Dark Photon Dark Matter Detection with Radio Telescopes

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2010.15836, 2207.05767, 2301.03622, 2405.12285

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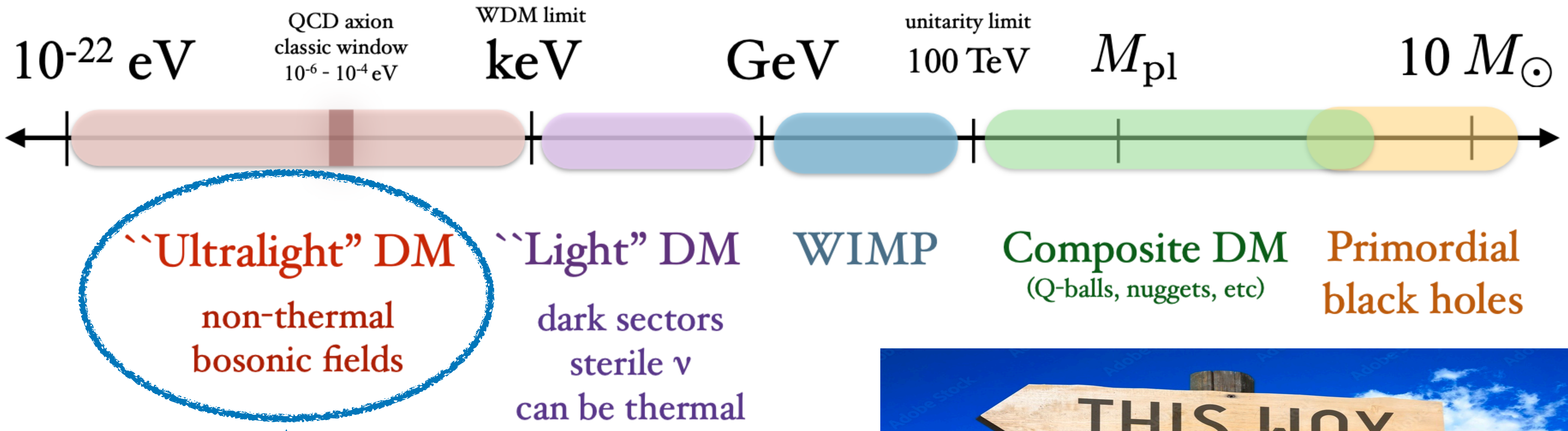
Outlines

- Ultralight bosonic dark matter
- Detection using radio telescopes
  - Resonant conversion at solar corona
  - Local conversion at radio telescope
- Summary

The dark matter candidate models

1904.07915， TASI lecture



Today's focus

HEP at a cross-road: explore all directions!

Ultralight Bosonic Dark Matter

- Ultralight: $m \lesssim \mathrm{keV}$, ultralight due to shift symmetry (pseudo-Nambu Goldstone, e.g. Axion)
- Bosonic: Pauli-exclusion for fermonic DM
- Exits as classical fields ($m \lesssim \mathcal{O}(1)\ \mathrm{eV}$)
- Typical models:
  - Pseudo-scalar: Axion, Axion-like Particle
  - Dark Scalar: dilaton-like coupling
  - Vector: kinetic mixing dark photon, $U(1)_{B-L}$ dark photon etc

Ultralight bosonic dark matter: Dark Photon

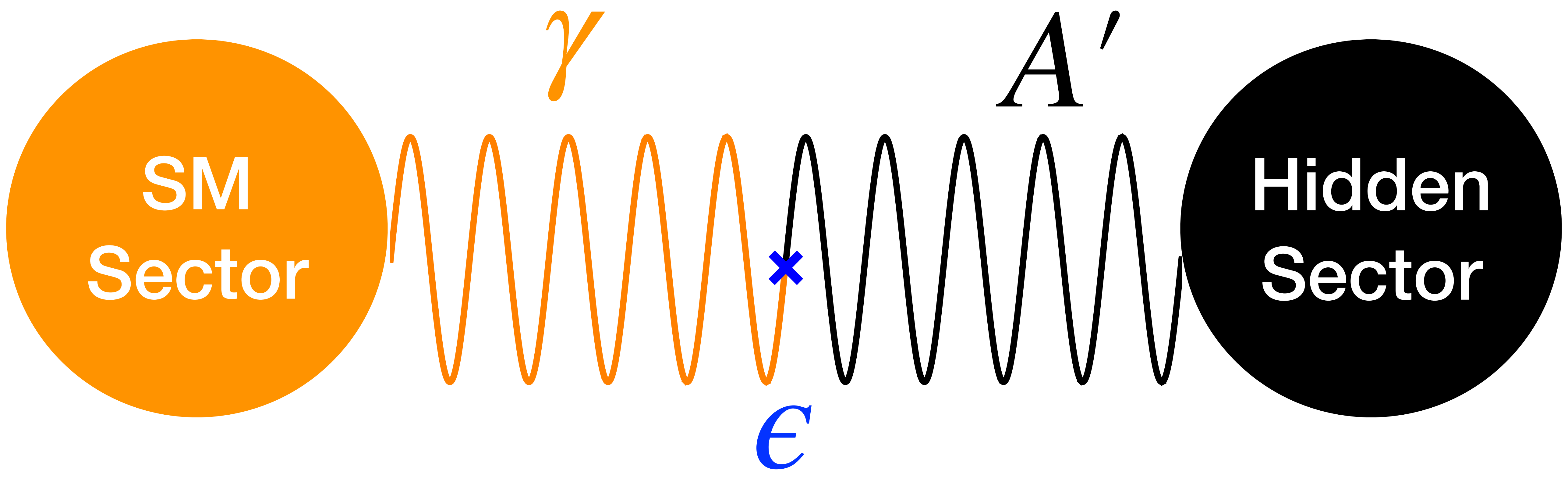
- Maxwell Equations: $\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + 0 \times A^{\mu}A_{\mu} - eA_{\mu}j^{\mu}_{\rm em}$
- Extra U(1) extension of Maxwell Equations

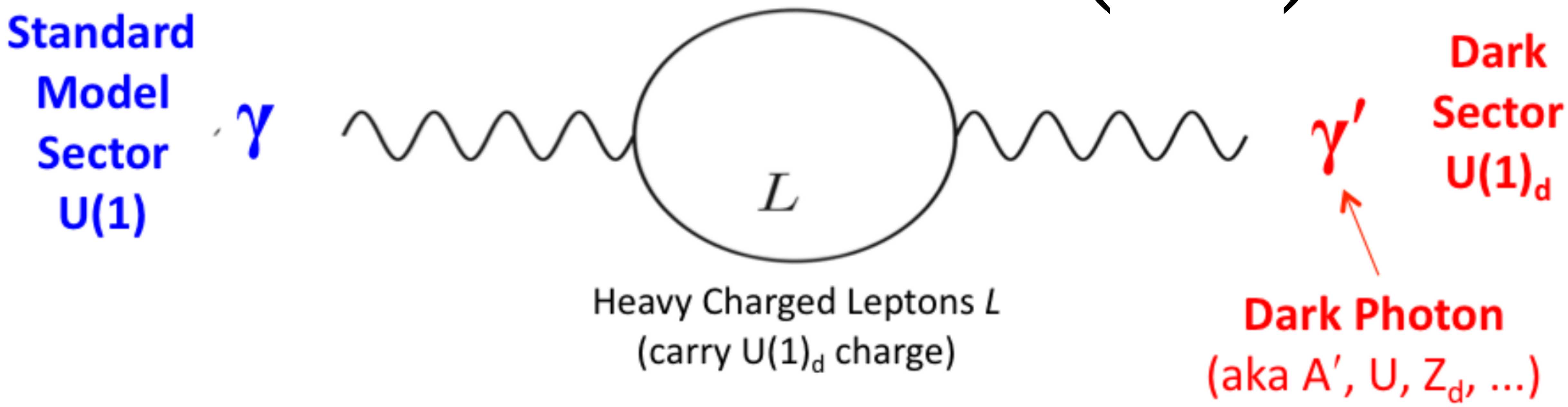
$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + 0 \times A^{\mu}A_{\mu} - eA_{\mu}j^{\mu}_{\rm em}$$

$$-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$$

A proper low energy model from UV physics
Log dependence of UV scale

$$\epsilon \sim -\frac{gg'}{16\pi^2}\log\left(\frac{m_L^2}{\mu^2}\right)$$





- Two free parameters: $m_{A'}$ and ϵ

Ultralight kinetic mixing dark photon dark matter

- The kinetic basis

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + 0 \times A^{\mu}A_{\mu} - eA_{\mu}j^{\mu}_{\text{em}}$$

$$-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$$

- Proper redefine and canonicalize the Lagrangian

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

The mass basis

$$\mathscr{L} = -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} + 0 \times \tilde{A}^{\mu}\tilde{A}_{\mu} - e\tilde{A}_{\mu}j^{\mu}_{\text{em}}$$

$$-\frac{1}{4}\tilde{F}'_{\mu\nu}\tilde{F}'^{\mu\nu} + \frac{1}{2}\frac{m^2_{A'}}{\sqrt{1-\epsilon^2}}\tilde{A}'^{\mu}\tilde{A}'_{\mu} + e\frac{\epsilon}{\sqrt{1-\epsilon^2}}\tilde{A}'_{\mu}j^{\mu}_{\text{em}}$$

Ultralight kinetic mixing dark photon dark matter

- Proper redefine and canonicalize the Lagrangian

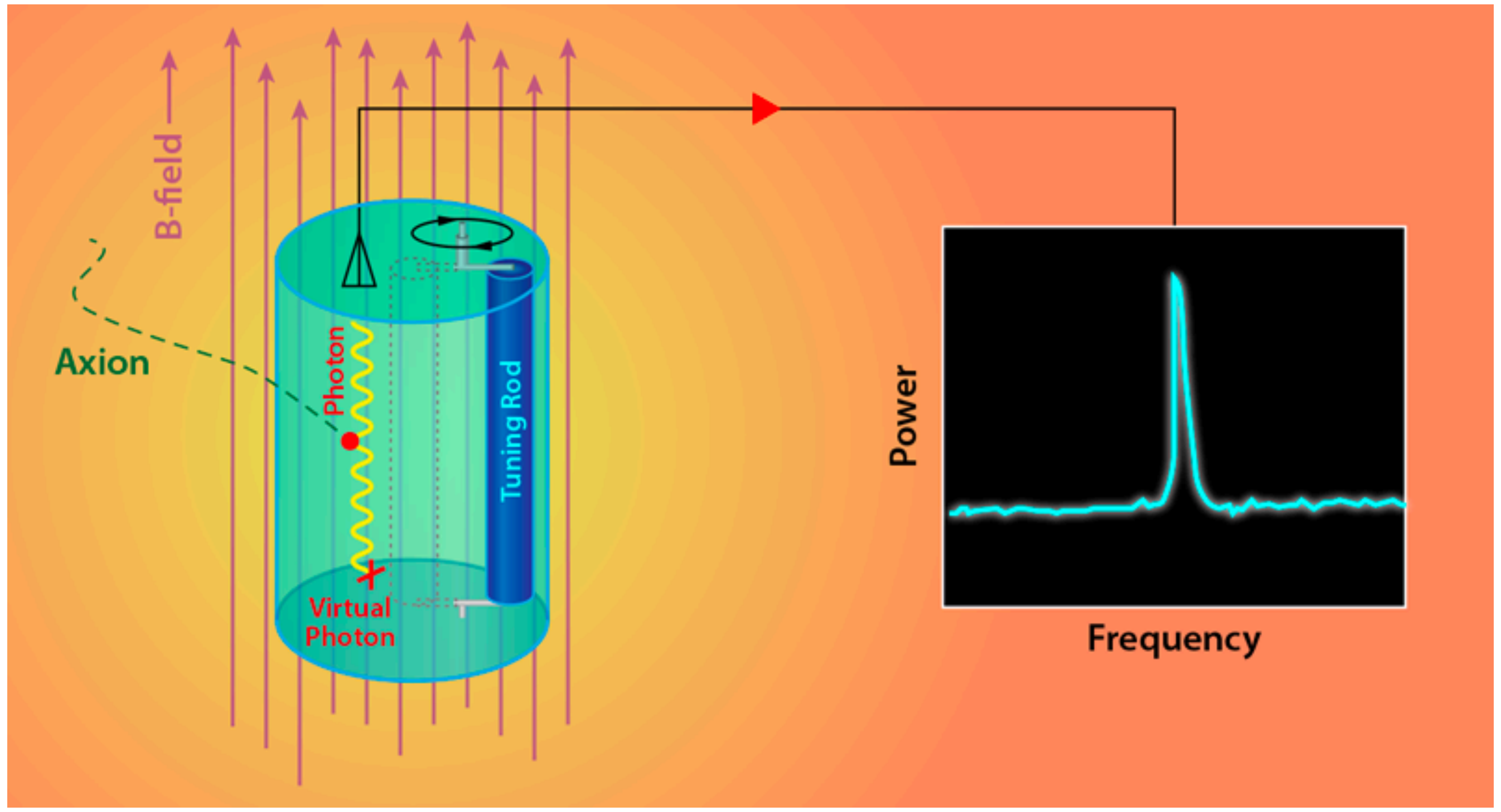
$$\mathscr{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}{}^2 A'_\mu A'^\mu - e\epsilon A'_\mu j^\mu_{\rm em}$$

at leading ϵ

- Two free parameters: $m_{A'}$ and ϵ
- Coupling to SM EM current $j_{\rm em}$ with suppression
  - Neutral atom is not charged!
- Stability: when $m_{A'} < 2m_e$, decay via highly suppressed $A' \to 3\gamma$
- Relic abundance: non-minimal Misalignment, inflationary fluctuations, parametric resonances, cosmic strings etc…
  - $\mathcal{O}(10^{-6})$ eV (Radio Wave) is the right mass for these mechanisms

The detection of ultralight bosonic dark matter

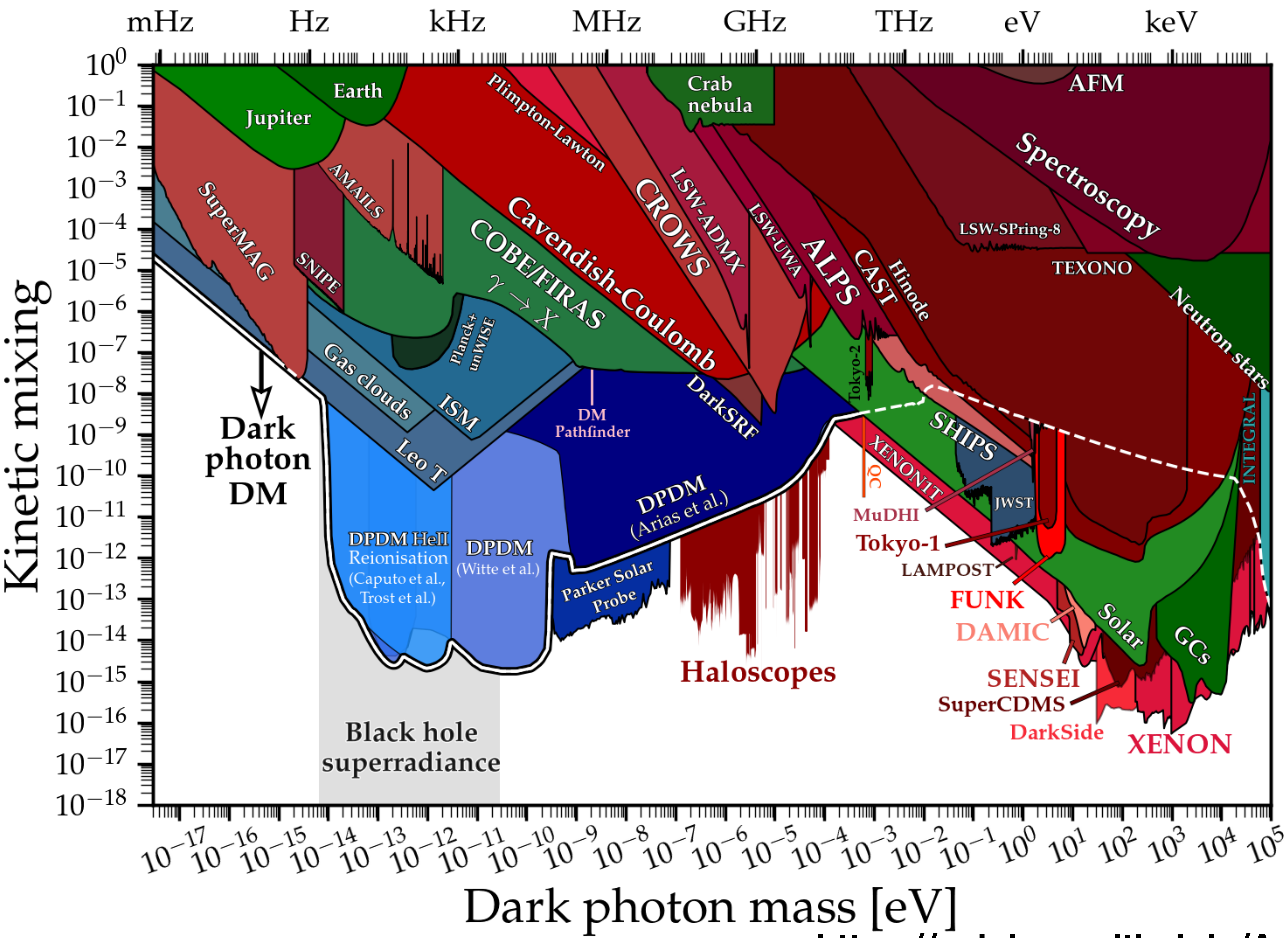
- Mass ranges from $[10^{-22}, 10^3]$ eV， DM exist as classical fields
  - Interacting feebly with SM sector, interdisciplinary collaboration with Atomic Molecular Optics, Astrophysics, Astronomy and Cosmology
  - Various detection methods:
    - Star as Laboratory： exotic energy loss （A’, ALP, S）
    - Early universe CMB, Gamma ray propagation, Black Hole picture and polarization (ALP、A’)
    - Lab resonant cavity searches: （ADMX, HAYSTAC …） (ALP, A’)
    - Lab broad-band searches（WISPDMX，Dark E-field …） （A’）
    - 5th force, Equivalent Principle test （S, A’）
    - DM direct detection experiments (XENONnT, PANDAX-4T, CDEX) (ALP, A’)
    - Radio astronomy (ALP, A’)



Experimental searches is related to model and couplings

$$g_{a\gamma\gamma} a F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \sim g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

Ultralight kinetic mixing dark photon dark matter



https://cajohare.github.io/AxionLimits/docs/dp.html

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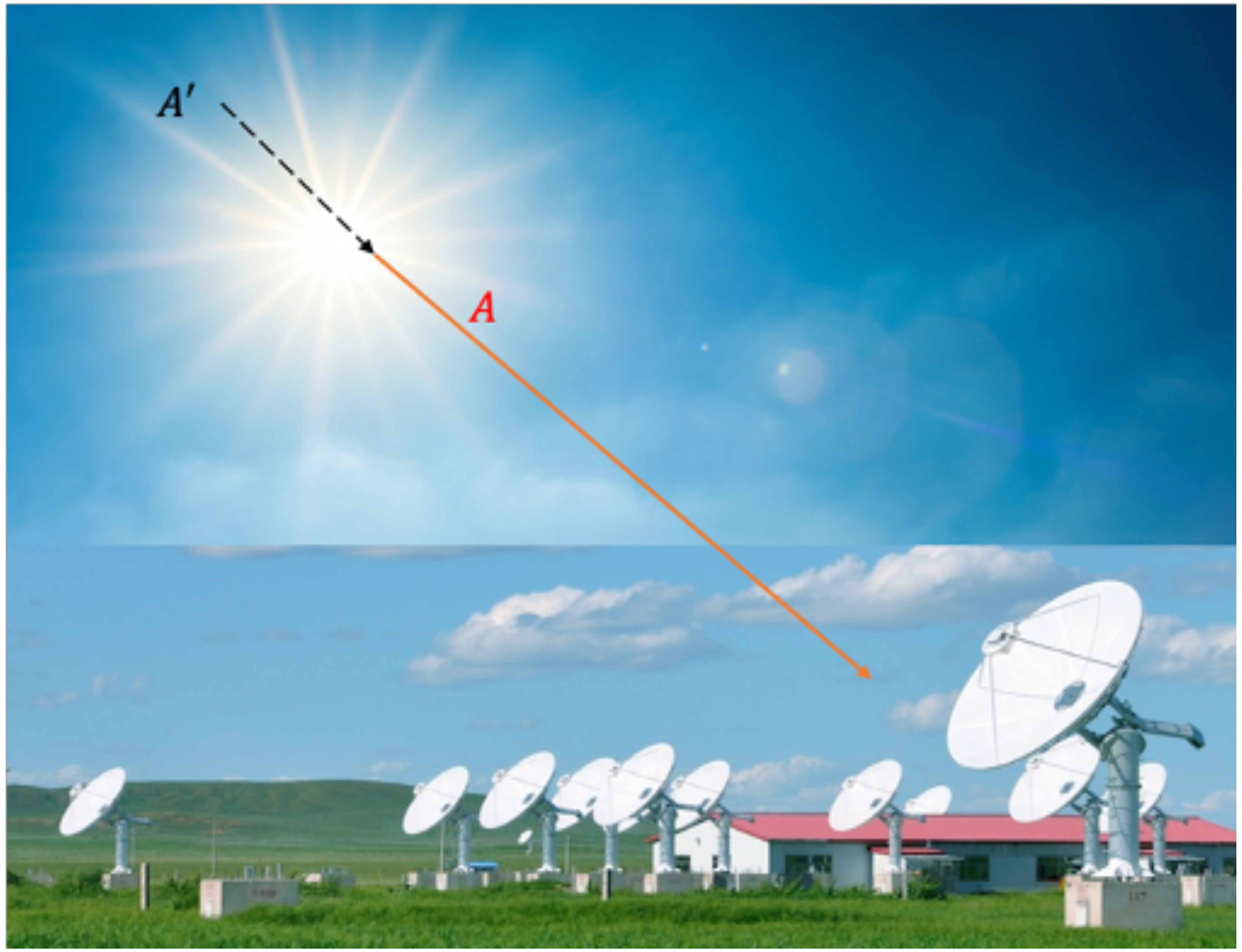
Existing constraints from radio telescopes

Solar physics



Dark photon dark matter
resonant conversion at solar corona

An, Huang, JL, Xue, 2010.15836
An, Chen, Ge, Liu, Luo, 2301.03622
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Radio telescope at Earth

Dark photon dark matter
conversion at radio telescope

An, Ge, Guo, Huang, JL, Lu, 2207.05767

Radio astronomy and ultralight bosonic dark matter

- Corresponding frequency (e.g. SKA)
  - Low band: 50 MHz - 350 MHz (0.2 - 1.44 μeV)
  - Mid band: 350 MHz - 14 GHz (1.44 - 57.8 μeV)

Artist's impression of a Low-Band SKA Sparse Aperture Array Station

Mono-chromatic signal

$A' \to \gamma$

Line signal spectral sensitivity
1000 μJy ~10^{-29}W $m^{-2}Hz^{-1}$ →

Bump hunting: bin size →

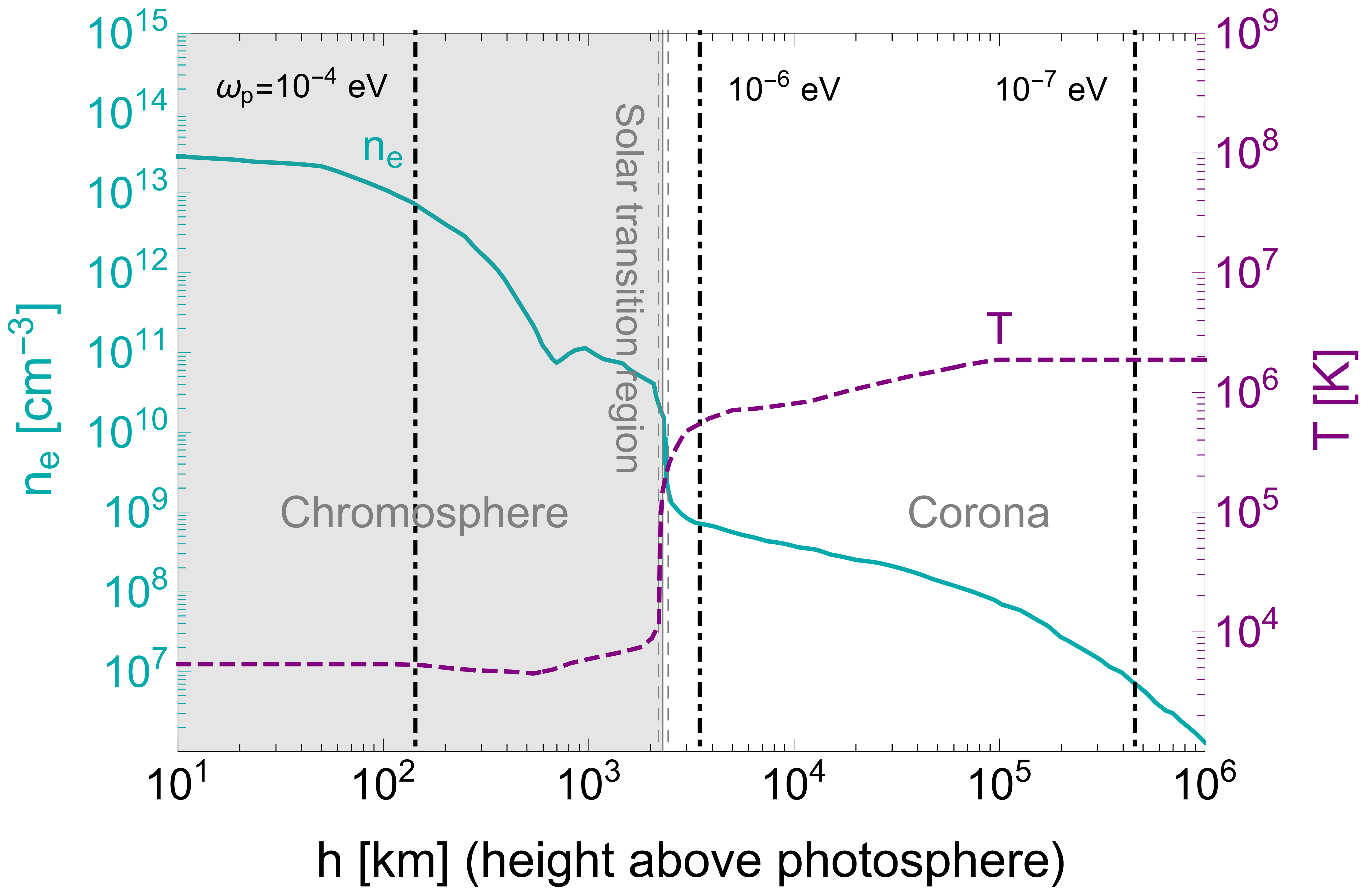
SKA1 Telescope Expected Performance – Imaging

Nominal Frequency	110 MHz	300 MHz	770 MHz	1.4 GHz	6.7 GHz	12.5 GHz
Range [GHz]	0.05-0.35	0.05-0.35	0.35-1.05	0.95-1.76	4.6-8.5	8.3-15.3
Telescope	Low	Low	Mid	Mid	Mid	Mid
FoV [arcmin]	327	120	109	60	12.5	6.7
Max. Resolution (arcsec)	11	4	0.7	0.4	0.08	0.04
Max. Bandwdith [GHz]	0.3	0.3	1	1	4	5
Cont. rms, 1 hr (μJy/beam)[a]	26	14	4.4	2	1.3	1.2
Line rms, 1 hr [μJy/beam][b]	1850	800	300	140	90	85
Resolution Range for Cont. and Line rms [arcsec][c]	12–600	6–300	1–145	0.6–78	0.13–17	0.07–9
Channel width (uniform resolution across max. bandwidth) [kHz]	5.4	5.4	15.2	15.2	61.0	79.3
Spectral zoom windows X narrowest bandwidth [MHz]	4 X 4.0	4 X 4.0	4 X 3.125	4 X 3.125	4 X 3.125	4 X 3.125
Finest zoom channel width [Hz]	244	244	190	190	190	190

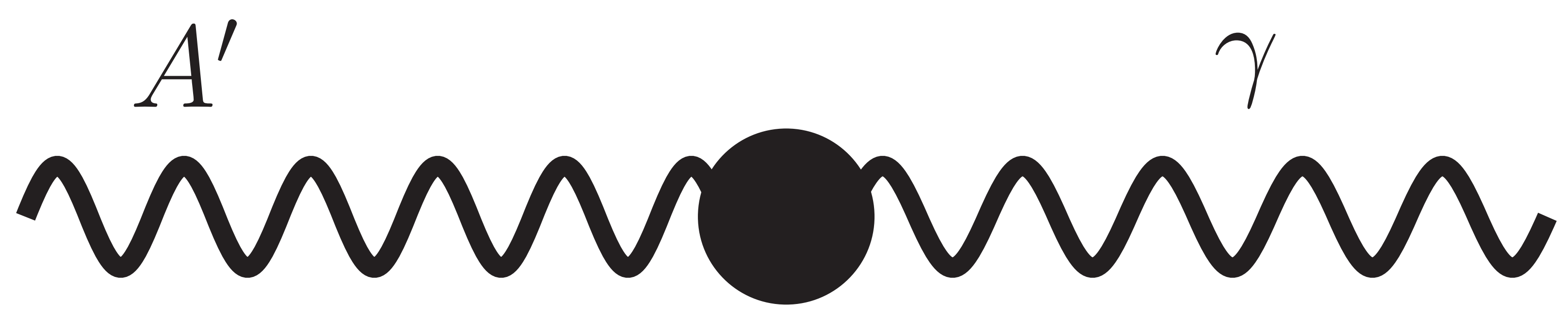
The photon mass in the solar corona

- The plasma frequency

$$\omega_p = \left(\frac{4\pi\alpha n_e}{m_e}\right)^{1/2} = \left(\frac{n_e}{7.3\times10^8\,\mathrm{cm}^{-3}}\right)^{1/2}\ \mu\mathrm{eV}$$



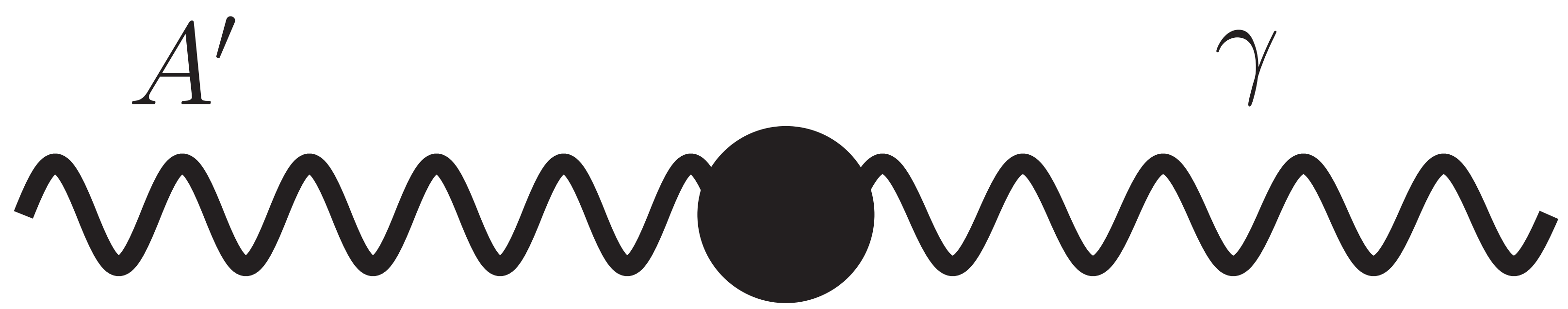
- Resonant conversion $A' \to \gamma$
  - When $m_{A'} = \omega_p$



- For any A' mass, it can happen at a radius r_c
  - $m_{A'} = \omega_p(r_c)$
  - Can set limits for mass range $m_{A'} \in [10^{-8}, 10^{-5}]$ eV

The dark photon dark matter conversion at solar corona

- The resonant conversion probability (QFT method)



$$\mathcal{L} \supset -\frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$$

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

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

$$\mathcal{M} = -\epsilon m^2_{A'}\left(\xi^*_\gamma(p)\cdot\xi_{A'}(p)\right)$$

$$\frac{1}{3}\sum_{\text{pol}}|\mathcal{M}|^2 = \frac{2}{3}\epsilon^2 m^4_{A'}$$

$$\int dt\,\delta(E_{A'} - E_\gamma) = 2\omega^{-1}\left(\frac{\partial\ln\omega_p^2}{\partial t}\right)^{-1}$$

- Due to the forced 4-momentum conservation, it applies to resonant conversion only.

- The wave method can work and is in agreement with QFT calculation

$$\left[\omega^2 - k^2 - \begin{pmatrix}\omega_p^2 & -\epsilon m^2_{A'}\\ -\epsilon m^2_{A'} & m^2_{A'}\end{pmatrix}\right]\begin{pmatrix}A(r,t)\\ A'(r,t)\end{pmatrix} = 0$$

The spectral power of the resonant conversion

- The radiation power per solid angle at conversion radius r_c

$$\frac{d\mathscr{P}}{d\Omega} \approx 2 \times \frac{1}{4\pi} \rho_{\rm DM}\, v_0 \int_0^b {\rm d}z\, 2\pi z\, P_{A'\to\gamma}(v_r)$$

$$= P_{A'\to\gamma}(v_0)\, \rho_{\rm DM}\, v(r_c)\; r_c^2$$

  - z is impact parameter for incoming A'
  - b is the max impact parameter which can reach r_c
  - v_0 ~ 220km/s is the DM local velocity dispersion

- The spectral power flux density per solid angle

$$\mathscr{B} = \max(B_{\rm sig}, B_{\rm res})$$

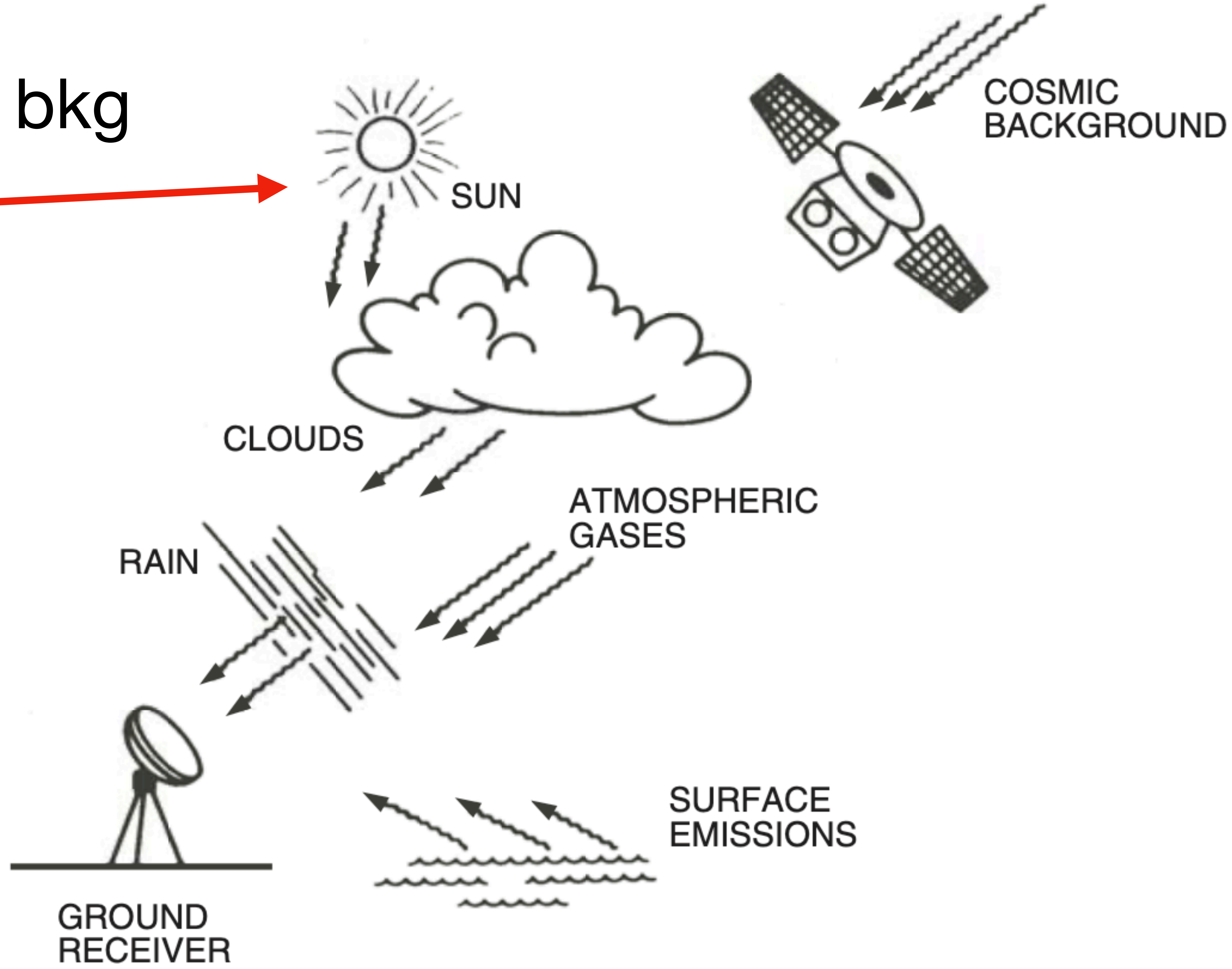
$$S_{\rm sig} = \frac{1}{1{\rm AU}^2} \frac{1}{\mathscr{B}} \frac{d\mathscr{P}}{d\Omega}$$

$$B_{\rm sig} \approx \frac{m_{A'} v_0^2}{2\pi} \sim 130\ {\rm Hz} \times \frac{m_{A'}}{\mu{\rm eV}}$$

Sensitivity of the radio telescope

- The system equivalent flux density
  - For solar observation, Sun is the largest bkg

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



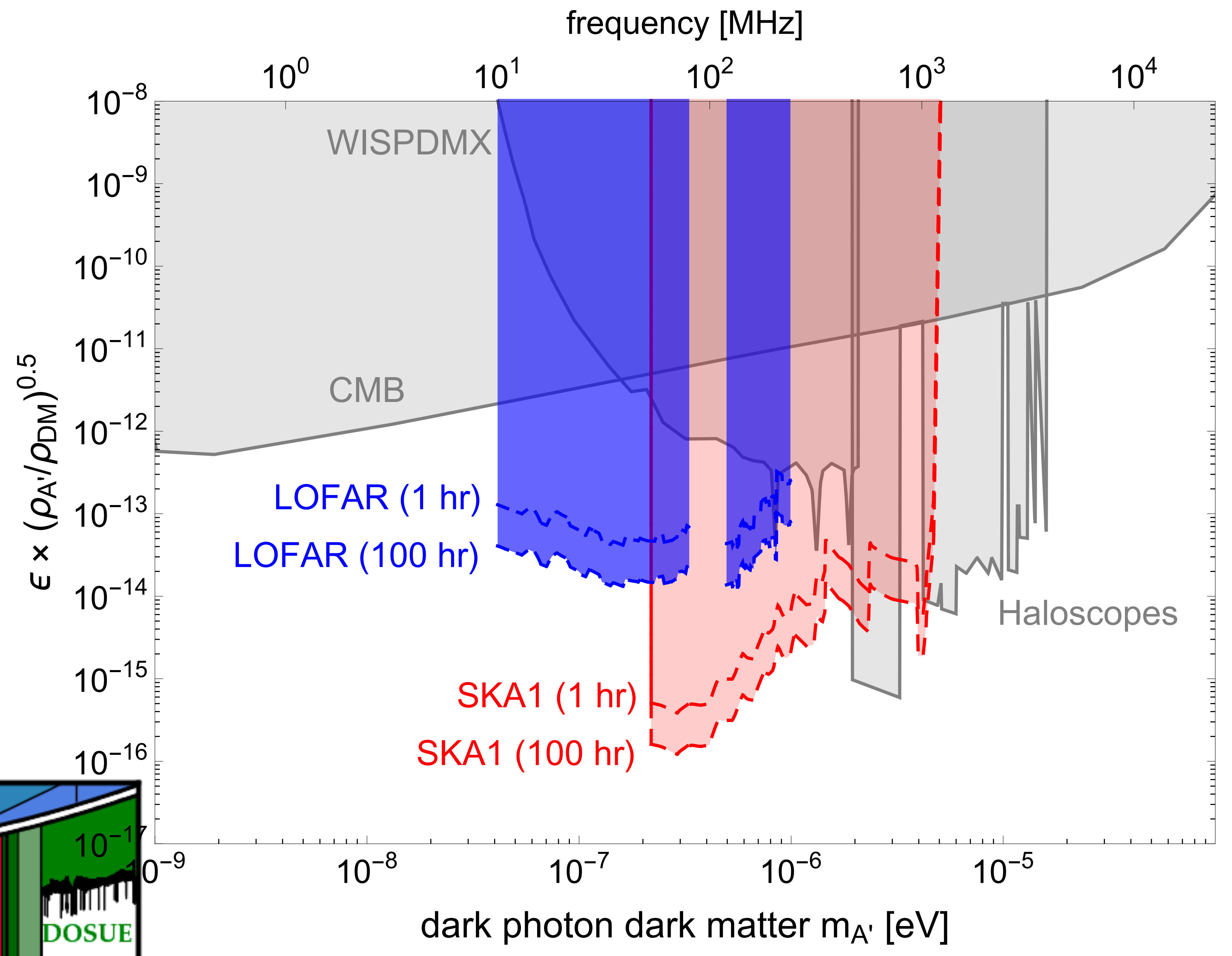
- The minimum detectable flux density

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

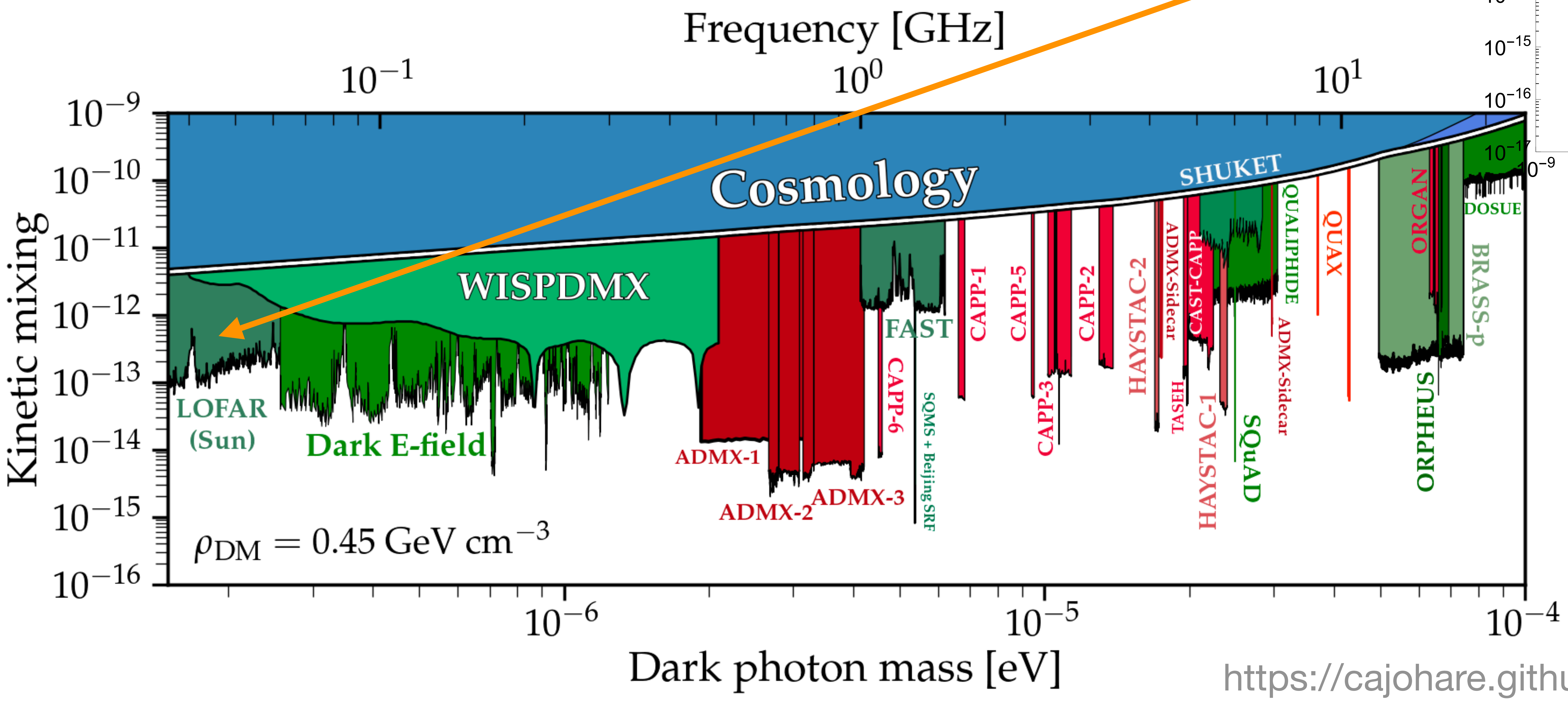
Name	f [MHz]	B_{res} [kHz]	$\langle T_{\mathrm{sys}} \rangle$ [K]	$\langle A_{\mathrm{eff}} \rangle$ [m^2]
SKA1-Low	(50, 350)	1	680	2.2×10^5
SKA1-Mid B1	(350, 1050)	3.9	28	2.7×10^4
SKA1-Mid B2	(950, 1760)	3.9	20	3.5×10^4
LOFAR	(10, 80)	195	28,110	1,830
LOFAR	(120, 240)	195	1,770	1,530

The sensitivity of DPDM from solar resonant conversion

- Attenuation of the mono-photon signal is considered,
  $S_{\text{sig}} \times P_s = S_{\text{min}}$
- 10 MHz lower end from LOFAR threshold
- 1 GHz higher end due to photon attenuation



Phys.Rev.Lett. 126 (2021) 18, 181102



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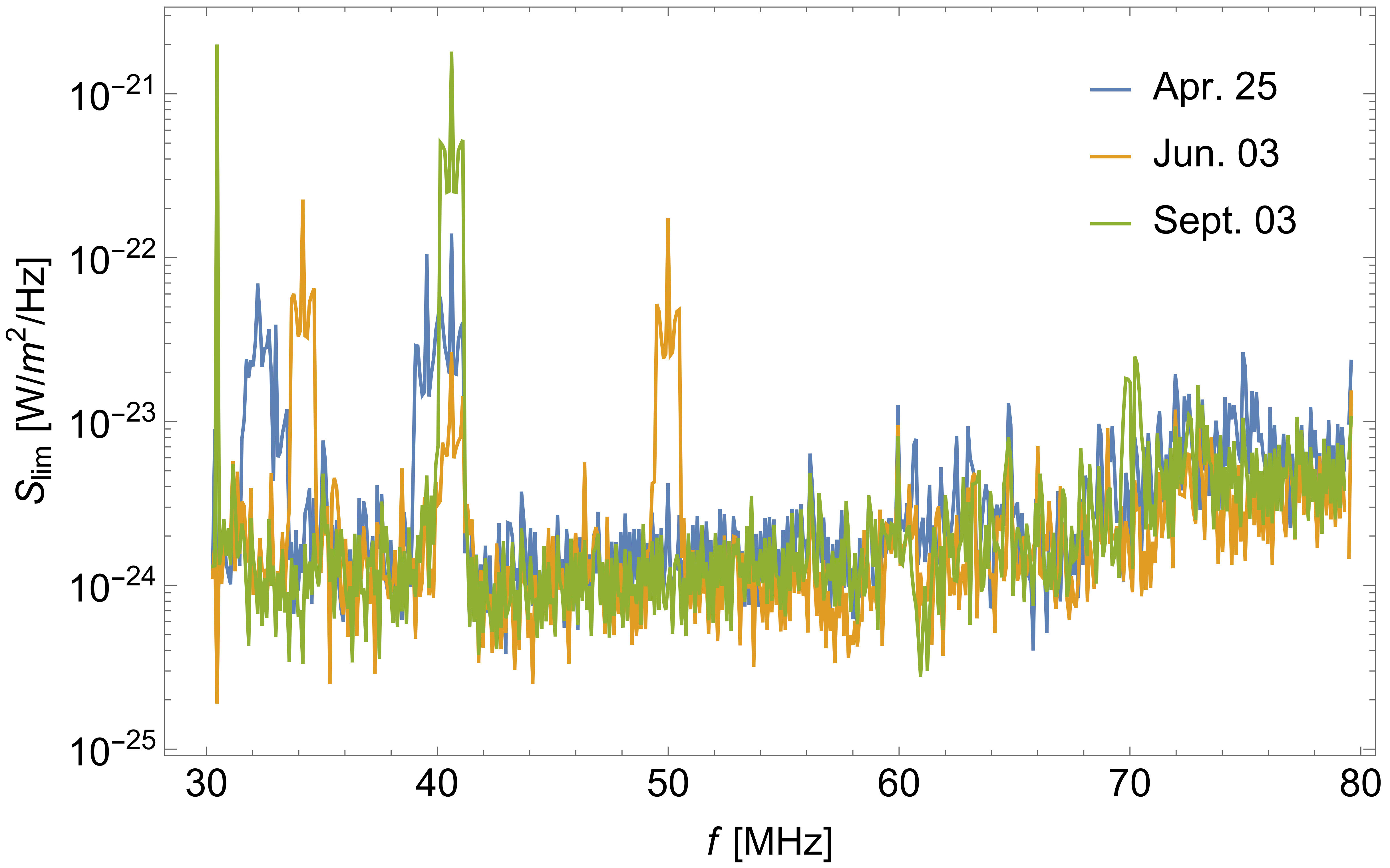
Experimental limits from LOFAR data

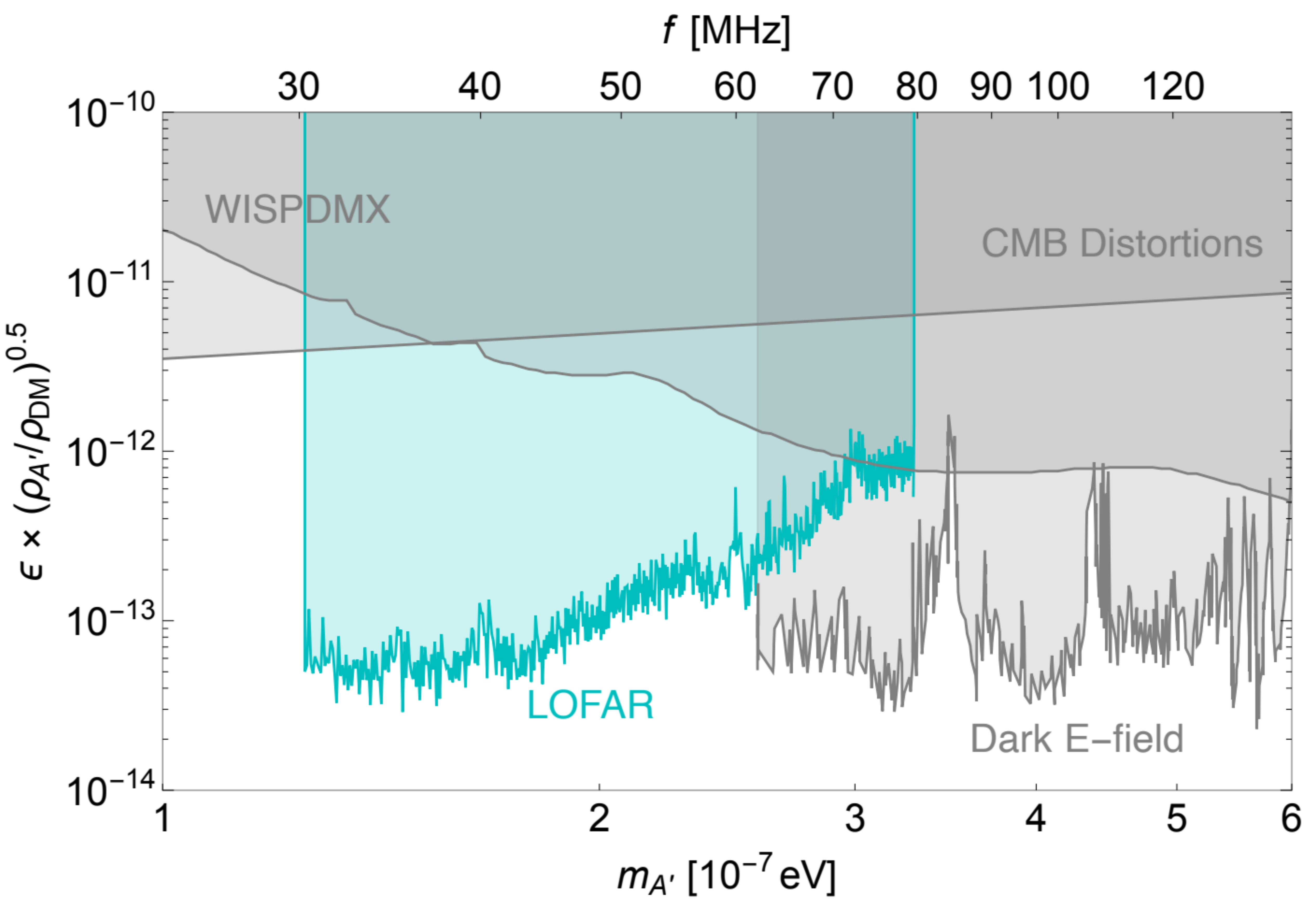
- Three sets of data lasting 17 minutes
- Low band of LOFAR, [30, 80] MHz
- Frequency resolution $B_{\rm res} = 97$ kHz
- We use Log likelihood Ratio test to set limits

$$L(S,a) = \prod_{i=i_0-5}^{i_0+5} \frac{1}{\sigma_i\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{B(a,f_i) + S\delta_{ii_0} - \bar{O}_i}{\sigma_i}\right)^2\right]$$

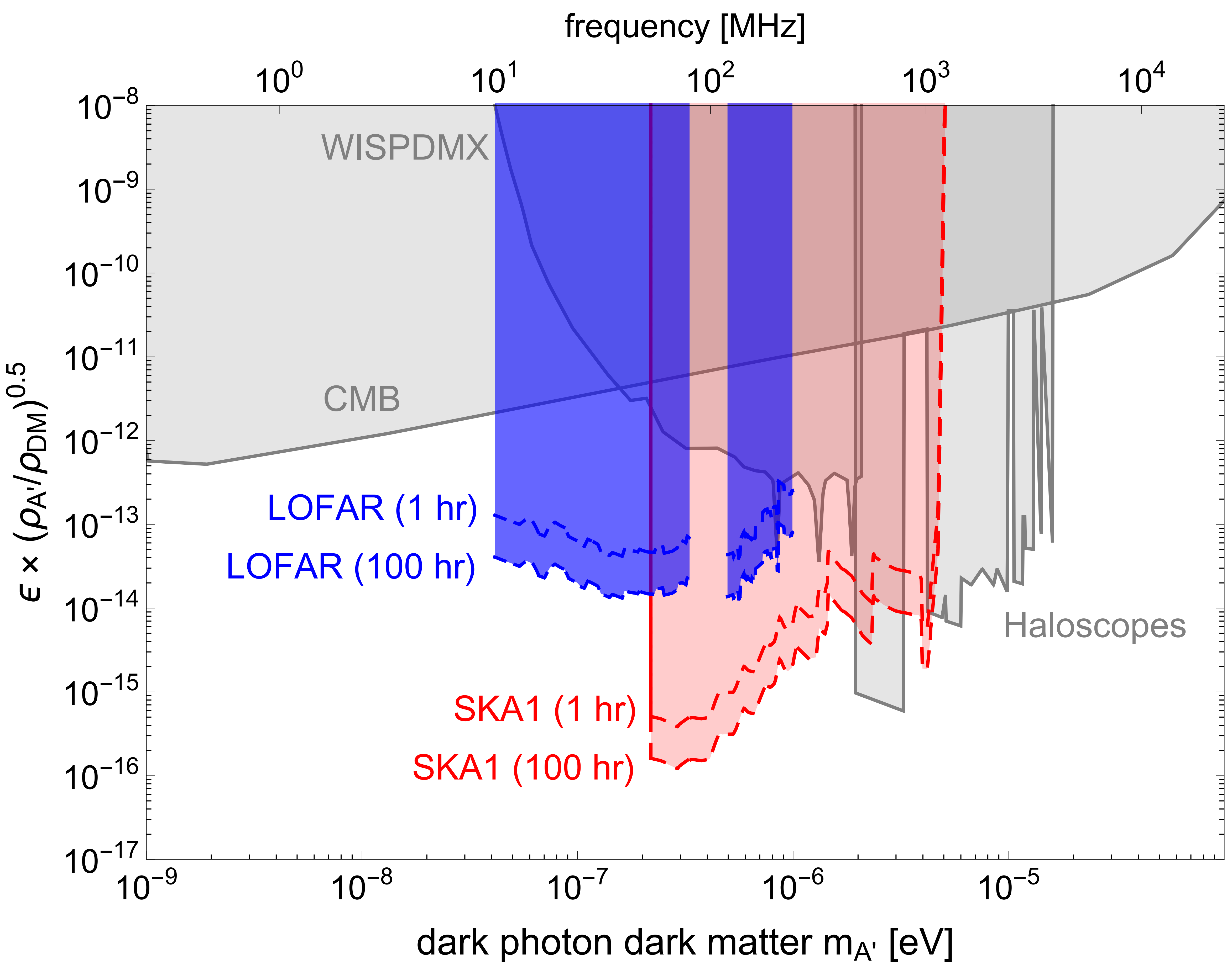


- The signal is narrow and inside one bin
  - We do side-band analysis with ± 5 near bins
  - We have included a detailed Monte Carlo simulation of absorption and scattering during the photon propagation

Experimental limits from LOFAR data



Nature Communications 15 (2024) 915



- The real experimental LOFAR limits can reach $\epsilon \sim \mathcal{O}(10^{-13})$

- The real data limits are similar to previous theoretical estimation

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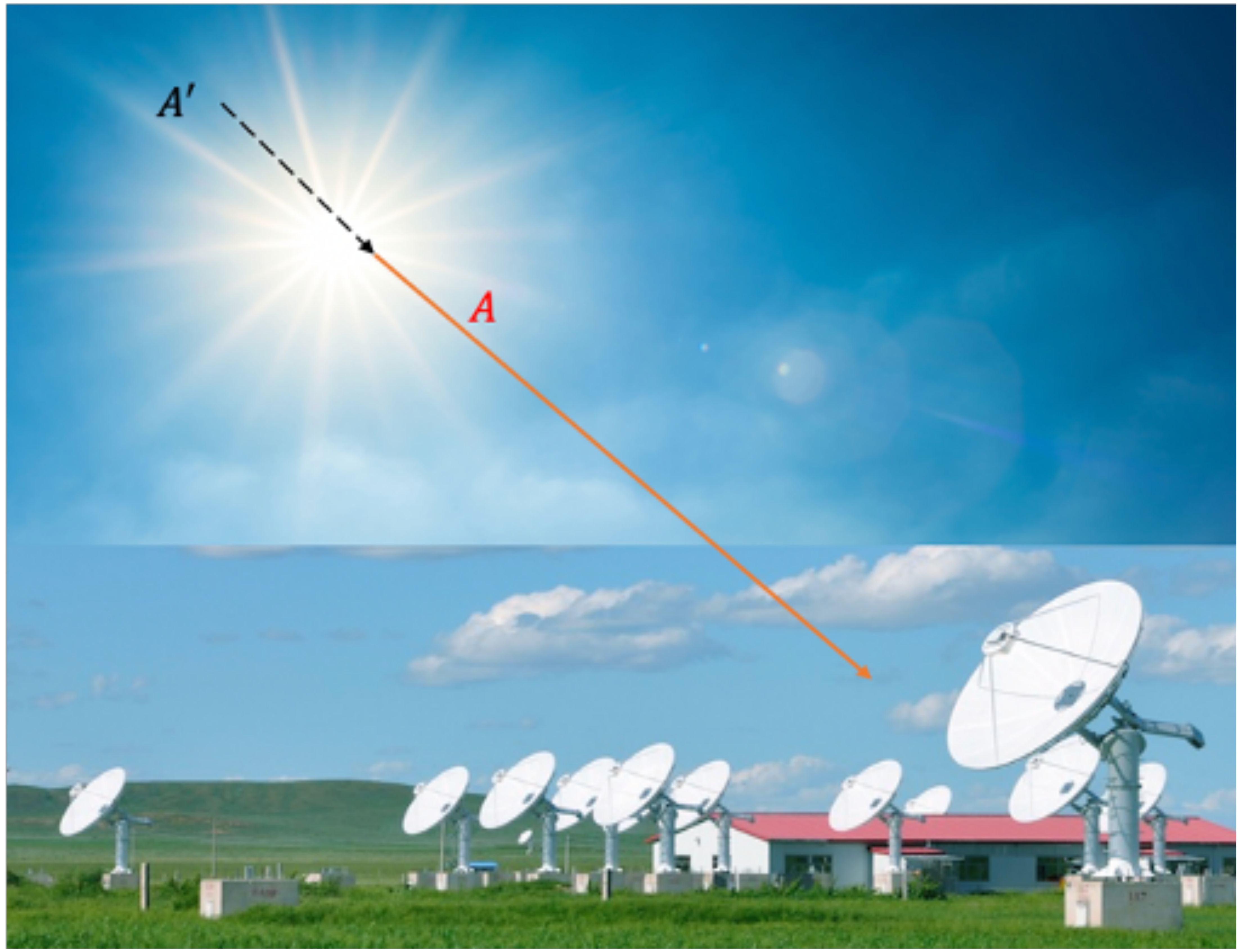
Existing constraints 6: radio telescopes

Solar physics



Dark photon dark matter resonant conversion at solar corona

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Radio telescope at Earth

Dark photon dark matter conversion at radio telescope

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Direct detection of DPDM using dish antenna radio telescope

- Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \epsilon e A'_\mu j^\mu_{\rm em} + e A_\mu j^\mu_{\rm em}.$$

- Extended Maxwell Eqs

$$\nabla \cdot \boldsymbol{E'} = -\epsilon\rho - m_{A'}^2 A'^0,$$
$$\nabla \cdot \boldsymbol{B'} = 0,$$
$$\nabla \times \boldsymbol{E'} + \frac{\partial \boldsymbol{B'}}{\partial t} = 0,$$
$$\nabla \times \boldsymbol{B'} - \frac{\partial \boldsymbol{E'}}{\partial t} = -\epsilon \boldsymbol{J} - m_{A'}^2 \boldsymbol{A'},$$

- Perfect conductor

$$\mathbf{J} = \sigma(\mathbf{E} - \epsilon \mathbf{E_D})$$

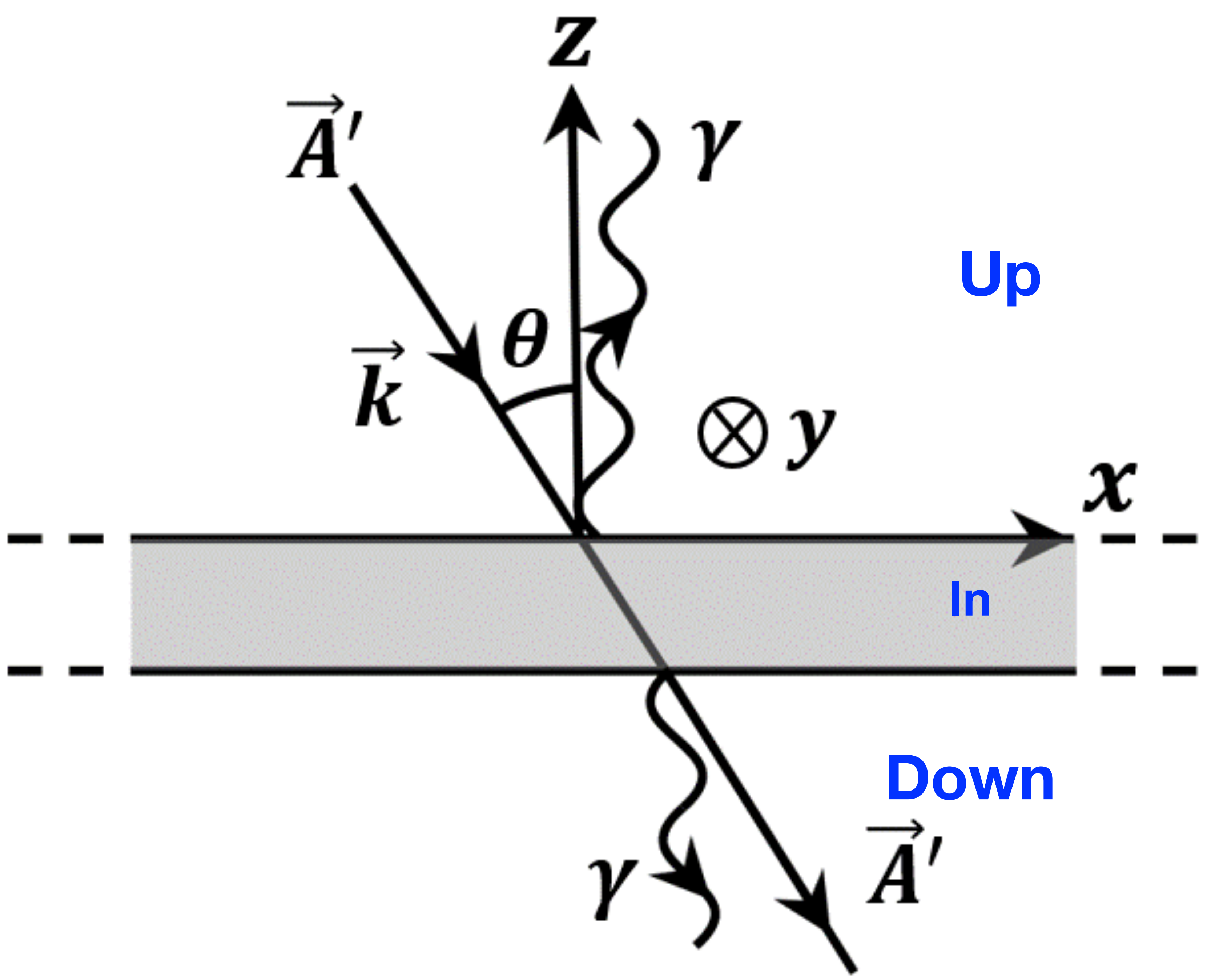
$$\nabla \cdot \mathbf{J} + \frac{\partial \rho}{\partial t} = 0$$

FAST radio telescope

Direct detection of DPDM using dish antenna radio telescope

- The feature of current on a metal conductor plate induced by DPDM

$$i_{tot,x} = i_{up,x} + i_{down,x} \approx -2i\epsilon m_{A'} A'_x,$$
$$i_{tot,y} = i_{up,y} + i_{down,y} \approx -2i\epsilon m_{A'} A'_y,$$
$$\boldsymbol{J} = 0.$$



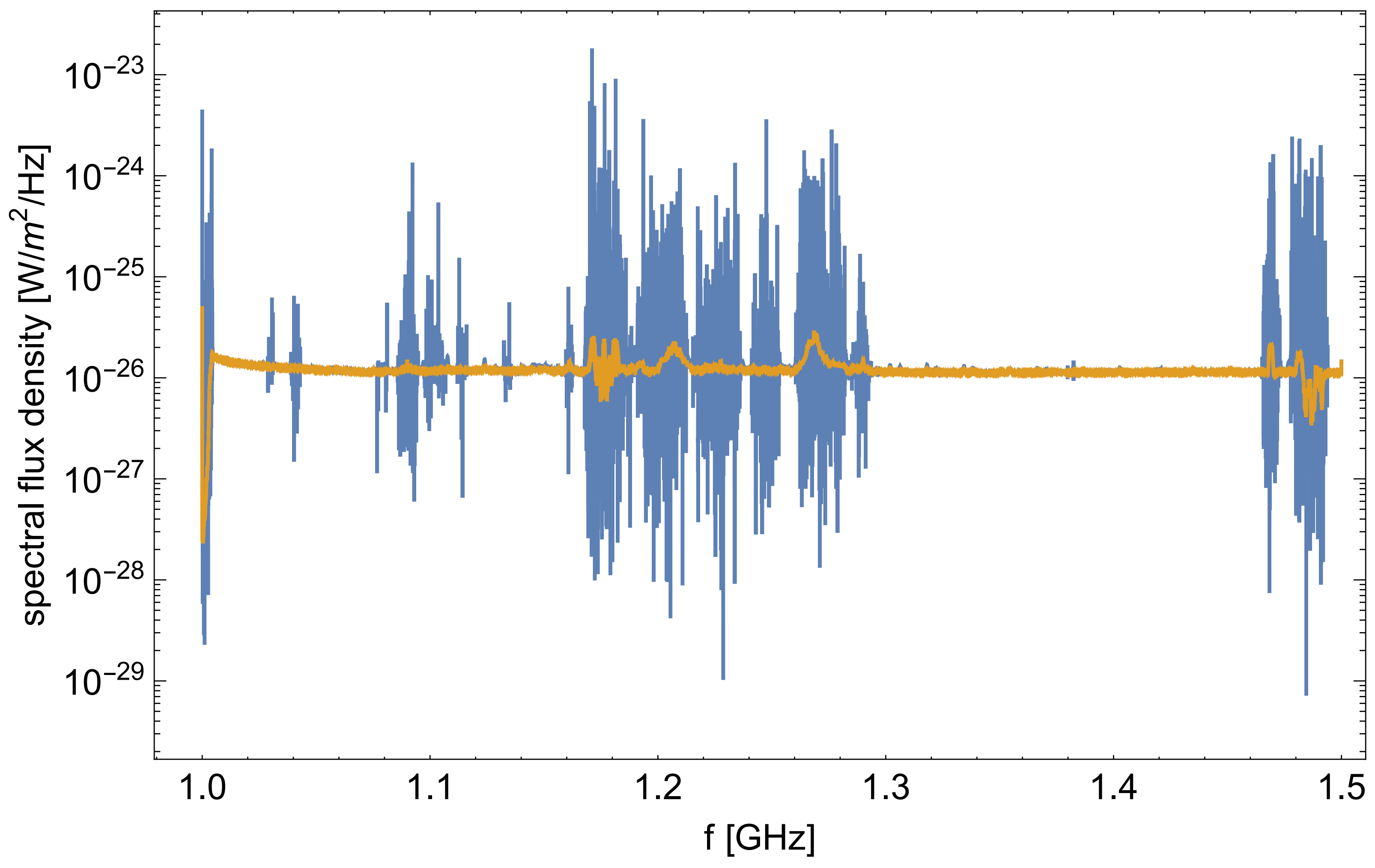
- Solving the reflected EM field
  - (always perpendicular to the surface)
  - Oscillating dipole unit

$$d\mathbf{p} = 2\epsilon \mathbf{A}'_{\|} dS \longrightarrow \mathbf{B} = -\frac{\epsilon m_{A'}^2}{2\pi} \int dS_1 \mathbf{A}'_{\|} \times (\mathbf{r} - \mathbf{r}_1) \frac{e^{i m_{A'} |\mathbf{r} - \mathbf{r}_1|}}{|\mathbf{r} - \mathbf{r}_1|^2}$$

  - Regular shapes of reflector can be solved
  - General shapes need numerical integration

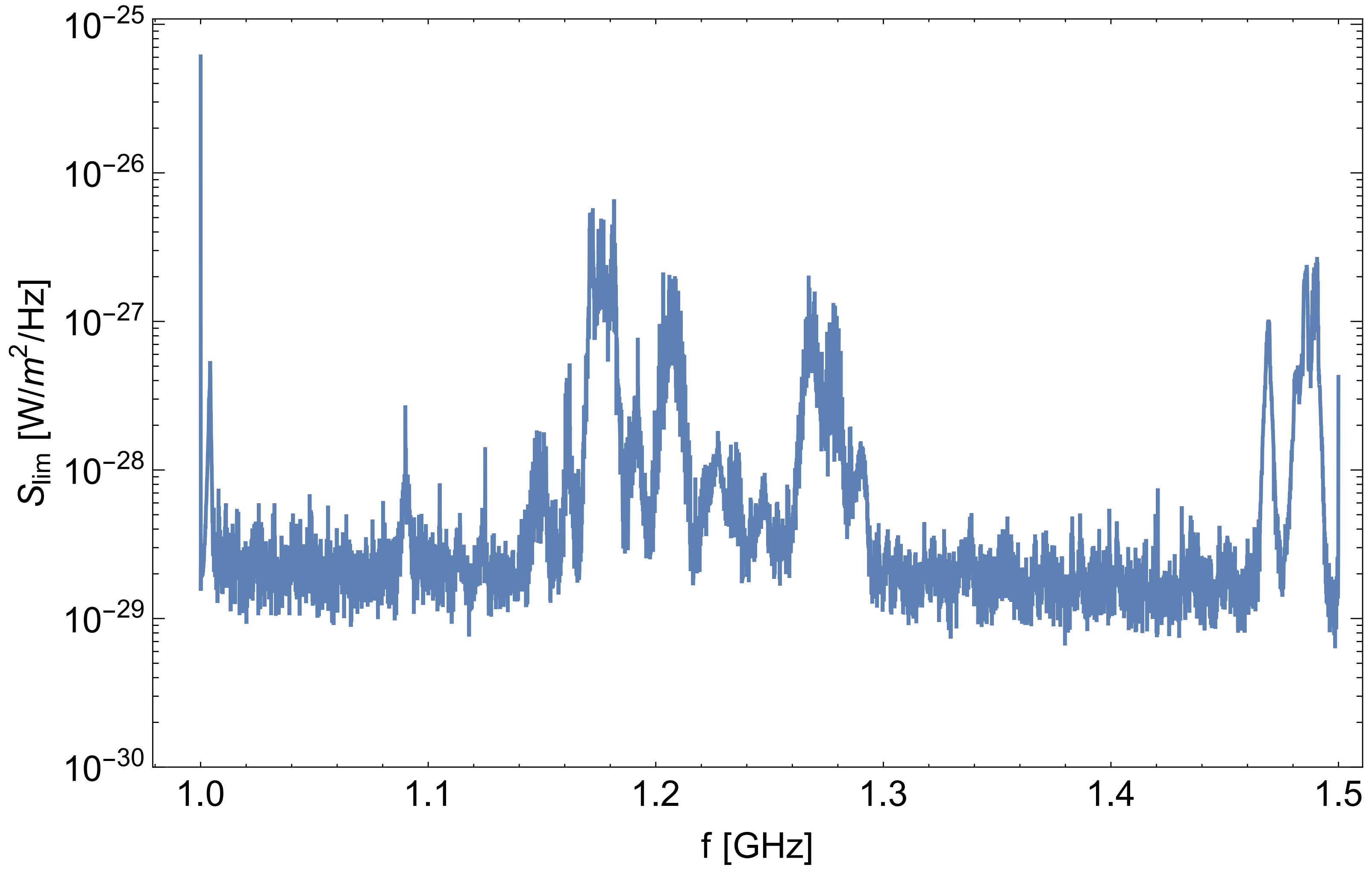
Constraints from FAST observation data

- ‘Bump hunting’ in the frequency data
  - Using likelihood-based statistical test



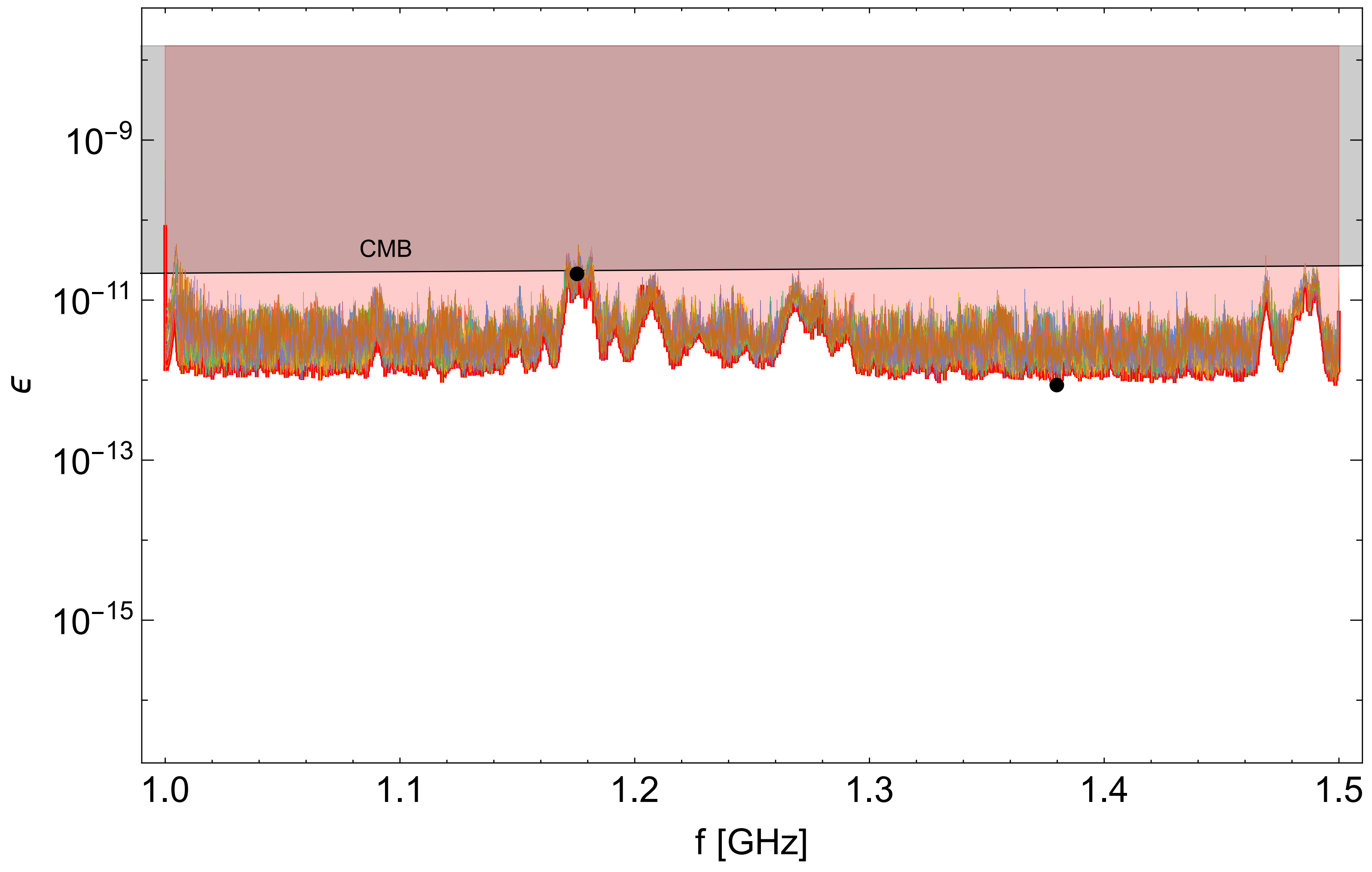
FAST data

$S_{\rm obs} \sim 10^{-26}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$



FAST limit on line signal

$S_{\rm lim} \sim 10^{-29}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$

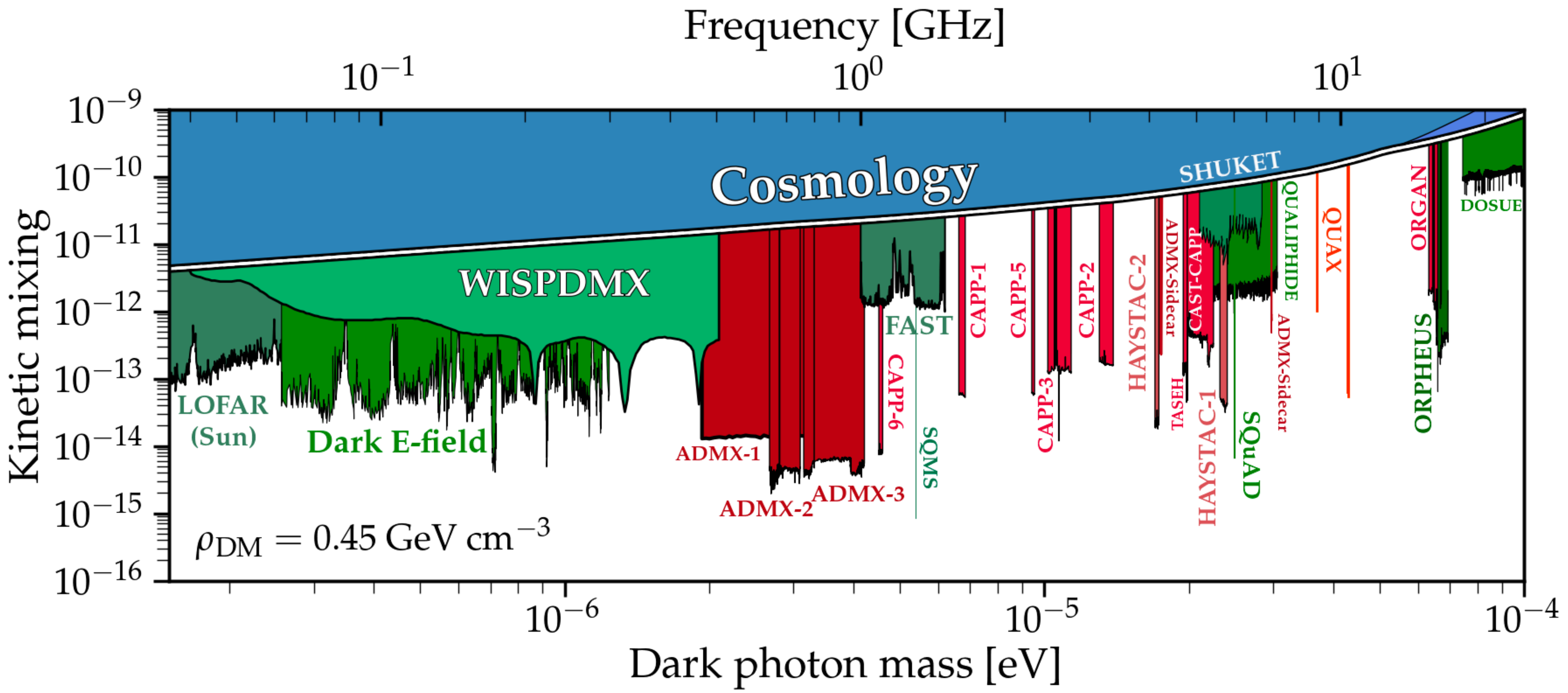


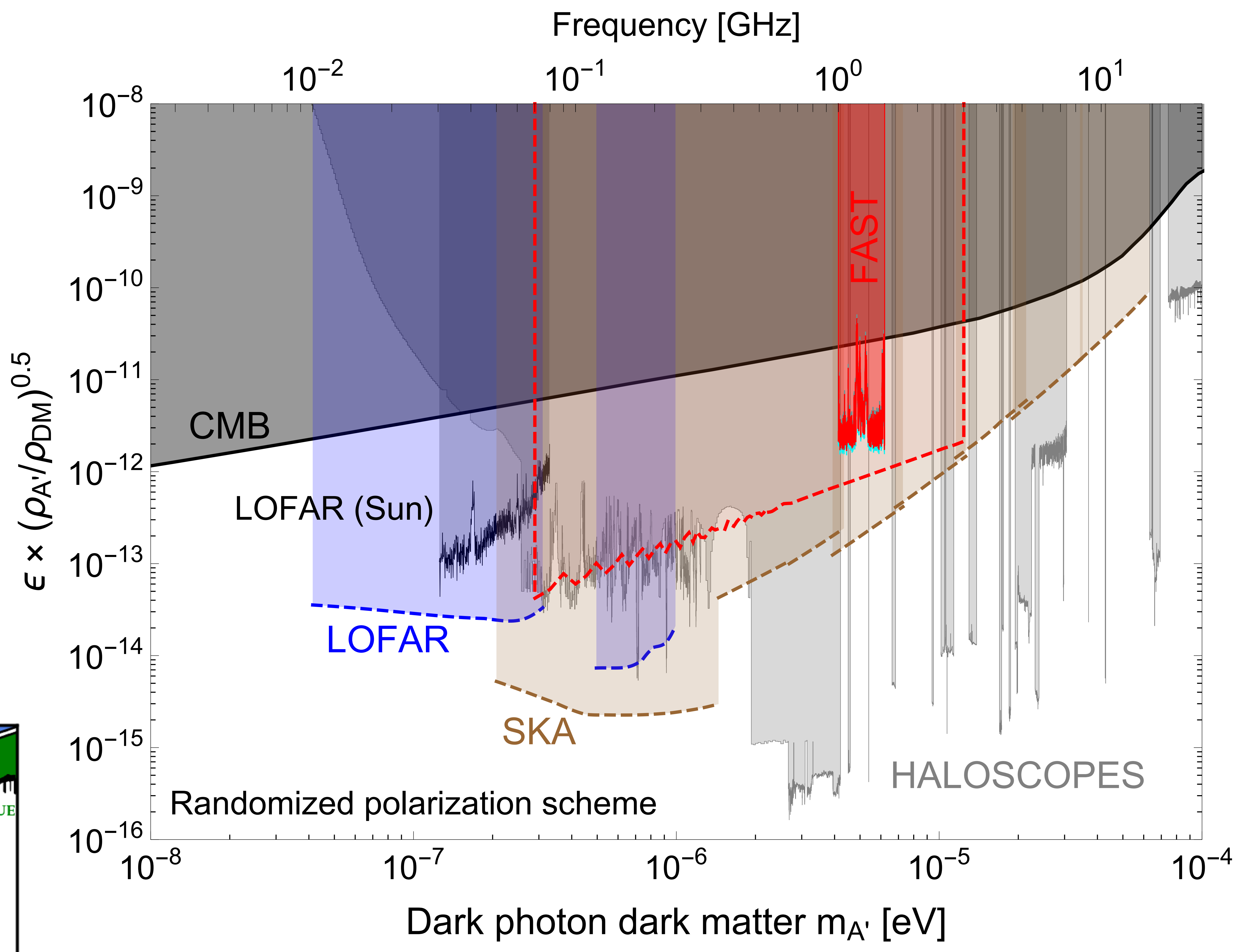
FAST limit on DPDM

$\epsilon \sim 10^{-12}$

The results for direct detection of DPDM using radio telescope

- The current constraints from FAST data using conversion at antenna dish
- The future sensitivities for dipole antenna array from LOFAR and SKA-low
- A comparison with other limits





An, Ge, Guo, Huang, JL, Lu, 2207.05767

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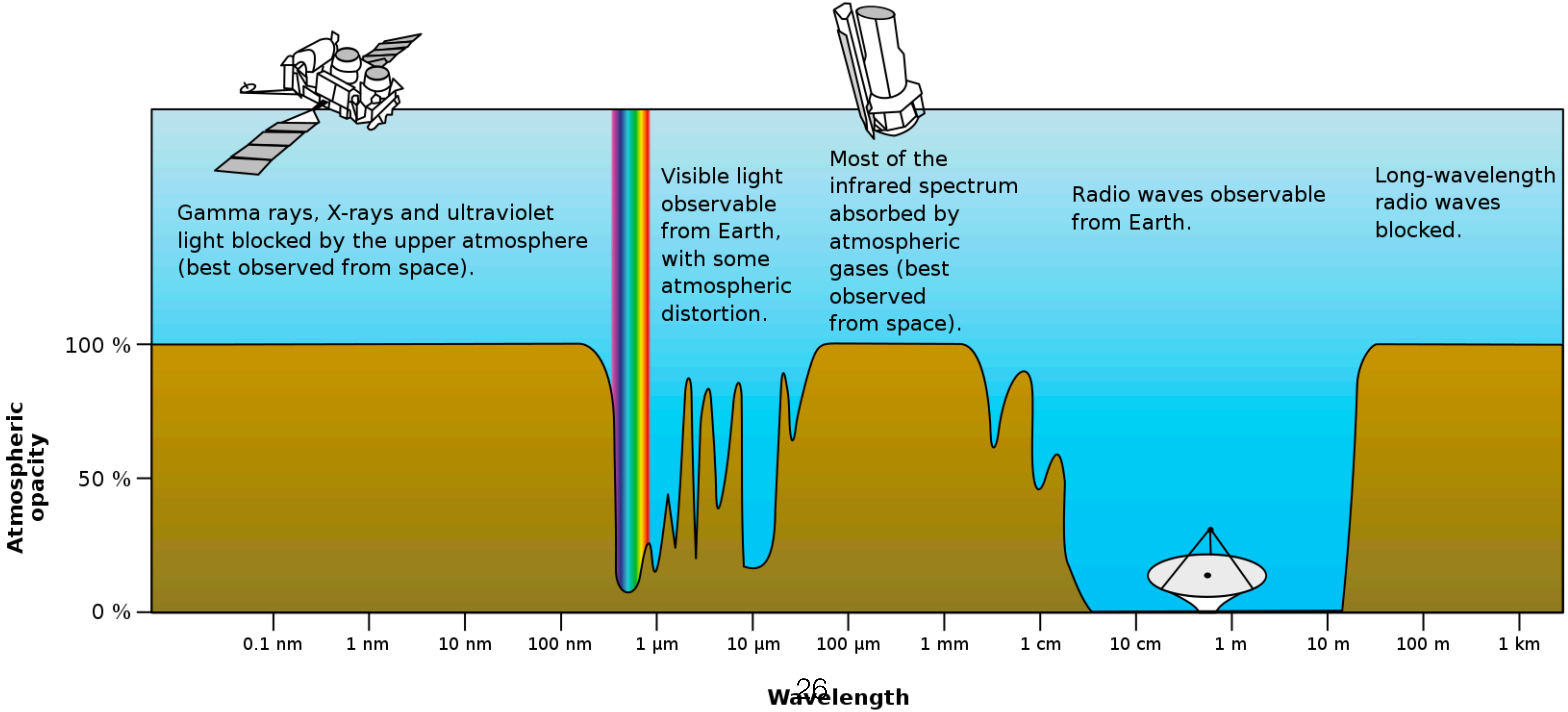
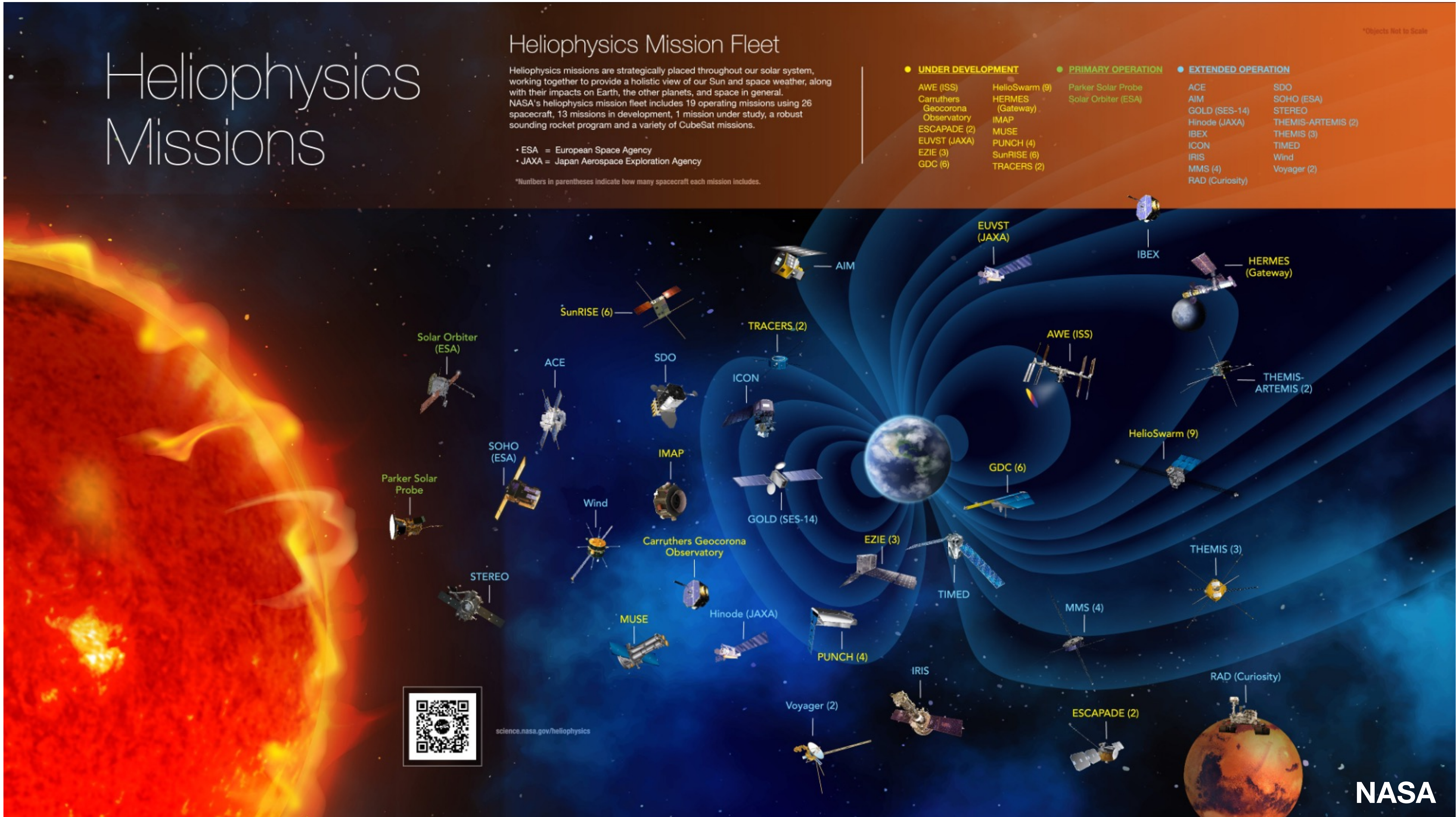
Future prospects：Going beyond Radio Window

- How to detect the frequencies outside the Radio Window?

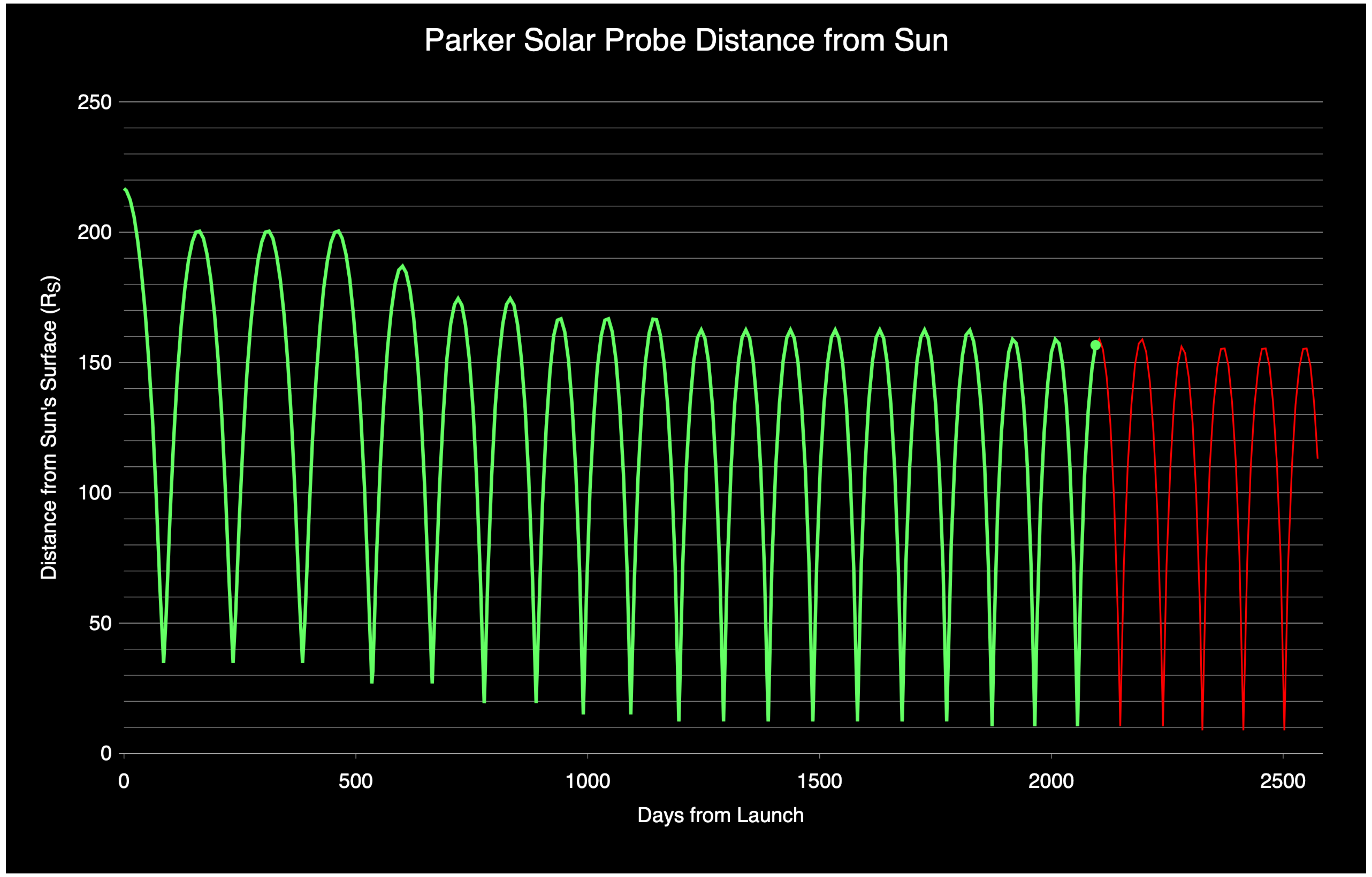


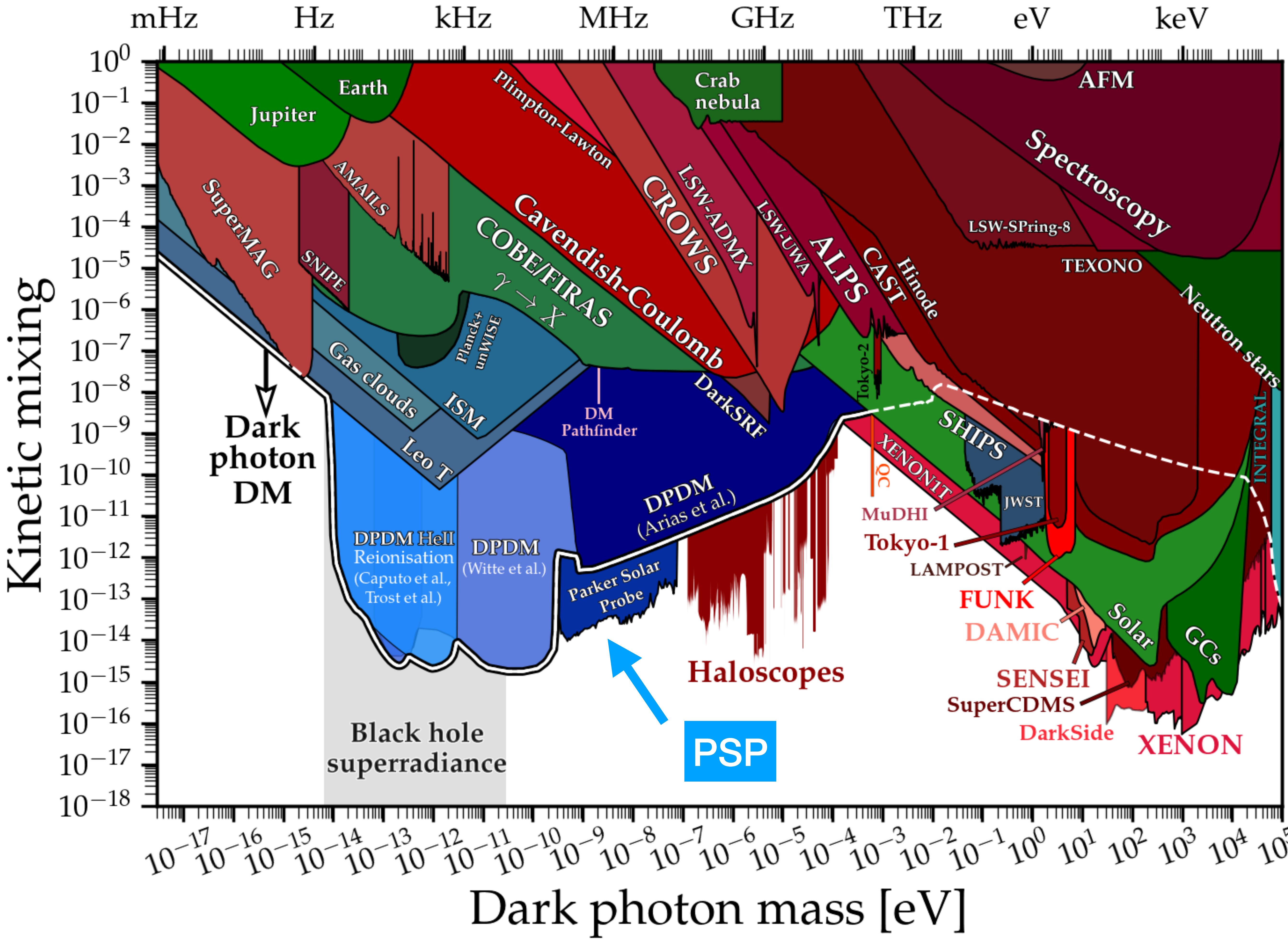
Future prospects：Space radio wave detections

- How to detect the frequencies outside the Radio Window?
- Solar signal: Go Space



Parker Solar Probe results





An, Ge, Liu, Liu, 2405.12285

Summary

- The detection of ultra-light bosonic dark matter and astronomical telescope observations can collaborate in a cross-disciplinary manner
  - DPDM can be converted into monochromatic photon signals within the solar plasma
    - Solar physics observation data can be used to detect ultra-light dark matter.
    - LOFAR、SKA、Daocheng Solar Radio Telescope
  - DPDM can be converted into monochromatic signals on the reflective surfaces or antenna arrays of telescopes.
    - Observing blank sky regions can help detect ultra-light dark matter.
    - FAST、LOFAR、SKA
  - Space-based radio telescopes can go beyond the radio window.

Thank you!

Backup slides