Or, how to do single-spectrum „break-through“ science in 2024+

A polarimetric focal station for a fiber-fed high-resolution spectrograph

Klaus G. Strassmeier + Igor Di Varano, Ilya Ilyin, Thorsten Carroll

Leibniz-Institute for Astrophysics (AIP)

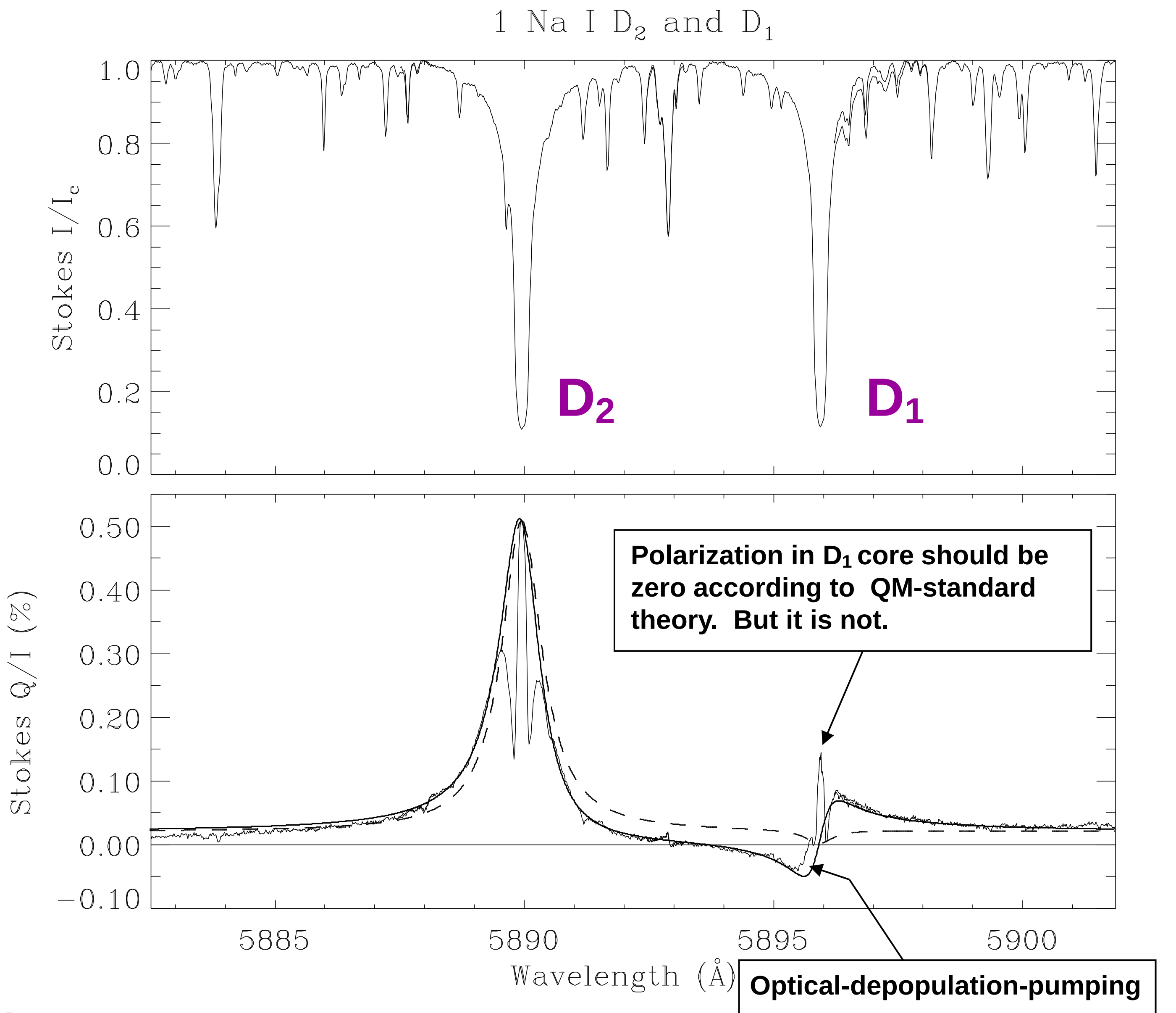
Discovery space in 2024+ ?

- A photon is the **connection** to quantum mechanics.
- We use Maxwell's eqs to describe it as a **wave** …
- … 8 parameters to fully describe it (x,y,t,ν,I_ν,Q/I,U/I,V/I)…we usually choose to ignore the latter
- Polarimetry is about **asymmetry,** i.p. in unresolved point sources (or unresolved spectral lines).
- Main relevant „asymmetries" are **magnetic fields**, **scattered light**, & **microscopic anisotropies**.
- **Synchrotron radiation** is inherently polarized.
- Polarization is subject to **Faraday rotation**.
- **Chirality** of biological molecules due to polarized radiation from space?

Solar physics guide: QM interference

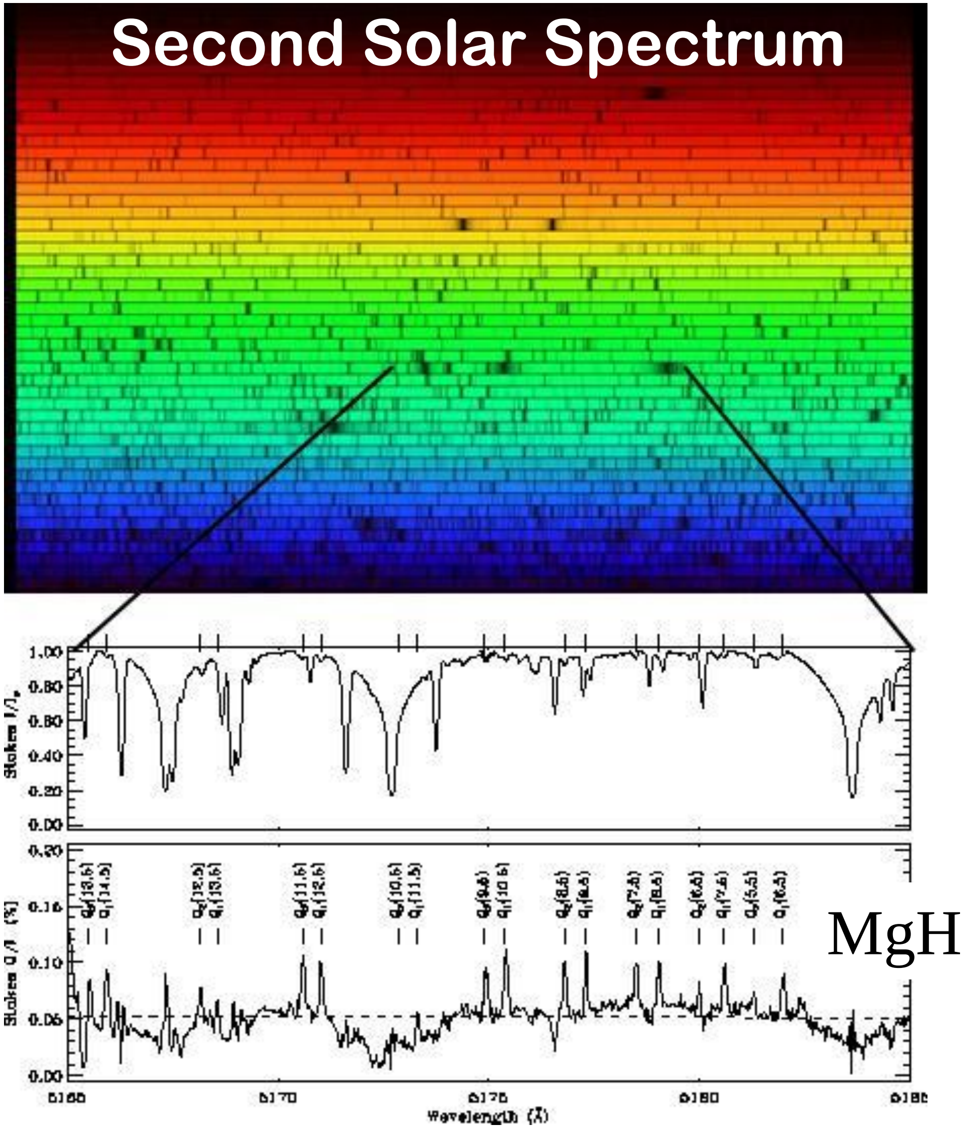
Integral light

Polarized light



Stenflo 1980, Landi degli Innogenti 1998

Hidden magnetic flux



Gandorfer et al. 2005, sss-atlas

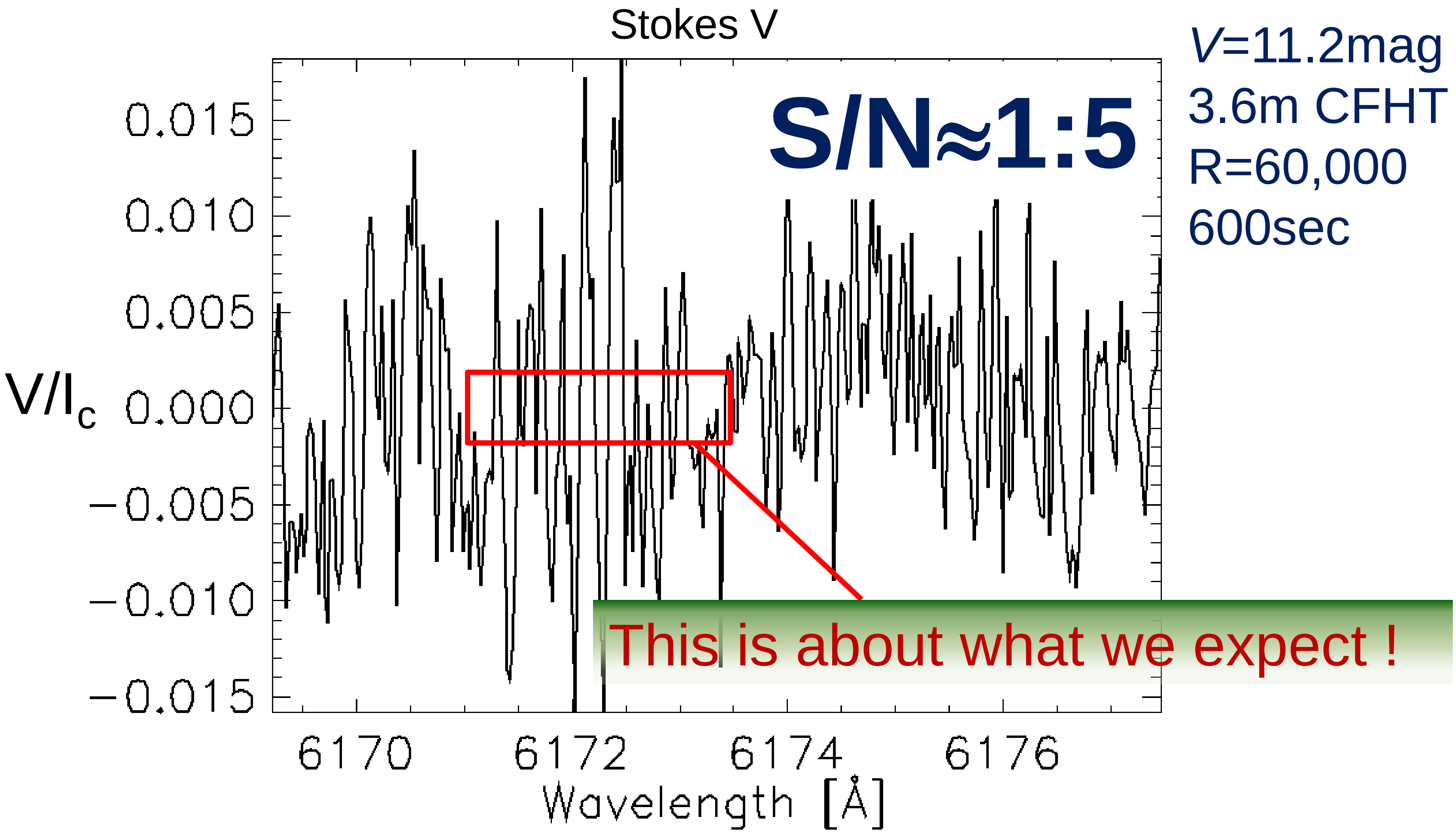
- Due to coherent scattering
- Magnetic fields modify Q thru the Hanle effect
- In Q the SS appears as a mixed absorption/emission line spectrum = SSS
- **Surprise on the Sun: phot hosts more magnetic flux than the kG „flux tubes“**
- It is significant for the overall energy budget of the solar atmosphere
- Other objects in the Universe? *not the slightest idea … but EELT*

Cosmic magnetic fields

‘*To understand the Universe, we examine galaxies and stars for radiation, small- and large-scale motions, temperatures, chemical composition, and much more. Anything we can’t explain after that, we attribute to magnetic fields.*’

- **Coherent scattering in spectral lines** (*e.g.* in magnetospheres).
- **Zeeman and Paschen-Back effects in magnetic fields** (*e.g.* on stellar surfaces).
- **Faraday rotation** (*i.e.* wavelength dependent rotation of the plane of linear polarization due to Galactic large-scale magnetic fields – synergy with radio data, e.g., from ALMA, LOFAR and SKA).

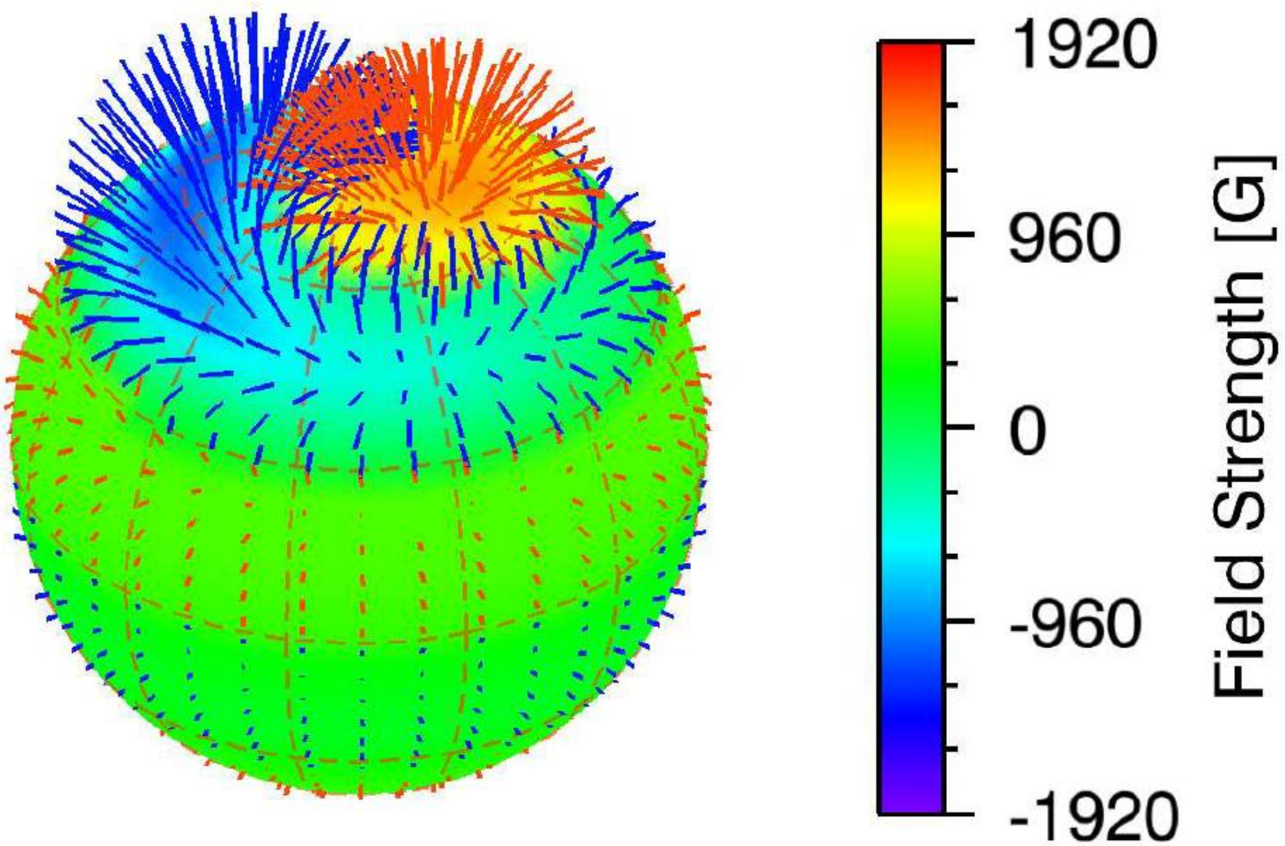
Spectropolarimetry is light starving



V=11.2mag
3.6m CFHT
R=60,000
600sec

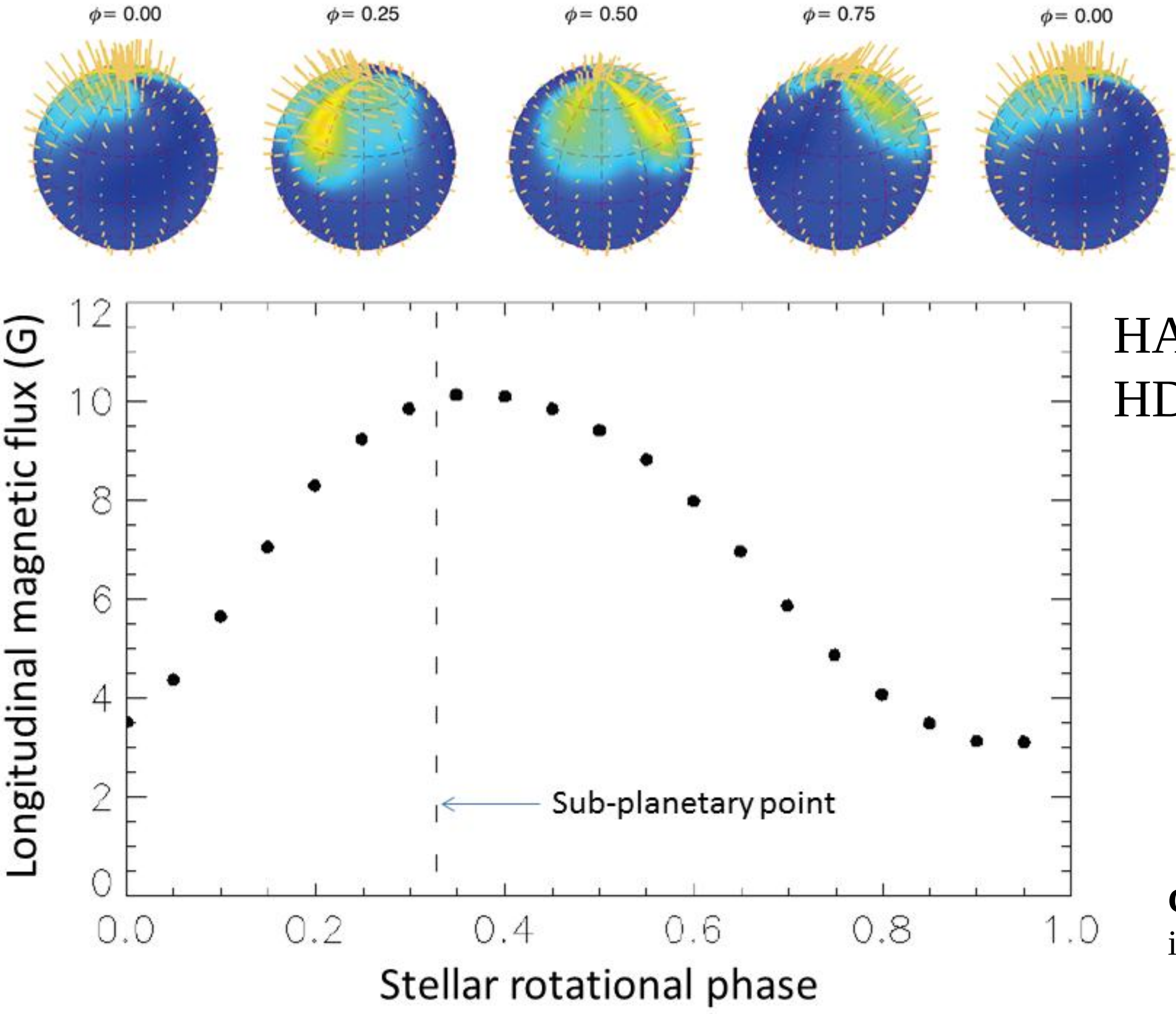
Cool starspots are magnetic fields!

Young Sun V410 Tau *T*eff and *B* map vs. an $\alpha^2\Omega$-dynamo simulation



Carroll+ 2012: A&A

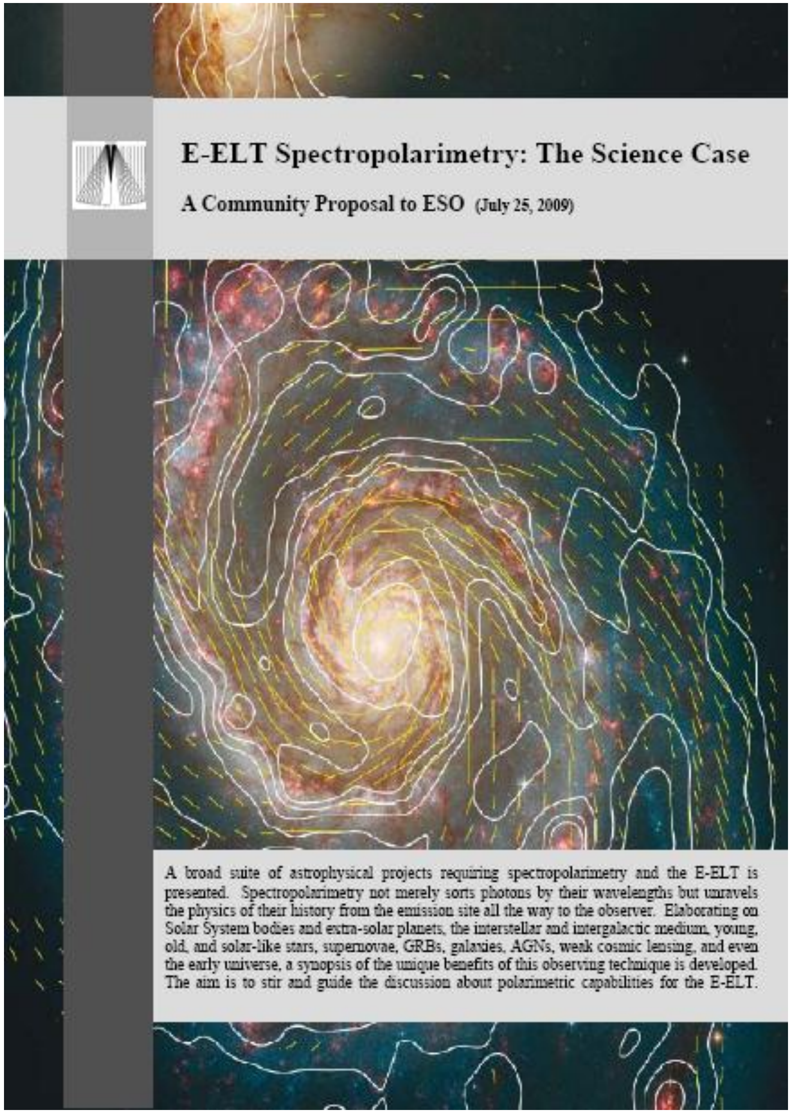
… and relates to exoplanets!



HARPS+P
HD179949

Carroll+ 2013, in prep

http://www.eso.org/sci/facilities/eelt/science/doc/



E-ELT Spectropolarimetry: The Science Case

A Community Proposal to ESO (July 25, 2009)

A broad suite of astrophysical projects requiring spectropolarimetry and the E-ELT is presented. Spectropolarimetry not merely sorts photons by their wavelengths but unravels the physics of their history from the emission site all the way to the observer. Elaborating on Solar System bodies and extra-solar planets, the interstellar and intergalactic medium, young, old, and solar-like stars, supernovae, GRBs, galaxies, AGNs, weak cosmic lensing, and even the early universe, a synopsis of the unique benefits of this observing technique is developed. The aim is to stir and guide the discussion about polarimetric capabilities for the E-ELT.

2009

C.1 Extra-solar Planets and Solar System Objects
The quest for exo-planets
Planetary atmospheres
Solid surfaces
Magnetism
The Vegetation Red Edge and other terrestrial-life markers
Comets

C.2 Stellar Formation, Structure, and Evolution
Protostars: the link to the star formation process
Magnetic braking and ambipolar diffusion in metal-poor protostars
Circumstellar disks and the formation of planets
Magnetic history of the Sun: analogs in open star clusters of different ages
At the hydrogen-burning limit: magnetic fields in fully convective stars
Massive stars: formation, evolution and impact on interstellar medium
Chemically peculiar stars
AGB stars and central stars of planetary nebulae
White dwarfs, magnetic genealogy, and cataclysmic variables
Isolated neutron stars
Soft Gamma-Ray Repeaters

C.3 The Interstellar Medium in the Milky Way and Nearby Galaxies
Interstellar dust
Interstellar magnetic fields
The Galactic Center

C.4 Extragalactic Astrophysics and Cosmology
Type Ia supernovae
Core-collapse supernovae
Collapsars and optical afterglows of Gamma-Ray Bursters
Active Galactic Nuclei - spectropolarimetry as a periscopic tool
Quasars, blazars, and high redshift galaxies
Interstellar and intergalactic magnetic fields
Cosmic gravitational lensing

http://www.eso.org/sci/facilities/eelt/science/doc/

by 80 authors

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http://www.eso.org/sci/facilities/eelt/science/doc/

Extra-solar planet and solar-system science enabled by spectropolarimetry with the E-ELT

- ❑ Direct detection of exoplanets in scattered light.
- ❑ Physical characterization of atmospheres of exoplanets (stratification, large-scale asymmetries, etc.) without restriction to transits.
- ❑ Remote mineralogy of rocky exoplanets and solar-system moons, TNOs, asteroids, and NEOs, incl. size and density measurements from polarimetric albedos.
- ❑ Search for magnetospheres around exoplanets as a possible requirement for habitability.
- ❑ Time- and position angle-dependent studies of the rings around Saturn and other giant planets.
- ❑ Volcanic activity of solar-system moons.
- ❑ Chemical stratification and evaporation processes in comets.
- ❑ Origin of chirality in terrestrial biochemistry.
- ❑ Verification, using an albedo-polarization relation, of Vegetation Red Edge detections.

http://www.eso.org/sci/facilities/eelt/science/doc/

Stellar astrophysics enabled by spectropolarimetry with the E-ELT

- Magnetic-field maps on the surfaces of protostars and in disks of T Tauri and Herbig Ae/Be stars.
- Constraints from molecular-line polarization on magnetic rotational braking as a function of metallicity.
- History of the solar dynamo from observations of solar analogs in open clusters of different ages.
- Incidence and importance of magnetic fields in brown dwarfs.
- Detailed stellar magnetic field topologies beyond the conventional simplifying low-order structures.
- The shapes and shaping of (pre-)PNe and the evolution of the magnetic fields until the WD phase.
- Magnetic genealogy of late phases of stellar evolution with important inferences for earlier phases.
- Detection, in circular polarization, of probably not otherwise visible optical spectral features in isolated neutron stars.
- Determination of the nature of Soft Gamma-Ray Repeaters from circular polarimetry of optical afterglows.

http://www.eso.org/sci/facilities/eelt/science/doc/

Galactic astrophysics enabled by spectropolarimetry with the E-ELT

- Quantitative extinction data for all studies requiring absolute luminosities, especially for objects without intrinsic color-magnitude calibrations.
- Study of the formation of dust out to the young Universe.
- Distant luminous stars as beacons to polarimetrically trace anomalies in the Galactic magnetic field, incl. possible alternative explanation to SNe of dust-free Galactic bubbles.
- Polarization of extreme Pop. II stars as a tracer of cosmic-ray electrons entering the Galaxy.
- Helicity of the magnetic field in the vicinity of the Galactic Center at NIR wavelengths.

http://www.eso.org/sci/facilities/eelt/science/doc/

Extra-galactic astrophysics enabled by spectropolarimetry with the E-ELT

- Search for systematic luminosity differences between local and high-z SNe of Type Ia, incl. aspect-angle dependencies due to asymmetries.
- Measurements at late stages of the intrinsic asymmetry of core-collapse SN explosions; 3-D maps of atomic species in SN ejecta for in-depth comparisons with theoretical models.
- Physical verification of the jet paradigm of GRBs and the nature of optical afterglows.
- Time-resolved maps of accretion and jet formation processes close to the central SMBH of representative AGNs and their relation to magnetic fields.
- Determination of the direction of the net mass in/outflow to/from Lyα-emitting sources at high redshifts.
- Validation of the assumption of randomly distributed intrinsic position angles of galaxies in weakly lensed fields.

From above scientific task list to instruments

1. **Imaging** polarimetry
   → EPICS+EPOL in „visual“ and with XAO
   → METIS in N band with AO

2. **Spectro** polarimetry
   → HIRES+SFPP in B to H band seeing limited

All require the <u>symmetric</u> intermediate focus (IF)

Requirements for HIRES+SFPP

- Spectral resolution *R* of **100,000+**
- Enable highest precision ever achieved, **<1‰**
- Be able to observe both **bright stars** and **faint quasars** down to E-ELT detection limit at *R*=100k, say, ***V*=0…20mag**
- Cover an extremely **large wavelength range** in a **single exposure**, say, **450-1800nm**
- „Easy“ calibration to maintain workhorse character

→ **symmetric IF and a dual-beam design**

E-ELT and spectropolarimetry

A spectropolarimetric focal station for the ESO E-ELT

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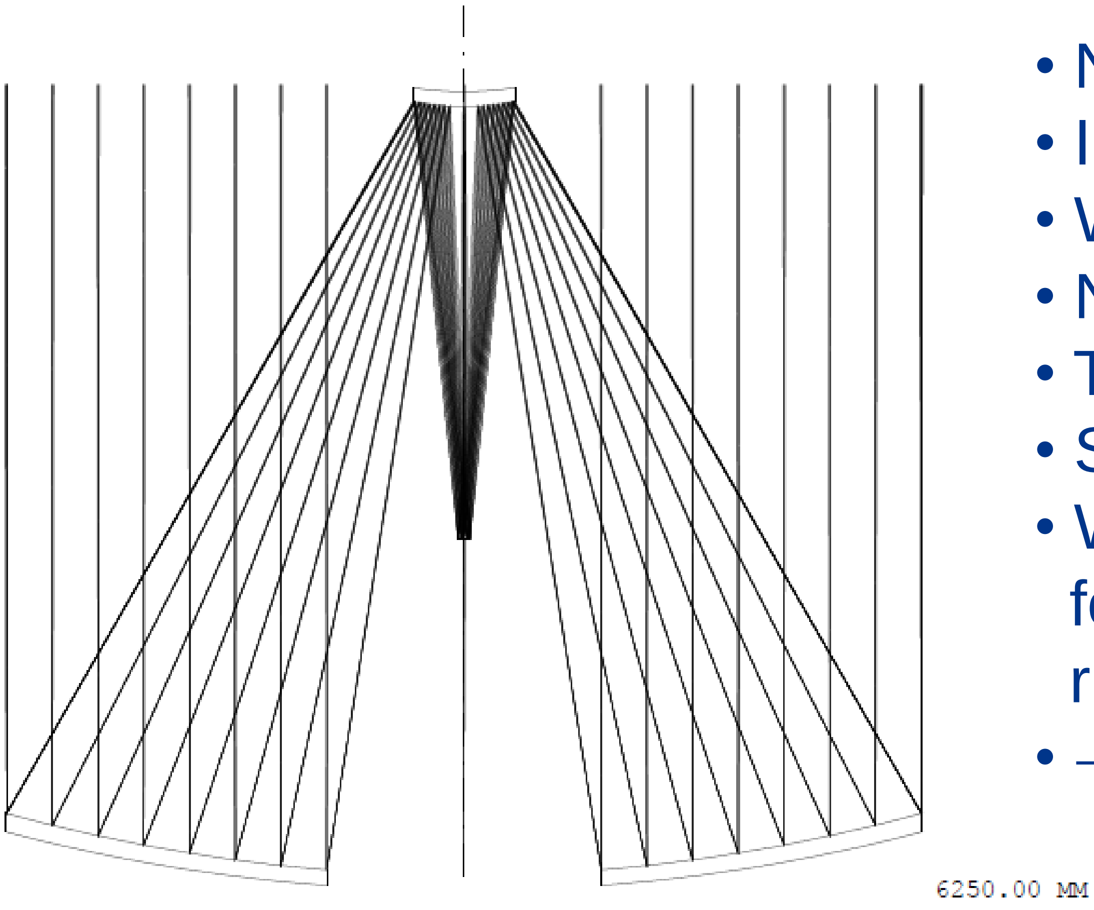
ABSTRACT

We present a conceptual design for a spectropolarimetric focal station for ESO's *European Extremely Large Telescope* (E-ELT). It uses the intermediate f/4.4 focus, the only symmetric focus of the telescope. A dual channel, full Stokes-vector polarimeter provides on-axis light for the wavelength range 380-1600nm to up to two spectrographs simultaneously via two pairs of fibers. With such spectropolarimetric capability and a proper spectrograph for the optical and the near infrared wavelengths, the E-ELT would be able to provide the full parameter space of an incoming wavefront. Because of the on-axis entrance location of the polarimeter collimator and an entrance aperture of just 1.3 arcsec, the expected poor image quality of the intermediate telescope focus is not directly relevant.

SPIE 8444, Amsterdam, 2012

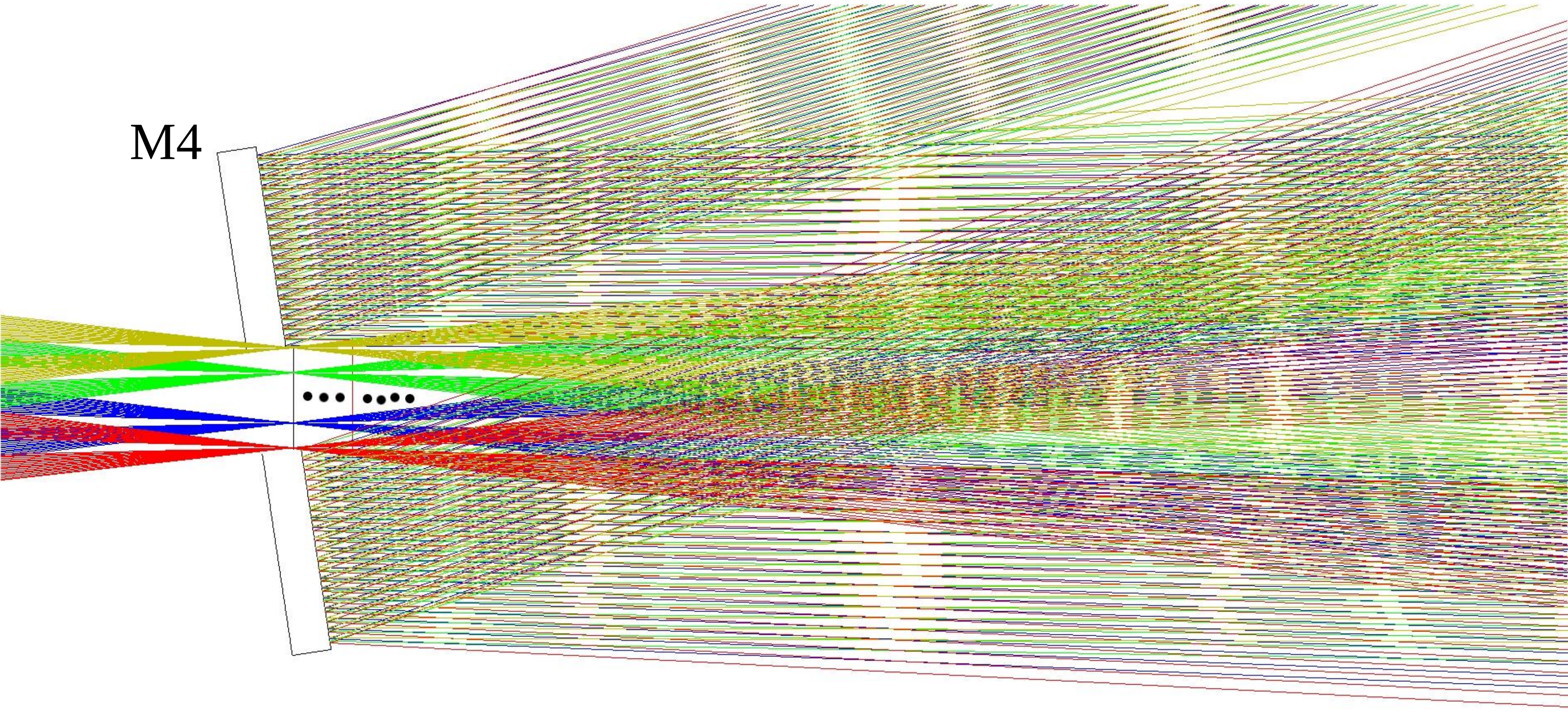
The (symmetric) intermediate f/4.4 focus



- Not open for science
- Image quality poor
- Within M4 hole
- Need to move out ADC
- Total FOV Ø 10 arcmin
- Science FOV Ø 1 arcmin
- Wavefront sensing for M1 in 5-10 arcmin ring in Nasmyth
- → severe vignetting issues in IF

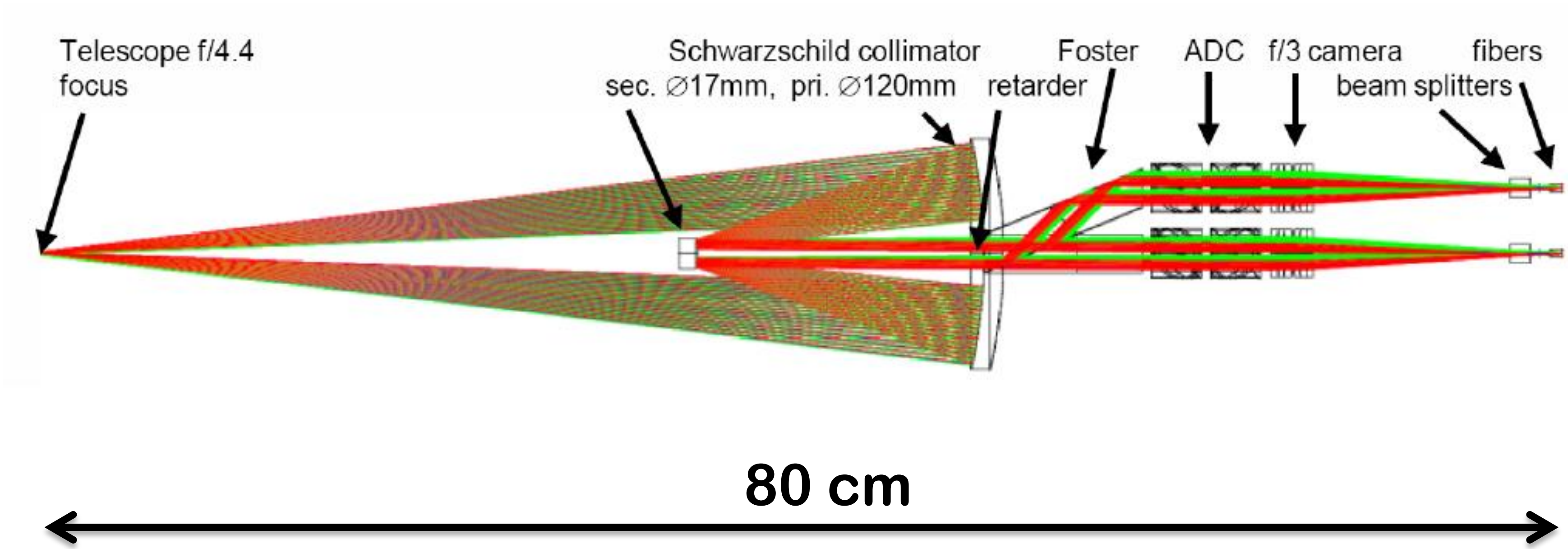
But fully o.k. for on-axis point source obs!

Space constraints at intermediate f/4.4 focus



••• = off limit due to d>30cm constraint; •••• = available space.

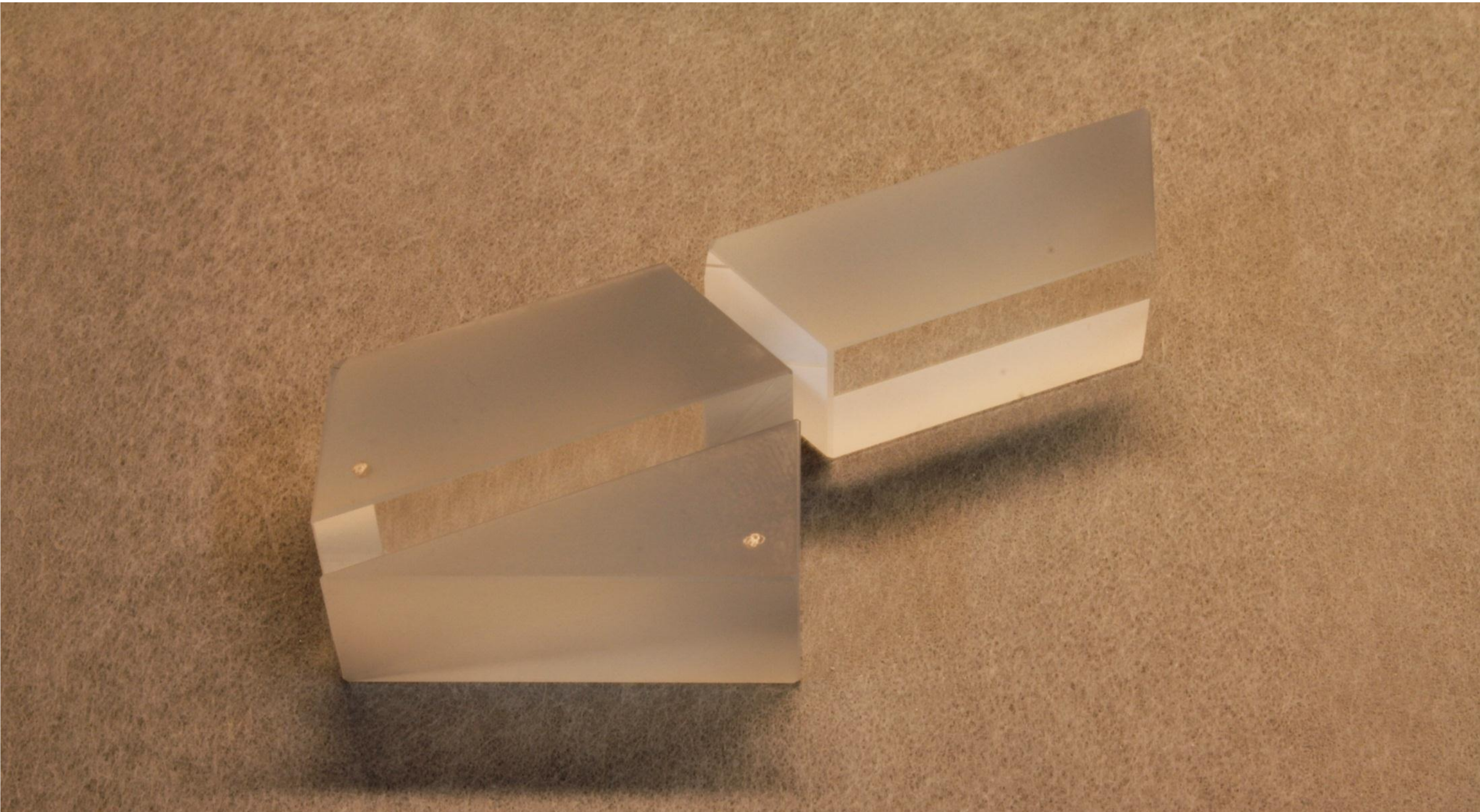
The polarimetric light feed



Reflective collimator induces zero stress birefringency and no residual chromatic abberations → *minimized cross talk*

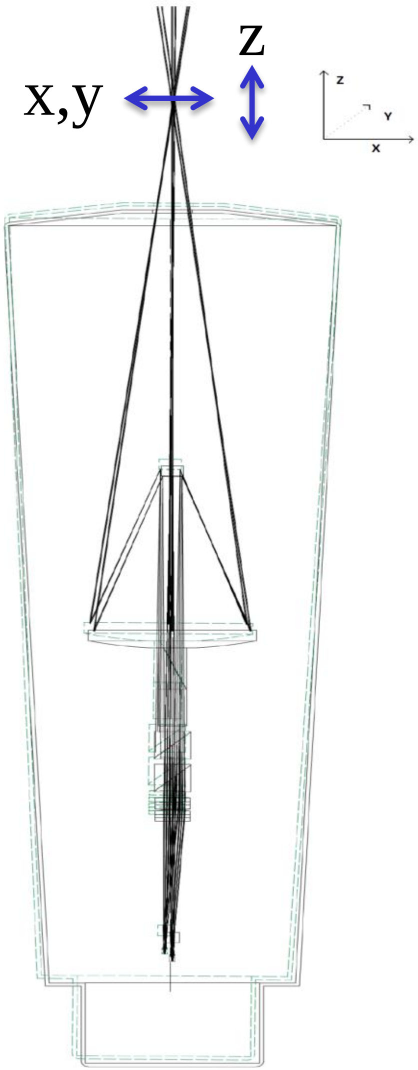
Foster unit is real heart of the feed → *prototyping needed*

Foster design and prototype production

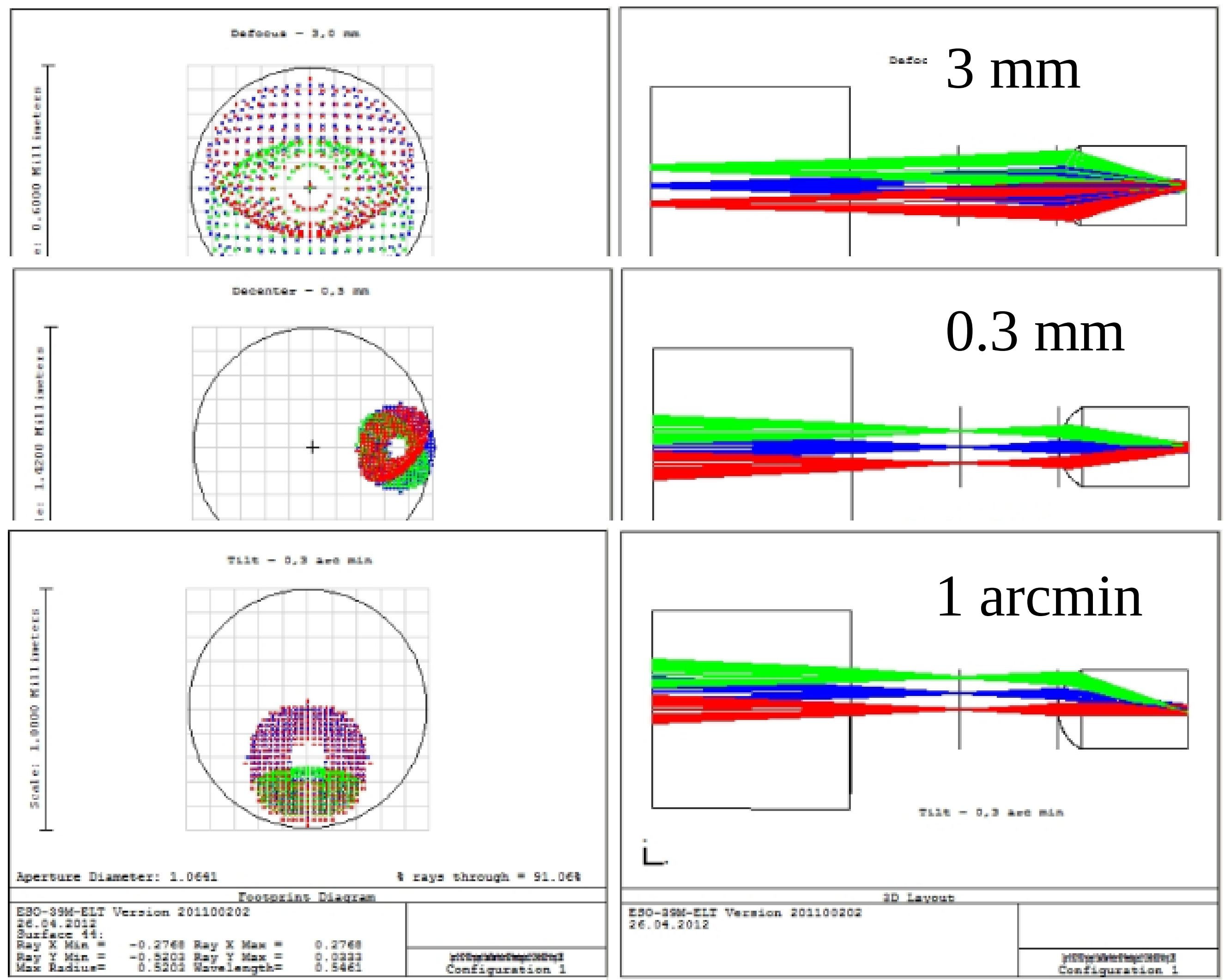


Calcite blocks for EELT/SFPP-dimensions currently not available on the market

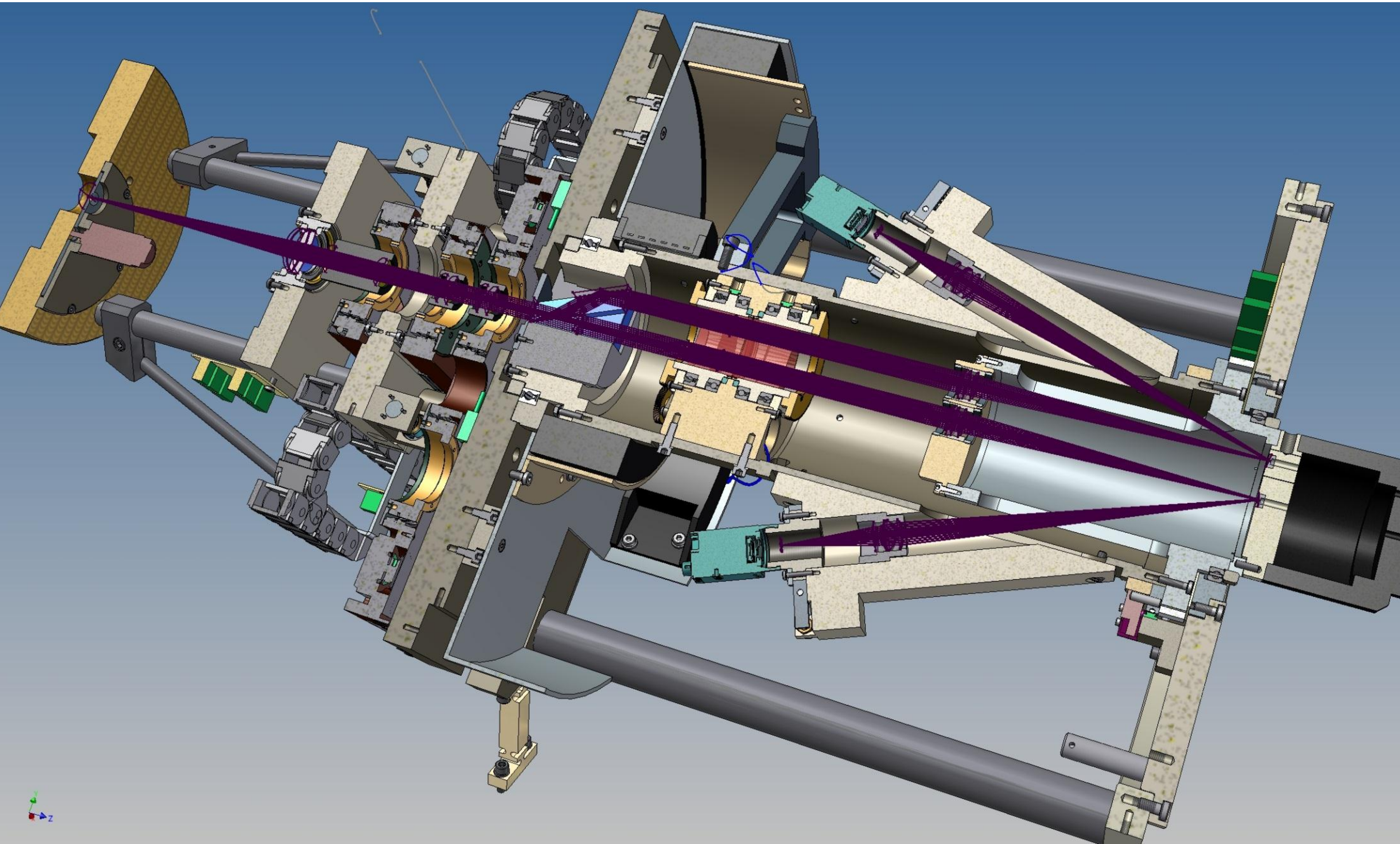
Sensitivity analysis



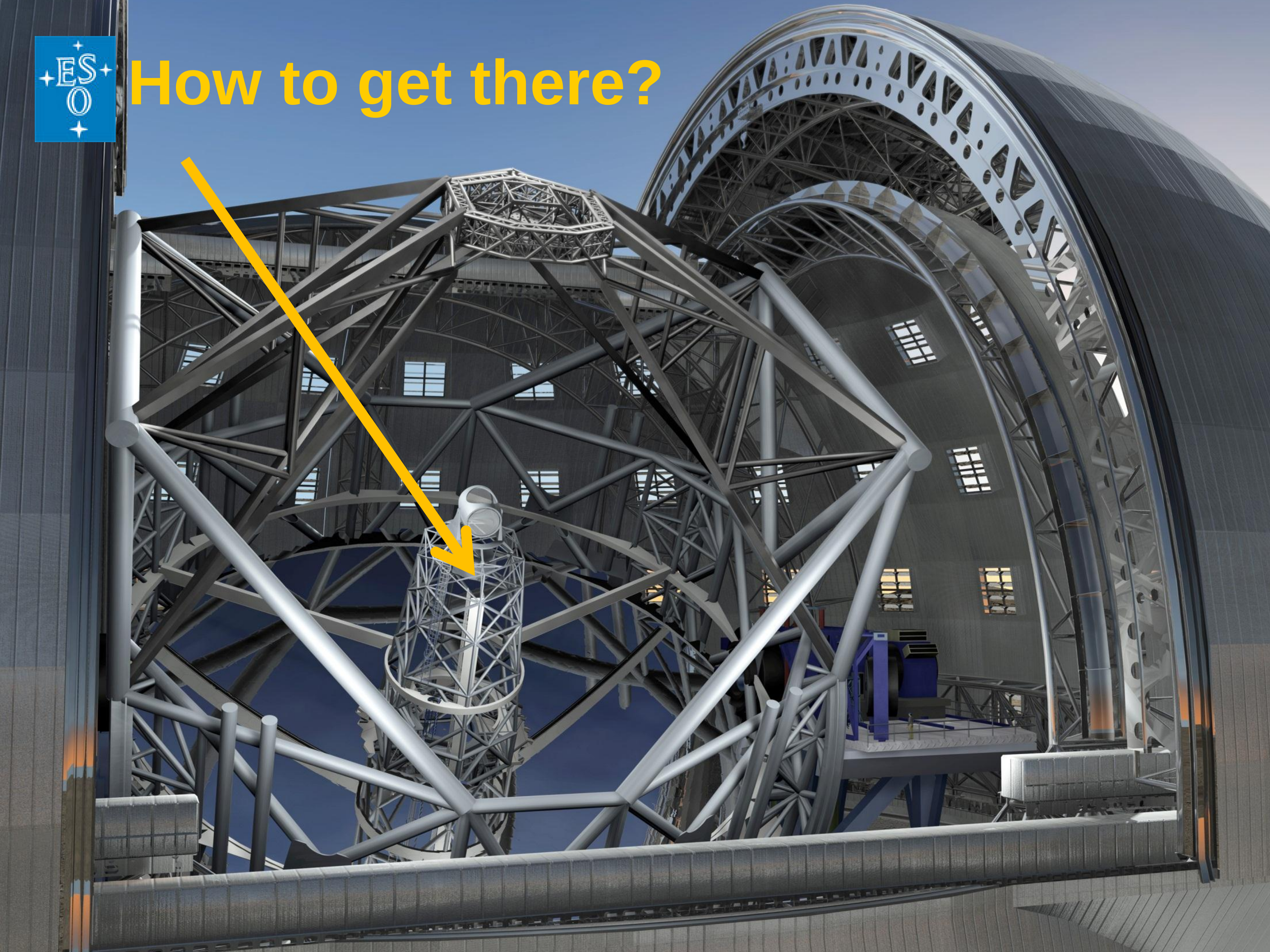
What happens at fiber entrance if x±dx,y±dy,z±dz?



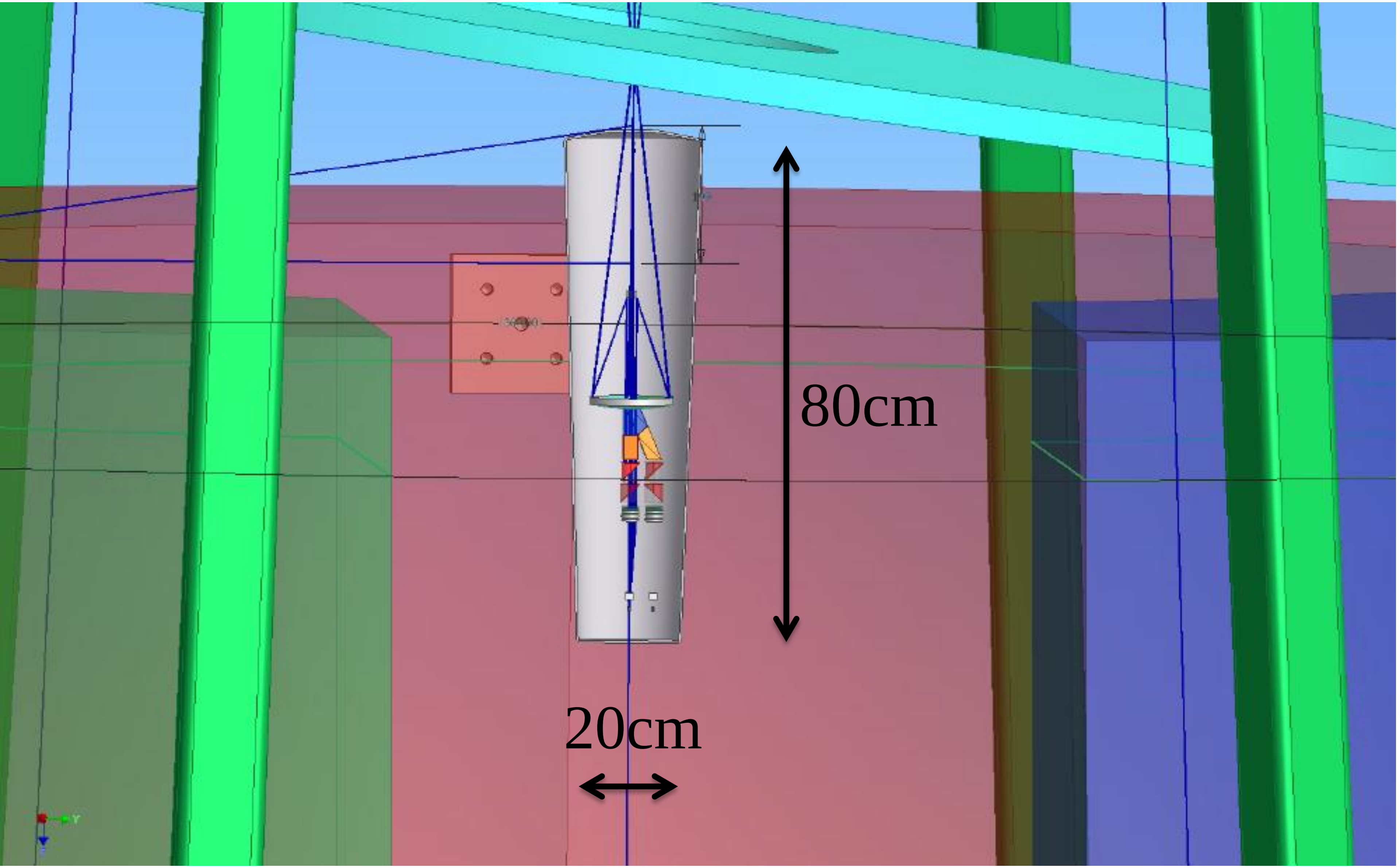
PEPSI at the LBT is the end-to-end prototype for E-ELT/HIRES

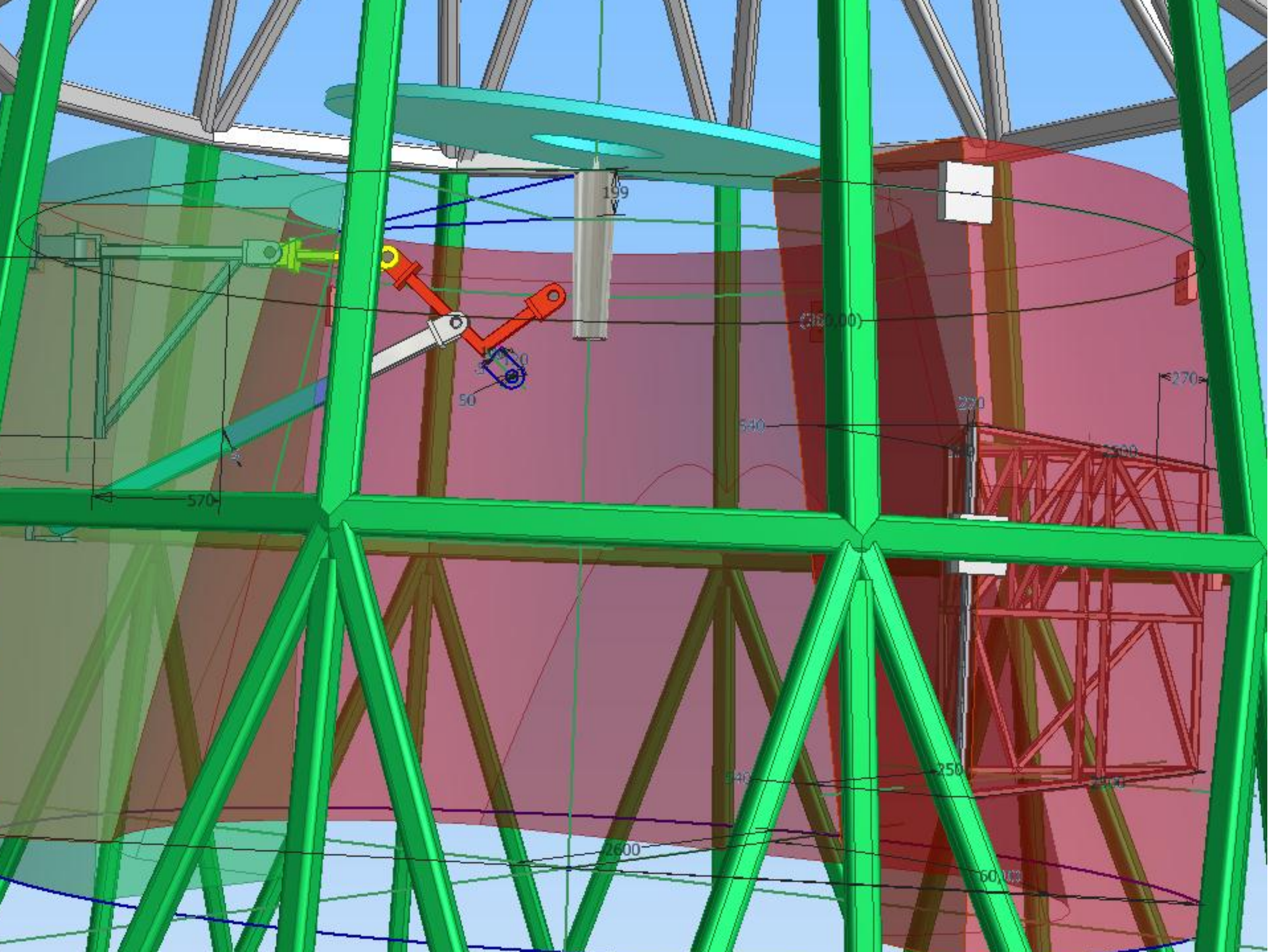


How to get there?

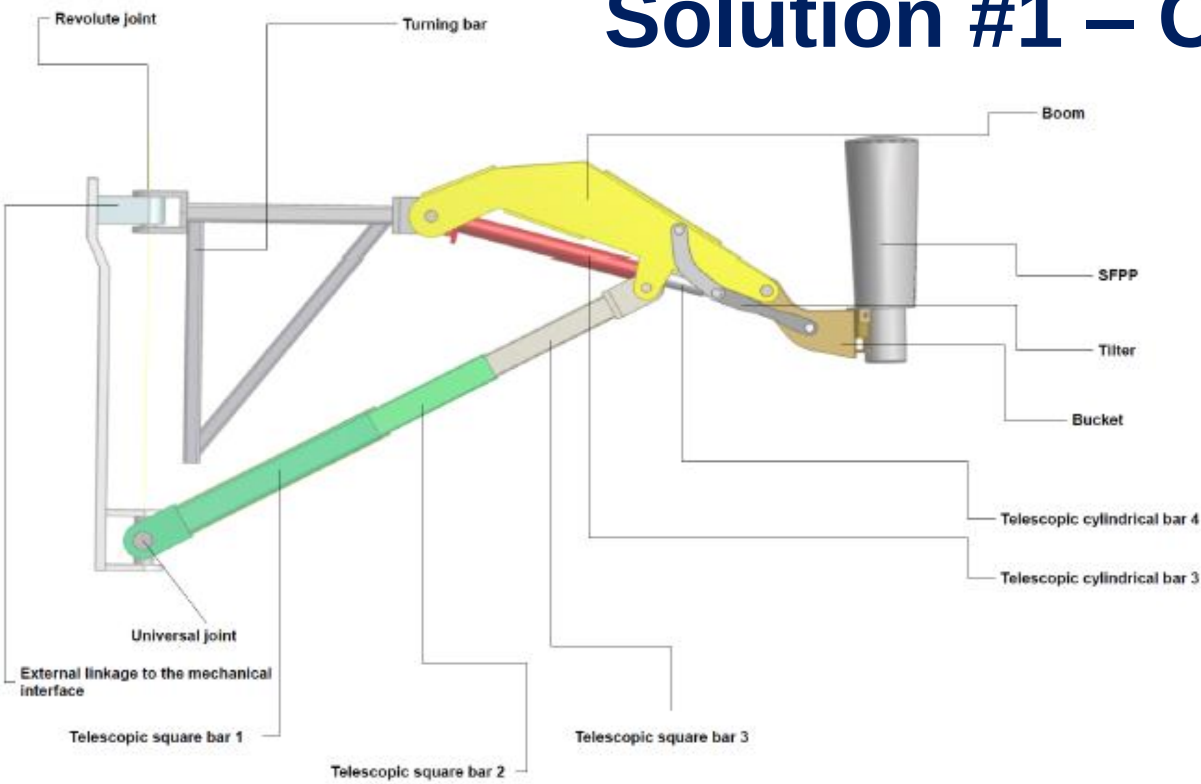


Think big, build small

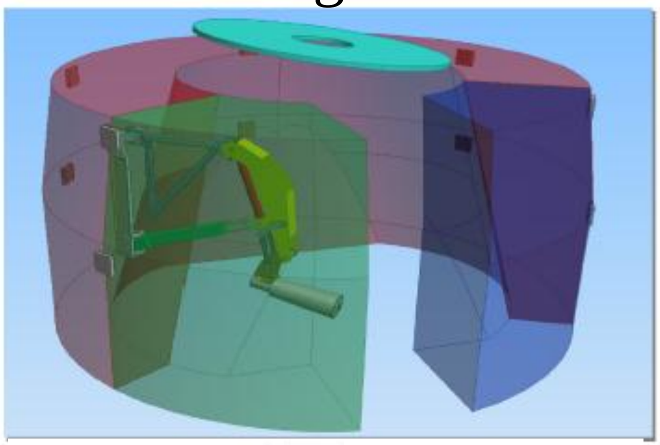



199
570
50
270
540
2600

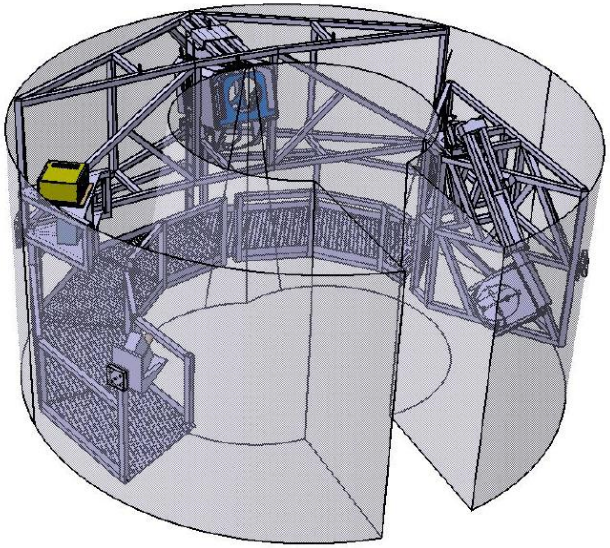
Solution #1 – Crane arm



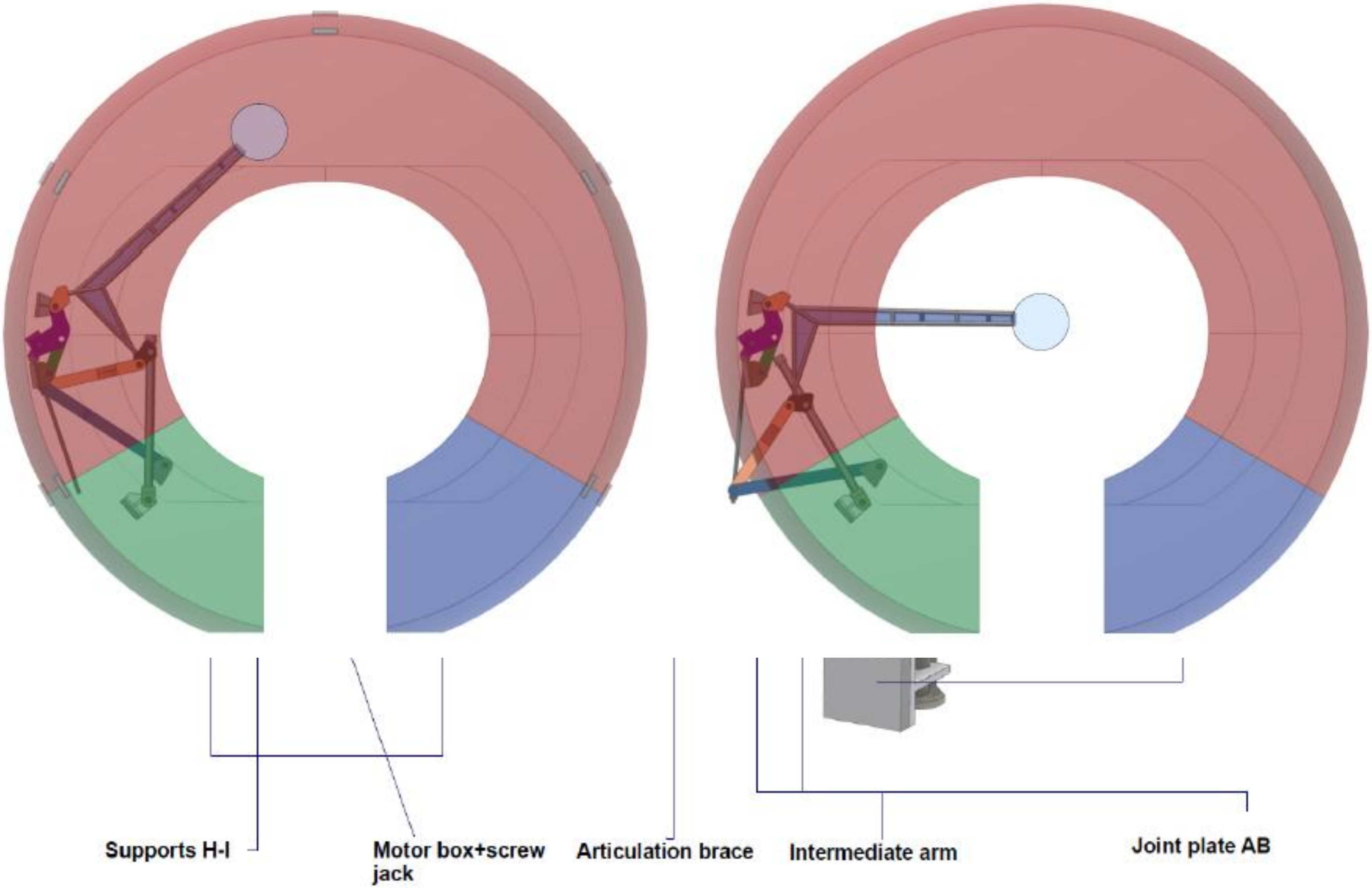
Parking mode



AOCU parking



Solution #2 – Swing arm



Summary & HIRES+P concept

- Science to be done in **12+ years** from now!
- Consider **sci ops** of „one-spectrum papers“.
- **Prime science case for spectropolarimetry**: characterize a habitable Earth-hosting stellar system down to $V \approx 20$mag.

→ Spectral resolution of ≈100k, even better 200k
→ 450-1800nm coverage: 2 or 3 spectrographs if K
→ cm/s-stability also in polarimetric light
→ HIRES integral-light feed from NF
→ Stokes IQUV feed from IF while standard off-axis AGW from NF but internal „on-axis AG“ from IF.

(Real) Summary slide

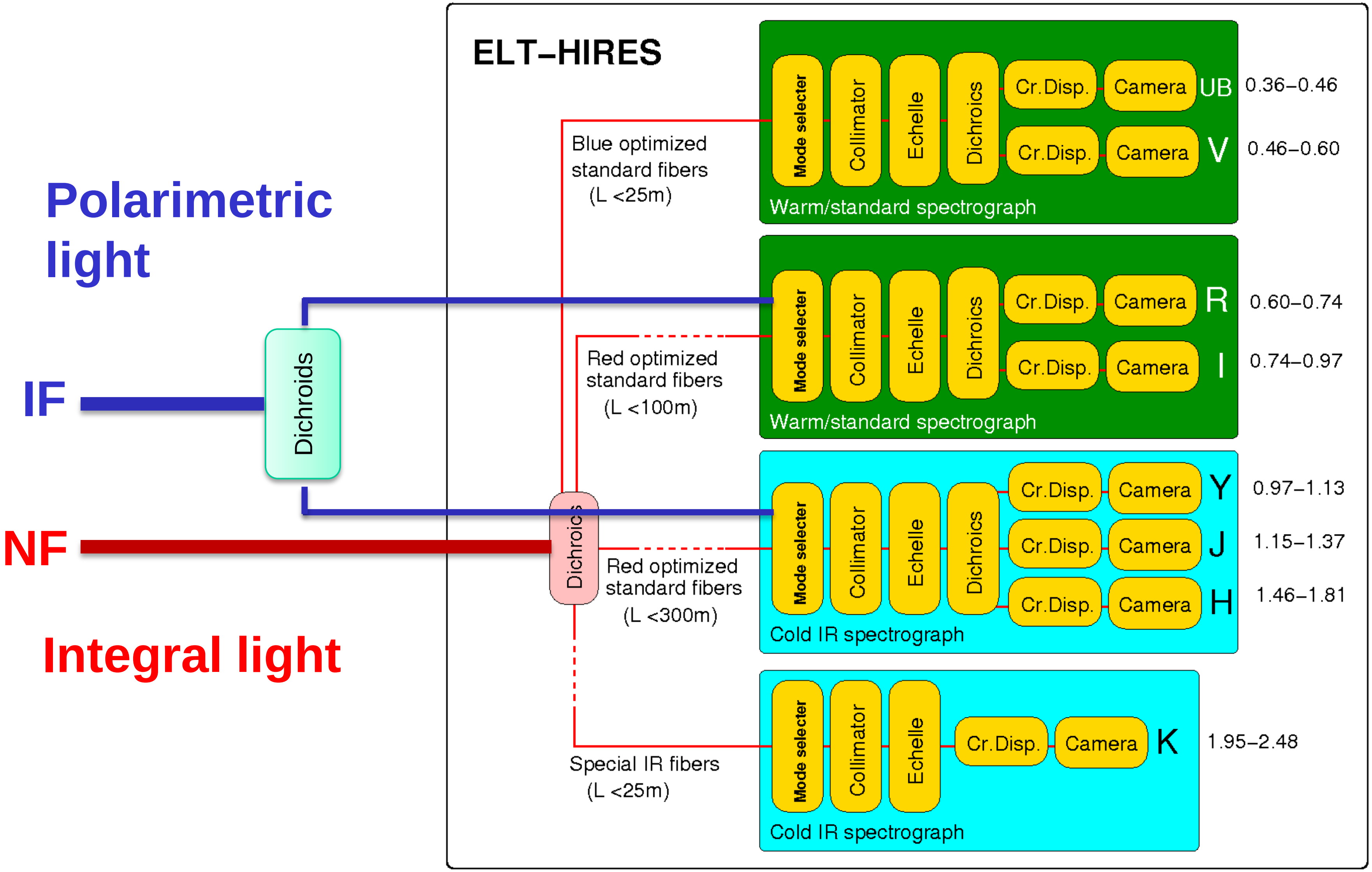
No hi-res spectro-polarimetry on …

- JWST
- TMT
- GMT
- VLT (now planned for CRIRES
- Keck
- Gemini
- Subaru
- HET
- SALT
- GTC (but Canaricam)
- Magellan

… but soon on the (11.8m) LBT for Stokes IQUV

We could be first

Possible HIRES modules



Oliva & Delabre 2012, http://www.ast.cam.ac.uk/ioa/meetings/elthires/

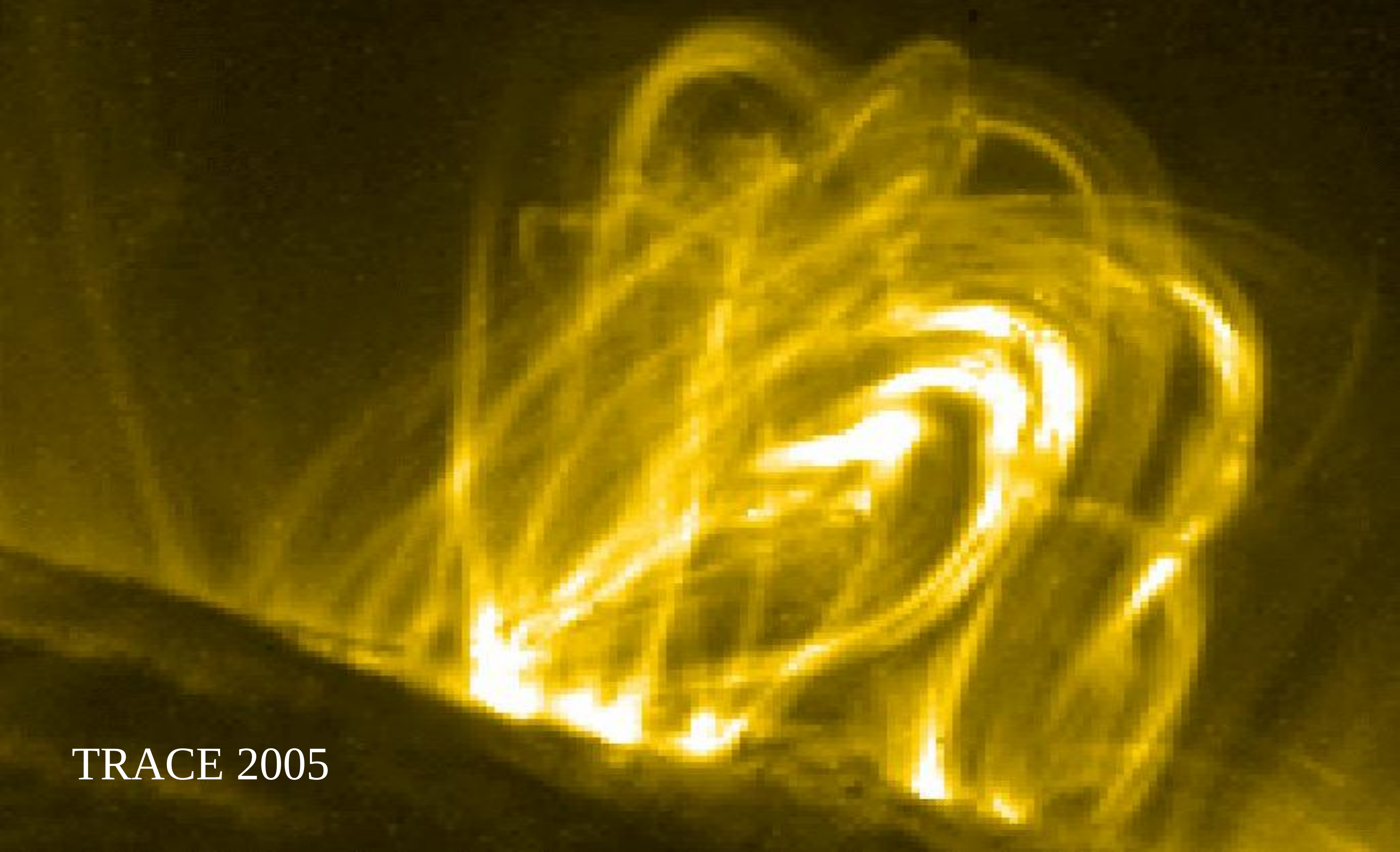
HIRES-P limiting magnitudes

IQUV mode covering 0.4-0.9µm & 1-1.8µm
for two separate instruments/arms with optimized fibers

$\delta P/P=10^{-5}$: **V≈ 3^{m}** ;
$\delta P/P=10^{-4}$: **V≈ 8^{m}** ;
$\delta P/P=10^{-3}$: **V≈13^{m}** ; **K≈12m (G2 star)**
$\delta P/P=10^{-2}$: **V≈18^{m}** ;
$\delta P/P=10^{-1}$: **V≈23^{m}** .

… allows direct access to bright Quasars, globular cluster K dwarfs, brown dwarfs in nearby Open Clusters, solar-system bodies as faint as Triton and all the way to the Galactic-Centre O & AGB stars.

Face the truth: most things turn out to be more complex than we originally thought



TRACE 2005

AIP

10th Potsdam Thinkshop

Leibniz-Institut für
Astrophysik Potsdam

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High resolution optical spectroscopy

From instruments to astrophysical models

Potsdam, May 28-31, 2013

SOC:

Carlos Allende-Prieto, IAC
Thomas Ayres, CASA
Dainis Dravins, Lund
Martin Haehnelt, Cambridge
Artie P. Hatzes, Tautenburg
Andreas Kaufer, ESO
Luca Pasquini, ESO
Monique Spite, Paris
Klaus G. Strassmeier, AIP (chair)
Steven S. Vogt, Lick

Topics:

Instrumentation on the block
Methods and scientific highlights
Normal stars, low-mass stars, binaries, exoplanets
Massive stars, ISM, IGM, quasars

Background image: Arcturus, c/o KPNO/NOAO