# Chpt.2 Fundamentals of radiation

# Escape probability

prev. sl.

$$I_\nu^{\text{out}} = I_\nu^{\text{in}} e^{-\tau_{\nu,0}} + \int_0^{\tau_{\nu,0}} S_\nu(\tau_\nu) e^{-\tau_\nu} d\tau_\nu$$

Without external emission ($I_\nu^{\text{in}} = 0$)

$$I_\nu^{\text{out}} = \int_0^{\tau_{\nu,0}} S_\nu(\tau_\nu) e^{-\tau_\nu} d\tau_\nu$$

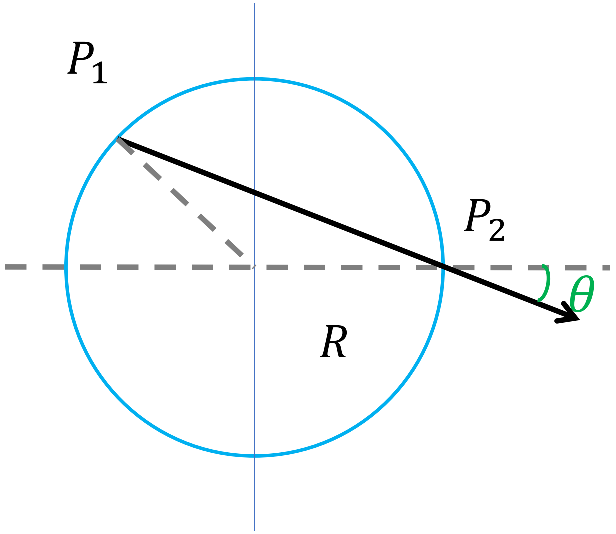
If we know the escape probability $P_{\text{esc}}$, it might be easier to calculate the emergent emission than a full radiative transfer calculation.

$$j_\nu^{\text{eff}} \equiv j_\nu P_{\text{esc}}$$

# Spherical geometry + homogenous medium

homogenous→ $\tau_\nu = \alpha_\nu R$

Radius: $R$, absorption coefficient $\alpha_\nu$, line emission coefficient $j_\nu$




Consider a photon emitted from $P_1$, when traveling to $P_2$, the optical depth is $2\tau_\nu \cos\theta$

prev. sl. $I_\nu^{\text{out}} = \int S_\nu(\tau_\nu) e^{-\tau_\nu} d\tau_\nu$

prev. sl. $\dfrac{j_\nu}{\alpha_\nu} = S_\nu$

$$I_\nu^{\text{out}} = \int_0^{2R\cos\theta} j_\nu e^{-\alpha_\nu r} dr$$

$$= \frac{j_\nu}{\alpha_\nu}\left(1 - \exp(-2\tau_\nu \cos\theta)\right)$$

$$\int_0^b \exp(-a\, r)\, dr = \frac{1 - \exp(-a\, b)}{a}$$

# Flux

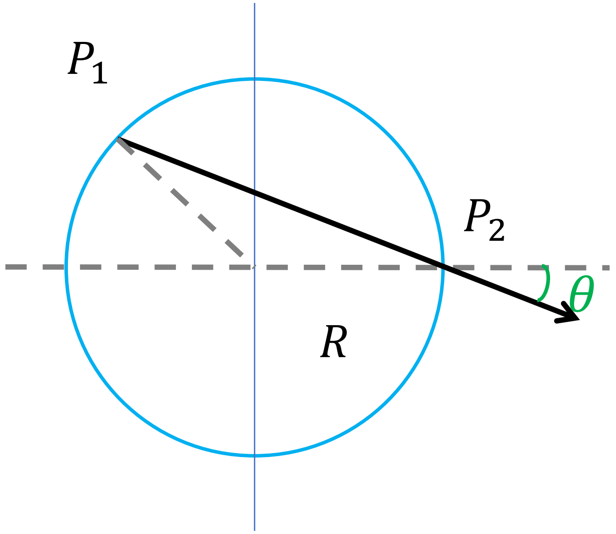
prev. sl.

$$I_\nu^{\text{out}} = \frac{j_\nu}{\alpha_\nu}(1 - \exp(-2\tau_\nu \cos\theta))$$

prev. sl.

$$dF = I \cos\theta \, d\Omega$$

homogenous→ $\tau_\nu = \alpha_\nu R$




Flux emitted from $P_2$

$$F_{\nu,\text{esc}} = \int I_\nu^{\text{out}} \cos\theta \; d\Omega = \int_0^{2\pi} d\phi \int_0^{\pi/2} I_\nu^{\text{out}} \cos\theta \sin\theta \, d\theta$$

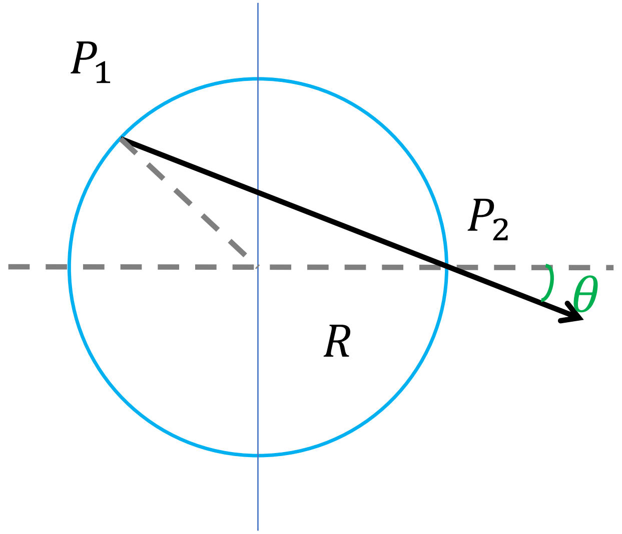
$$= \frac{\pi j_\nu}{2\alpha_\nu \tau_\nu^2}(2\tau_\nu^2 - 1 + e^{-2\tau_\nu}(2\tau_\nu + 1))$$

$$\int_0^{\pi/2} \cos\theta \sin\theta \, (1 - \exp(-2\, a \cos\theta)) d\theta = \frac{2a^2 - 1 + \exp(-2a)\,(2a+1)}{4\, a^2}$$

# Escape probability

prev. sl.

$$F_{\nu,\mathrm{esc}} = \frac{\pi j_\nu}{2\alpha_\nu \tau_\nu^2}\left(2\tau_\nu^2 - 1 + e^{-2\tau_\nu}(2\tau_\nu + 1)\right)$$




c.f. a photon emitted from $P_1$, when travelling to $P_2$ without any absorption

$$I_{\nu,0}^{\mathrm{out}} = \int_0^{2R\cos\theta} j_\nu dr = j_\nu 2R\cos\theta$$

prev. sl.

$$I_\nu^{\mathrm{out}} = \int_0^{2R\cos\theta} j_\nu e^{-\alpha_\nu r} dr$$

$$F_{\nu,0} = \int_0^{2\pi} d\phi \int_0^{\pi/2} I_{\nu,0}^{\mathrm{out}} \cos\theta \sin\theta \, d\theta = \frac{4\pi R\, j_\nu}{3}$$

$$\int_0^{\pi/2} \cos^2\theta \sin\theta \, d\theta = \frac{1}{3}$$

prev. sl.

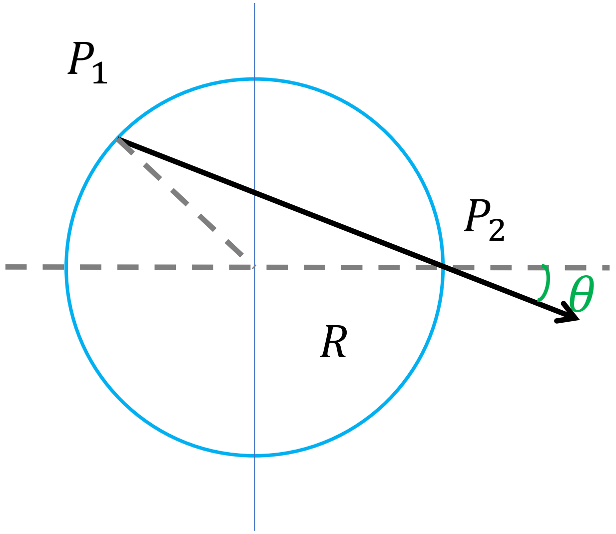
$$dF = I\cos\theta \, d\Omega$$

$$P_{\mathrm{esc}} = \frac{F_{\nu,\mathrm{esc}}}{F_{\nu,0}} = \frac{3}{8\tau_\nu^3}\left(2\tau_\nu^2 - 1 + e^{-2\tau_\nu}(2\tau_\nu + 1)\right)$$

# Asymptotic behavior

prev. sl.

$$P_{\text{esc}} = \frac{F_{\nu,\text{esc}}}{F_{\nu,0}} = \frac{3}{8\tau_\nu^3}\left(2\tau_\nu^2 - 1 + e^{-2\tau_\nu}(2\tau_\nu + 1)\right)$$




$$\tau_\nu \gg 1 \;\rightarrow P_{\text{esc}} \sim \frac{3}{4\,\tau_\nu} \sim \frac{1}{\tau_\nu} = \frac{1}{\alpha_\nu R}$$

$$\tau_\nu \sim 0 \;\rightarrow P_{\text{esc}} \sim 1$$

$$\frac{x^2}{2} - 1 + e^{-x}(x+1), x = 2\tau_\nu$$

$$= \frac{x^2}{2} - 1 + \left(1 - x + \frac{x^2}{2} - \frac{x^3}{6}\right)(x+1)$$

$$\exp(-x) = 1 - x + \frac{x^2}{2} - \frac{x^3}{6} + \cdots$$

$$\frac{3}{x^3}\left(\frac{x^2}{2} - 1 + x + 1 - x^2 - x + \frac{x^3}{2} + \frac{x^2}{2} - \frac{x^4}{6} - \frac{x^3}{6}\right) = \frac{3}{x^3}\left(\frac{x^3}{3} - \frac{x^4}{6}\right) \rightarrow 1$$

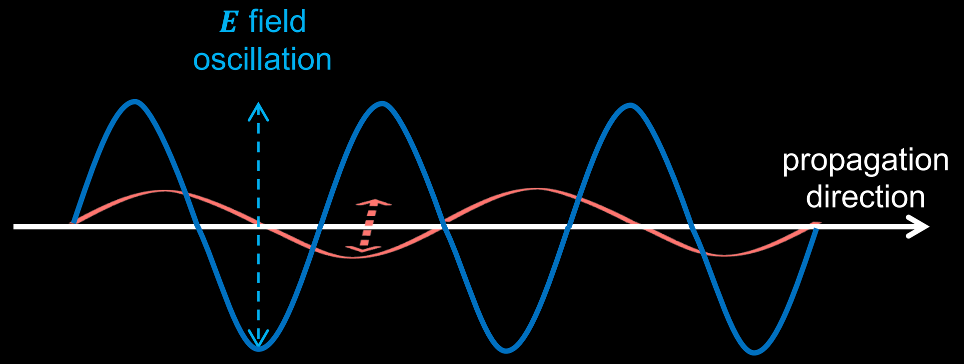
# Chpt.2 Fundamentals of radiation

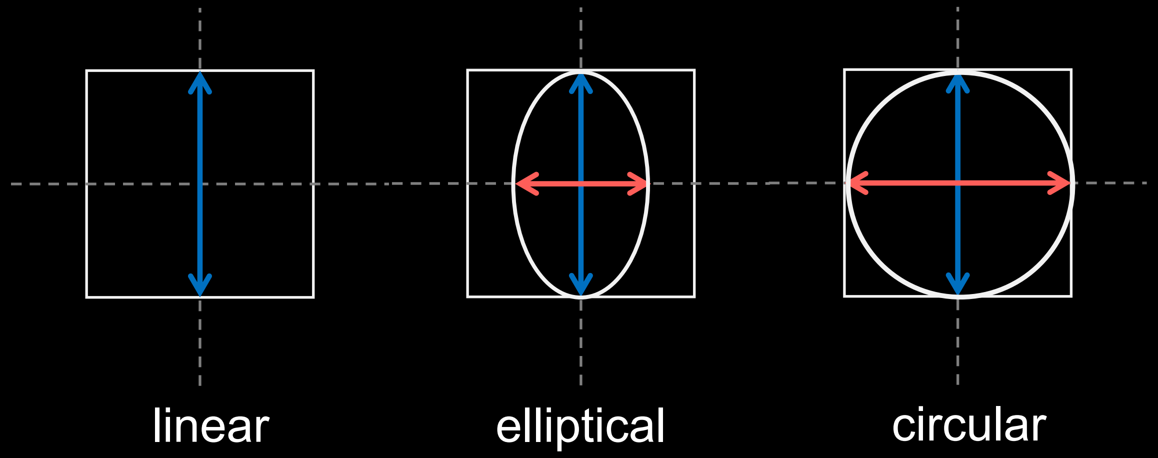
2.1 Elementary concepts of radiation
2.2 Radiative transfer
2.3 Thermal radiation
2.4 Escape probability
2.5 Scattering

2.6 Polarization
2.6.1 Stokes parameters
2.6.2 Polarization fraction

2.7 Dispersion and rotation measures

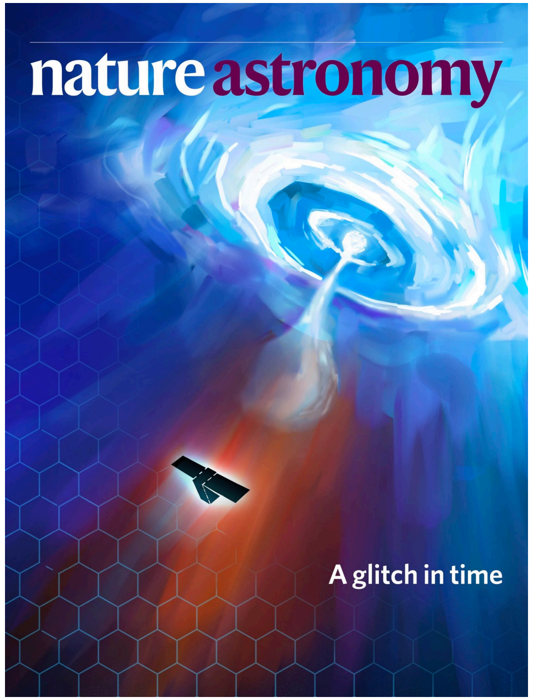
Image credit: Junjie Mao



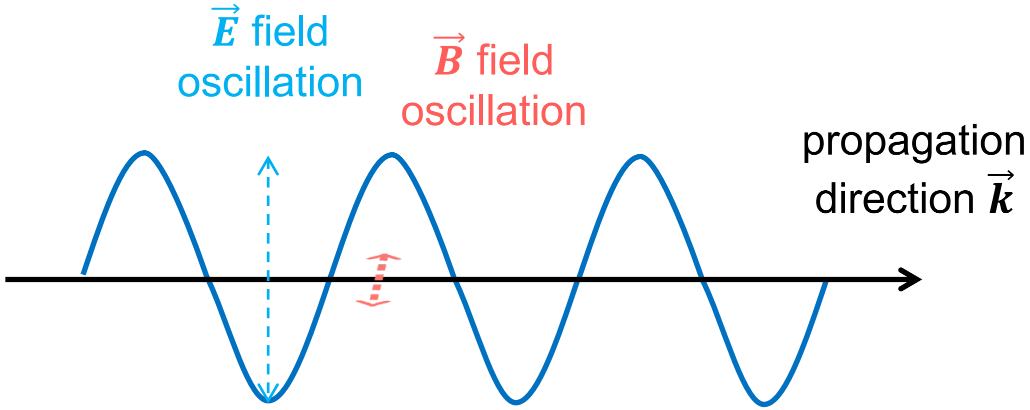



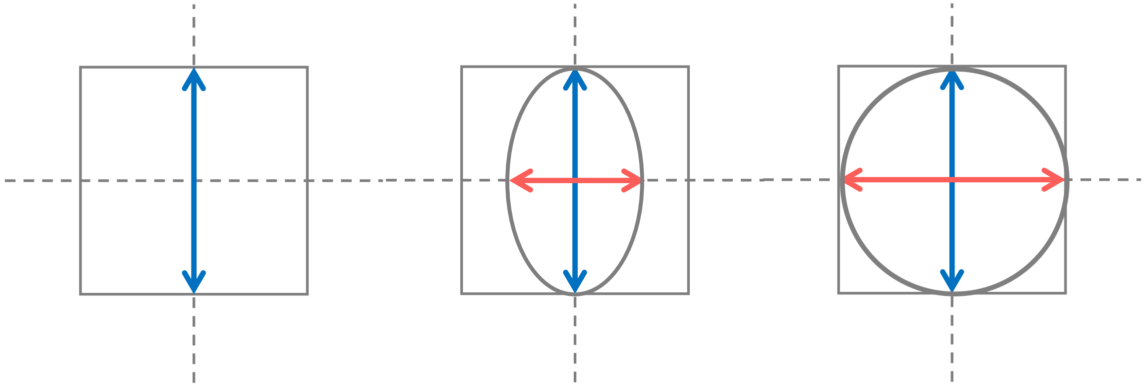
# Polarization

Polarization describes the specific orientation of the wave perpendicular to the propagation direction of (unpolarized wave has no particular orientation).



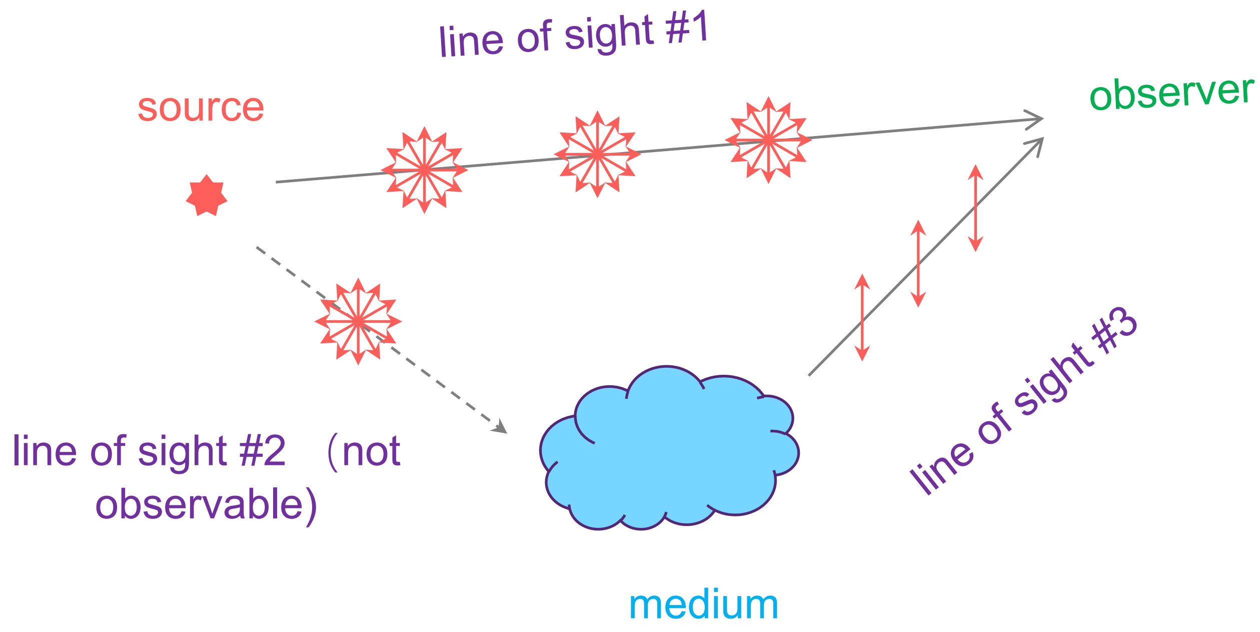

PolarLight (Feng et al. 2020), launched in 2018, reopened the soft X-ray polarization window. Before PolarLight, the Crab nebula was the only celestial object with a statistically significant detection in soft X-ray polarimetry, firstly measured in the 1970s (e.g., Novick et al. 1972).



# Why polarization

- ✓ Measure magnetic field
  - ❑ Faraday rotation
- ✓ Probe emission mechanism
  - ❑ e.g., cyclotron and synchrotron emissions
- ✓ Explore birefringence nature
  - ❑ e.g., CMB and cosmic inflation
- ✓ Constrain unresolved geometry




astrobites
THE ASTRO-PH READER'S DIGEST | SUPPORTED BY THE AAS

## Astrobites Guide to Polarimetry

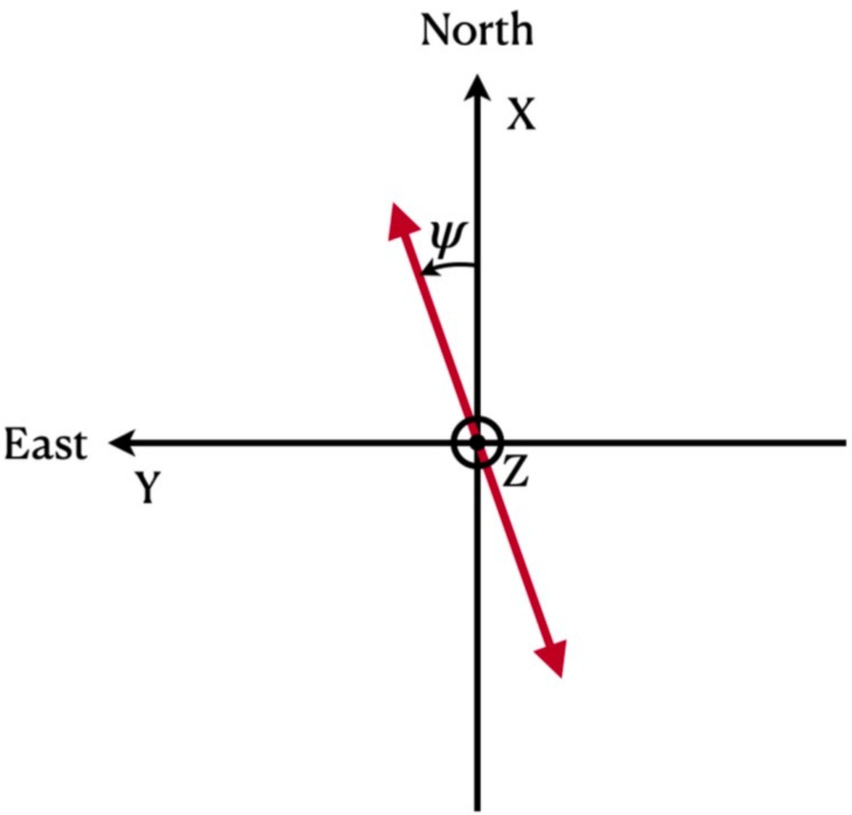
by Briley Lewis | Oct 23, 2022 | Guides | 0 comments

*Gemini Planet Imager* — Briefly mentioned earlier, the Gemini Planet Imager didn't just image planets, it also imaged debris disks! And it did so in polarized light, using polarimetric differential imaging, a technique that separates the starlight from the disk's light. They've got a whole survey sample of polarized debris disks, plus some neat in-depth studies of individual disks!

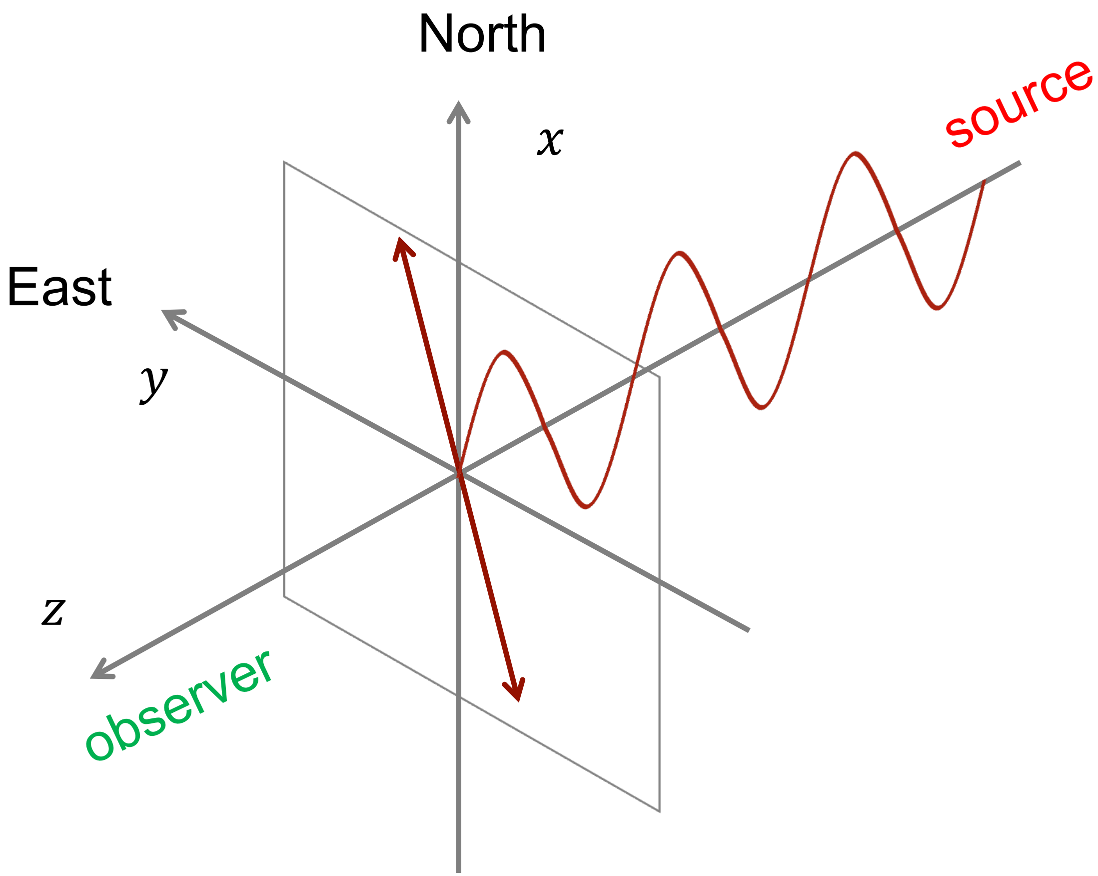
- New detections of exoplanet HD 95086 b with the Gemini Planet Imager
- A Deeper Look into the Atmospheres of HR8799 c and d with GPI

see a list of polarimetry instruments in the above astrobites

# IAU standard of polarization




IAU reference frame for polarization
(e.g., Ferriere et al. 2021)




IAU definition:

- ✓ X and Y are the Cartesian coordinates of the plane of the sky
- ✓ Z is along the line of sight (+Z towards the observer)
- ✓ $\psi$: linear polarization angle (measured counterclockwise from the North)

# Stokes parameters

Stokes parameters, all related to intensity, are **observable**

- $I$: Intensity
- $\sqrt{Q^2 + U^2}$: Intensity of linear polarization
- $V$: Intensity of circular polarization

$$
\begin{aligned}
S_0 &\equiv I \\
S_1 &\equiv Q = Ip \cos 2\chi \cos 2\psi \\
S_2 &\equiv U = Ip \cos 2\chi \sin 2\psi \\
S_3 &\equiv V = Ip \sin 2\chi
\end{aligned}
$$

$$\tan 2\chi = \frac{V}{\sqrt{Q^2 + U^2}}, -\frac{\pi}{4} \leq \chi \leq \frac{\pi}{4}$$

$$\tan 2\psi = U/Q, 0 \leq \psi \leq \pi$$

linear polarization angle

$$p = \sqrt{Q^2 + U^2 + V^2}/I$$

polarization fraction

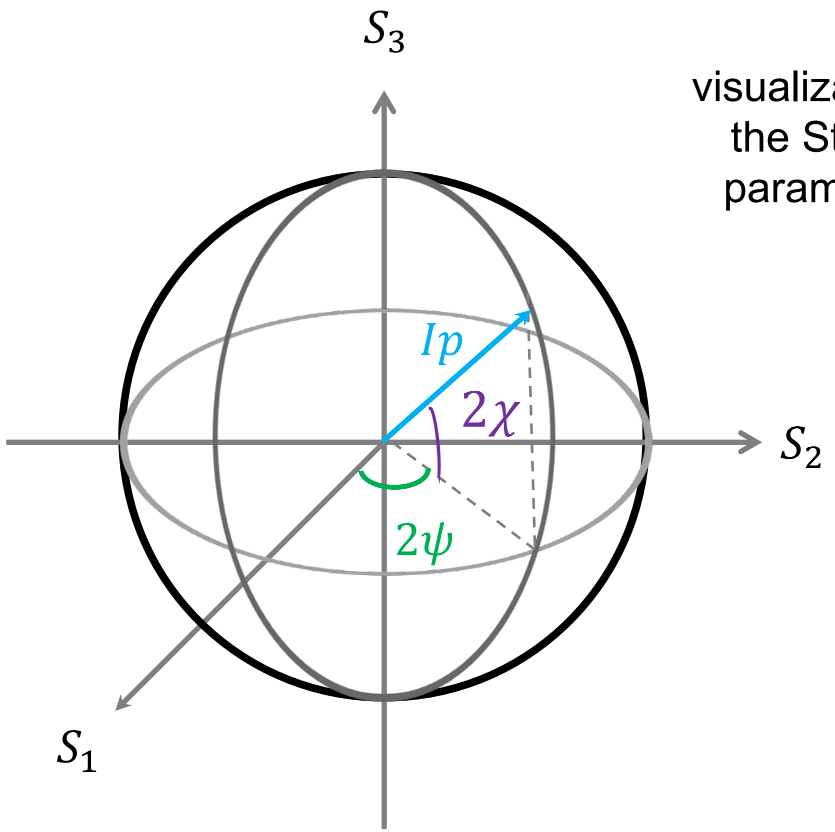
| | |
|---|---|
| $p = 1$ | completely polarized |
| $0 < p < 1$ | partially polarized |
| $p = 0$ | unpolarized |

# Poincaré sphere

prev. sl.

$$S_0 \equiv I$$
$$S_1 \equiv Q = Ip \cos 2\chi \cos 2\psi$$
$$S_2 \equiv U = Ip \cos 2\chi \sin 2\psi$$
$$S_3 \equiv V = Ip \sin 2\chi$$

$$\tan 2\chi = \frac{V}{\sqrt{Q^2 + U^2}}, -\frac{\pi}{4} \leq \chi \leq \frac{\pi}{4}$$
$$\tan 2\psi = U/Q \, , 0 \leq \psi \leq \pi$$




visualization of the Stokes parameters

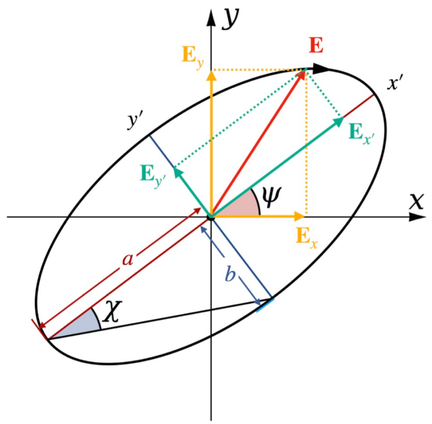


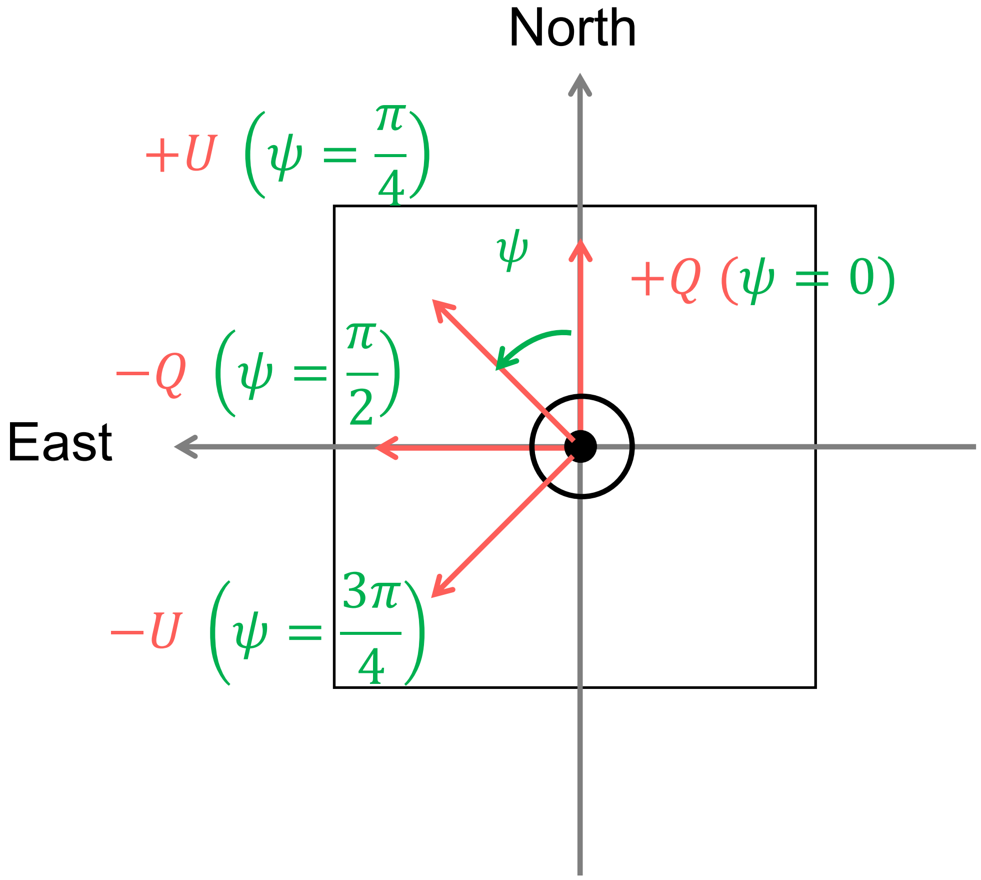

Image credit: Jiejia Liu

# Linear polarization

For $V = 0$ ($\chi = 0$), we have the linear polarization

$$S_0 = I$$
$$S_1 = Q = Ip\cos 2\psi$$
$$S_2 = U = Ip\sin 2\psi$$
$$S_3 = V = 0$$

$$\cos\pi = -1$$
$$\sin\left(\frac{3\pi}{2}\right) = -1$$




e.g., Hamaker & Bregman (1996)

prev. sl.

$$S_3 \equiv V = Ip\sin 2\chi$$
$$\tan 2\psi = U/Q$$

linear polarization angle

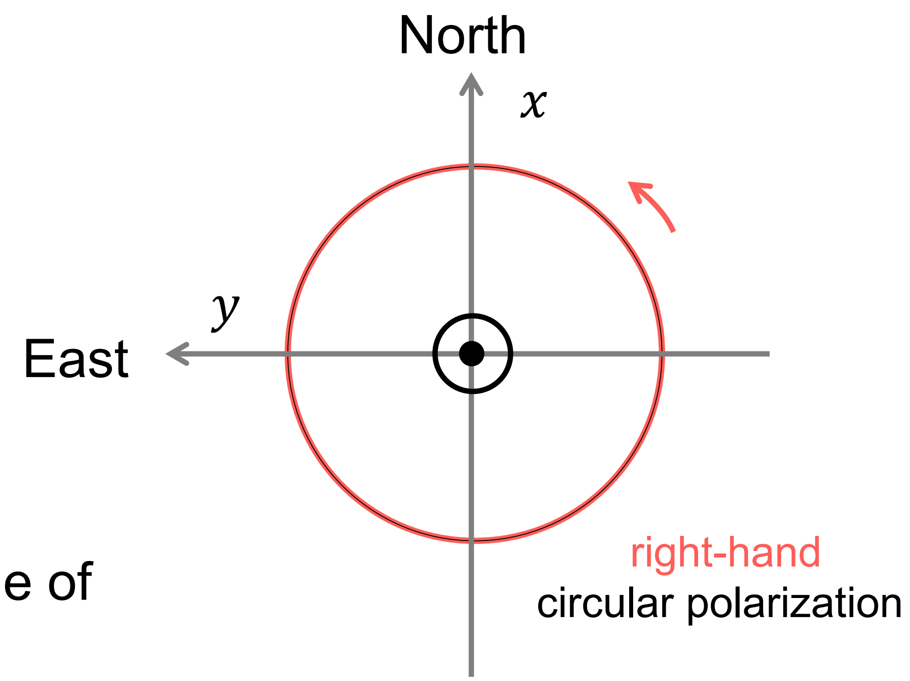
# Circular polarization

prev. sl.

$$S_1 \equiv Q = Ip\cos 2\chi \cos 2\psi$$
$$S_2 \equiv U = Ip\cos 2\chi \sin 2\psi$$

For $Q = U = 0$ ($\chi = \pm\pi/4$), we have the circular polarization

$$S_0 = I$$
$$S_1 = Q = 0$$
$$S_2 = U = 0$$
$$S_3 = V = Ip\sin 2\chi$$




IAU definition:

- ✓ $+V$ for the right-handed circular polarization
- ✓ For the right-handed circular polarization, the position angle of $\vec{E}$ at any point **increases** with time
- ✓ Along the $+z$ direction, $\vec{E}$ traces a left-handed circle at any time

e.g., Hamaker & Bregman (1996)

# Linear/circular polarization fraction

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} I - pI \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} pI \\ Q \\ U \\ V \end{pmatrix}$$

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} I - p_L I - p_C I \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} p_L I \\ Q \\ U \\ 0 \end{pmatrix} + \begin{pmatrix} p_C I \\ 0 \\ 0 \\ V \end{pmatrix}$$

polarization fraction

$$p = \sqrt{Q^2 + U^2 + V^2}/I$$

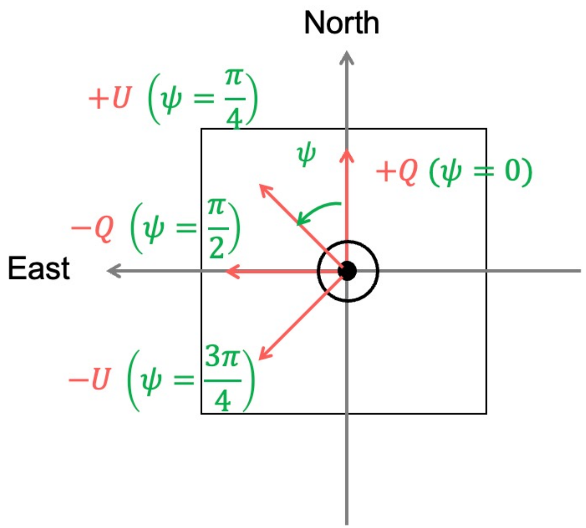
linear or circular polarization fraction

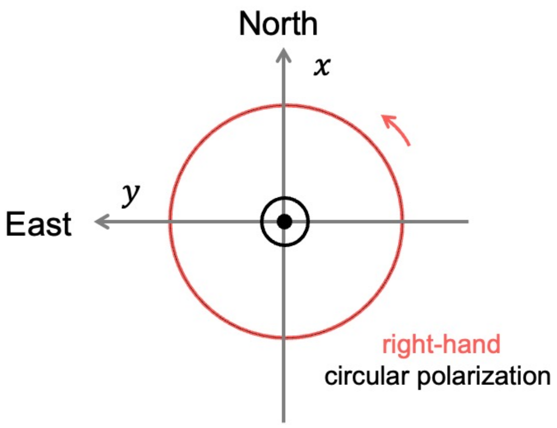
$$p_L = \sqrt{Q^2 + U^2}/I$$

$$p_C = V/I$$

prev. sl.

| | |
|---|---|
| $p = 1$ | completely polarized |
| $0 < p < 1$ | partially polarized |
| $p = 0$ | unpolarized |

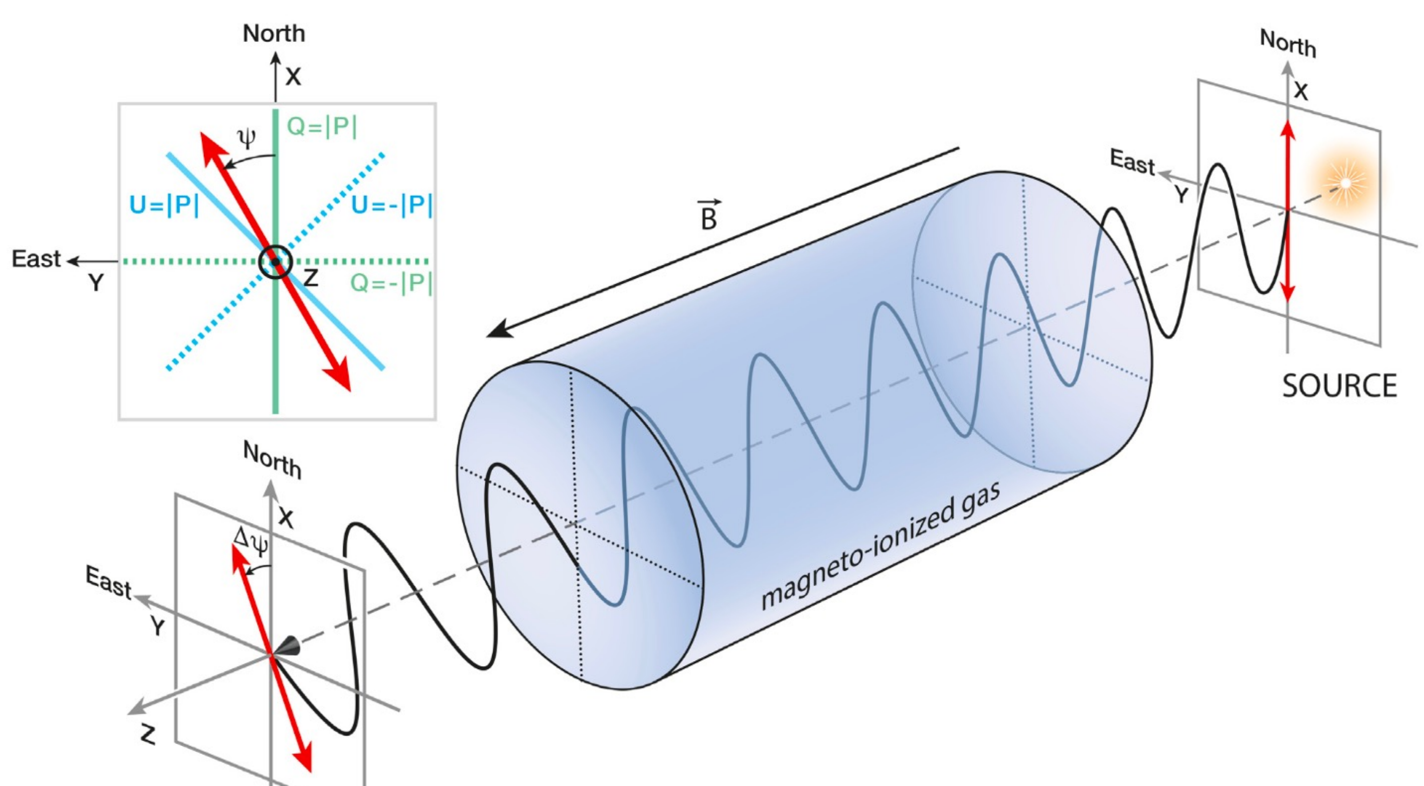


# Chpt.2 Fundamentals of radiation

2.1 Elementary concepts of radiation
2.2 Radiative transfer
2.3 Thermal radiation
2.4 Escape probability
2.5 Scattering
2.6 Polarization

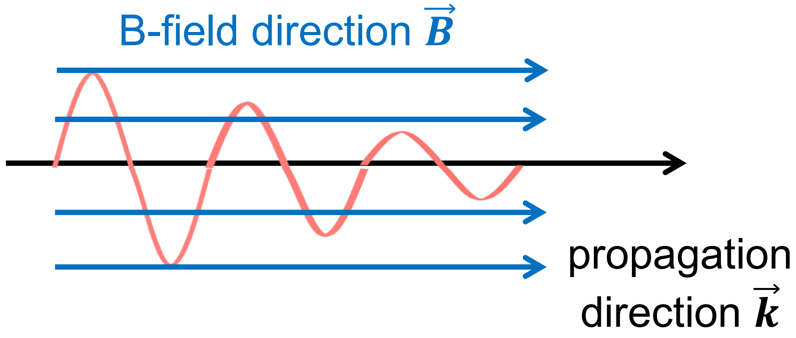
2.7 Dispersion and rotation measures
2.7.1 Dispersion relation
2.7.2 Refractive index
2.7.3 Time of arrival difference
2.7.4 Dispersion measure
2.7.5 Fast Radio Bursts
2.7.6 Phase difference
2.7.7 Rotation measure
2.7.8 Faraday rotation
2.7.9 CMB polarization




Ferriere et al. 2021

# Dispersion relation

Consider a pair of left- and right-handed circularly polarized waves propagate along the B-field with $\vec{\boldsymbol{k}} \parallel \vec{\boldsymbol{B}}$, the dispersion relation is




Eq. 1 of Ferriere et al. 2021

$$\omega^2 = c^2 k^2 + \frac{\omega_{\rm p}^2}{1 \mp \frac{\omega_{\rm L}}{\omega}}$$

angular frequency $\omega = 2\pi\nu$

wave number $k = \frac{2\pi}{\lambda}$

- Right circular polarized (RCP) mode: −
- Light circular polarized (LCP) mode: +

plasma frequency

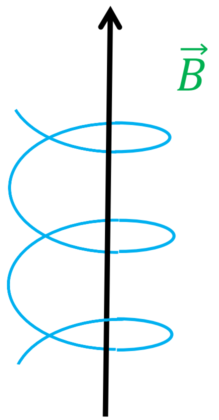
$$\omega_p \equiv \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

Larmor (or gyro) frequency

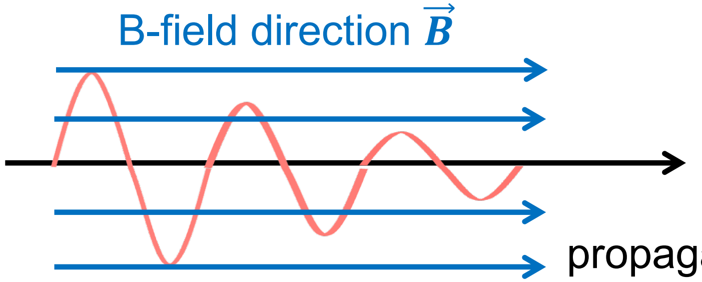
$$\omega_L \equiv \frac{eB}{m_e c}$$

《原子物理学》杨福家
3rd edition, p153 - 155

gyro motion



# Dispersion relation (cont.)




For astrophysical waves of interest, the following always apply (Assignment #3: Plasma frequency)

$$\omega_\mathrm{p} \ll \omega, \qquad \omega_L \ll \omega$$

prev. sl.

$$\omega_\mathrm{p} \equiv \sqrt{\frac{4\pi n_e e^2}{m_e}} \qquad \omega_L \equiv \frac{eB}{m_e c}$$

plasma frequency     Larmor frequency

prev. sl.

$$\omega^2 = c^2k^2 + \frac{\omega_\mathrm{p}^2}{1 \mp \frac{\omega_\mathrm{L}}{\omega}}$$

$$\frac{1}{1+x} = 1 - x + \ \ldots$$

$$= c^2k^2 + \omega_\mathrm{p}^2 \pm \frac{\omega_\mathrm{p}^2\omega_\mathrm{L}}{\omega}$$

EM wave in free space     electric force     magnetic force

$$c^2k^2 = \omega^2 - \omega_\mathrm{p}^2 \mp \frac{\omega_\mathrm{p}^2\omega_\mathrm{L}}{\omega} \simeq \omega^2$$

$$k(\omega) = \frac{\omega}{c}\sqrt{1 - \frac{\omega_\mathrm{p}^2}{\omega^2} \mp \frac{\omega_\mathrm{p}^2\omega_\mathrm{L}}{\omega^3}}$$

# Refractive index

Consider the propagation of EM waves through an unmagnetized plasma (mainly free electrons), the medium refractive index is

$$n = \sqrt{1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2}}$$

see Sect. 8.1 of the REF book (p227) by Rybicki & Lightman

prev. sl.

$$\omega_{\mathrm{p}} \equiv \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

plasma frequency

Only waves with $\omega > \omega_{\mathrm{p}}$ can propagate, which is not an issue in most cases

$$v_\phi = \frac{\omega}{k} = \frac{c}{n}$$

phase velocity

# Time of arrival difference

Consider a pulse propagates in a non-magnetized medium ($B = 0, \omega_\mathrm{L} = 0$), the group velocity is

$$v_\mathrm{grp}(\omega) = \frac{d\omega}{dk} = \frac{c^2 k}{\omega} = c\sqrt{1 - \frac{\omega_\mathrm{p}^2}{\omega^2}}$$

This leads to a frequency-dependent time of arrival

$$t_\mathrm{arv}(\omega) = \int_0^l \frac{1}{v_\mathrm{grp}(\omega)} dl = \int_0^l \frac{1}{c}\left(1 + \frac{\omega_\mathrm{p}^2}{2\omega^2}\right) dl$$

prev. sl.

$$c^2 k^2 = \omega^2 - \omega_\mathrm{p}^2 \mp \frac{\omega_\mathrm{p}^2 \omega_\mathrm{L}}{\omega} \simeq \omega^2$$

prev. sl.

$$\omega_\mathrm{p} \equiv \sqrt{\frac{4\pi n_e e^2}{m_e}} \qquad \omega_L \equiv \frac{eB}{m_e c}$$

plasma frequency    Larmor frequency

$$\frac{1}{\sqrt{1-x}} = 1 + \frac{x}{2} + \ \ldots$$

# Dispersion measure

For $\omega \gg \omega_p$ (Assignment #3: Plasma frequency), the time of arrival for a specific frequency is

traveling distance in the medium

prev. sl.

$$t_{\mathrm{arv}}(\omega) = \int_0^l \frac{1}{c}\left(1 + \frac{\omega_{\mathrm{p}}^2}{2\omega^2}\right) dl$$

prev. sl.

$$\omega_{\mathrm{p}} \equiv \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

plasma frequency

Waves with different frequencies arrive at different times

$$\Delta t_{\mathrm{arv}} = \frac{2\pi e^2}{m_e c}\left(\frac{1}{\omega_{\mathrm{low}}^2} - \frac{1}{\omega_{\mathrm{high}}^2}\right)\int_0^l n_e dl$$

High-frequency waves arrive earlier than the low-frequency ones

# Fast Radio Bursts (FRBs)

FRBs are radio bursts with extremely short duration (a few milliseconds) yet rather energetic ($\gtrsim 10\, L_\odot$). The first FRB was discovered in 2001 (Lorimer et al. 2007)

prev. sl.

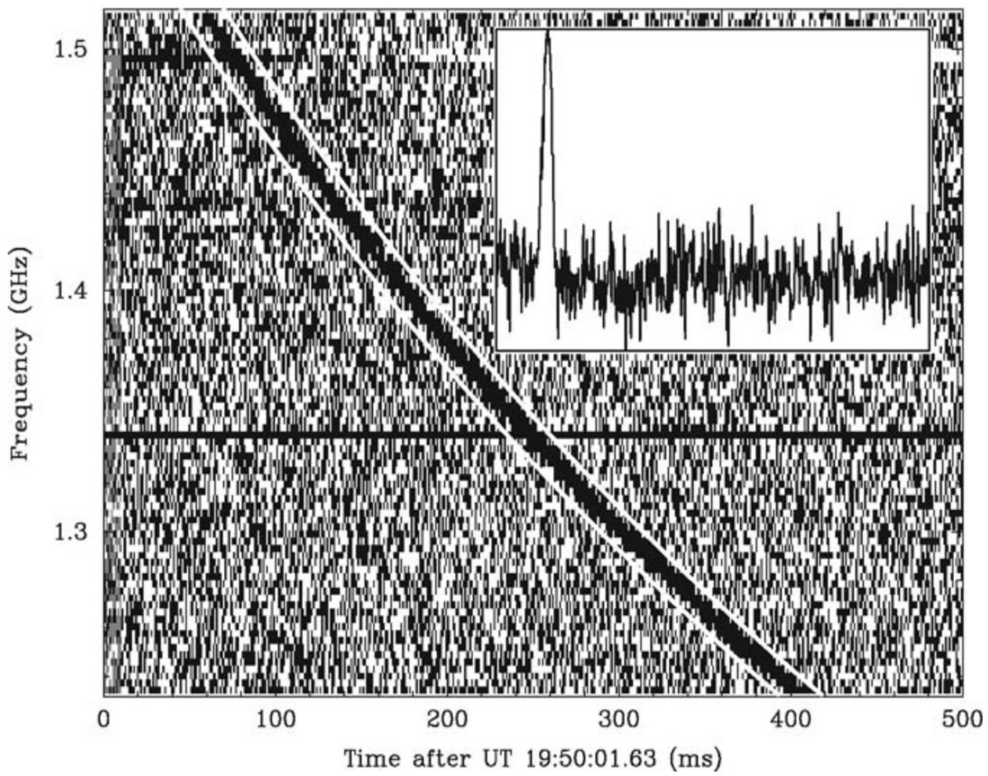
$$\Delta t_{\mathrm{arv}} = \frac{2\pi e^2}{m_e c}\left(\frac{1}{\omega_{\mathrm{low}}^2} - \frac{1}{\omega_{\mathrm{high}}^2}\right)\int_0^l n_e dl$$

Dispersion Measure (DM)

$$= \frac{4.149}{\mathrm{ms}}\left(\left(\frac{1\ \mathrm{GHz}}{\nu_{\mathrm{low}}}\right)^2 - \left(\frac{1\ \mathrm{GHz}}{\nu_{\mathrm{high}}}\right)^2\right)\left(\frac{\mathrm{DM}}{\mathrm{pc\ cm^{-3}}}\right)$$

Waterfall plot

measured DM= $375 \pm 1 \mathrm{pc\ cm^{-3}}$




Lorimer et al. 2007

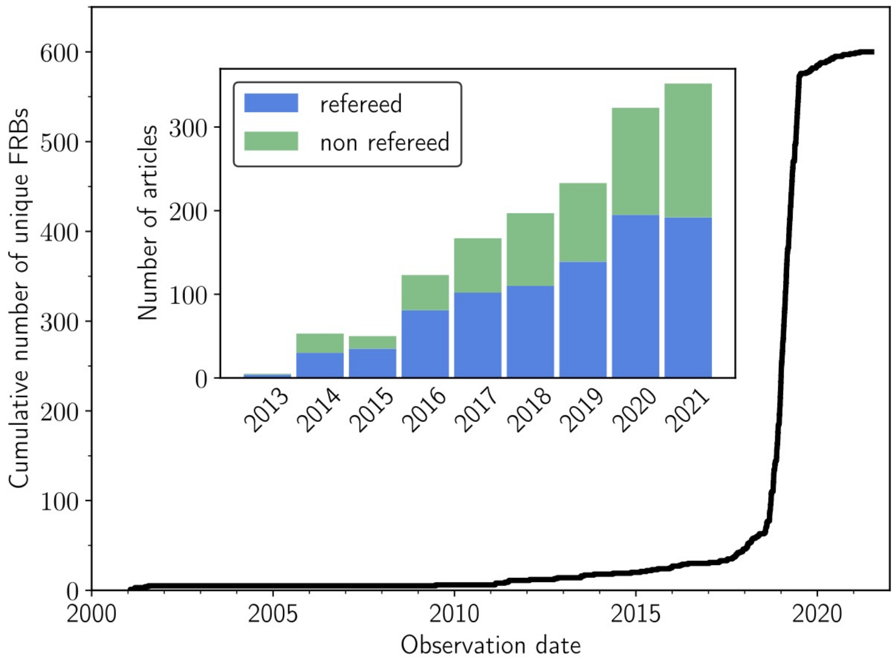
# Fast Radio Bursts (FRBs)

FRBs have been put in the spot light in the past decade:
- Repeating FRBs
- FRBs with known hosts
- FRBs with relatively long durations (slow)

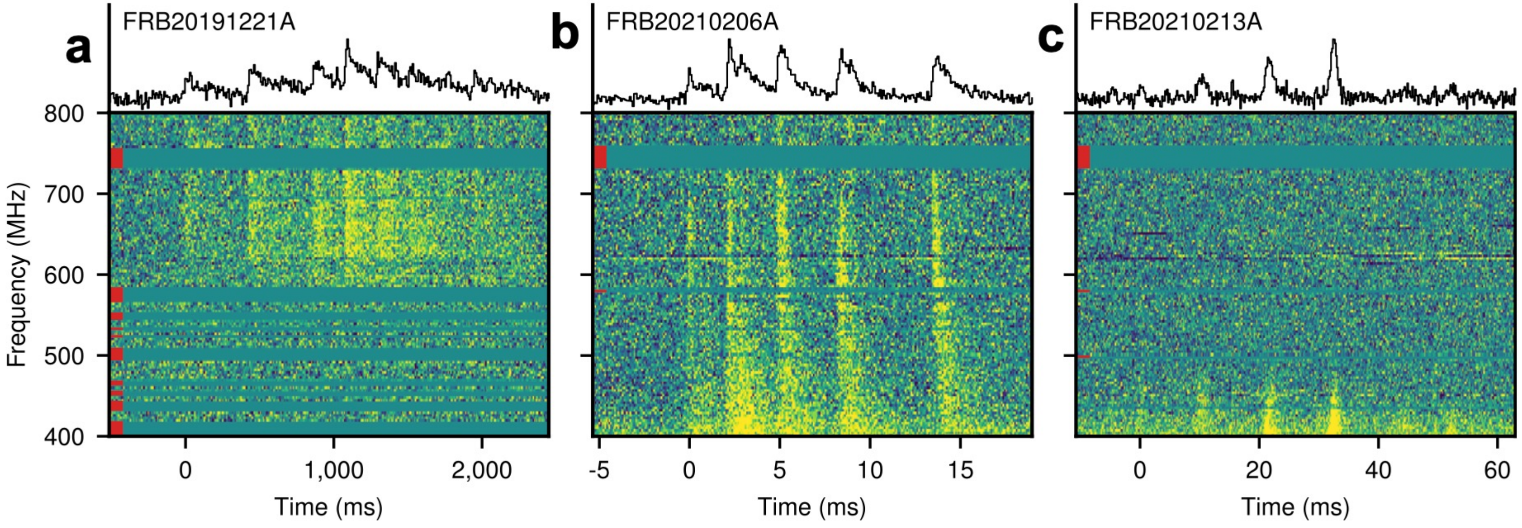
But, we still don’t know much about FRBs …

repeating FRBs (a small yet growing population)

Petroff et al. 2022




Publications on FRBs from ADS




# Phase difference

$\vec{\boldsymbol{k}} \parallel \vec{\boldsymbol{B}}$

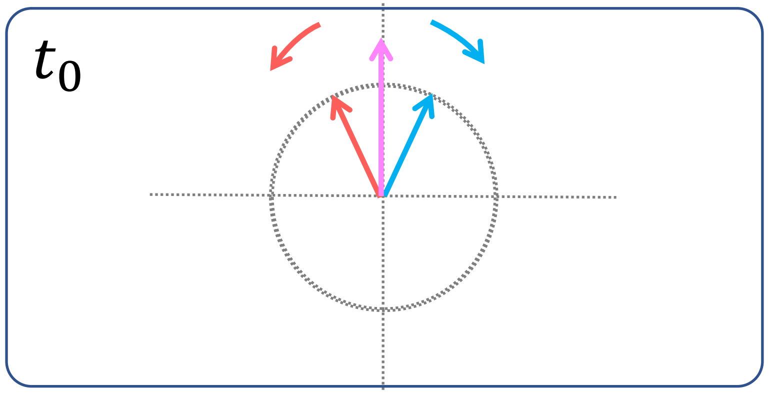
$\odot$

In a homogeneous plasma, the phase can be defined as one of the following

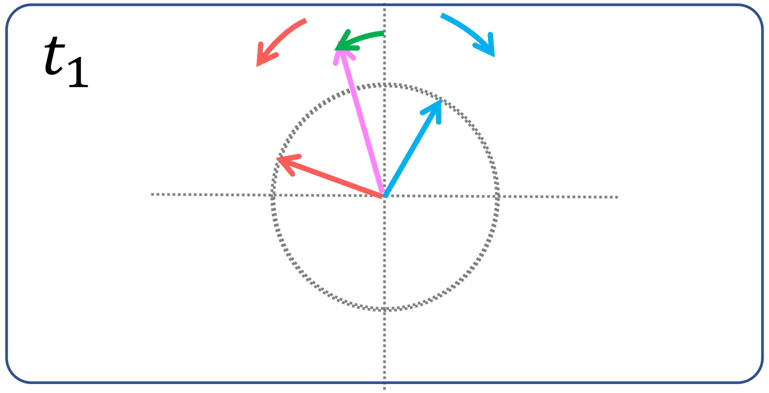
Eq. 4 of Ferriere et al. 2021

$$\phi \equiv \omega t - \int_0^l k\, dl$$

Decomposing a linearly polarized wave into a pair of left- and right-hand circular polarized waves. At the source ($l = 0$), the two waves have the same phase, as the waves propagates (with $\vec{\boldsymbol{k}} \parallel \vec{\boldsymbol{B}}$) in a magnetized medium, phase difference will occur




$$\Delta\psi = \frac{1}{2}\Delta\phi$$




prev. sl.

$$k = \frac{\omega}{c}\sqrt{1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2} \mp \frac{\omega_{\mathrm{p}}^2 \omega_{\mathrm{L}}}{\omega^3}}$$

$$\phi_{\mathrm{RCP}} > \phi_{\mathrm{LCP}}$$

- Right circular polarized (RCP) mode: $-$
- Light circular polarized (LCP) mode: $+$

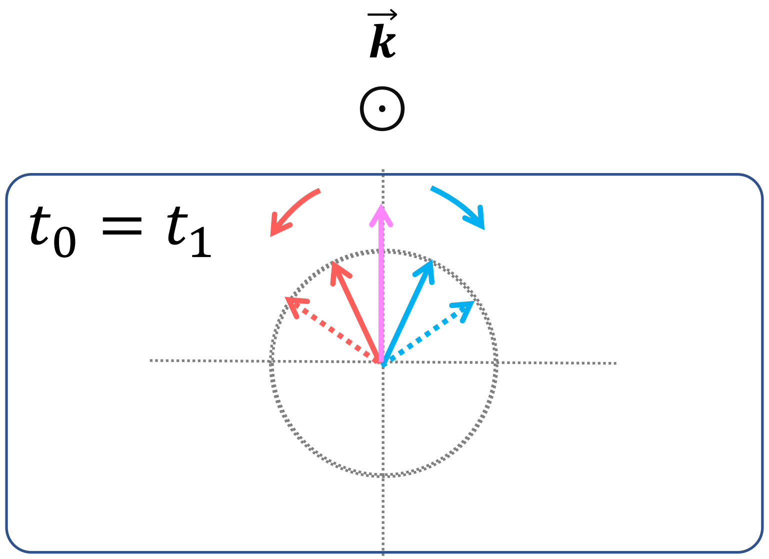
# Phase difference introduced by B-field

Eq. 4 of Ferriere et al. 2021

$$\phi \equiv \omega t - \int_0^l k \, dl$$

prev. sl.

$$k = \frac{\omega}{c}\sqrt{1 - \frac{\omega_\mathrm{p}^2}{\omega^2} \mp \frac{\omega_\mathrm{p}^2 \omega_\mathrm{L}}{\omega^3}}$$




- Right circular polarized (RCP) mode: –
- Light circular polarized (LCP) mode: +

When $B = 0$, $\omega_L = \frac{eB}{m_0 c} = 0$, there is no phase difference

$$k_\mathrm{RCP} = k_\mathrm{LCP}$$
$$\Delta\phi \equiv \phi_\mathrm{RCP} - \phi_\mathrm{LCP} = 0$$

# Phase difference in parallel B-field

$\vec{k} \parallel \vec{B}$

- $\vec{B}$ points towards the observer: + $\odot$
- $\vec{B}$ points away from the observer: – $\otimes$

Eq. 4 of Ferriere et al. 2021

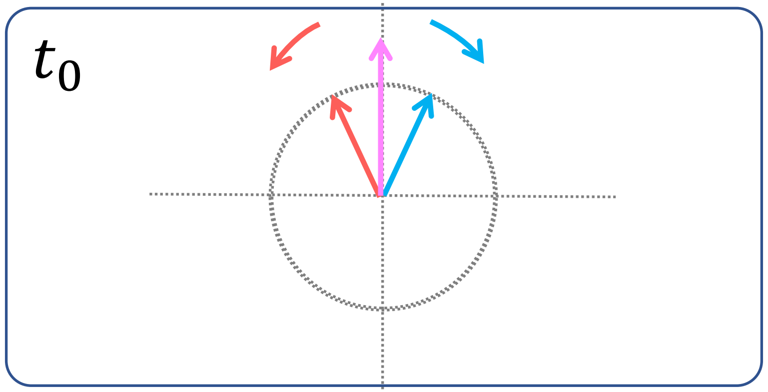
$$\phi \equiv \omega t - \int_0^l k \, dl$$

prev. sl.

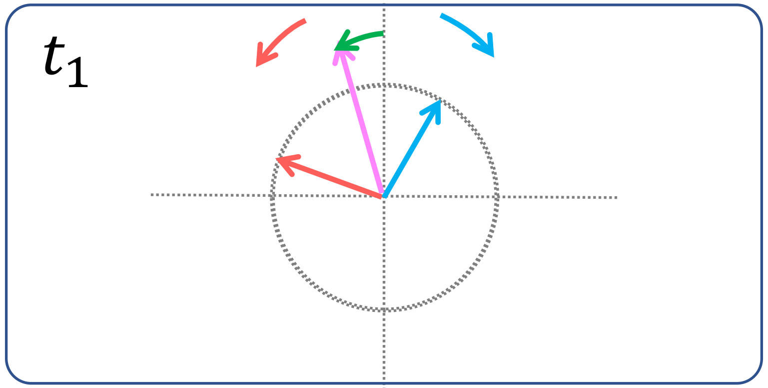
$$k = \frac{\omega}{c}\sqrt{1 - \frac{\omega_\mathrm{p}^2}{\omega^2} \mp \frac{\omega_\mathrm{p}^2 \omega_\mathrm{L}}{\omega^3}}$$

$$\sqrt{1+x} = 1 + \frac{x}{2} + \ \dots$$

$$k = \frac{\omega}{c}\left(1 - \frac{\omega_\mathrm{p}^2}{2\omega^2} \mp \frac{\omega_\mathrm{p}^2 \omega_\mathrm{L}}{2\omega^3}\right)$$




$$\Delta\psi = \frac{1}{2}\Delta\phi$$




$$\Delta\psi = \frac{1}{2}\Delta\phi = -\frac{1}{2}\int_0^l (k_\mathrm{RCP} - k_\mathrm{LCP}) dl$$

$$= \frac{1}{2}\int_0^l \frac{\omega_\mathrm{p}^2 \omega_\mathrm{L}}{c\omega^2} \, dl$$

- Right circular polarized (RCP) mode: –
- Light circular polarized (LCP) mode: +

# Rotation measure

prev. sl.

$$\Delta\psi = \frac{1}{2}\int_0^l \frac{\omega_\mathrm{p}^2\omega_\mathrm{L}}{c\omega^2}\,dl$$

prev. sl.

$$\omega_\mathrm{p} \equiv \sqrt{\frac{4\pi n_e e^2}{m_e}} \qquad \omega_L \equiv \frac{eB}{m_e c}$$

plasma frequency Larmor frequency

Eq. 9 of Ferriere et al. 2021

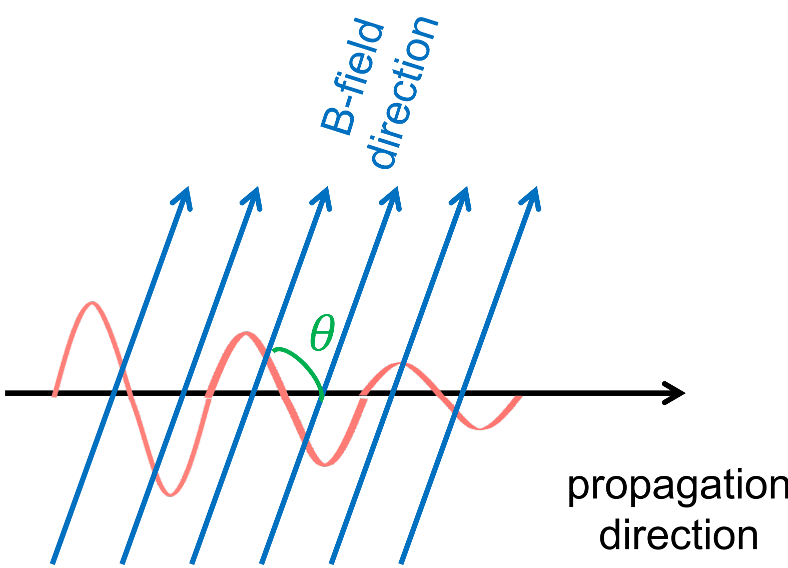
$$\Delta\psi = \frac{e^3}{2\pi\, m_e^2\, c^4}\lambda^2\int_0^l n_e(\pm B_\parallel)dl$$

- $\vec{B}$ points towards the observer: + $\odot$
- $\vec{B}$ points away from the observer: – $\otimes$

Rotation Measure (RM) $\longrightarrow$

$$\mathrm{RM} \equiv \frac{e^3}{2\pi m_e^2 c^4}\int_0^l n_e(\pm B_\parallel)dl$$

$$\mathrm{RM} = 0.812\ \mathrm{rad\ m^{-2}}\int_0^l \left(\frac{n_e}{\mathrm{cm^{-3}}}\right)\left(\pm\frac{B_\parallel}{\mu\mathrm{G}}\right)d\left(\frac{l}{\mathrm{pc}}\right)$$



# Faraday rotation

When a linearly polarized wave travels through a magnetized medium, its polarization angle will rotate (Burn 1966)

Eq. 9 of Ferriere et al. 2021

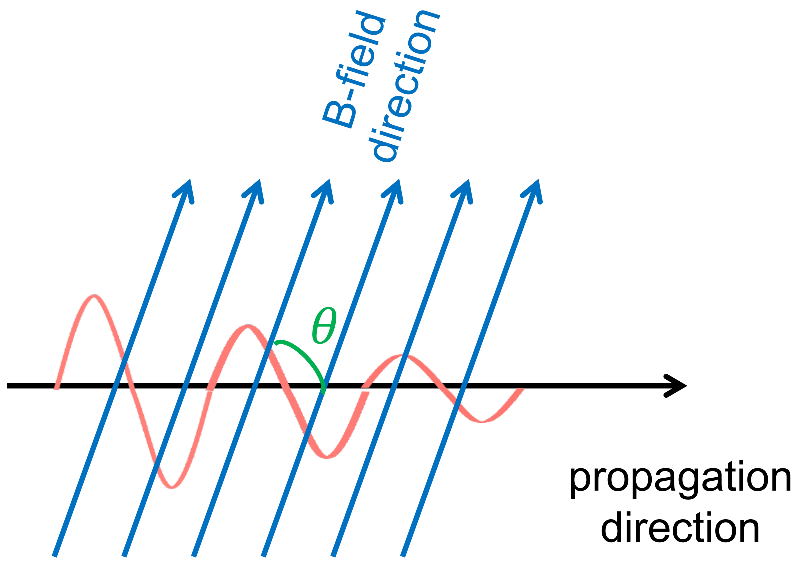
$$\Delta\psi = \frac{e^3}{2\pi\, m_e^2\, c^4} \lambda^2 \int_0^l n_e (\pm B_\parallel) dl$$

prev. sl.

$$\mathrm{RM} \equiv \frac{e^3}{2\pi m_e^2 c^4} \int_0^l n_e (\pm B_\parallel) dl$$

$$\psi_{\mathrm{obs}} = \psi_{\mathrm{src}} + \mathrm{RM} \cos\theta\, \lambda^2$$

- $\vec{B}$ points towards the observer: + ⊙
- $\vec{B}$ points away from the observer: – ⊗



# Cosmic Microwave Background

CMB is the leftover radiation from the Big Bang. It was firstly predicted by Gamow (1948).

In1965, CMB was observed by Arno Penzias and Robert Wilson using the 6-meter Holmdel Horn Antenna.

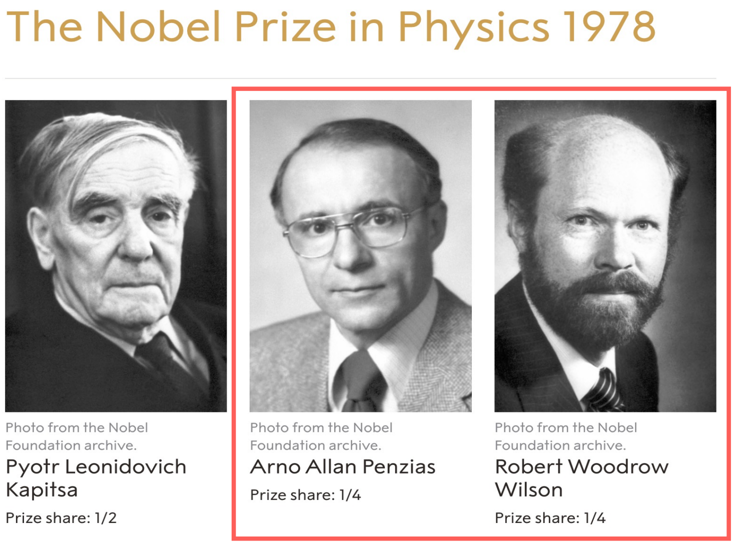



Image credit: nobelprize.org

Wrong data excluded


Image credit: wikipedia

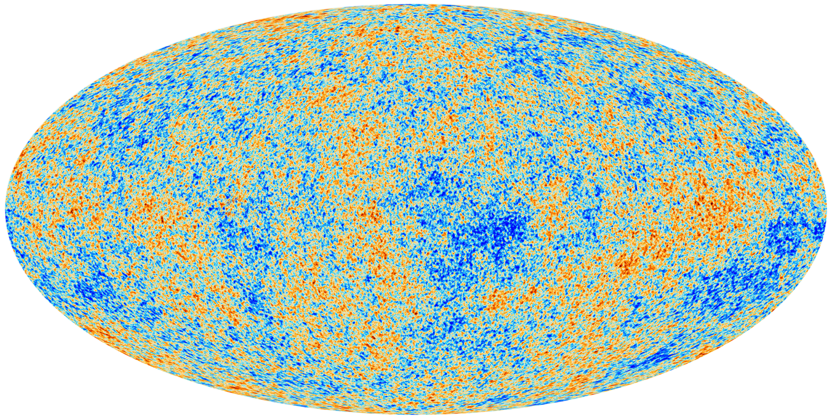


Image credit: ESA

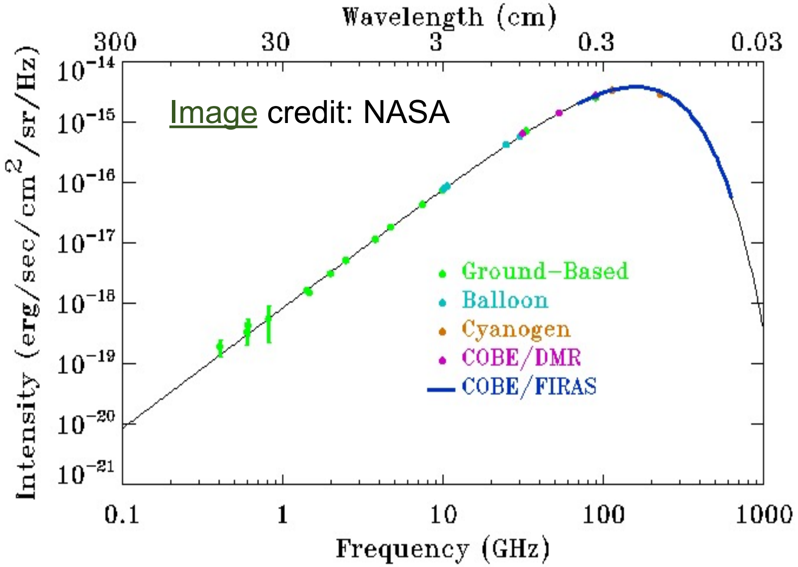
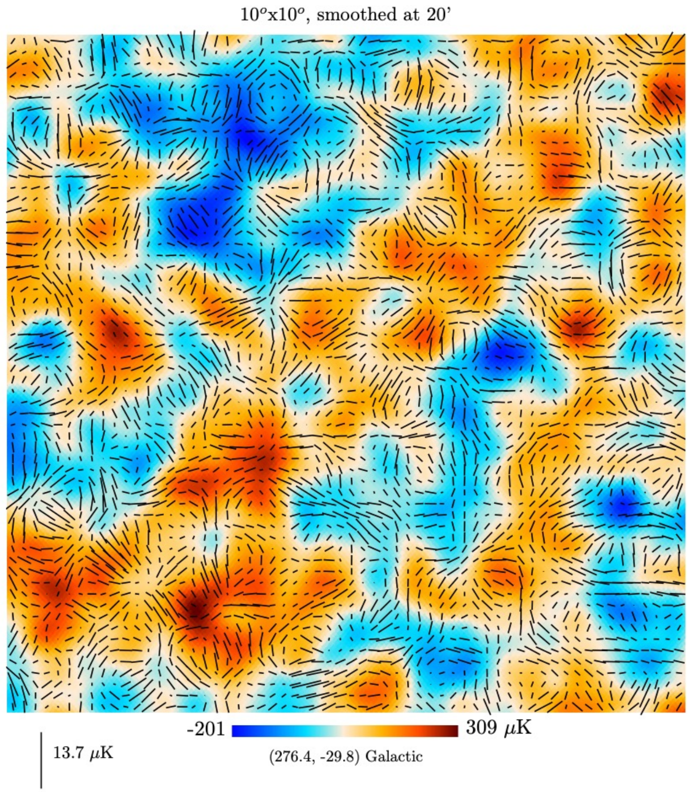
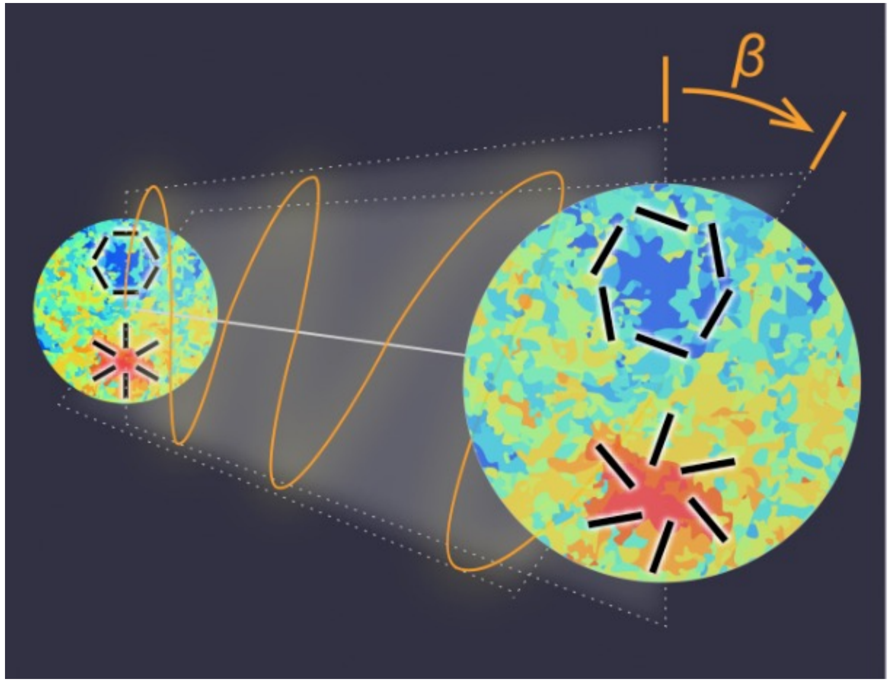



Image credit: NASA

# Cosmic Microwave Background polarization




Komatsu (2022, review): $\beta$ is the cosmic-birefringence-induced rotation angle

- ❑ B-mode (curl-like)
  - ➢ $\perp \vec{k}$ or $\parallel \vec{k}$
  - ➢ dominated by density perturbation
- ❑ E-mode (gradient-like)
  - ➢ $45°$ w.r.t. $\vec{k}$
  - ➢ fingerprints of GW background (too faint to detect directly nowadays) from cosmic inflation

CMB is linearly polarized (E-mode and B-mode), firstly detected in 2002 (Kovac et al. 2002).

Birefringence: the refractive index depends on the polarization direction. Typically, double refraction (ordinary and extraordinary indices)

# CMB B-mode

The detection of B-mode polarization will provide strong constraints for cosmic inflationary models.

The B-mode power is $\propto r^2$, where, $r < 0.07$ is the tensor-to-scalar ratio (BICEP2 collaboration 2016).

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## Do you see new physics in my CMB?

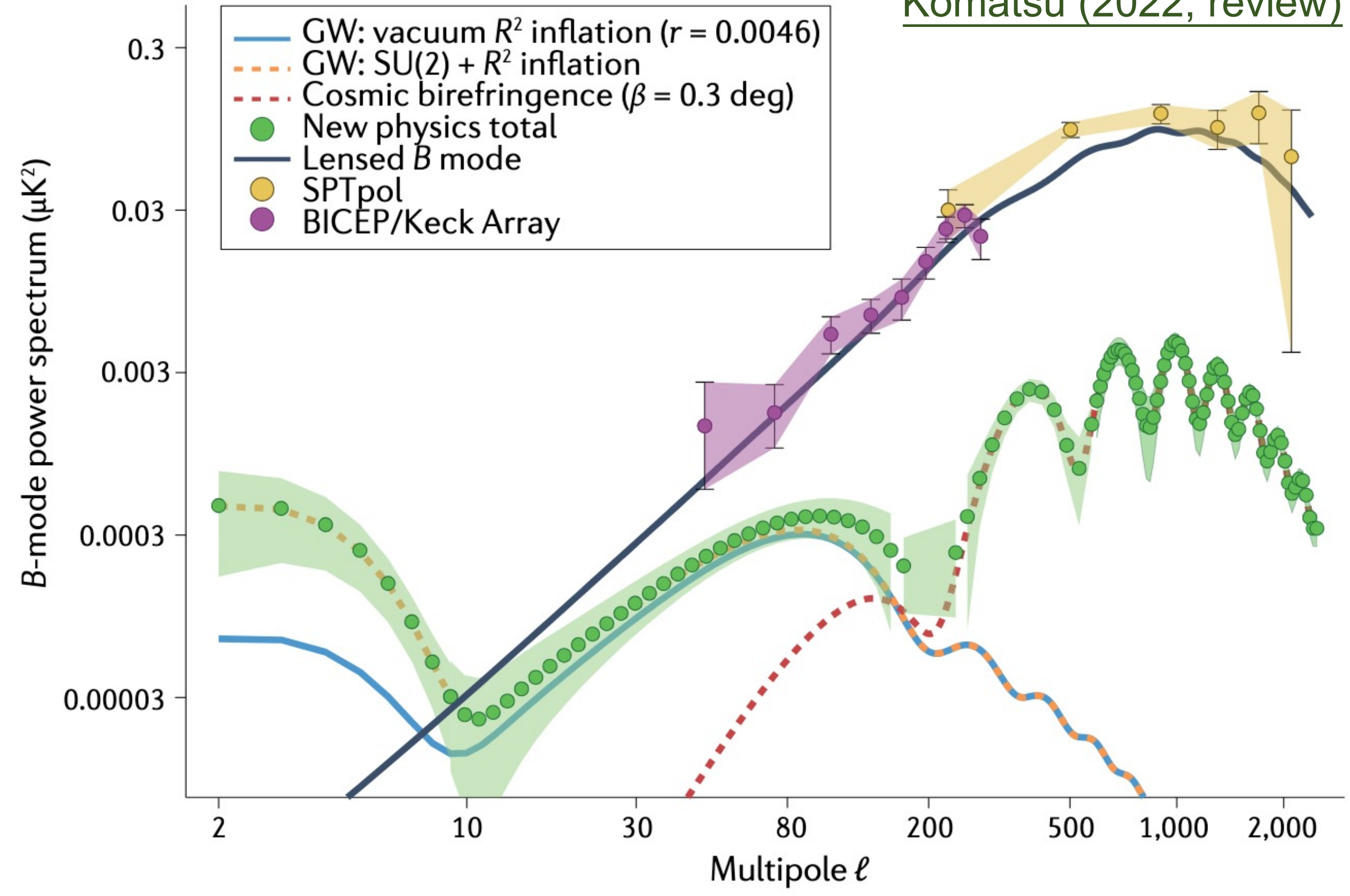
by Kayla Kornoelje | Jul 9, 2022 | Daily Paper Summaries | 0 comments

**Title:** New physics from the polarised light of the cosmic microwave background

**Authors:** Eiichiro Komatsu

**First Author's Institution:** Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Str. 1, 85741 Garching, Germany

Komatsu (2022, review)

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