# Dark Photon Dark Matter Detection with Radio Telescopes

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Based on 2010.15836 [PRL 2021], 2207.05767 [PRL 2023], 2301.03622 [NC 2024]

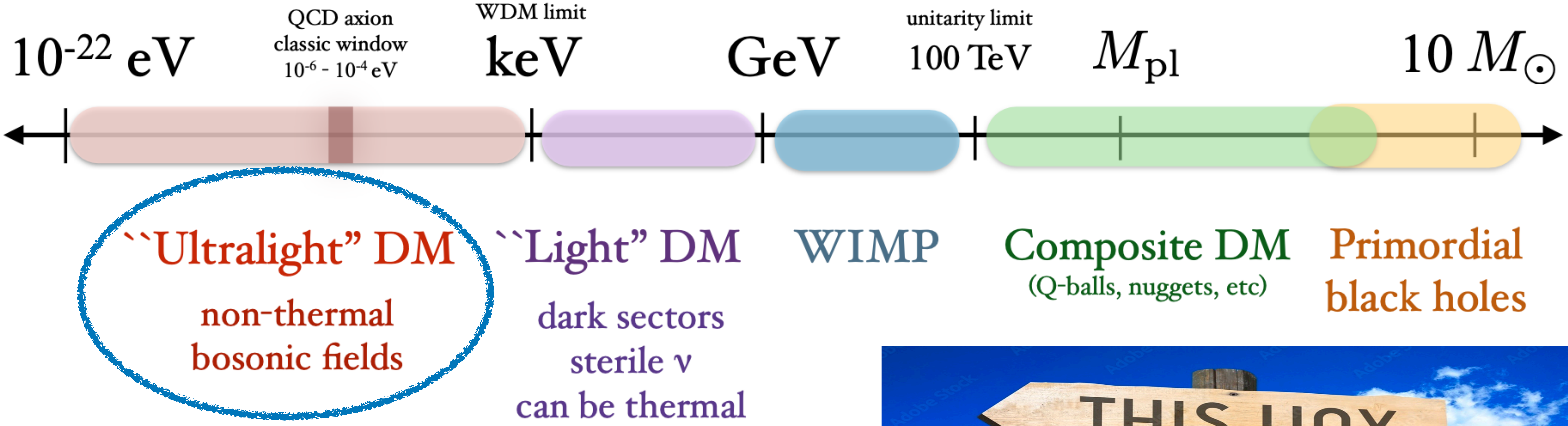
第三届地下和空间粒子物理与宇宙物理前沿问题研讨会
2024-05-09

# What is the nature of dark matter?

Unknown matter and energy $\sim$ 95%

# The dark matter candidate models

1904.07915， TASI lecture



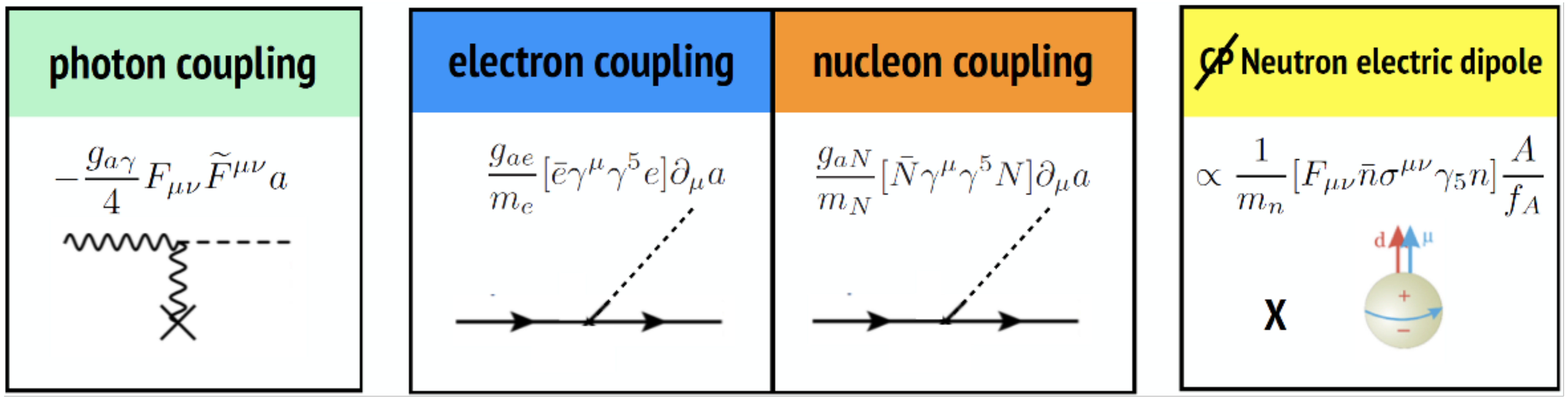

**Today’s focus**


**HEP at a cross-road: explore all directions!**

# Ultralight Bosonic Dark Matter

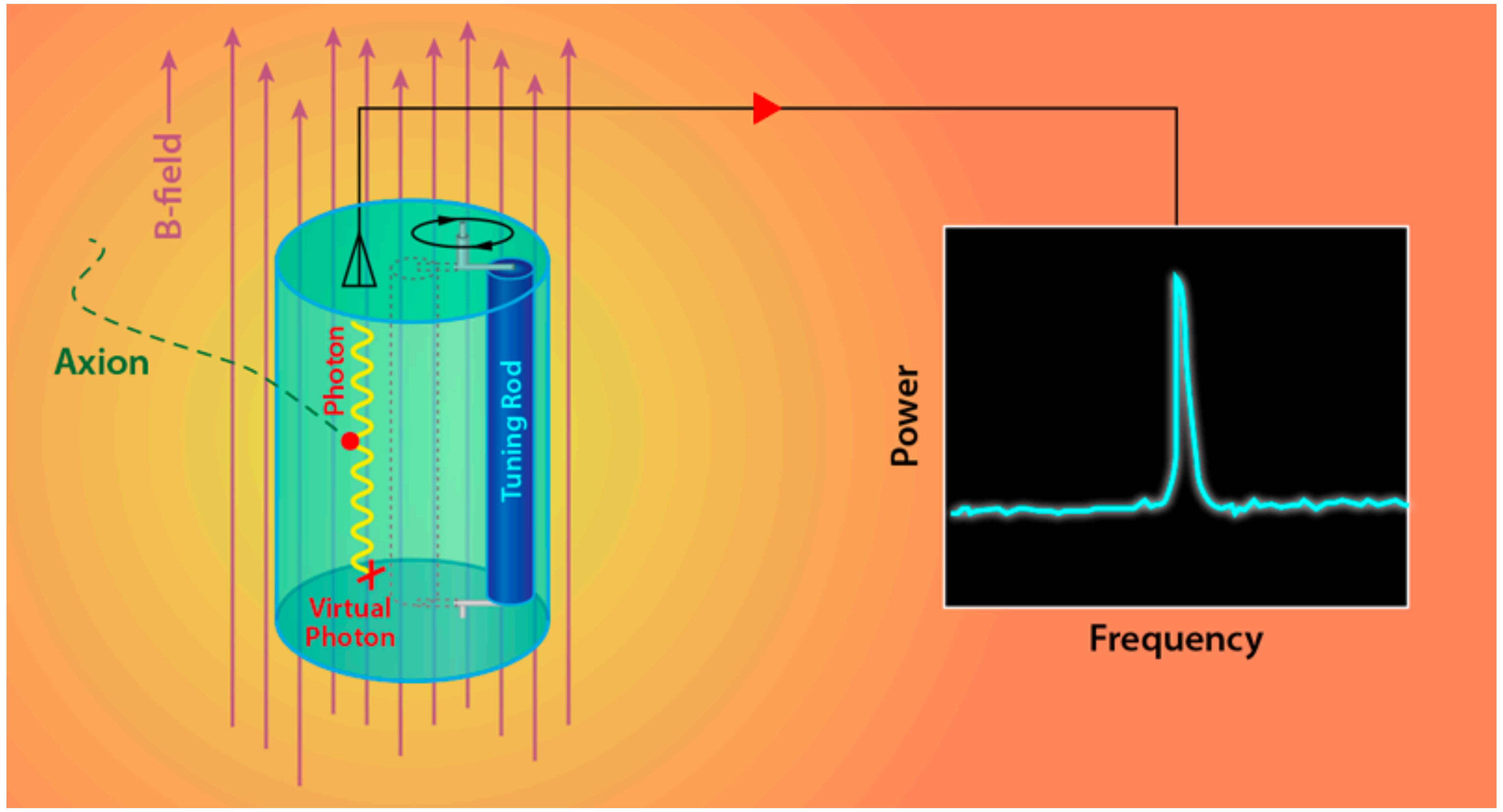
- Ultralight: $m \lesssim \mathrm{keV}$, ultralight due to shift symmetry (pseudo-Nambu Goldstone, e.g. Axion)
- Bosonic: Pauli-exclusion for fermonic DM
- Exits as classical fields ($m \lesssim \mathcal{O}(1)\ \mathrm{eV}$)
- Typical models:
  - Pseudo-scalar: Axion, Axion-like Particle
  - Dark Scalar: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

# 超轻暗物质：赝标量轴子




$$\mathscr{L}_{\mathrm{ALP}} = g_{ag}\frac{a}{f_a}G\tilde{G} + g_{a\gamma}\frac{a}{f_a}F\tilde{F} + g_{af}\frac{\partial_\mu a}{2f_a}\bar{f}\gamma^\mu\gamma_5 f$$

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

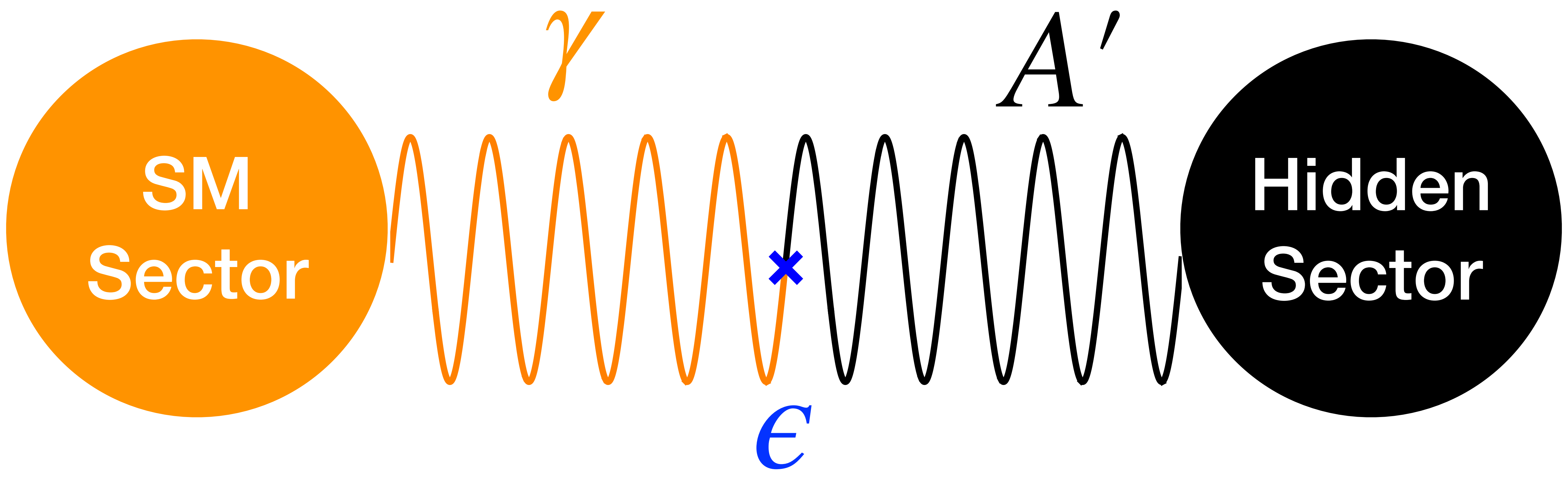


# 矢量型超轻暗物质：暗光子

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

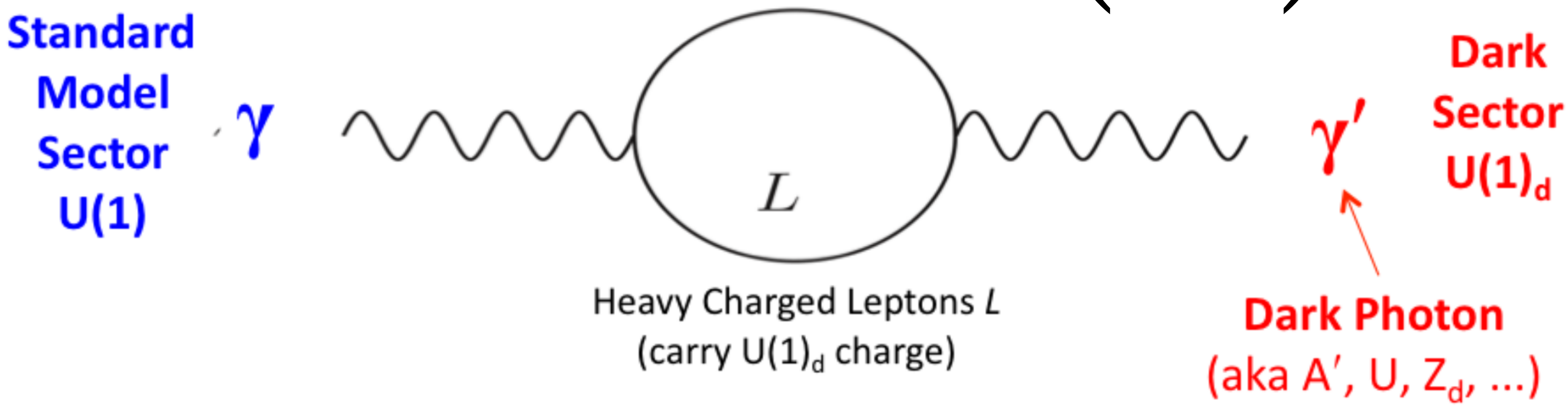
$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + 0 \times A^\mu A_\mu - eA_\mu j^\mu_{\text{em}}$$

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



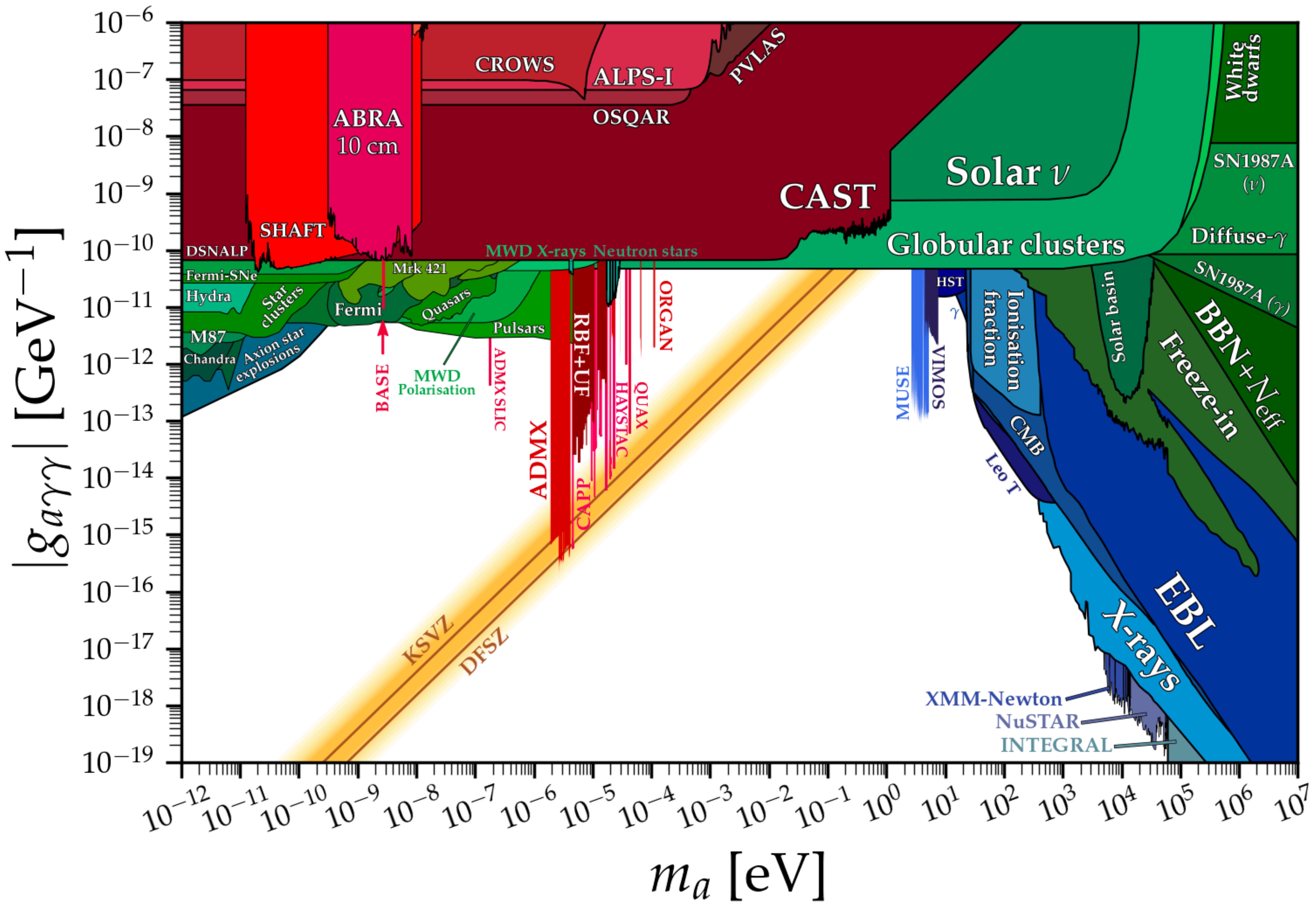

A proper low energy model from UV physics
Log dependence of UV scale

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



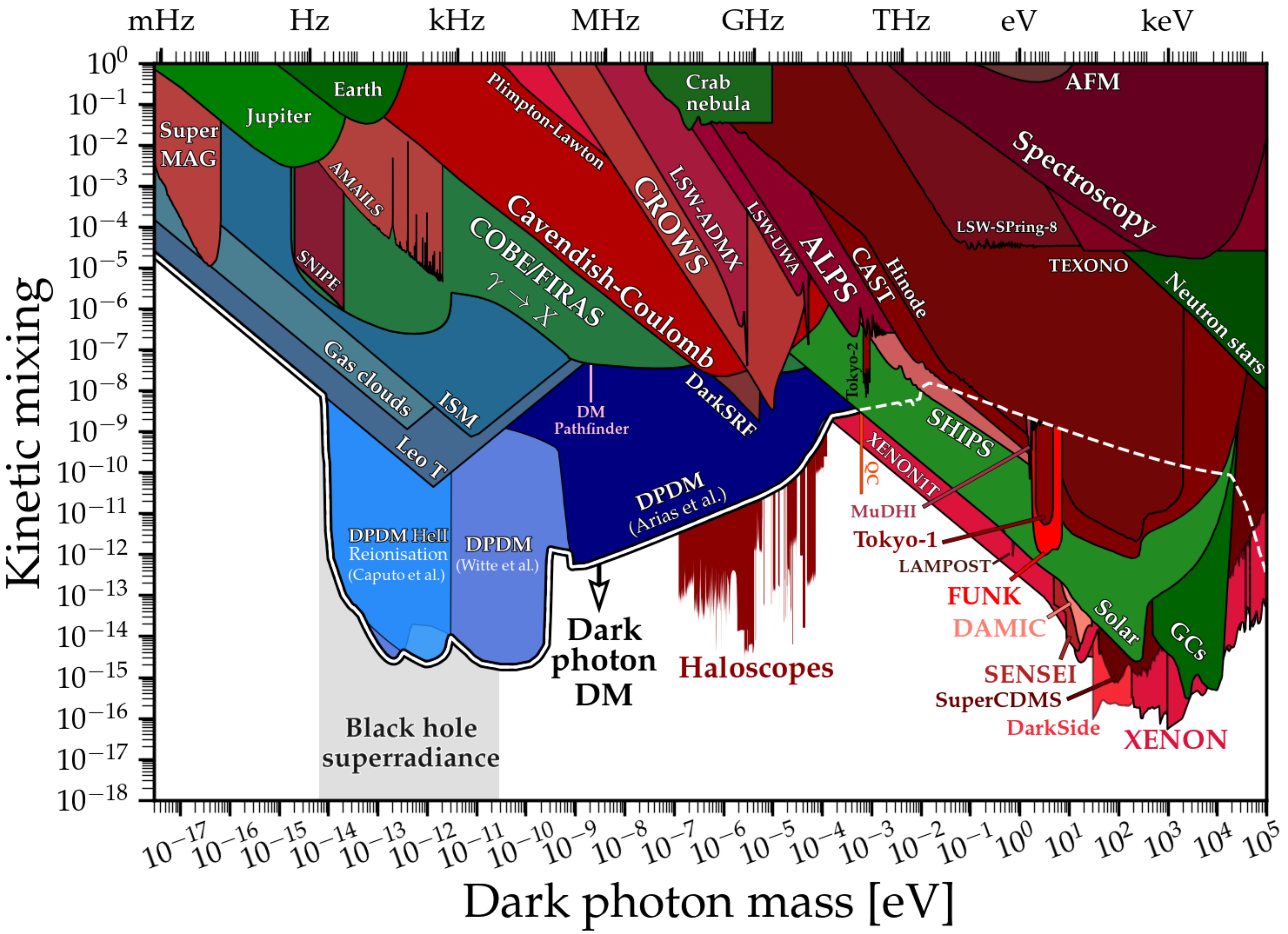

- Two free parameters: $m_{A'}$ and $\epsilon$

# 超轻玻色型暗物质探寻

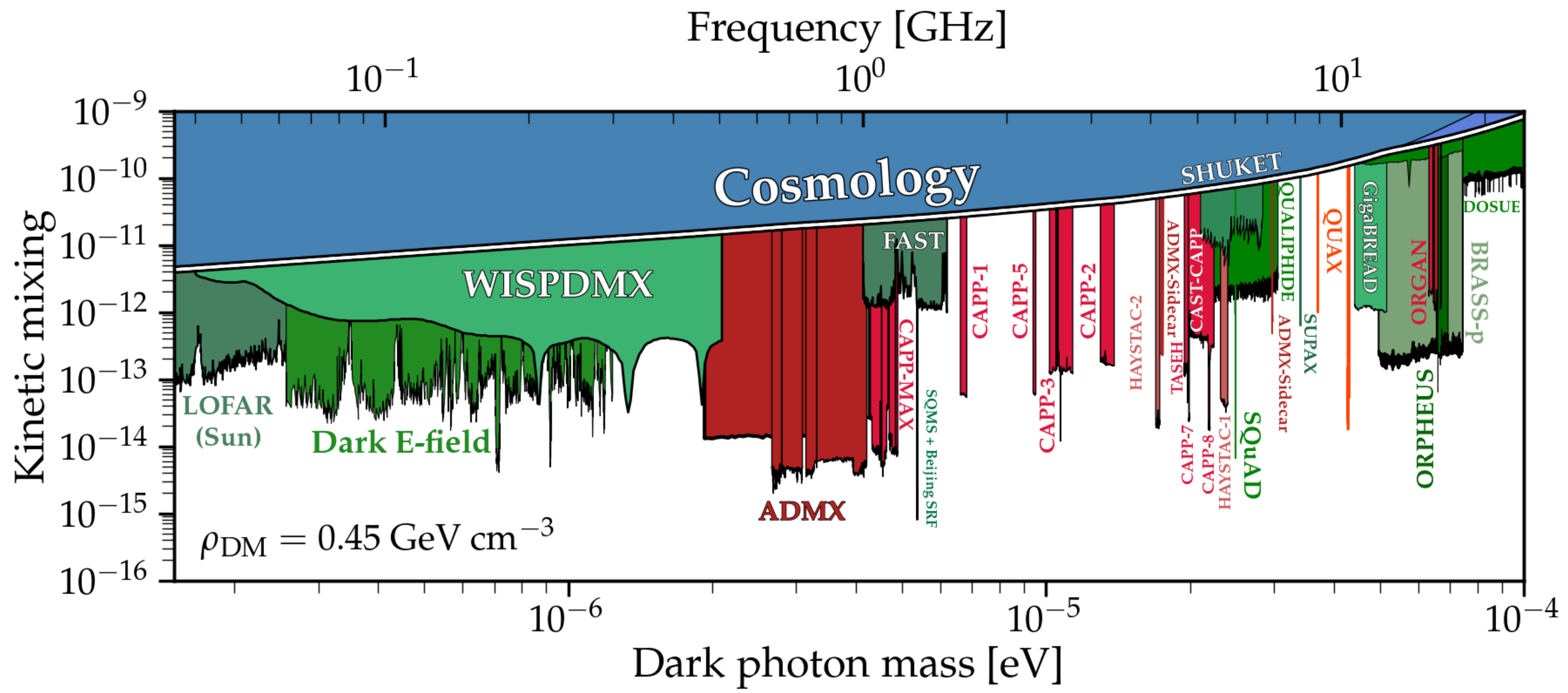


$|g_{a\gamma\gamma}|$ [GeV$^{-1}$]
$m_a$ [eV]
CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
SHAFT
CAST
Solar ν
Globular clusters
White dwarfs
SN1987A (ν)
Diffuse-γ
SN1987A (γ)
BBN+$N_{eff}$
Freeze-in
DSNALP
Fermi-SNe
Hydra
Star clusters
M87
Chandra
Axion star explosions
Fermi
Mrk 421
Quasars
Pulsars
MWD X-rays
Neutron stars
MWD Polarisation
BASE
ADMX SLIC
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
KSVZ
DFSZ
MUSE
VIMOS
HST
Ionisation fraction
Solar basin
CMB
Leo T
EBL
X-rays
XMM-Newton
NuSTAR
INTEGRAL

# 超轻玻色型暗物质探寻

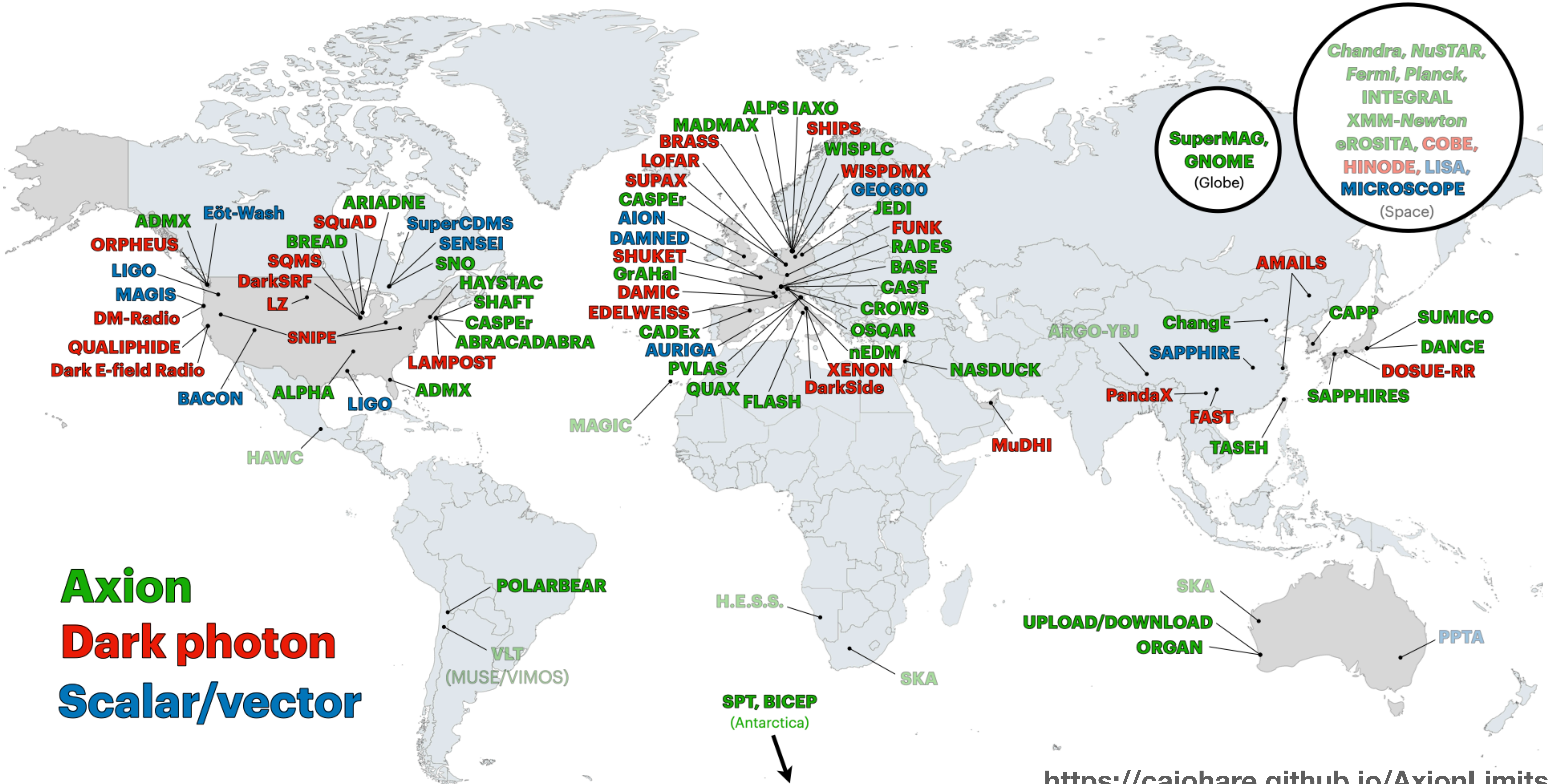


mHz Hz kHz MHz GHz THz eV keV
Kinetic mixing
Dark photon mass [eV]
Super MAG
Jupiter
Earth
Crab nebula
AFM
Spectroscopy
Plimpton-Lawton
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
Hinode
LSW-SPring-8
TEXONO
Neutron stars
AMAILS
SNIPE
Cavendish-Coulomb
COBE/FIRAS
$\gamma \to X$
Gas clouds
ISM
Leo T
DM Pathfinder
DarkSRF
DPDM (Arias et al.)
DPDM HeII Reionisation (Caputo et al.)
DPDM (Witte et al.)
Black hole superradiance
Dark photon DM
Haloscopes
Tokyo-2
QC
XENON1T
SHIPS
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
DarkSide
XENON
Solar
GCs

Frequency [GHz]
Kinetic mixing
Dark photon mass [eV]
Cosmology
SHUKET
WISPDMX
FAST
LOFAR (Sun)
Dark E-field
ADMX
CAPP-MAX
SQMS + Beijing SRF
CAPP-1
CAPP-5
CAPP-3
CAPP-2
HAYSTAC-2
ADMX-Sidecar
TASEH
CAST-CAPP
CAPP-7
CAPP-8
HAYSTAC-1
SQuAD
QUALIPHIDE
ADMX-Sidecar
SUPAX
QUAX
GigaBREAD
ORGAN
ORPHEUS
DOSUE
BRASS-p
$\rho_{DM} = 0.45$ GeV cm$^{-3}$

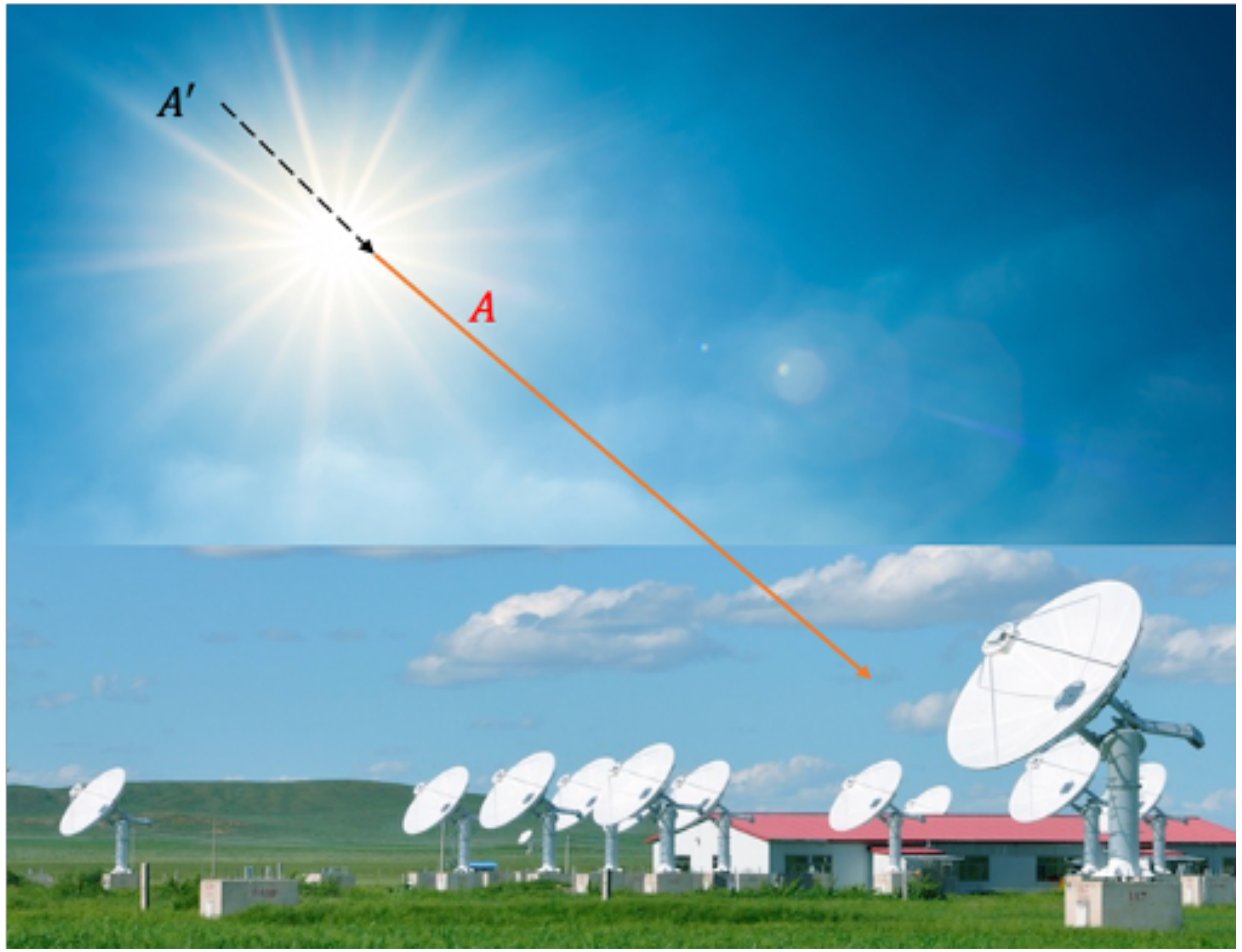
# 超轻玻色型暗物质探寻




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

# Radio astronomy and ultralight bosonic dark matter

**太阳物理**




**Dark photon dark matter**
**resonant conversion at solar corona**

An, Huang, JL, Xue, 2010.15836 (PRL 2021)
An, Chen, Ge, Liu, Luo, 2301.03622 (NC 2024)
Editor Highlights

**Radio telescope at Earth**

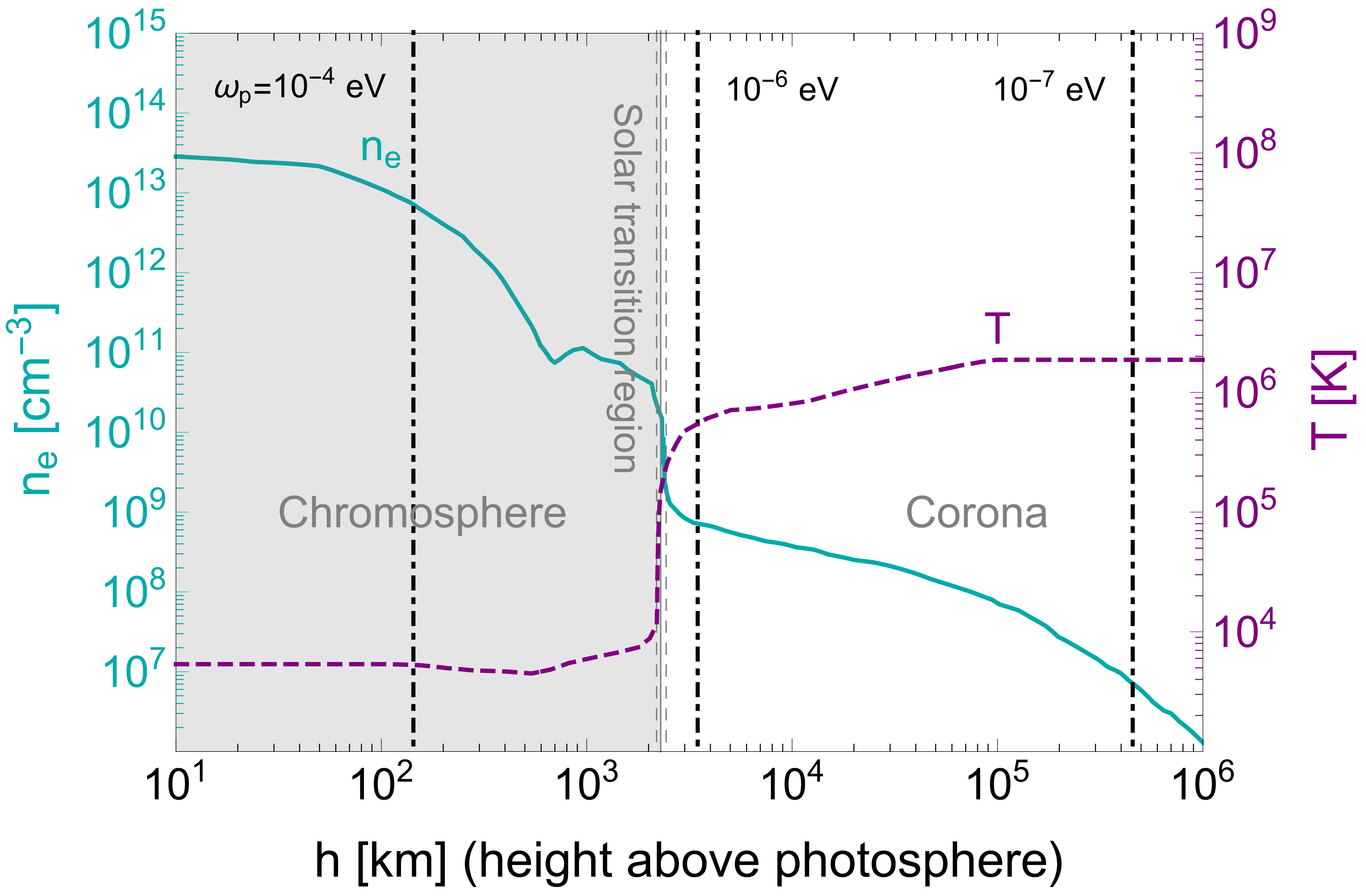

**Dark photon dark matter**
**conversion at radio telescope**

An, Ge, Guo, Huang, JL, Lu, 2207.05767 (PRL 2023, Featured in Physics)
reported by APS Physics, Phys.org, Physics Today

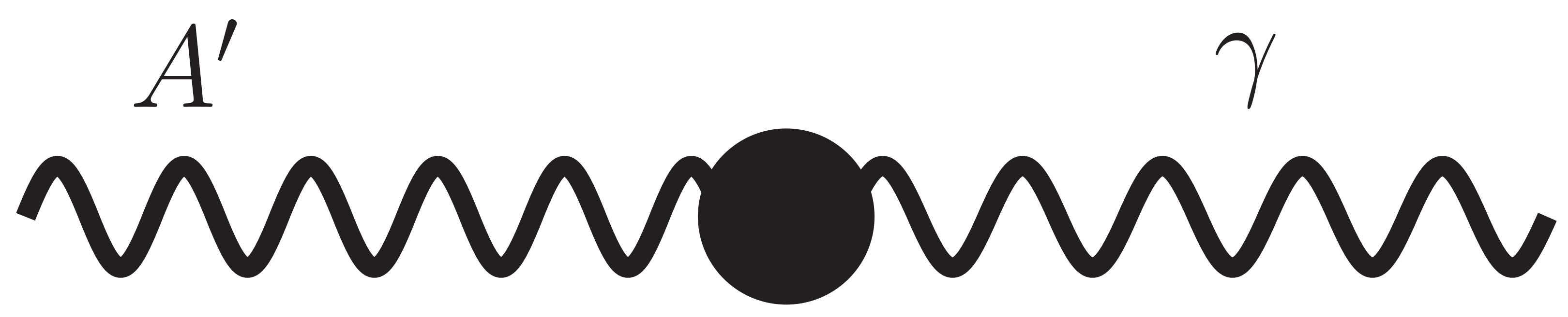
# The dark photon dark matter conversion at solar corona

- The plasma frequency

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



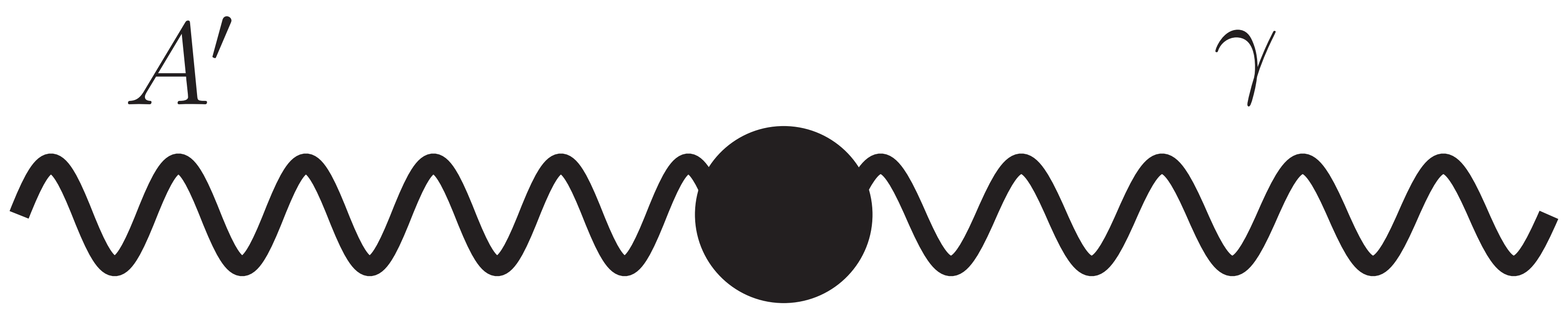

- Resonant conversion $A' \to \gamma$
  - When $m_{A'} = \omega_p$




- 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)




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

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

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

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

$$\frac{1}{3}\sum_{\text{pol}}|\mathscr{M}|^2 = \frac{2}{3}\epsilon^2 m_{A'}^4$$

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

- 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

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

# Sensitivity of the radio telescope

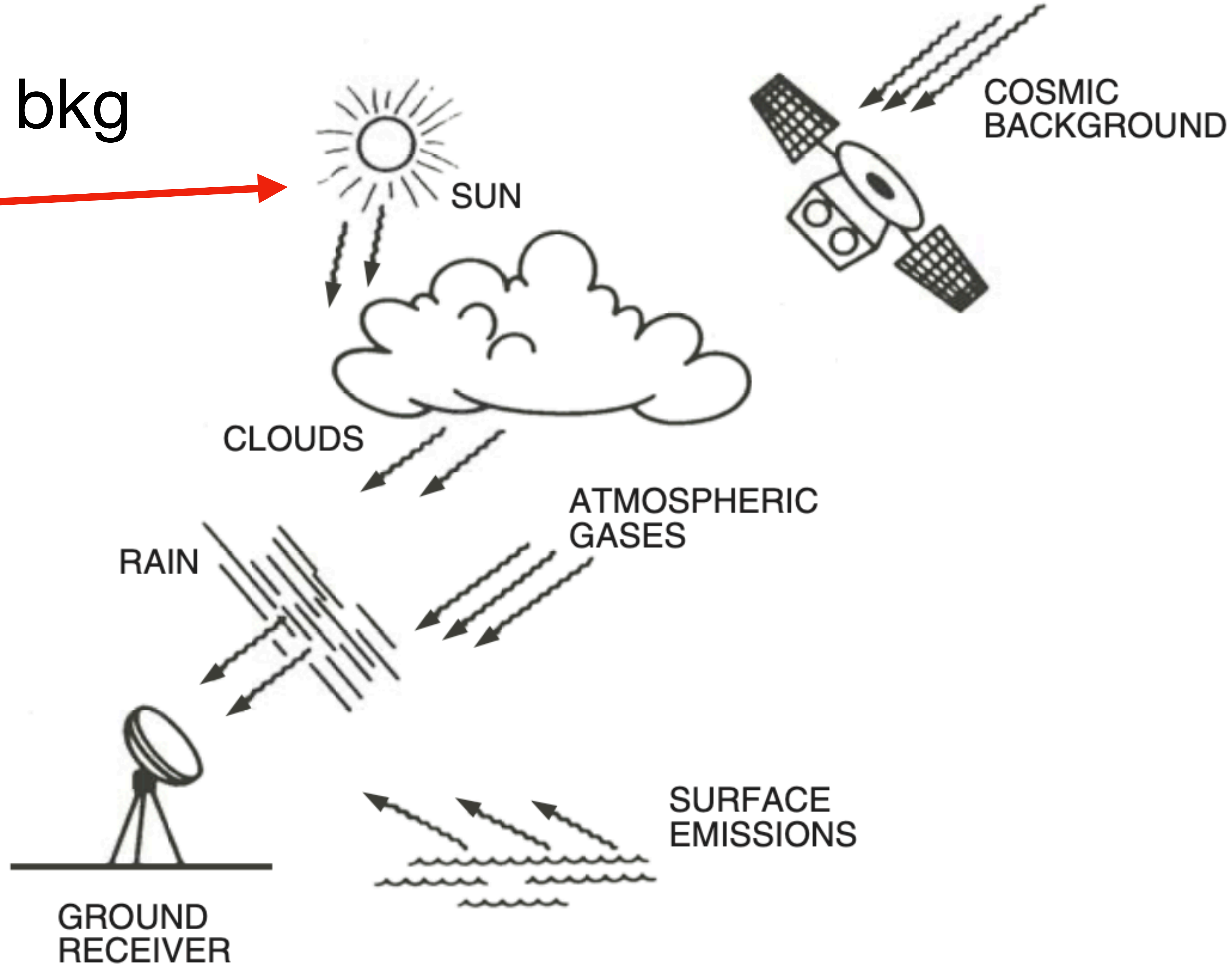
- The system equivalent flux density
  - For solar observation, Sun is the largest bkg

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

- The minimum detectable flux density

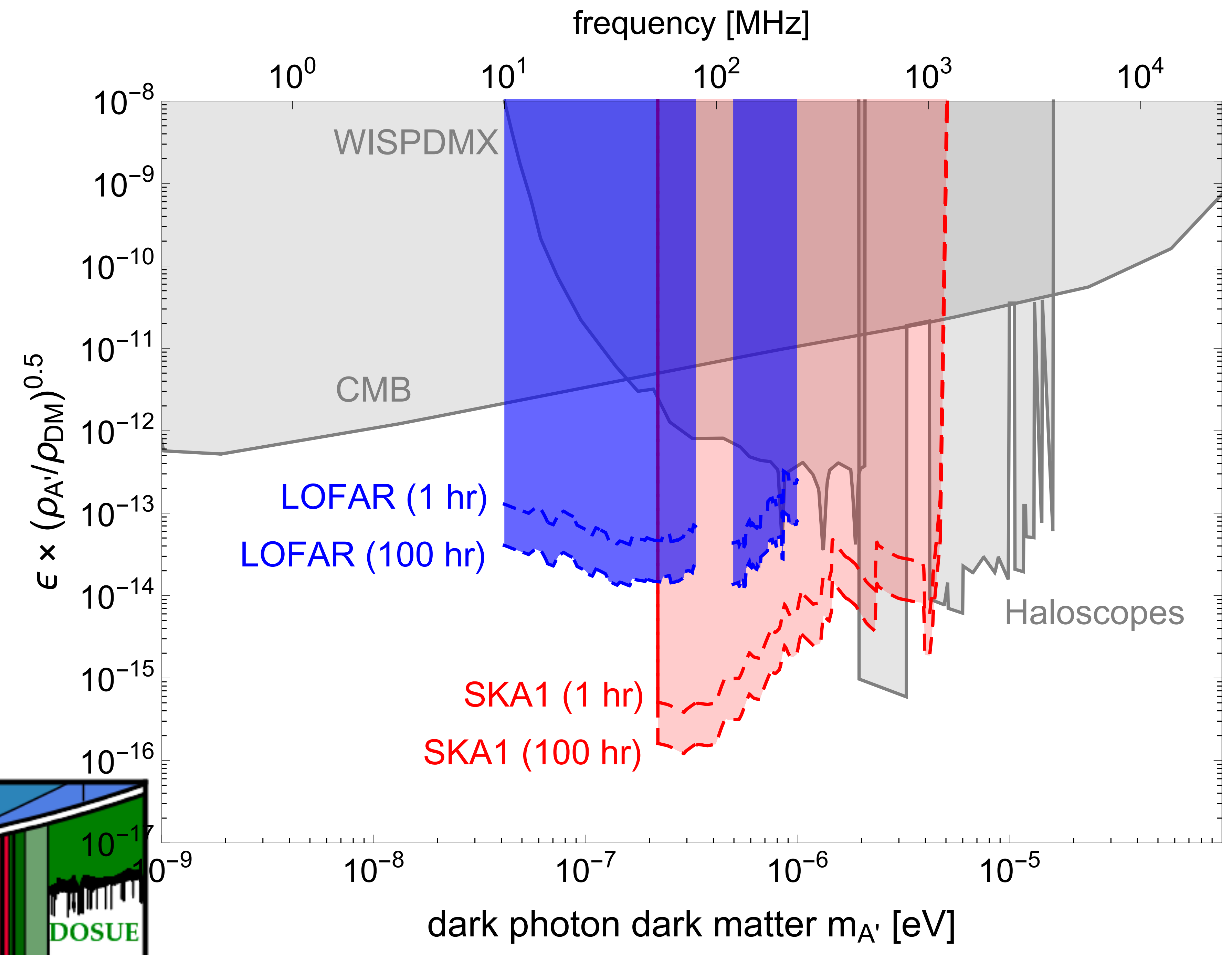
$$S_{\min} = \frac{\mathrm{SEFD}}{\eta_s \sqrt{n_{\mathrm{pol}} \mathscr{B}\, t_{\mathrm{obs}}}}$$

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

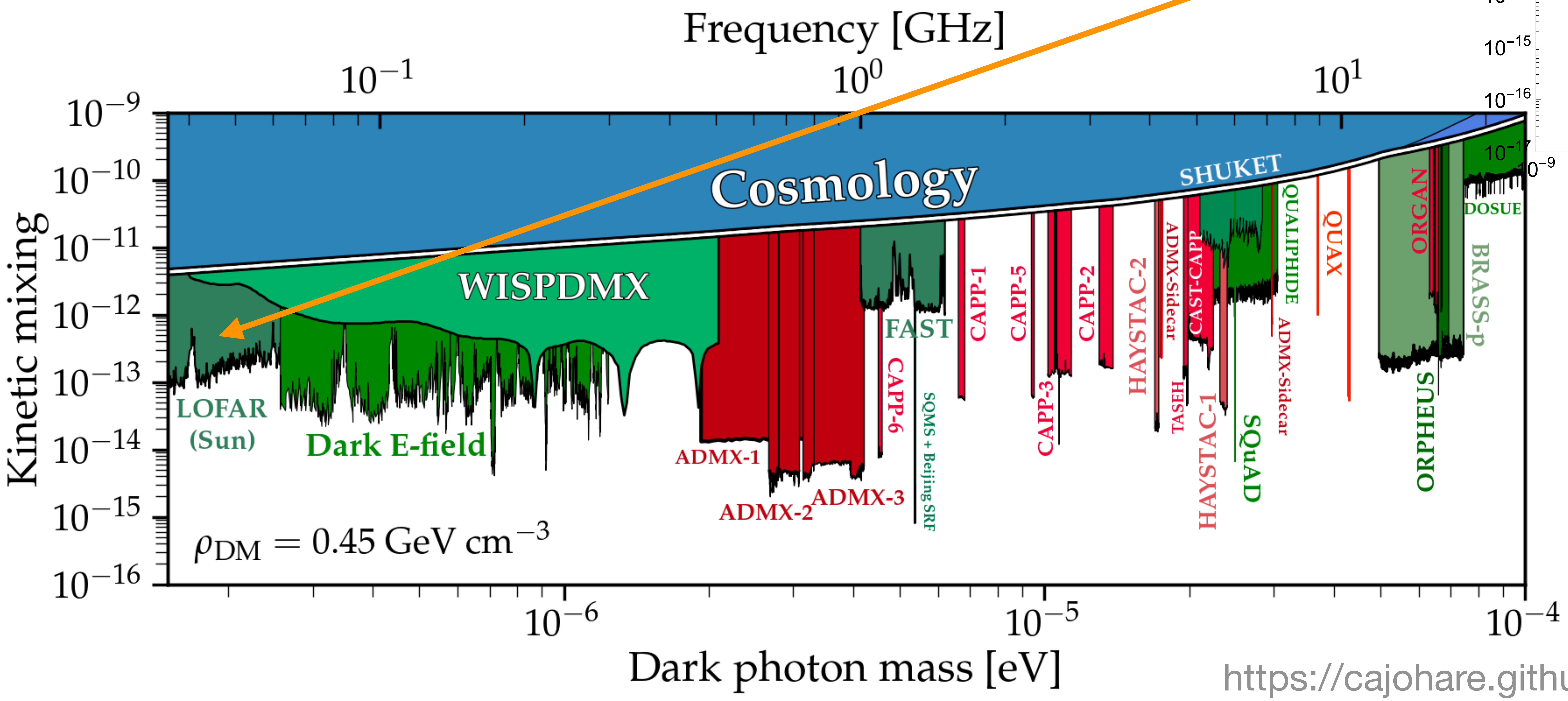


# The sensitivity of DPDM from solar resonant conversion

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

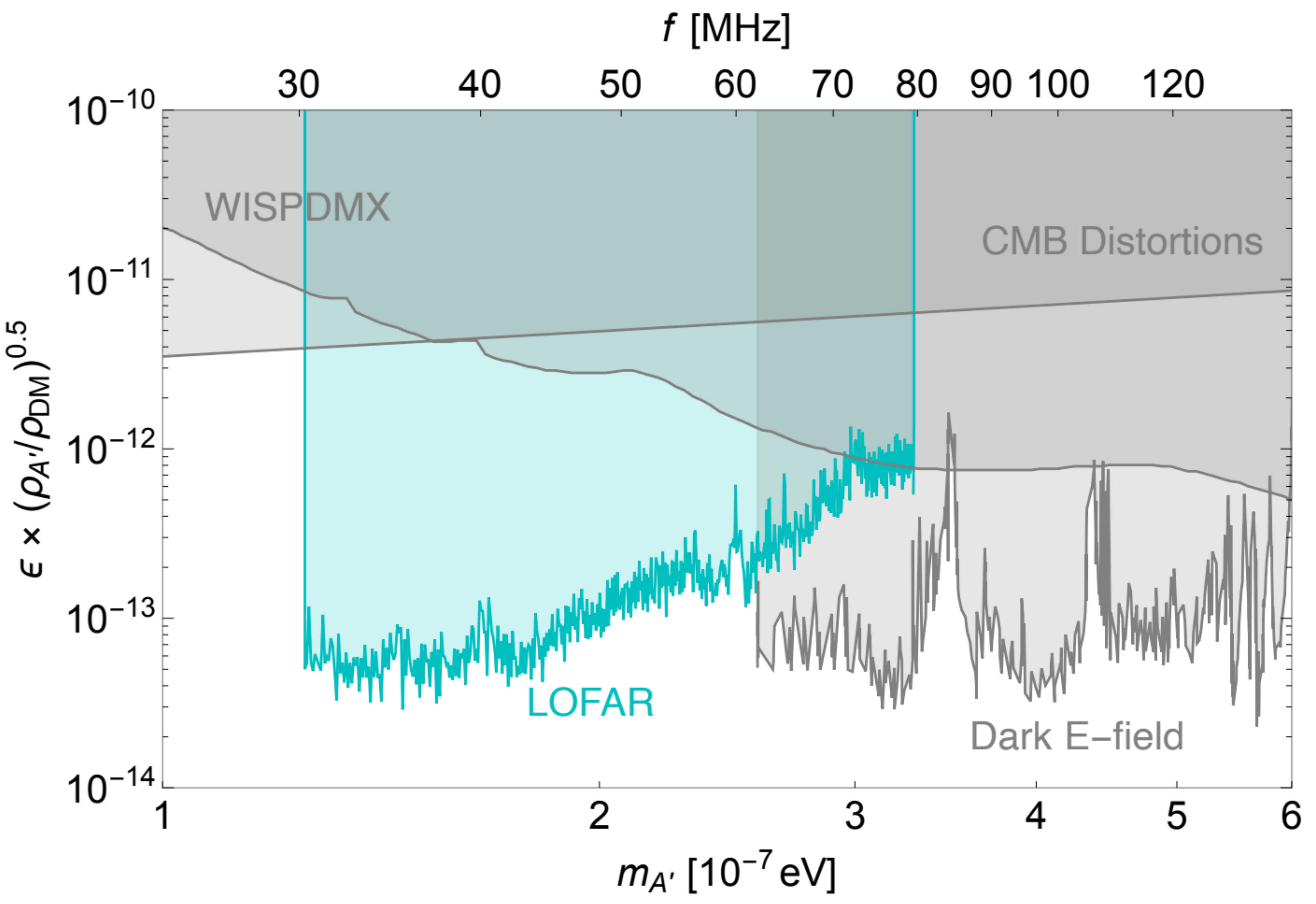



Phys.Rev.Lett. 126 (2021) 18, 181102

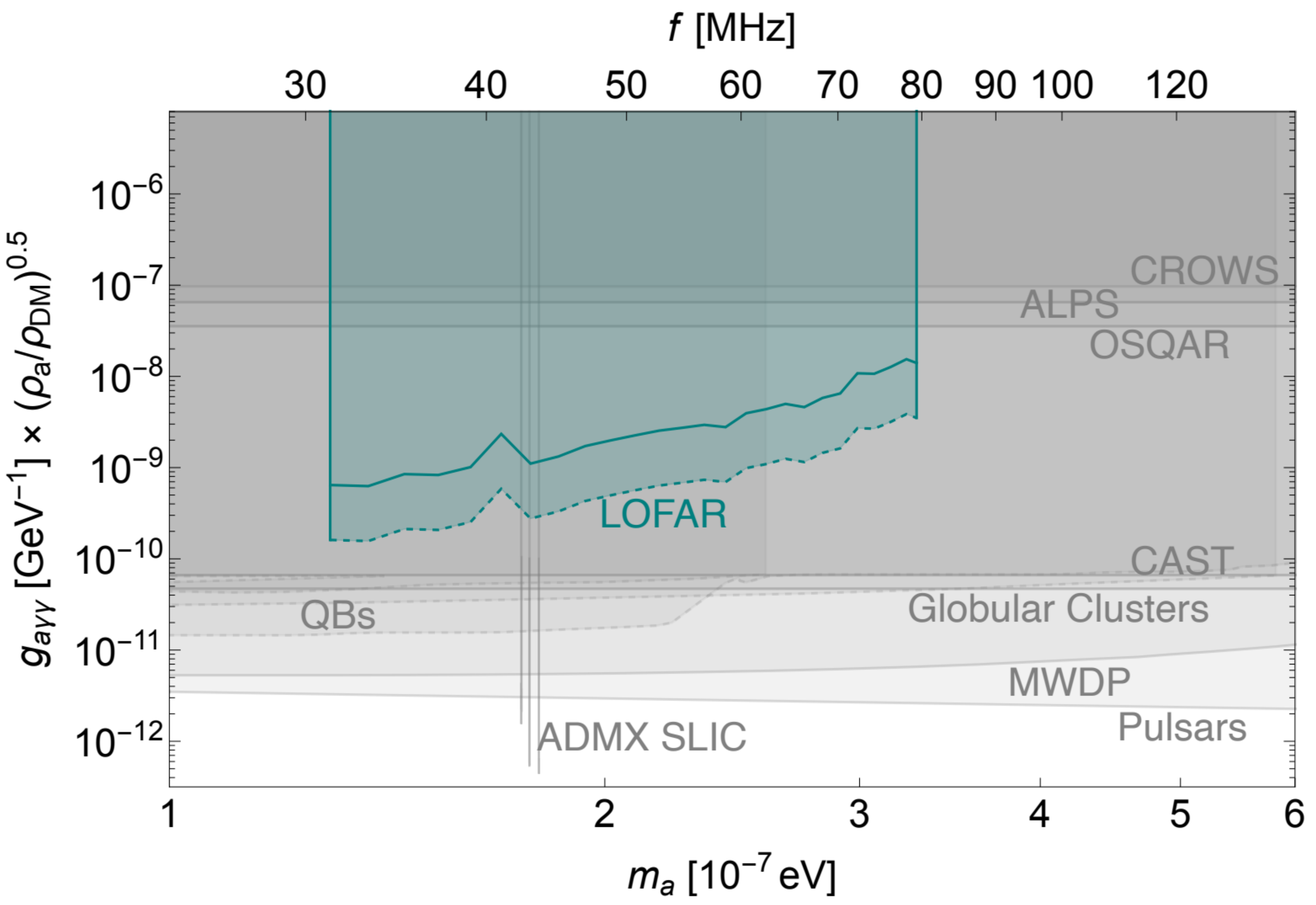



https://cajohare.github.io/AxionLimits/docs/dp.html

# The sensitivity of DPDM from LOFAR data




暗光子暗物质

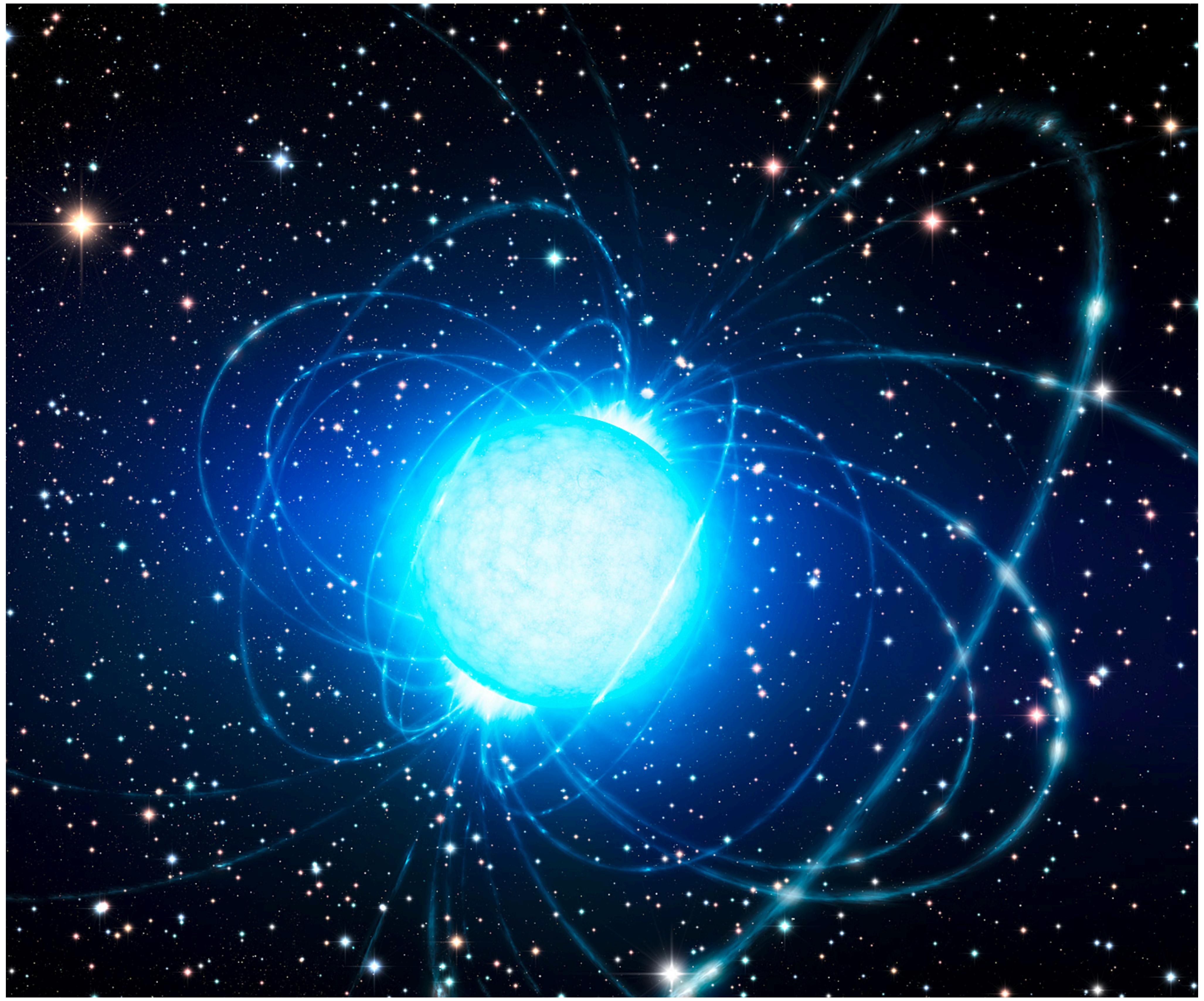


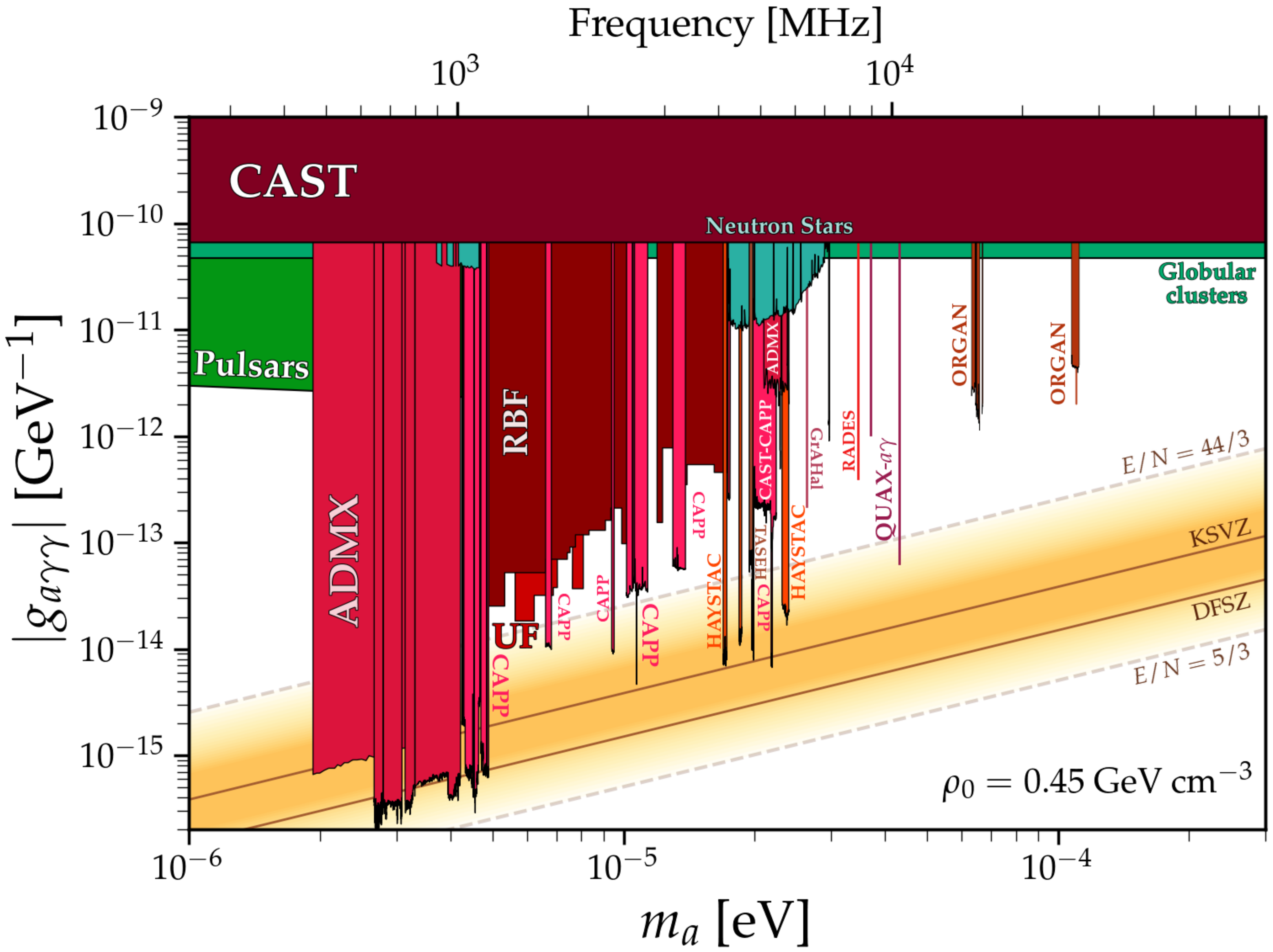

轴子暗物质

Nature Communications 15 (2024) 915

# 中子星观测与超轻轴子暗物质

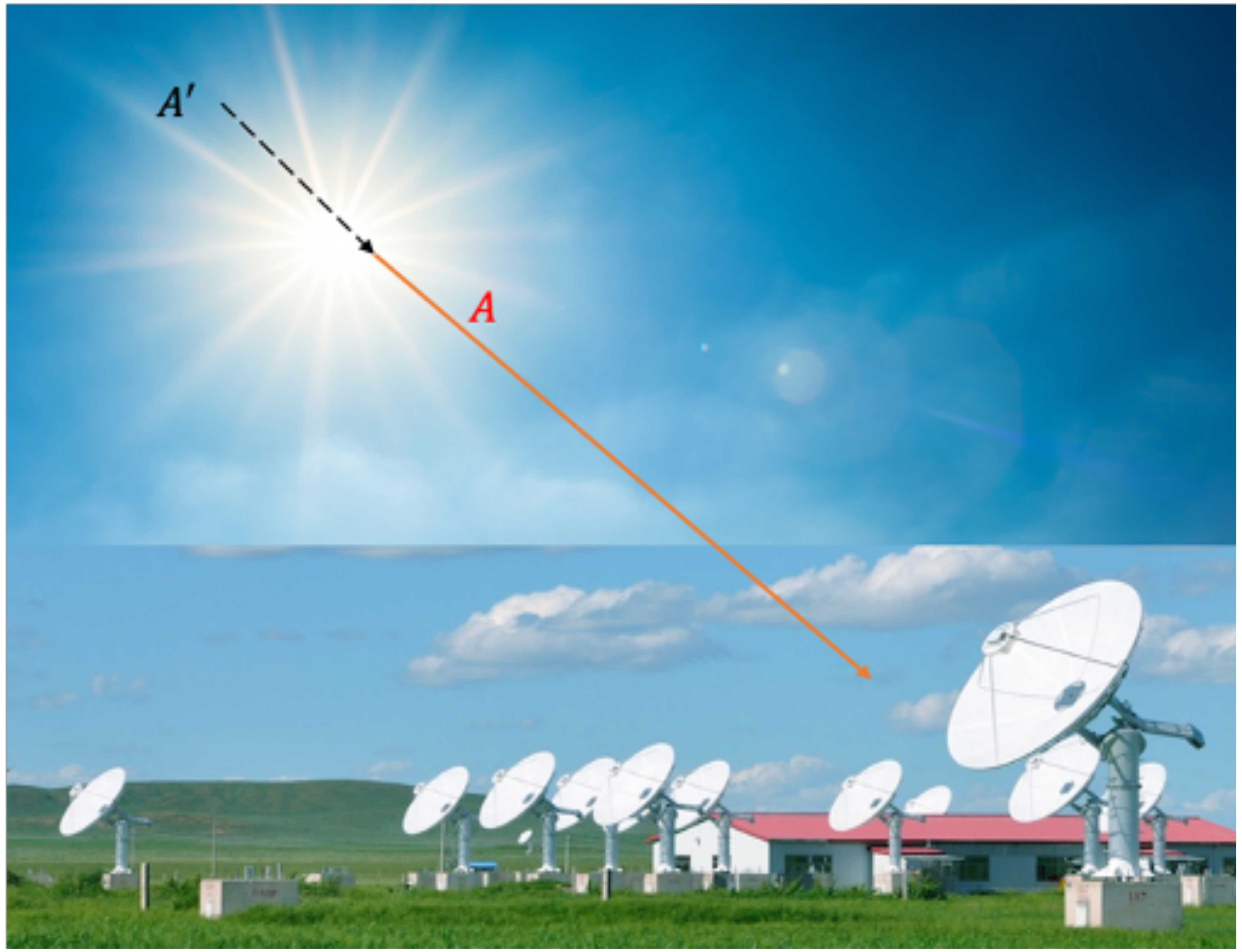
- 轴子在中子星(Magnetar)强磁场中转化为单频光子





# Radio astronomy and ultralight bosonic dark matter

**Solar Physics**

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# Direct detection of DPDM using dish antenna radio telescope

- Lagrangian

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

- Extended Maxwell Eqs

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

- Perfect conductor

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

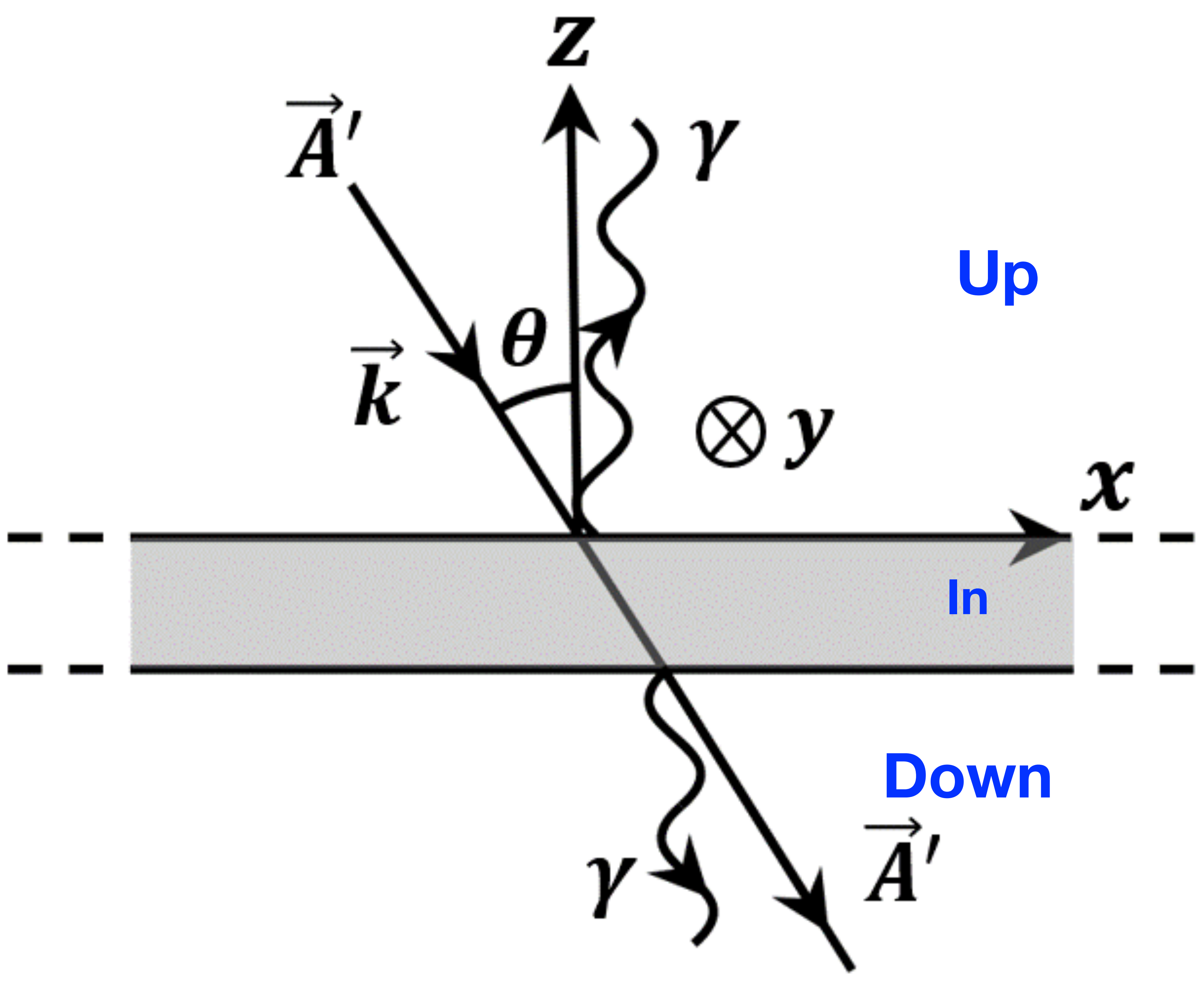
$$\nabla \cdot \mathbf{J} + \frac{\partial \rho}{\partial t} = 0$$


FAST radio telescope

# Direct detection of DPDM using dish antenna radio telescope

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

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



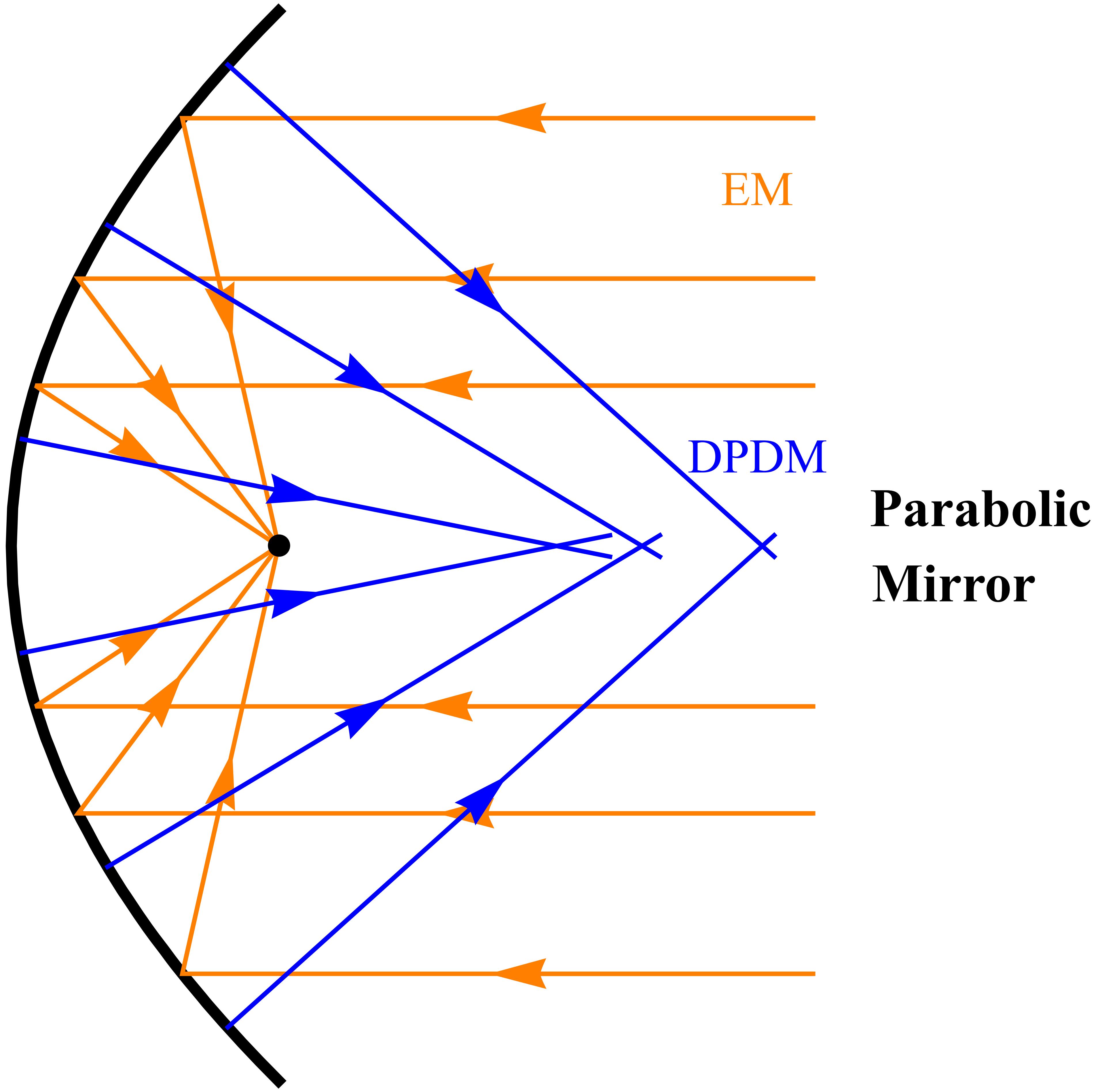

  - Solving the reflected EM field
    - (always perpendicular to the surface)
    - Oscillating dipole unit

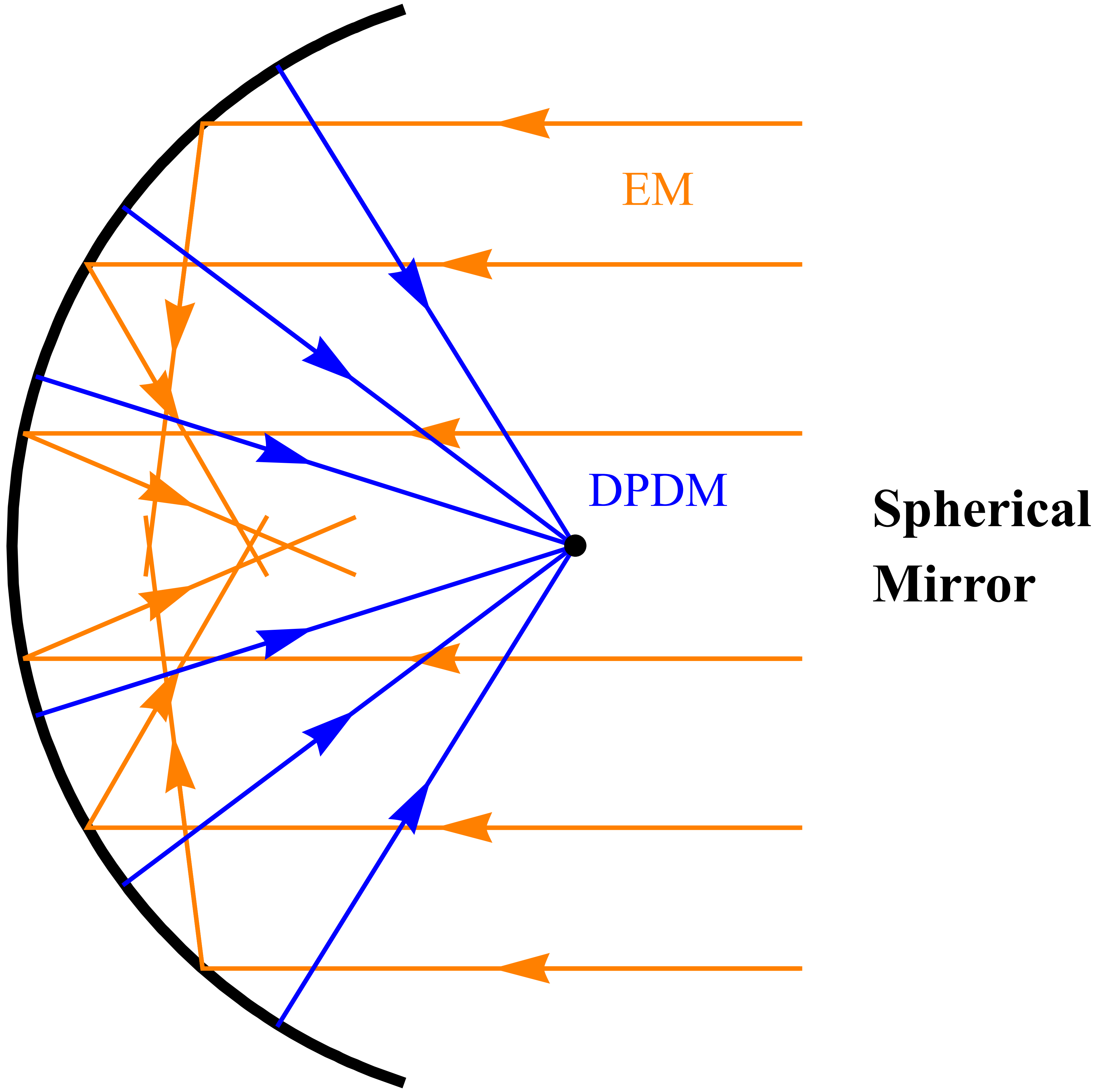
$$d\mathbf{p} = 2\epsilon \mathbf{A}'_{\|} dS \longrightarrow \mathbf{B} = -\frac{\epsilon m_{A'}^2}{2\pi} \int dS_1 \mathbf{A}'_{\|} \times (\mathbf{r} - \mathbf{r}_1) \frac{e^{i m_{A'} |\mathbf{r} - \mathbf{r}_1|}}{|\mathbf{r} - \mathbf{r}_1|^2}$$

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

# Direct detection of DPDM using dish antenna radio telescope

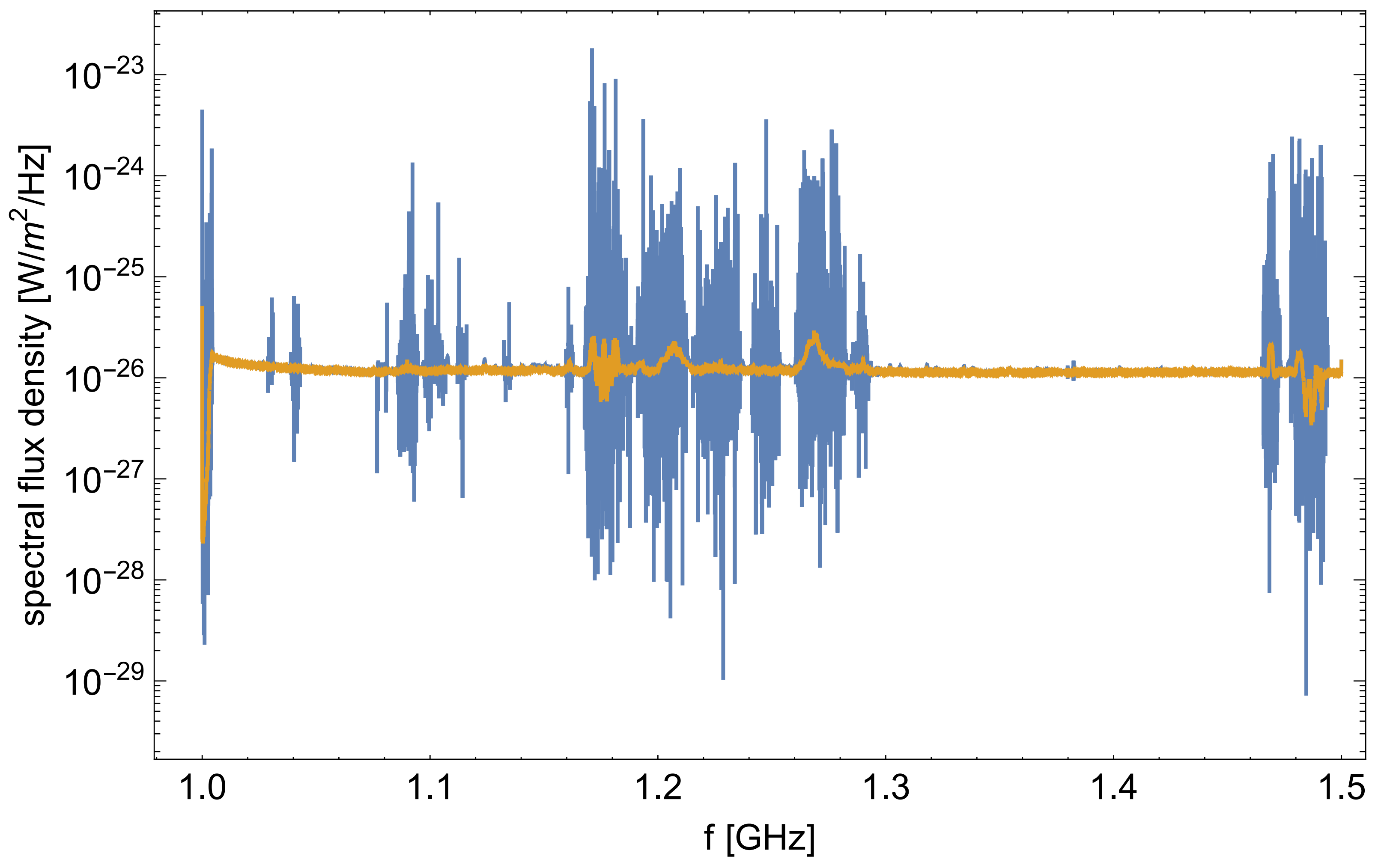
- The signal feature for DPDM with different mirrors



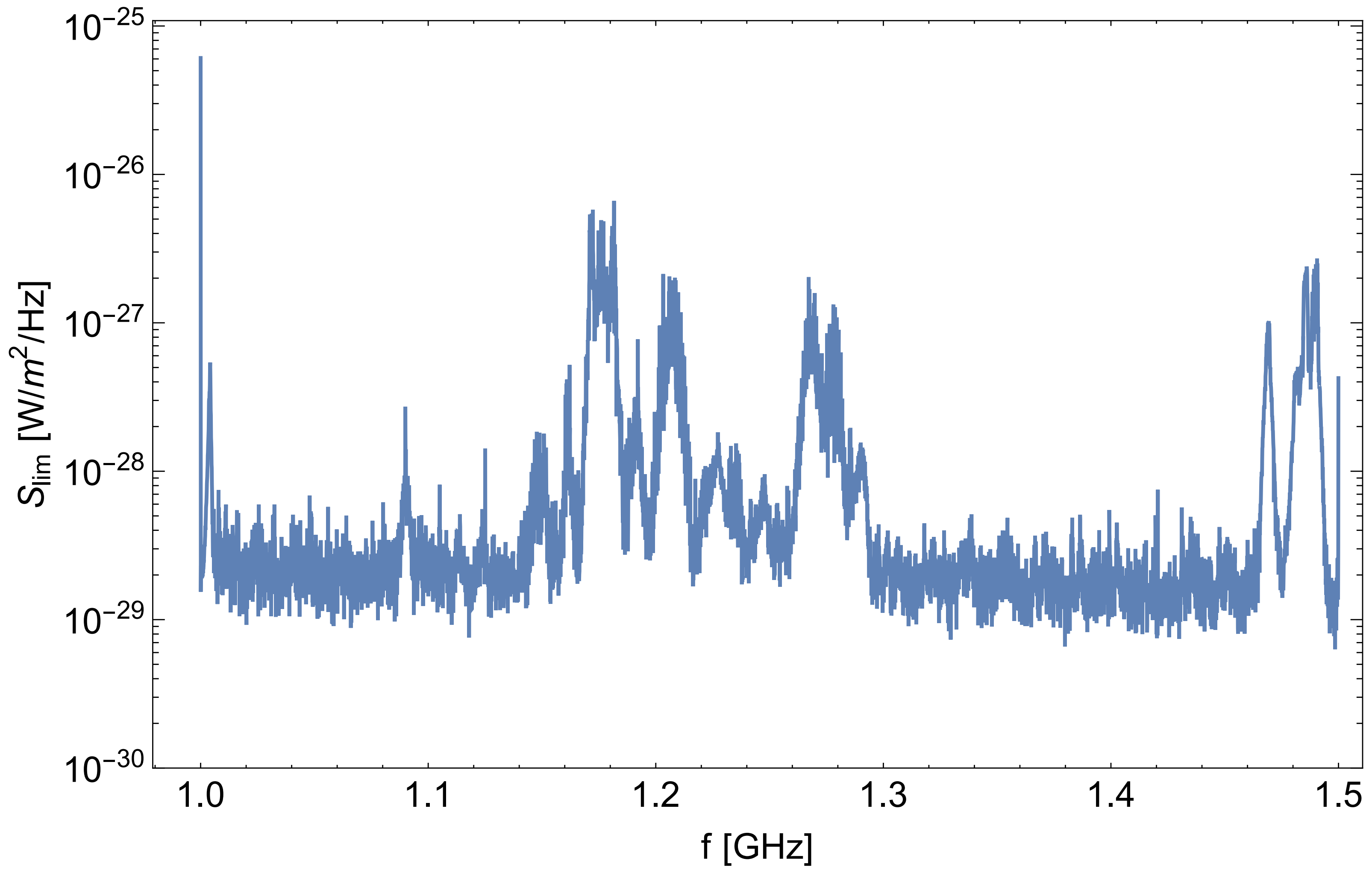
# Constraints from FAST observation data

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



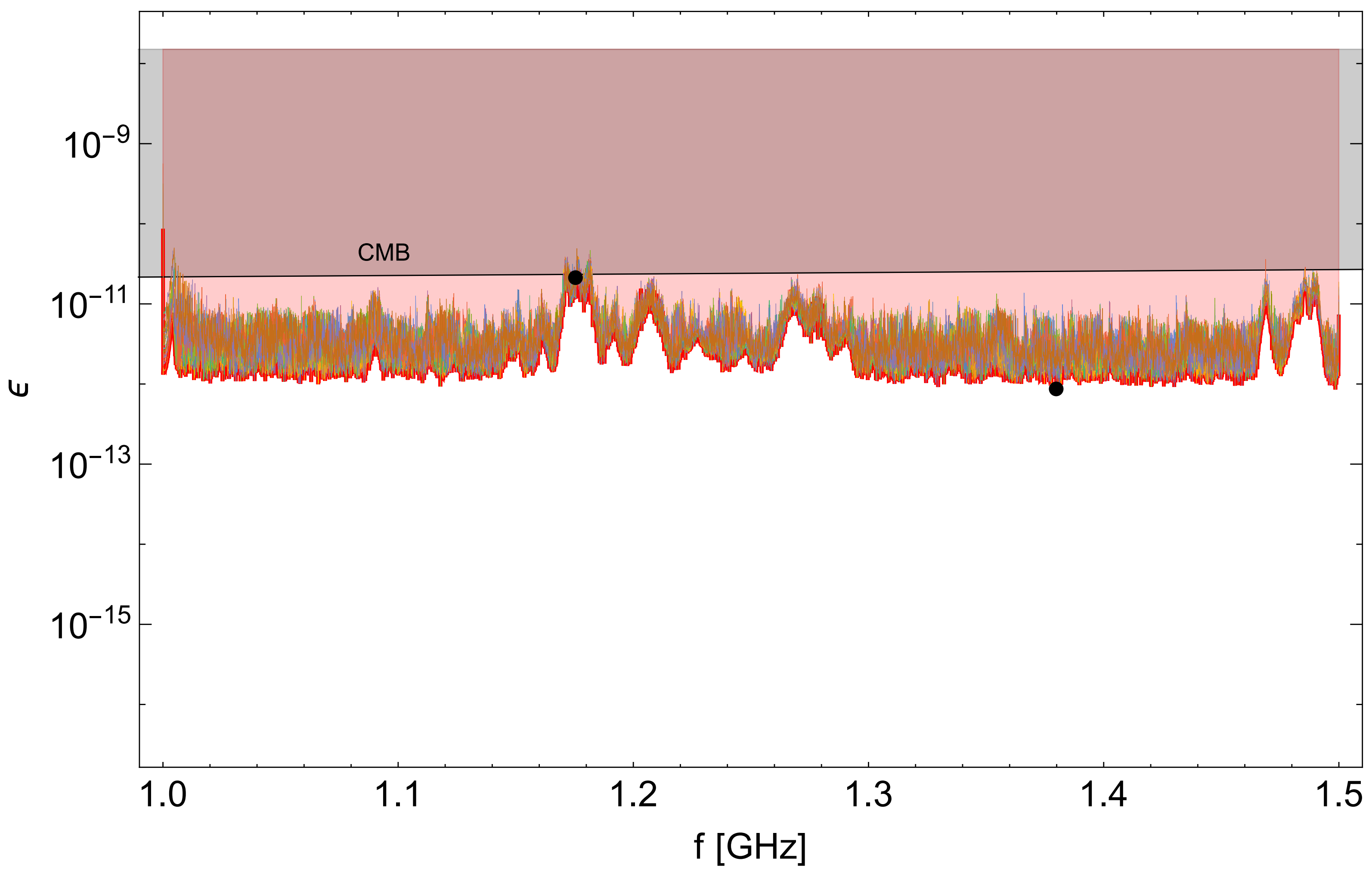

**FAST data**

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




**FAST limit on line signal**

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

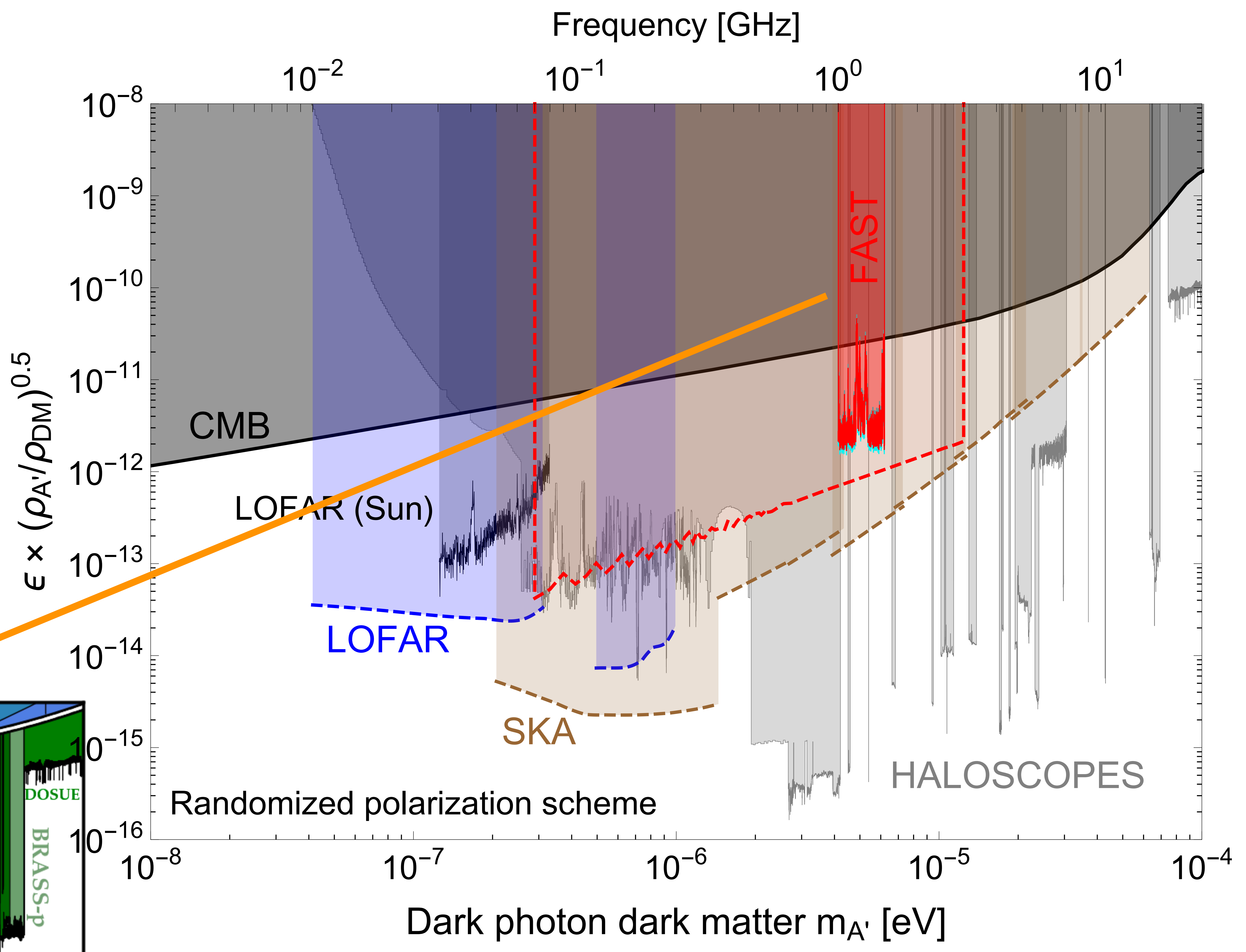



**FAST limit on DPDM**

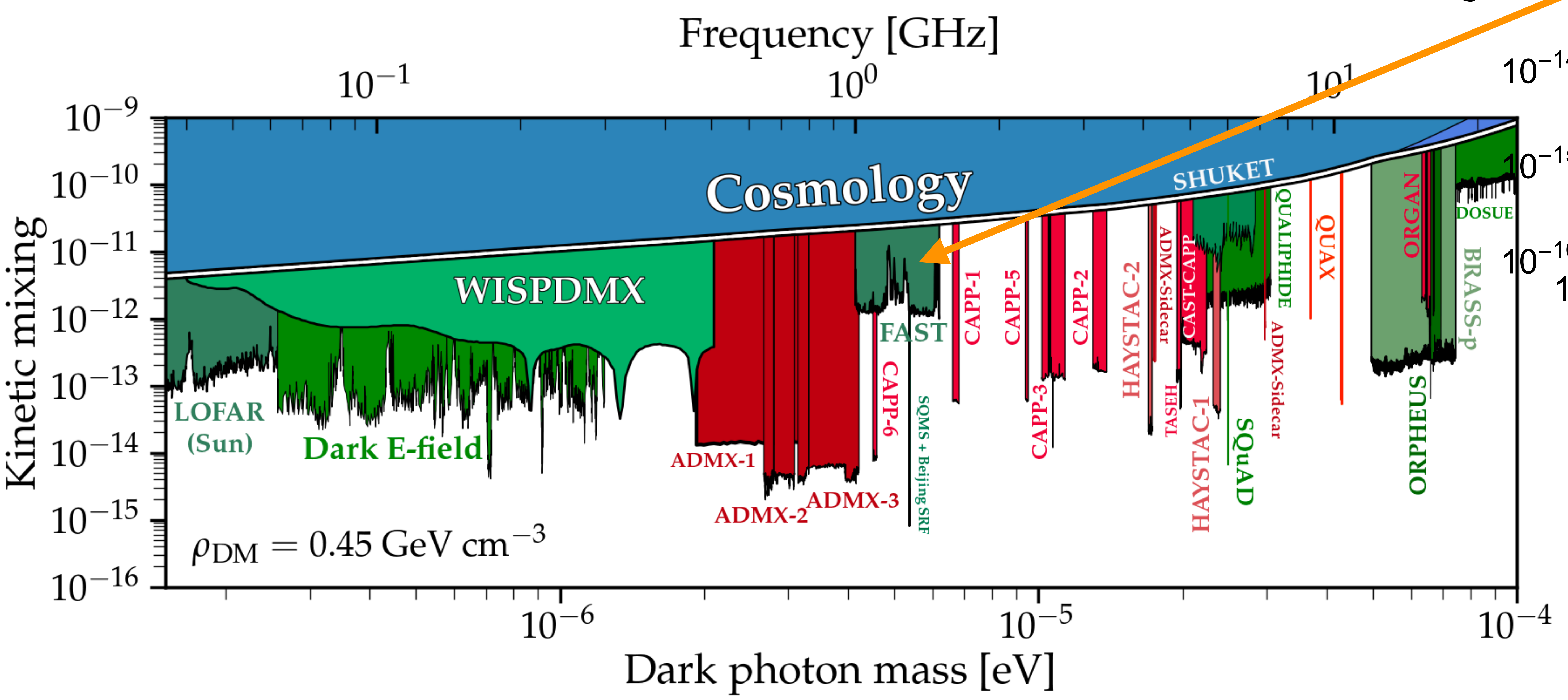
$\epsilon \sim 10^{-12}$

# The results for direct detection of DPDM using FAST 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



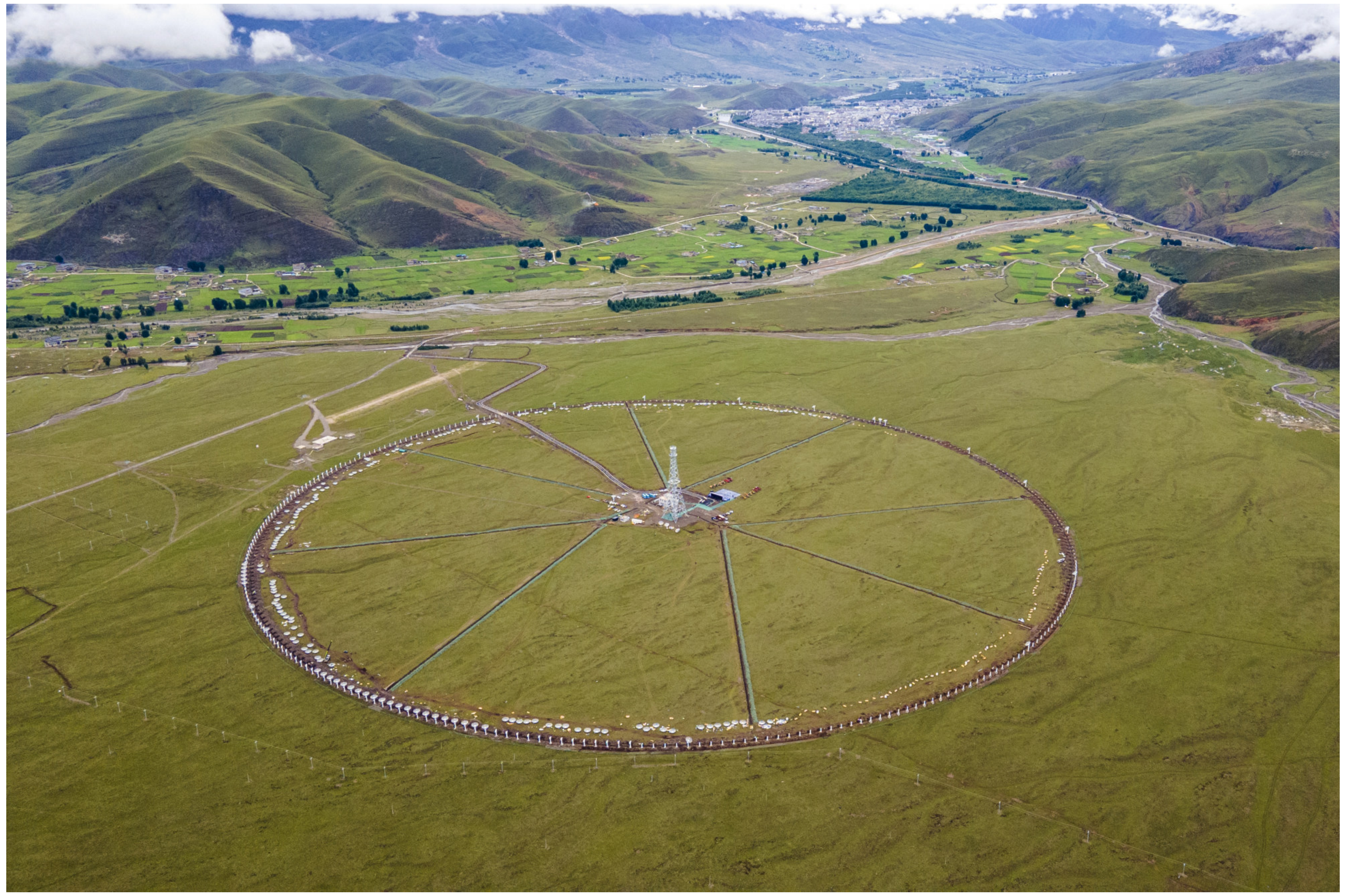

Phys.Rev.Lett. 130 (2023) 18, 181001




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

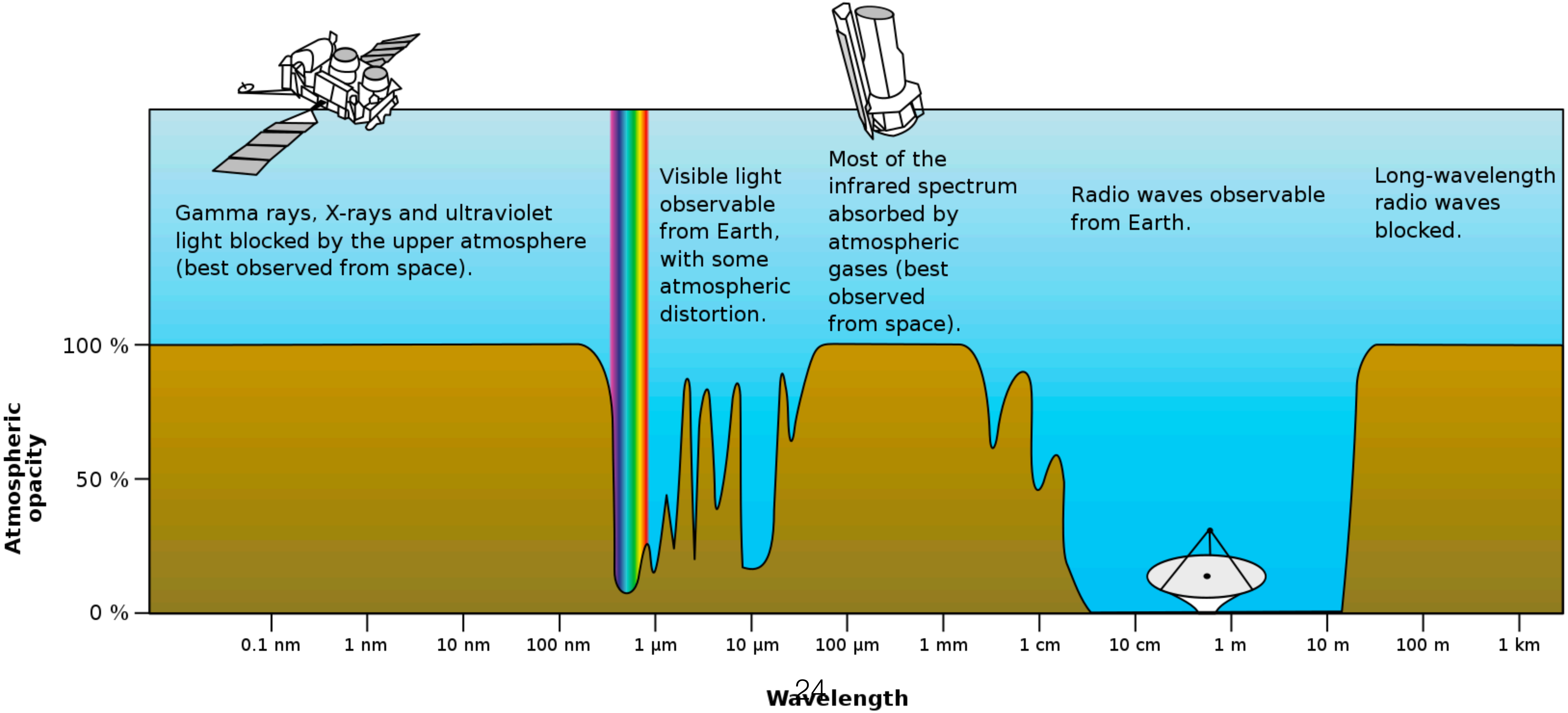
# 未来与展望：太阳物理观测与超轻暗物质探测

- “千眼天珠”稻城太阳射电望远 (Daocheng Solar Radio Telescope)
- 313 parabolic antennas of 6-meter diameter each
- Operational frequency: 150 MHz — 450 MHz



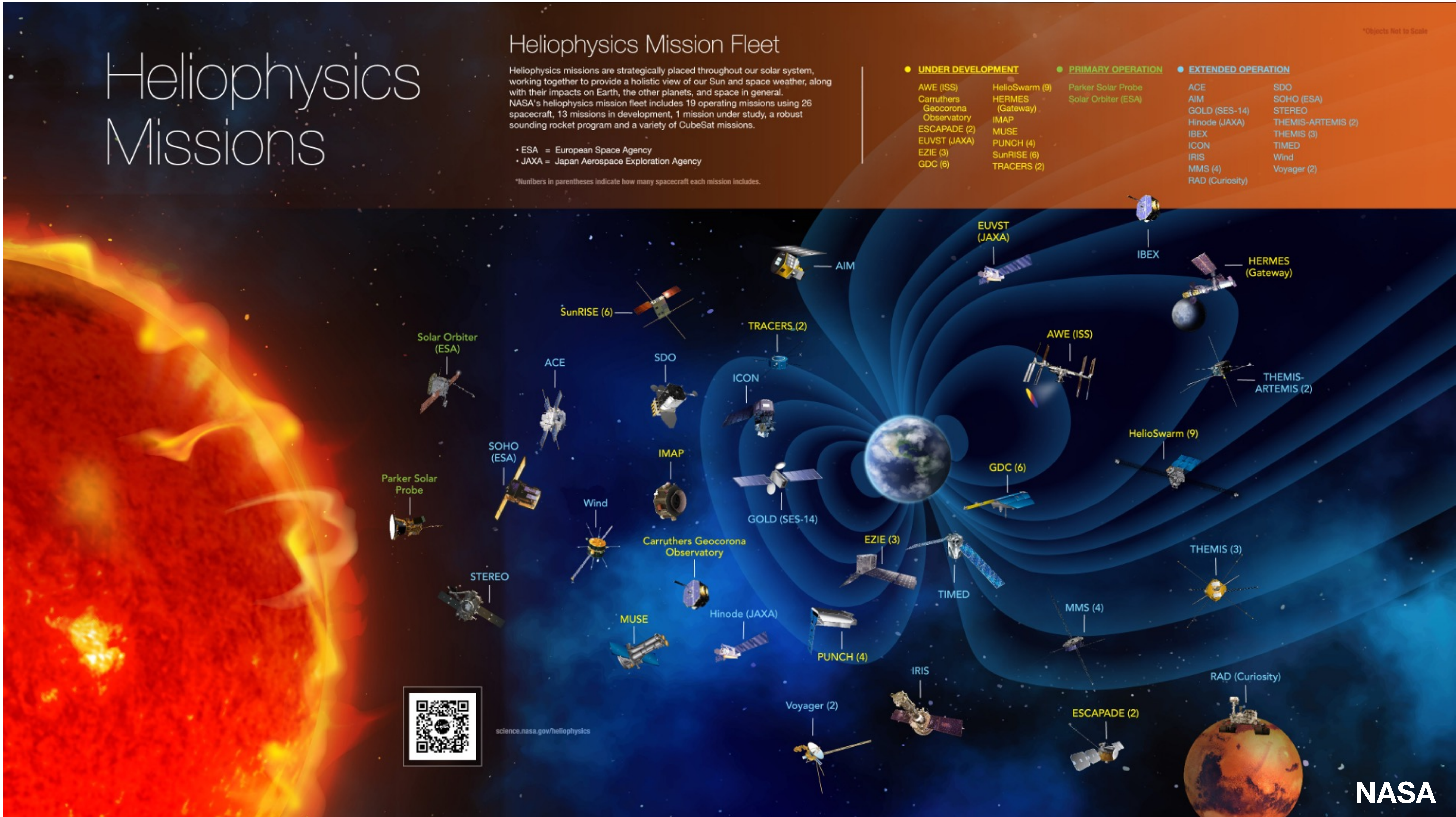
# 未来与展望：突破Radio Window

- How to detect the frequencies outside the Radio Window?

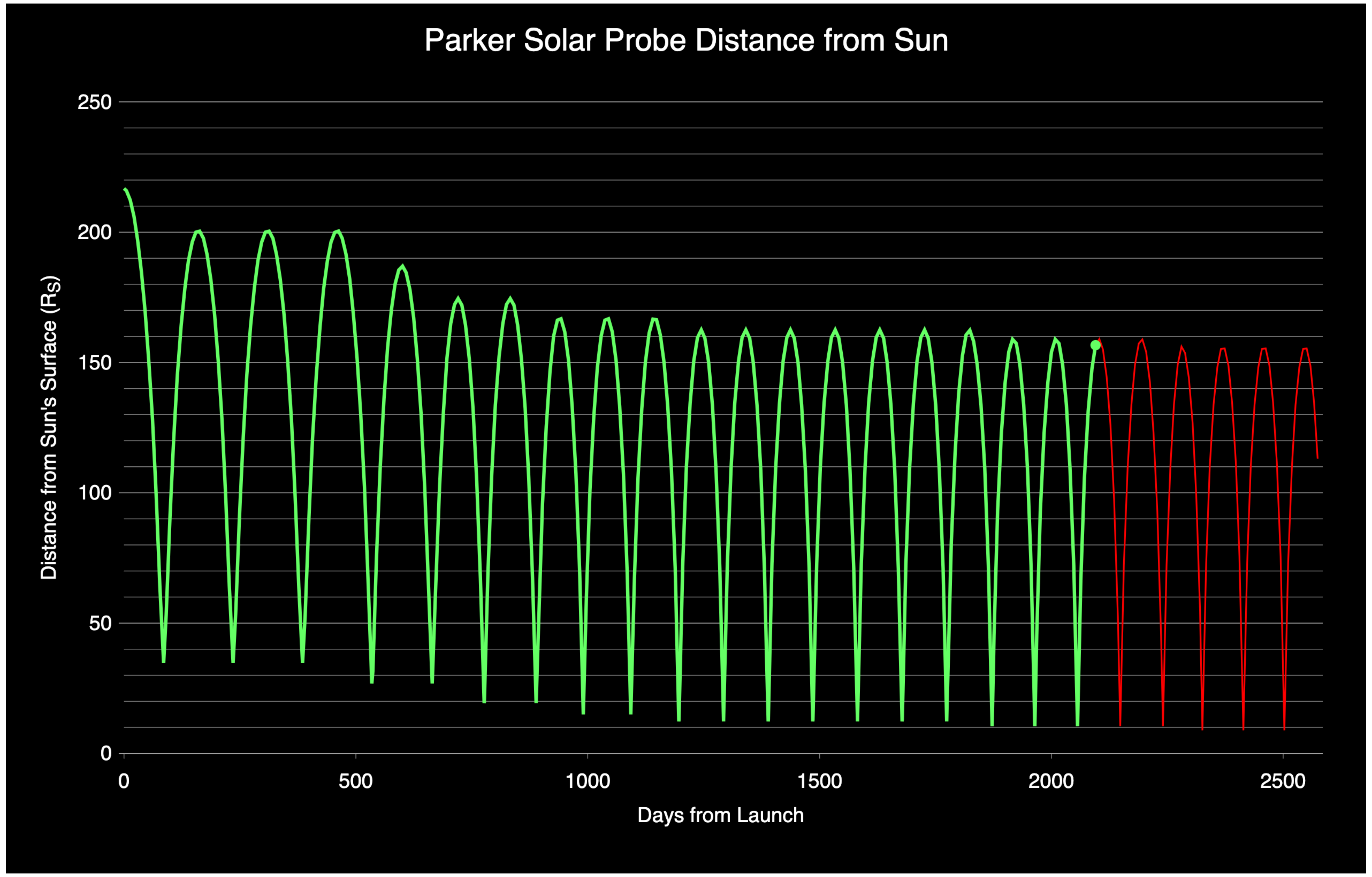


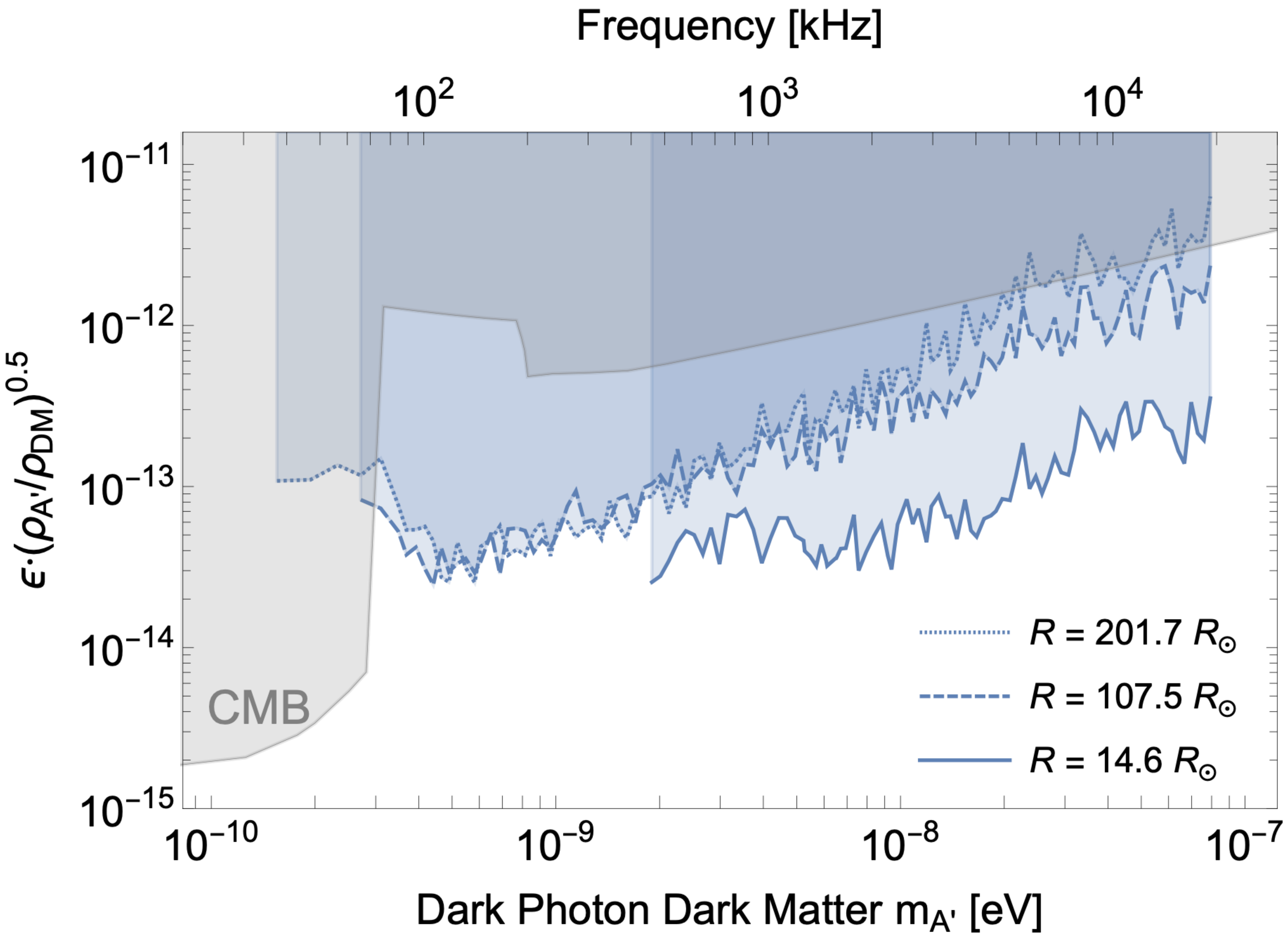
# 未来与展望：空间天文射电探测

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



# Parker Solar Probe preliminary results



# Summary

- 超轻玻色型暗物质探测与天文学望远镜观测可以交叉合作
  - 暗光子暗物质可以在太阳等离子体环境中转化为单频光子信号
    - 太阳物理观测数据可以探测超轻暗物质
    - LOFAR、SKA、Daocheng Solar Radio Telescope
  - 暗光子暗物质可以在望远镜反射面或天线阵列转化为单频信号
    - 观测空白天区可以探测超轻暗物质
    - FAST、LOFAR
- 未来可以通过太空射电望远镜探测射电窗口以外的质量区间

*Thank you!*