Radio-frequency Dark Photon Dark Matter across the Sun

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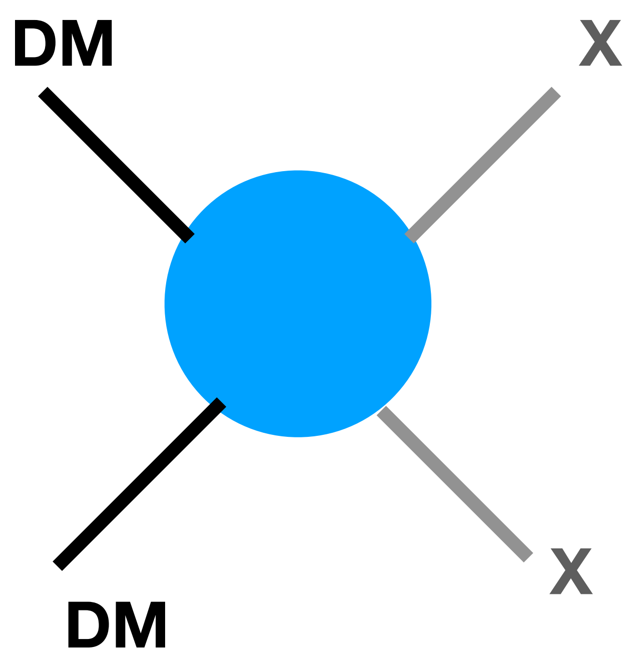
The outline

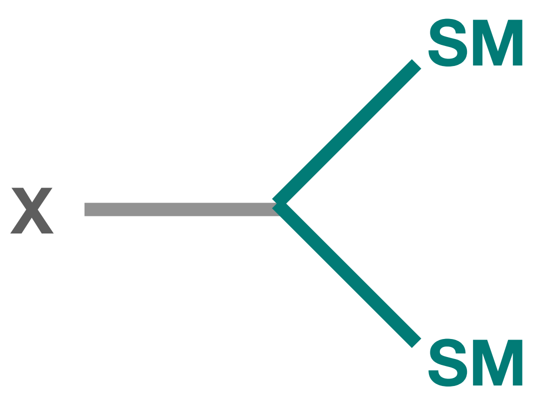
- From dark matter to the dark sector
- The dark photon DM and the Sun
- Summary

The physics motivation of Dark Sector (X)

- 1. Existence of dark matter
  - do not interact with strong, weak, or electromagnetic forces
  - A zoo of similar particles in the dark sector as in the visible sector



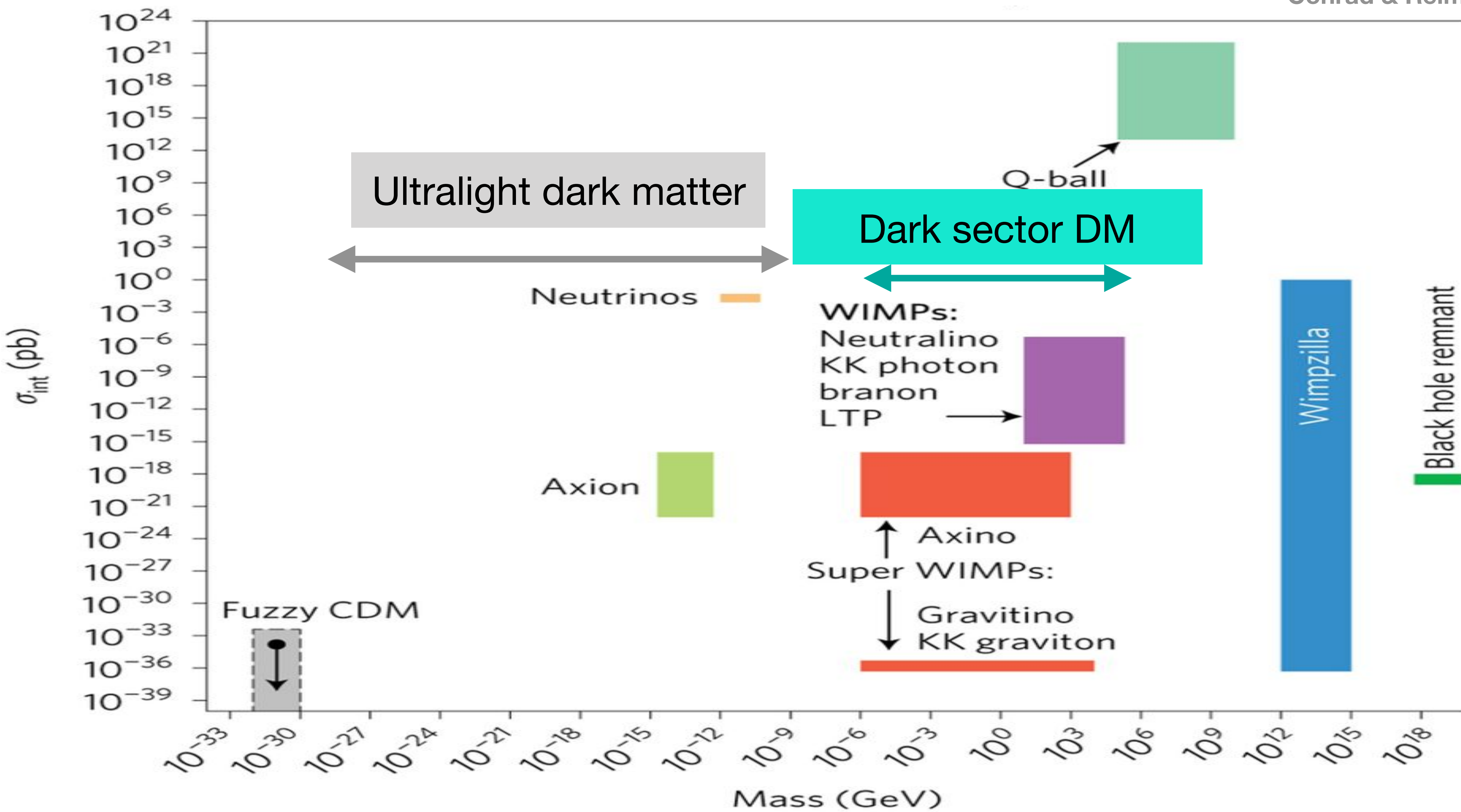
- 2. The null detection of dark matter
  - Secluded annihilation: DM + DM → X + X
  - X is light and weakly coupled to visible sector



The physics motivation of Dark Sector (X)

- 3. The experiment status
  - Technically difficult to increase E
  - Easier to accumulate higher luminosity

Conrad & Reimer



The examples of dark sector models

- Coupling through gauge singlet operators of SM
  - Kinetic mixing portal- Dark Photon $B_{\mu\nu}F'^{\mu\nu}$
  - Higher dimensional operators- Axion $\frac{a}{\Lambda}\tilde{F}F, \frac{a}{\Lambda}\tilde{G}G$
  - Neutrino portal LH
  - Higgs portal $H^\dagger H$

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Motivation for the dark photon

- A simple extension for NP from marginal operator portal

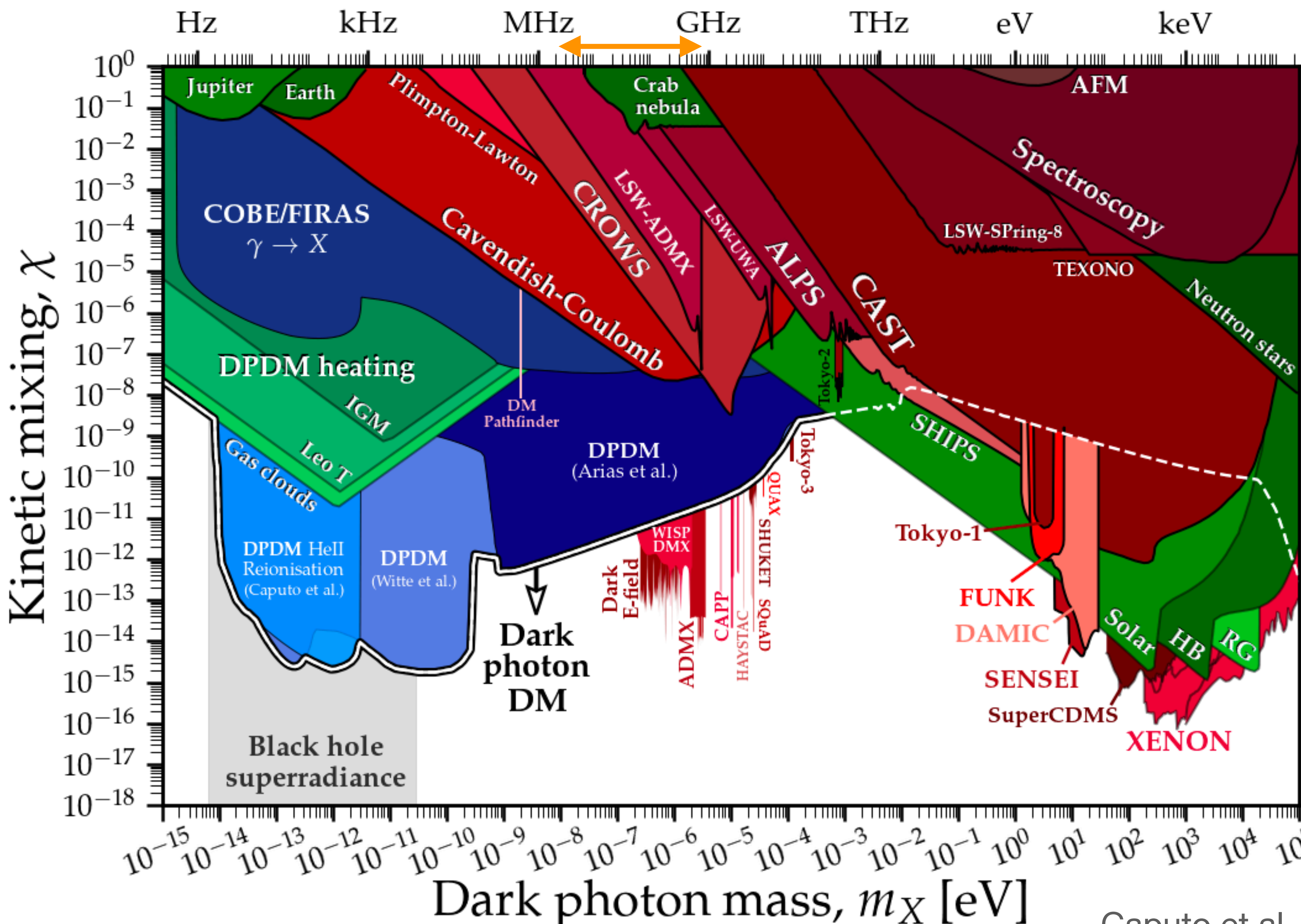
- An ultralight Dark Matter candidate

- A unique dark force carrier example, similar interaction as photon

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

$$\supset e\epsilon A'_\mu J^\mu_{\mathrm{EM}} - \frac{1}{2}m_{A'}^2 A'_\mu$$

The searches for dark photon

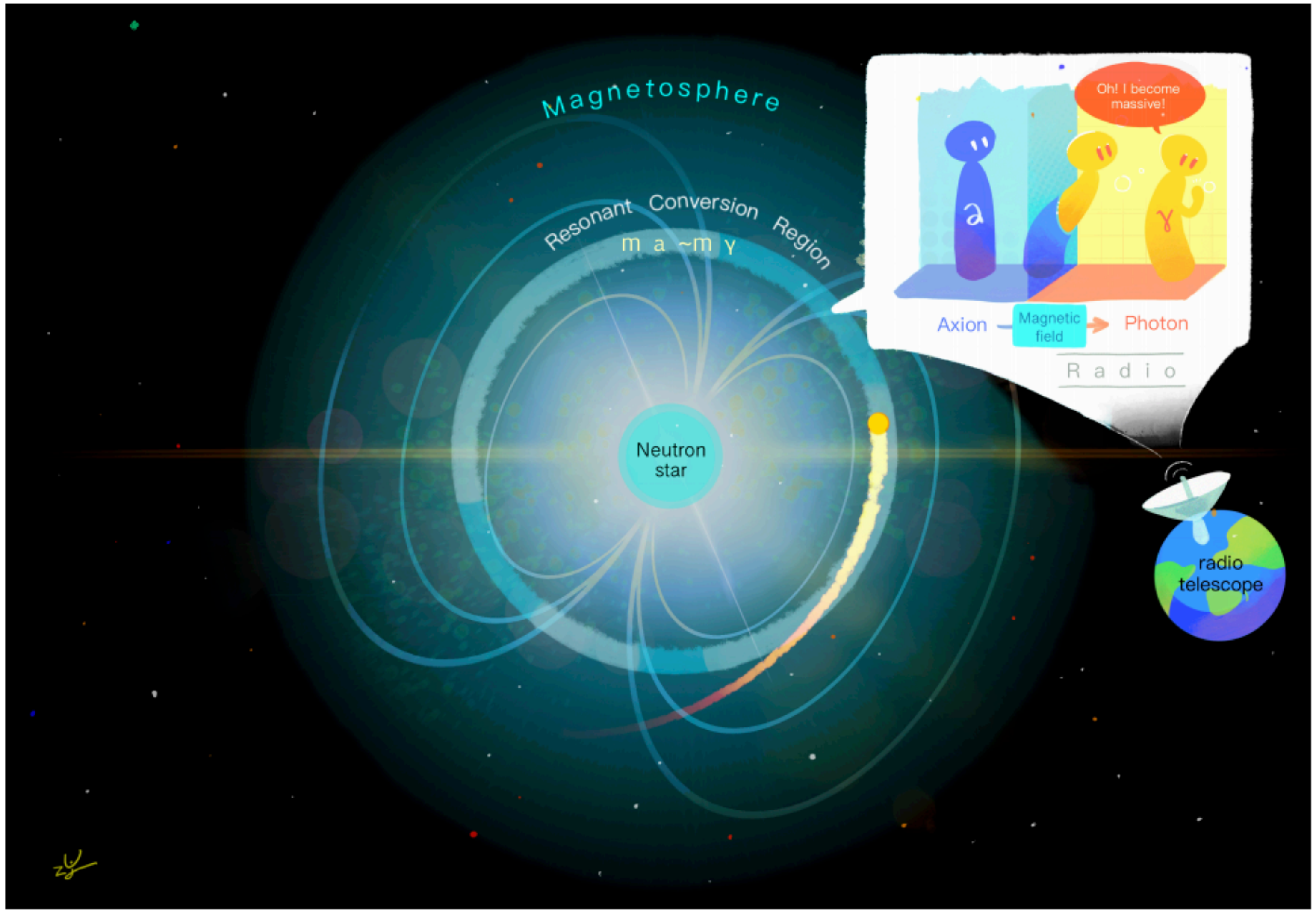


Caputo et al. 2105.04565

- Similar story to axion, but no B field needed.

Particle physics meets astrophysics

- Recent progress in axion searches with astrophysics telescopes
  - Axion DM conversion > radio telescope (magnetized astrophysical objects, e.g. neutron star, white dwarf) (see 1803.08230, 1804.03145, 1811.01020, 2004.00011)
  - Axion DM stimulated decay > radio telescope (photon rich environment) (see 1811.08436)
  - Axion conversion in magnetic WD > X-ray telescope (B-field) (see 1903.05088)



Courtesy of Fapeng Huang

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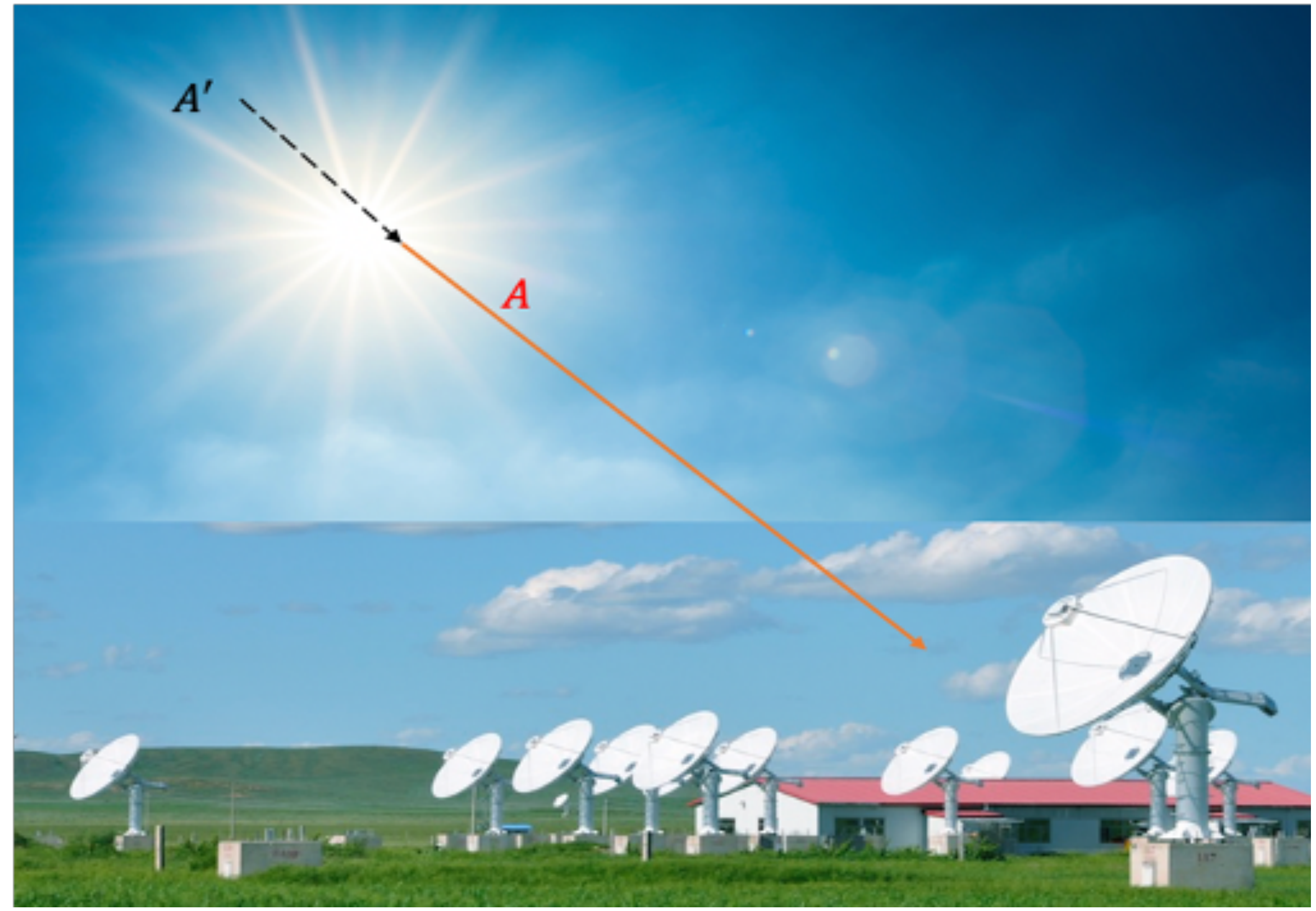


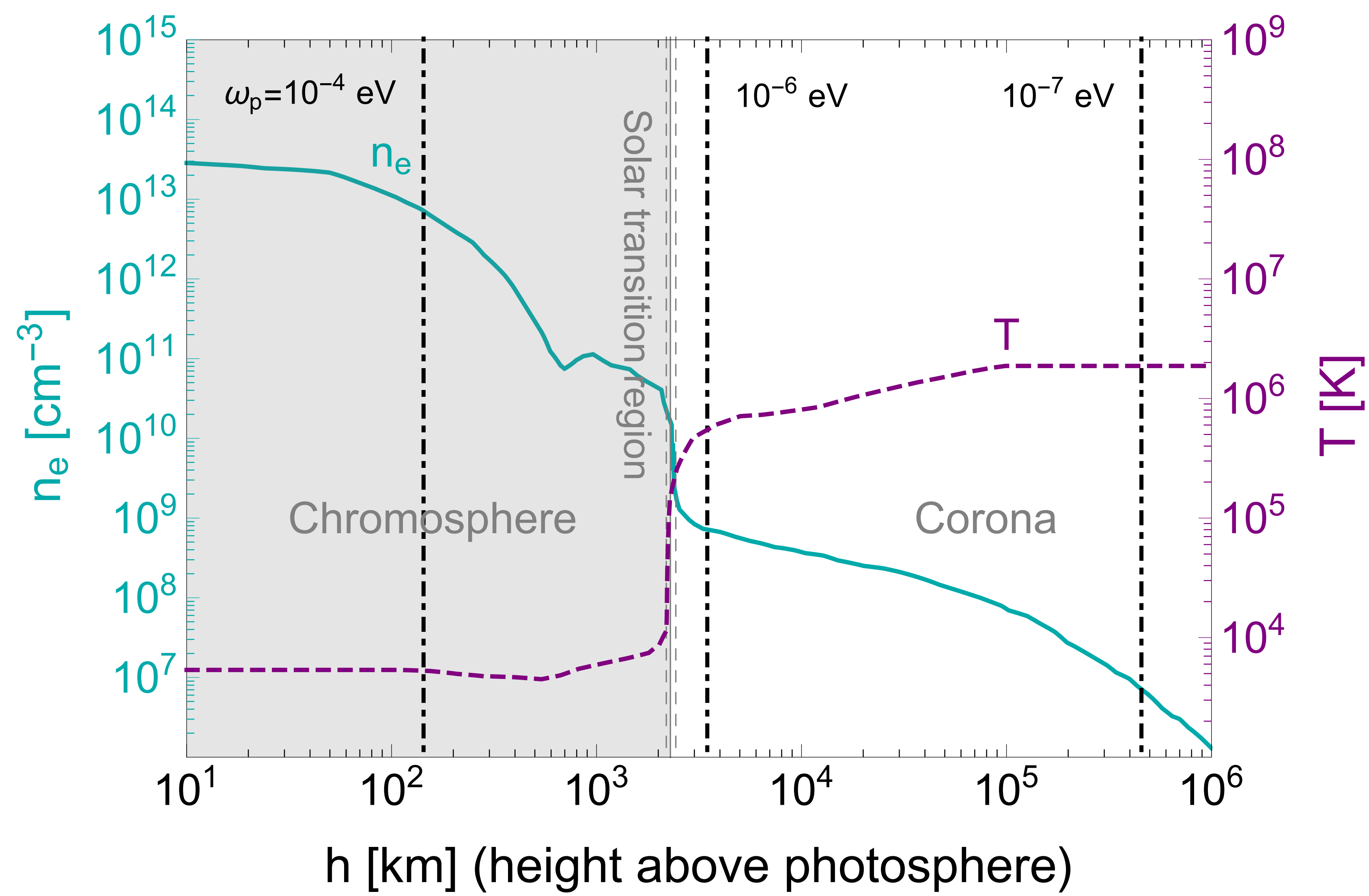
Courtesy of Haipeng An

Our difference: probing A' dark matter
No need of extreme B field
What about the closest star, the Sun?

The dark photon dark matter conversion at Sun

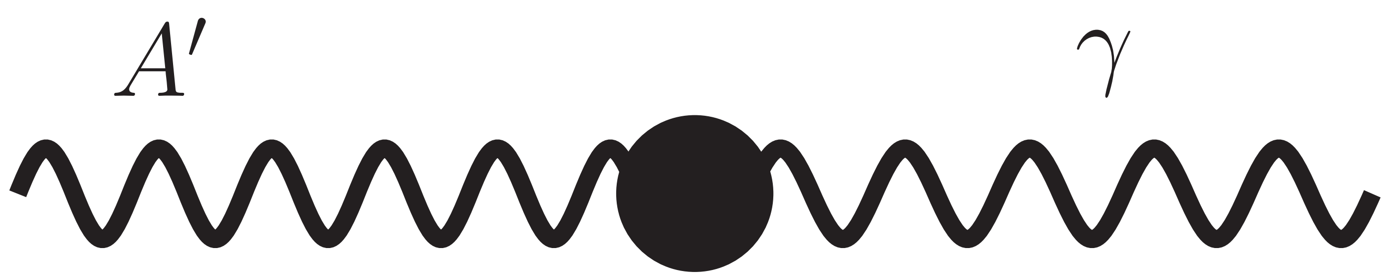
- The plasma frequency

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



The conversion calculation using QFT

- Resonant conversion probability $A' \to \gamma \; (1 \to 1)$



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

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

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

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

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

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

The conversion calculation using wave method

- Eliminating kinetic mixing term by redefinition

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

- Deplete the time dependence

$$\omega^2 - k^2 = m_{A'}^2 \qquad A(r,t) = e^{i(\omega t - rk)}\tilde{A}(r) \qquad A'(r,t) = e^{i(\omega t - rk)}\tilde{A}'(r)$$

- Substitute $\omega \to -i\frac{\partial}{\partial t}$ and $k \to i\frac{\partial}{\partial r}$
- Use WKB approximation $|\partial_r^2 \tilde{A}(r)| \ll |k\partial_r \tilde{A}(r)|$
- Obtain linearized wave equation

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

$$H_0 = \begin{pmatrix} \frac{m_{A'}^2 - \omega_p^2}{2k} & 0 \\ 0 & 0 \end{pmatrix}, \quad H_I = \begin{pmatrix} 0 & -\frac{\epsilon m_{A'}^2}{2k} \\ -\frac{\epsilon m_{A'}^2}{2k} & 0 \end{pmatrix}$$

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- 1st order solution for conversion probability

$$P_{A'\to\gamma} = \left| \int_0^\infty dr \frac{-\epsilon m_{A'}^2}{2k} e^{-i\int_0^r d\tilde{r} \frac{m_{A'}^2 - \omega_p^2(\tilde{r})}{2k}} \right|^2$$

Worked for both resonant and Non-resonant conversion

- Further simplification using Saddle point approximation

$$\int_{-\infty}^{\infty} dr e^{-f(r)} \approx e^{-f(r_0)} \sqrt{\frac{2\pi}{f''(r_0)}}$$

The conversion calculation using wave method

- Linearized wave equation

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- Further simplification using Saddle point approximation

$$\int_{-\infty}^{\infty} dr e^{-f(r)} \approx e^{-f(r_0)}\sqrt{\frac{2\pi}{f''(r_0)}}$$

$$f'(r_0) = 0$$

$$f(r) \approx f(r_0) + \frac{1}{2}(r-r_0)^2 f''(r_0)$$

$$f(r) = i\int_0^r d\tilde{r}\frac{m_{A'}^2-\omega_p^2(\tilde{r})}{2k}$$

QFT method = Wave method !

The dark photon dark matter conversion at Sun

- 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

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

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

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

The photon propagation

- Photon out-going direction

$$n(\omega) = (1 - \omega_p^2/\omega^2)^{1/2}$$

$$n_{\rm res} \sim 10^{-3} - 10^{-2}$$

$$\sin\theta_{\rm out} = \frac{n_{\rm res}}{n_{\rm out}} \times \sin\theta_{\rm res} \lesssim 10^{-3} - 10^{-2} \ .$$

- Absorption from inverse bremsstrahlung process

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

- The Compton scattering

$$\Gamma_{\rm Com} = \frac{8\pi\alpha^2}{3m_e^2} n_e$$

- Survival probability

$$P_s \equiv e^{-\int \Gamma_{\rm att} dt} \simeq \exp\left(-\int_{r_c}^{r_{\rm max}} \Gamma_{\rm att} dr/v_r\right)$$

Sensitivity of Radio Telescopes

- The system equivalent flux density

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

- The minimum detectable flux density

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

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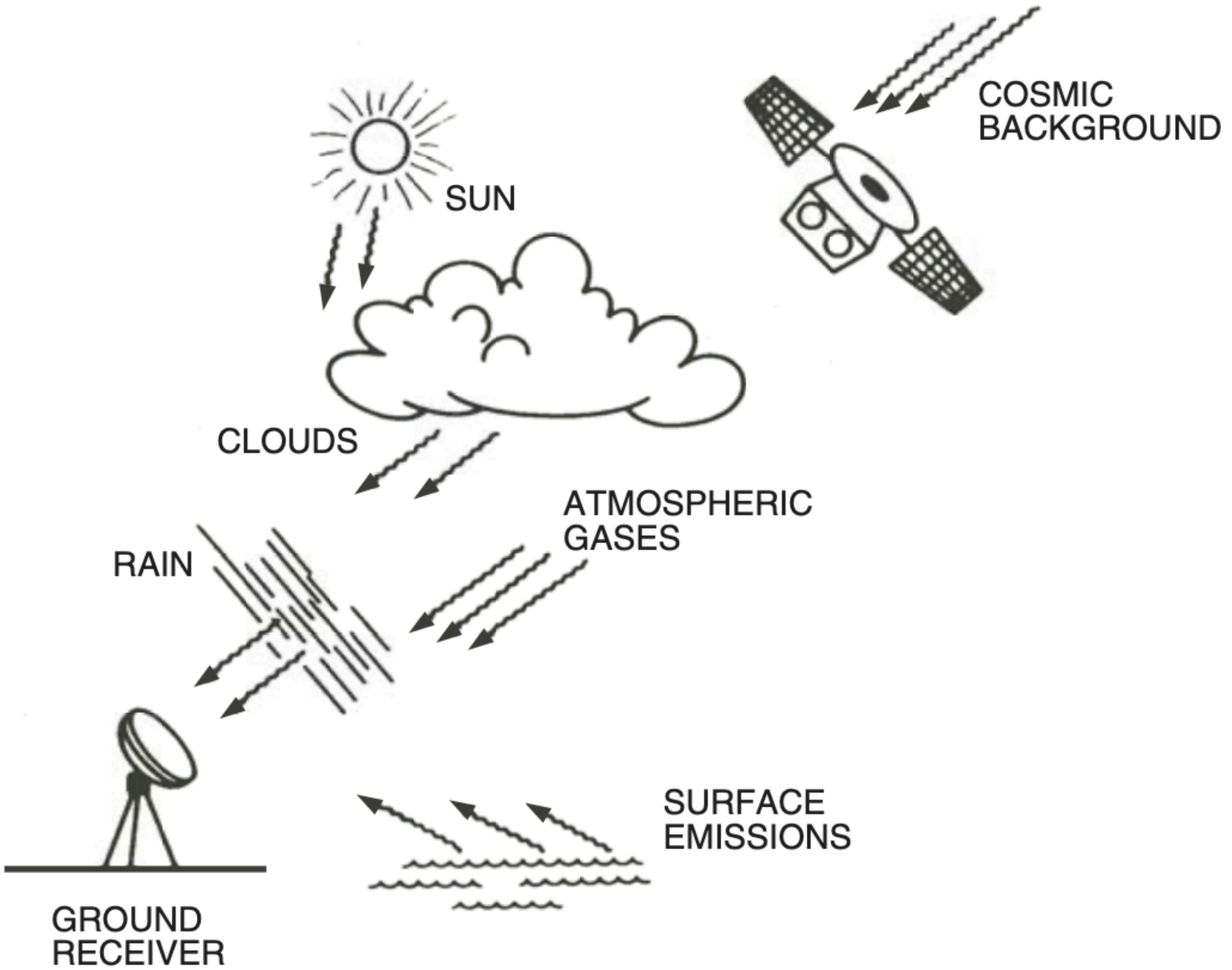

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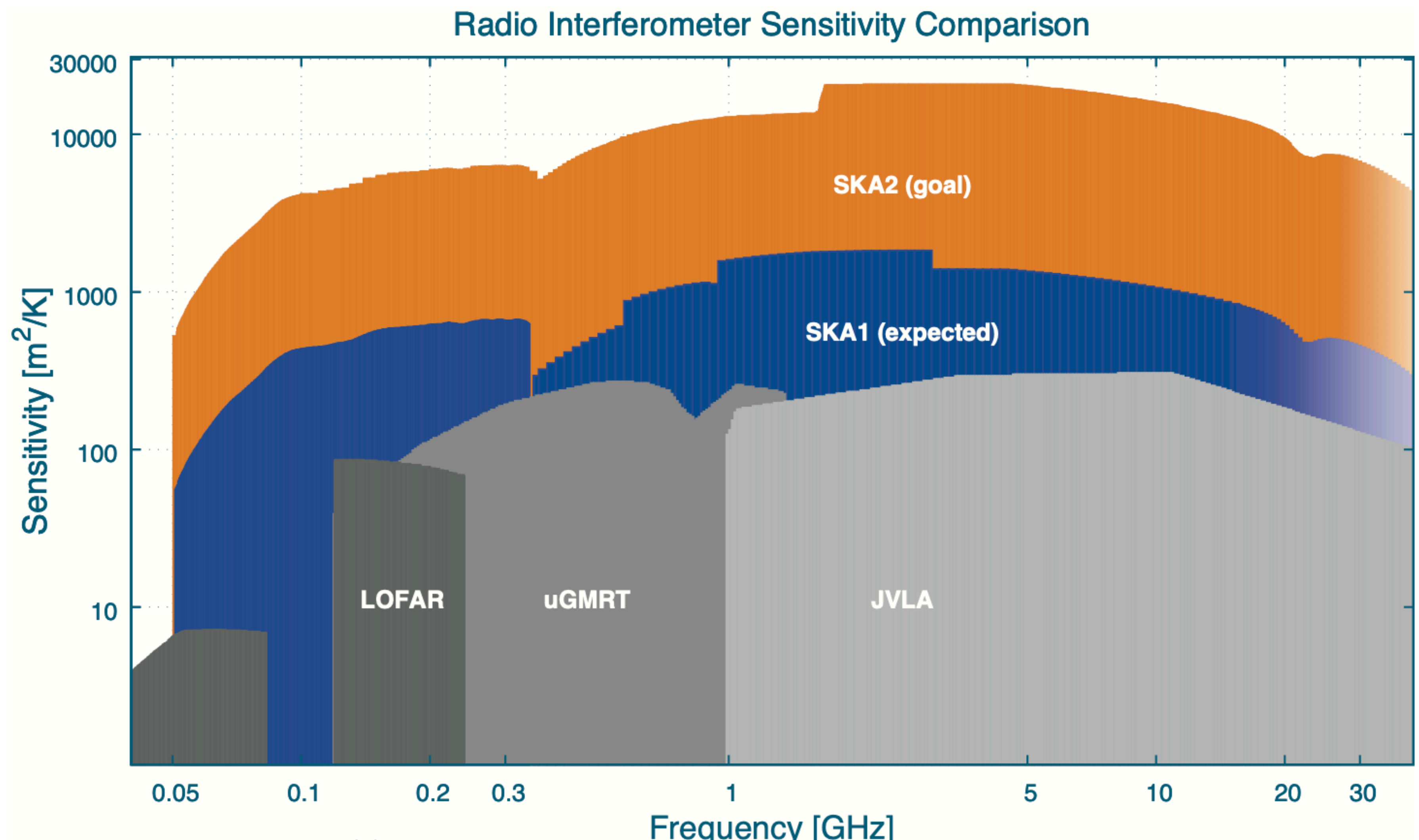
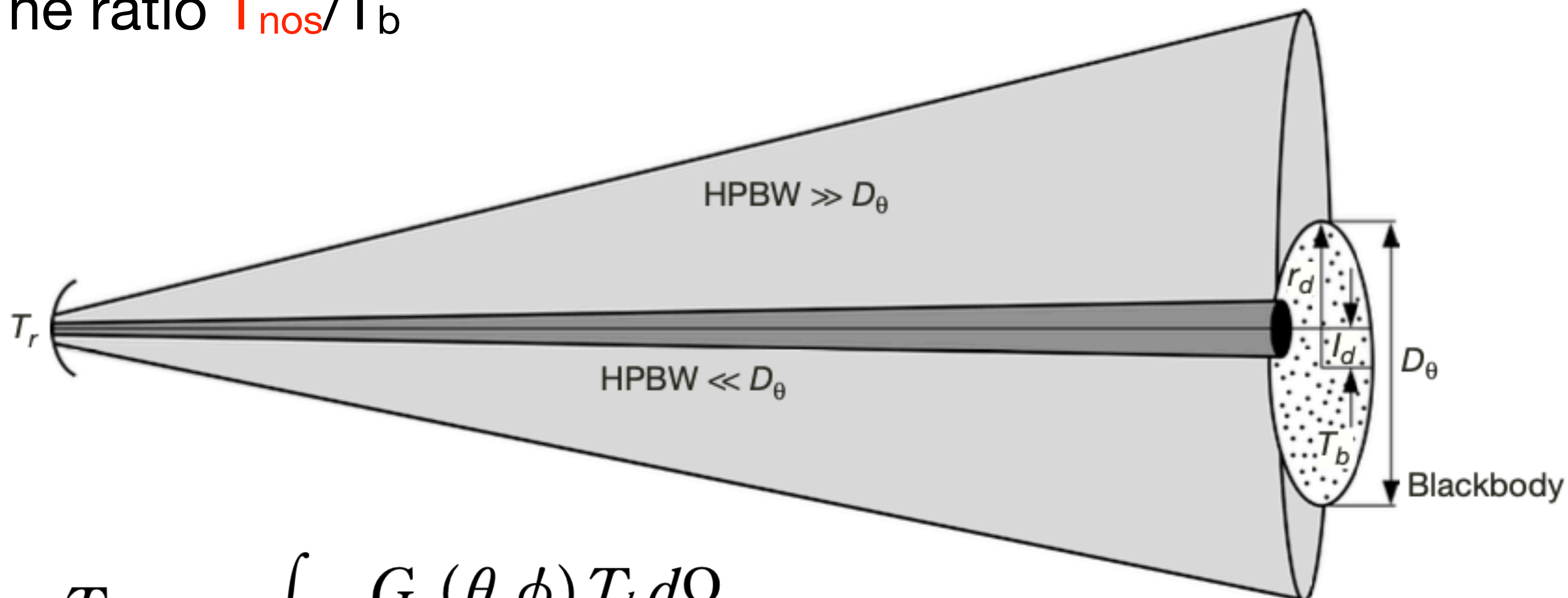
Name	f [MHz]	B_{res} [kHz]	$\langle T_{\mathrm{sys}} \rangle$ [K]	$\langle A_{\mathrm{eff}} \rangle$ [m^2]
SKA1-Low	(50, 350)	1	680	2.2×10^5
SKA1-Mid B1	(350, 1050)	3.9	28	2.7×10^4
SKA1-Mid B2	(950, 1760)	3.9	20	3.5×10^4
LOFAR	(10, 80)	195	28,110	1,830
LOFAR	(120, 240)	195	1,770	1,530



The noise from the Sun

- The ratio T_{nos}/T_b

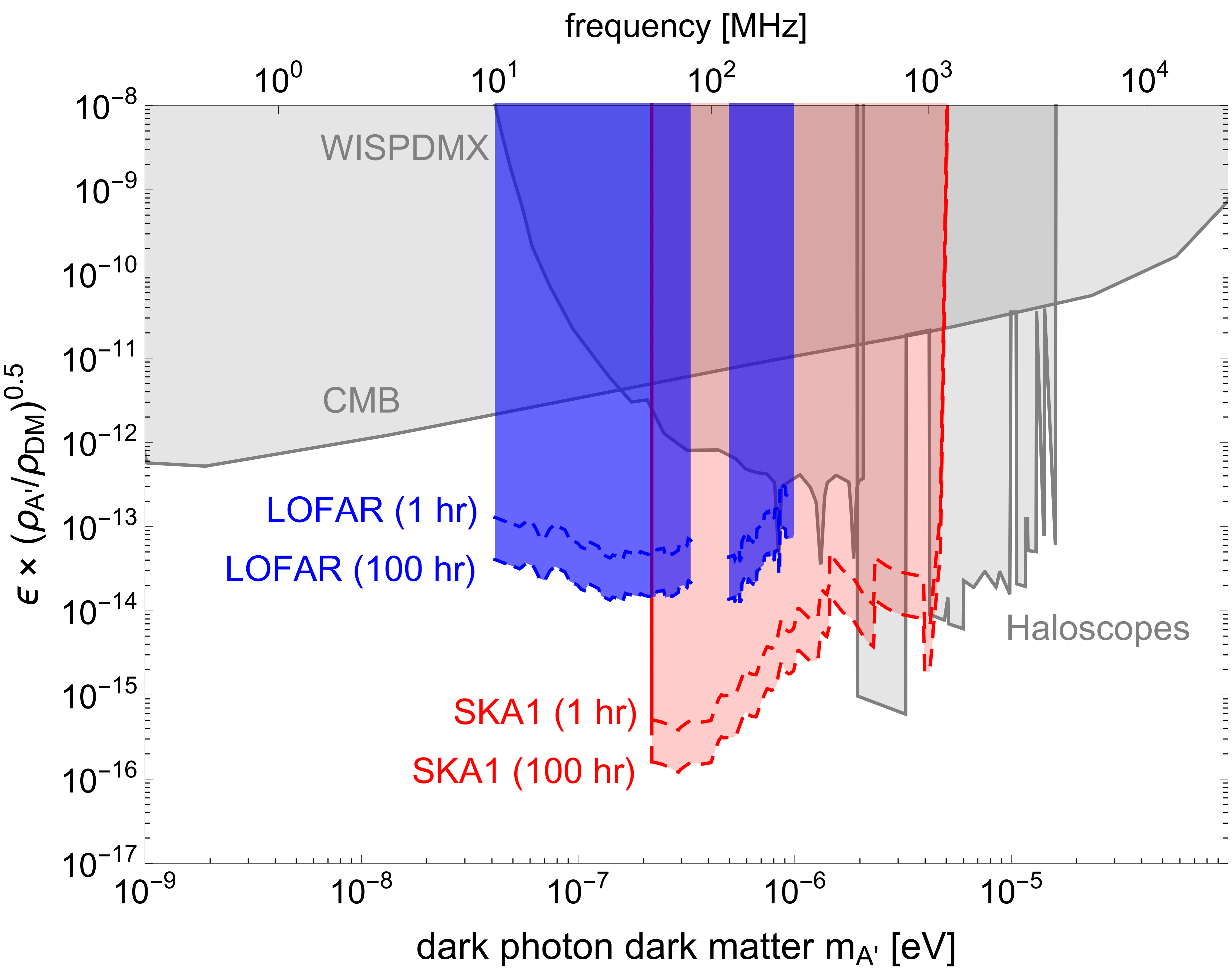


$$\frac{T_{incr}}{T_b} = \frac{\int_{disk} G_r(\theta,\phi)\, T_b\, d\Omega}{\int_{4\pi} G_r(\theta,\phi)\, T_b\, d\Omega}$$

HPBW = Half Power Beam Width

- For narrow HPBW (SKA1), $T_{nos}/T_b = 1$
- For wide HPBW (LOFAR), $T_{nos}/T_b \ll 1$

The physics reach for dark photon dark matter



$$S_{\rm sig} \times P_s = S_{\rm min}$$

- 10 MHz lower end from LOFAR, 1 GHz higher end due to opacity

Summary

- The inverse Primakoff effect should be included for solar axion detection
- Stellar cooling tension is mildly alleviated but still a problem, and the uncertainties in astrophysics calculation should be included
- We proposed search for radio frequency A' dark matter from 10 — 1000 MHz
- A' DM resonantly converts into radio photon
- Only conversion from solar corona can propagate out of the Sun
- 1 hour solar observation from LOFAR and SKA1 can provide strong sensitivity
- Future experiments like Arecibo, JVLA, FAST, TianLai etc can further explore the scenario if having solar program

Thank you!