# PROBING THE MAGNETIC UNIVERSE WITH FAST RADIO BURSTS

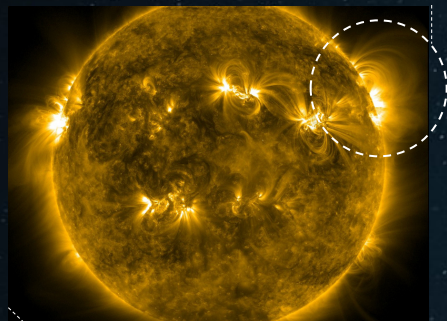in collaboration with Jennifer Chan, Kinwah Wu, Curtis Saxton and Lidia van Driel-Gesztelyi

Magnetic fields are ubiquitous.
Yet very little is known about their origin(s) and evolution.

The Northern lights – also known as the aurora borealis – dancing across the night sky in Alaska.

1

Background credit: The National Geographic's Short Film Showcase by Alexis Coram
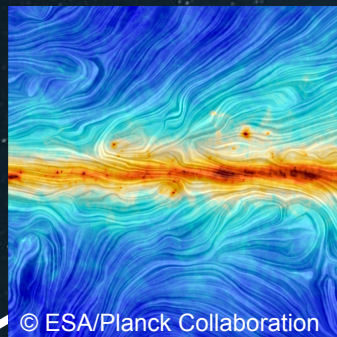
# SEEING THE INVISIBLE

Charged particles emit *light* as they spiral along the magnetic fields of the Sun and the Earth. Seeing the light allows us to trace the otherwise invisible magnetic fields!

The direction of the polarised light emitted by *dust* tells us the magnetic field orientation.

larger structure

weaker field

Magnetic arches towering over the active solar surface



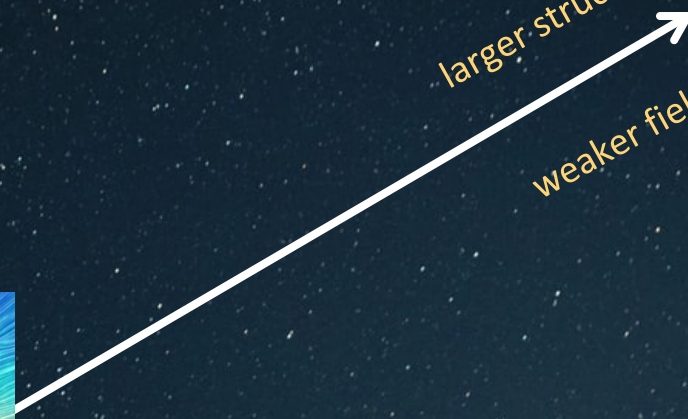© NASA/SDO and the AIA, EVE , and HMI science teams



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Magnetic fingerprint of our Galaxy – the Milky Way



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The solar wind carries with it the Sun's magnetic field that interacts with the Earth's magnetosphere (in blue).
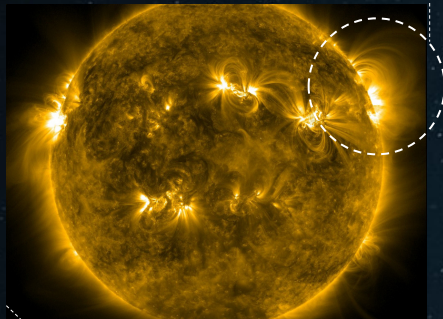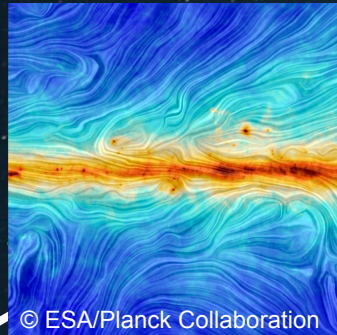
2

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On *larger* scales, we use *radio* observations to trace the magnetic fields.

*larger structure*

*weaker field*

Magnetic arches towering over the active solar surface



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Magnetic fingerprint of our Galaxy – the Milky Way



© MPIfR (R. Beck) and Newcastle University (A. Fletcher)

Magnetic field vectors of a nearby galaxy – M51, and

a galaxy group – Stephan's Quintet



© Nikiel-Wroczyński+ (2013)



© NASA

The solar wind carries with it the Sun's magnetic field that interacts with the Earth's magnetosphere (in blue).

Background credit: Just the night sky by Stefan Cosma

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Coma cluster © Brown+ (2011)

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Magnetic fingerprint of our Galaxy – the Milky Way
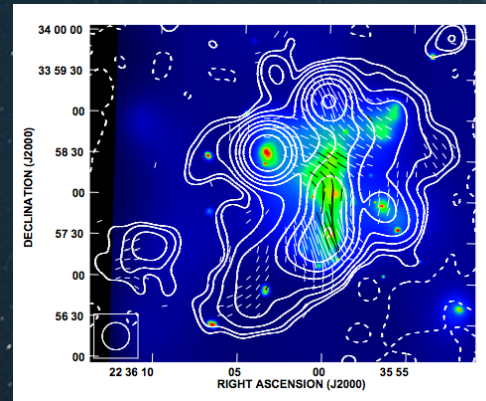
Magnetic field vectors of a nearby galaxy – M51, and

© MPIfR (R. Beck) and Newcastle University (A. Fletcher)
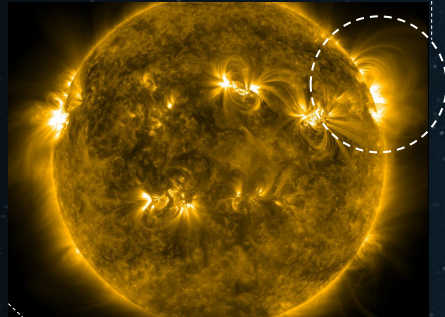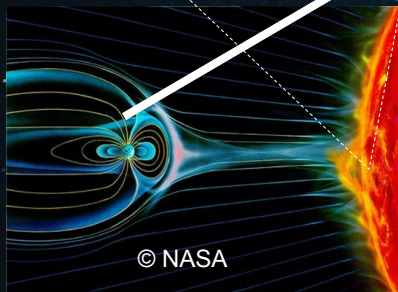
a galaxy group – Stephan's Quintet

Cosmic web of filaments and voids

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The solar wind carries with it the Sun's magnetic field that interacts with the Earth's magnetosphere (in blue).

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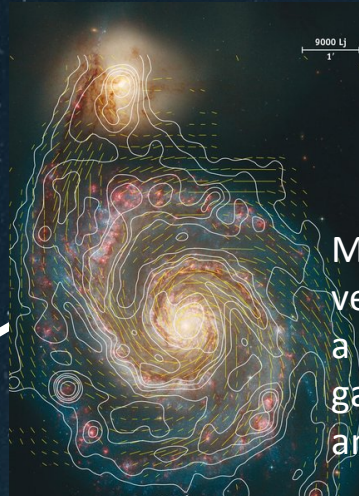
How do we correctly infer the magnetic field properties in galaxy clusters and beyond?

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Background credit: Just the night sky by Stefan Cosma

# THE COSMIC WEB

The first magnetic fields: primordial or astrophysical in origin?
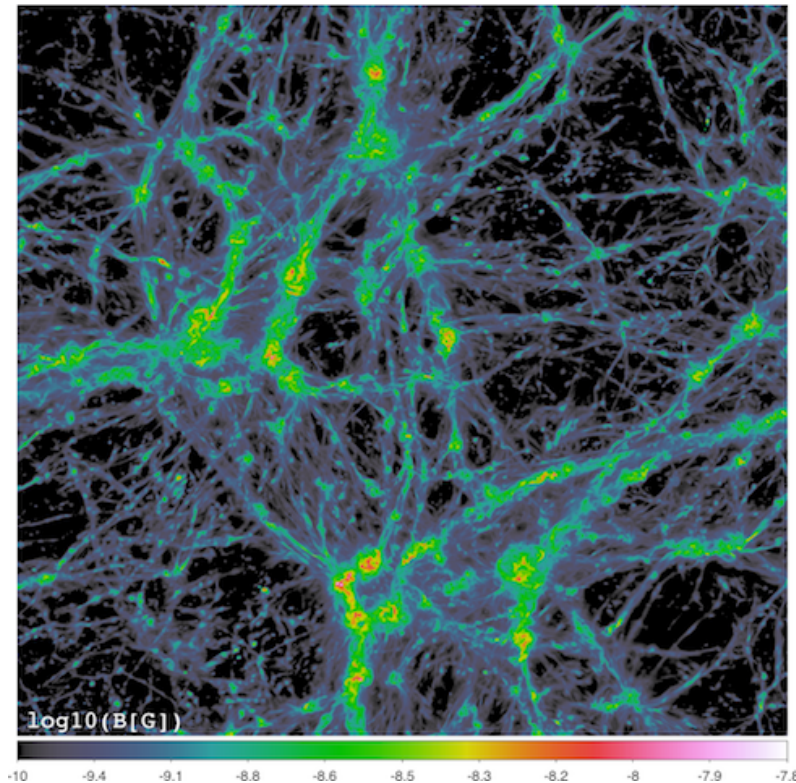


Projected magnetic field strength at z = 0
across a (50 Mpc)$^3$ cosmological simulation
(Vazza+ 2014)

Theory/numerical simulations
(see e.g. Ryu+ 1998; Ryu+ 2008;
Akahori & Ryu 2010; Vazza+ 2014;
Akahori+ 2014)

Radio observations
(see e.g. Xu+ 2006; Giovannini+ 2015;
Pshirkov+ 2016; Kaczmarek+ 2017;
Govoni+ 2019; O'Sullivan+ 2019, 2020)

# MEASURING THE INVISIBLE

Faraday rotation measure (RM) at radio wavelengths is commonly used to diagnose large-scale magnetic fields.

RM

observed wavelength

$$\mathcal{R} = (\Delta\varphi)\,\lambda^{-2} = (\varphi - \varphi_0)\,\lambda^{-2}$$

observed polarisation angle

intrinsic polarisation angle

# BEYOND GALACTIC SCALES

Magnetic fields are relatively weaker and more difficult to be observed

radio emission and Faraday rotation measure as probes

Colour: ROSAT X-ray

Colour: RM    Contour: Total radio intensity 1.4 GHz
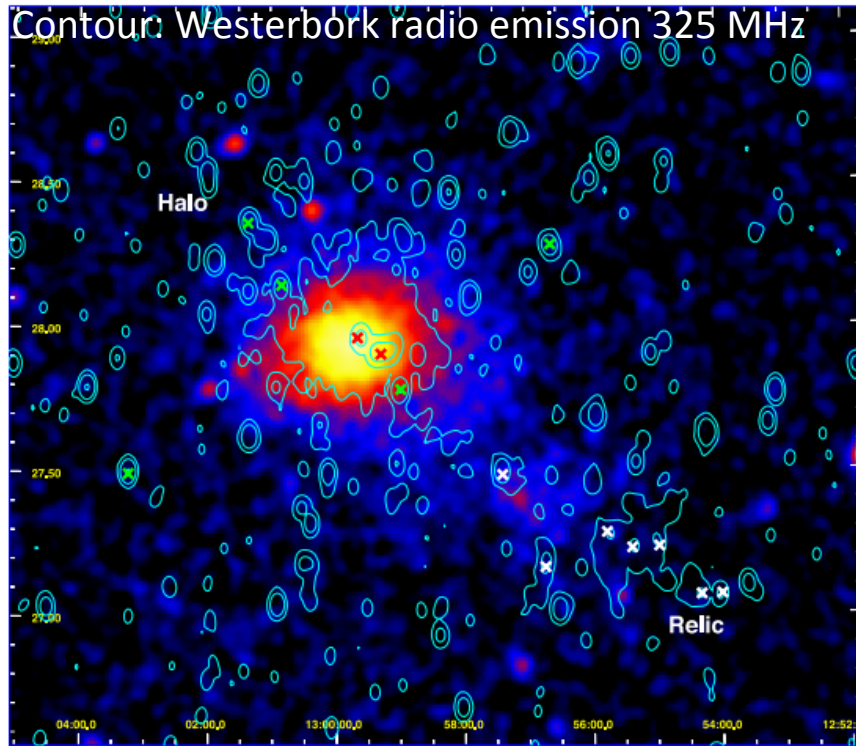


Coma cluster and NGC 4839 group
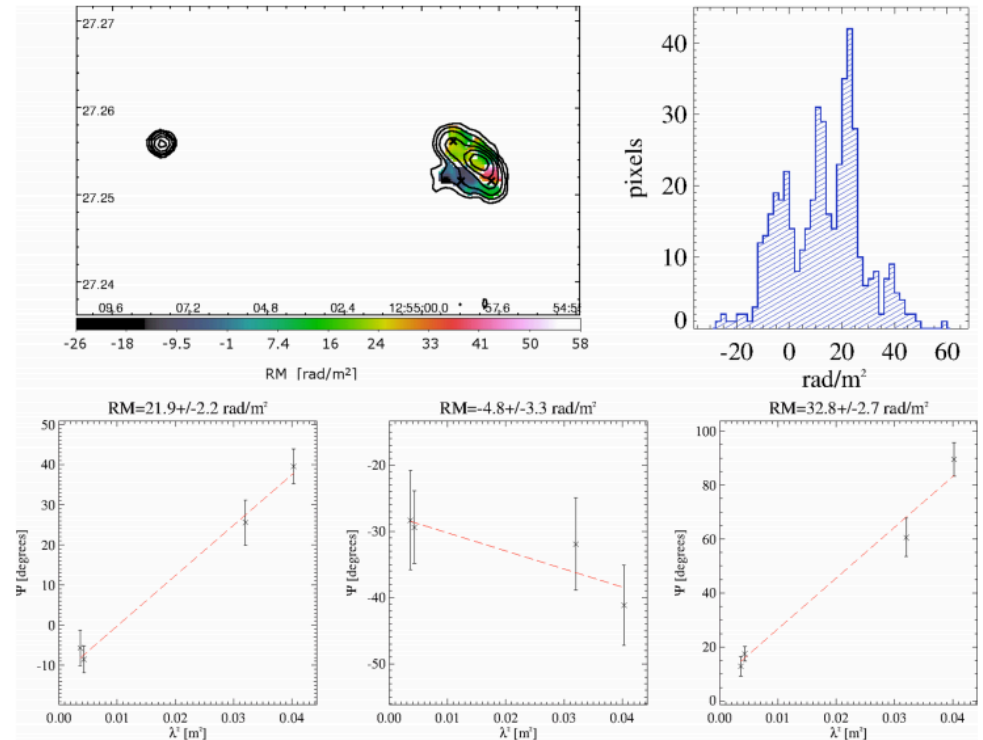
a radio background source 5C4.24

# FRBS AS COSMOLOGICAL PROBES

To diagnose large-scale magnetic fields using dispersion measure (DM)
and rotation measure (RM)

tells us about the line-of-sight
thermal electron density

B-field strength order:

< 10s nG

(see e.g. Zheng+ 2014; Ravi+ 2016;
Akahori+ 2016, 2018; Vazza+ 2017,
2018; Hackstein+ 2019)

An artist's impression of an FRB signal travelling towards the GBT: Danielle Futselaar/Shutterstock.com

# DECODING AN UNPRECEDENTED RADIO SKY

Square Kilometre Array (SKA) – the world's largest radio telescope
SKA Observatory (SKAO) officially launched last week!

Composite image of the SKA over the Milky Way centre: SKAO, ICRAR, SARAO, Natasha Hurley-Walker (Curtin/ICRAR) and the GLEAM team

# GALACTIC FARADAY ROTATION SKY

2012

2020 – arXiv last week!
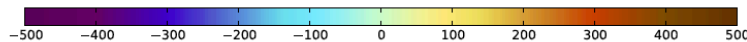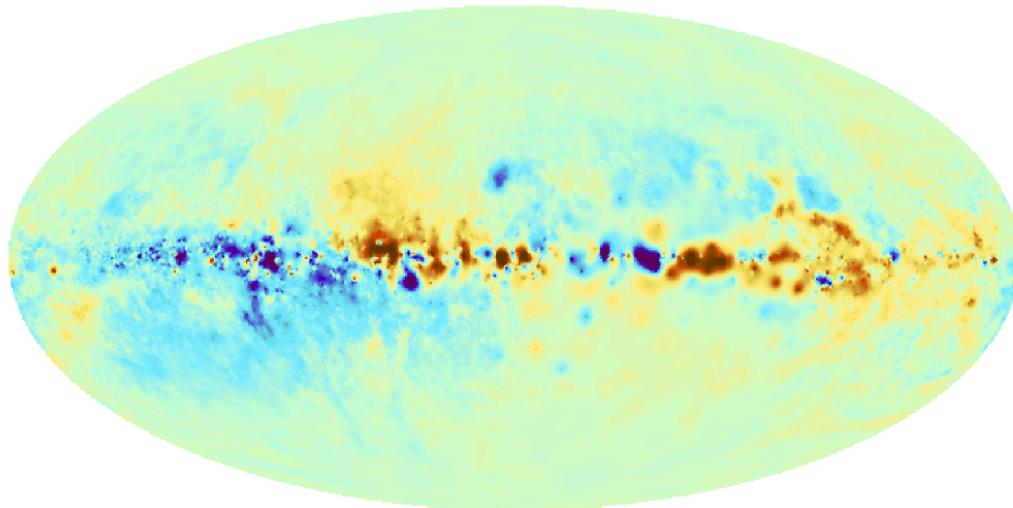


41330 RMs (Oppermann+ 2012)
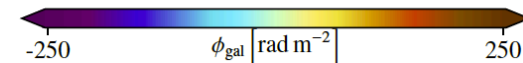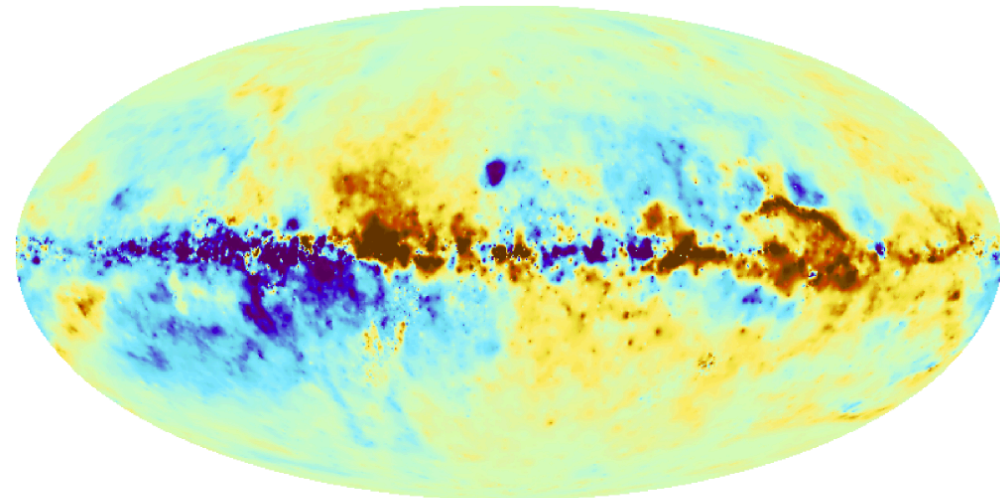
55190 RMs (Hutschenreuter+ 2021)

SKA1: first light (mid – end of 2020s)                                    ~ $10^4$ localised FRBs
        all-sky rotation measure (RM) grid of millions of extragalactic RMs
        (see e.g. Johnston-Hollitt+ 2014; Macquart+ 2014; Heald+ 2020)

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# ROTATION MEASURE

In the context of polarised radiative transfer

distance between the source
and observer

$$\mathcal{R}(s) = 0.812 \int_{s_0}^{s} \frac{\mathrm{d}s'}{\mathrm{pc}} \left( \frac{n_{\mathrm{e,th}}(s')}{\mathrm{cm}^{-3}} \right) \left( \frac{B_{\parallel}(s')}{\mu\mathrm{G}} \right) \, \mathrm{rad}\,\mathrm{m}^{-2}$$

thermal electron
number density

B-field strength
along line-of-sight

assuming:

no absorption, no emission, no Faraday conversion
only thermal electrons

The correlations in the observed RM fluctuations (RMF) are used
to probe the length scales on which magnetic fields vary.

# ROTATION MEASURE FLUCTUATIONS (RMF)

Conventional approach – pseudo random-walk process

equal step size $\overline{\Delta s}$
density and magnetic field uncorrelated
only thermal electrons present

standard
deviation
of RM

$$\sigma_{\mathcal{R}} = \frac{e^3}{2\pi m_e^2 c^4} \sqrt{\frac{L}{\overline{\Delta s}}} \, \overline{\Delta s} \, \overline{n}_{e,\text{th}} \, B_{\|\text{rms}}$$

$$= 0.812 \sqrt{\frac{L}{\overline{\Delta s}}} \left( \frac{\overline{\Delta s}}{\text{pc}} \right) \left( \frac{\overline{n}_{e,\text{th}}}{\text{cm}^{-3}} \right) \left( \frac{B_{\|\text{rms}}}{\mu\text{G}} \right) \text{rad m}^{-2} \qquad (1)$$

Most studies on large-scale magnetic fields use this expression.
(e.g. Sokoloff+ 1998; Blasi+ 1999; Dolag+ 2001; Govoni+ 2004; Subramanian+ 2006; Cho+ 2009; Sur 2019).

(**On**+ 2019)

YITP FRB Workshop
February 8 − 19, 2021          Alvina On

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# ASSESSING THE RMF APPROACH

When is it justified? When does it deserve caution?

- carried out Monte Carlo simulations to compute the RMF
- built models of various magnetic field configurations and thermal electron number density distributions
- applied divergence-free filter
- normalised to galaxy cluster scale

$$\mathcal{R}_\perp = 0.812 \sum_\parallel \frac{\overline{\Delta s}}{\text{pc}} \left[ \left( \frac{n_{\text{e,th}}(i,j,k)}{\text{cm}^{-3}} \right) \left( \frac{B(i,j,k)}{\mu\text{G}} \right) \right]_\parallel \text{rad m}^{-2} \qquad (2)$$

Calculated the standard deviation across the sky plane

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# AN EYE TEST

Can you spot any difference between each panel?



RM (rad m⁻²)

(**On**+ 2019)
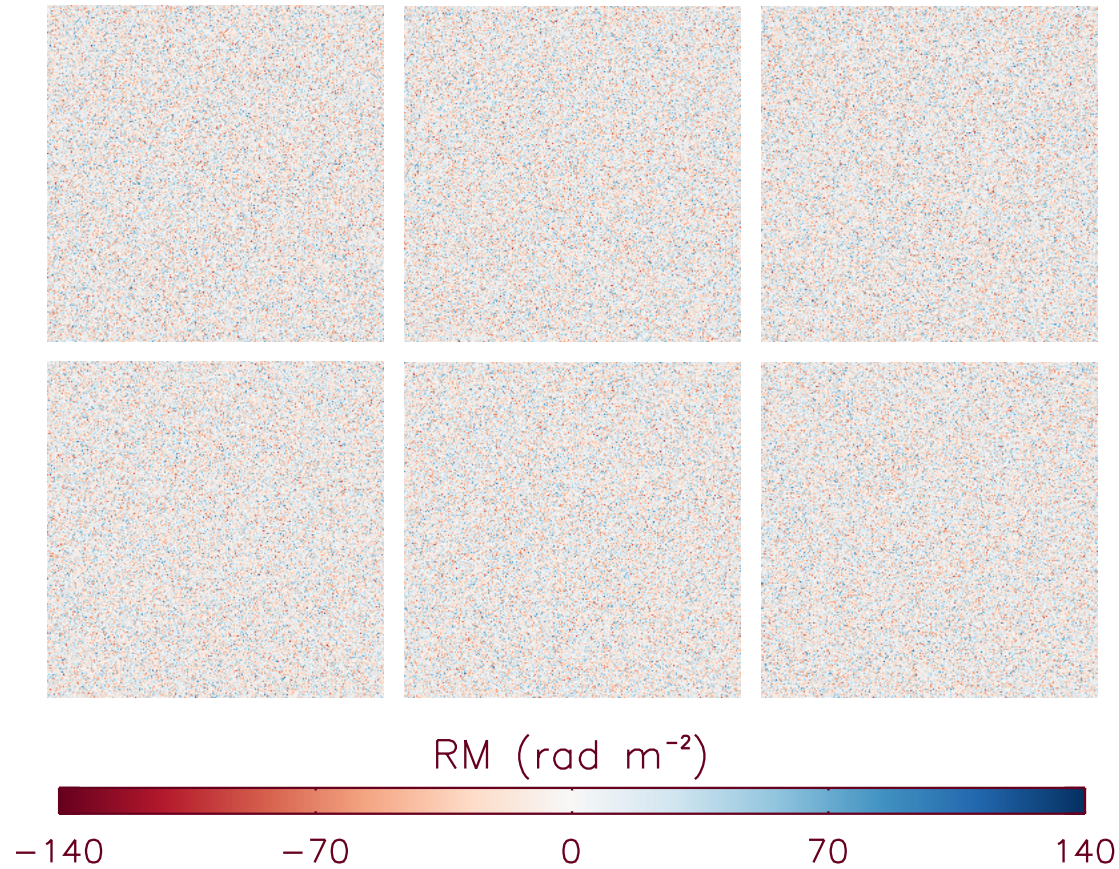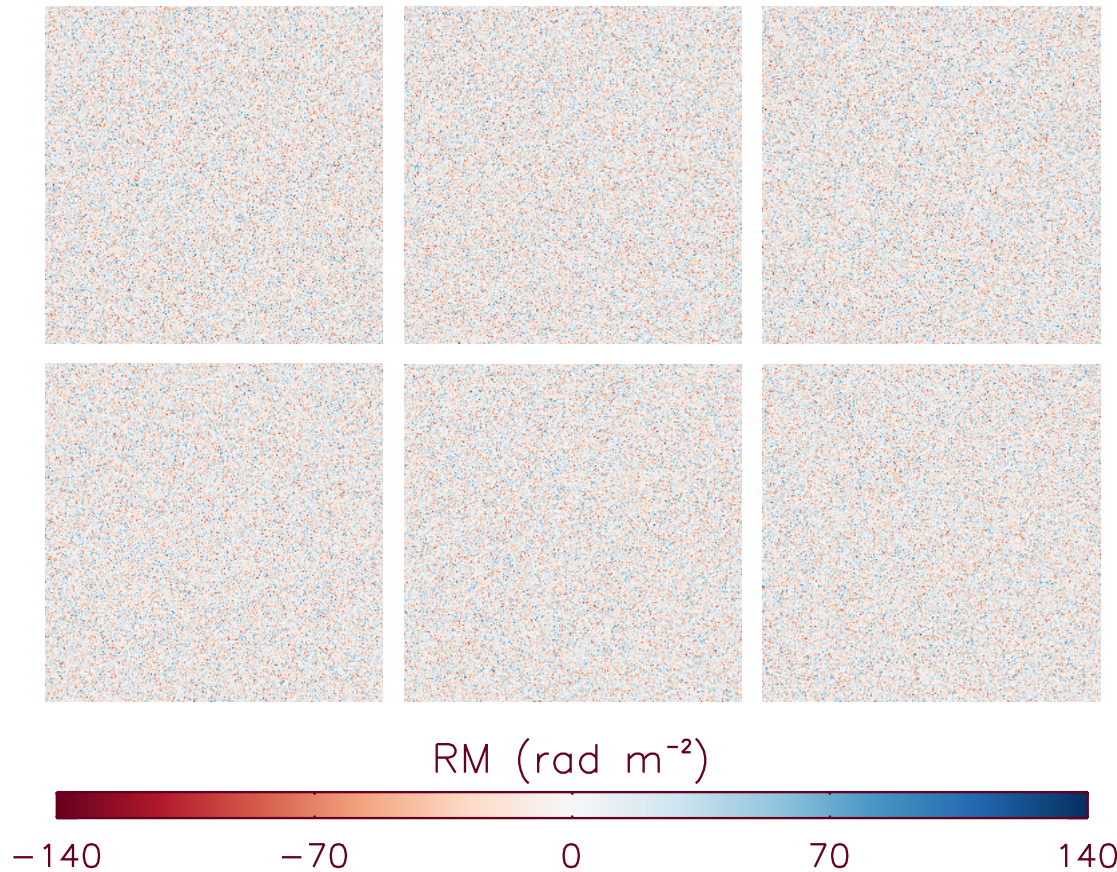
# SYNTHETIC RM MAPS

Indistinguishable



RM (rad m$^{-2}$)

−140          −70          0          70          140

(**On**+ 2019)

# SYNTHETIC RM MAPS

Indistinguishable



Gaussian-distributed densities

Gaussian-distributed magnetic field strengths
random magnetic field orientations

RM (rad m$^{-2}$)

−140          −70          0          70          140

16

(**On**+ 2019)

# SYNTHETIC RM MAPS

Indistinguishable



Gaussian-distributed densities

Gaussian-distributed magnetic field strengths
random magnetic field orientations

uniformly-distributed densities

uniformly-distributed magnetic field strengths
random magnetic field orientations
non-divergence free – unphysical!

RM (rad m⁻²)

$-140$    $-70$    $0$    $70$    $140$

17

(**On**+ 2019)

# SYNTHETIC RM MAPS

Indistinguishable – non-trivial to characterise the thermal
electron number densities and the magnetic field strengths from
the observed RM fluctuations alone
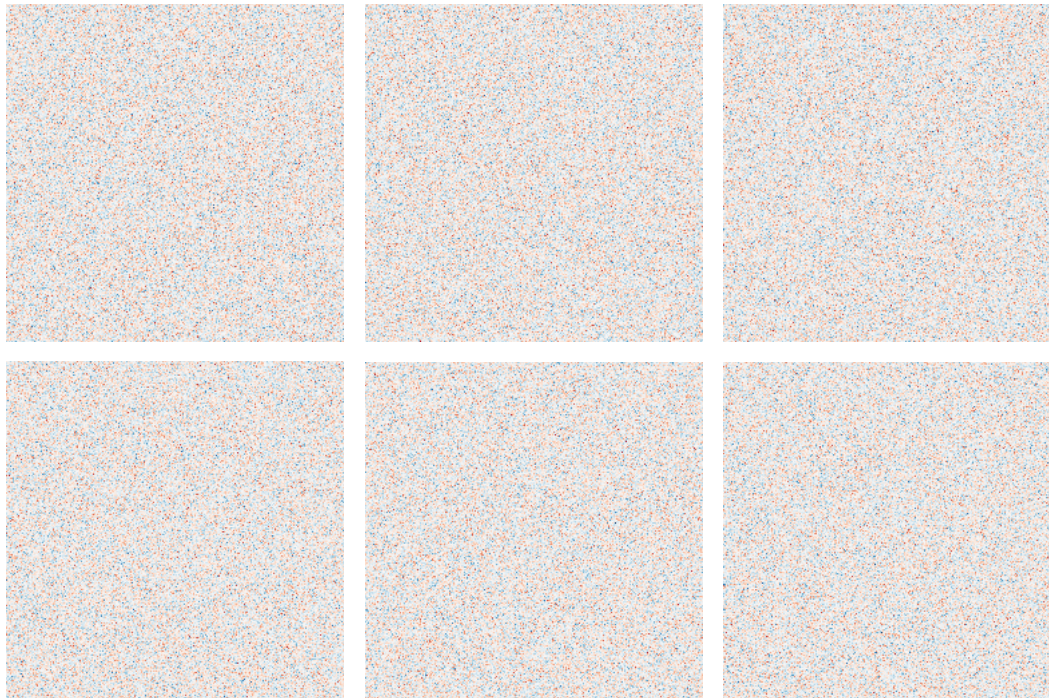


Gaussian-distributed densities

Gaussian-distributed magnetic field strengths
random magnetic field orientations

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uniformly-distributed magnetic field strengths
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RM (rad m$^{-2}$)

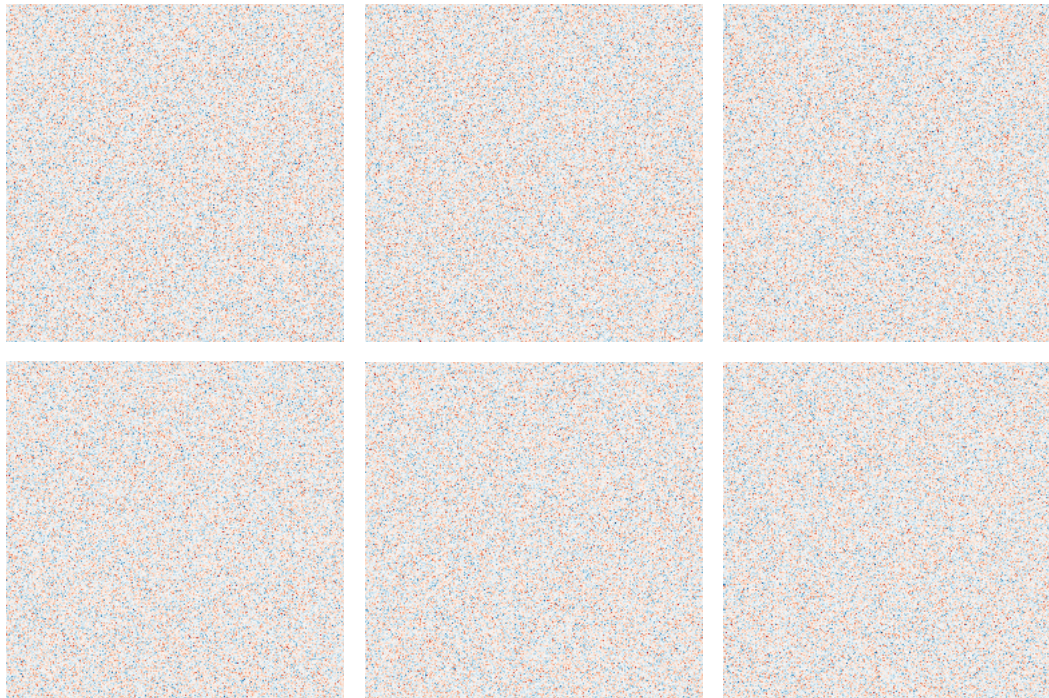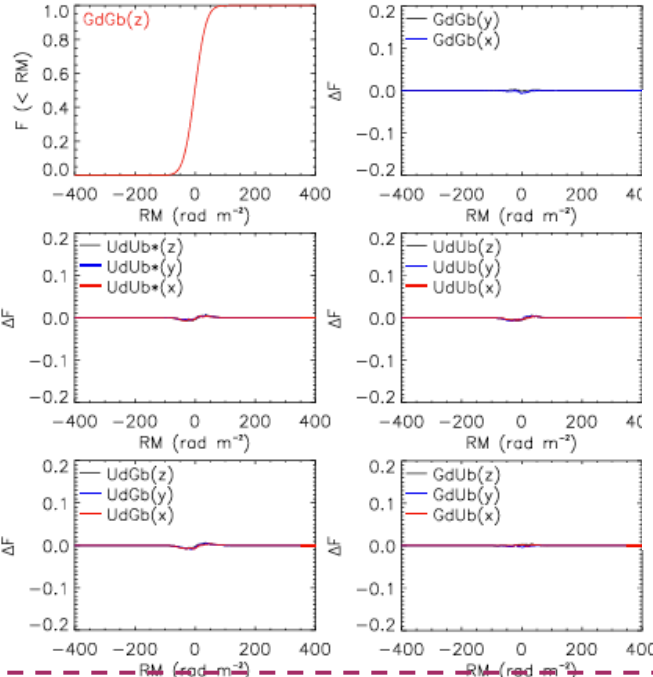−140          −70          0          70          140

18

(**On**+ 2019)

# ASSESSING THE CONVENTIONAL RMF ANALYSES



| distribution | | conventional (eq. 1) | | | standard deviation (eq. 2) | | |
|---|---|---|---|---|---|---|---|
| | | $\sigma_R^{xy}$ | $\sigma_R^{xz}$ | $\sigma_R^{yz}$ | $\varsigma_R^{xy}$ | $\varsigma_R^{xz}$ | $\varsigma_R^{yz}$ |
| Ud | Ub* | 29.2971 | 29.2975 | 29.2962 | 29.2861 | 29.3151 | 29.3042 |
| Ud | Ub | 29.2962 | 29.2977 | 29.2970 | 29.3101 | 29.3198 | 29.3278 |
| Ud | Gb | 29.2965 | 29.2965 | 29.2979 | 29.3231 | 29.2934 | 29.3299 |
| Gd | Ub | 29.2982 | 29.2961 | 29.2966 | 29.9263 | 29.8972 | 29.8994 |
| Gd | Gb | 29.2970 | 29.2973 | 29.2966 | 29.9113 | 29.8854 | 29.8902 |
| Fd | Ub | 29.2987 | 29.2965 | 29.2956 | 39.1187 | 39.1392 | 39.1134 |
| Fd | Gb | 29.2975 | 29.2966 | 29.2968 | 39.1185 | 39.1357 | 39.1186 |
| Ld | Ub | 29.2969 | 29.2968 | 29.2972 | 48.3524 | 48.3218 | 48.3327 |
| Ld | Gb | 29.2975 | 29.2964 | 29.2970 | 48.3058 | 48.3017 | 48.3146 |

The conventional RMF analyses *cannot distinguish* between various distinct distributions of densities and magnetic field strengths.

The conventional RMF analyses *do not work* for fractal and lognormal density distributions.

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(**On**+ 2019)

# SUBTLETIES IN QUANTIFYING THE RMF

Fluctuations of density and magnetic fields along the line-of-sight and across the sky plane can be different

A has *two* characteristic length scales

Polarisation angle changes along each line-of-sight

**A**

$\ell_{c_1, \parallel}$    $\ell_{c_2, \parallel}$

$\ell_{c, \perp}$

**B**

$\ell_{c_3, \parallel}$

B has *one* characteristic length scale

(1) Resulting polarisation angles we see on the sky are the same

(2) $l_{c, perp} \neq l_{c1, \parallel} \neq l_{c2, \parallel} \neq l_{c3, \parallel}$

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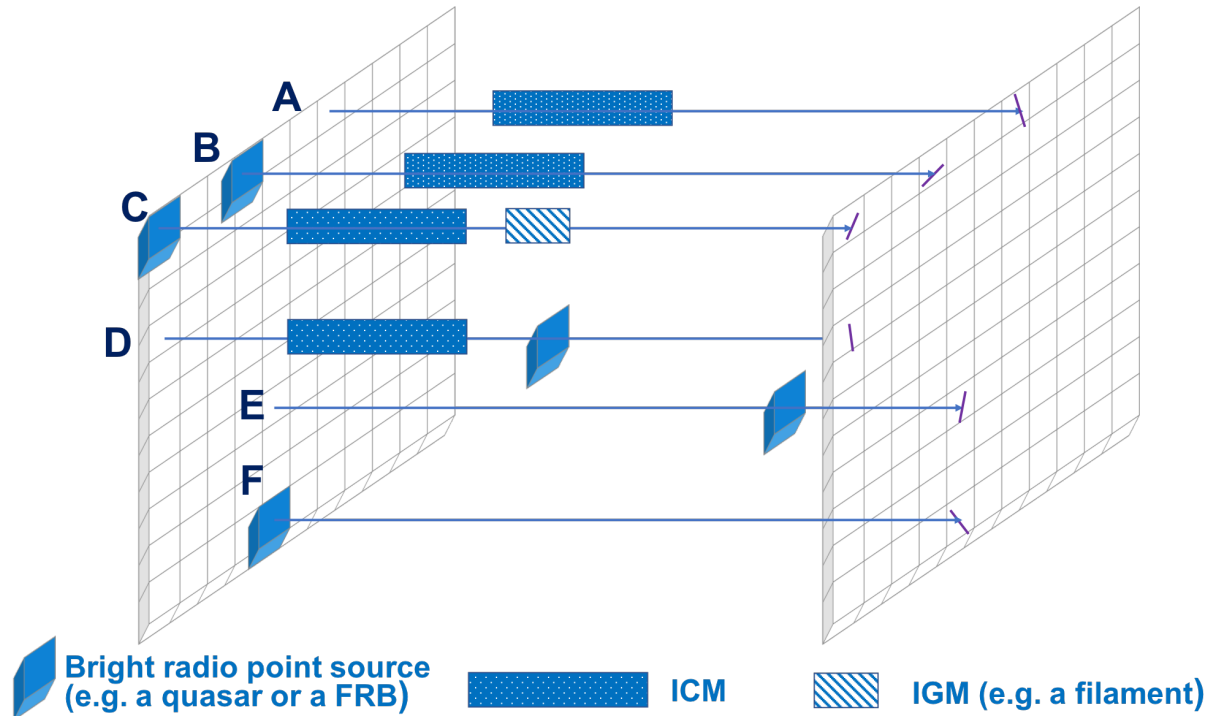(Chan, Wu, **On**+ 2018; **On**+ 2019)
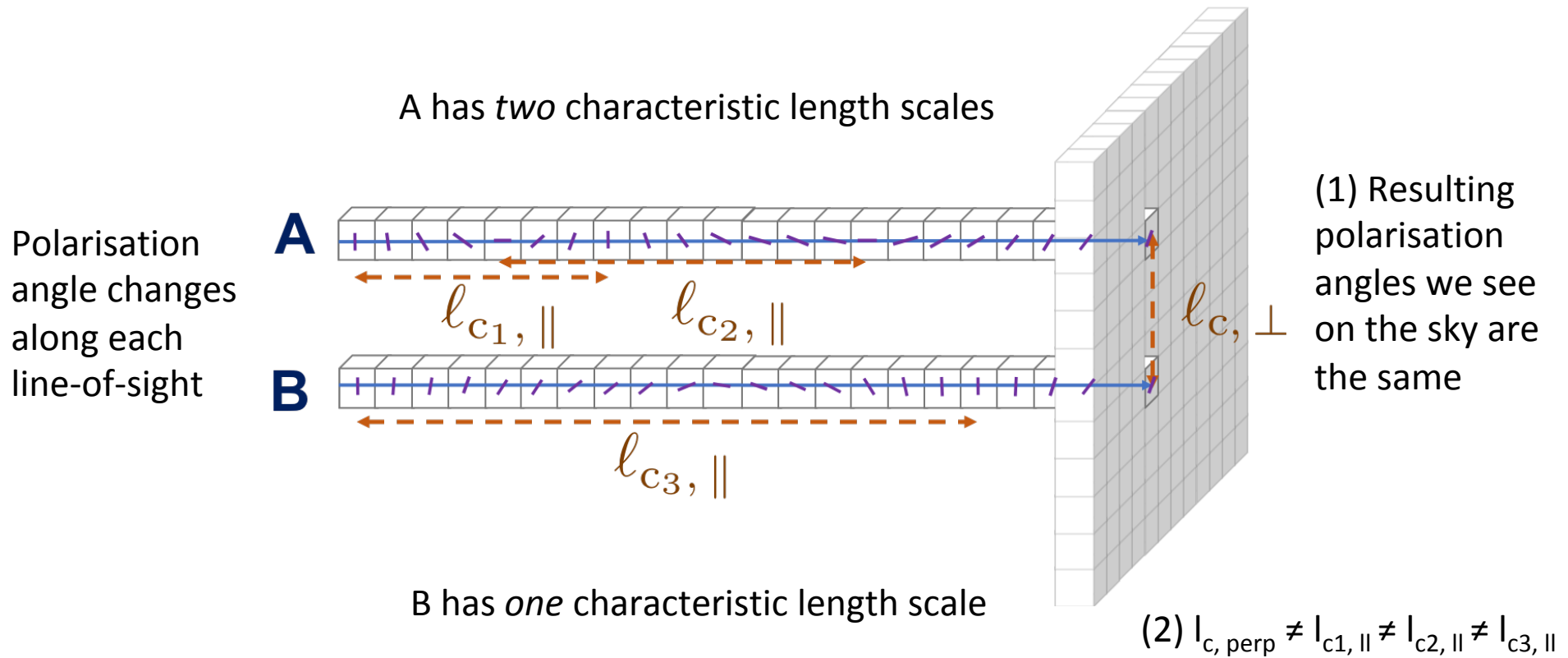
# SUBTLETIES IN QUANTIFYING THE RMF

Different astrophysical conditions give rise to different polarisation fluctuations

**A**: background source absent

**B**: background source present

**C**: multiple sources with various Faraday depths (vs. **B**)

**D**: different source positions (vs. **B**)

**E**: change of radiation frequency + low-z source

**F**: change of radiation frequency + high-z source



**Bright radio point source** (e.g. a quasar or a FRB)   **ICM**   **IGM (e.g. a filament)**

(Chan, Wu, **On**+ 2018; **On**+ 2019)

# CONTAMINATION IN THE POWER SPECTRUM

Higher-z structures can contaminate the observed P($k$) at a fixed $\nu_{\text{obs}}$

(3) Seeing higher power in the smaller scales – is it due to emissions from the medium and embedded sources, or truly from the magnetic field?

How about absorption?

$P(k)|_{z''}$

$(1 + z'')\,\nu_{\text{obs}}$

$(1 + z')\,\nu_{\text{obs}}$

$P(k)|_{z'}$

$P(k)|_{z=0}$

$\nu_{\text{obs}}$

$P(k)$

$k$
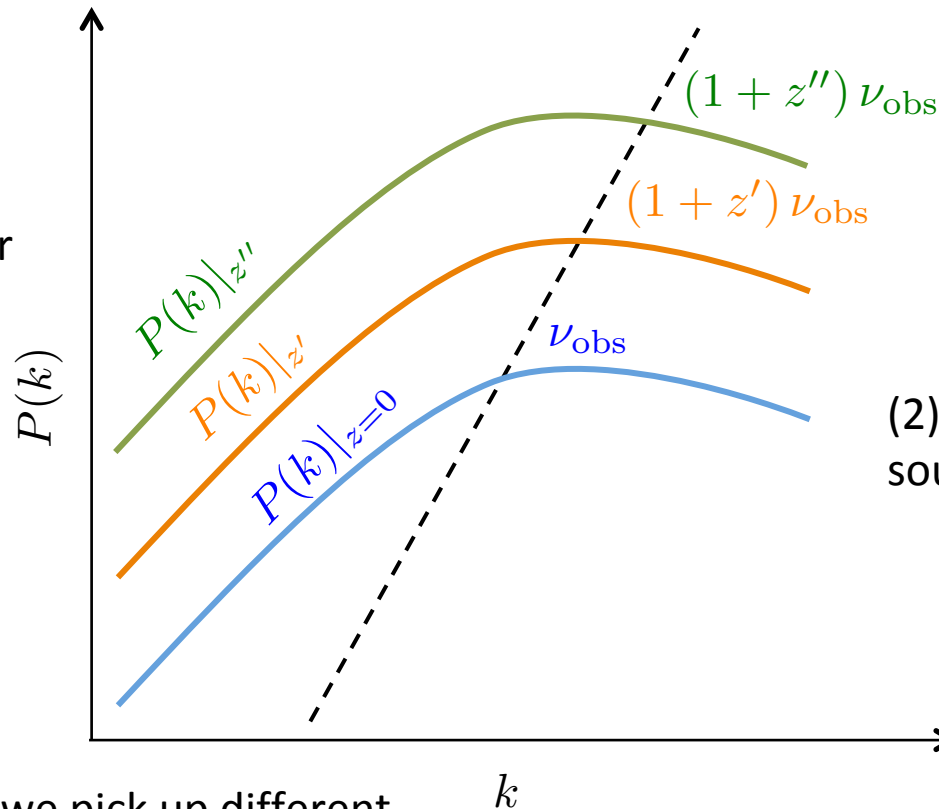
(2) Theoretically, we pick up all sources at a single z

(1) Observationally, we pick up different components at higher $k$ at a fixed $\nu_{\text{obs}}$

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(Chan, Wu, **On**+ 2018; **On**+ 2019)

# TAKE-HOME MESSAGES

- Density fluctuations can mask the effect of magnetic field fluctuations, affecting the correlation length of magnetic fields inferred from the conventional RMF analyses.

- We caution against interpretations of RMF analyses in lognormal-distributed and fractal-like density structures.

- The spatial correlations are generally not the same along the line-of-sight and across the sky plane.

- In complex situations, a covariant polarised radiative transfer calculation is essential to properly track all radiative and transport processes, otherwise the interpretations of magnetism in galaxy clusters and larger scale cosmological structures would be ambiguous.

## ABOUT THE AUTHOR

**Alvina Y. L. On** is in the Theoretical Astrophysics group at Mullard Space Science Laboratory, University College London, UK. She is also a visiting researcher at the Institute of Astronomy, National Tsing Hua University, Taiwan (ROC), where a part of this work has been carried out. This research is in collaboration with Jennifer Y. H. Chan, Kinwah Wu, Curtis J. Saxton, and Lidia van Driel-Gesztelyi.

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On+ (2019)        Chan+ (2018)