
The Design Reference Mission
of the
European Extremely Large Telescope
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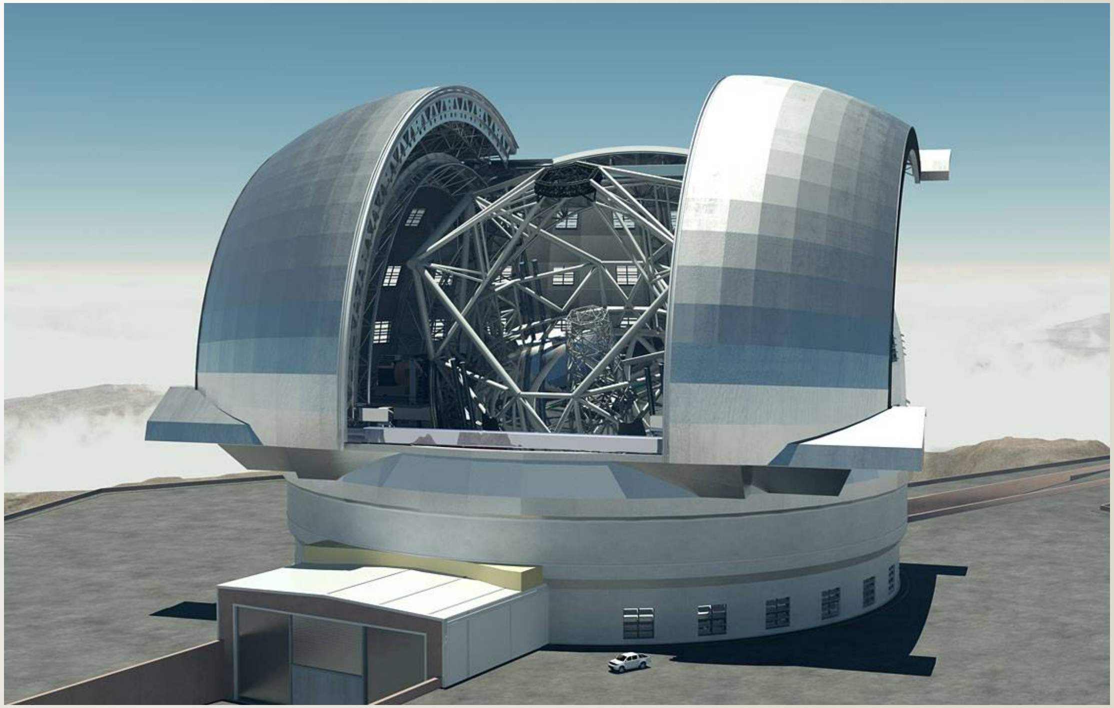
E-ELT Science Office

Background

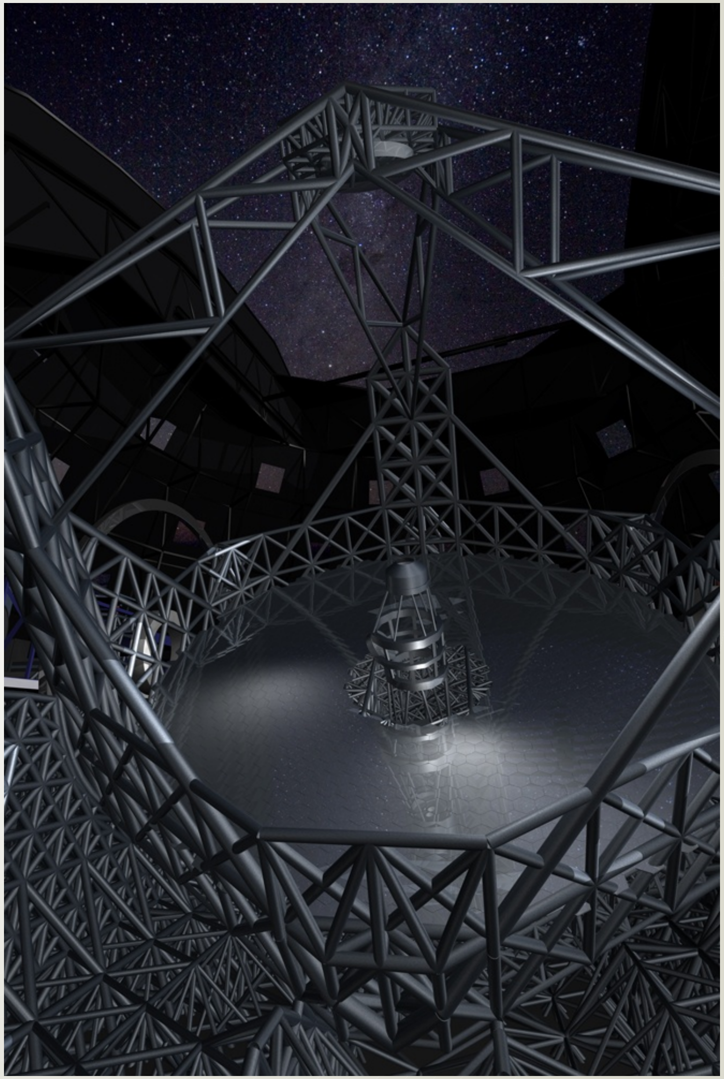
In 2004 ESO Council resolved that:

- ESO's highest priority strategic goal must be the European retention of astronomical leadership and excellence into the era of Extremely Large Telescopes...
- The construction of an Extremely Large Telescope on a competitive timescale will be addressed by radical strategic planning ... for fast implementation.



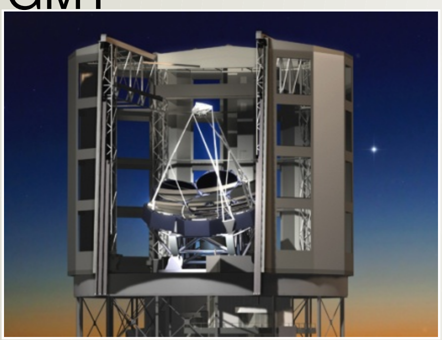
The E-ELT

- 40-m class telescope: largest optical-infrared telescope in the world
- Segmented primary mirror
- Active optics to maintain collimation and mirror figure
- Adaptive optics assisted telescope
- Diffraction limited performance
- Wide field of view: 10 arcmin
- Mid-latitude site (Armazones in Chile)
- Fast instrument changes
- VLT level of efficiency in operations



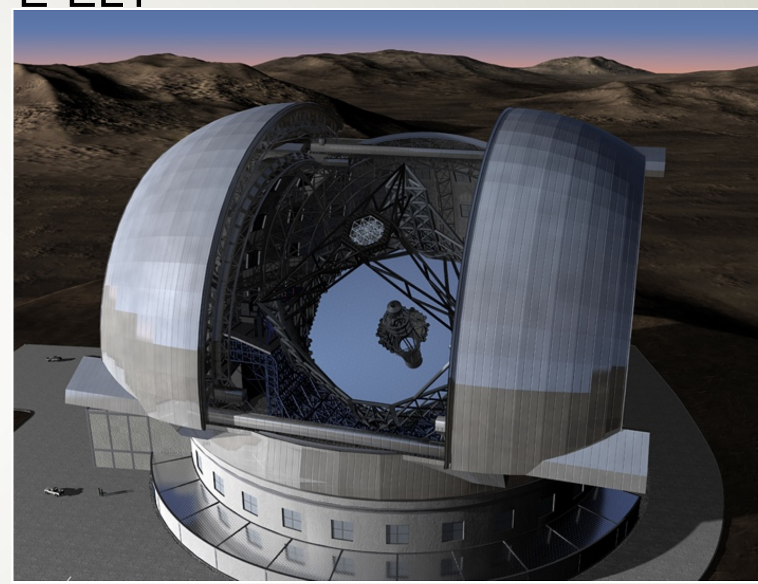
ELT comparison

GMT



TMT

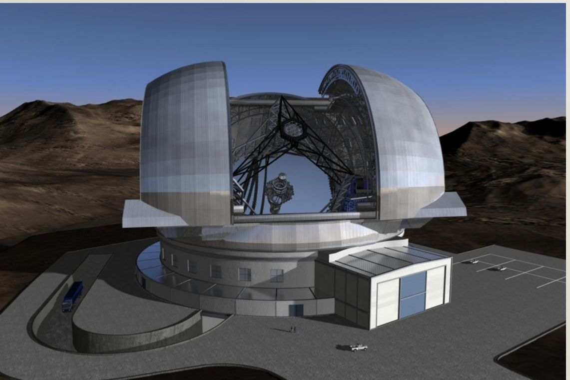
E-ELT

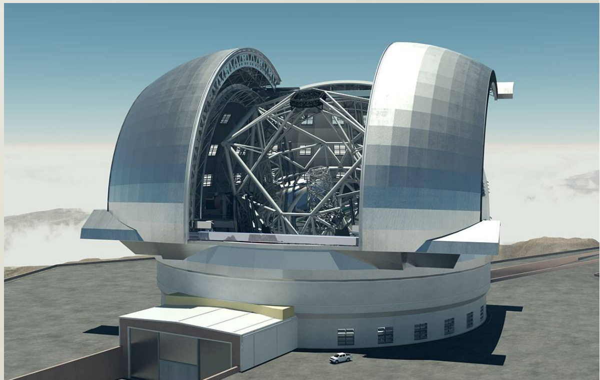


	GMT	TMT	E-ELT
Diameter:	25.4 m	30 m	39.3 m
Collecting area:	382 m^2	655 m^2	978 m^2
Diff. limit at 1µm:	9.9 mas	8.4 mas	6.4 mas

Current status in a nutshell

- Top priority of European ground-based astronomy (on Astronet and ESFRI lists).
- Project (led by ESO) completed its detailed design phase (Dec 2006 – Dec 2010), with a total budget of 64 M€ from ESO + 35 M€ from EC Framework Programmes (FP6/FP7).
- Final Design Review passed in Sep 2010.
- 8 instrument + 2 AO module concept studies completed → 2 first-light insts selected.
- Site selected: Cerro Armazones in Chile.
- Dec 2010 – Jun 2011: Delta Phase B: exploring options to reduce cost and risk.
- Jun 2011: change of baseline design: 42 m → 39 m.
- Cost review in Sep 2011.
- Construction planned to begin in 2012.
- Start of operations early next decade.
- Construction cost: ~1 B€ (incl first-light instrumentation).



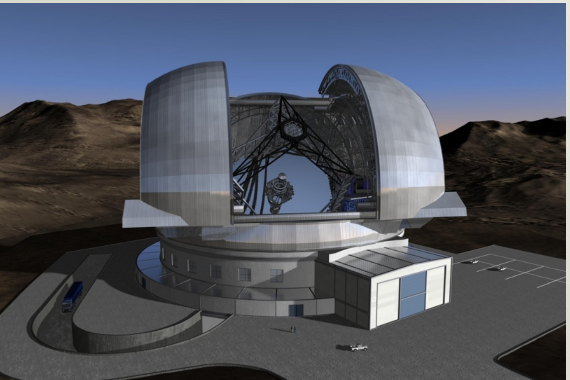


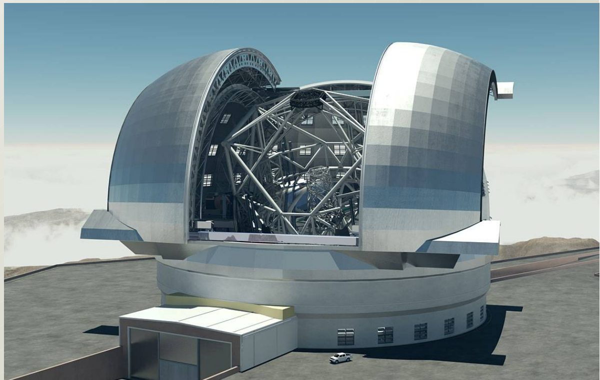
Recent design revision

- Result of Delta Phase B: in June 2011 ESO Council endorsed a revised baseline design for the E-ELT.
- The overall concept of the original design remains unchanged.
- Main changes:
  - Reduction of primary mirror diameter by removing two rings of segments:

	Largest fully enclosed D	Circumscribing D	Area	Segments
Original 42-m design:	41.3 m	43.2 m	1223 m^2	984
New design:	37.0 m	39.3 m	978 m^2	798

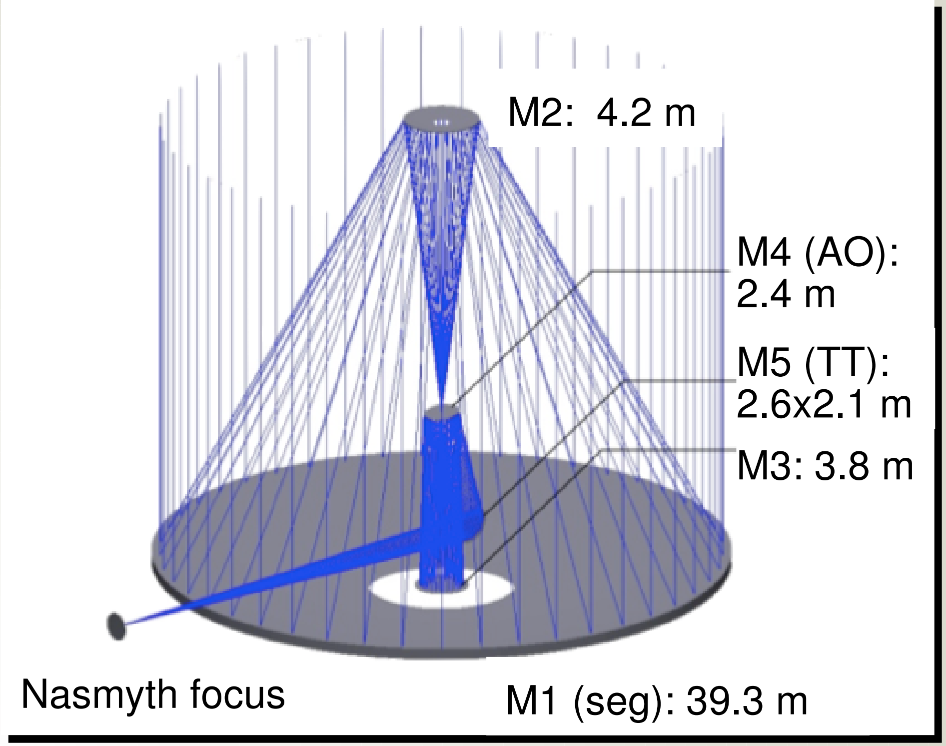
  - Faster f-ratio.
  - Loss of gravity invariant focal station.
- Instrumentation plans and budget remain unchanged.

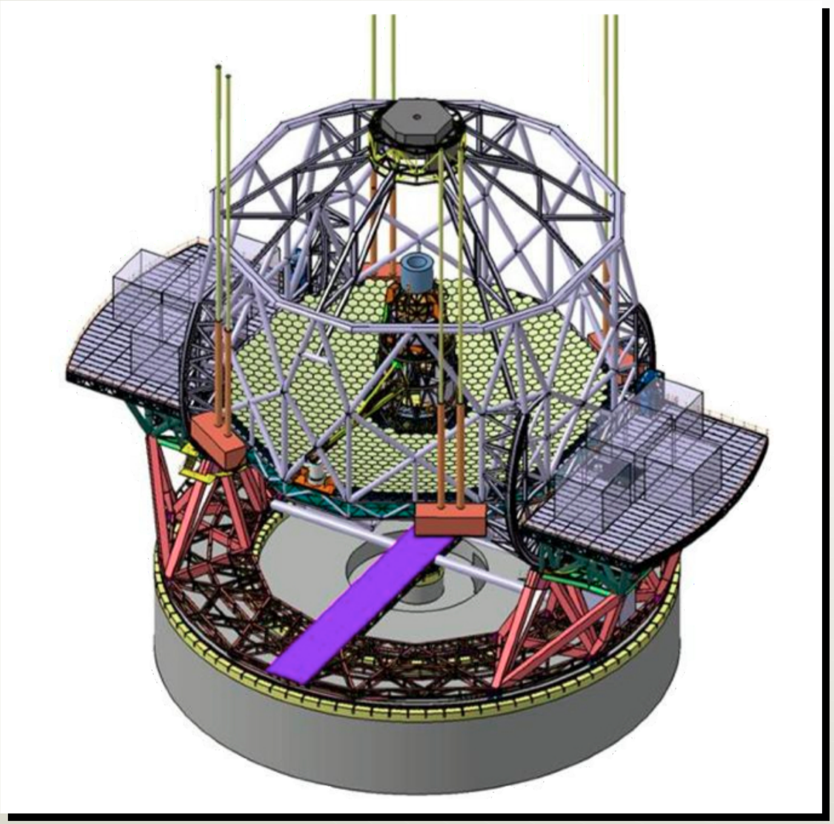




The Telescope

- Nasmyth telescope with a segmented primary mirror.
- Novel 5 mirror design to include adaptive optics in the telescope.
- Classical 3-mirror anastigmat + 2 flat fold mirrors (M4, M5).

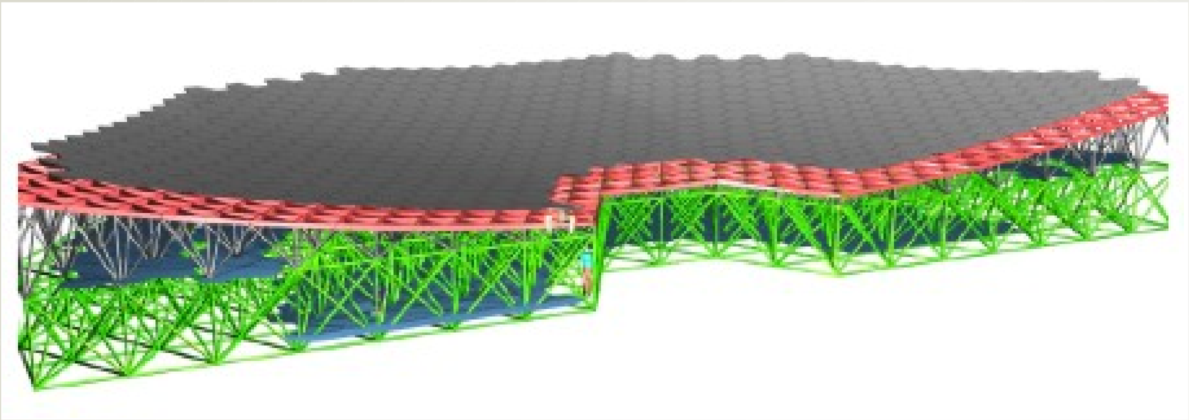


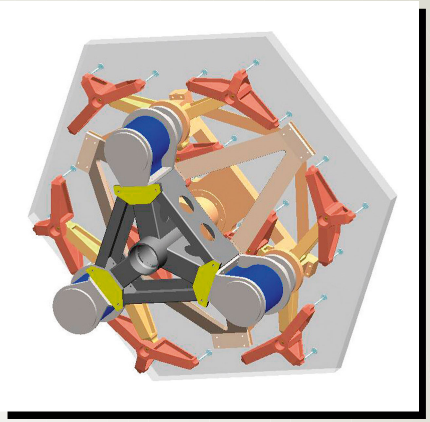


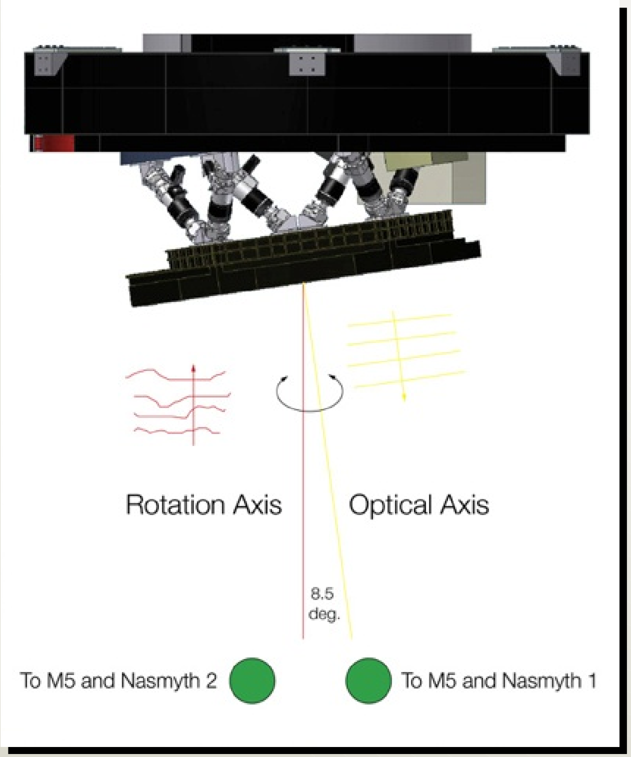
- Two instrument platforms nearly the size of tennis courts can host 3 instruments each + Coudé lab.
- Six laser guide stars (provisions for eight), launched from the side.
- Nearly 3000 tonnes of moving structure.

The Mirrors

M1: 39.3 m, 798 hexagonal segments of 1.45 m tip-to-tip: 978 m² collecting area





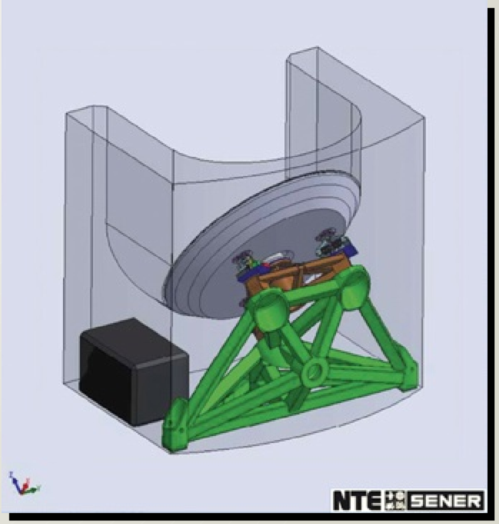


M4: 2.4 m, flat, adaptive

6000 to 8000 actuators

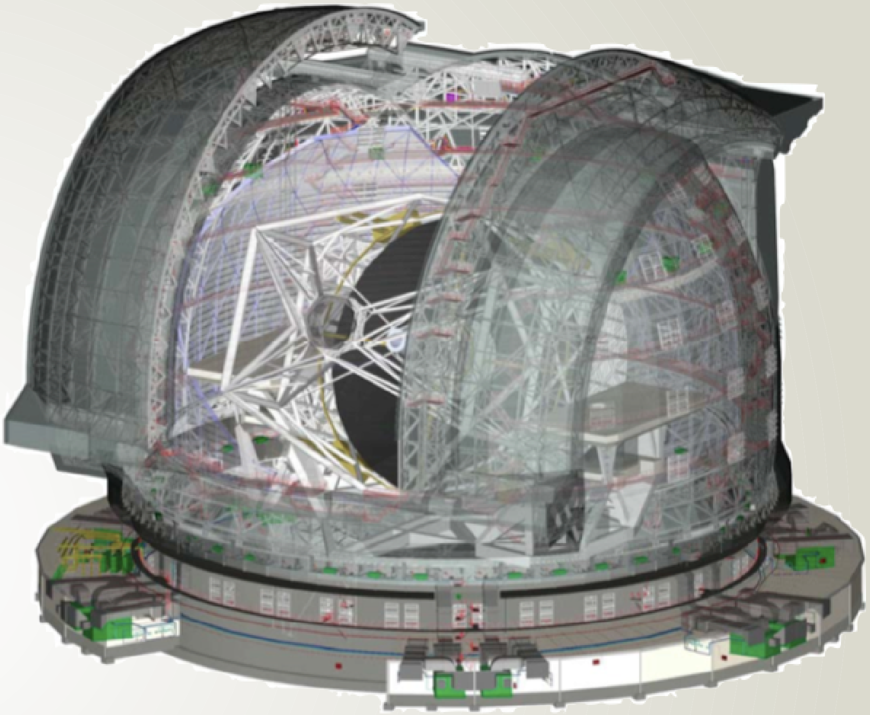
M5: 2.6 x 2.1 m, flat,

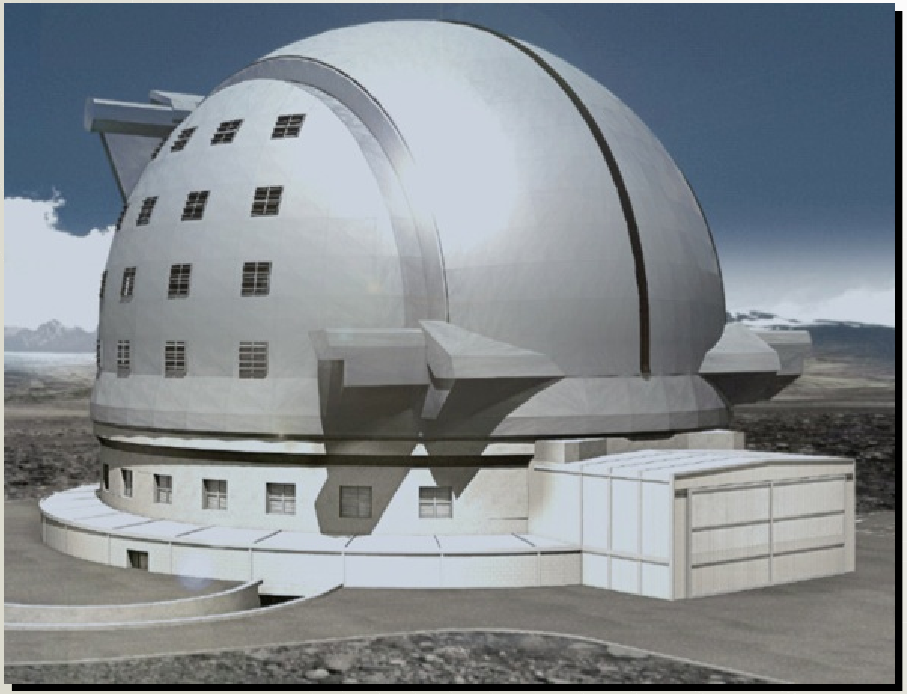
provides tip-tilt correction

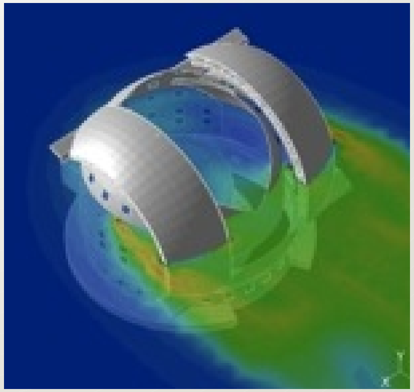


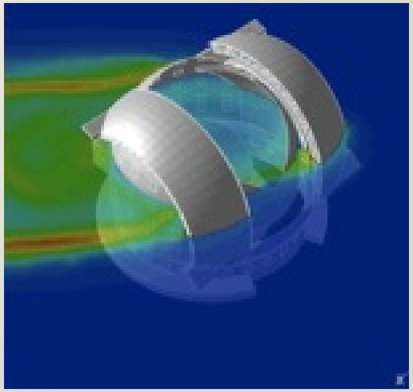
The Dome

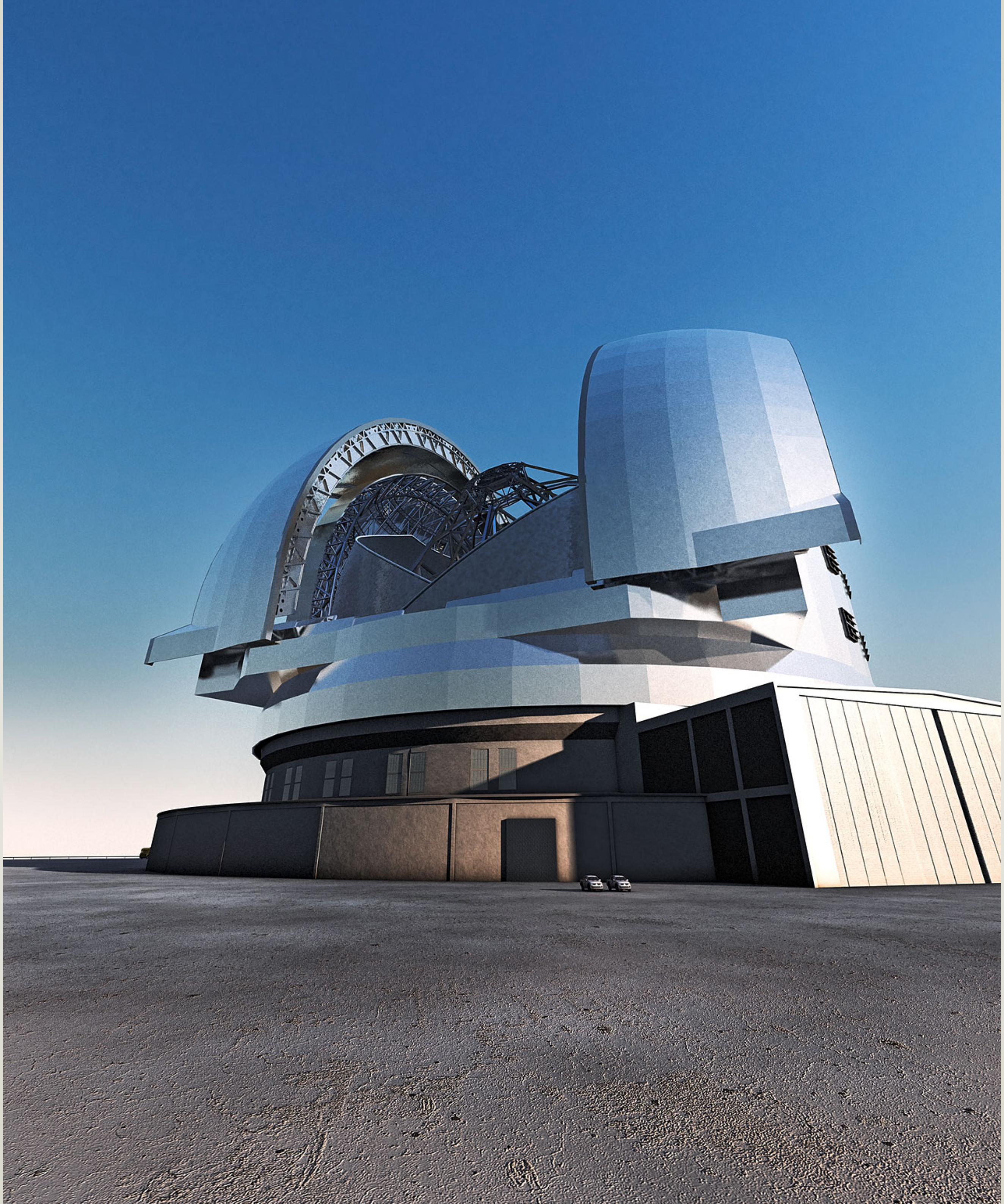
- Rather classical design.
- Diameter = 86 m, height = 74 m.
- ~3000 tonnes of steel.
- Fully air-conditioned and wind shielded.





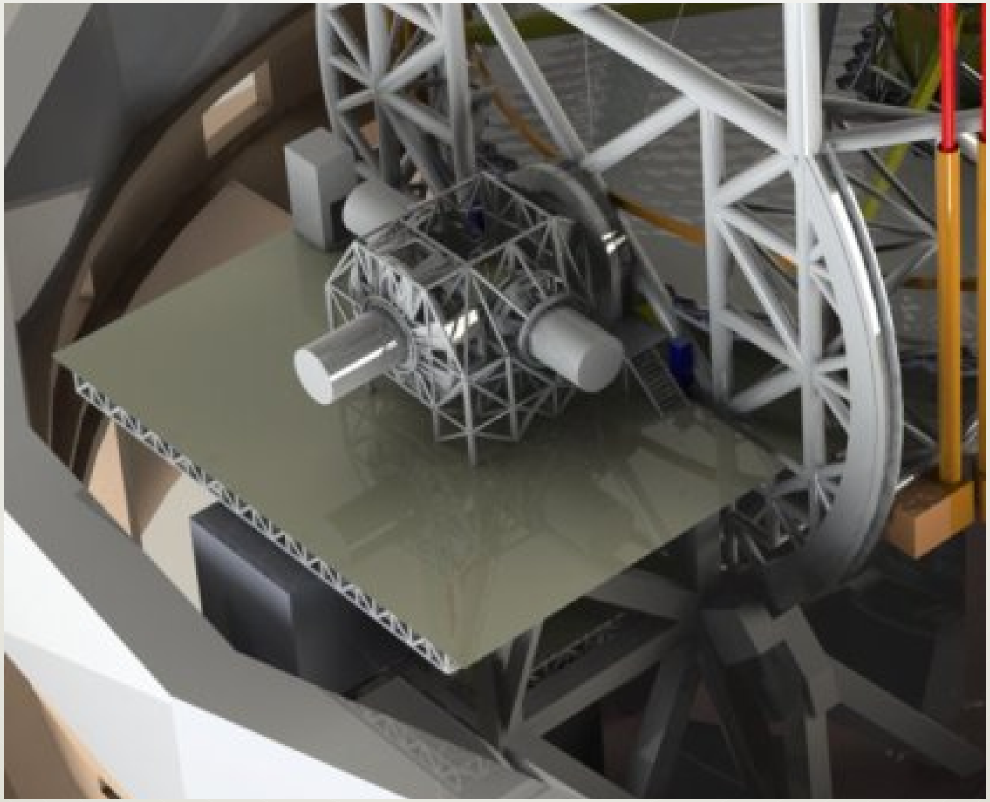






Instrumentation

In principle, the telescope can host up to 8 instruments:
3 on each Nasmyth platform, 2 in the Coudé lab.



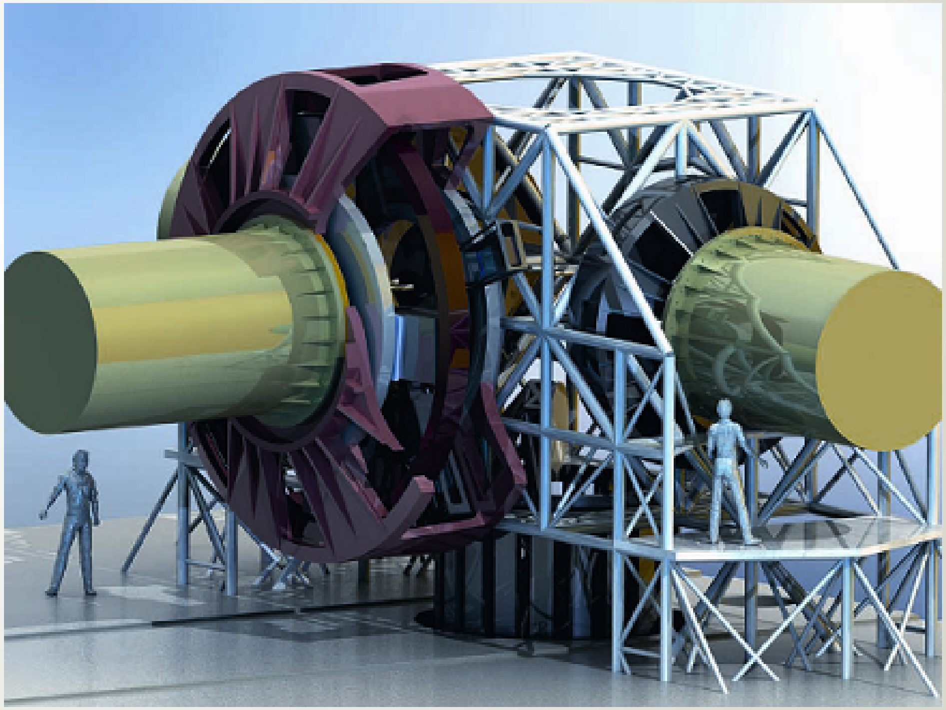
Instrument and AO modules study plan

April 2007

- Goal: definition of a first generation instrument set to be included in the E-ELT construction proposal.
- Scope:
  - Carry out a suitable number of instrument studies to verify that instruments can be built at an affordable cost and that they properly address the scientific goals of highest priority.
  - Work with the ESO community in studying 8 instruments + 2 AO modules and to prepare for construction.
  - Work with with telescope and operation POs to identify and define interfaces with the other subsystems and the observatory infrastructure.
- Budget: 2.3 M€ (2007 – 2010).

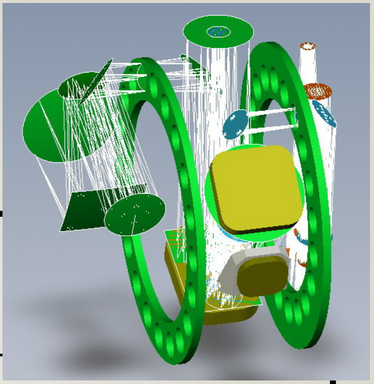
Instrumentation studies

- 8 instrument concept (phase A) studies
- 2 post-focal adaptive optics module studies
- Scope:
  - Detail the science case.
  - Finalize the instrument requirements.
  - Develop an instrument concept including cost and construction schedule.

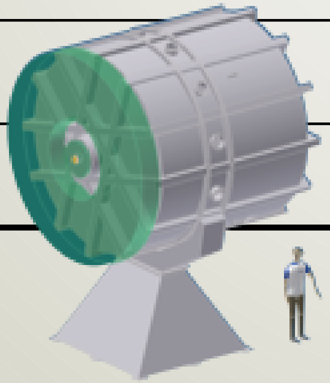


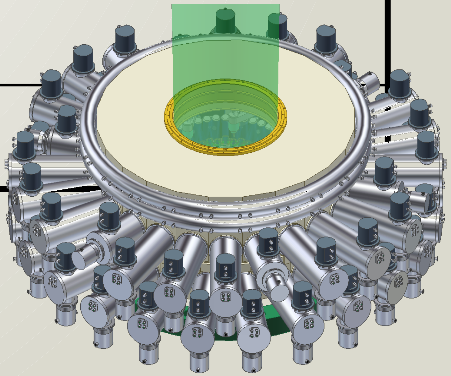
- All phase A studies were successfully completed by early 2010.

Phase A studies

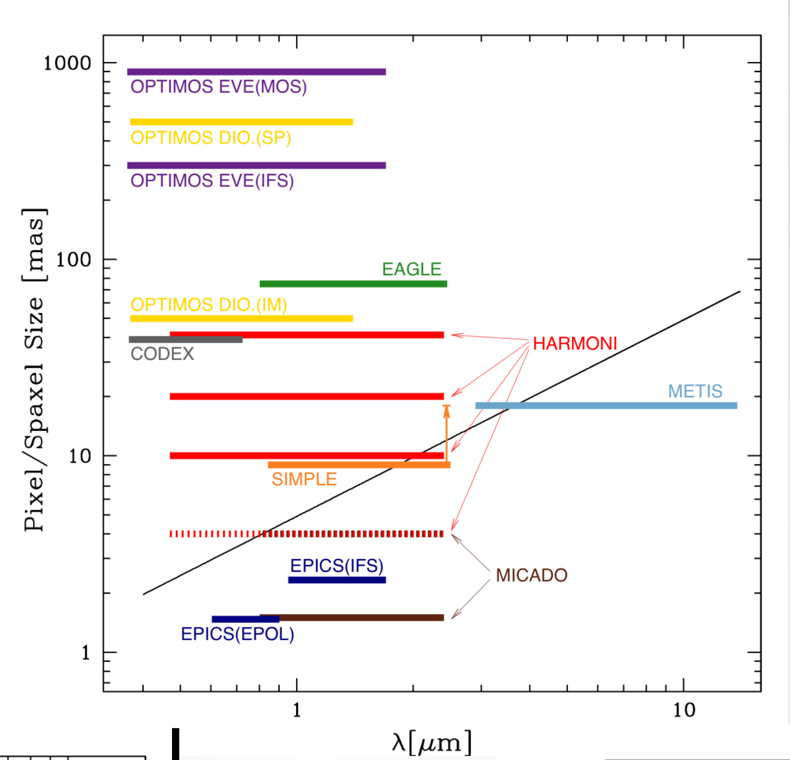


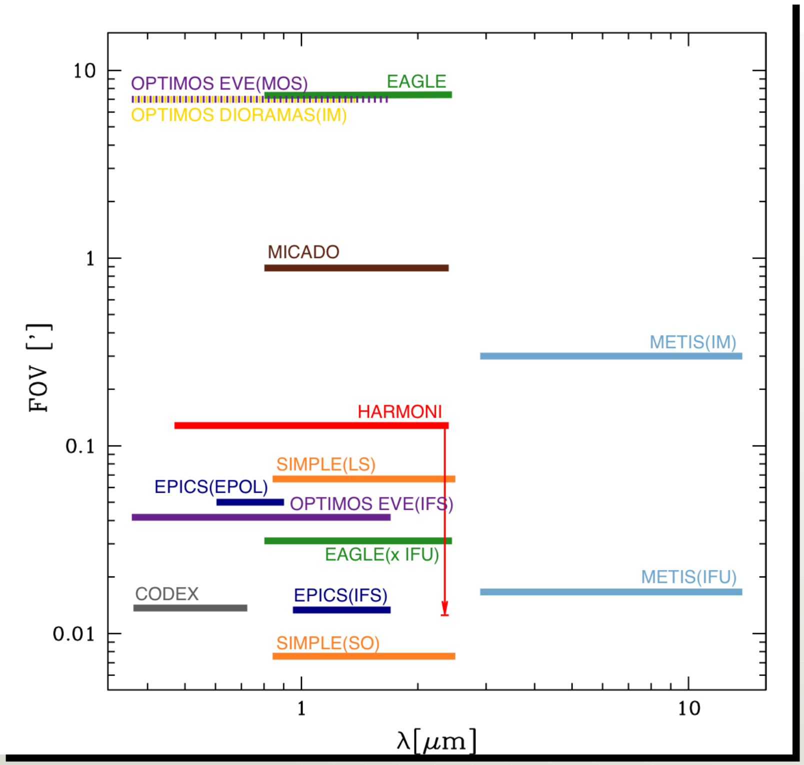
CODEX	High-resolution, high-stability optical spectrograph
EAGLE	Wide-field NIR multi-IFU
EPICS	Extreme AO planet imager and spectrograph
HARMONI	Single field NIR wide-band IFU
METIS	MIR imager and spectrograph
MICADO	Diffraction limited NIR imager
OPTIMOS	Wide-field optical MOS
SIMPLE	High-resolution NIR spectrograph
ATLAS	Laser Tomography AO module
MAORY	Multi Conjugate AO module

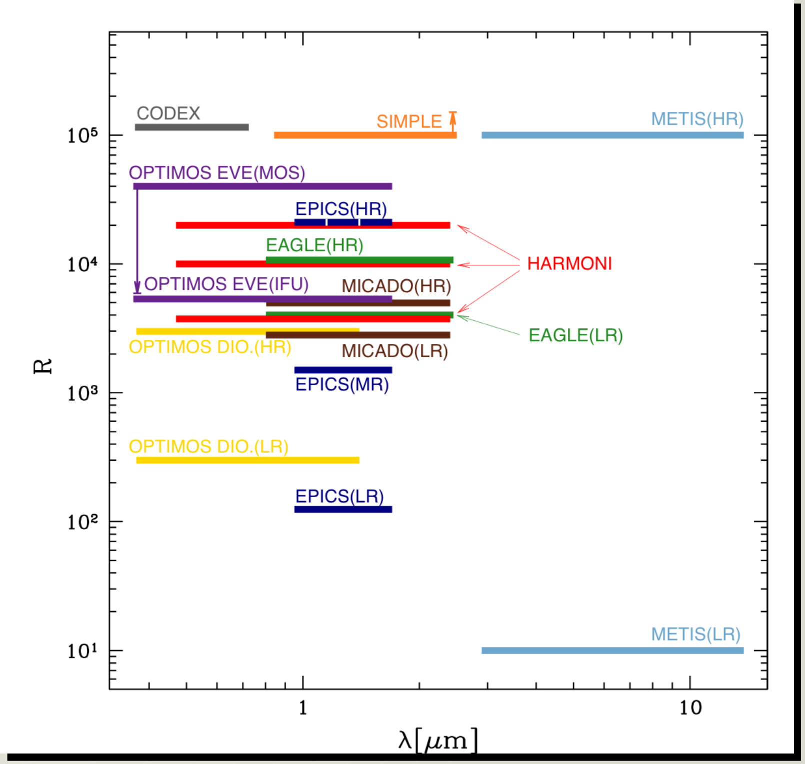




Parameter space covered by phase A studies



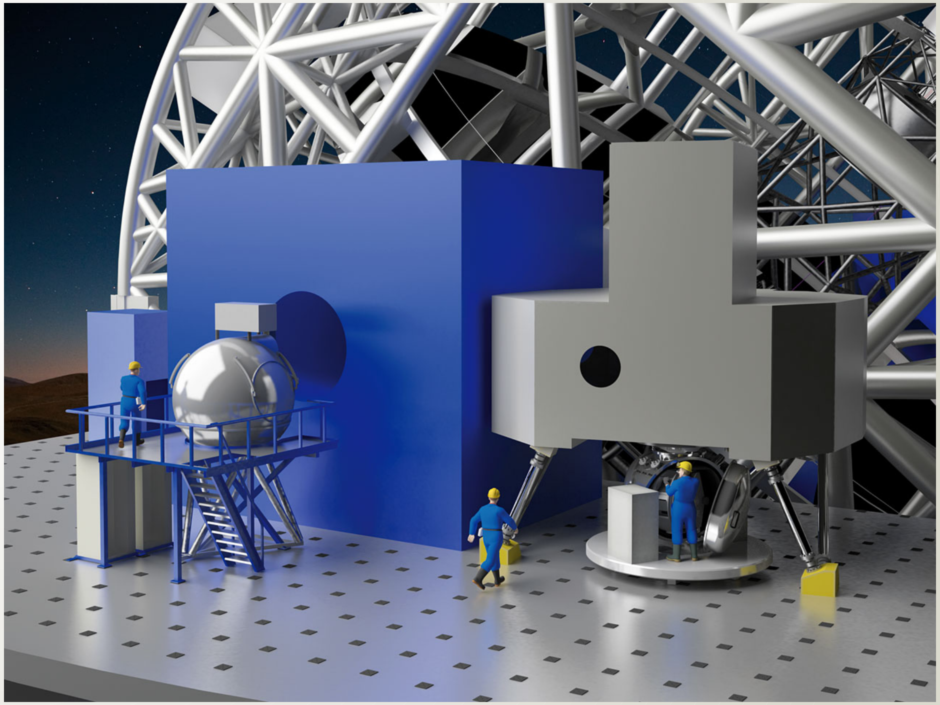




Instrumentation

Current plan (under development):

- Following recommendations by the SWG and STC, 2 first-light instruments have been identified.
- All phase A studies remain in the pool of possible instruments.
- Kick-off of first-light instruments: 2012.
- Kick-off for #3: 2014.
- Thereafter start a new instrument every 2 years.



The Site

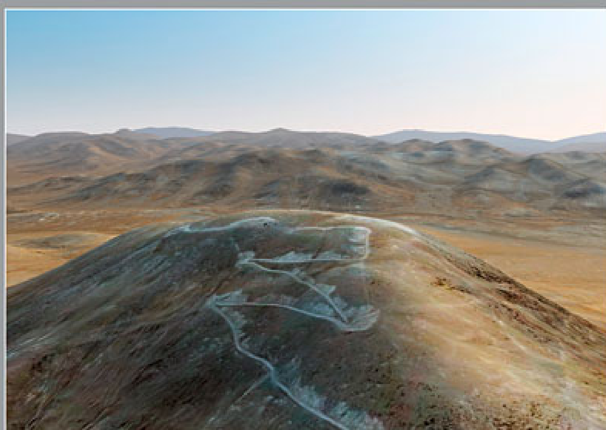
Following an extensive site testing campaign, involving several sites in Chile, Morocco, the Canary Islands, Argentina, Mexico, ... , ESO Council selected Cerro Armazones as the E-ELT site.

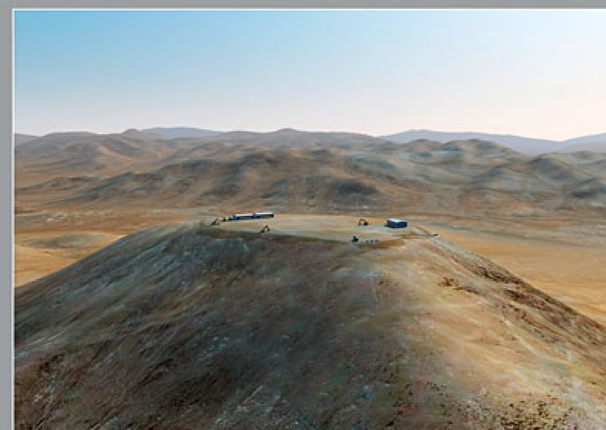
Selection criteria: impact on science, outstanding atmosphere, but also construction and operations logistics (roads, water, electricity, nearby cities, ...).

The Site

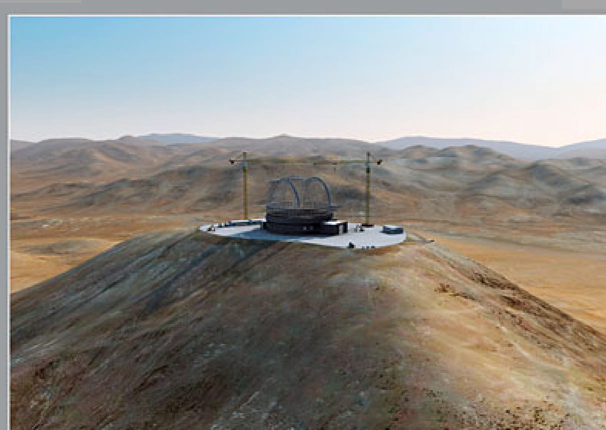
Looking ahead

- Mar 2012: Go-ahead for construction from ESO Council
- And then...


2012


2013

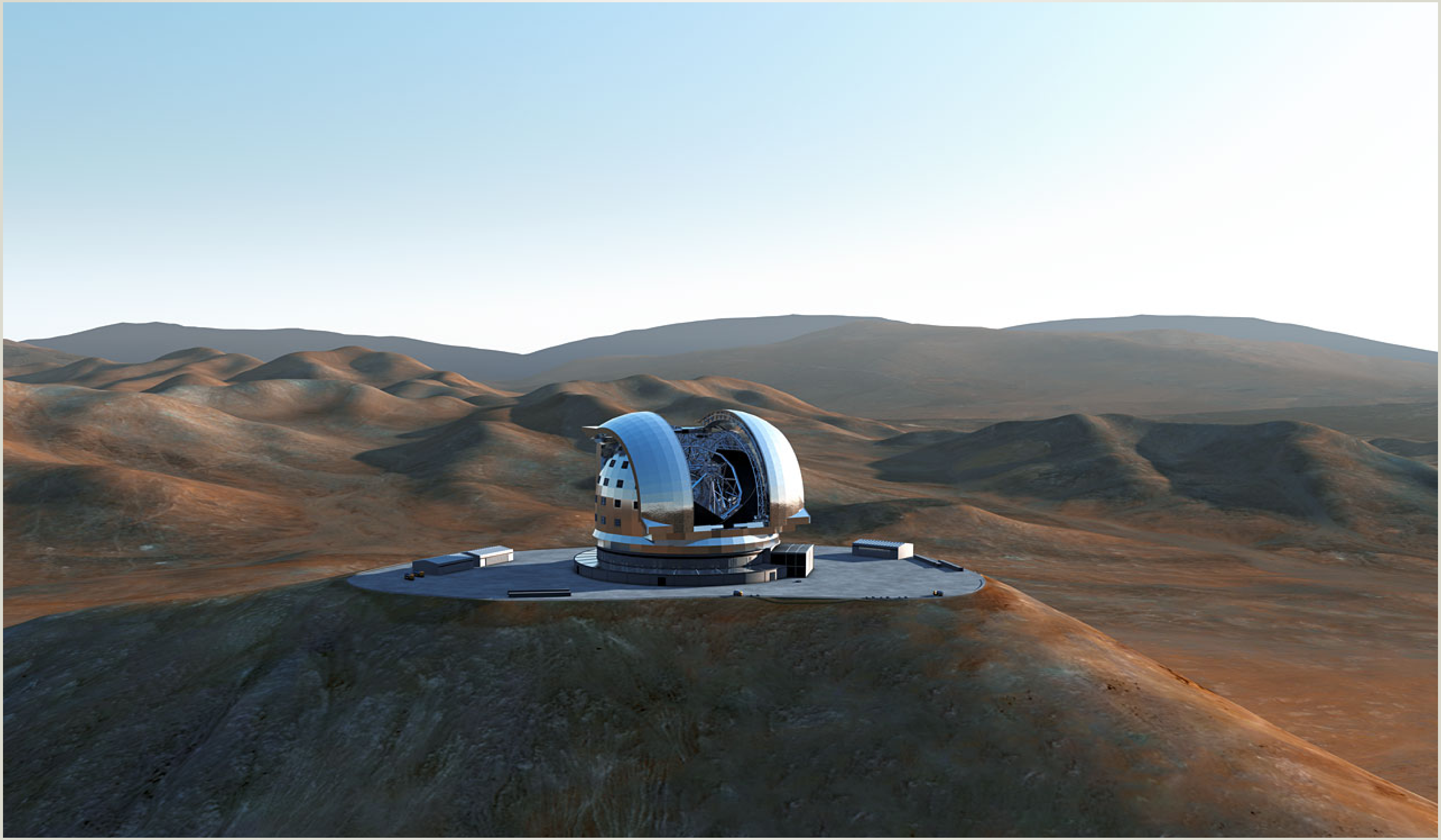

2014


2015


2016

Looking ahead

- Mar 2012: Go-ahead for construction from ESO Council
- And then...

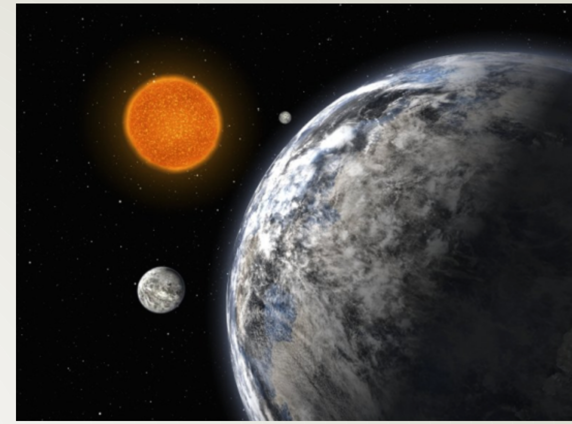


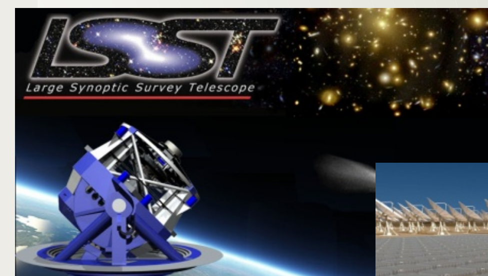
The Science

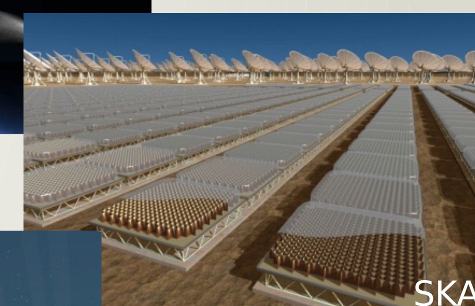
- Contemporary science:
  Exoplanets: radial velocity detections, direct imaging, proto-planetary disks
  Fundamental physics: GR in the strong field limit in the centre of the Milky Way, variation of fundamental constants, expansion history of the universe
  Resolved stellar populations: beyond the Local Group
  The physics of high redshift galaxies: the first galaxies
  and much more…

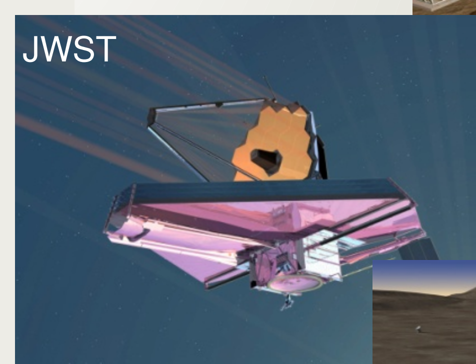
- Synergies with other top facilities:
  ALMA (workshop Garching 2009)
  JWST (workshop Garching 2010)
  SKA (workshop Crete 2010)
  LSST and other survey telescopes (workshop Ischia 2011)

- Discoveries:
  Opening new parameter space in terms of spatial resolution and sensitivity.





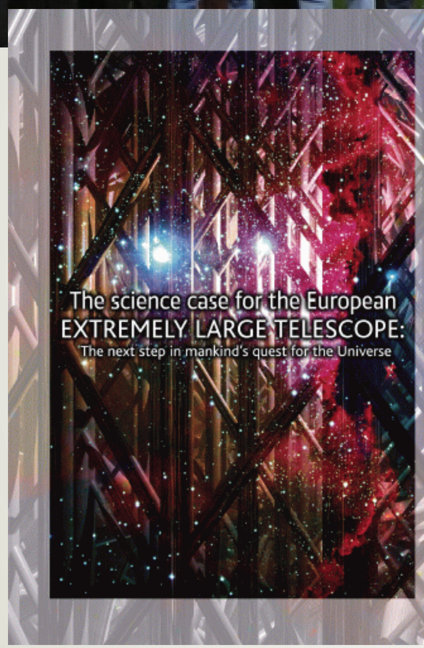


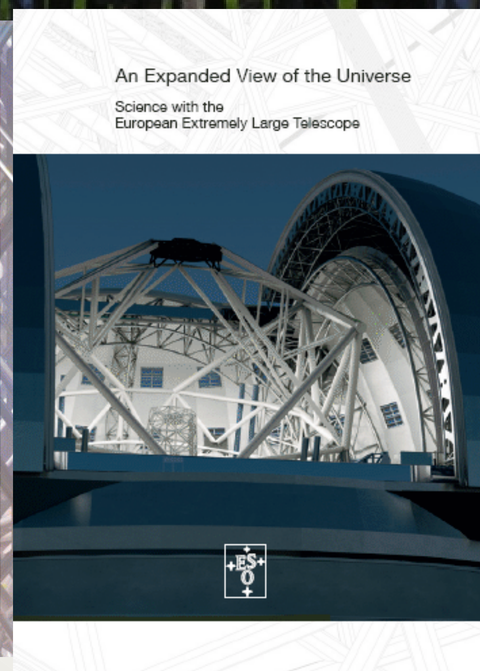


Science Case Development

Florence '04

Elba '08
Vienna '08
Garching '09
Edinburgh '09
Cambridge '09
Porto '09
London '10
Garching '10
Crete '10
Ischia '11





Marseille '03

Science Cases and Requirements for the ESO ELT

Report of the ELT Science Working Group

30 April 2006

Marseille '06

E-ELT Science Working Group

Isobel Hook (Chair)
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<u>With thanks to previous members:</u>
Arne Ardeberg
Willy Benz
Robert Fosbury
Marijn Franx
Vanessa Hill
Bruno Leibundgut
Markus Kissler-Patig
Didier Queloz
Peter Shaver
Stephane Udry

Dec 2005: ESO SWG formed

Science case re-evaluated for 30-60m (April 2006)

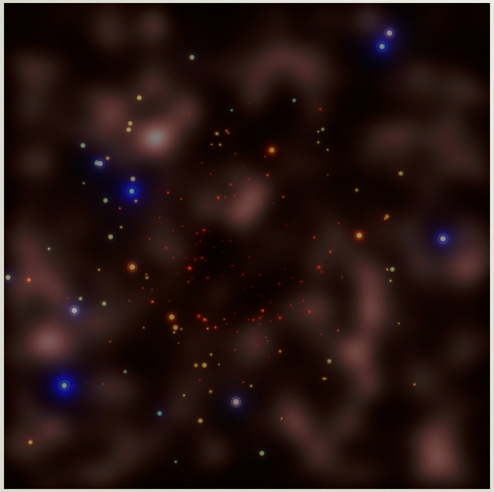
ESO SWG merged with OPTICON activity

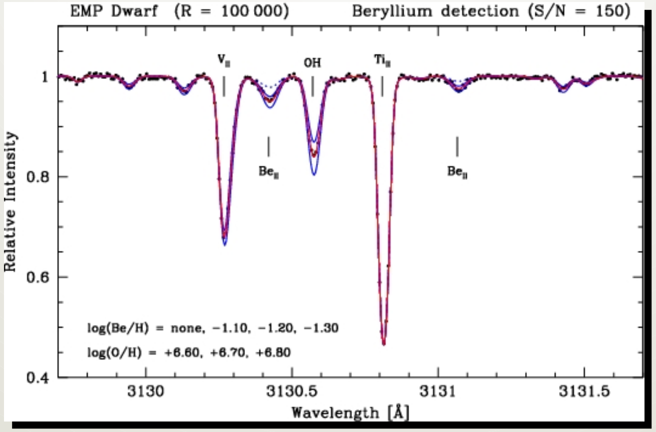
The E-ELT Design Reference Mission

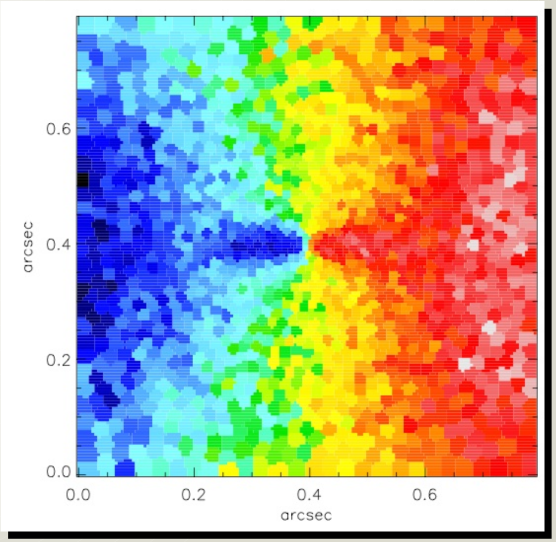
- Initiated by the ESO-OPTICON E-ELT Science Working Group, supported by ESO's E-ELT Science Office and in consultation with the community.
- Detailed, hands-on exploration of a selected sample of science cases through the analysis of simulated data.
- Purpose:
  - To provide a quantitative assessment of the extent to which the E-ELT will be capable of addressing key scientific questions.
  - To assist the project in making critical trade-off decisions by quantifying their consequences in terms of scientific gains and losses.
  - To support the development of the E-ELT Science Case.
- Duration: 2007 – 2010.

The E-ELT Design Reference Mission

- Intended as a DRM of the E-ELT observatory system: includes telescope, instrumentation, adaptive optics, site, science operations.
- Served as a quantitative reference for the entire design effort.
- Identified limiting factors and critical requirements for each of the science cases studied.
- Can be used to quantify science losses in case requirements cannot be met.







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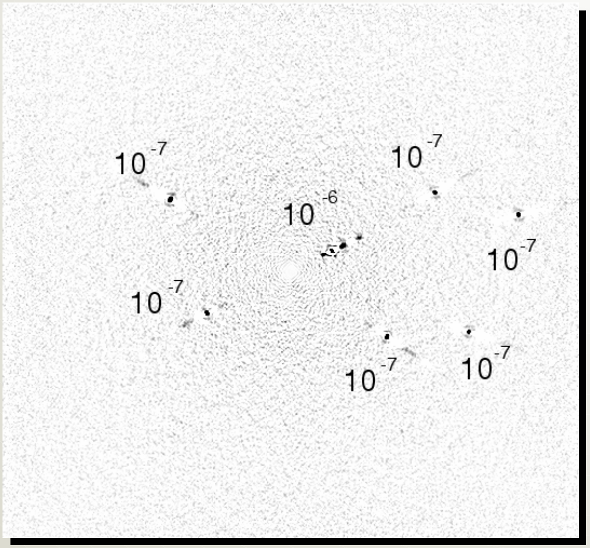
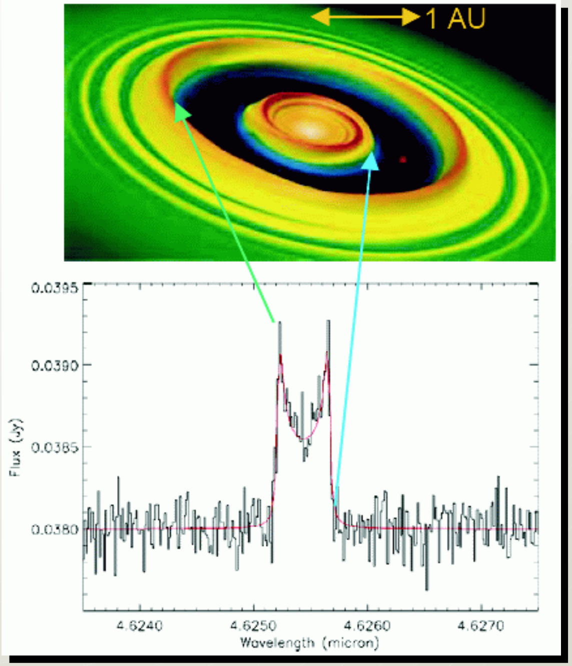
The DRM Science Cases

- Selected by the SWG from their own April 2006 report.
- Prominent cases – among the highlights of the E-ELT Science Sase, but not intended to be exhaustive.
- Chosen to encompass a wide range of different science topics, and to exemplify cases which exploit and highlight the key capabilities of the telescope.





The DRM Science Cases

- Planets & Stars
  - From giant to terrestrial exoplanets: detection, characterisation and evolution
    - Direct imaging of terrestrial and giant exoplanets
    - Earth twins in the habitable zone of solar-type stars
  - Imaging the planet-forming regions of circumstellar disks
  - Young stellar clusters
    - Characterising the lowest mass freely floating objects in star forming regions
    - The centres of massive dense young clusters: deep infrared imaging and 3D spectroscopy
    - Giant planet-mass objects in the Large Magellanic Cloud
- Stars & Galaxies
  - Imaging and spectroscopy of resolved stellar populations in galaxies
    - The resolved stellar populations of elliptical galaxies
    - The chemo-dynamical structure of galaxies
    - First stars relics in the Milky Way and satellites
  - A survey of black holes in different environments
- Galaxies & Cosmology
  - The physics of high redshift galaxies
    - The physics and mass assembly of galaxies out to z ~ 6
    - High resolution imaging of high redshift galaxies
  - First light – the highest redshift galaxies
  - A dynamical measurement of the expansion history of the Universe

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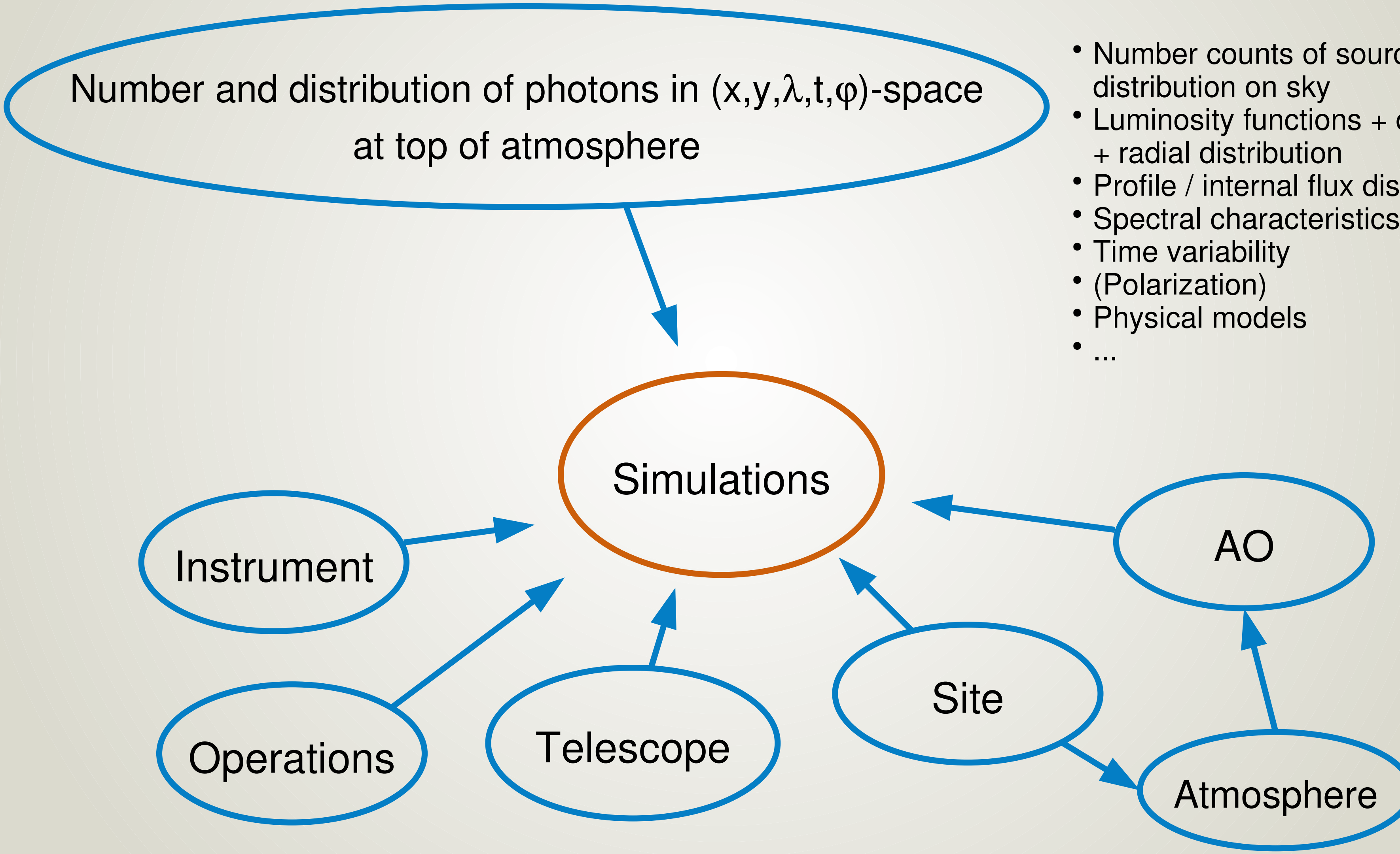
The DRM process

- Starting point: DRM proposal (SWG member)
  - Summary of the science case
  - Description of required E-ELT observations
- Refinement (EScO ↔ SWG member)
  - Definition of precise science goals
  - Definition of a metric / figure of merit and success
  - Provision of scientific input data
- Simulations and analysis (EScO). Key tasks:
  - What precisely can be achieved in a given amount of observing time, or, vice versa, how much observing time is required to achieve a given set of science goals?
  - How do these results depend on the properties of the telescope, the instrument, the AO performance and/or the site? Which features of the E-ELT system are critical to the success of the proposal?
  - Identification of key requirements and quantification of the scientific losses in case requirements cannot be met.
- End point: report with pre-defined structure (EScO and SWG member)

Contents

DRM inputs

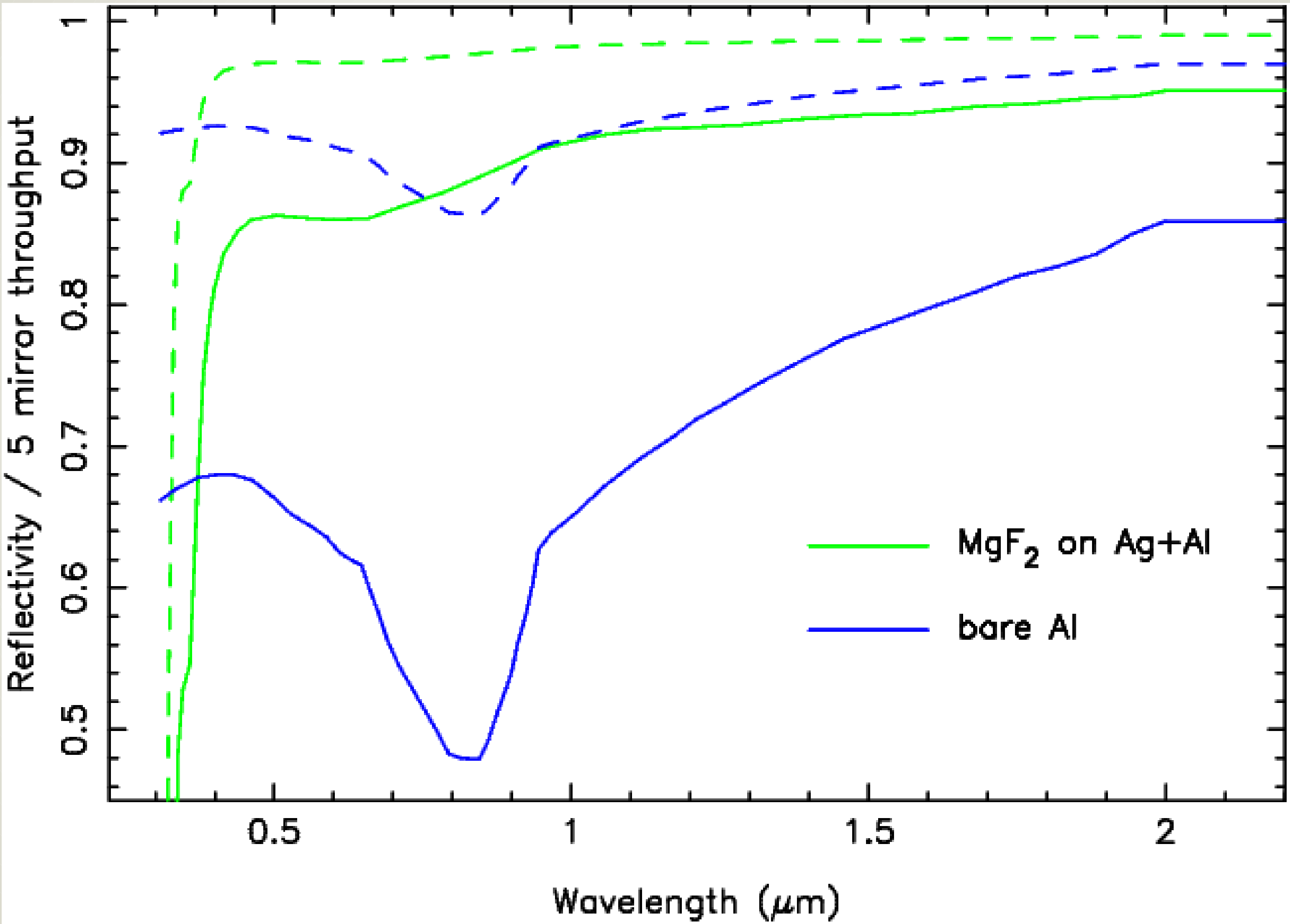
Scientific input data



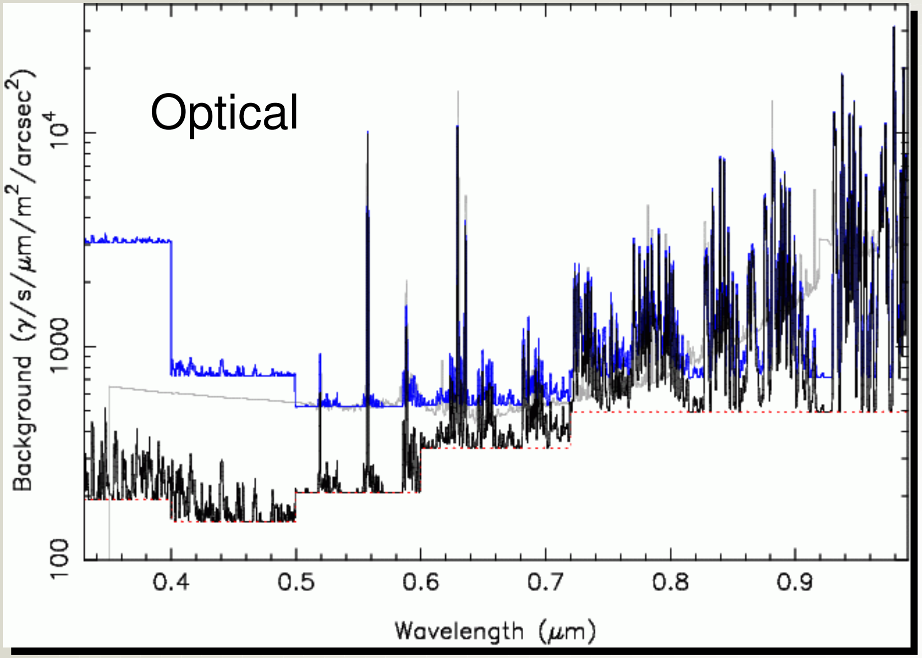
- Number counts of sources + distribution on sky
- Luminosity functions + distance + radial distribution
- Profile / internal flux distribution
- Spectral characteristics
- Time variability
- (Polarization)
- Physical models
- ...

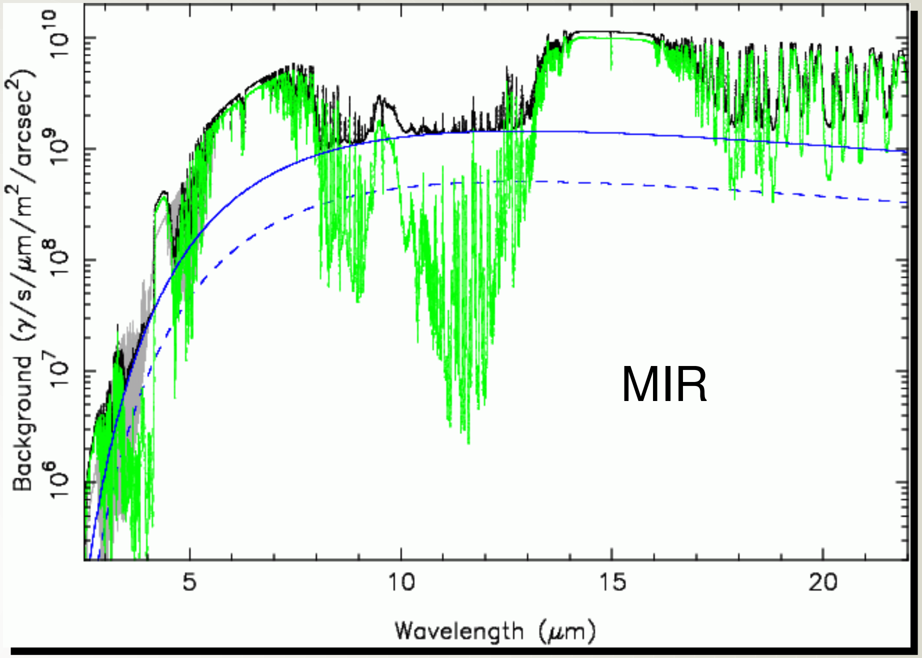
Technical input data

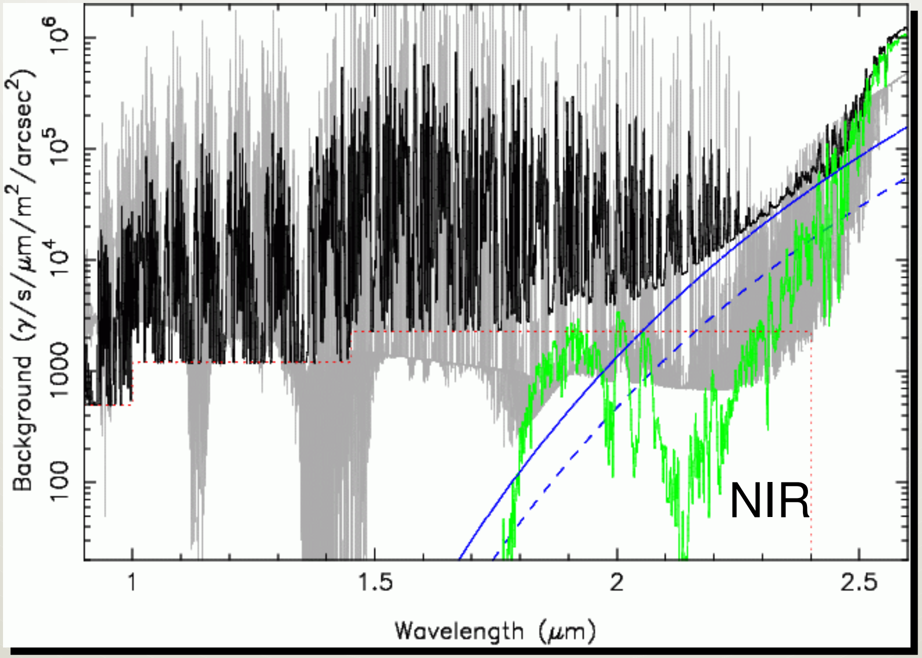
Technical data: coatings



Technical data: background model

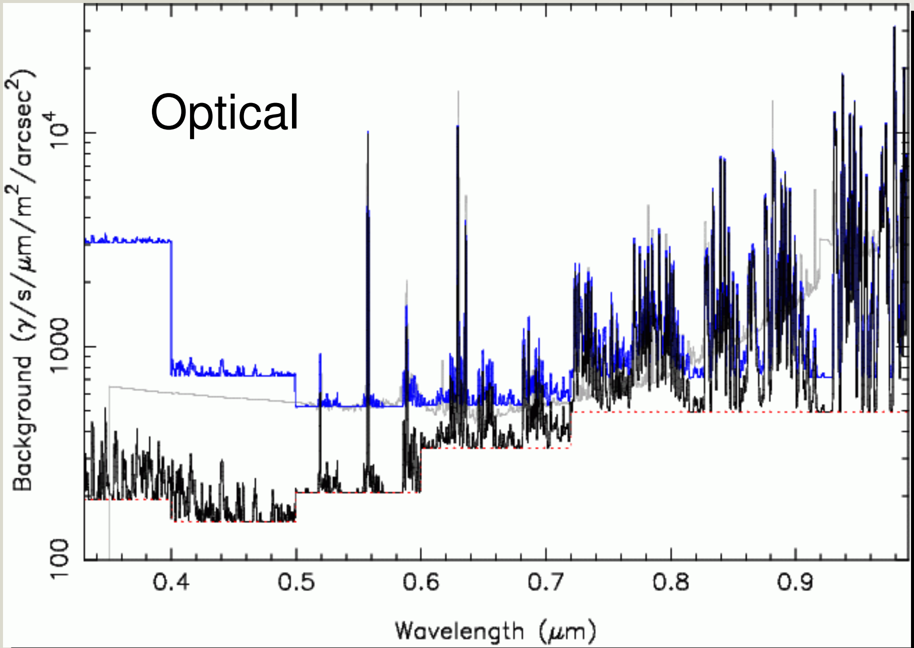


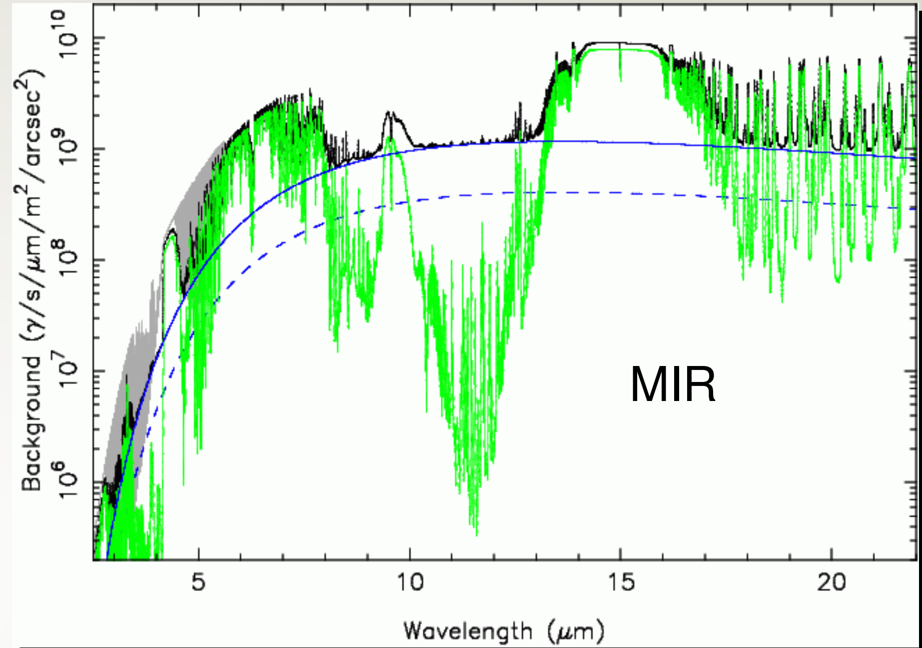


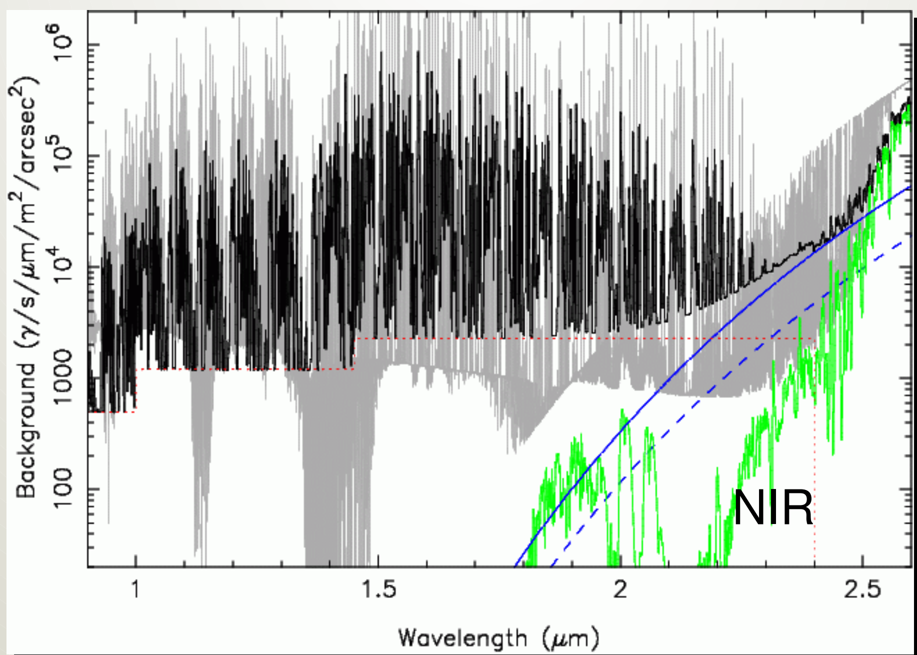


Paranal-like site

Technical data: background model







High & Dry site

Technical data: adaptive optics

- PSF simulations using ESO's numerical AO simulation tool OCTOPUS.
- Used to construct a database of PSFs as a function of:
  - type of AO (GLAO and LTAO)
  - zenith distance
  - wavelength
  - size of FoV
  - position within FoV

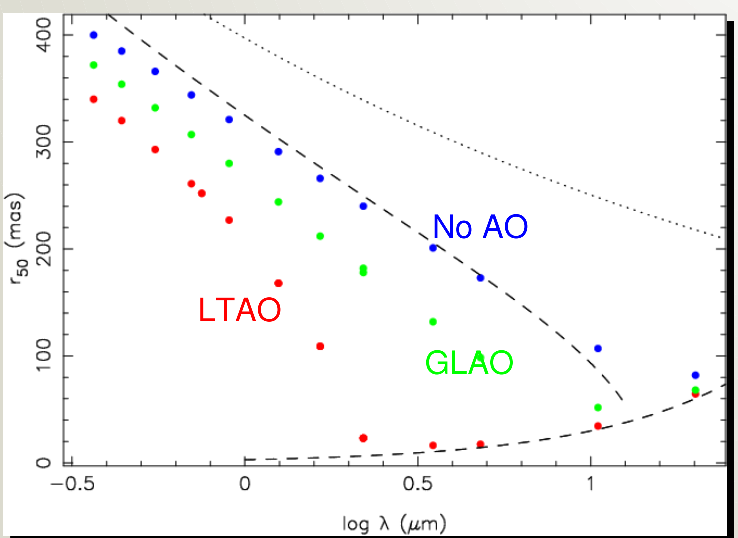
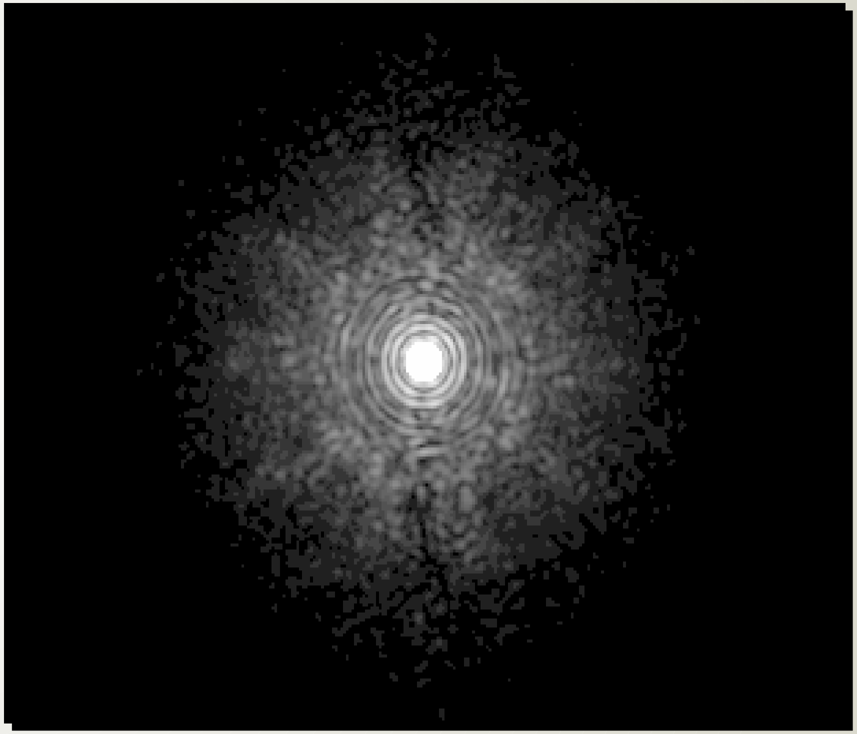


Table 8.1: PSF simulation parameters.

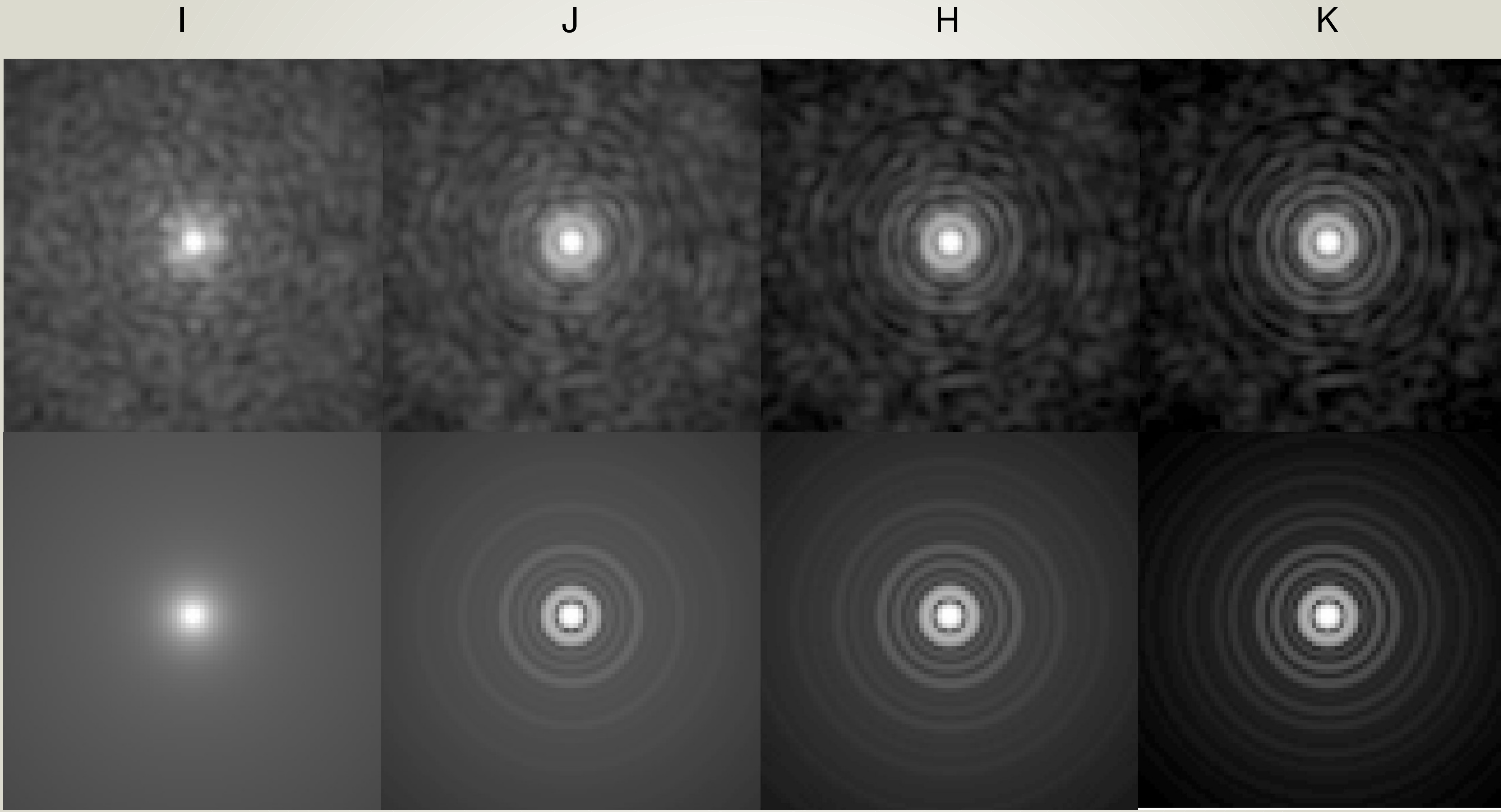
Atmosphere			
Fried parameter r_0	0.13 m at 0.5 μm		
Seeing	0.8 arcsec at 0.5 μm		
Turbulence power spectrum	von Karman		
Outer scale L_0	25 m		
Inner scale l_0	pixel size		
Number of turbulent layers	10		
Parameters of layers	Height [m]	Fractional C_n^2	Windspeed [m/s]
	0	0.335	12.1
	600	0.223	8.6
	1200	0.112	18.6
	2500	0.090	12.4
	5000	0.080	8.0
	9000	0.052	33.7
	11500	0.045	23.2
	12800	0.034	22.2
	14500	0.019	8.0
	18500	0.011	10.0
Laser guide stars	GLAO	LTAO	
Number of LGS	5	6	
LGS brightness	infinite	infinite	
LGS positions [arcmin from field centre, $i = 0...4$]	$x = 3\cos(i \times 72°)$ $y = 3\sin(i \times 72°)$	$0.75\cos(i \times 72°)$, 0 $0.75\sin(i \times 72°)$, 0	
Primary mirror			
Size and geometry	See Section 6.		
Wavefront sensors			
Number of WFS	equal to number of LGS		
Type	Shack-Hartmann		
Number of sub-apertures per WFS	84 × 84		
Number of CCD pixel per sub-aperture	6		
Noise	none (infinite flux, no read-out noise)		
Spot elongation	none		
Deformable mirrors			
Number of DMs	1		
Geometry	square		
Number of actuators per DM	85 × 85		
Actuator stroke	infinite		
Conjugation height	0 m		
Tile with respect to layers	none		
Influence function	linear spline		
Other parameters			
Frame rate	500 Hz		
Number of iterations	2000		
Total integration time	4 s		
Delay time	3 iterations		

Technical data: PSF fits

- Because ESO's PSF simulations are computationally so expensive only short integration PSFs (4s) have been simulated.
- Problem: speckle noise.
- Also: the PSF images have to be very large in order to sample a good contrast range.
- Solution: represent PSFs with a 'small' number of analytic components.

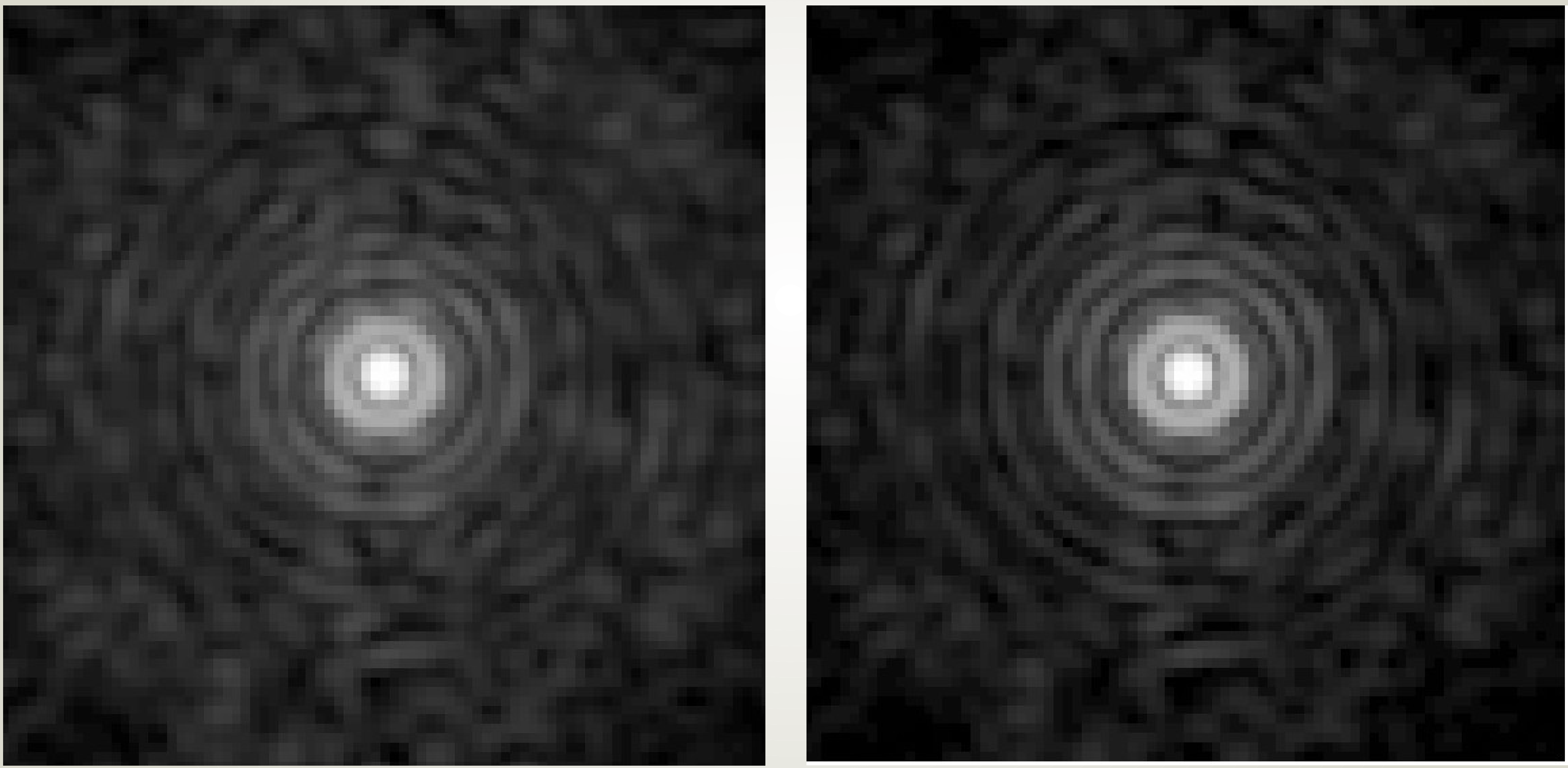


Technical data: PSF fits



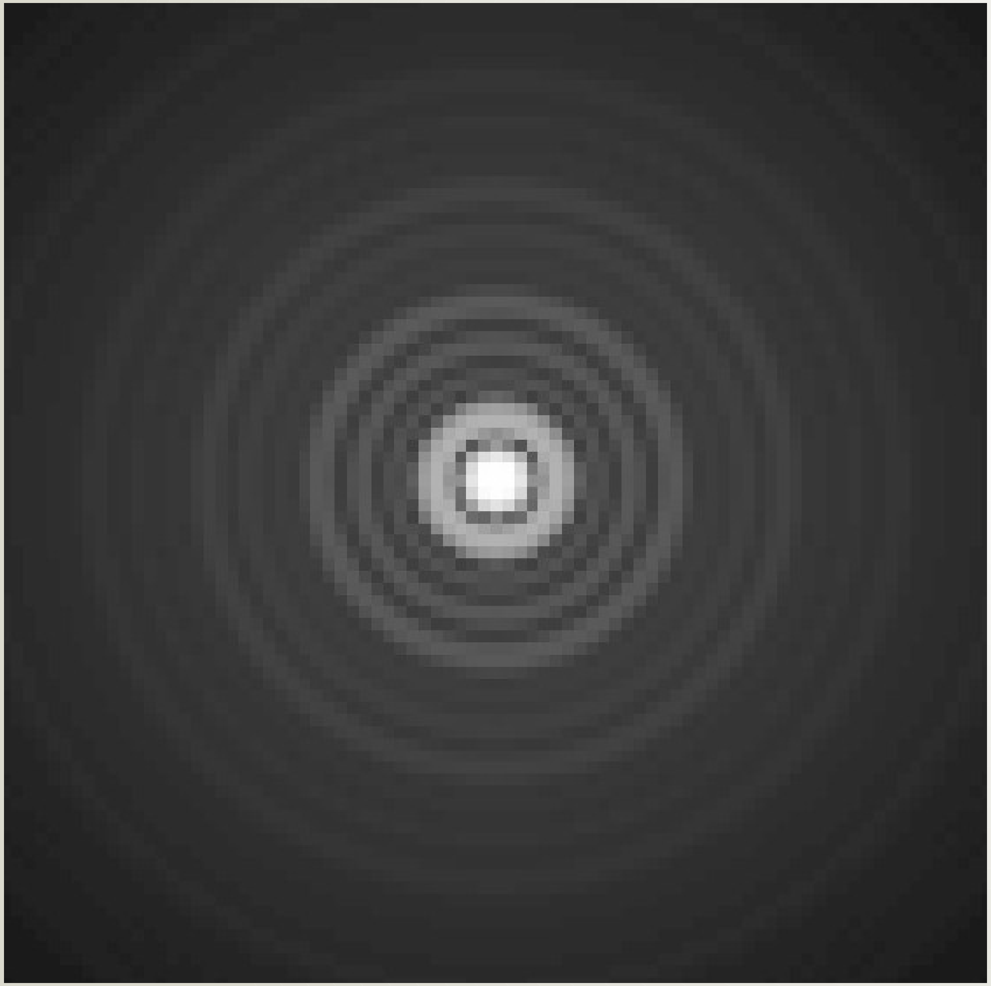
Technical data: PSF fits

H K

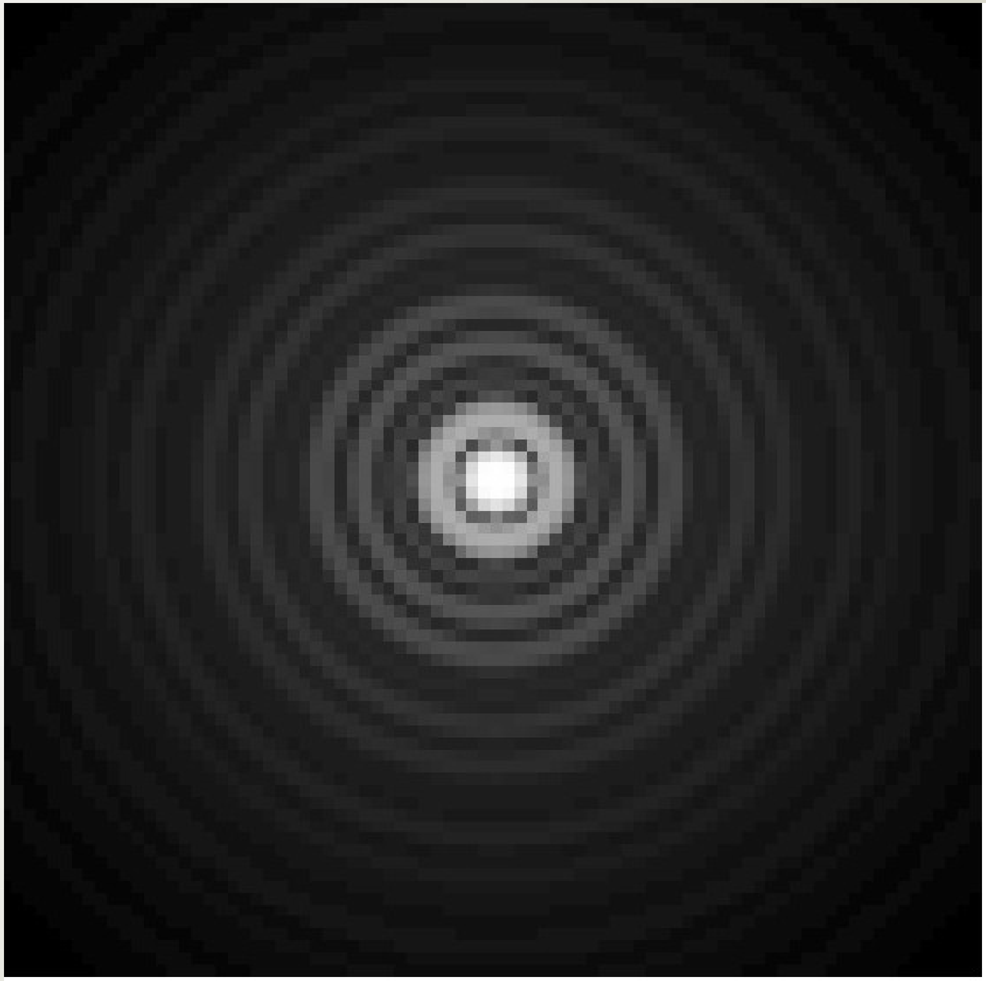


Technical data: PSF fits

H

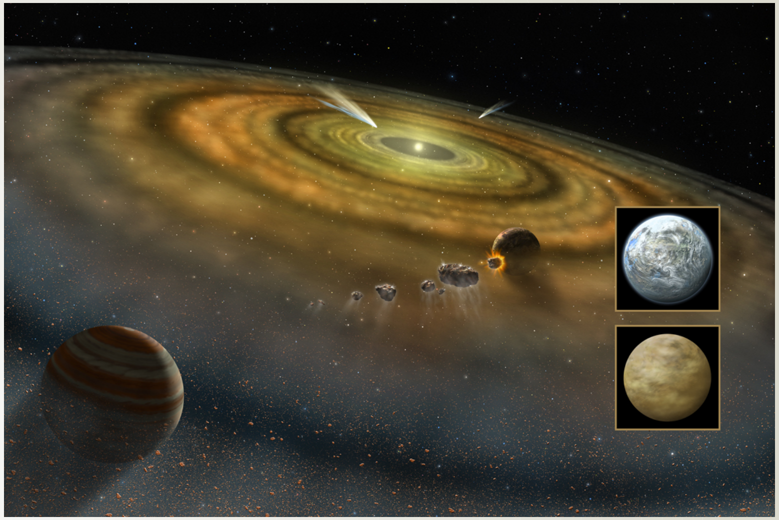


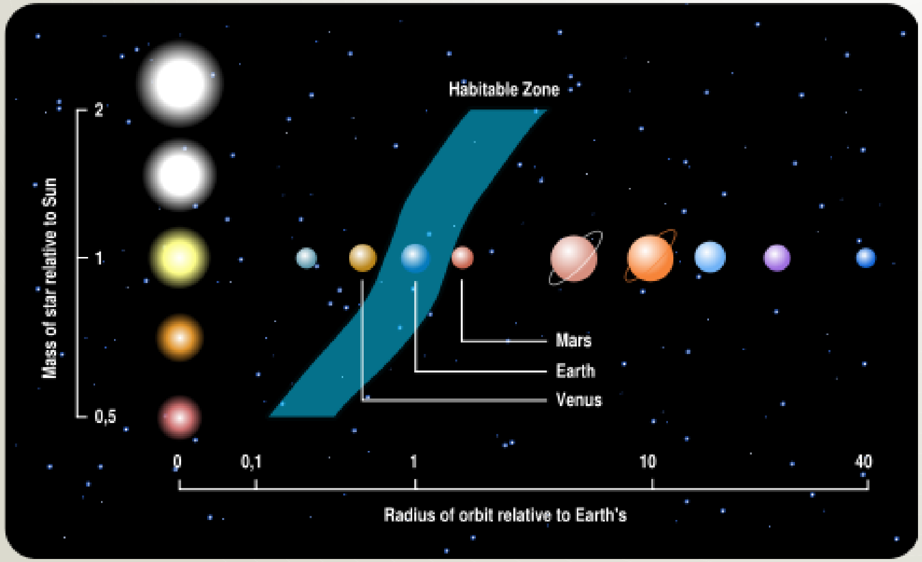
K

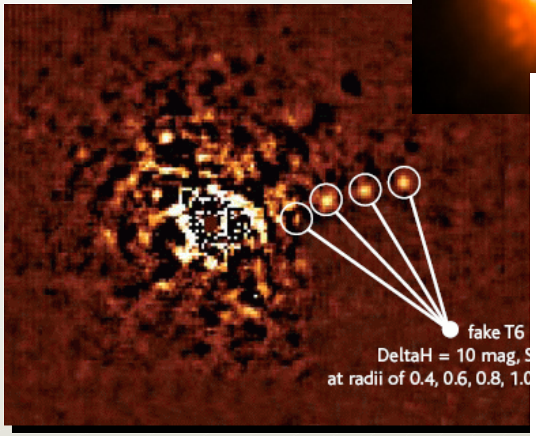


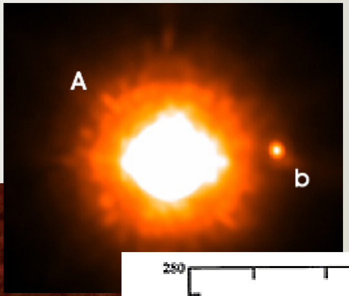
Planets & Stars: direct exoplanet imaging

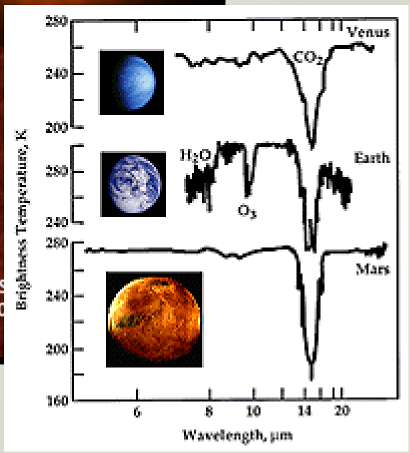
- Direct imaging of terrestrial and giant exoplanets orbiting Sun-like (FGK) stars at distances < 20 pc:
  - Planet properties (orbit, colour, mass, ...)
  - Demographics of planetary systems.
  - Targets for spectroscopy?











Specific questions for the DRM

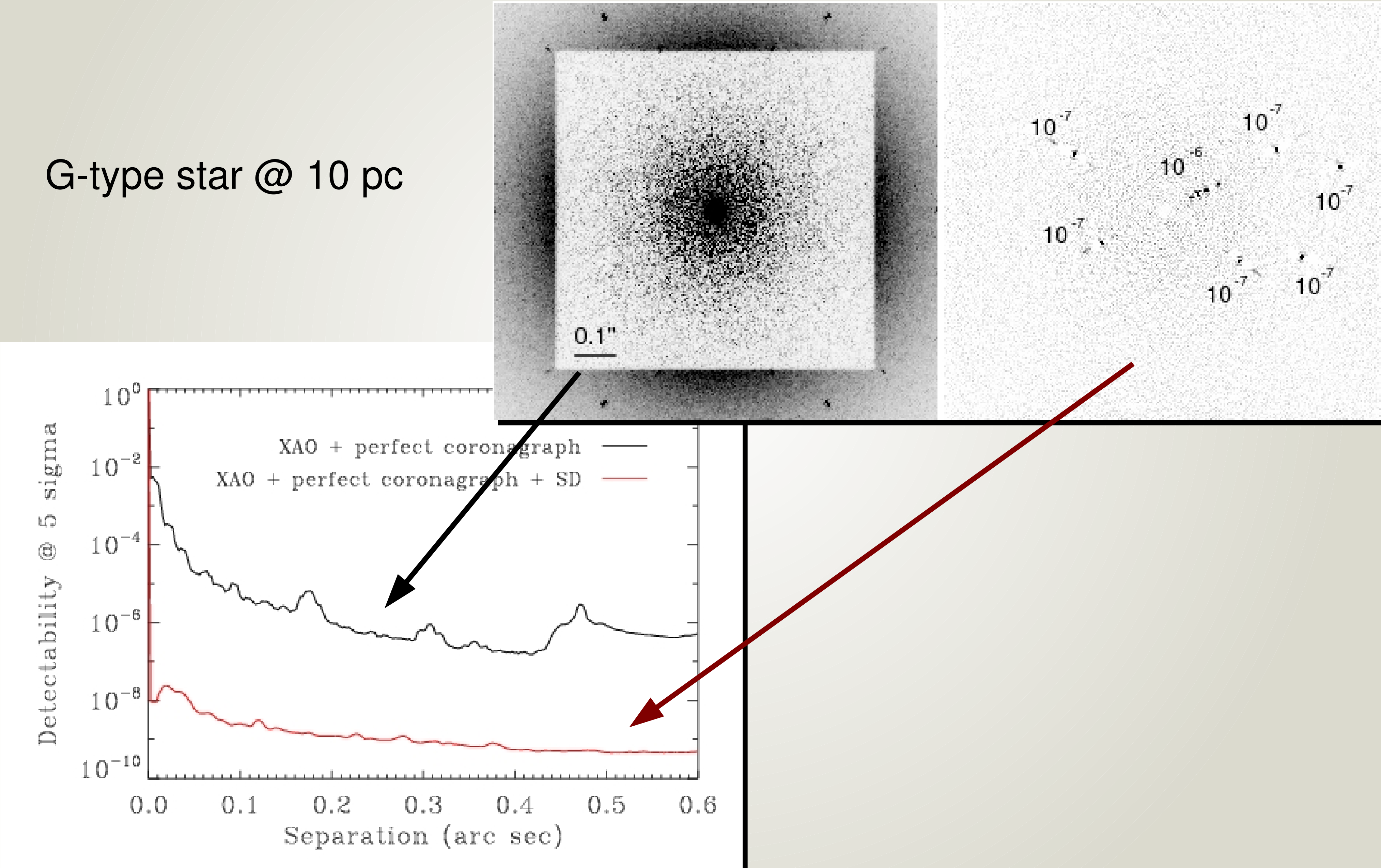
- What contrast can be achieved as a function of:
  - distance from the host star
  - distance of the host star from the Sun
  - type of the host star
  - type of coronagraph
  - post-AO aberrations
- Method: analytic system simulations including:
  - extreme adaptive optics
  - integral field spectrograph with coronagraph

followed by post-processing consisting of:

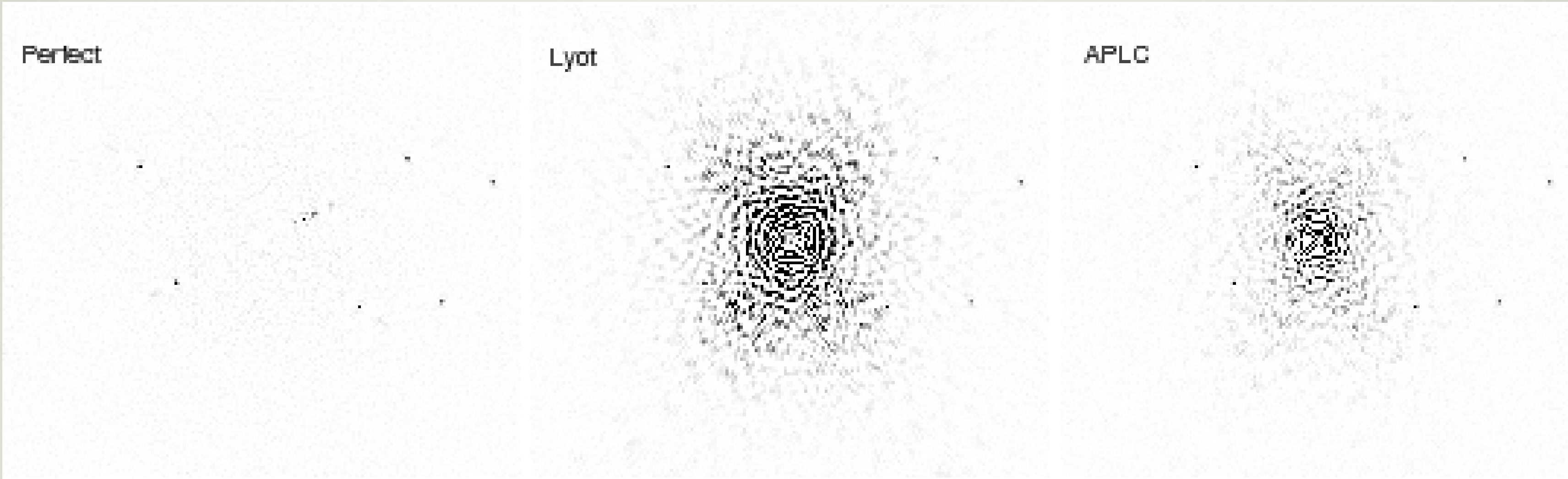
  - spectral deconvolution

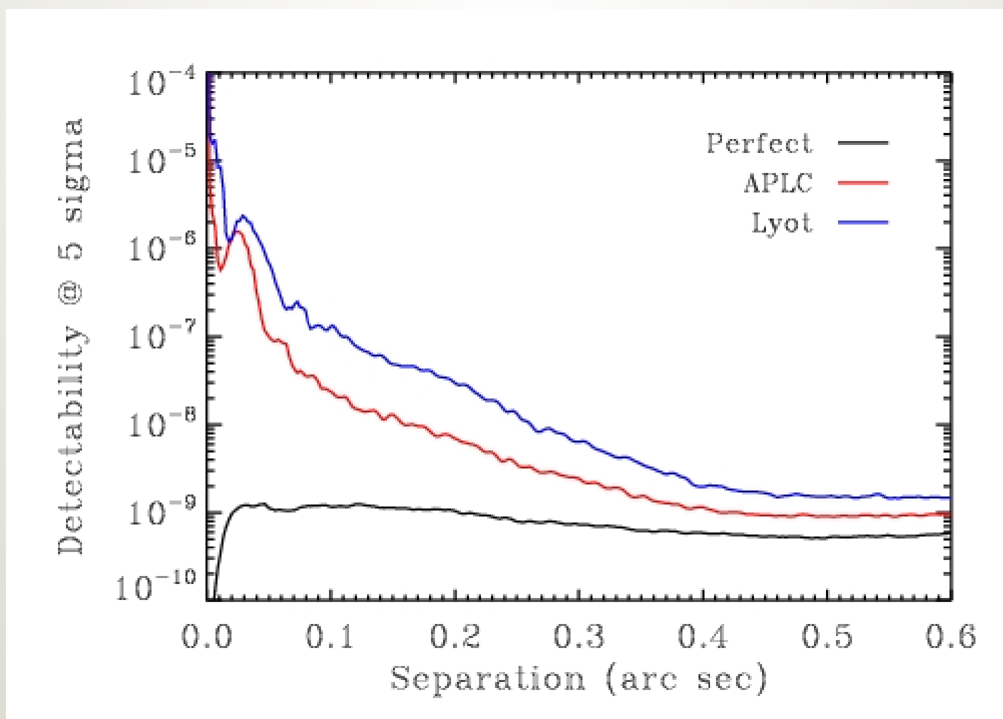
Results: spectral deconvolution

G-type star @ 10 pc

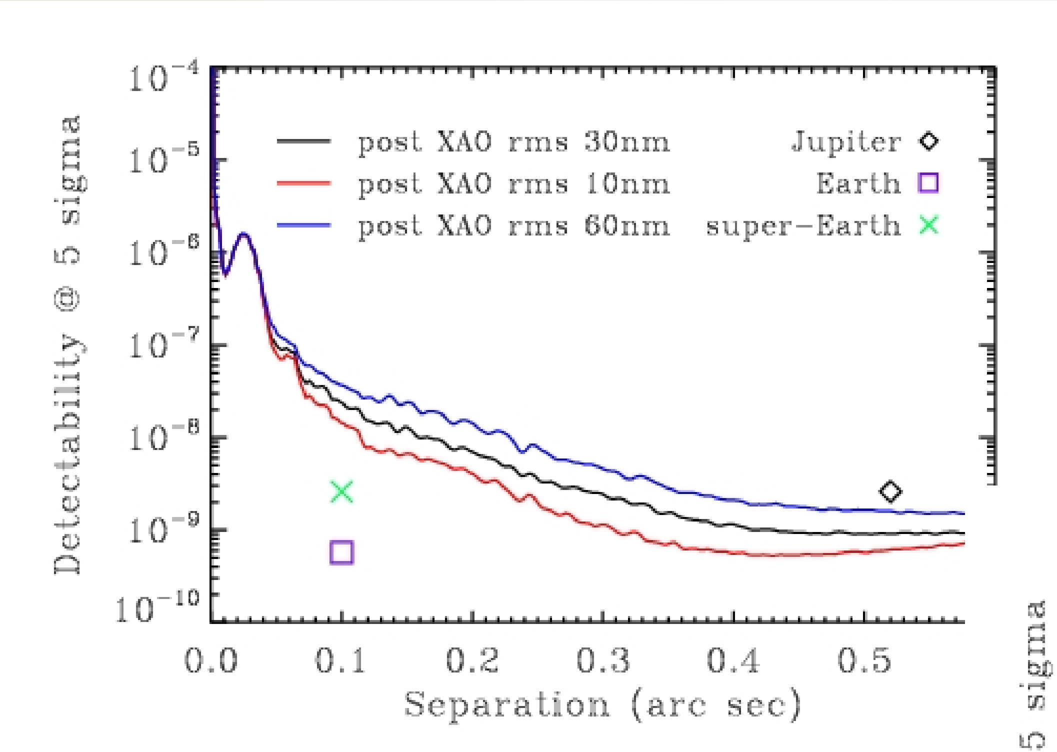


Results: coronagraphs

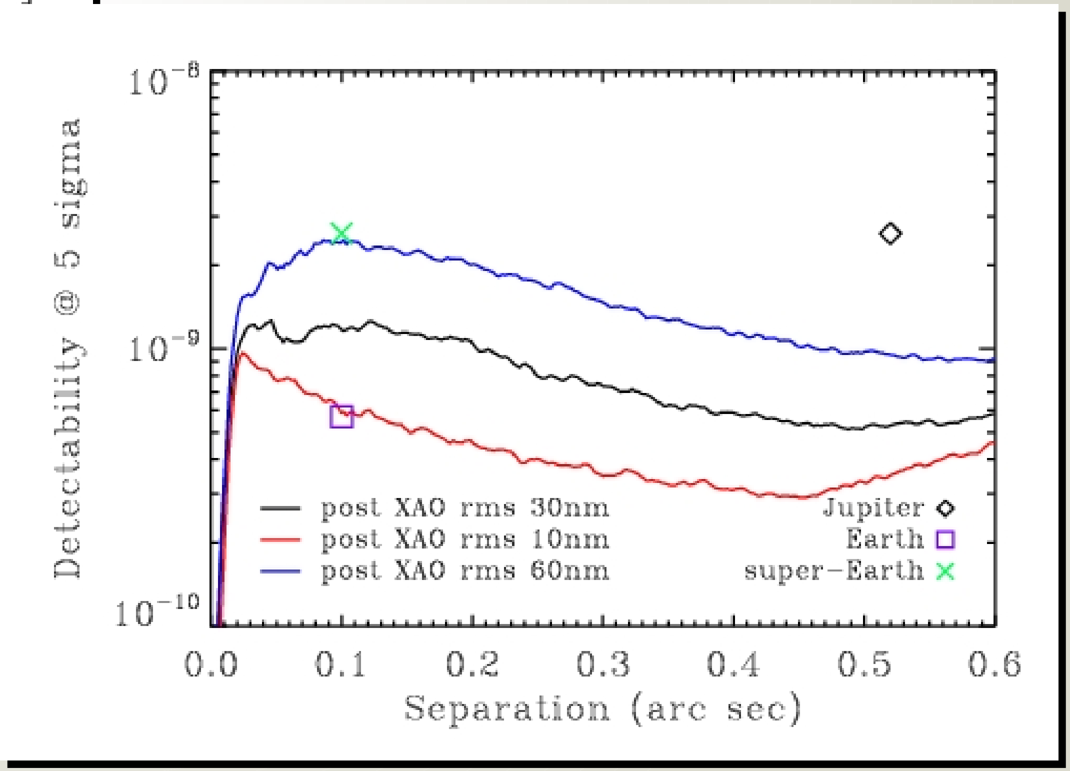




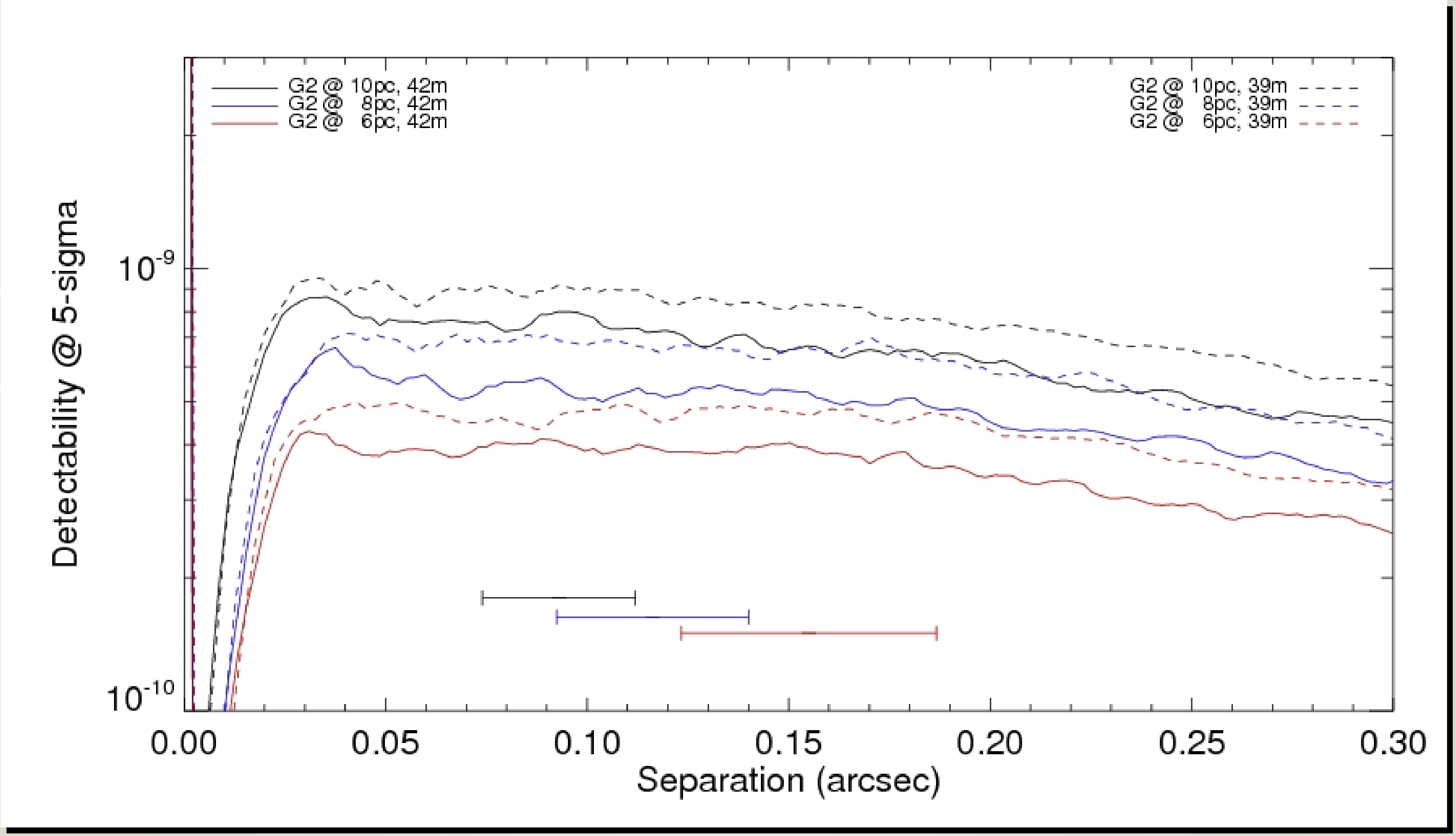
Results: post-AO aberrations



G-type star @ 10 pc



Results: D and distance

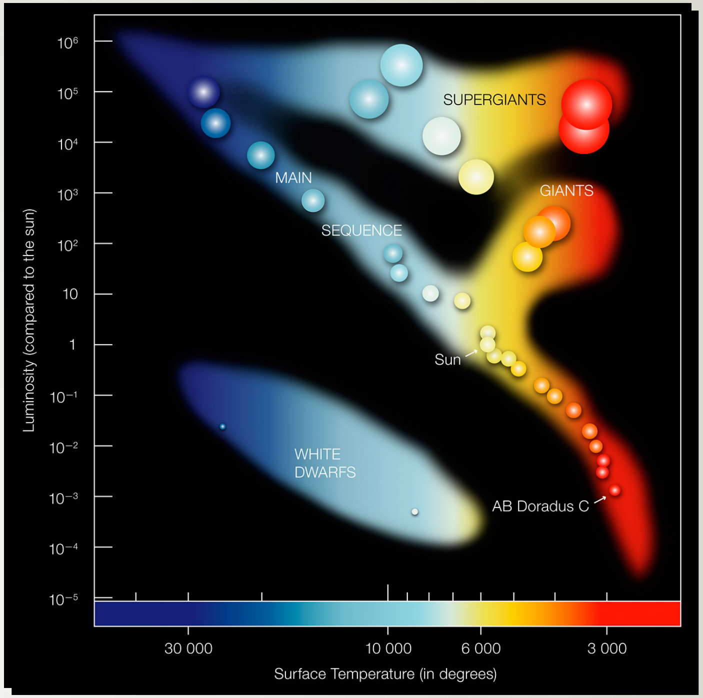


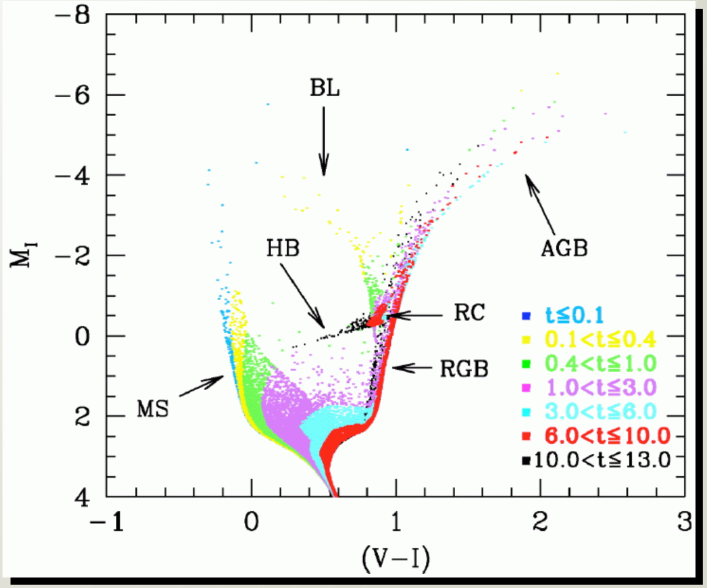
Stars & Galaxies: resolved stellar pops out to Virgo

- Present day population of stars in a galaxy = result of all of the star-formation it (or its precursors) experienced + stellar evolution.
- We understand stellar evolution.

➔ A galaxy's present-day stellar population can be used to deduce the galaxy's major episodes of star-formation and hence to reconstruct its assembly history.

- Stars retain a memory of the ISM out of which they formed. Some stars are very long-lived → handy tracer of star-formation conditions from the earliest times to the present.



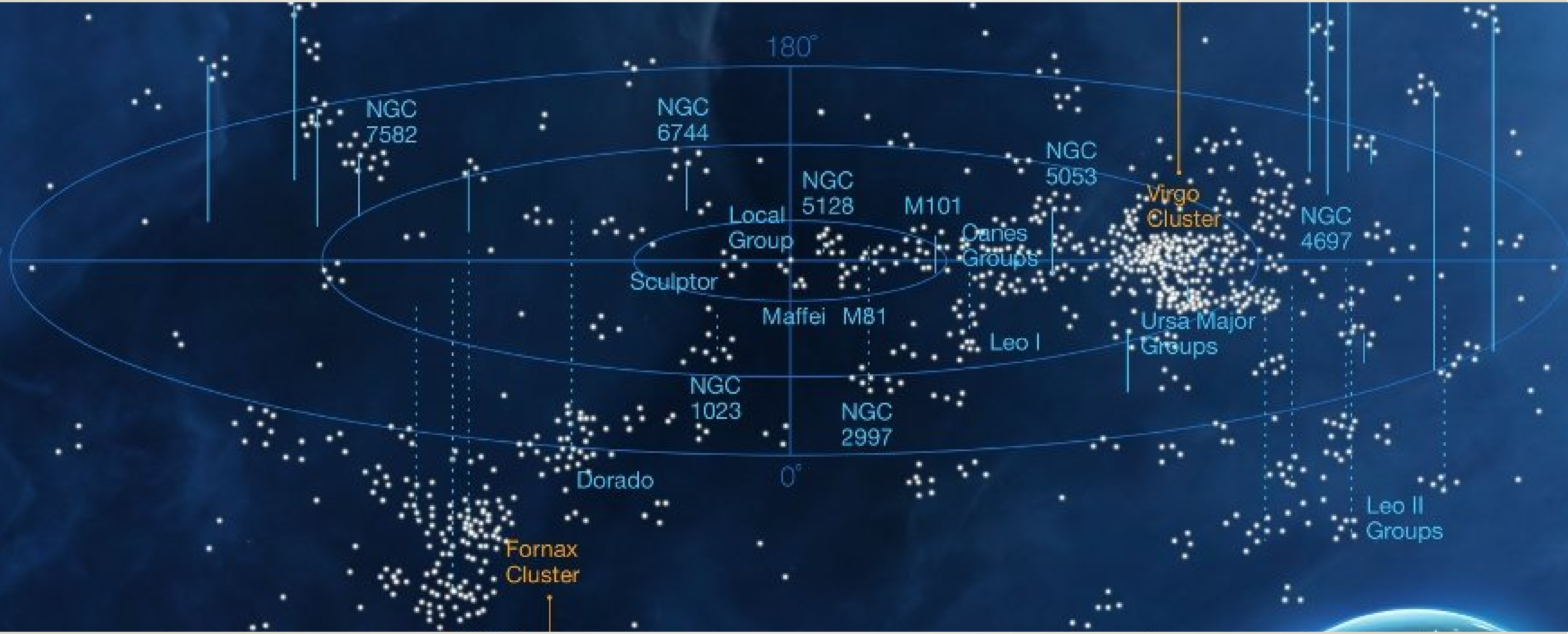


Resolved stellar populations → galaxy evolution

- Want to obtain precise photometry and spectroscopy of resolved stellar pops for a wide range of stellar systems:

Resolved stellar populations → galaxy evolution

- Want to obtain precise photometry and spectroscopy of resolved stellar pops for a wide range of stellar systems:



Resolved stellar populations and the E-ELT

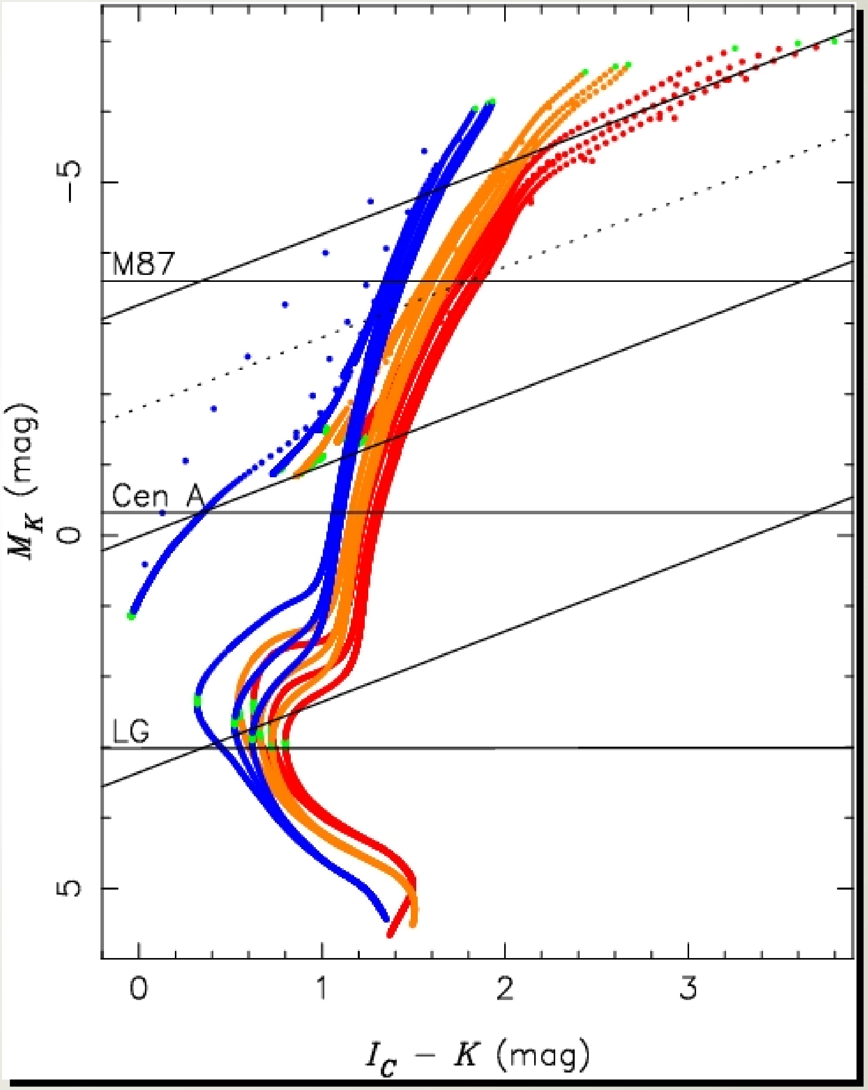
Quick look: what can we expect?

Isochrones:

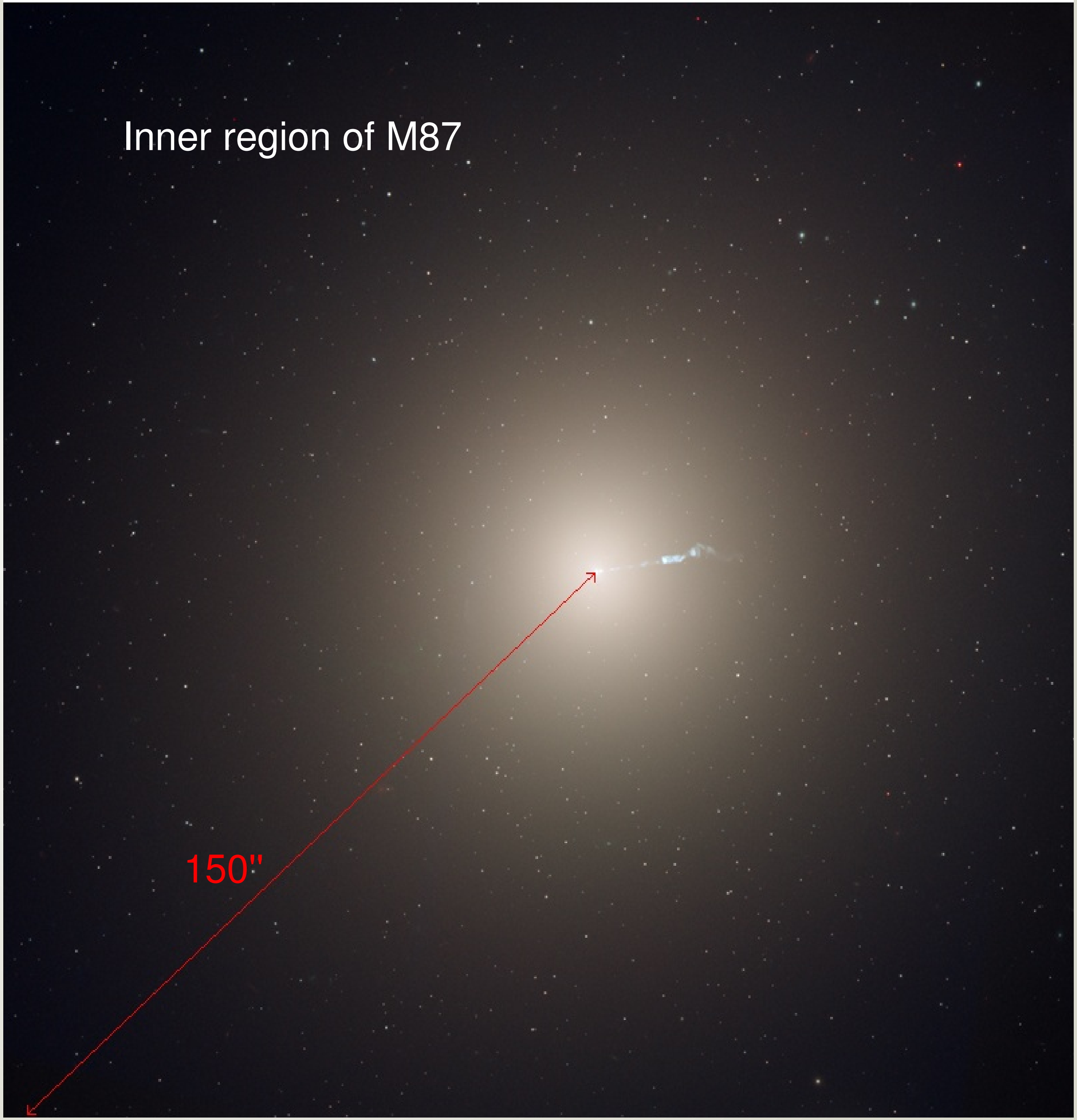
- [Fe/H] = -1.8, -1, -0.6
- Age = 5, 9, 13 Gyr

Mag limits:

- T_{exp} = 10 hours
- S/N = 20
- No crowding



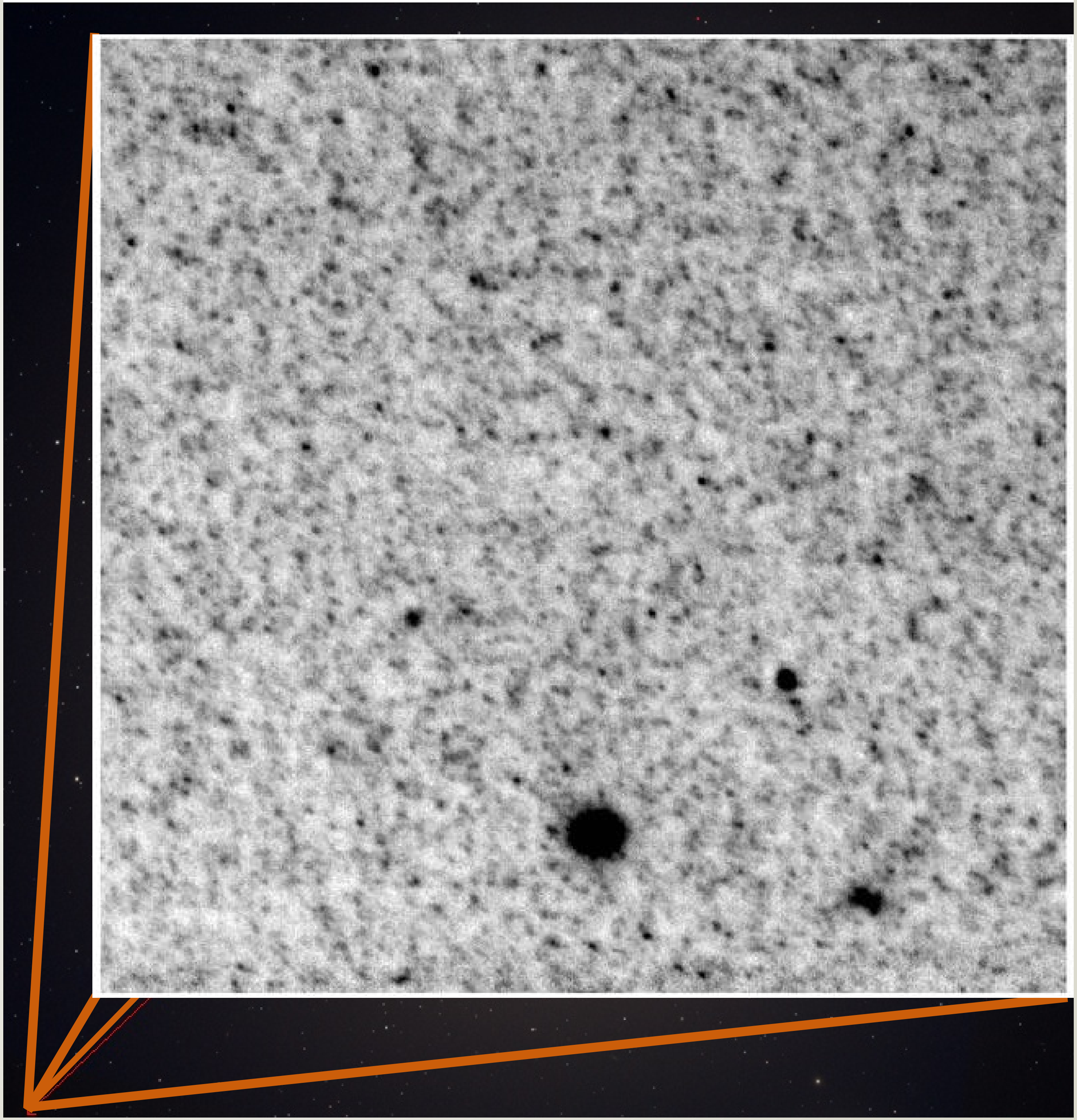
Virgo CMDs with HST



Virgo CMDs with HST

Bird et al. (2010):

- HST/ACS
- 12.5" x 12.5"
- F814W
- ~20 hours
- 0.025"/pixel

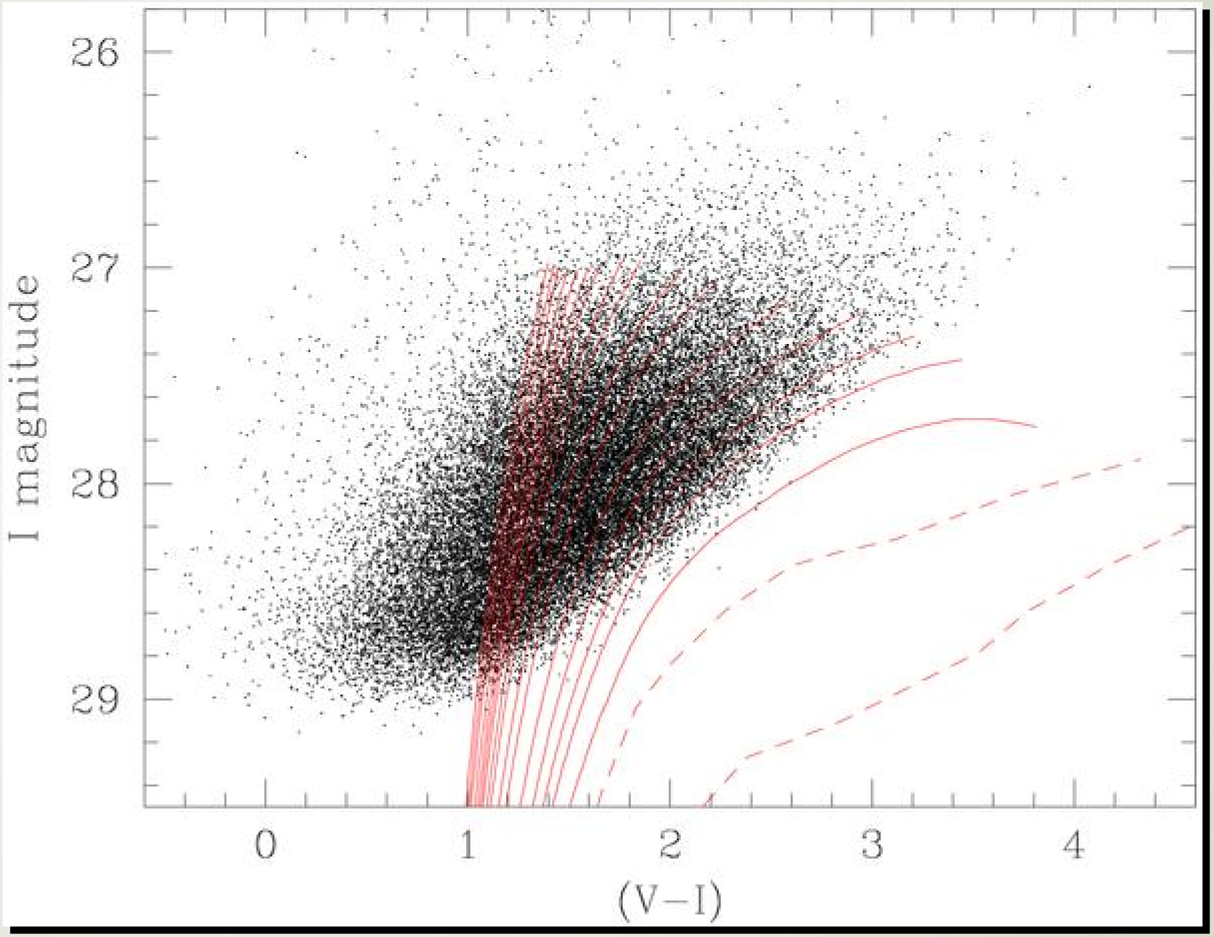


Virgo CMDs with HST

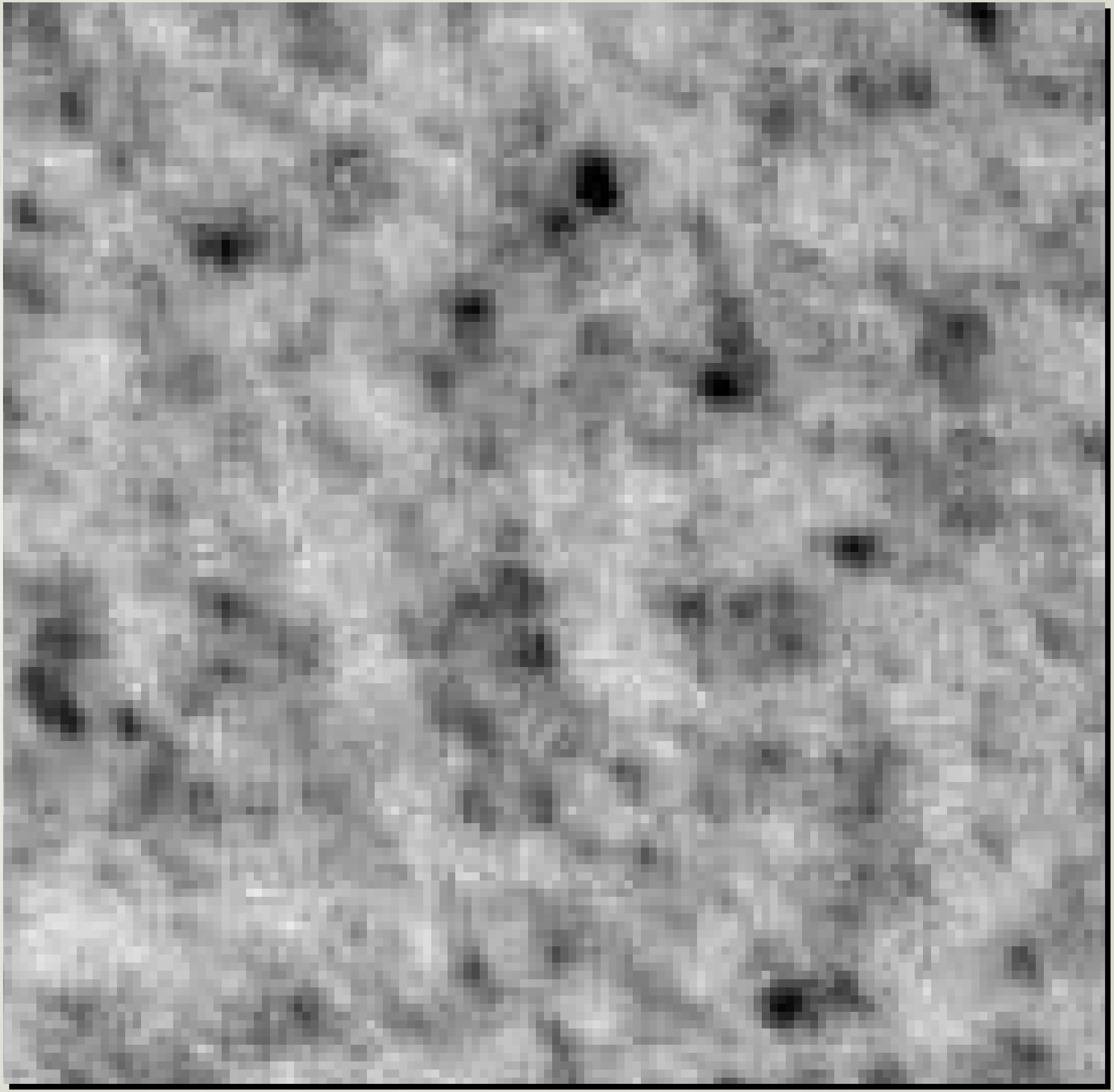
Bird et al. (2010):

- HST/ACS

- F814W
- ~20 hours
- 0.025''/pixel



Virgo CMDs with HST



Bird et al. (2010):

- HST/ACS
- 3'' x 3''
- F814W
- ~20 hours
- 0.025''/pixel

Simulation:

I-band

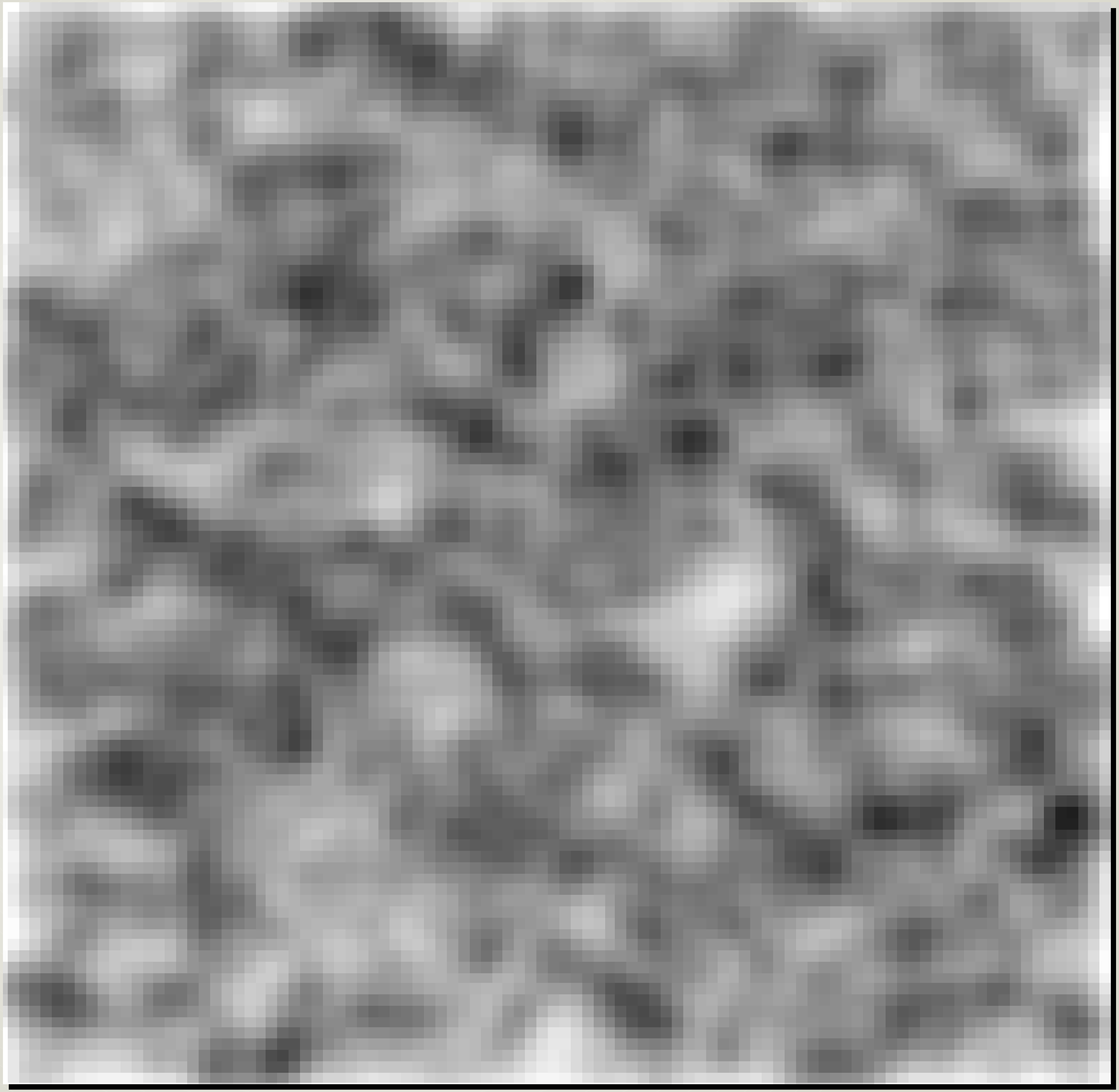
10 hours

3" x 3"

DM = 31.2

μ = 23 mag/arcsec^2

TinyTim model of HST ACS F814W PSF from Rhodes et al. (2007), no drizzling



Simulation:

I-band

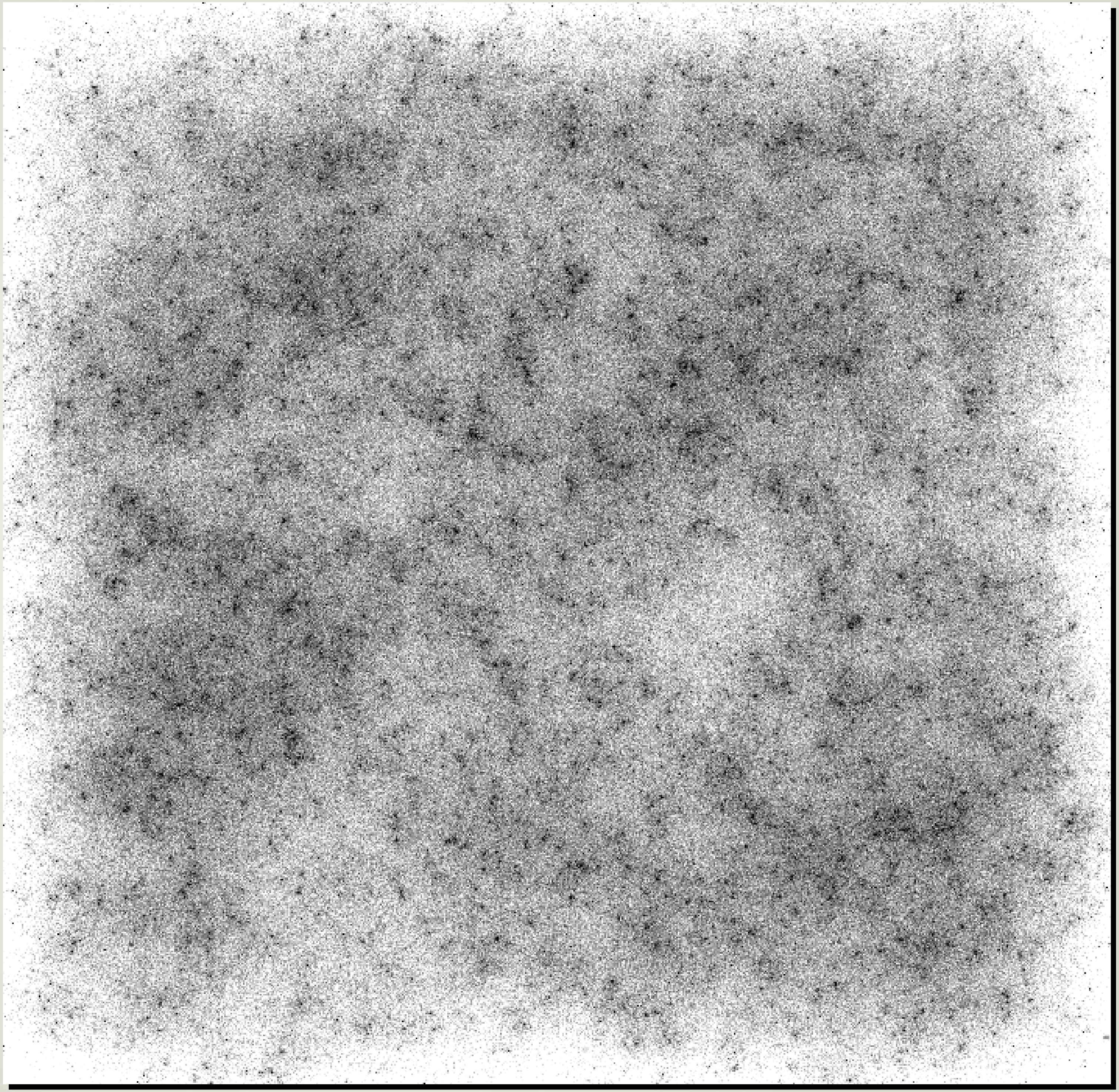
10 hours

3'' x 3''

DM = 31.2

μ = 23 mag/arcsec^2

E-ELT I-band PSF



Simulation:

I-band

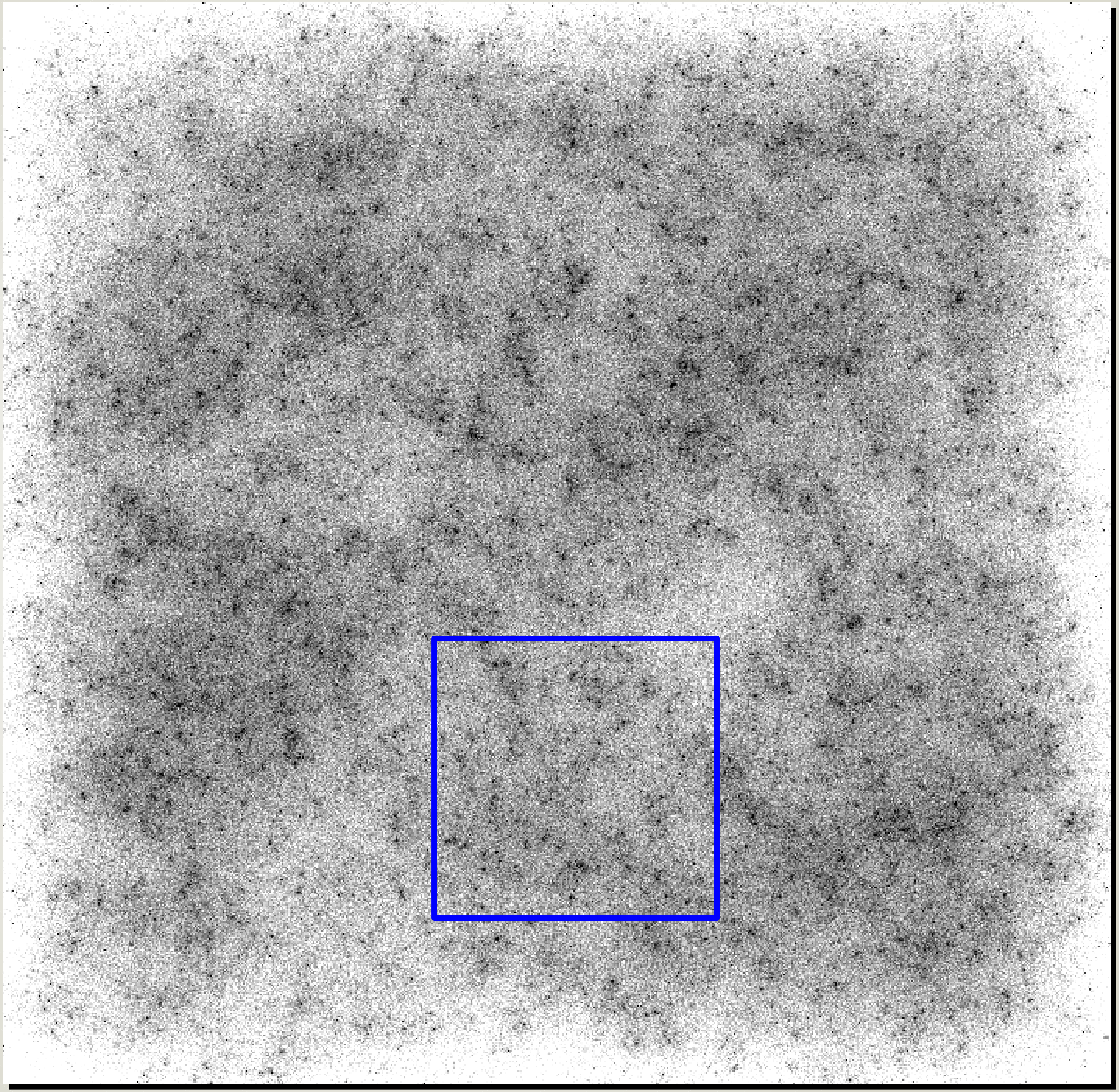
10 hours

3'' x 3''

DM = 31.2

μ = 23 mag/arcsec^2

E-ELT I-band PSF



Simulation:

I-band

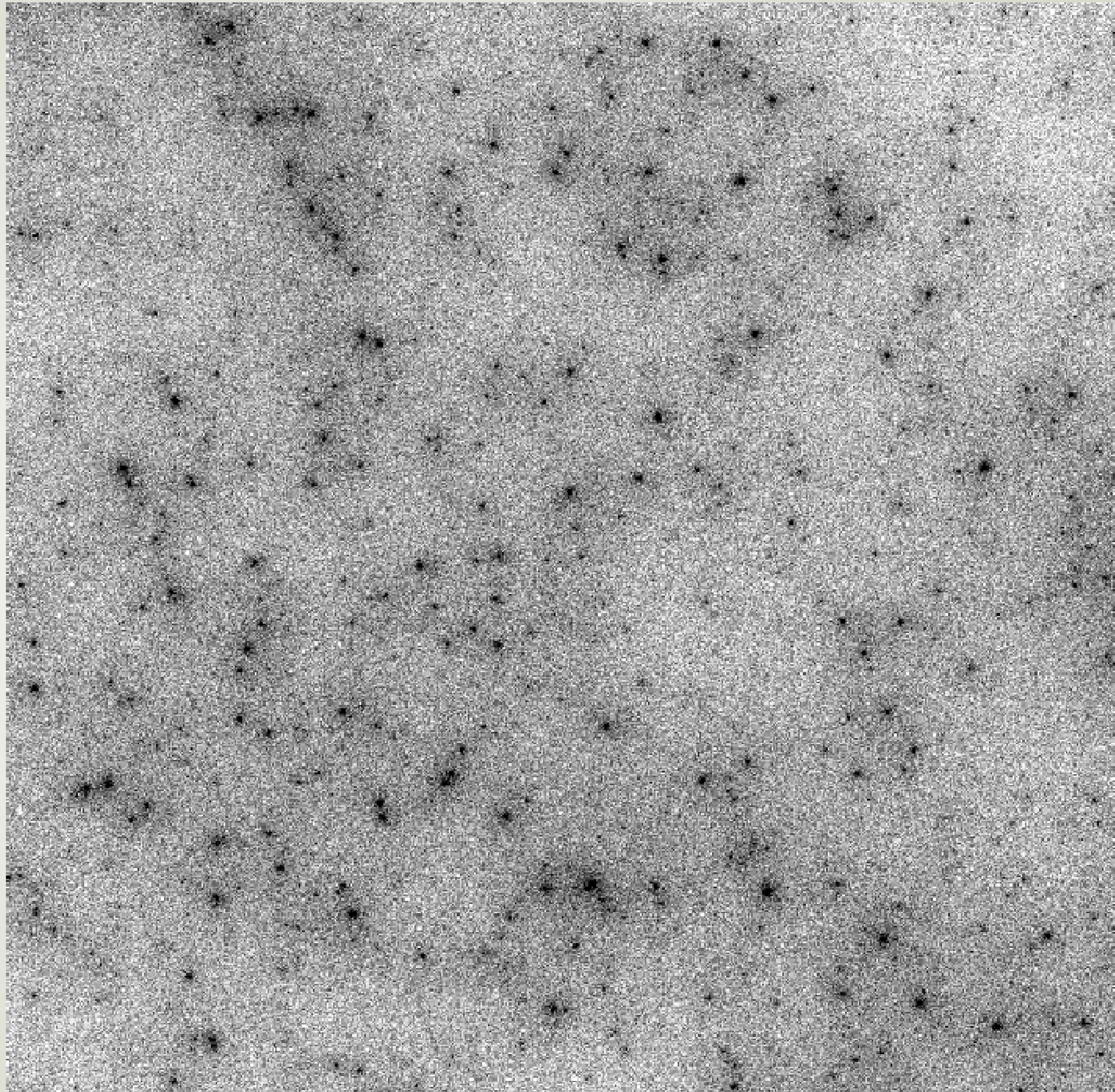
10 hours

0.8'' x 0.8''

DM = 31.2

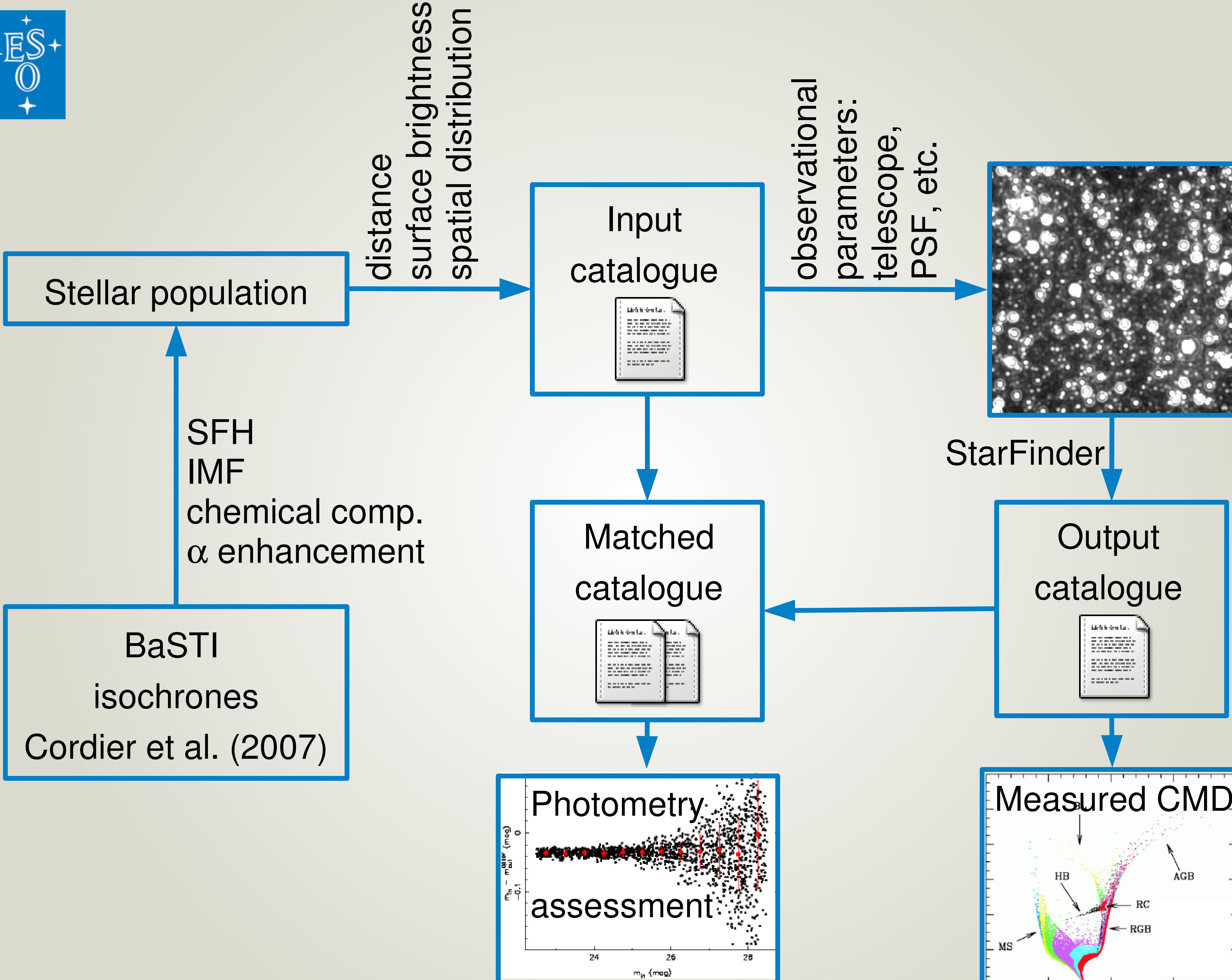
μ = 23 mag/arcsec^2

E-ELT I-band PSF



Specific questions for the DRM

- What is the limiting magnitude down to which accurate photometry of a galaxy's RSP is possible as a function of:
  - the galaxy's distance
  - the surface brightness within the galaxy (equivalent to galactocentric radius for a given profile)
  - the observing band (what is the best combination of bands to use?)
  - the performance of the AO
  - the assumed stellar population
- What is the effect of PSF uncertainties?
- Method: brute-force Monte Carlo simulations

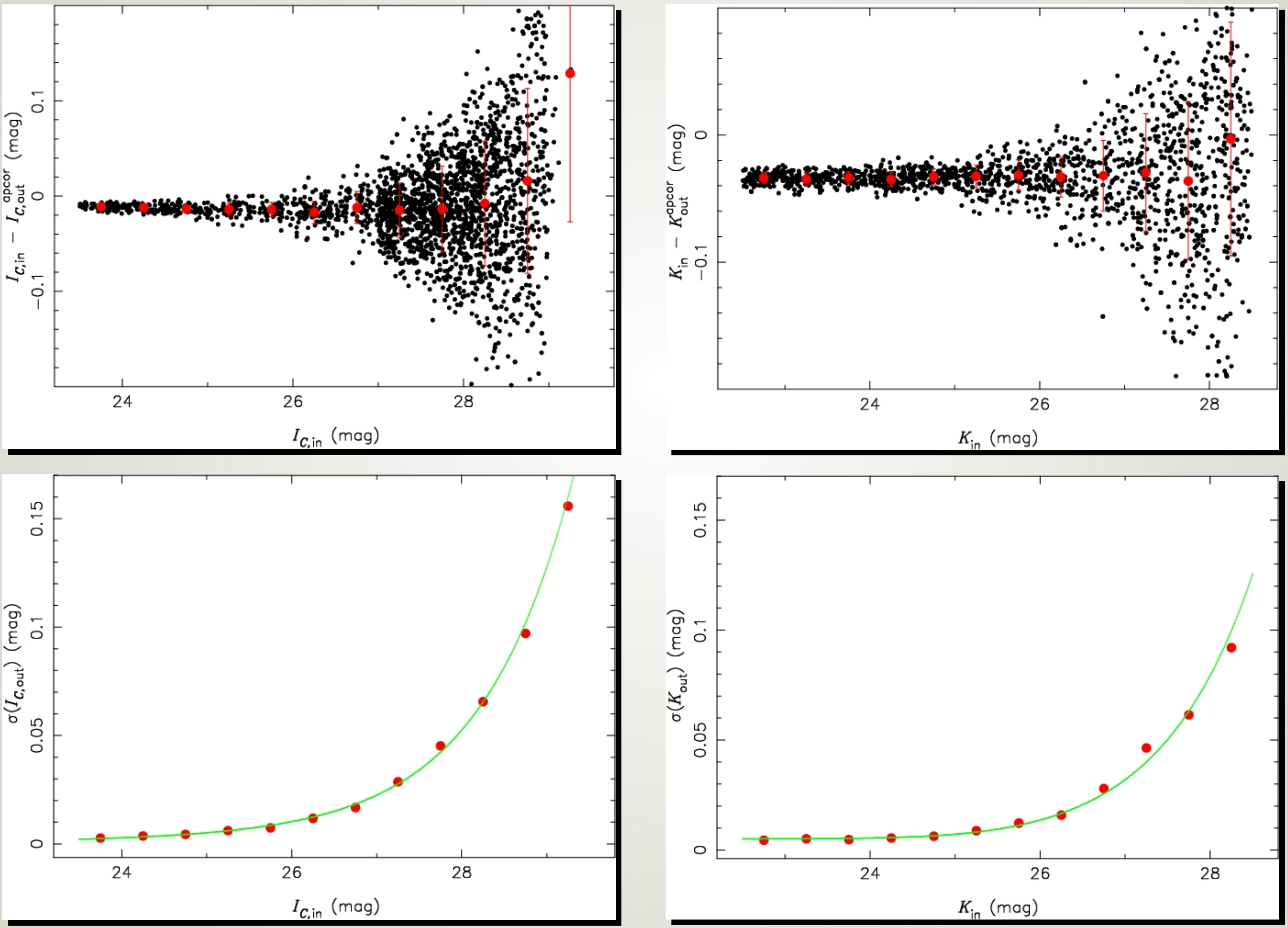

Stellar population
distance
surface brightness
spatial distribution
Input
catalogue
observational
parameters:
telescope,
PSF, etc.
SFH
IMF
chemical comp.
α enhancement
BaSTI
isochrones
Cordier et al. (2007)
StarFinder
Matched
catalogue
Output
catalogue
Photometry
assessment
24
26
28
Measured CMD
AGB
HB
RC
RGB
MS

Simulation parameters (science input)

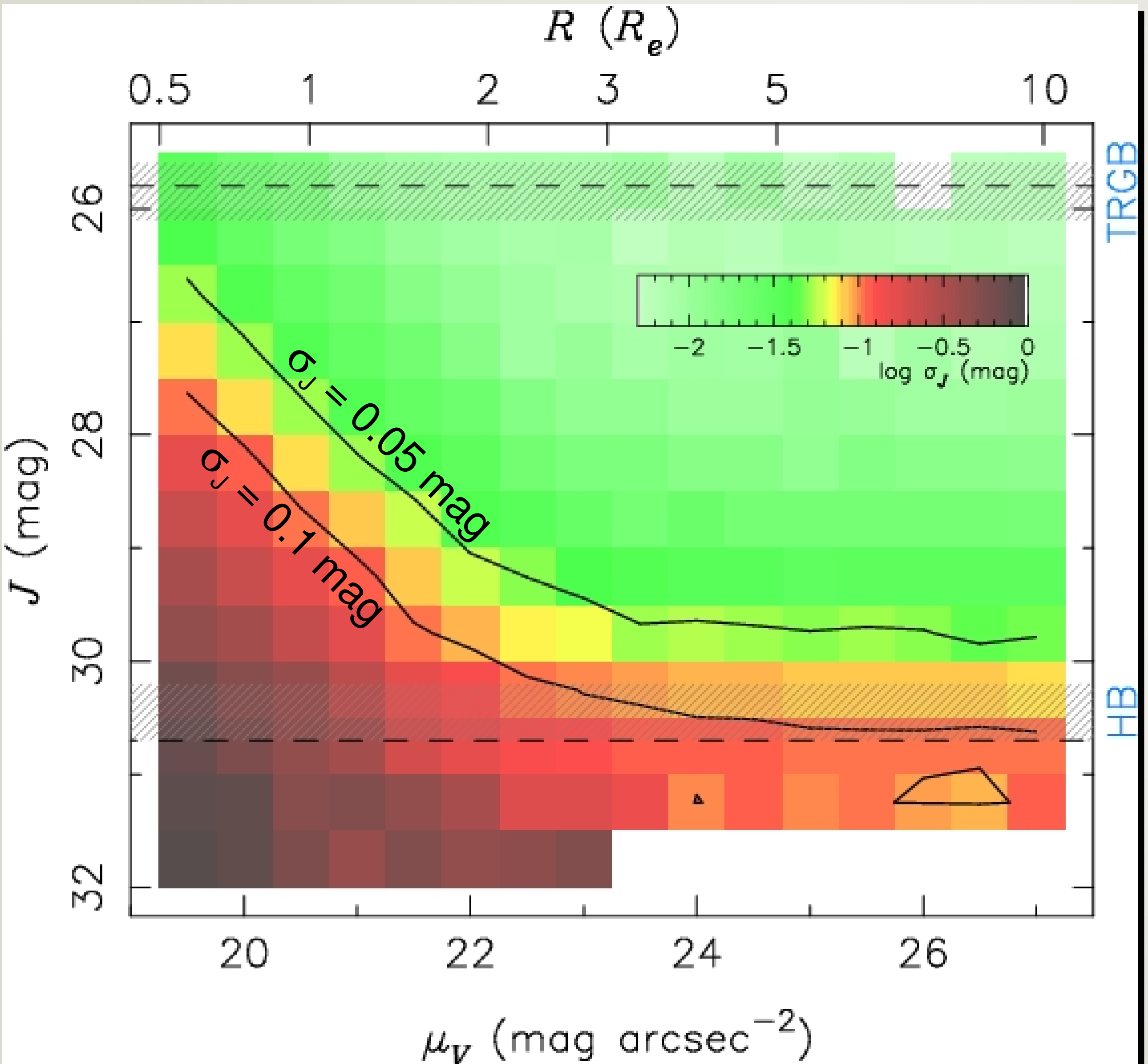
- Stellar population:
  - SFH: constant from 14 – 12 Gyr ago
  - IMF: Salpeter, i.e. $\alpha = -2.35$
  - [Fe/H] = -1.8, -1, -0.6
- Galaxy data:

	NGC 205 (LG)	Cen A (NGC 5128)	M87
DM	24.58	27.92	31.2
kpc/arcsec	0.00396	0.0186	0.084
kpc/arcmin	0.238	1.116	5.055
Profile	Exponential	de Vaucouleurs	de Vaucouleurs
Scale or effective radius (arcsec)	h = 102	R_e = 330	R_e = 105
Central or effective SB (mag arcsec^{-2})	μ_0 = 20.4	μ_e = 22.15	μ_e = 20.58

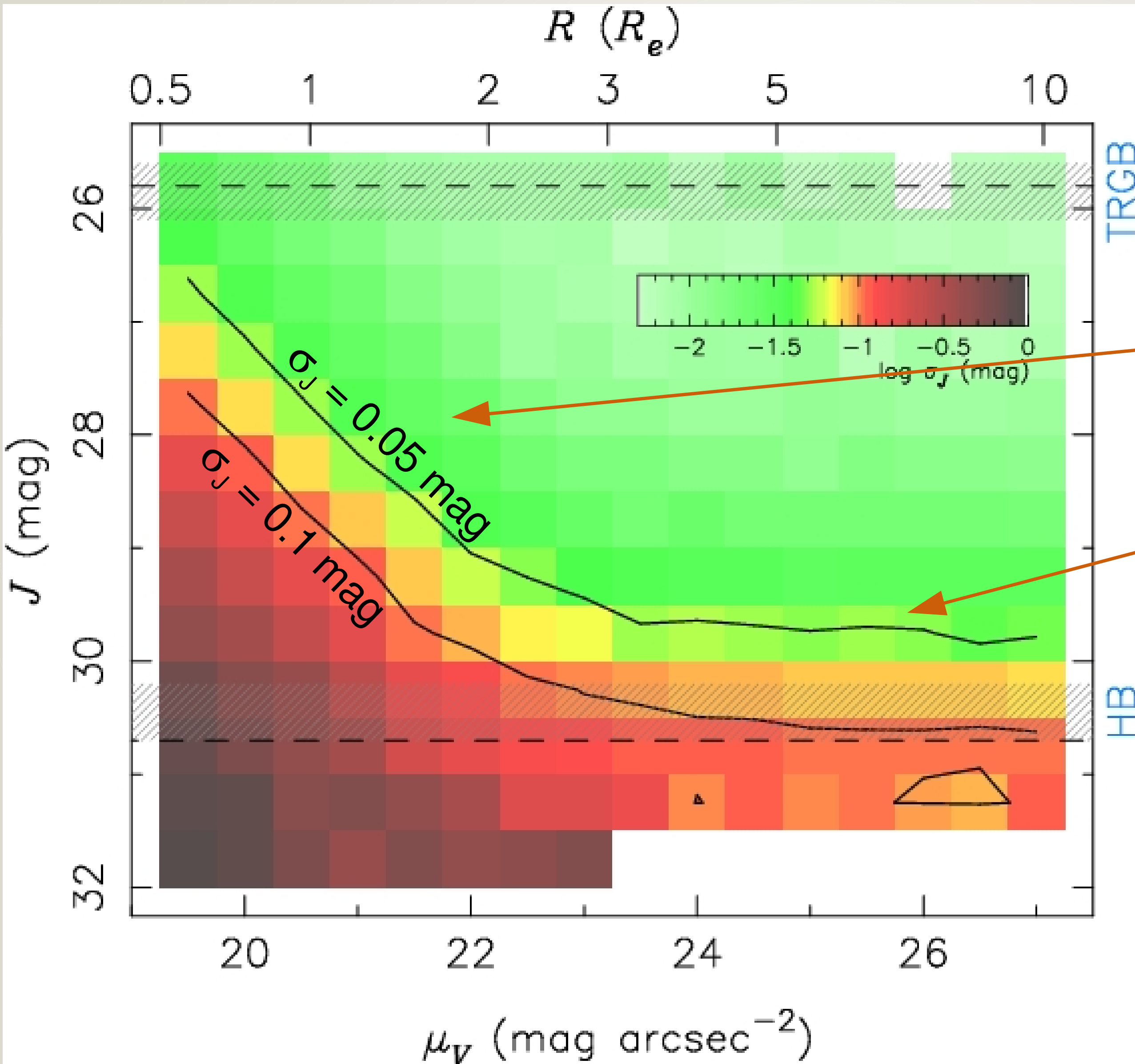
Simple test case: no crowding



Full result: M87



Full result: M87

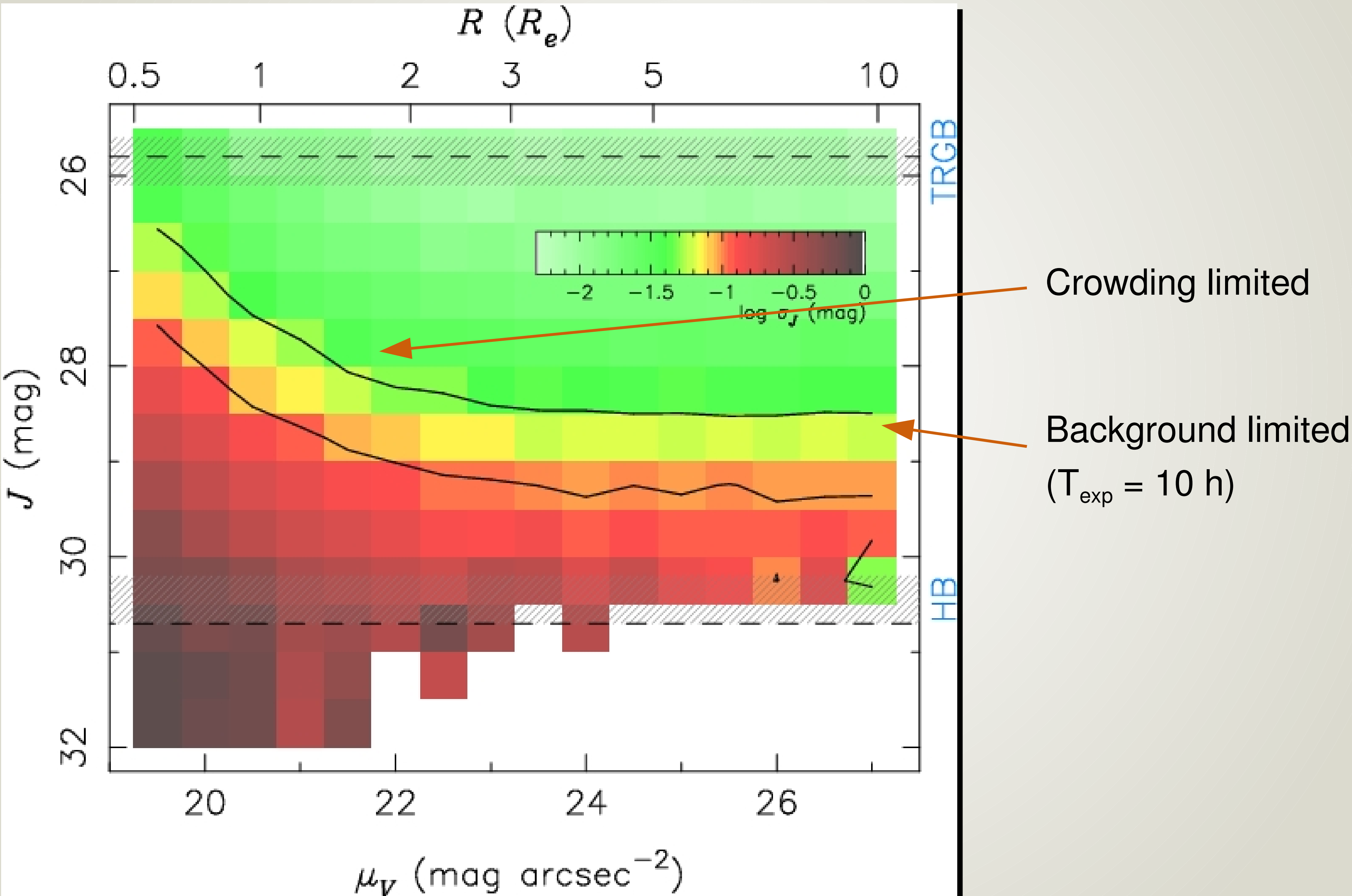


Crowding limited

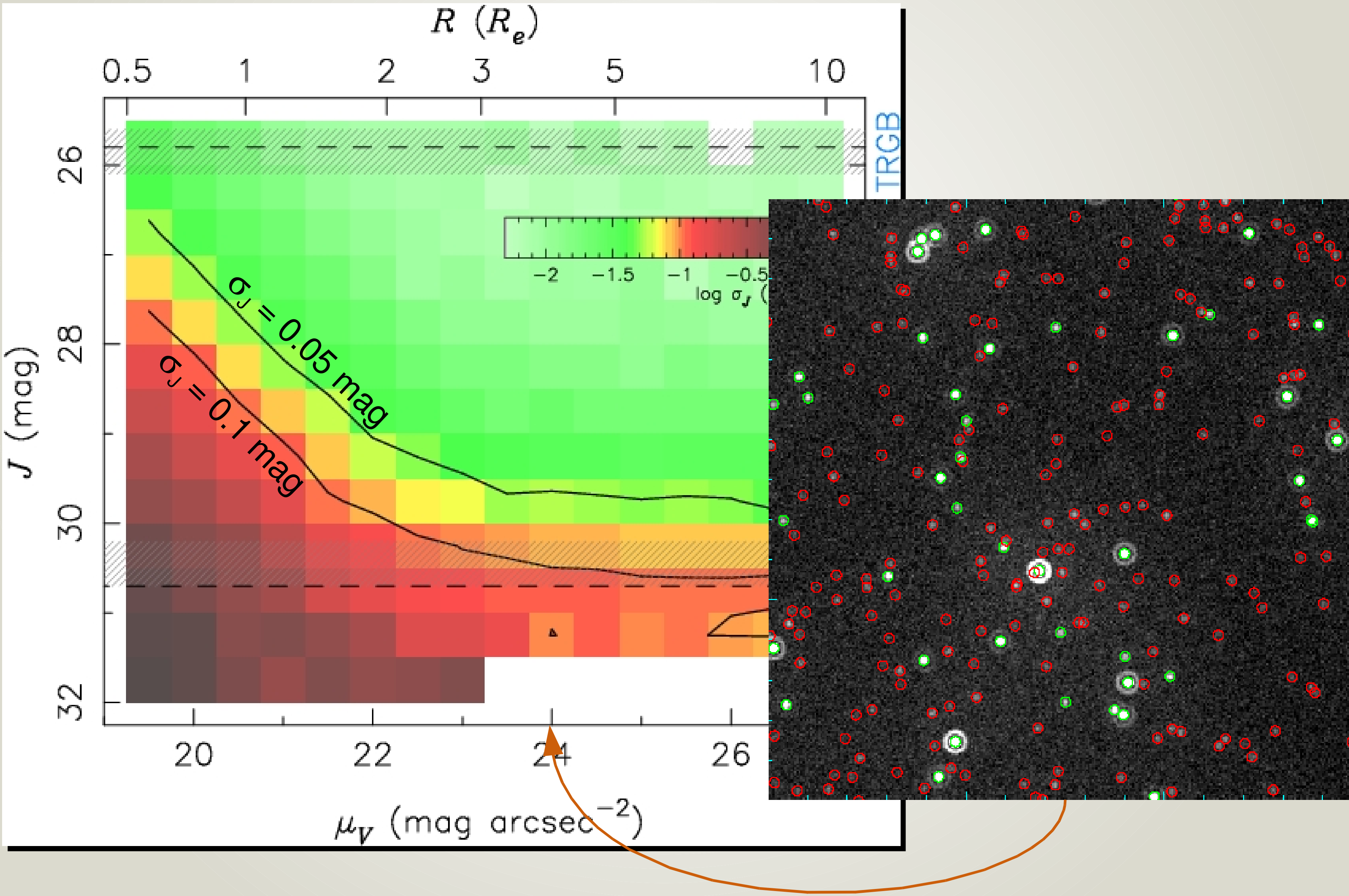
Background limited

(T_{exp} = 100 h)

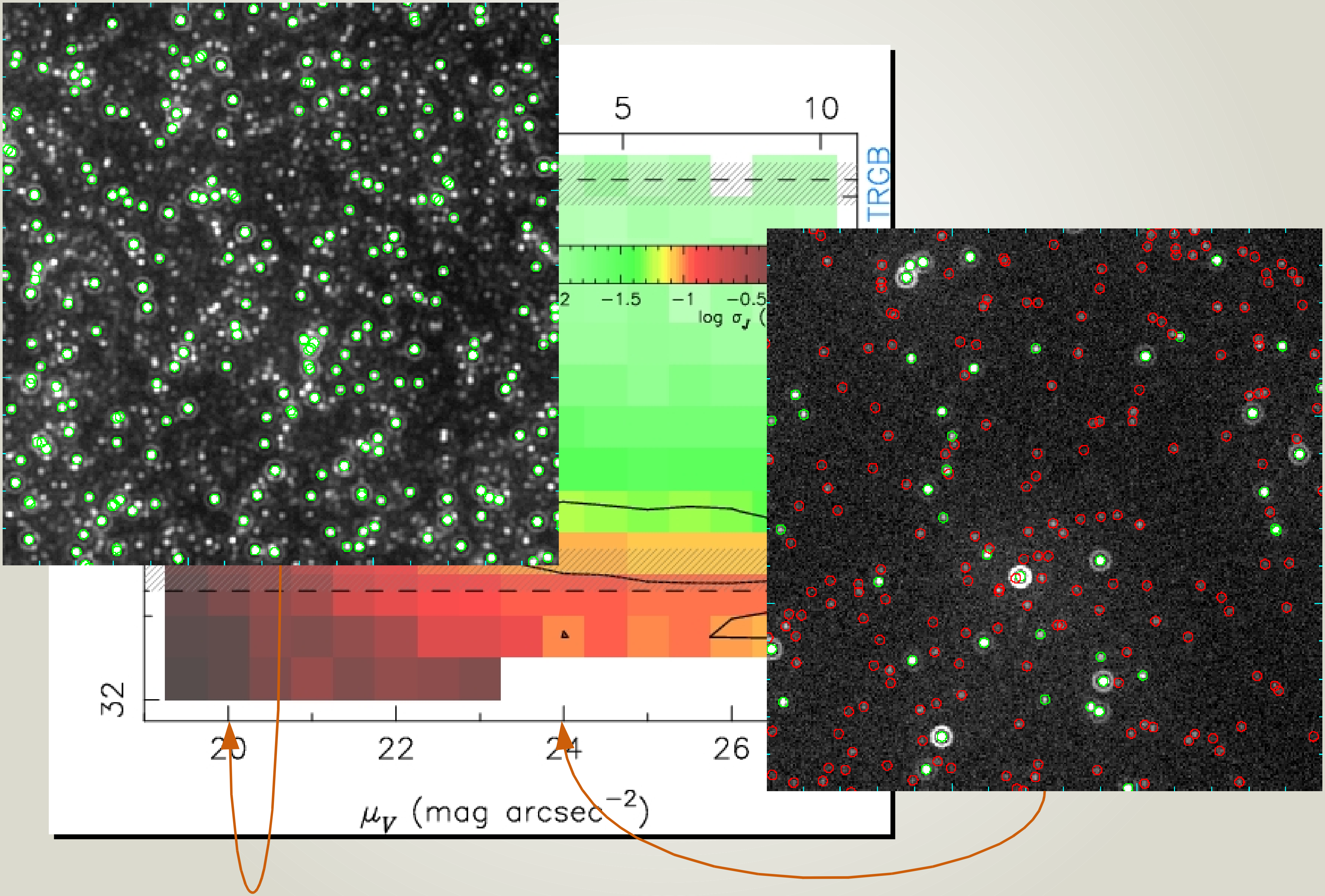
Full result: M87



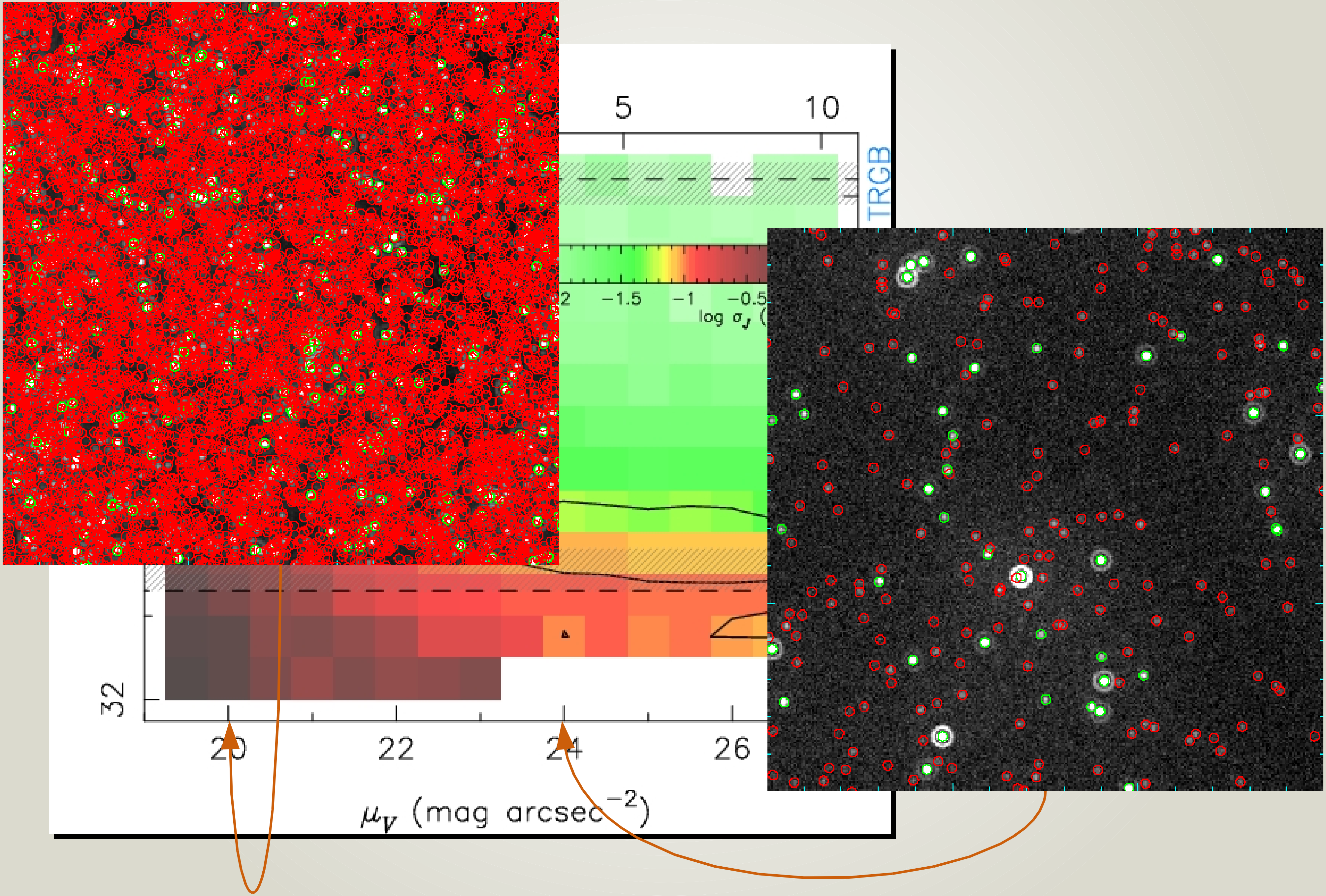
Full result: M87



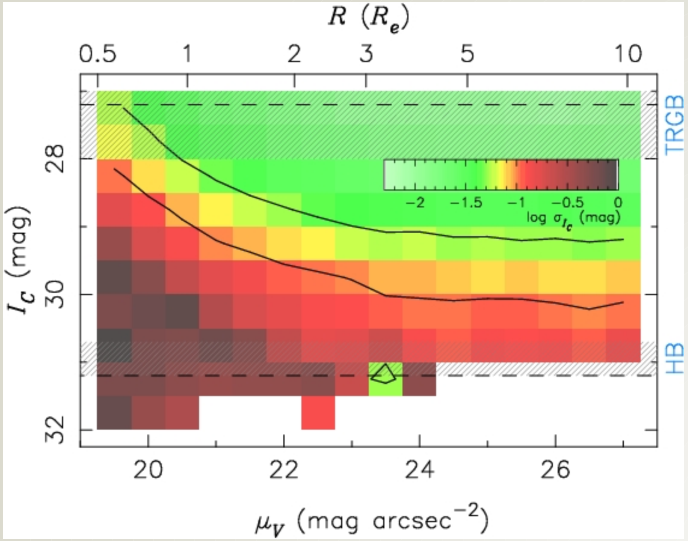
Full result: M87



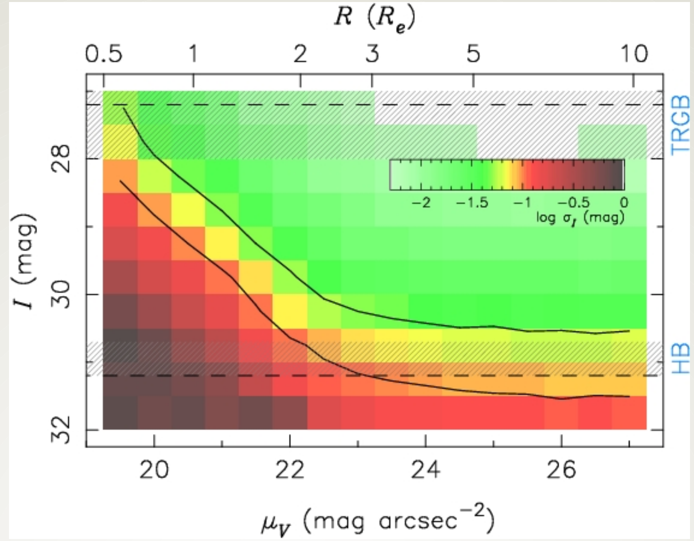
Full result: M87



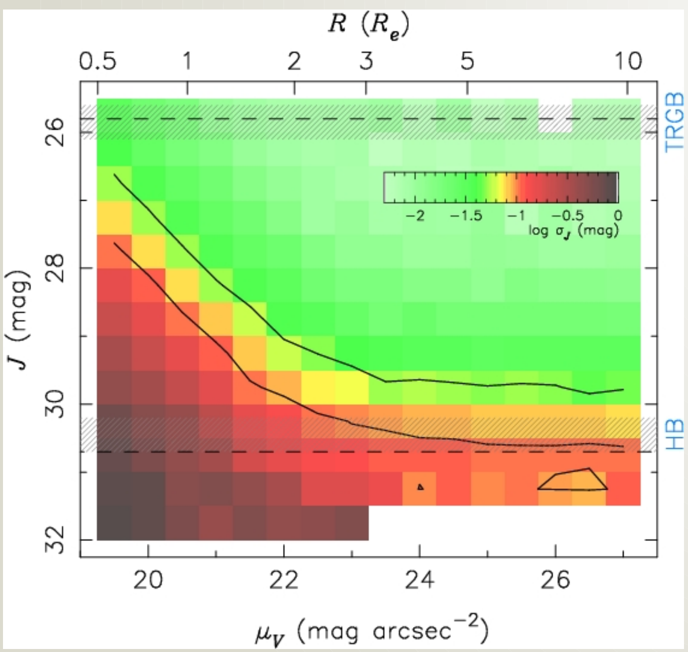
M87



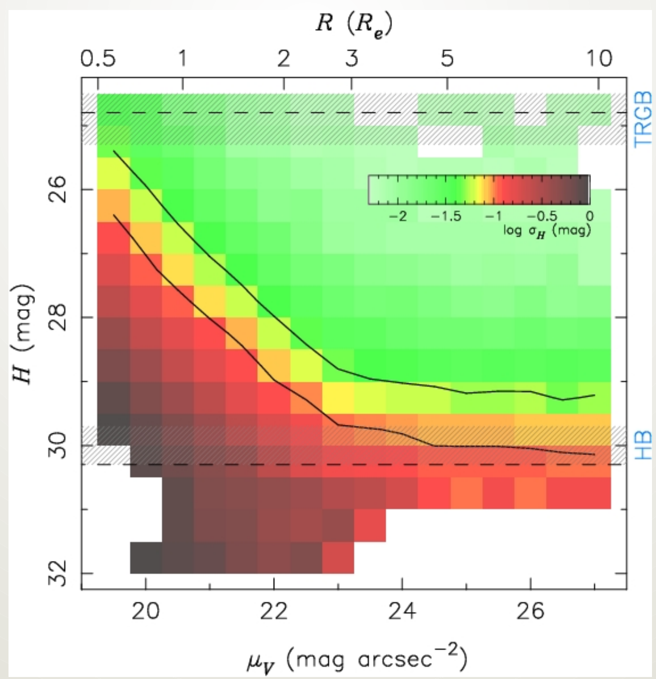
R (R_e)
0.5 1 2 3 5 10
TRGB
HB
−2 −1.5 −1 −0.5 0
log σ_Ic (mag)
I_C (mag)
28 30 32
20 22 24 26
μ_V (mag arcsec^−2)



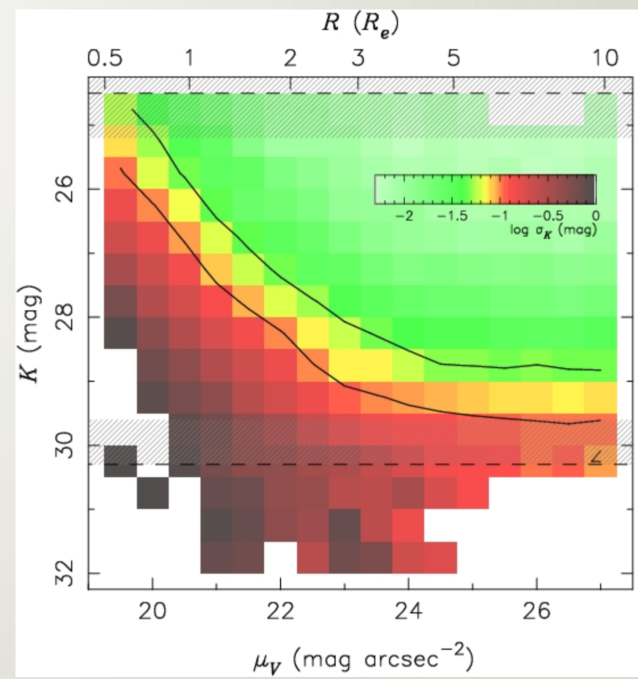
R (R_e)
0.5 1 2 3 5 10
TRGB
HB
−2 −1.5 −1 −0.5 0
log σ_I (mag)
I (mag)
28 30 32
20 22 24 26
μ_V (mag arcsec^−2)



R (R_e)
0.5 1 2 3 5 10
TRGB
HB
−2 −1.5 −1 −0.5 0
log σ_J (mag)
J (mag)
26 28 30 32
20 22 24 26
μ_V (mag arcsec^−2)

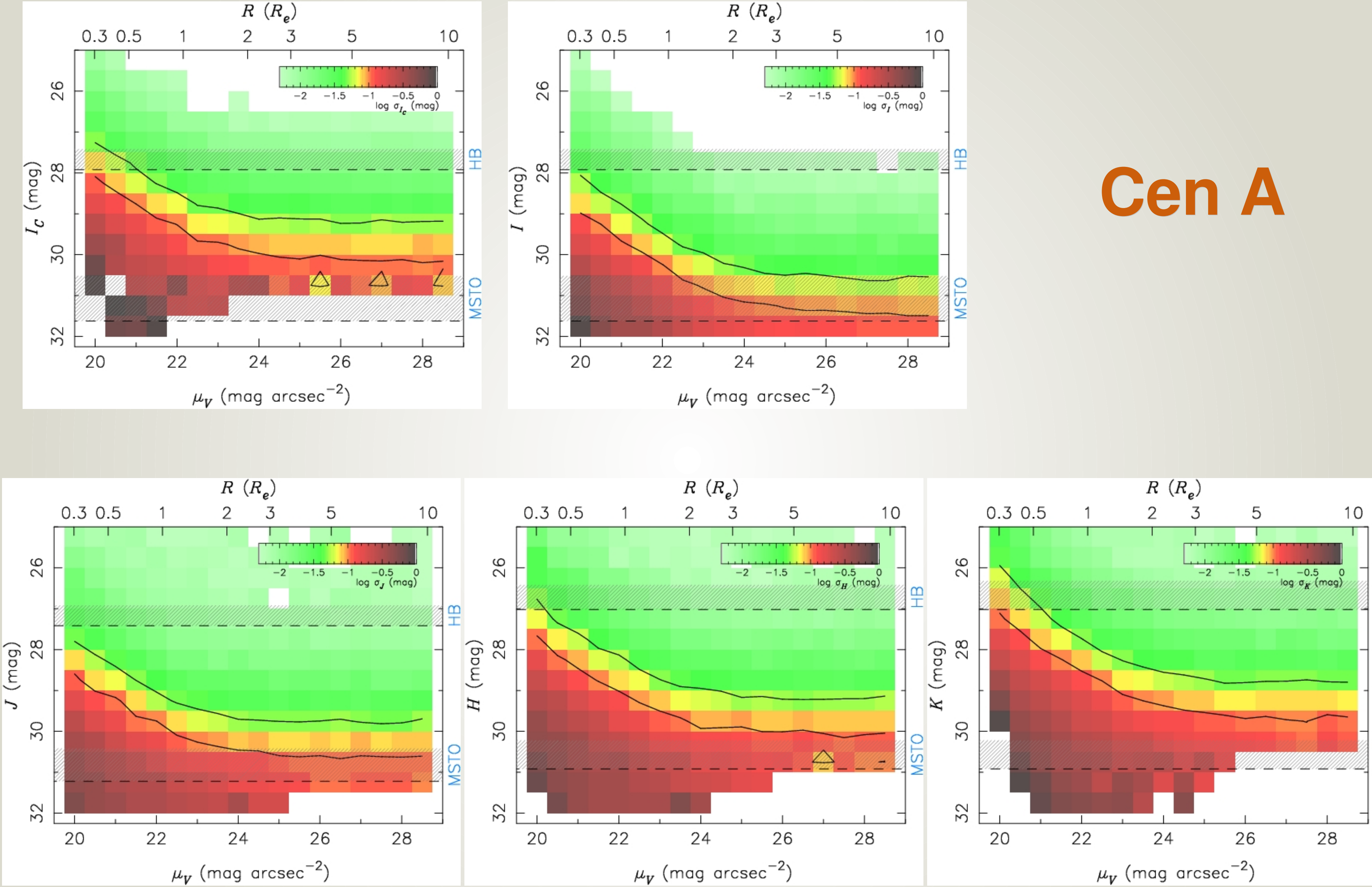


R (R_e)
0.5 1 2 3 5 10
TRGB
HB
−2 −1.5 −1 −0.5 0
log σ_H (mag)
H (mag)
26 28 30 32
20 22 24 26
μ_V (mag arcsec^−2)

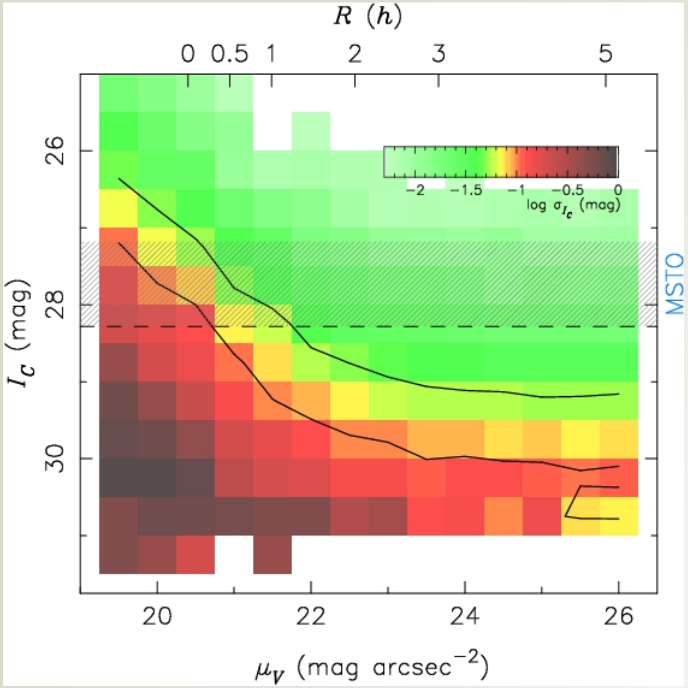


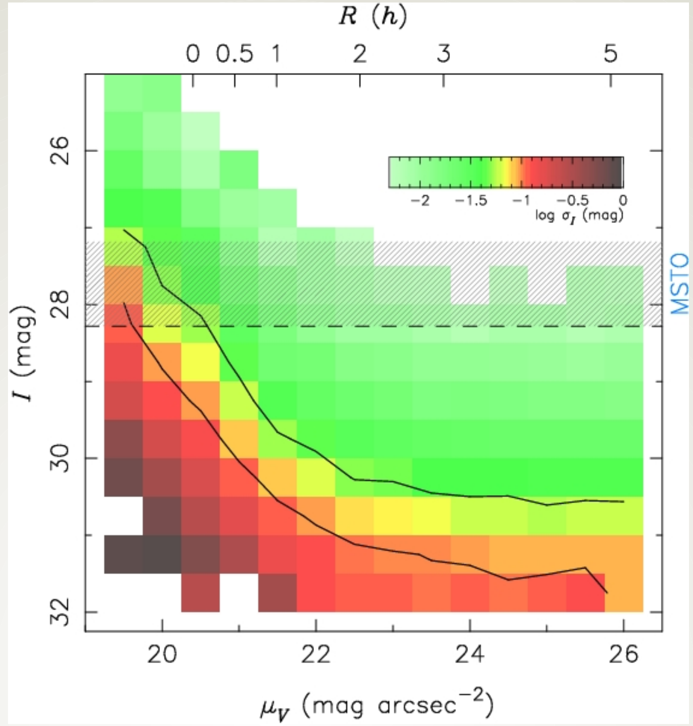
R (R_e)
0.5 1 2 3 5 10
TRGB
HB
−2 −1.5 −1 −0.5 0
log σ_K (mag)
K (mag)
26 28 30 32
20 22 24 26
μ_V (mag arcsec^−2)

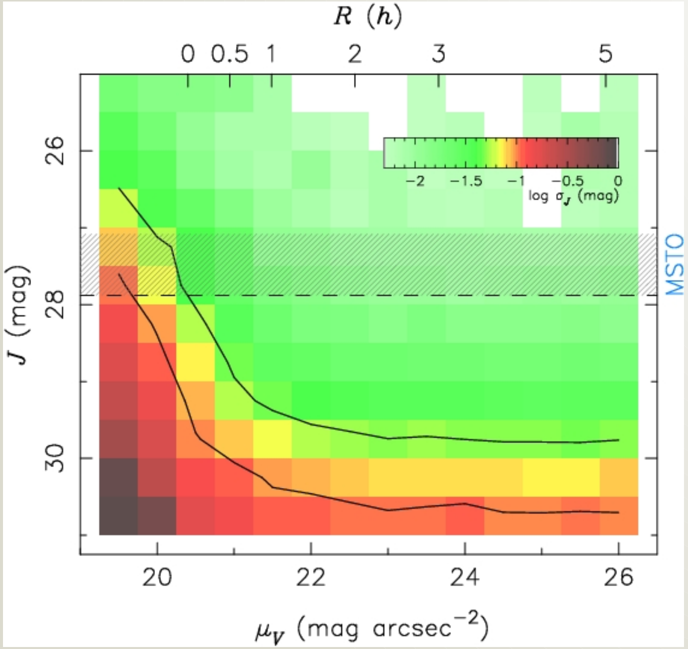
Cen A

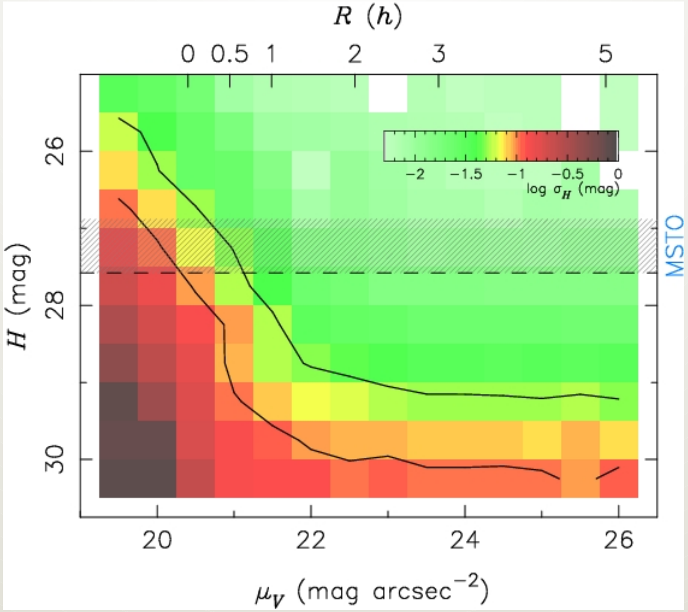

R (R_e)
0.3 0.5 1 2 3 5 10
I_C (mag)
log σ_{I_C} (mag)
HB
MSTO
μ_V (mag arcsec^{-2})
I (mag)
log σ_I (mag)
J (mag)
log σ_J (mag)
H (mag)
log σ_H (mag)
K (mag)
log σ_K (mag)

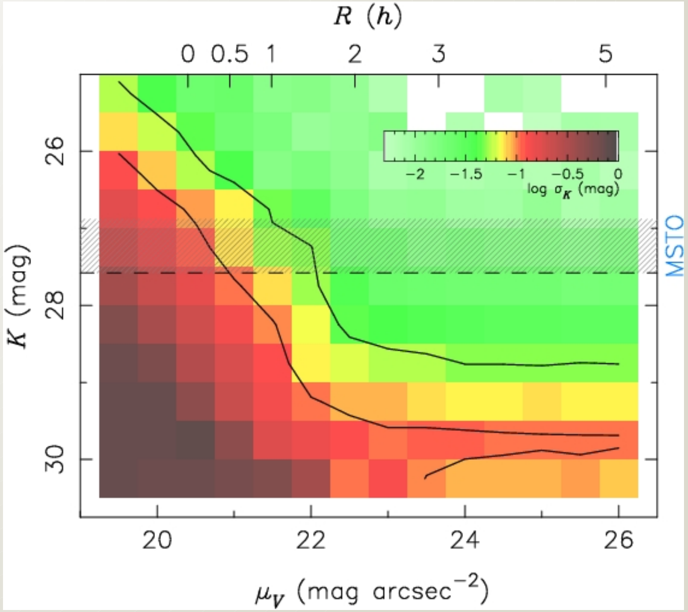
NGC 205


R (h)
0 0.5 1 2 3 5
I_C (mag)
26 28 30
−2 −1.5 −1 −0.5 0
log σ_{I_C} (mag)
MSTO
20 22 24 26
μ_V (mag arcsec^−2)

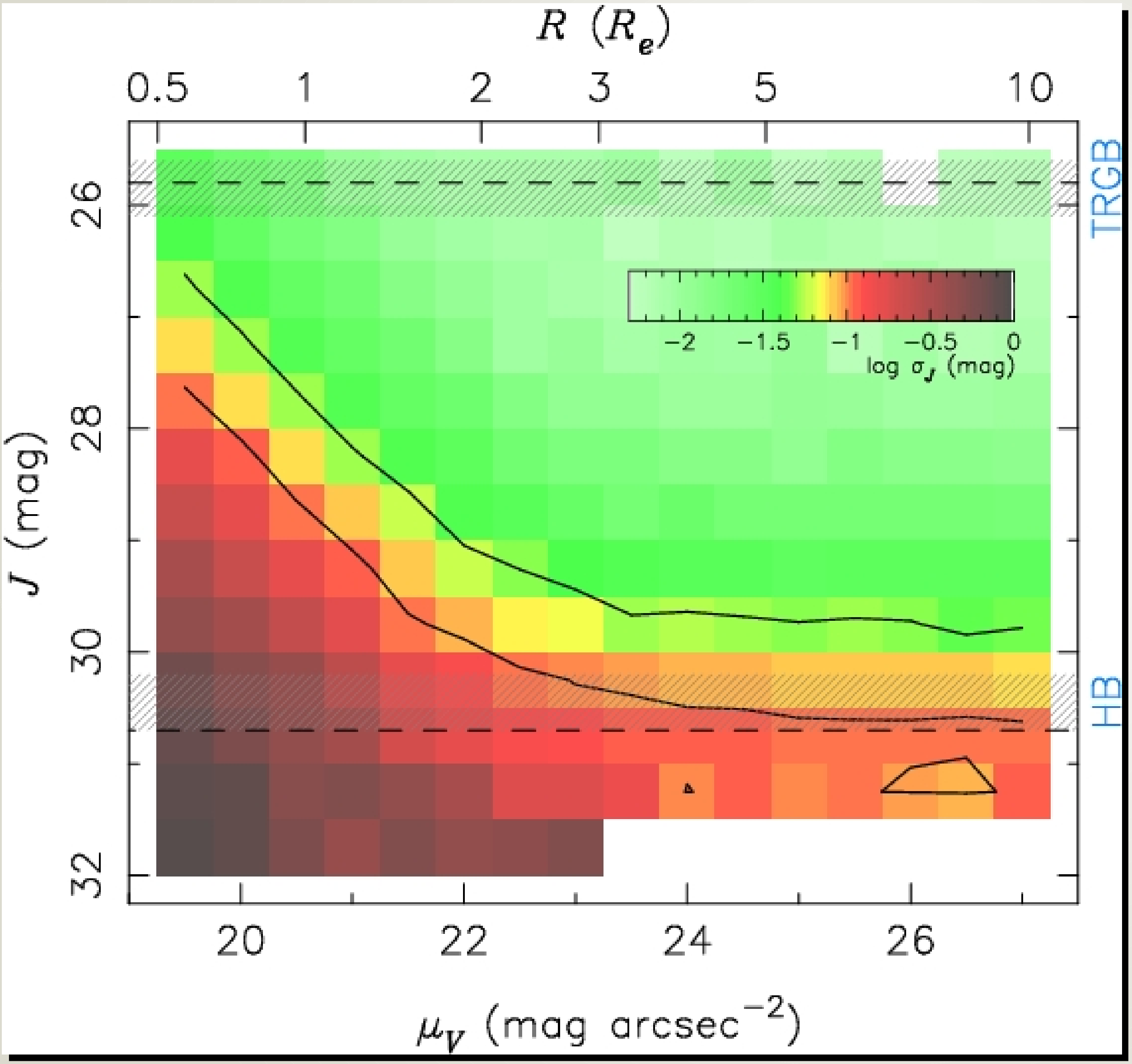

R (h)
0 0.5 1 2 3 5
I (mag)
26 28 30 32
−2 −1.5 −1 −0.5 0
log σ_I (mag)
MSTO
20 22 24 26
μ_V (mag arcsec^−2)


R (h)
0 0.5 1 2 3 5
J (mag)
26 28 30
−2 −1.5 −1 −0.5 0
log σ_J (mag)
MSTO
20 22 24 26
μ_V (mag arcsec^−2)

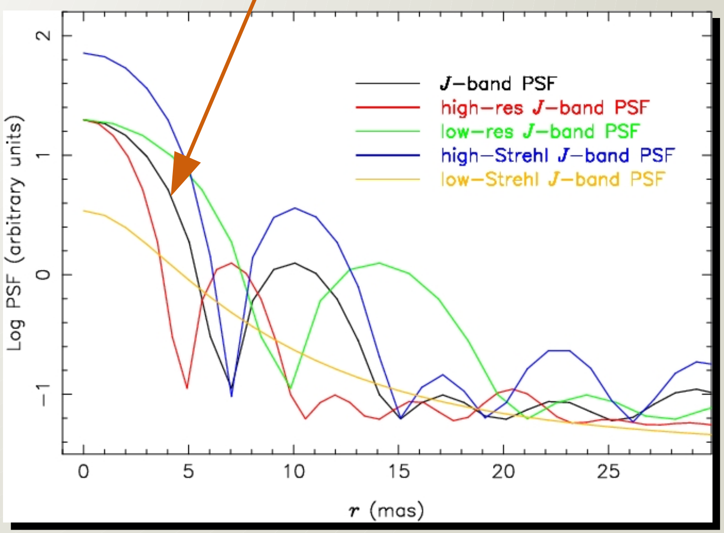

R (h)
0 0.5 1 2 3 5
H (mag)
26 28 30
−2 −1.5 −1 −0.5 0
log σ_H (mag)
MSTO
20 22 24 26
μ_V (mag arcsec^−2)


R (h)
0 0.5 1 2 3 5
K (mag)
26 28 30
−2 −1.5 −1 −0.5 0
log σ_K (mag)
MSTO
20 22 24 26
μ_V (mag arcsec^−2)

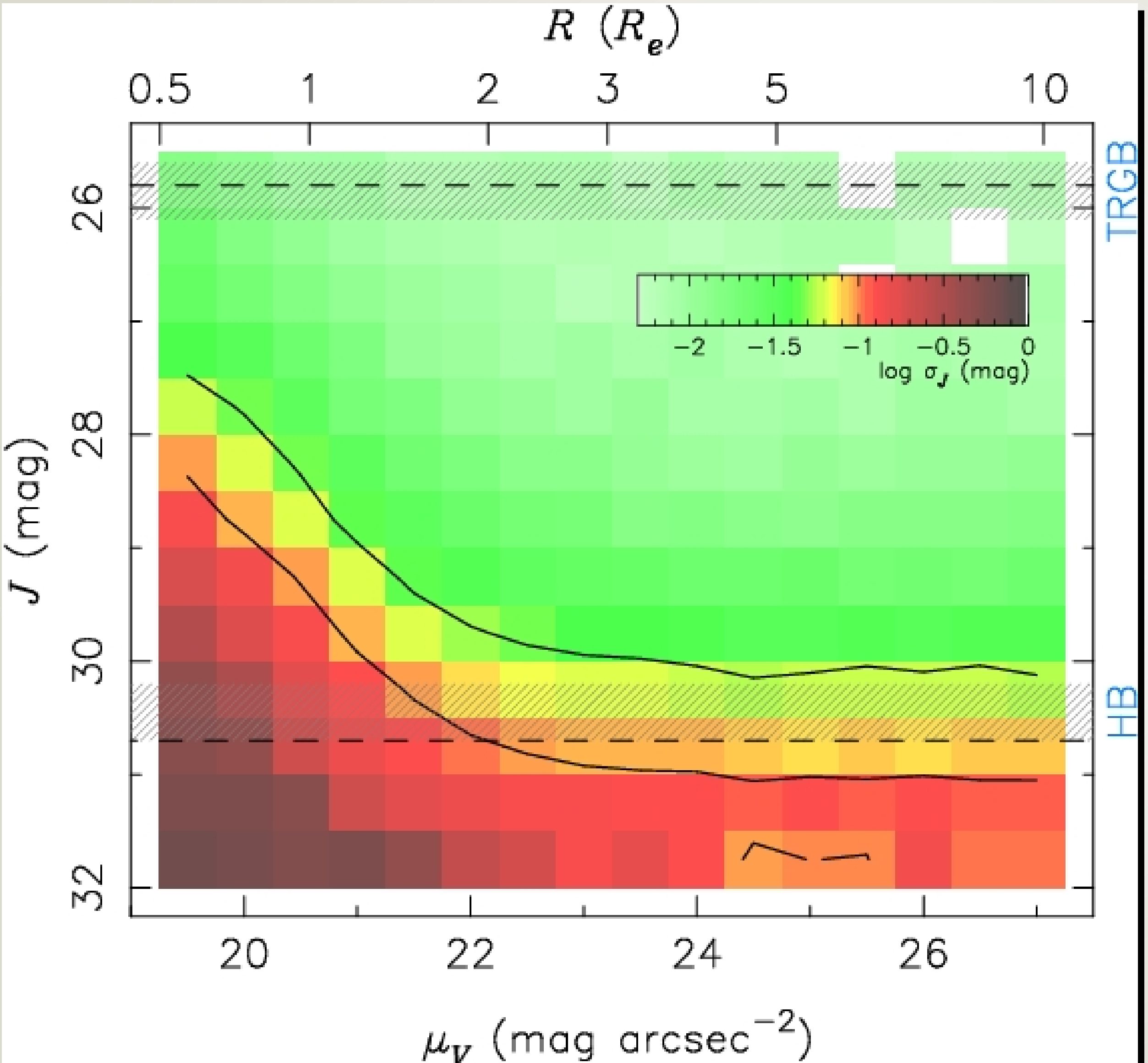
Effect of resolution



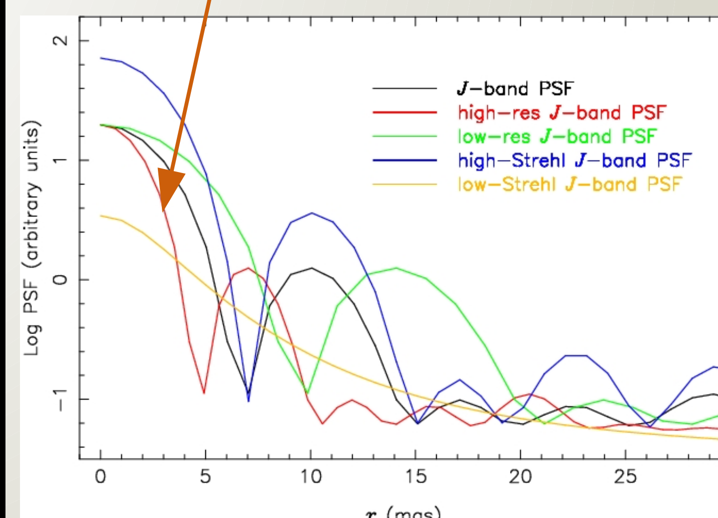
Original: D = 42 m



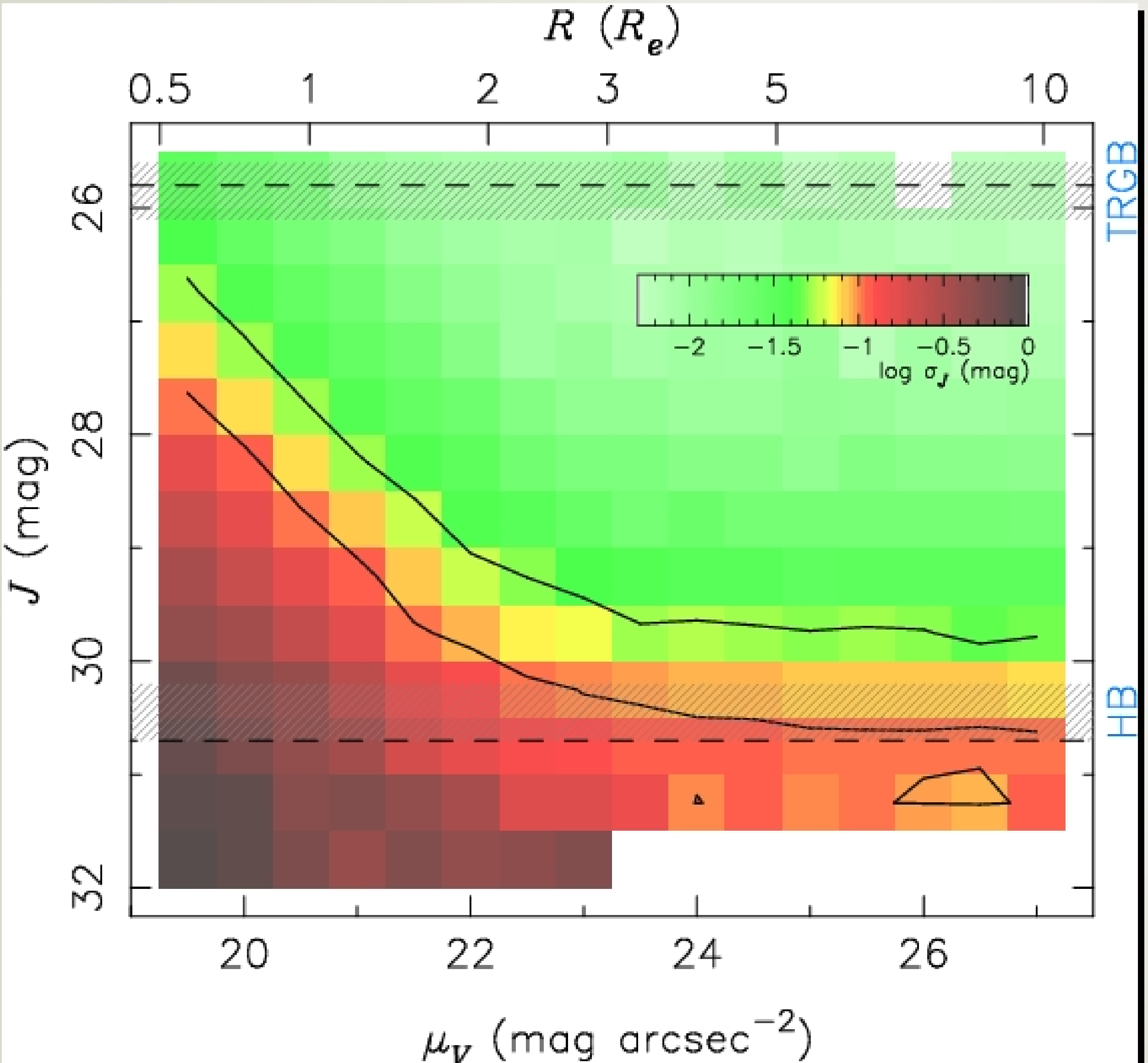
Effect of resolution



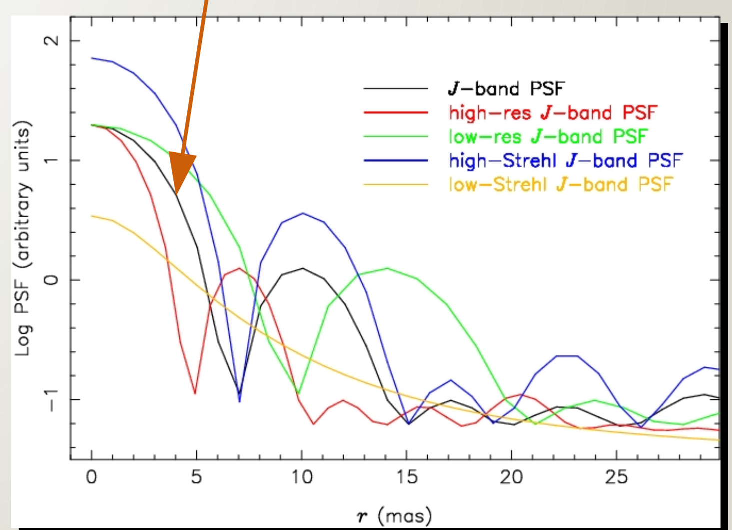
D = 60 m



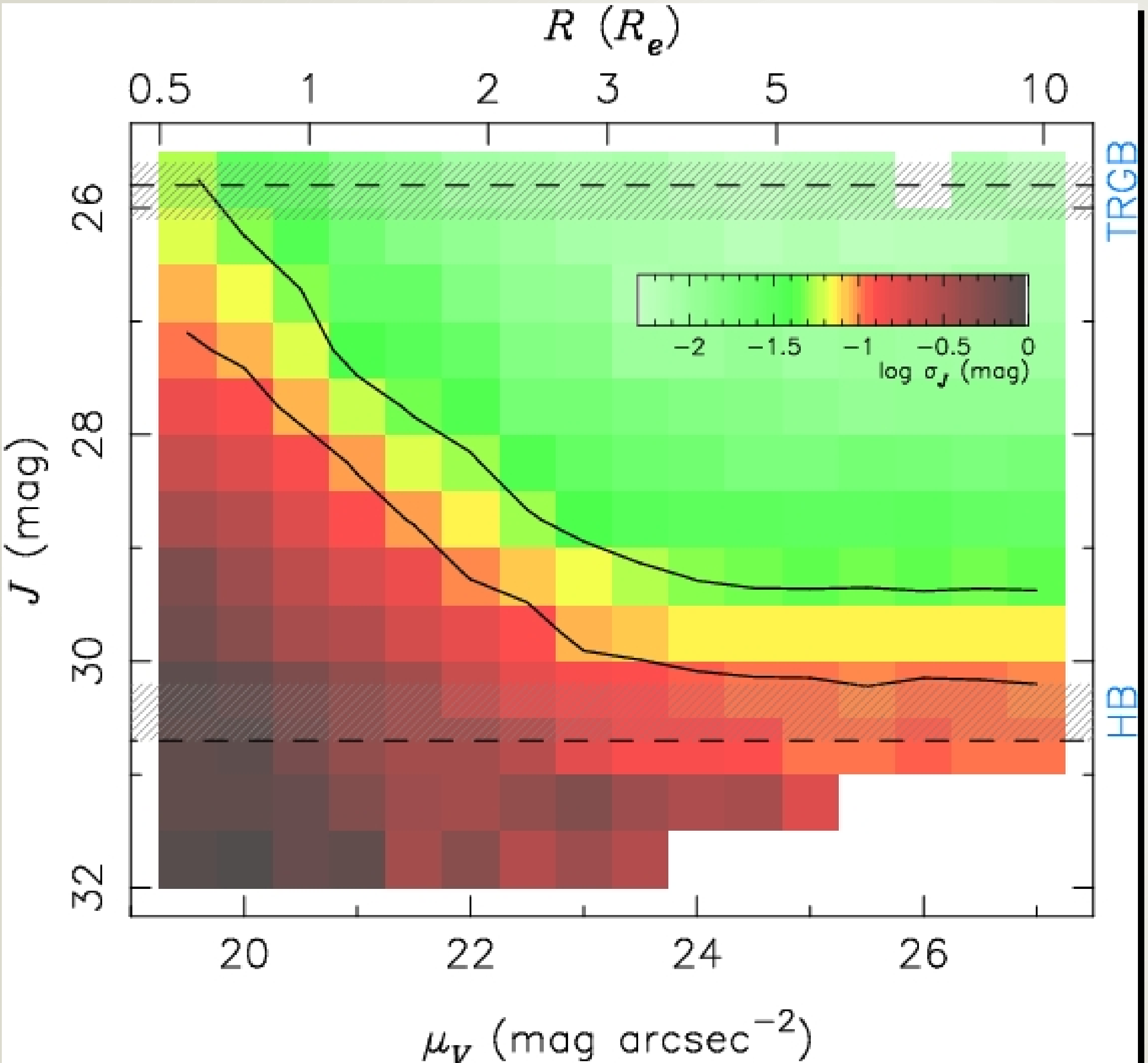
Effect of resolution



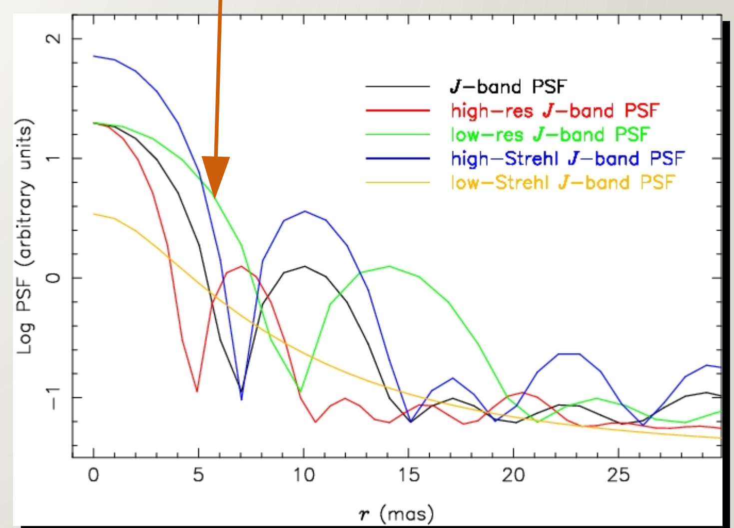
D = 42 m



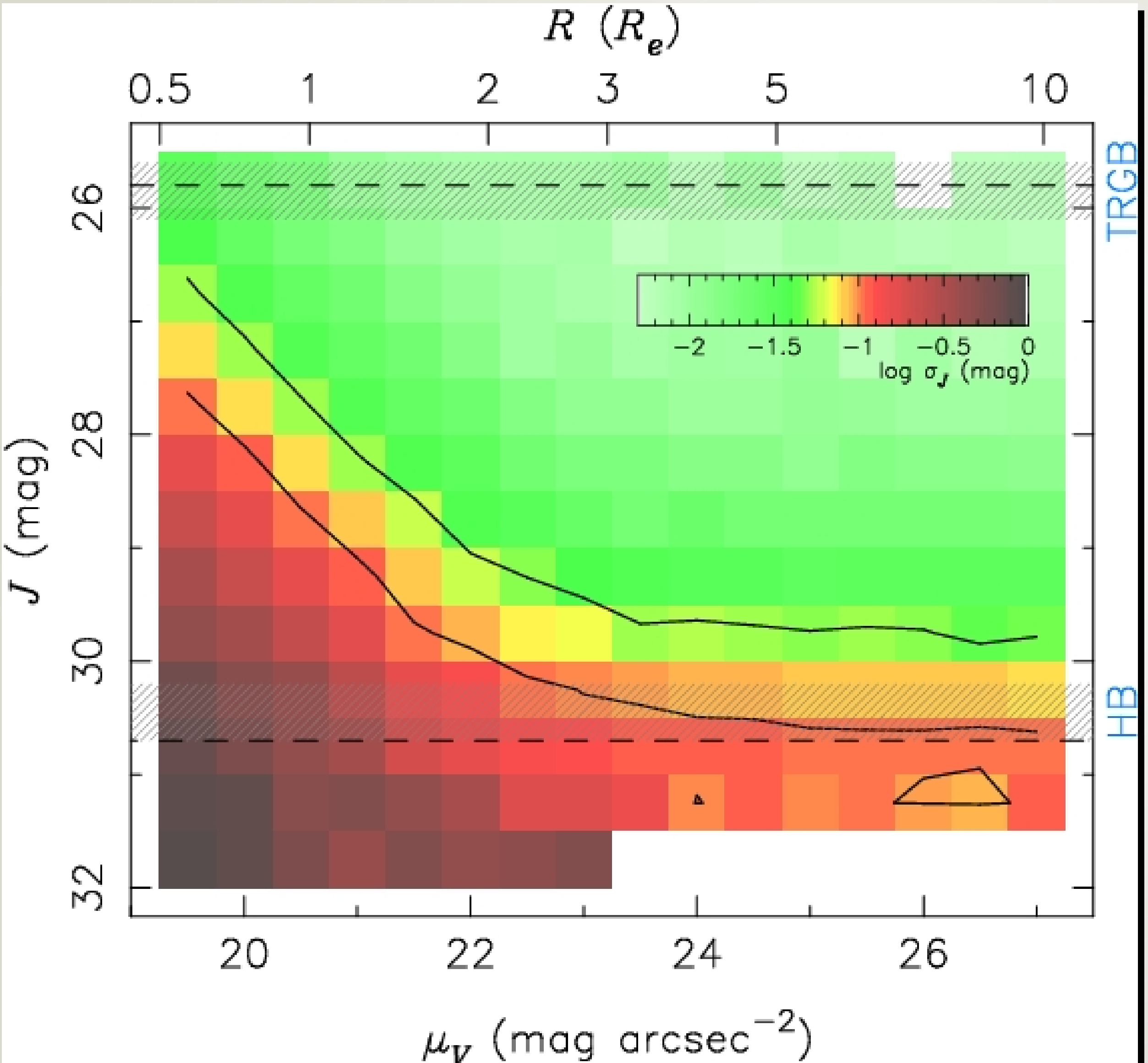
Effect of resolution



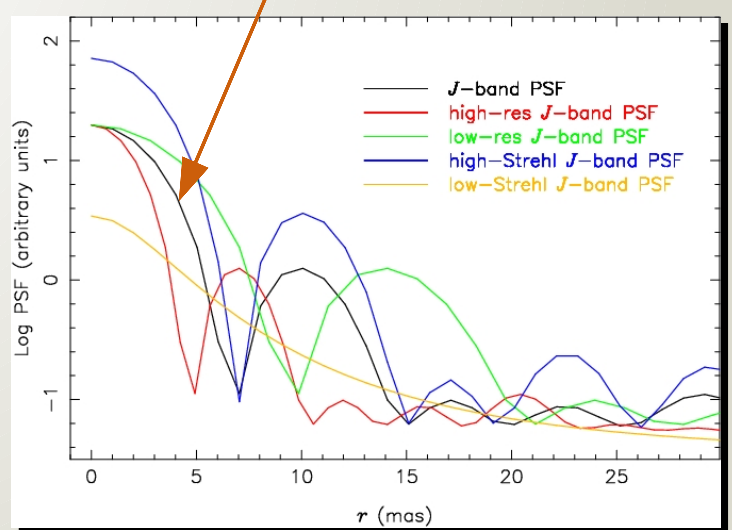
D = 30 m



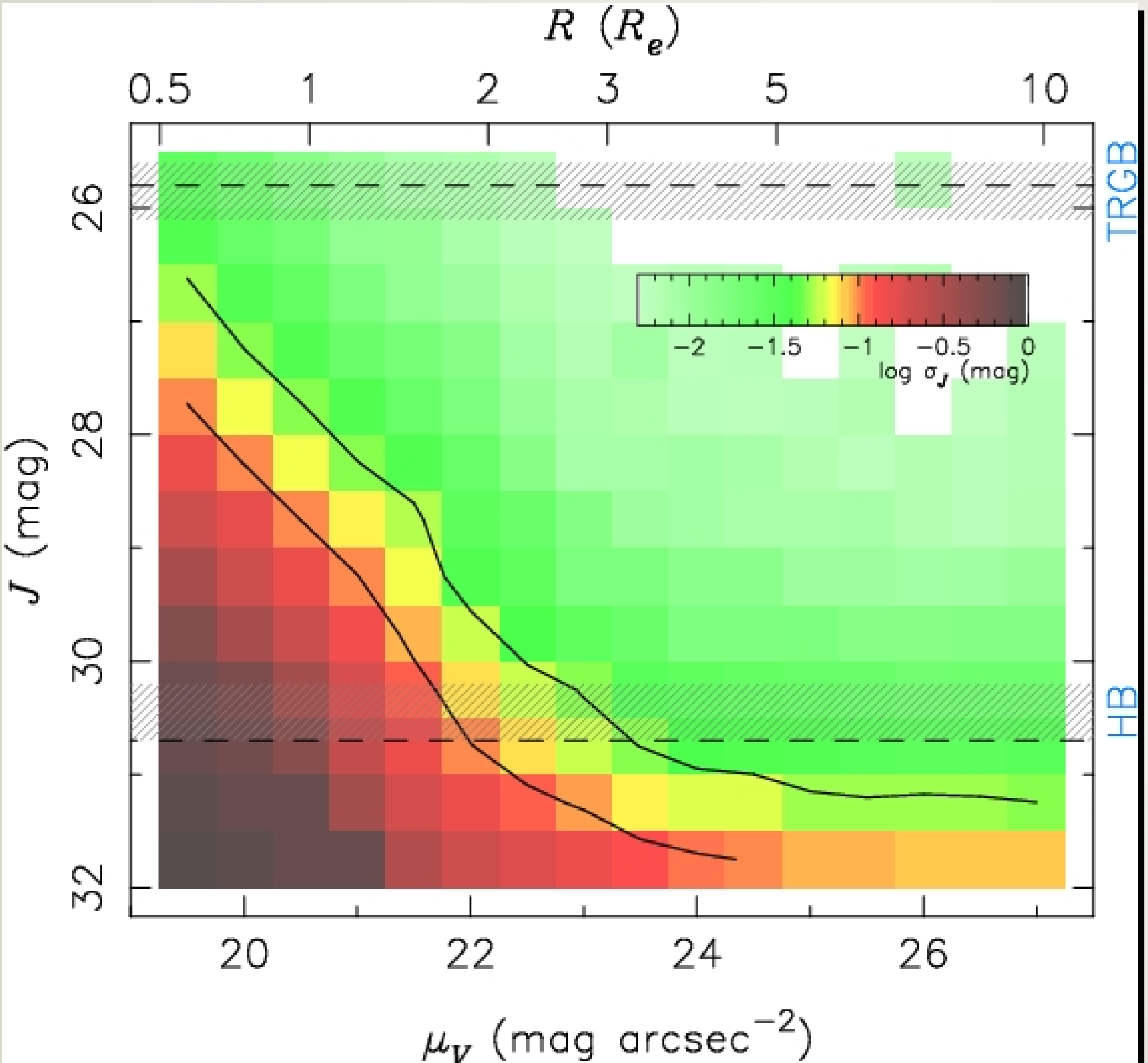
Effect of AO performance



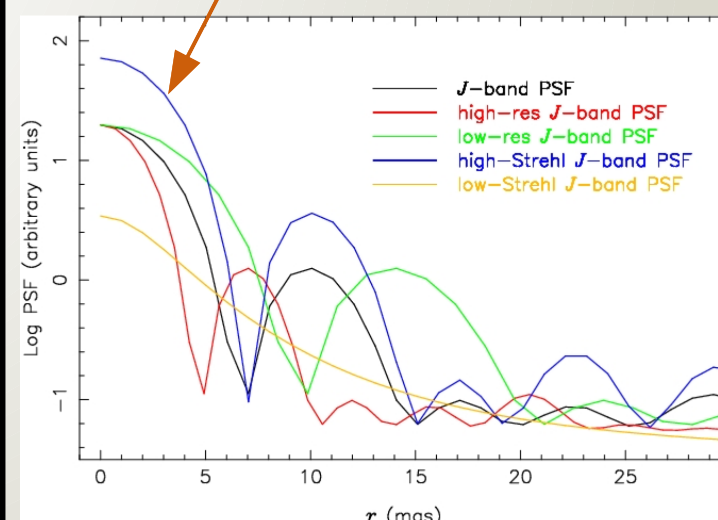
Original: intermediate Strehl



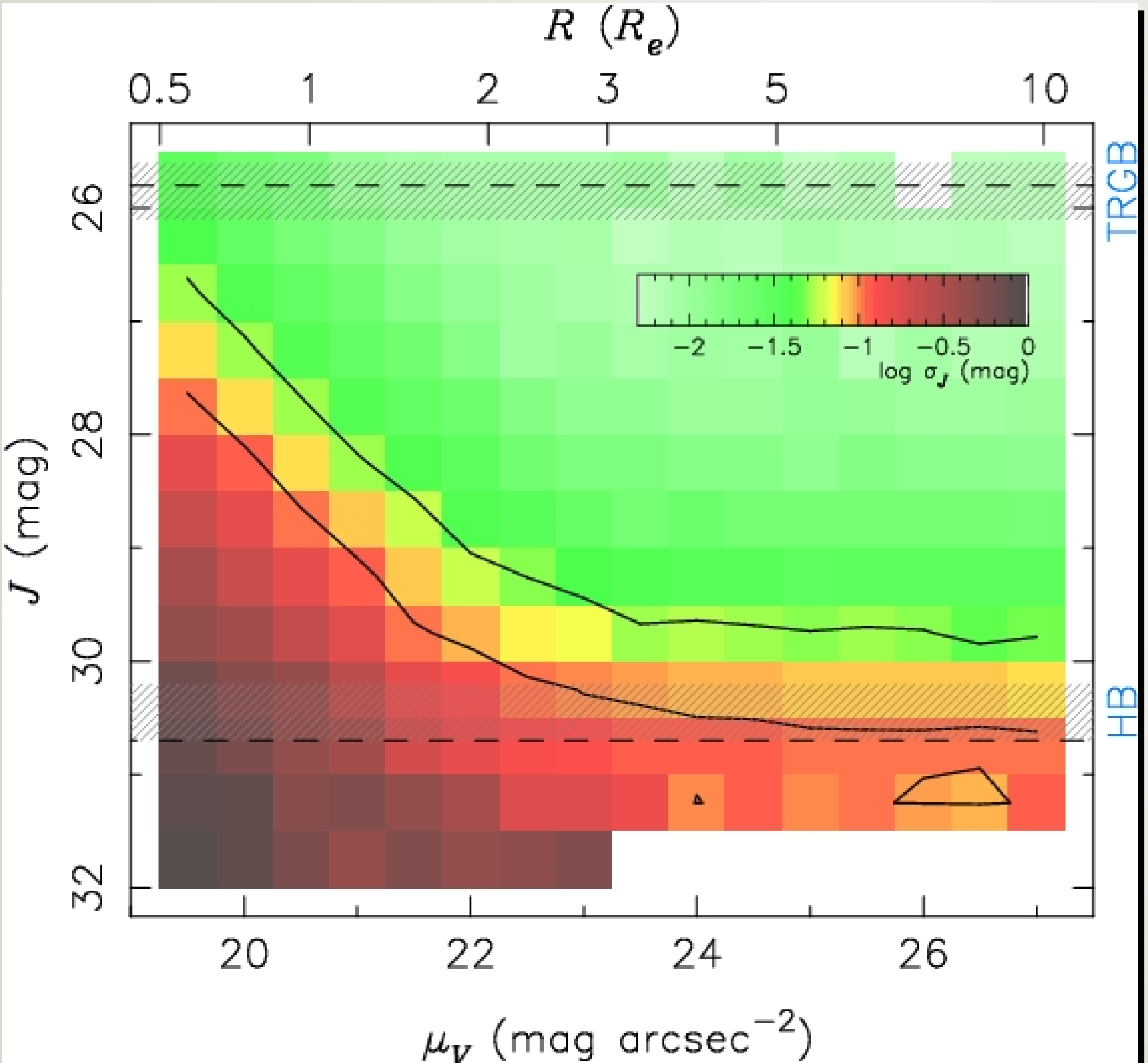
Effect of AO performance



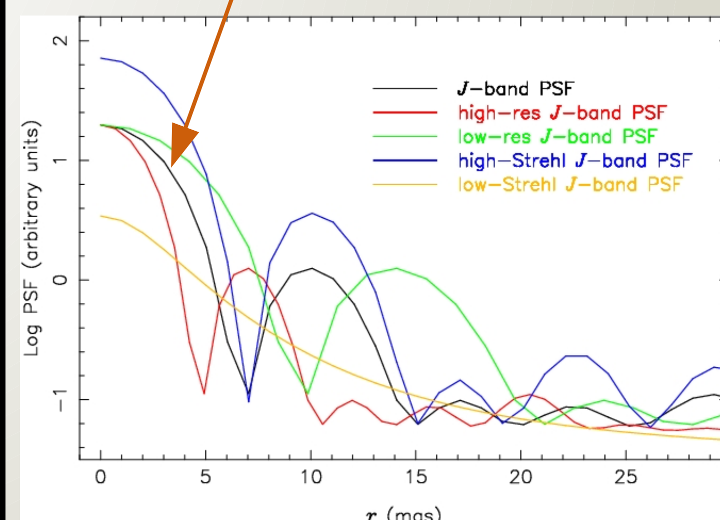
high Strehl



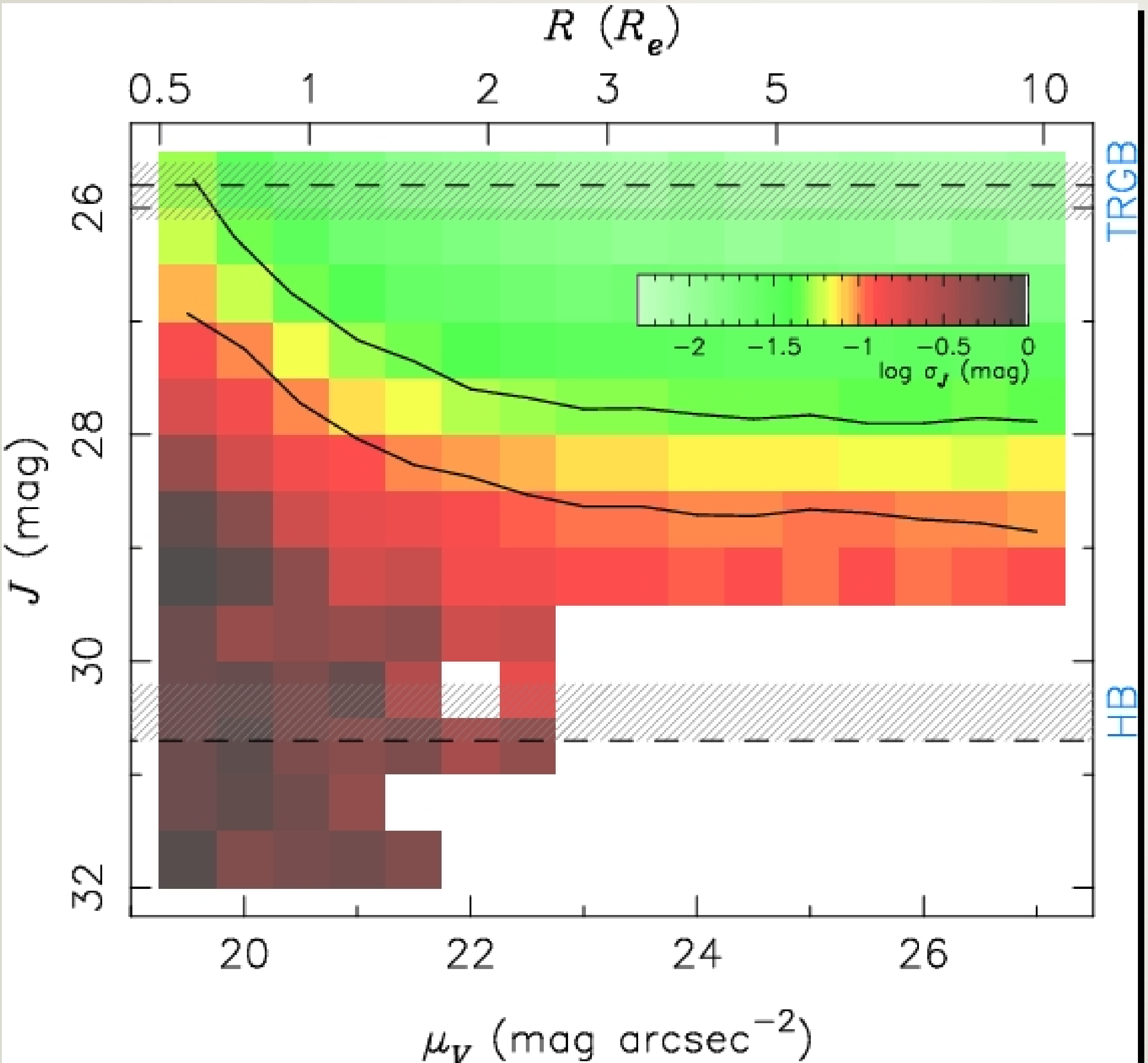
Effect of AO performance



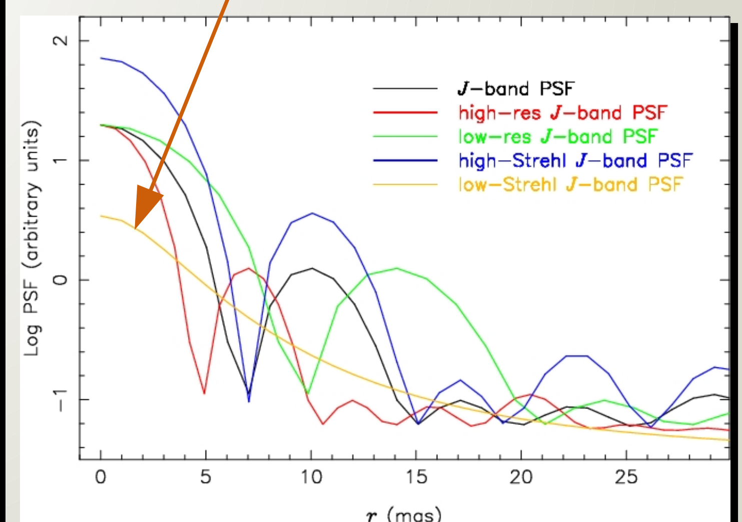
intermediate Strehl



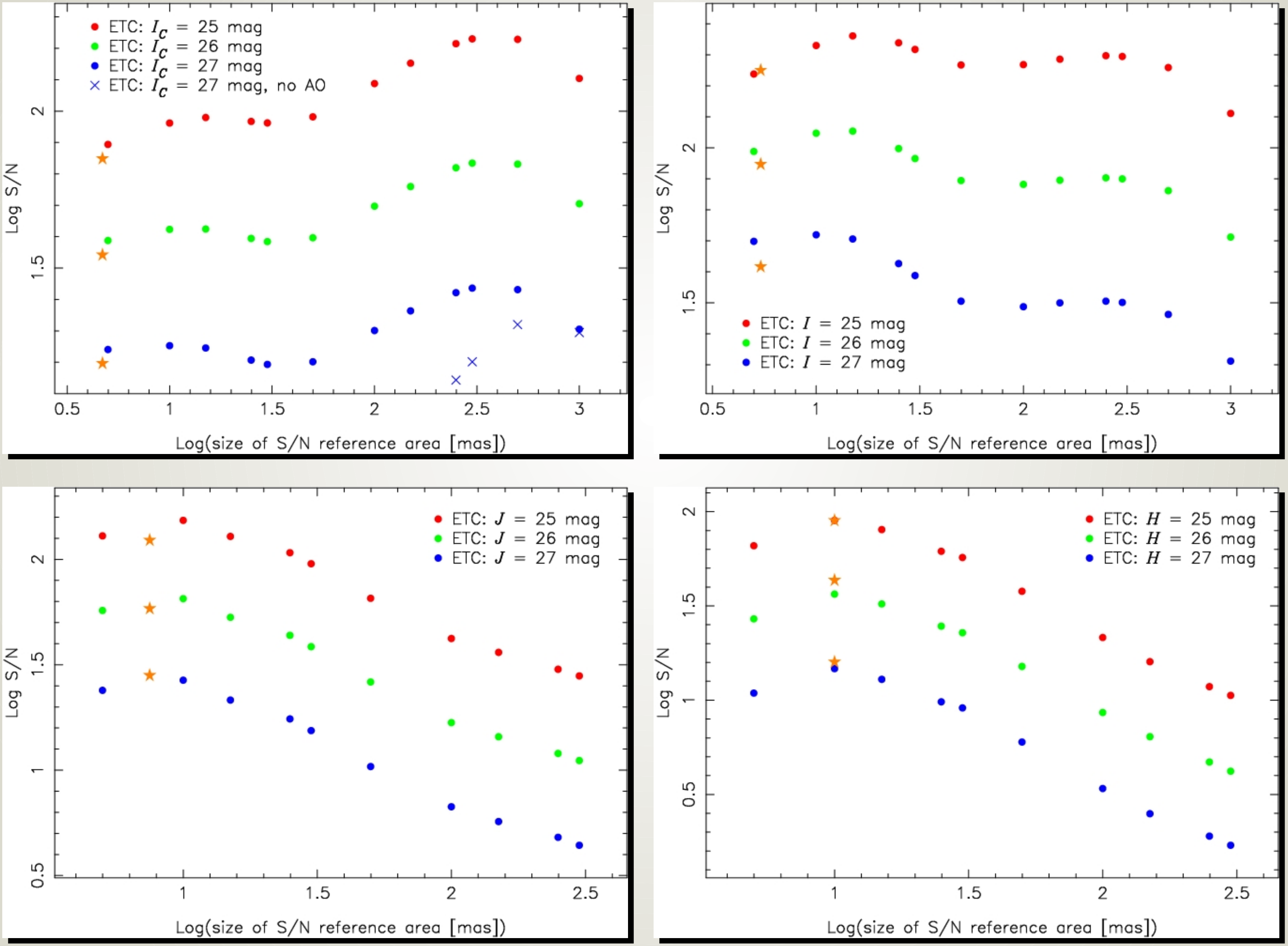
Effect of AO performance



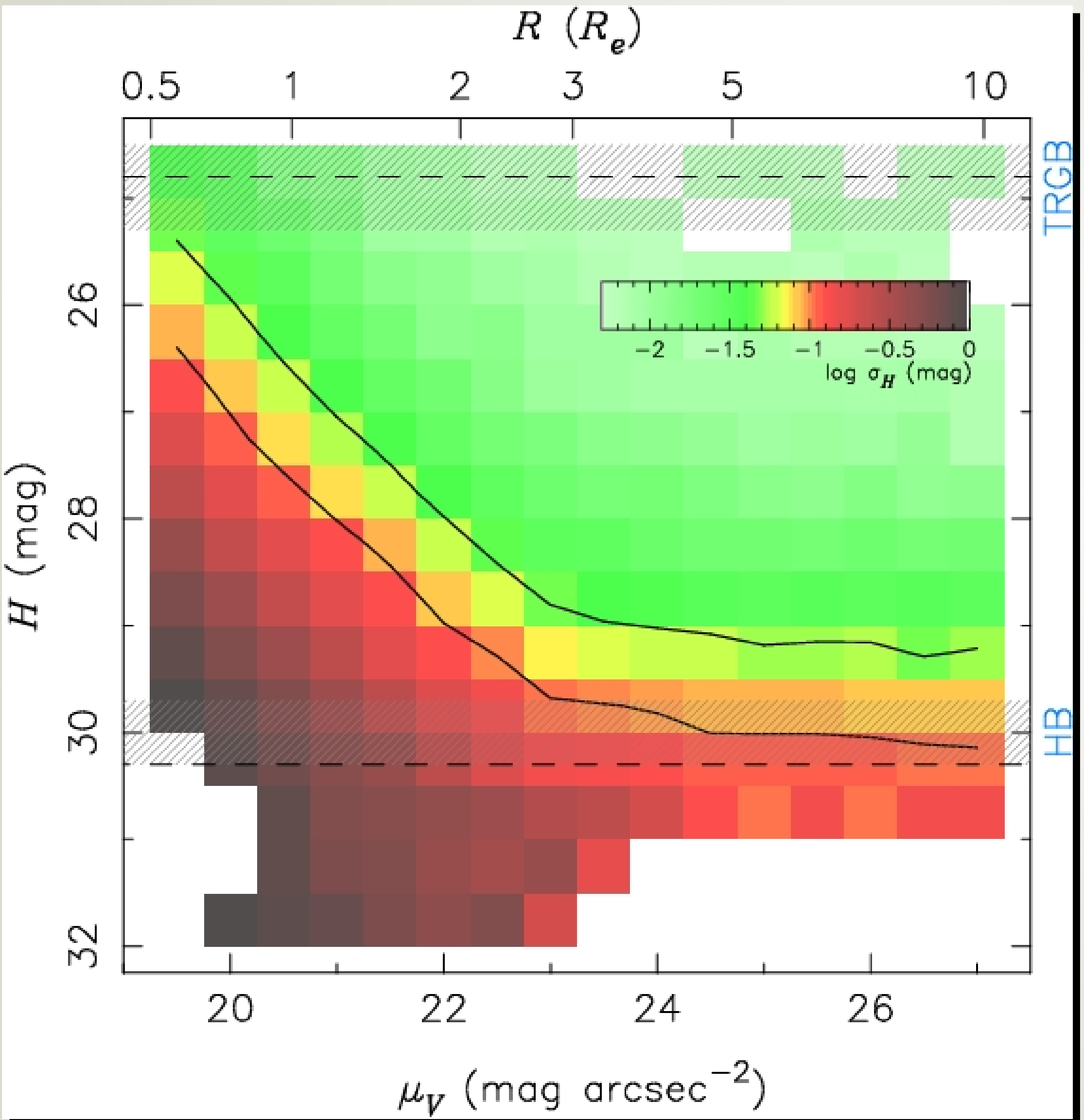
low Strehl



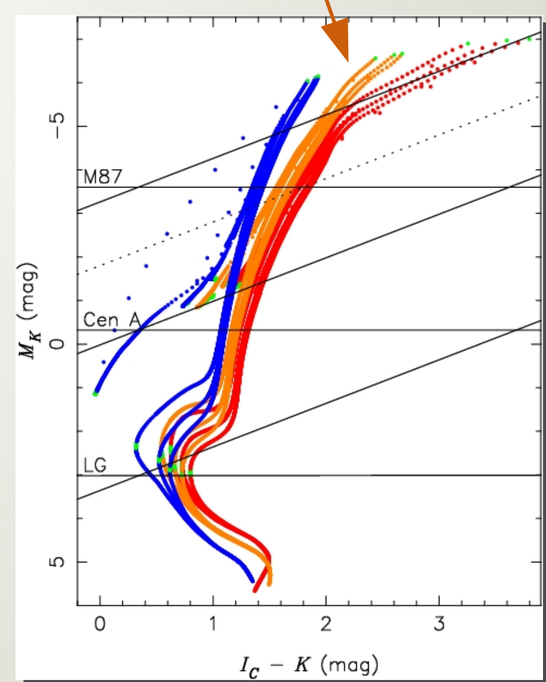
AO performance



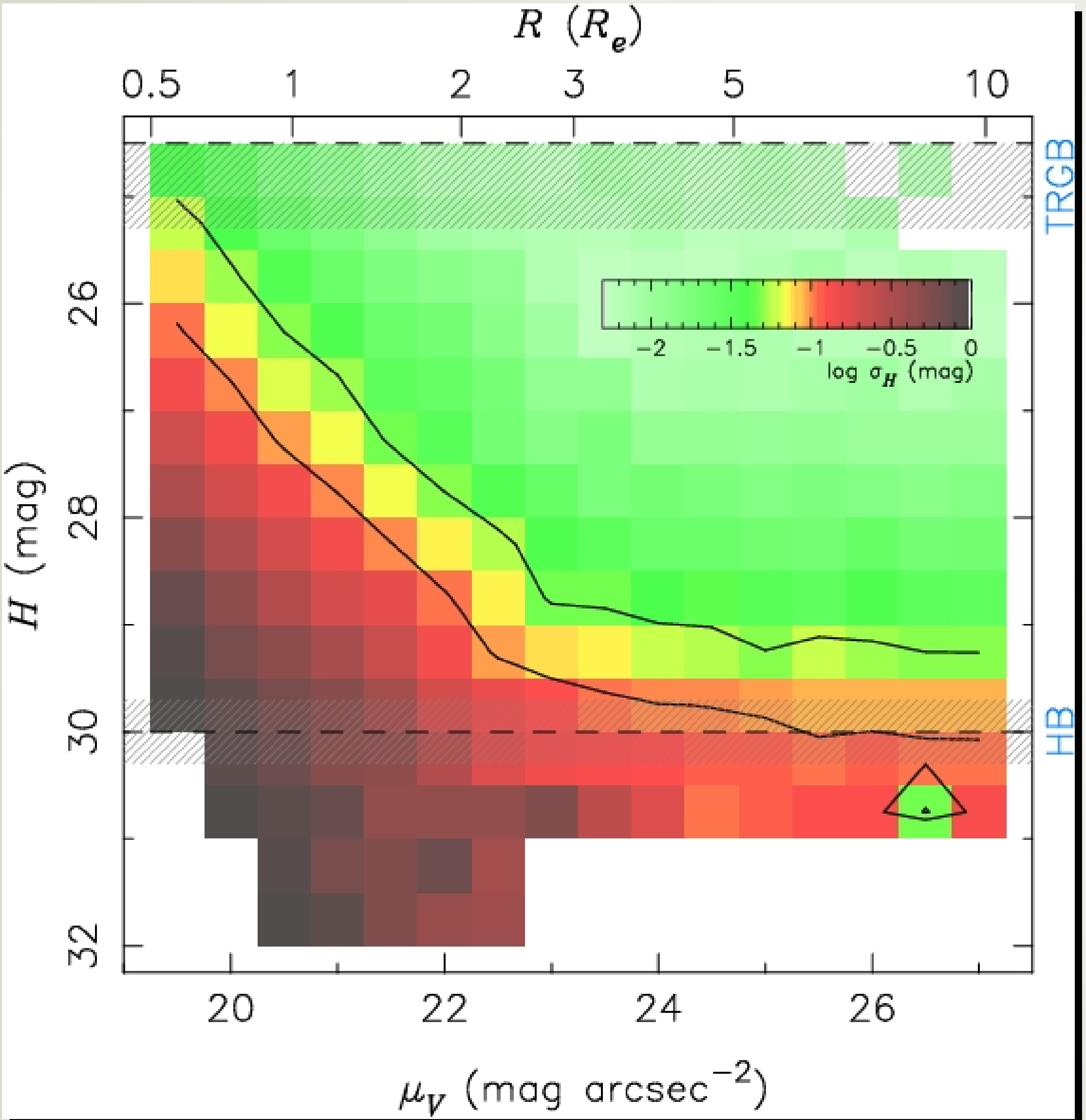
Effect of stellar population



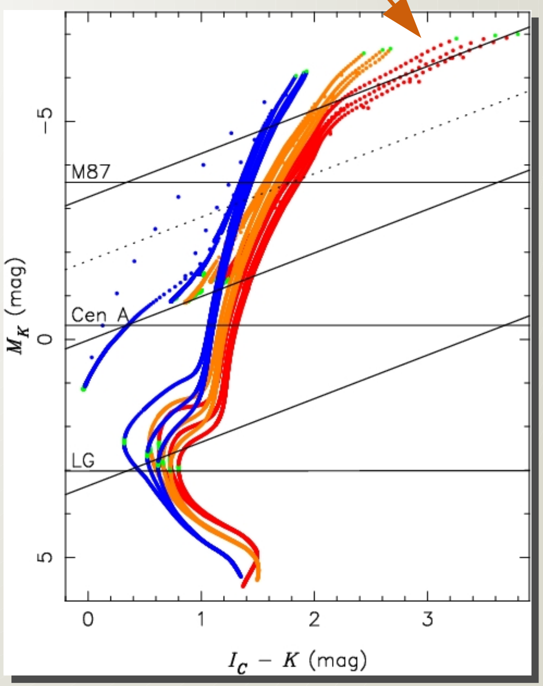
Original: intermediate metallicity



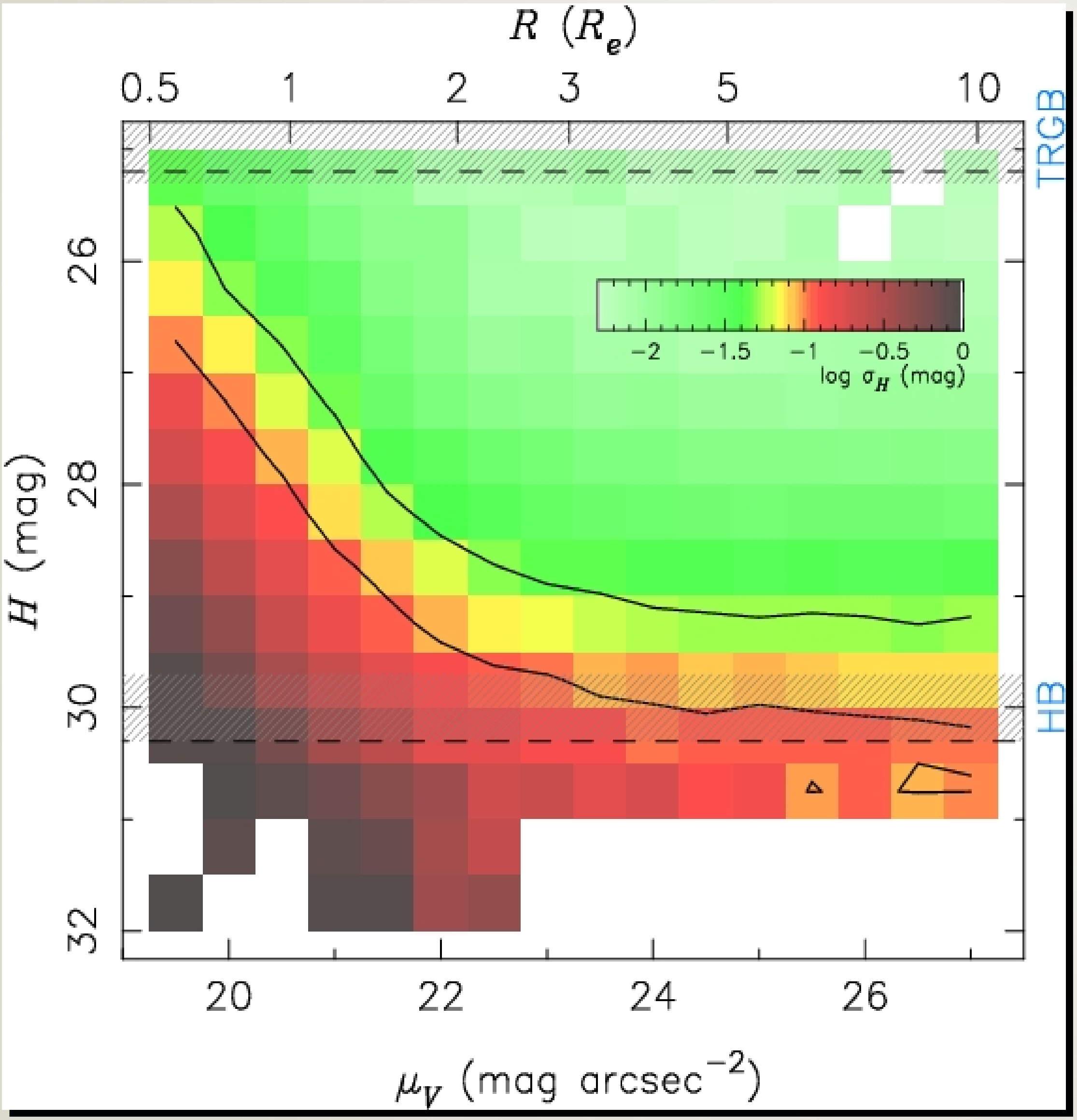
Effect of stellar population



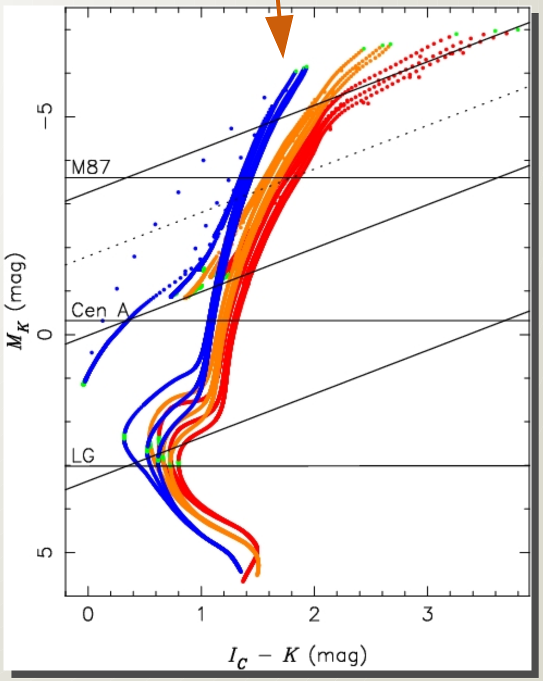
metal-rich



Effect of stellar population

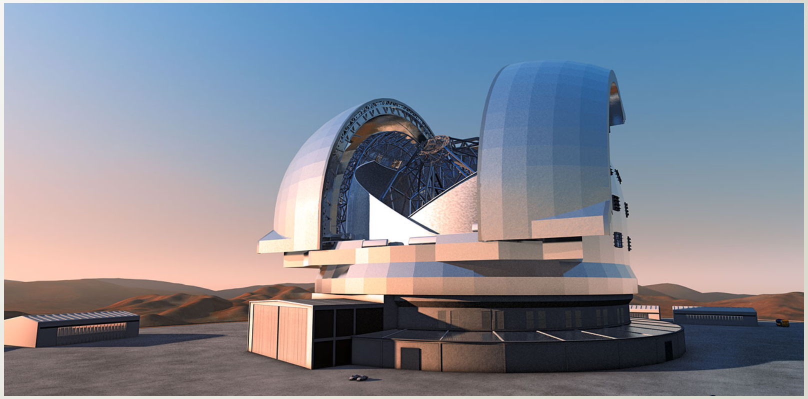


metal-poor



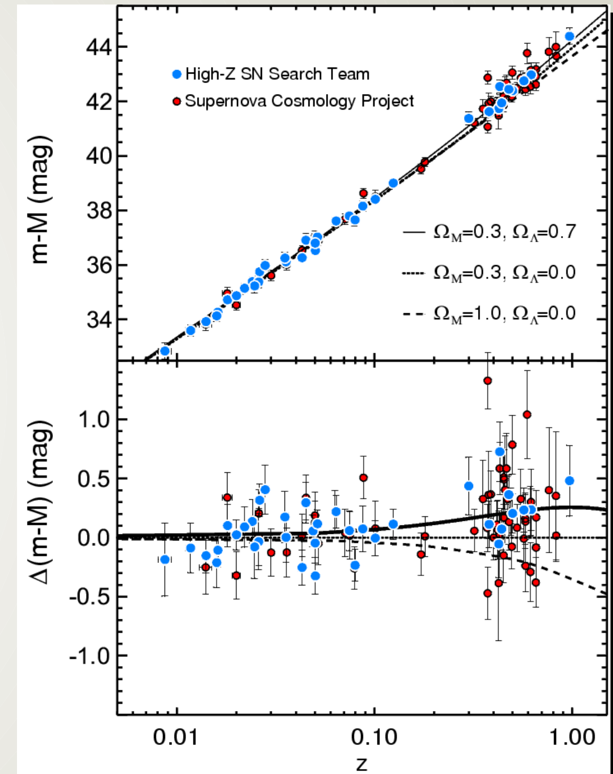
Summary

- For M87 in the Virgo cluster the E-ELT will be able to probe the TRGB with 0.05 mag accuracy all the way into the very dense central parts of the galaxy, down to ~0.5 R_e.
- The accuracy of the photometry in crowded stellar fields is entirely driven by resolution. It is independent of the quality of the AO correction as long as the correction is good enough to provide a reasonably well-developed diffraction-limited core in the PSF. Beyond this requirement the value of the Strehl ratio is immaterial.
- Given current AO predictions the above point will restrict RSP studies with the E-ELT to wavelengths > 0.9 µm.
- Calibration requirement: PSF variations will have to be tracked at a level of a few %.

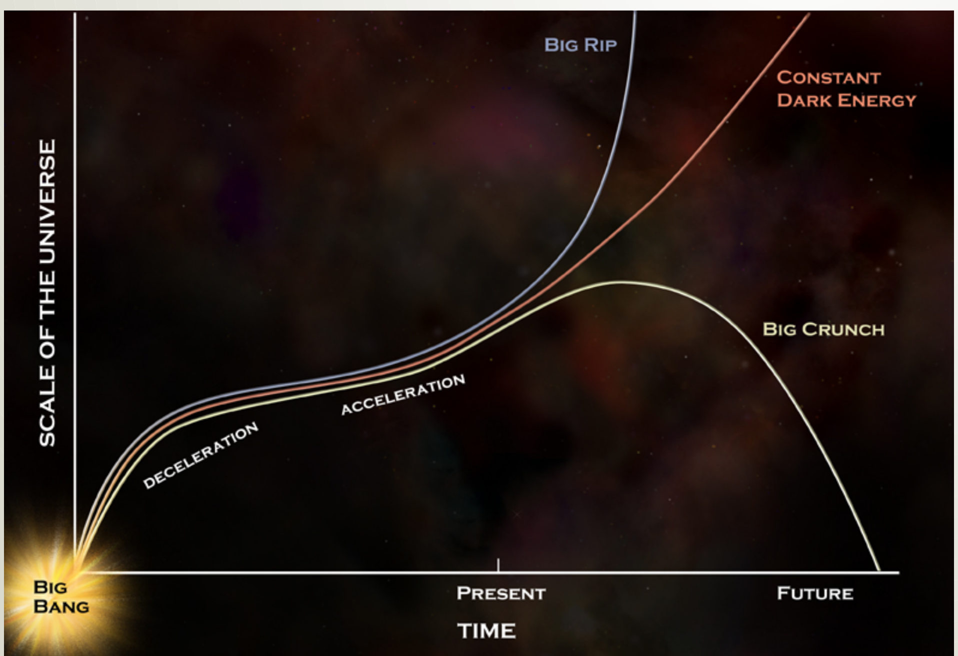


Cosmology: Accelerated Expansion

- Good evidence from SNIa that a period of decelerated expansion was followed 'recently' by a period of acceleration.
- The source of the acceleration is entirely unknown. Most explanations so far proposed require new physics.
  Dark energy: cosmological constant, quintessence, etc.
  Modification of gravity: Cardassian expansion, DGP, etc.
  Modification of Copernican Principle: LTB, backreaction.



Perlmutter & Schmidt (2003)



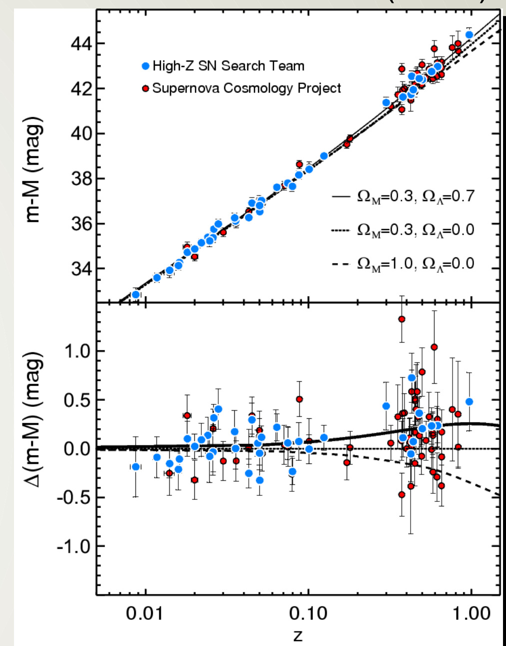
Cosmology: Accelerated Expansion

➝ Intense interest in the expansion history.

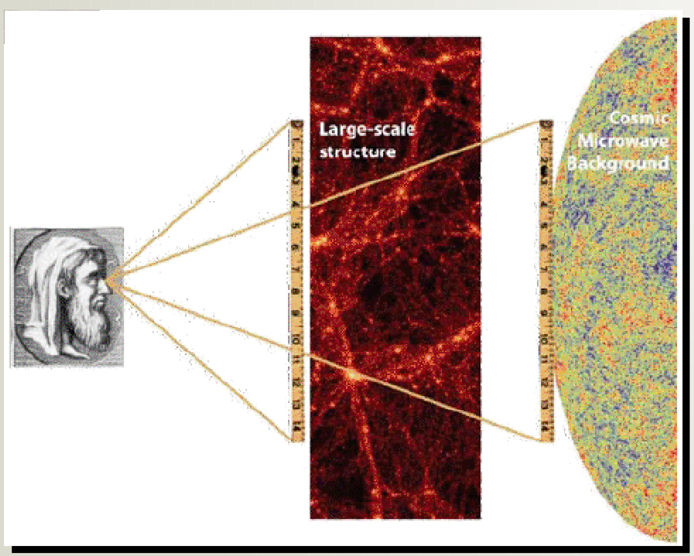
Best current methods of measuring H(z):

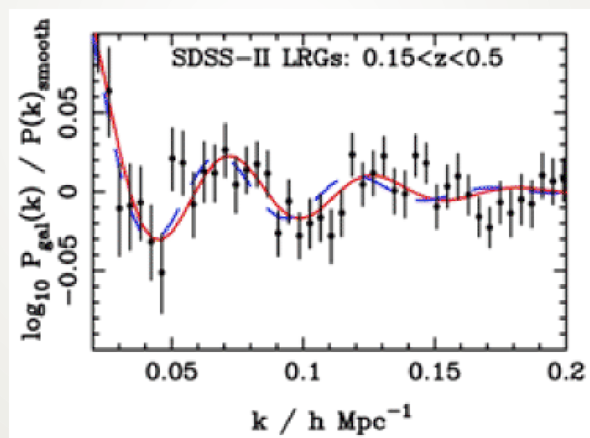
- SNIa
- Weak lensing
- Baryon Acoustic Oscillations (BAO)

Perlmutter & Schmidt (2003)

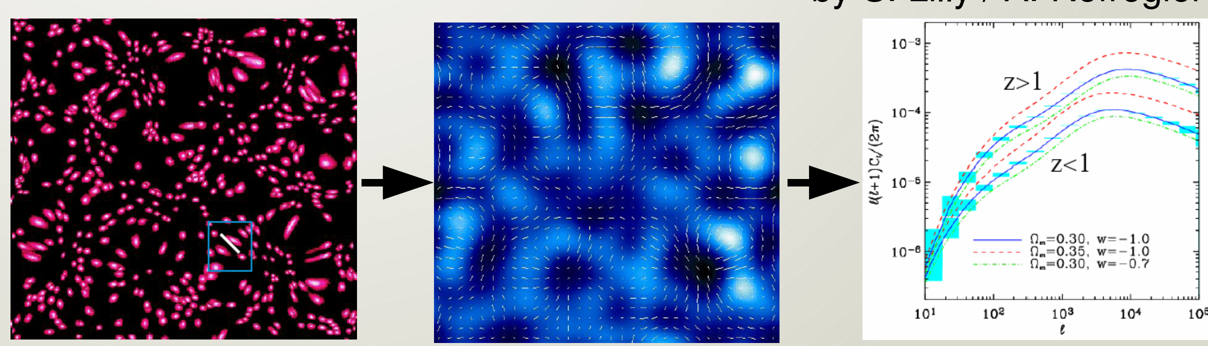


Percival et al. (2009)





by S. Lilly / A. Refregier



Cosmology: Accelerated Expansion

➛ Intense interest in the expansion history.

Best current methods of measuring H(z):

- SNIa
- Weak lensing
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These methods are essentially geometric in nature and/or probe the dynamics of localised density perturbations.

A measurement of the ***global dynamics*** has never been attempted. This would offer a direct, entirely model-independent route towards H(z).

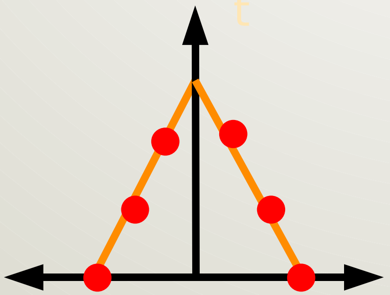
Cosmic Dynamics

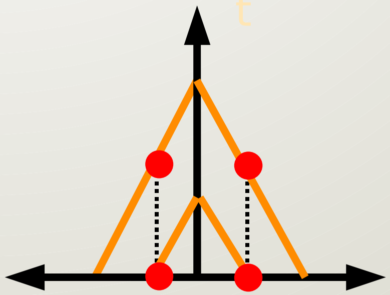
The de- or acceleration of the universal expansion rate between epoch z and today causes a small drift in the observed redshift as a function of time:

$$\dot{z} = (1+z)H_0 - H(z)$$

Two remarkable features:

- For this equation to be valid you only need:
  - gravity can be described by a metric theory
  - homogeneity and isotropy
- The redshift drift does not deduce the evolution of the expansion by mapping out our present-day past light-cone but directly measures the evolution by comparing our past light-cones at different times.





Cosmic Dynamics

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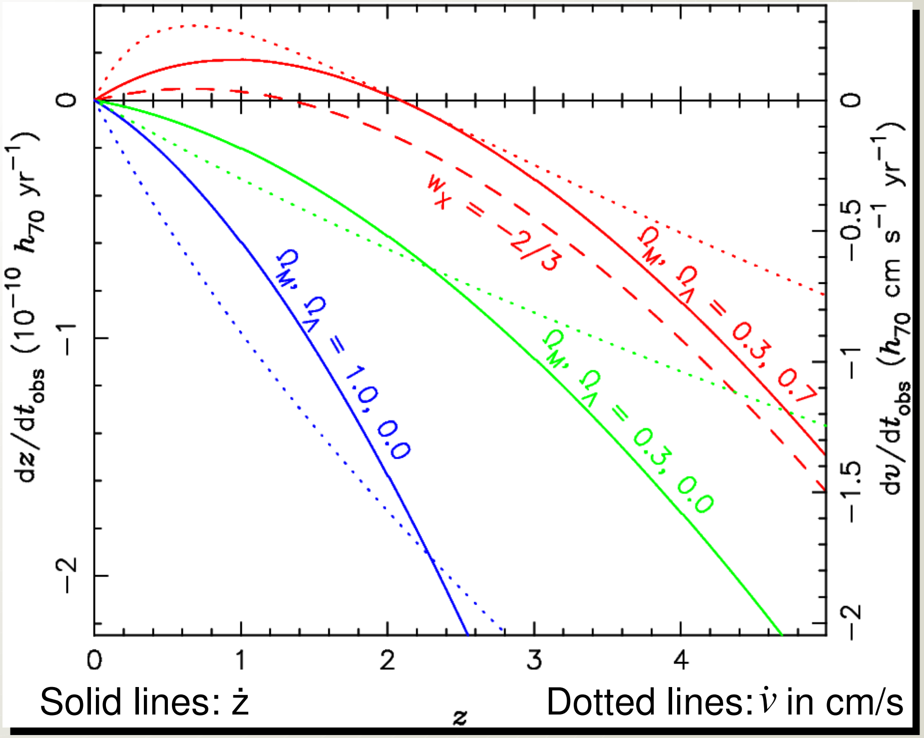
$$\dot{z} = (1+z)H_0 - H(z)$$

Measuring ż(z):

- Allows us to watch, in real time, the universe changing its expansion rate.
- Most direct and model-independent route to the expansion history and acceleration.
- First non-geometric measurement of the global FRW metric.
- Independent confirmation and quantification of accelerated expansion.
- H(z) determination in a redshift range inaccessible to other methods.



Size of the signal

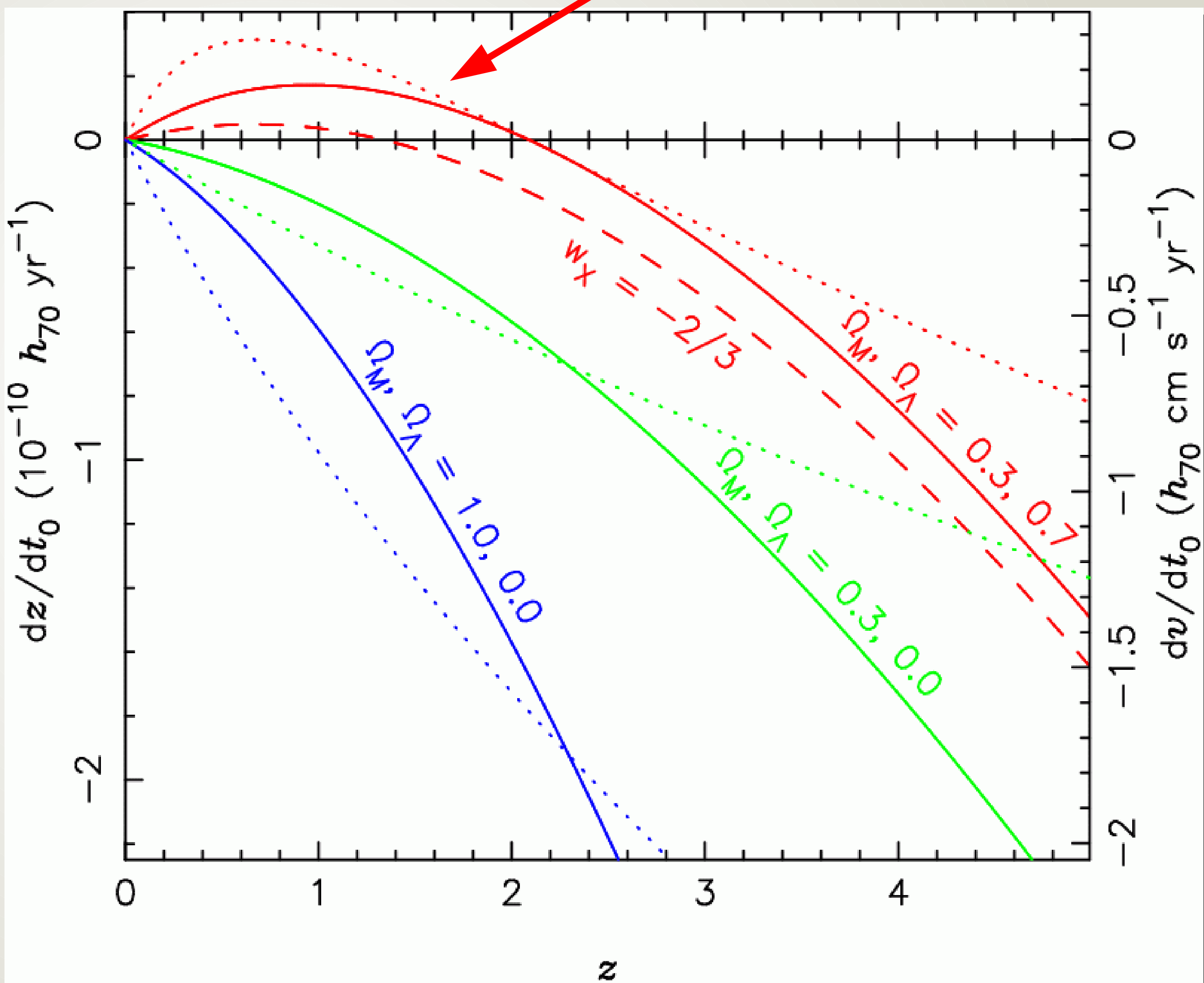
If Δt = 10 years then:

- $\Delta z \sim 10^{-9}$
- $\Delta\lambda = \lambda_{rest}\,\Delta z$
  - $\sim 10^{-6}$ Å
  - $\sim 10^{-4}$ pixel
  - ~ 1 nm on CCD
- $\Delta v = c\,\Delta z/(1+z)$
  - ~ 6 cm/s

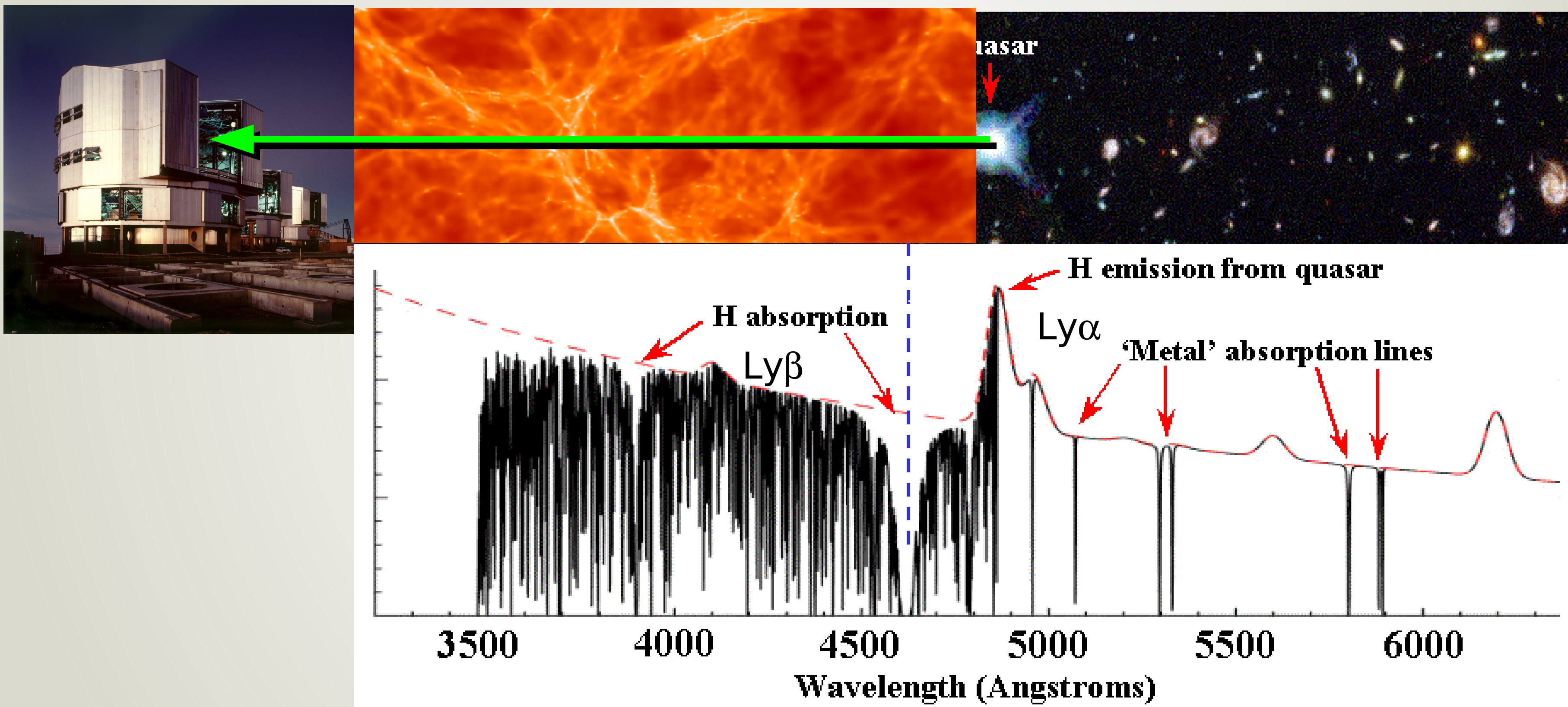
→ Tiny signal!

BUT: HARPS has already achieved a long-term accuracy of ~1 m/s with ~10 cm/s accuracy over a few hours.

Signature of $\Lambda > 0$



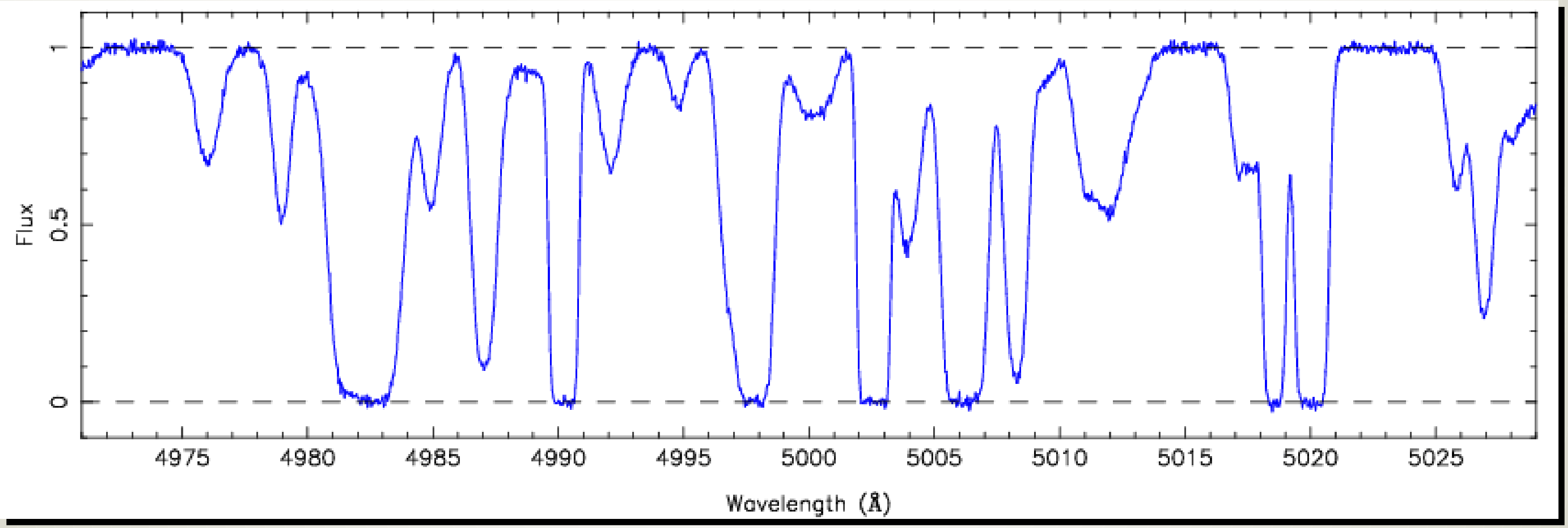
Measuring dz/dt in the IGM



by John Webb

Observing dz/dt in the Lyα Forest

Simulation of the Lyα forest at z ~ 3:



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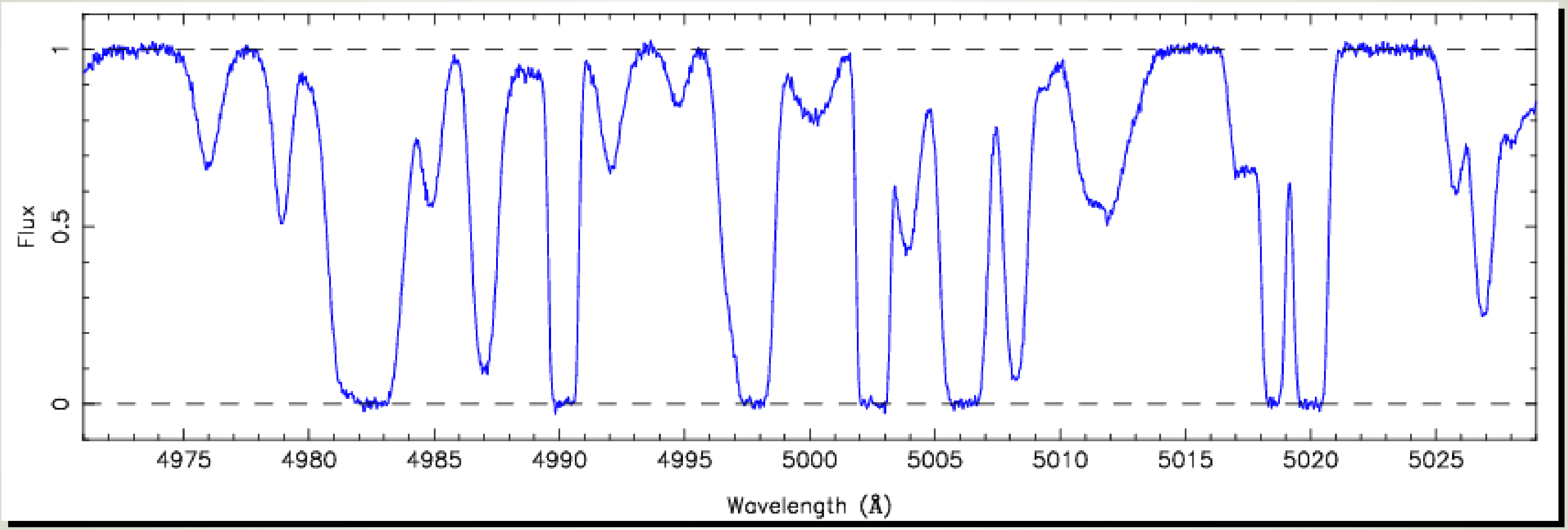

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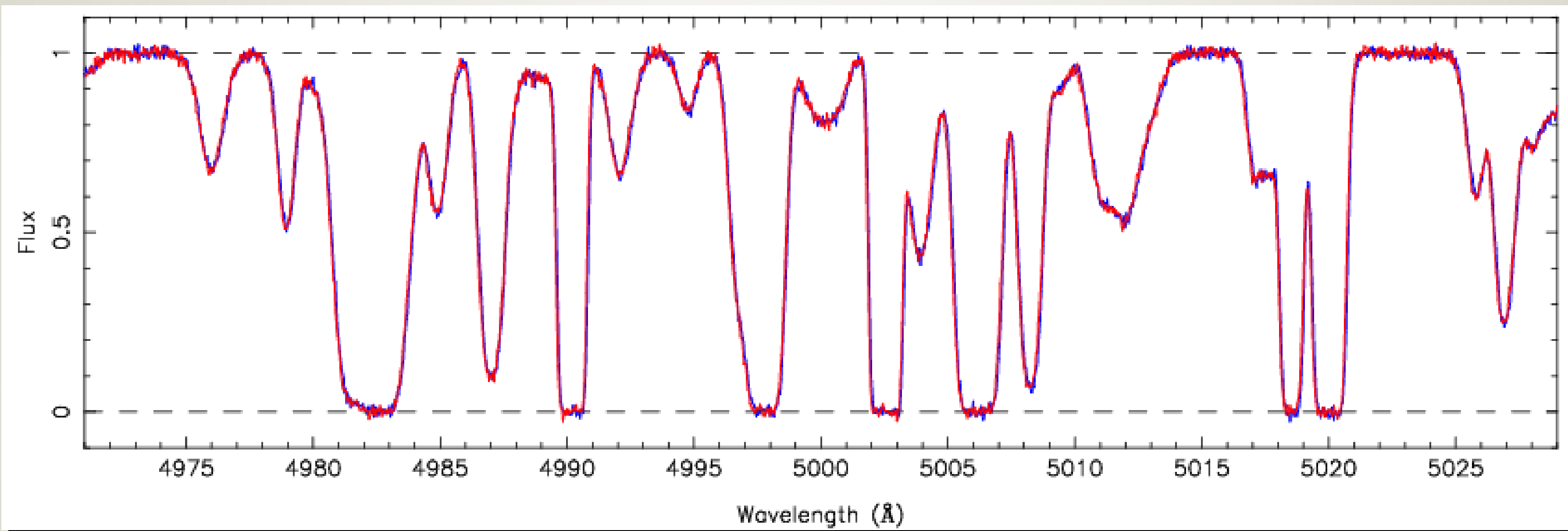


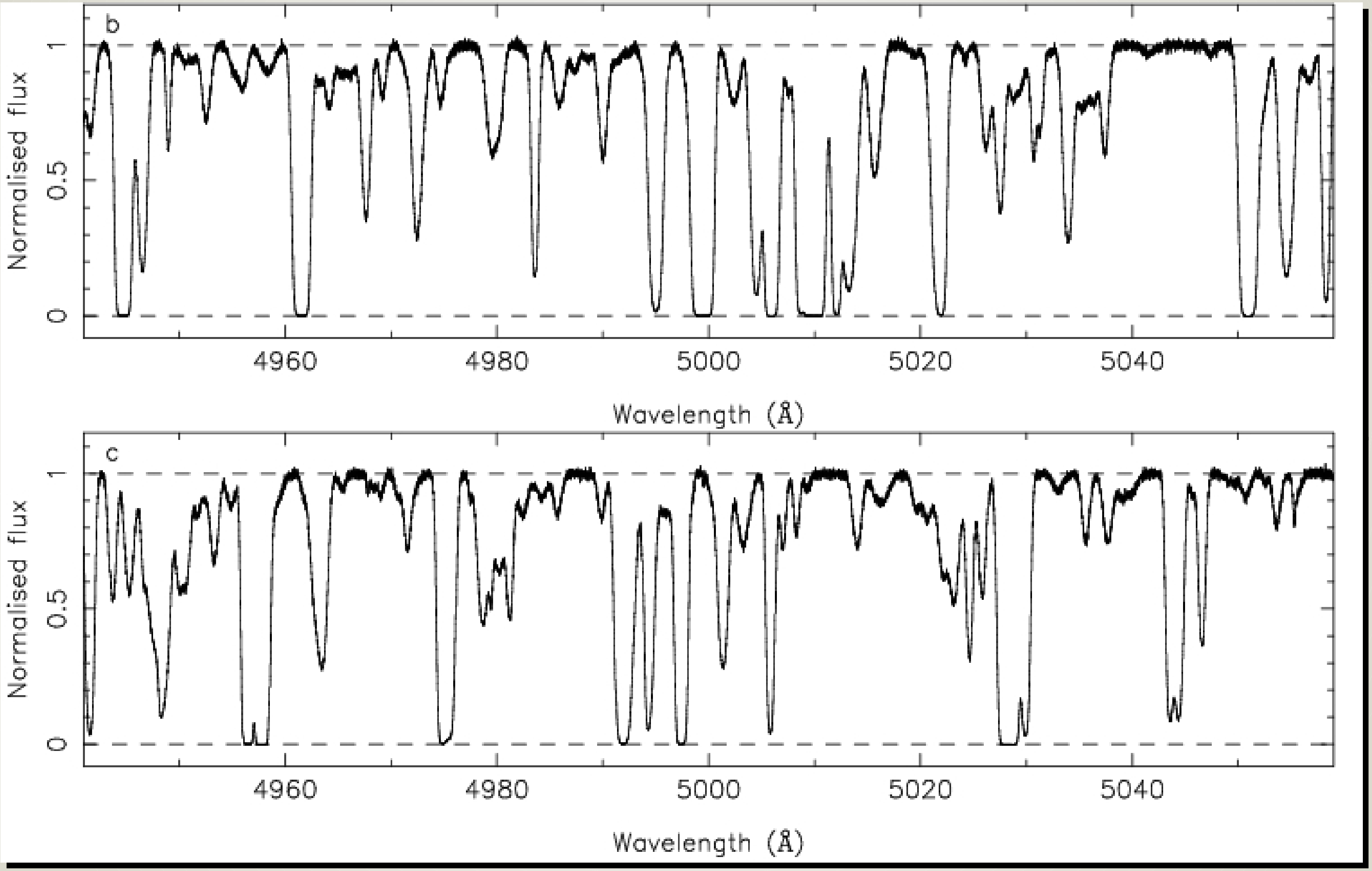
$\Delta t = 10^6$ years!

Specific questions for the DRM

- How do the properties of the Lyα forest translate to an accuracy with which one can determine radial velocity shifts?
- How does this accuracy depend on S/N, the redshift of the target QSO, and the distribution of the observing time within the duration of the experiment?
- Using the above results and assuming the known population of QSOs predict the overall accuracy of a redshift drift experiment.
- Predict constraints on cosmological parameters.

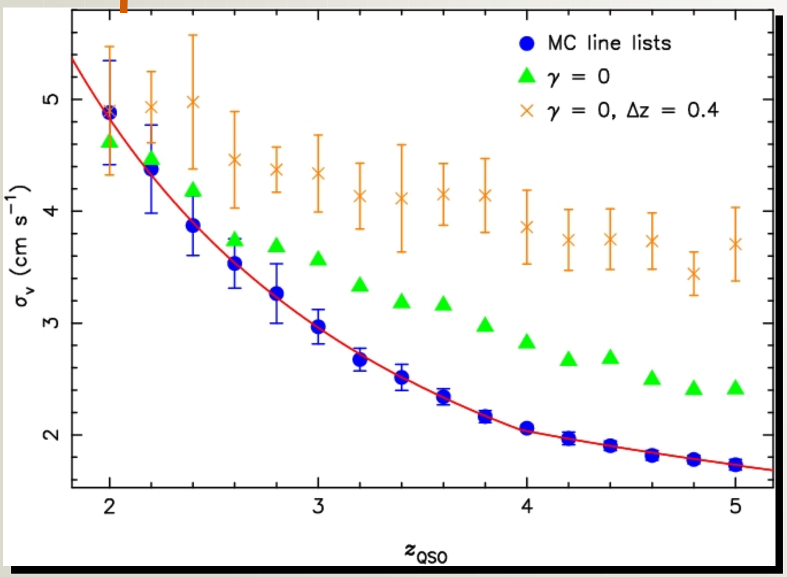
- Method: Monte Carlo simulations of Lyα forest spectra.

Lyα forest simulations



Results: scaling relation

$$\sigma_v = 1.35 \left[\frac{S/N}{3350}\right]^{-1} \left[\frac{N_{QSO}}{30}\right]^{-\frac{1}{2}} \left[\frac{1+z_{QSO}}{5}\right]^{-1.7} g(N_e, f_{1\ldots N_e})\ cm/s$$



Notes:

- S/N = total S/N (over all epochs) per 0.0125 Å
- G = 'form factor' that depends on the number of epochs and their distribution whithin the duration of the experiment (≈ 1.1)

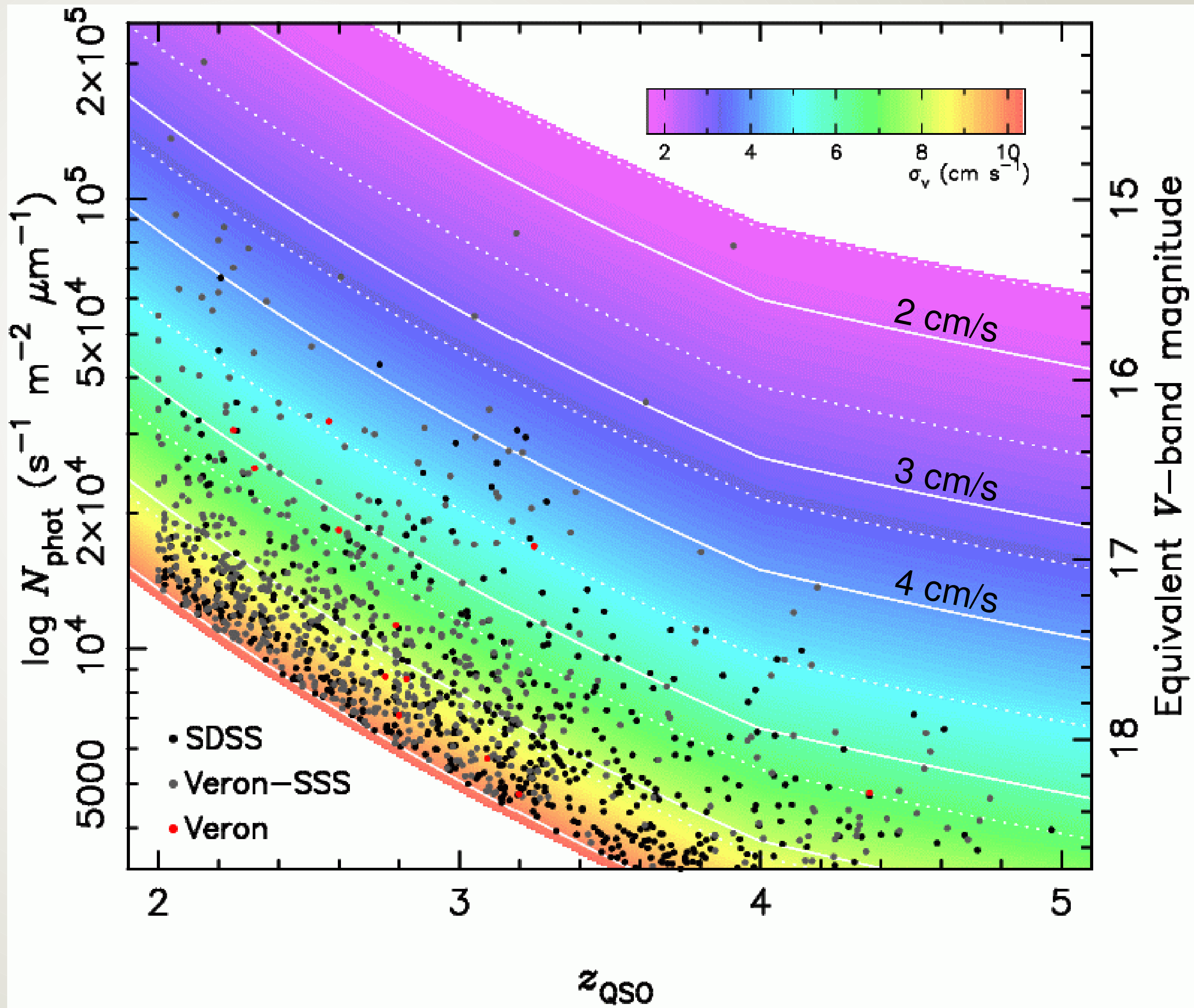
Science input: the known QSO population

Can we collect enough photons to achieve the required radial velocity accuracy?

QSOs from latest compilations (including SDSS):

Lines of constant σ_v assume:
D = 42 m
efficiency = 25%
t_{exp} = 2000 h

Yes: 18 known QSOs with 2 < z < 5 are bright enough to achieve a radial velocity accuracy of 4 cm/s using 2000 hours on a 42-m E-ELT.

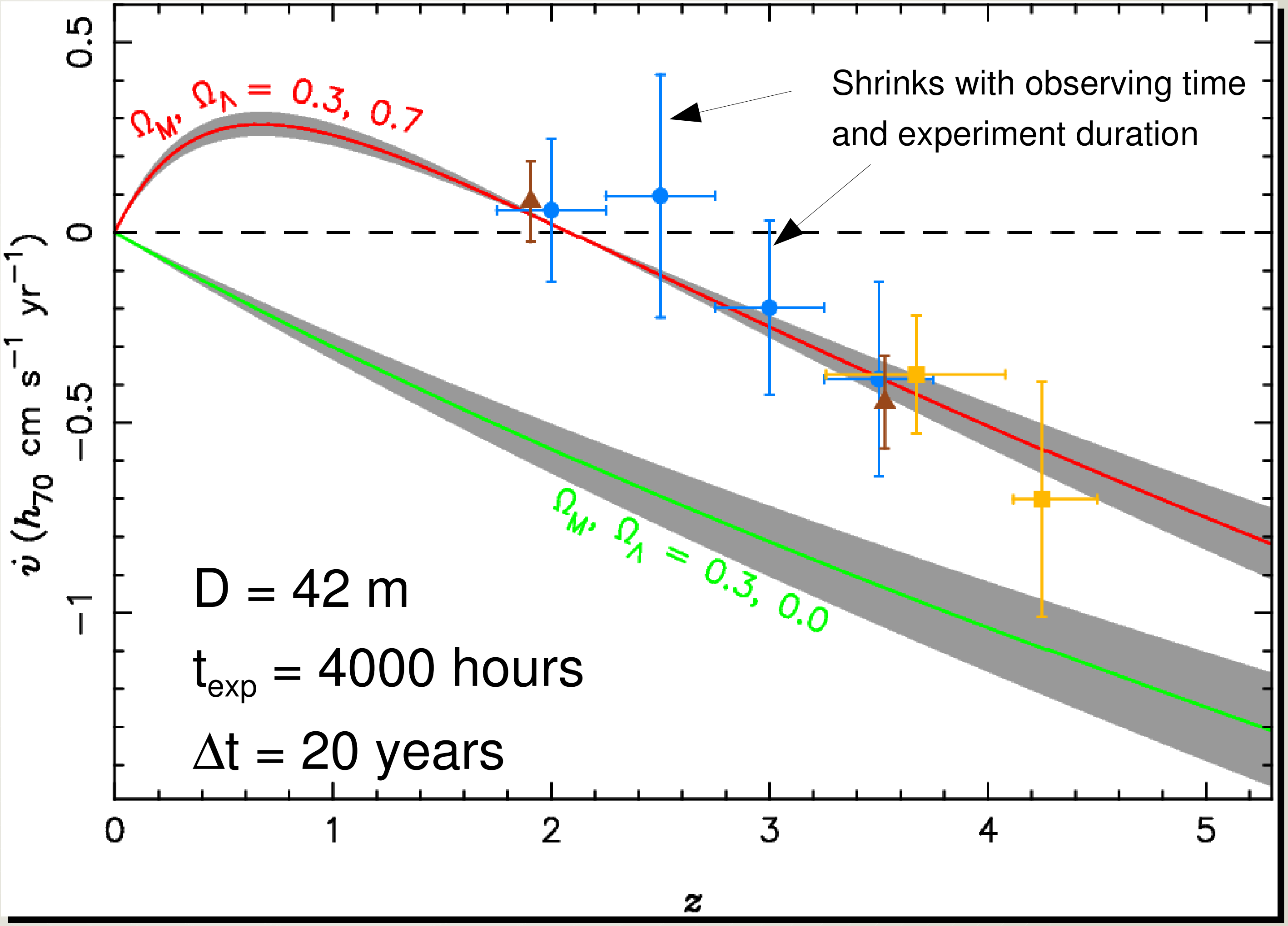


Liske et al. (2008)

Simulation results

4000 h on a 42-m ELT over 20 years will deliver any *one* of these sets of points.

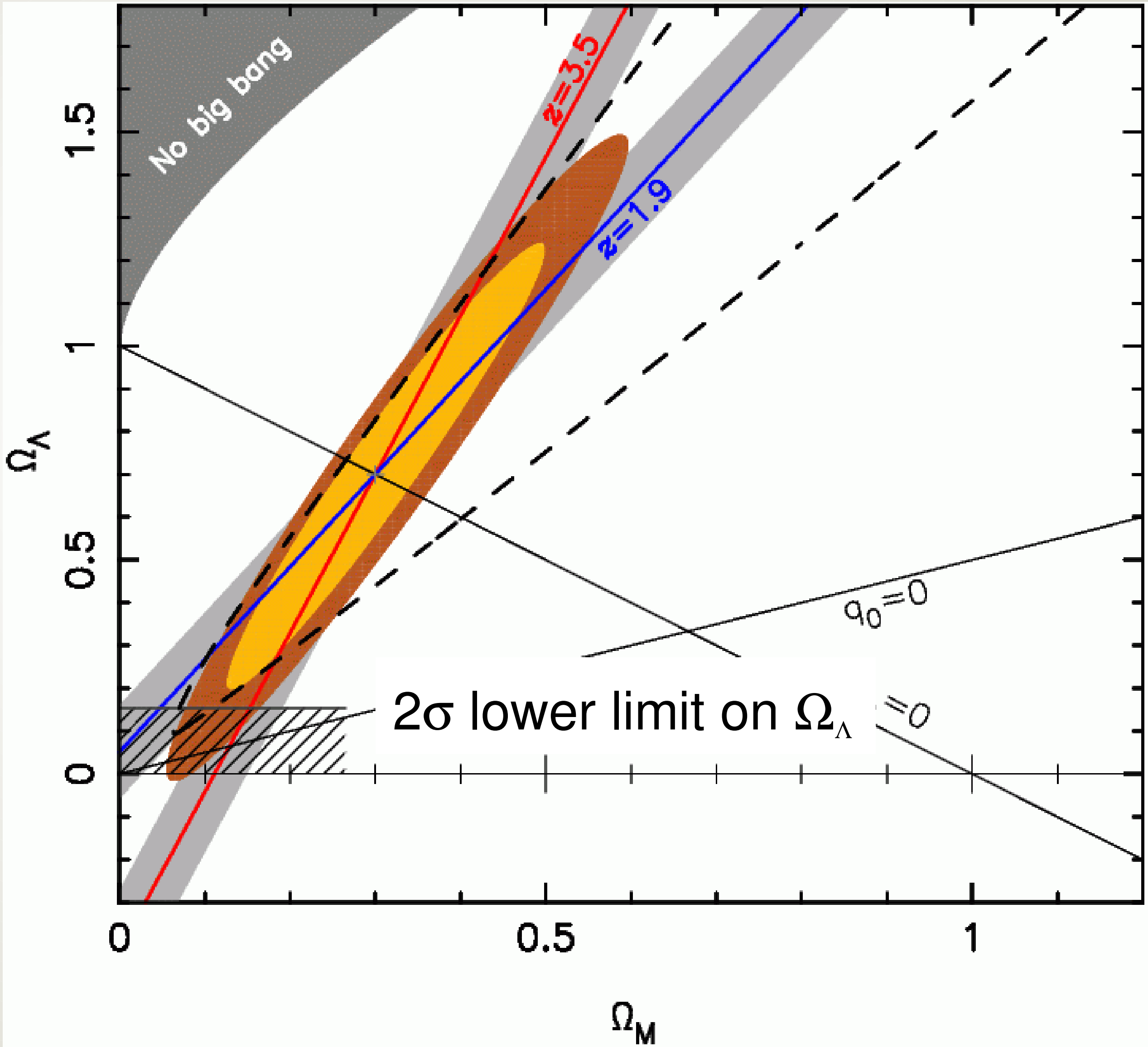
Different sets correspond to different target selection strategies.



Liske et al. (2008)

Results: constraints on cosmology

- 4000 hours over 20 years will unequivocally prove the existence of dark energy without assuming flatness, using any other cosmological constraints or making any other astrophysical assumption whatsoever.
- Provides independent confirmation of SNIa results, using a different method and a complementary redshift range.



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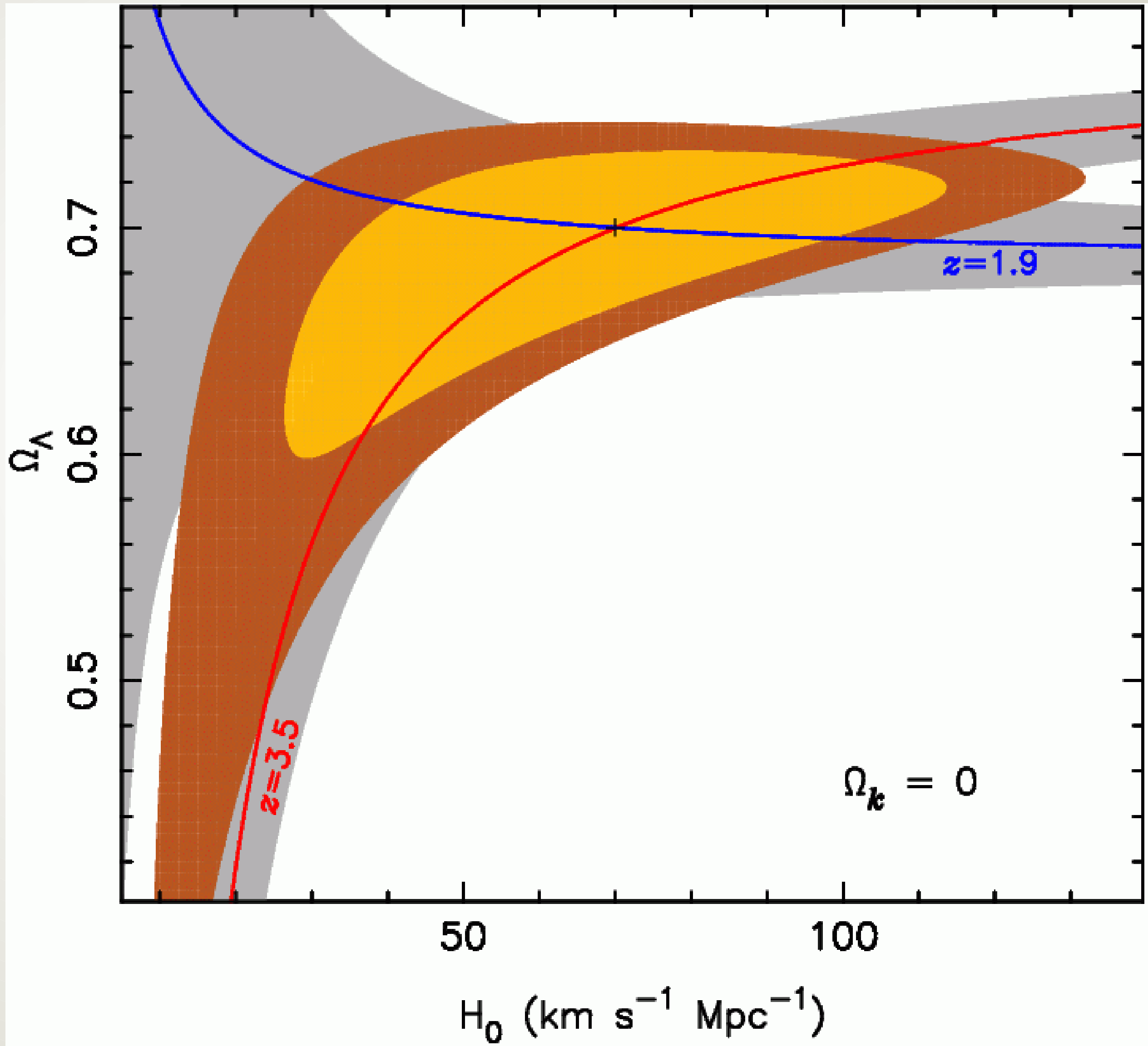
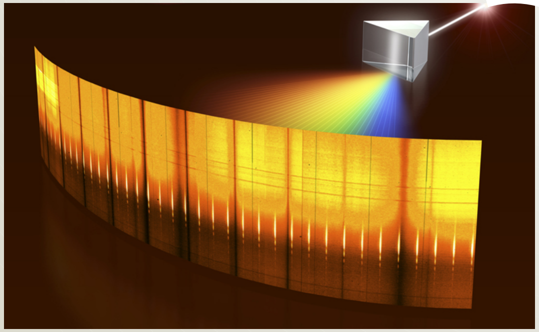
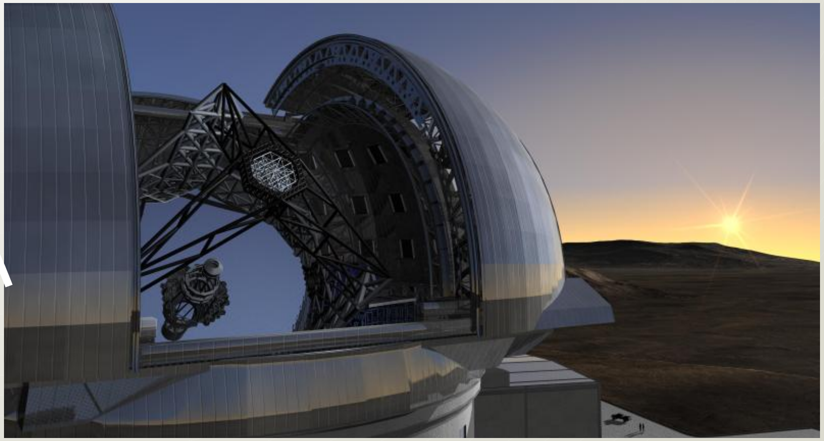


Liske et al. (2008)

Summary

- A redshift drift experiment on the E-ELT can detect the difference between $(\Omega_M, \Omega_\Lambda)$ = (0.3,0.7) and (0.3,0.0) at 3σ significance in 15 yr, using 20 QSOs and 2500 h of observing time.
- $D^2 \times$ system throughput (photon collecting power) is the most crucial parameter → do **not** build a smaller telescope; coatings; need to optimise throughput of instrument.
- Calibration requirement: the error on radial velocity measurements must remain photon noise dominated over the duration of the experiment.
- Results depend on precise QSO sample available → need to search for (and monitor) more bright QSOs, especially in the south (VISTA, LSST).



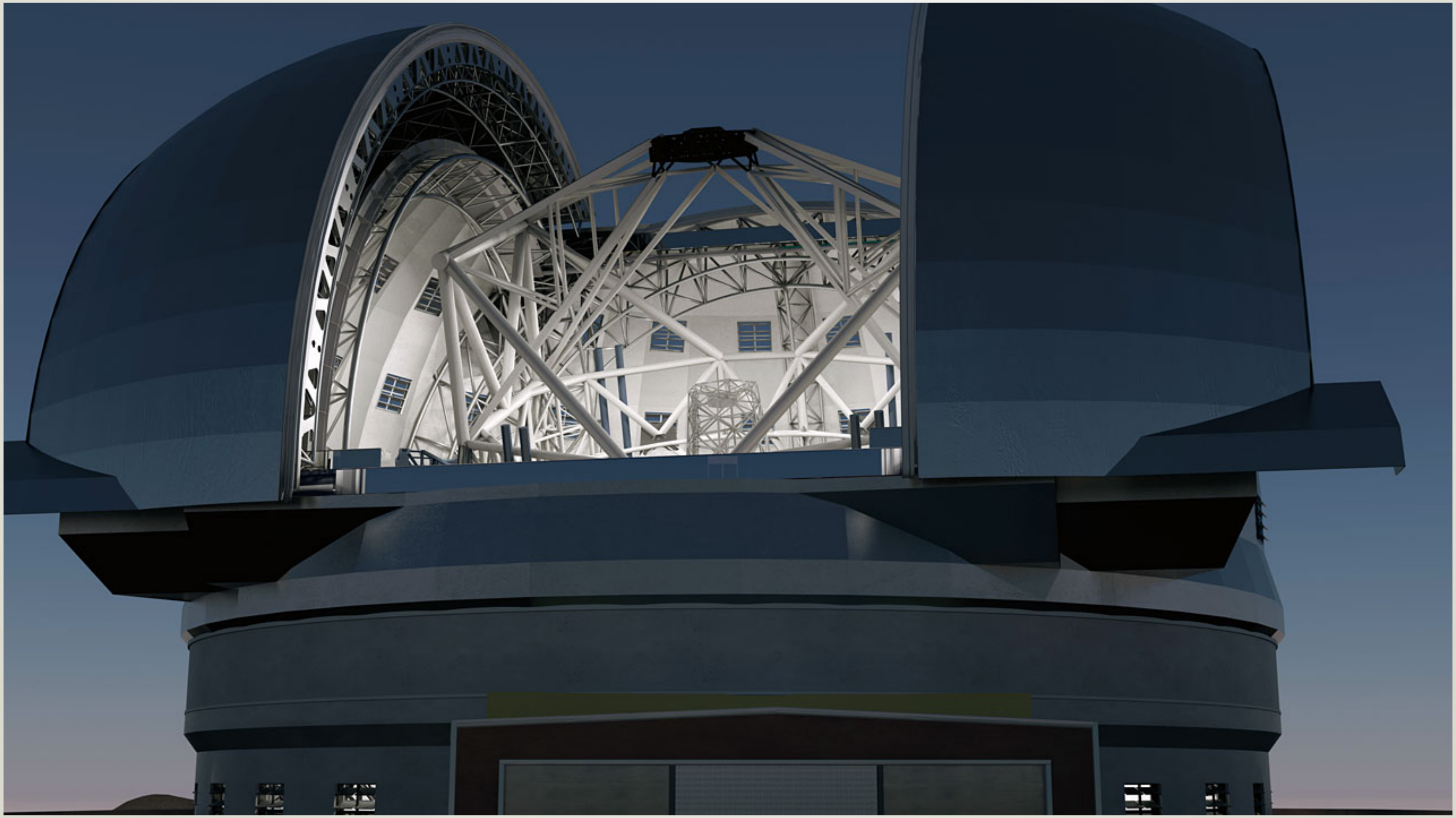


DRM conclusions

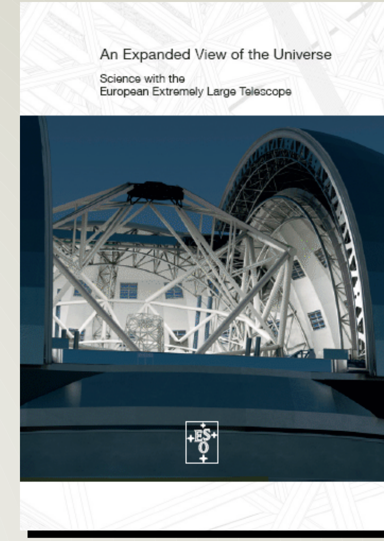
- Telescope
  - Many science cases at the edge of feasibility: need D ≈ 40 m.
  - Only weak requirement for FoV ≈ 25 $arcmin^2$.
  - Difficult trade-off: protected Ag/Al coating generally preferred over Al, but lose some important stellar archaeology science in the UV.
- Instrumentation
  - Capabilities provided by the phase A instrumentation studies are an excellent match to the DRM science cases. No important capabilities have been overlooked.
- Site
  - Many DRM cases would have preferred the High & Dry site, but only marginally → Armazones was the right choice.
- Operations
  - Must be able to deal with very large programmes (100s of nights) with very specific cadences, and over very long timescales (decades).

Conclusions

DRM = Indispensable tool for a quantitative understanding of key system parameters and for the development of the overall Science Case.



More information?



The science users web pages:

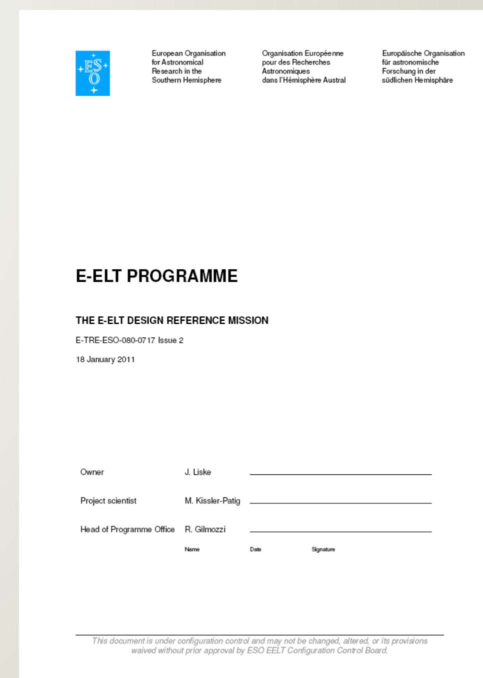
http://www.eso.org/sci/facilities/eelt/

The E-ELT Science Case:

http://www.eso.org/sci/facilities/eelt/science/doc/eelt_sciencecase.pdf

The E-ELT Design Reference Mission:

http://www.eso.org/sci/facilities/eelt/science/drm/



European Organisation for Astronomical Research in the Southern Hemisphere

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral

Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

E-ELT PROGRAMME

THE E-ELT DESIGN REFERENCE MISSION

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The public web pages:

http://www.eso.org/public/teles-instr/e-elt.html

Brochures, Posters, etc:

http://www.eso.org/public/products/brochures/

Gallery:

http://www.eso.org/public/images/archive/category/e-elt/