Exo**P**lanets **I**maging **C**amera **S**pectrograph for the **E**uropean **ELT**

Simulations

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and

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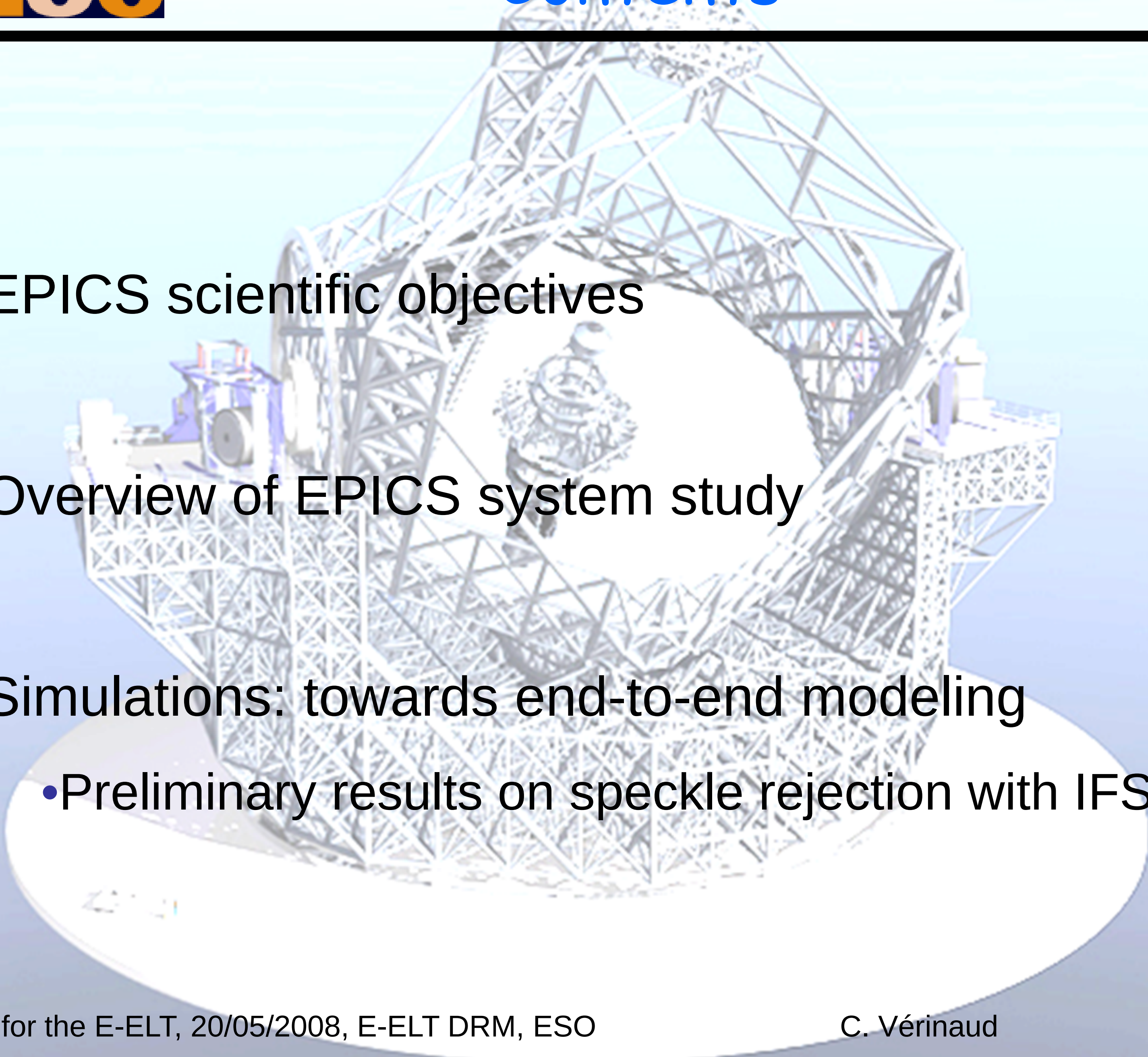
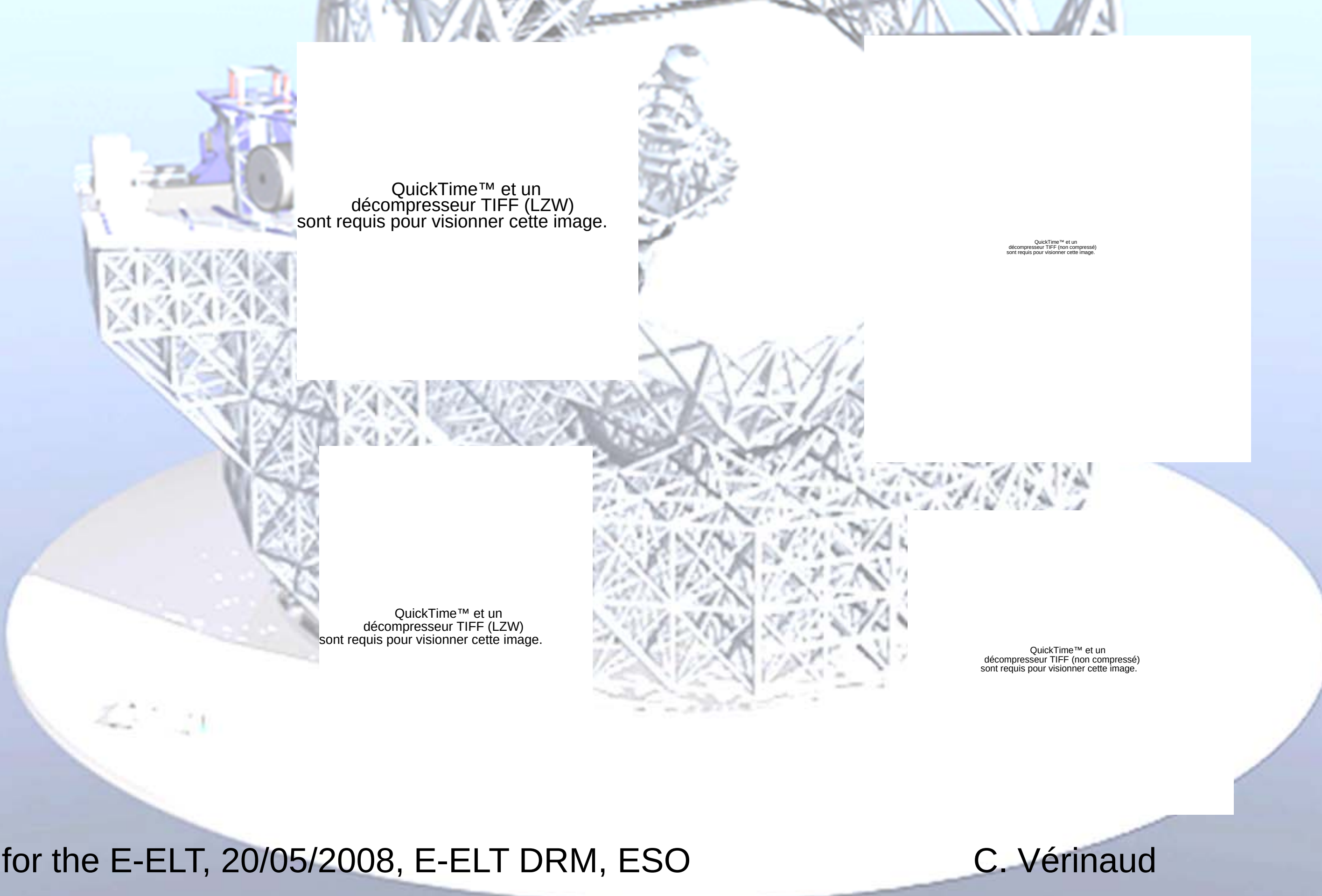


- EPICS scientific objectives
- Overview of EPICS system study
- Simulations: towards end-to-end modeling
    - Preliminary results on speckle rejection with IFS

Direct imaging from ground: today

- Imaging: Direct detection of planet photons
  - **Precise determination of orbit, mass, chemical composition, temperature,…**
  - **5 planet-mass objects discovered (NAOS, VLT)** contrast 10^{-2} 10^{-3}



Direct Imaging from ground: next steps

- Parameters for direct imaging:

α : angular separation

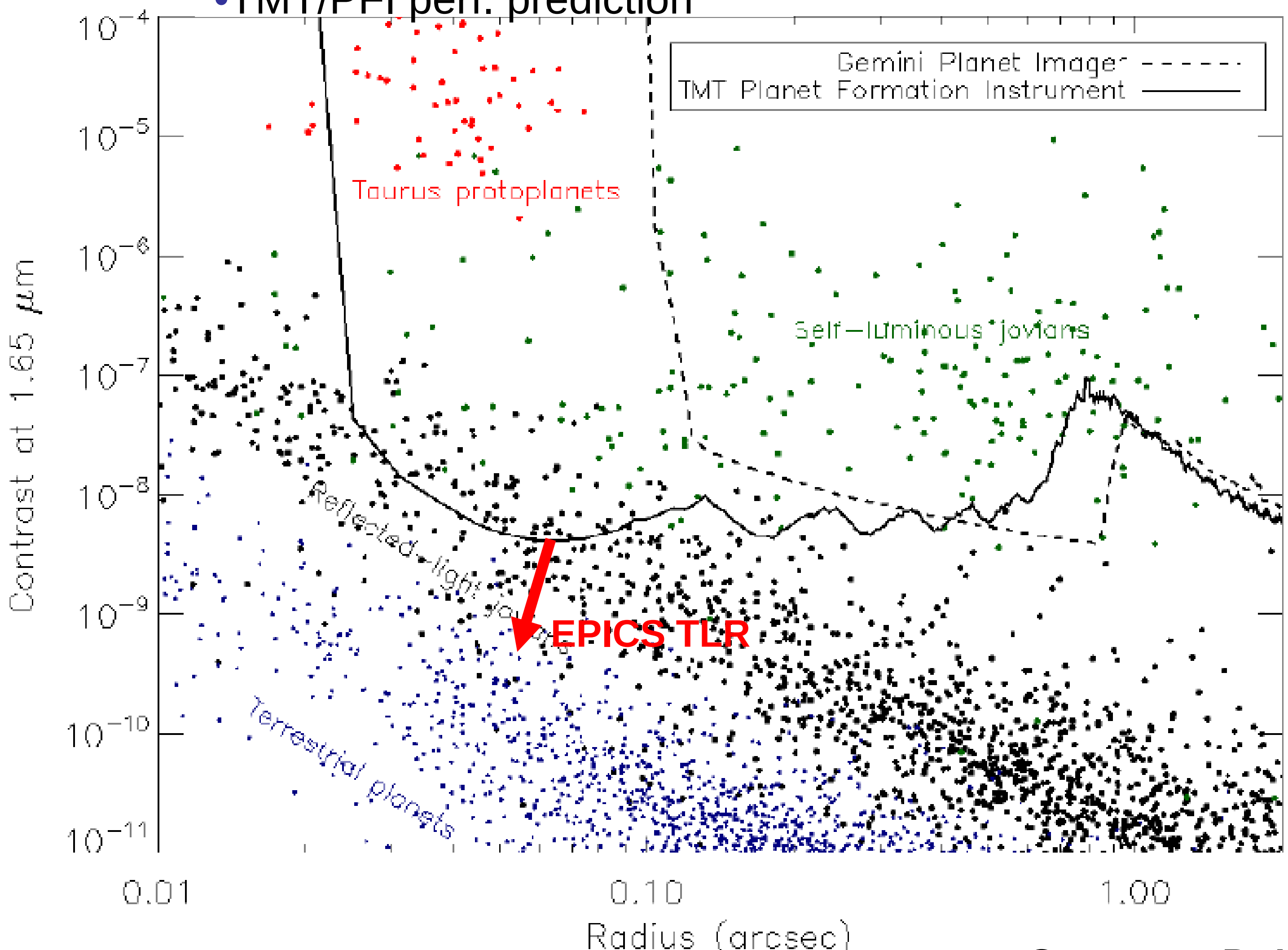
$$\frac{I_{planet}}{I_{star}} = C = \text{Contrast in luminosity}$$

- **SPHERE** (VLT), **GPI** (GEMINI), 8-m telescope : 2011
  - Angular separation: **0.1 < α < 1 arcsec**
  - Contrast (1.6 microns): $\mathbf{10^{-4}}$ **-** $\mathbf{10^{-6}}$
    (young gas planets)

- **EPICS** (E-ELT), **PFI** (TMT), 30-40-m telescope :~2020
  - Angular separation: **0.03 < α < 1 arcsec**
  - Contrast (1.6 microns): $\mathbf{10^{-7}}$ **-** $\mathbf{10^{-9}}$
    (mature gas planets and massive rocky planets)

EPICS Science Objectives

- TMT/PFI perf. prediction



- Courtesy: B. Machintosh

EPICS Science cases

- 1. Young self-luminous gas giants in star forming regions or young associations
- 2. Detection and characterization of mature jovian gas giants in reflected light
- 3. Imaging and characterization of warm Jupiters known by radial velocity
- 4. Detection of warm Neptunes and massive rocky planets, ultimately located in habitable zone

TLRs

Brightness ratio at Distance [mas]	30 (goal 20)	100	300	Limiting stellar magnitude I band
Science Case 1	10^{-6}	10^{-6}	10^{-6}	9 (goal 10)
Science Case 2		$2\ 10^{-9}$ (goal 10^{-9})	10^{-9} (goal $4\ 10^{-10}$)	7 (goal 8)
Science Case 3	10^{-8}	10^{-9}	10^{-8}	7 (goal 8)
Science Case 4	$2\ 10^{-9}$ (goal 10^{-9})	10^{-9} (goal $4\ 10^{-10}$)	$5\ 10^{-10}$ (goal $2\ 10^{-10}$)	5 (goal 6)

EPICS phase A

- **Phase 1: November 2007 - July-2008**
  - **Intensive Development of modeling tools**
    - E-ELT optics
    - XAO and coronagraphy
    - Instruments: IFSs, Diff. Pola, Self Coherent Camera
    - Signal extraction (IFS)
  - **Trade-off study**
    - System: instruments concept vs. science objectives
    - Coronagraphy and WF control: review of existing concepts and new ideas
  - **Phase 2 workplan preparation**
  - **Experiments preparation**

EPICS phase A

- **Phase 2: September 2008- November 2008**
  - **Conceptual Design** (Baseline + further generation ?)
    - Opto-mechanical design
    - Risk and cost estimate, Schedule
  - **Performance analysis**
    - Detailed end-to-end simulations for 1st generation EPICS
    - Extrapolation for next generations
  - **Experiments (FP7 preparatory phase)**
    - **Extreme AO on an ELT**
      - HOT bench (ESO): Woofer-Tweeter, co-phasing residuals, etc.
      - Speckles active correction (LAOG, LESIA)
    - Coronagraphy: ESO, LESIA, LAM, FIZEAU
    - **Integral Field Spectroscopy**
      - Oxford Univ.: SLICER IFS
      - Padua Obs.: BIGRE IFS
    - **Differential polarimetry**: ETHZ

EPICS simulations strategy

OCTOPUS (ESO/LAOG)

- End-to-End XAO modeling

-Correction of atmospheric turbulence (temporally correlated phase screens)

-Correction of instrumental errors on top of AO residuals (post-corono WFS)

Scale of real time simulated : ~seconds

(Christophe Vérinaud, Visa Korkiakoski)

PESCA (LAOG)

- End-to-End modeling of EPICS system

-Uncorrelated phase screens

-Precise modeling of telescope and EPICS Instrumental optical defects (common and differential errors)

- Precise modeling of instrument, signal extraction and detection noise

(Christophe Vérinaud, Visa Korkiakoski)

Scale of real time simulated : ~hours

Phase screens generation

Model Adjustments

Model Adjustments

Analytical model for high contrast imaging (IAC/LAOG)

-XAO analytical modeling

-AO residuals power spectra (à la PAOLA or CAOS_SPHERE)

-Signal extraction analytical modeling

- Based on photon noise (SNR/integ. time) and speckle noise (‘hard’ limit)

- →Explore large parameter space beyond EPICS

-DRM

(Bruno Femenia, Christophe vérinaud)

EPICS simulations

- **High contrast imaging modeling is very complex**
  - Needs time to develop code
  - Needs time to run it

- **Different level of approximations**
  - The simplest (the one used up to now)
    - AO Analytical modeling : **Photon noise limit** imposed by AO halo
      - 1D model
      - Need of 2D model cross-checked with simulations (collab. IAC)
      - Wll be used for de-correlated phase screens generation

- **The critical issues investigated in priority in phase 1** :
  - Detailed simulations of Fourier Optics: **speckle noise limit**

–Static aberrations

–Coronagraphy

–Science Instruments modeling and Signal extraction: IFS

•Photon noise limit: assumptions

- Seeing: 0.6″, 10 hours on-source integration (or 30 hours for 1″ seeing)

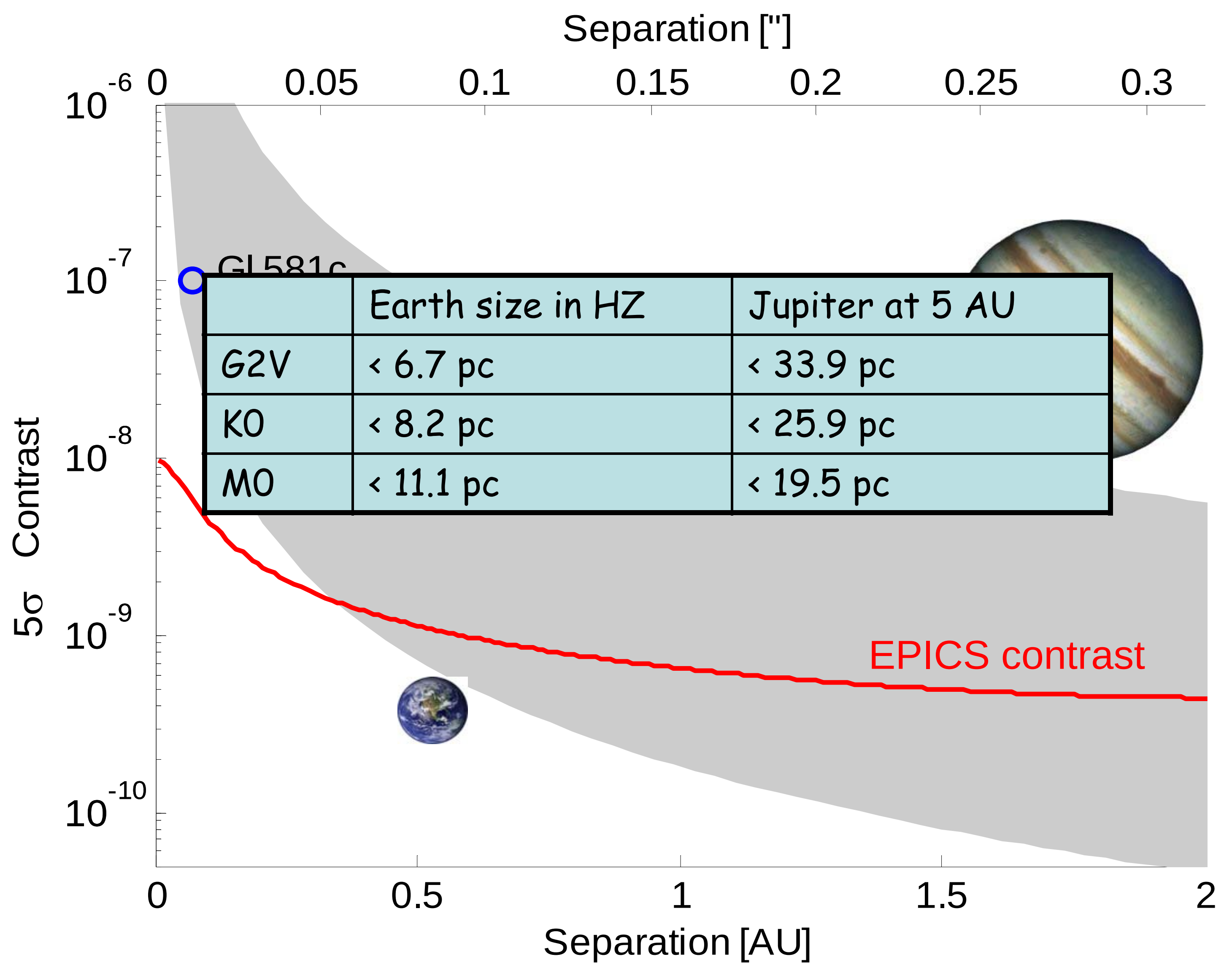
- Overall efficiency to science detector: 10%

- Observations: dual-band imaging in J-band with 100nm bandwidth

- XAO system main characteristics
  - –Pyramid WFS : optimal for ELT and halo rejection at small angular separations.
  - –0.2-m actuator spacing (~**30.000 actuators** for 42-m ELT) 3 kHz

Photon noise limit

- 10 H integration . Seeing 0.6 arcsec (photon noise limit). 1600-nm, 100nm bandwidth



	Earth size in HZ	Jupiter at 5 AU
G2V	< 6.7 pc	< 33.9 pc
K0	< 8.2 pc	< 25.9 pc
M0	< 11.1 pc	< 19.5 pc

Speckle noise

- Main contributor:
  - Static optical errors
- Also: speckle lifetime about 1 sec. on a 42-m (not yet implemented)

Error source	Nominal values	Comments
Seg. Piston and tip-tilt	90-nm rms	Can be directly scaled by rms improv. ratio
Seg. Mis-figure	30-nm rms	Can be directly scaled by rms improv. ratio
EELT 5 mirrors HF	sqrt(5) *20 nm rms	Can be directly scaled by rms rms improv. ratio
XAO static in band	5-nm rms	Typical f^0 (phase meas.)
Reflectivity dispersion	1% rms	Scaling must be applied on dispersion and not on overall value

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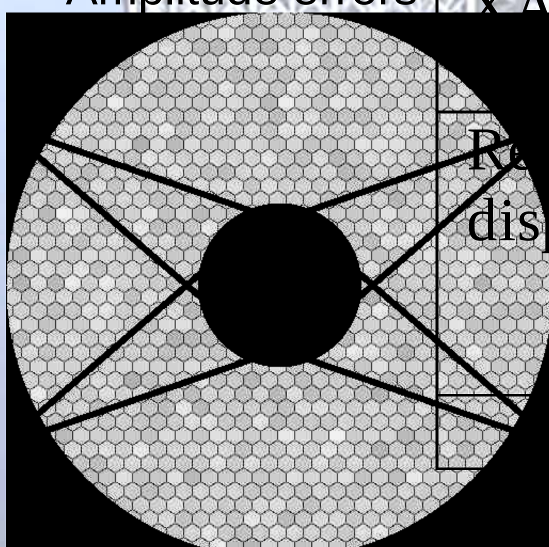
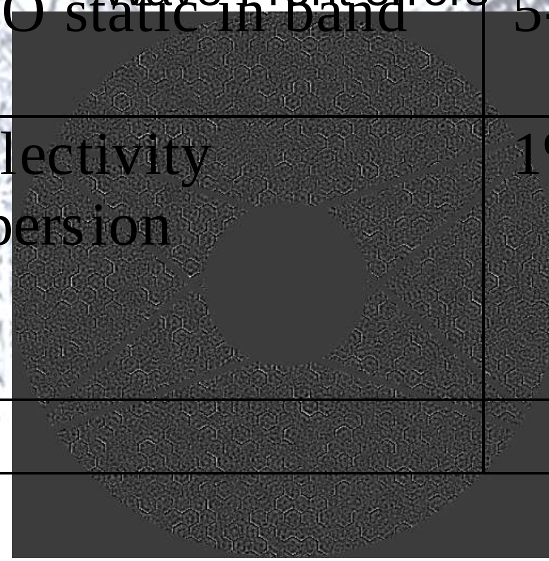
Reflectivity dispersion	1% rms

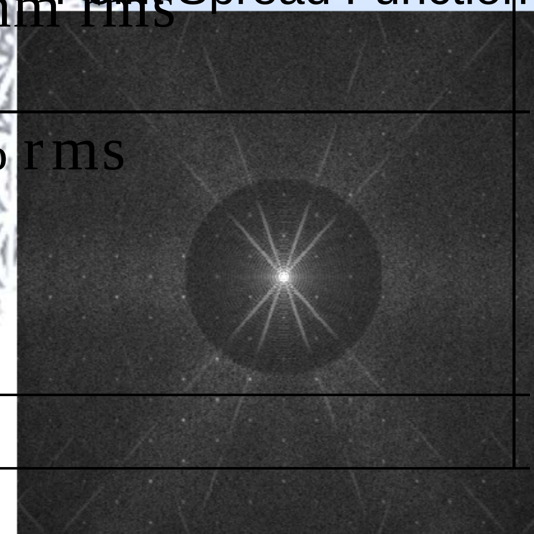
- Amplitude errors



- Wave-Front errors

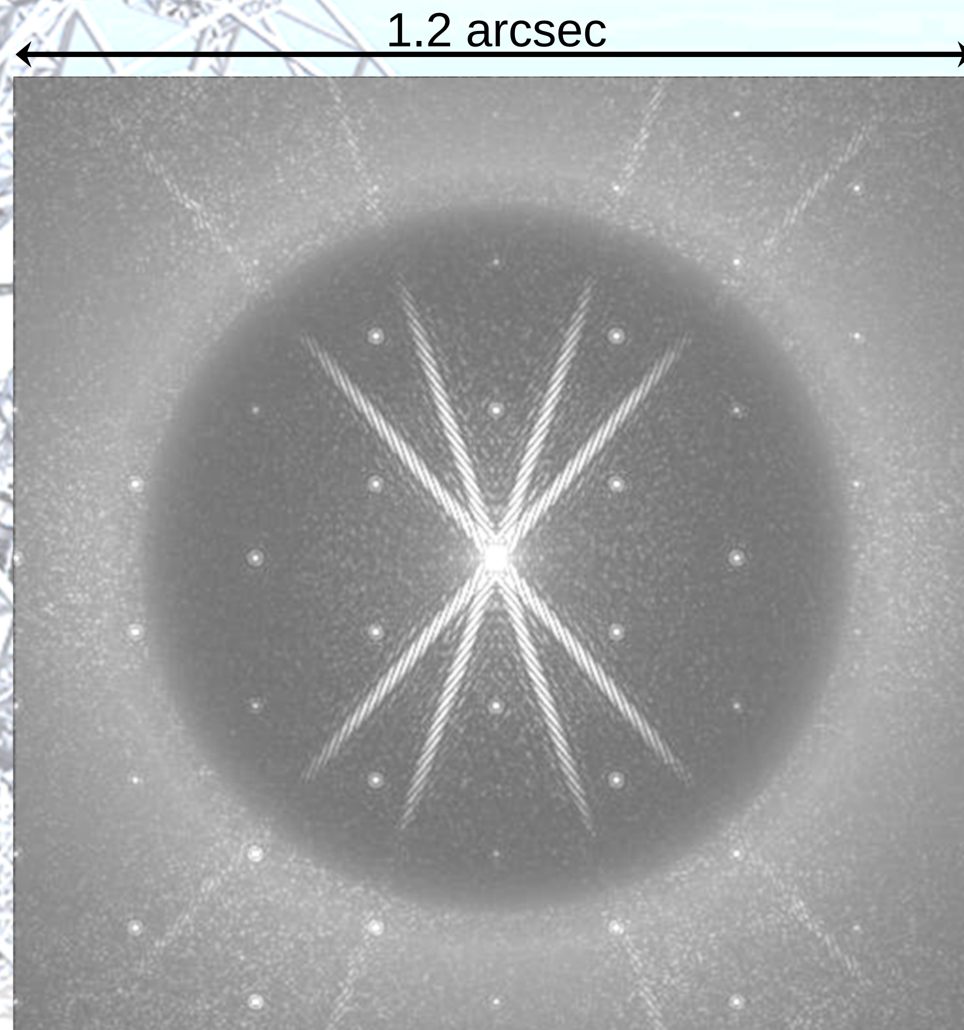


- Point Spread Function



Coronagraphic image after XAO

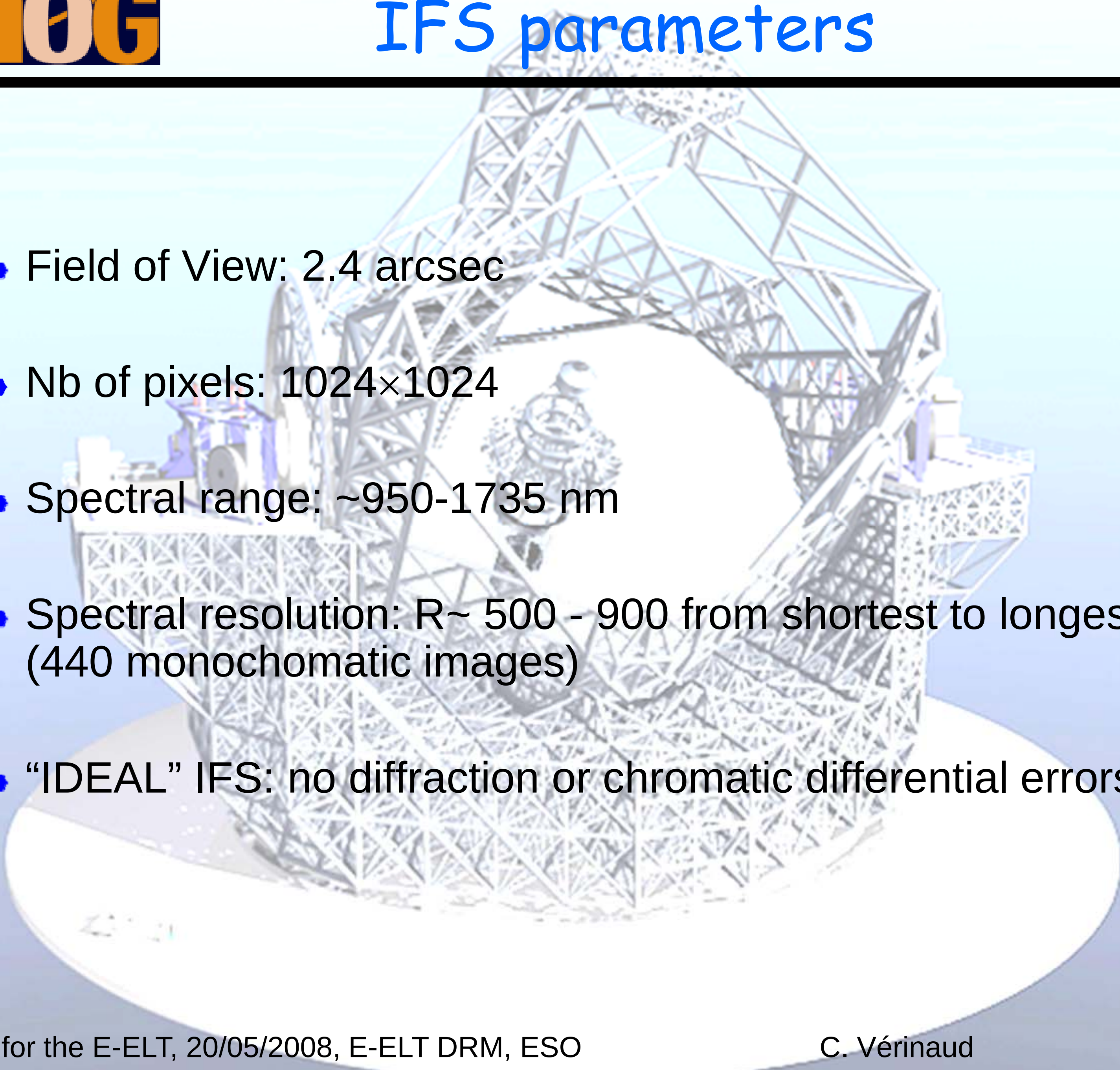
- Image at 1000-nm
- Almost « ideal » achromatic coronagraph , not optimized for spider
- Seeing : 0.85 arcsec, i0=3ms
- XAO: Pyramid, 200x200, 3 KHz
- SR=80% at 1000-nm



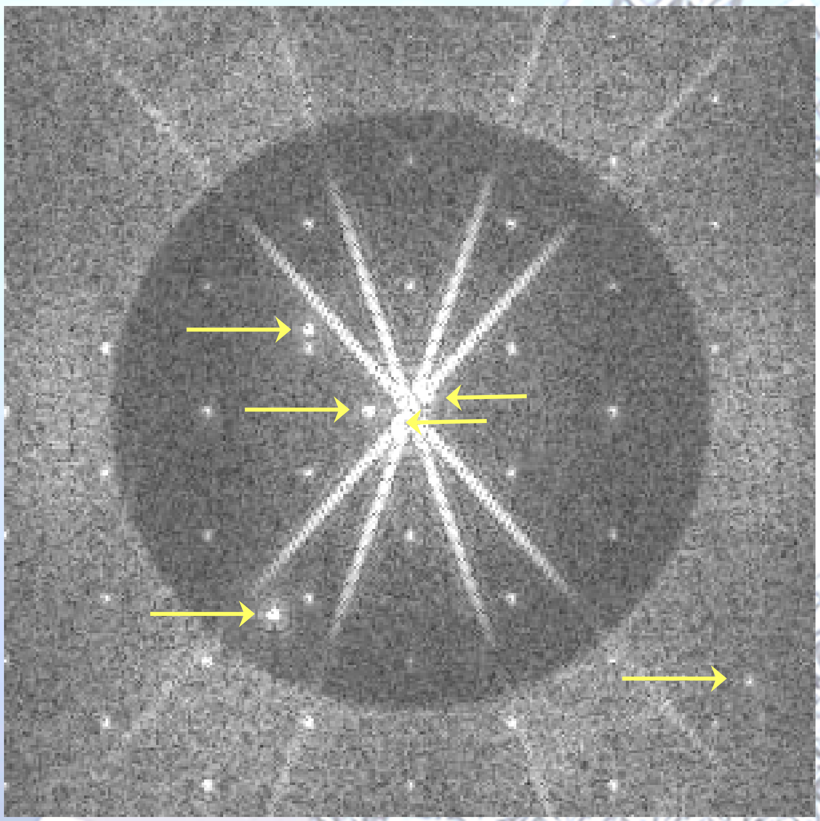
- E-ELT on the moon
- E-ELT on Earth

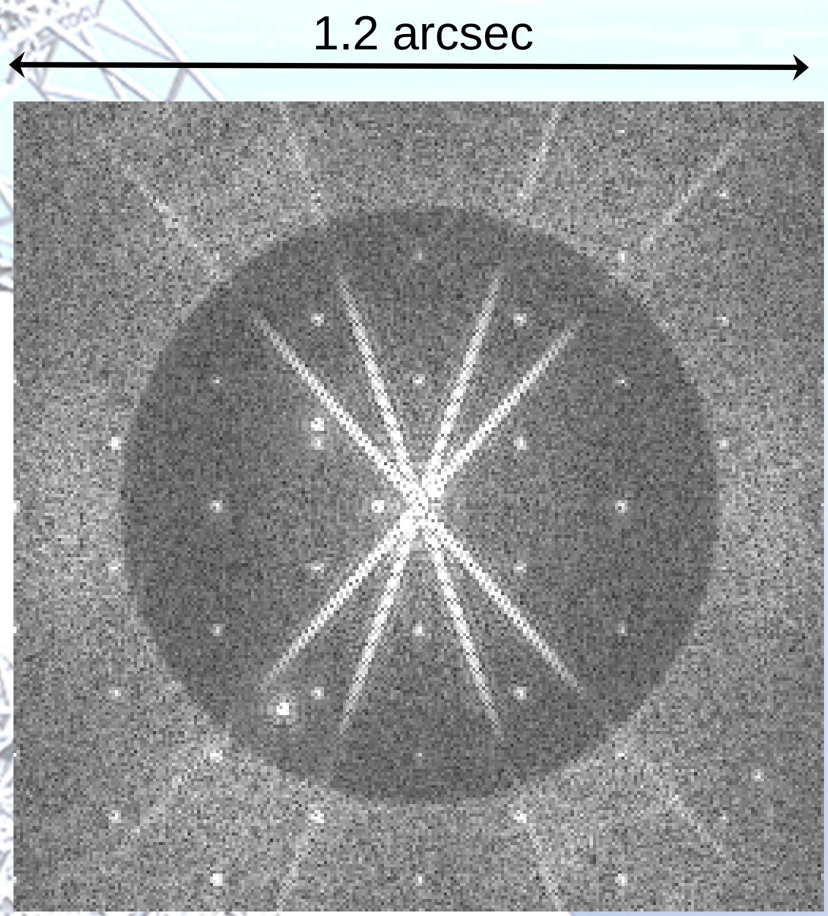
IFS parameters

- Field of View: 2.4 arcsec
- Nb of pixels: 1024×1024
- Spectral range: ~950-1735 nm
- Spectral resolution: R~ 500 - 900 from shortest to longest wavelength (440 monochomatic images)
- “IDEAL” IFS: no diffraction or chromatic differential errors



Beating the speckle noise: IFS



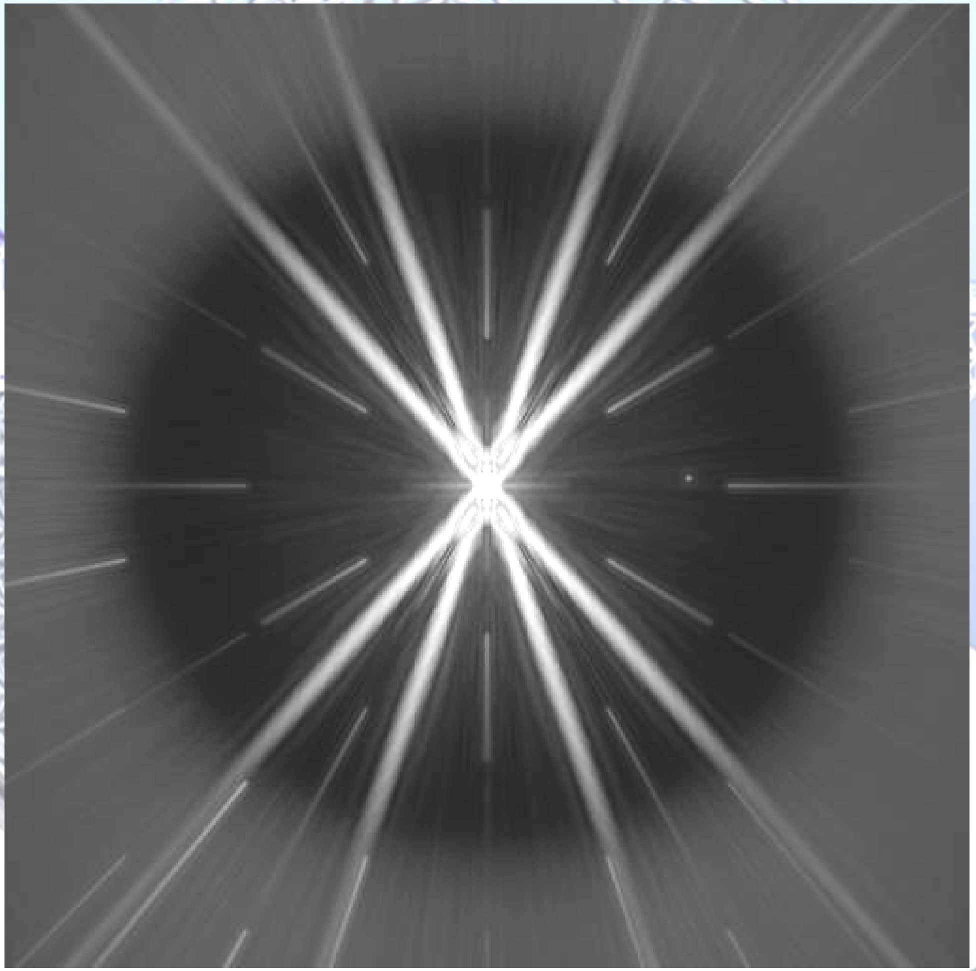


- Coronagraphic image at shortest wave-length + bright point sources

- « Ideal » IFS Coronagraphic images: movie from 950-nm to 1735-nm

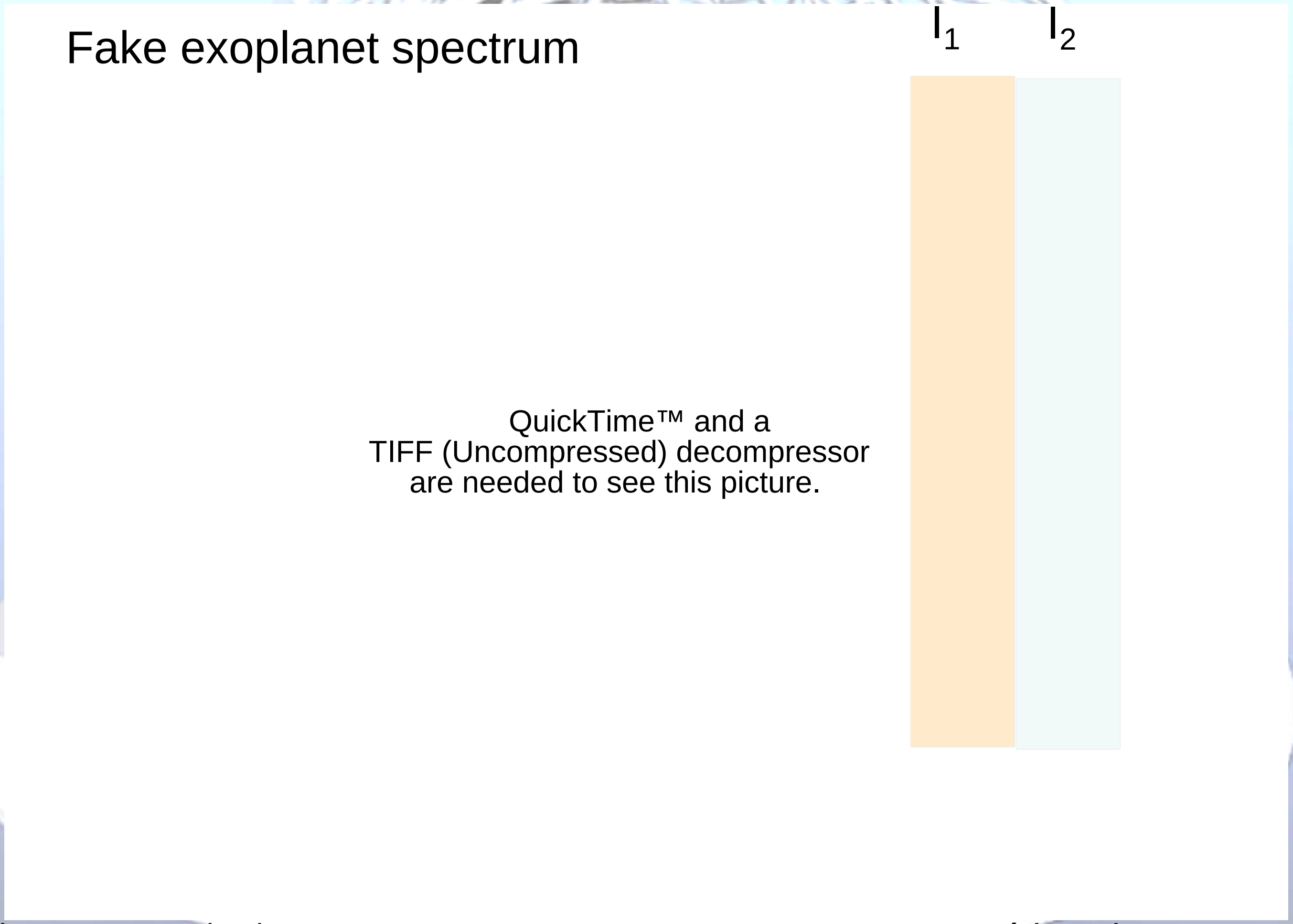
Integrated image: speckle elongation

- Integral of 440 monochromatic images from 950 to 1735 nm



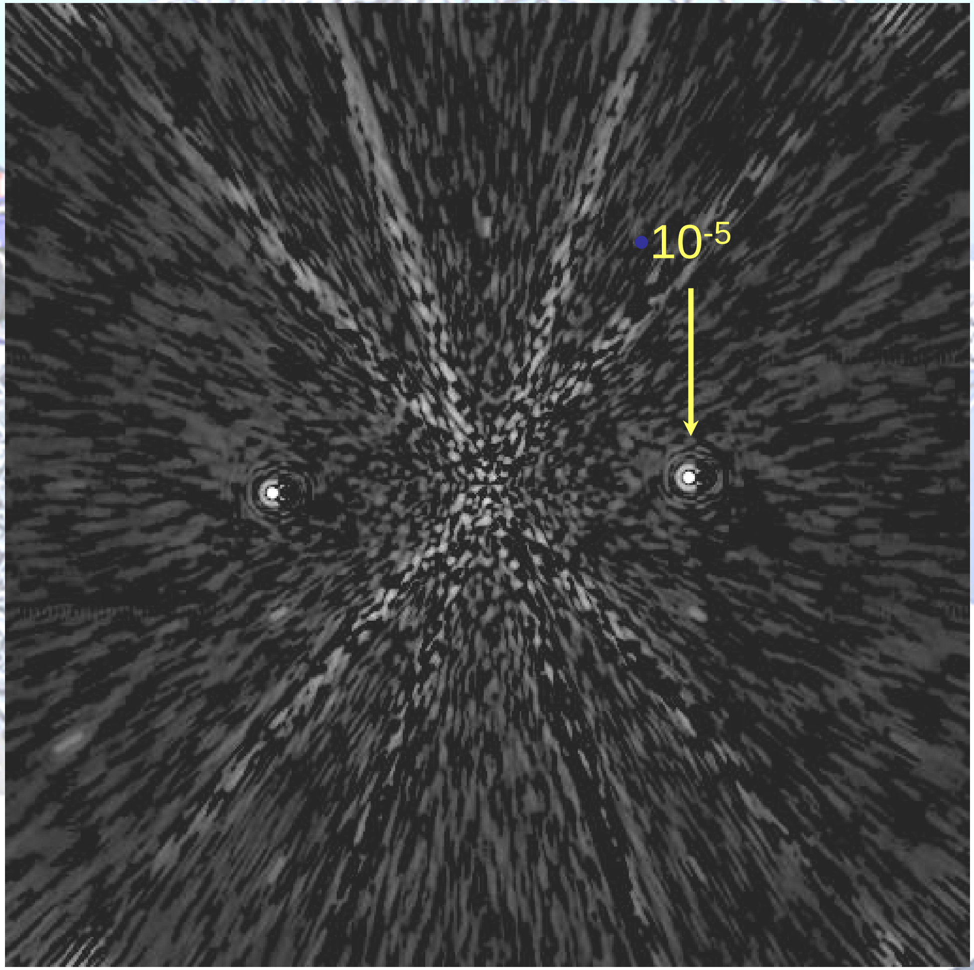
Signal extraction « classic» method

- Differential imaging using CH4 spectral feature
- Scaling, integration over 2 bands
- Subtraction $I_1 - I_2$



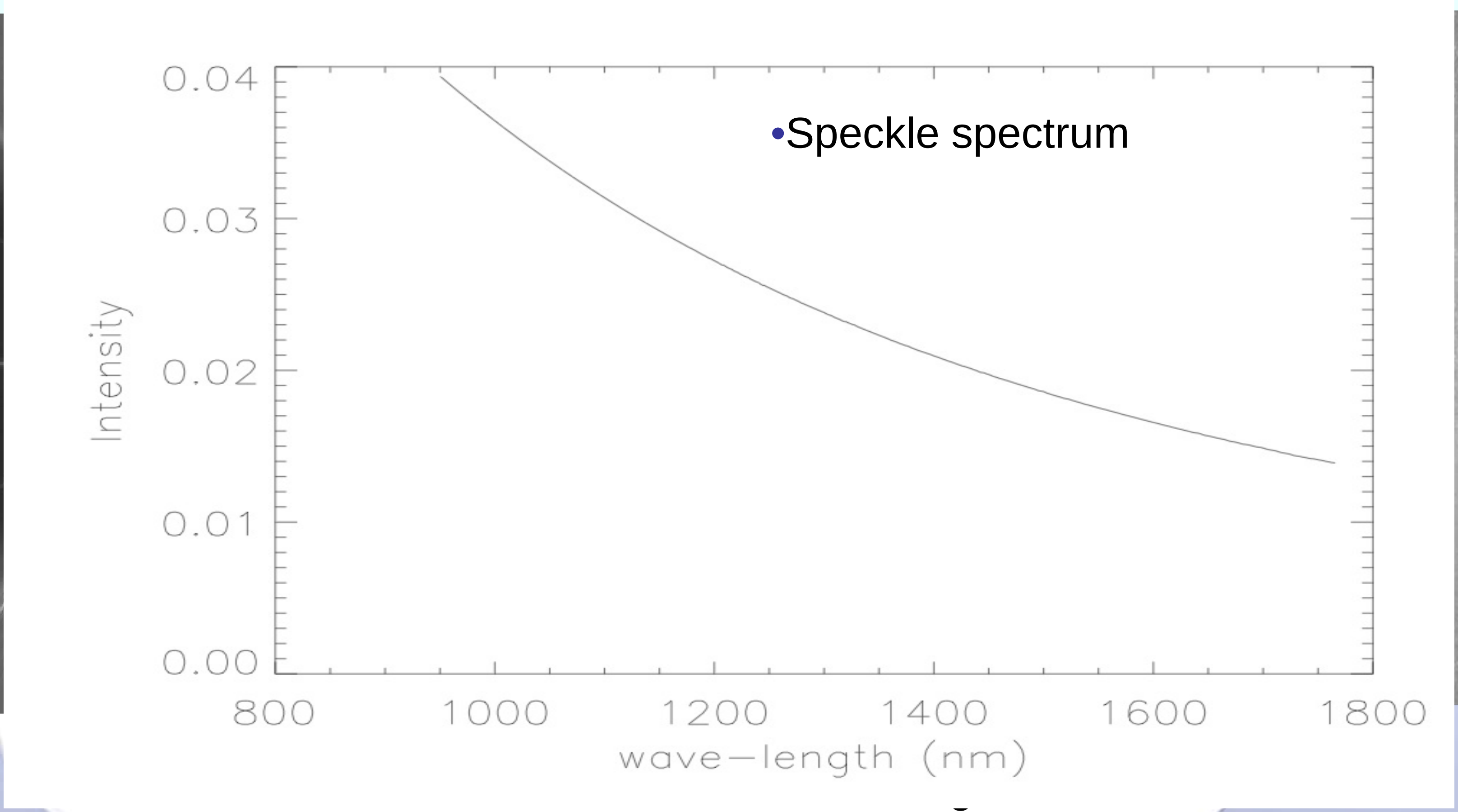
Signal extraction method 1

- Use of spectral feature (CH4 in H band)
- Symetrical subtraction + Differential imaging in and out absorption and

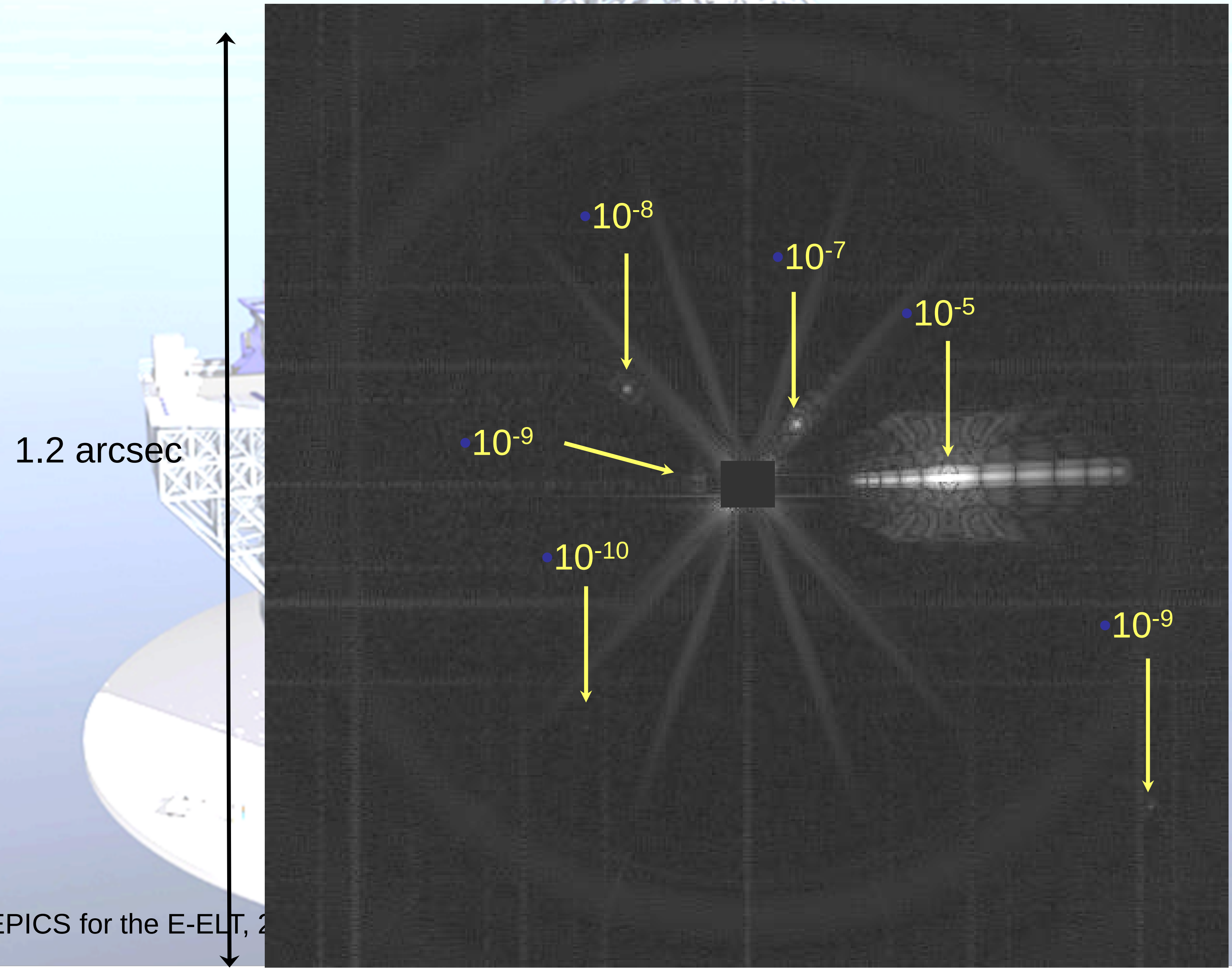


Signal extraction method 2

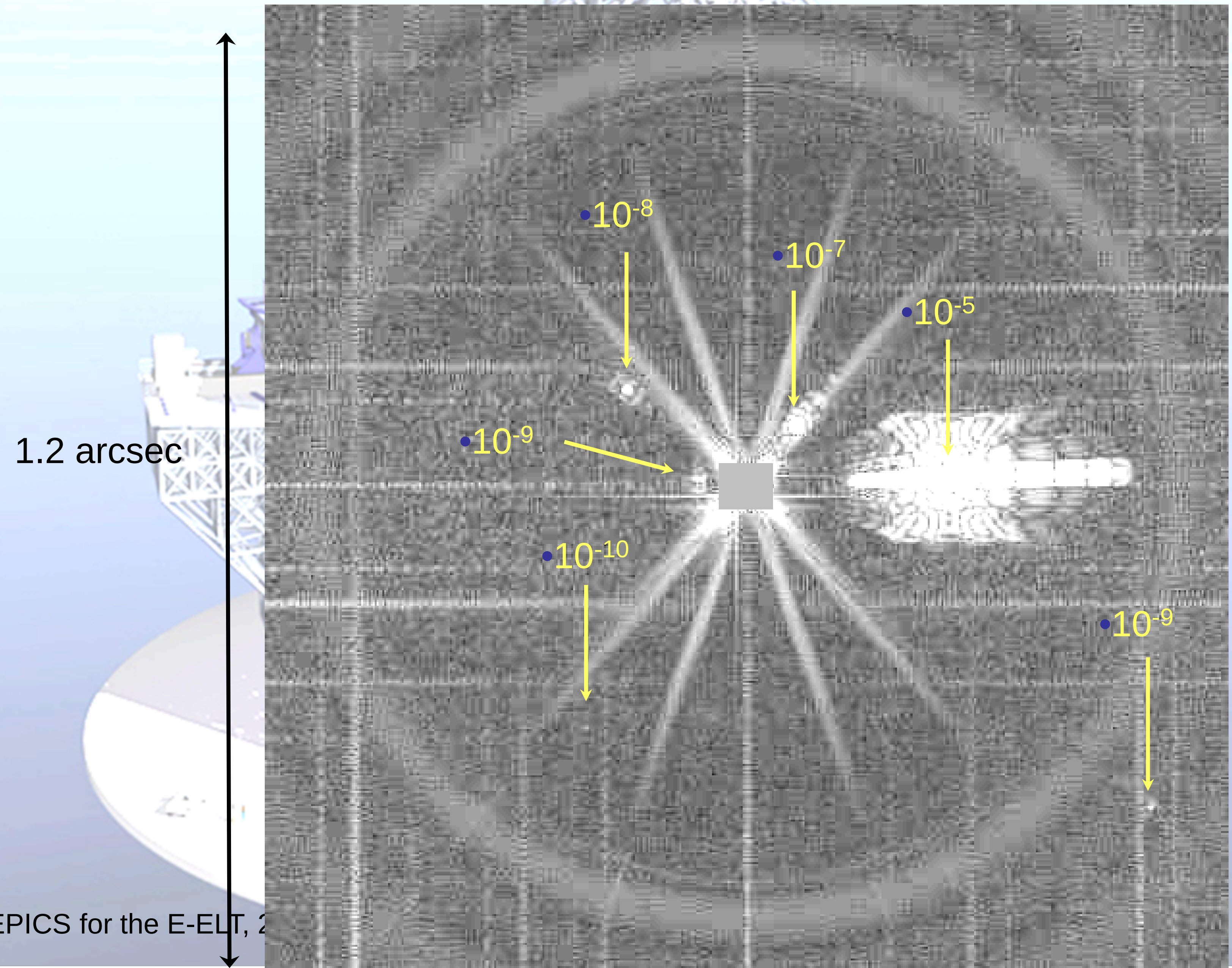
- Speckle Spectral fitting (Sparks and Ford, 2002):
  - Scaling wrt. wavelengths, fitting the speckles spectrum, subtract, de-scale



Signal extraction method 2

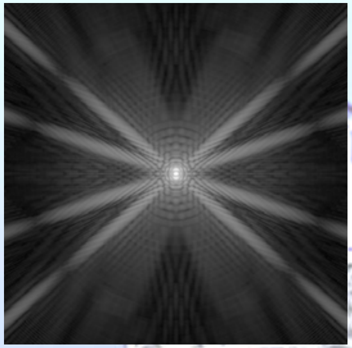


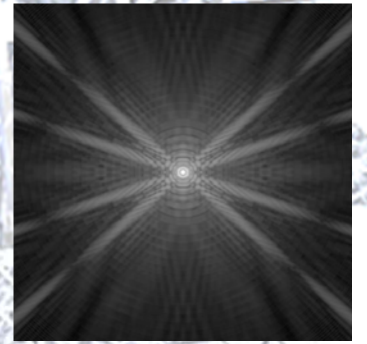
Signal extraction method 2

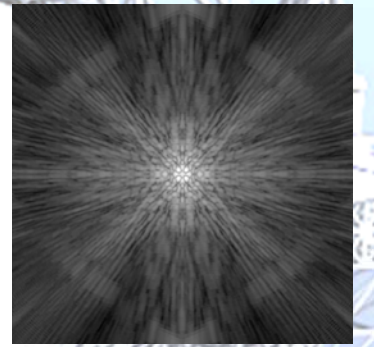


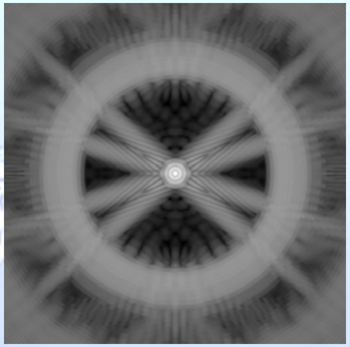
Next steps

- Effect of Spectral resolution (IFS feasibility)
- Chromaticity: ADC residuals, chromatic beams shifts, Fresnel diffraction (Talbot)
- Include Coronagraphy end-to-end model


Apodized Lyot


Dual Zone


Multi-4 quadrant


Binary pupil

•Include IFS end-to-end model: LENSLET vs SLICER

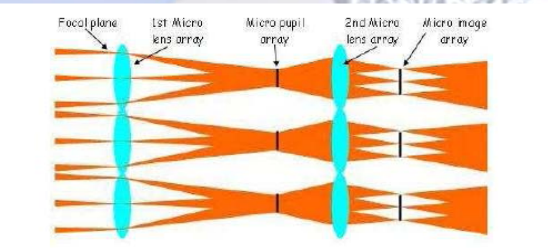
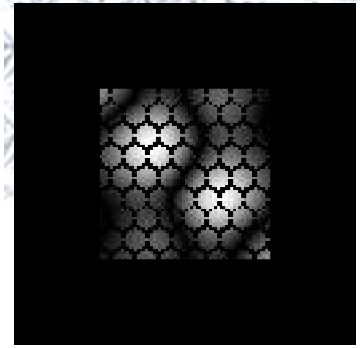
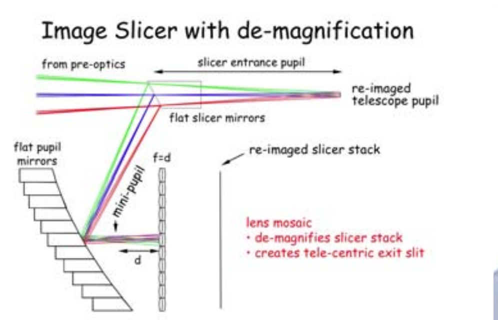
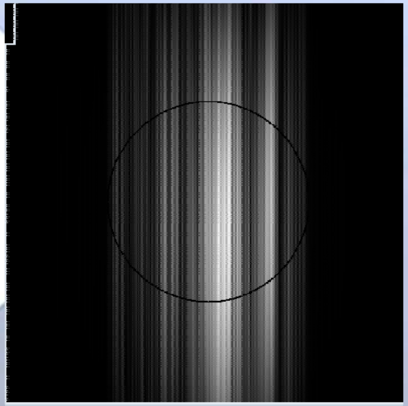


FIG. 10.— Optical concept of a BIGRE IFU: the IFS slits plane is filled with an array of micro-images of the telescope focal plane.

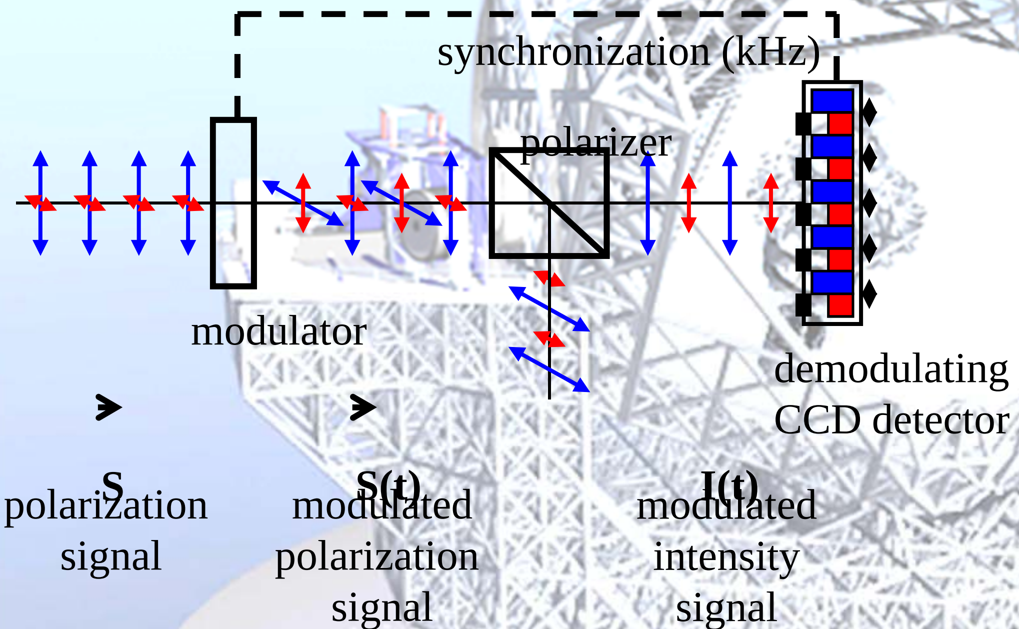


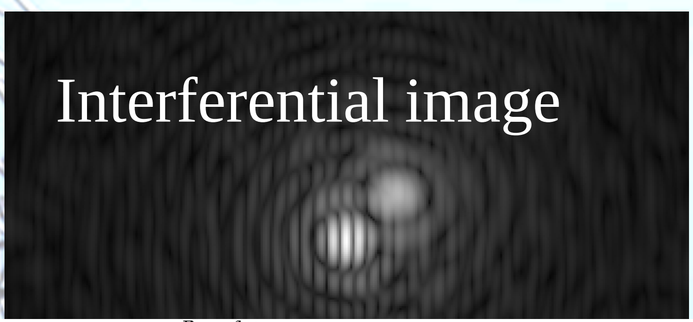


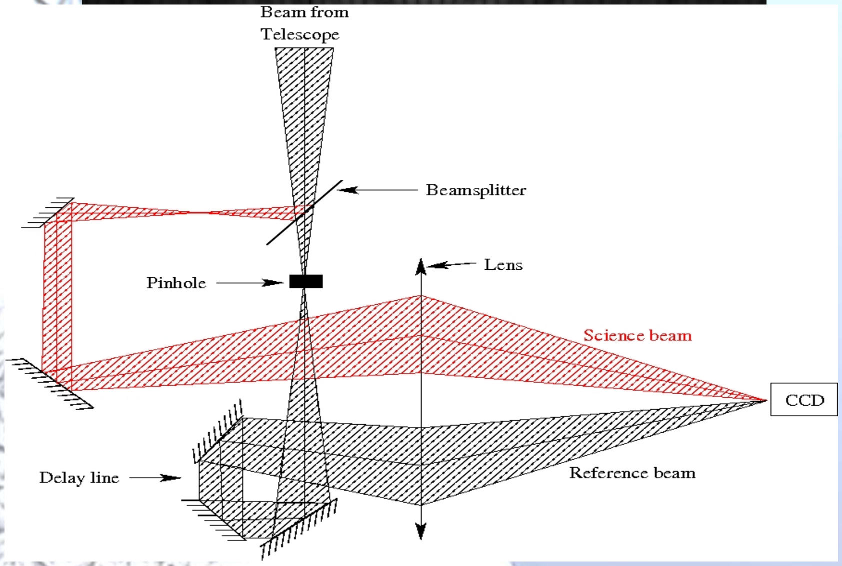


Other Instrument concepts

- ~V-R band instruments







•DIFFERENTIAL POLARIMETER

•SELF-COHERENT CAMERA

Conclusions

- **Major effort done on simulation work: static speckles**
  - E-ELT optics model well advanced
  - End-to-end model of IFSs on the way
  - Signal extraction:
    - On an ELT speckle elongation is important
    - →IFS with high Resolution looks very promising (achromatic case)
  - Next step: include chromaticity (corono, ADC, Talbot, IFS errors…), jitter, AO,etc.

- **In theory, better the R and λ range, better the speckle rejection**
  - Constrains on IFS are important: > 10Kx10K detector
  - Trade-off for optimized design is complex: IFS optics, read-noise, etc…

- **Result presented here are preliminary!**
  - Need to add several other error sources before:
    - Beeing able to specify EPICS instrument
    - Beeing able to give feed back on Compliance of telescope specifications
  - **Important effort on signal extraction methods with system priors needed.**