Searching Dark Photon Dark Matter with Radio Telescopes

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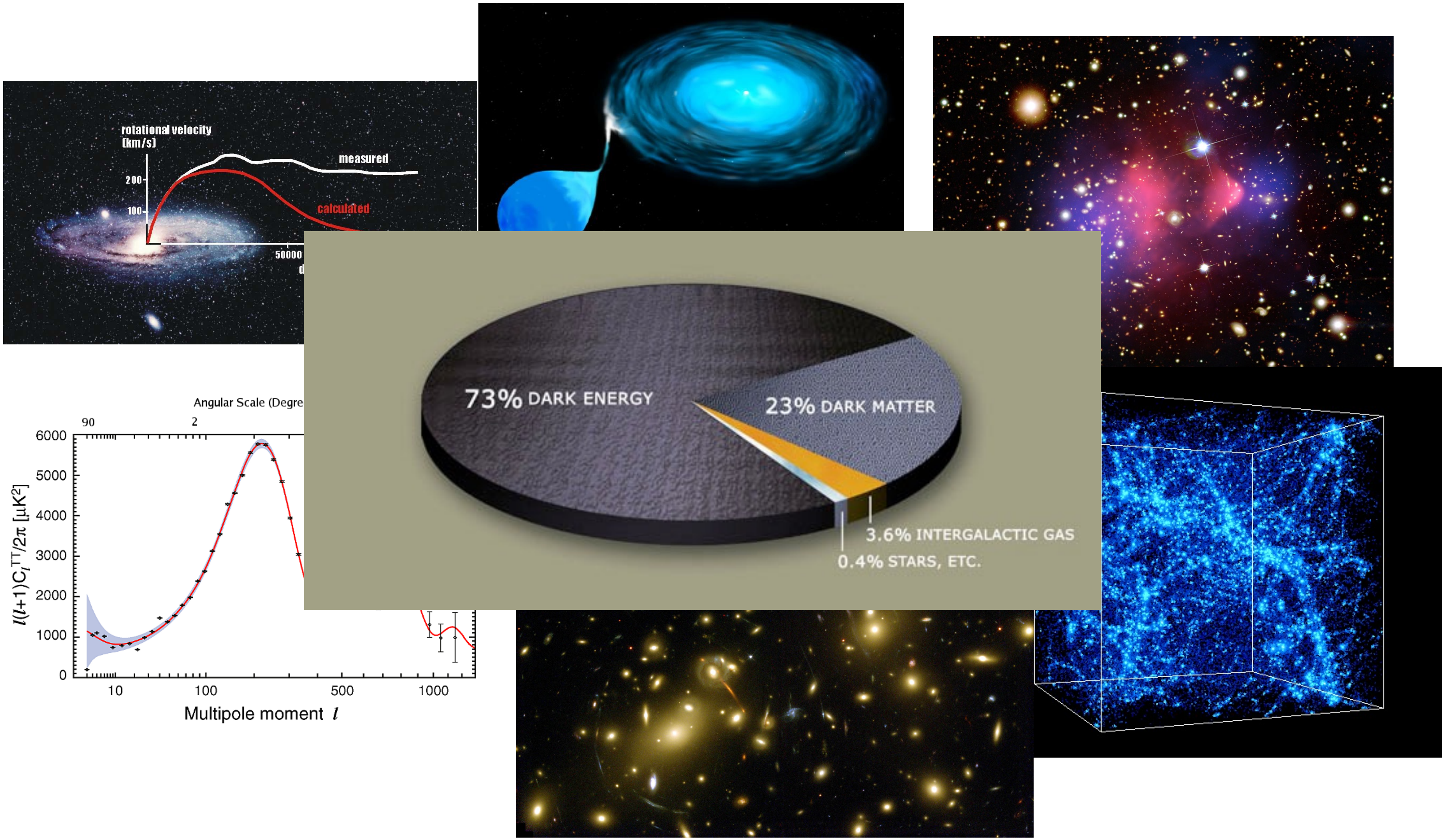
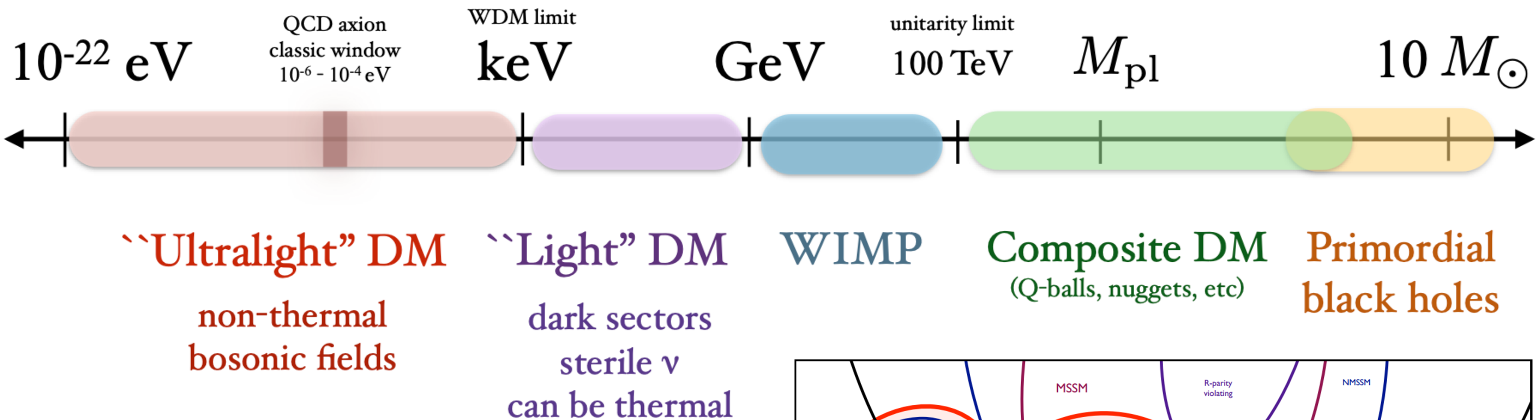
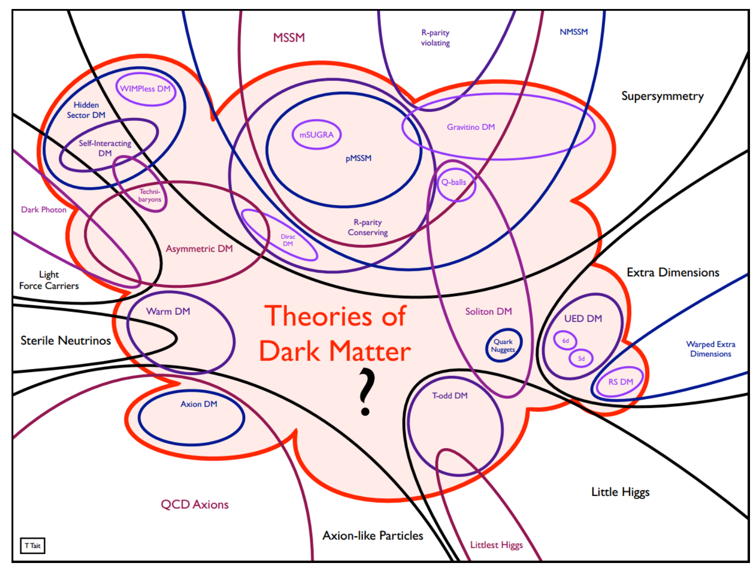
In collaboration with Xingyao Chen, Shuailiang Ge, Wen-Qing Guo, Xiaoyuan Huang, Jia Liu, Zheming Liu, Zhiyao Lu , Yan Luo

Existence of DM at all scales

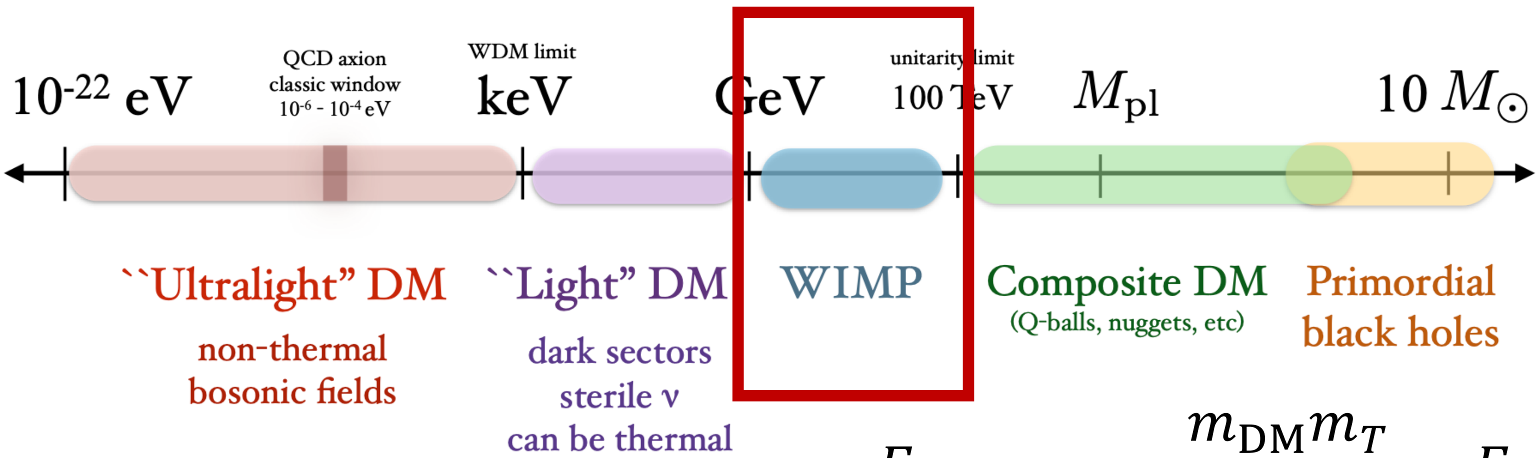


Searching for Dark Matter

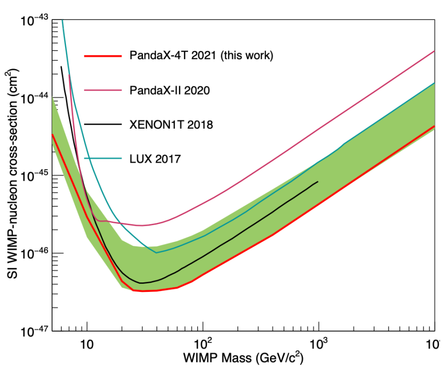


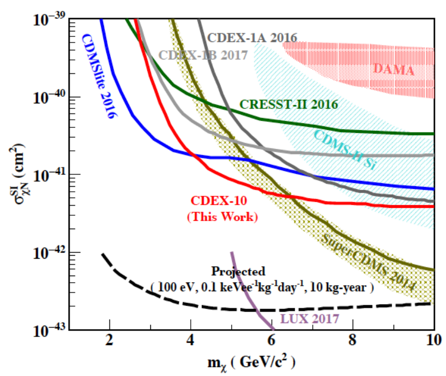


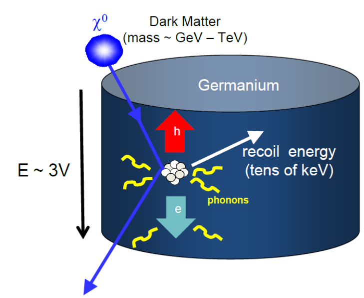
Searching for GeV-TeV DM

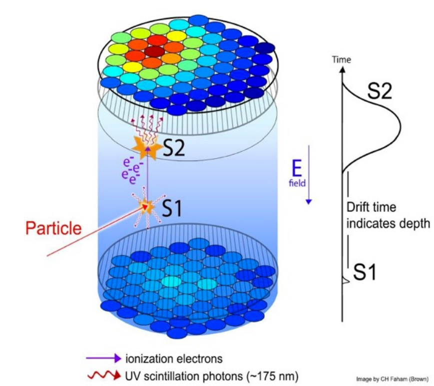


$$E_{recoil} \sim \frac{m_{DM} m_T}{(m_{DM} + m_T)^2} E_k$$

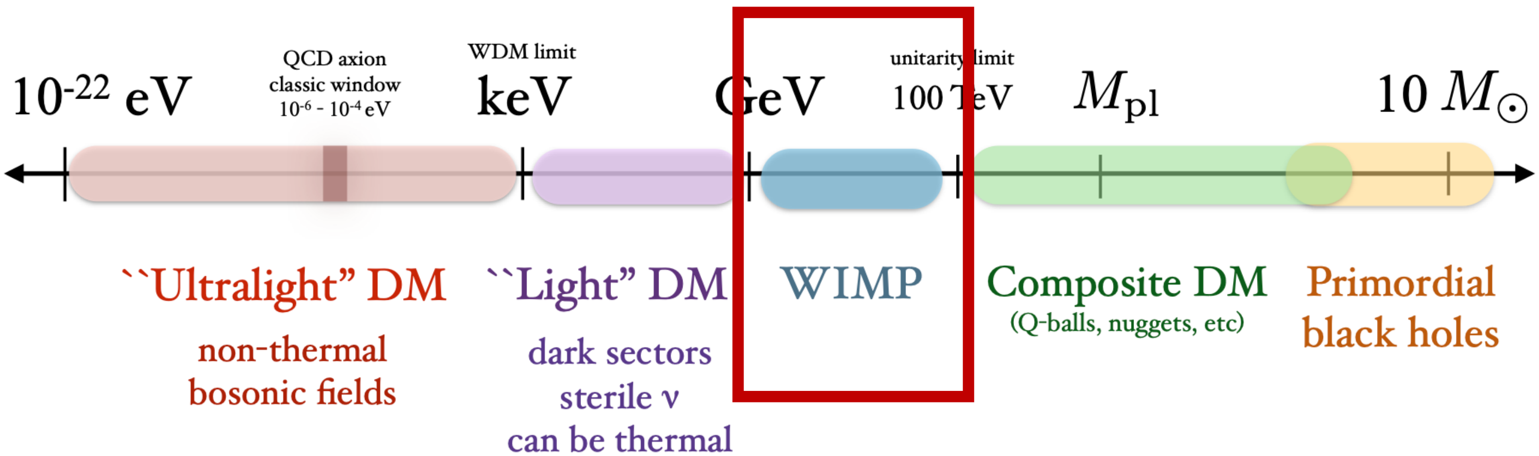


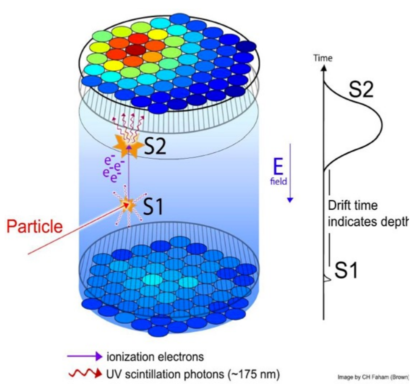


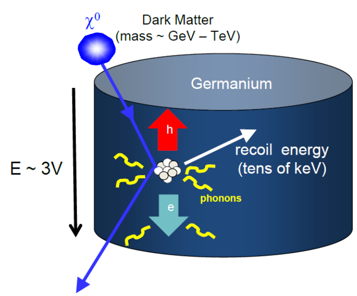


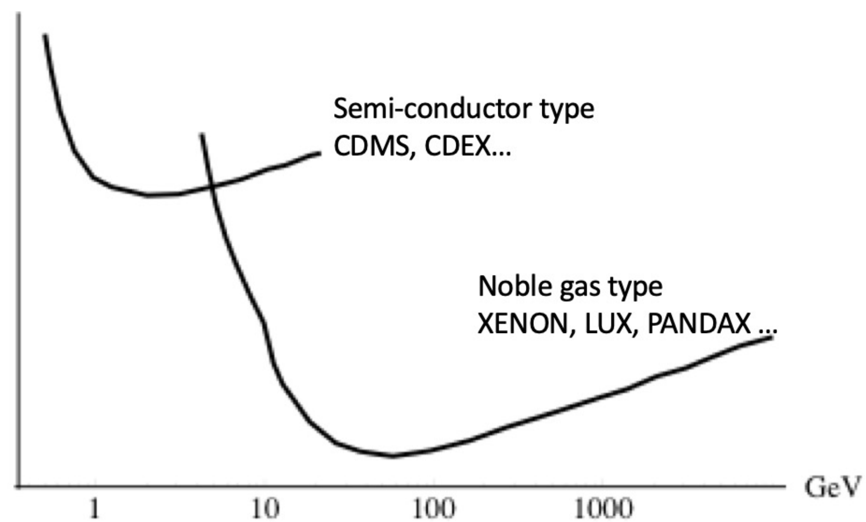


Searching for GeV-TeV DM

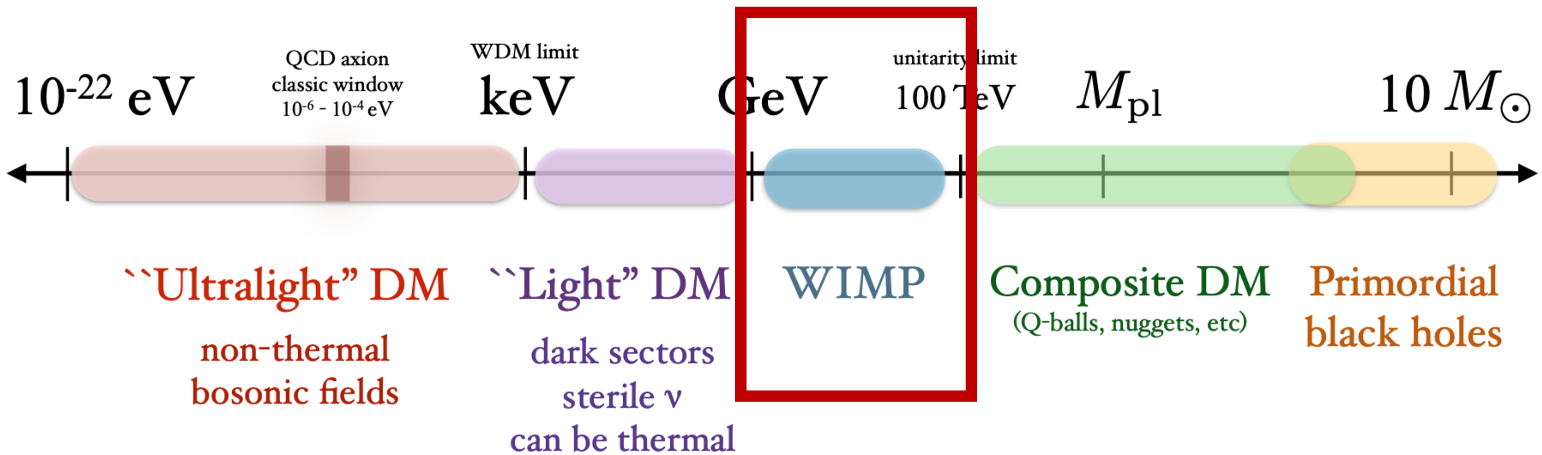


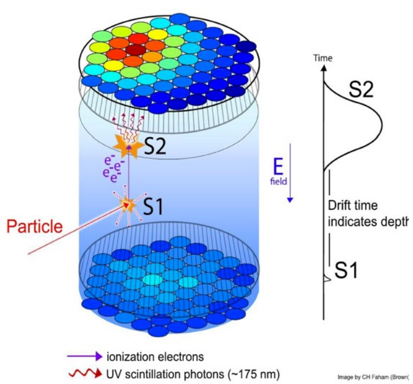


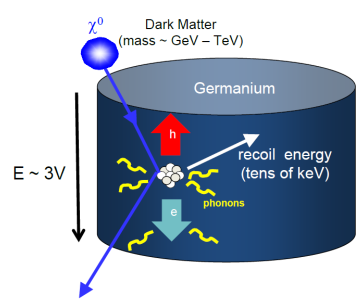


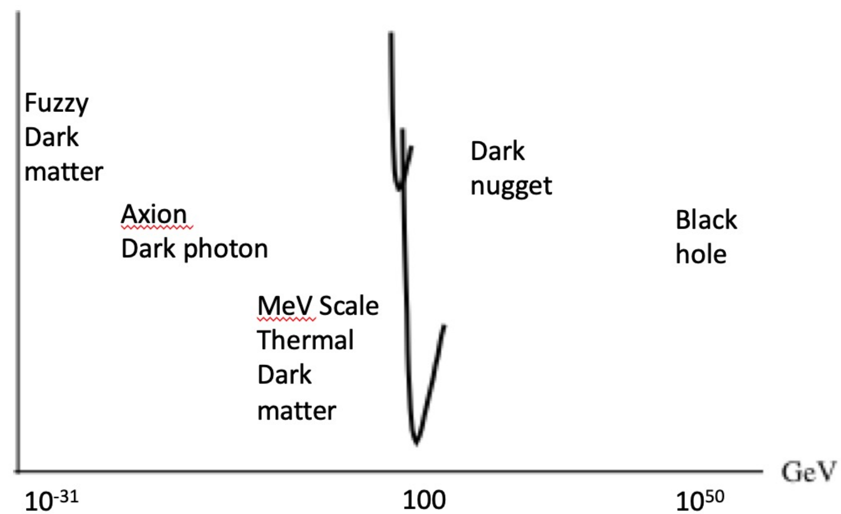


Searching for GeV-TeV DM









Ultralight dark photon DM

Dark photon dark matter

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + eA_\mu J^\mu$$

- Dark photon can decay through the three-photon channel and neutrino channel. Both are highly suppressed!

$$\Gamma_{V\to 3\gamma} \sim \frac{\kappa^2 m_V^9}{m_e^8}$$

$$\Gamma_{V\to \nu\nu} \sim \frac{\kappa^2 m_V^5}{m_Z^4}$$

Photon Dark Photon Oscillation

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + eA_\mu J^\mu$$

$$\Big\downarrow \quad A \to A - \kappa V$$

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + eA_\mu J^\mu - \kappa e V_\mu J^\mu$$

V_μ and A_μ are in mass eigenstate.

The field configuration

- $$\mathbf{E}_D(t,\mathbf{x}) = \mathbf{E}_D^{(0)} \cos(\omega_D t - \mathbf{k}_D \cdot \mathbf{x})$$

  $$\omega_D \approx m_V + \frac{\mathbf{k}_D^2}{2m_V}$$

  $$\frac{k_D}{m_V} \approx v_D \sim 10^{-3}$$

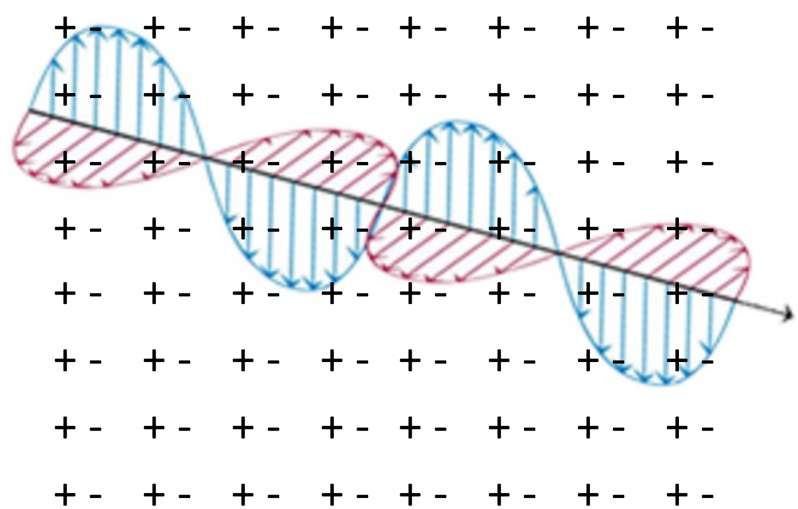
  $$\lambda_D \sim \frac{2\pi}{k_D} \approx \frac{2\pi}{m_V v_D} \approx 10^3 \times \frac{2\pi}{m_V}$$

Photon Dark Photon Oscillation

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + eA_\mu J^\mu - \kappa e V_\mu J^\mu$$

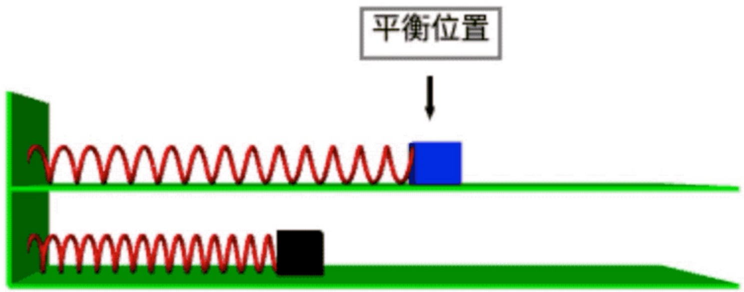
V_μ and A_μ are in mass eigenstate.

- In the vacuum, V cannot be converted into A, no interaction
- In the plasma, (1) a mixing between V and A is generated. (2) a mass for A is also generated.



Photon Dark Photon Oscillation

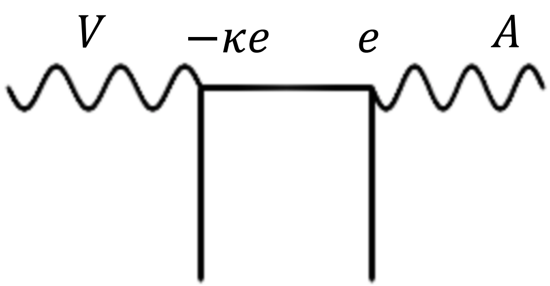
$$\begin{pmatrix} A_T & V_T \end{pmatrix} \begin{pmatrix} \mathbf{k}^2 + \omega_p^2 & \kappa\omega_p^2 \\ 0 & \mathbf{k}^2 + m_V^2 \end{pmatrix} \begin{pmatrix} A_T \\ V_T \end{pmatrix}$$



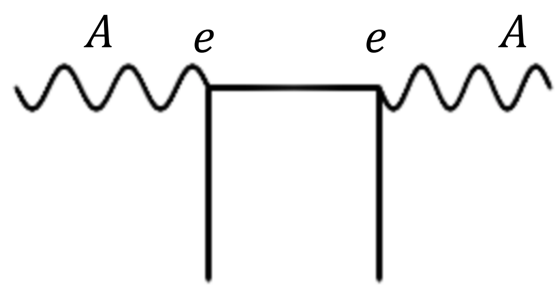
- When $\omega_p = m_V$, photon and dark photon resonantly convert into each other.

Photon Dark Photon Oscillation

- Projecting onto the transverse modes



$$-\kappa\omega_p^2 A_i^T V_i^T$$



$$\omega_p^2 A_i^T A_i^T$$

- One to one transition matrix element

$$\mathcal{M}_{V_T \to A_T} = -\kappa\omega_p^2 \epsilon_A \cdot \epsilon_V$$

Polarization vectors

Photon dark photon oscillation

- The transition probability

$$\omega_p^2 = m_V^2$$

$$P_{V\to A} = \int dt \Gamma_{V\to A} = \int \frac{dt}{2\omega}\frac{d^3p}{(2\pi)^3 2\omega}(2\pi)^4\delta^4(p_V - p_A)\frac{1}{3}\sum_{\text{pol}}|\mathcal{M}|^2$$

$$= \frac{2}{3}\pi\kappa^2 m_V v_r^{-1}\left|\frac{\partial \log \omega_p^2}{\partial r}\right|_{r=r_c}^{-1}$$

Resonant region

Average of polarization

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

Searching for ultralight DM with radio telescopes

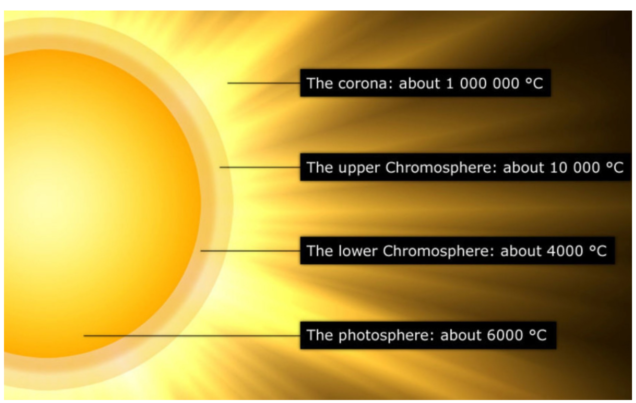
- For dark photon:

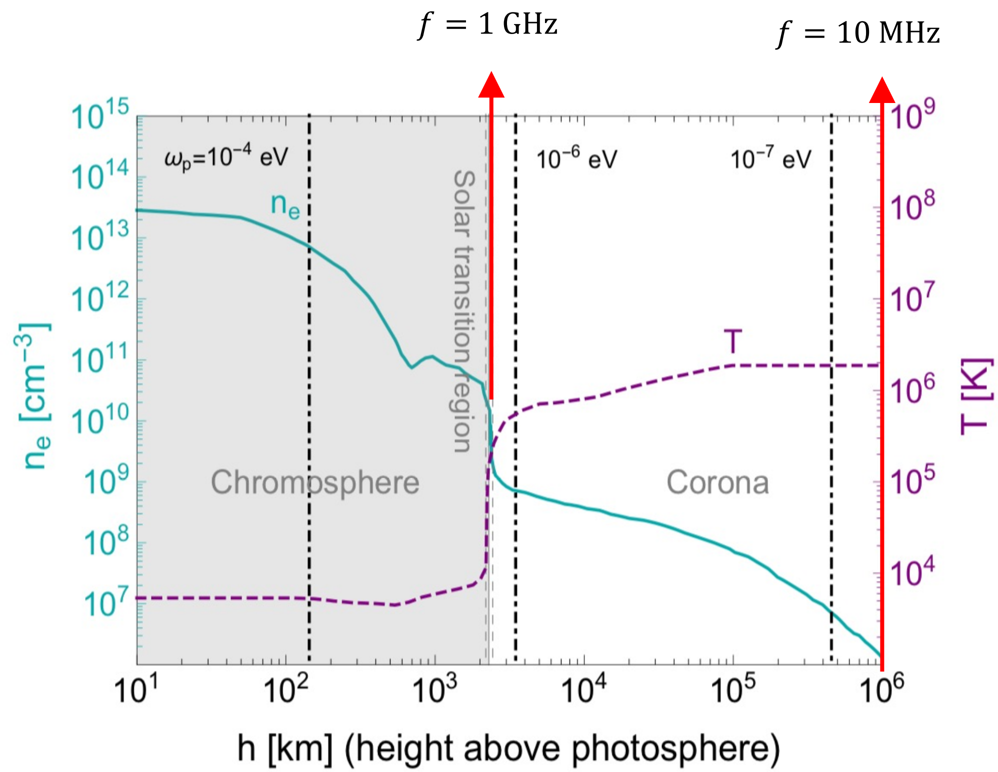
$$\omega^2 - k^2 = m_V^2$$

- For photon in plasma:

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

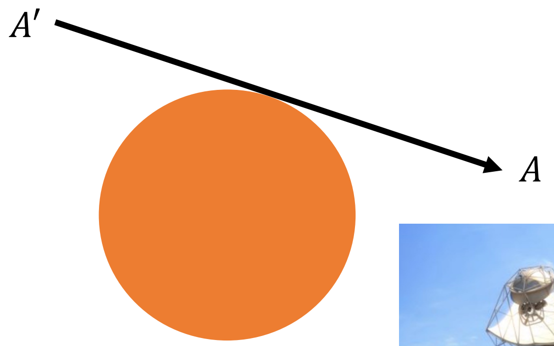
- We need plasma.





Dark photon dark matter converted at the Sun's atmosphere

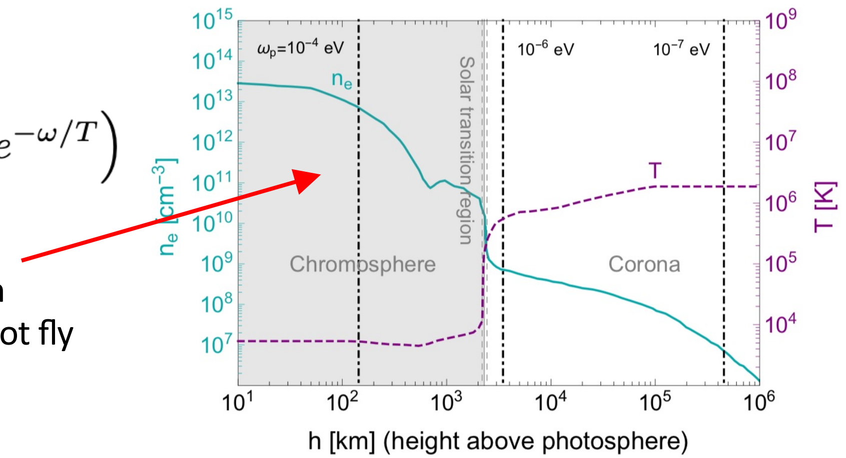
- Resonant conversion
  - $\omega_p = m_V$
- Inside the dark matter halo
  - $v_{DM} \sim 10^{-3}$
- The frequency of the converted photon
  - $\omega \approx m_V$ with the dispersion $\sim 10^{-6}$.
- The signal is a sharp peak in the solar spectrum



Absorption of the converted photon during propagation

- Inverse bremsstrahlung absorption

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



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

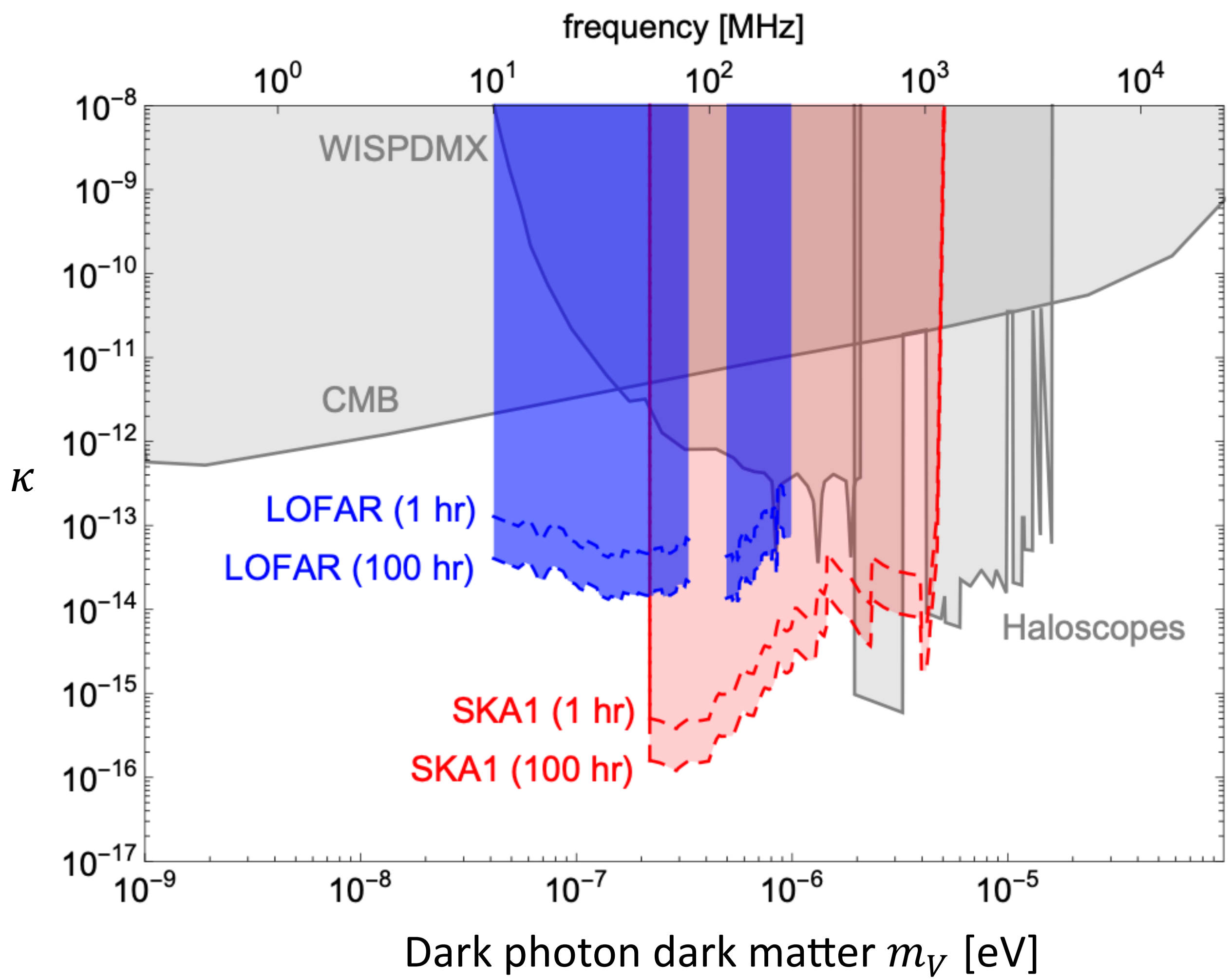
- The minimal detectable flux $S_{\min} = \dfrac{\text{SEFD}}{\eta_s \sqrt{n_{\text{pol}} \mathcal{B}\, t_{\text{obs}}}}$ $\text{SEFD} = 2k_B \dfrac{T_{\text{sys}} + T_{\odot}^{\text{nos}}}{A_{\text{eff}}}$

Name	f [MHz]	B_{res} [kHz]	$\langle T_{\text{sys}} \rangle$ [K]	$\langle A_{\text{eff}} \rangle$ [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

Netherland

Searching for DPDM with radio telescopes

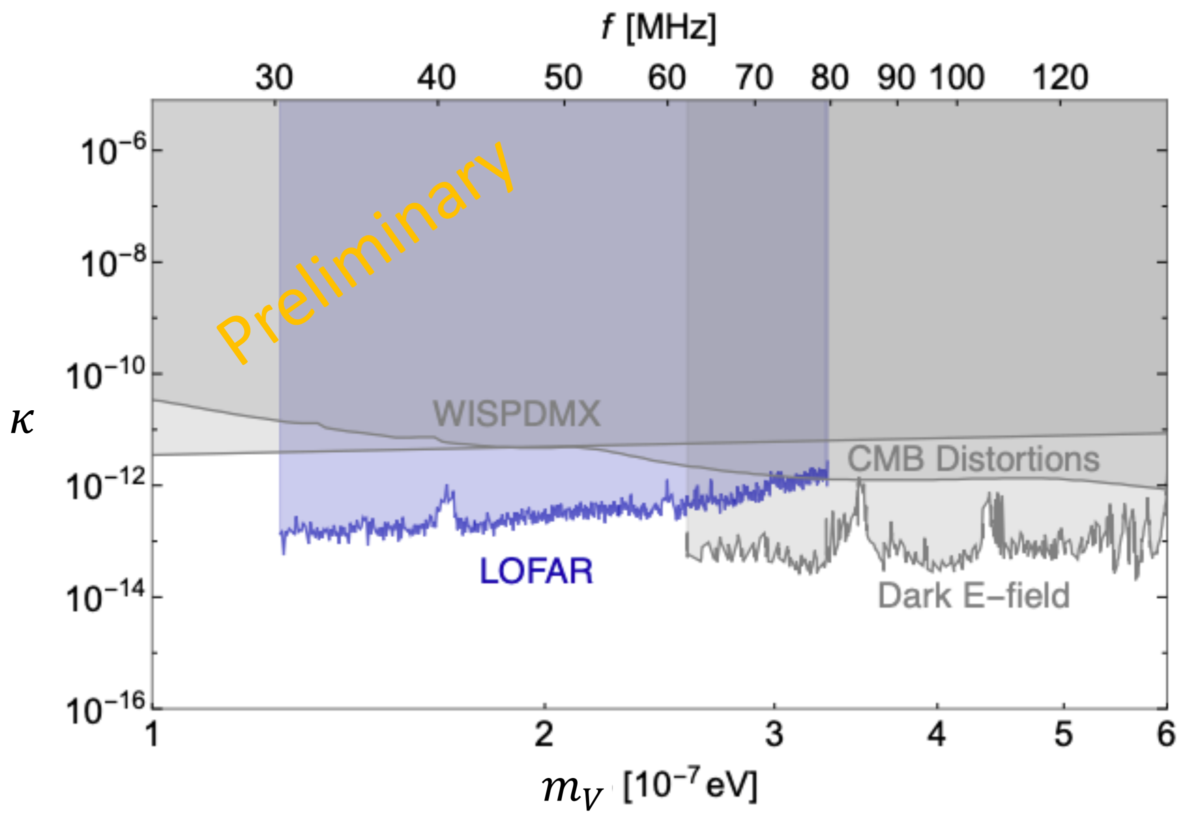


HA, F.P. Huang, J.Liu, W.Xue, Phys.Rev.Lett. 126 (2021) 181102

Searching for DPDM in LOFAR

Work in progress with Xingyao Chen, Shuailiang Ge, Jia Liu and Yan Luo

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

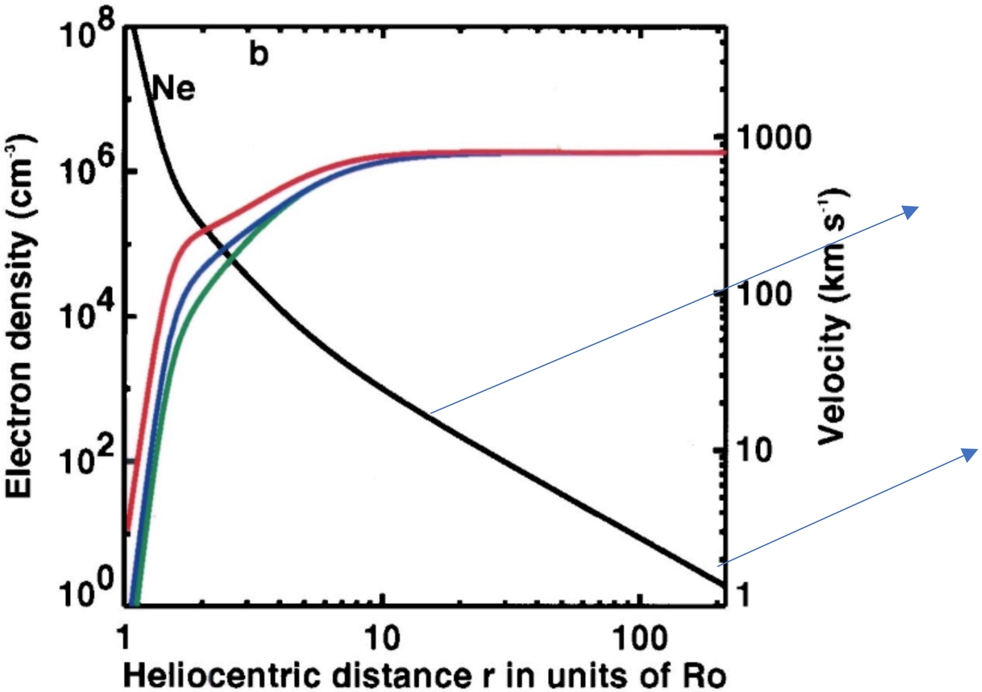


For dark photon dark matter with smaller mass

- 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



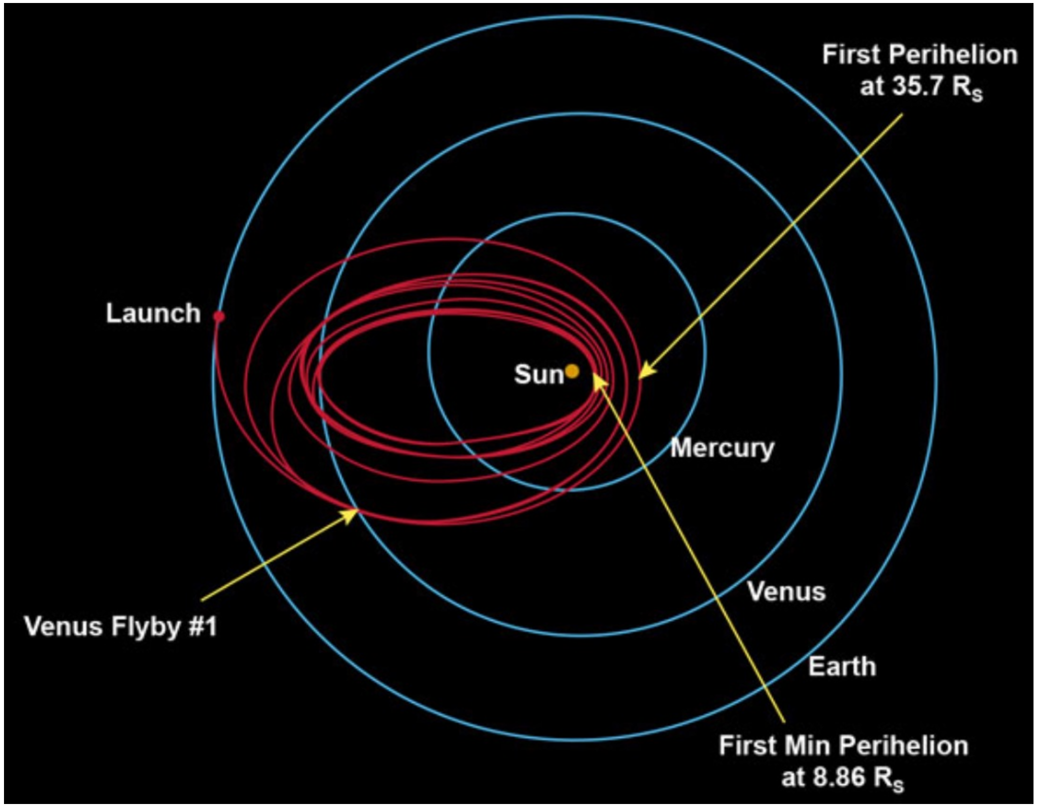
$$\frac{\omega_p}{2\pi} = 1 \text{ MHz}$$

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

For dark photon dark matter with even smaller mass

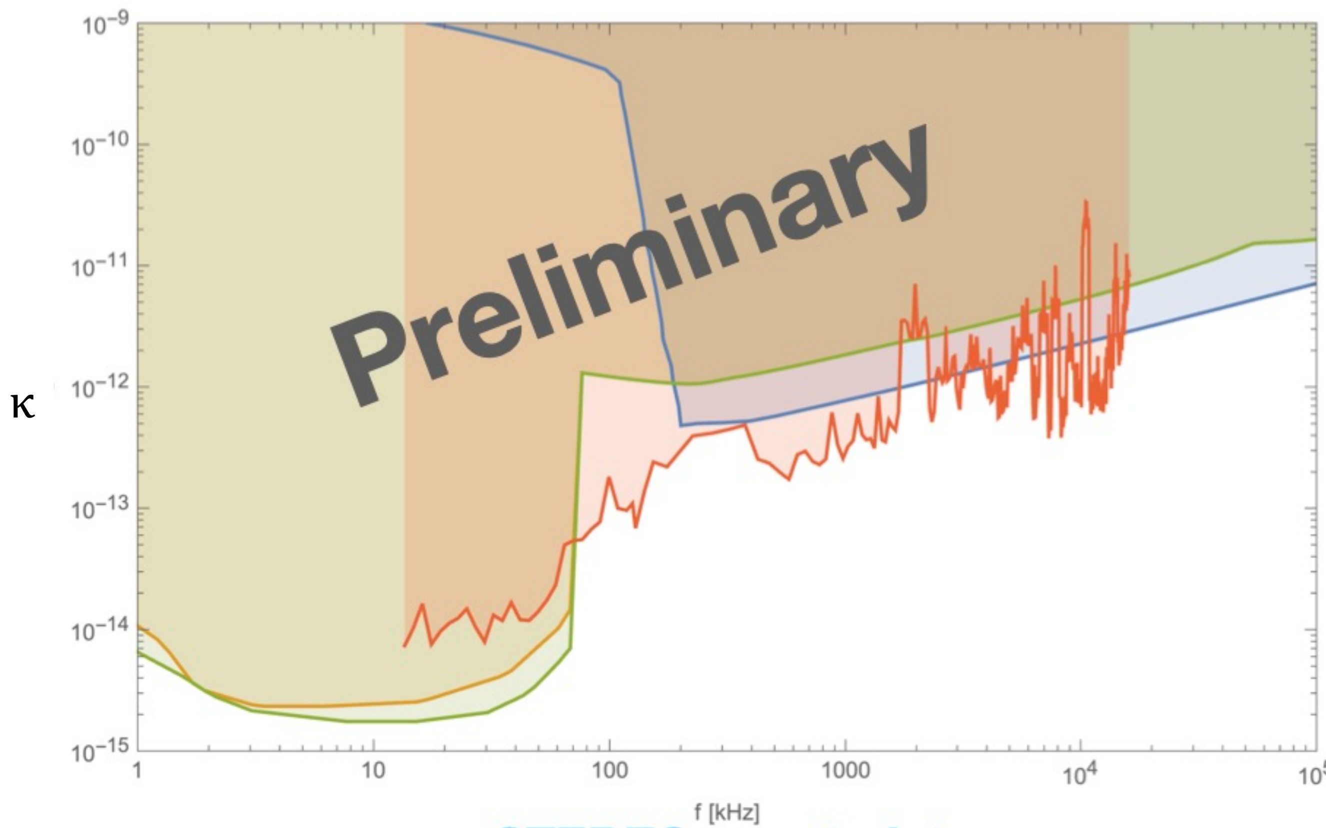
Work in progress with Jia Liu, Shuailiang Ge and Zheming Liu

- STEREO A/B
- Parker Solar Probe



Using solar probes to search for DPDM

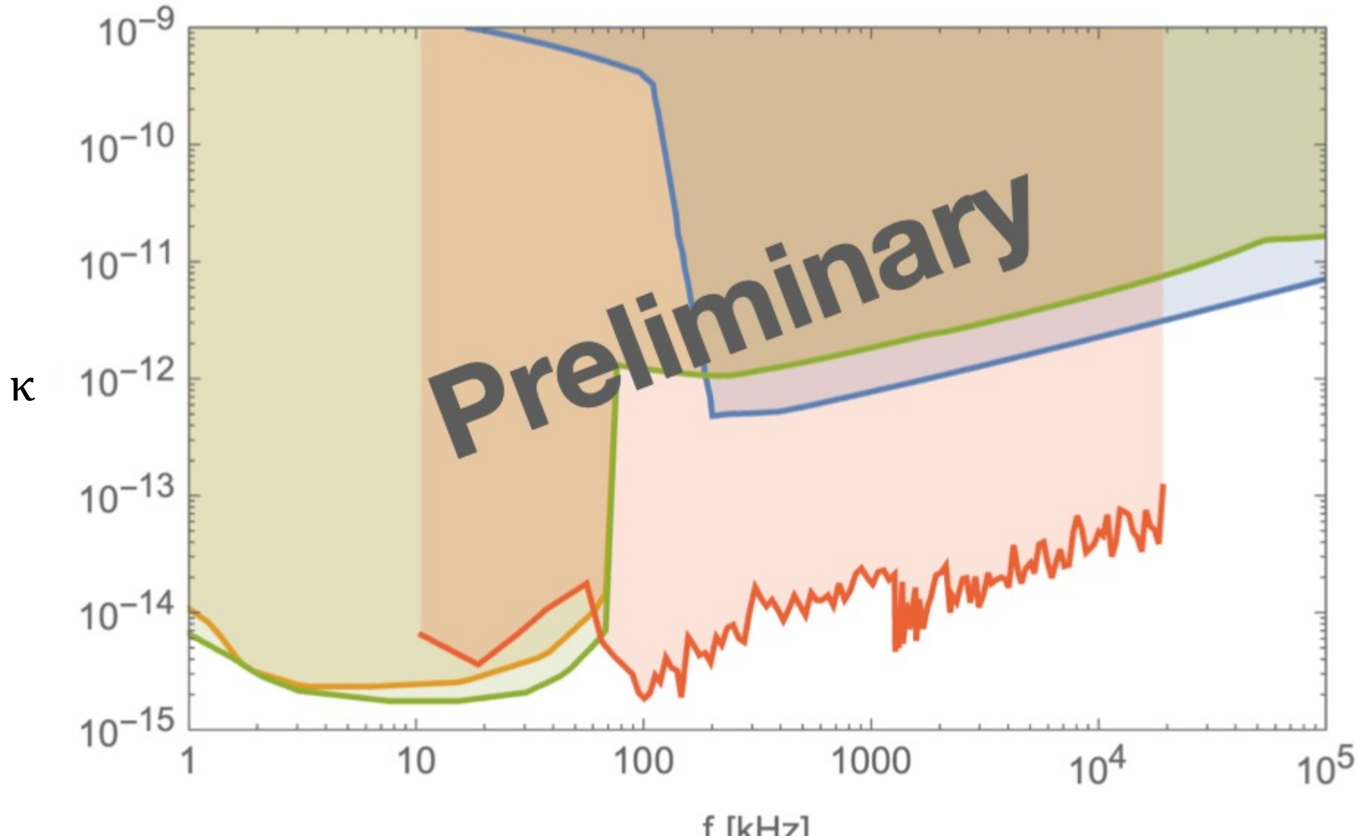
Work in progress with Shuailiang Ge, Jia Liu and Zheming Liu



STEREO constraint

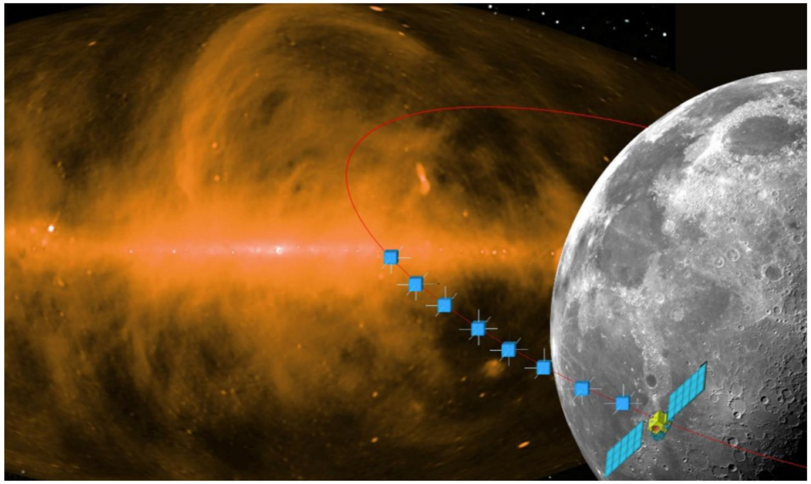
Using solar probes to search for DPDM

Work in progress with Shuailiang Ge, Jia Liu and Zheming Liu

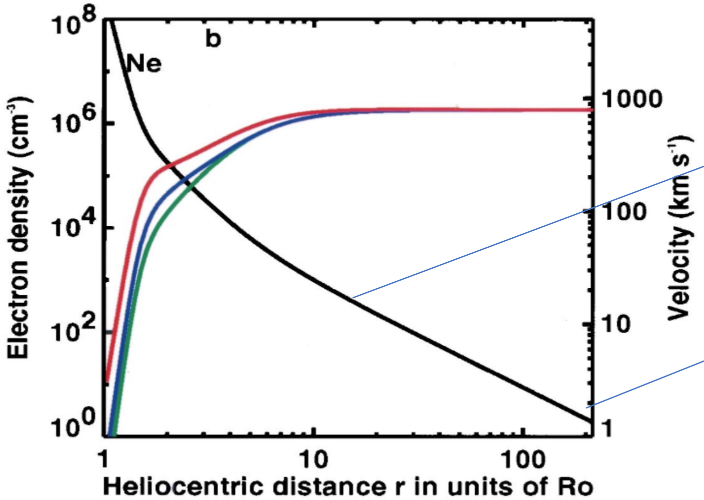


PSP constraint

Outlook: Hongmeng Project



Satellite array around the moon may give us the perfect opportunity to search for kHz-MHz frequency DPDM.



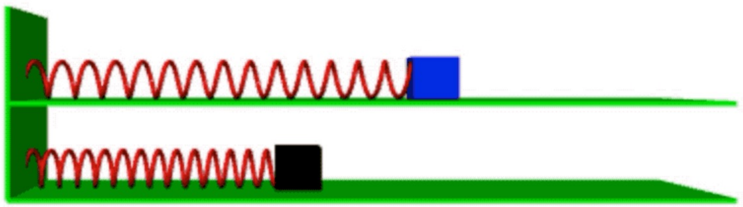
$$\frac{\omega_p}{2\pi} = 1\ \text{MHz}$$

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

Dark photon in plasma

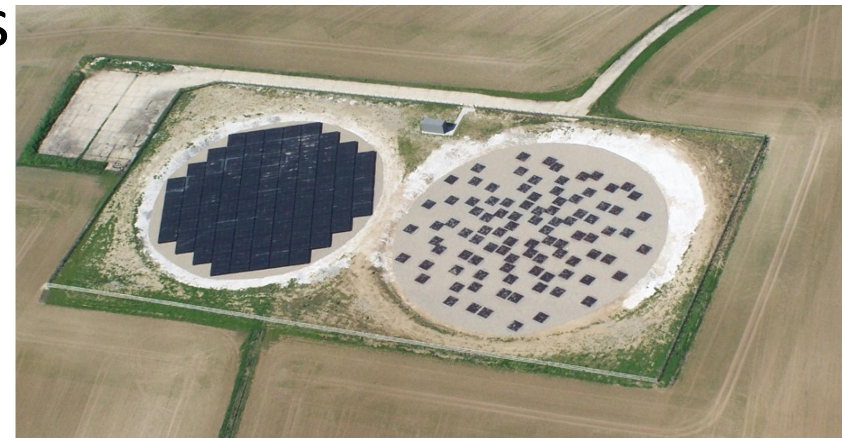
Plasma effect

$$\begin{pmatrix} A_T & V_T \end{pmatrix} \begin{pmatrix} \mathbf{k}^2 + \omega_p^2 & \kappa\omega_p^2 \\ 0 & \mathbf{k}^2 + m_V^2 \end{pmatrix} \begin{pmatrix} A_T \\ V_T \end{pmatrix}$$



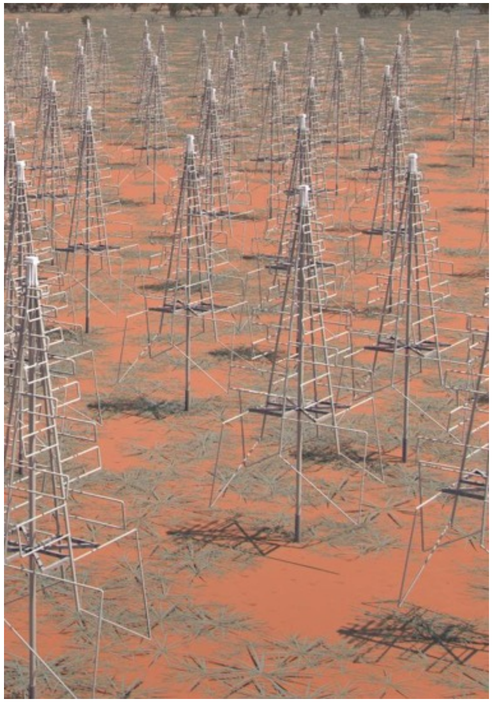
Searching for dark photon dark matter directly with radio telescopes

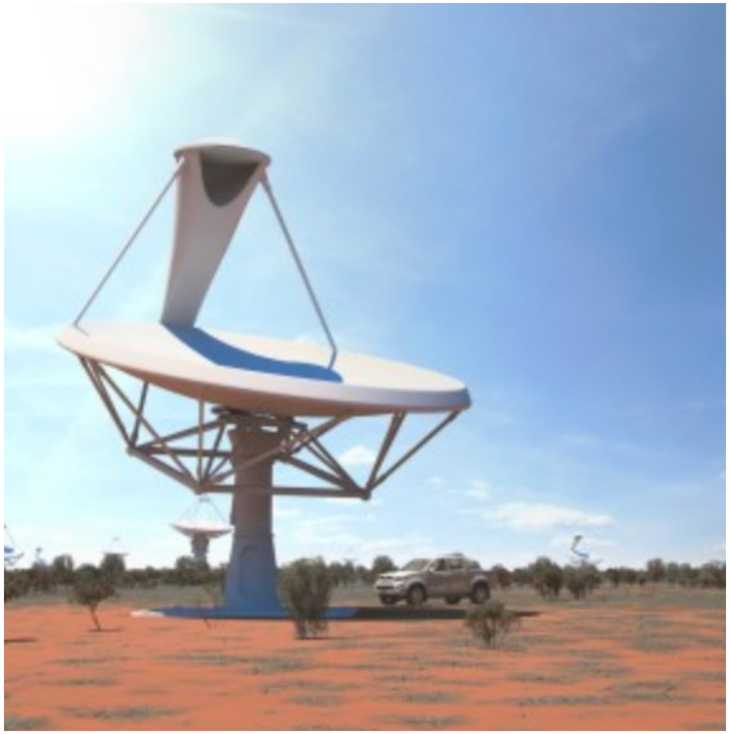
- Large scale radio telescopes



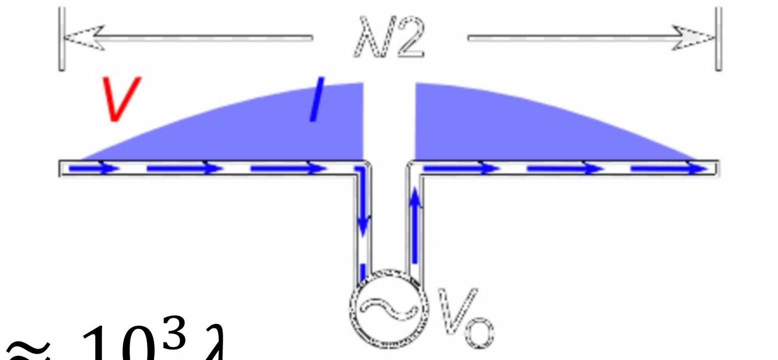
Searching for dark photon dark matter directly with radio telescopes

- The dark photon dark matter has an interaction with the electric current, $\kappa e V_\mu J^\mu$ (although suppressed)





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:

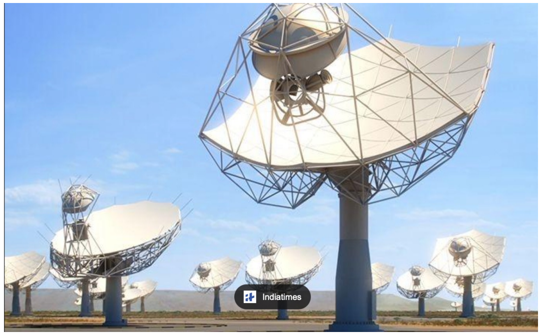
$$E_{\rm EM}^{\rm eqv} = \kappa E_D^{(0)} \cos(2\pi f t)$$

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

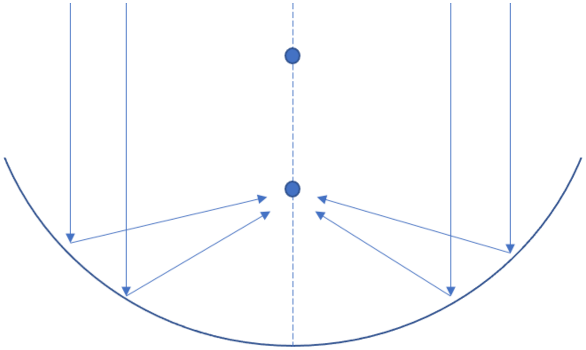
$\rho_{\rm DM}$ → 0.4 GeV/cm^3

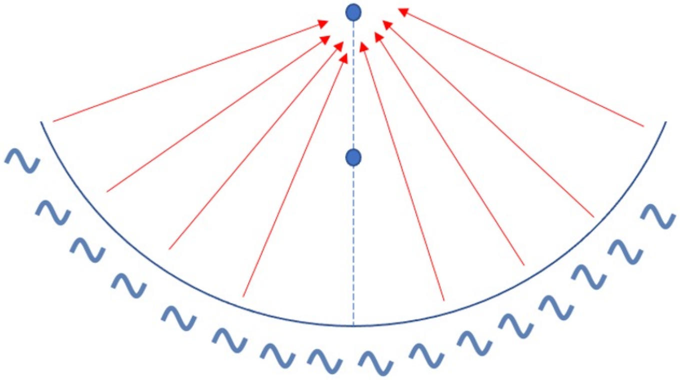
$\mathcal{C}$ → Order one parameter, determined by the detailed shape of the antenna

Dish antennas



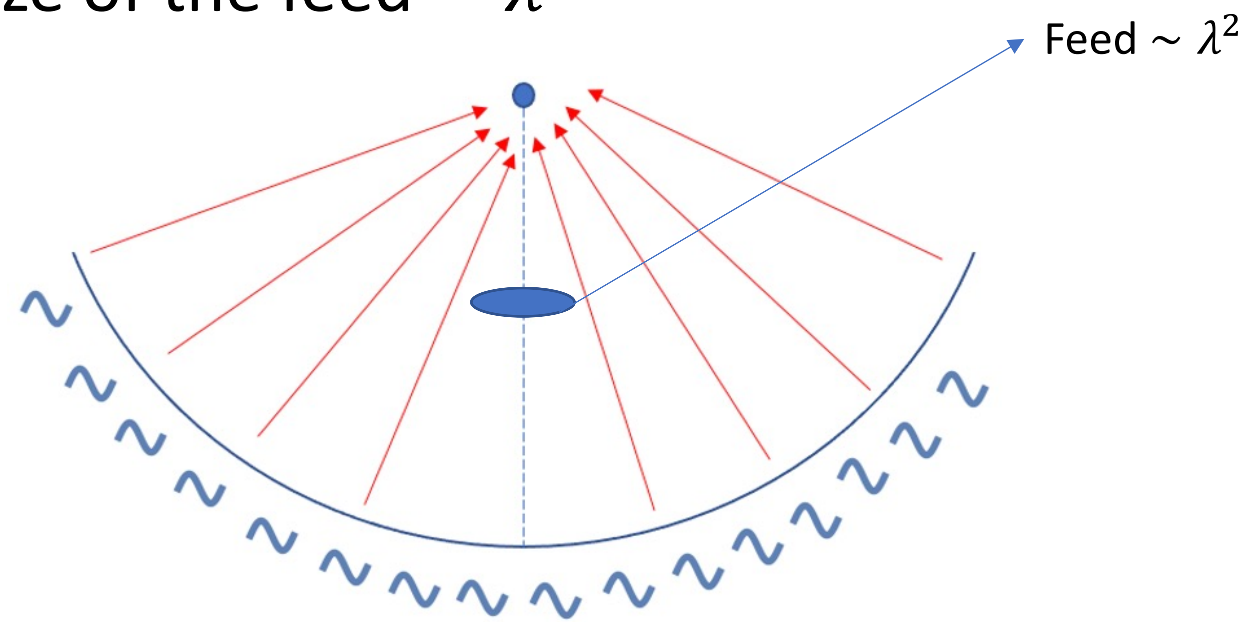
- For dish antennas, the oscillation of the dark photon field induces the oscillation of the electrons in the reflector plate, and produces EM waves, which can be detected by the feed.





Dish antennas

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



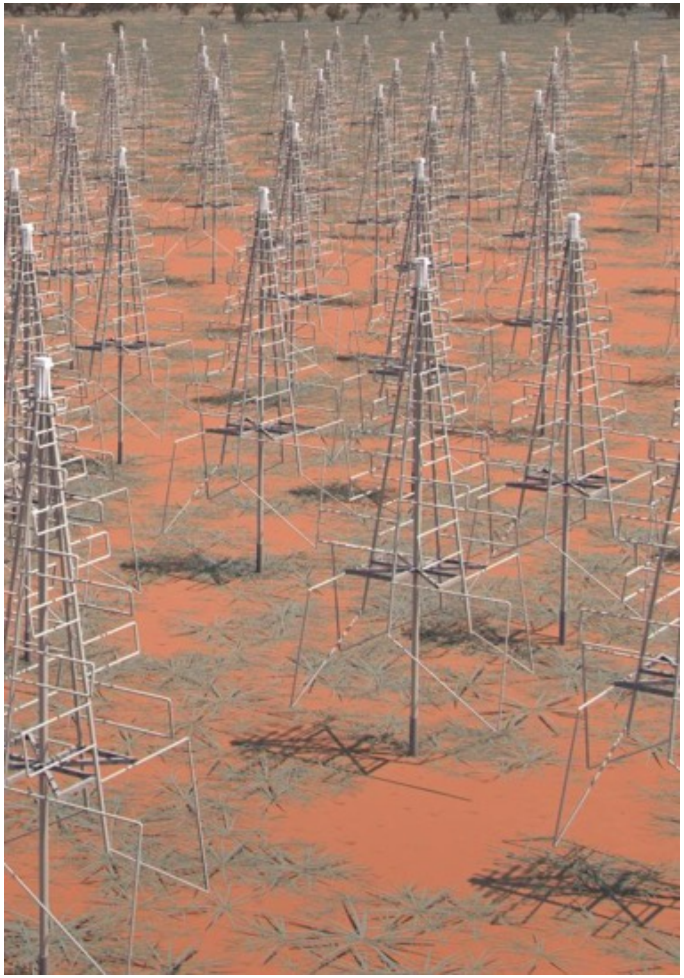
$$I^{\rm eqv}_{\rm dish} = \mathcal{C}\kappa^2 \rho_{\rm DM} \times \frac{\lambda^2}{\mathcal{A}}$$

$\mathcal{A}$ → Area of the telescope

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.

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



Limits from antenna arrays

- The signal is a peak,

$$f_{\text{signal}} = m_V / 2\pi \qquad \Delta f_{\text{signal}} \approx 10^{-6} f$$

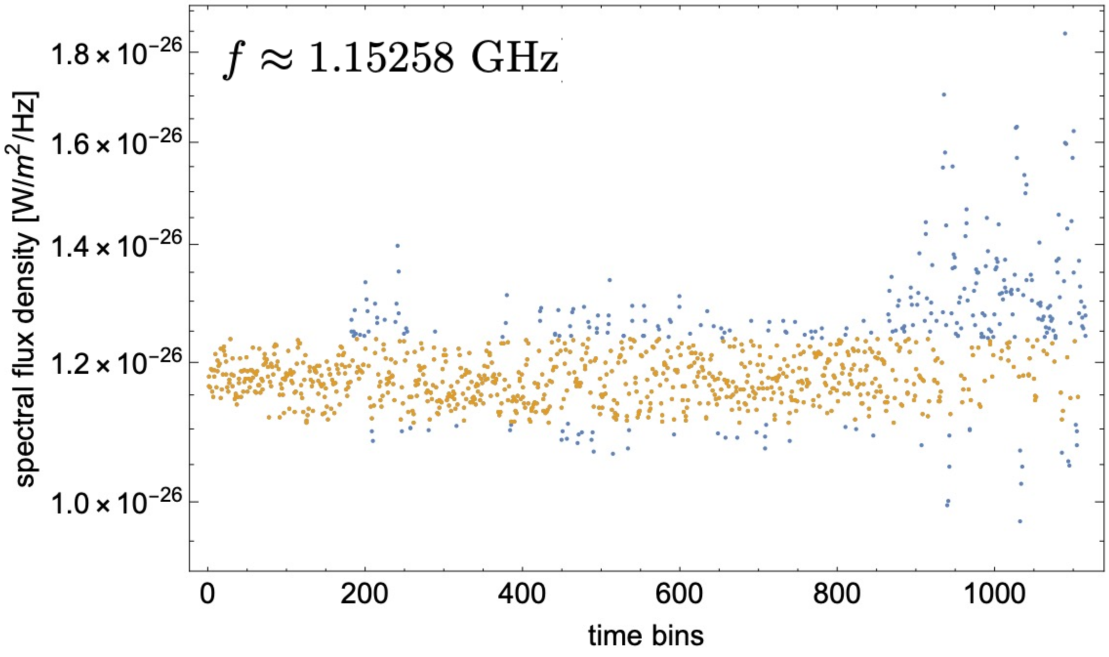
- Minimum detectable spectral flux

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

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

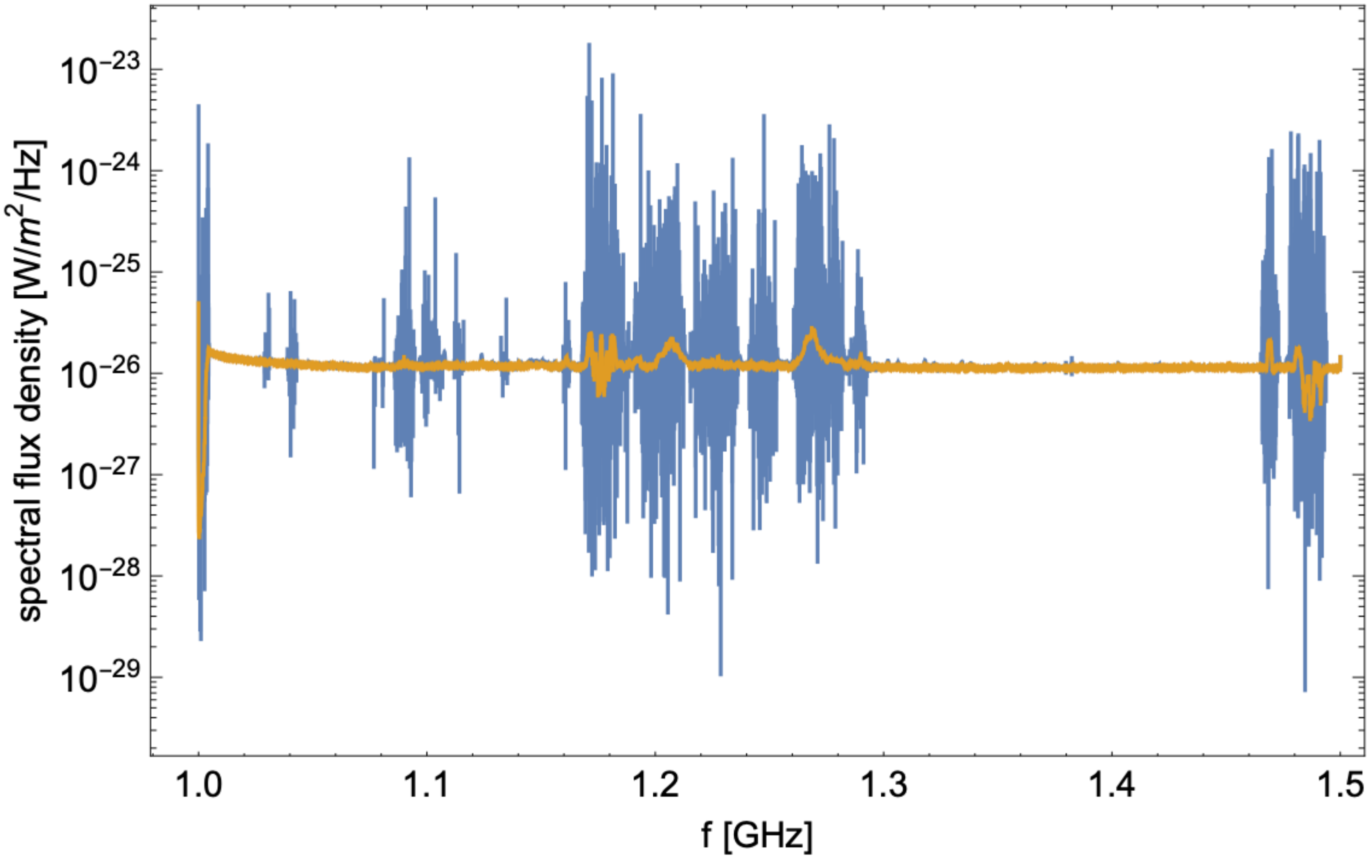
FAST data

- 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.



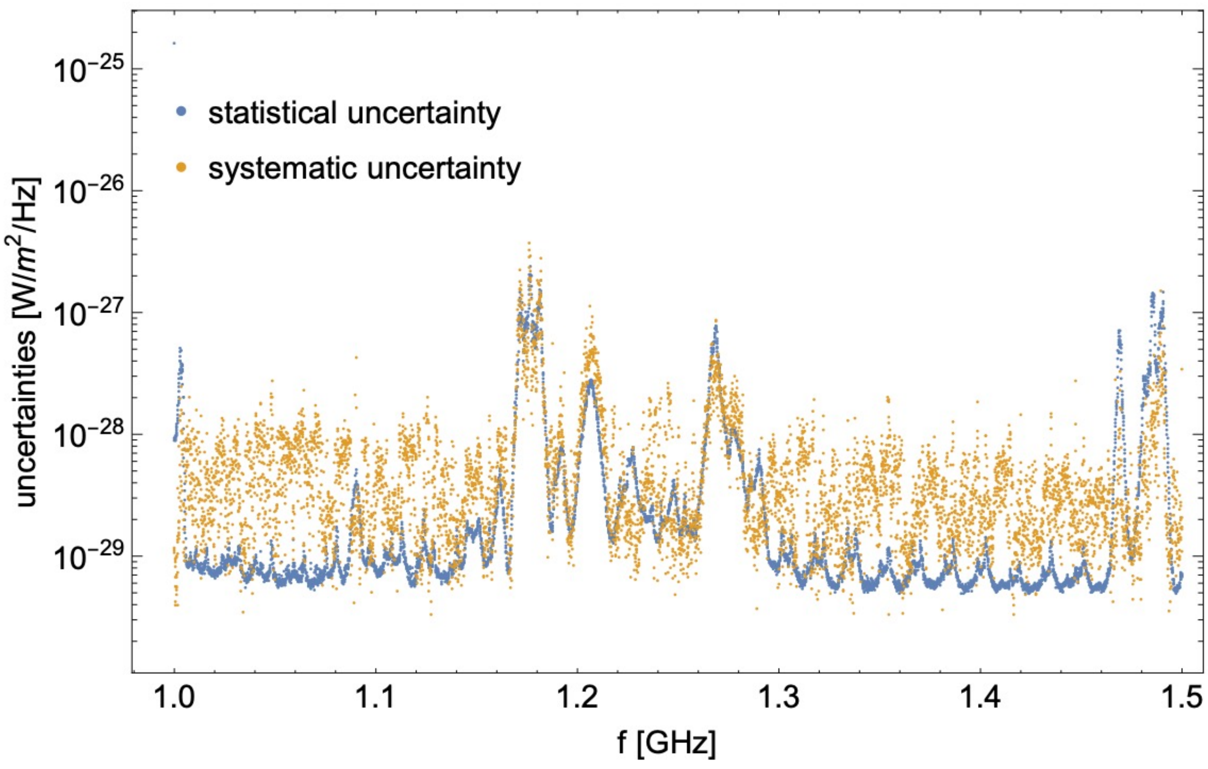
FAST data

- Spectrum after data cleasing

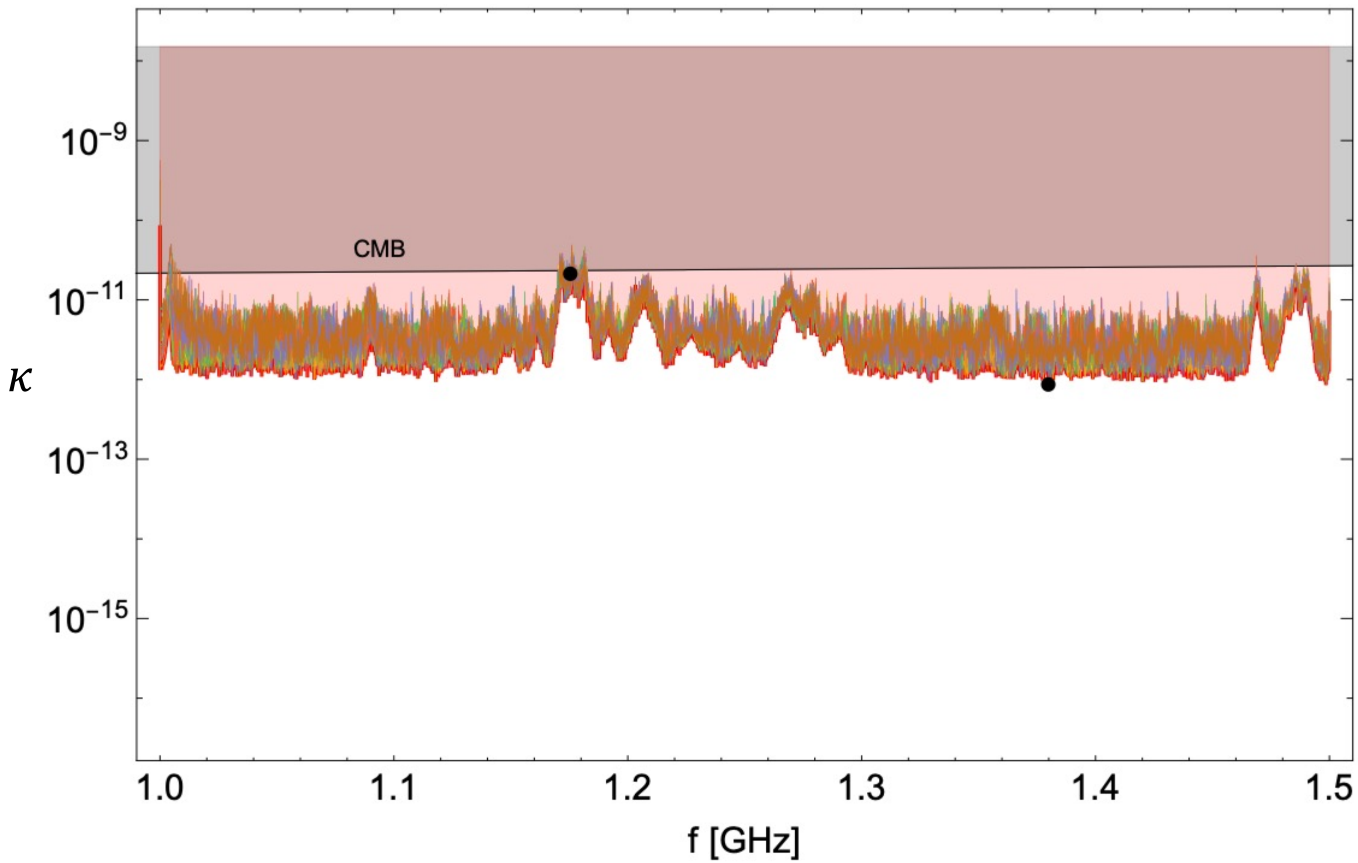


FAST data

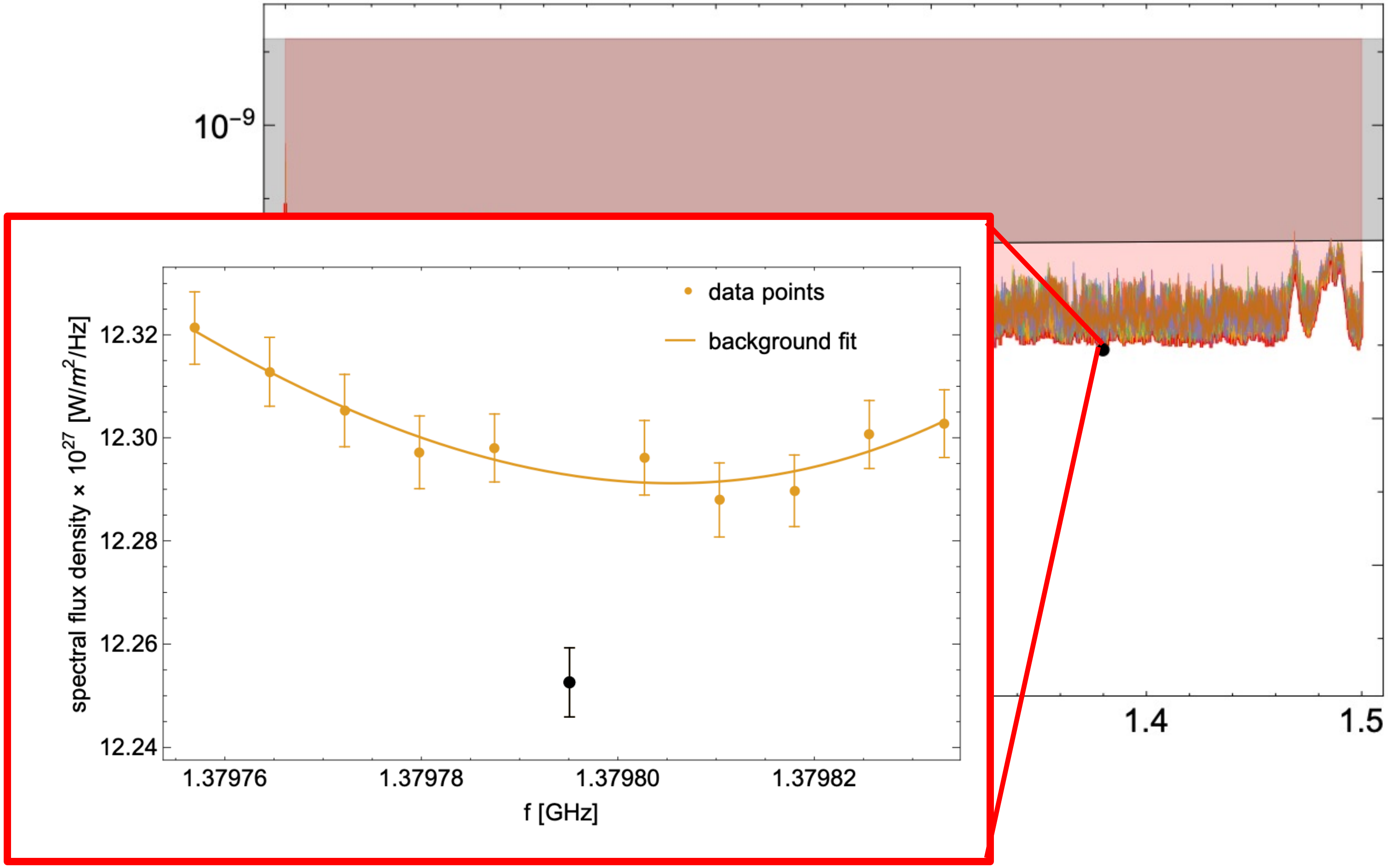
- We calculate the uncertainties from the fluctuations of the data.



Constraint FAST data



Constraint FAST data



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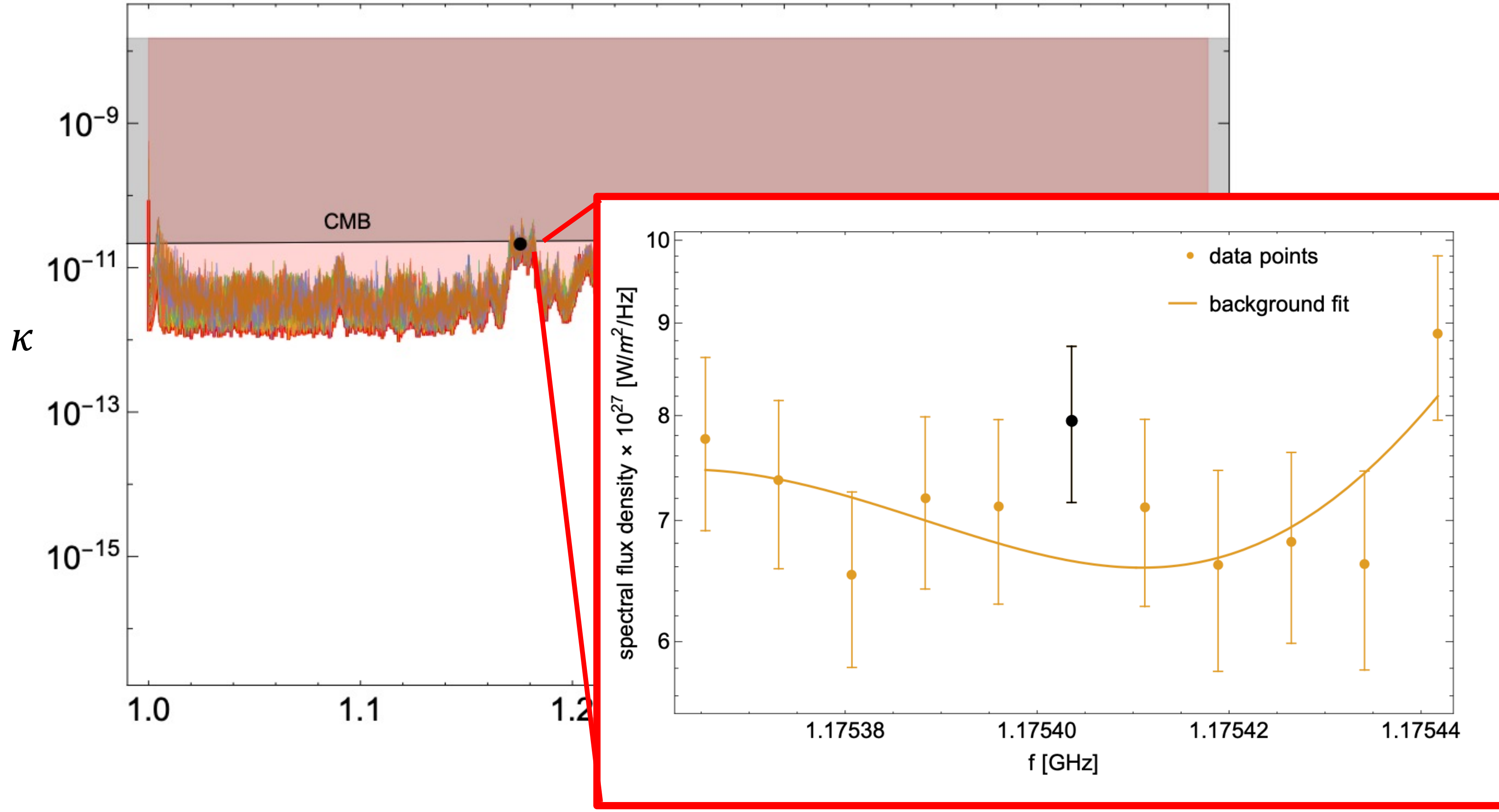
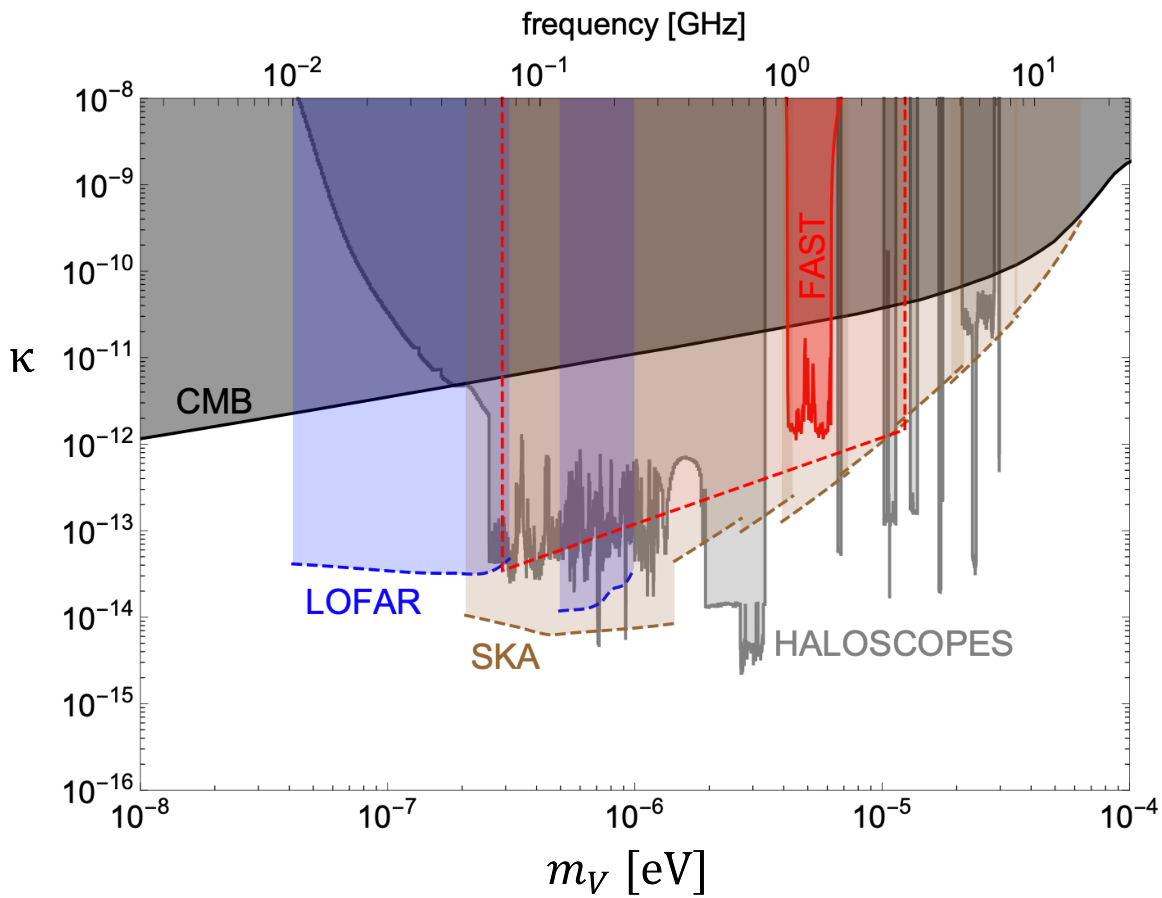
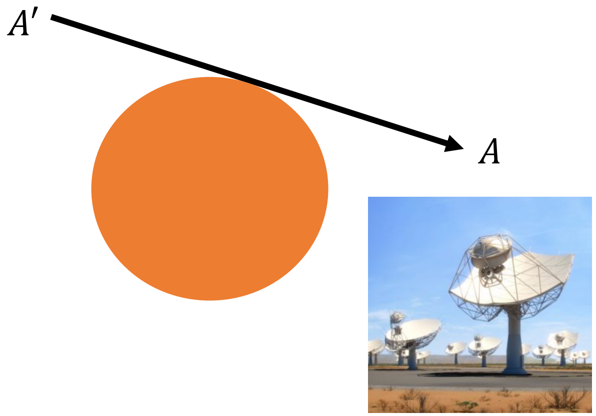


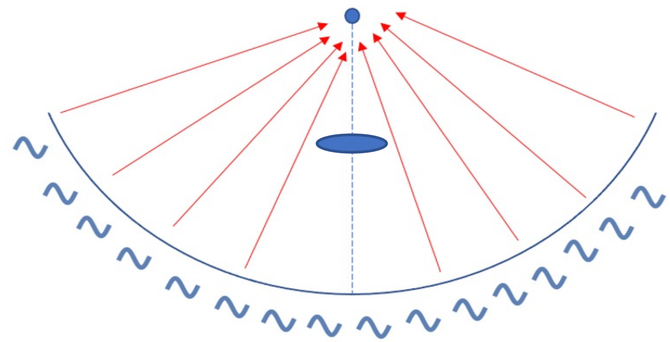
Direct detection of dark photon dark matter with radio telescopes



HA, S Ge, W-Q Guo, X Huang, J Liu, Z Lu, 2207.05767

Summary





- We convert all photon detectors to dark photon detectors.