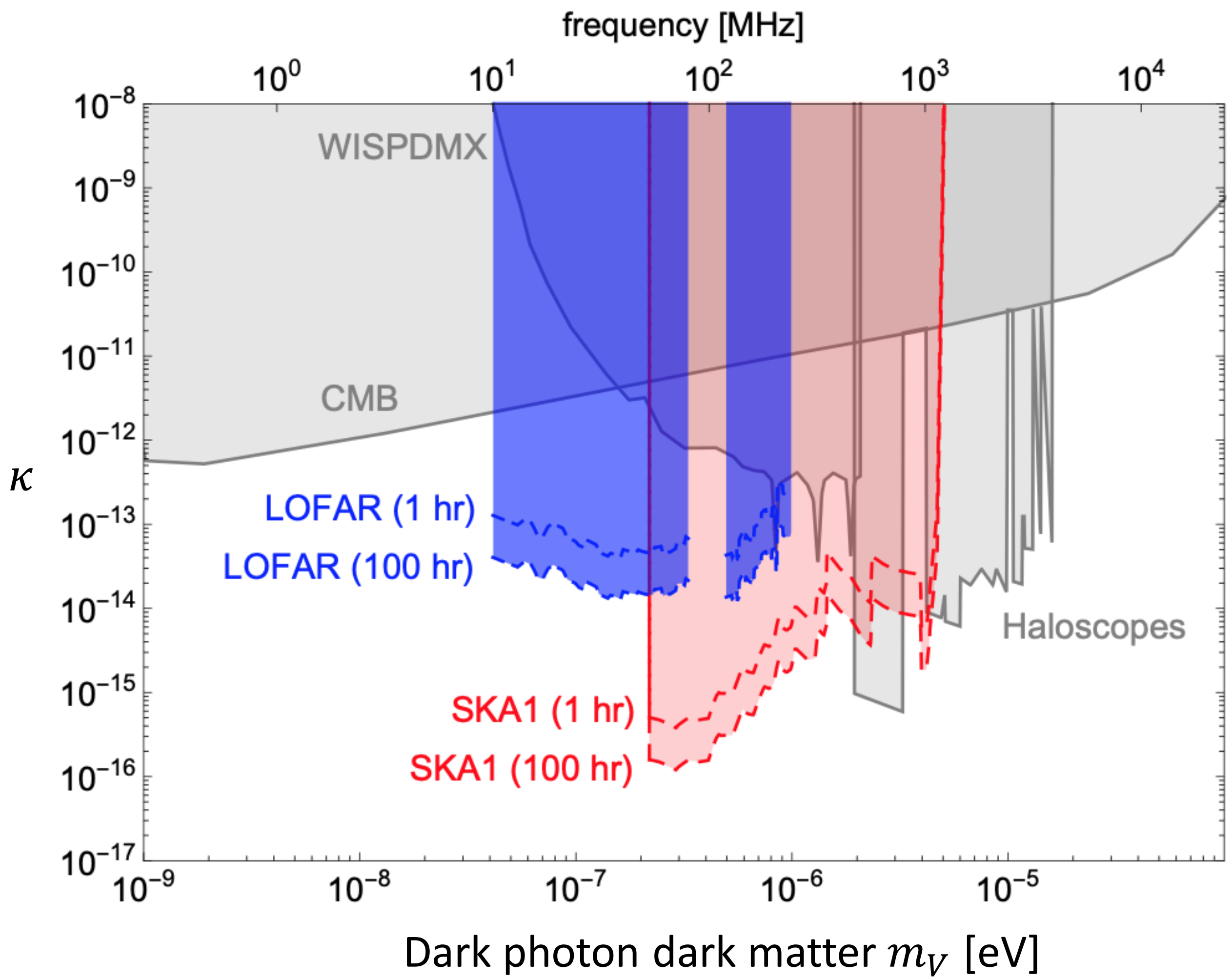
$${\rm SEFD} = 2k_B \frac{T_{\rm sys} + T_{\odot}^{\rm nos}}{A_{\rm eff}}$$

Name	f [MHz]	$B_{\rm res}$ [kHz]	$\langle T_{\rm sys} \rangle$ [K]	$\langle A_{\rm eff} \rangle$ [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 and south Africa

Europe

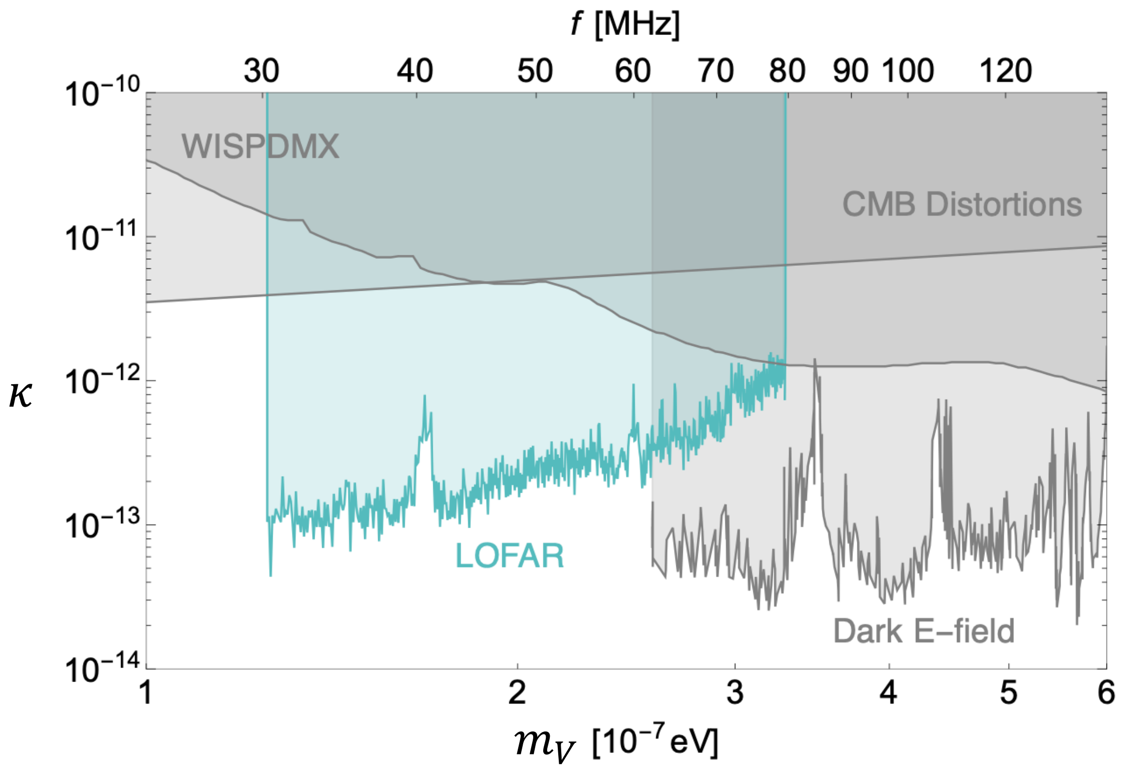
Searching for DPDM with radio telescopes



HA, F.P. Huang, J.Liu, W.Xue, Phys.Rev.Lett. 126 (2021) 181102

Searching for DPDM in LOFAR

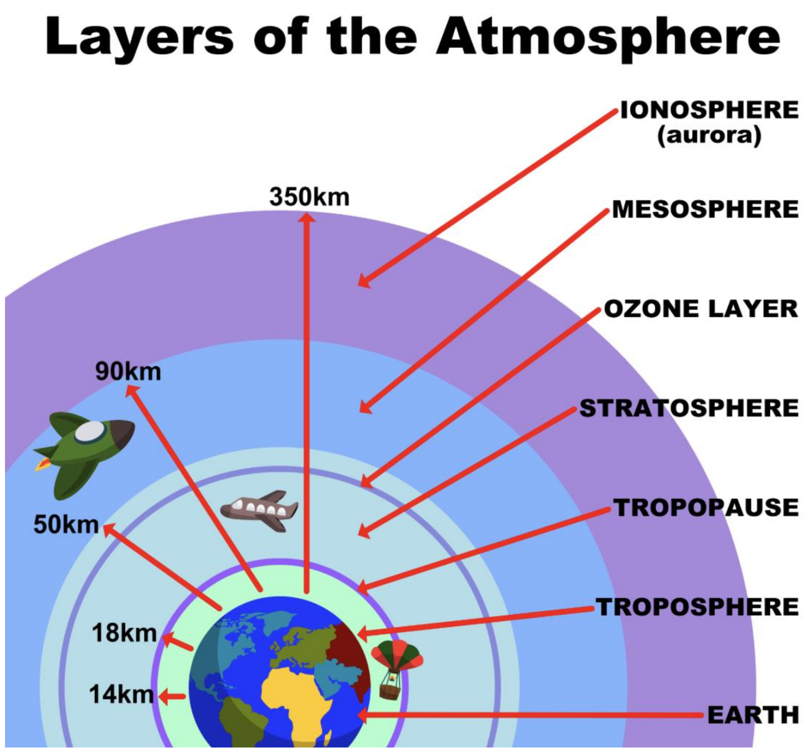
- We obtain LOFAR real data $f \sim 30 - 80$ MHz in total of 51 minute observation.



HA, X. Chen, S. Ge, J. Liu, Y. Luo, Nature Communications 15 (2024) 1, 915

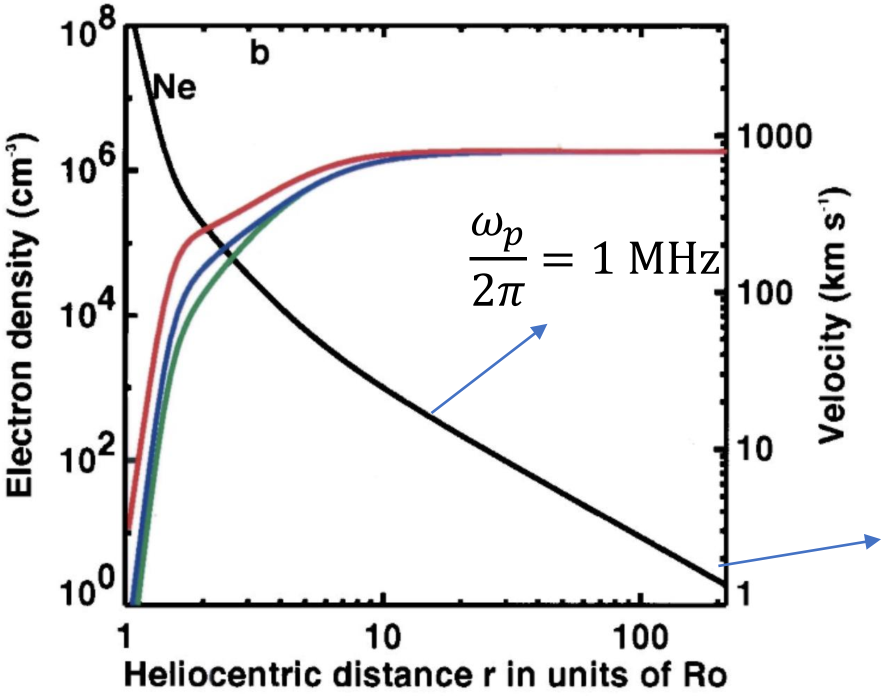
For dark photon dark matter with smaller mass

- Because of the ionosphere, no terrestrial telescopes can cover $f < 10$ MHz.
- Go to outer space.

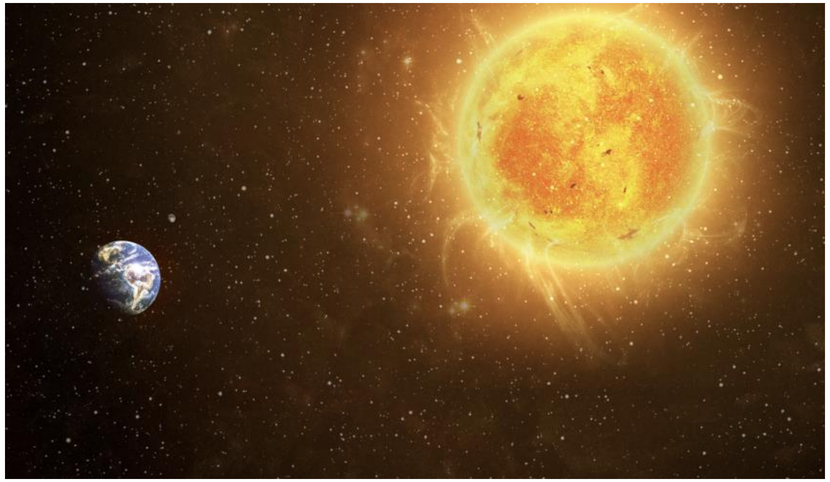


Plasma in solar wind

- Free electrons between Earth and Sun

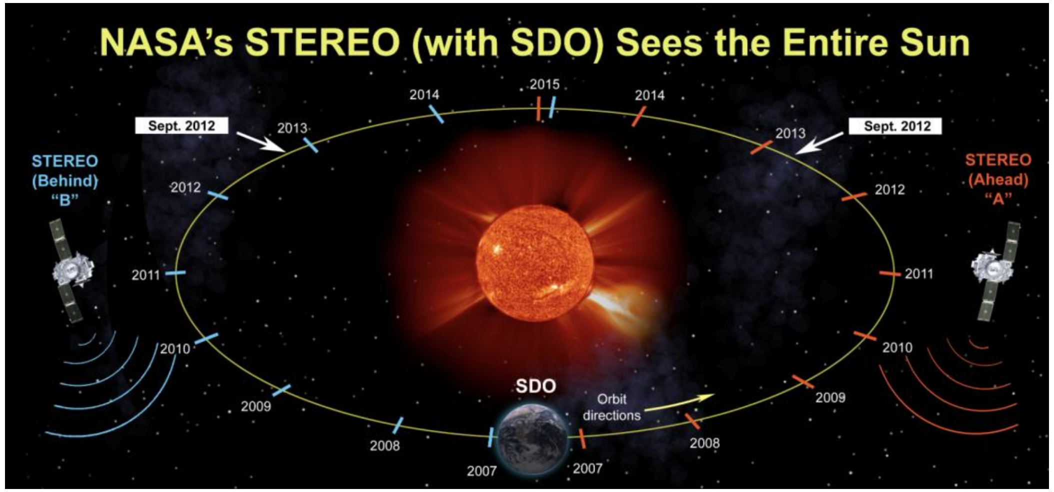


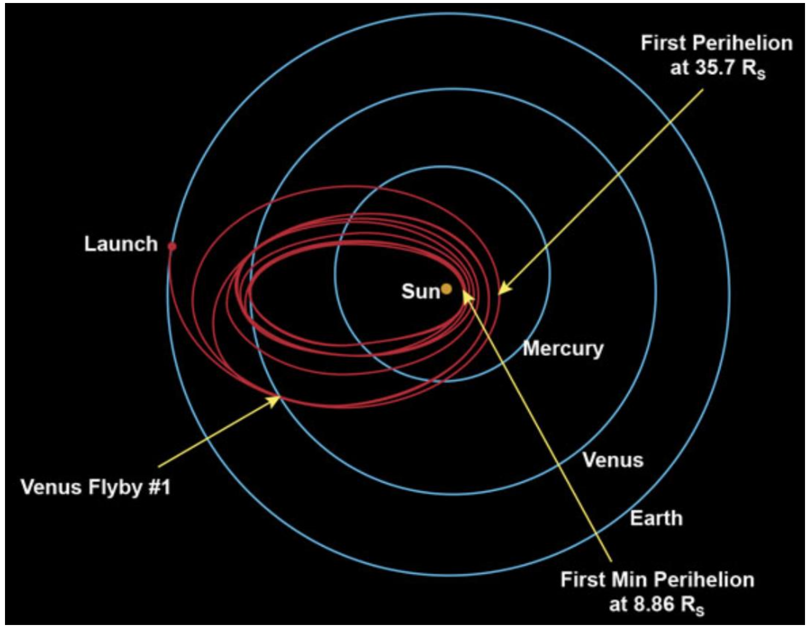
$$\frac{\omega_p}{2\pi} = 20\ \mathrm{kHz}$$



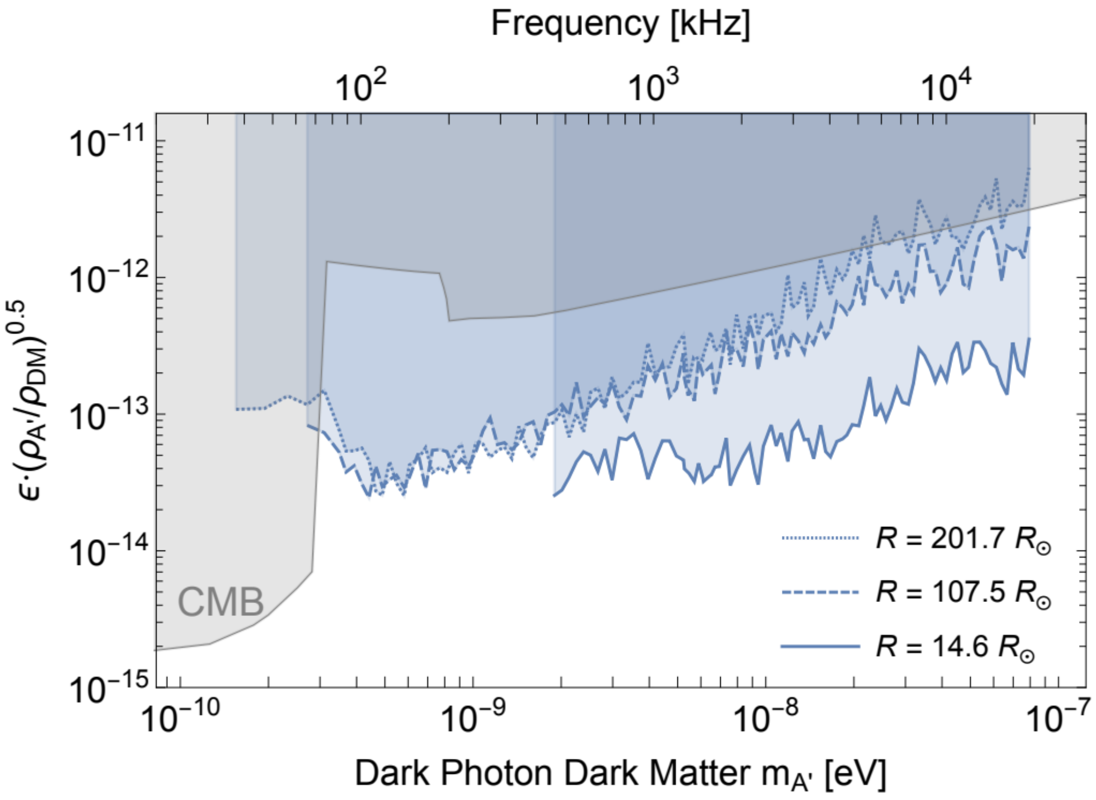
For dark photon dark matter with even smaller mass

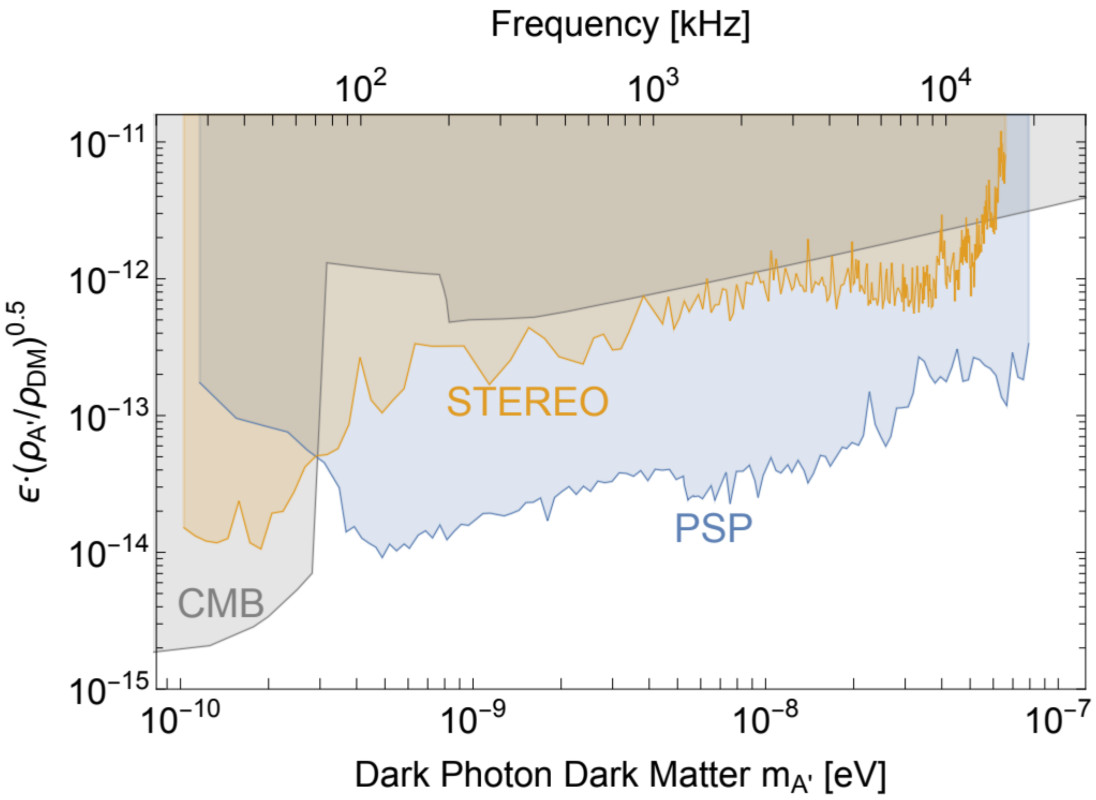
- STEREO A/B
- Parker Solar Probe





Using solar probes to search for DPDM



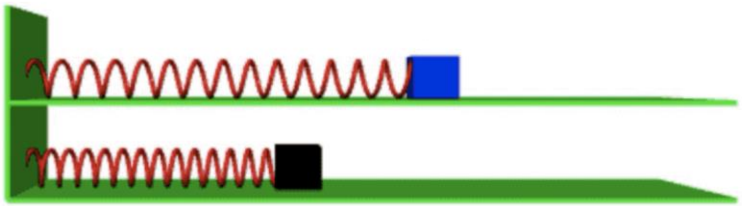


HA, Shuailiang Ge, Jia Liu, Mingzhe Liu, arXiv: 2405.12285

Dark photon in plasma

Plasma effect

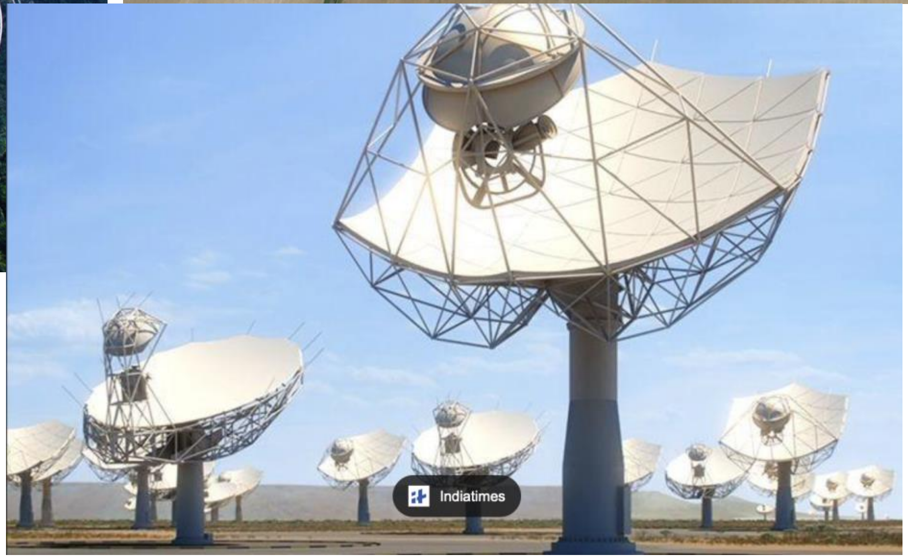
$$\begin{pmatrix} A_T & V_T \end{pmatrix} \begin{pmatrix} \mathbf{k}^2 + \omega_p^2 & \kappa\omega_p^2 \\ 0 & \mathbf{k}^2 + m_V^2 \end{pmatrix} \begin{pmatrix} A_T \\ V_T \end{pmatrix}$$



What we really need are free electrons!

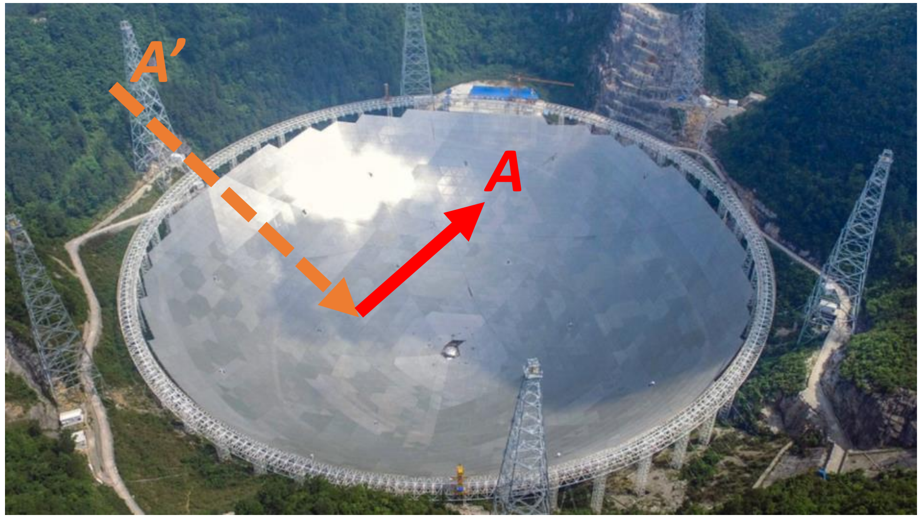
Searching for dark photon dark matter directly with radio telescopes

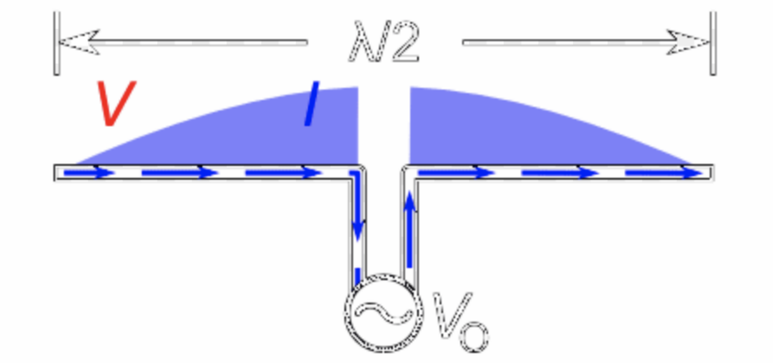
- Large scale radio telescopes



Searching for dark photon dark matter directly with radio telescopes

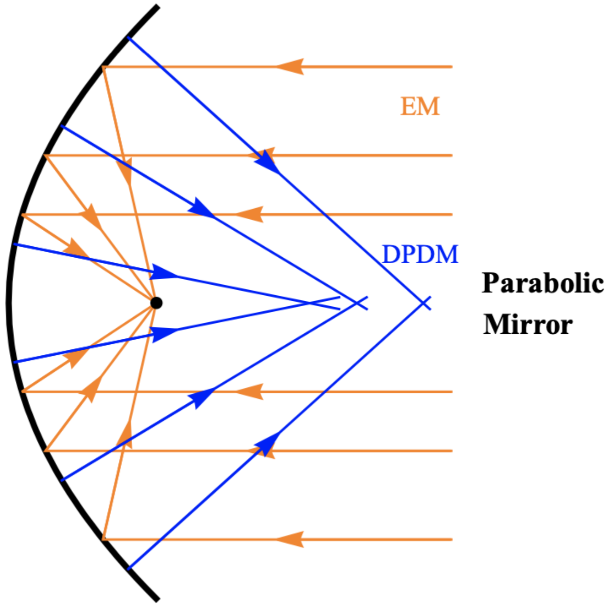
- The dark photon dark matter has an interaction with the electric current, $\kappa e V_\mu J^\mu$ (although suppressed)

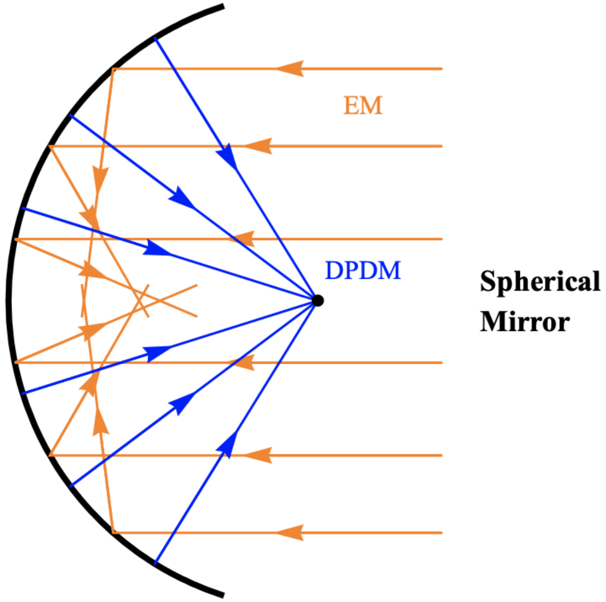


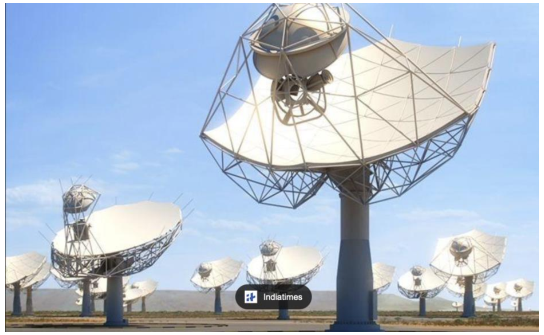


Dish antennas

- For dish antennas, the oscillation of the dark photon field induces the oscillation of the electrons in the reflector plate, and produces EM waves, which can be detected by the feed.

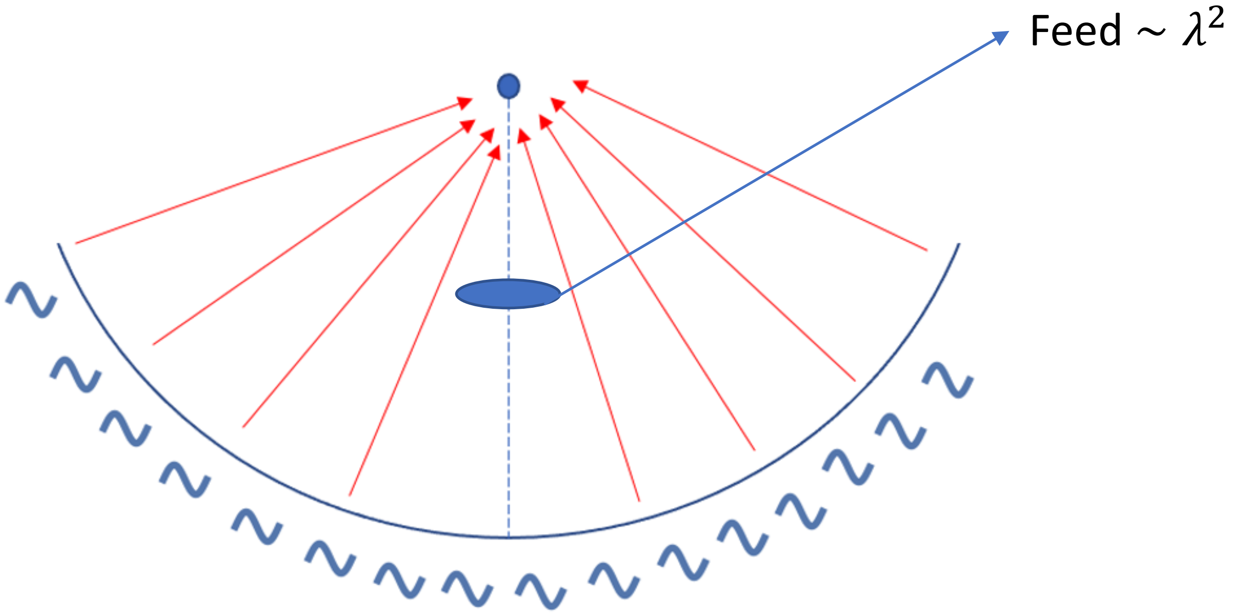






Dish antennas

- The size of the feed $\sim \lambda$

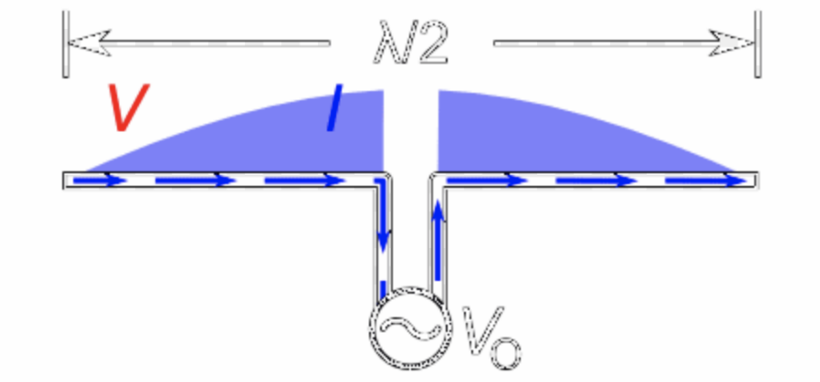


$$I_{\rm dish}^{\rm eqv} = \mathcal{C}\kappa^2 \rho_{\rm DM} \times \frac{\lambda^2}{\mathcal{A}}$$

$\mathcal{A}$ → Area of the telescope

Dipole antennas

- Usually $\ell \leq \frac{\lambda}{2}$
- For photon, $\lambda = \frac{1}{f}$
- For dark photon, $\lambda_D = \frac{1}{f \times v_D} \approx 10^3 \lambda$
- Equivalent electric signal:



$$E_{\rm EM}^{\rm eqv} = \kappa E_D^{(0)} \cos(2\pi f t)$$

$$I_{\rm dipole}^{\rm eqv} = \mathcal{C}\kappa^2 \rho_{\rm DM}$$

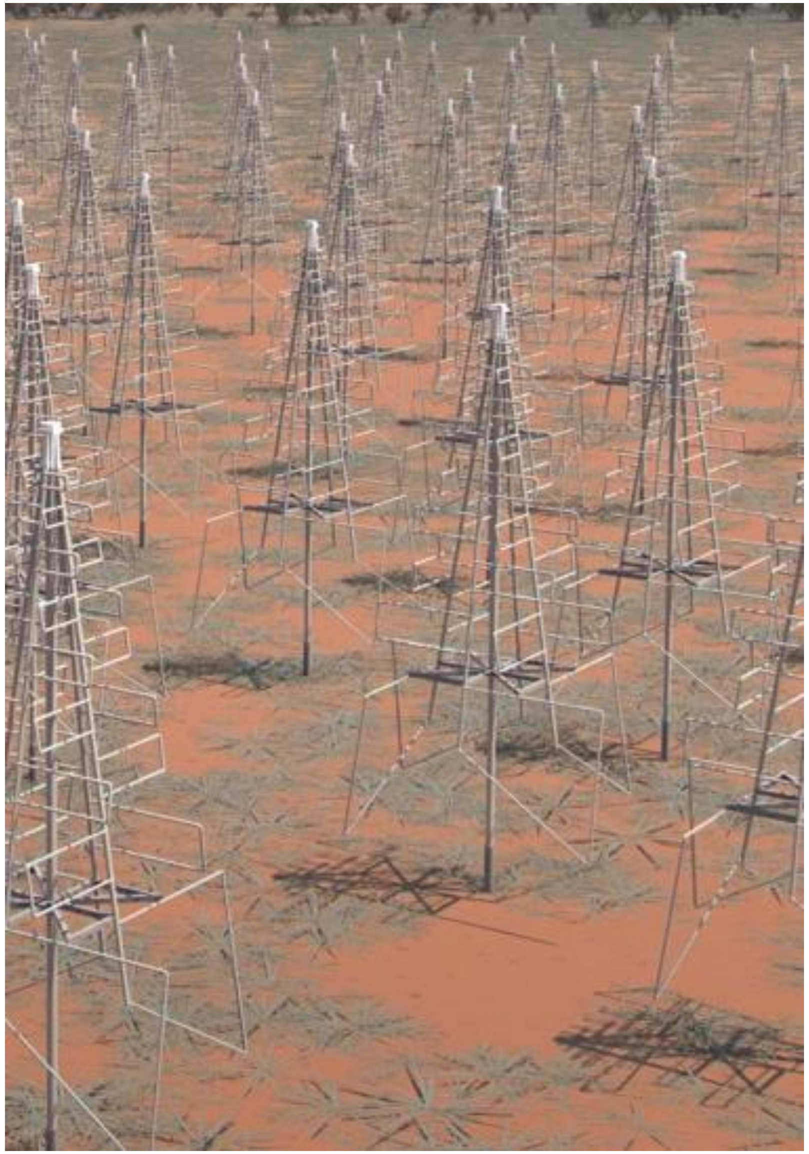
$\rho_{\rm DM} \rightarrow$ 0.4 GeV/cm^3

$\mathcal{C} \rightarrow$ Order one parameter, determined by the detailed shape of the antenna

Antenna arrays

- $\lambda_D \sim 10^3 \lambda$
  - $\lambda_D \approx 4$ km for $f = 70$ MHz
  - $\lambda_D \approx 150$m for $f = 2$ GHz
- Interferometry techniques can be used.
- Correlation suppressed when the distance of two antennas is larger than λ_D.

$$\mathcal{S}_{mn} = \exp(-m_{A'}^2 \sigma_v^2 d_{mn}^2 / 4)$$



Limits from antenna arrays

- The signal is a peak,

$$f_{\text{signal}} = m_V/2\pi \qquad \Delta f_{\text{signal}} \approx 10^{-6} f$$

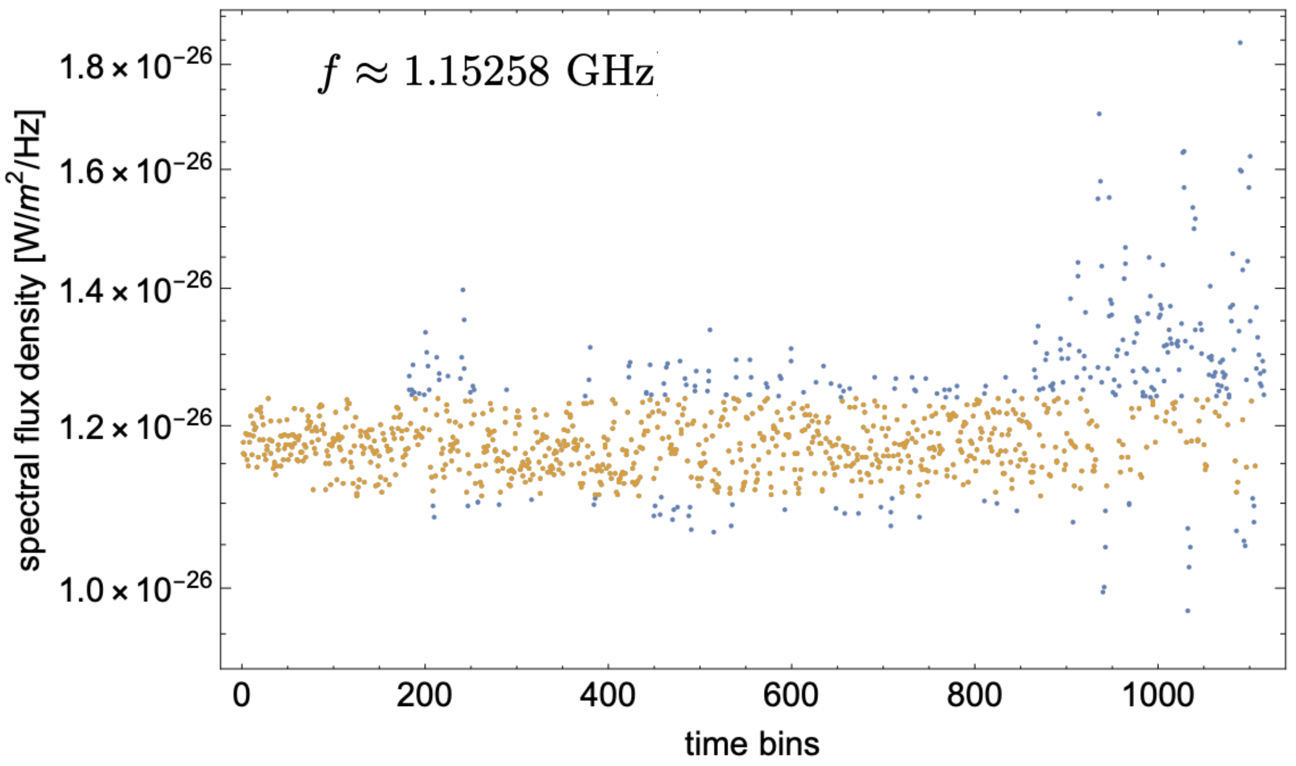
- Minimum detectable spectral flux

$$S_{\text{min}} = \frac{\text{SEFD}}{\eta_s \sqrt{n_{\text{pol}} \mathcal{B} t_{\text{obs}}}} \qquad \text{SEFD} = \frac{2k_B T_{\text{sys}}}{A_{\text{eff}}}$$

- We require $I_{array}^{eqv}/B > S_{min}$ to calculate the sensitivities of the antenna arrays.

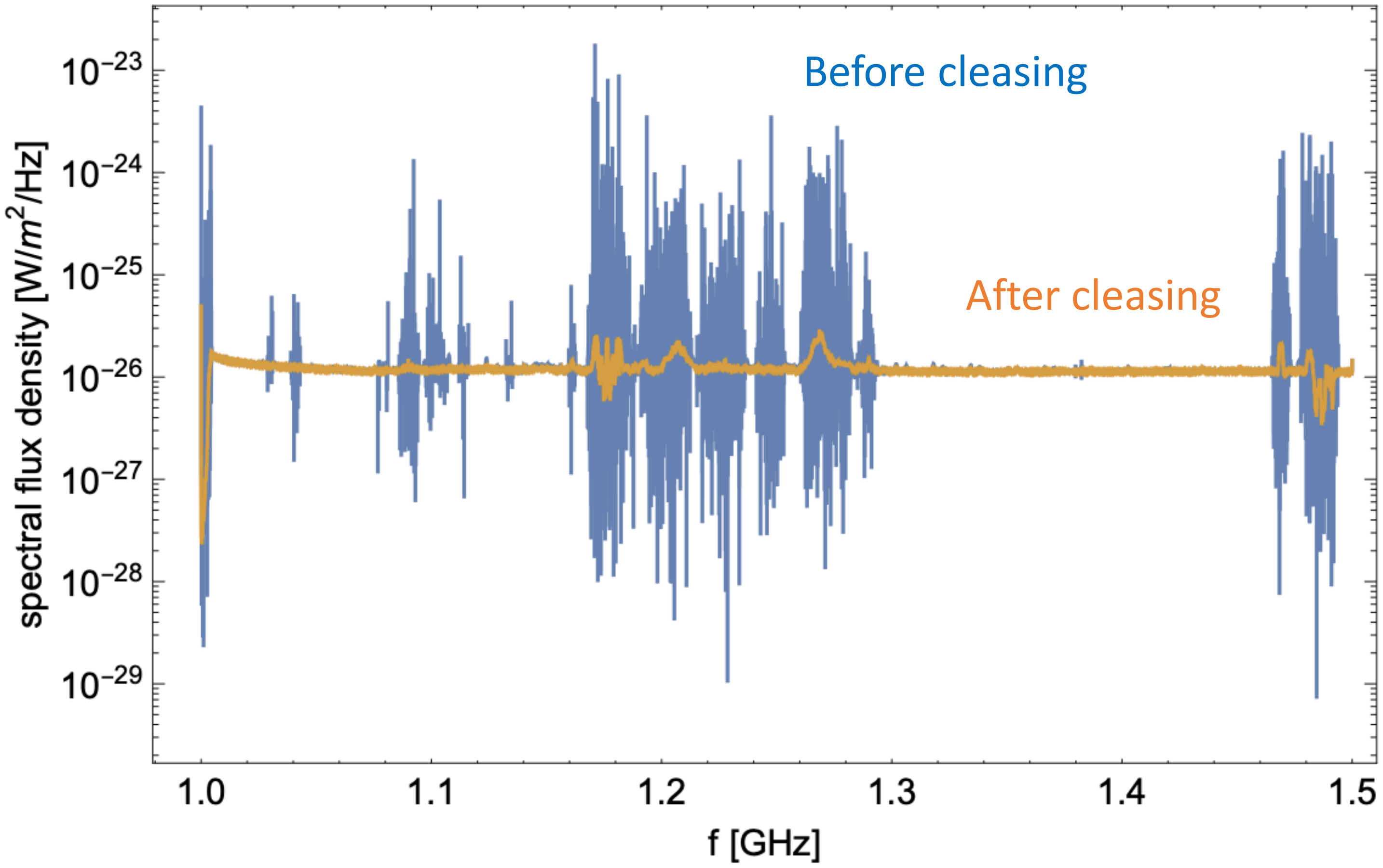
FAST data

- 1– 1.5 GHz, Band width = 7.63 kHz, data observed on Dec 14, 2020.
- The signal is constant, we remove data with large variation in time.

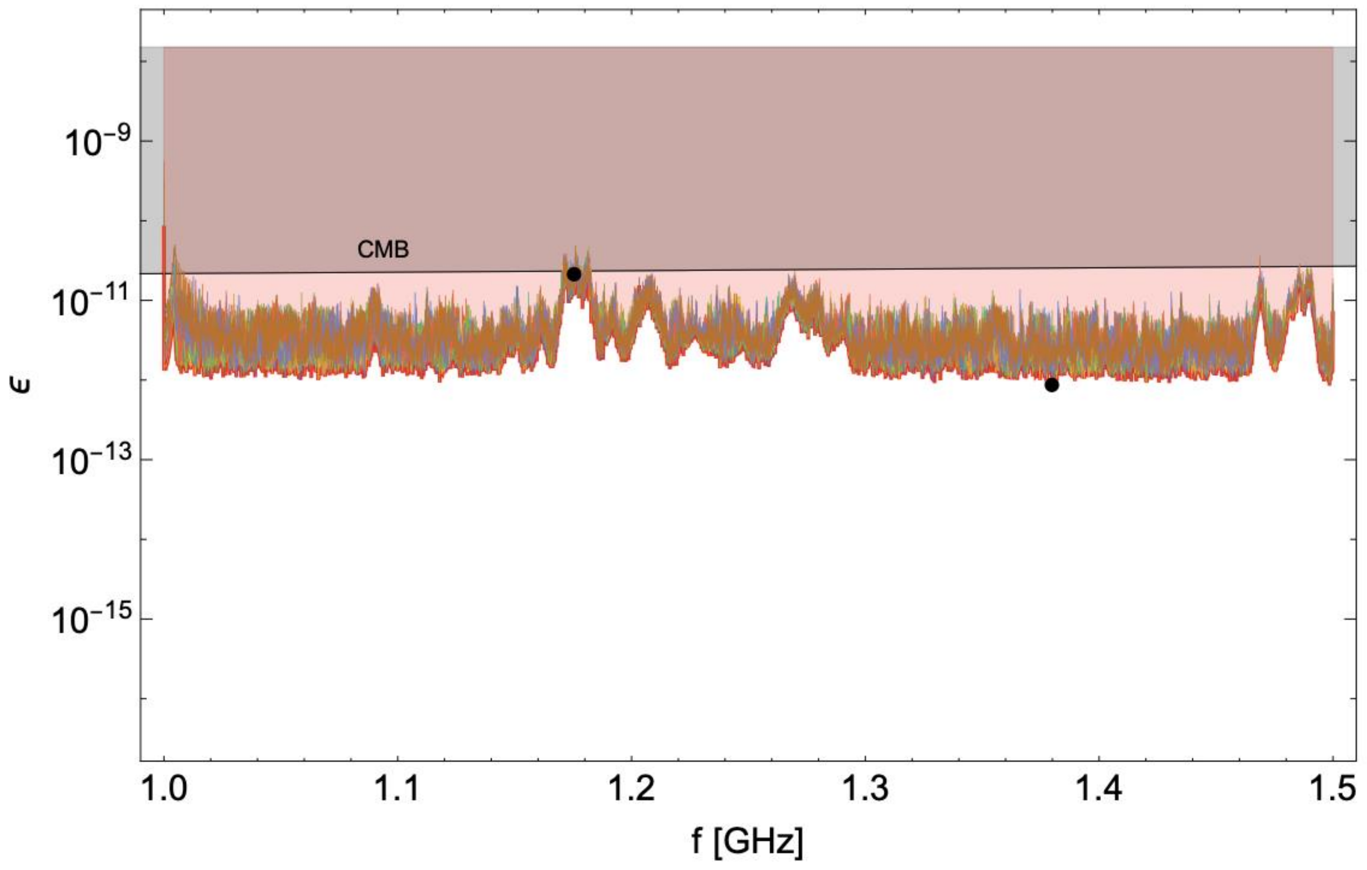


FAST data

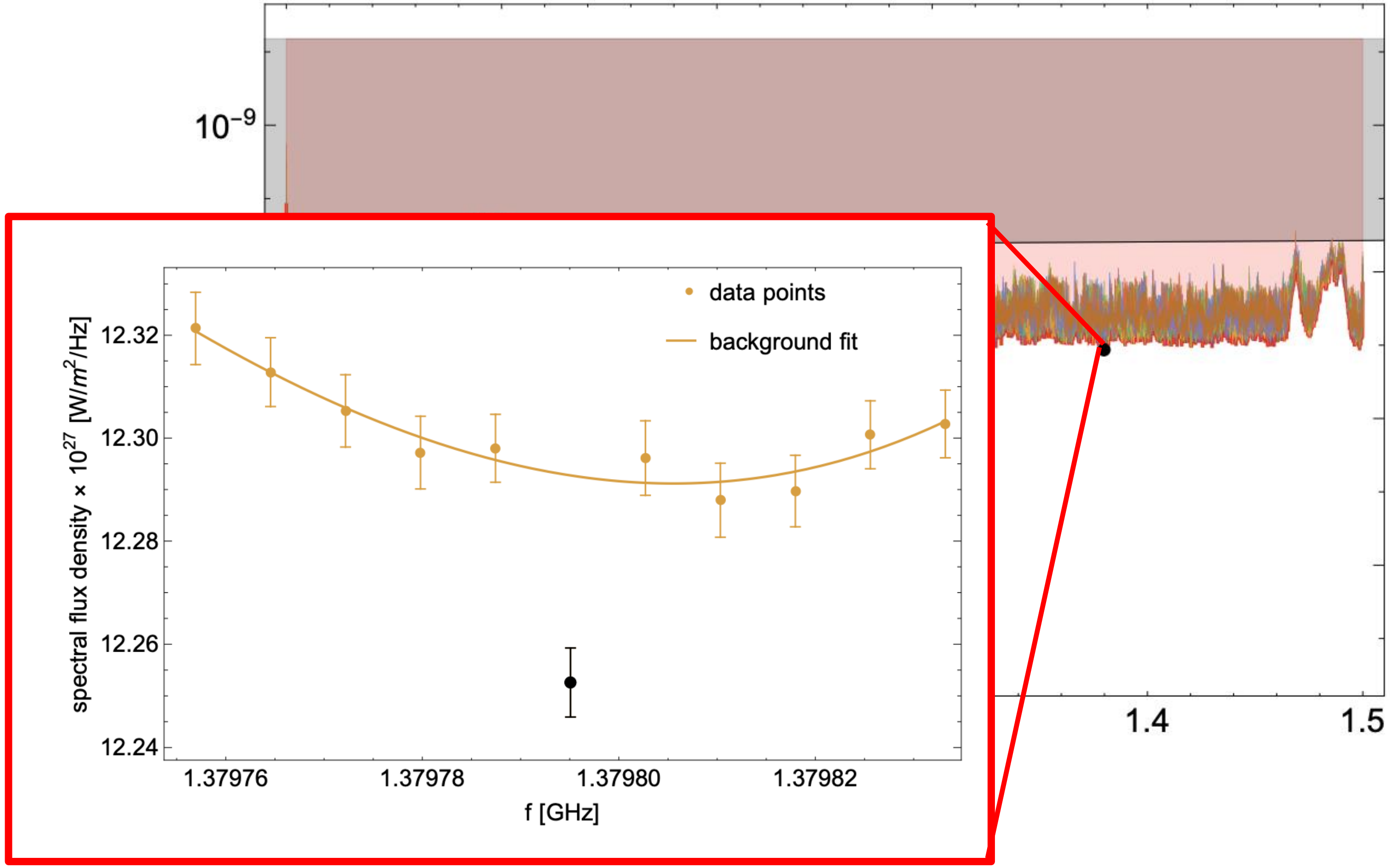
- Spectrum after data cleasing



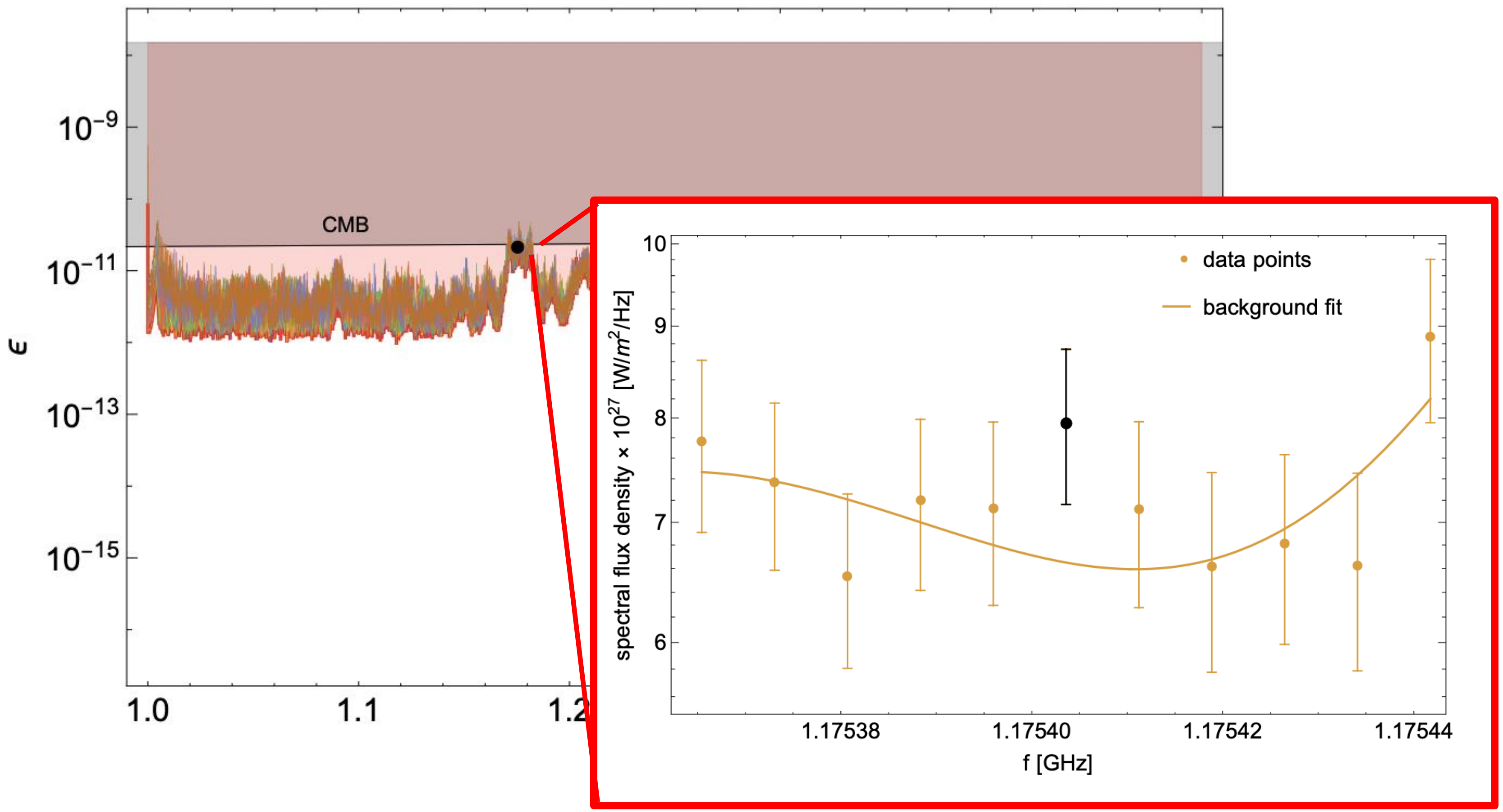
Constraint FAST data



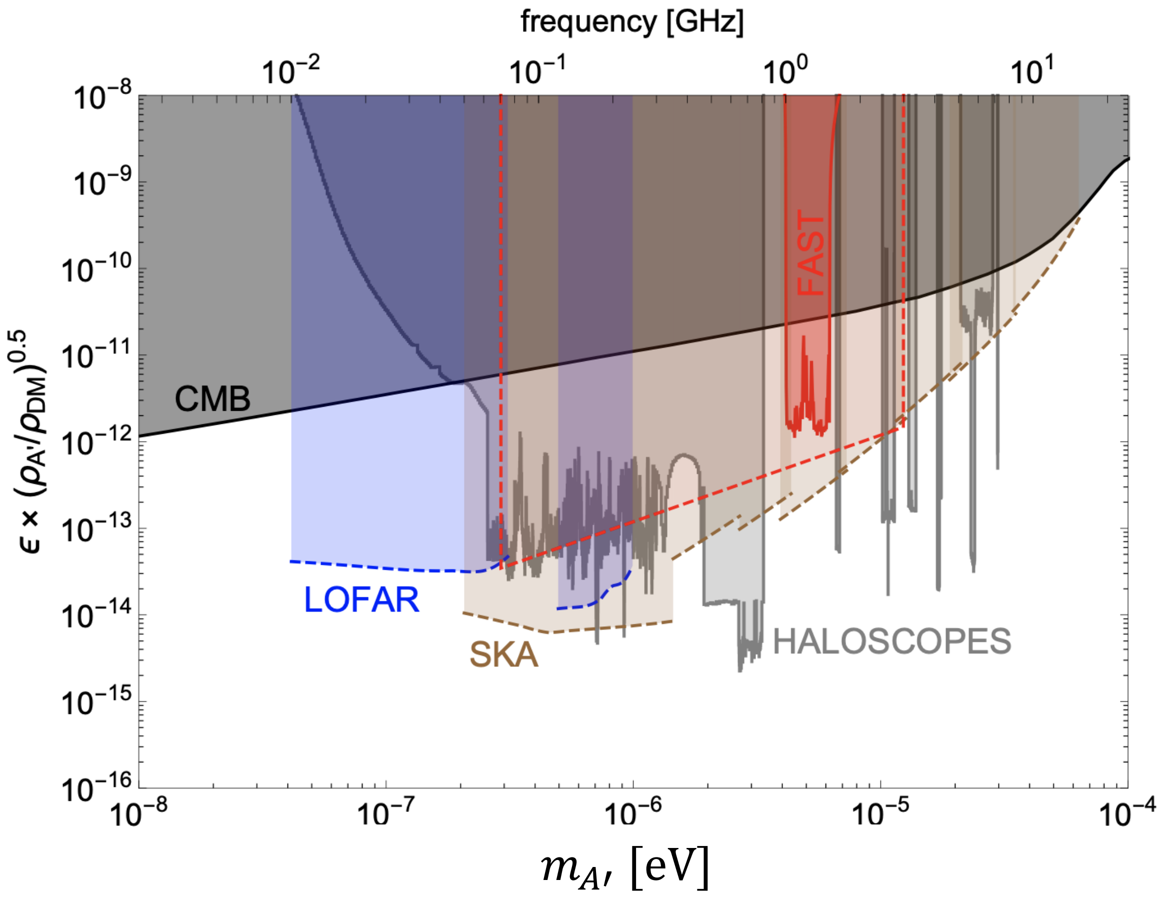
Constraint FAST data



Constraint FAST data



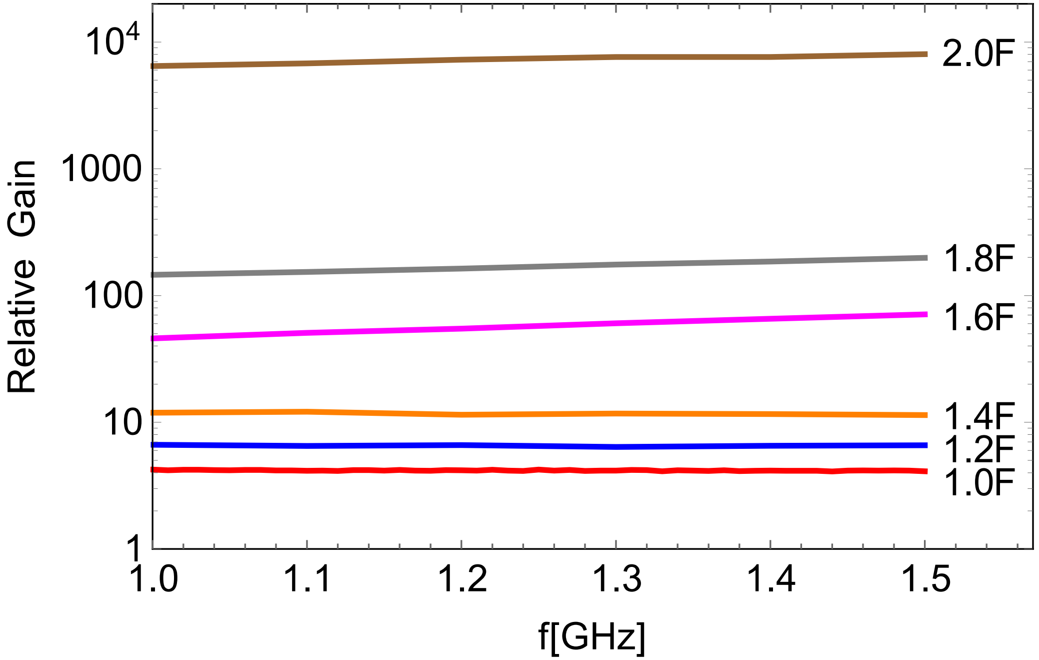
Direct detection of dark photon dark matter with radio telescopes



***HA**, S Ge, W-Q Guo, X Huang, Jia Liu, Z Lu, 2207.05767, PRL accepted*

Our own prototype detector

- For parabolic mirror, it is better for the detector to be around 2F.



With Jia Liu, Qiang Yuan, Quan Guo, and Xiaoxing Yang

Searching for dark photon dark matter using gravitational wave detectors

- Dark photon interacts with baryon number. $e' A'_\mu J_B^\mu$ or $e' A'_\mu J_{B-L}^\mu$.

  Pierce, Riles, Zhao, 1801.10161 & PRL

- For LIGO:

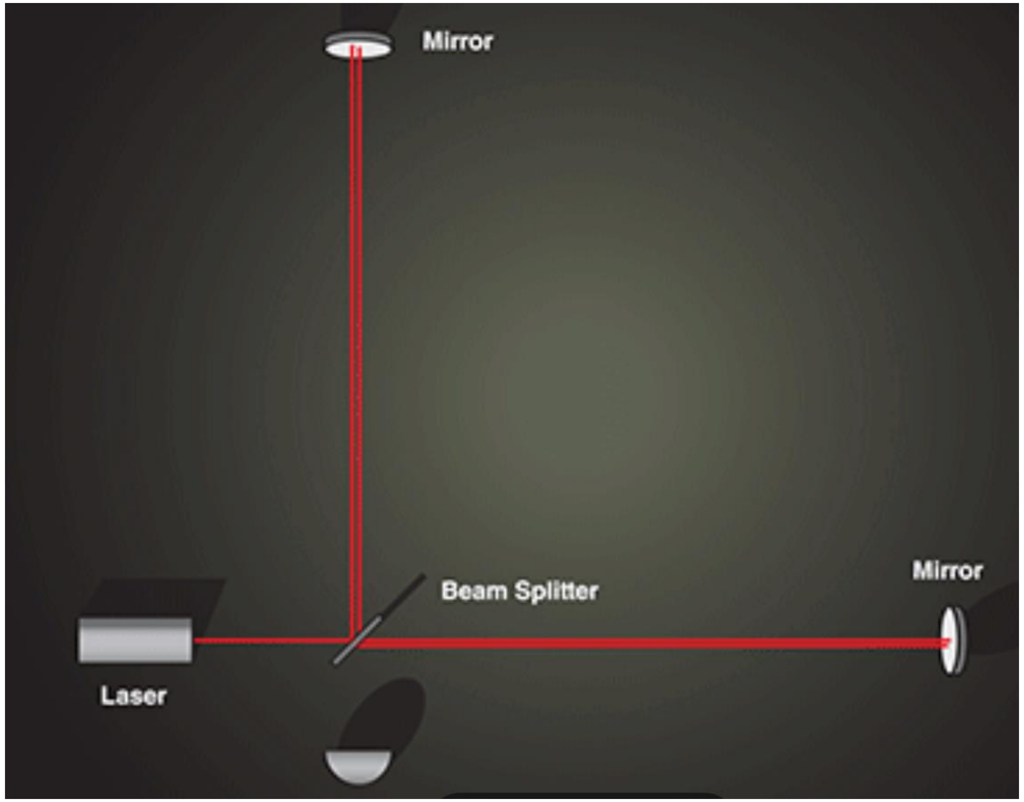
  Guo, Riles, Yang, Zhao, 1905.04316

- For LISA pathfinder

  Frerick, Jaeckel, Kahlhoefer, Schmidt-Hoberg, 2310.06017

- For PTAs

  PPTA Collaboration . Xiao Xue et al, 2112.07684



Production of DPDM

- It is indeed not easy. The simplest story of using misalignment mechanism like in the case of axion dark matter does not work!
- The reason for this is that the dark photon field must point in a direction. Producing dark photons completely at rest would involve breaking rotation invariance. Therefore, they cannot be fully homogeneous and the produced dark photons must have a velocity. Reconciling this non-zero momentum with dark matter's non-relativistic nature is why producing very light dark photon dark matter is difficult.

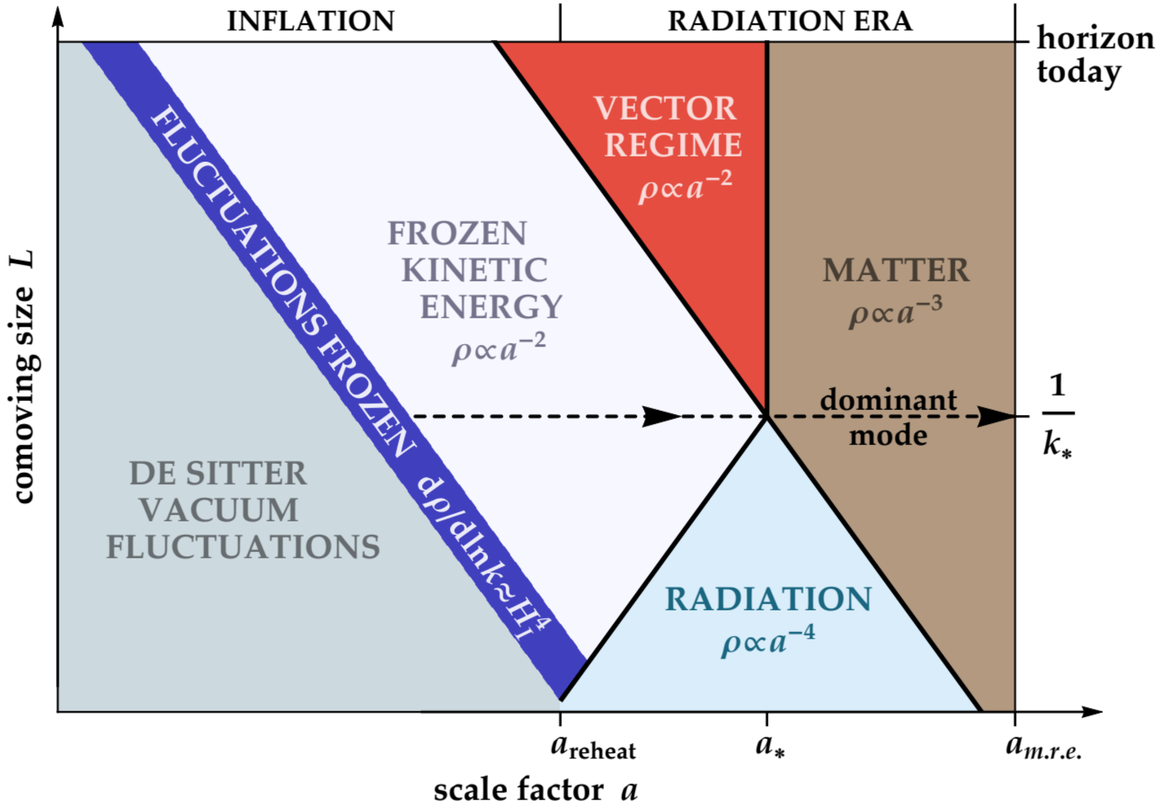
Broadberry, Das, Hook, Tavares, 2408.03370

DPDM production

- The longitudinal mode can be Produced through quantum fluctuations during inflation.

  Graham, Mardon, Rajendran (2015)

$$\frac{\Omega_{\rm vector}}{\Omega_{\rm cdm}} = \sqrt{\frac{m}{6\times 10^{-6}\,{\rm eV}}}\left(\frac{H_I}{10^{14}\,{\rm GeV}}\right)^2$$

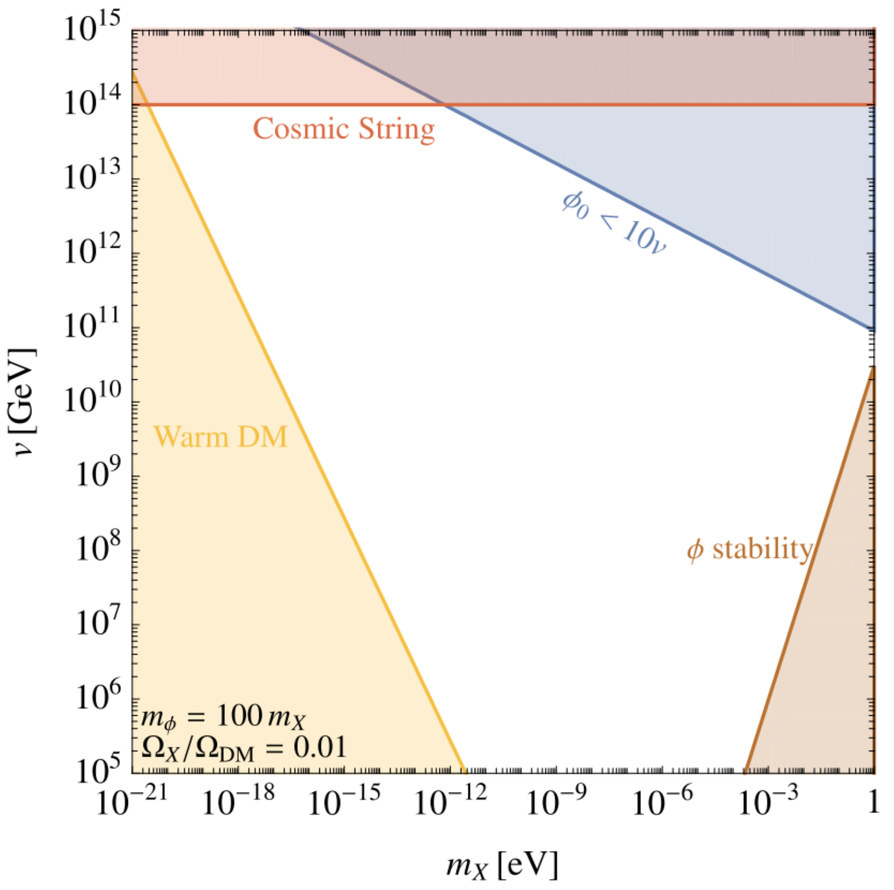


DPDM production via scalar oscillation

$$\mathcal{L}_{\phi A'A'} = \frac{\alpha_D}{8\pi f_D}\phi\, F'_{\mu\nu}\tilde{F}'^{\mu\nu}$$

$$\frac{\partial^2 A'_\pm}{\partial\eta^2} + \left(m_{A'}^2 + k_{A'}^2 \pm \frac{\alpha_D k_{A'}}{2\pi f_D}\frac{\partial\phi}{\partial\eta}\right)A'_\pm = 0$$

Co, Pierce, Zhang, Zhao (2018)
Dror, Harigaya, Narayan (2018)
Bastero-Gil, Santiago, Ubaldi, Vega-Morales (2018)
Agrawal, Kitajima, Reece, Sekiguchi, Takahashi (2018)



DPDM production via scalar misalignment and primordial magnetic field

Broadway, Das, Hook, Tavares, 2408.03370

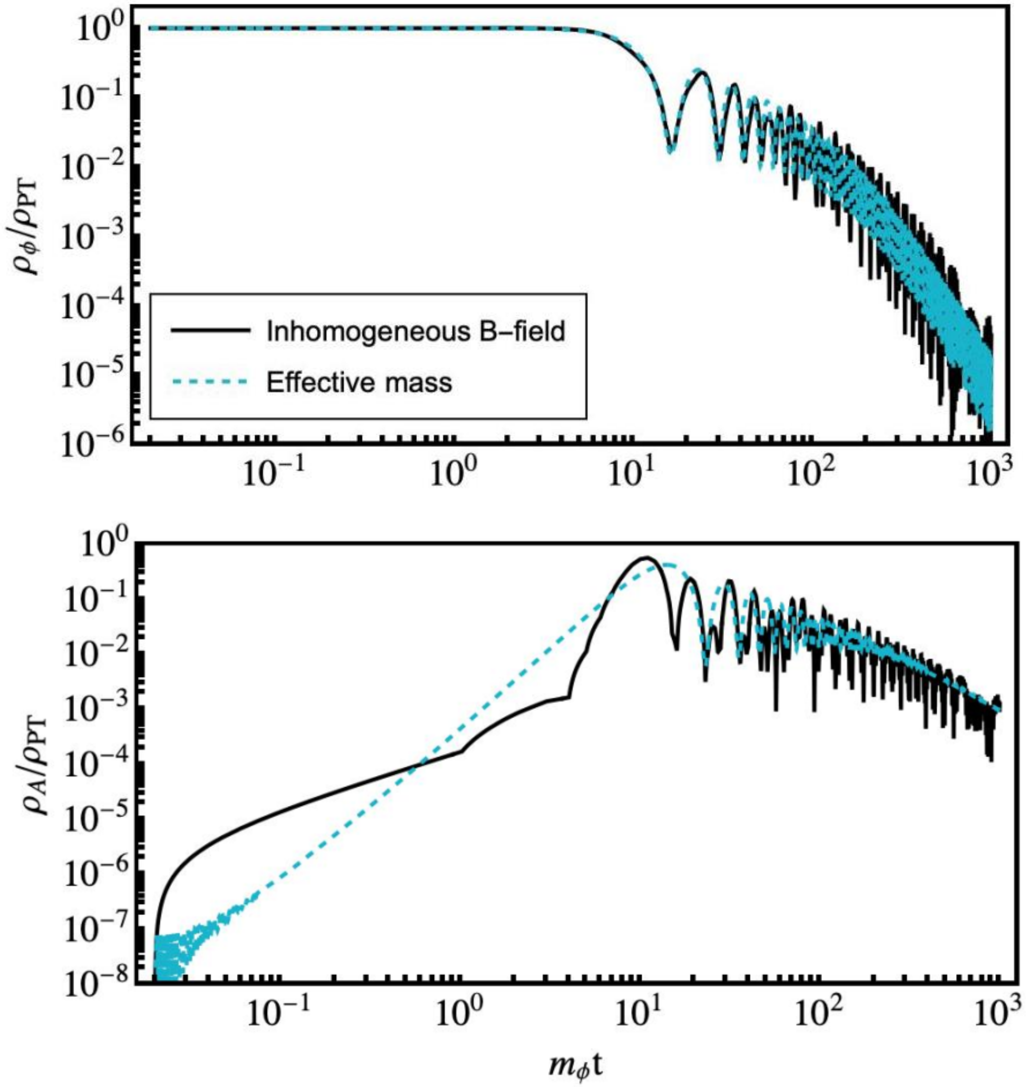
$$\frac{\phi}{f} F'_{\mu\nu} F'^{\mu\nu} \longrightarrow \frac{\phi}{f} F_{\mu\nu} F'^{\mu\nu}$$

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = \frac{b}{a} \dot{A}_D,$$

$$\ddot{A}_D + H\dot{A}_D + m_A^2 A_D = -ab\dot{\phi},$$

$$b(t) = B(t)/f$$

$$m_{A'} > 10^{-13}\ \mathrm{eV}$$



Constraints from theoretical considerations

Reece 1808.09966

- From the weak gravity conjecture.
- For spin-1 vector boson with coupling e, and Stuekelberg mass m, local quantum field theory breaks down at energies at or below

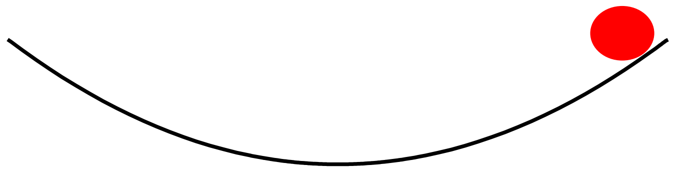
$$\Lambda_{\rm UV} = \min((m_{A'} M_{\rm pl}/e')^{1/2}, e'^{1/3} M_{\rm pl})$$

- We also expect $\epsilon < e'$.
- If $\Lambda_{UV} \sim H_{inf} = 10^{14}$ GeV, $m_{A'} = 10^{-6}$ eV, we have $\epsilon < 10^{-25}$.
- No current experiments can reach it.
- There are several ways out, requiring model building scales.
- But it does not have effect on scalar parametric resonant models.

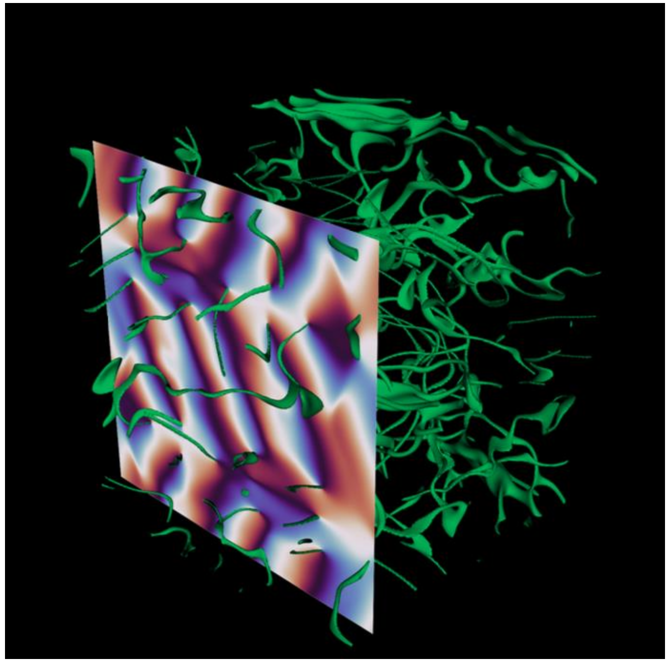
Constraints on Higgsed DPDM

- Coherent oscillation of dark photon is not the ground state when the amplitude is large and the dark photon is Higgsed.

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + (D^\mu\phi)^* D_\mu\phi - \lambda(|\phi|^2 - v^2)^2$$



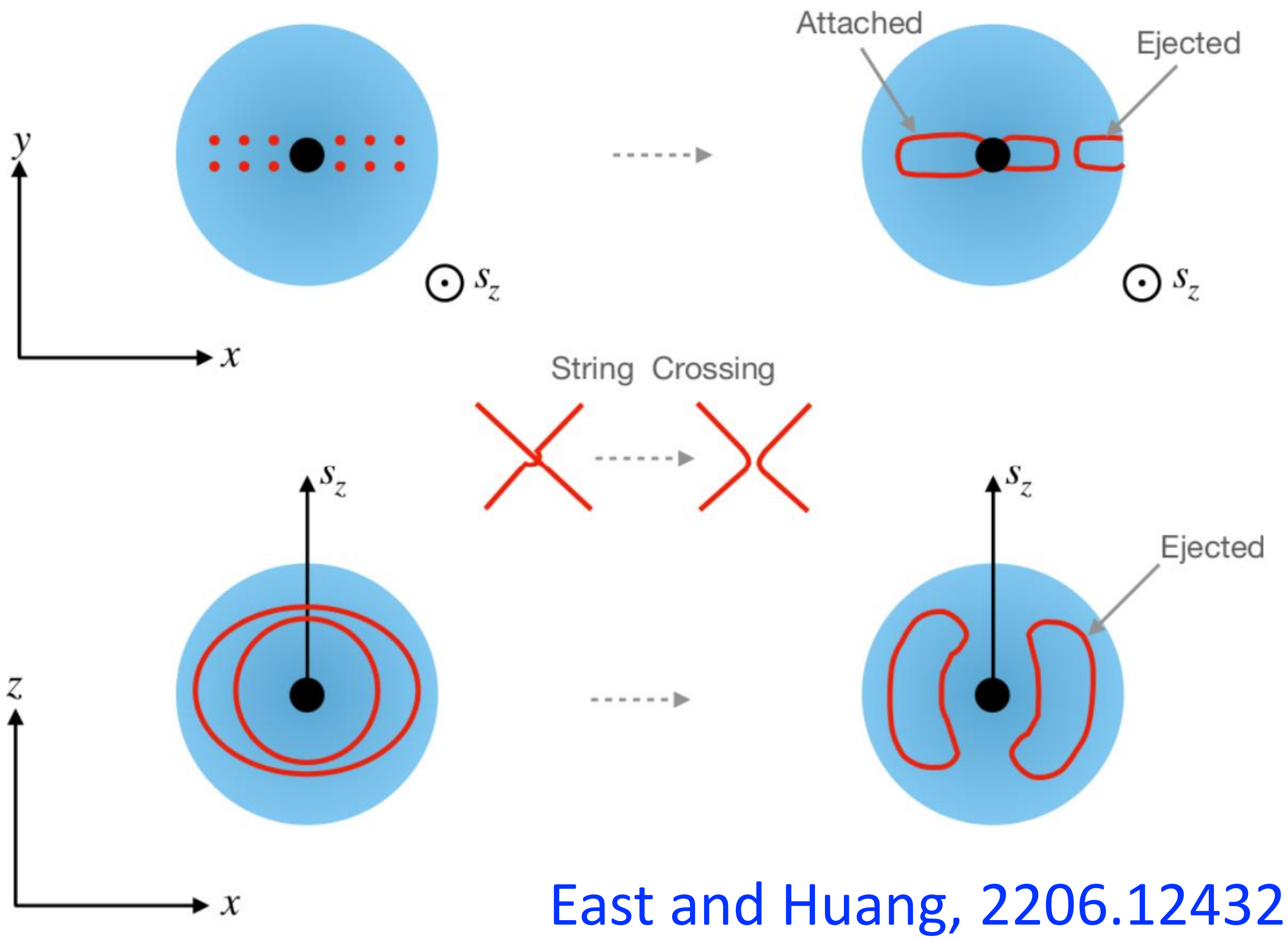
$|A'| > v$

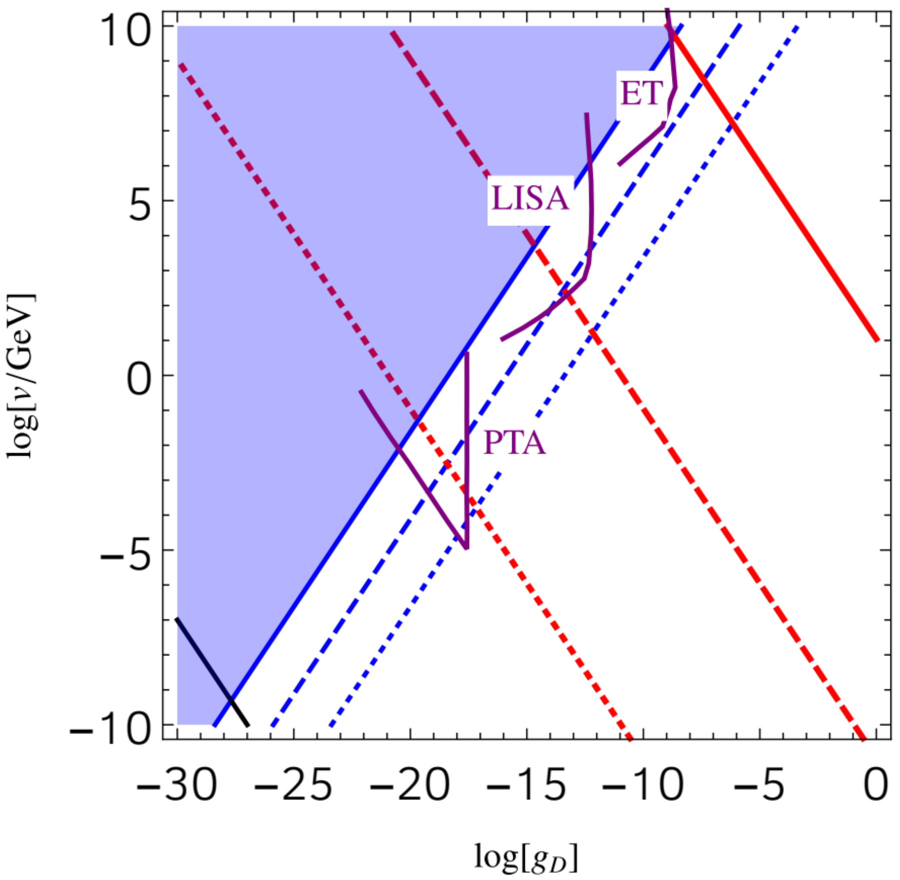


- In the early universe $|A'|$ is huge, models with Higgs are not favored.

East and Huang, 2206.12432

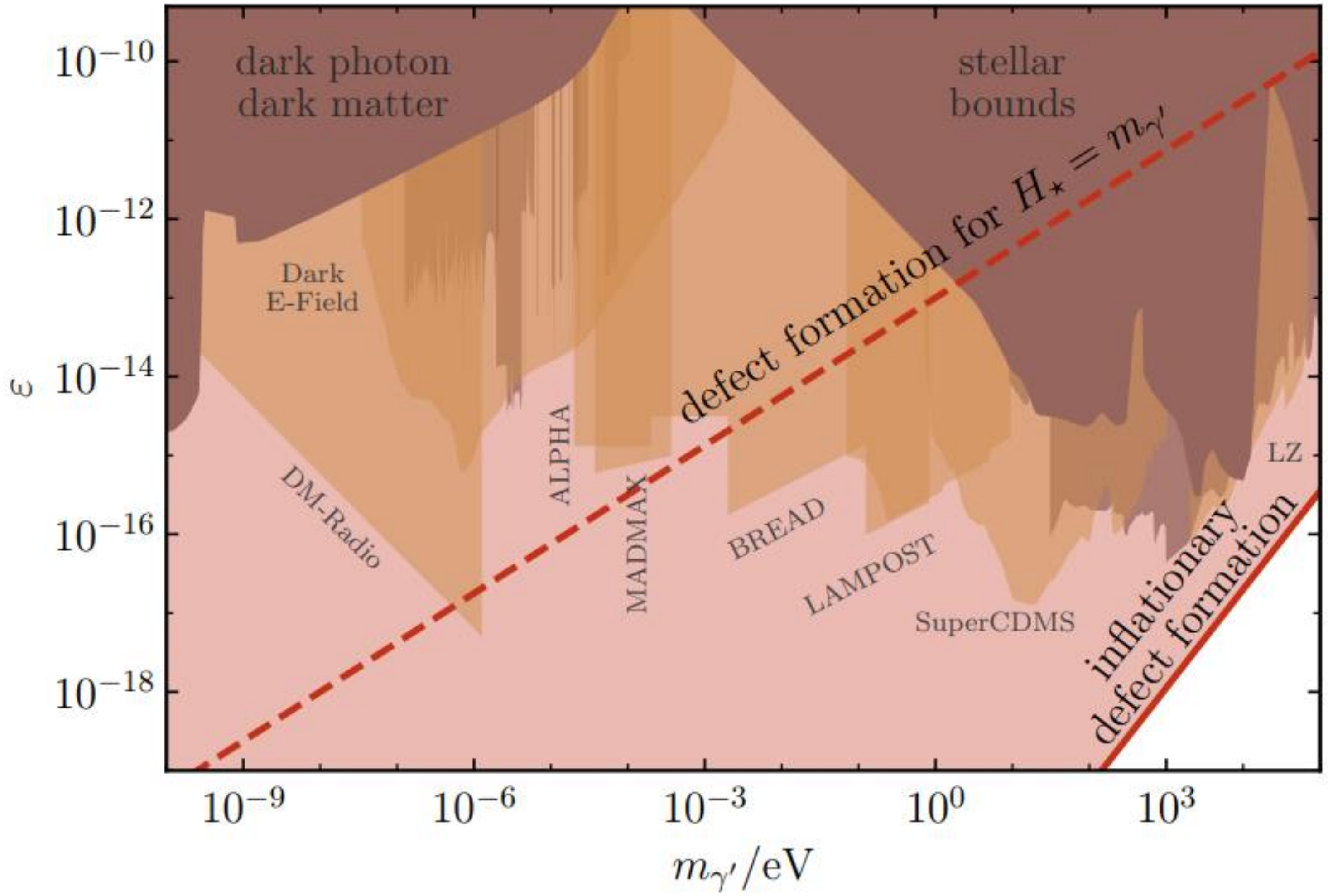
Cosmic string from superradiance





East and Huang, 2206.12432

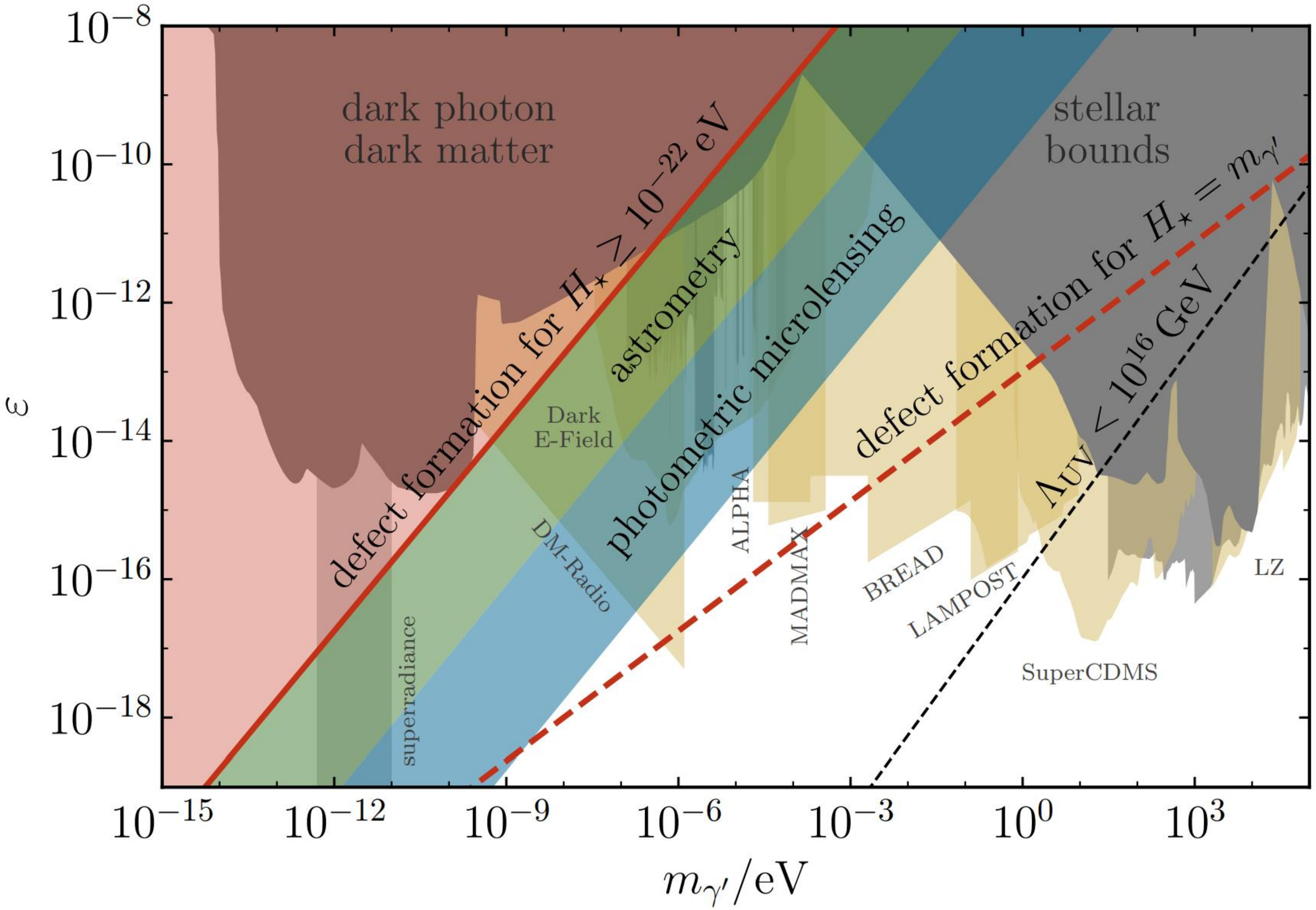
Constraints on Higgsed DPDM



$$\varepsilon \sim e g_D / 16\pi^2$$

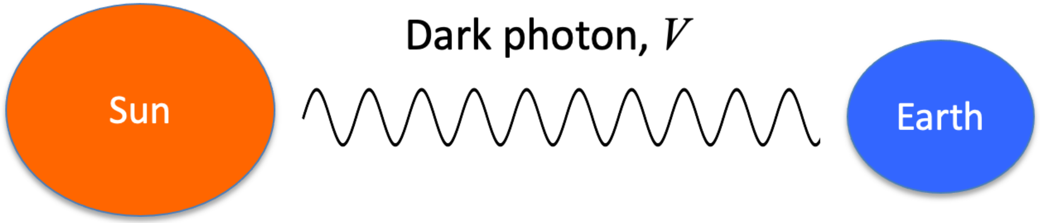
Time dependent couplings and mass

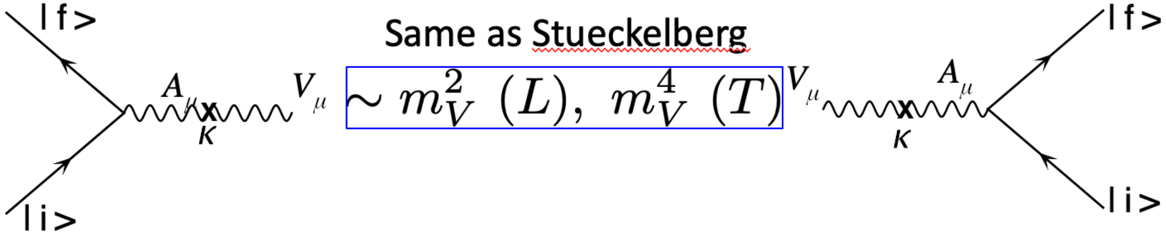
Cyncynates, Weiner, 2310.18397



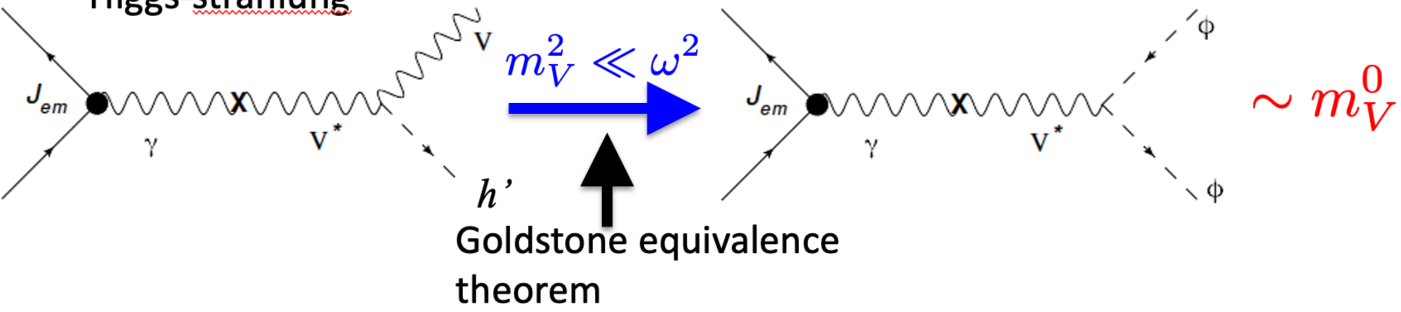
$$\mathcal{L} = -\frac{W(\phi)}{4} F_{\mu\nu} F^{\mu\nu} + \frac{X(\phi)}{2} D_\mu \Phi \left(D^\mu \Phi\right)^* + Y(\phi) V_\Phi(\Phi) + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi).$$

Stellar bound for Higgsed case



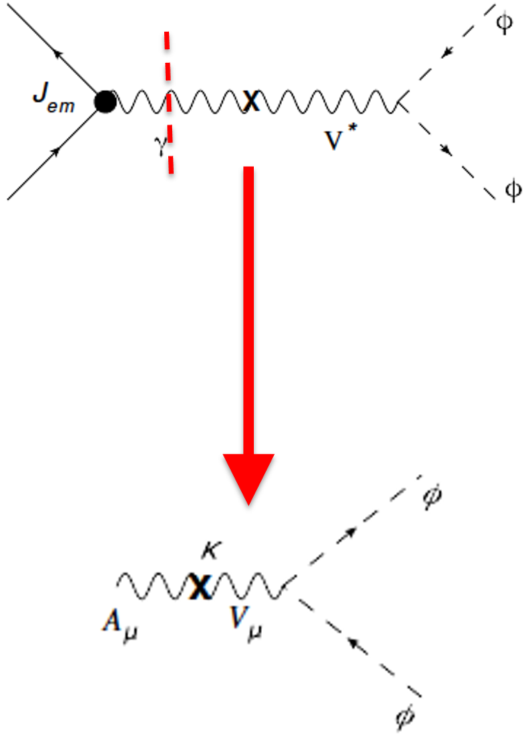


Higgs-strahlung

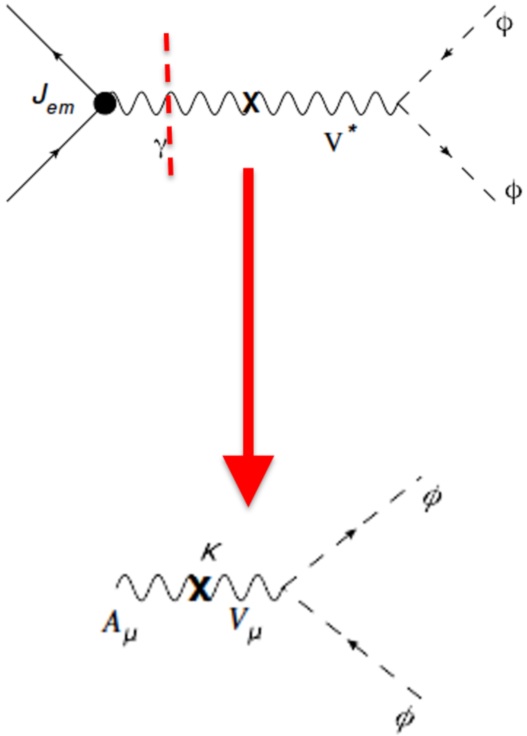


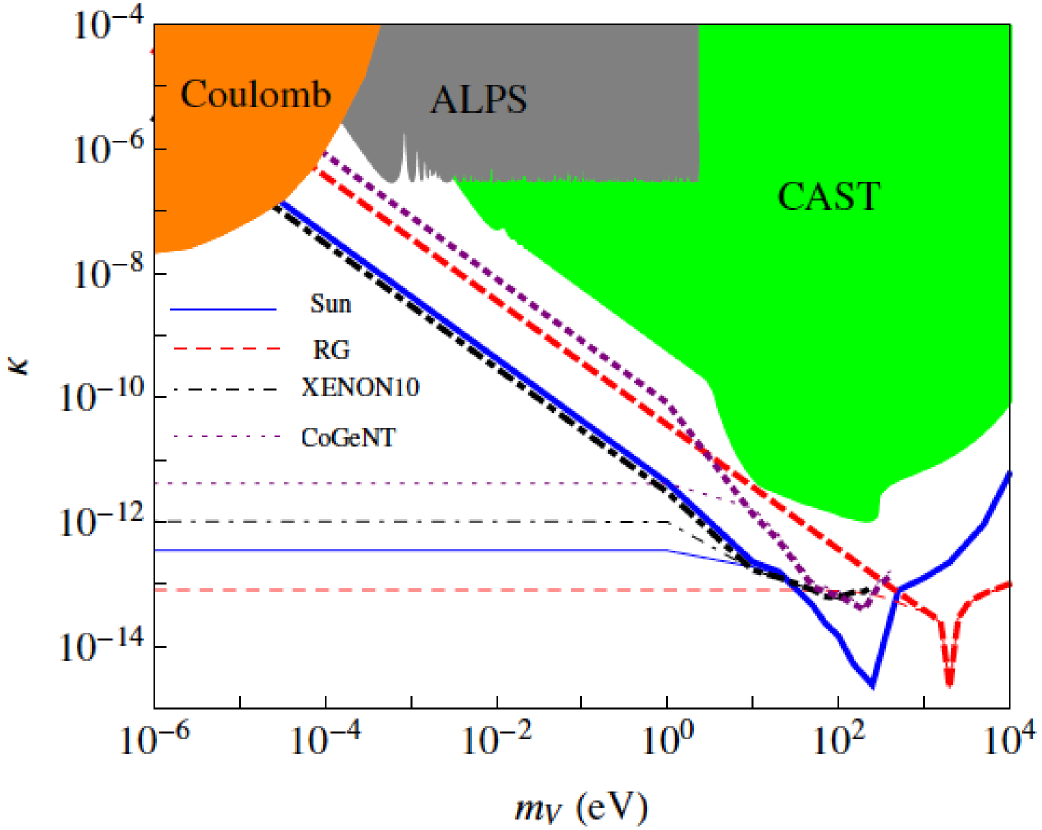
- Higgs-strahlung

Dominant, $m_V \ll \omega_p$,
subdominant, $m_V \sim \omega_p$.



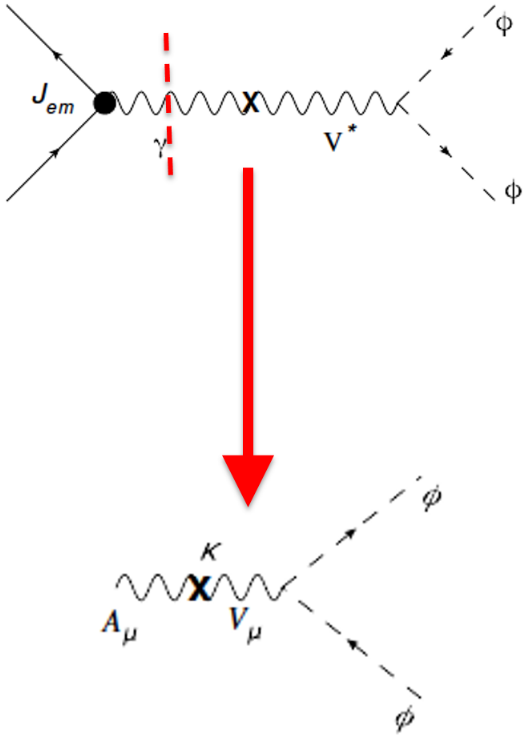
Stellar bound for Higgsed case

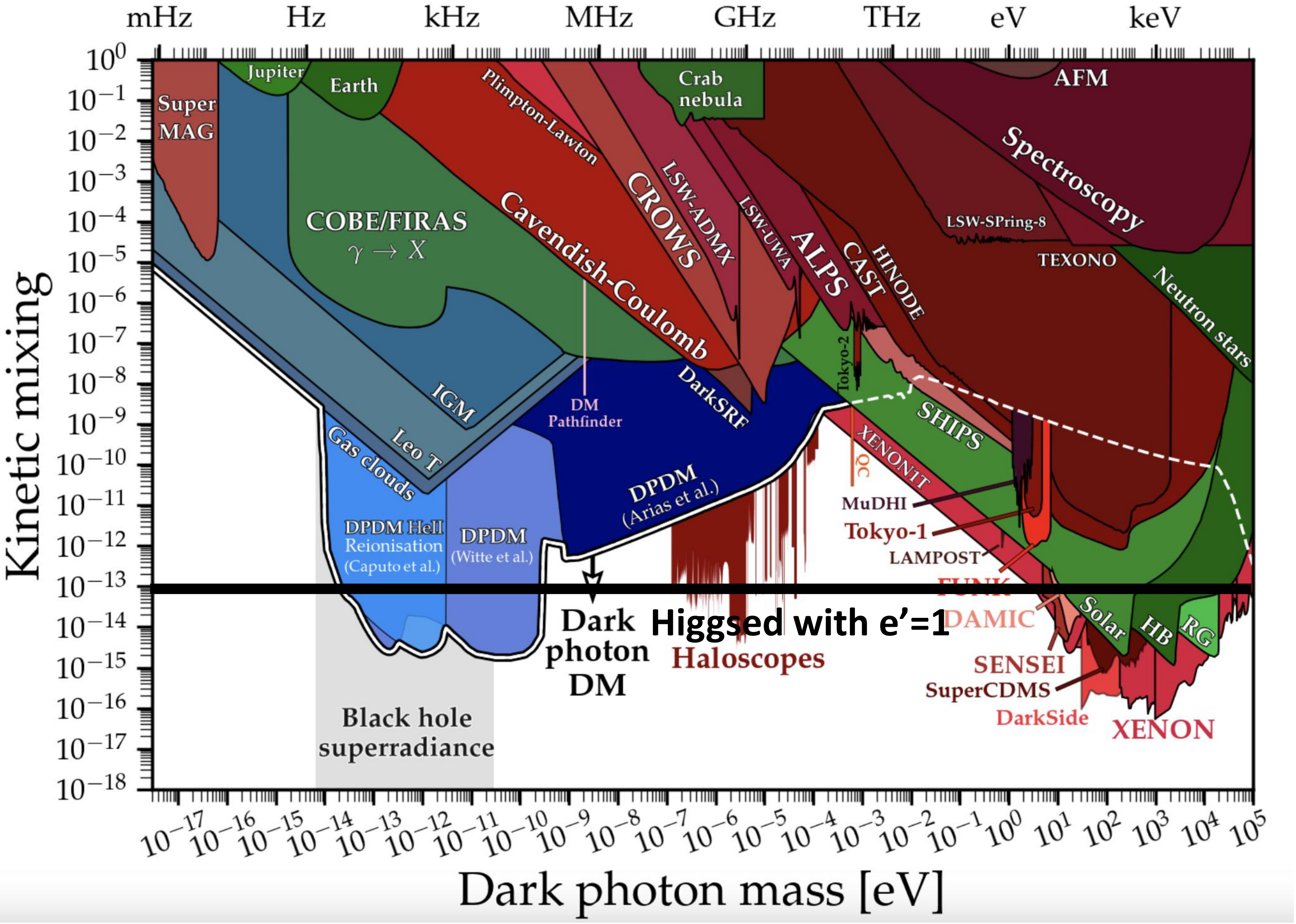




HA, Maxim Pospelov, Josef Pradler, PRL 111 (2013) 041302, 1304.3461

Stellar bound for Higgsed case





Summary

- A lot of searches and model buildings are going on.
- For Higgsed DPDM, it is challenging to find a production mechanism.
- For the Stuckelberg case, there are models that can produce DPDM.
- The scalar parametric resonant model does not care if the DPDM is Higgsed or Stueckelberg.