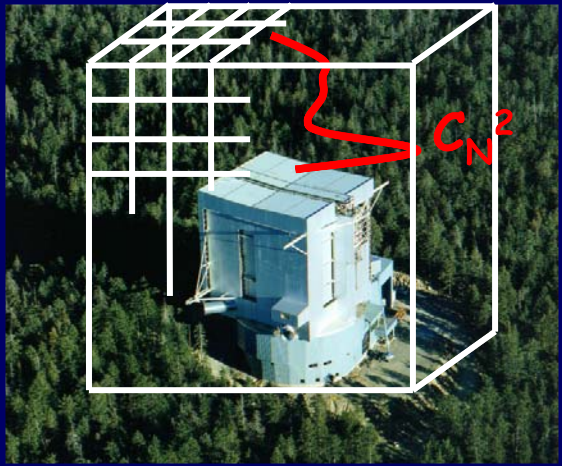
Optical Turbulence Characterization and Forecasts for Ground-Based Astronomy



Elena Masciadri

Osservatorio Astrofisico di Arcetri - Firenze

Outline

- Why astronomers should be concerned about *optical turbulence* ?
- Measurements and simulations: two approaches to answer to different questions
- Which are the main challenges for this research topic ?
- What has already been done so far and what we would like to do and to know ?
- How can the optical turbulence characterization concretely support the AO systems and the astronomical observations ?

Why astronomers should be concerned about optical turbulence ?

Research Topic Relevance

<u>Ground-based astronomy competitive with respect to the space-based one</u>

- Lower financial investments
- Longer typical telescopes lifetime
- Better angular resolution due to the larger pupils size of ground-based telescopes

AO techniques can correct perturbations induced by atmospheric turbulence

↓

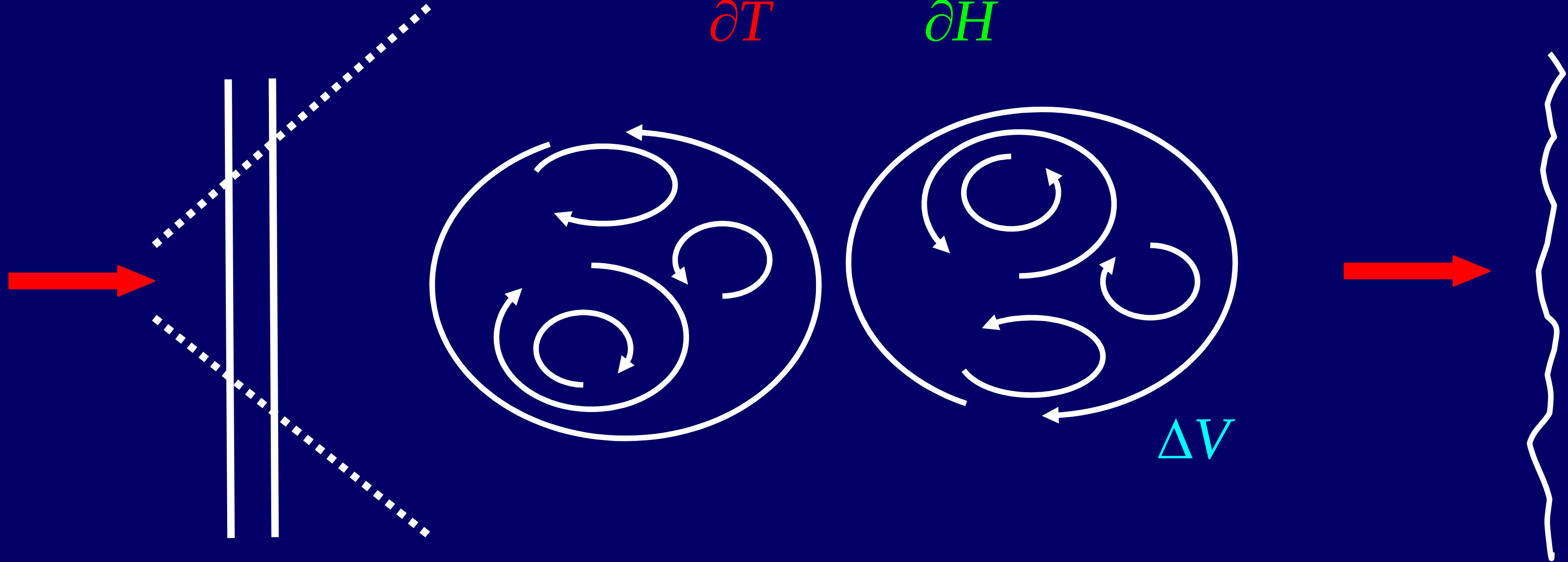
To correct turbulence we need to know that

LIGHT — TURBULENCE — LIGHT

dominant in optical, near, middle and far infrared (→ $\frac{\partial n}{\partial T}\Delta T$)

dominant in millimetric and radio (→ $\frac{\partial n}{\partial H}\Delta H$)

$$\Delta n = \frac{\partial n}{\partial T}\Delta T + \frac{\partial n}{\partial H}\Delta H$$



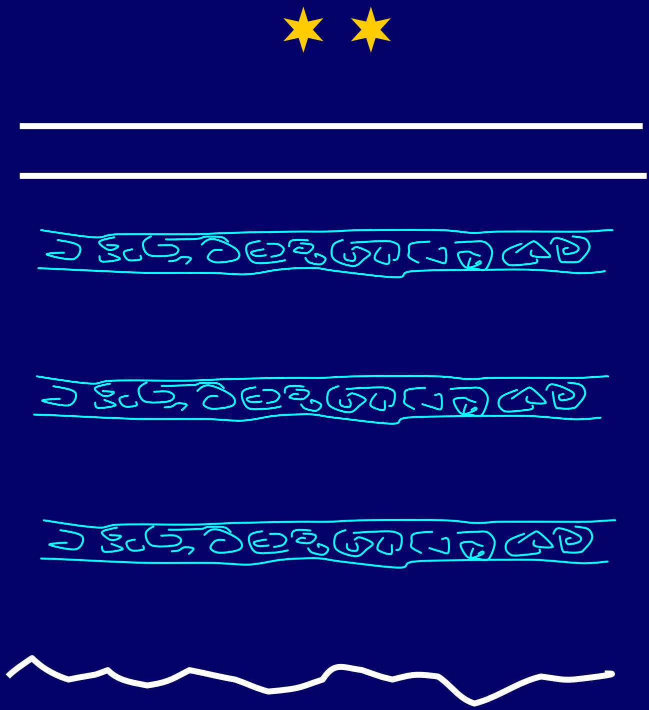
$$E(x,y) = A(x,y)\cdot e^{i\varphi(x,y)}$$

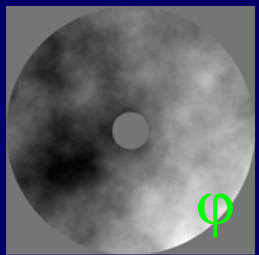
$$\begin{matrix}\Delta T(x,y,z) \\ \Delta H(x,y,z)\end{matrix} \longrightarrow \Delta n(x,y,z) \longrightarrow \left[\Delta A(x,y)\ \&\ \Delta\varphi(x,y)\right]$$

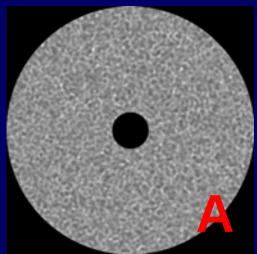
GROUND-BASED OBSERVATIONS

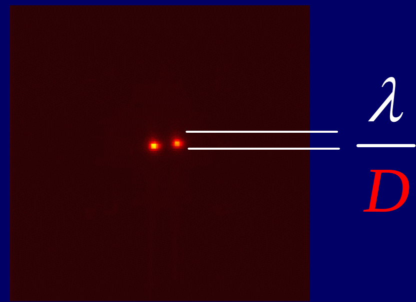
(F. Roddier 1981)

PLANE WAVEFRONT









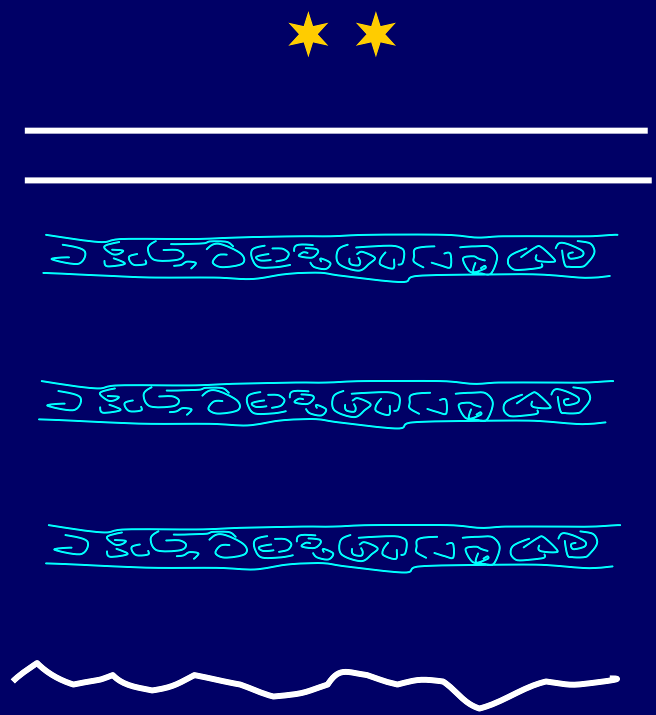
space

$$E = \Delta A \cdot e^{i\Delta\varphi}$$

GROUND-BASED OBSERVATIONS

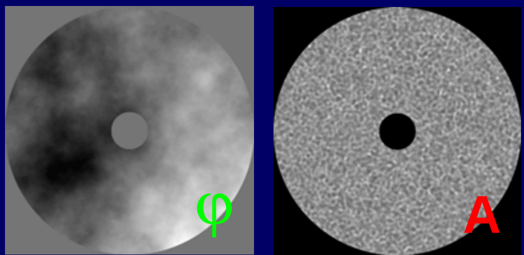
(F. Roddier 1981)

PLANE WAVEFRONT

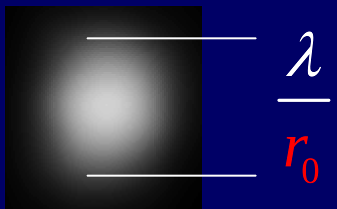


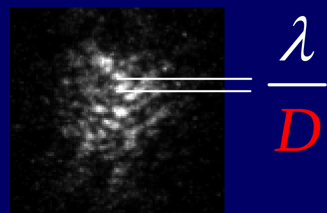
EFFECTS

1. Angular resolution 0.01" → 1"
2. Limit magnitude decreases



$$E = \Delta A \cdot e^{i\Delta\varphi}$$

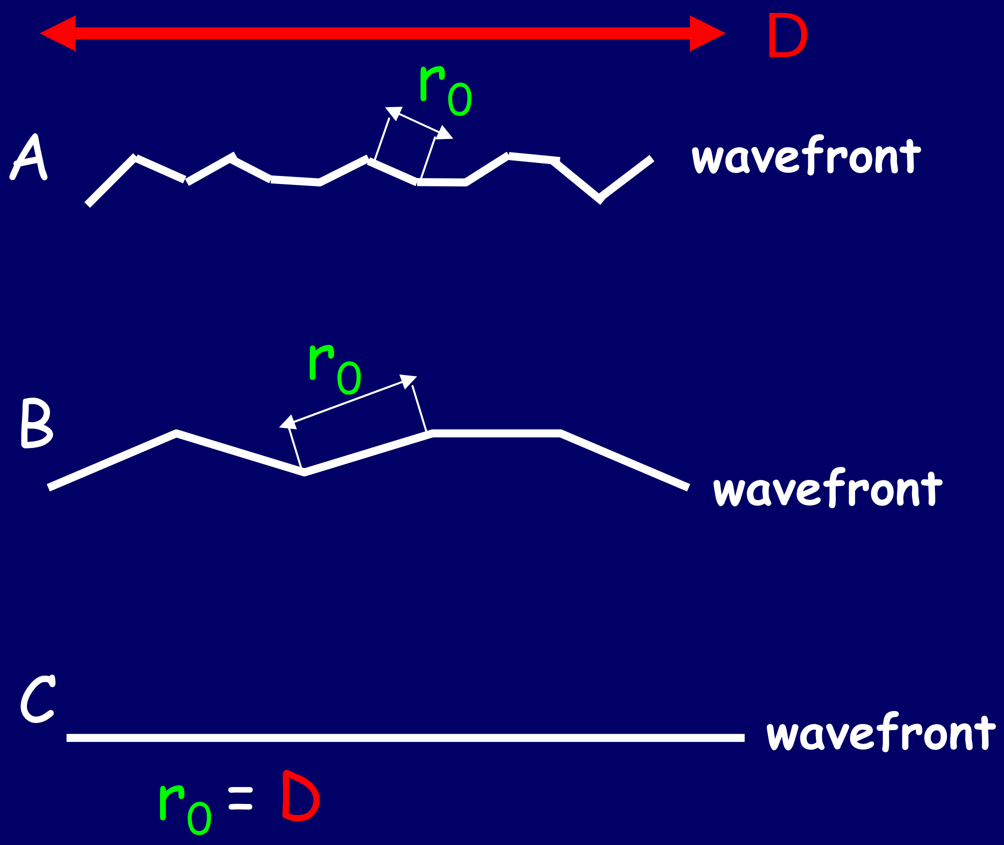


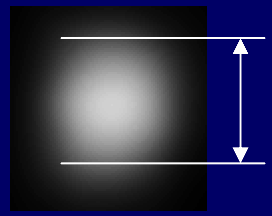


LONG EXPOSURE

SHORT EXPOSURE

FRIED PARAMETR r_0





$$\varepsilon \sim \frac{\lambda}{r_0}$$

- λ = 0.5 μm
  V band
- $r_0 \sim \lambda^{6/5}$

FRIED PARAMETR r_0

	V 0.5 μm	J 1.25 μm	H 1.64 μm	K 2.2 μm	N 10 μm
ε (")	r_0 (cm)	r_0 (cm)	r_0 (cm)	r_0 (cm)	r_0 (cm)
0.5	20	51	67	90	408
0.7	14	36	47	64	291
1	10	25	33	45	204

visible (V) — near-infrared (J, H, K) — infrared (N)

OPTICAL TURBULENCE and "ASTROCLIMATIC" PARAMETERS

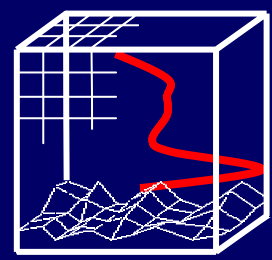
$$D_N(\rho) = \left\langle \left[n(r) - n(r+\rho) \right]^2 \right\rangle = C_N^2 \cdot \rho^{2/3}$$

$l_0 < \rho < L_0$

Kolmogorov Model

3D (x,y,z)

V wind intensity
P pression
T temperature
L_0 dynamical outer scale
$C_N^2 = F\,(V,\ p,\ T,\ L_0)$



C_N^2

2D (x,y)

$$\int_0^\infty F(h, V, L_0) \cdot C_N^2\, dh$$

ε: ***seeing*** $\quad \varepsilon \sim \lambda^{-1/5} \left(\int_0^\infty C_N^2(h)\, dh \right)^{3/5}$ ⟷ r_0: ***Fried paramter*** $\quad r_0 \sim \lambda^{6/5} \left(\int_0^\infty C_N^2(h)\, dh \right)^{-3/5}$

θ_0: ***isoplanatic angle*** $\quad \vartheta_0 \sim \lambda^{6/5} \left(\int_0^\infty h^{5/3} \cdot C_N^2(h)\, dh \right)^{-3/5}$

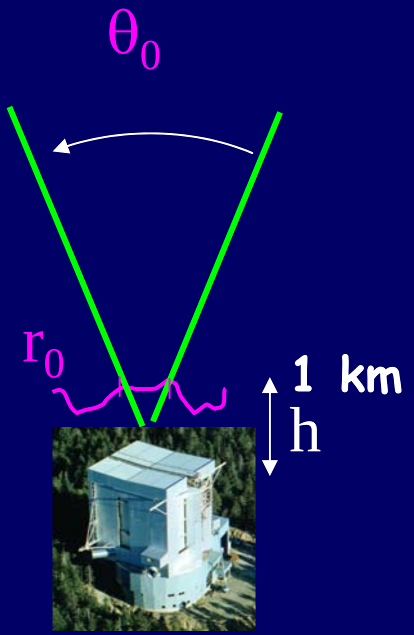
τ_0: ***wavefront coherence time*** $\quad \tau_0 \sim \lambda^{6/5} \left(\int_0^\infty V(h)^{5/3} \cdot C_N^2(h)\, dh \right)^{-3/5}$

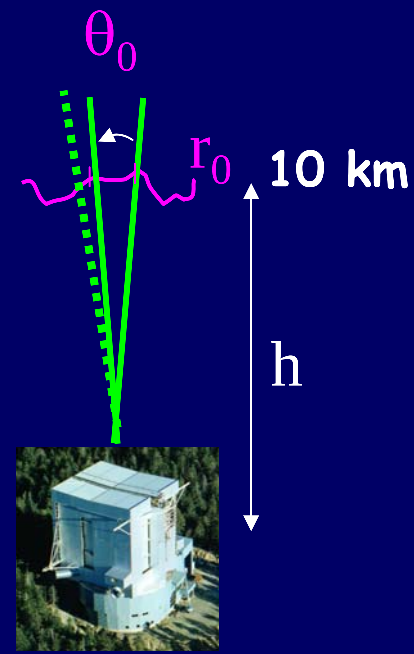
θ_M: ***isoplanatic angle for the MCAO*** $\quad \vartheta_M \sim \lambda^{6/5} \left(\int_0^\infty F_M(h) \cdot C_N^2(h)\, dh \right)^{-3/5}$

$\mathcal{L}_0$: ***spatial coherence outer scale*** $\quad \mathcal{L}_0 \sim \left(\int_0^\infty L_0(h)^{-1/3} \cdot C_N^2(h)\, dh \Big/ \int_0^\infty C_N^2(h)\, dh \right)^{-3}$

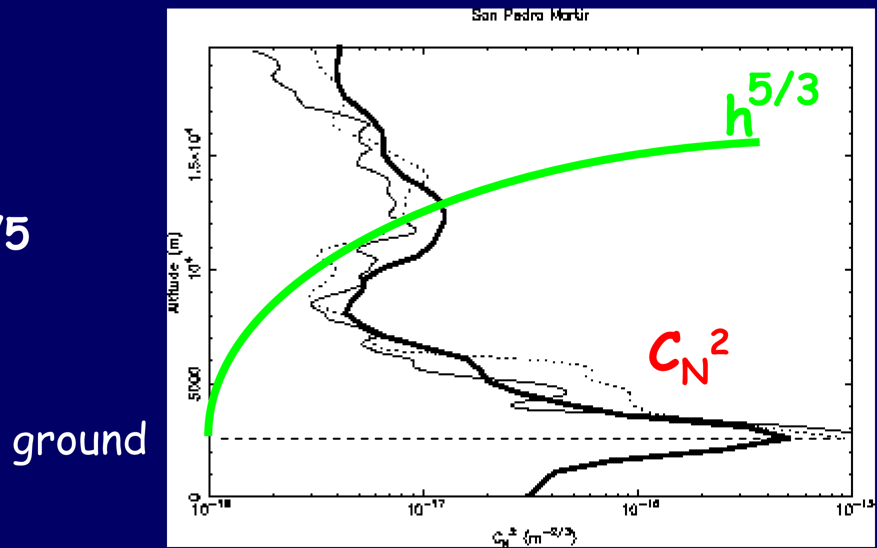
σ^2: ***scintillation rate*** $\quad \sigma^2 \sim \lambda^{-7/6} \left(\int_0^\infty h^{5/6} \cdot C_N^2(h)\, dh \right)$

Isoplanatic angle: θ_0





$$\theta_0 = \lambda^{6/5} \left[\int_0^{\infty} h^{5/3} \cdot C_N^2(h)\,dh \right]^{-3/5}$$



***Measurements* and *simulations*: two approaches to answer to different questions**

INSTRUMENTS

- Generalized Scidar: $C_N^2(h)$, V(h) Δh~300-1000 m
- Radio-soundings: $C_N^2(h)$, V(h), T(h), p(h), H(h), $L_O(h)$ Δh~6 m
- MASS: $C_N^2(h)$, τ_O Δh~h/2

Vertical profilers

- ✶ DIMM: ε, τ_O, θ_O
- GSM: $\mathcal{L}_O$, ε, τ_O, θ_O
- Scintillometer: σ^2

Integral-based Instruments

- SODAR: $C_N^2(h)$ first 1 km
- MAST: $C_N^2(h)$ first 20-30 m
- Sonic Anemometer: V(h), $C_N^2(h)$ first 20-30 m

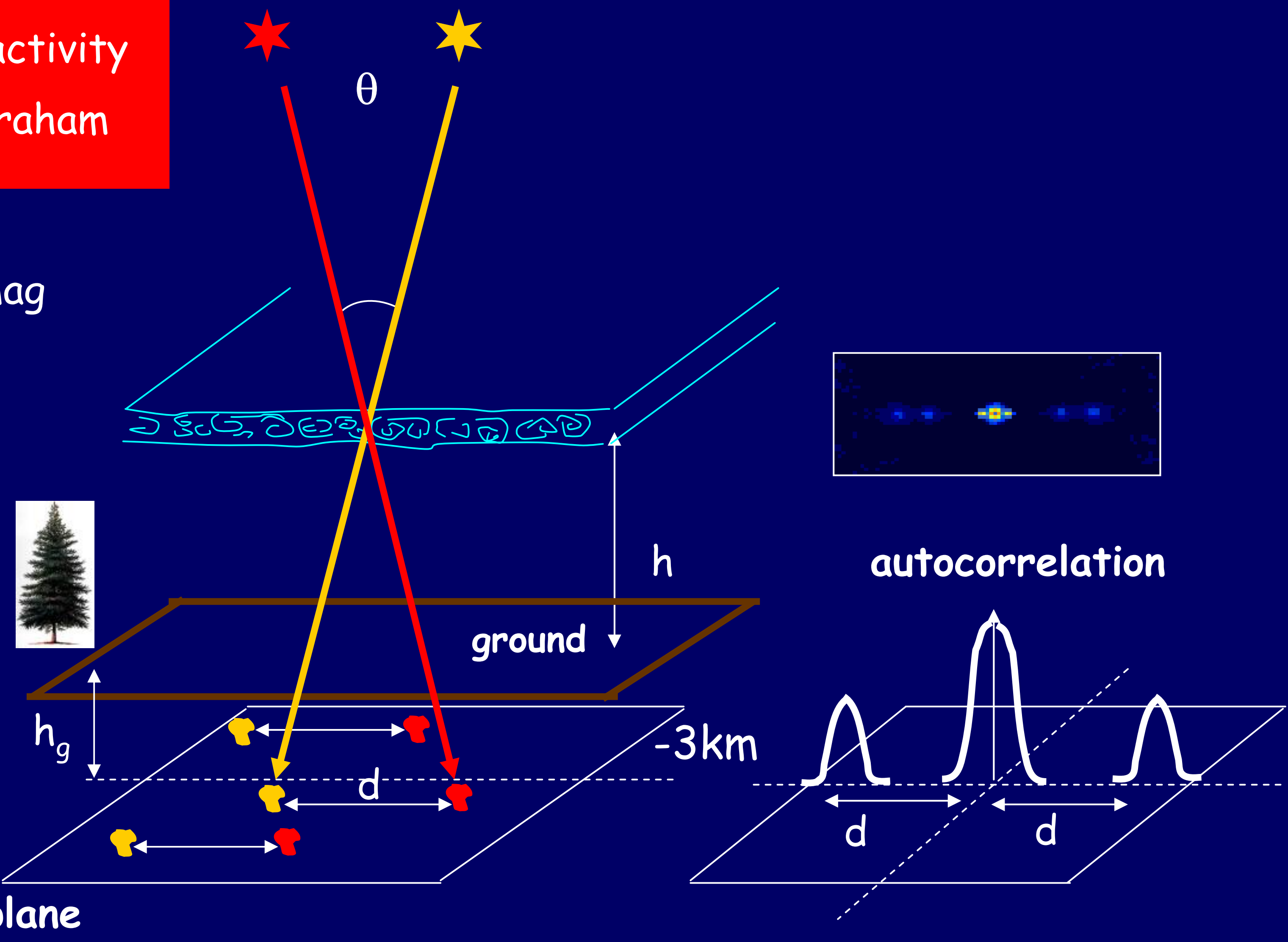
Instruments dedicated to ground based turbulence

1. *Based on different physical principles*
2. *Different vertical resolution*
3. *They monitor different regions of the atmosphere*

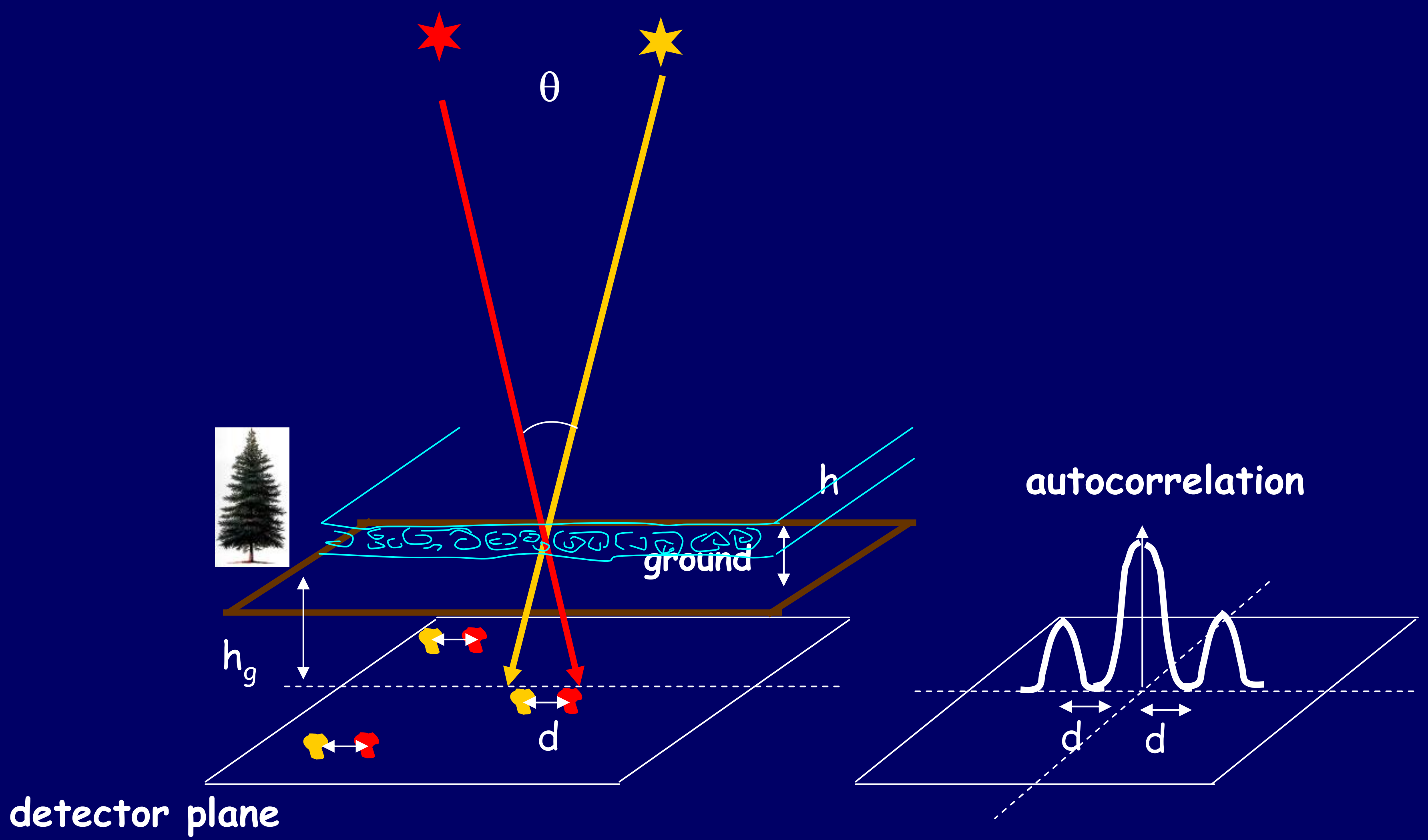
Generalized Scidar - PRINCIPLE

FOROT activity
@ Mt. Graham

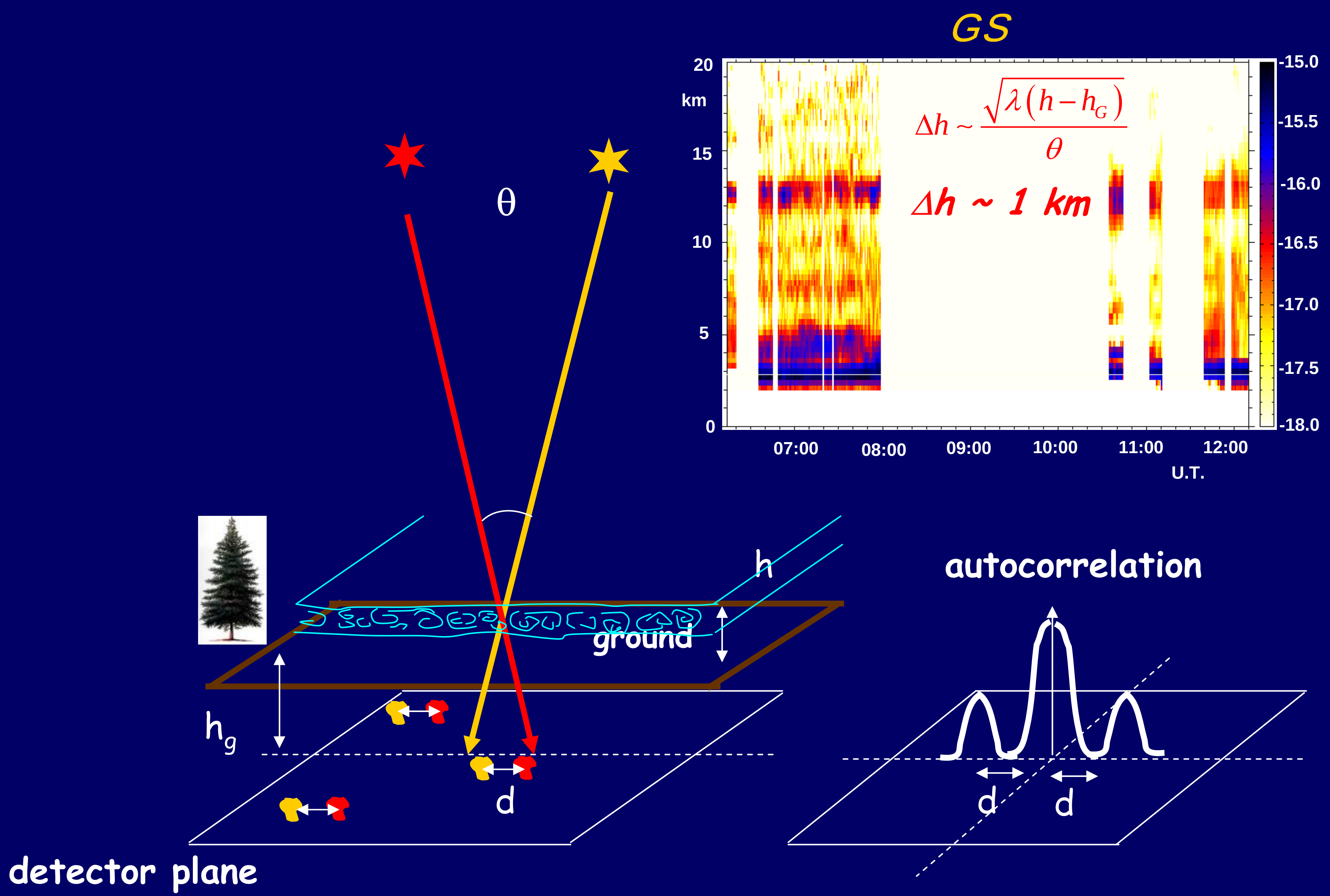
D > 1.5 m
m < 5-6 mag
θ < 3"-14"



Generalized Scidar - PRINCIPLE



Generalized Scidar - PRINCIPLE



Micro-thermal Probes

Temporal sampling between successive measurements $\Delta t \sim 1$sec

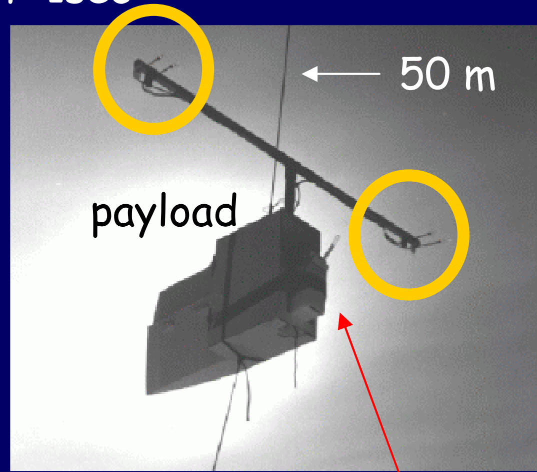
Wolfram wire
D= 5 μm

Bufton et al., 1972, JOSA

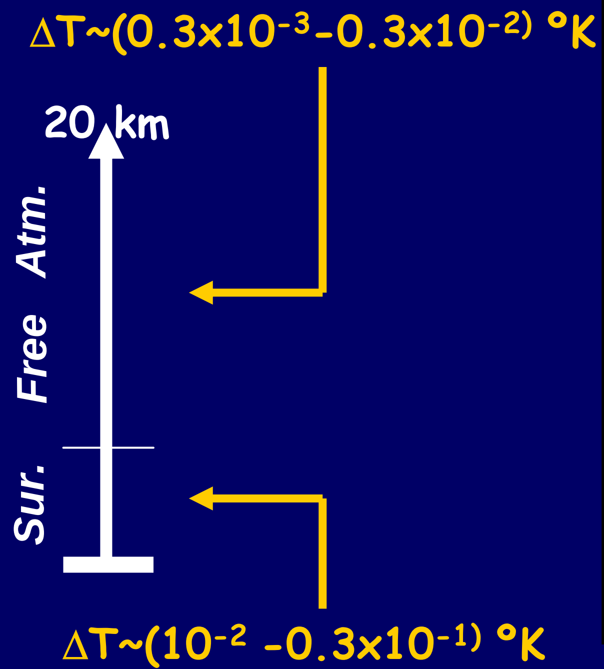
(P, T, V, H, C_N^2)

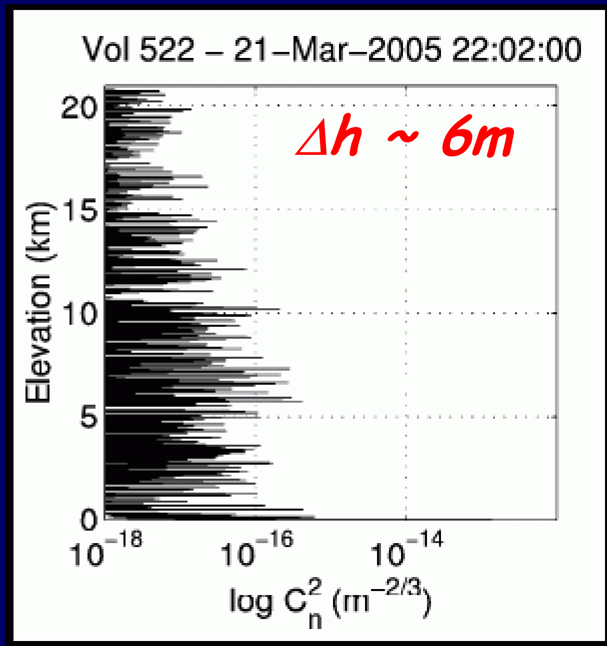
$$D_T^{\ 2} = C_T^{\ 2} \cdot 1^{2/3}$$

$$C_N^{\ 2} = \left[\frac{0.8 \times 10^{-6} P}{T^2} \right]^2 C_T^{\ 2}$$



RS80-15E VAISALA





- **Highest vertical resolution**
- **Unique NOT-optical vertical profiler**
- **Extremely delicate technology**

thermocouples
diodes
} L. Gori

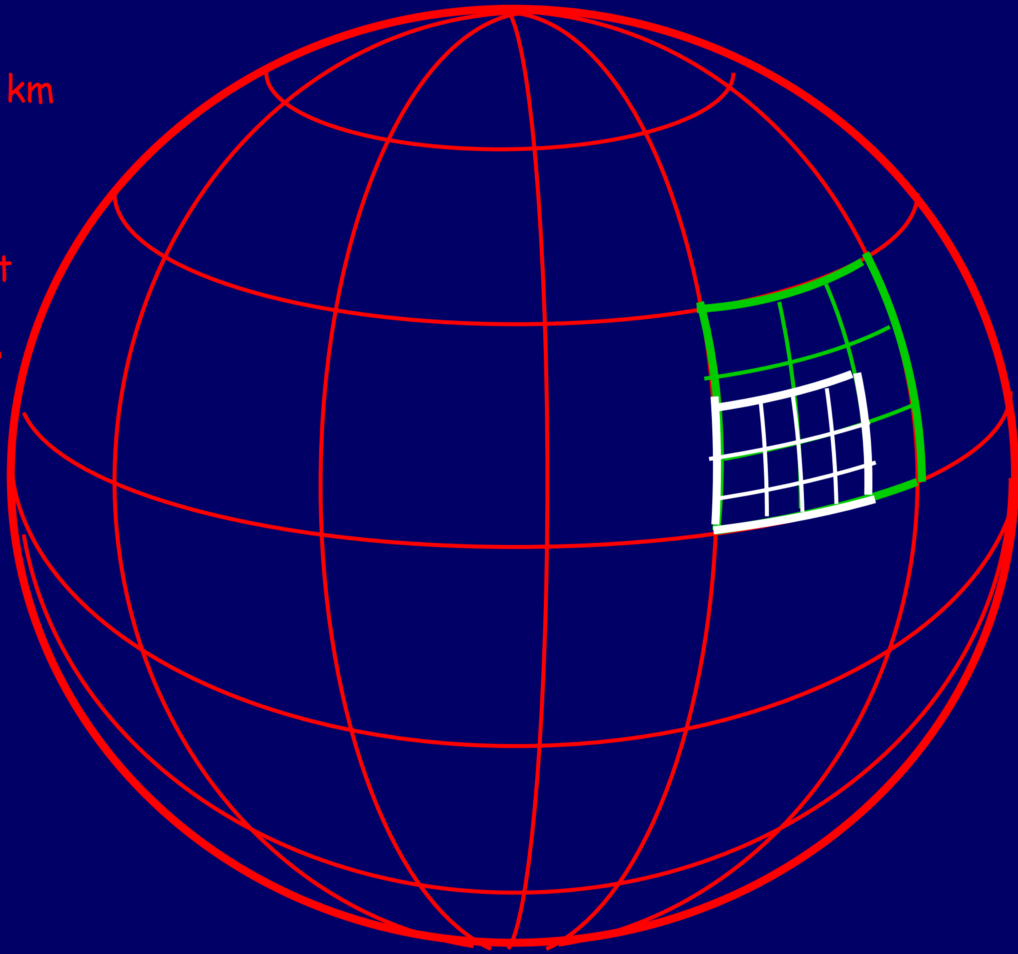
WHICH KIND OF MODELS ?

GCM

Res: 100 km
L = 100 km - 10000 km
T = 1 day - 10 days

climat forecast
weather forecast

V,T,p,r,cloud cover



LAM

Res: 7 km - 50 km
L = 20 km - 200 km
T = 12 hours - 3 days

#convection
weather forecast

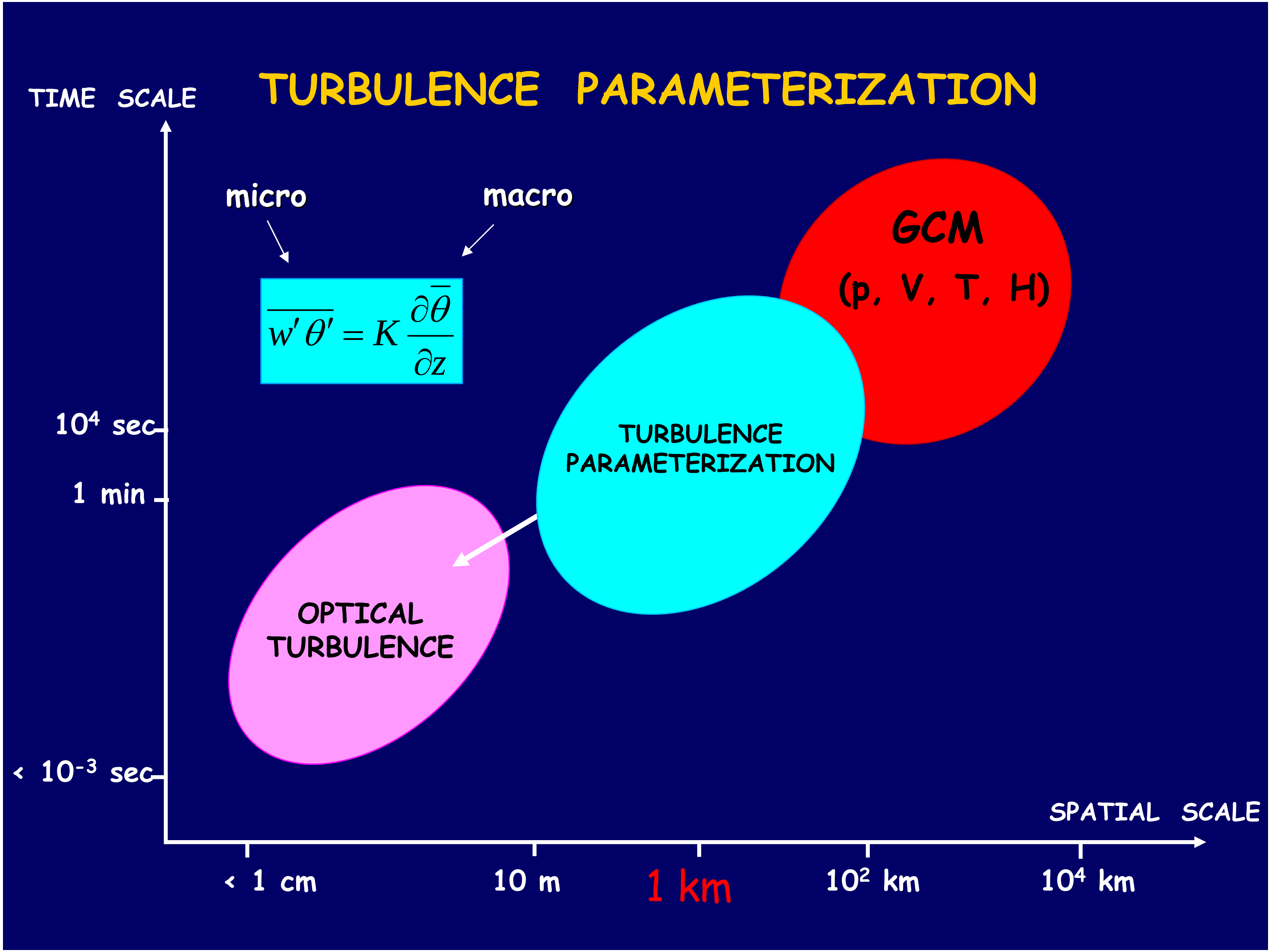
V,T,p,r,cloud cover

NMM

Res: 50 m - 10 km
L = 20 m - 200 km
T = 1 minute - 1 day

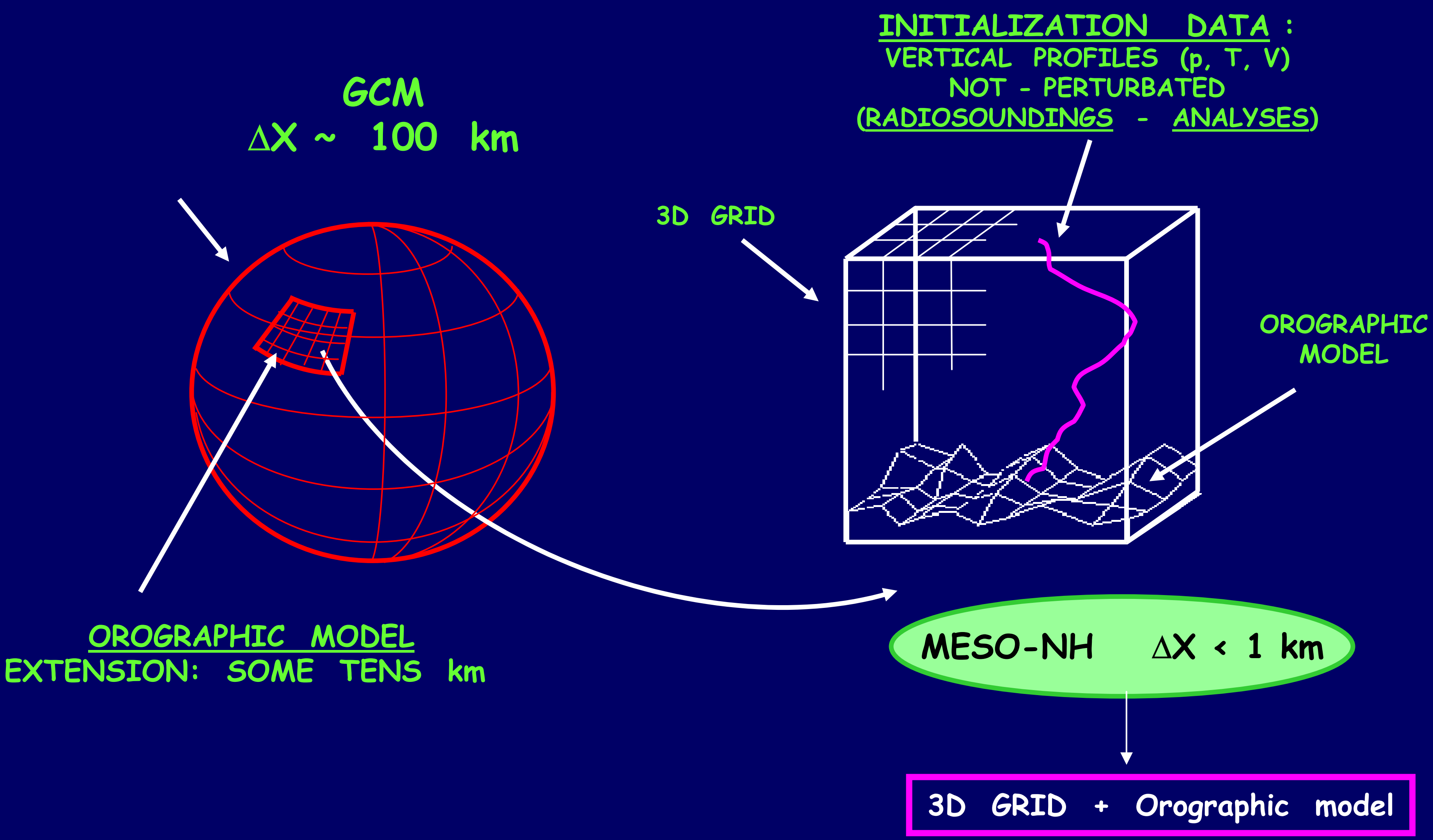
orographic waves
turbulence
deep convection

V,T,p,r,cloud cover, C_N^2 !!!

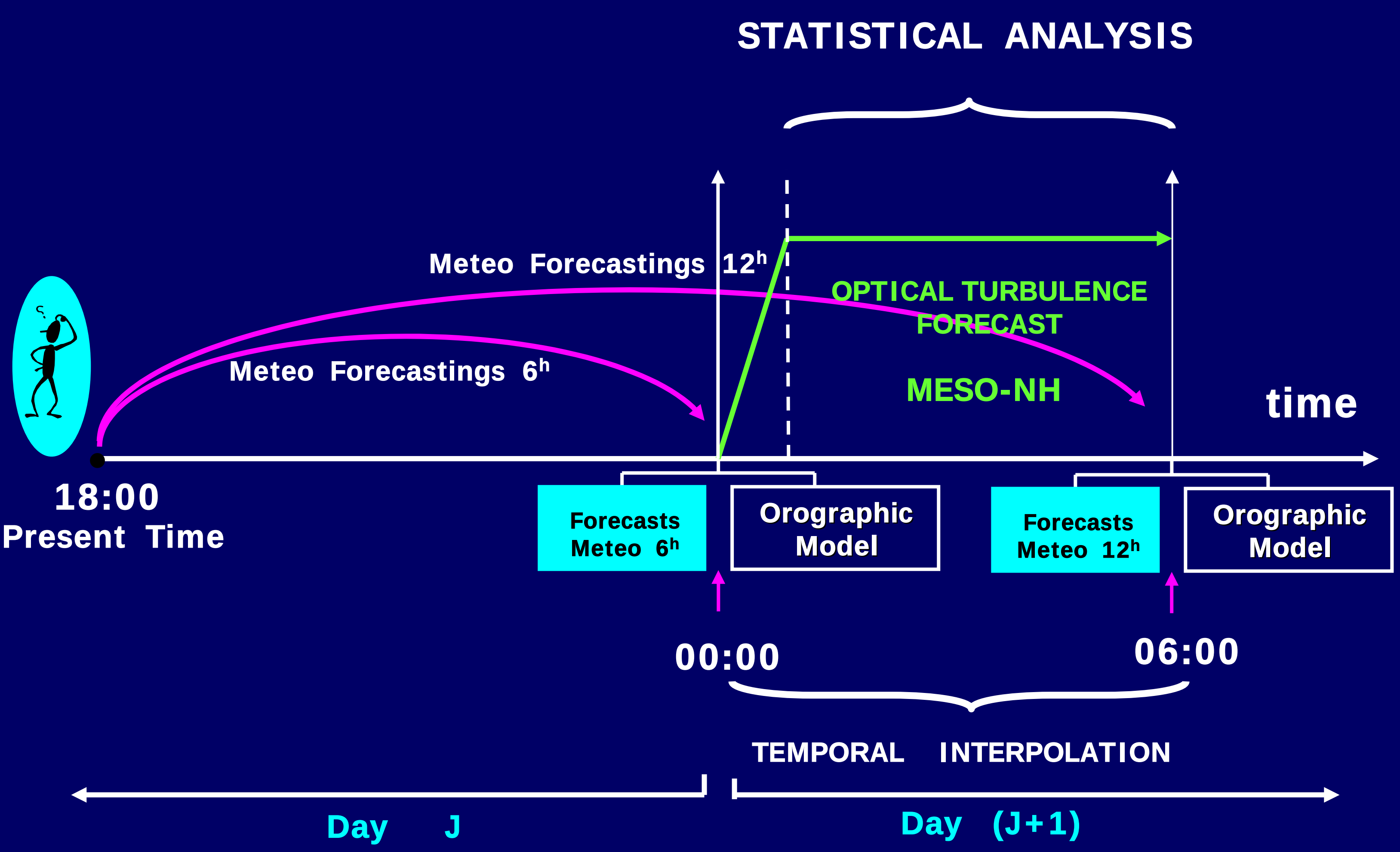


TURBULENCE PARAMETERIZATION
TIME SCALE
micro
macro
$\overline{w'\theta'} = K \frac{\partial \overline{\theta}}{\partial z}$
GCM
(p, V, T, H)
TURBULENCE PARAMETERIZATION
OPTICAL TURBULENCE
10^4 sec
1 min
< 10^{-3} sec
SPATIAL SCALE
< 1 cm
10 m
1 km
10^2 km
10^4 km

DYNAMICAL ADAPTATION



OPTICAL TURBULENCE FORECAST



Answers to different questions

Measurements

1. Real-time estimates → turbulence changes on time scales of fraction of seconds
2. Measurements access ALL spatial and temporal scales typical of turbulence
3. Measurements better approach the "veracity" than simulations

Simulations

1. 3D C_N^2 maps
2. Forecast → Flexible-scheduling
3. Climatology of the C_N^2 and the astroclimatic parameters (access to the "Past")
4. Extremely less expensive and fast

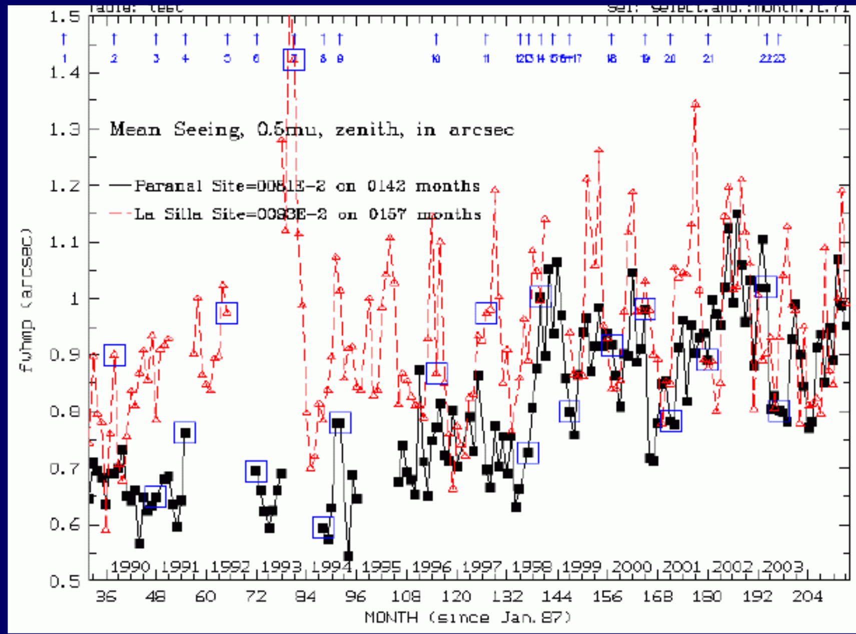
Answers to different questions

Measurements

1. Real-time estimates ➔ turbulence c seconds

2. Measurements access ALL spatial an turbulence

3. Measurements better approach the



Simulations

1. 3D C_N^2 maps

2. Forecast ➔ Flexible-scheduling

3. Climatology of the C_N^2 and the astroclimatic parameters (access to the "Past")

4. Extremely less expensive and fast

Fields of applications: measurements & simulations

- **SITE TESTING**
  - Characterization of the existant sites
  - Search of **NEW** sites
  - Climatology and Seasonal Variation of the Optical Turbulence
- **SUPPORT TO THE *AO & MCAO* TECHNIQUES**
  - MCAO: where, how and when to conjugate the DMs
  - **FOV** estimate for different lines of sight and **FOV** seasonal variation
  - Seasonal variation of sky coverage for Layer Oriented - MCAO
  - $C^2_N(x,y,z)$ or $C^2_N(z)$? 3D or 1D ?
- **FLEXIBLE-SCHEDULING**
  - Optimization of the management of the observation time

Which are the main challenges for this research topic ?

- Intrinsic difficulty in measuring turbulence
- Extremely narrow range [0.5" – 1"]
- Turbulence characteristics in the <u>surface</u>, <u>boundary layer</u> and <u>free atmosphere</u> are quite different
- Each instrument shows advantages and disadvantages
- Raw data are rarely accessible

↓

Instrumentation development at home

VISITOR MODE

Traditional management

Observation programs pre-allocated following criteria of scientific excellence

Paradox !!!

High scientific challenges → Low probablity of executing programs

Solution ?

SERVICE MODE (FLEXIBLE-SCHEDULING)

- Observation programs inserted in a queue
- Selection made <u>the day before or the same night</u> following the criteria :
  - ☐ Scientific excellence of the programs
  - ☐ Level of the <u>OPTICAL TURBULENCE</u>

Roddier , Léna (1984) - J. Optics Paris (15), 771

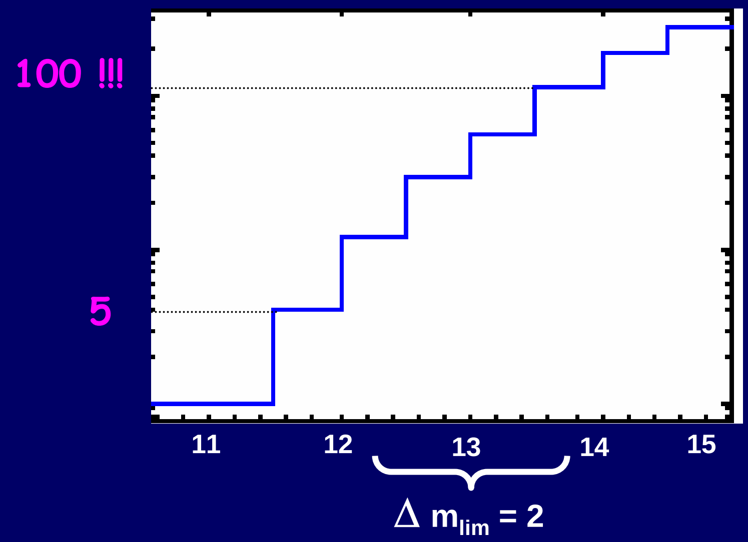
SNR at least ~ r_0^3

r_0 = 10 cm → r_0 = 20 cm

ε = 1" → ε = 0.5"

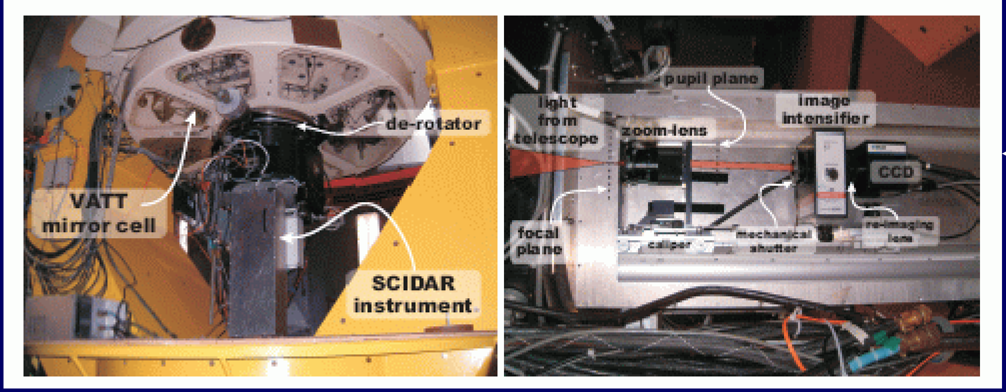
Δm_{lim} = 2

Cumulative histogram of the AGN magnitudes
declinaison (-70, +10) degres
http : // www-loag.obs.ujf-grenoble.fr



What has already been done so far and what we would like to do and to know ?

Generalized Scidar @ Mt. Graham



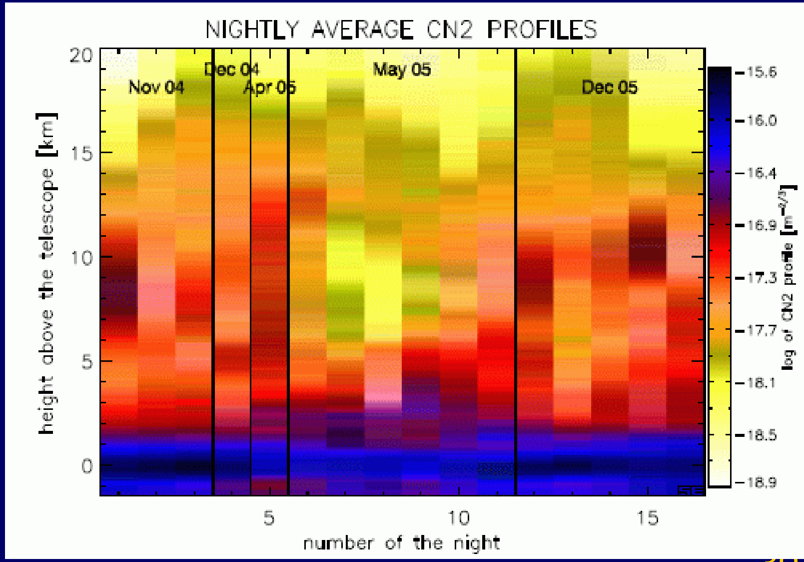
Dan McKenna (VATT)

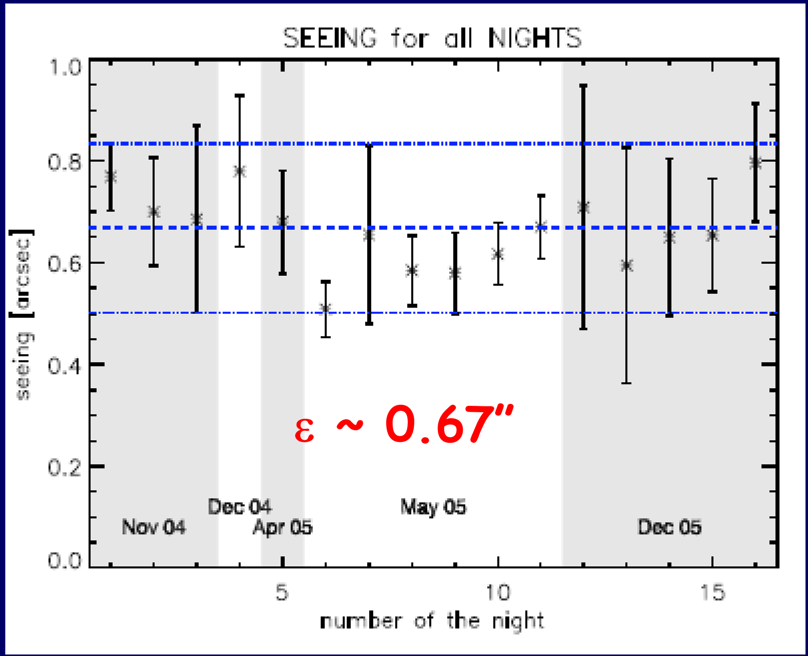
Egner, Masciadri, McKenna, PASP, in preparation

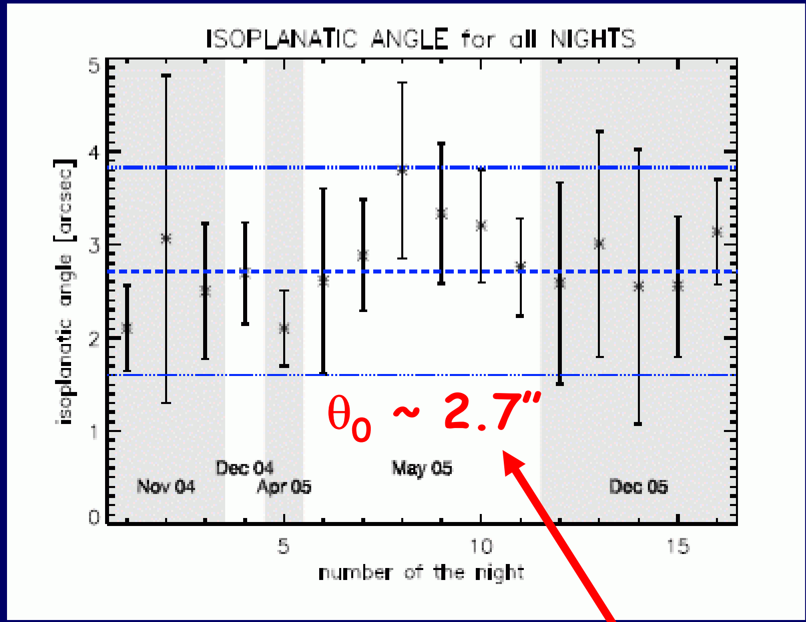
S. Egner (PhD, MPIA)
J. Stoesz (FOROT)

16 nights

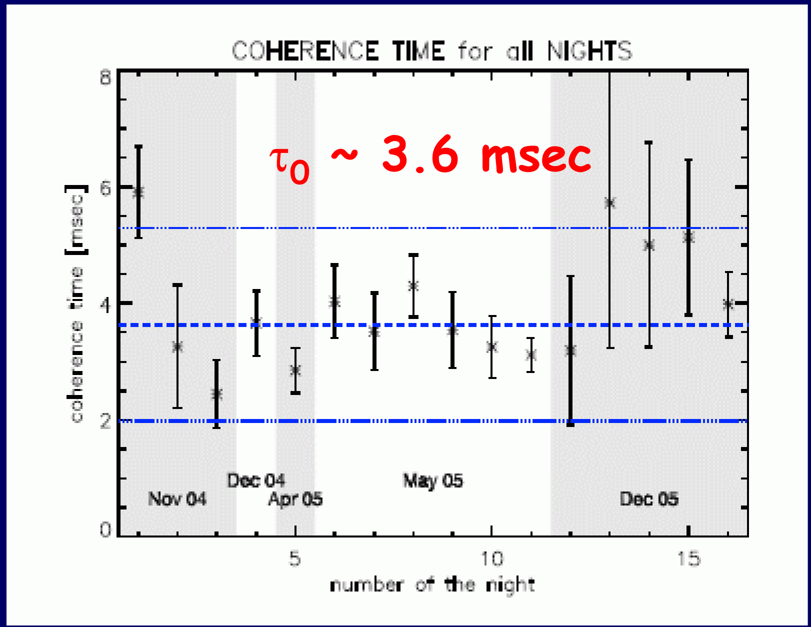
New run in spring time







quite good for GLAO

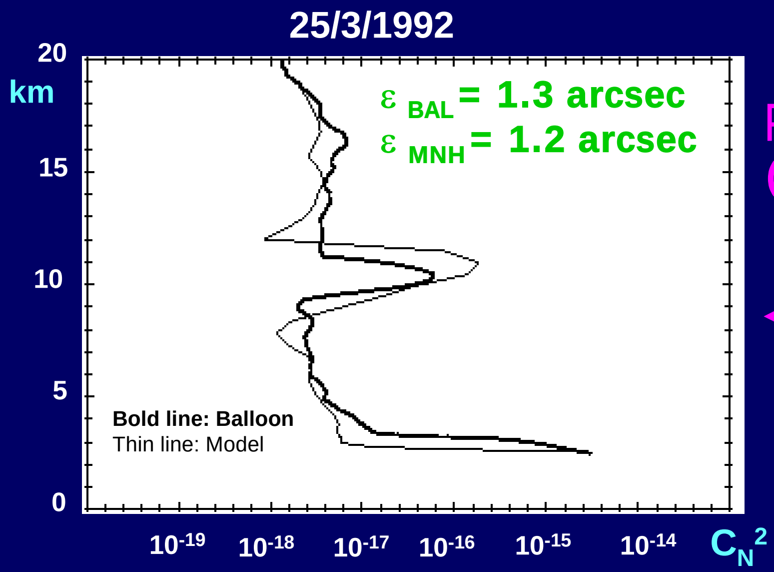


Median values

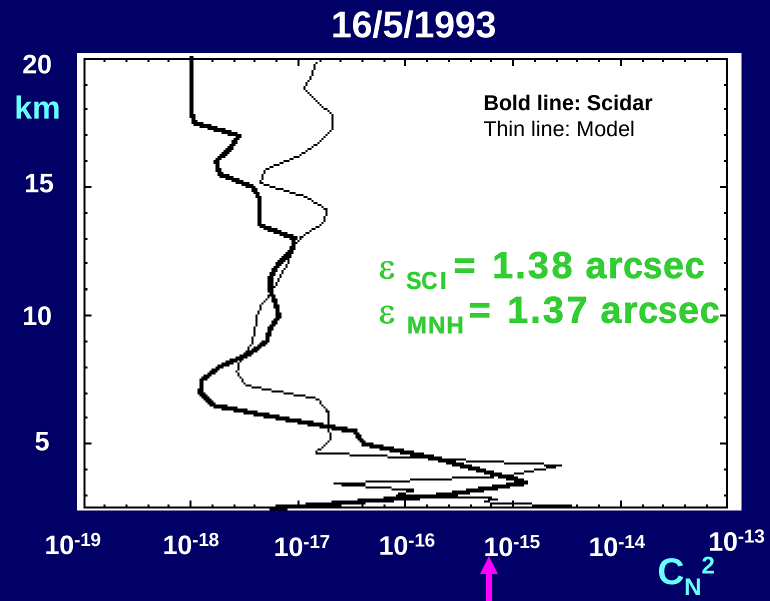
16 nights

@ Mt. Graham

CAN WE SIMULATE THE OPTICAL TURBULENCE ?

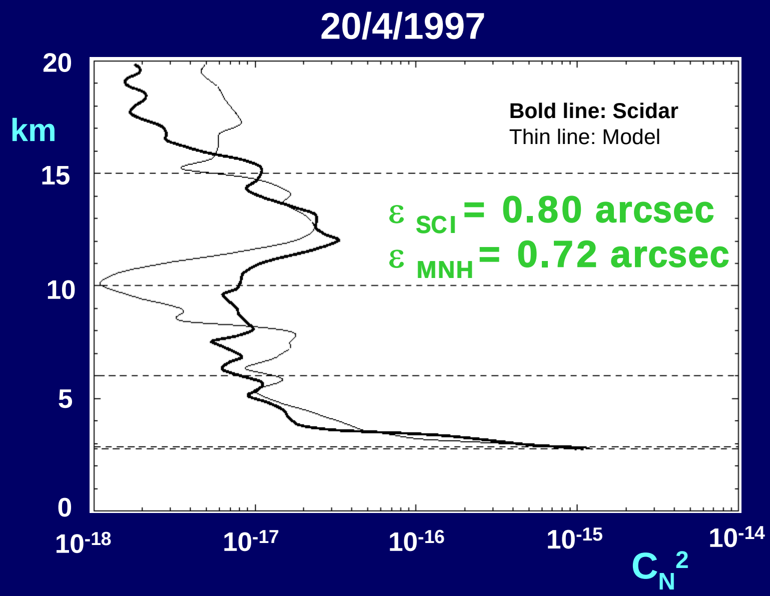


Paranal 1992
(VLT site testing)



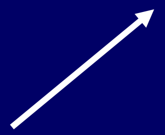
Paranal 1993
(VLT site testing)

San Pedro Martir
1997



San Pedro Mártir

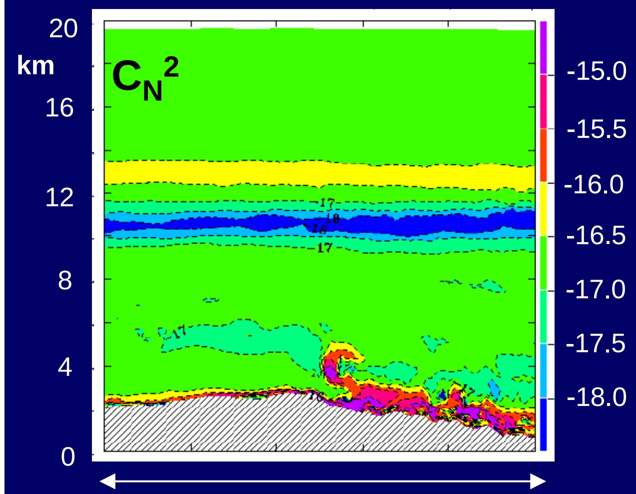
WIND (5-6 m/sec)



60 km

RES = 400 m

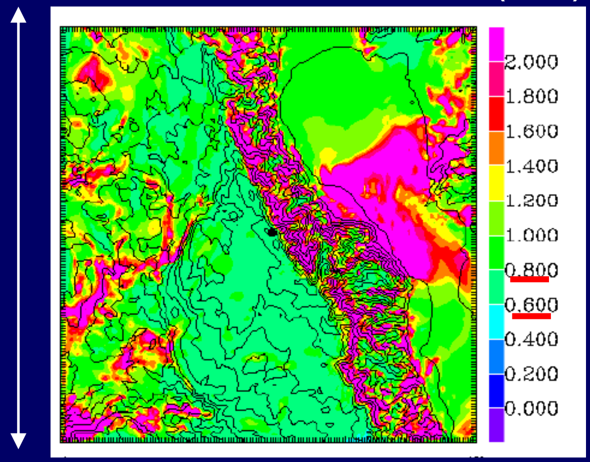
South North



32 km

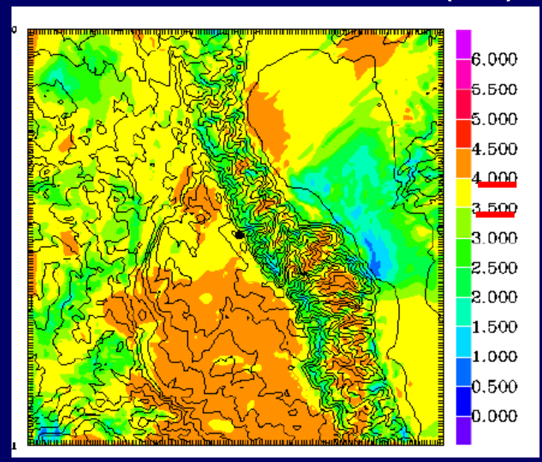
SEEING

(arcsec)



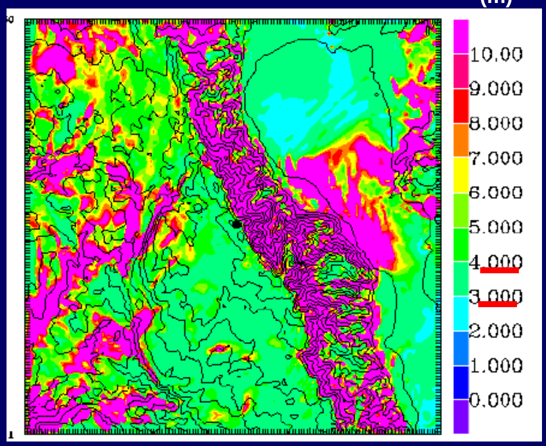
WAVEFRONT COHERENCE TIME

(msec)



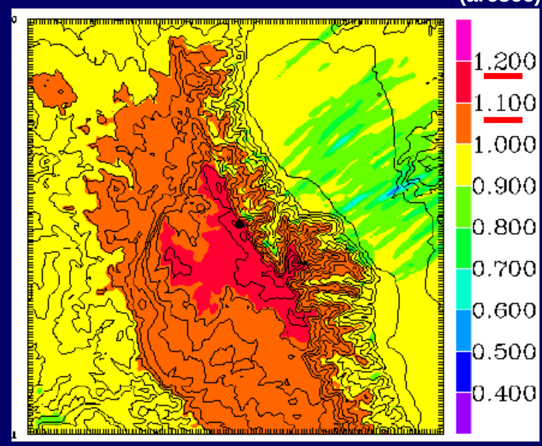
SPATIAL COHERENCE OUTER SCALE

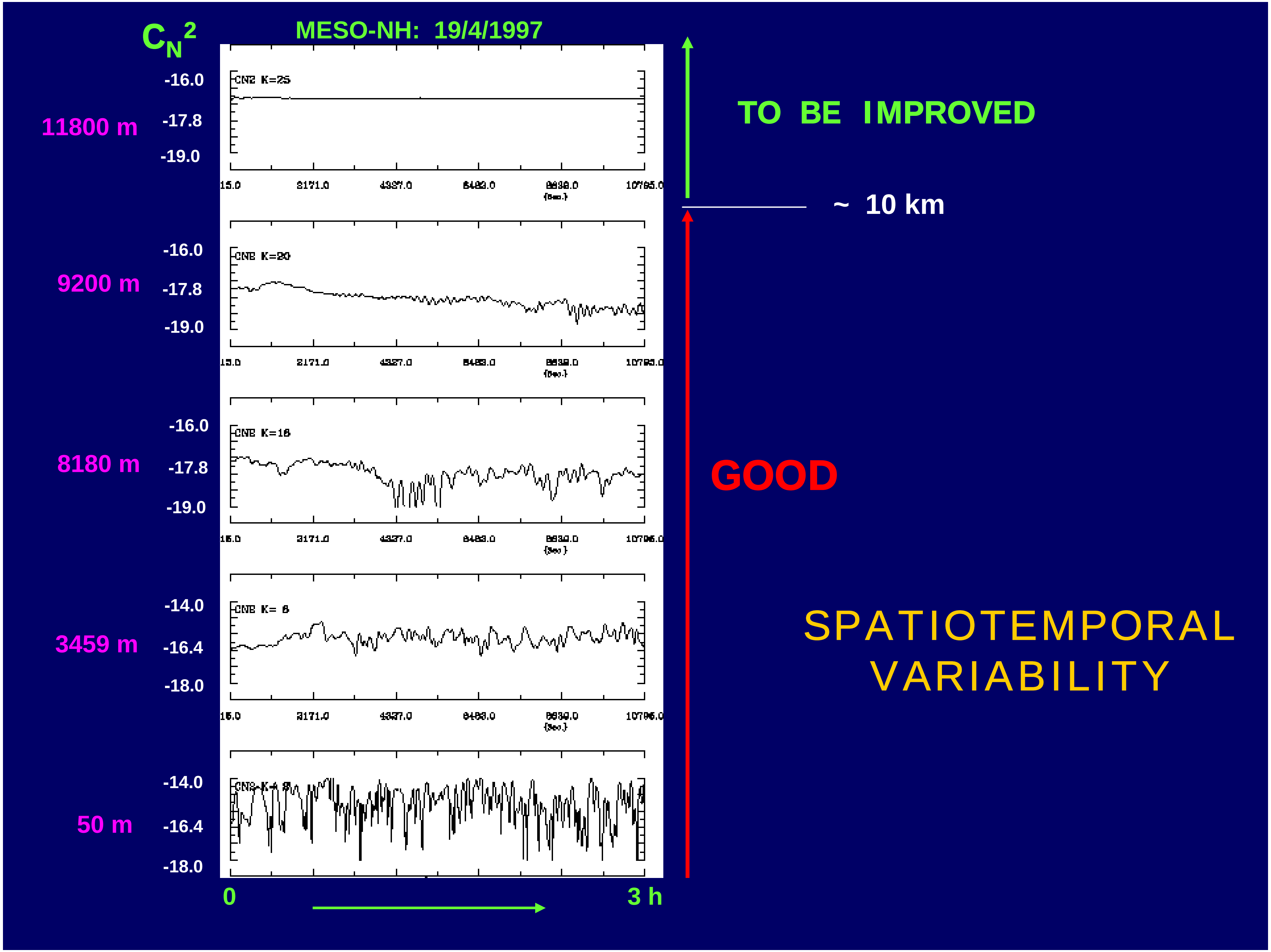
(m)



ISOPLANATIC ANGLE

(arcsec)



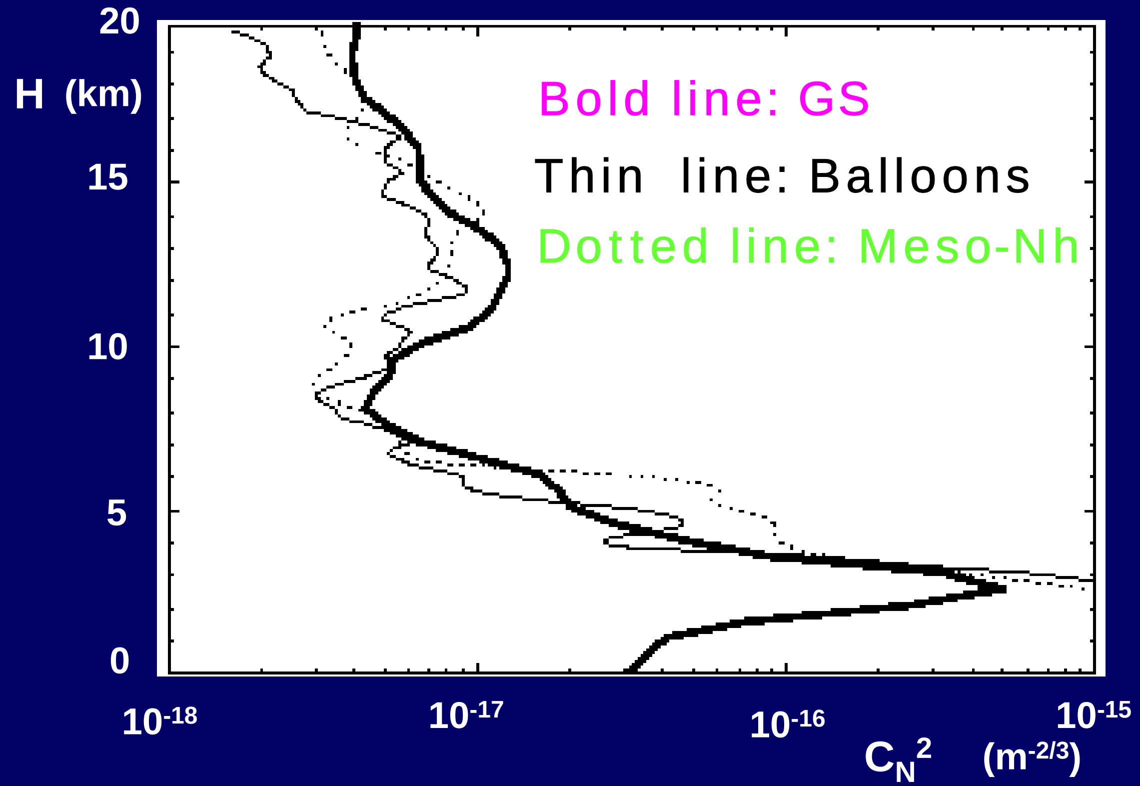


MESO-NH: 19/4/1997
C_N^2
11800 m
9200 m
8180 m
3459 m
50 m
-16.0
-17.8
-19.0
-14.0
-16.4
-18.0
CN2 K=25
CN2 K=20
CN2 K=16
CN2 K= 6
15.0
2171.0
4327.0
6483.0
8639.0
10795.0
(Sec.)
0
3 h
TO BE IMPROVED
~ 10 km
GOOD
SPATIOTEMPORAL
VARIABILITY

MODEL RELIABILITY

Averaged estimate over 10 nights

Masciadri, Avila & Sanchez, 2004, RMxAA, 40, 3



	GS - dome	MNH - surf.
ε_{TOT}	0.79 ''	0.93 ''
ε_{BL}	0.62 ''	0.77 ''
ε_{FA}	0.42 ''	0.45 ''

$\Delta\varepsilon_{TOT} \sim 0.14$ ''

SCORE OF SUCCESS

GS – Meso-Nh $\Delta\varepsilon \sim 30\ \%$

- Masciadri, Avila & Sanchez, 2004, RMxAA, 40, 3

GS – Balloons $\Delta\varepsilon \sim 30\ \%$

- Azouit & Vernin, PASP, 2005

- Masciadri, Avila & Sanchez, 2004, RMxAA, 40, 3

GS – MASS $\Delta\varepsilon \sim 20\ \%$ @ **[8 - 16] km**

$\Delta\varepsilon \sim 50\text{-}100\ \%$ @ **[0 - 4] km**

- **Tokovinin et al., Report**
  http://www.ctio.noao.edu/~atokovinin/profiler/mk.html

SCORE OF SUCCESS

GS – Meso-Nh $\Delta\varepsilon \sim 30$ %

- **Masciadri, Avila & Sanchez, 2004, RMxAA, 40, 3**

GS – B

- **Azouit**

- **Mascia**

GS – M

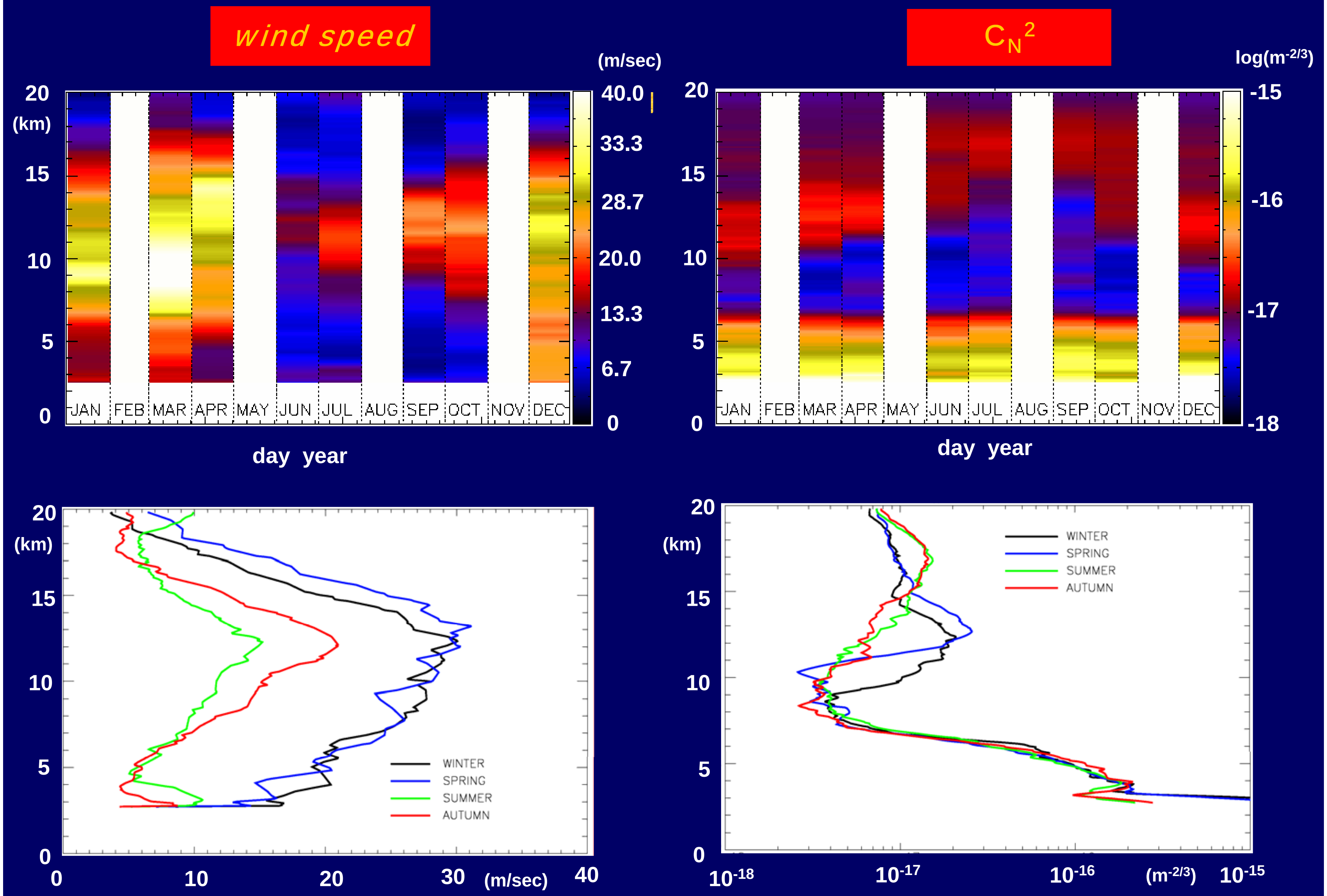
$\Delta\varepsilon \sim 50\text{-}100$ % **@ [0 - 4] km**

- **Tokovinin et al., Report**
  http://www.ctio.noao.edu/~atokovinin/profiler/mk.html

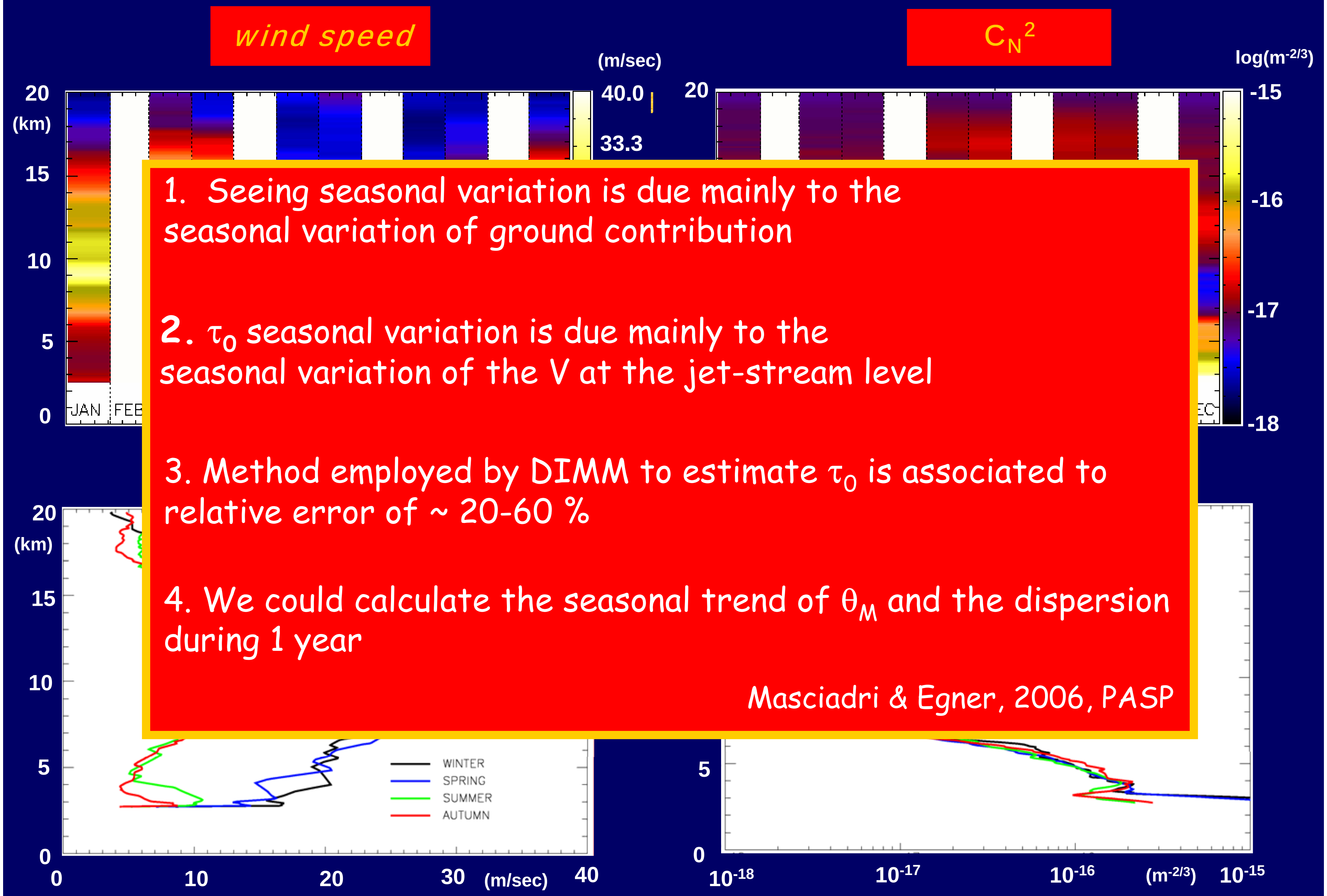
1. Meso-Nh can be considered a vertical profiler

2. Meso-Nh can be run autonomously

San Pedro Martir (Baja California)



San Pedro Martir (Baja California)



1. Seeing seasonal variation is due mainly to the seasonal variation of ground contribution

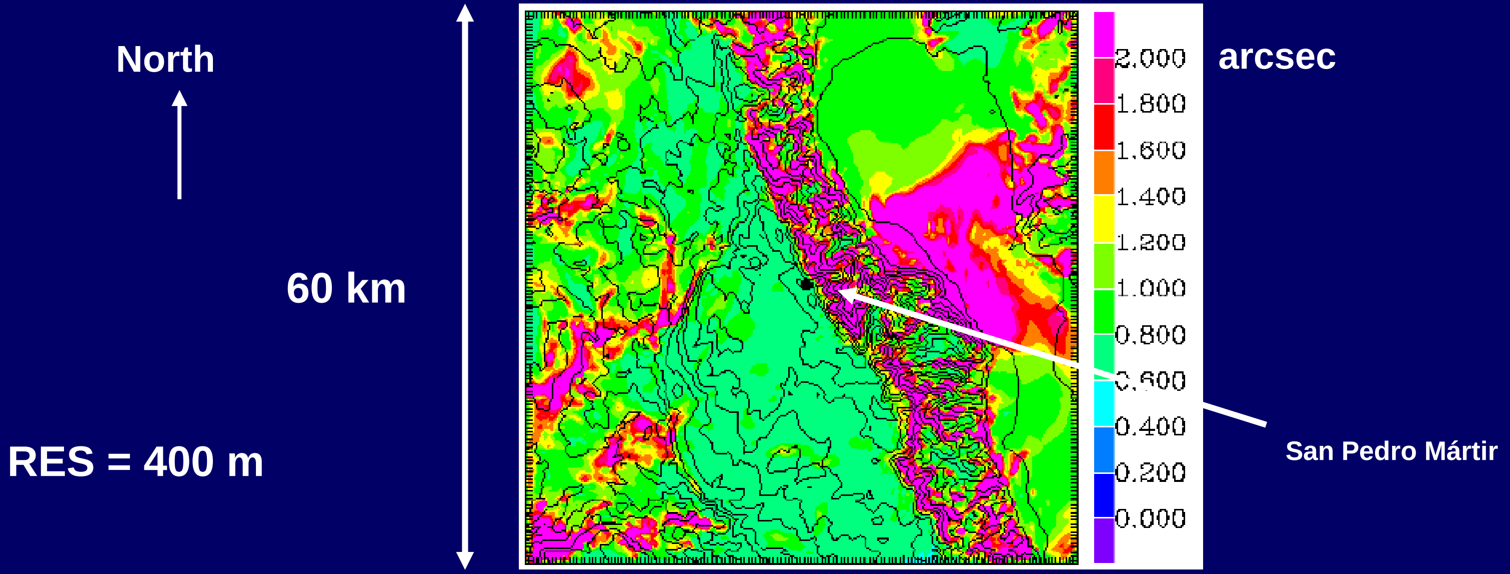
2. τ_0 seasonal variation is due mainly to the seasonal variation of the V at the jet-stream level

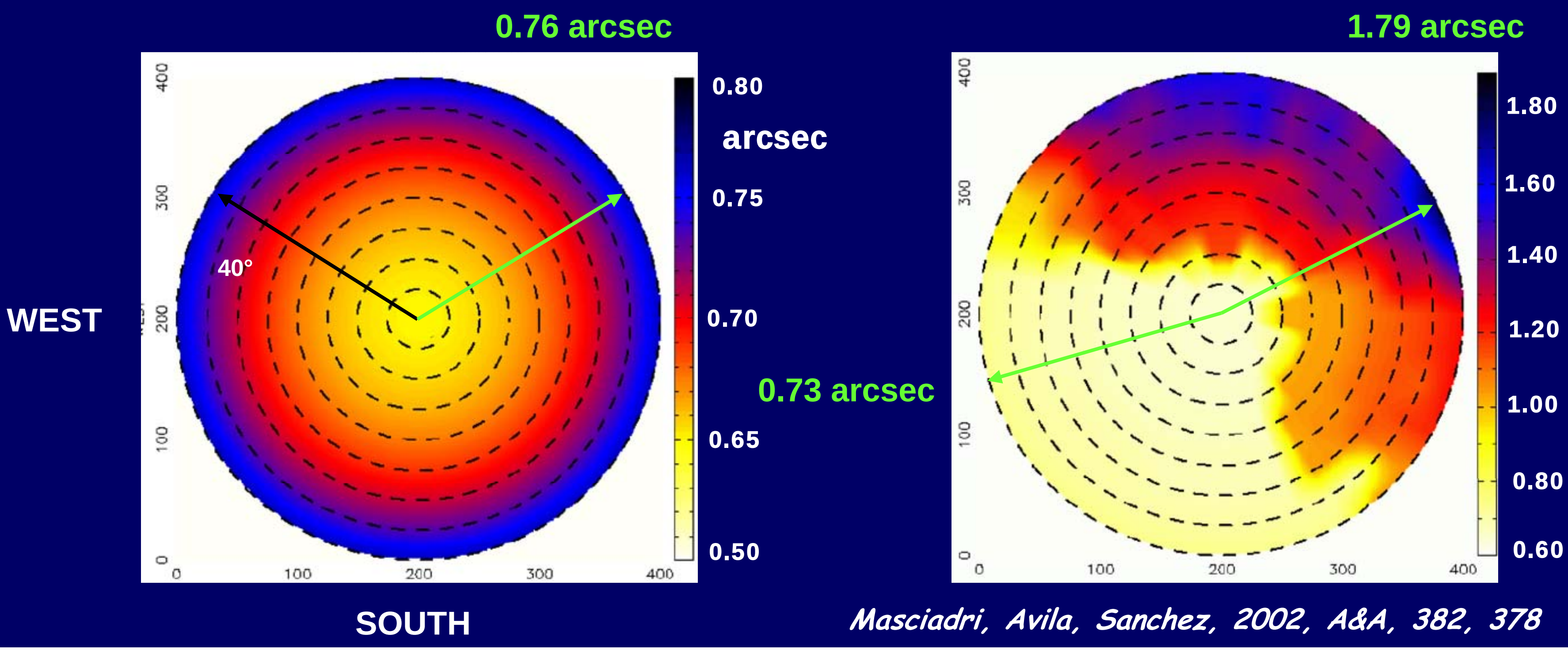
3. Method employed by DIMM to estimate τ_0 is associated to relative error of ~ 20-60 %

4. We could calculate the seasonal trend of θ_M and the dispersion during 1 year

Masciadri & Egner, 2006, PASP

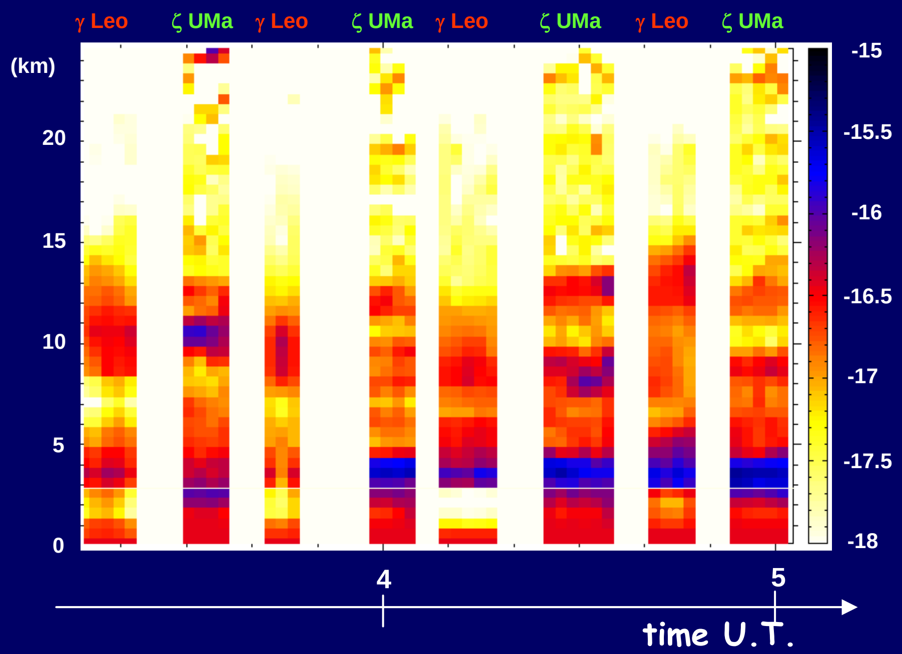
SEEING: San Pedro Mártir (Mx)

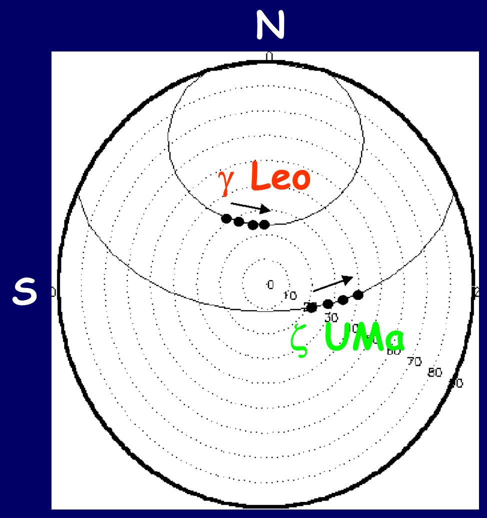




Masciadri, Avila, Sanchez, 2002, A&A, 382, 378

San Pedro Martir 22 May 2000



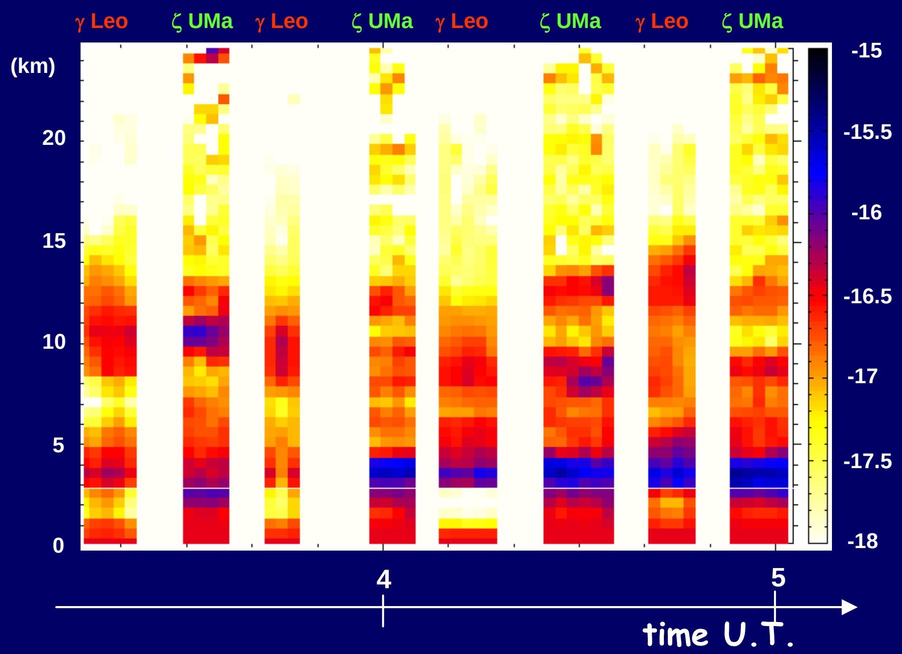


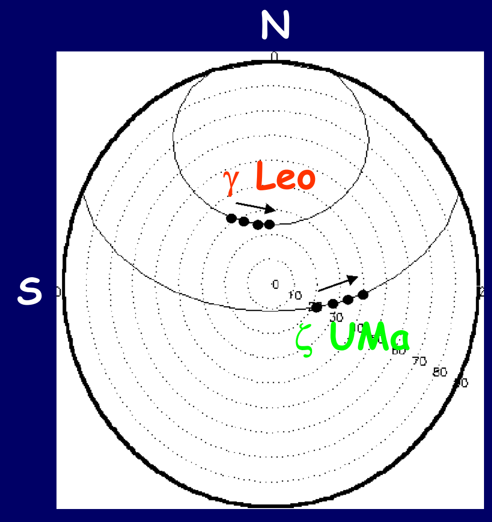
SKY MAP

Param.(")	γLeo	ζUMa	γLeo	ζUMa	γLeo	ζUMa	γLeo	ζUMa
$\varepsilon_{[0-10km]}$	0.38	0.58	0.38	0.76	0.58	0.84	0.71	0.91
$\varepsilon_{[10km-20km]}$	0.30	0.44	0.24	0.27	0.29	0.31	0.35	0.26
ε_{TOT}	0.52	0.78	0.48	0.84	0.63	0.93	0.83	0.97

Masciadri, Avila, Sanchez, 2002, A&A, 382, 378

San Pedro Martir 22 May 2000





SKY MAP

Δε ~ 0.3" for θ < 40°
up to high altitudes

Param.(")	γLeo					a	γLeo	ζUMa
$\varepsilon_{[0-10km]}$	0.38	0.38	0.38	0.76	0.38	0.84	0.71	0.91
$\varepsilon_{[10km-20km]}$	0.30	0.44	0.24	0.27	0.29	0.31	0.35	0.26
ε_{TOT}	0.52	0.78	0.48	0.84	0.63	0.93	0.83	0.97

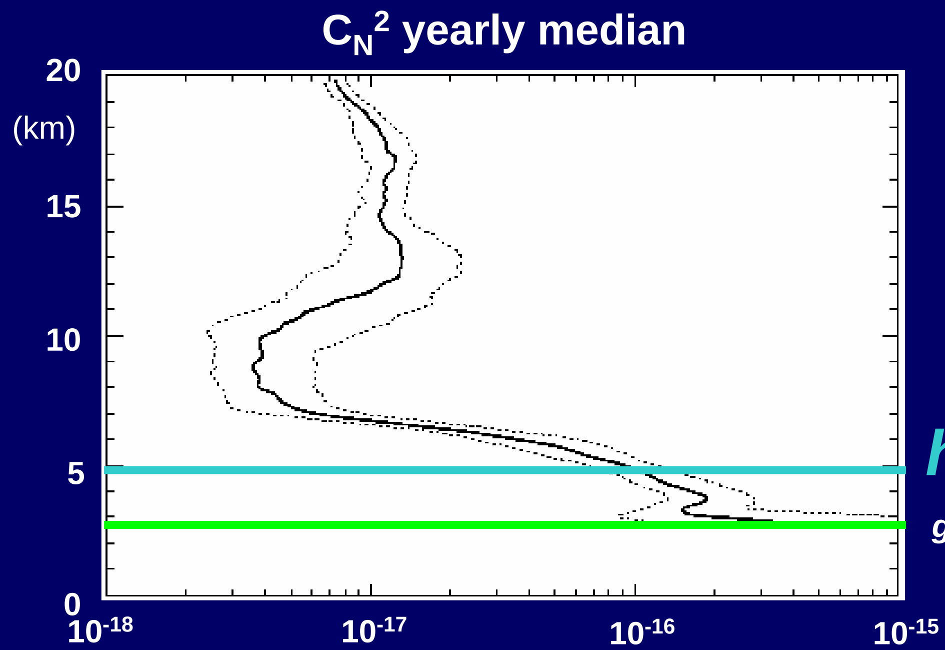
Masciadri, Avila, Sanchez, 2002, A&A, 382, 378

How can the optical turbulence characterization concretely support:

1. AO systems

2. Astronomical Observations

Do we really need to know where the turbulence is ?



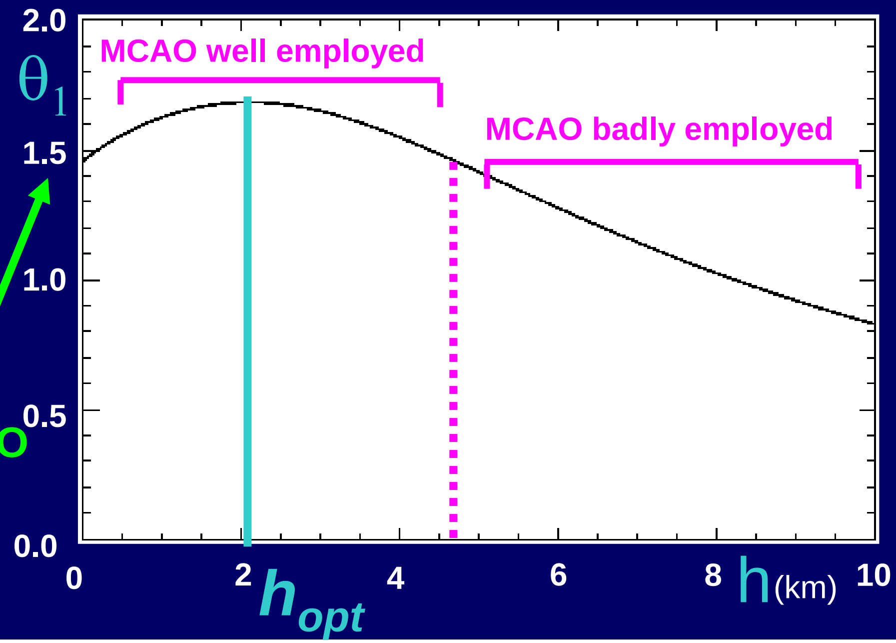
Masciadri & Egner, 2006, PASP, 118, 849

$$\vartheta_M = \left[2.9 \cdot \left(\frac{2\pi}{\lambda} \right)^2 \cdot (\sec z)^{8/3} \cdot \int_0^{h_{max}} C_N^2(h) F_M(h, h_{opt}) dh \right]^{-3/5}$$

$$F_0(h) = h^{5/3}; h_{opt} = 0$$

$$F_1(h) = \left| h - h_{opt} \right|^{5/3}$$

classical AO



EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	74	NACO	22h	any	n	$\leq 0.6''$	CLR	s

M_J. We should thus be able to detect any methane rich planetary-mass object around the selected targets.

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	74	NACO	22h	any	n	$\leq 0.6''$	CLR	s

Observing constraints

4. Number of nights/hours | Telescope(s) | Amount of time

a) already awarded to this project:

b) still required to complete this project:

5. Special remarks. (e.g., indicate here if this is a ToO proposal applying for RRM)

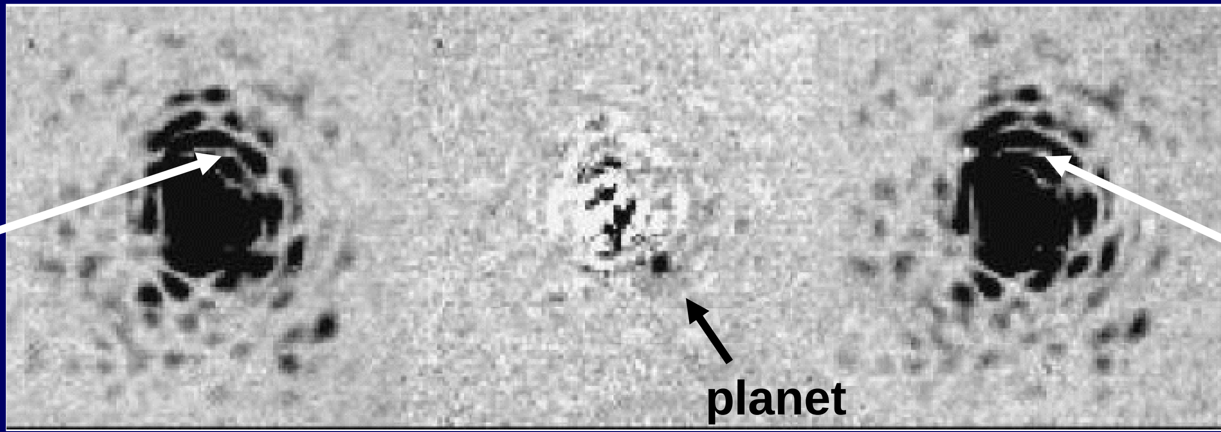
6. Principal Investigator: E. Masciadri (MPIA, Heidelberg, D, masciadr@mpia.de)

CoI(s): S. Kellner (MPIA, D), W. Brandner (MPIA, D), Th. Henning (MPIA, D), R. Lenzen (MPIA, D), L. Close (Steward Observatory, USA), B. Biller (Steward Observatory, USA)

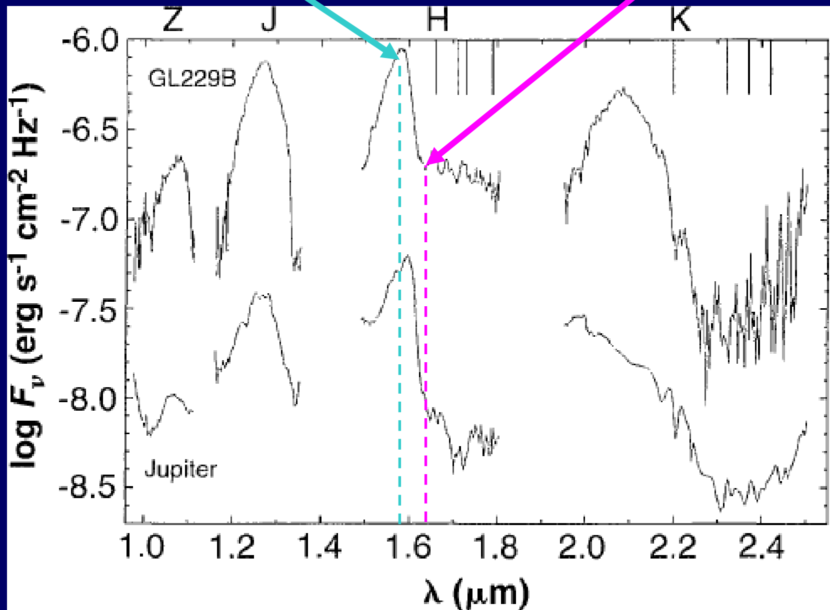
7. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

Simultaneous Differential Imaging → SDI

λ_1=1.57 μm $\lambda_1 - \lambda_2$ λ_2=1.62 μm

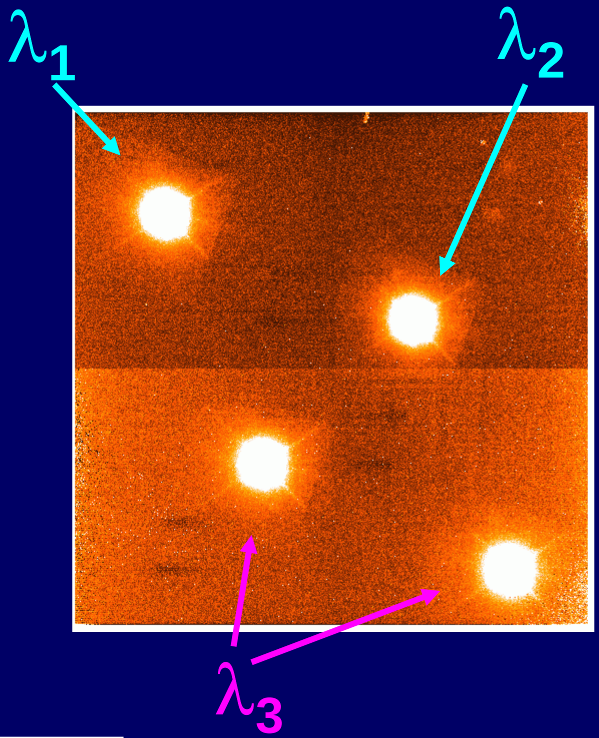


λ_1 λ_2 (CH$_4$ absorption)



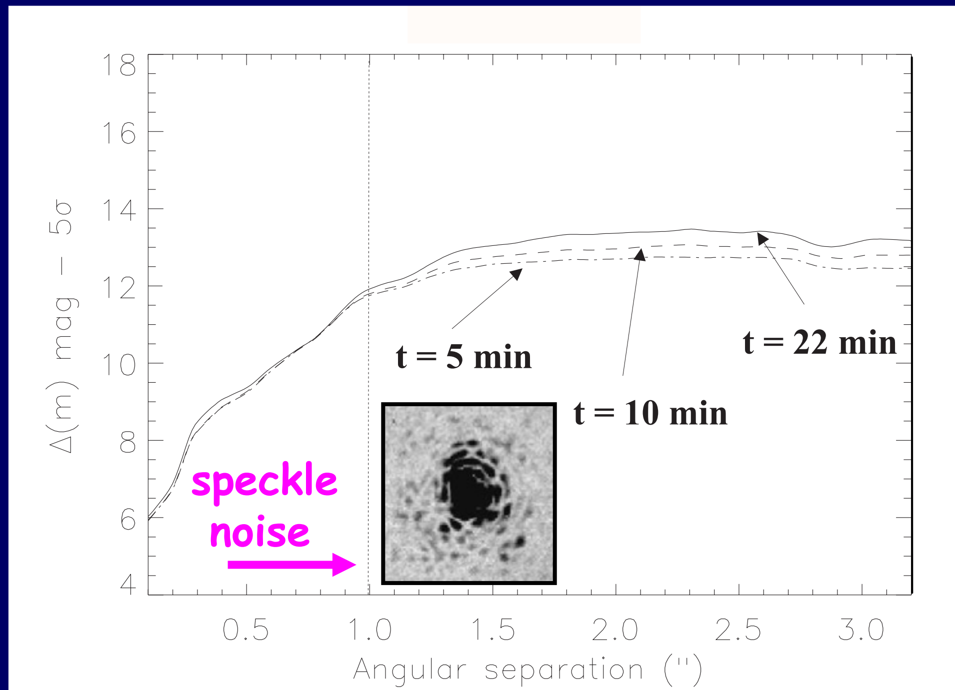
SDI/NACO available from P74

'off' CH4 absorption band



'on' CH4 absorption band

SDI/NACO detector



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3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	74	NACO	22h	any	n	$\leq 0.6''$	CLR	s

"Better" Service Mode

ε: **seeing**

τ_0: **wavefront coherence time**

θ_0: **isoplanatic angle**

ect.

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	74	NACO	22h	any	n	$\leq 0.6''$	CLR	s

Observing constraints

τ_0 > 5-6 msec

4. Number of nights/hours   Telescope(s)   Amount of time
a) already awarded to this project:
b) still required to complete this project:

5. Special remarks. (e.g., indicate here if this is a ToO proposal applying for RRM)

6. Principal Investigator: E. Masciadri (MPIA, Heidelberg, D, masciadr@mpia.de)
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7. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

My vision of FLEXIBLE-SCHEDULING

Optimization of programs management

↓

Analytic Operator

Imaging
Spectroscopy
Interferometry

Turbulence

target magnitude

- $$SNR_{\lambda,MODE} = \overbrace{r_0^{\,a}(\lambda)\cdot\vartheta_0^{\,b}(\lambda)\cdot\tau_0^{c}(\lambda)\cdot\mathcal{L}_0^{d}(\lambda)}\cdot M^{\,f}$$

- $$FS_{\lambda,MODE} = {\color{red}PS}\cdot C\cdot SNR_{\lambda,MODE}$$

Scientific Program

Cloud cover

END