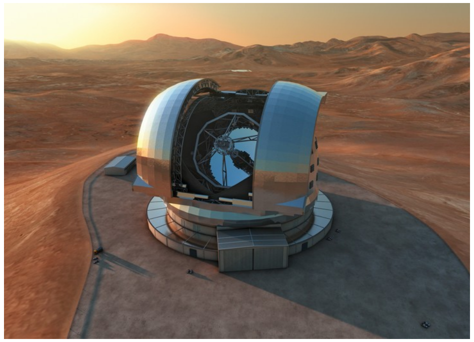
Phase prediction under Taylor hypothesis using zonal models in LQG AO control



Léonard PRENGÈRE[1,2]
Caroline Kulcsár[1],
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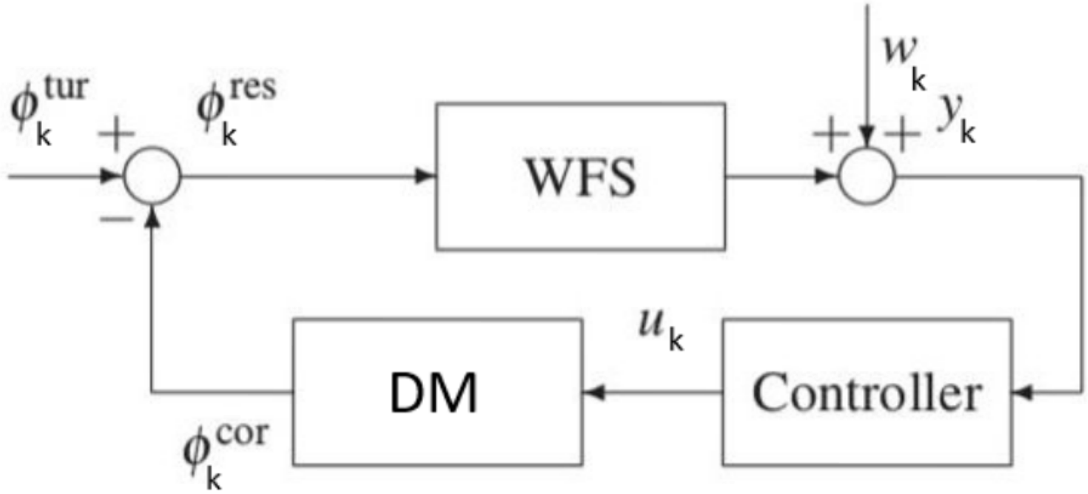
Jean-Marc Conan[2]

Affiliations:
[1]: Laboratoire Charles Fabry, Institut d'Optique Graduate School
[2]: ONERA, The French Aerospace Lab

High Performance control for AO systems



- Control loop delays:

  - WaveFront Sensor (WFS): Integration and read-out time

  - Controller: commands computation time

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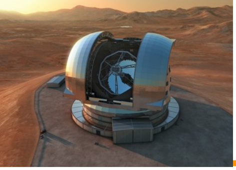

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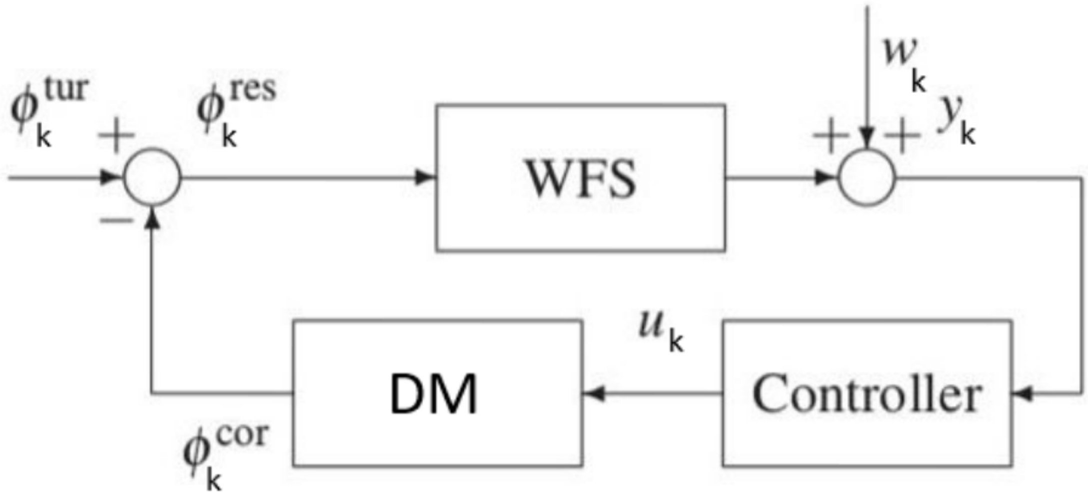

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Delays + High performance controller ⟶ Turbulent phase prediction

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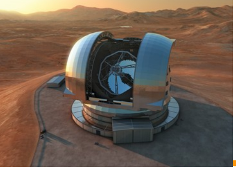

Turbulent Phase model

- For prediction:

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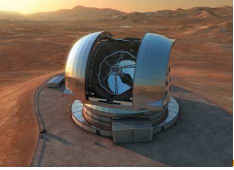
  Dynamical Phase models:

  → MULTILAYER ATMOSPHERE WITH FROZEN FLOW HYPOTHESIS



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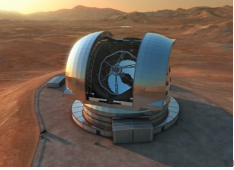
- Frozen Flow dynamical models in zonal basis: $$\boxed{\phi_{k+1} = h_{\mathrm{ff}} * \phi_k}$$



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  Well suited for highly parallelizable Distributed Kalman Filter (DKF) structure

Massioni & al, JOSAA 2011

Gilles & al, JOSAA 2013

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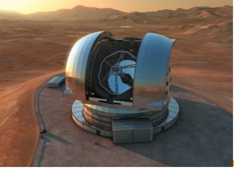

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Frozen Flow models in zonal basis: good candidate for Linear Quadratic Gaussian (LQG) regulators towards ELT scale AO systems

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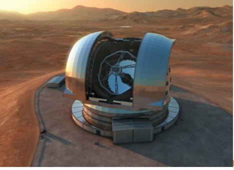
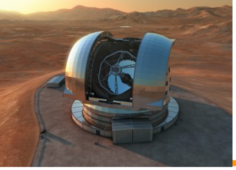


Outline

- Zonal basis sampling impact on Linear Quadratic Gaussian (LQG) Regulator
- LQG regulators using Frozen Flow hypothesis with edge compensation
- Performance comparison with others controllers



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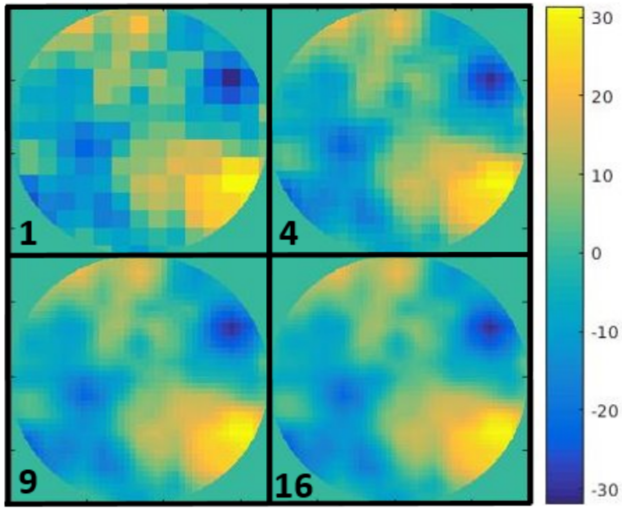

Sampling of one subaperture area	Strehl Ratio @ 1.65 µm
1 point / subaperture	42.2 %
4 points / subaperture	50.9 %
9 points / subaperture	51.7 %
16 points / subaperture	52.1 %

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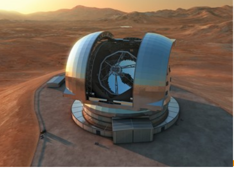

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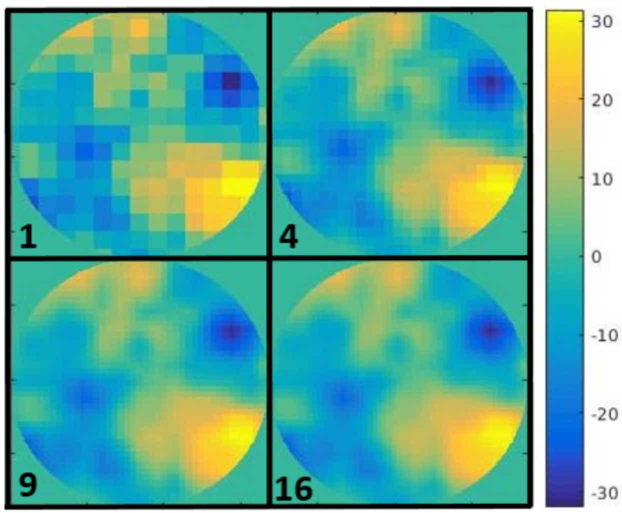

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- **Better sampling improves LQG controller performance**
- **4 points / subaperture enough to analyse performance**

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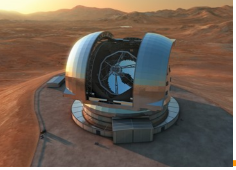

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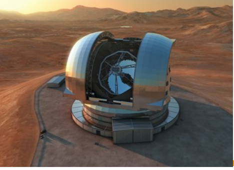
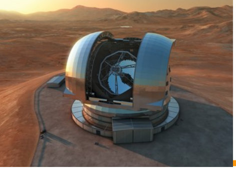


Taylor model with edge compensation

- Frozen Flow hypothesis on turbulent phase model:

$$\phi_{k+1} = h_{\mathrm{ff}} * \phi_k$$



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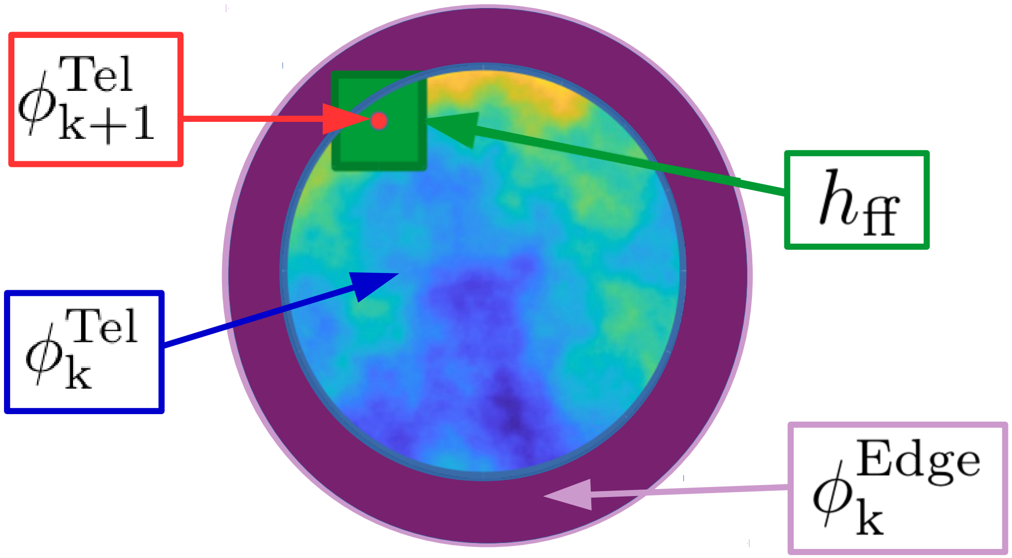

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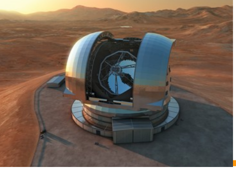

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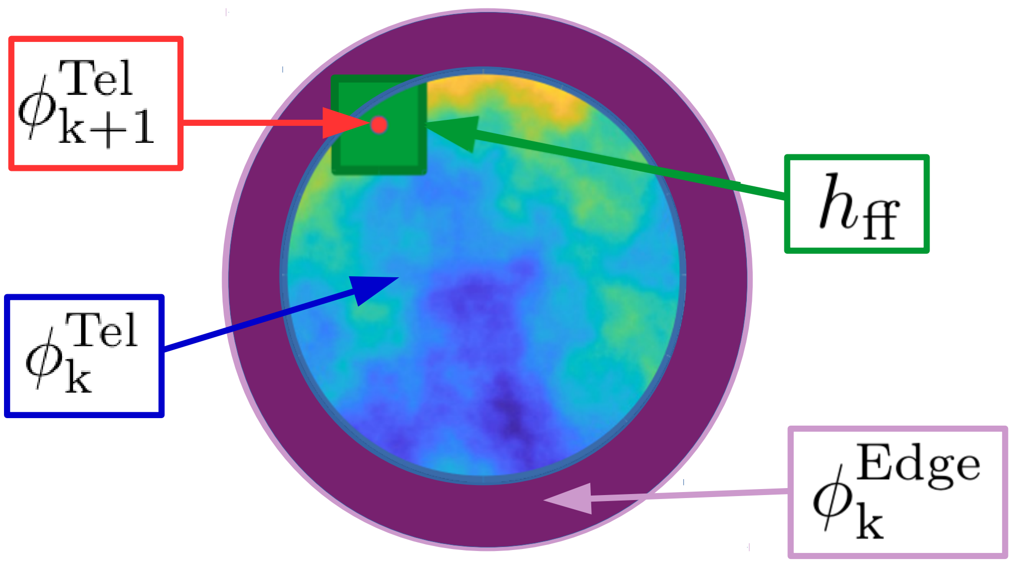
- Frozen Flow hypothesis on turbulent phase model:

$$\phi_{k+1} = h_{\text{ff}} * \phi_k \xrightarrow[\textit{IN THE TELESCOPE PUPIL}]{} \phi^{\text{Tel}}_{\text{k+1}} = A^{\text{Tel}}\phi^{\text{Tel}}_{\text{k}} + A^{\text{Edge}}\phi^{\text{Edge}}_{\text{k}}$$



A^{Tel}: Part of h_{ff} inside the telescope pupil

A^{Edge}: Part of h_{ff} outside the telescope pupil

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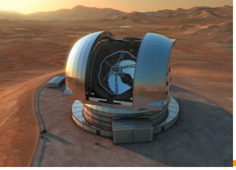

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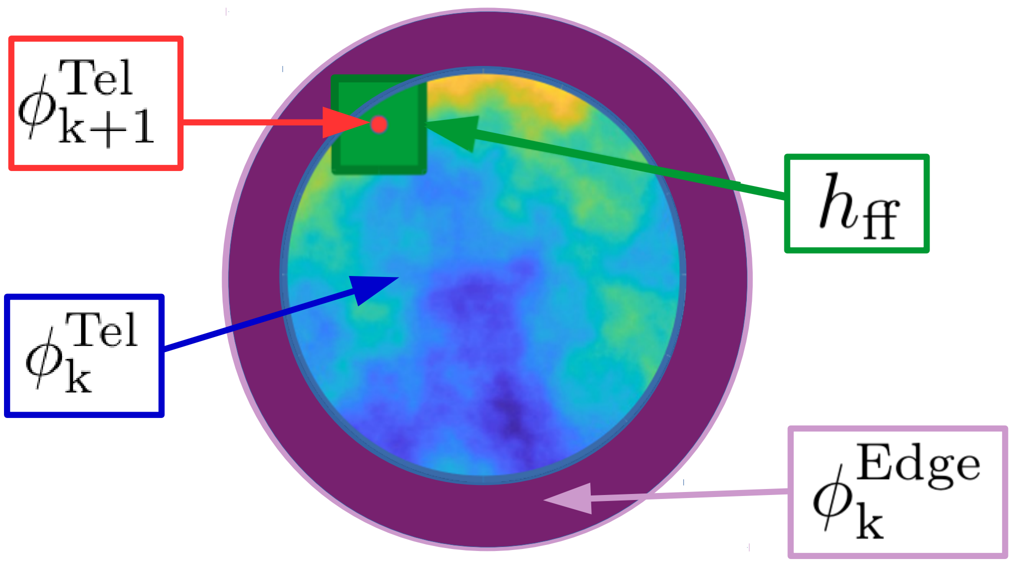

A^{Tel} : Part of h_{ff} inside the telescope pupil

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No points outside telescope pupil → ϕ^{Edge} ?

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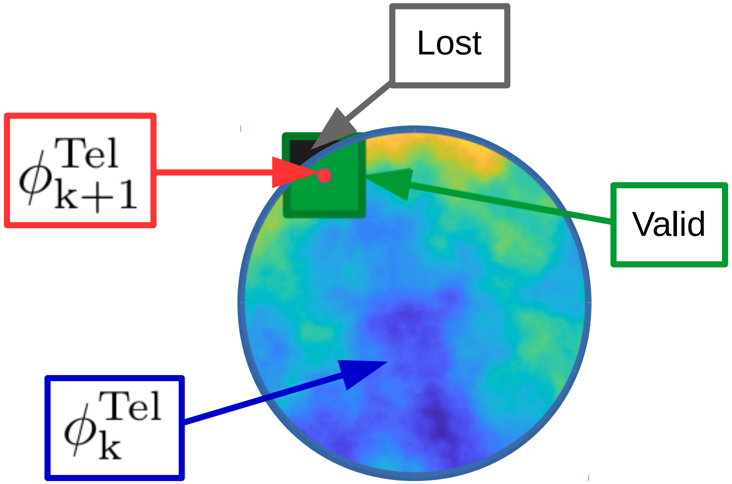
Taylor model with edge compensation

- **1st solution:**

No edge compensation $\phi_{\mathrm{k}}^{\mathrm{Edge}} = 0$



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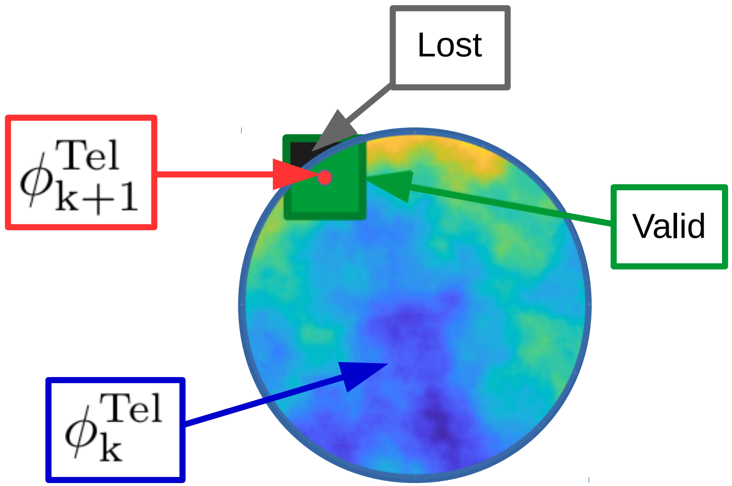

$$\phi_{\mathrm{k+1}}^{\mathrm{Tel}} = A^{\mathrm{Tel}} \phi_{\mathrm{k}}^{\mathrm{Tel}}$$

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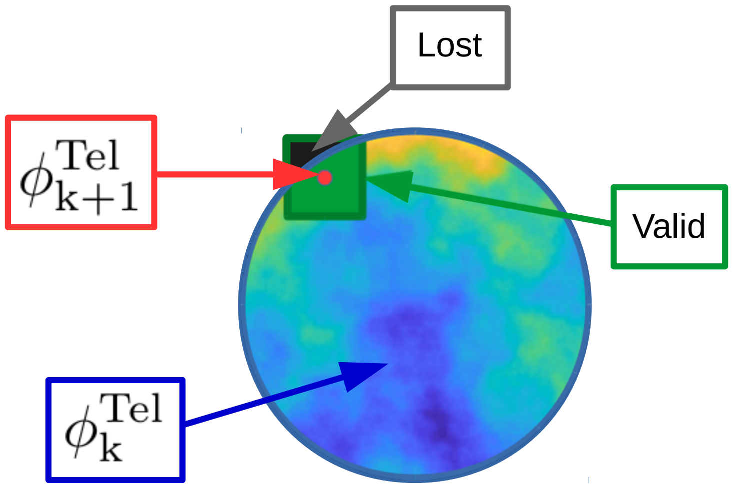

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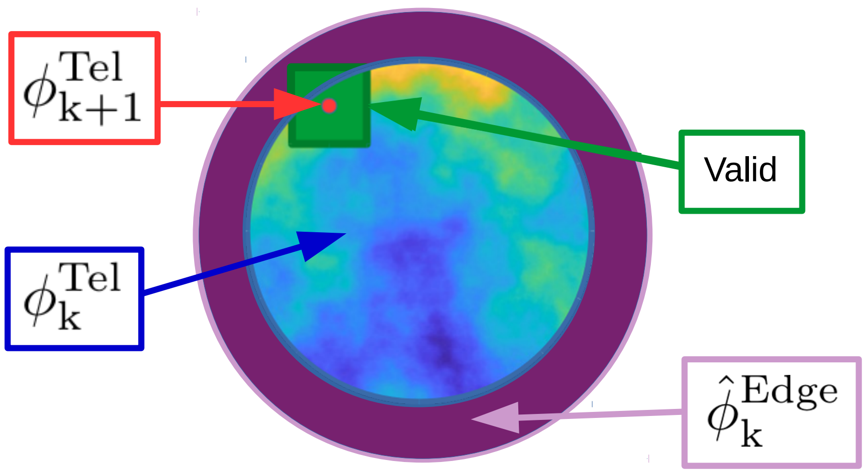
- **2nd solution:**

Static MAP estimation $\hat{\phi}_{\mathrm{k}}^{\mathrm{Edge}} = M^{\mathrm{Map}} \phi_{\mathrm{k}}^{\mathrm{Tel}}$

MAP very local, need few points of $\phi_{\mathrm{k}}^{\mathrm{Tel}}$



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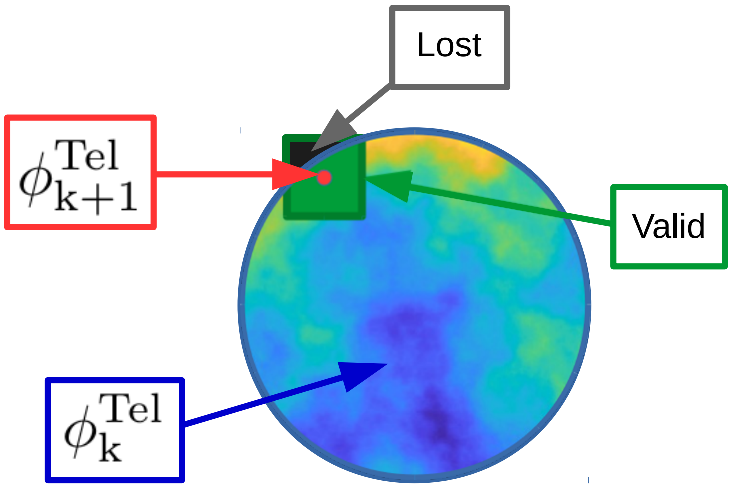

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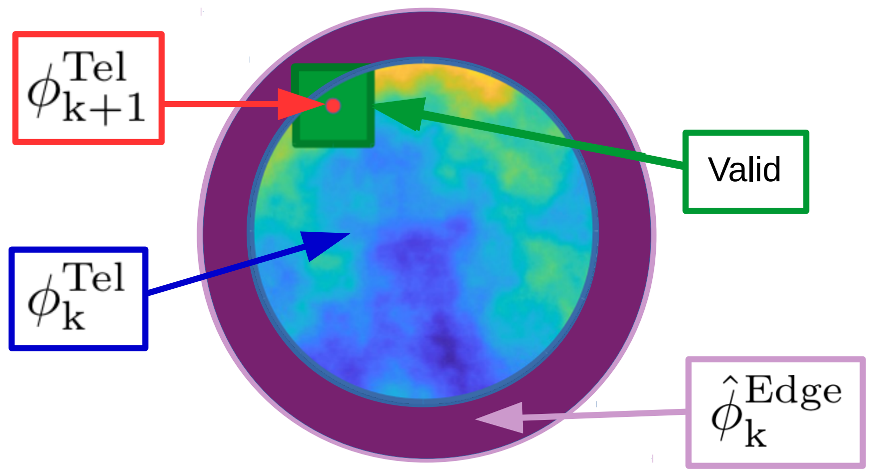

$$\boxed{\phi_{\mathrm{k+1}}^{\mathrm{Tel}} = (A^{\mathrm{Tel}} + A^{\mathrm{Edge}} M^{\mathrm{Map}}) \phi_{\mathrm{k}}^{\mathrm{Tel}}}$$

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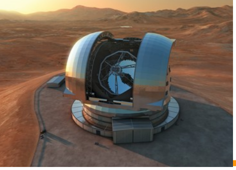

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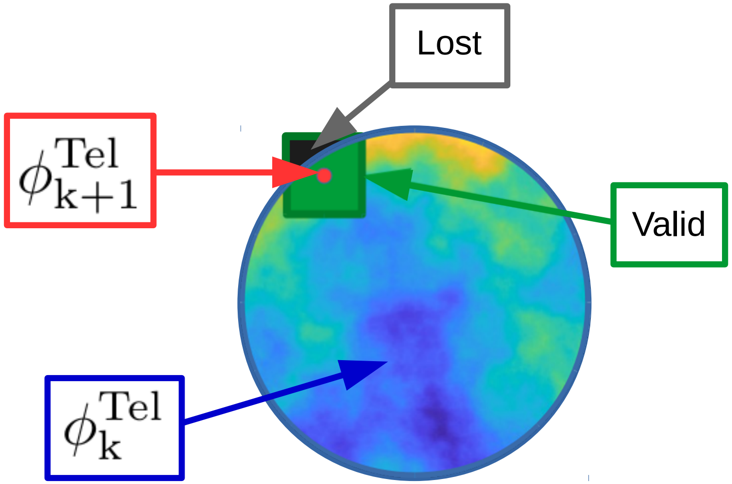

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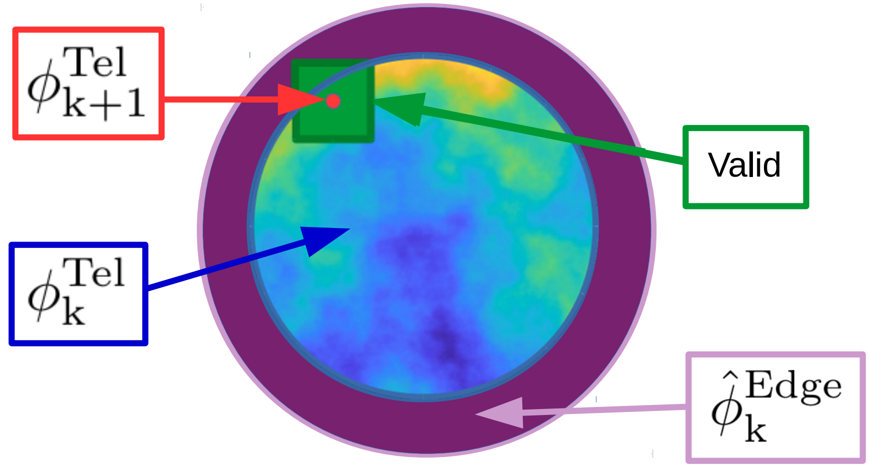

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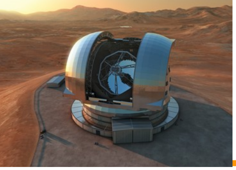
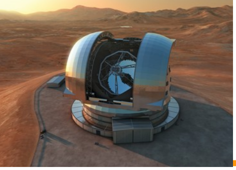
New dynamical model compensating edge degradation under Taylor hypothesis



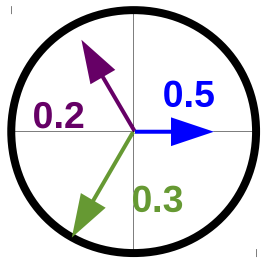
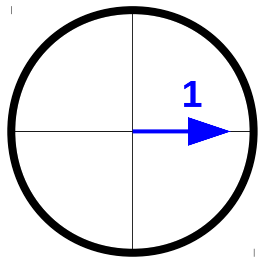
Atmosphere configuration

Simulations with different atmosphere configurations:



Atmosphere configurations

Simulations with different atmosphere configurations:

ATMOSPHERE BEHAVIOUR	BOILING (3 layers)			FROZEN FLOW (1 layer)
Cn2 Profile (%)	0.5	0.2	0.3	1
Wind Values (m/s)	7.5	12.5	15	10
Wind Direction (°)	0	120	240	0
REPRESENTATION				

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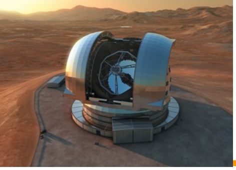
Performance with edge compensation

- VLT NAOS-like case: Diameter = 8m, 15 x 15 actuators grid, ASO SH 14 x 14 ml, 500 Hz

  Typical turbulence condition r0 = 0.1 m @ 0.55 µm

  Multilayer atmosphere reconstruction with LQG regulator



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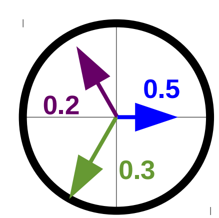
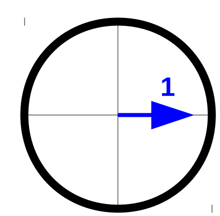
Strehl Ratio @ 1,65 µm:

Regulator & zonal basis sampling	Edge compensation	Atmosphere	
		Boiling	Frozen Flow
LQG, 4 points / subap area	none	52.5%	41.6%
LQG, 4 points / subap area	MAP	53.6%	56.2%





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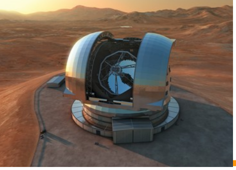

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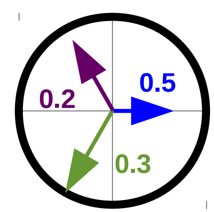

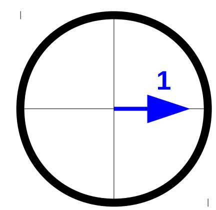

- **Strong degradation with pure Frozen Flow**
- **Edge compensation always effective**

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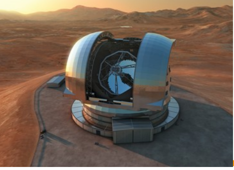

Outline

- Zonal basis sampling impact on Linear Quadratic Gaussian (LQG) Regulator
- LQG regulators using Frozen Flow hypothesis with edge compensation
- Performance comparison with others controllers

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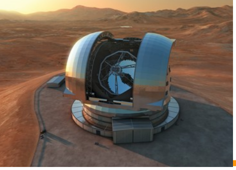
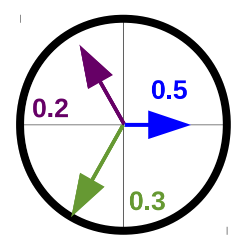


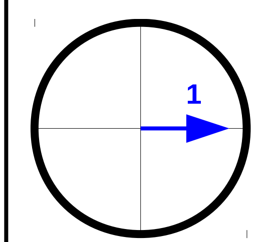
Atmosphere configuration

Simulations with different atmosphere configurations:

ATMOSPHERE BEHAVIOUR	BOILING (3 layers)		
Cn2 Profile (%)	0.5	0.2	0.3
Wind Values (m/s)	7.5	12.5	15
Wind Direction (°)	0	120	240



FROZEN FLOW (1 layer)
1
10
0



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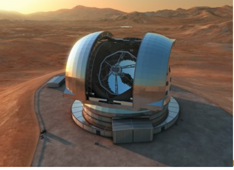
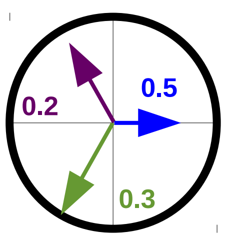
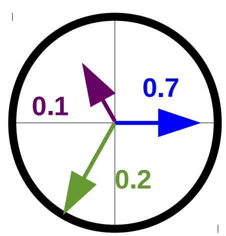


Atmosphere configuration

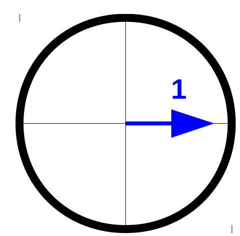
Simulations with different atmosphere configurations:

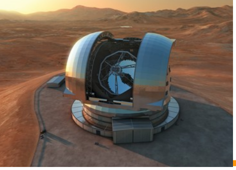
ATMOSPHERE BEHAVIOUR	BOILING (3 layers)			MAINLY BOILING (3 layers)		
Cn2 Profile (%)	0.5	0.2	0.3	0.7	0.1	0.2
Wind Values (m/s)	7.5	12.5	15	10	7	15
Wind Direction (°)	0	120	240	IDEM BOILING		





FROZEN FLOW (1 layer)
1
10
0

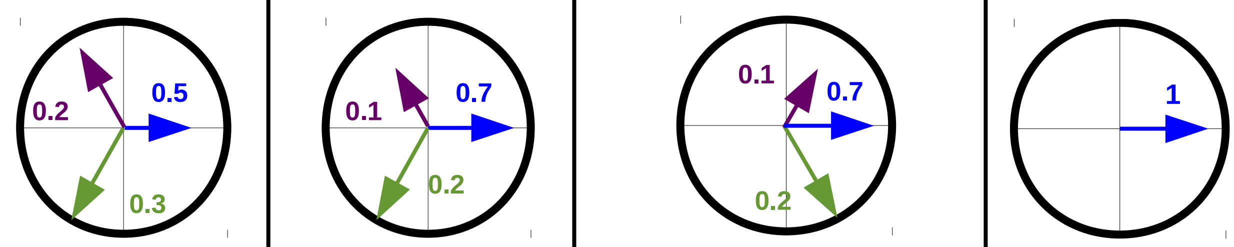




Atmosphere configuration

Simulations with different atmosphere configurations:

ATMOSPHERE BEHAVIOUR	BOILING (3 layers)			MAINLY BOILING (3 layers)			MAINLY FROZEN FLOW (3 layers)			FROZEN FLOW (1 layer)
Cn2 Profile (%)	0.5	0.2	0.3	0.7	0.1	0.2	IDEM MAINLY BOILING			1
Wind Values (m/s)	7.5	12.5	15	10	7	15	IDEM MAINLY BOILING			10
Wind Direction (°)	0	120	240	IDEM BOILING			0	60	-60	0



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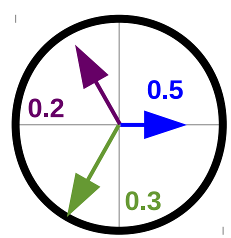
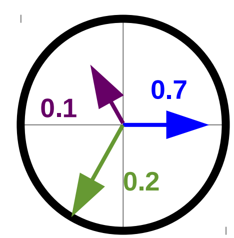
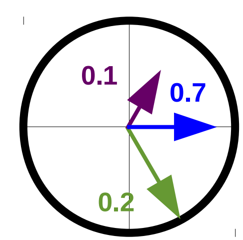
Atmosphere configurations

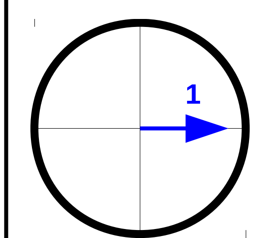
Simulations with different atmosphere configurations:

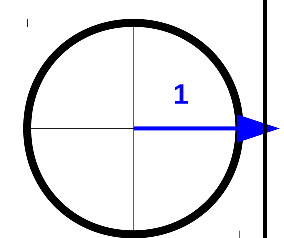
ATMOSPHERE BEHAVIOUR	BOILING (3 layers)			MAINLY BOILING (3 layers)			MAINLY FROZEN FLOW (3 layers)			FROZEN FLOW (1 layer)	FROZEN FLOW (1 layer)
Cn2 Profile (%)	0.5	0.2	0.3	0.7	0.1	0.2	IDEM MAINLY BOILING			1	1
Wind Values (m/s)	7.5	12.5	15	10	7	15	IDEM MAINLY BOILING			10	20
Wind Direction (°)	0	120	240	IDEM BOILING			0	60	-60	0	0

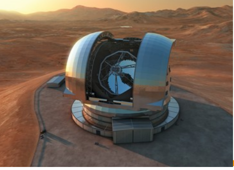












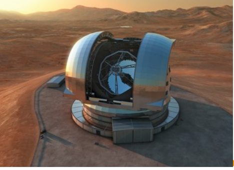
Performance comparison with other regulators

- VLT NAOS-like case: Diameter = 8m, 15 x 15 actuators grid, ASO SH 14 x 14 ml, 500 Hz

Typical turbulence condition r0 = 0.1 m @ 0.55 µm

Strehl Ratio @ 1.65 µm

Regulator	Basis & sampling	Edge Compensation
Integral action	/	/
LQG - AR2	495 Zernike modes	/
LQG –AR1 multilayer	Zonal, 16 points / subap area	MAP



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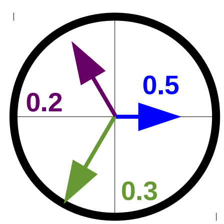
Regulator	Basis & sampling	Edge Compensation	ATMOSPHERE
			Boiling
Integral action	/	/	50.5%
LQG - AR2	495 Zernike modes	/	53.7%
LQG –AR1 multilayer	Zonal, 16 points / subap area	MAP	53.9%



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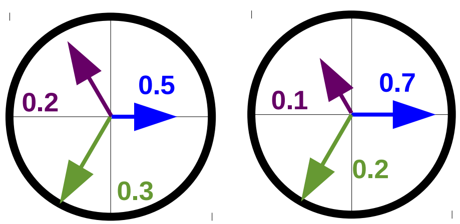
Strehl Ratio @ 1.65 µm

Regulator	Basis & sampling	Edge Compensation	ATMOSPHERE	
			Boiling	Mainly Boiling
Integral action	/	/	50.5%	50.6%
LQG - AR2	495 Zernike modes	/	53.7%	53.7%
LQG –AR1 multilayer	Zonal, 16 points / subap area	MAP	53.9%	54.4%



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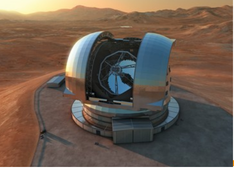

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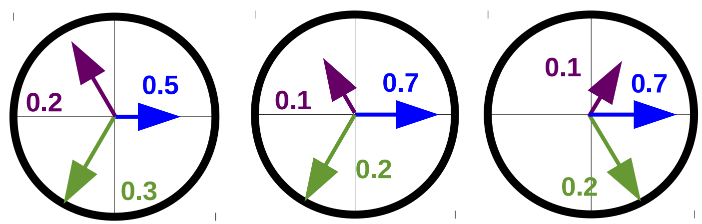
Strehl Ratio @ 1.65 µm

Regulator	Basis & sampling	Edge Compensation	ATMOSPHERE		
			Boiling	Mainly Boiling	Mainly Frozen Flow
Integral action	/	/	50.5%	50.6%	50.3%
LQG - AR2	495 Zernike modes	/	53.7%	53.7%	53.6%
LQG –AR1 multilayer	Zonal, 16 points / subap area	MAP	53.9%	54.4%	55.5%



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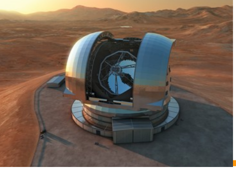

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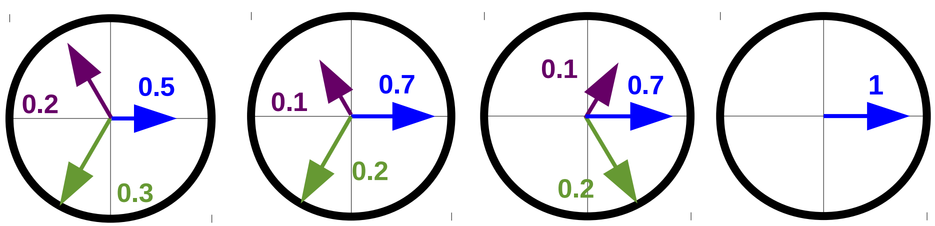
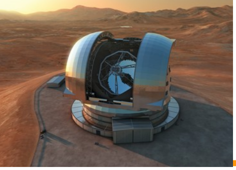
Typical turbulence condition r0 = 0.1 m @ 0.55 µm

Strehl Ratio @ 1.65 µm

Regulator	Basis & sampling	Edge Compensation	ATMOSPHERE			
			Boiling	Mainly Boiling	Mainly Frozen Flow	Frozen Flow 10 m/s
Integral action	/	/	50.5%	50.6%	50.3%	50.7%
LQG - AR2	495 Zernike modes	/	53.7%	53.7%	53.6%	53.8%
LQG –AR1 multilayer	Zonal, 16 points / subap area	MAP	53.9%	54.4%	55.5%	56.8%





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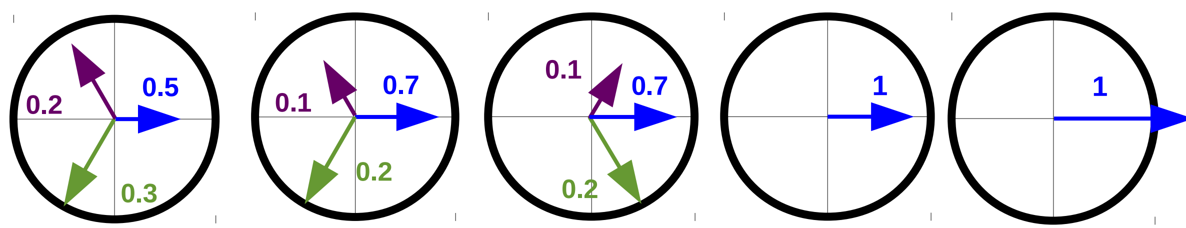
Regulator	Basis & sampling	Edge Compensation	ATMOSPHERE				
			Boiling	Mainly Boiling	Mainly Frozen Flow	Frozen Flow 10 m/s	Frozen Flow 20 m/s
Integral action	/	/	50.5%	50.6%	50.3%	50.7%	46.4%
LQG - AR2	495 Zernike modes	/	53.7%	53.7%	53.6%	53.8%	51.8%
LQG –AR1 multilayer	Zonal, 16 points / subap area	MAP	53.9%	54.4%	55.5%	56.8%	56.8%



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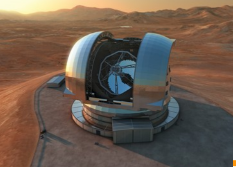

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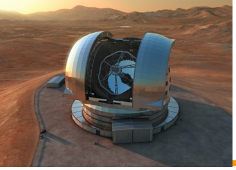
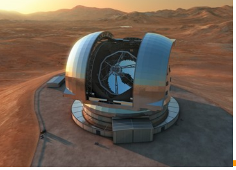
LQG-KF with Frozen Flow models and MAP compensation is efficient



Conclusion

- Multilayer Frozen Flow models:

  + multilayer atmosphere model → High performance control

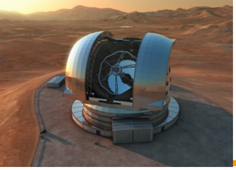


Conclusion

- Multilayer Frozen Flow models:

  + multilayer atmosphere model → High performance control

  + Highly parallelizable structure → Fast and well adapted to ELT scale AO



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  - Edge effects → deeply affects control performance of LQG regulators

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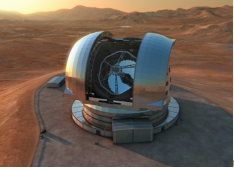

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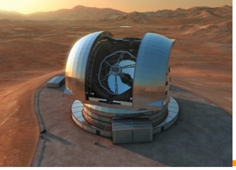
  - Edge effects → deeply affects control performance of LQG regulators

  + Very local edge compensation with MAP → Highly parallelizable and efficient



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  + multilayer atmosphere model → High performance control
  + Highly parallelizable structure → Fast and well adapted to ELT scale AO
  - Edge effects → deeply affects control performance of LQG regulators
  + Very local edge compensation with MAP → Highly parallelizable and efficient

- LQG regulator with multilayer Frozen Flow models and edge compensation with MAP:
  + Competitive and better than AR2 Zernike LQG regulator for any atmosphere behavior

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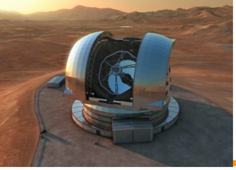

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  + multilayer atmosphere model → High performance control

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  - Edge effects → deeply affects control performance of LQG regulators

  + Very local edge compensation with MAP → Highly parallelizable and efficient

- LQG regulator with multilayer Frozen Flow models and edge compensation with MAP:

  + Competitive and better than AR2 Zernike LQG regulator for any atmosphere behavior

  - Only tested with full knowledge of atmosphere and wind profiles

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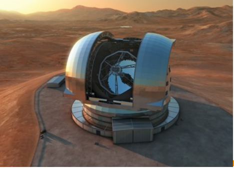

Perspectives

- **Robustness in performance in the presence of model errors**

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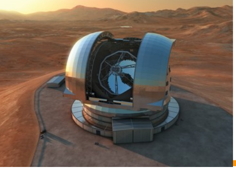
- **Extension of control strategy and edge degradation study to ELT-sized systems**



Perspectives

- **Robustness in performance in the presence of model errors**

- **Extension of control strategy and edge degradation study to ELT-sized systems**

- **LQG with edge compensation efficient with Frozen Flow atmosphere:**

  + well adapted to high altitude layers with strong wind

  + interesting for satellites tracking

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