Searching for dark photon dark matter using radio technology

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CTPU-CKC Joint Focus Program:

Let there be light (particles) Workshop

Dec. 2-6, 2024 @ IBS

2405.12285 with Shuailiang Ge, Jia Liu, Mingzhe Liu
2301.03622 with Xingyao Chen, Shuailiang Ge, Jia Liu, Yan Luo
2207.05767 with Shuailiang Ge, Wen-Qing Guo, Xiaoyuan Huang, Jia Liu, Zhiyao Lu
2010.15836 with Fa Peng Huang, Jia Liu, Wei Xue

Outline

- Basic dark photon models
- Searching for dark photon dark matter (DPDM) resonant conversion in solar plasma
- Searching for DPDM directly using radio telescopes
- DPDM production mechanisms
- Summary

Dark photon models

- The simplest dark photon model

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

- 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

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_{A'}^2 \left(A'_\mu - \frac{\partial_\mu a}{m_{A'}} \right)^2$$

Would-be goldstone

- Should there be a dark Higgs?

Stueckelberg case

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_{A'}^2 A'^{\,2}_\mu$$

Higgsed case

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} m_{A'}^2 A'^2_\mu + e_D m_{A'} A'_\mu A'^\mu h_D + e_D^2 A'_\mu A'^\mu h_D^2$$

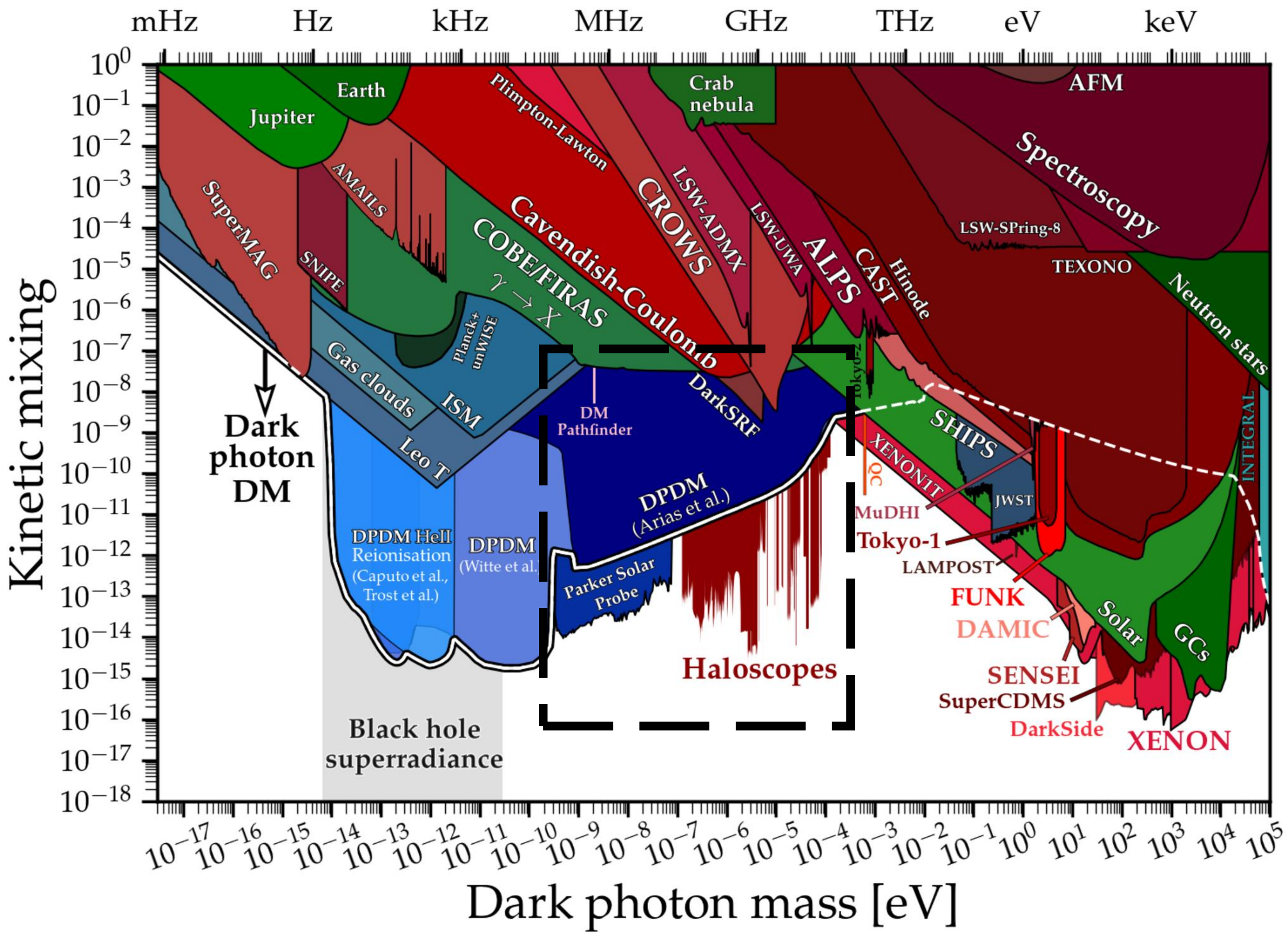
Diagonalization

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

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

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

Searches for dark photon



Photon Dark Photon Oscillation in plasma

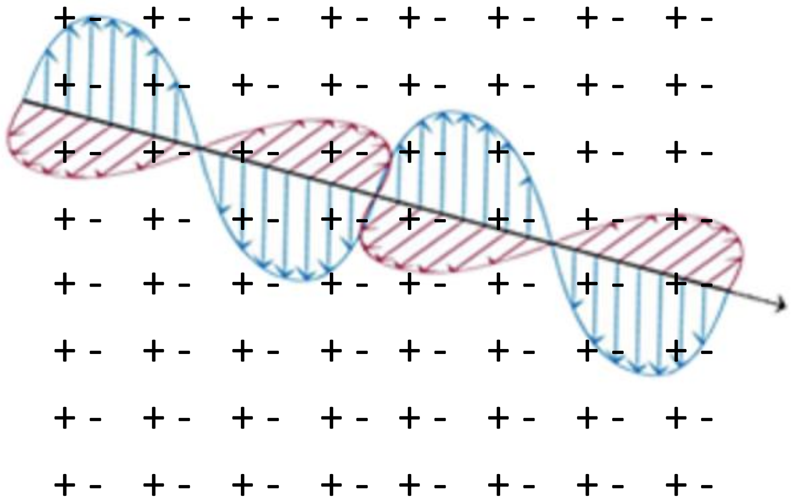
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + eA_\mu J^\mu - \epsilon e A'_\mu J^\mu$$

A'_μ and A_μ are in mass eigenstate.

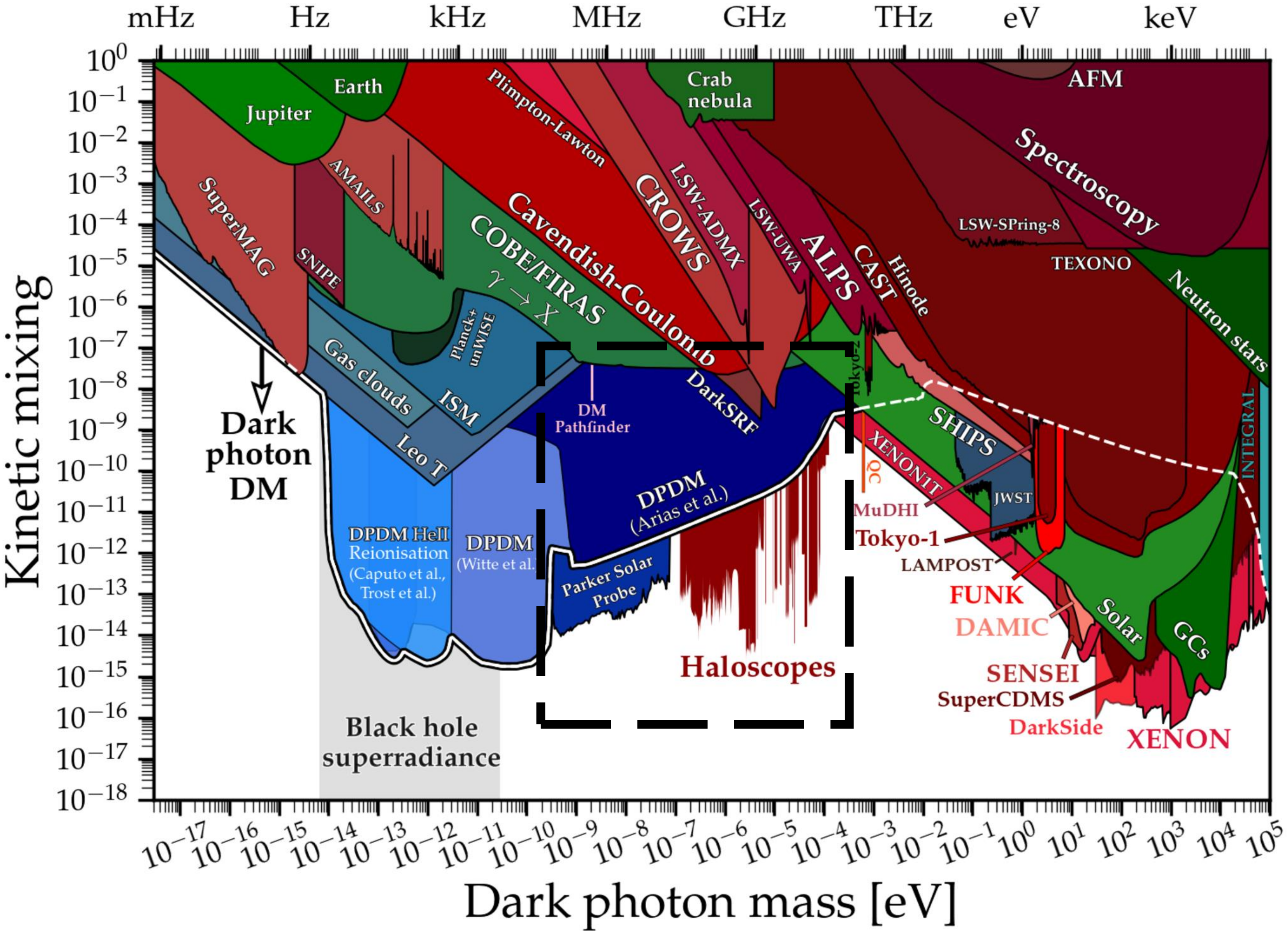
- In the vacuum, A' cannot be converted into A, no interaction
- In the plasma,

(1) a mixing between A' and A is generated

(2) a mass for A is also generated.

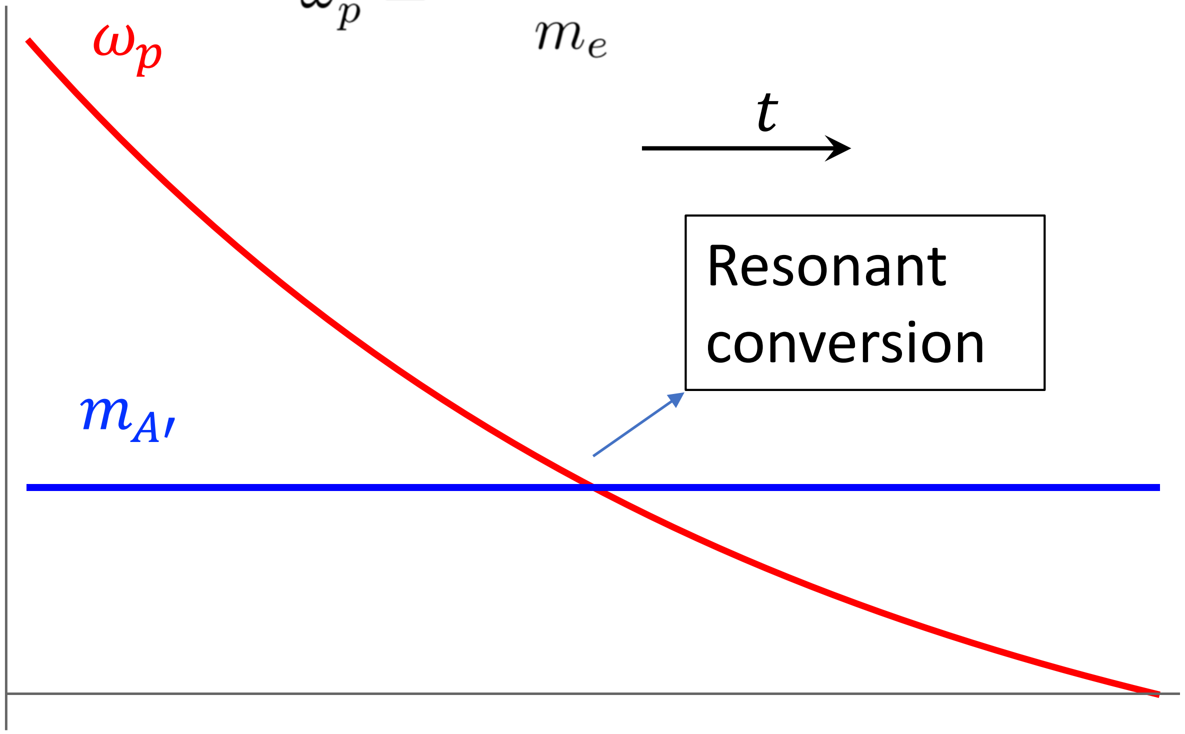


Searches for dark photon



CMB constraints from distortion

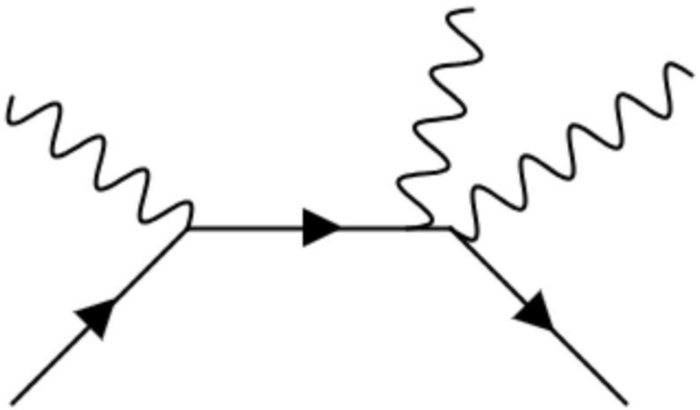
$$\omega_p^2 = \frac{4\pi\alpha_{\rm EM} n_e}{m_e}$$



- 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.



CMB constraints from distortion

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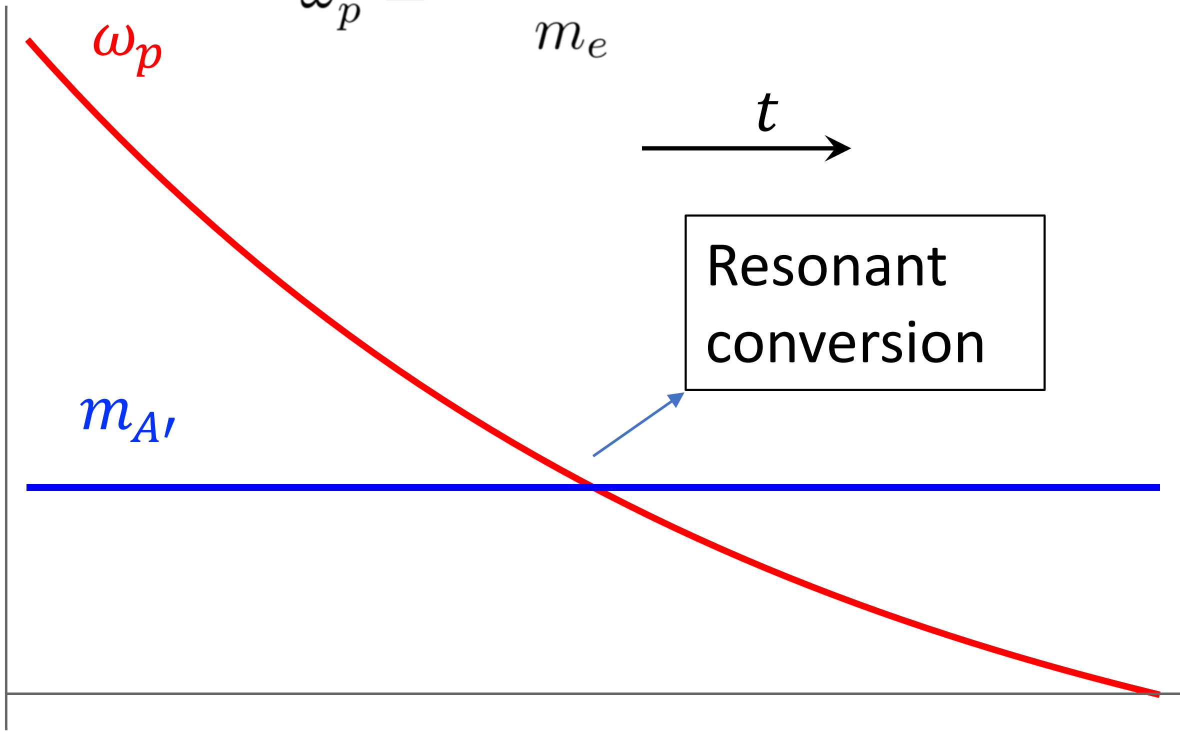


- Why the constraint is flat?

Jaeckel, Redondo, 0804.4157

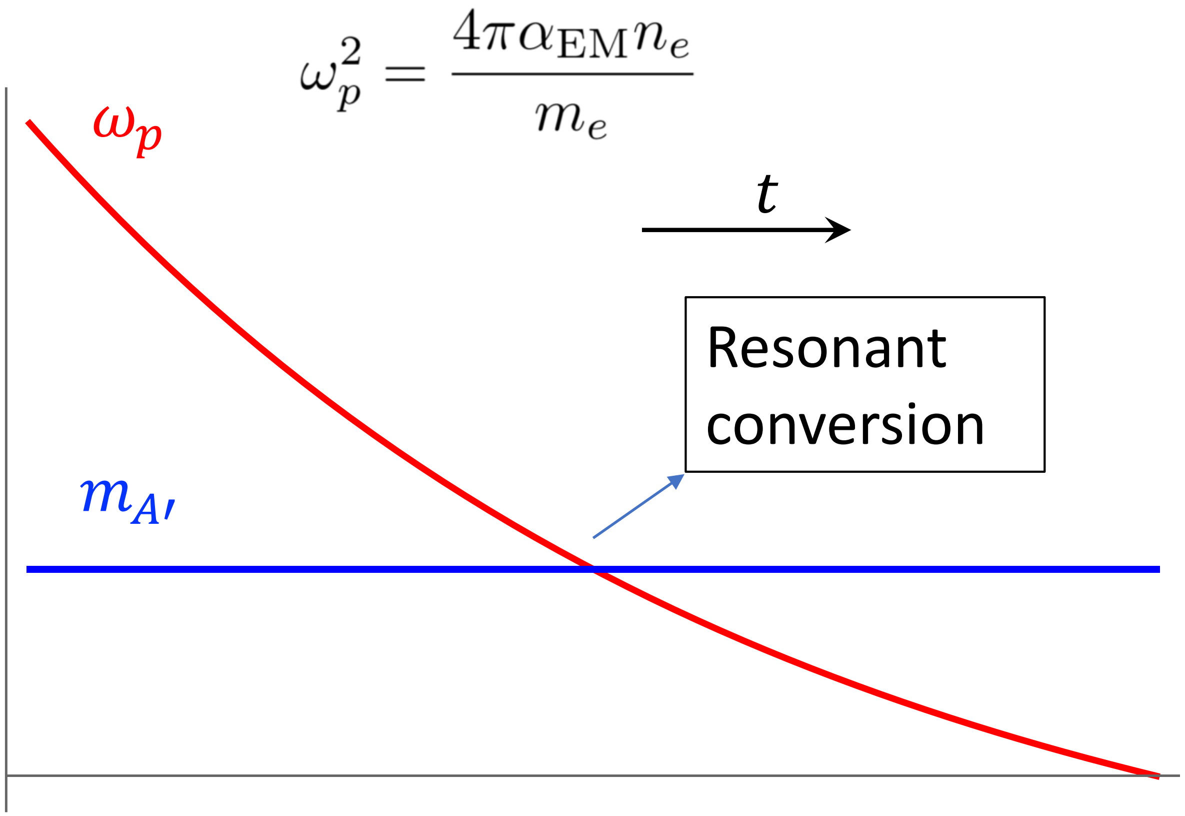
$$\mathcal{M} = \epsilon m_{A'}^2 \varepsilon_\mu \epsilon_{A'}^\mu (2\pi)^4 \delta^4(k^\mu - k'^\mu)$$

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

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

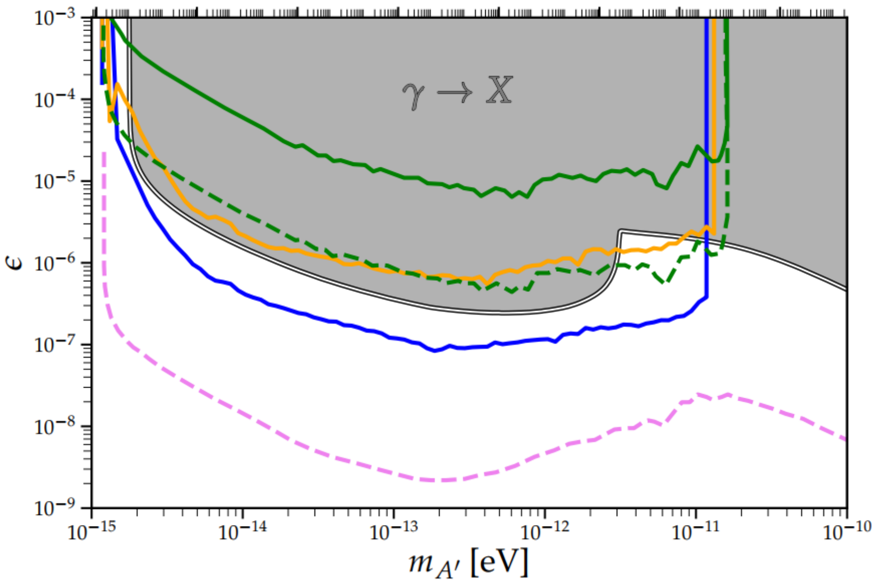
$\sim Hubble^{-1}$

CMB constraints from anisotropy

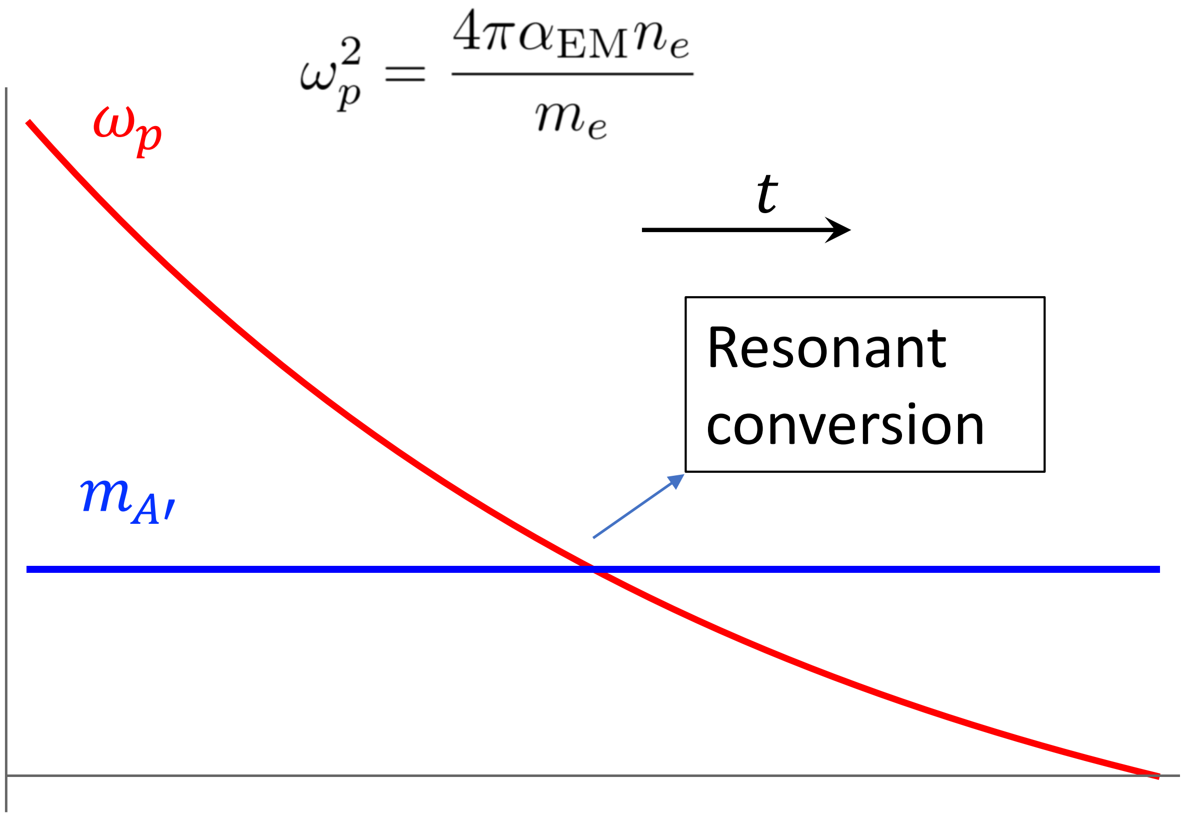


- Enhance the CMB temperature anisotropy. Aramburo-Garcia et al, 2405.05104

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



CMB constraints from anisotropy



- 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.

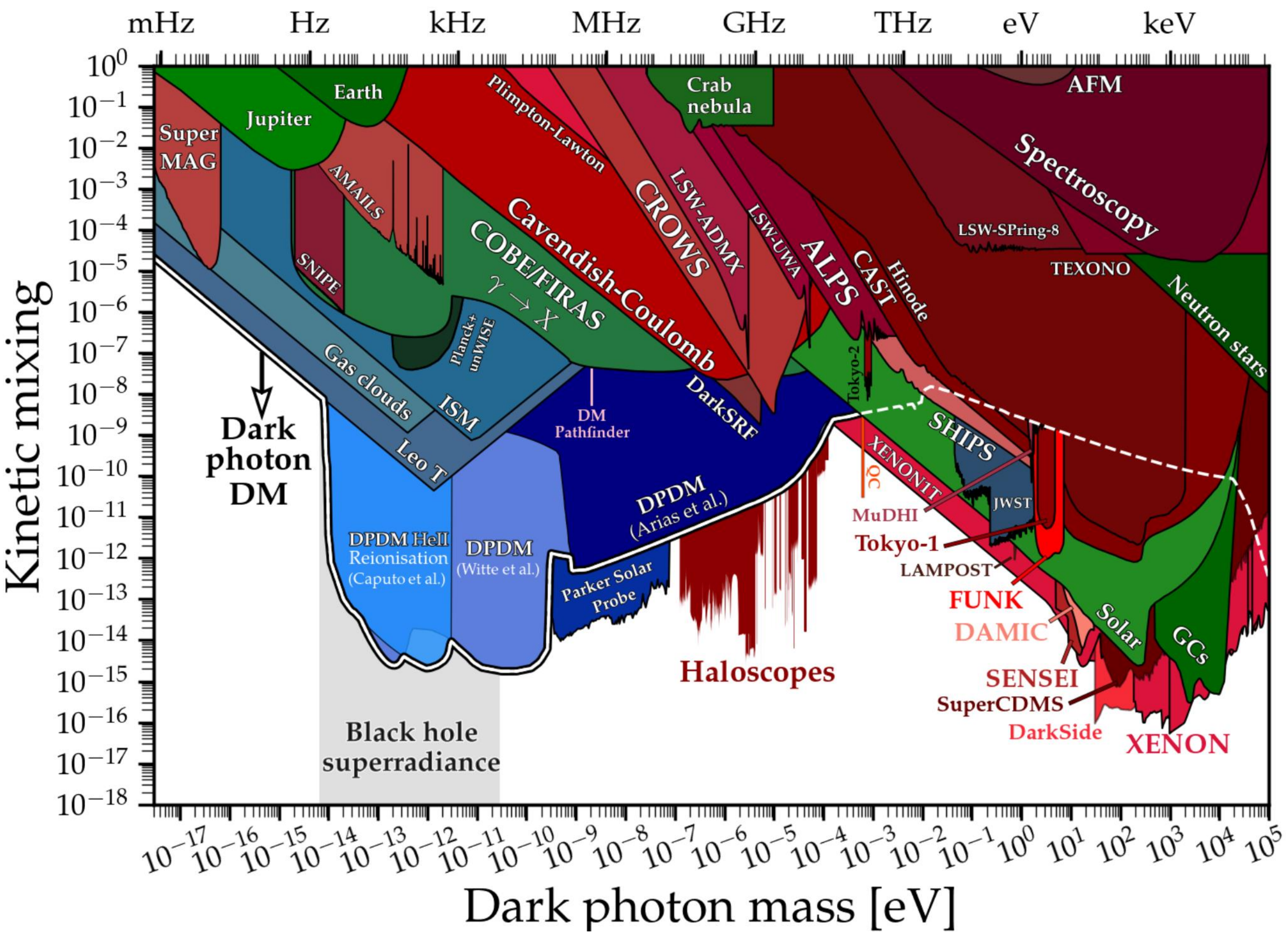
This leads to the correlation between the induced CMB anisotropy and the large scale structure.

Searching for dark photon dark matter

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

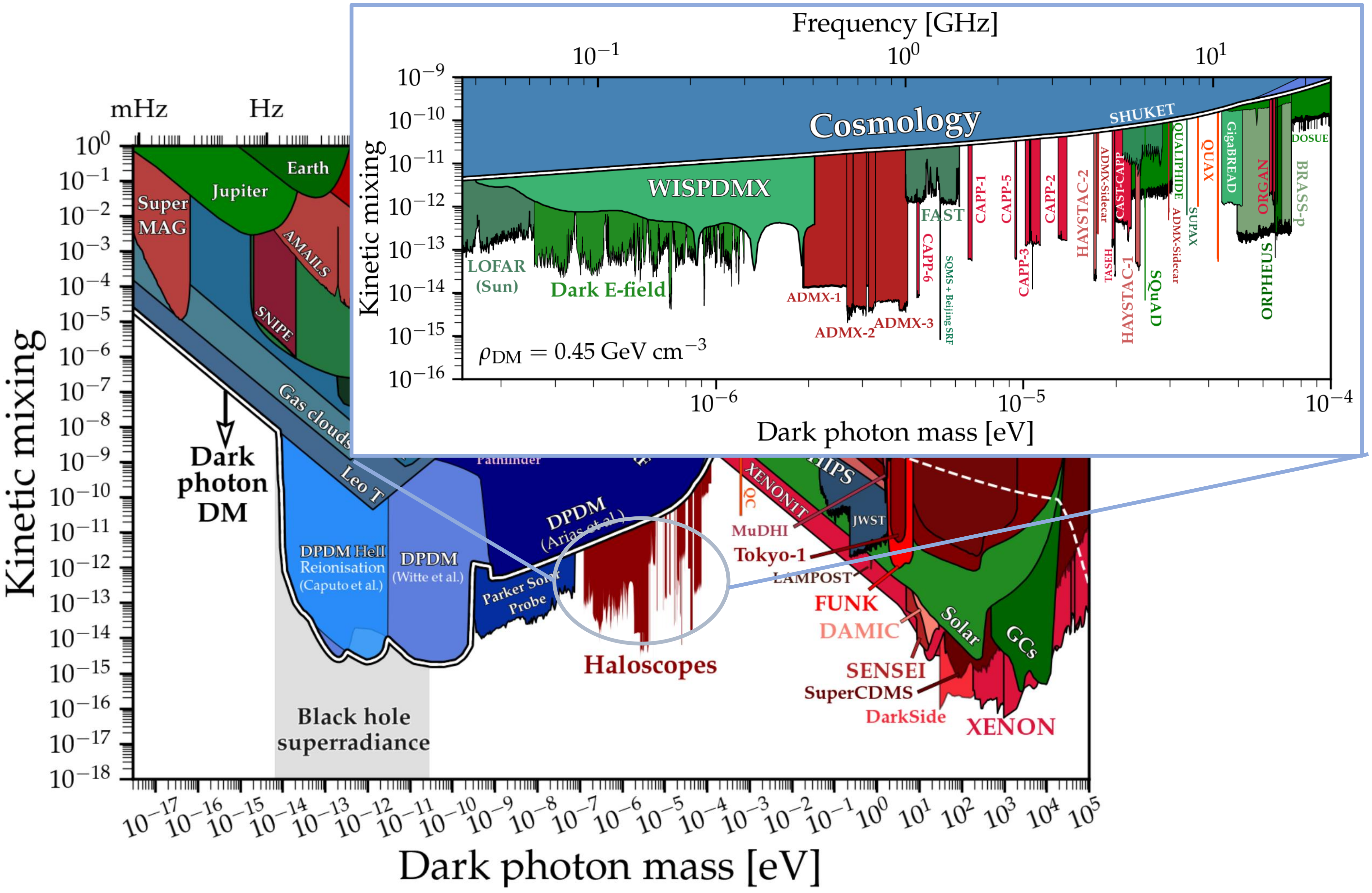
$$\Gamma_{A'\to 3A} \sim \frac{\epsilon^2 m_{A'}^9}{m_e^8} \qquad \Gamma_{A'\to \nu\nu} \sim \frac{\epsilon^2 m_{A'}^5}{m_Z^4}$$

Searching for dark photon dark matter



longer than the age of

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



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
DOSUE
SQuAD
$\rho_{DM} = 0.45$ 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
XENON1T
HIPS
JWST
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
DarkSide
XENON
Solar
GCs
Black hole superradiance

Photon Dark Photon Oscillation

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

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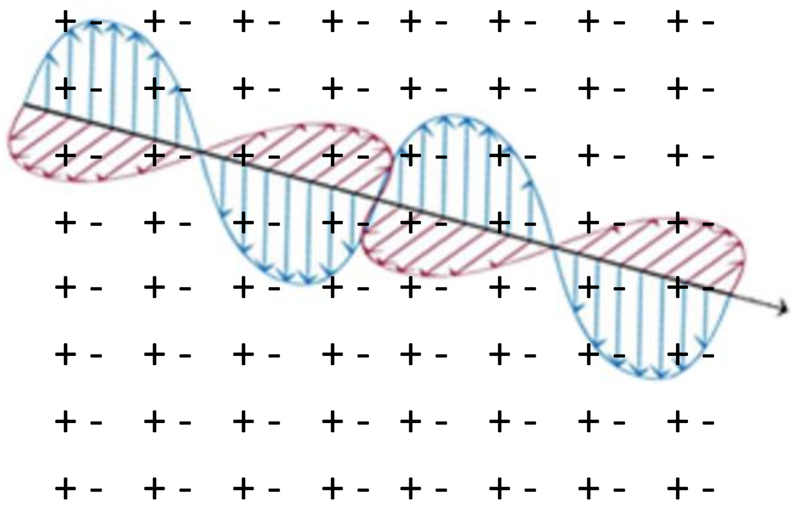
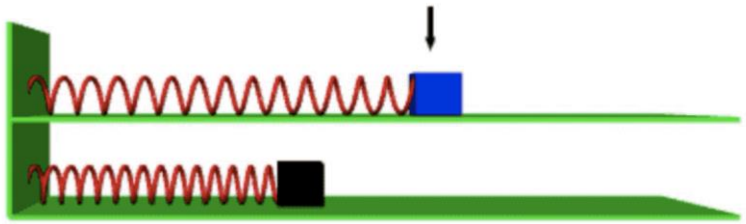
- In the plasma, (1) a mixing between A' and A is generated. (2) a mass for A is also generated.



Photon Dark Photon Oscillation

$$\begin{pmatrix} A_T & A'_T \end{pmatrix} \begin{pmatrix} \mathbf{k}^2 + \omega_p^2 & \epsilon\omega_p^2 \\ \epsilon\omega_p^2 & \mathbf{k}^2 + m_{A'}^2 \end{pmatrix} \begin{pmatrix} A_T \\ A'_T \end{pmatrix}$$



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

- When $\omega_p = m_{A'}$, photon and dark photon resonantly convert into each other.

Photon dark photon oscillation

- The transition probability

$\omega_p^2 = m_V^2$

$$P_{A'\to\gamma}(v_r) = \int \frac{\mathrm{d}t}{2\omega}\frac{\mathrm{d}^3p}{(2\pi)^3 2\omega}(2\pi)^4\delta^4\left(p^\mu_{A'} - p^\mu_\gamma\right)\,\frac{1}{3}\sum_{\mathrm{pol}}|\mathcal{M}|^2$$

$$= \frac{2}{3}\times\pi\,\epsilon^2\,m_{A'}\,v_r^{-1}\left|\frac{\partial\ln\omega_p^2(r)}{\partial r}\right|^{-1}_{\omega_p(r)=m_{A'}}$$

Average of polarization

Size of the resonant region

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

Searching for ultralight DM with radio telescopes

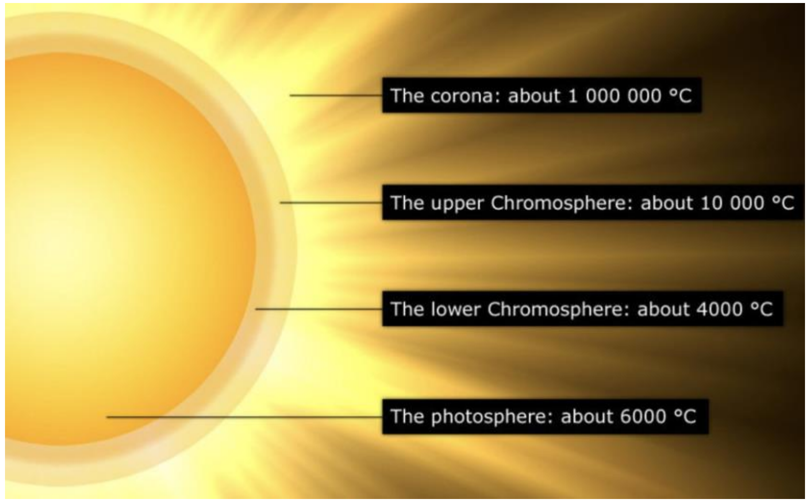
- For dark photon:

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

- For photon in plasma:

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

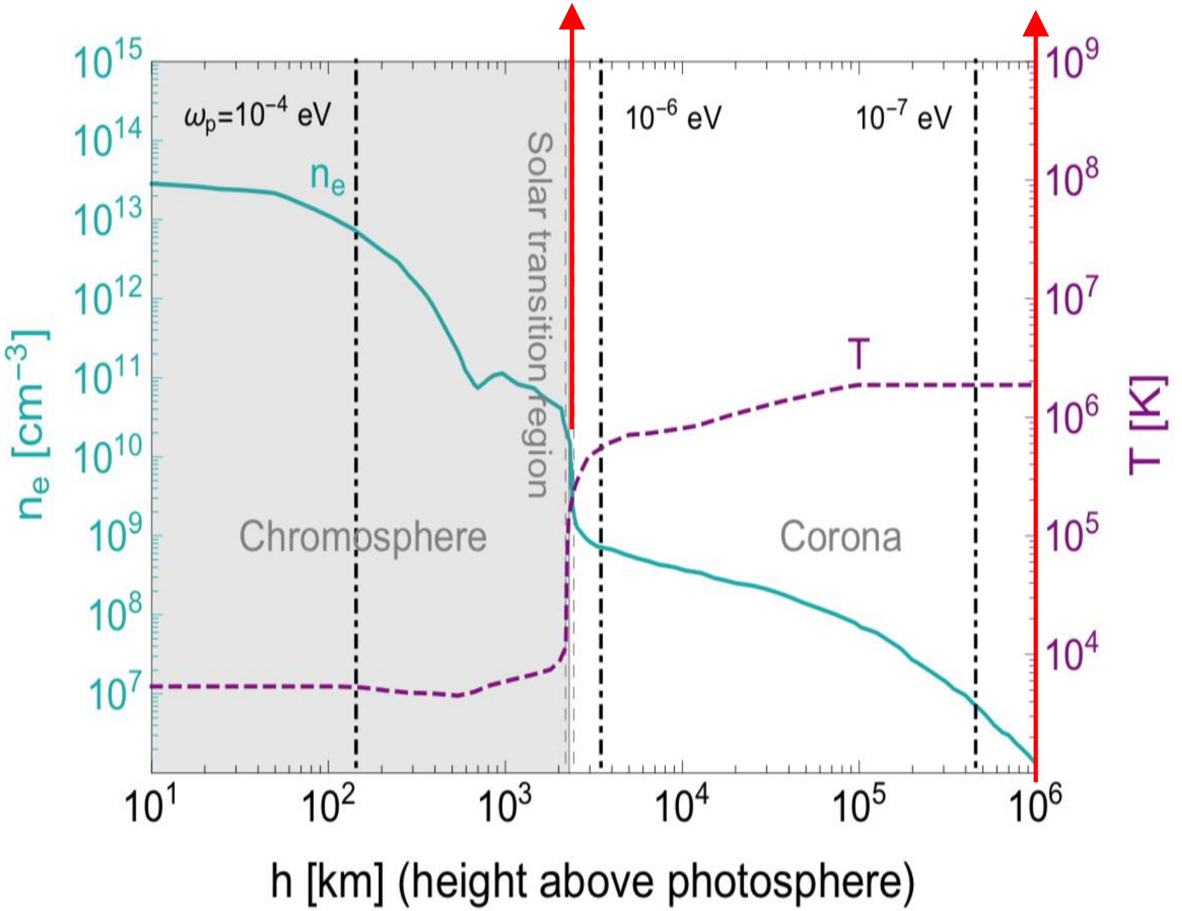
- We need plasma.



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

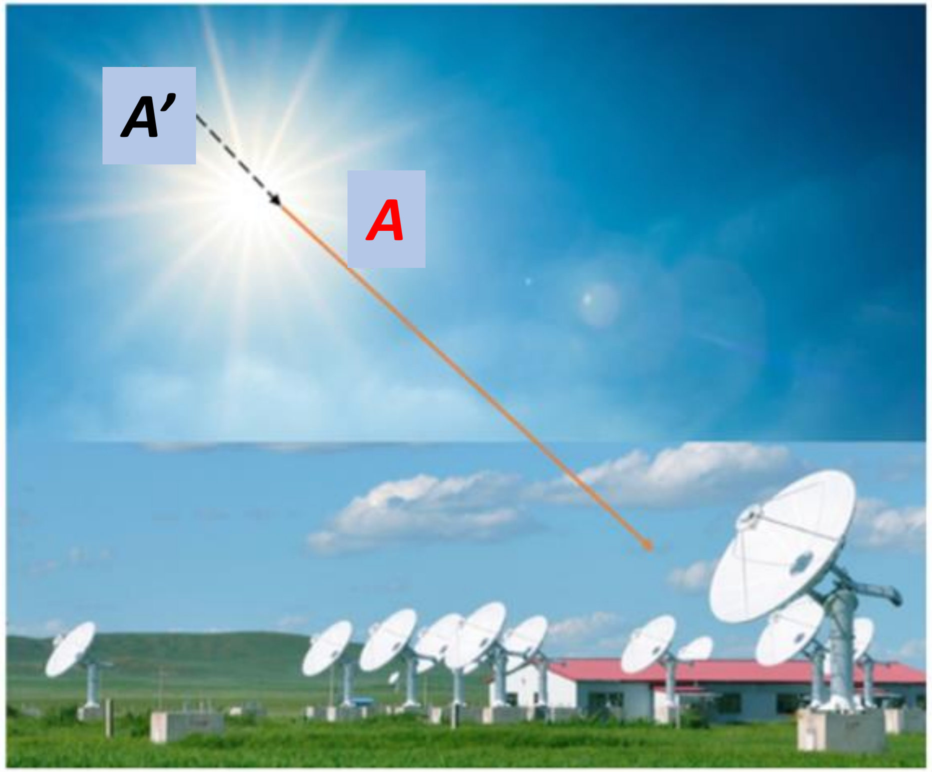
$f = 1$ GHz

$f = 10$ MHz



Dark photon dark matter converted at the Sun's atmosphere

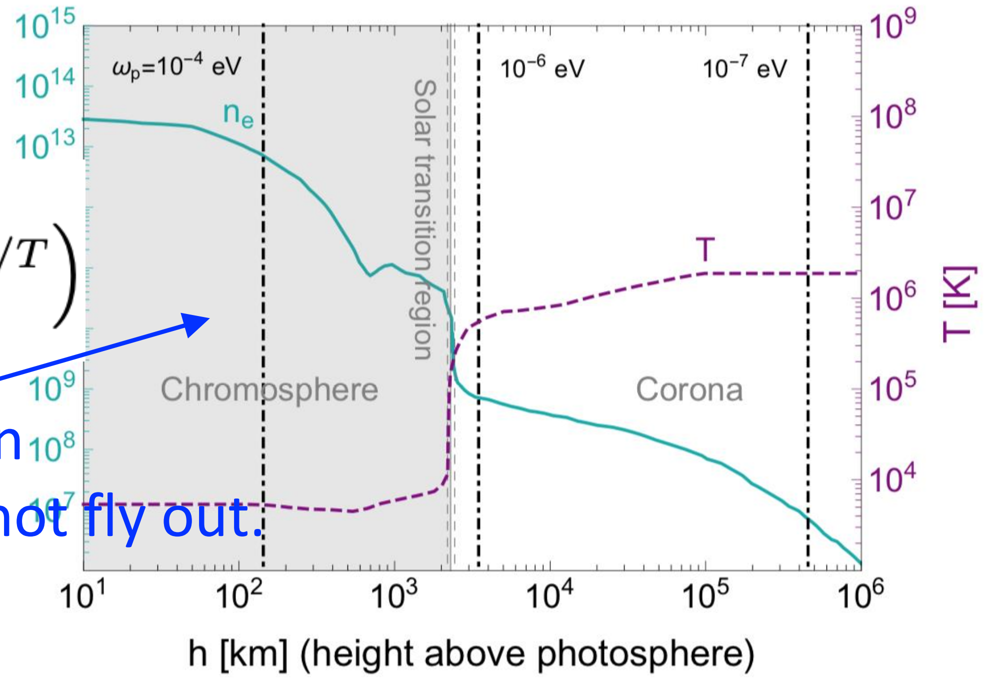
- Resonant conversion
  - $\omega_p = m_{A'}$
- Inside the dark matter halo
  - $v_{DM} \sim 10^{-3}$
- The frequency of the converted photon $\omega \approx m_{A'}$ with the dispersion $\sim 10^{-6}$.
- The signal is a sharp peak in the solar spectrum



Absorption of the converted photon during propagation

- Inverse bremsstrahlung absorption

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



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

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

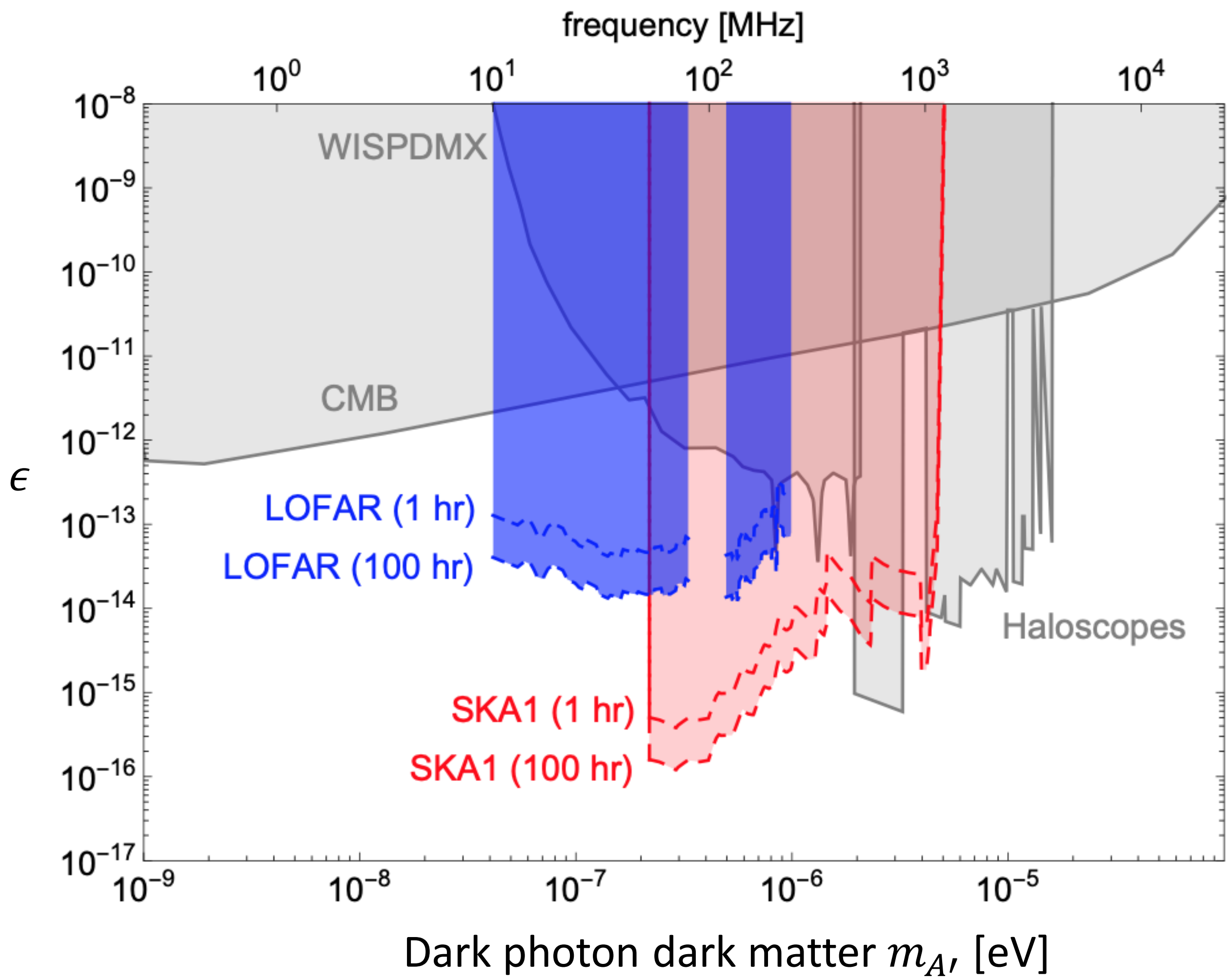
$$\mathrm{SEFD} = 2k_B \frac{T_{\rm sys} + T_{\odot}^{\rm nos}}{A_{\rm eff}}$$

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

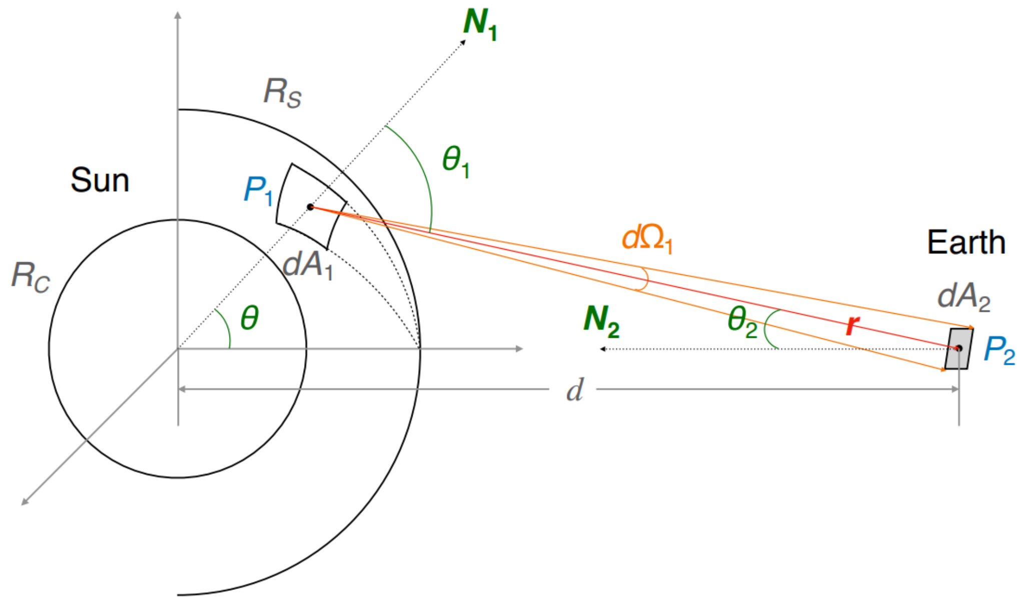
Searching for DPDM with radio telescopes

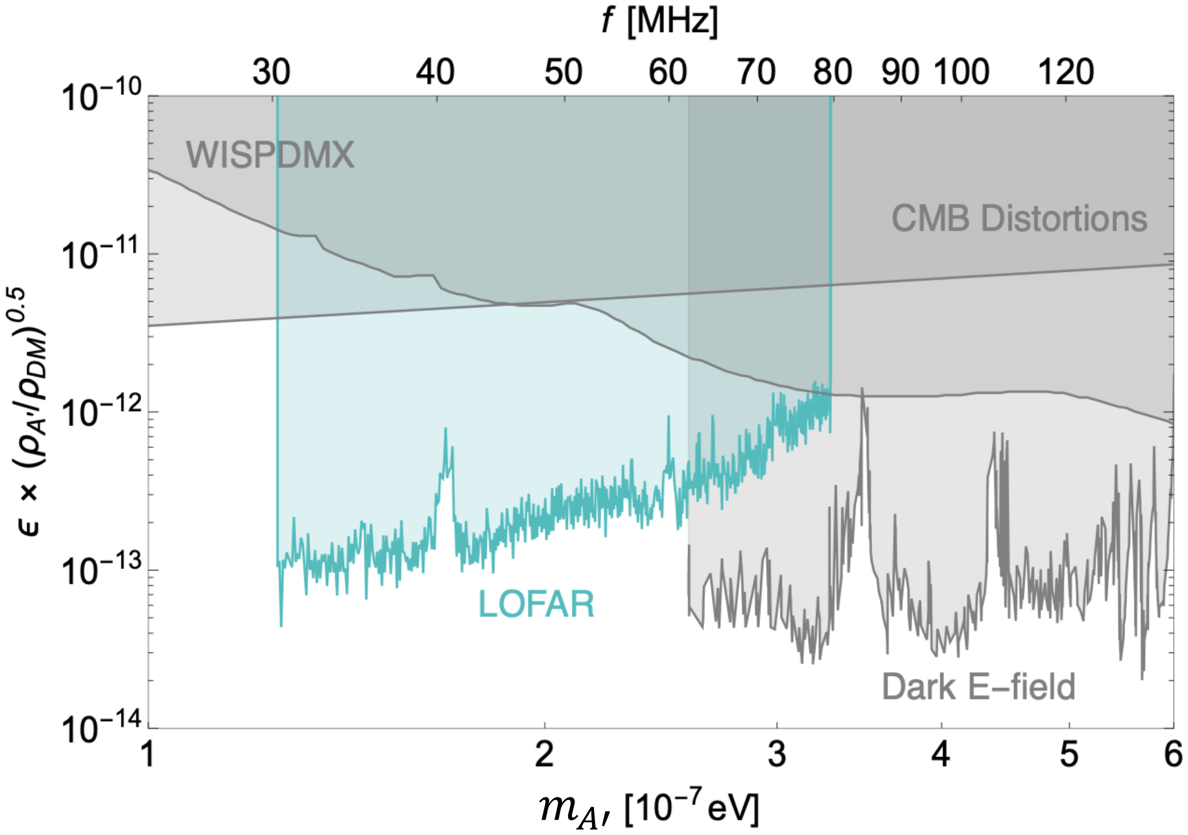


HA, F.P. Huang, J.Liu, W.Xue, Phys.Rev.Lett. 126 (2021) 181102

Searching for DPDM in LOFAR

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

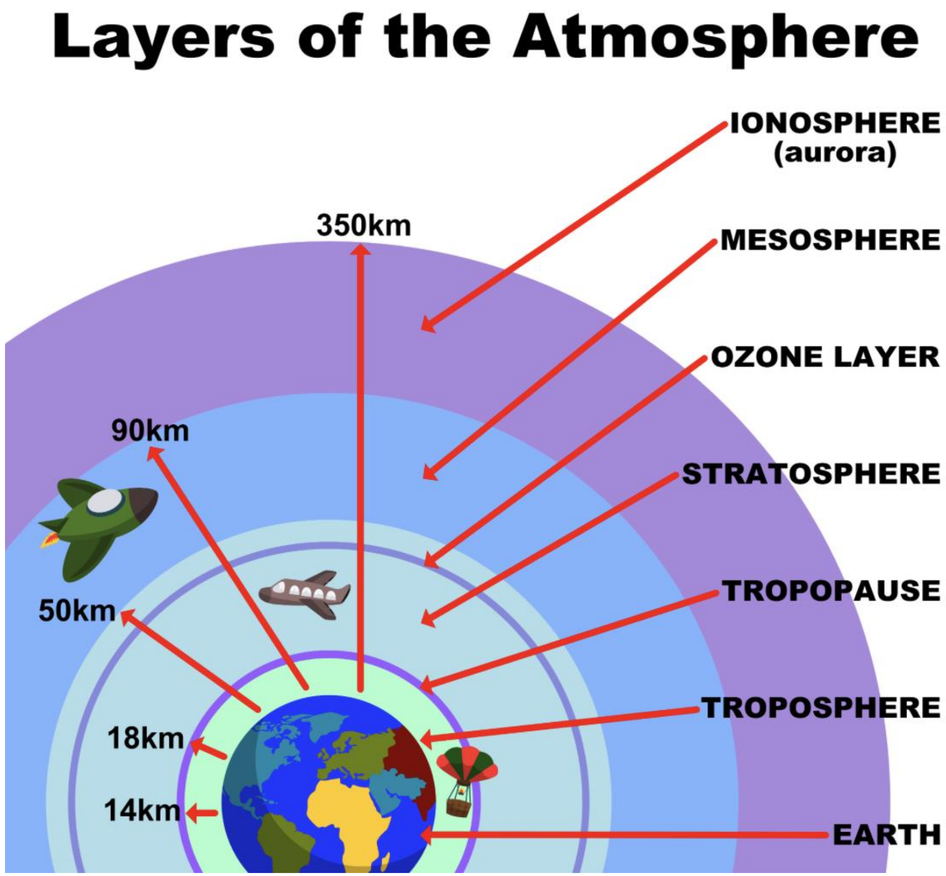




HA, X. Chen, S. Ge, J. Liu, Y. Luo, 2301.03622, Nature Communications 15 (2024) 1, 915

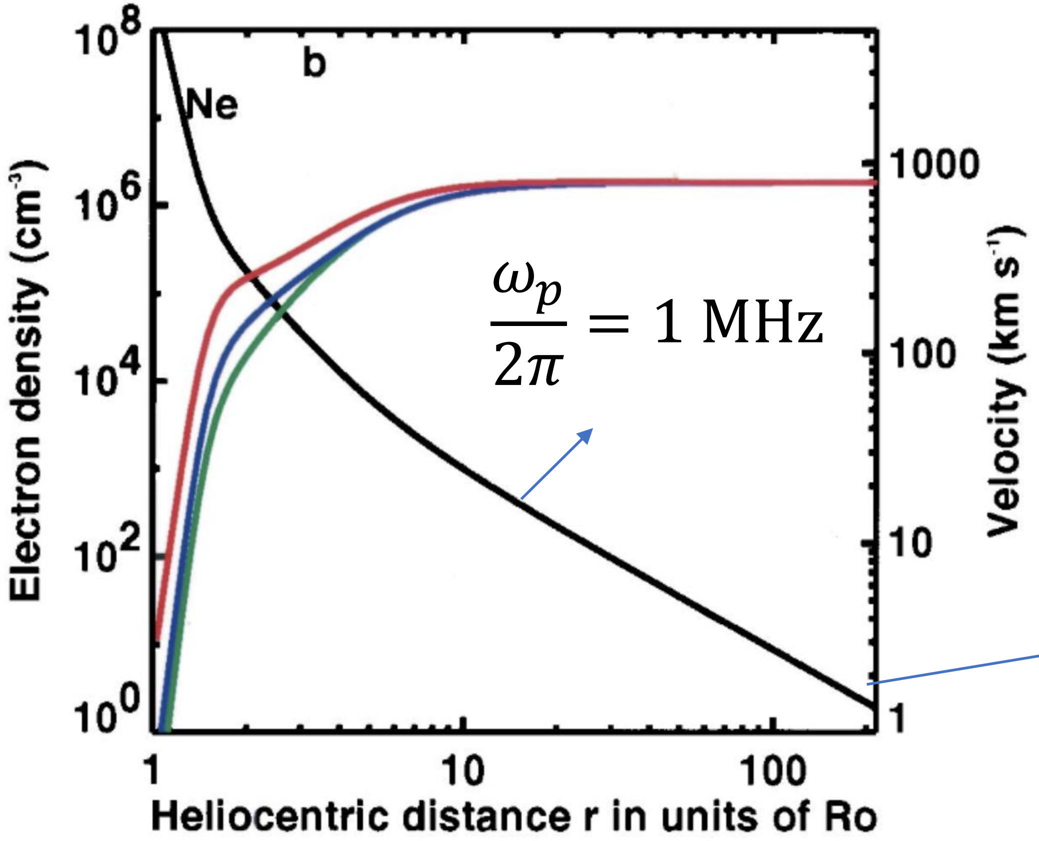
For dark photon dark matter with smaller mass

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



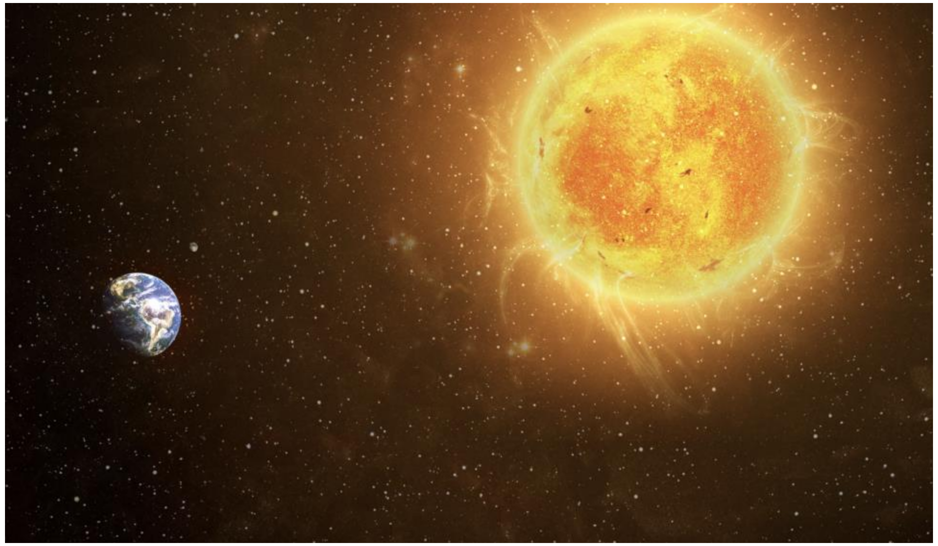
Plasma in solar wind

- Free electrons between Earth and Sun



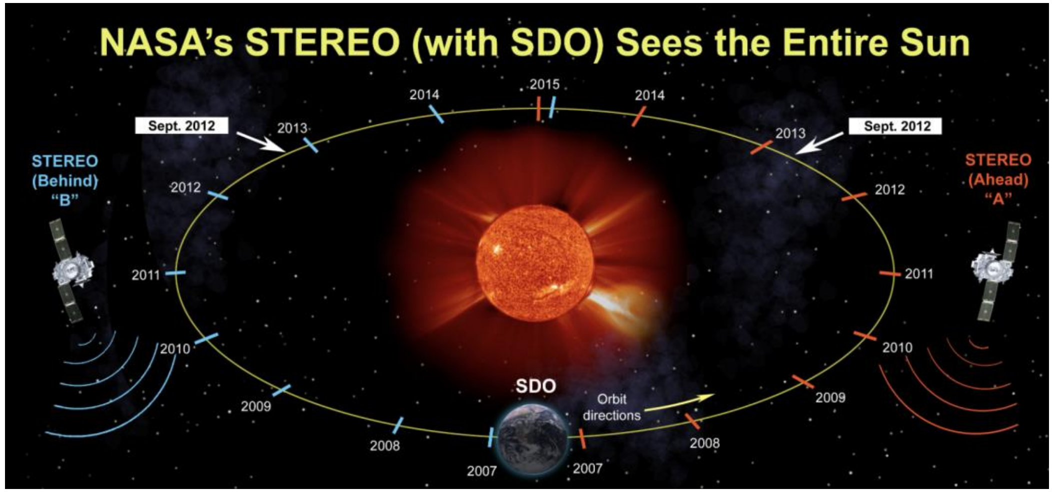
$$\frac{\omega_p}{2\pi} = 1 \text{ MHz}$$

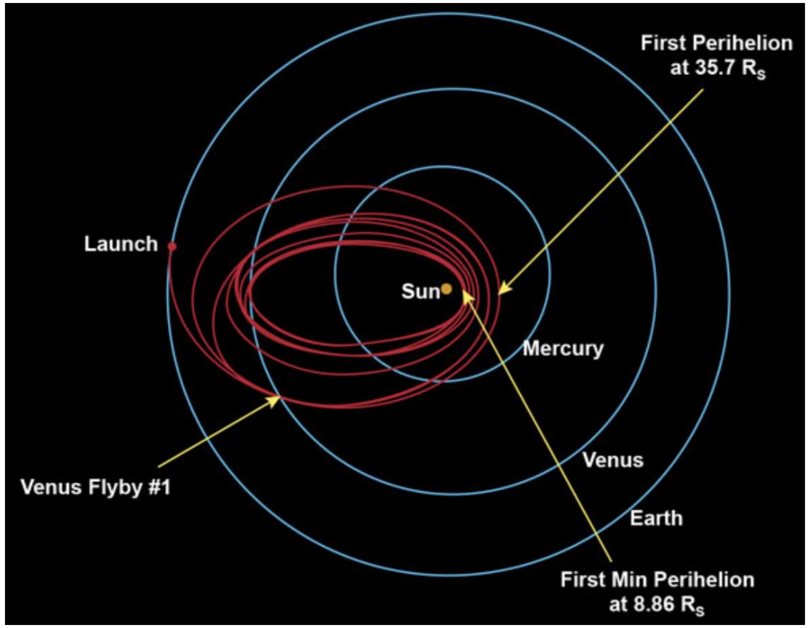
$$\frac{\omega_p}{2\pi} = 20 \text{ kHz}$$



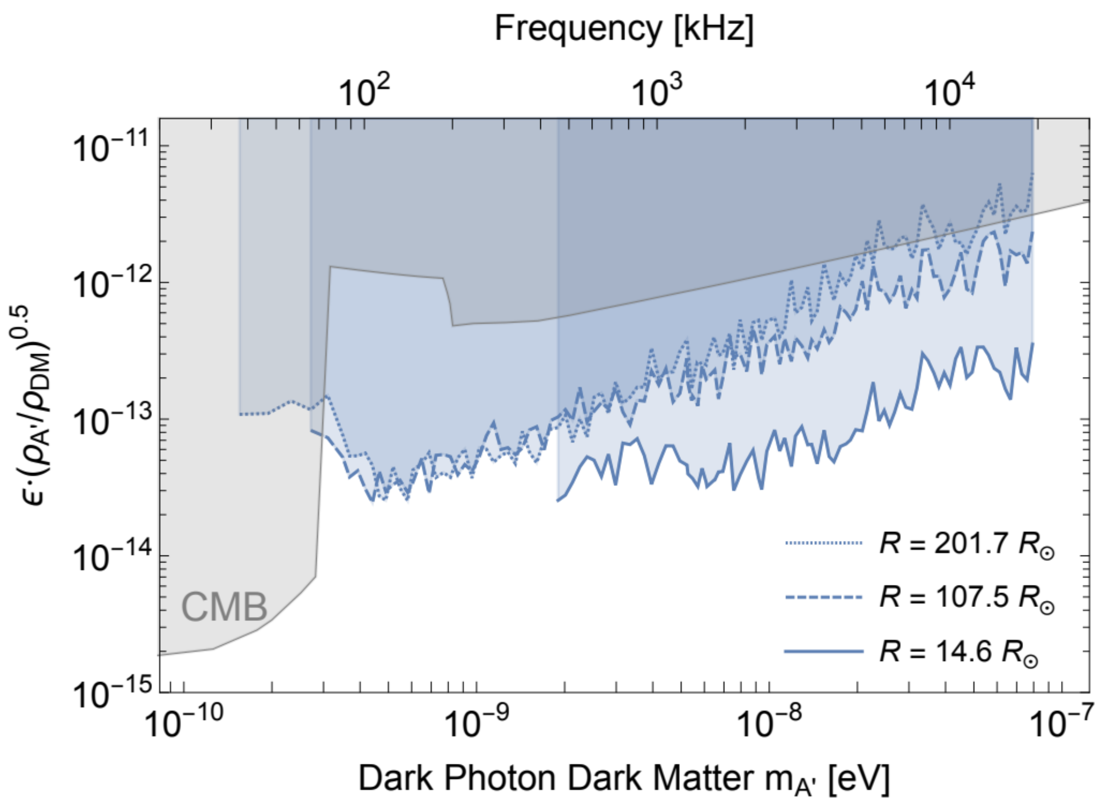
For dark photon dark matter with even smaller mass

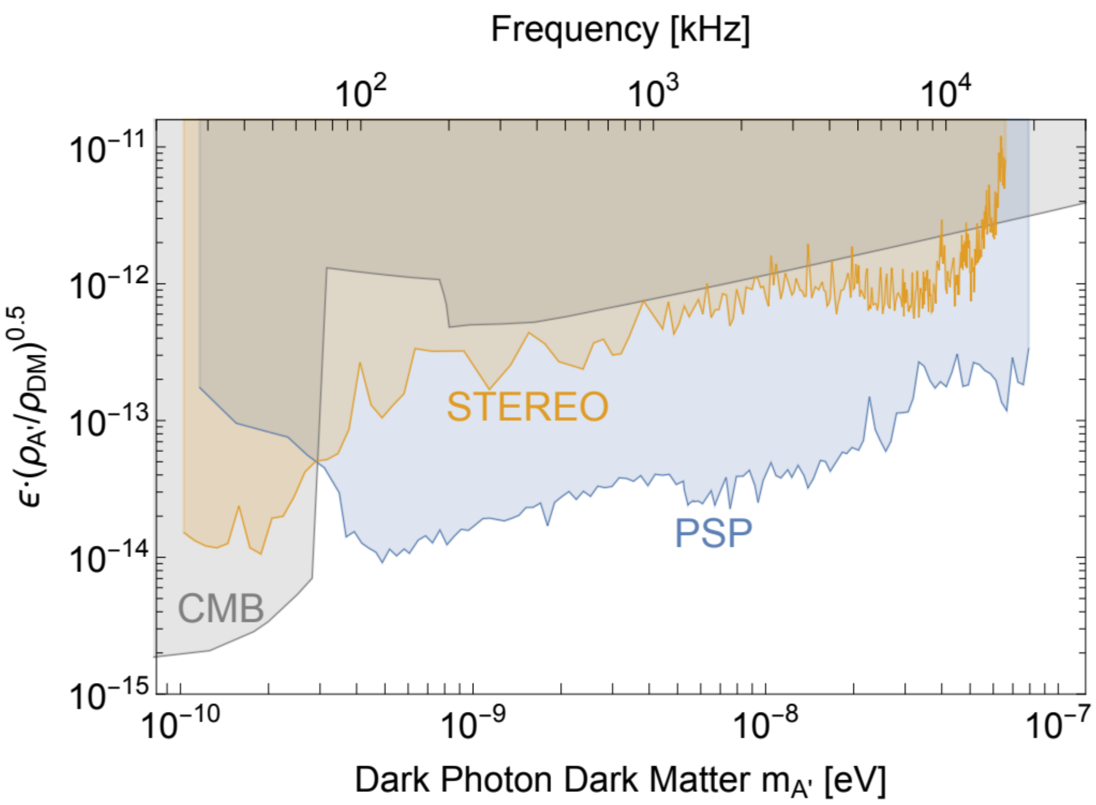
- STEREO A/B
- Parker Solar Probe





Using solar probes to search for DPDM



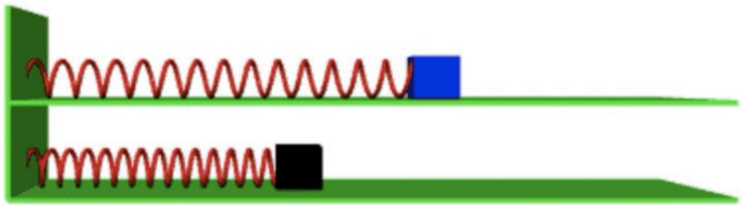


HA, Shuailiang Ge, Jia Liu, Mingzhe Liu, arXiv: 2405.12285

Dark photon in plasma

Plasma effect

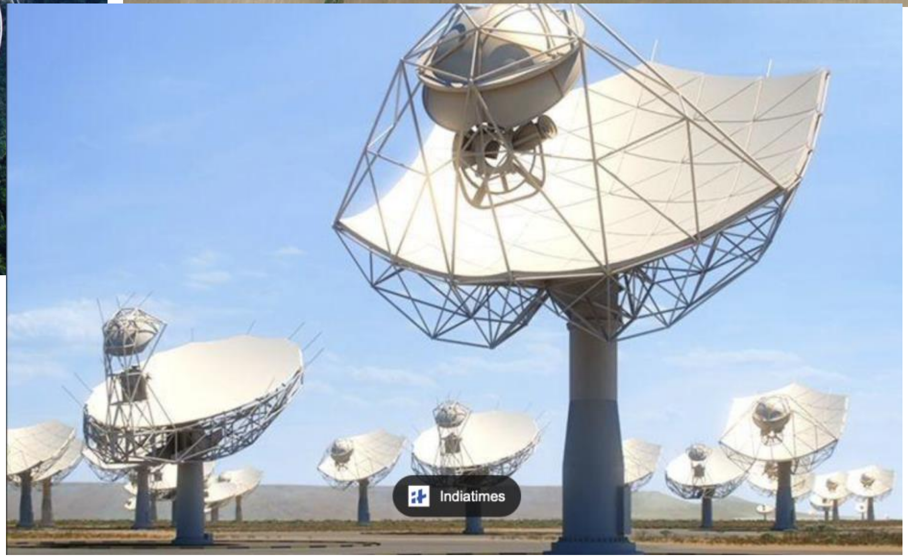
$$\begin{pmatrix} A_T & A'_T \end{pmatrix} \begin{pmatrix} \mathbf{k}^2 + \omega_p^2 & \epsilon\omega_p^2 \\ \epsilon\omega_p^2 & \mathbf{k}^2 + m_{A'}^2 \end{pmatrix} \begin{pmatrix} A_T \\ A'_T \end{pmatrix}$$



If we give up resonances, what we really need are free electrons!

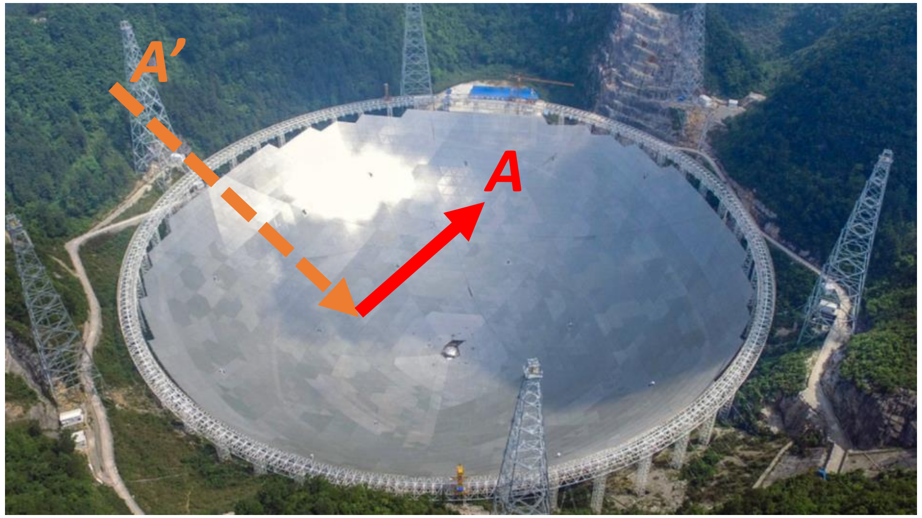
Searching for dark photon dark matter directly with radio telescopes

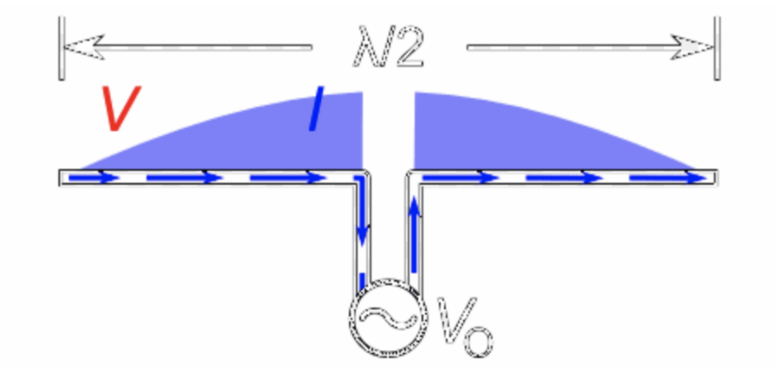
- Large scale radio telescopes



Searching for dark photon dark matter directly with radio telescopes

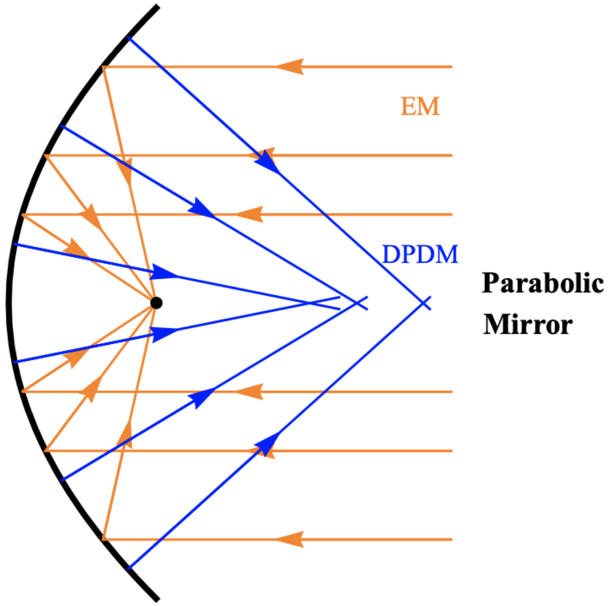
- The dark photon dark matter has an interaction with the electric current, $\epsilon e A'_{\mu} J^{\mu}$ (although suppressed)

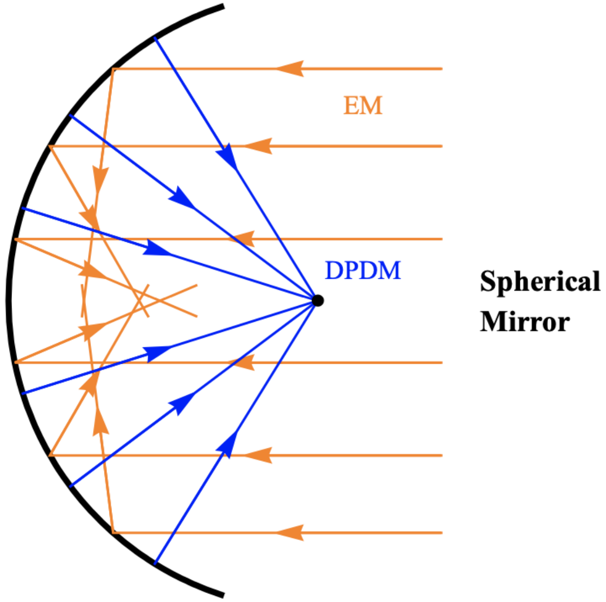


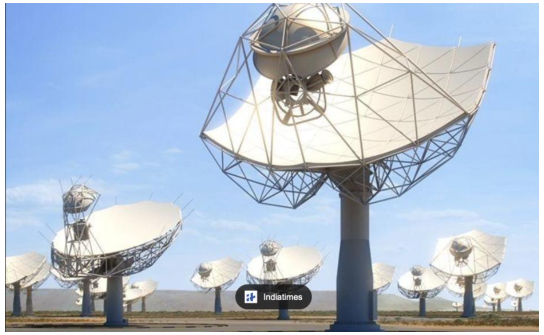


Dish antennas

- 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.

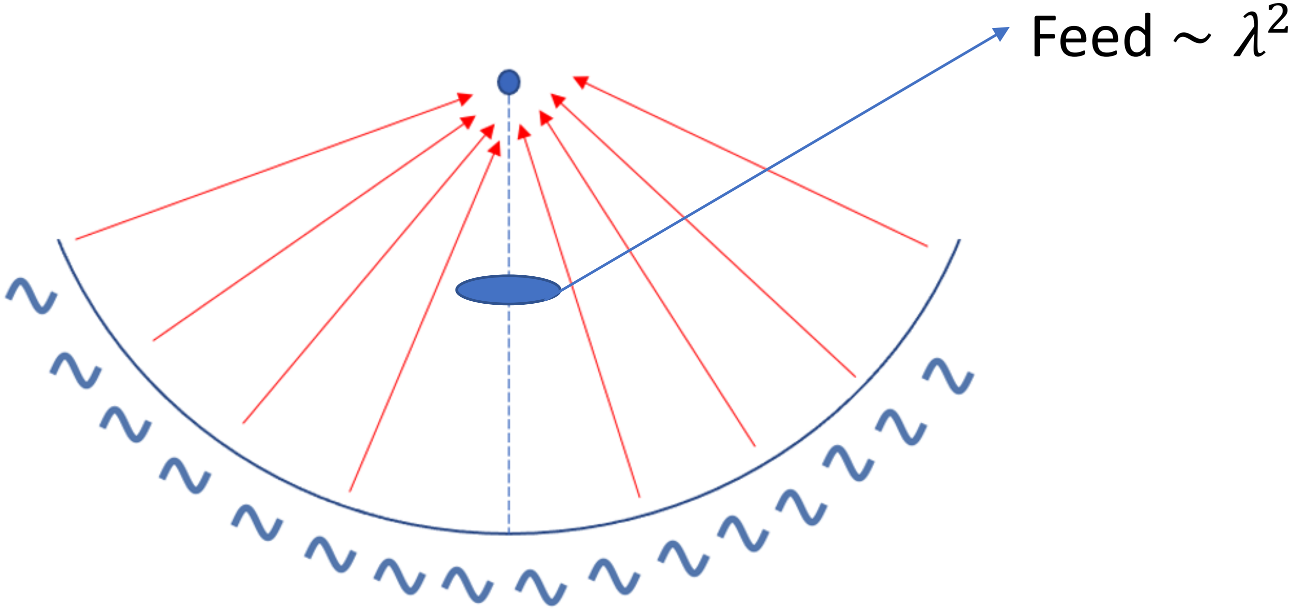






Dish antennas

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

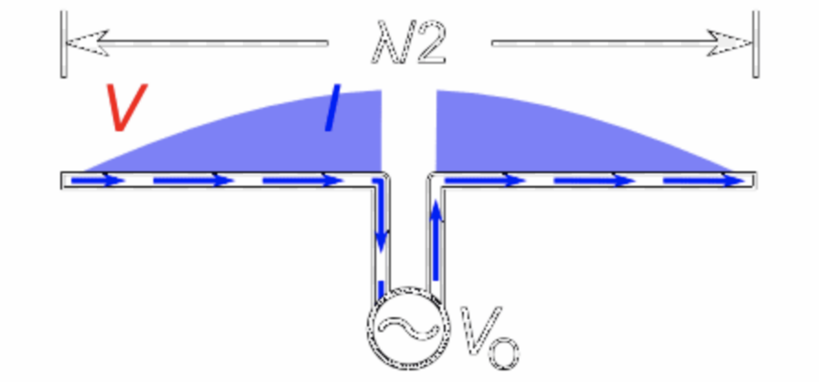


$$I_{\rm dish}^{\rm eqv} = \mathcal{C}\epsilon^2 \rho_{\rm DM} \times \frac{\lambda^2}{\mathcal{A}}$$

→ 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:



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

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

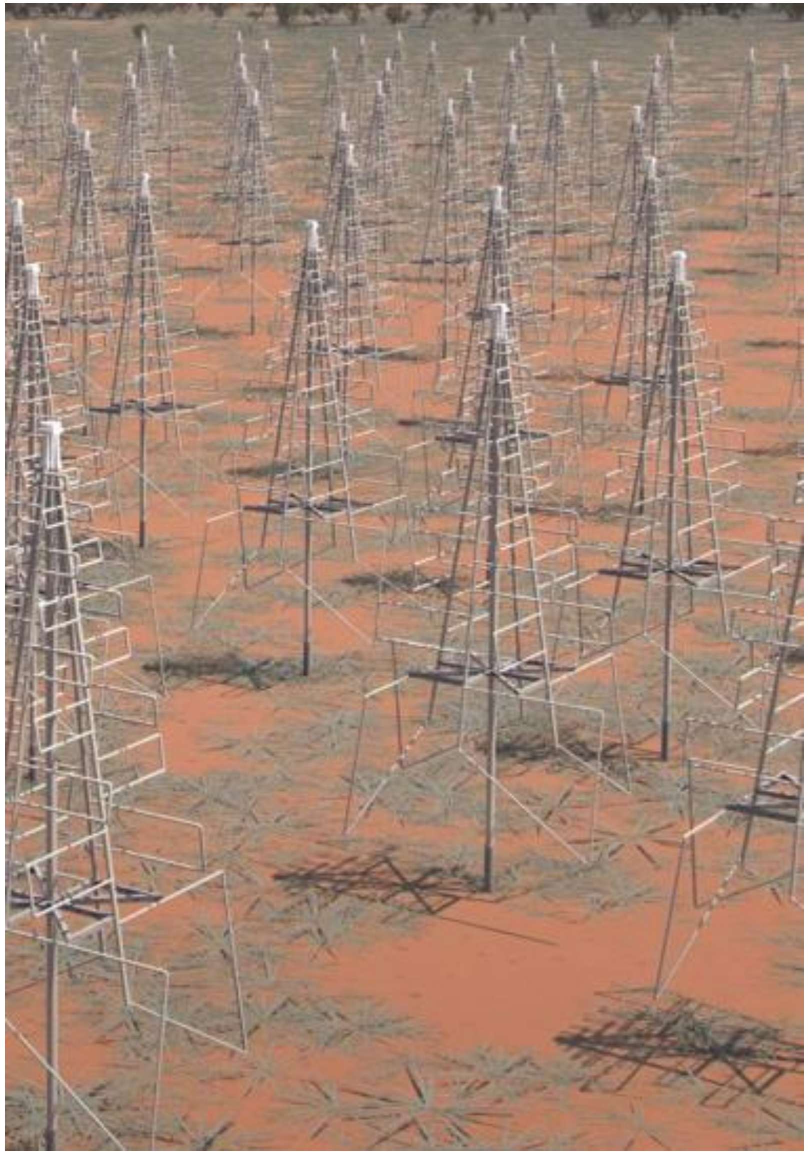
→ 0.4 GeV/cm³

↓ 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.

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



Limits from antenna arrays

- The signal is a peak,

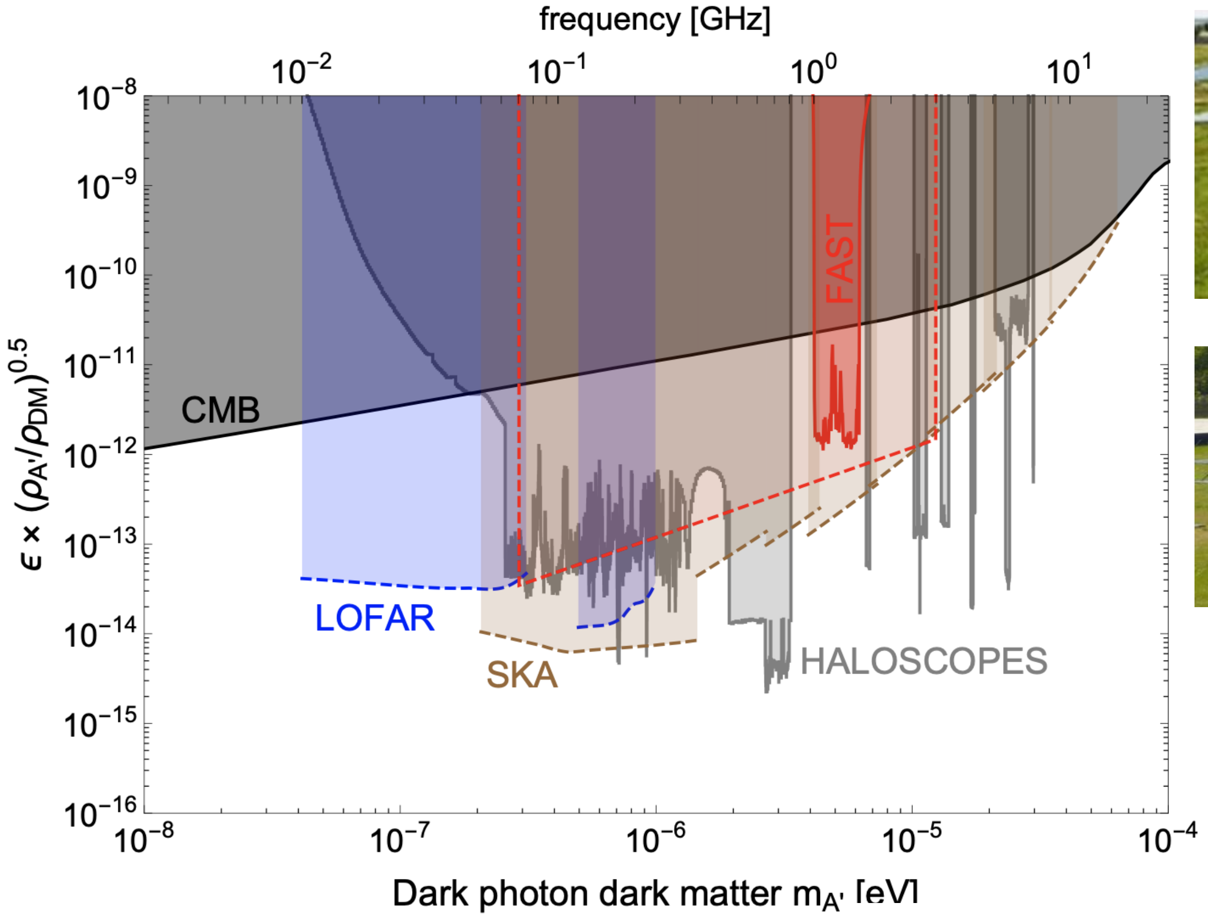
$$f_{\text{signal}} = \frac{m_{A'}}{2\pi} \qquad \Delta f_{\text{signal}} \approx 10^{-6} f$$

- Minimum detectable spectral flux

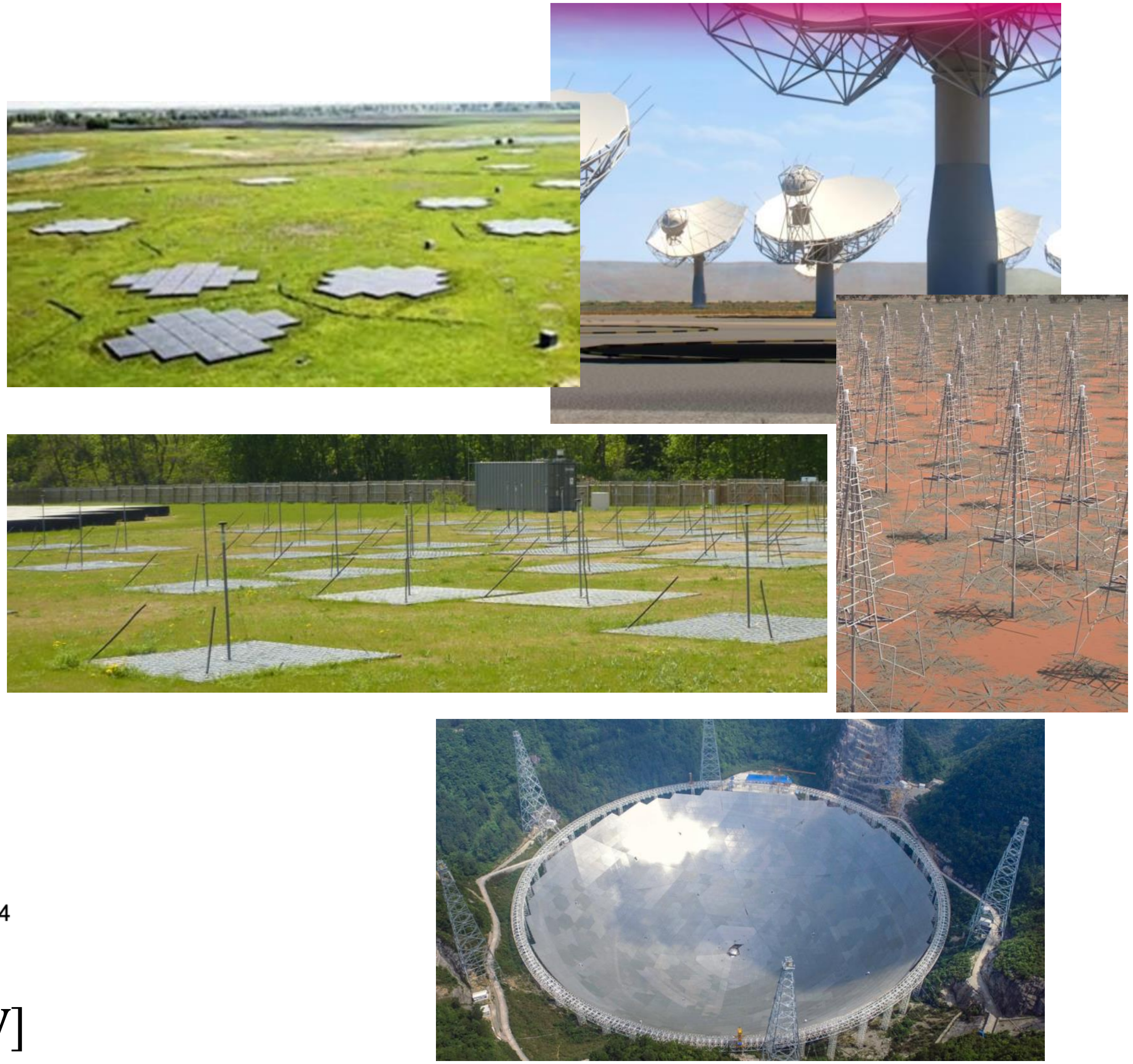
$$S_{\text{min}} = \frac{\text{SEFD}}{\eta_s \sqrt{n_{\text{pol}} \mathcal{B} t_{\text{obs}}}} \qquad \text{SEFD} = \frac{2k_B T_{\text{sys}}}{A_{\text{eff}}}$$

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

Sensitivity forecasts



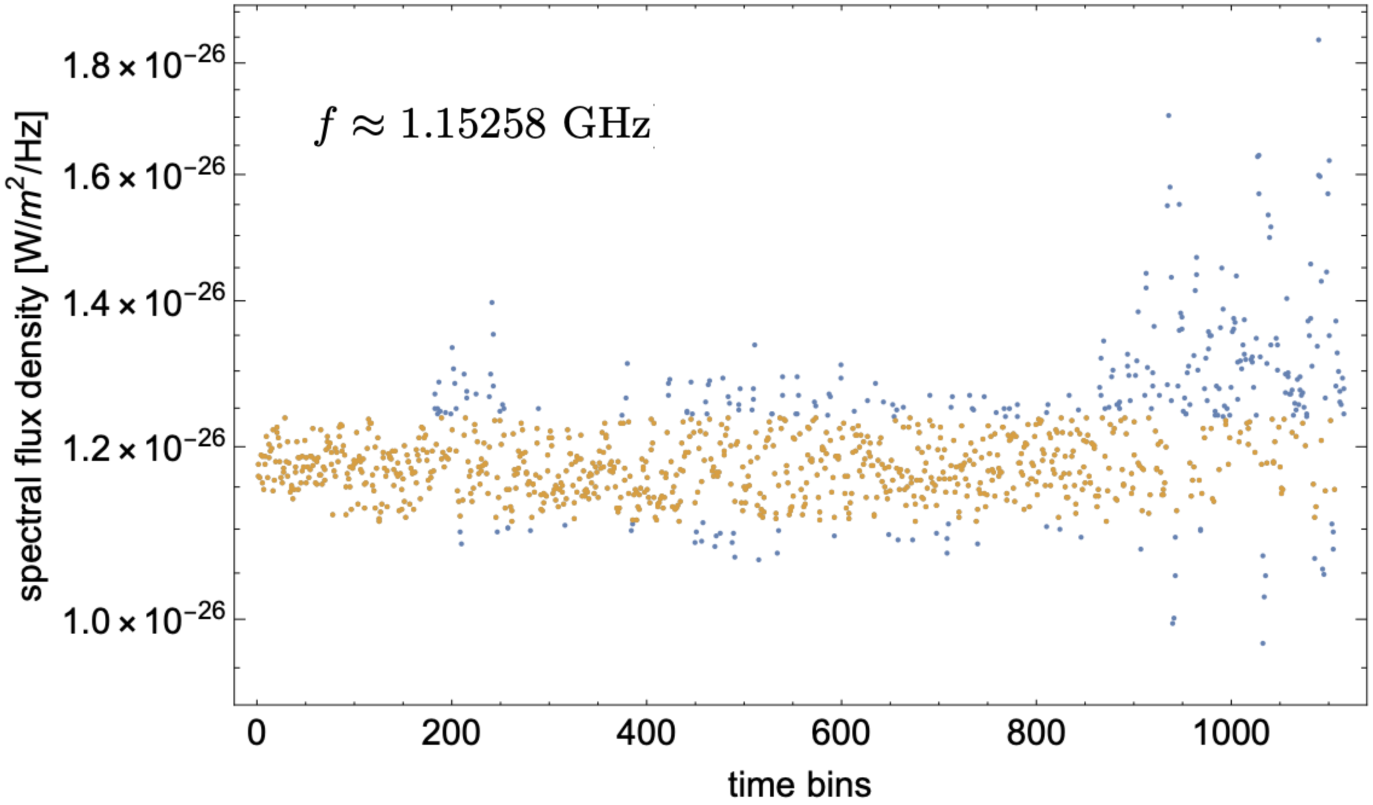
$m_{A'}$ [eV]



HA, S Ge, W-Q Guo, X Huang, Jia Liu, Z Lu, 2207.05767, PRL 130 (2023) 181001

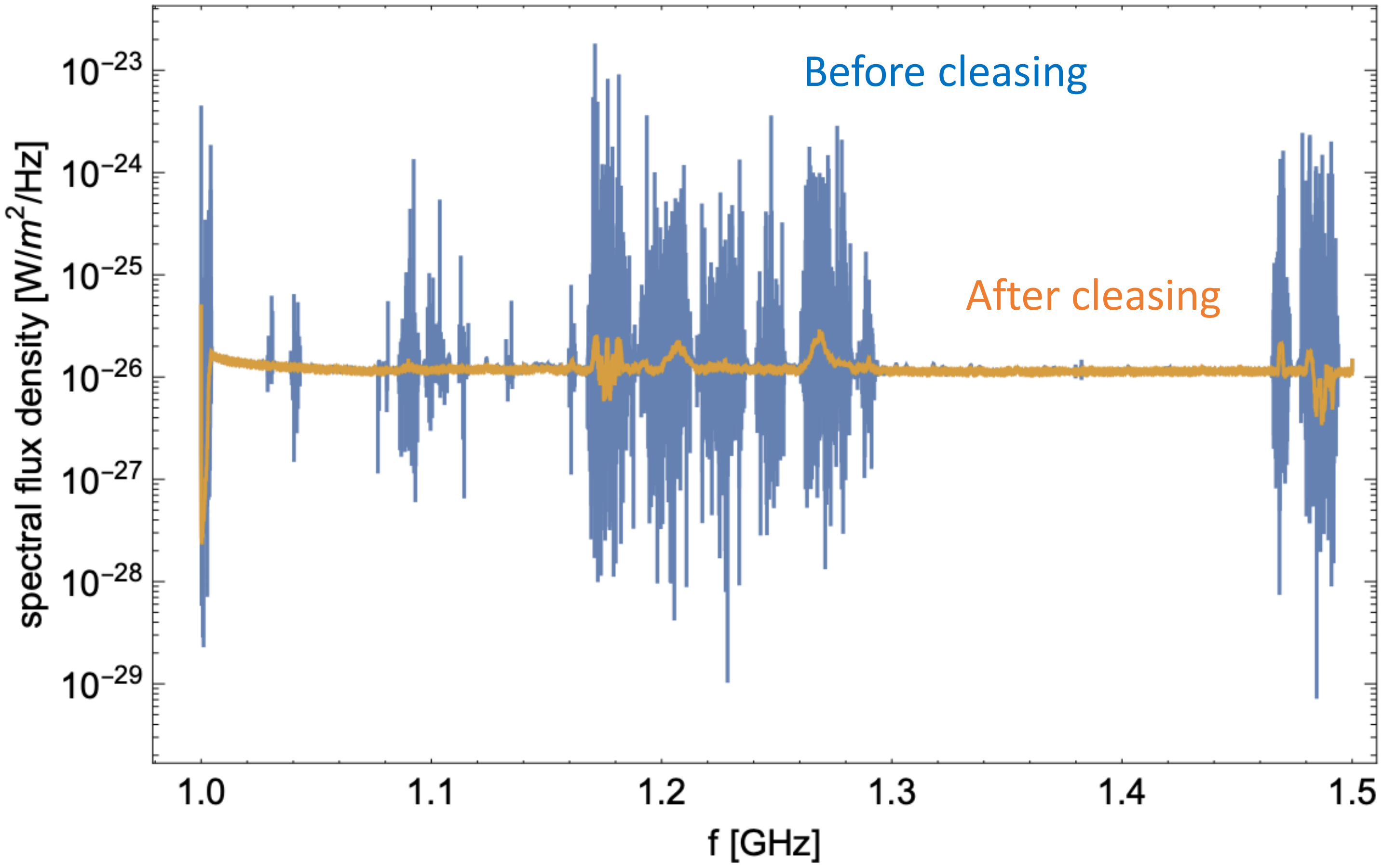
FAST data

- 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.

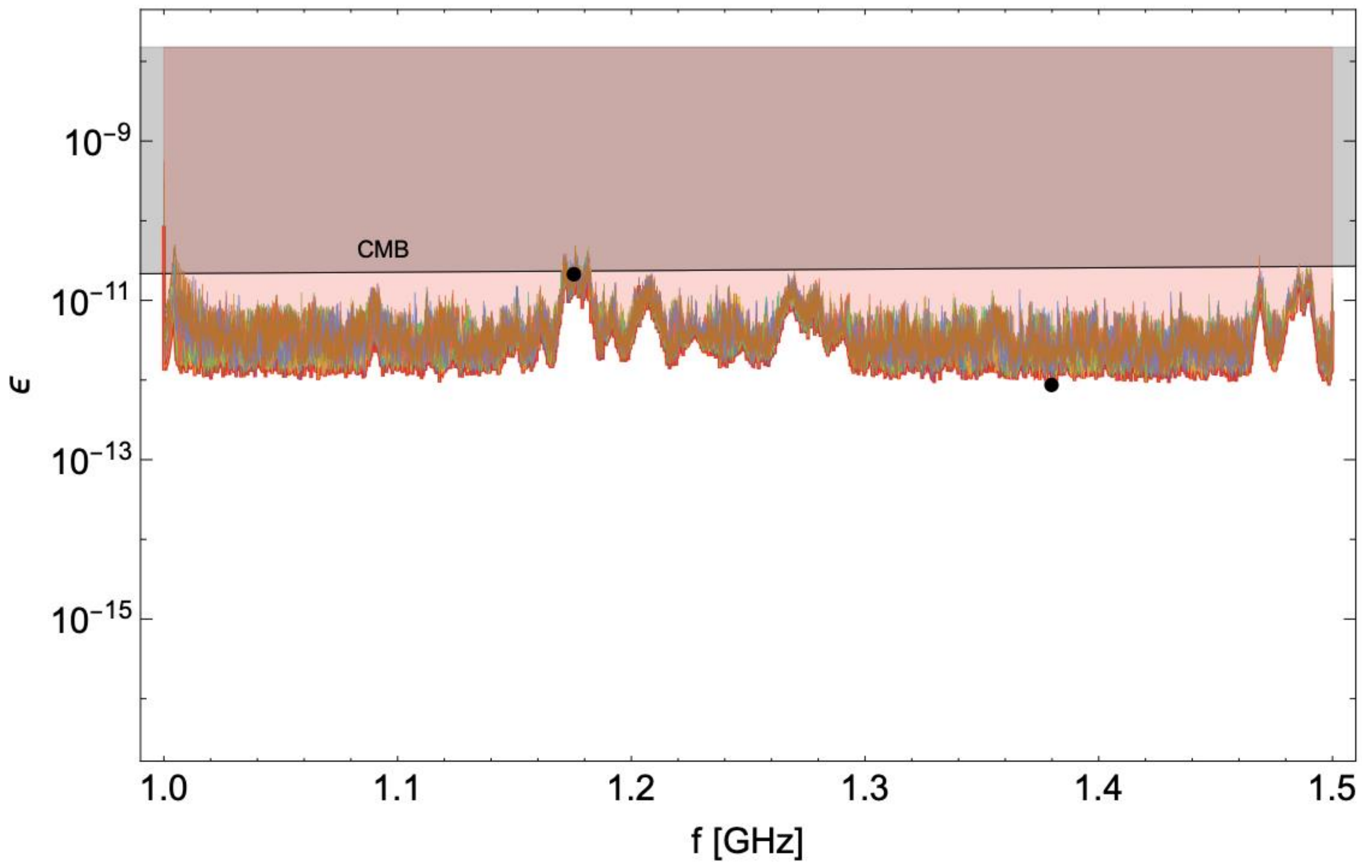


FAST data

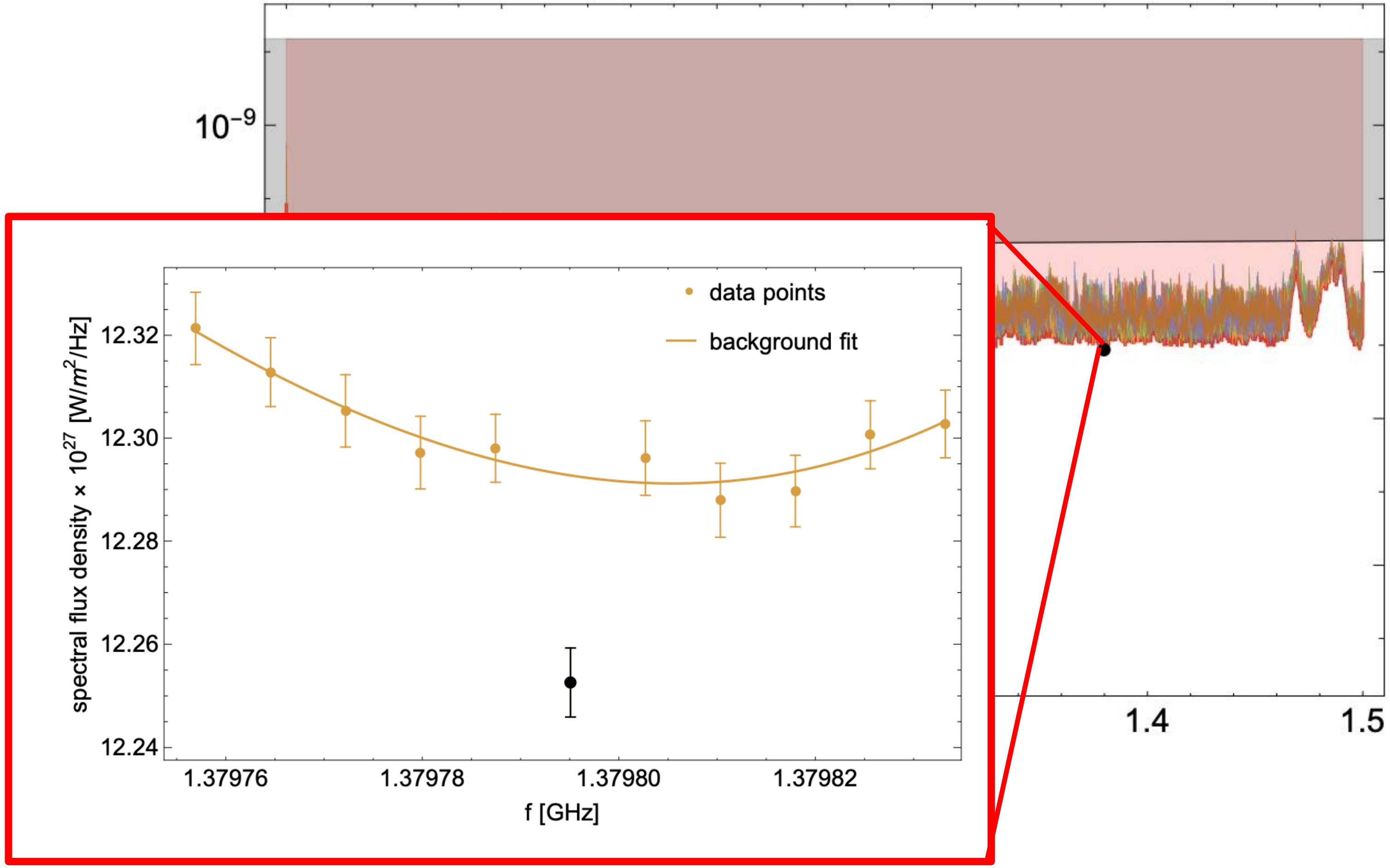
- Spectrum after data cleasing



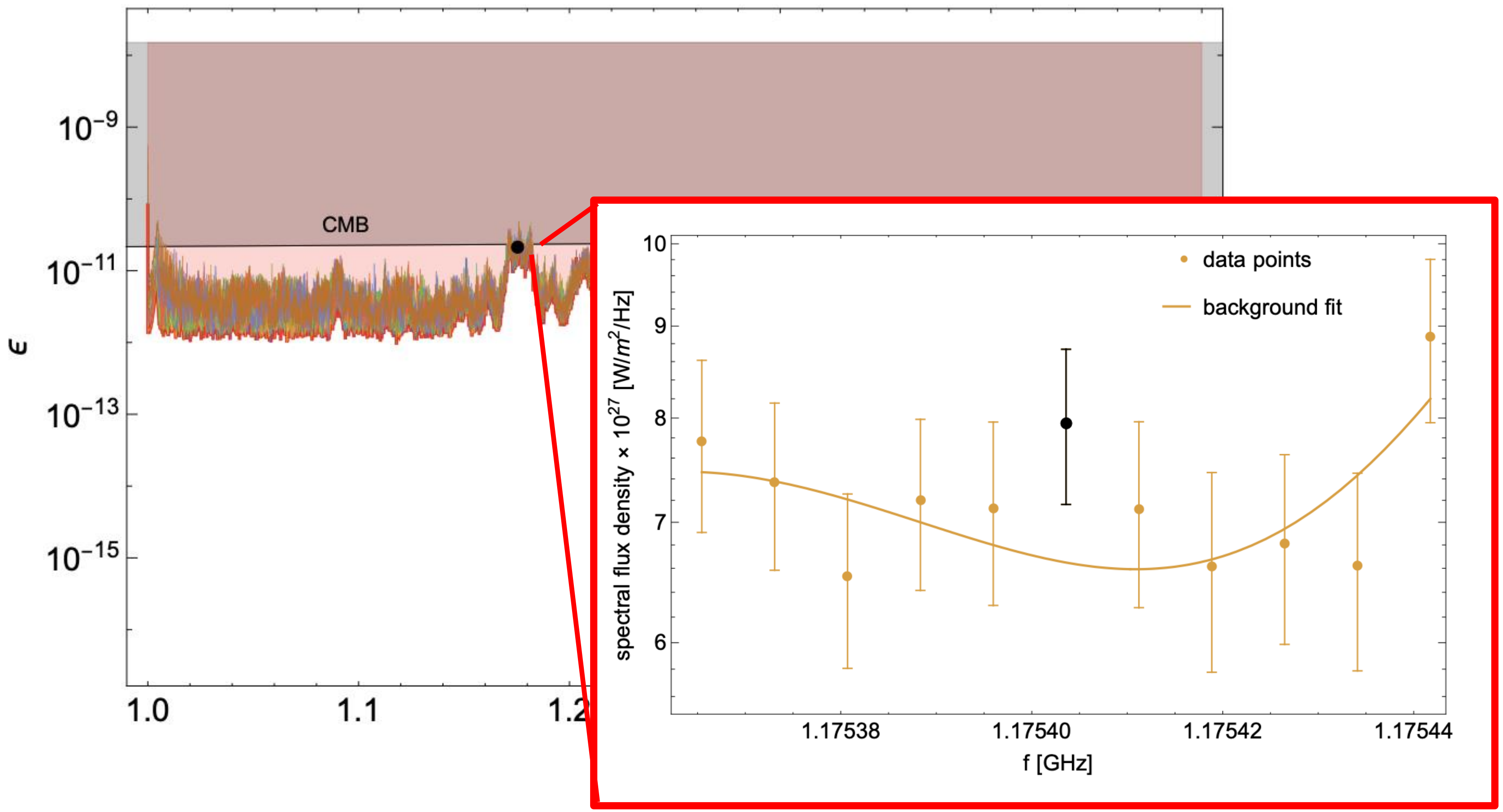
Constraint FAST data



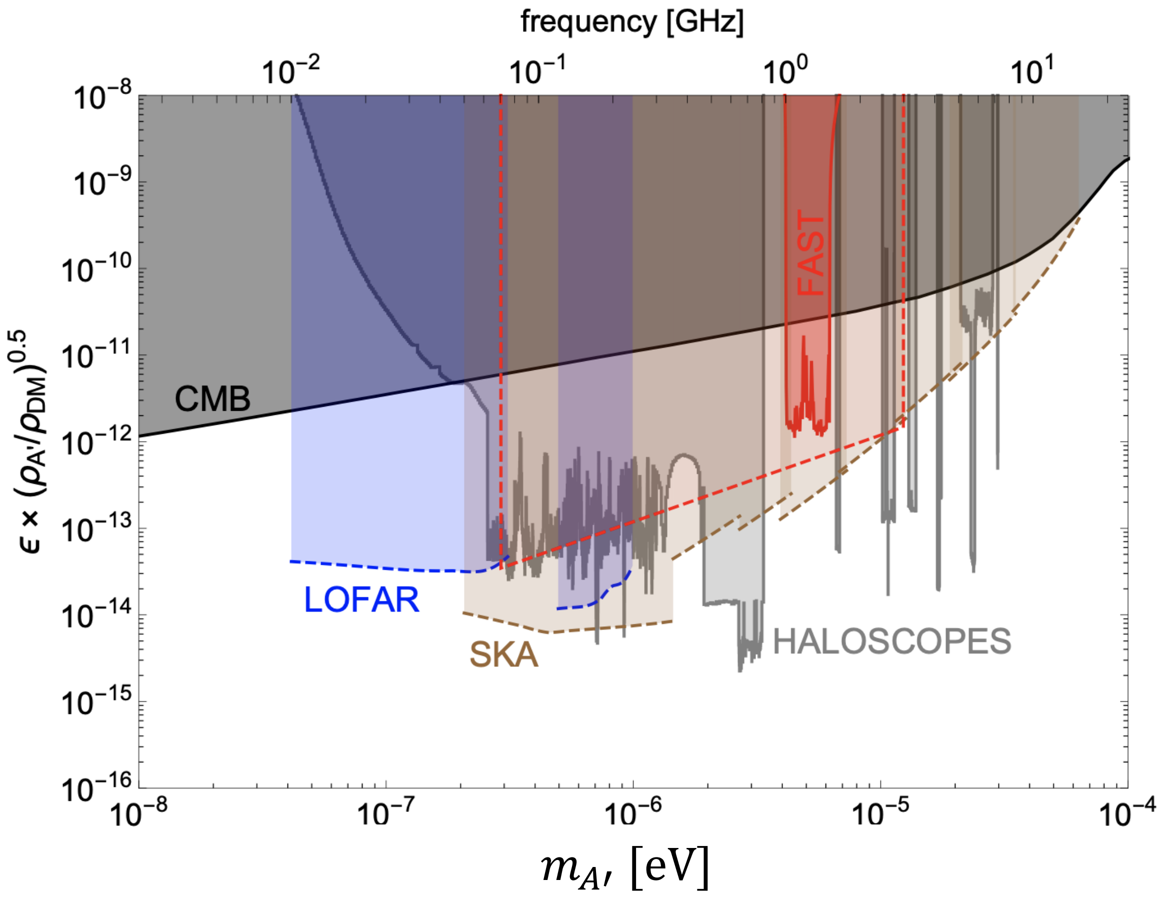
Constraint FAST data



Constraint FAST data



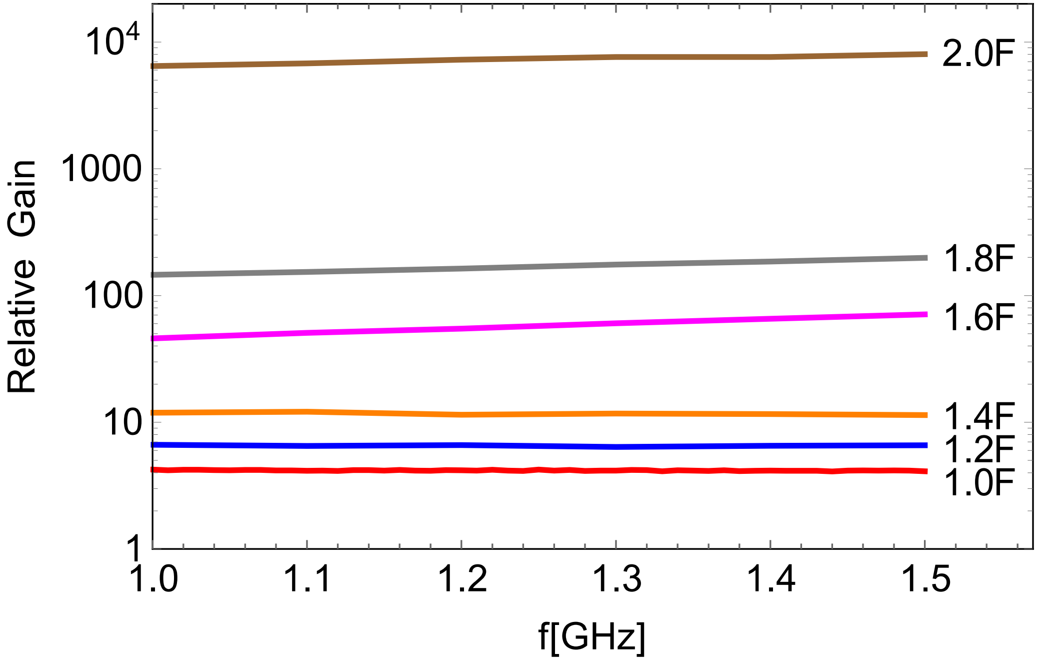
Direct detection of dark photon dark matter with radio telescopes



HA, S Ge, W-Q Guo, X Huang, Jia Liu, Z Lu, 2207.05767, PRL 130 (2023) 181001

Our own prototype detector

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



Work in progress with Jia Liu, Qiang Yuan, Quan Guo, Xiaoxing Yang, and …

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.

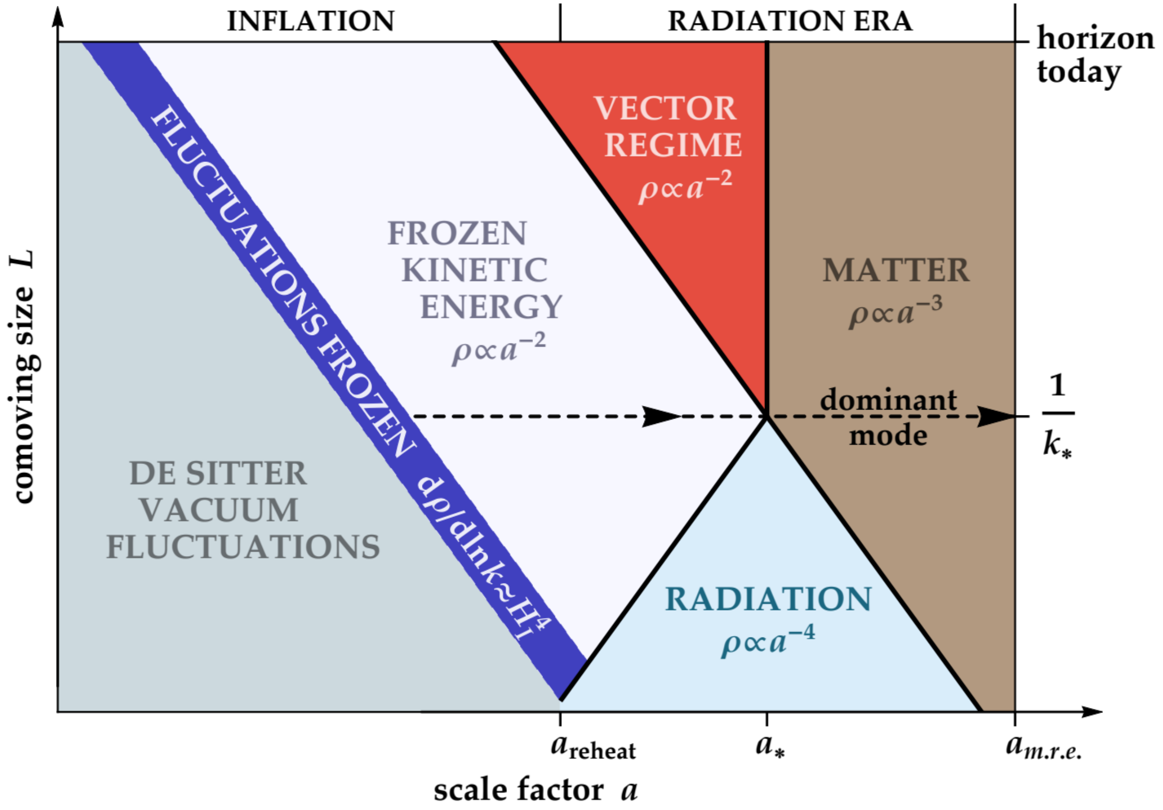
Broadberry, Das, Hook, Tavares, 2408.03370

DPDM production

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

Graham, Mardon, Rajendran (2015)

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

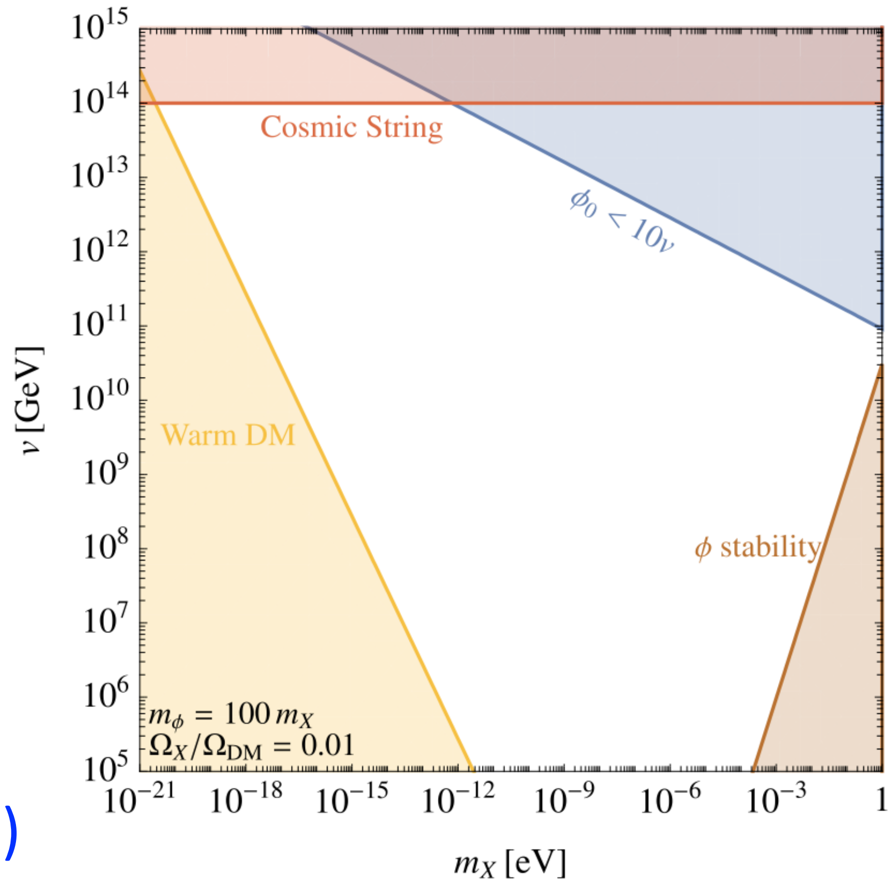


DPDM production via scalar oscillation

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

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

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

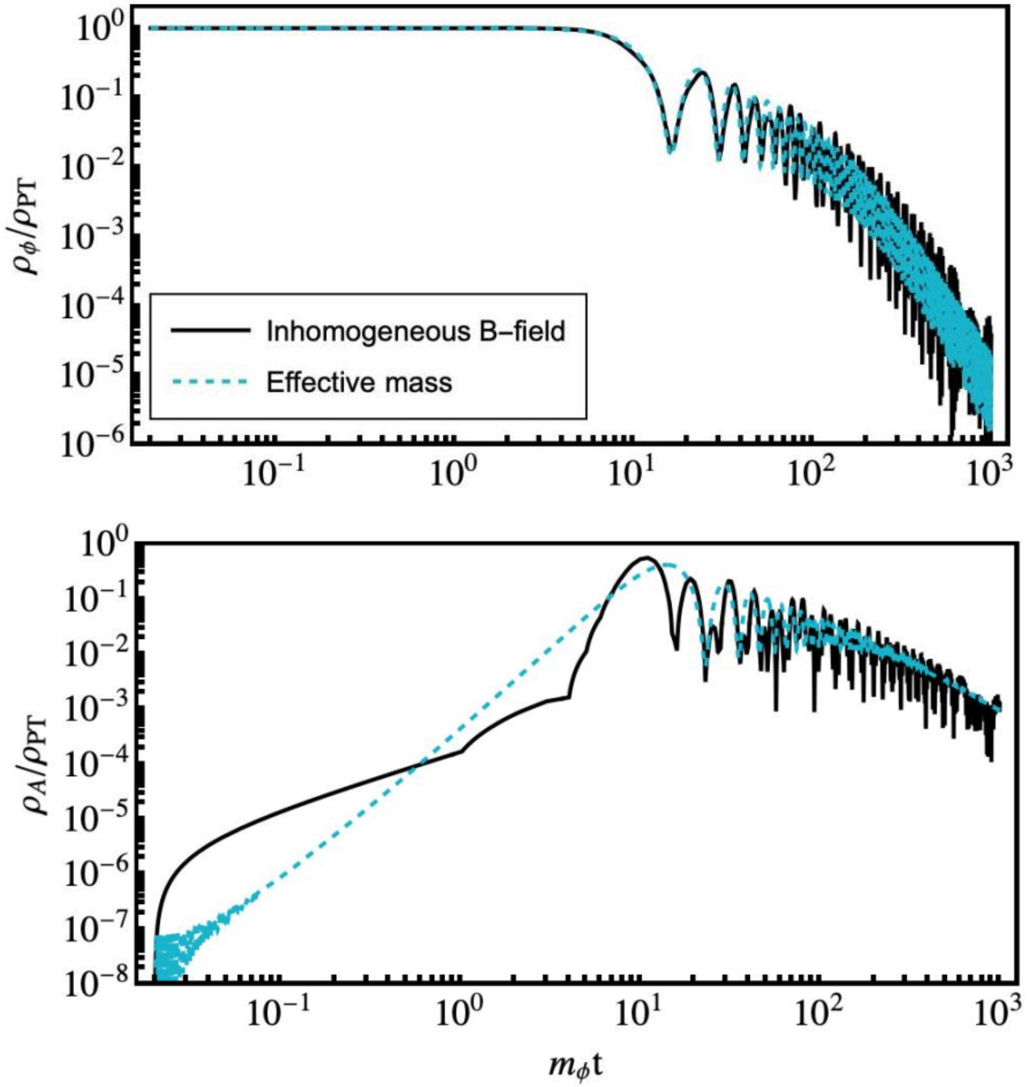
$$\frac{\phi}{f} F'_{\mu\nu} F'^{\mu\nu} \longrightarrow \frac{\phi}{f} F_{\mu\nu} F'^{\mu\nu}$$

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

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

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

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



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

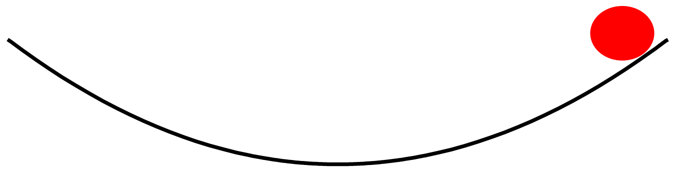
$$\Lambda_{\rm UV} = \min((m_{A'} M_{\rm pl}/e')^{1/2}, e'^{1/3} M_{\rm pl})$$

- 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 skills.
- But it does not have effect on scalar parametric resonant models.

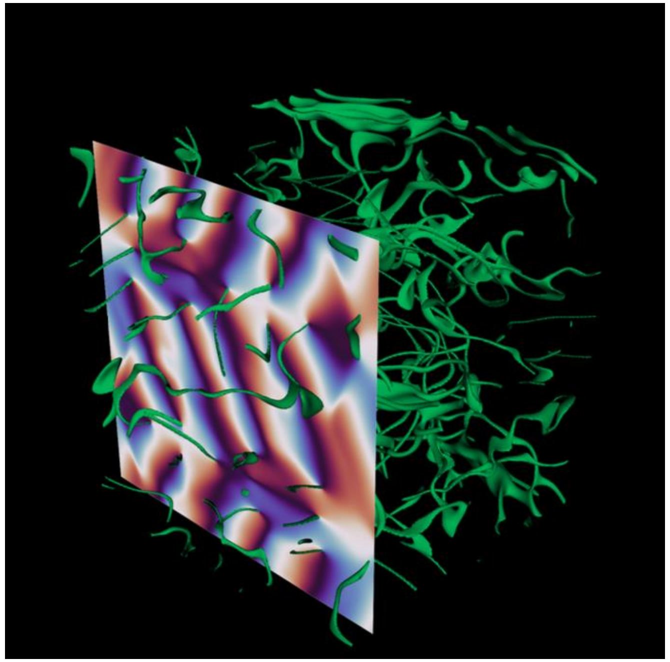
Constraints on Higgsed DPDM

- 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

Summary

- A lot of searches and model buildings are going on.
- We can in principle turn all the photon detectors to dark photon detectors.
- 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.

Backups

Wave method

- Wave equations

$$\left[\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial r^2} + \begin{pmatrix} \omega_p^2 & -\epsilon m_{A'}^2 \\ -\epsilon m_{A'}^2 & m_{A'}^2 \end{pmatrix}\right]\begin{pmatrix} A(r,t) \\ A'(r,t) \end{pmatrix} = 0,$$

- WKB approximation

$$(i\partial_r - H_0 - H_I)\begin{pmatrix} \tilde{A}(r) \\ \tilde{A}'(r) \end{pmatrix} = 0,$$

$$H_0 = \frac{1}{2k_r}\begin{pmatrix} \omega_p^2 - m_{A'}^2 - k_T^2 & 0 \\ 0 & -k_T^2 \end{pmatrix}$$

$$H_I = \frac{1}{2k_r}\begin{pmatrix} 0 & -\epsilon m_{A'}^2 \\ -\epsilon m_{A'}^2 & 0. \end{pmatrix}.$$

Wave method

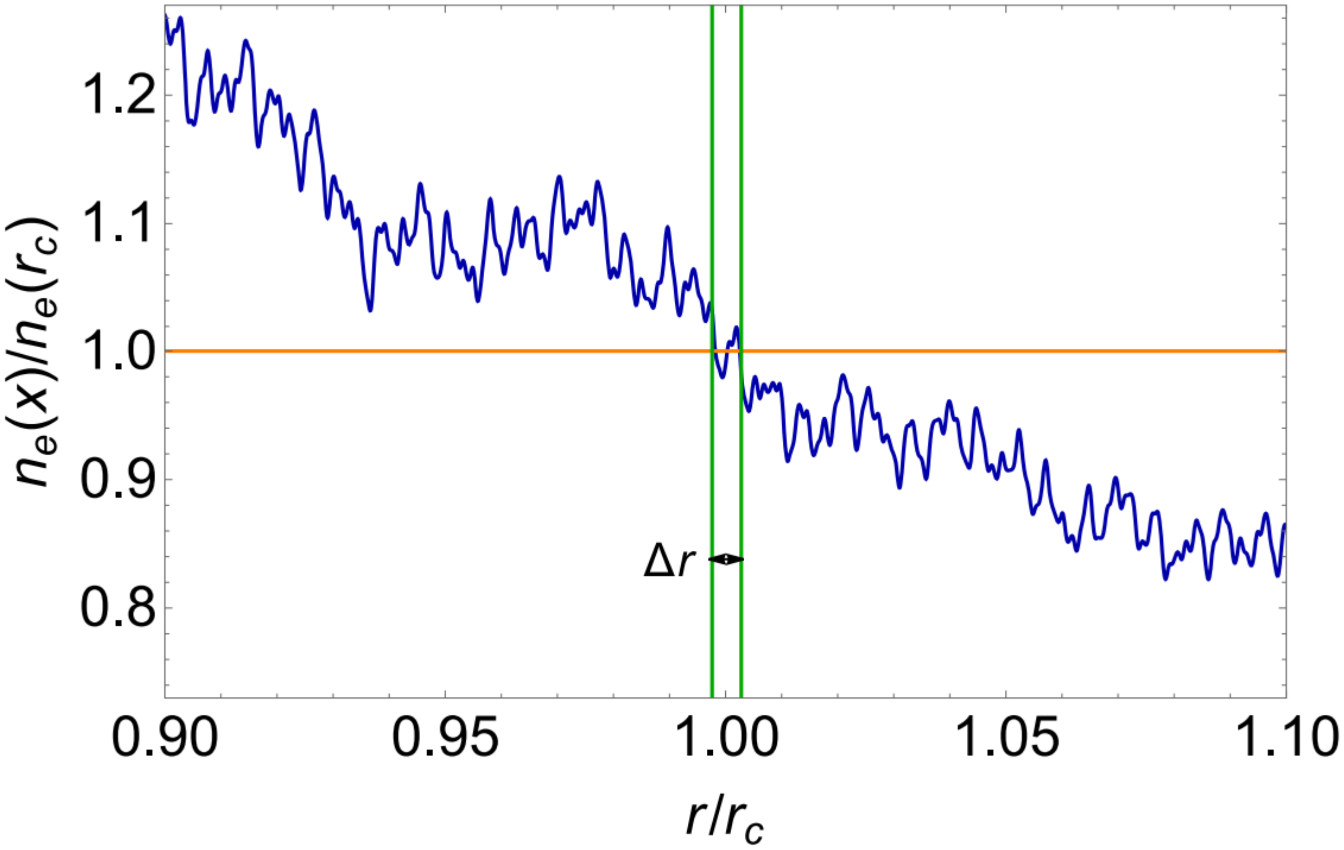
- Conversion probability

$$P_{A' \to \gamma} = \left| \int_{r_0}^{r} dr' \frac{-\epsilon m_{A'}^2}{2k_r} e^{i \int_{r_0}^{r'} dr'' \frac{1}{2k_r} \left[\omega_p(r'')^2 - m_{A'}^2 \right]} \right|^2$$

- Radiation power per solid angle

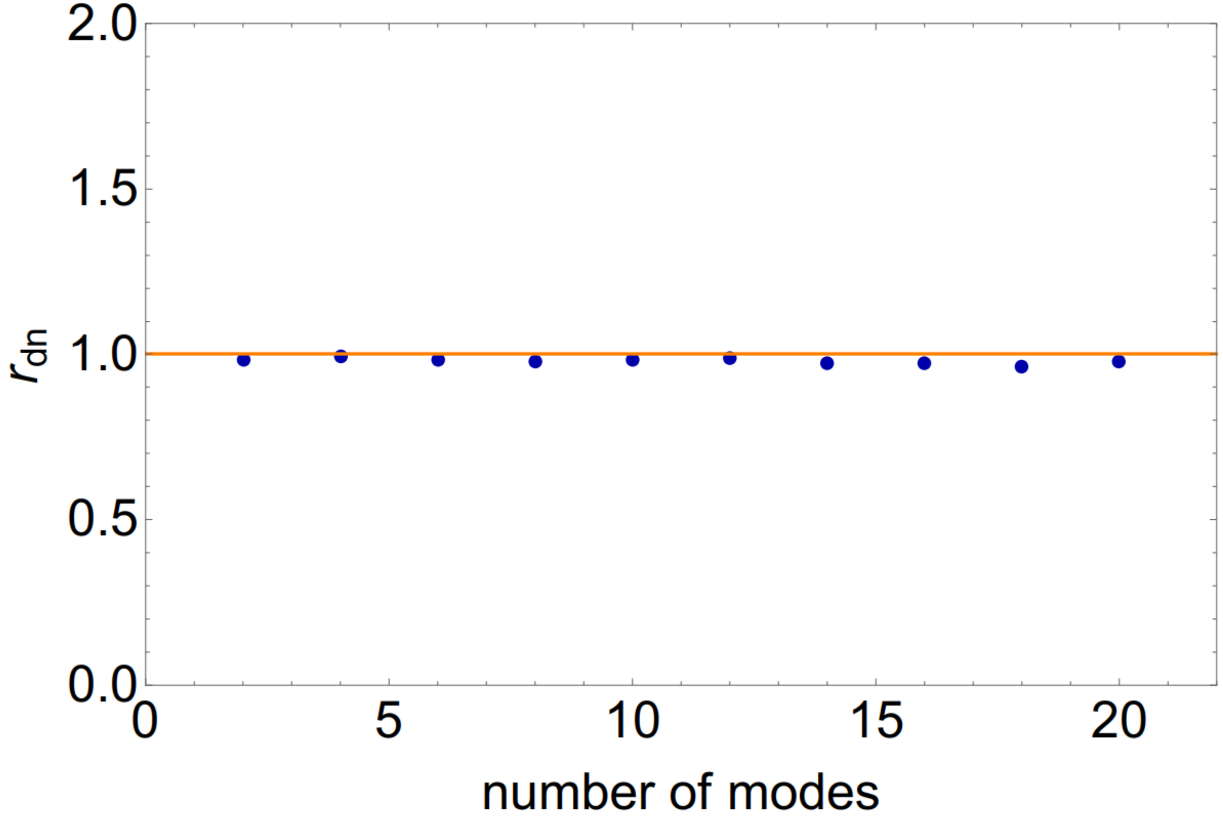
$$\begin{aligned} \frac{d\mathcal{P}}{d\Omega} &\approx 2 \frac{1}{4\pi} \rho_{\rm DM} \int d\mathbf{v}_0 f_{\rm DM} v_0 \int_0^b dz 2\pi z P_{A' \to \gamma}(v_r) \\ &= \rho_{\rm DM} \int d\mathbf{v}_0 f_{\rm DM} P_{A' \to \gamma}(v_0) v(r_c) r_c^2, \end{aligned}$$

Impact of small scale fluctuations



$$r_{\rm dn} = \frac{\sum_{n_e(r')=n_e(r_c)} \left| \frac{1}{n_e(r)} \frac{dn_e(r)}{dr} \right|^{-1}_{r=r'}}{\left| \frac{1}{n_{e,\rm bkg}(r)} \frac{dn_{e,\rm bkg}(r)}{dr} \right|^{-1}_{r=r_c}} = \frac{\sum_{n_e(r')=n_e(r_c)} \left| \frac{dr}{dn_e(r)} \right|_{r=r'}}{\left| \frac{dr}{dn_{e,\rm bkg}(r)} \right|_{r=r_c}}.$$

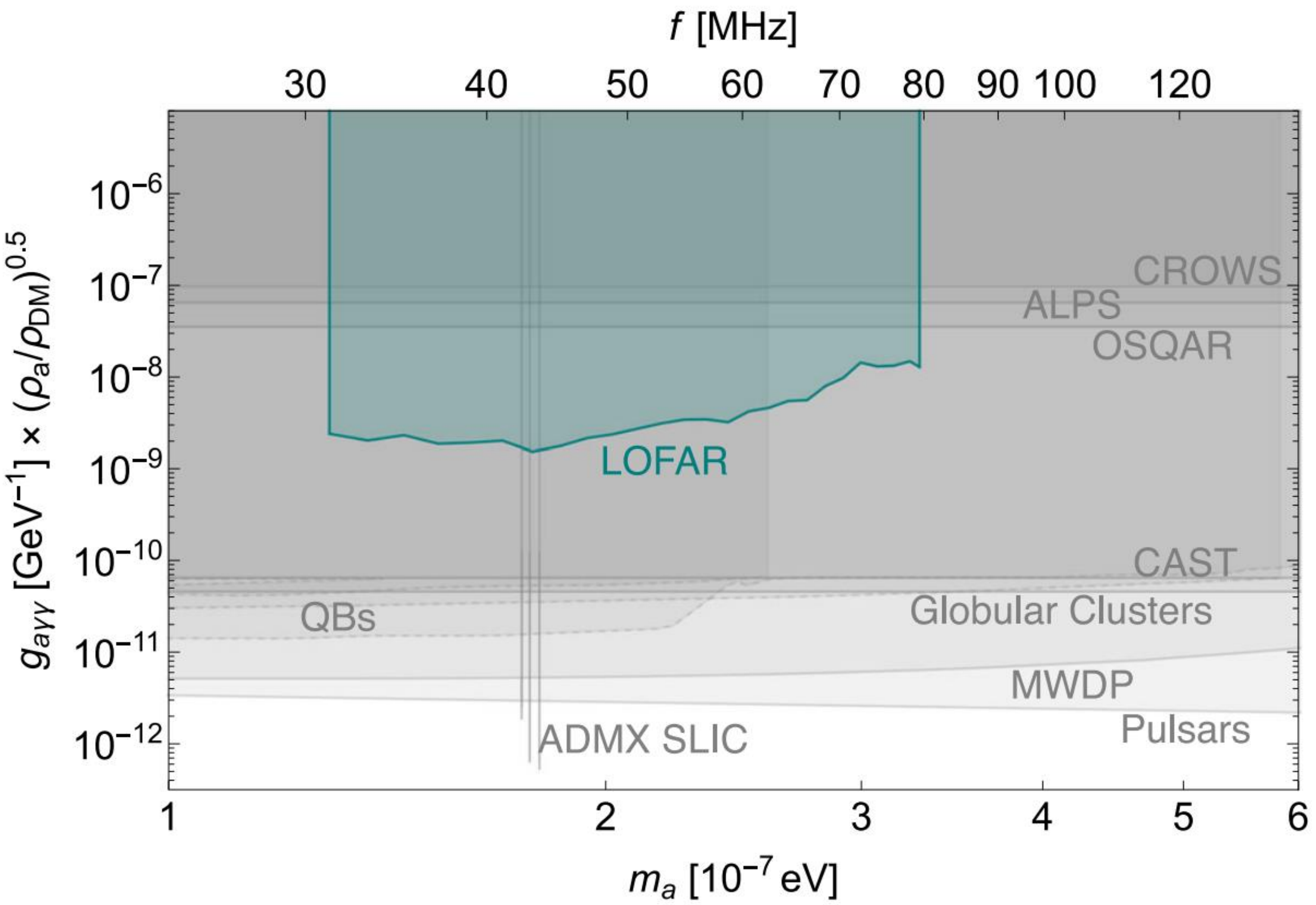
Impact of small scale fluctuations



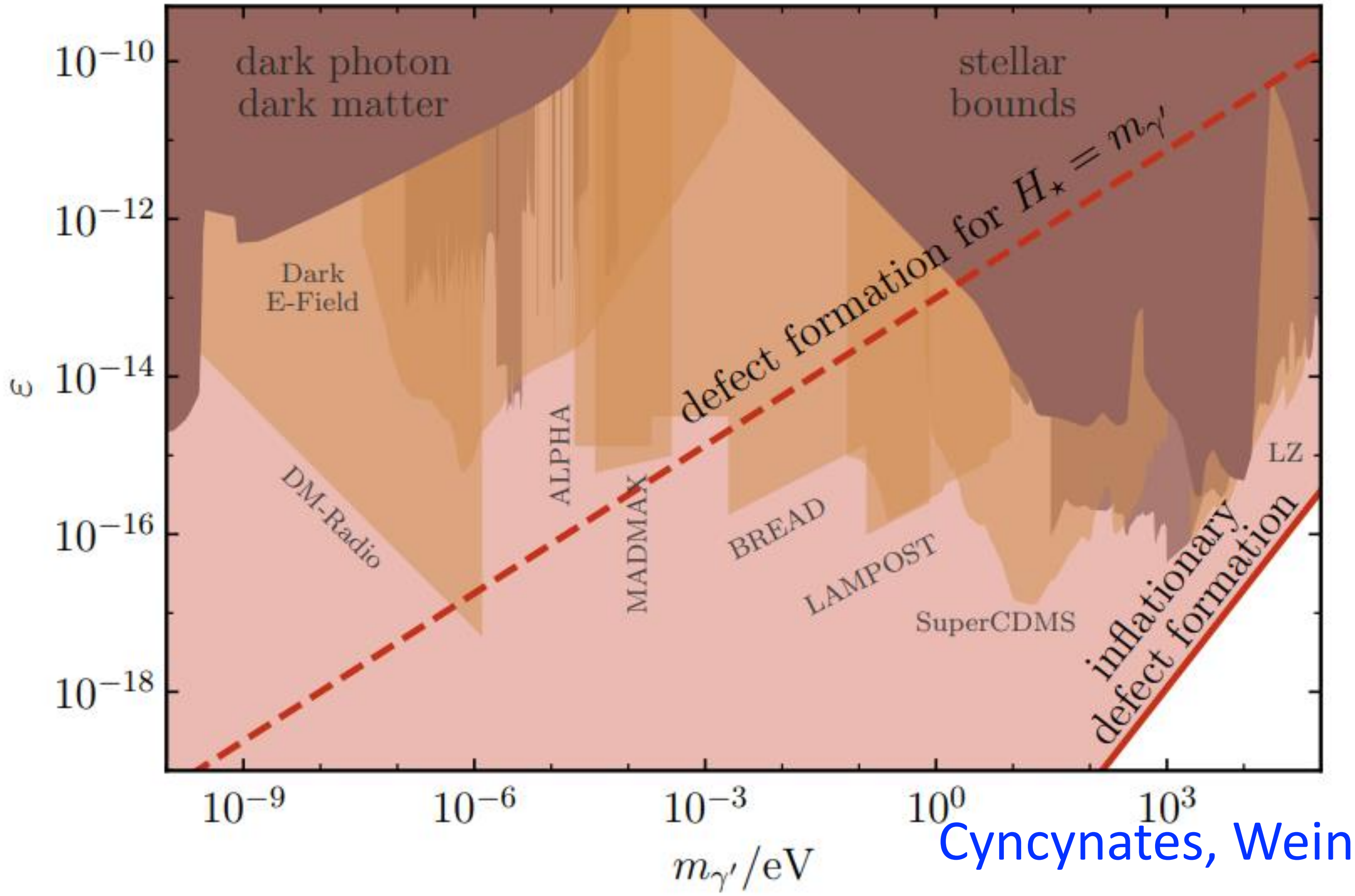
$$r_{\rm dn} = \frac{\sum_{n_e(r')=n_e(r_c)} \left| \frac{1}{n_e(r)} \frac{dn_e(r)}{dr} \right|^{-1}_{r=r'}}{\left| \frac{1}{n_{e,{\rm bkg}}(r)} \frac{dn_{e,{\rm bkg}}(r)}{dr} \right|^{-1}_{r=r_c}}$$

$$= \frac{\sum_{n_e(r')=n_e(r_c)} \left| \frac{dr}{dn_e(r)} \right|_{r=r'}}{\left| \frac{dr}{dn_{e,{\rm bkg}}(r)} \right|_{r=r_c}}.$$

Axion DM search



Constraints on Higgsed DPDM

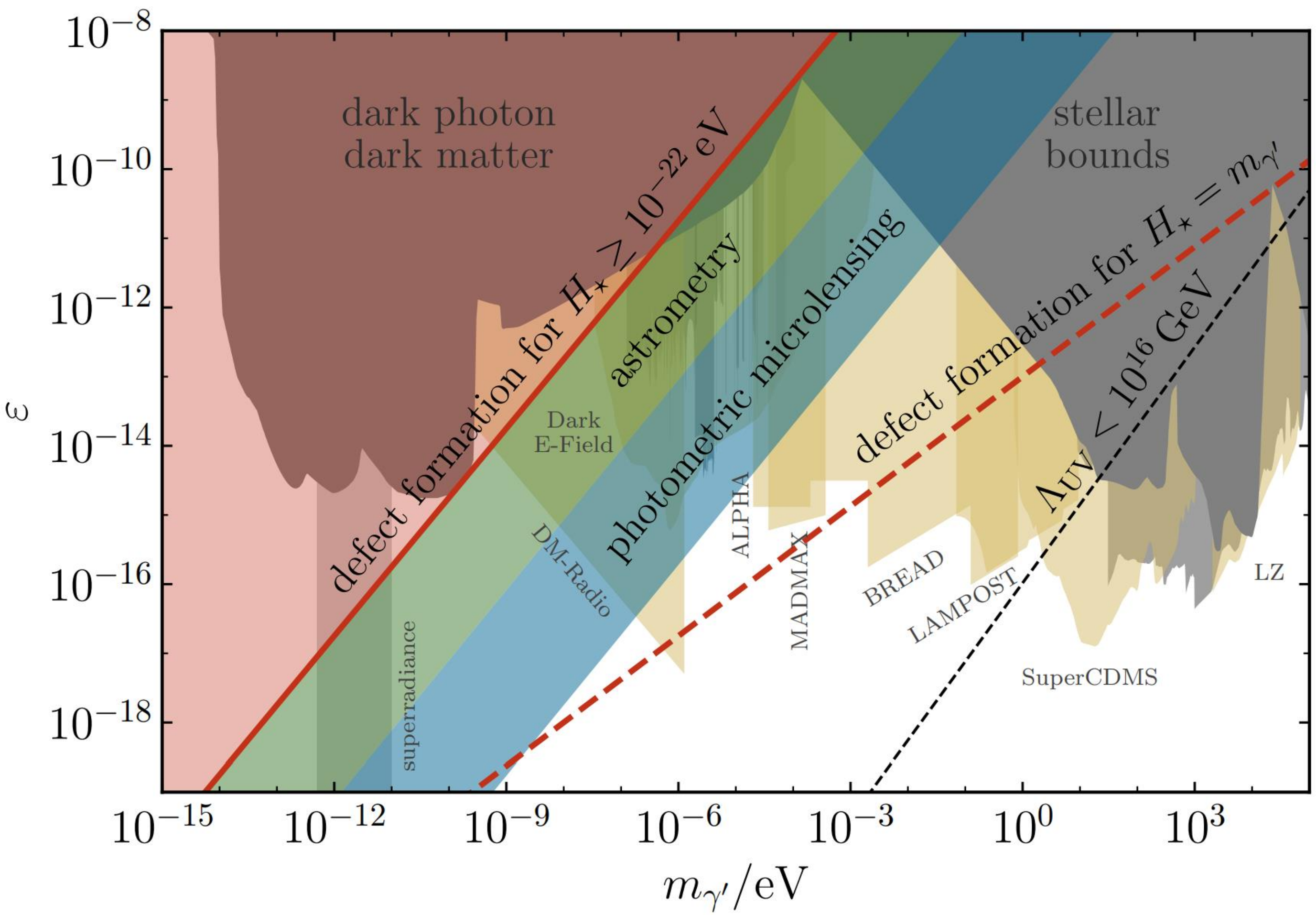


$$\epsilon \sim \frac{e g_D}{16\pi^2}$$

Cyncynates, Weiner, 2310.18397

Time dependent couplings and mass

Cyncynates, Weiner, 2310.18397



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

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