Tracing large-scale gas outflows from spiral galaxies in clusters with LOFAR

A. Ignesti [INAF-Padova]
& the GASP team

Based on Ignesti et al., 2023, A&A, 675, A118

GAs Stripping Phenomena in galaxies

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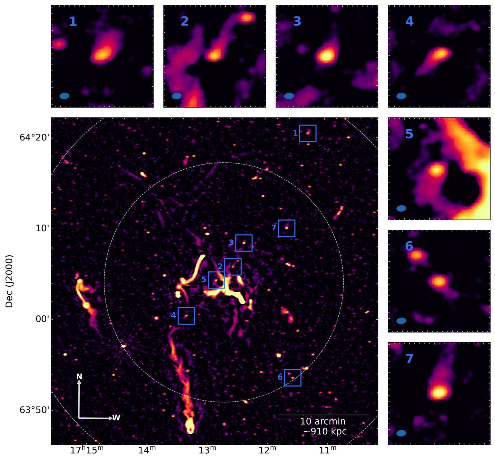
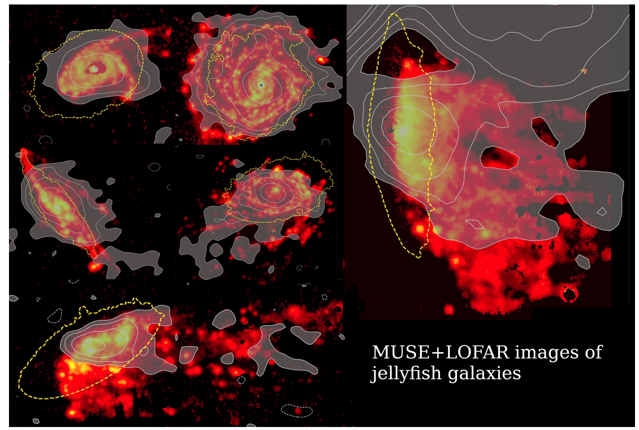
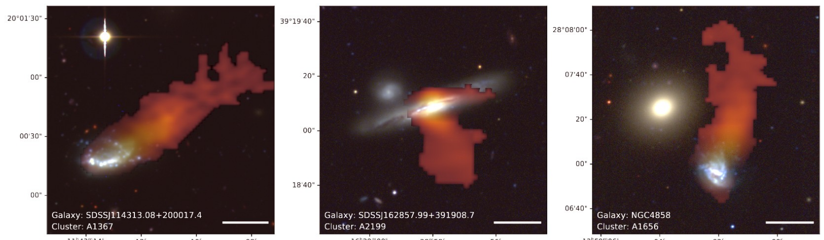
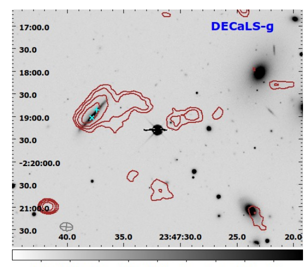
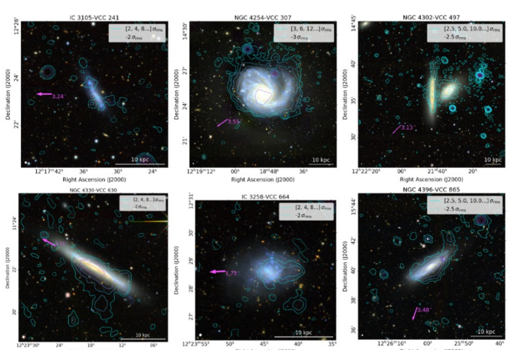
Intro: Spiral galaxies in clusters have radio continuum tails (and LOFAR is very good at detecting them)

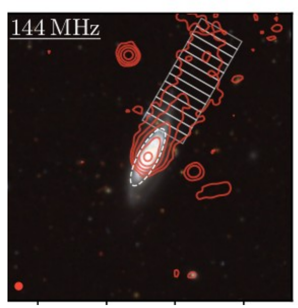


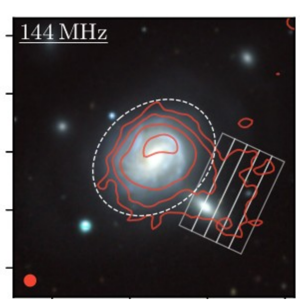


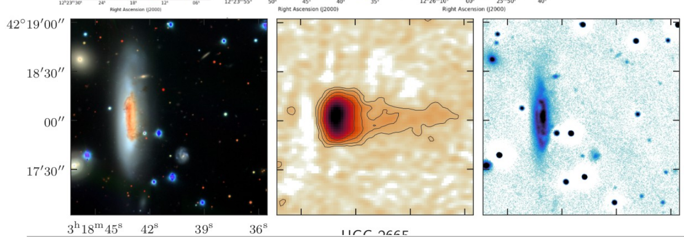


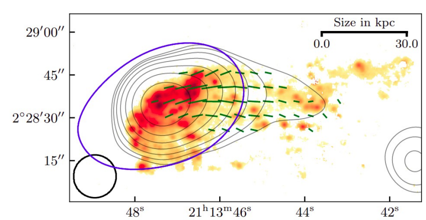




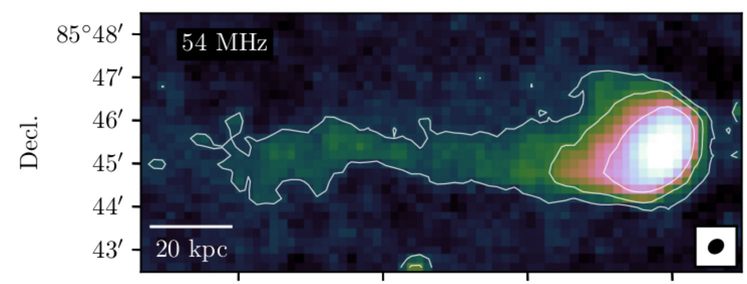








- 172 out of 875 RPS galaxies (**~20%**) show radio continuum tails (from Crosset et al., in preparation, for $z<0.25$)
- Radio tails **are present in both clusters and groups** (Roberts+2021b)
- They are **10-60 kpc long**, typically oriented away from the clusters center (Roberts+2021, Smith+2022)

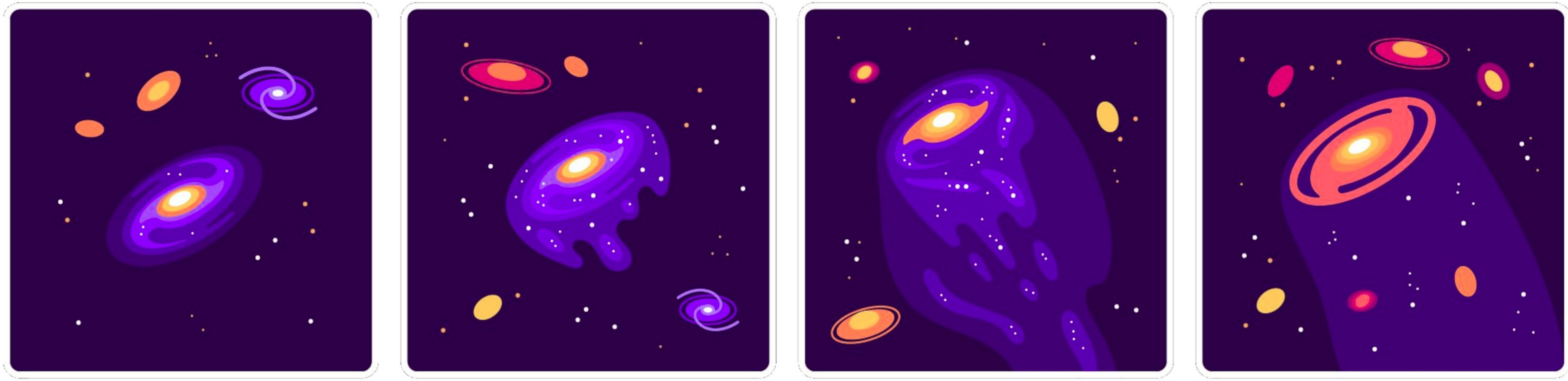


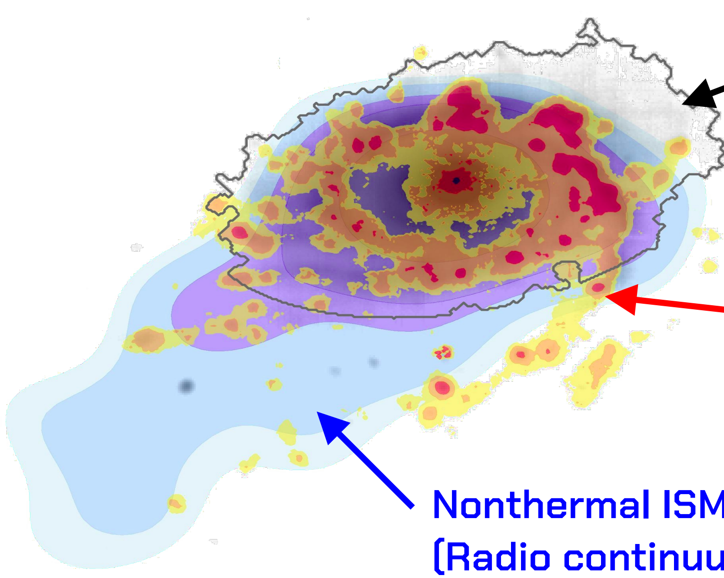
From:
- Ignesti+2022, 2023
- Roberts+2021a,c, 2023 (with AI)
- Hedler et al., submitted (with AI)
- Hu+2023 (with AI)
- Muller+2021 (with AI)

Intro: Ram pressure stripping in galaxy clusters

ICM ram pressure stripping

$P=\rho_{ICM}V^2$ *[Gunn&Gott 1972]*



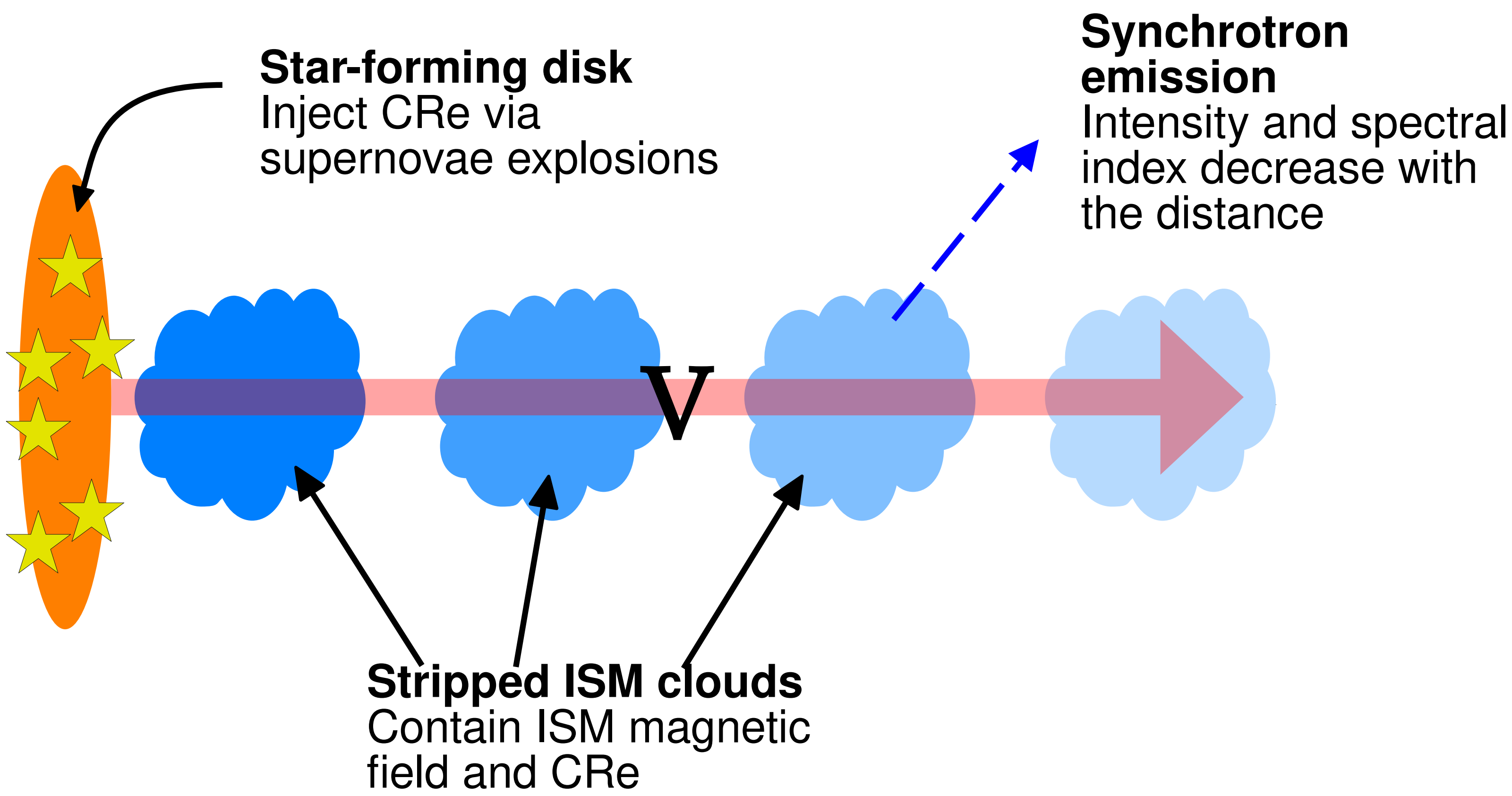


Composite MUSE+LOFAR image of JO36 (Ignesti+2022)

For reference:

- *van Gorkom 2003*
- *Boselli & Gavazzi 2006*
- *Poggianti+2016*
- *Boselli+2021*

A qualitative model of RPS radio tail



- Proposed for the first time by **Vollmer+2004** for NGC 4522
- Supported by **spectral index steepening** (e.g., Vollmer+2004, 2021, Chen+2020, Muller+2021, Ignesti+2022c, Roberts+2023)
- Observed radio length **D** depends on observed frequency **v** (Ignesti+2022c)

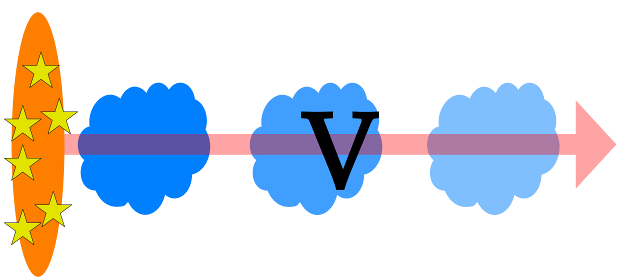
$$\frac{D_1}{D_2} = \sqrt{\frac{\nu_2}{\nu_1}}$$

A ~~qualitative~~ quantitative model of RPS radio tail

1) CRe moving with velocity **V** from the stellar disk get older with the distance

2) Old CRe → Steep/ curved synchrotron spectrum

3) Radio emission fades with the distance at observed v



Assumptions:

- Uniform magnetic field ($B=B_{CMB}/\sqrt{3}$)
- Uniform projected velocity V
- Only synchrotron and IC losses

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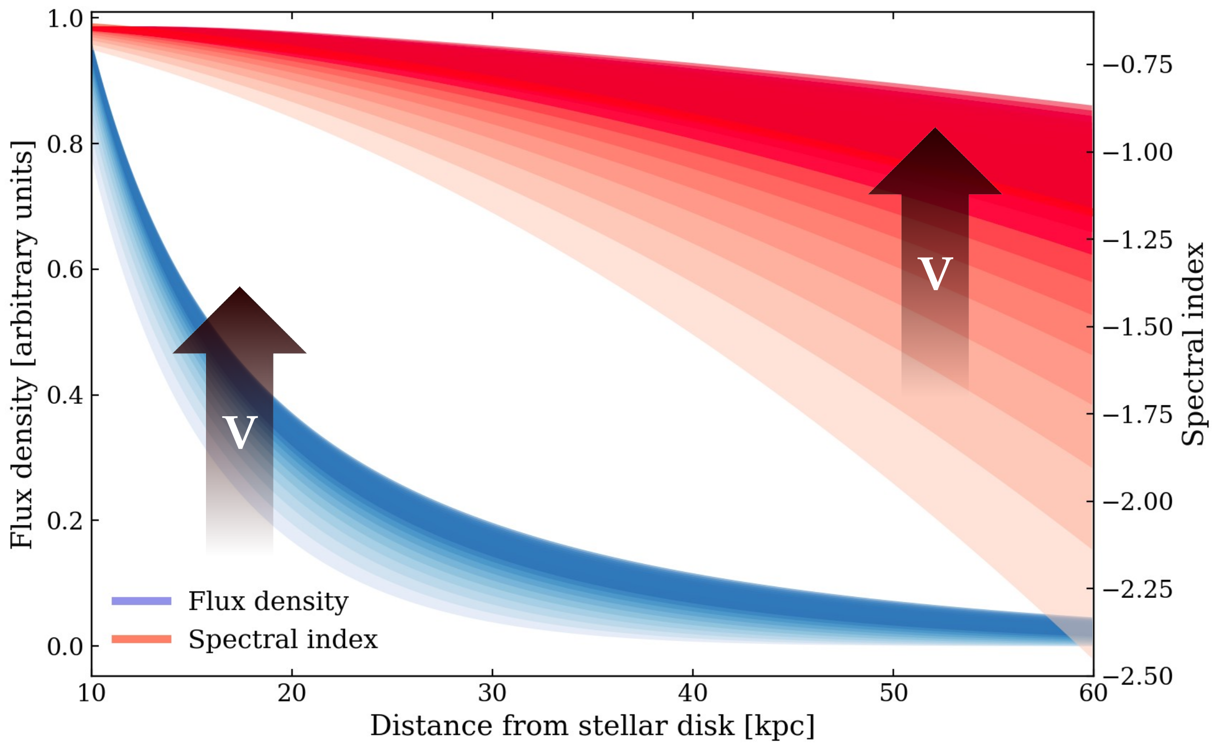

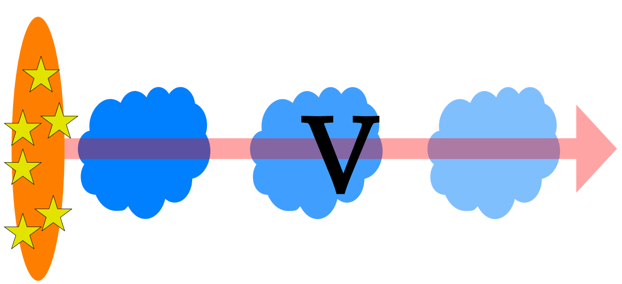

→ Fit flux density/spectral index profile to constrain stripped cloud velocity V

Assumptions:

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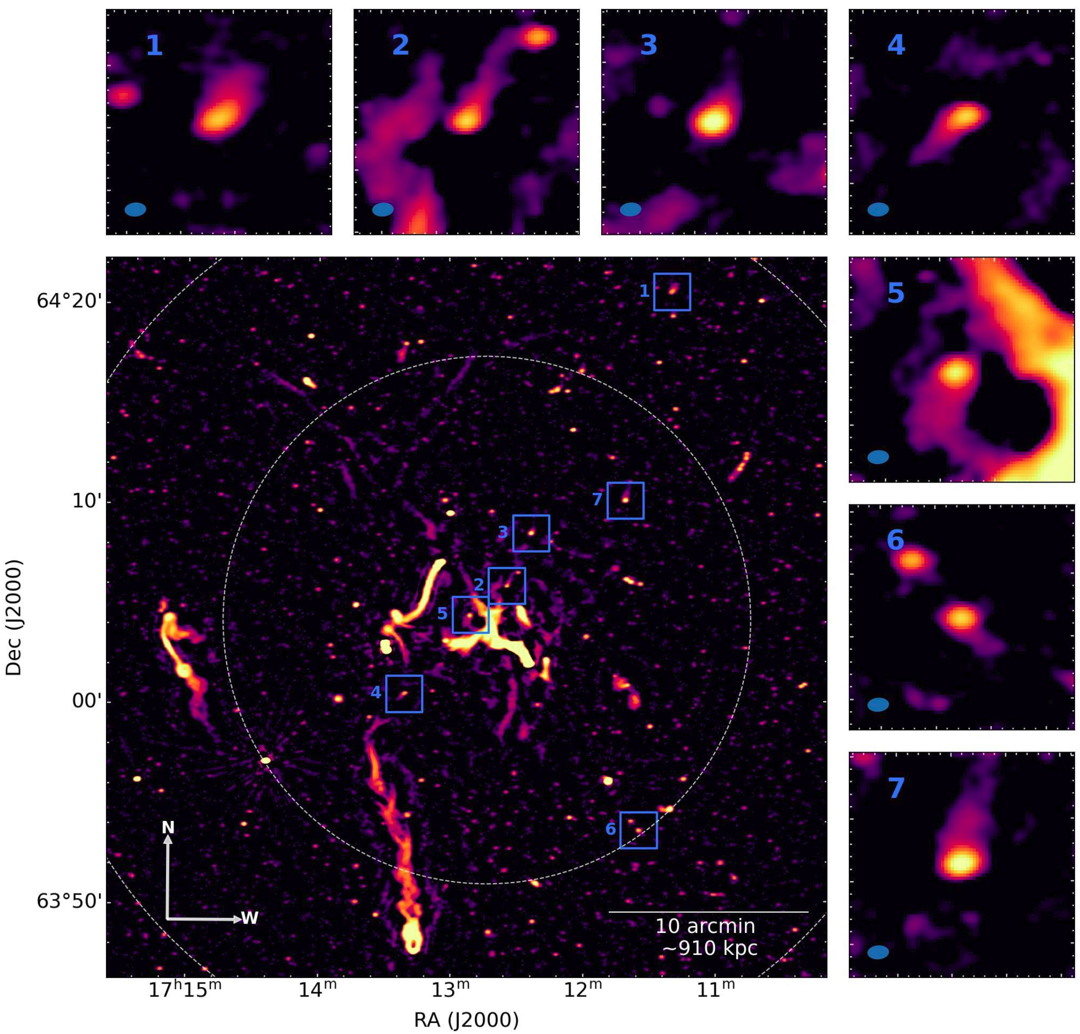
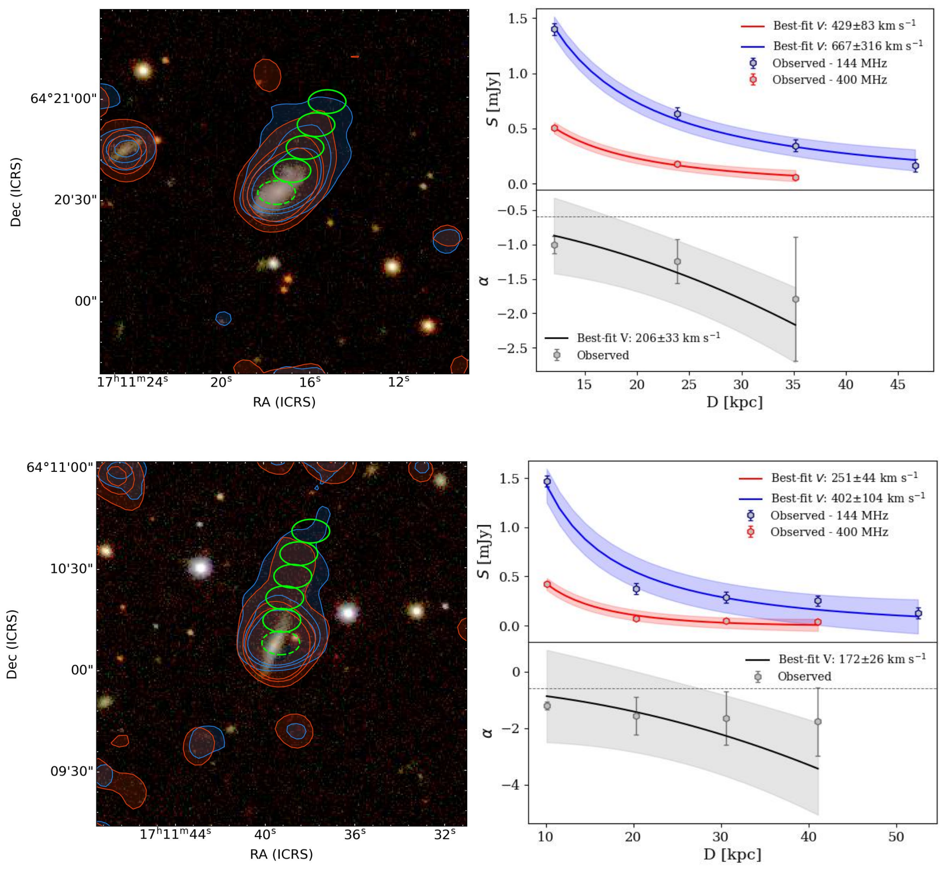
Testing the model in Abell 2255 with LOFAR and uGMRT



7 galaxies with radio tails from A2255 (z=0.08)
Ultra-deep LOFAR and uGMRT observations
(Botteon+2021, Rajpurohit+2023)



For each galaxy: fit of flux density profiles at 144 and 400 MHz
+ spectral index

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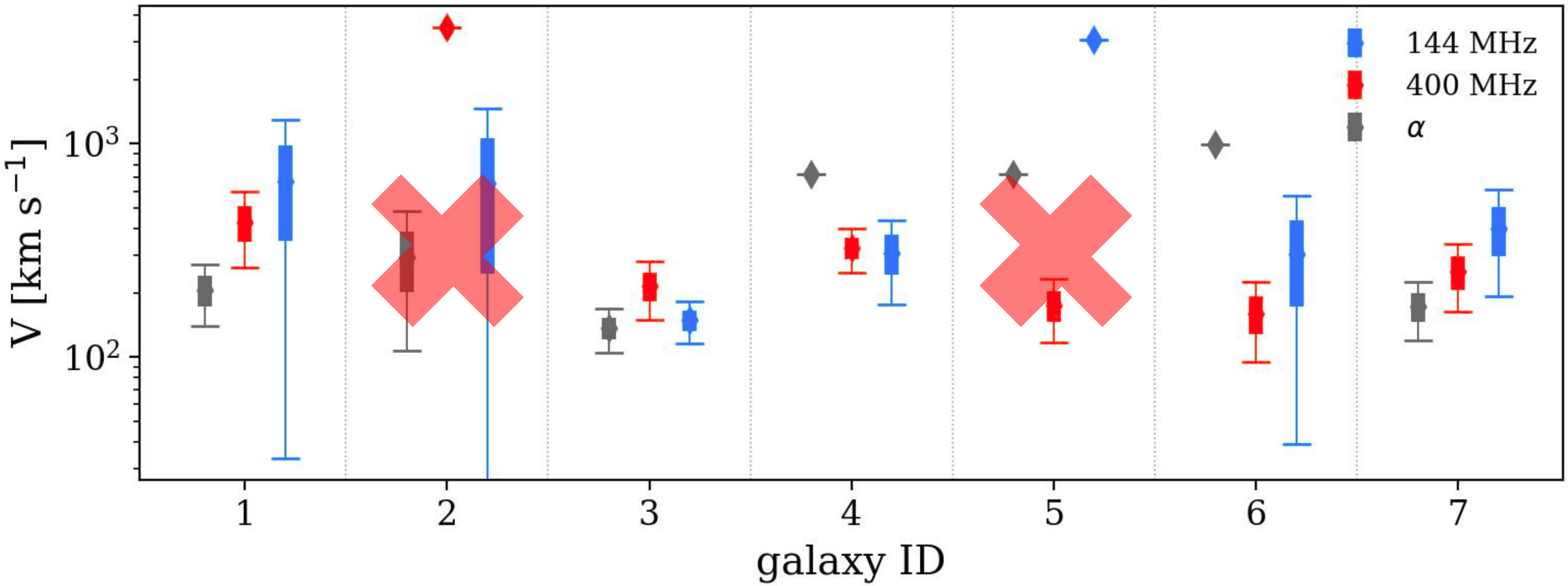
Results



- Succesfull fit on **5 out of 7** galaxies
- Consistent results between flux density at 144 MHz, 400 MHz, and spectral index
- **V=160-430 km/s** → **FIRST MEASURE OF STRIPPED OUTFLOW VELOCITY**

→ **Model of uniform advection of 'radio' clouds can reproduce the observations**

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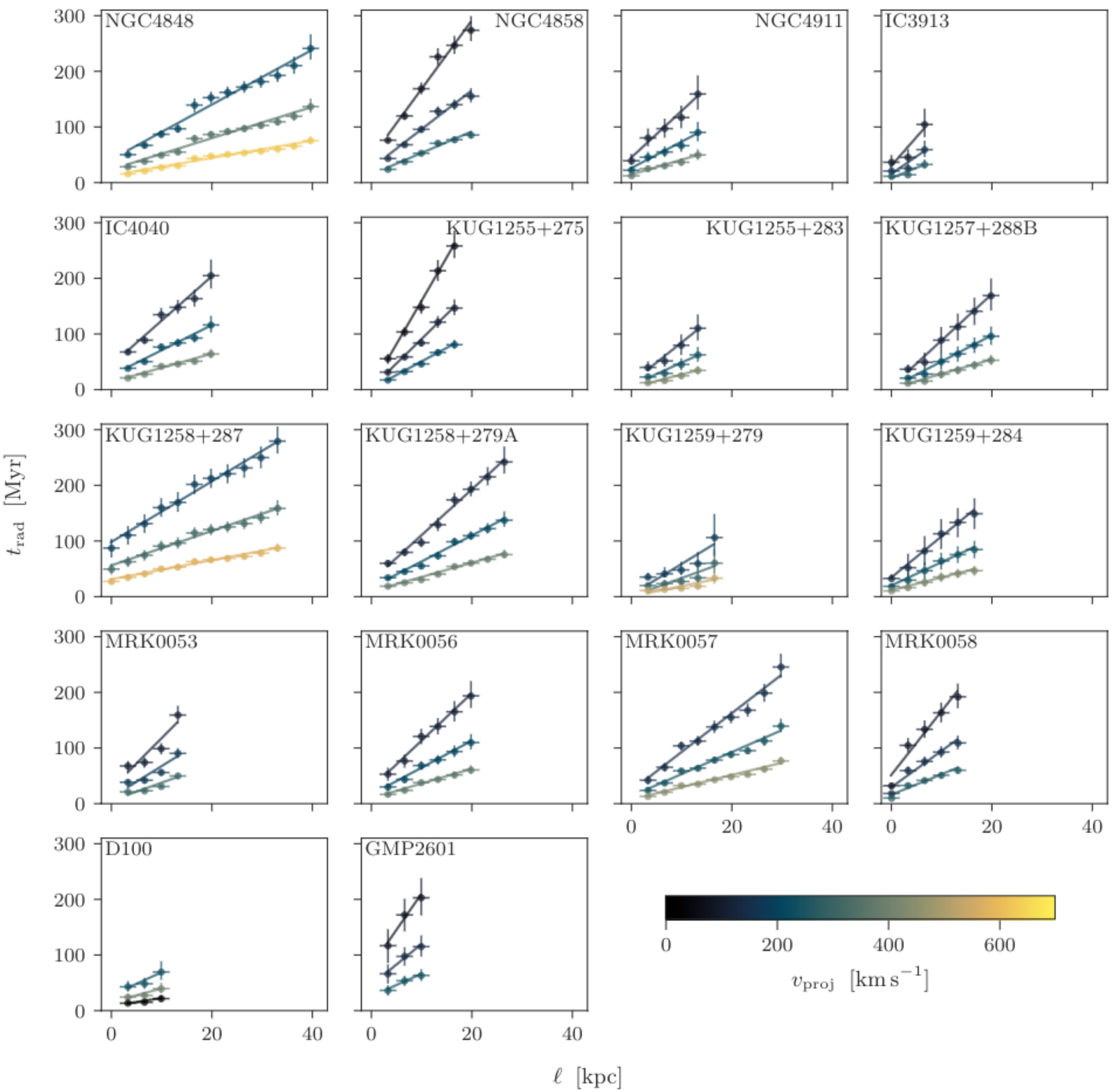
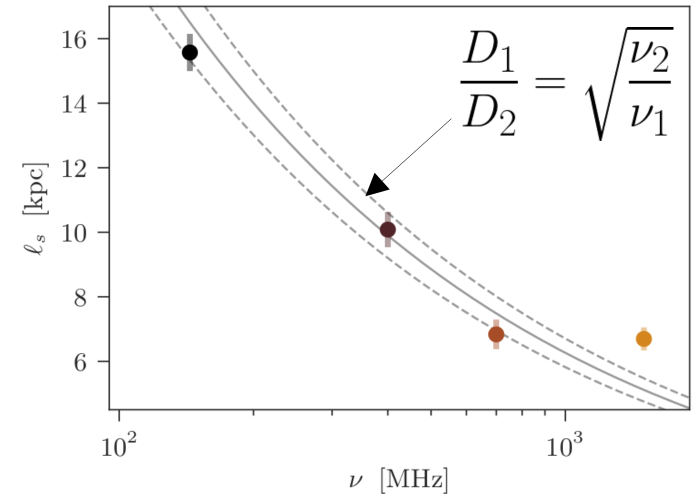
Testing the model in the Coma cluster *(Roberts et al., 2023, with AI)*



- Same method applied on **18 RPS galaxies** in Coma
- Large frequency coverage: 144, 400, 700 and 1500 MHz
- **The model fits the data and constrains V in the same range as A2255**



Proof-of-concept uses for this new tool

Stripped cloud velocity [V=160-430 km s^{-1}]

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Stripped (radio) clouds survival time-scale [$\tau > t_{rad,\,144} \sim (1\text{-}3) \times 10^8$ yr]

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    - **Magnetic field constraint** [$t_{rad,\ 144} < t_{adb}$ for B~4-7 μG]
    - **Time-scales constraint**
      - **Turbulence development**
      - **Cloud crushing**

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    - **3D galactic velocity**
      [$V_{3D} = (V_{\perp}^{2} + V_{\parallel}^{2})^{1/2}$=330-1029 km s^{-1}]
      - **Exact ICM ram pressure**
        [$P = \rho_{ICM} V_{3D}^{2} = (0.14\text{-}2.91)\times 10^{-11}$ erg cm^{-3}]
    - **Disk-wind angle**

$$\Theta = \arccos(\hat{v} \cdot \hat{n})$$

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Summary and conclusions

1) A new model to constrain the ISM outflow speed induced by ram pressure stripping in clusters

2) Tested on Abell 2255 (***Ignesti et al., 2023***) and Coma (***Roberts et al., 2023, with AI***), it constrains the stripped ISM outflows velocity in **100-600 km/s**

3) Stripped ISM clouds velocity provide crucial constraints on ram pressure stripping in clusters
→ Only possible by combining **radio, optical and X-ray observations**

Low-frequency radio continuum observations can be fundamental in the future of galaxy evolution studies in clusters and groups

Thank you for your attention

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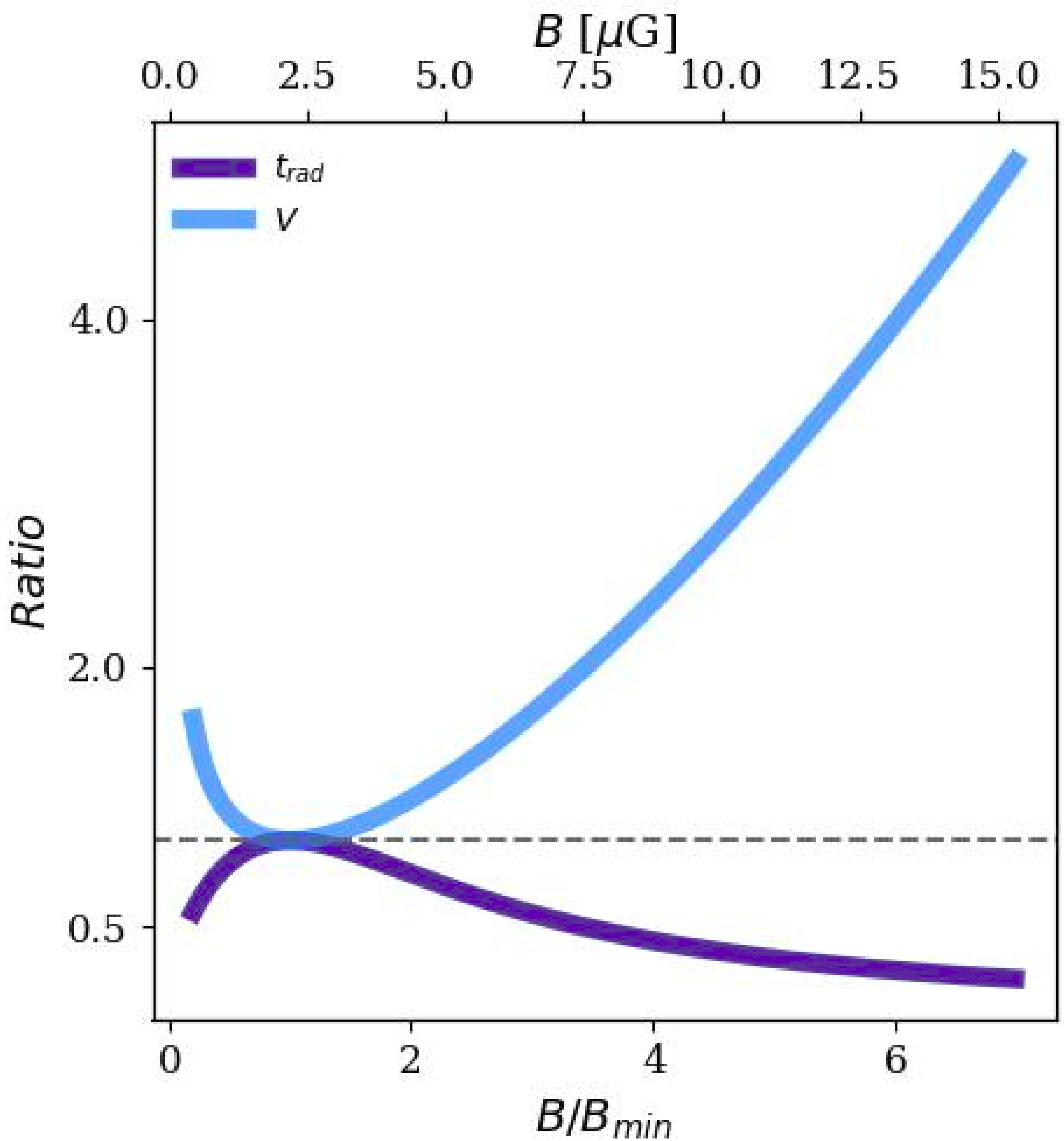
EXTRA

On the magnetic field



Resulting 3D velocity