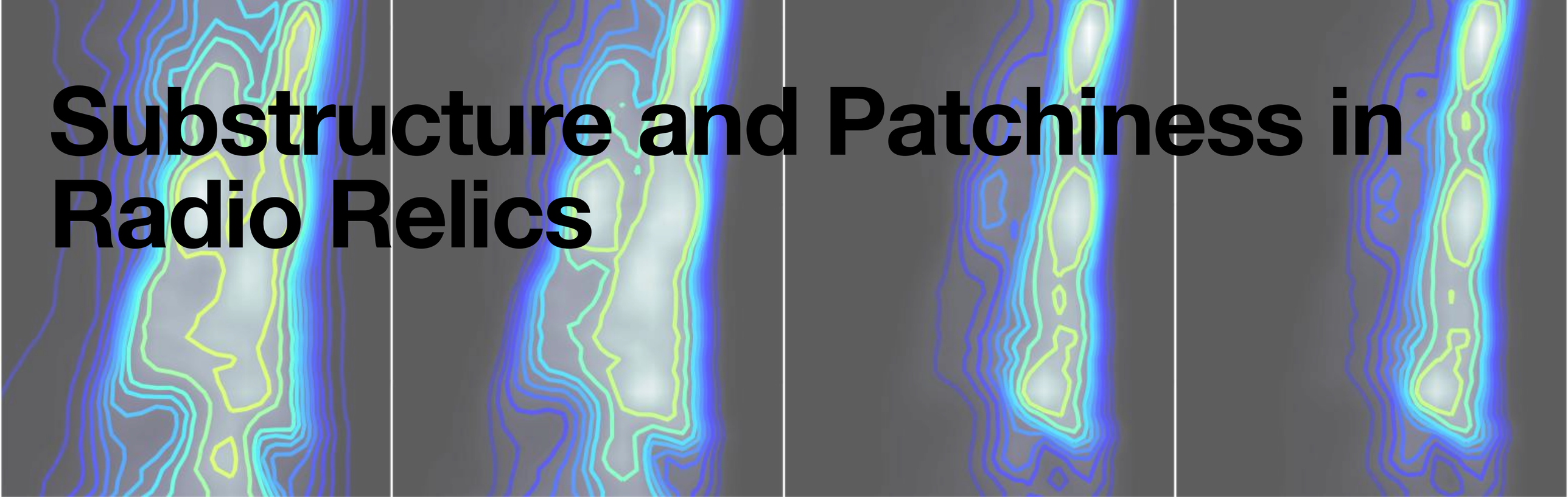


# Substructure and Patchiness in Radio Relics

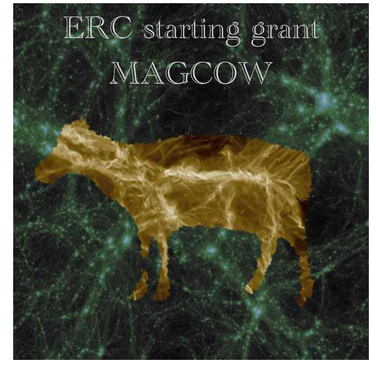

## Paola Domínguez Fernández

University of Bologna

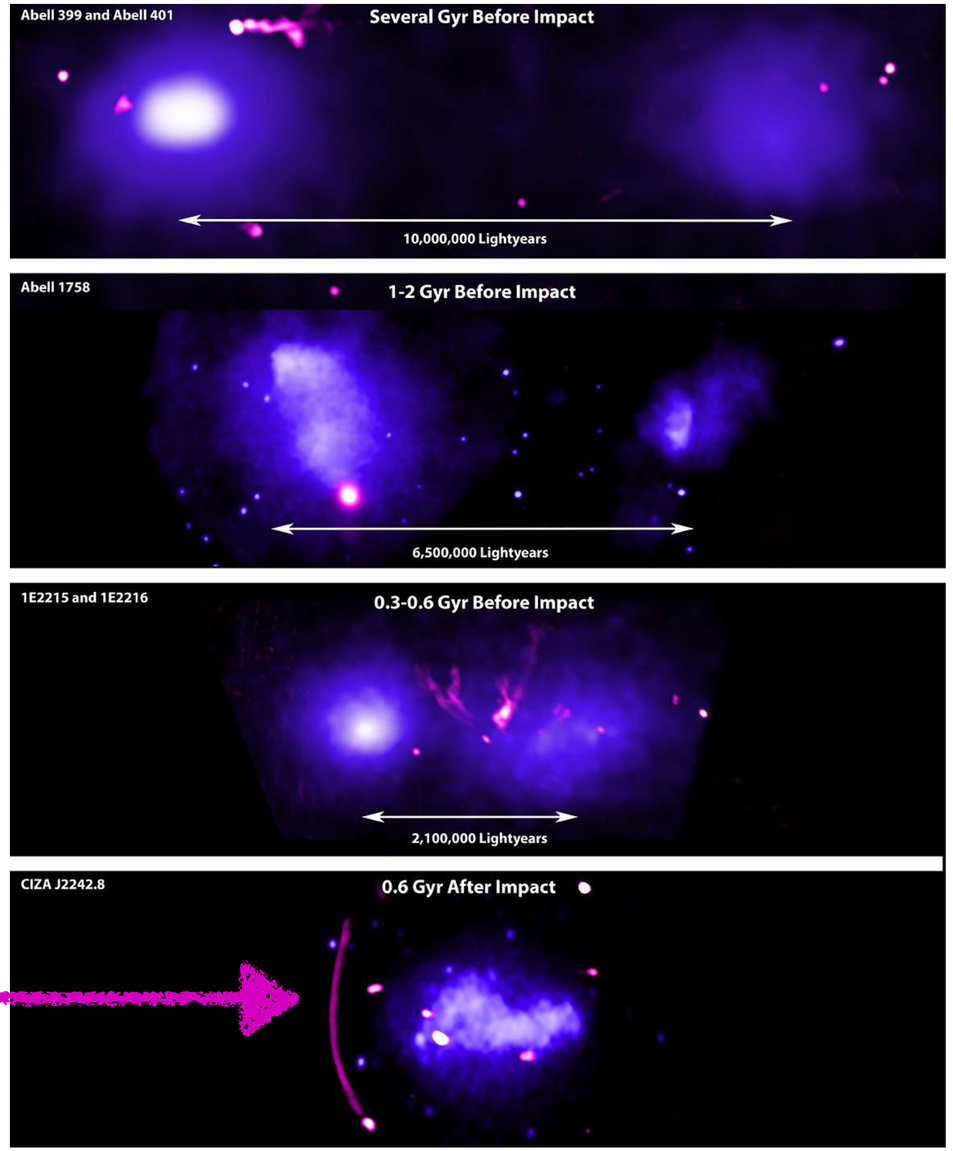
Collaborators: Dongsu Ryu and Hyesung Kang



IAUGA Busan FM6 | 2022

# Galaxy cluster mergers

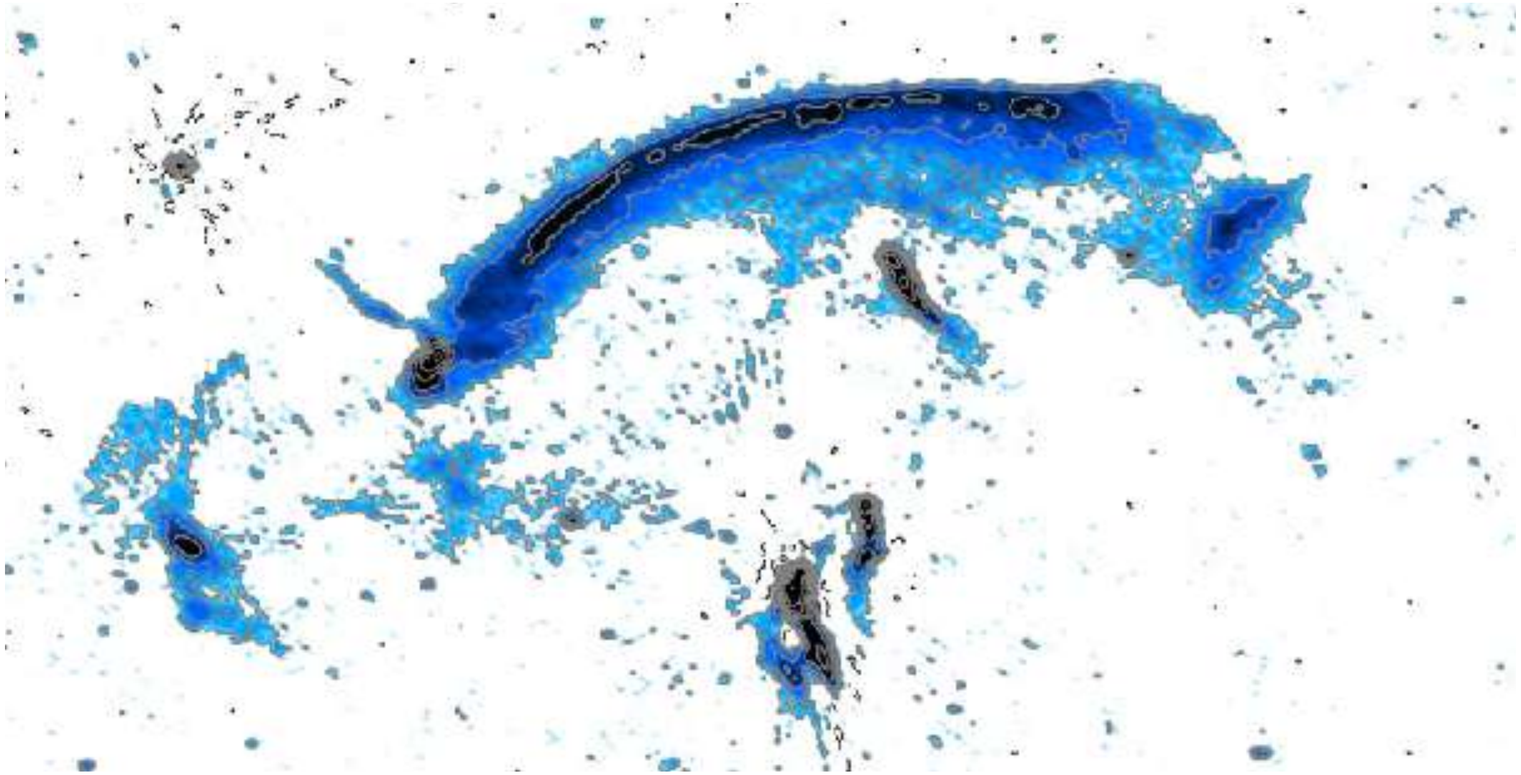



X-ray
Radio

Radio relics!

[X-ray: NASA/CXC/RIKEN/L. Gu et al; Radio: NCRA/TIFR/GMRT; Optical: SDSS]

# The CIZA relic at different frequencies



**145 MHz**
Hoang et. al 2017

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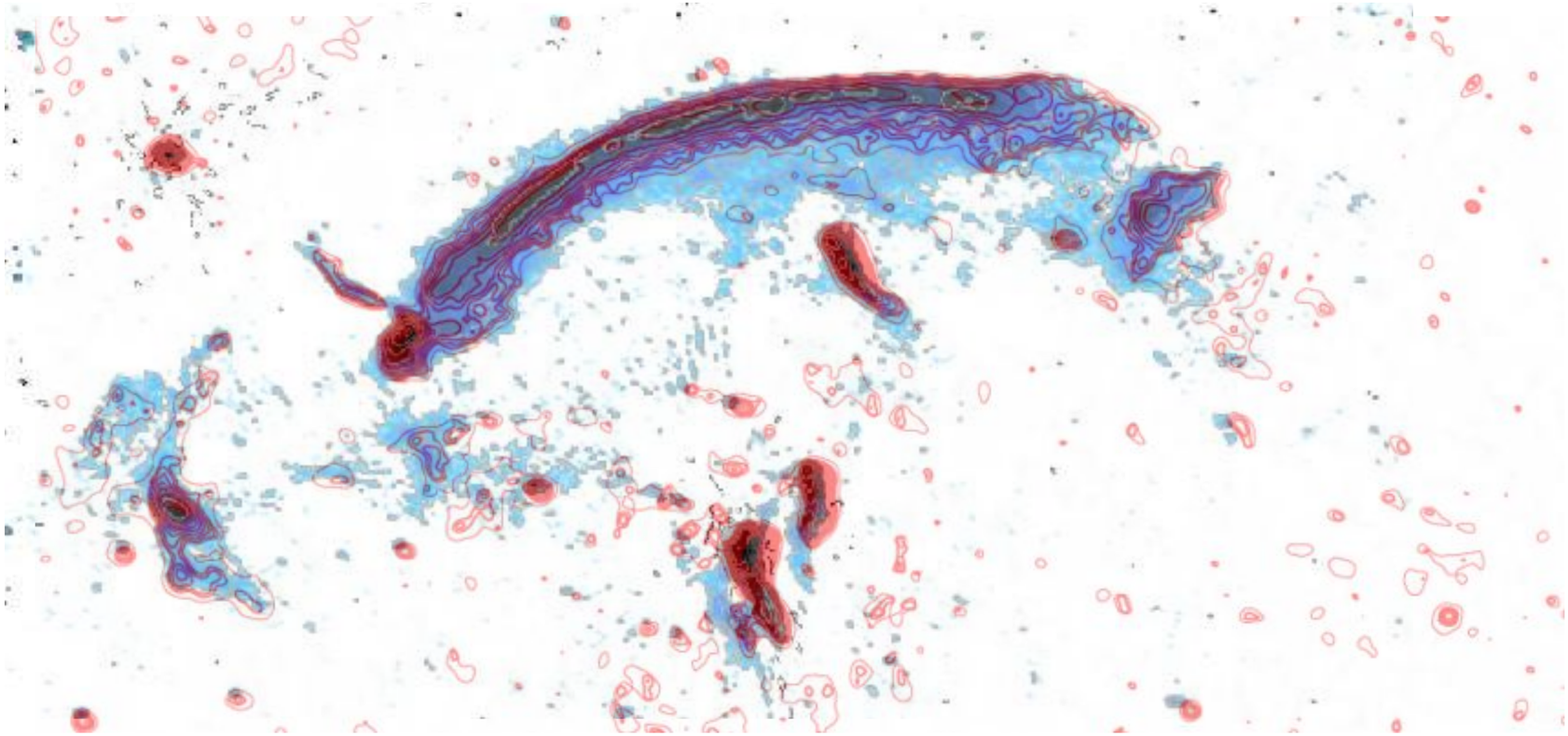

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Hoang et. al 2017

**325 MHz**
van Weeren et. al 2011

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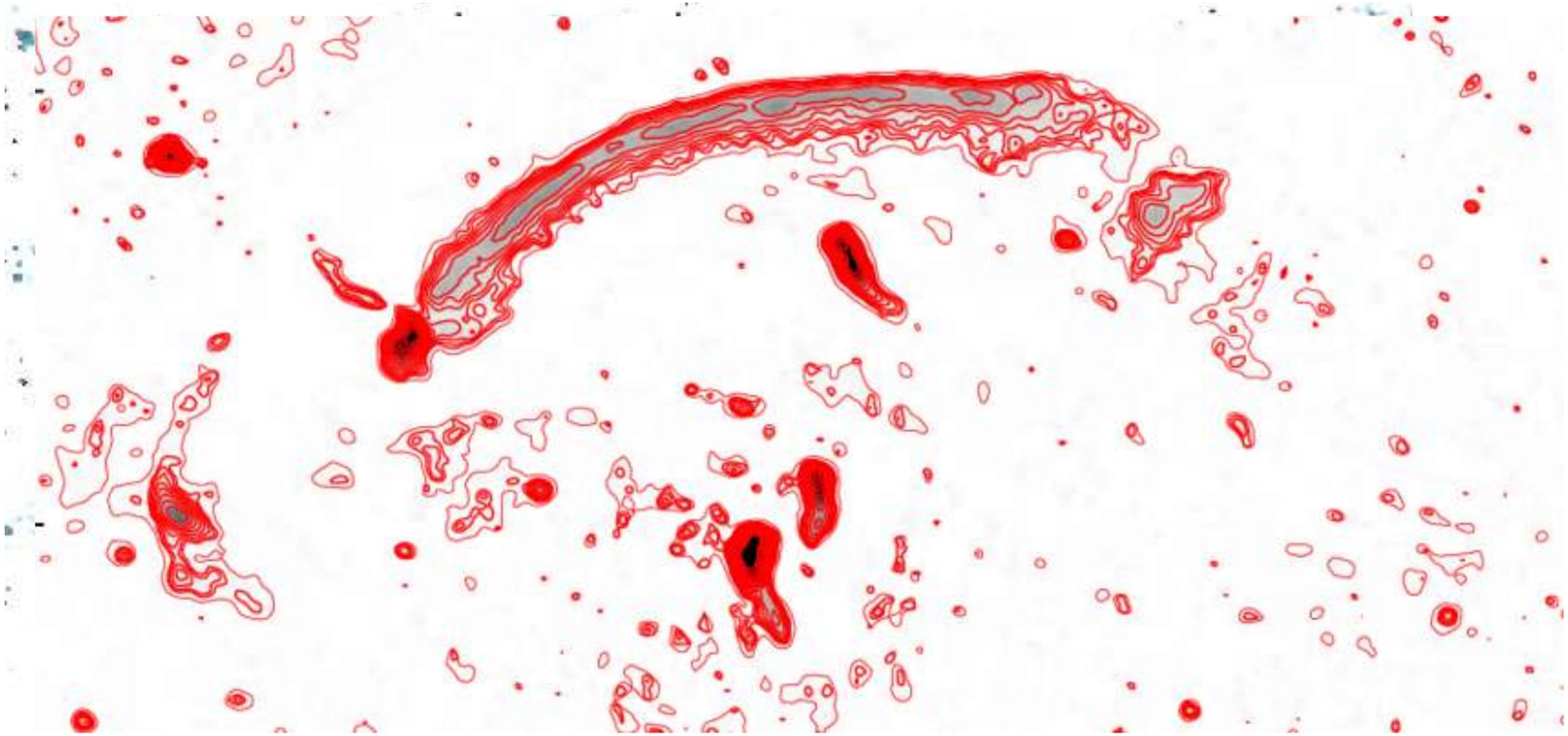

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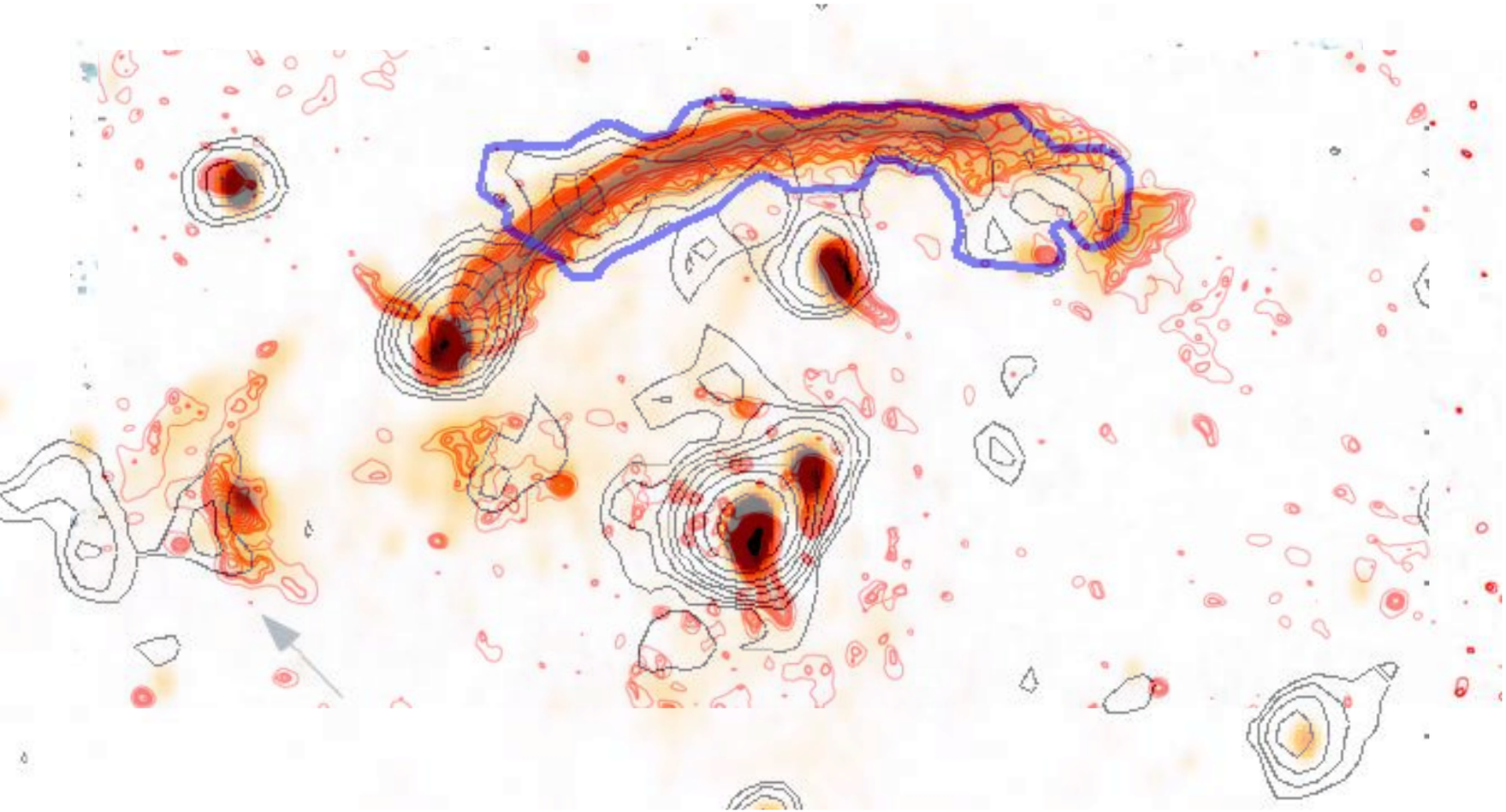

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**1.4 GHz**
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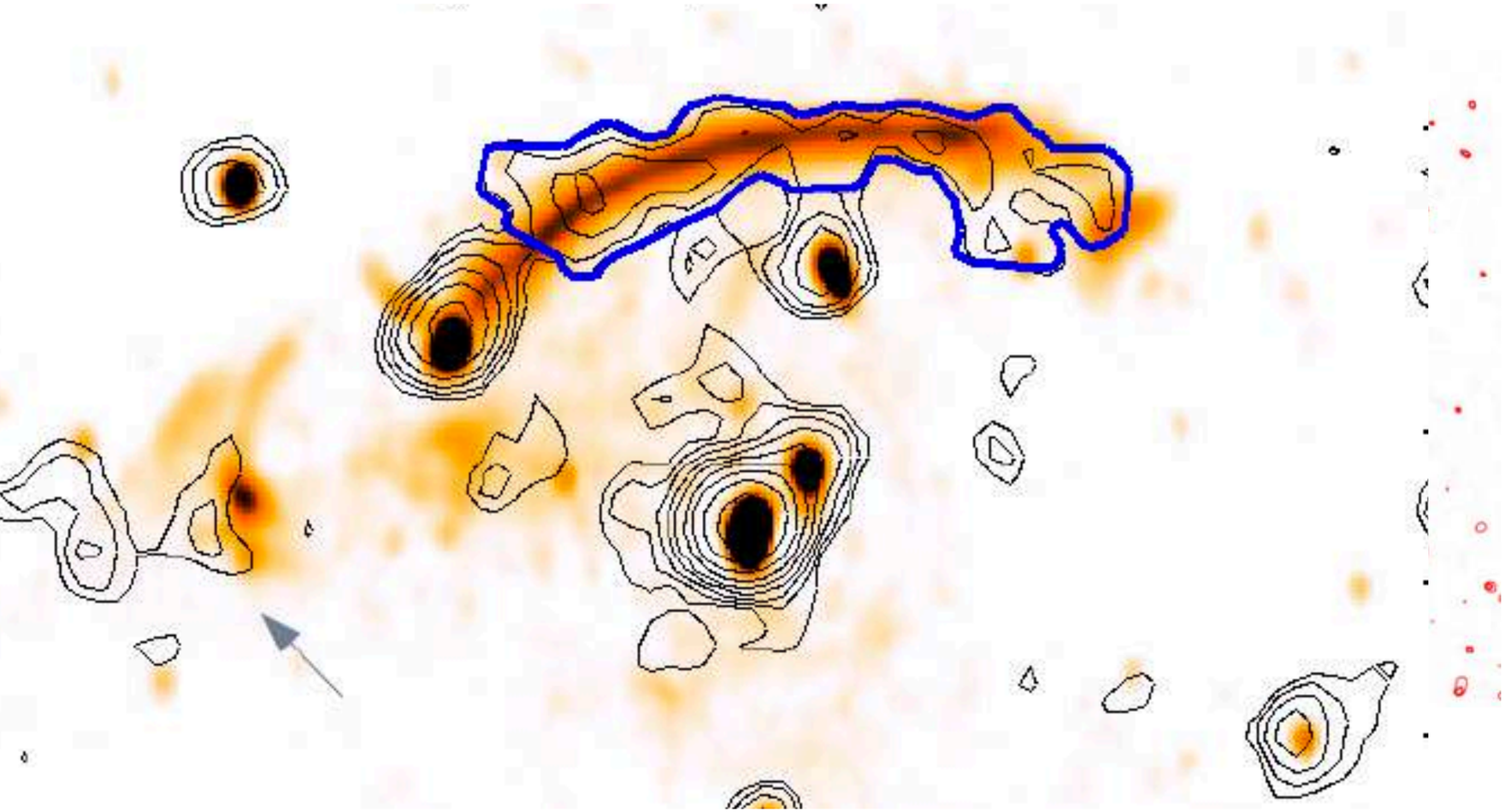

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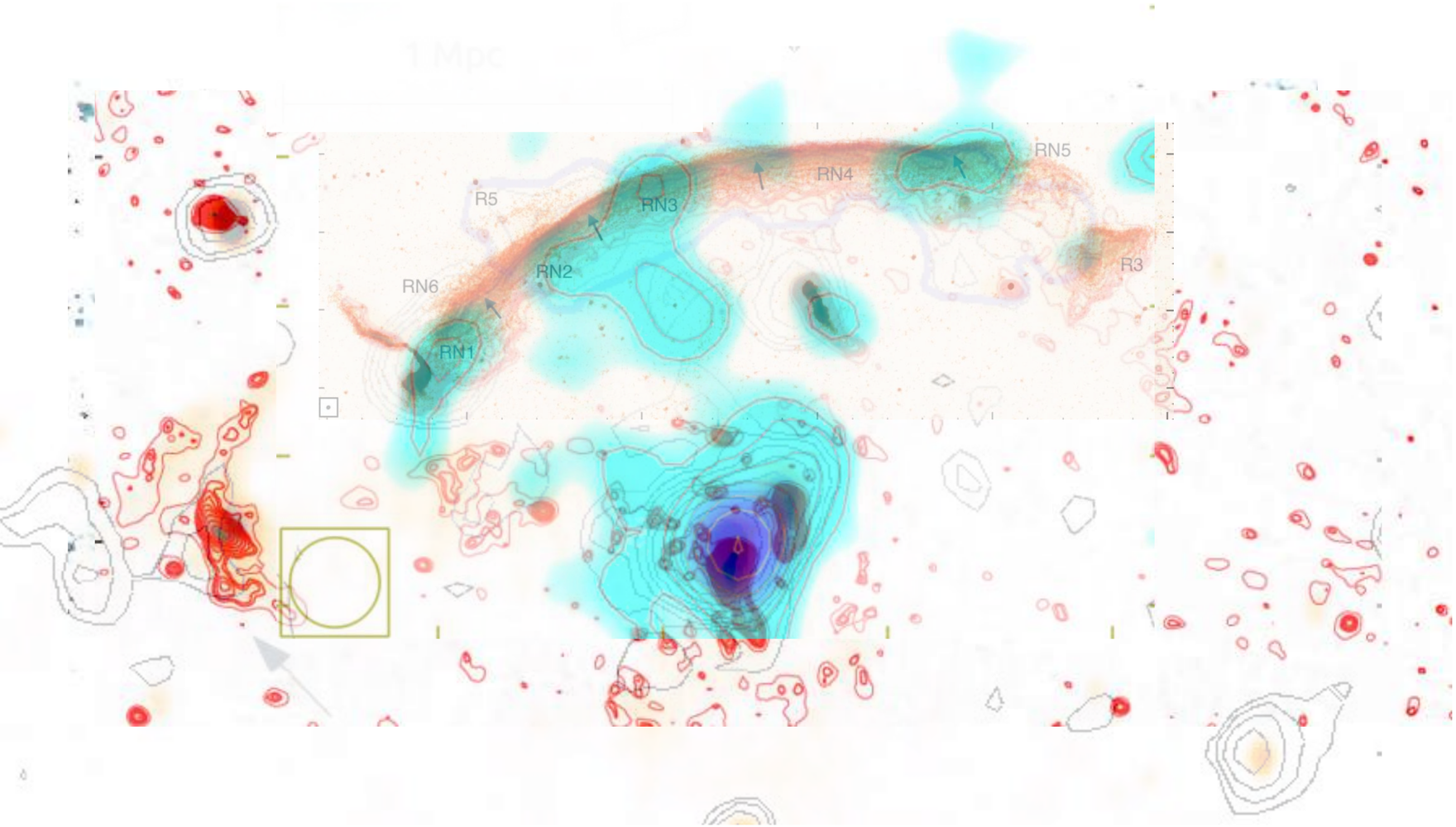


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Loi et. al 2020

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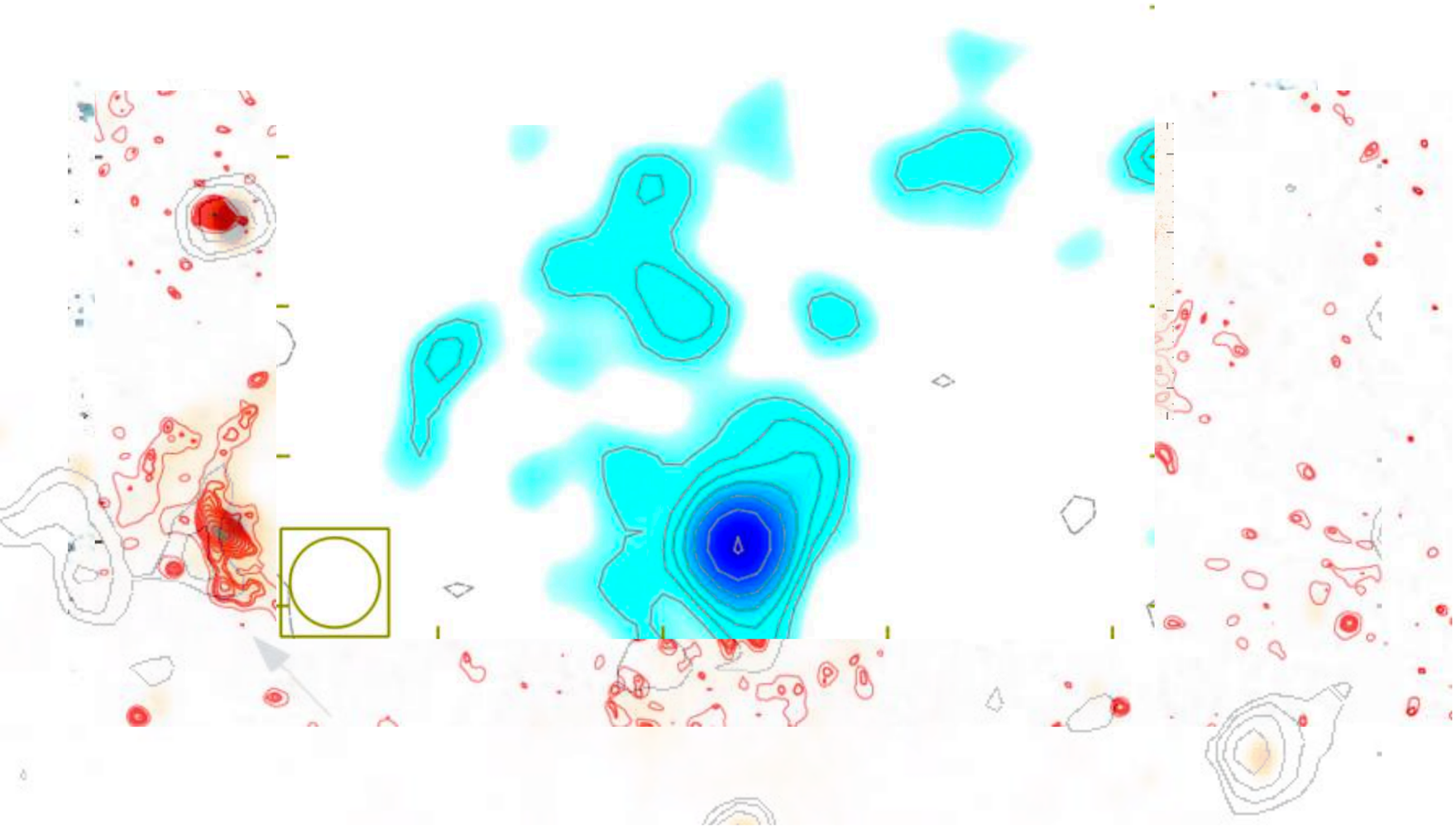

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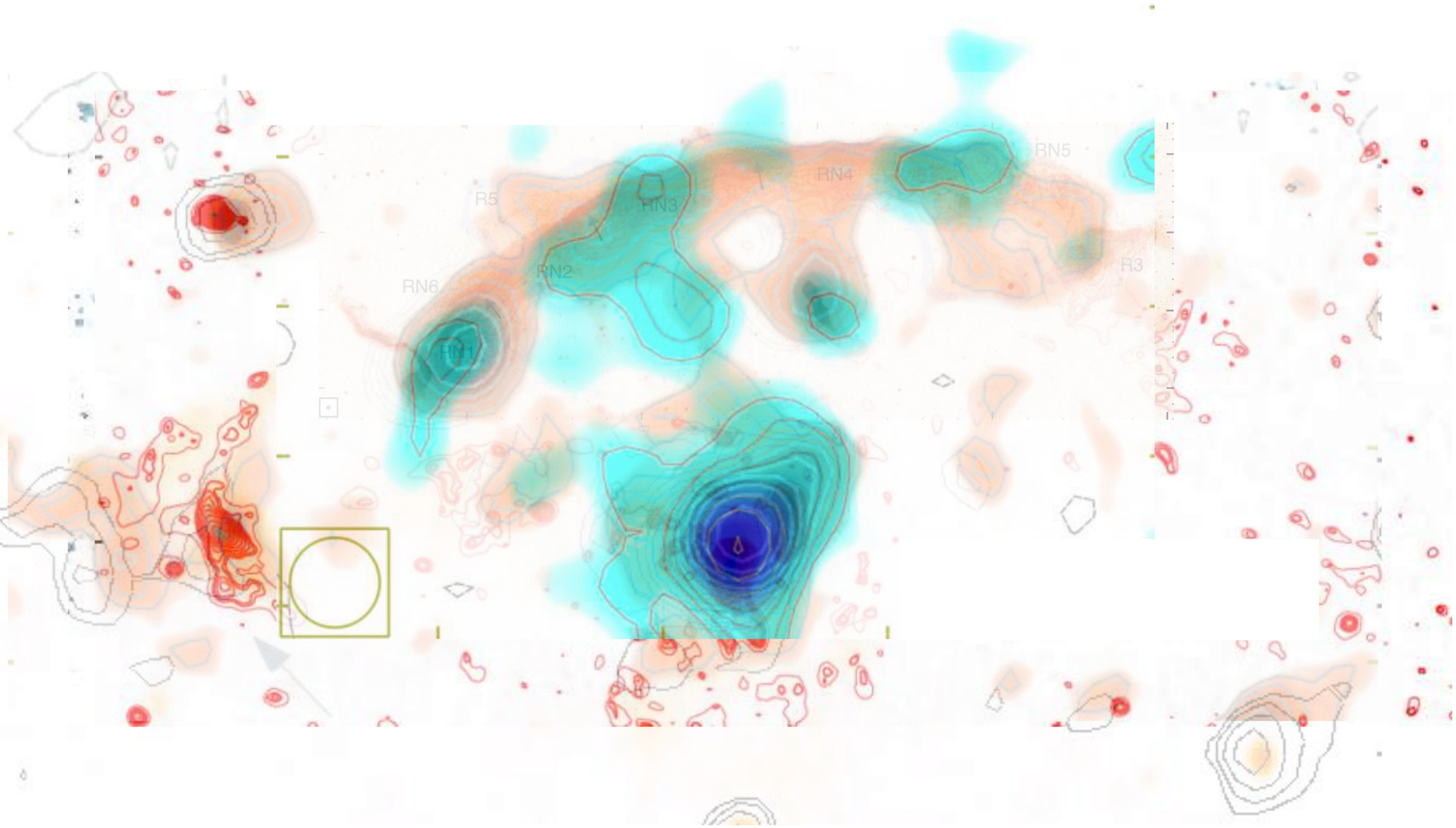
# The CIZA relic at different frequencies

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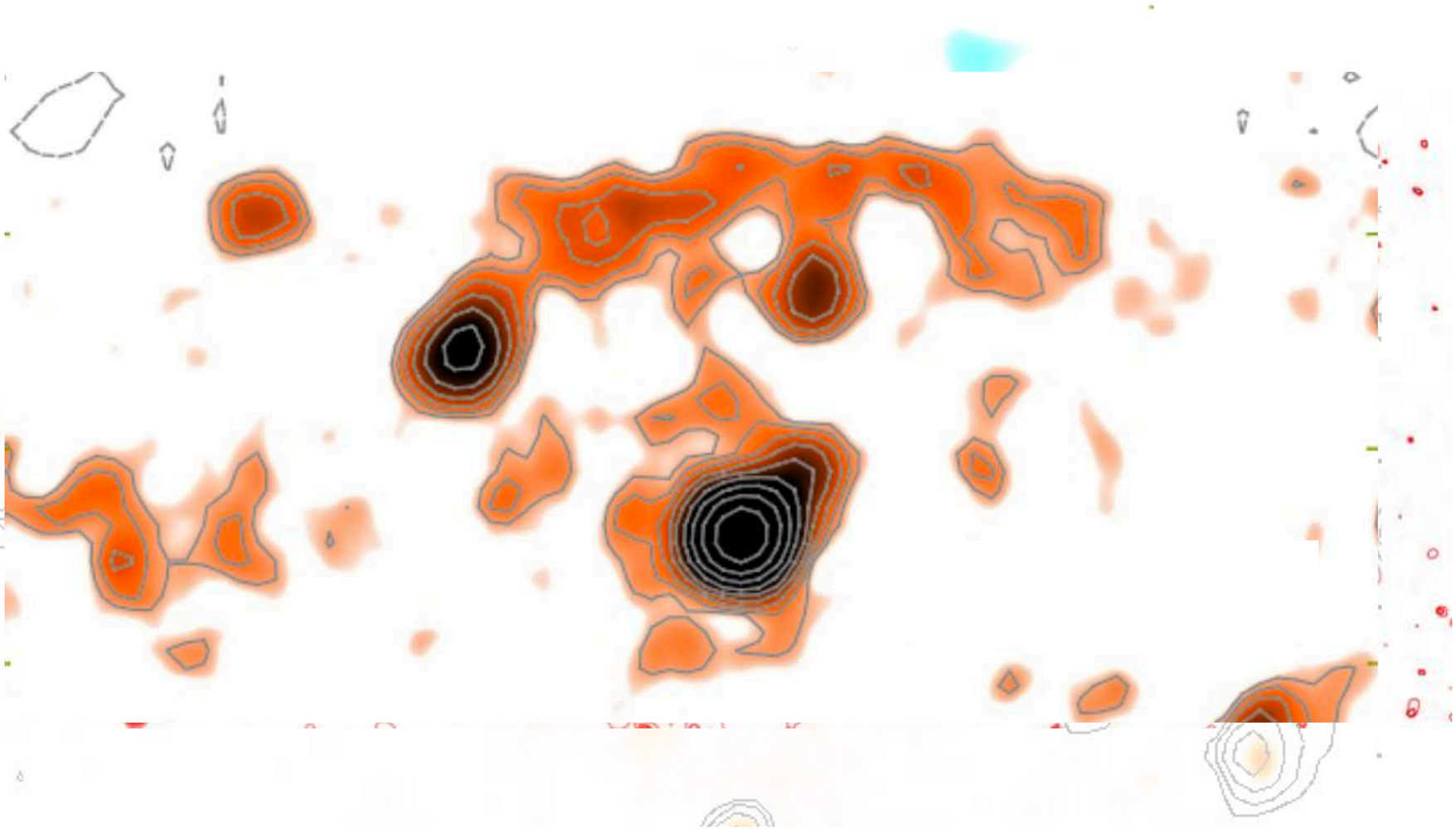

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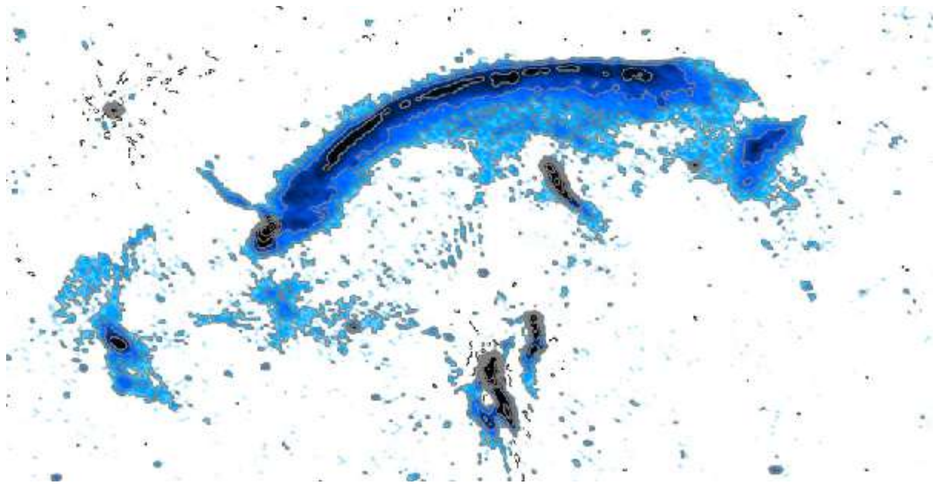

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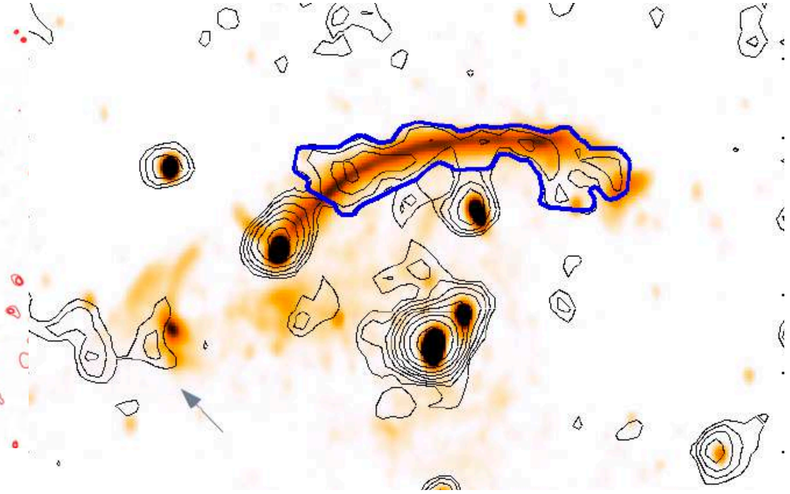
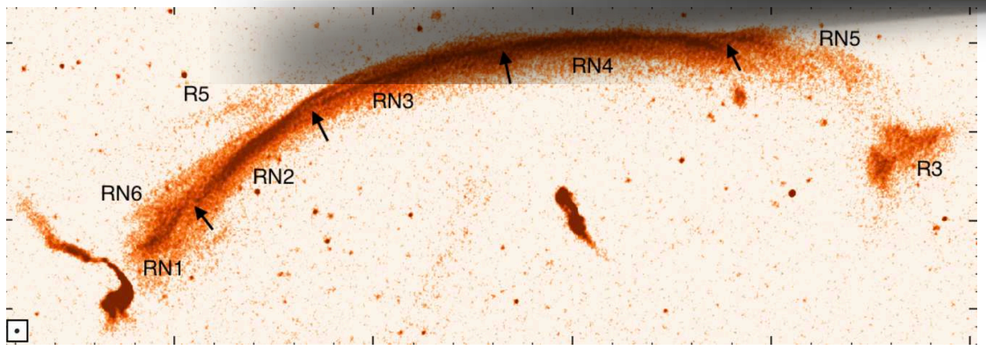
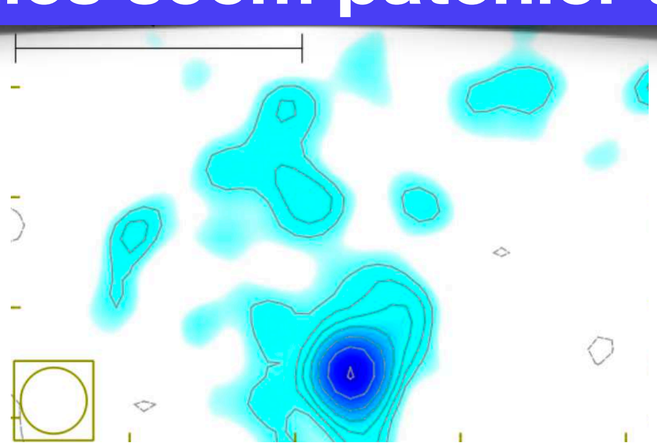


1.4 GHz

## Why do some radio relics seem patchier at high frequencies?




**1.5 - 4 GHz**
Di Gennaro et. al 2018



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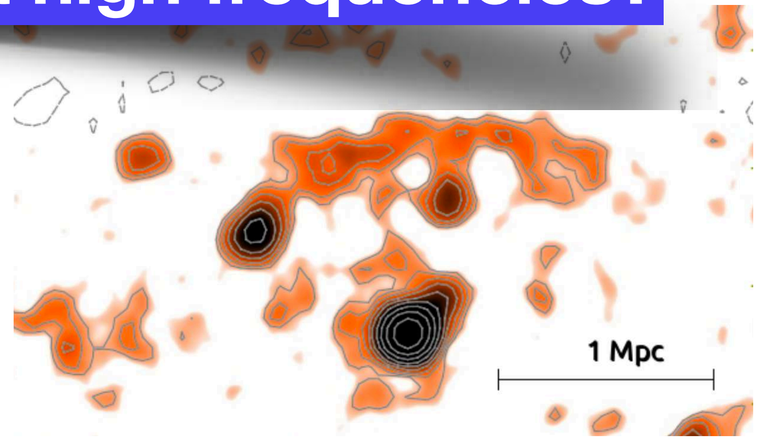
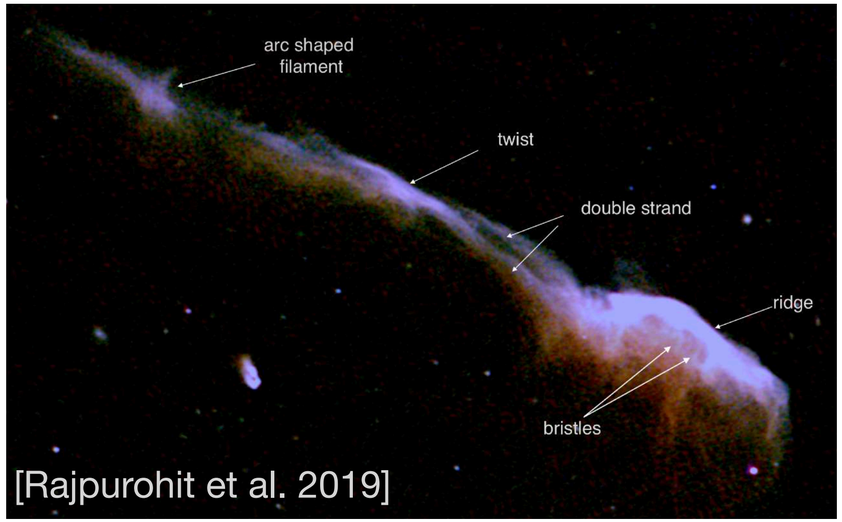
Loi et. al 2020



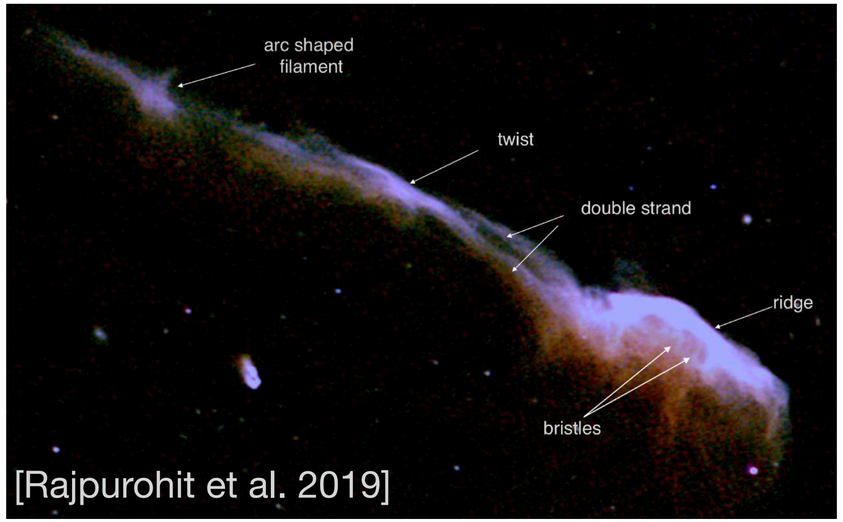

**18.6 GHz**
Loi et. al 2020

# Mach numbers & patchiness




[Rajpurohit et al. 2019]

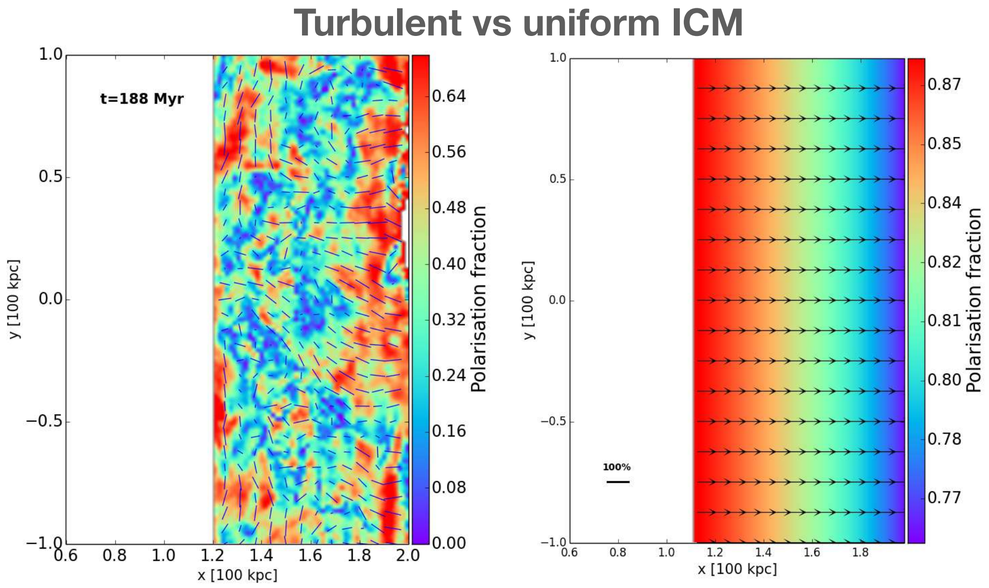
# Mach numbers & patchiness



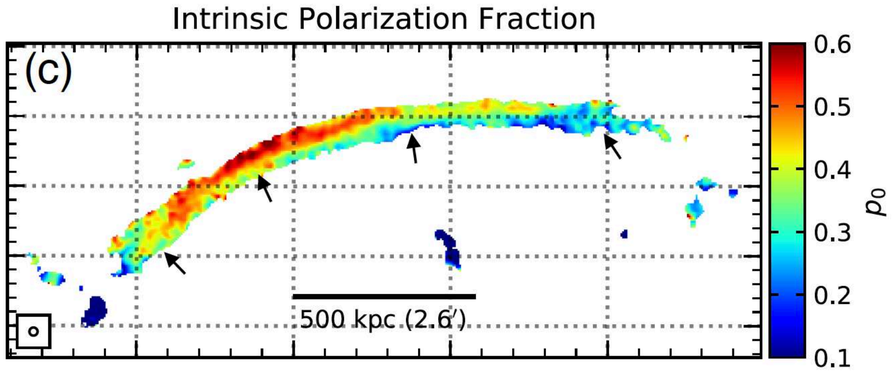

[Rajpurohit et al. 2019]

**A shock front is characterised by a distribution of Mach numbers**

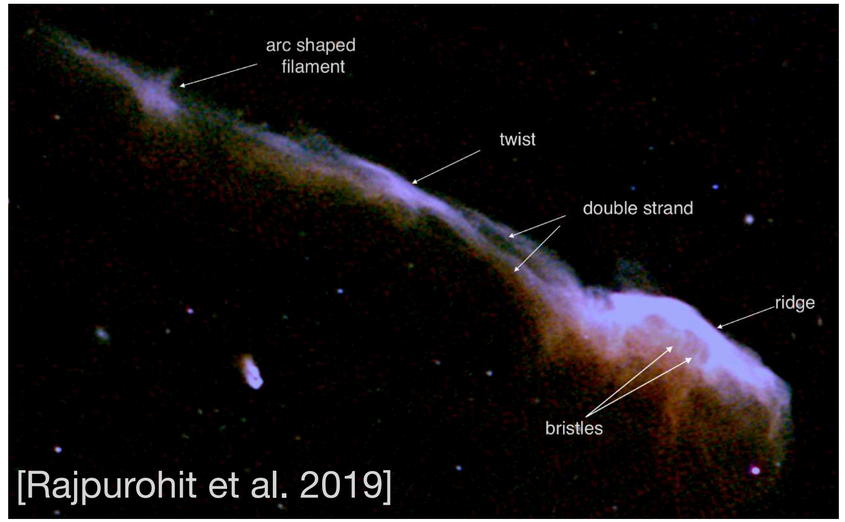
# Mach numbers & patchiness




Domínguez-Fernández et al. 2021]

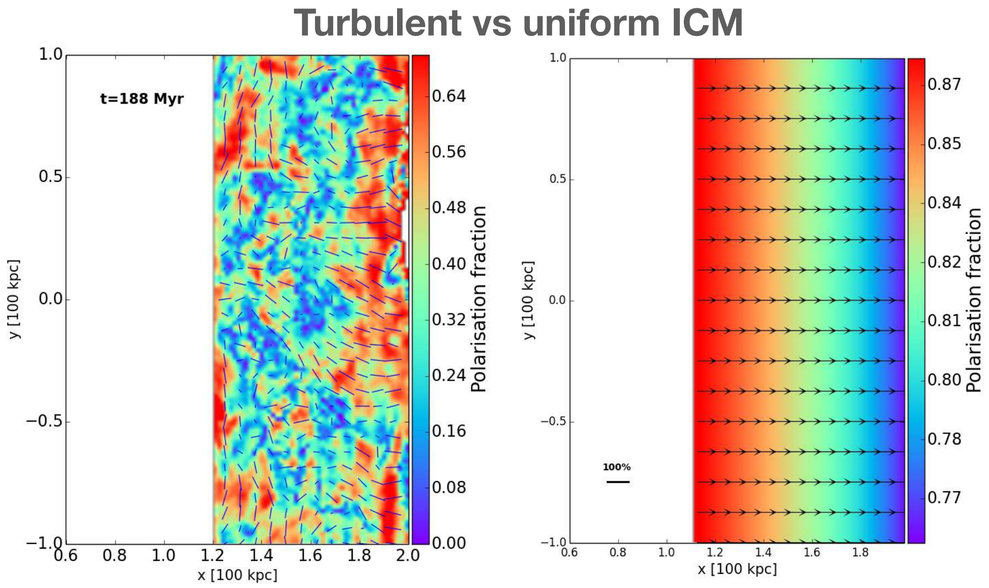



[di Gennaro et al. 2021]

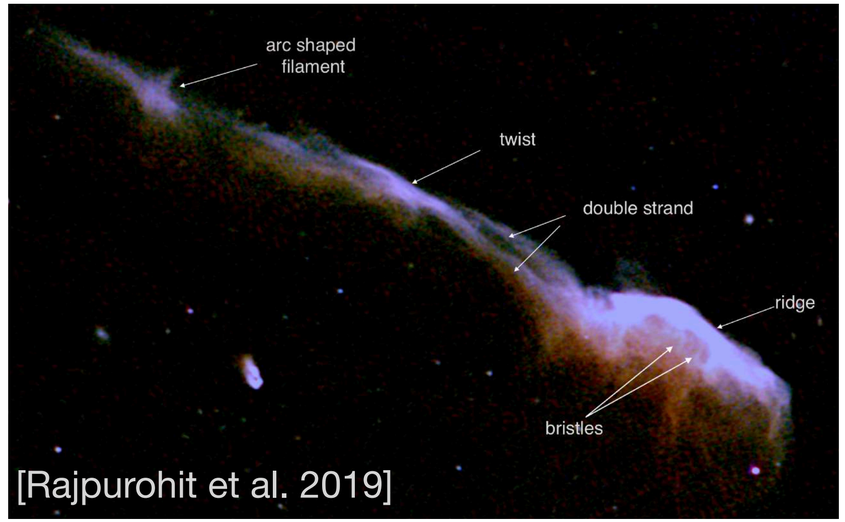



**A shock front is characterised by a distribution of Mach numbers**

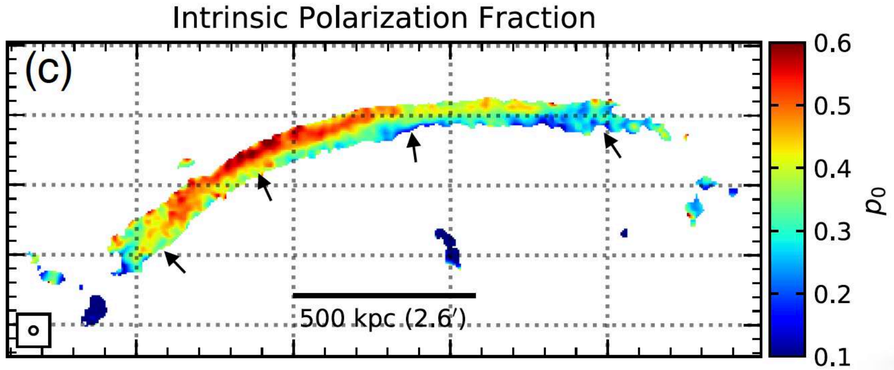
# Mach numbers & patchiness




Domínguez-Fernández et al. 2021]




**A shock front is characterised by a distribution of Mach numbers**

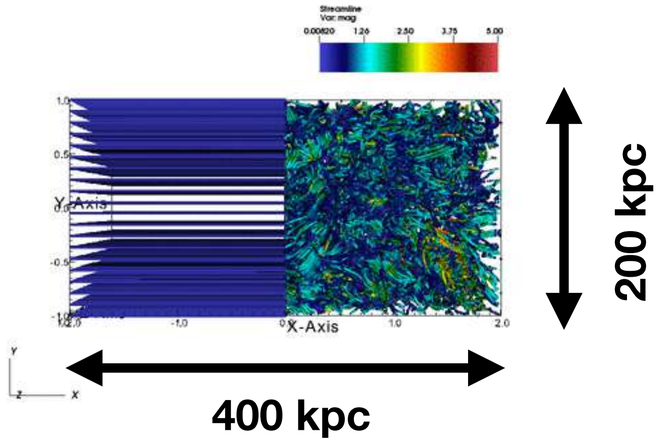



[di Gennaro et al. 2021]

**Pre-shock ICM is then indeed turbulent**

# Our work

**1. Set-up a shock-tube MHD simulation**




[Domínguez-Fernández et al. 2020,2021]

# Our work

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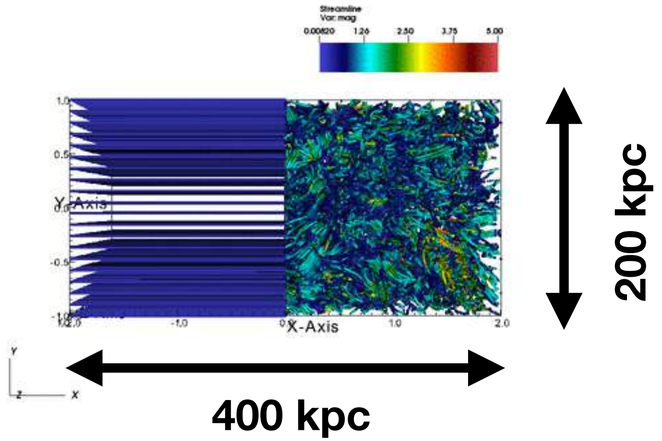



[Domínguez-Fernández et al. 2020,2021]

Hybrid numerical framework:
MHD + Lagrangian particles

[Vaidya et al. 2018]

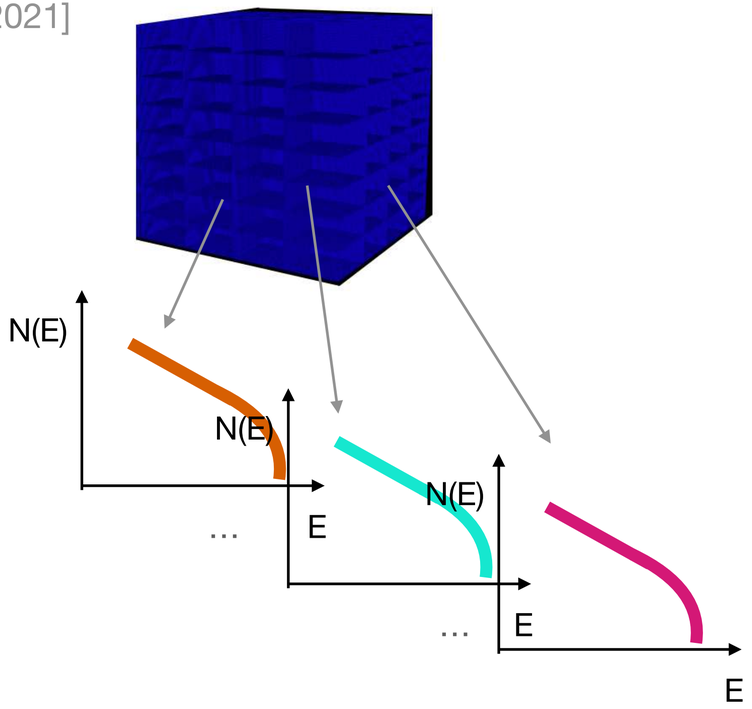
2. Particle acceleration at shock front

**Model A: Fresh injection**

Electrons from the thermal pool

**Model B: Re-acceleration**

Pre-existing mildly relativistic electrons



# Our work

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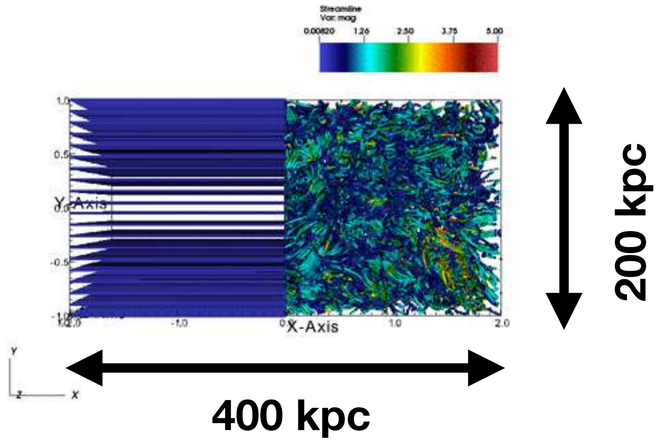


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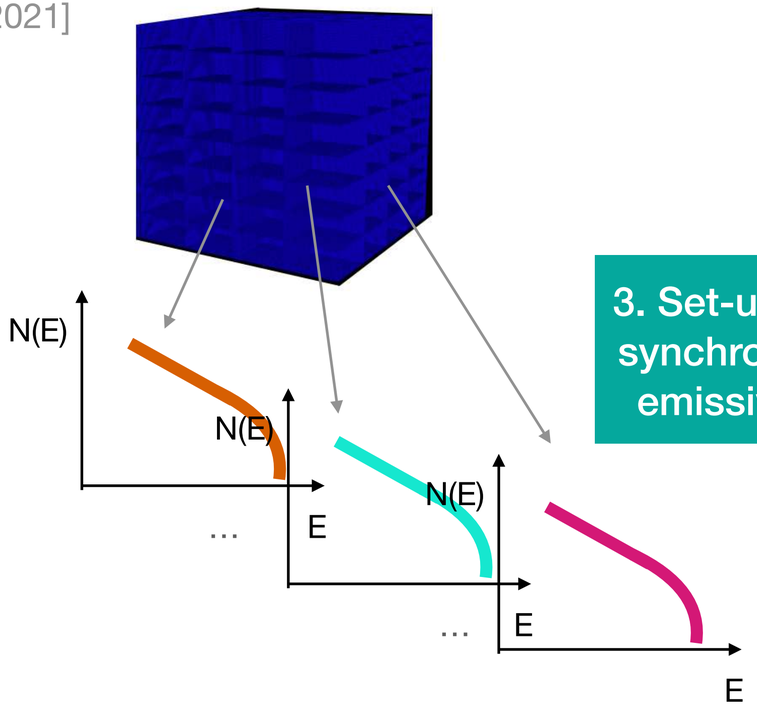


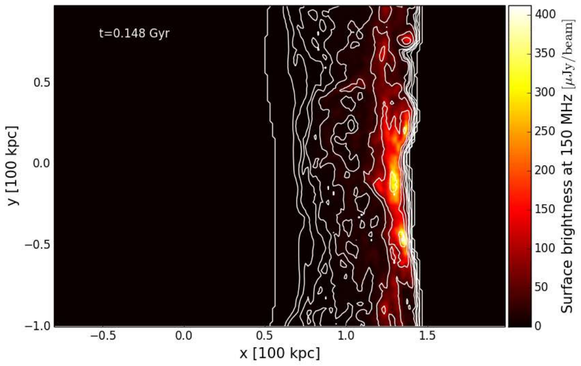

**Model A: Fresh injection**

Electrons from the thermal pool

**Model B: Re-acceleration**

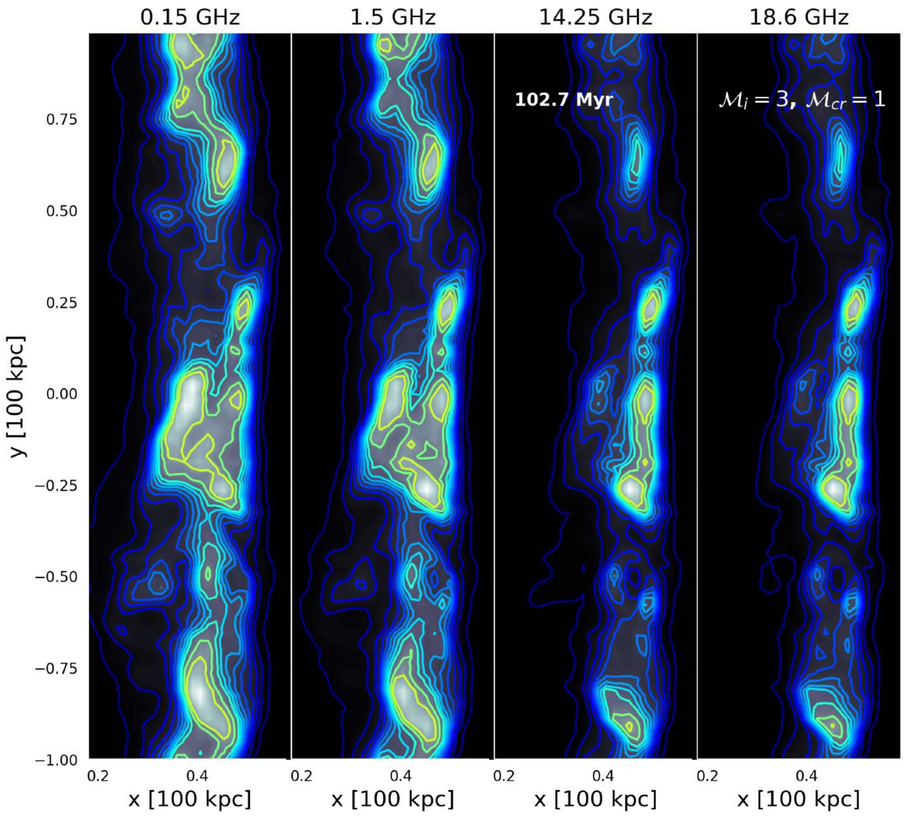
Pre-existing mildly relativistic electrons

3. Set-up for synchrotron emissivity



# Fresh-injection model vs re-acceleration

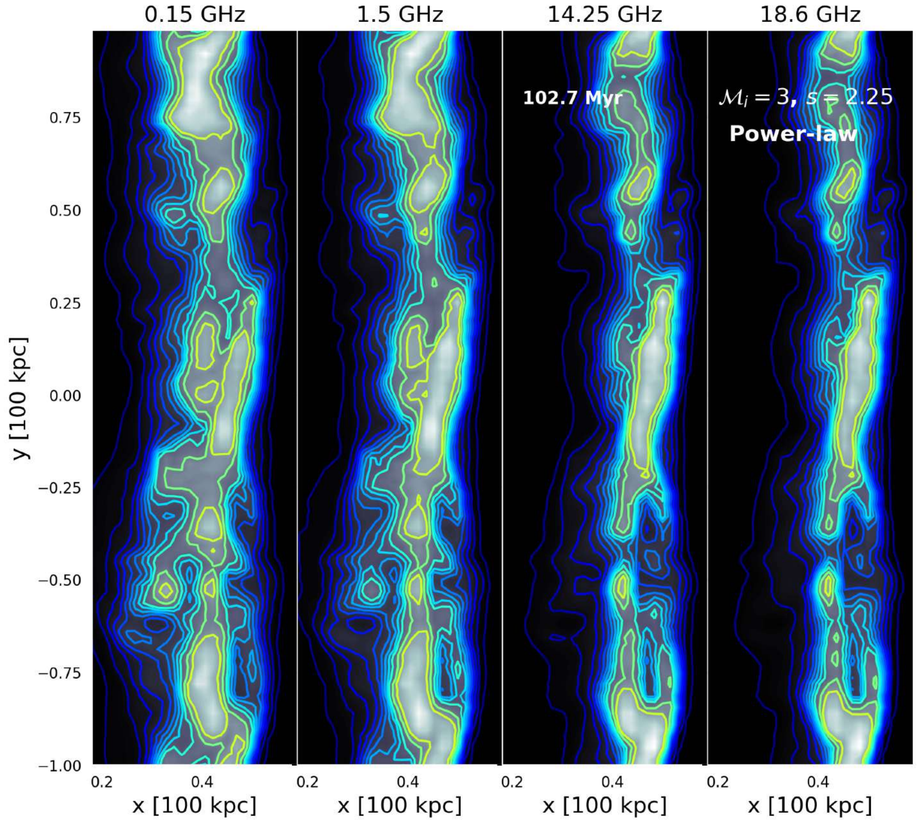
**Fresh-injection**




**Fresh injection model:**
**Too patchy substructure**

**Re-acceleration model:**
**Smoother substructure**

**Re-acceleration**



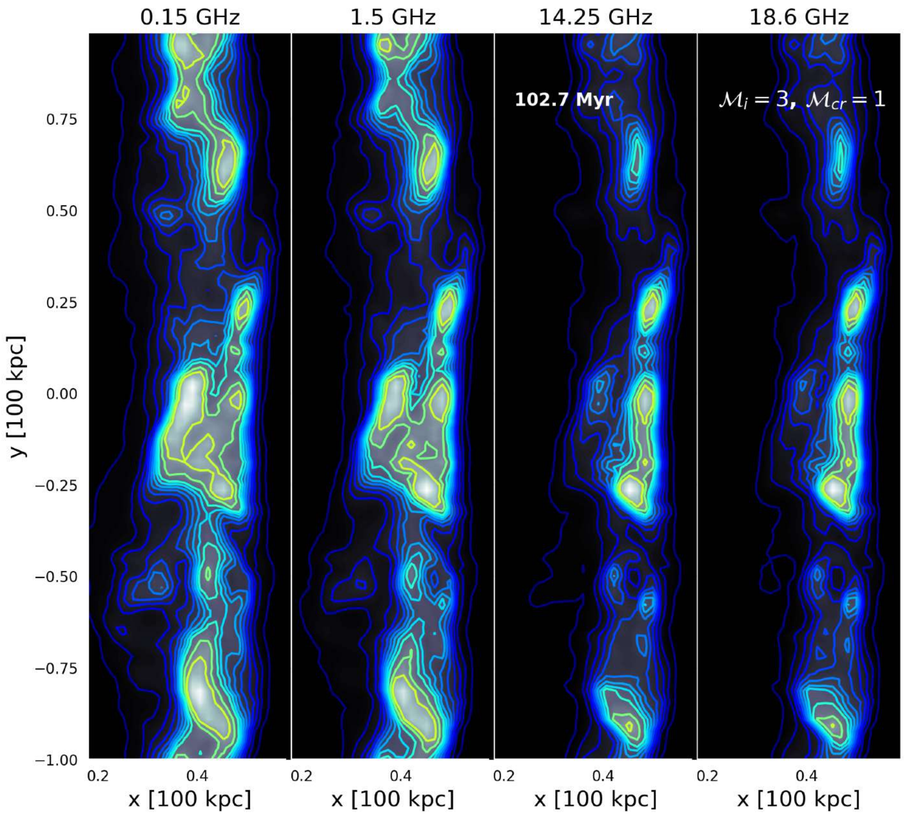

**Low freq** **High freq**

**Low freq** **High freq**

[Domínguez-Fernández, Ryu & Kang to be submitted.]

# Fresh-injection model vs re-acceleration

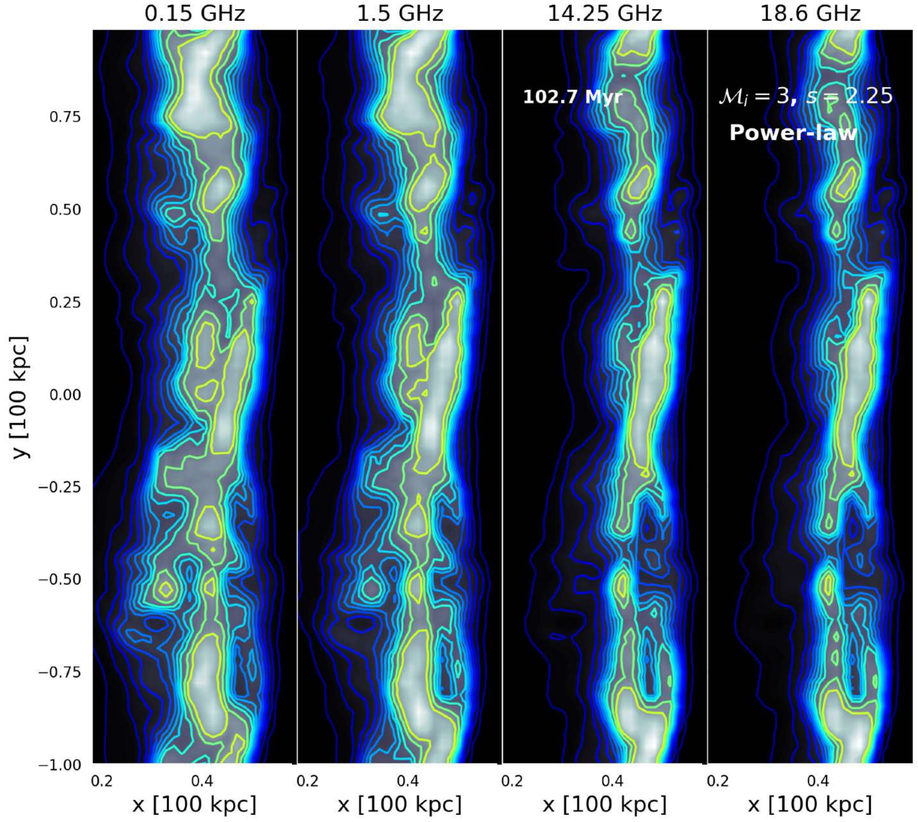
**Fresh-injection**




**Fresh injection model: Patchier at high frequencies**

**Re-acceleration model: Patchier at high frequencies (subtle difference)**

**Re-acceleration**

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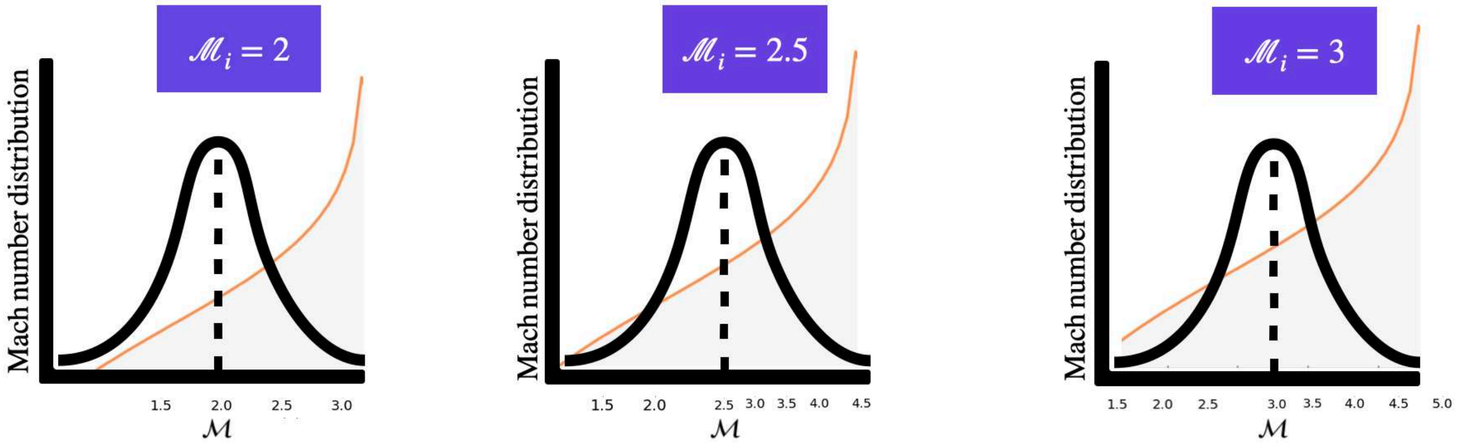
[Domínguez-Fernández, Ryu & Kang to be submitted.]

# Fresh-injection model vs re-acceleration



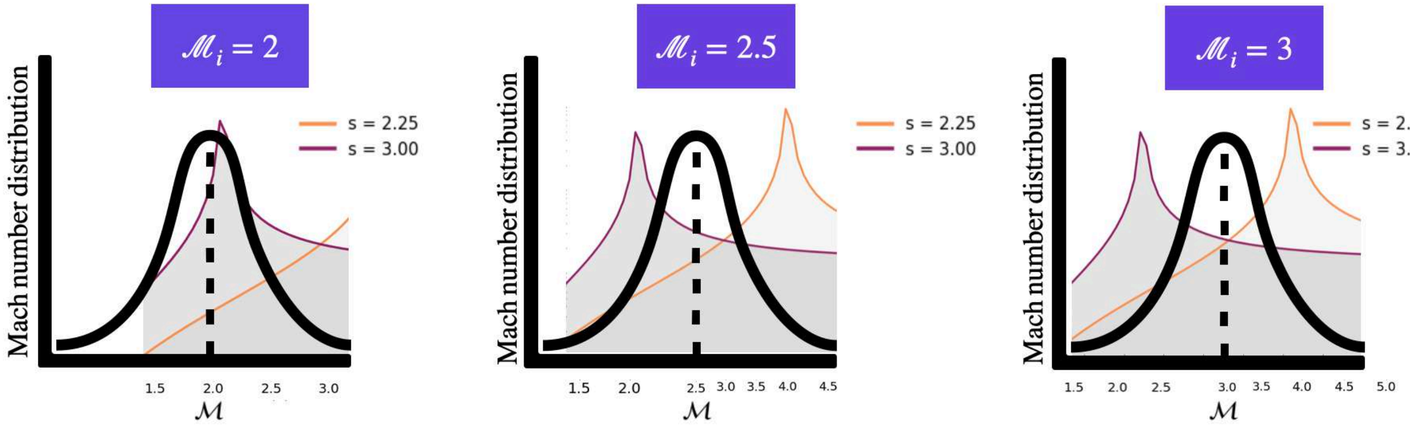

**Fresh injection model:**

[Domínguez-Fernández, Ryu & Kang to be submitted.]

$$f_2^{inj}(p) \propto \eta(\mathcal{M})\mathcal{M}^3 p^{-q}$$

Depending on $\mathcal{M}$

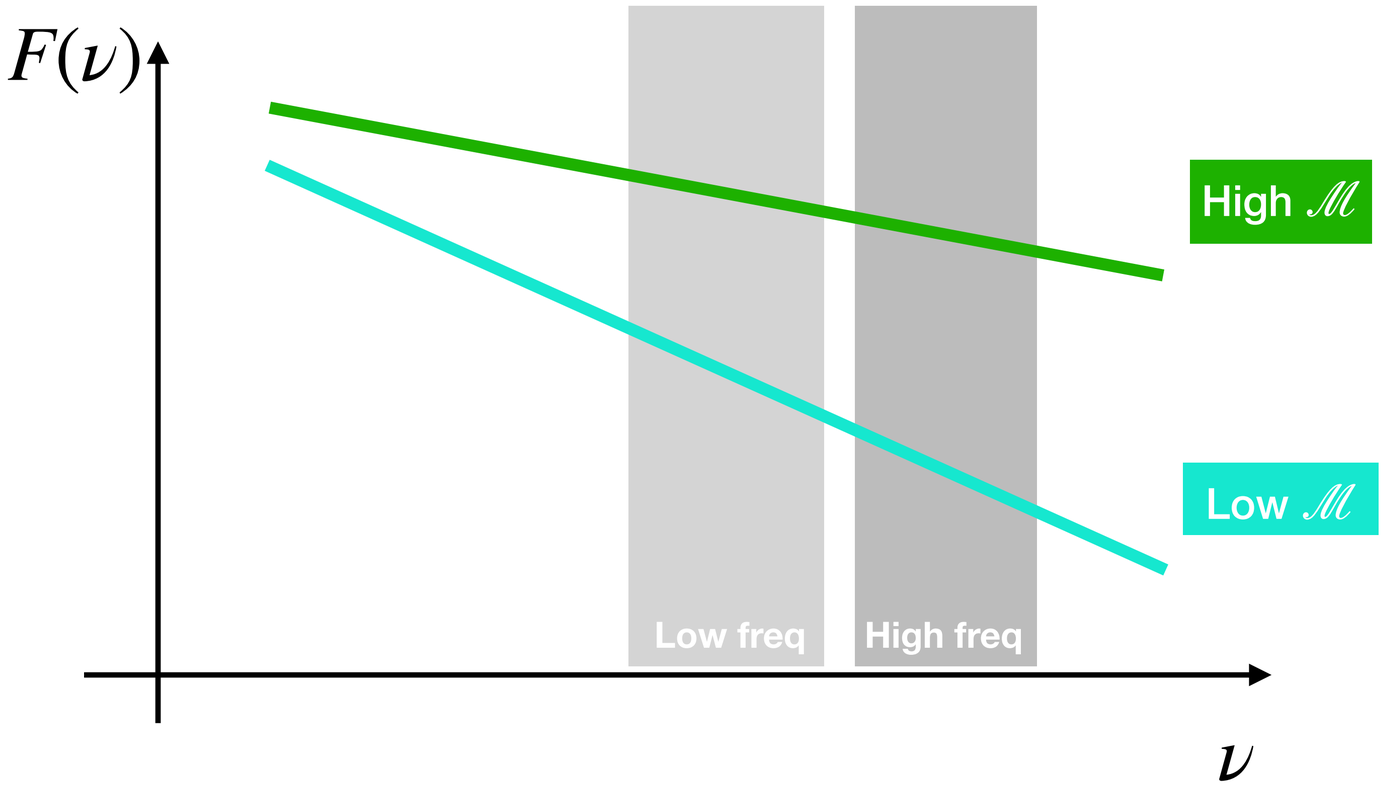
**Re-acceleration model:**




$$f_2^{reac}(p) = \frac{q}{|q-s|} f_{pre} \left(\frac{p}{p_{inj}}\right)^{-r} \qquad r = \min(q, s).$$

Depending on $\mathcal{M}$

# Mach numbers & patchiness



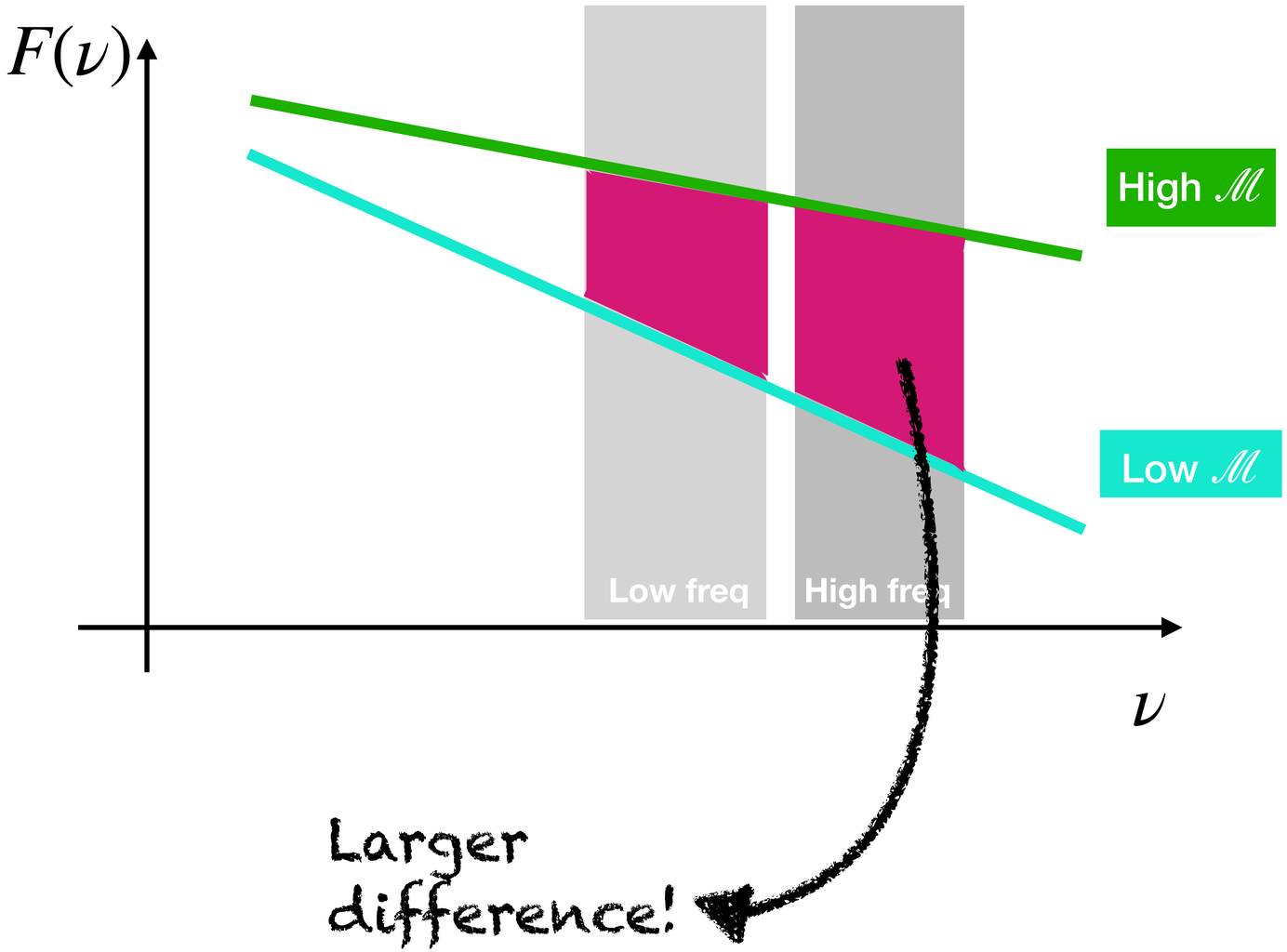

DSA theory

[Blandford & Ostriker 1978; Drury 1983]

$$\mathscr{M} = \sqrt{\frac{2\alpha + 3}{2\alpha - 1}}$$

$$S(\nu) \propto \nu^{-\alpha}$$

# Mach numbers & patchiness

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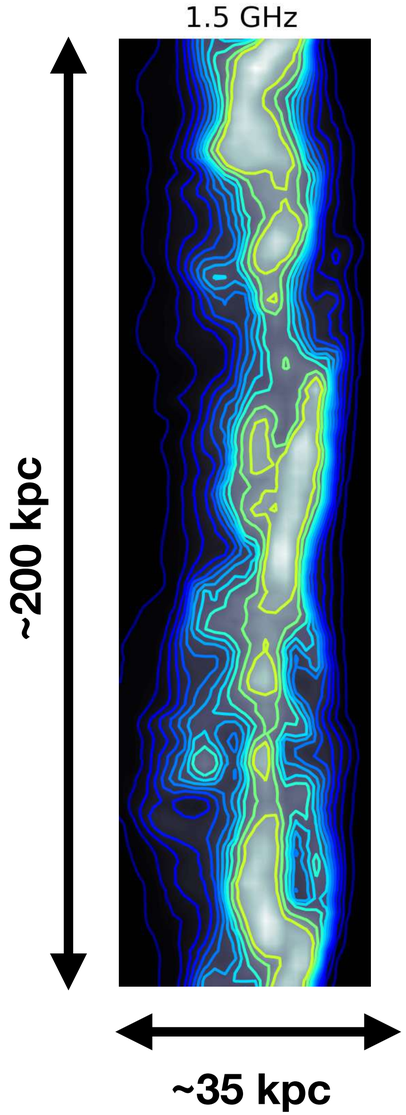
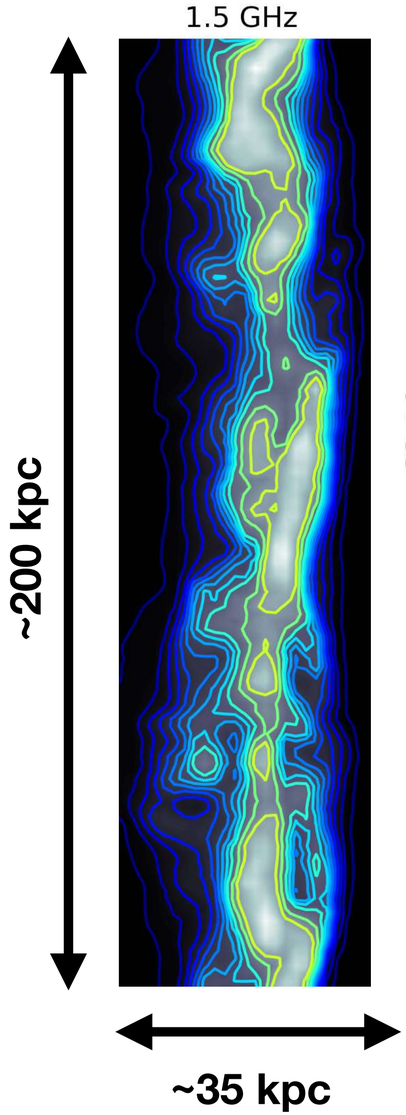
# Patchiness at the shock front




**Relative surface brightness variations:** $\delta_{S_\nu} = S_\nu / \bar{S}_\nu - 1$

# Patchiness at the shock front

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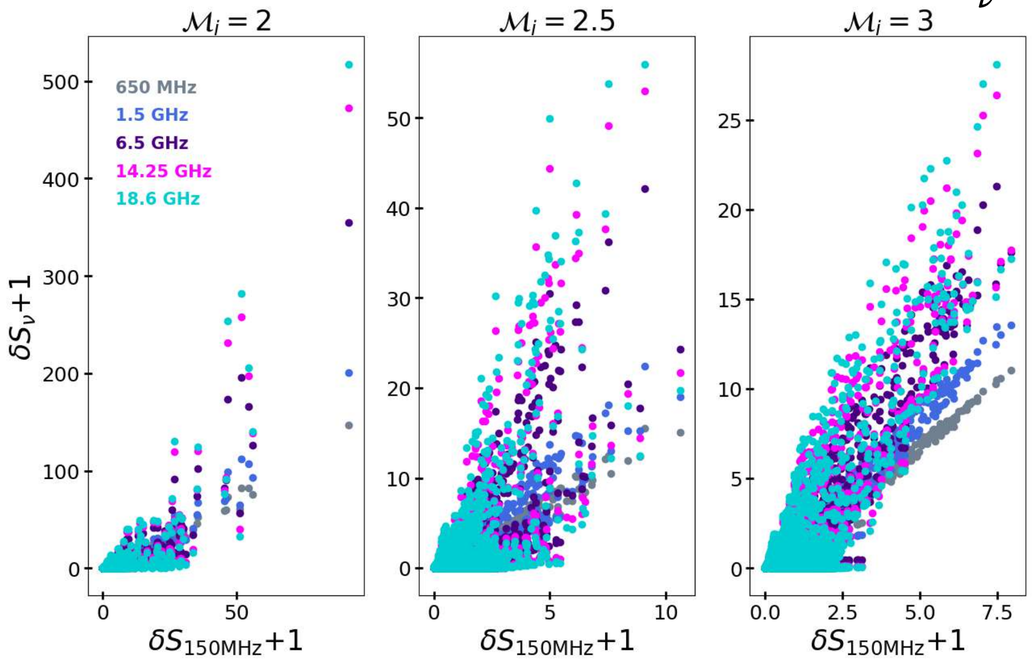
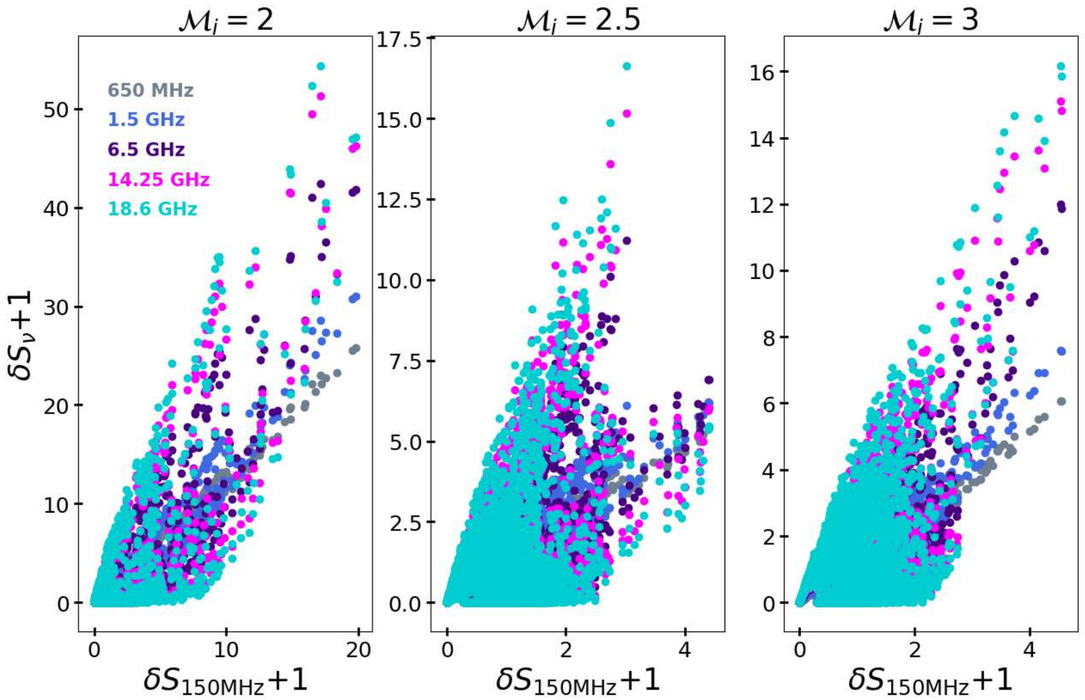


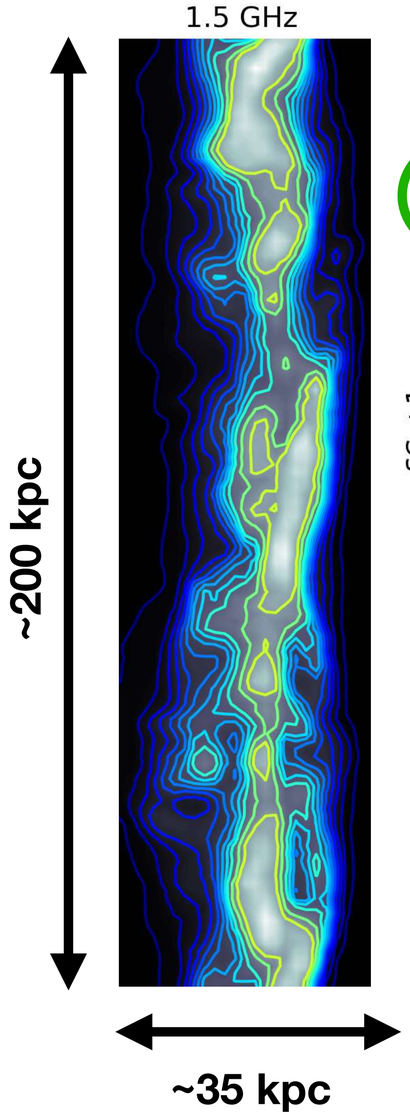

**Fresh-injection**

**Re-acceleration**

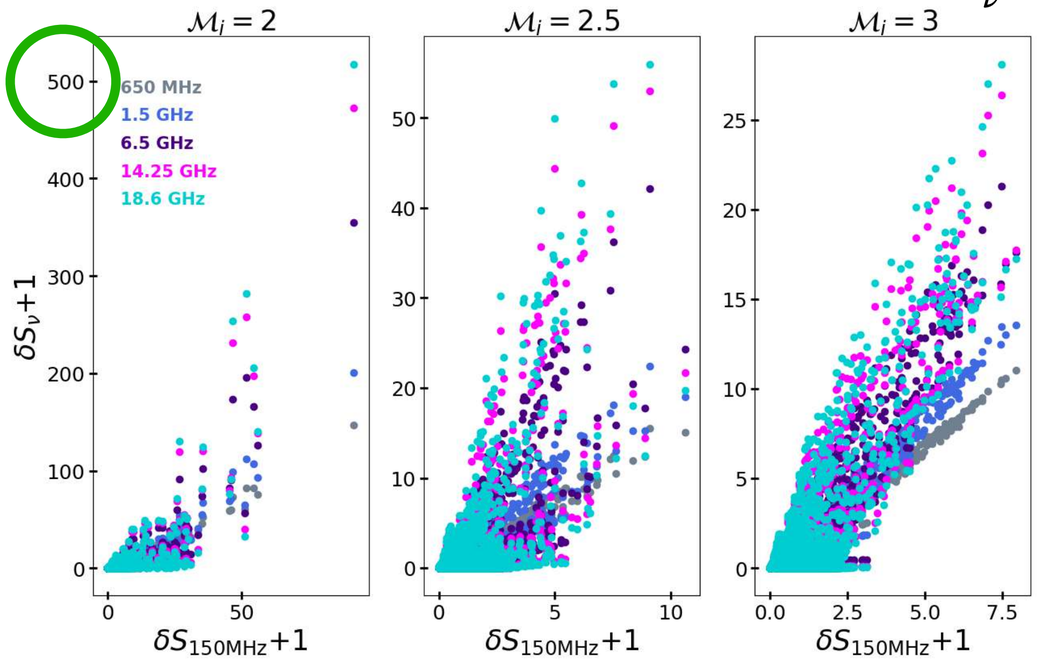



[Domínguez-Fernández, Ryu & Kang to be submitted.]

# Patchiness at the shock front

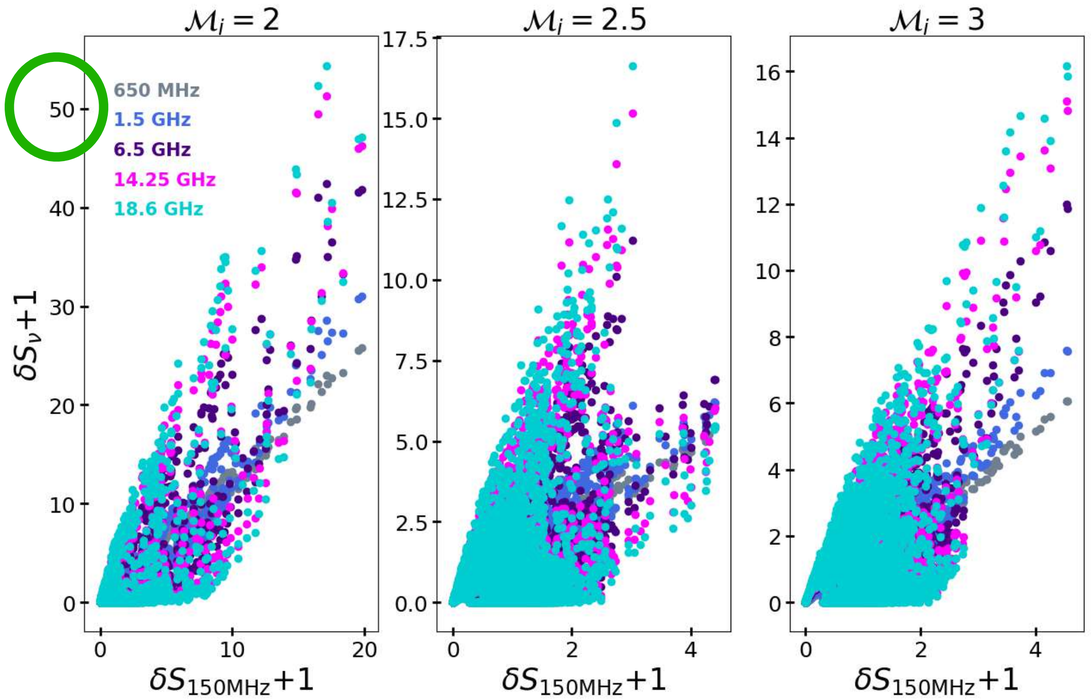



**Relative surface brightness variations:** $\delta_{S_\nu} = S_\nu / \bar{S}_\nu - 1$




**Fresh-injection**

**Re-acceleration**

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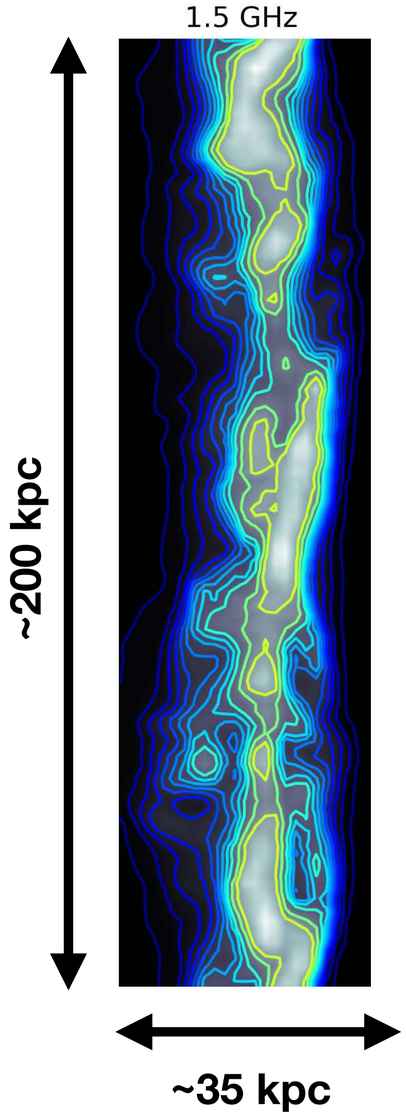
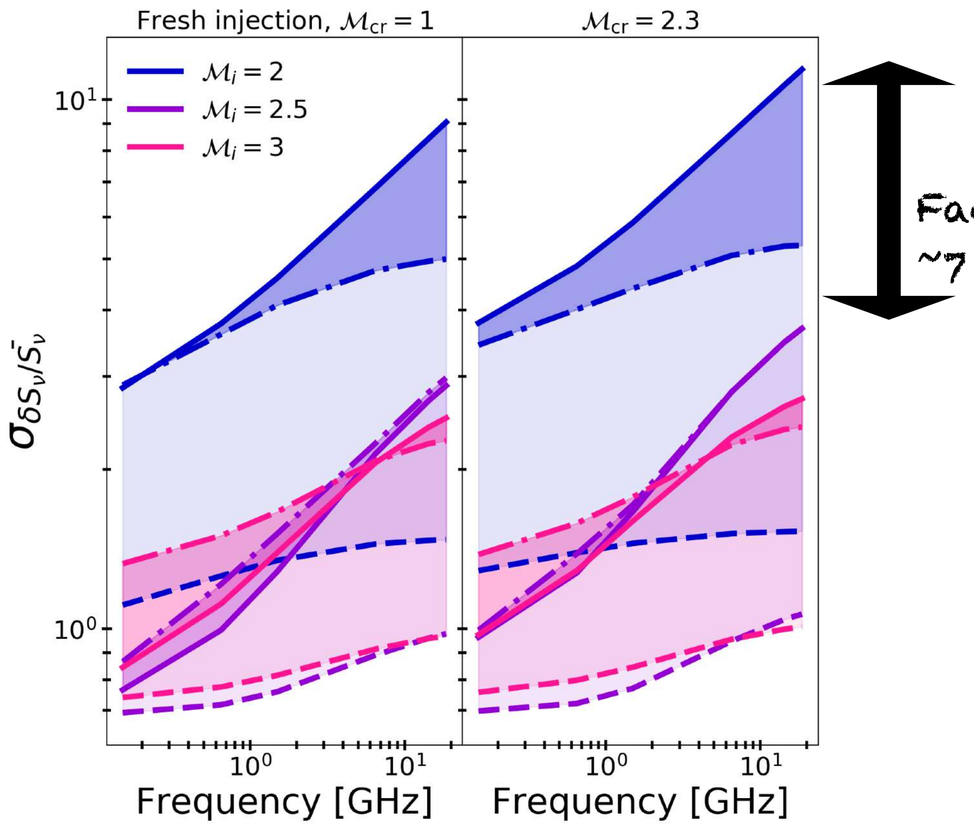
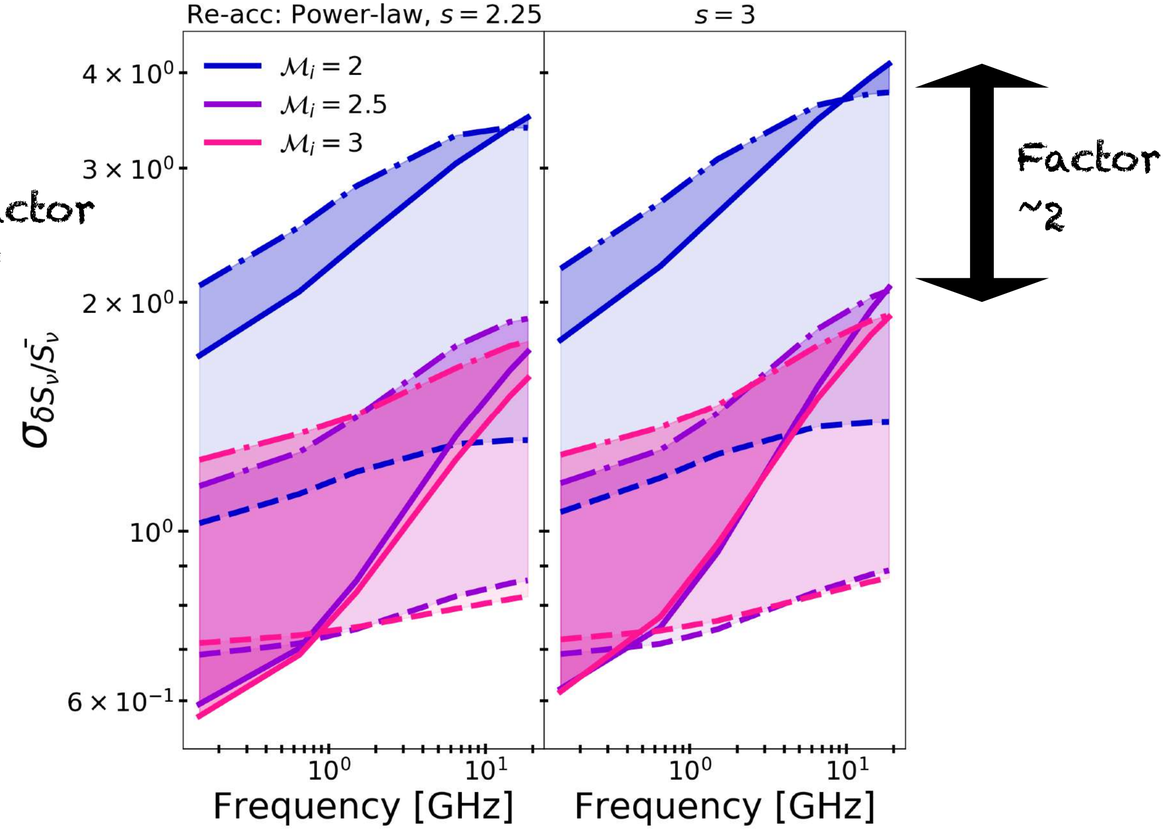



**Relative surface brightness variations:** $\delta_{S_\nu} = S_\nu / \bar{S}_\nu - 1$

**Fresh-injection**

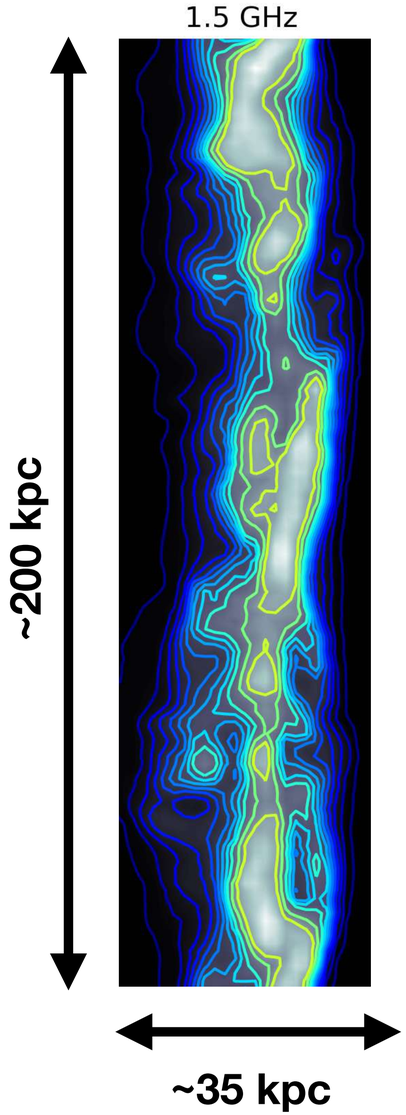



**Re-acceleration**




[Domínguez-Fernández, Ryu & Kang to be submitted.]

# Patchiness at the shock front

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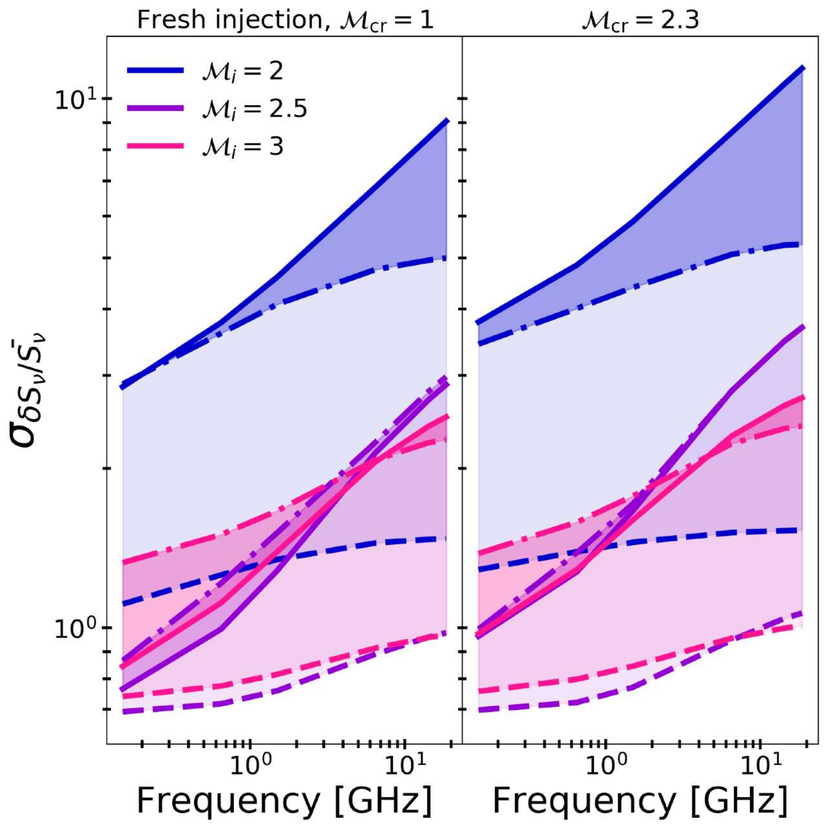
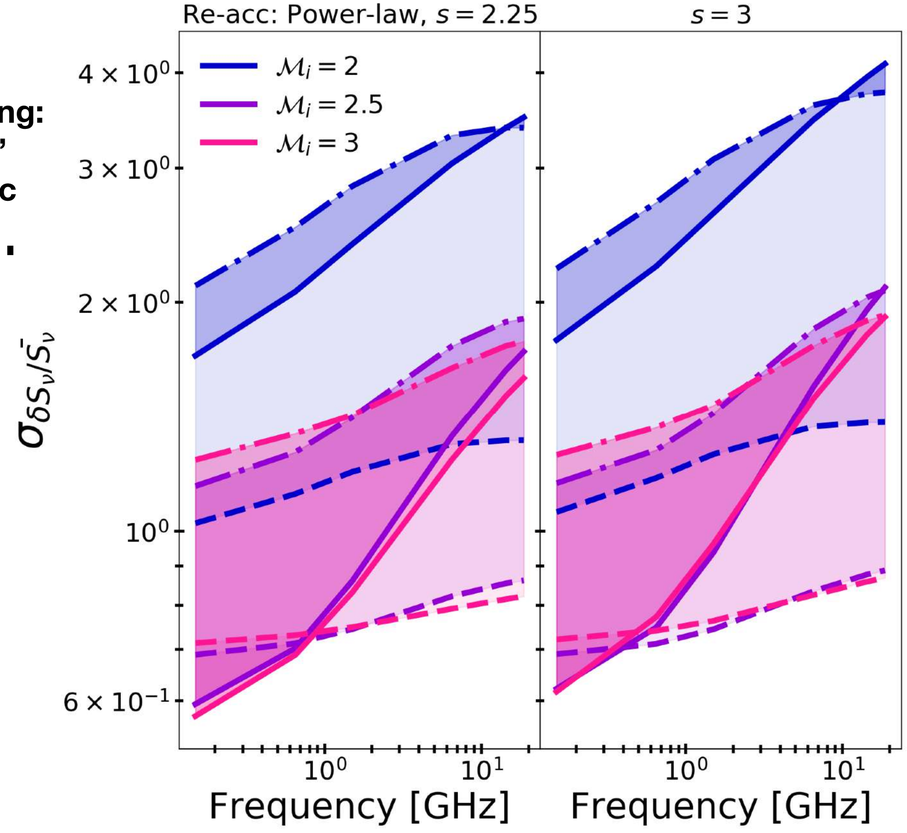



**Smoothing: 5” x 5” ~20 kpc**

**Re-acceleration**

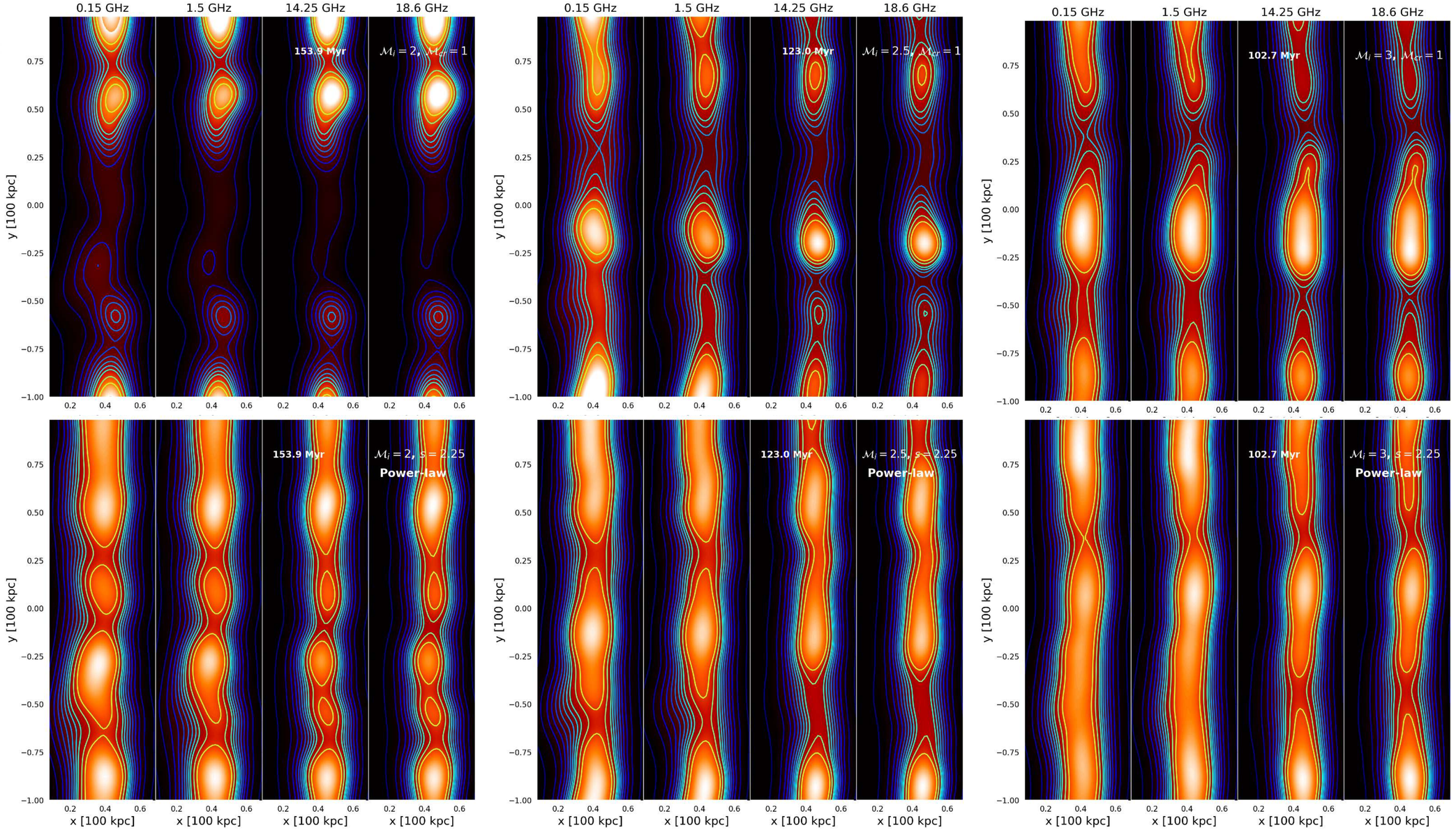



**Smoothing: 20” x 20” ~66 kpc**

[Domínguez-Fernández, Ryu & Kang to be submitted.]

# Fresh-injection model vs re-acceleration

**Smoothing:**
**5” x 5”**




[Domínguez-Fernández, Ryu & Kang to be submitted.]

# Summary

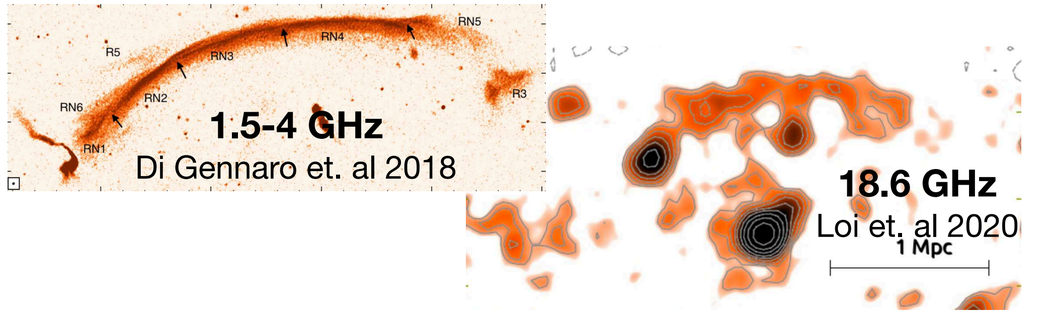
**Why do some radio relics seem smooth at low frequencies and patchier at high frequencies?**

1. The fresh injection model reproduces patchier structures at high frequencies, but

   I. **Too patchy substructures**

   II. **If a relic is patchy at very high frequencies, then it necessarily also is at low frequencies**

not entirely in line with observations



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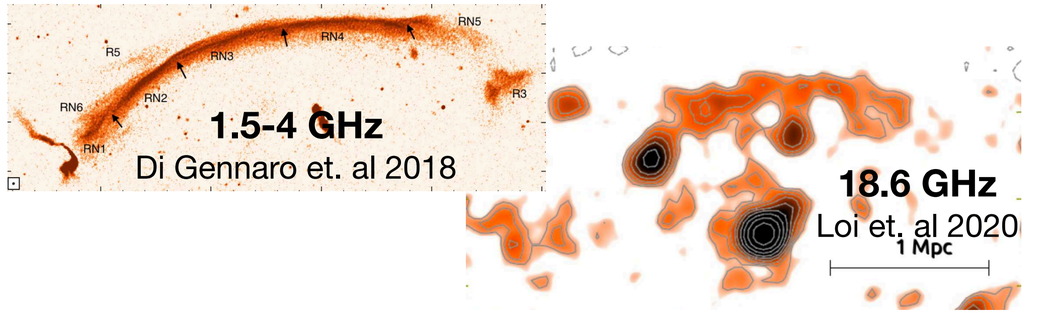


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2. Re-acceleration also reproduces patchier structures at high frequencies, but

   I. **The degree of patchiness is smaller than in the injection model**

   II. **The substructure at high and low frequencies differs less than in the injection model**

also not entirely in line with observations but a bit closer! *

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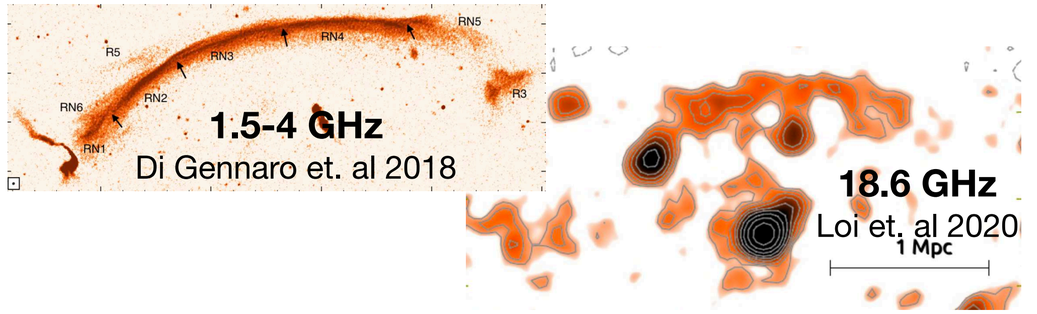


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Thank you!

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