CALIBRATION OF A **TUNABLE PHOTONIC KERNEL-NULLING** INTERFEROMETER FOR DIRECT DETECTION OF EXOPLANETS

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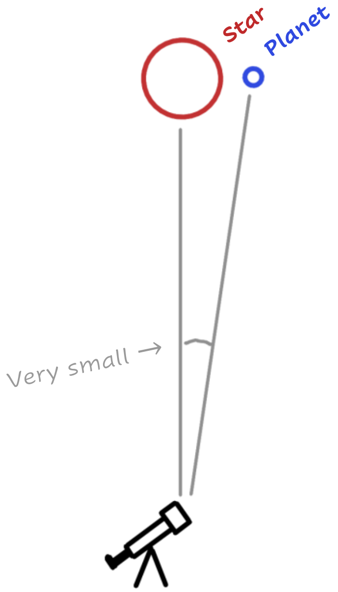
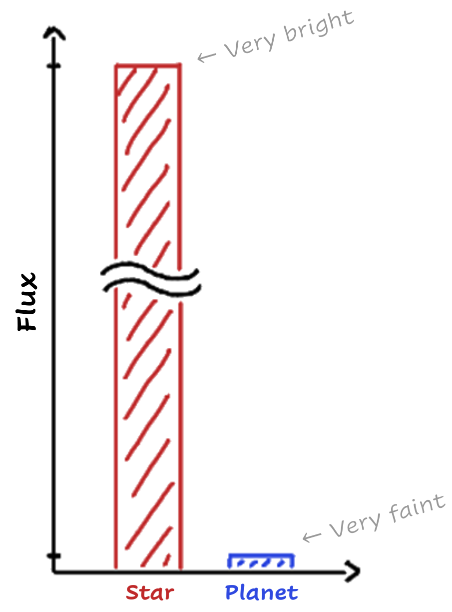
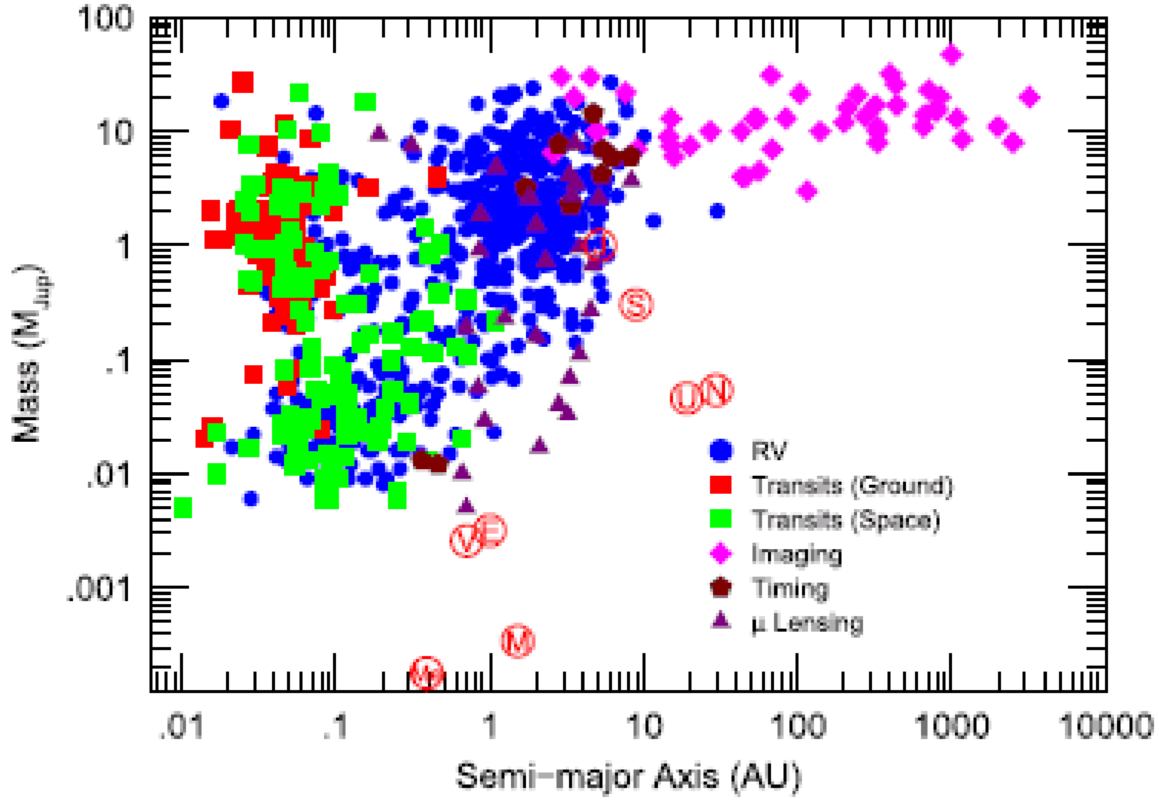
Challenges of direct detection

Challenge 1:
Angular resolution



Challenge 2:
Contrast





Hatzes 2016

Nulling Interferometry

Bracewell et al. (1978)

- Destructive interferences
- Off-axis sources will not be cancelled
- Angular resolution:

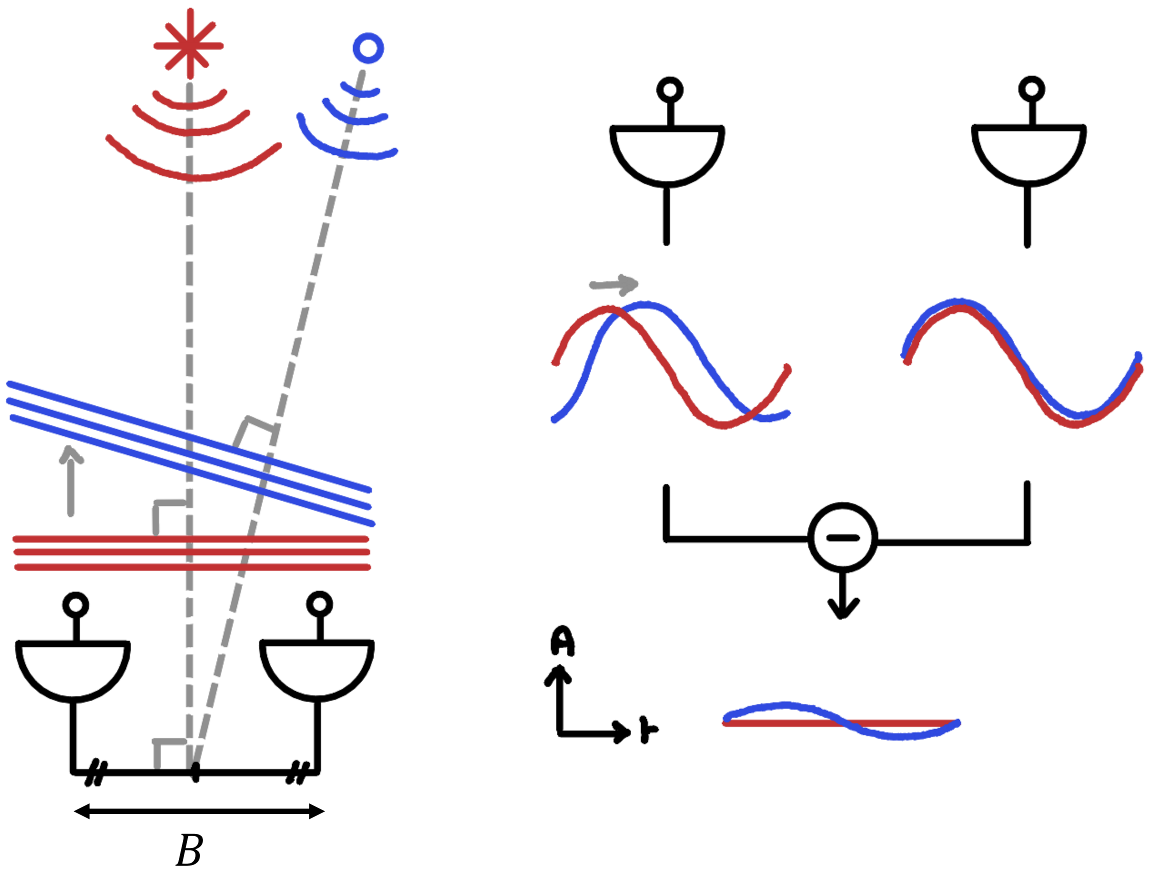
$$\theta \propto \frac{\lambda}{B}$$

- **Null Depth** (contrast):

$$\boxed{d = \frac{I_-}{I_+}}$$

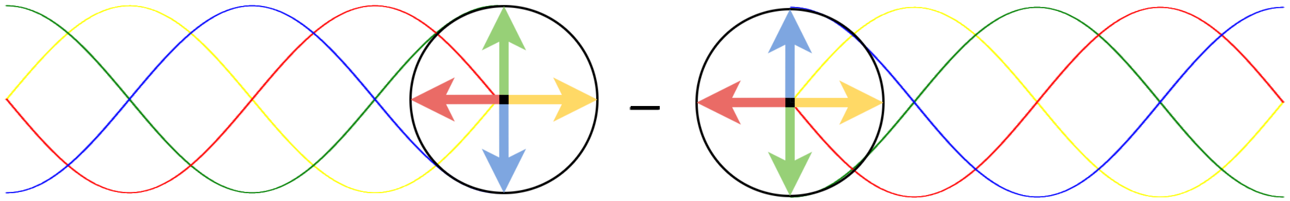
- Demonstrated on sky at $d = 10^{-4}$

  Norris et al. (2019)

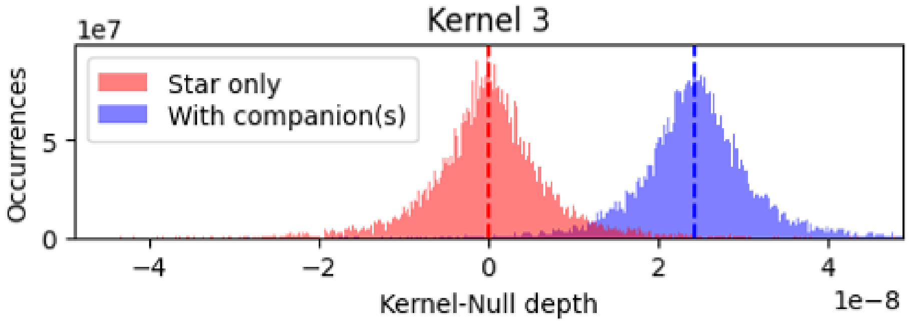


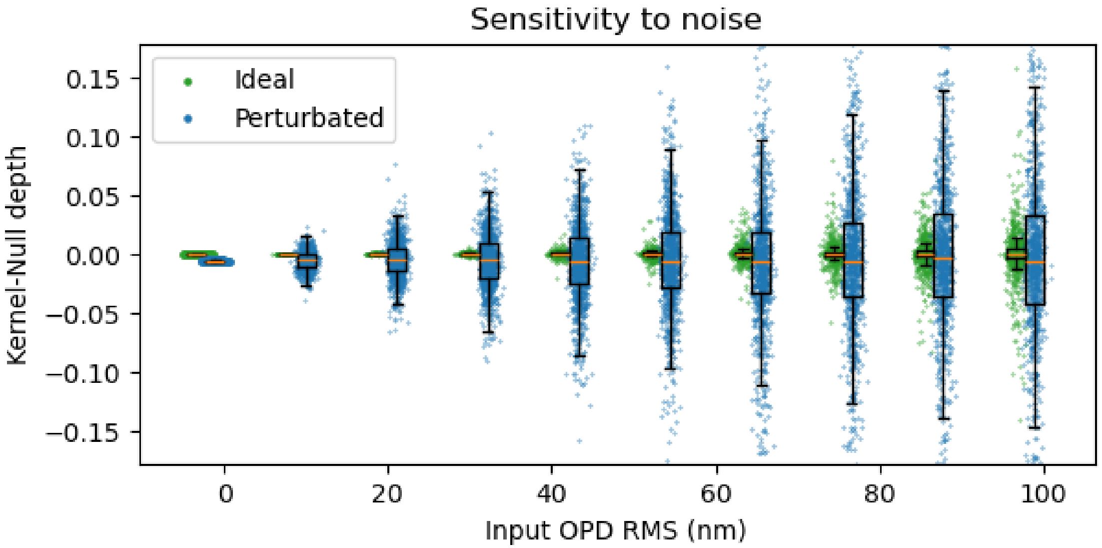
Kernel-Nulling

Martinache & Ireland (2018)

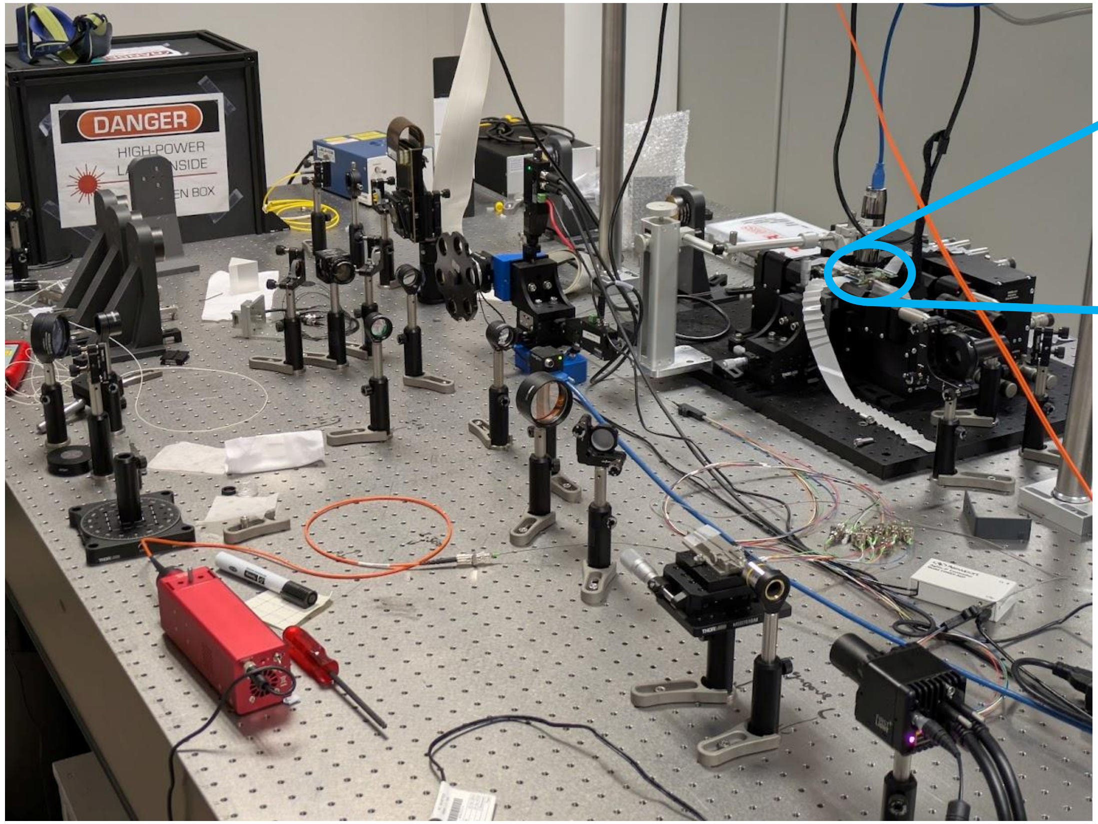


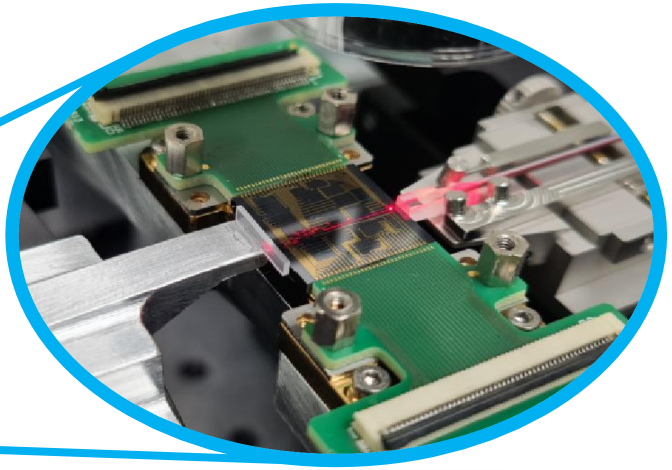
- Intensity difference between two phase quadrature combinations
- Self-calibrated observable
- Showing **phase closure characteristics**
  - Robust to first order phase aberration
  - Insensitive to symetric sources





Photonic technology



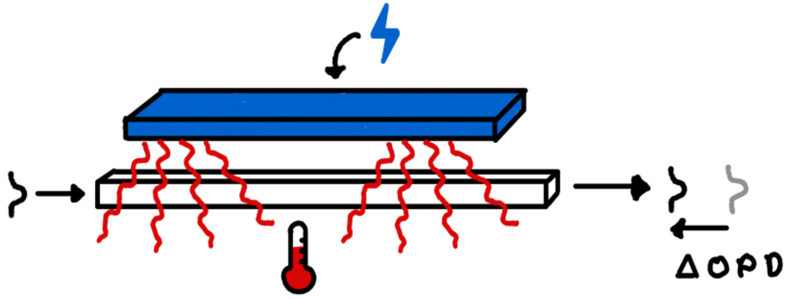


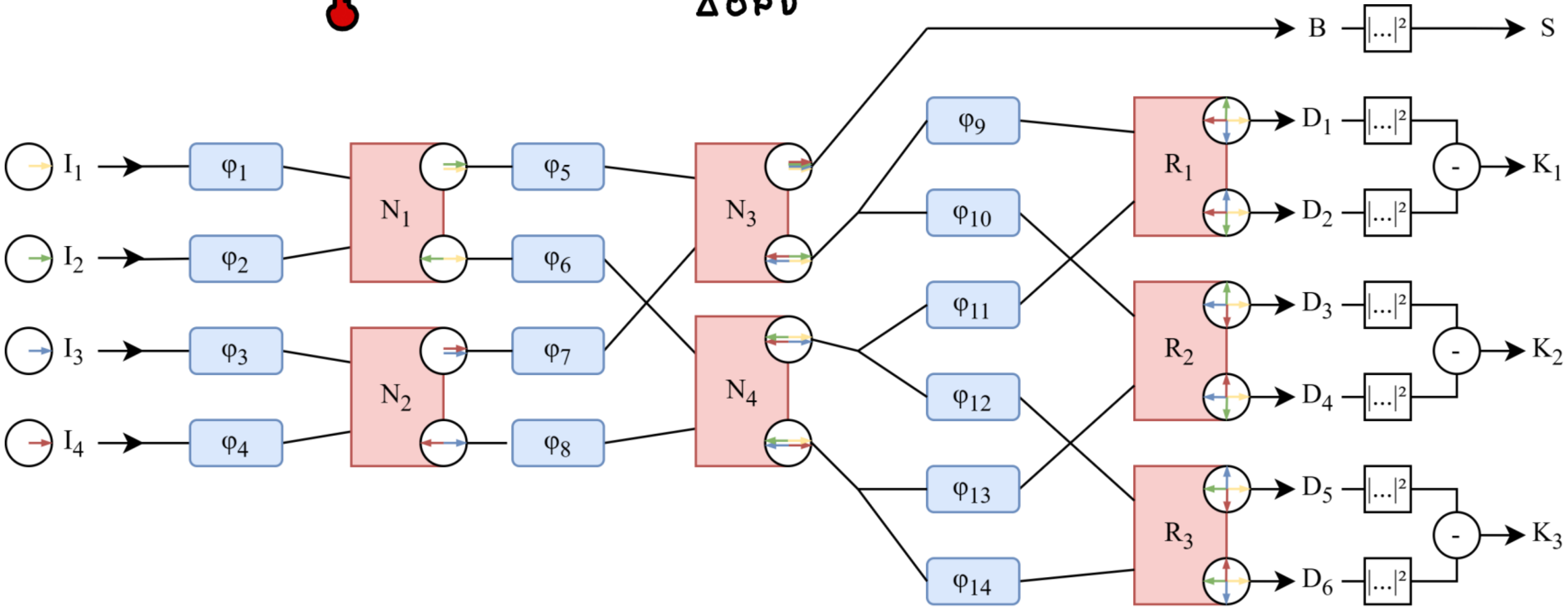
Photonic chip made of SiN (16mm large)
$\lambda_0 = 1{,}55 \mu m$

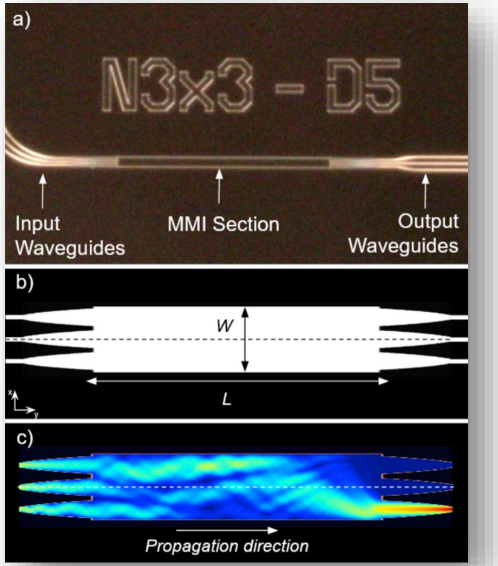
- Stable
- Compact
- Light

Space friendly 🚀

Tunable architecture







Wave propagation simulation in a MMI (Multi Mode Interferometer)
Cvetojevic et al. (2022)

Trial & Error approach

Initial

$\varphi_1 \quad \varphi_2 \quad \varphi_3 \quad \cdots \quad \varphi_N \xrightarrow{\text{Measurement}} d(\boldsymbol{\varphi})$ Null Depth $d := \frac{I_-}{I_+}$ → should be **minimized**

Step 1

$\cancel{\varphi_1 + \Delta\phi} \quad \varphi_2 \quad \varphi_3 \quad \cdots \quad \varphi_N \longrightarrow d(\boldsymbol{\varphi}') > d(\boldsymbol{\varphi})$ 👎

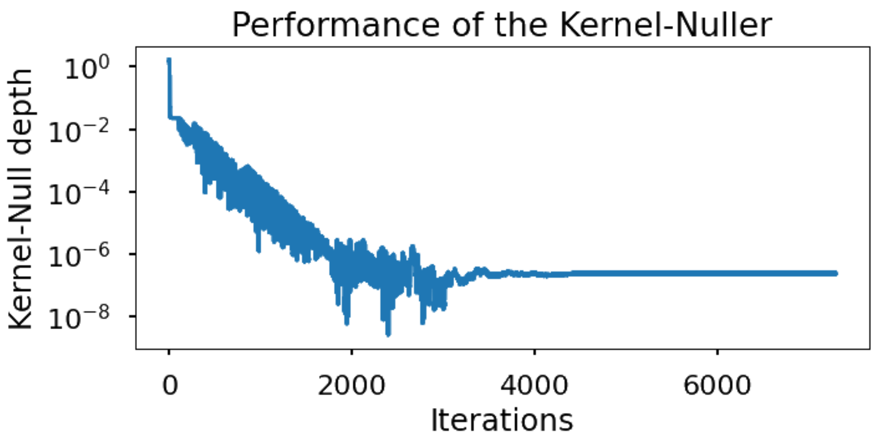
Step 2

$\varphi_1 \quad \underbrace{\varphi_2 + \Delta\phi}_{= \varphi_2'} \quad \varphi_3 \quad \cdots \quad \varphi_N \longrightarrow d(\boldsymbol{\varphi}'') < d(\boldsymbol{\varphi})$ 👍

⋮

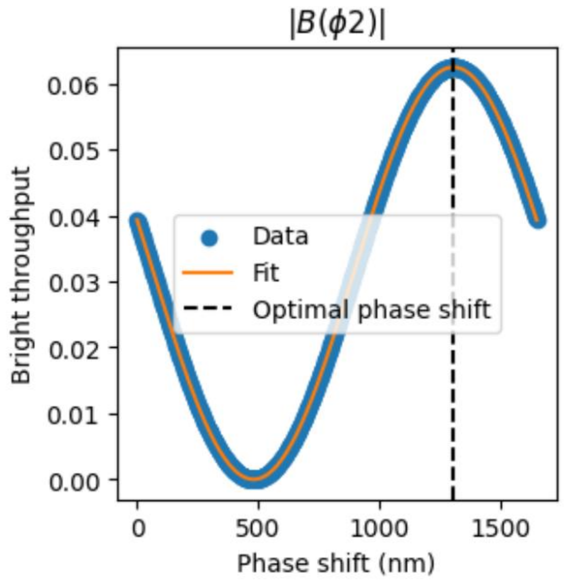
Final

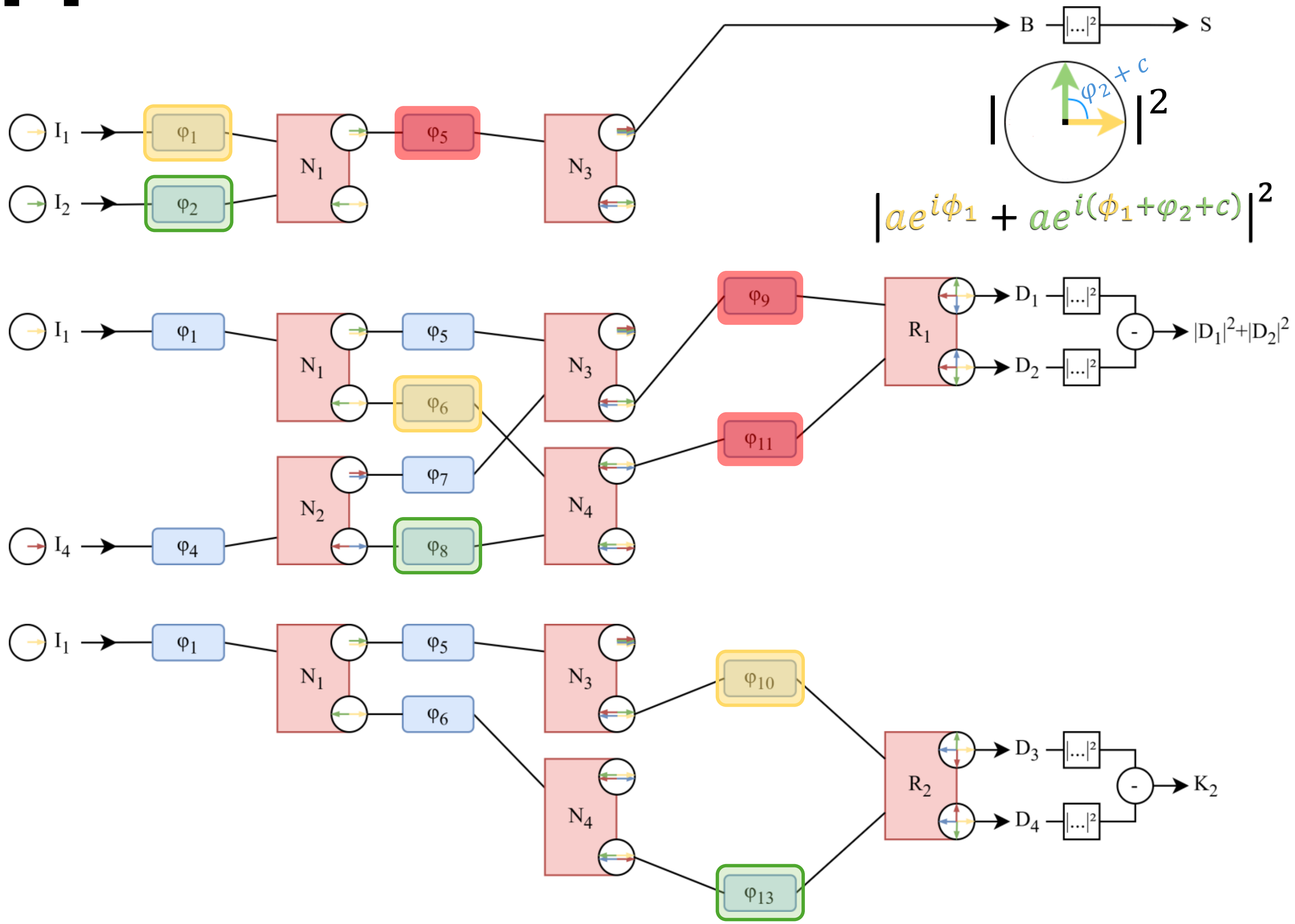
$\varphi_1^* \quad \varphi_2^* \quad \varphi_3^* \quad \cdots \quad \varphi_N^* \longrightarrow d(\boldsymbol{\varphi}^*)$ 👌



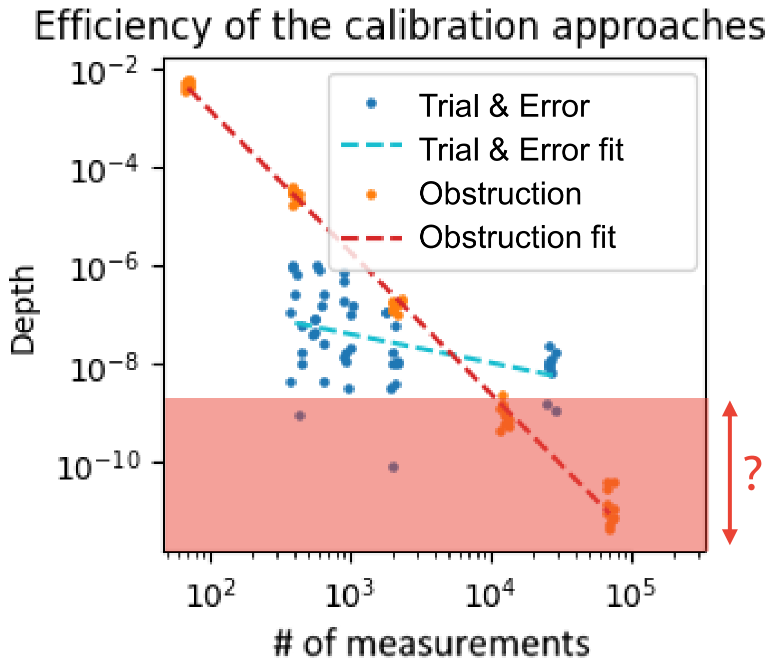
Obstruction approach

- Isolate a single MMI
- Scan on one shifter
- Fit output response

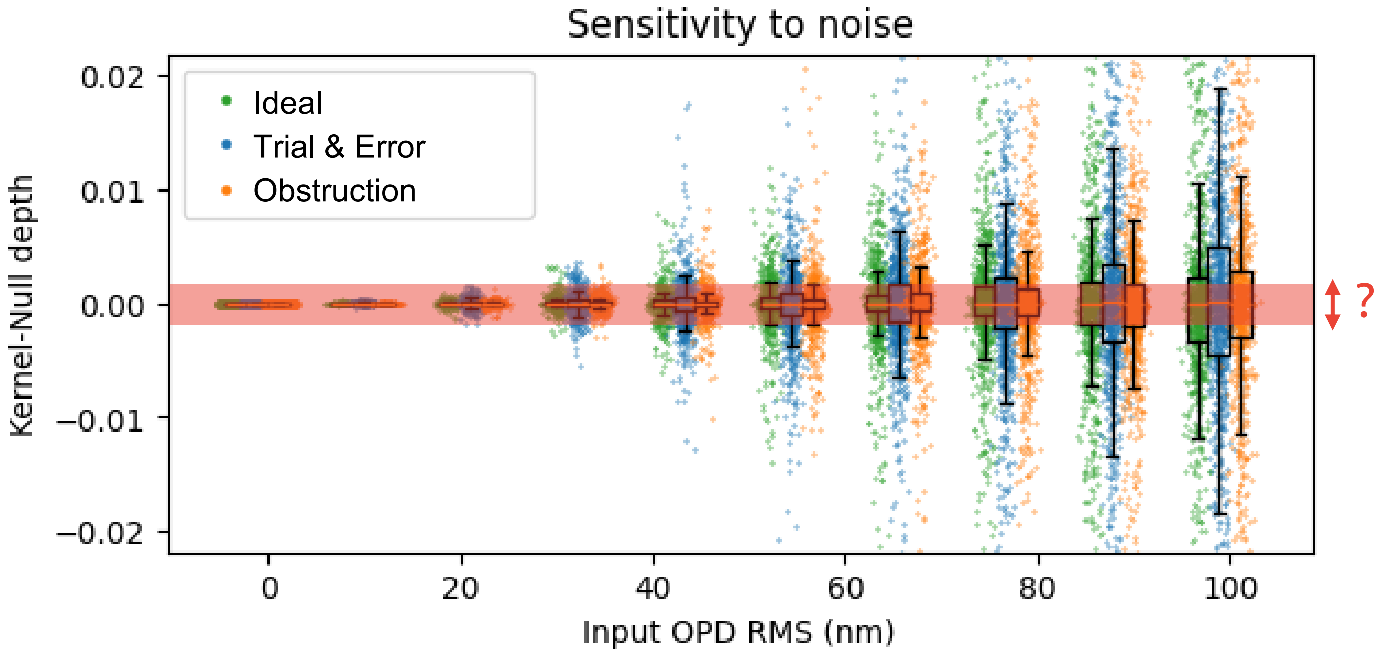




Comparison



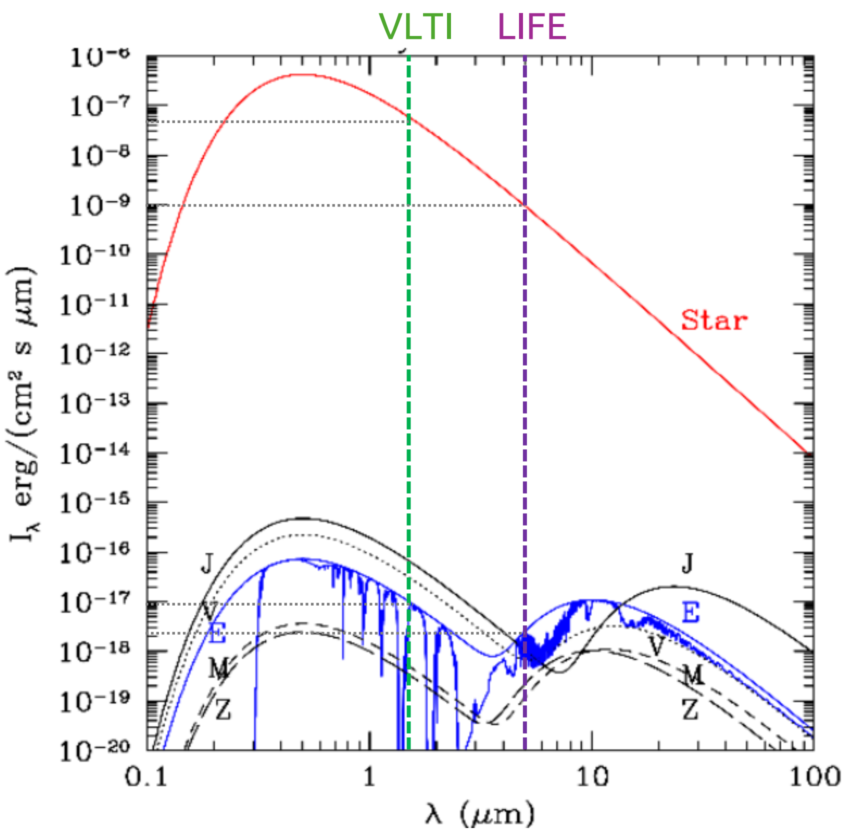
Efficiency of the calibration approaches
Trial & Error
Trial & Error fit
Obstruction
Obstruction fit
Depth
# of measurements
?



Sensitivity to noise
Ideal
Trial & Error
Obstruction
Kernel-Null depth
Input OPD RMS (nm)
?

Detection capability

- VLTI conditions: up to $\mathbf{10^{-4}}$
  - → Performances mainly limited by atmosphere
  - → In accordance with the literature 📚 *Norris et al. (2019)*
- LIFE conditions: up to $\mathbf{10^{-9}}$
  - → Possible exo-earth detection
  - → Missing perturbation sources in the numercial model?
- ⚠️ Numerical simulations
  - → Soon to be validated in lab



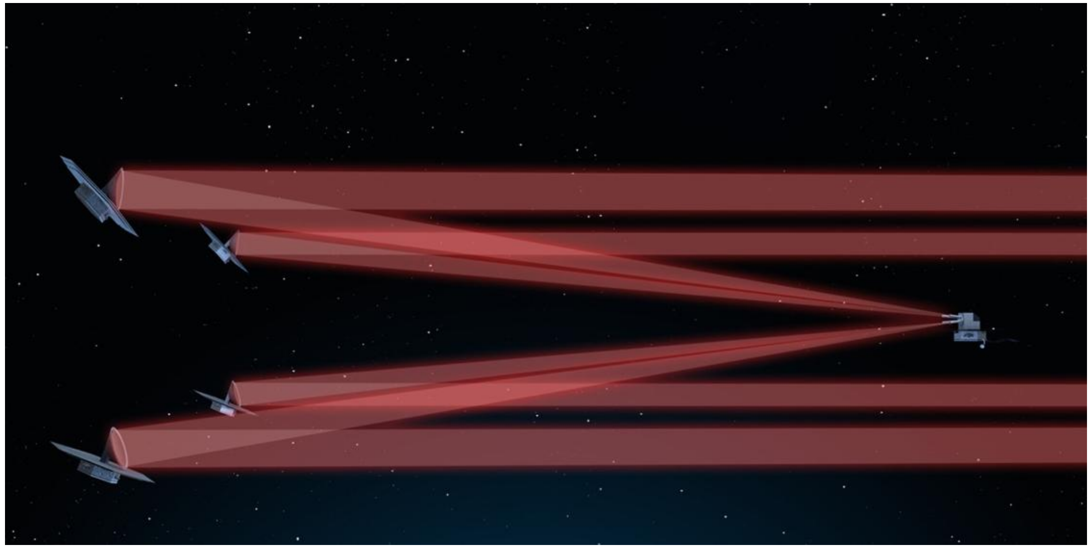
SAO model of our solar system
📚 *Kaltenegger et al. (2010)*

Conclusion

- Compact, stable, light
- Possibility to make it almost ideal

Future prospects

- VLTI ASGARD/NOTT
- LIFE

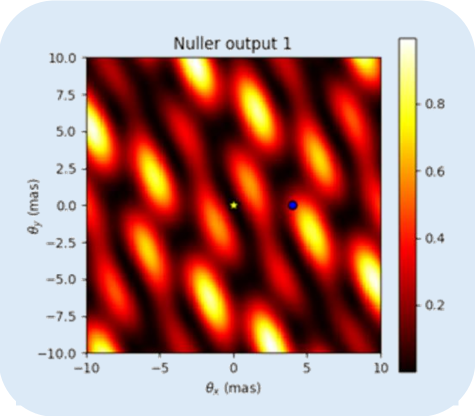


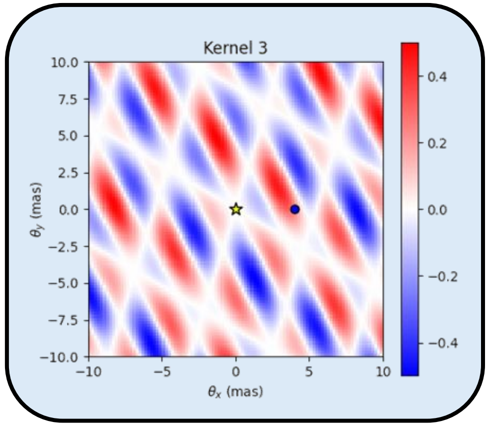
Thank you!

Backup slide

Kernel-Nulling

Martinache & Ireland (2018)





🔎 Why is it more robust?

An output intensity is a combination of the input fields

$$I = \left|\left|E_1 + E_2 + E_3 + E_4\right|\right|$$

$$E = a\,e^{i\phi}$$

If we introduce small perturbations on these fields

$$e^{i\theta} \approx 1 + i\theta$$

We can then express a pair of output intensity such as

$$I_A \approx \left|\left|a - a(1+i\theta_2) + ia(1+i\theta_3) - ia(1+i\theta_4)\right|\right|^2$$

$$I_B \approx \left|\left|a - a(1+i\theta_2) - ia(1+i\theta_3) + ia(1+i\theta_4)\right|\right|^2$$

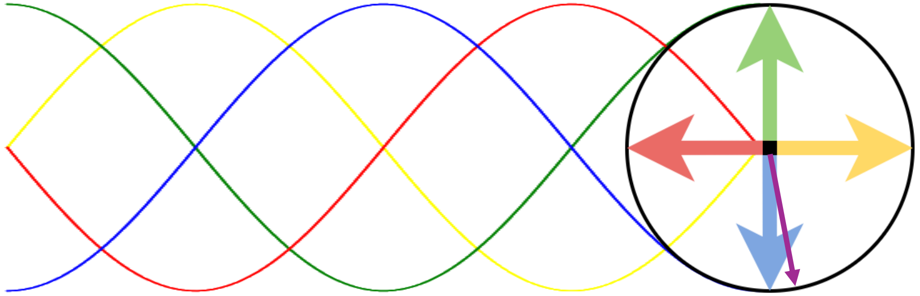
By simplifying, we obtain

$$I_A \approx I_B \approx \left|\left|a\right|\right|^2 \times \left(\theta_2^2 + (\theta_3 - \theta_4)^2\right)$$

So

$$I_A - I_B \approx 0$$

Martinache & Ireland (2018)



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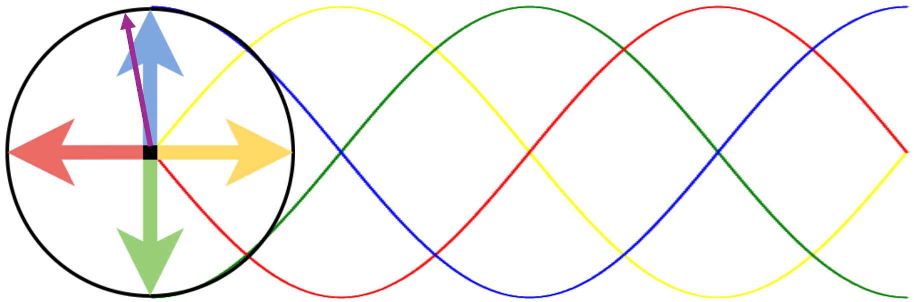


$$\left|ae^{i\phi_1} + ae^{i\left(\phi_1+\frac{\pi}{2}\right)} + ae^{i(\phi_1+\pi)} + ae^{i\left(\phi_1+\frac{3\pi}{2}+\theta\right)}\right|^2 - \left|ae^{i\phi_1} + ae^{i\left(\phi_1+\frac{\pi}{2}+\theta\right)} + ae^{i(\phi_1+\pi)} + ae^{i\left(\phi_1+\frac{3\pi}{2}\right)}\right|^2 = 0$$

For $\theta \ll \pi$, such as $e^{i\theta} \approx 1 + \theta$

Backup slide

MMI: Multi Mode Interferometer

Self-imaging multi mode waveguide

Operation defined by the length L

🔎 How does it work?

A single-mode light entering a multimode region will excite several transverse modes that will interfere. These interferences will produce an image of the input at specific positions: L_π, $L_\pi/2$, $L_\pi/3$, ...

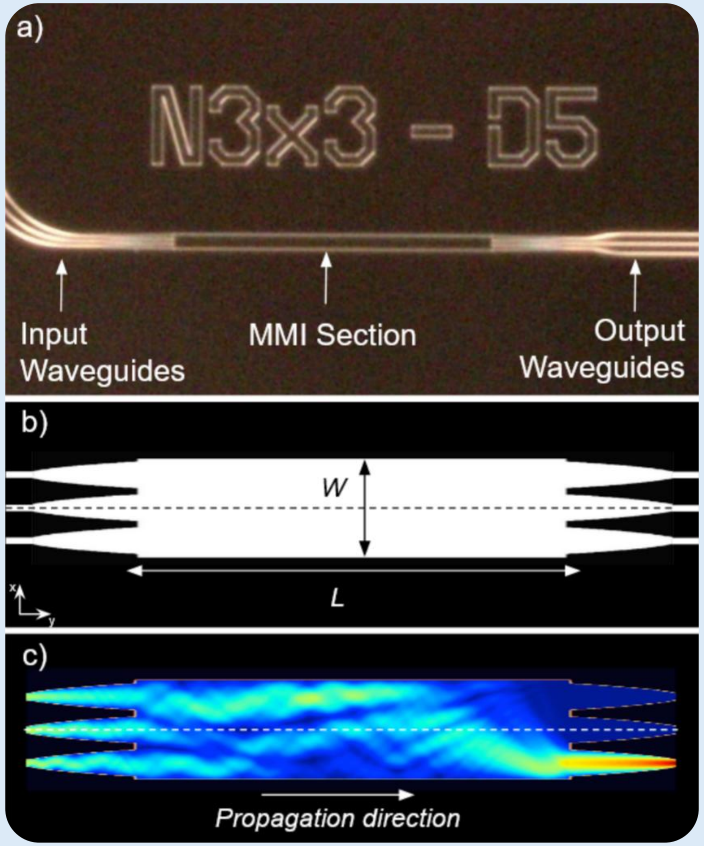
$$L_\pi = \frac{4n_{eff}W^2}{3\lambda}$$

🤔 What is a mode?

In a waveguide (fiber optics), the light doesn't propagate freely, it is constrained between the borders. Like a guitar string that vibrates when pinched on both sides, the light wave can only take specific shapes that respect theses constraints.

Monomode fiber

Multimode fiber



Wave propagation simulation in a MMI cavity

📚 *Cvetojevic et al. (2022)*

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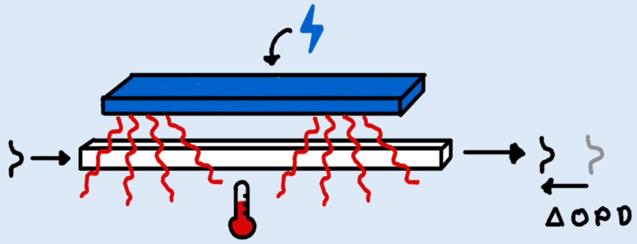
Thermo-optic phase shifters



Recipe:

Electric resistance
↳ Heat
↳ Optical index modification
↳ Phase delay

Response time ~ 1 µs

Phase range > 2λ

🔎 What's the physics behind?

In a material, the light speed is defined such as

$$v = \frac{c}{n}$$

The refractive index n is related to the material's polarizability and its electronic band structure. When the temperature increases:

- Thermal vibrations (phonons) increase → atomic bonds become more flexible → the electronic response to an electromagnetic field is modified.
- This affects the dielectric permittivity ϵ, hence $\sqrt{\epsilon\mu}$ (with $\mu \approx 1$ for non-magnetic optical materials).
- The broadening of electronic transitions or absorption bands can also modify $n(\lambda)$, according to Sellmeier dispersion.

There is no universal exact expression of $n(\lambda, T)$. However, we empirically use the following linear approximation which is valid for small temperature variation:

$$n(\lambda, T) = n_0(\lambda) + \frac{dn(\lambda)}{dT}(T - T_0)$$

Were T_0 is the reference temperature (typically $300K$)
📚 *Wikipedia*

Backup slide

Output data analysis

- Kernel outputs follows an **unknown distribution**
- Companions affect this distribution
- In practice, **SNR << 1**
- Searching for most efficient **specific** statistical test