National Center for Theoretical Sciences
Physics Division 國家理論科學研究中心 物理組

High Energy Astrophysics

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NCTS Postdoctoral Fellow

I study the magnetic fingerprints in space using radio polarisation.

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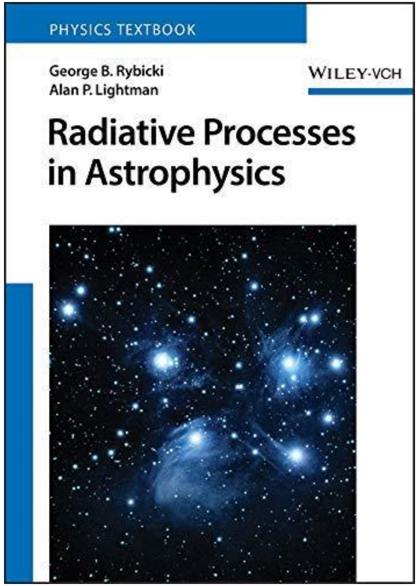
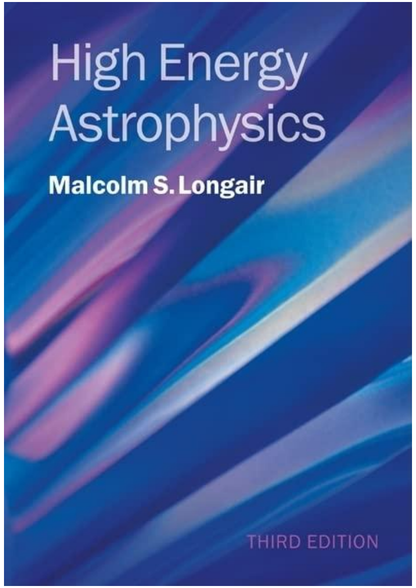
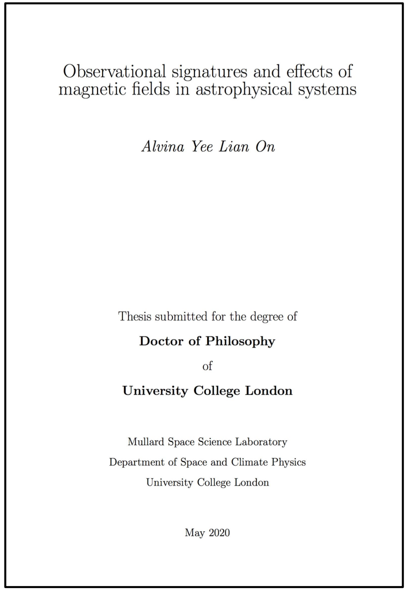
Suggested readings






Observational signatures and effects of magnetic fields in astrophysical systems

Alvina Yee Lian On

Thesis submitted for the degree of

Doctor of Philosophy

of

University College London

Mullard Space Science Laboratory
Department of Space and Climate Physics
University College London

May 2020

Radiative Processes in Astrophysics, Rybicki and Lightman (1985)
High Energy Astrophysics, Longair (2011)
Observational signatures and effects of magnetic fields in astrophysical systems, On (2021, Ph.D thesis)

Outline

1. What is high–energy astrophysics?
2. Origins and acceleration of high–energy cosmic rays
3. Radiative transfer
4. Radiation processes
5. Basics of polarisation
6. How about magnetic fields?

What is high-energy astrophysics?

Google says

Princeton University
https://web.astro.princeton.edu › research › high-ener...

High-Energy Astrophysics

High-energy astrophysics **studies the Universe at the extreme**. Black holes, neutron stars, exploding supernovae, and relativistically moving jets continually ...

Wikipedia
https://en.wikipedia.org › wiki › High-energy_astrono...

High-energy astronomy

High energy astronomy is **the study of astronomical objects that release electromagnetic radiation of highly energetic wavelengths**. It includes X-ray ...

Harvard University
https://astronomy.fas.harvard.edu › high-energy-astro...

High-Energy Astrophysics | Department of Astronomy

High Energy Astrophysics **explores energetic events in the Universe with energies extending from the far UV through the keV X-rays and into the Y-ray band**.
You visited this page on 6/27/23.

Marvel superheroes?

as a result of cosmic-ray exposure


Kl'rt (Earth-616)


Bruce Banner (Earth-616)


Reed Richards (Earth-616)


Franklin Richards (Earth-616)


Susan Storm (Earth-616)


Benjamin Grimm (Earth-616)

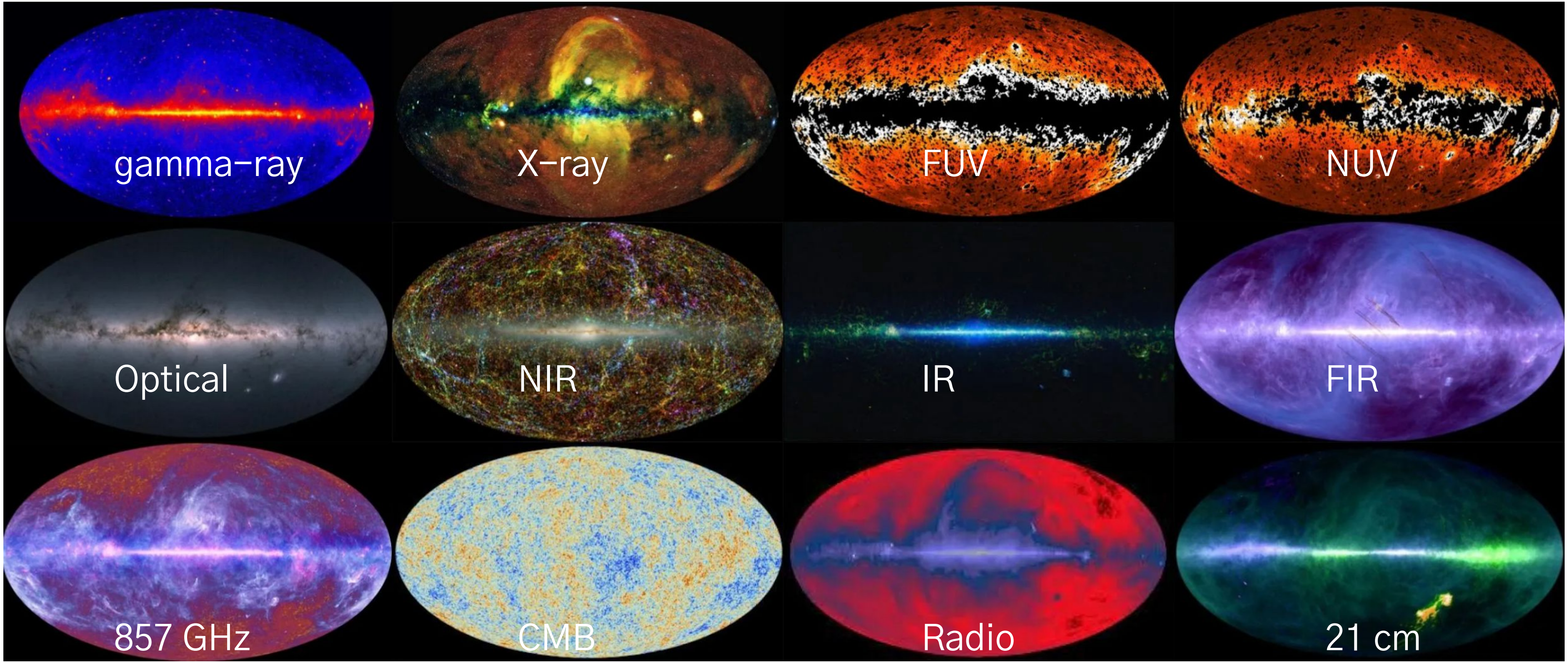

Jonathan Storm (Earth-616)


Jessica Jones (Earth-616)

Credit: Marvel Fandom

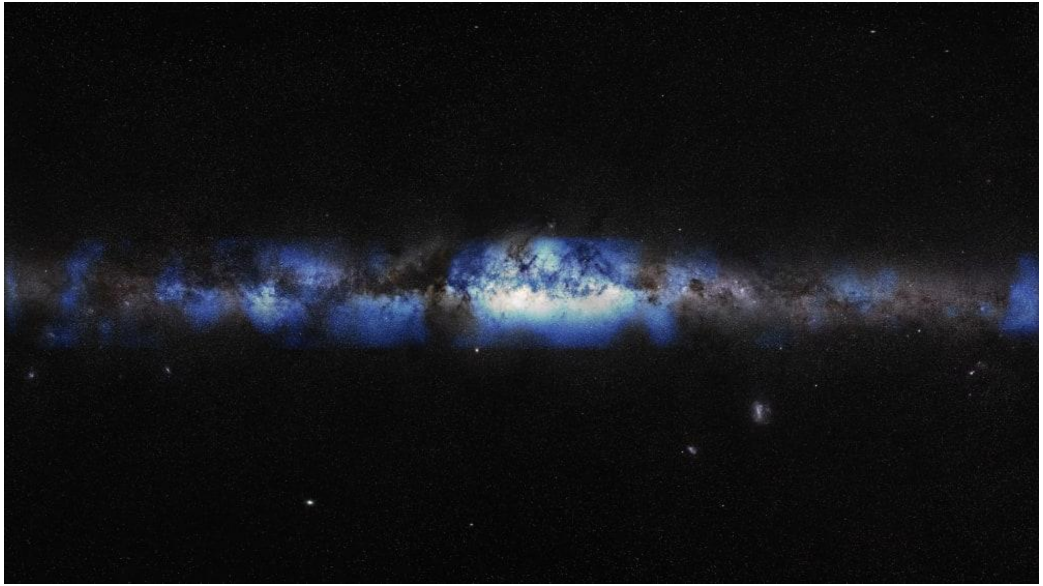
Our sky at different energies

(Ansh Mittal 2020)



A few days ago

IceCube detected high-energy neutrino emission from the Milky Way

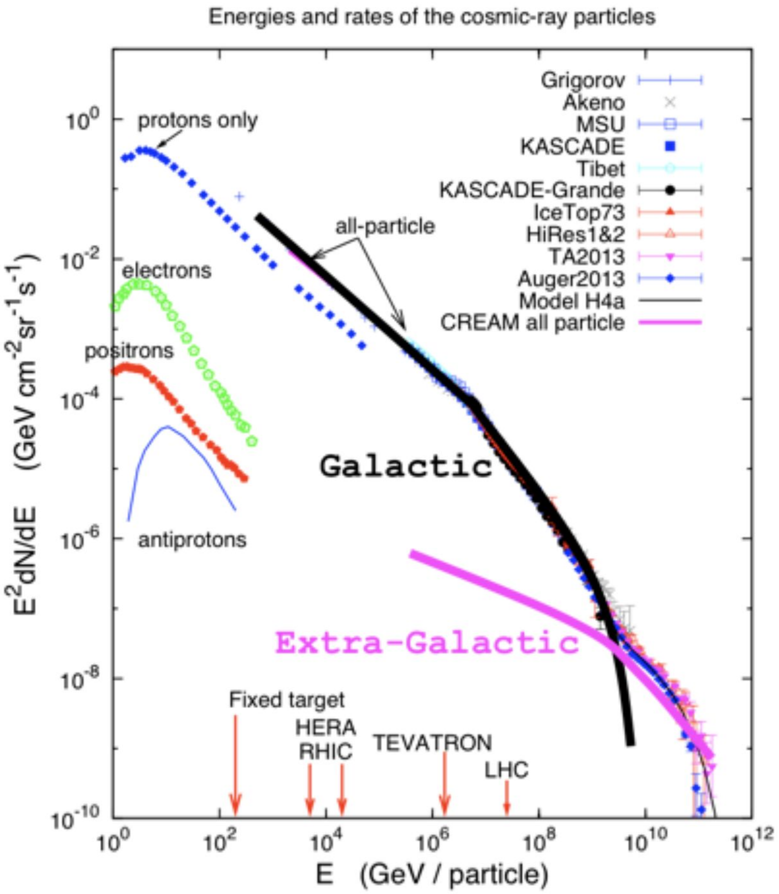


Credit: IceCube Collaboration/U.S. National Science Foundation (Lily Le & Shawn Johnson)/ESO (S. Brunier)

What is cosmic ray?

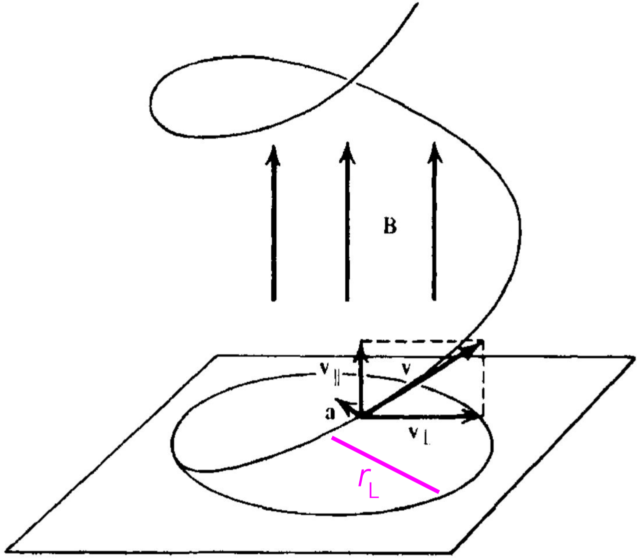
Cosmic–ray energy spectrum

flux against energy



(IceCube Masterclass)

Gyroradius r_L



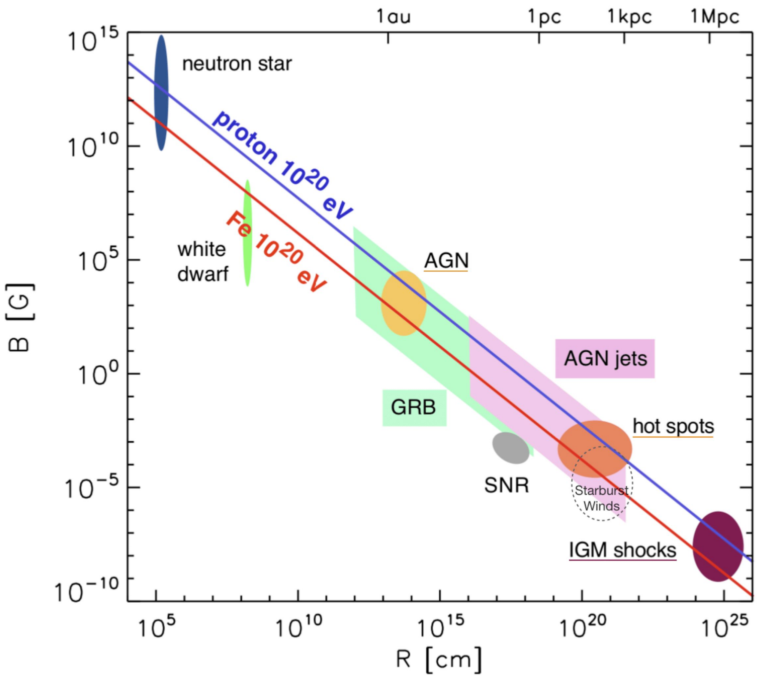
(Rybicki & Lightman 1985)

aka Larmor radius

$$r_\mathrm{L} = \frac{1.07\times10^{-5}}{|Z|}\left(\frac{E}{100\ \mathrm{MeV}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)^{-1}\ \mathrm{pc}$$

see also H.–Y. Pu's lecture

Origins and acceleration of ultra–high energy cosmic rays



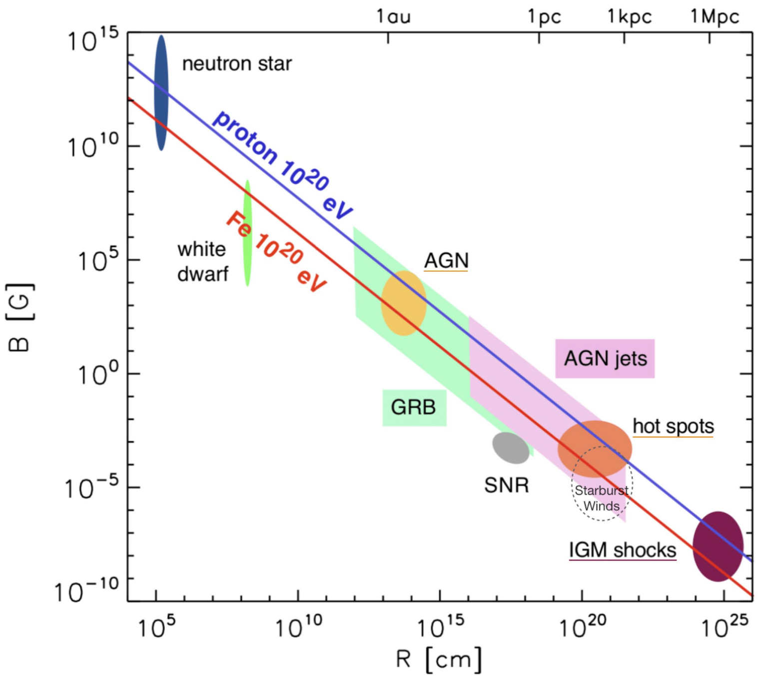
(Kotera & Olinto 2011; Rieger 2022)

$E \gtrsim 10^{20}$ eV

Hillas criterion (1984):
the particle gyroradius cannot exceed the size of the accelerator

Q: Can the Milky Way confine the UHECRs?

Origins and acceleration of ultra-high energy cosmic rays



(Kotera & Olinto 2011; Rieger 2022)

$E \gtrsim 10^{20}$ eV

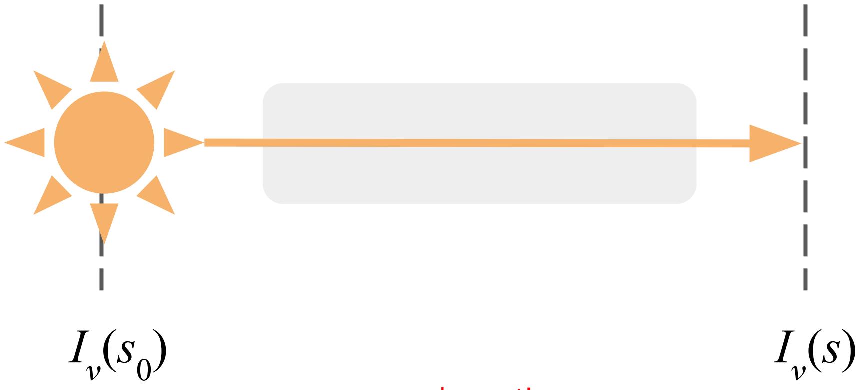
Hillas criterion (1984):
the particle gyroradius cannot exceed the size of the accelerator

Q: Can the Milky Way confine the UHECRs?
Barely, so they are likely to be of extragalactic origin.

Radiative transfer

Radiative transfer – general equation

Consider a ray of light travelling from a source at s_0 to an observer at s through a medium that can absorb and emit light



first-order ODE

absorption

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\alpha_\nu I_\nu + \epsilon_\nu$$

emission

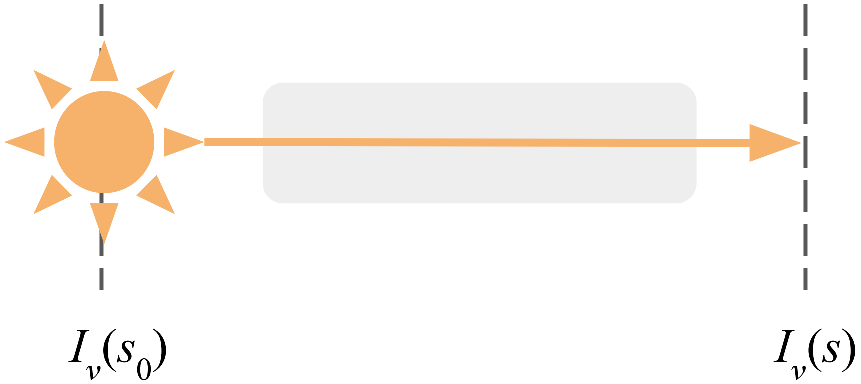
Radiative transfer – case 1

Consider no absorption and no emission

absorption

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\alpha_\nu I_\nu + \epsilon_\nu = 0$$

emission



Q: What is I_ν ?

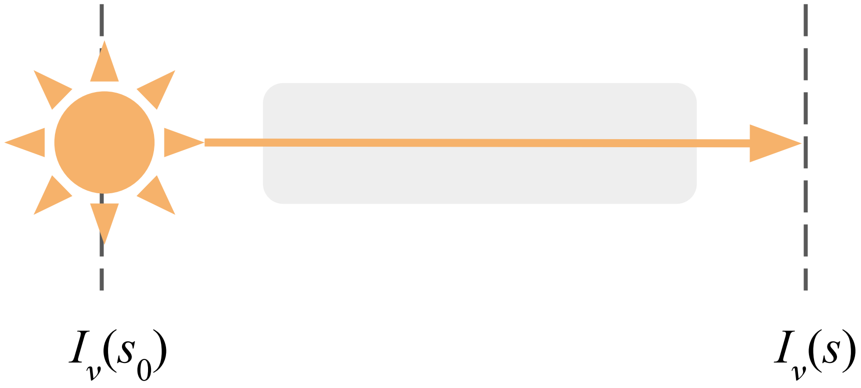
Radiative transfer – case 1

Consider no absorption and no emission

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\alpha_\nu I_\nu + \epsilon_\nu = 0$$

absorption

emission



Q: What is I_ν ?

$$I_\nu = \text{constant} = I_\nu(s_0)$$

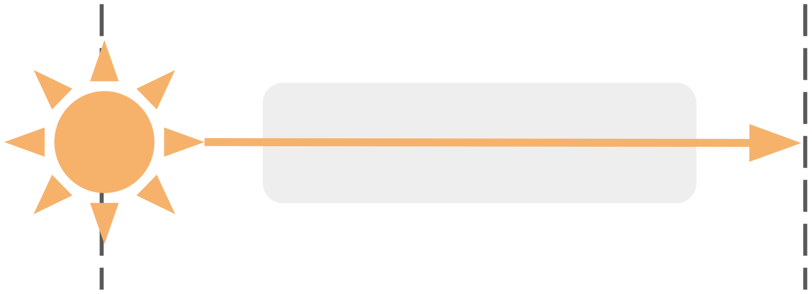
Radiative transfer – case 2

Consider no absorption

absorption

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\alpha_\nu I_\nu + \epsilon_\nu$$

emission



$I_\nu(s_0)$ $I_\nu(s)$

$$I_\nu(s) = I_\nu(s_0) + \int_{s_0}^{s} \epsilon_\nu(s')\,\mathrm{d}s'$$

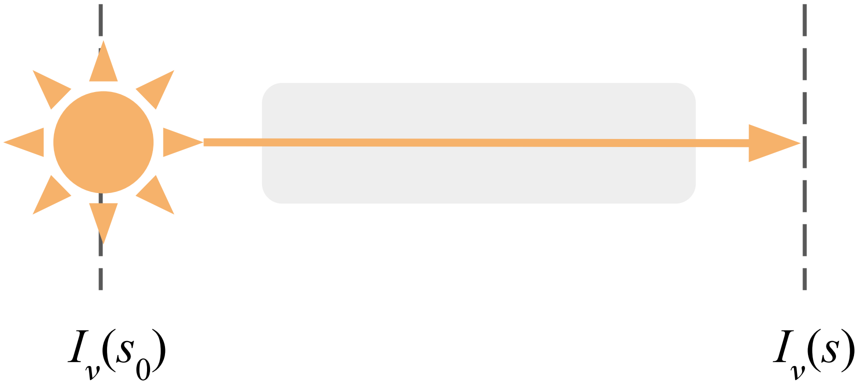
Radiative transfer – case 3

Consider no emission

absorption

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\alpha_\nu I_\nu + \epsilon_\nu$$

emission



$$I_\nu(s) = I_\nu(s_0)\ e^{-\int_{s_0}^{s} \alpha_\nu(s')\ \mathrm{d}s'}$$

Optical depth

"optical thickness" – how much light gets absorbed along the line–of–sight

$$\mathrm{d}\tau_\nu = \alpha_\nu \, \mathrm{d}s$$

differential optical depth

Rewrite the previous solution

$$I_\nu(s) = I_\nu(s_0)\; e^{-\int_{s_0}^{s} \alpha_\nu(s')\; \mathrm{d}s'}$$

$$I_\nu(s) = I_\nu(s_0)\; e^{-\tau_\nu(s)}$$

Two scenarios

$\tau_\nu > 1$ optically thick or opaque
most light is absorbed

$\tau_\nu < 1$ optically thin or transparent
most light passes through easily

Radiative transfer – case 4

Consider both absorption and emission

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\alpha_\nu I_\nu + \epsilon_\nu$$

In terms of optical depth,

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + S_\nu$$

Hint: $S_\nu \equiv \frac{\epsilon_\nu}{\alpha_\nu}$

source function

which gives the formal solution

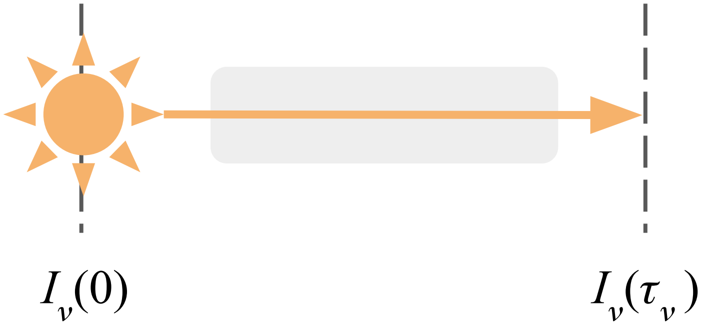
$$I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + \int_0^{\tau_\nu} \mathrm{d}\tau'_\nu\, S_\nu(\tau'_\nu)\, e^{-(\tau_\nu - \tau'_\nu)}$$

(Rybicki & Lightman 1985)

Radiative transfer – case 4

Consider both absorption and emission

$$I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + \int_0^{\tau_\nu} \mathrm{d}\tau'_\nu\, S_\nu(\tau'_\nu)\, e^{-(\tau_\nu - \tau'_\nu)}$$



$$S_\nu \equiv \frac{\epsilon_\nu}{\alpha_\nu}$$

constant source function

$$I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + S_\nu(1 - e^{-\tau_\nu})$$

optically thick medium

$$\tau_\nu \to \infty \qquad I_\nu(\tau_\nu) = S_\nu$$

optically thin medium

$$\tau_\nu \to 0 \qquad I_\nu(\tau_\nu) = I_\nu(0)$$

(Rybicki & Lightman 1985)

Radiation processes

Thermal radiation

Depends on the source temperature only

A **blackbody** absorbs all light. To remain in thermodynamic equilibrium, it must also emit the same amount of light.

Q: Any good examples in astrophysics?

Thermal radiation

Depends on the source temperature only

A **blackbody** absorbs all light. To remain in thermal equilibrium, it must also emit the same amount of light.

Some common examples in astrophysics:

1. Earth
2. Sun

} to a "good" approximation — see also H. Shang's lecture

3. cosmic microwave background (CMB)

Planck's law

describes the spectrum of blackbody radiation at various temperatures

Hint: $c = \lambda \nu$

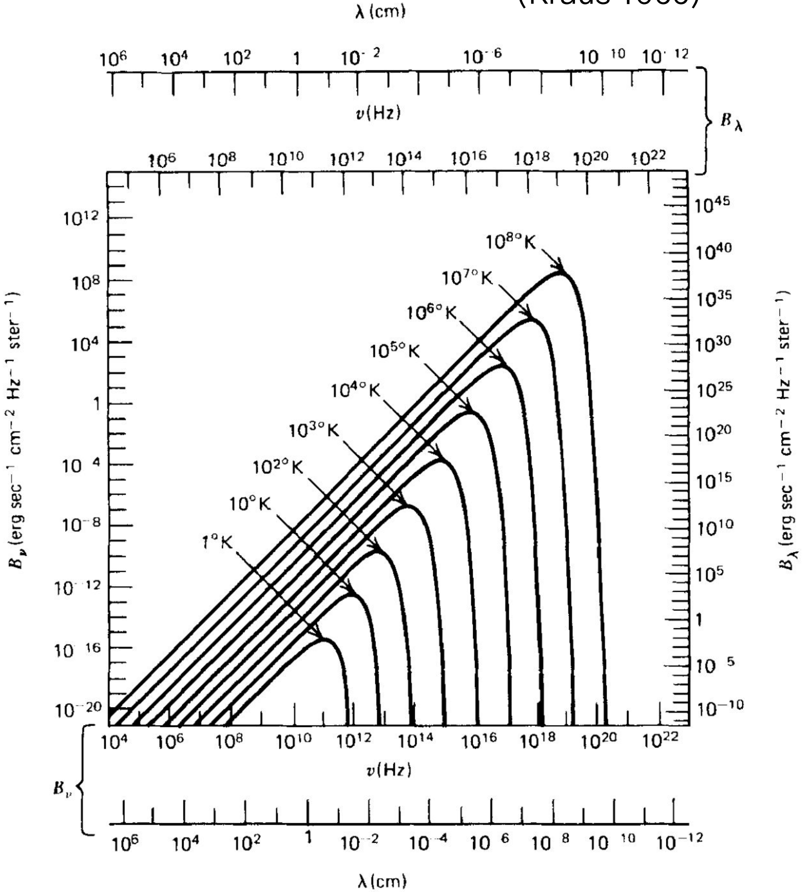
in terms of frequency

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{(h\nu/k_\mathrm{B}T)} - 1}$$

in terms of wavelength

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{(hc/\lambda k_\mathrm{B}T)} - 1}$$

(Kraus 1966)



Kirchhoff's law for thermal radiation

Recall $$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + S_\nu$$ RT equation in terms of optical depth

$$\epsilon_\nu = \alpha_\nu \, B_\nu(T)$$ Kirchhoff's law

$$S_\nu = B_\nu(T)$$ thermal radiation

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + B_\nu(T)$$

When $\tau > 1$, thermal radiation becomes blackbody radiation.

(Rybicki & Lightman 1985)

Non-thermal radiation

Does not depend on the source temperature

Some common examples in astrophysics:

1. Compton and Inverse Compton scattering
2. Synchrotron emission
3. Thick-target Bremssthrahlung (e.g. solar flare)

Non-thermal radiation

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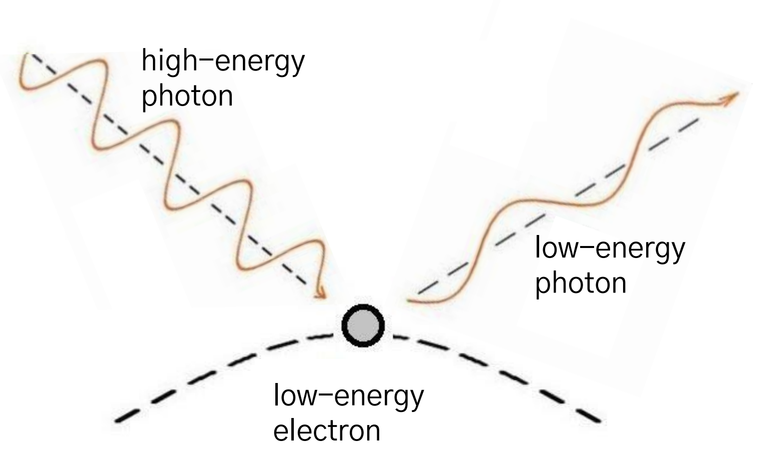
Compton scattering

Ingredients

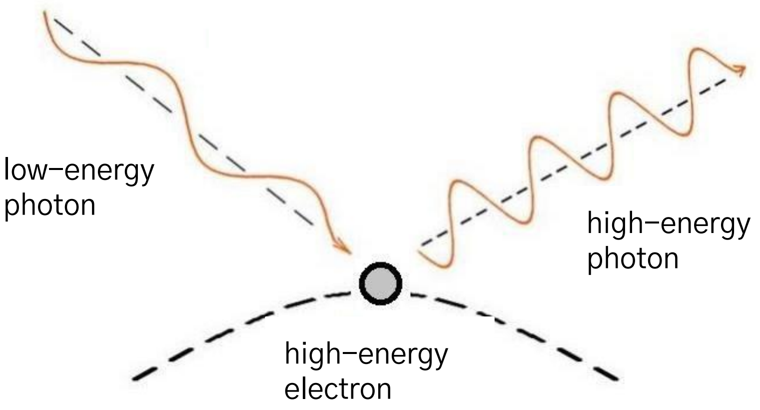
1. High-energy charged particles
2. Radiation field

(adapted from Bennun 2020)

Compton scattering



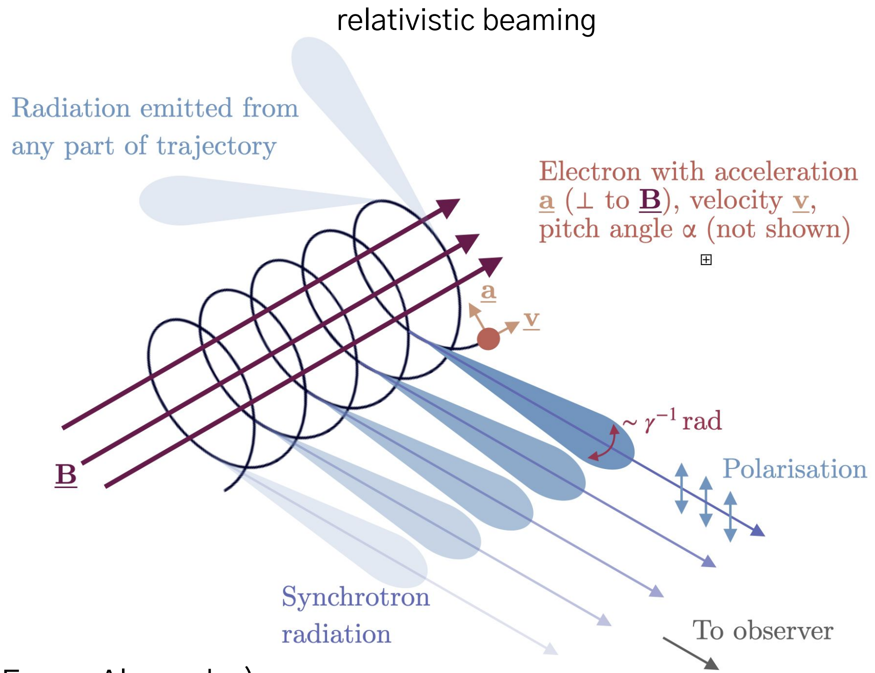
Inverse Compton scattering



Synchrotron emission

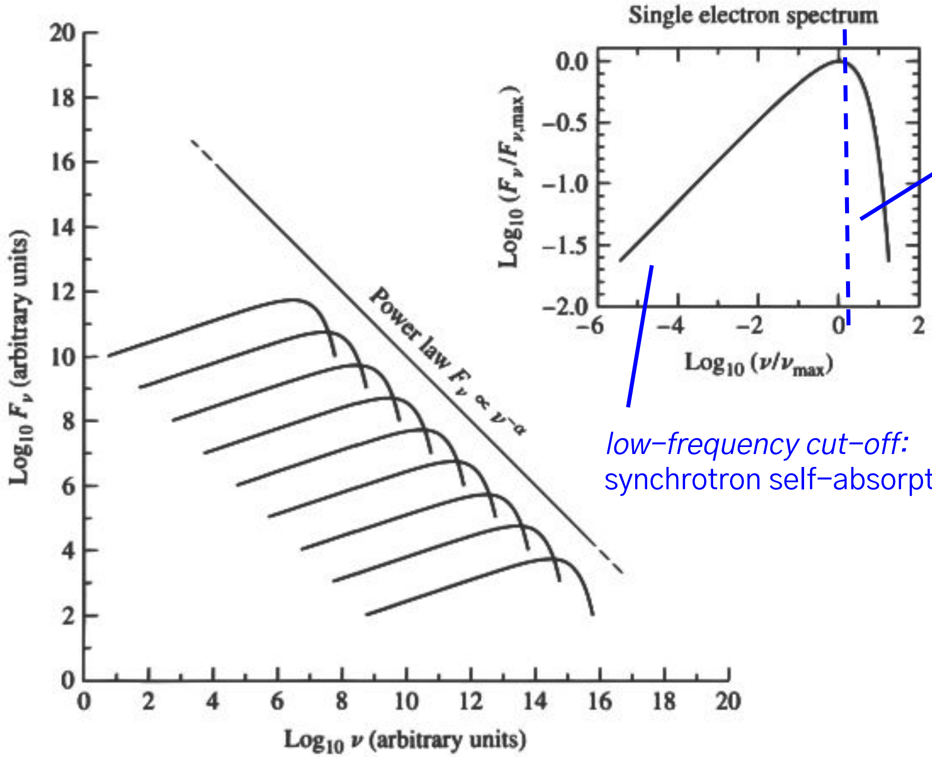
Ingredients

1. High-energy charged particles
2. Magnetic field



(Emma Alexander)

Power–law spectrum



high–frequency cut–off:
rapid cooling of
high–energy electrons

low–frequency cut–off:
synchrotron self–absorption

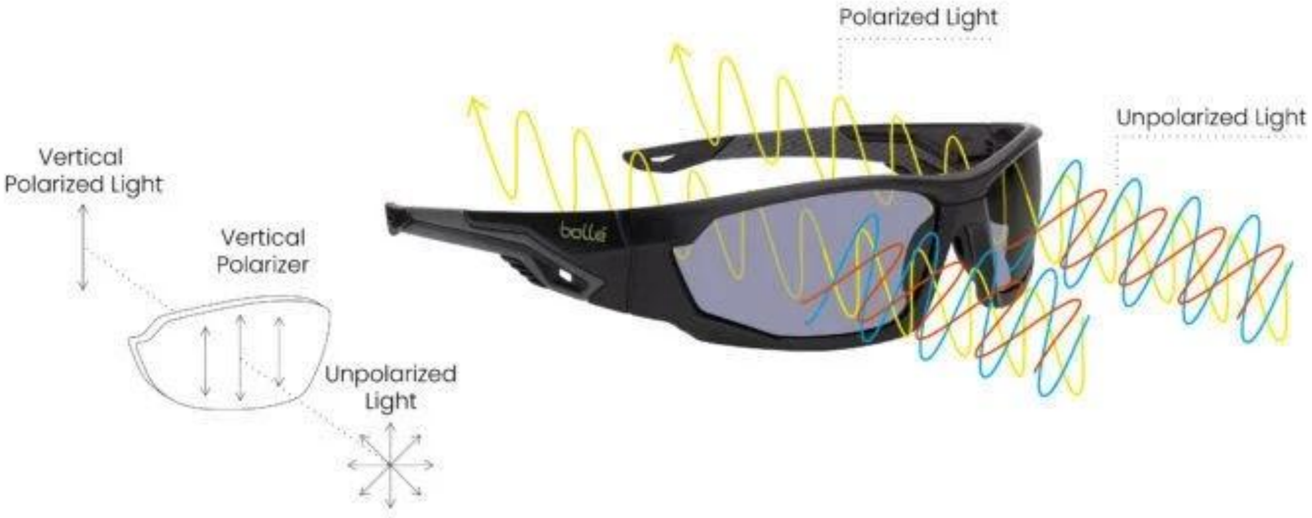
(Carroll & Ostlie 2007)

Basics of polarisation

What is polarisation?

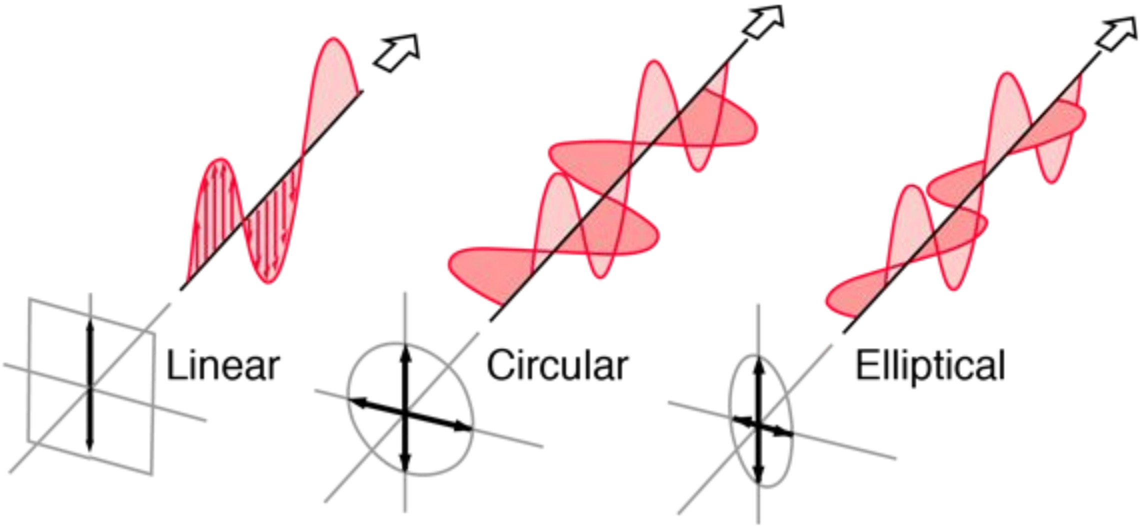
(SportRX)

How do sunglasses work?



(Bollé Safety)

Types of polarisation



(HyperPhysics, R. Nave 2016)

Stokes parameters of polarisation and the Poincaré sphere

$$I \equiv \varepsilon_1^2 + \varepsilon_2^2 = \varepsilon_0^2 \,,$$ total intensity

$$Q \equiv \varepsilon_1^2 - \varepsilon_2^2 = \varepsilon_0^2 \cos 2\chi \cos 2\psi \,,$$

$$U \equiv 2\varepsilon_1 \varepsilon_2 \cos(\phi_1 - \phi_2) = \varepsilon_0^2 \cos 2\chi \sin 2\psi \,,$$

(Q and U:) linearly–polarised intensity

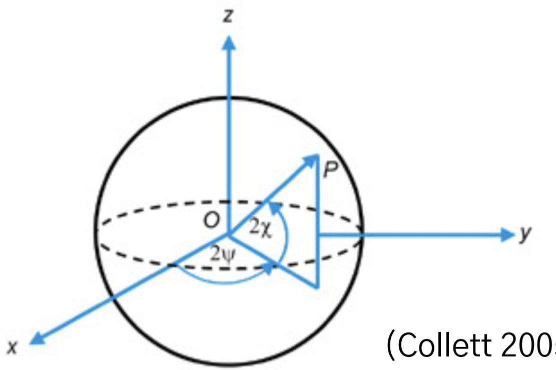
$$V \equiv 2\varepsilon_1 \varepsilon_2 \sin(\phi_1 - \phi_2) = \varepsilon_0^2 \sin 2\chi \,,$$ circularly–polarised intensity

$$\varepsilon_0 = \sqrt{I} \,,$$

$$\sin 2\psi = \frac{V}{I} \,,$$

$$\tan 2\chi = \frac{U}{Q}$$

(Rybicki & Lightman 1985)

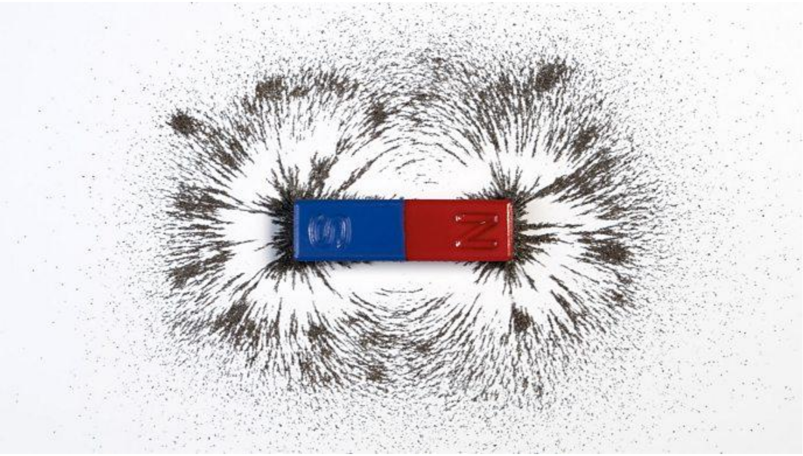


(Collett 2005)

How about magnetic fields?

Magnetic fields are invisible

We cannot see or measure them directly, thus magnetic field studies are challenging



(BBC Bitesize)

Q: So why bother to study magnetic fields?

So why bother to study magnetic fields?

Because they are "everywhere", and therefore must play an important role in almost every astrophysical phenomenon

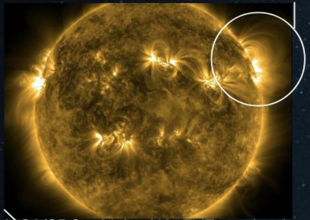
SEEING THE INVISIBLE

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!

larger structure

weaker field

Magnetic arches towering over the active solar surface



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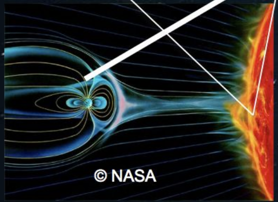
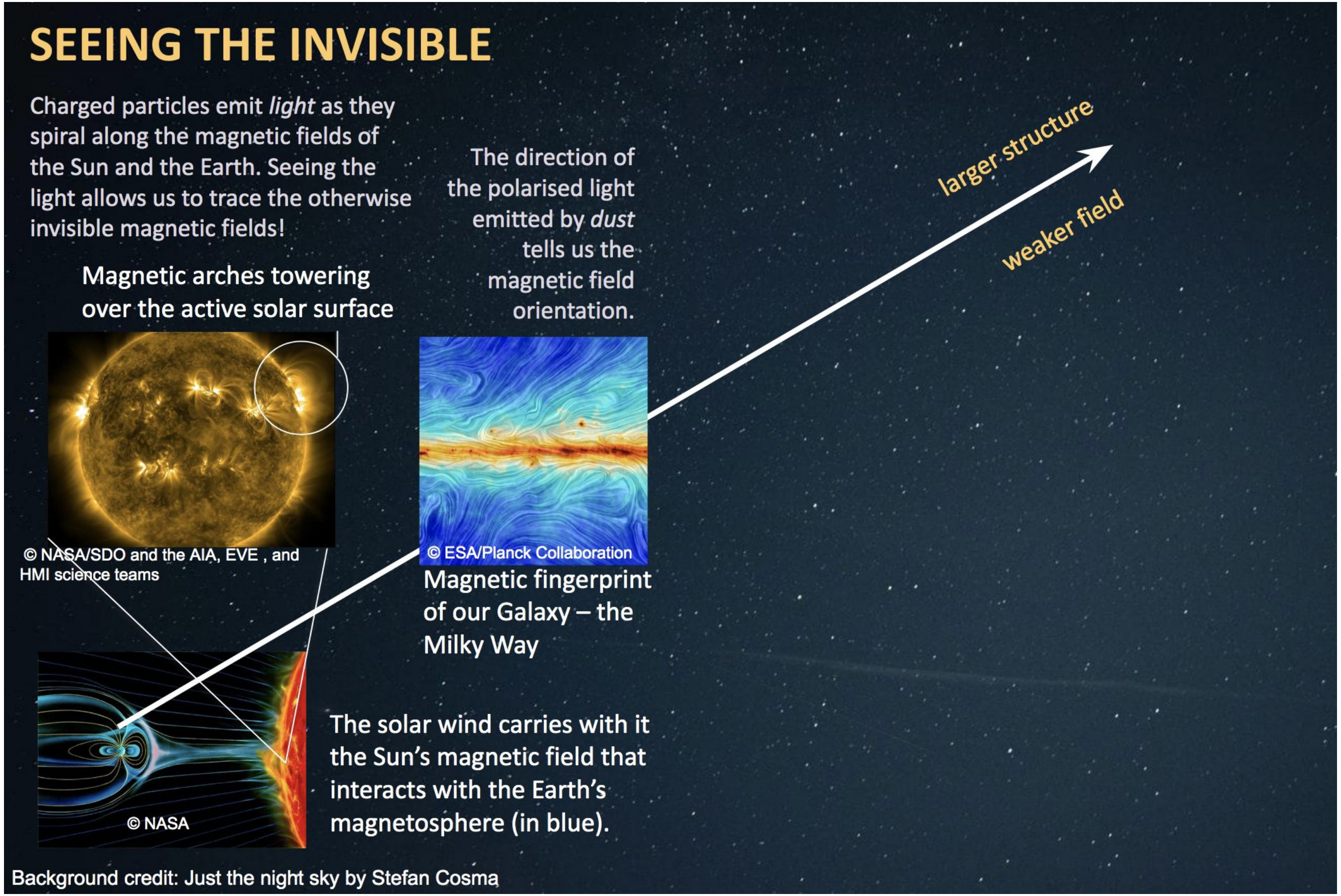


The solar wind carries with it the Sun's magnetic field that interacts with the Earth's magnetosphere (in blue).

Background credit: Just the night sky by Stefan Cosma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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
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Magnetic fingerprint of our Galaxy – the Milky Way
© NASA
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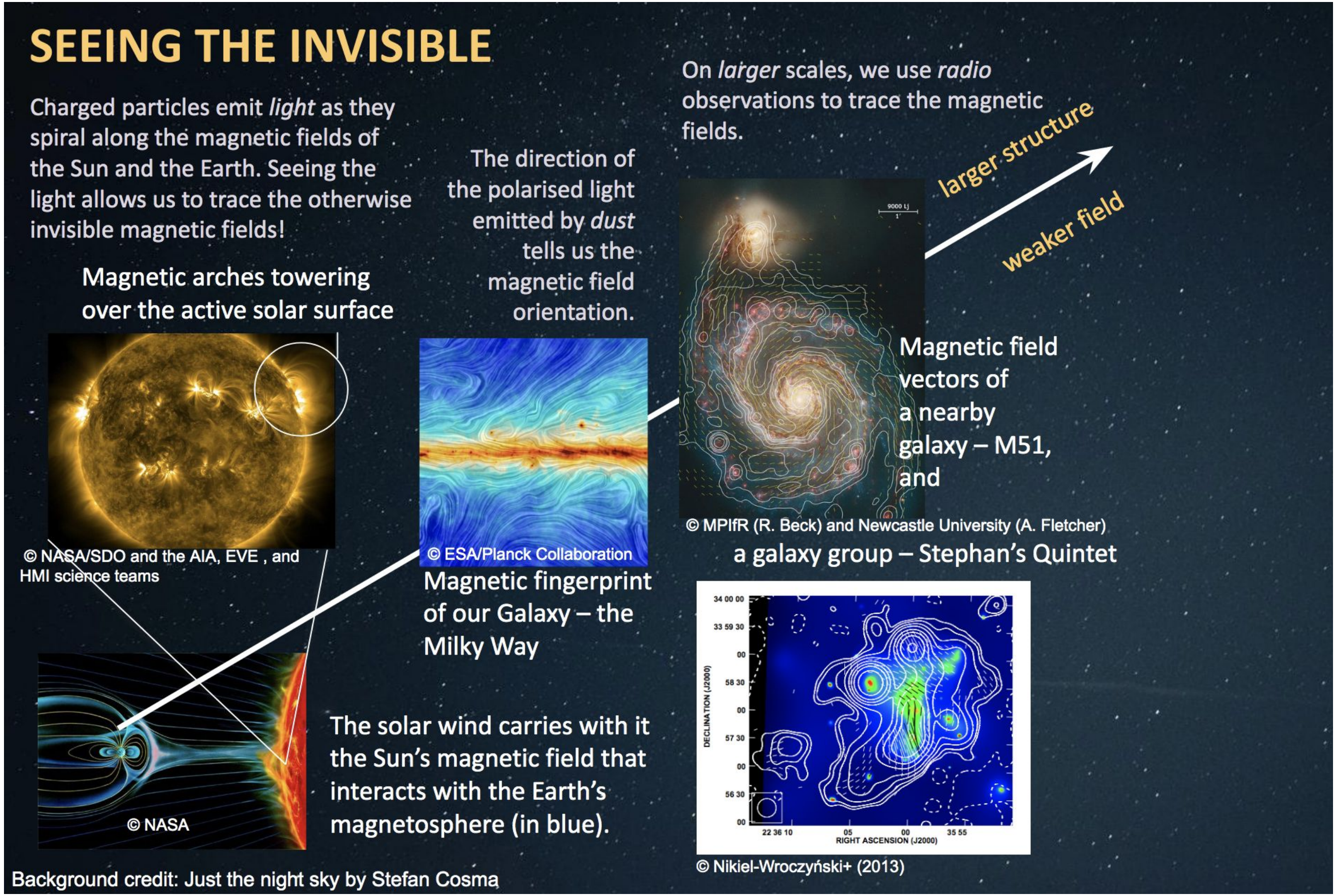
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Magnetic fingerprint of our Galaxy – the Milky Way
On *larger* scales, we use *radio* observations to trace the magnetic fields.
larger structure
weaker field
Magnetic field vectors of a nearby galaxy – M51, and
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a galaxy group – Stephan's Quintet
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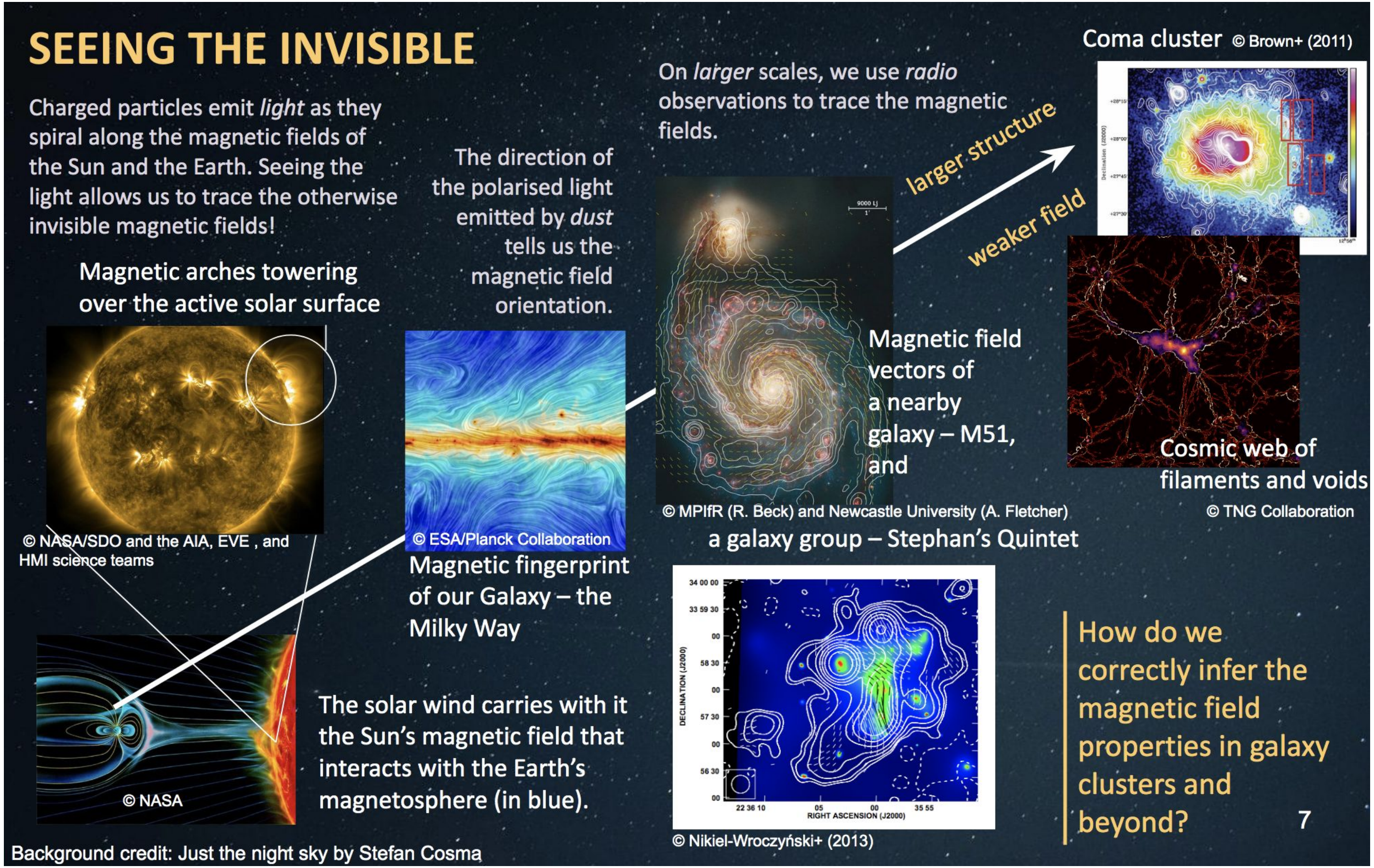
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Coma cluster © Brown+ (2011)
Cosmic web of filaments and voids
© TNG Collaboration
How do we correctly infer the magnetic field properties in galaxy clusters and beyond?
7
Background credit: Just the night sky by Stefan Cosma

How do we see and measure magnetic fields?

Some common ways in astrophysics:

1. Zeeman effect
2. Goldreich–Kylafis effect
3. Interstellar dust
4. Faraday rotation

Faraday rotation

Occurs when the polarisation plane of light rotates in a magnetic field

distance between the source and the observer

B–field strength along the line–of–sight

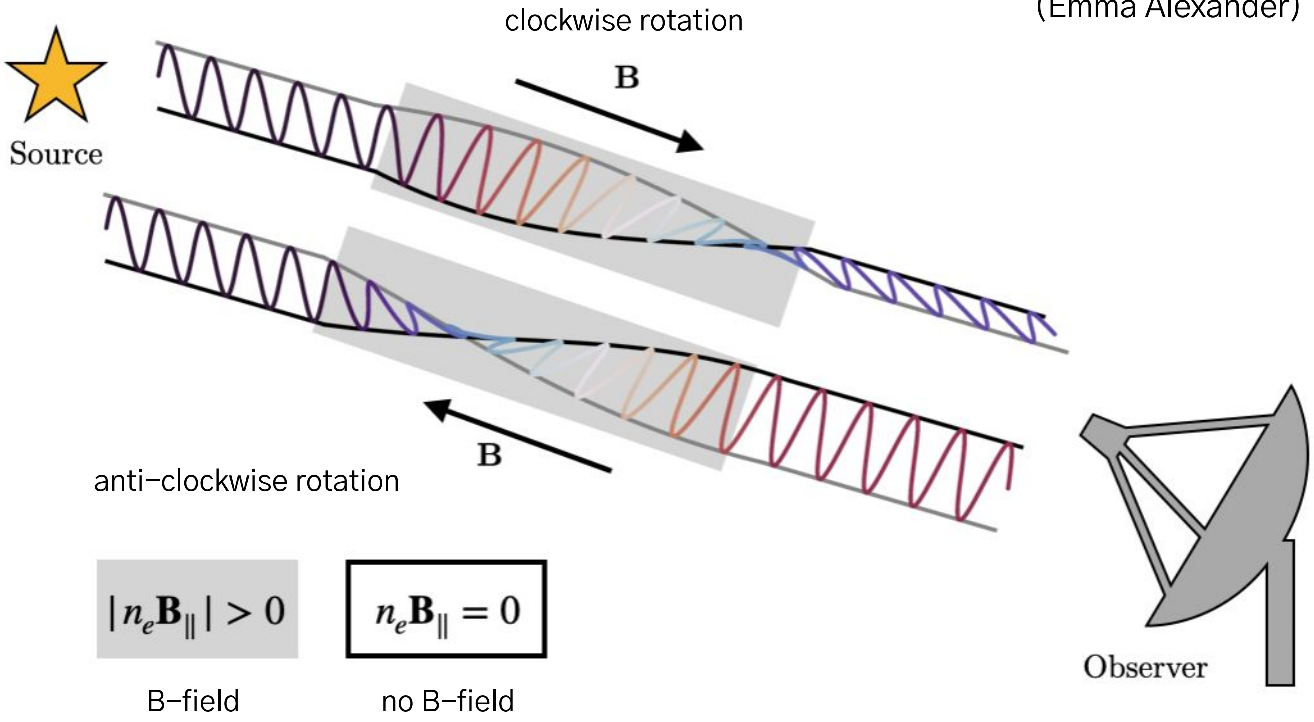
$$\mathcal{R}(s) = 0.812 \int_{s_0}^{s} \frac{\mathrm{d}s'}{\mathrm{pc}} \left(\frac{n_{\mathrm{e,th}}(s')}{\mathrm{cm}^{-3}} \right) \left(\frac{B_{\parallel}(s')}{\mu\mathrm{G}} \right) \mathrm{rad\,m}^{-2}$$

rotation measure

thermal electron number density

Faraday rotation

(Emma Alexander)



Measuring the invisible

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

RM

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

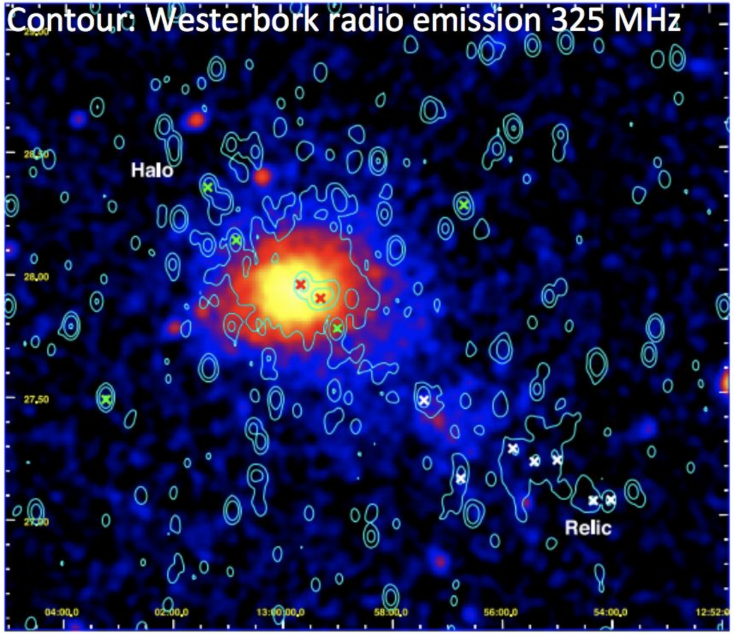
observed wavelength

observed polarisation angle

intrinsic polarisation angle

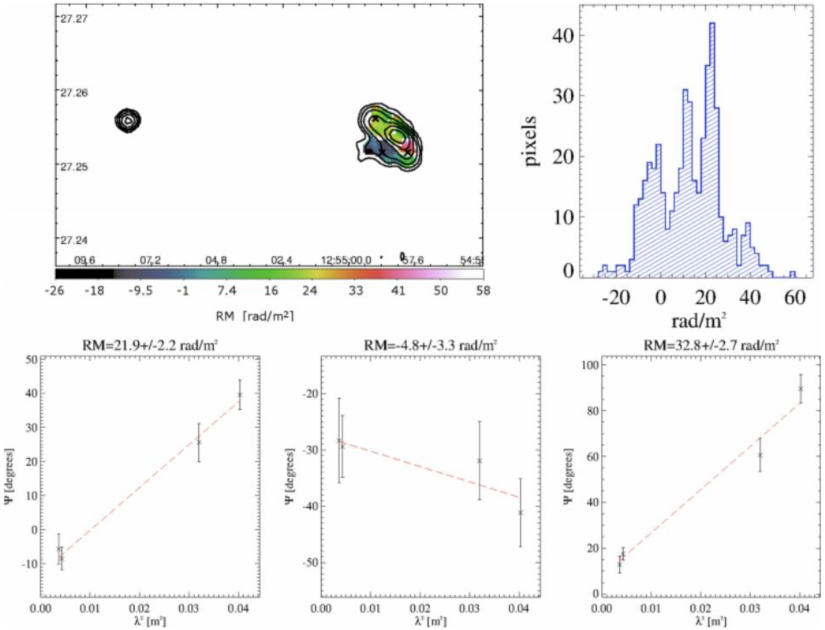
Beyond Galactic scales

Colour: ROSAT X-ray
Contour: Westerbork radio emission 325 MHz



Coma cluster and NGC 4839 group

Colour: RM Contour: Total radio intensity 1.4 GHz



a radio background source 5C4.24

12

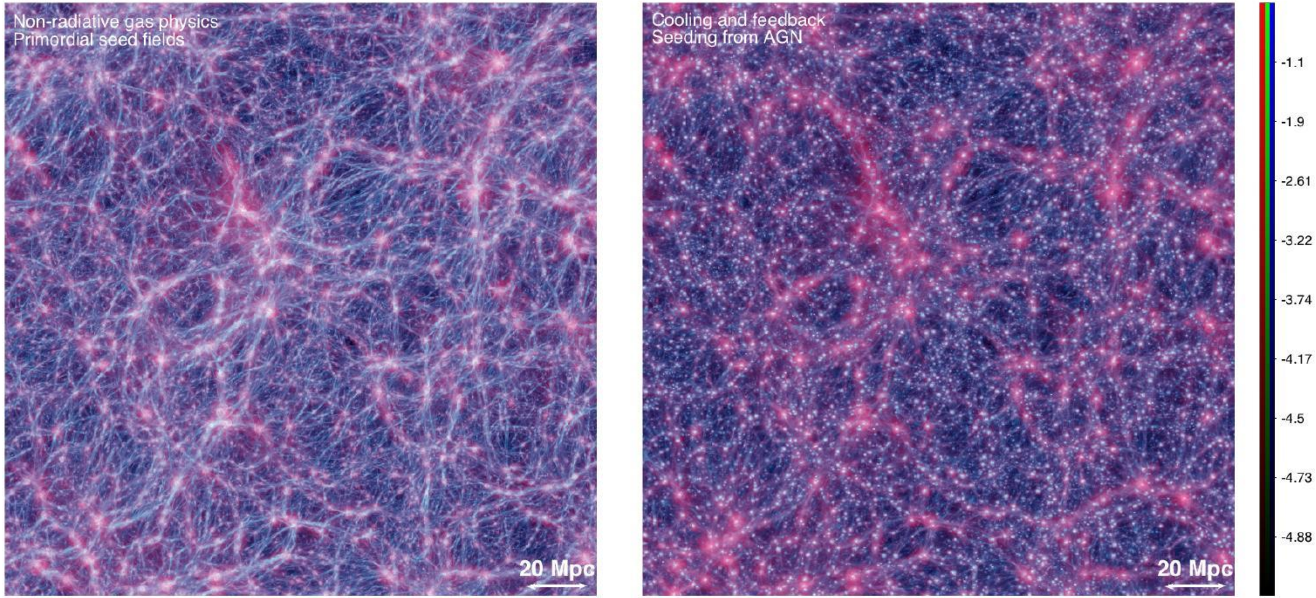
(Bonafede+ 2013)

The cosmic web

see also H.–Y. Schive's lecture

The first "seed" magnetic fields

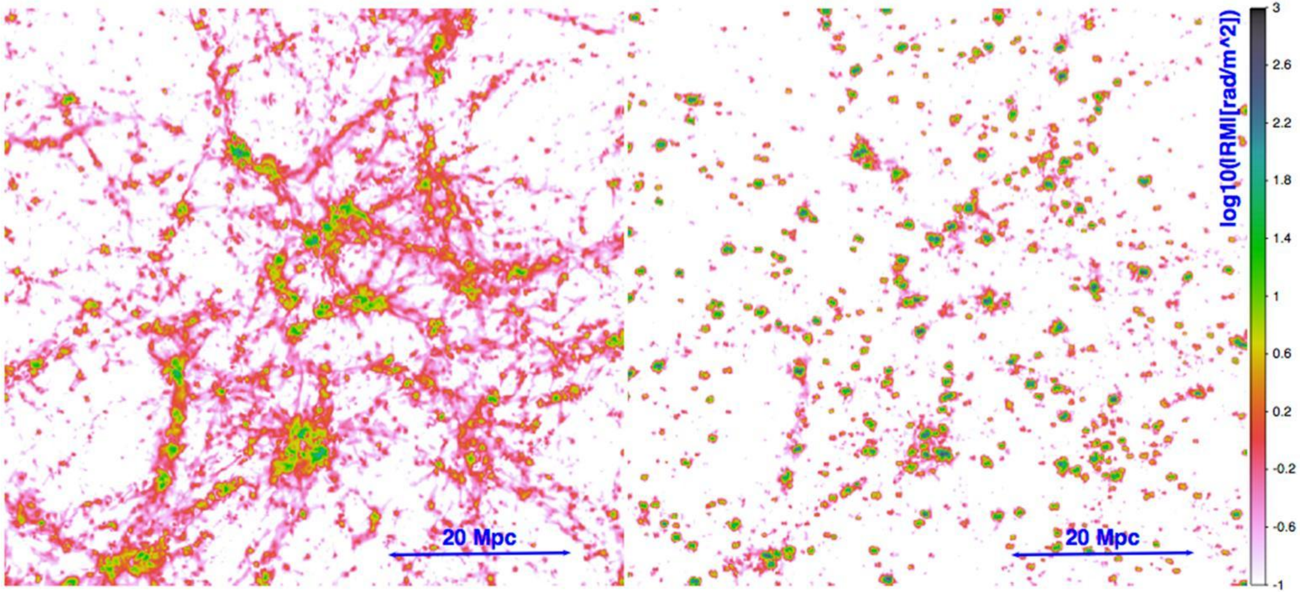
(Vazza+ 2017)



primordial astrophysical

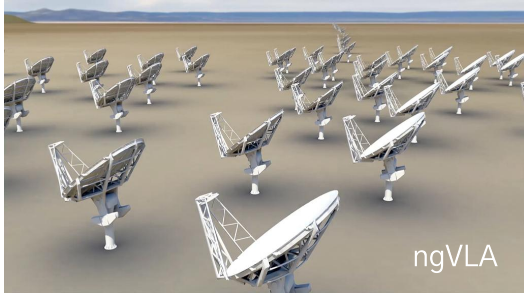
The cosmic web

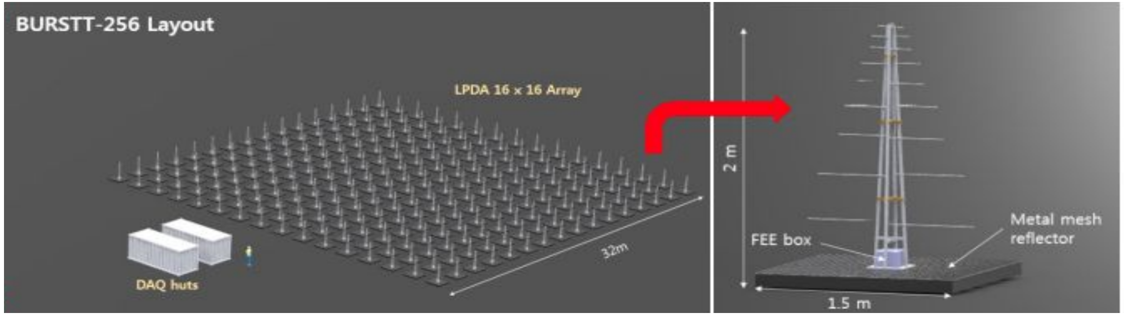
Faraday RM – difference of order >10 outside of clusters (Vazza+ 2017)



primordial astrophysical

Seeing the radio sky





Configuration of the ngVLA (From the ngVLA NRAO official website)
Composite image of the SKA over the Milky Way centre: SKAO, ICRAR, SARAO, Natasha Hurley-Walker (Curtin/ICRAR) and the GLEAM team
BURSTT antenna design and 256 array (From the BURSTT official leaflet)

Recall: rotation measure

In the context of polarised radiative transfer

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

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 (RMFs)

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

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

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

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; 2021)

(On+ 2019)

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

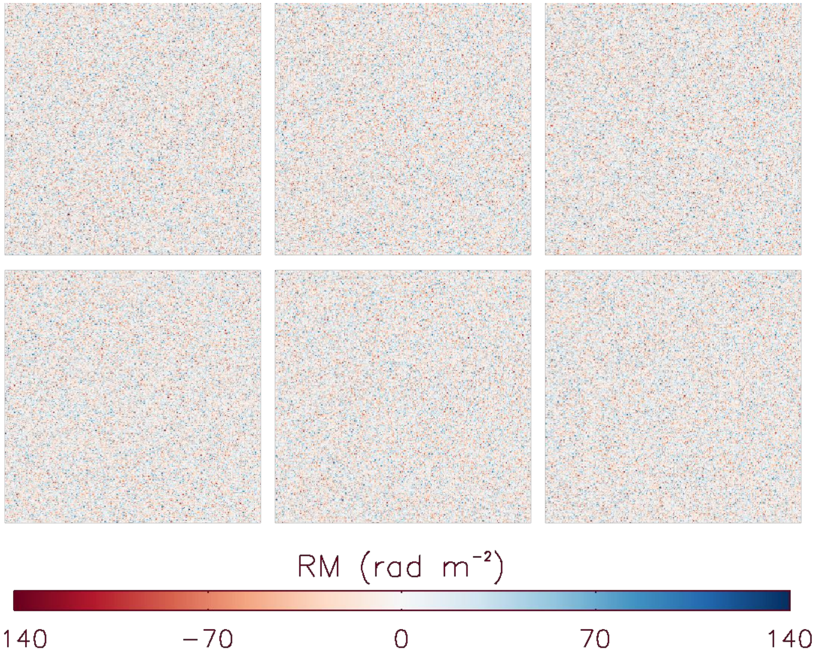
$$\mathcal{R}_{\perp} = 0.812 \sum_{\parallel} \frac{\overline{\Delta s}}{\mathrm{pc}} \left[\left(\frac{n_{\mathrm{e,th}}(i,j,k)}{\mathrm{cm}^{-3}} \right) \left(\frac{B(i,j,k)}{\mu\mathrm{G}} \right) \right]_{\parallel} \mathrm{rad\ m}^{-2} \qquad (2)$$

Calculated the standard deviation across the sky plane

(On+ 2019)

Let's do an eye test

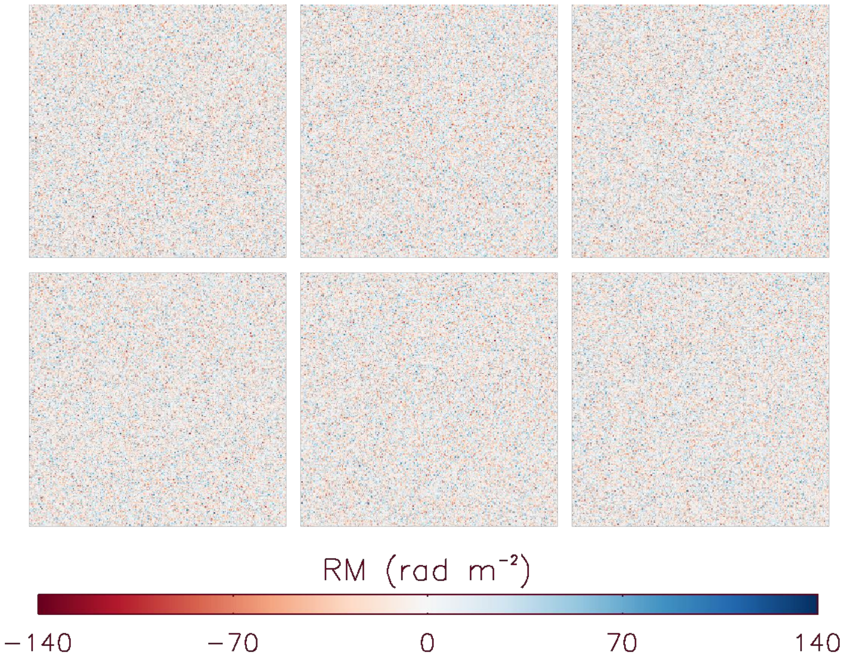
Q: Can you spot any difference between the panels?



(On+ 2019)

Synthetic RM maps

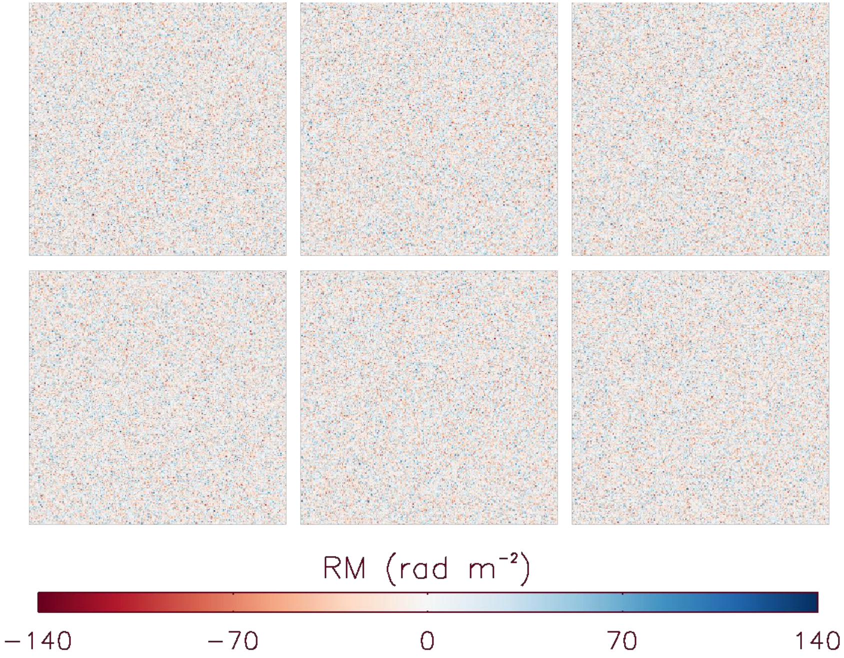
Indistinguishable



(On+ 2019)

Synthetic RM maps

Indistinguishable



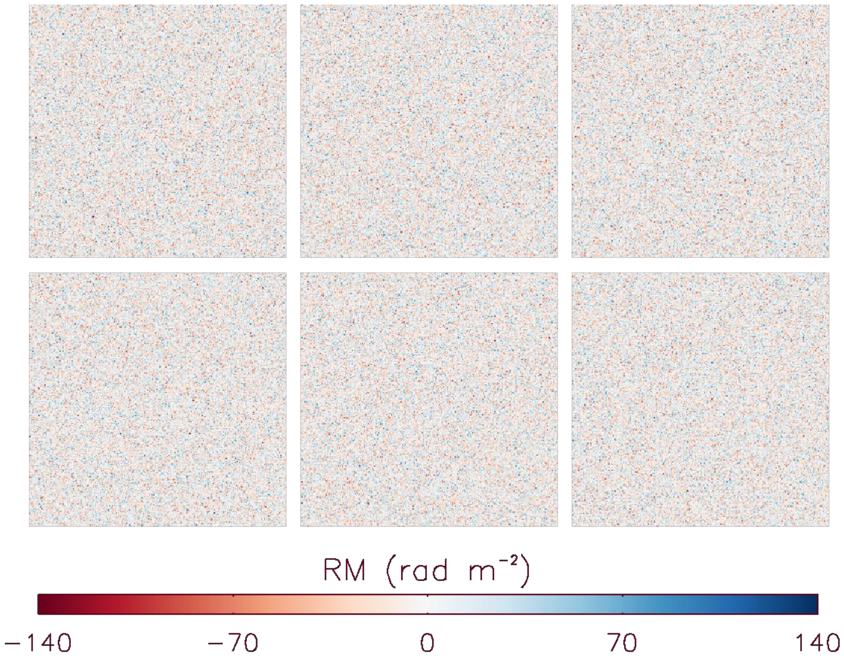
Gaussian–distributed densities

Gaussian–distributed magnetic field strengths
random magnetic field orientations

(On+ 2019)

Synthetic RM maps

Indistinguishable



Gaussian–distributed densities

Gaussian–distributed magnetic field strengths
random magnetic field orientations

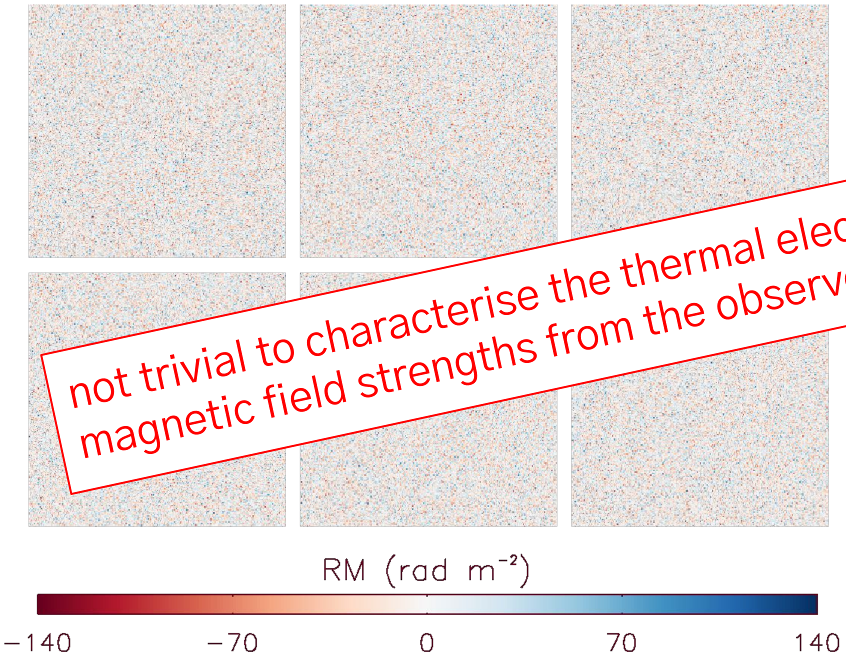
uniformly–distributed densities

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

(On+ 2019)

Synthetic RM maps

Indistinguishable



not trivial to characterise the thermal electron number densities and the magnetic field strengths from the observed RM fluctuations alone

Gaussian–distributed densities

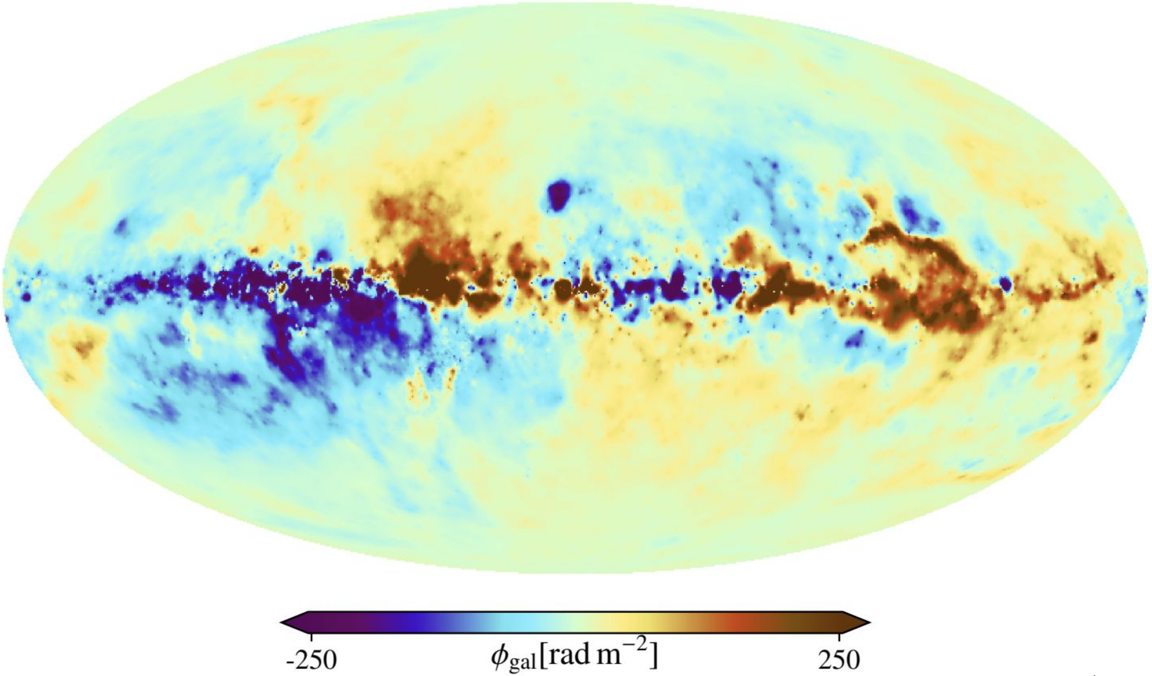
Gaussian ... ths

uniformly–distributed densities

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

(On+ 2019)

The Galactic Faraday rotation sky 2020



(Hutschenreuter+ 2022)

Summary

Keep the Stokes polarisation!

In complex situations, a covariant polarised radiative transfer (CPRT) 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.

(On+ 2019) (Chan+ 2018)