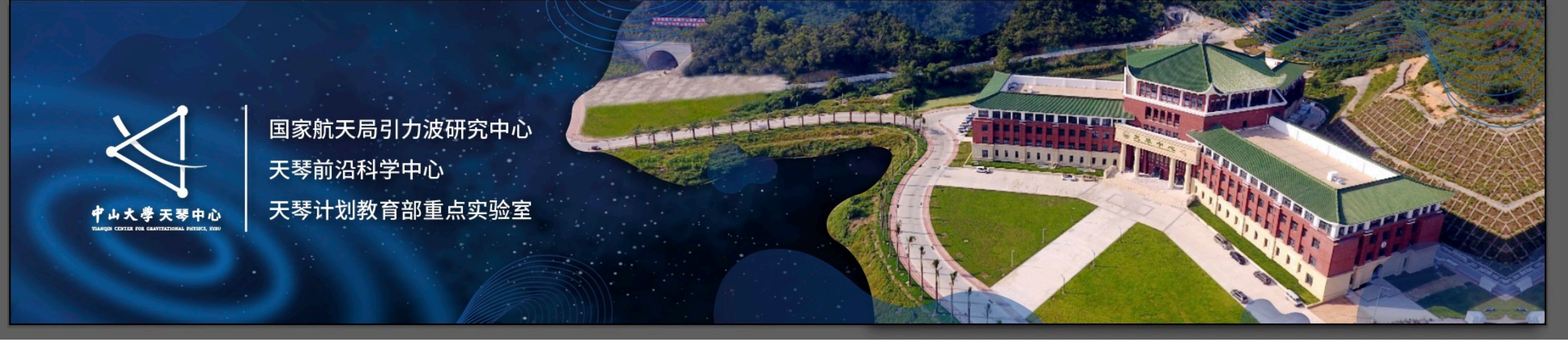

Exploring the light dark matter by SKA

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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) no.12, 123001
and work in progress

26th International Symposium on Particle Physics, String Theory, and Cosmology (PASCOS2021)
@CTPU, IBS, South Korea(zoom online)
June 17th, 2021

Outline

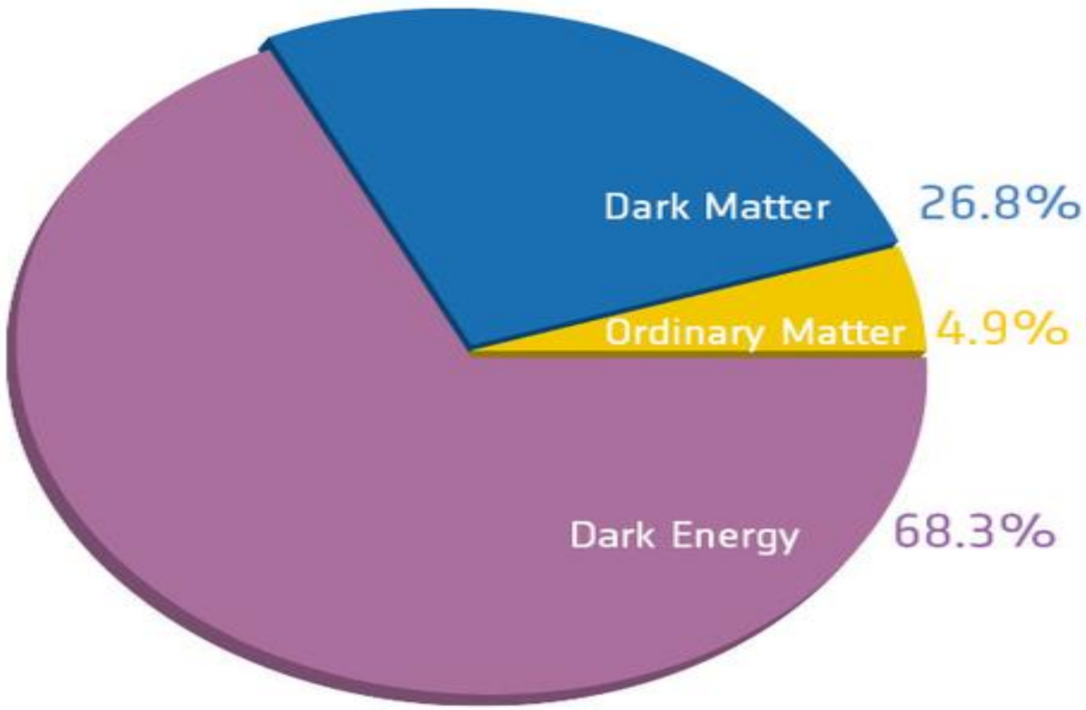
- ➢Research Motivation

- ➢Explore light axion dark matter (DM) by SKA-like experiments

- ➢Explore light dark photon DM by SKA

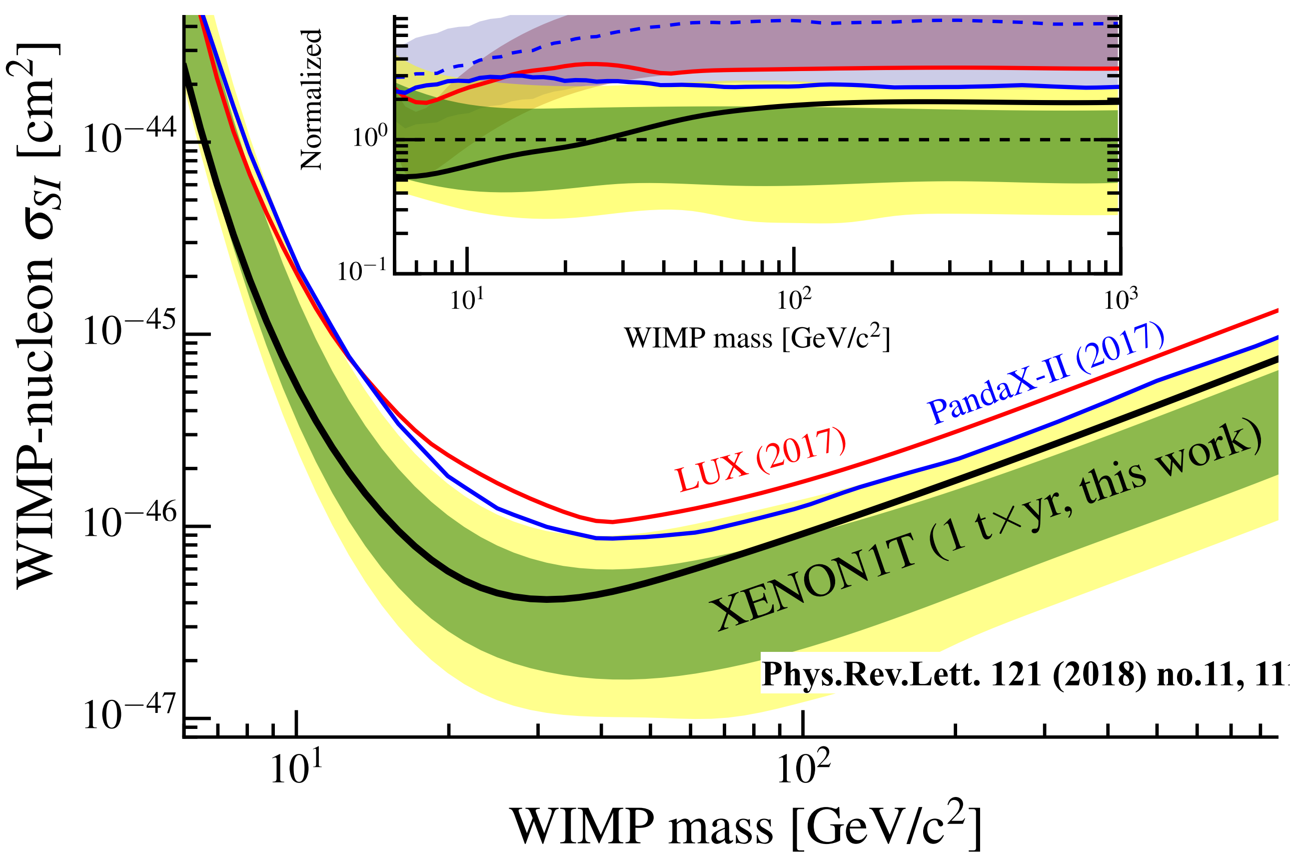
- ➢Conclusion

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.



Phys.Rev.Lett. 121 (2018) no.11, 111302

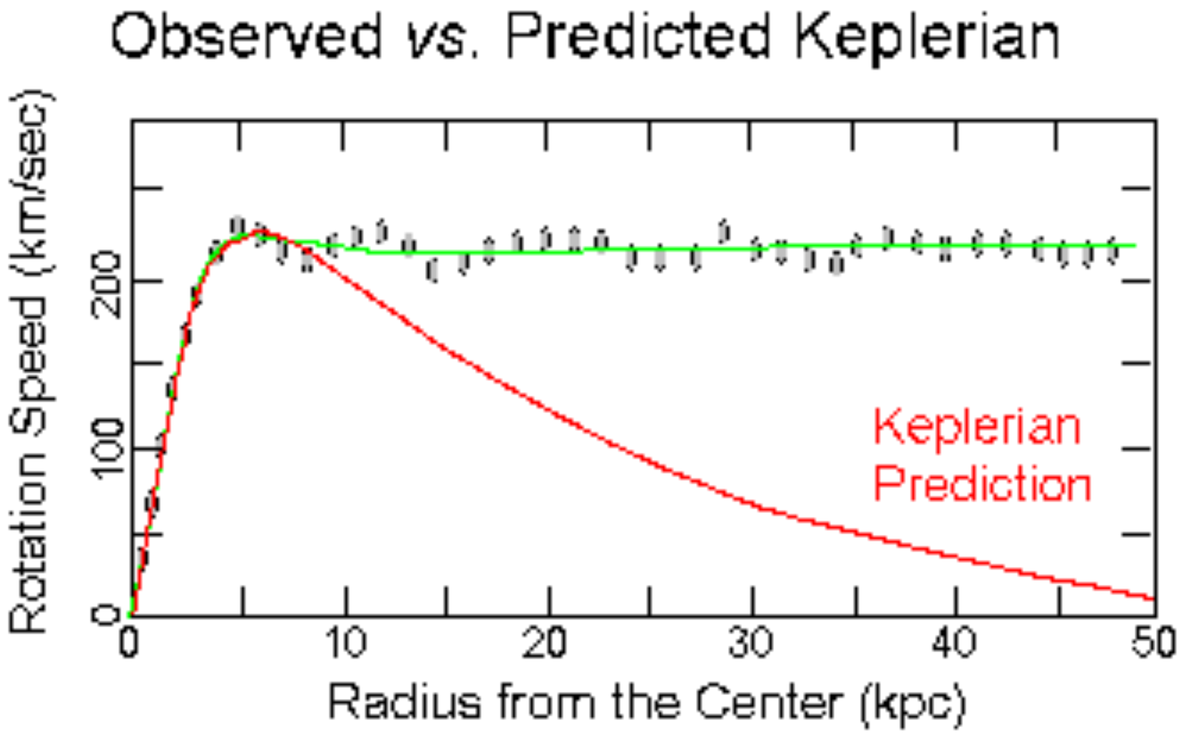
This situation may point us towards new ways, such as

Radio telescope(SKA/FAST)

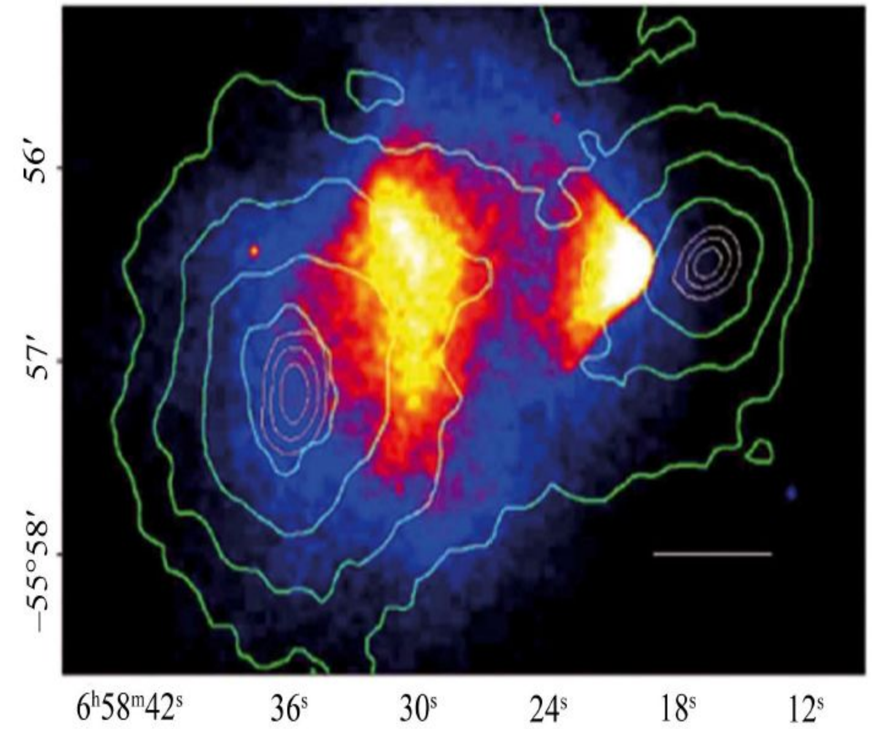
Laser Interferometer (LISA/TianQin)

Towards light DM

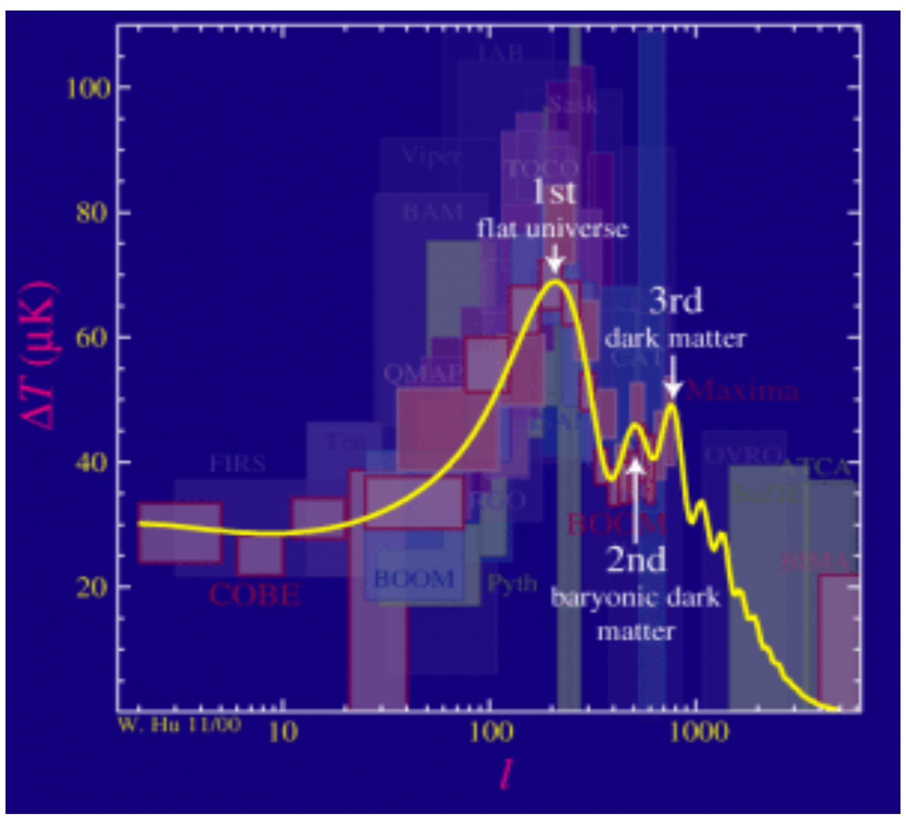
What is dark matter?



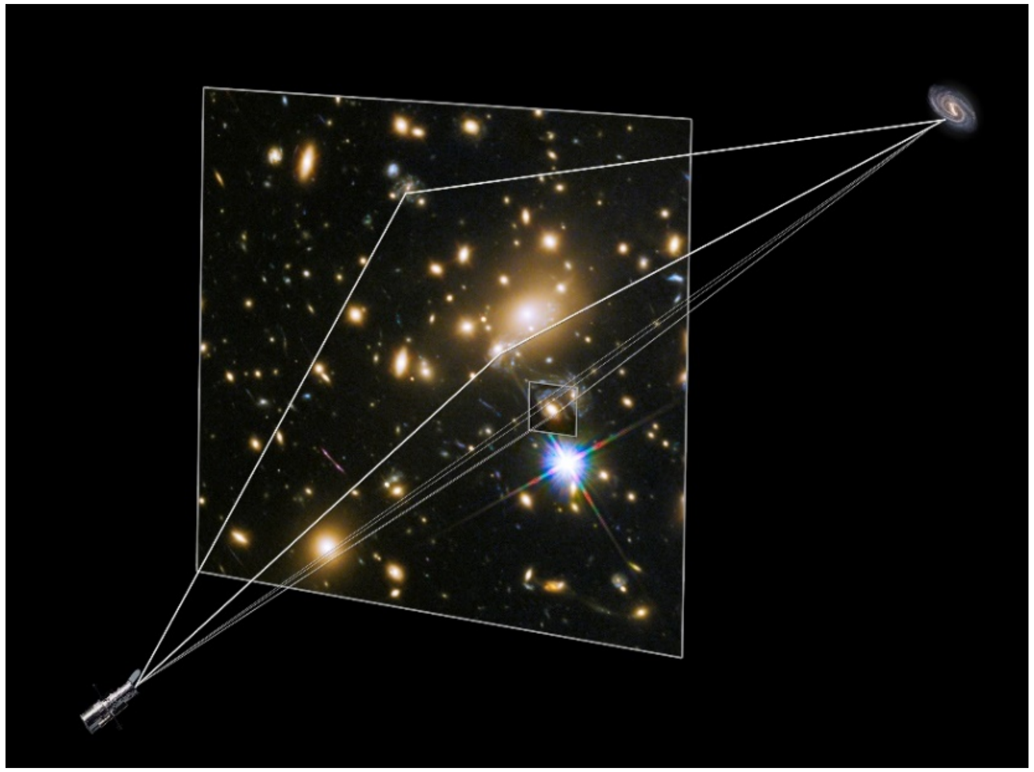
Galaxy rotation curve



Bullet cluster collision



CMB spectrum



Gravitational lensing

The Square Kilometre Array (SKA)

Early science observations are expected to start in 2021 with a partial array,
High sensitivity sub μJ

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

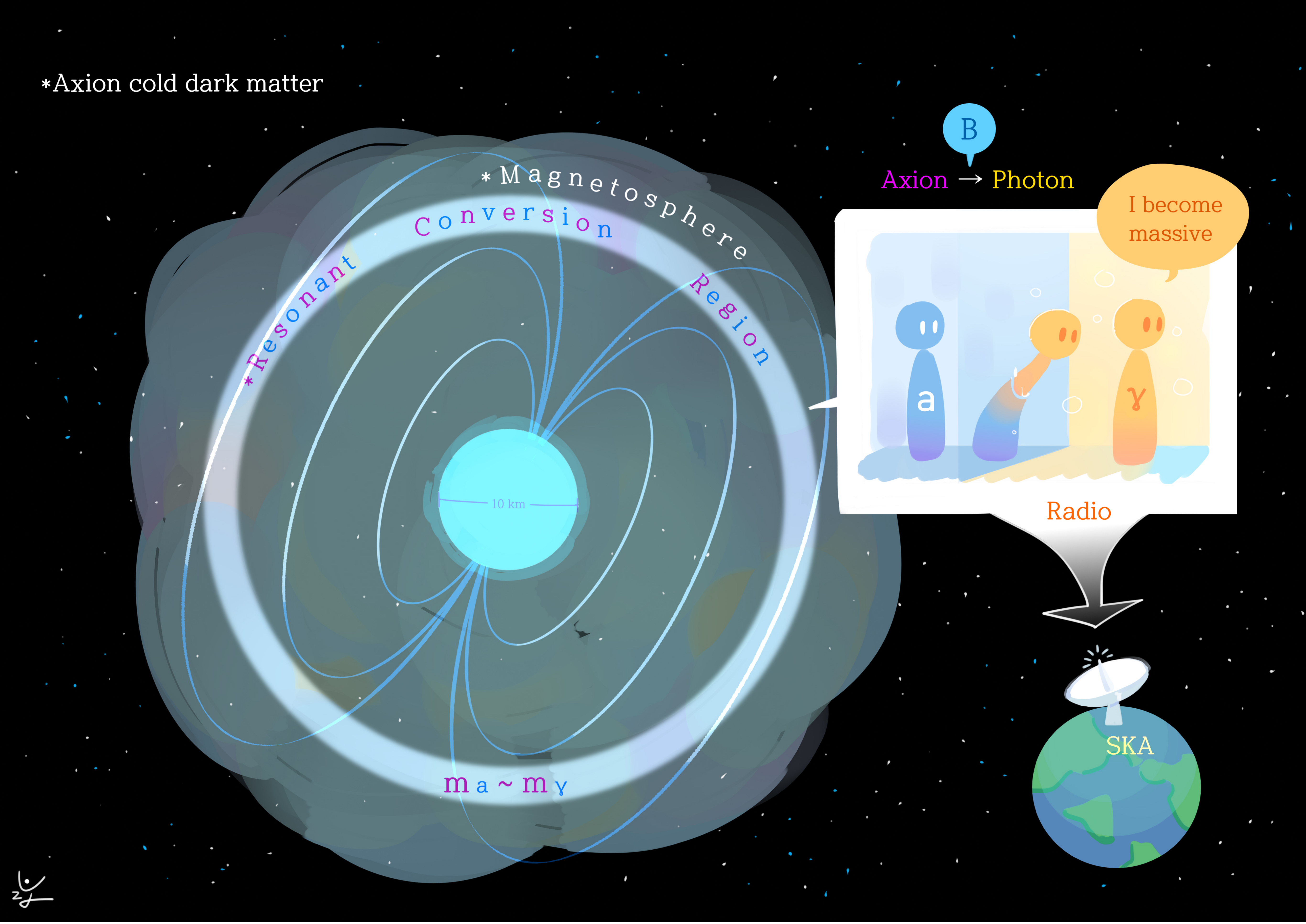
credit:GBT website

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

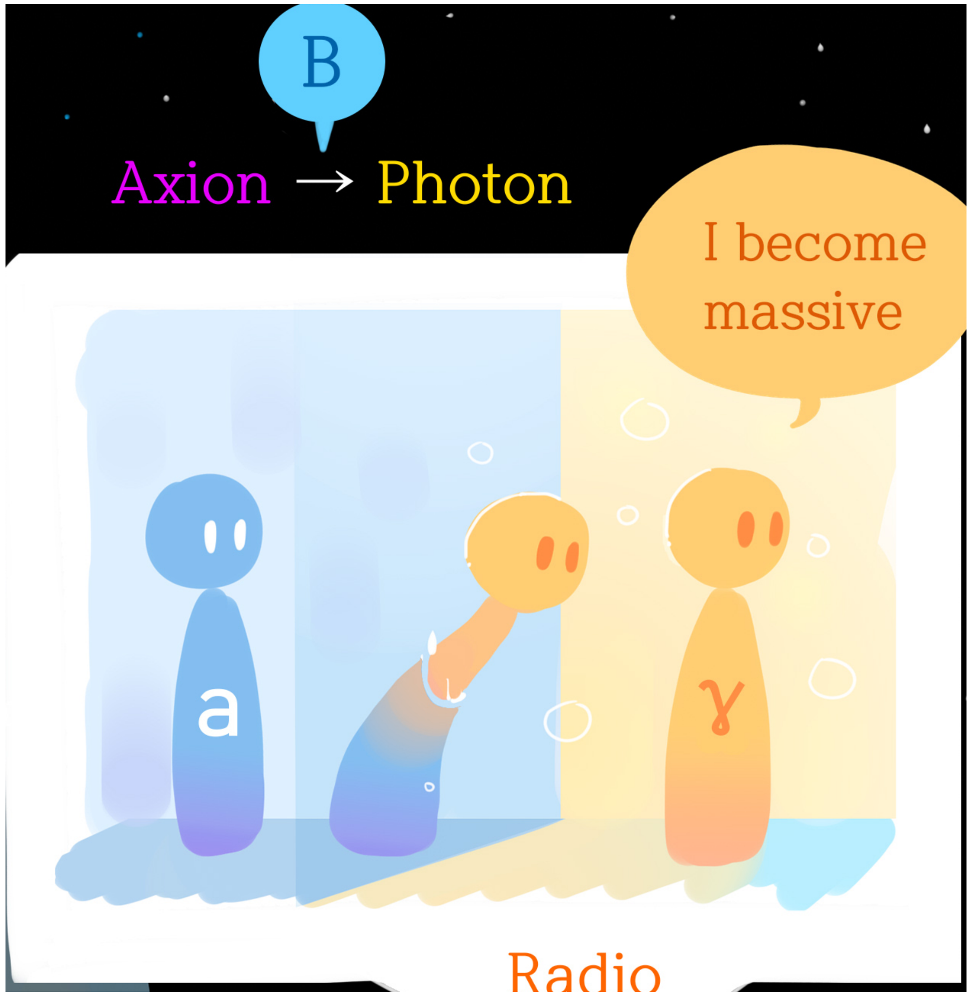
$$L_{\rm int} = \frac{1}{4} g \tilde{F}^{\mu\nu} F_{\mu\nu} a = -g\mathbf{E}\cdot\mathbf{B}a,$$

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

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

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

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.

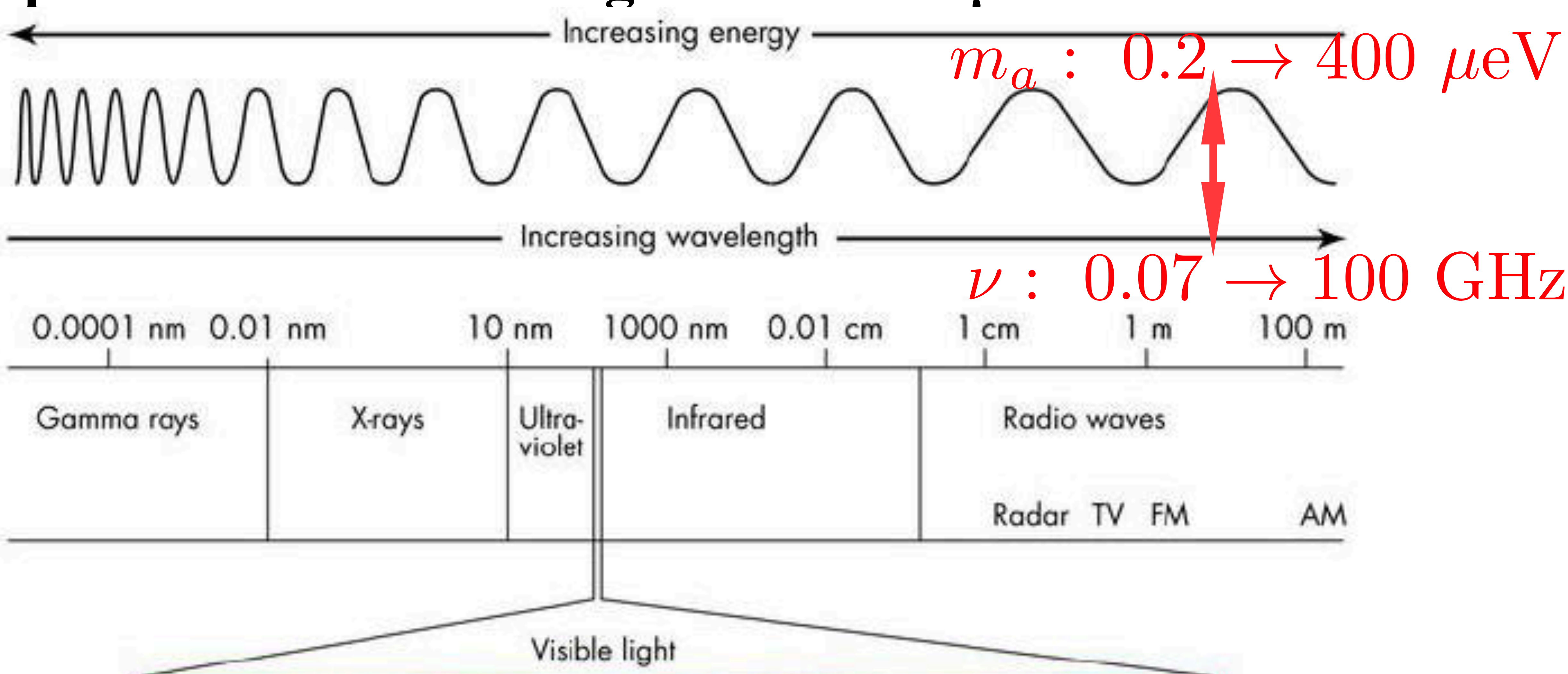
Radio Signal

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

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

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 $S_\gamma \sim 0.51\ \mu$Jy.

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.

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.

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

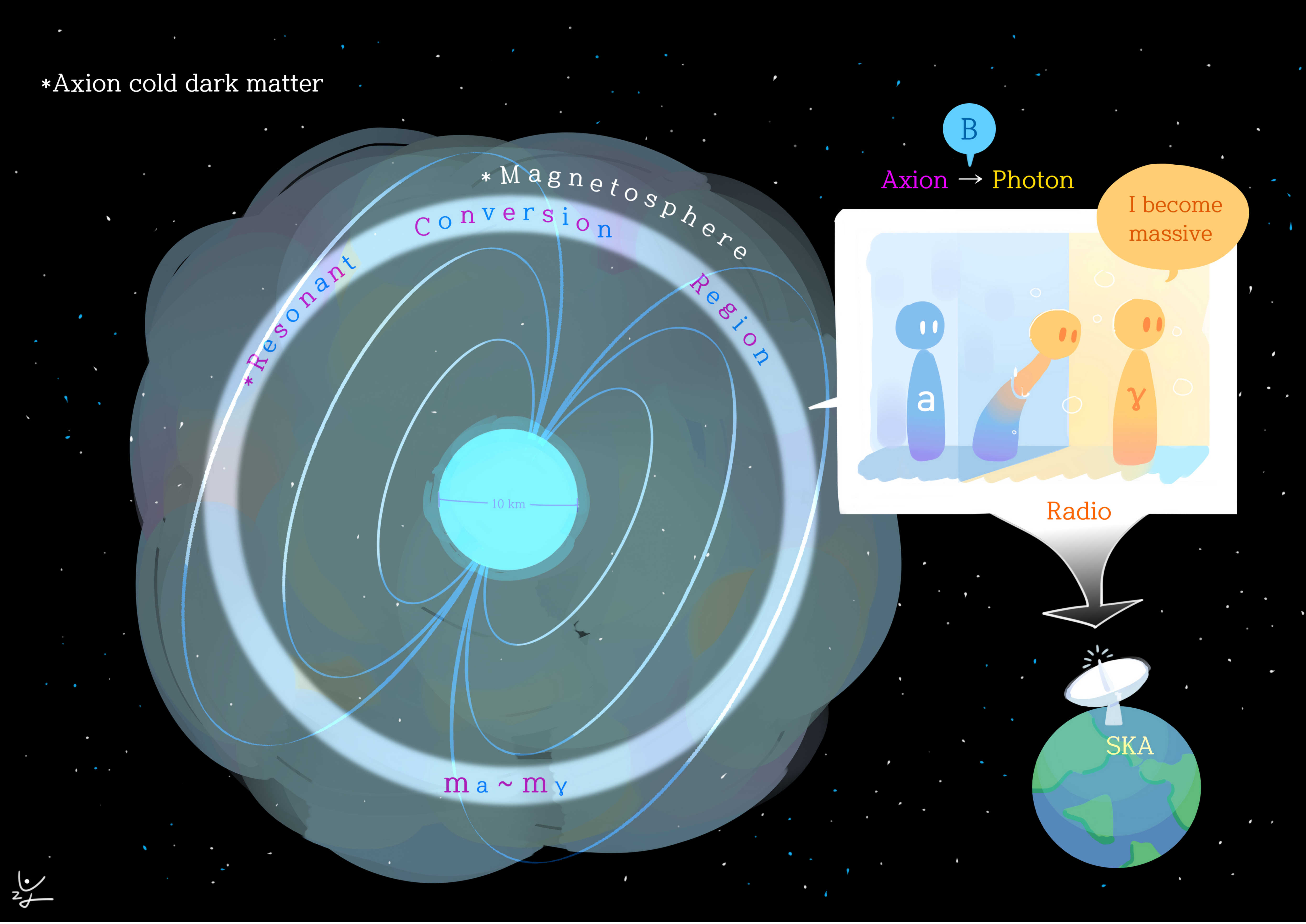
Radio searches for the conversion of axion/ALP dark matter into photons inside the magnetosphere of neutron stars can have sensitivity [630–632] for ALP masses in the range ~ 0.2–$40\,\mu$eV, and potentially above. The signature is the emission of a narrow radio line from individual neutron stars, with 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)

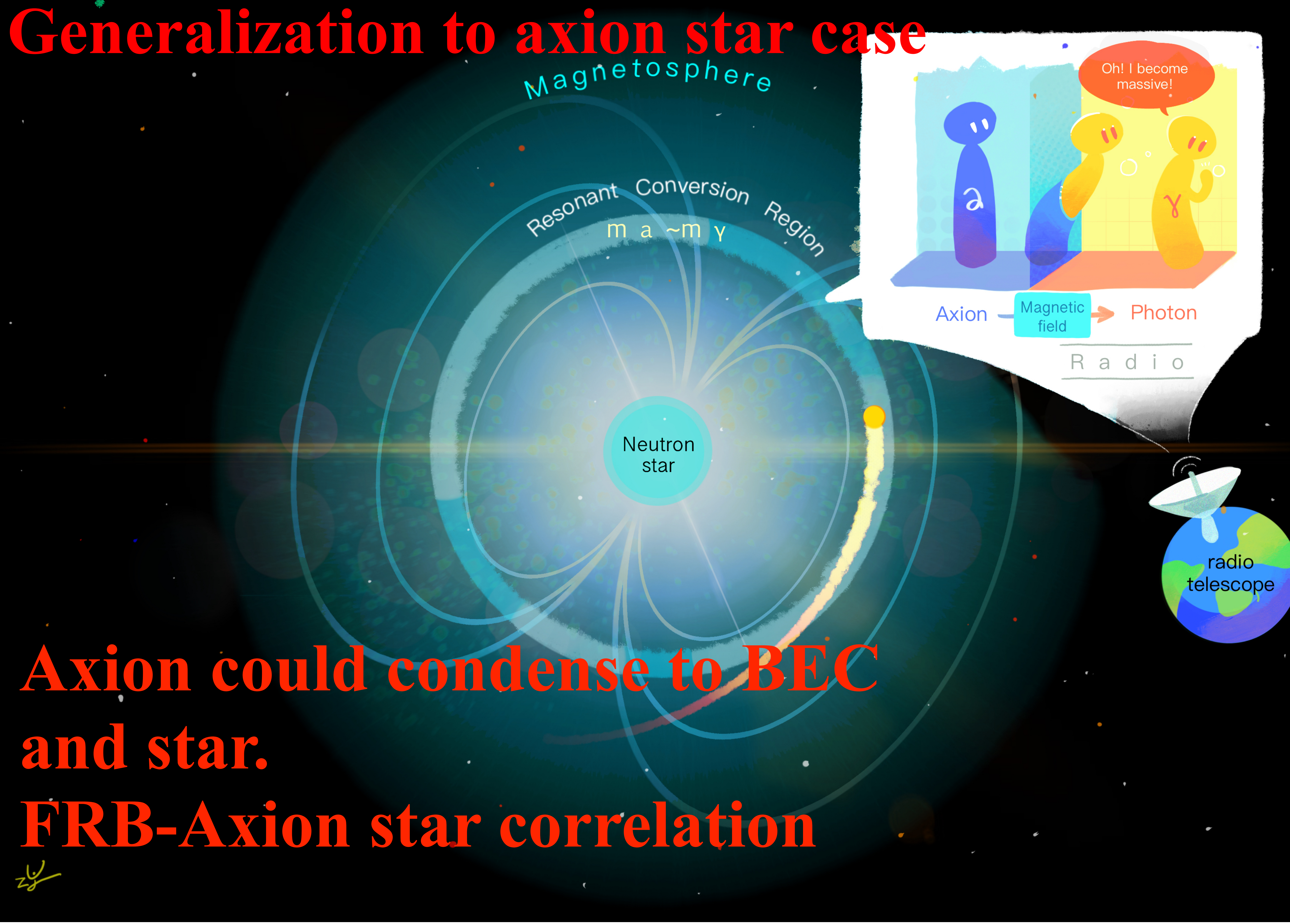
Published in: *Rev.Mod.Phys.* 93 (2021) 1, 015004 • e-Print: 2003.02206 [hep-ph]

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



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

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)**

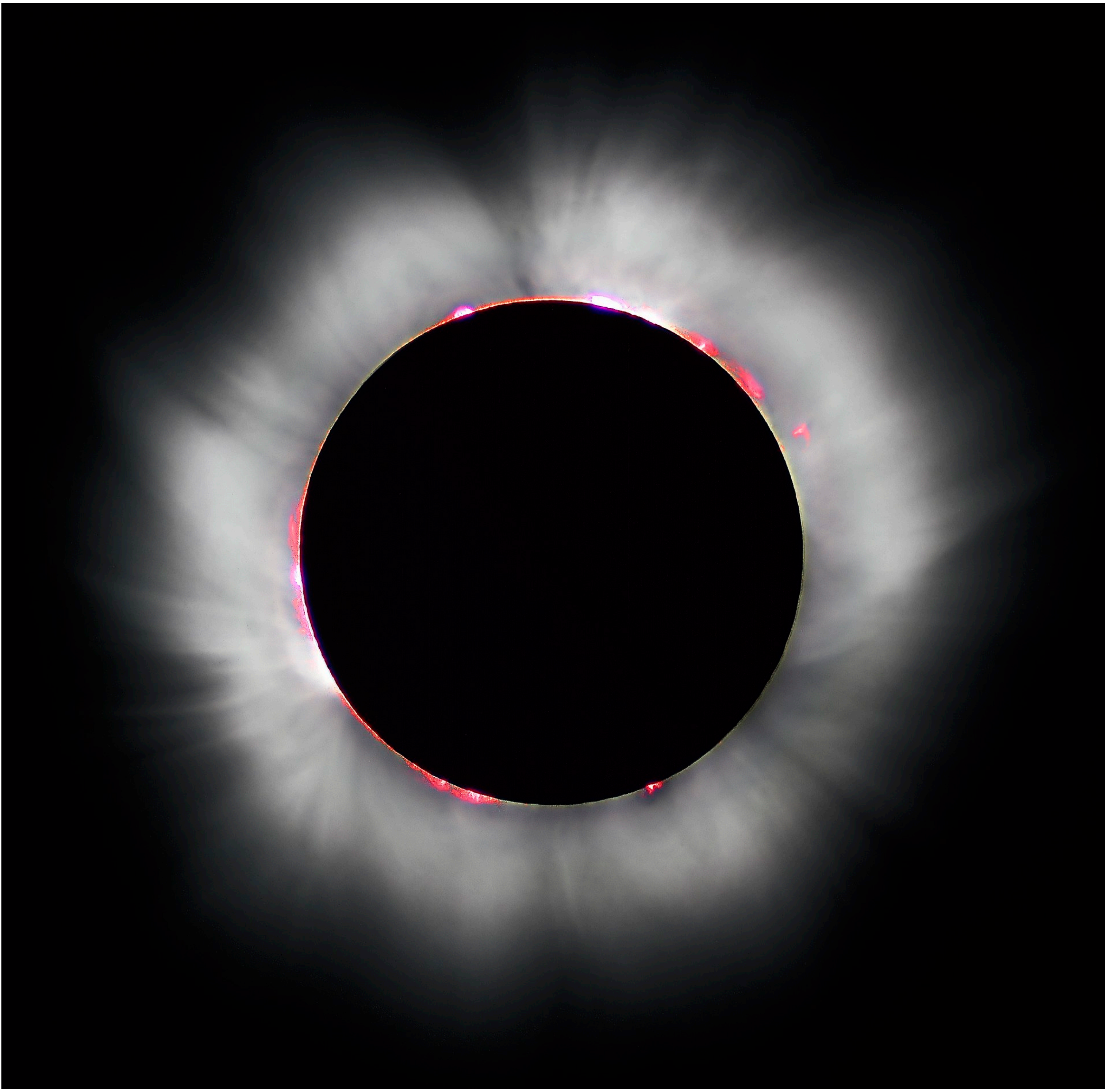
Recently, people realize light dark photon can be a promising DM candidate.

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.

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

Generalisation to dark photon DM case



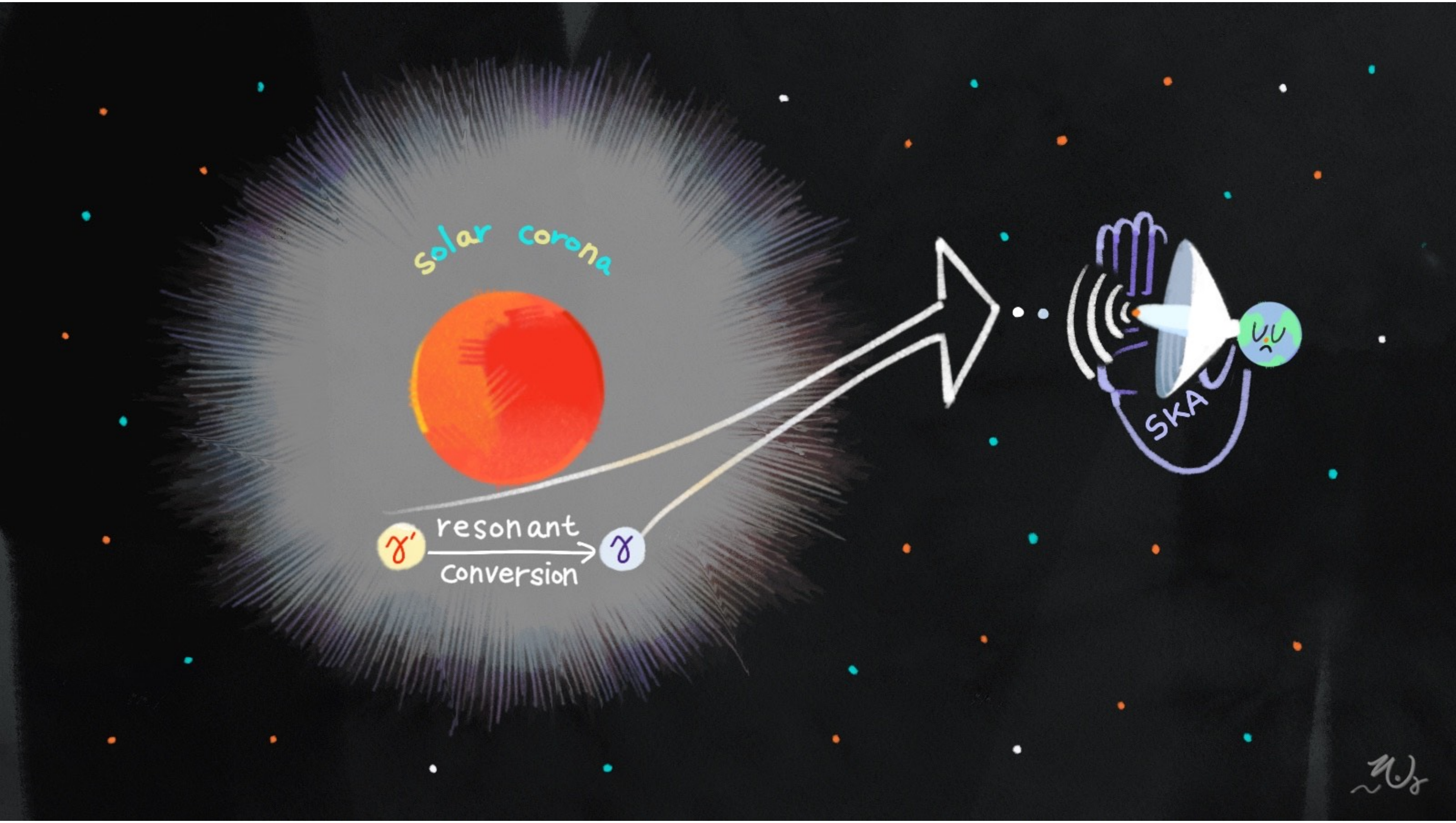
For dark photon DM， the resonant conversion could happen without magnetic field. We can directly study the resonant conversion process in the solar corona.

Two advantages: closer and larger conversion volume. Disadvantage: stronger background

During a total solar eclipse, the Sun's corona and prominences are visible to the naked eye.

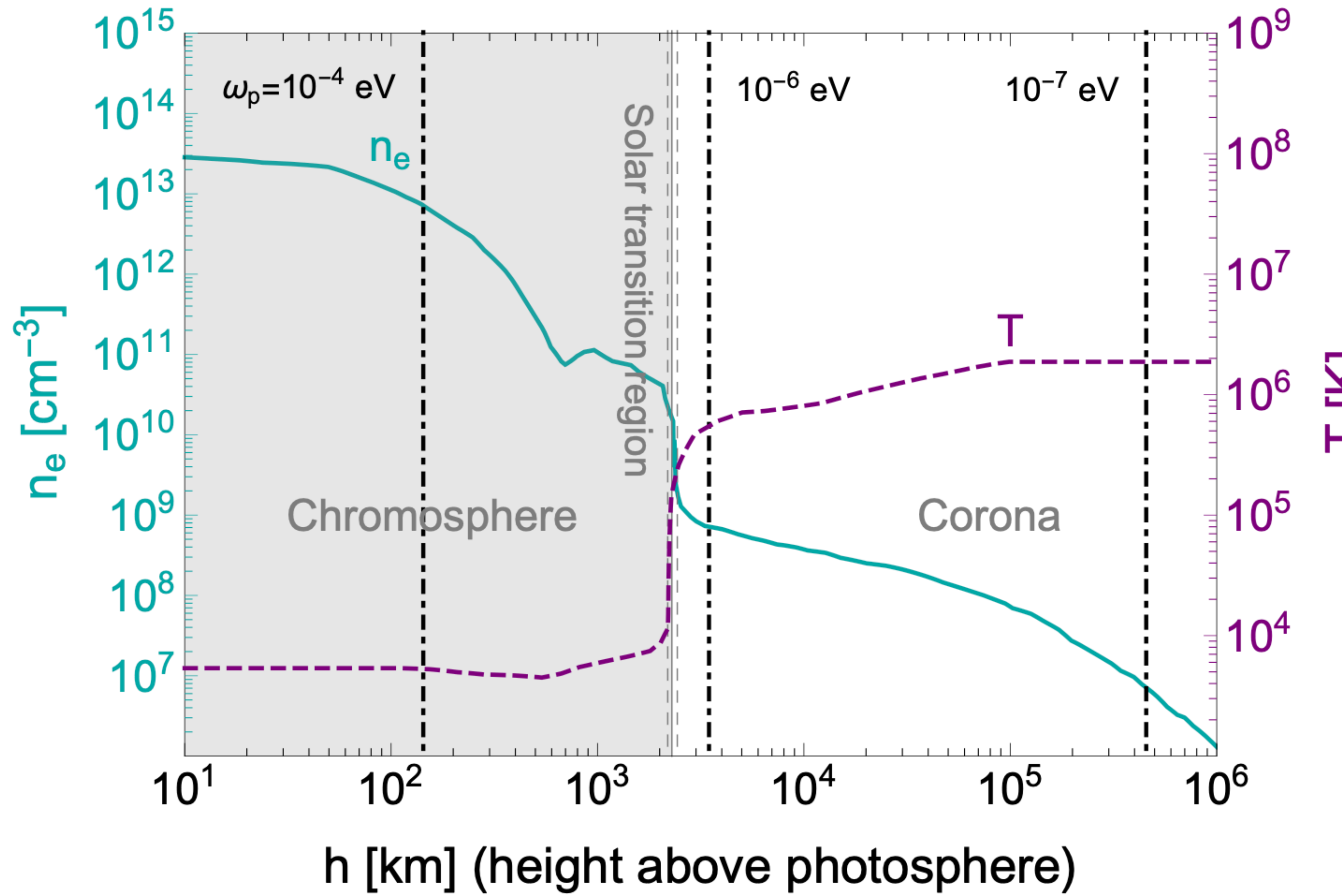
Resonant conversion process

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



Generalisation 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)**



Resonant production

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

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

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

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

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

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

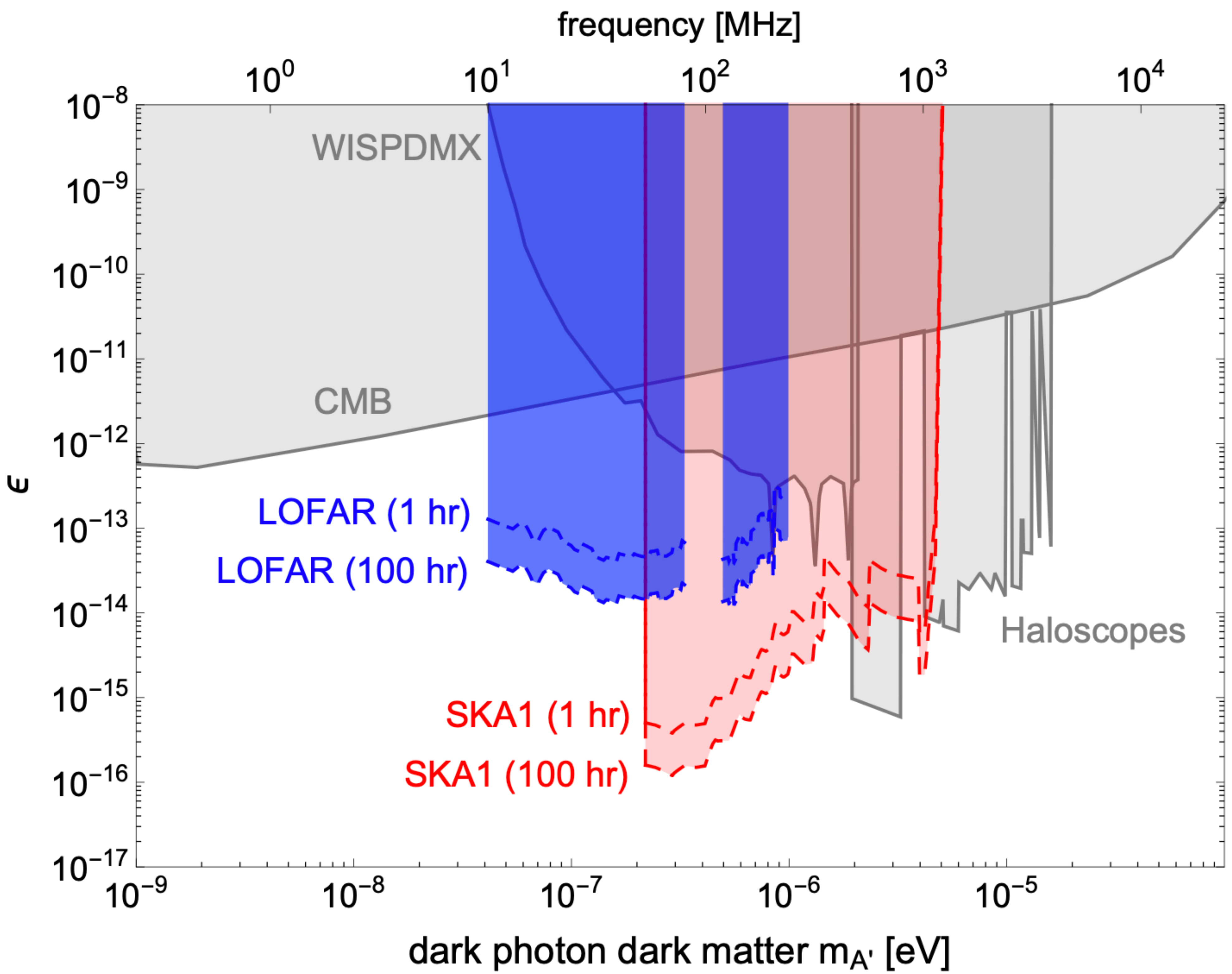
$$S_{\min} = \frac{\mathrm{SEFD}}{\eta_s \sqrt{n_{\mathrm{pol}}\, \mathcal{B}\, t_{\mathrm{obs}}}}$$

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

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 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:

TianQin@sysu.edu.cn

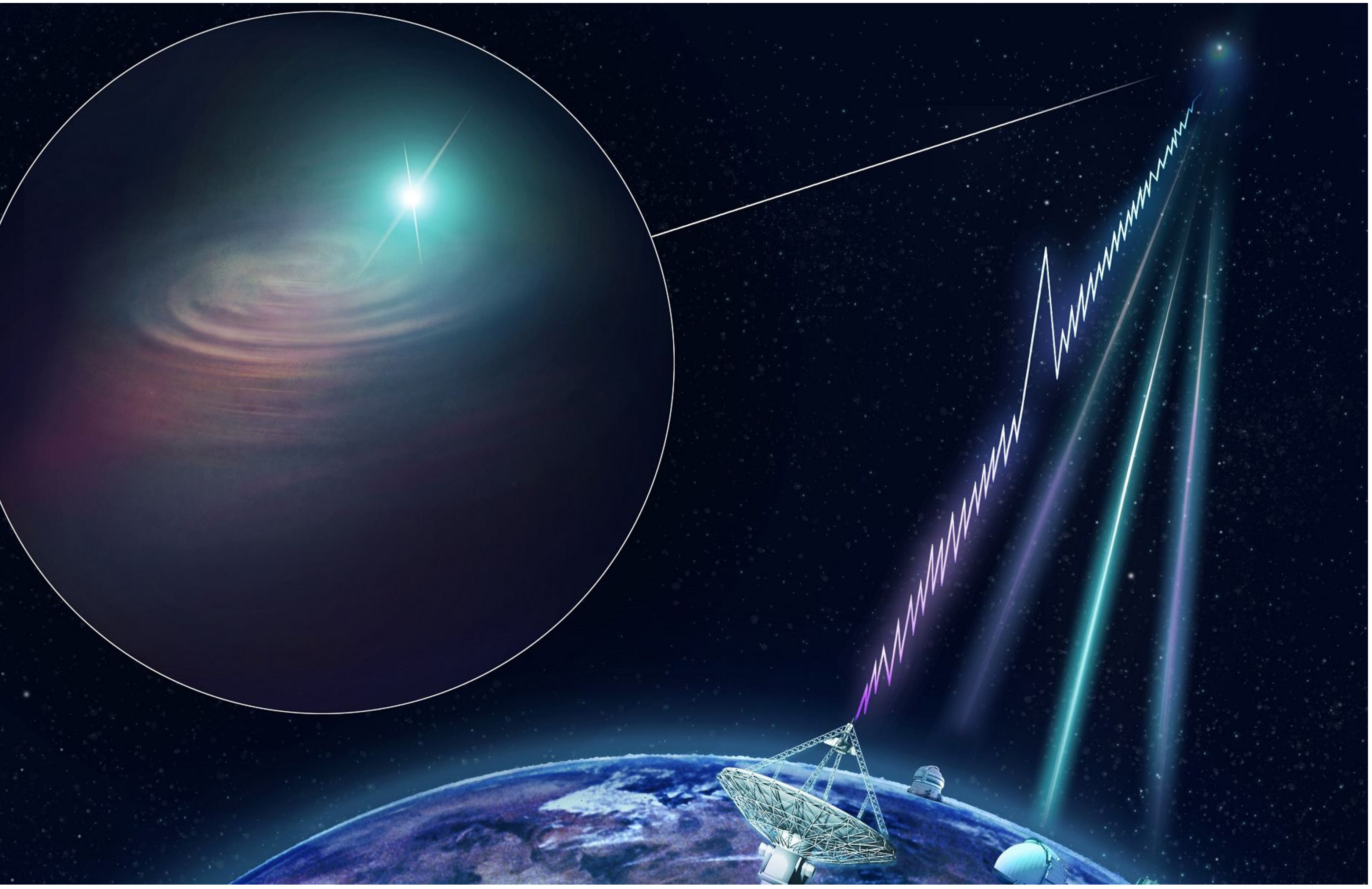
Or huangfp8@sysu.edu.cn

Final Remark:

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

Mysterious Fast Radio Bursts (FRBs)

In recent years, FRBs become the most mysterious phenomenon in astrophysics and cosmology, especially from 2013(D. Thornton, et al., (2013) Science, 341, 53). They are intense, transient radio signals with large dispersion measure, light years away. However, their origin and physical nature are still obscure.



$\mathcal{O}(0.1)$ to $\mathcal{O}(100)$ Jy

$\mathcal{O}(10^{38})$ to $\mathcal{O}(10^{40})$ erg

Duration: milliseconds

$$0.1 \lesssim z \lesssim 2.2$$

We focus on FRBs events with frequency range 800 MHz to 1.4GHz mainly observed by Parkes, ASKAP, and UTMOST.

We do not include other non-repeating FRBs with frequencies lower than 800 MHz, like the events from CHIME and Pushchino, which may be better explained by a lighter axion or other sources.

From Universe Today

FRB-Axion star correlation

A collection of axions can condense into a bound Bose-Einstein condensate called an axion star. The typical axion star mass is $10^{-13} M_\odot$

The fact that the energy released by FRBs is close to $10^{-13} M_\odot$ **, which is the typical axion star mass, and that their frequency (several hundred MHz to several GHz) coincides with that expected from** μ**eV axion, motivates us to further explore the axion-FRB connection can be made viable in a pulsar magnetosphere and tested with the future data.**