

arXiv: 2309.07256

Refractive lensing of scintillating FRBs by sub-parsec cloudlets in the multi-phase CGM

Dylan L. Jow,^{2,3,6}★ Xiaohan Wu,² and Ue-Li Pen^{1,2,3,4,5,6}

¹*Institute of Astronomy and Astrophysics, Academia Sinica, Astronomy-Mathematics Building, No. 1, Section 4, Roosevelt Road, Taipei 10617, Taiwan*

²*Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H8, Canada*

³*Department of Physics, University of Toronto, 60 St. George Street, Toronto, ON M5S 1A7, Canada*

⁴*Perimeter Institute for Theoretical Physics, 31 Caroline St. North, Waterloo, ON, Canada N2L 2Y5*

⁵*Canadian Institute for Advanced Research, CIFAR program in Gravitation and Cosmology*

⁶*Dunlap Institute for Astronomy & Astrophysics, University of Toronto, AB 120-50 St. George Street, Toronto, ON M5S 3H4, Canada*

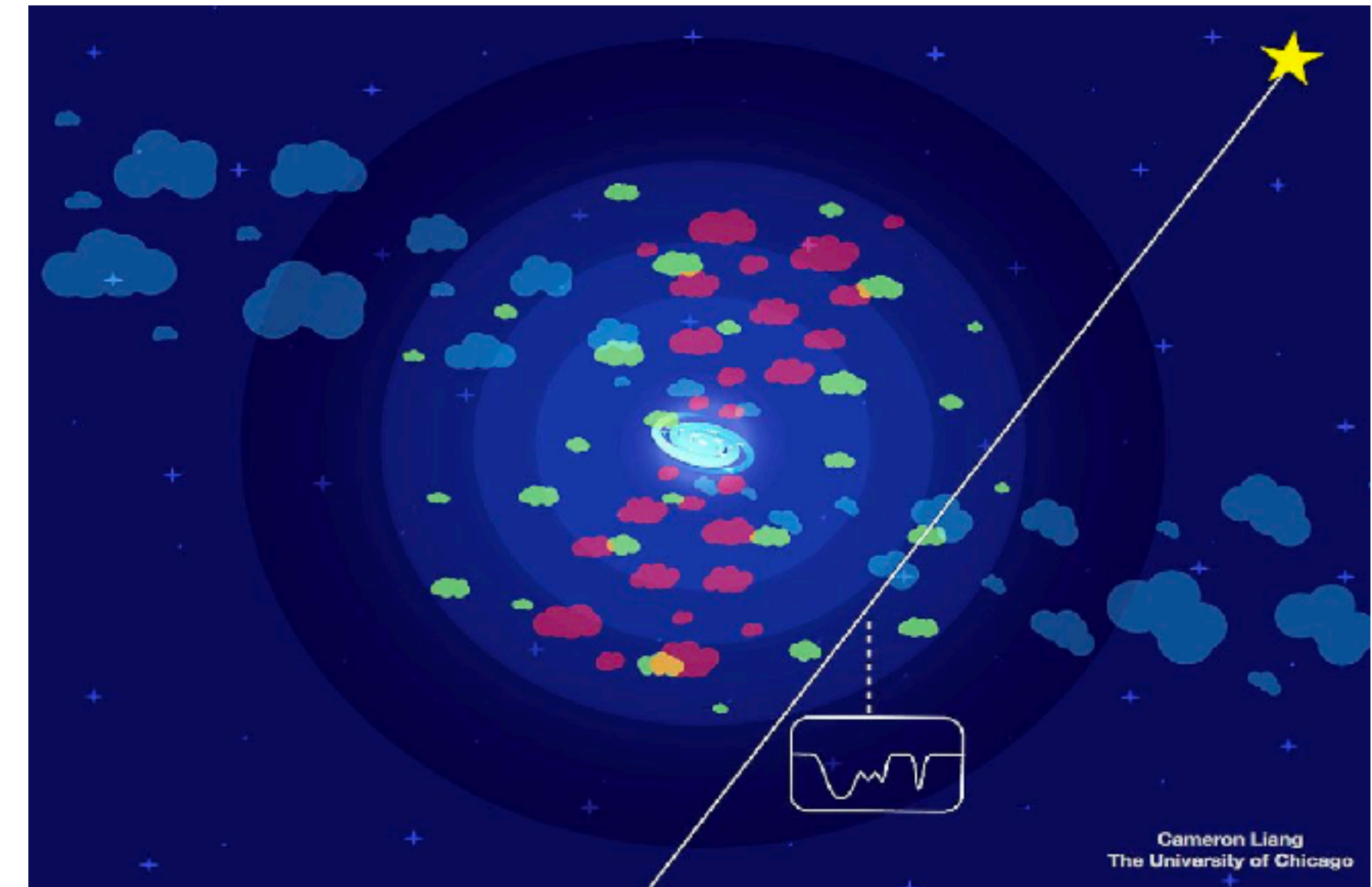


Presented by Xun Shi (SWIFAR Room 1212)

Nov 2023

Facts about **cool** ($\sim 10^4\text{K}$)
circumgalactic medium (**CGM**)
from **quasar absorption line**
observations

1. high density \rightarrow **small** volume
filling fraction f_V
2. very **large** area covering fraction f_A



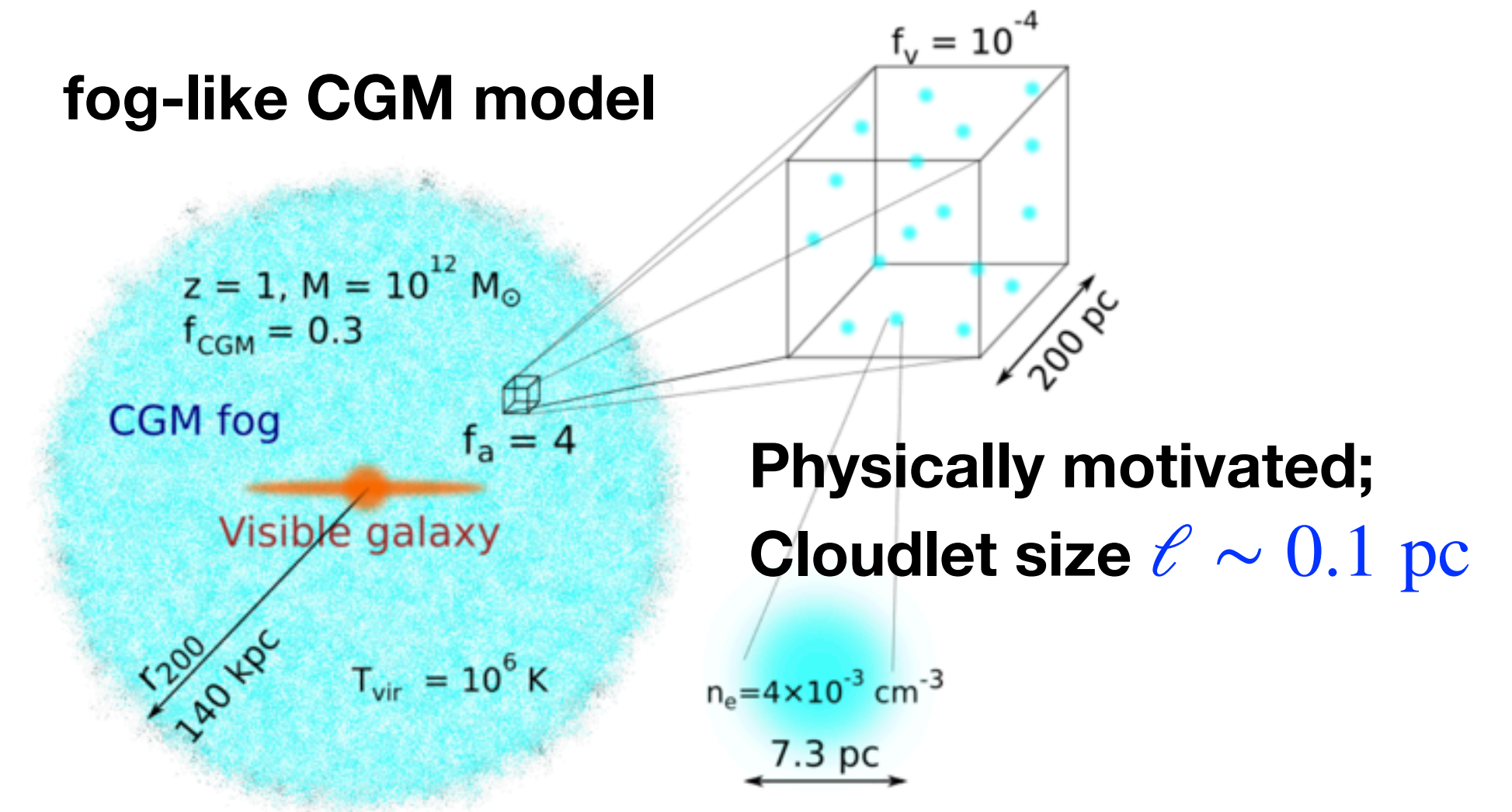
Facts about **cool** ($\sim 10^4\text{K}$)
circumgalactic medium (**CGM**)
from **quasar absorption line**
observations

1. high density \rightarrow **small** volume
filling fraction f_V
2. very **large** area covering fraction f_A

A geometry problem: how to reconcile small f_V and large f_A ?

Facts about **cool** ($\sim 10^4\text{K}$)
circumgalactic medium (**CGM**)
from **quasar absorption line**
observations

1. high density \rightarrow **small** volume
filling fraction f_V
2. very **large** area covering fraction f_A



McCourt et al. 2017

(Picture from Vedantham & Phinney 2018)

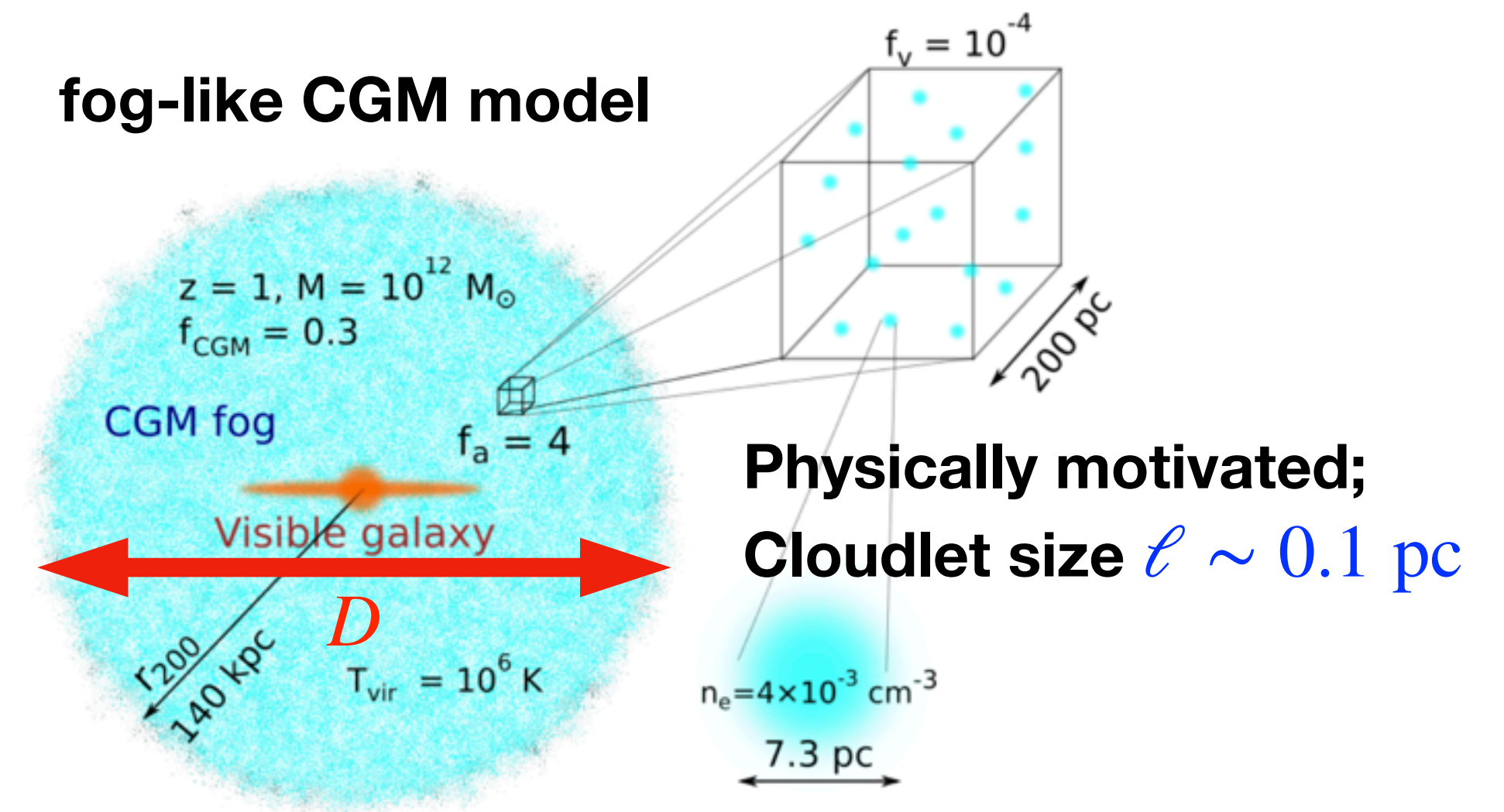
A geometry problem: how to reconcile small f_V and large f_A ?

Facts about **cool** ($\sim 10^4\text{K}$)
circumgalactic medium (**CGM**)
from **quasar absorption line**
observations

1. high density \rightarrow **small** volume
filling fraction f_V

2. very **large** area covering fraction f_A

$$\frac{f_A}{f_V} \sim \frac{D}{\ell}$$



McCourt et al. 2017

(Picture from Vedantham & Phinney 2018)

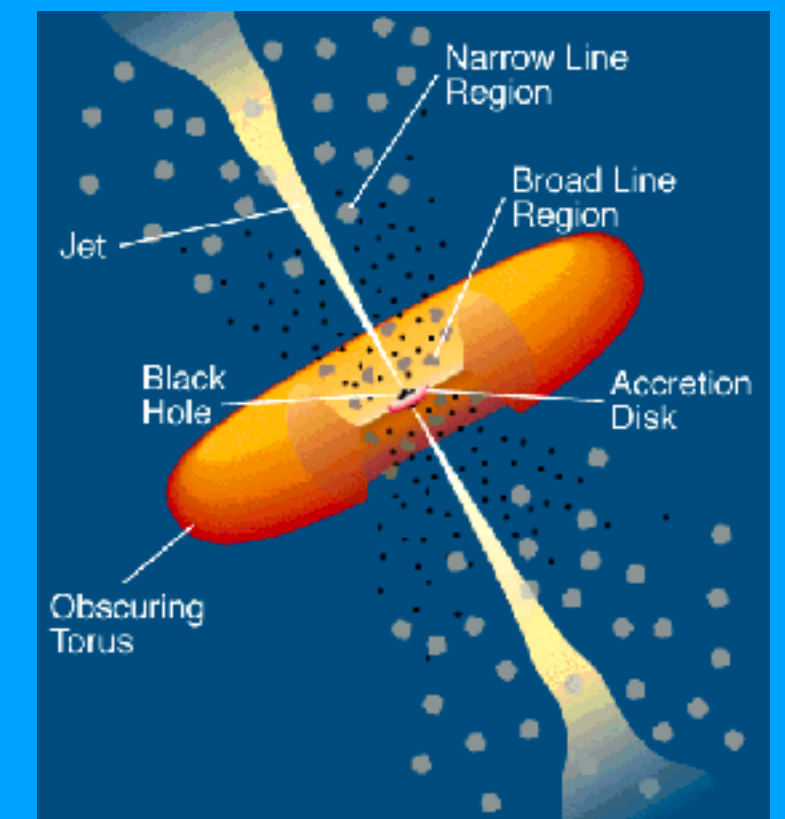
A geometry problem: how to reconcile small f_V and large f_A ?

Facts about **cool** ($\sim 10^4\text{K}$)
circumgalactic medium (**CGM**)
from **quasar absorption line**
observations

1. high density \rightarrow **small** volume
filling fraction f_V

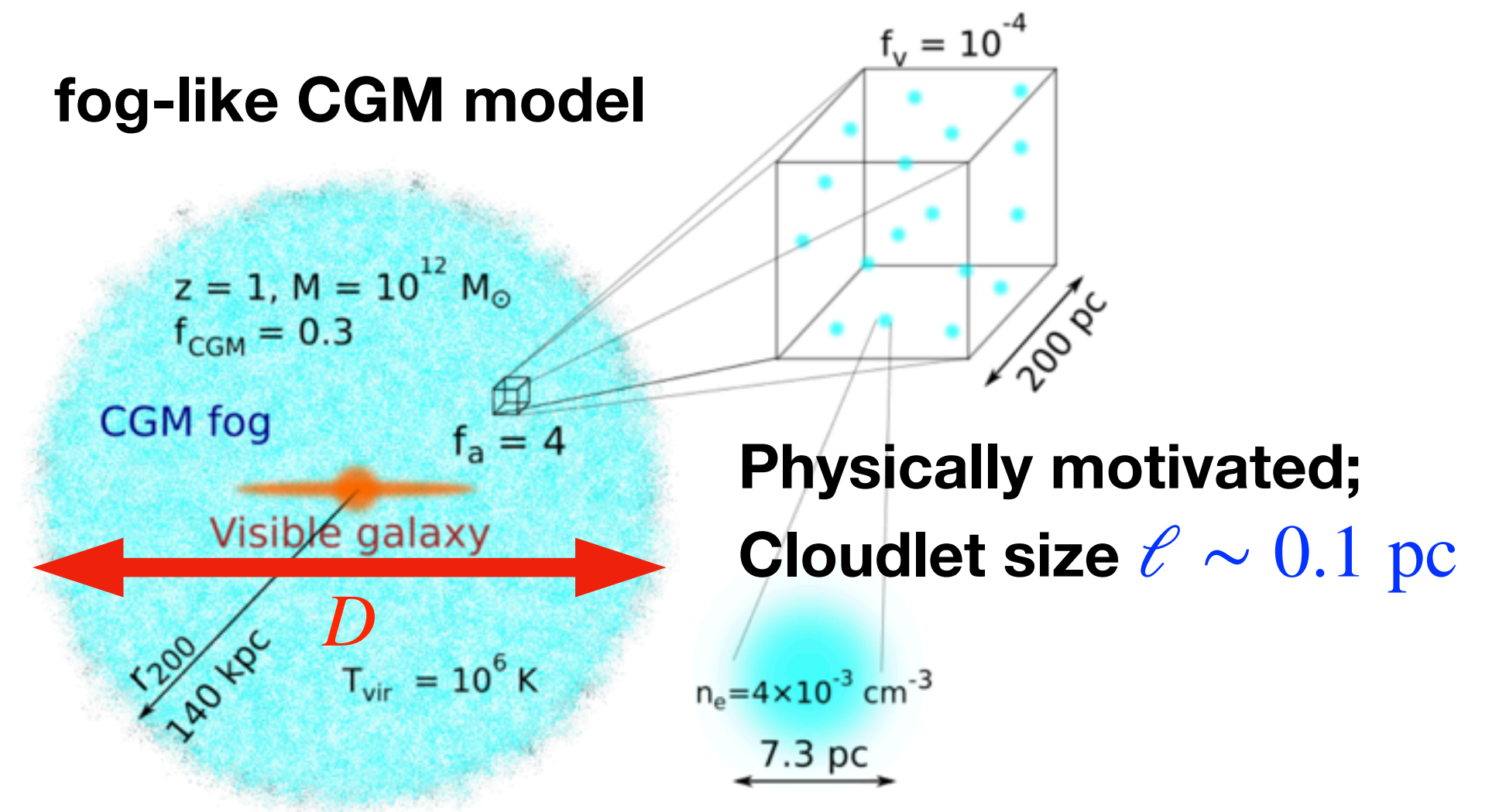
2. very **large** area covering fraction f_A

$$\frac{f_A}{f_V} \sim \frac{D}{\ell}$$



\sim geometry of AGN broad line region

fog-like CGM model



McCourt et al. 2017

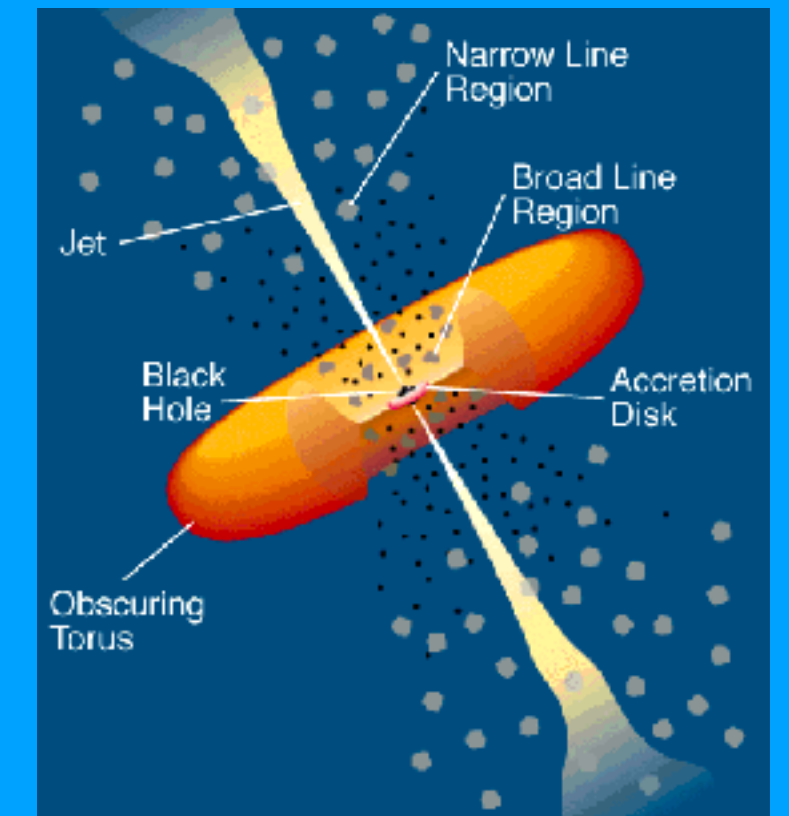
(Picture from Vedantham & Phinney 2018)

A geometry problem: how to reconcile small f_V and large f_A ?

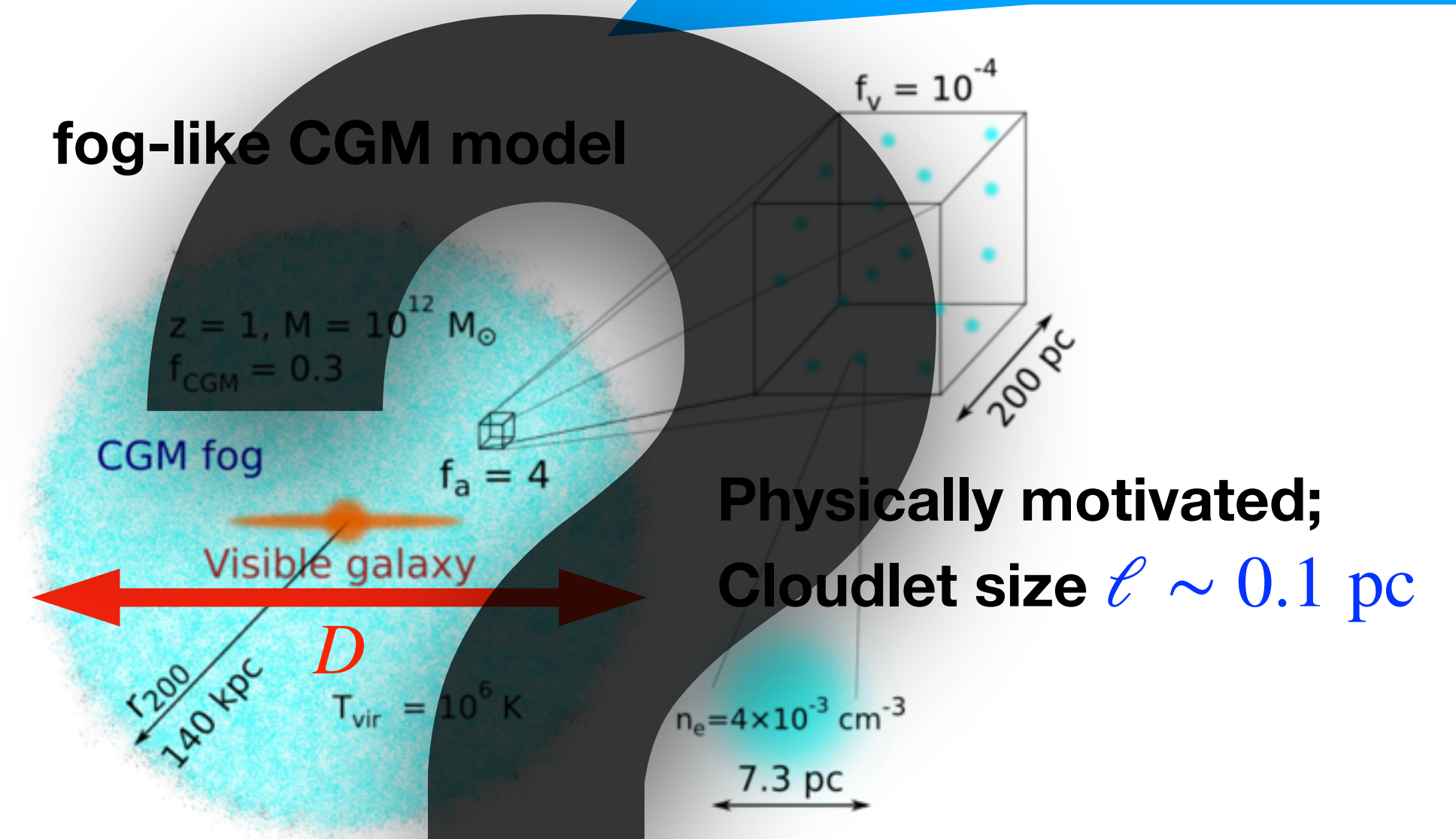
Facts about **cool** ($\sim 10^4\text{K}$)
circumgalactic medium (**CGM**)
from **quasar absorption line**
observations

1. high density \rightarrow **small** volume
filling fraction $f_V \lesssim 10^{-3}$
2. very **large** area covering fraction f_A

$$\frac{f_A}{f_V} \sim \frac{D}{\ell}$$



\sim geometry of AGN broad line region



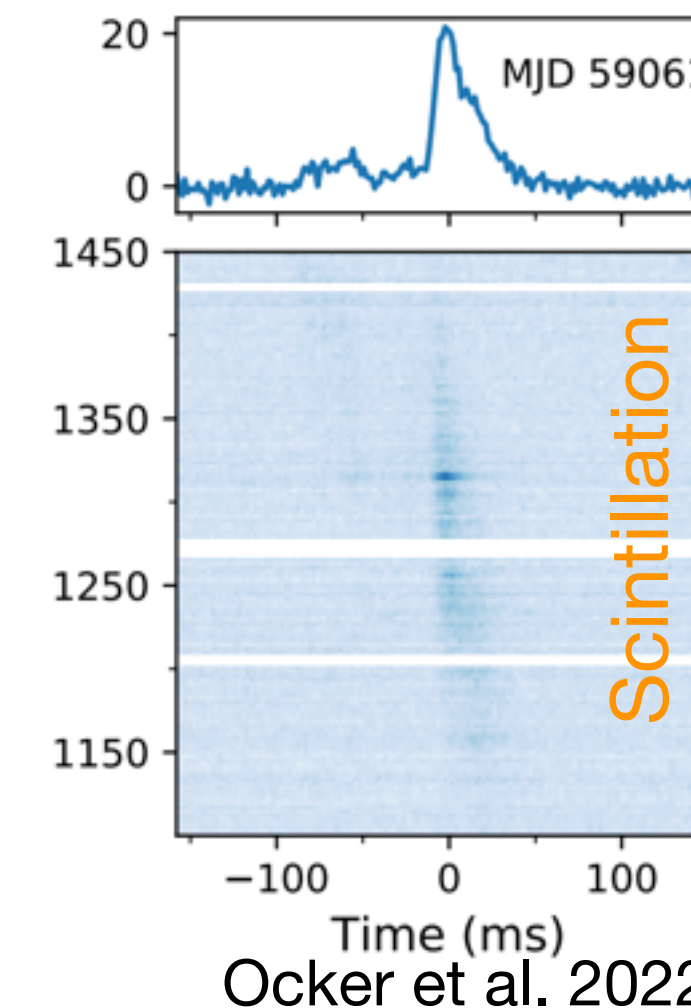
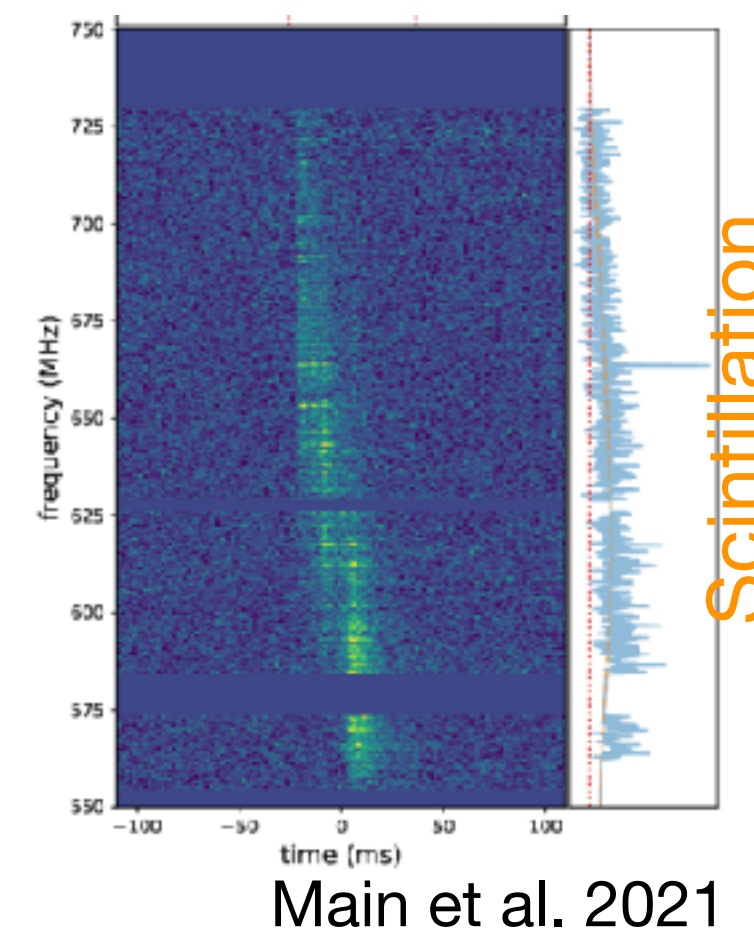
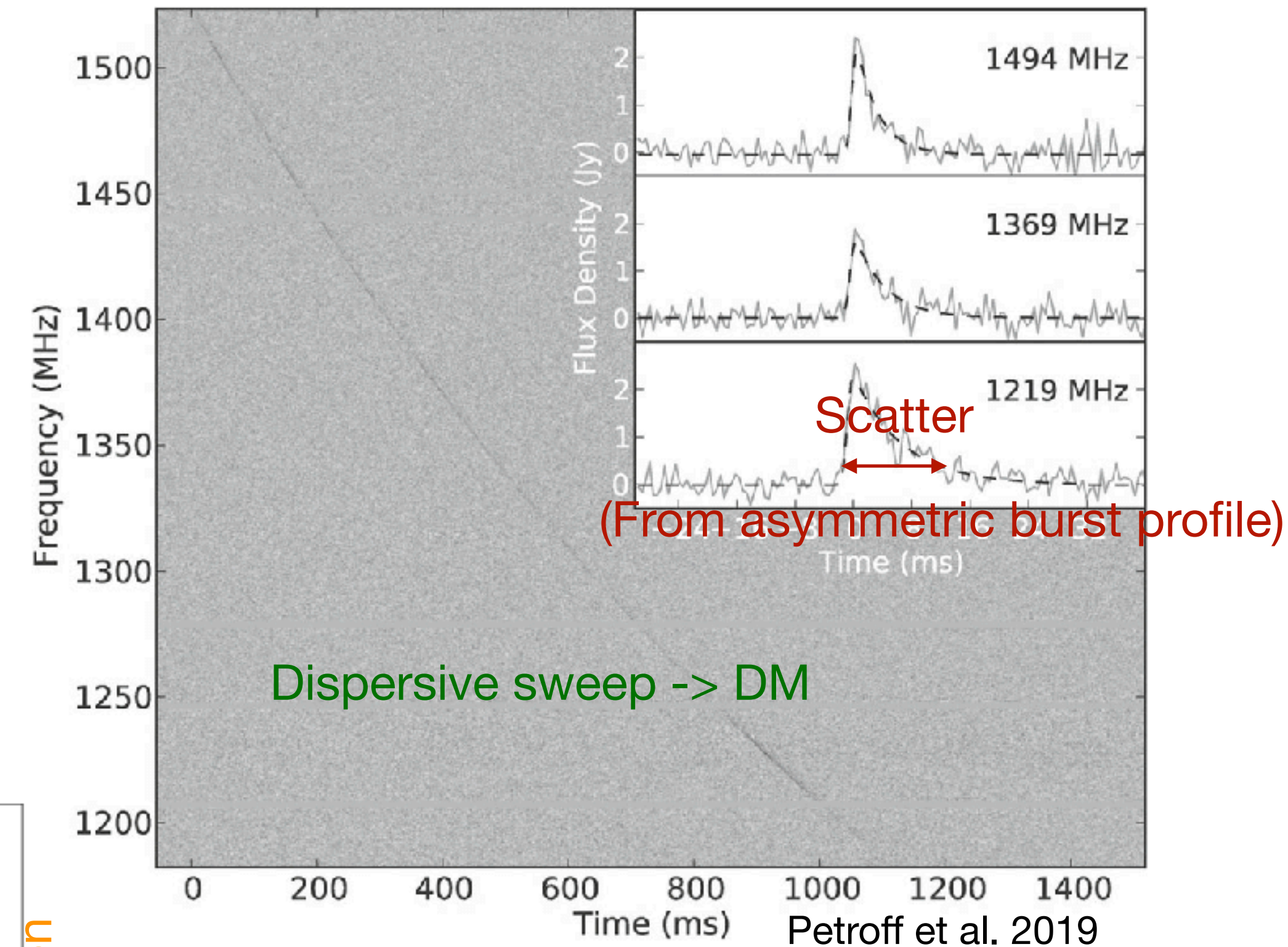
McCourt et al. 2017

(Picture from Vedantham & Phinney 2018)

A geometry problem: how to reconcile small f_V and large f_A ?

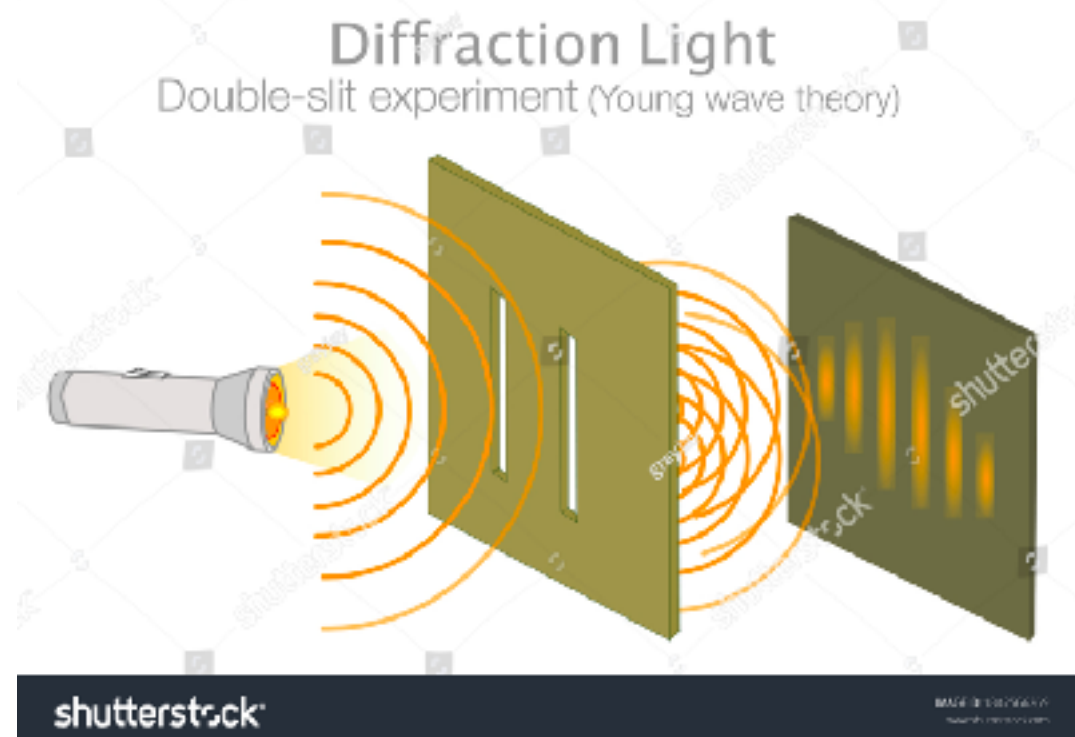
Facts about **FRB**

1. Large dispersion measure (**DM** $> \sim 10^3$)
2. Many with large **scatter** (\sim ms at \sim GHz)
3. Many **scintillate** (modulation of flux in frequency due to interference of multiple images)

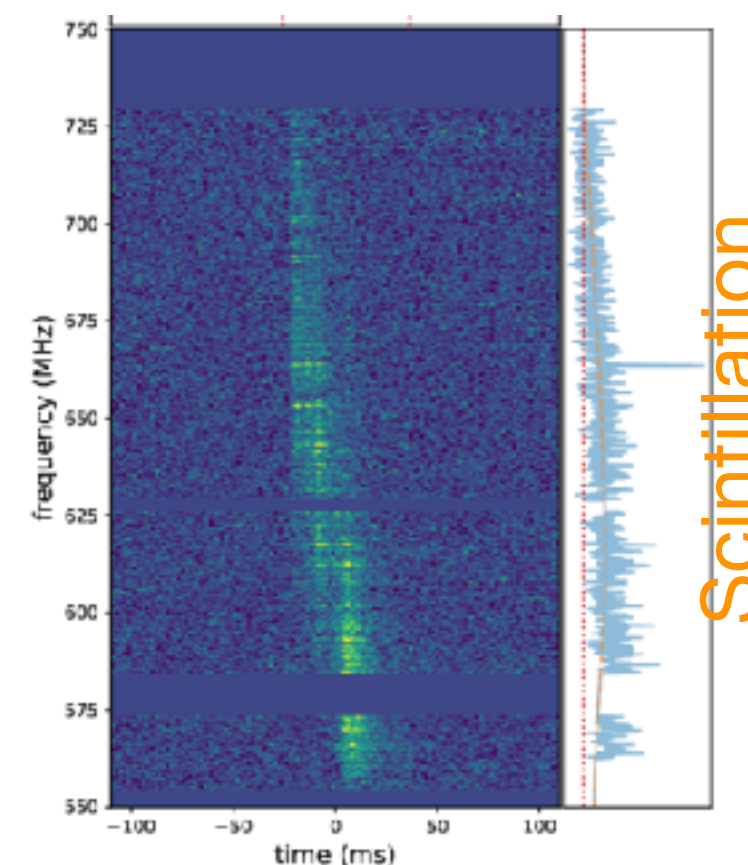


Facts about **FRB**

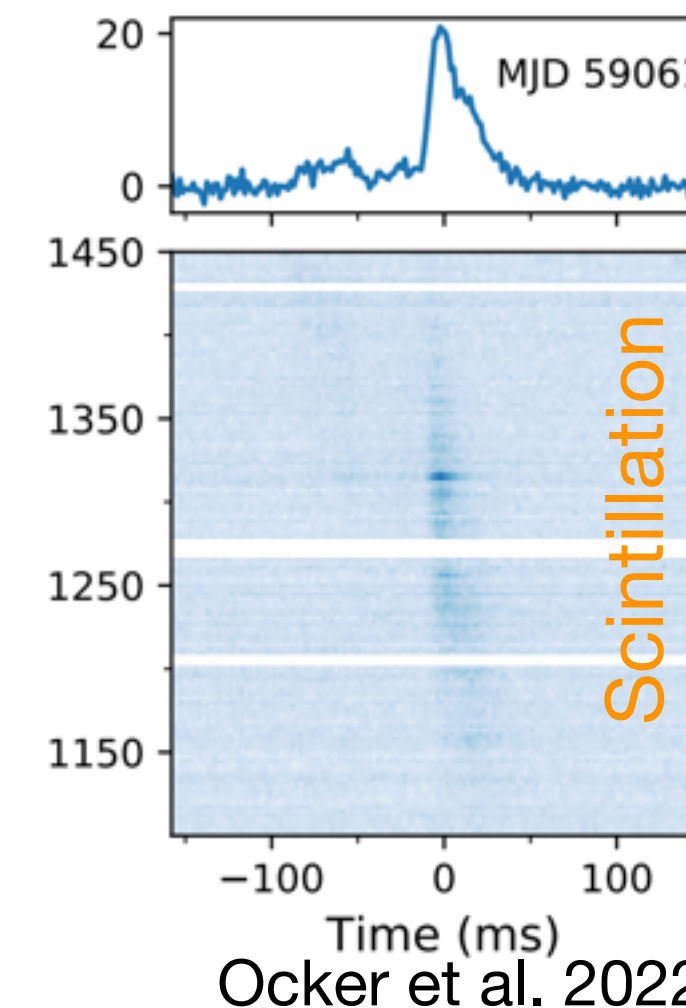
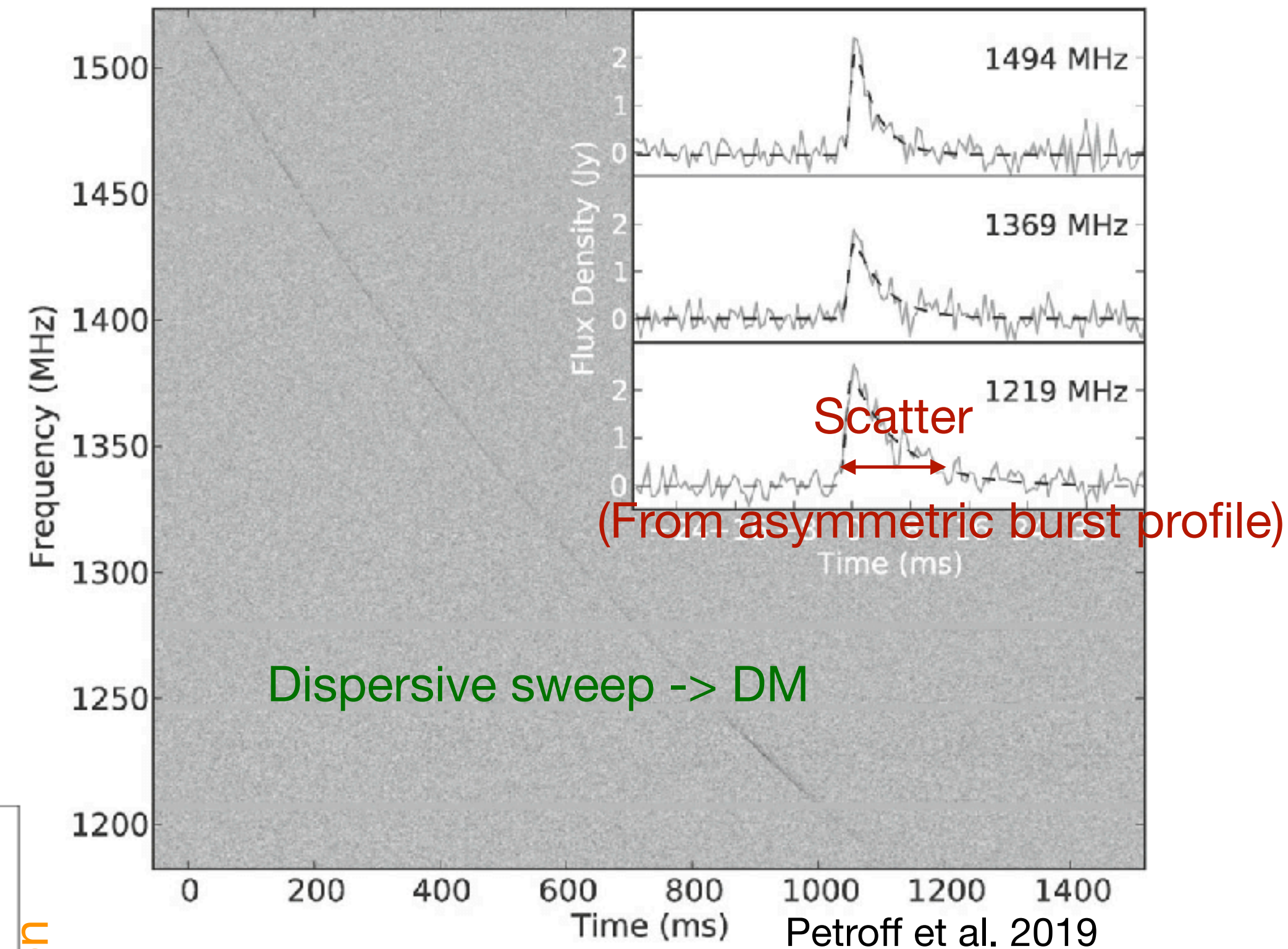
1. Large dispersion measure (**DM** $> \sim 10^3$)
2. Many with large **scatter** (\sim ms at \sim GHz)
3. Many **scintillate** (modulation of flux in frequency due to interference of multiple images)



interference between images
-> flux modulation

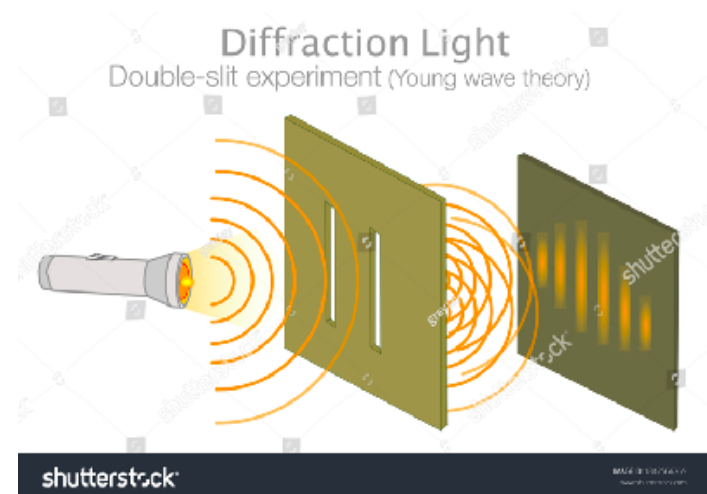
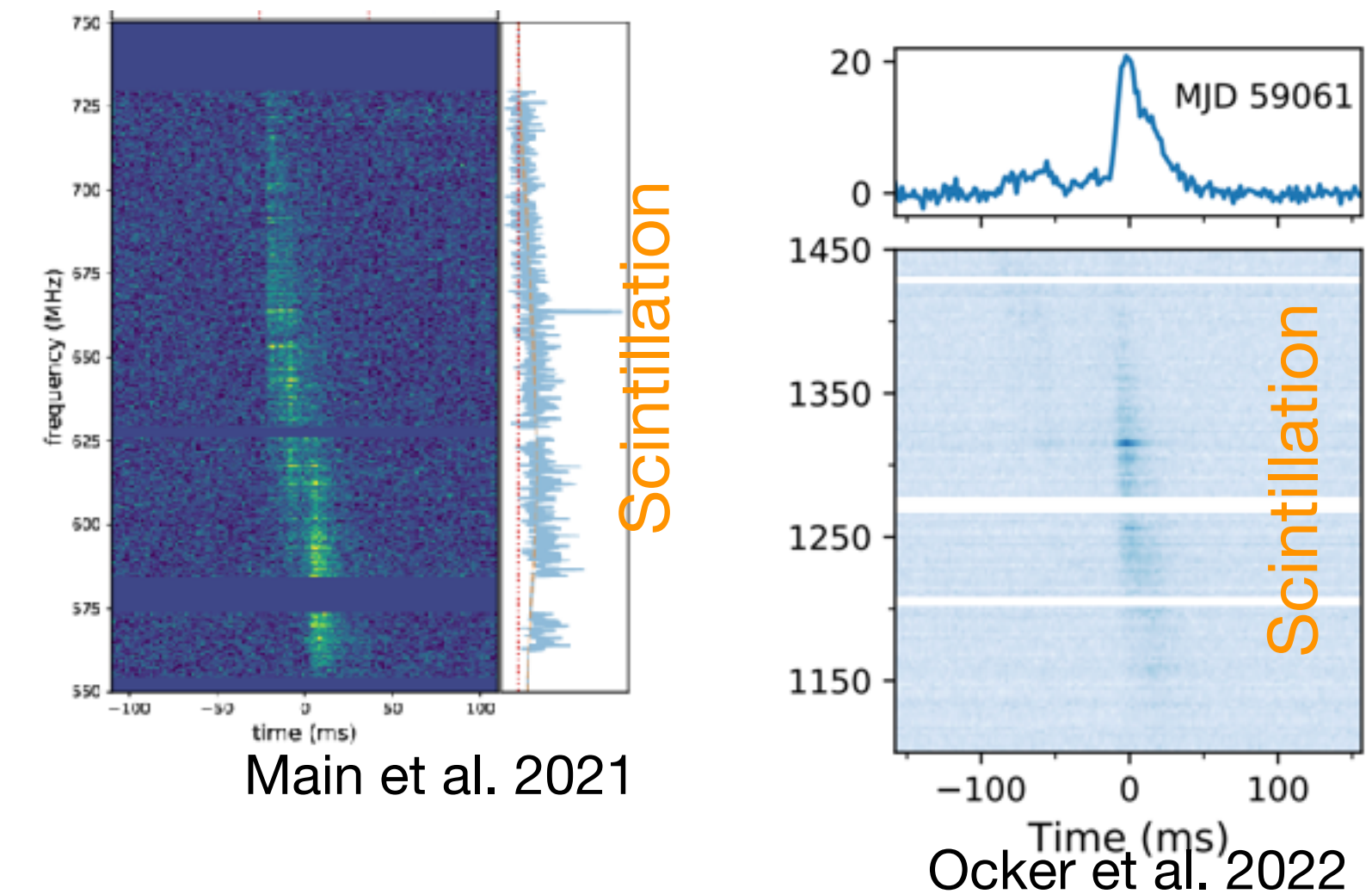


Main et al. 2021

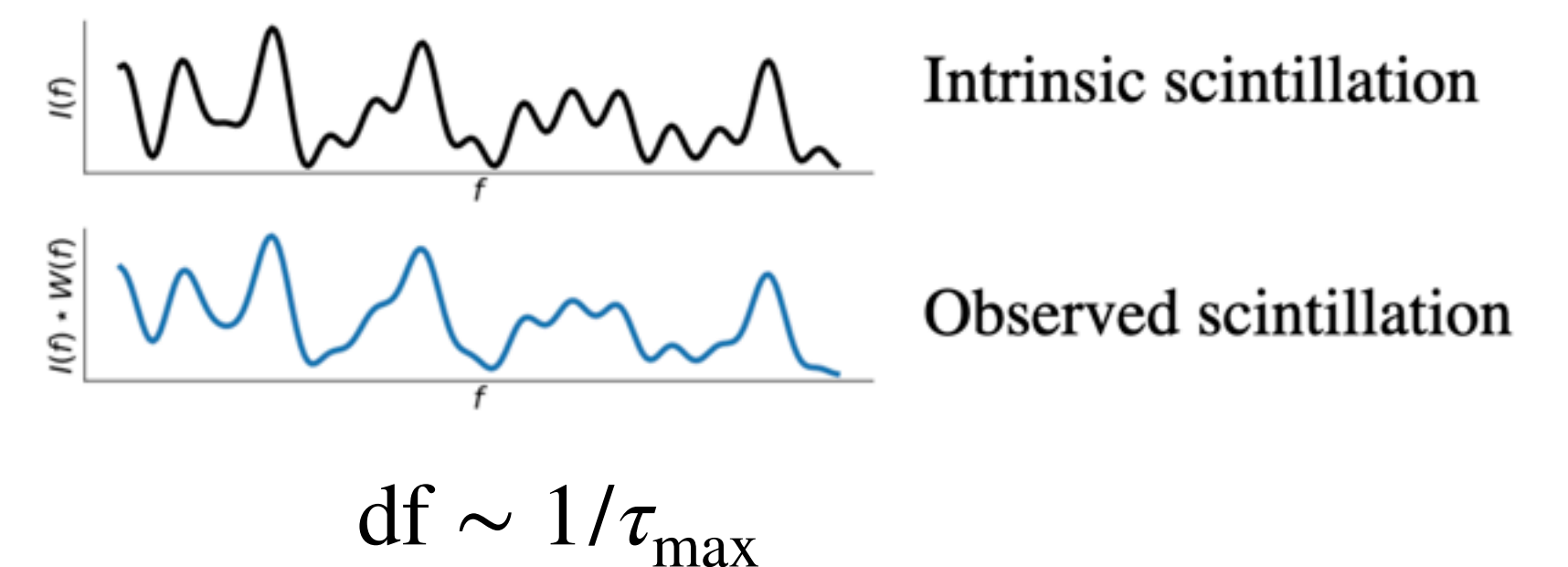
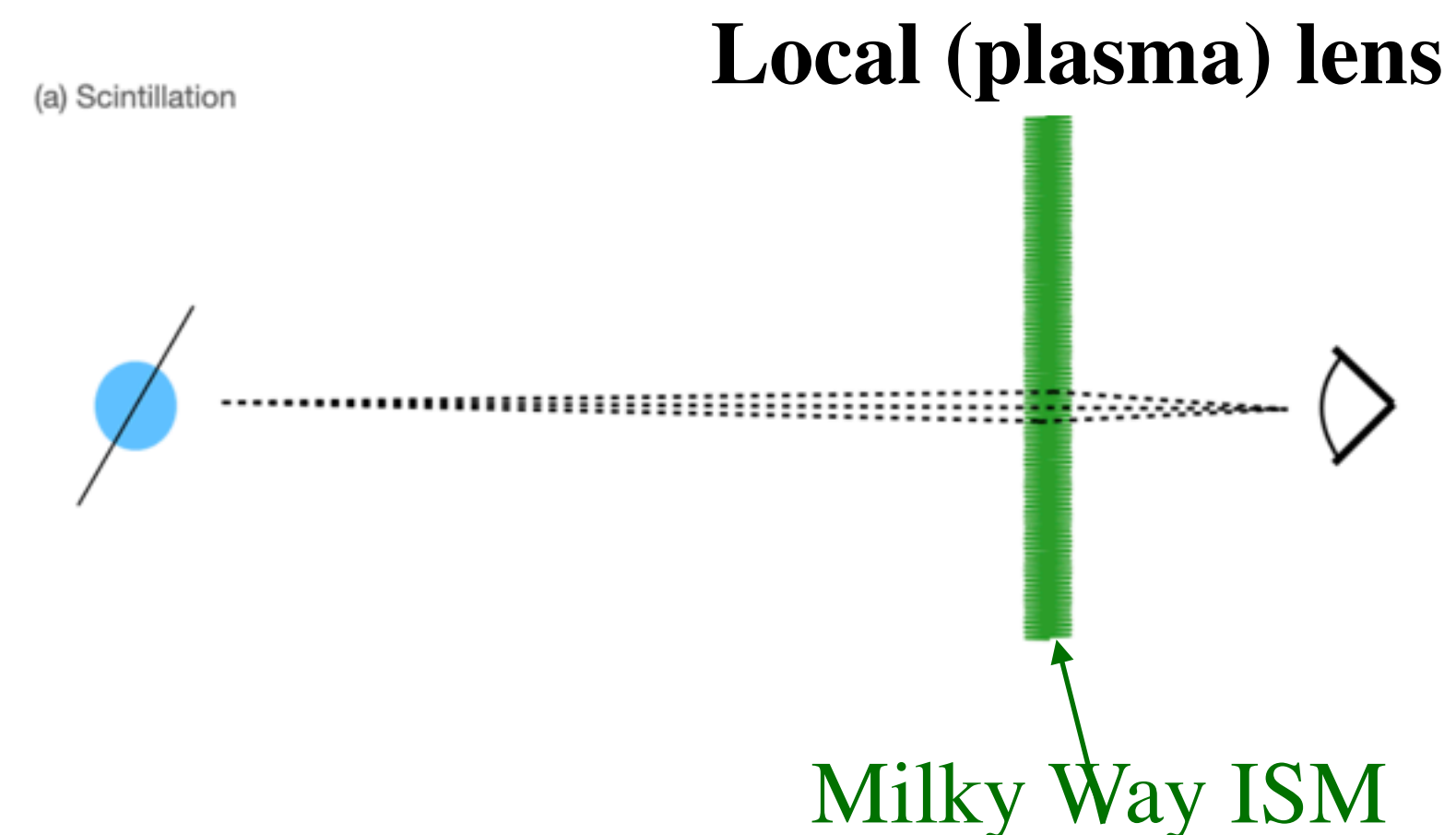


Facts about **FRB**

1. Large dispersion measure (**DM** $> \sim 10^3$)
2. Many with large **scatter** (\sim ms at \sim GHz)
3. Many **scintillate** (modulation of flux in frequency due to interference of multiple images) **from Milky Way ISM** (like pulsars)

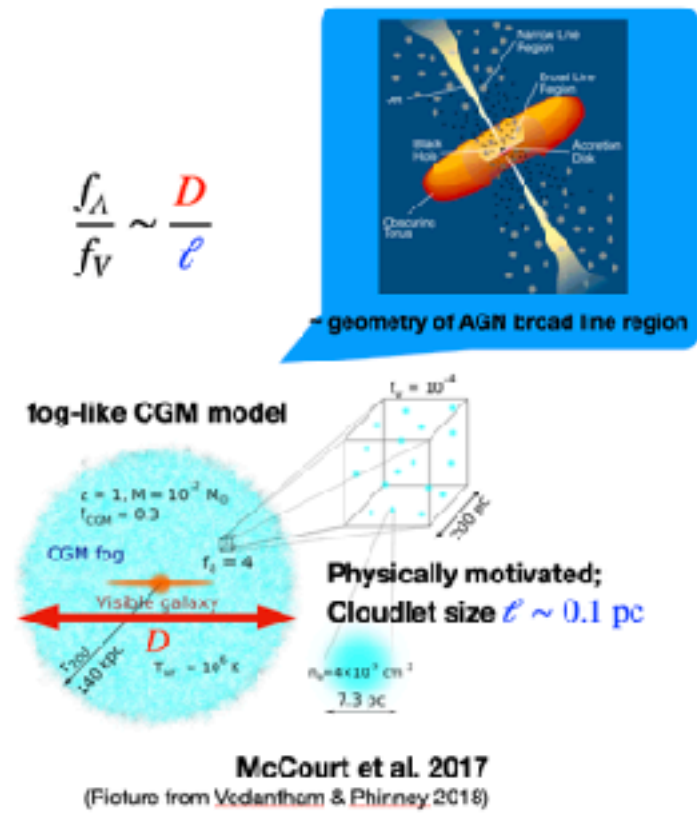


interference between images
-> flux modulation

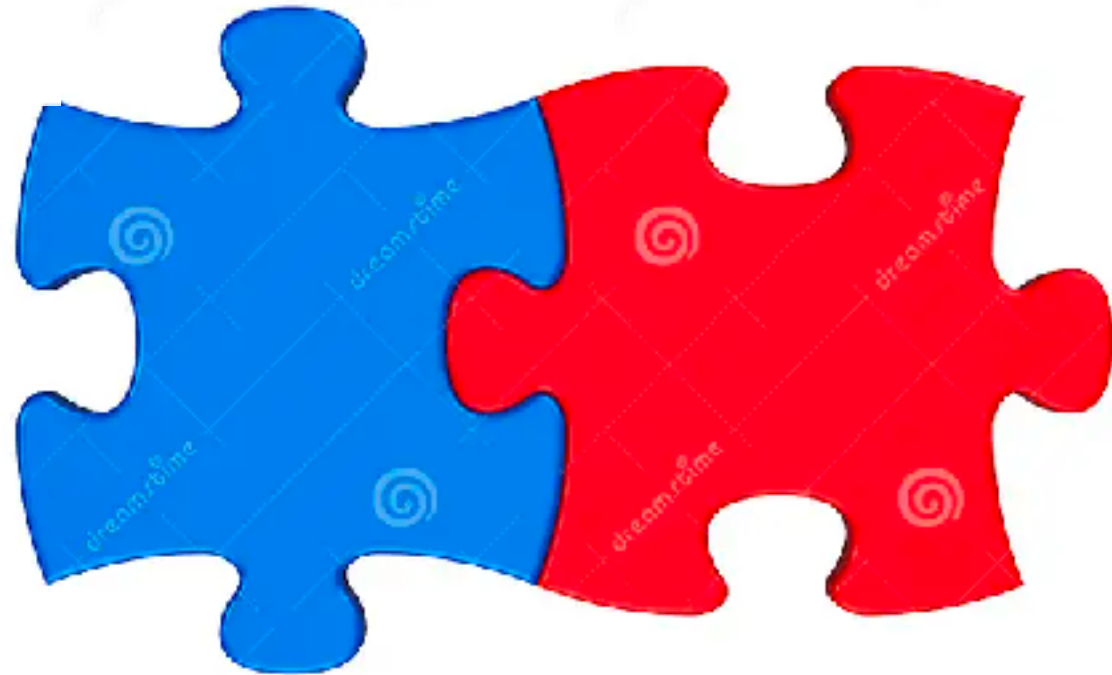


Facts about **cool** ($\sim 10^4\text{K}$) circus-
galactic material (**CGM**)
from **quasar absorption line**
observations

- 1. high density -> **small** volume
fraction filling fraction f_V
- 2. very **large** area covering fraction f_A

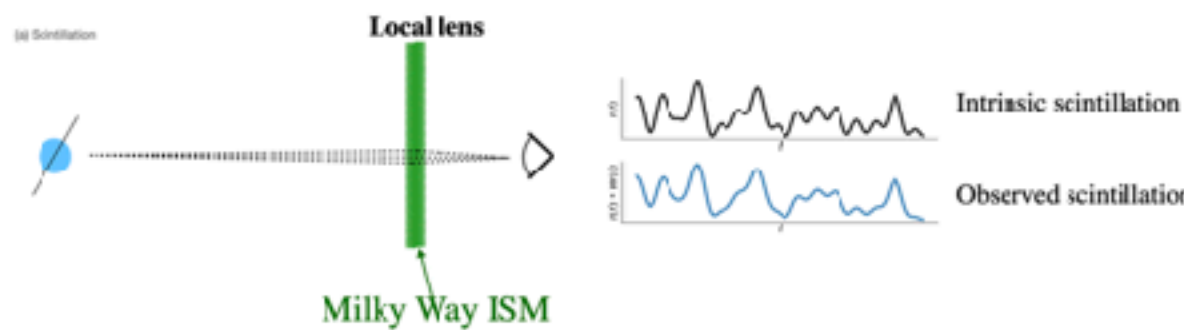
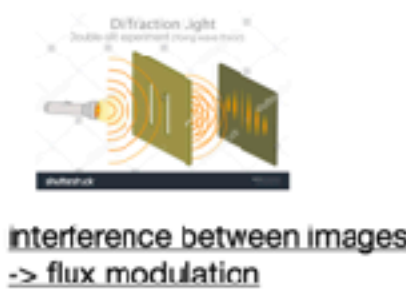
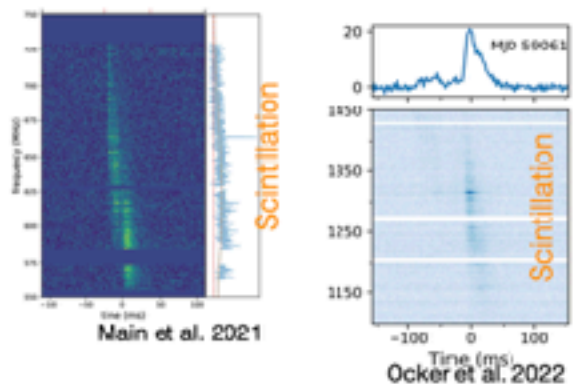


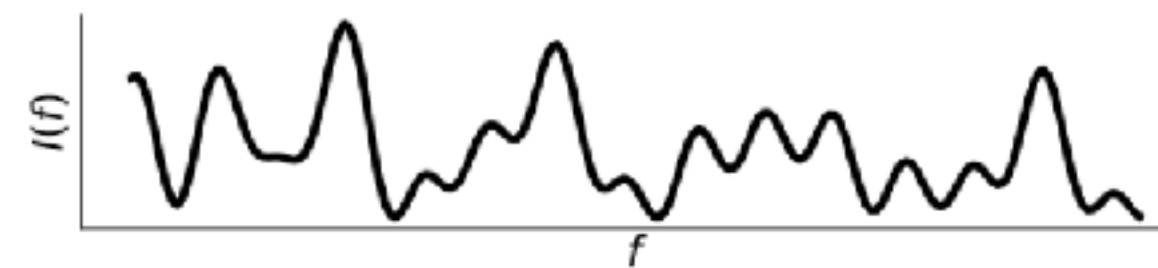
A geometry problem: how to reconcile small f_V and large f_A ?



Facts about **FRB**

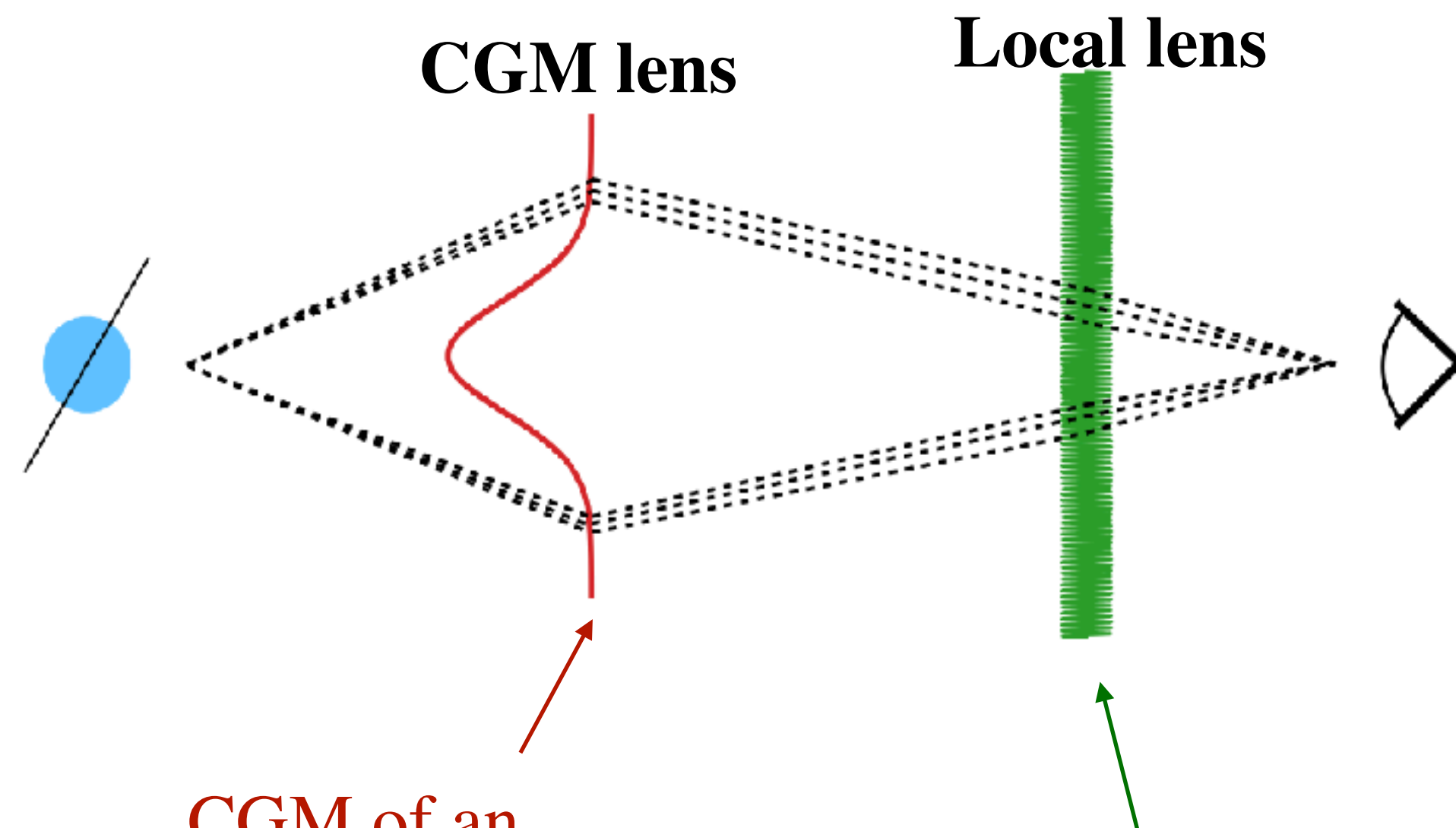
- 1. Large dispersion measure (**DM** $> \sim 10^3$)
- 2. Many with large **scatter** ($\sim \text{ms}$ at $\sim \text{GHz}$)
- 3. Many **scintillate** (modulation of flux in frequency due to interference of multiple images) **from Milky Way ISM** (like pulsars)





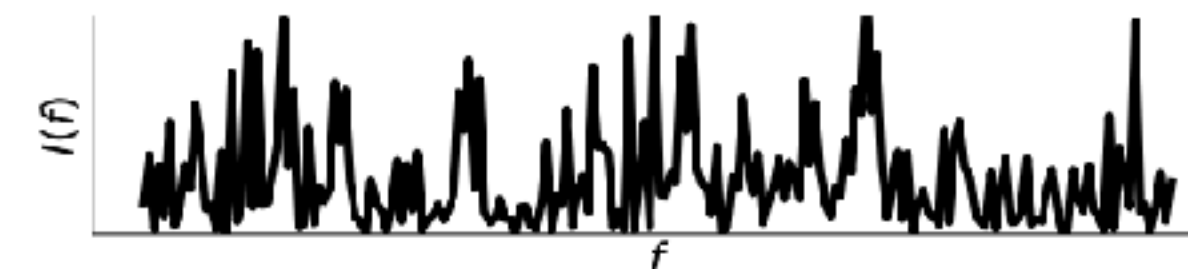
Intrinsic scintillation (local lens only)

(b) Scintillation with background lens

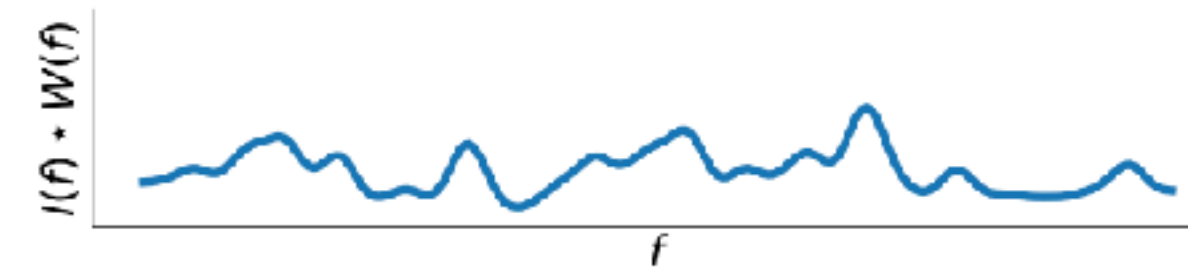


CGM of an
intervening galaxy
(In fact many images
across R_{vir})

Milky Way ISM



Intrinsic scintillation

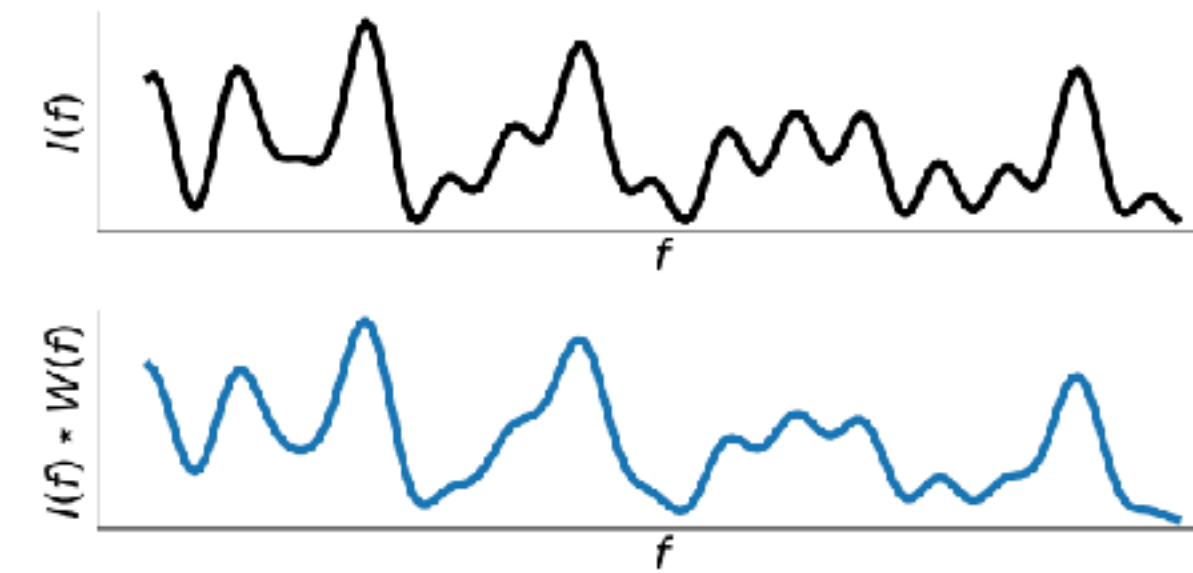
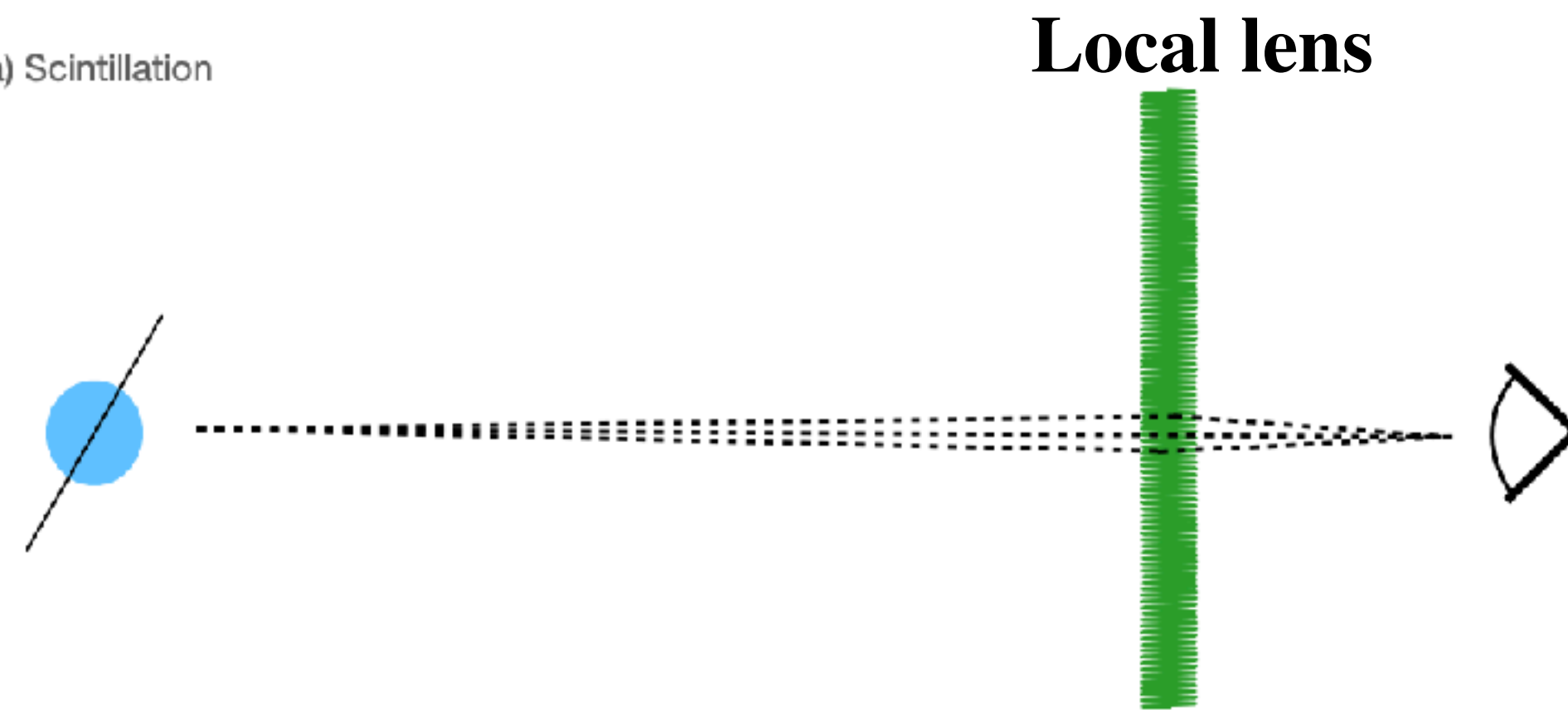


Observed scintillation

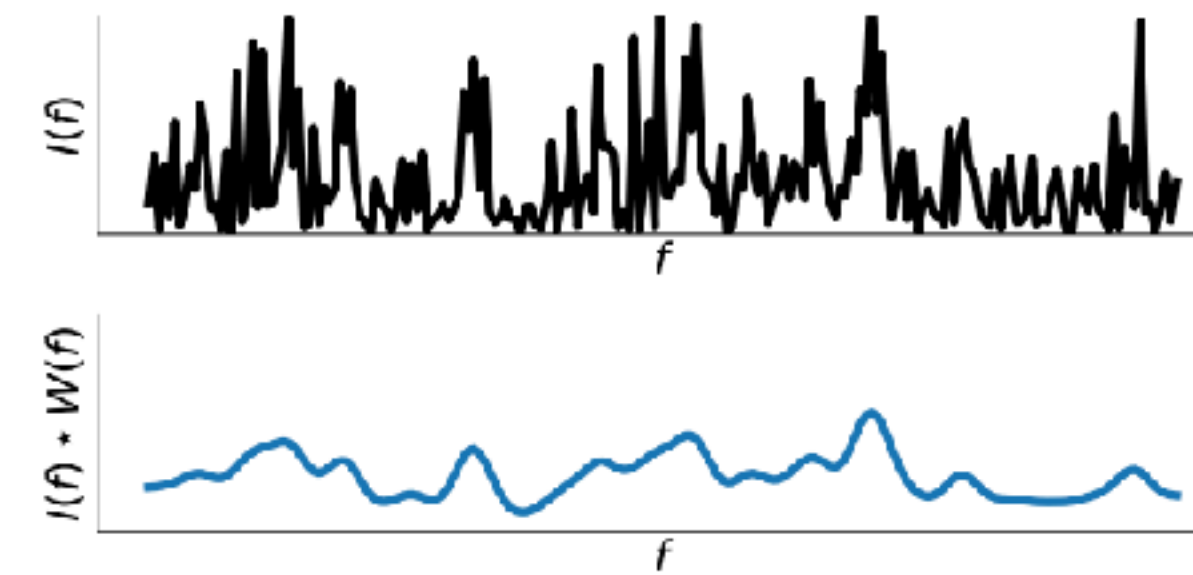
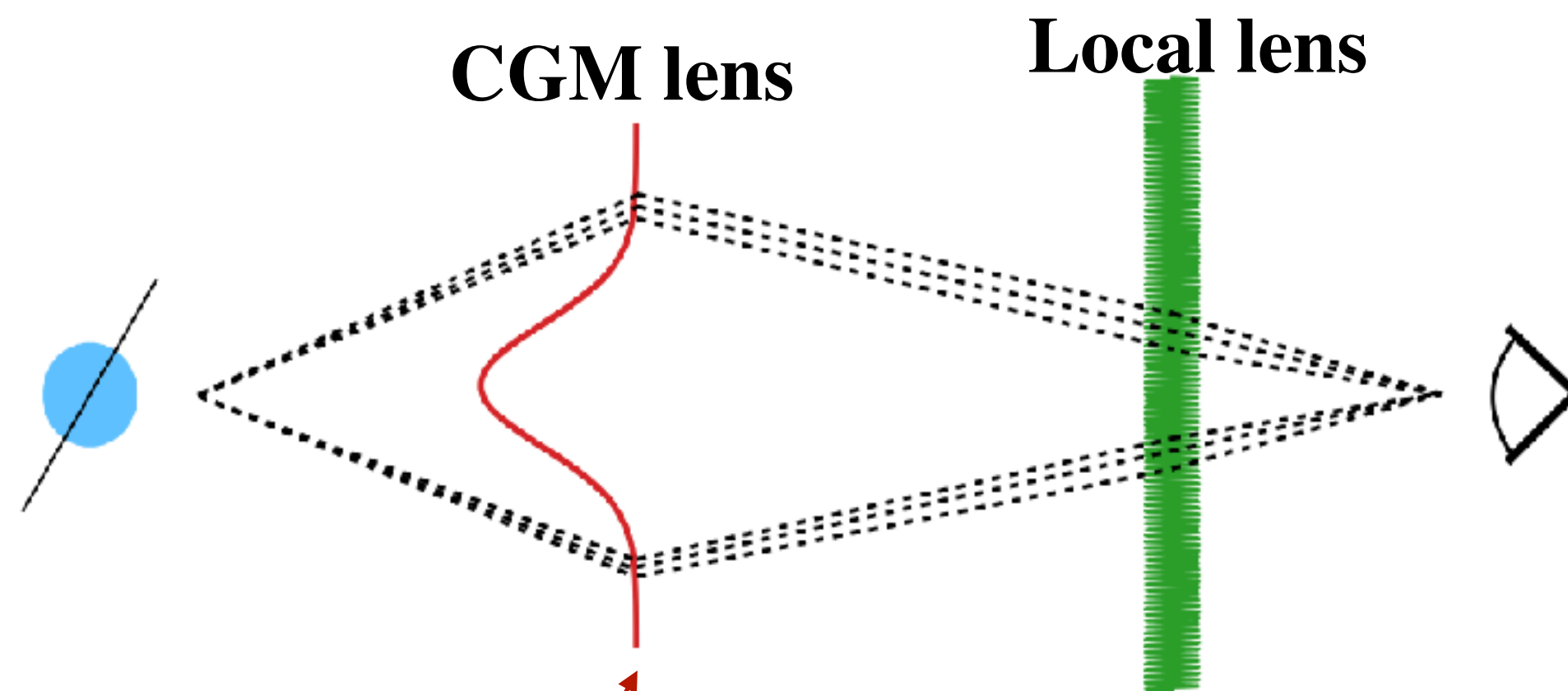
$$df \sim 1/\Delta\tau_{\text{max}}$$

CGM lens \rightarrow increase maximum time delay among
images $\Delta\tau_{\text{max}} \rightarrow$ reduce intrinsic decorrelation
frequency $df \rightarrow$ suppress scintillation when $df <$
frequency resolution

(a) Scintillation



(b) Scintillation with background lens



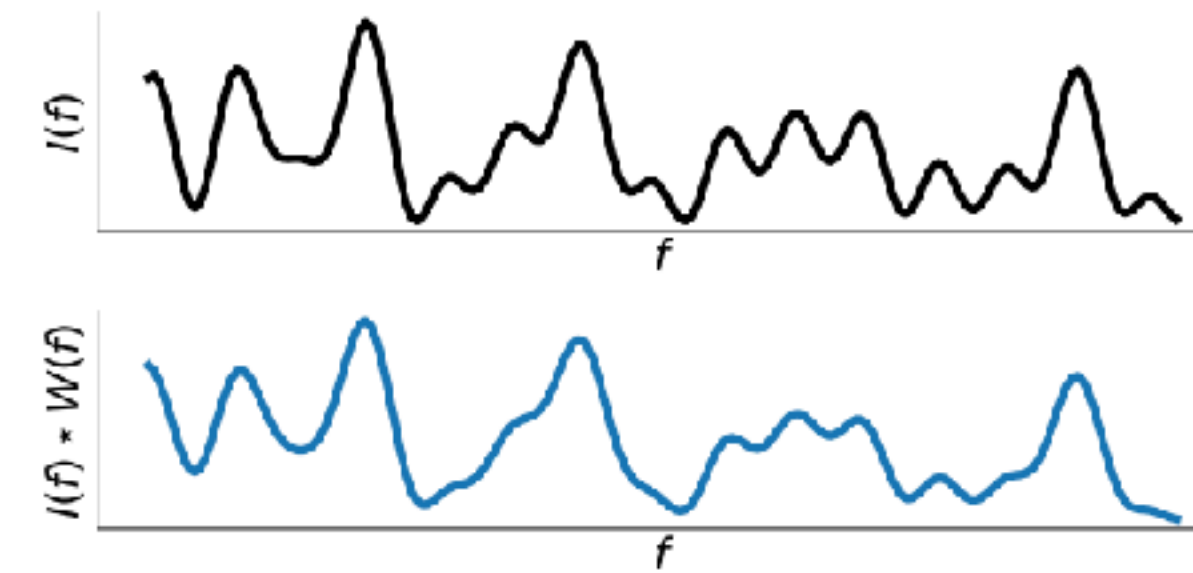
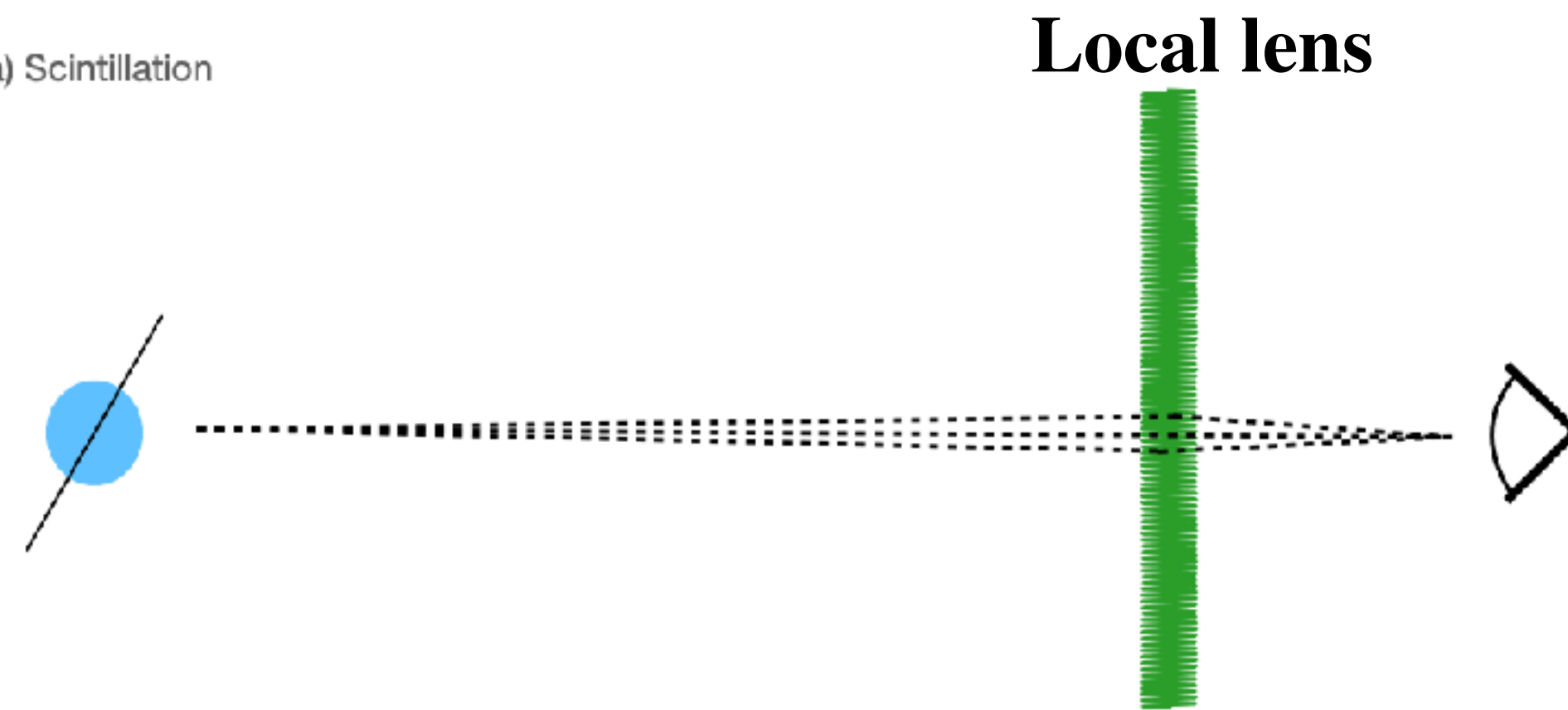
CGM of an
intervening galaxy
(In fact many images
across R_{vir})

Milky Way ISM

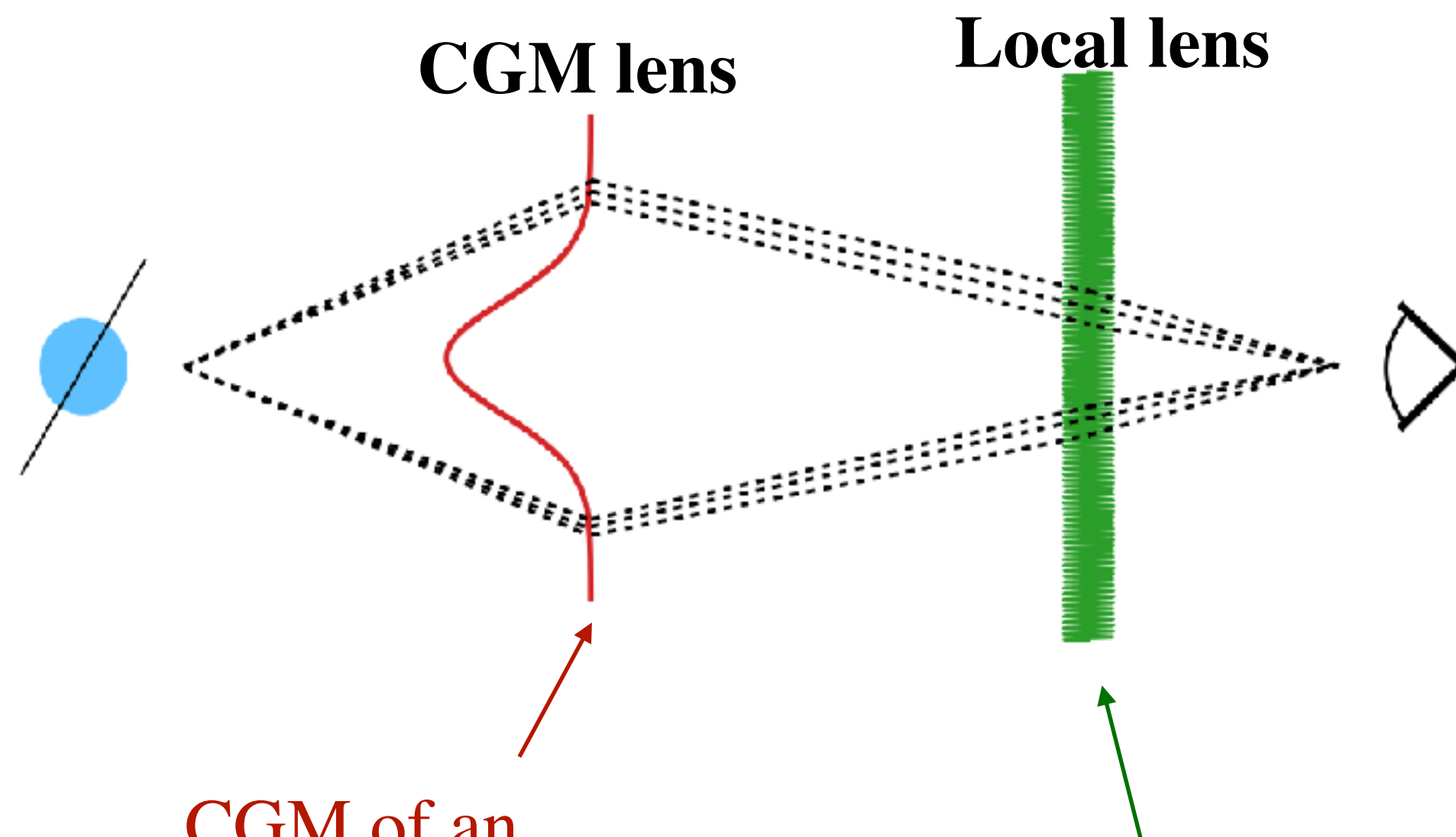
Bottom line: Fog-like CGM -> suppress observable scintillation

Strong FRB scintillation observed + FRB sight line typically lies within R_{vir} of some galaxy -> CGM likely not fog-like

(a) Scintillation

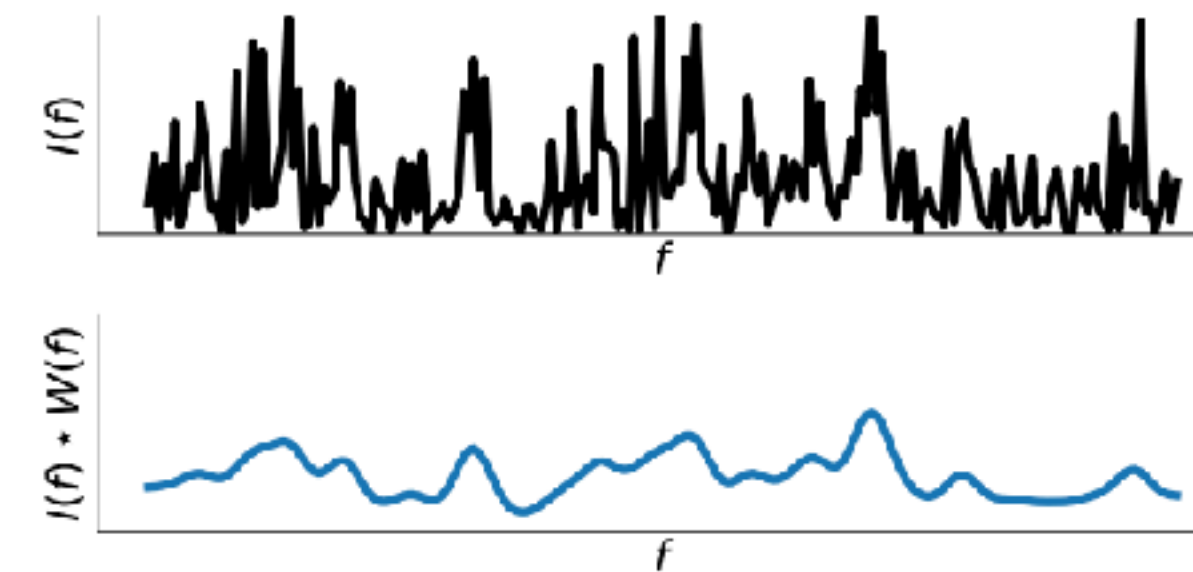


(b) Scintillation with background lens



CGM of an
intervening galaxy
(In fact many images
across R_{vir})

Milky Way ISM



Bottom line: Fog-like CGM -> suppress observable scintillation

Strong FRB scintillation observed + FRB sight line typically lies within R_{vir} of some galaxy -> CGM likely not fog-like

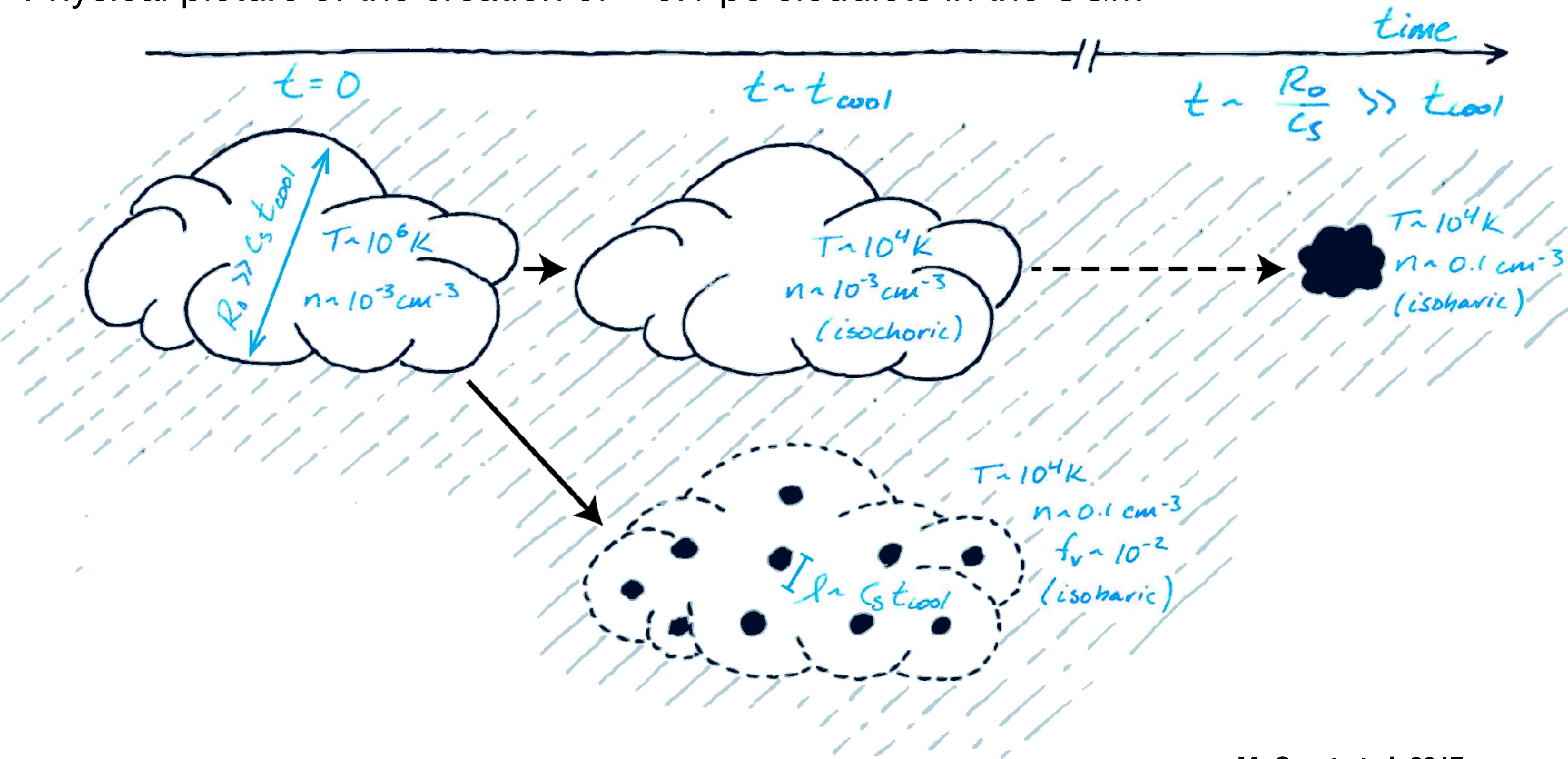
Way out: sheet-like CGM -> fewer deflected flux at the CGM lens -> less suppression

Why I recommend this paper:

1. Links different research areas: CGM, FRB, radio wave scintillation, 2-screen lensing
2. Good logical inferences: CGM lens screen (if fog-like) + ISM lens screen -> suppress observed frequency modulation of FRB
3. Meaningful implications: CGM is likely not fog-like, can be possibly sheet-like
4. Testable predictions (falsifiable): more FRB scintillation observations; relative suppression at different frequencies; other observations of CGM...

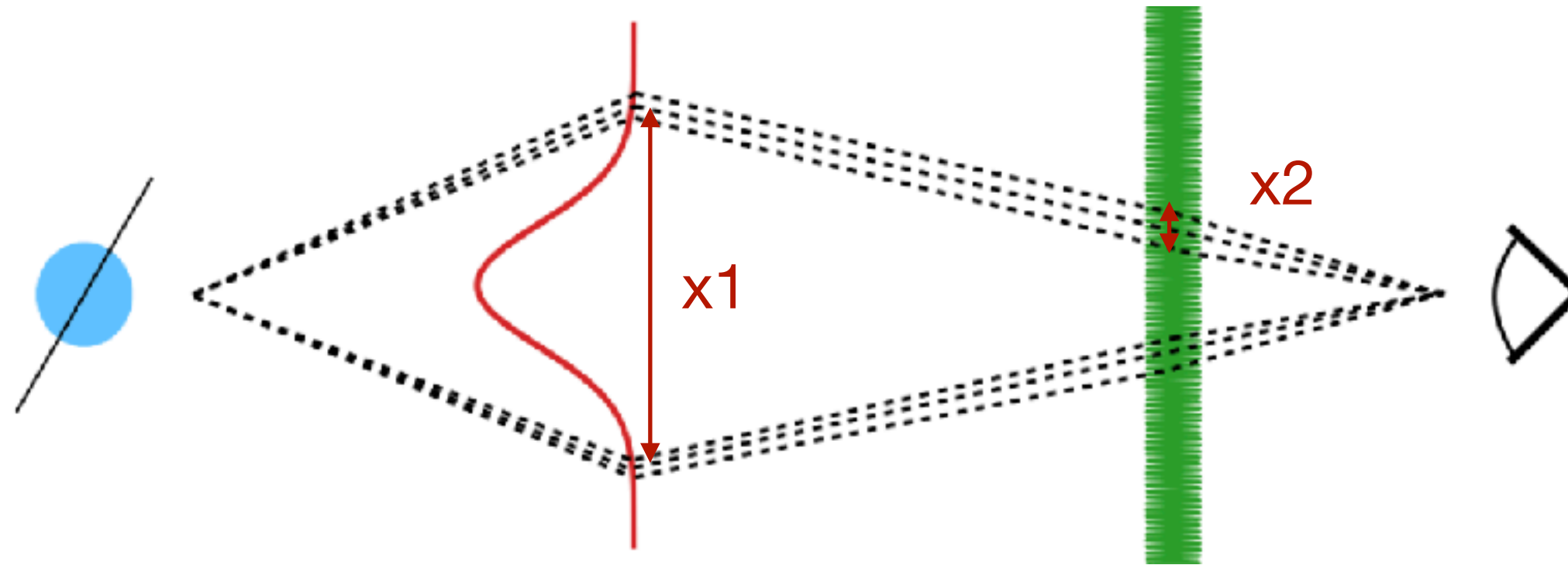
Backup slides

Physical picture of the creation of ~ 0.1 pc cloudlets in the CGM



Suppression of scintillation by the 2nd screen

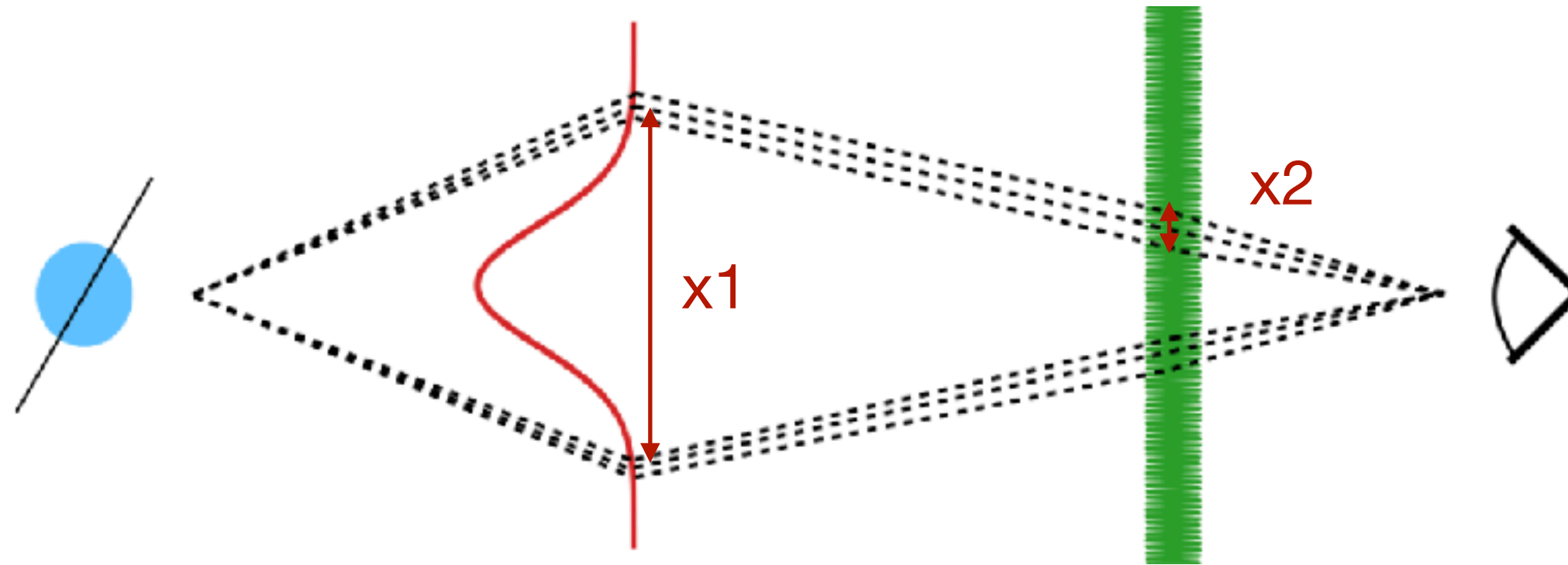
- A condition for suppression: screen1 and screen2 '**resolve**' each other



resolve: $x_1 x_2 > D_{12} \lambda$

Suppression of scintillation by the 2nd screen

- A condition for suppression: screen1 and screen2 ‘**resolve**’ each other



resolve: $x_1 x_2 > D_{12} \lambda$

Other examples of such suppression

- in the argument that FRB scattering is dominated by the host galaxy
- Low scintillation modulation of the Crab pulsar (suppression by lensing by the Crab Nebula)

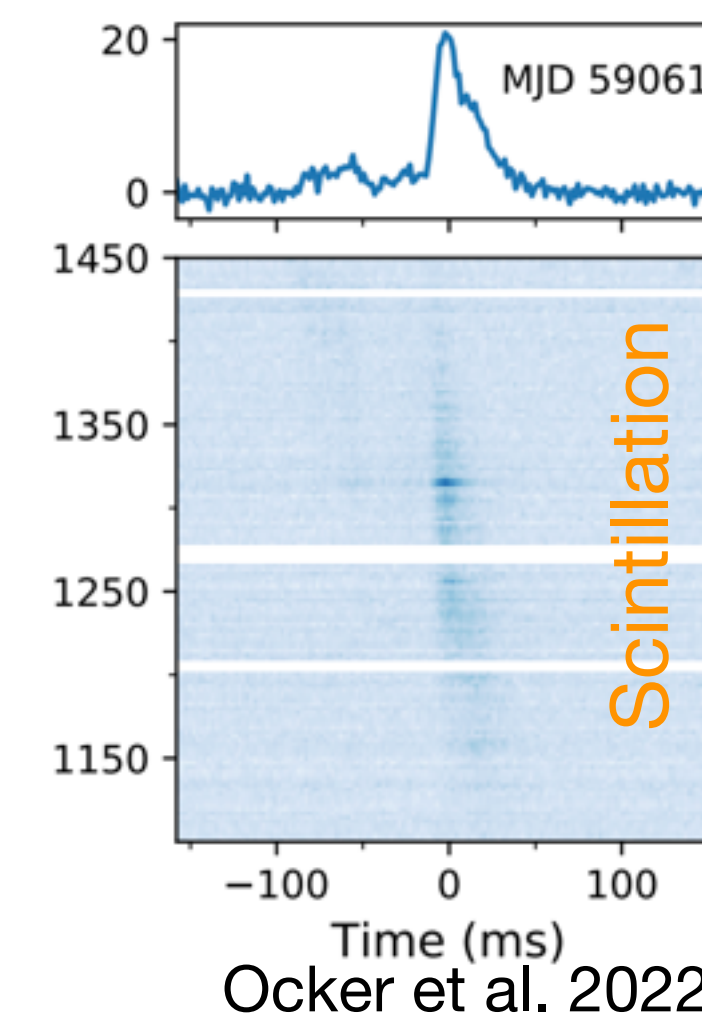
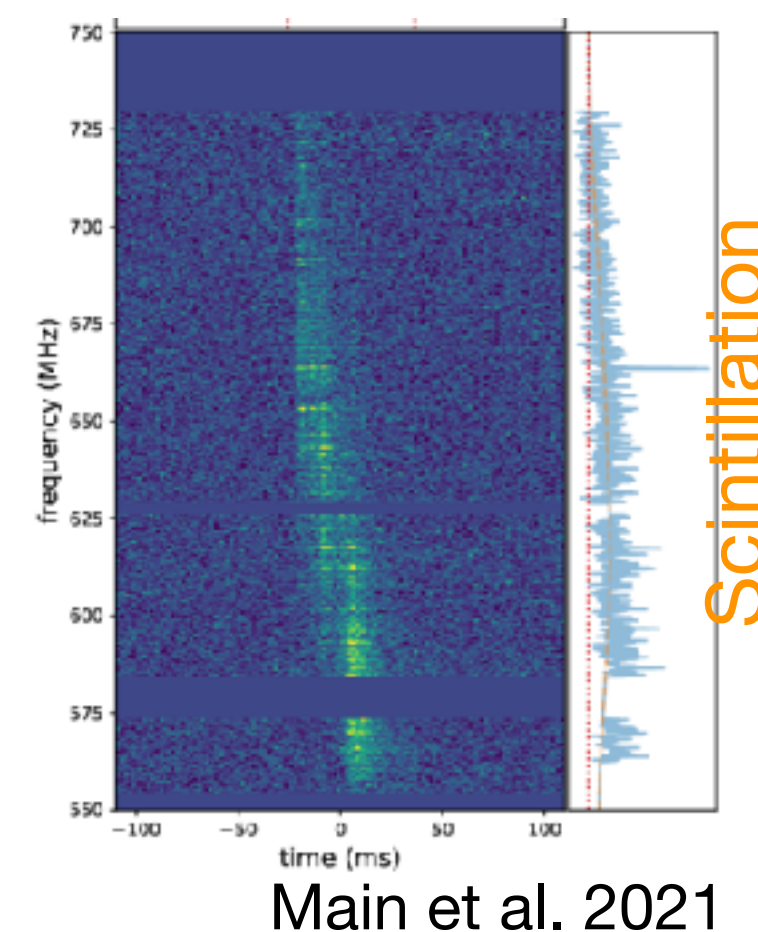
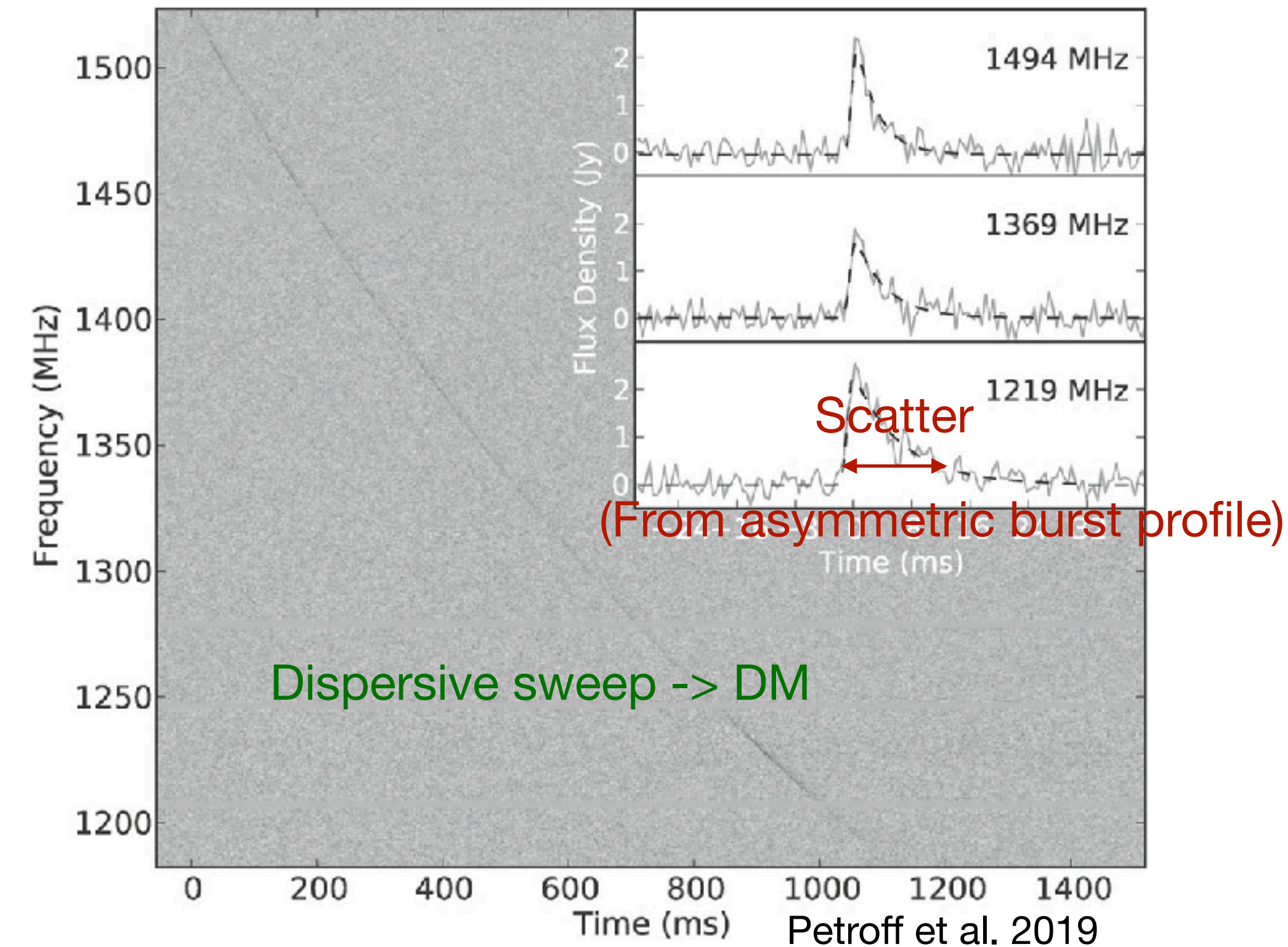
From pulsar scintillation we know $x_2 \sim \text{AU}$. Take $D_{12} \sim \text{Gpc}$, $\lambda \sim \text{m}$. To resolve, we need $x_1 > 10^3 \text{ AU} \sim 10^{-2} \text{ pc}$

For a screen1 within the Galaxy (in the case of Crab pulsar), take $D_{12} \sim \text{kpc}$, $\lambda \sim \text{m}$. To resolve, we need $x_1 > 10^{-3} \text{ AU} \sim 10^5 \text{ km}$

Facts about **FRB**

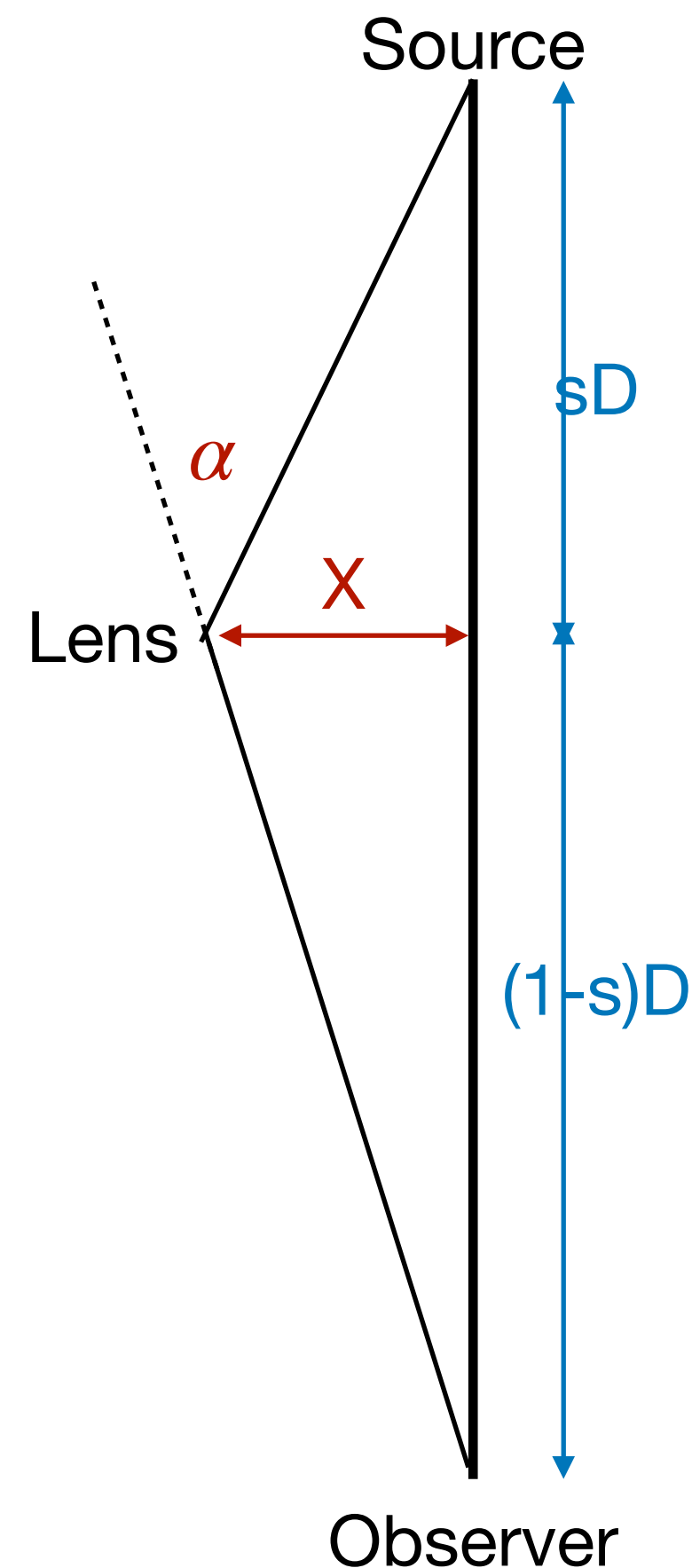
1. Large dispersion measure (**DM** $> \sim 10^3$)
w. large IGM contribution
2. Many with large **scatter** (\sim ms at \sim GHz)
from host galaxy
3. Many **scintillate** (modulation of flux in frequency due to interference of multiple images) from Milky Way ISM

Why observed DM, scatter and frequency modulation are associated with different medium?



Why observed DM, scatter and frequency modulation are associated with different medium? Esp. why scatter is attributed to the host galaxy?

— Again related to a geometry problem!



Scatter \sim time difference $\Delta\tau$ of the two paths

$$\Delta\tau = \frac{x^2}{2cDs(1-s)} = \frac{s(1-s)D\alpha^2}{2c}$$

Lensing strength is characterized by the largest deflection angle α .

At a fixed α :

Largest $\Delta\tau$ when $s = 0.5$;

When $s \sim 0$ (host galaxy) or $s \sim 1$ (Milky Way), very small $\Delta\tau$

At a fixed $\Delta\tau$:

Largest x when $s=0.5 \rightarrow$ easy to 'resolve'

Take $D \sim \text{Gpc}$, $\Delta\tau \sim \text{ms}$, we have $x \sim 0.1 \text{ pc} \sqrt{s(1-s)} \rightarrow$ can resolve x^2 when $0.1 < s < 0.9 \rightarrow$ only when $s \sim 0$ or $s \sim 1$, suppression of scintillation does not happen. We know Galactic $\Delta\tau$ is insufficient (rule out $s \sim 1$) \rightarrow attribute $\Delta\tau$ to host galaxy.