

Constraining Cosmic Filament Magnetism using LOFAR

LOFAR Annual Meeting

June 2026

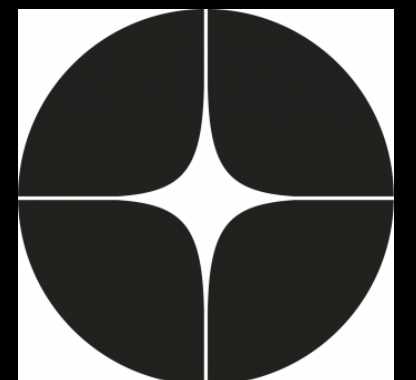


Mousumi Mahato
PhD Student

Tartu Observatory, University of Tartu, Estonia

Supervisors:

Prof Elmo Tempel, Dr Pratik Dabhade & Dr Shishir Sankhayayn

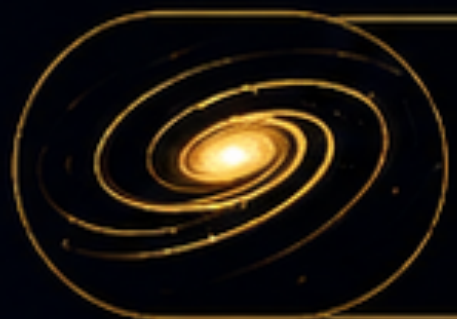


Cosmic Web Filaments

What they are and their typical properties



Filaments are faint, extended bridges that trace large-scale structure and host diffuse warm-hot baryons.



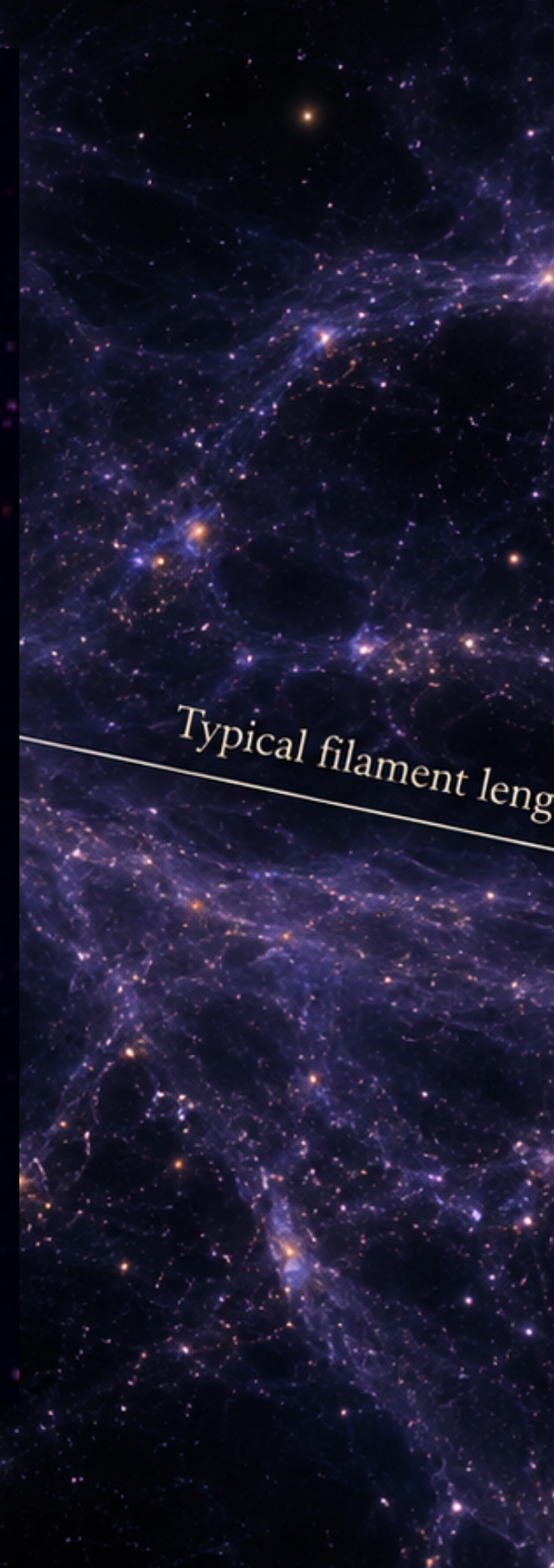
Cosmic Web Filaments

What they are and their typical properties



1. What are they?

- Diffuse bridges linking clusters, groups, and galaxies
- Major components of the large-scale structure
- Structural backbone of the cosmic web



2. Typical properties



Lengths: $\sim 5\text{--}50$ Mpc
(sometimes longer)



Widths: $\sim 1\text{--}5$ Mpc



Overdensities: $\sim 5\text{--}50 \times$
the cosmic mean



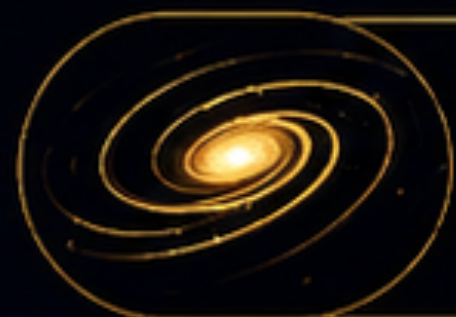
Physical state: warm-hot
intergalactic medium (WHIM)



Typical electron density:
 $n_e \sim 10^{-6}$ to 10^{-5} cm^{-3}



Gas temperature: $\sim 10^5\text{--}10^7$ K



Filaments are faint, extended bridges that trace large-scale structure and host diffuse warm-hot baryons.



Why Study Cosmic Web Filaments?

Why they matter and why they are difficult to observe



1. Why important?



Connect clusters, groups, and galaxies across megaparsec scales



Channel matter and gas toward dense cosmic nodes



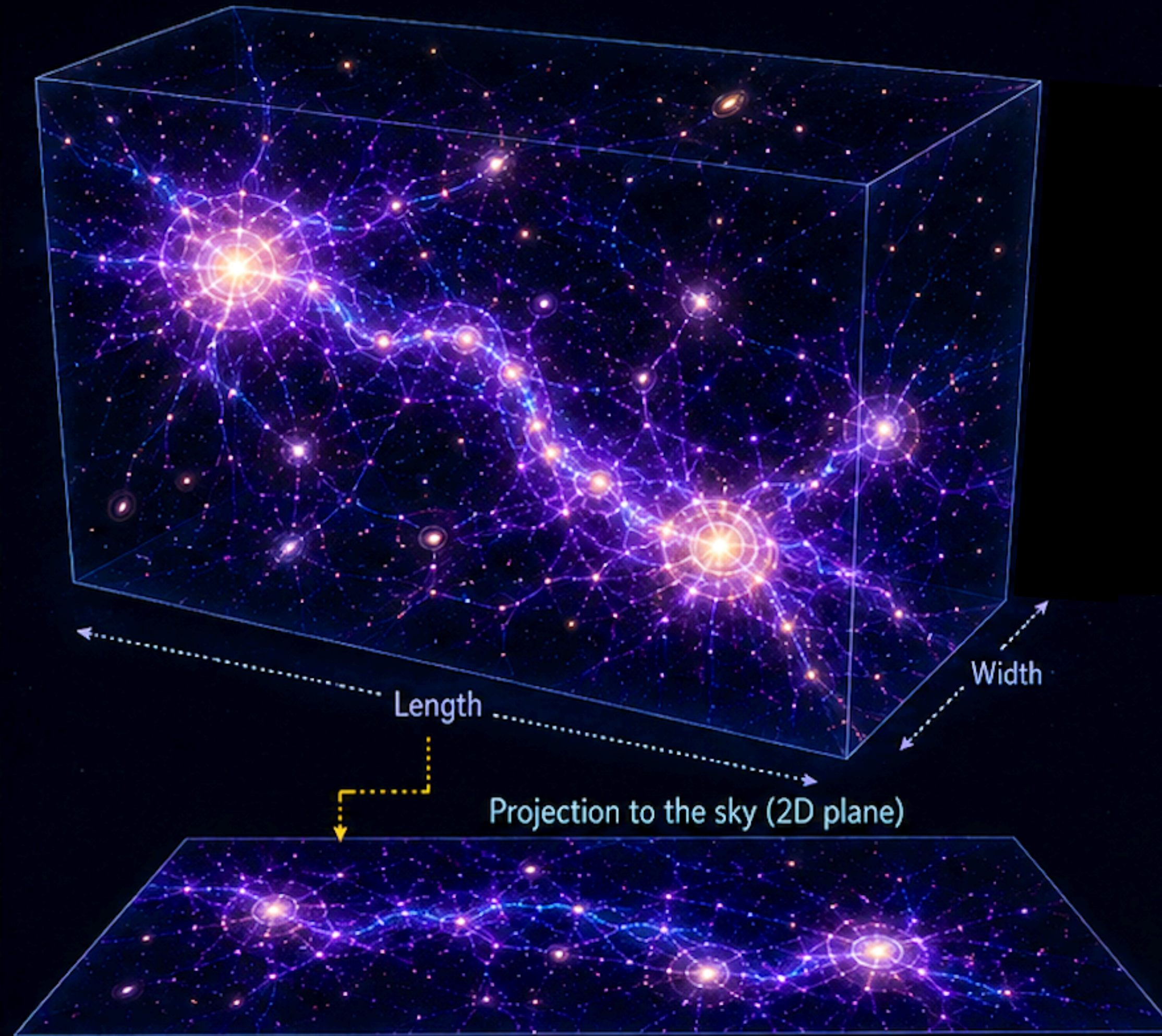
Likely host a significant fraction of the low-redshift missing baryons



Influence galaxy evolution and environmental pre-processing before cluster infall



Trace matter flows and large-scale environmental effects



2. Why challenging to study?



Extremely faint, diffuse, and low surface brightness



Boundaries are fuzzy and not sharply defined



Filaments are extended 3D structures, not simple 2D lines



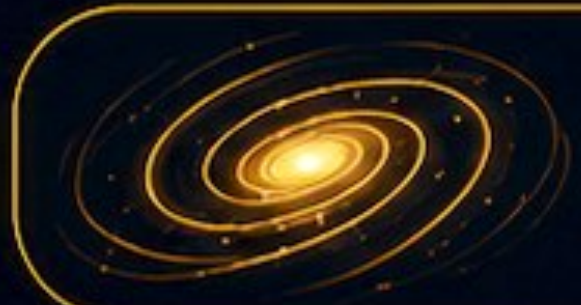
Projection effects and redshift-space distortions complicate interpretation



Redshift information is needed to place structures in 3D



Catalogue properties depend on galaxy sampling, survey geometry, redshift accuracy, and filament-finding method



To understand filaments, we must combine large-scale structure, baryon physics, and careful 3D interpretation.



Importance of Radio Galaxies

Extended radio AGN as environmental probes of cosmic-web filaments

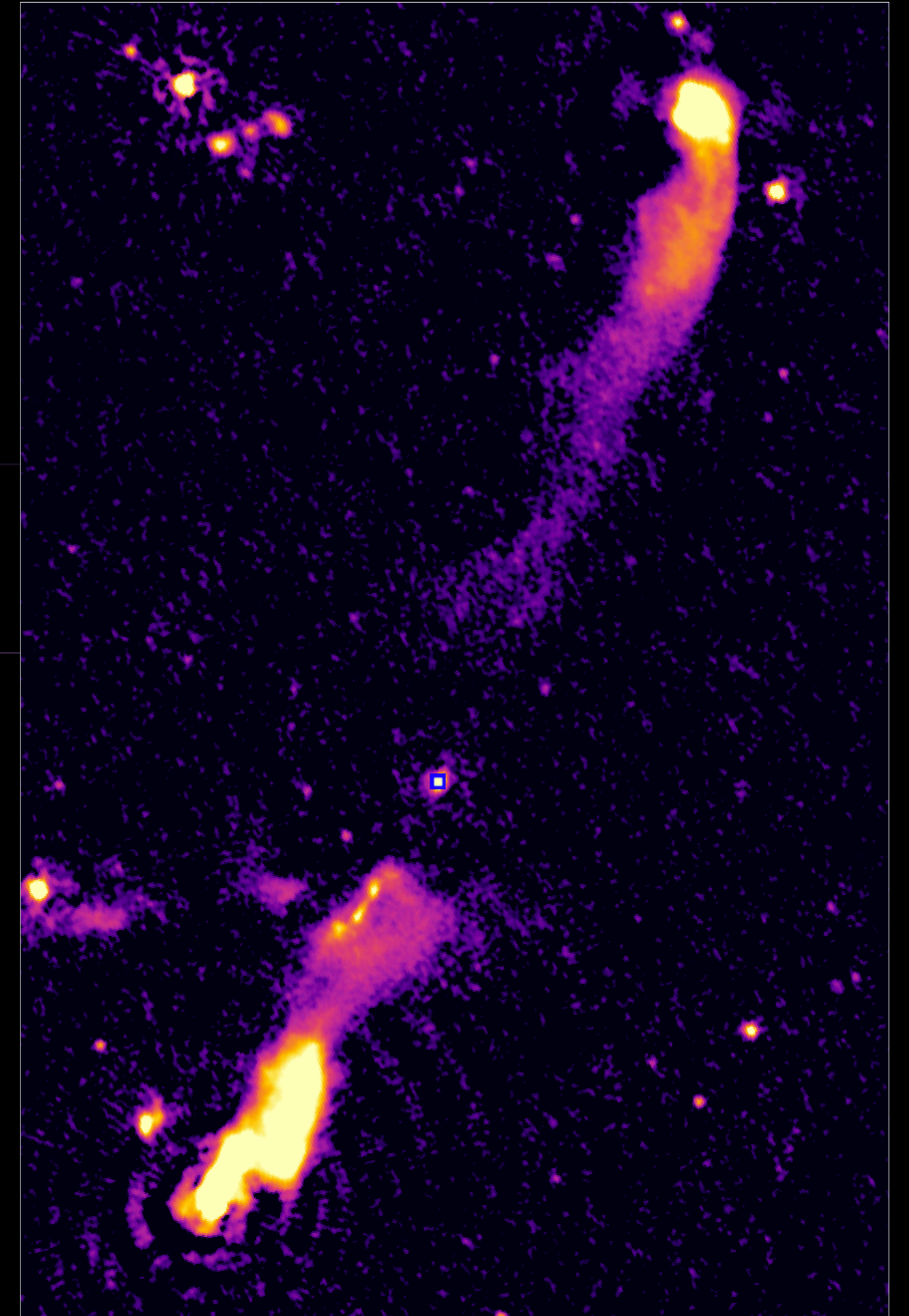
Key idea: Radio galaxies make the invisible cosmic web observable; their jets, lobes, morphology and polarisation can record the physical conditions of the surrounding medium.

Why they are useful:

- ❖ Large-scale structures: jets and lobes can extend from galaxy to group / cluster scales, sampling gas beyond the host galaxy.
- ❖ Sensitive to environment: radio plasma is shaped by external density, pressure gradients, ram pressure and accretion flows.
- ❖ Structured-environment signposts: bent or asymmetric sources can indicate dense or dynamically active surroundings.
- ❖ Indirect access to faint gas: useful where filament plasma is too diffuse for direct optical or X-ray detection.

What they can probe:

- ❖ Faraday rotation: traces magnetised ionised plasma along the line of sight.
- ❖ Depolarisation: sensitive to turbulence and small-scale magnetic-field structure.
- ❖ Morphology: jet bending, lobe asymmetry and confinement can reveal external pressure and flows.
- ❖ Orientation / alignment: tests whether radio structures correlate with filament axes or anisotropic environments.



SAGAN-VI: When jets meet filaments

First solve the association problem

Mahato et al. (2026)

Before asking whether radio galaxies probe filament gas, pressure structure, or magnetism, we need to identify which sources are genuinely associated with filaments.

Challenges:

- ❖ A 2D sky overlap with a filament is not enough.
- ❖ Projection can place unrelated foreground/background sources on the same sky region.
- ❖ Large radio structures require source-level morphology checks, not just host positions.

What robust association needs:

- ❖ Sky separation from the filament spine.
- ❖ Redshift consistency between the radio source and filament.
- ❖ Filament 3D geometry: spine location, local orientation, and width criterion.
- ❖ Radio morphology: source extent, lobes, bending, and orientation relative to the filament.

Scientific payoff:

- ❖ A clean sample enables environmental tests.
- ❖ Morphology, size, asymmetry, and polarisation can then be interpreted physically.
- ❖ A reproducible 3D association framework.

SAGAN-VI: When jets meet filaments

A practical template for radio galaxies in filament environments

Mahato et al. (2026)

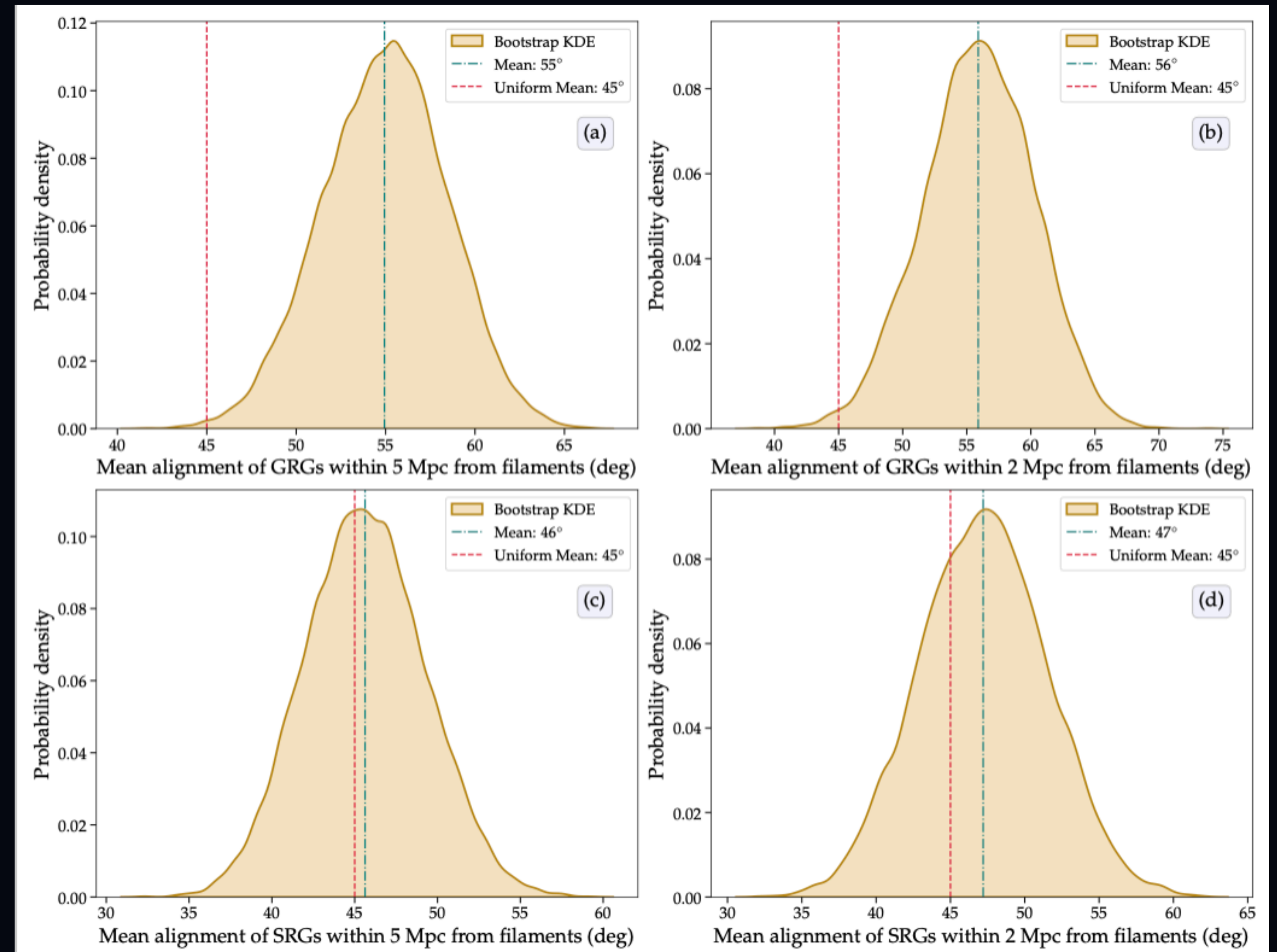
Methodology:

- ❖ Uses a 3D filament catalogue based on the Tempel et al. (2014) Bisous framework.
- ❖ Represents filaments as spines with sampling points and local orientation vectors.
- ❖ Measures 3D comoving distance from each radio-galaxy host to the nearest filament spine.
- ❖ Uses jet–filament alignment angles and lobe arm-length ratios as diagnostics.
- ❖ Compares giant radio galaxies with a smaller radio galaxy control sample.

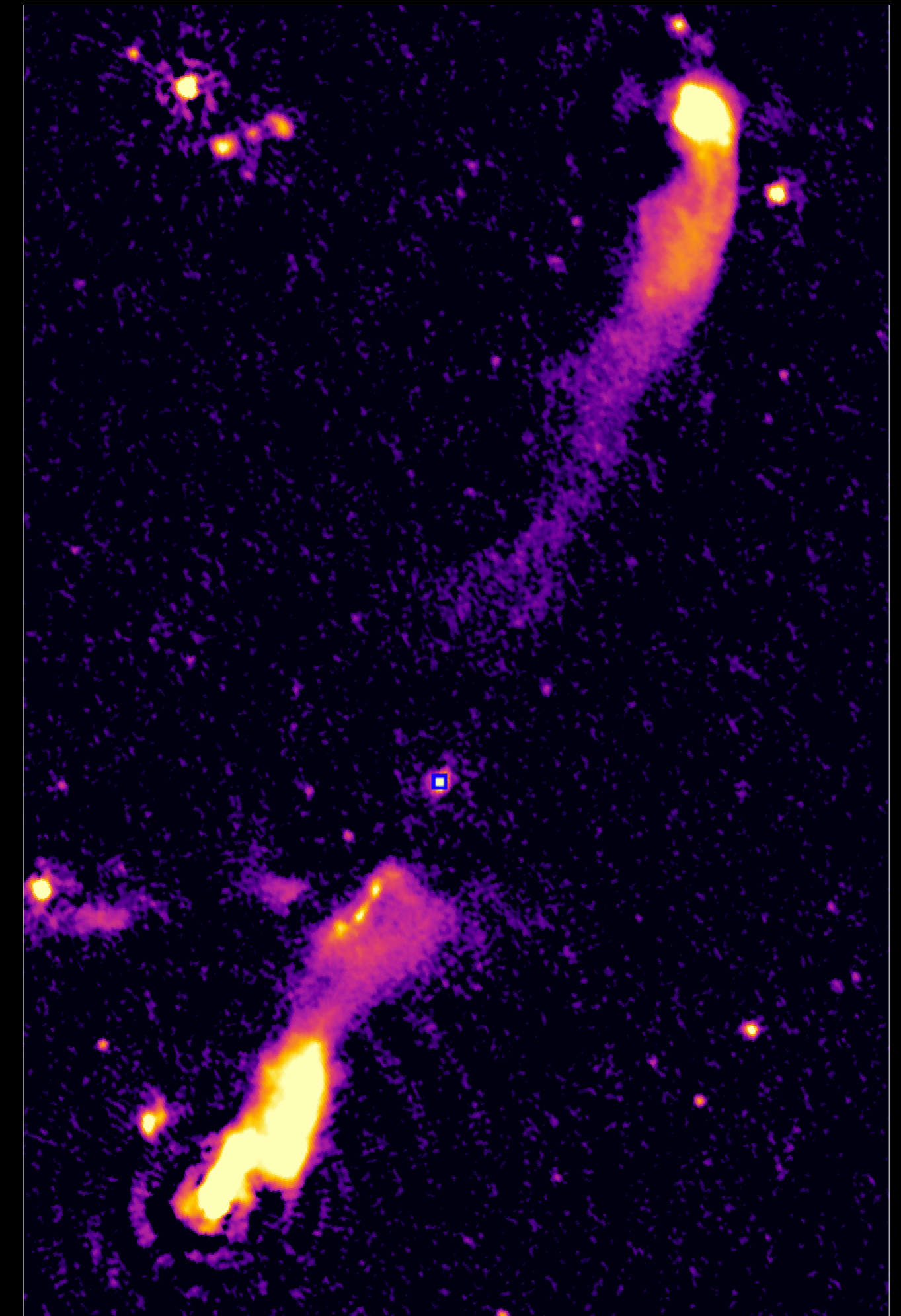
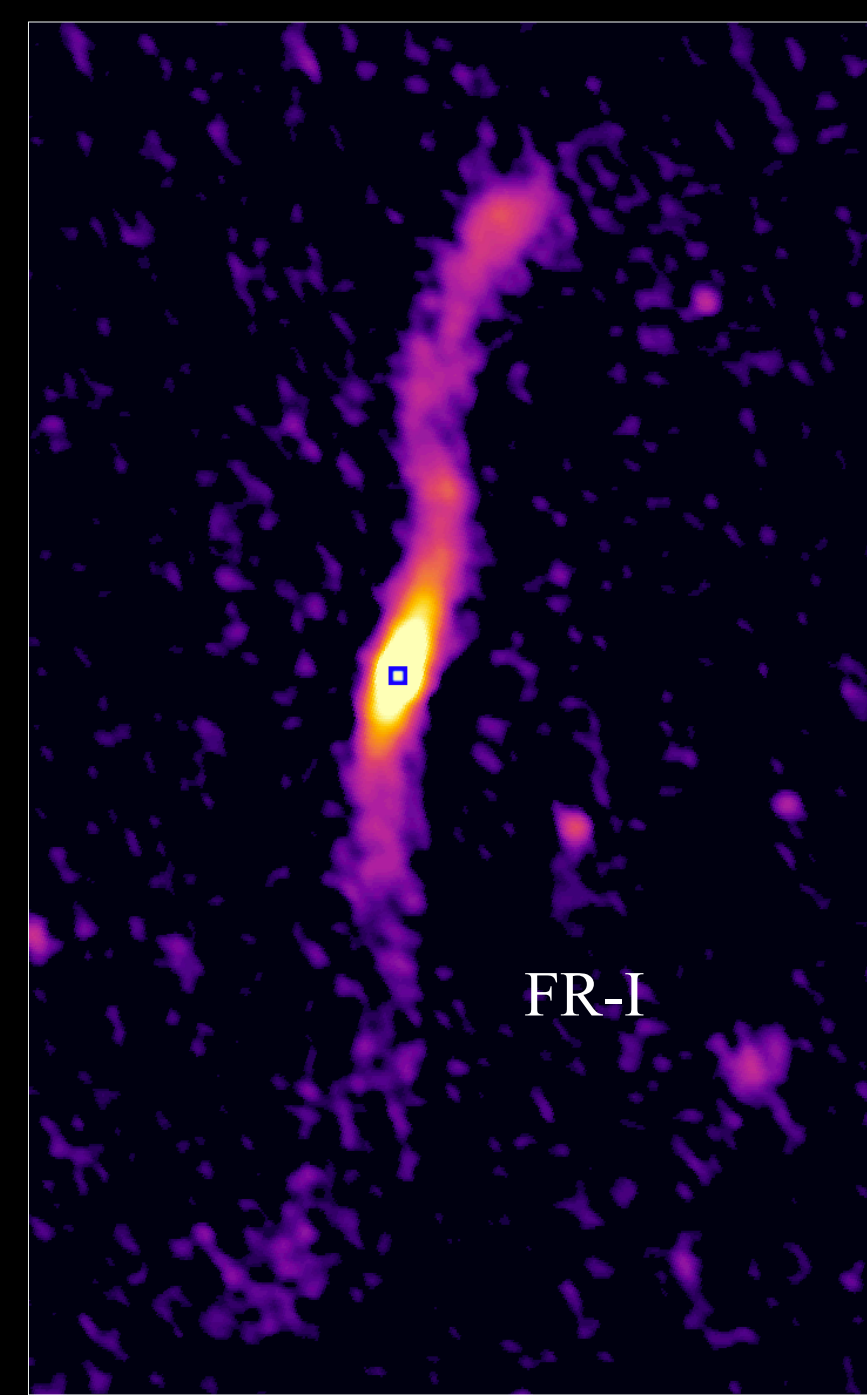
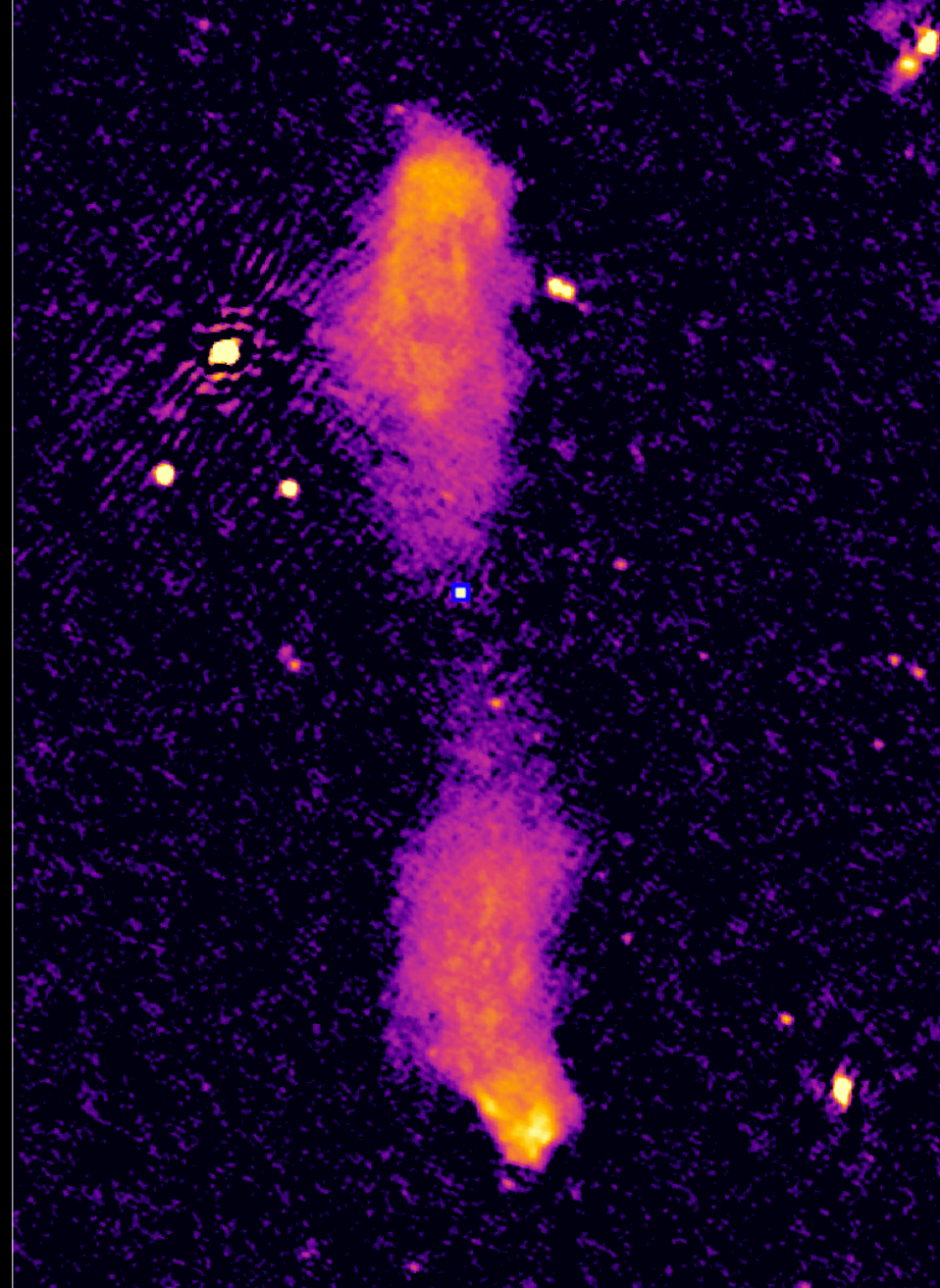
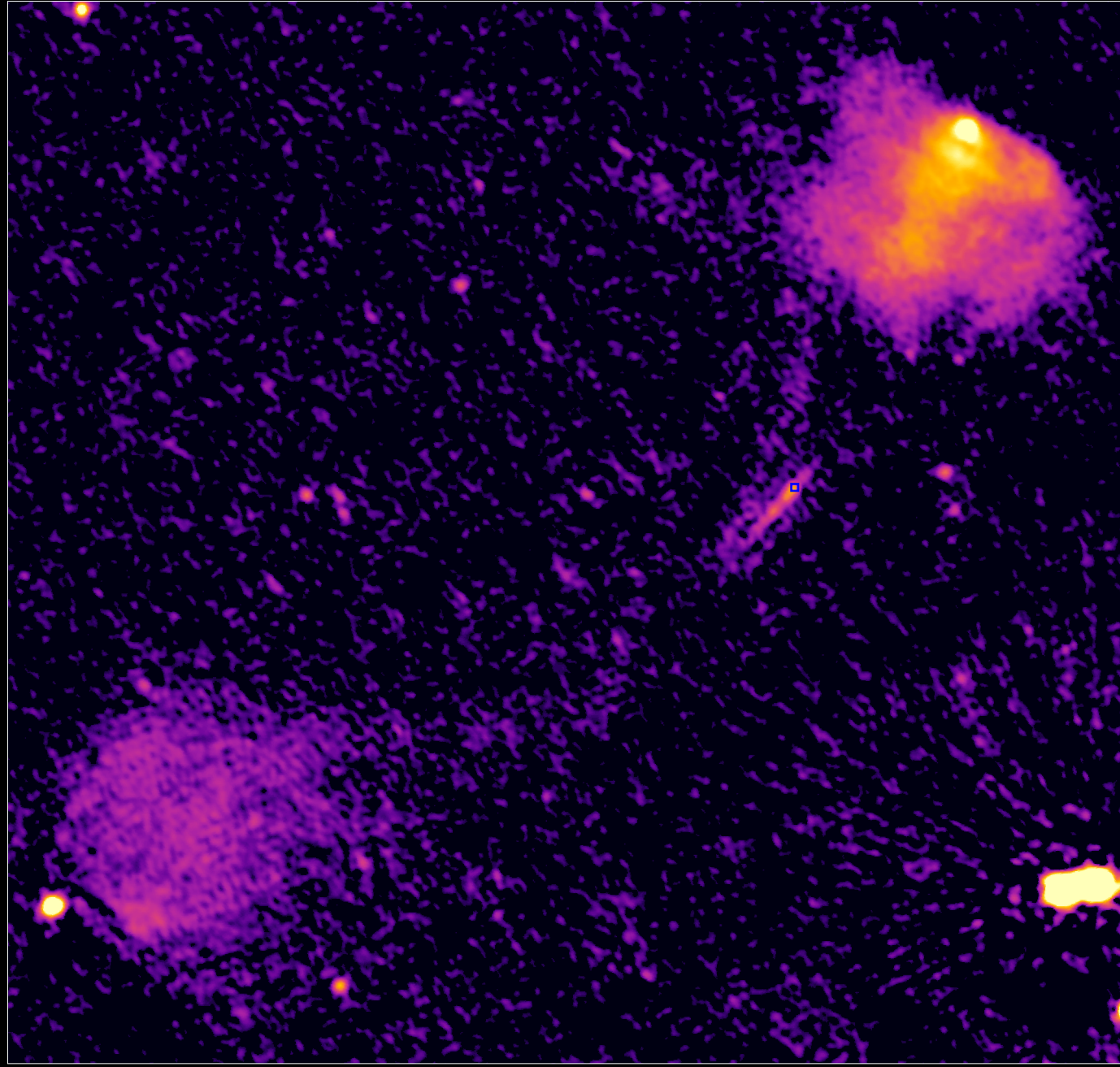
Key lessons for our analysis:

- ❖ Do not infer physical association from proximity alone.
- ❖ Avoid ambiguous filament end-points where the local axis is poorly defined.
- ❖ Test trends statistically: distance-to-spine, orientation, morphology, and asymmetry.
- ❖ Interpret results comparatively, ideally with a control sample
- ❖ Population-level claims need systematic selection.

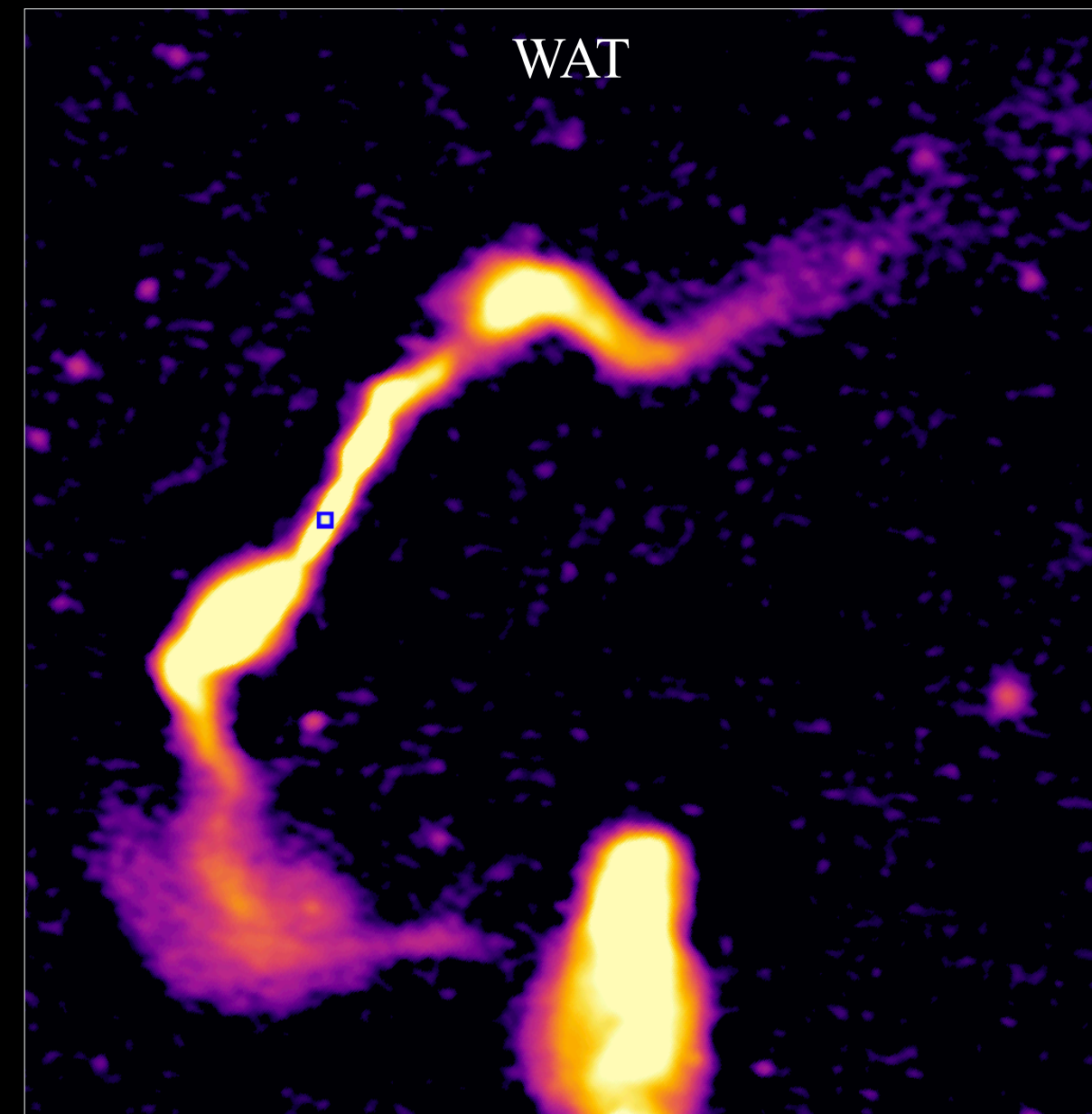
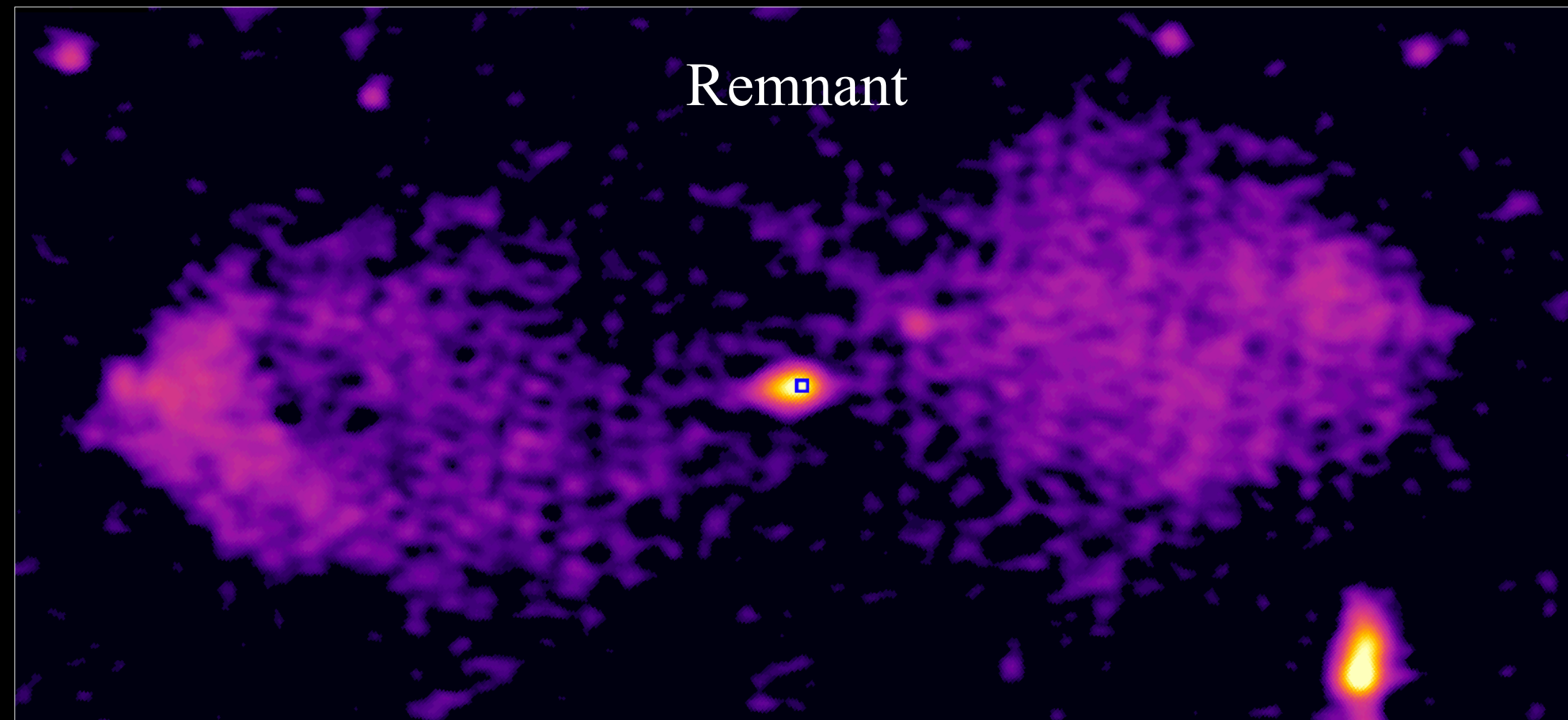
Results



GRGs from our sample



Standard FRII Morphologies

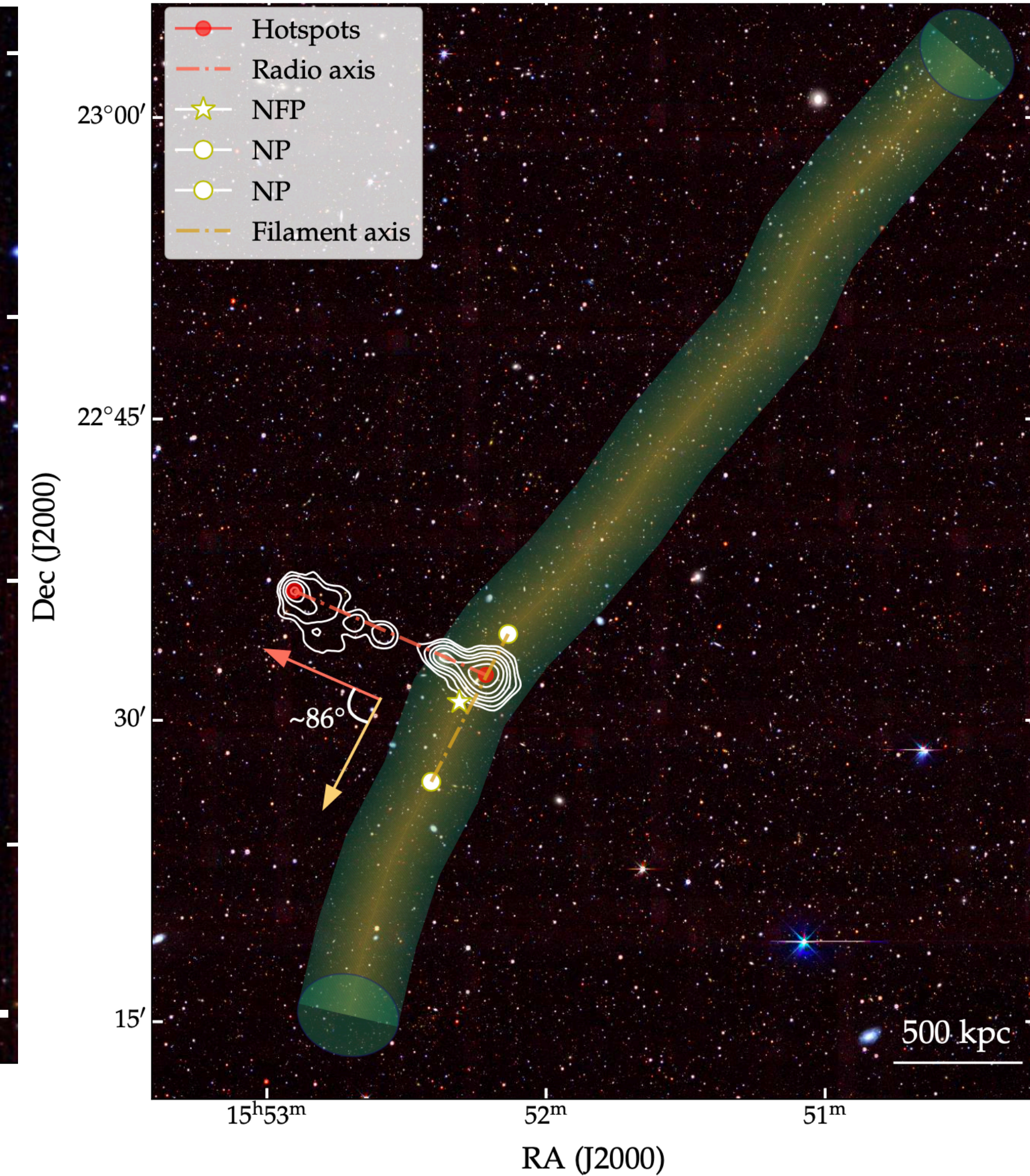
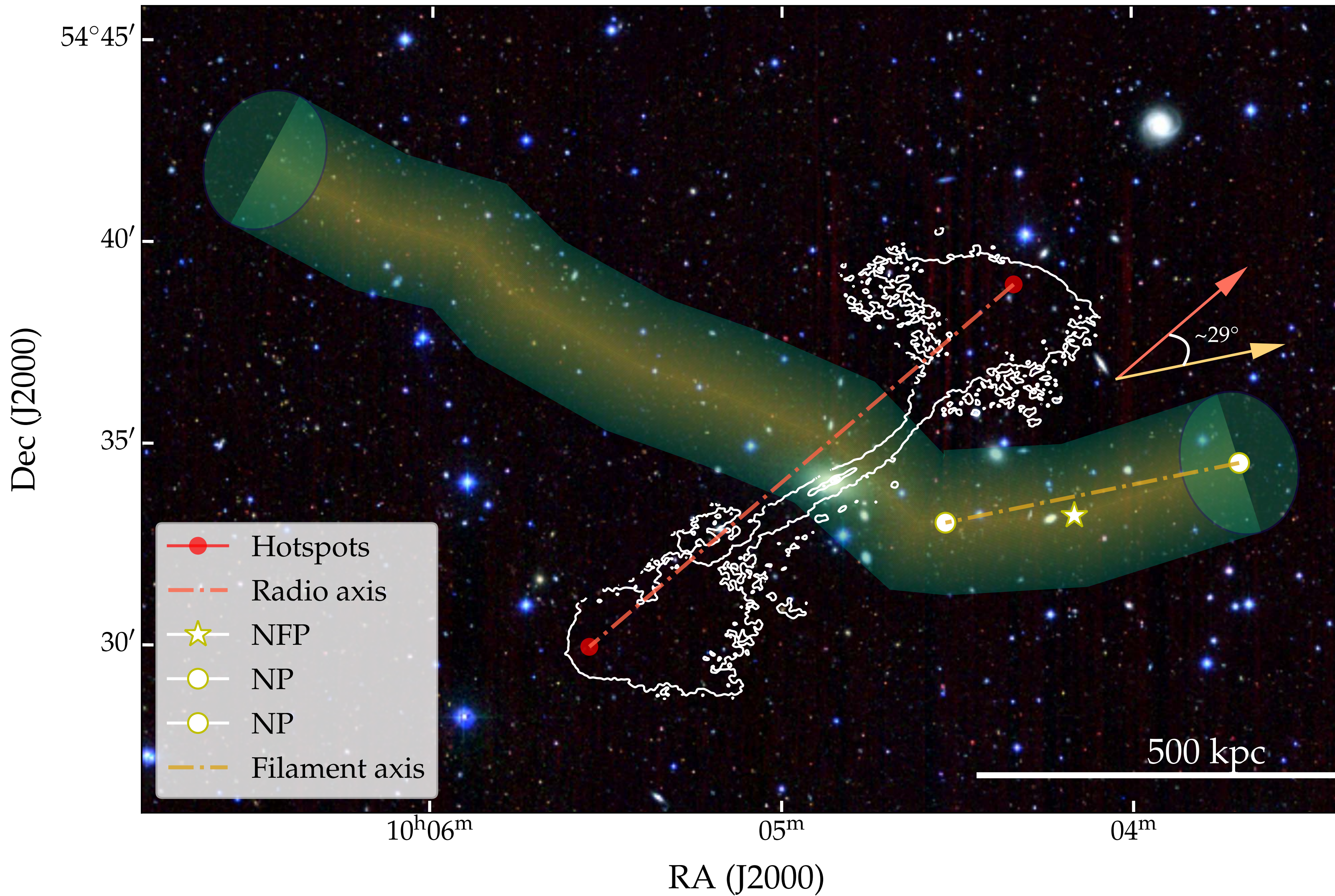


Radio: 144 MHz LoTSS 6''

SAGAN-VI: When jets meet filaments

What the filament - radio association tell us

Mahato et al. (2026)



SAGAN-VI: When jets meet filaments

What the filament - radio association tell us

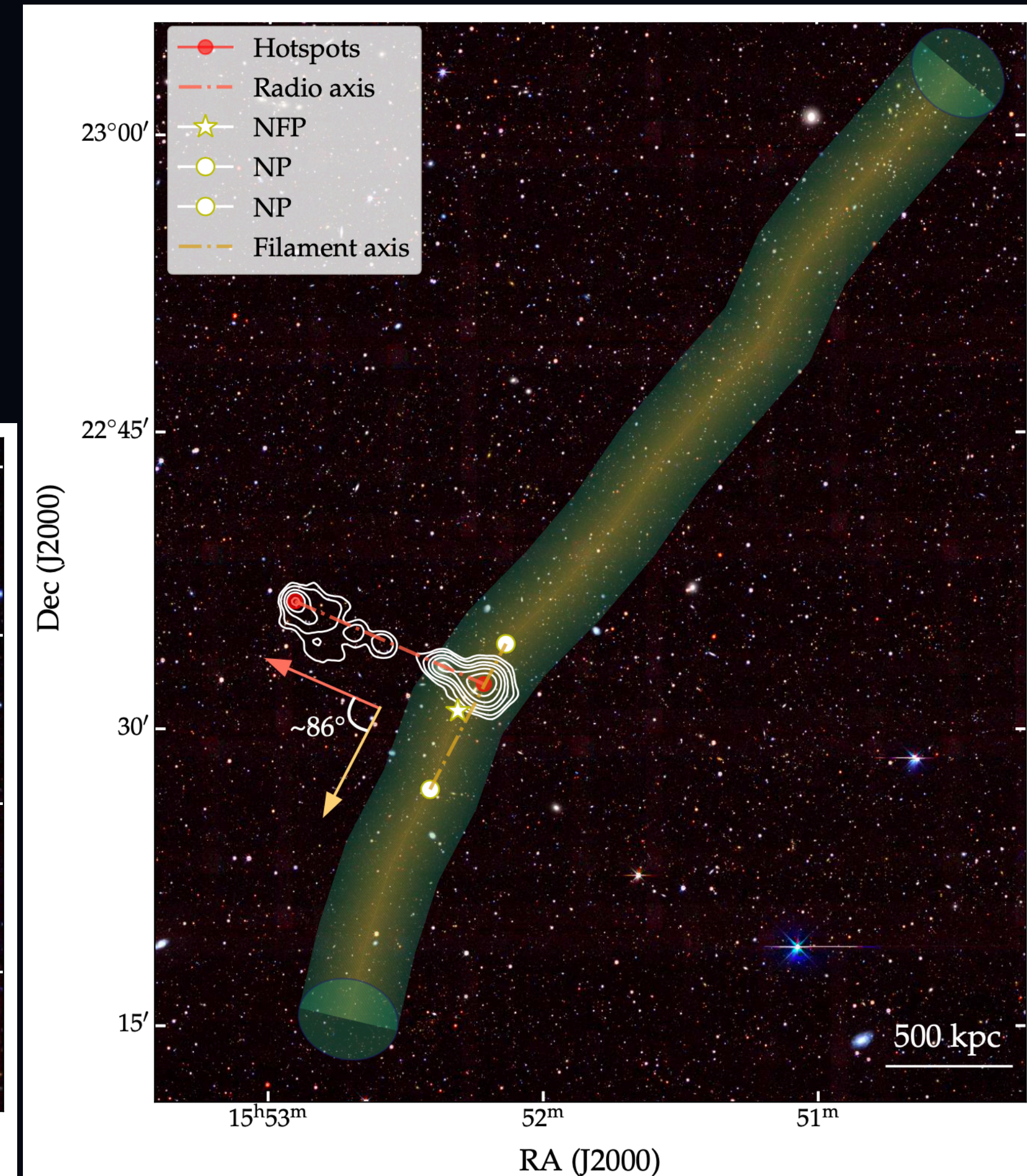
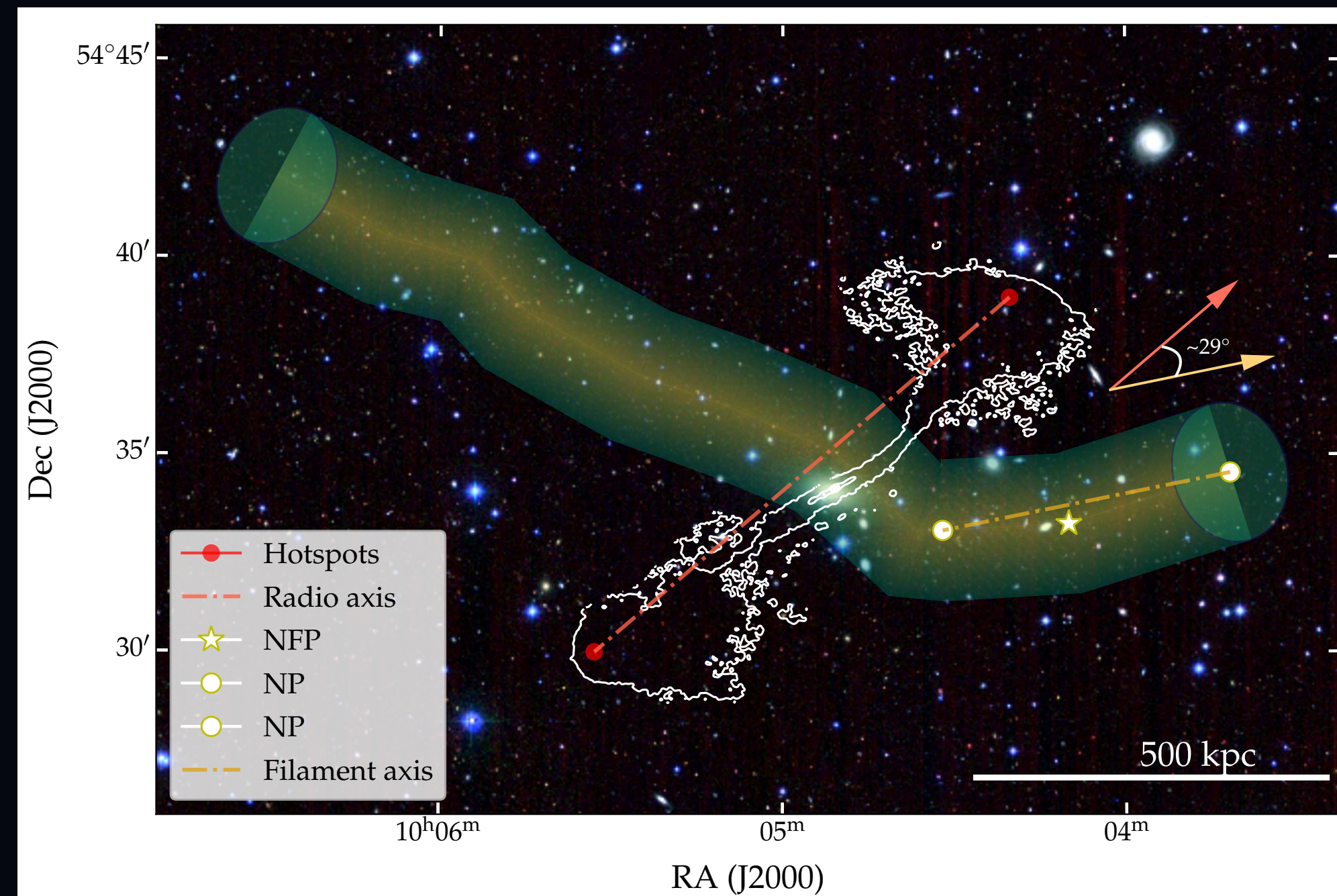
Mahato et al. (2026)

Interpretation:

- ❖ Filament proximity alone may not determine whether a radio galaxy reaches giant size.
- ❖ Jet orientation relative to the filament can matter because the surrounding medium is anisotropic.
- ❖ Large radio structures may be more sensitive to spine-to-outskirts density and pressure gradients.
- ❖ Complex morphologies close to spines may indicate stronger environmental modulation.

Key Inference-

A rigorous filament-association framework is the bridge between radio galaxies and physical claims about gas, flows, and magnetic fields in the cosmic web.



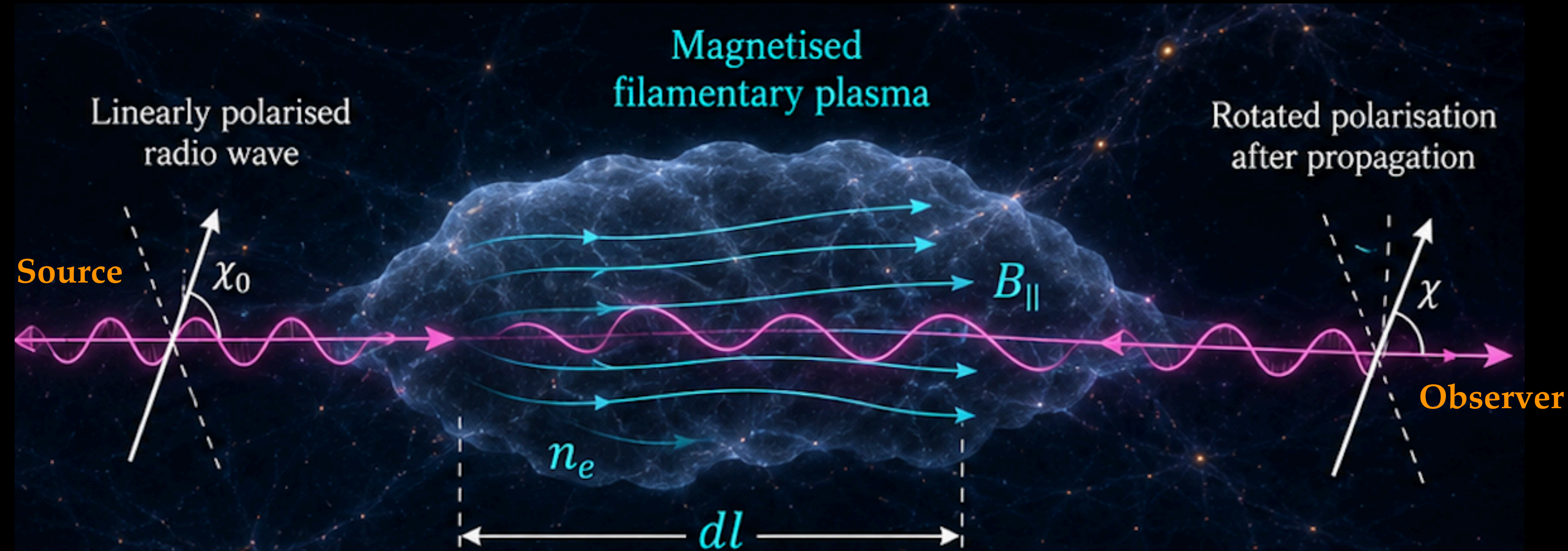
Probing Magnetic Fields of Filaments

“Once radio galaxies and filaments can be connected geometrically, the next question is whether radio polarisation can probe the magnetised plasma in and around filaments.”

- ❖ Filaments are less evolved than clusters → preserve information on early magnetisation.
- ❖ Filaments are practical observational targets → difficult to detect directly, but easier than voids
- ❖ Weak magnetic fields → possibly with a significant ordered component.

Probing Magnetic Fields of Filaments

Key idea: Use polarised background sources and radio galaxies to probe the magnetised plasma of filaments



Low-frequency observations:

- ✓ Extremely sensitive to small Faraday depths
- ✓ High sensitivity to weak RM signals and weak magnetic fields
- ✓ Good probes for large-scale intervening screens, such as filaments.

$$\chi(\lambda) = \chi_0 + \text{RM} \lambda^2$$

Polarisation angle rotation

$$\text{RM} = 0.81 \int n_e B_{||} dl$$

Rotation Measure (rad m⁻²)

n_e = electron density (cm⁻³) $B_{||}$ = line-of-sight magnetic field (μG) dl = path length (pc)

Why interpretation is difficult

- **Galactic foreground subtraction:** Milky Way RM can dominate and vary on the sky.
- **Source-intrinsic RM:** the AGN, host galaxy, and local environment can contribute.
- **Multiple intervening structures:** groups, clusters, haloes, and other filaments can add RM.
- **Uncertain filament density and path length:** converting RM to $B_{\parallel}$ requires assumptions about n_e and L .
- **Limited number of clean sightlines:** sparse polarised sources reduce statistical power.

Disentangling the signal

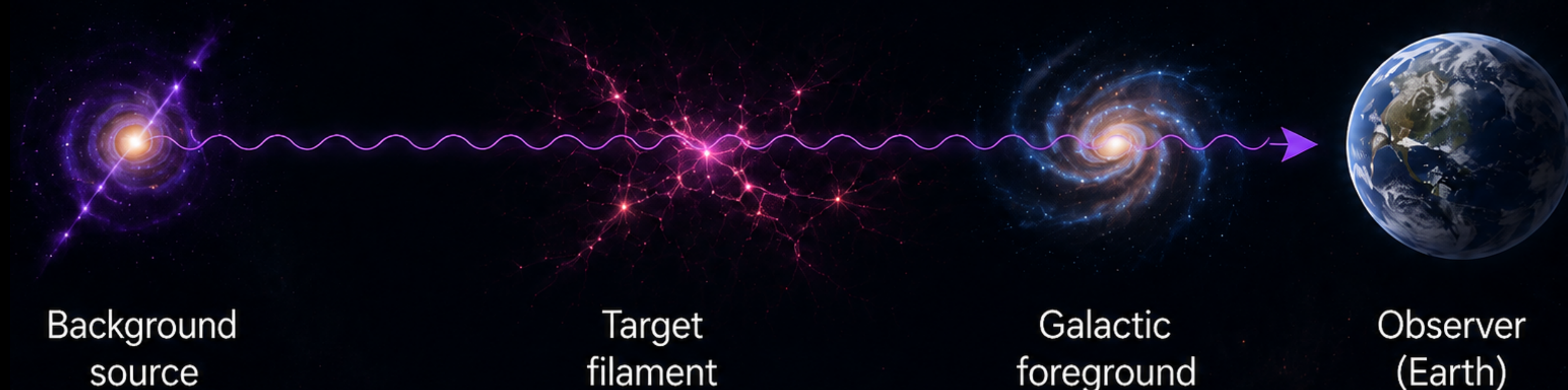
What is needed

- ✓ Careful sightline selection and control samples
- ✓ Galactic RM maps or local RM grids
- ✓ Large statistical samples / stacking
- ✓ Independent constraints on gas density and geometry

Observed Faraday rotation is simplified into its main components along the line of sight.

$$\text{RM}_{\text{obs}} = \text{RM}_{\text{Galactic}} + \text{RM}_{\text{filament}}$$

$$\text{RRM} \approx \text{RM}_{\text{obs}} - \text{RM}_{\text{Galactic}}$$



Filament 3D Geometry & Clean Sightlines

From robust filament geometry to clean polarised sightlines

1 Robust filament geometry

- Tempel et al. (2014): filament catalogue within $z < 0.155$ (~44,000 filaments)
- 3D filament network represented as connected cylindrical segments

Why this helps

- ▶ Low-redshift catalogue with dense galaxy sampling
- ▶ Better positional and geometrical accuracy
- ▶ Larger angular extent on the sky
- ▶ Higher probability of finding clean background radio sources
- ▶ Enables studies of individual filaments

2 Sightlines as clean as possible

- Polarised LoTSS DR2 sources with $z < 0.35$ (~2,400 sources)

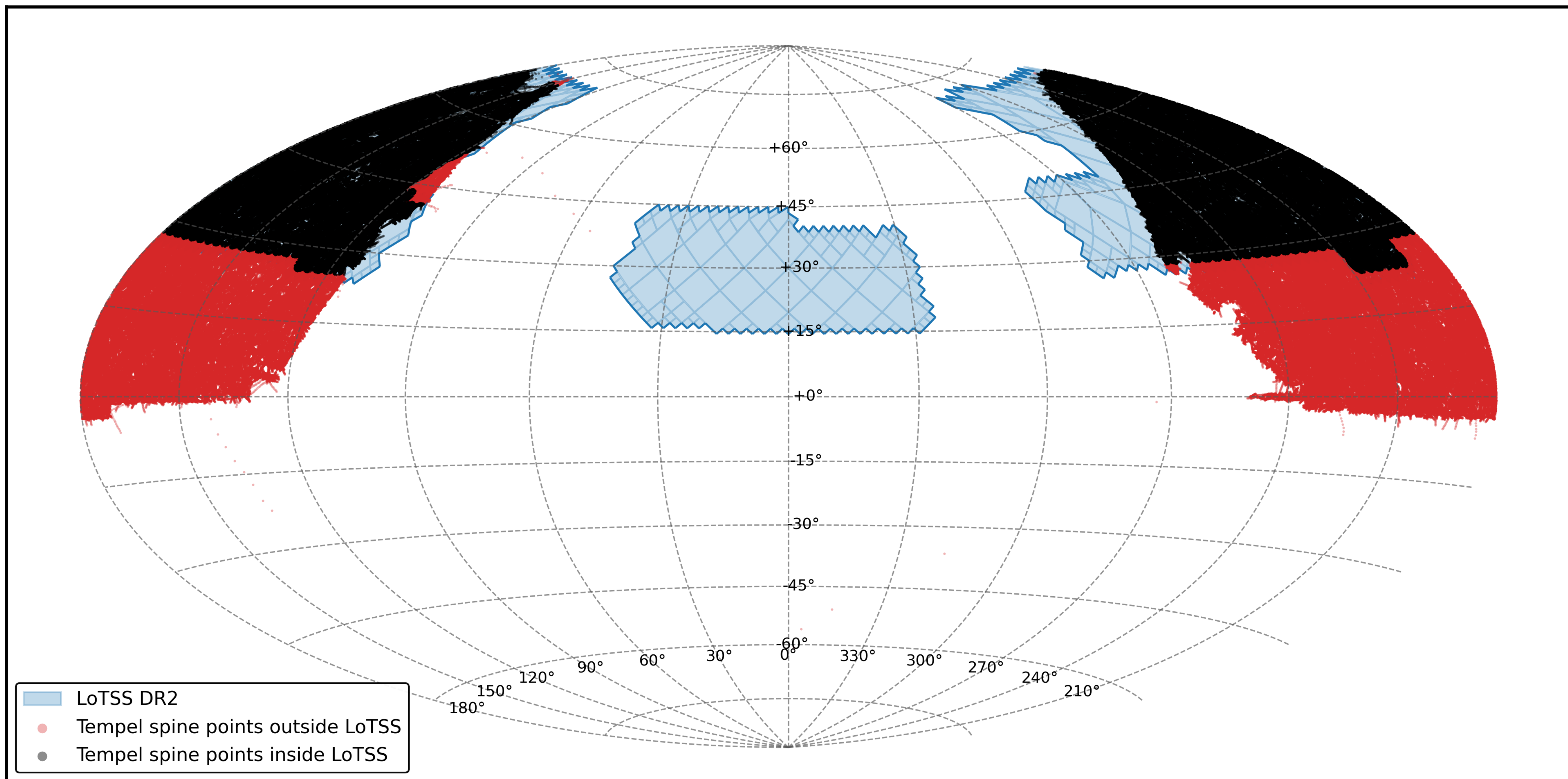
Selection criteria

- ▶ Background source: $z_{\text{src}} > z_{\text{fil,max}} + dz$
- ▶ Unclean source: sightline crosses multiple foreground filaments
- ▶ Clean source: sightline crosses only one foreground filament
- ▶ Projected search radii: 0.75, 1.0, 1.5, and 2.0 Mpc
- ▶ Exclude sources located inside galaxy clusters



Goal: combine robust filament geometry with clean polarised sightlines to isolate the filament contribution.

Declination



Right Ascension

50% Overlap

Complications in Filament 3D Geometry

Projection effects



Filament radius is typically ≈ 2 Mpc.
Same filament segments may overlap in projection.



Discrete spine tracing

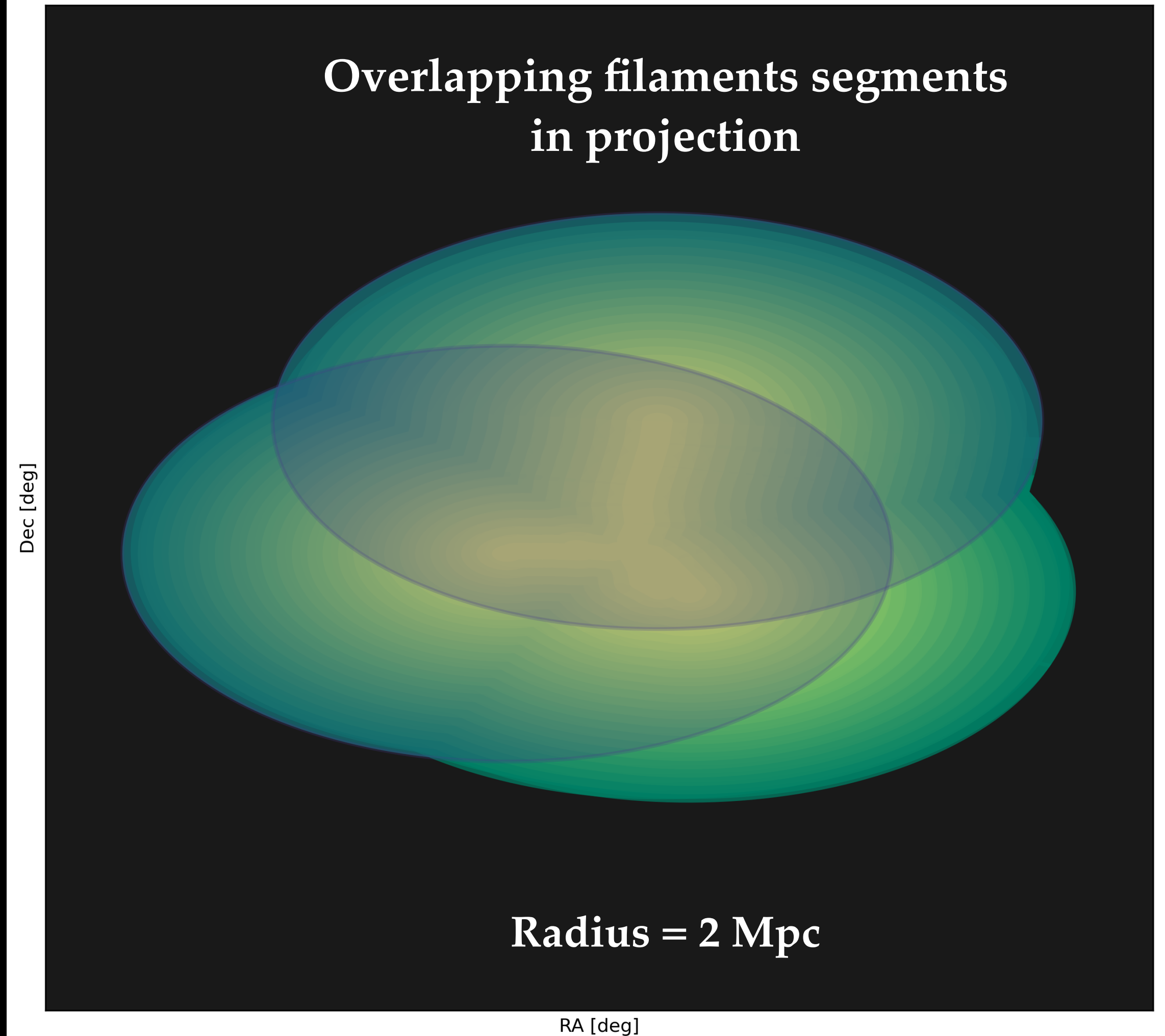
Filaments are traced along spine points; the true thickness is poorly constrained.



RM interpretation impact

A measured Faraday signal may include multiple foreground contributions from the same target filament.

Overlapping filaments segments
in projection



Complications in Filament 3D Geometry

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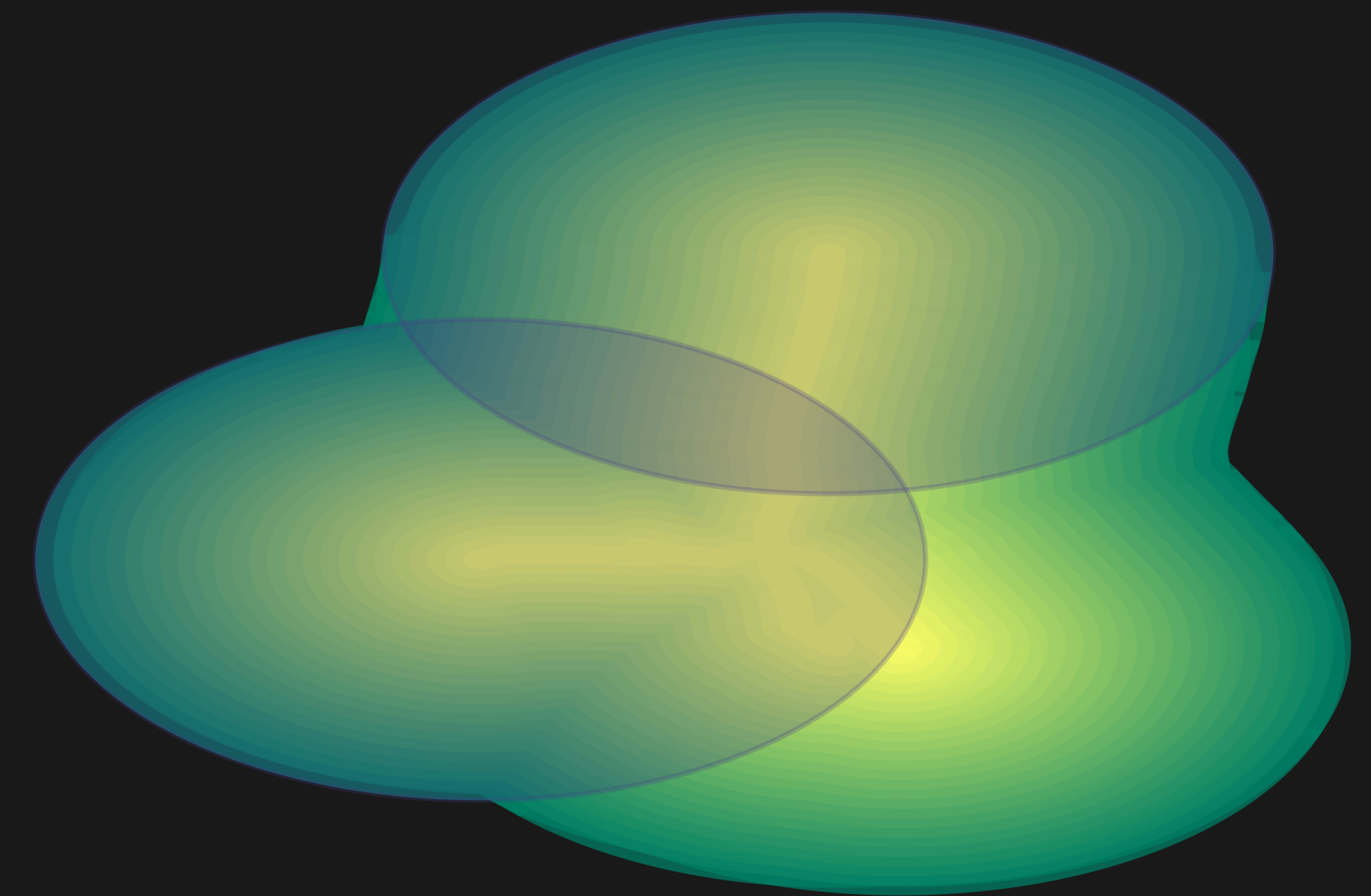


RM interpretation impact

A measured Faraday signal may include multiple foreground contributions from the same target filament.

Overlapping filaments segments in projection

Dec [deg]



Radius = 1 Mpc

RA [deg]

Complications in Filament 3D Geometry

Projection effects



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Discrete spine tracing

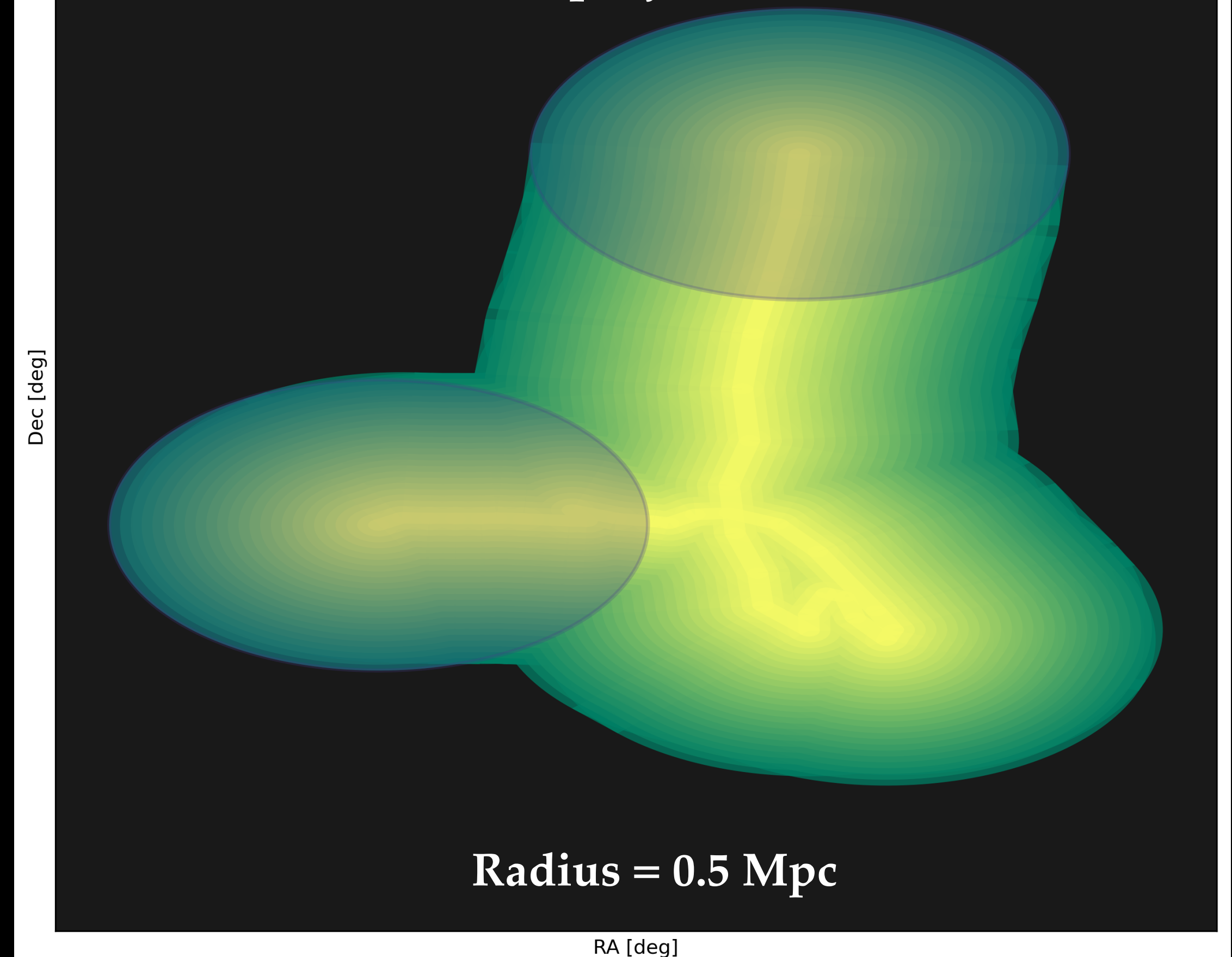
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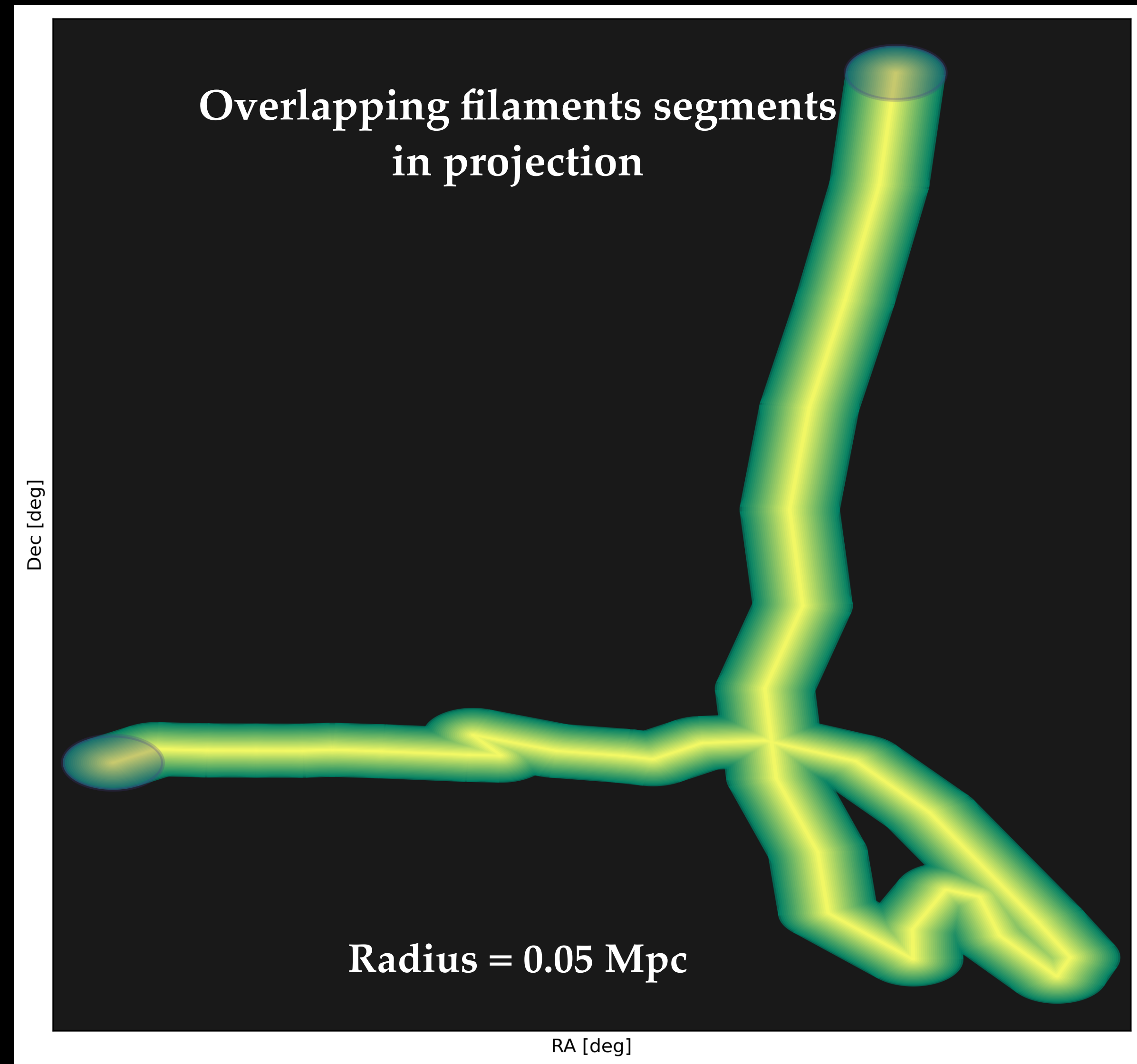
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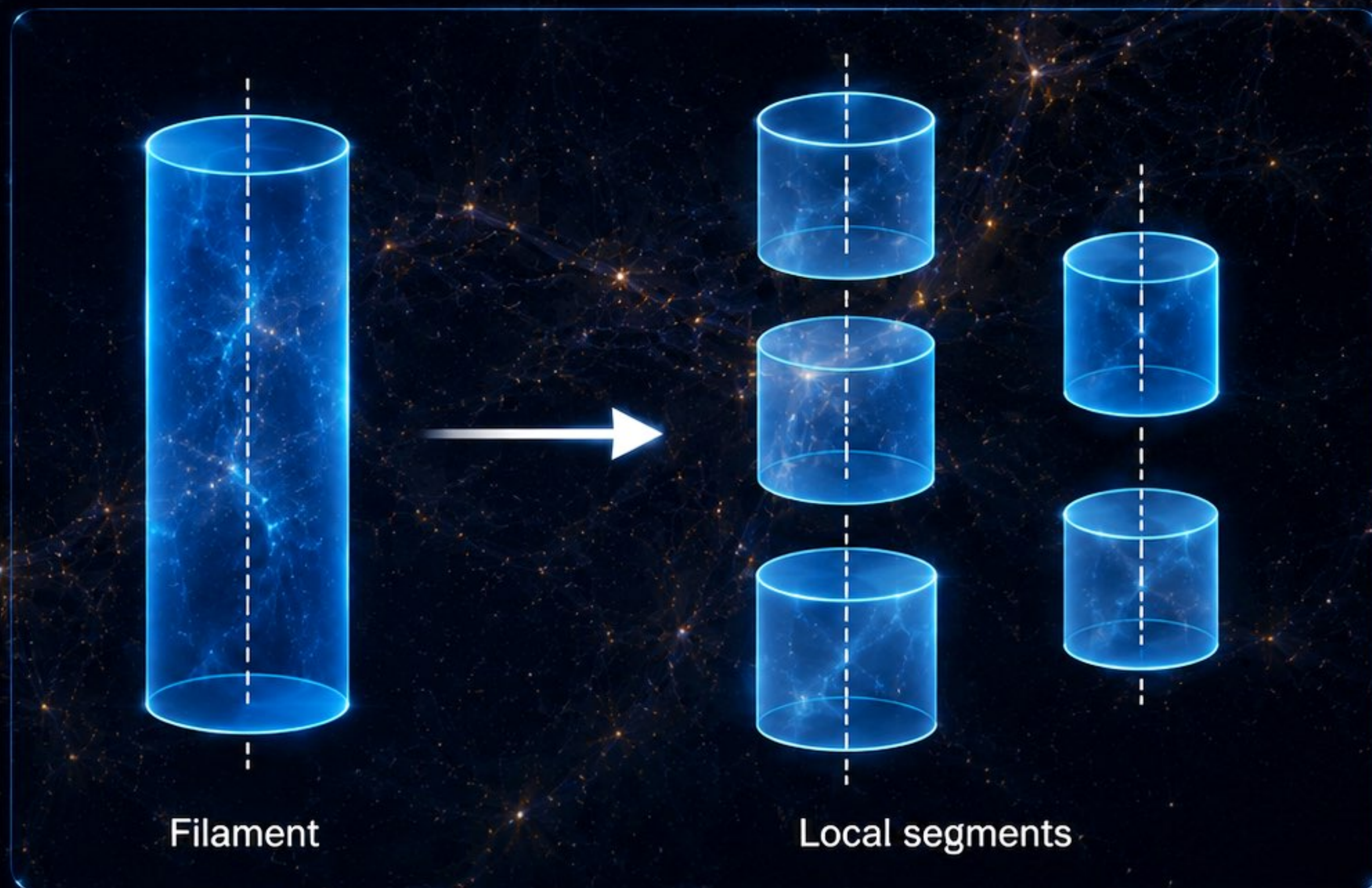


Filament 3D Geometry

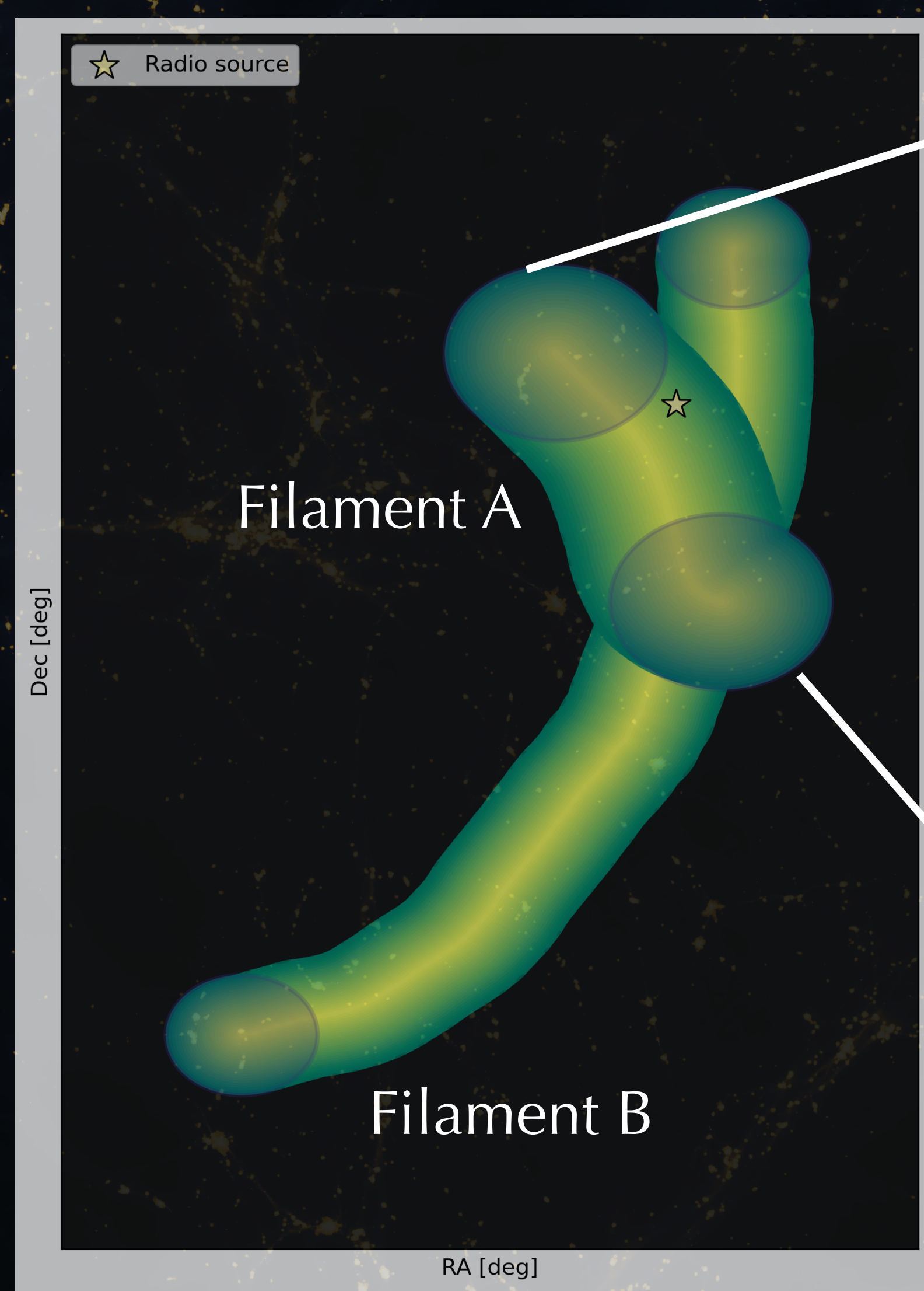
A practical route toward cleaner line-of-sight selection

Approach

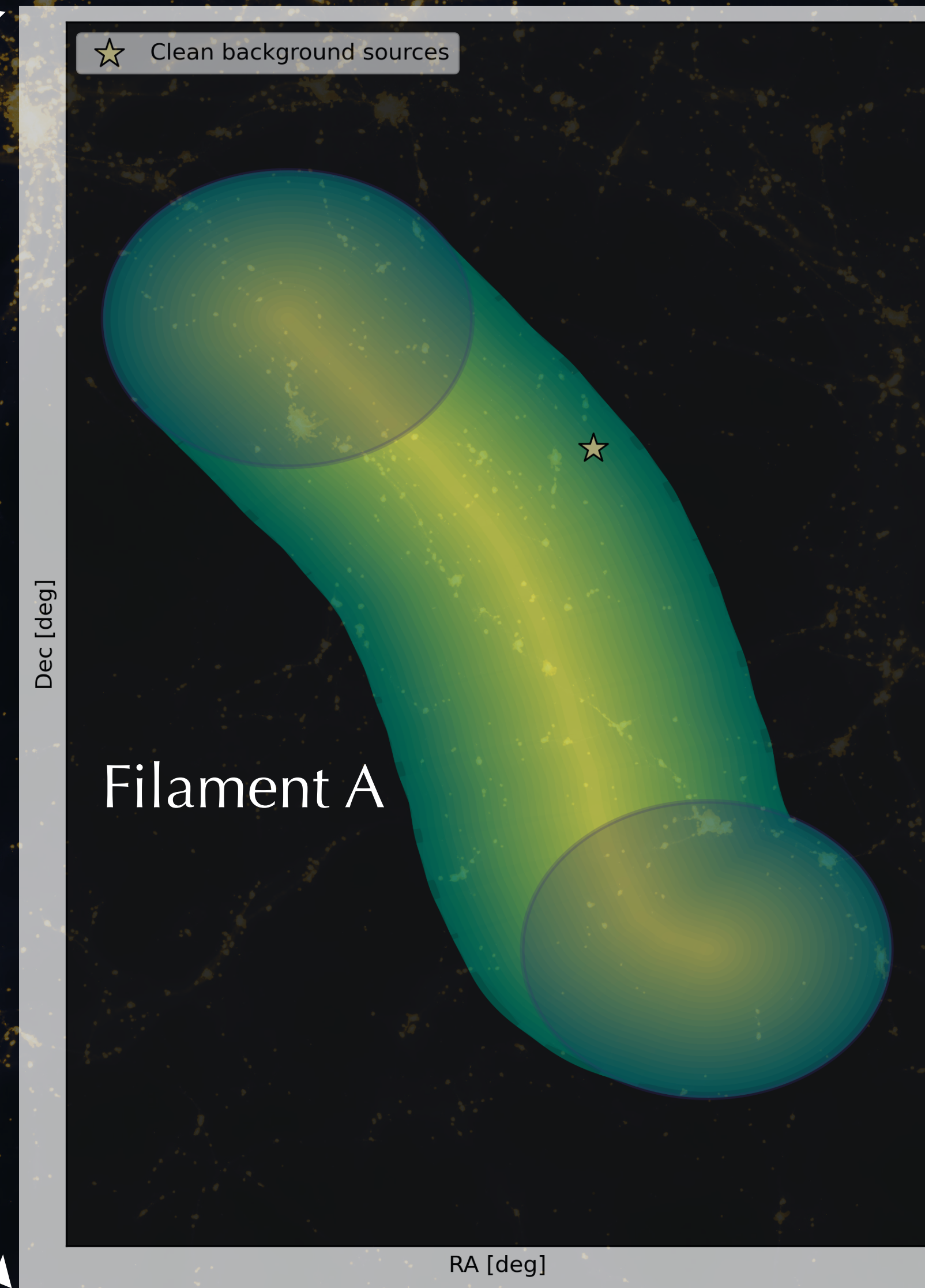
- Divide each filament into short local segments.
- Treat each segment using its local 3D geometry and orientation.
- Identify background radio sources located behind the segment and as close as possible to the filament axis.
- Require the source line of sight to intersect the segment volume.
- This helps isolate cleaner filament-specific sightlines.



Filament 3D Geometry & Clean Sightlines

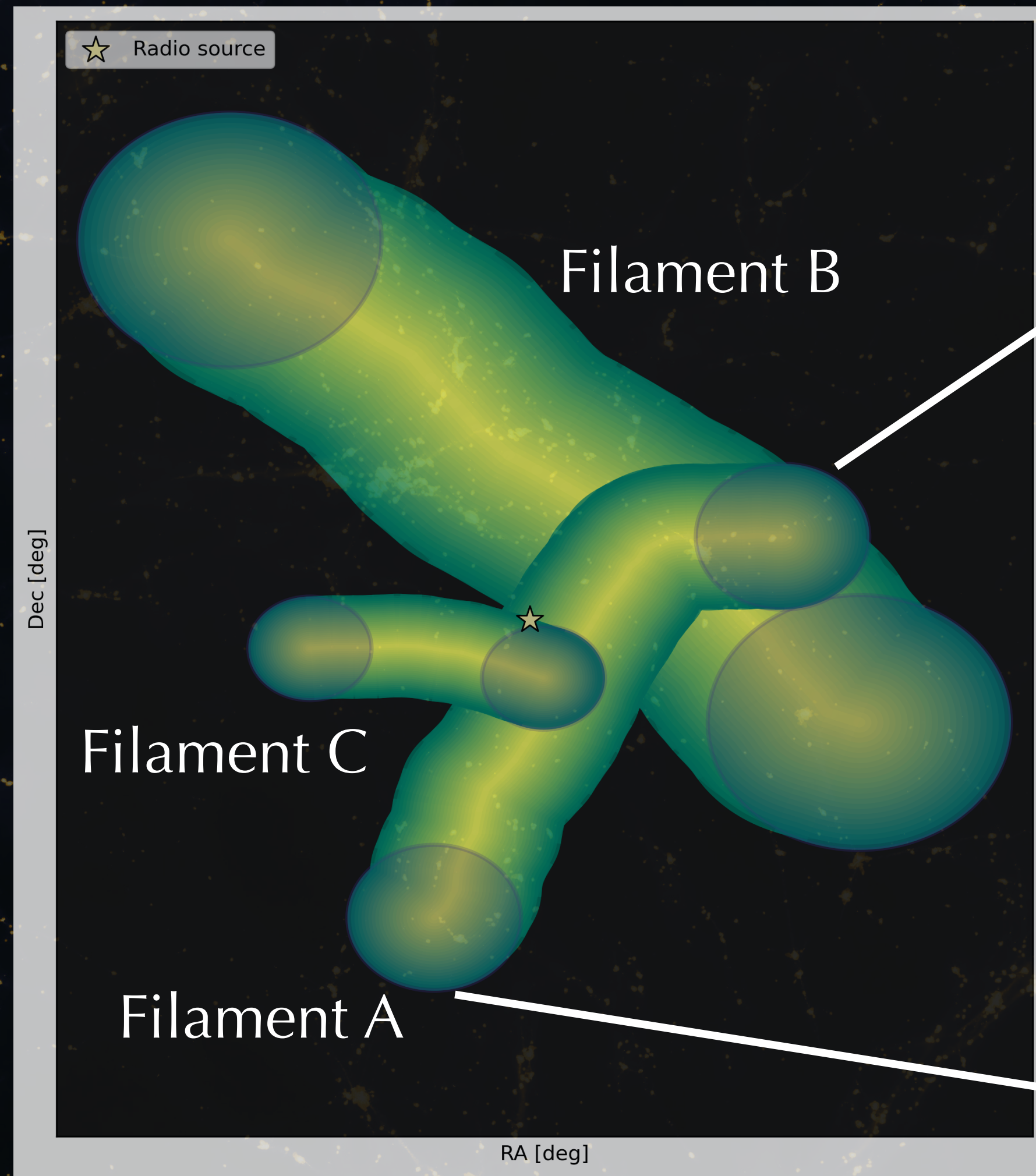


Radius = 1.5 Mpc

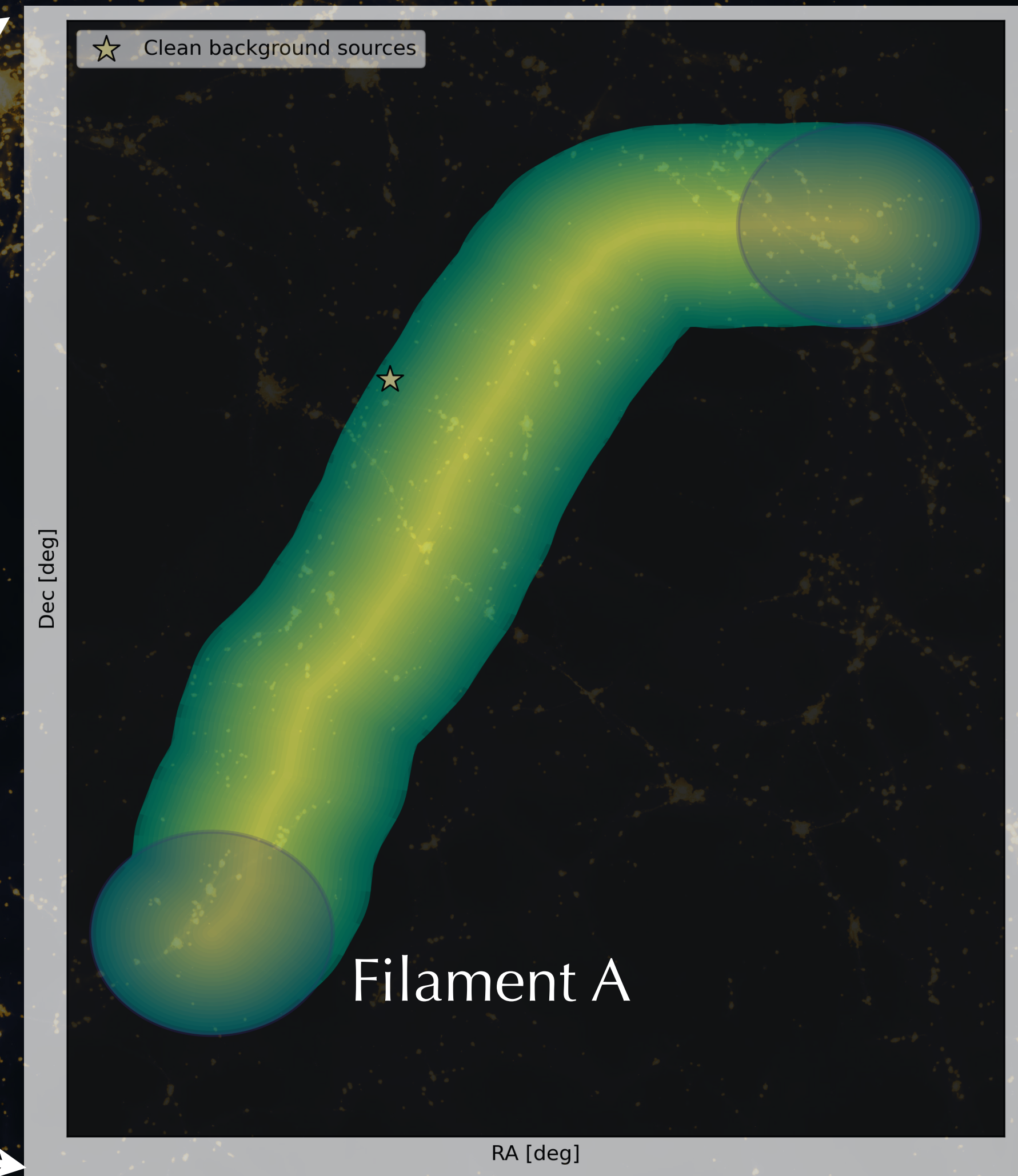


Radius = 1 Mpc

Filament 3D Geometry & Clean Sightlines



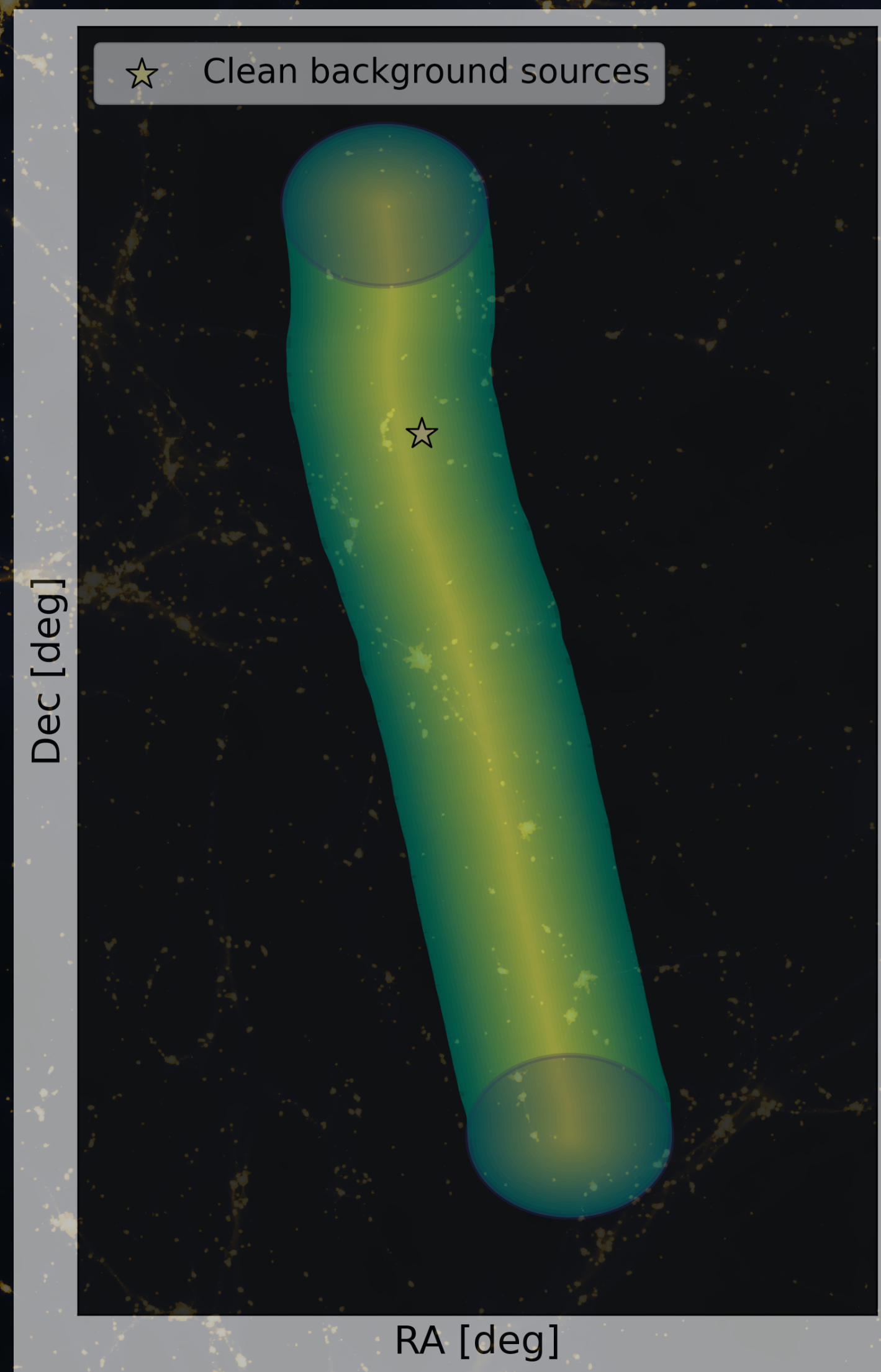
Radius = 1 Mpc



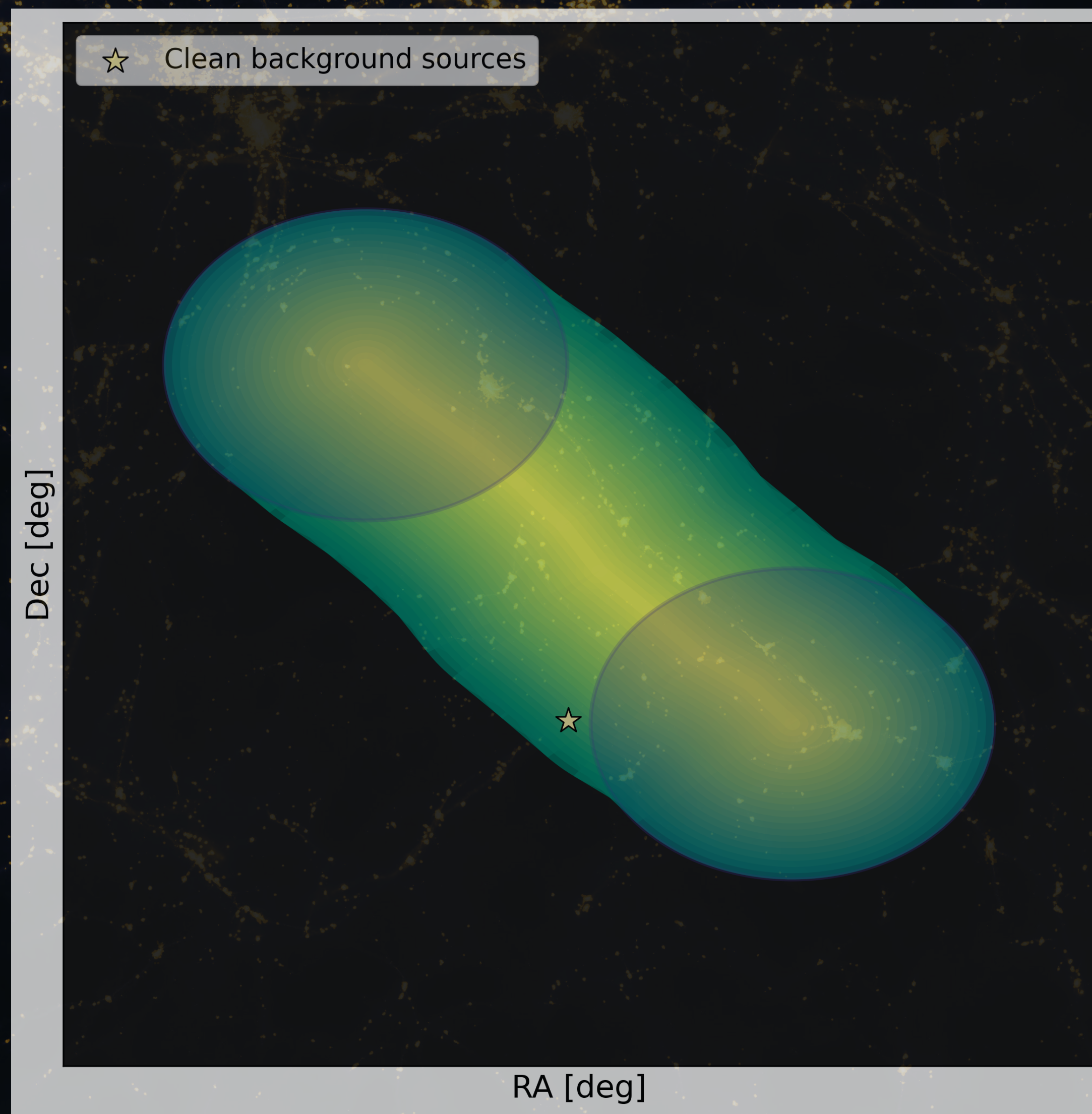
Radius = 0.75 Mpc

Mahato et al. -In prep

Filament 3D Geometry & Clean Sightlines



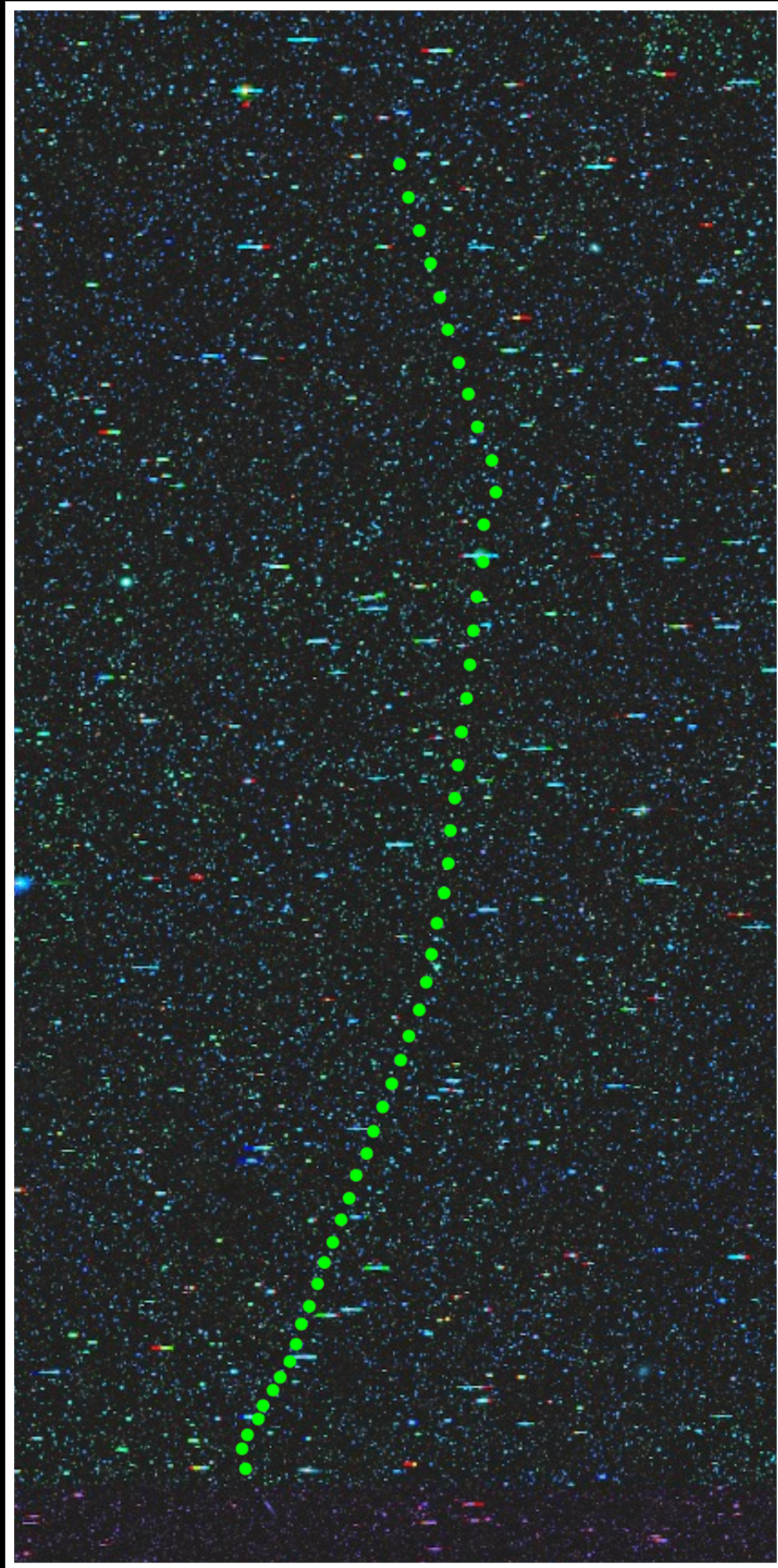
Radius = 2 Mpc



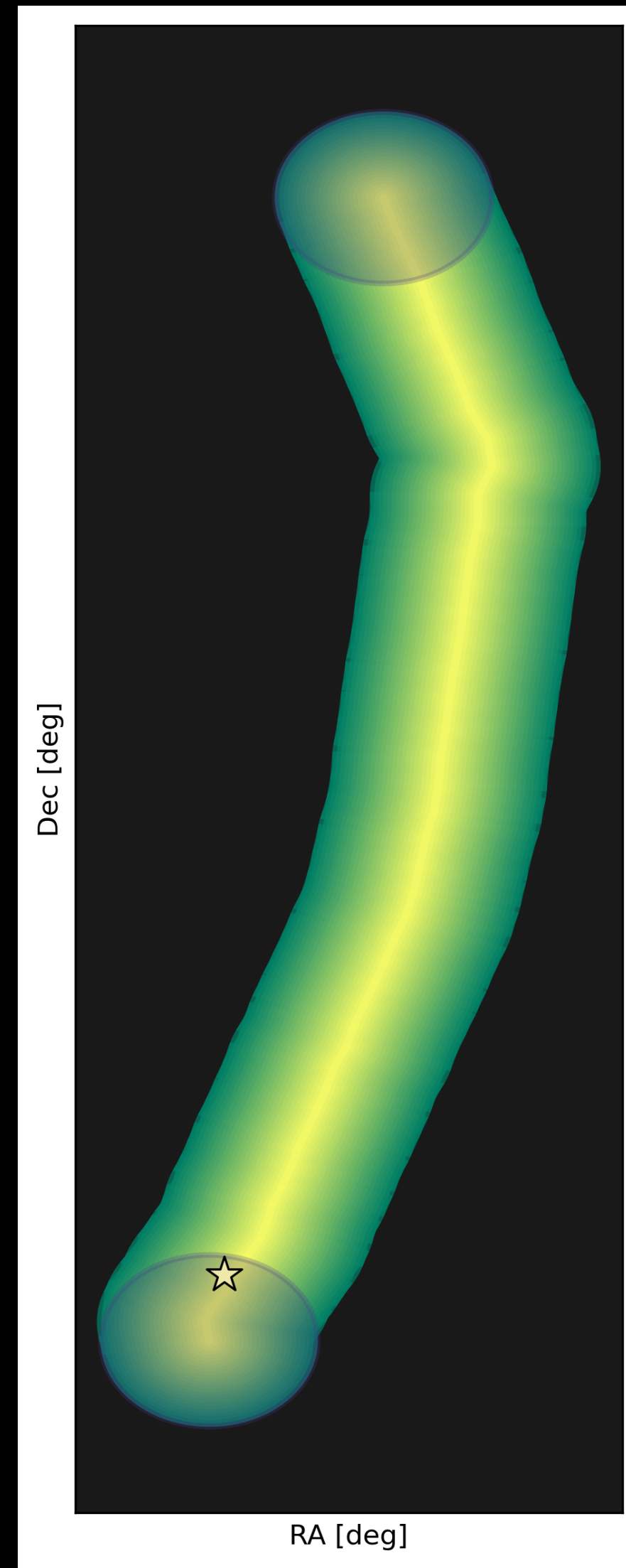
Radius = 2 Mpc

Mahato et al. -In prep

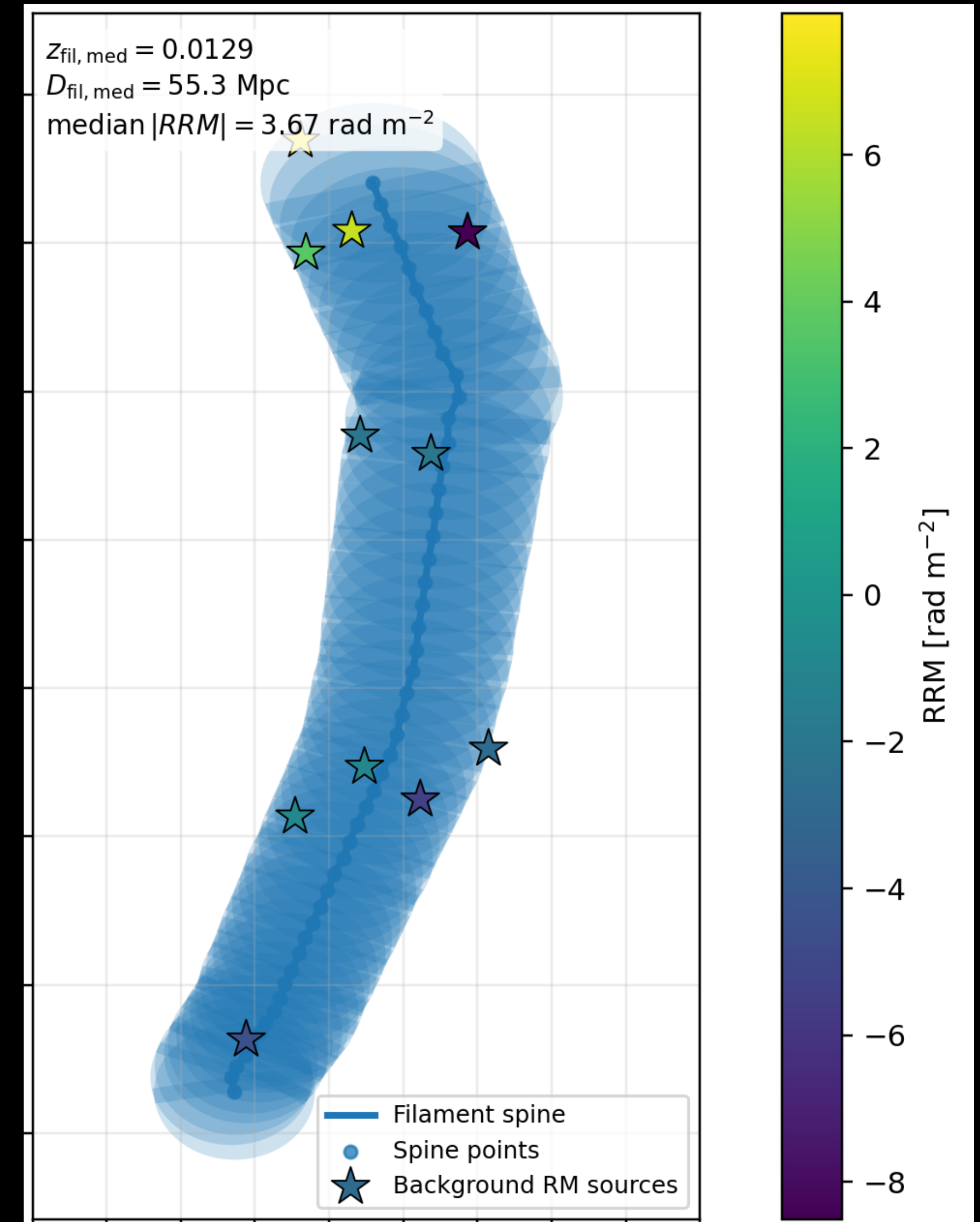
Filament 3D Geometry & Clean Sightlines



Spine points on legacy image



Clean Bg source



Background sources = clean + unclean

Results

From clean source selection to filament magnetic-field estimates



1. SAMPLE SELECTION



Clean sources behind filaments

25

Identified from the cleaned polarised source sample behind filament sightlines.



Final clean polarised radio sources

24

Used for the next stage of analysis.



EXCEPTION



One source was found to lie inside a galaxy cluster

Excluded from the filament sample



3. NEXT CALCULATIONS



Estimate the effective path length, L_{eff}



For assumed electron density n_e , infer the line-of-sight magnetic field, $B_{\parallel}$



CURRENT MEASURED SCATTER

$$\sigma_{\text{RRM}} = 7.47 \text{ rad m}^{-2}$$

Filament Magnetism

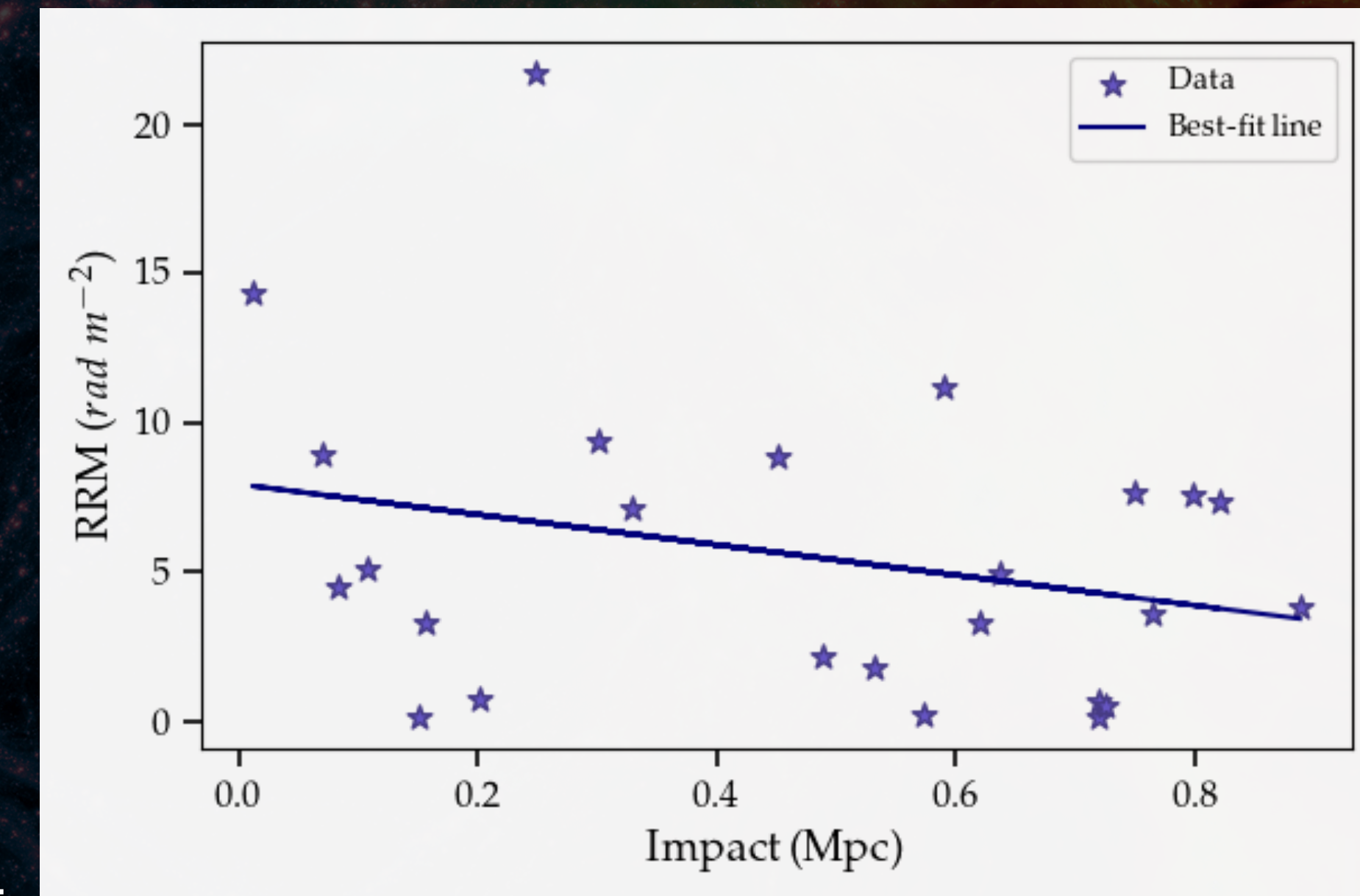
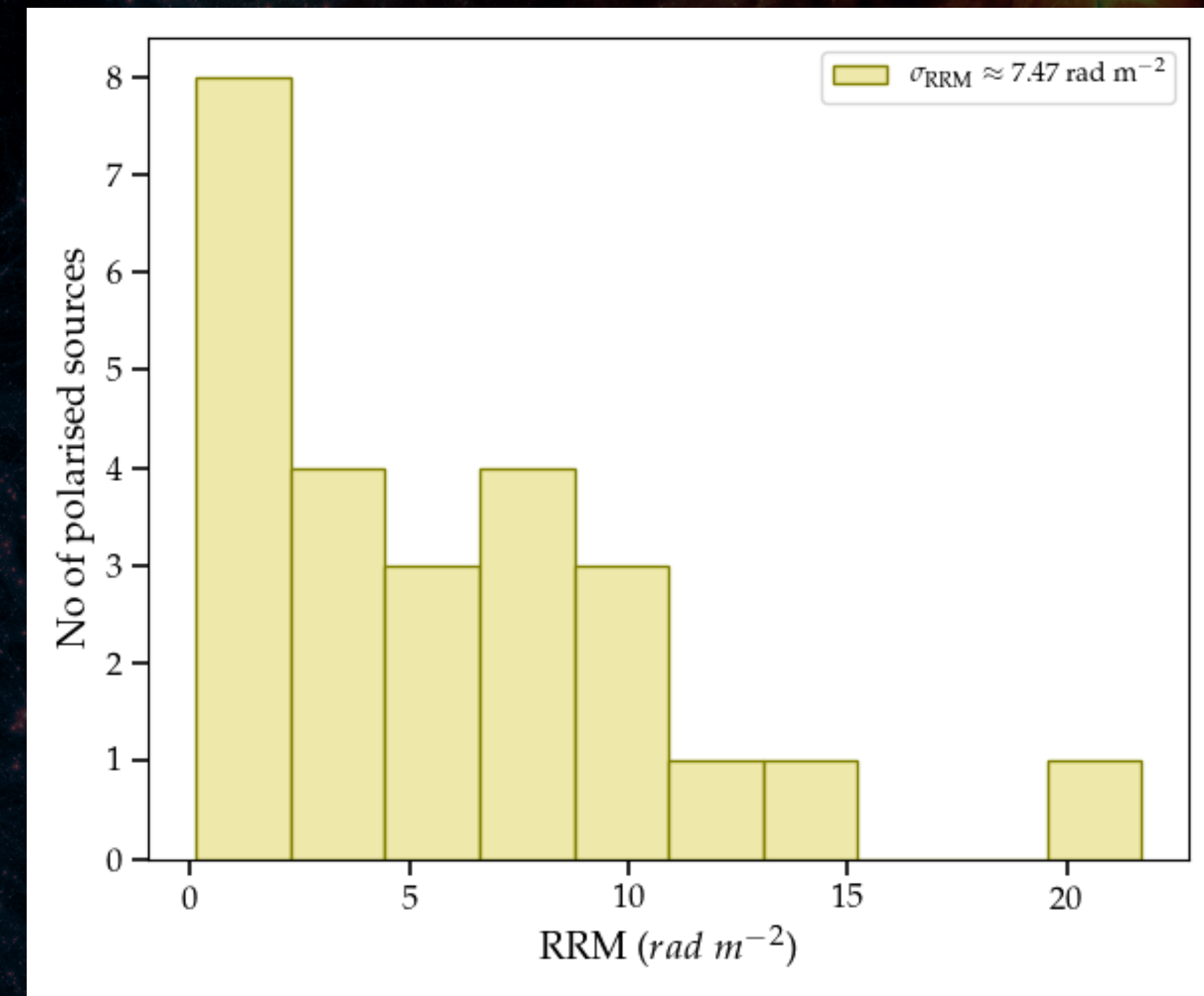
Preliminary results

Estimated Magnetic Field Strengths for Assumed Electron Densities

Magnetic field values are in nanogauss (nG).

Assumed n_e (cm $^{-3}$)	$B_{\min}$ (nG)	$B_{\max}$ (nG)	B_{median} (nG)
1×10^{-5}	4.1	750	157.8
5×10^{-5}	0.82	150	31.6
1×10^{-4}	0.4	75	15.8

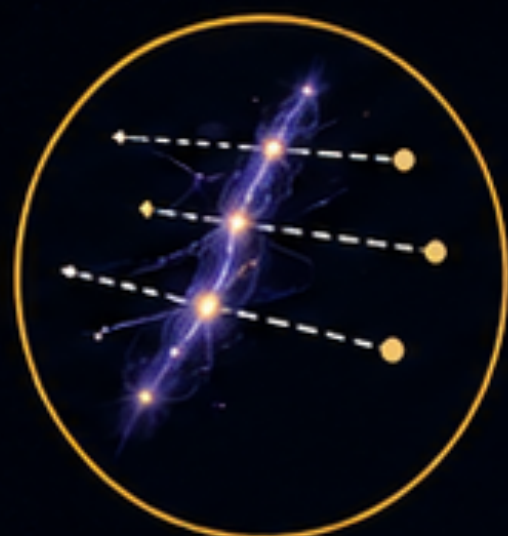
Mahato et al. -In prep



Future Outlook

Towards robust filament magnetism and radio-galaxy environment studies

Now



- Pilot clean and complex filament-RM framework
- Finite-cylinder geometry implemented
- Single-filament cases identified

Next



- Use both clean and crowded sightlines differently
- Add better cluster / group decontamination
- Compare RRM and RRM_{-1deg} as a systematic test
- Move from fixed assumptions to ensemble statistics

SKA era



- Denser RM grids and larger samples
- Better impact-parameter and burden statistics
- Stronger constraints on cosmic-web magnetisation
- Unified framework linking radio galaxies and RM probes



Ensemble statistics will drive the main science



Clean cases remain essential as physical benchmarks



Foreground control is critical



Future RM grids will transform the field



Outlook: this pilot framework can evolve into a LOFAR and SKA-era programme in which radio galaxies trace filament environments and RM grids statistically measure the magnetised cosmic web.