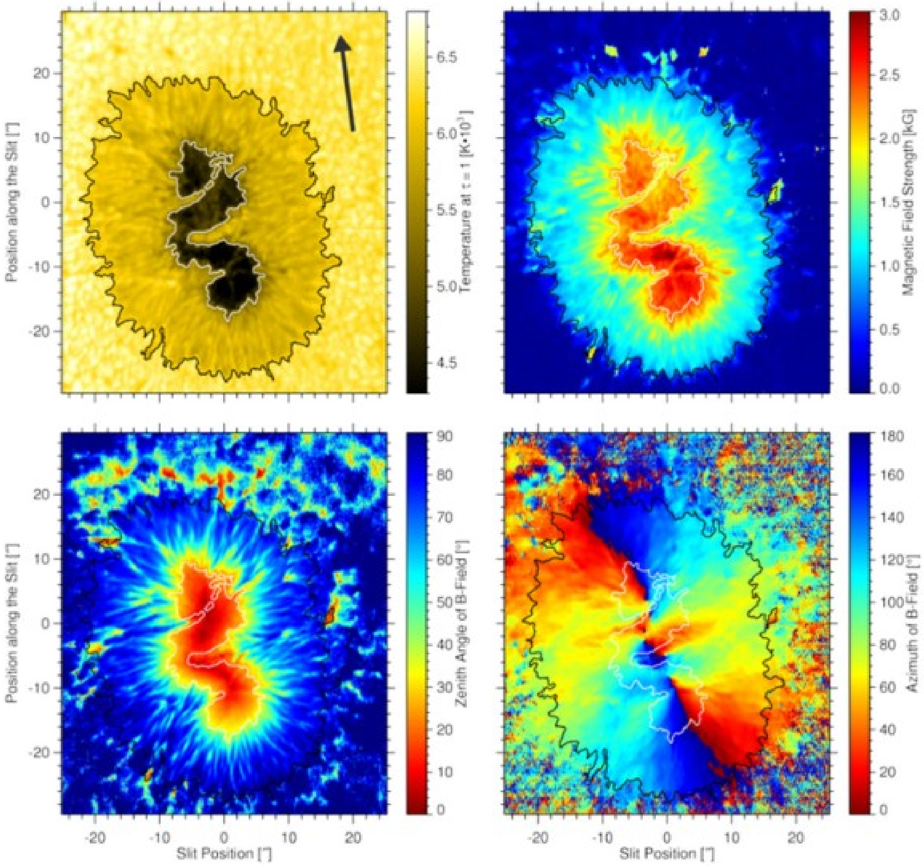
(Day 10)

Astronomical Polarimetry

(Wollaston prism; Credit:ThorLabs)

Today

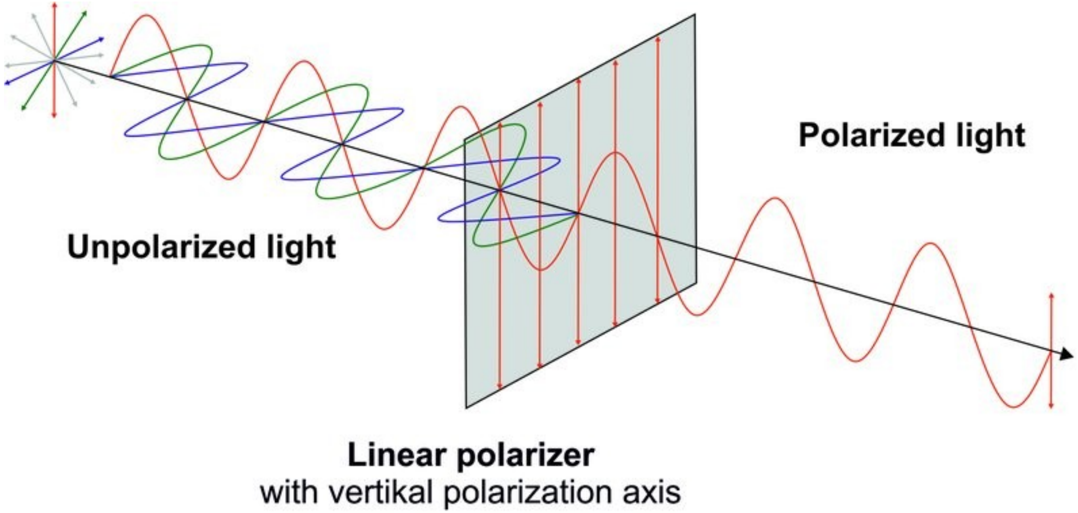


(Kleint & Gandorfer 2017)

1. Polarimetry
2. FORS2
3. Sphere

What is polarimetry?

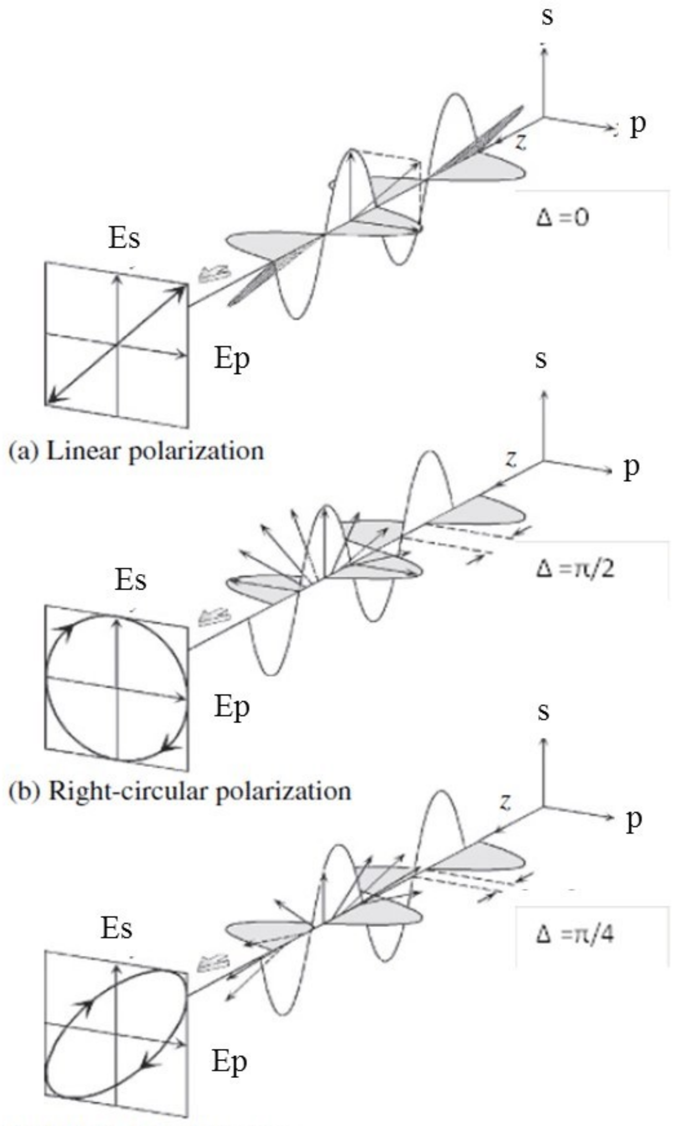
- Measuring the polarization of light
- Light is a transverse wave (the electric and magnetic fields vibrating perpendicular to the direction of propagation)
- Polarization describes the geometrical orientation of the vibrations
- Normally random (unpolarized). Excess of a certain polarization gives some physical insight
- Astronomical sources of polarization:
  - ➔ Scattering by dust (circumstellar, ISM)
  - ➔ Magnetic fields
  - ➔ Reflection (e.g. solar system objects)



(Credit: CODIXX)

Light polarization

- **Linear:** oscillations contained in one direction
- **Circular:** two directions with same amplitude, delayed by 90 deg
- **Elliptical:** different amplitudes and/or delay different than 90 deg

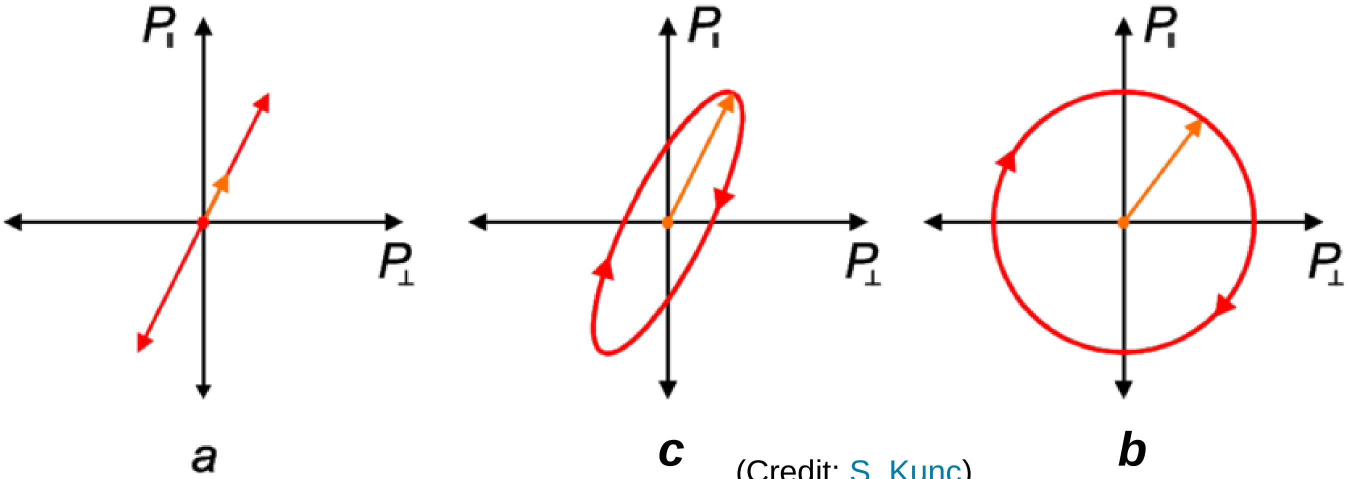


(a) Linear polarization

(b) Right-circular polarization

(c) Elliptical polarization

(Credit: M. Karakaya)



(Credit: S. Kunc)

Stokes parameters

- Electric field vector along x and y:

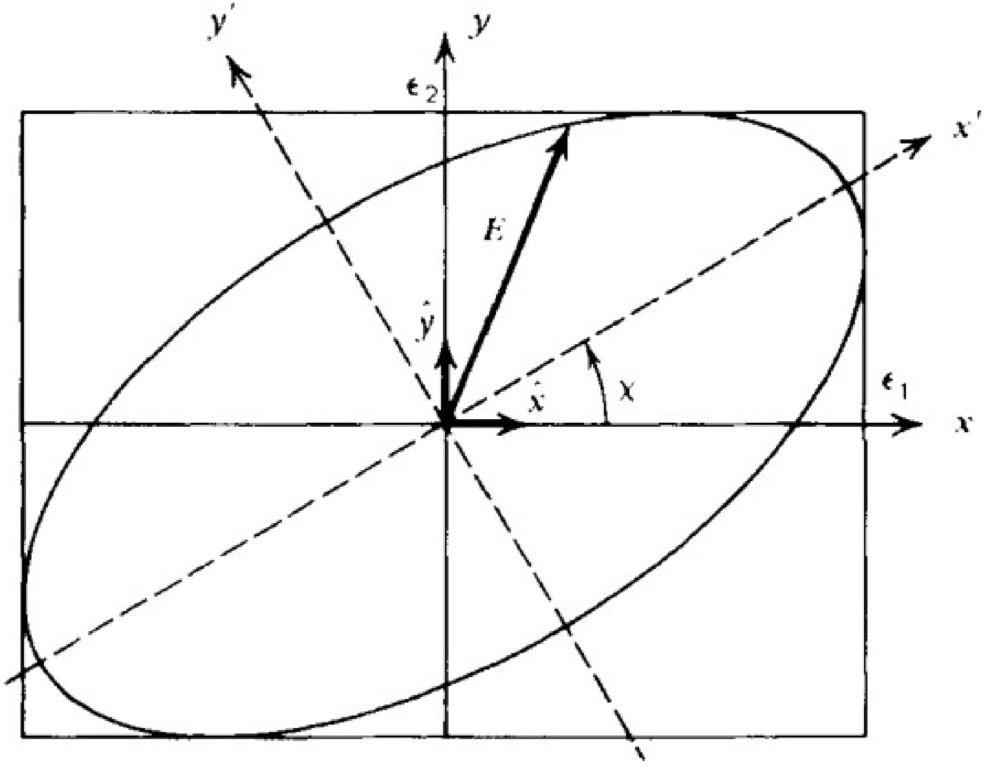
$$E_x(t) = e_1 \cos(2\pi\nu t)$$

$$E_y(t) = e_2 \cos(2\pi\nu t + \delta)$$

- Stokes parameters:

$$I = e_1^2 + e_2^2$$
$$Q = e_1^2 - e_2^2$$
$$U = 2\, e_1\, e_2\, \cos\delta$$
$$V = 2\, e_1\, e_2\, \sin\delta,$$

- Four parameters to describe: the ellipse size, the azimuth of the major axis, the ellipticity and the sense of the rotation.



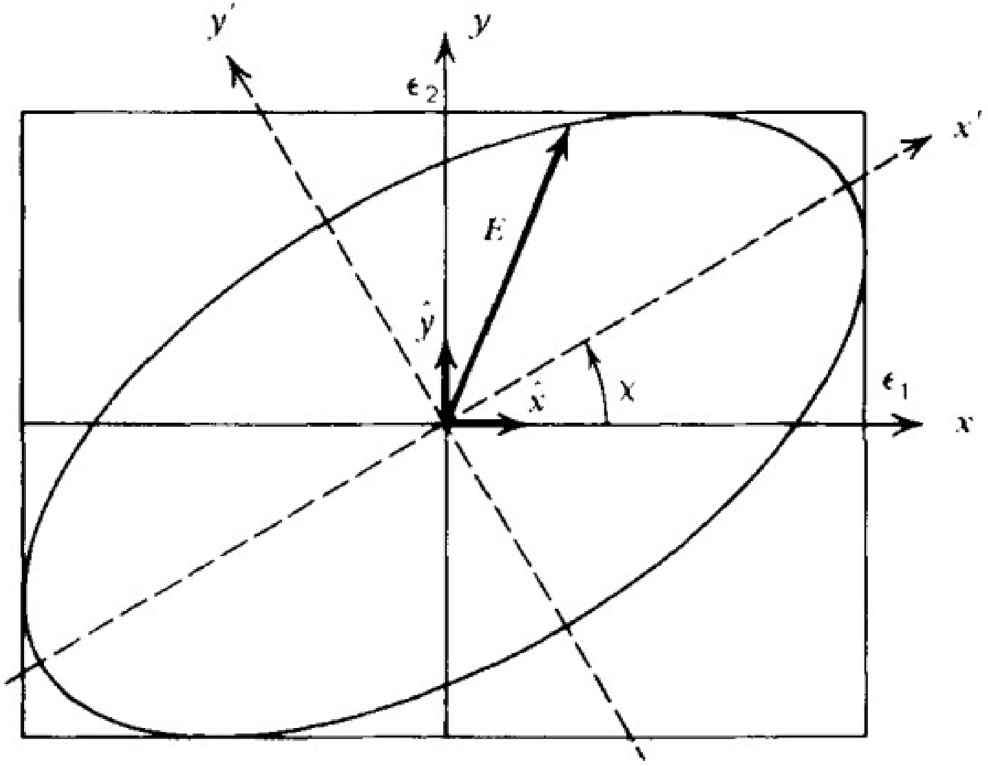
(Rybicki & Lightman)

Stokes parameters

- Stokes parameters:

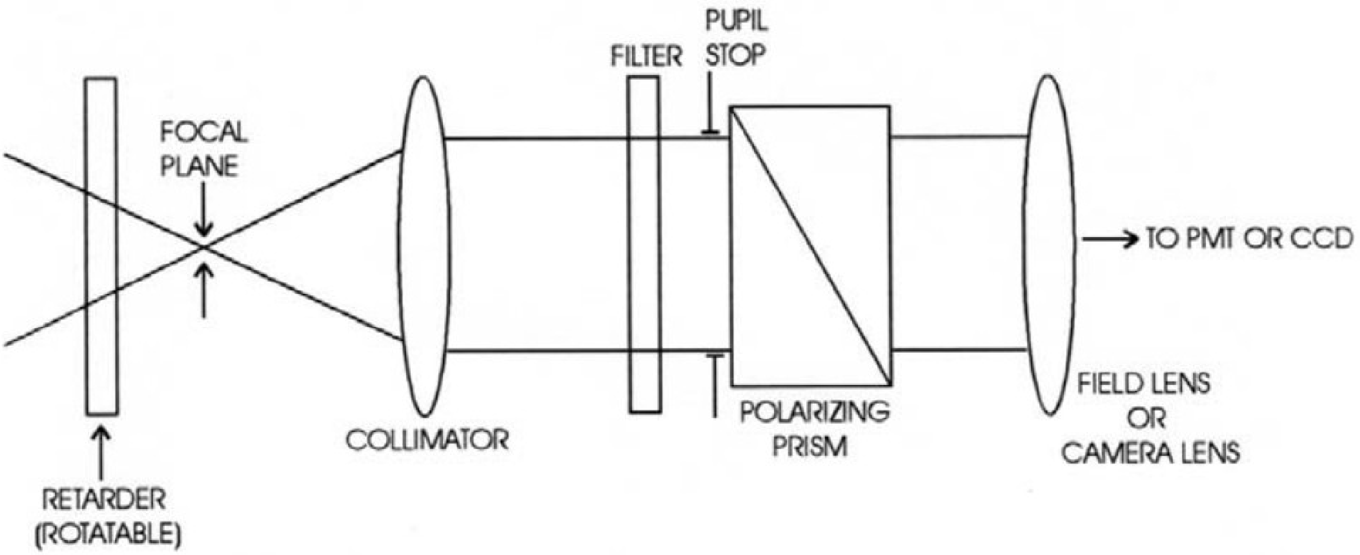
$$
\begin{aligned}
I &= e_1^2 + e_2^2 \\
Q &= e_1^2 - e_2^2 \\
U &= 2\, e_1\, e_2 \cos\delta \\
V &= 2\, e_1\, e_2 \sin\delta,
\end{aligned}
$$

- *I* : non-negative; total energy flux
- V: positive or negative; circular polarizati (right-handed or left-handed); *V* = 0 mea linear polarization
- *Q* and *U*: two-dimensional state of linear polarization; *Q* = *U* = 0 means circular polarization
- Unpolarized light: *Q* = *U* = *V* = 0



(Rybicki & Lightman)

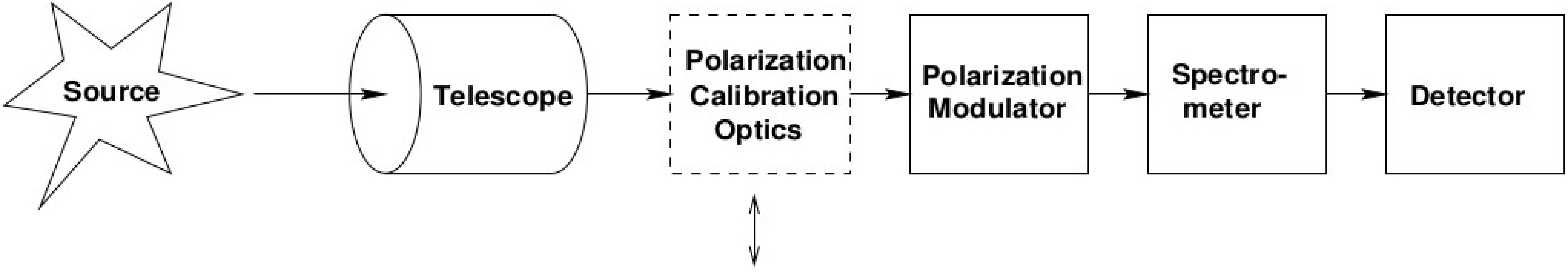
Basic layout of a photo-polarimeter



(McLean 2008)

- Photometer or camera with some additional optical elements:
- **Modulator (retarder or converter)**: changes phase difference of the electric field components, converting elliptically polarized light into linear polarized (or vice versa)
- **Polariser (analyser)**: emergent beam is linearly polarized, regardless of the polarization state of the incident beam

Basic layout of a spectro-polarimeter



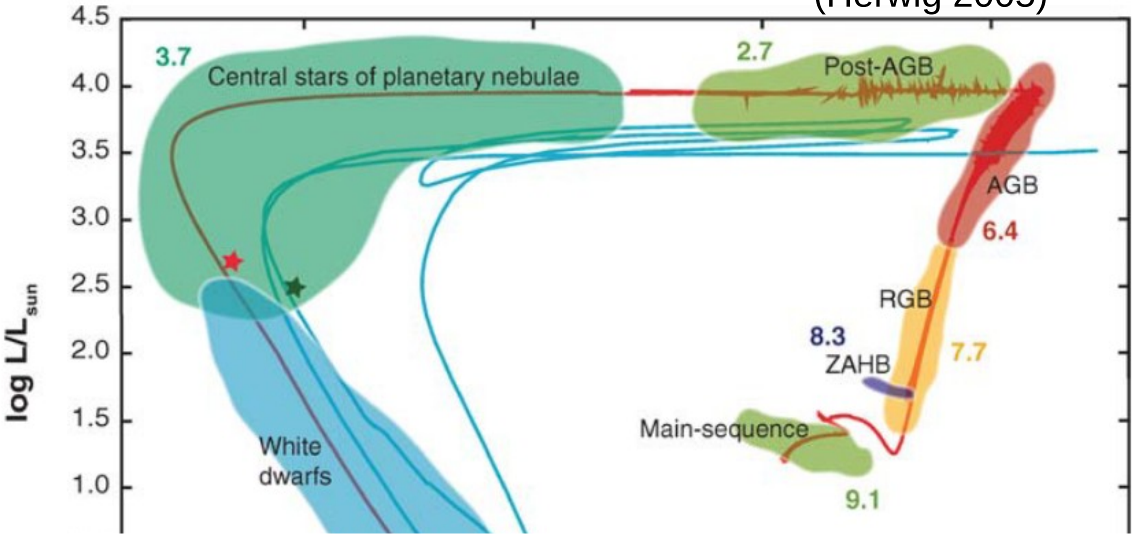
(Keller 2002)

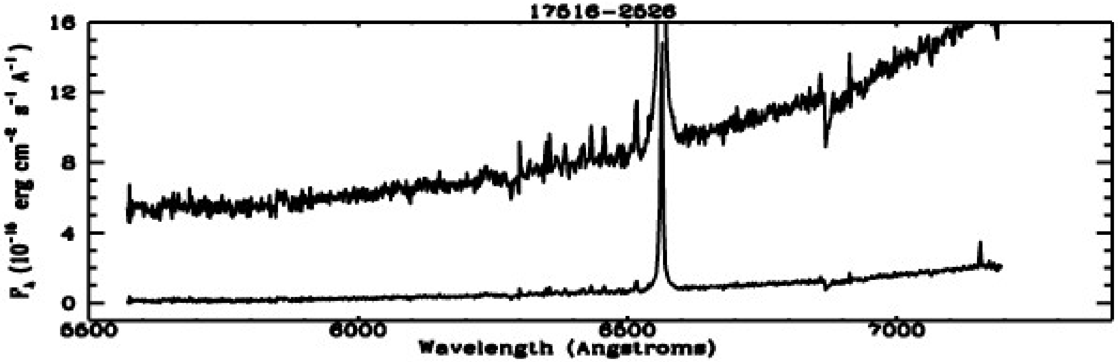
- Spectrograph with polarimetric optics before the dispersion element:
- **Modulator**: Spatial or temporal variation of the polarization
- **Calibration optics**: (removable) inject light with known polarization states into the polarimetric instrument, before the polarization modulator

Remember our science case?

- We looked at an overdensity of stars found by Gaia
- Confirmed with photometric observations as a cluster
- Spectroscopy gave a list of members
- One star in the field is an RV member and has Hα in emission
- Infrared observations to search for dust shell
- **We can look for more information about the dust around the star with polarimetry (non-spherical symmetry of the envelope)**

(Herwig 2005)





(Suarez et al. 2006)

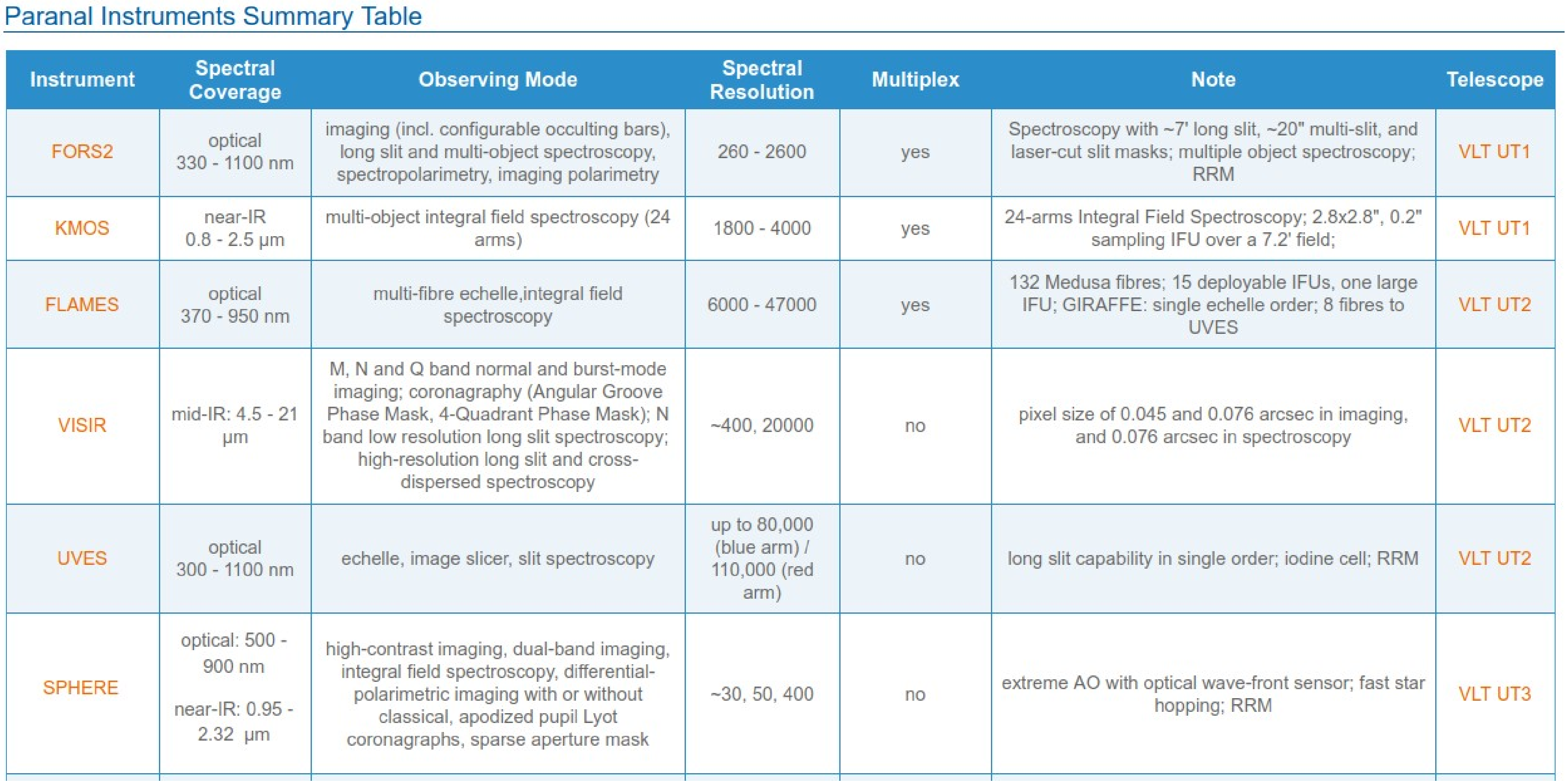
If you want to observe with the VLT, read the call for proposals

- Updated list of offered instruments
- Informs on recent policy changes
- and on future plans for the instruments
- Describes important definitions (proposal types, observing modes, OBs, ...)
- Several links for additional information
- Binding document if the proposal is approved
- **Reading is a must for 1st time users!**

ESO Call for Proposals – P109

Proposal Deadline: 23 September 2021, 12:00 noon CEST

Polarimetry @VLT



Paranal Instruments Summary Table

Instrument	Spectral Coverage	Observing Mode	Spectral Resolution	Multiplex	Note	Telescope
FORS2	optical 330 - 1100 nm	imaging (incl. configurable occulting bars), long slit and multi-object spectroscopy, spectropolarimetry, imaging polarimetry	260 - 2600	yes	Spectroscopy with ~7' long slit, ~20" multi-slit, and laser-cut slit masks; multiple object spectroscopy; RRM	VLT UT1
KMOS	near-IR 0.8 - 2.5 µm	multi-object integral field spectroscopy (24 arms)	1800 - 4000	yes	24-arms Integral Field Spectroscopy; 2.8x2.8", 0.2" sampling IFU over a 7.2' field;	VLT UT1
FLAMES	optical 370 - 950 nm	multi-fibre echelle,integral field spectroscopy	6000 - 47000	yes	132 Medusa fibres; 15 deployable IFUs, one large IFU; GIRAFFE: single echelle order; 8 fibres to UVES	VLT UT2
VISIR	mid-IR: 4.5 - 21 µm	M, N and Q band normal and burst-mode imaging; coronagraphy (Angular Groove Phase Mask, 4-Quadrant Phase Mask); N band low resolution long slit spectroscopy; high-resolution long slit and cross-dispersed spectroscopy	~400, 20000	no	pixel size of 0.045 and 0.076 arcsec in imaging, and 0.076 arcsec in spectroscopy	VLT UT2
UVES	optical 300 - 1100 nm	echelle, image slicer, slit spectroscopy	up to 80,000 (blue arm) / 110,000 (red arm)	no	long slit capability in single order; iodine cell; RRM	VLT UT2
SPHERE	optical: 500 - 900 nm near-IR: 0.95 - 2.32 µm	high-contrast imaging, dual-band imaging, integral field spectroscopy, differential-polarimetric imaging with or without classical, apodized pupil Lyot coronagraphs, sparse aperture mask	~30, 50, 400	no	extreme AO with optical wave-front sensor; fast star hopping; RRM	VLT UT3

https://www.eso.org/sci/facilities/lpo/cfp/cfp109/instrument_summary.html

Polarimetry @VLT

X-SHOOTER	UV-optical-NIR 300 - 2500 nm	echelle, slit and integral field spectroscopy	~5000-17000	no	full spectral coverage with one pointing; slit + IFU; RRM	VLT UT3
CRIRES	near-IR 0.95-5.3 µm	echelle, slit spectroscopy, spectro-polarimetry	~40,000-80,000	no	AO assisted, 29 wavelength settings, 0.2"x10" and 0.4"x10" slits, gas cells for precision RV measurements, linear and circular polarimetry below 2500 nm.	VLT UT3
HAWK-I	near-IR 0.85-2.5 µm	broand and narrow band imaging, fast photometry	-	-	pixel size of 0.106"; field: 7.5'x7.5', subwindow readout capability; GLAO; RRM	VLT UT4
MUSE	optical 465 - 930 nm	integral field spectroscopy	1770 @ 480nm 3590 @ 930nm	no	IFU size on sky 60"x60" with spaxel size 0.2" (WFM) or 7.5"x7.5" with spaxel size 0.025" (NFM); GLAO, LTAO, no AO; RRM.	VLT UT4
ESPRESSO	optical 380 - 788 nm	fibre-fed échelle spectroscopy	140,000, 190,000, or 70,000 (median)	no	2 fibres (1 object, 1 sky or simultaneous reference); RV precision < 1 m/s (with the ultimate goal of reaching 10 cm/s); 1-UT and 4-UT modes	VLT UT1, VLT UT2, VLT UT3, or/and VLT UT4
GRAVITY	near-IR 2.05 - 2.45 µm	spectro-interferometry	R ~ 20, 500, & 4000	no	4 beam combiner - delivers spectrally dispersed visibilities, differential and closure phases	VLTI - ATs VLTI - UTs

https://www.eso.org/sci/facilities/lpo/cfp/cfp109/instrument_summary.html

FORS2

- **FO**cal **R**educer and low dispersion **S**pectrograph (Appenzeller et al. 1998).
- Cassegrain focus of UT1, operation since 2000.
- All-dioptric (lenses), ~330 to 1100 nm

- Imaging polarimetry (dual-beam polarimeter)
- Spectropolarimetry

- Measure linear and circular polarization in both imaging and spectroscopic modes
- Determination of the position angle and the degree of linear or circular polarization

(Credit: ESO)

Degree of polarization and angle

- The Stokes parameters of a combined beam is the sum of parameters of the individual beams travelling in that direction
- Partially polarized beam = unpolarized + fully polarized:

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I_p \\ Q_p \\ U_p \\ V_p \end{bmatrix} + \begin{bmatrix} I_u \\ Q_u \\ U_u \\ V_u \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} I_p \\ Q_p \\ U_p \\ V_p \end{bmatrix} + \begin{bmatrix} I_u \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

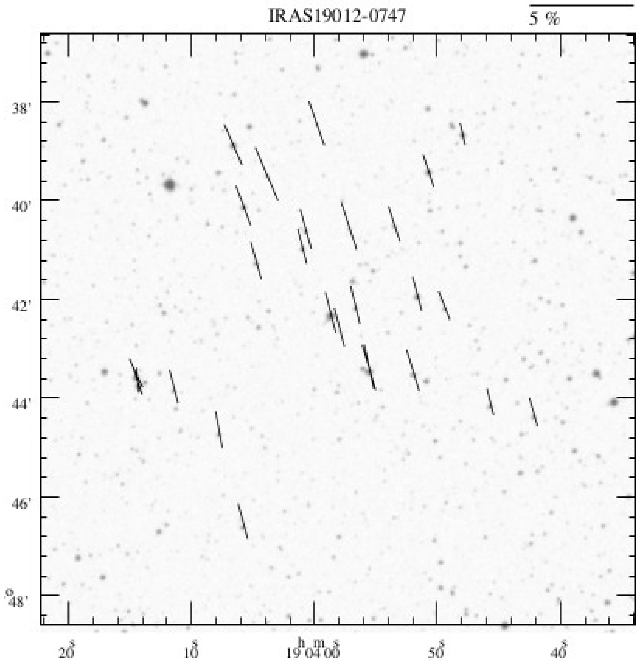
- Degree of polarization (or separately of linear and circular polarization):

$$P = \frac{\sqrt{Q_p^2 + U_p^2 + V_p^2}}{I_p + I_u} = \frac{\sqrt{Q_p^2 + U_p^2 + V_p^2}}{I}.$$

or

$$P_L = \frac{\sqrt{Q_p^2 + U_p^2}}{I}$$

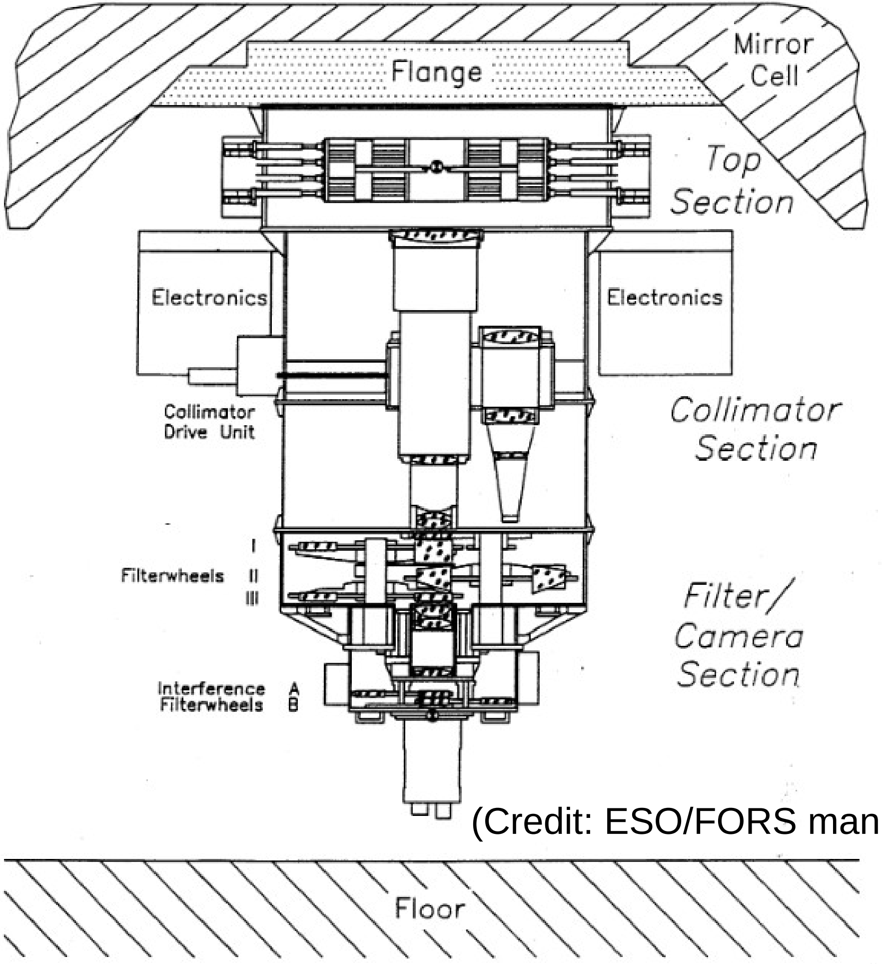
$$P_V = \frac{V_p}{I}$$



(Pereyra et al. 2006)

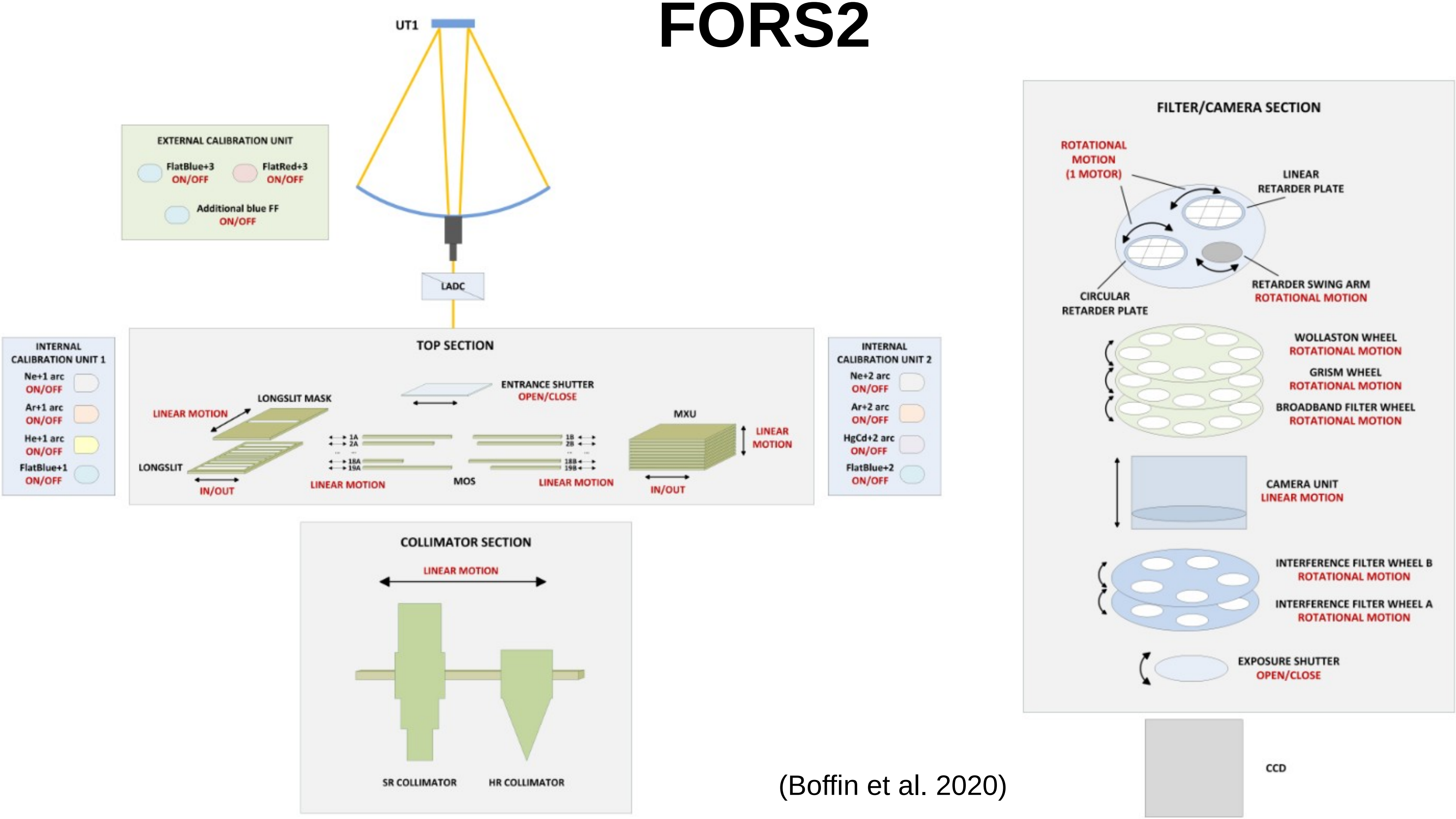
Imaging-polarimetry with FORS2

- Polarization optics located at the parallel beam (after the collimator)
- Two superachromatic phase plate retarder mosaics:
  - Quarter wave plate (circular polarization)
  - Half wave plate (linear polarization)
- Both mosaic can be rotated (at fixed pre-defined angles)
- Wollaston prism in one of the filter wheels (beam splitting analyser)
- A “strip mask” using the MOS slit jaws can be used for extended objects or crowded fields
- All imaging filters (not in the Wollaston wheel)can be used



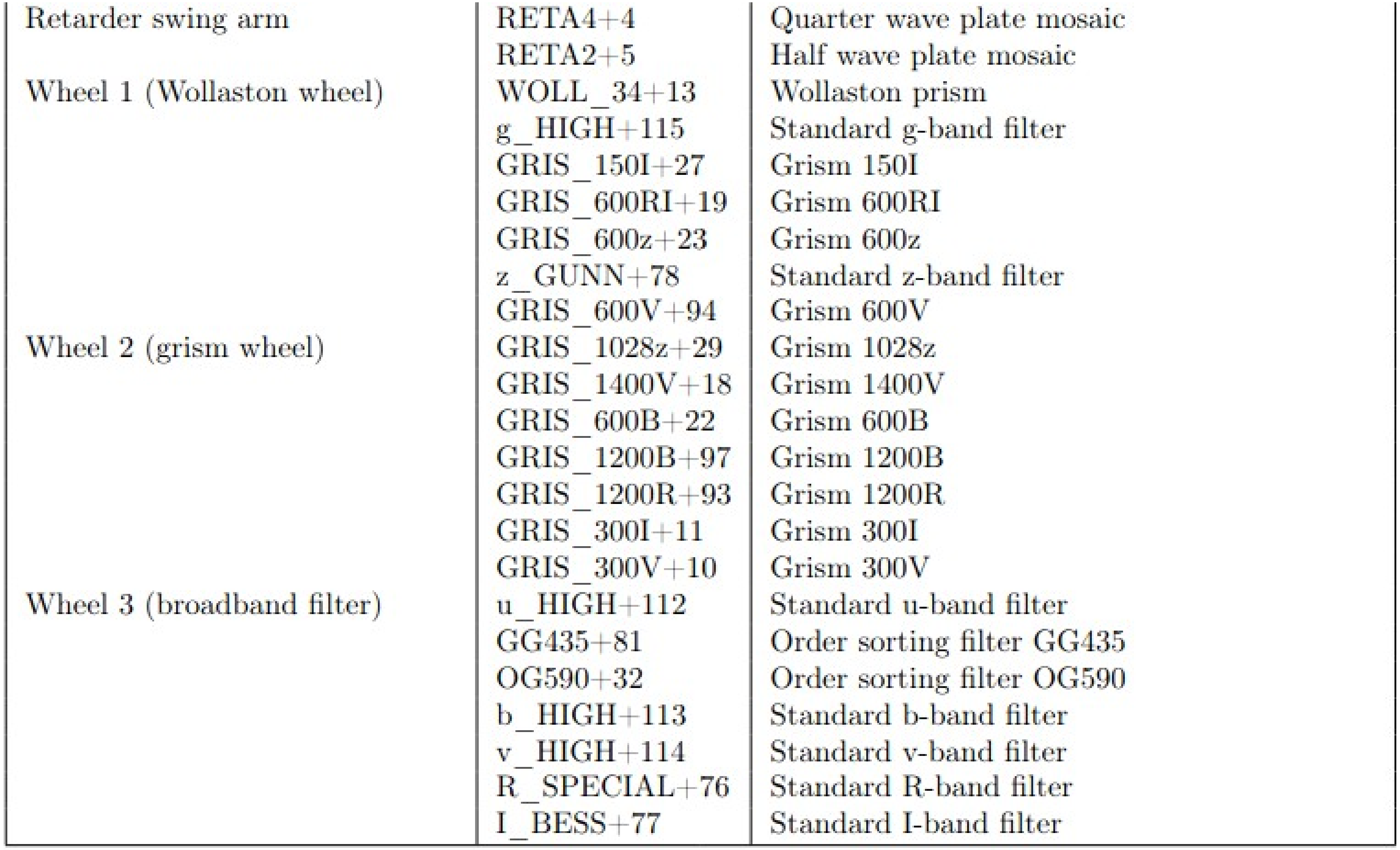
(Credit: ESO/FORS manual)

FORS2



(Boffin et al. 2020)

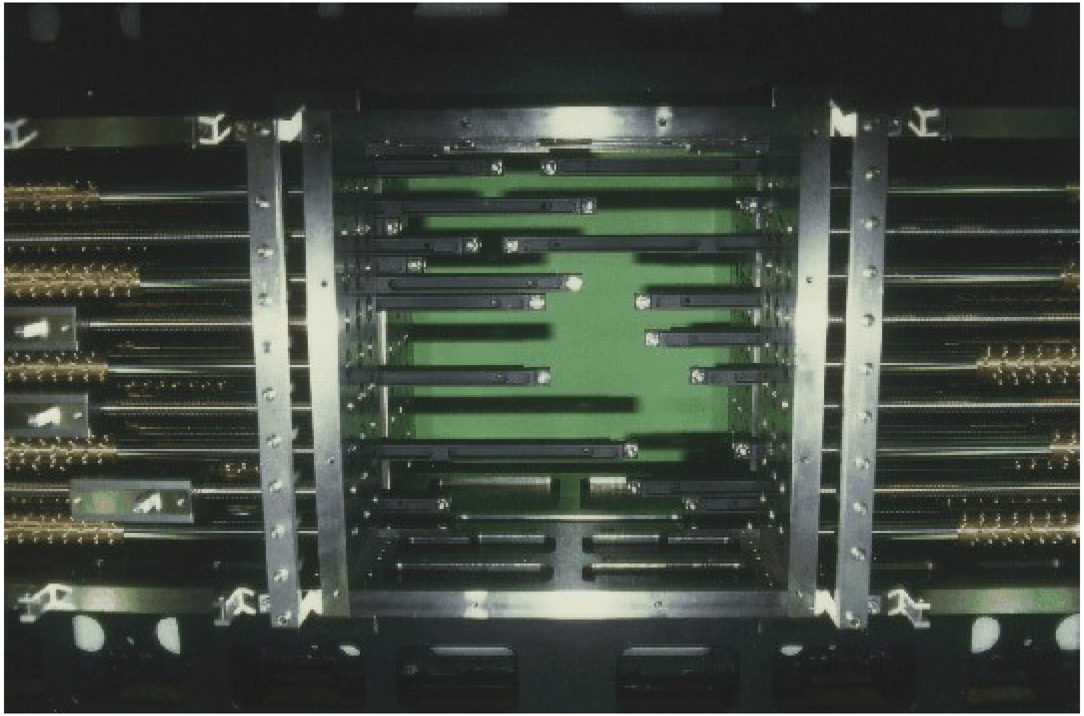
Filters for IPOL mode



Retarder swing arm	RETA4+4	Quarter wave plate mosaic
	RETA2+5	Half wave plate mosaic
Wheel 1 (Wollaston wheel)	WOLL_34+13	Wollaston prism
	g_HIGH+115	Standard g-band filter
	GRIS_150I+27	Grism 150I
	GRIS_600RI+19	Grism 600RI
	GRIS_600z+23	Grism 600z
	z_GUNN+78	Standard z-band filter
	GRIS_600V+94	Grism 600V
Wheel 2 (grism wheel)	GRIS_1028z+29	Grism 1028z
	GRIS_1400V+18	Grism 1400V
	GRIS_600B+22	Grism 600B
	GRIS_1200B+97	Grism 1200B
	GRIS_1200R+93	Grism 1200R
	GRIS_300I+11	Grism 300I
	GRIS_300V+10	Grism 300V
Wheel 3 (broadband filter)	u_HIGH+112	Standard u-band filter
	GG435+81	Order sorting filter GG435
	OG590+32	Order sorting filter OG590
	b_HIGH+113	Standard b-band filter
	v_HIGH+114	Standard v-band filter
	R_SPECIAL+76	Standard R-band filter
	I_BESS+77	Standard I-band filter

(Credit: ESO)

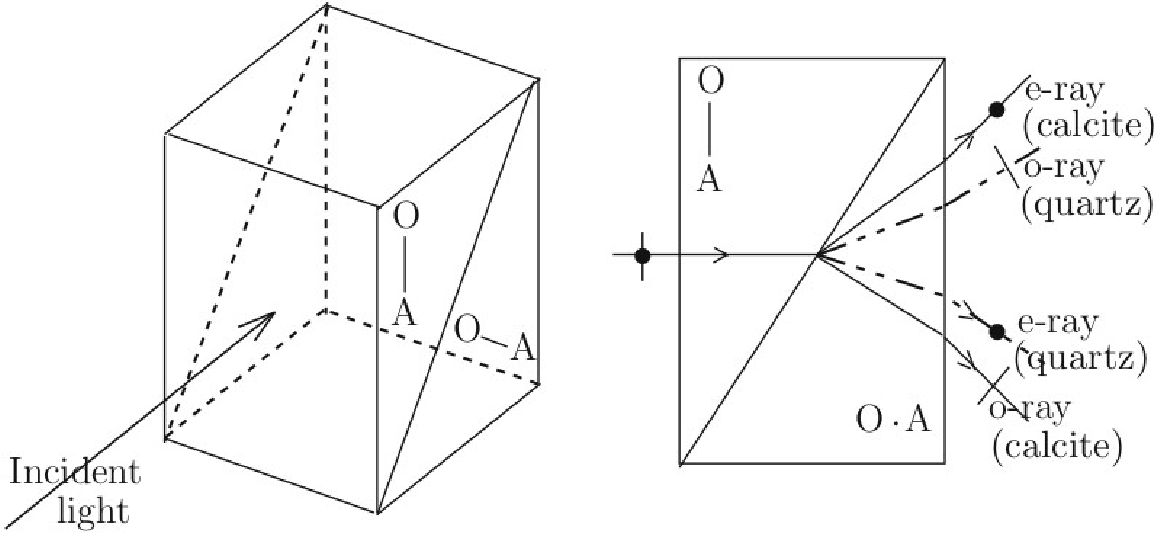
FORS2 MOS Slit Jaws



(Credit: ESO)

Wollaston prism

- Two prisms of uniaxial birefringent material cemented together
- “Beam-splitter”
- The two directions of vibration of the electric field split and exit the Wollaston prism
- The two beams exit at an angle, deviating to different directions
- The angle can be changed by design
- Positioned at a pupil, it creates a split field of view at the image plane

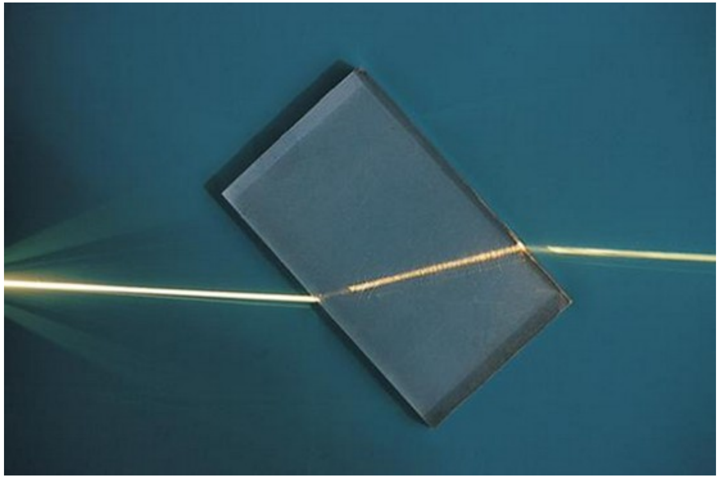


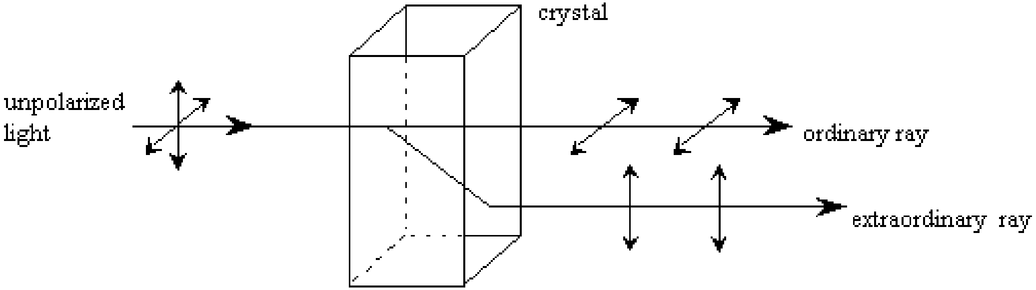
(Credit: Clarke 2009)

Birefringence

- Refractive index (*n*): related to how fast light travels in a material
- Birefringent materials have refractive index that depend on the orientation of the electric vector of the incident radiation
- $n_x \neq n_y \neq n_z$
- Uniaxial materials have one direction with distinct refractive index ($n_x = n_y \neq n_z$)
- This distinct direction is called the “optic axis”
- The axis with smallest refractive index is the “fast axis”
- Calcite (a form of calcium carbonate, $CaCO_3$, quartz, and magnesium fluoride, MgF_2)

(Credit: Wikipedia)

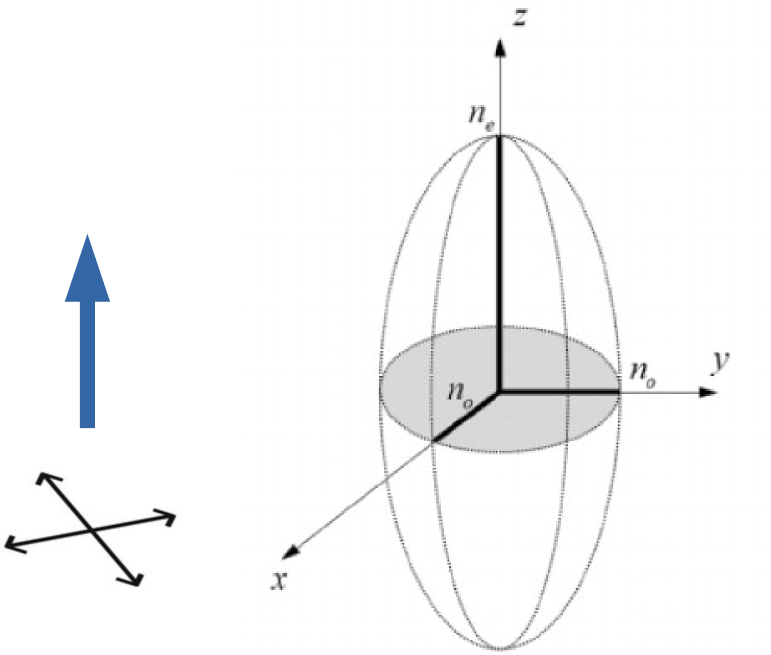




(Credit: Harvard University)

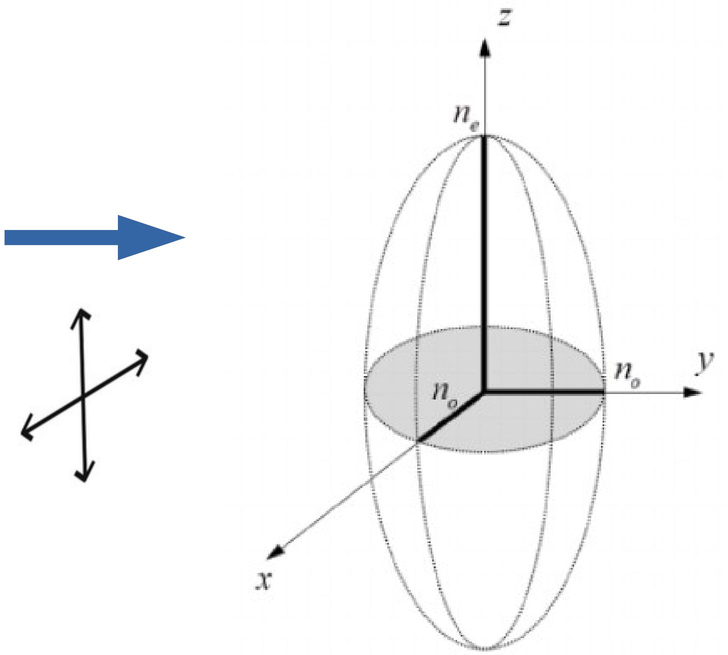
Uniaxial Birefringence

Travel along the optic axis:



- Both vibration directions are subject to the same refractive index

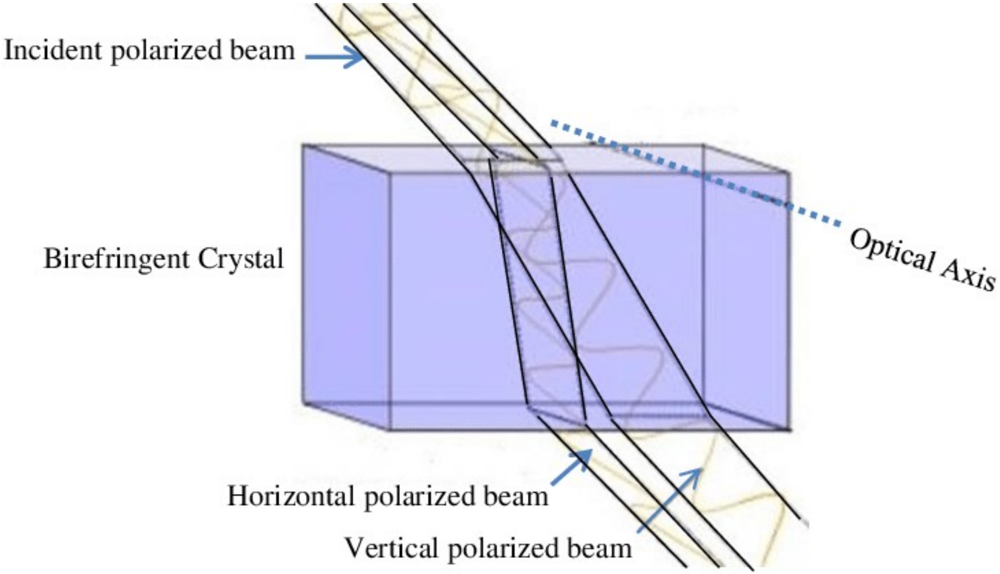
Travel perpendicular to optic axis:



- Each vibration directions are subject to different refractive indices

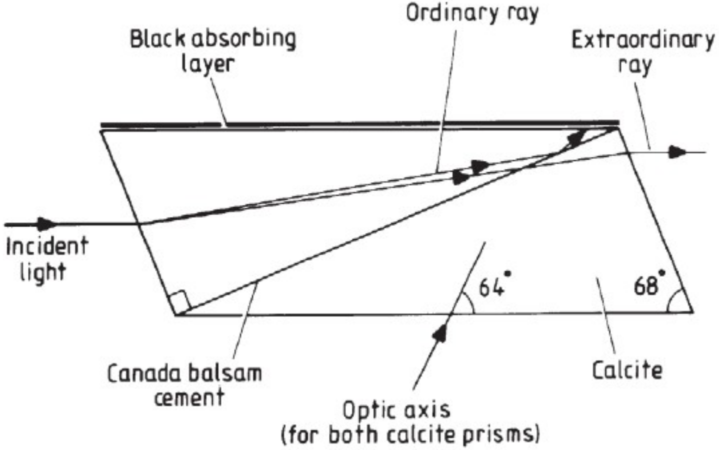
Birefringence

- The incident beam splits into two beams with orthogonal linear polarizations
- Upon rotation of the material, one beam does not change (the ordinary ray)
- The second beam changes its direction of travel (the extraordinary ray)
- The ordinary beam is always subject to the same refractive index (n_o)
- The extraordinary ray is subject to a variable refractive index (n_e when parallel to the optic axis)
- Birefringence of a material: $\Delta n = n_e - n_o$



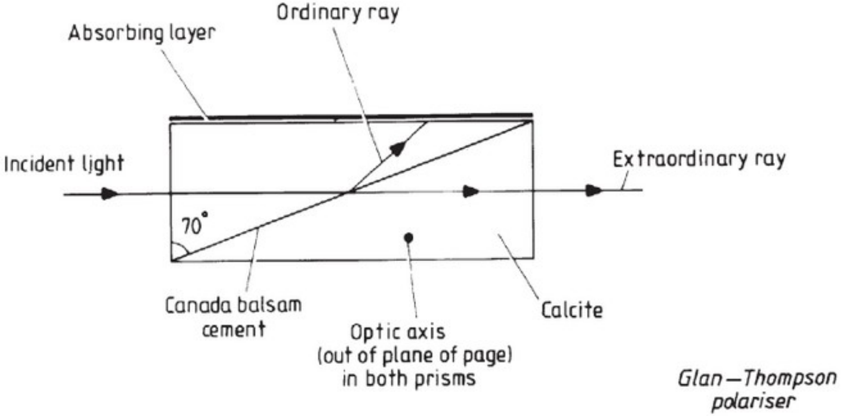
Birefringent beam splitters

Nicol prism:

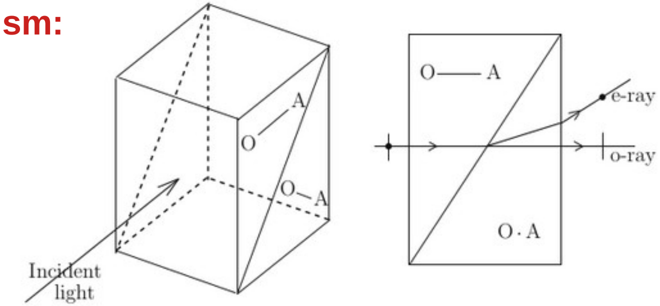


Glan-Thompson prism:

(Credit: Kitchin 2003)

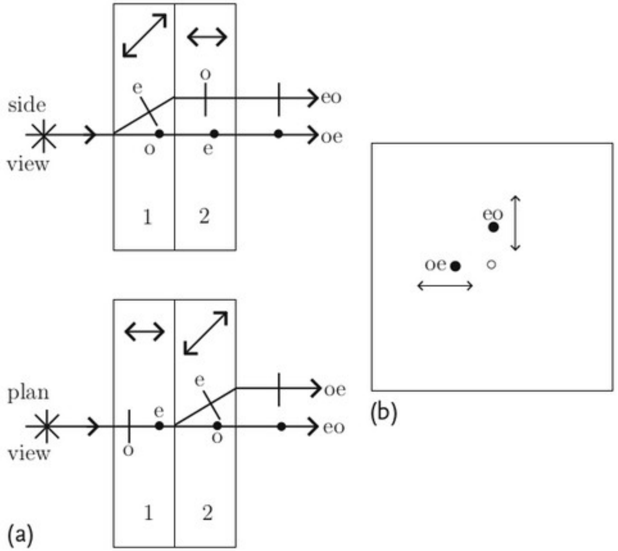


Rochon prism:



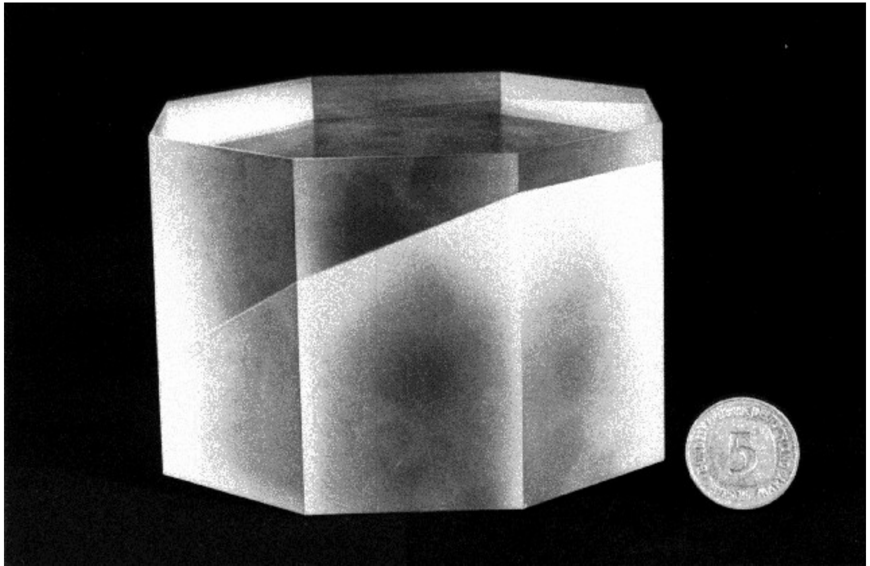
(Credit: Clarke 2009)

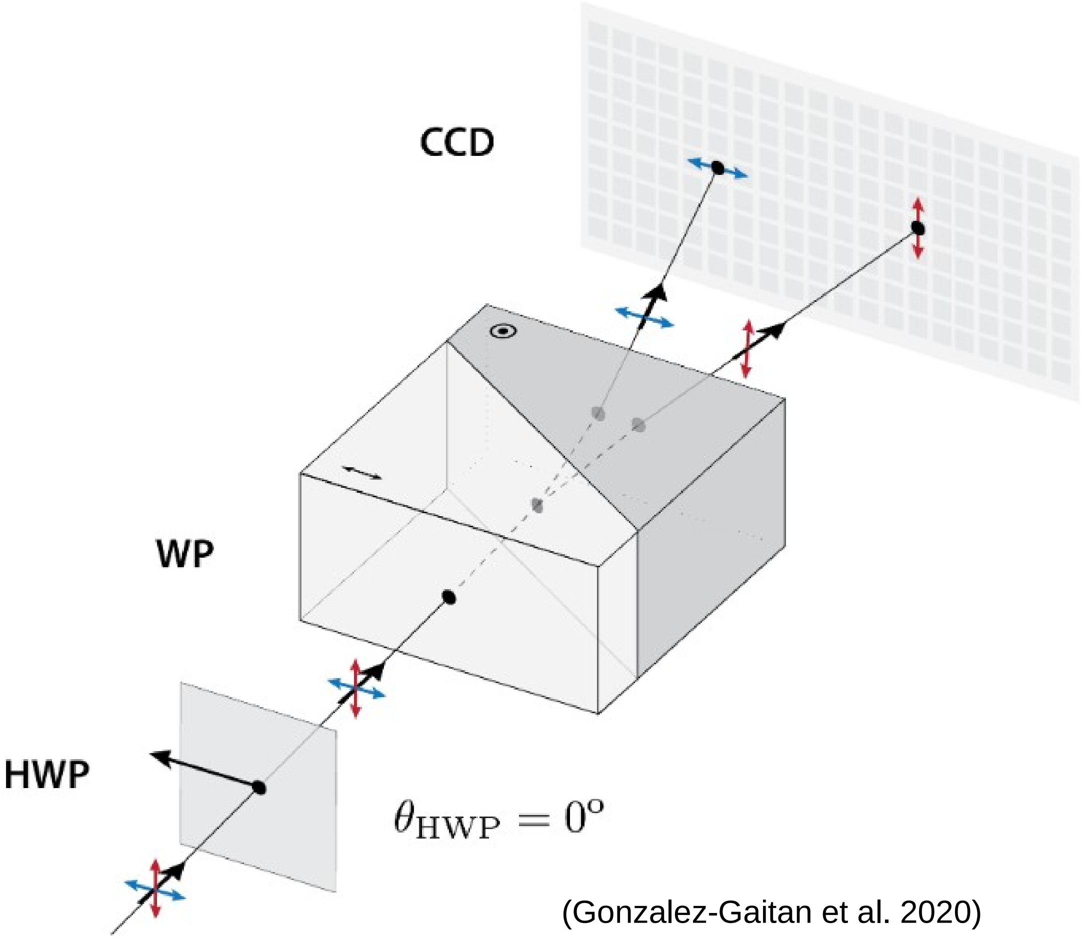
Savart plate:



Wollaston @ FORS2

- Made of quartz; 92.3 mm thick (Seifert & Furtig 1994)
- Two optic axis perpendicular to each other
- Separation of 22 arcsec on the image plane

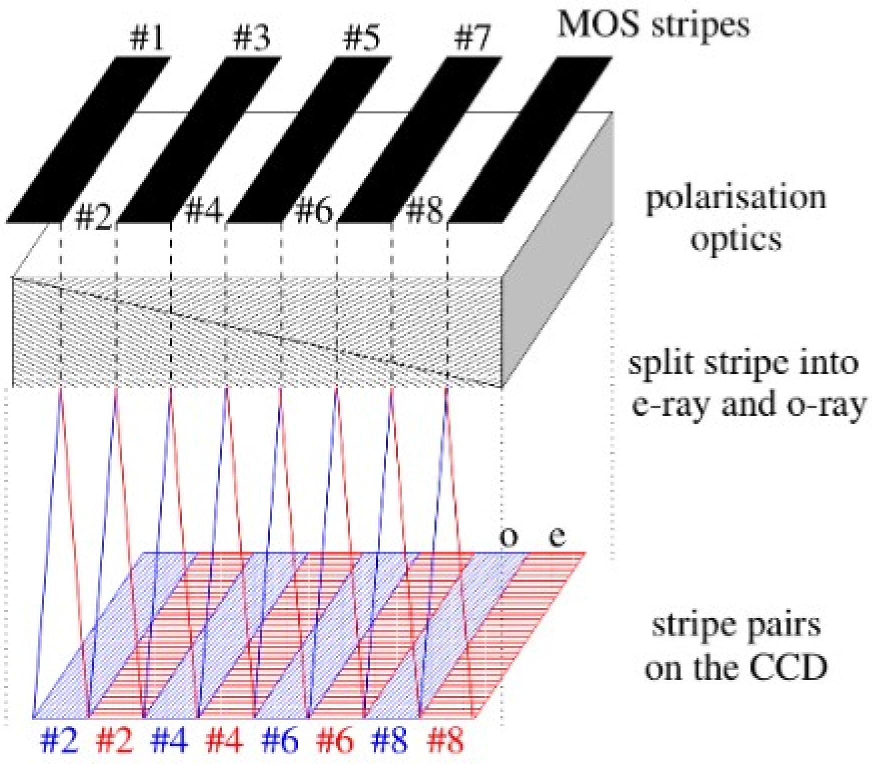




(Gonzalez-Gaitan et al. 2020)

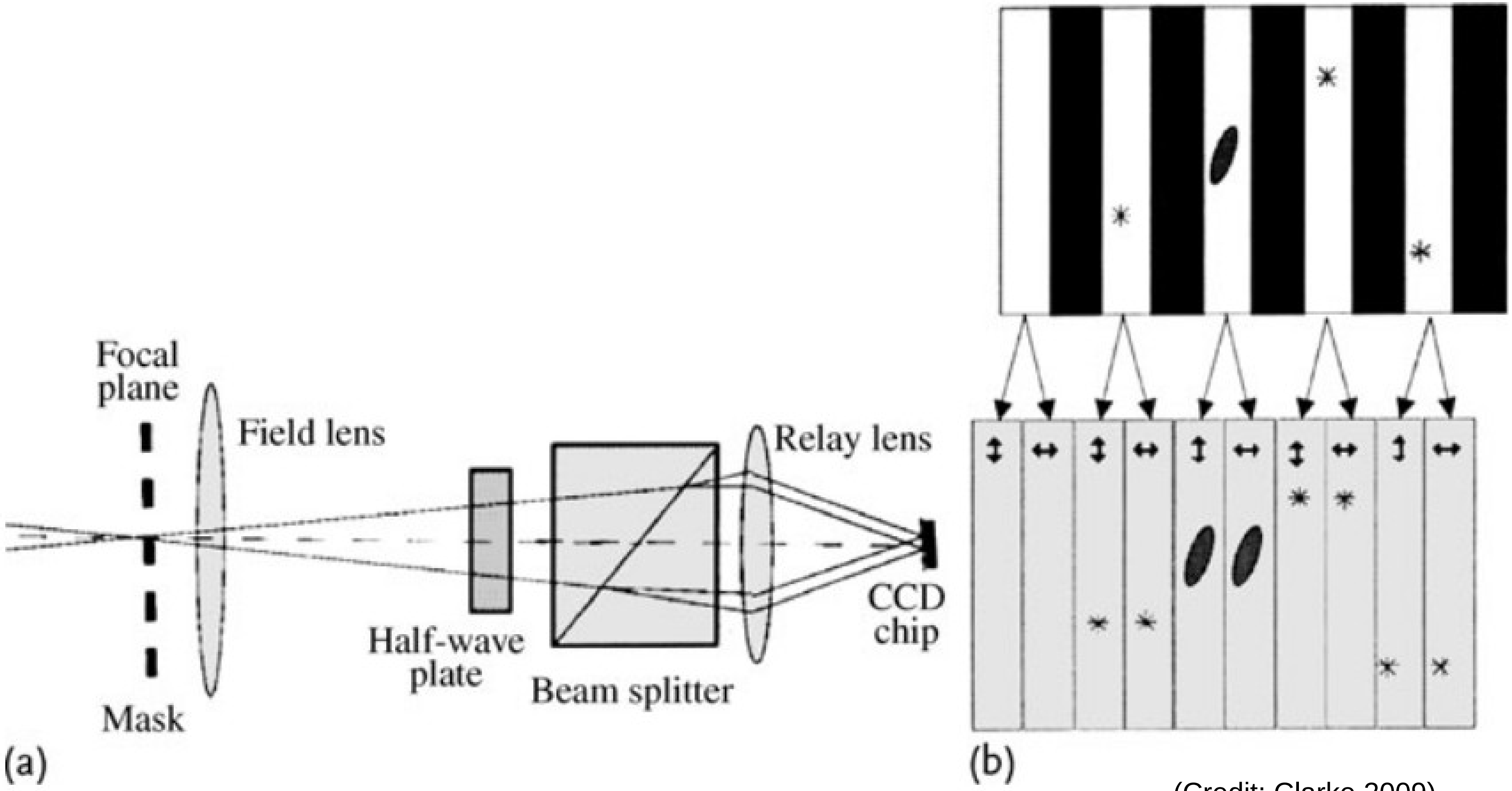
Strip mask

- The beam splitter creates two images of the field
- For extended objects or crowded regions, there would be a lot of superposition
- The “Strip mask” covers half the field in alternate stripes
- The image of ordinary and extraordinary beams alternate in stripes
- Every second bar of the MOS slit jaw used (to mask 22 arcsec slits)
- Full field image requires dithering by ~22” (in principle 2 but 3 recommended to correct for the edges)



(Gonzalez-Gaitan et al. 2020)

Strip mask



(Credit: Clarke 2009)

Retarders

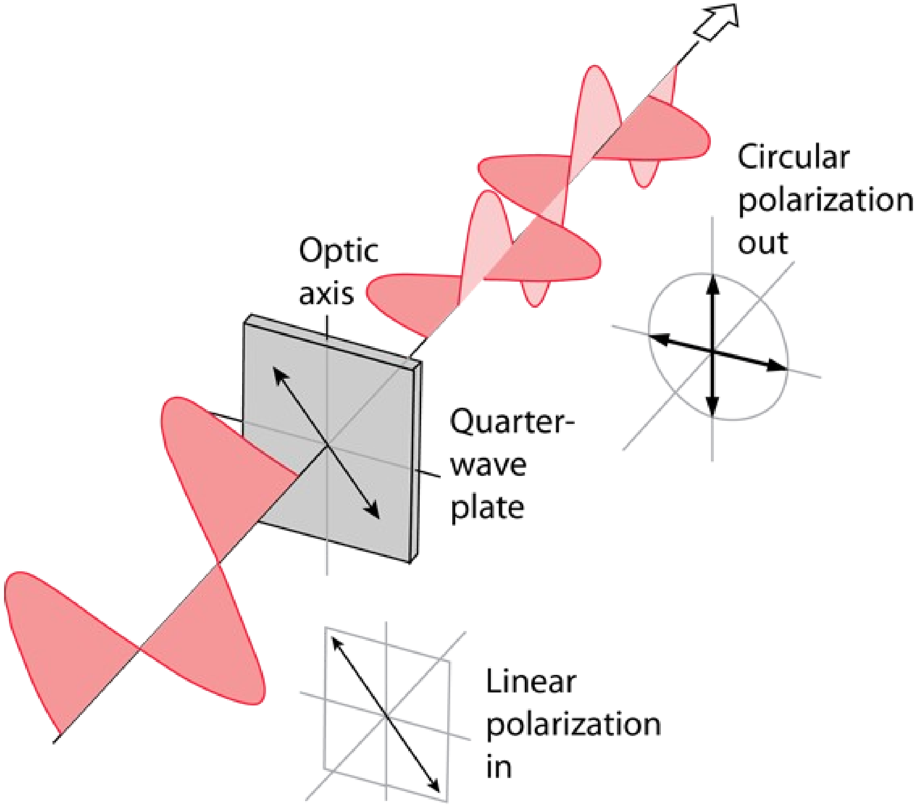
- Element that delays the phase of one polarization state with respect to the orthogonal state
- Retarders that use birefringence are called “phase plates” or “wave plates”
- Plate with optic axis aligned to the face
- The beam that enters splits into two, that travel with different velocities
- The optical path delay is a function of the thickness:

$$\Delta = \frac{2\pi d}{\lambda}(n_e - n_o)$$

(Credit: A-Star Photonics)

Wave plates

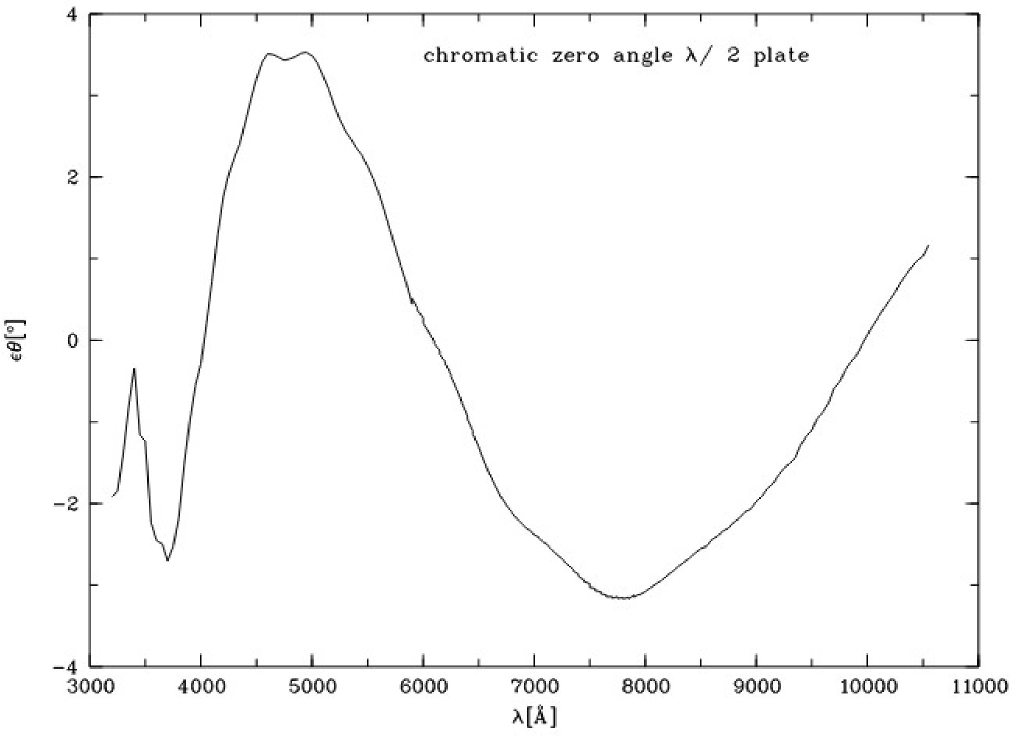
- Mostly two types are used:
  - Quarter-wave plate (delay 90 deg)
  - Half-wave plate (delay 180 deg)
- QWP: transforms linear into circular polarization (and vice versa)
- HWP: rotates the linear polarization without affecting circular polarization
- Multiples of 90 or 180 possible, for thicker plates
- True zero-order wave plates: those that achieve phase delay of exactly 90 or 180 degrees



(Credit: Hyperphysics)

Chromatic dispersion

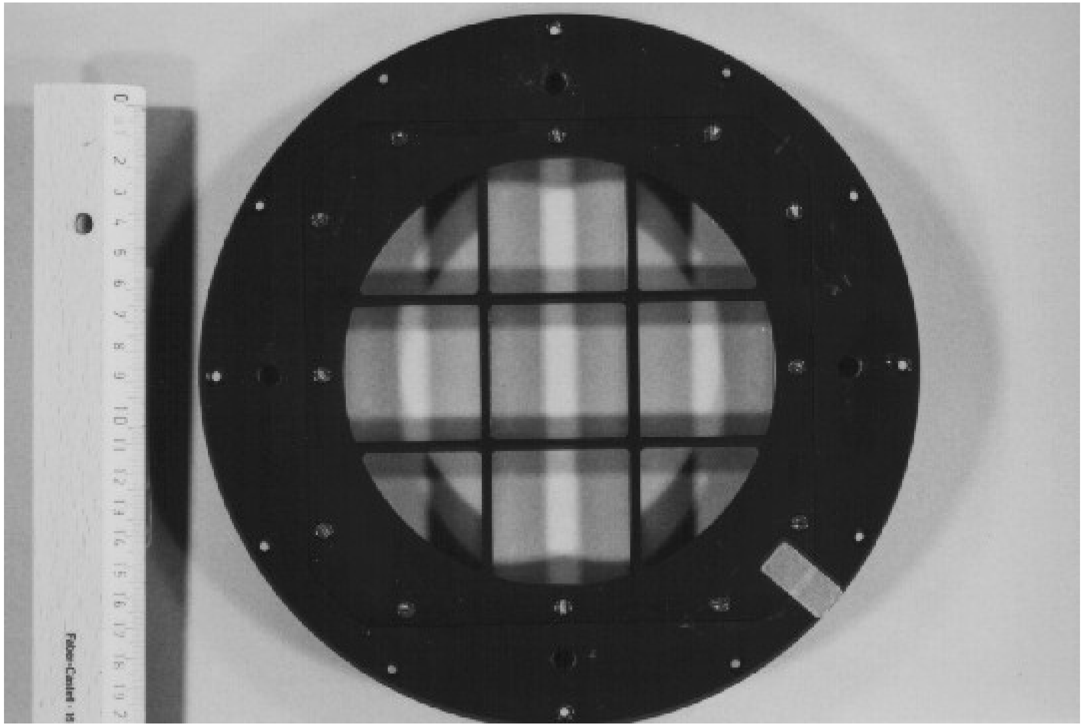
- Refractive index is a function of wavelength
- Some chromatic dispersion introduced
- A quarter-wave plate at 800 nm will be close to a half-wave plate for light with 400 nm
- **Achromatic wave plates:** combination of two plates of different material (bi-crystalline retarder)
    - Works well at two wavelengths, with small spectral variation
- **Pancharatnam retarders:** three or five plates of same material, optic axes in different orientation
- **Superchromatic wave plates:** combine both designs above



(Chromatism HWP; Credit: ESO, FORS2 manual)

Wave plates @ FORS2

- Two plates available:
  - Circular wave-plate (quarter-wave plate)
  - Linear wave-plate (half-wave plate)
- Mosaic of 9 (3x3) plates (138mm of diameter)
- Superchromatic type
- The position angles can estimated with an accuracy of 0.1 degree (correcting for the chromatic zero point angles)
- Spurious polarization introduced in the corners of the field of view



(Credit: ESO)

Observing with wave plates

- The angles are rotated, with a certain time modulation
- The effect of a wave plate at a certain orientation angle can be modelled as a matrix operation on the Stokes parameters
- What the detector measures are the intensities of the ordinary and extraordinary beams:

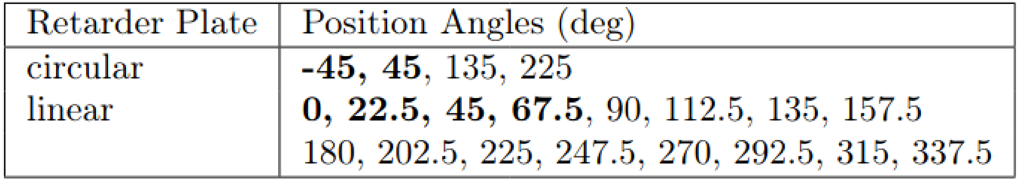
$$f_{O,\,i} = \frac{1}{2}\left[I + Q\cos 4\theta_i + U\sin 4\theta_i\right],$$

$$f_{E,\,i} = \frac{1}{2}\left[I - Q\cos 4\theta_i - U\sin 4\theta_i\right].$$

- For linear polarization, measurements at steps of π/8 (see Patat & Romaniello 2006; Gonzalez-Gaitan et al. 2020)

$$\mathbf{M}_{pol}(\theta) = \frac{1}{2}\begin{pmatrix} 1 & \cos 2\theta & \sin 2\theta & 0 \\ \cos 2\theta & \cos^2 2\theta & \sin 2\theta\cos 2\theta & 0 \\ \sin 2\theta & \sin 2\theta\cos 2\theta & \sin^2 2\theta & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

(SPIE Guide of Astronomical Instrumentation)

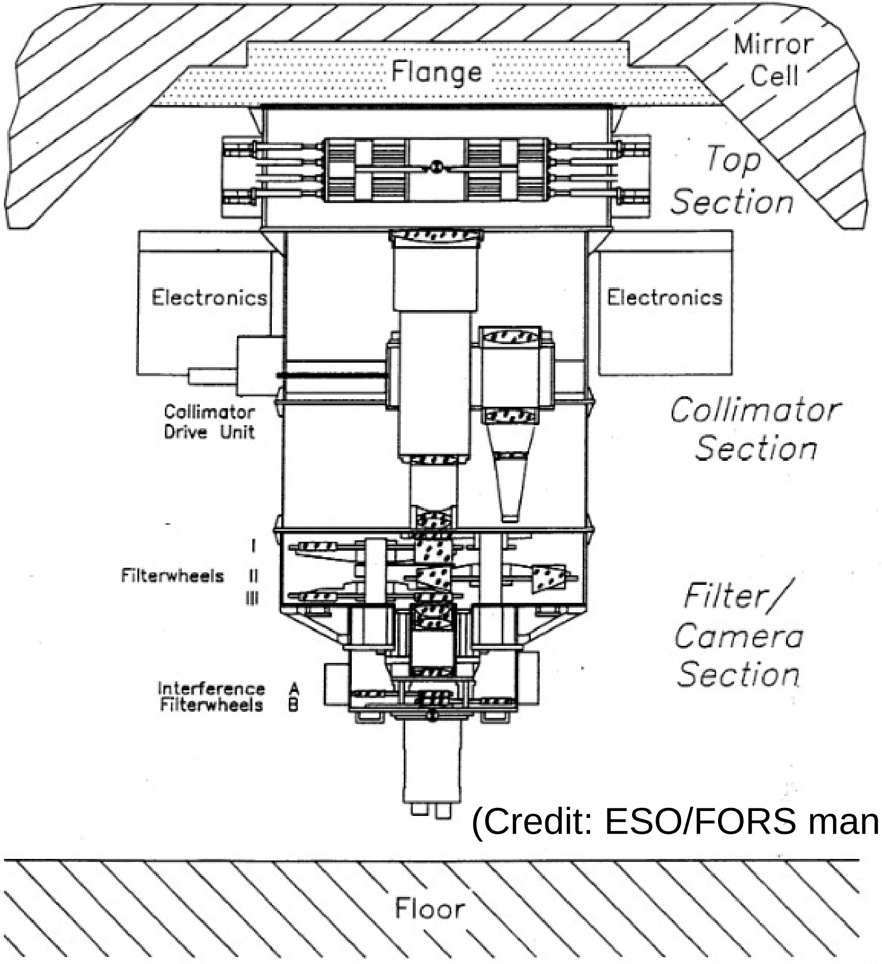


Retarder Plate	Position Angles (deg)
circular	**-45, 45**, 135, 225
linear	**0, 22.5, 45, 67.5**, 90, 112.5, 135, 157.5 180, 202.5, 225, 247.5, 270, 292.5, 315, 337.5

(Credit: ESO)

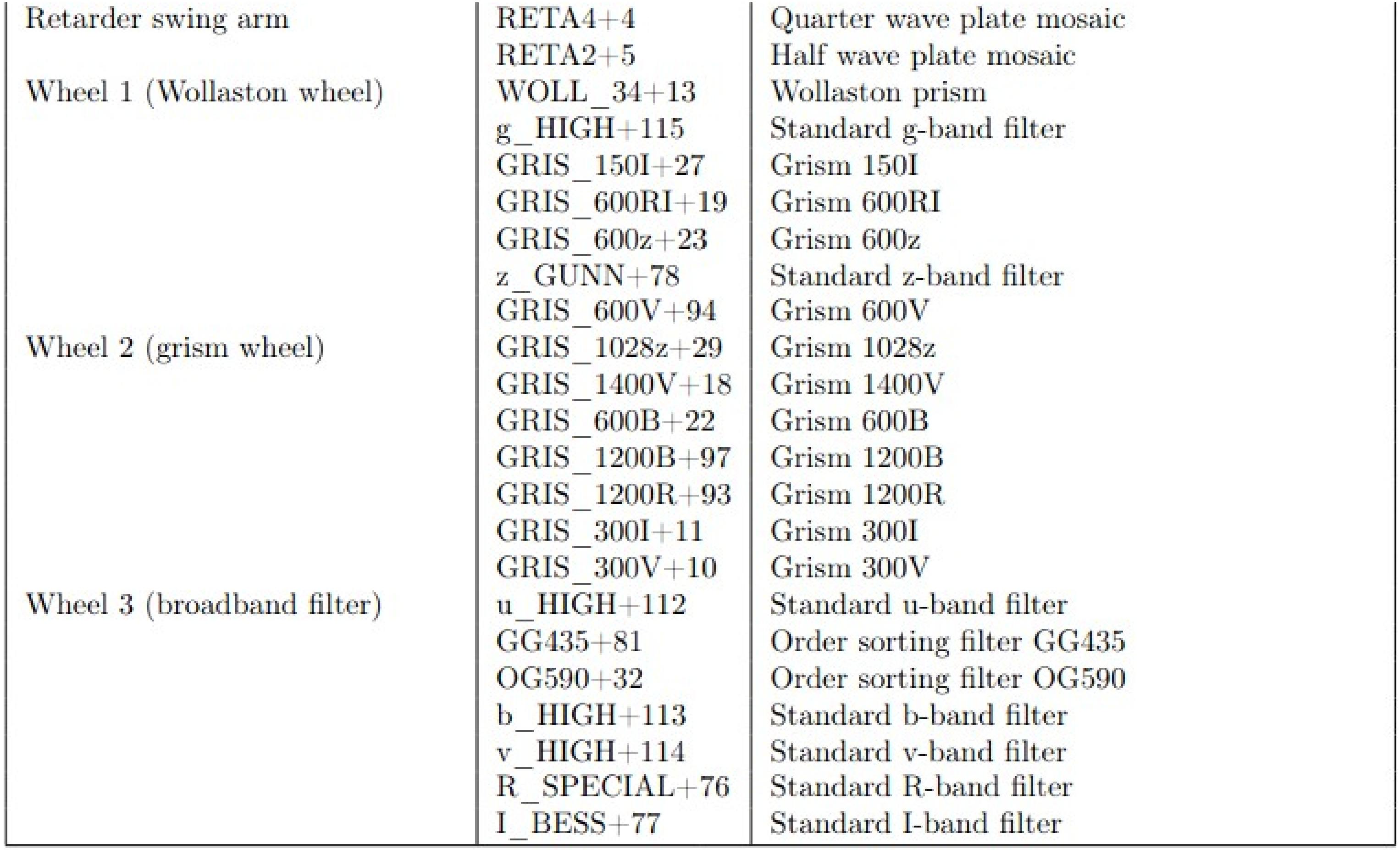
Spectropolarimetry with FORS2

- MOS slit jaws are used:
  - Odd numbered jaws make the strip mask
  - Even numbered position the slits
- Slitless spectroscopy also possible
- All grisms in the “grism wheel” can be used
- Order separation filters can be used
- Retarder plate angles with standard values
- For multi-object, the FIMS software has to be used for the slit configuration
- Single object uses “slit 10” in the centre of the field, and the other slits take sky spectra



(Credit: ESO/FORS manual)

Filters for IPOL mode

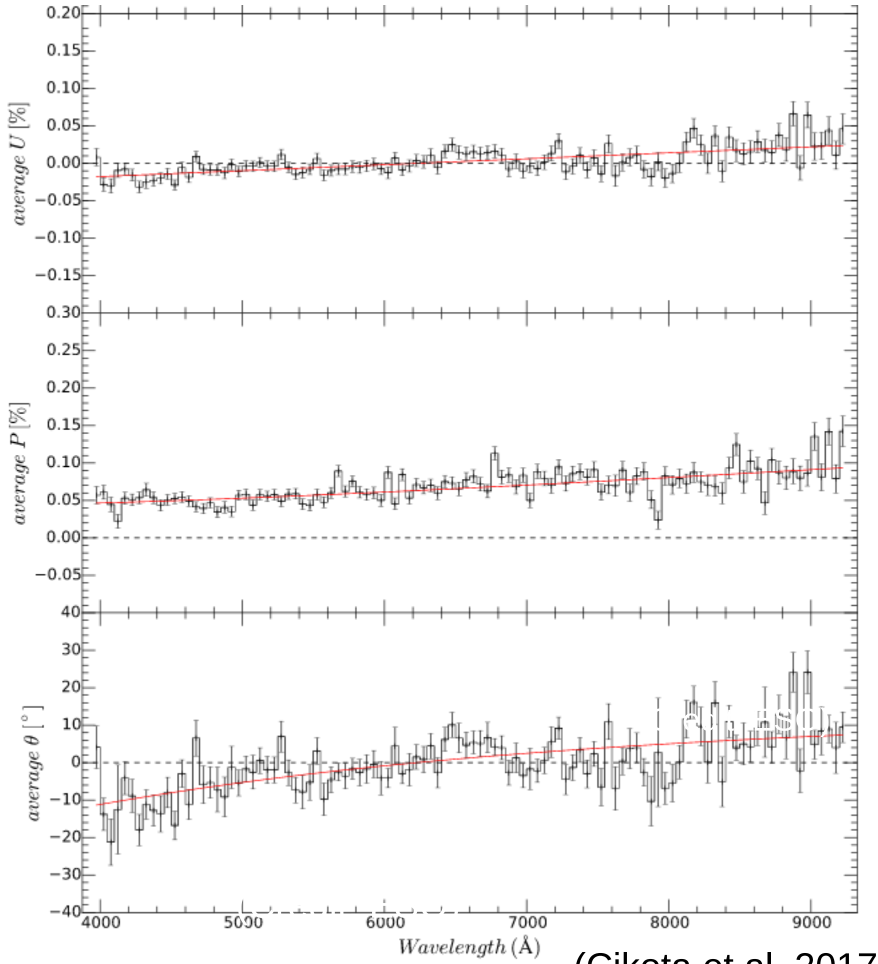


Retarder swing arm	RETA4+4	Quarter wave plate mosaic
	RETA2+5	Half wave plate mosaic
Wheel 1 (Wollaston wheel)	WOLL_34+13	Wollaston prism
	g_HIGH+115	Standard g-band filter
	GRIS_150I+27	Grism 150I
	GRIS_600RI+19	Grism 600RI
	GRIS_600z+23	Grism 600z
	z_GUNN+78	Standard z-band filter
	GRIS_600V+94	Grism 600V
Wheel 2 (grism wheel)	GRIS_1028z+29	Grism 1028z
	GRIS_1400V+18	Grism 1400V
	GRIS_600B+22	Grism 600B
	GRIS_1200B+97	Grism 1200B
	GRIS_1200R+93	Grism 1200R
	GRIS_300I+11	Grism 300I
	GRIS_300V+10	Grism 300V
Wheel 3 (broadband filter)	u_HIGH+112	Standard u-band filter
	GG435+81	Order sorting filter GG435
	OG590+32	Order sorting filter OG590
	b_HIGH+113	Standard b-band filter
	v_HIGH+114	Standard v-band filter
	R_SPECIAL+76	Standard R-band filter
	I_BESS+77	Standard I-band filter

(Credit: ESO)

Polarimetric standards

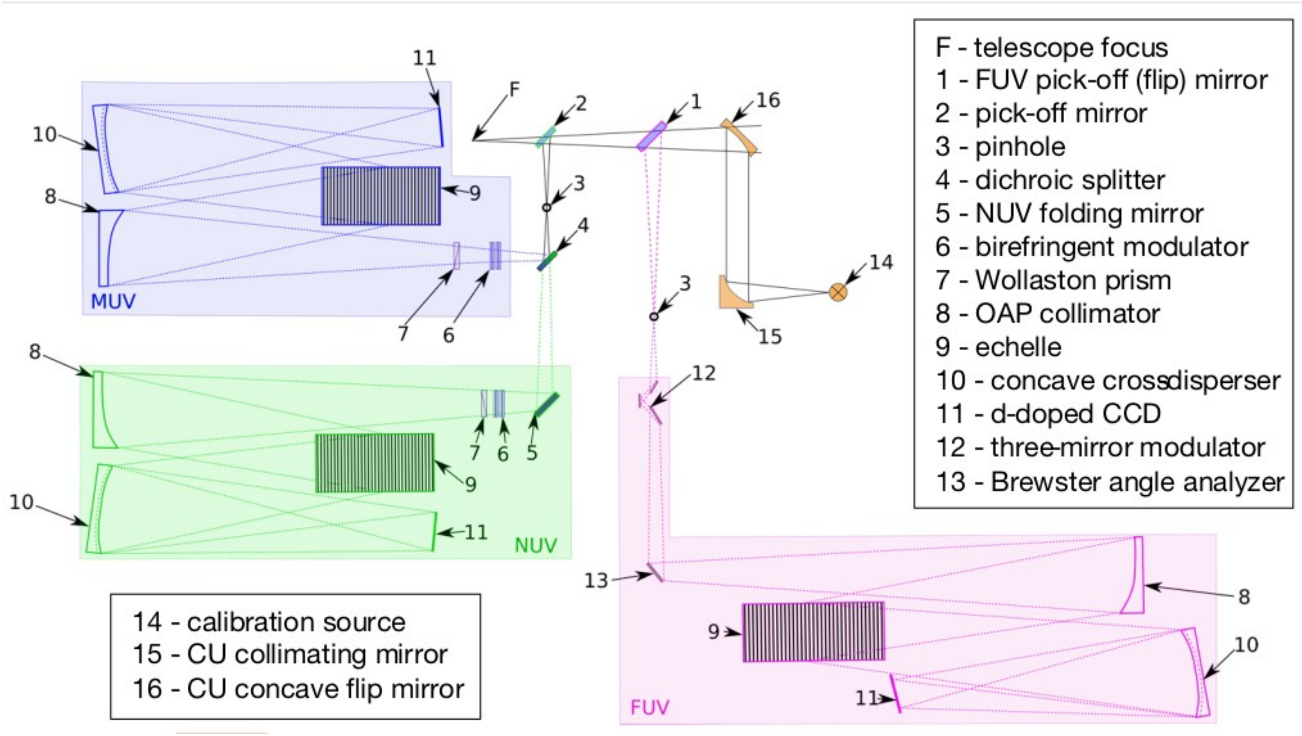
- **Unpolarized stars**: To calibrate and correct the polarization properties of the telescope and instrument
- **Polarized stars**: to provide the reference axis of the instrument attached to the telescope and to calibrate the modulation efficiency
- A list for use with FORS2 is available at the website; OBs for those observations are ready
- For linear polarization:
  - Two angles would be ok for U and Q
  - Four angles are needed to avoid problems with flat fielding (the pre-prepared OBs include four angles)
  - 16 angles are recommended for the highest accuracy



(Cikota et al. 2017)

Remarks about polarimeters

- Usually in a Cassegrain focus
- Folding mirrors (non-normal incidence) can introduce some degree of polarization (e.g., Nasmyth and Coude focii)
- Coating imperfections can also create spurious polarization in certain areas of the mirror
- Some instruments will have a calibration unit that injects with known polarization state in front of the modulator
- In space, a polarimeter power budget is a concern (changing angles of the modulator)



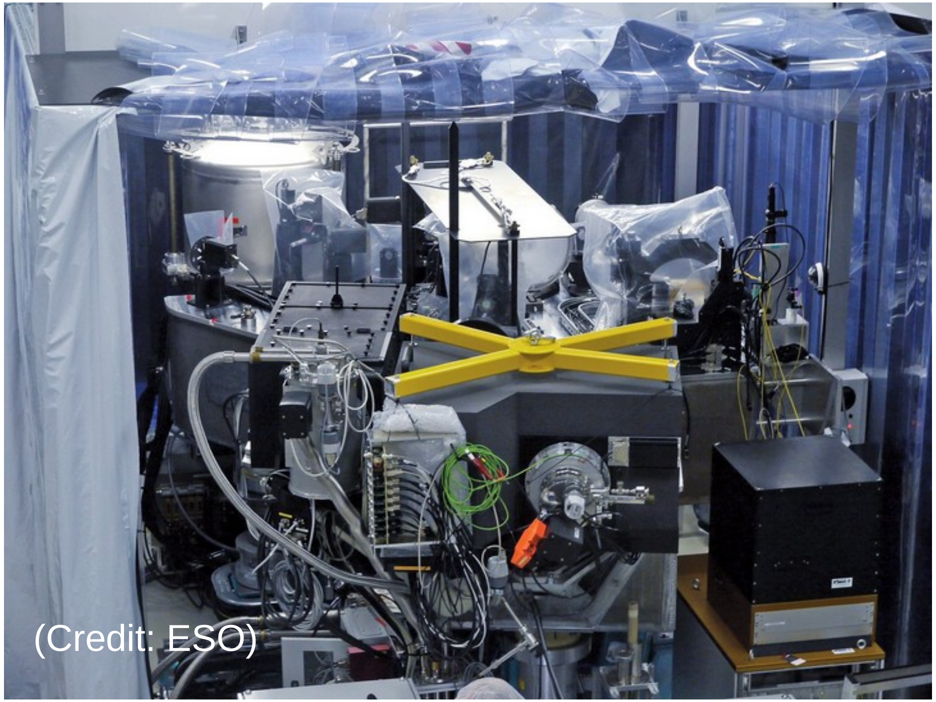
(POLLUX Optical Design for LUVOIR)

Questions?

(Credit: Shutterstock)

SPHERE

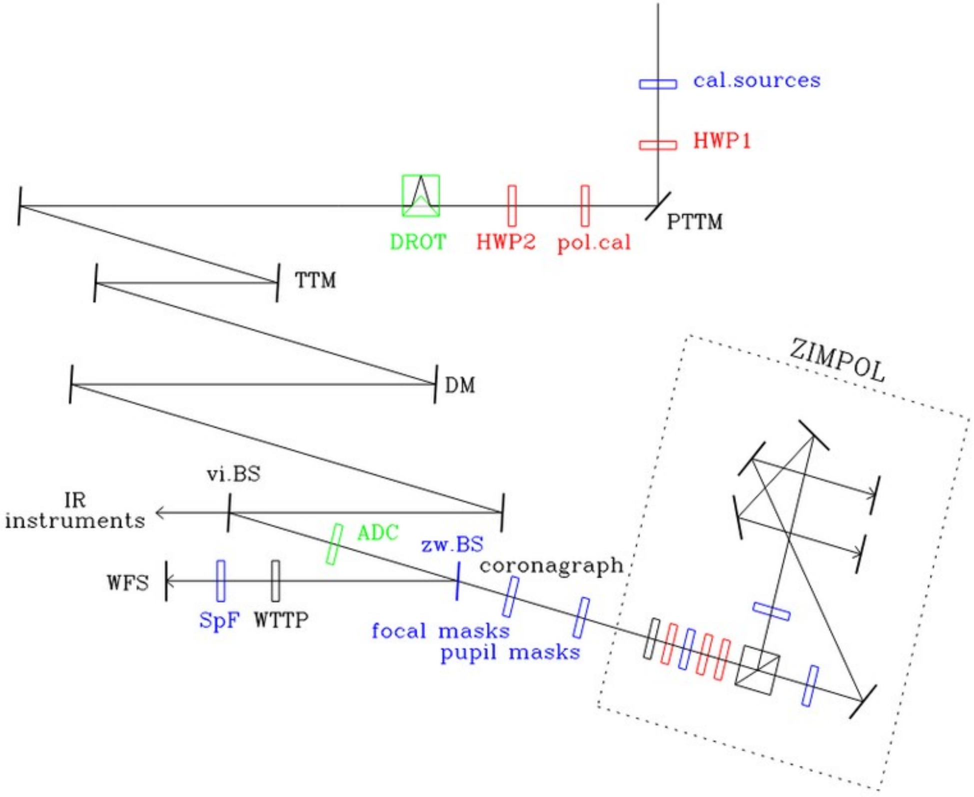
- **S**pectro-**P**olarimetric **H**igh-contrast **E**xoplanet **RE**search (Beuzit et al. 2019).
- Extreme adaptive optics system and a coronagraphic facility that feed three science instruments:
  - IRDIS (Infra-Red Dual Imaging and Spectrograph, Dohlen et al. 2009)
  - IFS (integral field spectrograph, Claudi et al. 2008)
  - **ZIMPOL (Zurich Imaging Polarimeter, Schmid et al. 2018)**
- Imaging, low-resolution spectroscopic, and polarimetric characterization of extra-solar planetary systems
- IFS and IRDIS operate at NIR
- ZIMPOL: high contrast imaging polarimetry in the visible
- UT3 Nasmyth focus (M3 introduces ~4% polarization)



(Credit: ESO)

ZIMPOL: common path & infrastructure

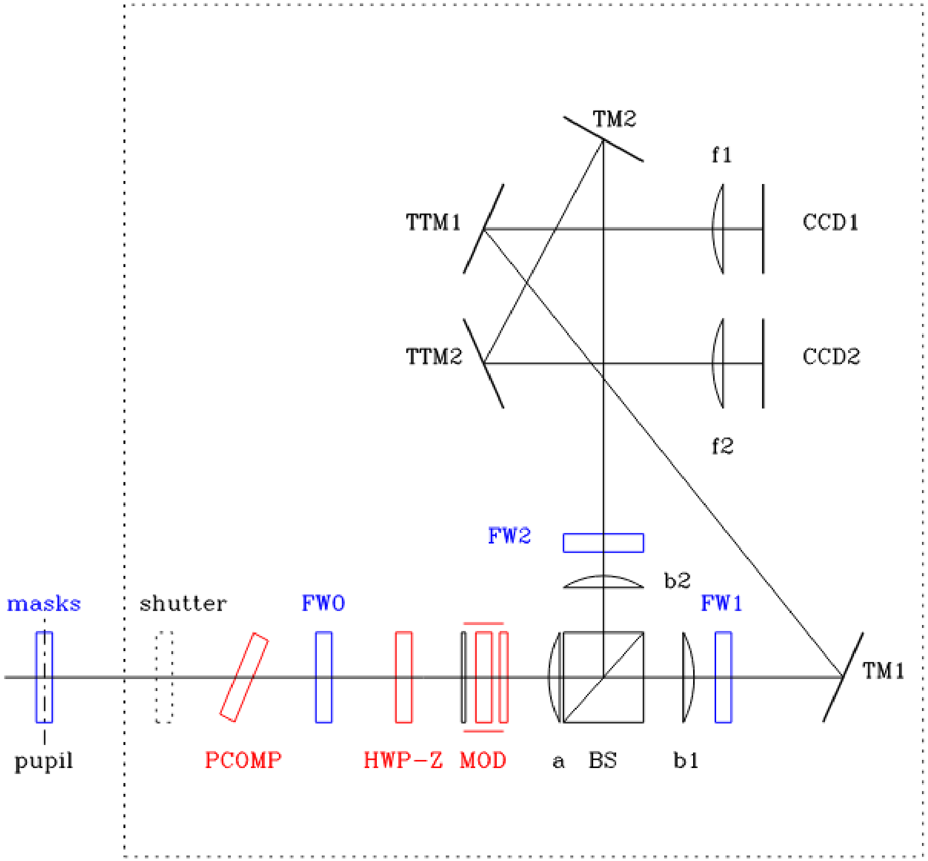
- Imaging with resolution 20-30mas, at 500-900 nm, within 4 arcsec of a bright star (thanks to the AO system and visual coronagraph)
- Very high-contrast polarimetry of reflected light from planetary systems
  - Spectral differential imaging
  - Angular differential imaging
  - Polarimetric differential imaging
- Half-wave plate 1 + PTTM: correct for the M3 polarization
- HWP2: switch that inverts the polarization of target + telescope, but does not correct for the following elements. Subtracting the signals cancels the remaining instrument polarization
- Pol.cal: polarimetric calibration components



(Schmid et al. 2018: red are for polarimetry only; blue are exchangeable; green ones rotate)

ZIMPOL

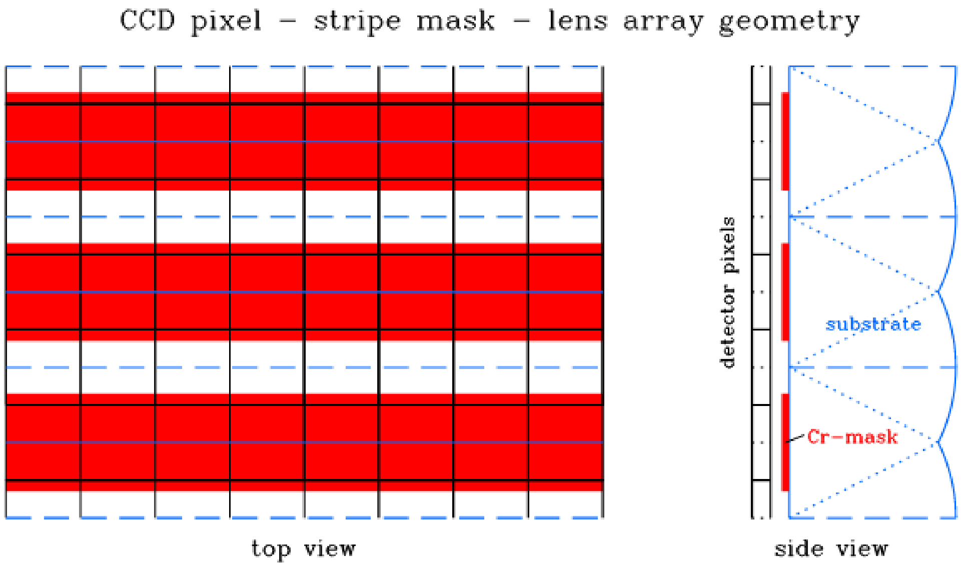
- **PCOMP**: compensates for the polarization from the derotator (2-3%). Inclined glass plate of fused silica
- **FW0**: Filter wheel for non-polarimetric imaging, neutral density filters, elements for calibration
- **HWP-Z**: corrects the orientation (Zimpol only measures polarization parallel and perpendicular to its bench)
- **MOD**: ferro-electric liquid crystal; equivalent to zero order half-wave plate where the orientation of the optic axis can changes 45deg by changing the sign of the applied voltage (time scale 50 μs)
- **Polarization beam splitter**: transmitted beam is 99.9% parallel polarization; reflected beam is 97% perpendicular + 3% parallel
- **TTMs and TMs** can be moved for off-axis imaging (3.6” of 8” FoV on the detectors)



(Schmid et al. 2018: red are for polarimetry only; blue are exchangeable)

ZIMPOL Operation

- Polarimetric modulation at 1kHz which “freezes” the speckle variations of atmospheric turbulence
- Uses 4kx2k with 15 µm pixels CCDs in frame transfer mode (so they are 2kx2k of imaging area)
- Pixels are binned 2x2 (exposed area works as a 1k by 1k CCD with 30 µm pixels)
- Stripe mask covers 512 rows with width 40 µm and open area of 20 µm
- Cylindrical micro-lenses of 60 µm focus the light through the gaps onto the CCD
- In one cycle, the signal of a given polarization accumulates
- Then that signal moves below the masks and the signal of the second polarization accumulates
- Then it shifts back, hides the second polarization, and add the first to what was accumulated before

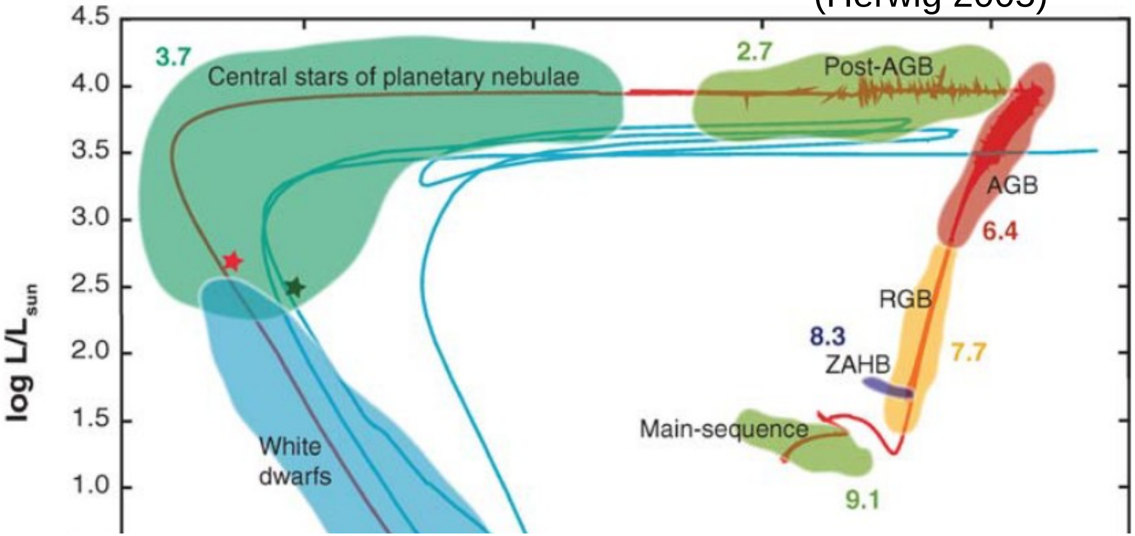


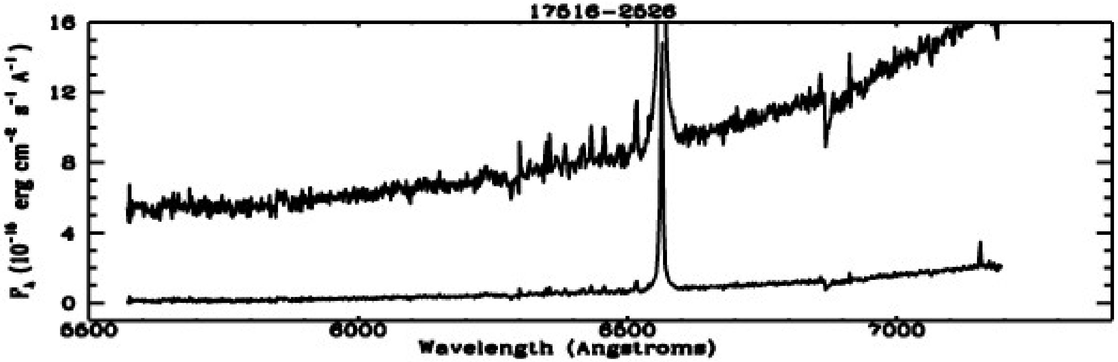
(Schmid et al. 2018)

Our science case?

- FORS2:
  - seeing limited, imaging and spectrograph polarimeter;
  - absolute polarization measured to 0.1%
- ZIMPOL:
  - diffraction limited, imaging polarimeter with very small FoV.
  - Absolute accuracy to 0.5%;
  - differential polarimetric imaging to reveal faint structure
  - Seeing < 0.8” for R = 10mag; <0.6” for R fainter

(Herwig 2005)

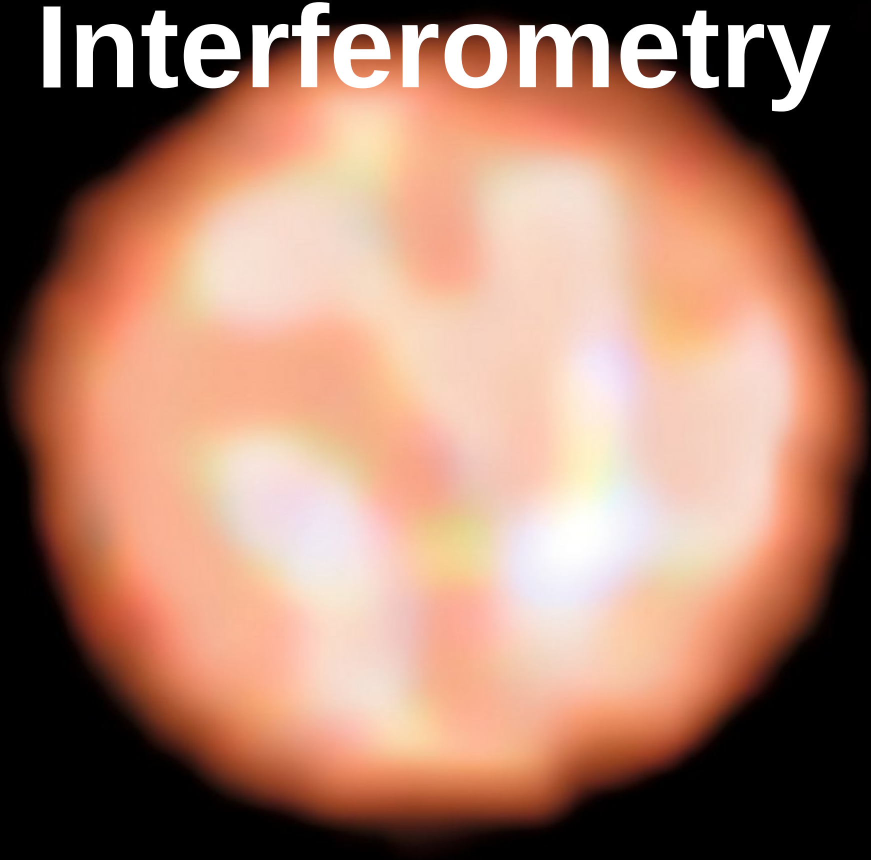




(Suarez et al. 2006)

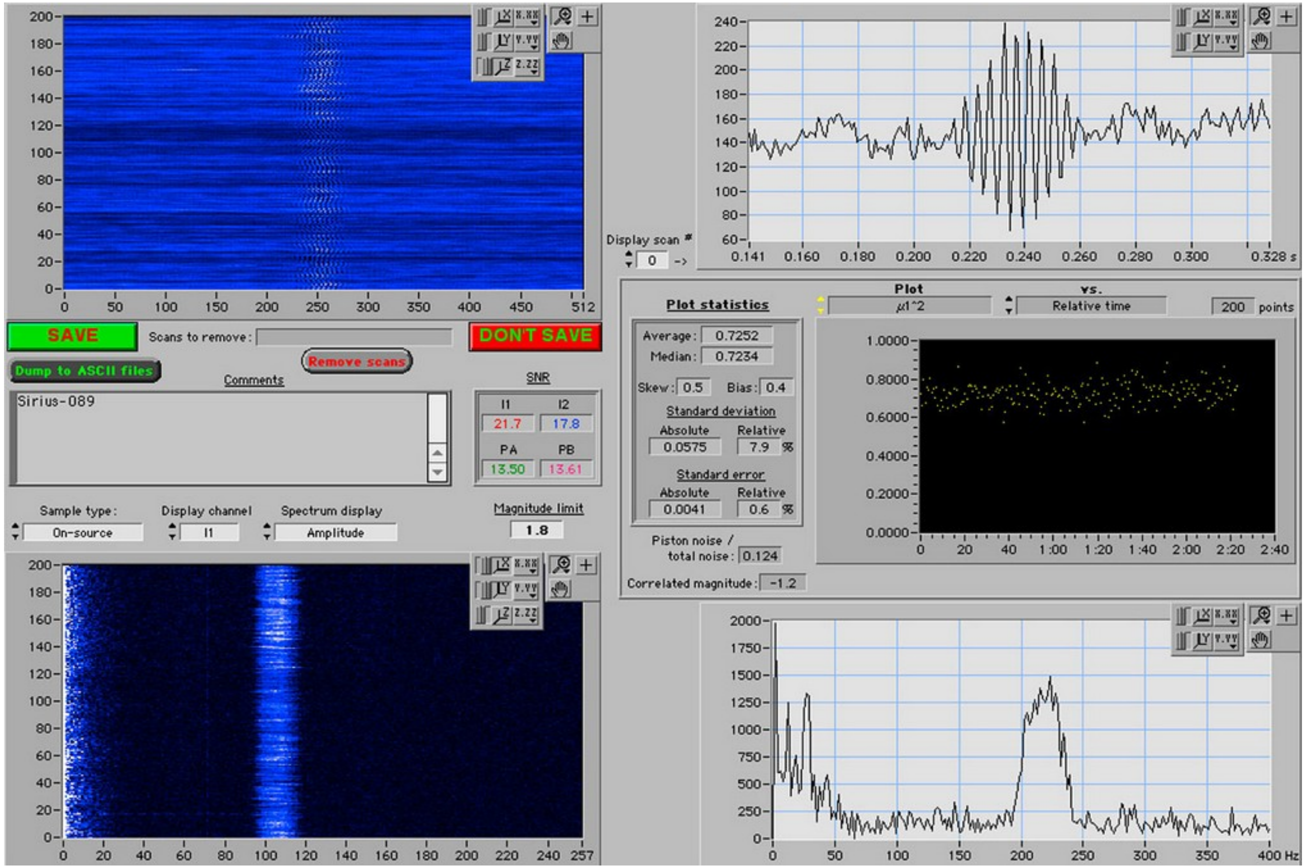
Optical Interferometry

(Day 10)



(Red giant π^1 Gruis with PIONIER@VLTI;
Credit: ESO)

Today



Scans to remove:

Comments

Sirius-089

SNR

I1	I2
21.7	17.8
PA	**PB**
13.50	13.61

Sample type: On-source

Display channel: I1

Spectrum display: Amplitude

Magnitude limit: 1.8

Display scan #: 0 ->

Plot: µ1^2 vs. Relative time 200 points

Plot statistics

Average: 0.7252

Median: 0.7234

Skew: 0.5 Bias: 0.4

Standard deviation

Absolute	Relative
0.0575	7.9 %

Standard error

Absolute	Relative
0.0041	0.6 %

Piston noise / total noise: 0.124

Correlated magnitude: -1.2

(First VLTI fringes; Credit: ESO)

1. Optical interferometry
2. VLTI

What is interferometry?

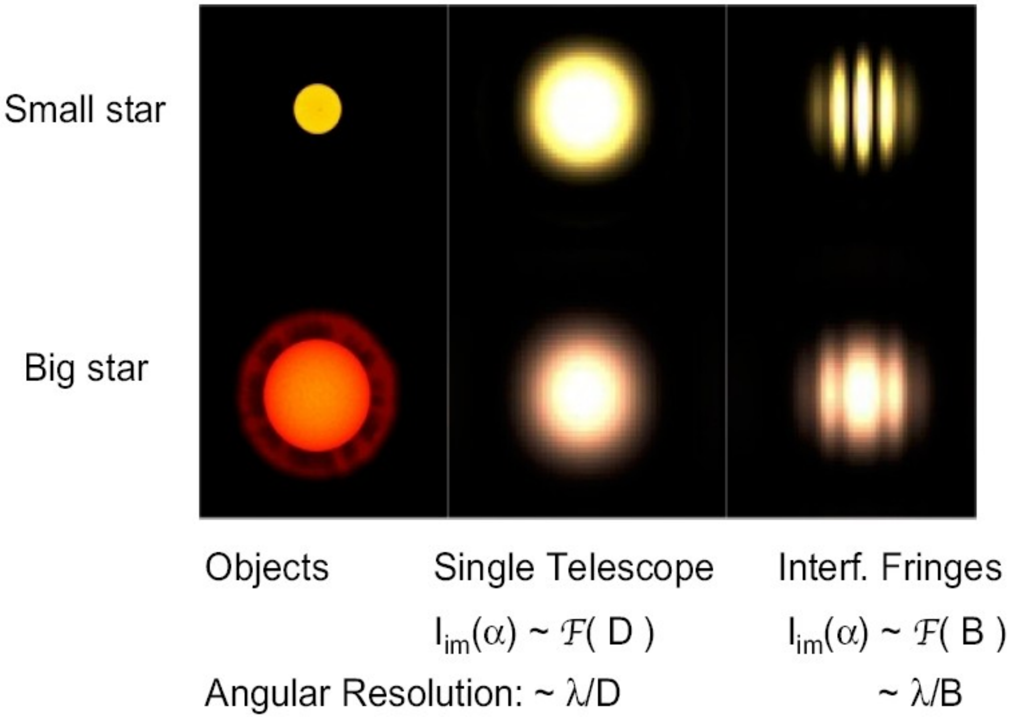
- Measure angular sizes with high resolution using an array of telescopes (or dishes)
- Measuring angular size ≠ imaging the source
- A single diffraction limited telescope of aperture D:

$$\Delta\theta \propto \lambda/D$$

- A combination of telescopes separated by a baseline B:

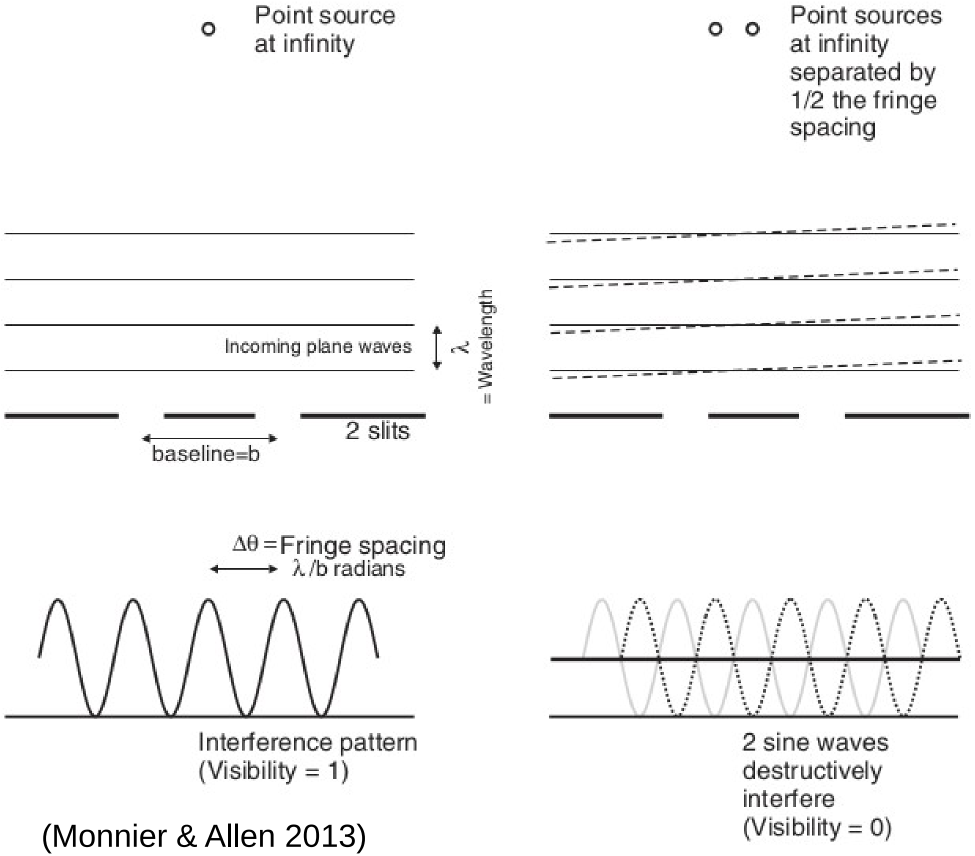
$$\Delta\theta \propto \lambda/B$$

- Optical here: near UV to mid-IR (incoherent detection with photo-counting detectors)
- The phase is not detected, interference happens before detection

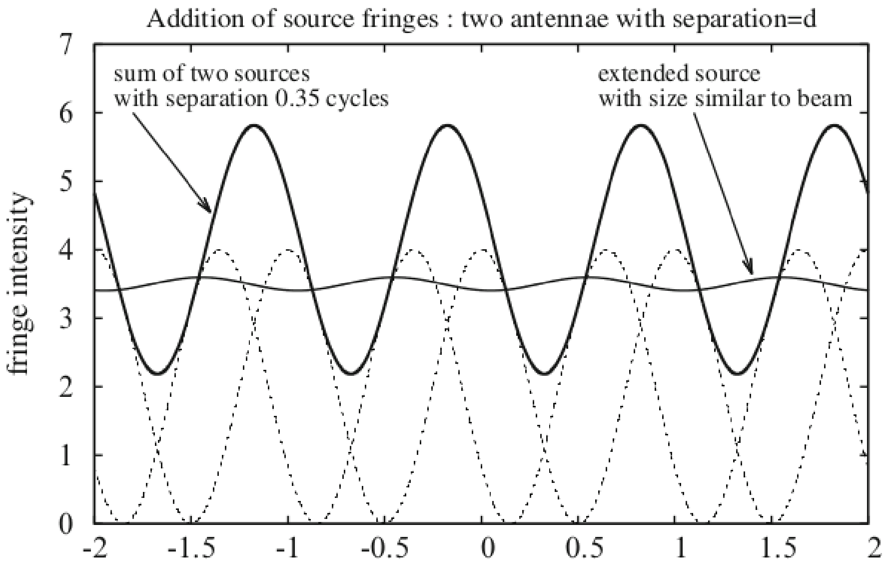


(Credit: University of Jena)

Interference



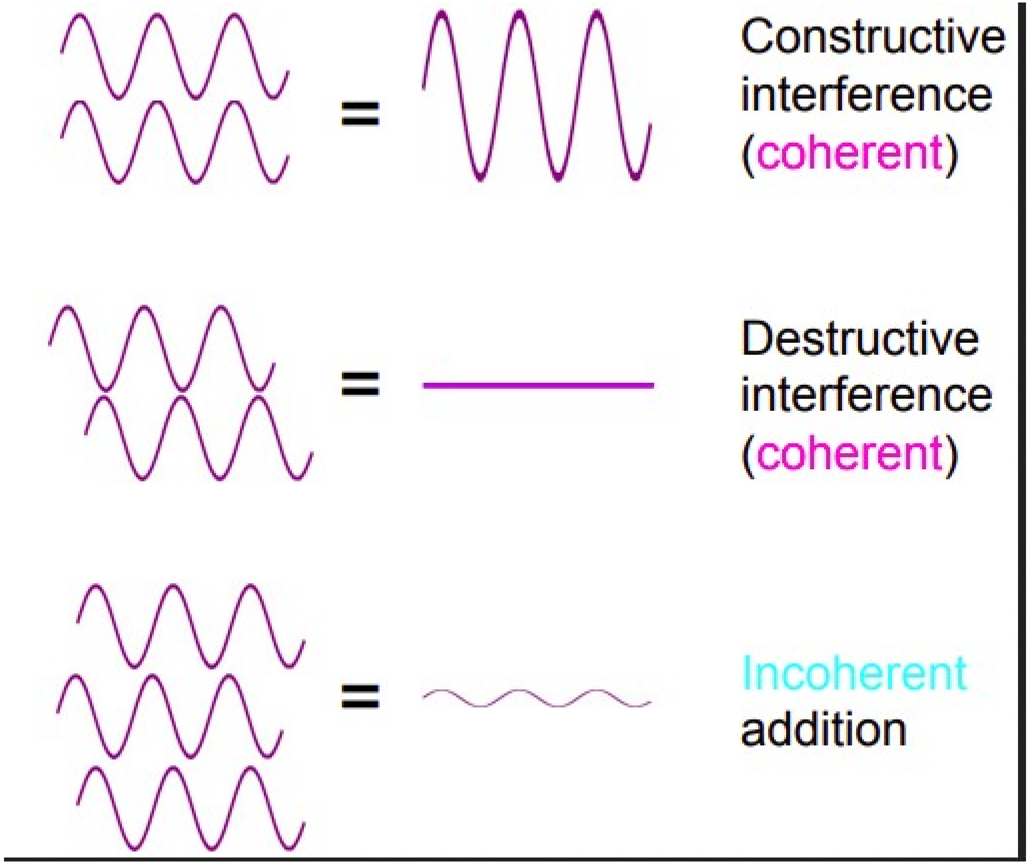
(Monnier & Allen 2013)



(Lawrence 2014)

Coherence

- The combined fringe pattern has information about the spatial structure of the source
- To a scale that is much smaller than possible to be studied with images
- Waves should be coherent over a certain time, so that the fringe pattern is stable
- However, light from astronomical sources is incoherent (not masers and pulsars)
    - The different spatial regions of a source are independent and the processes of photon emission have very short timescales.



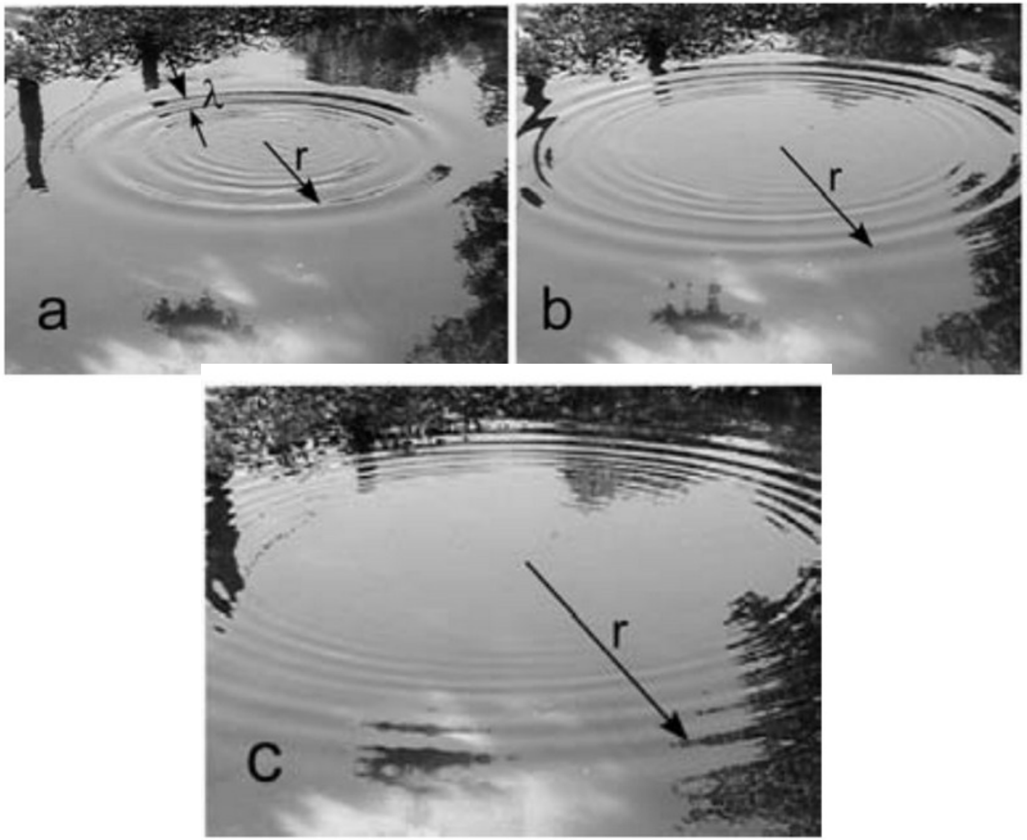
(Credit: C. Lai, MSU)

Van Cittert-Zernike theorem

- If the distance is large enough, wavefronts will spread-out, overlap, and merge
- Acquire a degree of spatial coherence over a certain time frame (coherence timescale)
- The Fourier transform of the intensity distribution becomes equal to its complex visibility

$$\tilde{\mathcal{V}} = |\mathcal{V}|e^{i\phi\mathcal{V}} = \int_{\text{sky}} A_N(\vec{\sigma})I(\vec{\sigma})e^{-\frac{2\pi i}{\lambda}\vec{B}\cdot\vec{\sigma}}d\Omega$$

- Atmospheric turbulence adds phase delays and incoherence
- Coherence timescale of the order of milliseconds



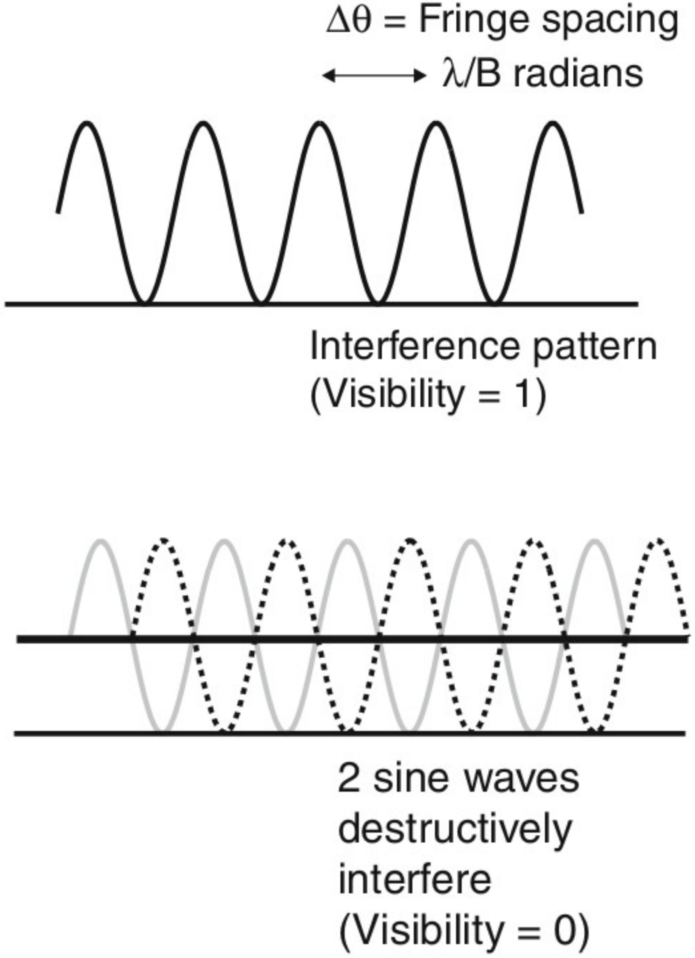
(Labeyrie 2014)

Visibility

- The complex visibility has two arguments:
- Fringe visibility or fringe contrast (peak-to-valley):

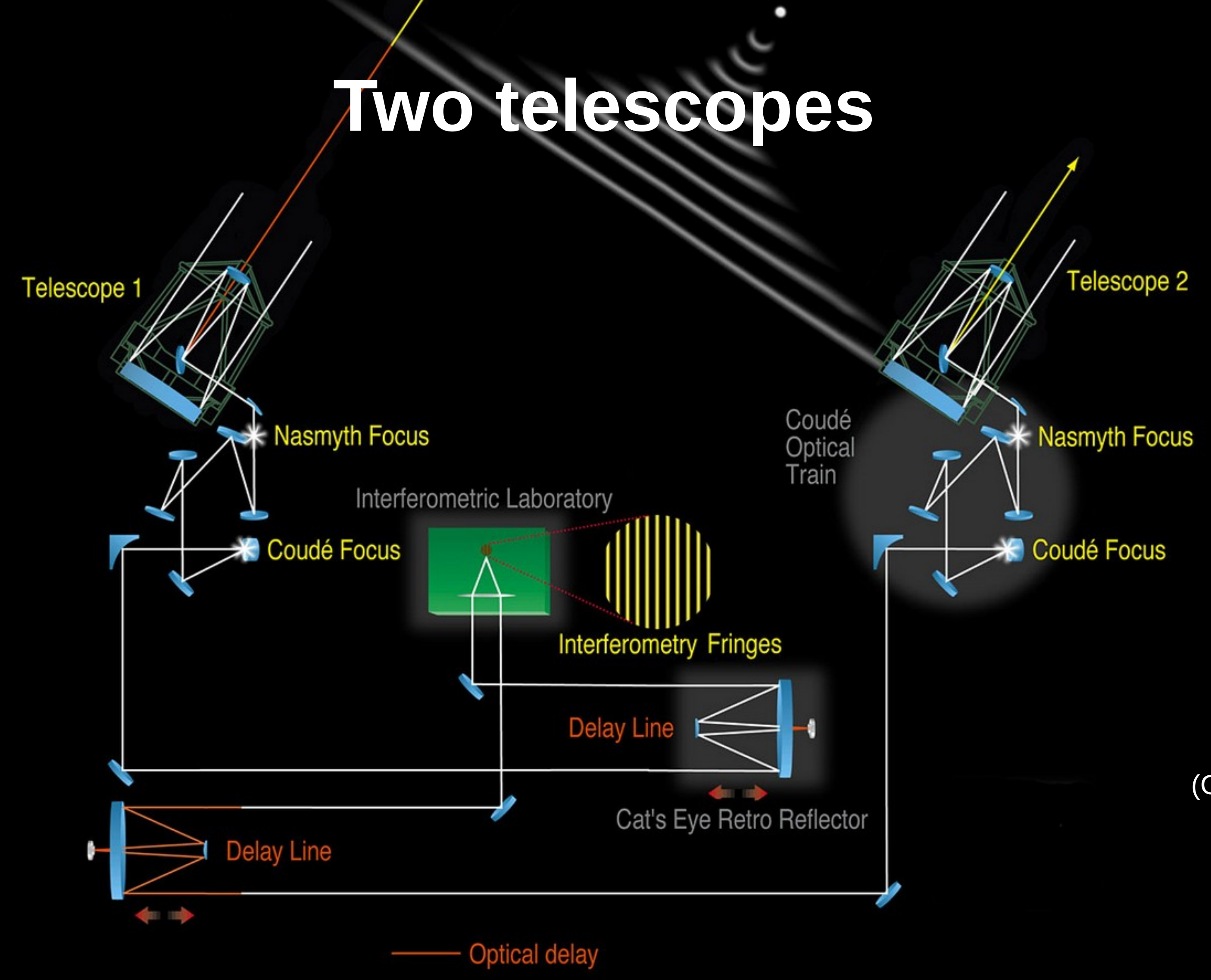
$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \, ,$$

- Fringe phase (Φ_V)
- The visibility is straightforward from the recorded data
- The fringe phase is a problem…
    - Continually changing in random way because of the atmosphere



(Monnier & Allen 2013)

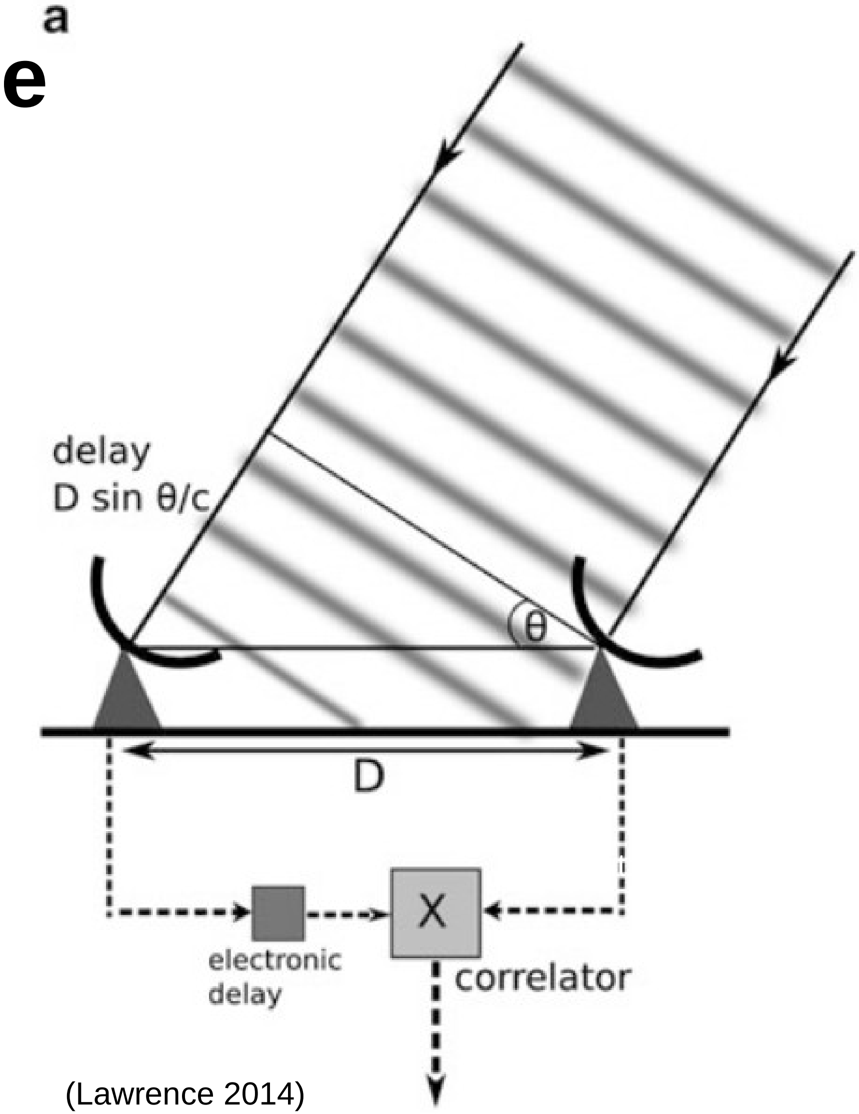
Two telescopes



(Credit: ESO)

Delay line

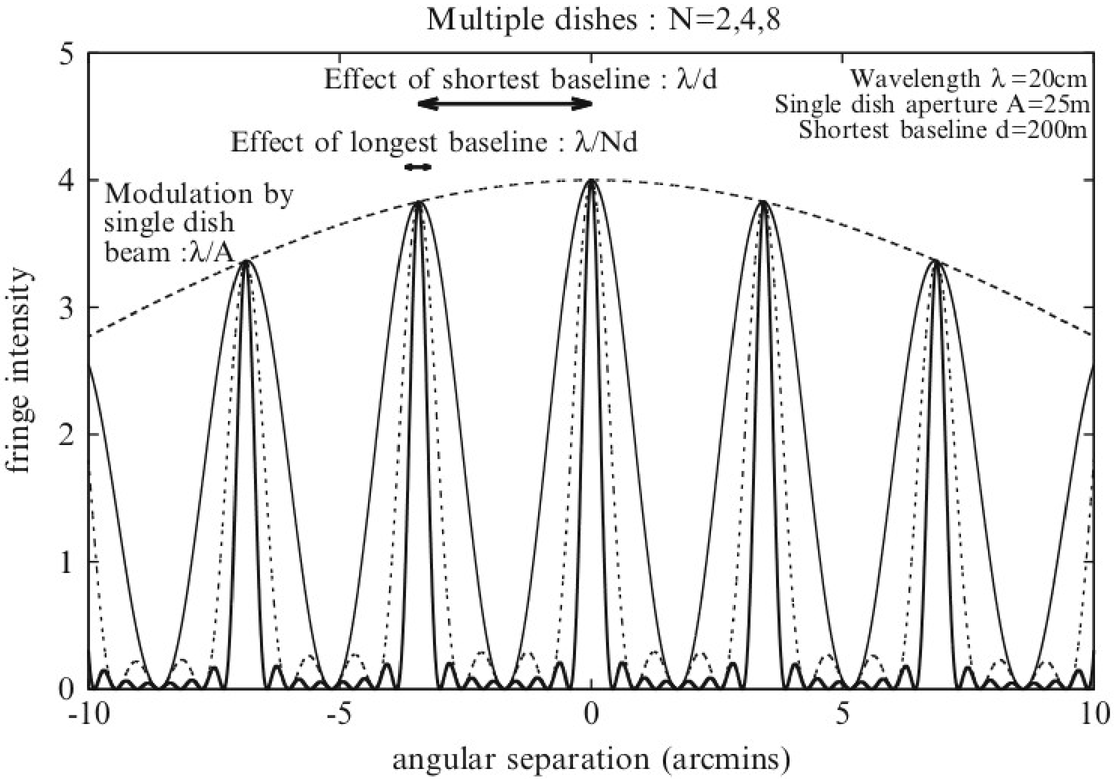
- At a given moment each telescope is actually measuring a different wavefront
- If the signal was completely coherent, this would not matter
- To recover the coherence, the beam combiner has to introduce a phase delay
- Easily 10-20 reflections needed for that, causing some loss of light
- The atmosphere is constantly changing so the delay has also to change
- Adaptive optics is very useful to increase the coherence time



(Lawrence 2014)

Arrays of telescopes

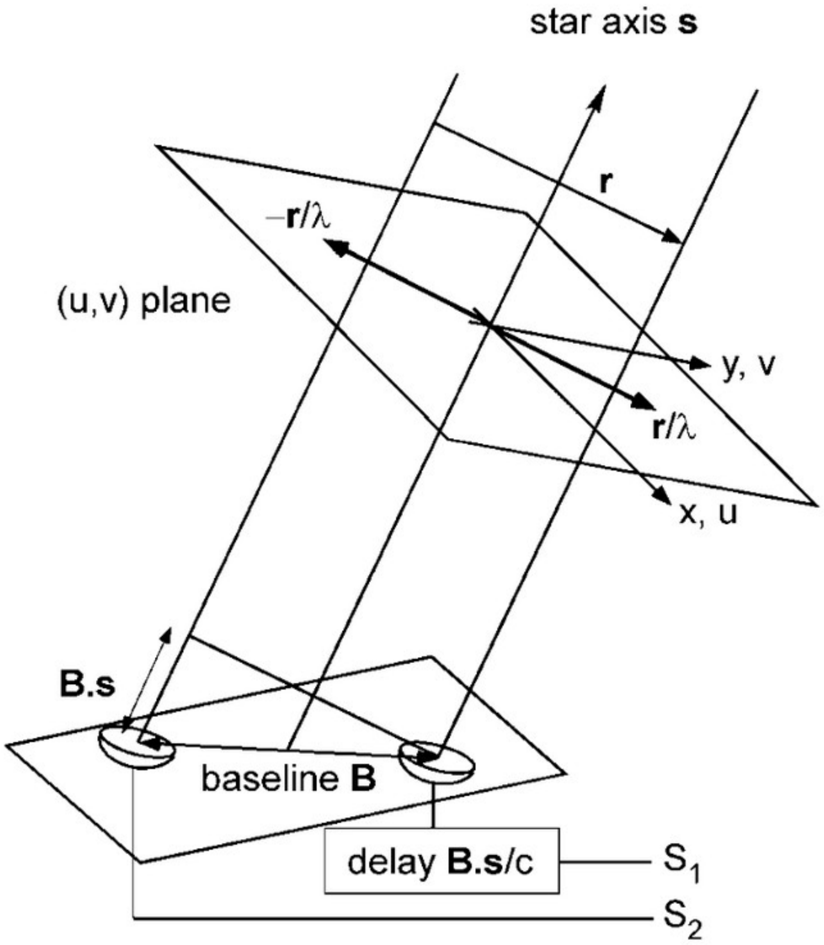
- Fringe pattern is relatively simple for the case of two monochromatic sources
- In real life: multiple sources, with various strengths, a background, and/or an extended source, with size comparable to or bigger than the fringe separation
- **A single fringe pattern is not enough!**
- More telescopes to create an interferometric array
- The more telescopes, the narrower the fringe peaks



(Lawrence 2014)

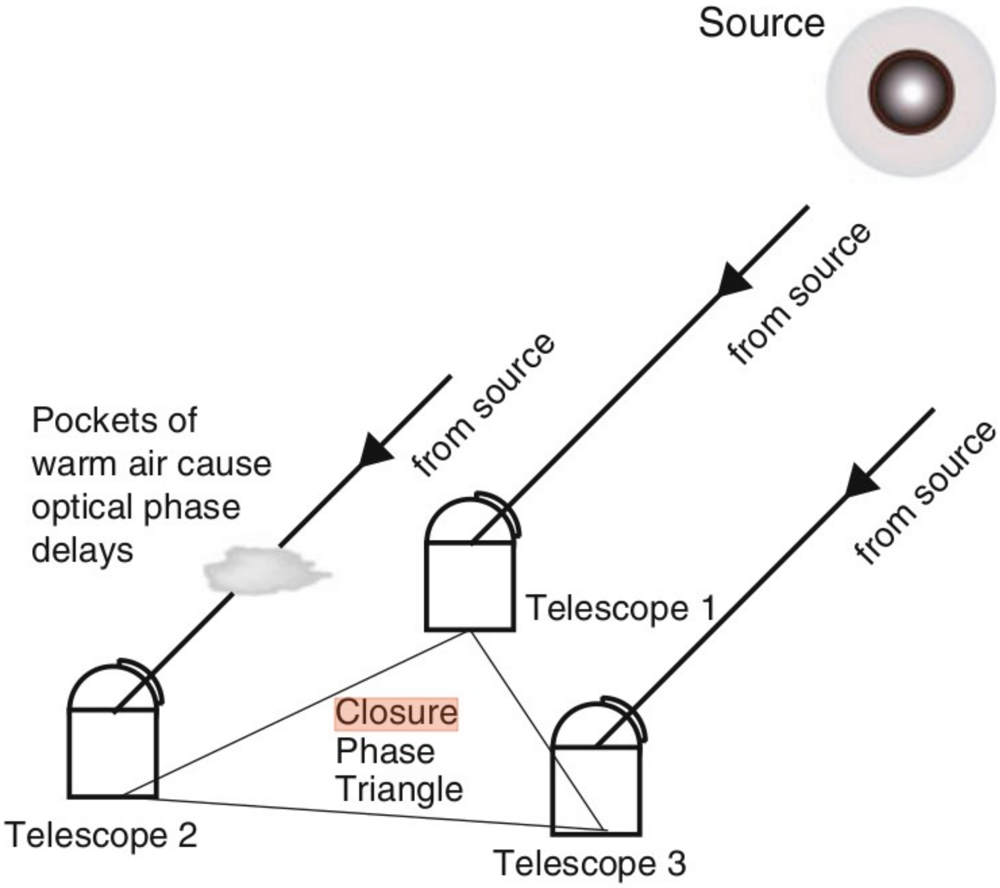
The (*u,v*) plane

- To recover the 2D spatial distribution of brightness of a source, one line (or configuration) is not enough
- Multiple baselines that can observe at different projected angles at the sky
- The (*u,v*) plane: baseline vector (x, y) projected on the sky, normalized by the wavelength
- Earth rotation naturally changes the projection of the grid of telescopes
- Or arrays of telescopes/dishes that can move around
- Aperture synthesis: method to mix the signals and invert the measurements



Phase information

- Some science can be done with visibilities only
  - Symmetric objects (circular or elliptical star)
  - Well behaved intensity distribution (uniform or limb darkened)
- Recovering the phase information:
  - Phase referencing: bright calibrator to stabilize the fringes
  - Fringe tracking: separates the light in two channels
  - Closure phase: makes use of three baselines. The phase delay in one cancels when the three are combined



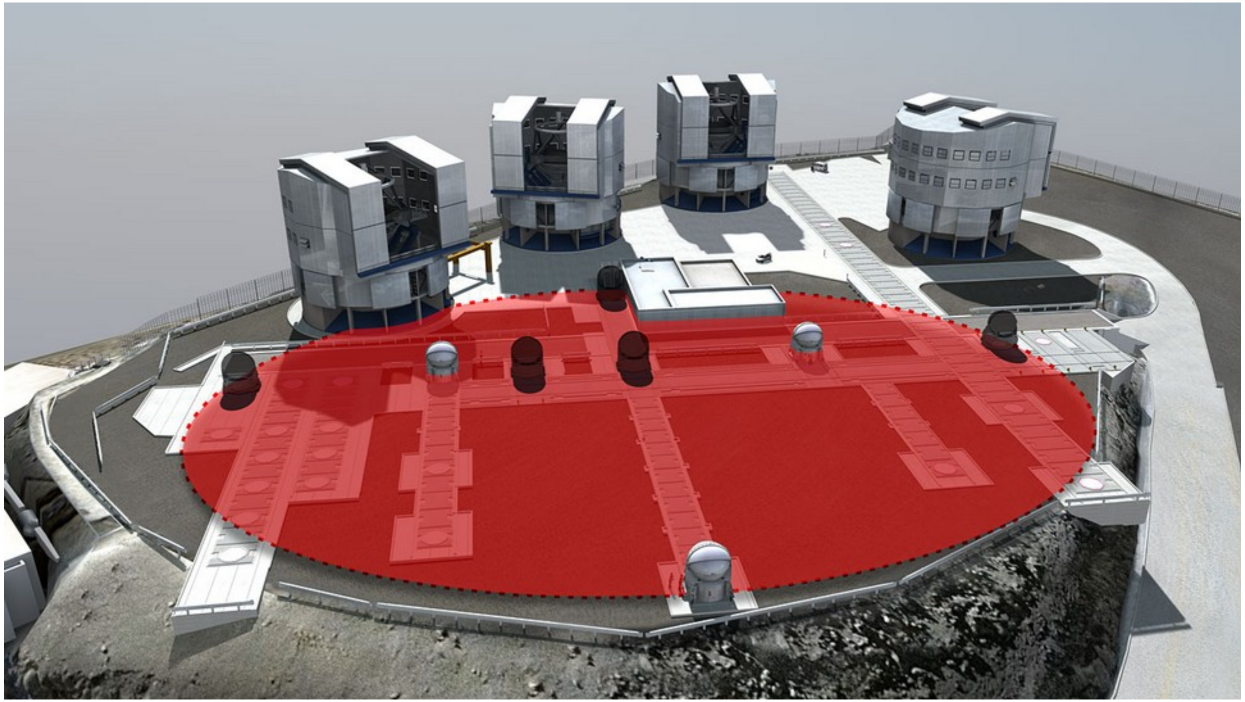
(Monnier & Allen 2013)

Questions?

(Credit: Shutterstock)

The VLTI

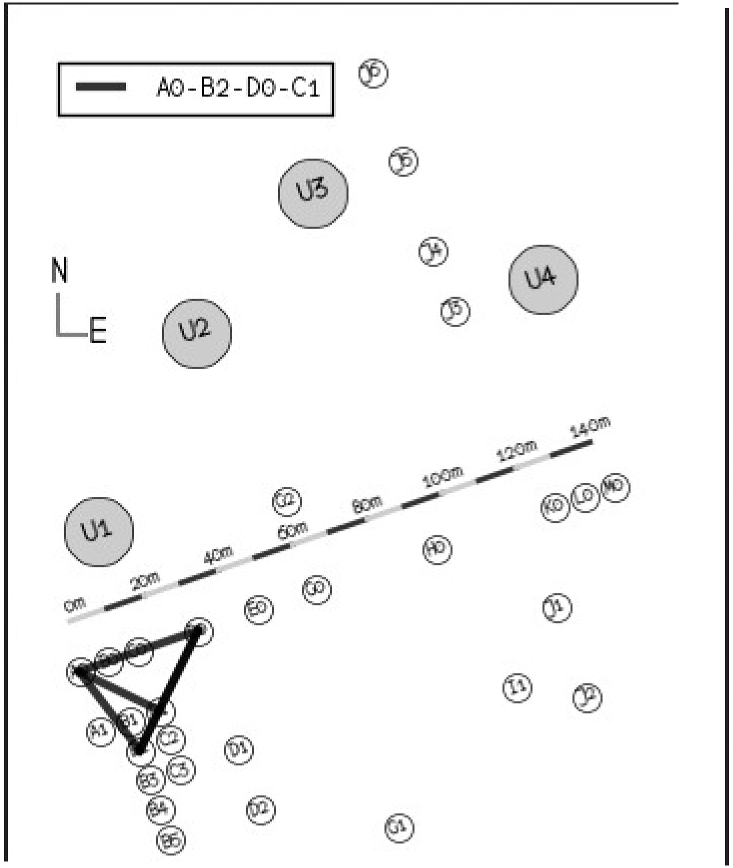
- Might use the 4 UTs or the 4 ATs
- ATs: 1.8m telescopes used for VLTI only
- Platform with 30 positions, multiple baselines possible
- Max UT baseline is 130m
- Max AT baseline is 202m
- Each UT and AT has an adaptive optics system for use with the VLTI
- Underground lab with mirrors, delay lines, stabilization devices



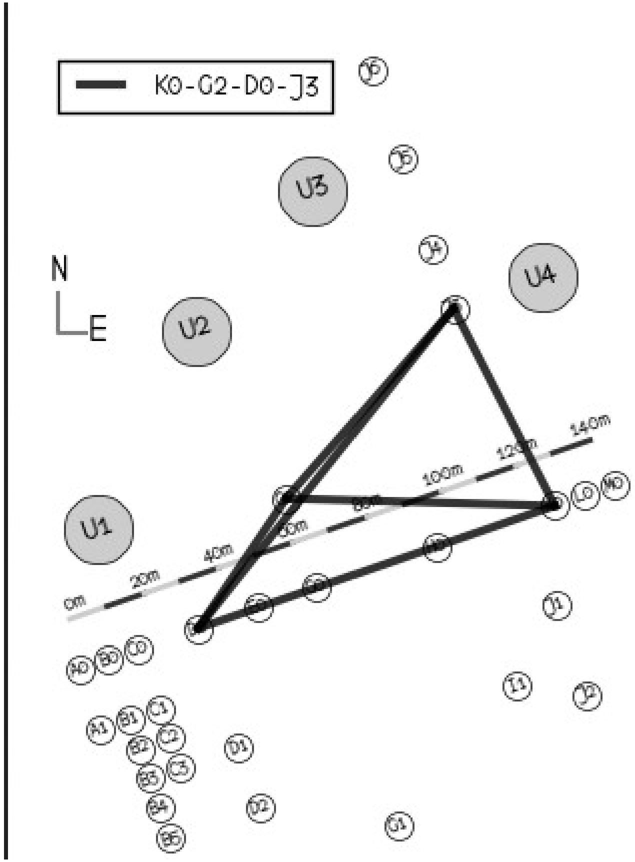
(Credit: ESO)

Baselines (4 telescopes)

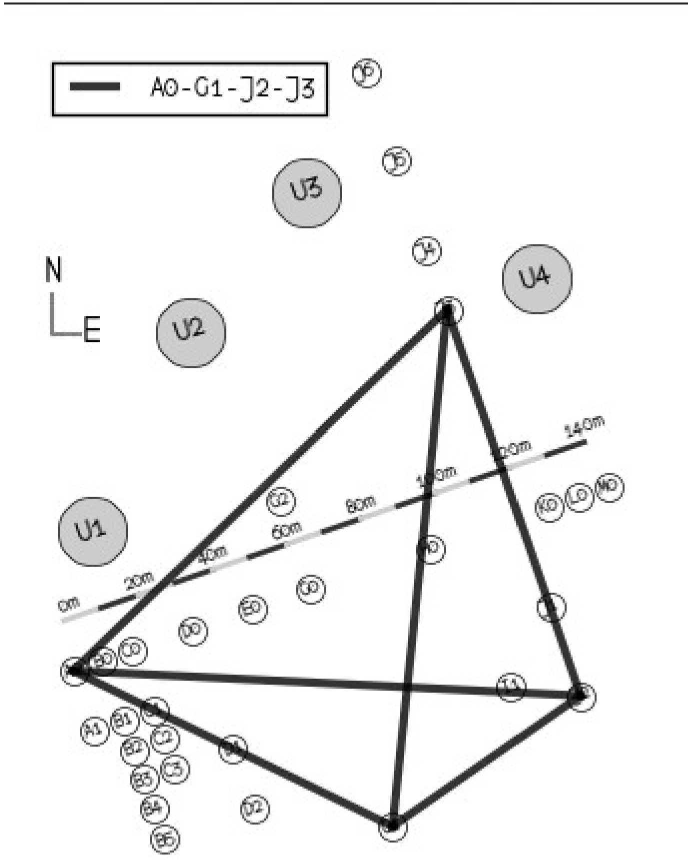
(Credit: ESO)



(Small)



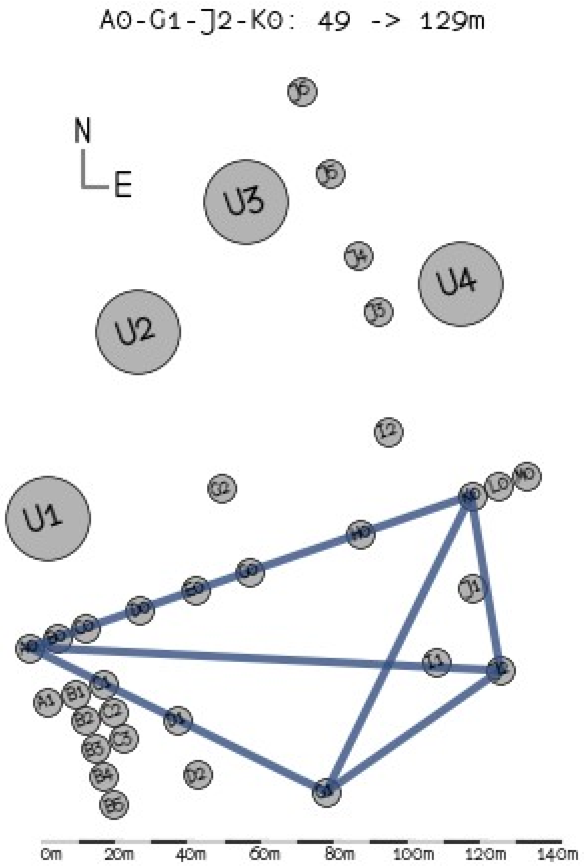
(Medium)



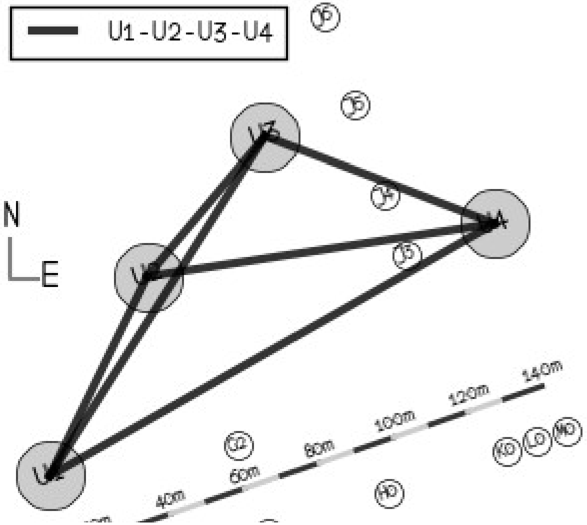
(Large)

Baselines (4 telescopes)

(Credit: ESO)



(Astrometric)



AT Configurations	PIONIER, MATISSE (from P103),GRAVITY single-feed	GRAVITY dual-feed
Small	yes	yes
Medium	yes	no
Large	yes	no
Astrometric	no	yes

VLTI Expertise Centres

https://european-interferometry.eu/centres-network/

- Several across Europe
- Organise observing preparation and data reduction schools
- Assistance to prepare their VLTI proposals
- Support for data reduction and interpretation

The present network of VLTI Expertise Centres includes three partners from the OPTICON Horizon 2020 networking activity:

- Jean-Marie Mariotti Centre (JMMC) - Service aux Utilisateurs du VLTI, (SUV) France - a structure that aggregates manpower from different observatories:
  - Observatoire des Sciences de l´Univers de Grenoble (OSUG)
  - Observatoire des Sciences de l´Univers de Lyon (OSUL)
  - Observatoire de Paris-Meudon (OPM)
  - Observatoire de la Côte d'Azur (OCA)
- Portuguese VLTI Expertise Centre, Portugal
- University of Exeter, United Kingdom

two interferometry JRA (Joint Research Activities; WP8) lead partners:

- Lagrange Laboratory/OCA, France
- KU Leuven, Belgium

and two new nodes from the OPTICON/RadioNet Pilot (ORP) program:

- Leiden Observatory, The Netherlands
- Konkoly Observatory, Hungary

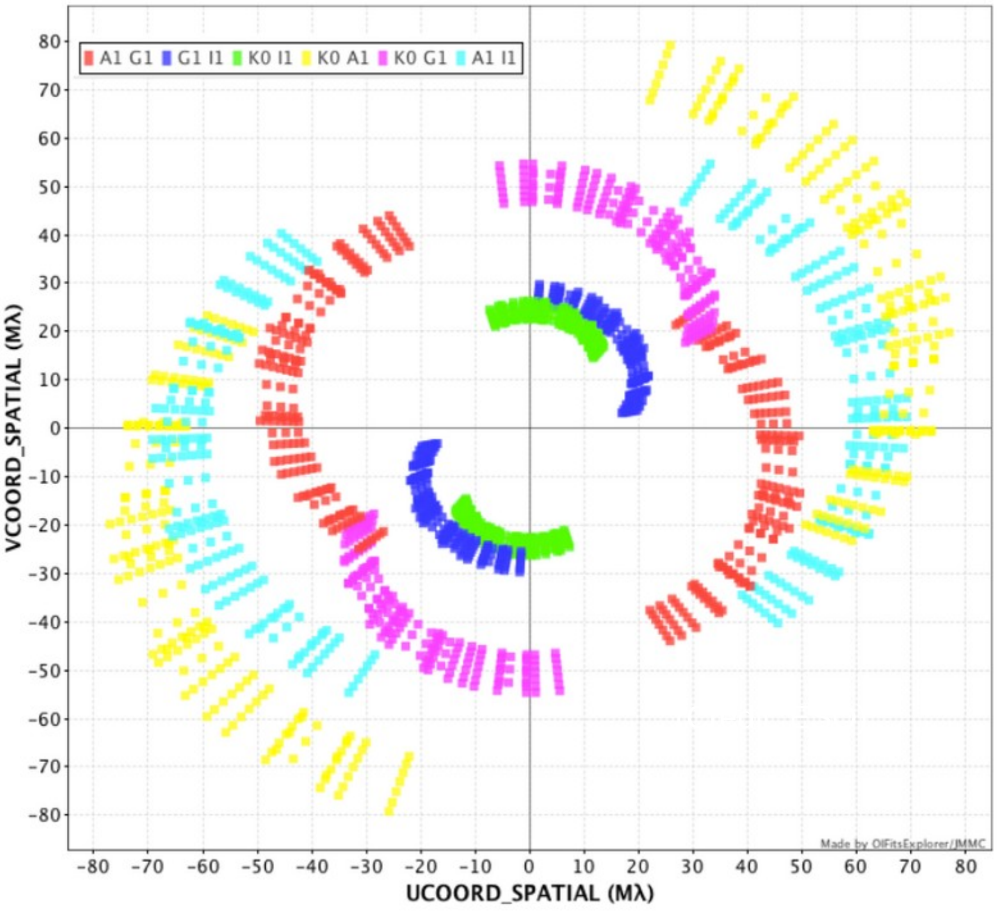
Observations

- The observed visibility is always lower than the theoretical expectation
    - Calibrator with known visibility needed, to define the transfer function
- Moon not a big problem (IR observations in a very small field of view)
    - But too close will affect the AO correction
- Three instruments:

1) MATISSE (spectroimaging: L, N, M bands)

2) Gravity (imaging K-band, astrometry by phase referencing)

3) PIONIER (imaging H-band, 6 baselines and 4 closure phases)



(Domiciano de Souza et al. 2014)

MATISSE

- Multi AperTure mid-Infrared SpectroScopic Experiment (Lopez et al. 2014)
- Study of the inner regions of protoplanetary disks, planet formation, dusty tori around AGNs
- L (3.2-3.9 µm), M (4.5-5.0 µm), and N (8.0-13.0 µm) bands
- Grisms for R ~ 35 to 950
- Has no fringe tracking capabilities (adding different exposures only if fringes can be centered)
- Gravity can be used as an external fringe tracker
- Resolution down to 3.5 or 8mas in the L-or N-band (ATs); 5-12.5mas with the UTs.

(Credit: ESO)

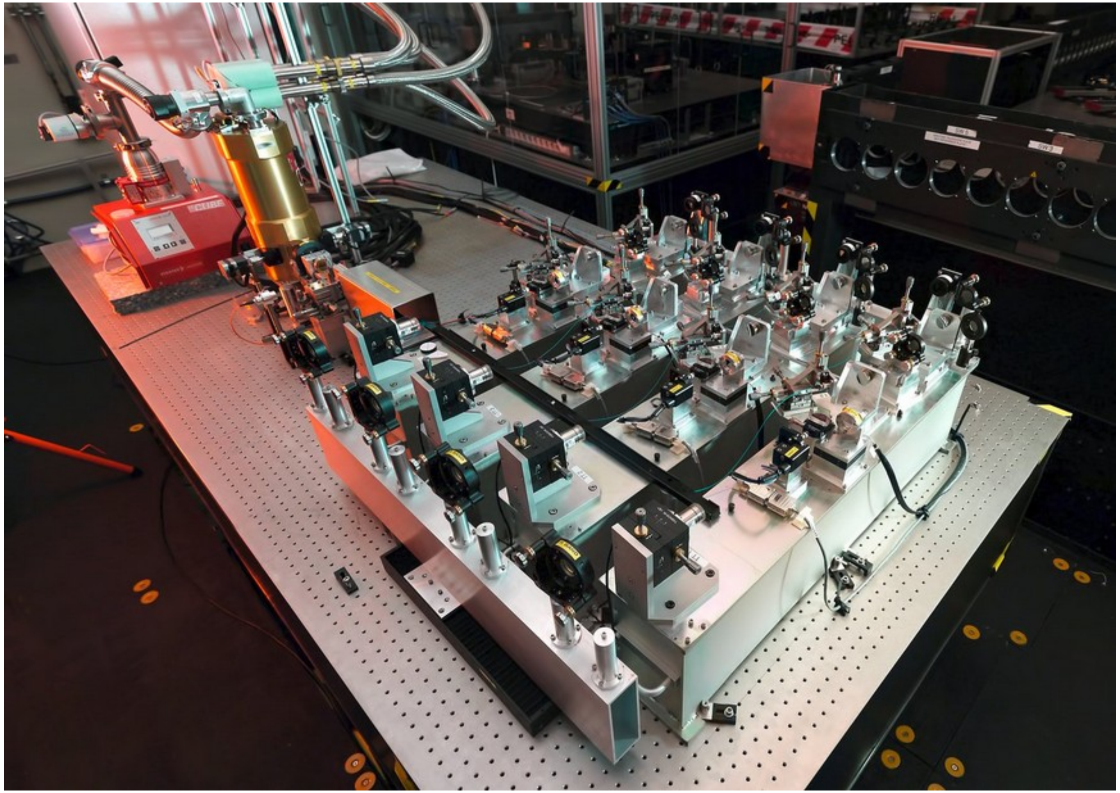
Gravity

- Gravity (Gravity collaboration 2017)
- Study of the black-hole in the Galactic centre, broad-line region of AGNs, circumstellar disks, jets, exoplanets
- K band (2.0-2.4 μm)
- Single-field mode (one source) or dual-field mode (two sources)
- Phase referenced observations in dual-field mode
- Spatial resolution 4-50 mas with UTs, 2-140 with the ATs
- Astrometric accuracy between 10-100 μas.

(Credit: ESO)

PIONIER

- Precision Integrated-Optics Near-infrared Imaging ExpeRiment (Le Bouquin et al. 2011)
- Visitor instrument turned into a facility instrument
- Study of young stellar objects, debris disks, binaries, hot Jupiters
- H-band (~1.65 μm)
- Low-resolution spectroscopic capabilities (R ~ 40) measuring six visibilities and three independent closure phases



(Credit: ESO)

Questions?

(Credit: Shutterstock)