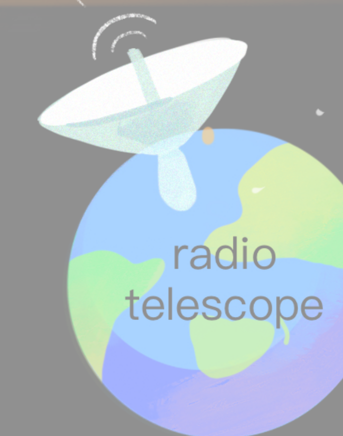
Fast Radio Bursts from Axion Star



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based on the work with James H. Buckley, P. S. Bhupal Dev, Francesc Ferrer, arXiv:2004.06486

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Outline

- ➢**Research motivation, Fast Radio Bursts and axion star**

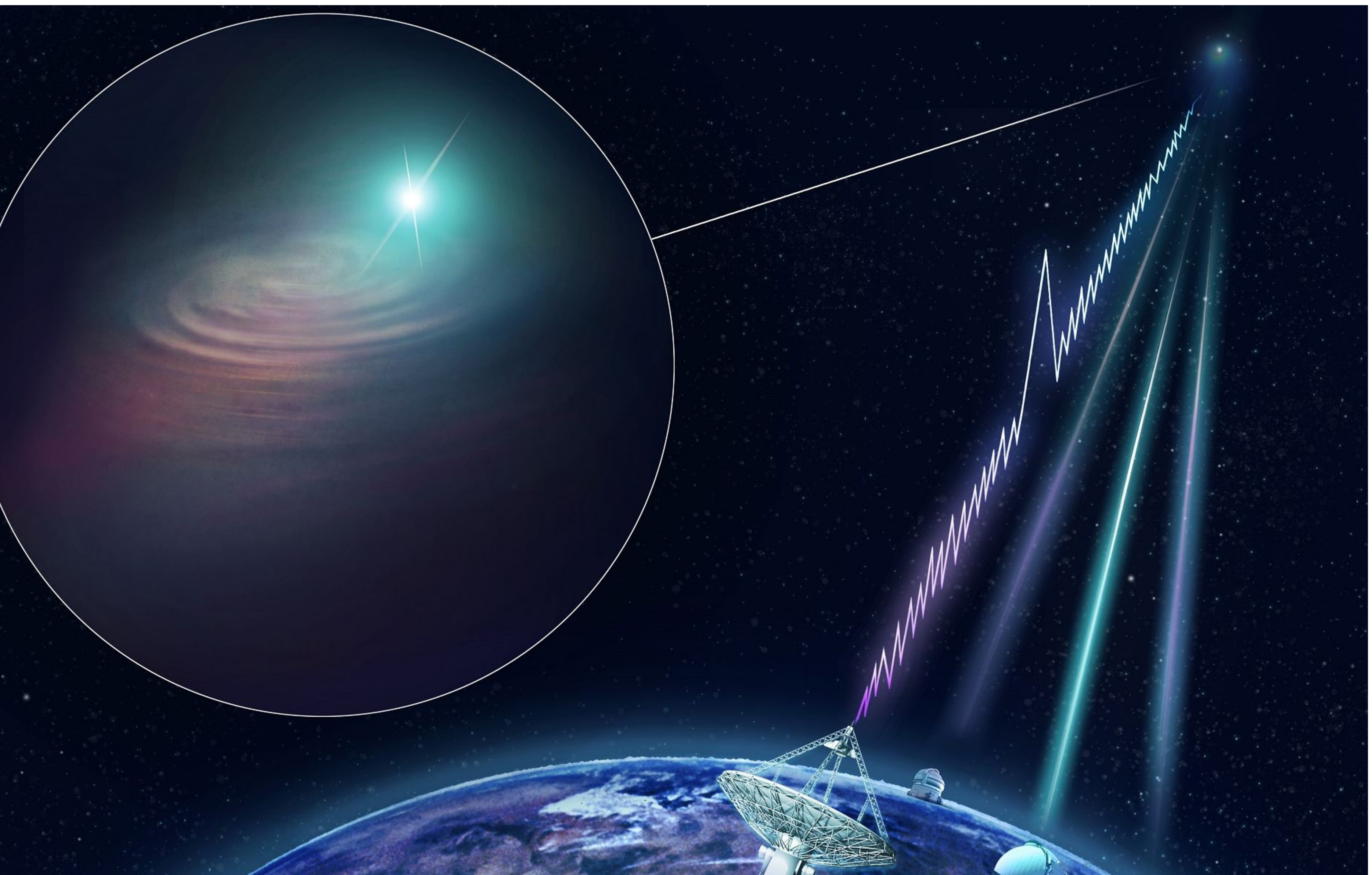
- ➢**Fast radio bursts from axion stars moving through pulsar magnetospheres**

- ➢**Summary and outlook**

Motivation: FRBs

In recent ten years, Fast Radio Bursts (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

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

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 particles, motivates us to further explore whether the axion-FRB connection can be made viable in a pulsar magnetosphere and tested with the future data.**

Axion star-Neutron star encounter

Dilute axion star is balanced by kinetic pressure and self-gravity, with the following radius

$$R_a^{\rm dilute} \sim \frac{1}{G_N M_a m_a^2} \cong 270 \left(\frac{10\ \mu{\rm eV}}{m_a}\right)^2 \left(\frac{10^{-12} M_\odot}{M_a}\right)\ {\rm km}$$

In this work, we assume that dense axion stars with a mass around $10^{-13} M_\odot$ can survive to the present, and have a chance to encounter a neutron star. The radius of a dense axion star is

$$R_a^{\rm dense} \sim 0.47 \sqrt{g_{a\gamma\gamma} \times 10^{13}\ {\rm GeV}} \times \sqrt{\frac{10\ \mu{\rm eV}}{m_a}} \left(\frac{M_a}{10^{-13} M_\odot}\right)^{0.3}\ {\rm m}$$

Tidal effects

A gravitationally bound object approaching a star closer than Roche limit will be disrupted by tidal effects. The Roche limit is

$$r_t = R_a \left(\frac{2M_{\rm NS}}{M_a} \right)^{1/3}$$

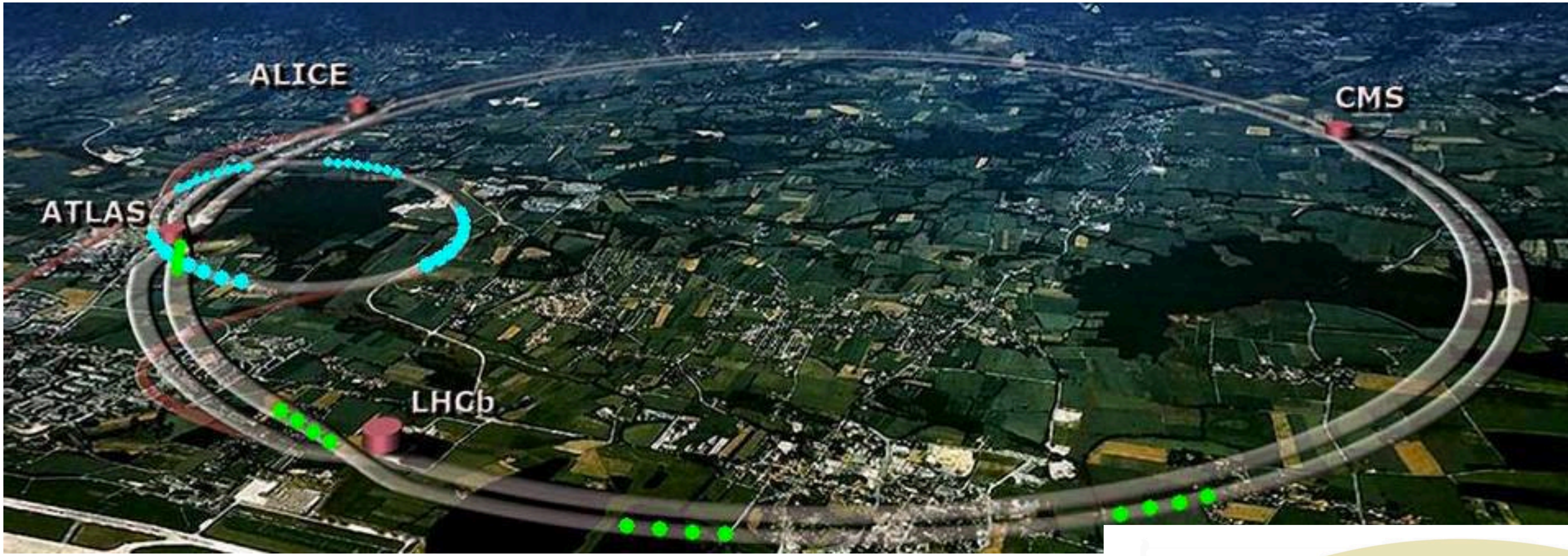
Tidal disruption may quickly rip apart the dilute axion star, producing a stream of axion debris, long before a dilute axion star enters the magnetosphere of neutron star. For100 km dilute axion, the Roche limit is about 10^6 km.

For a dense axion star, the radius is smaller than 1m and the Roche limit is below 10 km. Thus, a dense axion star can reach the resonant conversion region without being tidally ripped.

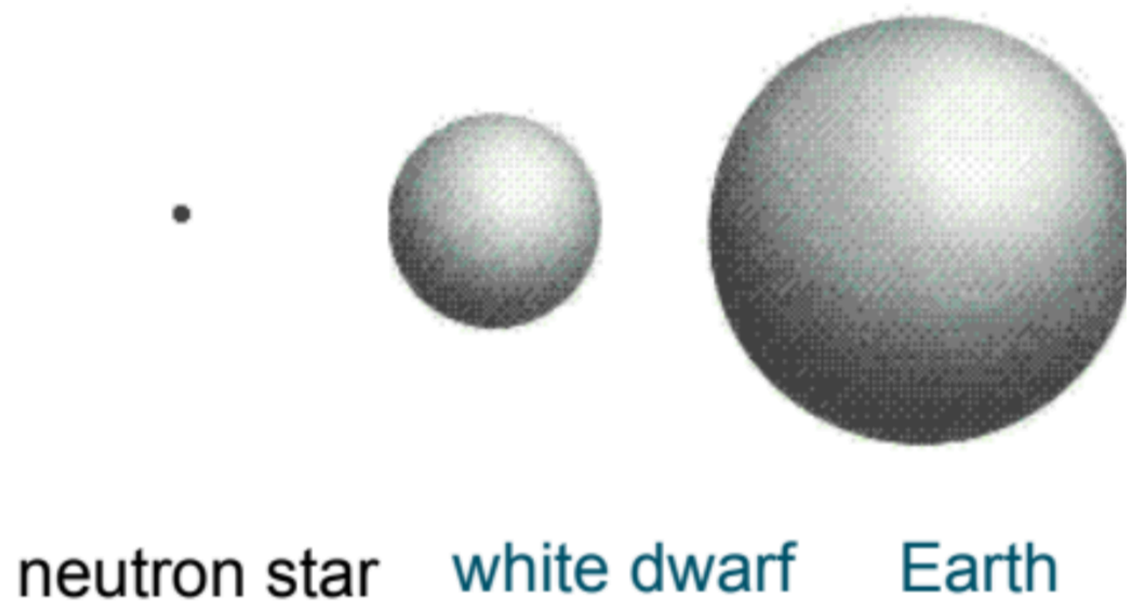
tidal deformation ratio

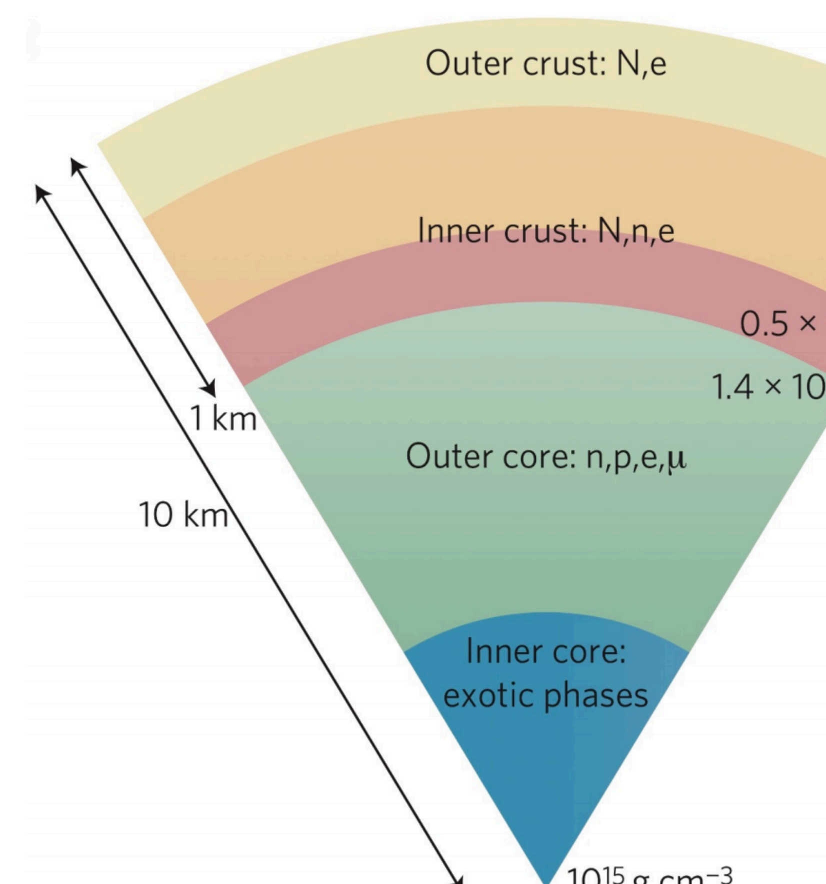
$$\frac{\delta R_a}{R_a} = \frac{9M_{\rm NS}}{8\pi\rho_{\rm AS} r^3}$$

Quick sketch of the neutron star size

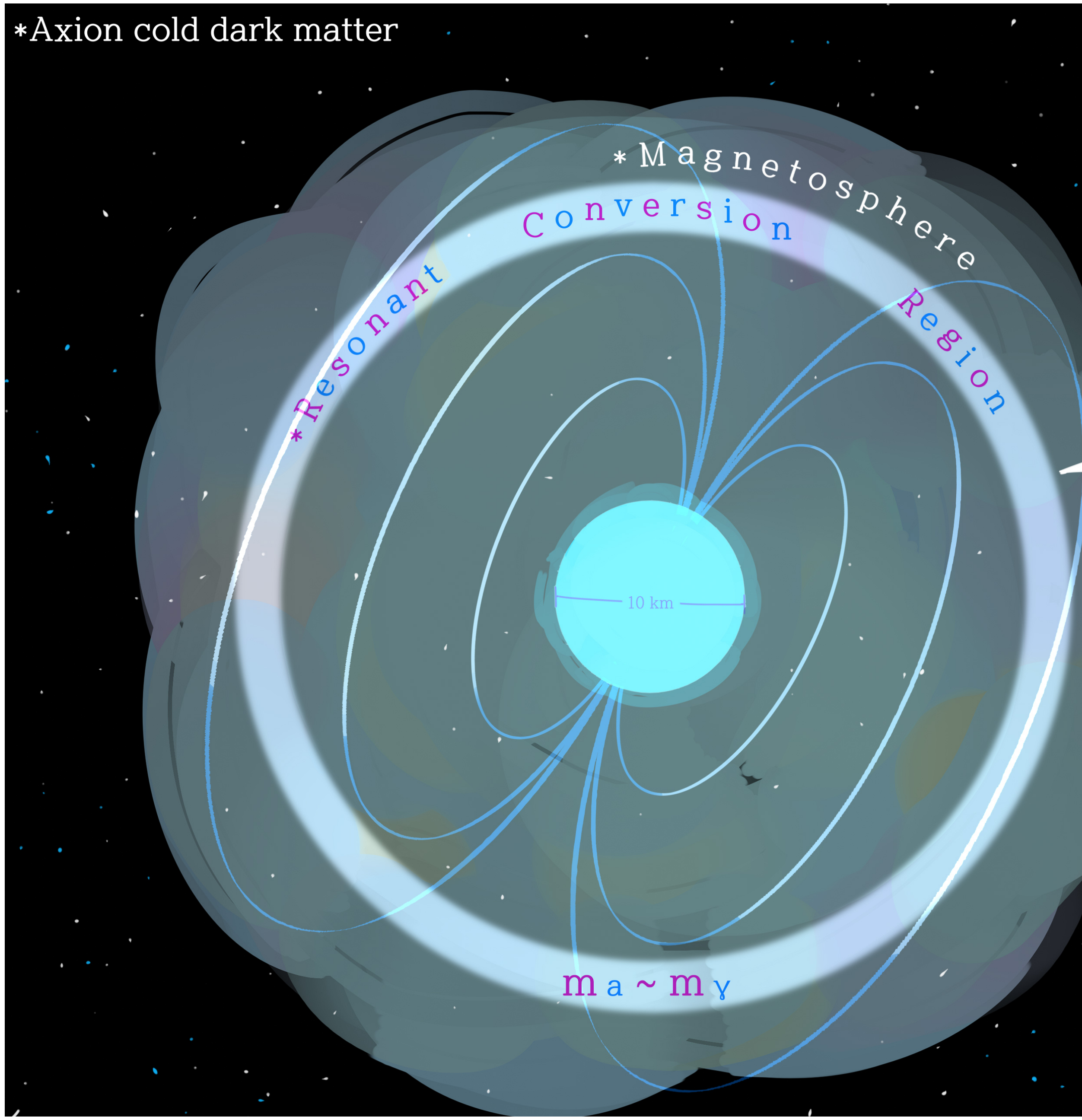


Radius of the neutron star is slightly larger than the radius of the LHC circle.





Strong magnetic field in the magnetosphere of Neutron star, Pulsar, Magnetar: the strongest magnetic field in the Universe



1. **Mass: from 1 to 2 solar mass**

2. **Radius:** $r_0 \sim 10 - 20\text{km}$

   The typical diameter of neutron star is just half-Marathon.

3. **Strongest magnetic field at the surface of the neutron star**

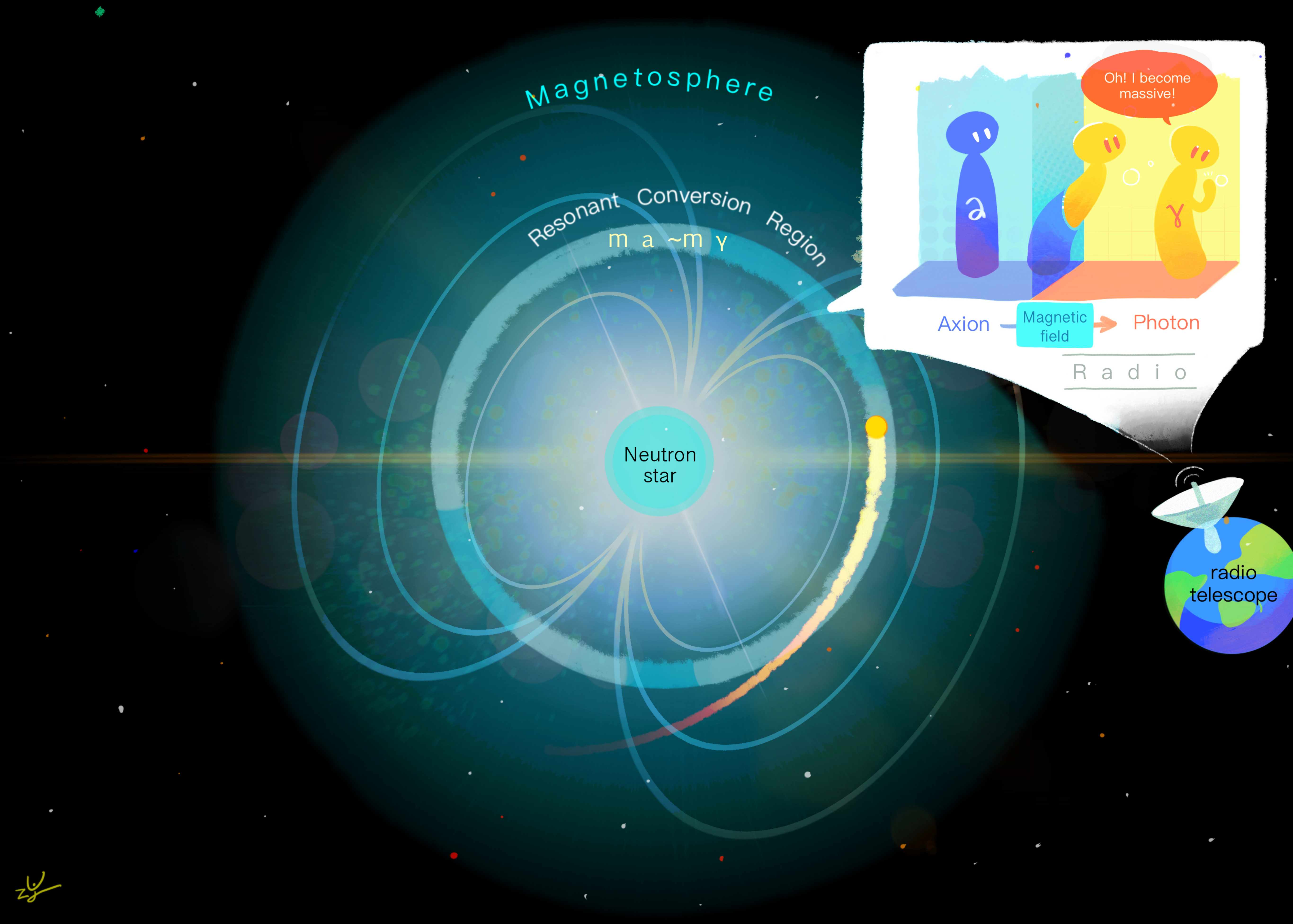
$$B_0 \approx 10^{12} - 10^{15}\text{G}$$

$$B_0 \sim 3.3 \times 10^{19}\sqrt{P\dot{P}} \quad \text{G}$$

P is the period of neutron star

4. **Neutron star is surrounded by large region of magnetosphere, where photon becomes massive.**

Alfven $r \sim 100 r_0$



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Axion-photon conversion in magnetosphere

The Lagrangian for axion-photon conversion the magnetosphere

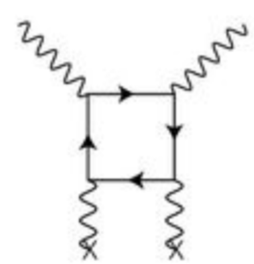
$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 a^2) + L_{\rm int} + L_{\rm QED}$$

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

$$L_{\rm QED} = \frac{\alpha^2}{90 m_e^4}\frac{7}{4}(F_{\mu\nu}\tilde{F}^{\mu\nu})^2 + \ldots$$

$$m_\gamma^2 = Q_{\rm pl} - Q_{\rm QED}$$

$$Q_{\rm QED} = \frac{7\alpha}{45\pi}\omega^2\frac{B^2}{B_{\rm crit}^2}$$



$$Q_{\rm plasma} = \omega_{\rm plasma}^2 = 4\pi\alpha\frac{n_e}{m_e}$$

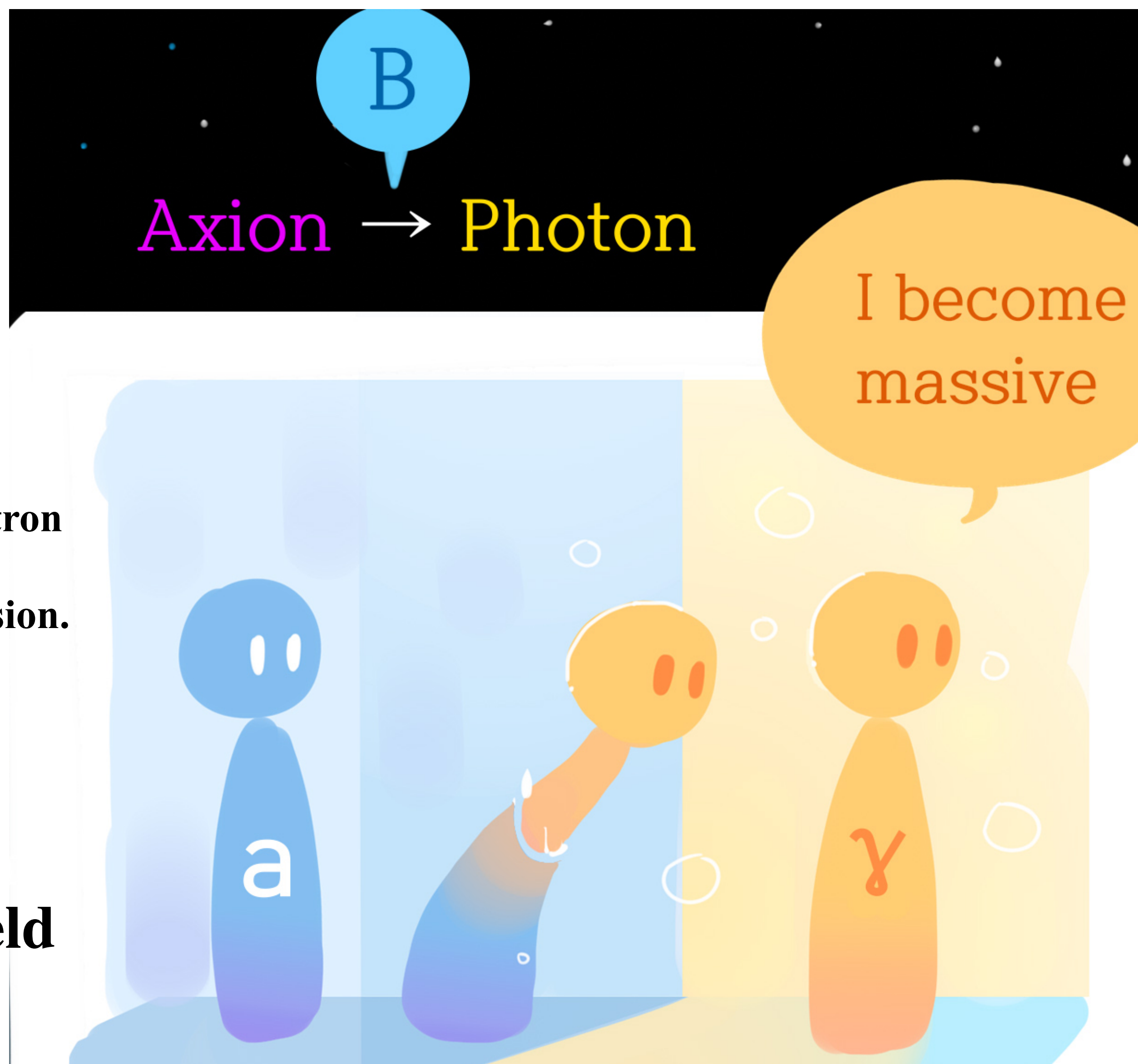
$$\frac{Q_{\rm pl}}{Q_{\rm QED}} \sim 5\times 10^8\left(\frac{\mu{\rm eV}}{\omega}\right)^2 \frac{10^{12}\ {\rm G}}{B}\frac{1\ \ {\rm sec}}{P}$$

For relativistic axion from neutron star, QED mass dominates and there is no resonant conversion.

$$\mathcal{L} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu}\tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E}\cdot\vec{B}$$

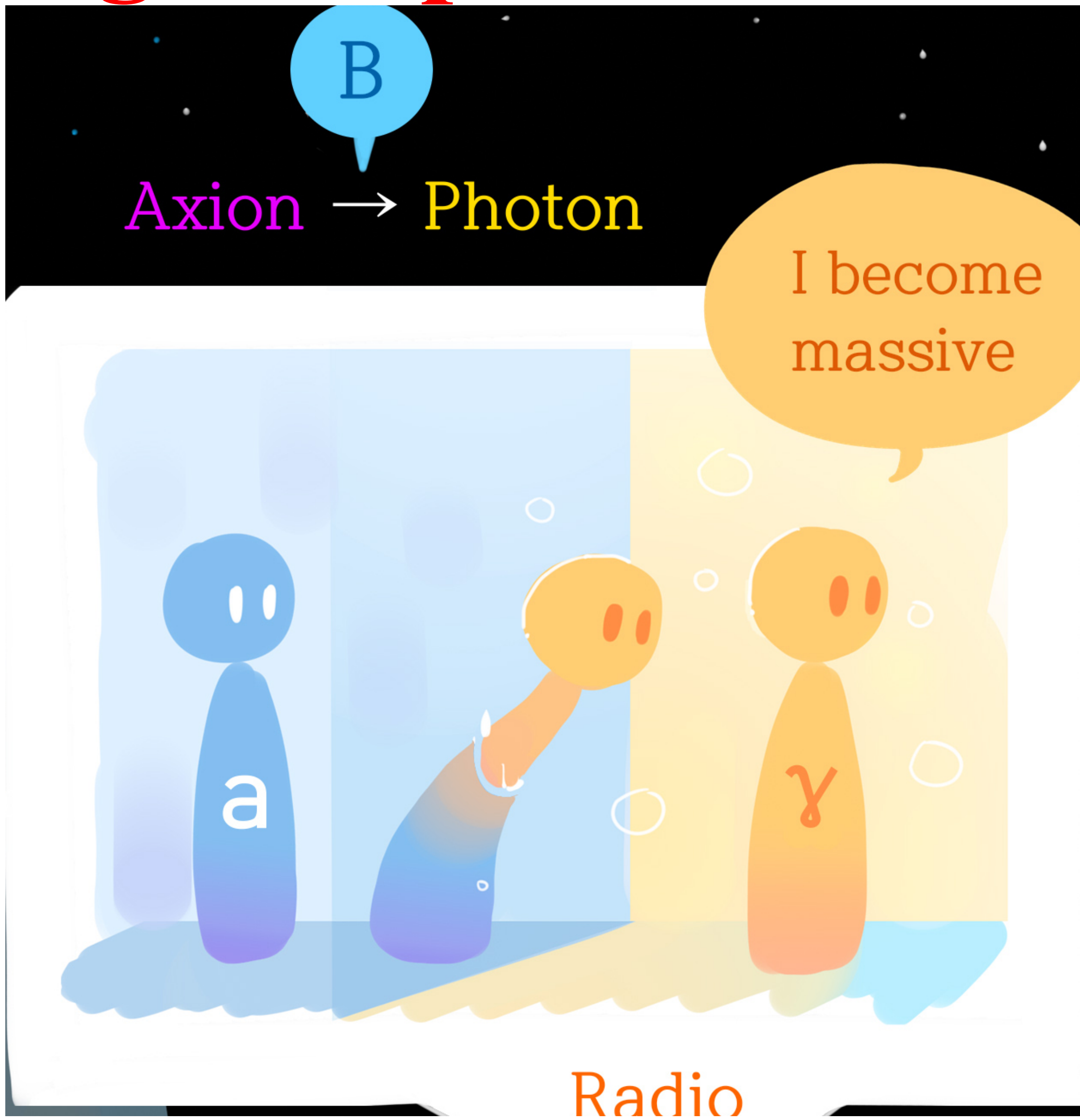
Axion-photon conversion in external magnetic field

G. Raffelt and L. Stodolsky, Phys. Rev. D 37, 1237 (1988)



Axion-photon conversion in magnetosphere

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



$$m_\gamma(r) = \omega_p = \sqrt{\frac{e^2 n_e}{m_e}} = \sqrt{\frac{n_e}{7.3\times 10^8\ \mathrm{cm}^{-3}}}\ \mu\mathrm{eV}$$

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

$$B(r) = B_0\left(\frac{r_{\mathrm{NS}}}{r}\right)^3$$

Here, we choose the simplest electron density distribution and magnetic field configuration to clearly see the physics process.

Thus, the photon mass is position r dependent, and within some region the photon mass is close to the axion mass.

The Non-adiabatic Resonant Conversion

In the resonant conversion region, the photon effectively has almost the same mass as the axion due to plasma effects:

$$\left(\frac{r_{\rm NS}}{r_c}\right)^3 \sim \left(\frac{m_a}{\mu{\rm eV}}\right)^2 \frac{10^{10}\ {\rm G}}{B_0} \frac{P}{1\ {\rm s}} \qquad \left.\frac{{\rm d}\omega_p^2}{{\rm d}r}\right|_{r=r_c} = \left.\frac{3\omega_p^2}{r}\right|_{r=r_c}$$

Landau-Zener probability:

$$P_{a\to\gamma} = 1 - e^{-2\pi\beta}.$$

The non-adiabatic limit corresponds to small β, and we have $P_{a\to\gamma} \approx 2\pi\beta$ with

$$\beta = \left.\frac{\left(g_{a\gamma\gamma}\omega B_0\right)^2 / 2\bar{k}}{\left|{\rm d}\omega_p^2/{\rm d}r\right|}\right|_{r=r_c}.$$

$\mathcal{FRBs}$

Signal: For resonant conversion the radiated power is

$$\dot{W} \sim \left(\frac{M_a}{10^{-13} M_\odot}\right) \left(10^7 \times P_{a\to\gamma}\right) \left(10^{44}\ \mathrm{GeV \cdot s^{-1}}\right)$$

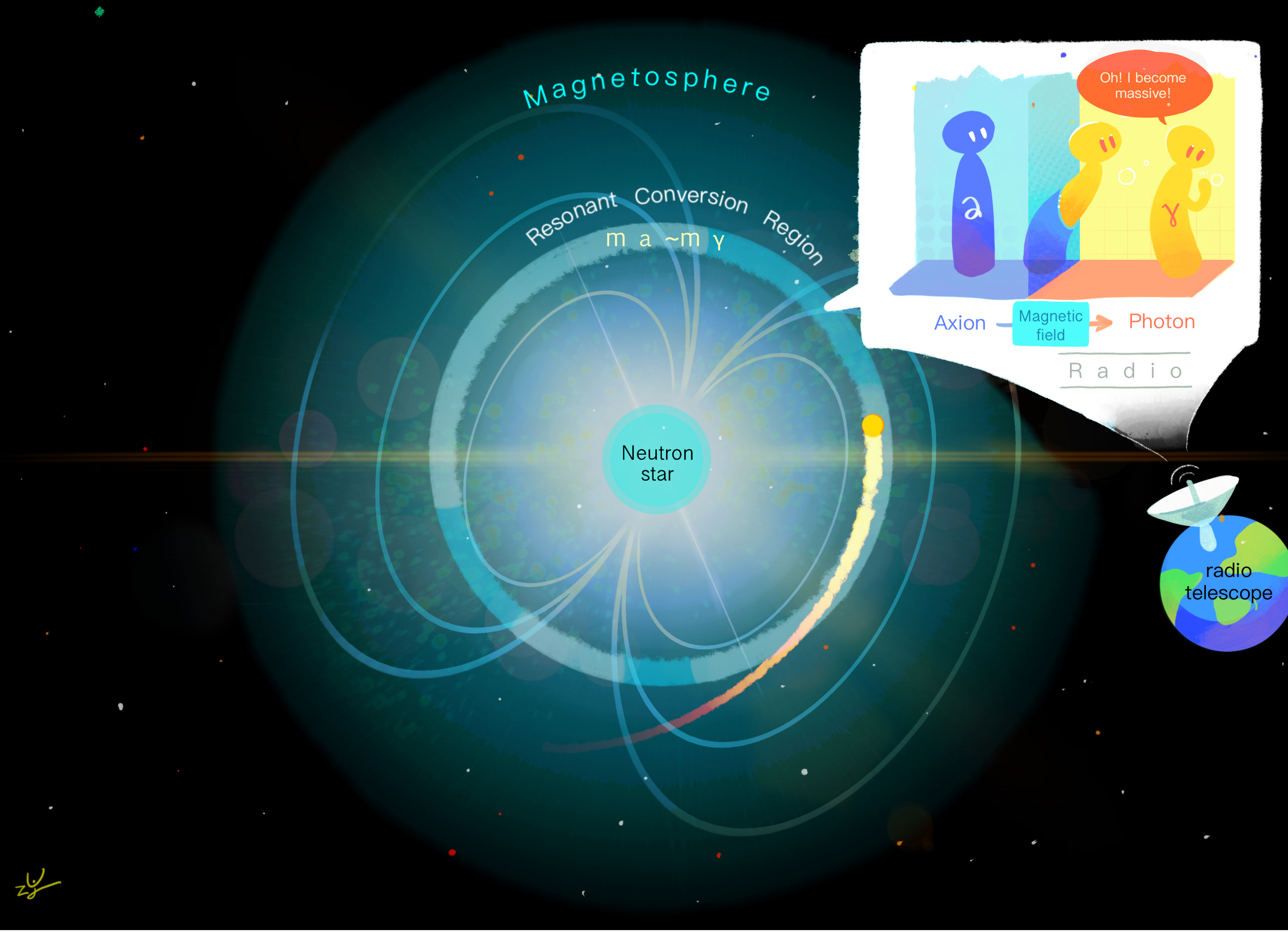
$$\mathrm{FRBs},\ \dot{W} \sim 10^{44}\ \mathrm{GeV \cdot s^{-1}}$$

$$\mathcal{S} = \frac{\dot{W}}{4\pi d^2 \Delta B} \qquad \frac{E_{\mathrm{FRB}}}{\mathrm{J}} = \frac{F_{\mathrm{obs}}}{\mathrm{Jy \cdot ms}} \frac{\Delta B}{\mathrm{Hz}} \left(\frac{d}{\mathrm{m}}\right)^2 \times 10^{-29} (1+z)$$

For the benchmark values $m_a = 10\ \mu\mathrm{eV}$, $M_a = 10^{-13} M_\odot$, $g_{a\gamma\gamma} = 10^{-13}\ \mathrm{GeV}^{-1}$ we can naturally explain **FRBs.**

Sensitivity: The smallest detectable flux density of the radio telescope is of order, taking SKA as example

$$S_{\mathrm{min}} \approx 0.09\ \mathrm{Jy} \left(\frac{1\ \mathrm{MHz}}{\Delta B}\right)^{1/2} \left(\frac{1\ \mathrm{ms}}{t_{\mathrm{obs}}}\right)^{1/2} \left(\frac{10^3 \mathrm{m}^2/\mathrm{K}}{A_{\mathrm{eff}}/T_{\mathrm{sys}}}\right)$$



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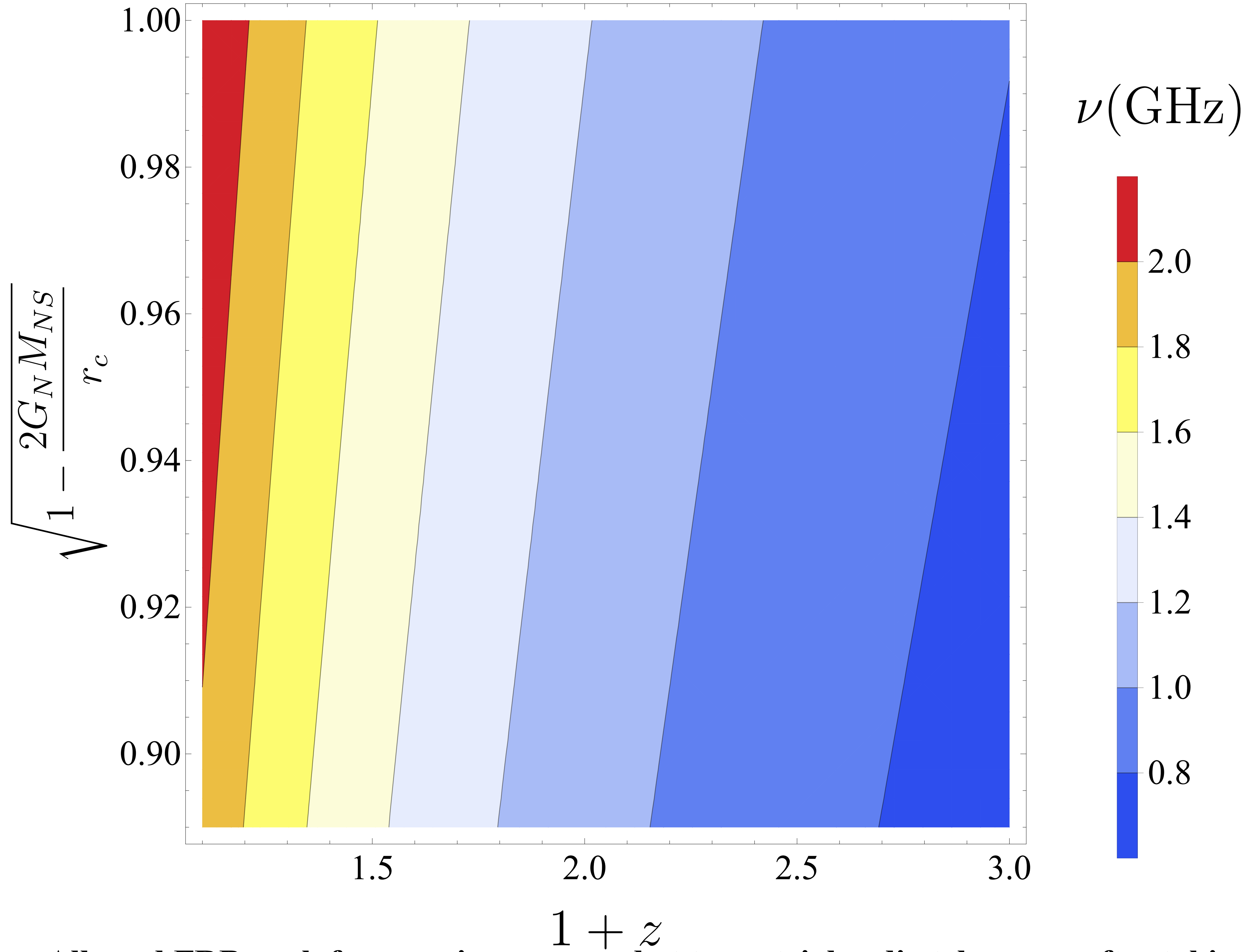
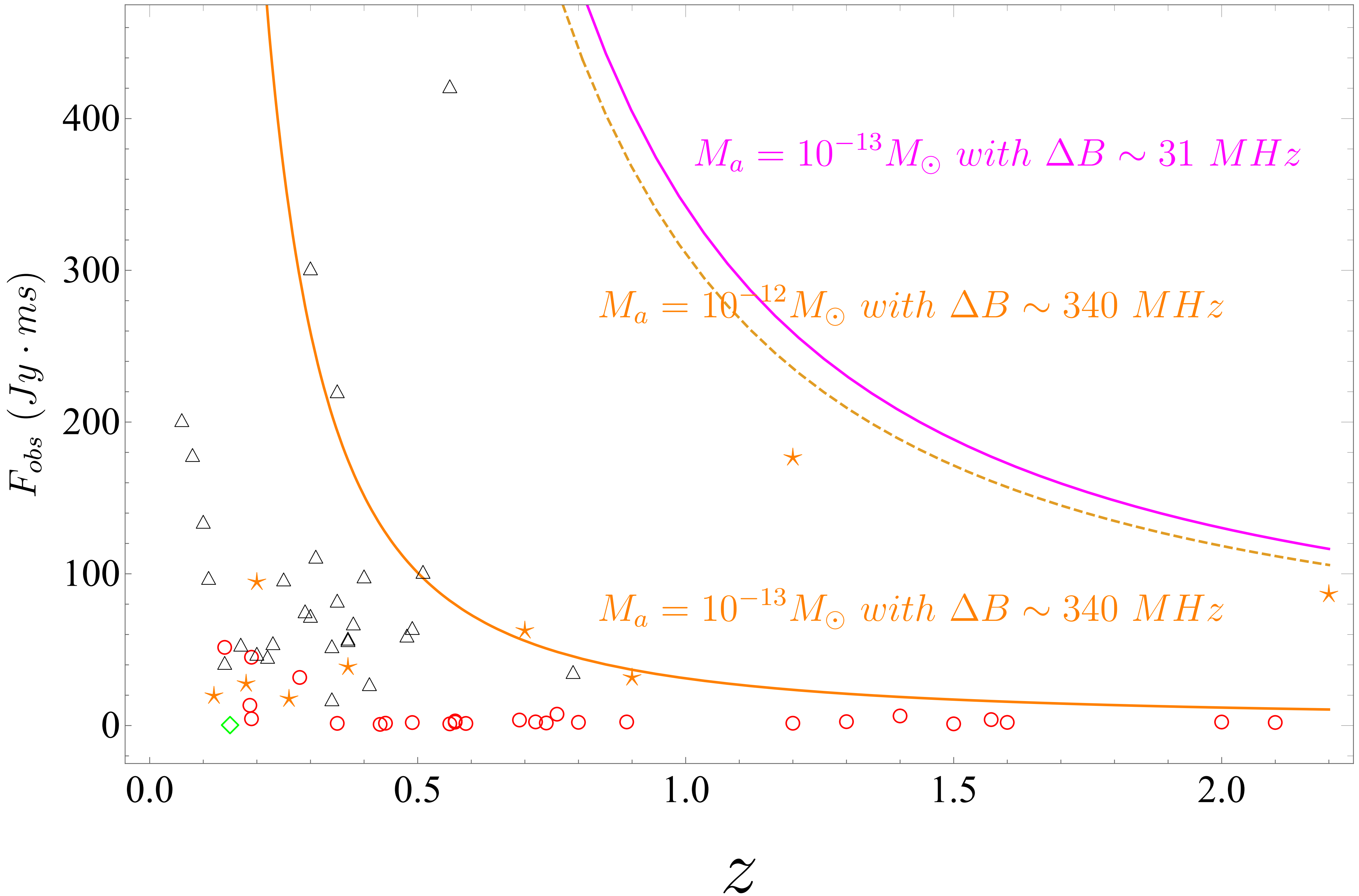


Allowed FRB peak frequencies measured at terrestrial radio telescopes after taking into account the cosmological and gravitational redshifts.

$$\nu_0 = m_a/2\pi = 2.42\ \mathrm{GHz}(m_a/10\ \mu\mathrm{eV})$$

$$\nu = \frac{\nu_0}{1+z}\sqrt{1-\frac{2G_N M_{\mathrm{NS}}}{r_c}}$$



Upper limit on the fluence as a function of redshift z. The solid orange line depicts the upper limit for $M_a = 10^{-13} M_\odot$ with bandwidth $\Delta B \sim 340$ MHz. The dashed orange line represents the upper limit for $M_a = 10^{-12} M_\odot$ and the same bandwidth $\Delta B \sim 340$ MHz. The magenta line corresponds to the upper limit for $M_a = 10^{-13} M_\odot$ and $\Delta B \sim 31$ MHz.

Event rate

$$\frac{N}{\mathrm{year}} = \sigma v_0 n_{\rm AS} n_{\rm NS} f_{\rm NS} V$$

$$\sigma = \pi b^2 = \pi r_c^2 v_c^2 / v_0^2 (1 - 2G_N M_{\rm NS}/r_c)^{-1}$$

For the whole Universe, the event rate per day is: $10^{13} \kappa_{\rm AS} f_{\rm NS}/365 \sim 1000$

$\kappa_{\rm AS}$ is the fraction of the total DM density in axion stars.

$f_{\rm NS}$ represents the ratio of neutron stars with magnetic fields larger than 10^{13} G on their surface.

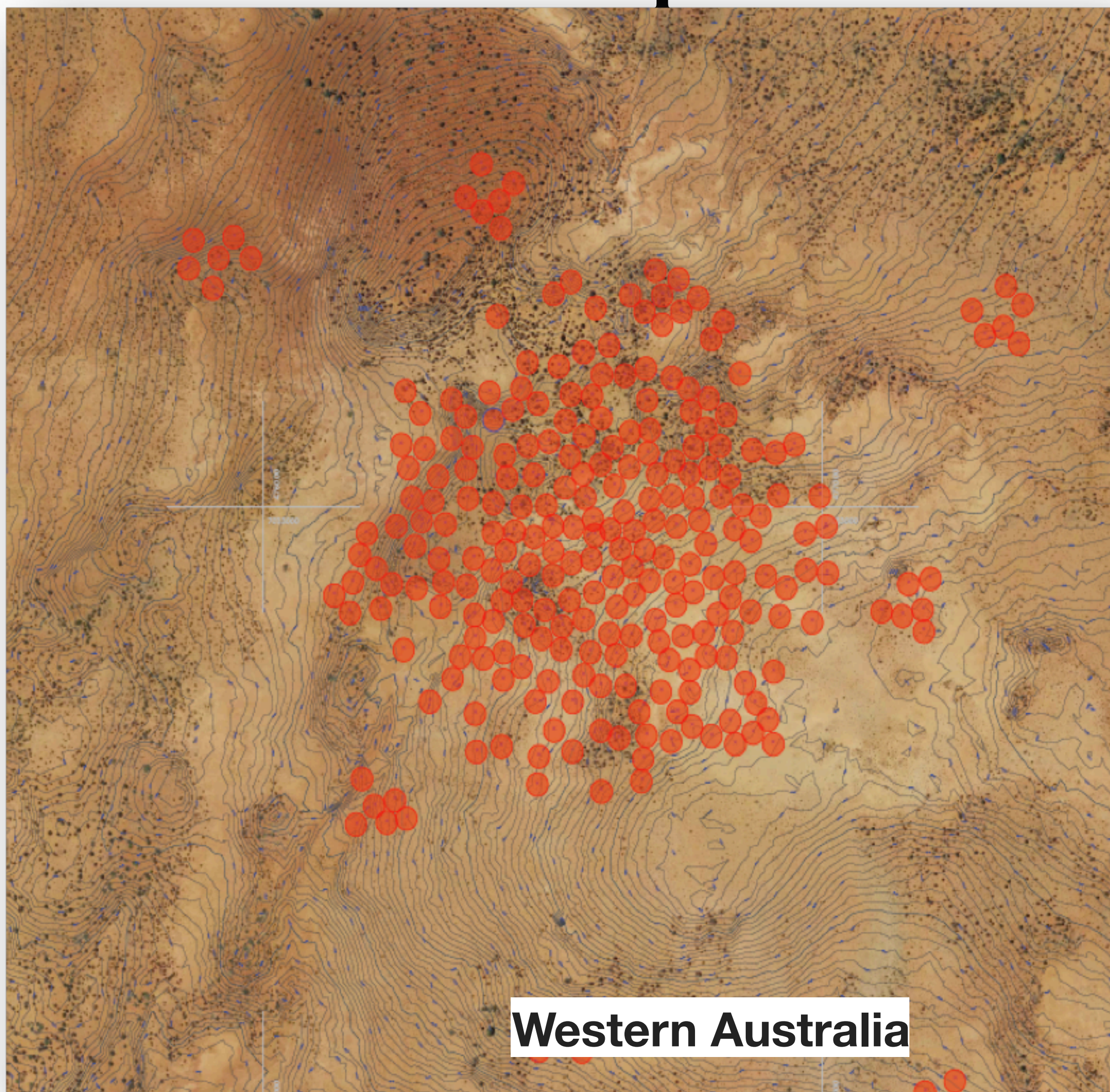
the SKA can detect more and more FRB events and provide us with more detailed and accurate information to test our proposed axion-star explanation.

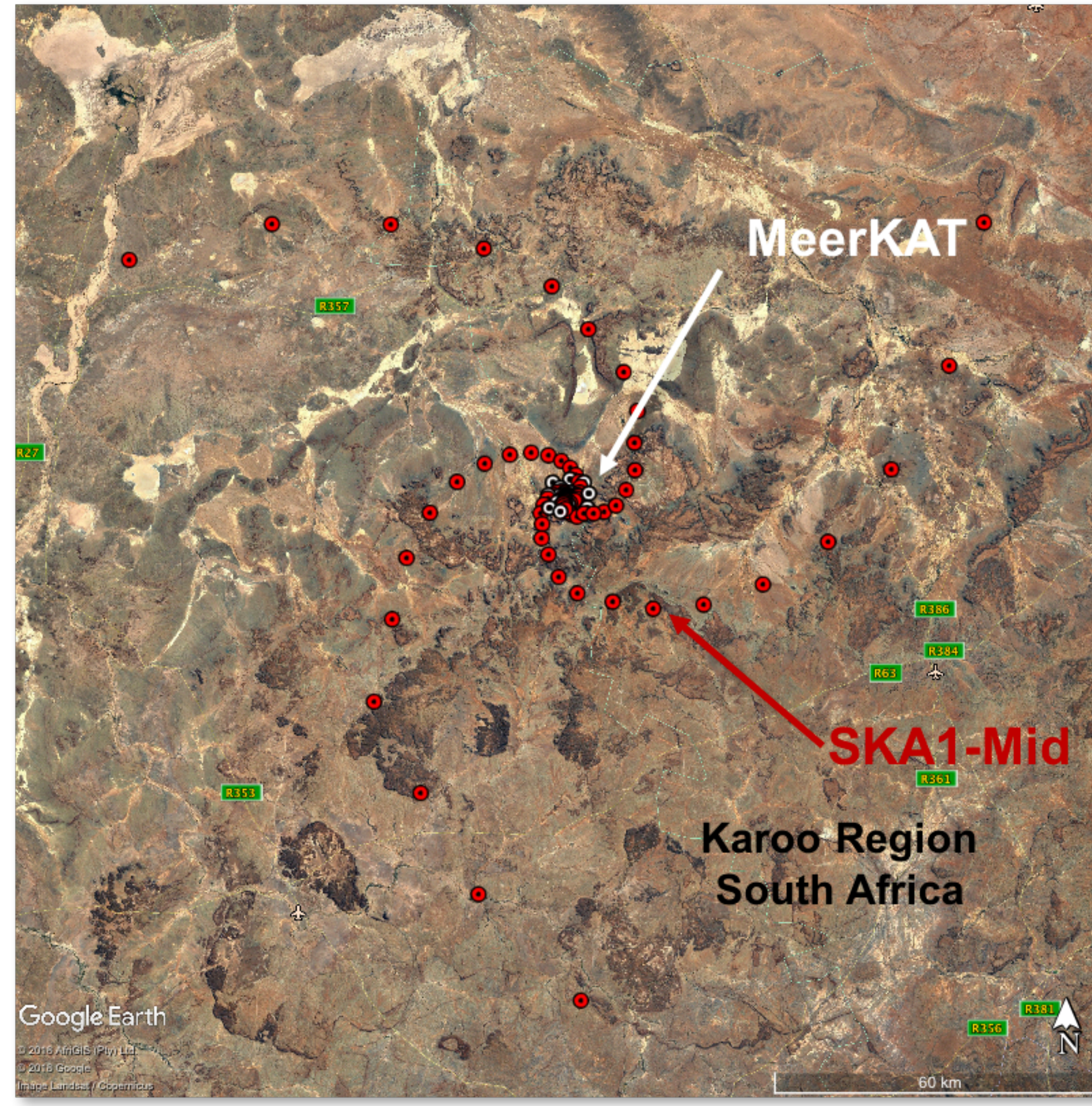
SKA(Square Kilometre Array)

Early science observations are expected to start in one year with a partial array.

credit: SKA website

The Square Kilometre Array (SKA)





Organisations from 13 countries are members of the SKA Organisation – Australia, Canada, China, France, Germany, India, Italy, New Zealand, Spain, South Africa, Sweden, The Netherlands and the United Kingdom.

In the future, the unprecedented sensitivity of SKA and other radio telescopes may unravel the spectral properties of FRBs. The many observed events in the 0.6 to 2.2 GHz range correspond to the same intrinsic peak frequency at the emission time, which could provide further support for this scenario.

credit: SKA website

Comments

1. We stress that this paper is aimed at explaining the broad features of FRBs, but there are a number of complicated astrophysical effects that are likely important in describing the detailed emission mechanisms for radiation from these events. Details of the geometry of the magnetosphere (e.g., the position of gaps and the neutral sheet) have a significant impact on the observed signals. Moreover, there are likely to be significant feedback effects in the conversion region. As the axion star moves through the field and plasma comprising the magnetosphere, it may exert radiation pressure on the surrounding plasma, exceeding the relatively small Thomson pressure due to the complicated plasma effects.

2.Tidally disrupted dilute axion stars may be responsible for the repeating FRBs, working in progress.

Summary

We have proposed a new explanation for the origin of FRBs, based on the axion to photon conversion that ensues when a dense axion star moves through the resonant region in the magnetosphere of a pulsar.

SKA is expected to observe many more FRBs, and might allow to pin down the correlation between FRBs, axions and dark matter.

Thanks for your attention!

Comments and collaborations are welcome!