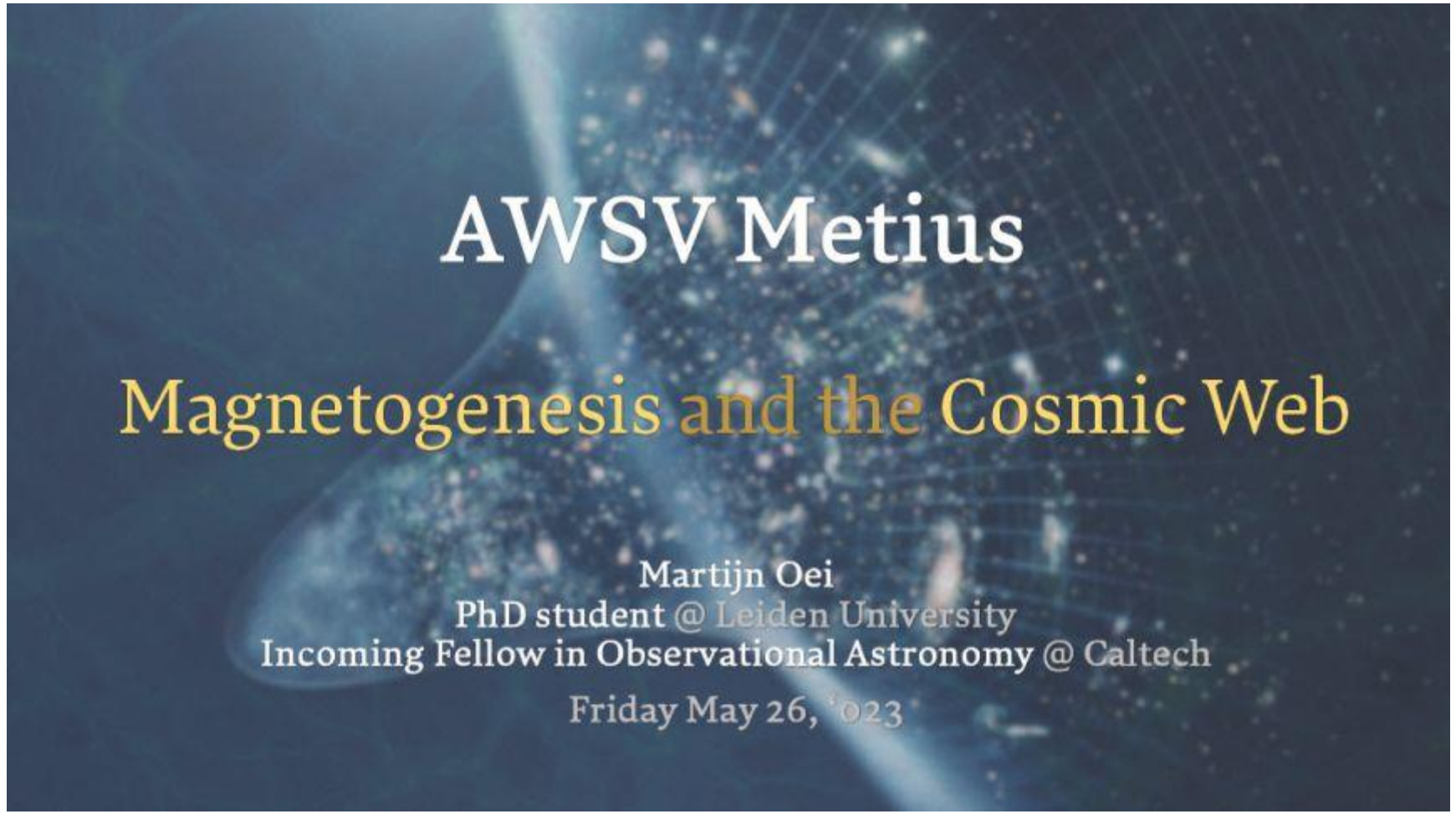
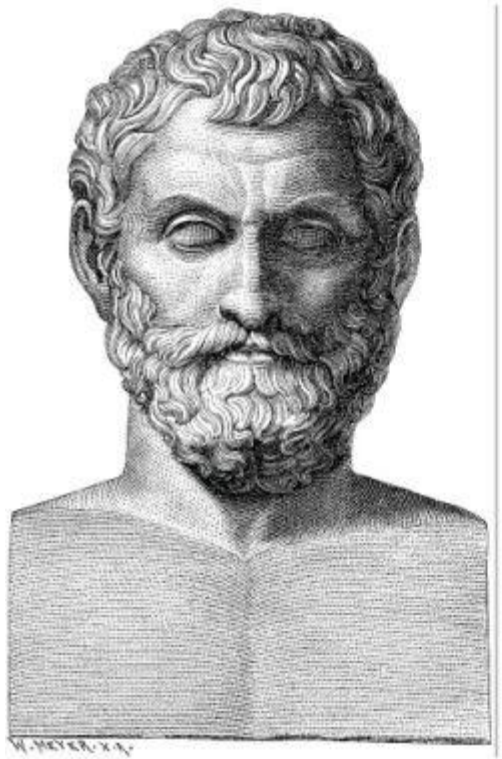

AWSV Metius
Magnetogenesis and the Cosmic Web
Martijn Oei
PhD student @ Leiden University
Incoming Fellow in Observational Astronomy @ Caltech
Friday May 26, '023

Magnetite and lodestones

Lodestones: quantum stones



Bohr-van Leeuwen theorem:

A consistent application of classical and statistical mechanics rules out macroscopic magnetisation for non-rotating, isolated systems in thermal equilibrium

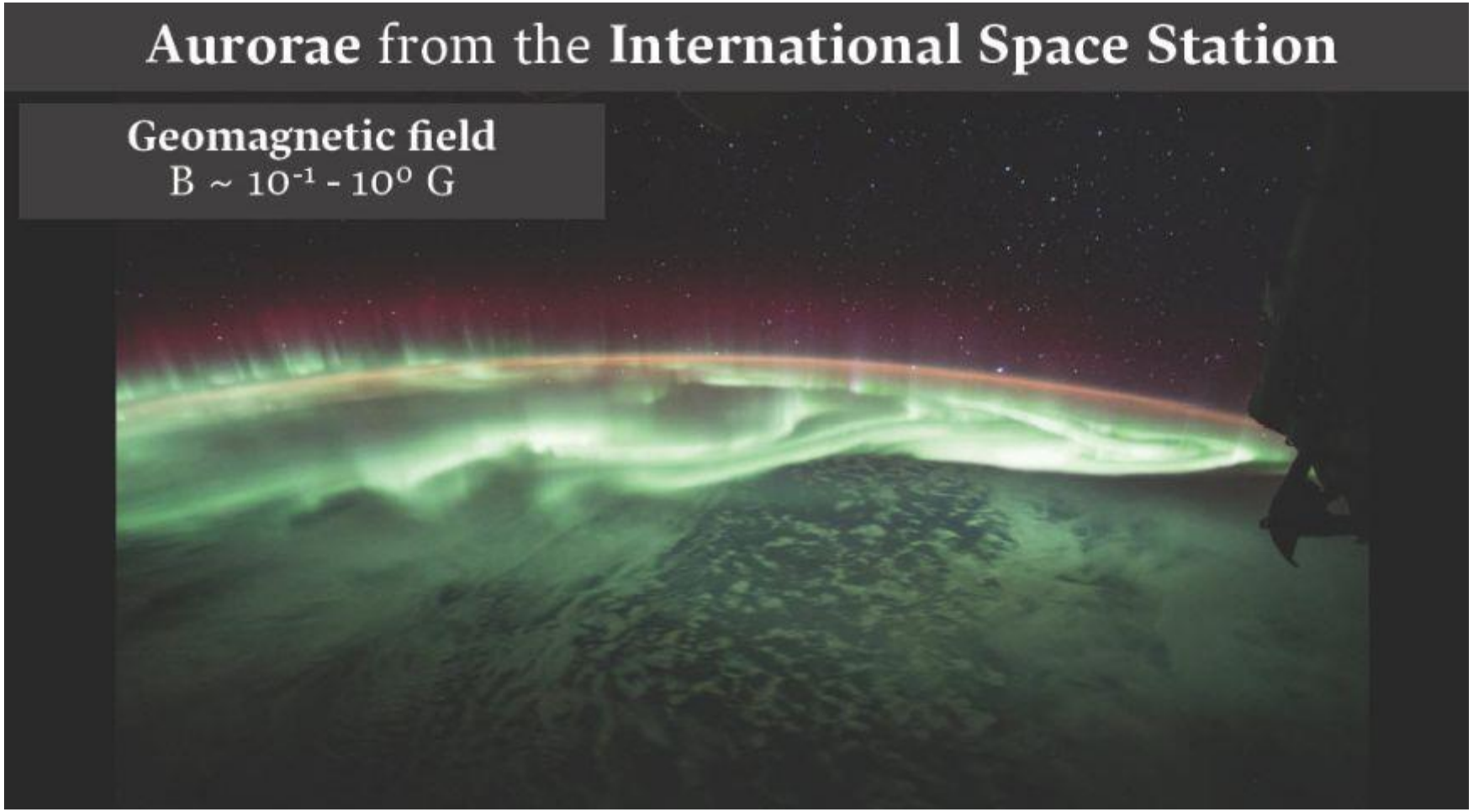
Electromagnetism: inspiration for spacetime

From *Zur Elektrodynamik bewegter Körper* (1905):

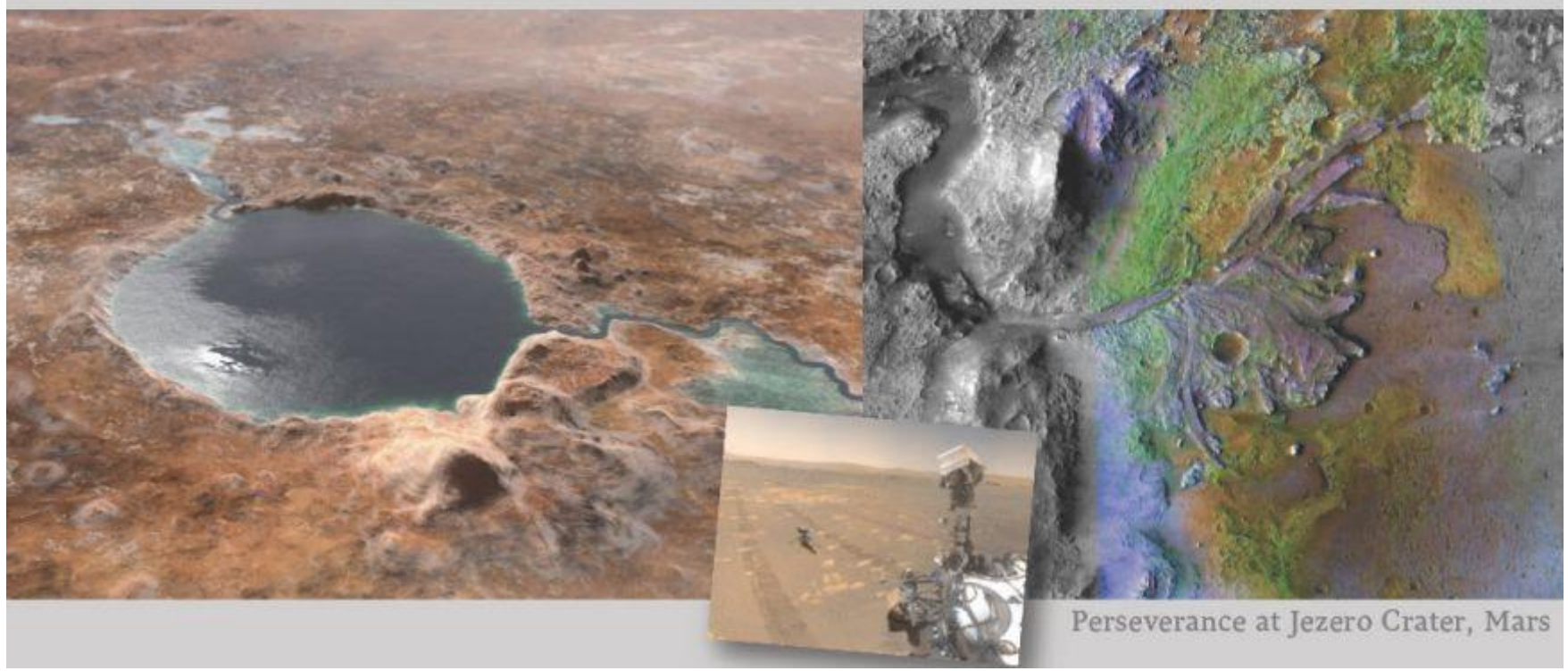
It is known that Maxwell's electrodynamics — as usually understood at the present time — when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise — assuming equality of relative motion in the two cases discussed — to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Examples of this sort, together with the unsuccessful attempts to discover any motion of the Earth relatively to the 'light medium', **suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest.**

Aurorae from the **International Space Station**

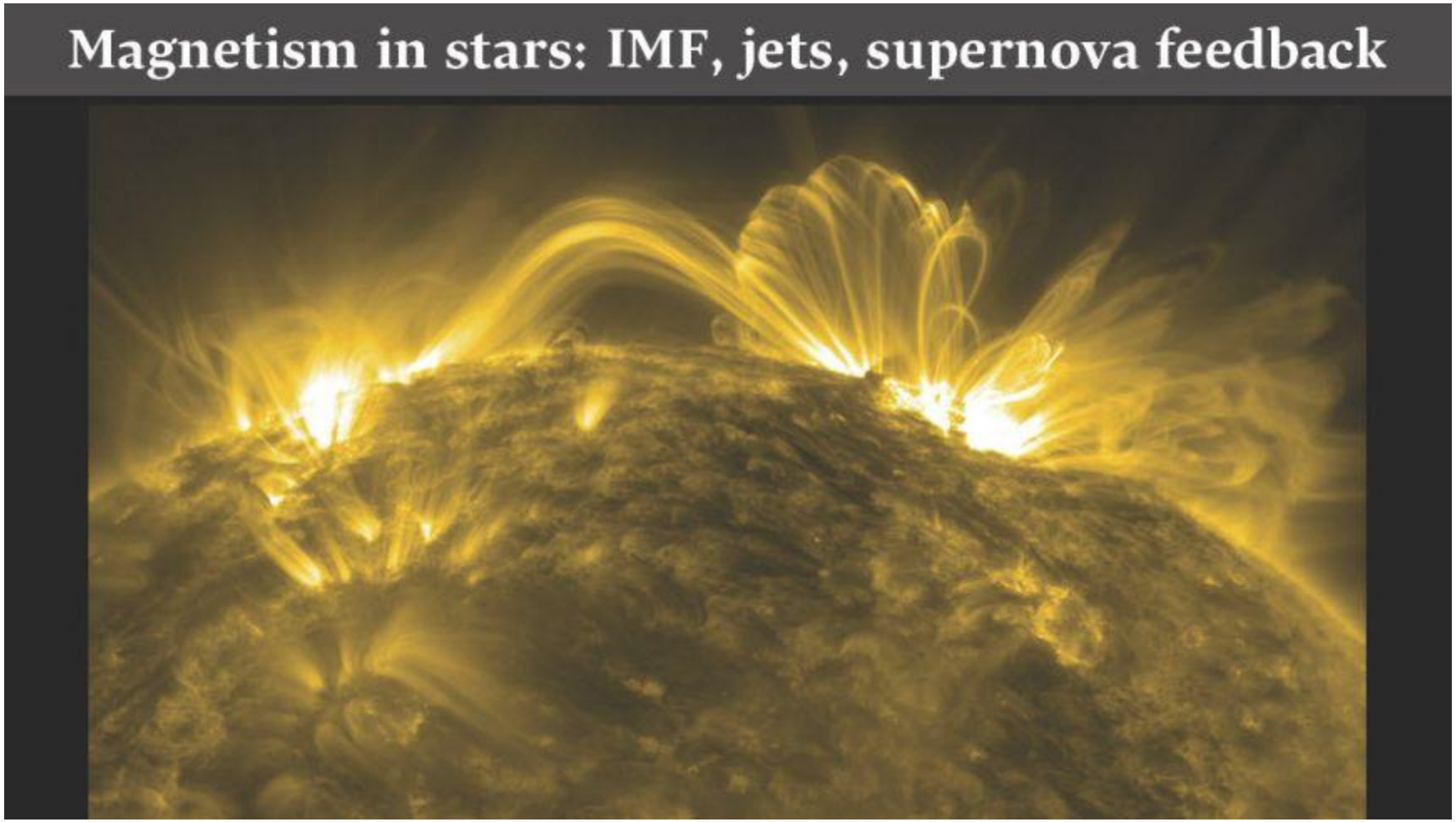


Mars was once **habitable**, but when its **magnetic field** disappeared, the **Solar wind** blew its **atmosphere** away

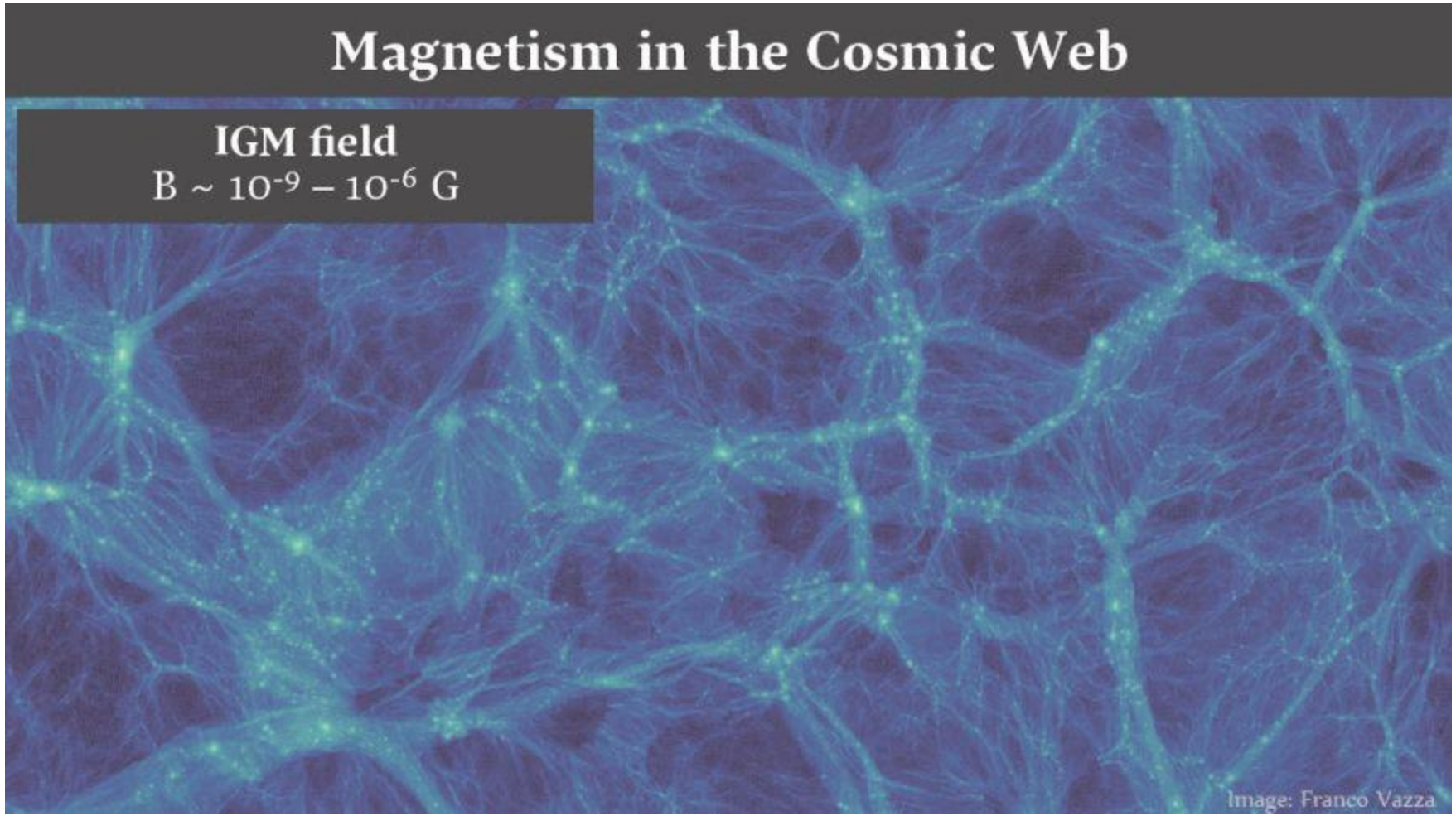


Perseverance at Jezero Crater, Mars

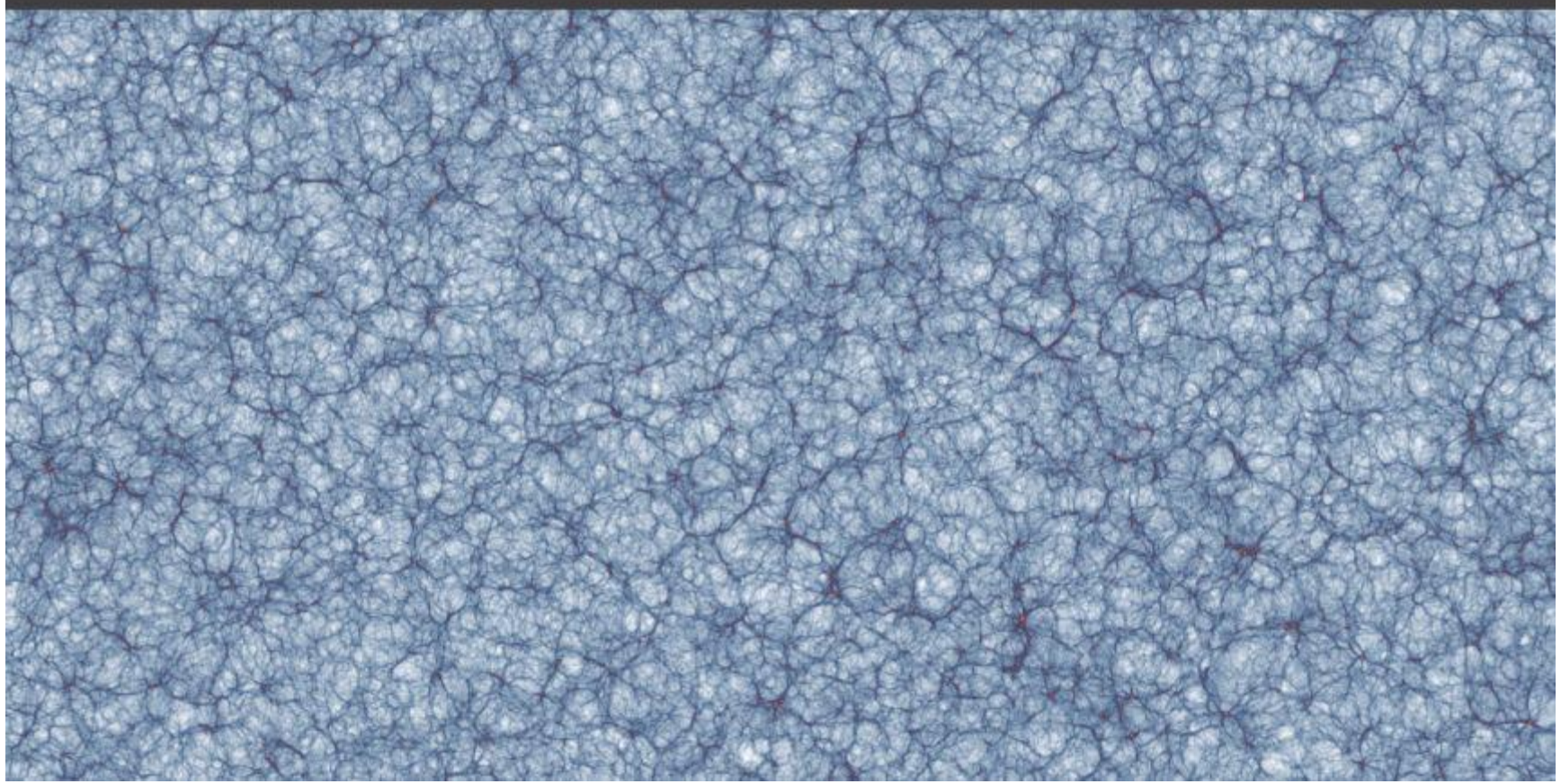
Magnetism in stars: IMF, jets, supernova feedback



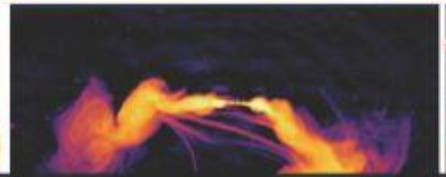
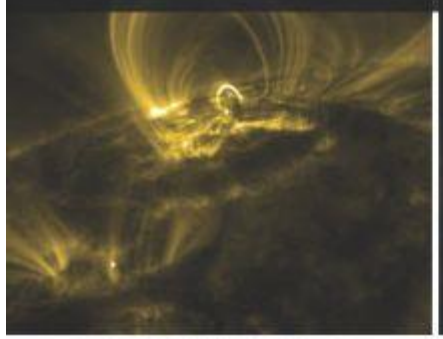
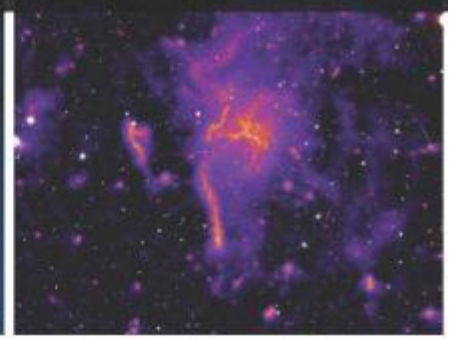
Magnetism in the Cosmic Web



The Cosmic Web: the ‘End of Greatness’



Magnetism pervades the Universe – is there a unified origin?

Planetary and stellar scale	Galactic scale	Cosmological scale: galaxy clusters, filaments, voids	
			
			
Top: Aurora Borealis in Iceland (own observation) Bottom: coronal loop by TRACE (NASA)	Top: Milky Way dust by Planck (ESA) Bottom: Messier 77 (NASA and SOFIA)	Top: ESO 137-006 by MeerKAT (M. Ramatsoku, SARAO) Bottom: Perseus cluster by LOFAR (R. Timmerman, F. Sweijen)	Top: Abell 399–401 by LOFAR (J. de Jong, F. Sweijen) Bottom: Abell 2255 by LOFAR (A. Botteon, F. Sweijen)

My PhD: Contributing to the search for the origin of magnetism

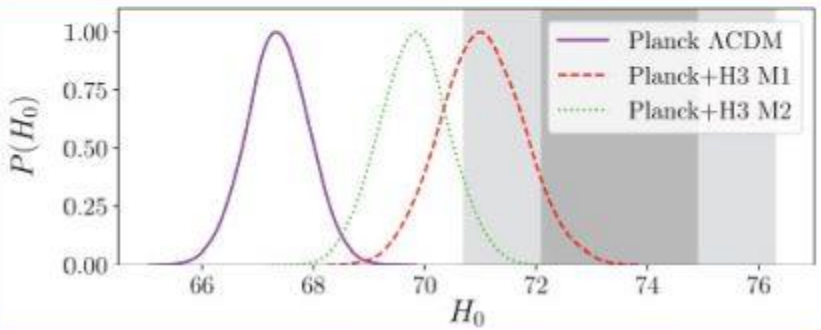
Cosmic magnetogenesis: a frontier

In galaxy evolution and cosmology, the origin of magnetism is still poorly understood...

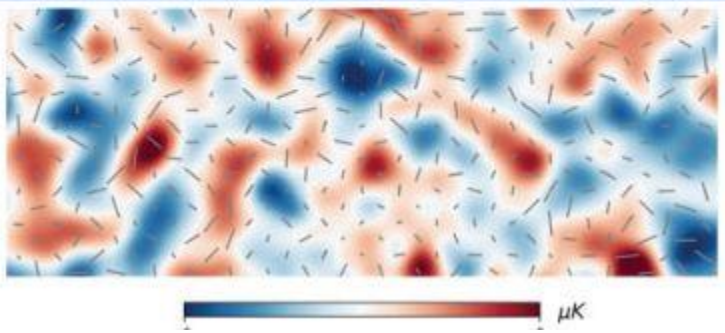
Galactic and cluster dynamos need a seed field!

- **Astrophysical origin**
  - Supernovae and radio galaxies
- **Primordial origin**
  - Between end of inflation and recombination: coherence length too small
  - Before the end of inflation: too weak
    - Solution: new physics?

Primordial magnetic fields could resolve the Hubble tension (Jedamzik & Pogosian, Phys. Rev. Lett. 2020)



Primordial magnetic fields via CMB B-modes

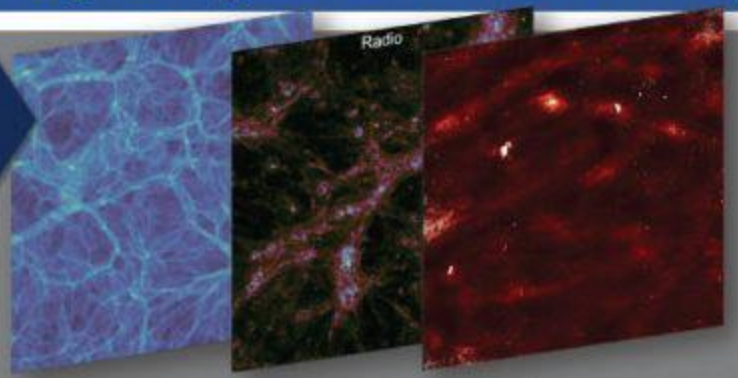


Primordial magnetic fields via radio Cosmic Web

My PhD work

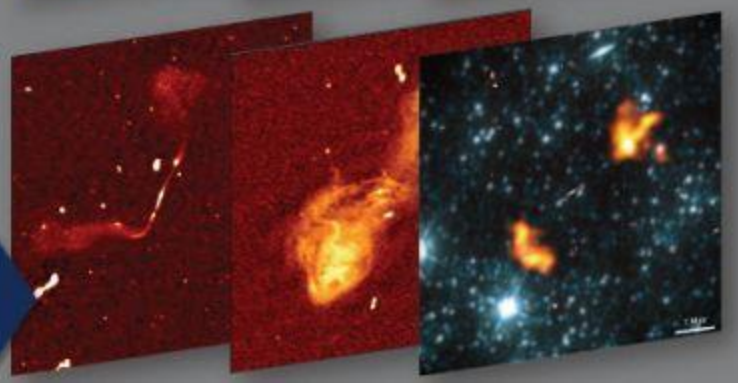
Magnetogenesis from two angles:

Radio Cosmic Web



Infer **total** magnetic field
$B_{\text{primordial}} + B_{\text{astrophysical}}$

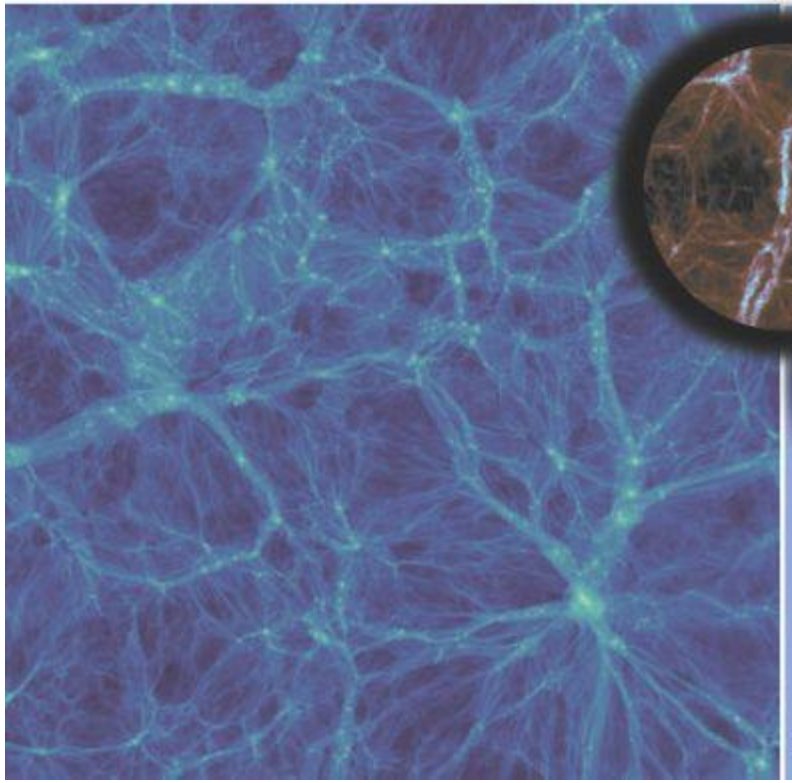
Astrophysical seeding by RGs

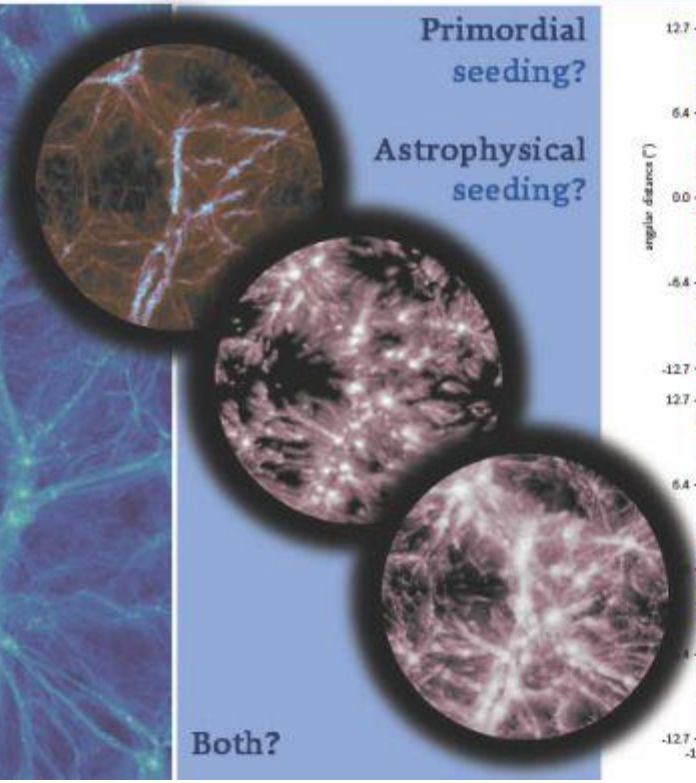


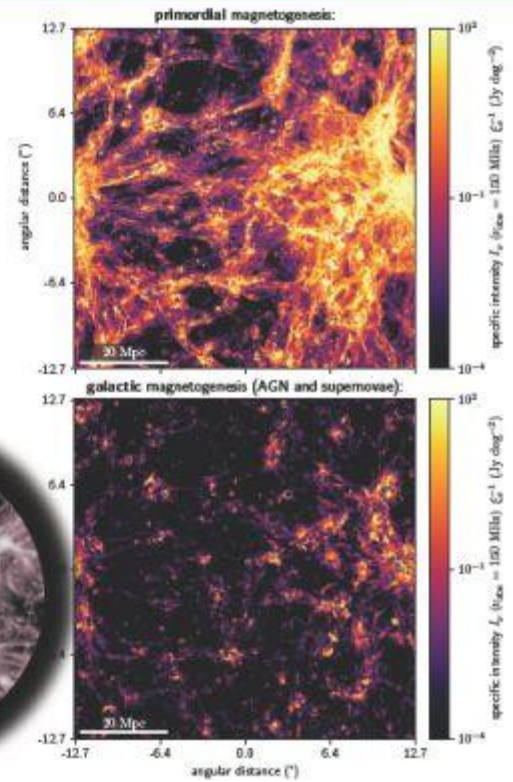
Infer **astrophysical** magnetic field
$B_{\text{astrophysical}}$

Magnetogenesis and the radio Cosmic Web

Baryonic and dark matter density field	Magnetic field?	Synchrotron radiation at λ = 2 m?





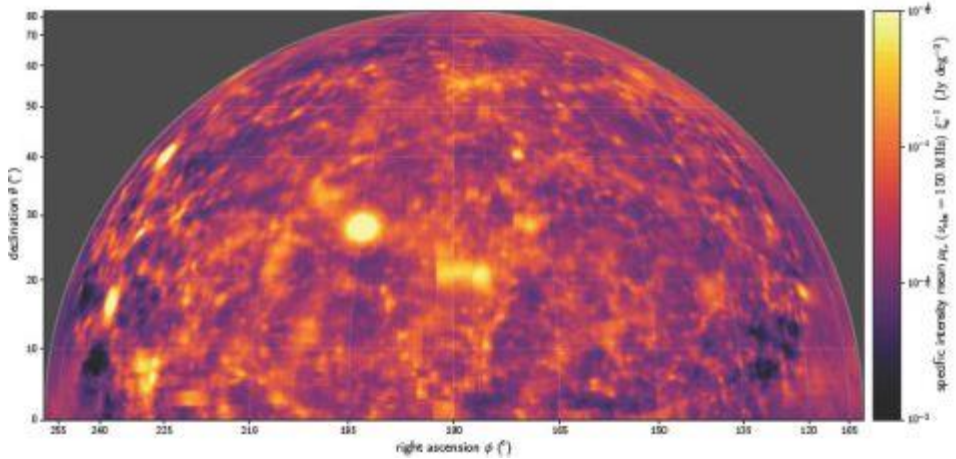


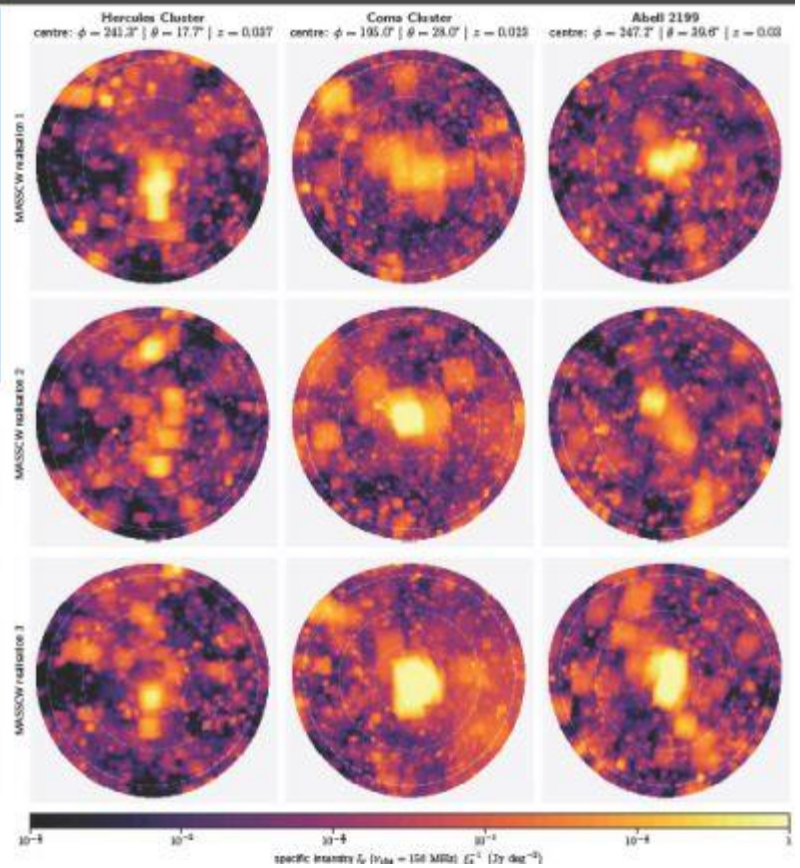
Probabilistic radio Cosmic Web predictions

Radiation mechanism: DSA by merger and accretion shocks during large-scale structure formation

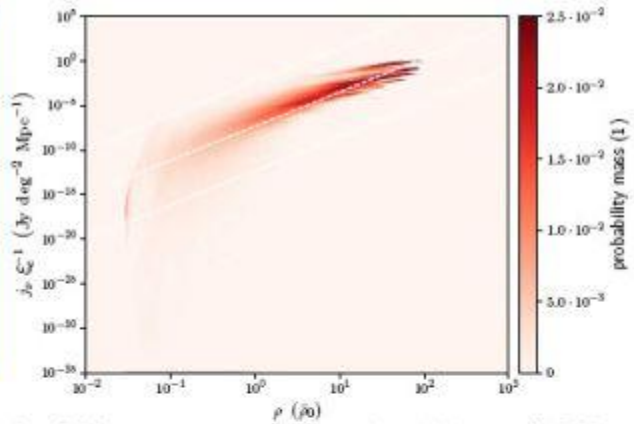
Right: Three predictions for three galaxy clusters

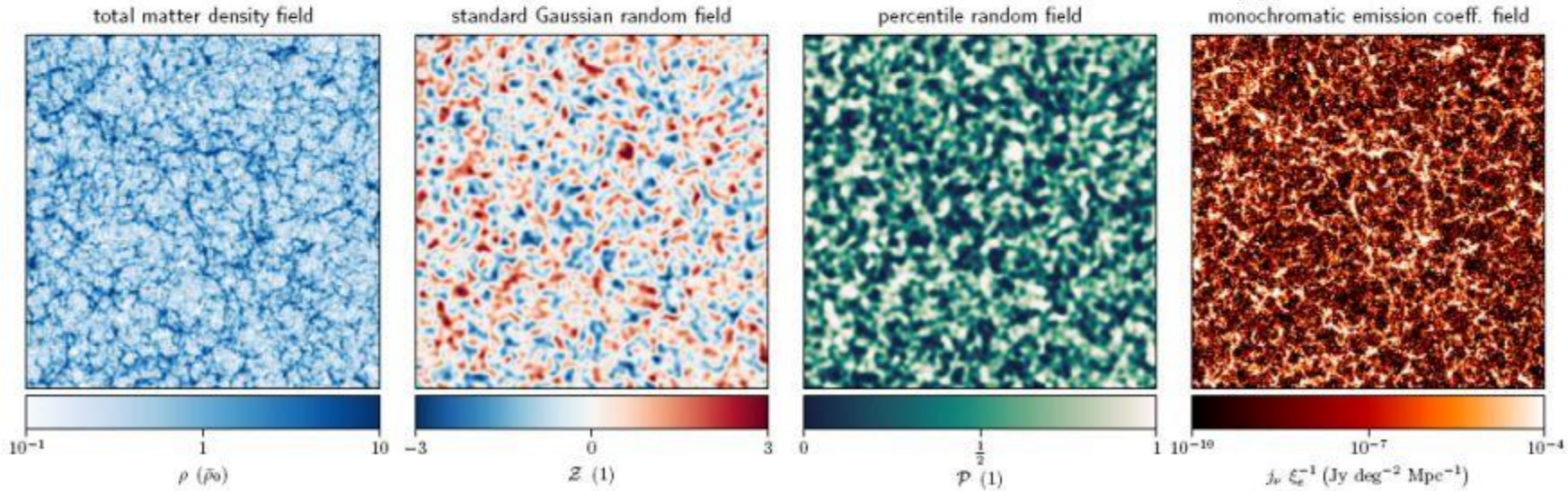
Bottom: Mean prediction for half of Northern Sky





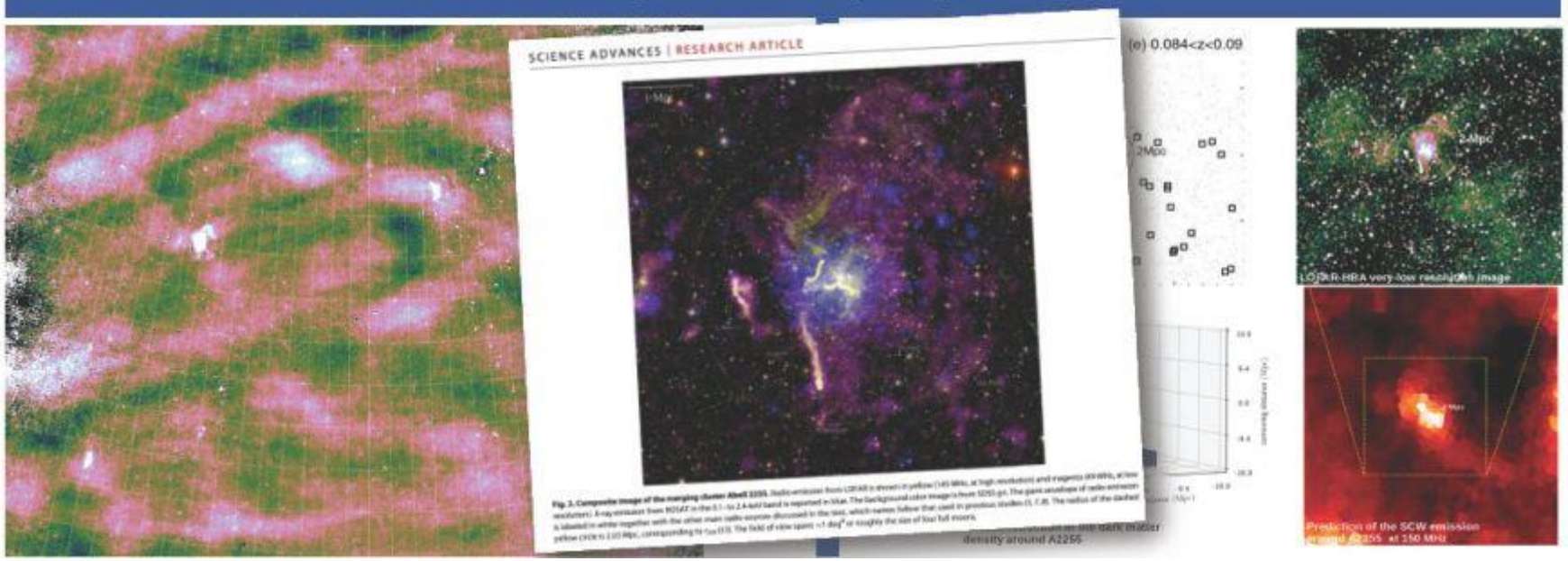
- ‘Paint’ density fields with radio emission using a probabilistic relation learnt from a high-res MHD simulation
- Allow for the possibility that neighbouring voxels have correlated radio emission
- ‘Correct’ up to global scaling factor

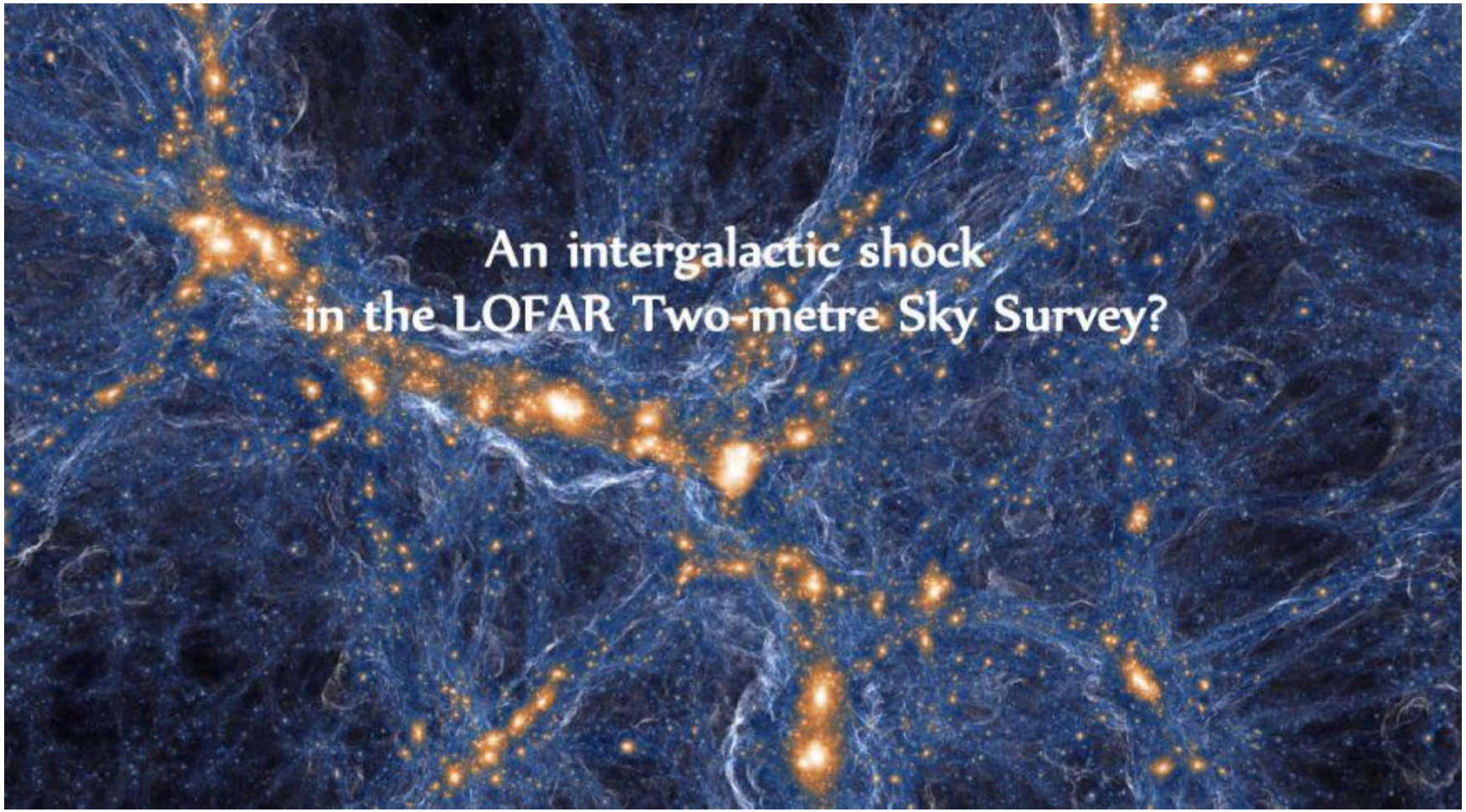


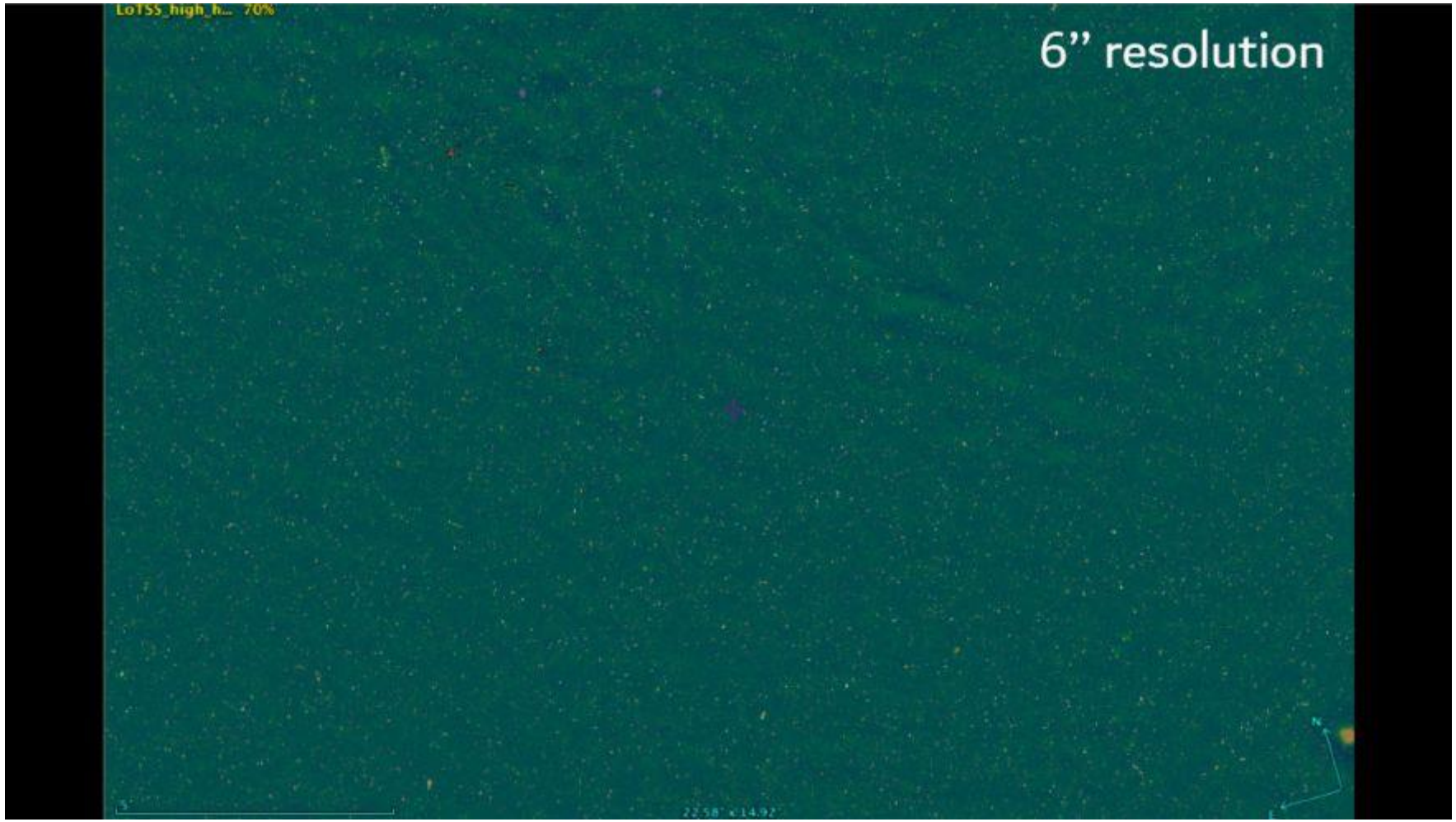


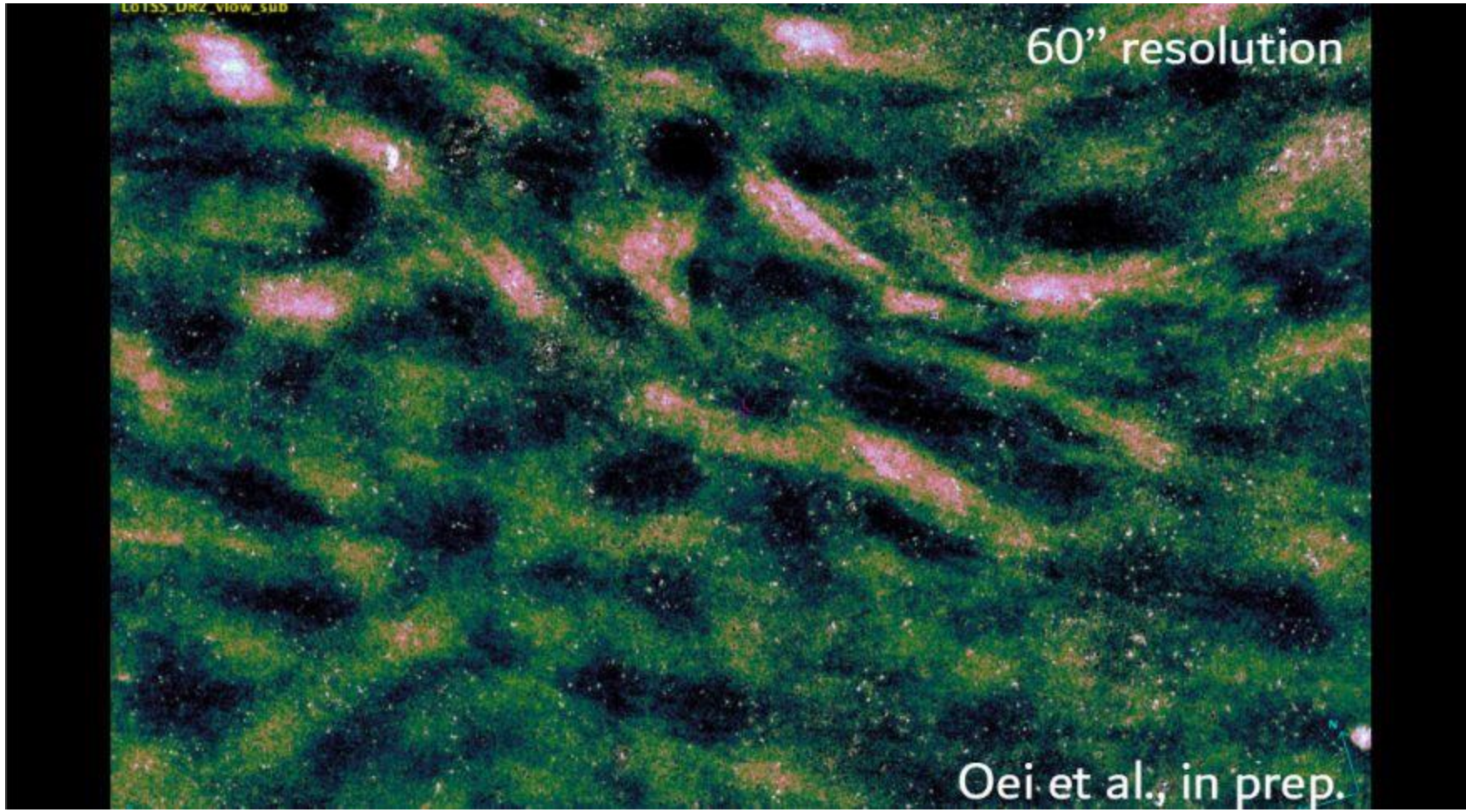
Radio Cosmic Web: observational hints

- Low-resolution, source-subtracted LOFAR images reveal filamentary structures on the sky
- Cosmic Web filaments, or the Milky Way?
- Cross-correlate with our new predicted sky maps

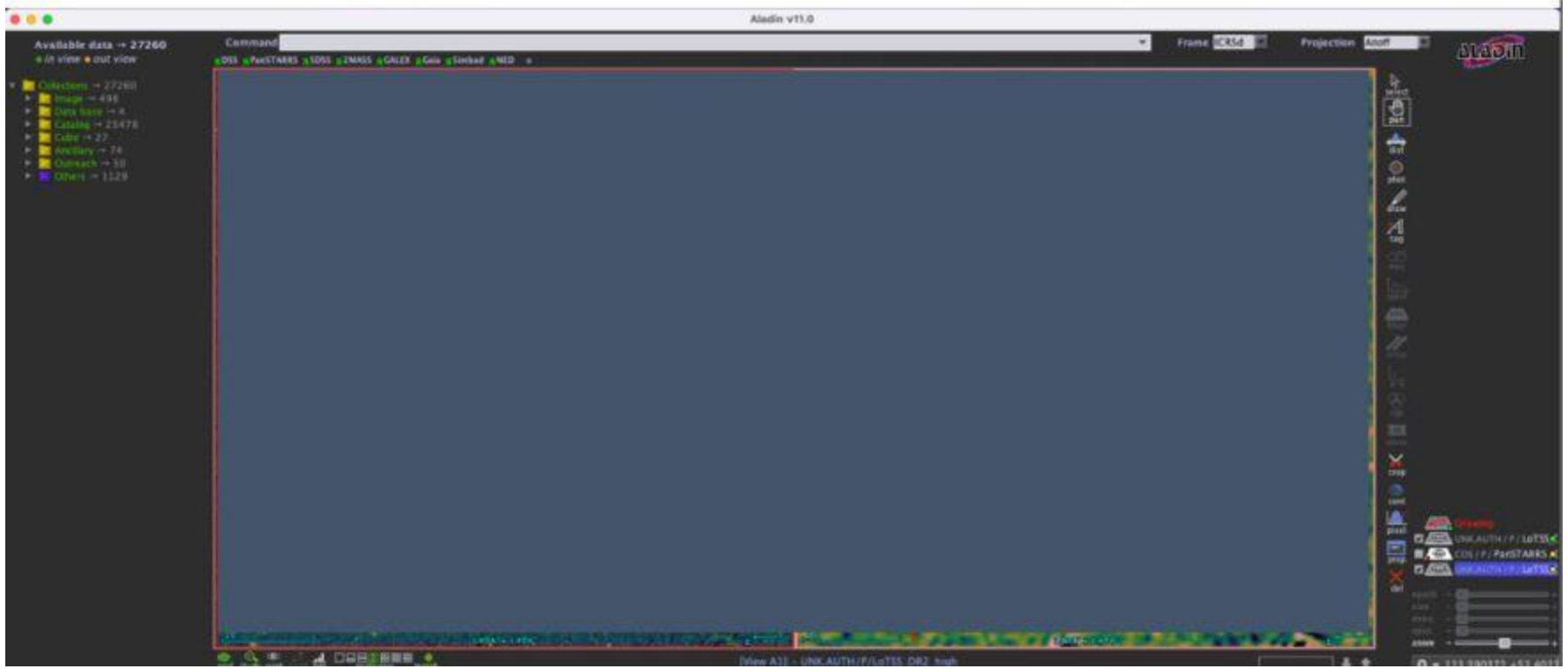



An intergalactic shock
in the LOFAR Two-metre Sky Survey?


LoTSS_high_fi... 70%
6” resolution
N
E

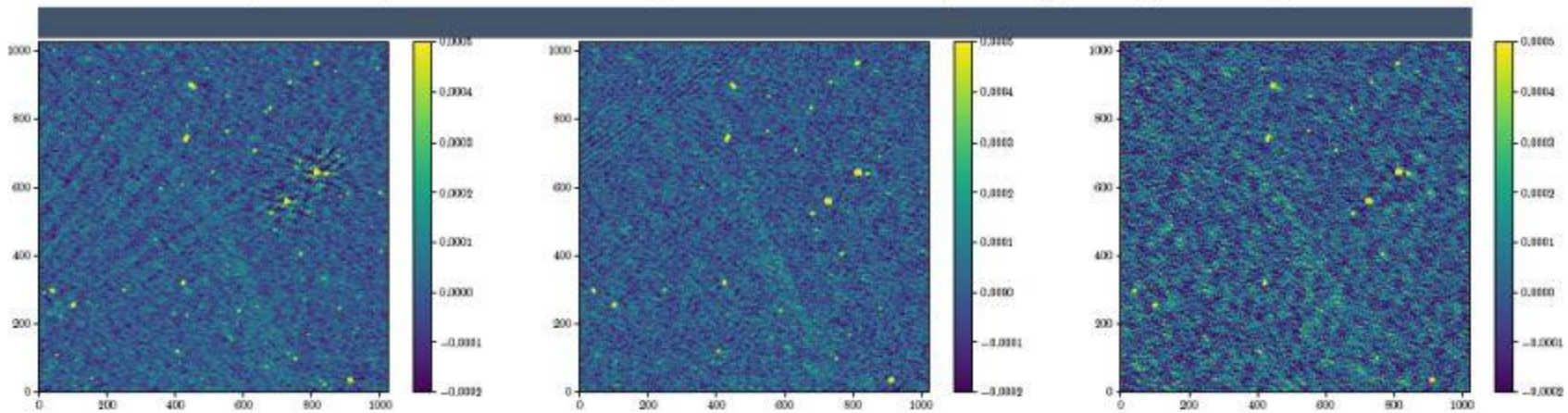

60” resolution
Oei et al., in prep.

While scanning the LoTSS DR2, we found an unidentified structure at 6” and 60”...



The source is not a one-off imaging artefact, because it occurs in three independent 8-hour LoTSS pointings

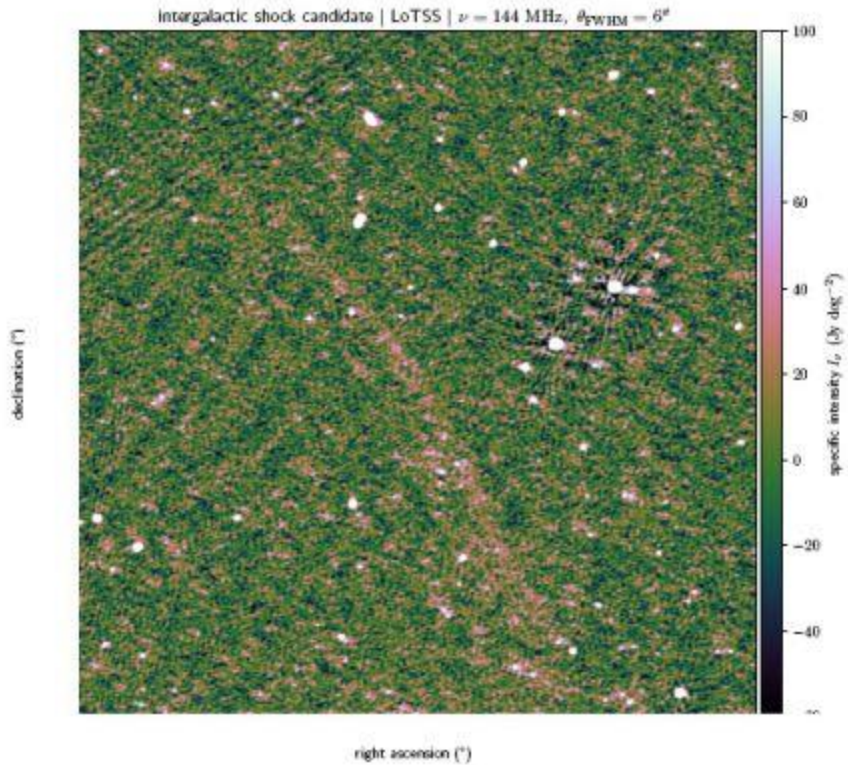
Titles: pointing names and angular distances (in deg.) to pointing centre

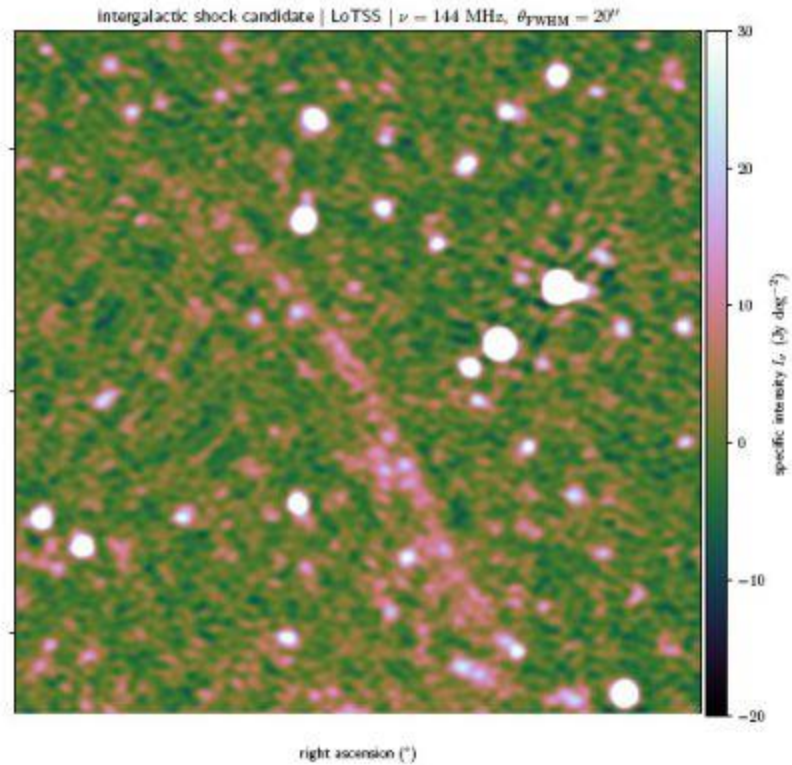


(And there is a hint of the source in a fourth pointing, if you know where to look...)

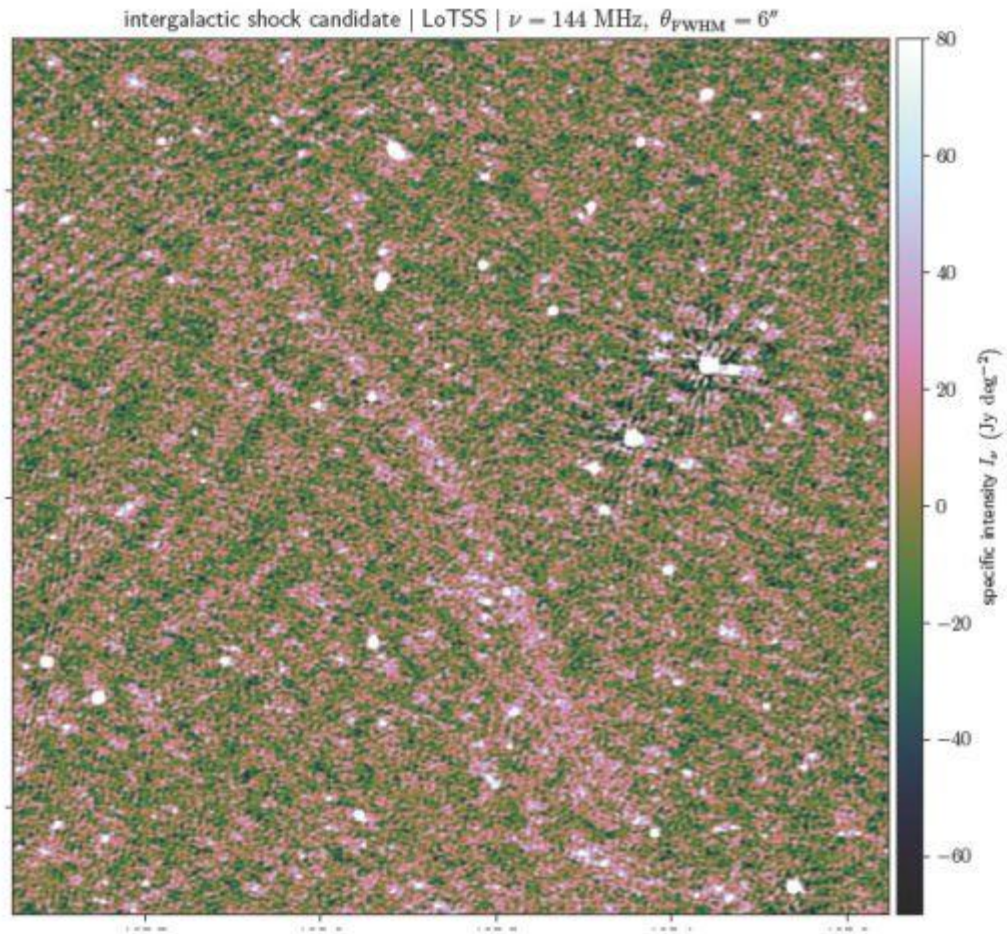
Detection significance

at 6": 1σ | at 20": 2σ-3σ

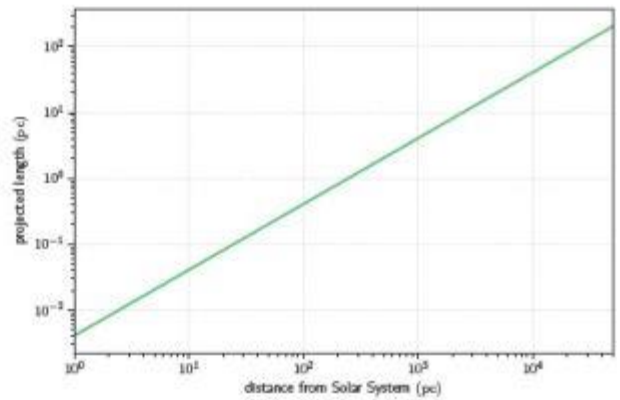


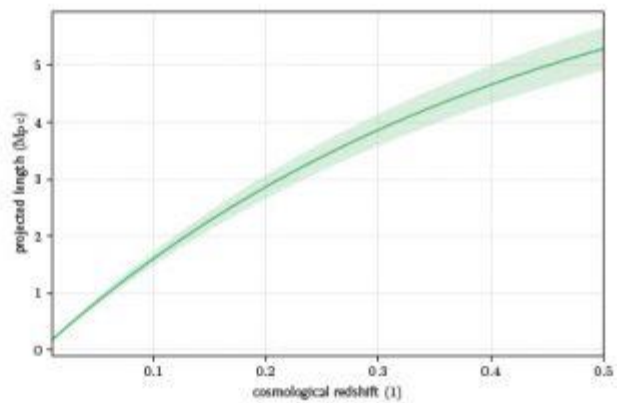


Last year: follow-up with the uGMRT

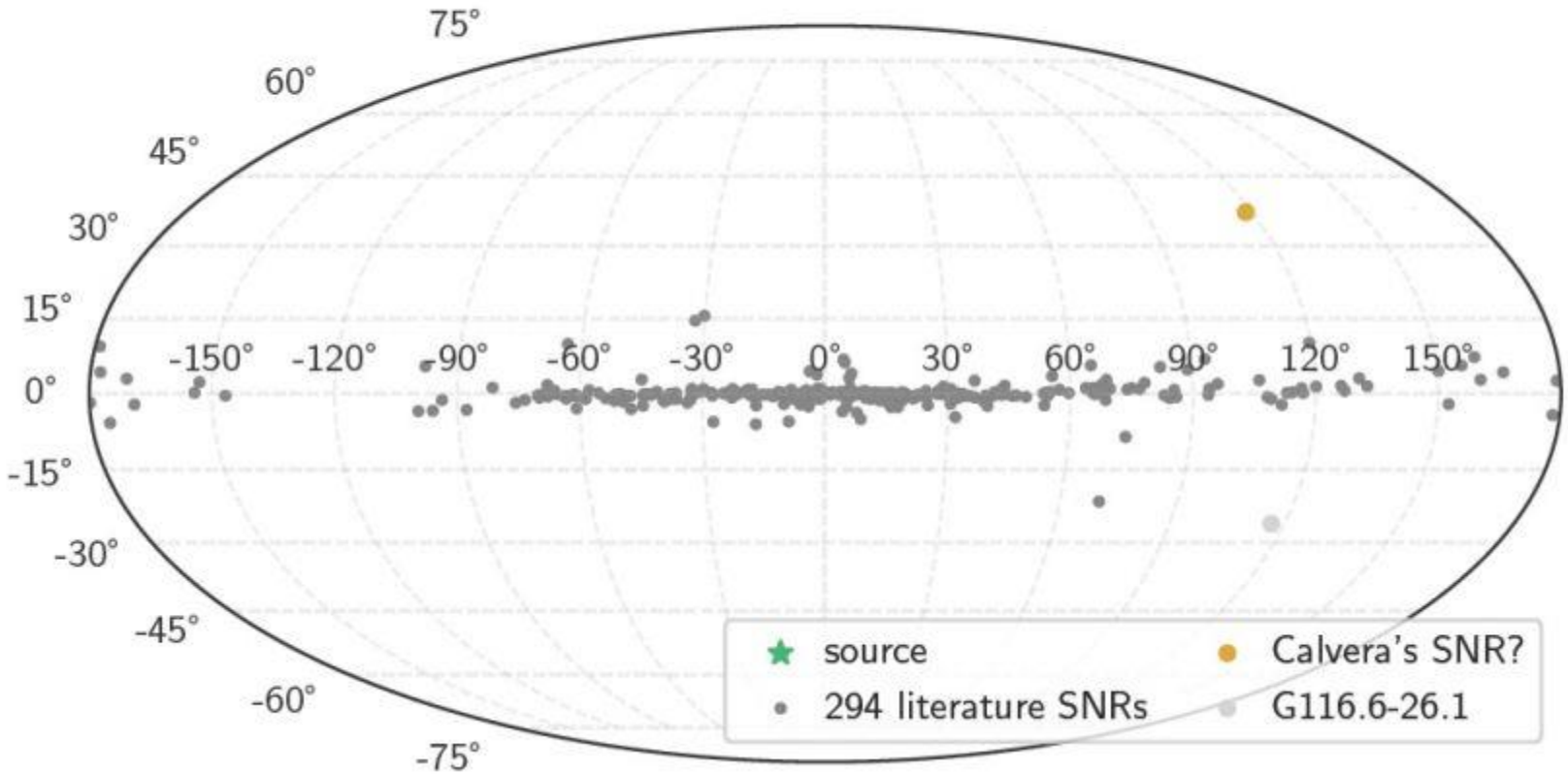


Angular length: 14'

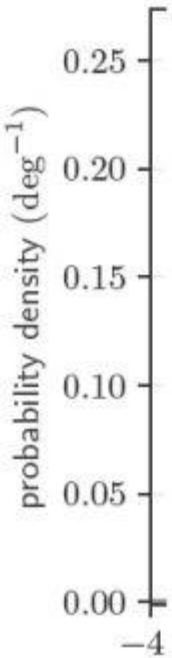




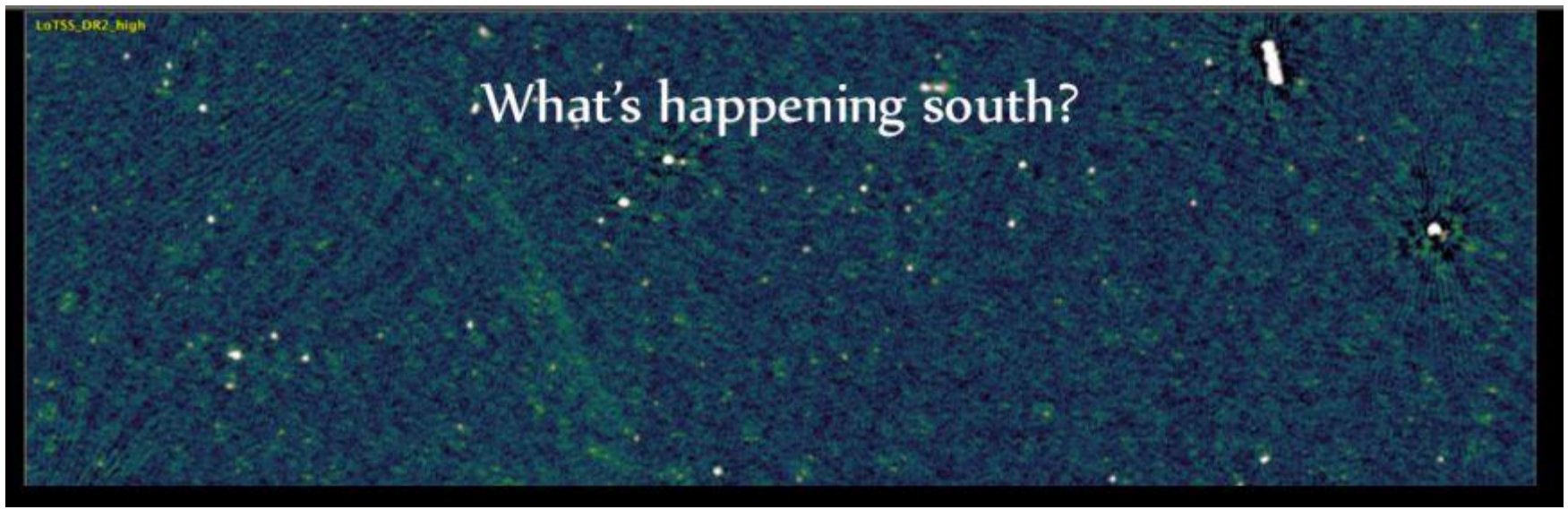
Could this be a Milky Way supernova shock?



Could this be a Milky Way supernova shock?



... And the Galactic longitude would be atypical as well!


LoTSS_DR2_high
What's happening south?

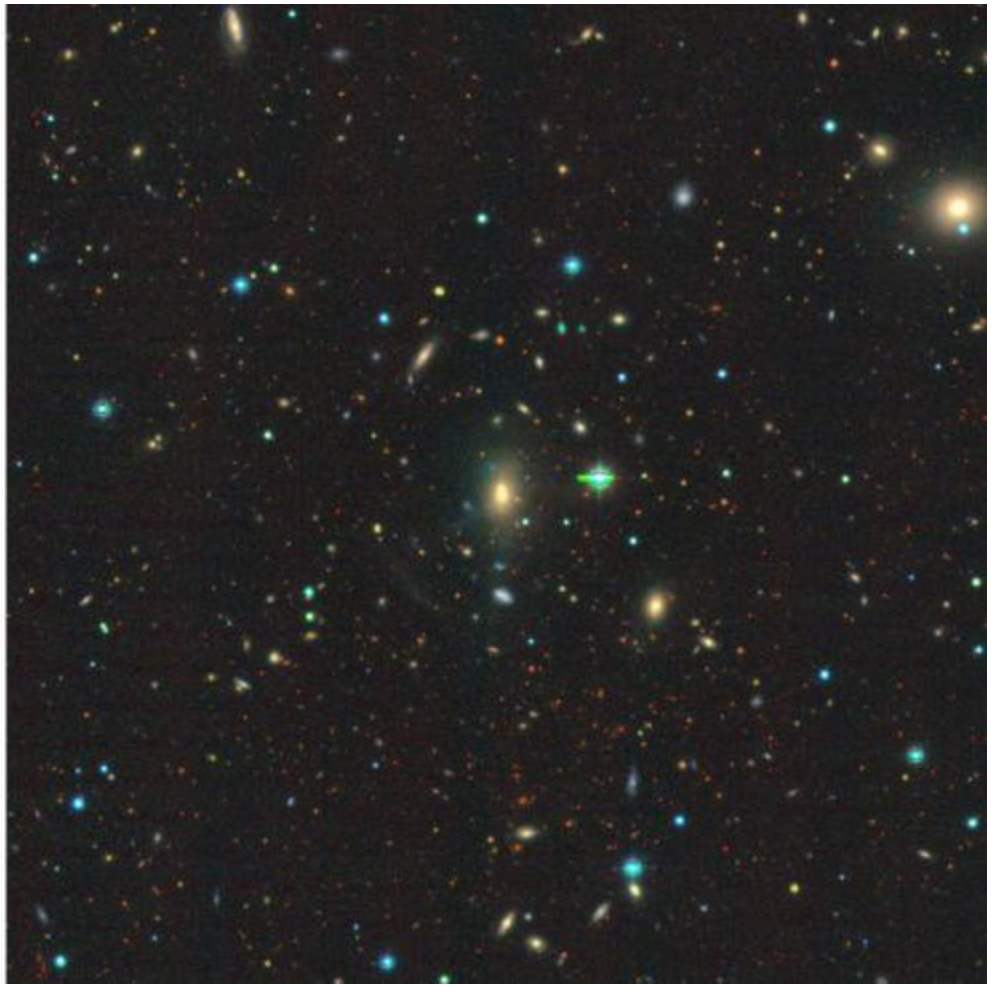
Merging galaxy group or low-mass galaxy cluster?

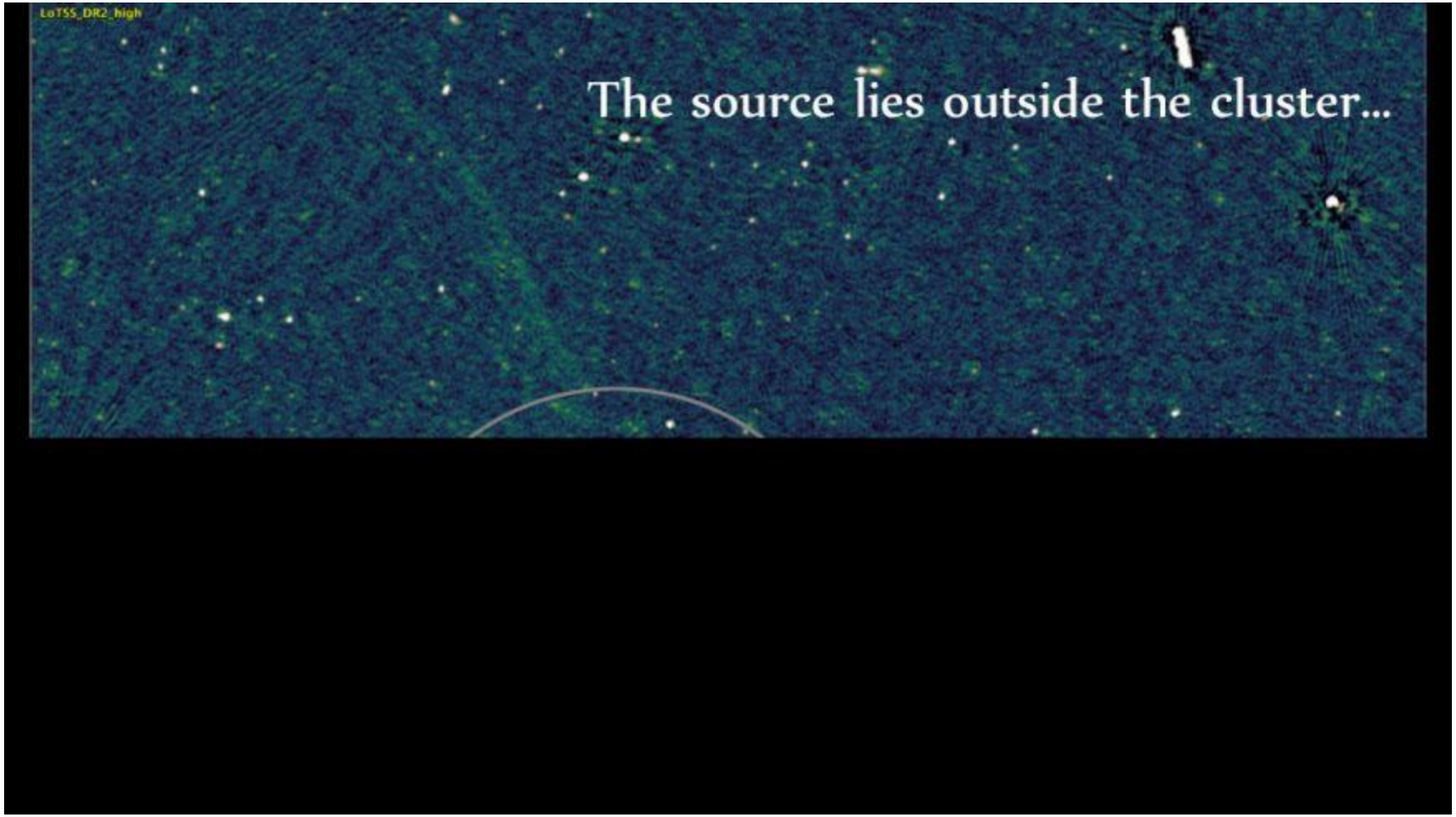
- Large-scale structure at $z = 0.08$
- Source at angular distance $\varphi = 15'$

- Evidence for a tidally disrupted galaxy (rather than a gravity lens; thanks Ian!) near BCG
- Wang et al. 12014: $L_X = 2 \times 10^{36}$ W
- Saulder et al. 12016: $M = 2 \times 10^{14}\ M_\odot$
- Wen et al. 12018: $M_{500} = 0.7 \times 10^{14}\ M_\odot$
- Not in PSZ2 catalogue: $M < 2 \times 10^{14}\ M_\odot$

- More large-scale structure in adjacent sky?

Image: Legacy Surveys (via Frits' legacystamps code)




LoTSS_DR2_high
The source lies outside the cluster...

Probability of random association

- Large-scale structure at $z = 0.08$
- Source at angular distance $\varphi = 15'$

If the source is unrelated, what is the probability that it is this near on the sky from a cluster at $z < 0.1$?

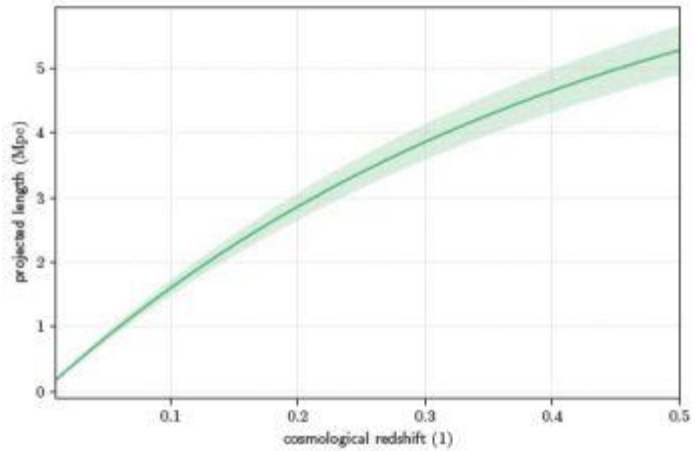
Adopt Monte Carlo approach using cluster catalogue from Wen, Han and Liu (12012) by distributing mock sources uniformly in the sky:

$P(\varphi < 10') = 1\%$ (to source end)

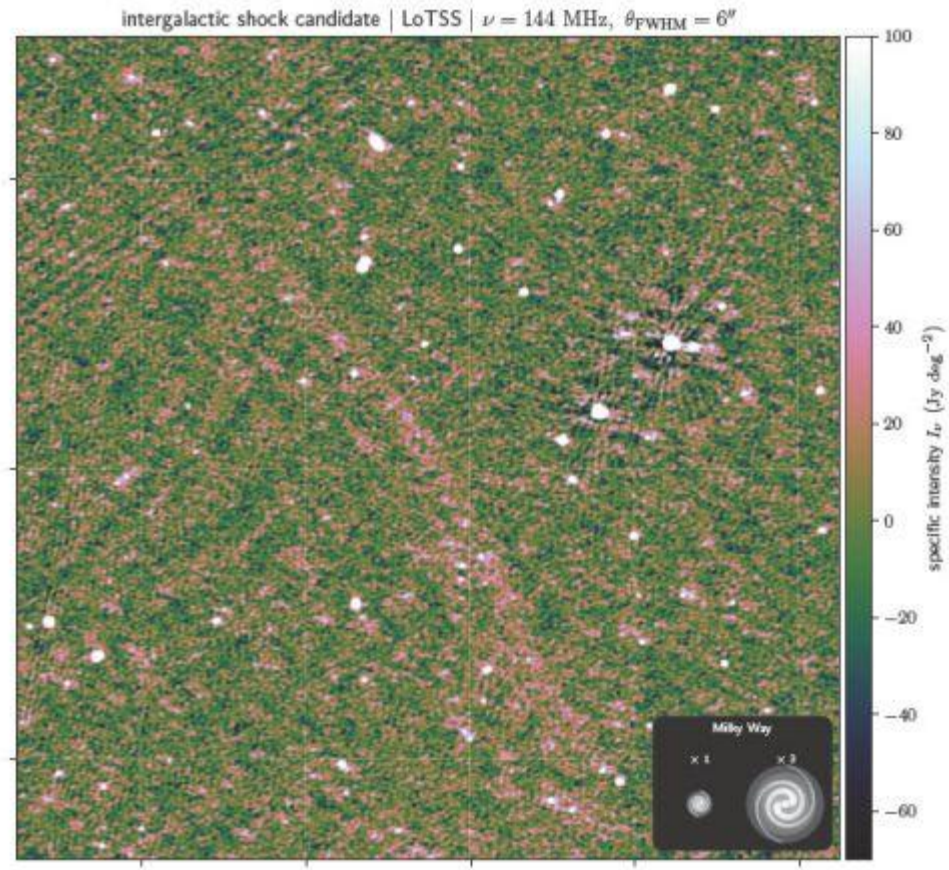
$P(\varphi < 15') = 3\%$ (to source centre)

Image: Legacy Surveys (via legacystamps code)

If we accept that the source relates to this low-mass cluster (in whatever way), its projected proper length is 1.2 Mpc:

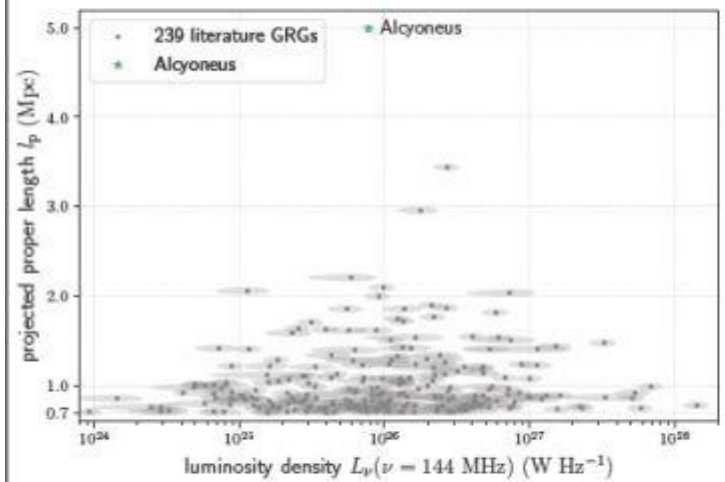


... and its 144 MHz luminosity density is 1.2 x 10^{24} W / Hz.

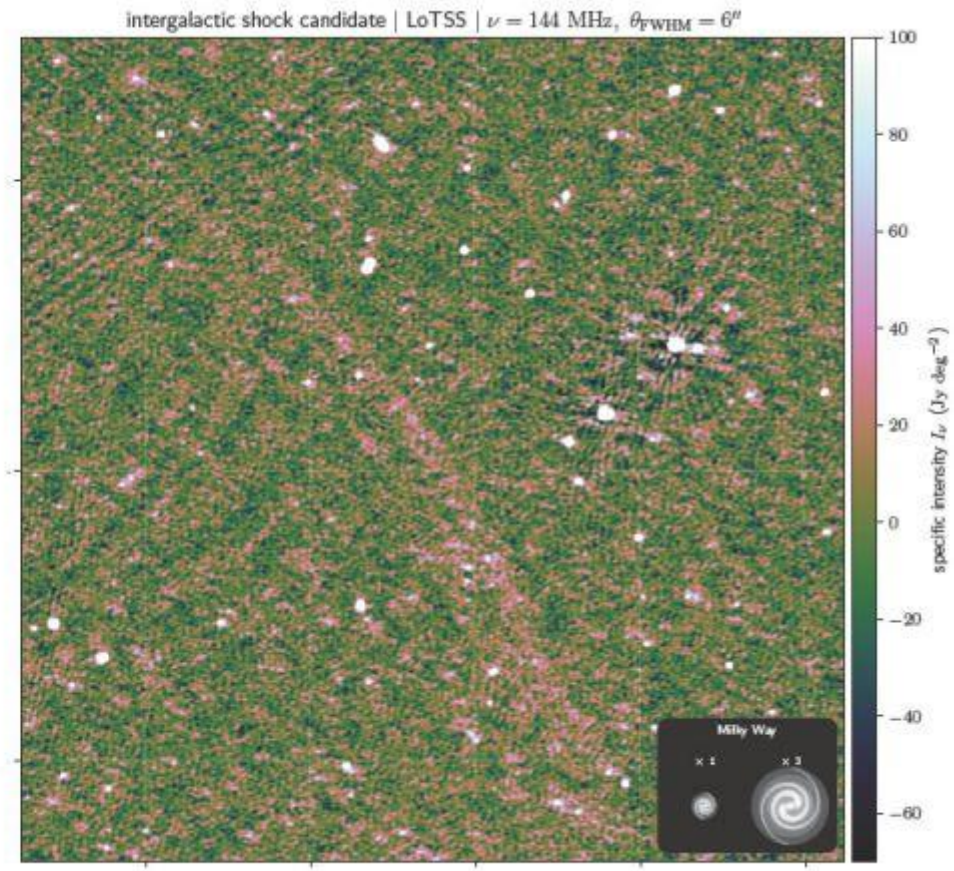


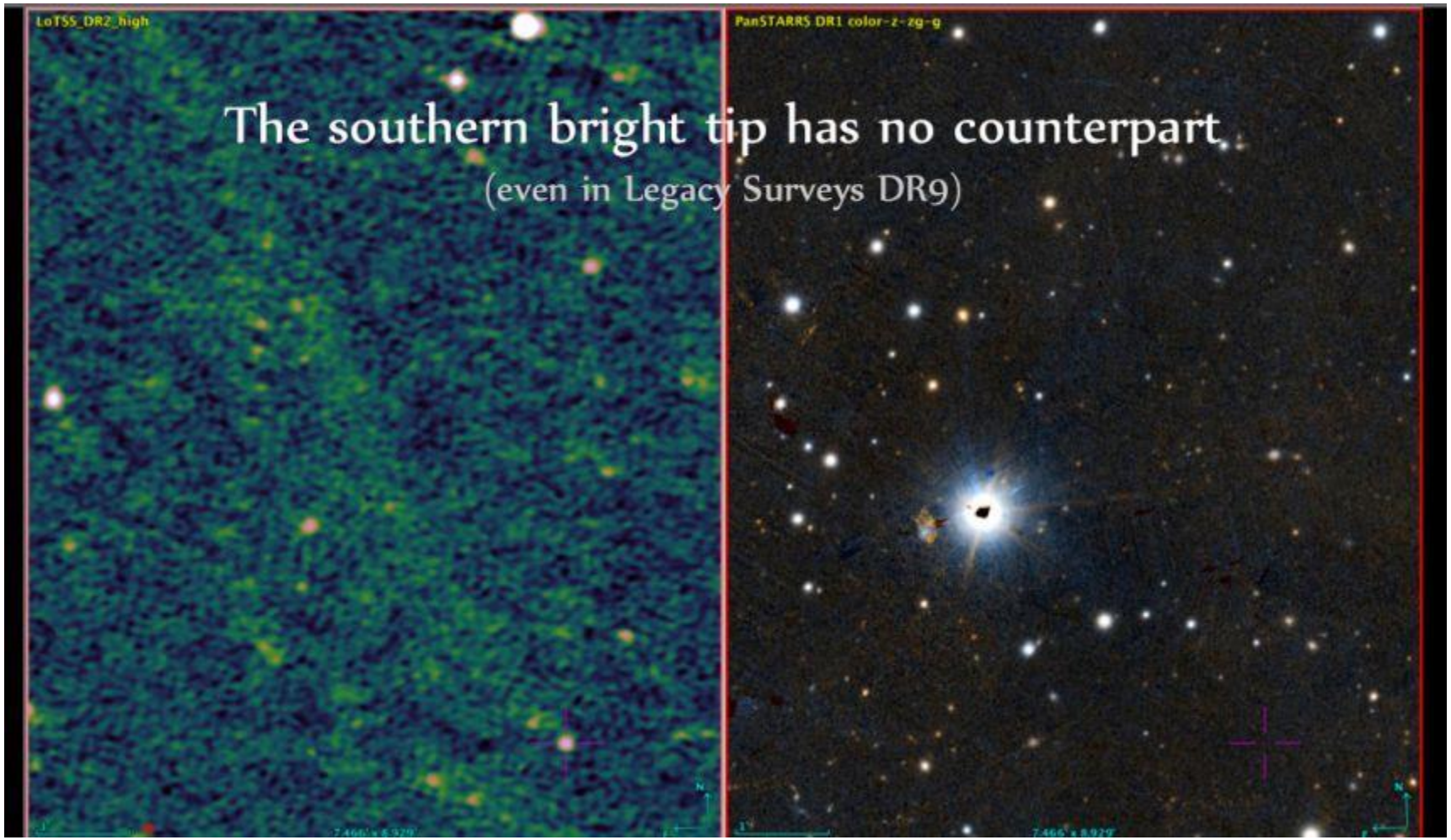
Is this a giant radio galaxy?

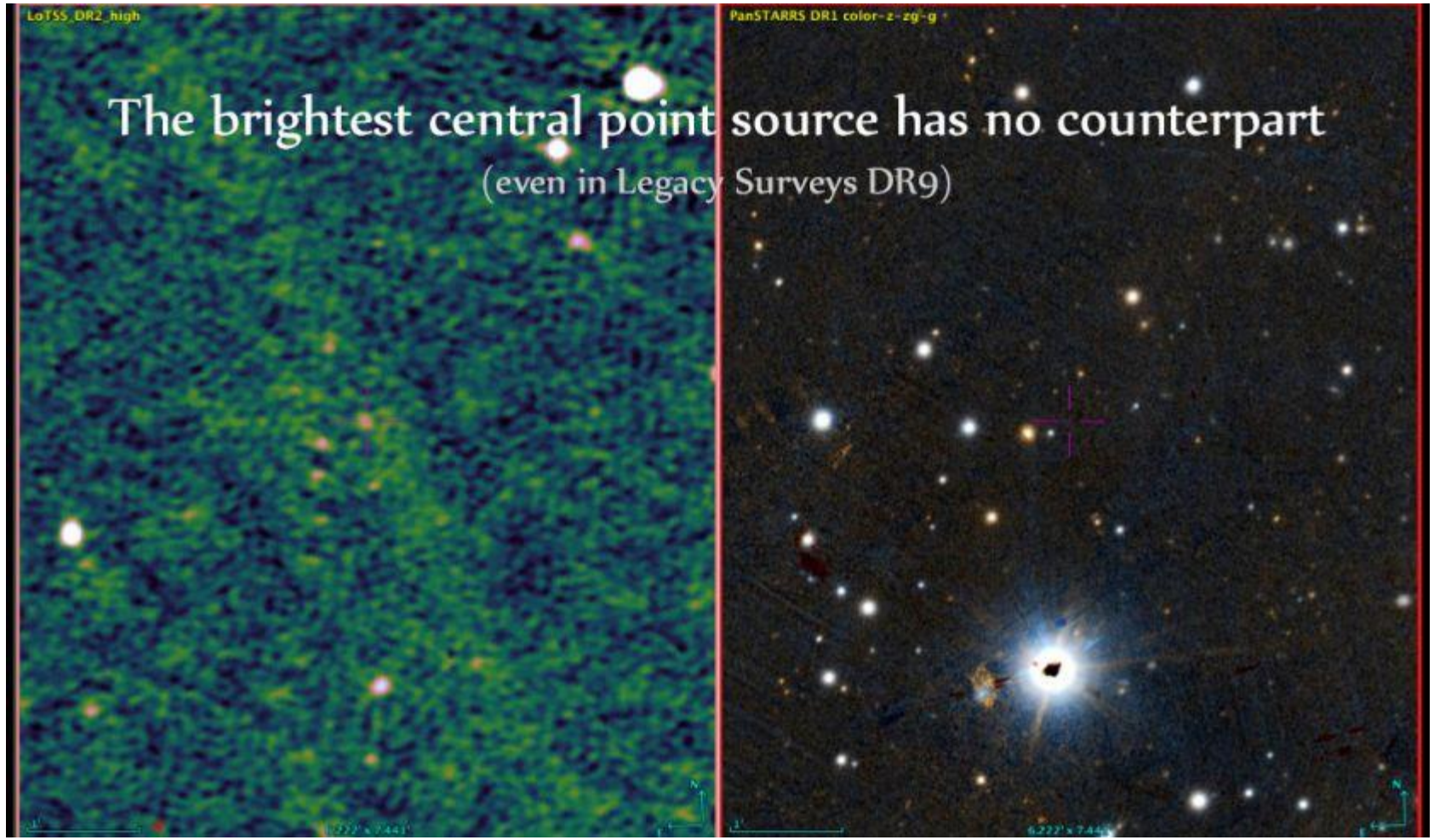
GRGs are rare: absent in most clusters
No obvious host galaxy nor jets...



If so, it would be among the 1% faintest LoTSS GRGs!



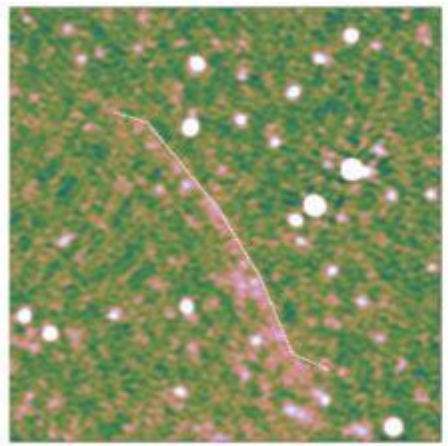

LoTSS_DR2_high
PanSTARRS DR1 color-z-zg-g
The southern bright tip has no counterpart
(even in Legacy Surveys DR9)

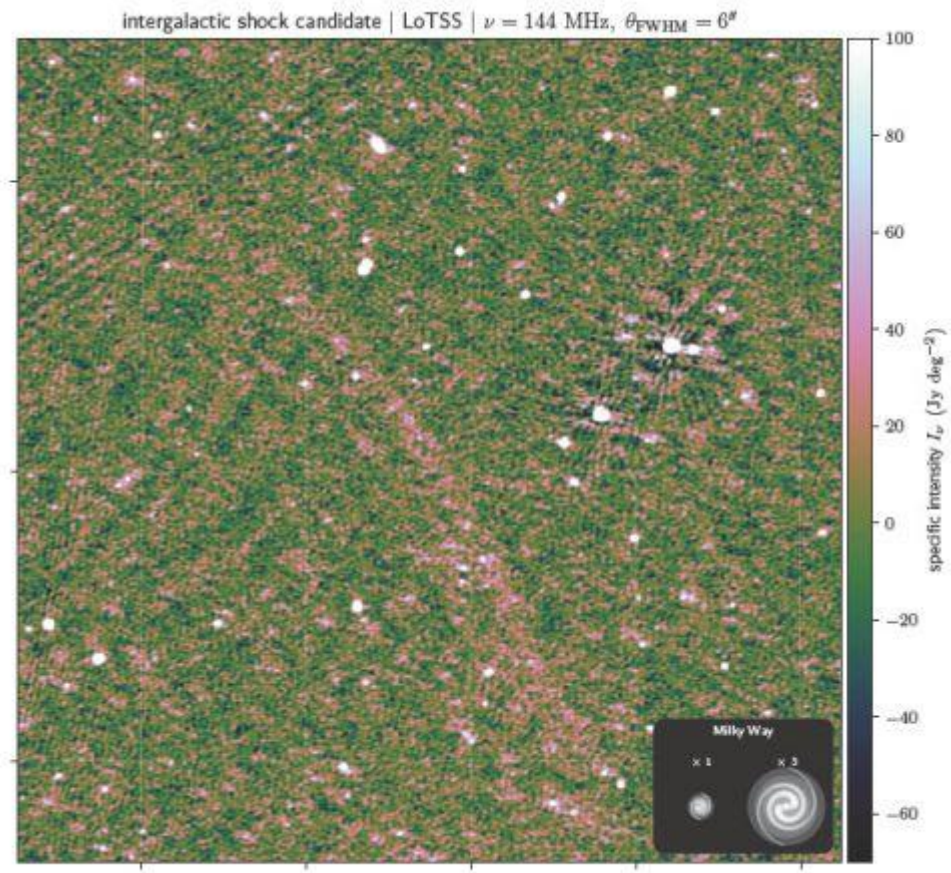

LoTSS_DR2_high
The brightest central point source has no counterpart
(even in Legacy Surveys DR9)
PanSTARRS DR1 color-z-zg-g

Is this an intergalactic shock?

Shocks feature discontinuities.
By eye: tentative evidence for a sharp and a not-so-sharp side!

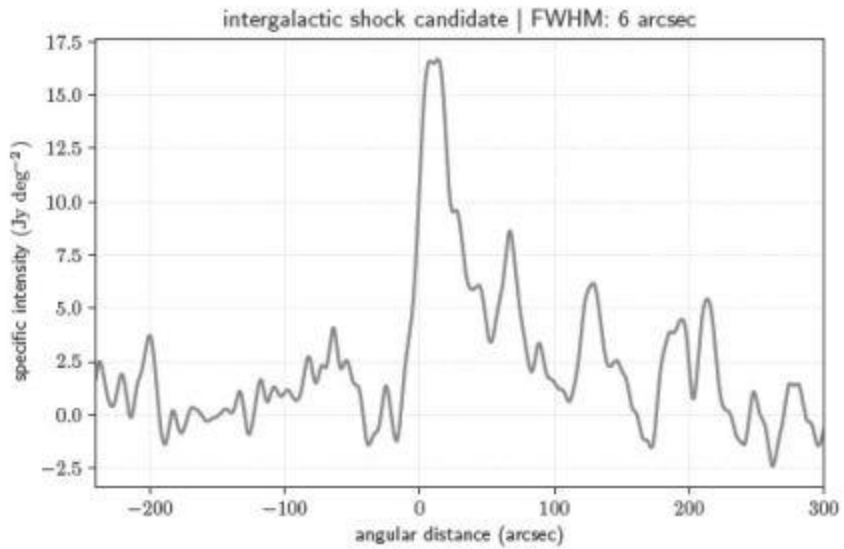
Let's create a 1D profile...

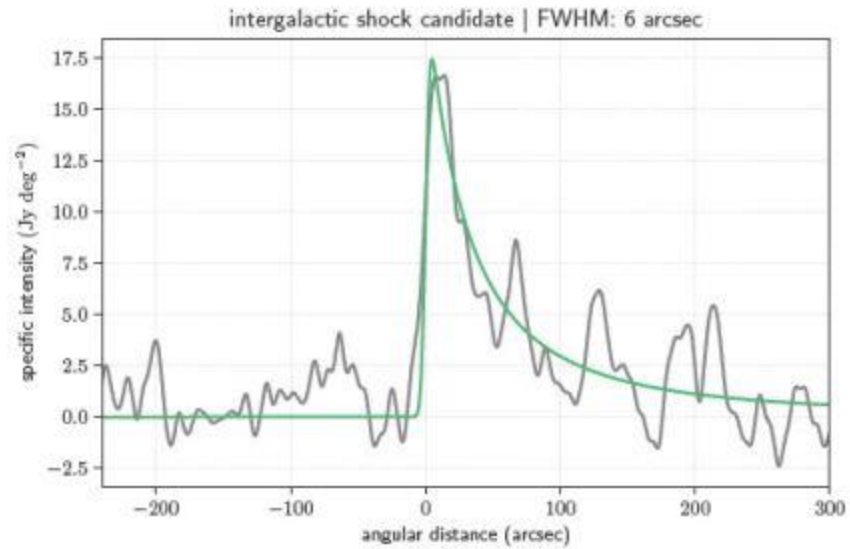




Intergalactic shock hypothesis

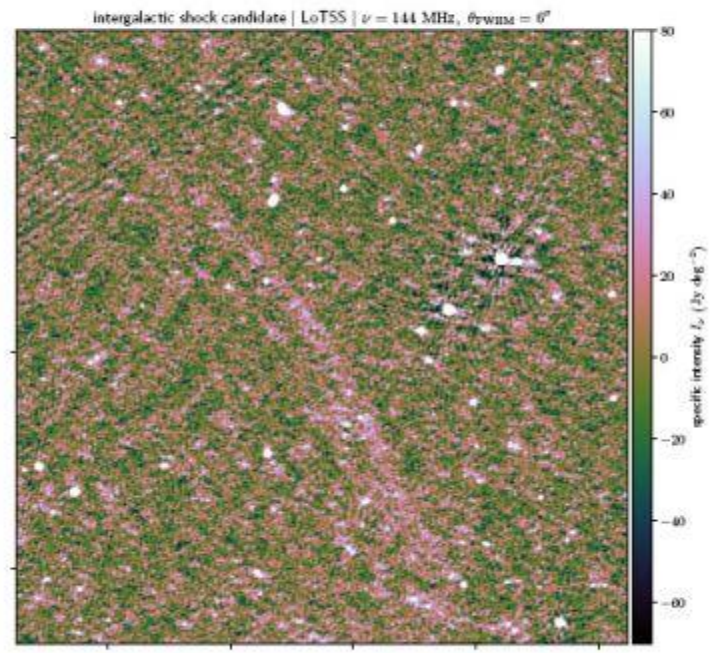
Average along line segment chain, and fit with model with sharp discontinuity, blurred to the observation resolution





Conclusions

- We have found a 14' long, thin astrophysical source in LoTSS data at 6", 20" and 60" resolution, with evidence for a **surface brightness discontinuity**.
- If the source were a **Milky Way supernova remnant** (SNR), it would be atypical in its class: no known SNR is so far from the Galactic Plane.
- If the source were a **giant radio galaxy** (GRG), it would be atypical in its class: there are no clear host, jets or lobes, and the 144 MHz luminosity density would be among the lowest 1%.
- Instead, the source could be an Mpc-scale **intergalactic shock** near a merging cluster at $z = 0.08$.



Band 4 direct imaging of a candidate shock in the Cosmic Web

1 Venturing beyond galaxy clusters

Detecting synchrotron radiation from the intergalactic medium (IGM) in filaments of the Cosmic Web constitutes an upcoming frontier to test models of astrophysical shocks and their radiation mechanisms, trace the missing baryons, and constrain magnetogenesis: the origin and evolution of extragalactic magnetic fields (e.g. Vazza et al., 2014). Measuring *today's* extragalactic magnetic fields — especially in pristine filament environments — is of intense interest in observational cosmology, because their strength relates to that of those filling the *Early* Universe (e.g. Vazza et al., 2017). Primordial magnetism strong enough to produce the magnetic fields of modern galaxy clusters without dynamo amplification also causes significant baryon density inhomogeneities in the Early Universe. Recently, it has been shown that the latter effect could be large enough to resolve the hotly debated Hubble tension while upholding the ΛCDM paradigm (Jedamzik & Pogosian, 2020).

At the moment of writing, the first synchrotron detections of the IGM within filaments have been claimed, showing that observations of large-scale structure beyond galaxy clusters are within the reach of modern low-frequency radio telescopes. Most notably, Bonnon et al. (2018); Govoni et al. (2019); Bonnon et al. (2020) report the discovery of two *radio bridges*: highly compressed filaments between clusters bound to merge in the near cosmological future. Additionally, Vernstrom et al. (2021) have presented statistical evidence of synchrotron emission from the filament IGM buried in the noise of GLEAM and OVRO-LWA images.[1]

However, to this day, no compelling direct imaging exists of non-thermal phenomena in the IGM of *typical* Cosmic Web filaments. Might it be too early, after all, to witness observational cosmology in the radio window push decisively beyond galaxy clusters? During a recent search for giant radio galaxies (GRGs) in the LOFAR Two-metre Sky Survey (LoTSS, Shimwell et al., 2017, 2019) DR2 (Shimwell et al., 2022), we reimaged at 60″ resolution and visually inspected more than five thousand square degrees of Northern Sky (Oei et al., 2022a). Enticingly, this search has led to the discovery of a 24′ long enigmatic radio source that occurs in the angular vicinity of a galaxy cluster, but cannot lie within it, and that features a surface brightness discontinuity — the tell-tale sign of a shock wave. For reasons described

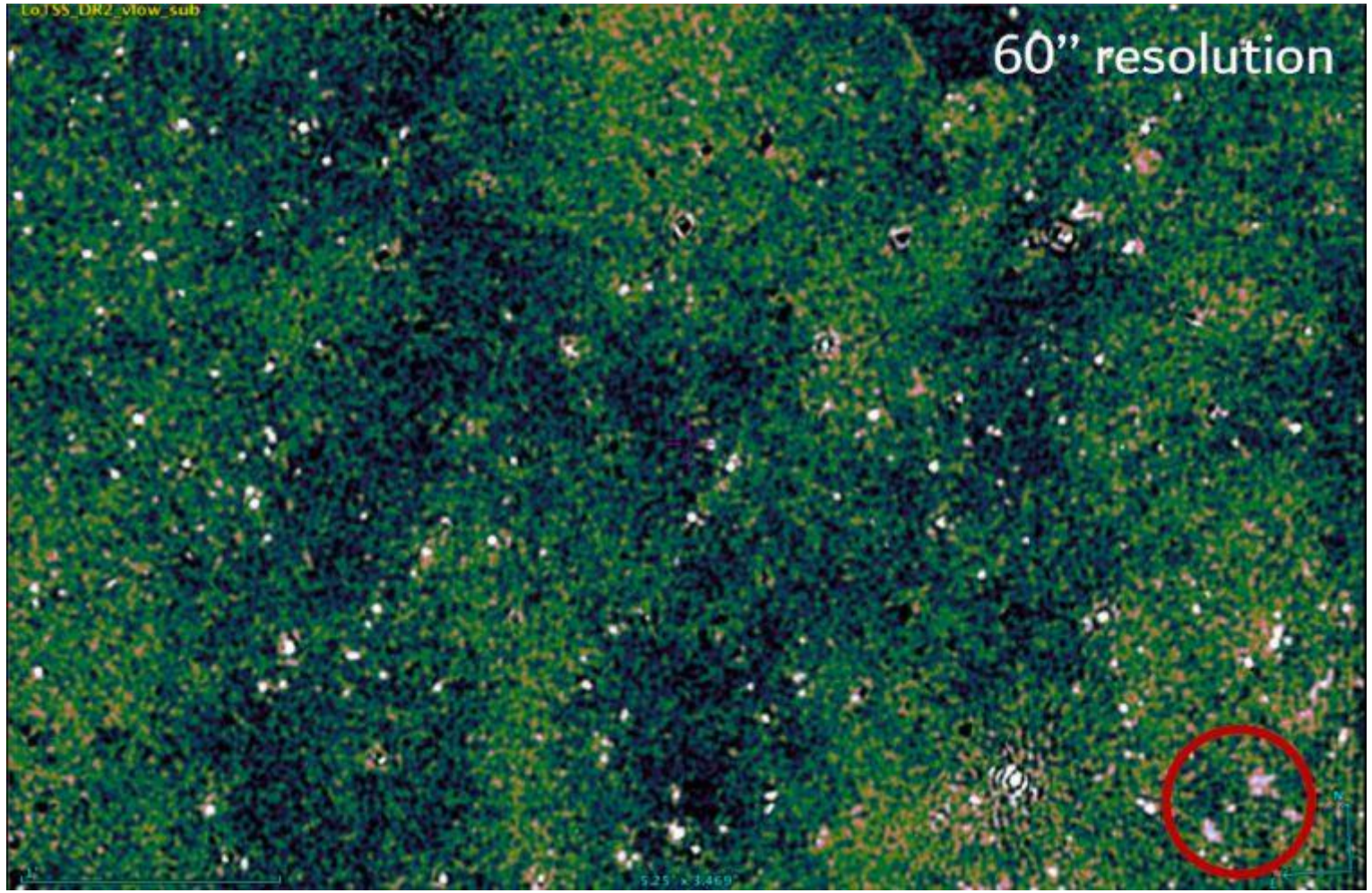
[1] Tritly, recent images reveal emission from the periphery of isolated galaxy clusters (Cuciti et al., 2021; Botteon et al., 2022), where connections to filaments are likely.

right ascension (°)

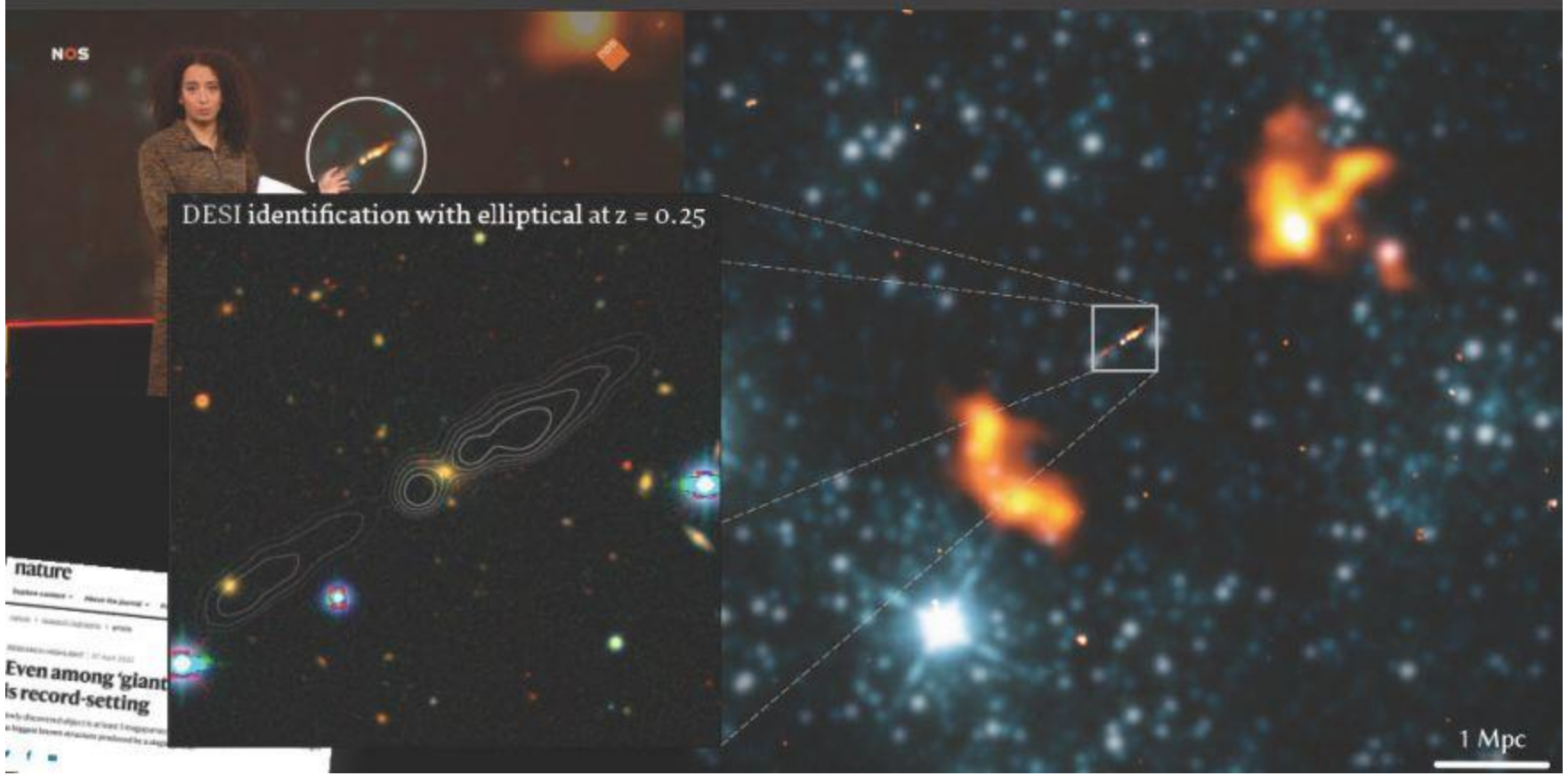
Figure 1: By stacking images of several overlapping LoTSS pointings, we obtain 6″ (*top*) and 20″ (*bottom*) images at 144 MHz featuring a thin, 24′ long, arc-shaped and sharp-edged source of astrophysical origin. The 6″ noise level is $\sigma_{6''} = 68$ μJy beam^{-1}.

below, **we believe that this source could be the first example of a shock wave running through the filament IGM.** We show LoTSS DR2 images at 6″ and 20″ of this intergalactic shock candidate in Fig. 1.

If uGMRT observations would confirm this candidate to be an intergalactic shock, there are immediate implications for the broader search for synchrotron radiation from filaments. Oei et al. (2022b) have recently produced probabilistic sky predictions to guide this search, considering only the radiation contribution from merger and accretion shocks arising from large-scale structure formation (Ensslin et al., 1998; Miniati et al., 2000; Ryu et al., 2003; Hoeft &


LoTSS_DR2_vlow_sub
60'' resolution

Giants: the largest known radio galaxies



Cornell University

arXiv > astro-ph > arXiv:2202.05427

Astrophysics > Astrophysics of Galaxies

[Submitted on 11 Feb 2022]

The discovery of a radio galaxy of at least 5 Mpc

Martijn S.S.L. Oei, Reinout J. van Weeren, Martin J. Hardcastle, Andrea Botteon, Tim W. Shimwell, Pratik Dabhade, Alvin R.D.J.G.I.B. Röttgering, Marcus Brüggen, Cyril Tasse, Wendy L. Williams, Aleksandar Shulevski

We discover what is in projection the largest known structure of galactic origin: a giant radio galaxy with a projected proper length of 4.99 ± 0.04 Mp named Alcyoneus, was first identified in low-resolution LOFAR Two-metre Sky Survey images from which angularly compact sources had been remov example in its class, Alcyoneus could shed light on the main mechanisms that drive radio galaxy growth. We find that – beyond geometry – Alcyoneu appear suspiciously ordinary: the total low-frequency luminosity density, stellar mass and supermassive black hole mass are all lower than, though si medial giant radio galaxy (percentiles 45 ± 3%, 25 ± 9% and 23 ± 11%, respectively). The source resides in a filament of the Cosmic Web, with whic significant thermodynamic interaction. At 5 · 10^{-15} Pa, the pressures in the lobes are the lowest hitherto found, and Alcyoneus therefore represents promising radio galaxies yet to probe the warm–hot intergalactic medium.

HP **Pettit, Harry**
Huge galaxy story
To: Martijn Simon Soen Liong Oei

Hi Martin

I hope you are well. I write about science for The Sun newspaper and recently stumbled across your radio galaxy pape

Would you happen to be free for a chat about the research over the phone or Zoom either tomorrow or Wednesday?

Best wishes

--

Harry Pettit
Deputy Technology and Science Editor, The Sun
Serving 170 million monthly unique users

Twitter: @Harry_Pettit
Address: 1 London Bridge Street, SE1 9GF

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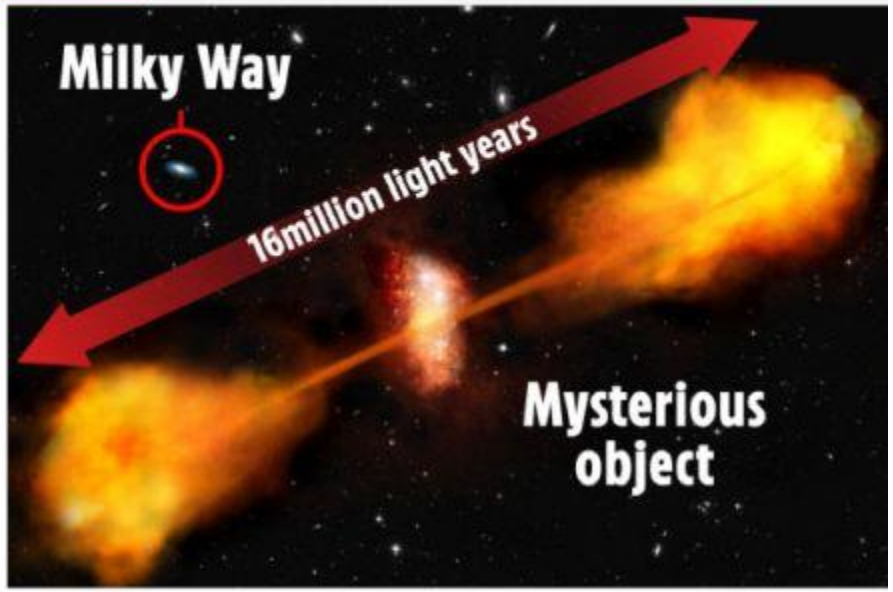

Tech > News Tech

SPACE ODDITY Mysterious object 100x larger than the Milky Way discovered by astronomers in deep space

Harry Pettit, Deputy Technology and Science Editor
17:29, 16 Feb 2022 | Updated: 17:38, 16 Feb 2022

thesun.co.uk

The Sun

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MONSTER CAGED Evil husband who pushed pregnant wife off cliff during selfie is jailed

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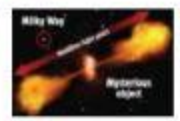
TV



SPACE ODDITY Mysterious object 100x larger than the Milky Way discovered by astronomers

News Tech

DEBT FREE I cleared £4k of debt with an easy 'salary bucketing' method - here's how

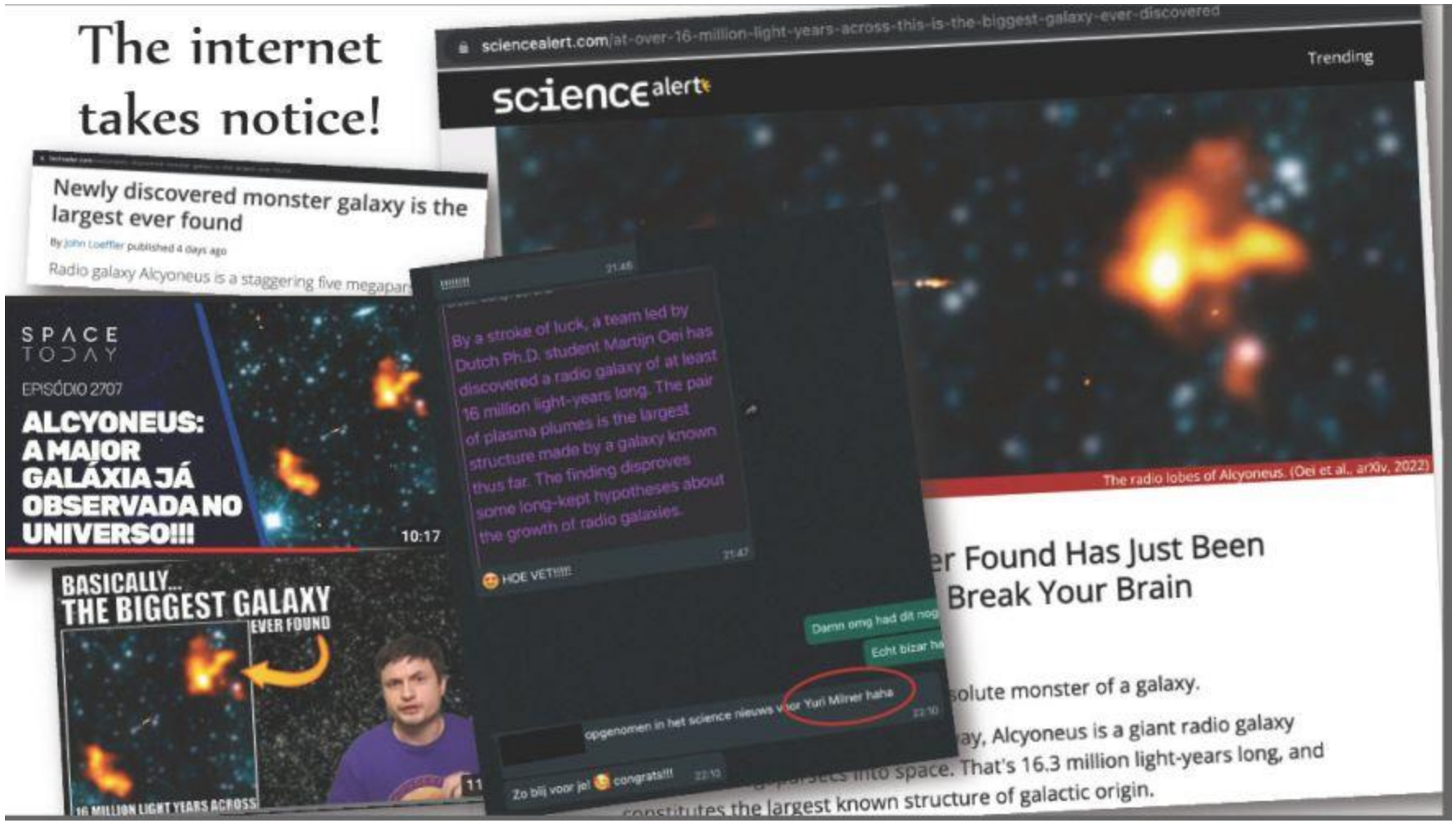
Tips

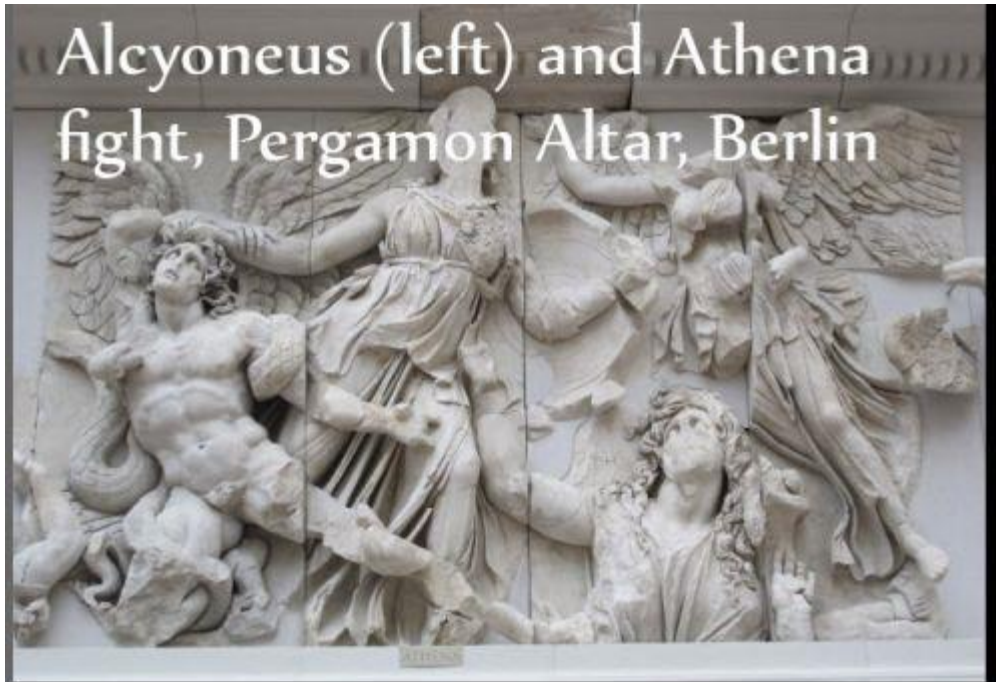
'JUST A LAUGH' Storage Hunters star Boudicca Scherazade unrecognisable in lingerie snaps

Celebrity

THE MANE TOPIC Katie Price fans saying the same thing as she posts birthday message to

The internet takes notice!





Um tostão de voz
@ContaQuase

Existe galáxia com o nome mais perfeito que Alcyoneus?

Translate Tweet

5:39 PM · Feb 16, 2022 · Twitter Web App

← **Tweet**

Tom Kerss FRAS
@tomkerss

This is mind-blowing. Seriously. Well done to those astronomers who chose the name Alcyoneus!

sciandnature.com
The Biggest Galaxy Ever Found Has Just Been Discovered, And It Will Break Yo...
The Biggest Galaxy Ever Found Has Just Been Discovered, And It Will Break Your Brain

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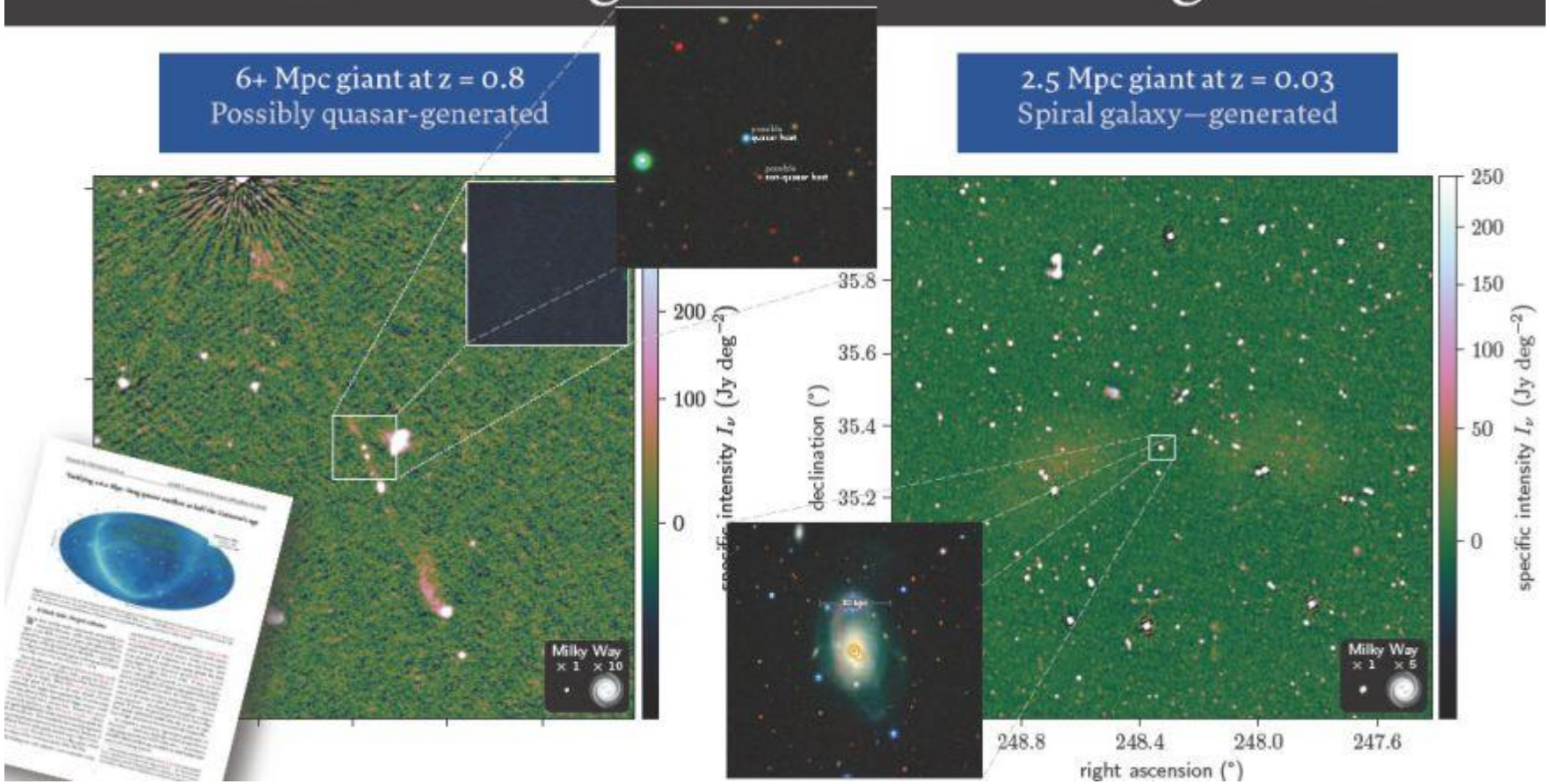
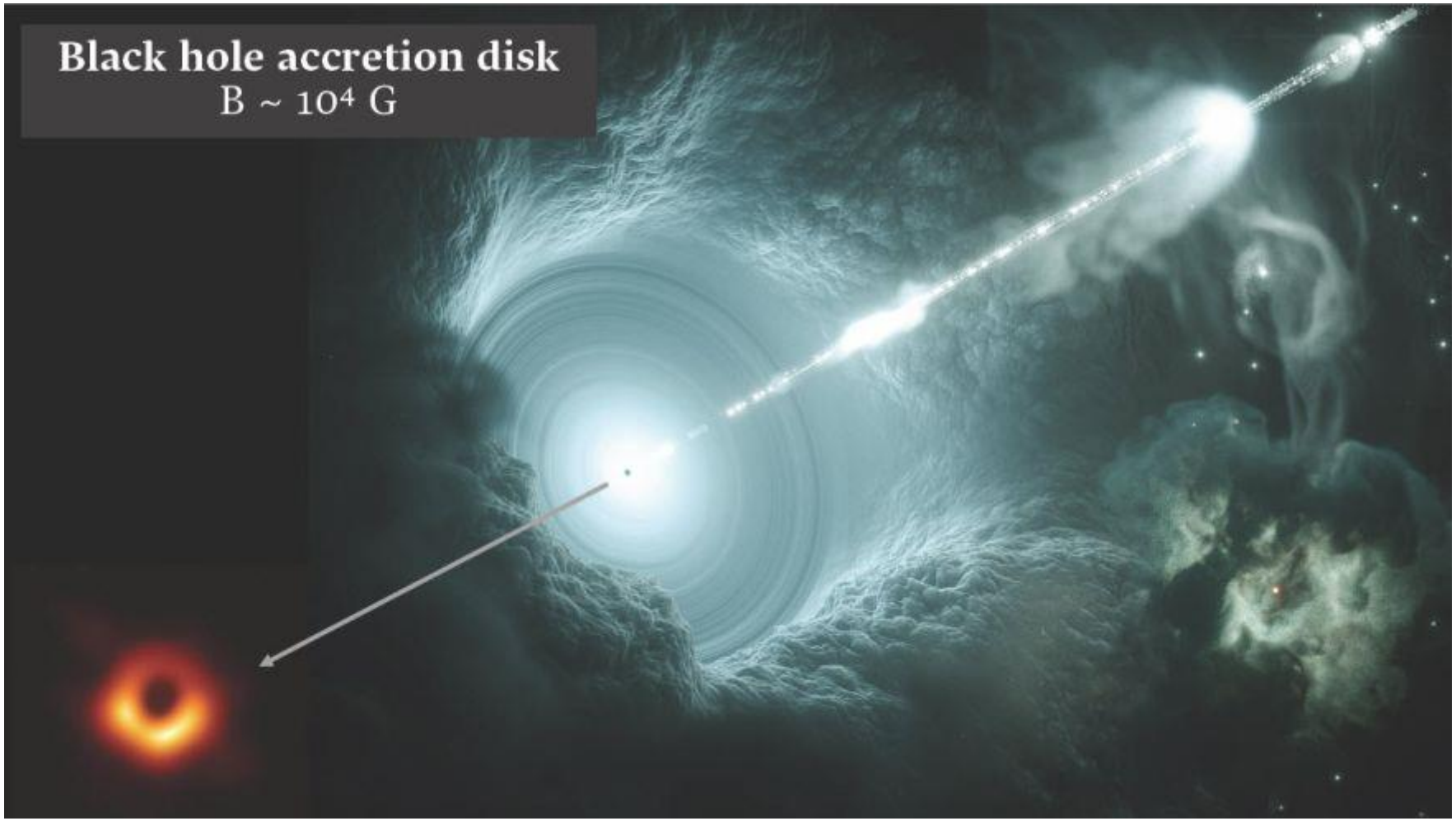
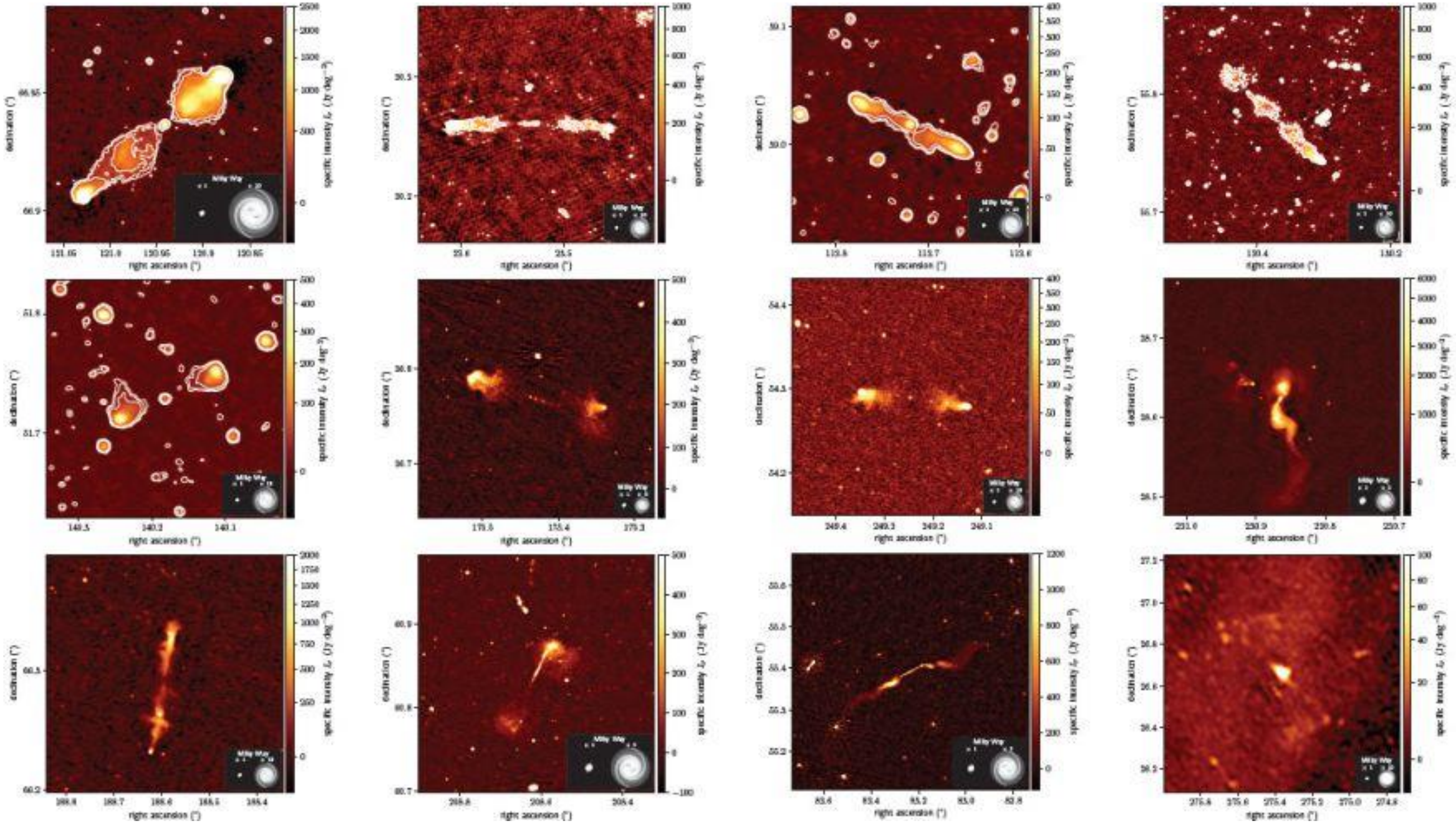
1 Retweet **6** Likes

Giants: the largest known radio galaxies

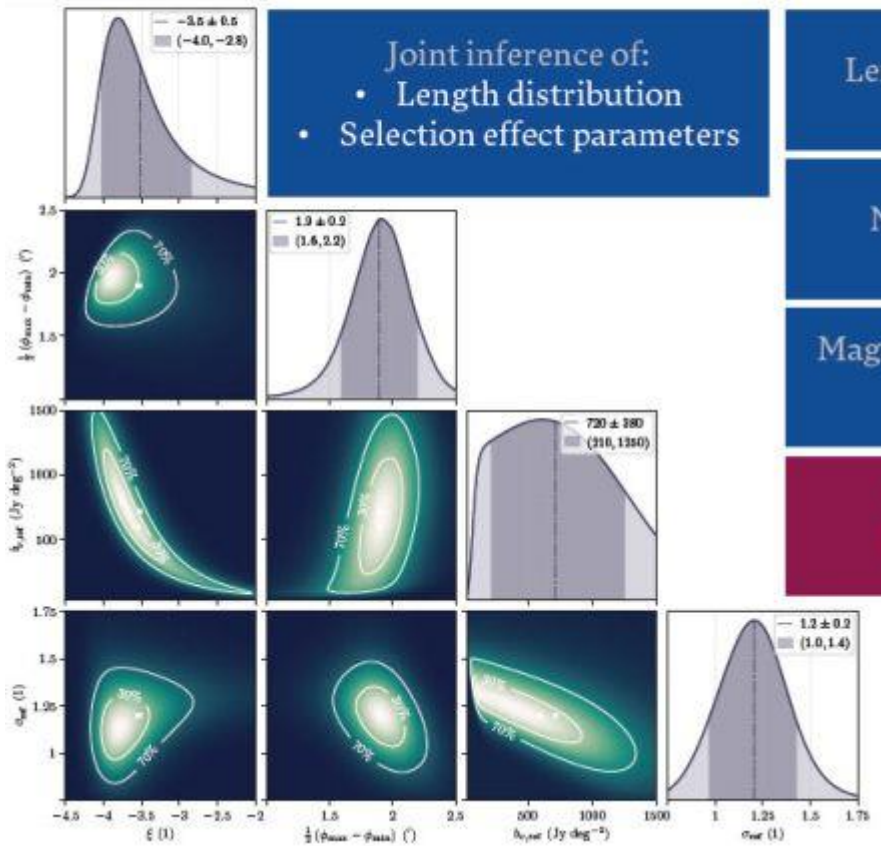



Black hole accretion disk
B ~ 10⁴ G

Astrophysical magnetogenesis by giants


declination (°)
right ascension (°)
specific intensity I_ν (Jy deg^{-2})
Milky Way

Astrophysical magnetogenesis by giants



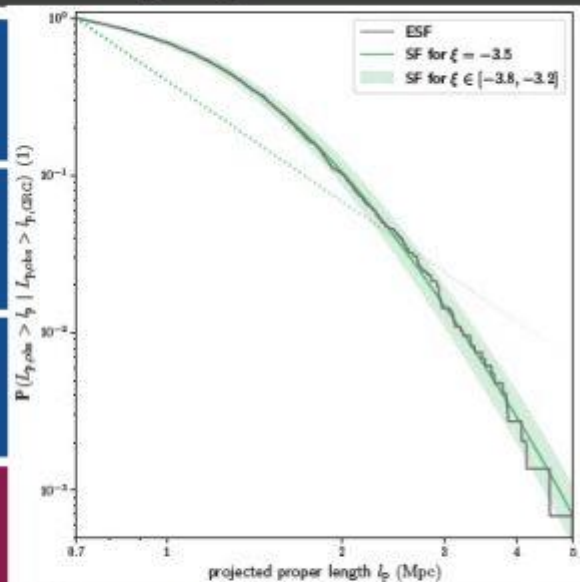
Joint inference of:
- Length distribution
- Selection effect parameters

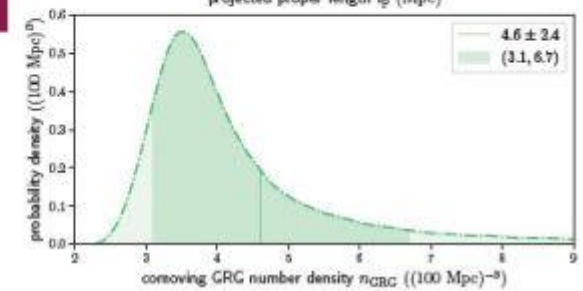
Length distribution

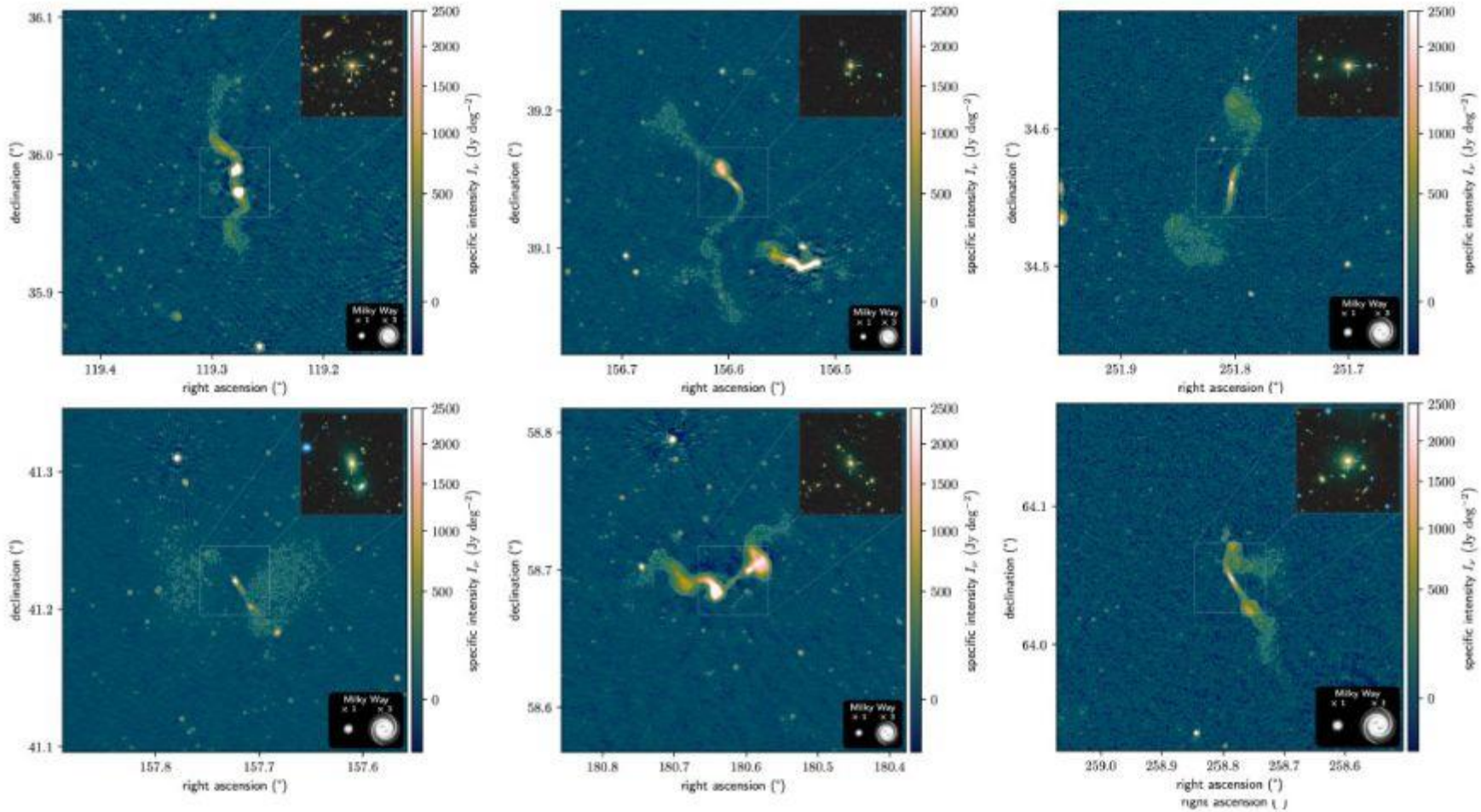
Number density

Magnetic field strength distribution

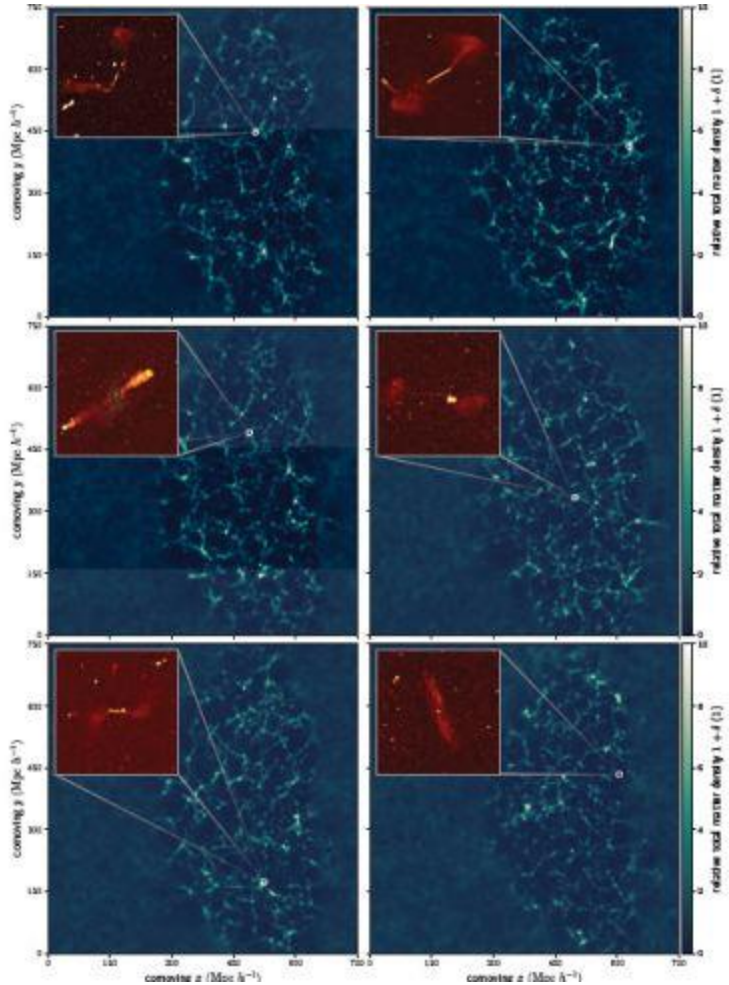
Cosmic Web environments






declination (°)
right ascension (°)
specific intensity I_ν (Jy deg^{-2})
Milky Way

Does the **Cosmic Web environment** of a radio galaxy determine if it becomes a giant?



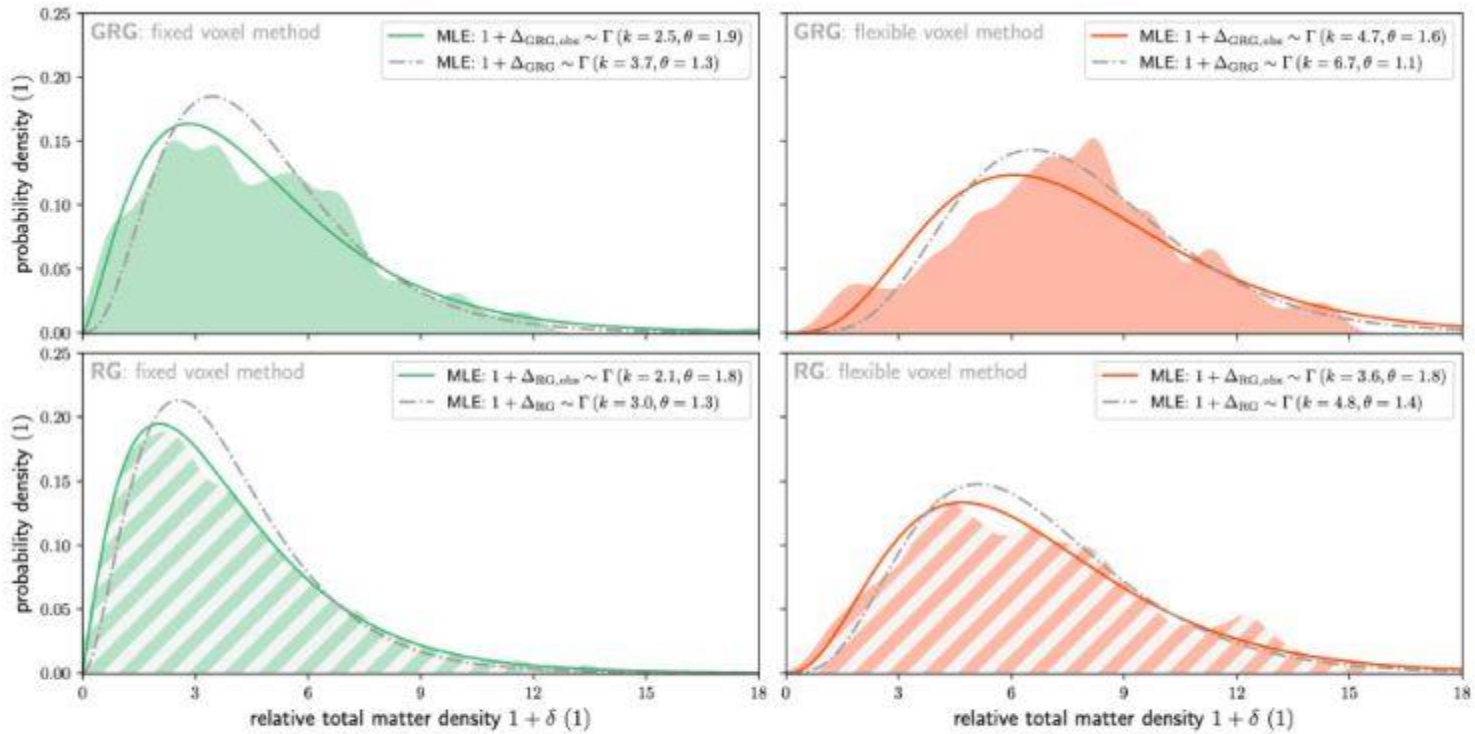


Figure 6. Probability density functions (PDFs) of the relative total matter density RV of 260 Local Universe giants (top row), and of 1443 Local Universe RGs (bottom row), determined through the fixed voxel method (left column) and flexible voxel method (right column). These RVs correspond to the density field smoothed to a scale of 2.9 Mpc h^{-1}. We also show PDFs (solid lines) of gamma-distributed RVs with parameters obtained via maximum likelihood estimation (MLE), alongside PDFs (dash-dotted lines) of gamma-distributed RVs with parameters obtained via MLE with a heteroskedasticity correction. We warn that these distributions are affected by surface brightness selection, and thus represent observed populations only.

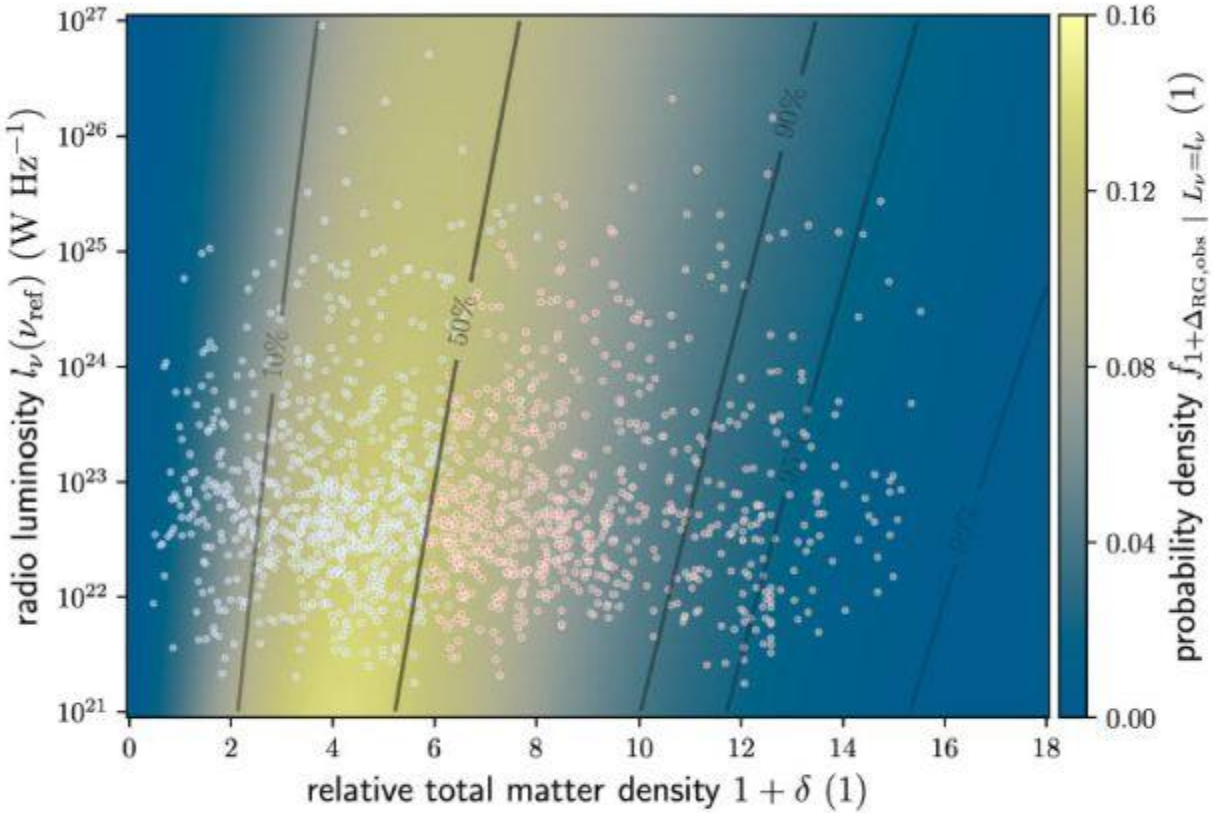


Figure 8. PDFs of the observed RG relative total matter density RV given a radio luminosity at $\nu_{\rm ref}$ = 150 MHz, using MLE parameter values for the model described in Sect. 4.2. The black contours denote CDF values. We overplot all 1443 selected LoTSS DR1 RGs (dots), with those above the empirical median density coloured red, and those below coloured blue. We use flexible voxel method densities here. For fixed voxel method densities, see Fig. F1.

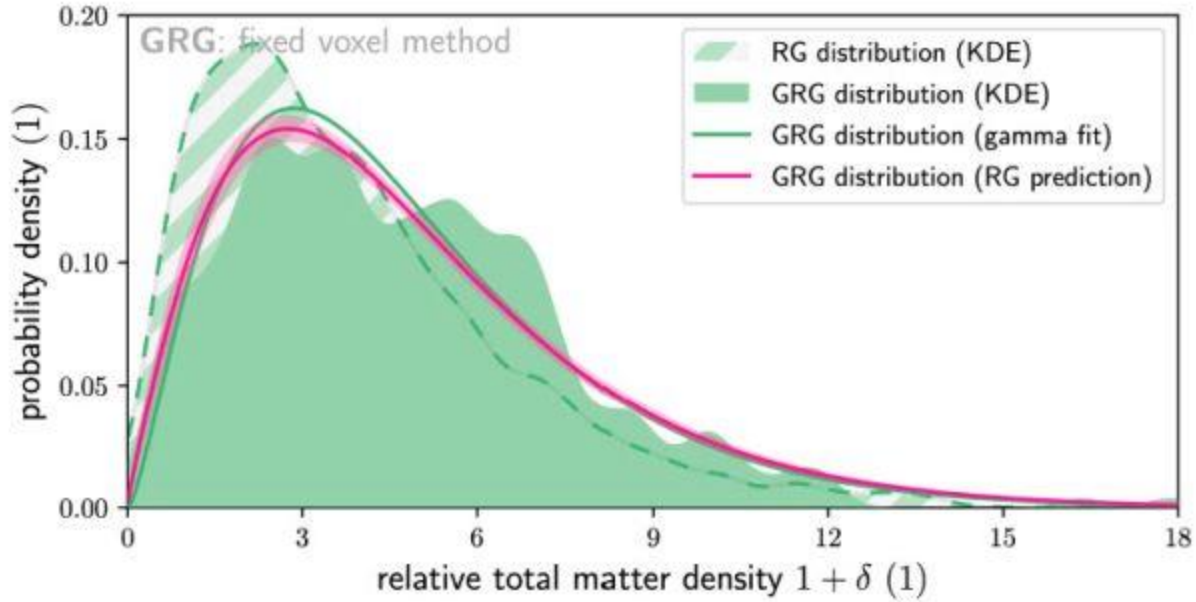


Figure 11. Density distribution predicted for observed giants combining Sect. 4.2's RG radio luminosity–Cosmic Web density relation and a radio luminosity cut-off $l_{\nu,\mathrm{min}} = 10^{25}$ W Hz^{-1} (pink); in addition, we show the KDE density distributions for giants with gamma distribution MLE fit (solid green) and for general RGs (hatched green) — all as in the left column of Fig. 6.

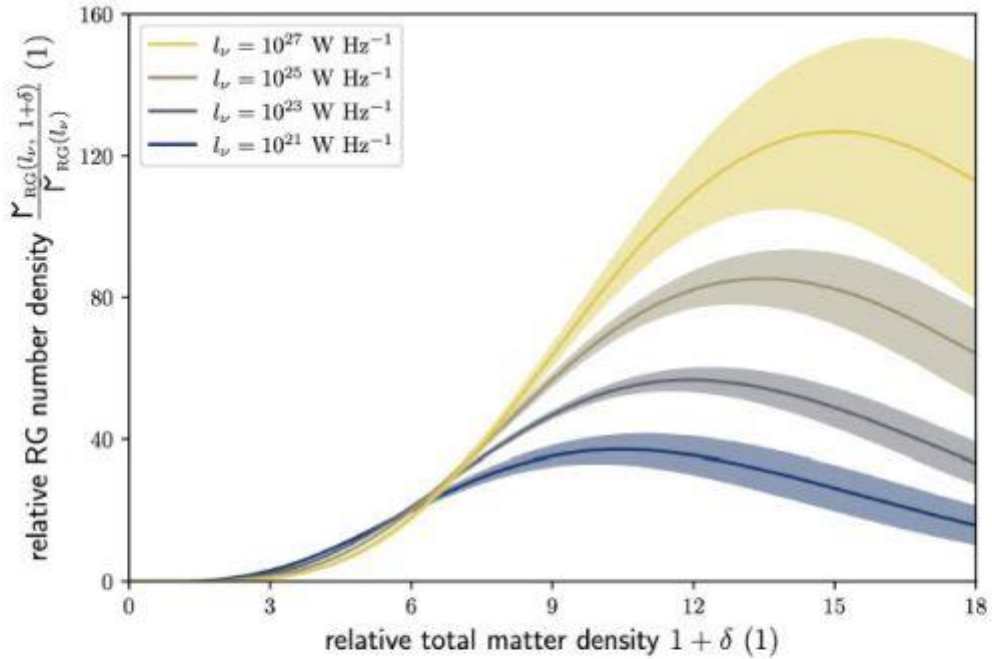


Figure 12. Number densities of RGs with a given radio luminosity l_ν, as a function of Cosmic Web density at the 2.9 Mpc h^{-1} scale. The number density functions reflect conditions in the Local Universe, and are given relative to the cosmic mean number density at l_ν. The solid curves reflect the posterior mean, whilst the shaded areas around the mean denote -1 to $+1$ posterior standard deviation ranges. We use flexible voxel method densities here.

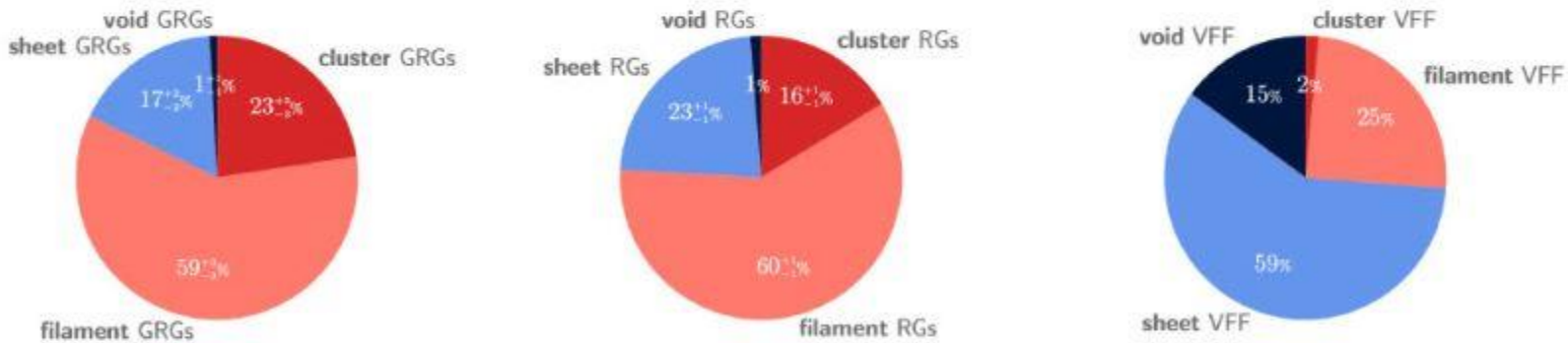
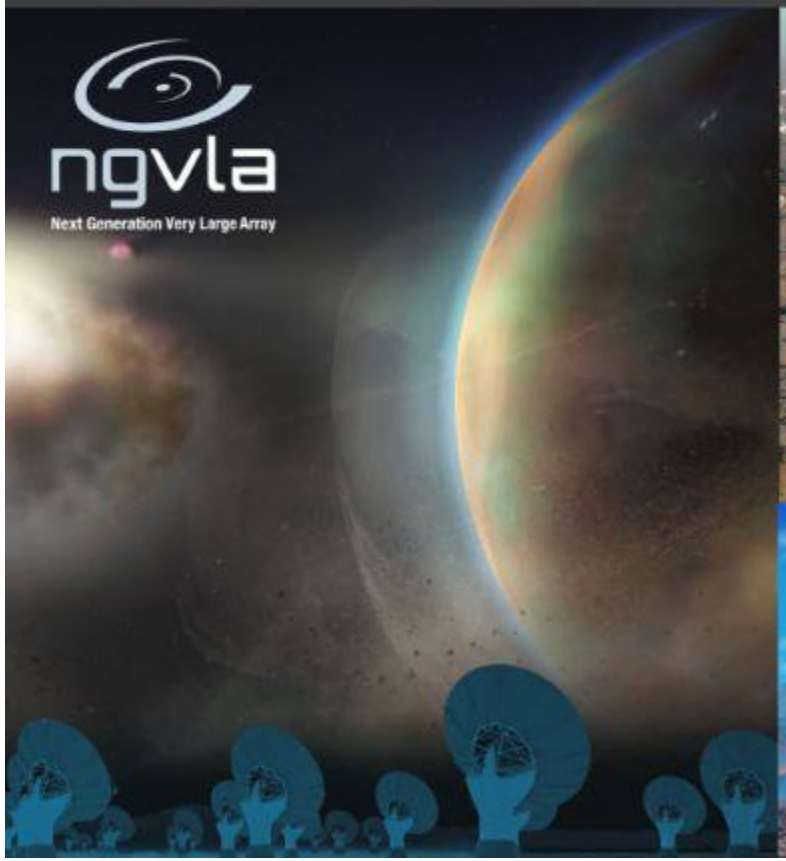
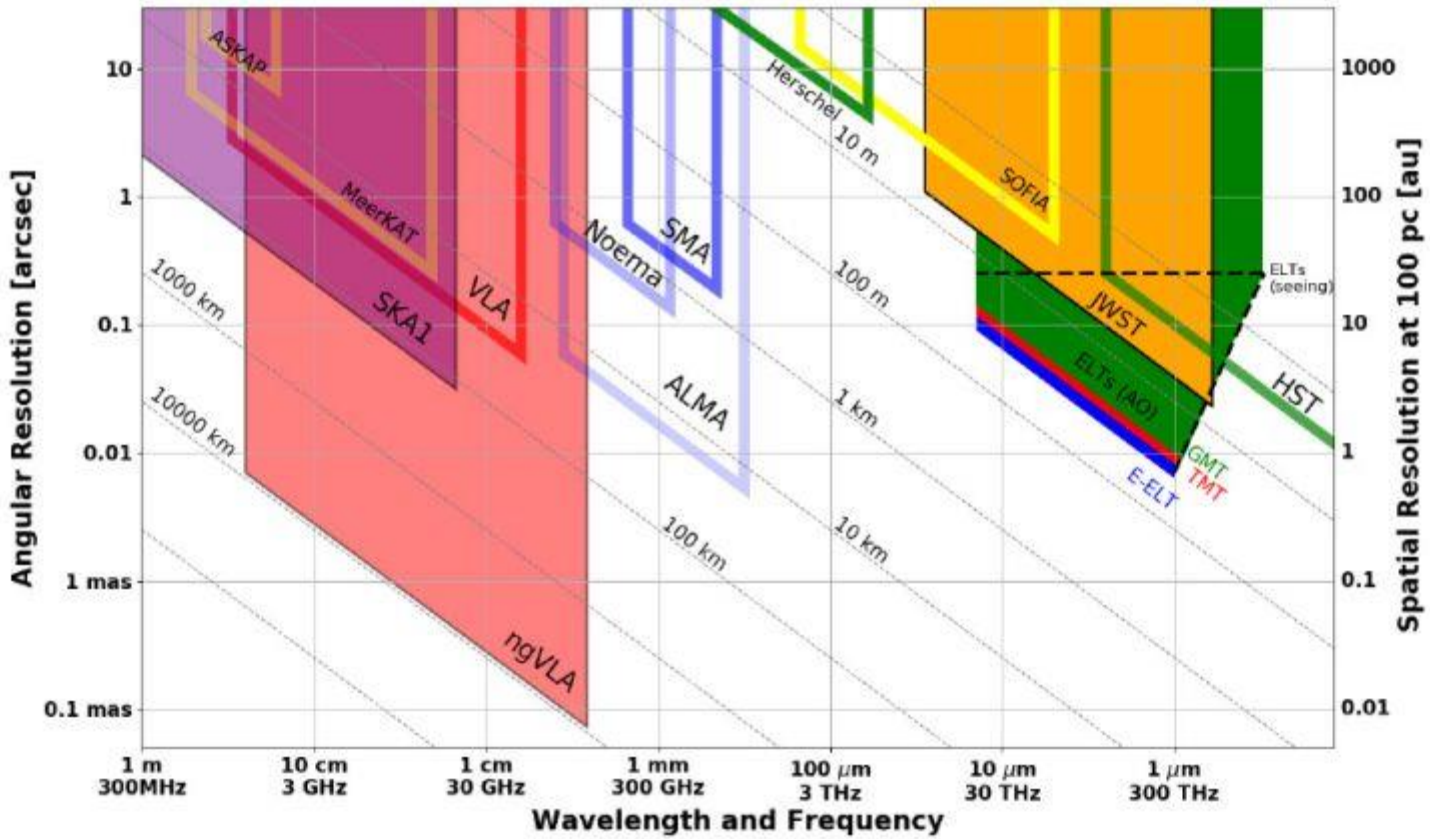


Figure 15. Dynamical environment classification of giant radio galaxies (left), radio galaxies in general (centre), and the Local Universe in its entirety (right; from Table 3 of Leclercq et al. 2015). We define clusters, filaments, sheets, and voids in the T-web sense. These distributions depend on the scale to which the Cosmic Web density field is smoothed; in this case, the smoothing scale is 2.9 Mpc h^{-1}. If giants and RGs were scattered uniformly throughout the Cosmic Web, their distributions would be similar to that of the volume-filling fractions (VFFs). Instead, observed RGs — and observed giants in particular — favour cluster and filament environments.

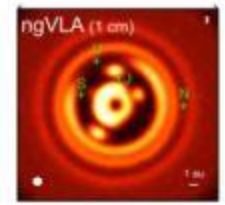
New great radio observatories

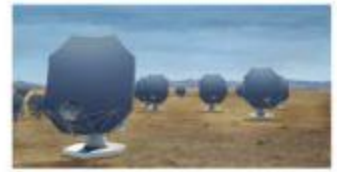


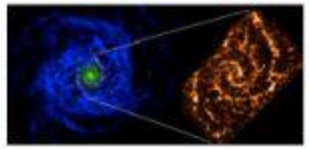
The next-generation Very Large Array



The next-generation Very Large Array







2019 2021 2023 2025 2026 2029 2035

ngVLA Submission to Astro2020

Astro2020 Recommendation Published

Submit ngVLA Proposal to NSF/MREFC

Prototype Delivered to VLA Site

Complete NSF/MREFC FDR

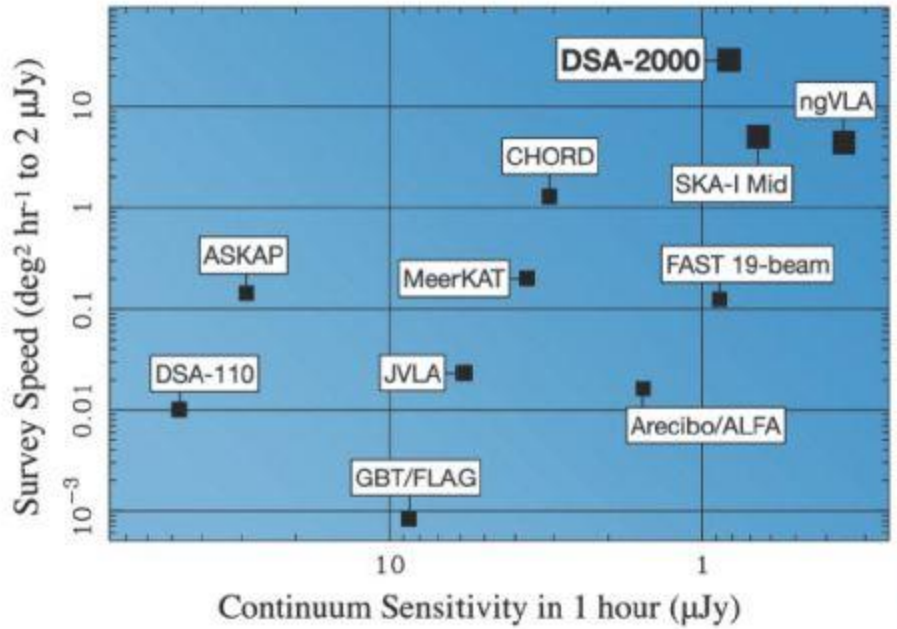
ngVLA Construction →

Initiate ngVLA Early Science (> VLA capabilities)

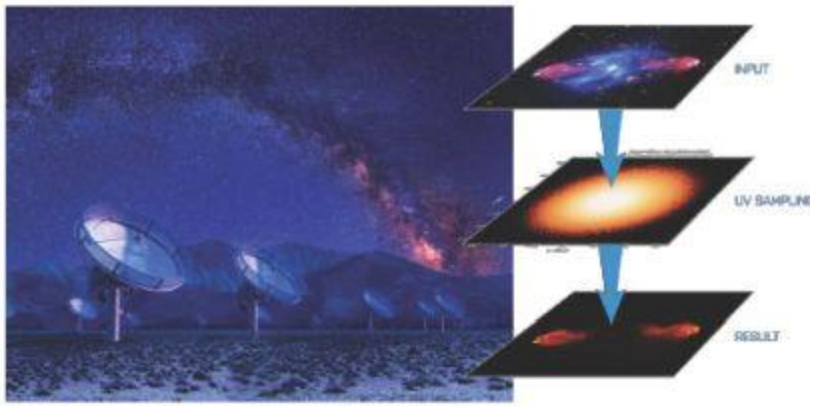
Achieve Full Science Operations

The radio Vera Rubin Observatory

Unparalleled Survey Speed



Survey speed and sensitivity of the DSA-2000 and other current [small squares] and planned [large squares] radio telescopes that operate at 1.4 GHz.

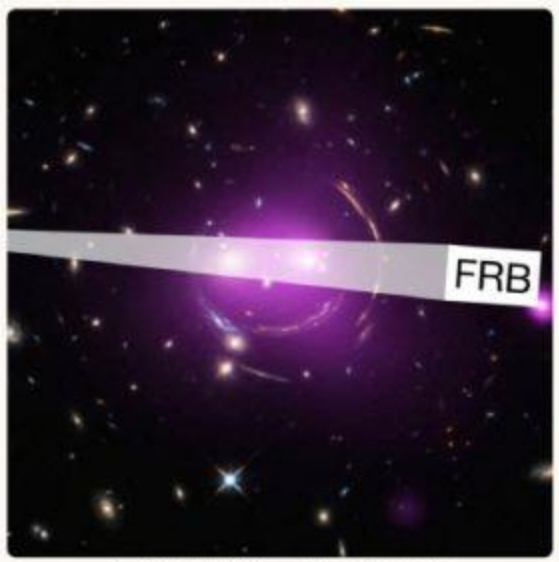


The radio Vera Rubin Observatory

The DSA-2000 will detect and pinpoint the locations of > 10,000 FRBs per year!

10^3 - 10^4 FRBs

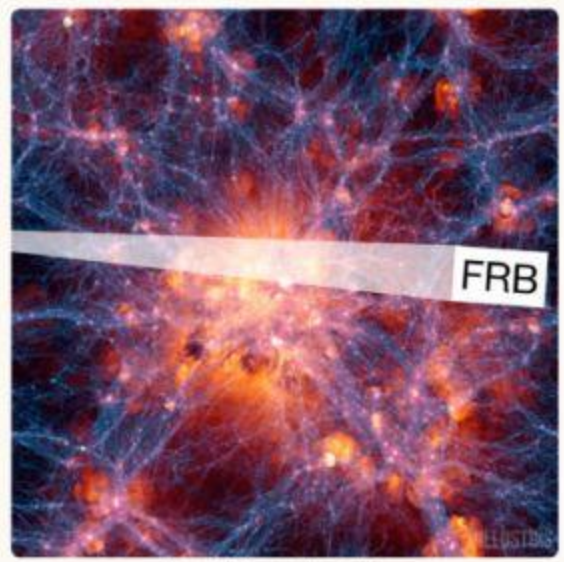
Detection of CGM/IGrM/ICM — CGM cooling — compact-object dark matter



X-ray: NASA/CXC/UA/J.Irwin et al; Optical: NASA/STScI

10^4 - 10^5 FRBs

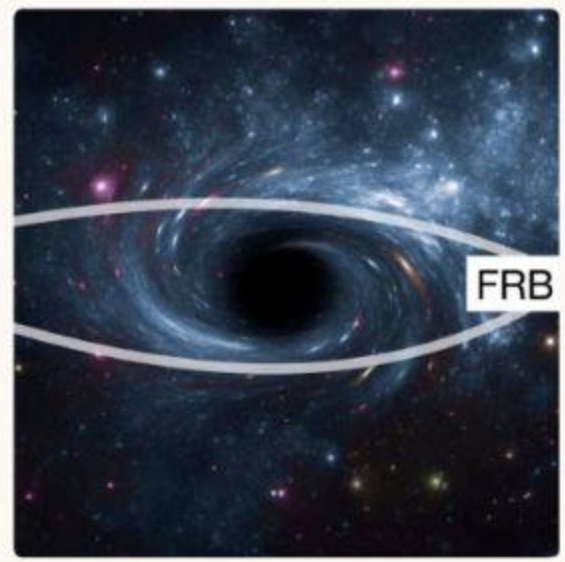
Cosmic web density — Helium reionization — DM-space clustering

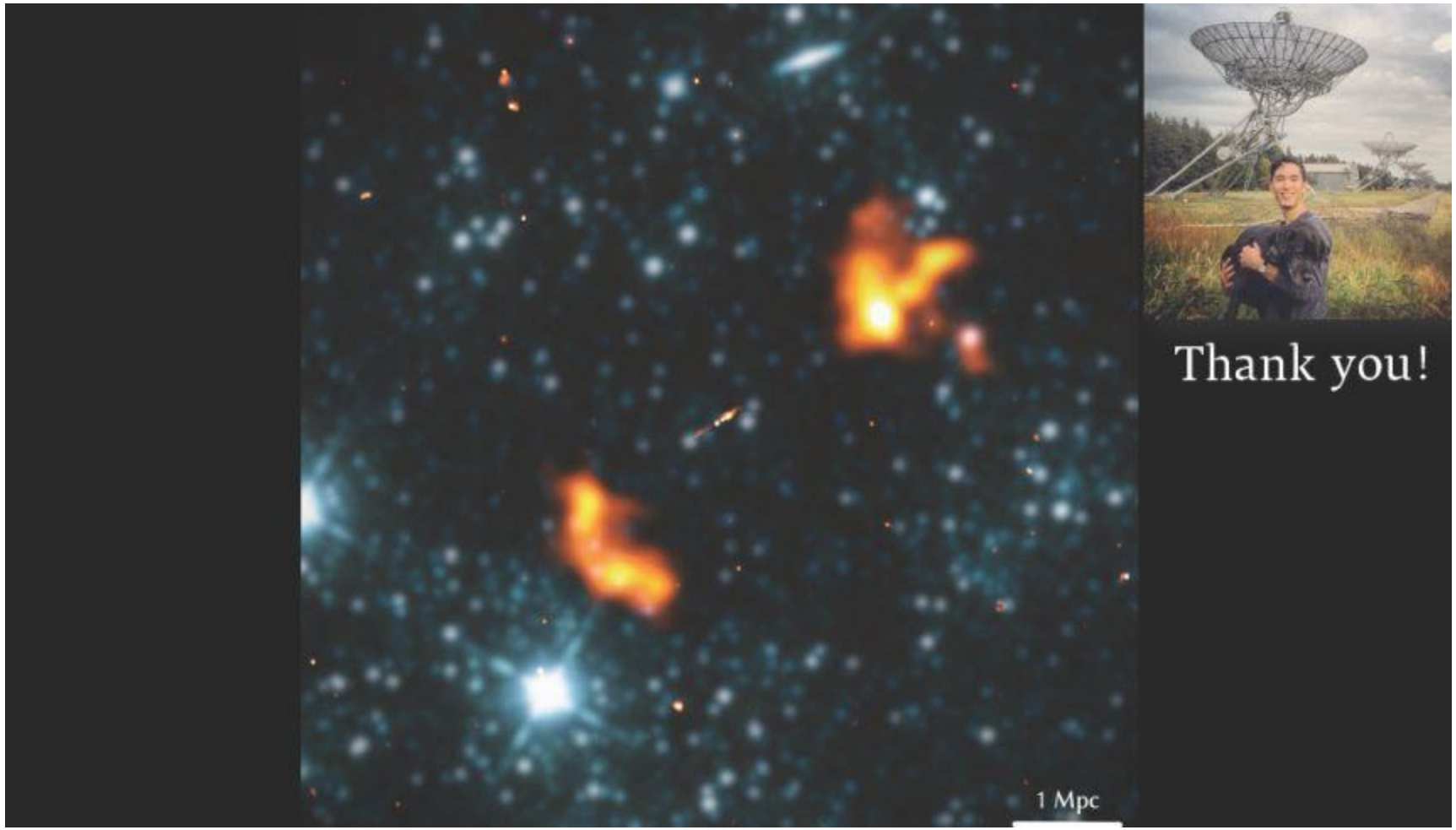


Illustris Collaboration / Illustris Simulation

10^5 - 10^6 FRBs

kSZ synergy — extragalactic micro- and nano-lenses





Thank you!