北京大學
PEKING UNIVERSITY

Searching for ultralight dark matter using radio telescopes

Shuailiang Ge

(Peking University)

2207.05767 (PRL)
with Haipeng An, Wen-qing Guo, Xiaoyuan Huang, Jia Liu, Zhiyao Lu
2301.03622 with Haipeng An, Xingyao Chen, Jia Liu, Yan Luo
2304.01056 with Haipeng An, Jia Liu

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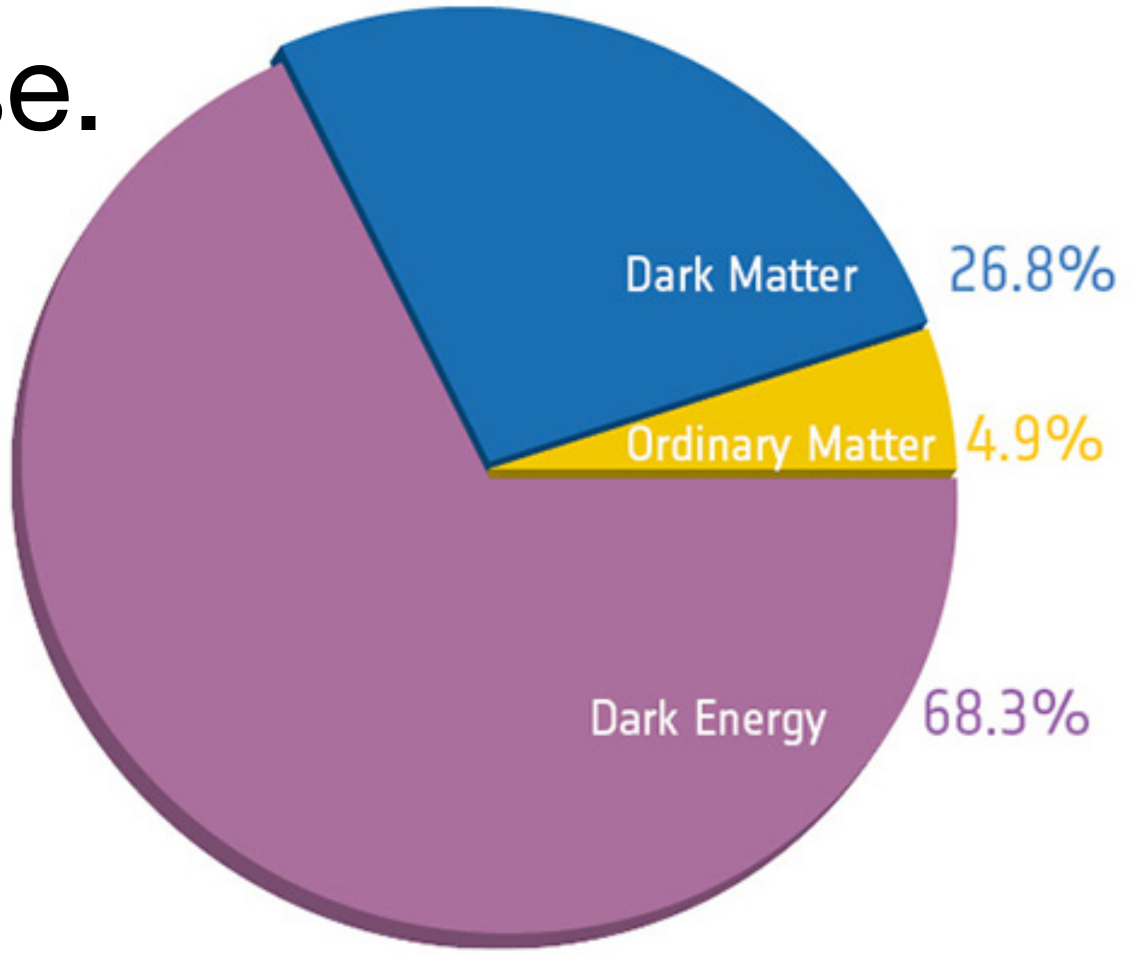
Dark Matter

Dark matter accounts for ~27% of the total mass-energy of the Universe.

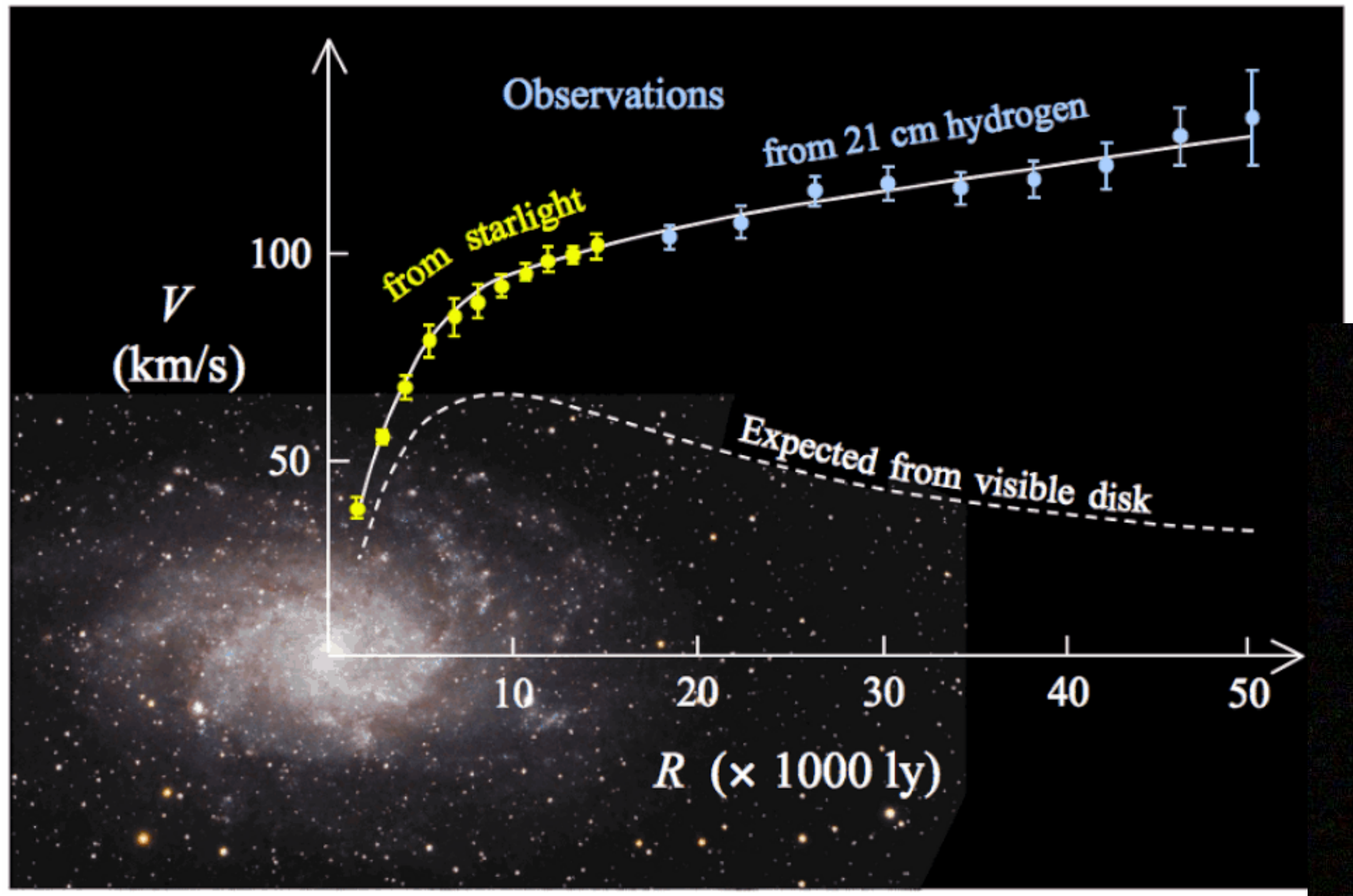
~10^24 DM particles pass your body every second!

(assuming $m_{\rm DM}$~10^-5 eV)

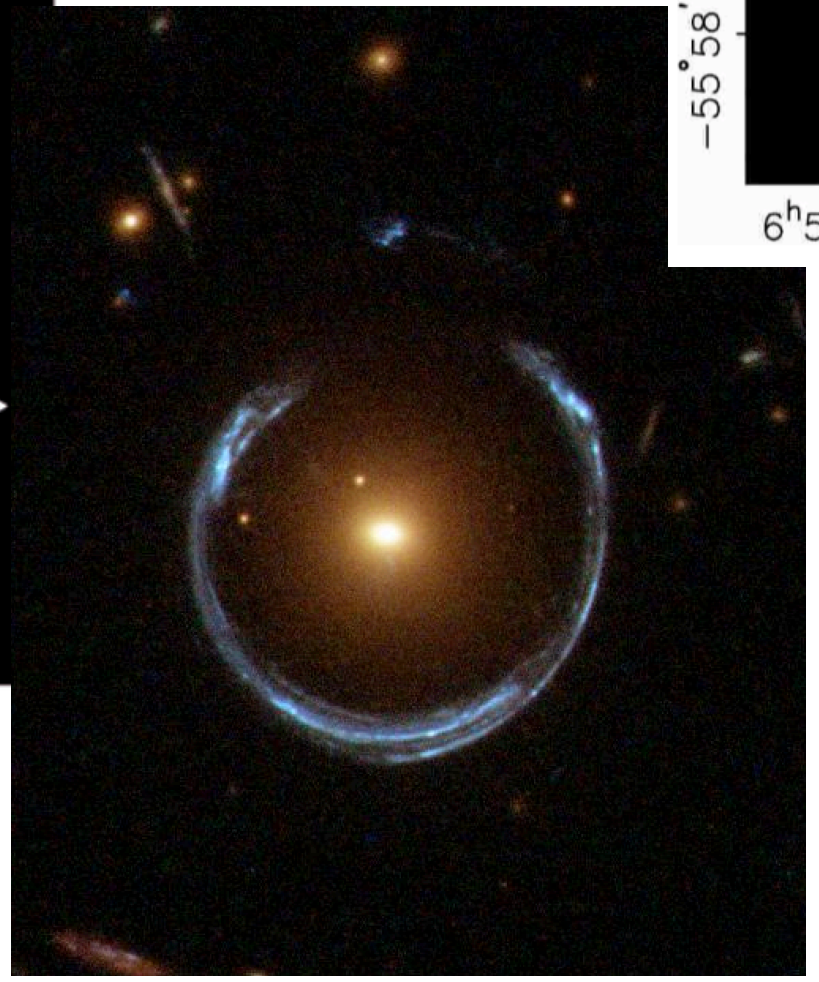


ΛCDM model

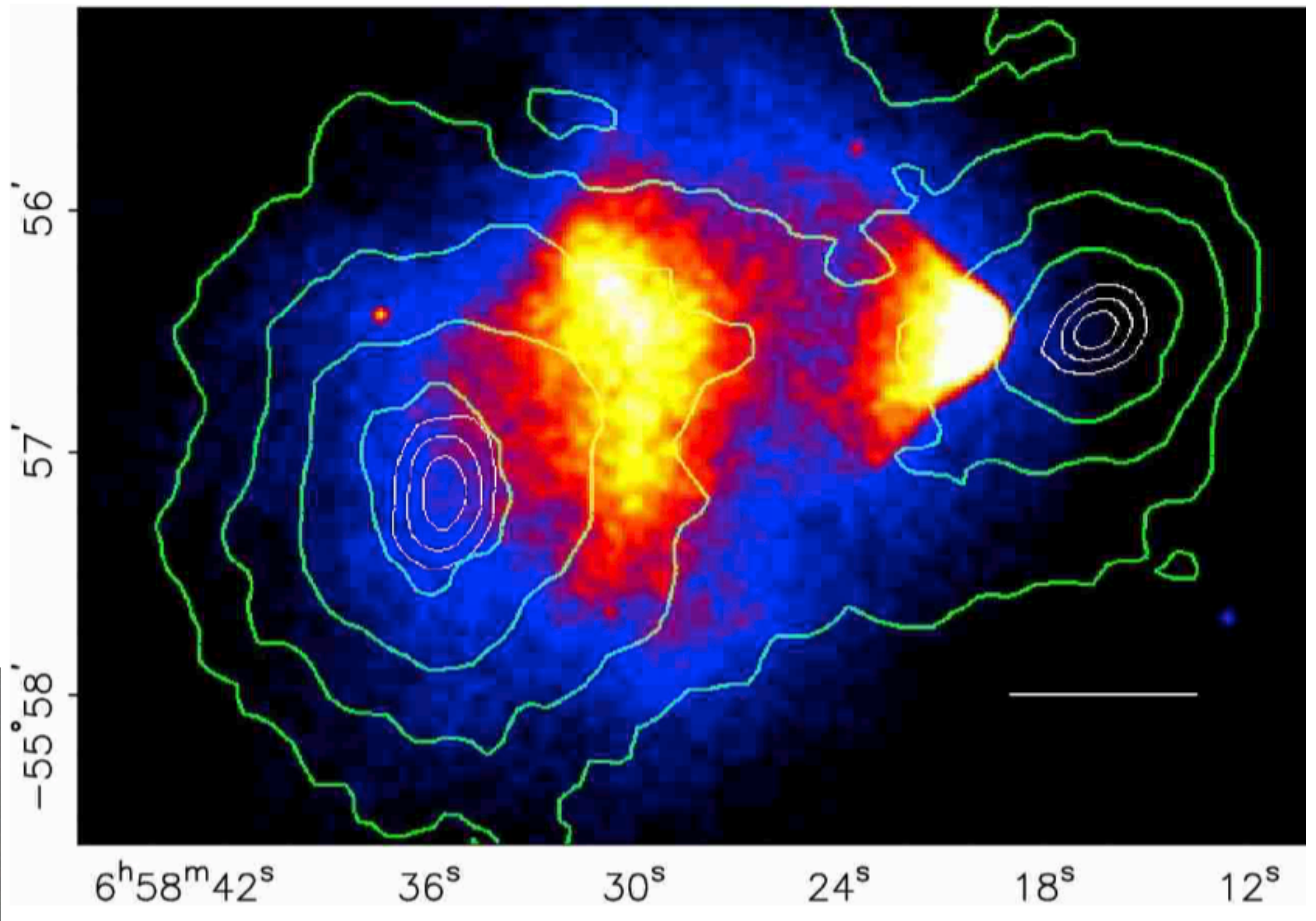
Observational evidence:



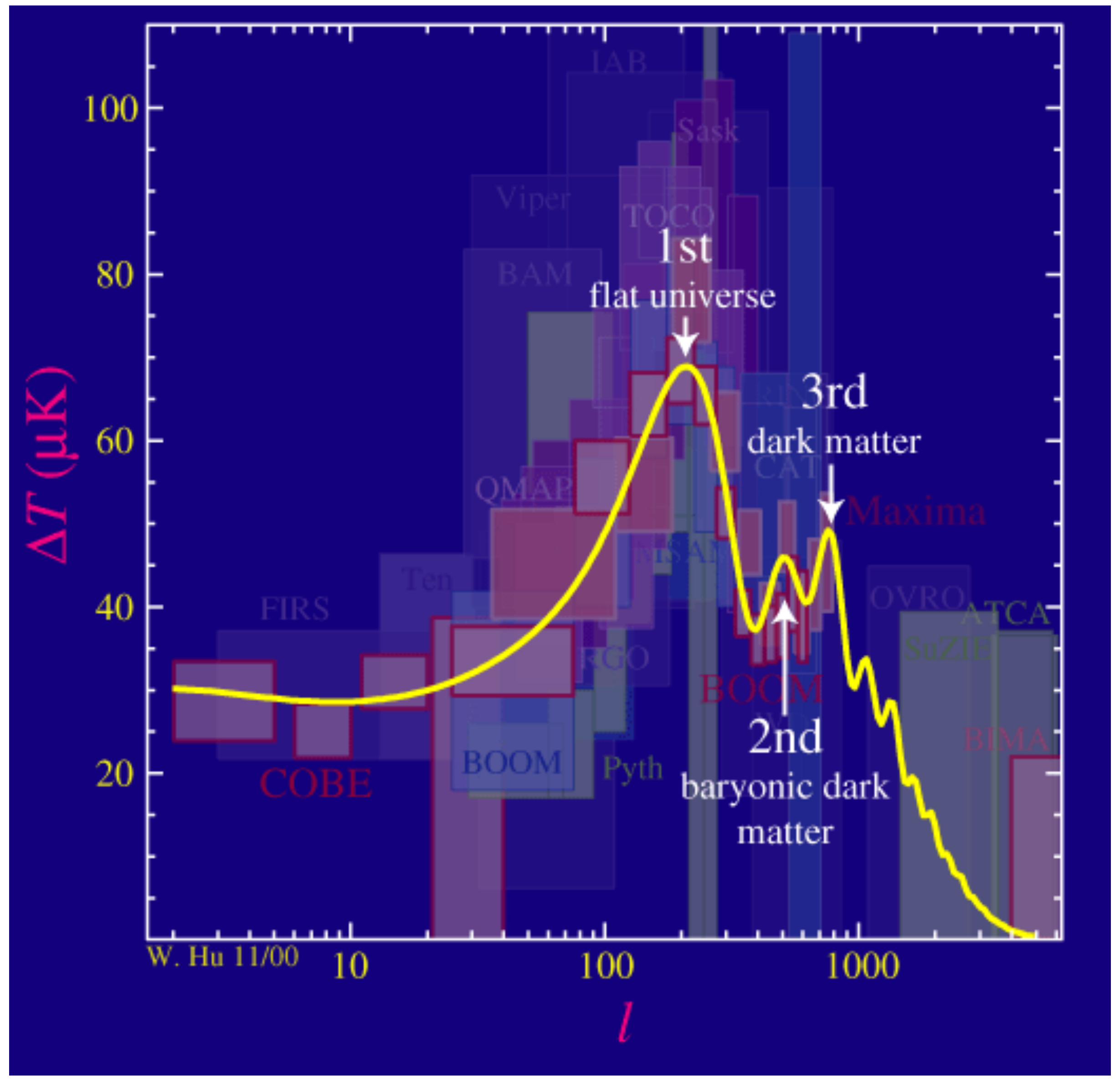
Galaxy rotation curve



gravitational lensing



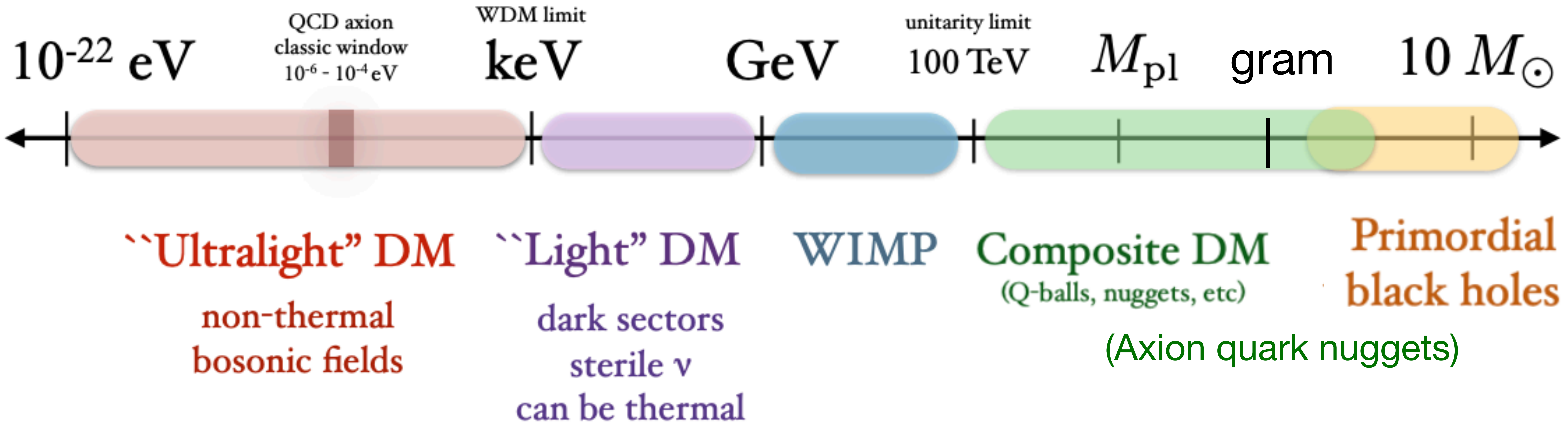
mass distribution of Bullet Cluster



CMB observation

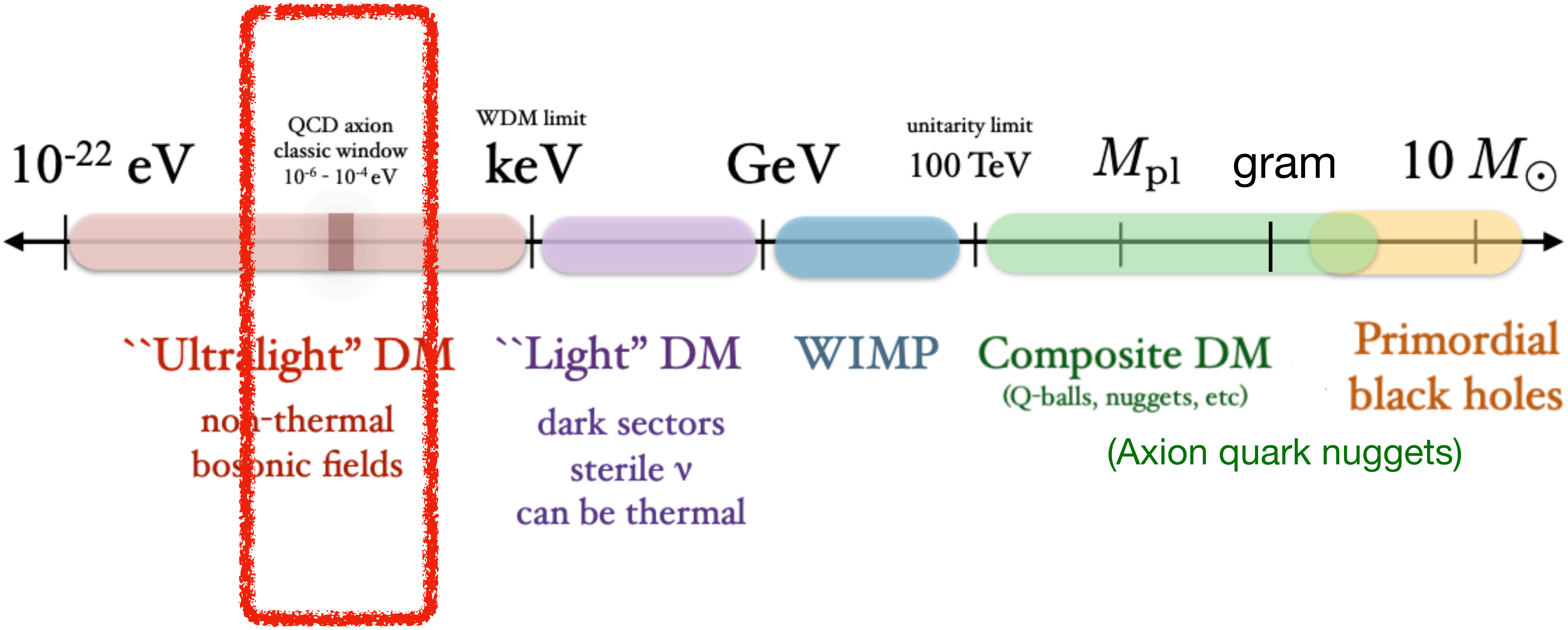
…… ……

Dark matter candidates



(adapted from 1904.07915, TASI lecture)

Dark matter candidates



(adapted from 1904.07915, TASI lecture)

Dark Photon

Extended the standard model by $U(1)_d$.

Kinetic mixing ϵ

$$\mathscr{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - A_\mu j^\mu - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2 - \frac{\epsilon}{2}F'^{\mu\nu}F_{\mu\nu}$$

Higgs mechanism,
or Stueckelberg mechanism

$m_{A'}$ and ϵ: two free parameters

Dark Photon

Fields redefinition (mass basis):

$$\begin{pmatrix} A \\ A' \end{pmatrix} \rightarrow \begin{pmatrix} 1 & \frac{-\epsilon}{\sqrt{1-\epsilon^2}} \\ 0 & \frac{1}{\sqrt{1-\epsilon^2}} \end{pmatrix} \begin{pmatrix} A \\ A' \end{pmatrix}$$

$$\mathscr{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2 - A_\mu j^\mu + \epsilon A'_\mu j^\mu$$

Dark electric field:

$$\mathbf{E}_{tot} = \mathbf{E} - \epsilon\mathbf{E}' \qquad \mathbf{E}' = -\dot{\mathbf{A}}' - \nabla A'^0$$

Searching for Dark Photon directly using antennas

Dark electric field:

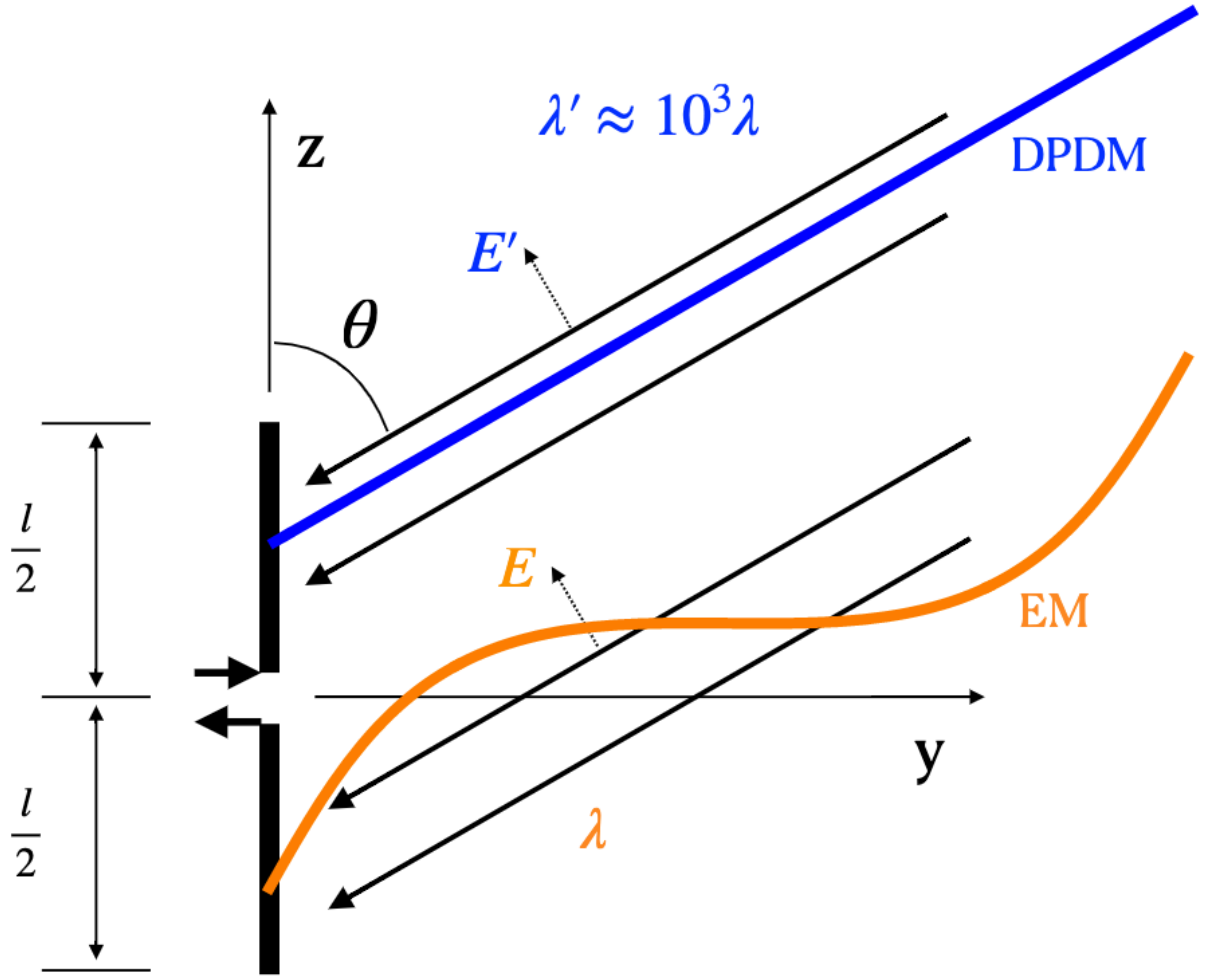
$$\mathbf{E}'_z = \mathbf{E}'_0 \sin\theta \cdot \cos(\omega t - \mathbf{k}'\mathbf{r}) \simeq \mathbf{E}'_0 \sin\theta \cdot \cos(\omega t)$$

($\mathbf{k}'\mathbf{r} \ll 1$ because $k'/\omega = v_{\rm DM} \sim 10^{-3}c$.)

Induced equivalent flux density:

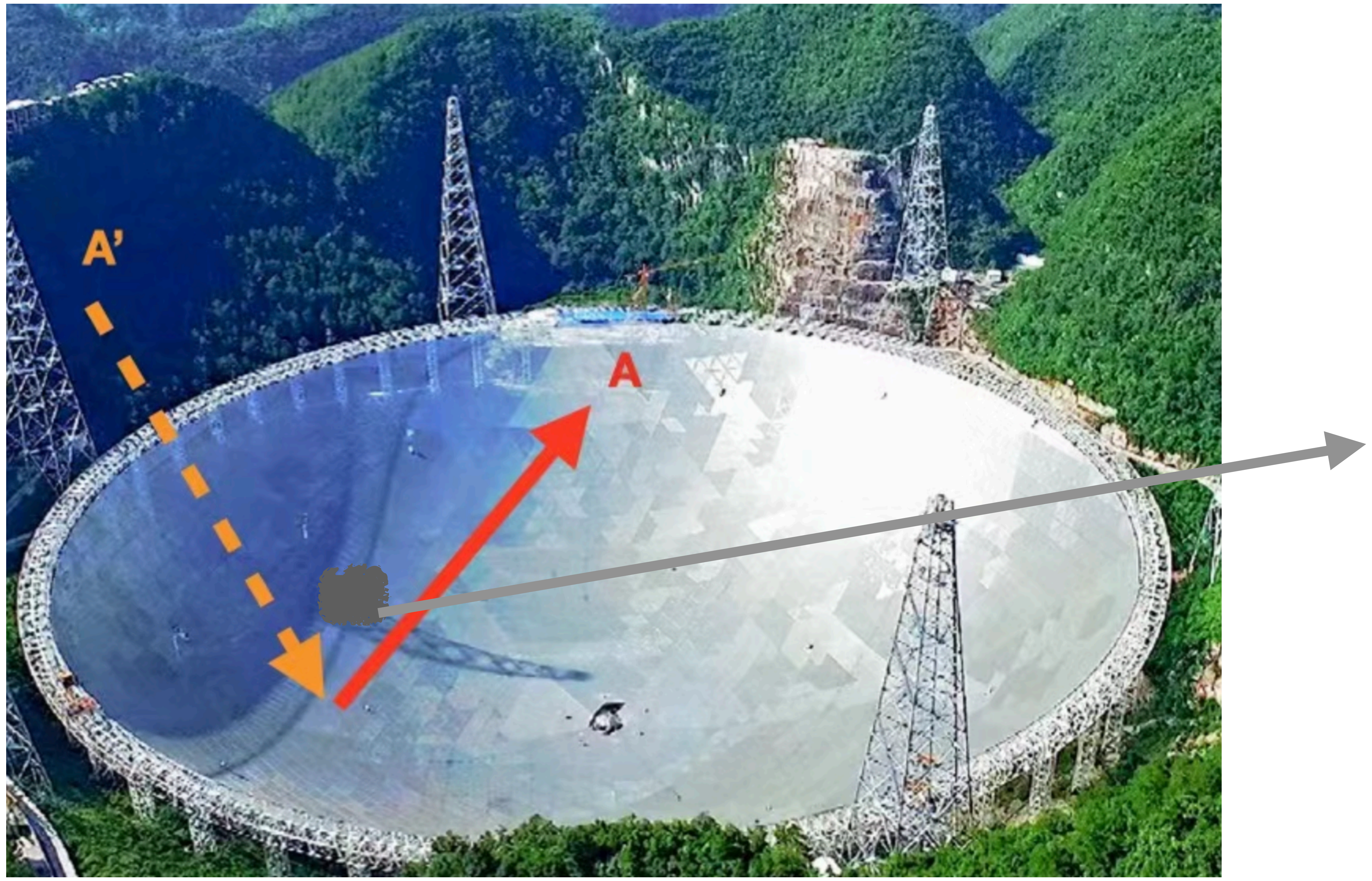
$$I^{\rm eqv}_{\rm dipole} \equiv \mathcal{C}\epsilon^2 \langle \mathbf{E}'^2 \rangle = \mathcal{C}\epsilon^2 \rho_{\rm DM}$$

C: $\mathcal{O}(1)$ numerical factor,
depending on detailed antenna configuration



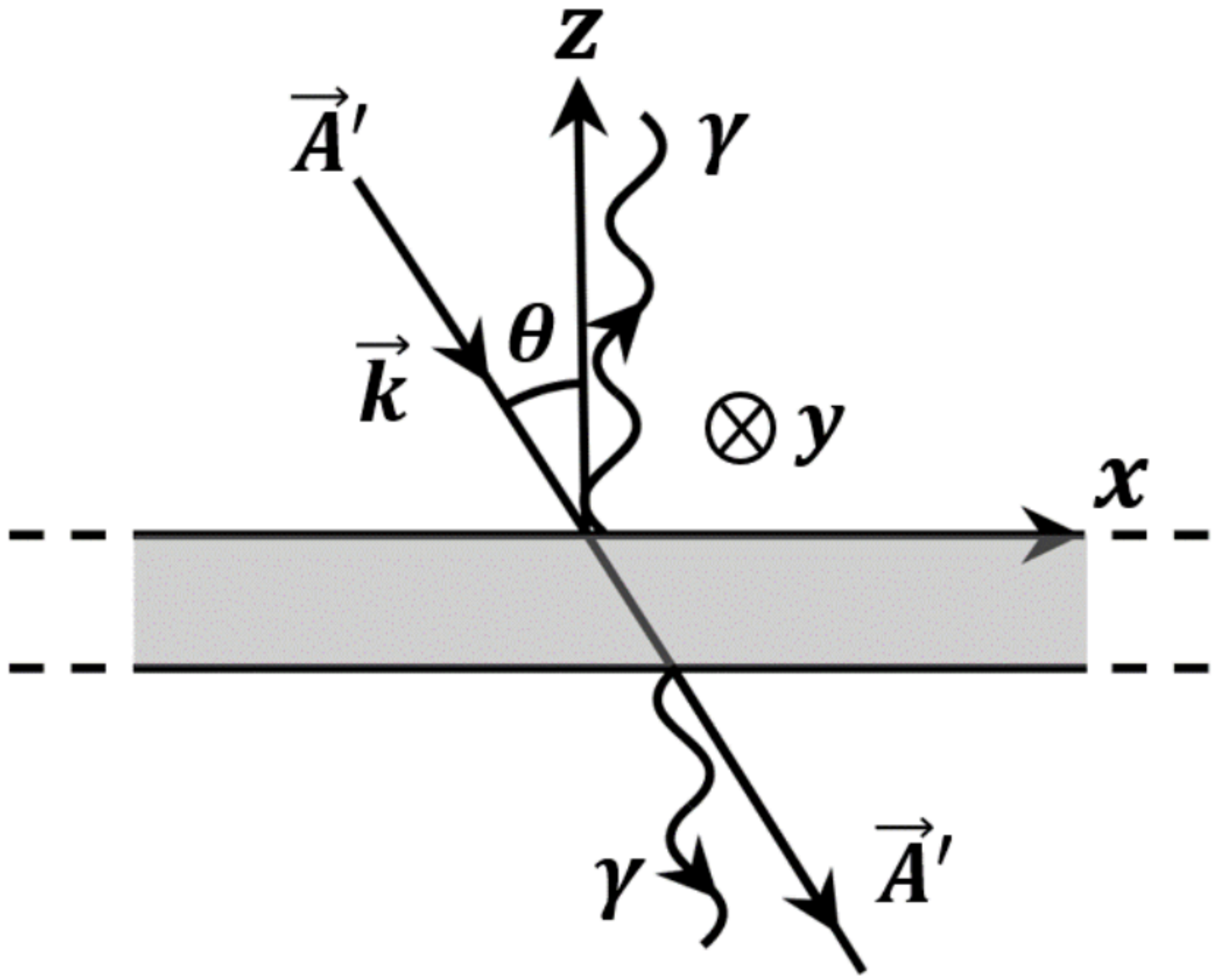
dipole antenna

Searching for Dark Photon directly using antennas



FAST
(Five-hundred-meter Aperture Spherical radio Telescope)

dish antenna

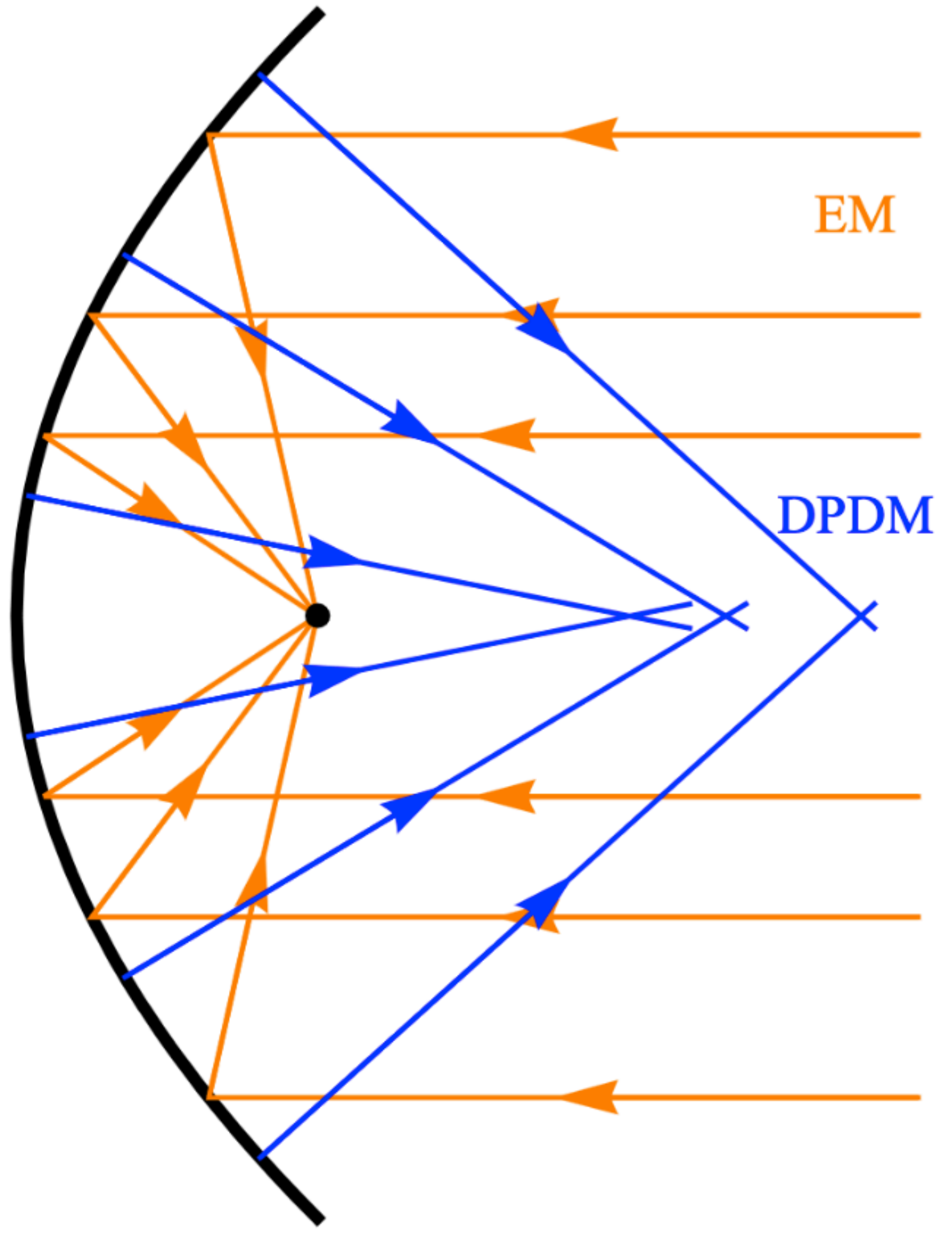


Dark electric field

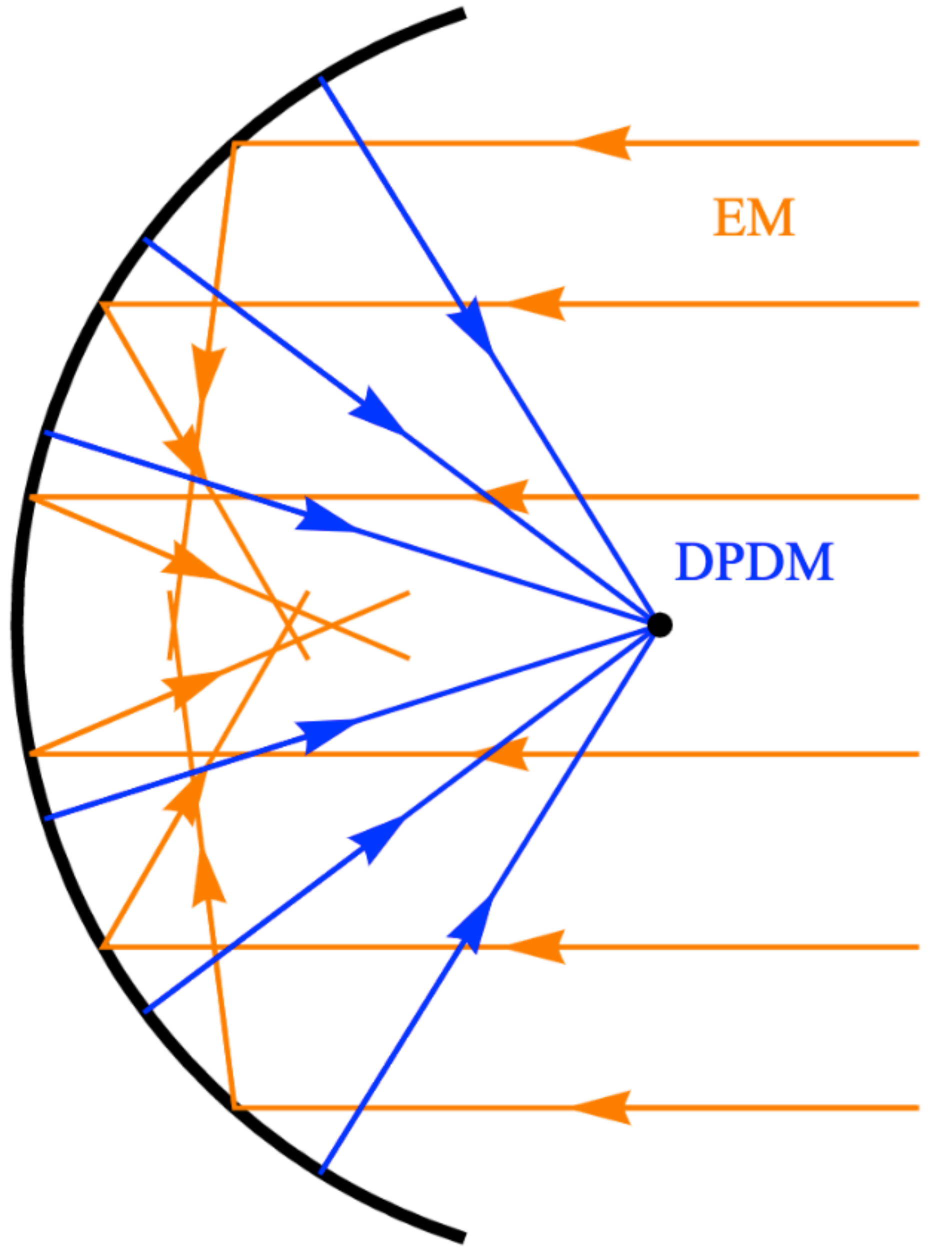
electrons oscillations

dipole emission $d\mathbf{p} = 2\epsilon \mathbf{A}'_{||} dS$

Dark-photon-induced signal in antenna: dish antenna



(FAST)



Direction of the reflecting EM wave:

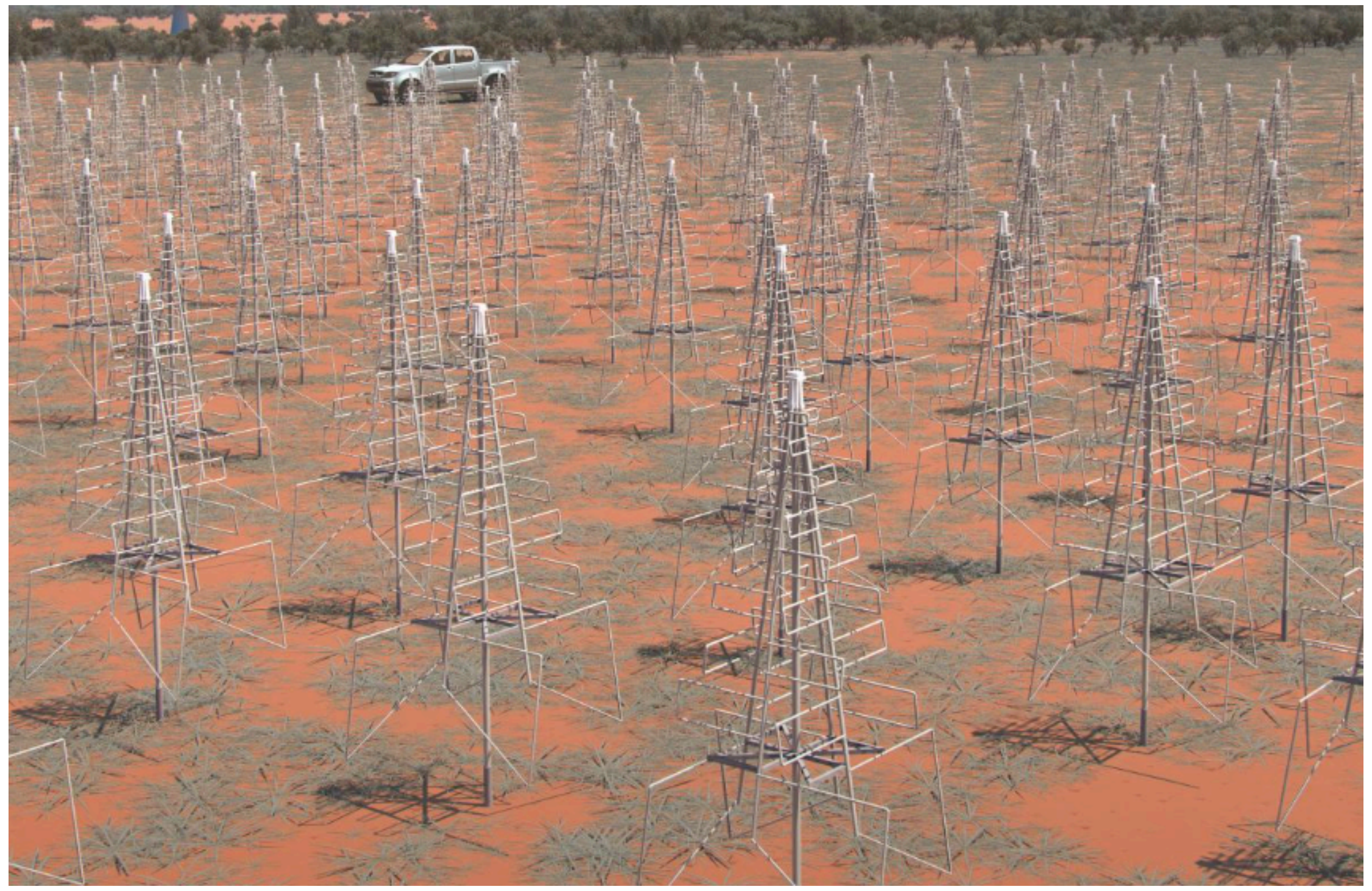
$$k_{||}^{\mathrm{out}} = k_{||}^{\mathrm{in}}, \quad k_{\perp}^{\mathrm{out}} = \sqrt{\omega^2 - (k_{||}^{\mathrm{out}})^2}, \quad k_{||}^{\mathrm{out}}/k_{\perp}^{\mathrm{out}} \simeq 10^{-3}$$

(perpendicular to the surface.)

(Ge+, 2207.05767)

Searching for Dark Photon directly using antennas

LOFAR array



SKA-Low array

SKA-mid array

For two antennas with distance d_{mn},
the correlation signal is suppressed by

$$S_{mn} \approx \exp(-m_{A'}^2 v_0^2 d_{mn}^2 / 8)$$

antenna arrays

Detection ability

Dark photon induced EM flux is

B: telescope frequency resolution

$$S_{\rm DP} = I_{\rm DP}/B \sim \epsilon^2 \rho_{\rm DM}/B$$

$$(B_{\rm sig} \ll B)$$

The signal is monochromatic with a small dispersion $B_{\rm sig}$:

$$B_{sig} \simeq \frac{1}{2\pi} \cdot \frac{k^2}{m_{A'}} \simeq 0.15 \text{ kHz} \left(\frac{m_{A'}}{\mu\text{eV}}\right)$$

Detection ability

The telescope detection ability is:

$$S_{\min} = \frac{\mathrm{SEFD}}{\eta_s \sqrt{n_{\mathrm{pol}} B \cdot t_{obs}}}$$

$$\mathrm{SEFD} = \frac{2k_B T_{\mathrm{sys}}}{A_{\mathrm{eff}}}$$

SEFD: system equivalent (spectral) flux density.

T_{sys} : antenna temperature.

A_{eff} : antenna effective area.

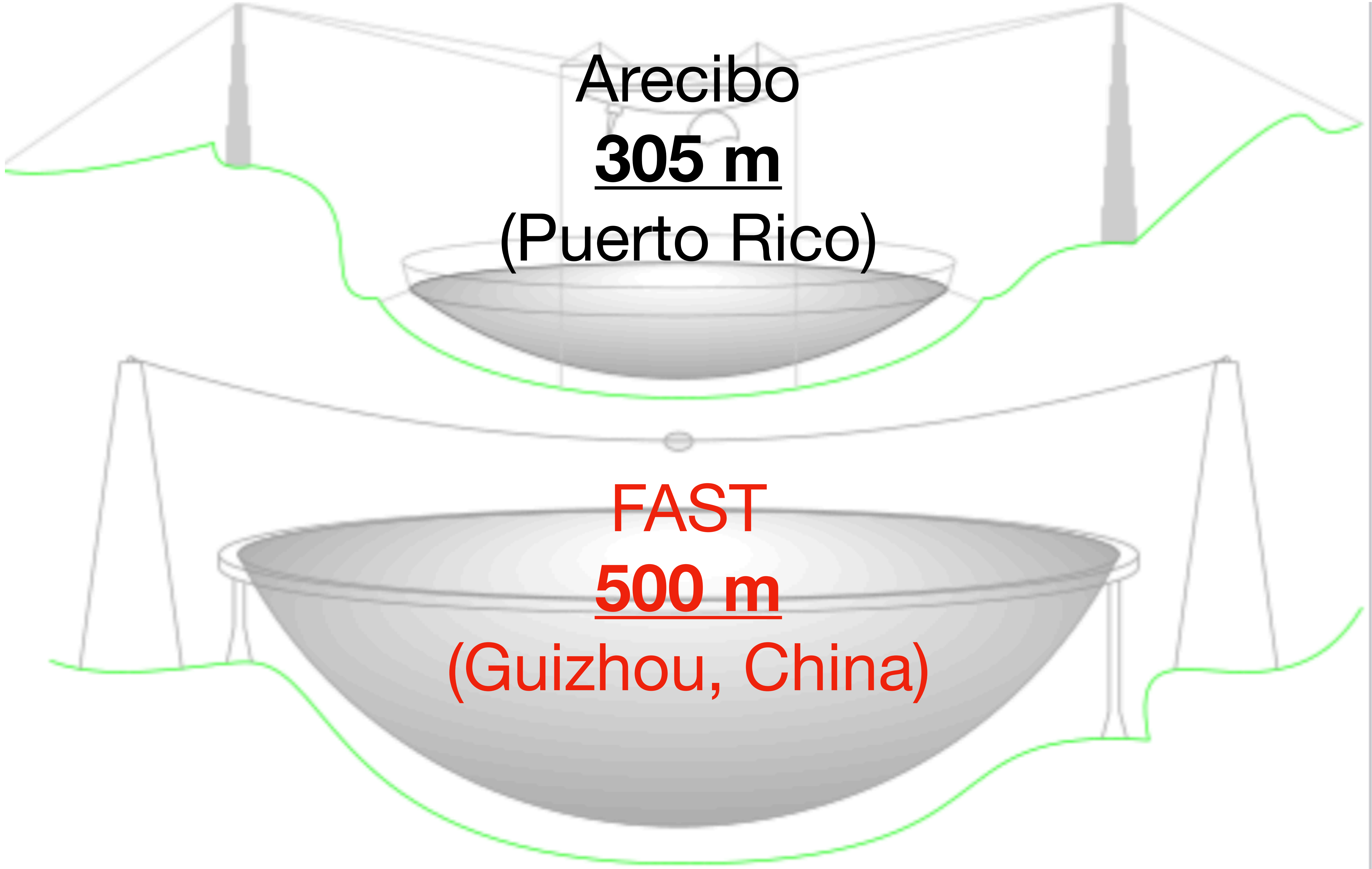
t_{obs}: observation time

Set the limits:

$$S_{\mathrm{DP}} \geq S_{\min} \quad \Rightarrow \quad \epsilon^2 \propto \rho_{\mathrm{DM}} \cdot \mathrm{SEFD} \cdot \sqrt{\frac{B}{t_{obs}}}$$

FAST telescope

Five-hundred-meter
Aperture Spherical radio Telescope
(FAST)



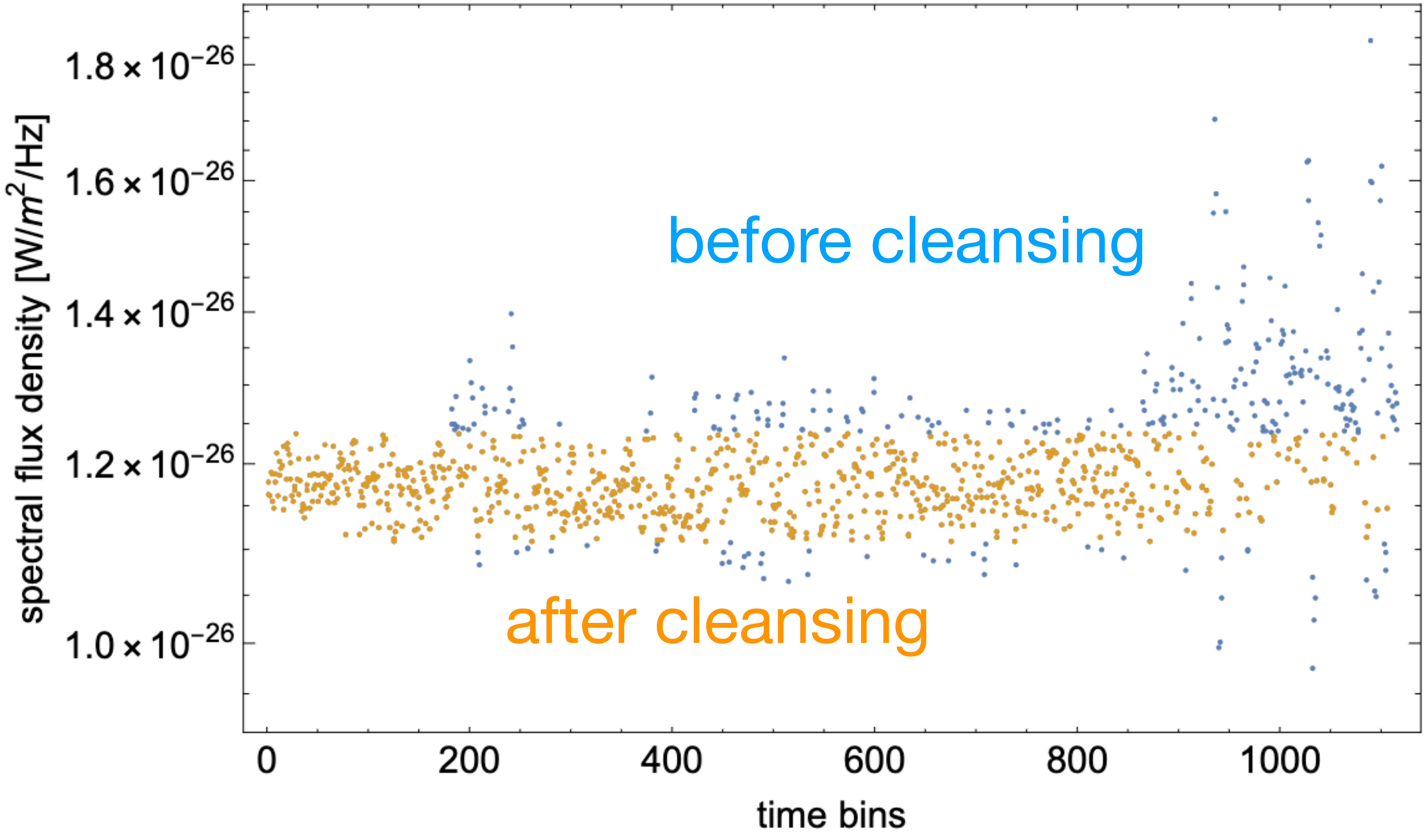
FAST vs. Arecibo

FAST Data

Frequency range 1-1.5 GHz. Good frequency resolution 7.63 kHz.
Observed on December 14, 2020 (110 min)

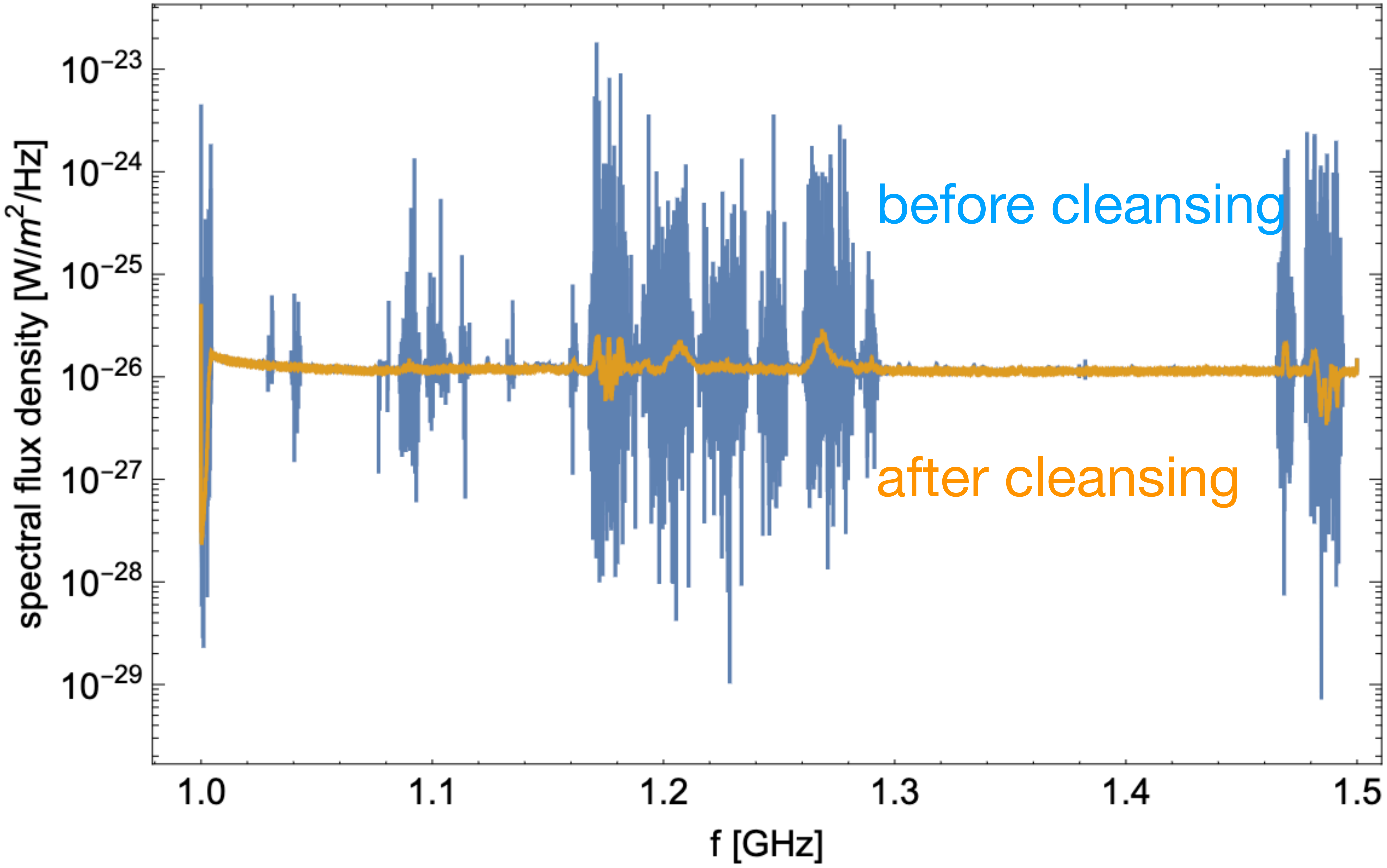
Dark photon induced signal is constant with time.

Remove large fluctuations for each frequency bin.

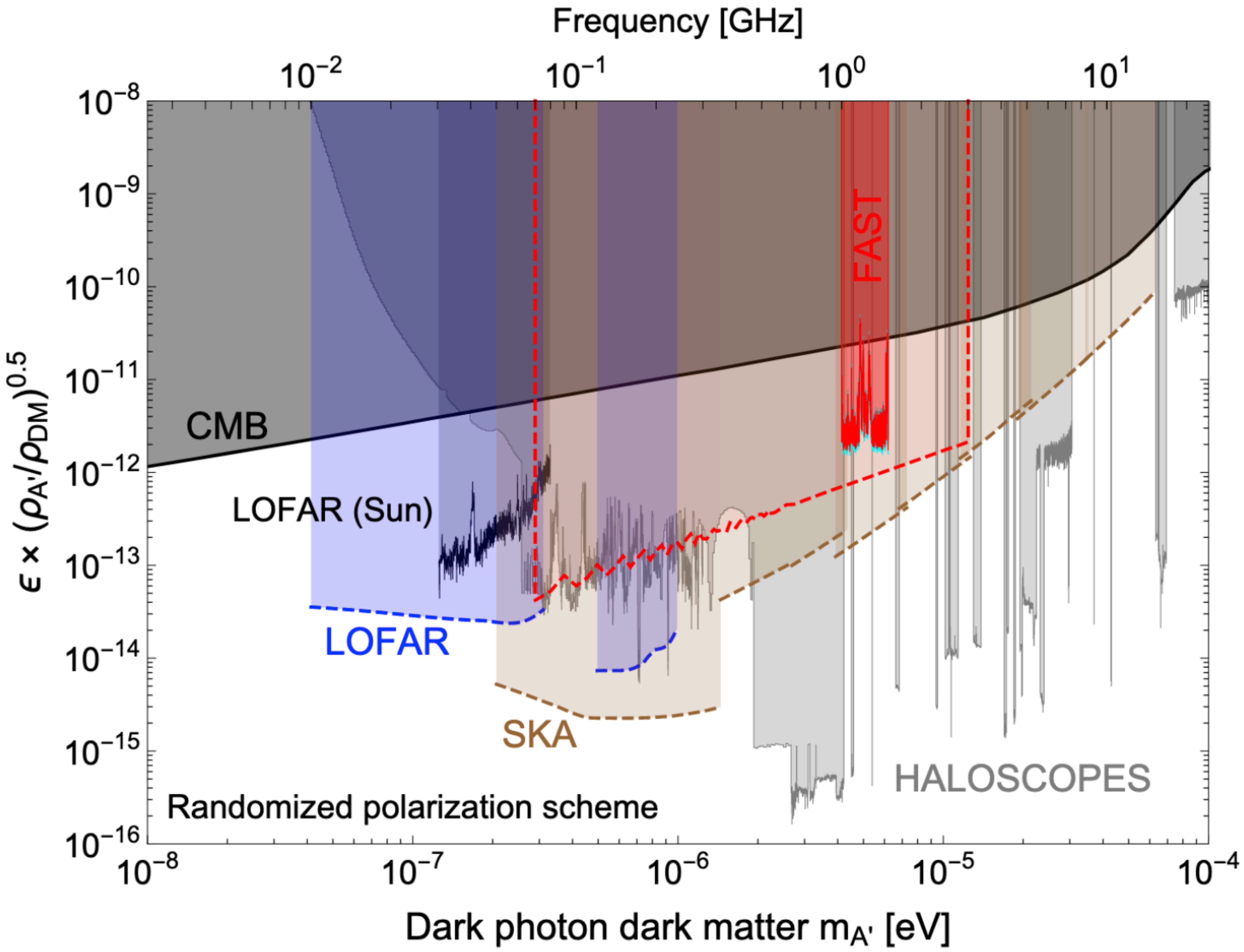


FAST Data

Data cleansing



Searching for Dark Photon directly using antennas



H. An, **SG,** W.Q. Guo, X.Huang, J.Liu, Z.Lu
2207.05767
(PRL)

Featured in Physics

Another mechanism:

Dark photons resonantly convert into photons in the solar plasma

Dark Photon

$$\mathscr{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - A_\mu j^\mu - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2 - \frac{\epsilon}{2}F'^{\mu\nu}F_{\mu\nu}$$

Fields redefinition (interaction basis):

$$\begin{pmatrix} A \\ A' \end{pmatrix} \to \begin{pmatrix} \frac{1}{\sqrt{1-\epsilon^2}} & 0 \\ \frac{-\epsilon}{\sqrt{1-\epsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} A \\ A' \end{pmatrix},$$

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

Dark photon converts into photon

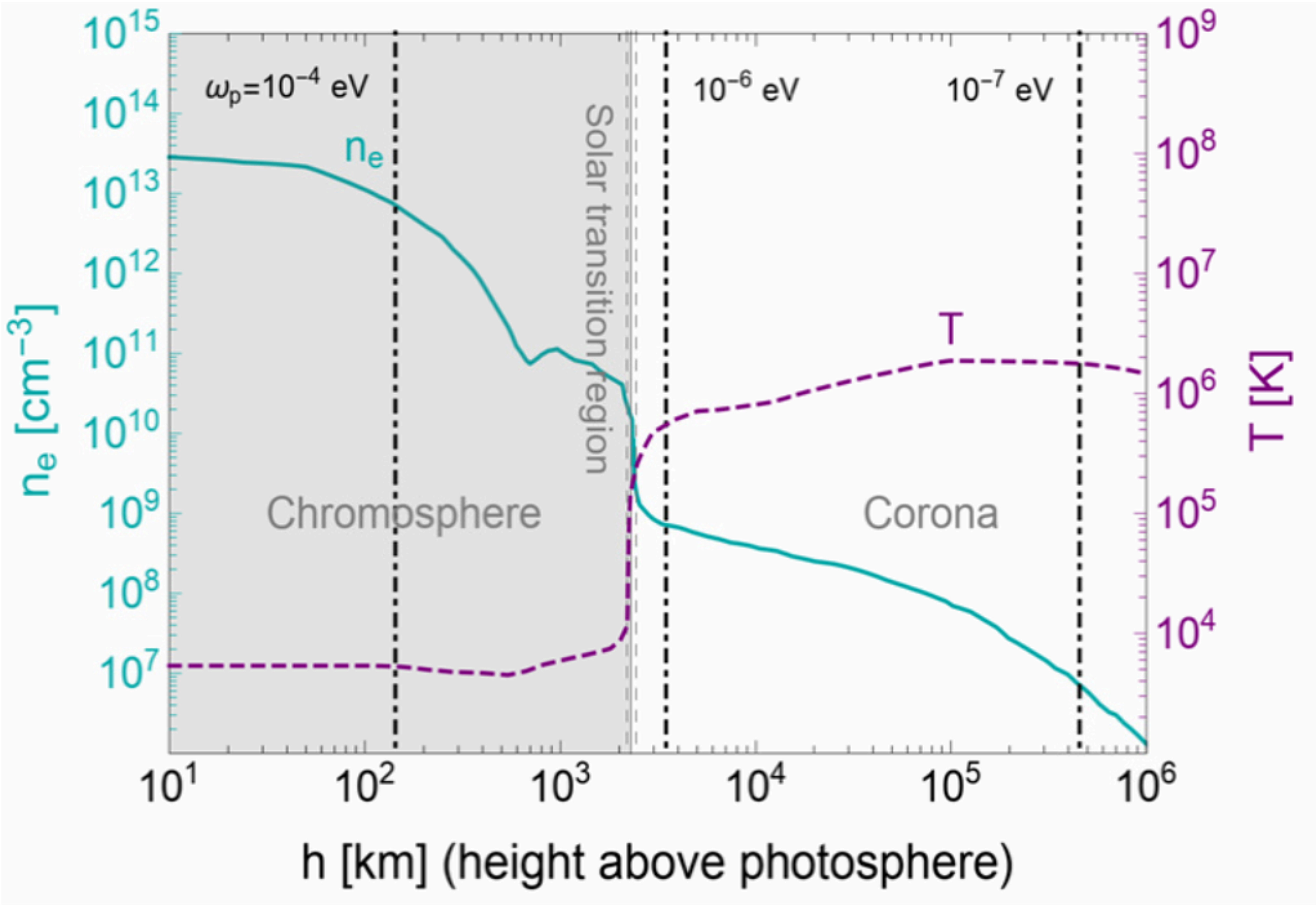
Equations of motion for dark photon-photon conversion:

$$\left(\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial r^2} + \tilde{M}\right)\begin{pmatrix} A \\ A' \end{pmatrix} = 0, \quad \tilde{M} = \begin{pmatrix} m_A^2 & -\epsilon m_{A'}^2 \\ -\epsilon m_{A'}^2 & m_{A'}^2 \end{pmatrix}.$$

ω_p: photon effective mass (plasma frequency)

$$m_A = \omega_p = \sqrt{\frac{4\pi\alpha_{EM} n_e}{m_e}}$$

Dark photon converts into photon



Solar corona plasma

(H. An, F. P. Huang, J. Liu and W. Xue, 2010.15836, taken from V. De La Luz, et al. *Geofisica Internacional* 47 (Jul, 2008) 197-203)

Dark photon converts into photon

Conversion probability: $$P_{X\to\gamma} = \left| \int_{r_0}^{r} dr' \Delta_{AX}(r') \exp\left\{ i \int_{r_0}^{r'} dr'' \frac{1}{2k_r} \left[\omega_p^2(r'') - m_X^2 \right] \right\} \right|^2.$$

Applying Saddle-point method: $$P_{A'\to\gamma} \simeq \frac{2}{3}\pi\epsilon^2 m_{A'} \frac{1}{v_r(r_c)} \left| \frac{\partial \ln \omega_p^2}{\partial r} \right|^{-1}_{r=r_c}$$

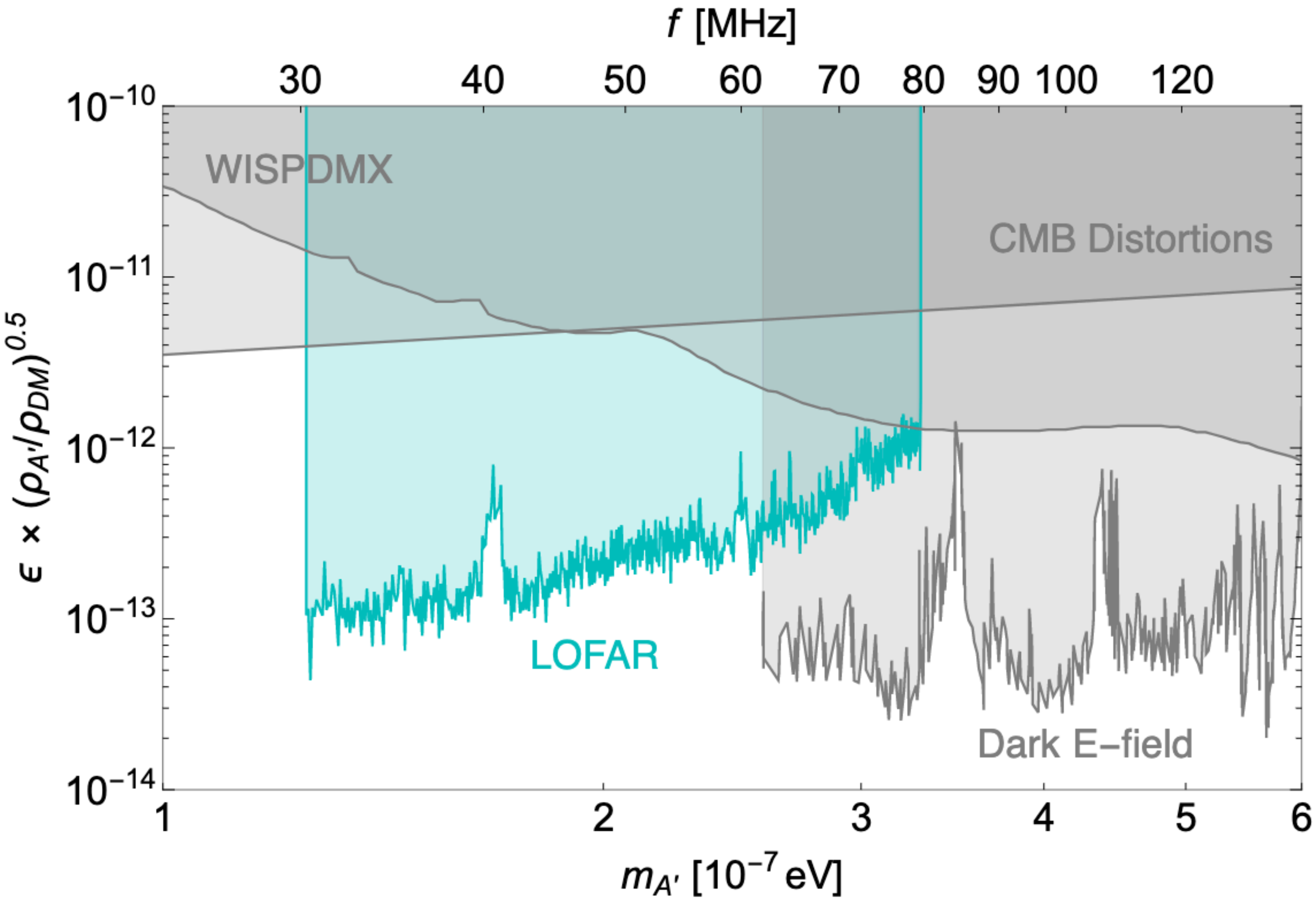
Conversion power: $$\frac{d\mathcal{P}_0}{d\Omega} = 2 \times \frac{1}{4\pi} \rho_{\rm DM} v_0 \cdot \int_0^{b_{\max}} db 2\pi b \cdot P_{X\to\gamma} = r_c^2 P_{X\to\gamma}(v_0) \rho_{\rm DM} v(r_c).$$

Signal strength observed on the Earth: $$S_{\rm sig} = \frac{1}{d^2} \frac{1}{\mathcal{B}} \frac{d\mathcal{P}}{d\Omega}$$

(H. An, F. P. Huang, J. Liu and W. Xue, 2010.15836)

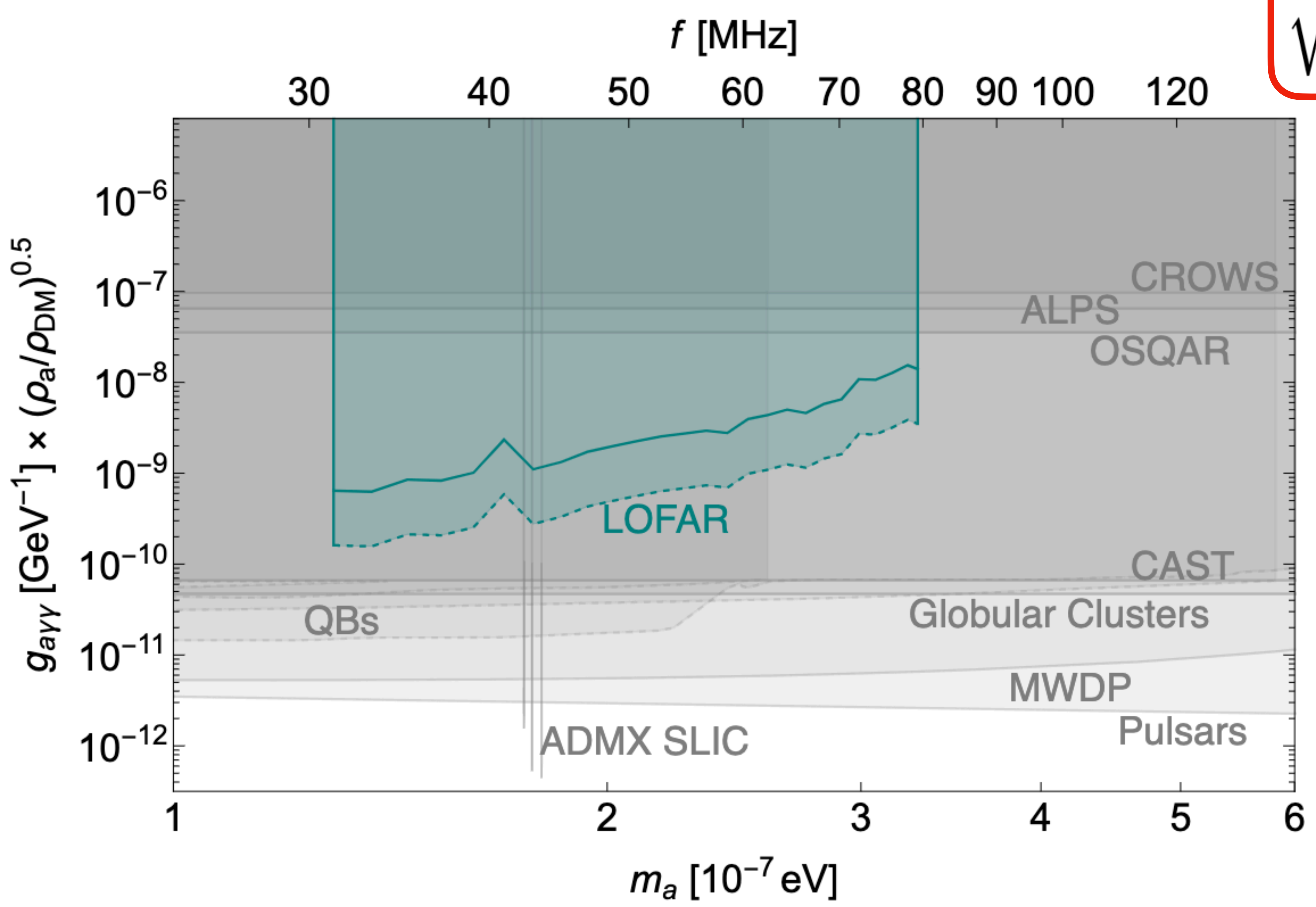
(H. An, **SG**, J. Liu, 2304.01056)

LOFAR data



(H.An, X.Chen, **SG**, J.Liu, Y.Luo 2301.03622)

LOFAR data



Axion case

$$\sqrt{\frac{2}{3}}\epsilon m_{A'}^2 \Leftrightarrow g_{a\gamma\gamma}|\boldsymbol{B}_T|\omega, \quad (\omega \simeq m_a, \text{non-relativistic}).$$

Constraints for the axion case are not so good in comparison with the dark photon case.

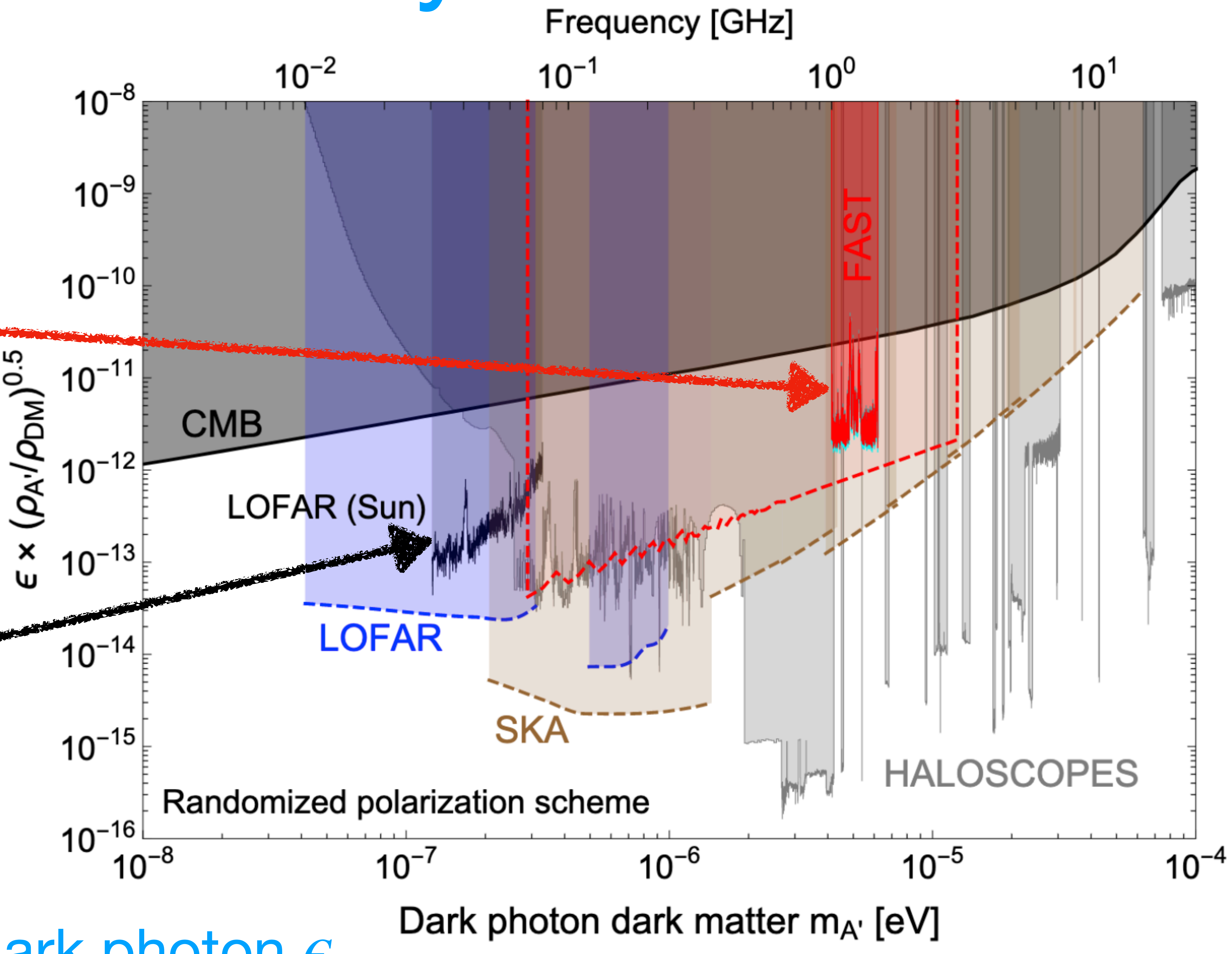
Because solar magnetic field in solar corona is relatively weak, 1~4 Gauss. (Yang et al, Science 2020, 369, 694–697)

(H.An, X.Chen, **SG**, J.Liu, Y.Luo 2301.03622)

Summary

local signal induced on telescope antennas

distant signal of resonant conversion in solar corona



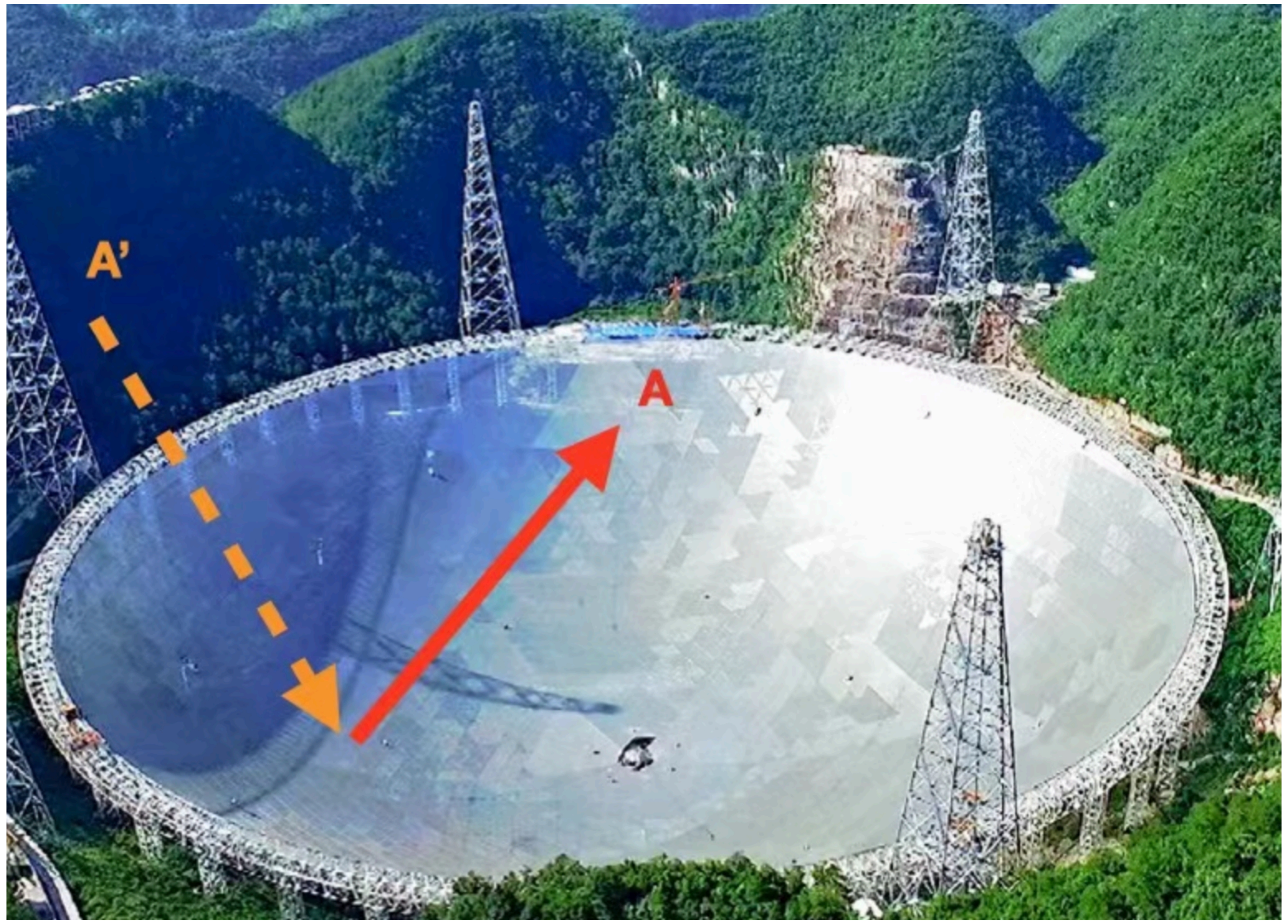
Constraints on dark photon ϵ

Thank you for watching

Questions?

Backup Slides

Dark-photon-induced signal in antenna: dish antenna



FAST
(Five-hundred-meter Aperture Spherical radio Telescope, “中国天眼”)

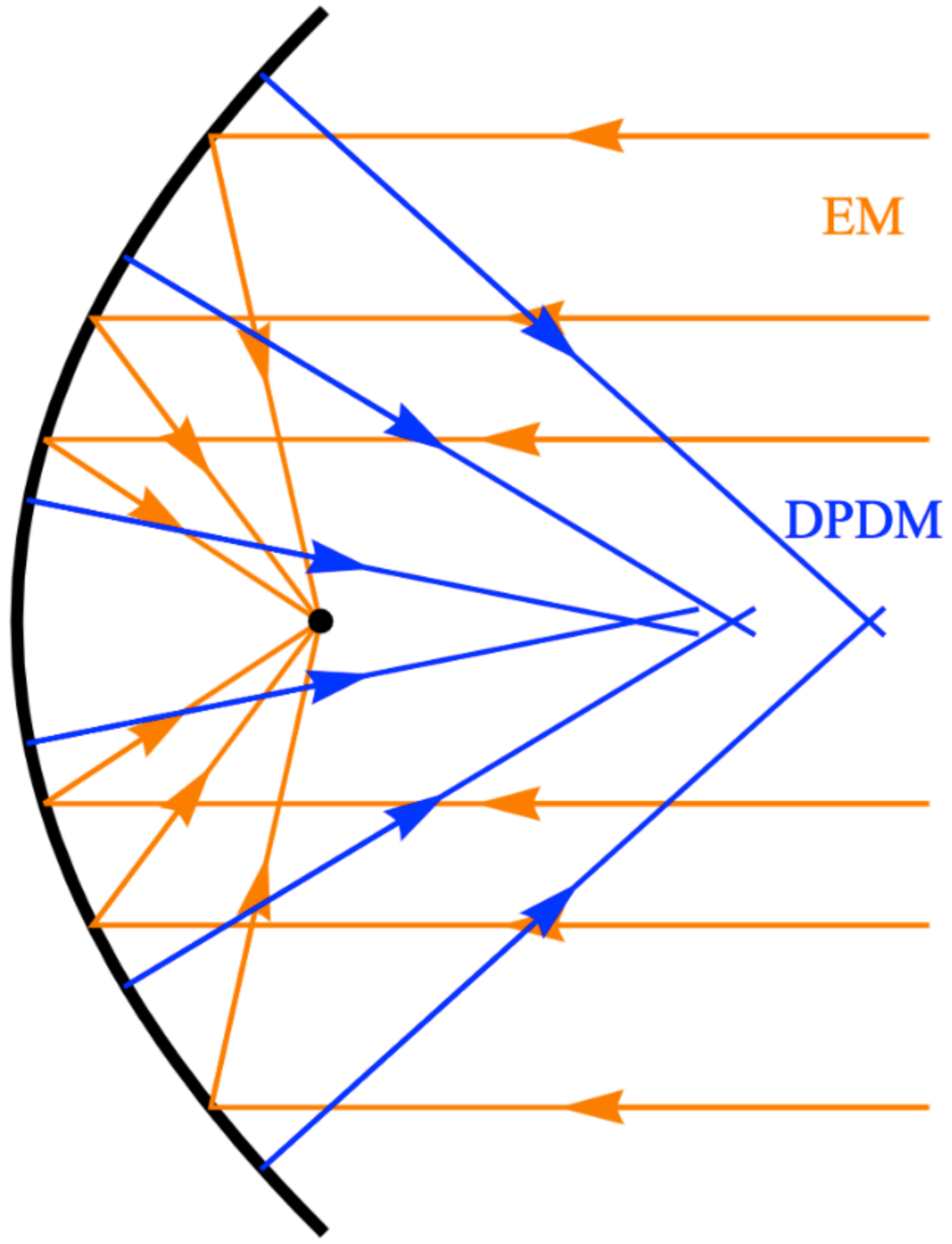
covering 1-1.5 GHz,
good resolution 7.63 kHz.

Direction of the reflecting EM wave:

$$k_{||}^{\rm out} = k_{||}^{\rm in}, \quad k_{\perp}^{\rm out} = \sqrt{\omega^2 - (k_{||}^{\rm out})^2}, \quad k_{||}^{\rm out}/k_{\perp}^{\rm out} \simeq 10^{-3}$$

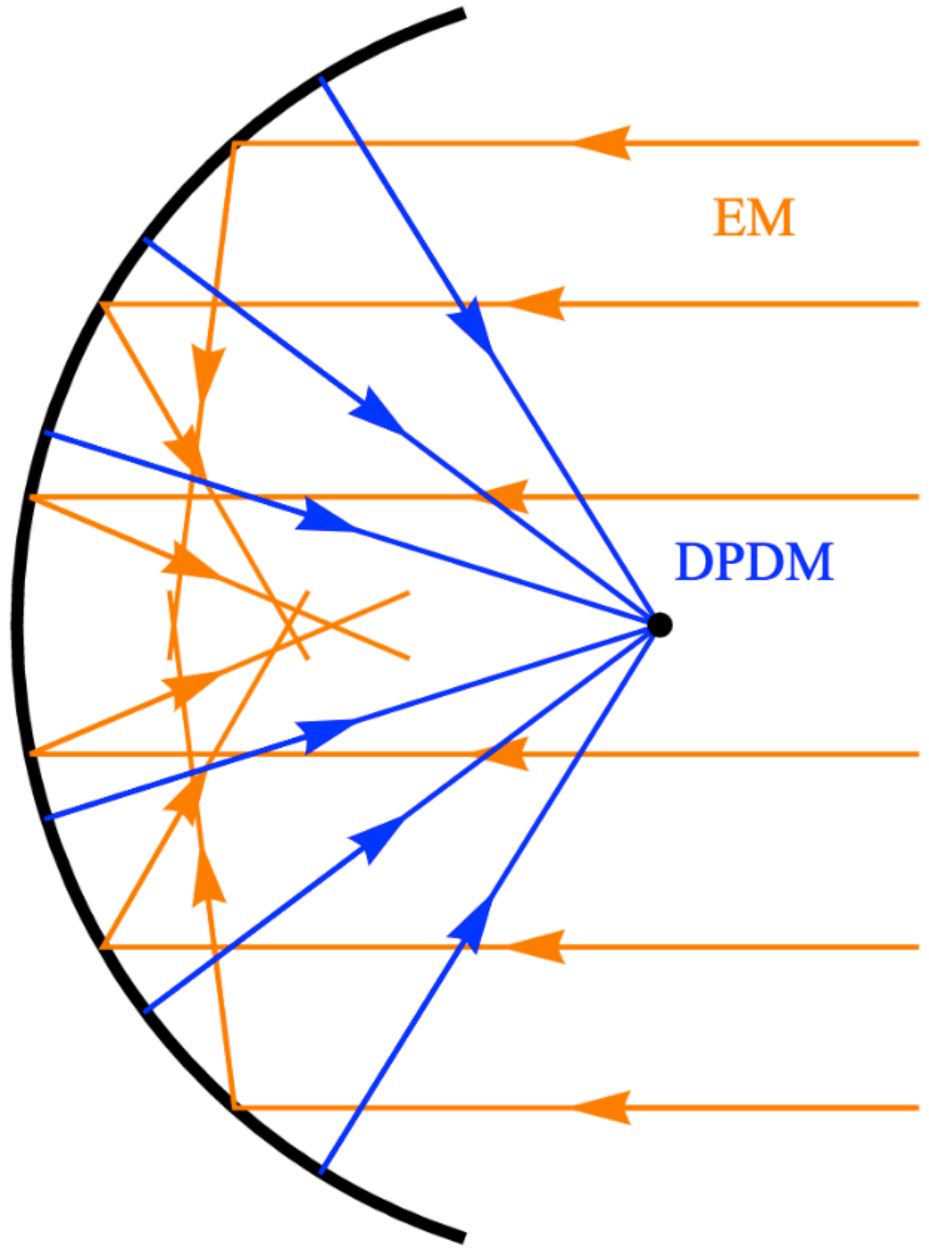
(perpendicular to the surface.)

Dark-photon-induced signal in antenna: dish antenna



Parabolic Mirror

(FAST)



Spherical Mirror

(Ge+, 2207.05767)

Direction of the reflecting EM wave:

$$k_{||}^{\rm out} = k_{||}^{\rm in}, \quad k_{\perp}^{\rm out} = \sqrt{\omega^2 - (k_{||}^{\rm out})^2}, \quad k_{||}^{\rm out}/k_{\perp}^{\rm out} \simeq 10^{-3}$$

(perpendicular to the surface.)

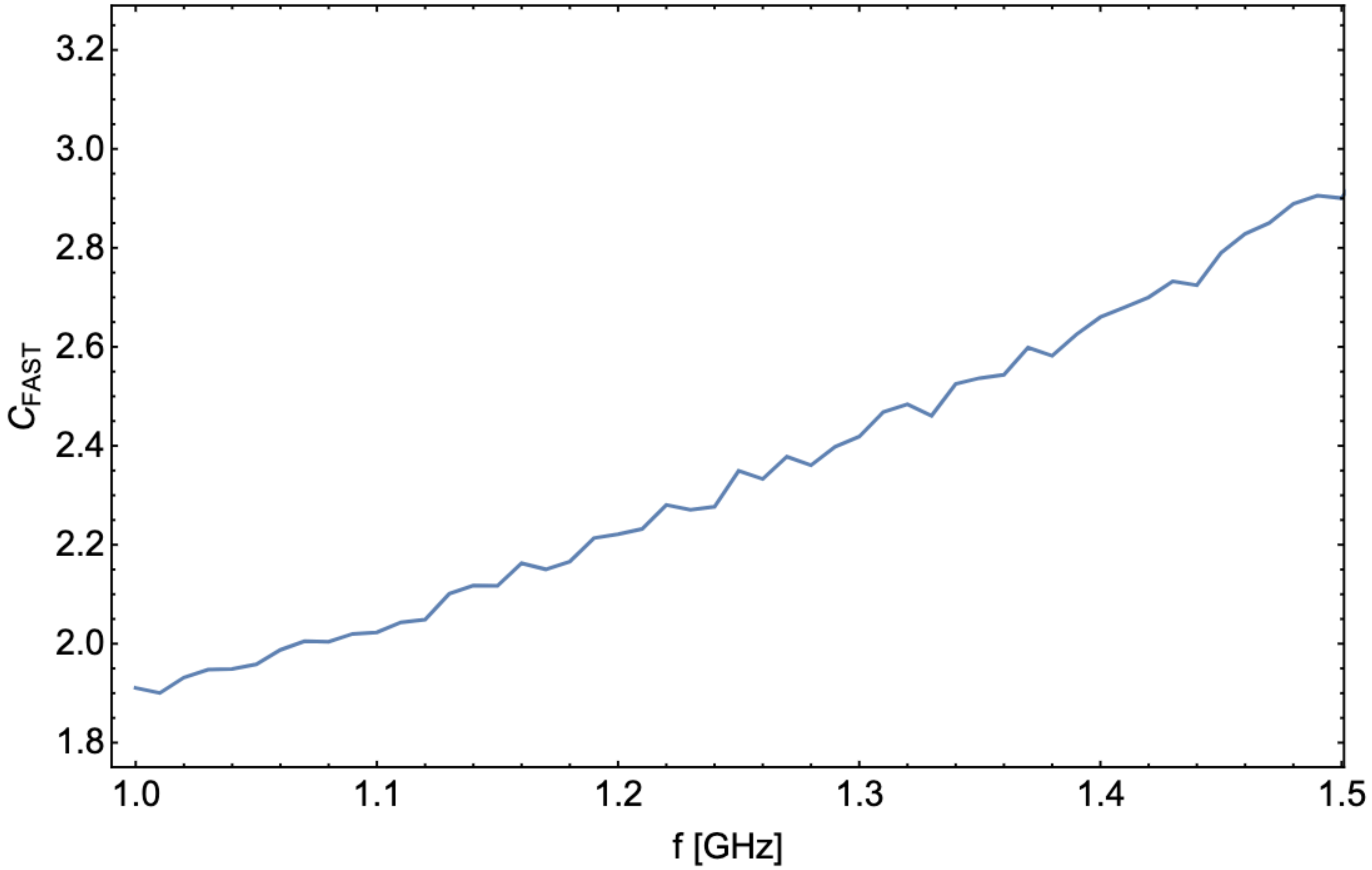
Numerical simulation of FAST telescope

The DP-induced equivalent flux density:

$$I^{\rm eqv}_{\rm dish} = \mathcal{C}\epsilon^2 \langle \mathbf{E}'^2 \rangle \times \boxed{\frac{\lambda^2}{\mathcal{A}}} = \mathcal{C}\epsilon^2 \rho_{\rm DM} \frac{\lambda^2}{\mathcal{A}}$$

suppression factor compared with the ordinary EM, due to non-focusing.

Numerical simulation of C:



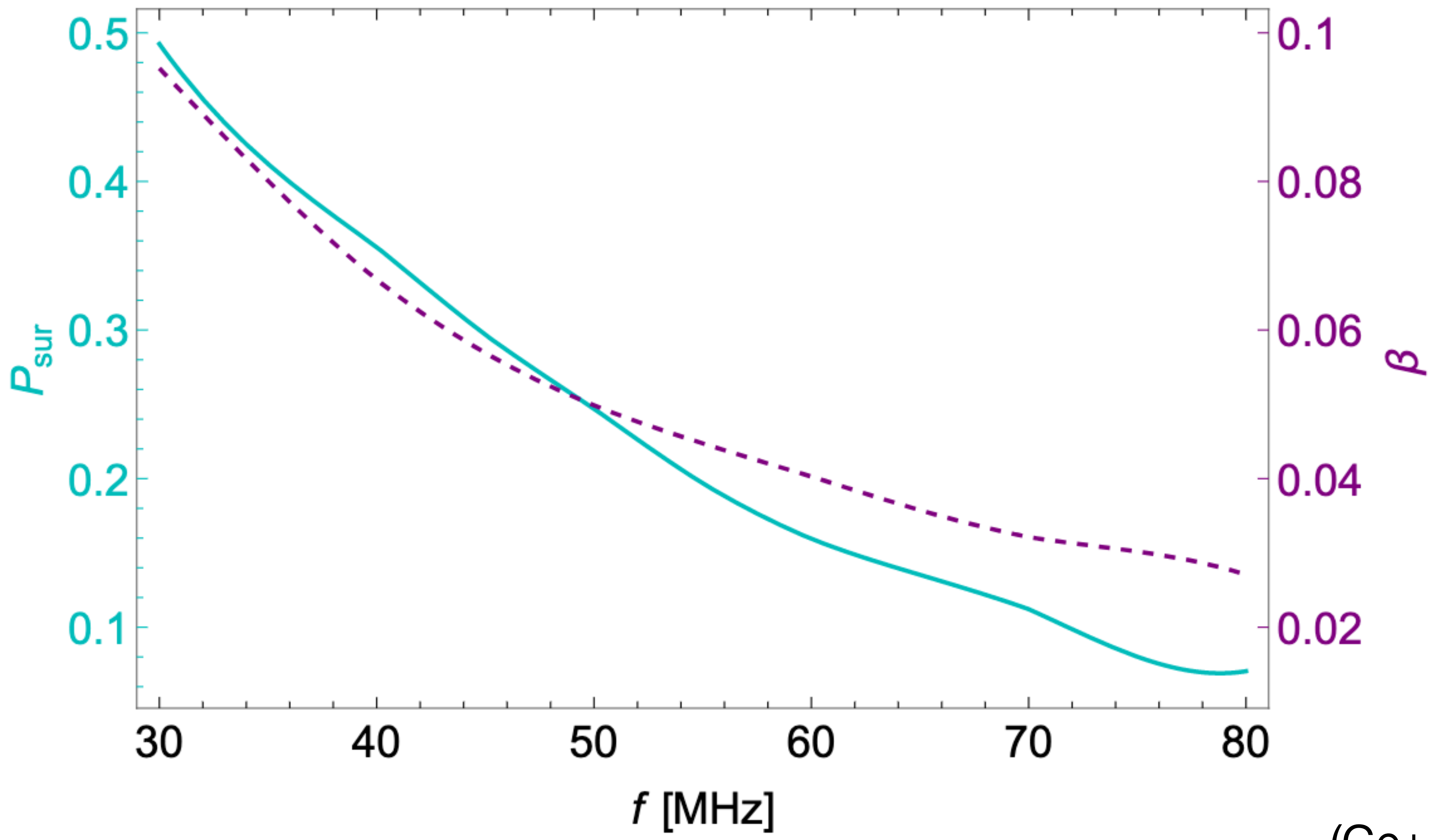
(Ge+, 2207.05767)

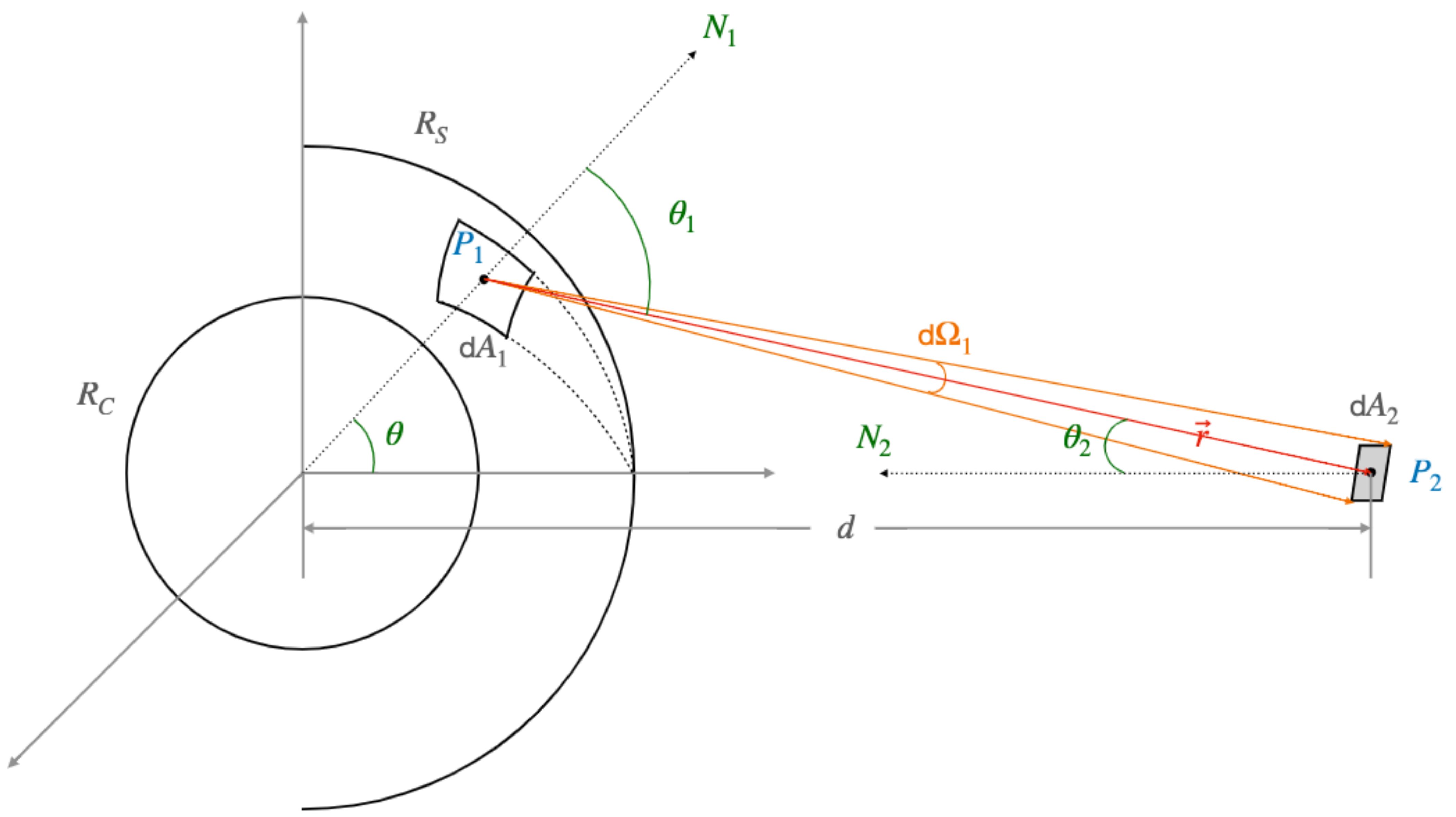
$$S^{\rm eqv}_{\rm FAST}(f) \equiv \frac{I^{\rm eqv}_{\rm FAST}}{\mathcal{B}} \approx 4.6 \times 10^{-6} \epsilon^2 \frac{\mathcal{C}_{\rm FAST}(f)}{\mathcal{C}_{\rm FAST}(1{\rm GHz})} \frac{\rm W}{\rm m^2\ Hz}.$$

Detection on Earth

Photon propagation in the solar plasma:
> Refraction effect
> Absorption effect (inverse bremsstrahlung)
> Scattering effects (Compton + irregular refraction by electron density fluctuations)

Ray-tracing Monte Carlo simulation:

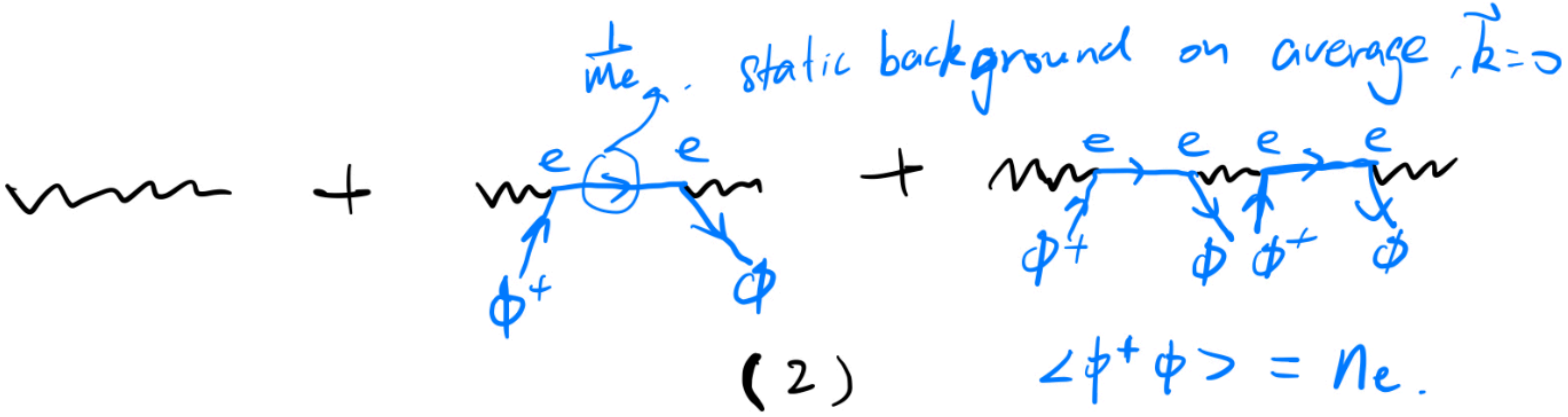




(Ge+, 2301.03622)

Dark photon converts into photon

forward scattering changes the photon's dispersion relation:



photon effective mass in plasma:

$$m_A = \omega_p = \sqrt{\frac{4\pi\alpha_{EM} n_e}{m_e}}$$