Telescope Bernard Lyot/Narval
The Observatory of Stellar Magnetism

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Telescope Bernard Lyot (TBL)

2-m Telescope at Pic du Midi
(CFHT 30 yr-old design.)

Cassegrain focus f/25

Dome was originally designed to
be coupled with the telescope tube.

TBL was used as a prime national facility
until 1990's.

Pic du Midi has built an expertise in polarimetry
over the years: Leroy, Semel, Catala, Donati

Sterenn, Musicos, LJR

TBL is now specialized in spectro-polarimetry

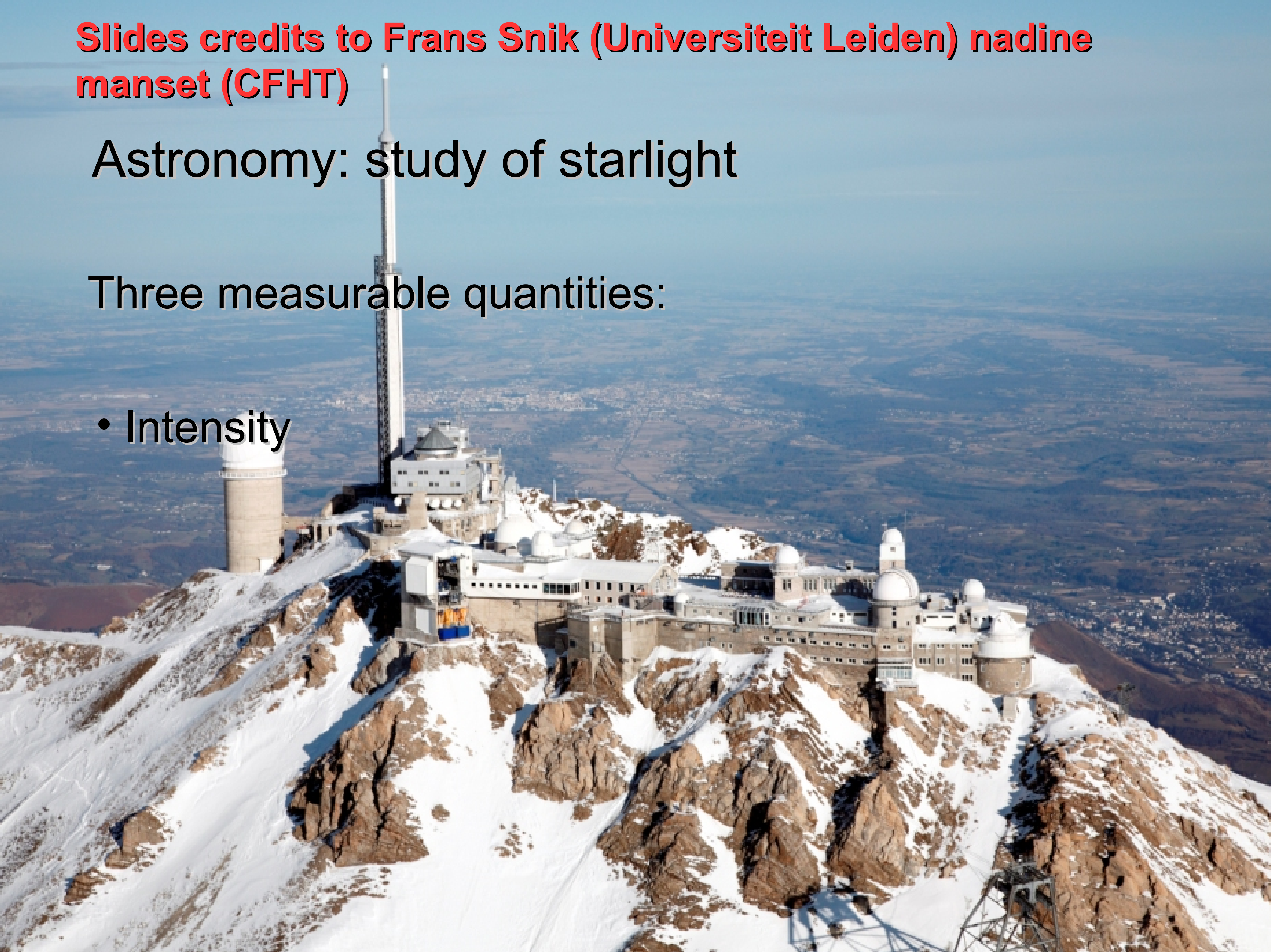
With **Narval**

Slides credits to Frans Snik (Universiteit Leiden) nadine manset (CFHT)

Astronomy: study of starlight

Three measurable quantities:

- Intensity



Astronomy: study of starlight

Three measurable quantities:

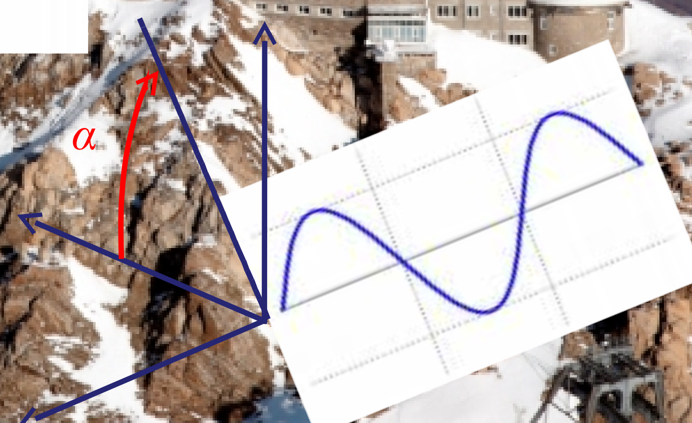
- Intensity
- Wavelength:

Astronomy: study of starlight

Three measurable quantities:

- Intensity
- Wavelength:

- Polarization:

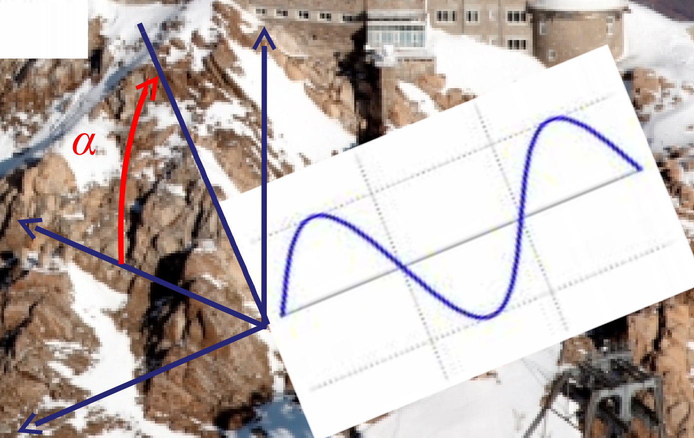


Astronomy: study of starlight

Three measurable quantities:

- Intensity
- Wavelength:

- Polarization:

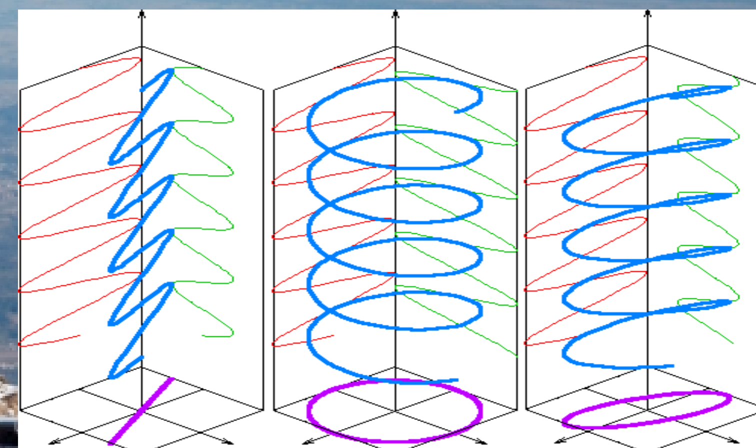


… as a function of [x,y] and/or t

Polarimetry fundamentals

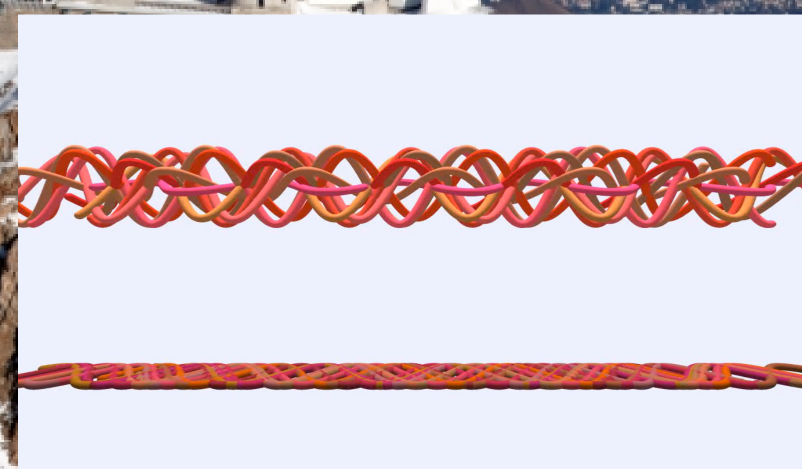
- E vector parametrization

$$E_x = a_1 \cos(2\pi\nu t - \mathbf{k}\cdot\mathbf{r} + \varphi_1), E_y = a_2 \cos(2\pi\nu t - \mathbf{k}\cdot\mathbf{r} + \varphi_2) \text{ avec } \varphi = \varphi_2 - \varphi_1$$



- Polarization of an EM wave is a natural consequence of Maxwell's equations

- "General" light: Not monochromatic Superposition of polarization of many photons



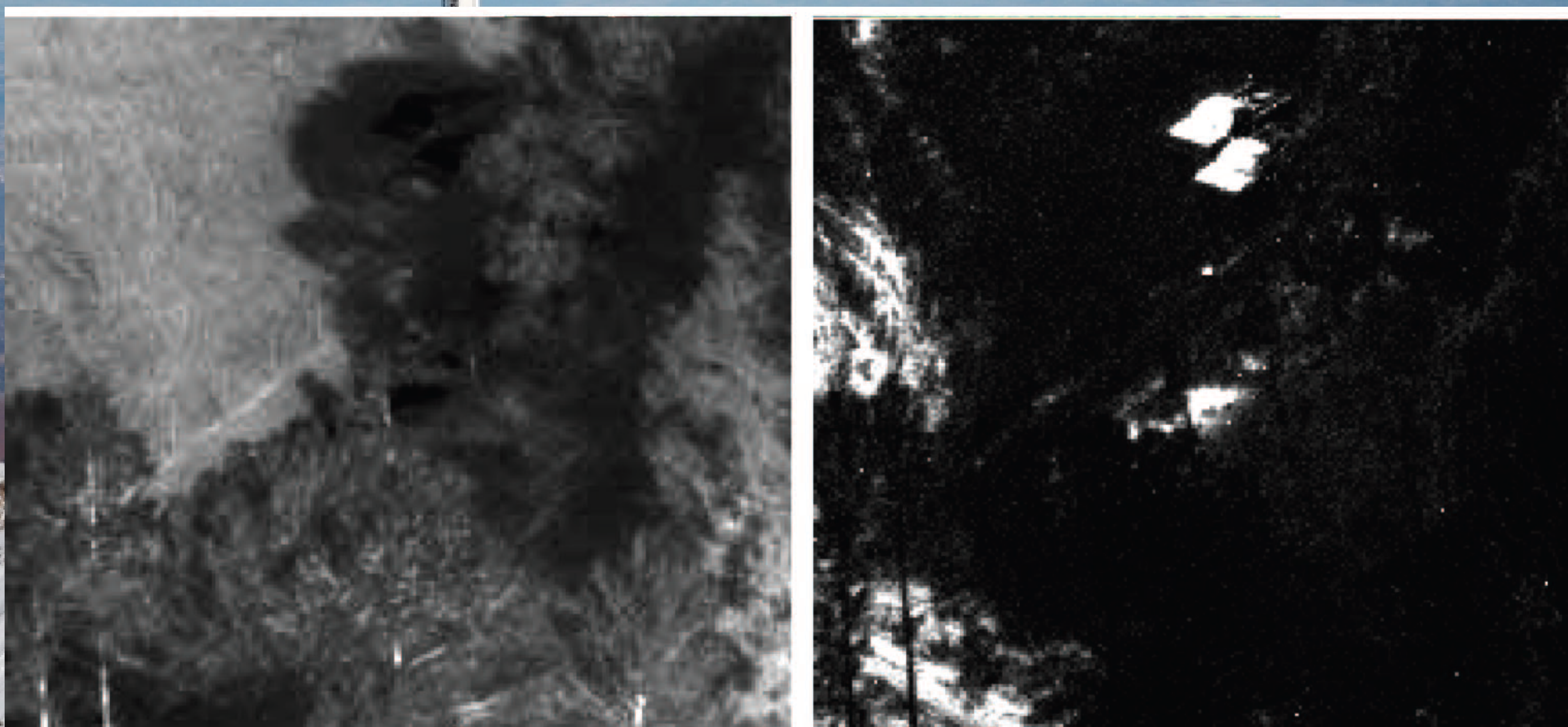
- Unpolarized light: No preferred orientation of polarization

Polarization creation

- Polarization is created (and/or modified) wherever perfect spherical symmetry is broken:
  - Reflection/scattering
  - Magnetic/electric fields
  - Anisotropic materials

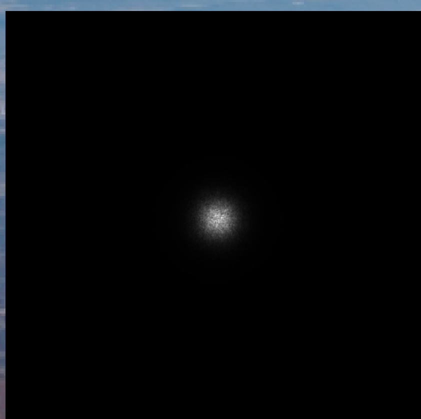
¡ Polarimetry provides information on the symmetry-breaking process/event.

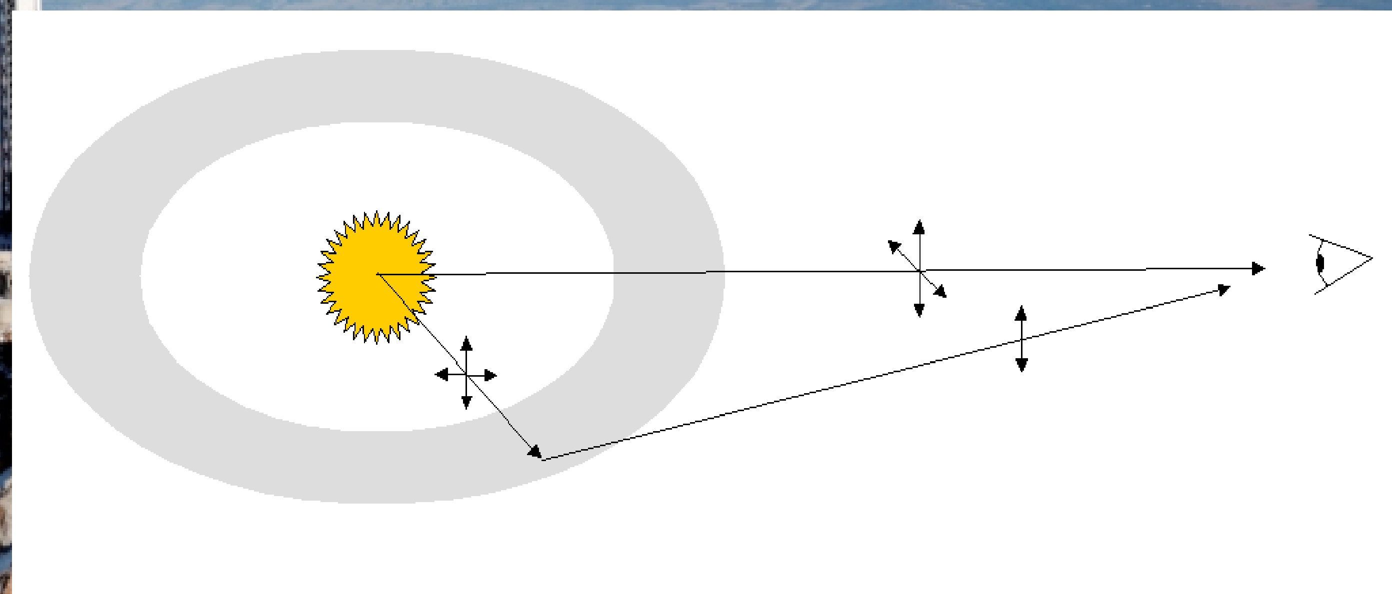
Examples - Military



Examples - Astronomy

Scattering polarization:





Examples: degree of polarization

Optics

• LCD screen	100%
• 45^{o} reflection off glass	~90%
• clear blue sky	~75%
• 45^{o} reflection off mirror	~5%

Astrophysical objects

• solar/stellar magnetic fields	~1%
• exoplanet in stellar halo	$\sim 10^{-5}$-10^{-6}
• cosmic microwave background	$\sim 10^{-6}$-10^{-7}

Polarimetry Measurement principles

The basics

- Polarimetry in the optical regime is the measurement of (part of) the Stokes vector.
- Essentially differential photometry: polarization is always calculated from the ratio of a difference of 2 quantities to sum of those 2 quantities.
- Susceptible to all kinds of differential effects!

Polarimetry Measurement principles

Stokes vector

$$\vec{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

Q = ↕ - ↔

U = ⤡ - ⤢

V = ↺ - ↻

I = ↕ + ↔

= ⤡ + ⤢

= ↺ + ↻

↕ : ½(I+Q)

↔ : ½(I-Q)

⤡ : ½(I+U)

⤢ : ½(I-U)

↺ : ½(I+V)

↻ : ½(I-V)

Q/I, U/I, V/I = normalized/fractional polarization

$(Q^2+U^2+V^2)^{1/2}/I$ = polarization degree

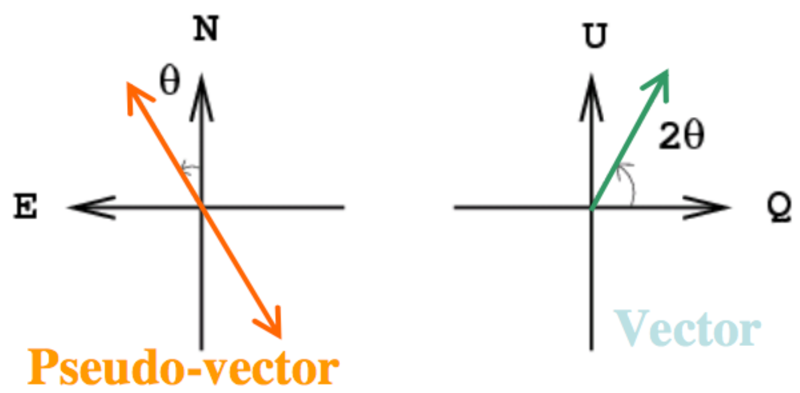
Polarimetry Measurement principles

(Q,U) to plane of the sky

In the case of linear polarization (V=0):

$$P = \frac{\sqrt{Q^2 + U^2}}{I} \qquad \theta = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$$

$$Q = P\cos 2\theta \qquad U = P\sin 2\theta$$



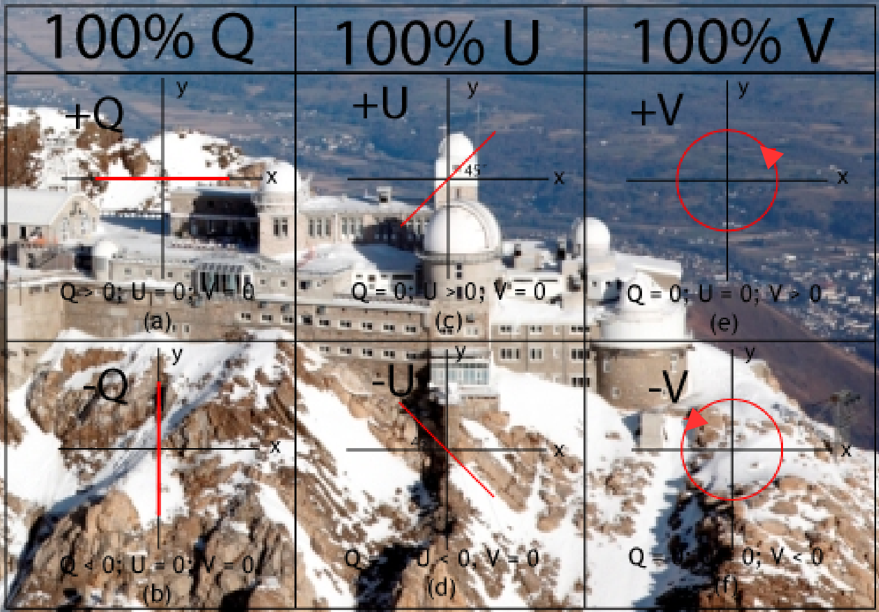
N-S	**is +Q**
45°	**is +U**
E-W	**is –Q**
135°	**is –U**

Polarimetry Measurement principles

$$E_x = a_1 \cos(2\pi\nu t - \mathbf{k}\cdot\mathbf{r} + \varphi_1), E_y = a_2 \cos(2\pi\nu t - \mathbf{k}\cdot\mathbf{r} + \varphi_2) \text{ avec } \varphi = \varphi_2 - \varphi_1$$

$$\begin{aligned}
I &= a_1^2 + a_2^2 \\
Q &= a_1^2 - a_2^2 = I\cos(2\chi)\cos(2\psi) \\
U &= 2a_1 a_2 \cos(\varphi) = I\cos(2\chi)\sin(2\psi) \\
V &= 2a_1 a_2 \sin(\varphi) = I\sin(2\psi) \\
I^2 &= Q^2 + U^2 + V^2
\end{aligned}$$

$$\Pi = \frac{[Q^2 + U^2 + V^2]^{1/2}}{I}$$



Polarimetry Measurement principles

Multidimensional data

General case: $S(x, y, \quad, t)$

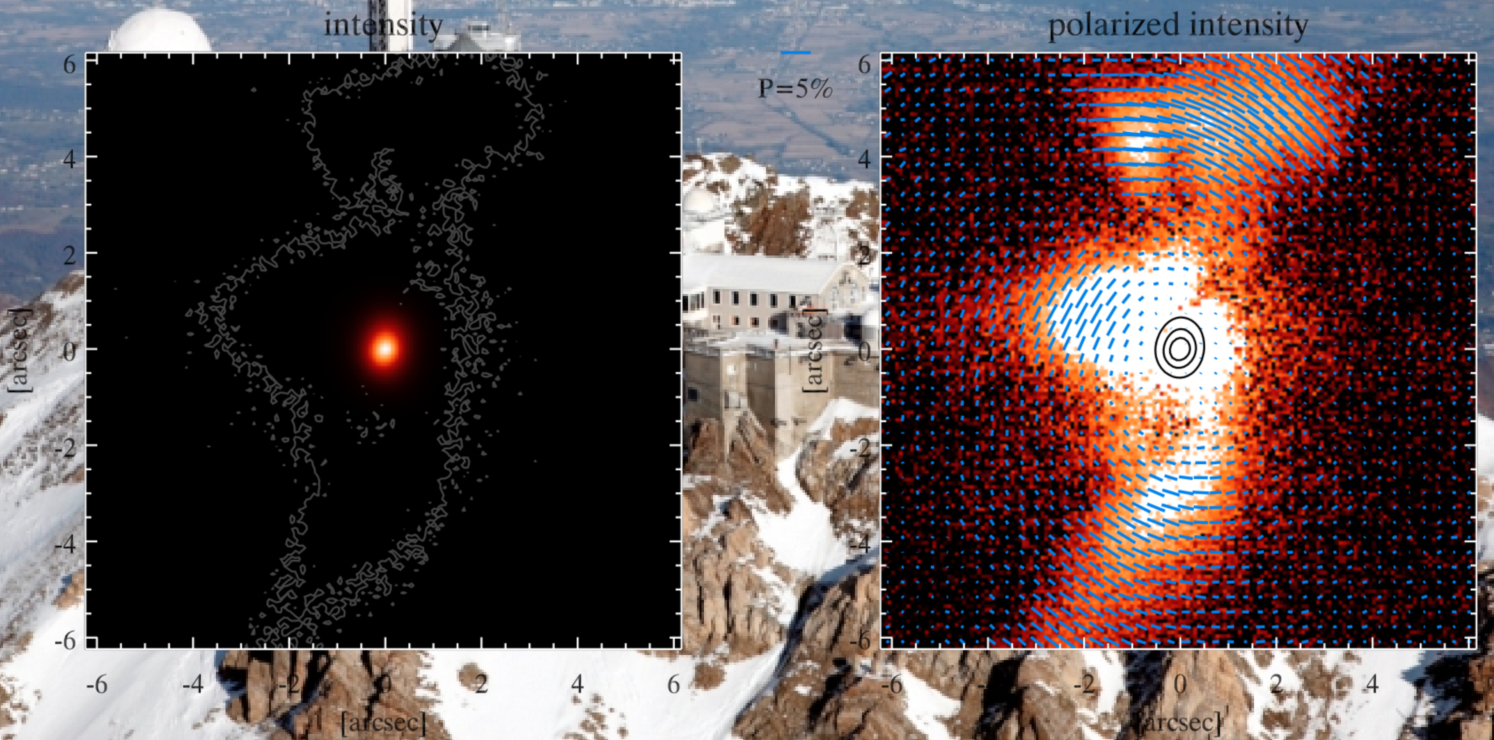
But detectors are only two-dimensional…

Polarimetry Measurement principles

Multidimensional data

General case: $S(x, y, \;\; , t)$

Combining $\;\; , t$: ➔ Imaging polarimetry



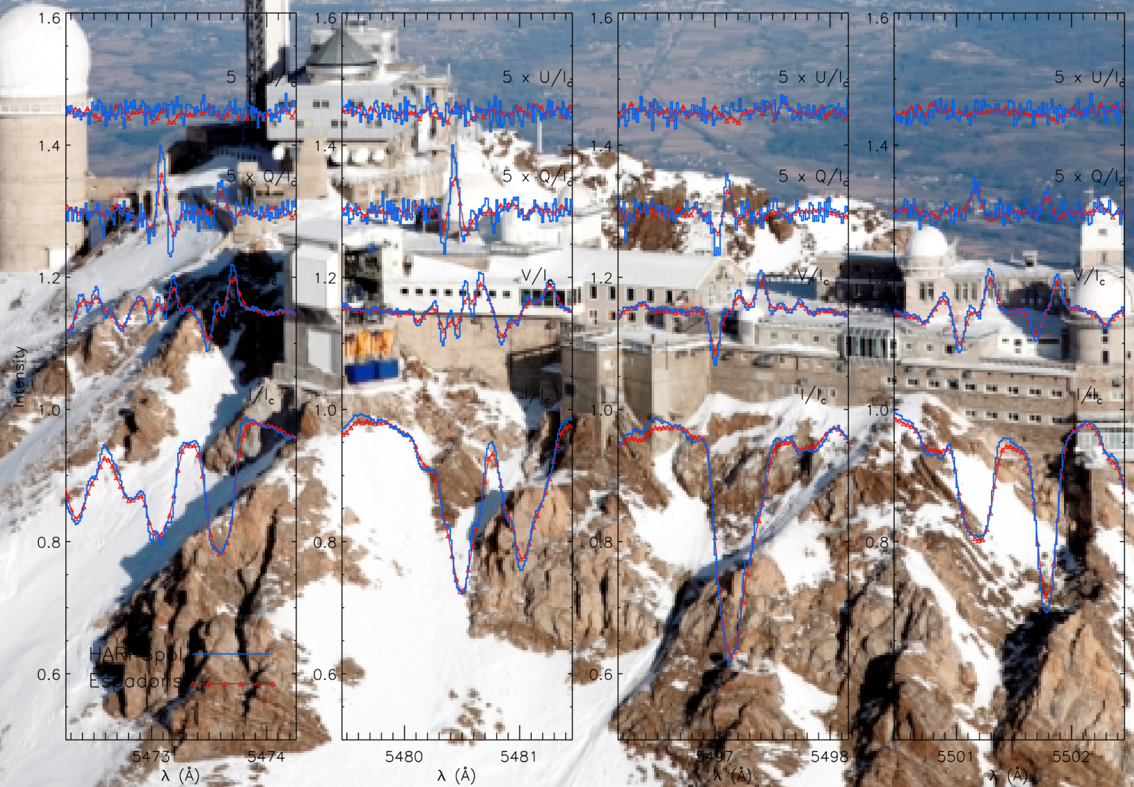
Separate images of the Stokes vector elements

Polarimetry Measurement principles

Multidimensional data

General case: $S(x, y, \quad, t)$

Combining x, y, t: ➔ Spectropolarimetry



Separate spectra of the Stokes vector elements

Polarimetry Measurement principles

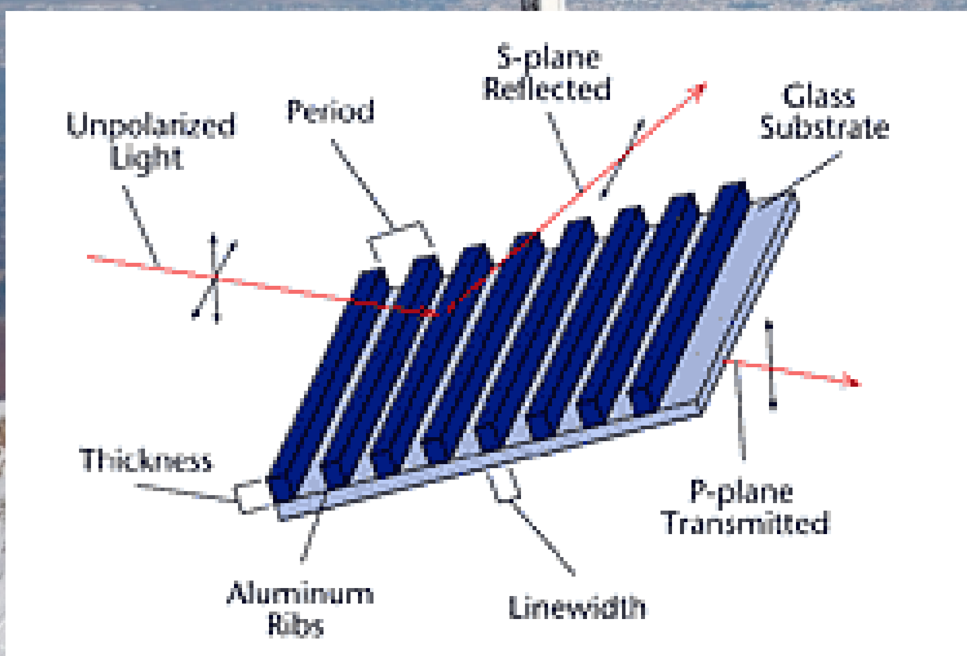
General polarimeter set-up

1. …
2. modulator = retarder
3. …
4. analyzer = (fixed) polarizer
5. …
6. Detector = (demodulator)

Polarimetry Measurement principles

Polarizers

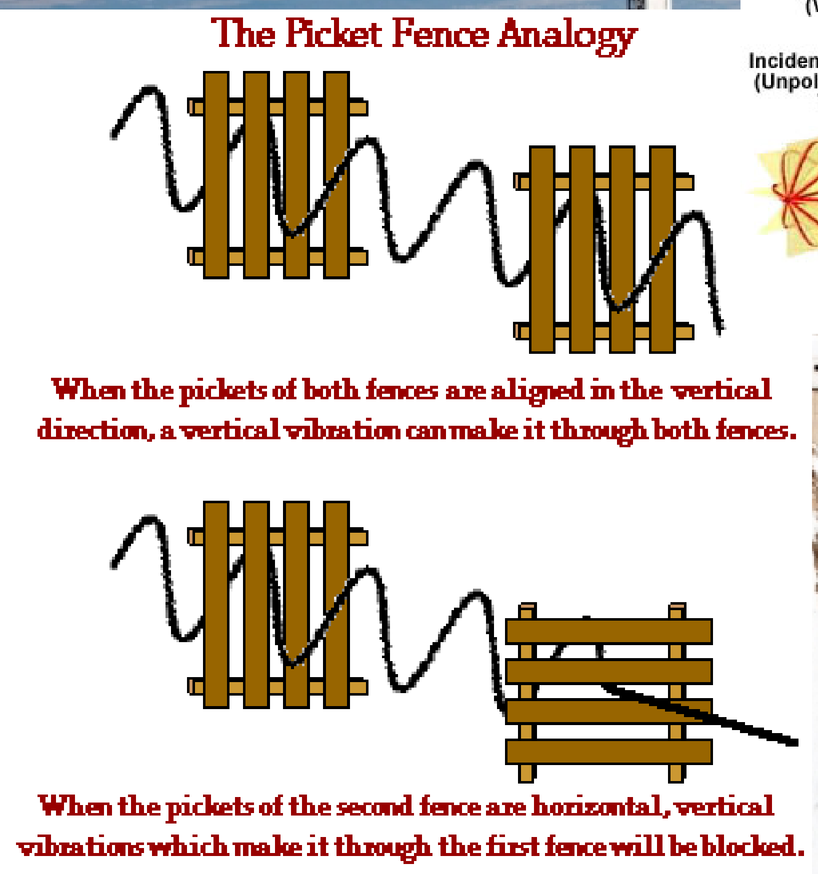
- e grid

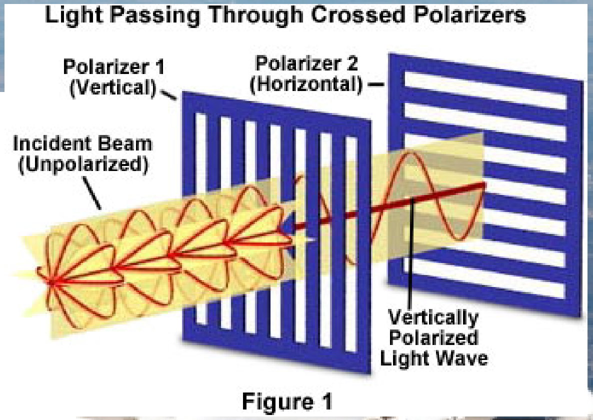


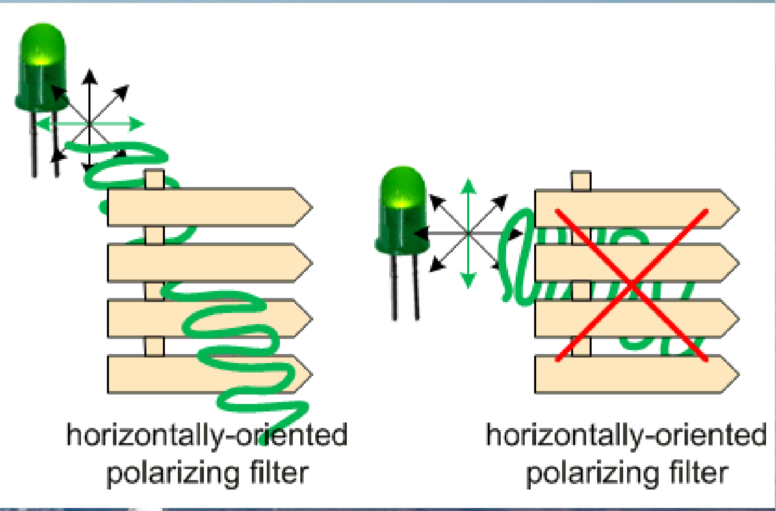
Polarimetry Measurement principles

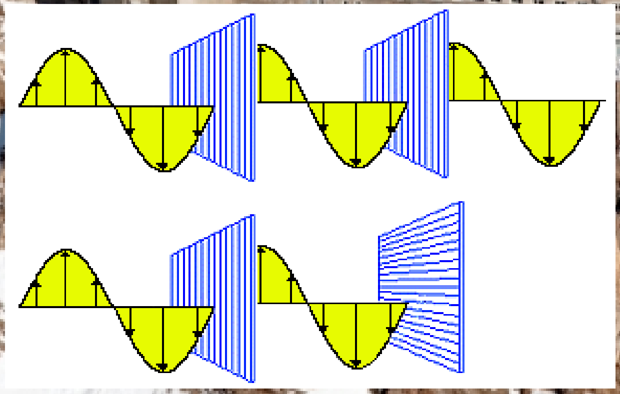
Polarizers

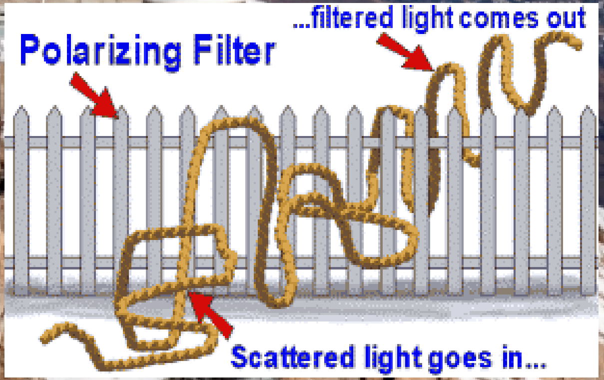
- e grid







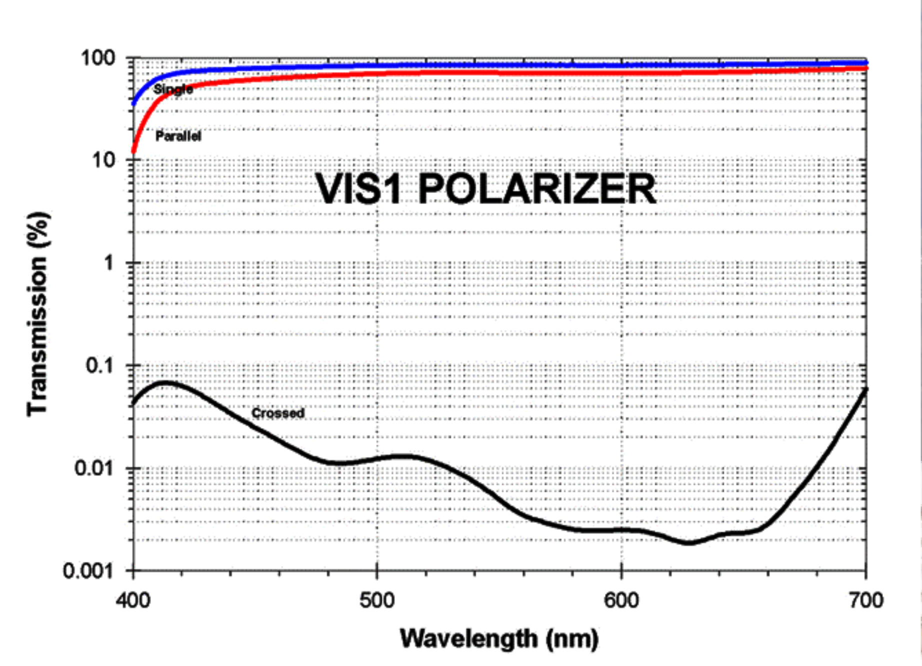




Polarimetry Measurement principles

Polarizers

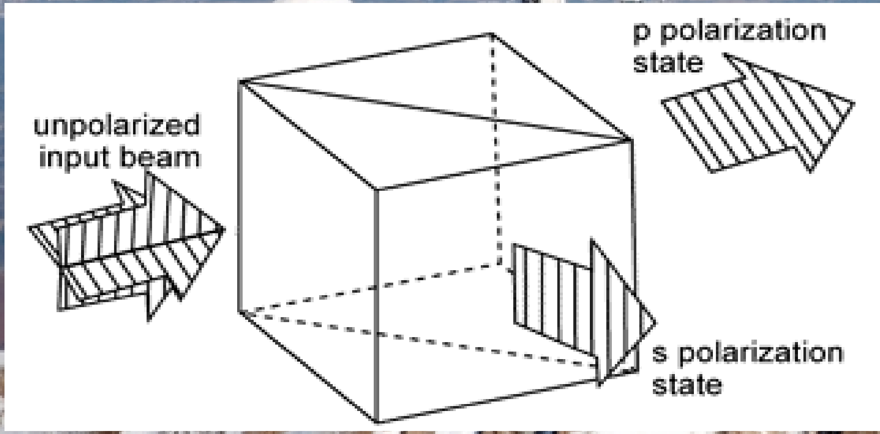
- stretched polymer (dichroism)



Polarimetry Measurement principles

Polarizers

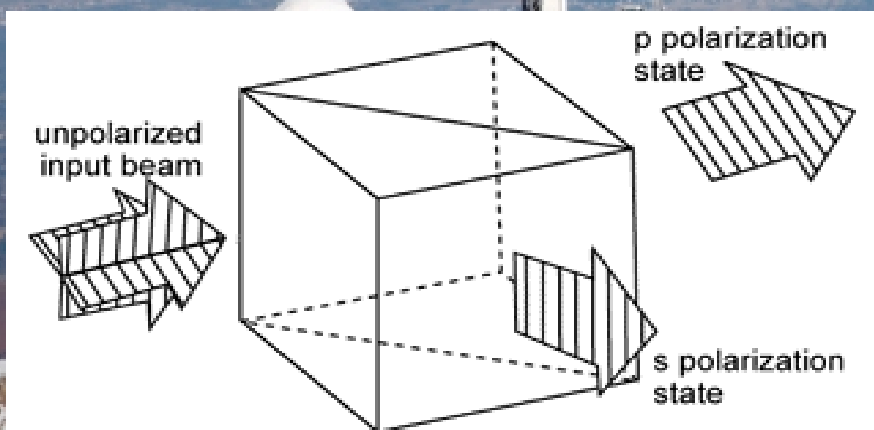
- cube beam-splitter

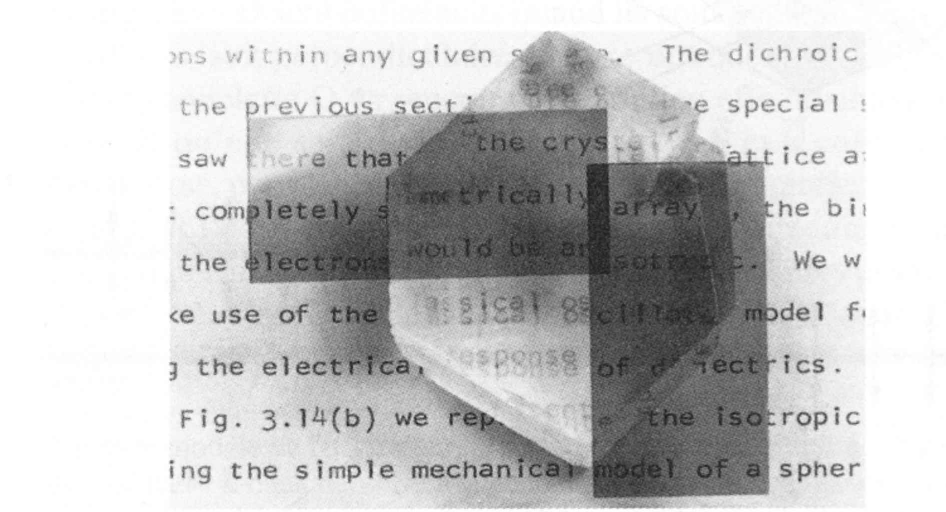


Polarimetry Measurement principles

Polarizers

- cube beam-splitter + birefringent crystal (n_o & n_e)





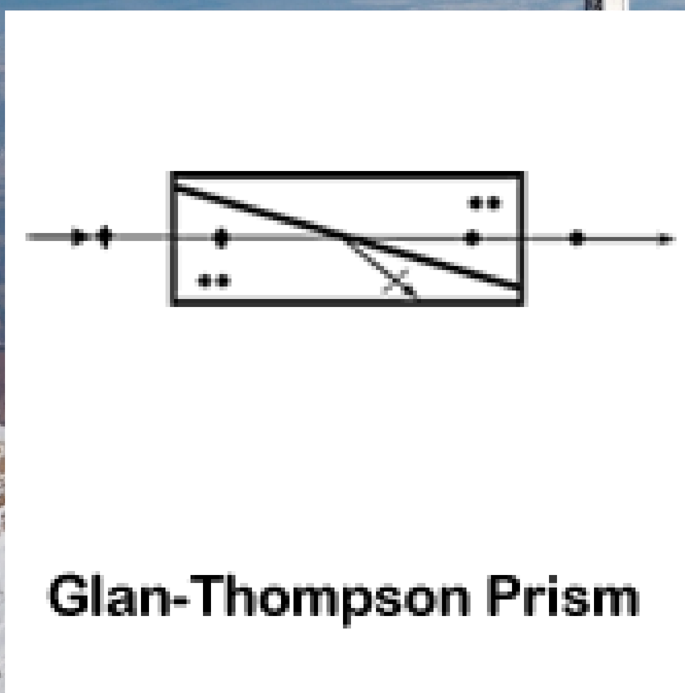
Un cristal de calcite (le coin non saillant est en bas). Les axes de transmission des deux polariseurs sont parallèles à leurs petits côtés. Là où l'image est double, celle du bas, non défléchie, est l'image ordinaire. Regarder attentivement cette image : il y a beaucoup à voir. (Photo E.H.)

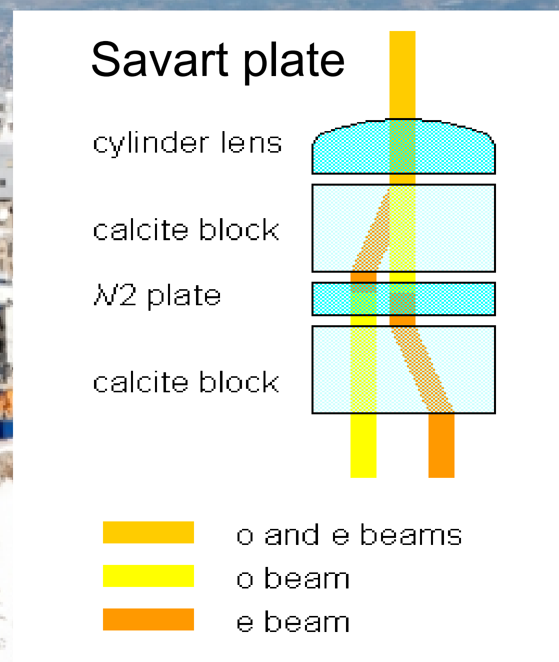
Calcite $CaCO_3$ $n_o = 1.6584$ $n_e = 1.4864$

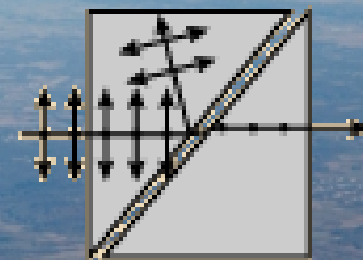
Sodium Nitrate $NaNO_3$ $n_o = 1.5854$ $n_e = 1.3369$

Polarimetry Measurement principles

Polarizers



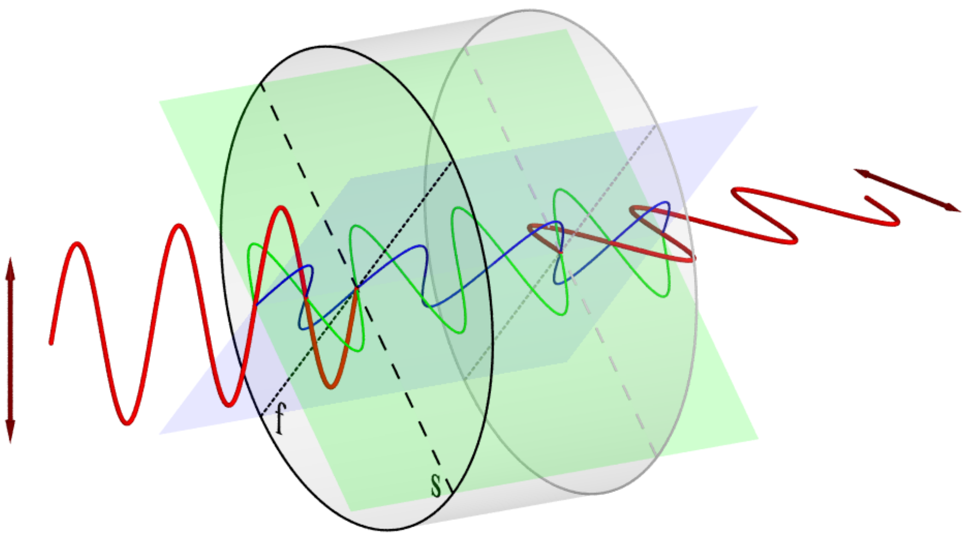




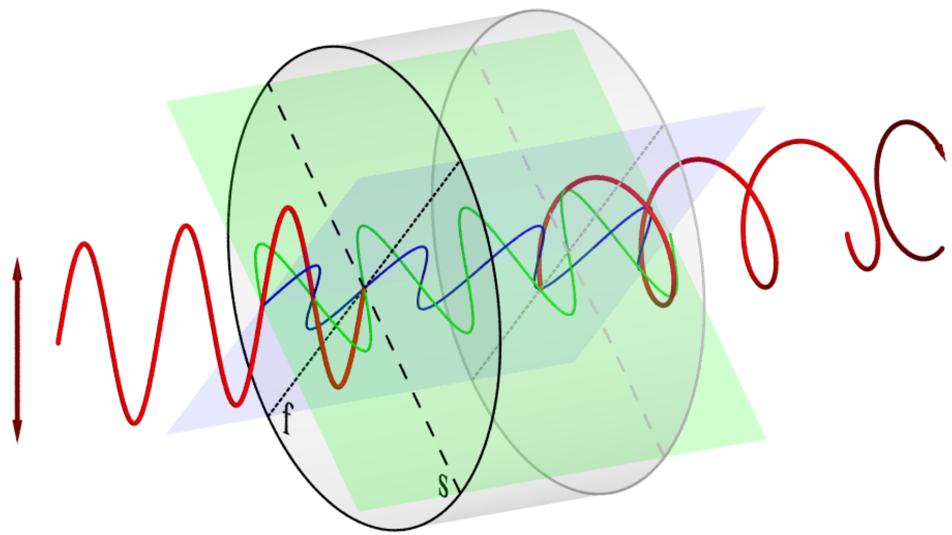
Polarimetry Measurement principles

Retarders

- introduction of phase difference



half wave plate



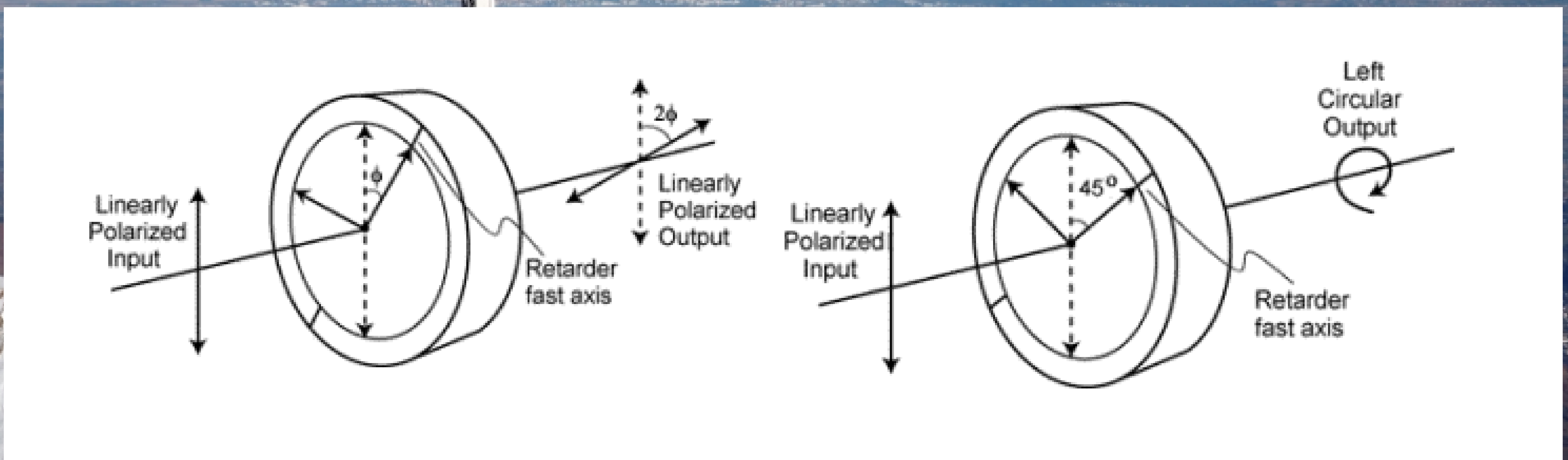
quarter wave plate

Polarimetry Measurement principles

Retarders

- introduction of phase difference

$$E_x = a_1 \cos(2\pi\nu t - \mathbf{k}\cdot\mathbf{r} + \varphi_1), E_y = a_2 \cos(2\pi\nu t - \mathbf{k}\cdot\mathbf{r} + \varphi_2) \text{ avec } \varphi = \varphi_2 - \varphi_1$$



half-wave plate (Δphase=π) quarter-wave plate (Δphase=π/2)

Polarimetry Measurement principles

Retarders

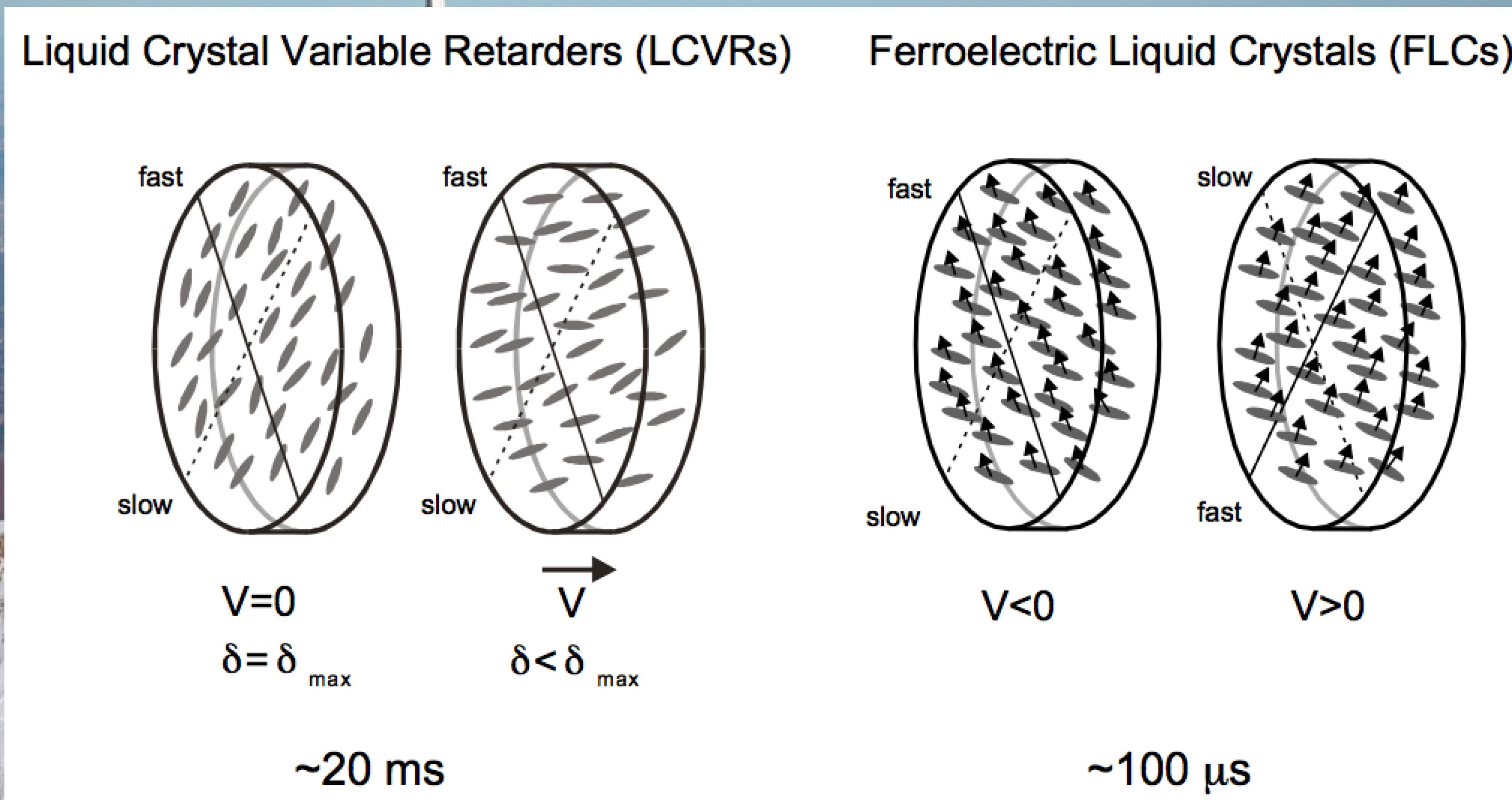
- Crystal wave plates

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

Chromatic and temperature sensitive for birefringent crystal plates.

Polarimetry Measurement principles

Retarders – Liquid crystals



Polarimetry Measurement principles

Retarders – Fresnel rhomb

- Phase difference through total internal reflections

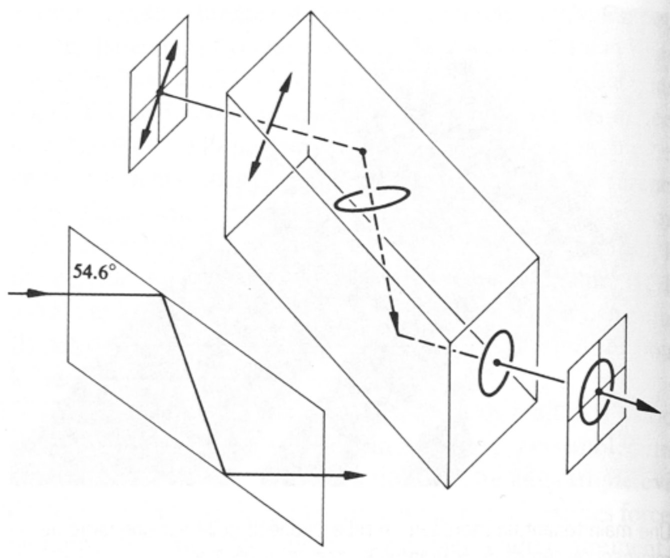


Figure 8.41 Rhomboèdre de Fresnel.

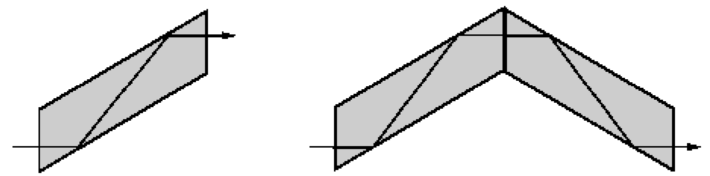
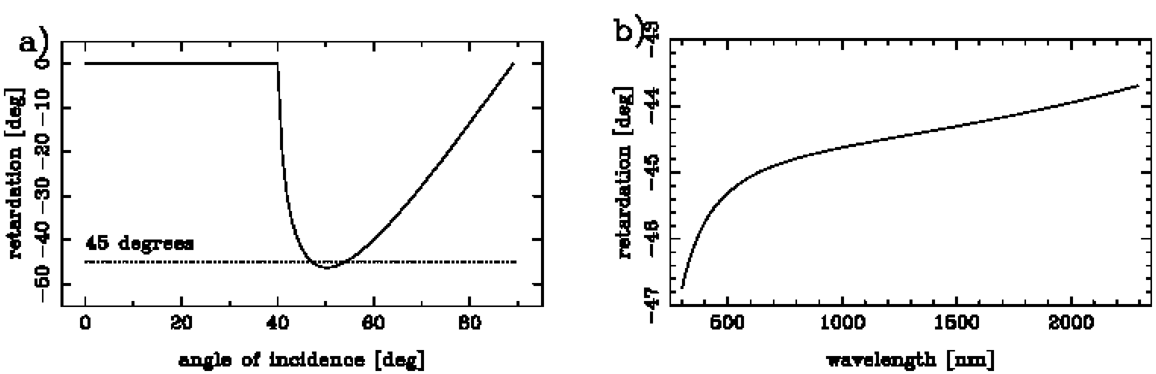


FIGURE 8. Traditional arrangements for quarter-wave (left) and half-wave (right) Fresnel rhombs.



Polarimetry Measurement principles

Retarders – PEMs

- Piezo-Elastic Modulators
  - Birefringence induced in normal glass by stress.
  - Resonance frequency: fast variation of retardance (~10 kHz).

Polarimetry Measurement principles

Mueller matrices

$$\vec{S}_{out} = M_n \cdot M_{n-1} \cdot \ldots \cdot M_2 \cdot M_1 \cdot \vec{S}_{in}$$

$$M_{pol} = \frac{1}{2}\begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$M_{rot} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$M_{ret} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta & -\sin\delta \\ 0 & 0 & \sin\delta & \cos\delta \end{pmatrix}$$

Polarimetry Measurement principles

Modulation

1. Spatial

- Measuring different polarization states at different locations

2. Temporal

- Measuring different polarization states at different times

3. Spectral

Polarimetry Measurement principles

Spatial modulation

+ Strictly simultaneous measurements.
- Different (parts of) detectors.
- Differential alignment / aberrations.
- Limited detector gain calibration.
- 2 to 6 beams.

Polarimetry Measurement principles

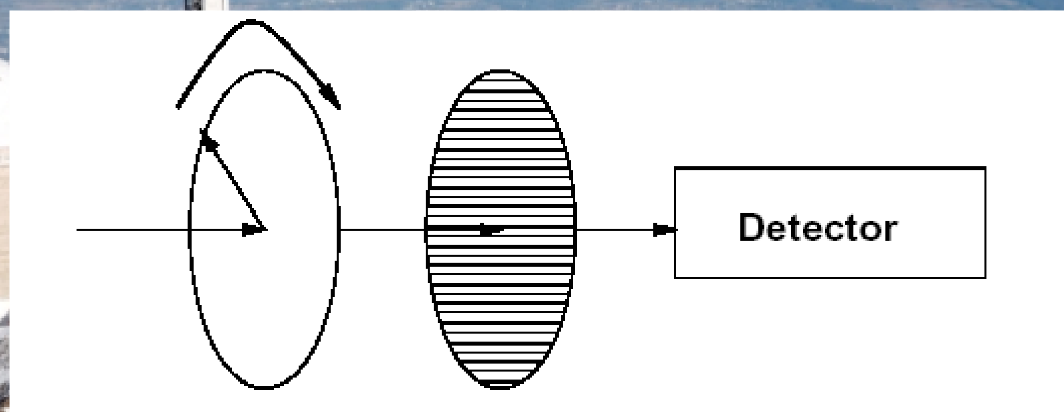
Temporal modulation

+ All measurements with same detector.
- Image motion / seeing / variability issues.
- Requires active component.
- Fast modulation and demodulation desirable but often not possible.

Polarimetry Measurement principles

Temporal modulation

- Rotating waveplate + polarizer analyzer + demodulating detector.

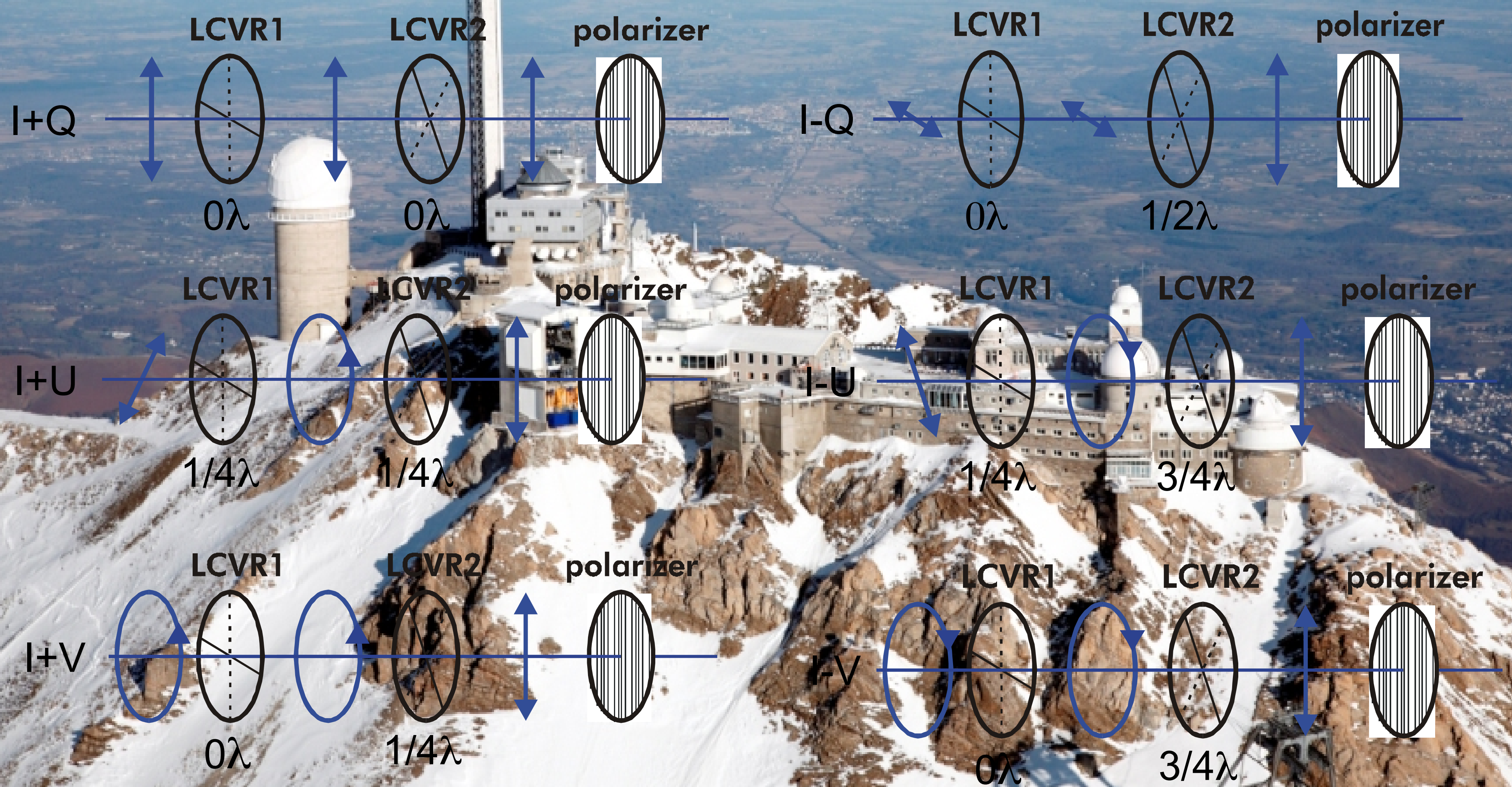


→ Intensity measurements are linear combinations of I with Q, U and V

Polarimetry Measurement principles

Temporal modulation

2 LCVRs + polarizer + also 4-fold modulation scheme



Instrumental polarization

- Every reflection polarizes...
- Every piece of glass is birefringent...

... to some degree.

So one has to be very careful that the measured polarization is not due to the instrument itself!

Instrumental polarization

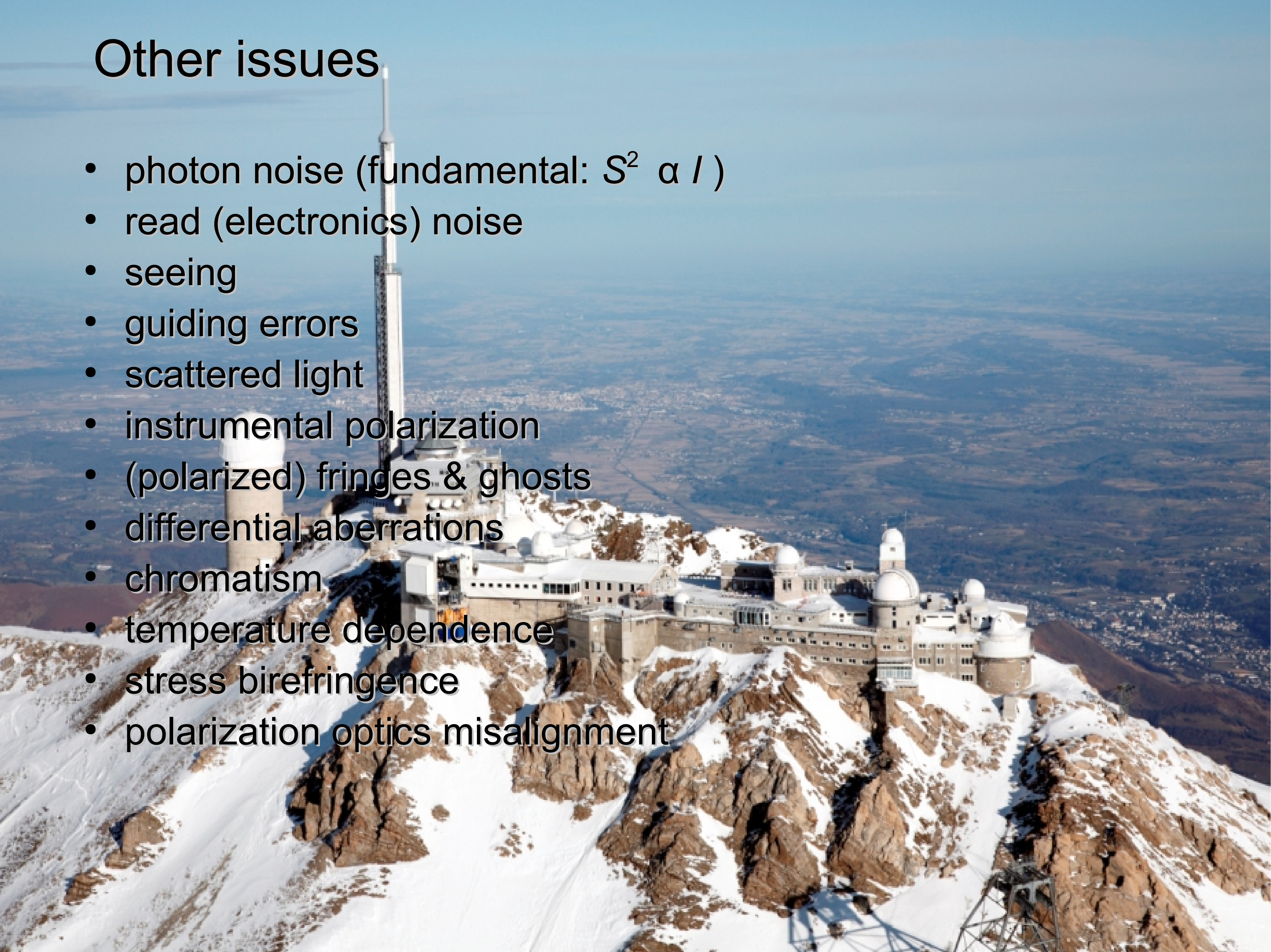
Polarization cross-talk

- 45° Al mirror (very common in telescopes!)

$$M_{mir} = \begin{pmatrix} 1.000 & 0.028 & 0 & 0 \\ 0.028 & 1.000 & 0 & 0 \\ 0 & 0 & -0.983 & -0.180 \\ 0 & 0 & 0.180 & -0.983 \end{pmatrix}$$

- Also effect due to growing Al_2O_3 layer.

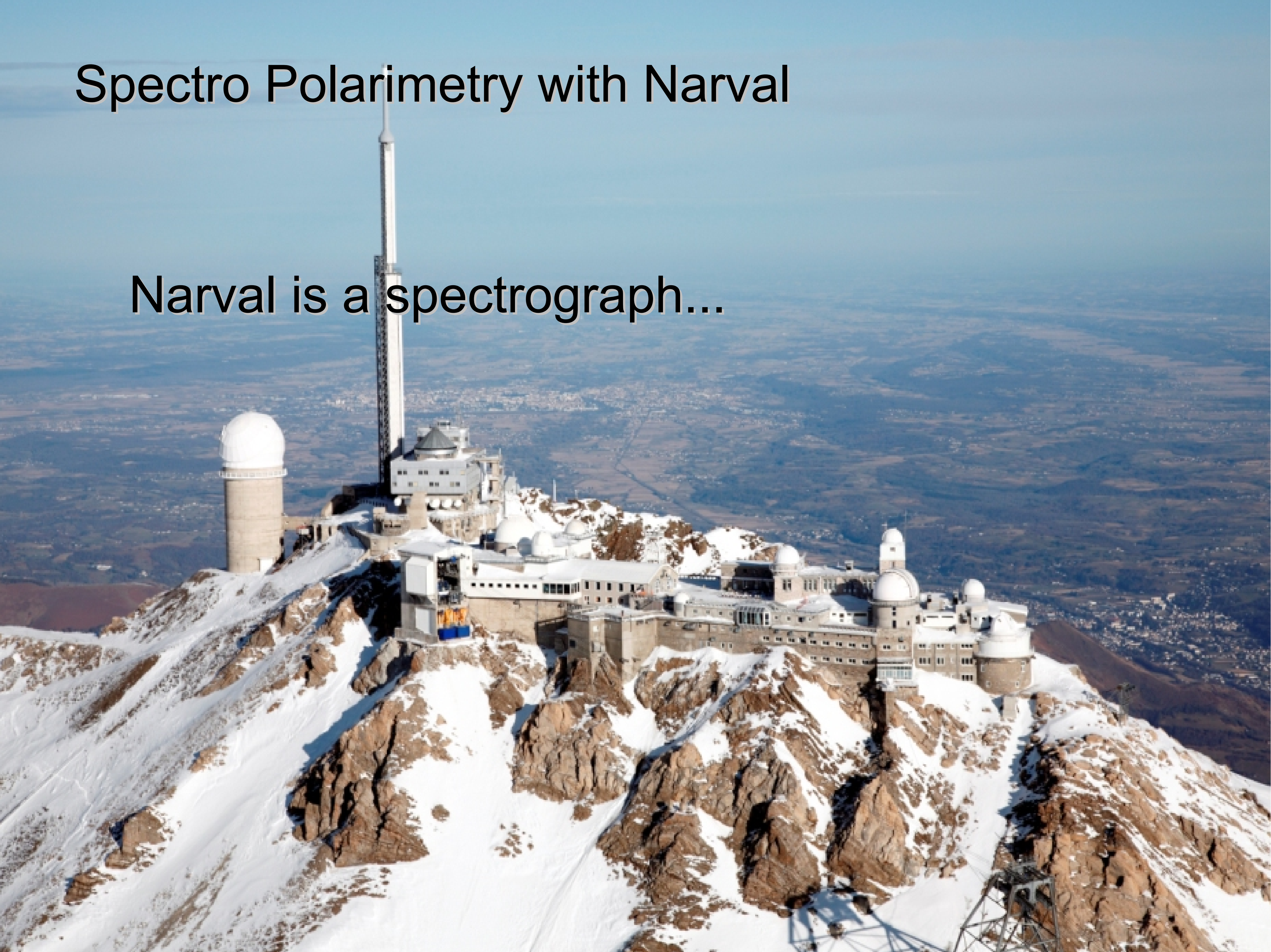
Other issues

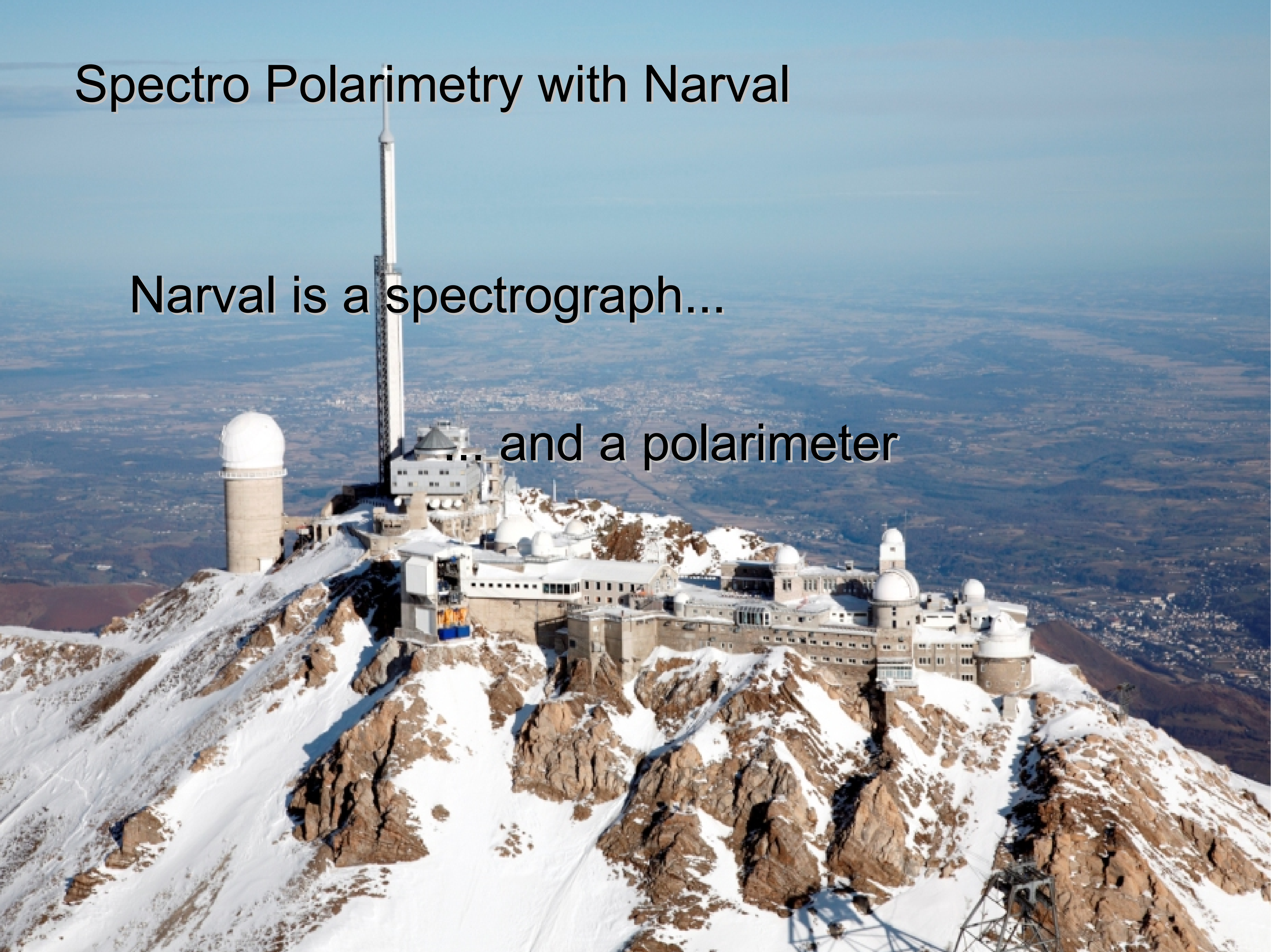


- photon noise (fundamental: $S^2 \;\alpha\; I$)
- read (electronics) noise
- seeing
- guiding errors
- scattered light
- instrumental polarization
- (polarized) fringes & ghosts
- differential aberrations
- chromatism
- temperature dependence
- stress birefringence
- polarization optics misalignment

Spectro Polarimetry with Narval

Narval is a spectrograph...



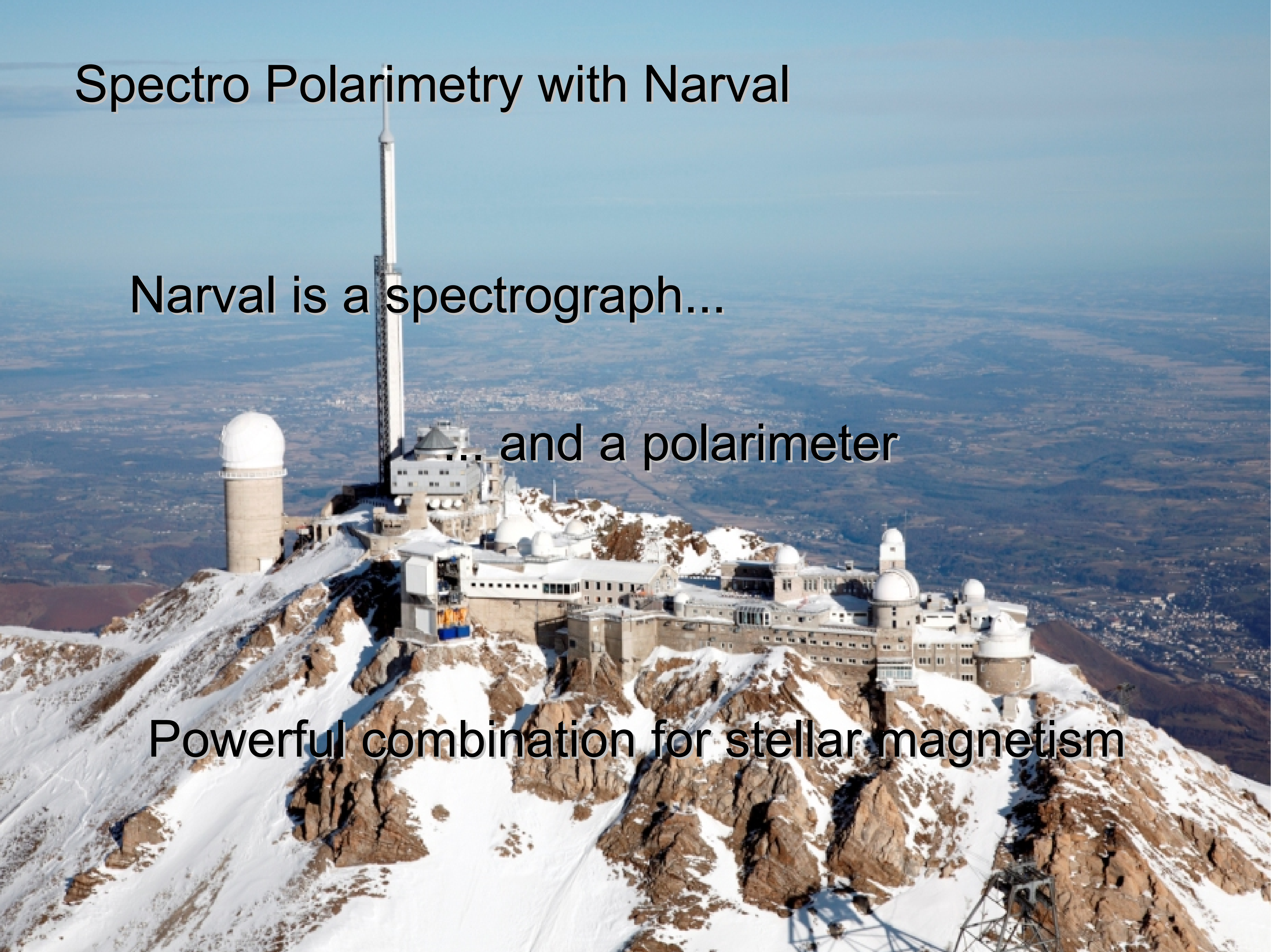

Spectro Polarimetry with Narval
Narval is a spectrograph...
... and a polarimeter

Spectro Polarimetry with Narval

Narval is a spectrograph...

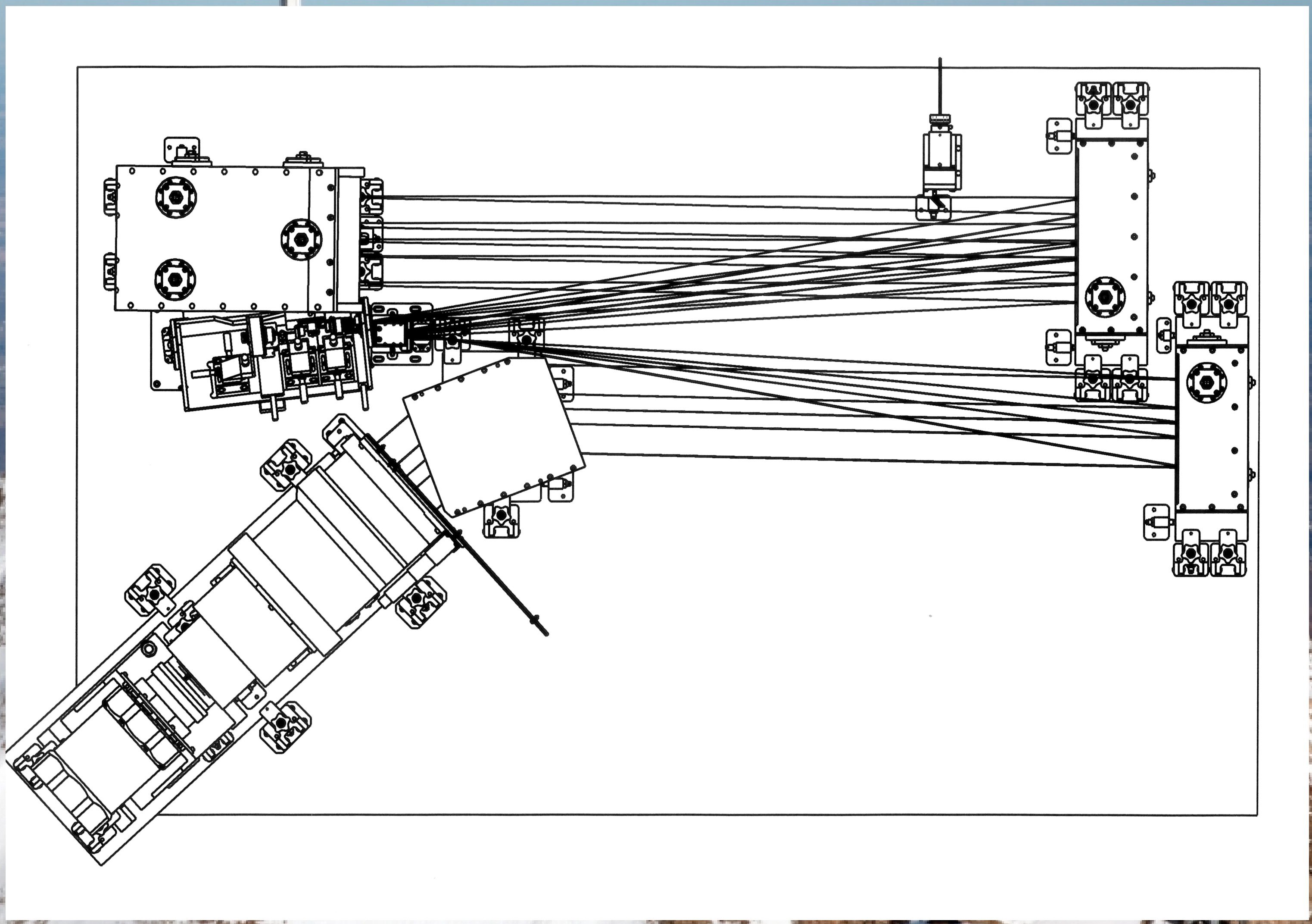
... and a polarimeter

Powerful combination for stellar magnetism



Narval is a spectrograph...

Copy of the echelle spectrograph FEROS: temperature controled enclosure, optical bench, stable (~40 m/s in a night)



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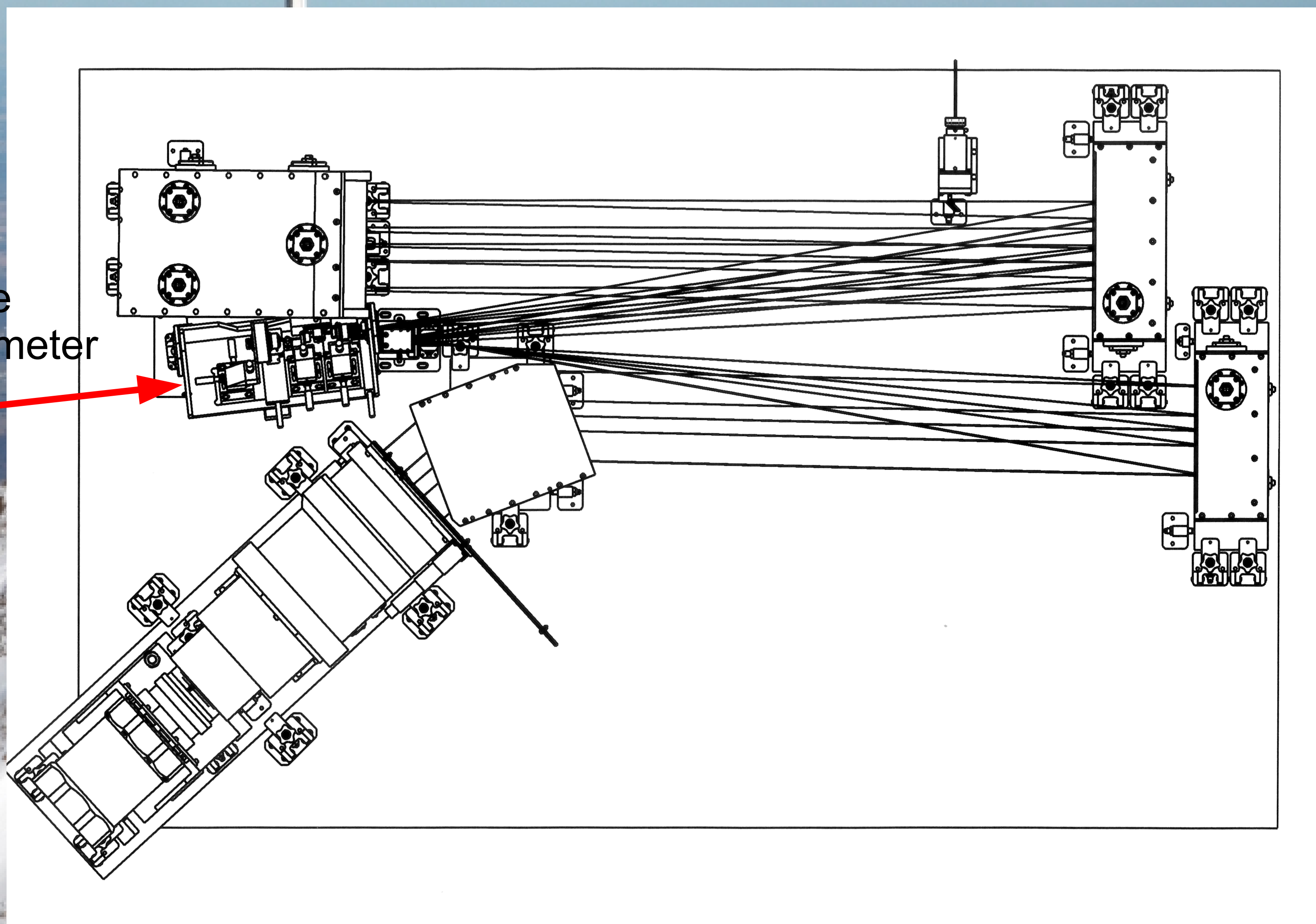
Copy of the echelle spectrograph FEROS: temperature controled enclosure, optical bench, stable (~40 m/s in a night)

Fiber bundle
From polarimeter



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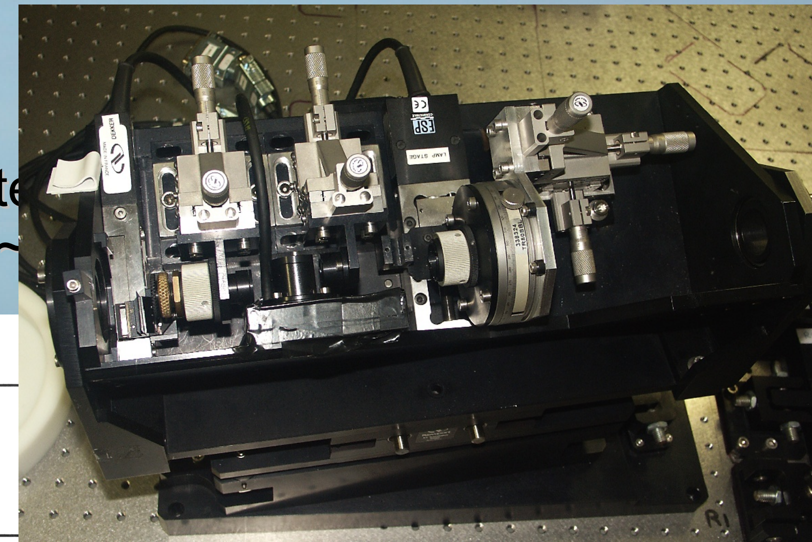
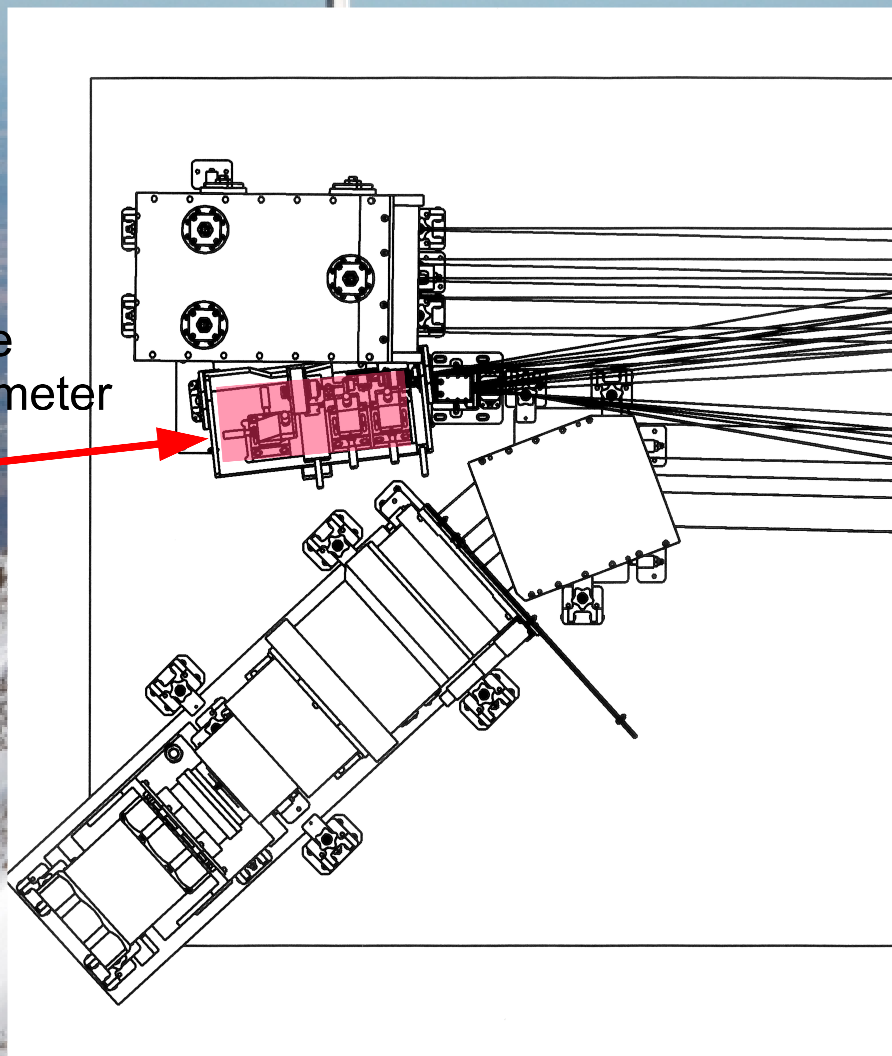
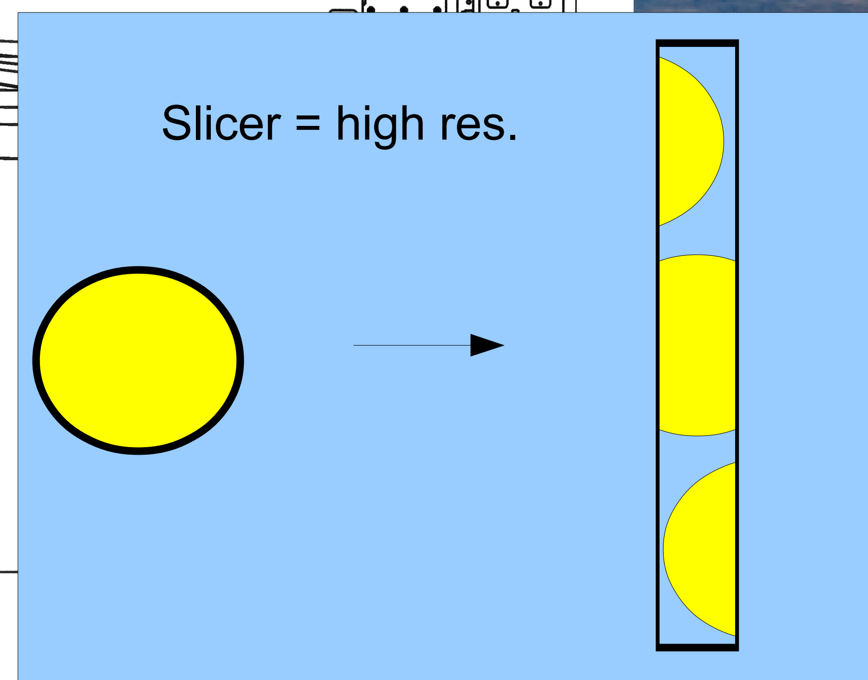


Fiber bundle
From polarimeter





Narval is a spectrograph...

Copy of the echelle spectrograph FEROS: temper
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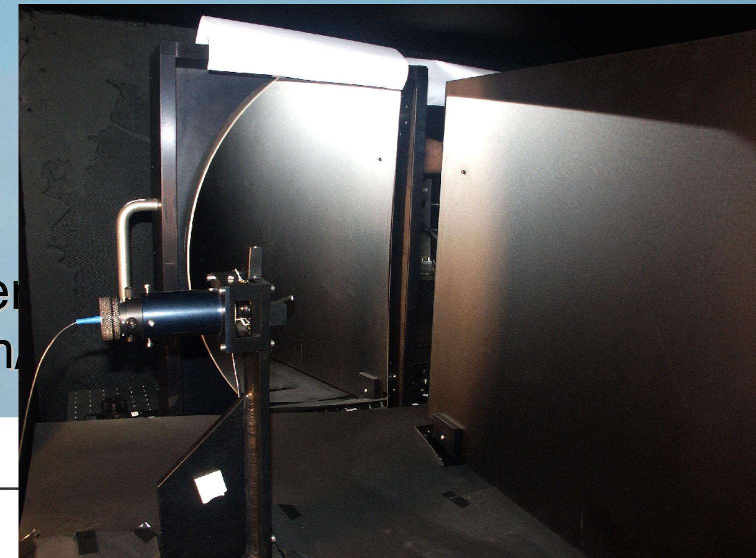
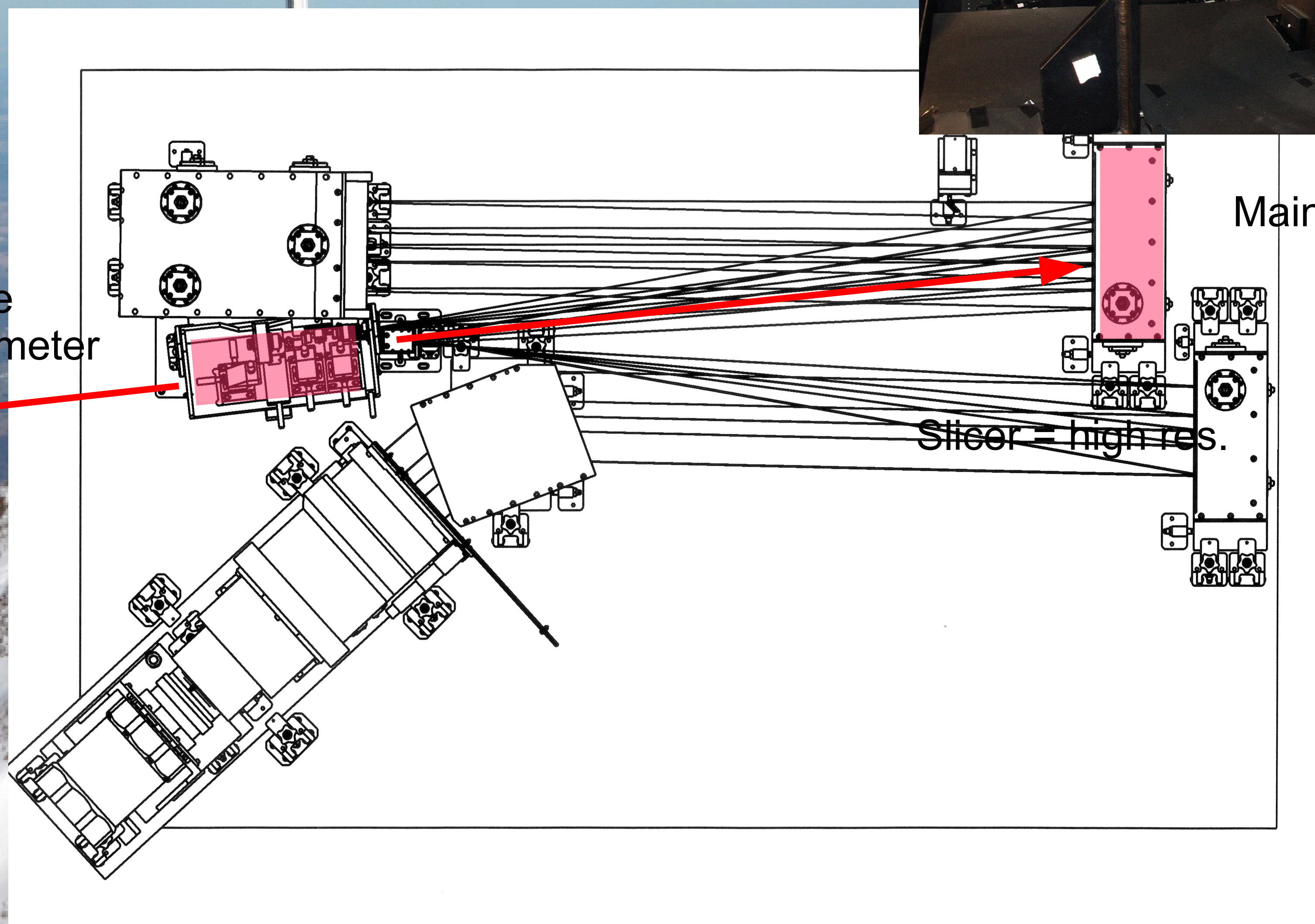
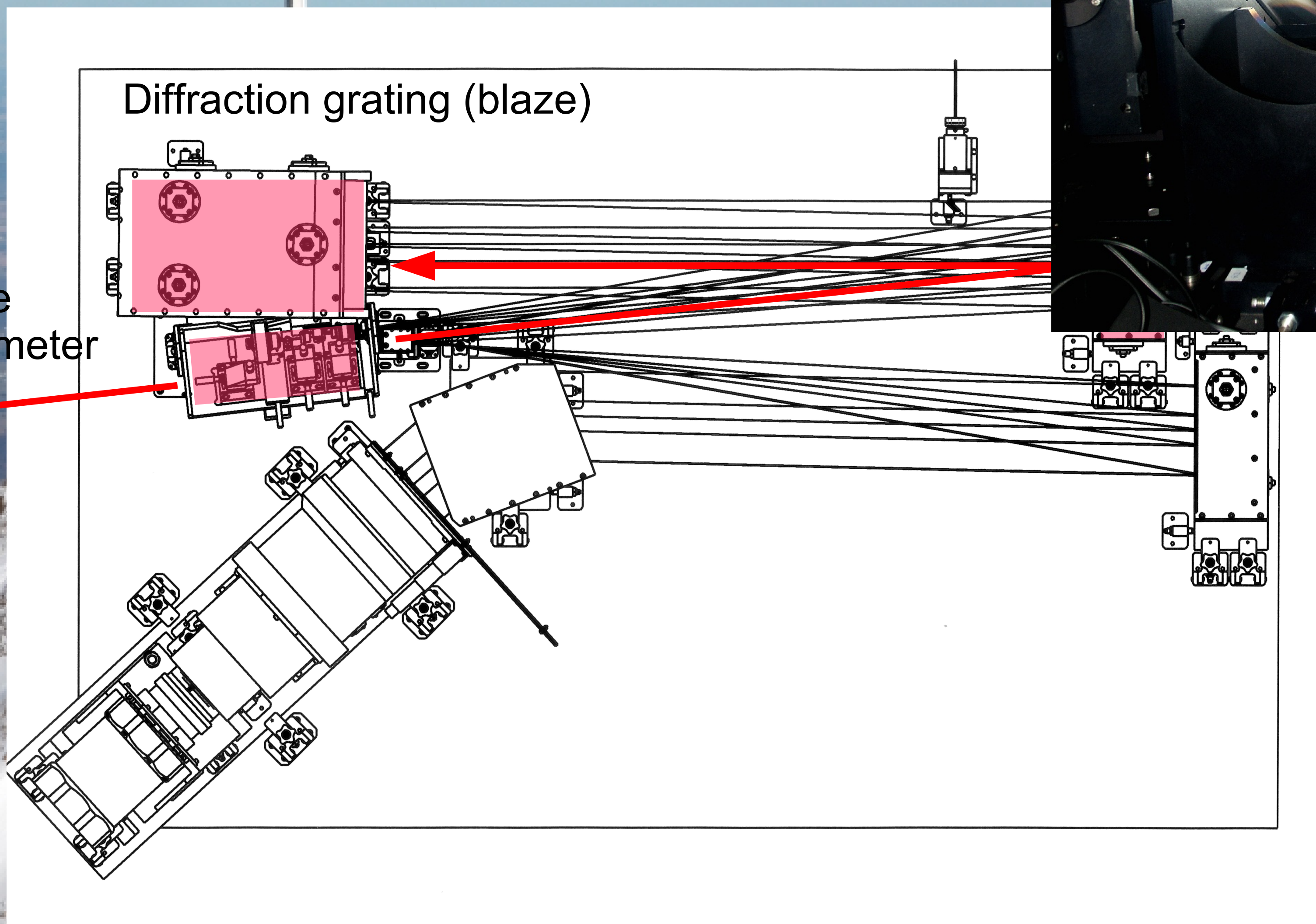
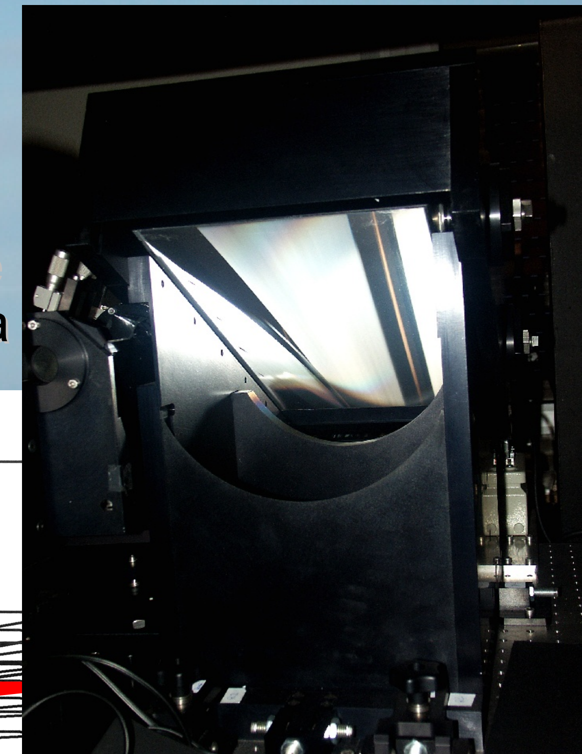




Narval is a spectrograph...

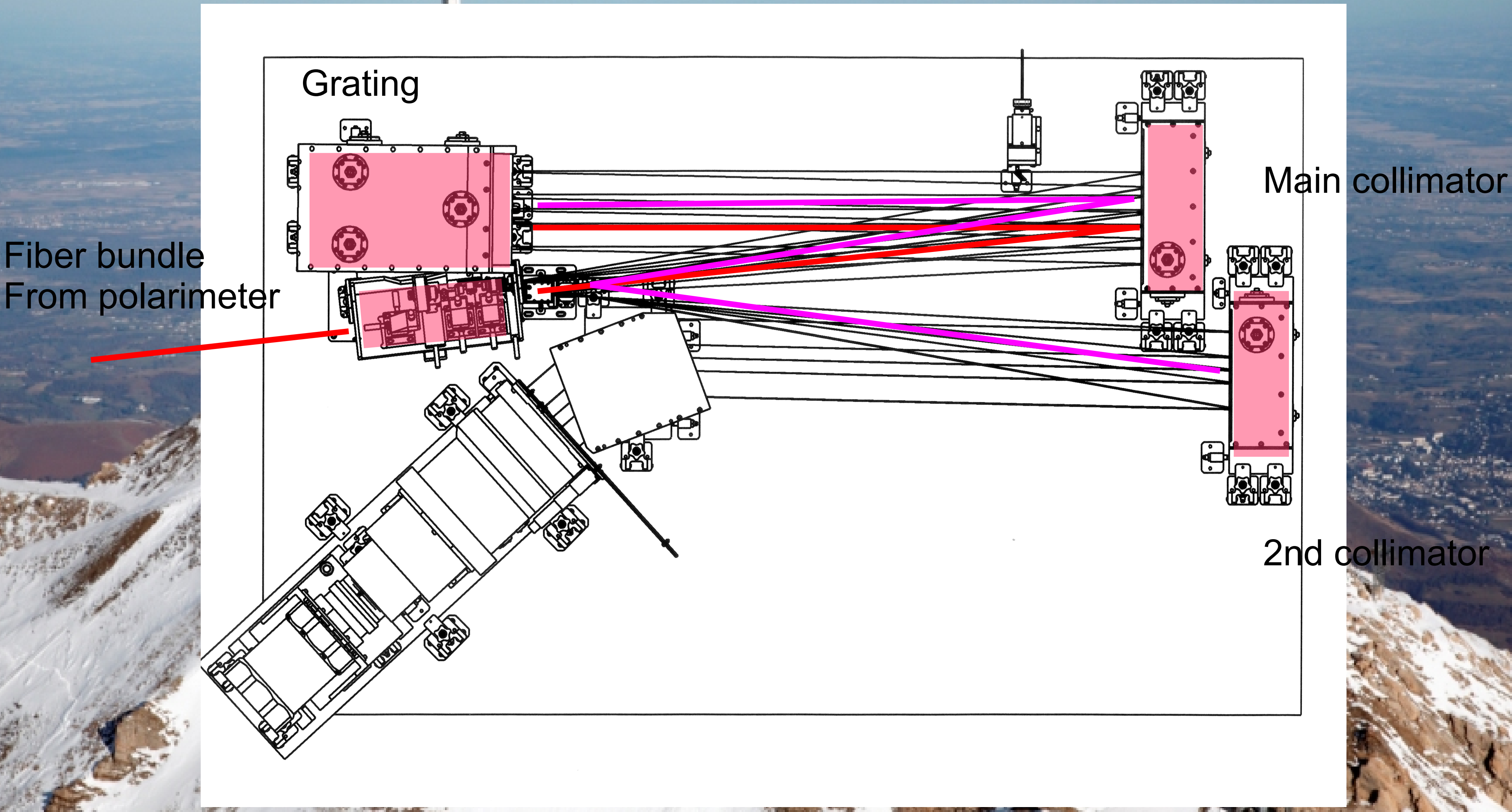
Copy of the echelle spectrograph FEROS: temperature controled enclosure, optical bench, stable (~40 m/s in a





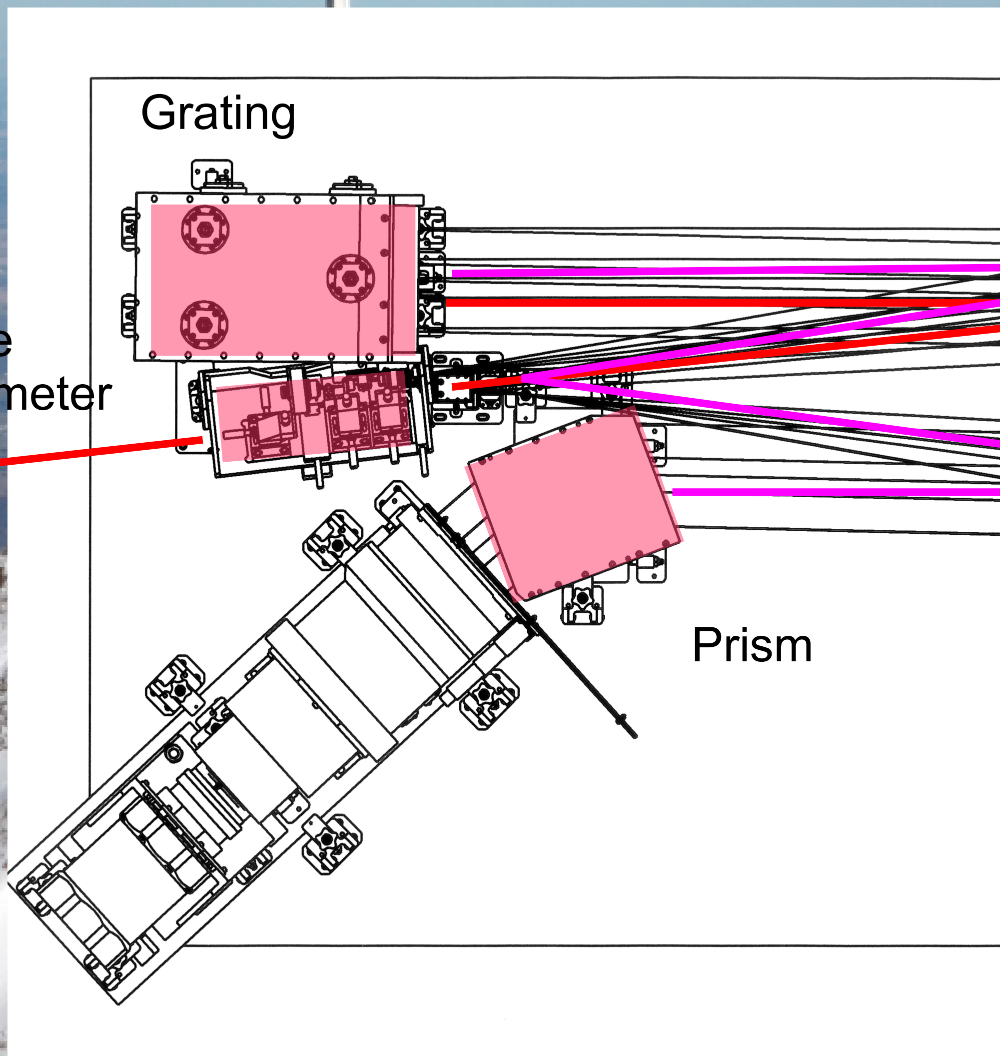
Narval is a spectrograph...

Copy of the echelle spectrograph FEROS: temperature controled enclosure, optical bench, stable (~40 m/s in a night)



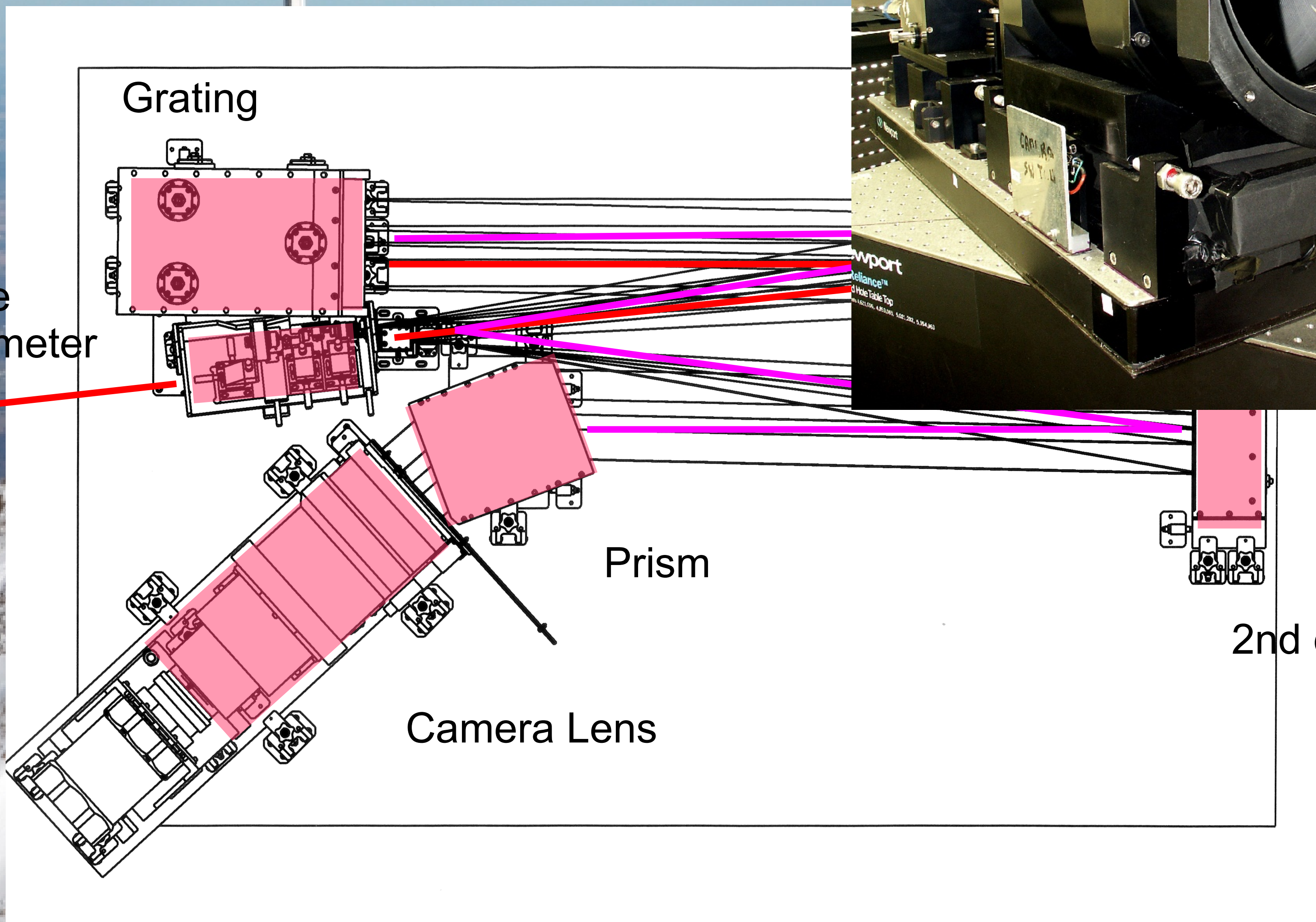
Narval is a spectrograph...

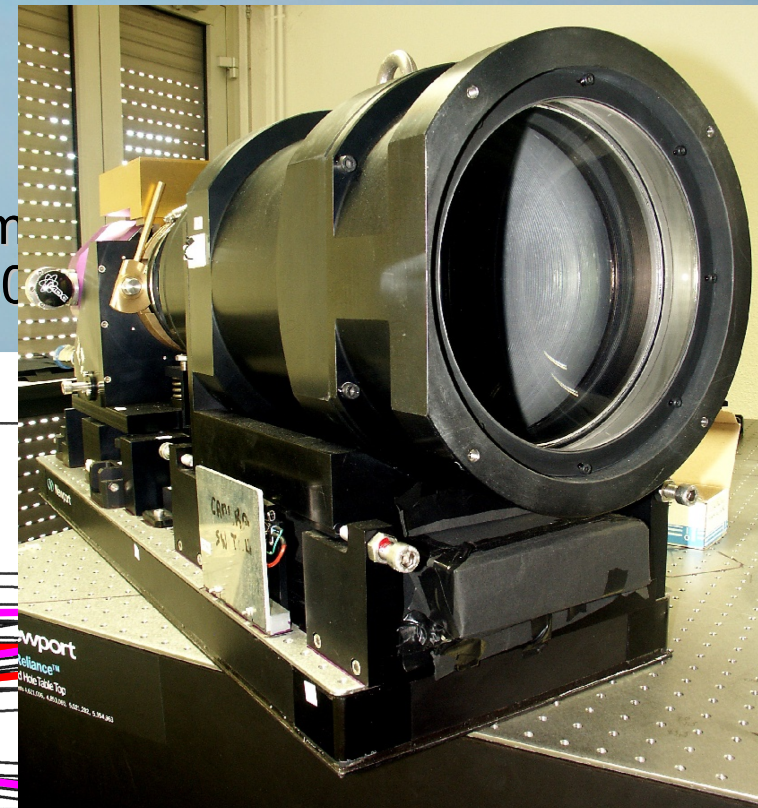
Copy of the echelle spectrograph FEROS: temperature controled enclosure, optical bench, stable (~40



Narval is a spectrograph...

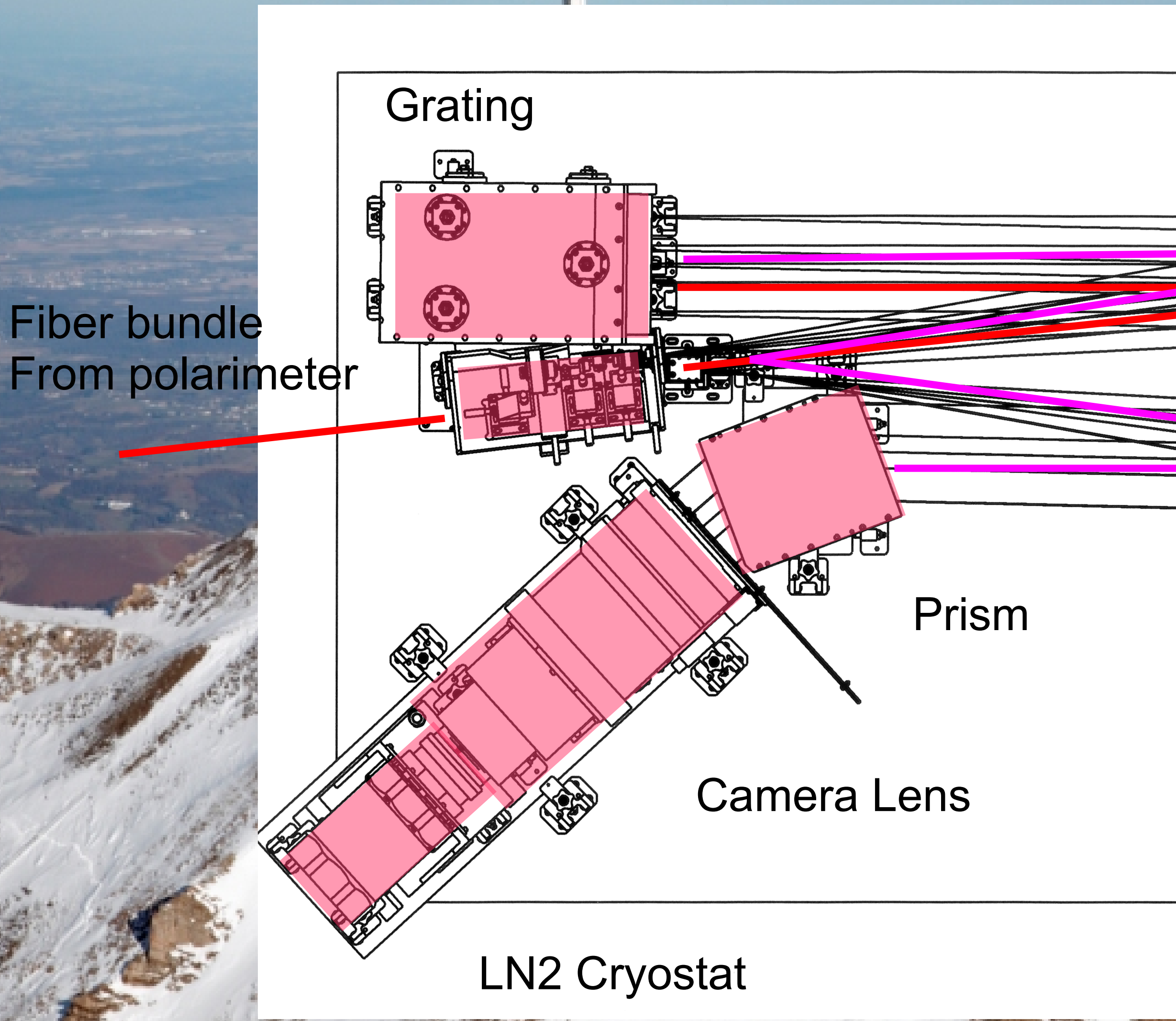
Copy of the echelle spectrograph FEROS: tem
controled enclosure, optical bench, stable (~40

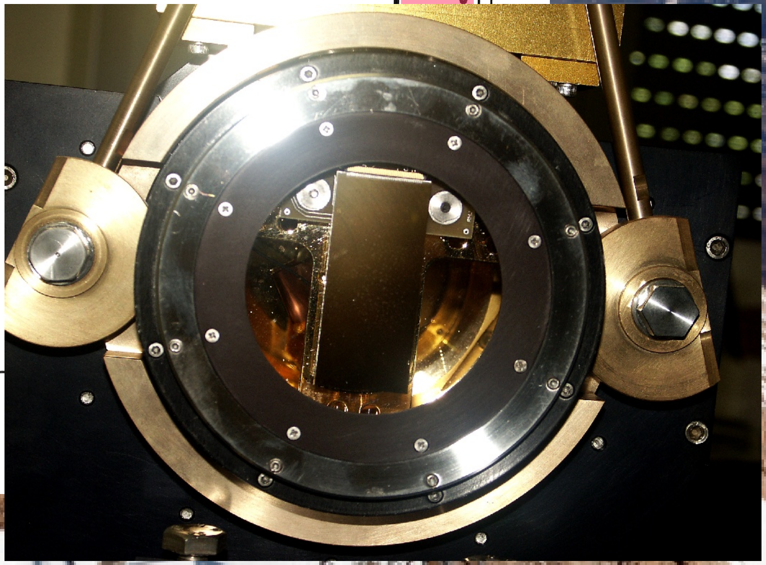


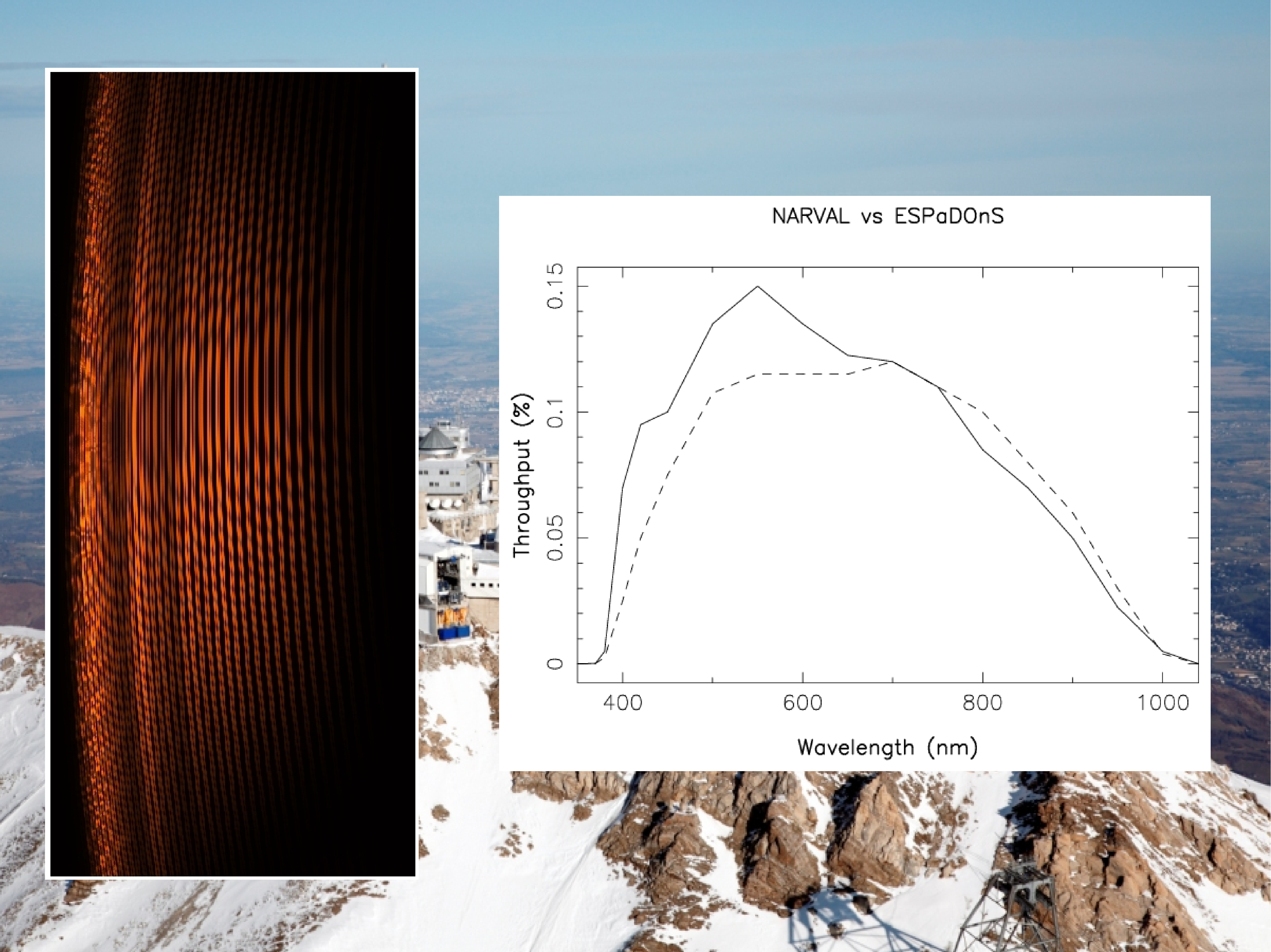


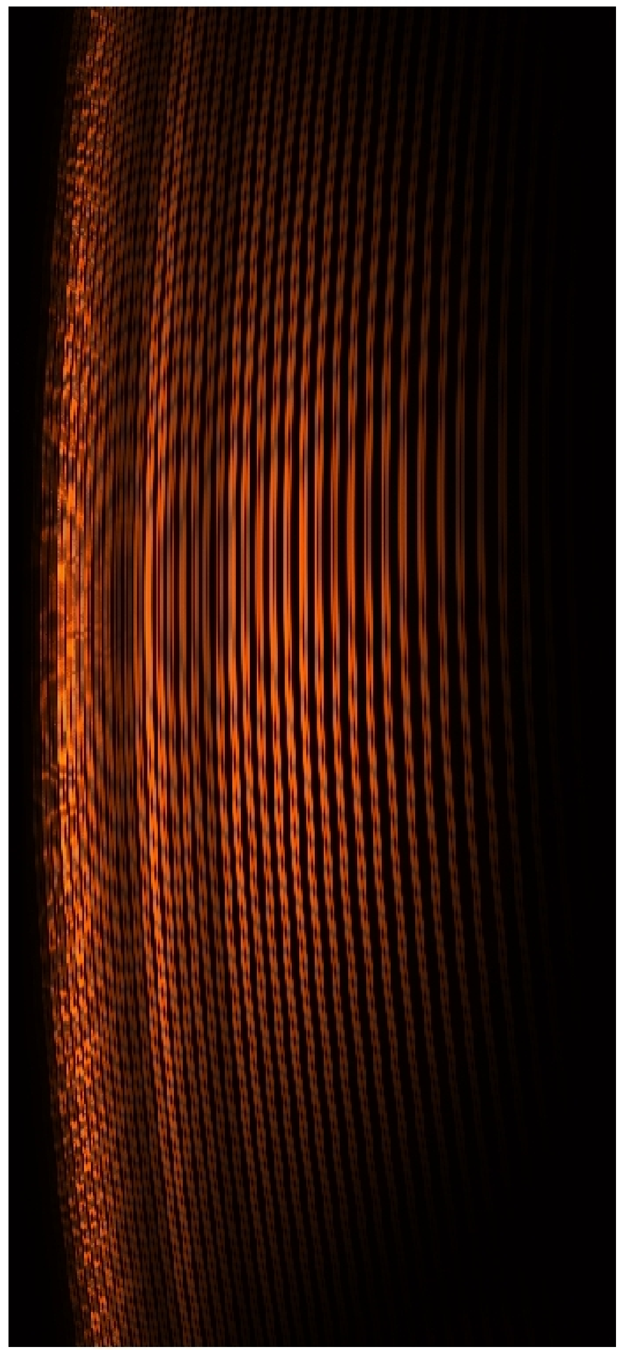
Narval is a spectrograph...

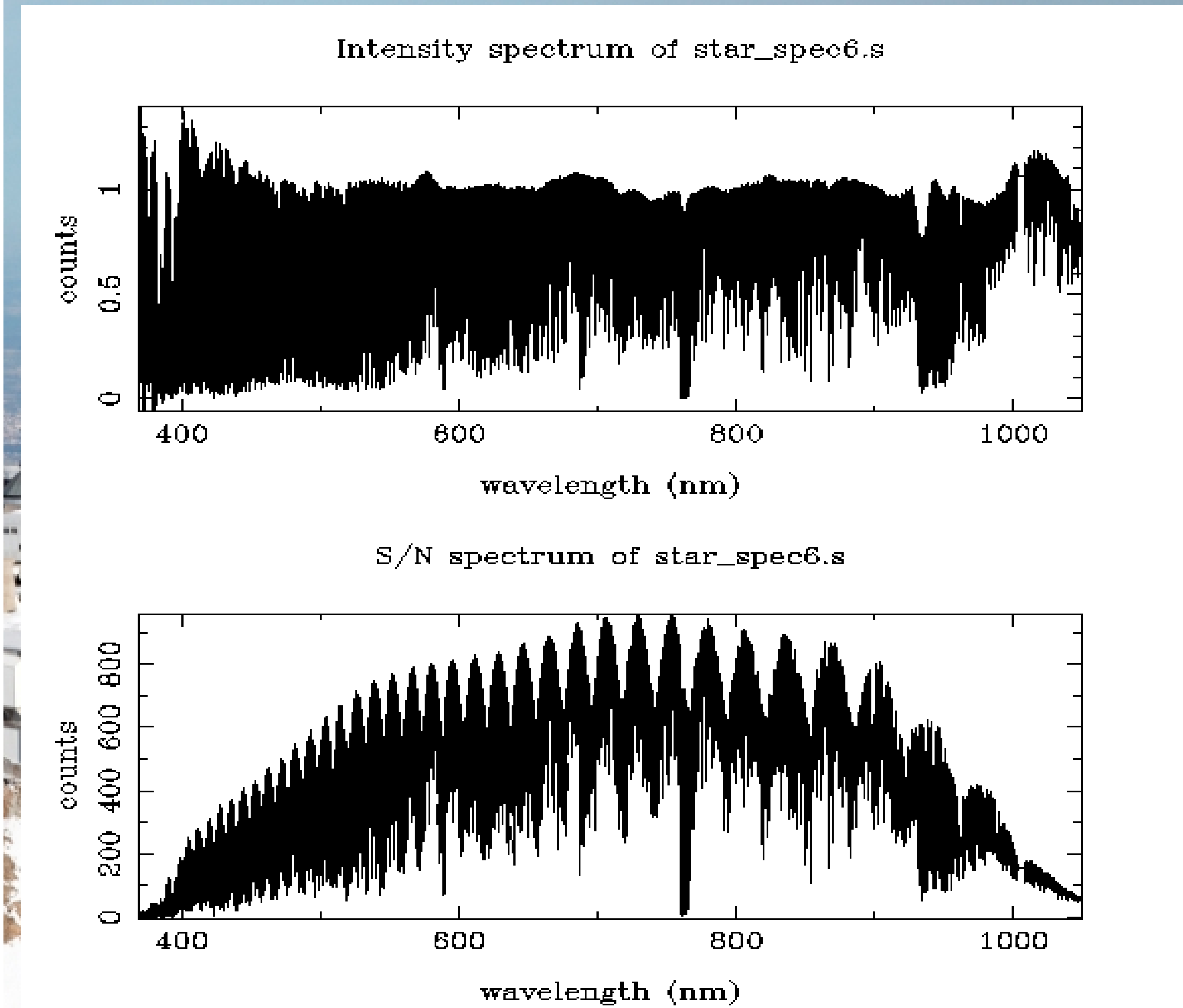
Copy of the echelle spectrograph FEROS: tem
controled enclosure, optical bench, stable (~40






NARVAL vs ESPaDOnS
Throughput (%)
0
0.05
0.1
0.15
400
600
800
1000
Wavelength (nm)




Intensity spectrum of star_spec6.s
counts
0
0.5
1
400
600
800
1000
wavelength (nm)
S/N spectrum of star_spec6.s
counts
0
200
400
600
800
400
600
800
1000
wavelength (nm)

How to measure polarisation

Une onde décrite par :

$$E_x = a_1 \cos(2\pi\nu t - \mathbf{k}\cdot\mathbf{r} + \varphi_1), E_y = a_2 \cos(2\pi\nu t - \mathbf{k}\cdot\mathbf{r} + \varphi_2) \text{ avec } \varphi = \varphi_2 - \varphi_1$$

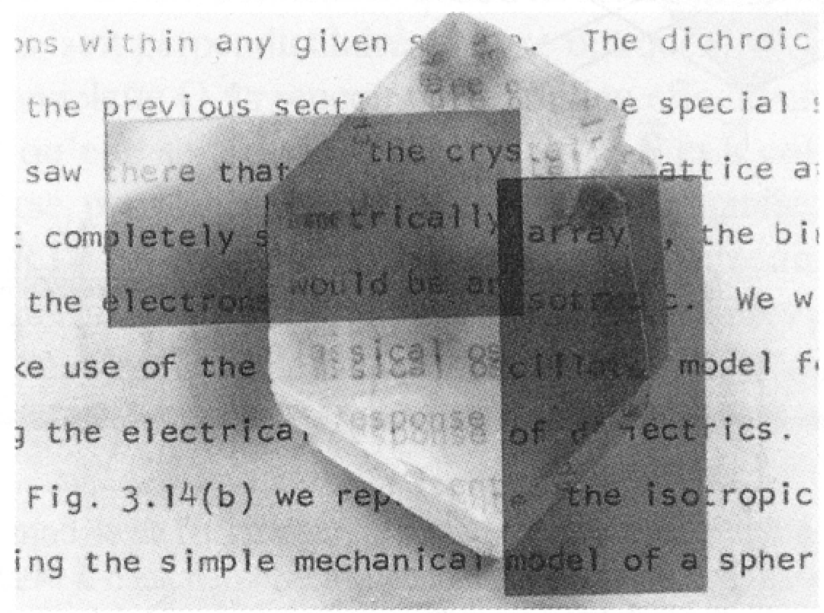
Etat de polarisation caractérisé par ses *paramètres de Stokes* :

$$\begin{aligned}
I &= a_1^2 + a_2^2 \\
Q &= a_1^2 - a_2^2 = I\cos(2\chi)\cos(2\psi) \\
U &= 2a_1a_2\cos(\varphi) = I\cos(2\chi)\sin(2\psi) \\
V &= 2a_1a_2\sin(\varphi) = I\sin(2\psi) \\
I^2 &= Q^2 + U^2 + V^2
\end{aligned}$$

Degre

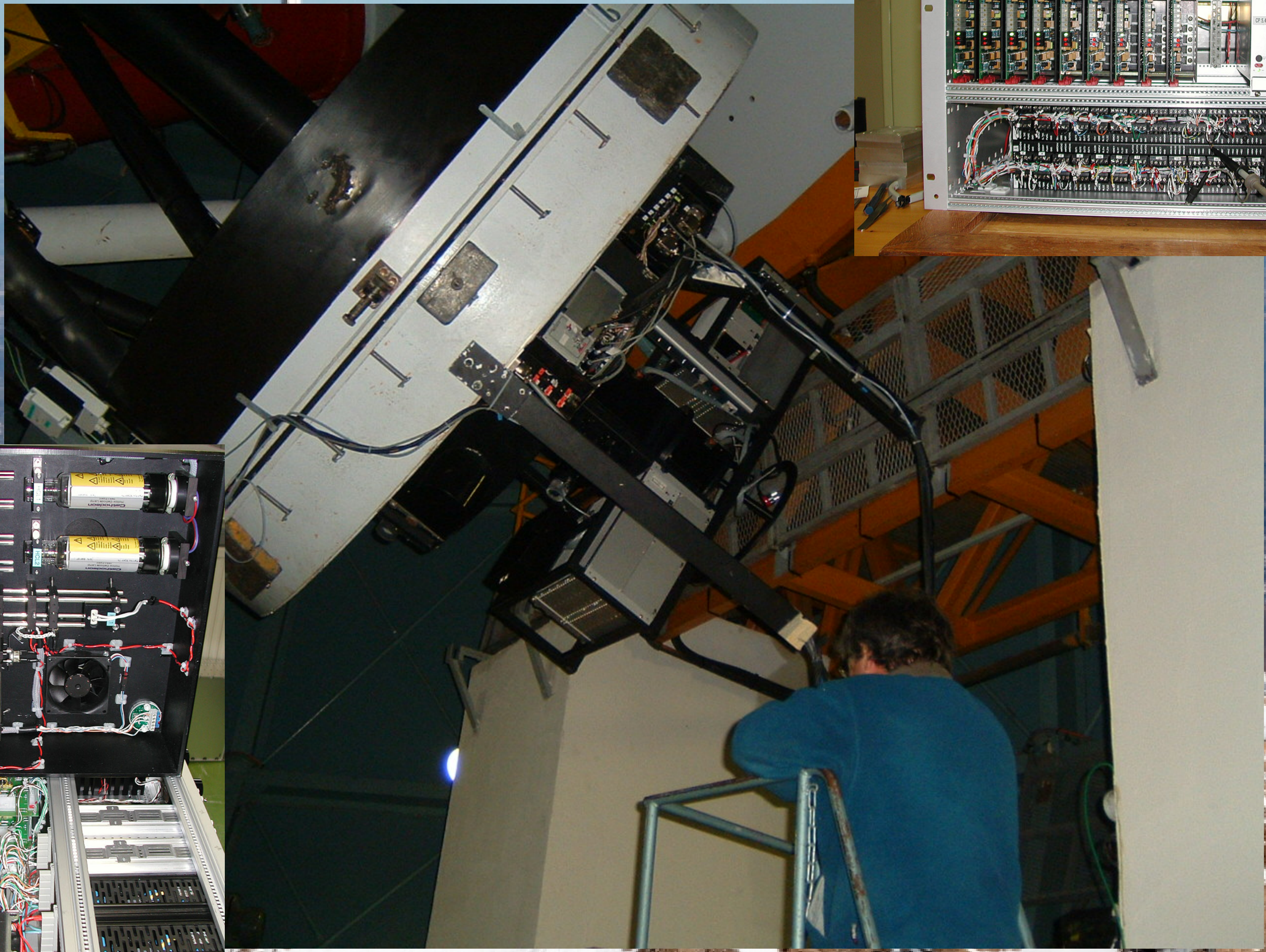
Tableau 8.1 Indices de réfraction de quelques cristaux uniaxes biréfringents (λ_0 = 589,3 nm)

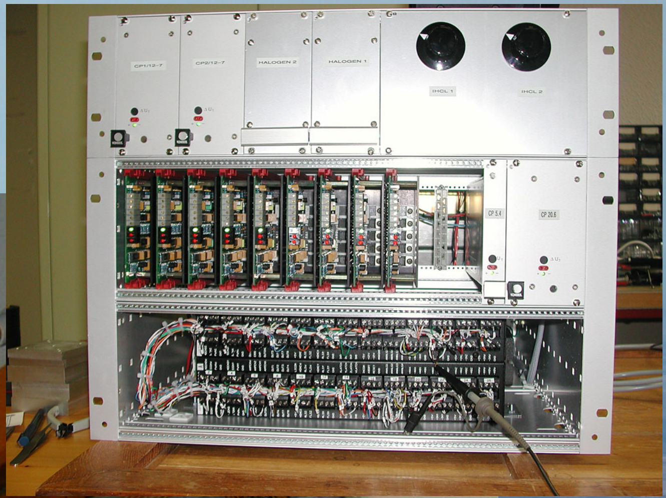
Cristal	n_o	n_e
Tourmaline	1,669	1,638
Calcite	1,6584	1,4864
Quartz	1,5443	1,5534
Nitrate de sodium	1,5854	1,3369
Glace	1,309	1,313
Rutile (TiO_2)	2,616	2,903

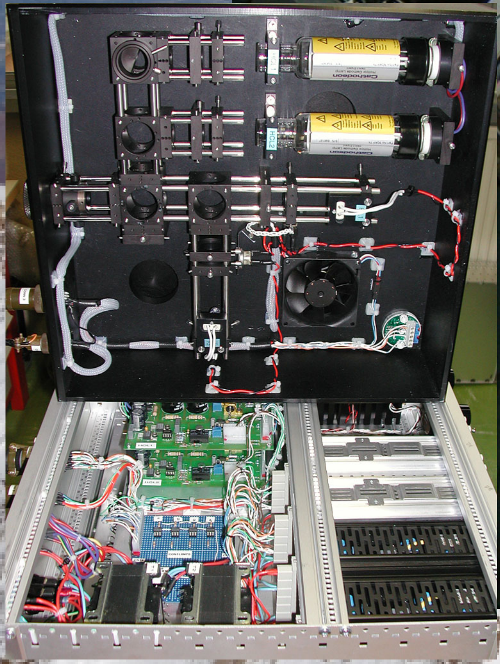


Un cristal de calcite (le coin non saillant est en bas). Les axes de transmission des deux polariseurs sont parallèles à leurs petits côtés. Là où l'image est double, celle du bas, non défléchie, est l'image ordinaire. Regarder attentivement cette image : il y a beaucoup à voir. (Photo E.H.)

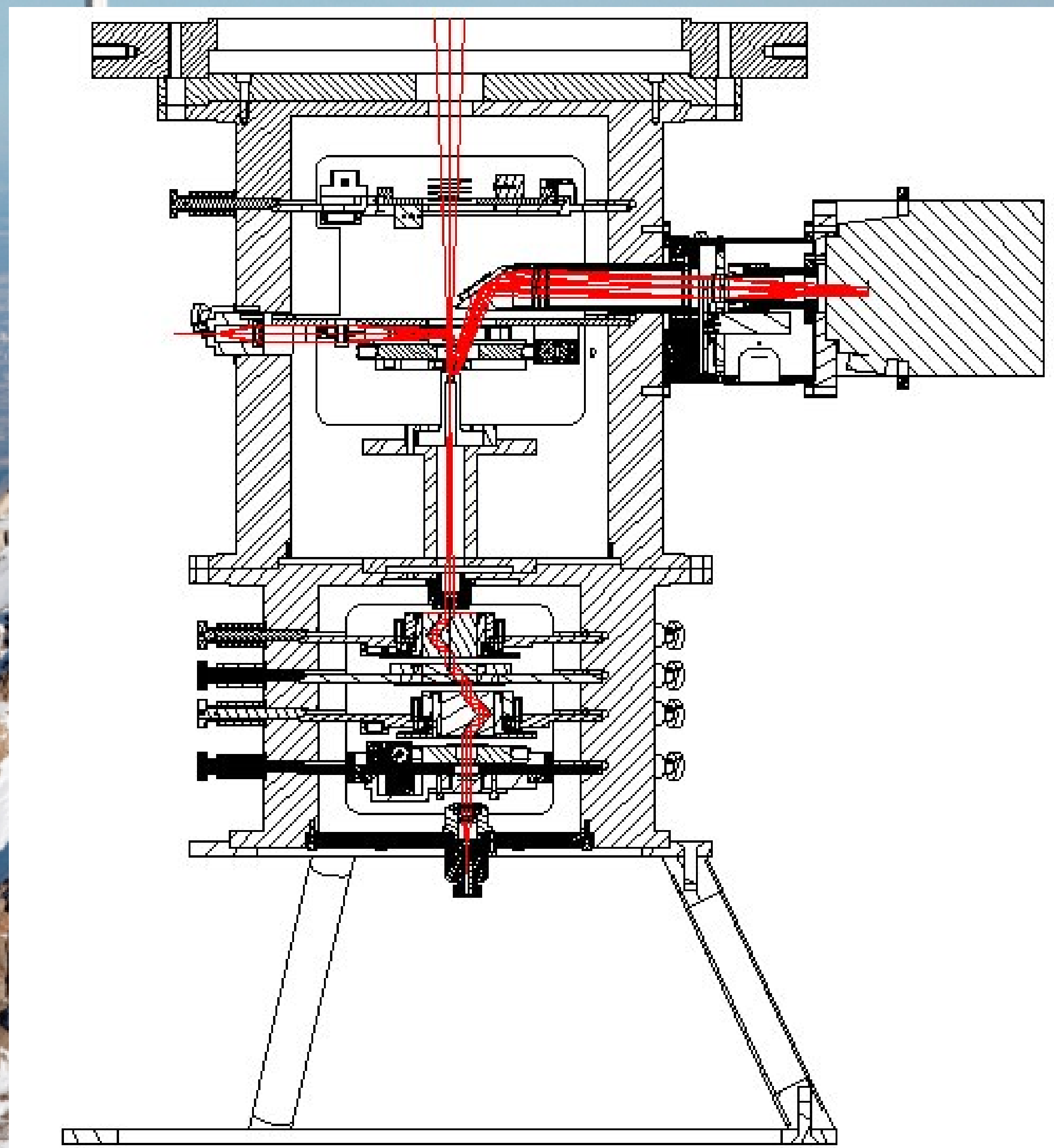
… and a Polarimeter







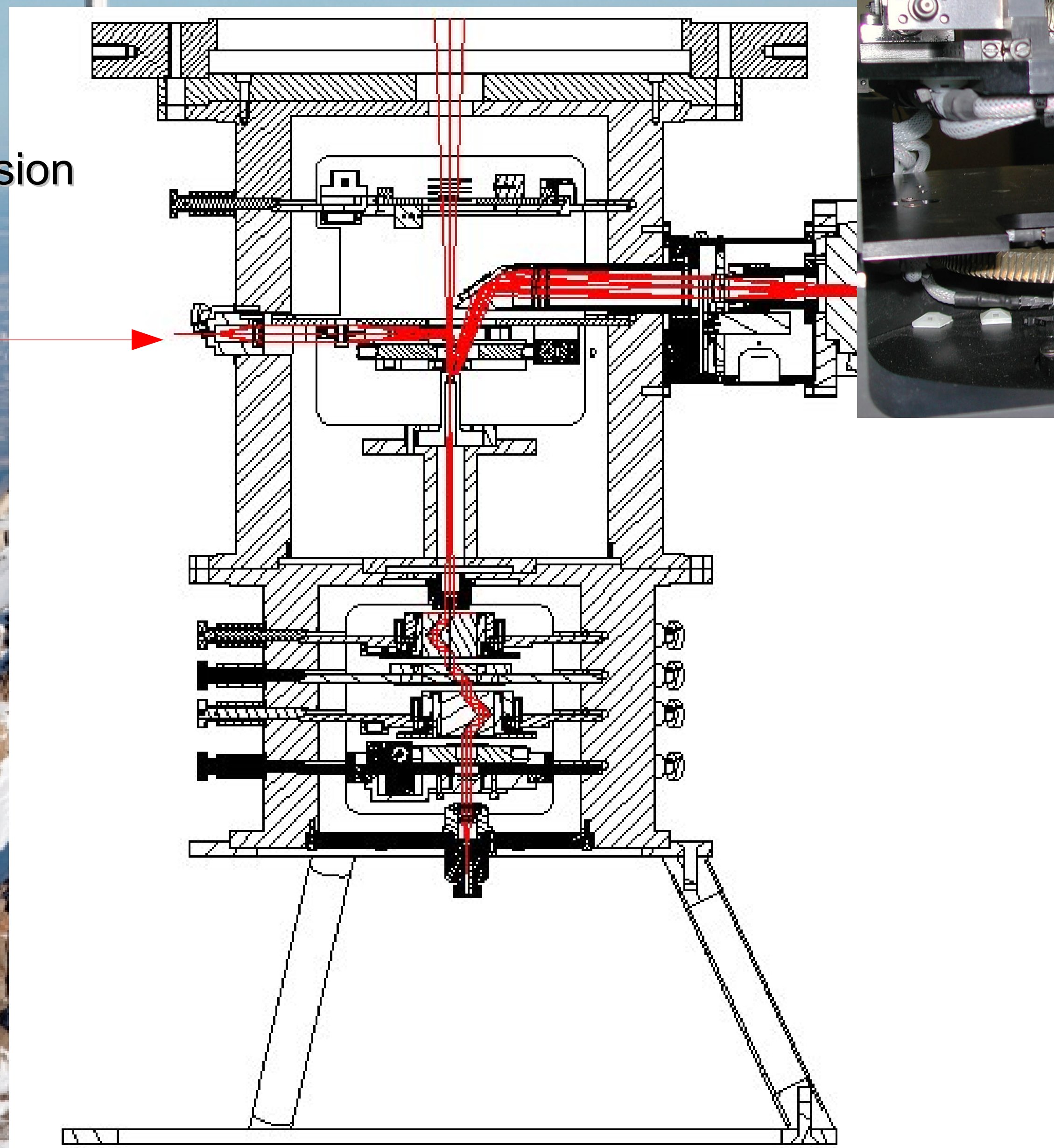
… and a Polarimeter

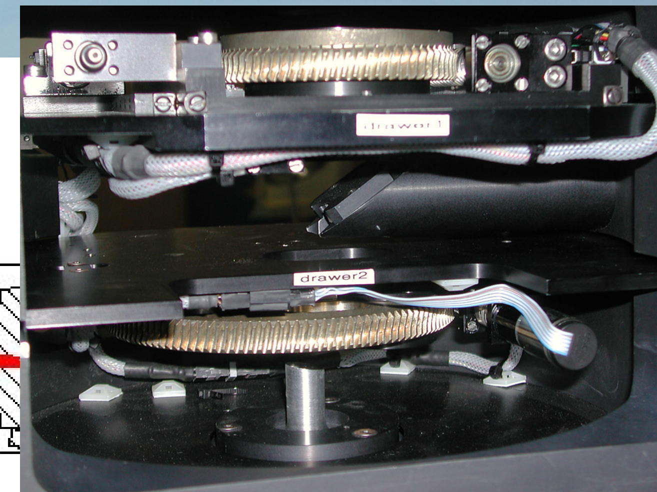


… and a Polarimeter

Atmospheric Dispersion Corrector (ADC)

Calibration Unit



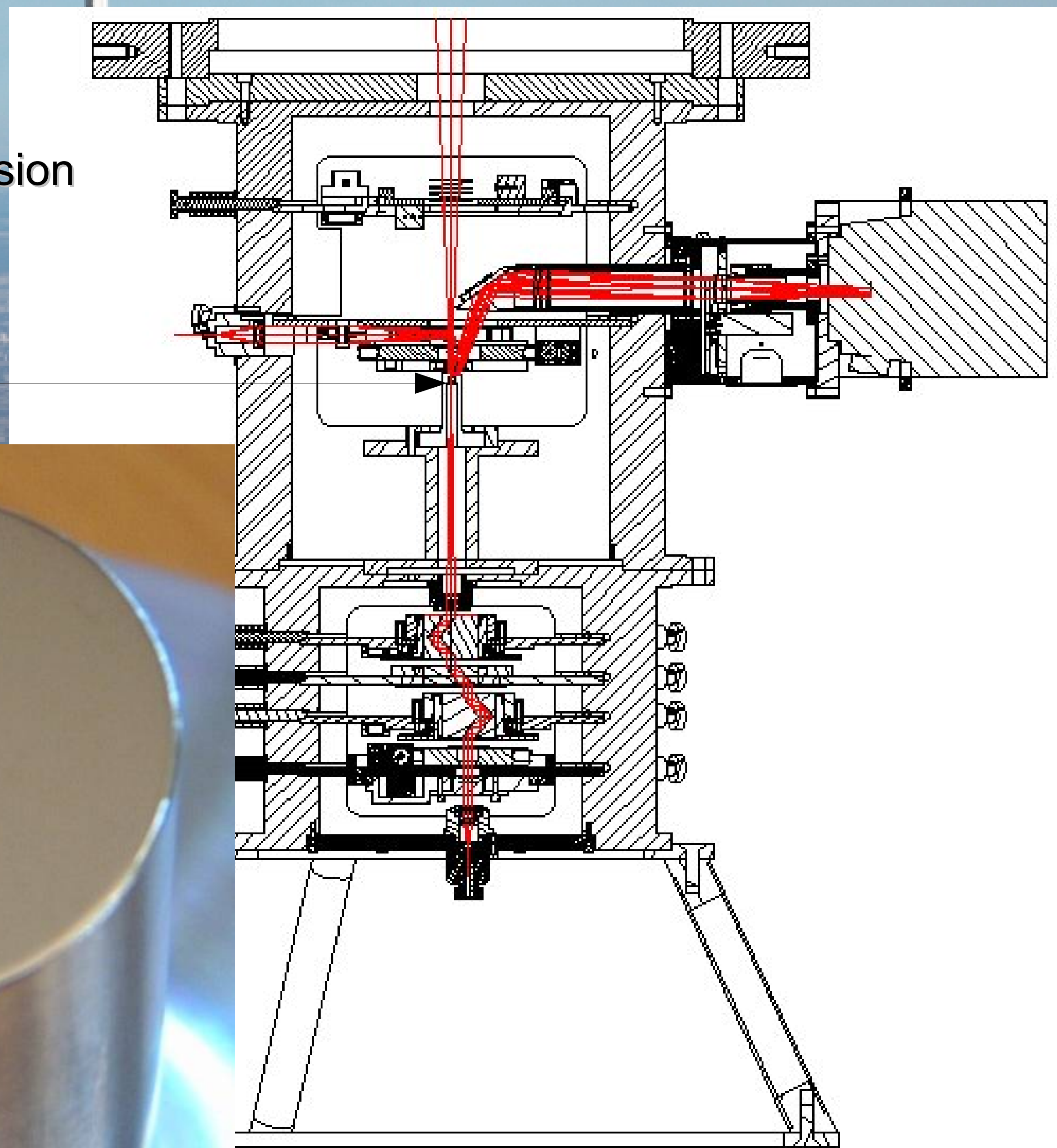


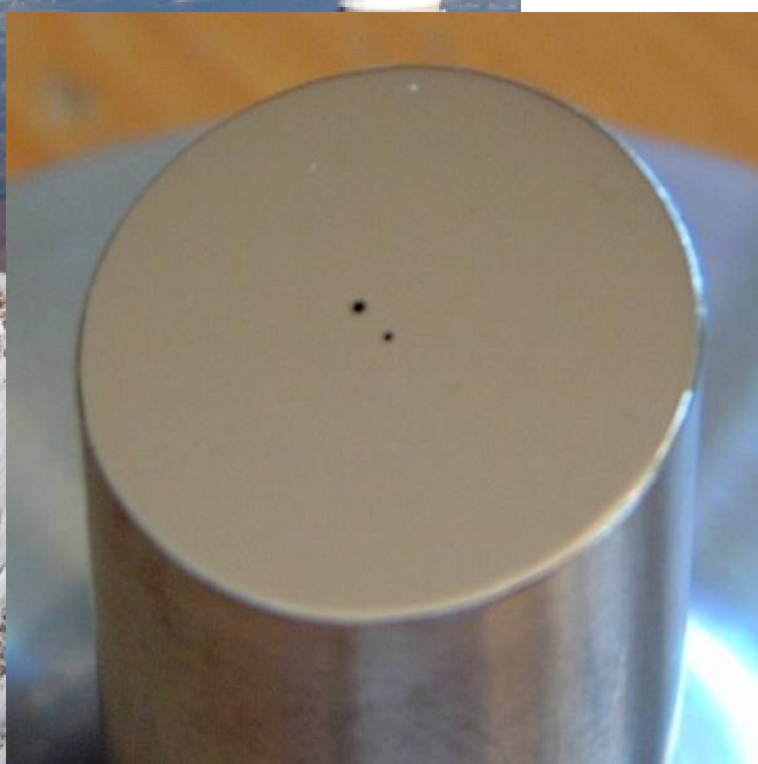
… and a Polarimeter

Atmospheric Dispersion Corrector (ADC)

Calibration Unit

Mirror pupil





Guiding

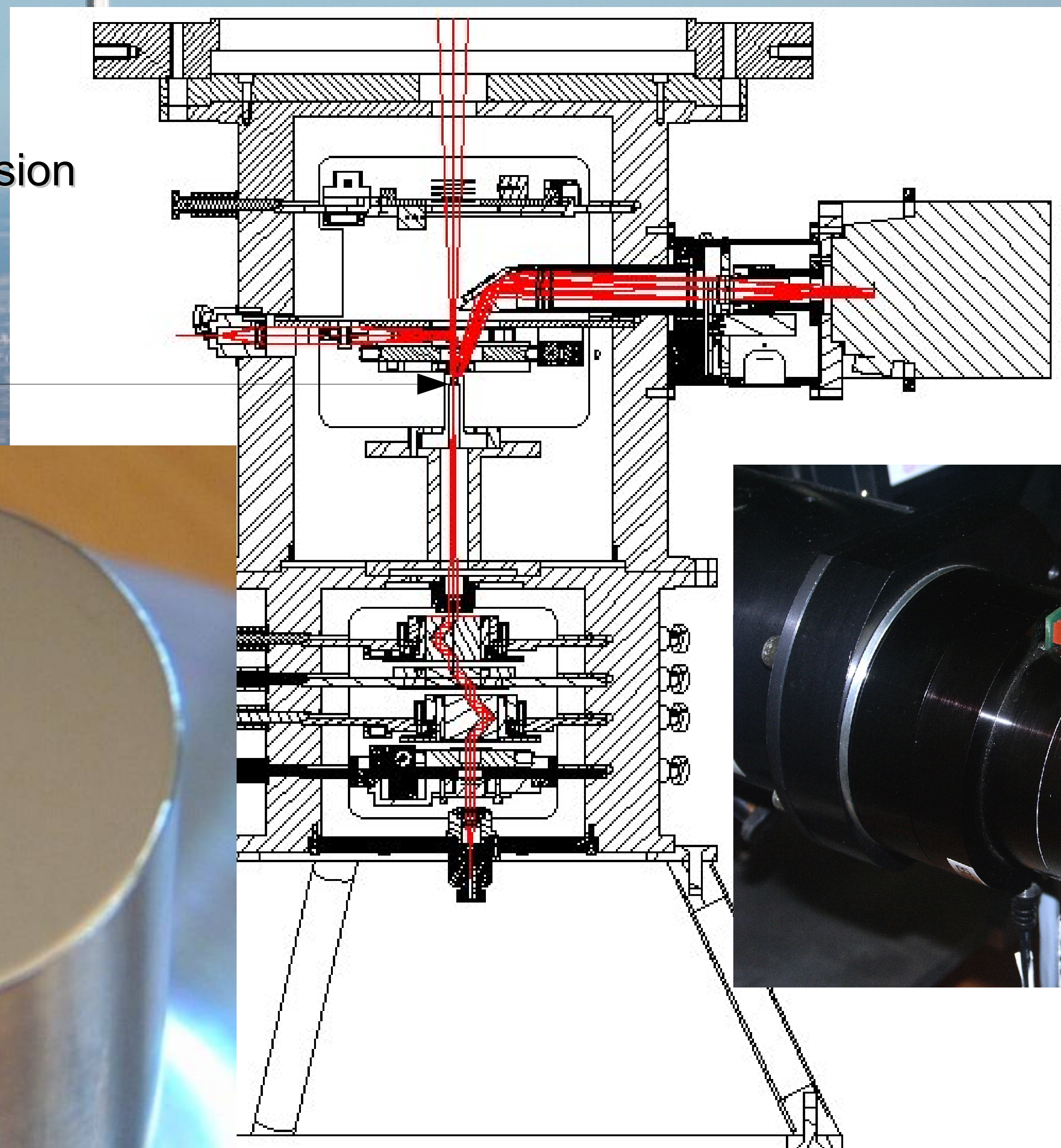
… and a Polarimeter

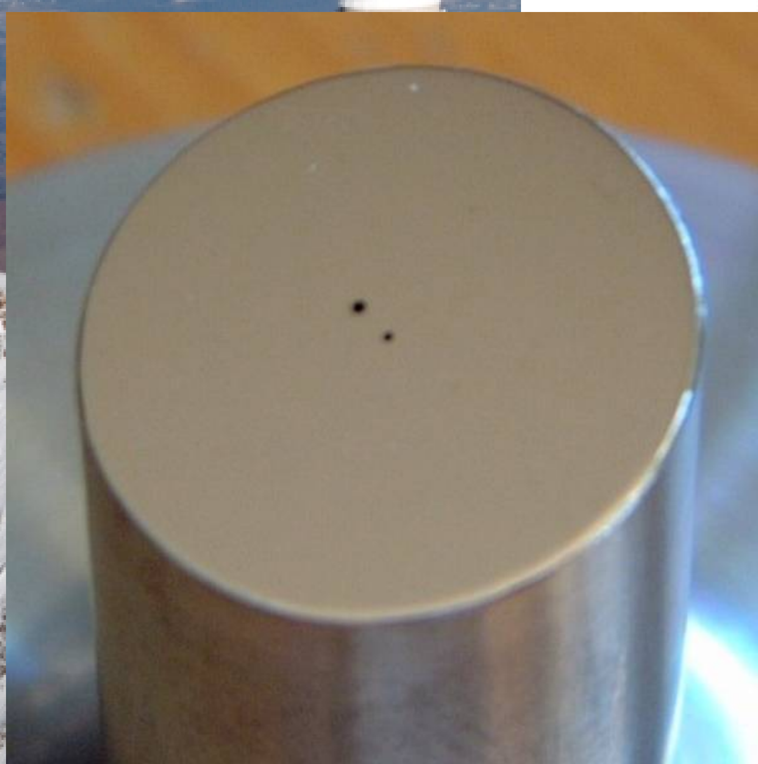
Atmospheric Dispersion Corrector (ADC)

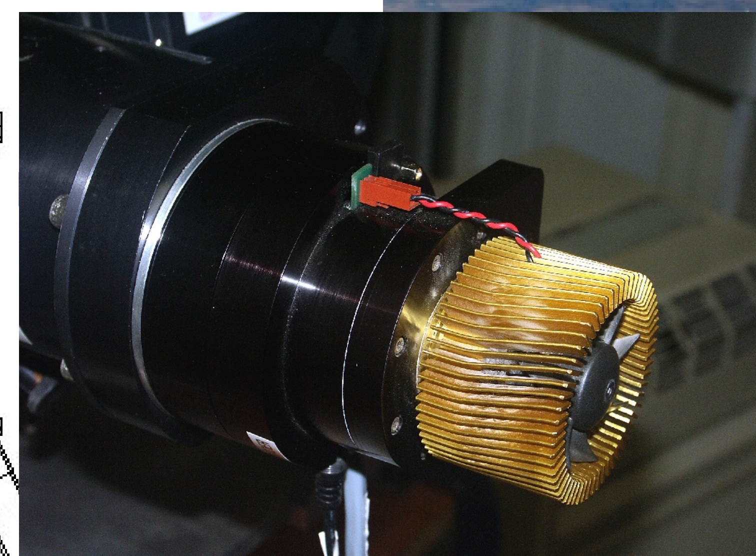
Calibration Unit

Mirror pupil

Guiding



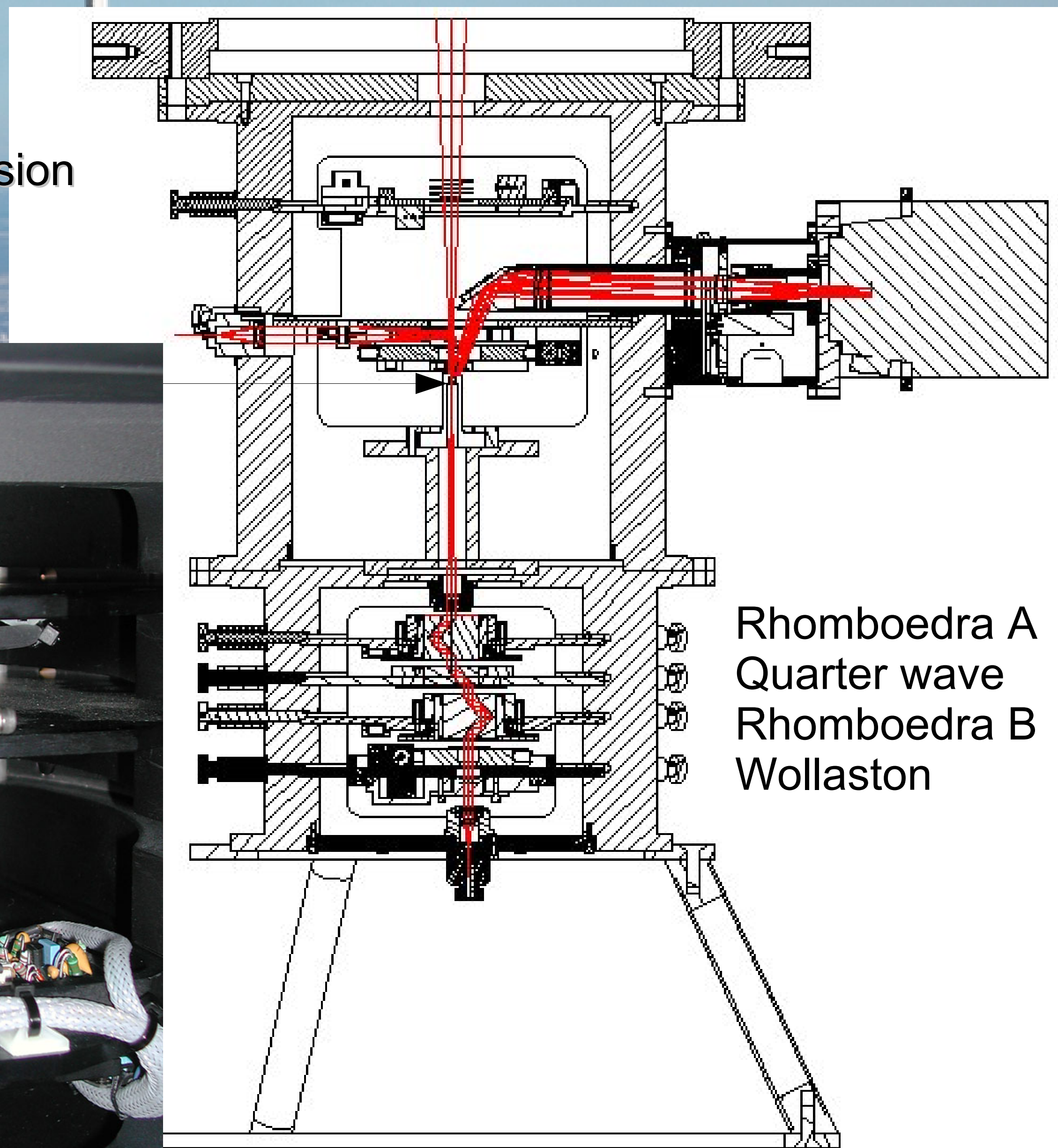




… and a Polarimeter

Atmospheric Dispersion Corrector (ADC)

Calibration Unit



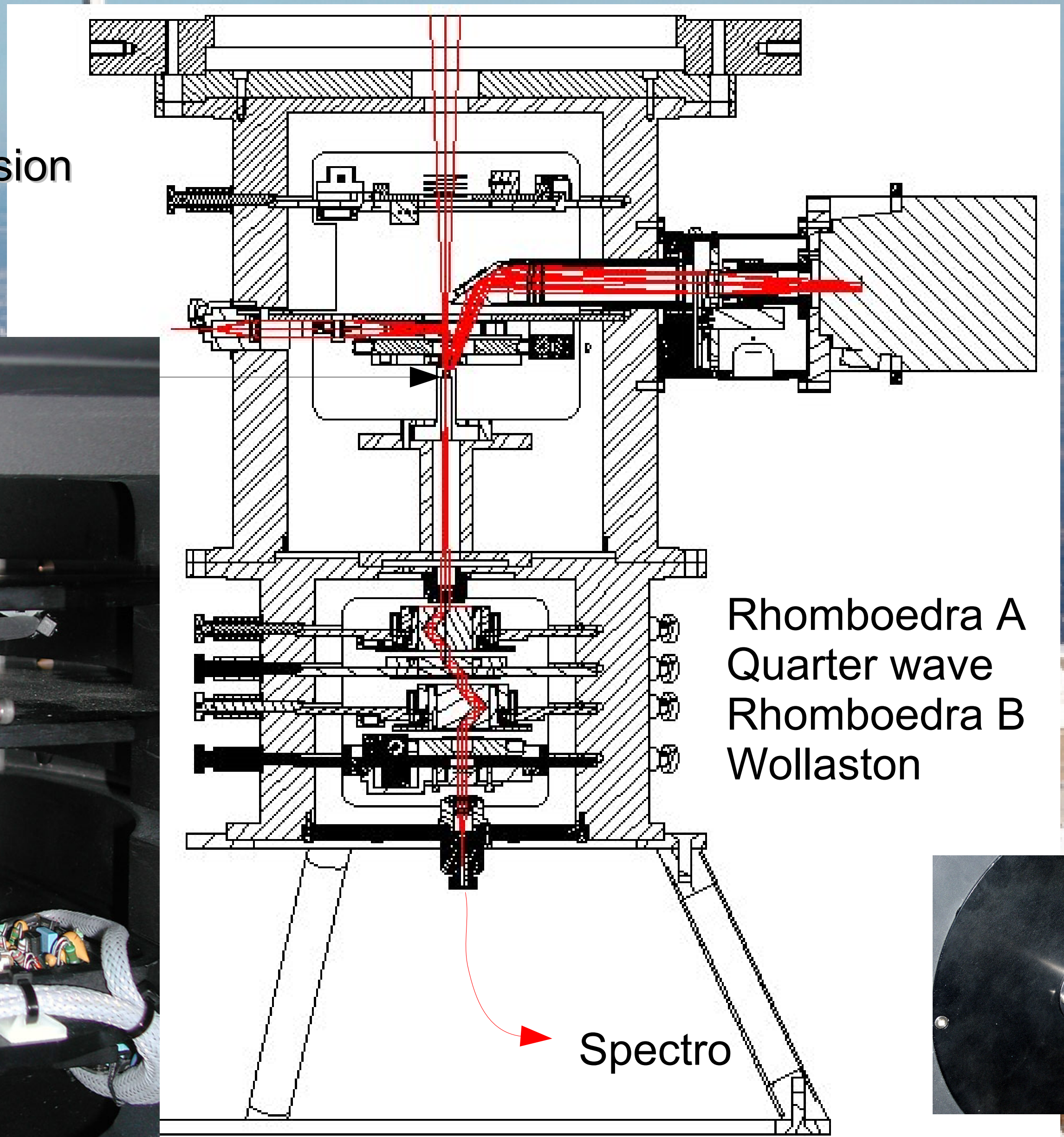
Guiding

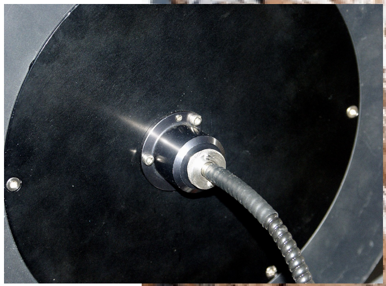
… and a Polarimeter

Atmospheric Dispersion Corrector (ADC)

Calibration Unit

Guiding





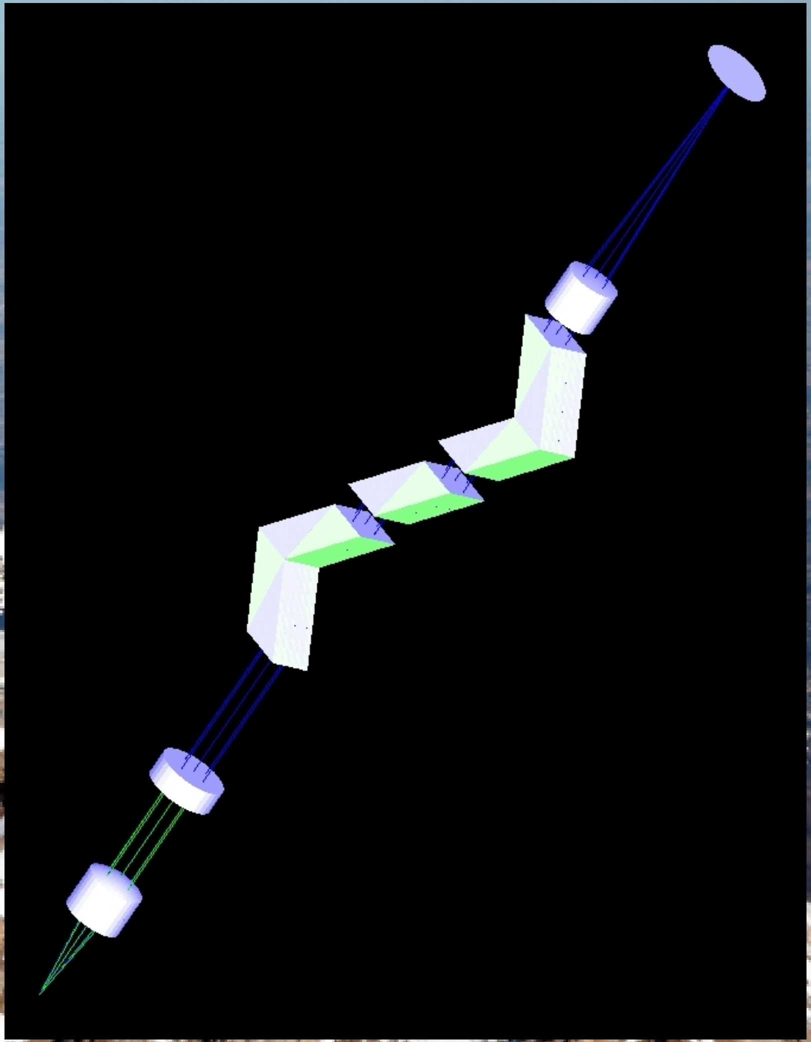
How to measure polarisation

Measure of light polarisation (usually on the optical axis Cassegrain!):

A- Classical Method : spatial and temporal modulation

A filter must be introduced on the post-focal beam -> extract polarisation in a given direction.

Filter: series of movable polarising optical components and a Birefringent plate (e.g. Calcite $CaCO_3$) to separate orthogonal polarisation channels.



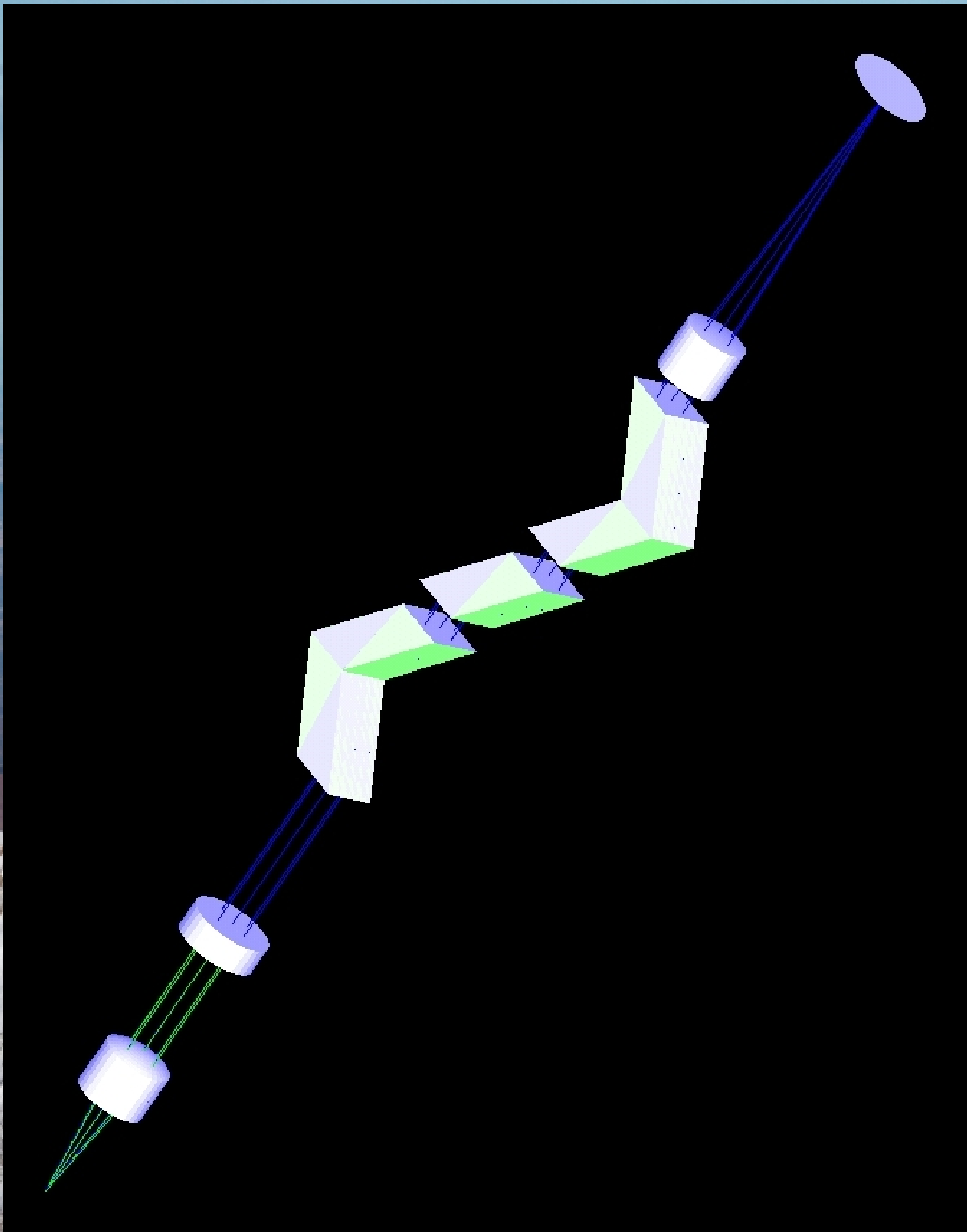
Astrophysical object polarisation is small (~1%) -> Differential methods work better.

Examples of polarimeters :

Narval (Telescope Bernard Lyot, Donati et al.)

PEPSI (Large Binocular Telescope, Strassmeier et al.)

HARPS pol (ESO 3.6 ; Snik et al., ZIMPOL)



Fresnel rhomboedra (half-wave)

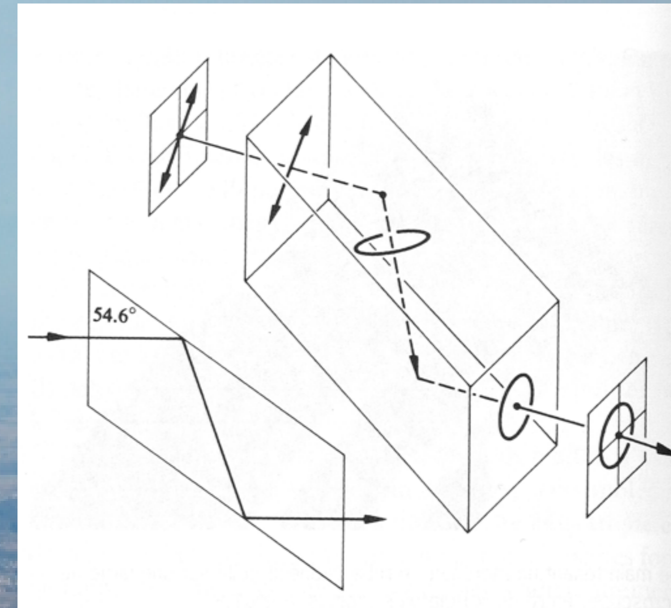


Figure 8.41 Rhomboèdre de Fresnel.

Quarter-wave

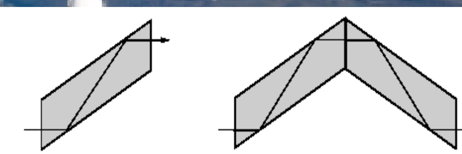
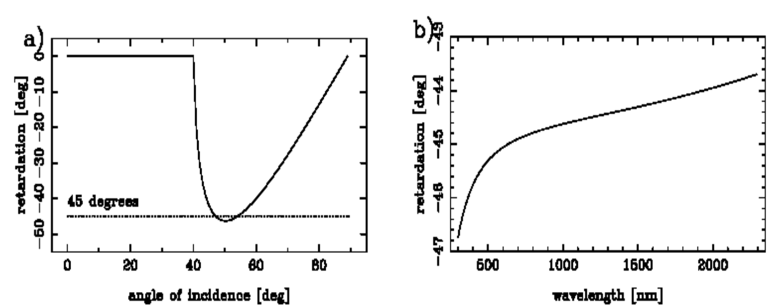
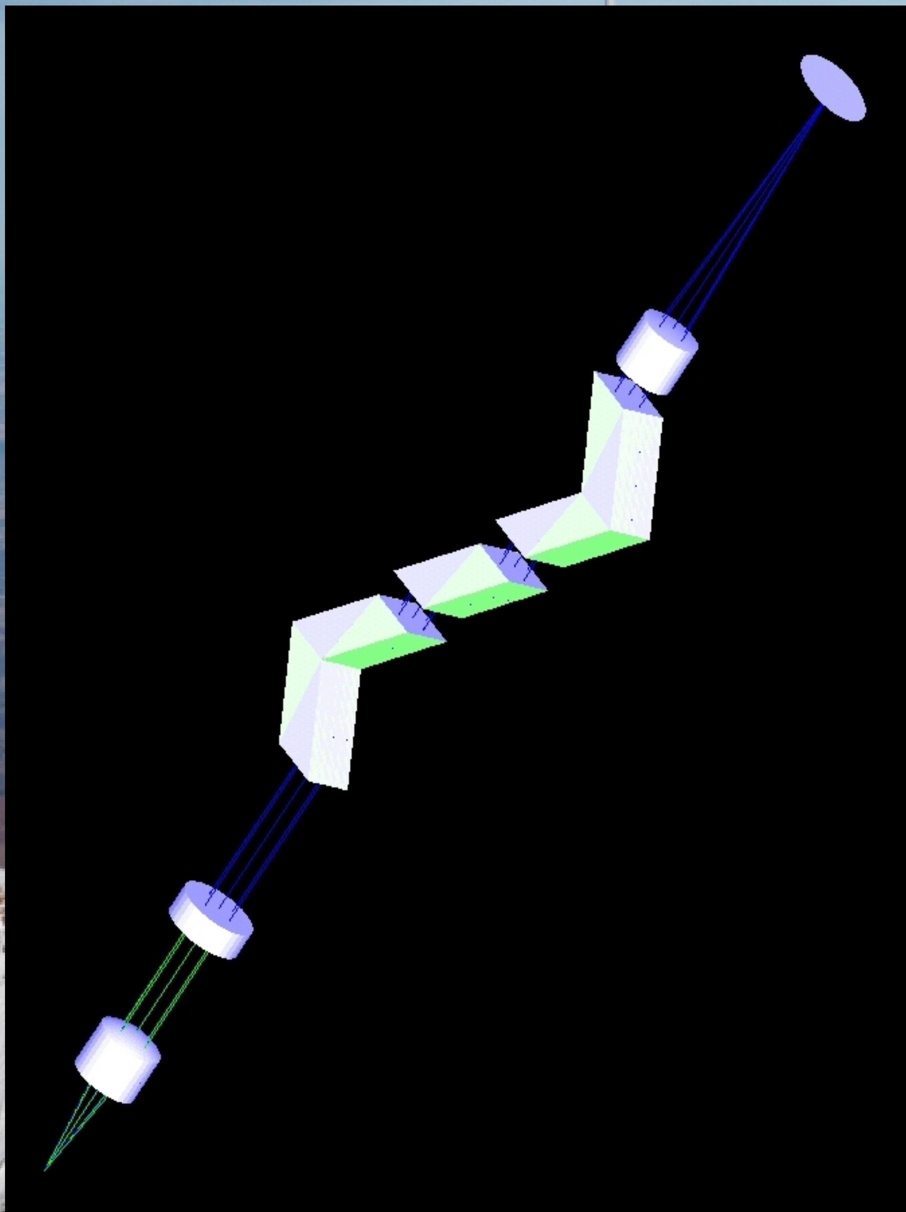


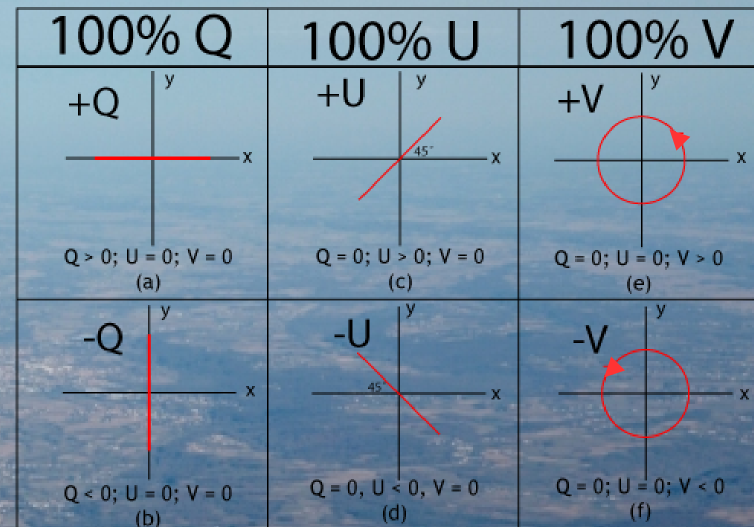
FIGURE 8. Traditional arrangements for quarter-wave (left) and half-wave (right) Fresnel rhombs.



Final signal always in linear polarization



Polarisation parametrized through the Stokes parameters (E Field pola.):



4 rel. pos. of Rhomb A, B and λ/4 plate leads to 4 pairs of orthogonally polarized spectra

Polarized spectrum

$$\frac{P}{I} = \frac{R-1}{R+1},$$

where

$$R^4 = \frac{i_{1,\perp}/i_{1,\parallel}}{i_{2,\perp}/i_{2,\parallel}} \frac{i_{4,\perp}/i_{4,\parallel}}{i_{3,\perp}/i_{3,\parallel}}$$

Null spectra

$$R^4 = \frac{i_{1,\perp}/i_{1,\parallel}}{i_{4,\perp}/i_{4,\parallel}} \frac{i_{3,\perp}/i_{3,\parallel}}{i_{2,\perp}/i_{2,\parallel}},$$

$$R^4 = \frac{i_{1,\perp}/i_{1,\parallel}}{i_{4,\perp}/i_{4,\parallel}} \frac{i_{2,\perp}/i_{2,\parallel}}{i_{3,\perp}/i_{3,\parallel}}.$$

Operations with TBL/Narval

Narval is operated since 2007... popular (pressure 2-3)

Offers 3 modes of operations:

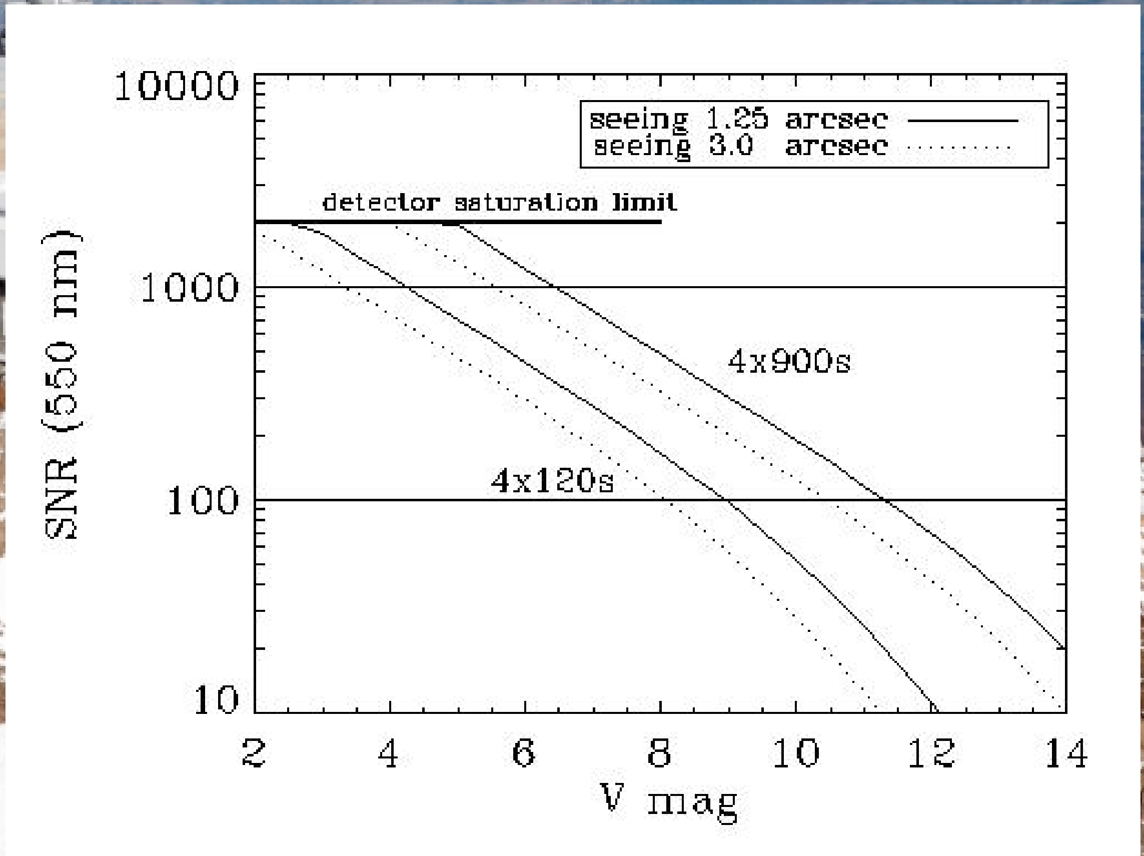
- Spectroscopic mode star only, resolution ~ 77000
- Spectroscopic mode star+sky, resolution ~ 65000
- Polarimetric mode: Q U or V, resolution ~ 65000

Sensitivity of TBL/Narval:

S/N = 100 in 1h V=12

Specialized in

bright objects!



Operations with TBL/Narval

TBL is run in Queue service observing:

End-to-end data processing:

- call for proposals (next deadline 2016A → 10 oct 15)
http://northstar.bagn.obs-mip.fr:8080/

- Service Observers (training of young astronomers)

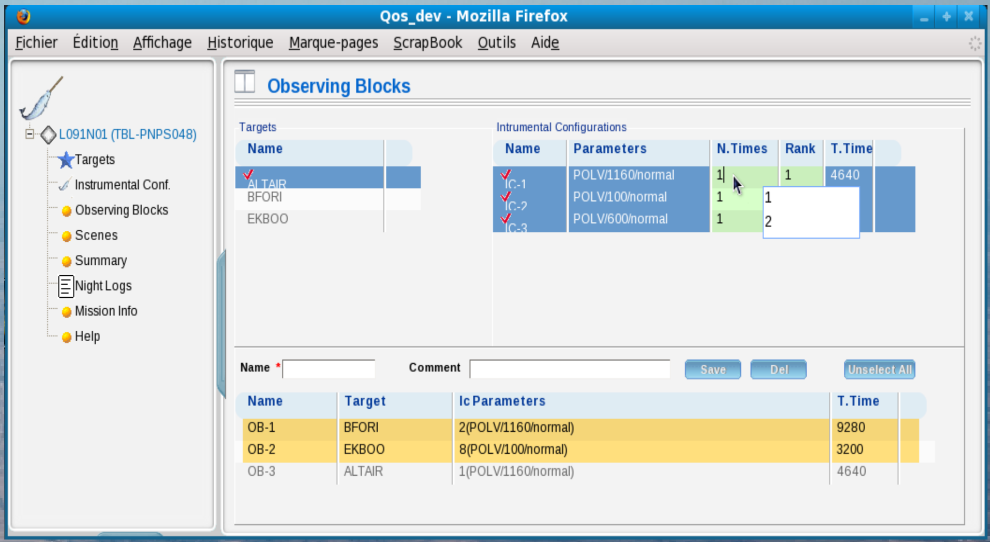
- Complete quality control and data processing: delivers reduced normalized/unormalized 1D spectra + error

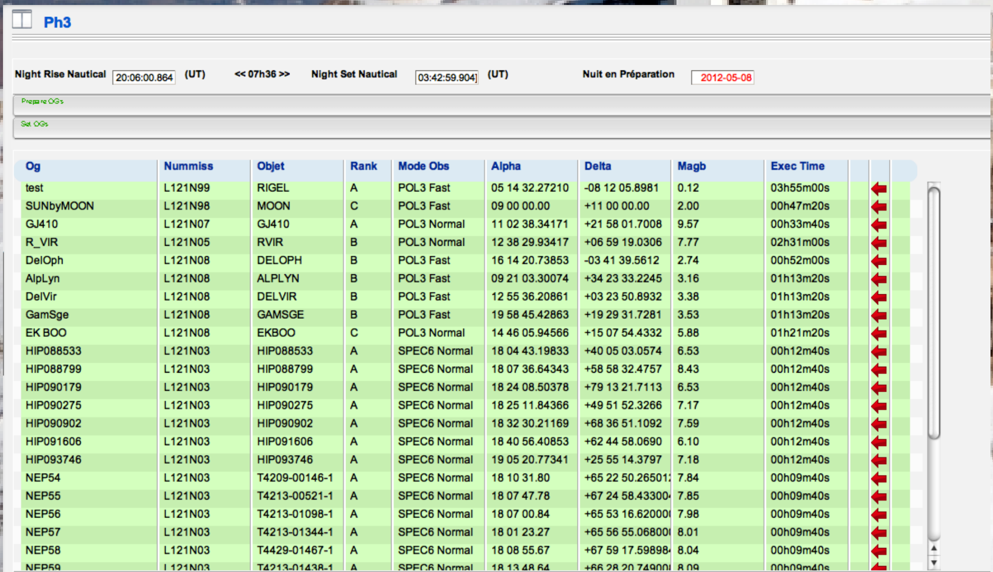
- Higher level tools (Least-Square Deconvolution)

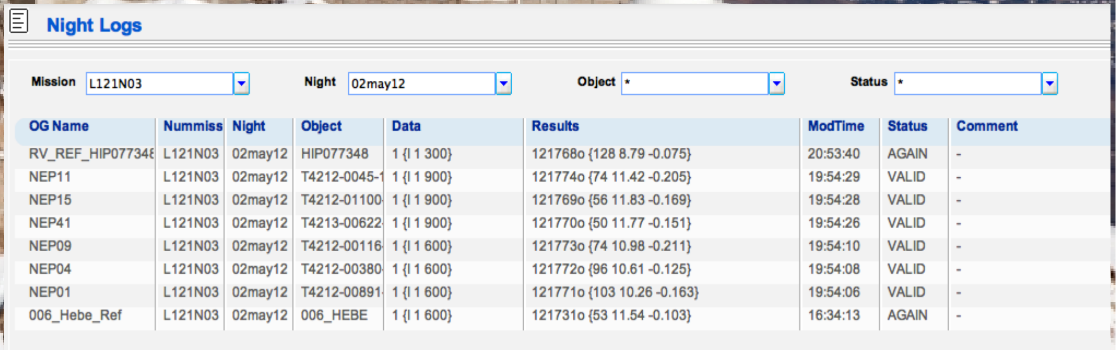
- TBL/Narval reduced data are released 1yr after PI release (for Intensity spectra, 2 yr for polar data), fully compliant with VO spec

www.sciops.esa.int/index.php?project=ESAVO&page=vospec

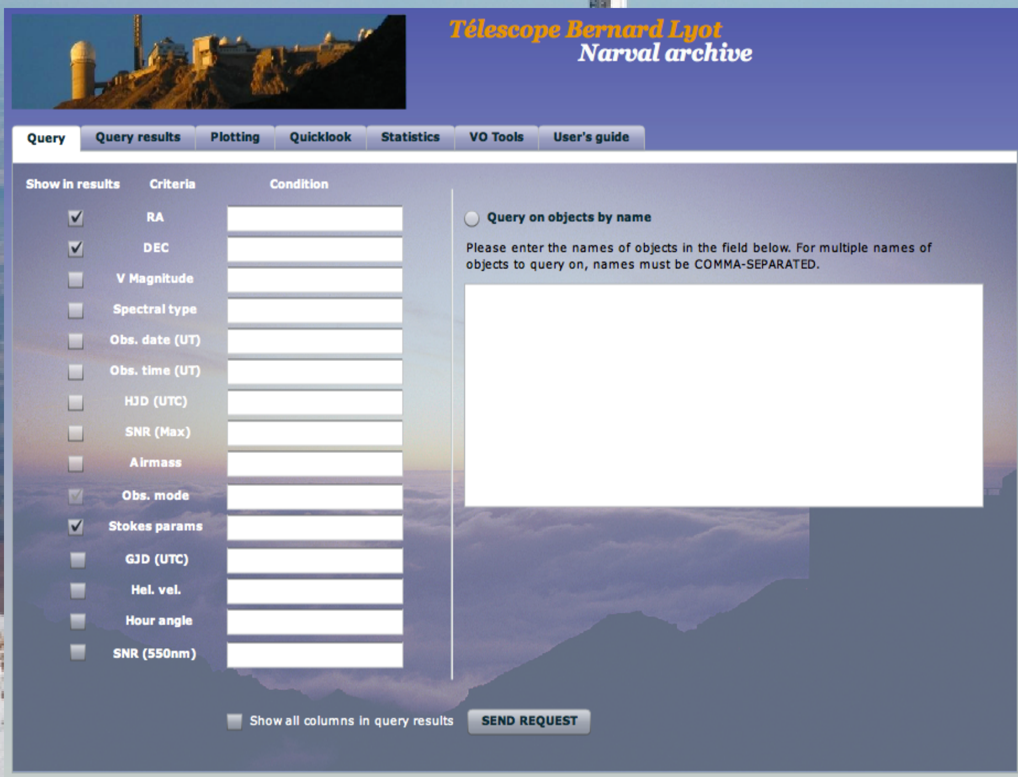
Operations with TBL/Narval

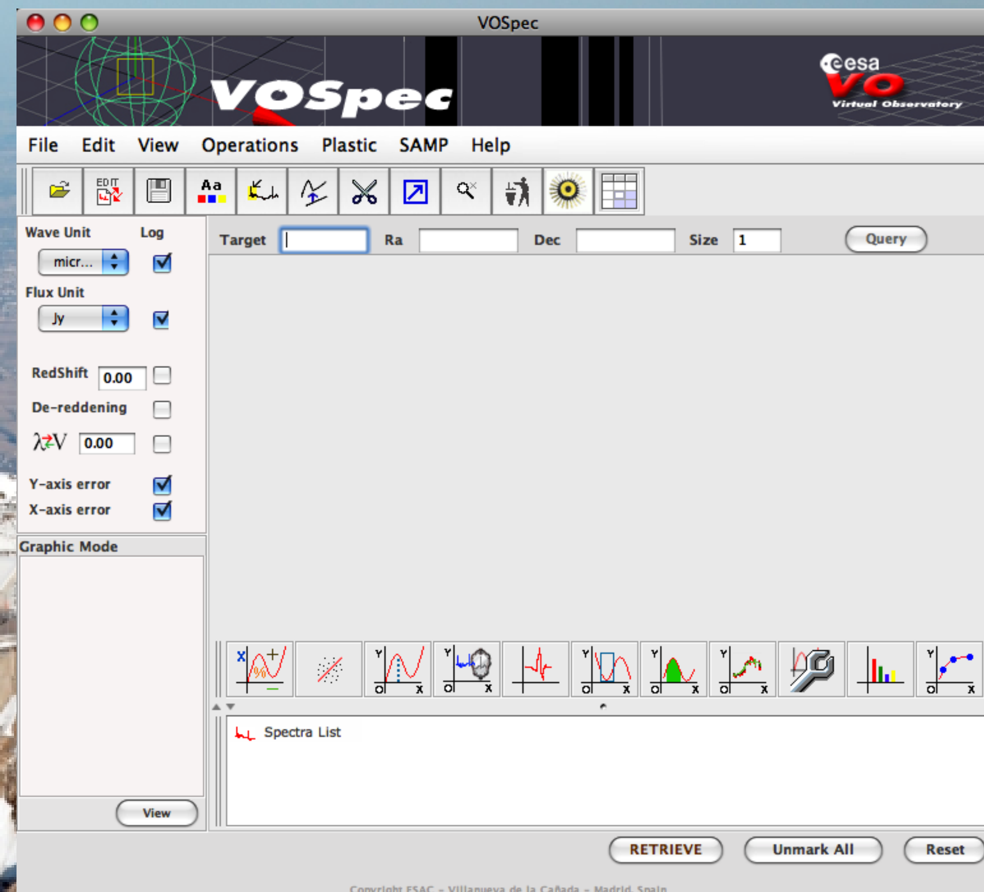






Operations with TBL/Narval





Proposed Training sessions with TBL/Narval

Create an observing block through TBL/PH2

Start the observing night on TBL/narval

- Remote control of Narval
- Calibrations

Observations of an Alpha CVn star (highly polarised) with TBL
(if weather allows!)

Data reduction of the observed stars (Done realtime and on my laptop)

Computation of Stokes parameters (Done on my laptop)

Computation of magnetic field (Done on my laptop)

Data mining on the same stars to measure polarization evolution
(if any) → Star $P_{rotation}$

- Saturday 15h-17h + 1h from sunset
- Tuesday 16h-18h30 + 1h from sunset

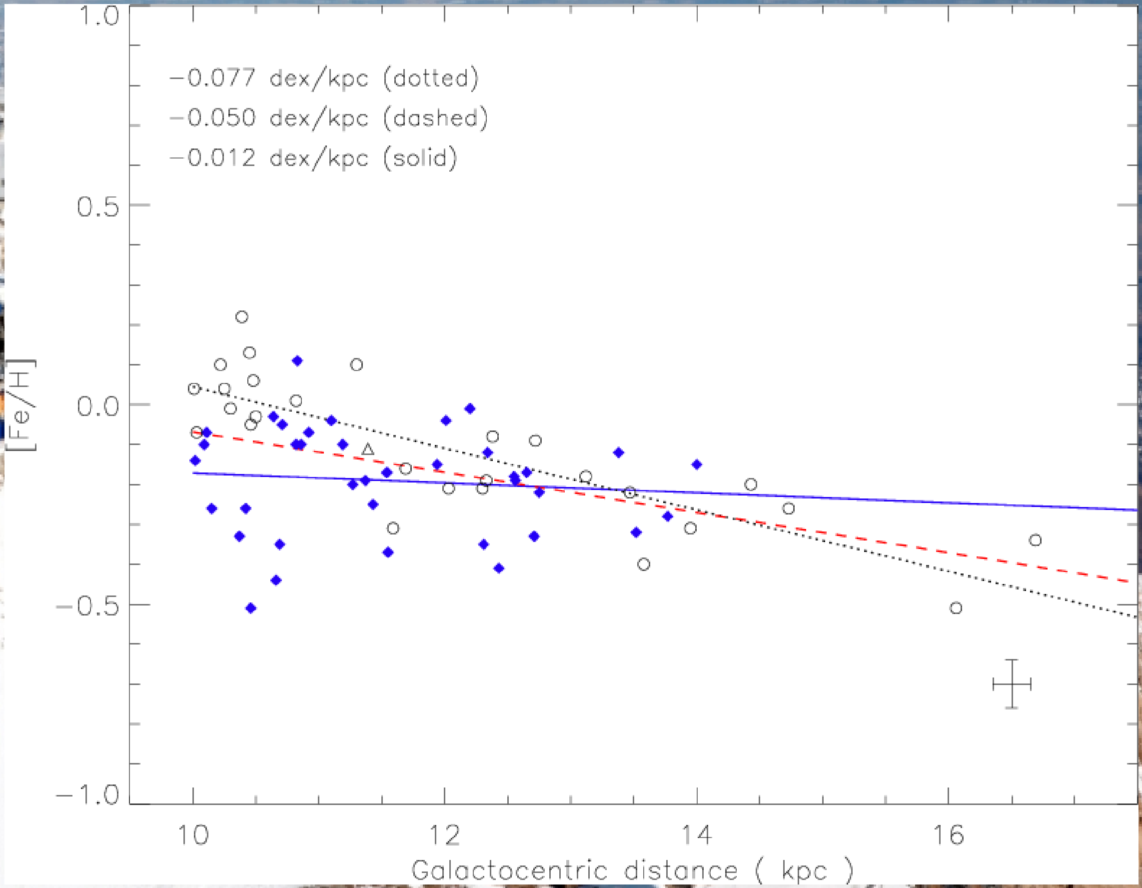
SCIENCE WITH NARVAL

Science with TBL/Narval

In Spectroscopy:

- Narval has a unique combination of resolution and sensitivity in the near IR for the preparation of GAIA. Large program dedicated to GAIA standard. (Soubiran et al): 12 n/yr

- Cepheid studies (Lemasle et al 2008)



Science with TBL/Narval

In Spectroscopy:

- Narval has a unique combination of resolution and sensitivity in the near IR for the preparation of GAIA. Large program dedicated to GAIA standard. (Soubiran et al): 12 n/yr

- Cepheid studies (Lemasle et al 2008)

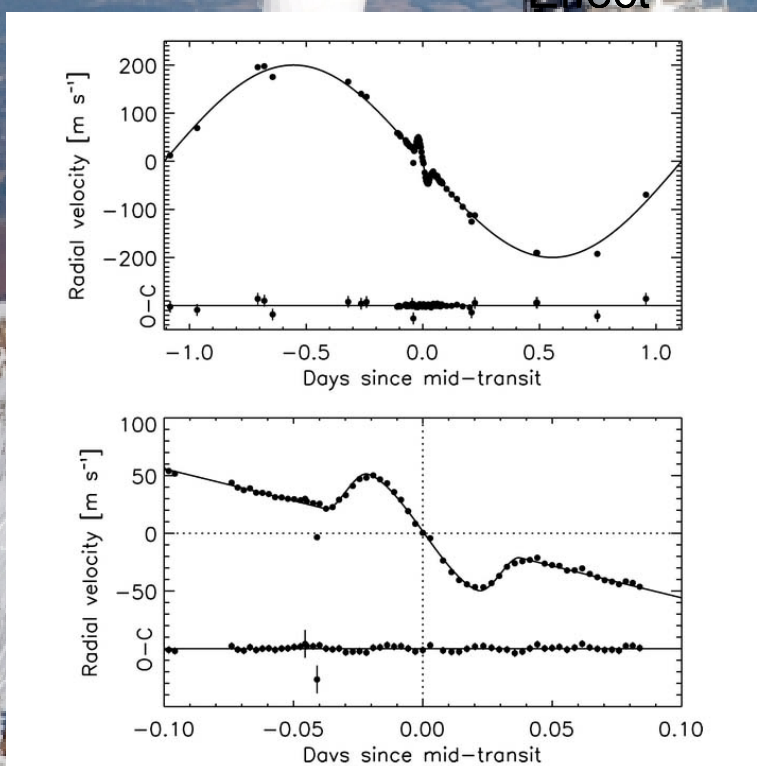
- Micro-structures in the ISM (~0.1-10 pc), by monitoring absorption line profile Evolution in bright stars Ca II (3933Å), Na I (5889, 5895Å) and K I (7698Å) at different epochs (Smoker et al., 2007) in the direction of star clusters or North Galactic Pole (Lallement et al.)

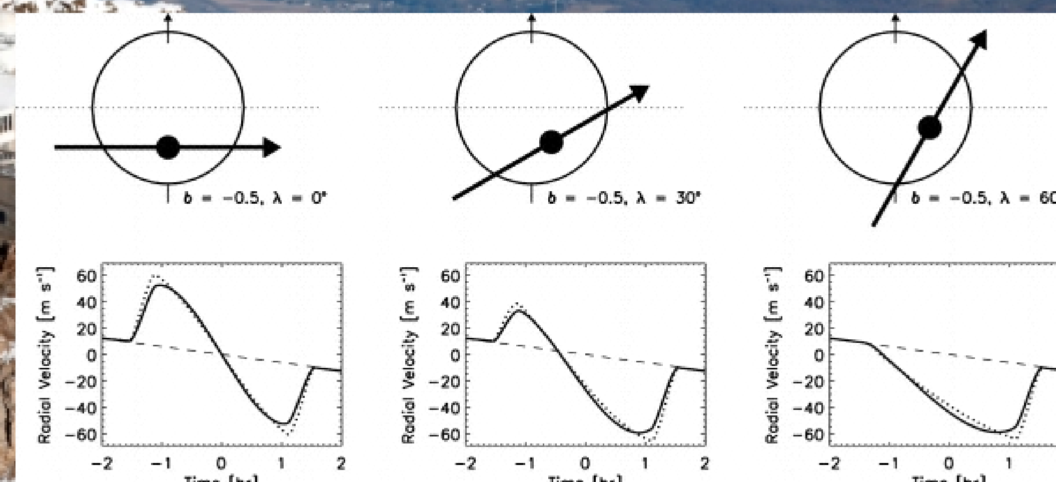
Science with TBL/Narval

In Spectroscopy:

- Planet studies: Moon eclipses (Ferlet et al.)
- Spectro follow-up exoplanet transits (Miller et al.)

The Rossiter-McLaughlin Effect





Science with TBL/Narval

In Spectroscopy:

- Planet studies: Moon eclipses (Vidal-Madjar, Ferlet, Gronoff et al.), Venus (Lilensten)

Moon eclipses: test of observability exoplanet atmospheres thru transit,
Next eclipse 31 dec 09

Detect water, methane, carbon dioxide, etc...

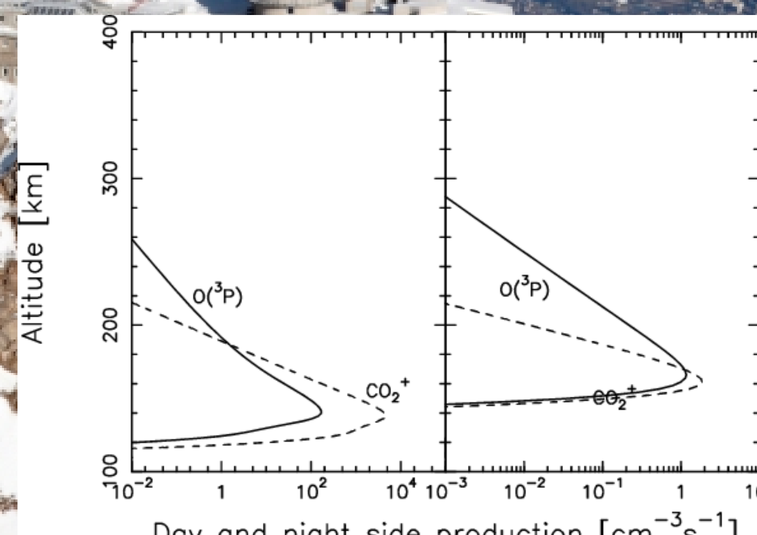
Science with TBL/Narval

In Spectroscopy/Polarimetry:

- Planet studies: Moon eclipses (Ferlet et al.), Venus (Lilensten, Gronoff ...)

Venus auroral emission/ Venus Express: combined observations

Is there any OI in the atmosphere of Venus? What differences between Venus night and day emissions?




Stellar magnetism
with
TBL/Narval

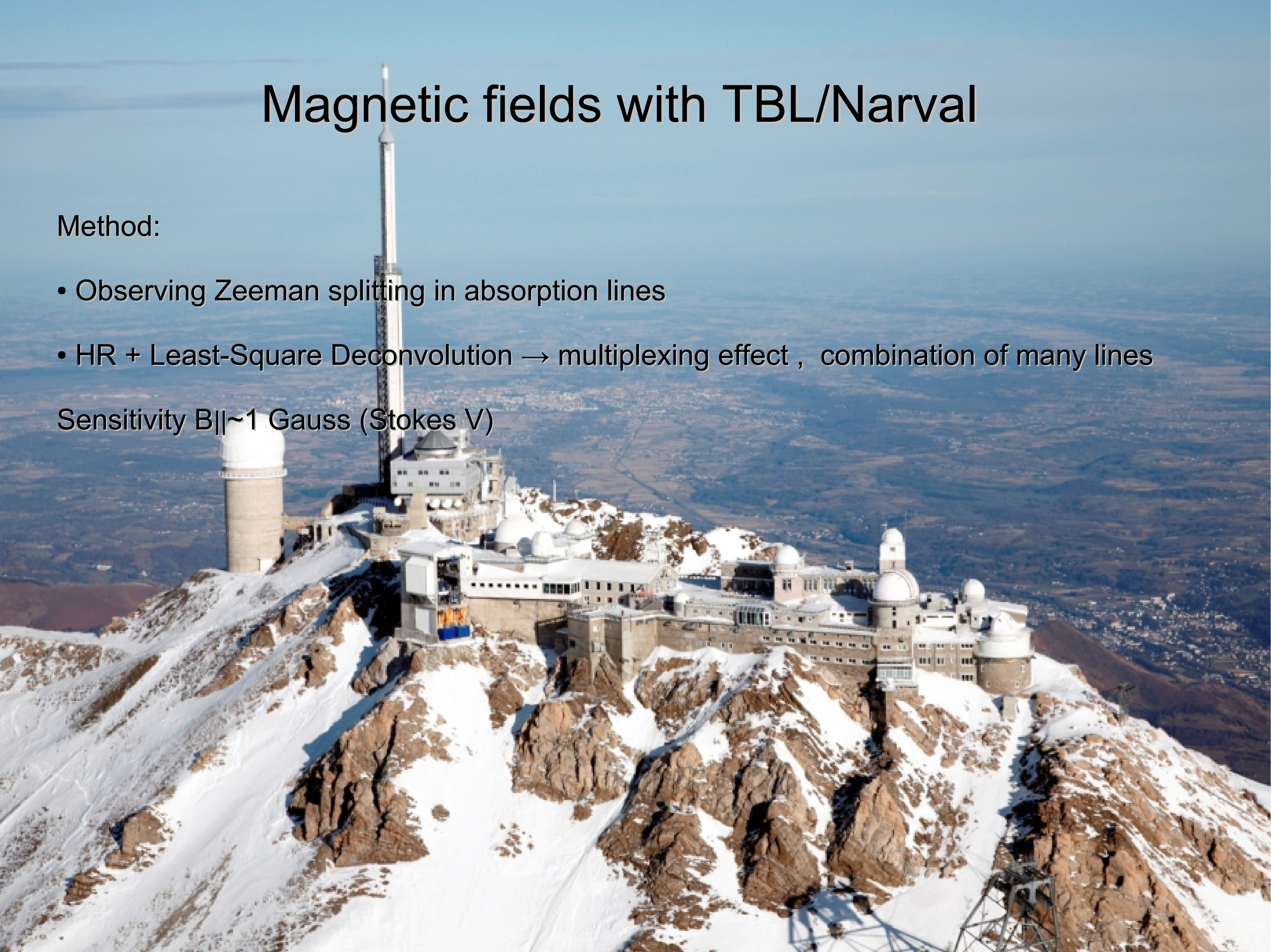
How do we measure stellar magnetic fields with Narval ?

Magnetic fields with TBL/Narval

Method:

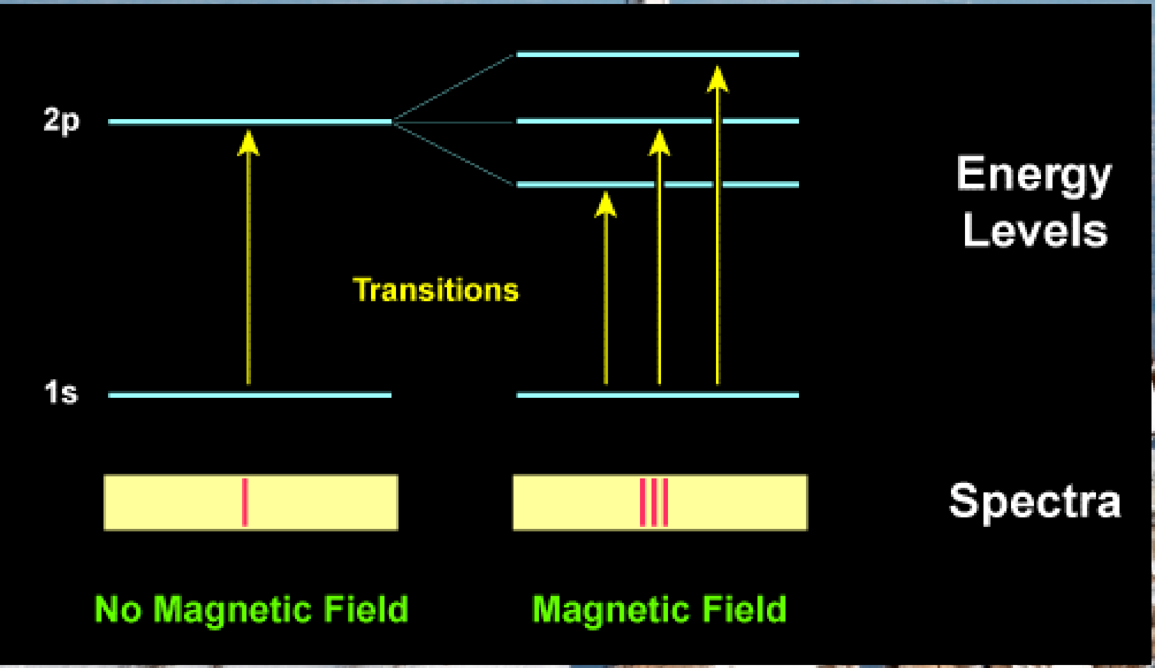
- Observing Zeeman splitting in absorption lines
- HR + Least-Square Deconvolution → multiplexing effect , combination of many lines

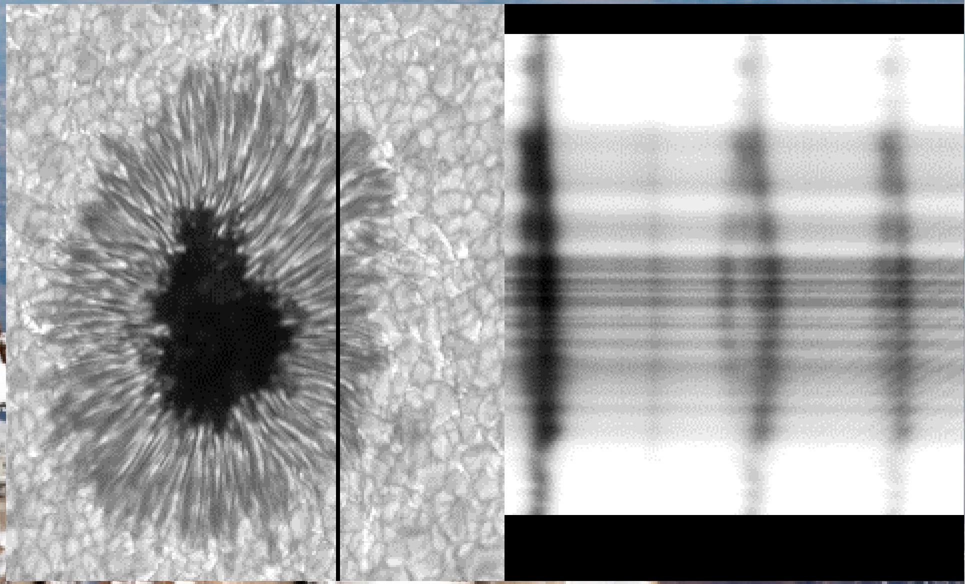
Sensitivity B||~1 Gauss (Stokes V)



Zeeman effect

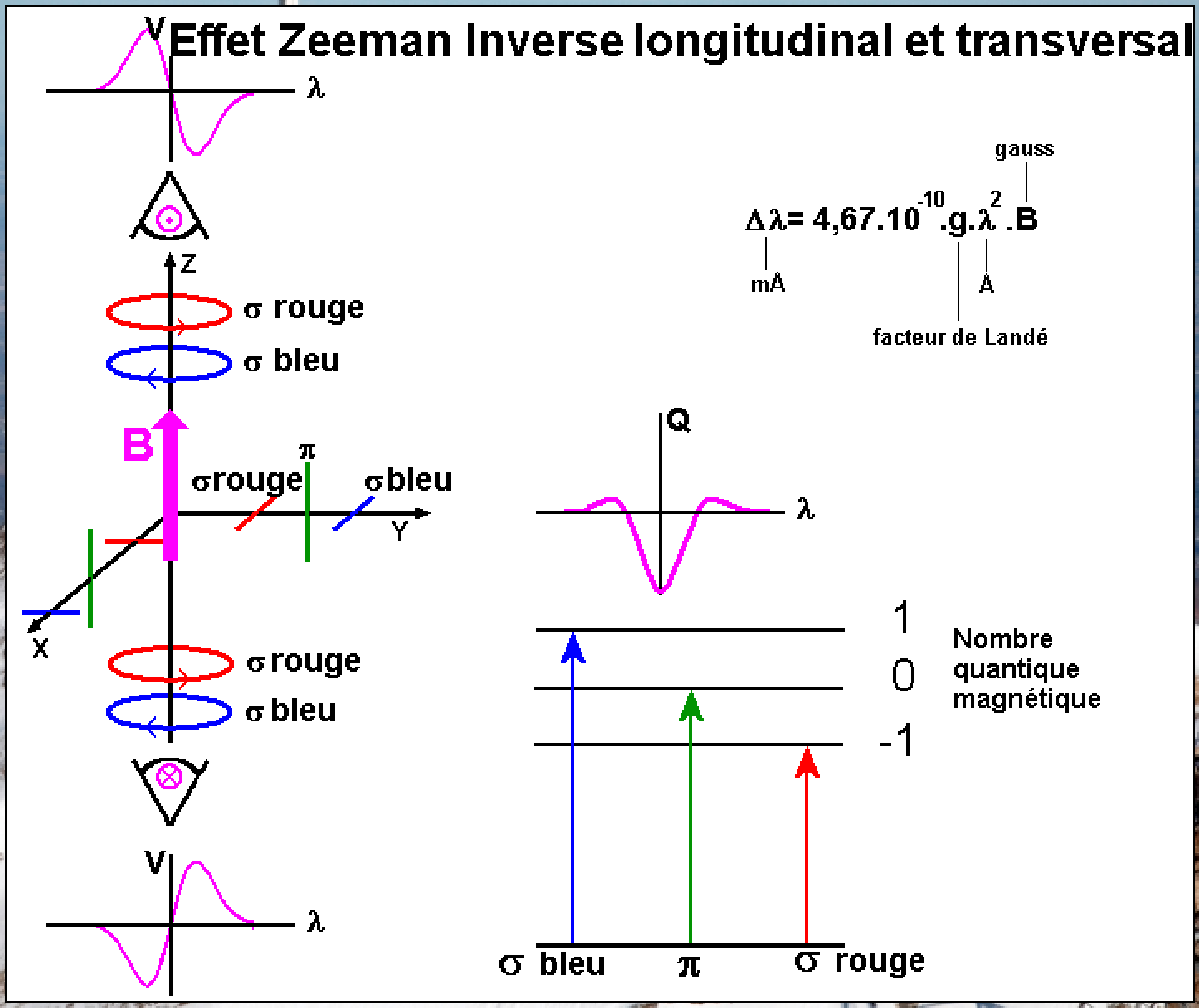
- Lift hyperfine structure of levels 2l+1



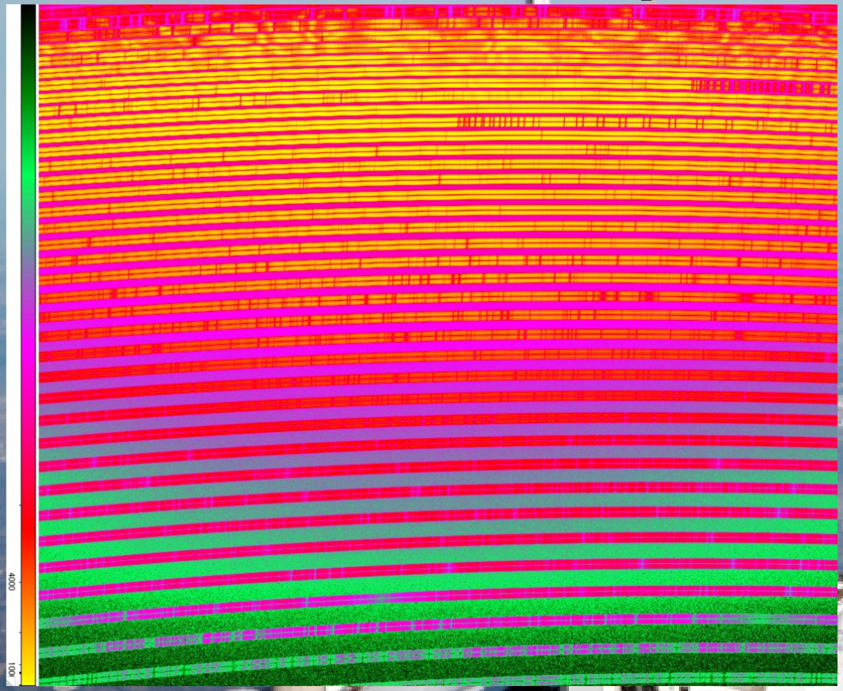


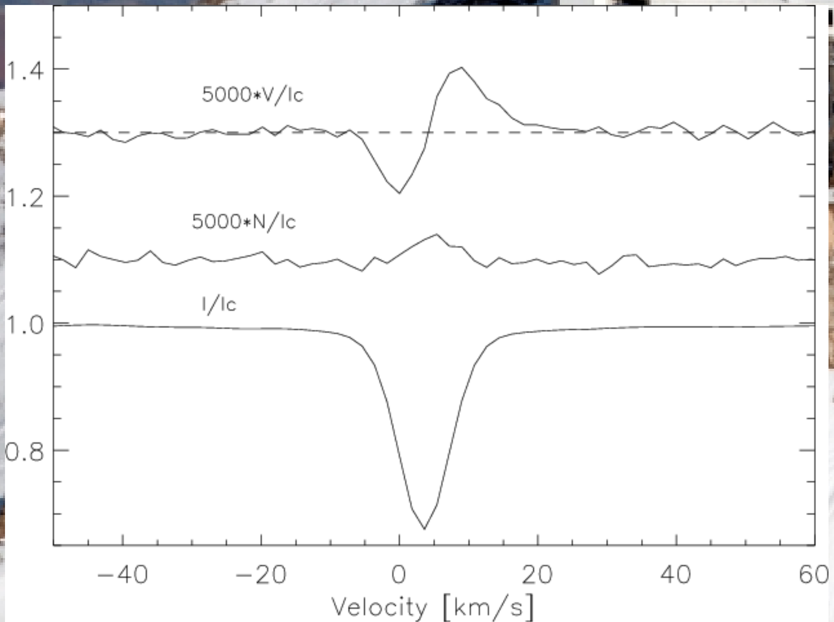
« Splitting » hardly measurable
(requires a large spatial spectral and temporal resolution)

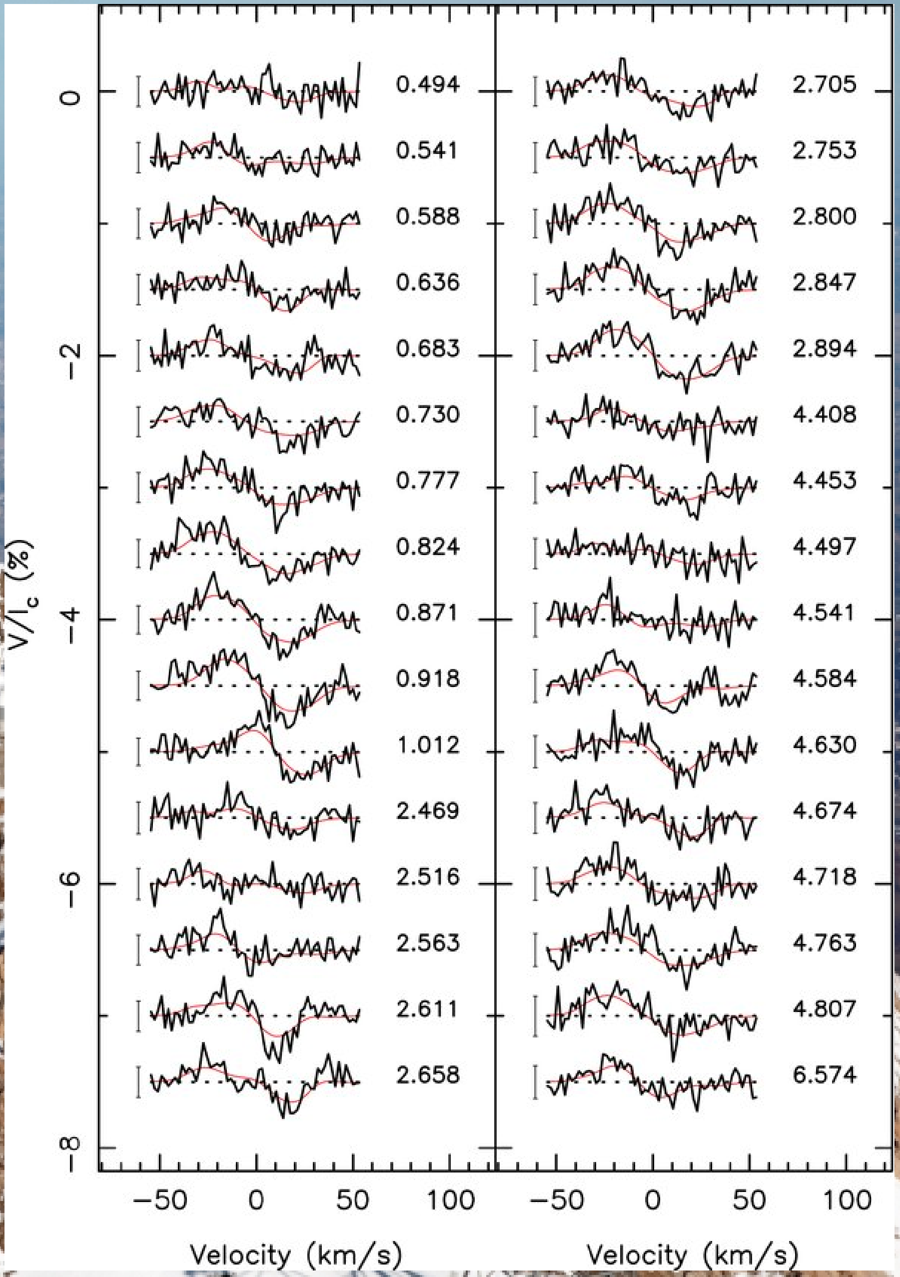
Zeeman effect and polarisation



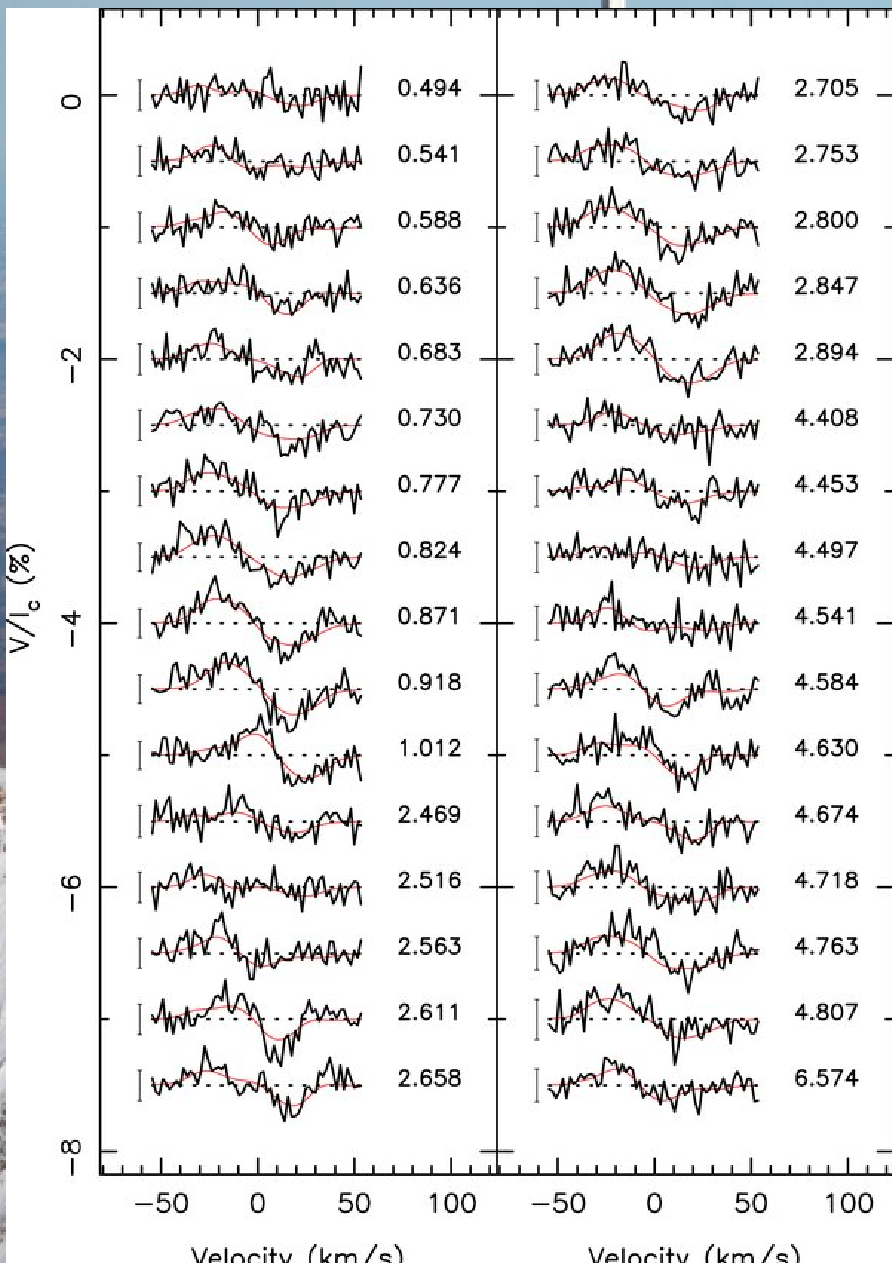
Least Square Deconvolution



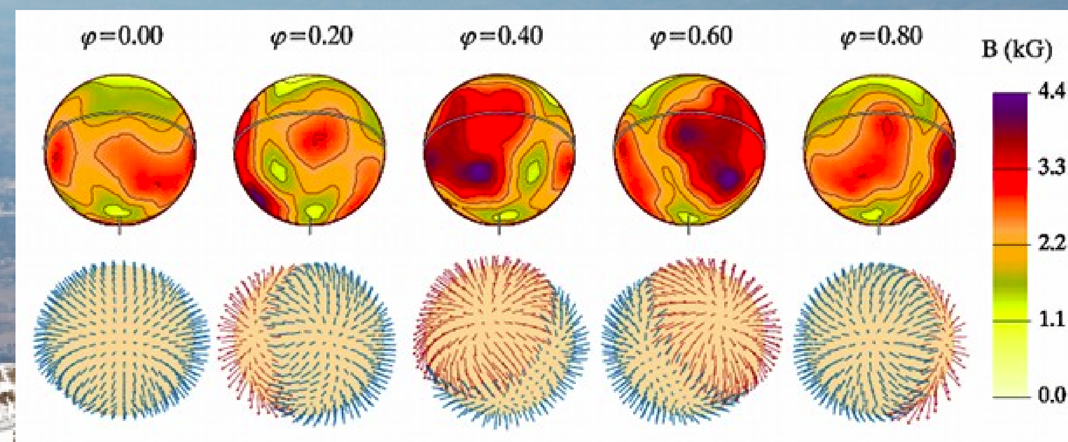




Stellar magnetic fields



Graal : B field 3D structure



- Model a stellar surface is an inverse problem
- many hypotheses on the field structure (poloidal vs toroidal)

Stellar magnetic fields

Some stars are more equal than others !

Hot stars/fast rotators → more difficult to measure
Cool giant/MS → extreme sensitivities ±0.2 Gauss (Stokes V)

POLLUX K0III (34 ly) ~ 0.5-1 G

VEGA A0V (25 ly) ~0.6±0.3G

Pollux, averaged LSD profile

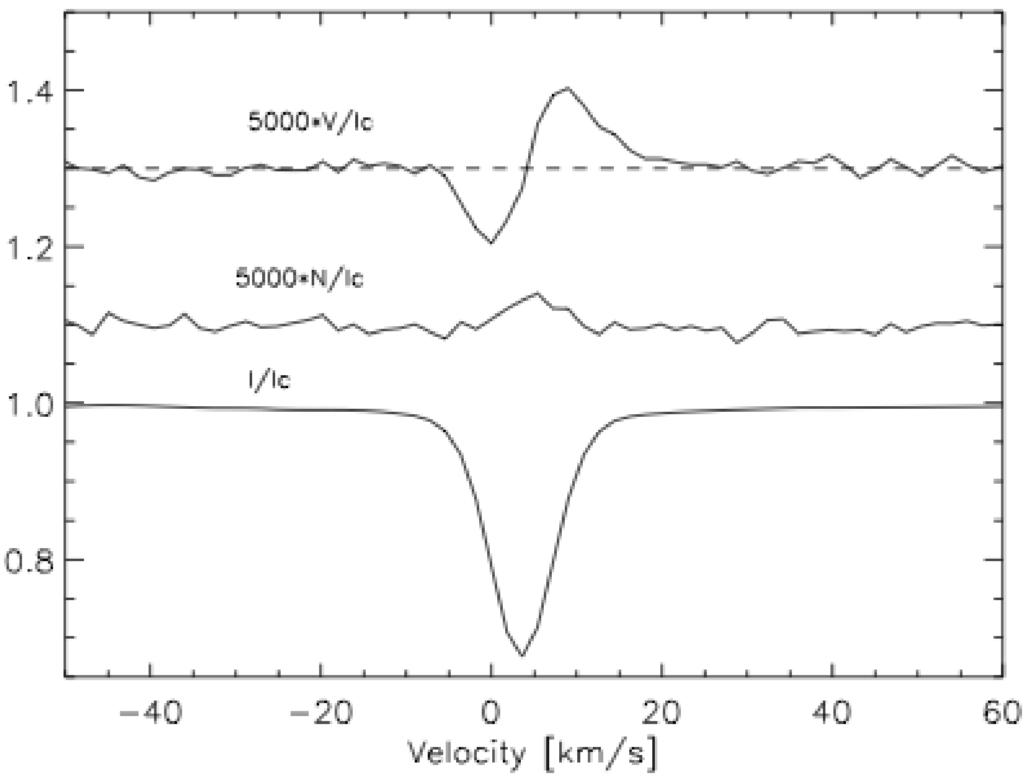


Fig. 1. Mean LSD profiles of Pollux from all 91 spectra acquired with ESPaDOnS and NARVAL in the September 2007–March 2009 period. From top to bottom are Stokes V, null polarisation N, and Stokes I

Vega, averaged LSD profile

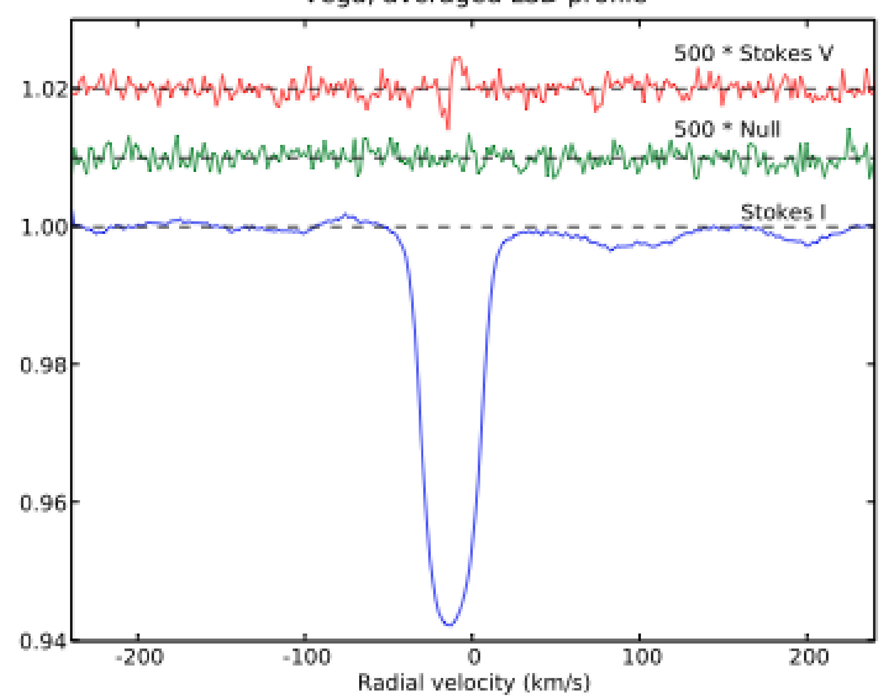


Fig. 1. Average of the 257 normalized Stokes I (blue/bottom) and Stokes V (red/upper) LSD profiles of Vega, as a function of the radial velocity. The green/middle curve is the "null" profile. The Stokes V and null curves are shifted vertically and expanded by a factor of 500. Dashed lines indicate the continuum level for Stokes I, and the zero


Stellar magnetic fields
What should be expect ?

Stellar magnetic fields

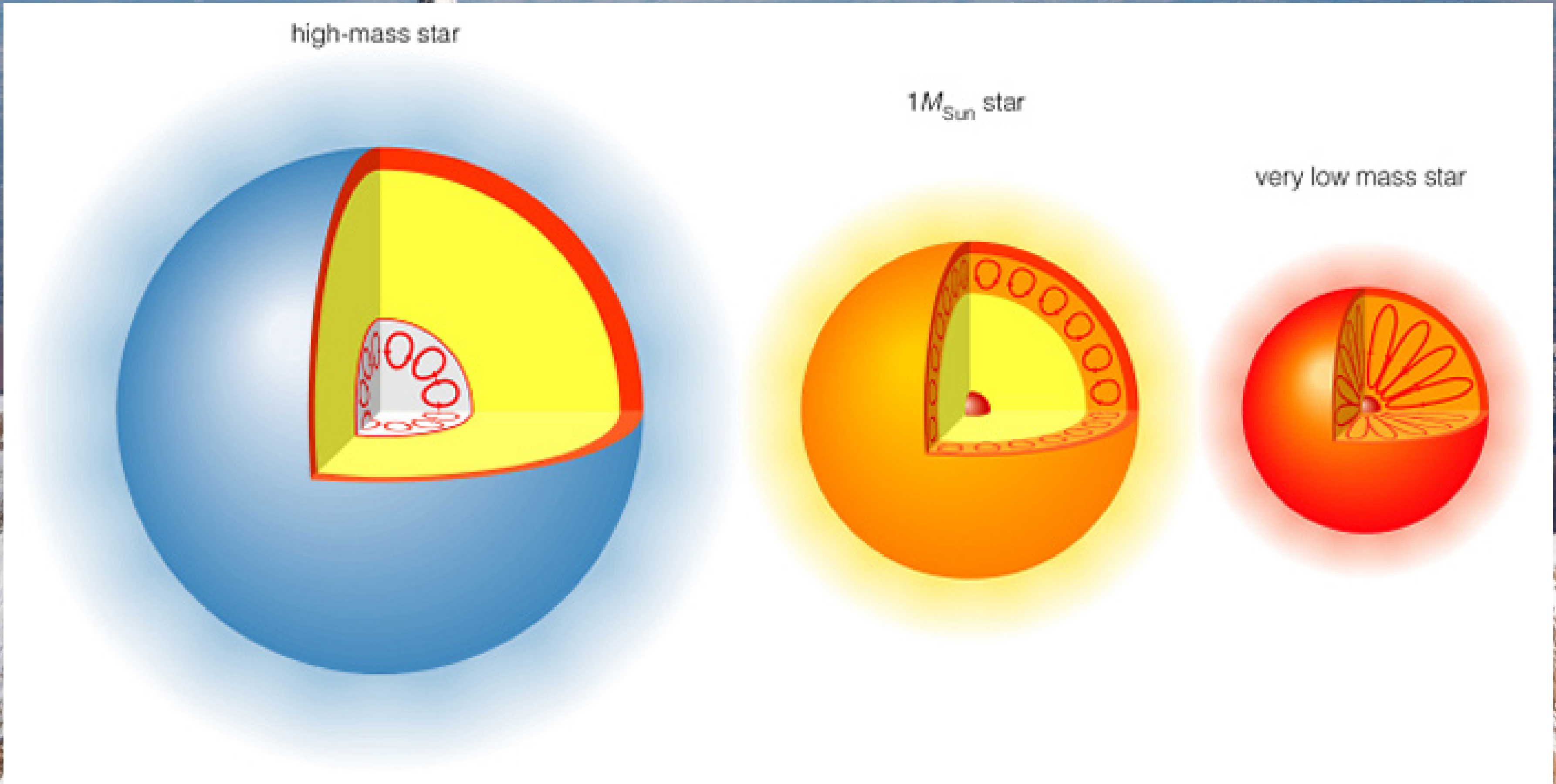
A short summary on theory:

2 contenders for the origin of stellar magnetic fields

NURTURE	**NATURE**
Star rotation + convection (Dynamo)	Fossil remnants (Ap-Bp, few %)
Low mass stars (mostly)	Large scale
Complex toroidal structure	Simple polloidal structure
Variable	No variability

Stellar structure

- Mass dependent : dynamo and tachoclyne

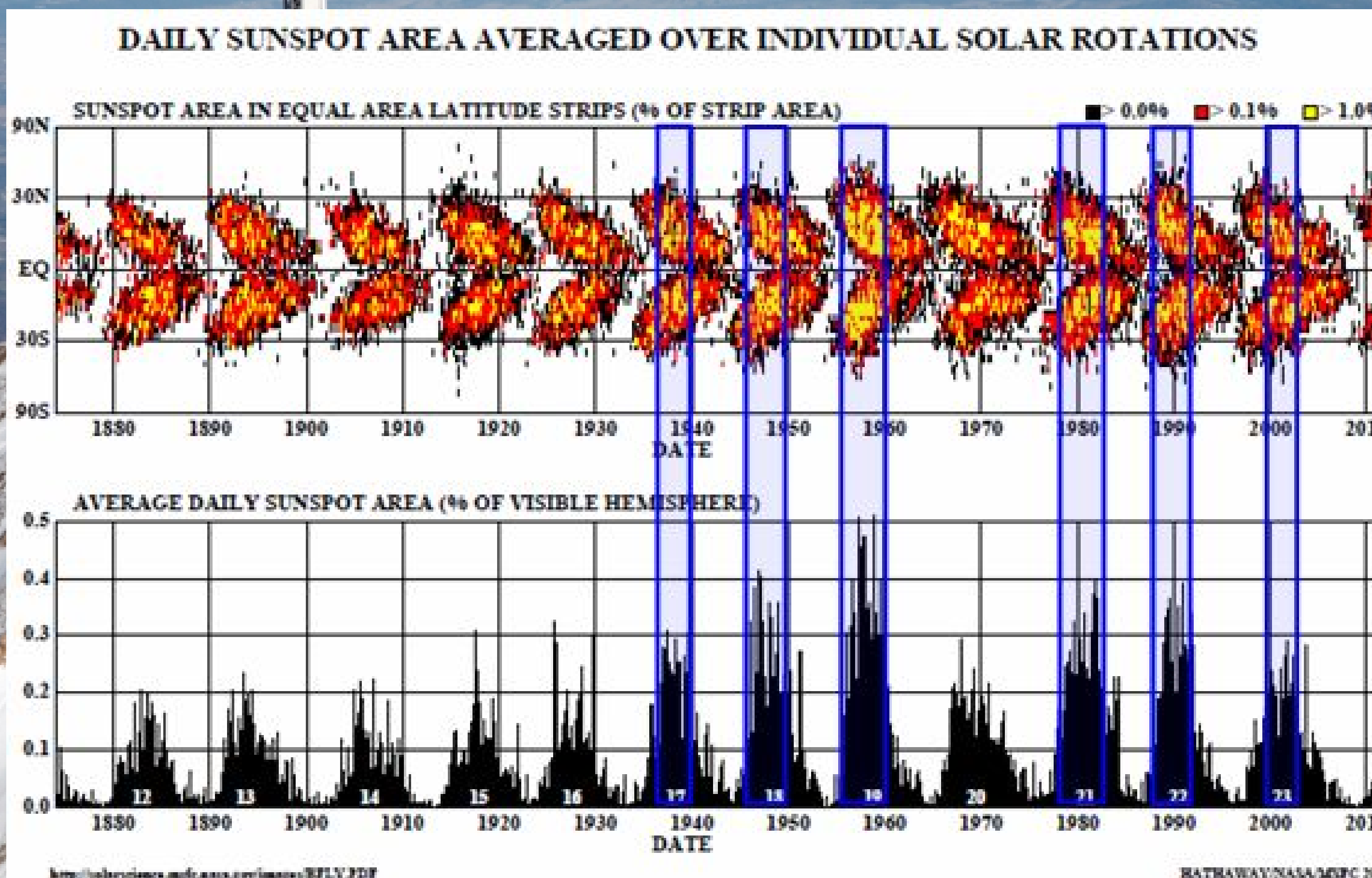


Stellar magnetic field observations

What do we see so far ?

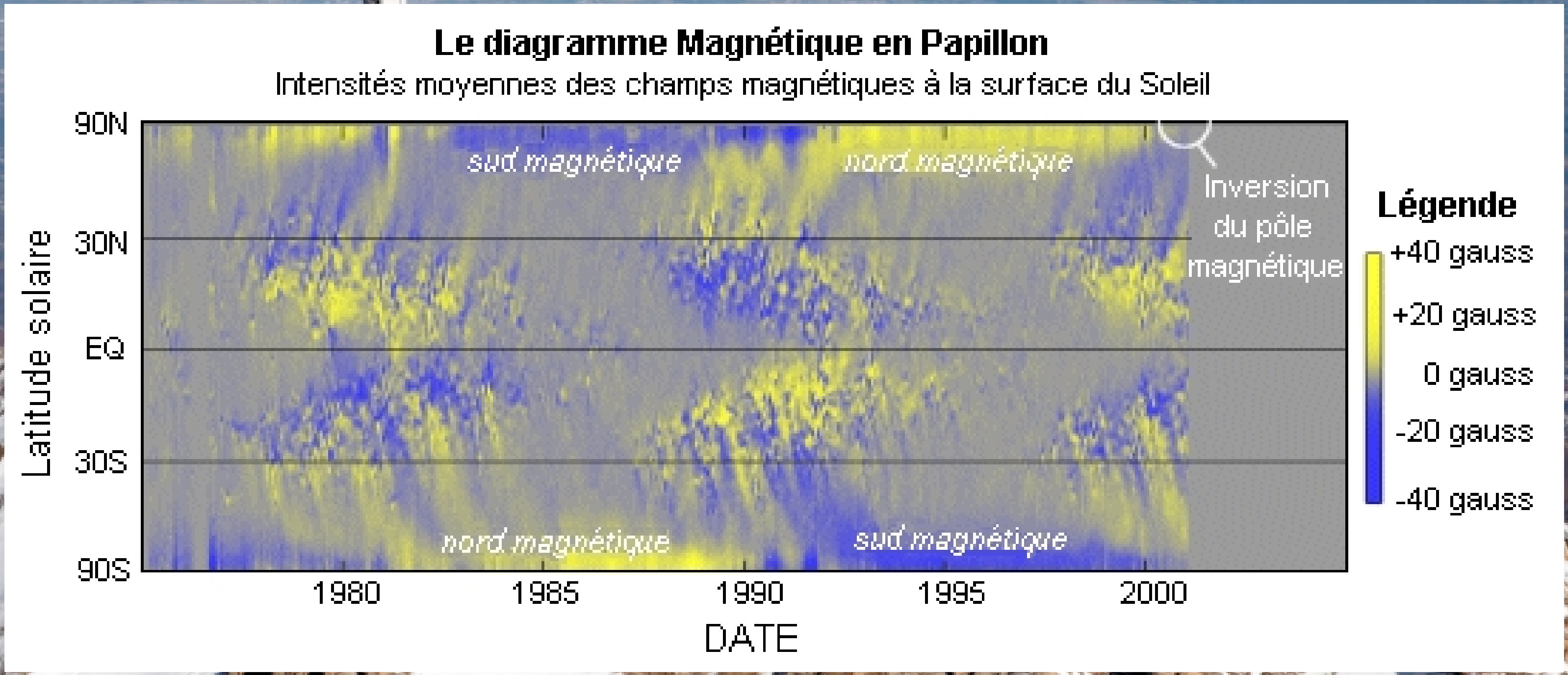
A known case : The Sun

- Spots appear near poles at cycle beginning and migrate toward the equator near end of cycle



A known case : The Sun

- Flipping magnetic poles every 11 years



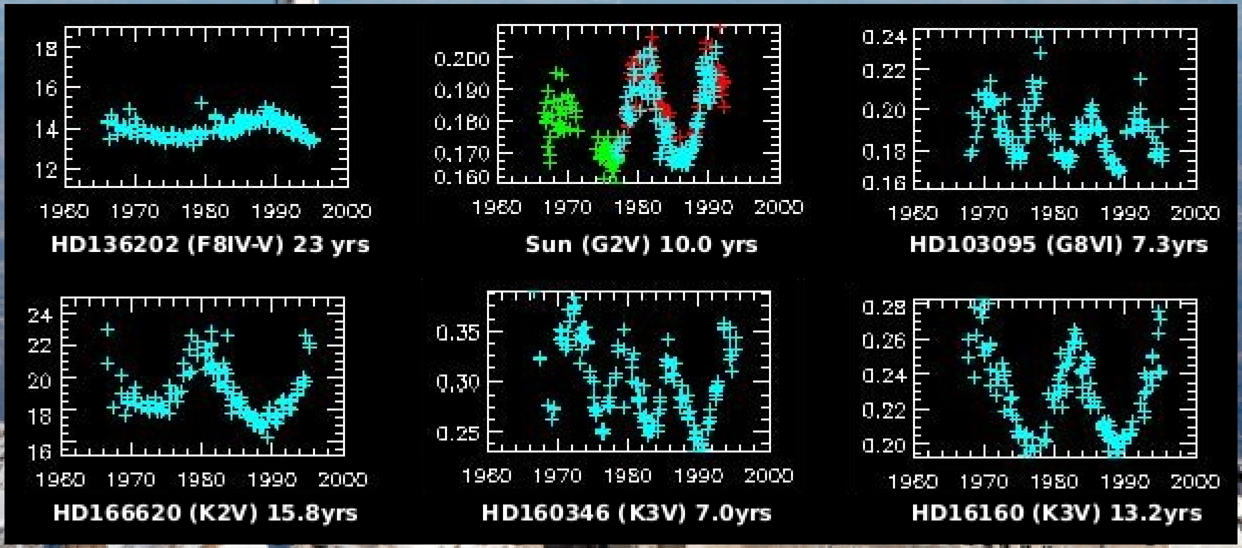
Other solar type stars and dwarfs

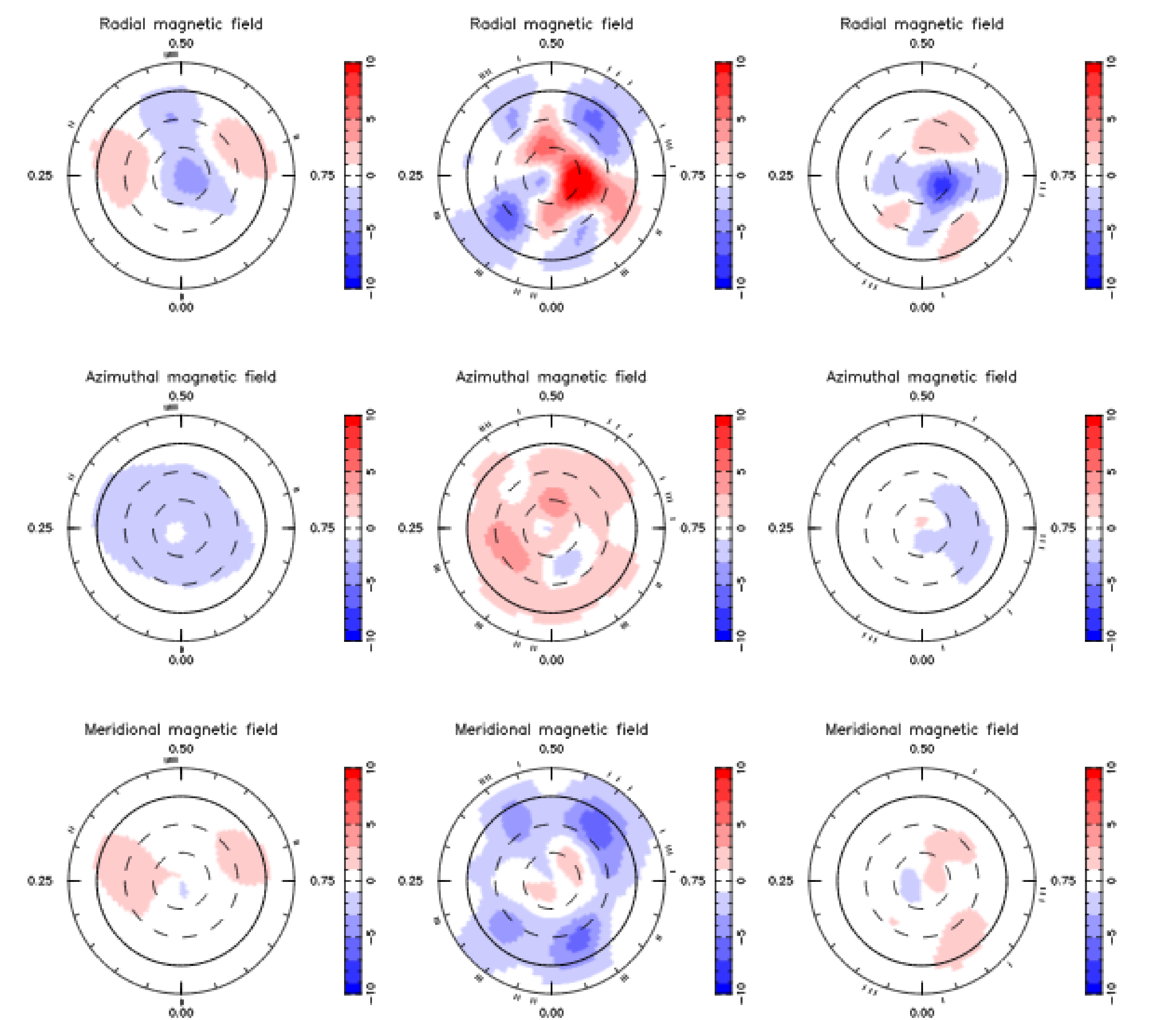
NB : Not trivial to interpret the Sun as a star

→ Contrasted observations with Narval/Espadons

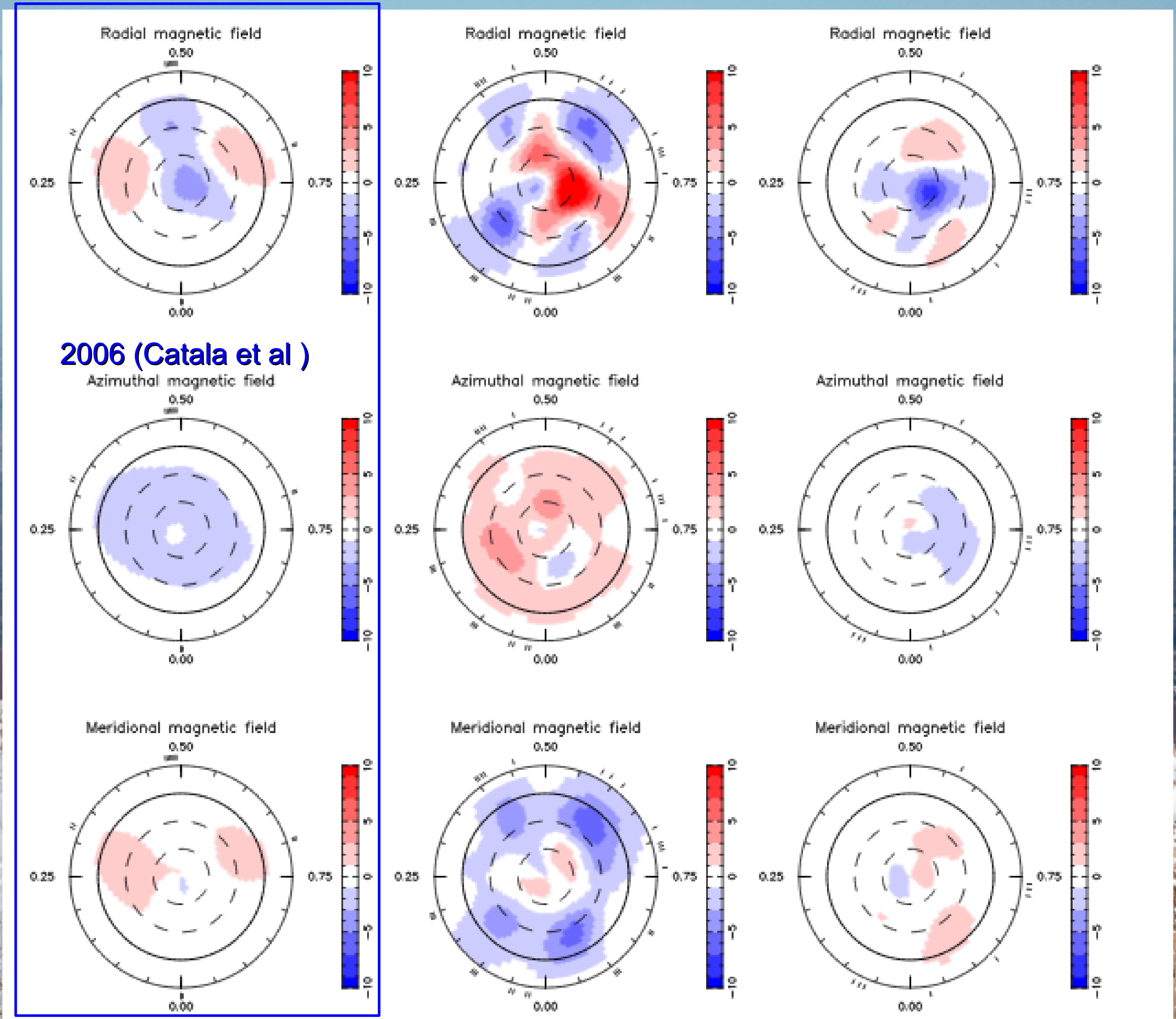
Activity cycles in stars

- A large range of cycle periods

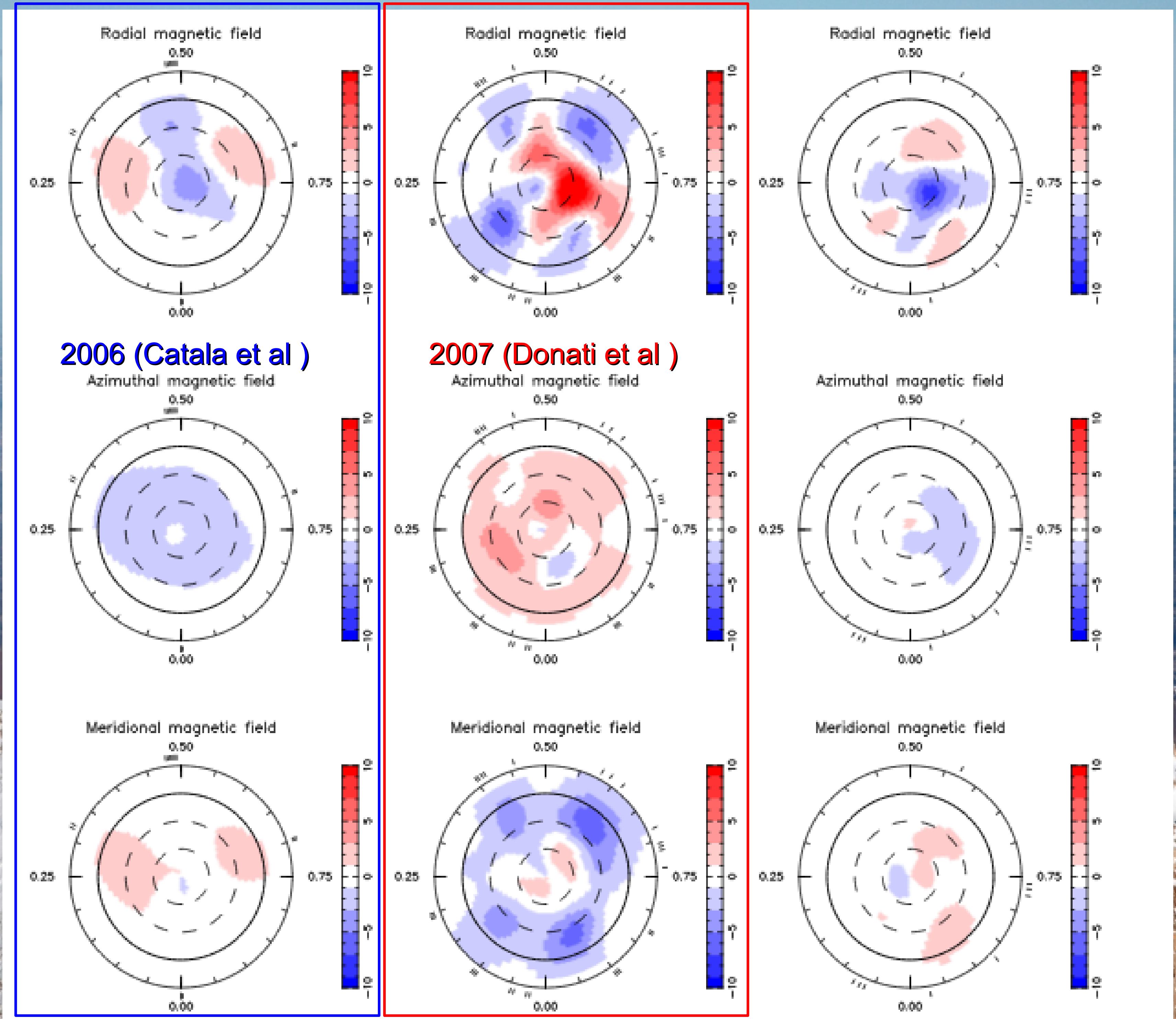




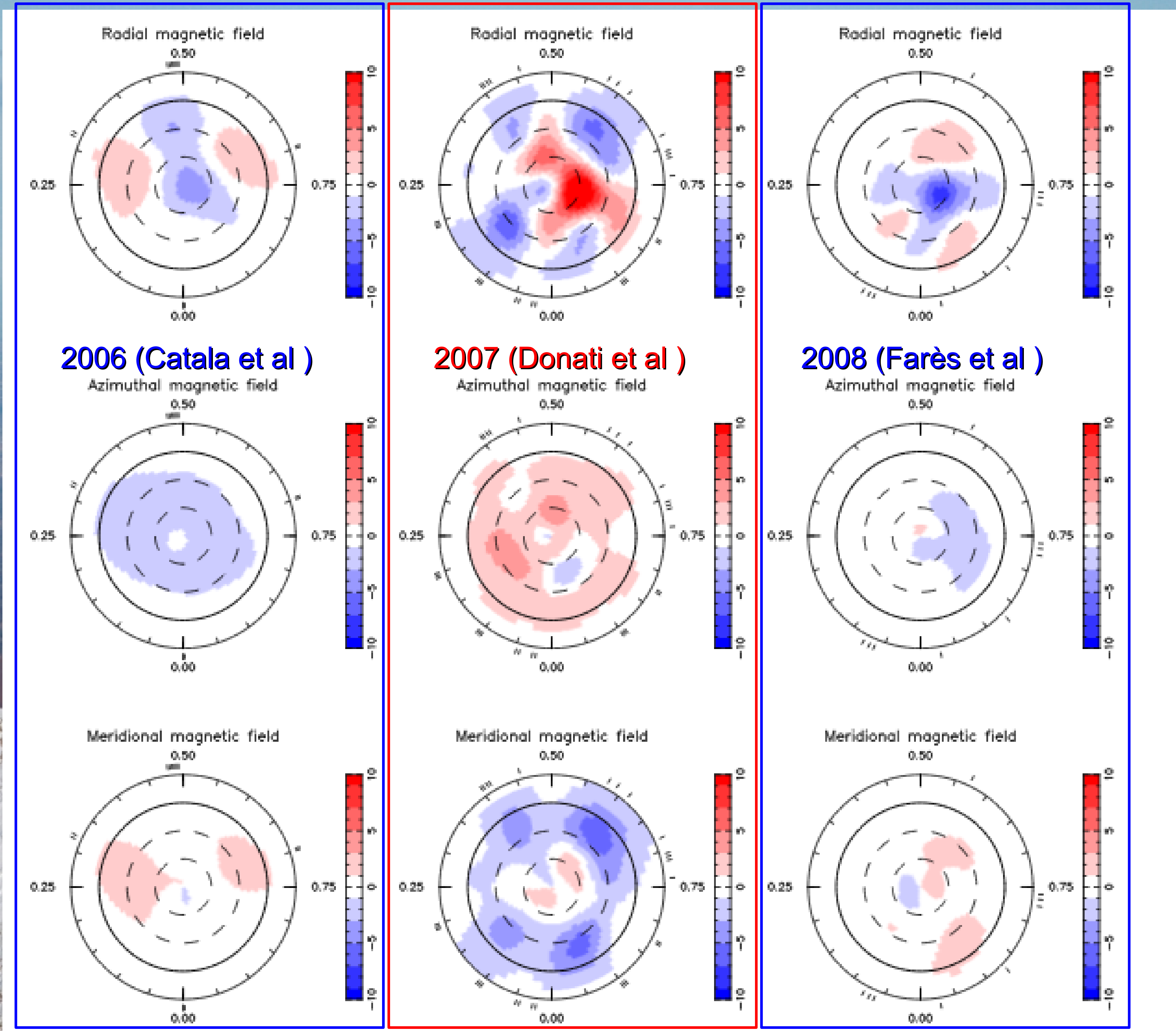
Planet hosting τ Boo magnetic polarity flip



Planet hosting τ Boo magnetic polarity flip

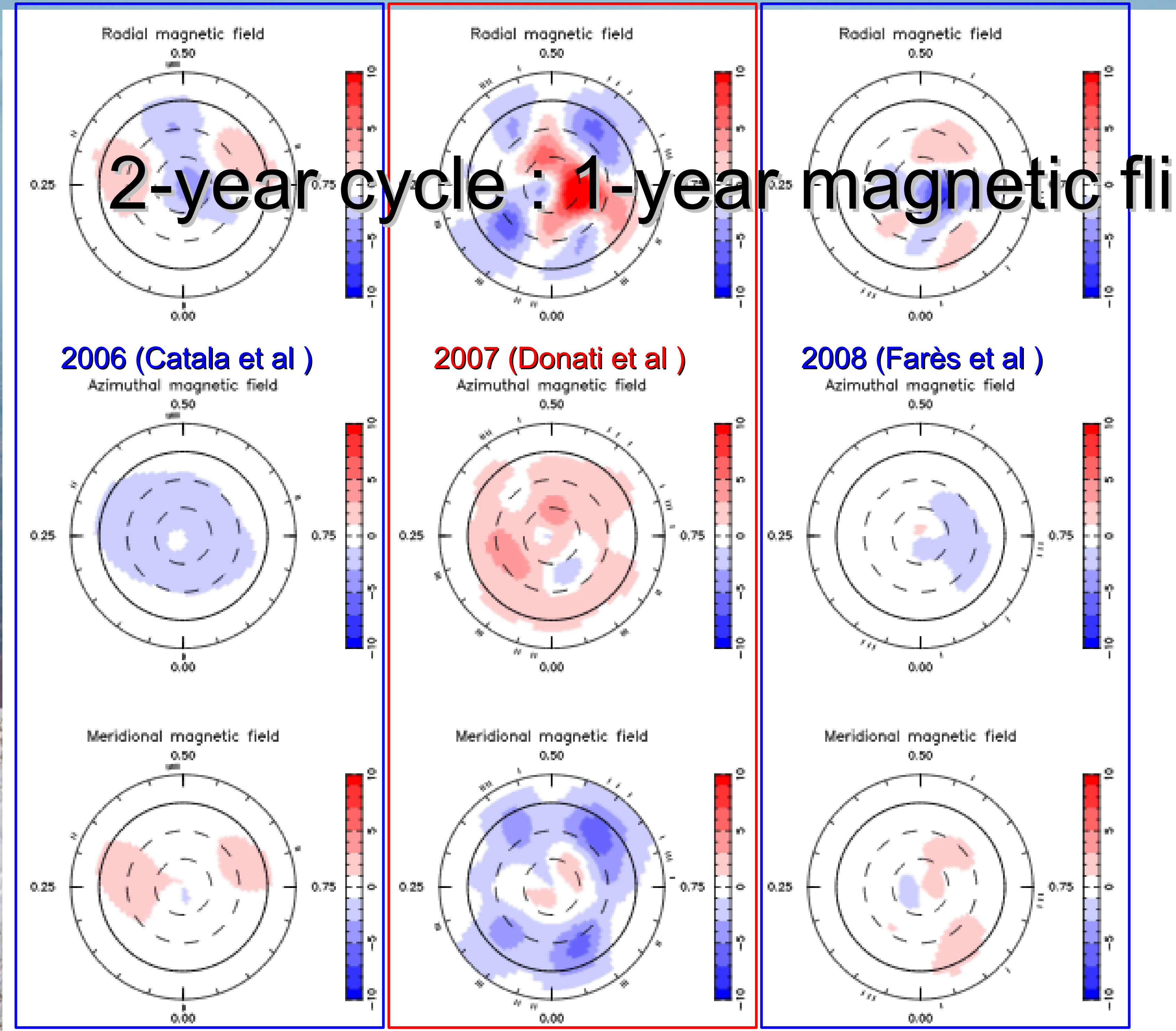


Planet hosting τ Boo magnetic polarity flip



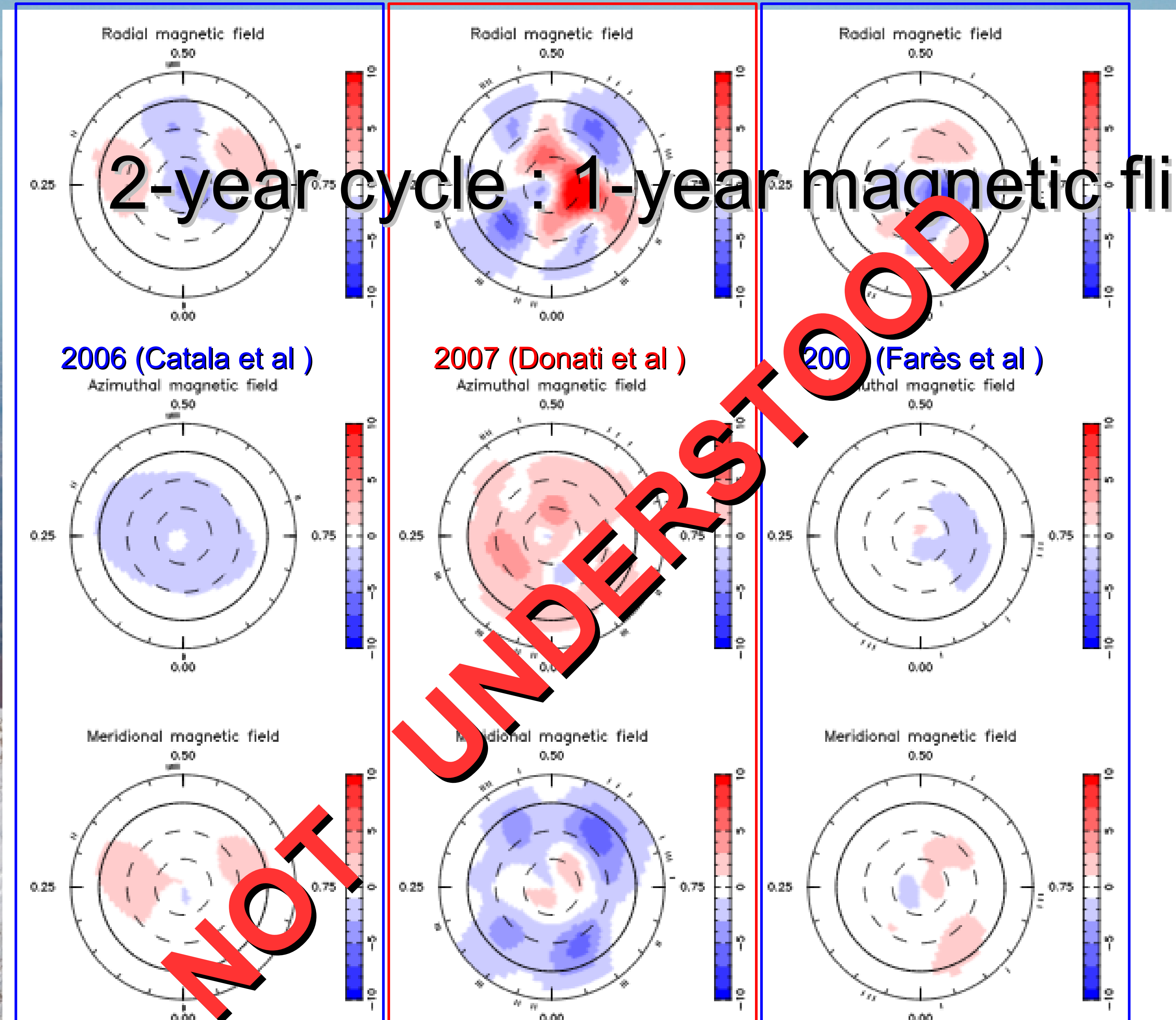
Planet hosting τ Boo magnetic polarity flip

2-year cycle : 1-year magnetic flip



Planet hosting τ Boo magnetic polarity flip

2-year cycle : 1-year magnetic flip

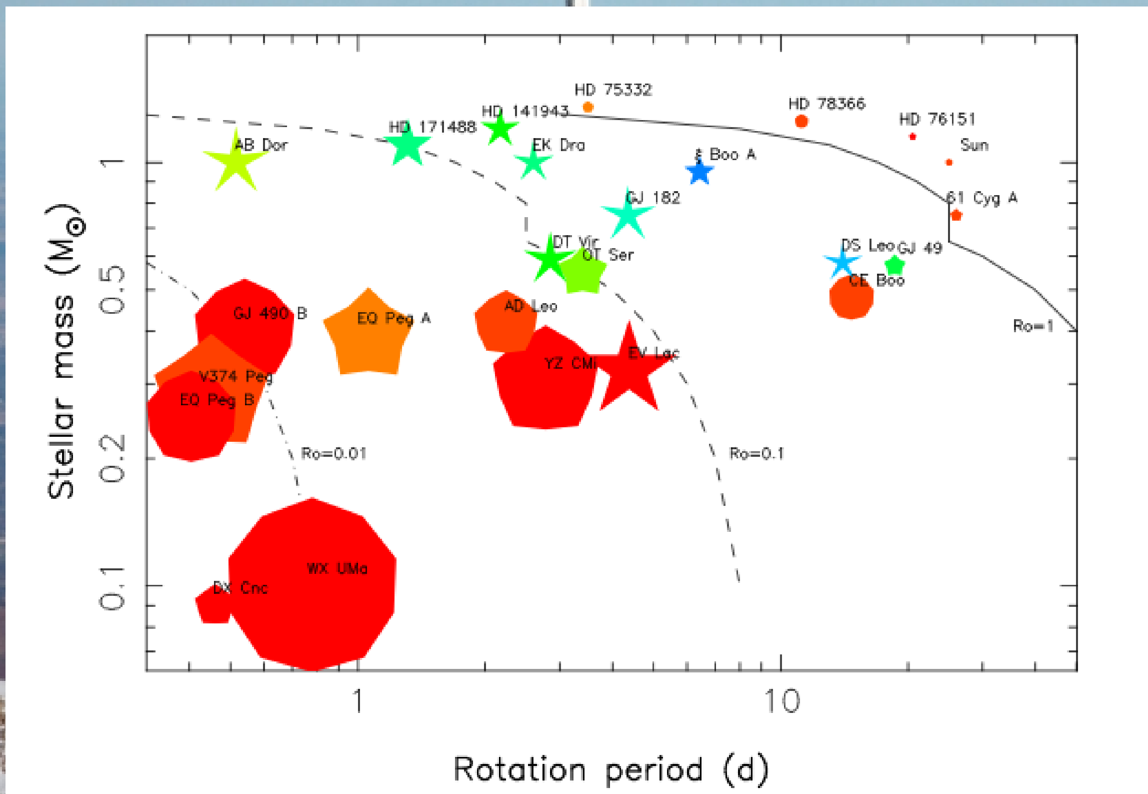


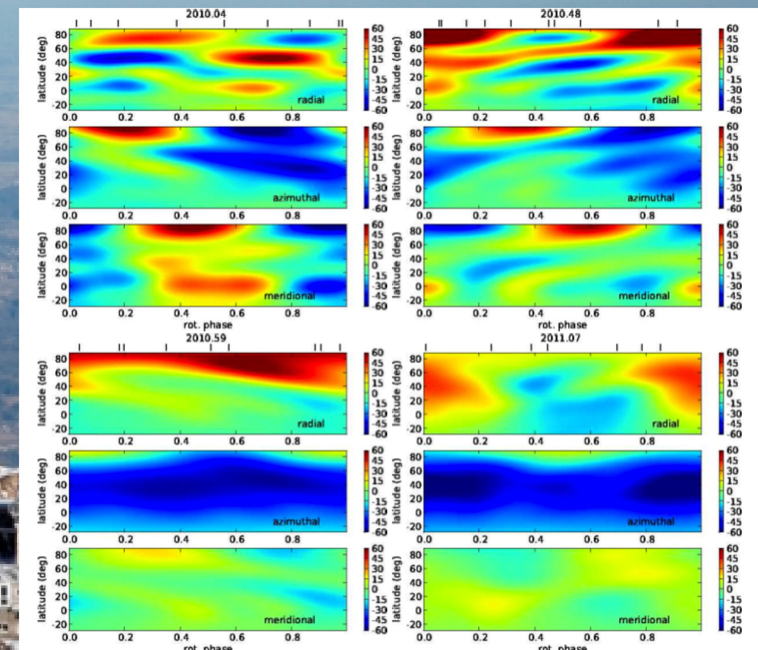
Planet hosting τ Boo magnetic polarity flip

Synoptic view on low-mass stars

Average Magnetic field HR mapping

Long-term follow-ups





bootis A Zeeman Doppler Imaging
(76 spectra 2007-2011, Morgenthaler et al.)

Donati & Landstreet (ARAA 47, 2009), Morin et al., Petit et al.

Massive stars

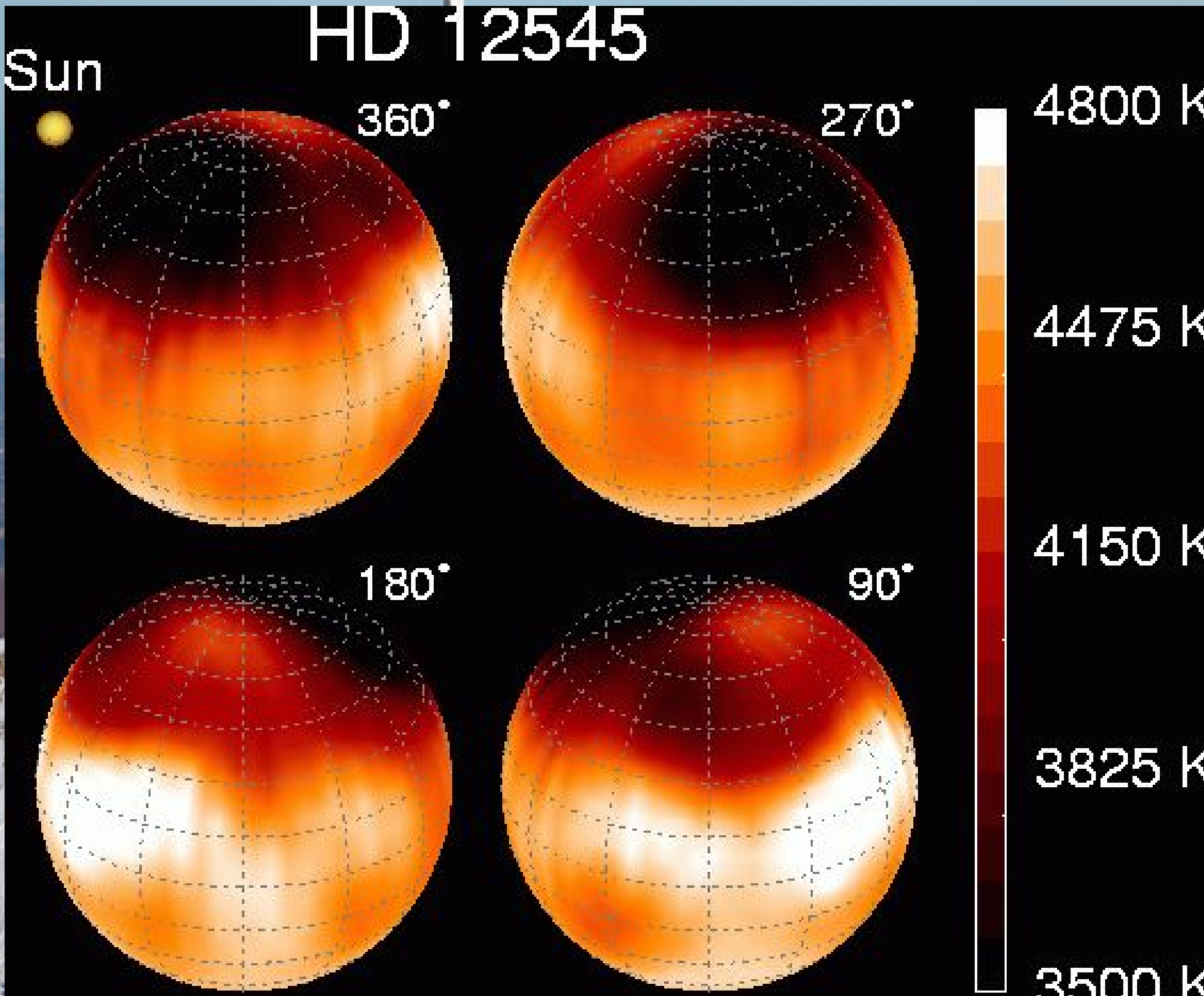
Expected :

Nature scenario : Magnetic fields of fossil origin

Simple morphology poloidal field, no variation

→ Constrasted observations !

Large polar spots for HD12545

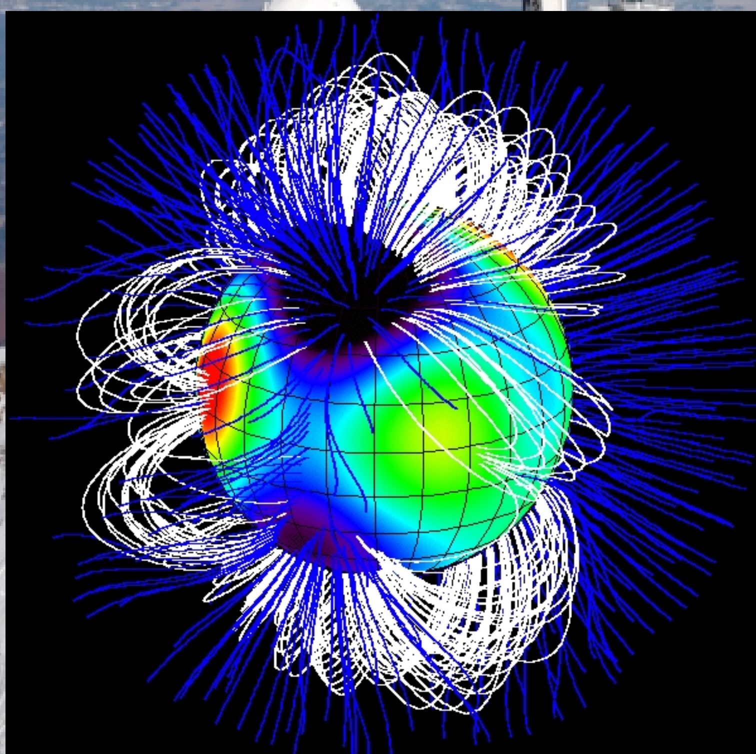


Massive stars

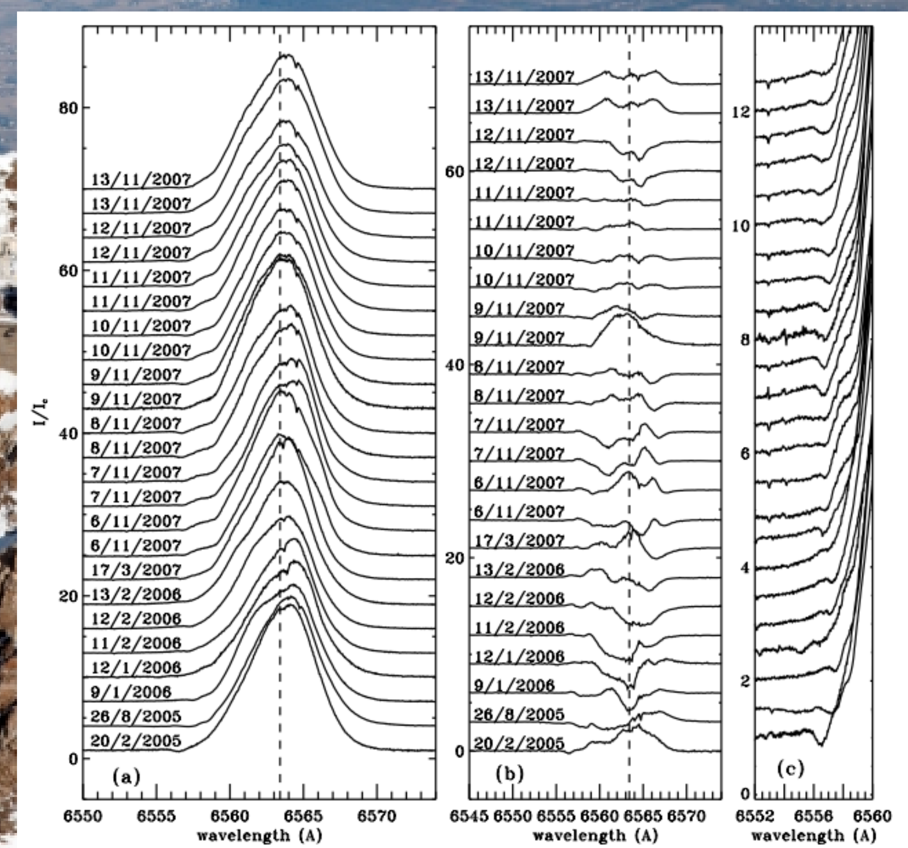
The case of OB stars (Bourret, Neiner, Alecian, Wade et al.)

Program Magnetism in Massive Stars (MiMeS): origins and evolution of magnetic fields in hot stars, Herbig, OB

Complex field on Tau Sco (Jardine et al.)



Herbig V380 Ori (Alecian et al)



Also work on ζ Ori O9 (Bouret et al., 2009)

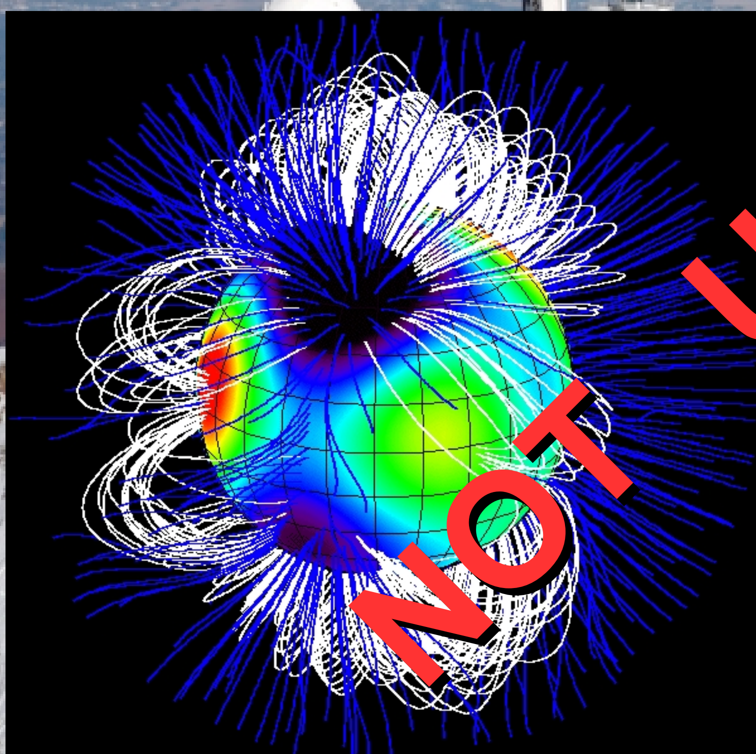
Massive stars

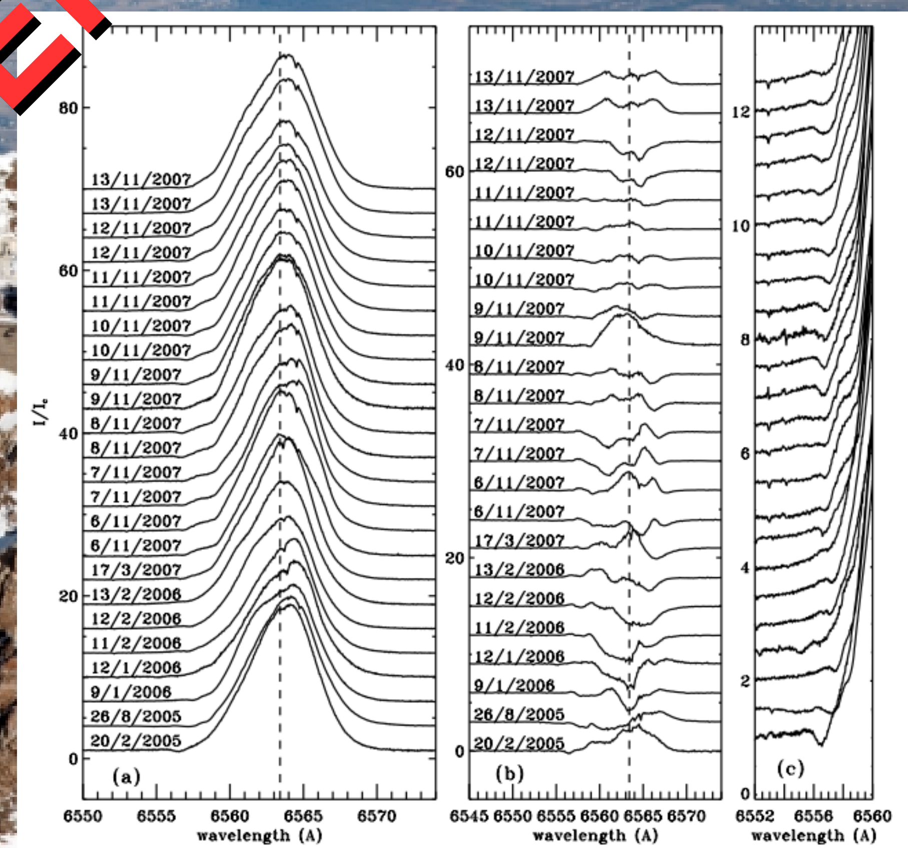
NOT UNDERSTOOD

The case of OB stars (Bourret, Neiner, Alecian, Wade et al.)

Program Magnetism in Massive Stars (MiMeS): origins and evolution of magnetic fields in hot stars, Herbig, OB

Complex field on Tau Sco (Jardine et al.) Herbig V380 Ori (Alecian et al)

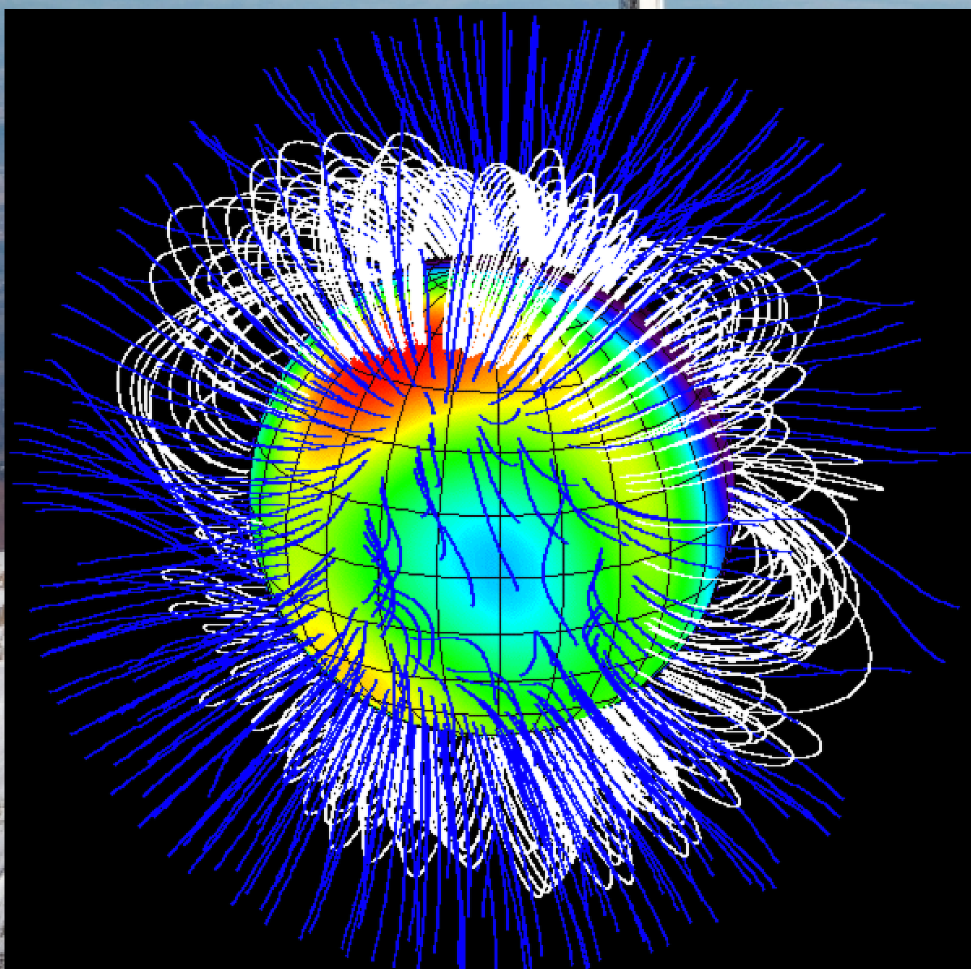




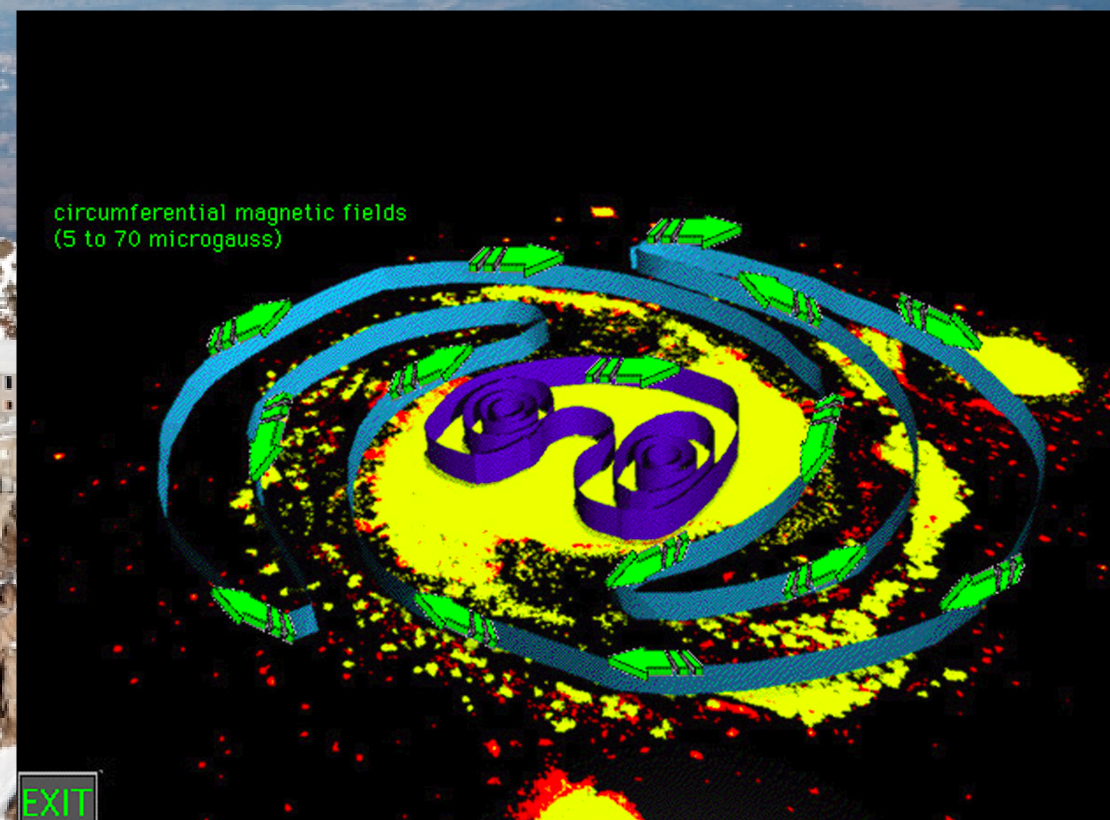
Also work on ζ Ori O9 (Bouret et al., 2009)

Massive stars

- ~10% show a magnetic field : Fossil ?

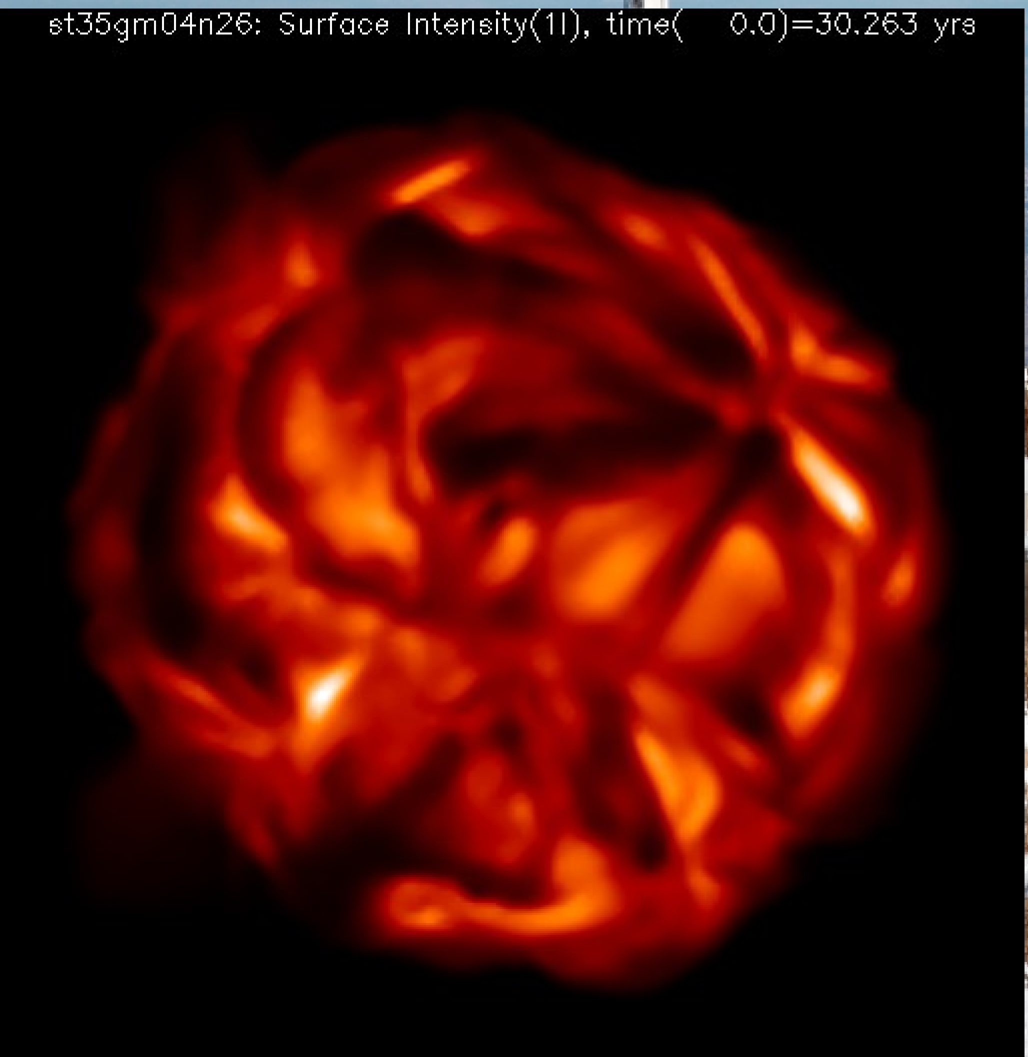


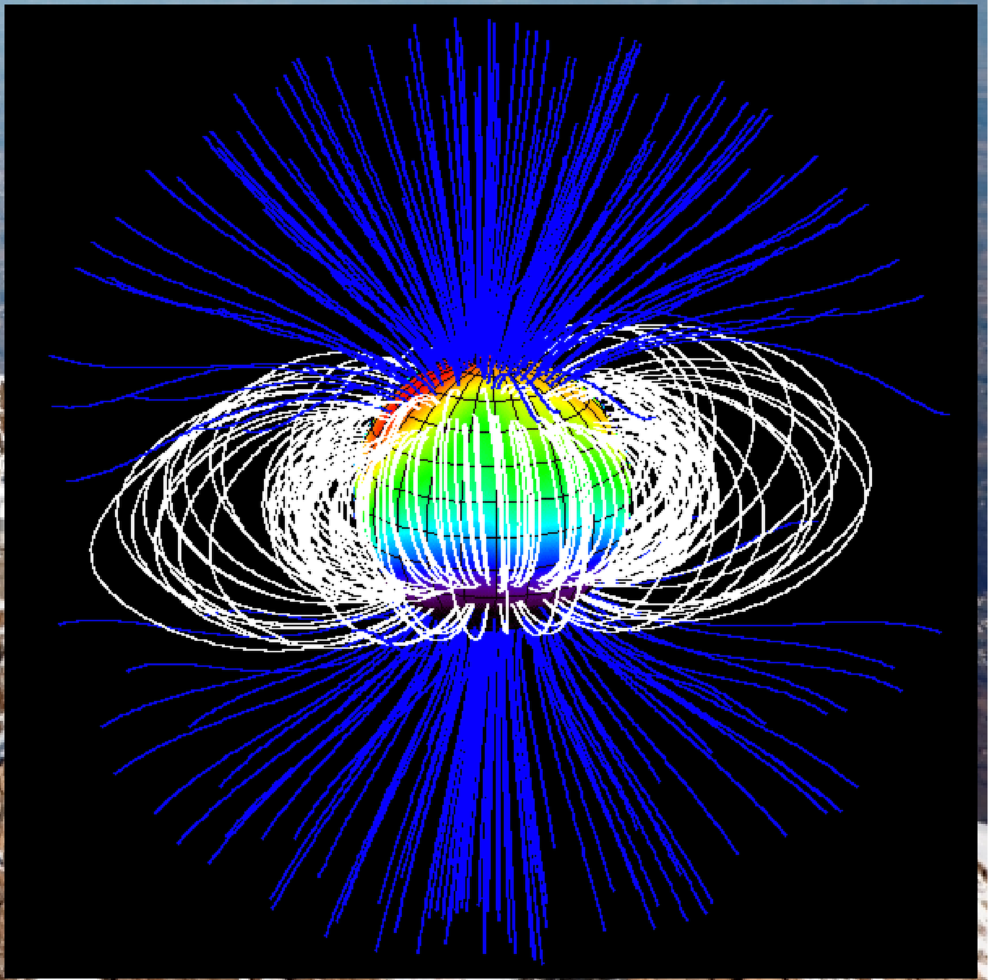
Tau Scorpii (15Mo)



Low Mass/Young Stars

- Large convective enveloppe : Nurture expected messy dynamo fields





3-D geometry too simple ?

BP Tau

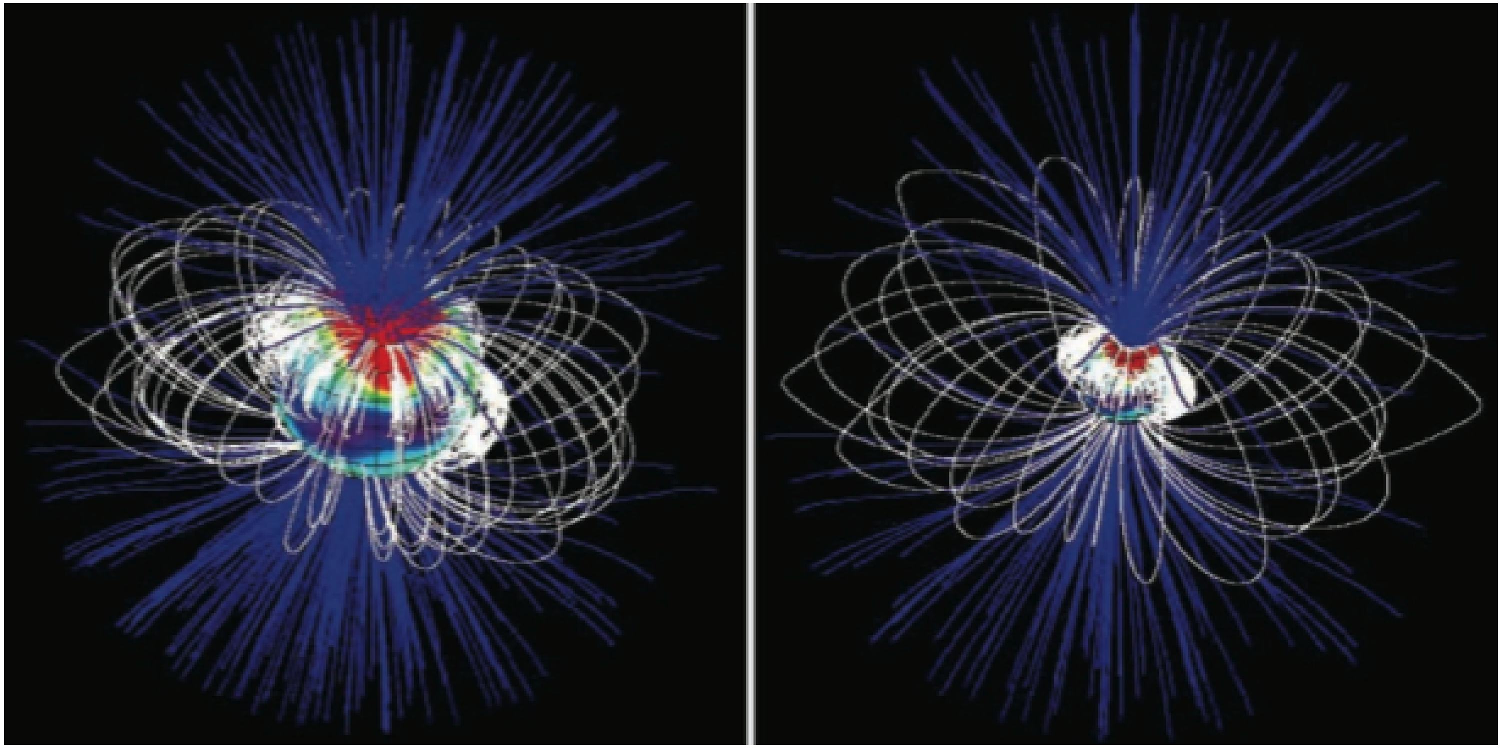
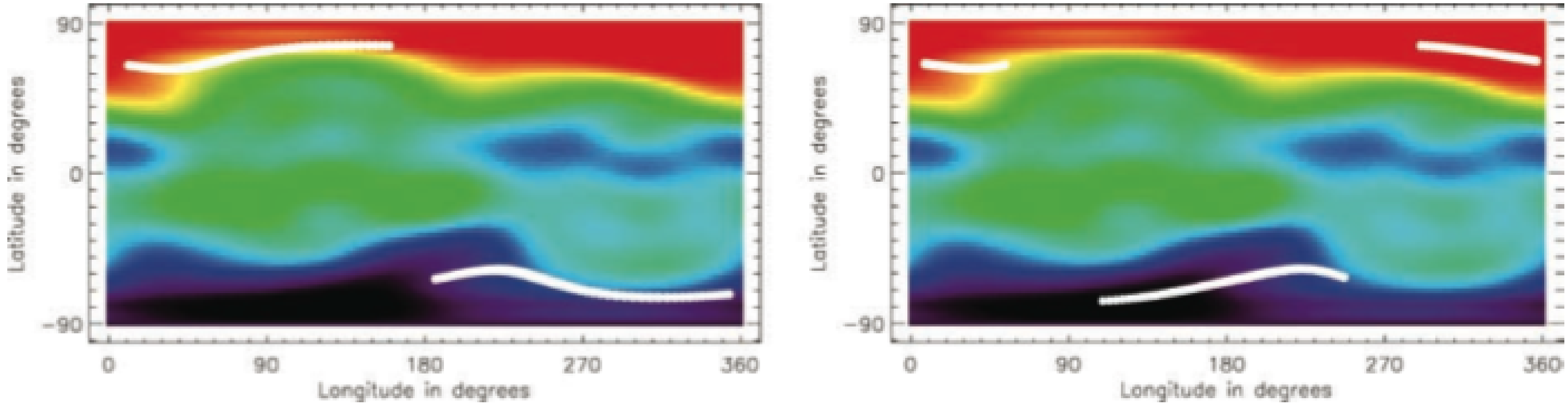


Figure 15. Magnetospheric topology of BP Tau as derived from potential extrapolations of the Feb06 surface magnetic field distribution (top panel of Fig. 14). The magnetosphere is assumed to extend up to the inner disc radius, equal to 3.5 and $7.5R_*$ in the left- and right-hand panels, respectively. The complex magnetic topology close to the surface of the star is very obvious. In both cases, the star is shown at rotational phase 0.0. The colour patches at the surface of the star represent the radial component of the field (with red and blue corresponding to positive and negative polarities); open and closed field lines are shown in blue and white, respectively.



Low Mass/Young Stars

Proto-stars and accretion disks: FU Ori & TTauri stars
(large program MAPP; Bouvier & Donati)

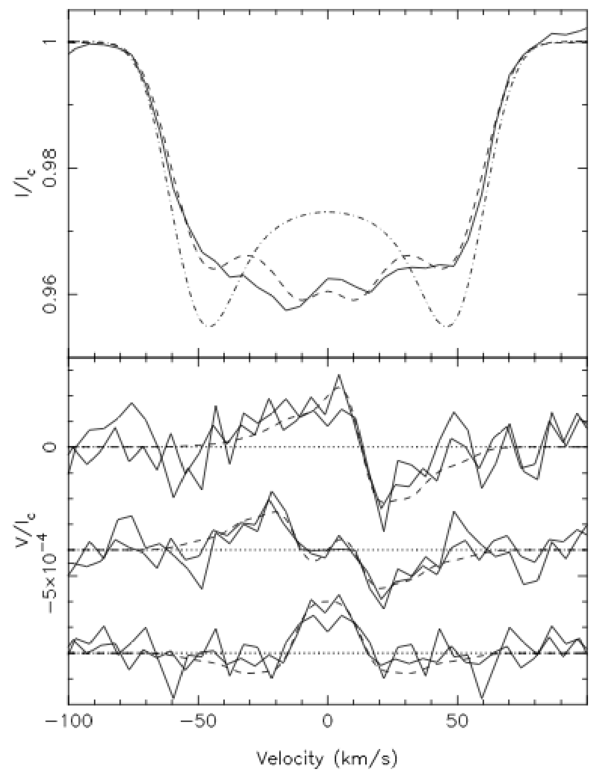


Fig. 6. Unpolarised and circularly polarised profiles of the protostellar accretion disc FU Ori. **Top panel**: observed Stokes *I* profile (solid line) and model profiles assuming either a Keplerian disc (dash-dot line) or a non-Keplerian disc (with 20% of the plasma rotating at strongly sub-Keplerian velocities, dashed line). **Bottom panel**: observed Zeeman signature (top curve) split into its anti-symmetric and symmetric components (middle and bottom curves, shifted by -4 and -8×10^{-4}) respectively characterising the vertical and azimuthal axisymmetric magnetic fields. The model (dashed line) requires the slowly rotating disc plasma to host a 1 kG vertical field plus a 0.5 kG azimuthal field (from Donati et al. 2005).

- SPIROU precursors
- GAIA preparation
- Corot follow-ups

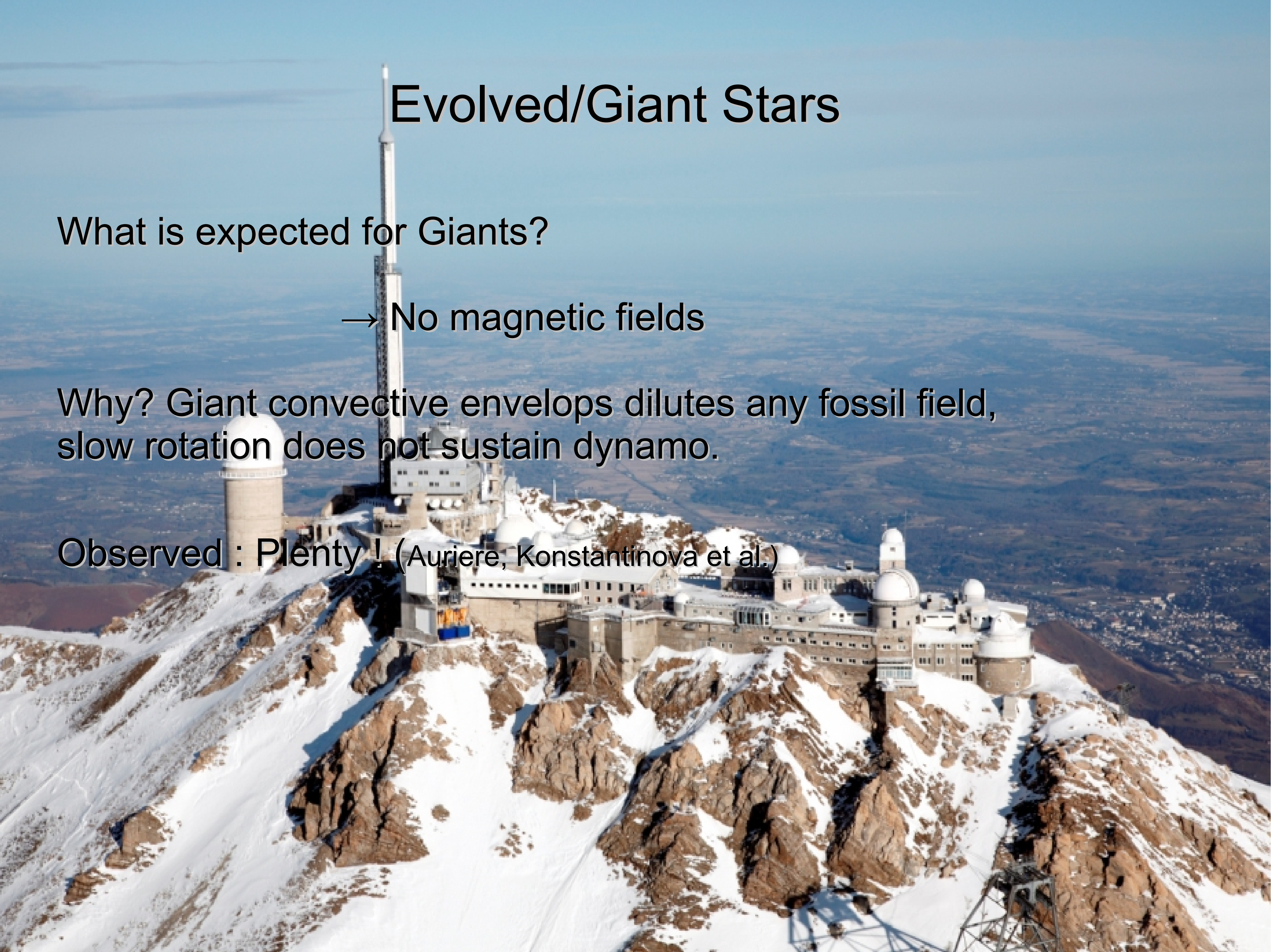
Evolved/Giant Stars

What is expected for Giants?

→ No magnetic fields

Why? Giant convective envelops dilutes any fossil field, slow rotation does not sustain dynamo.

Observed : Plenty ! (Auriere, Konstantinova et al.)



Evolved/Giant Stars

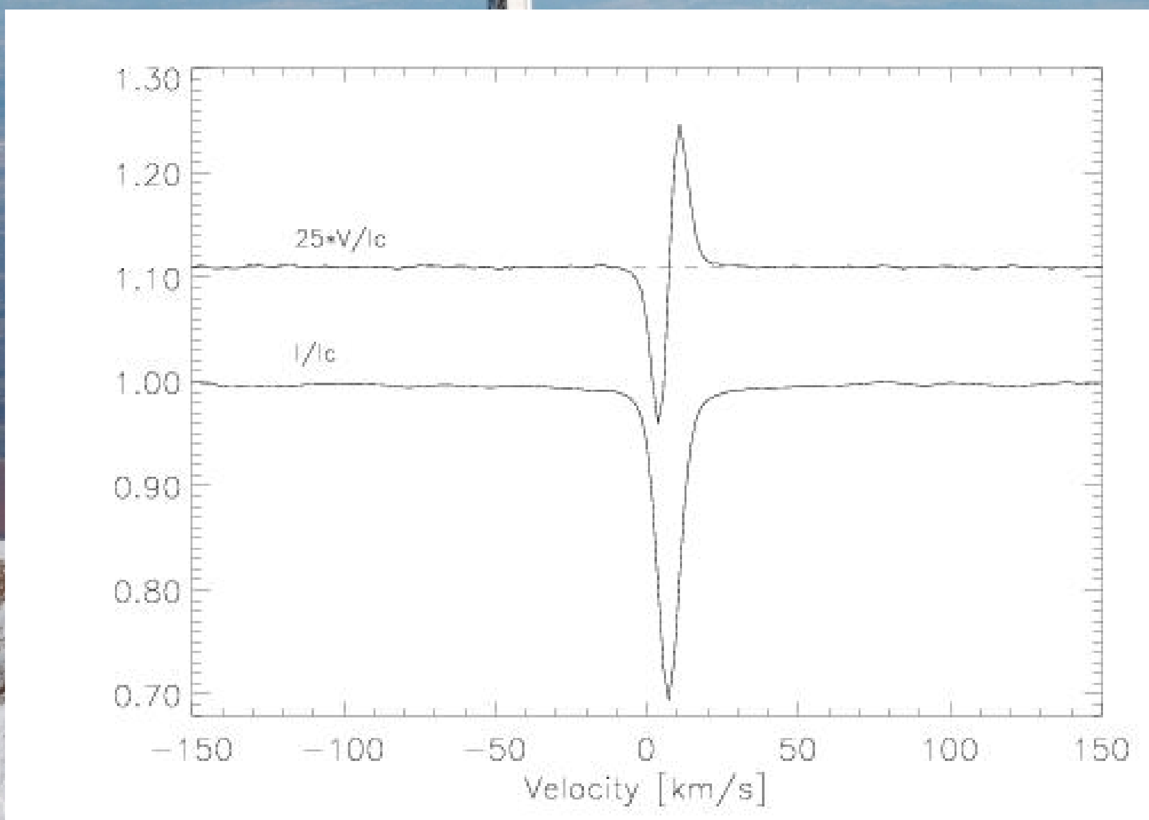
What is expected for Giants?

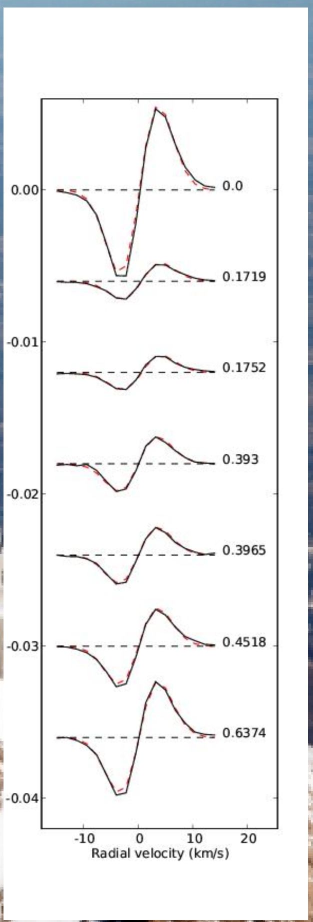
(Auriere, Konstantinova et al.)

Name	Sp	vsini (km/s)	P d	Lx (10^{27} erg/s)	Blmax < G
iot Cap	G8III		68	4482	4.9
77 Tau	K0IIIb	1.5	140	1996	2.6
del Crb	G3.5III		59	1456	3.7
bet Cet	K0III	3.5		1138	8.0
EK Eri	G8III-IV	1.5	307	1000	101.6
24 UMa	G4III-IV	5.5		901	10.5
14 Cet	F5IV	5.		336	35.0
bet Boo	G8IIIa	2.5		153	ND
eta Her	G7.5IIIb	1.7		63	8.4
Pollux	K0III	1.7		5	0.9

Evolved/Giant Stars

What abouty giants? (Auriere, Konstantinova et al.)





EK Eri G8III magnetic variable! (An evolved Ap star ?)

Evolved/Giant Stars

Giant stars. (Auriere, Konstantinova, Charbonnel et al. in prep)
Mira (cf N. Fabas talk)

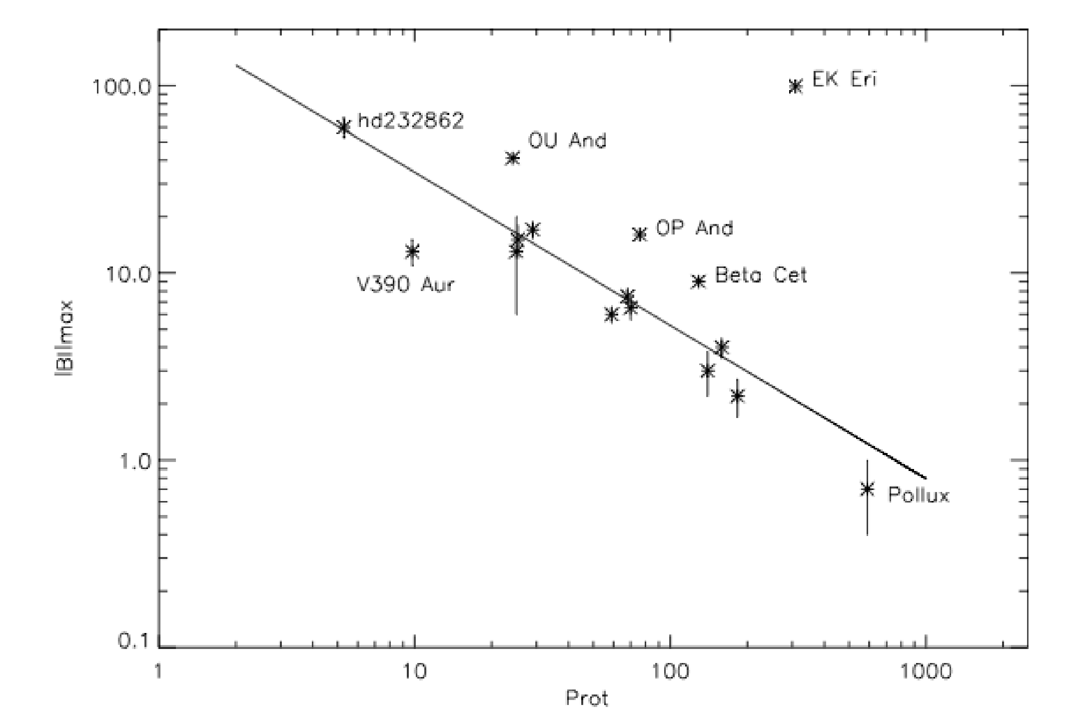


Fig. 8. Variations of the strength of the magnetic field ($|B_\ell|_{max}$) with the rotational period.

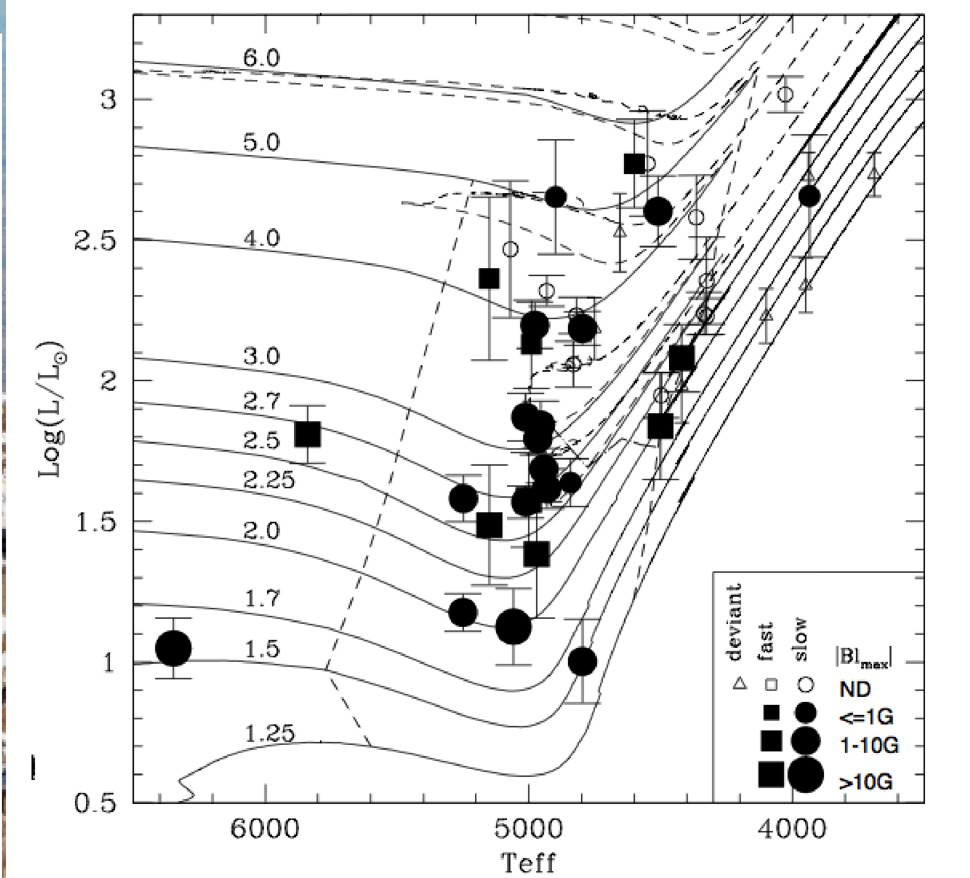
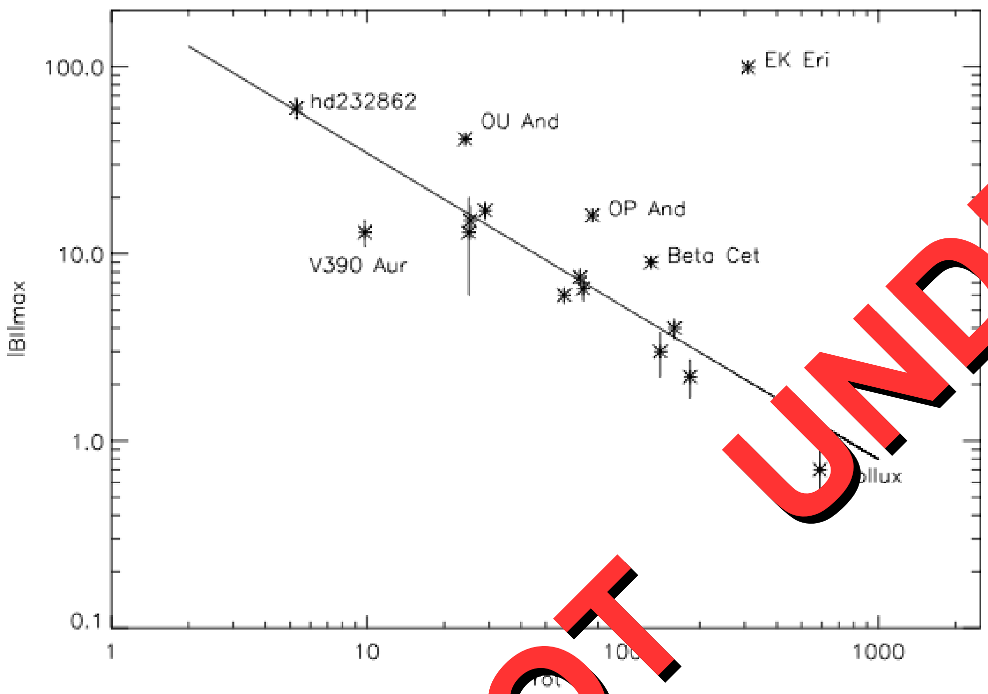


Fig. 3. Position of the Red Giants of our sample in the Hertzprung-Russel Diagram. Tracks of the standard evolutionnary models of Charbonnel and Lagarde (2010) are shown.

Evolved/Giant Stars

Giant stars. (Auriere, Konstantinova, Charbonnel et al. in prep)
Mira (cf N. Fabas talk)

NOT UNDERSTOOD



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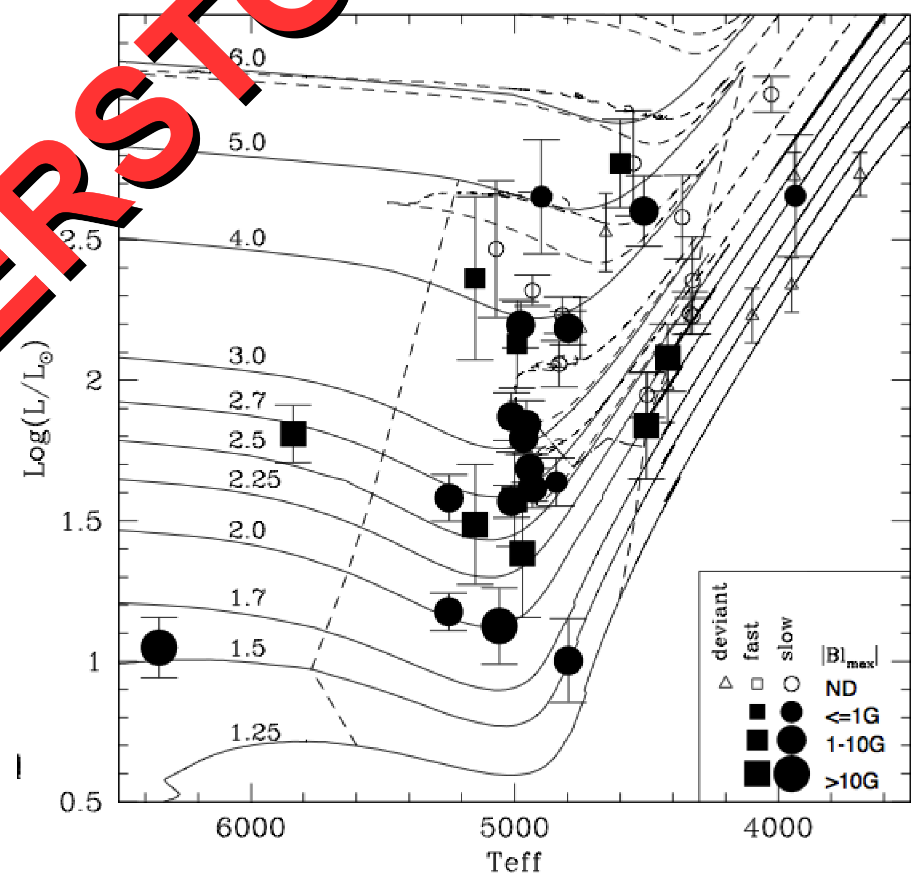

Fig. 3. Position of the Red Giants of our sample in the Hertzprung-Russel Diagram. Tracks of the standard evolutionary models of Charbonnel and Lagarde (2010) are shown.

Future

NeoNarval : continue the studies on stellar magnetism + evolved exoplanetary systems -> improve Narval

- better stability RV (2m/s long range)

SPIP (SPIrou @ Pic du midi) : study young stellar system and planet formation

SPIP is a copy of SPIRou (CFHT) , i.e. Narval in range 1-2.4µm

http://www.tbl.obs-mip.fr/

Specifications from main science drivers

- spectral domain: 0.98-2.4µm (w/ full coverage up to at least 2.3µm)
- spectral resolution >70,000 (goal 75,000) w/ 2 km/s sampling
- radial velocity precision < 1m/s
- S/N=110 per 2 km/s pixel in 1hr @ J=12 & K=11
- thermal background from instrument smaller than telescope emission @ 2.4µm
- all polarisation states accessible with <1% crosstalk over full spectral domain

CONCLUSIONS

TBL/Narval, CFHT/ESPADONS are still very unique instrument for the Study of polarisation in high-res spectra.

… But also PEPSI, HARPSPol, etc.

A lot of interesting science besides stellar magnetism

Up to 20% of TBL can be used by European astronomers
(Ongoing proposal for shared telescope time in Horizon 2020)

For the extragalactic guys: PEPSI on LBT since 2015

Narval is on TBL now, NeoNarval (2018) and SPIP (2021)

Proposed Training sessions with TBL/Narval

Create an observing block through TBL/PH2

Start the observing night on TBL/narval
- Remote control of Narval
- Calibrations

Observations of an Alpha CVn star (highly polarised) with TBL (if weather allows!)

Data reduction of the observed stars

Computation of Stokes parameters

Computation of magnetic field

Data mining on the same stars to measure polarization evolution (if any) → Star $P_{rotation}$

- Saturday 15h-17h + 1h from sunset
- Tuesday 16h-18h30 + 1h from sunset