Magnetic fields inside and beyond galaxy clusters with LOFAR

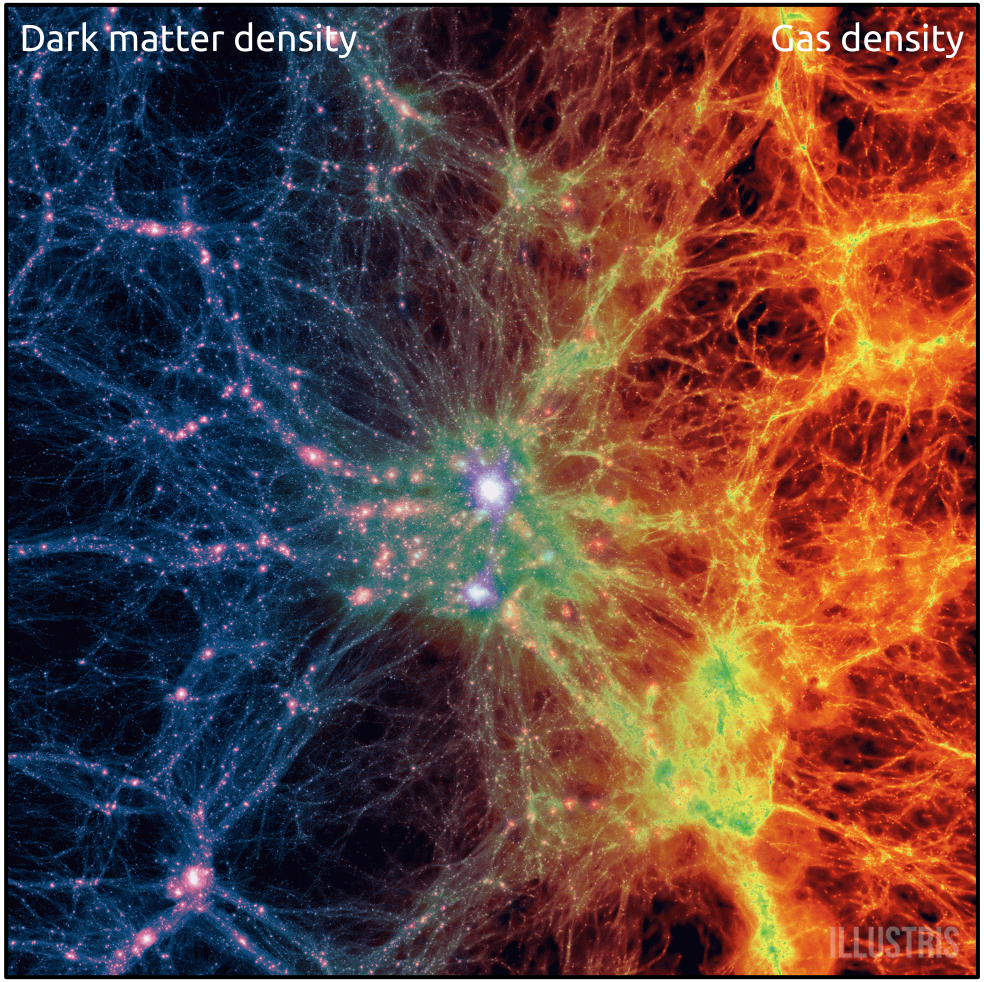
LOFAR Family Meeting 2025

22 Sept 2025

Chiara Stuardi
INAF - Istituto di Radioastronomia (Italy)

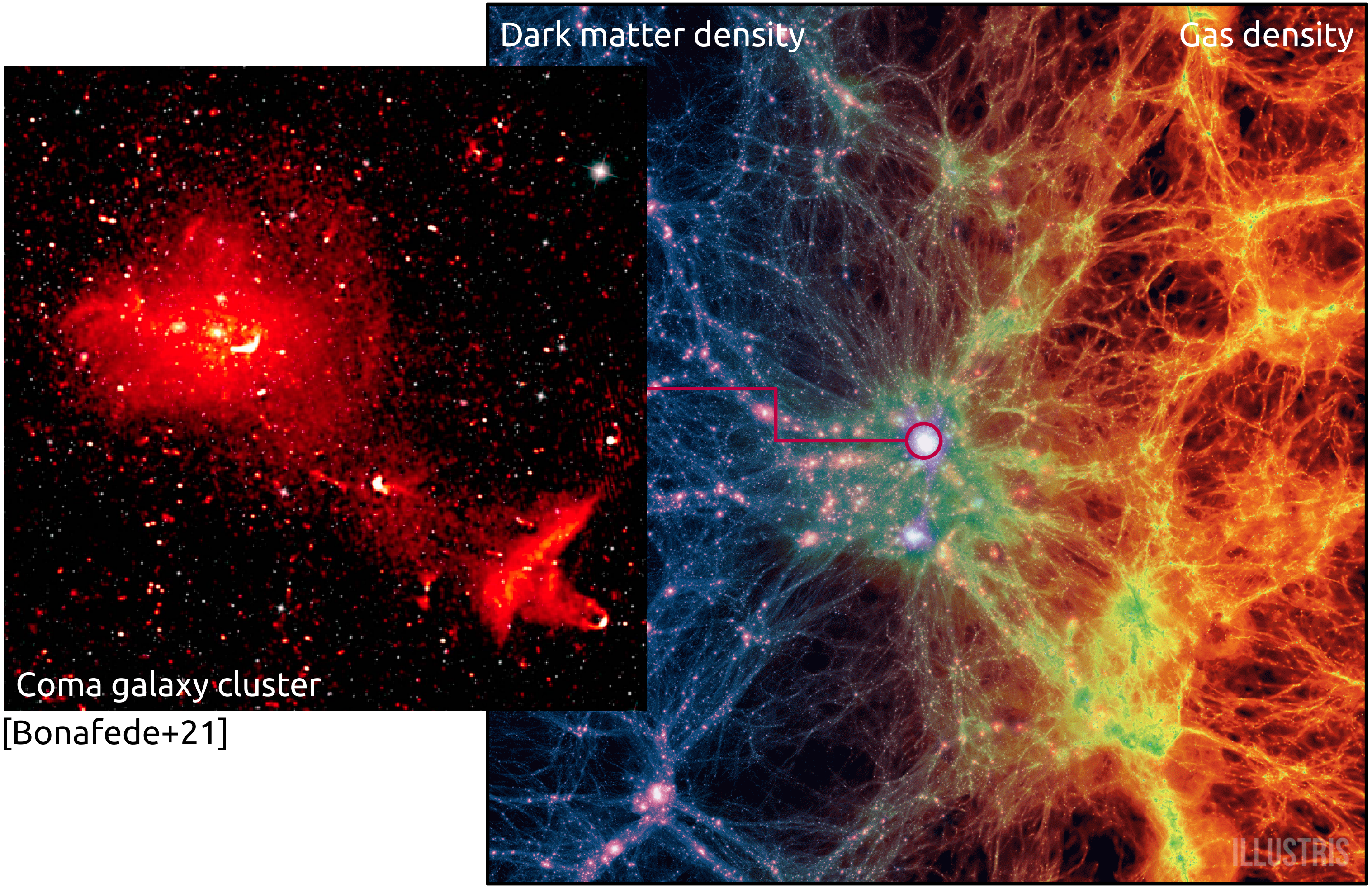
LOFAR Surveys & Magnetism Key Science Projects

A magnetised Universe



Vogelsberger+ 2014

A magnetised Universe



[Bonafede+21]

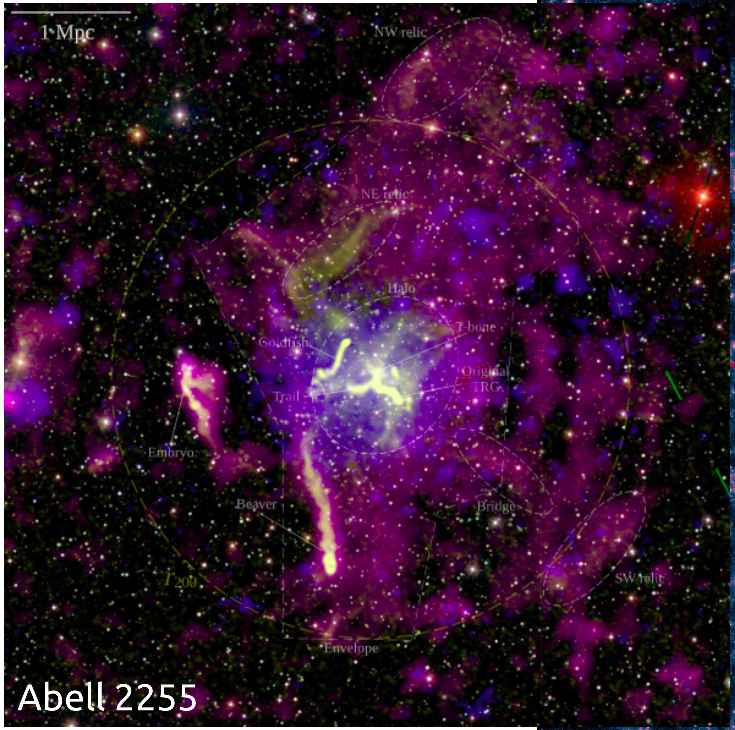
Vogelsberger+ 2014

Diffuse synchrotron sources provide evidences of magnetic fields on Mpc scales.

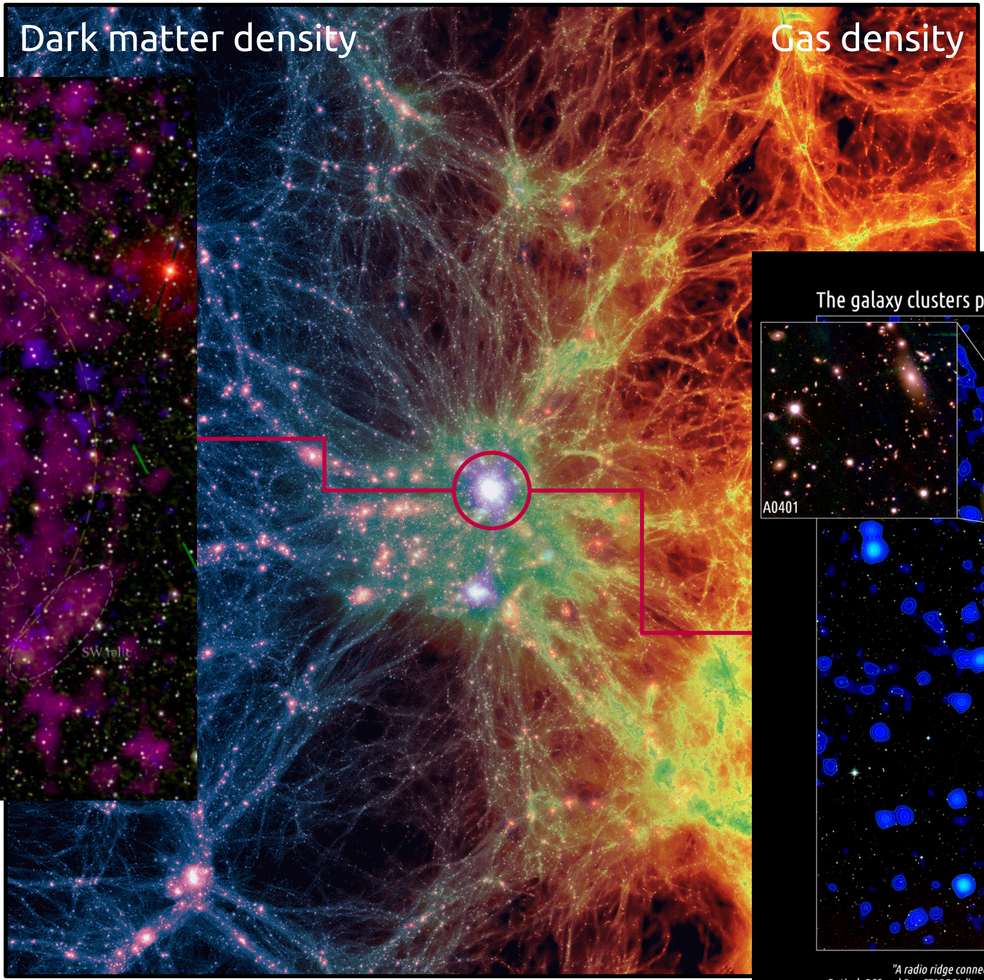
A magnetised Universe

Even outside the periphery of galaxy clusters.

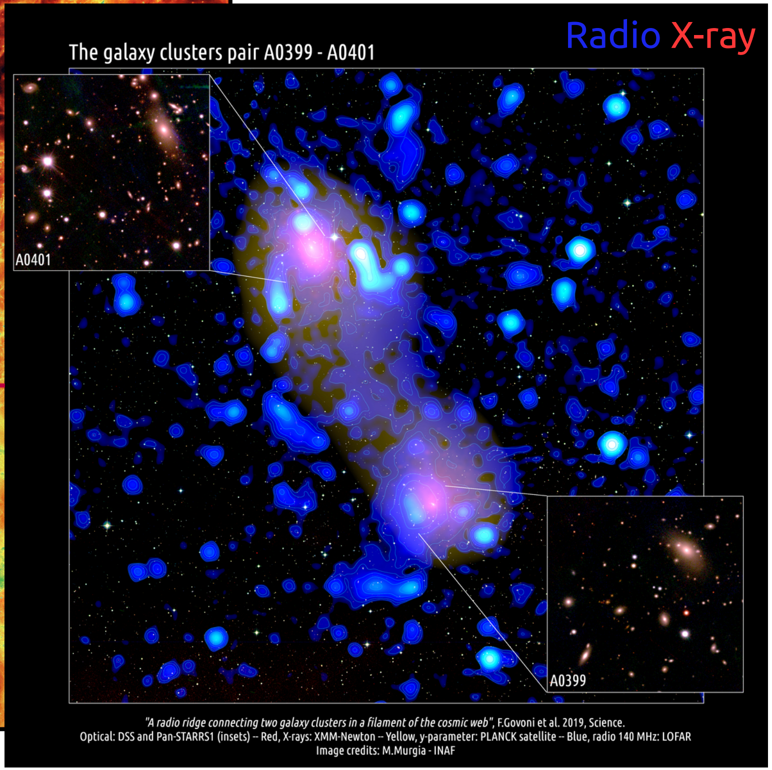
[Govoni+19]



[Botteon+22]

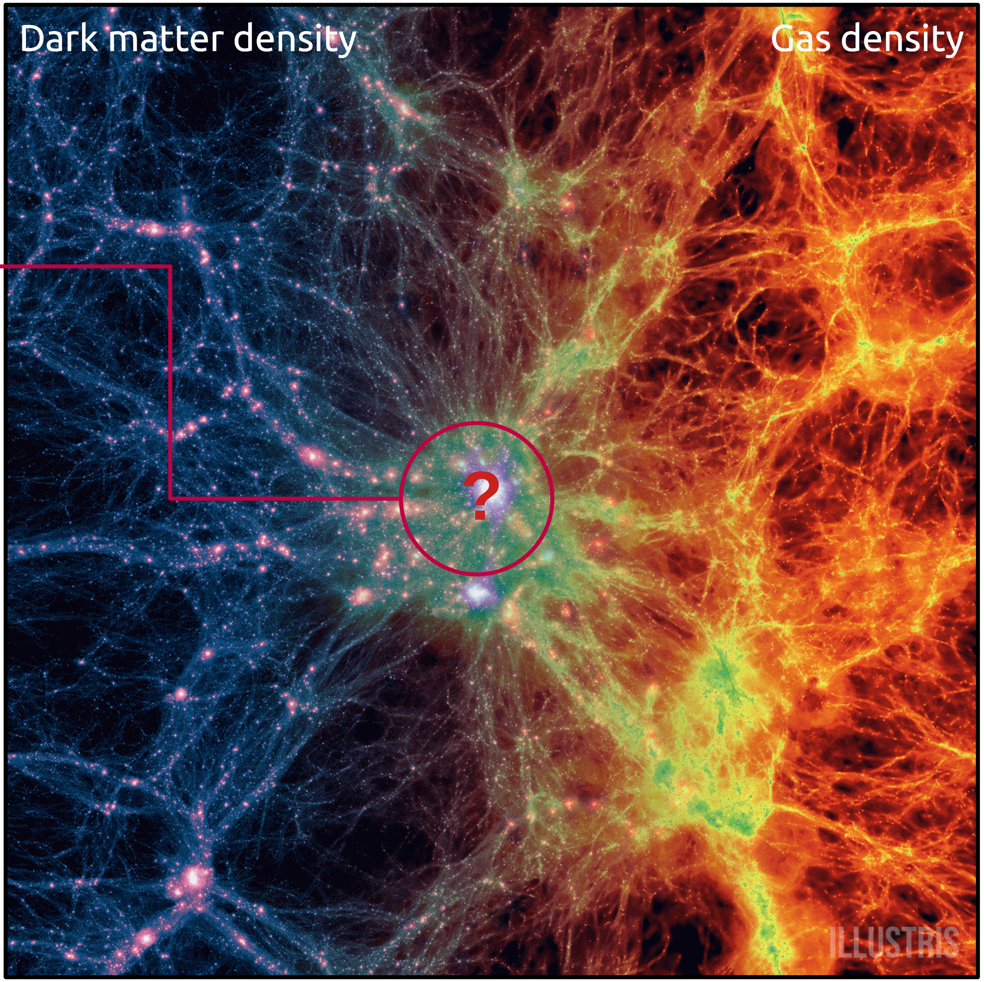


Vogelsberger+ 2014



A magnetised Universe

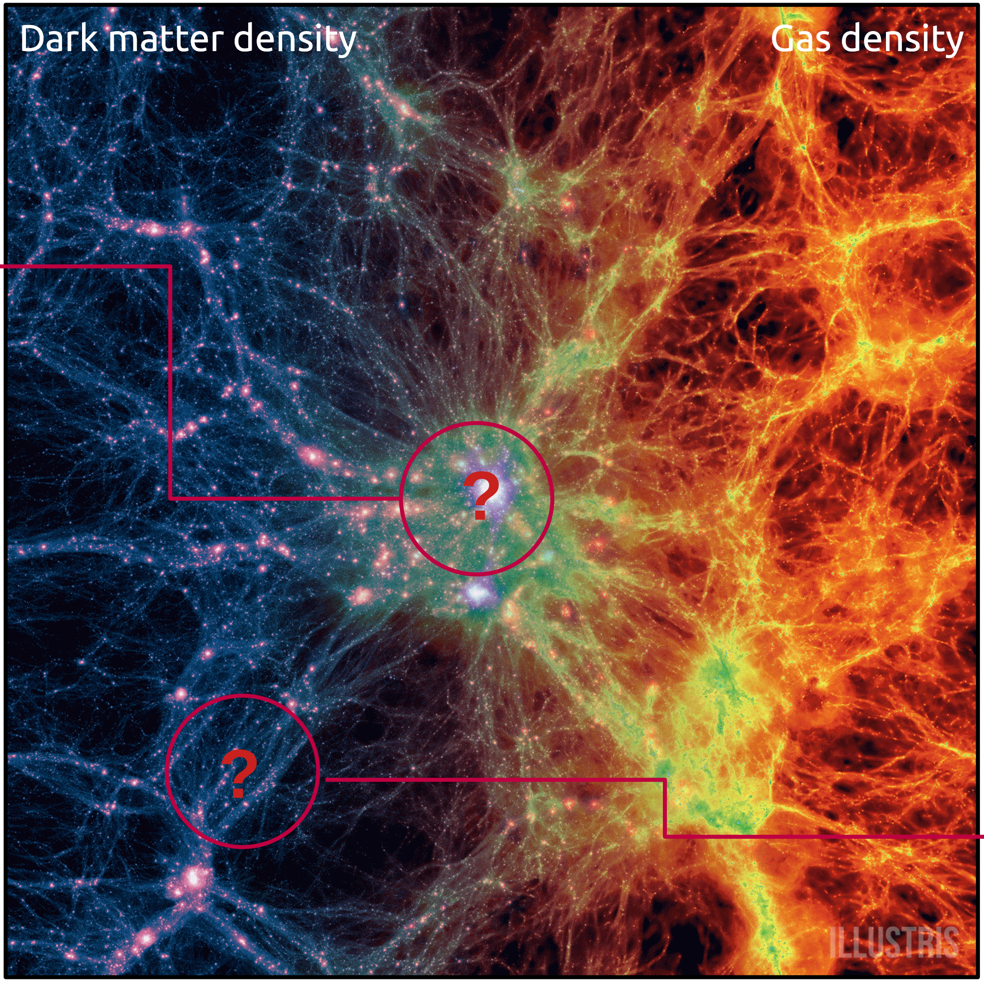
Understand the origin of diffuse radio sources and physics of galaxy clusters



Vogelsberger+ 2014

A magnetised Universe

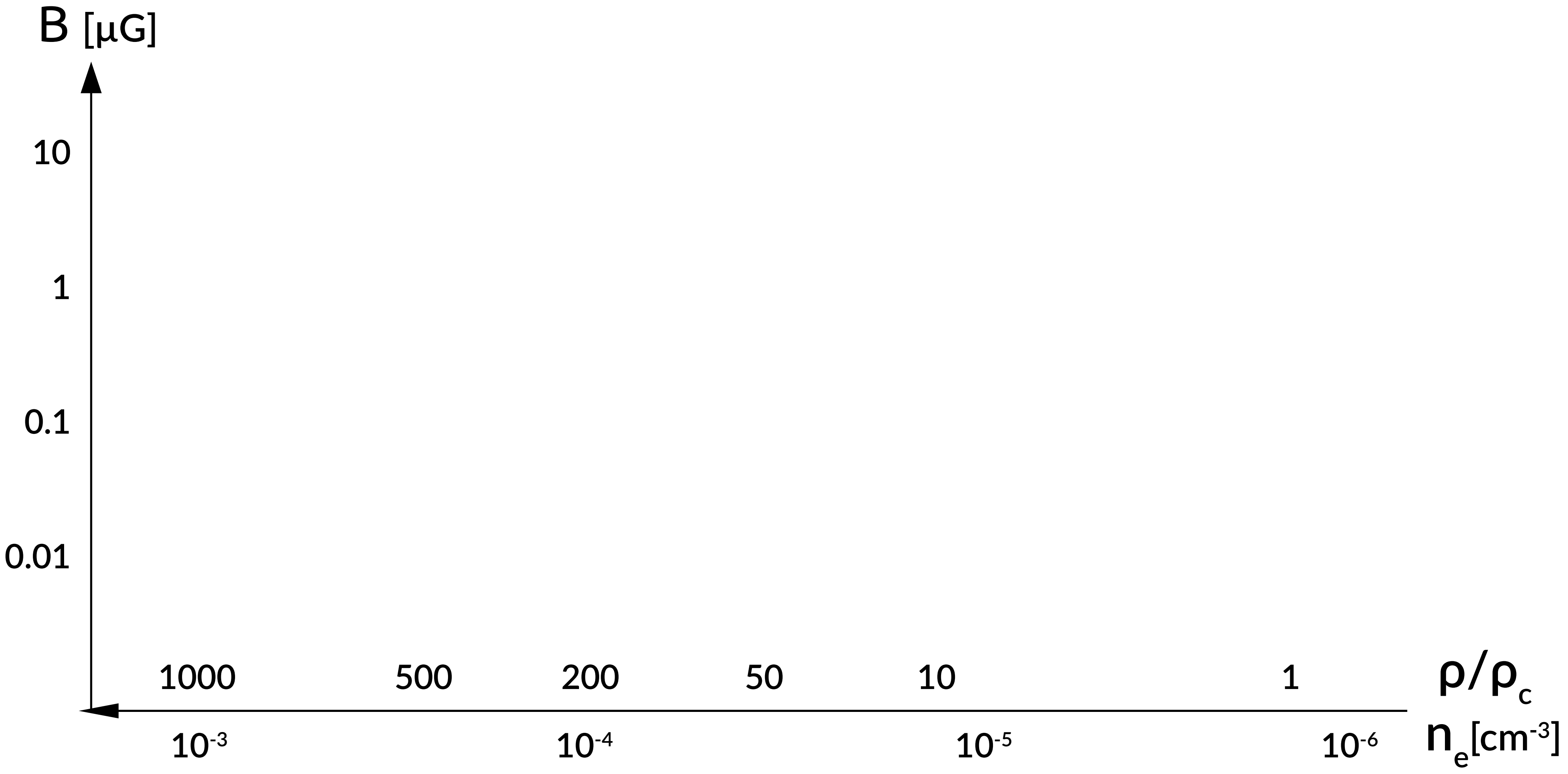
Understand the origin of diffuse radio sources and physics of galaxy clusters



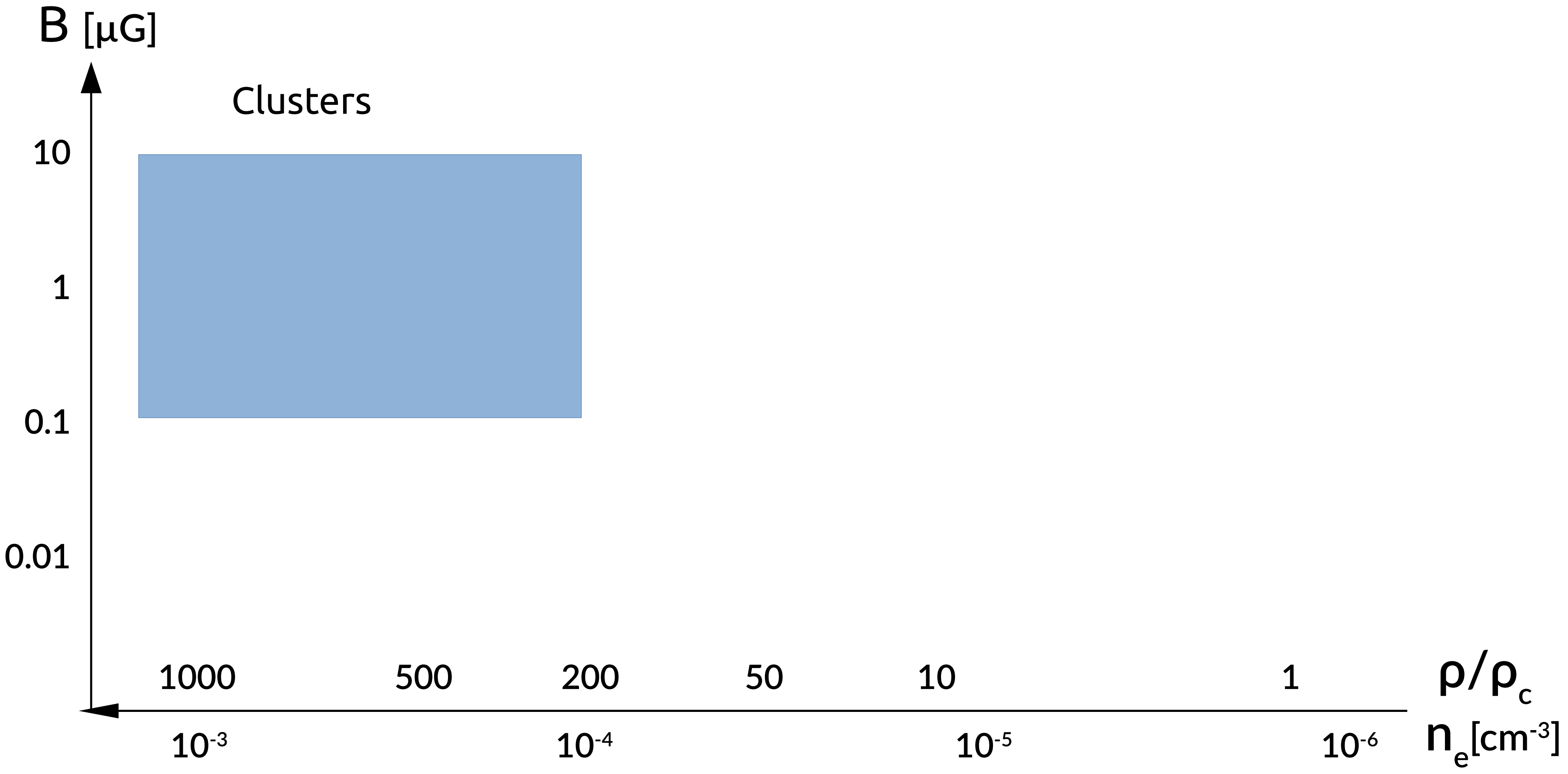
Vogelsberger+ 2014

Understand magneto-genesis and its cosmological implications

The big picture



The big picture



The big picture

B [μG]

[Murgia+04,Bonafede+10,Vacca+12,Govoni+17,Stuardi+21,Osinga+22,25]

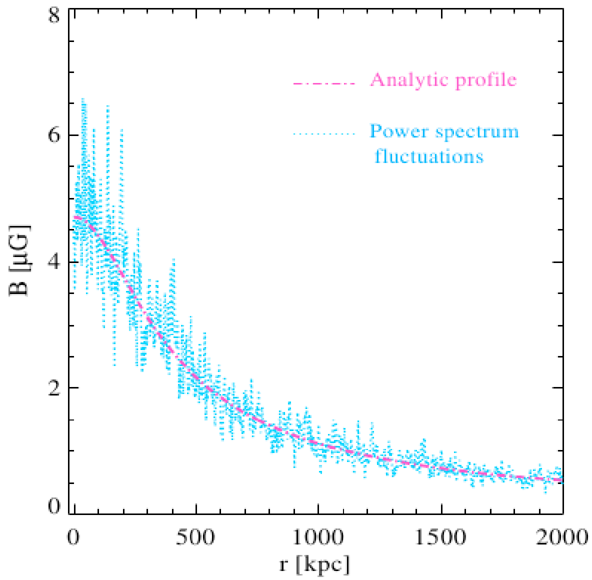
Clusters

10

1

0.1

0.01



Radial profile

$$|\boldsymbol{B}(r)| = \langle B_0 \rangle [n_{THe}(r)/n_0]^{\eta}$$

η=0.5-1

Power spectrum

$$E_B(k) \propto k^{-n}$$

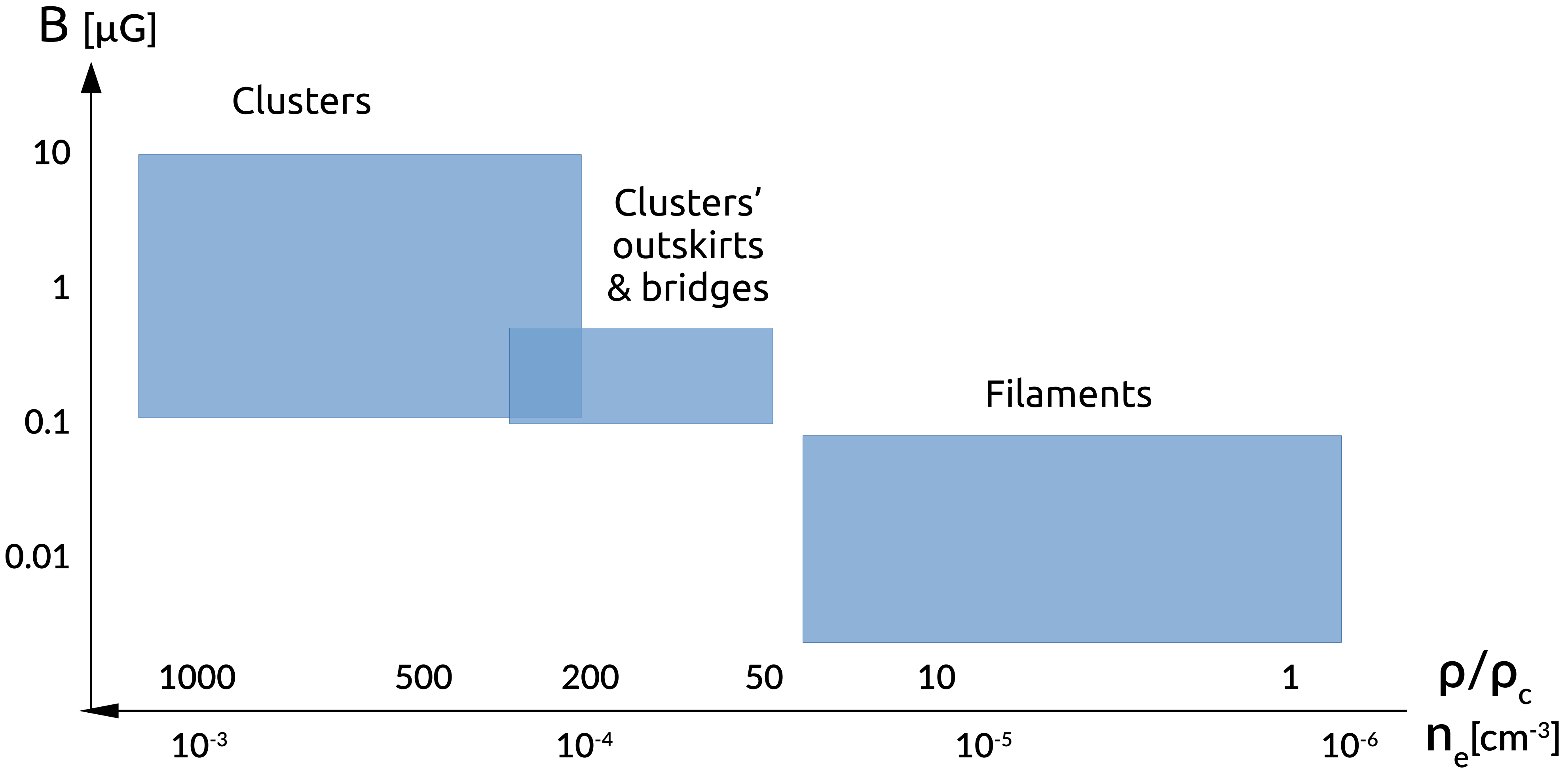
Kolmogorof-like: n=-5/3

[see also Dominguez-Fernandez+19]

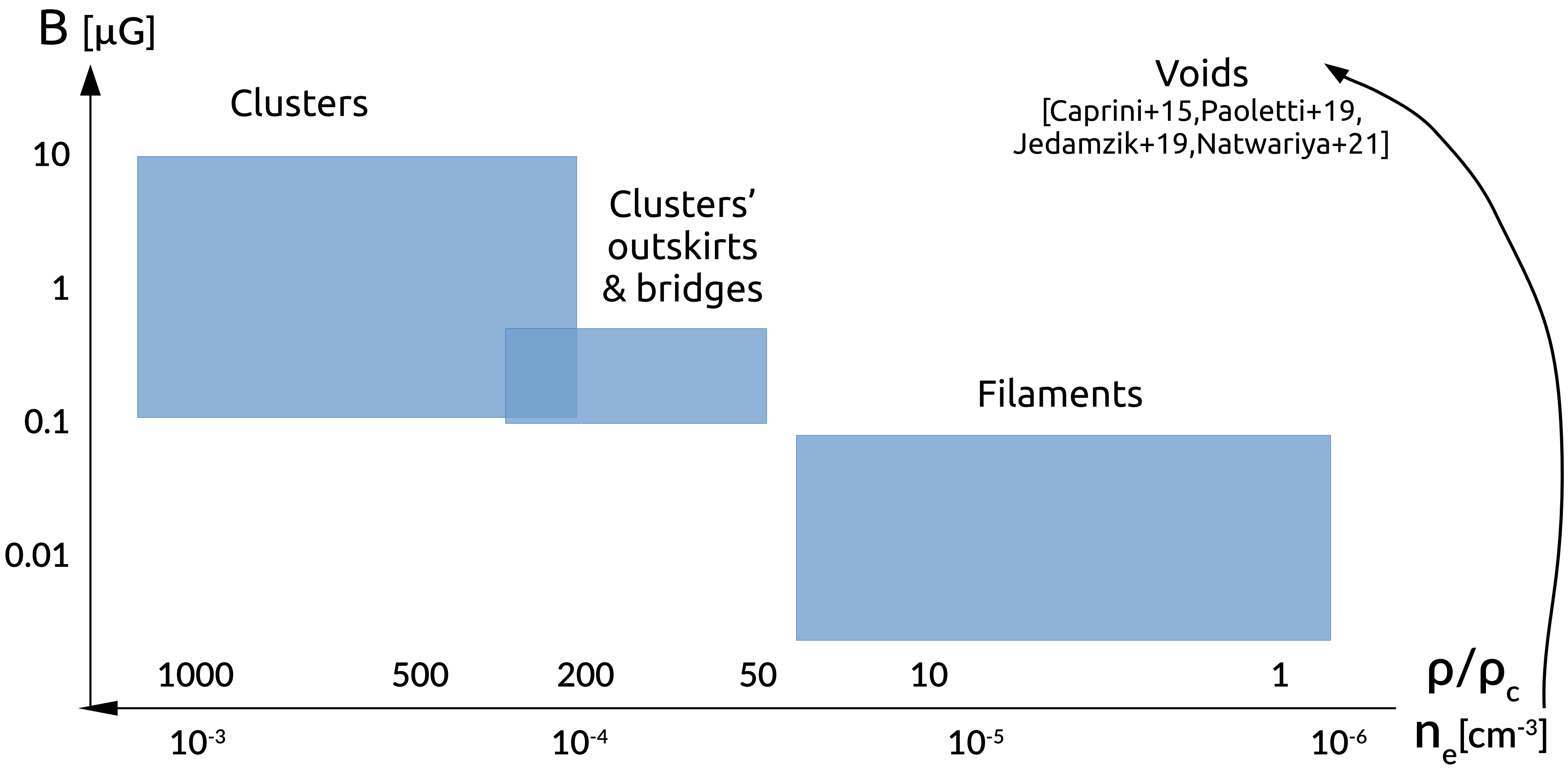
1000 500 200 50 10 1 ρ/ρ_c

10^{-3} 10^{-4} 10^{-5} 10^{-6} $n_e[cm^{-3}]$

The big picture

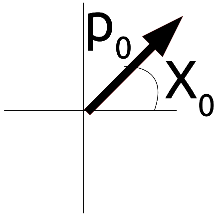


The big picture

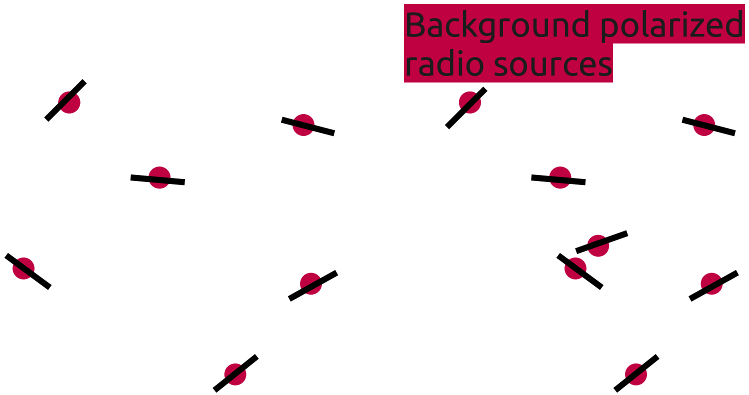


Polariazation and Faraday Rotation Measure (RM)

$$\boldsymbol{p_0} = p_0 e^{2i\chi_0}$$



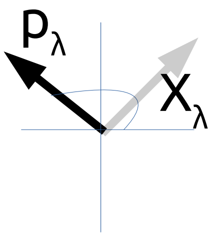
Intrinsic polarization



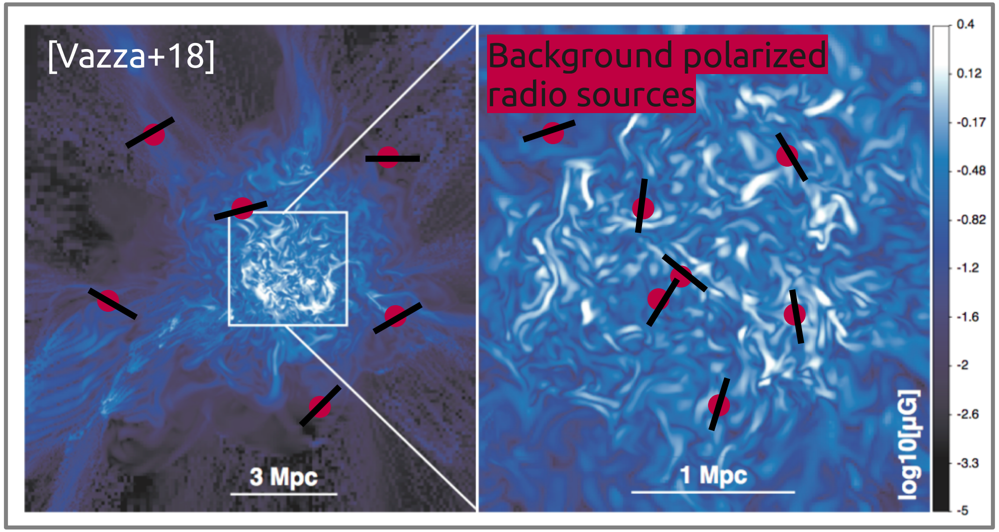
Polariazation and Faraday Rotation Measure (RM)

$$\boldsymbol{p}_\lambda = p_0 \, e^{2i(\chi_0 + RM\,\lambda^2)}$$

Rotation $\propto \lambda^2$



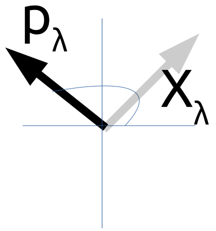
Observed polarization



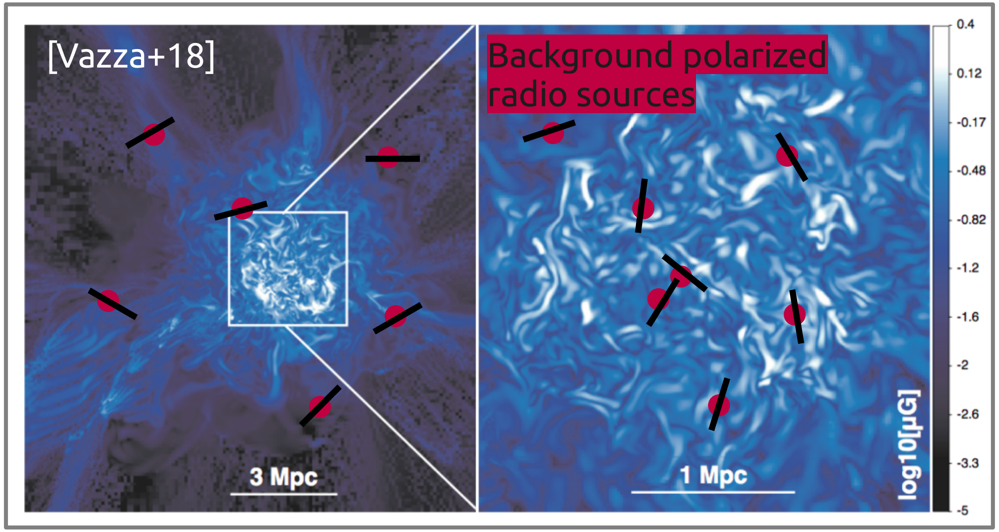
Polariazation and Faraday Rotation Measure (RM)

$$\boldsymbol{p}_{\lambda} = p_0 e^{2i(\chi_0 + RM\lambda^2)}$$

Rotation $\propto \lambda^2$



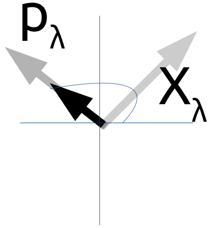
Observed polarization



$$RM \propto \int_{source}^{observer} n_{THe} B_{LOS} dl_{LOS}$$

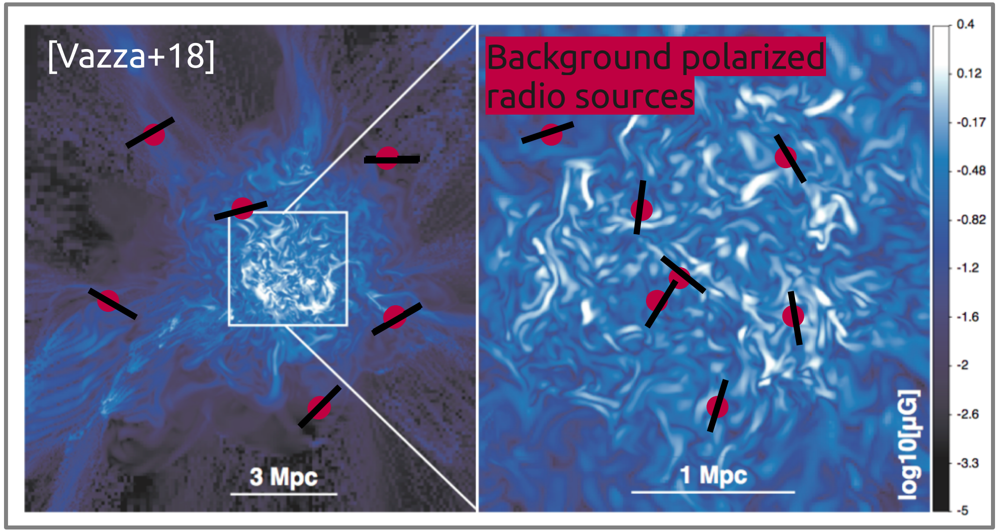
Polariazation and Faraday Rotation Measure (RM)

$$\boldsymbol{p}_{\lambda} = p_0 e^{2i(\chi_0 + RM\,\lambda^2)} e^{-2\sigma_{RM}^2 \lambda^4}$$

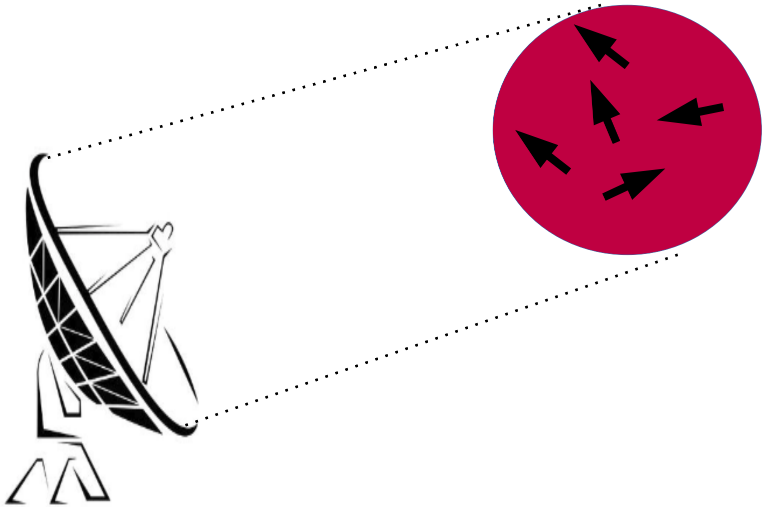


Observed polarization

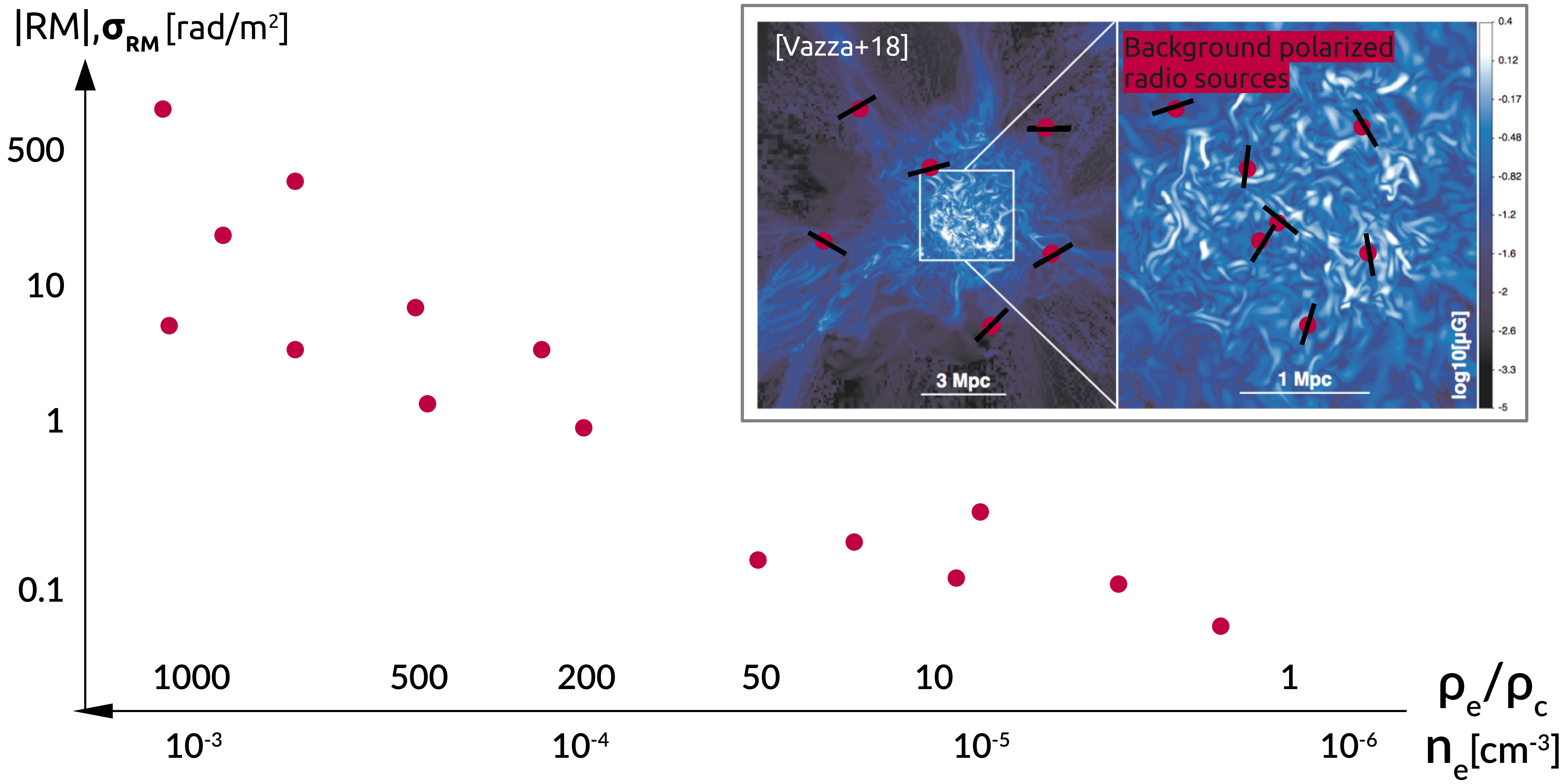
Rotation ∝ λ^2
Depolarization ∝ λ^4
[see also Arshakian+11]



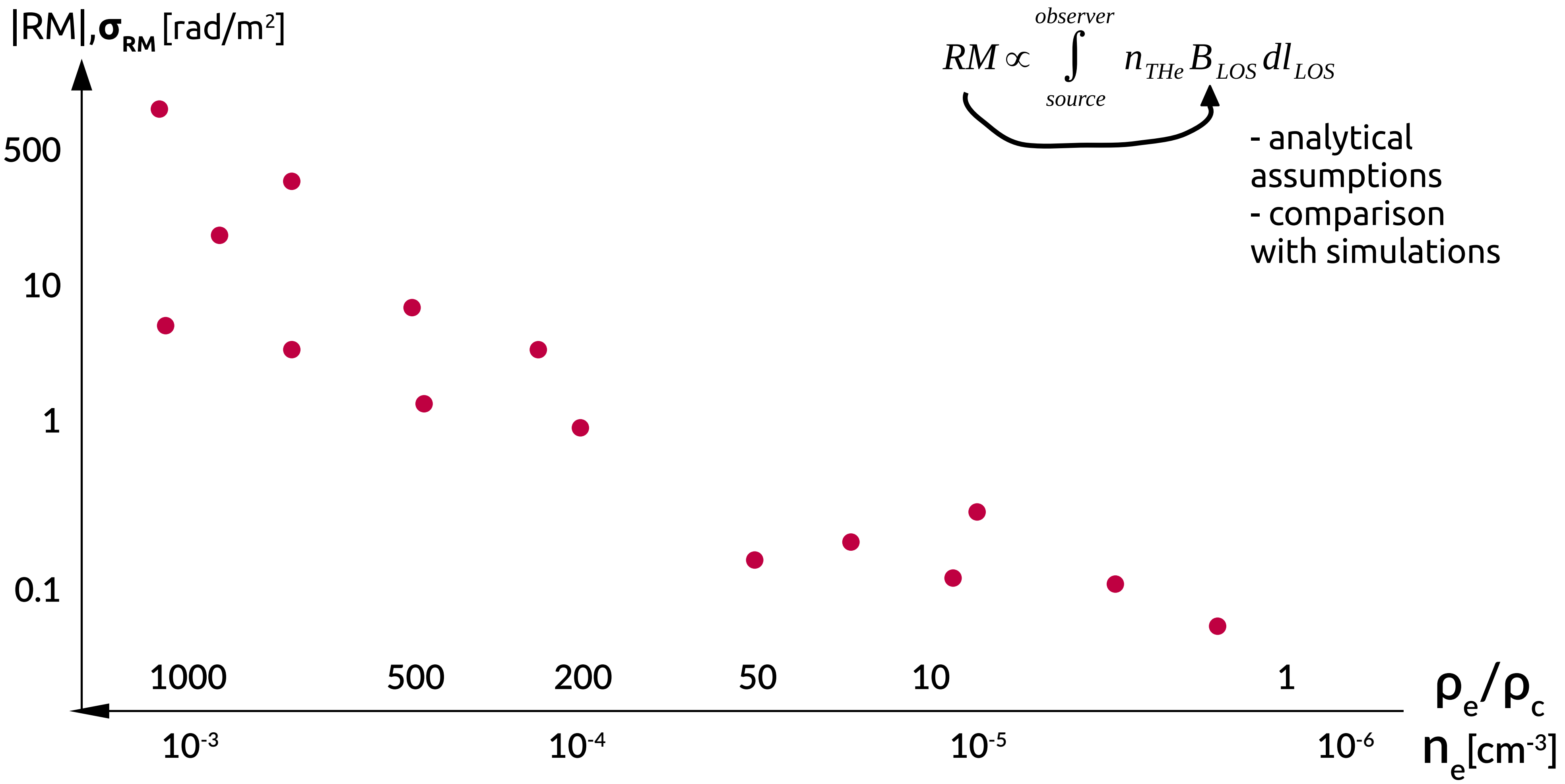
$$RM \propto \int_{source}^{observer} n_{THe} B_{LOS}\, dl_{LOS}$$



Polariazation and Faraday Rotation Measure (RM)



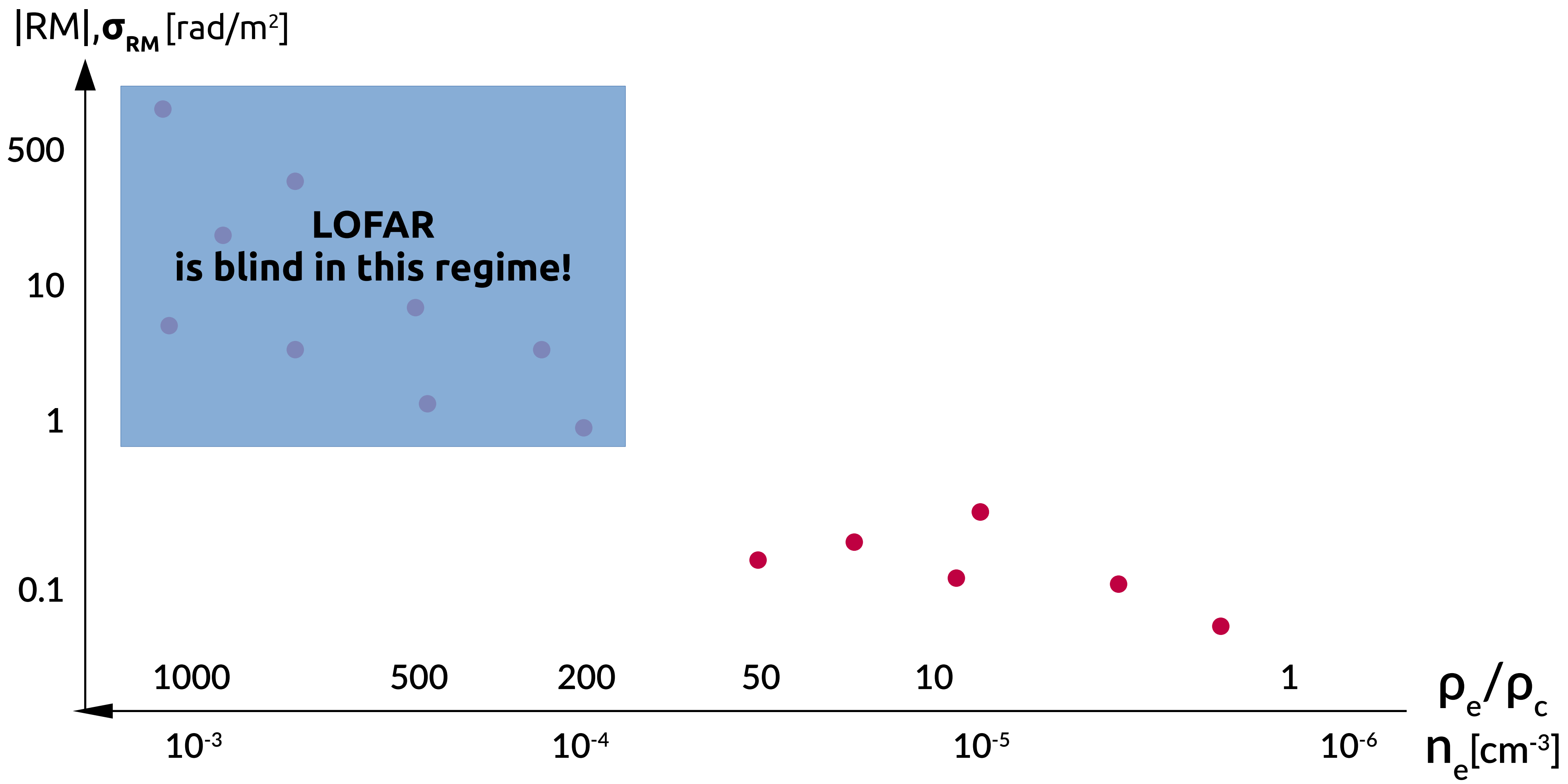
Polariazation and Faraday Rotation Measure (RM)



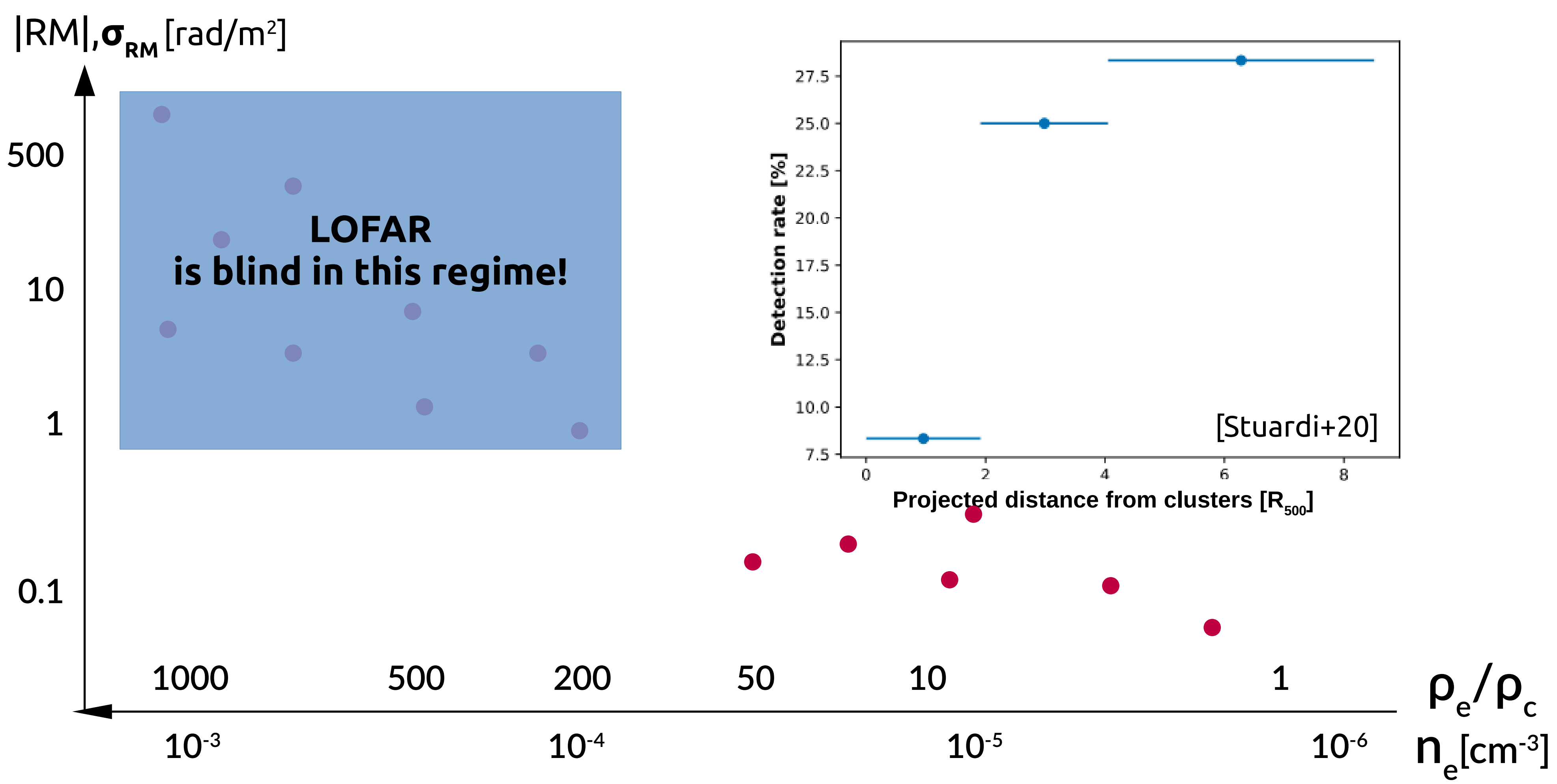
$$RM \propto \int_{source}^{observer} n_{THe} B_{LOS} dl_{LOS}$$

- analytical assumptions
- comparison with simulations

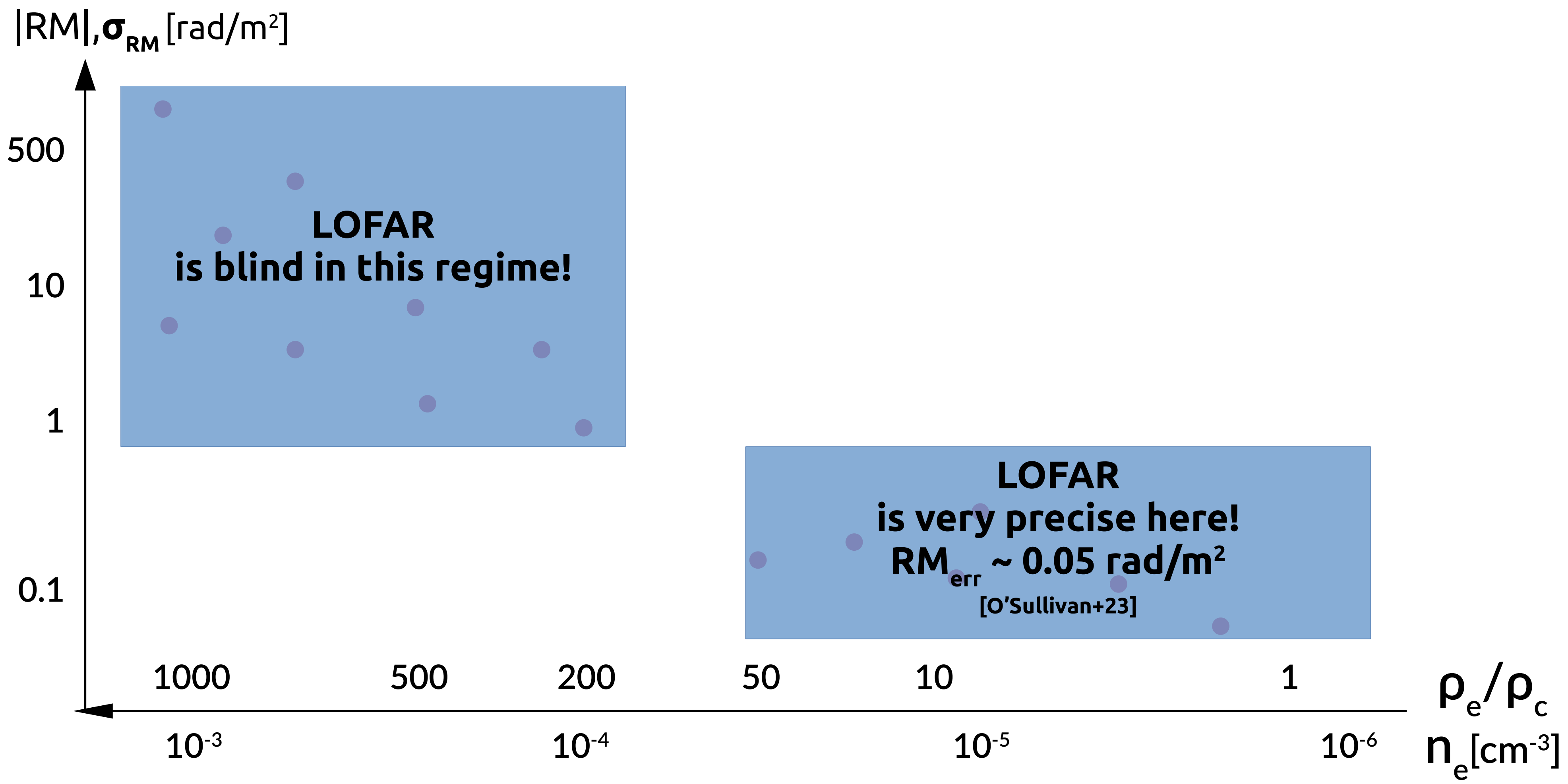
Polariazation and Faraday Rotation Measure (RM)



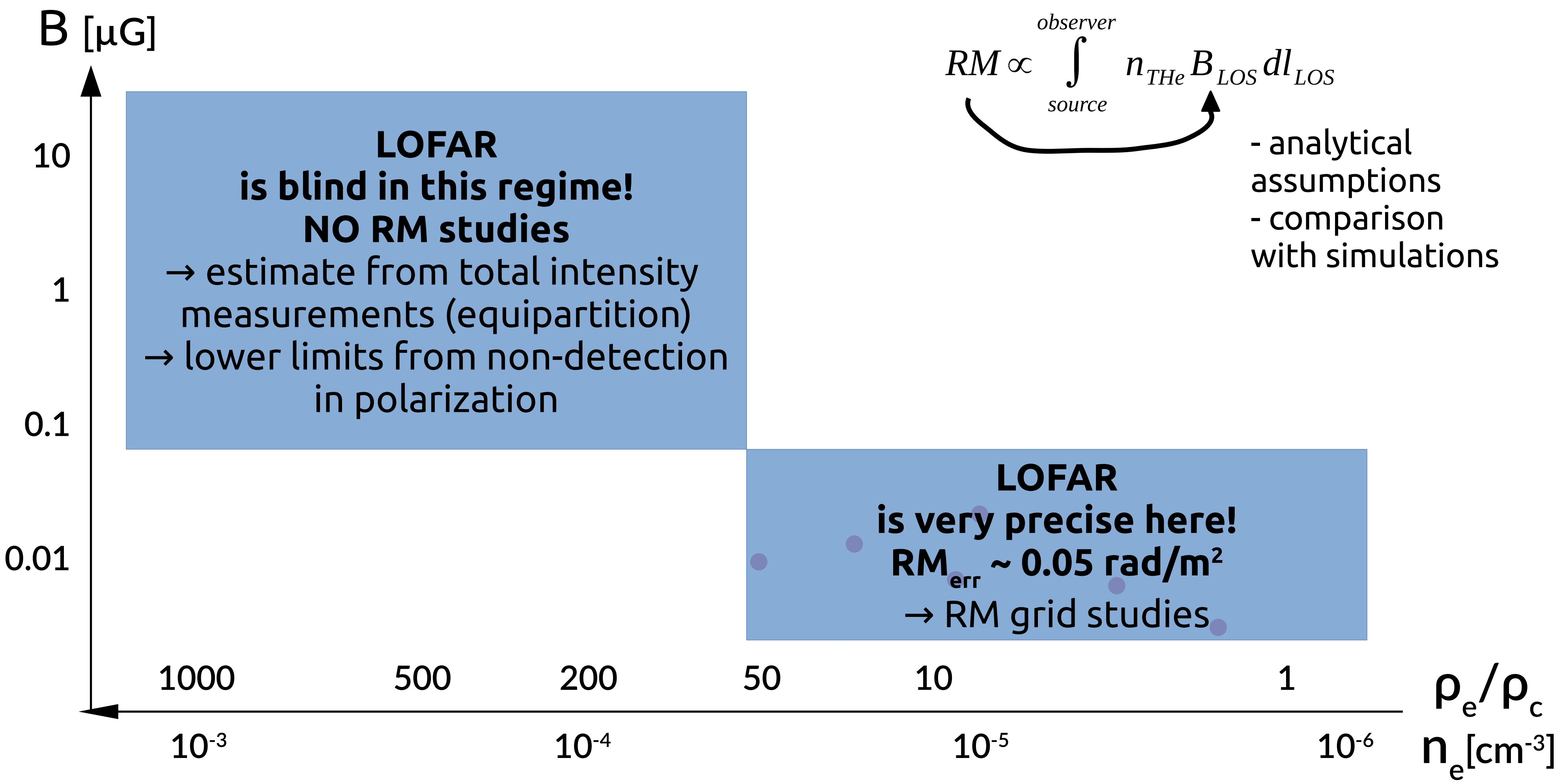
Polariazation and Faraday Rotation Measure (RM)



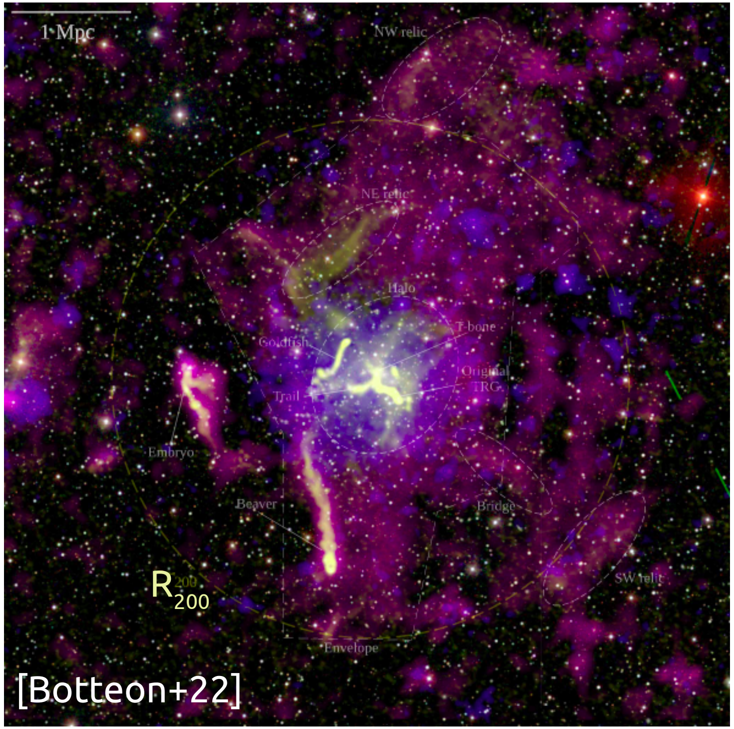
Polariazation and Faraday Rotation Measure (RM)



Polariazation and Faraday Rotation Measure (RM)

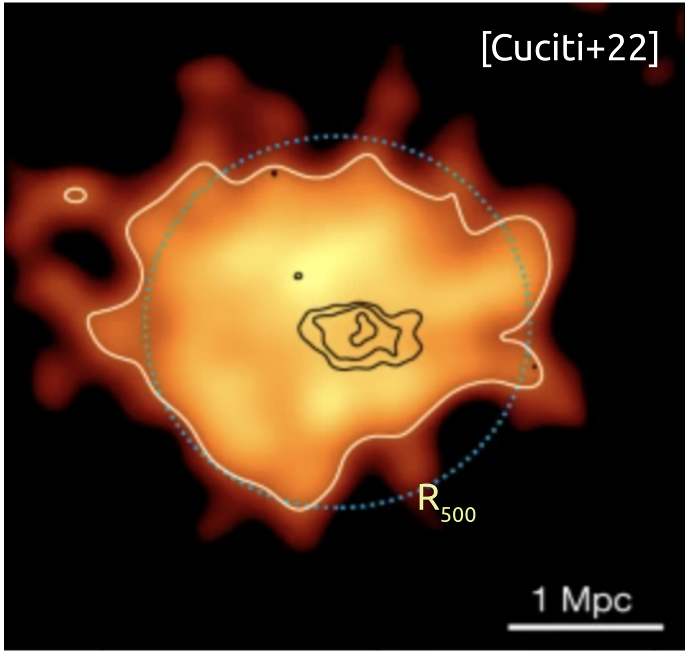


Magnetic fields in galaxy clusters outskirts

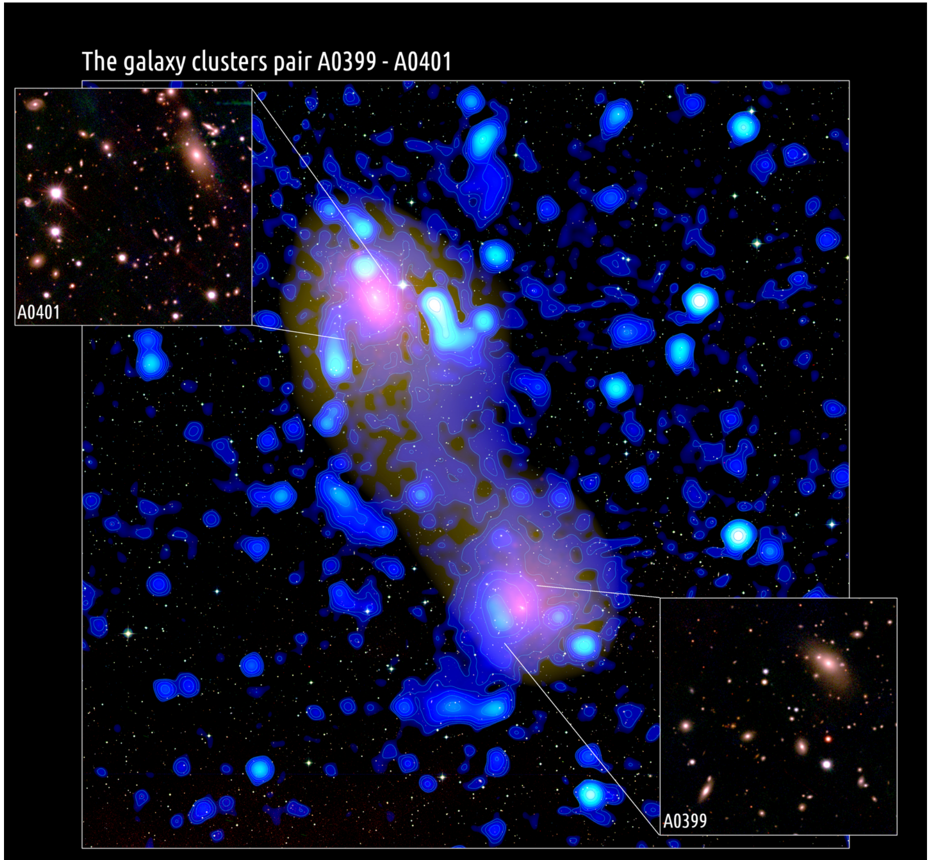


- From equipartition:
  B~0.1-1.7 μG at ~ R_{200}
  [Botteon+22]

- Reproduced in cosmological simulations
  - turbulent acceleration
  - B amplification via dynamo
  B~0.1-0.5 μG at ~ R_{500}
  [Beduzzi+24]



Magnetic fields in bridges

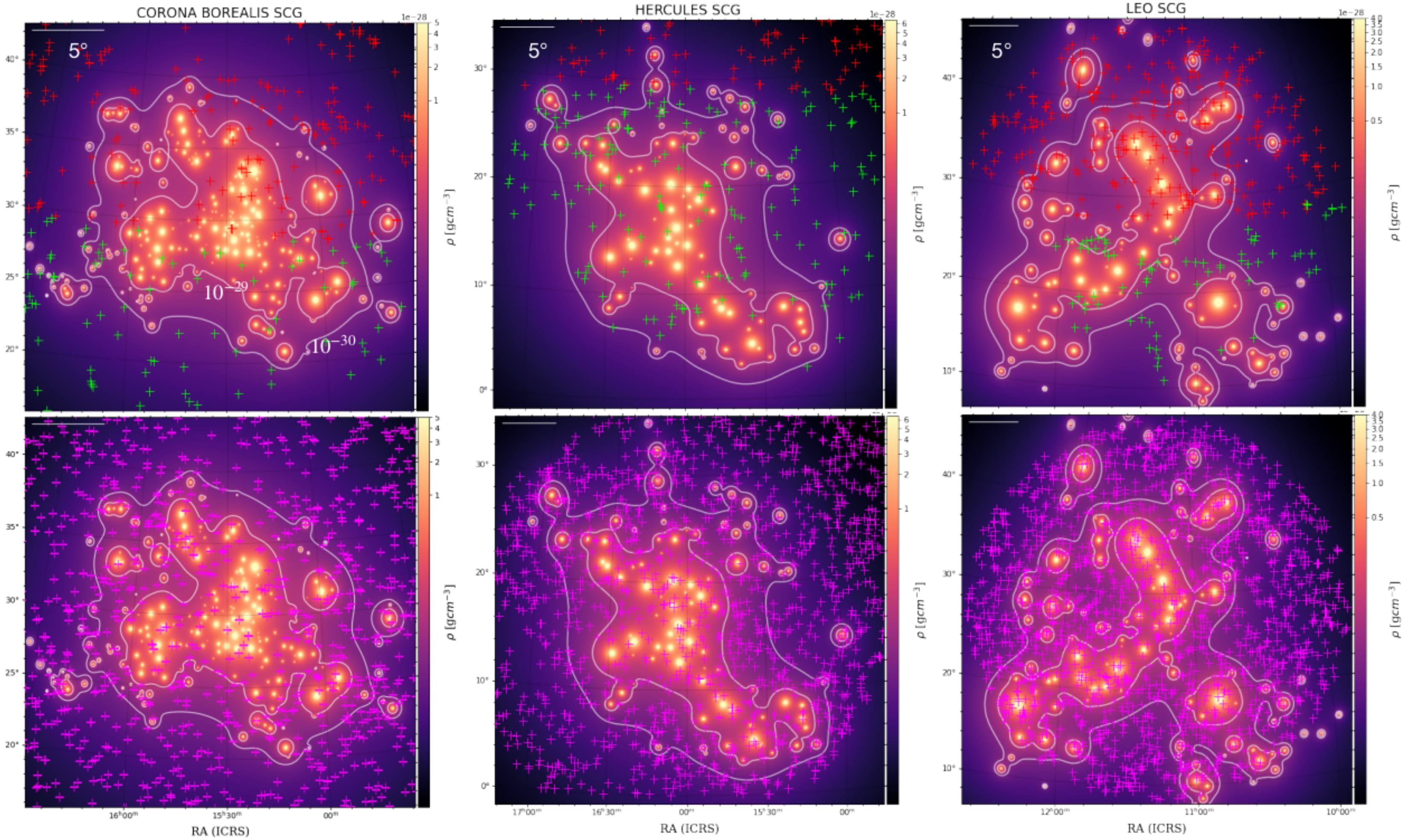


"A radio ridge connecting two galaxy clusters in a filament of the cosmic web", F.Govoni et al. 2019, Science.
Optical: DSS and Pan-STARRS1 (insets) -- Red, X-rays: XMM-Newton -- Yellow, y-parameter: PLANCK satellite -- Blue, radio 140 MHz: LOFAR
Image credits: M.Murgia - INAF

- Two possible origins for cosmic rays:
  - low Mach number shocks
  → B~0.1 μG
  [Govoni+19]
  - turbulence
  → B~0.5-0.6 μG
  [Brunetti&Vazza2020]

- Polarized emission non-detected at 150 MHz
  σ_{RM} > 0.1 rad/m² (in front of the bridge)
  B > 0.46 nG
  with fluctuations on scales <140kpc
  [Balboni+2023]

Magnetic fields filaments: super-clusters [Pignataro+25]

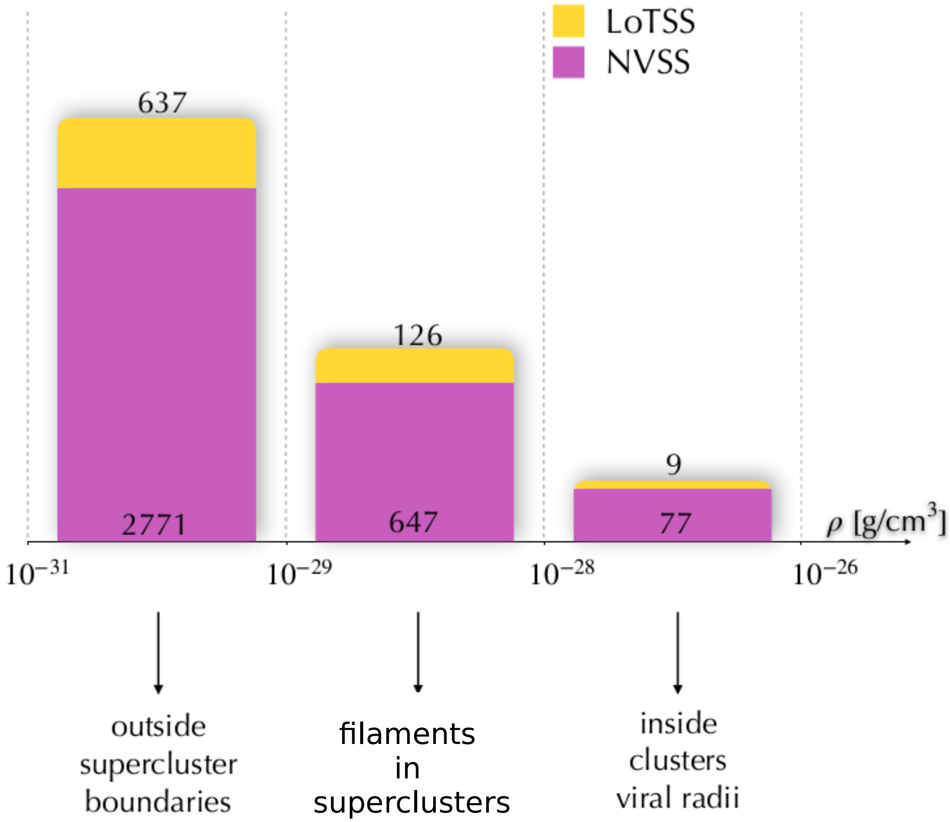


Stacked RM of three super-clusters

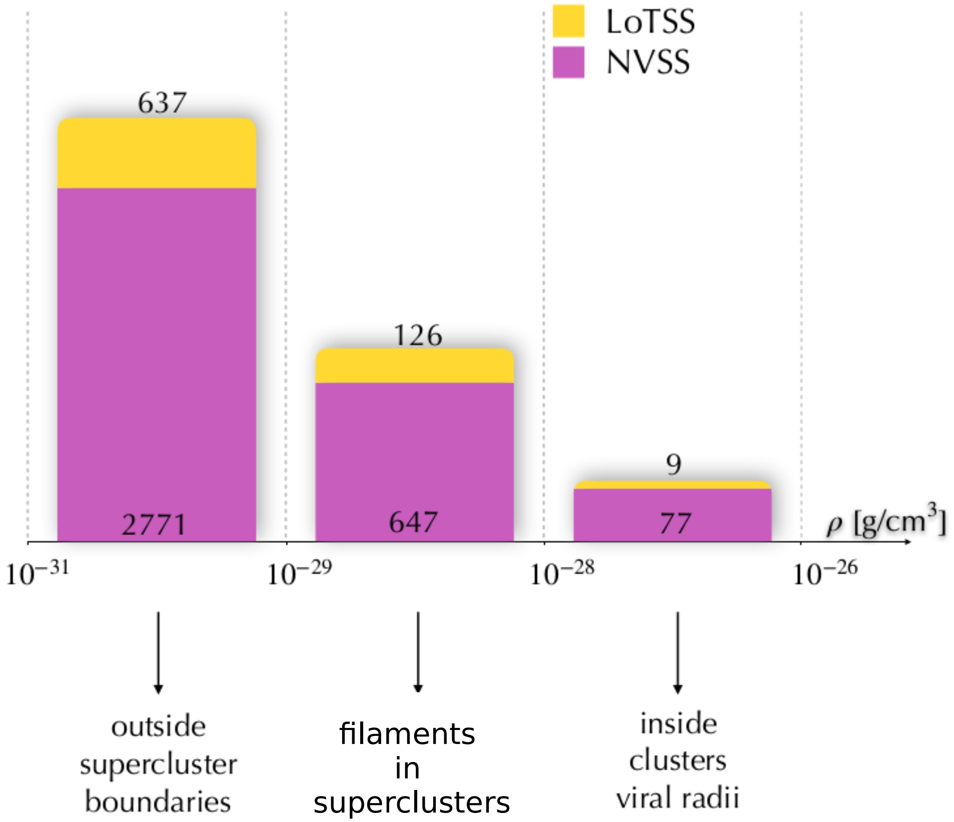
LoTSS (144MHz)

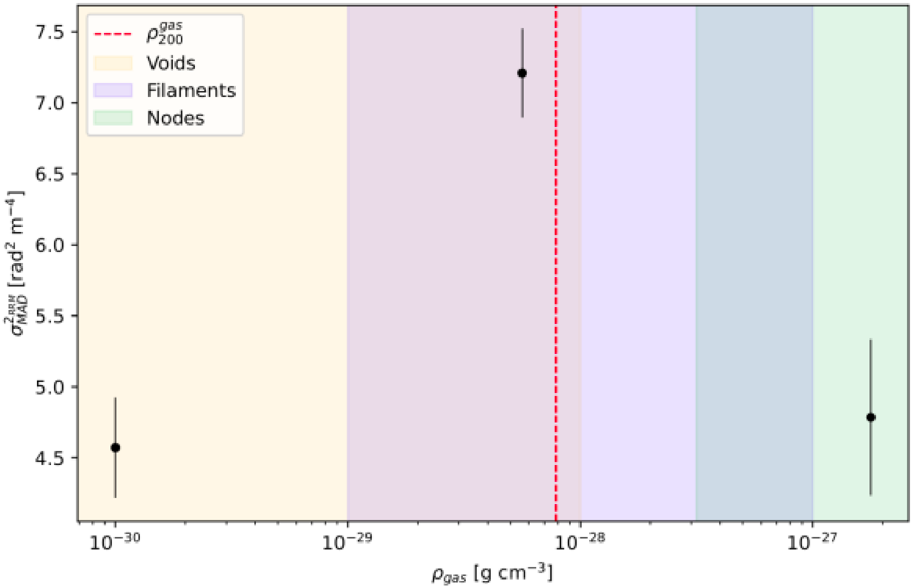
and NVSS (1.4GHz)

Magnetic fields filaments: super-clusters [Pignataro+25]



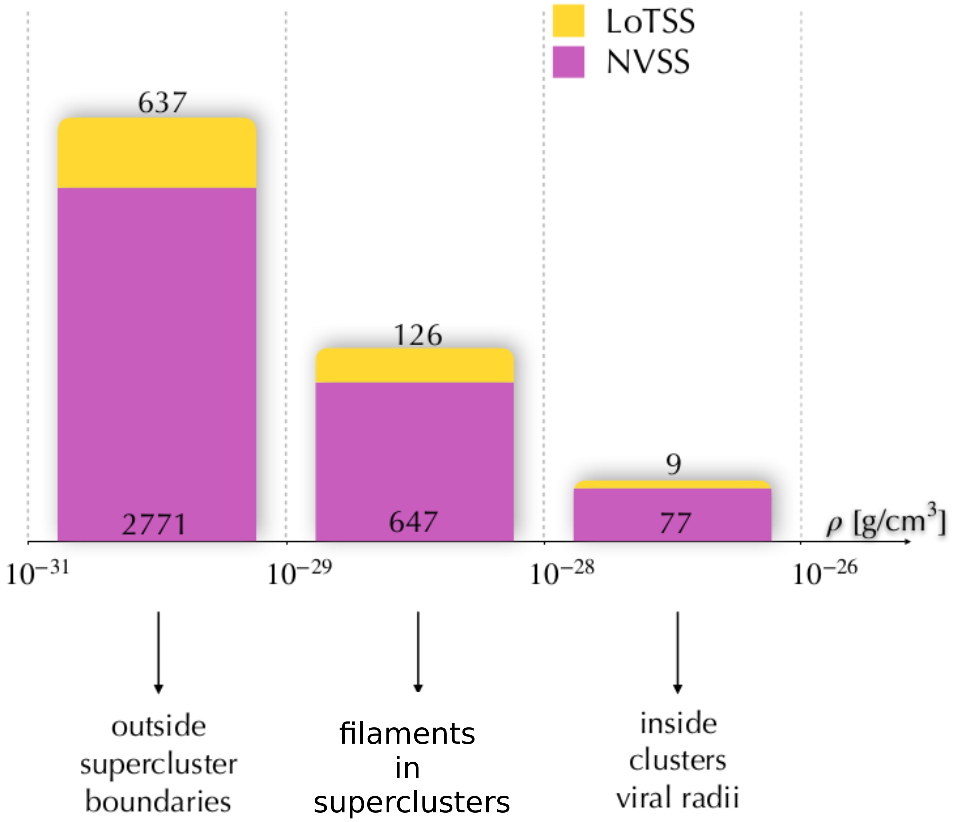
Magnetic fields filaments: super-clusters [Pignataro+25]



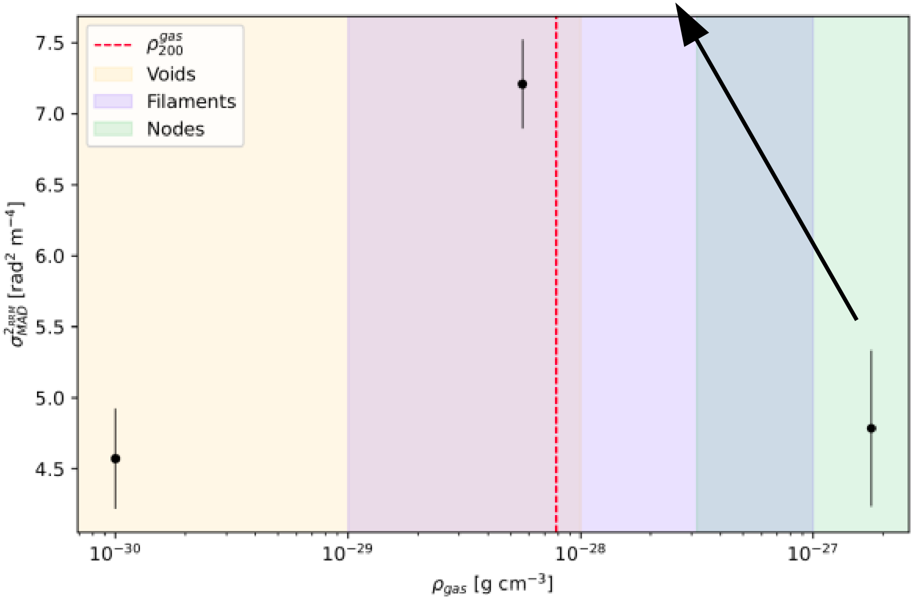


RM scatter in different density bins

Magnetic fields filaments: super-clusters [Pignataro+25]

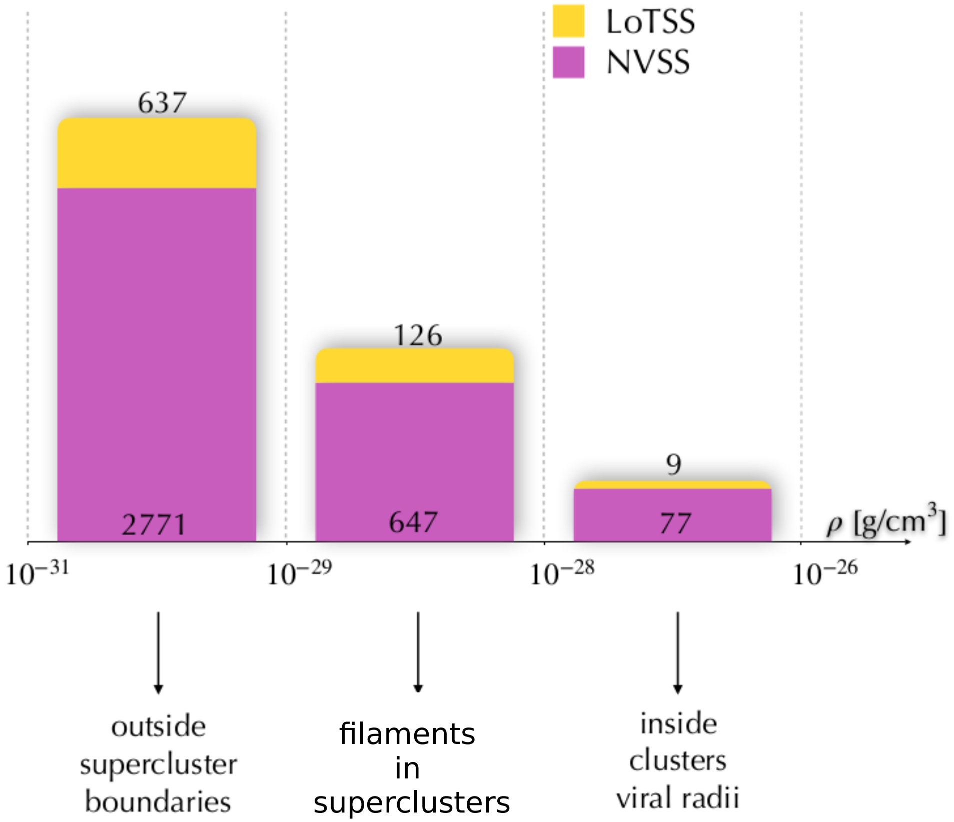


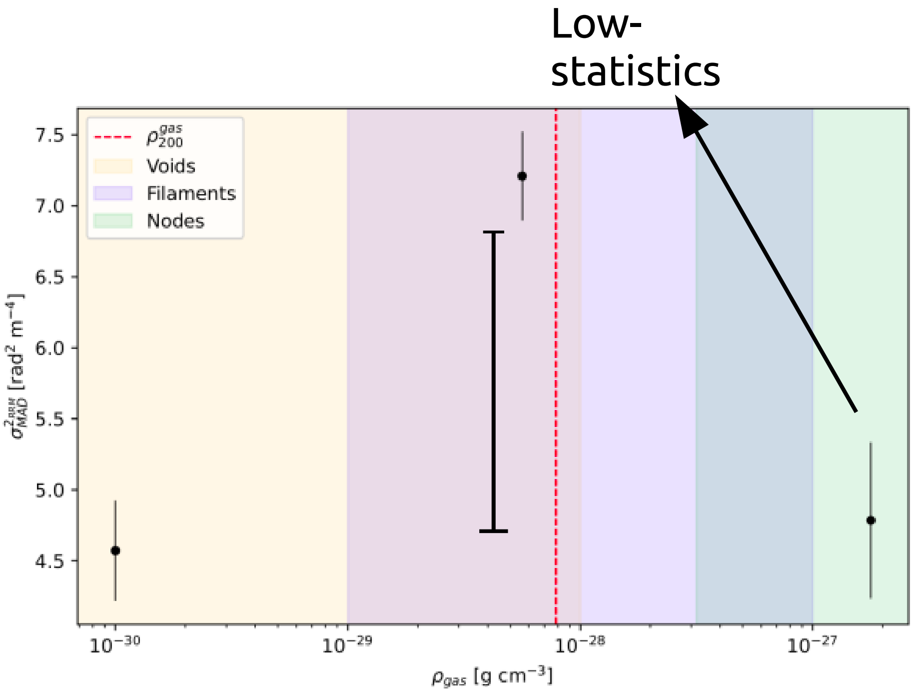
Low-statistics



RM scatter in different density bins

Magnetic fields filaments: super-clusters [Pignataro+25]



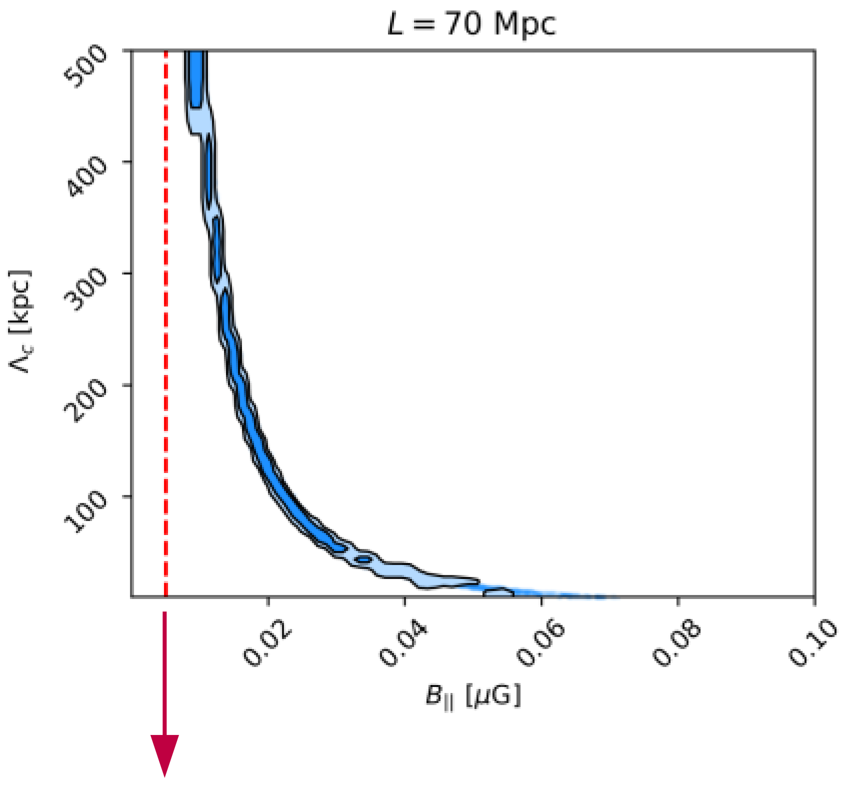


RM scatter in different density bins

Significant contribution from filaments:

σ^2_{RM} = 2.5±0.5 rad²/m⁴

Magnetic fields filaments: super-clusters [Pignataro+25]

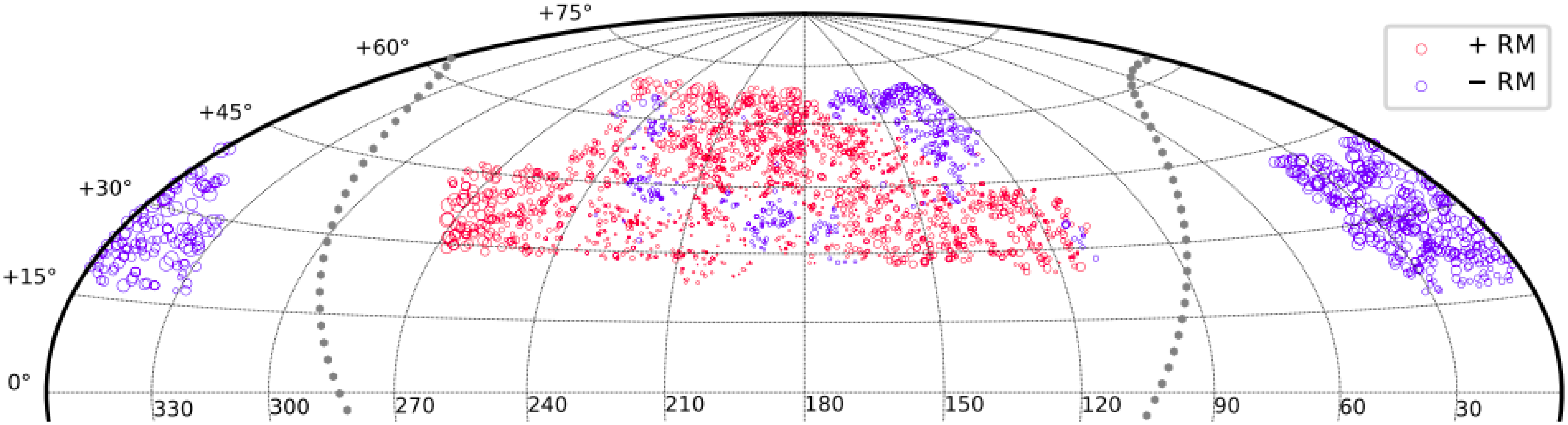


Adiabatic compression from B_{in}=0.1 nG

$$\sigma_{\rm th}^{2_{\rm RRM}} = 0.812^2 \left(\frac{\Lambda_c}{\rm pc}\right) \int \left(\frac{n_e}{\rm cm^{-3}} \frac{B_\parallel}{\mu\rm G}\right)^2 \frac{{\rm d}l}{\rm pc},$$

RM scatter in different density bins
Significant contribition from filaments:
σ^2_{RM} = 2.5±0.5 rad²/m⁴
→ **B = 19^{+50}_{-8} nG**

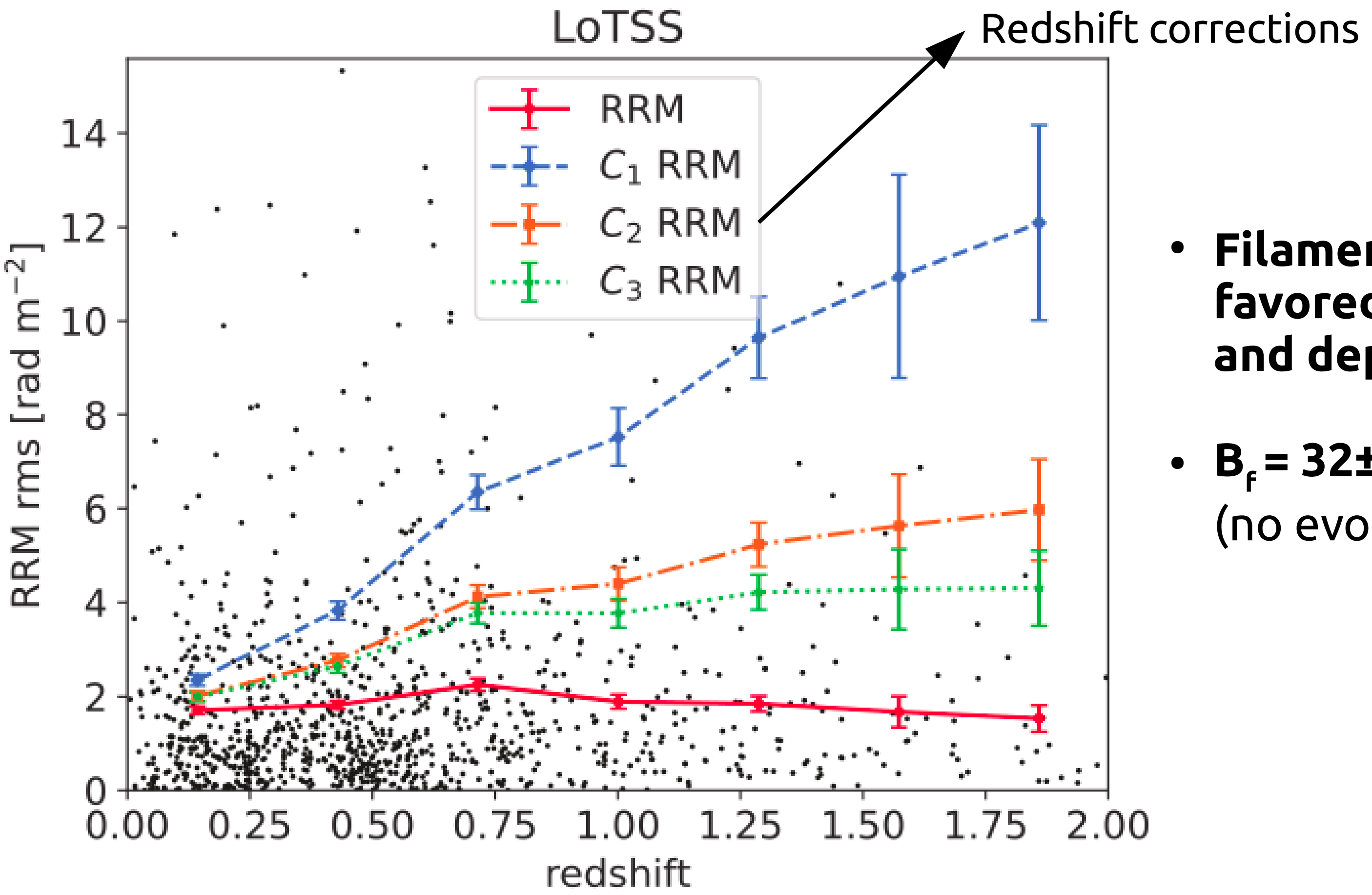
Magnetic fields in filaments: LoTSS DR2 RM grid



- 2461 RM sources
- 79% with redshift
- Large scale patterns due to our Galaxy
  $RRM=RM-RM_{Galactic}$

O'Sullivan+23

Magnetic fields in filaments: LoTSS DR2 RM grid

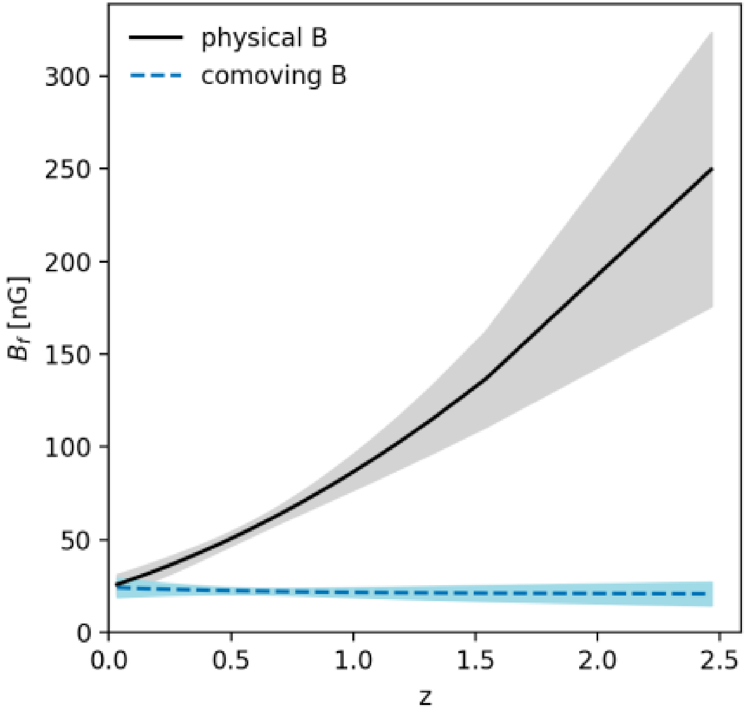


- **Filaments of the cosmic web favored as the origin of the RRM and depolarization trend with z**

- **B_f = 32±3 nG**
  (no evolution of n_e and B)

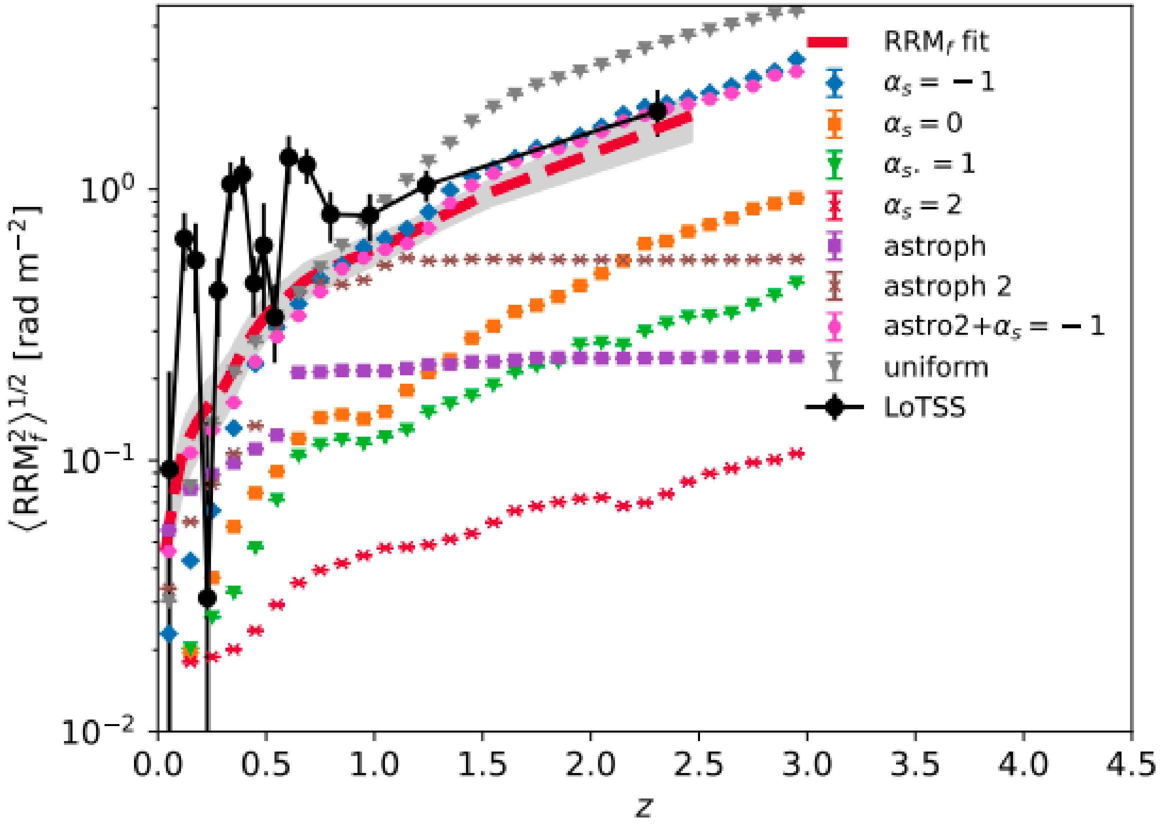
Carretti,CS+22

Magnetic fields in filaments – LoTSS DR2 RM grid



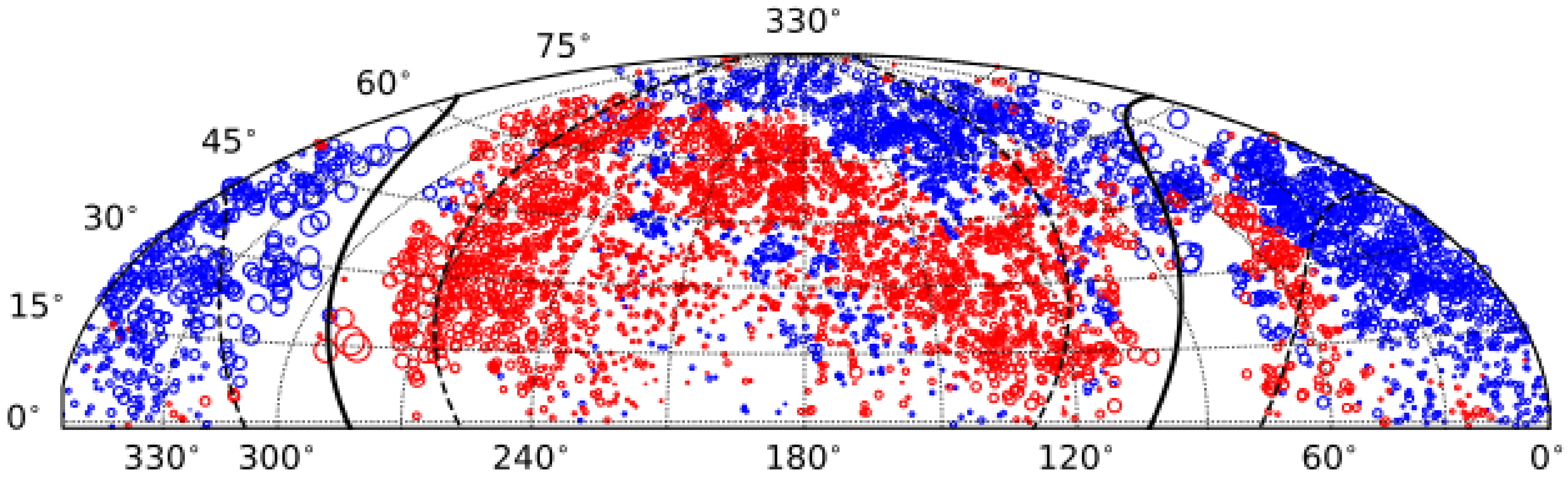
- $B_f = B_{f,0}\,(1 + z)^{\alpha}$
  $B_{f,0}$ = 11–15 nG ± 4 nG,
  α = 2.3–2.6 ± 0.5
- Strongly favors **primordial origin**

Comparison with MHD cosmological simulations



Carretti+23,25

Looking forward: LoTSS DR3 RM grid



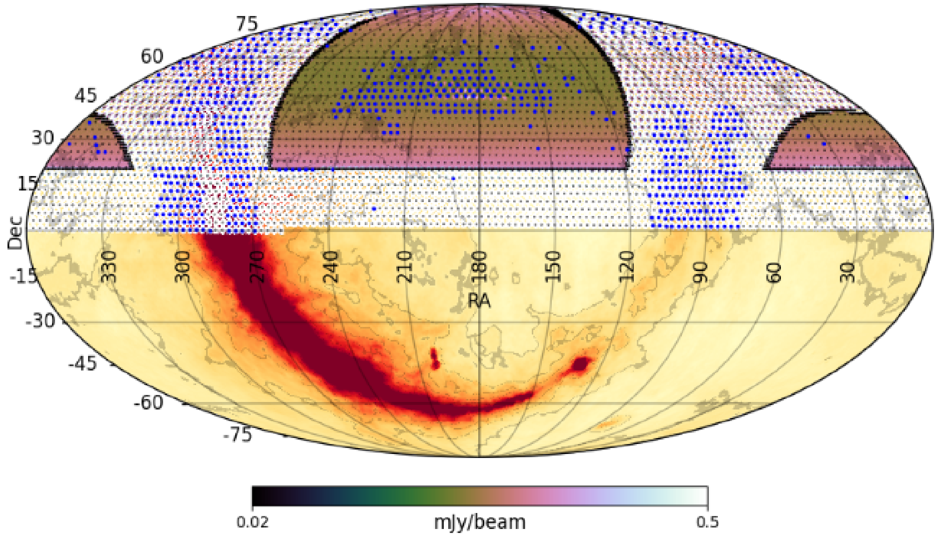
- x3 sky area
- ~5000 RMs
- preliminary catalogue available internally to survey and magnetism KSPs

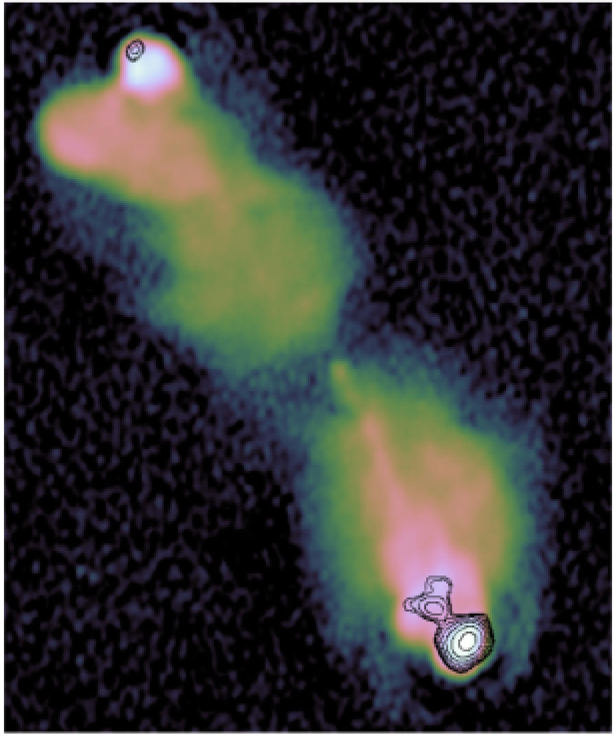
Courtesy of S. O'Sullivan

Looking forward: LOFAR 2.0

The International LoTSS (ILoTSS, Shimwell, O'Sullivan+) proposing to image extragalactic sky at 0.3" to ~30 uJy (overlap with EUCLID)
& finish LoTSS in Galactic plane

- more than x1.5 areal polarised source density





[ILoTSS proposal]

Synergies with GHz-surveys

- increase polarised source density in intermediate density regimes
- disentangle astrophysical from primordial contribution to RRM(z)

Synergies with GHz-surveys

- increase polarised source density in intermediate density regimes
- disentangle astrophysical from primordial contribution to RRM(z)

APERTIF
APERture Tile In Focus

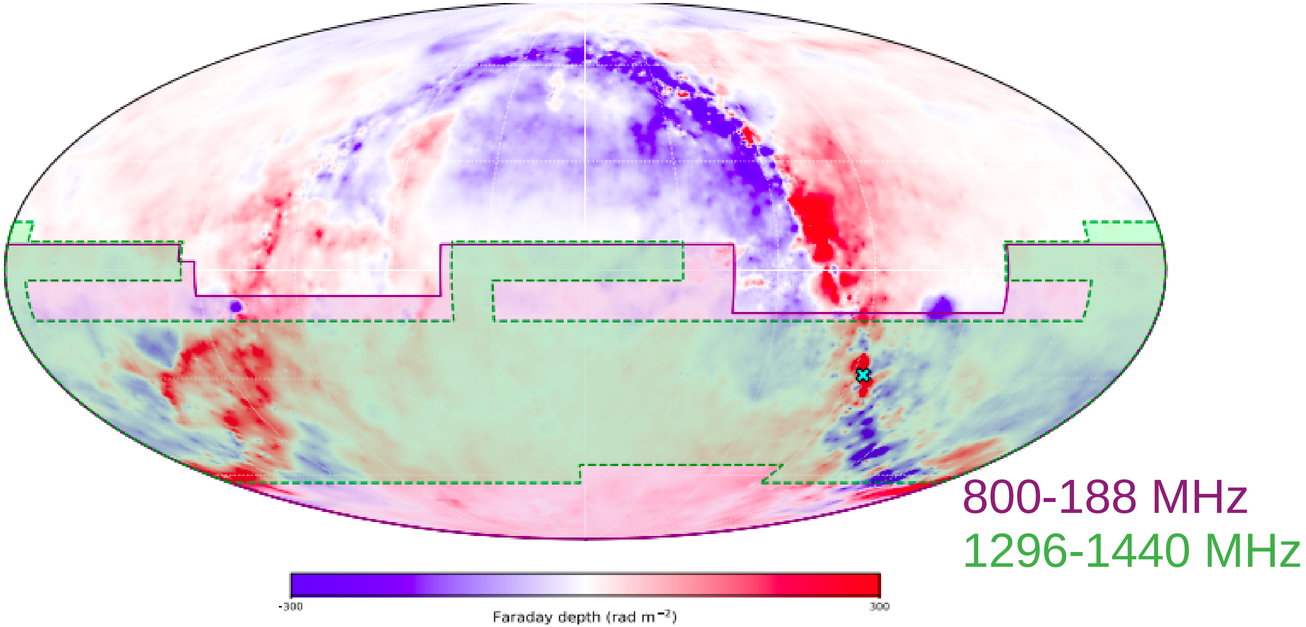
A. Berger's talk on ApPolLo

Synergies with GHz-surveys

- increase polarised source density in intermediate density regimes
- disentangle astrophysical from primordial contribution to RRM(z)

APERTIF
APERture Tile In Focus

POSSUM
POLARISATION SKY SURVEY OF THE UNIVERSE'S MAGNETISM



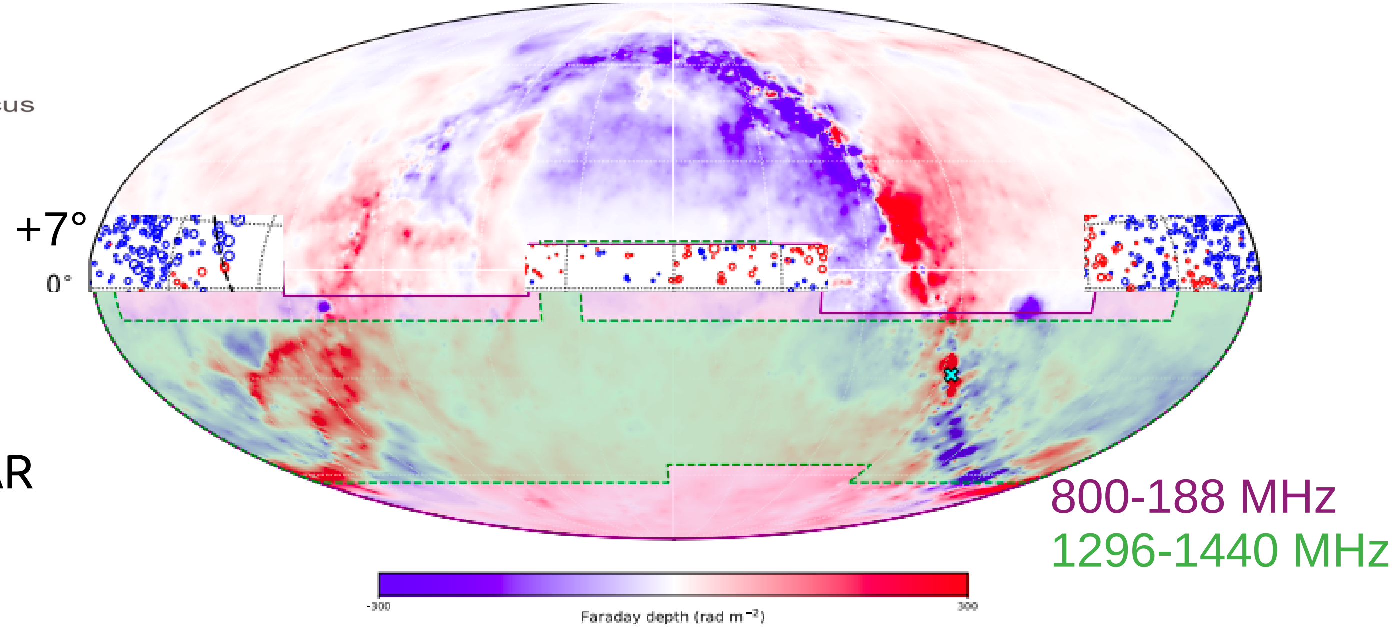
Synergies with GHz-surveys

- increase polarised source density in intermediate density regimes
- disentangle astrophysical from primordial contribution to RRM(z)

APERTIF
APERture Tile In Focus

POSSUM
POLARISATION SKY SURVEY OF THE UNIVERSE'S MAGNETISM

Small overlap with LOFAR



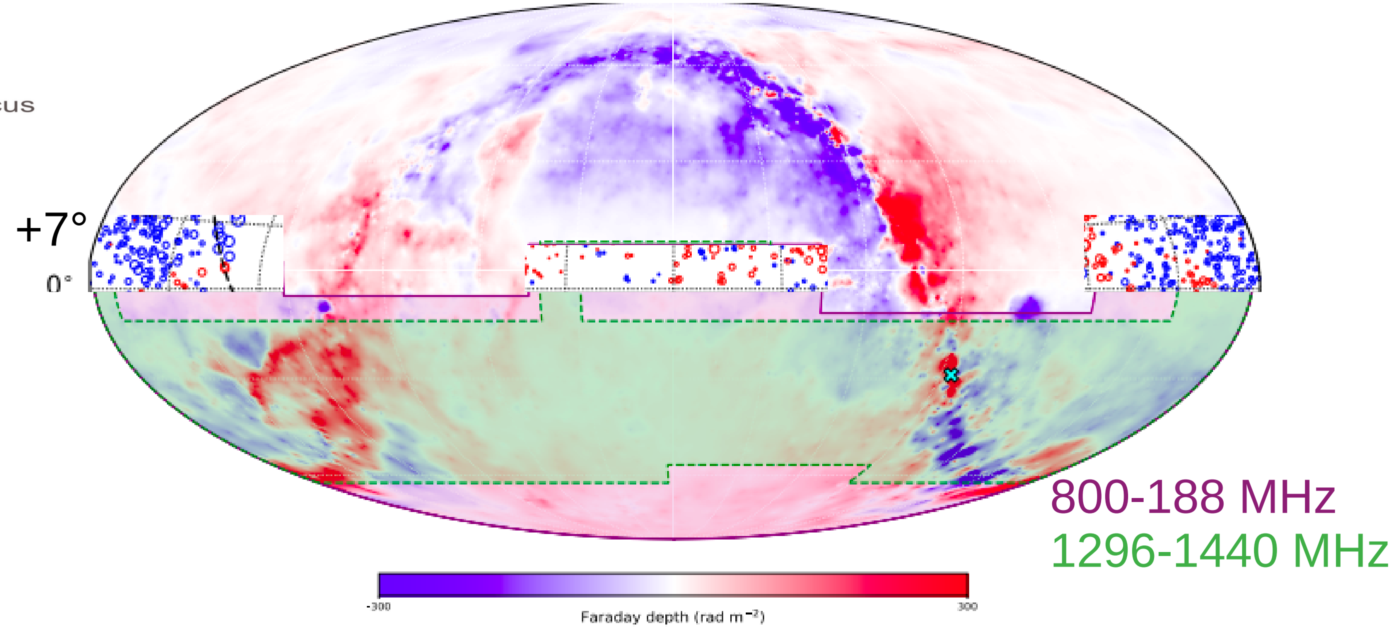
Synergies with GHz-surveys

- increase polarised source density in intermediate density regimes
- disentangle astrophysical from primordial contribution to RRM(z)

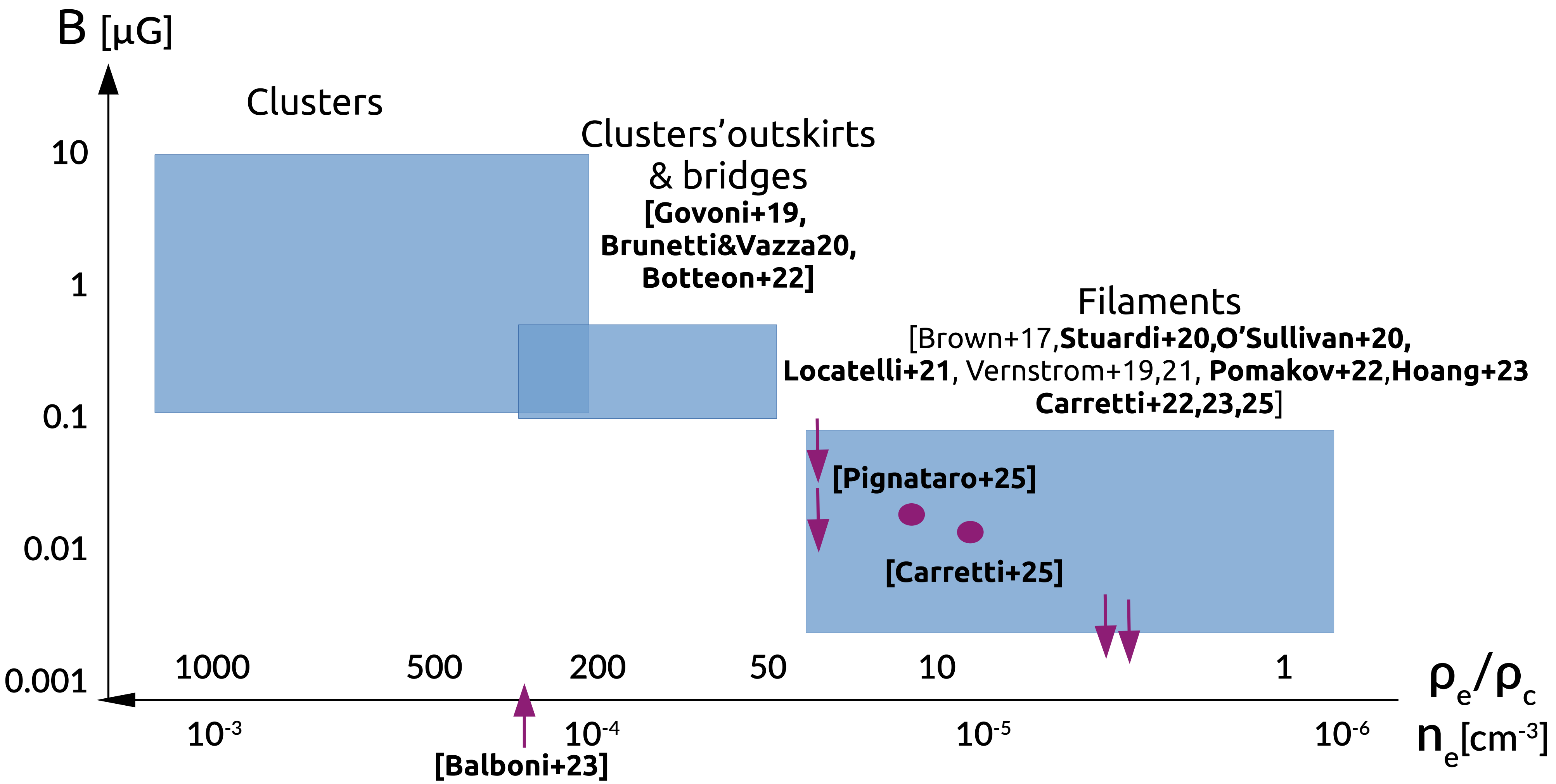
APERTIF
APERture Tile In Focus

POSSUM
POLARISATION SKY SURVEY OF THE UNIVERSE'S MAGNETISM

SKAO



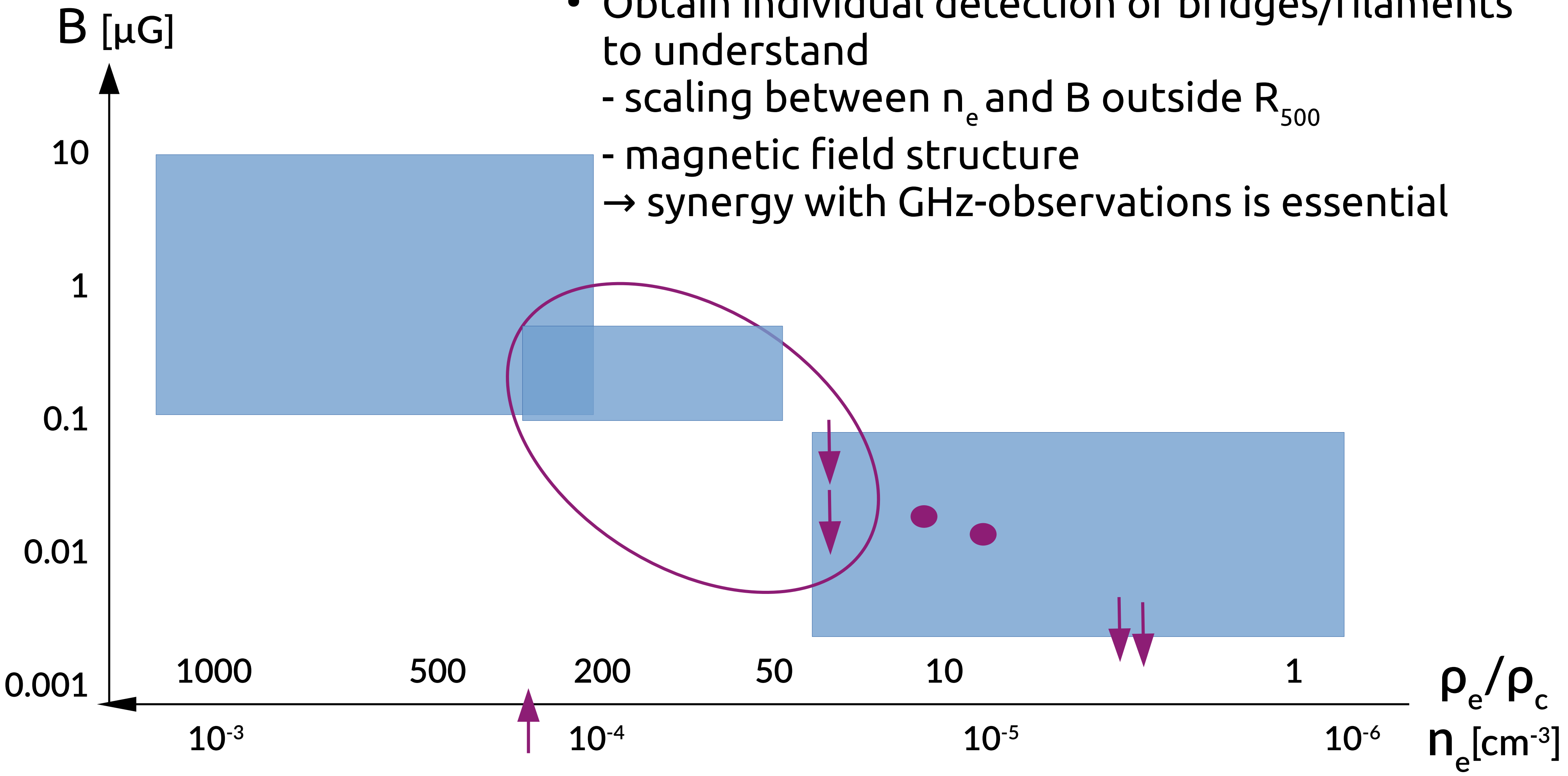
The big picture: the LOFAR contirbution



Final remarks

- Fill the gap between filaments and clusters
- Obtain individual detection of bridges/filaments to understand
  - scaling between n_e and B outside R_{500}
  - magnetic field structure

  → synergy with GHz-observations is essential



Final remarks

- Fill the gap between filaments and clusters
- Obtain individual detection of bridges/filaments to understand
  - scaling between n_e and B outside R_{500}
  - magnetic field structure

  → synergy with GHz-observations is essential

Thank you for your attention!