Axion stars and repeating fast radio bursts with finite bandwidths

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arXiv:1707.04827

Phys. Rev. D91(2015)
arXiv:1412.7825; arXiv:1512.06245

ここでは、repeating fast radio burst の様々な観測結果をアクシオン星と膠着円盤との衝突で説明
(non repeating FRB は、アクシオン星と中性子星との衝突; 以前に発表)

Fast Radio Bursts

Fast radio bursts

- **non repeating**
- **repeating**

More than 20 events observed
Only one of them is
the repeating FRB121102

only one event　　**1年前までの観測結果（場所を特定できず）**

観測された周波数 → Frequency 700MHz～1.5GHz , no X ray or gamma ray for non repeating FRBs　(no after glow)

持続時間 → duration $\sim 10^{-3}$ sec.

発生頻度 → event rate～$(10^3 \sim 10^4)$ / day

large dispersion measure(> 500pc/cm^3) ; $0.2 < z < 1$

DMから予想されるエネルギー → emission rate～ $10^{43} GeV/s (\sim 10^{40} erg/s)$

Spectral index　$\alpha ; \nu^{-\alpha}$　positive and negative;　volatility

スペクトル指数が正、負、あるいはゼロ；不定

Repeating Fast Radio Burst

この1年間の観測(repeating FRBの発見)

The repeating FRB121102 **母銀河を特定 z=0.19**
has been detected in **various** **（矮小銀河）**
radio frequencies. **様々な周波数帯で同時観測**

Frequencies observed
(1.2GHz~1.5GHz),（1.7GHz~2.3GHz), (2.5GHz~ 3.5GHz)
バーストが観測された周波数

Frequencies not observed
(50MHz~100MHz),（~5GHz),（13GHz~18GHz)
バーストが観測されない周波数（低周波数、高周波数）

Narrow bandwidths have been observed **狭いバンド幅が観測された**
(spectrum is not power low $\nu^{-\alpha}$) **シンクロトロン放射から期待されるものと異なる**
Host galaxy is identified z~0.19

Repeating Fast Radio Burst

The repeating FRB121102
has been detected in various
radio frequencies.

There are no periodicity in the repeating bursts
バーストの発生に周期性はない
Bursts are clustered
(several ten seconds ~ several minutes)
一度発生すると続けて発生する
There are periods with no bursts
(several hours ~ several weeks)
しばらく休止期間がある

Repeating Fast Radio Burst

The repeating FRB121102 has been detected in various radio frequencies.

多周波数同時観測で得られたバーストの特徴

Remarkable features

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

arXiv:1705.07553

スペクトルはガウシアンで近似可（様々なcenter frequency ν_cのバーストがある）

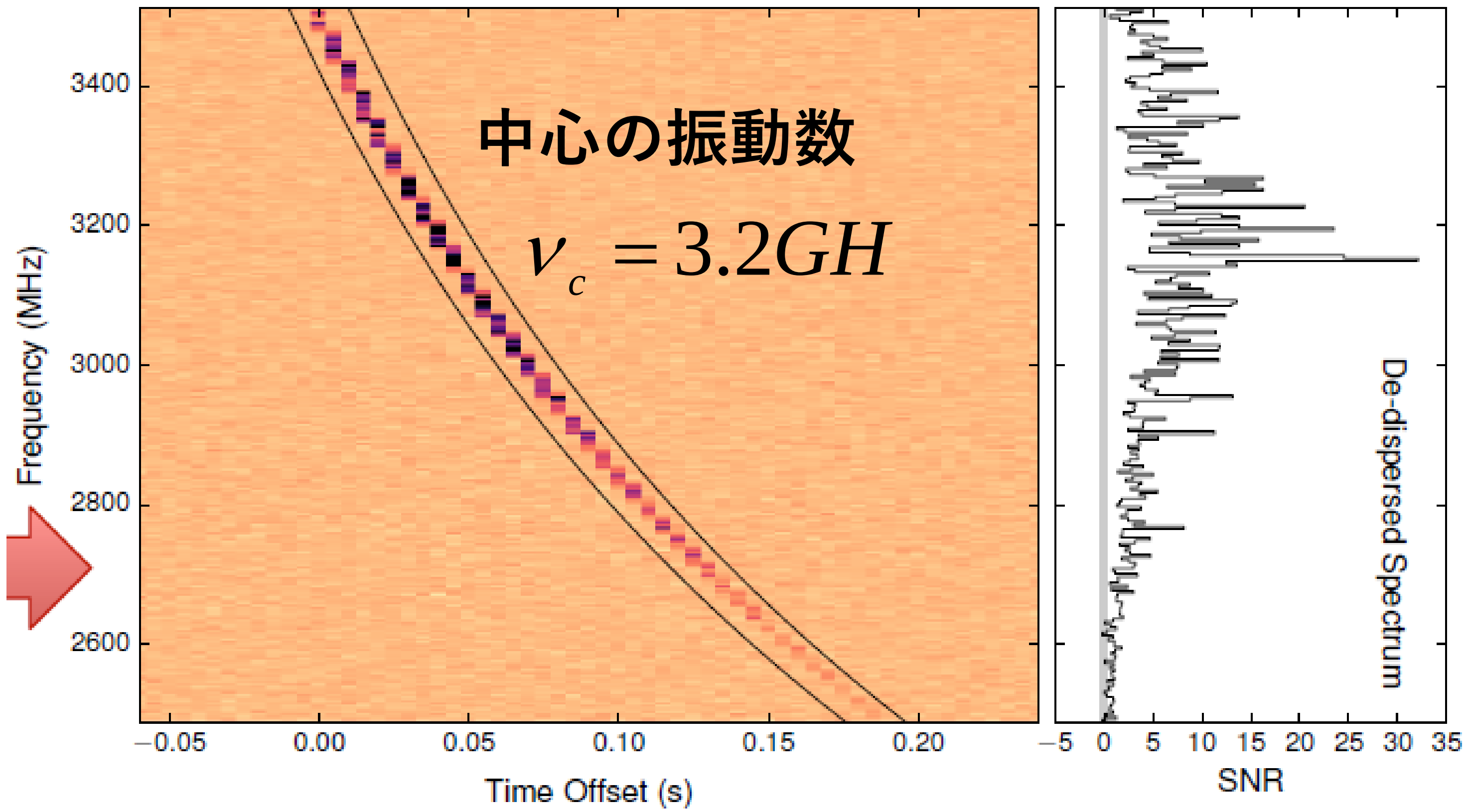
It seems that widths $\delta\nu$ are proportional to the center frequency ν_c

得られたバンド幅 ➡ $\delta\nu \sim 500MHz \quad for\ \nu_c = 3GHz,$ **arXiv:1705.07553**

観測値から読み取り
$\delta\nu \sim 300MHz \quad for\ \nu_c = 2GHz,$
$\delta\nu \sim 200MHz \quad for\ \nu_c = 1.3GHz$

$\delta\nu \propto \nu_c$
比例するように見える

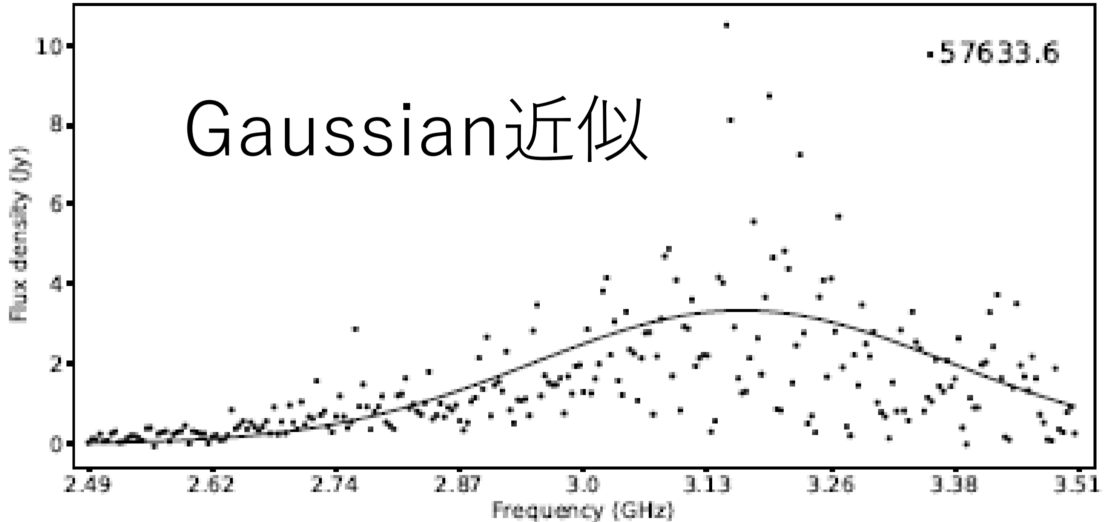
Sharp cut off in the spectrum has been observed in a non repeating FRB170707 **Non repeating FRBs もGaussianの可能性** **Spectral index $\alpha; \nu^{-\alpha}$ が正、負様々**



repeating FRB121102

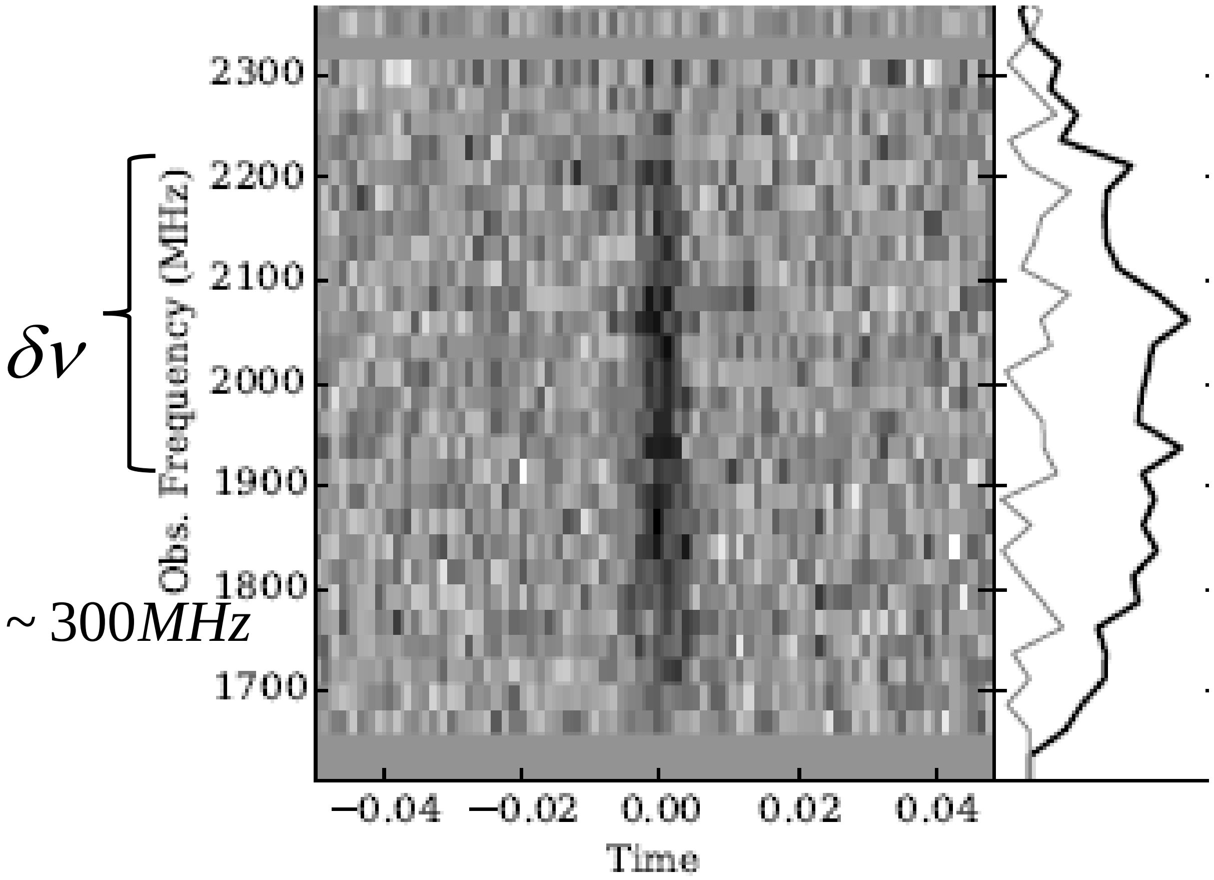
arXiv:1705.07553

$$\delta\nu \cong 500MHz \quad for\ \nu_c = 3GH$$



repeating FRB121102

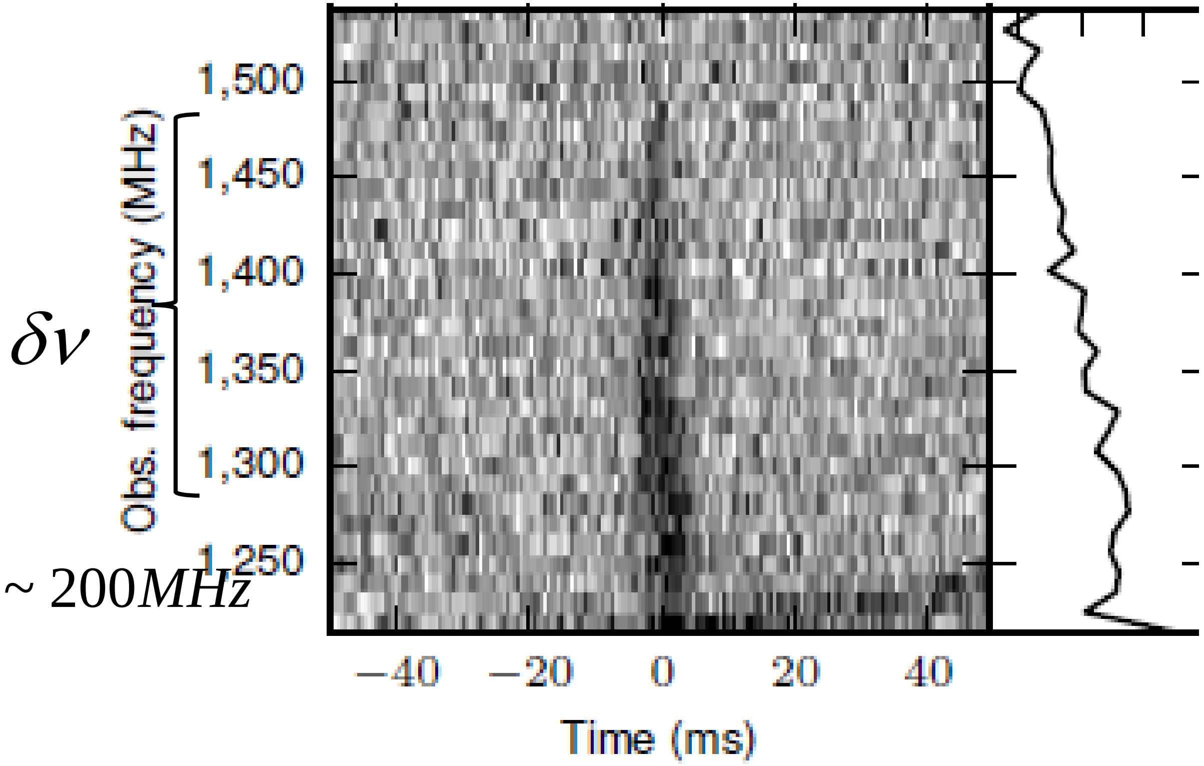
Astrophys.J. 833 (2016) no.2, 177



中心の振動数 $\nu_c \sim 2GHz$

$$\delta\nu \sim 300MHz \quad for\ \nu_c = 2GHz$$

Nature 531 (2016) 202



中心の振動数 $\nu_c \sim 1.3GHz$

$$\delta\nu \sim 200MHz \quad for\ \nu_c = 1.3GHz$$

ABSTRACT

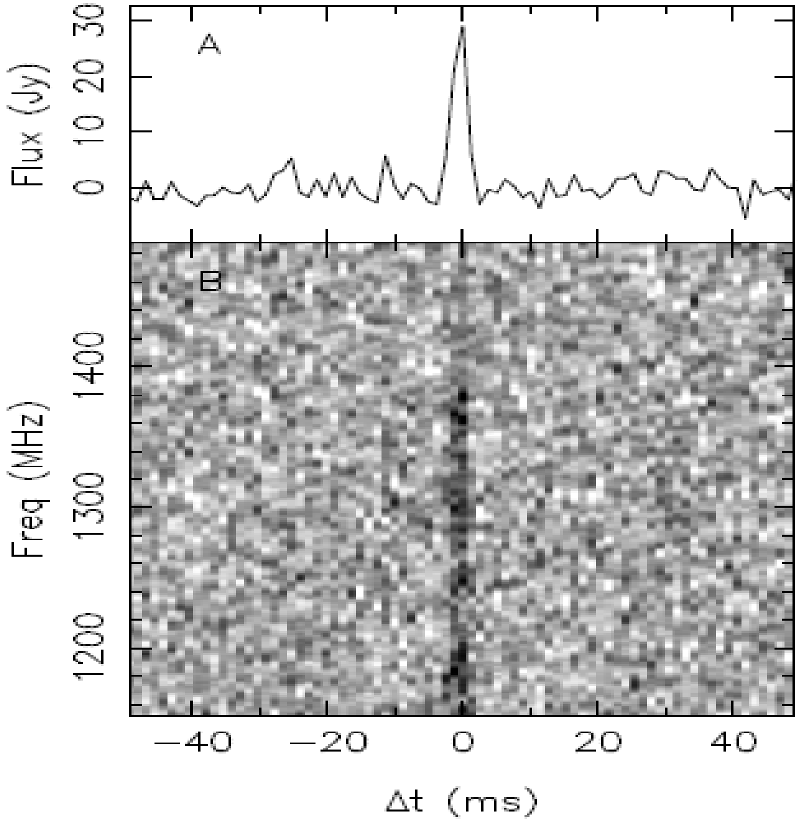
We report the detection of an ultra-bright fast radio burst (FRB) from a modest, 3.4-day pilot survey with the Australian Square Kilometre Array Pathfinder. The survey was conducted in a wide-field fly's-eye configuration using the phased-array-feed technology deployed on the array to instantaneously observe an effective area of 160 deg^2, and achieve an exposure totaling 13200 deg^2 hr . We constrain the position of FRB 170107 to a region $8' \times 8'$ in size (90% containment) and its fluence to be 58 ± 6 Jy ms. The spectrum of the burst shows a sharp cutoff above 1400 MHz, which could be either due to scintillation or an intrinsic feature of the burst. This confirms the existence of an ultra-bright (> 20 Jy ms) population of FRBs.

arXiv:1705.07581

Non repeating FRBでも
スペクトルはGaussianの可能性

Non repeating FRB170107

観測されたこれまでのFRBの
spectral indexが正、あるいは負
が、それを示唆



Our generation mechanism of FRBs

Collisions between dark matter axion stars and neutron stars or magnetized accretions disk of giant (galactic) black holes

外部磁場(in neutron star or accretion disk)中で
アクシオン星が振動する電場を発生し、電子ガスを振動させ、コヒーレントな放射を発生させる

Iwazaki, Phys.Lett. B451 (1999)

What are axions and axion stars ?

アクシオンやアクシオン星とは何か？

What are axions and axion stars ?

Axion is a Nambu Goldstone boson
associated with Pecci-Quinn symmetry.
The symmetry cures strong CP violation.
The symmetry is a chiral symmetry, which
is broken by QCD instantons.
The axion is one of the most probable candidates
of dark matter. Axion stars are gravitational bound
states of axions.

アクシオンは最も確からしい暗黒物質の候補。重力的に緩く束縛された星を作っている可能性がある。Axion star

Axion star

Iwazaki
arXiv:1412.7825

Gravitational bound state of axions

重力的に束縛された
アクシオン。束縛エネルギー
が質量に比べ十分小さい時の解
アクシオンの質量で振動している

Axion field
(real scalar)

$$a \equiv f_a \theta, \quad f_a \simeq \frac{10^{12}\,GeV}{m_a / 6\times 10^{-6}\,eV}$$

m_a = axion mass

f_a ; breaking scale of Pecci-Quinn symmetry

Configuration of axion star with weakly bounded axions

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

$$a_0 \simeq 3\times 10^{-8}\left(\frac{700km}{R_a}\right)^2 \frac{0.6\times 10^{-5}\,eV}{m_a}$$

M_a ; mass of axion star

Planck mass

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

Axion star

Iwazaki
Phys. Rev. D (2015),
arXiv:1412.7825

Theoretical parameters

- Axion mass m_a
- Mass（radius）of axion star $M_a\,(R_a)$

理論上の不定パラメータ2つ。
これら2つは、観測から決定される

Observational determination

Radio frequency of FRBs
（affected by cosmic expansion)

$$\nu_{obs} = \nu_{\rm int} /(1+z)$$

アクシオンの質量は、バーストの振動数で決まる

$$\nu_{\rm int} \equiv \frac{m_a}{2\pi} \simeq 1.4GHz\left(\frac{m_a}{0.6\times 10^{-5}eV}\right)$$

アクシオン星の質量は、Non repeating FRBs の発生率で決まる

non repeating FRBs

Iwazaki, Phys. Rev. D91(2015)
Non repeating FRBs は中性子星との衝突で発生

Event rate of non repeating FRBs
（collisions with neutron stars）

$$M_a \simeq 10^{-12} M_{sun}$$

All parameters are fixed

Coherence of axions in axion stars

非常にコヒーレンスが強い。
(Bose condensation)
コンプトン波長内
にものすごい数の
アクシオン数

Number of axions in the volume
is huge $\approx 10^{40}$

$$\lambda_a^3 = \left(\frac{2\pi}{m_a}\right)^3 \sim (20cm)^3$$

$$M_a \left(\frac{\lambda_a}{R_a}\right)^3 / m_a \approx 10^{-12} M_{sun} \left(\frac{20cm}{7\times 10^7 cm}\right)^3 / (0.6\times 10^{-5} eV) \approx 10^{40}$$

潮汐力で変形、分裂するが、コヒーレンスは失われない。axion場,a(t,x)は変形、しかし強さは大きくは変わらない

The coherence is very rigid.
Tidal forces of black holes deform the shapes of the axion stars, but do not make them incoherent.

Generation mechanism of FRBs

Axion-electromagnetic interaction

Axion star under magnetic field

$$L = k\alpha \frac{a(t,r)\vec{E}\cdot\vec{B}}{f_a \pi} + \frac{\vec{E}^2 - \vec{B}^2}{2}, \quad k = O(1), \quad \alpha = \frac{e^2}{4\pi} \cong \frac{1}{137}$$

Axion場 a(t, r)と電磁場の相互作用

$\vec{E}$ ($\vec{B}$):electric (magnetic) field

Gauss law

磁場中のアクシオン星は振動する電場を発生する

$$\vec{\partial}\cdot\vec{E} = -\alpha\vec{\partial}\cdot\left(a(t,r)\vec{B}\right)/\ f_a\pi + \text{“charge density”}$$

solution

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

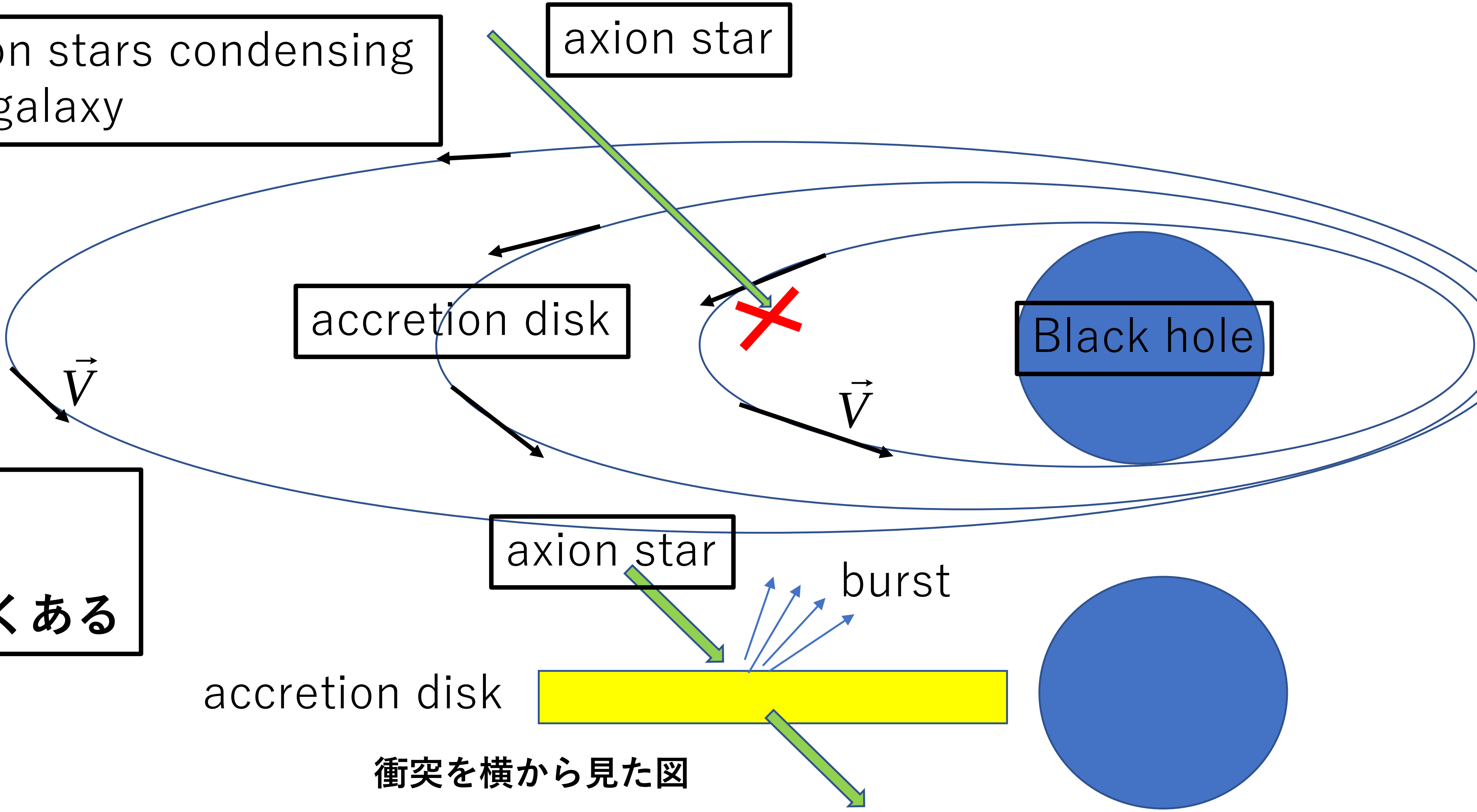
Generation of oscillating electric field under external magnetic field

Induction of coherent oscillation of electrons Iwazaki 1997

電場は、電子系にコヒーレントな振動を起こす

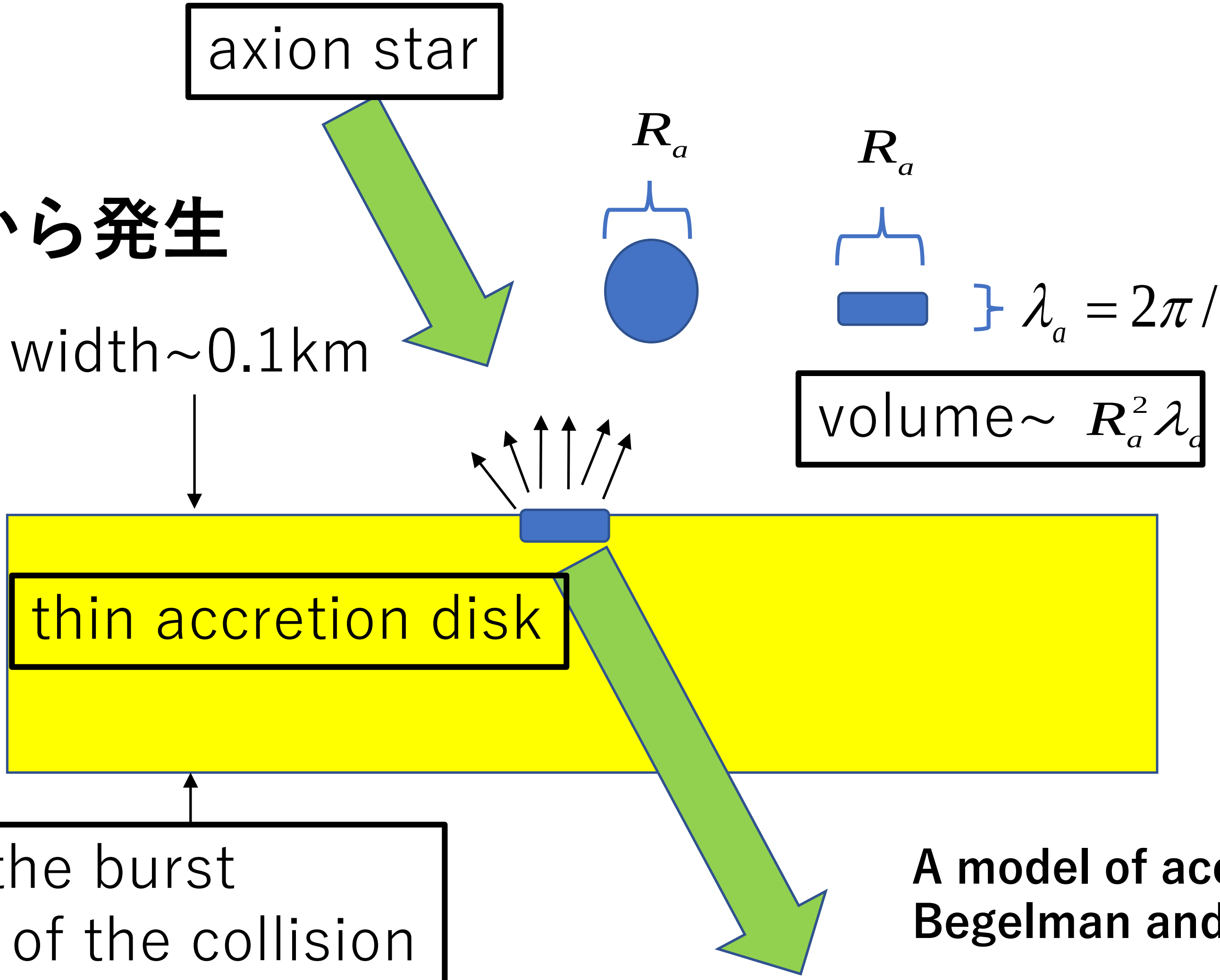
Collision between axion star and accretion disk
アクシオン星と膠着円盤の衝突

Dark matter axion stars condensing in the center of galaxy



暗黒物質として
アクシオン星は
銀河中心に数多くある

バーストは表面から発生



$\lambda_a = 2\pi / m_a \sim 20cm \dfrac{0.6\times10^{-5}eV}{m_a}$

emission rate of the burst
from the location of the collision

A model of accretion disk
Begelman and Silk (2017)

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

高電子密度 **強い磁場**

十分強いバーストを発生

termination of coherent radiations

Oscillating electric field $\vec{E} \propto \cos(m_a t)$

oscillating electrons

$$\frac{d\vec{p}}{dt} = e\vec{E}$$

電場による電子の振動は、振動エネルギーの熱化のために、温度上昇により、そのコヒーレントはストップしてしまう。

oscillation energy $p^2/2m_e \sim (eE)^2/m_e m_a^2 \sim 10^5 eV\left(\frac{B}{10^{11}G}\right)^2 \approx T_c$ temperature

電子ガスの温度が振動のエネルギーに等しくなるとこで、コヒーレントな放射は止まる

Temperature of electron gas increases and reaches $T_c \sim 10^5 eV\left(\frac{B}{10^{11}G}\right)^2$

Thermal fluctuations terminate the coherent oscillation.

熱揺らぎでコヒーレンスが消える

Line spectrum thermally broaden

熱揺らぎを受けて、ラインスペクトルは広がる。幅$\delta\nu$ は電子ガスの温度T_cで決まる

$$S(\nu) \propto \exp\left(-\frac{(\nu-\nu_c)^2}{2(\delta\nu)^2}\right), \qquad \delta\nu = \nu_c\sqrt{\frac{T_c}{m_e}}, \quad T_c \approx 10^5 eV\left(\frac{B}{10^{11}G}\right)^2$$

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

$\delta\nu \propto \nu_c$ バンド幅はセンター振動数 ν_c に比例

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

coincident with recent observation; arXiv:1705.07553

エネルギー発生率とバンド幅を説明するのに必要な磁場の強さが一致

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

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

バンド幅 $\delta\nu$ はセンター振動数 ν_c に比例

（熱効果でスペクトルの広がりを示唆）

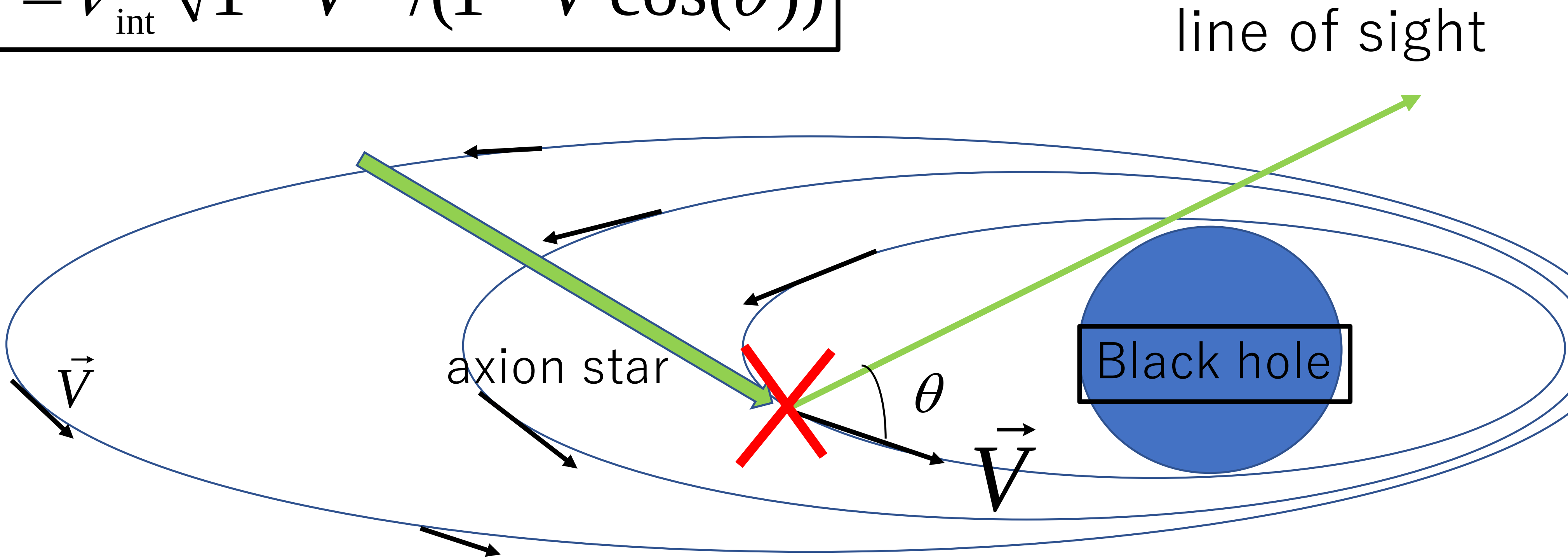
Our model is almost coincident with recent observations !!!

様々なセンター振動数の存在は、衝突地点の膠着円盤の速度の違い（ドップラー効果）

Various center frequencies ν_c arise from the velocities $\vec{V}$ of the accretion disk $\nu_c = 1.3Ghz \sim 3GHz$; **Doppler effect**

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

$$\nu_{int} = \frac{m_a}{2\pi}$$



高振動数(>5GHz)、低振動数(<100MHz)のバーストが観測されない理由

No observations of bursts with high frequencies > 5GHz

No observations of bursts with low frequencies < 100MHz

These facts can be understood in the following

極めて高速な円盤との衝突、あるいは視線方向が速度方向と一致

We need large $V \sim 0.95$ for $\nu_c > 5GHz$
The collision might be very rare.

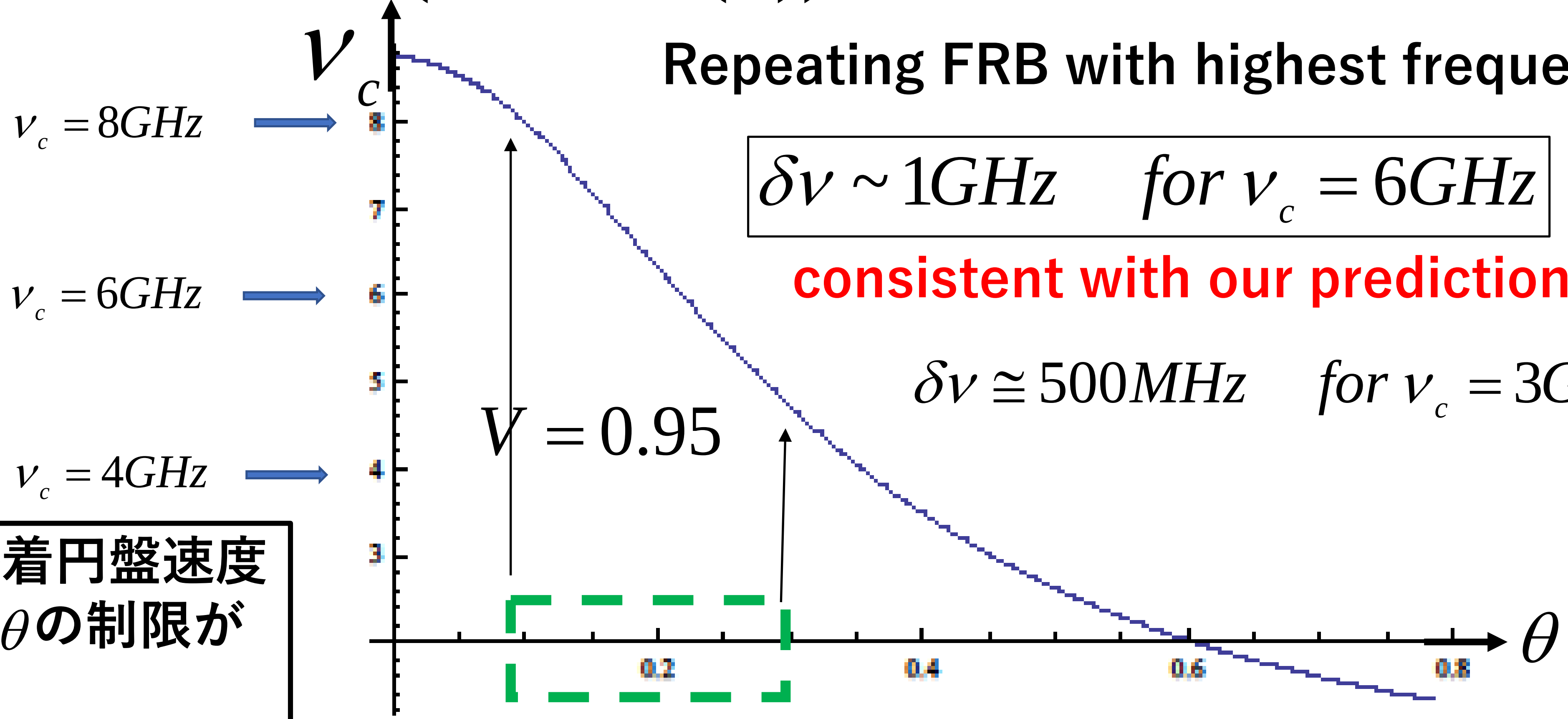
まれな現象

We need very large $V > 0.99$ and $\theta \sim \pi$ for $\nu_c < 100MHz$
The collision is very rare.

極めてまれな現象！！！

Very new observations using the Green Bank telescope
4GHz< ν_c < 8GHz, <u>showing finite bandwidths!!</u>
15 events in FRB121102

$$\nu_c = 1.4GHz\sqrt{1-V^2}/(1-V\cos(\theta))$$



Repeating FRB with highest frequencies

$\delta\nu \sim 1GHz \quad for\ \nu_c = 6GHz$

consistent with our prediction!!!

$\delta\nu \cong 500MHz \quad for\ \nu_c = 3GHz$

視線方向と膠着円盤速度方向との角度θの制限が緩くてもＯＫ

conclusion

We propose a model that repeating and non repeating FRBs are generated by the collisions between axion stars and magnetized ionized gas (neutron star or accretion disk)

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

$\delta\nu \cong 500MHz \quad for\ \nu_c = 3GHz,$

$\delta\nu \cong 300MHz \quad for\ \nu_c = 2GHz,$

$\delta\nu \cong 200MHz \quad for\ \nu_c = 1.2GHz$

- **Bandwidth** $\delta\nu = 3GHz\sqrt{\frac{T_c}{m_e}} \cong 430MHz\frac{B}{3.3\times10^{10}G}$

Large emission rate ↕ **Identical magnetic field**

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

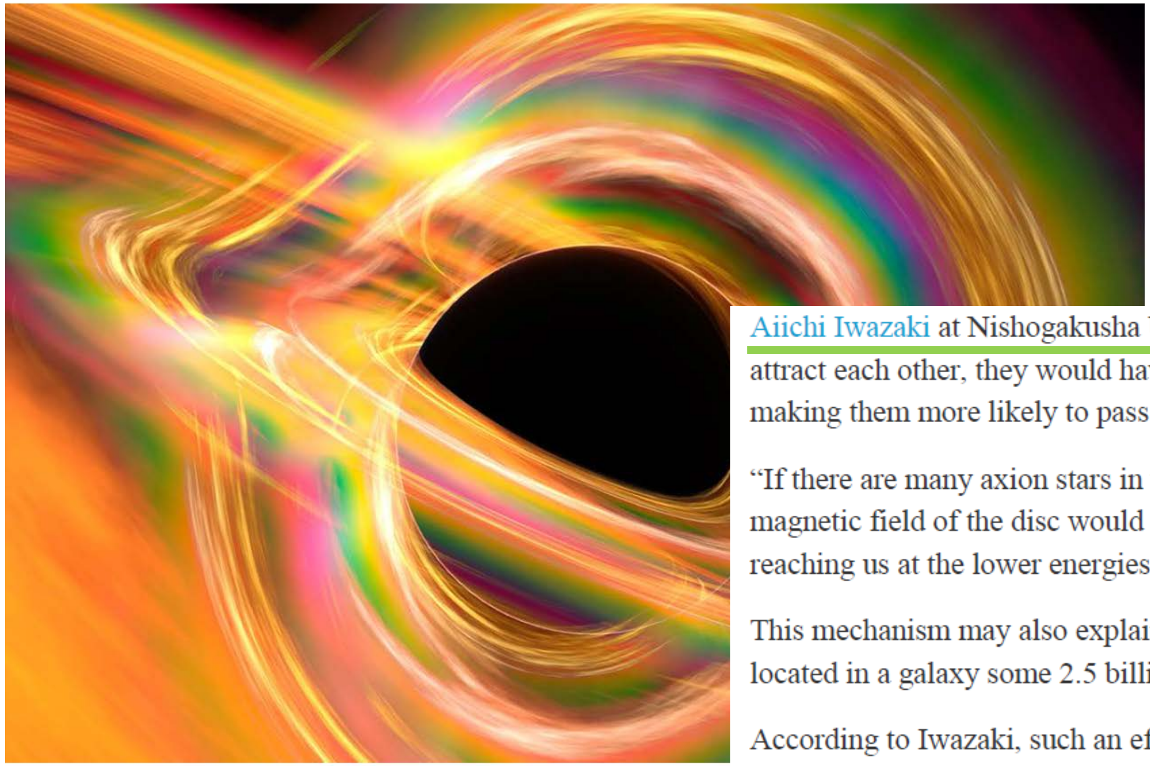
- **Various center frequencies** $\nu_c = \nu_{\rm int}\sqrt{1-V^2}/(1-V\cos(\theta))$ **from Doppler effect**

  $\nu_c = 1.2Ghz \sim 3GHz$

- **No observations of bursts with low frequencies <100MHz**
- **Repeating bursts from several collisions of a single axion star orbiting black hole**
  Such collisions subsequently take place; many dark matter axion stars in galactic center

Fast radio bursts may be dark matter 'stars' hitting black holes

"New Scientist"



Fit to burst
Alfred Pasieka/SPL

Aiichi Iwazaki at Nishogakusha University in Tokyo says that because the early universe was smaller and offered more chances for axions to attract each other, they would have clumped together to form axion "stars". Their tendency would be to cluster near the centre of galaxies, making them more likely to pass near the supermassive black holes that sit there and run into the accretion discs of gas that surround them.

"If there are many axion stars in the centres, we expect that some of them collide with the black hole accretion disc," says Iwazaki. The magnetic field of the disc would cause some axions to decay into individual photons that are then seen on Earth as a fast radio burst (FRB), reaching us at the lower energies of radio wavelengths. There would be enough photons that the signal would still be bright.

This mechanism may also explain why some FRBs repeat at irregular intervals. So far, only one repeating burst has been found: FRB 121102, located in a galaxy some 2.5 billion light years away.

According to Iwazaki, such an effect could result from an axion star passing through a black hole's accretion disc over and over. It would do so at irregular intervals until the disc's magnetic field converted enough axions to photons that the axions could no longer form a compact clump.

In 2015, Iwazaki theorised that FRBs were the product of axion stars hitting the magnetic fields of neutron stars, the corpses of stars several times the sun's mass. That wouldn't explain the repetition seen from FRB 121102, because neutron stars don't have accretion discs that would simply pull material off the axions rather than destroying them.

Axion reaction

Leslie Rosenberg at the University of Washington in Seattle says Iwazaki's idea could be supported by mainstream physics, and that suggesting exotic sources for unexplained phenomena can be useful in any case.

One issue with Iwazaki's model is that he assumes axions interact more strongly with magnetic fields than is suggested by many other theories, says Rosenberg.

Dark matter may be source of mysterious «alien radio»

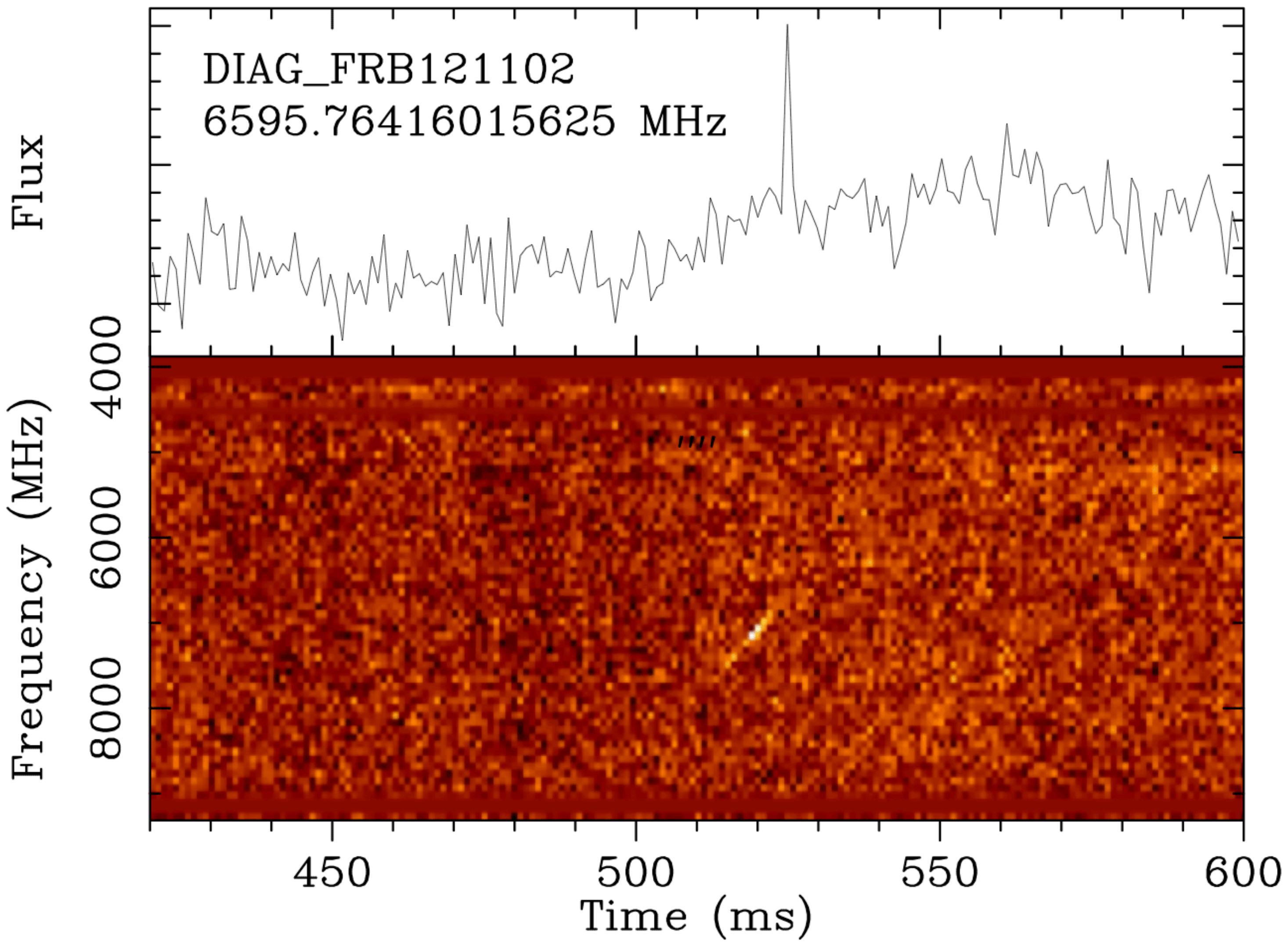
POSTED BY: NEWSMAKER 02.08.2017

© NASA / JPL-CaltechРисунок stars that is absorbed by a supermassive black hole

© NASA / JPL-Caltech

. Mysterious fast radiospace, the nature of which scientists argue for ten years, can occur as a result of collision of large concentrations of dark matter with black holes, according to the online magazine New Scientist.

«If in the centers of galaxies have a large number of clusters of axion dark matter, then such «dark stars» frequently collide with the accretion disk of a supermassive black hole. The powerful magnetic field of the disk should cause some of the axions to decay and to produce a flash, reaching to us in the form of a quick burst,» says Eiichi, Iwazaki (Aiichi Iwazaki), astronomer from the University of Nishogakusha in Tokyo (Japan).


DIAG_FRB121102
6595.76416015625 MHz
Flux
Frequency (MHz)
4000
6000
8000
450
500
550
600
Time (ms)