



高速電波バーストの 連星モデルとFRB121102

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arXiv : 2105.14480

2021 8/21 Extreme Outflows in Astrophysical Transients



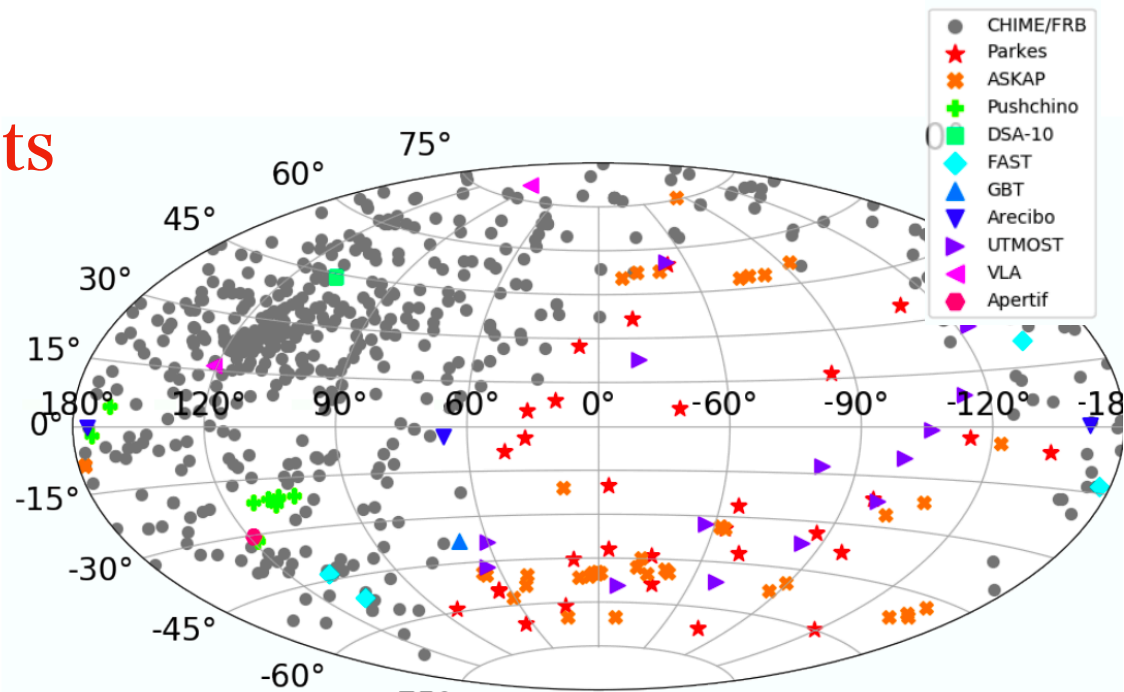
Introduction : FRB

Most luminous radio transients

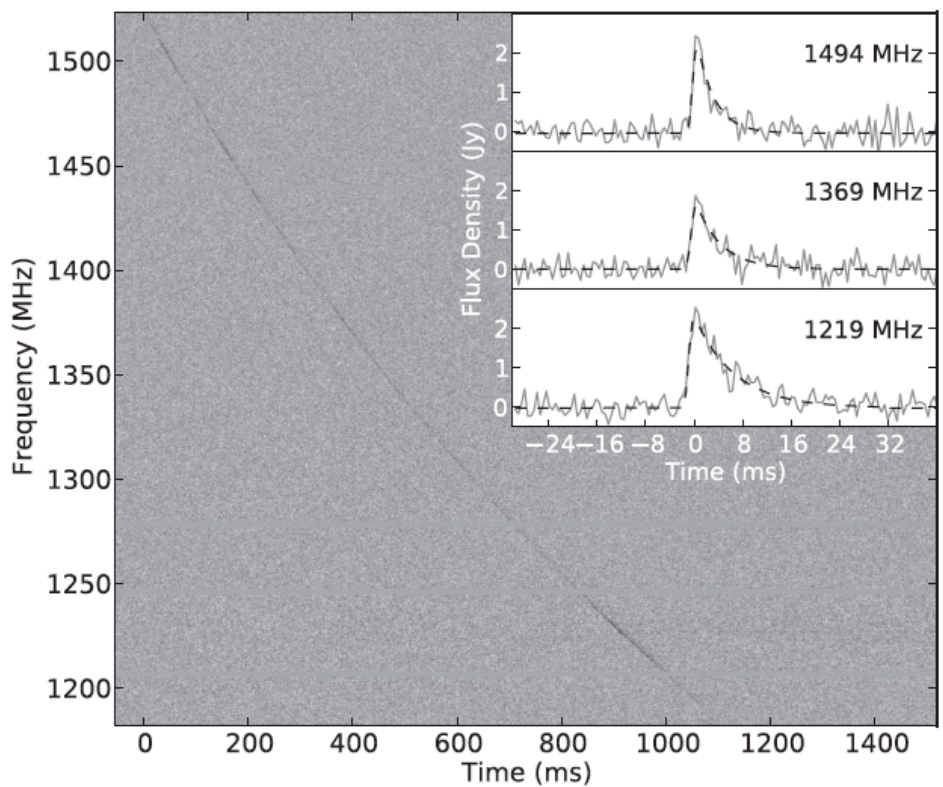
Fast : $\Delta t \sim O(\text{ms})$

Radio : $\nu \sim 150 \text{ MHz} - 8 \text{ GHz}$

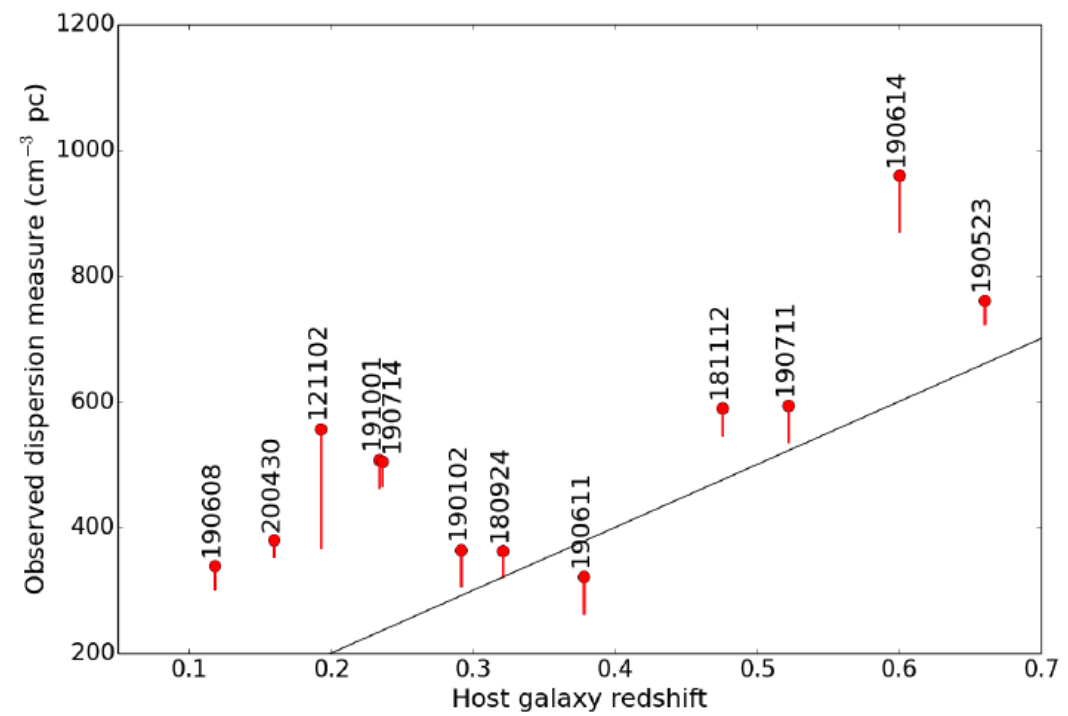
Burst : $L \sim 10^{37} \text{ erg s}^{-1} - 10^{46} \text{ erg s}^{-1}$



(Petroff et al. 2021)



(Thornton et al. 2013)

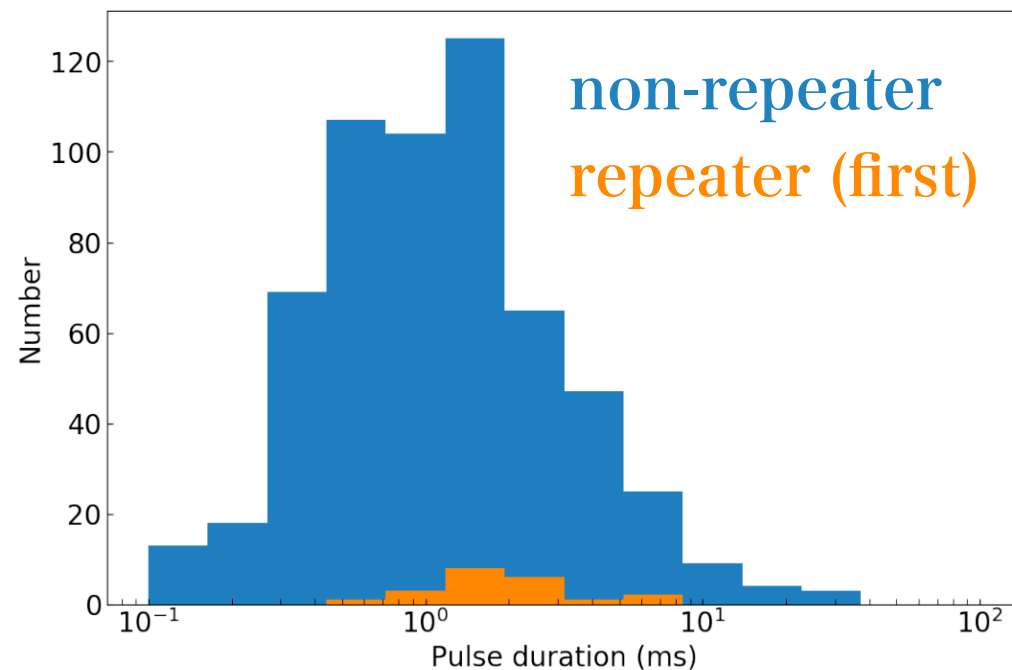
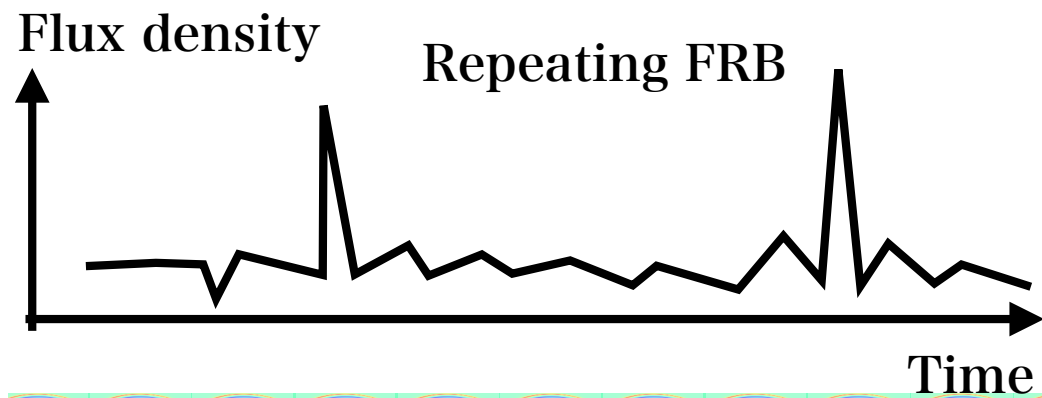
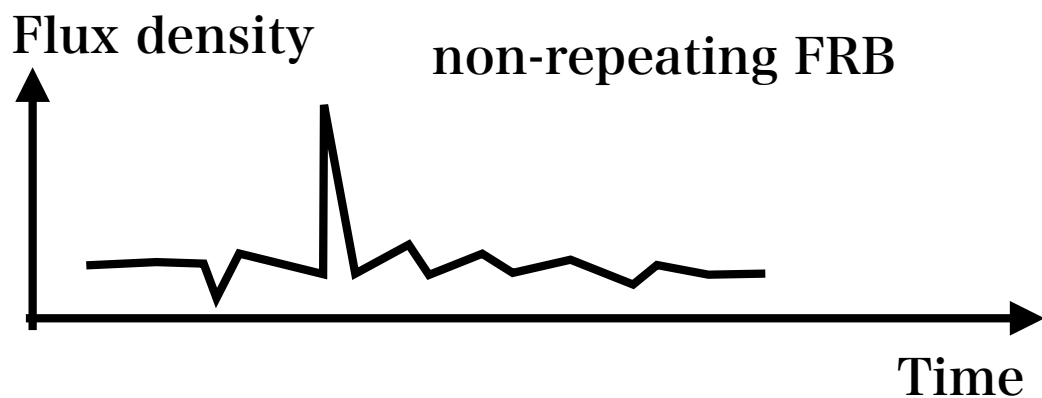


(Petroff et al. 2021)

リピーター&ノンリピーター

観測されているFRBのうち、いくつかは繰り返し観測されている。

- non-repeater … 600 以上
- repeater … 24 sources
 - > うち2例で周期性が観測されている。
(FRB 180916, FRB 121102)



(Petroff et al. 2021)

FRB 121102

Burst properties

Energy peak

$$E_0 \sim 5 \times 10^{37} \text{ erg}$$

Change in DM

$$\Delta\text{DM} \simeq 6 \text{ cm}^{-3} \text{ pc}$$

High rotation measure

$$\text{RM} = 1.46 - 1.33 \times 10^5 \text{ rad/m}^2$$

Host galaxy

Dwarf galaxy @ $z = 0.193$

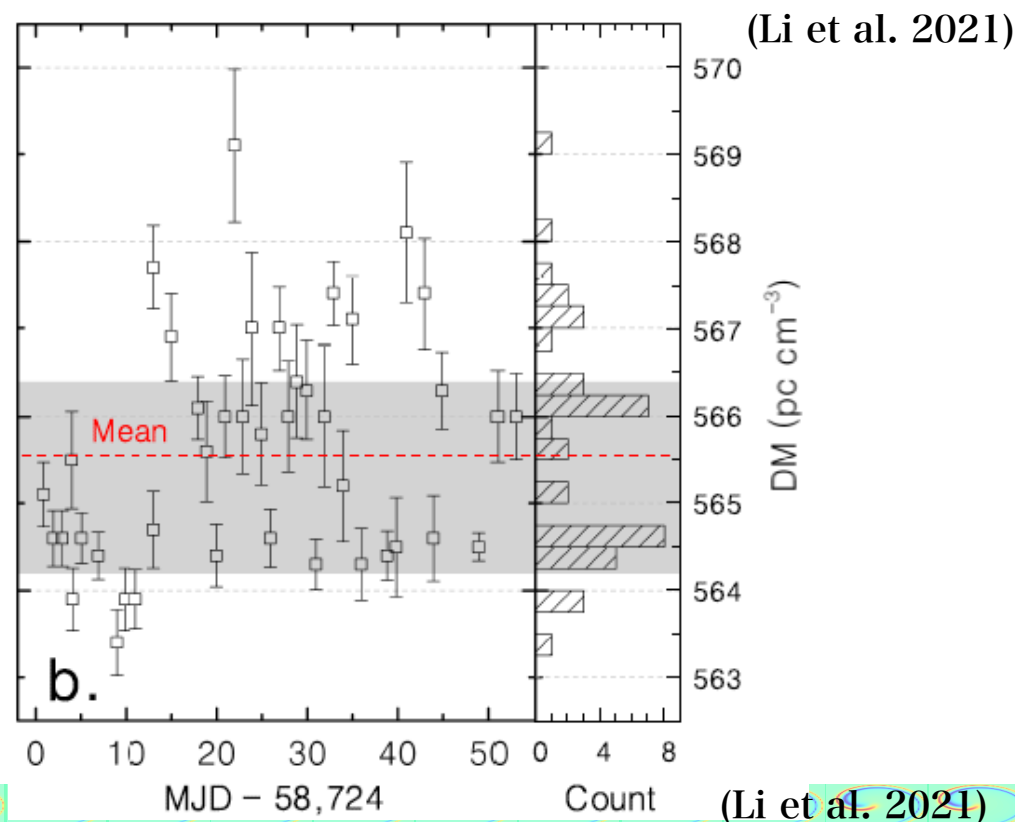
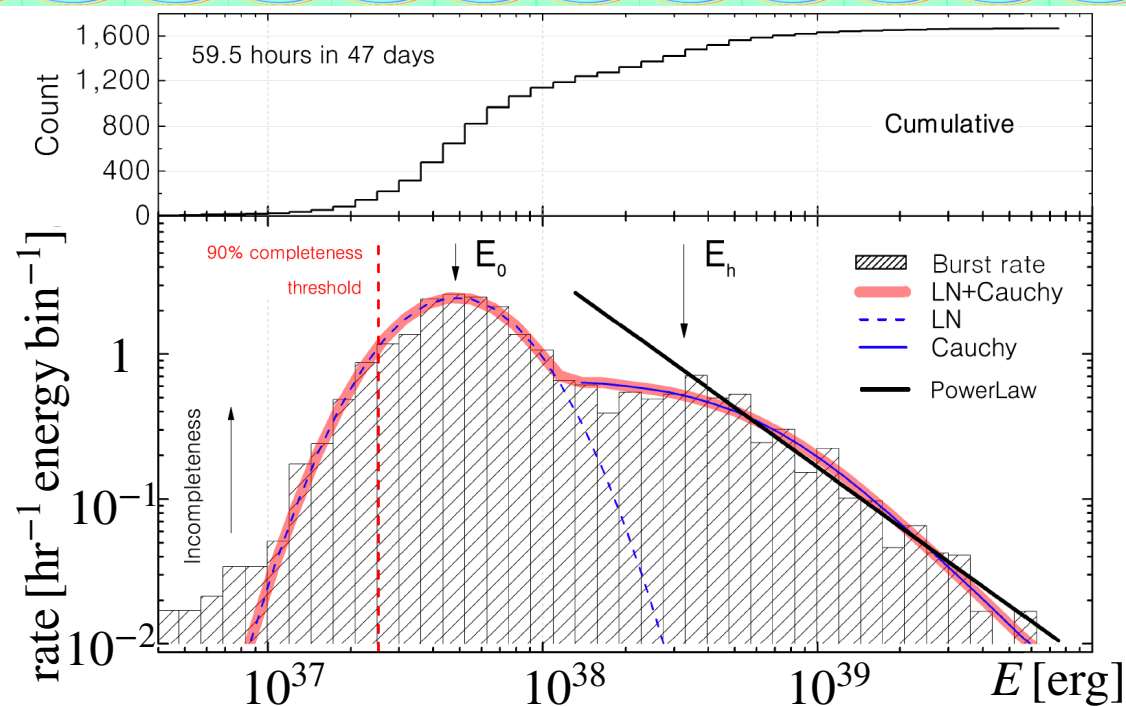
$$(D_L = 972 \text{ Mpc})$$

Mass $M_* \sim 4 - 7 \times 10^7 M_\odot$

Persistent radio emission

$$\nu L_\nu \sim 10^{39} \text{ erg/s}$$

size $< 0.7 \text{ pc}$, off center



FRB 121102

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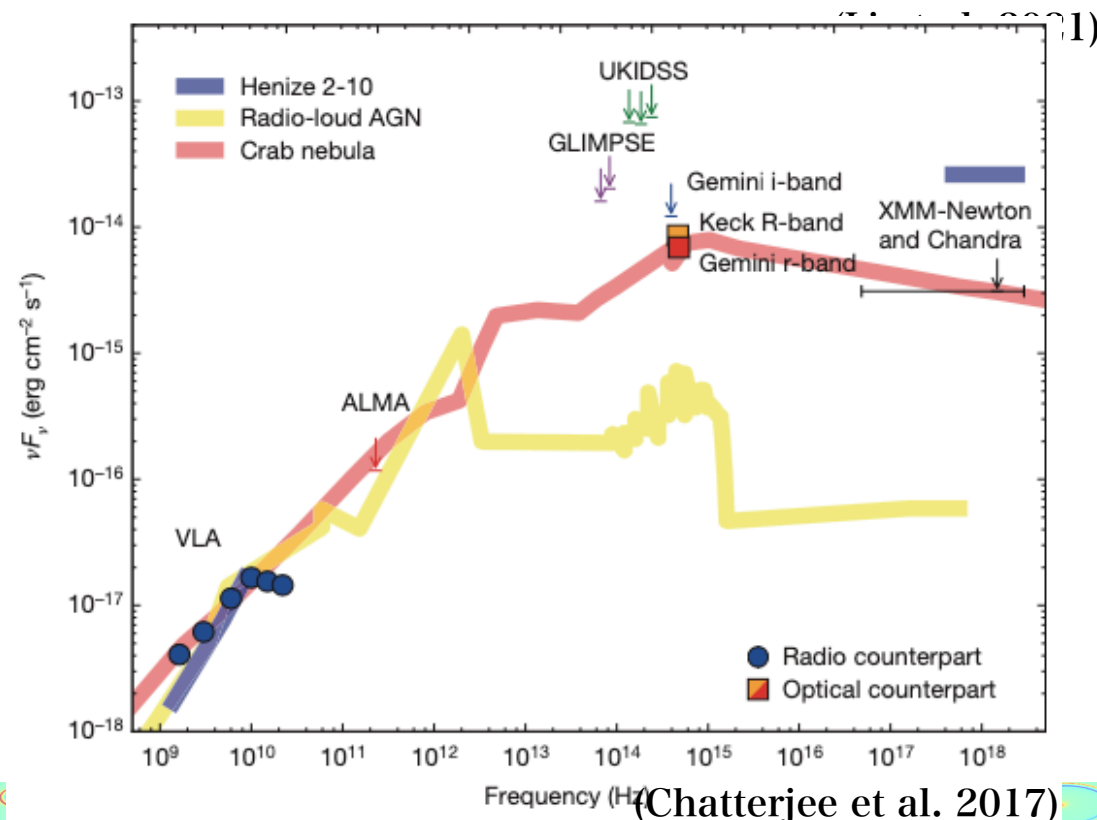
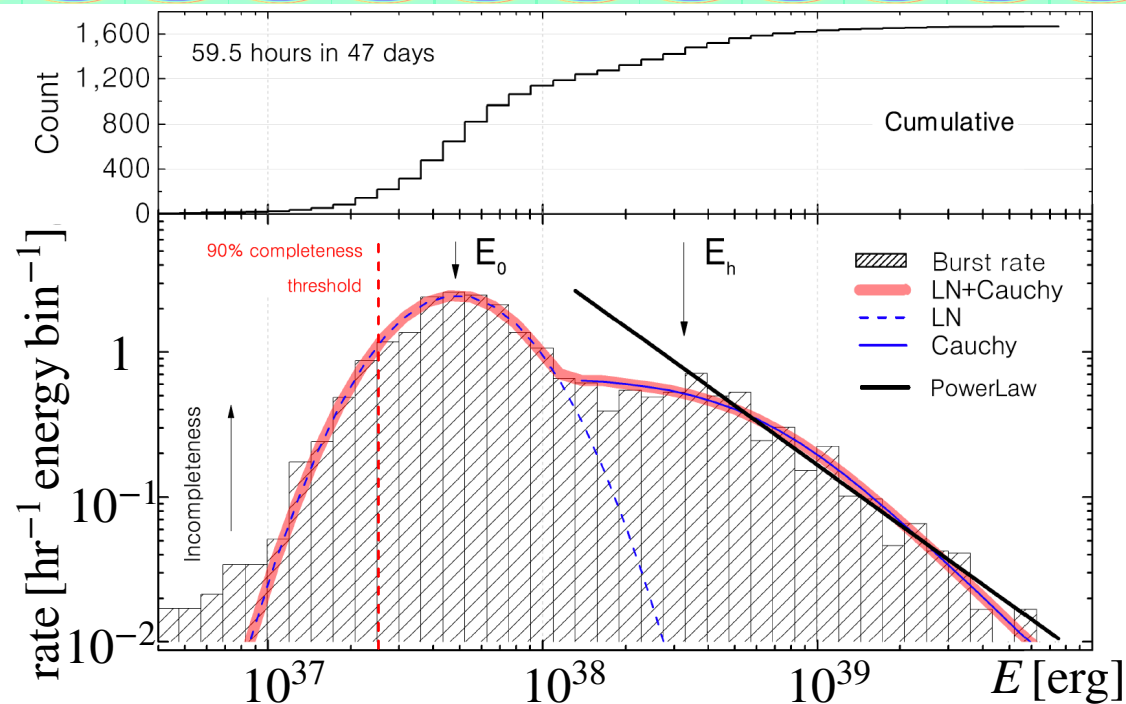
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FRB 121102の周期性

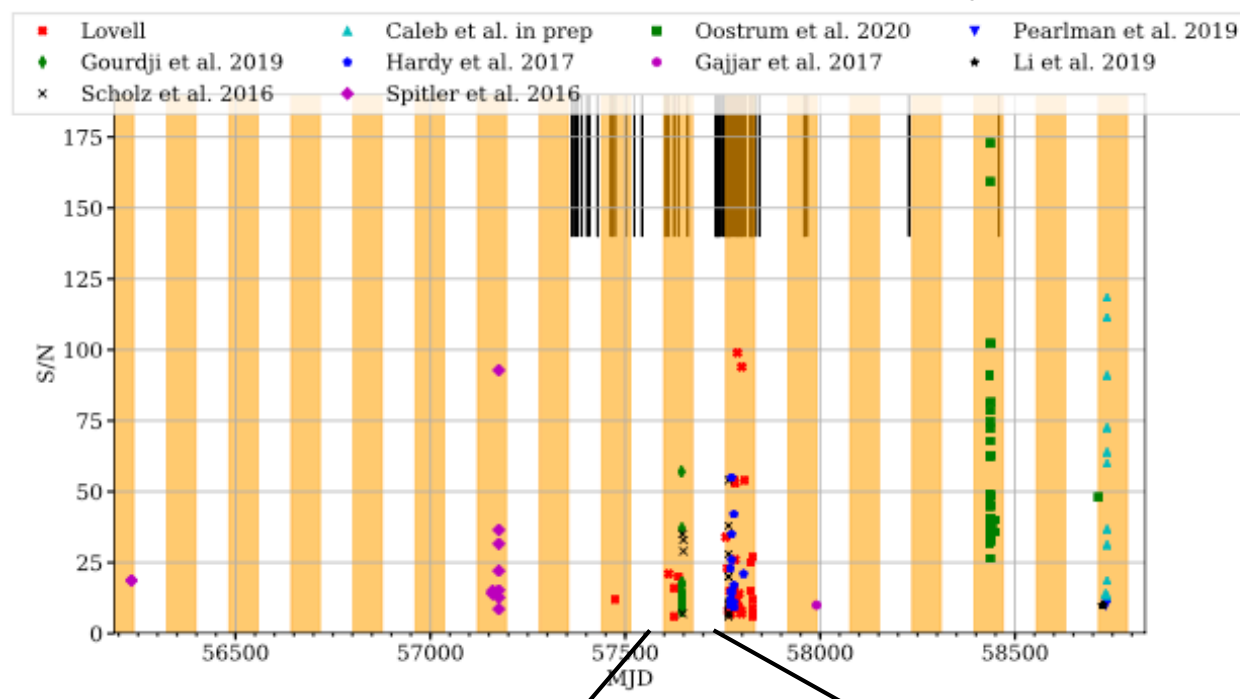
Rajwade+ 2020

FRB 121102 : 周期的な活動

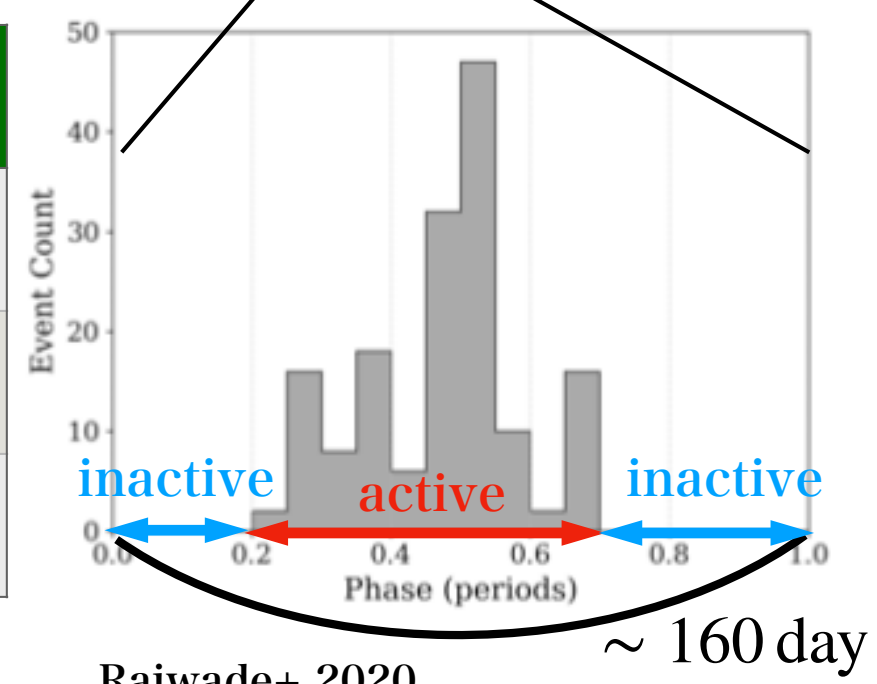
周期 ~ 160 day

active window ~ 47 – 60 %

160日周期のうち、
active windowの間だけ、
バーストが観測されている。



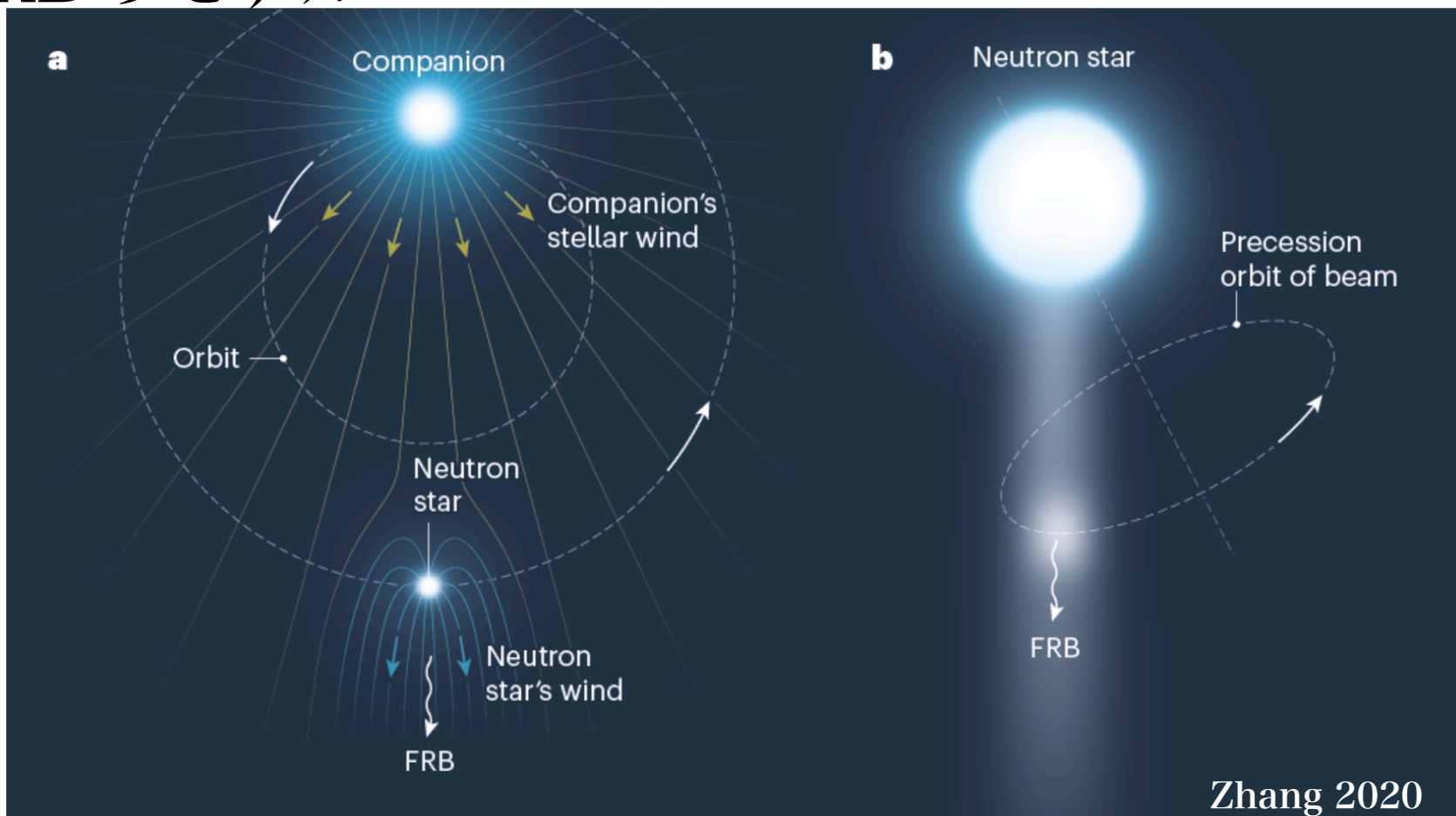
	period	active window
Rajwade + 2020	159^{+3}_{-8} day	47 %
Cruces + 2020	161 ± 5 day	54 %
Fast 2021?	157 day	57 – 60 %



Rajwade+ 2020

~ 160 day

周期FRBのモデル



FRBの周期が..

- 連星の軌道周期由来
- 中性子星の歳差運動周期由来
- 中性子星の自転周期由来

(Lyutikov+2020, Ioka & Zhang2020, Du+2020, Kuerban+2021, Deng+2021,...)

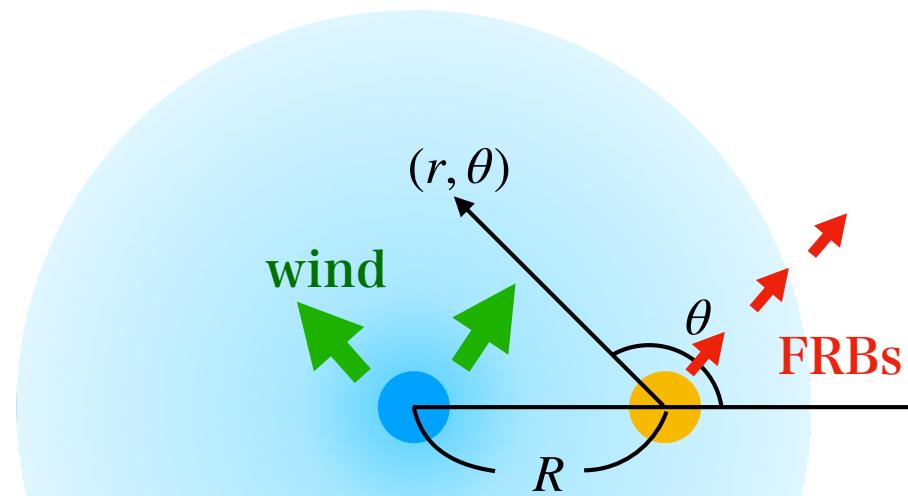
(Levin+2020, Zanazzi & Lai 2020, Yang+2020, Li & Zanazzi 2021, Sridhar+2021,...)

(Beniamini+ 2020,Xu+ 2021,...)

連星のopacity

伴星のウインド(outflow)の粒子数密度

$$n(r) = \frac{\dot{M}}{4\pi m_p V (r^2 + R^2 + 2Rr \cos \theta)}$$



Thomson scattering

$$\tau_{\text{Th}} \sim 6.7 \times 10^{-2} \left(\frac{\dot{M}}{10^{-5} M_{\odot} \text{yr}^{-1}} \right) \left(\frac{V}{10^{-2} c} \right)^{-1} R_{13}^{-1} \begin{cases} \frac{\pi}{2} - \varphi & (\theta \neq 0, \pi) \\ (1 + r/R)^{-1} & (\theta = 0, \pi) \end{cases}$$

$$\sin \theta \tan \varphi = r/R + \cos \theta$$

Free-free absorption

$$\tau_{\text{ff}}(r) \sim 1.8 \times 10^5 T_4^{-3/2} \nu_9^{-2} \bar{g}_{\text{ff}} \left(\frac{\dot{M}}{10^{-5} M_{\odot} \text{yr}^{-1}} \right)^2 \left(\frac{V}{10^{-2} c} \right)^{-2} R_{13}^{-3} \begin{cases} \frac{1}{2 \sin^3 \theta} \left(\frac{\pi}{2} - \varphi - \frac{\sin 2\varphi}{2} \right) & (\theta \neq 0, \pi) \\ \frac{1}{3(1 + r/R)^3} & (\theta = 0, \pi) \end{cases}$$

Induced Compton scattering

$$\tau_{\text{IdC}}(r) \sim 2.1 \times 10^4 \nu_9^{-3} \left(\frac{\dot{M}}{10^{-5} M_{\odot} \text{yr}^{-1}} \right) \left(\frac{V}{10^{-2} c} \right)^{-1} R_{13}^{-4} (L_{\text{FRB}} \Delta t)_{38} \left[\frac{1}{x^2 (1 + x^2 + 2x \cos \theta)} \right]_{x=r/R},$$

連星はFRBに対して光学的に厚くなりうる -> 見えない

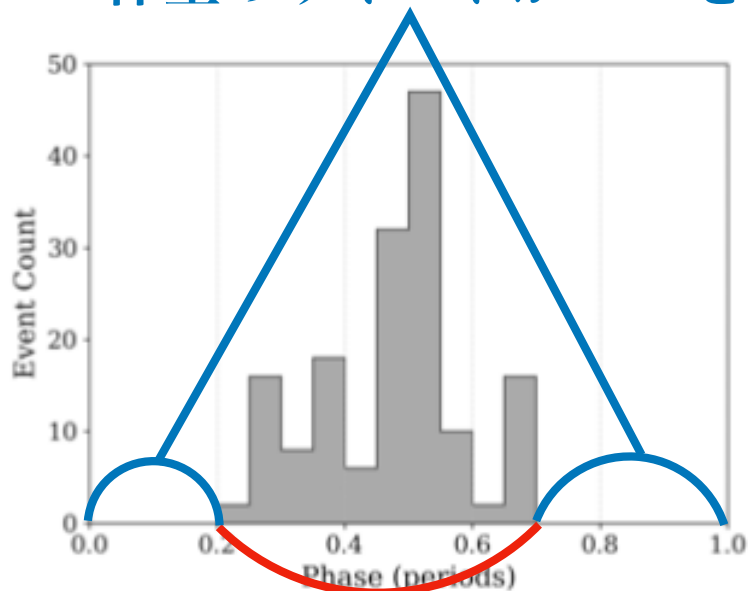
Funnel mode

Q. optically thick 連星でどのように周期が実現されるのか?

A1. FRBを出すパルサーが穴を開ける

視線方向が穴の外側

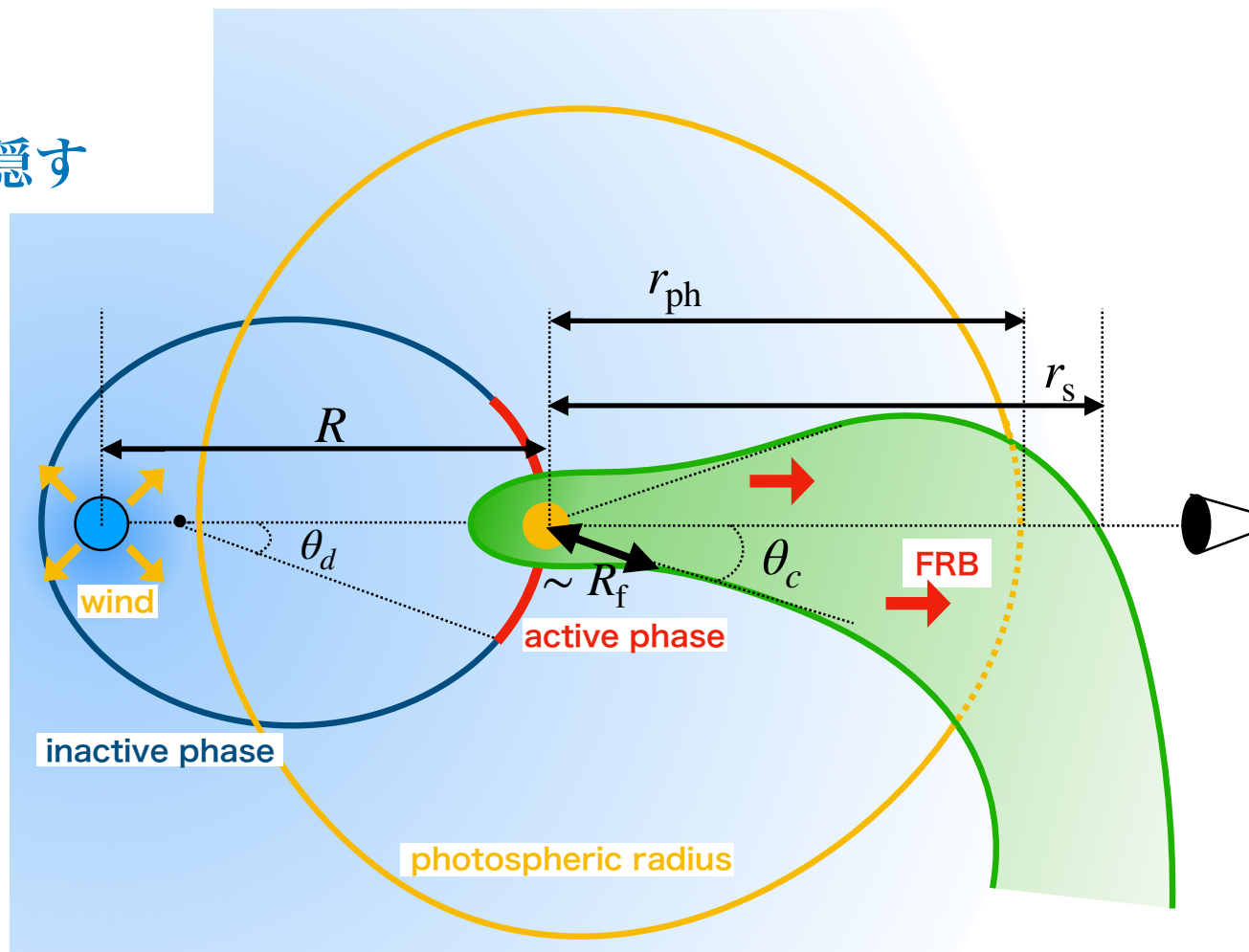
-> 伴星のウインドがFRBを隠す



視線方向が穴の内側

-> FRBは穴を通り

観測可能になる



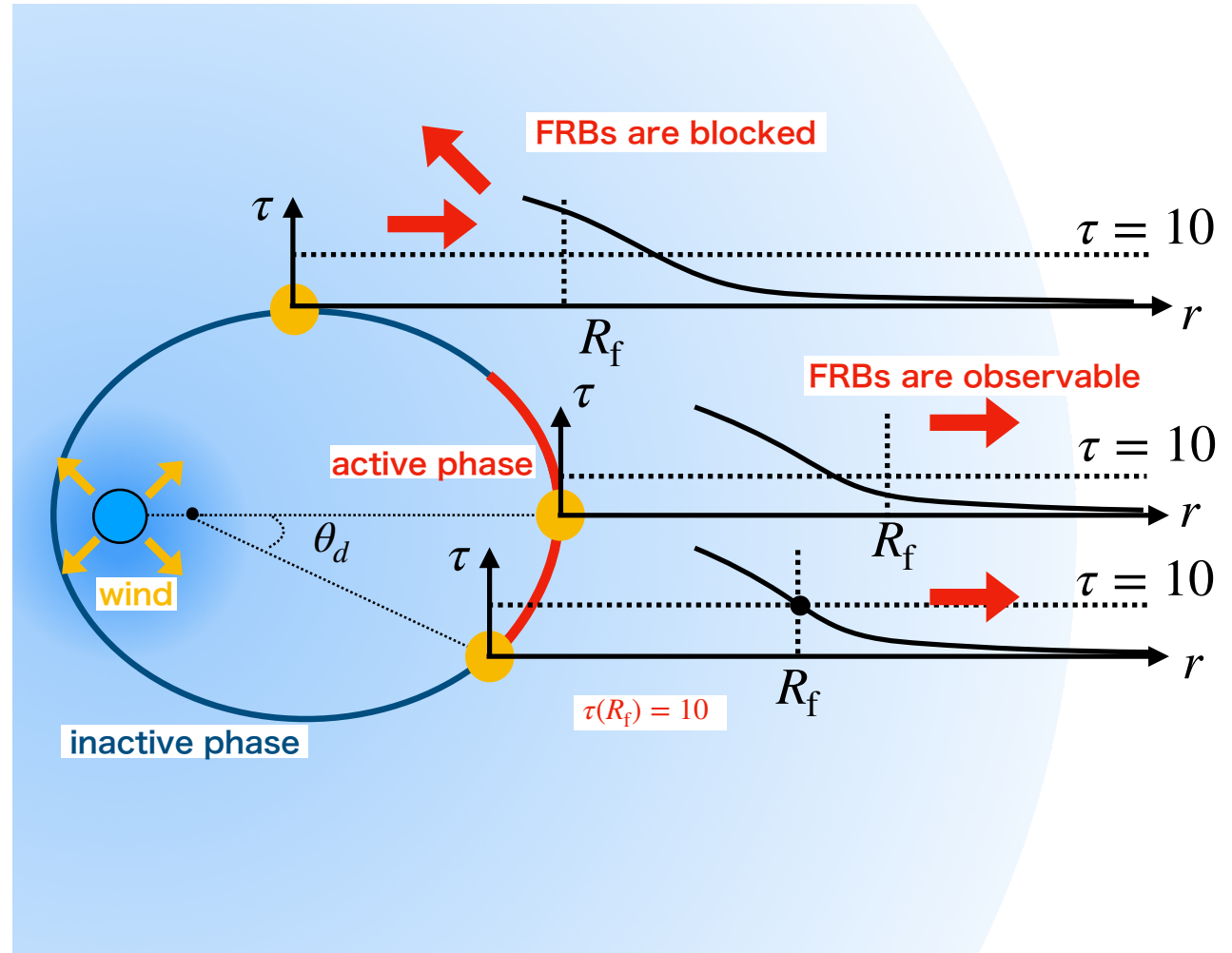
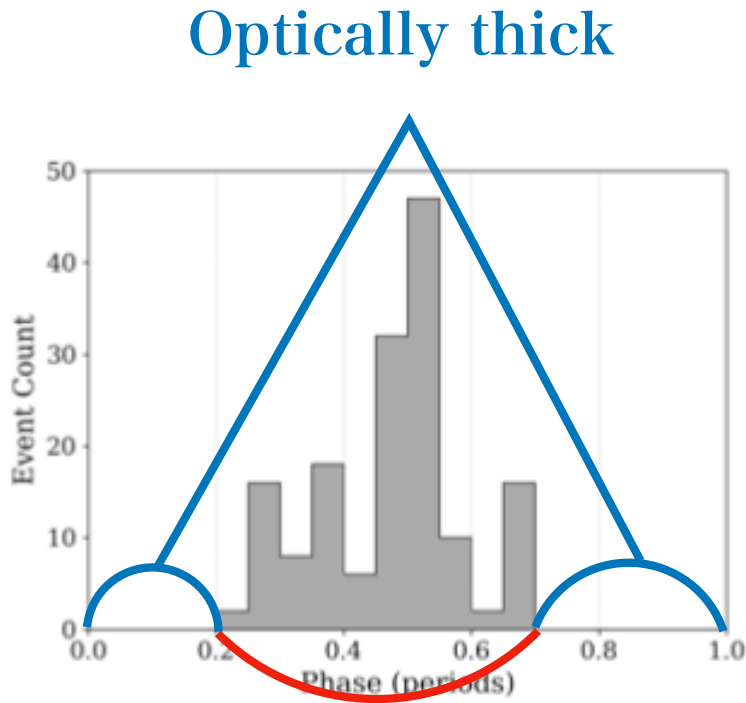
系がみたすべき条件

optically thick & active windowを説明する θ_c & $r_s > r_{ph}$

τ -crossing mode

Q. optically thick 連星でどのように周期が実現されるのか?

A2. 視線方向のoptical depthが位置によって変化する



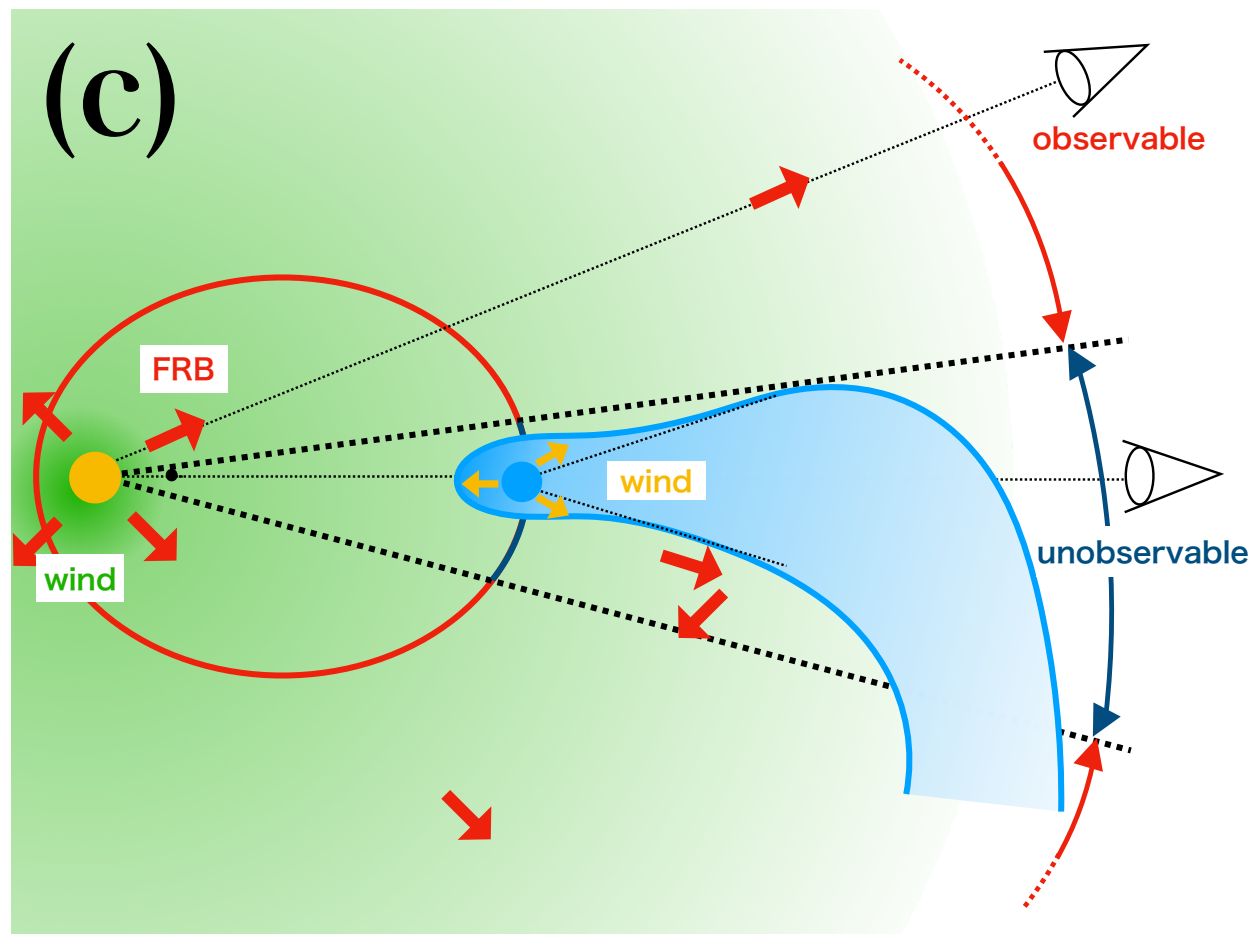
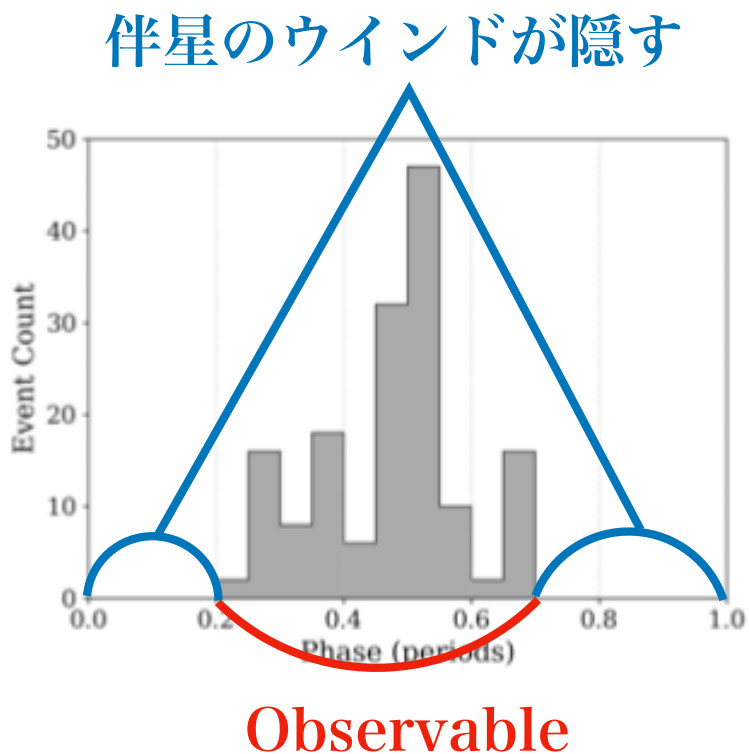
系がみたすべき条件

Optically thin@ active phase & thick@ inactive phase

Inverse funnel mode

Q. optically thick 連星でどのように周期が実現されるのか？

A3. FRBパルサーウインドが強いと伴星のウインドを押し返すことができる。



系が満たすべき条件

FRBパルサーウインドが $L_{\text{wind}} > \dot{M}cV$ を満たす

Binary comb model for FRB 121102

Q. 以上のモデルでどのような連星がFRB 121102のソースとなりうるか？

3種類の伴星を考える。

Companions	Mass	Wind velocity
Massive star	$10M_{\odot}$	$0.01c$
IMBH	10^3M_{\odot}	$0.1c$
SMBH	10^5M_{\odot}	$0.1c$

伴星質量とウインド速度を固定して、
FRBパルサー風の光度・伴星の質量放出率・連星の離心率を制限

使用したその他のパラメータ

period = 160 day, active window = 47%, change in DM $\Delta DM < 6 \text{ cm}^{-3} \text{ pc}$,

burst energy $L_{\text{FRB}} \Delta t = 1 \times 10^{38} \text{ erg s}^{-1}$, and persistent radio emission $L = 10^{39} \text{ erg/s}$.

Observer @ edge-on, from the direction of the apoapsis.

Supermassive black hole companion

$$M_c = 10^5 M_\odot$$

FRB pulsar wind
luminosity [erg/s]

$$V = 0.1c$$

$$a = 4 \times 10^{14} \text{ cm}$$

Persistent radio emission

-> AGN jet, nebula emission,
or disk wind で説明

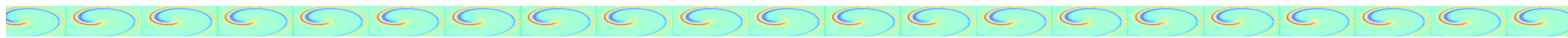
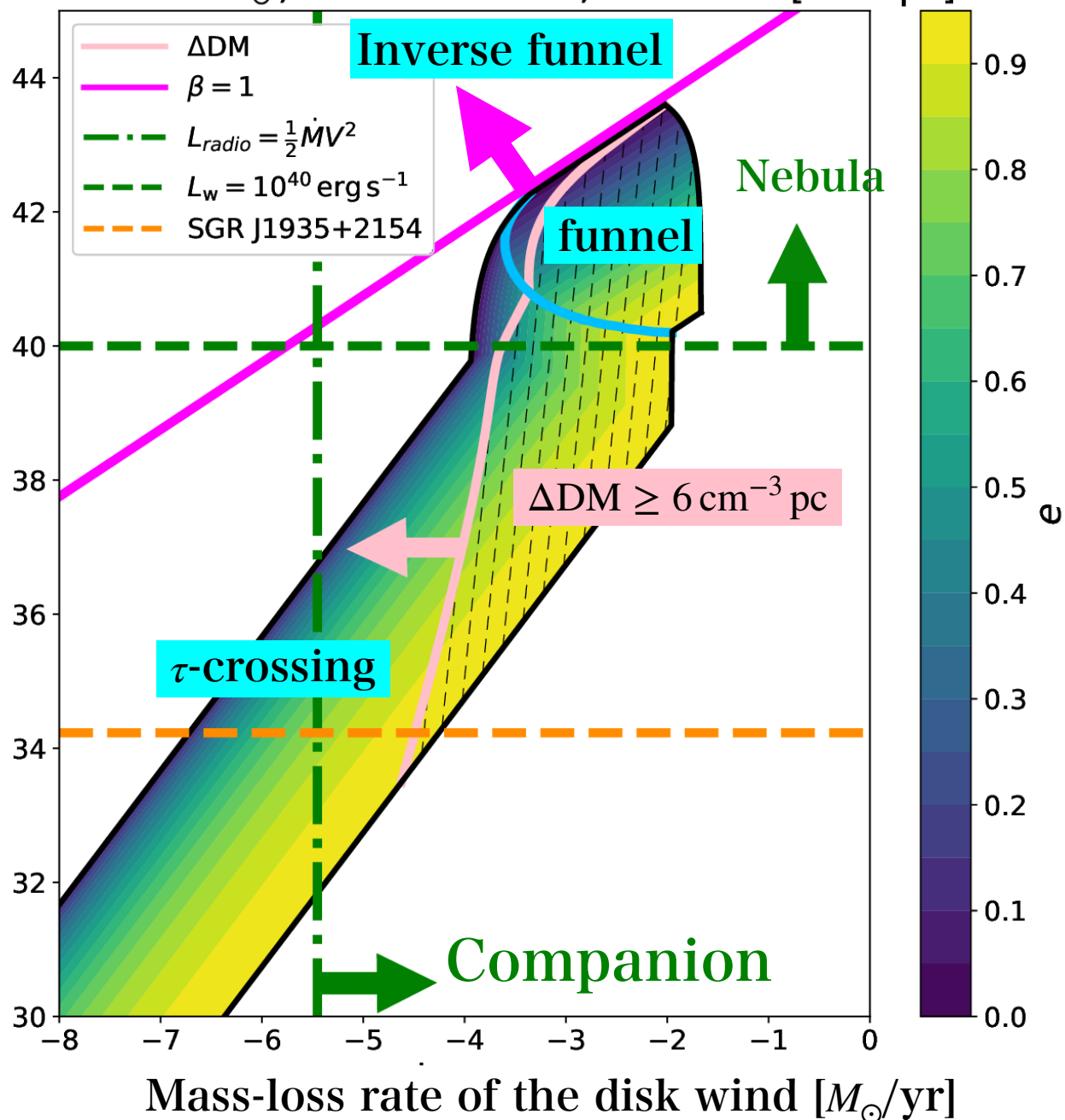
(radio emissivity $\gtrsim 10^{-4}$)

DMの変化 & high RM

-> 円盤風の時間変化

& SMBH 周辺の強磁場だろう

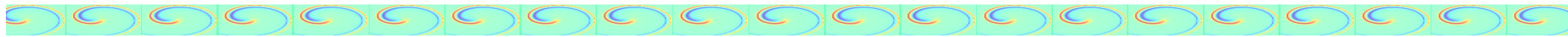
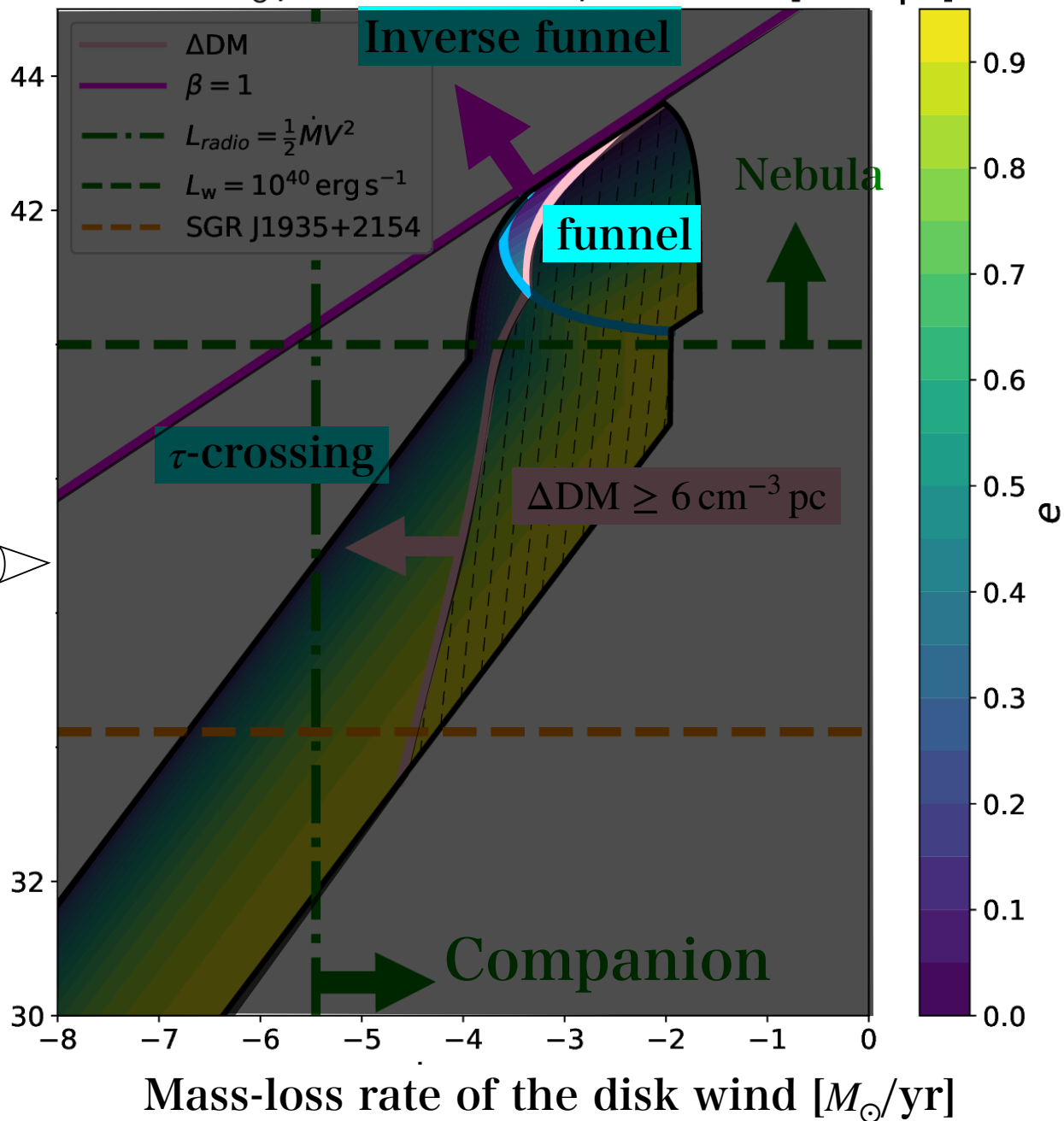
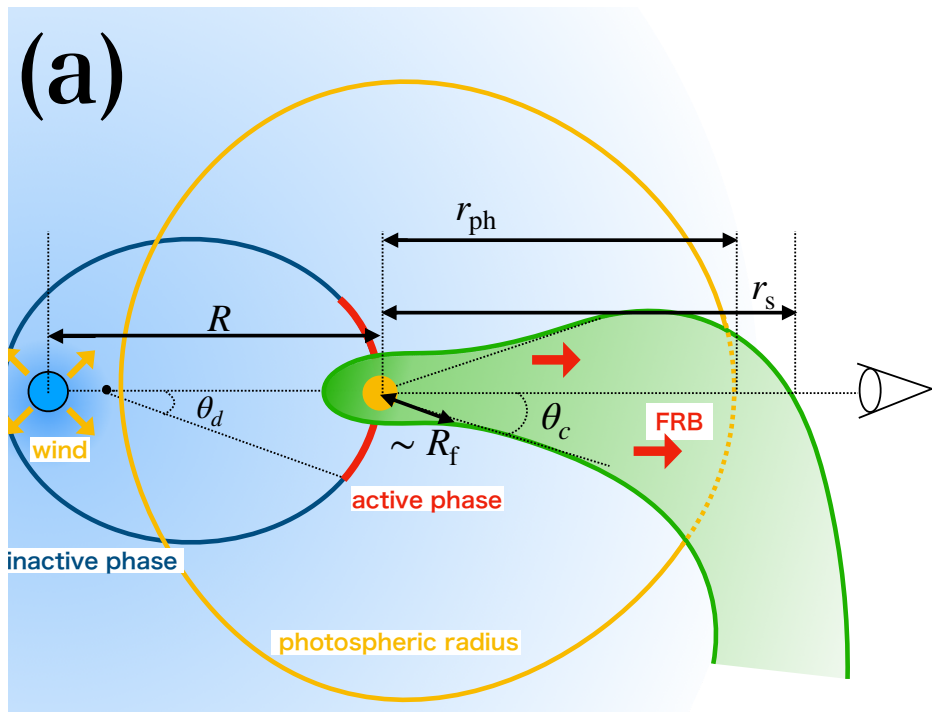
$$M = 1.0 \times 10^5 M_\odot, V = 1.0 \times 10^{-1} c, \Delta DM = 6.0 [\text{cm}^{-3} \text{ pc}]$$



Supermassive black hole companion

$M = 1.0 \times 10^5 M_\odot$, $V = 1.0 \times 10^{-1} c$, $\Delta DM = 6.0 [\text{cm}^{-3} \text{pc}]$

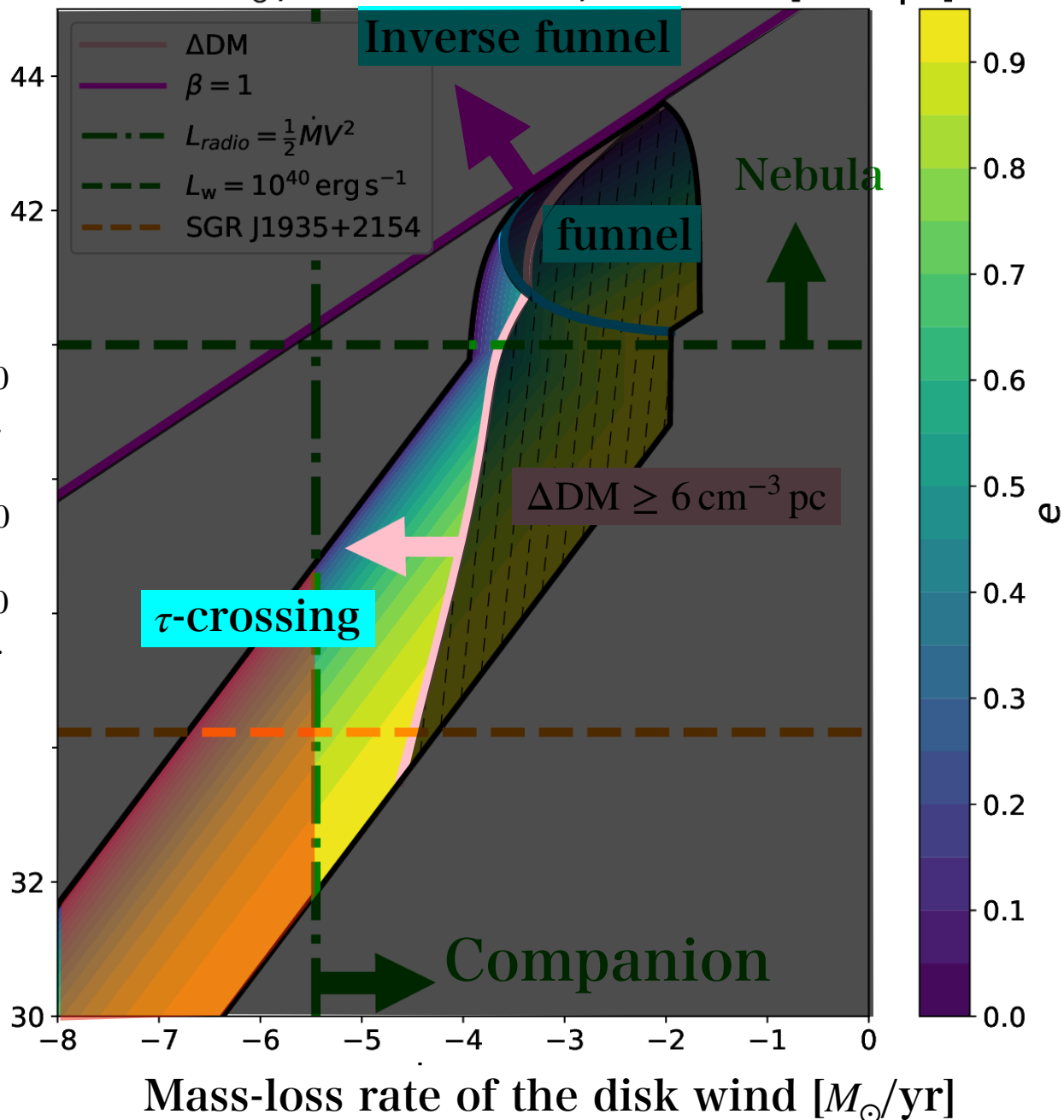
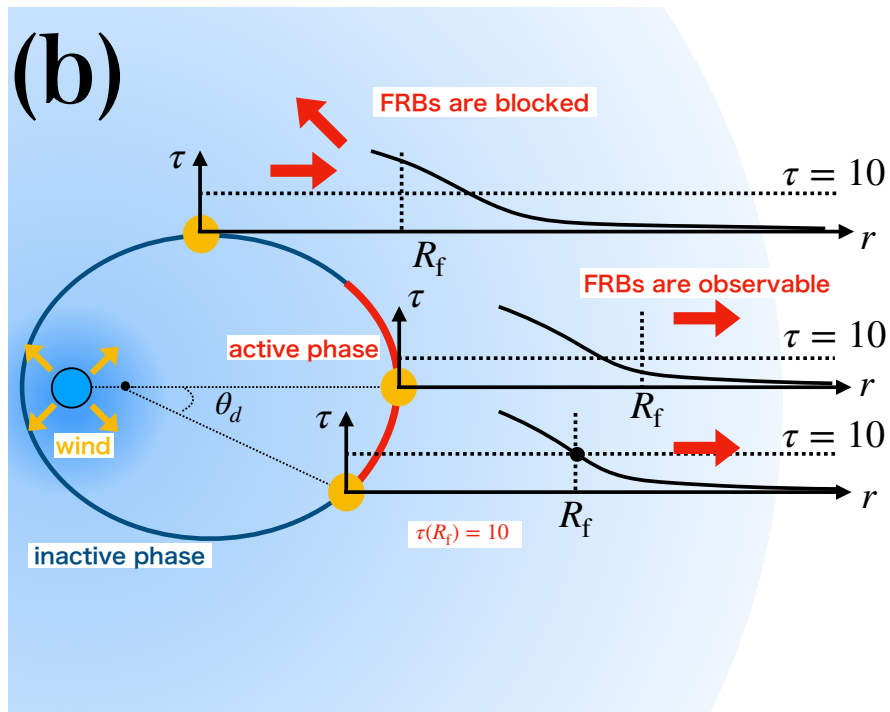
FRB pulsar wind
luminosity [erg/s]



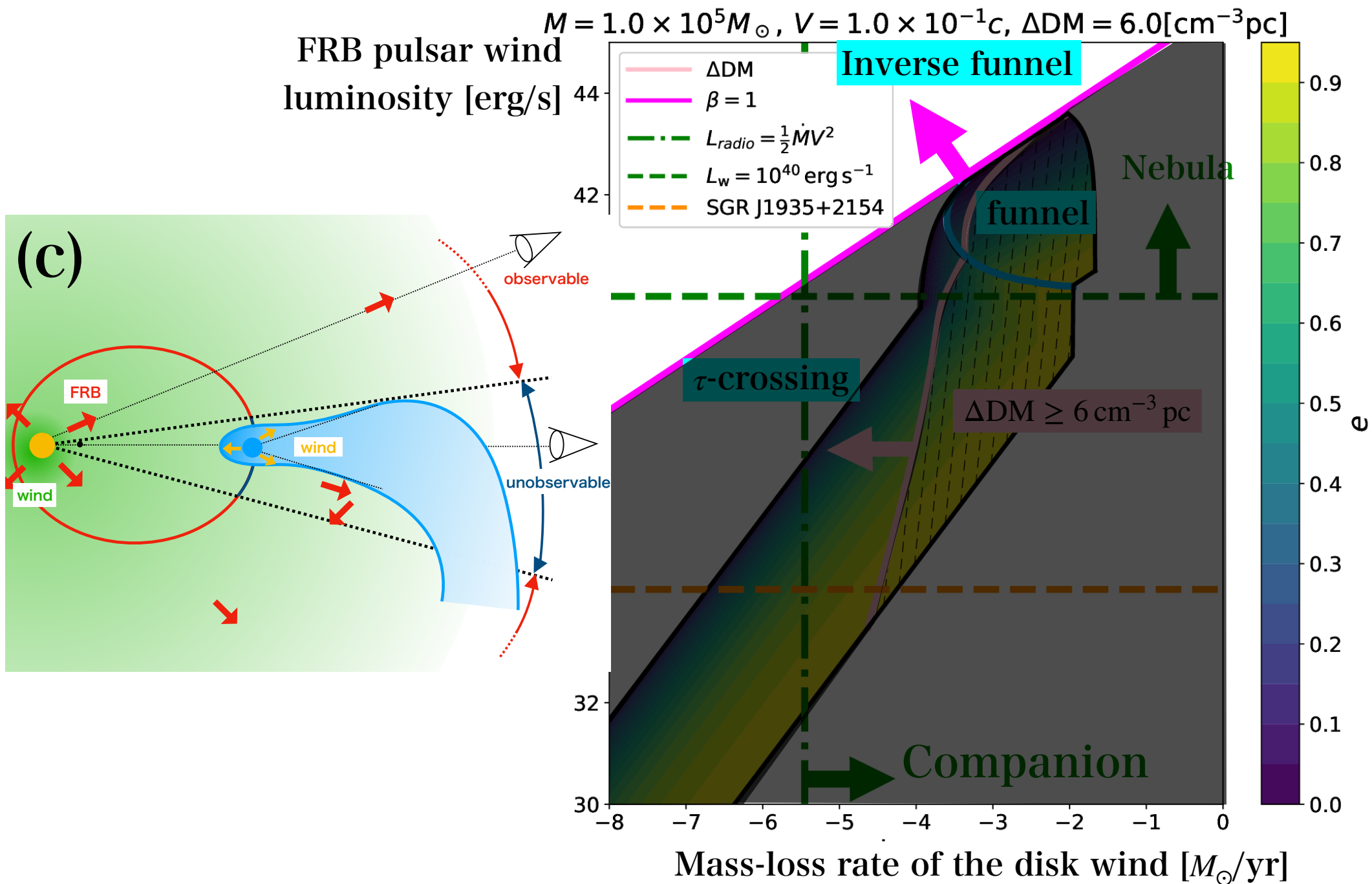
Supermassive black hole companion

$M = 1.0 \times 10^5 M_\odot$, $V = 1.0 \times 10^{-1} c$, $\Delta DM = 6.0 [\text{cm}^{-3} \text{pc}]$

FRB pulsar wind
luminosity [erg/s]



Supermassive black hole companion



Supermassive black hole companion

$$M_c = 10^5 M_\odot$$

FRB pulsar wind
luminosity [erg/s]

$$V = 0.1c$$

$$a = 4 \times 10^{14} \text{ cm}$$

Persistent radio emission

-> AGN jet, nebula emission,
or disk wind で説明

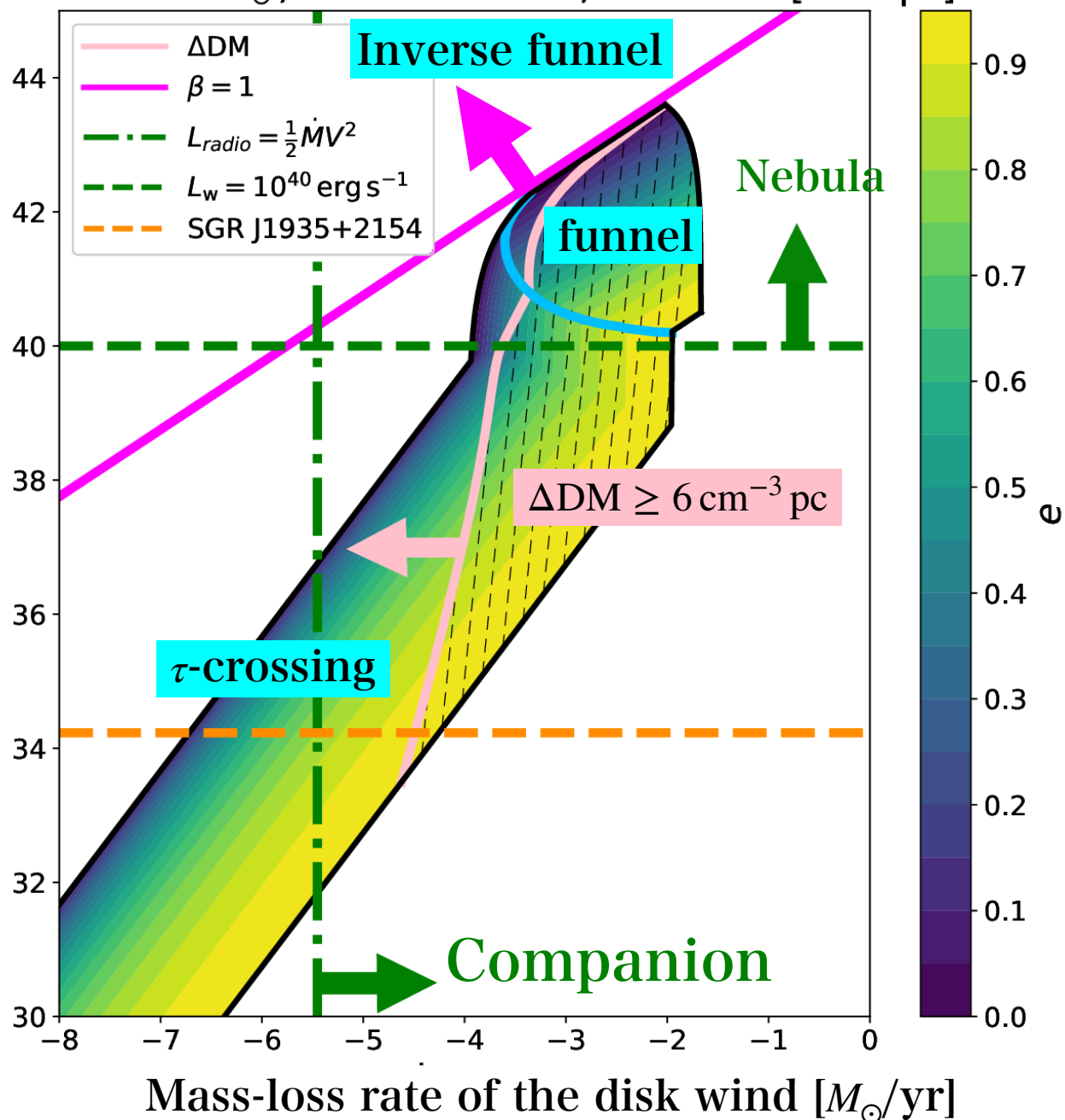
(radio emissivity $\gtrsim 10^{-4}$)

DMの変化 & high RM

-> 円盤風の時間変化

& SMBH 周辺の強磁場だろう

$$M = 1.0 \times 10^5 M_\odot, V = 1.0 \times 10^{-1} c, \Delta DM = 6.0 [\text{cm}^{-3} \text{ pc}]$$



Massive star companion

$$M_c = 10M_\odot$$

$$V = 0.01c$$

$$a = 2 \times 10^{13} \text{ cm}$$

FRB pulsar wind
luminosity [erg/s]

funnel or τ -crossing mode

-> 観測されている

persistent radio emission
の光度を説明できない。

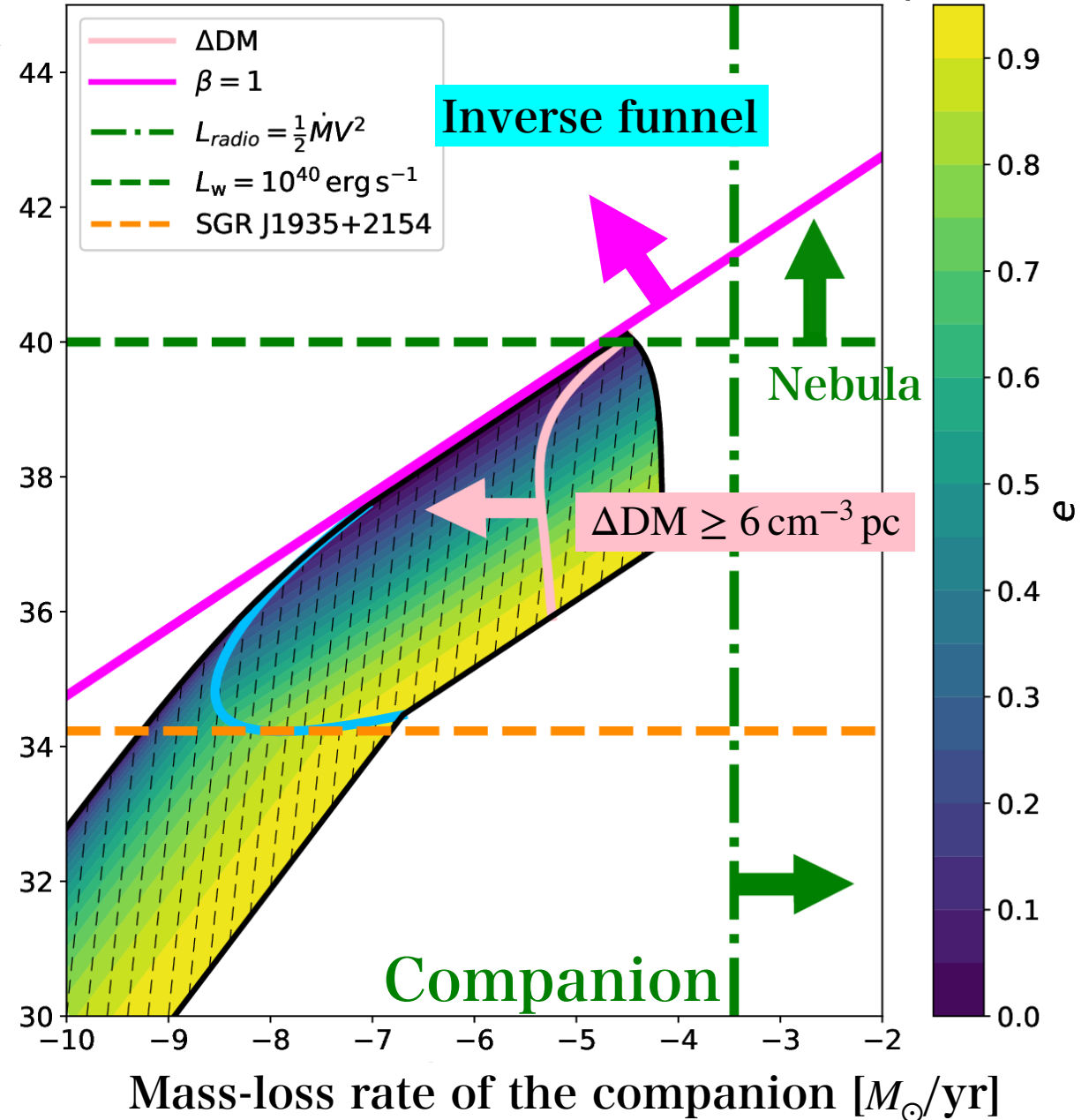
inverse funnel mode

-> FRBパルサーウインドの

nebula emission で

persistent radio emission

$$M = 1.0 \times 10M_\odot, V = 1.0 \times 10^{-2}c, \Delta DM = 6.0 [\text{cm}^{-3}\text{pc}]$$



Intermediate-mass black hole

$$M_c = 10^3 M_\odot$$

FRB pulsar wind

$$V = 0.1c$$

luminosity [erg/s]

$$a = 9 \times 10^{13} \text{ cm}$$

Persistent radio emission

-> AGN jet, nebula emission,
or disk wind で説明

(radio emissivity $\gtrsim 10^{-4}$)

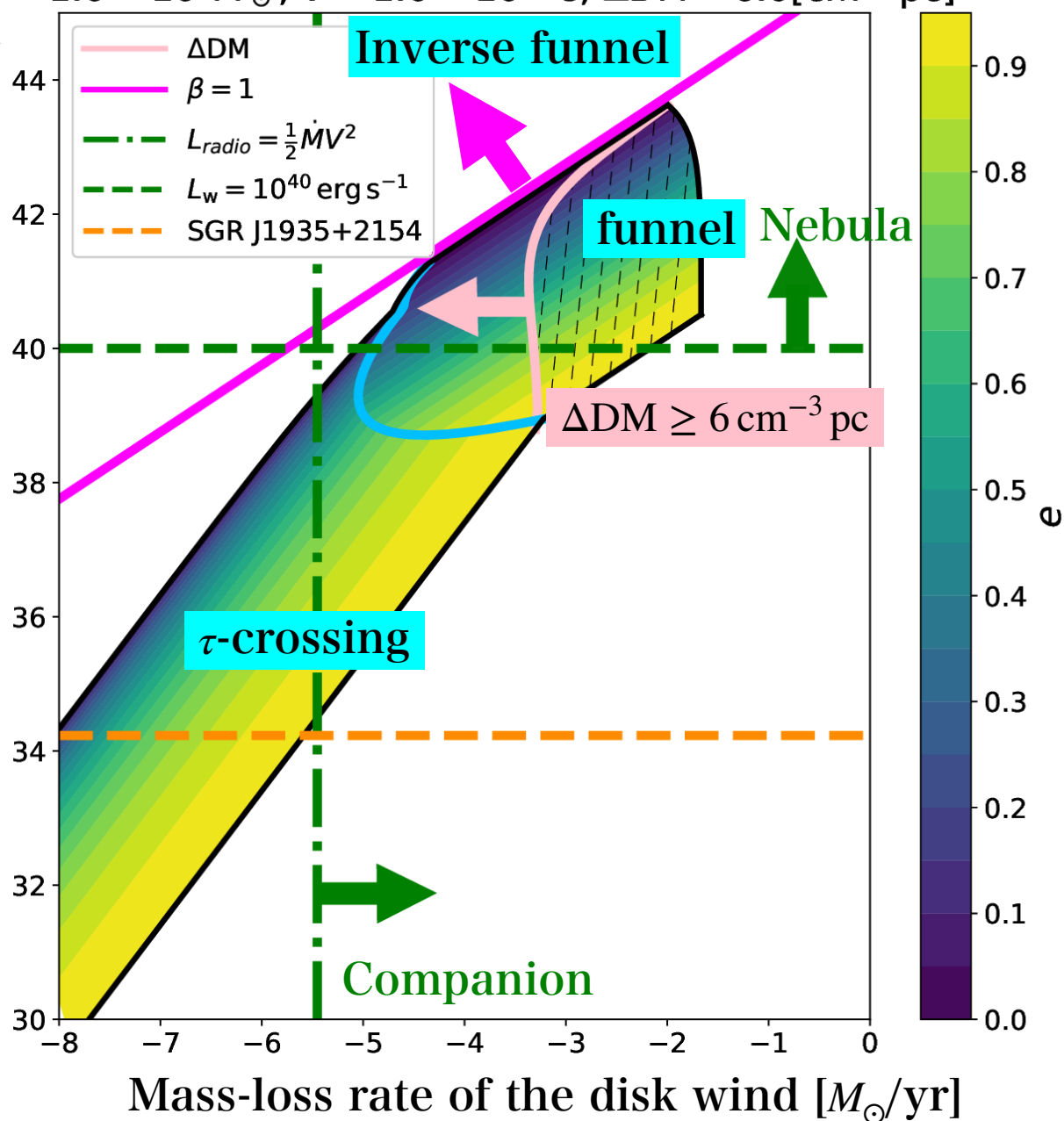
高速のウインド (アウトフロー)

-> r_s 大 : funnel が長くなる

$n(r)$ 小 : ΔDM が小さくなる。

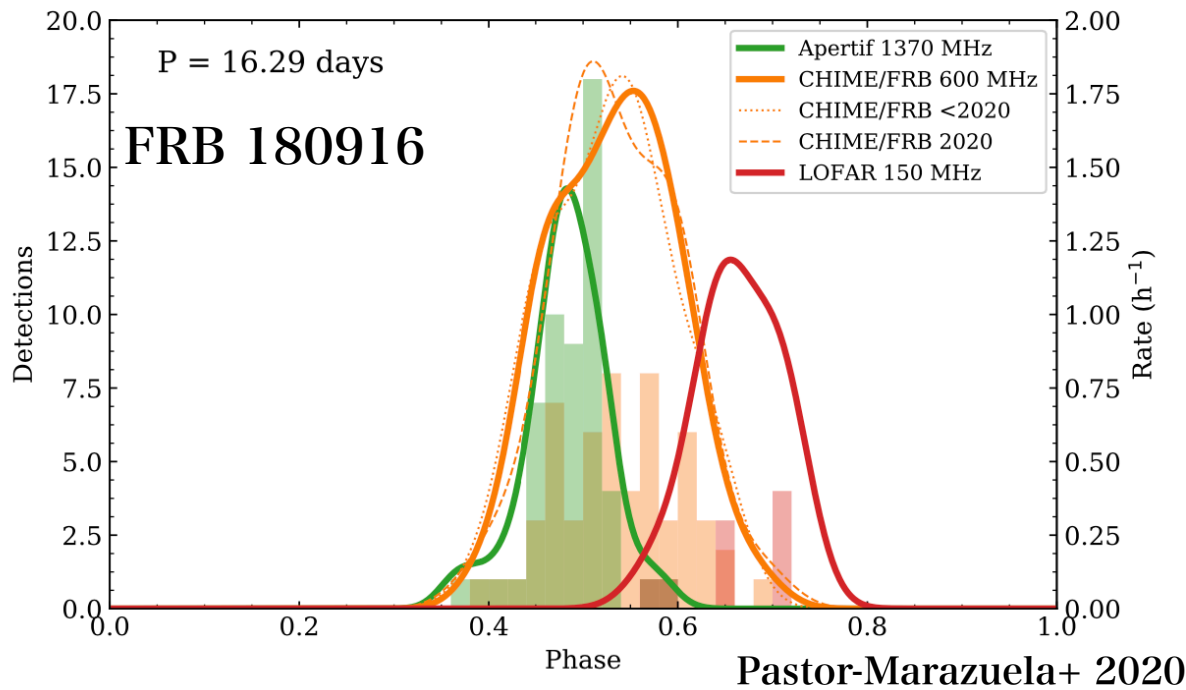
kinetic luminosity 大

$$M = 1.0 \times 10^3 M_\odot, V = 1.0 \times 10^{-1} c, \Delta DM = 6.0 [\text{cm}^{-3} \text{ pc}]$$



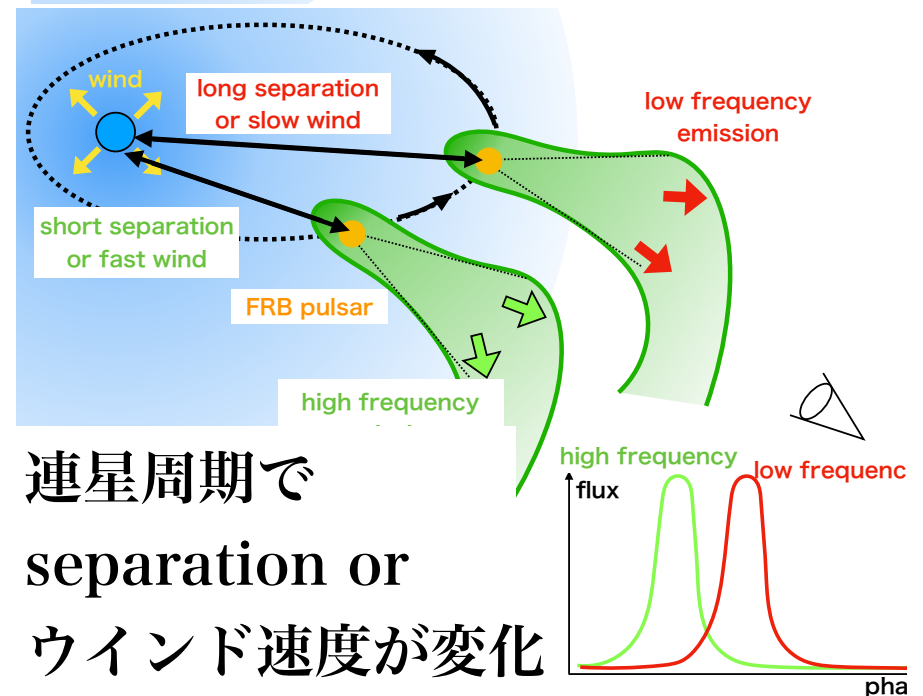
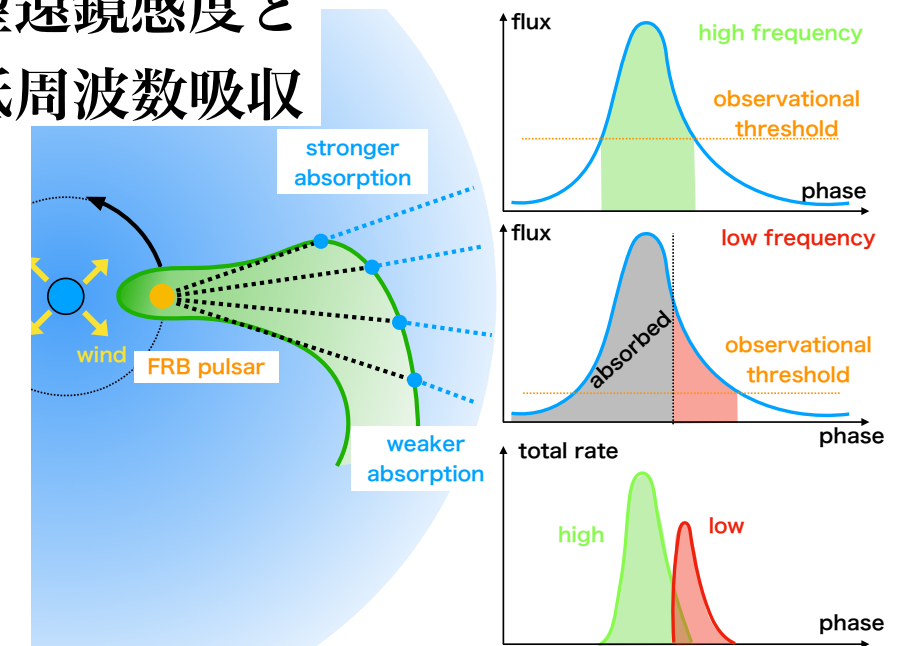
Frequency-dependence of the active window

連星モデルでも周波数依存する active windowは説明できる。



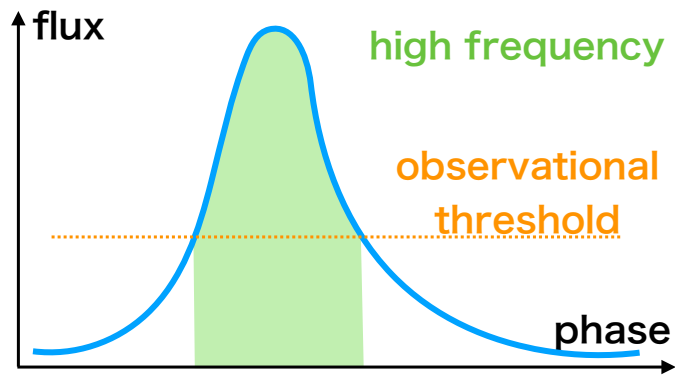
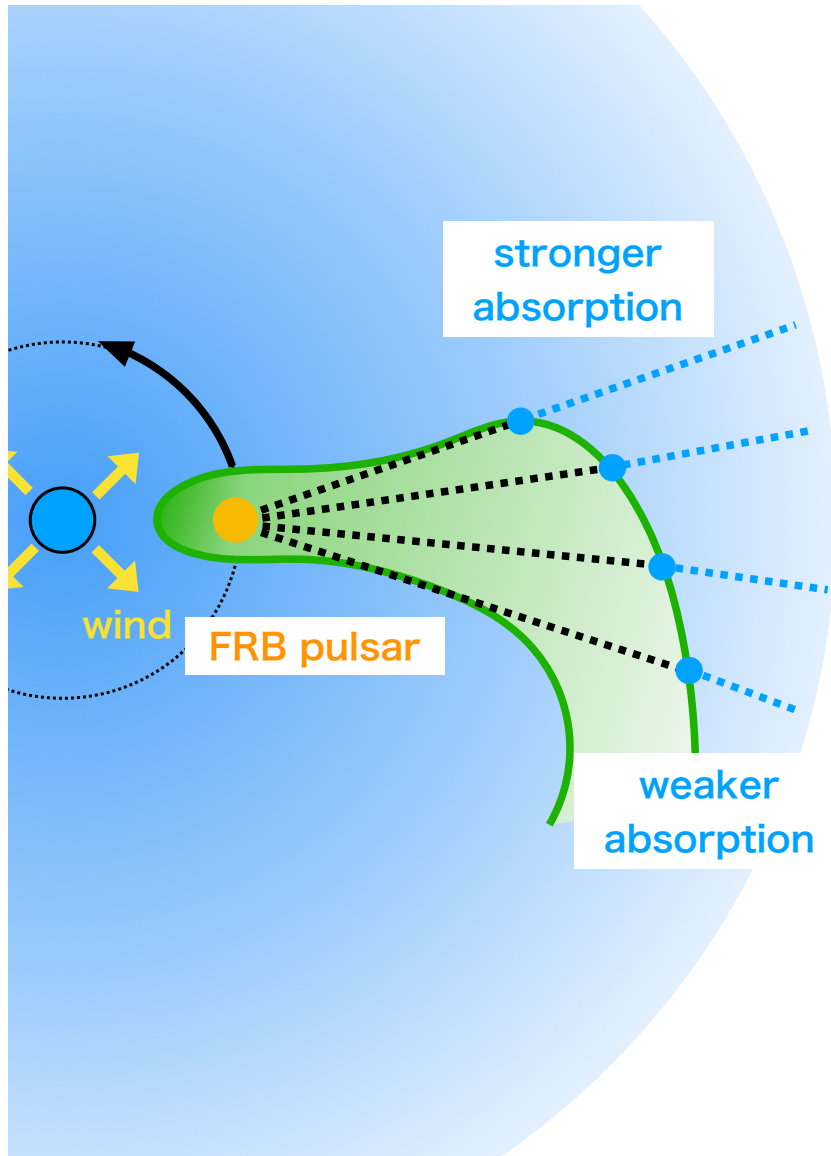
Frequency	phase	active window
High freq.	: early	short
Low freq.	: later	relatively long
Mid freq.	: early & middle	long

望遠鏡感度と
低周波数吸収

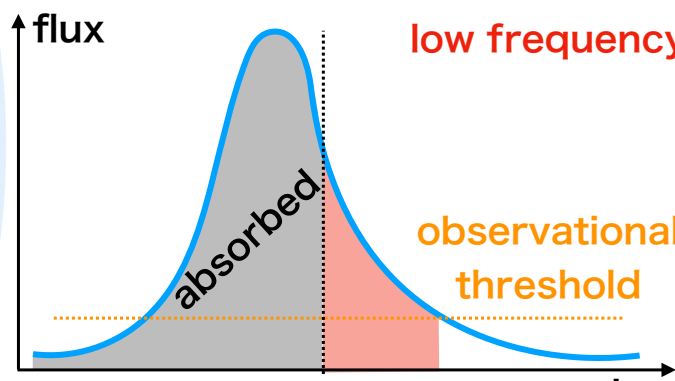


連星周期で
separation or
ウインド速度が変化

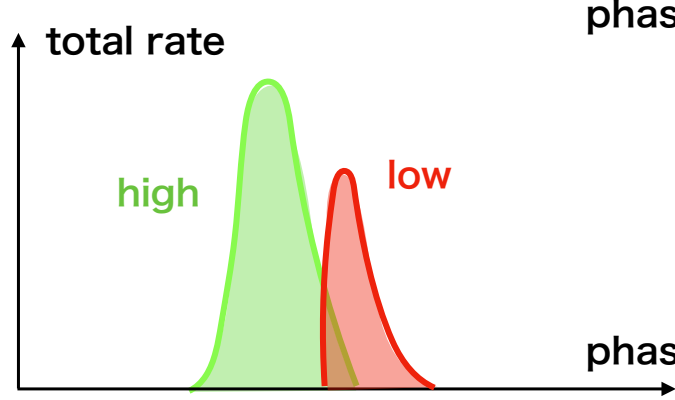
Frequency-dependence of the active window



High freq.
Observational threshold shorten the duty cycle



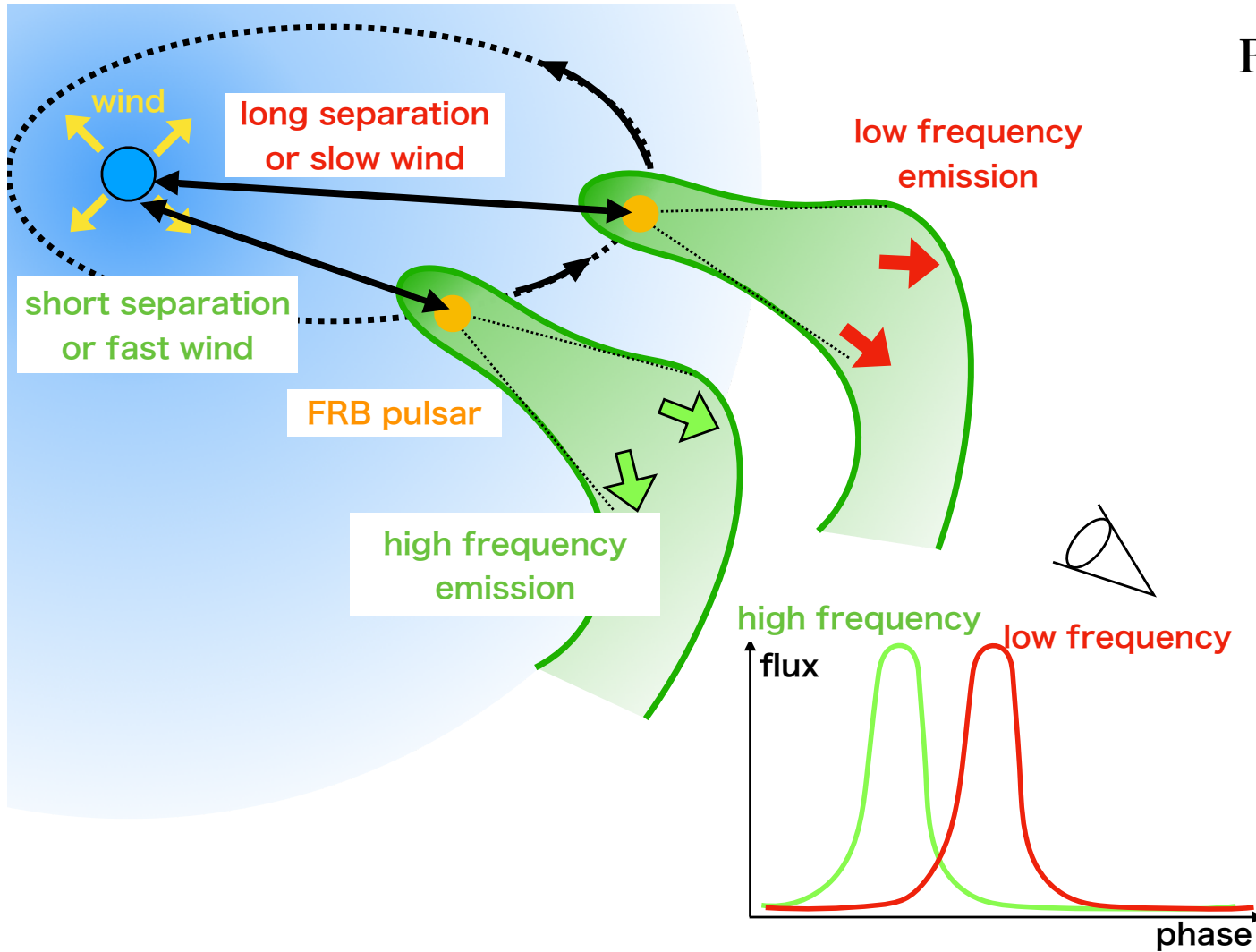
Low freq.
 $\tau_{\text{ff}} \propto \nu^{-2}$
 $\tau_{\text{IdC}} \propto \nu^{-3}$
FRBs in low frequency are scattered efficiently



Different sensitivities of the different telescopes
& Absorption in low frequency

-> The frequency-dependence of the active window

Frequency-dependence of the active window



For example,,

High freq.

Due to short separation or fast wind

Low freq.

Due to long separation or slow wind?

Unknown intrinsic emission mechanism
& Eccentric orbit

-> The frequency-dependence of the active window

Summary

- 連星モデルでFRB 121102 の周期的な活動性をその他の観測事実と矛盾なく説明できる。
- 連星モデルでは周期性が作られる3つのモードが考えられる。
(funnel mode, τ -crossing mode, & inverse funnel mode)
- SMBH & IMBH ->どのモードでも周期性を実現できる
MS -> inverse funnel modeなら周期性を実現できる
- RM/DMの周期変化で検証できる可能性がある。