Photo Controlled Deformable Mirrors: a new approach to adaptive optics

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Deformable mirrors for Adaptive Optics

Adaptive Optics (AO) compensates for the wavefront distortions in optical systems

Change in the Optical Path

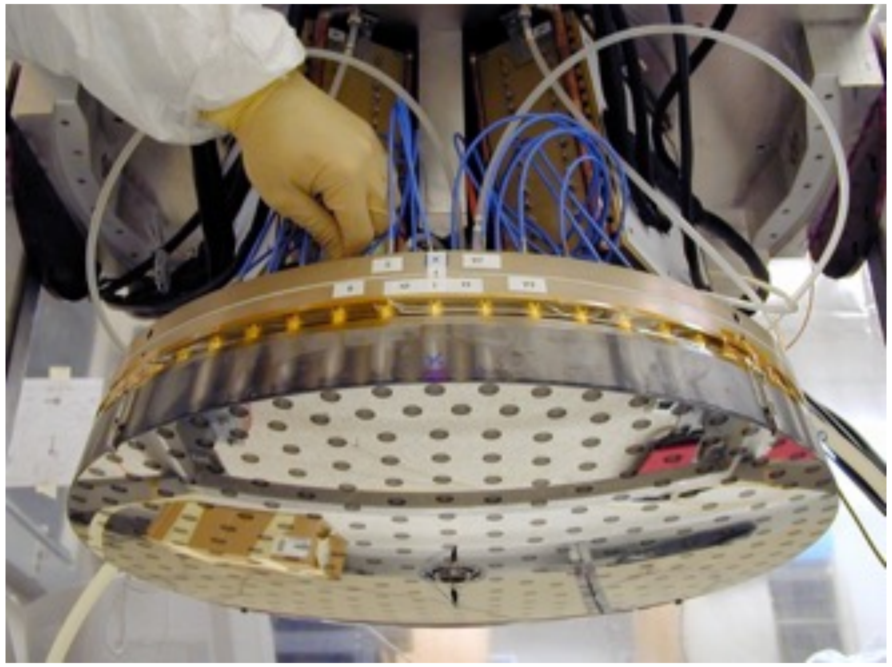
$$OP = n \, \boxed{d}$$

refractive index

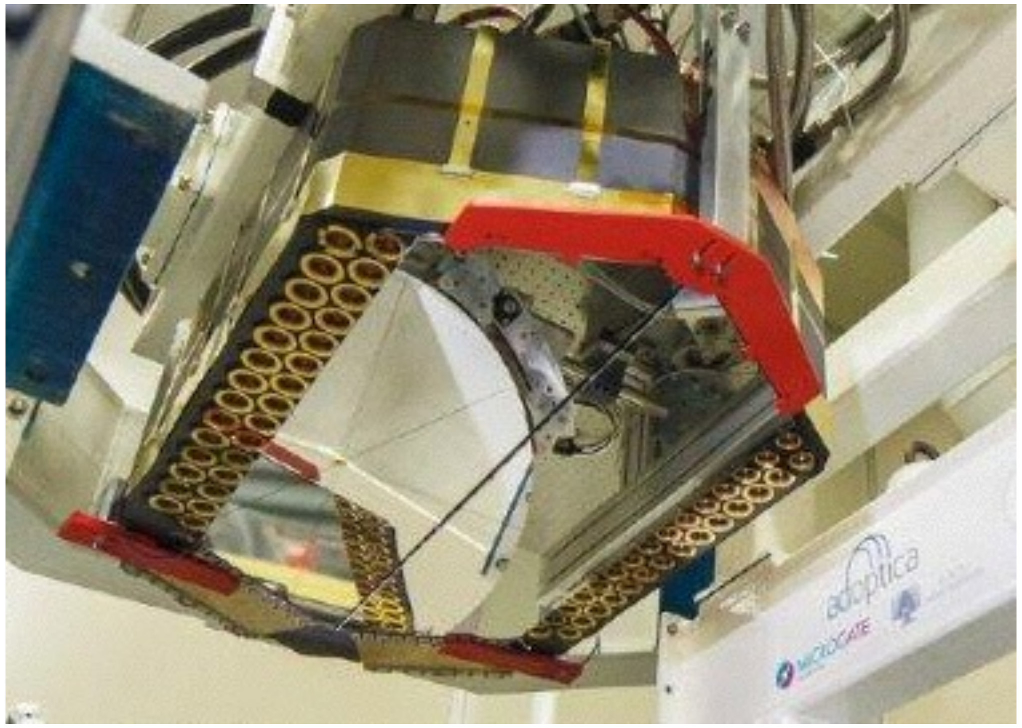
physical distance

Usually performed with **deformable mirrors**

Direction towards very large and complex mirrors



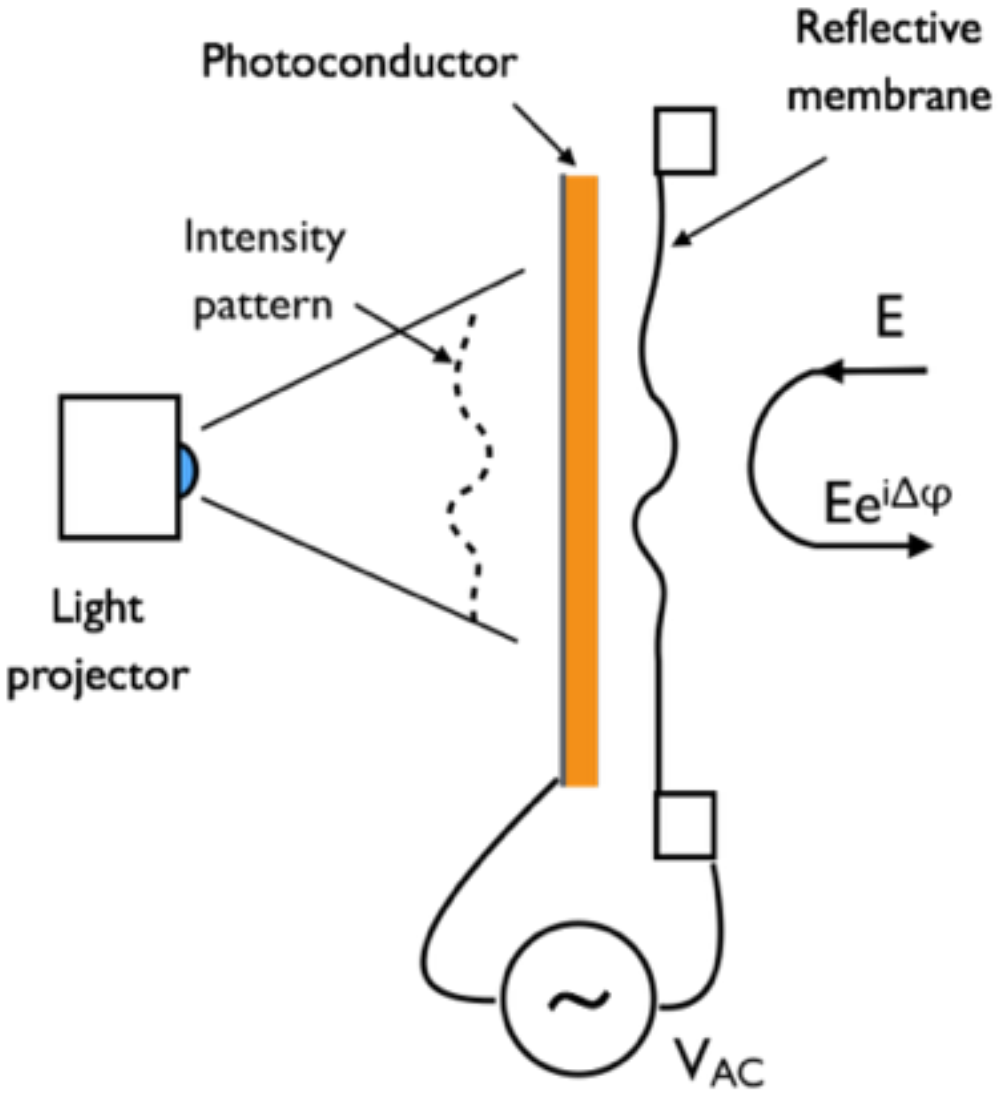
MMT adaptive secondary mirror (640 mm)



EELT M4 (2.4 m)
Demonstration Prototype (620 x 350 mm)
at Brera Observatory

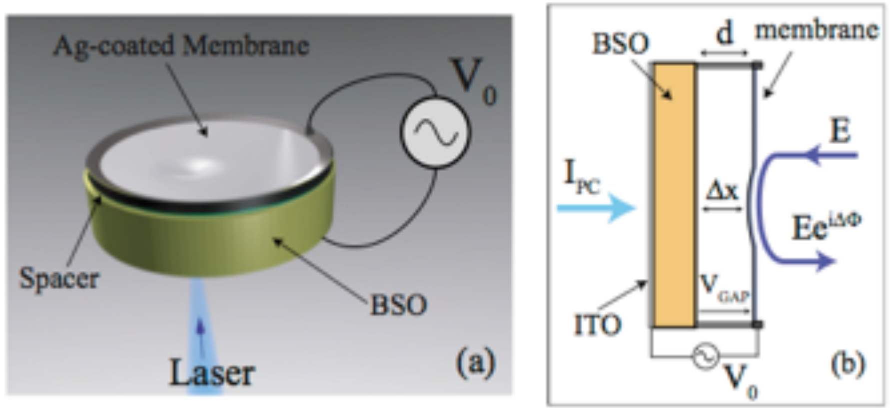
Photo Controlled Deformable Mirrors

Idea: to have an optically addressable optical element whose shape is determined by a light pattern



Advantages:

- displace the complexity away from the instrumentation
- possibility to vary the resolution arbitrarily
- only one HV source



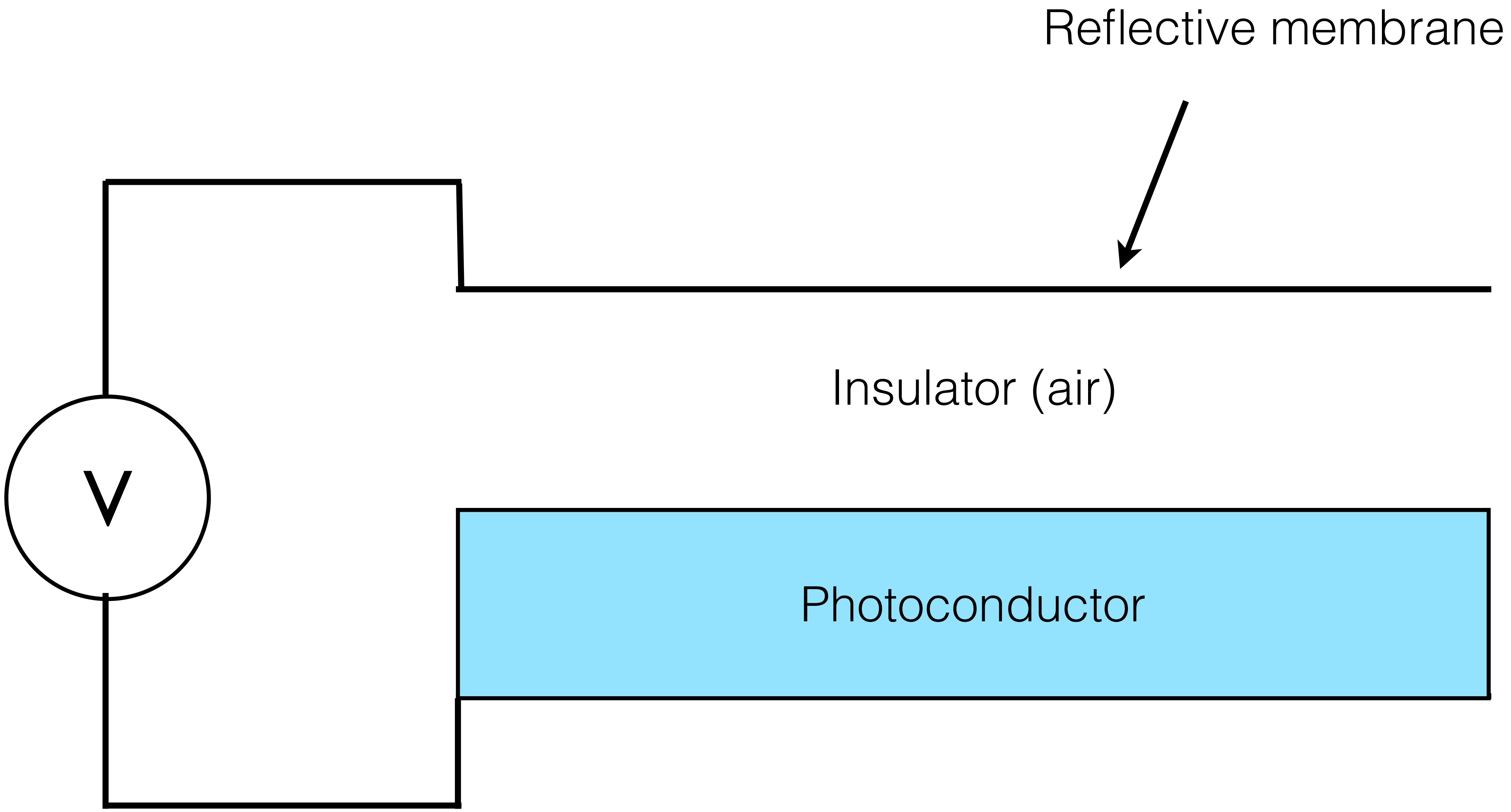
S. Bonora, *Apple. Phys. Lett,* 2010

Devices of 1” have been developed so far

Just a few examples in the literature

Photo Controlled Deformable Mirrors

How does a PCDM work?



Reflective membrane

Insulator (air)

Photoconductor

Photo Controlled Deformable Mirrors

How does a PCDM work?

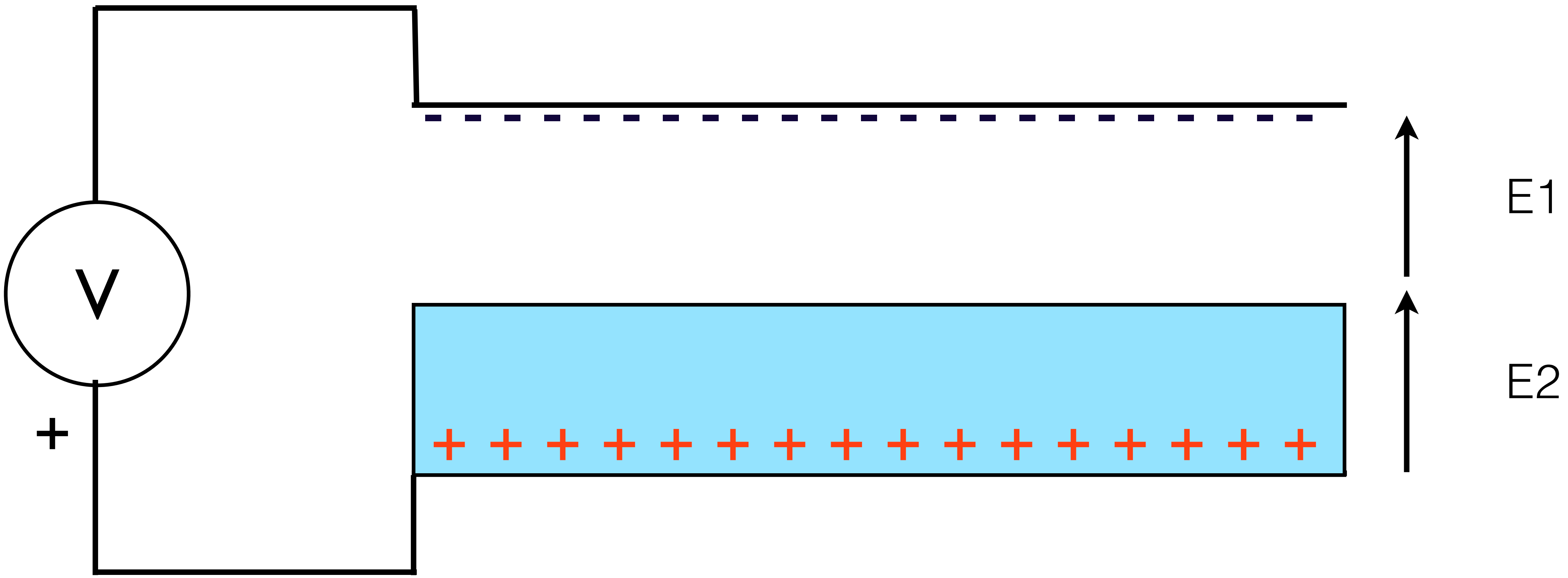


Photo Controlled Deformable Mirrors

How does a PCDM work?

electrostatic pressure $P_{el} = \frac{1}{2}\varepsilon_0\varepsilon_r E_1^2$ → membrane displacement M

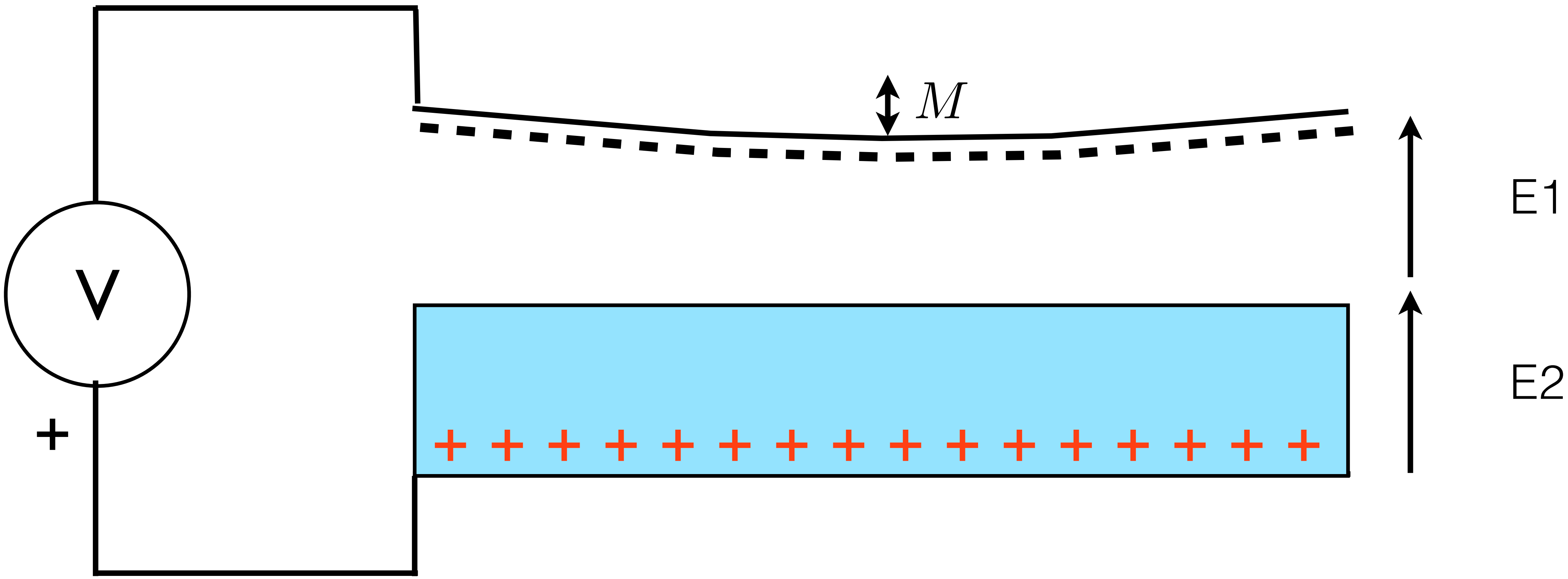
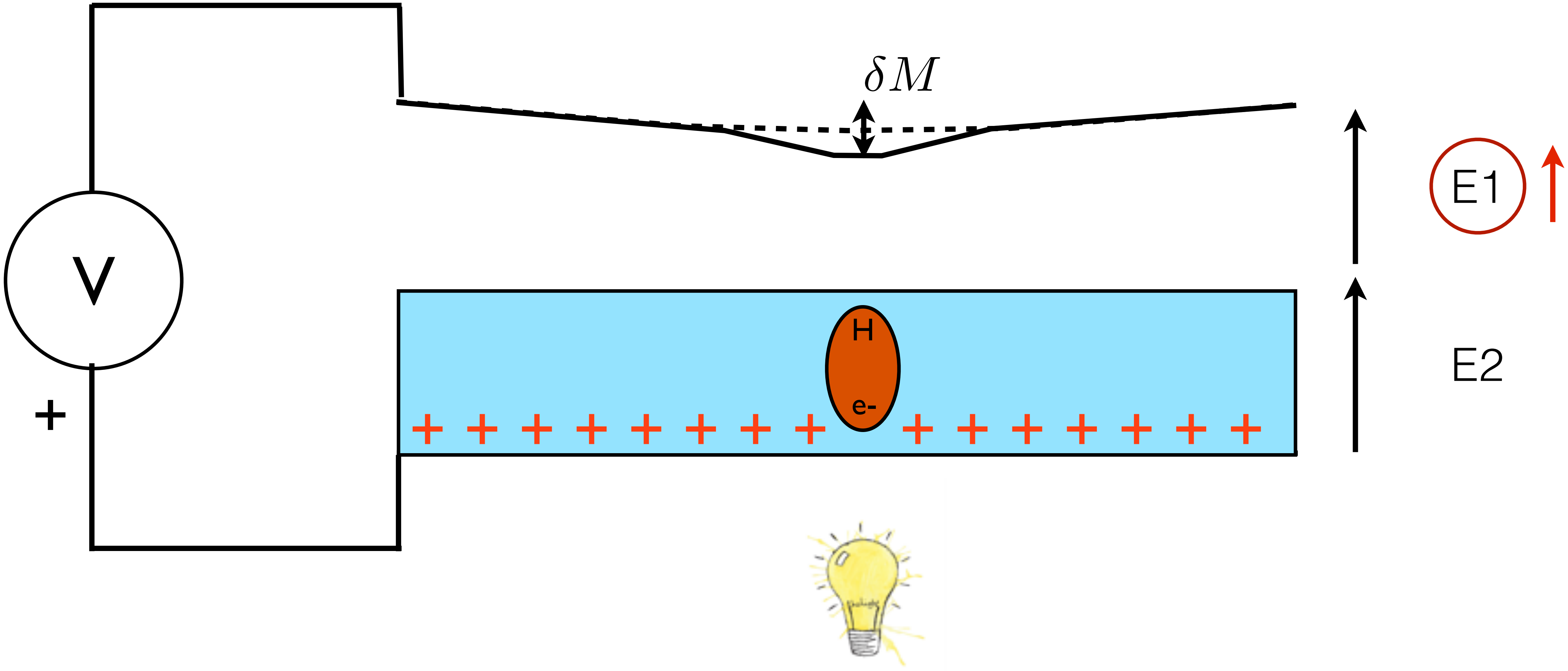


Photo Controlled Deformable Mirrors

How does a PCDM work?

$$\Delta P_{el} = \frac{1}{2}\varepsilon_0\varepsilon_r(\Delta E_1)^2 \quad \rightarrow \quad \delta M$$



PCDMs: material development

Descriptive model to correlate the material's properties to the performances

It is possible to determine the deformation from Pel, but what about Pel?

The surface deformation (M) is a complex function of many parameters

photoresponse
- absorption
- photogeneration
- photoconduction

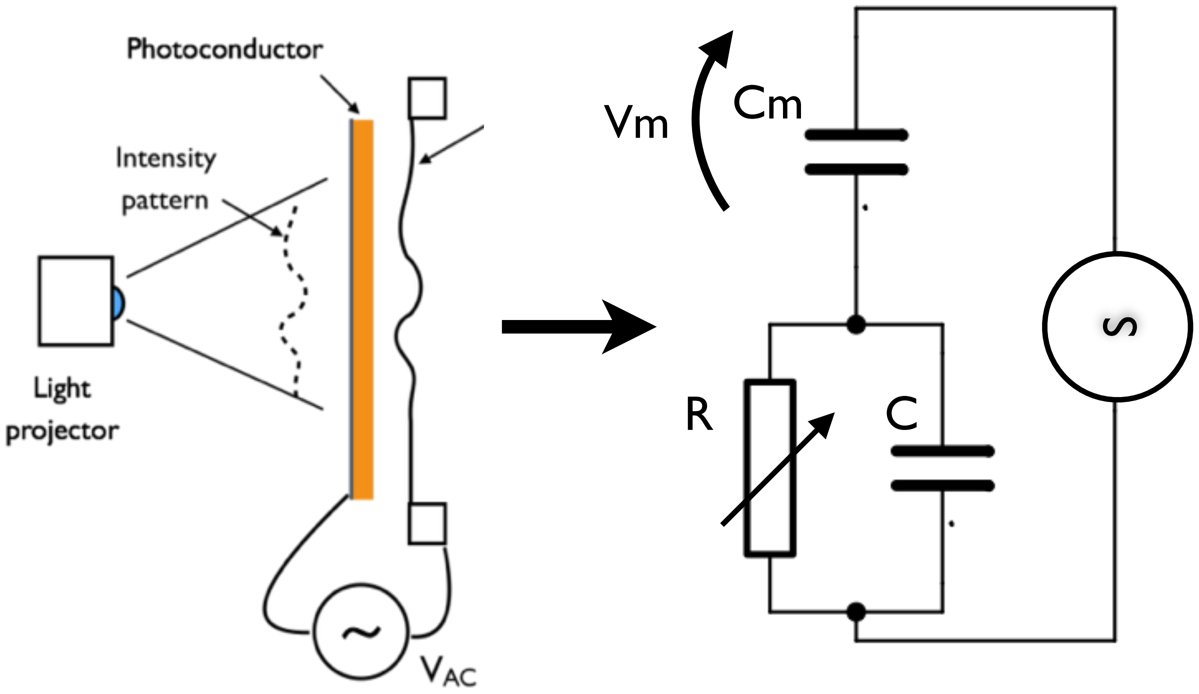
→ ΔP_{es} → Mechanical deformation δM

$$\delta M = f(\underbrace{V, \omega, I_{lum},}_{\text{external parameters}} \dots, \underbrace{d_1, d_2, A,}_{\text{geometrical parameters}} \dots, \underbrace{\varepsilon_1, \varepsilon_2, \mu, \alpha, \eta,}_{\text{opto-electronic properties}} \dots)$$

Materials matter, but we need a model!

PCDMs modeling: electric model

Electric model to correlate the material's properties to the performances



Characterized by:

Response time

$$\tau = \frac{\epsilon_m + \epsilon_p(L_m/L_p)}{\sigma_{light}(L_m/L_p)}$$

Dynamic range

$$\left|V_m^{light}\right| / \left|V_m^{dark}\right| = \left| \frac{\sigma_{light}/\epsilon_p + i\omega}{\frac{\sigma_{light}(L_m/L_p)}{\epsilon_e+\epsilon_p(L_m/L_p)} + i\omega} \right|$$

Conductance in photoconductors

quantum efficiency

lifetime

irradiance

mobilities

$$\sigma_{light} = \frac{\eta\tau_c I(\mu_e + \mu_h)\mathrm{e}}{\mathrm{h}\nu L_p}$$

Both strongly depend on the photoconductor properties!

high μ → short response time

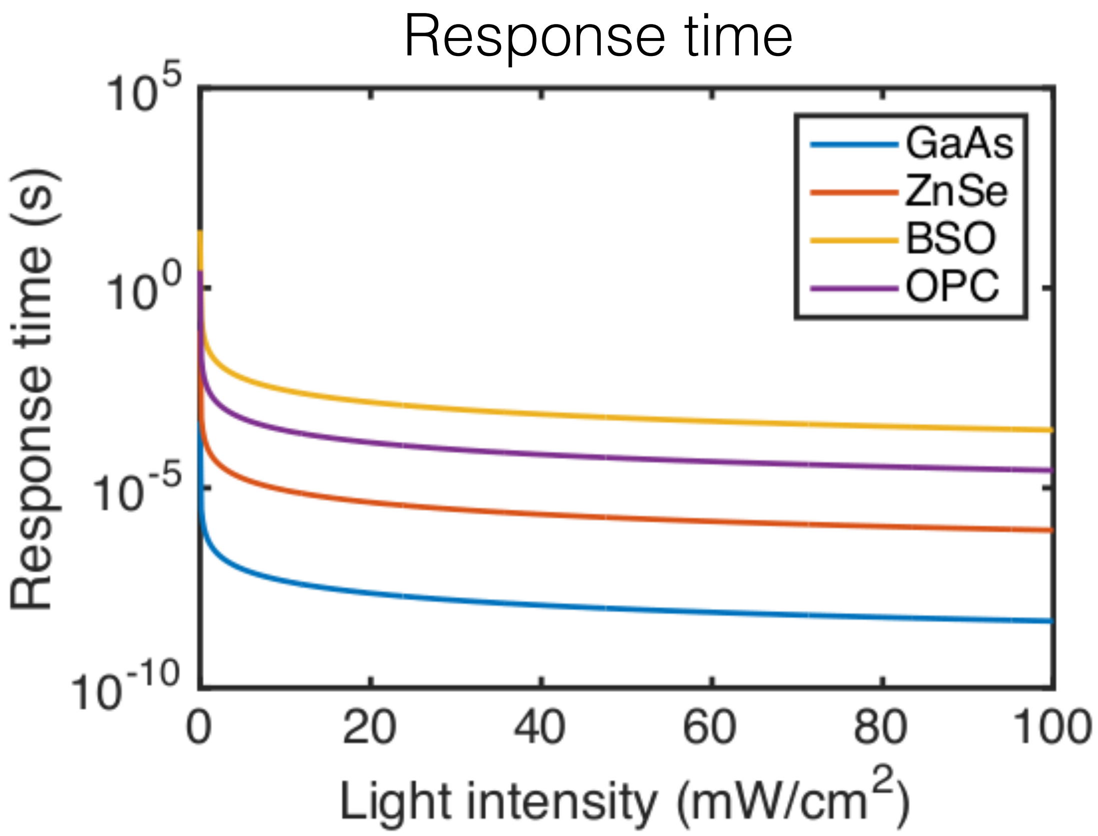
photoconductor thickness

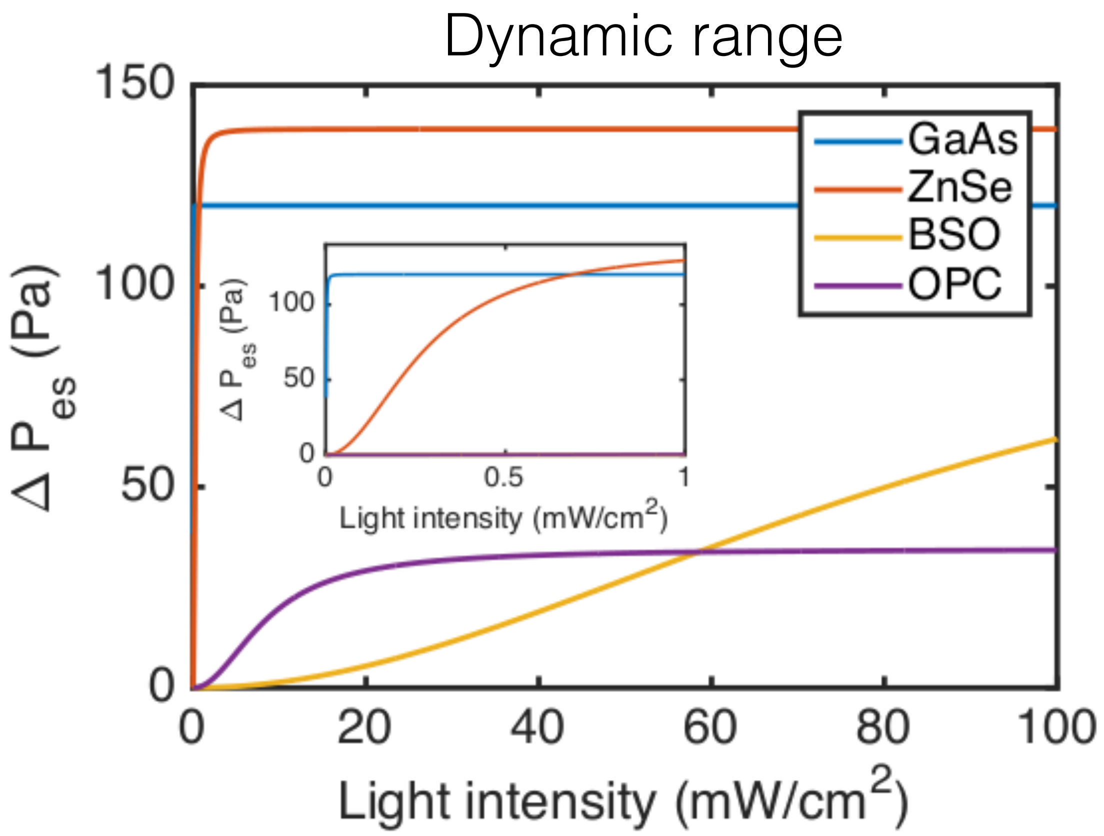
high $\frac{L_p}{\varepsilon}$ → large dynamic range

PCDMs electric simulation

Electric model: comparison between different materials

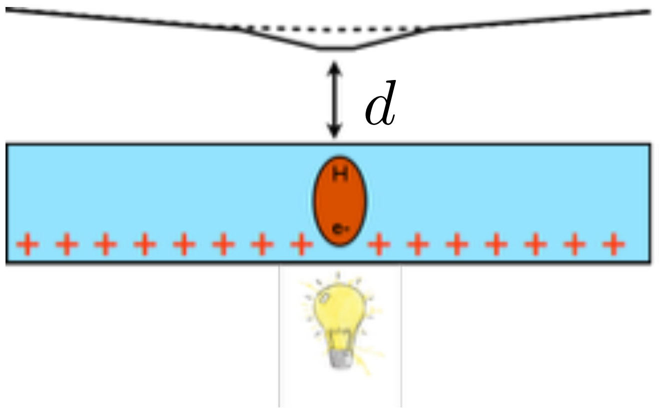
photoconductor	ε_R	cutoff λ (nm)	μ (cm^2/Vs)	d_{typ} (mm)	∅ (mm)	μ/ε_R	Lp/ε_R
BSO	55	390	3.5	2	30	0.06	0.03
GaAs	13	870	8500	0.5	100	650	0,04
ZnSe	9	460	540	2	100	54	0,22
OPCs	~4	visible	10^{-8}	10^{-2}	1000	10^{-8}	10^{-2}





PCDMs: multi physics modeling

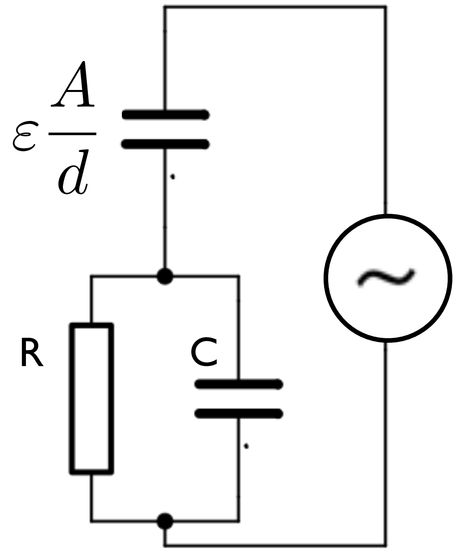
Membrane displacement affects the electric properties of the PCDM



d cannot be considered fixed!

Poisson equation

$$\nabla^2 M = -\frac{\varepsilon}{2T}\frac{V^2}{d^2}$$



$$Cm = \varepsilon\frac{A}{d}$$

Finite-differences iterative method on a circular domain

The model considers physical limitations of the device:

- pull-in threshold
- dielectric breakdown threshold

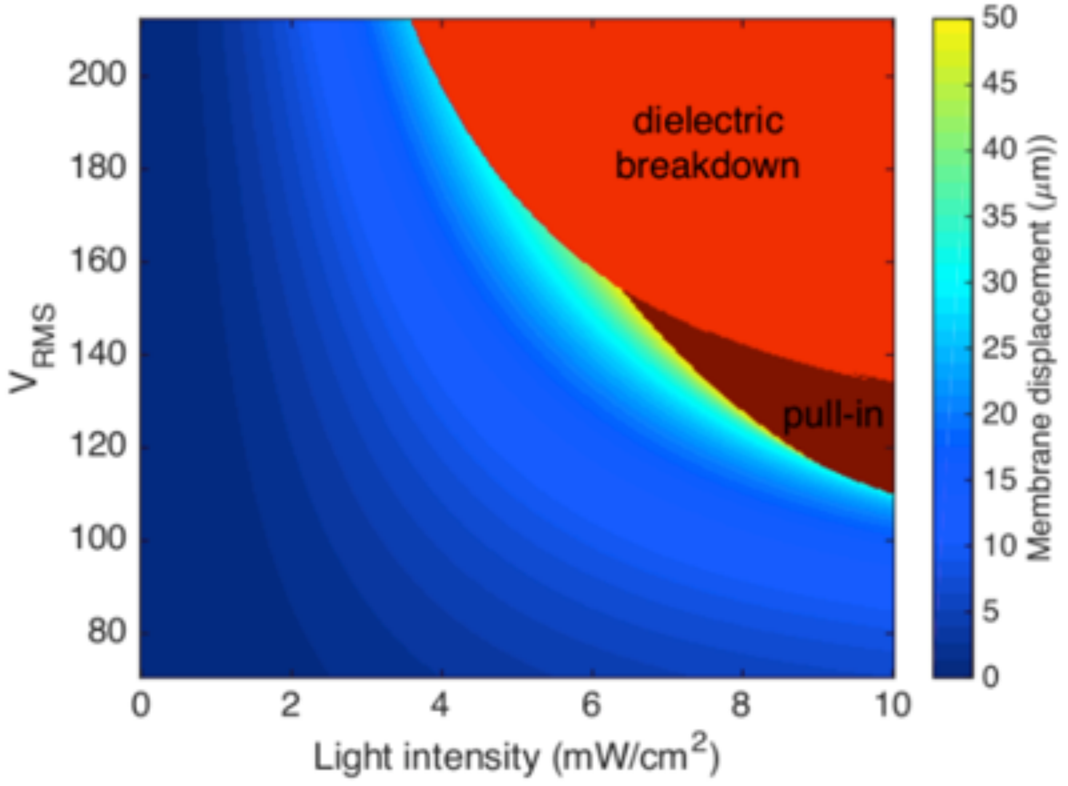
↓

Identification of a safe working zone

Realistic description for large displacements

Response to arbitrary light patterns

Simulation of a 1” dameter ZnSe PCDM @100 Hz



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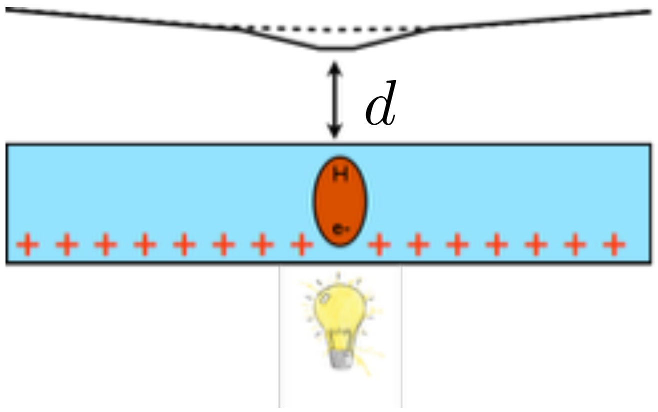

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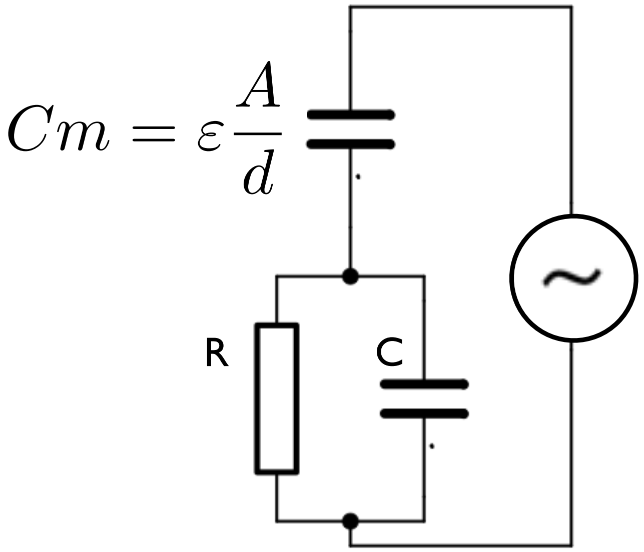
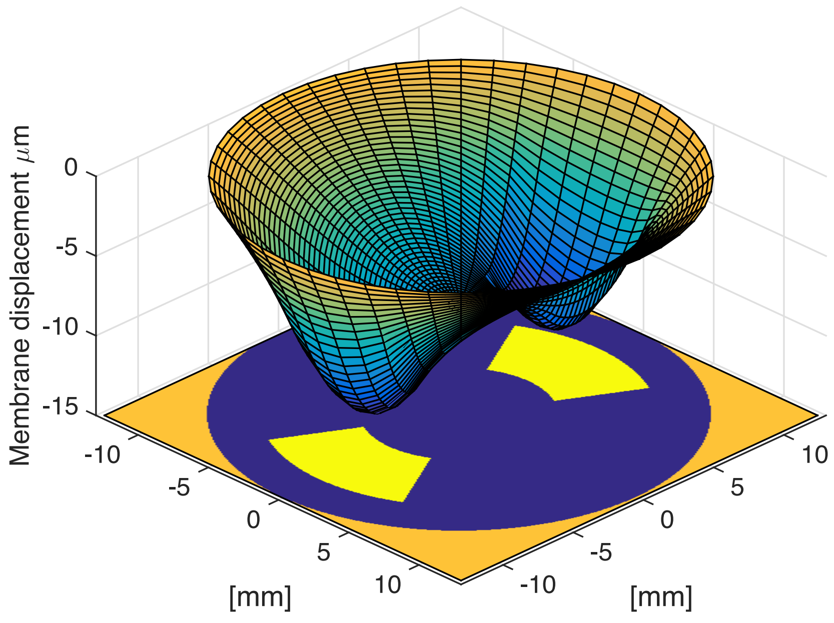
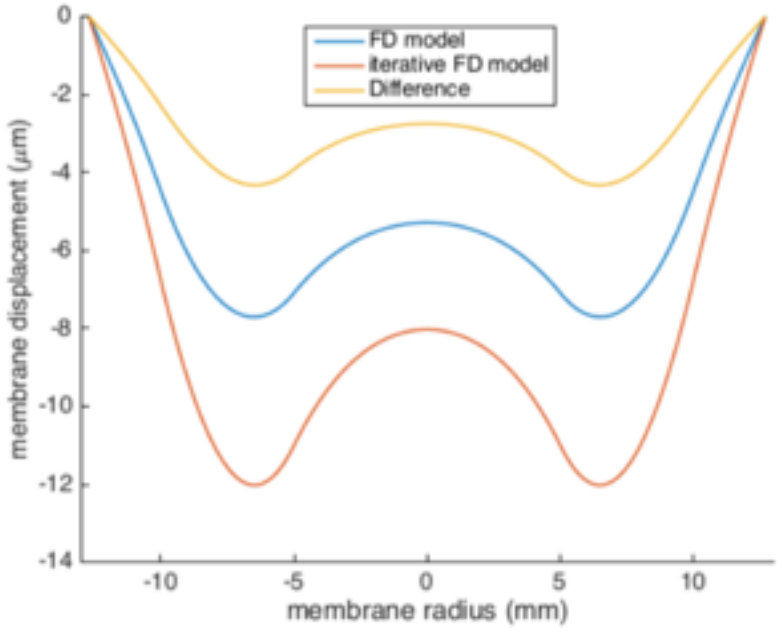


$$Cm = \varepsilon \frac{A}{d}$$

Response to arbitrary light patterns



High accuracy



M. Quintavalla, S. Bonora, D. Natali, A. Bianco, Photo Controlled Deformable Mirrors: materials choice and device modeling, *Opt. Mat. Expr.* (accepted)

Materials choice towards new devices

How can we choose among a lot of semiconductors?

A suitable photoconductor should have high D, high μ and low ε

But also:
suitable driving wavelength
suitable dimension
…

photoconductor	ε_R	cutoff λ (nm)	μ (cm^2/Vs)	d_{typ} (mm)	∅ (mm)	μ/ε_R	Lp/ε_R
BSO	55	390	3.5	2	30	0.06	0.03
Si	12	1100	1500	0.5	300	125	0.04
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ZnSe	9	460	540	2	100	54	0,22
OPCs	~4	visible	10^{-8}	10^{-2}	1000	10^{-8}	10^{-2}

Large size Zinc Selenide substrates are easily available!

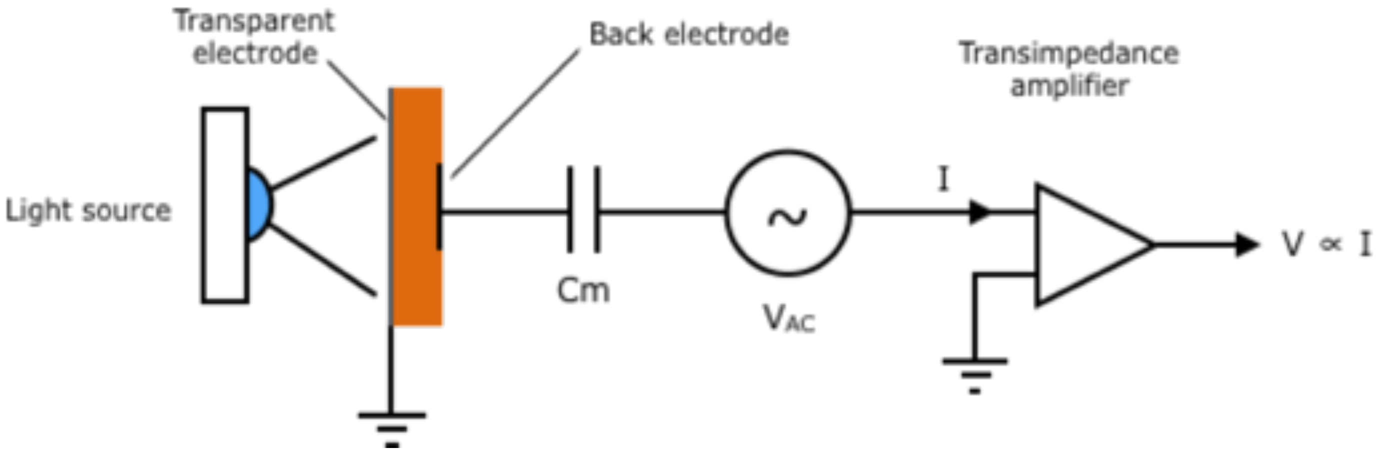
ZnSe-based PCDM: ZnSe characterization

We need some more info about the photoconductor

$$\sigma(I_{light}) = \frac{\boxed{\eta\tau_C} I_{light}(\mu_e + \mu_h)e}{h\nu D} = K \cdot I_{light}$$

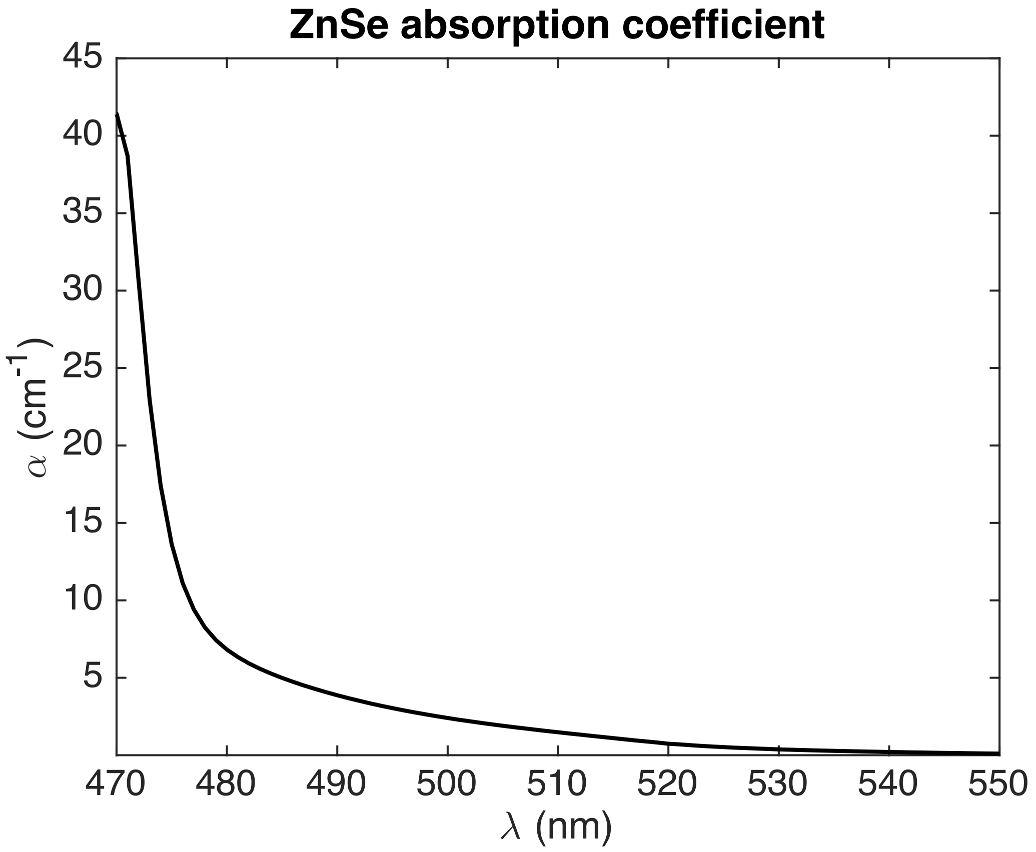
η = quantum efficiency (# of carriers per photon)
τ = charge carriers lifetime
μ = charge carriers mobility
ε = dielectric constant
D = photoconductor thickness

Setup that mimic the mirror to retrieve the photoconductor characteristics



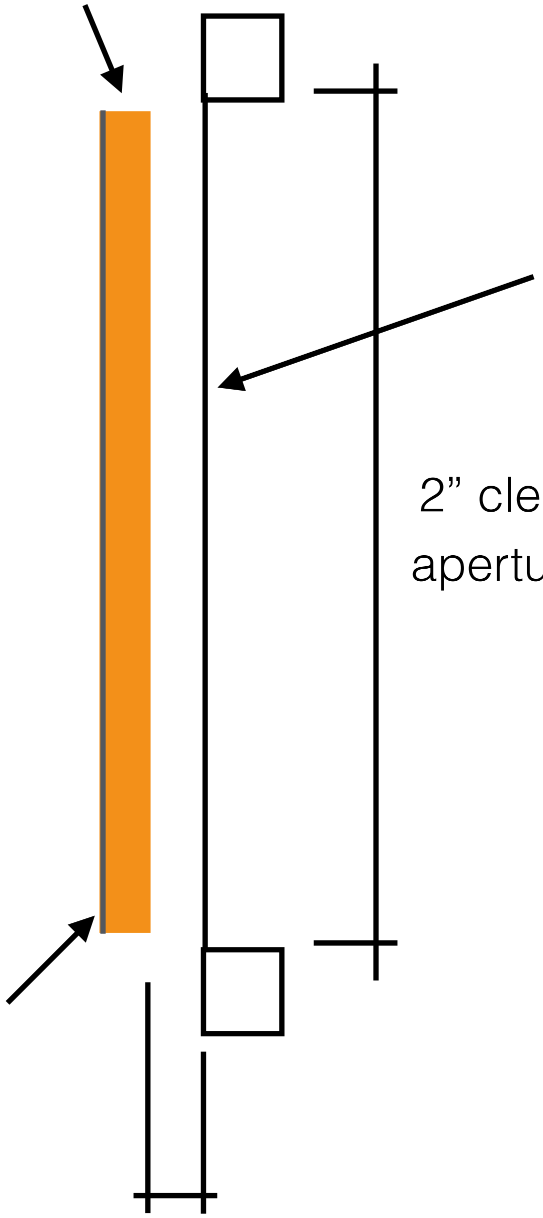
From current measurement we can determine:

- ZnSe resistance → $\eta\tau_C$
- Voltage bias on the membrane → deformation
- ZnSe best driving wavelength



2” ZnSe PCDM

Device realization: first 2” clear aperture PCDM



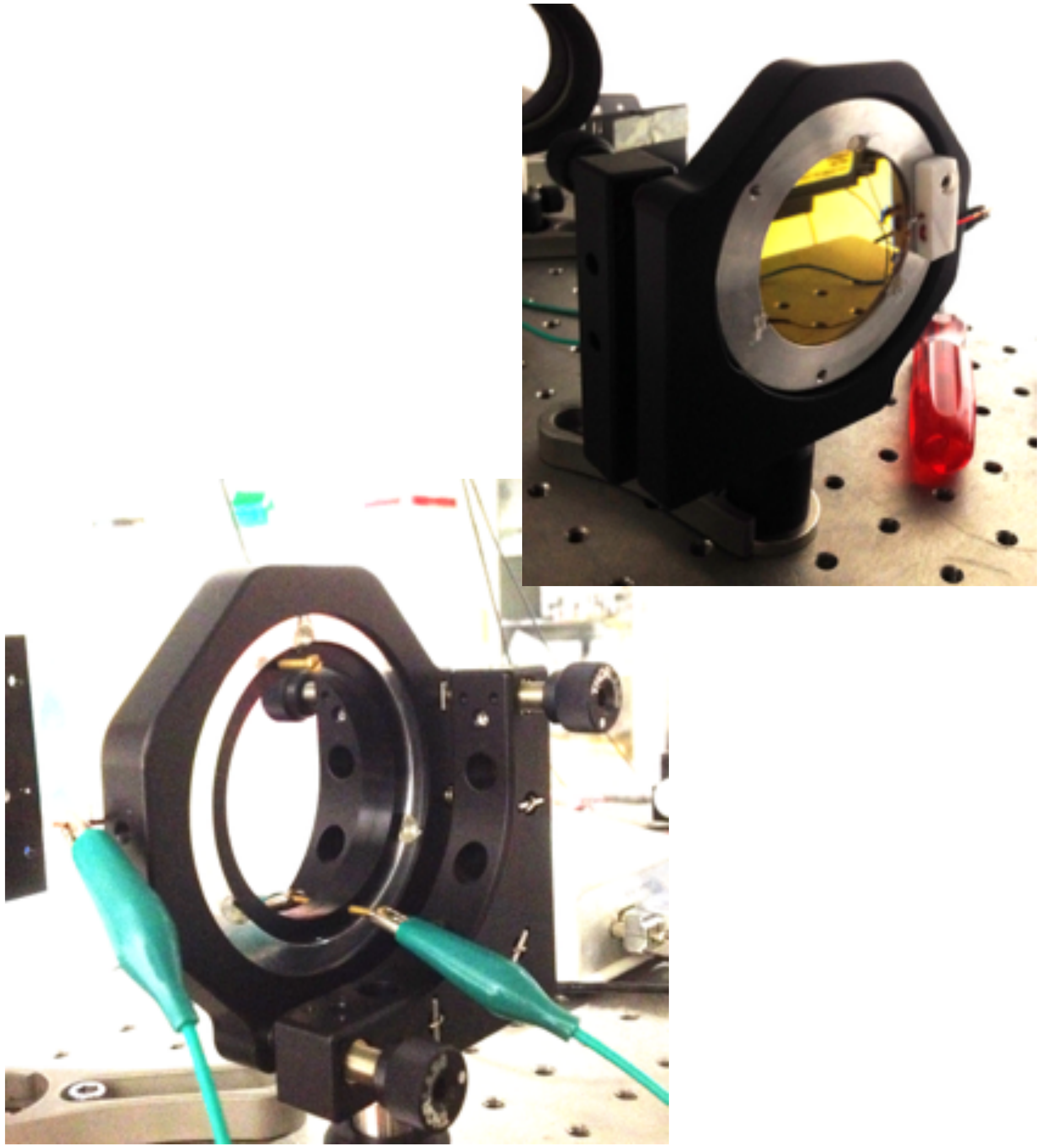
2”⌀ 2mm thick
ZnSe substrate

5 µm polymeric
membrane

2” clear
aperture

Transparent
ITO contact

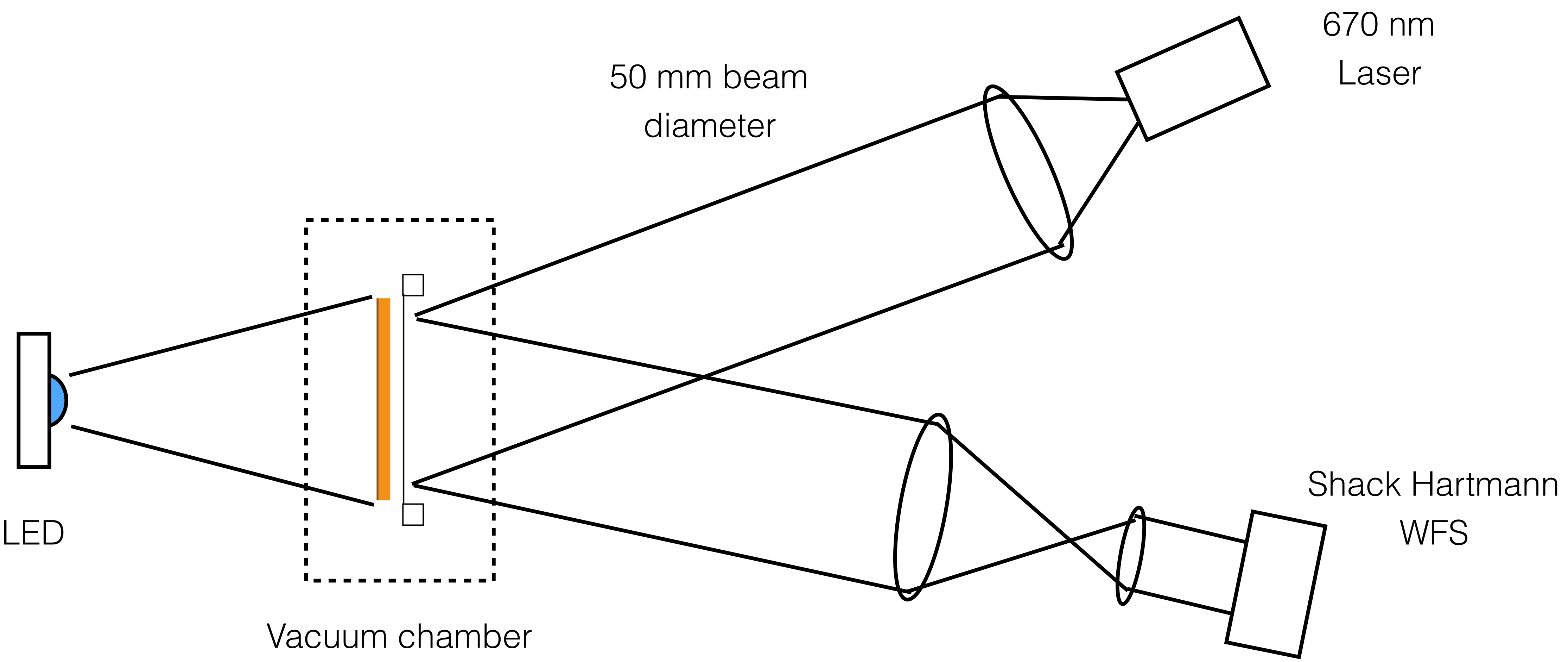
75µm



2” ZnSe PCDM: optical tests

1) Mirror deformation as function of light intensity, voltage and frequency

Uniform illumination

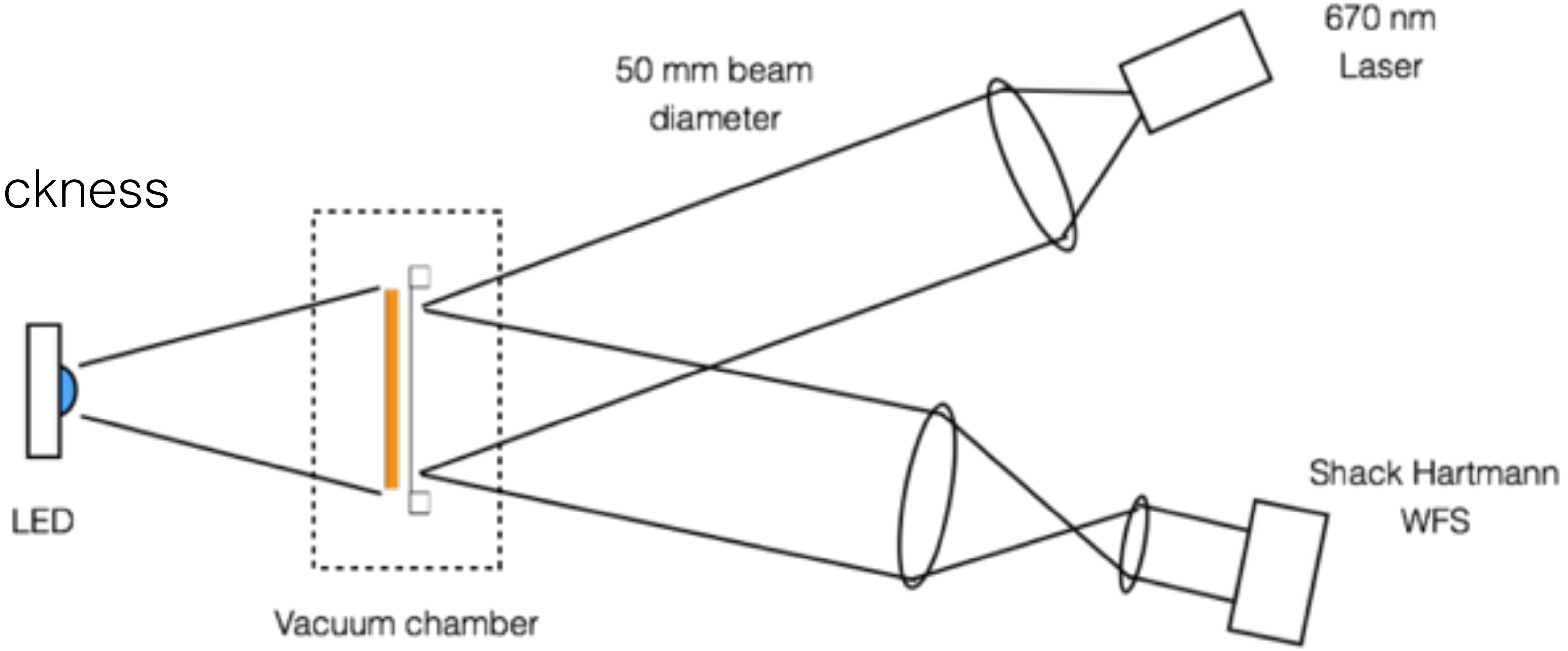


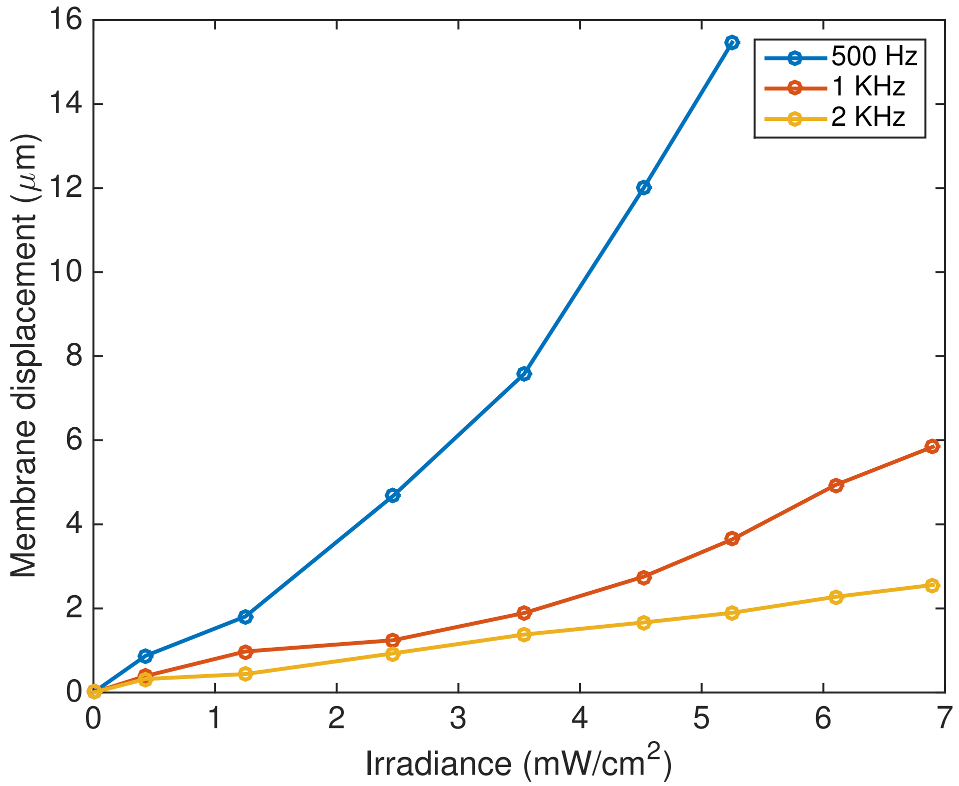
2” ZnSe PCDM: optical tests

1) Mirror deformation as function of light intensity, voltage and frequency

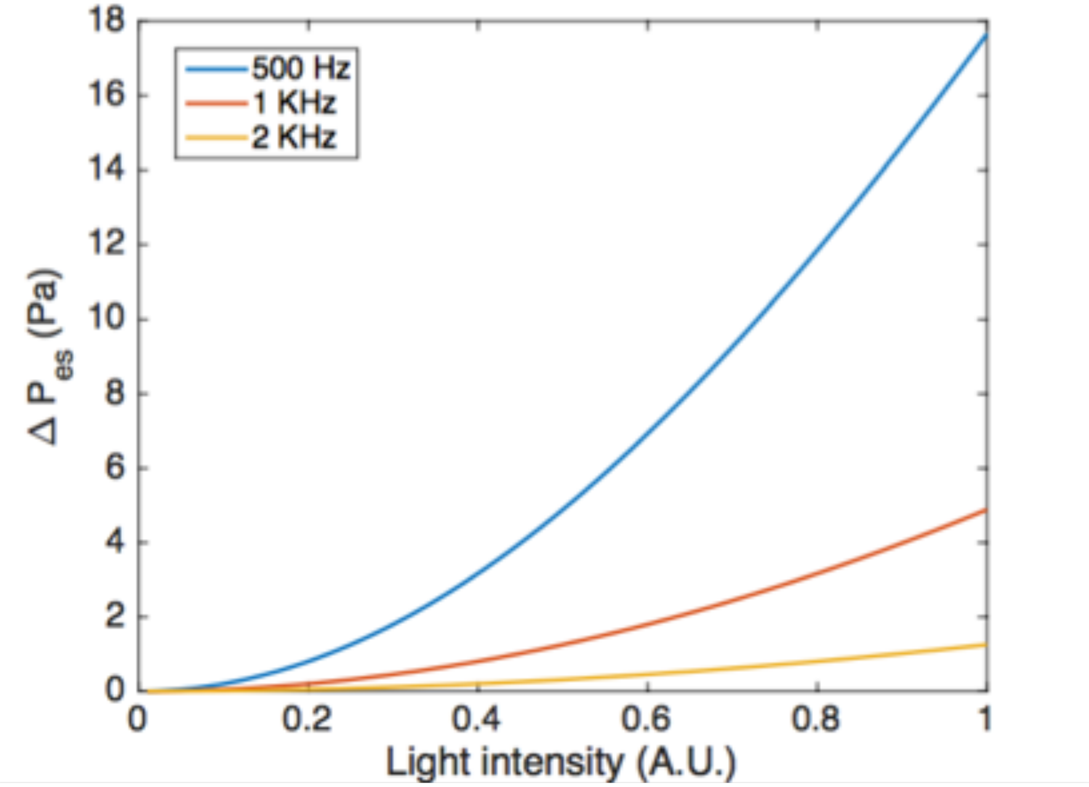
525 nm, 400 V_{pp}

Illumination through the whole thickness



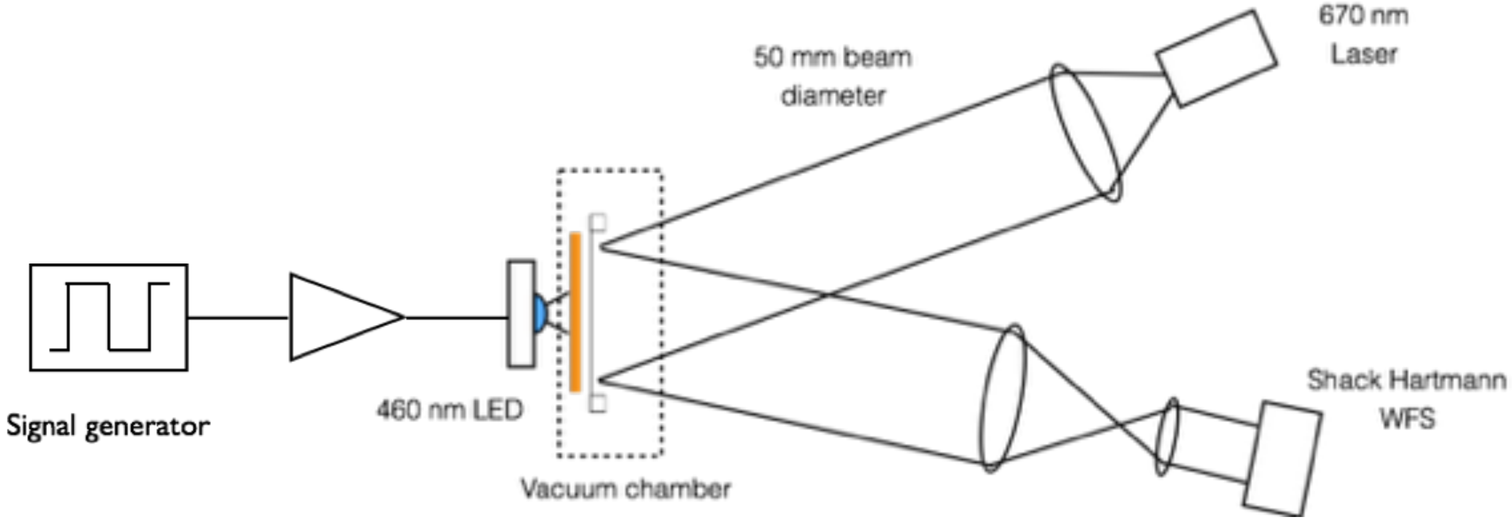


consistent with the model →

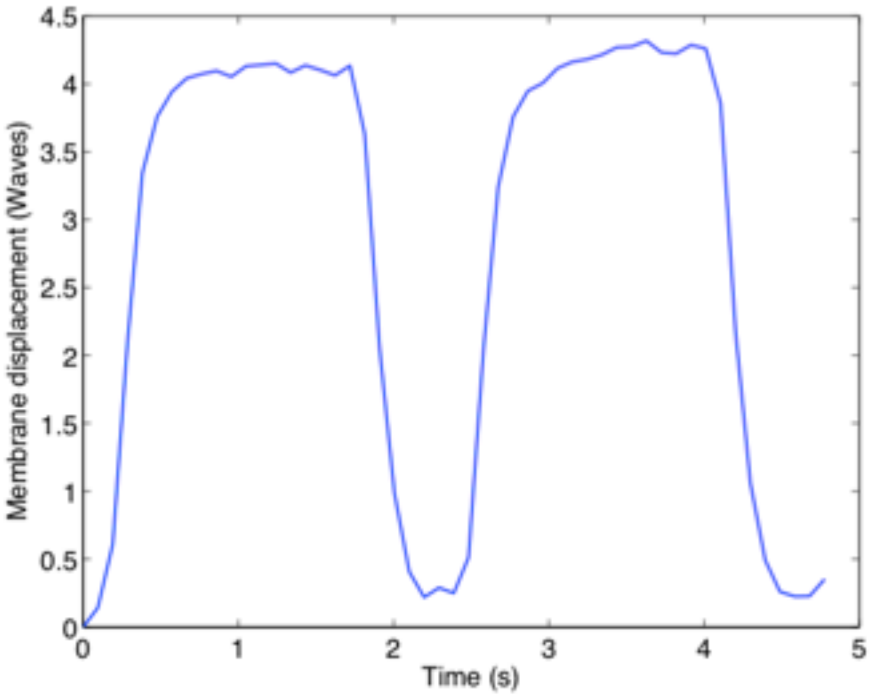


2” ZnSe PCDM: optical tests

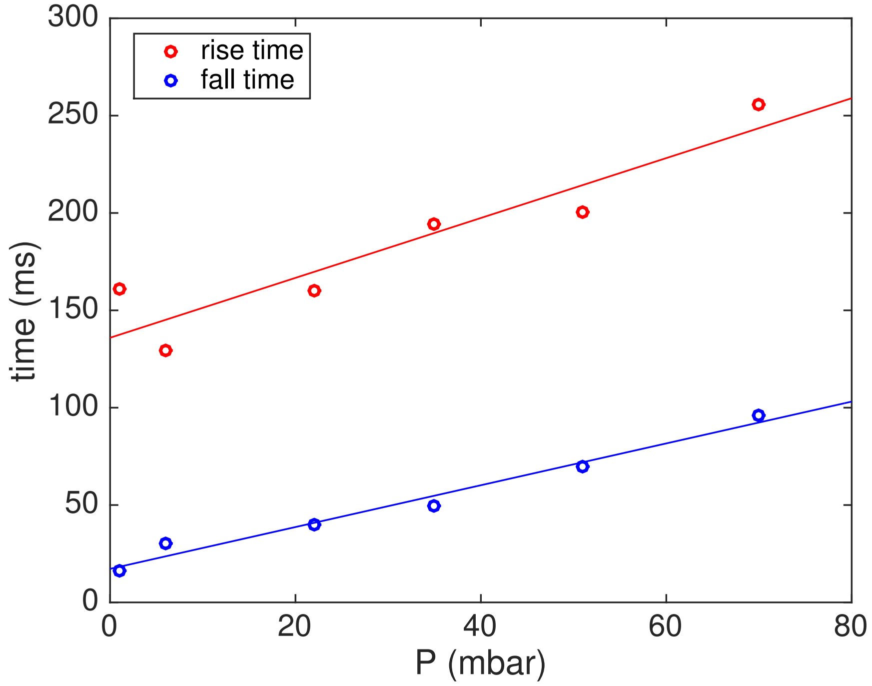
2) Measurement of the response time in air and in reduced pressure



525 nm, 400 V_{pp}, 500 Hz
response to light step in air ~ 0.3 s

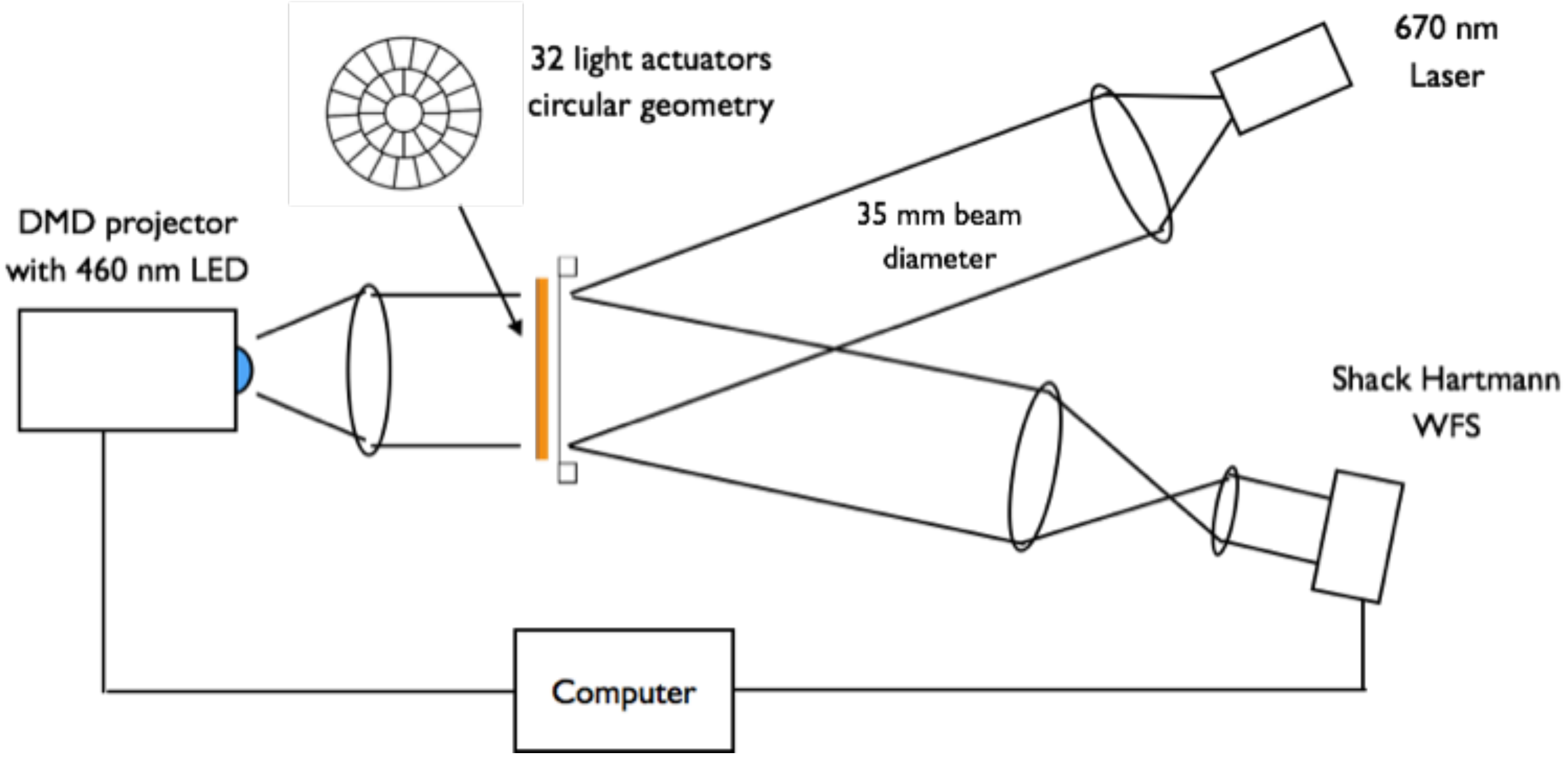


525 nm, 400 V_{pp}, 500 Hz
response to light step at low pressure

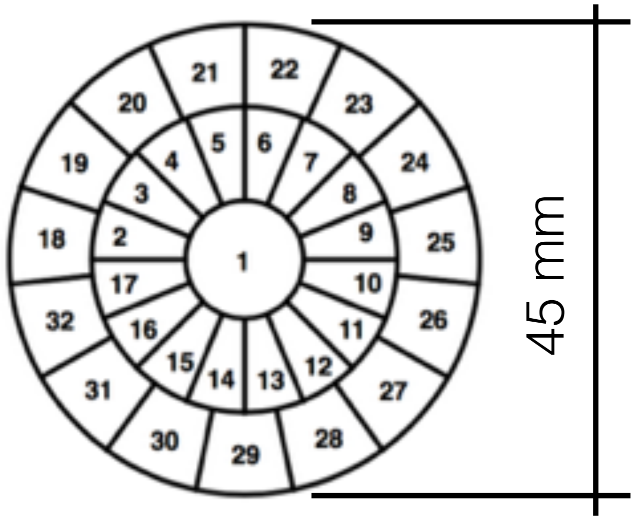


2” ZnSe PCDM: optical tests

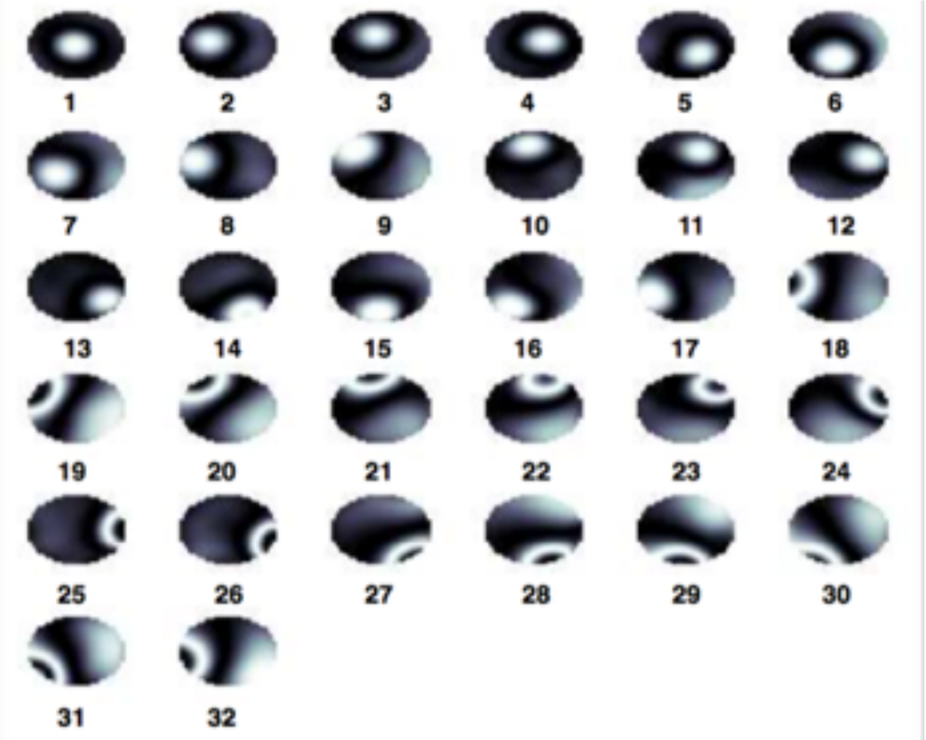
3) AO closed loop demonstration 400 Vpp, 500 Hz, correction speed 1 Hz



Actuation on an area that is smaller than the beam width to allow actuation at the periphery



AO loop influence functions



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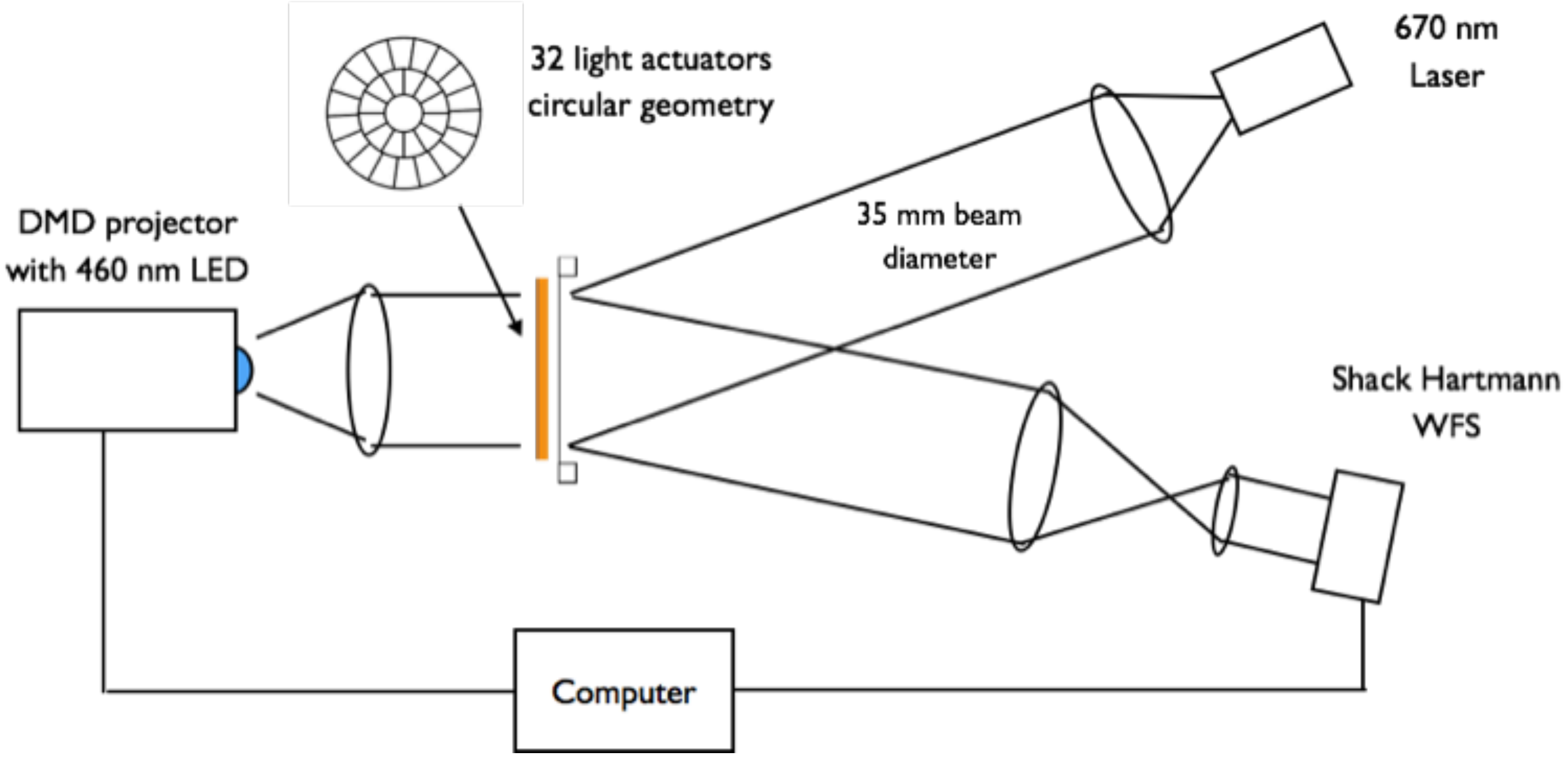

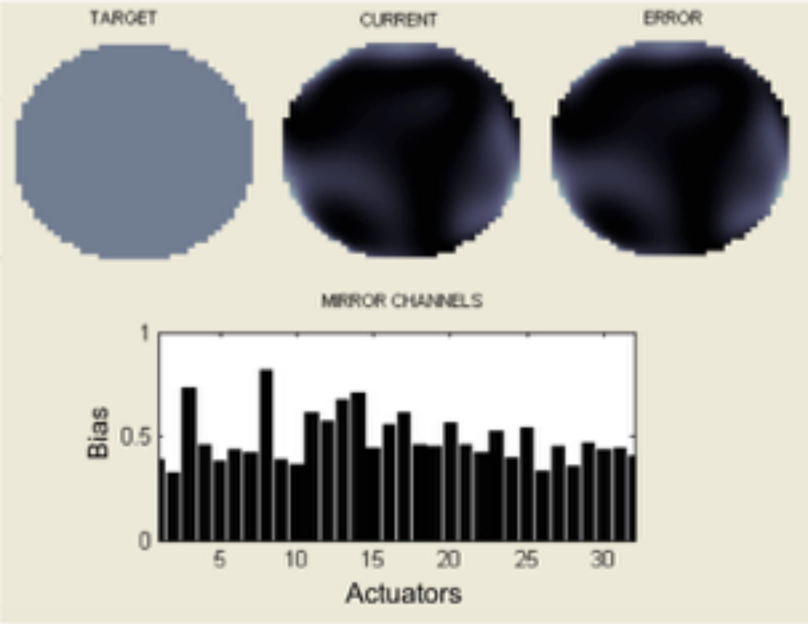

Example of maintenance of a **flat wavefront**

Accomplished within 0.015 waves (λ/65)

2” ZnSe PCDM: optical tests

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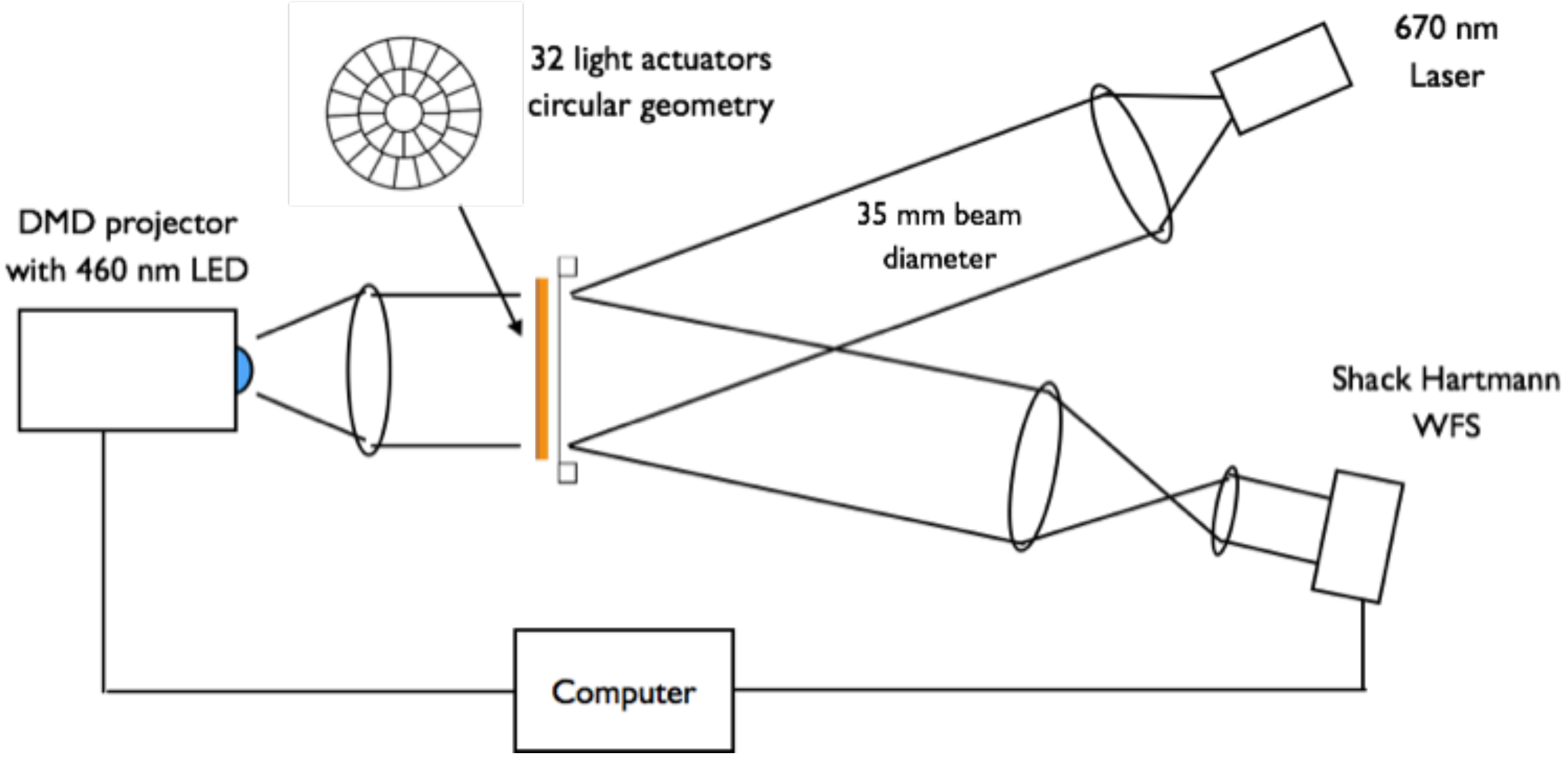
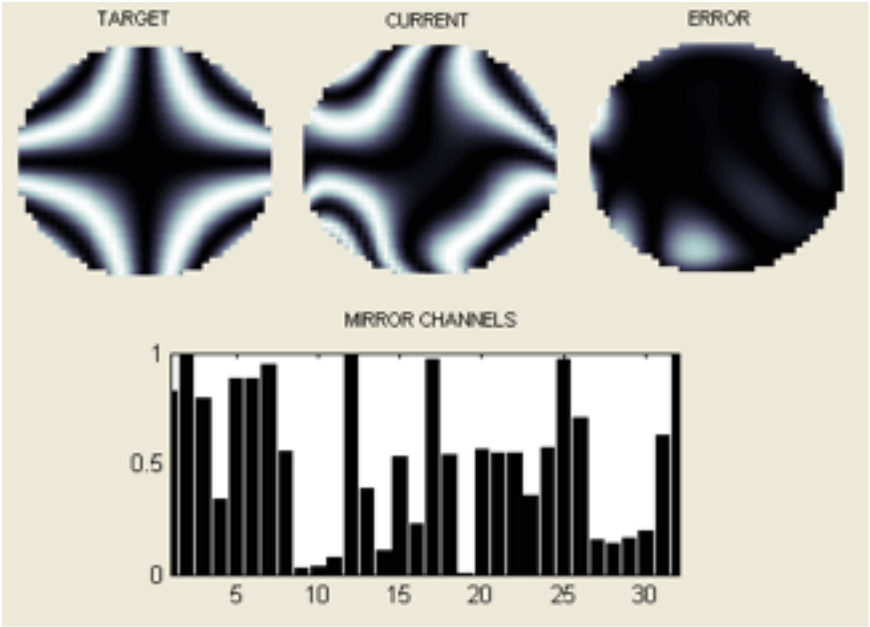


Example of **Zernike polynomials** generation



M. Quintavalla, S. Bonora, D. Natali, A. Bianco, Zinc selenide-based large aperture Photo Controlled Deformable Mirrors: *Opt. Lett.* (submitted)

Perspectives

- Achieve a complete model of the PCDM including the description of the dynamic behavior

- Obtain better mirror performances, in particular a quicker response to light stimuli

- Realize a PCDM with an aperture the range of 100 mm to approach the astronomical field