Axion and Fast Radio Bursts
(a model for generation mechanism of fast radio bursts)

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arXiv: 1707.04827

Fast Radio Bursts(FRBs)

Mysterious radio bursts from extragalactic universe (originally reported in 2007 and then there are more than 30 FRBs observed until now)

- Duration ~ millisecond (intrinsic one < millisecond)

- Large dispersion measure ~ >500pc/cm^(-3)
  (indicates z>0.1 and so large emission energies ~10^(43)GeV/s)

FRBs are coherent radiations because of extremely large flux

- Only observed at radio frequencies ~ (700MHz~8GHz)
  No visible light, X ray, and gamma ray (no afterglow)
  coherent radiations at radio frequency just like maser

- Event rate (10^3~10^4)/day

Fast Radio Bursts(FRBs)

All of FRBs are non-repeating except
only one (FRB121102) is repeating
Bursts from an identical source are repeated many times even now.
(detail observations have been performed)

Non-repeating FRBs were observed only once at only narrow frequency band 700MHz~1.6GHz .
Celestial objects causing the FRBs are not identified.
(no observations at low frequencies 100MHz~400MHz)

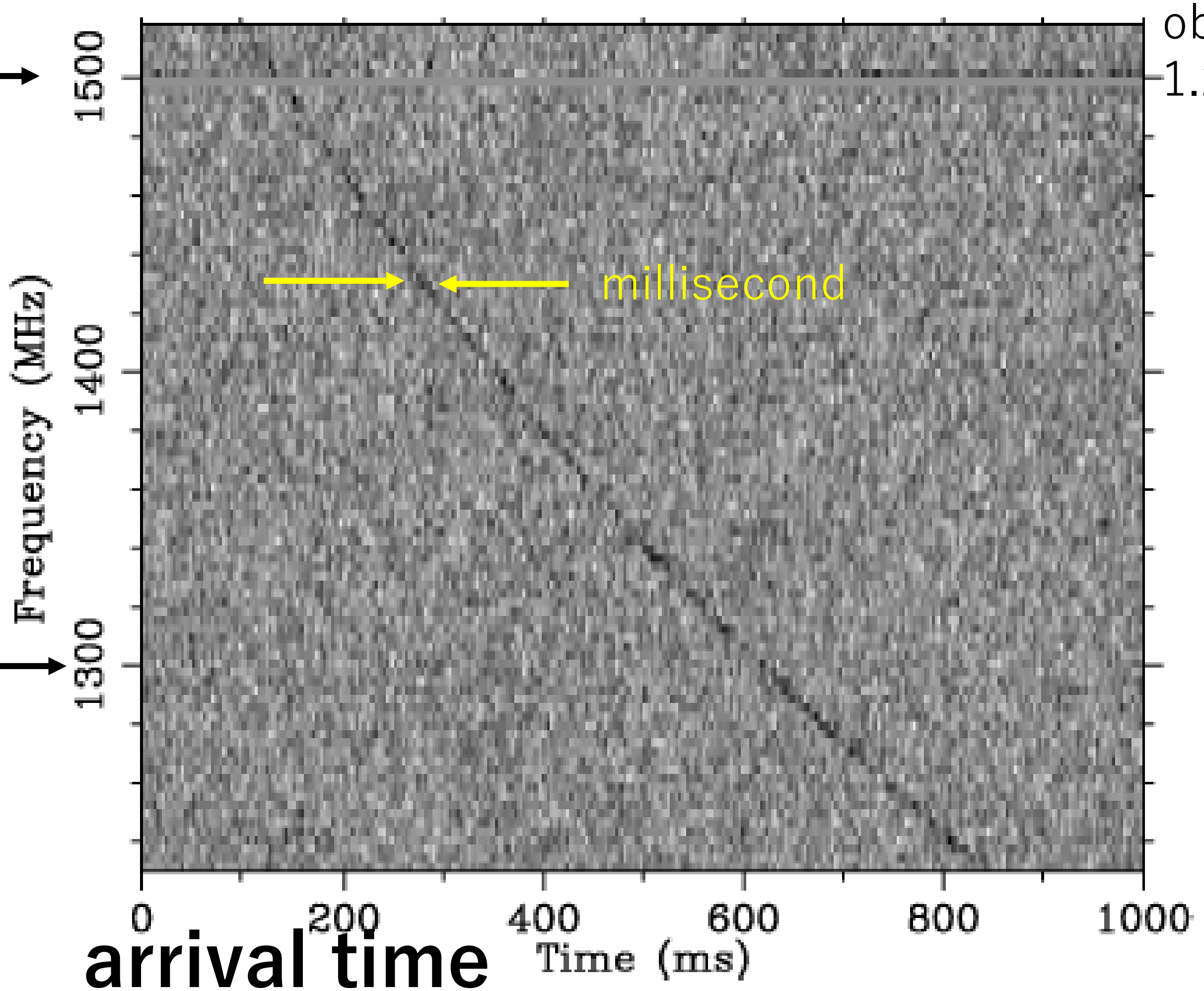
Karastergiou, et al. 2015

The repeating FRB was observed with multiple (interferometric) observations at wide frequency band 1.2GHz~8GHz and a host galaxy was identified as a dwarf galaxy z=0.19. **Tendulkar, et al. 2017**

1.5GHz

frequency

1.3GHz



arrival time

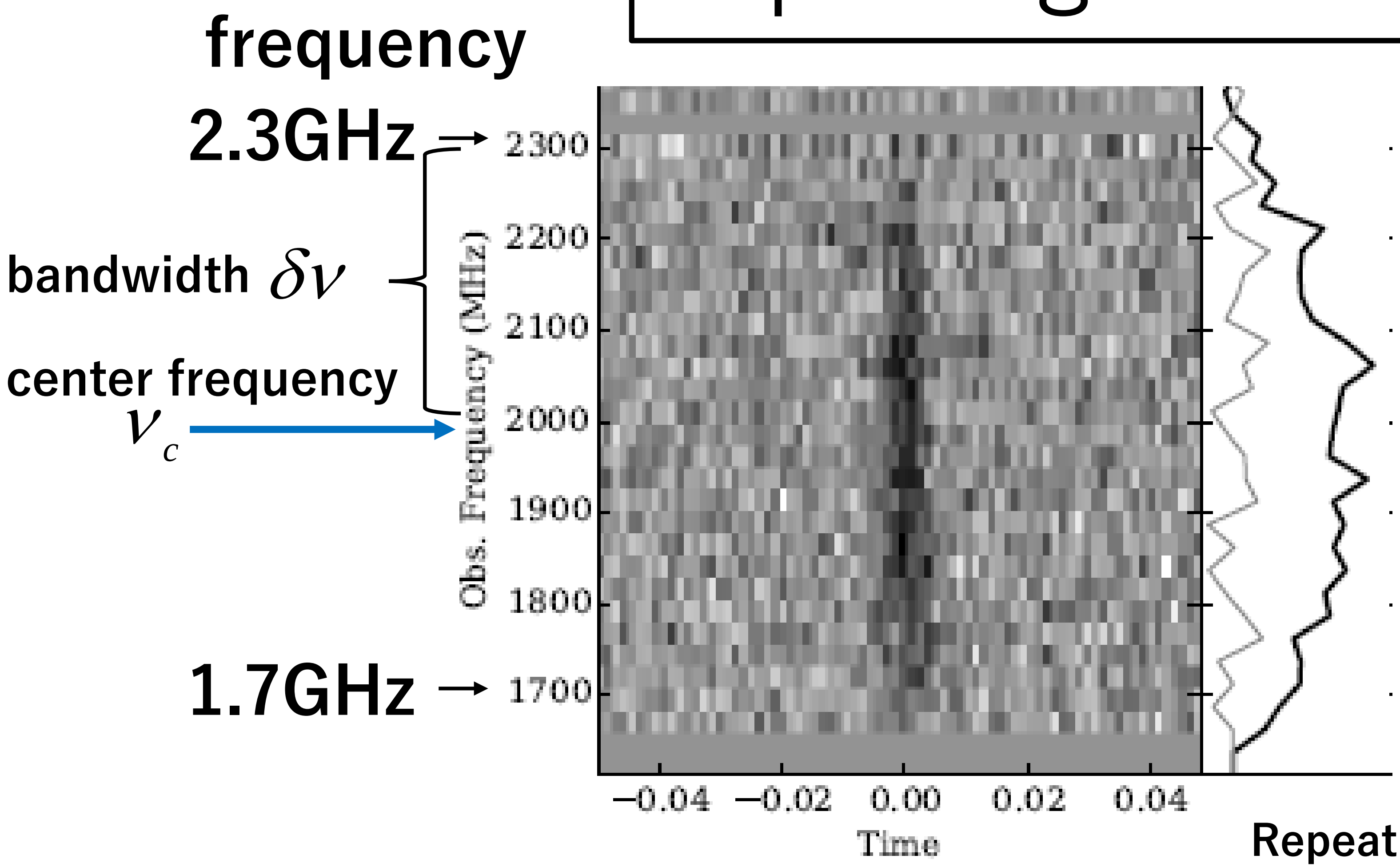
Almost of all non-repeating FRBs were observed in the frequency range 1.2GHz~1.6GHz

Parkes observatory
（Australia）

Arrival time depending on frequency
(dispersion measure)

Photons acquire a mass, i.e. plasma frequency owing to plasma in intergalactic space

Repeating FRB121102



Astrophys.J. 833 (2016) no.2, 177

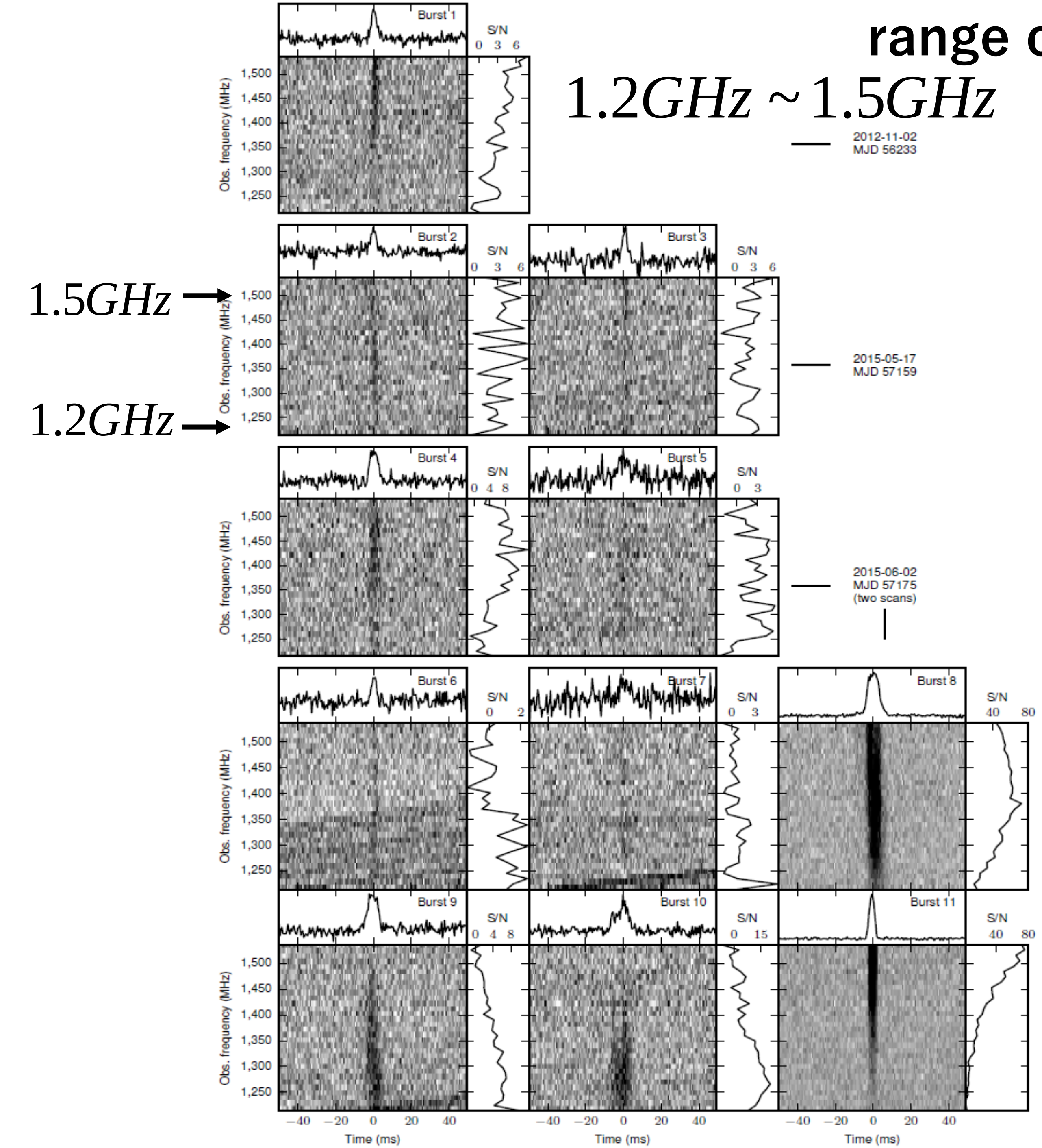
The figure shows that the burst is <u>narrowband.</u>
All of the FRBs including non-repeating ones might be narrowband

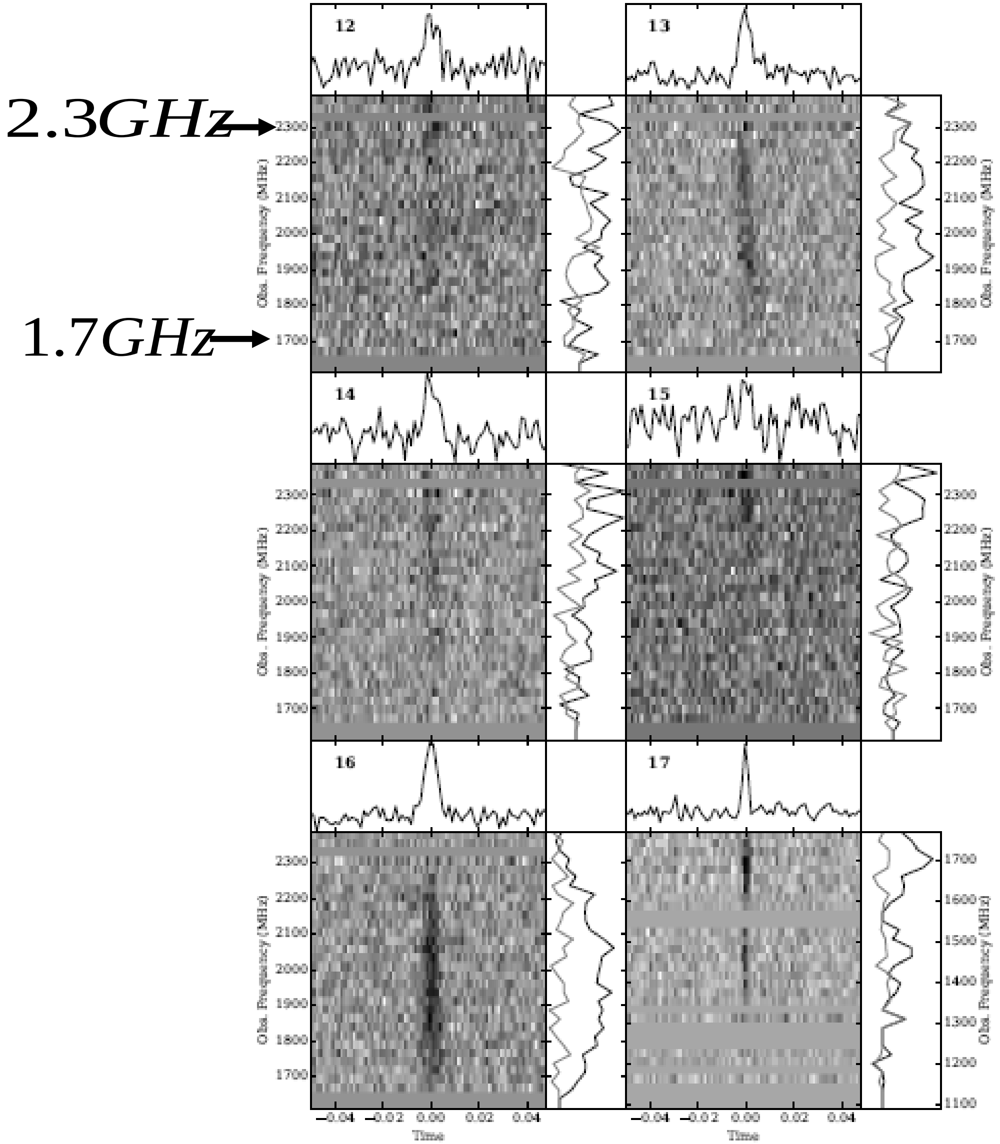
Repeating FRBs were observed in the frequency range 1.2GHz~8GHz with multiple telescopes

range of observed spectra

$1.2GHz \sim 1.5GHz$

$1.7GHz \sim 2.3GHz$





Origin of the FRBs is unknown

Astrophysical models have been proposed simply for accommodating burst energy and duration, but have no explicit emission mechanism

Black hole-neutron star merger

Massive neutron star collapsing into black hole

Asteroid collisions with neutron star

No explanation why there are no emissions of visible light, X ray, etc.

Neutron star-neutron star merger

“and more”

No association with gamma ray bursts,
No explanation why there are no emissions of visible light, X ray, etc.

Observation of the Repeating FRB

Giant flare of magnetars

No observation associated with SGR1806-20

A remaining astrophysical candidate

Giant radio pulsars（e.g. Crab pulsar）
observed only at radio frequencies
similar to FRBs although they are broadband

Too small fluence compared with FRBs,
Broadband, not narrowband

Repeating Fast Radio Burst (FRB121102)

(It is important to see the features of the FRB because detail observations have been performed)

Specific features

1) Bursts are clustered in a short period and after the bursts there is a long or short period with no bursts
(any regularity in the period has not been observed)

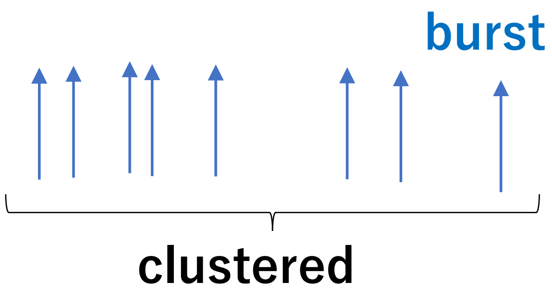
2) Spectra of bursts are narrowband, not broadband.
(it appears that bandwidths $\delta\nu$ are proportional to center frequencies ν_c) $1.5GHz < \nu_c < 7GHz$, $200MHz < \delta\nu < 1GHz$

3) no bursts observed with low frequencies <100MHz and high frequencies >10GHz

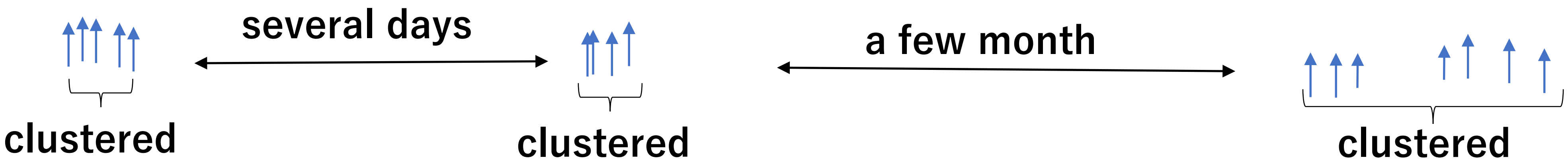
Repeating Fast Radio Burst (FRB121102)

Bursts are clustered in a short period, but no regularity

Bursts arise in an interval of several 10 seconds to several hours



There are periods with no bursts which are several hours to several days or months



Repeating Fast Radio Burst (FRB121102)

The repeating FRB121102 has been observed simultaneously in various radio frequencies.

Remarkable features (narrowband, not broadband)

Law et al. arXiv:1705.07553

Gaussian spectrum $\propto \exp\left(-\frac{(\nu-\nu_c)^2}{2(\delta\nu)^2}\right)$

There are bursts with various center frequencies

$1.5GHz < \nu_c < 7GHz$

center frequency ν_c

bandwidth $\delta\nu$

It seems that widths $\delta\nu$ are proportional to the center frequency ν_c

$$\delta\nu \sim 500MHz \quad for\ \nu_c = 3GHz,$$
$$\delta\nu \sim 300MHz \quad for\ \nu_c = 2GHz,$$
$$\delta\nu \sim 200MHz \quad for\ \nu_c = 1.3GHz$$

$$\delta\nu \propto \nu_c$$

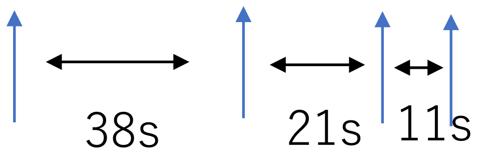
Repeating Fast Radio Burst (FRB121102)

Very remarkable observation reported at Aug. 2017
(not yet published in a paper; V. Gajjar, et.al. ATel No.10675.)
15 bursts were observed by Green Bank Telescope covering frequencies 4GHz~8GHz.
The frequencies are higher frequencies than ones of any other bursts.

All of the bursts are shown to be narrowband.

We wish to note; the feature may indicate the origin of the bursts.

→ Intervals between neighboring bursts are gradually becoming shorter !!
38s, 21s, 11s, or 94s, 51s, 27s



Axion model of FRBs

We assume the presence of coherent axion states called as **axion stars** and assume axion mass, (0.6~1) × 10^(-5)eV to explain observed radio frequencies~1.4GHz.

Non-repeating FRBs are caused by the collision between the axion stars and neutron stars.

The repeating FRBs are caused by the collision between the axion star orbiting galactic black hole and magnetized accretion disk . Axion stars condense in galactic center as dark matter. The collisions repeatedly take place.

The point is that strongly magnetized electron gases emit coherent radiations (FRBs) when they touch the axion stars

Axion model of FRBs

Axion stars are coherent axion states formed by gravitational attraction, which are described by solutions of the axion field equation coupled with gravity.

Note the star is oscillating

$$a(r,t) = a_0 f_a \exp(-r/R_a)\underline{\cos(m_a t)}$$

A.I, 2015

$$a_0 \cong 3\times10^{-8}\left(\frac{700km}{R_a}\right)^2 \frac{0.6\times10^{-5}eV}{m_a}$$

$$R_a = \frac{m_{pl}^2}{m_a^2 M_a} \cong 720km\left(\frac{0.6\times10^{-5}eV}{m_a}\right)^2\left(\frac{10^{-12}M_{sun}}{M_a}\right)$$

m_a Axion mass

M_a mass of axion star

R_a Radius

m_{pl} Planck mass

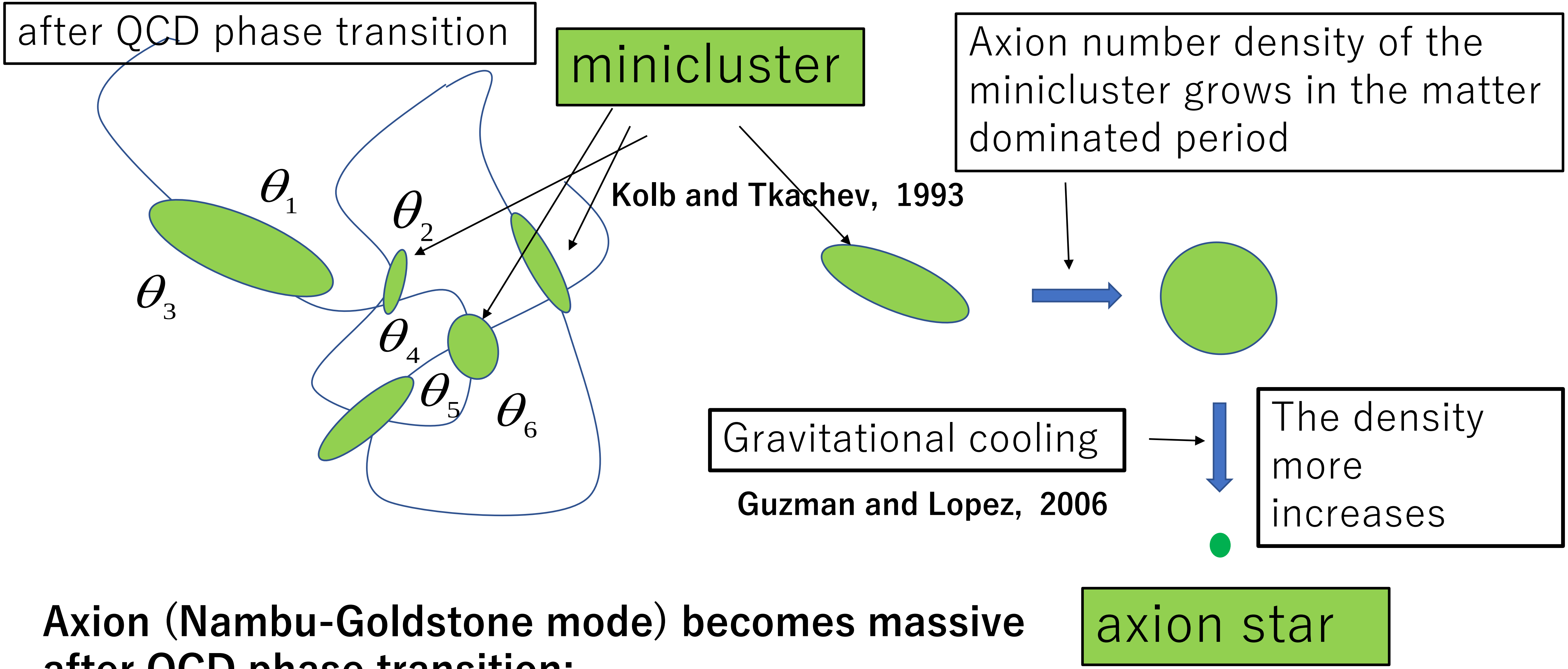
The spherical solutions are not important for the explanation of various properties of FRBs. The point is the oscillation as $\cos(m_a t)$ and the value of amplitude $a/f_a \cong a_0 \sim 3\times10^{-8}$

Axion model of FRBs

Masses of axion stars $(M_a = (10^{11} \sim 10^{-12}) M_{sun})$ are estimated by comparing the event rate (10^3~10^4/day)of FRBs and the rate of the collision between axion star and neutron star

Axion stars are formed by gravitational cooling of axion mini clusters. It is well known that the axion miniclusters are formed after QCD phase transition owing to the misalignment of the phases $\theta = a / f_a$ in causally disconnected regions.

$\Phi_{PQ} = |\Phi_{PQ}| \exp(i\theta)$, θ **; Nambu-Goldstone boson (axion)**



Axion (Nambu-Goldstone mode) becomes massive after QCD phase transition;
There are different phases θ_i coherently oscillating in causally disconnected regions.

Axion model of FRBs

Generation of electric fields by axion stars in background magnetic field

$$L = k\alpha \frac{a(t,r)\vec{E}\cdot\vec{B}}{f_a \pi}\ , \quad k = O(1), \quad \alpha \cong \frac{1}{137}$$

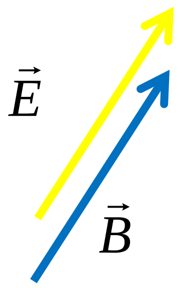
$\vec{B}$ **magnetic field of neutron star or accretion disk**

$$\vec{E} = -\frac{-\alpha a(t,r)\vec{B}}{f_a \pi} \propto \underline{\cos(m_a t)}$$

The electric field <u>uniformly oscillates</u> over the star

Electrons in neutron star or accretion disk coherently oscillate and <u>emit coherent radiations ,</u> when they are hit by the axion star

Dipole radiation with frequency $= \dfrac{m_a}{2\pi}$



Oscillation of electrons

Energy emitted by a single electron

$$w = \frac{2e^2\overline{(eE)^2}}{3m_e^2} \cong 1.0\times10^{-12}\frac{GeV}{s}\left(\frac{7\times10^2\,km}{R_a}\right)^4\left(\frac{0.6\times10^{-5}\,eV}{m_a}\right)^2\left(\frac{B}{10^{10}\,G}\right)^2$$

Coherent radiations from electron gas in the volume $\lambda^3 = (2\pi/m_a)^3$

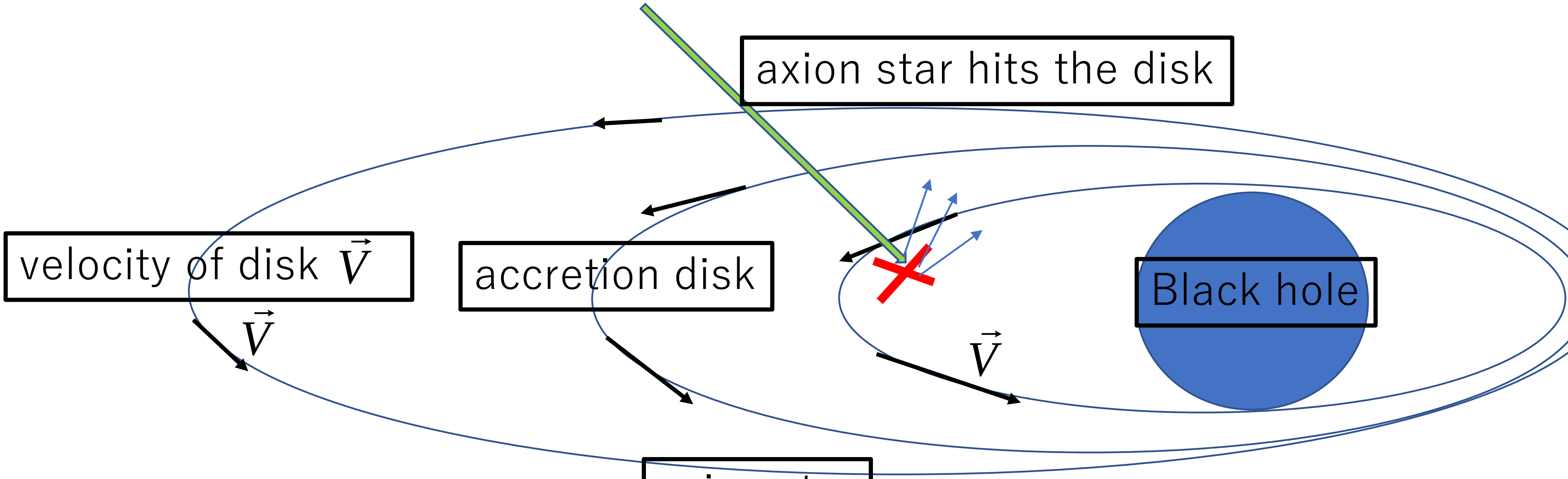
$$wN^2 = w(n_e\lambda^3)^2 \cong 10^{32}\,GeV/s\left(\frac{n_e}{10^{18}\,cm^{-3}}\right)^2\left(\frac{7\times10^2\,km}{R_a}\right)^4\left(\frac{0.6\times10^{-5}\,eV}{m_a}\right)^8\left(\frac{B}{10^{10}\,G}\right)^2$$

$$\lambda = \frac{2\pi}{m_a} \cong 20cm\left(\frac{0.6\times10^{-5}\,eV}{m_a}\right)$$

Sufficiently large energies $\sim 10^{40}\,erg/s$ **are emitted to be consistent with observations**

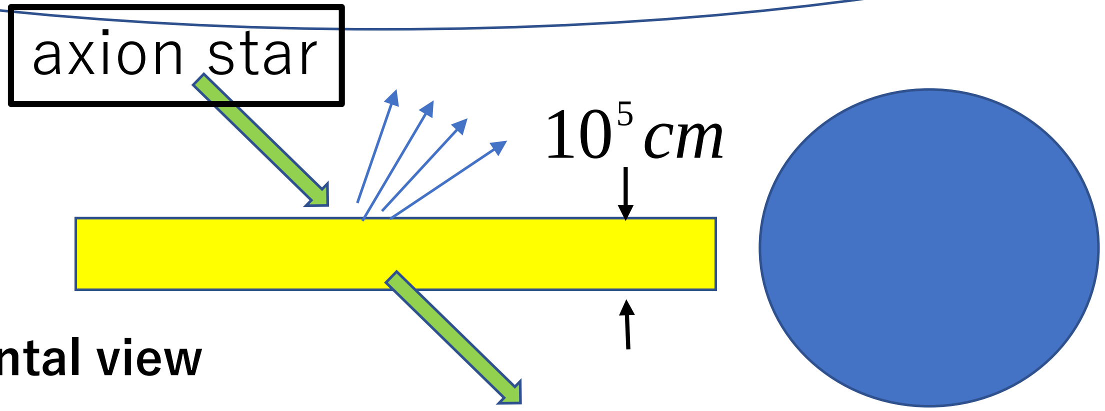
production of repeating FRB

Collision between axion star and accretion disk of black hole



We assume
geometrical thin accretion disk
with strong magnetic field

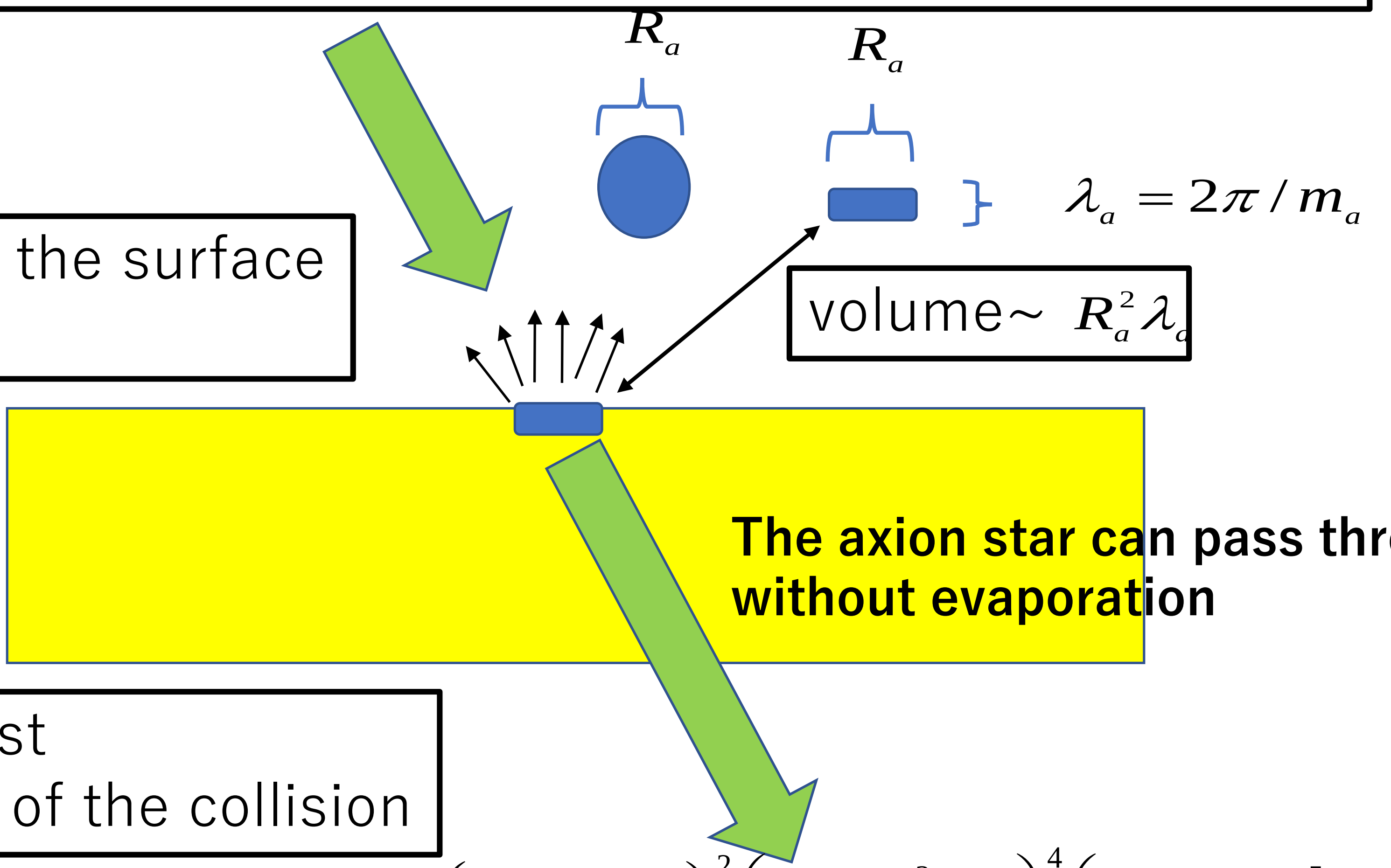
A model of accretion disk
Begelman and Silk (2017)



horizontal view

production of repeating FRB

Emissions arise from the surface of the disk



volume~ $R_a^2 \lambda_a$

The axion star can pass through the disk without evaporation

energy of the burst
from the location of the collision

$$W = wN^2 = w(n_e R_a^2 \lambda_a)^2 \cong 10^{42} erg/s \left(\frac{n_e}{10^{18} cm^{-3}}\right)^2 \left(\frac{7\times10^2 km}{R_a}\right)^4 \left(\frac{0.6\times10^{-5} eV}{m_a}\right)^8 \left(\frac{B}{10^{10} G}\right)^2$$

We need strong magnetic field and high electron density

$B \geq 10^{10} G$

$n_e \geq 10^{18} / cm^3$

termination of coherent radiations

Oscillation energy of an electron $p^2/2m_e \sim (eE)^2/m_e m_a^2 \sim 10^5 eV\left(\frac{B}{10^{11}G}\right)^2$
is larger than initial temperature of the electron gas.

The temperature increases and reaches a critical temperature
given by the oscillation energy $T_c \sim 10^5 eV\left(\frac{B}{10^{11}G}\right)^2$ within a millisecond

Thermal fluctuations terminate the coherent oscillation.

The increase of the temperature is caused by
thermalization of the oscillation energies

Line spectrum is thermally broaden

$$S(\nu) \propto \exp\left(-\frac{(\nu-\nu_c)^2}{2(\delta\nu)^2}\right), \quad \delta\nu = \nu_c\sqrt{\frac{T_c}{m_e}}$$

; width proportional to center frequency ν_c

Bandwidths $\delta\nu$ are proportional to the center frequencies ν_c

Model prediction of bandwidth, e.g.

$$\delta\nu = 3GHz\sqrt{\frac{T_c}{m_e}} \cong 430MHz\frac{B}{3.3\times10^{10}G} \quad \text{for} \quad \nu_c = 3GHz$$

observations

$$\begin{cases} \delta\nu \approx 1GHz & for\ 6GHz \\ \delta\nu \approx 500MHz & for\ 3GHz \\ \delta\nu \approx 300MHz & for\ 2GHz \\ \delta\nu \approx 200MHz & for\ 1.2GHz \end{cases}$$

We should note that the strengths $\sim 10^{10}G$ of magnetic fields are almost identical to the strengths needed for large emission energies $\sim 10^{40} erg/s$

Presence of various center frequencies in repeating FRB

<u>Doppler shifts</u> owing to the velocities $\vec{V}$ of the accretion disk

There are various center frequencies observed

$$\nu_c = 1.2GHz \sim 7GHz$$

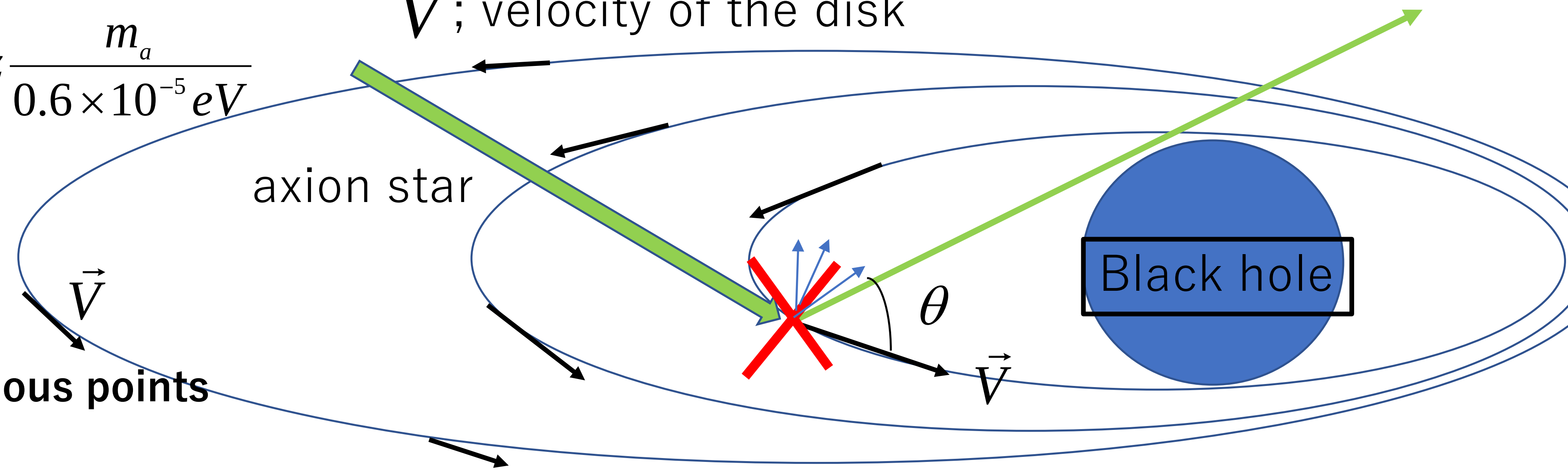
Doppler shifted one → intrinsic frequency

$$\nu_c = \nu_{\text{int}}\sqrt{1-V^2}/(1-V\cos(\theta))$$

$$\nu_{\text{int}} = \frac{m_a}{2\pi} = 1.4GHz\frac{m_a}{0.6\times10^{-5}eV}$$

V; velocity of the disk

line of sight



Axion stars hit various points in the disk.

Different point hit in the disk has different velocity, which leads to a burst with a different frequency

- No observations of repeating bursts with low frequencies < 100MHz . For the emission of bursts with low frequencies $\nu_c < 100MHz$, the velocity of the disk must be large such as $V > 0.99$ and the angle θ must be such as $\theta \cong \pi$
  Such bursts are very rare.

- Our model predicts no non-repeating FRBs with high frequencies >3GHz because of no large Doppler shift.
  They arise from collisions with neutron stars
  No observations of non-repeating bursts with low frequencies 100MHz~400MHz
  We need large redshift z>3($\nu_{\text{int}}/(1+z)$)of the intrinsic frequency
  $\nu_{\text{int}} = \frac{m_a}{2\pi} = 1.4GHz \frac{m_a}{0.6 \times 10^{-5} eV}$ Such FRBs are very faint.

A regularity in intervals between bursts has been observed

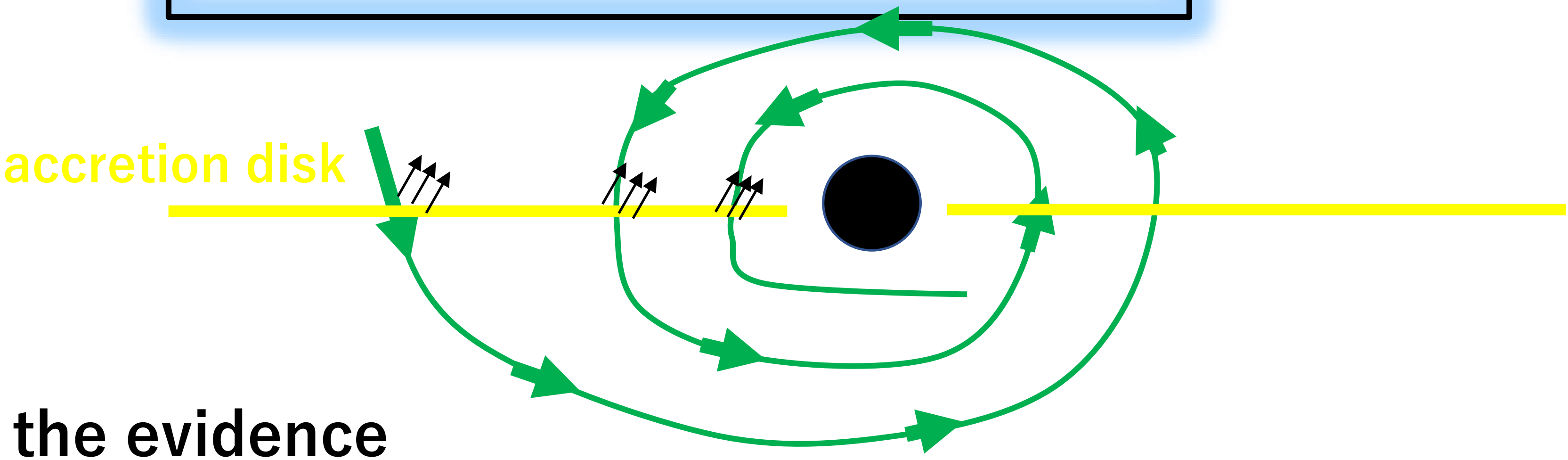
Intervals between neighboring bursts become shorter

V. Gajjar, et.al. ATel No.10675

Axion star is orbiting and falling into black hole, accelerating its speed

Time interval(second)

A group of bursts	Another group of bursts
180.5s	94.2s
37.9s	51.2s
21.4s	26.8s
11.3s	



The fact strongly indicates the evidence of axion star orbiting black hole

Conclusions

We have presented a model of fast radio bursts;

Axion stars hitting neutron stars or accretion disks produce the fast radio bursts

Energies of FRBs （$\sim 10^{40} erg/s$ ）

Duration （ ~millisecond ）

The following features can not be explain by any astrophysical models

Narrowband (bandwidths proportional to center frequencies)

(line spectra are thermally broaden)

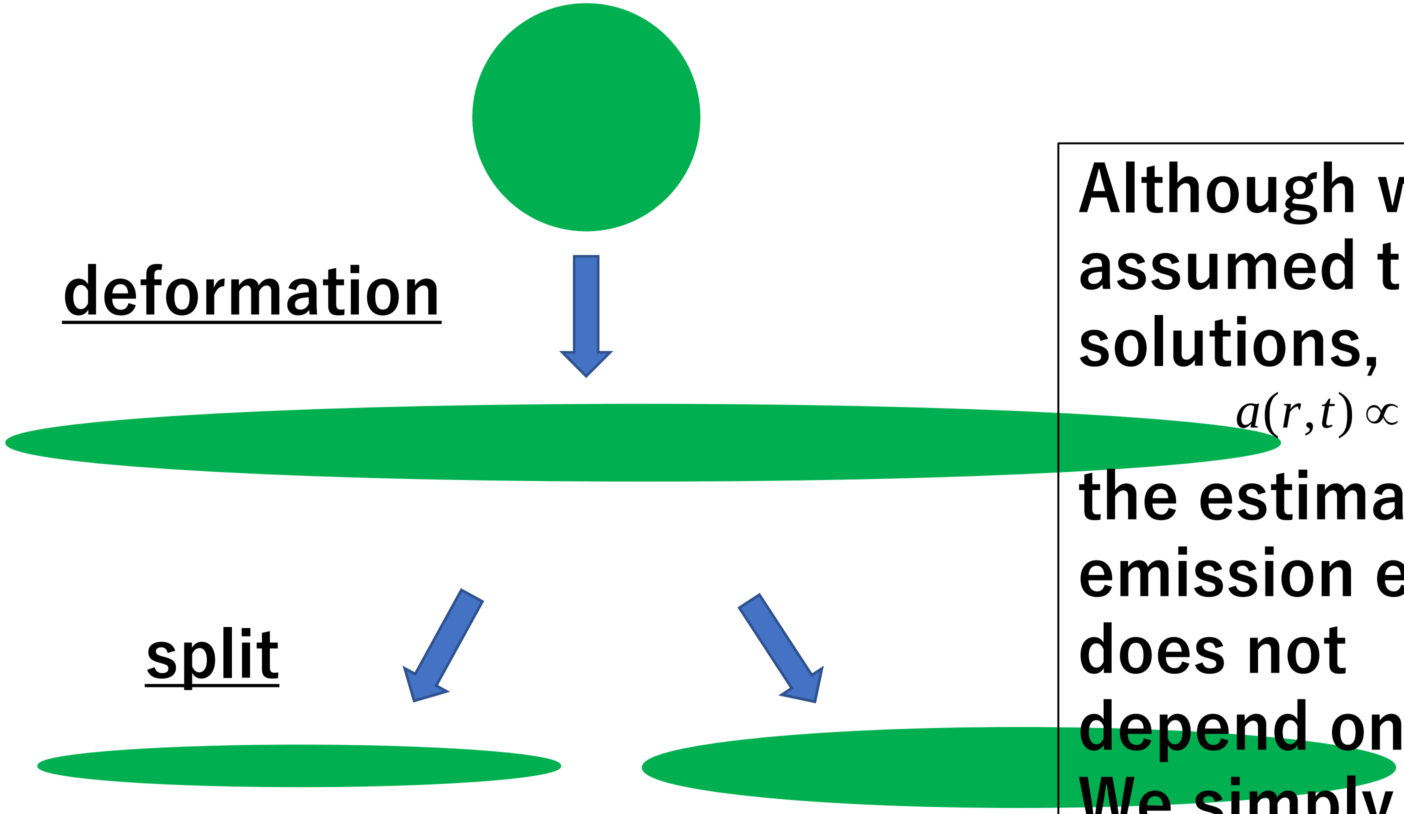
e.g. 500WHz for $\nu_c = 3GHz$

Presence of various center frequencies of repeating FRB

$\nu_c = 1.2GHz \sim 7GHz$ from Doppler shifts of intrinsic frequency

Presence of irregular bursts in repeating FRBs

(axion stars hit accretion disk, orbing black hole)



Amplitude of 'a' does not change so much even if the axion star is deformed or split because the mass M_a does not change so much

$$M_a \sim (m_a a)^2 \times volume$$

Although we have assumed the spherical solutions,

$$a(r,t) \propto \exp(-r/R_a)\cos(m_a t)$$

the estimation of emission energies e.t.c does not depend on the solutions. We simply use the amplitude $a(r,t) \propto \cos(m_a t)$ for the derivation

Coherence of the axion star is very rigid

Number of axions in the volume $(1/m_a)$^3
is huge ~10^(40), although the amplitude $\theta = a/f_a \approx 10^{-8}$
is very small.

Thus, the coherence is not lost when the star is deformed by tidal forces of neutron stars or black holes.
It means that the classical treatment of the axion stars is valid for the estimation of emission energies, etc.