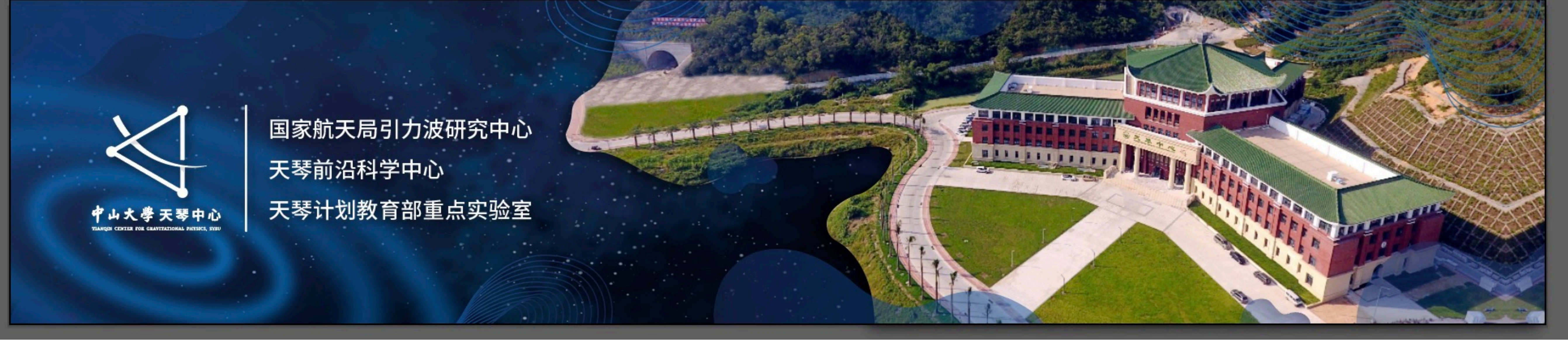



# New approaches to explore dark matter

黄发朋(FPH)
TianQin Center, Sun Yat-sen University

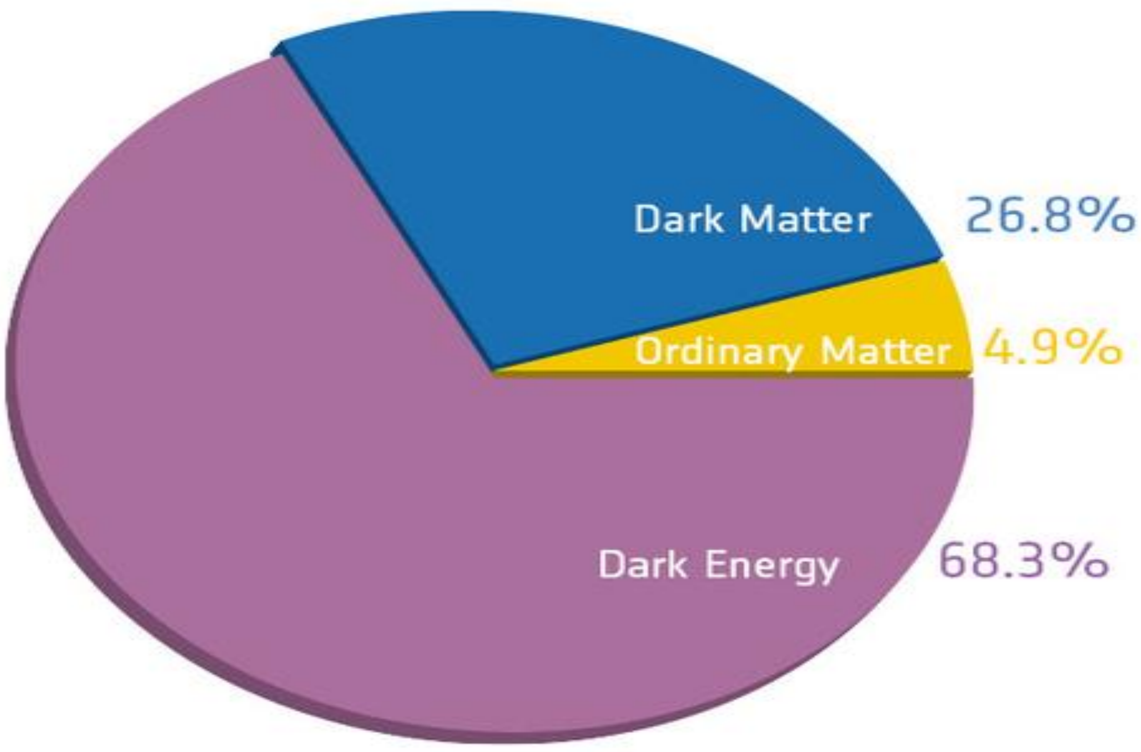
Haipeng An, FPH, Jia Liu, Wei Xue, Phy. Rev. Lett.126, 181102 (2021)
James Buckley, Bhupal Dev, Francesc Ferrer, FPH,
Phys.Rev.D 103 (2021) 4, 043015,
FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) 12, 123001
and work in progress

第十三届全国粒子物理学术会议（2021）
@山东大学(青岛)，zoom online
Aug. 17th, 2021

# Outline

- ➢Research Motivation
- ➢Explore light axion dark matter (DM) by SKA-like experiments
- ➢Explore light dark photon DM by SKA
- ➢Conclusion

# Motivation




**What is the nature of DM ?**

**Many experiments have been done to unravel the long-standing problem. No expected signals at LHC and DM direct search.**

**(See Prof. Ang haipeng's review talk.)**

**This situation may point us towards new ways, such as radio telescope (SKA/FAST) gravitational wave experiments (LISA/TianQin/Taiji).**

**Focus on exploring light DM by SKA, not mention new DM mechanism from phase transition and its gravitational wave detection.**

# The Square Kilometre Array (SKA)

**Early science observations are expected to start in 2021 with a partial array,**

**High sensitivity sub $\mu J$**

credit: SKA website

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

**From 25 Sep. 2016**

Credit:FAST website

# The Green Bank Telescope (GBT)

**GBT is running observations roughly 6,500 hours each year**

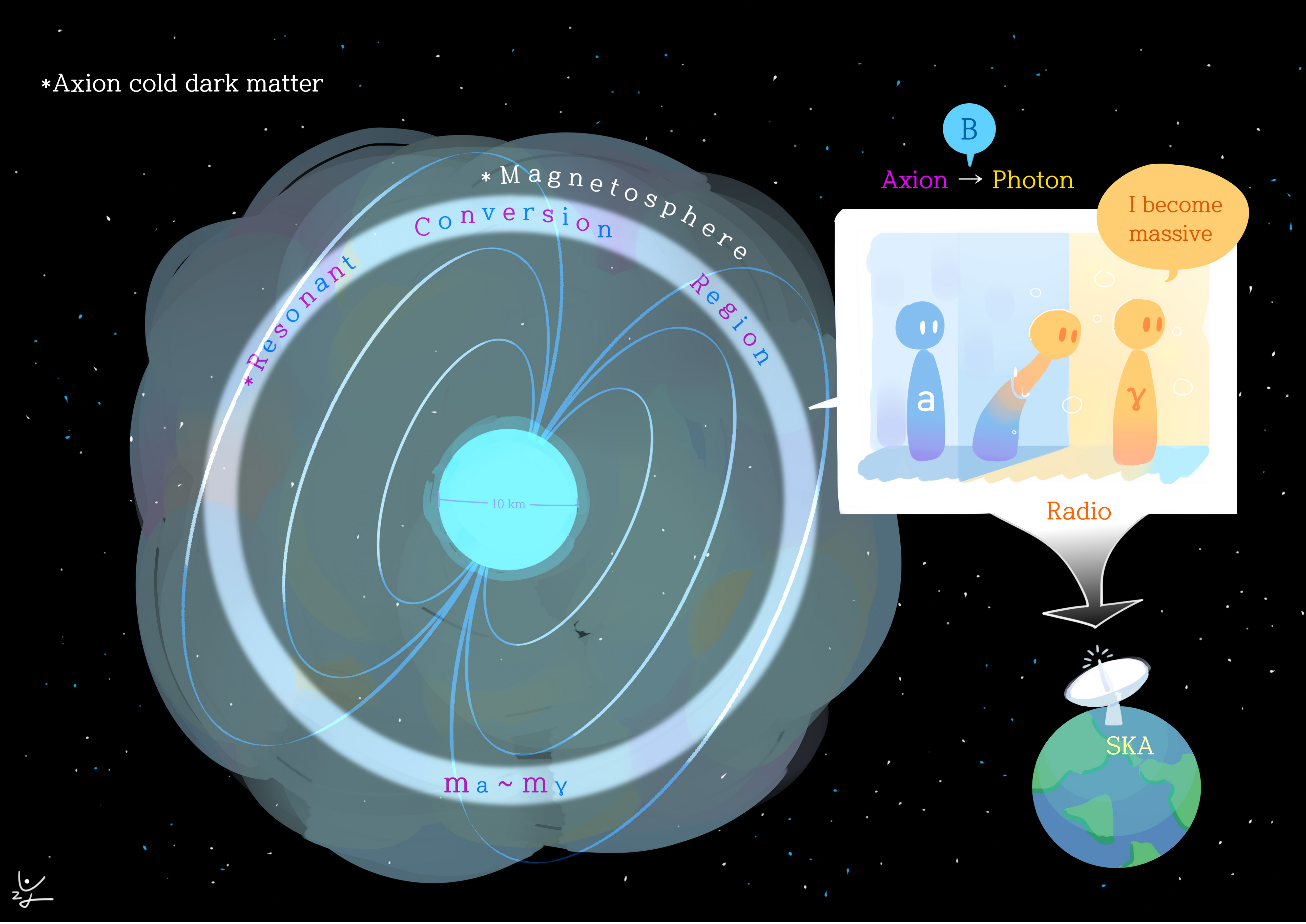
credit:GBT website

# Ⅰ.Explore light axion dark matter

**Axion or axion-like particle motivated from strong CP problem or string theory is still one of the most attractive and promising DM candidate.**

**We firstly study using the SKA-like experiments to explore the resonant conversion of axion cold DM to radio signal from magnetized astrophysical sources, such as neutron star, magnetar and pulsar.**

**FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001, arXiv:1803.08230**



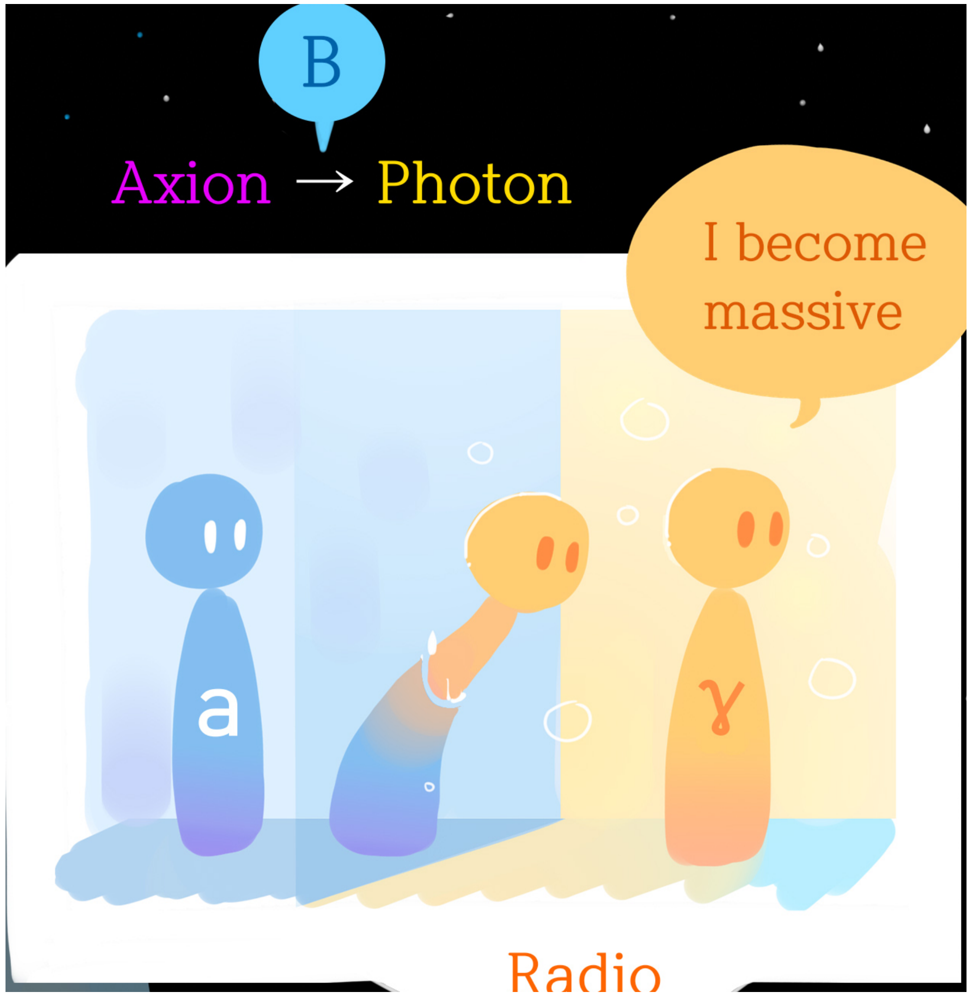

**FPH,** K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001

# Axion-photon conversion in the magnetosphere

$$L_{\rm int} = \frac{1}{4} g \tilde{F}^{\mu\nu} F_{\mu\nu} a = -g \mathbf{E} \cdot \mathbf{B} a,$$

**Massive Photon: In the magnetosphere of the neutron star, photon obtains effective mass in the plasma.**

$$m_\gamma^2 = \omega_{plasma}^2 = 4\pi\alpha \frac{n_e}{m_e}$$




$$n_e(r) = n_e^{\rm GJ}(r) = 7 \times 10^{-2} \frac{1s}{P} \frac{B(r)}{1\ {\rm G}} \frac{1}{{\rm cm}^3}$$

$$B(r) = B_0 \left(\frac{r}{r_0}\right)^{-3}$$

**Thus, the photon mass is location dependent, and within some region**

$$m_\gamma^2(r_{\rm res}) = m_a^2$$

# The Adiabatic Resonant Conversion

**Within the resonance region, the axion-photon conversion rate is greatly enhanced due to resonant effects.**

$$\sin 2\tilde{\theta} = \frac{2gB\omega}{\sqrt{4g^2B^2\omega^2 + (m_\gamma^2 - m_a^2)^2}} \qquad m_\gamma^2(r_{\rm res}) = m_a^2$$

**The adiabatic resonant conversion requires the resonance region is valid inside the resonance width.**

**Coherent condition is also needed.**

**Resonant conversion is essential to observe the radio signal from axion DM.**

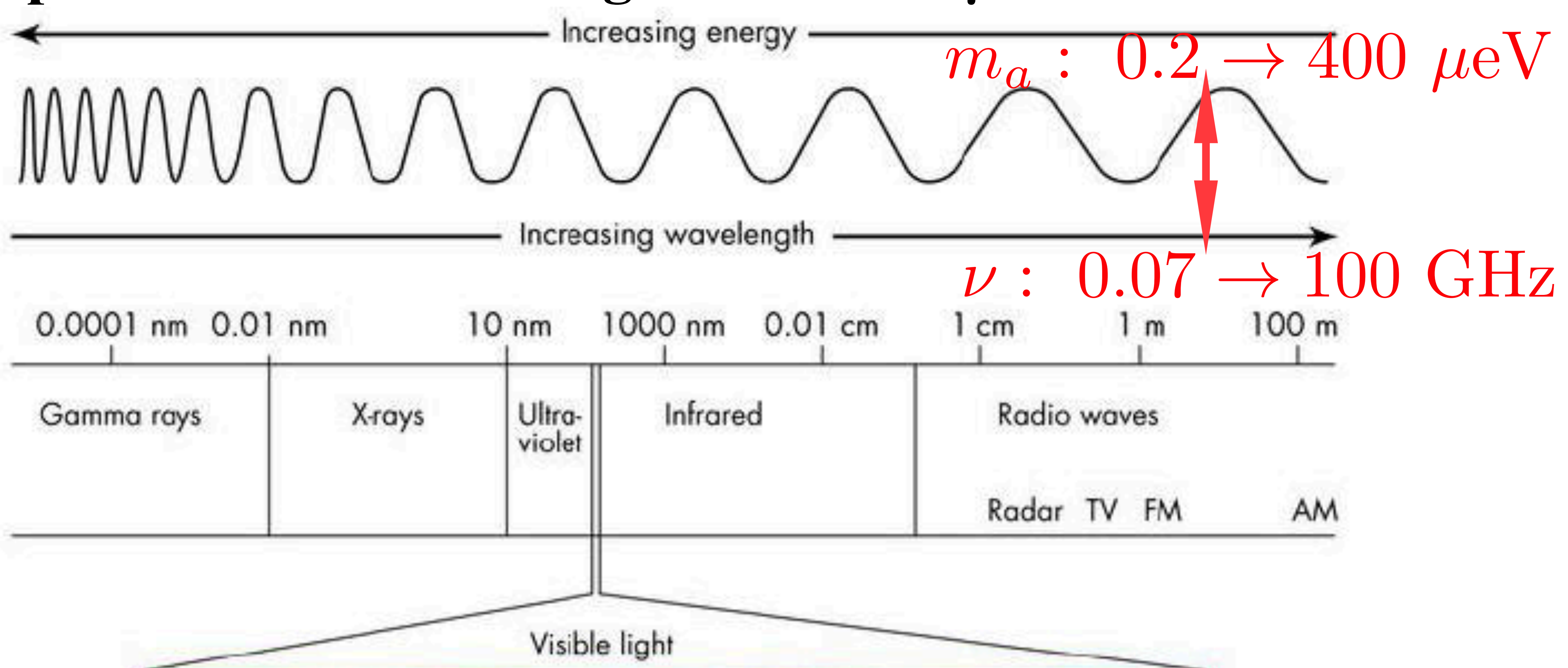
# *Radio Signal*

**Line-like radio signal for non-relativistic axion conversion:**

$$\nu_{\rm peak} \approx \frac{m_a}{2\pi} \approx 240 \frac{m_a}{\mu eV} {\rm MHz}$$

**1 GHz ~ 4 μeV**

**FAST covers 70 MHz–3 GHz, SKA covers 50 MHz–14 GHz, and GBT covers 0.3–100 GHz, so that the radio telescopes can probe axion mass range of 0.2–400 μeV**



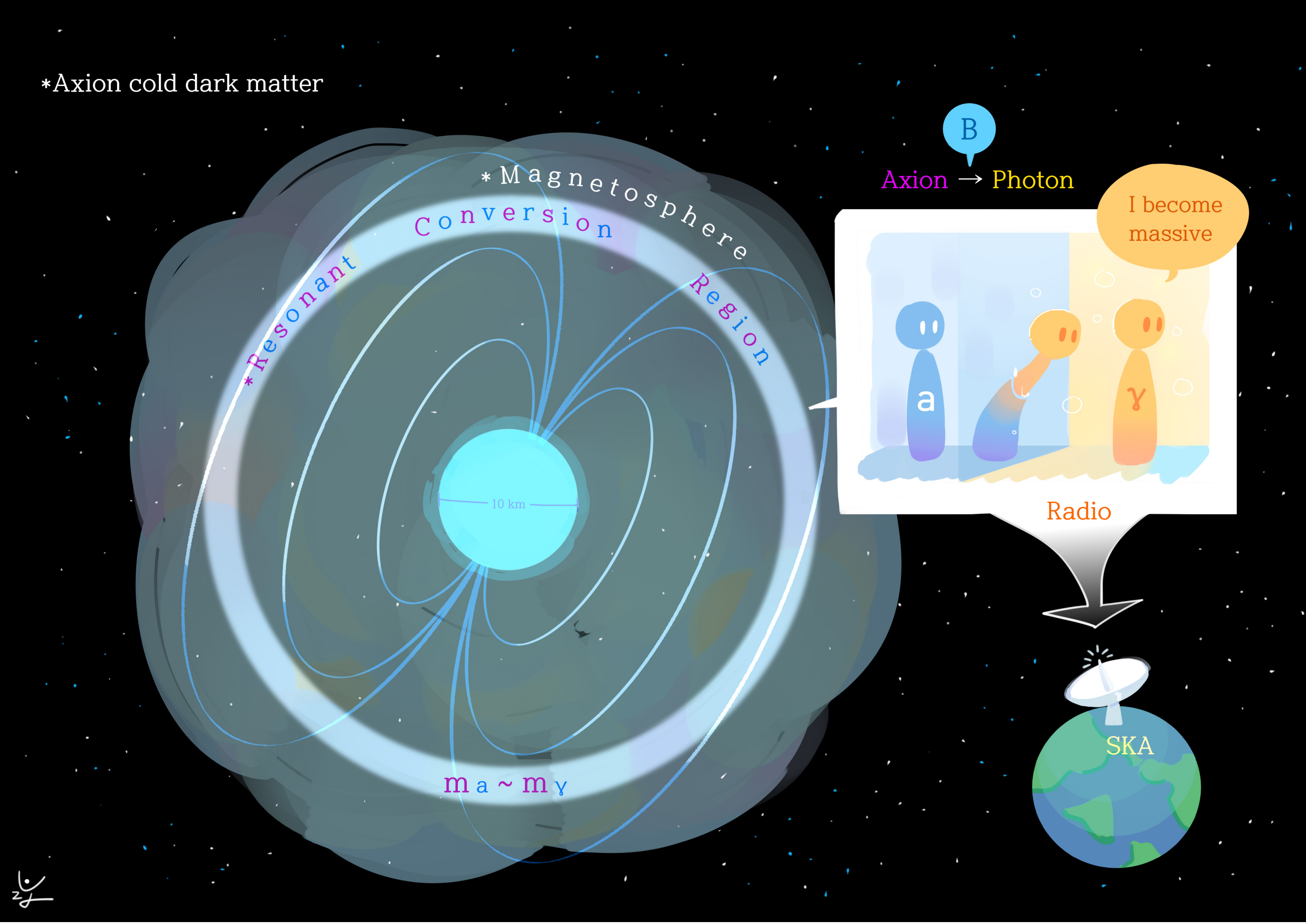
# *Radio Signal*

**Signal: For a trial parameter set,** $B_0 = 10^{15}$ G, $m_a = 50\ \mu$eV
$P = 10$ s, $g = 5 \times 10^{-11}$ GeV$^{-1}$, $r_0 = 10$ km, $M = 1.5 M_{\rm sun}$, $d = 1$kpc
**satisfies the conditions for the adiabatic resonance conditions and the existed axion search constraints with signal** $S_\gamma \sim 0.51$ μJy.

**Sensitivity:** $S_{\rm min} \sim 0.48 \mu Jy$ for the SKA1

$S_{min} \sim 0.016 \mu Jy$ for SKA2 with 100 hours observation time.

**SKA-like experiment can probe the axion DM and the axion mass which corresponds to peak frequency.**




**FPH,** K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001

# Comments on the radio probe of axion DM

1. **Astrophysical uncertainties:the magnetic field distribution, DM density distribution, the velocity dispersion, the plasma effects…**

**2. There are more and more detailed studies after our simple estimation on the radio signal:**

**arXiv:1804.03145 They consider more details and extremely high dark matter density around the neutron star, thus the signal is more stronger.**

**arXiv:1811.01020 by Benjamin R. Safdi, Zhiquan Sun, Alexander Y. Chen**

**arXiv:1905.04686,They consider multi-messenger of axion DM detection. Namely, using LISA to detect the DM density around the neutron star, which can determine the radio strength detected by SKA.**

**Up to now, the most precise study is arXiv:2104.08290**

# This idea becomes a hot topic.

FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001, Cited by 43 times

**FAST+SKA**

Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020
Richard Keith Ellis (Durham U., IPPP) *et al.*. Oct 25, 2019. 254 pp.
CERN-ESU-004
e-Print: arXiv:1910.11775 [

### 9.5.3 Complementarity with direct and indirect detection searches

Radio searches for the conversion of axion/ALP dark matter into photons inside the magnetosphere of neutron stars can have sensitivity [630–632] for ALP masses in the range $\sim 0.2$–$40\,\mu$eV, and potentially above. The signature is the emission of a narrow radio line from individual neutron stars, with a frequency that corresponds to the mass of the ALP. Several of such searches are now underway, with expected sensitivities to the photon-ALP coupling down to $g_{a\gamma\gamma} \sim 10^{-12}\,\text{GeV}^{-1}$. The future SKA may have the ability to probe significant parts of the QCD axion parameter space [633].

**Invisible Axion Search Methods**

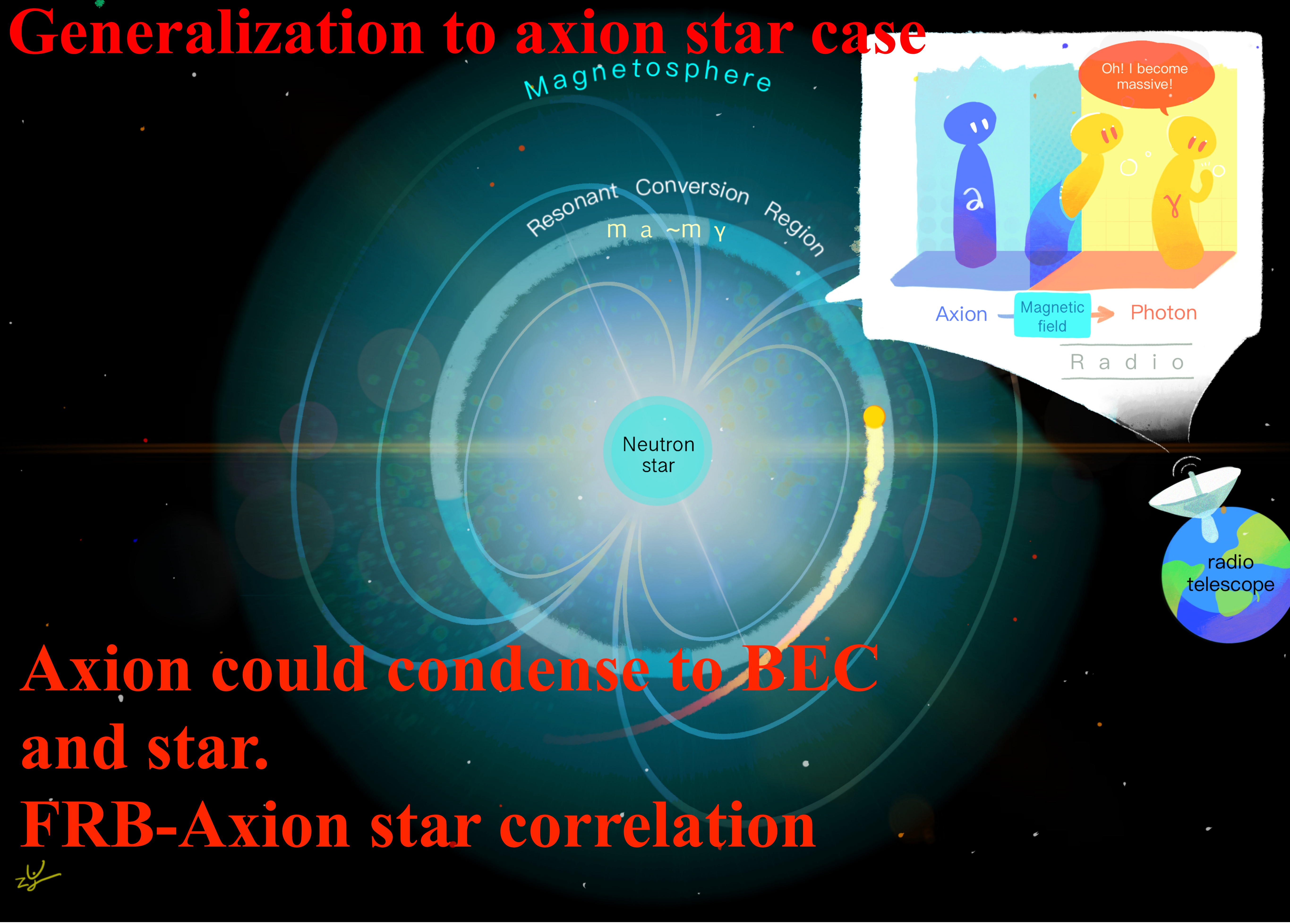
Pierre Sikivie (Florida U.) (Mar 4, 2020)

Published in: *Rev.Mod.Phys.* 93 (2021) 1, 015004 • e-Print: 2003.02206 [hep-ph]

Axion-photon conversion can occur in astrophysical magnetic fields, and may have implications for observation. Axions can readily convert to photons, and vice-versa, in the magnetospheres of neutron stars (Hook *et al.*, 2018; Huang *et al.*, 2018; Morris, 1986). With

**See Yin Peng-Fei's talk for axion search by white dwarf**

# Generalization to axion star case




**Axion could condense to BEC and star.**
**FRB-Axion star correlation**

James Buckley, Bhupal Dev, Francesc Ferrer, FPH, *Phys.Rev.D* 103 (2021) 4, 043015

# II.Generalize to dark photon DM case

*Radio-frequency Dark Photon Dark Matter across the Sun,* **Haipeng An, FPH, Jia Liu, Wei Xue**, **Phy. Rev. Lett.126, 181102 (2021)**

**Recently, people realize light dark photon can be a promising DM candidate.**

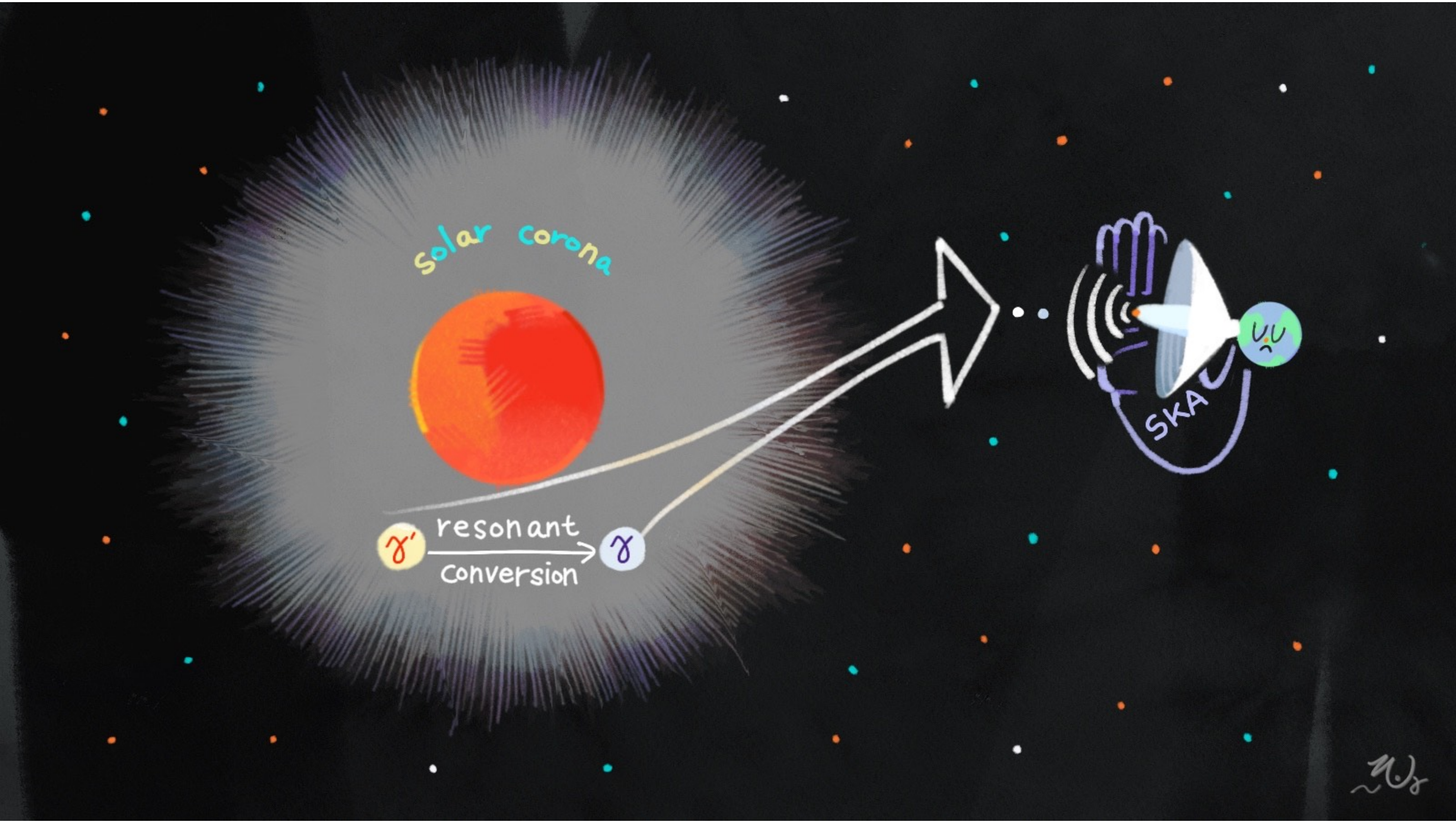
P. W. Graham, J. Mardon, and S. Rajendran, Phys. Rev. D 93, 103520 (2016).
A.J. Long and L.-T. Wang, Phys. Rev. D 99, 063529 (2019)
B. G. Alonso-Álvarez, T. Hugle, and J. Jaeckel, J. Cosmol. Astropart. Phys. 02 (2020) 014.
C. K. Nakayama, J. Cosmol. Astropart. Phys. 10 (2019) 019.
P. Agrawal, N. Kitajima, M. Reece, T. Sekiguchi, and F. Takahashi, Phys. Lett. B 801, 135136 (2020).
R. T. Co, A. Pierce, Z. Zhang, and Y. Zhao, Phys. Rev. D 99, 075002 (2019).
D. Y. Nakai, R. Namba, and Z. Wang, J. High Energy Phys. 12 (2020) 170

**We study how to detect light dark photon DM by radio telescope, following the same idea as the axion DM case.**

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

# Resonant conversion process

*Radio-frequency Dark Photon Dark Matter across the Sun,* **Haipeng An, FPH, Jia Liu, Wei Xue**, **Phy. Rev. Lett.126, 181102 (2021)**



# Resonant production

*Radio-frequency Dark Photon Dark Matter across the Sun,* **Haipeng An, FPH, Jia Liu, Wei Xue**，**Phy. Rev. Lett.126, 181102 (2021)**

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

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

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

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

# Propagation effects

**It turns out that the dominant absorption process is the inverse bremsstrahlung process.**

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

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

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

# Sensitivity of radio telescope

**The minimum detectable flux density of a radio telescope is**

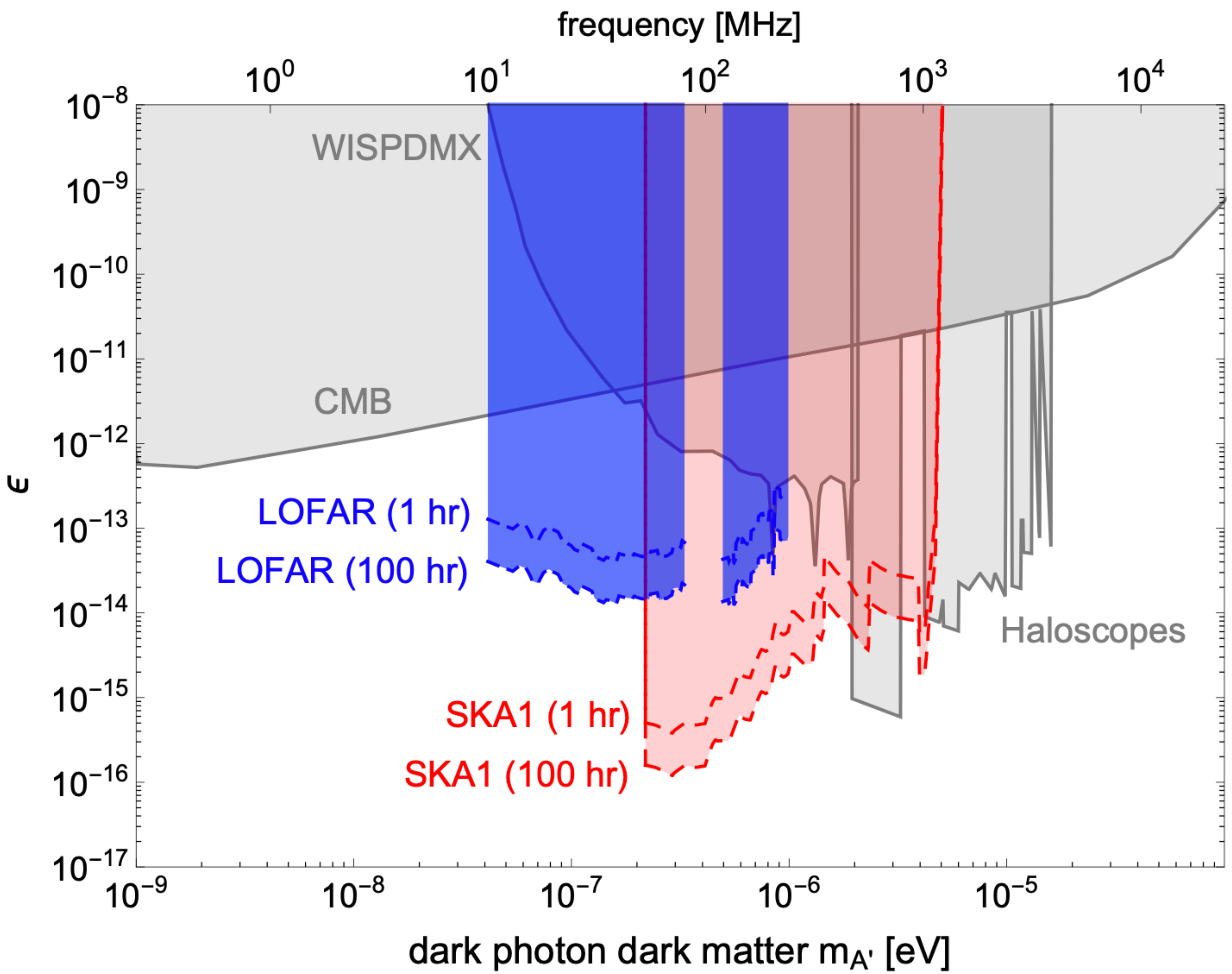
$$S_{\rm min} = \frac{\rm SEFD}{\eta_s \sqrt{n_{\rm pol}\, \mathcal{B}\, t_{\rm obs}}}$$

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

| Name | $f$ [MHz] | $B_{\rm res}$ [kHz] | $\langle T_{\rm sys} \rangle$ [K] | $\langle A_{\rm eff} \rangle$ [$m^2$] |
|---|---|---|---|---|
| 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 reach

*Radio-frequency Dark Photon Dark Matter across the Sun,* **Haipeng An, FPH, Jia Liu, Wei Xue, Phy. Rev. Lett.126, 181102 (2021)**




# Conclusion

**SKA-like radio telescope could provide new ideas to explore the light dark matter.**

**Work in progress:**
**multi-messenger(radio signal plus gravitational wave signal) to explore light dark matter**

**Thanks for your attention!**

**Comments and collaborations are welcome!**


# Thank you!

Contact: huangfp8@sysu.edu.cn

## Final Remark:

1. Collaboration is welcome!
2. Welcome to join as faculty.
3. http://tianqin.sysu.edu.cn