# Imaging power of multi-fibered nulling telescopes for extra-solar planet characterization

François Hénault
UMR 6525 H. Fizeau, Université de Nice-Sophia Antipolis
Centre National de la Recherche Scientifique
Observatoire de la Côte d'Azur
Parc Valrose, 06108 Nice – France

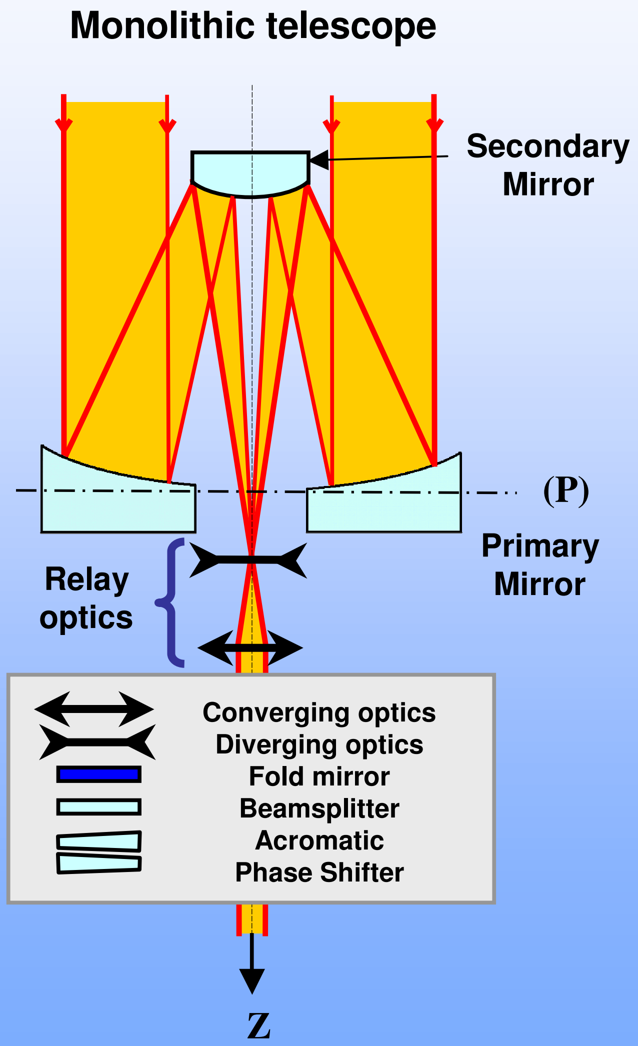
# Three reasons to build space nulling telescopes

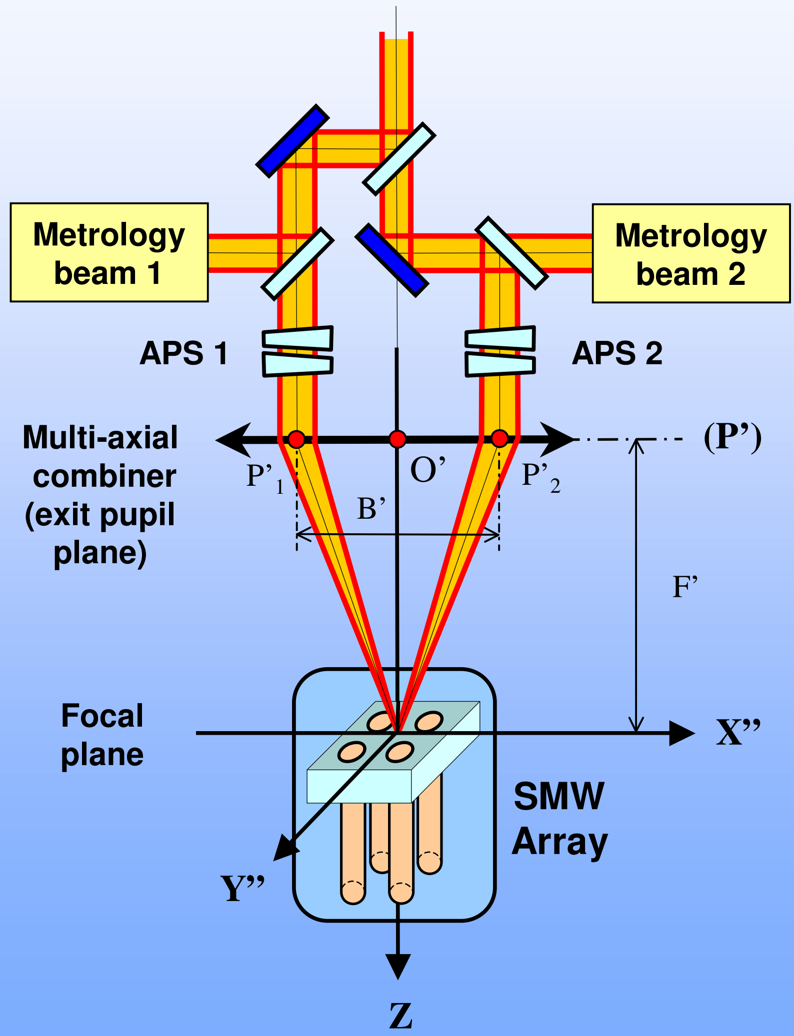
- Usable for exploratory science missions: exo-zodiacal clouds characterization, hot and cold Jupiter-like planets…
- Allows validating most of Darwin/TPF-I required technologies (achromatic phase shifters, WFE filtering, OPD control…)
- If rotating, allows validating the envisioned algorithms for planet finding and characterization

# Previous publications

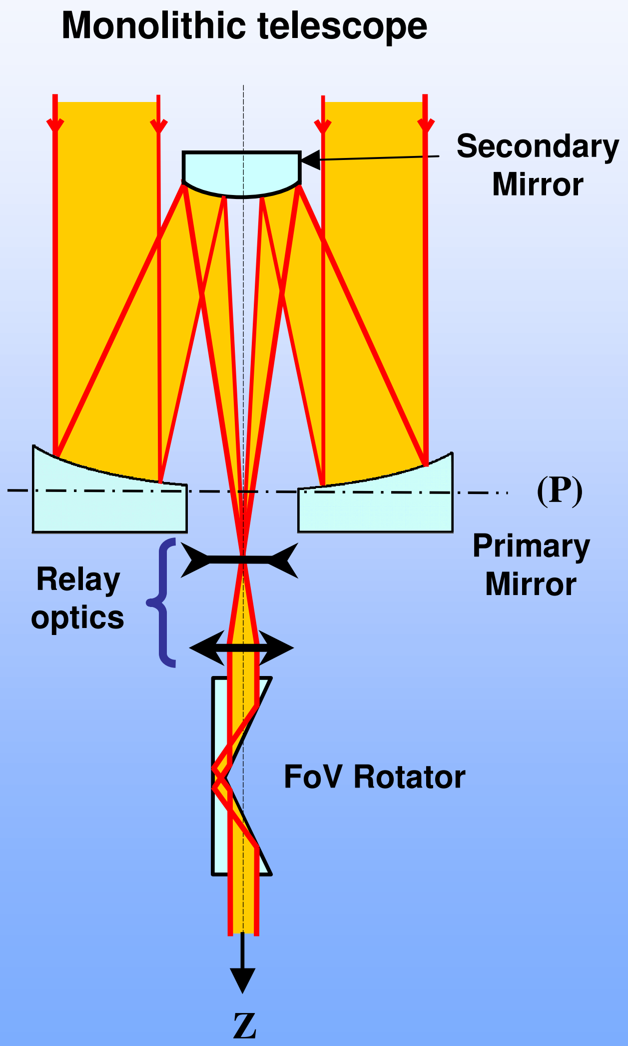

- “Fibered nulling telescope for extra-solar coronagraphy,” Optics Letters **34**, n° 7, p. 1096–1098 (2009)
- “Simple Fourier optics formalism for high angular resolution systems and nulling interferometry,” JOSA A **27**, p. 435-449 (2010)
- “PSF and Field of View characteristics of imaging and nulling interferometers,” Proceedings of the SPIE **7734**, p. 773419 (2010)

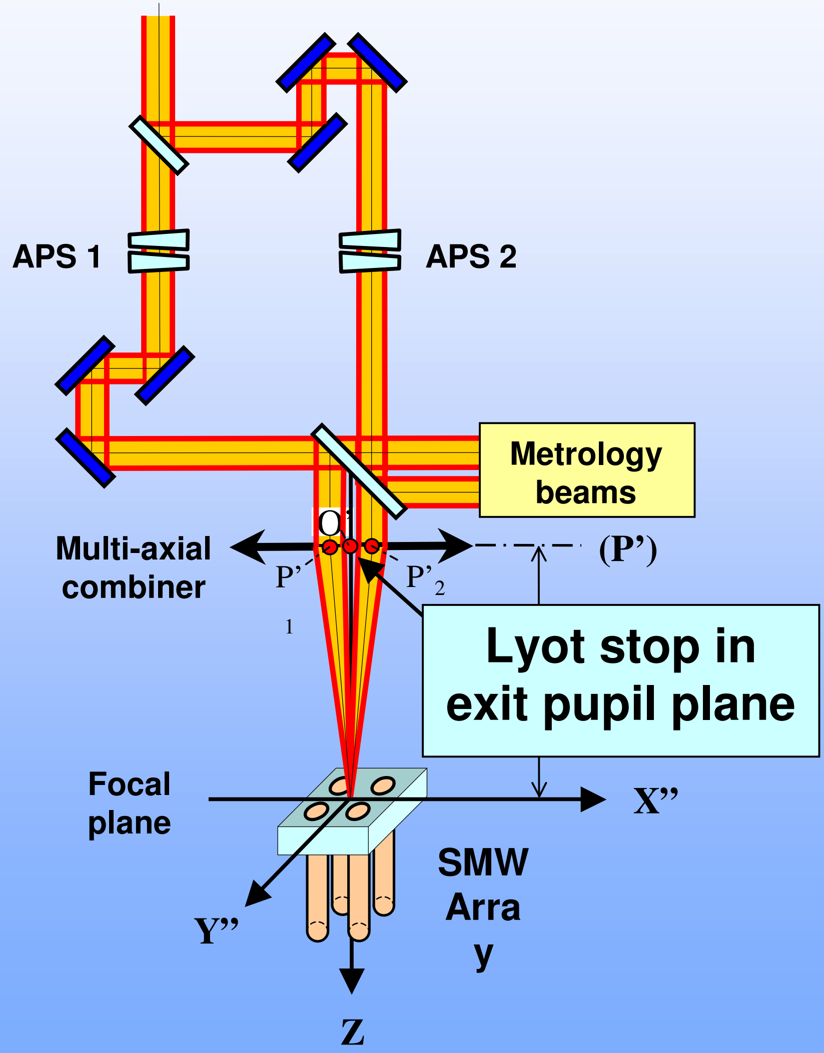
# Super-Resolving Telescope (SRT)



# Sheared-Pupil Telescope (SPT)



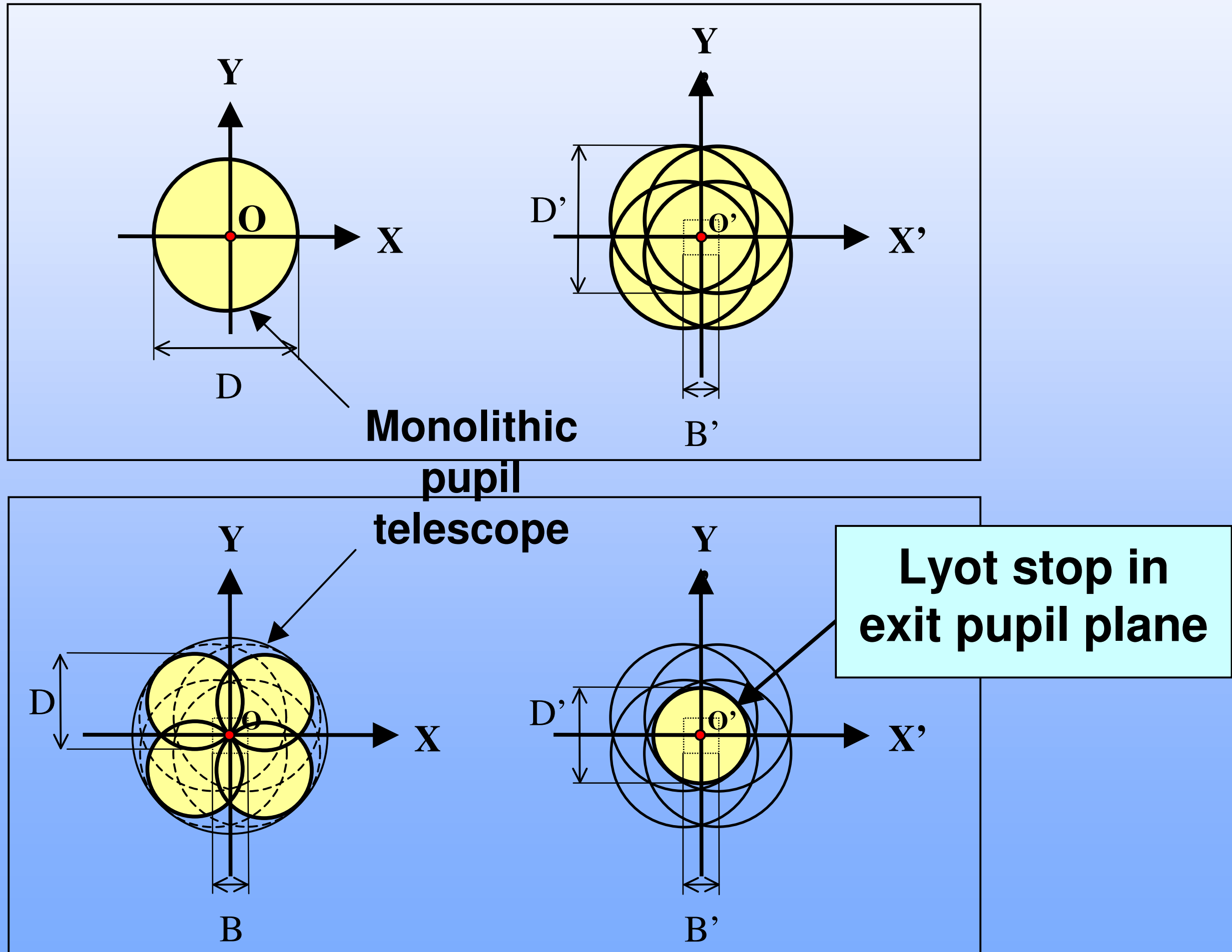
# Two different types of nulling telescopes

Unmasked output sub-pupils (SRT)

All input and output sub-pupils are identical and optically conjugated

Masked output sub-pupils (SPT)

Input pupil plane | Output pupil plane



# Analytical expression of SRT nulling maps

- Star leakage into SMW pointed along direction **s**

$$P_S(\mathbf{s}) = I_S \left| G^*(\mathbf{s}) \otimes \left\{ \hat{B}_D(\mathbf{s}) \sum_{n=1}^{N} a_n \exp[i\varphi_n] \exp[-ik\,\mathbf{s}\,\mathbf{O'P'_n}/m] \right\} \right|^2$$

- Planet signal coupled into SMW

$$P_P(\mathbf{s}) \approx I_P \left| G^* \hat{B}_D(\mathbf{s}) \otimes \left\{ \sum_{n=1}^{N} a_n \exp[i\varphi_n] \exp[-ik\,\mathbf{s}\,\mathbf{O'P'_n}/m] \right\} \right|^2$$

- Where:
  - $G(\mathbf{s})$ : SMW filtering function
  - $\hat{B}_D(\mathbf{s})$ : complex amplitude generated by one single sub-pupil, back projected onto the sky
  - $a_n$ : amplitude transmission factor for sub-pupil #n
  - $\varphi_n$ : phase-shift for sub-pupil #n
  - $k = 2\pi/\lambda$ where $\lambda$ is the monochromatic wavelength
  - $\mathbf{O'P'_n}$ : coordinates of sub-pupil #n
  - $m$ : optical compression factor of relaying optics (= D'/D)

# SPT nulling maps

- Star leakage into SMW = ideal null + “null floor” $N_0$

$$P_S(\mathbf{s}) = I_S \left| \sum_{n=1}^{N} a_n \exp[i\varphi_n] \right|^2 + N_0$$

- Planet signal coupled into SMW

$$P_P(\mathbf{s}) \approx I_P \left| \sum_{n=1}^{N} a_n \exp[i\varphi_n] \exp\left[ik\,\mathbf{s}\,\mathbf{OP_n}\right] \right|^2$$

- Signal to Noise Ratio (SNR)

$$\mathrm{SNR}(\mathbf{s}) \approx \frac{P_P(\mathbf{s})\,\eta\,A\,\tau}{\sqrt{\left[P_S(\mathbf{s}) + N_0\, I_S + I_{EZ}\right]\eta\,A\,\tau + \sigma_N^2}}$$

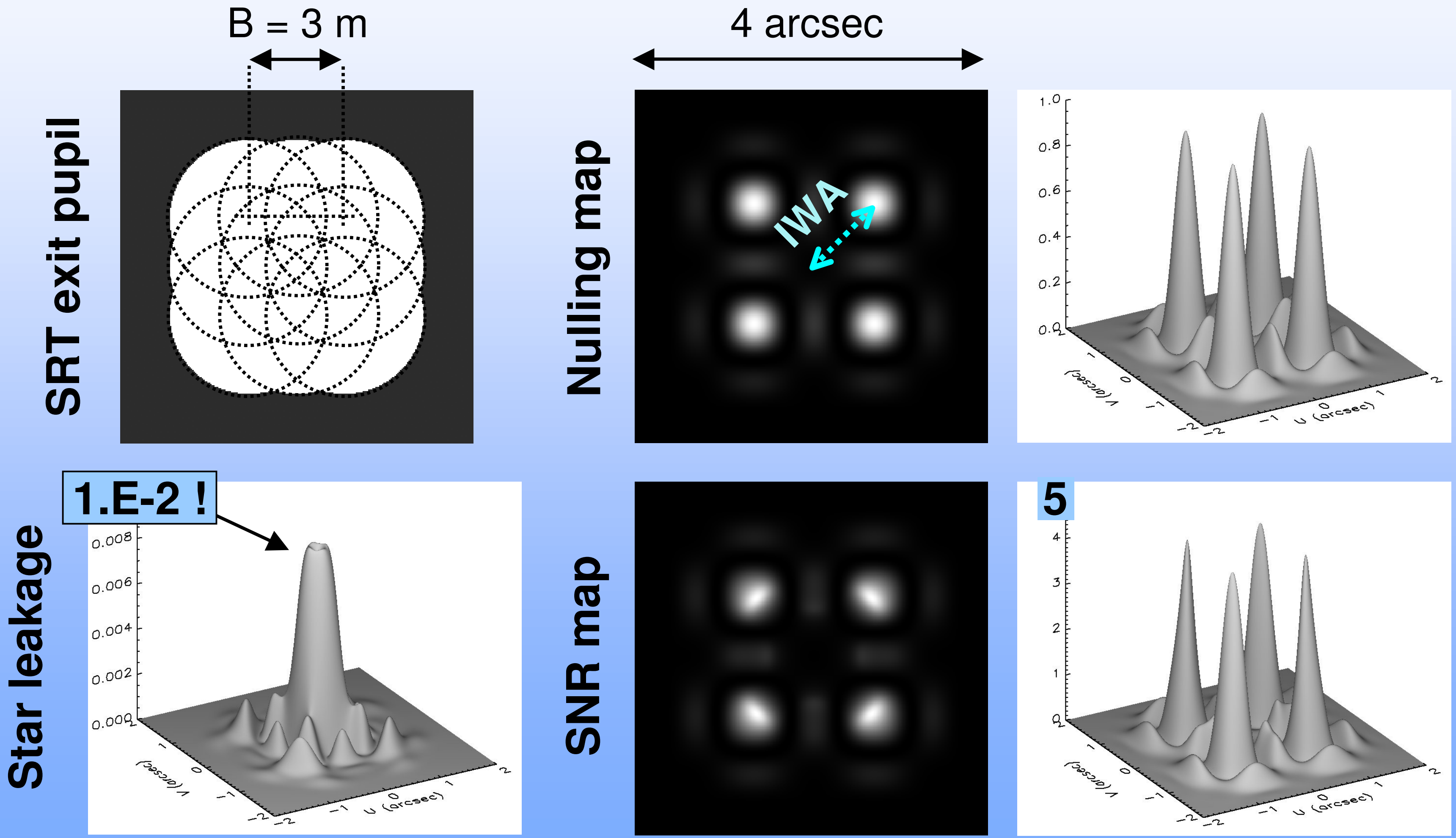
**Effective collecting area** ($A$)

**Integration time** ($\tau$)

**Exo-zodiacal cloud / Background** ($I_{EZ}$)

**Detection noise** ($\sigma_N^2$)

# Example of SRT numerical simulation

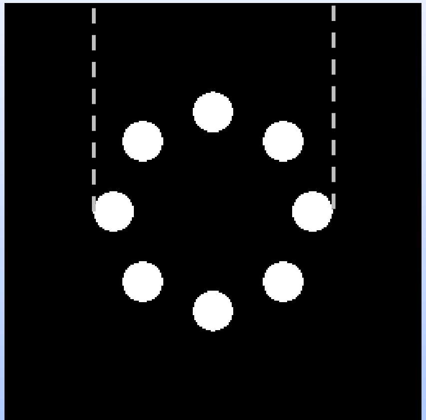


# SPT numerical simulation

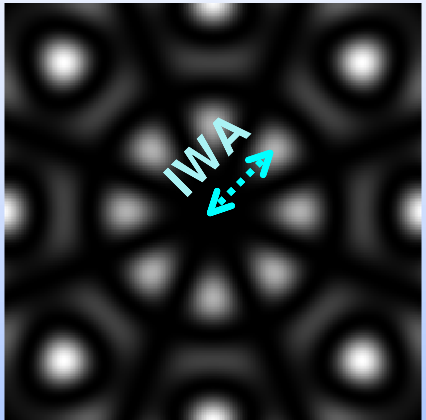
D = 5 m

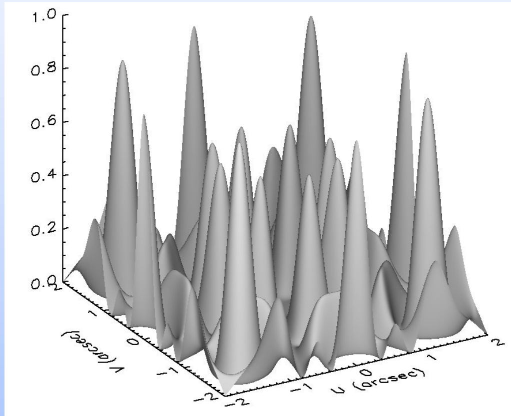
4 arcsec

SPT effective entrance pupil



Nulling map

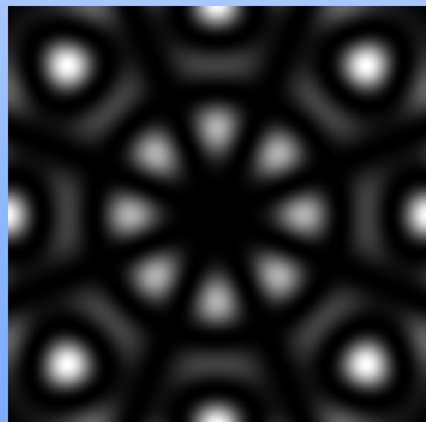


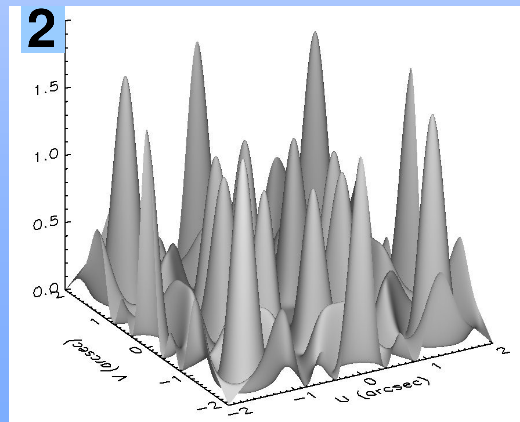




Star leakage

**Constant, equal to nulll floor 1.E-4**

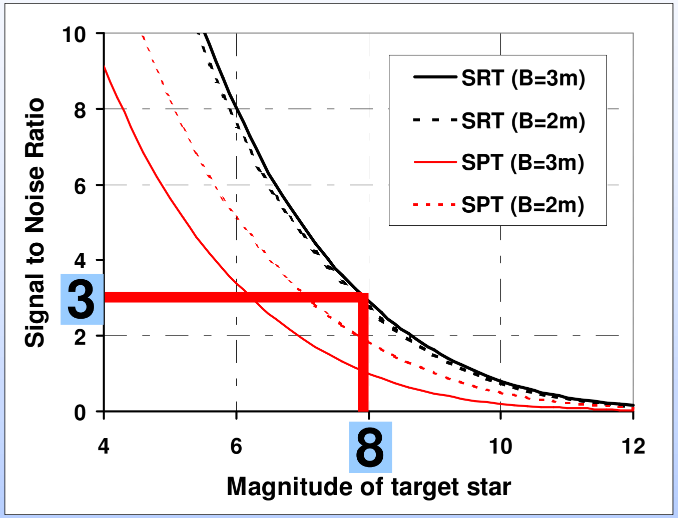
SNR map



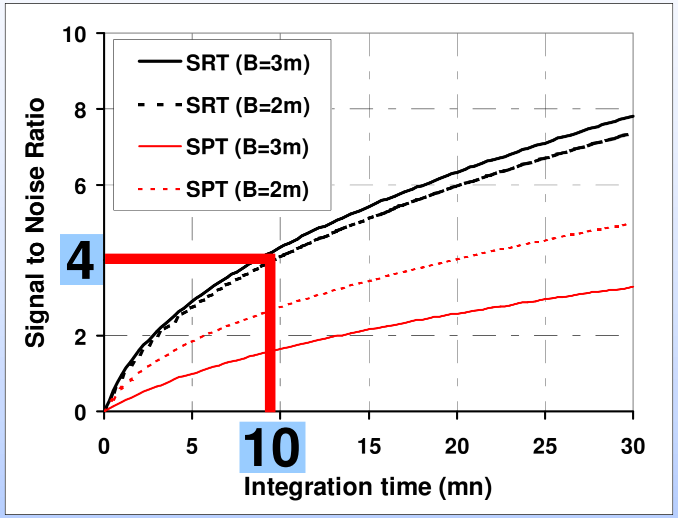


# SNR sensitivity curves

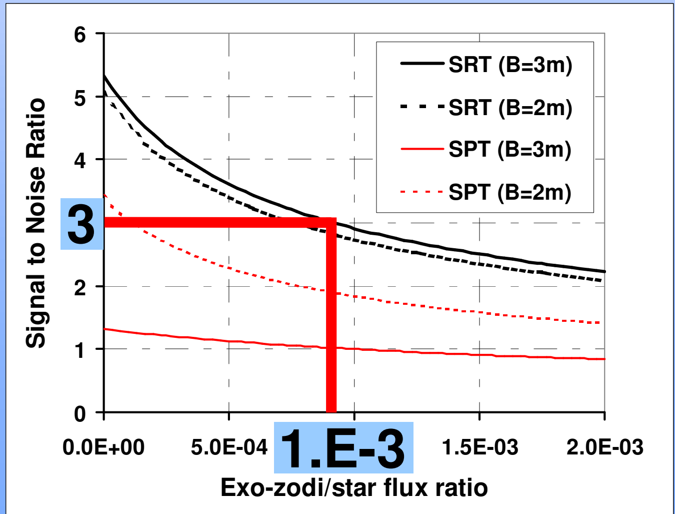
## Magnitude of target star



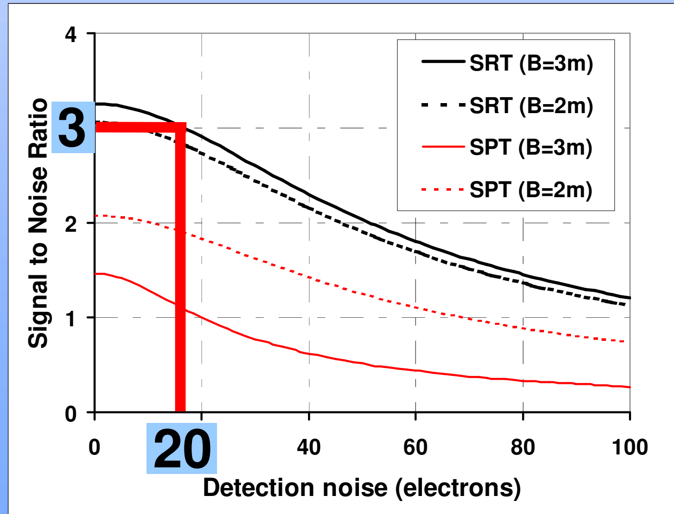

## Integration time in minutes



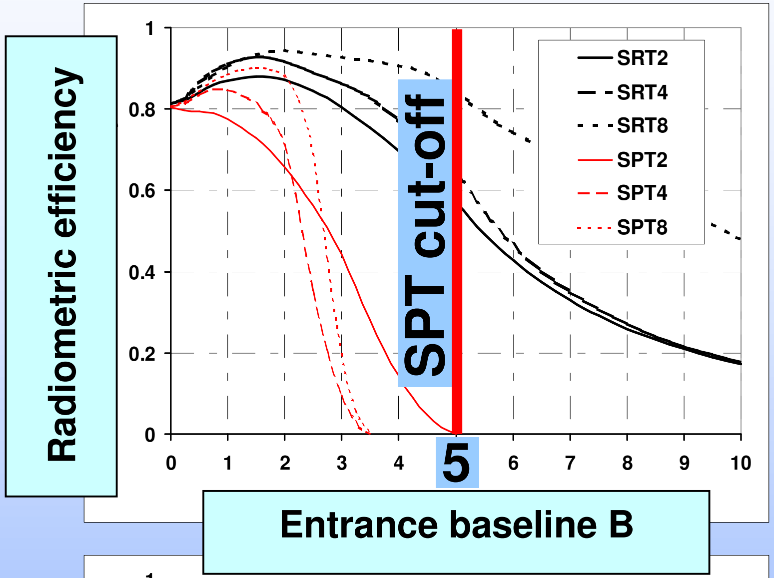

## Background/ Star flux ratio

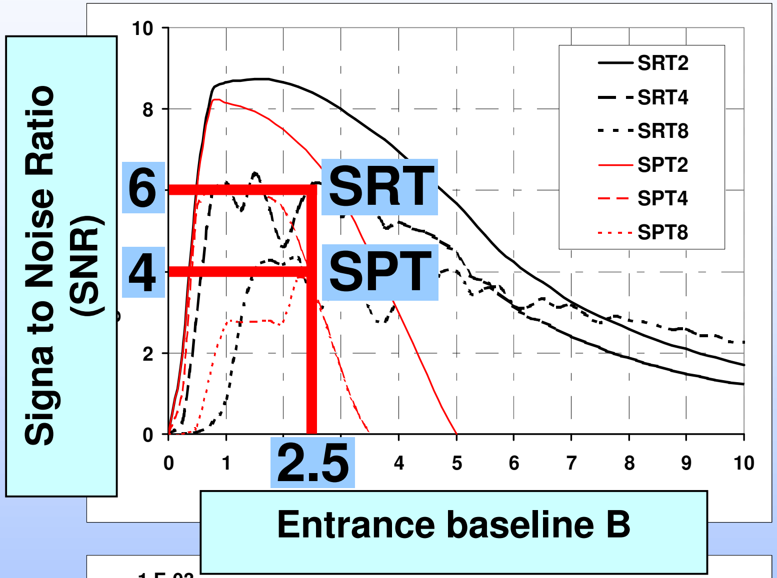


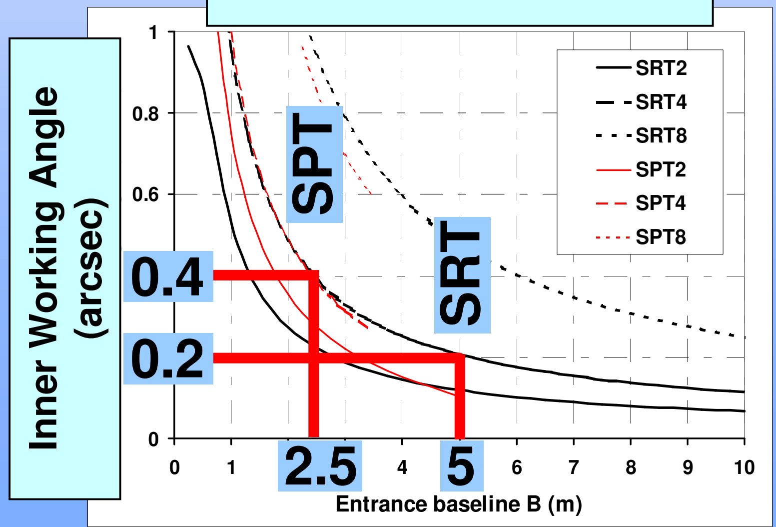

## Detection noise in # electrons

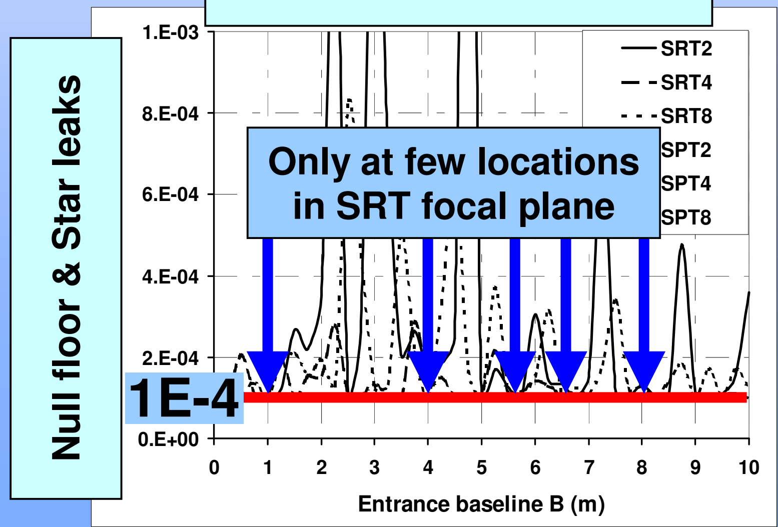


# Performance vs. shear/entrance baseline B



# Conclusion

- Both concepts of nulling telescopes seem suitable for **hot Jupiters and exo-zodiacal clouds** characterization
- SRT and SPT show adverse advantages and drawbacks:
  - **SRT** → Better radiometric and SNR performance, smaller Inner Working Angle (IWA), but suffers from non-uniform nulling rates
  - **SPT** → Better and uniform nulling rates, but limited by larger IWA and lower SNR (requires longer integration times)
- Possible remedies:
  - Adjustable/removable Lyot stop in the exit pupil plane
  - Use “blinded” SMWs to calibrate and subtract SRT stellar leaks
  - Add anamorphic optics into the optical train…