Darwin: required performance

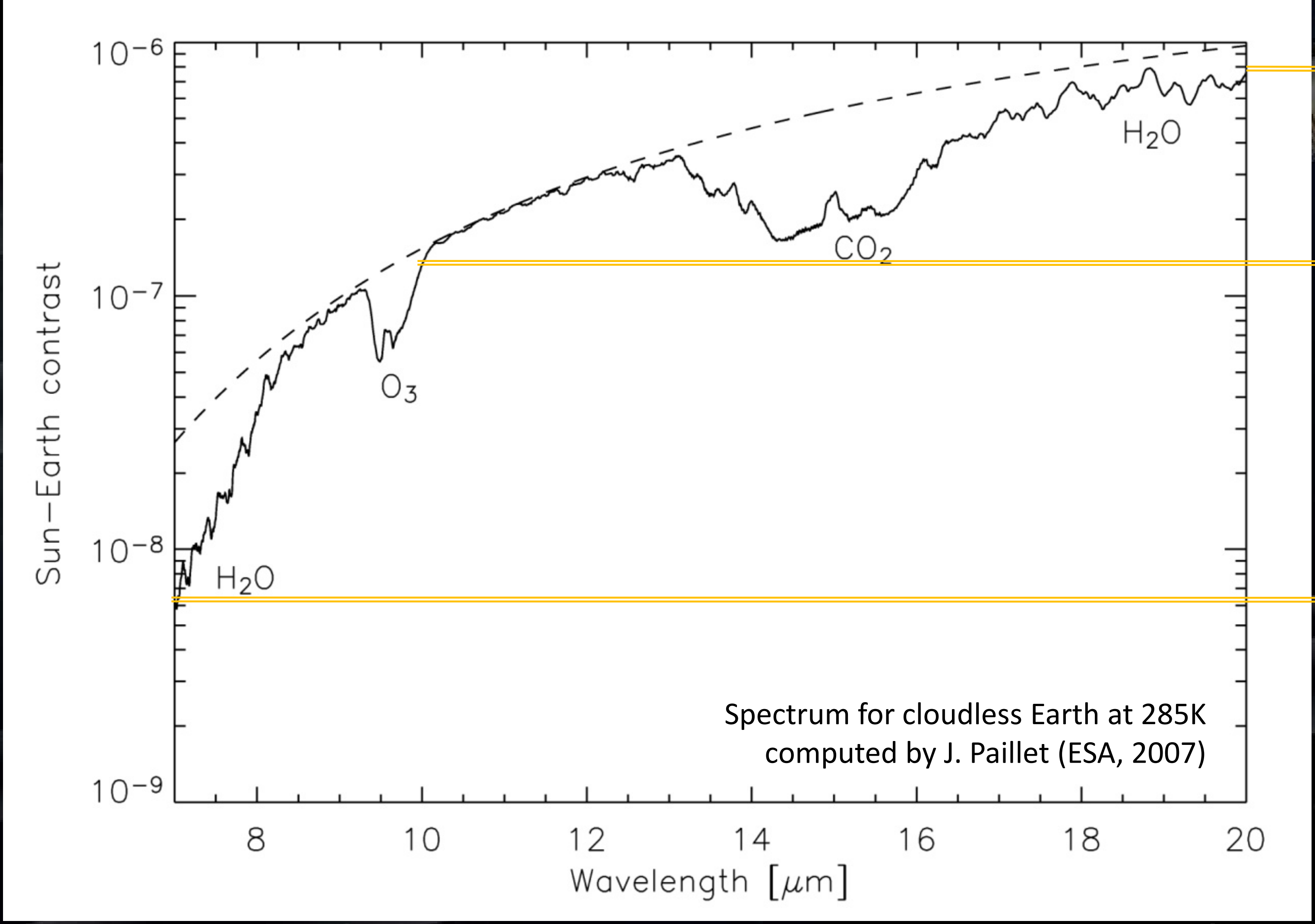
Olivier ABSIL

Laboratoire d'Astrophysique de Grenoble

Darwin meeting at IAS

December 6th, 2007

The Sun-Earth contrast



At 20 μm:
7.8×10^{-7}
(1.3×10^{6})

At 10 μm:
1.3×10^{-7}
(7.6×10^{6})

At 7 μm:
6.2×10^{-9}
(1.6×10^{8})

Required SNR

- During the detection phase
  - SNR of 5 on the integrated waveband
- During the spectroscopic phase (λ/Δλ=20)
  - O_3 [9.2µm-10µm]: SNR of 5
  - CO_2 [13µm-16µm]: SNR of 5
  - H_2O: most critical
    - [6.0µm-7.2µm]: SNR of 5 (too difficult → discarded)
    - [7.2µm-8.5µm]: SNR of 10
- Goal for this study
  - SNR=10 at 7 µm with λ/Δλ=20

Geometric nulling: integration times

- Assume Bracewell with minimum baseline = 7m
  - 2 × 2m telescopes and 10% throughput
  - Rotation modulation efficiency ~ 50%
- Put bright fringe on planet (middle of HZ)
- Earth flux: 0.3 ph/m²/s for [7.0µm-7.35µm] at 10pc
- Compute integration time for SNR = 10
  - Closer targets (forced b=7m): integration time does not change
    - Nulling and planetary flux $\propto$ distance^{-2}

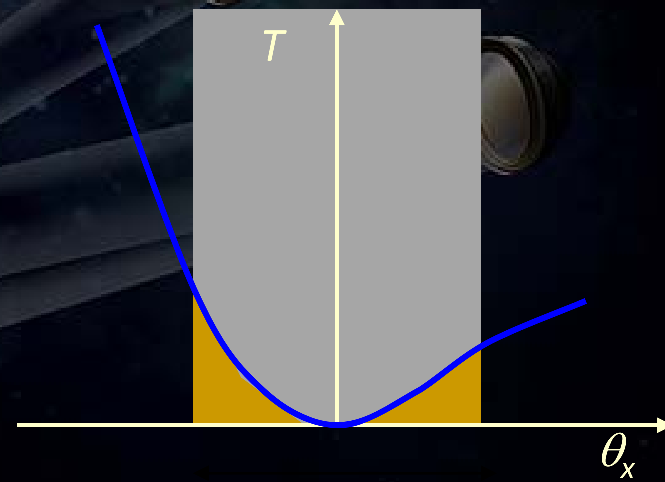
At λ = 7µm	F0V	G0V	K0V	M0V	M5V
Middle of HZ	2.4 AU	1.16 AU	0.68 AU	0.27 AU	0.08 AU
Dist. for b=7m	23 pc	11 pc	6.5 pc	2.6 pc	0.8 pc
Star diameter	0.61 mas	0.93 mas	1.22 mas	2.15 mas	3.14 mas
Nulling ratio	5.2e-6	1.2e-5	2.1e-5	6.8e-5	1.5e-4
Contrast	2.1e-9	5.0e-9	1.0e-8	2.8e-8	1.8e-7
Integration time	57 days	13 days	3.9 days	0.7 days	0.02 days

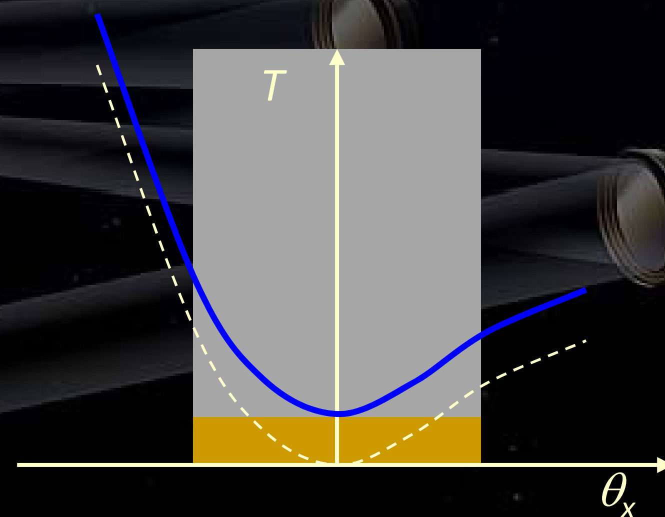
CONCLUSION #1

- No fundamental show-stopper to H_2O spectroscopy around Sun-like stars with θ^2 configurations
- Warning: availability of short baselines is crucial
  - A minimum baseline of 20m would ruin the performance
- We will assume a K0V star in the following study

The various flavours of stellar leakage

- Geometric stellar leakage
  → set by target
- Instrumental stellar leakage
  - Avg removed by rotation
    - Shot noise remains
    - Requirement: smaller than geometric leakage
  - Fluctuations: instability noise
    - Instrumental imperfections
      - Amplitude and phase of beams
      - Polarisation errors
      - Collector position
    - Requirement: SNR of 10 → σ(null) < flux ratio/10





CONCLUSION #2

- Requirements on
  - Mean instrumental leakage: ‹null› < 2×10^{-5}
  - Instability noise: $\sigma_{null} < 10^{-9}$ on 60 days
- The latter is (almost) always dominant

“Naive” stability requirements

- Separating each individual contribution
- Assuming that $\sigma_{null} \approx \langle null \rangle$

	Phase	Intensity	Polarisation
Analytical null	$\Delta\phi^2/4$	$\Delta I^2/16$	$\Delta\theta^2/4$
Result at 7µm for null = 10^{-9}	ΔOPD < 0.07 nm rms	ΔI < 0.01% rms	Diff. rotation < 13'' rms

- Does not seem within reach
  - But note: to measure them is to correct them!

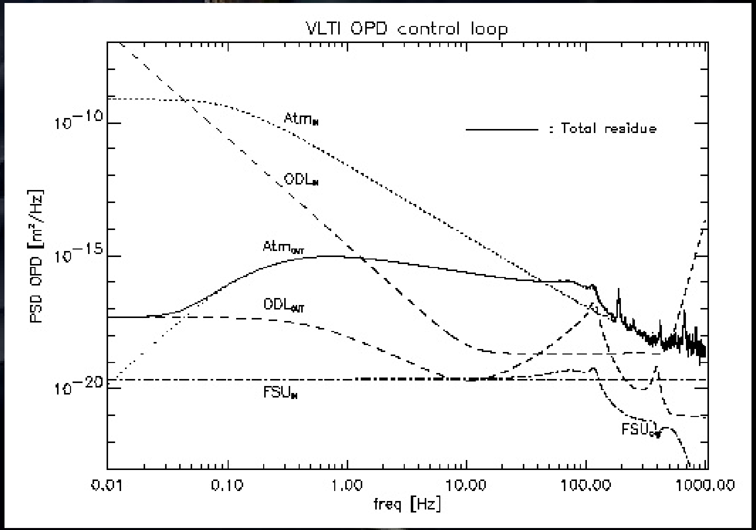
Relaxing the requirements with time

- Back to definition: $\sigma_{null} = \sigma_{leakage} / F_\star$
- Time behaviour depends on power spectra of all instrumental perturbations
- Naive assumption: white noise
  - $\sigma_{leakage}(t) \propto t^{1/2}$, while $F_\star(t) \propto t$
  - $\sigma_{null} \propto t^{-1/2} \rightarrow \sigma_{null} = 2.3 \times 10^{-6}$ in 1 sec
- Revised requirements on a 1 sec integration time

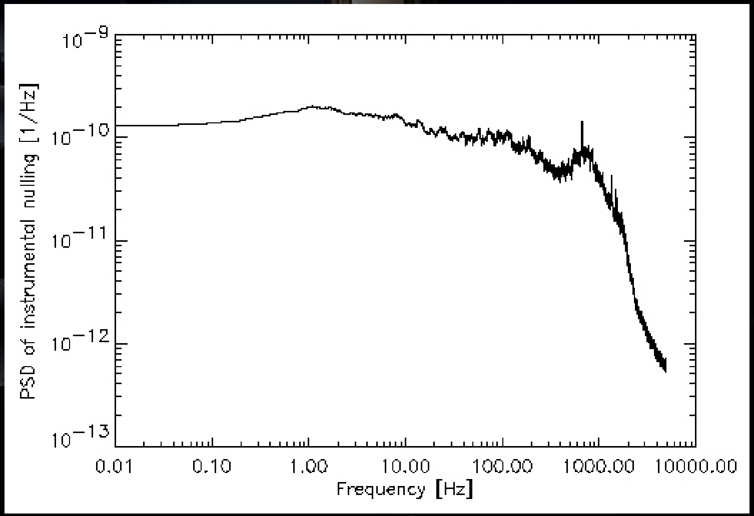
	Phase	Intensity	Polarisation
Result at 7μm for 1 sec integration	ΔOPD < 3.4nm rms	ΔI < 0.6% rms	Diff. rotation < 10' rms

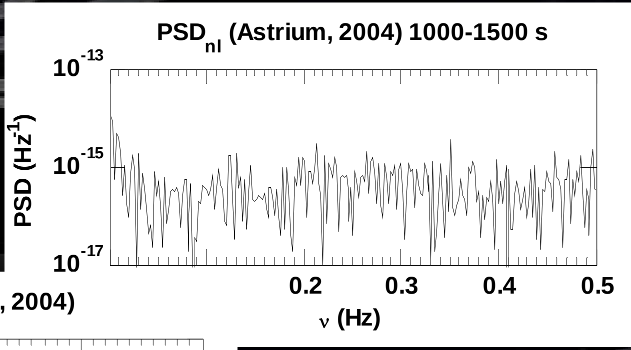
Is white noise realistic?

- Control loops simulations
  - Power reduced at low frequencies
- Tests in laboratory
  - White noise within reach
  - Control loop drifts?

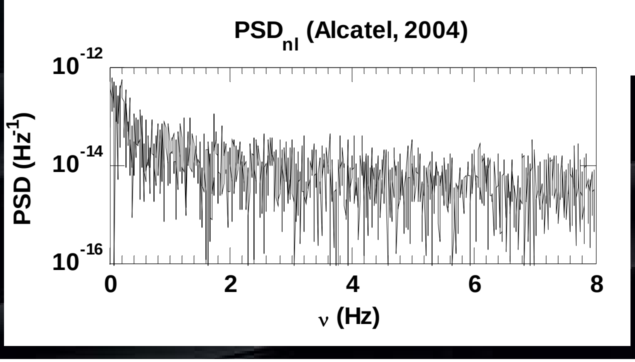


Absil et al. 2006 (GENIEsim)

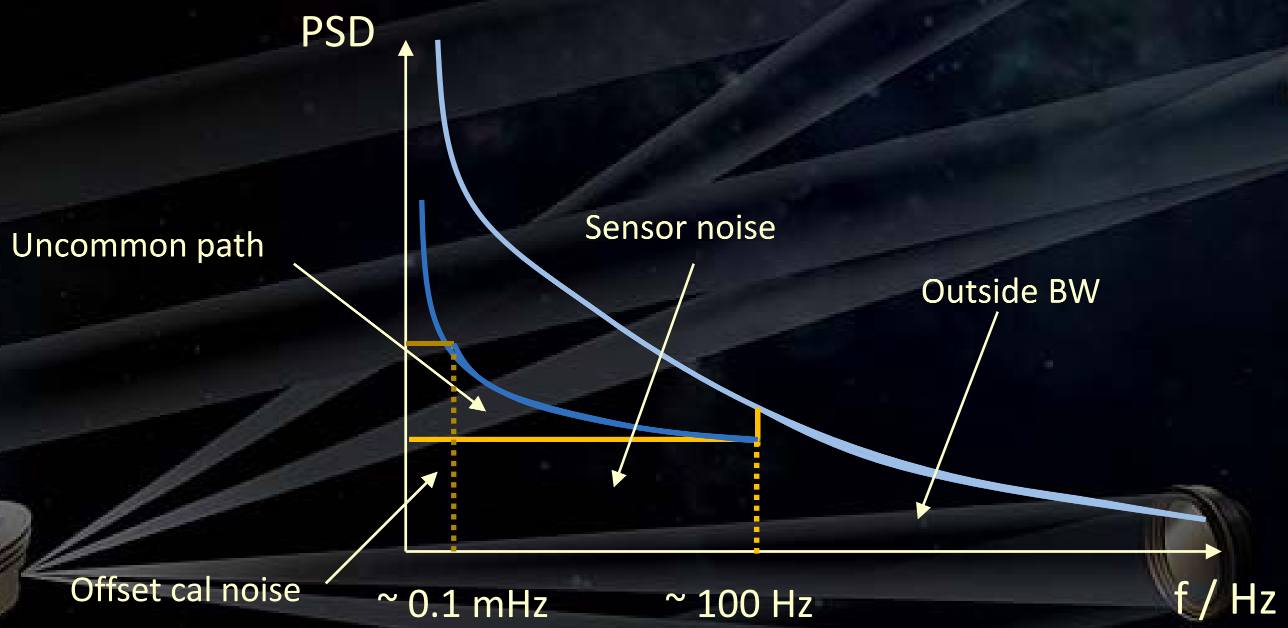




Chazelas et al. 2006



Fighting long-term drifts



- Control can be based on the nulled output
  - Produce offsets in phase and amplitude to re-centre the null with a low frequency

CONCLUSION #3

- Stability requirements in 1 sec
  - OPD < 3.4nm rms
  - Intensity mismatch < 0.6% rms
- Requires white noise for frequencies < 1Hz
  - Control loops + correction of long-term drifts

Instability noise: advanced description

- Expansion of instrumental null (Lay 2004)

$$\begin{aligned}
\delta N_* \approx \sum_j \Bigg[& \frac{\partial N_*}{\partial A_j} A_j \delta a_j + \frac{\partial N_*}{\partial \phi_j} \delta \phi_j + \frac{\partial N_*}{\partial x_j} \delta x_j \\
& + \frac{\partial N_*}{\partial y_j} \delta y_j \Bigg] + \sum_j \sum_k \Bigg[\frac{1}{2} \frac{\partial^2 N_*}{\partial A_j \partial A_k} A_j A_k \delta a_j \delta a_k \\
& + \frac{\partial^2 N_*}{\partial A_j \partial \phi_k} A_j \delta a_j \delta \phi_k + \frac{1}{2} \frac{\partial^2 N_*}{\partial \phi_j \partial \phi_k} \delta \phi_j \delta \phi_k \Bigg] \\
\approx & \sum_j C_{Aj}{}^* \delta a_j + C_{\phi j}{}^* \delta \phi_j + C_{xj}{}^* \delta x_j + C_{yj}{}^* \delta y_j \\
& + \sum_j \sum_k [C_{AAjk}{}^* \delta a_j \delta a_k + C_{A\phi jk}{}^* \delta a_j \delta \phi_k \\
& + C_{\phi\phi jk}{}^* \delta \phi_j \delta \phi_k]. \qquad (14)
\end{aligned}$$

- 1^{st} order terms close to zero → 2^{nd} order not negligible

- If η = template with odd harmonics, the demodulated output:

$$O = O_{\text{planet}} + O_{\text{ran}} + O_{\text{sys}}.$$

$$O_{\text{planet}} = \frac{1}{T} \int_0^T N_{\text{planet}} \eta \, dt = \widehat{N_{\text{planet}}}.$$

$$\begin{aligned}
O_{\text{sys}} = & \sum_j C_{Aj} \widehat{\delta a_j} + C_{\phi j} \widehat{\delta \phi_j} + C_{xj} \widehat{\delta x_j} + C_{yj} \widehat{\delta y_j} \\
& + \sum_j \sum_k [C_{AAjk} \widehat{\delta a_j \delta a_k} + C_{A\phi jk} \widehat{\delta a_j \delta \phi_k} \\
& + C_{\phi\phi jk} \widehat{\delta \phi_j \delta \phi_k}], \qquad (38)
\end{aligned}$$

- Variance:

$$\begin{aligned}
\langle O_{\text{sys}}{}^2 \rangle = & \sum_j C_{Aj}{}^2 \langle \widehat{\delta a_j}^2 \rangle + \sum_j C_{\phi j}{}^2 \langle \widehat{\delta \phi_j}^2 \rangle + \sum_j C_{xj}{}^2 \langle \widehat{\delta x_j}^2 \rangle \\
& + \sum_j C_{yj}{}^2 \langle \widehat{\delta y_j}^2 \rangle + \sum_j \sum_k C_{AAjk}{}^2 \langle \widehat{\delta a_j \delta a_k}^2 \rangle \\
& + \sum_j \sum_k C_{A\phi jk}{}^2 \langle \widehat{\delta a_j \delta \phi_k}^2 \rangle \\
& + \sum_j \sum_k C_{\phi\phi jk}{}^2 \langle \widehat{\delta \phi_j \delta \phi_k}^2 \rangle. \qquad (39)
\end{aligned}$$

Influence on power spectra

- Expansion in Fourier series (T = rot. period)

$$\delta a_j = \sum_{p=-\infty}^{\infty} \beta_p \exp(i2\pi p t/T).$$

$$\langle|\beta_p|^2\rangle \approx \frac{1}{2T}\,\mathrm{PSD}_a\!\left(\frac{p}{T}\right),$$

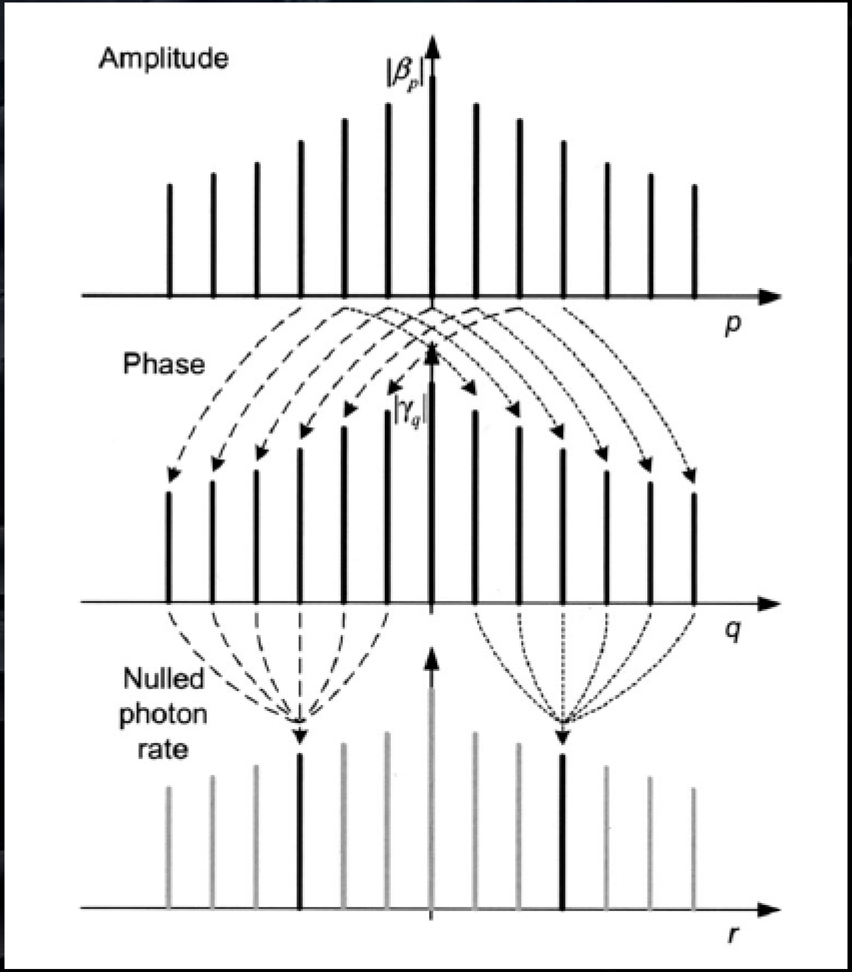
$$\eta = \sum_{r=-\infty}^{\infty} \varepsilon_r \exp(i2\pi r t/T).$$

- Linear terms
  - Only at planet frequency

$$\langle\widehat{\delta a_j}^2\rangle = \left\langle\left[\int_0^T \delta a_j \eta\, dt\right]^2\right\rangle = \sum_{r=-\infty}^{\infty} |\varepsilon_r|^2 \langle|\beta_r|^2\rangle.$$

- Bilinear/quadratic terms
  - At all frequencies

$$\langle\widehat{\delta a_j \delta\phi_k}^2\rangle = \left\langle\left[\int_0^T \delta a_j \delta\phi_k \eta\, dt\right]^2\right\rangle = \sum_{r=-\infty}^{\infty} |\varepsilon_r|^2 \sum_{p=-\infty}^{\infty} \langle|\beta_p|^2\rangle\langle|\gamma_{p-r}|^2\rangle.$$

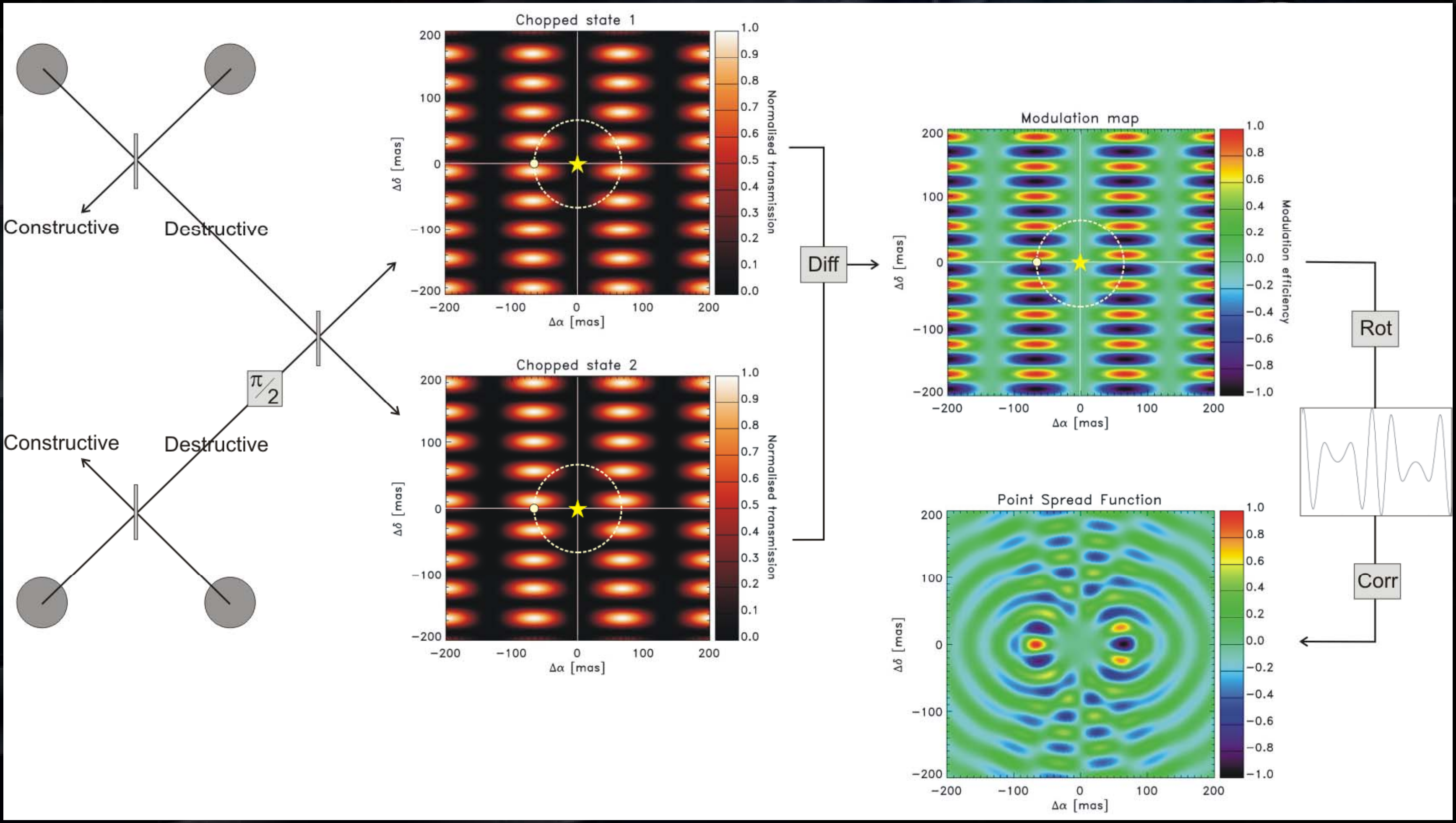


Ex: phase at 100Hz, amplitude at 101Hz → beating at 1Hz

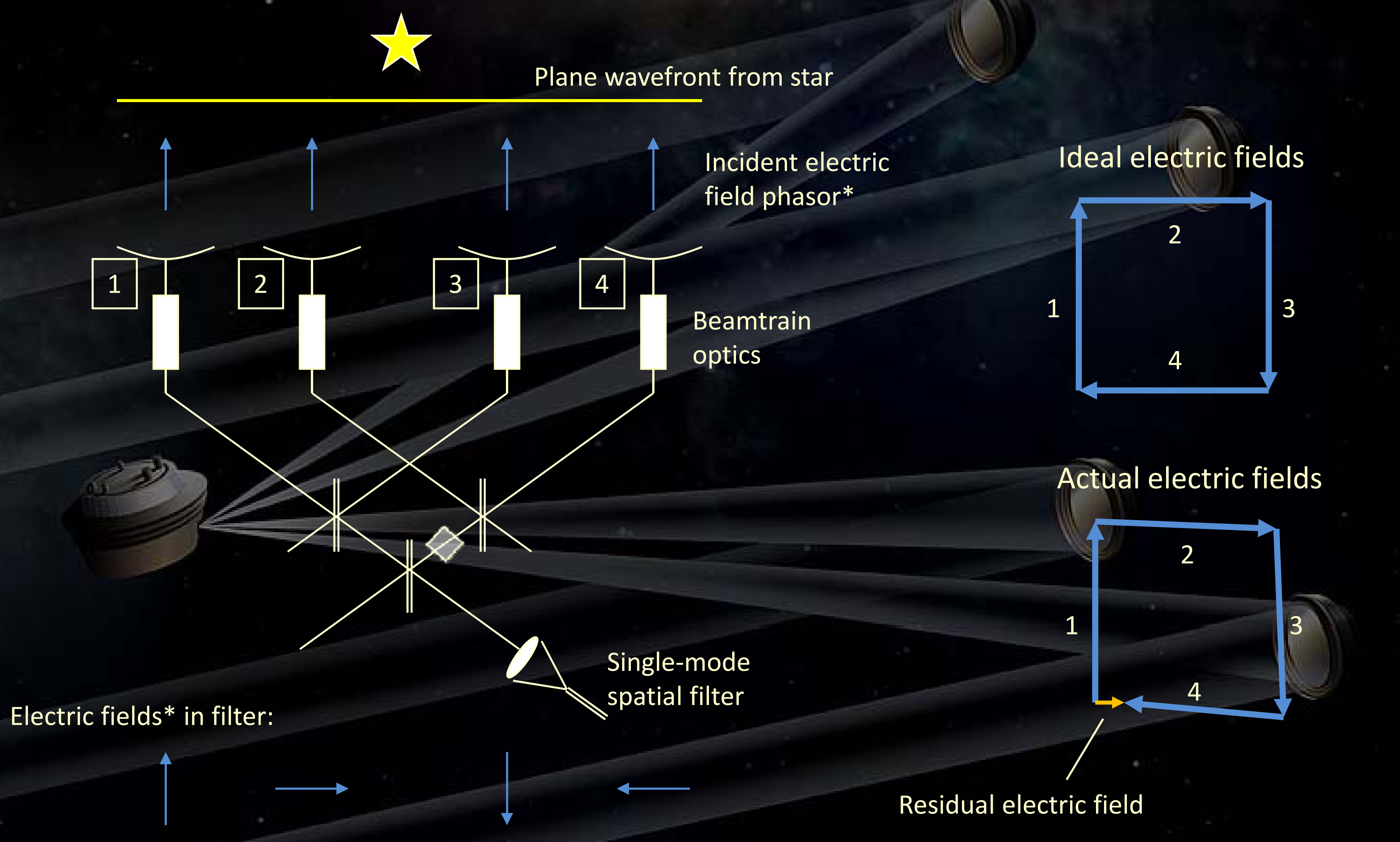
CONCLUSION #4

- Bilinear/quadratic terms in phase and amplitude
  - Dominant contribution in instability noise
  - Convolution of power spectra (~~a posteriori correction~~)
- Naive approach is simply not valid
  - $\sigma_{null} \neq \langle null \rangle$
  - All frequencies do not contribute in the same way

Introducing phase chopping



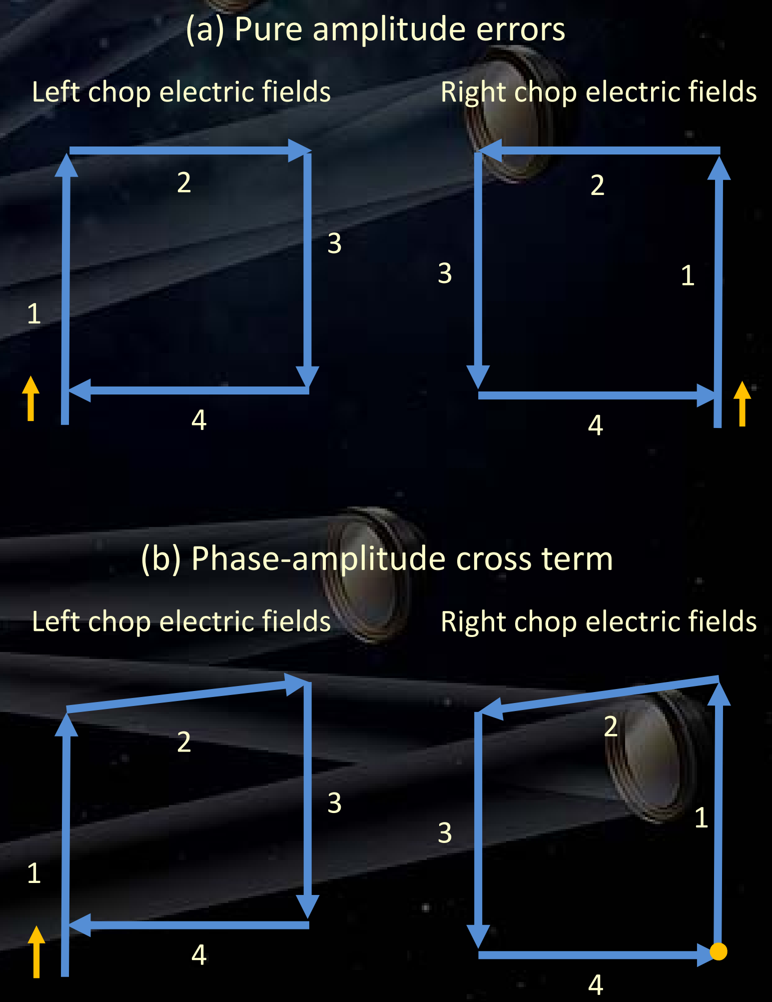
A different view: electric fields



* Phasor angle represents electric field phase, not polarization

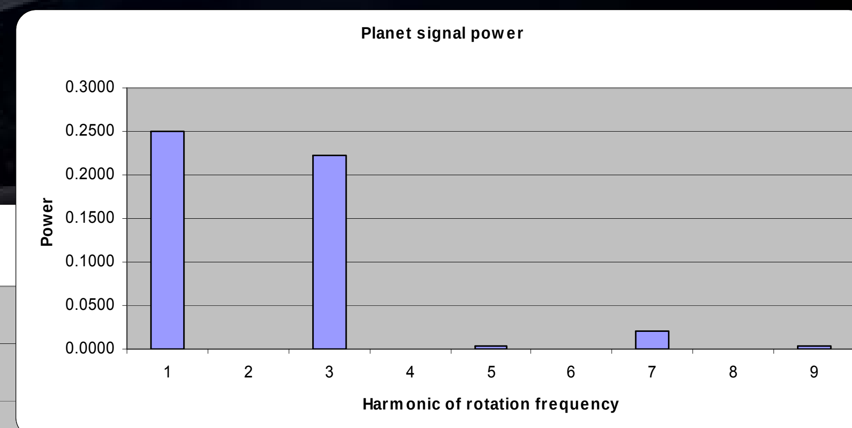
Influence of phase chopping (Lay '04)

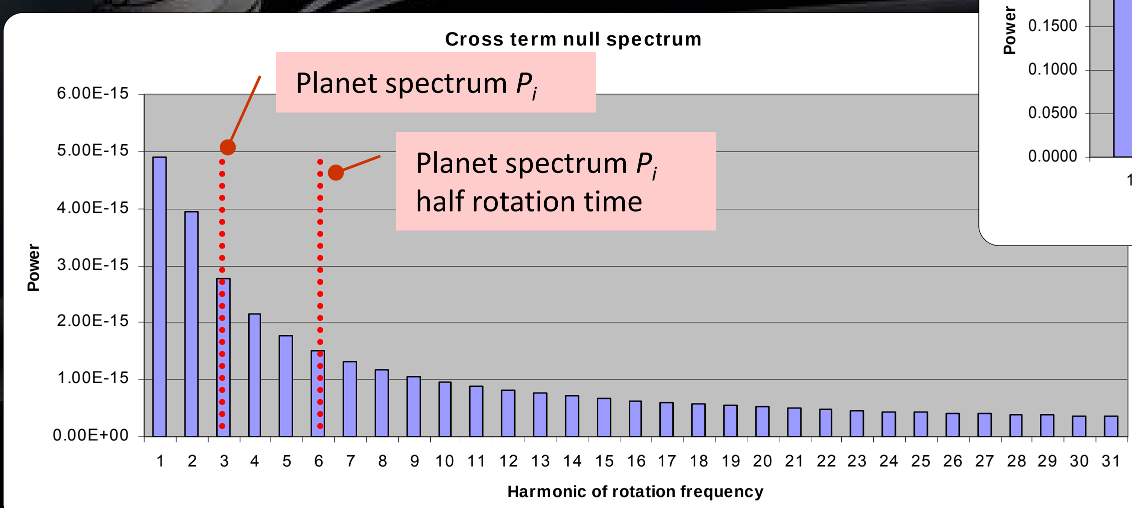
- Removes the "symmetric part" of instability noise
  - Pure amplitude errors and pure quadratic phase errors
  - Polarisation errors
  - Collector position errors
- 1st order phase errors and bilinear phase-amplitude errors remain
  - Most important contributors
  - PSDs mix together as in rotational case
- Other "instrumental" contributions
  - Stray light, thermal emission, detector drifts
    - Mean value cancelled by phase chopping
    - Low-frequency drifts also cancelled
  - Beware of chop asymmetry



Effect of rotation on a chopped array

- If systematic noise not correlated to rotation
  - SNR $\propto n_{rot}^{1/2}$ (optimistic)
- Higher rotation speed shifts the planet signal to higher frequencies
  - (Small) gain if noise $\propto$ 1/f





Revised stability requirements

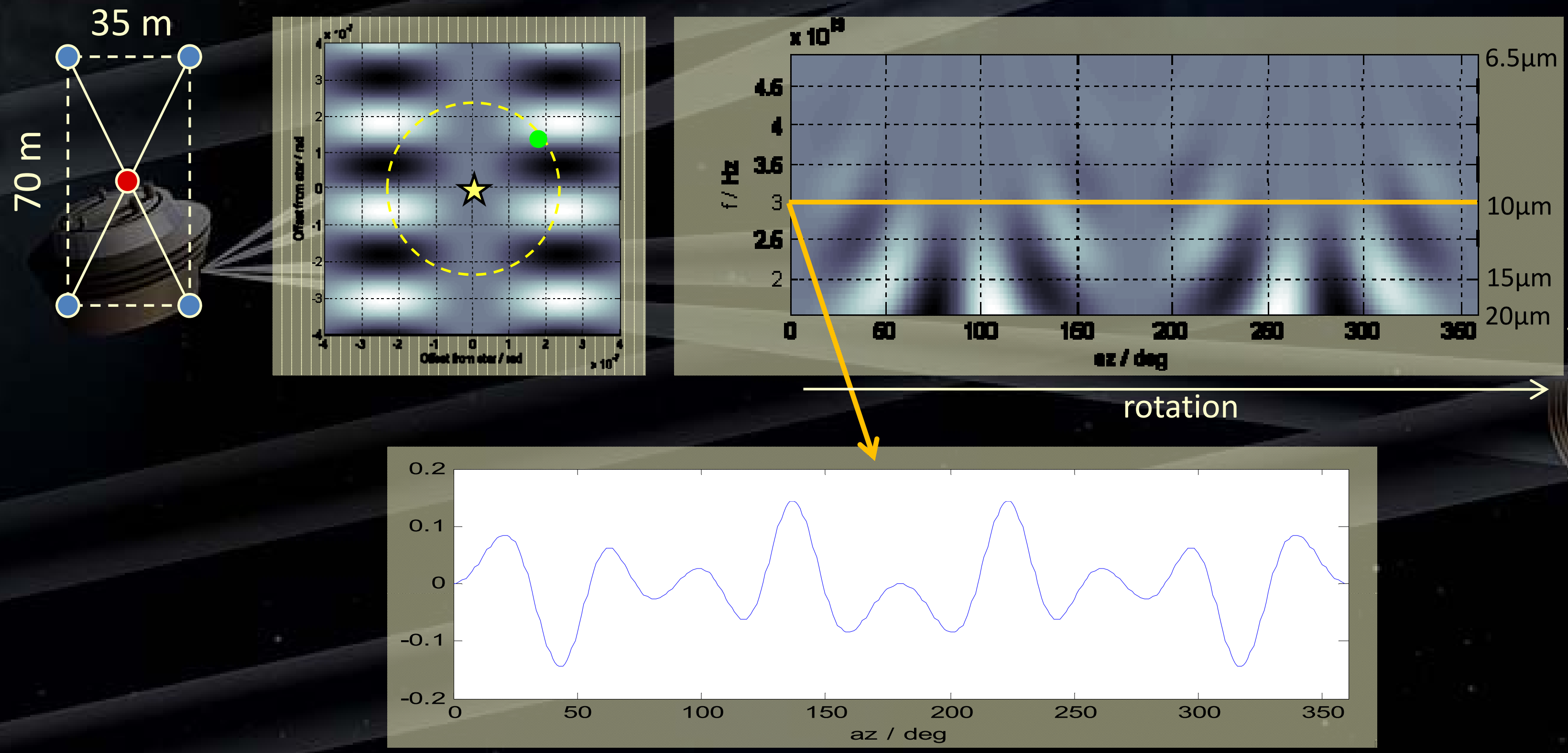
- Analytical approach becomes complicated
  - Computation of sensitivity coefficients
  - Analytical or tabulated description of input power spectra across “infinite” frequency domain
- Lay 2004 (Applied Optics)
  - Sun-Earth at 15pc, λ=10μm, R=20
  - Dual Bracewell, 4m diameter, 0.5 day integration
  - Assumes 1/f power spectra with no DC
  - Requirements for O_3 spectroscopy
    - OPD: 1.5nm rms
    - Intensity: 0.1% rms

CONCLUSION #5

- Revised requirements: 1.5nm, 0.1% (eq. null = 5×10^{-7})
  - Challenging at 10µm → unrealistic at 7µm?
- Need to be revisited
  - Configuration and target parameters
  - Realistic power spectra (1/f is pessimistic)
- Noise reduction techniques should be investigated

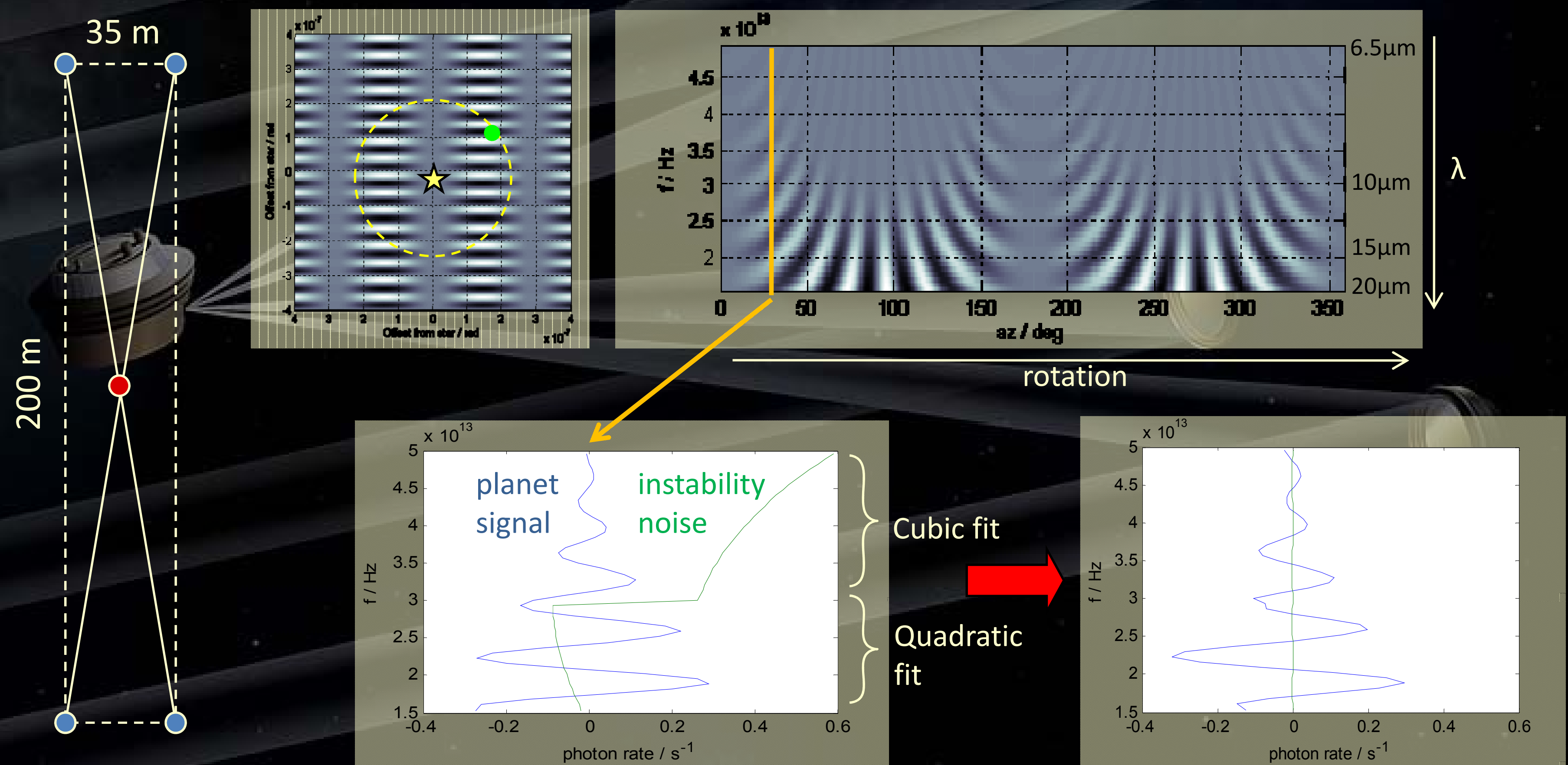
Spectral fitting (Lay 2006)

- Separating signal and noise in time domain is challenging
  - Noise contributions at all frequencies



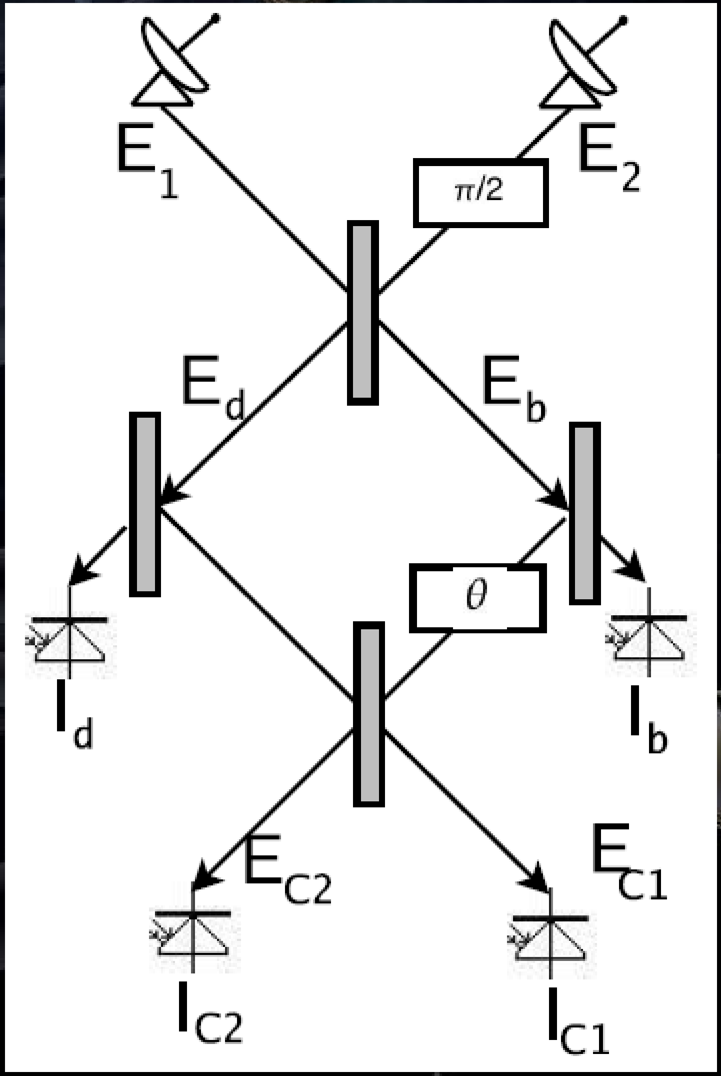
Spectral fitting (Lay 2006)

- Separation in wavelength domain easier
  - Instability noise is a slow function of λ
  - Need to stretch the array and to fit the noise



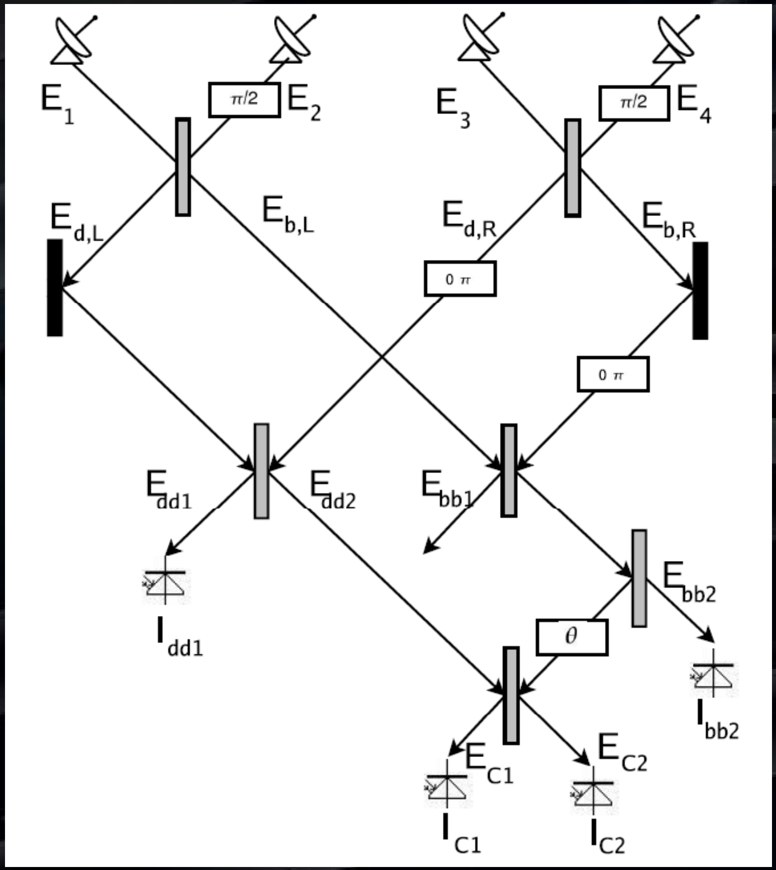
Post-nulling calibration (Lane 2006)

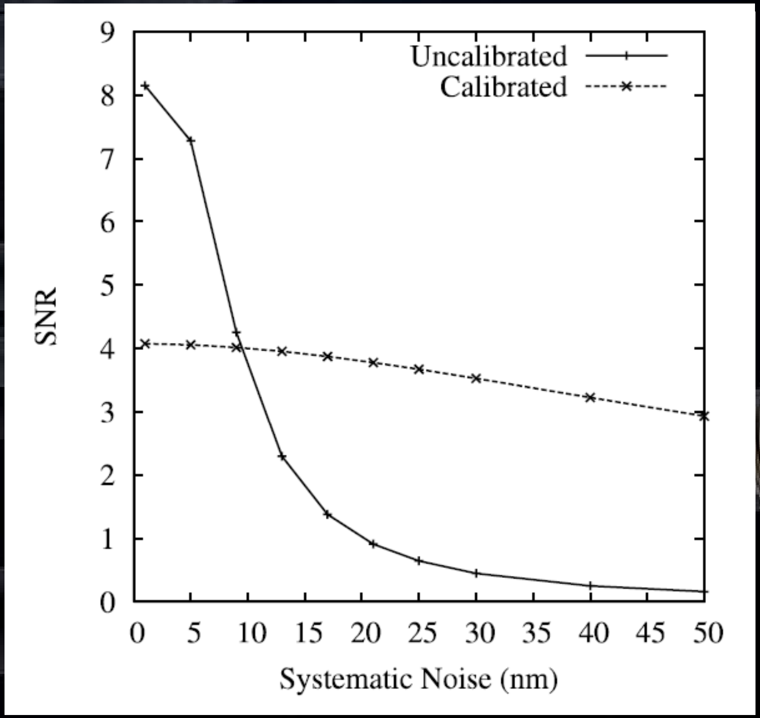
- Based on coherence properties of stellar light
  - Calibration interferometer with the two outputs
  - Modulation of θ
  - Fringe pattern forms
    - Star and planet separately
    - Fringes ratio: ‹null›$^{0.5}F_{\star}/F_p$
  - Estimation of stellar leakage is possible
    - Can be subtracted from destructive output a posteriori



Post-nulling calibration (Lane 2006)

- Straightforward adaptation to the X-array
- May not be appropriate for low perturbations





CONCLUSION #6

- Instability noise reduction techniques
  - Stability requirement could be driven by ‹null› instead of σ_{null}
    - New requirements about 5nm rms and 0.5% rms (?)
  - Part of the planetary signal is lost
  - Further testing required (simulations and lab)

What needs to be done?

- Make sure that H_2O at 7µm is really needed
  - Dropping it would relax the stability requirements
- Update the Lay 2004 analysis at 7µm
  - Seems easy with Oliver's spreadsheets
- Validation with numerical simulations
  - DarwinSim: the machinery is already available!
    - Control loops properly described
  - Need accurate modelling of input power spectra
    - May require FEM study of Darwin spacecrafts
  - Include the effect of noise reduction techniques
- Validation on test benches (PRIORITY!)
  - Under "space-like" conditions
  - Star/planet simulator and proper data reduction