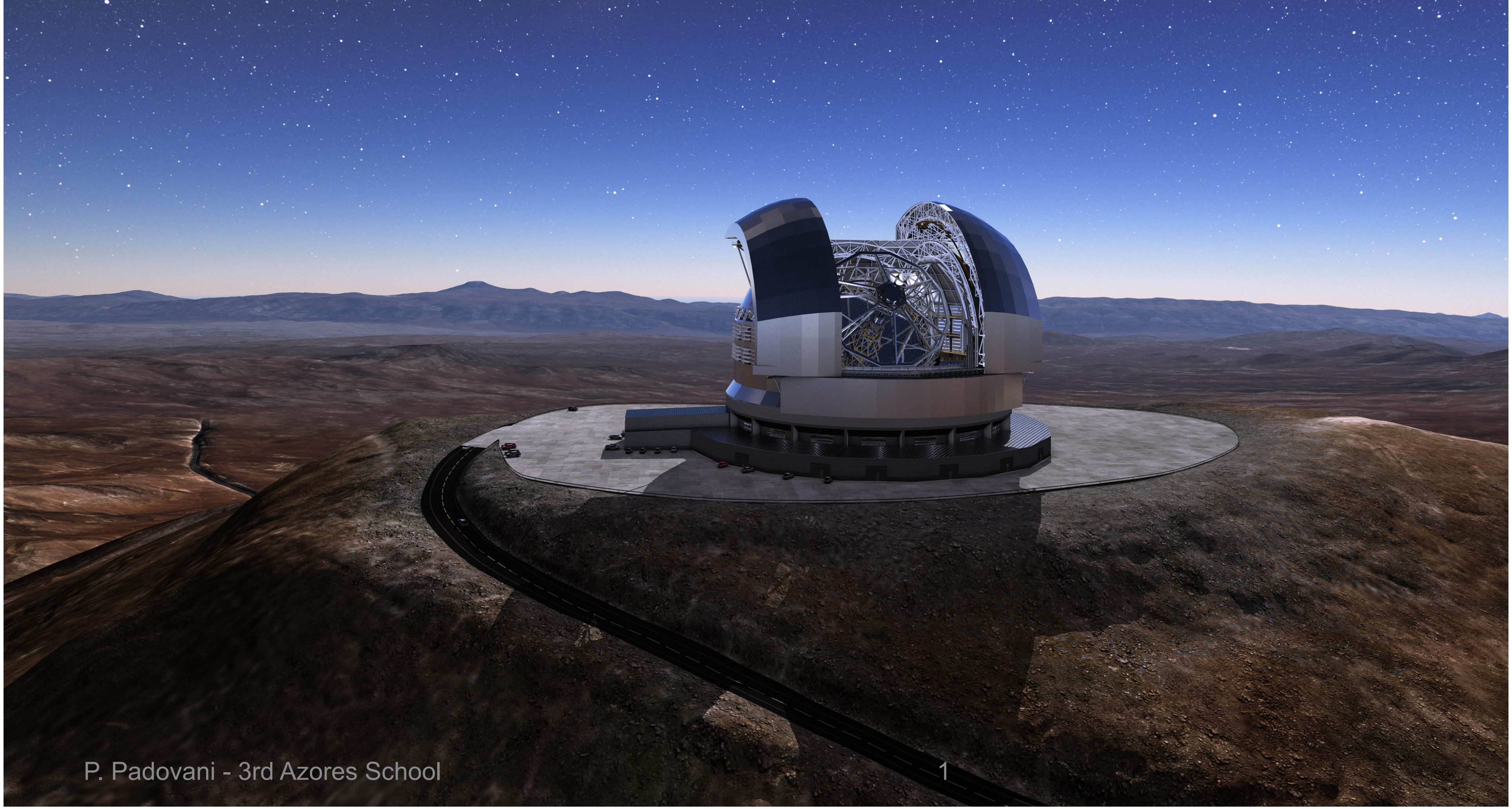
The Extremely Large Telescope and other future ESO facilities

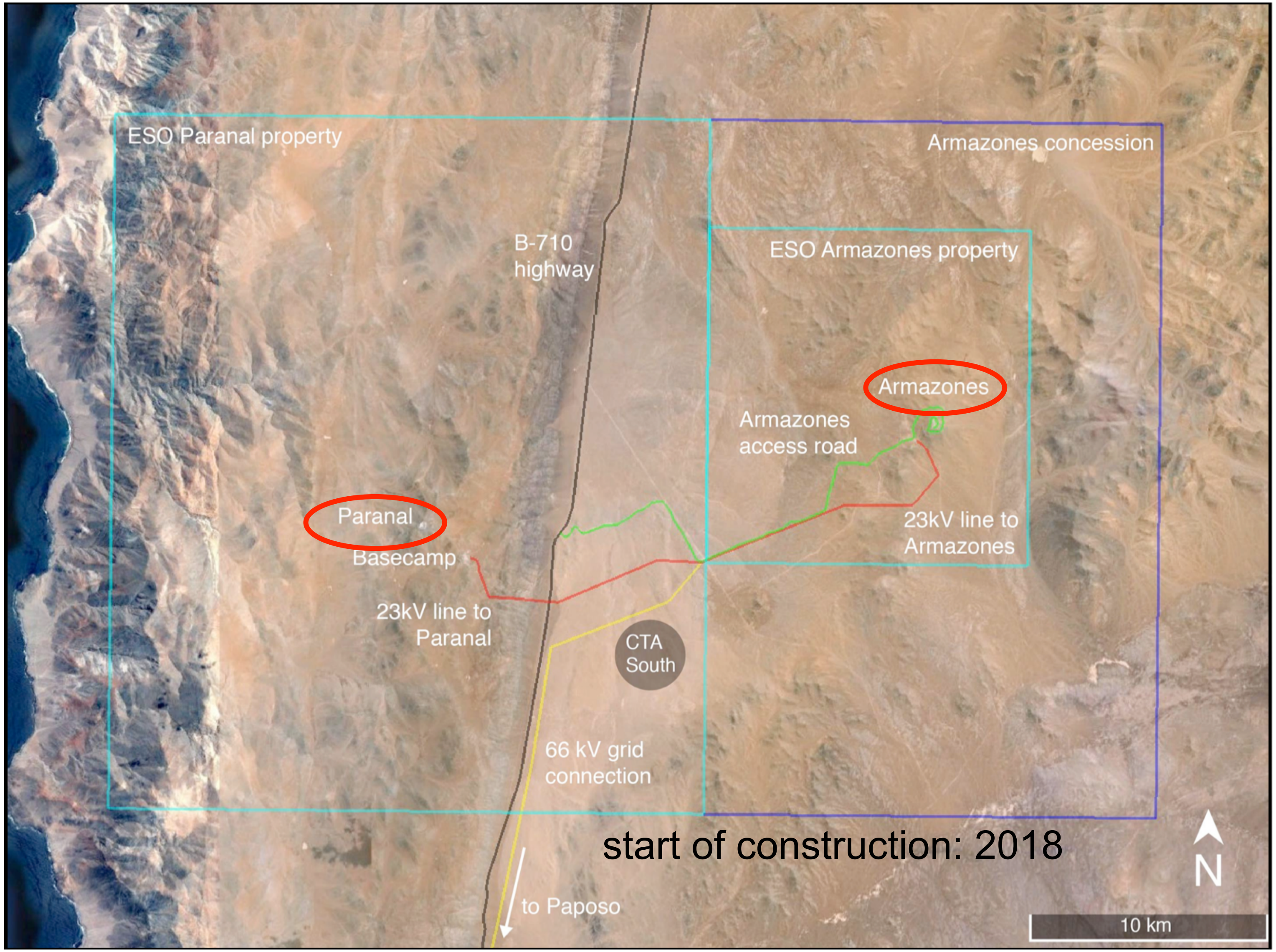
Paolo Padovani, ESO, Garching bei München
ELT Science Office



Outline

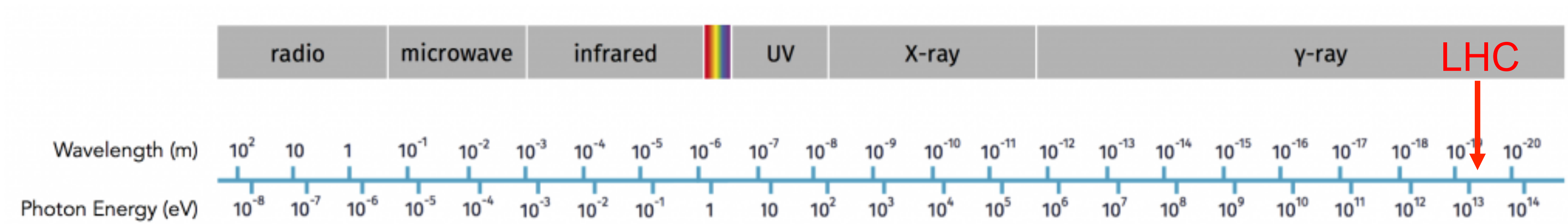
- Future ESO facilities: Cherenkov Telescope Array (CTA), MOONS, 4MOST
- The ELT
- ELT Instrument Highlights
- ELT (selected!) science

Cherenkov Telescope Array (CTA)



Gamma-rays

LPO



20 GeV – 300 TeV

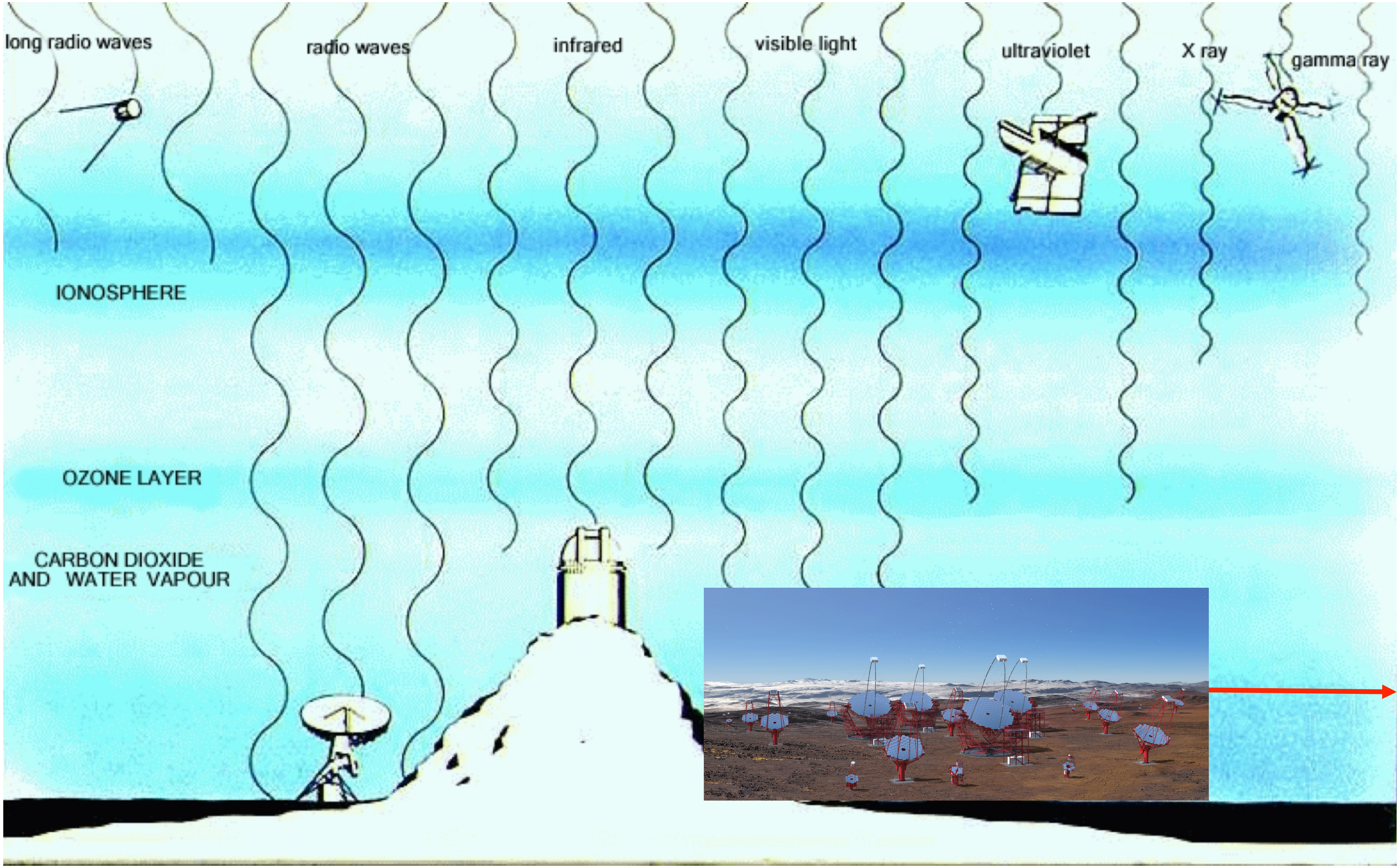
(future)

(future)

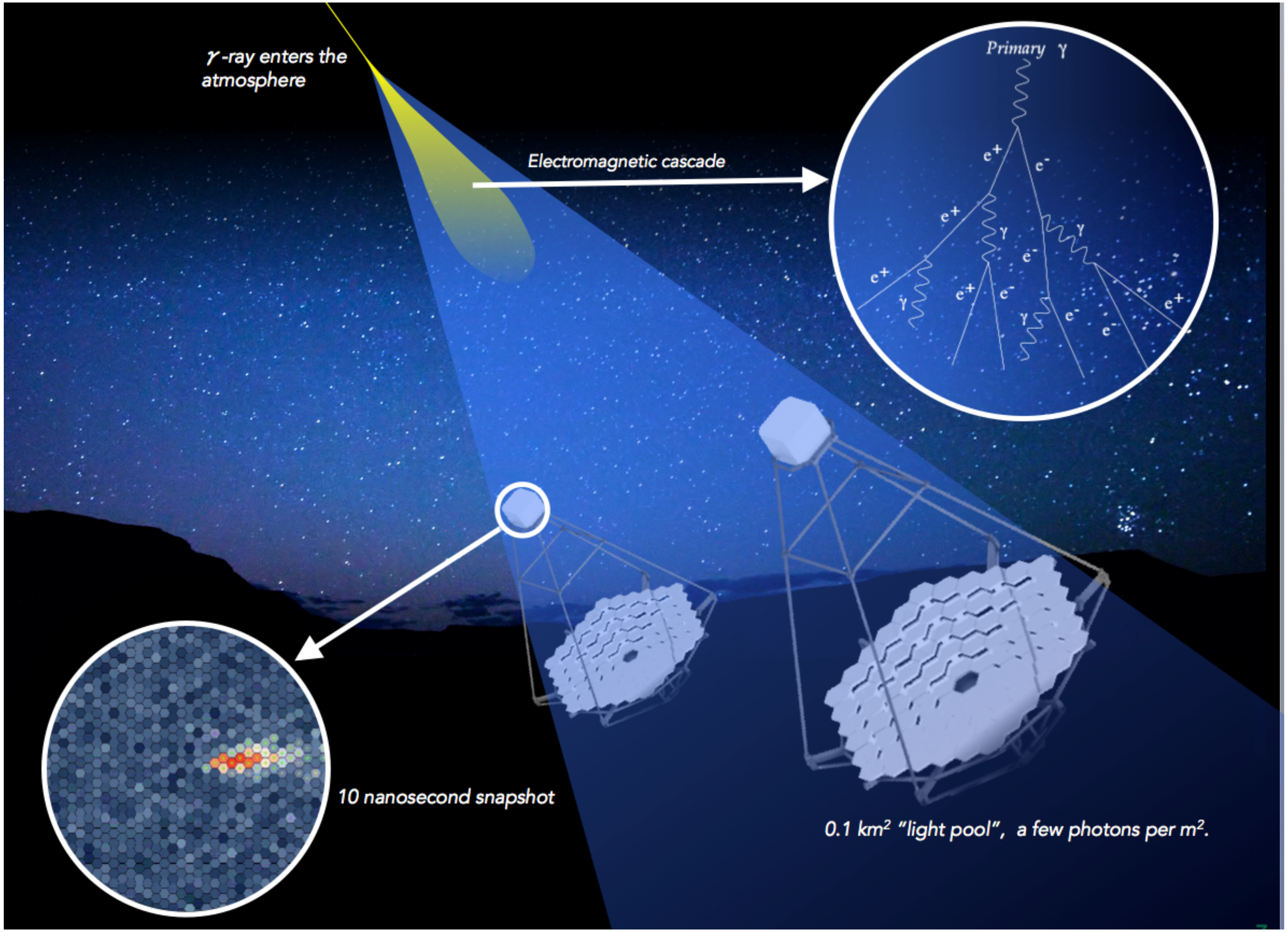
1 TeV = 2.4 10^{26} Hz

Higher energies than those of the LHC at CERN!

Gamma-rays


long radio waves
radio waves
infrared
visible light
ultraviolet
X ray
gamma ray
IONOSPHERE
OZONE LAYER
CARBON DIOXIDE
AND WATER VAPOUR

How CTA will work



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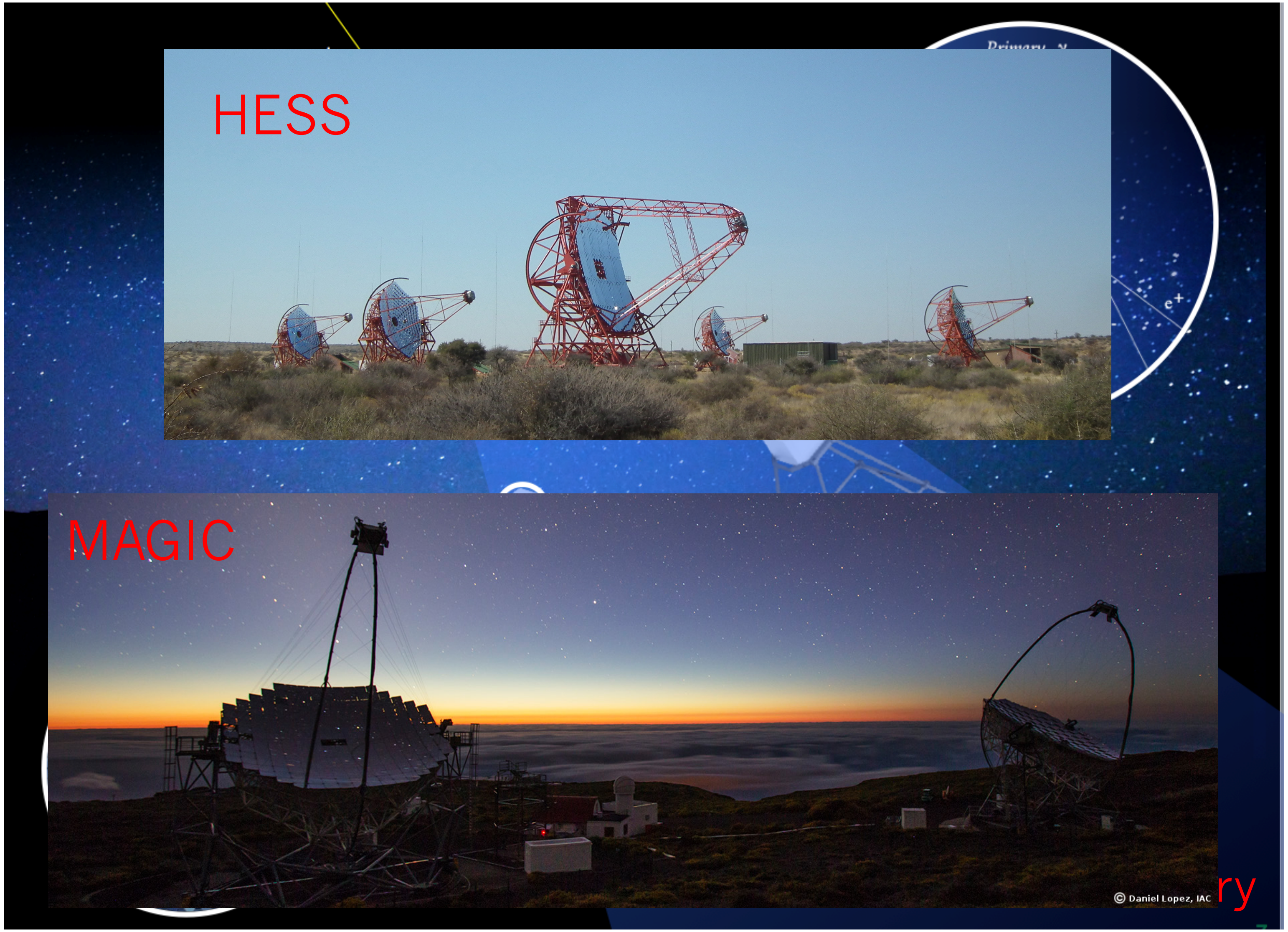


Why is CTA important?

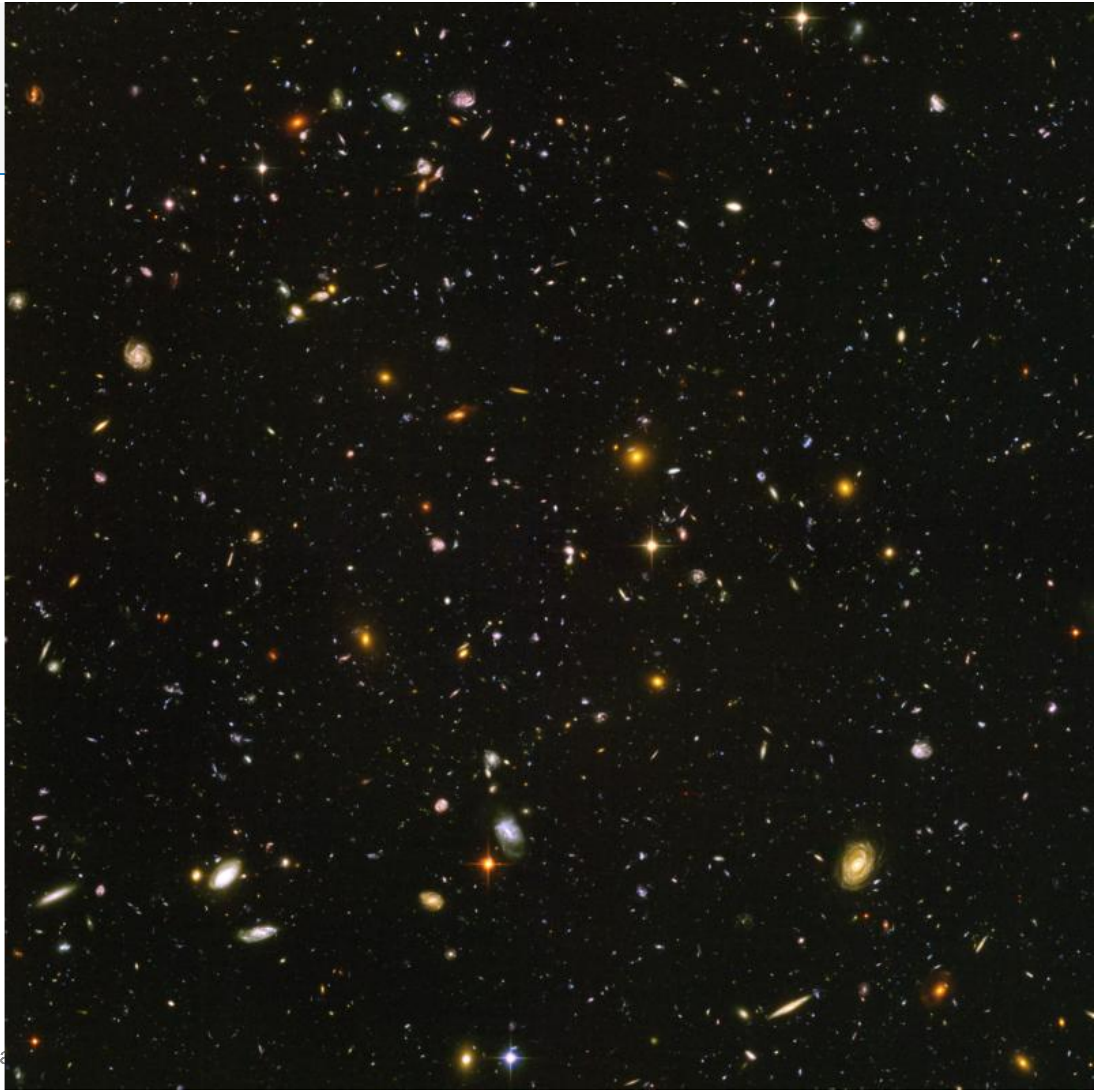
- Why is detecting very high energy gamma-rays relevant for astrophysics?
  - Gamma-ray radiation is the most energetic radiation of the electromagnetic spectrum → it allows us to study some of the most extreme physics in the Universe
- CTA will address many topics including:
  - Supernova remnants
  - Pulsars
  - Dark matter
  - Blazar physics

CTA Observatory

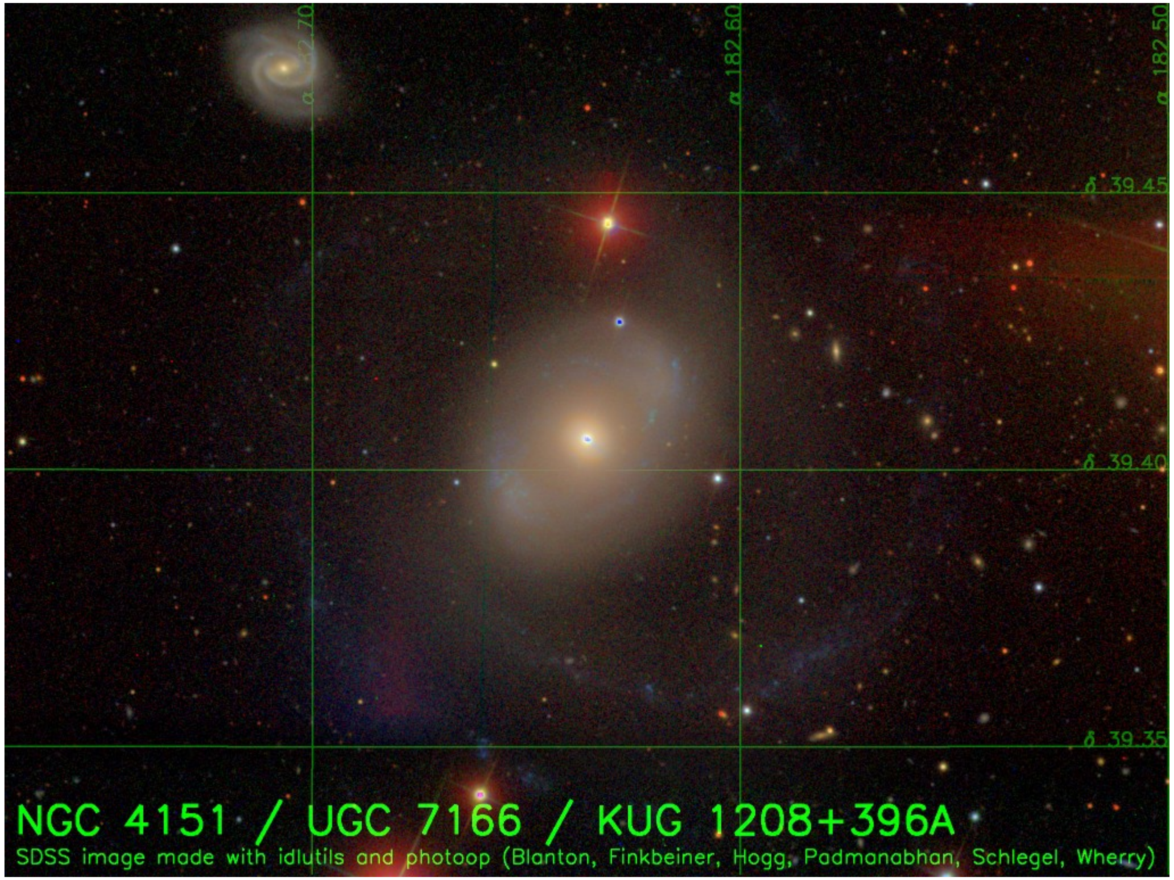
Why is CTA important?

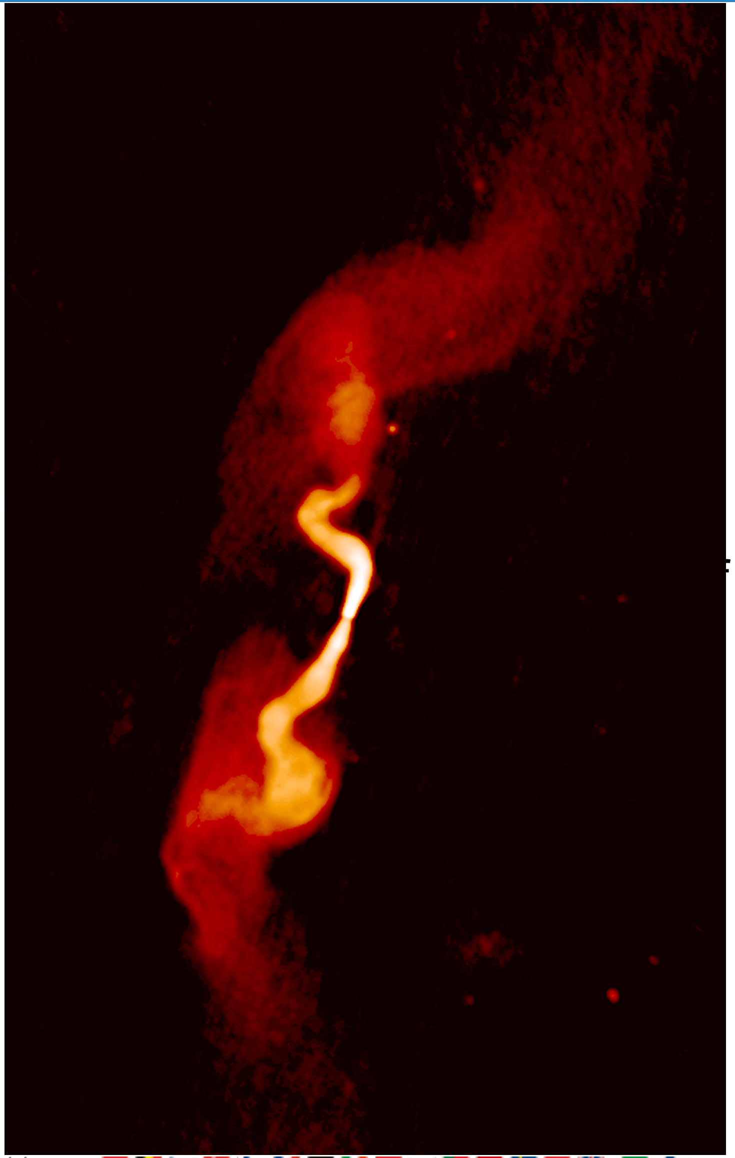
- W
  r
  f

- C

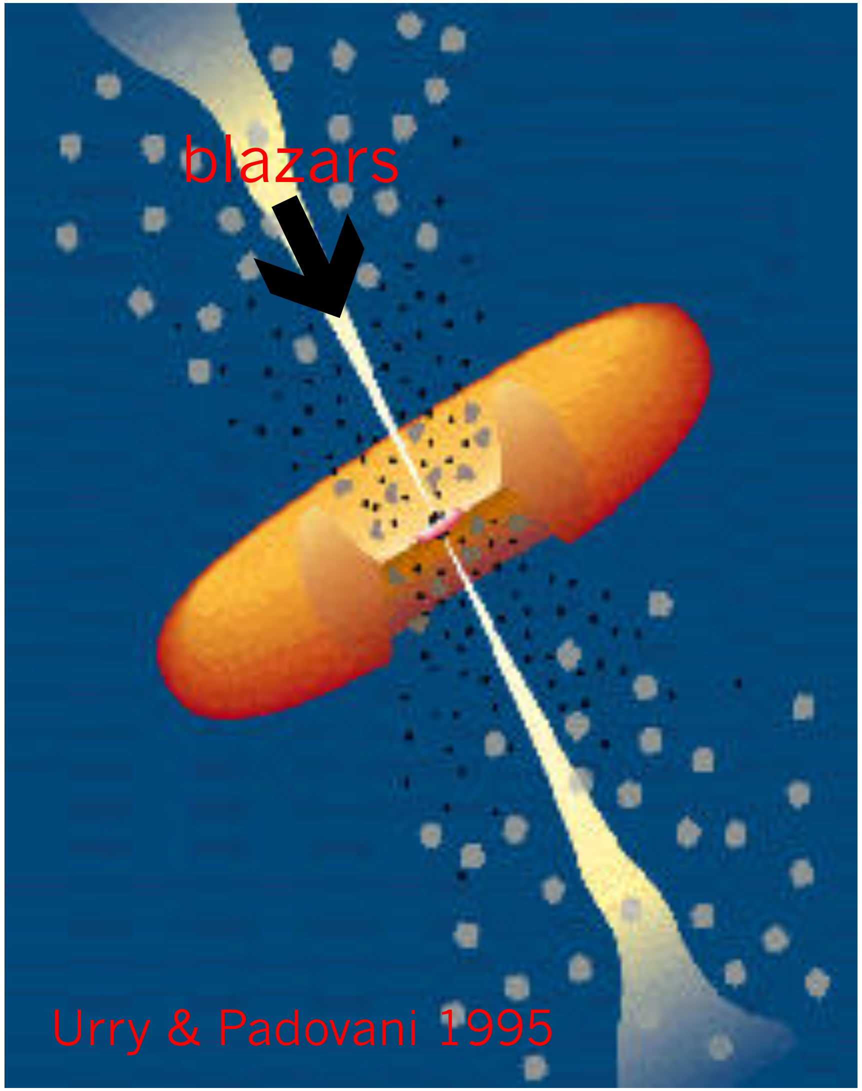


What is a blazar?





What is a blazar?

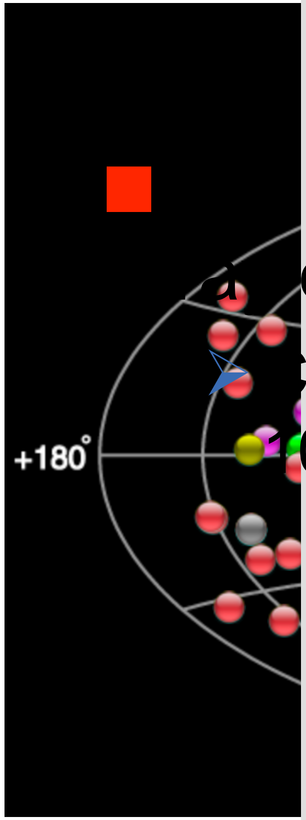


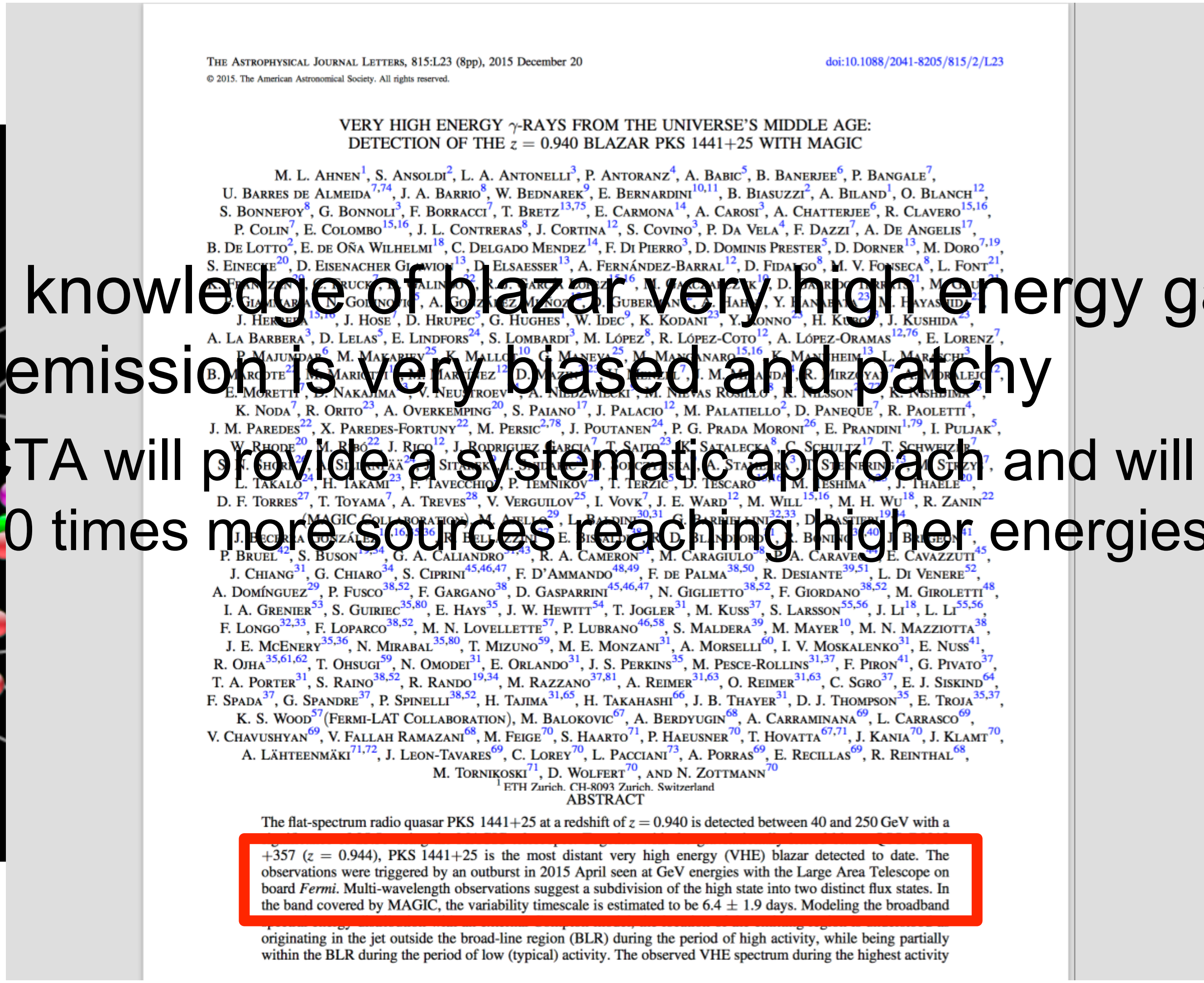
Less than 1 galaxy out of 20,000 is a blazar!

The importance of being a blazar

- Sites of very high energy phenomena:
  E_{max} ~ 20 TeV (5 x 10^{27} Hz) and v_{max} ~ 0.9998c
- Nature's free (and very efficient!) accelerators

CTA and blazars





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VERY HIGH ENERGY γ-RAYS FROM THE UNIVERSE'S MIDDLE AGE: DETECTION OF THE $z = 0.940$ BLAZAR PKS 1441+25 WITH MAGIC

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ABSTRACT

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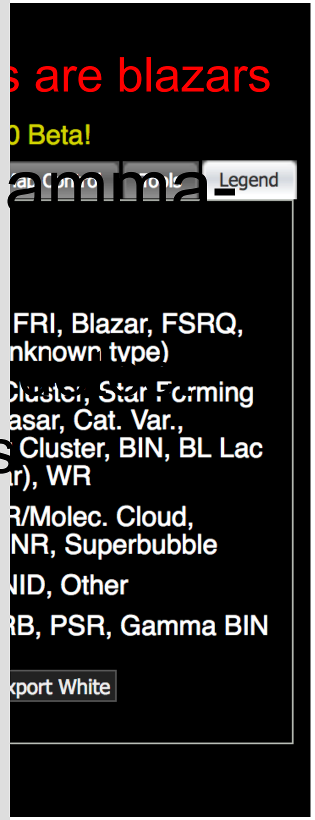
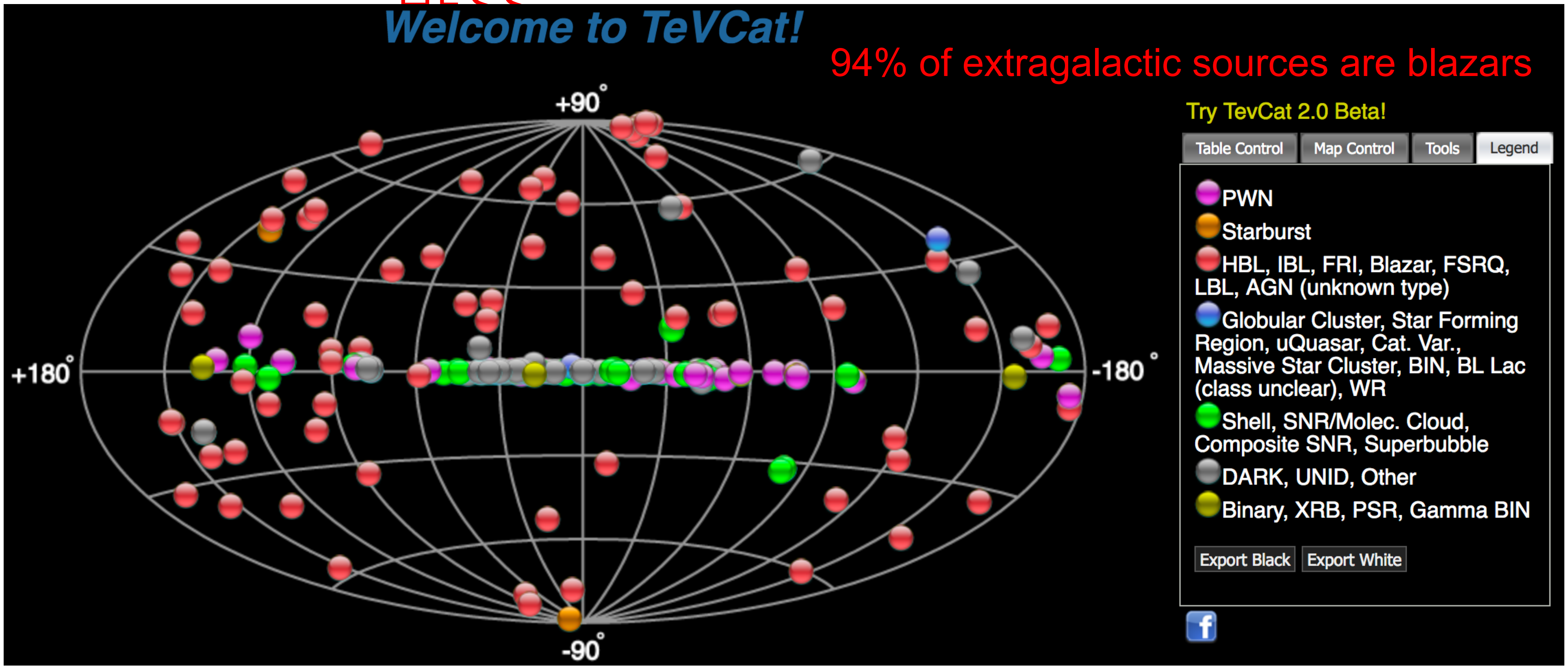


- knowledge of blazar very high energy gamma-ray emission is very biased and patchy
  - CTA will provide a systematic approach and will … 0 times more sources reaching higher energies

CTA and blazars



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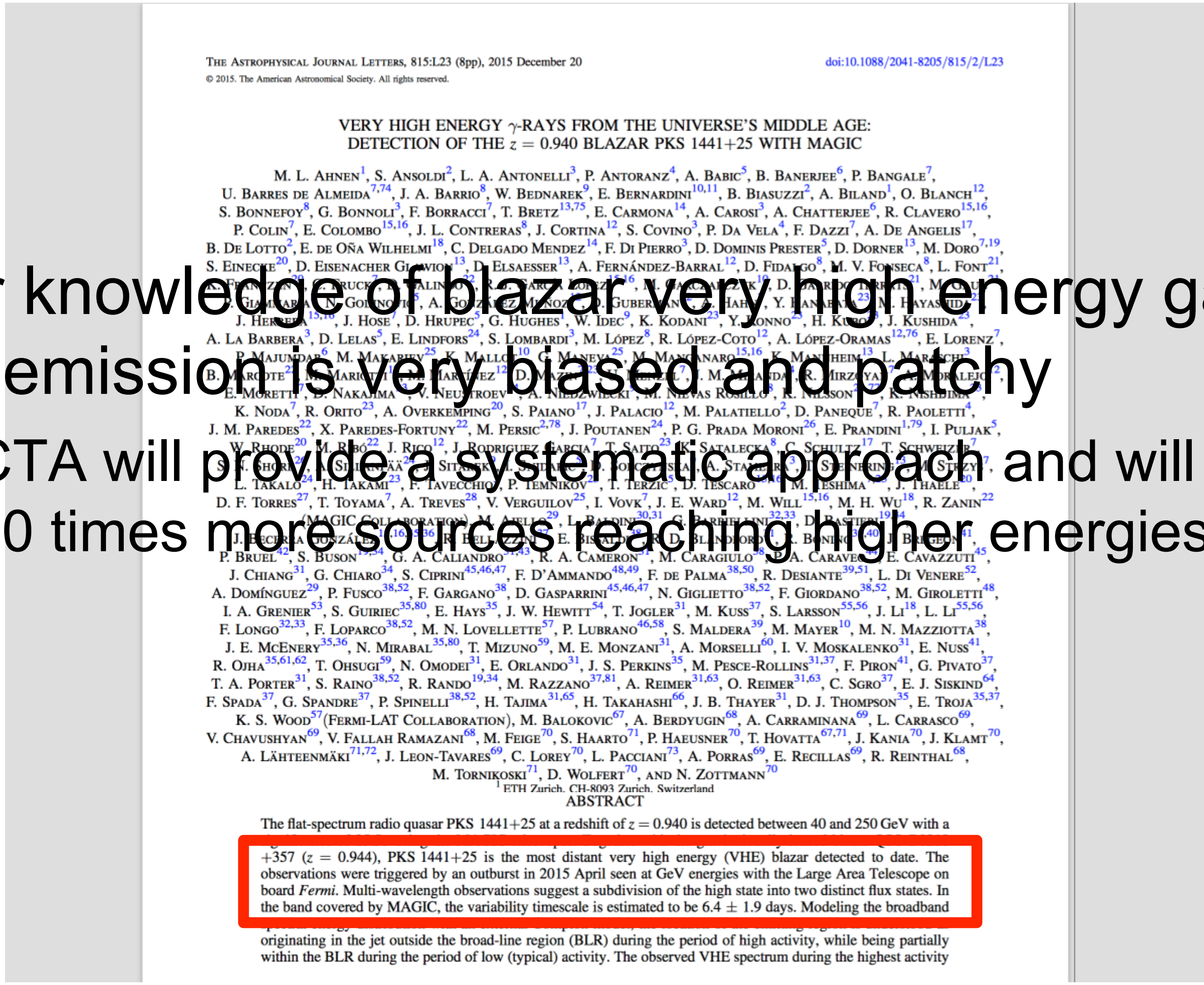

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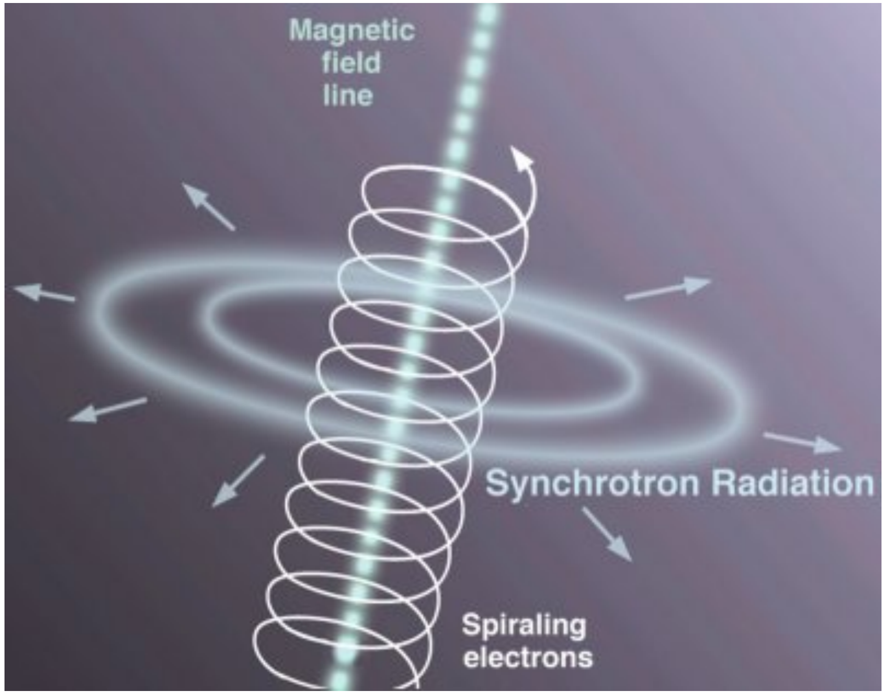
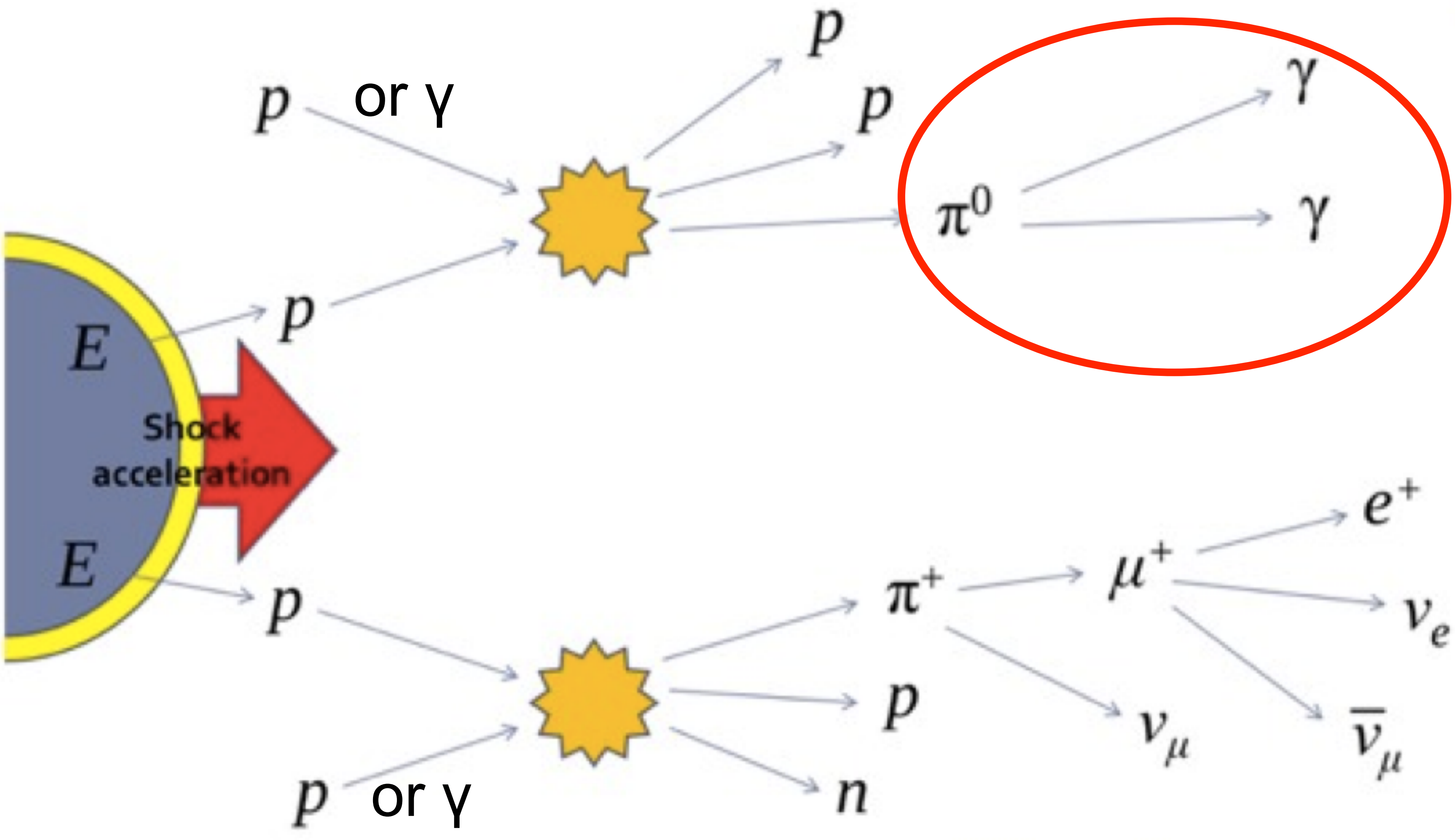
The mystery of gamma-ray photons

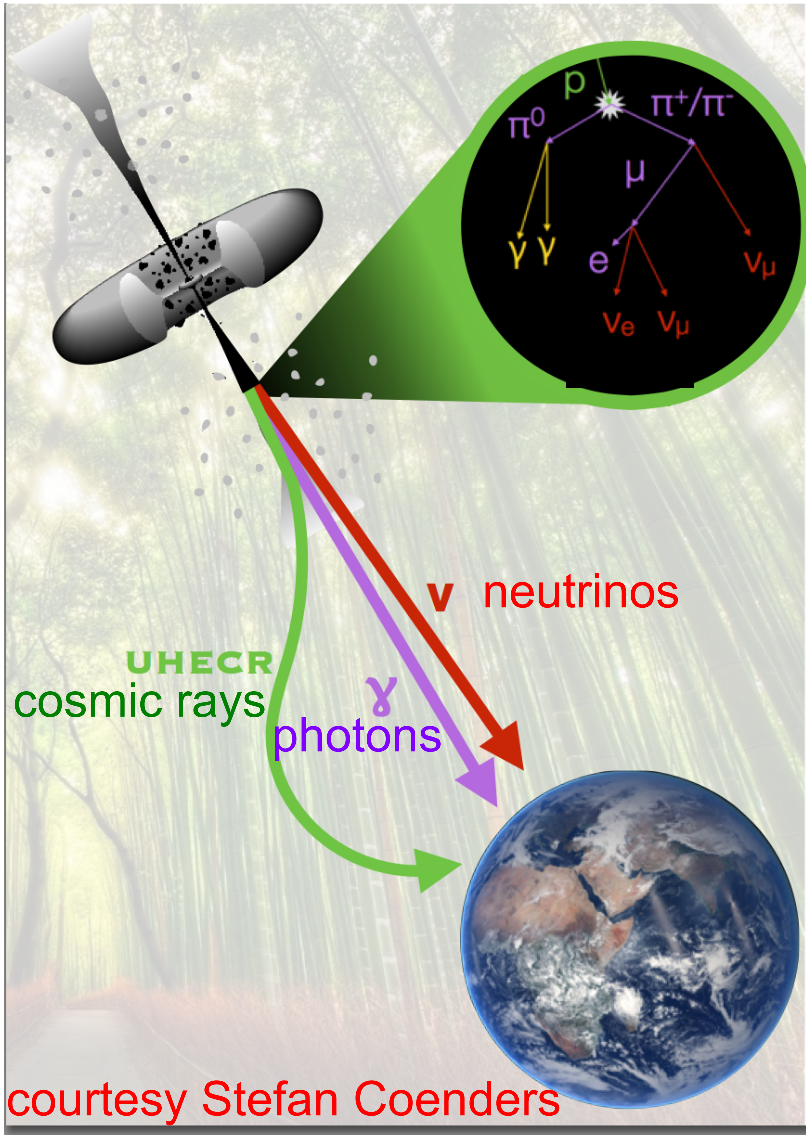


$$e^- + \gamma_{low\text{-}energy} \rightarrow \gamma_{high\text{-}energy}$$

The mystery of gamma-ray photons



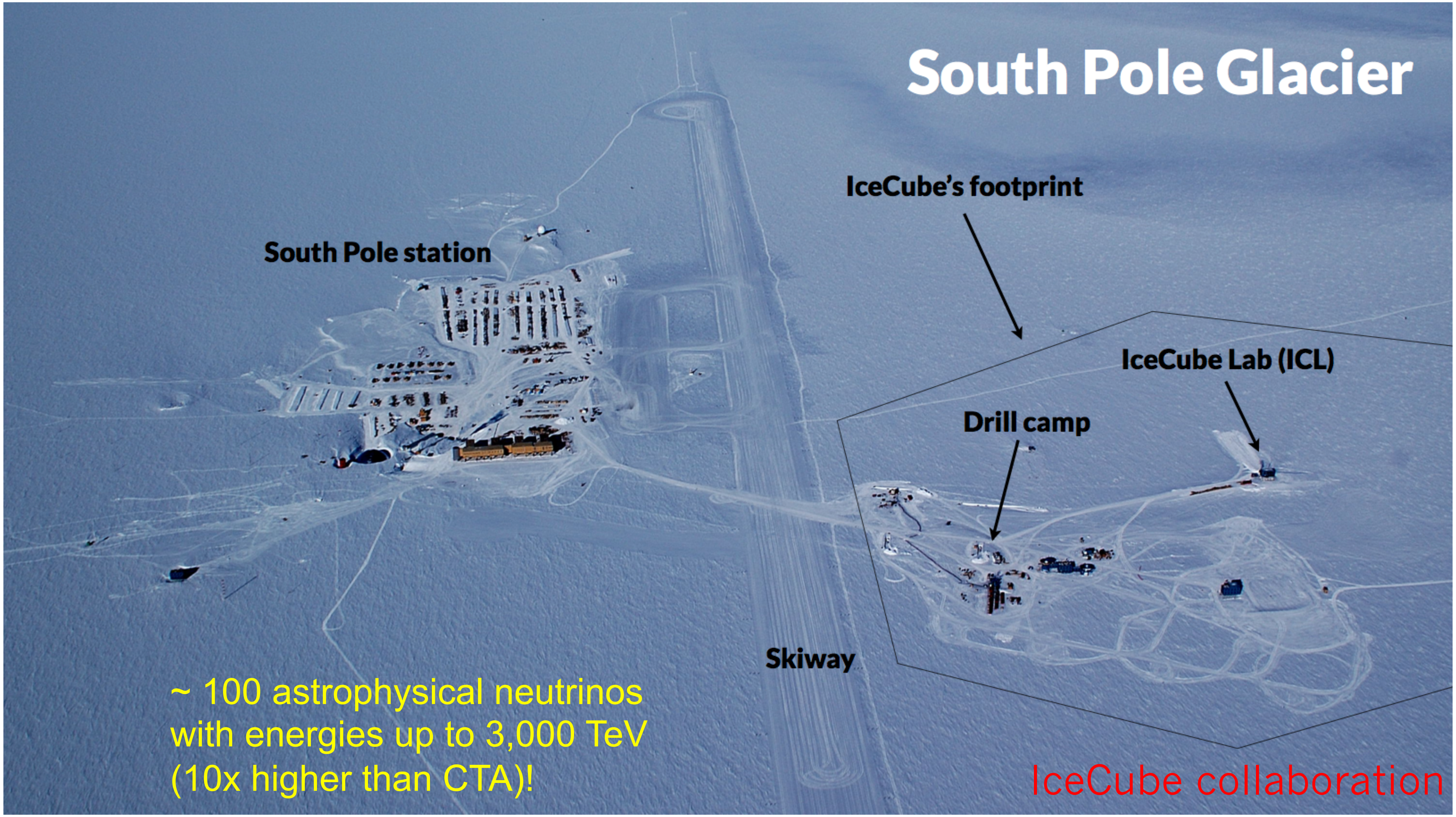
Multi-messenger astrophysics



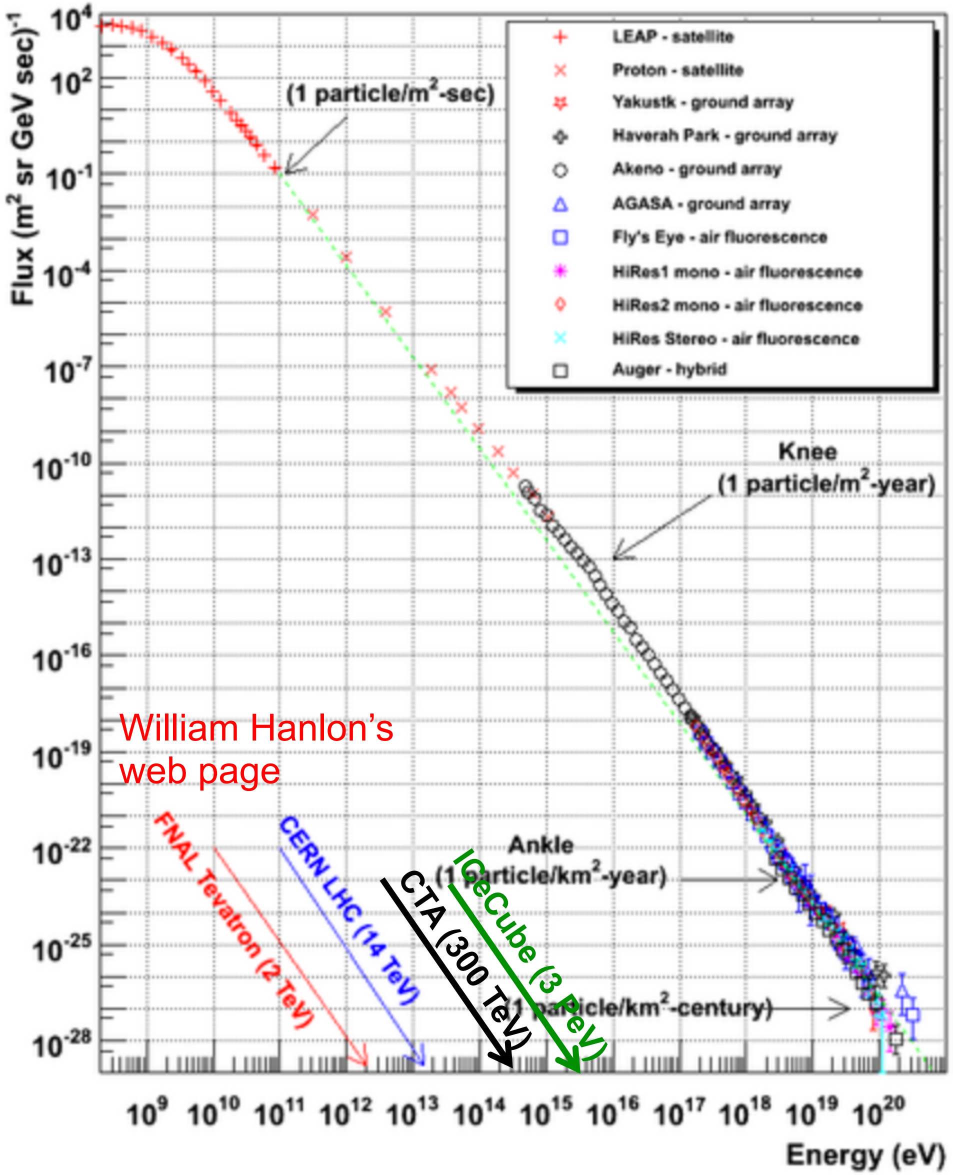
SFB 1258 Neutrinos Dark Matter Messengers

DFG Deutsche Forschungsgemeinschaft

The mystery of astrophysical neutrinos

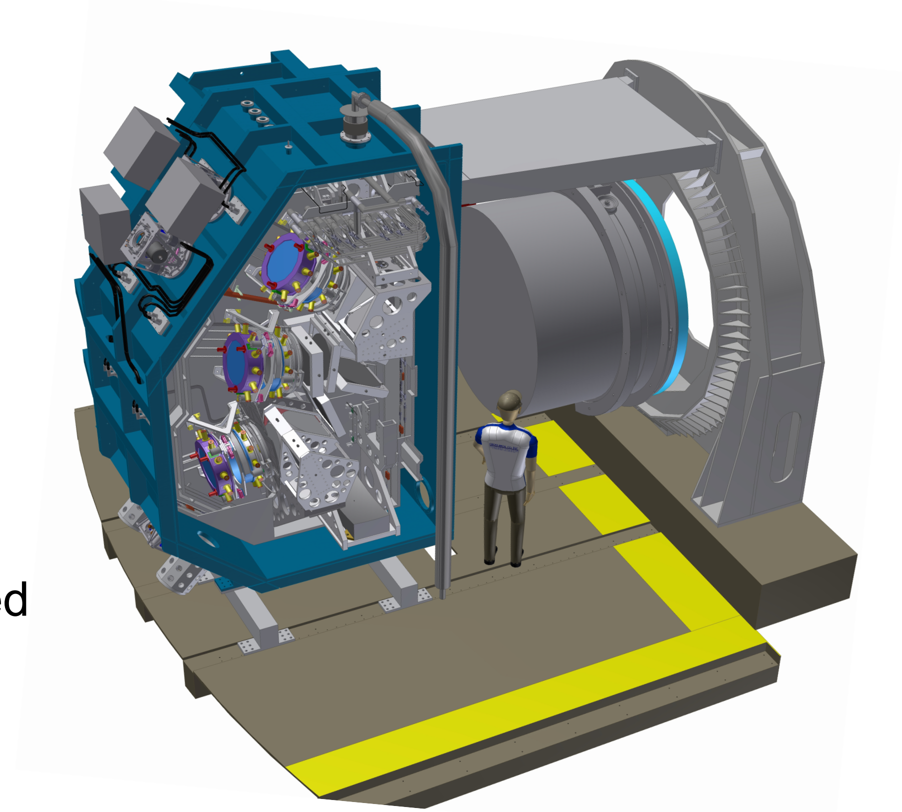


The mystery of cosmic rays



VLT-MOONS

Multi Object Optical and Near-infrared Spectrograph for the VLT



AIUC CENTRO DE ASTRO-INGENIERIA UC

CAAUL CENTRO DE ASTRONOMIA E ASTROFISICA DA UNIVERSIDADE DE LISBOA

FACULDADE DE CIÊNCIAS UNIVERSIDADE DE LISBOA

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

INAF ISTITUTO NAZIONALE DI ASTROFISICA

UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES Département d'astronomie

l'Observatoire de Paris GEPI Galaxies Étoiles Physique et Instrumentation

ESO

UNIVERSITY OF CAMBRIDGE

Science & Technology Facilities Council UK Astronomy Technology Centre

VLT-MOONS

Field of view	500 sq. arcmin
Multiplex	1000 fibres
Medium resolution mode	R = 4,000-6000 λ = 0.64μm – 1.8μm simultaneously
High resolution mode	0.76-0.90μm at R=9,000 + 0.95-1.35μm at R=4,000 + 1.52-1.63μm at R=20,000 simultaneously
Throughput	> 30 %

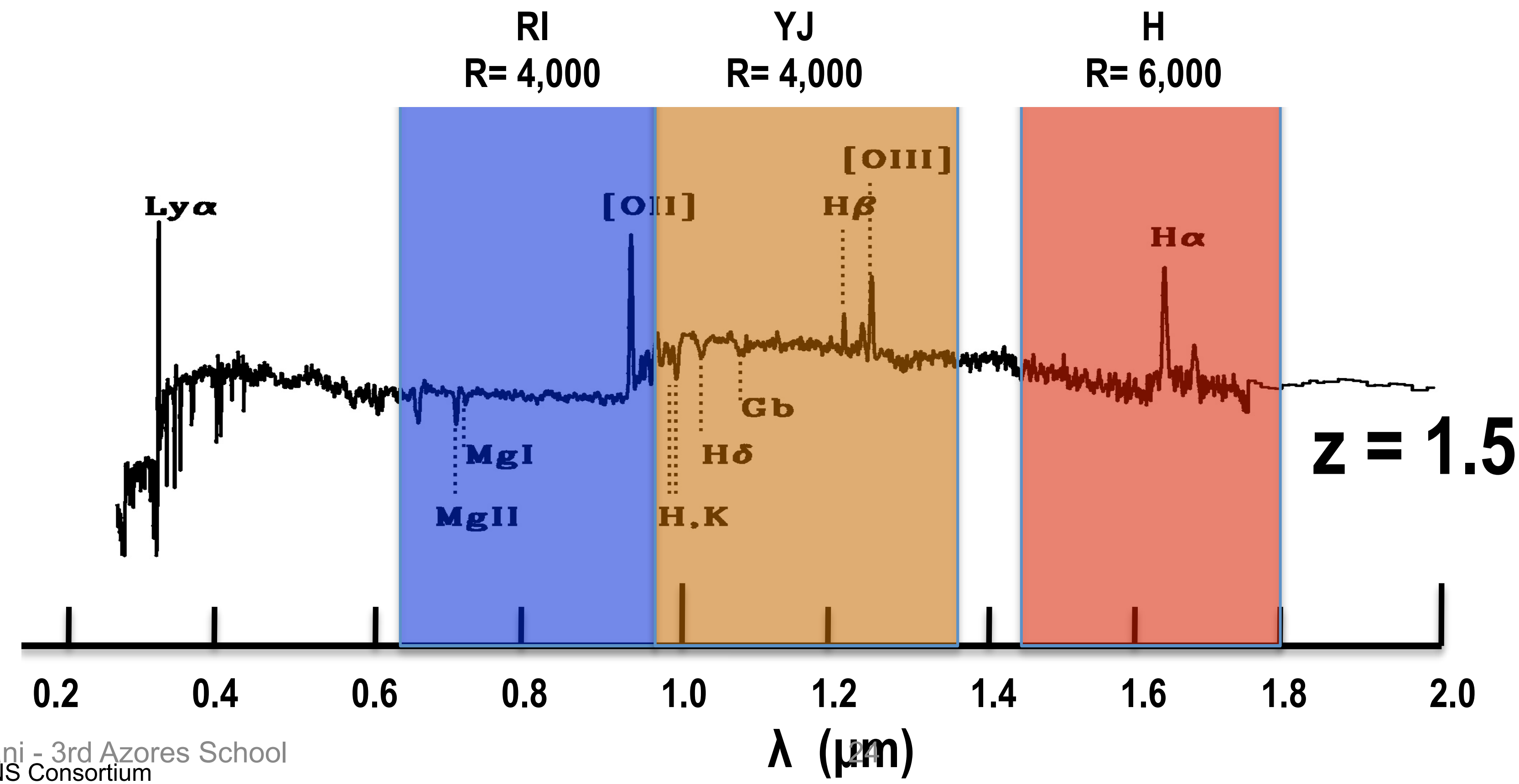
Start of scientific operations: 2020

Courtesy MOONS Consortium

MOONS Extragalactic Surveys

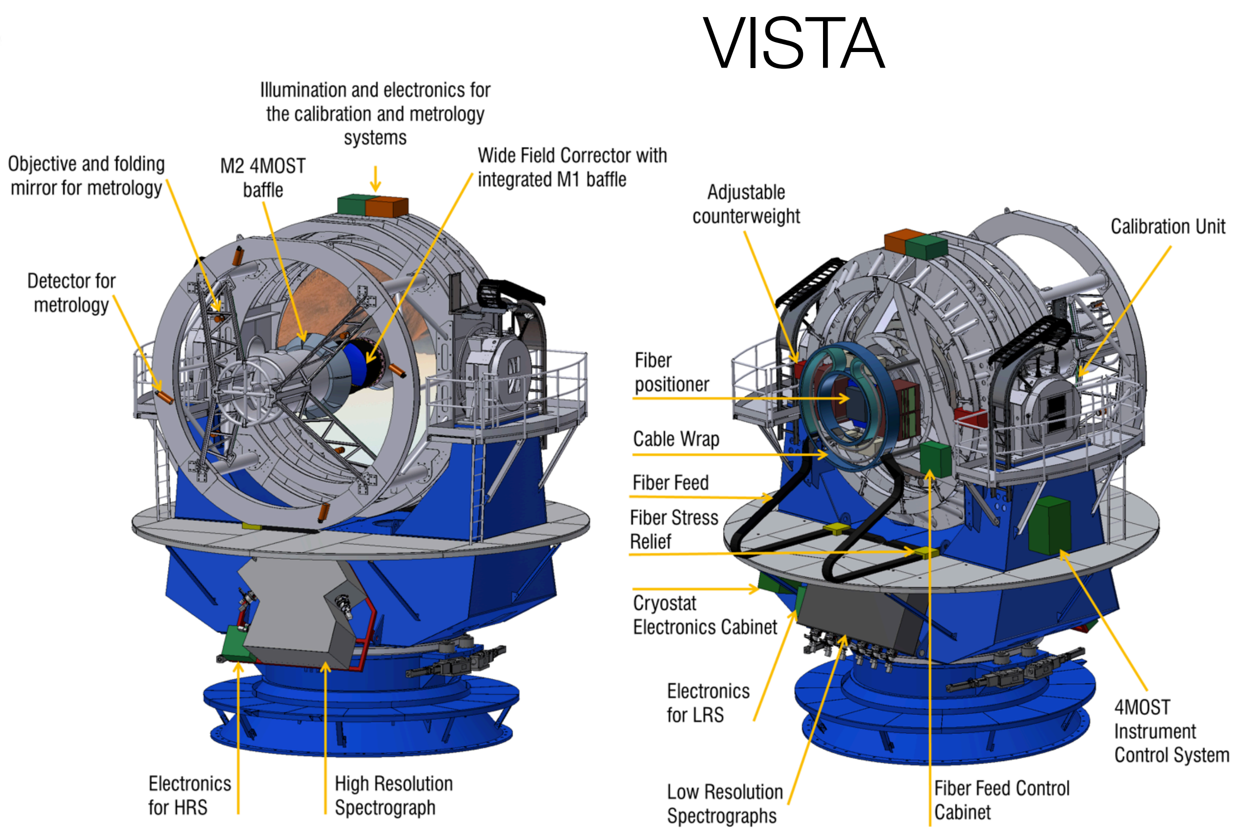
SDSS-like (in wavelength coverage rest-frame) +
Deep Surveys

Physical, Chemical and Environmental properties for
~1M galaxies at 0.8 < z < 10



Courtesy MOONS Consortium

4MOST – 4m Multi-Object Spectroscopic Telescope

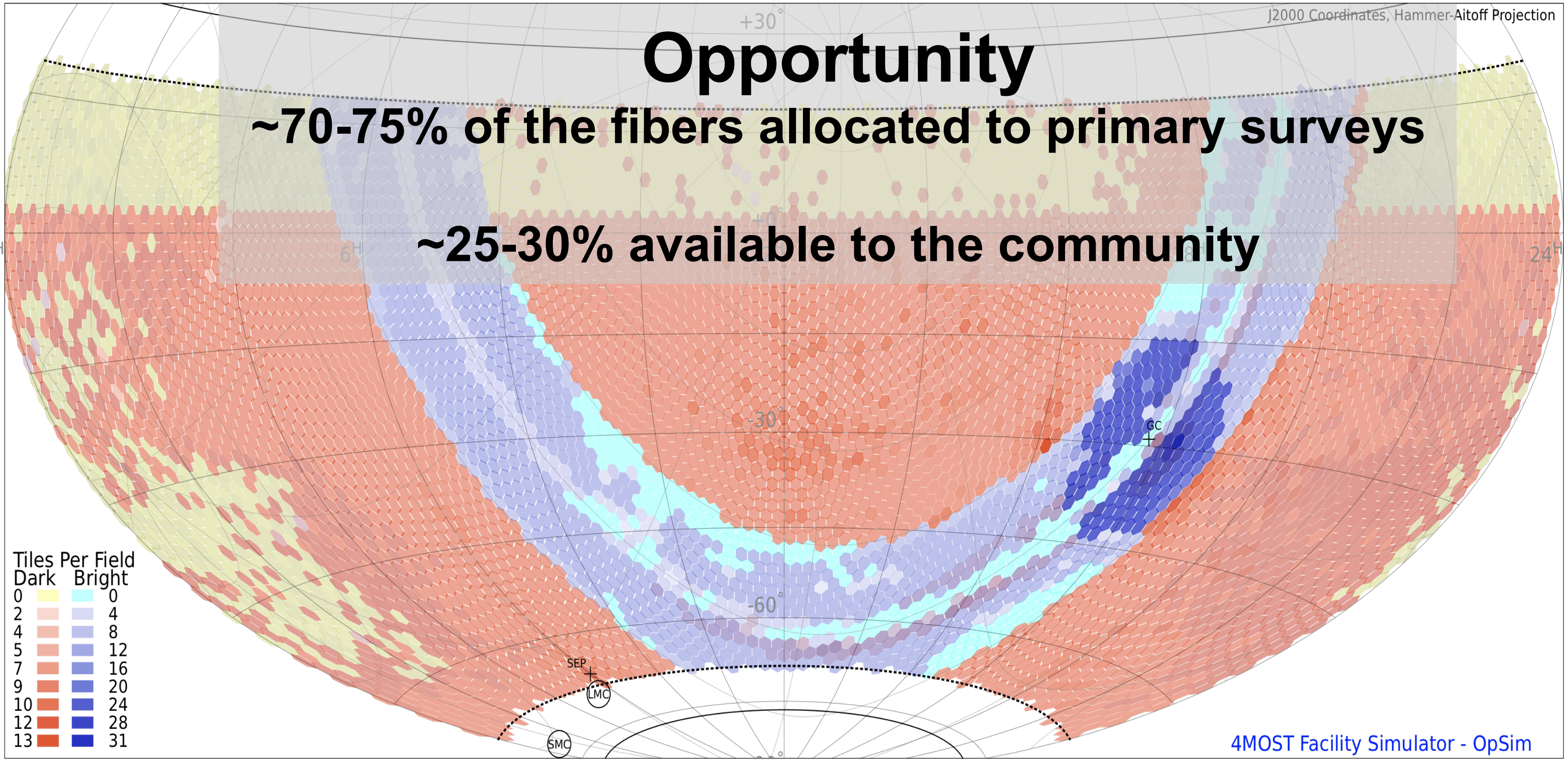


Instrument specifications

Field of view	4.0 sq. deg
Multiplex	2400 fibres
Medium resolution	R = 5,000-7000 1600 fibers λ = 0.390μm – 0.930μm
High resolution	R ~ 20,000 800 fibers 0.392μm – 0.437μm + 0.515μm – 0.572μm + 0.605μm – 0.675μm
Fiber diameter	1.4 arcsec

Start of scientific operations: 2022

4MOST Surveys



Several million spectra in Galactic and extragalactic surveys and follow-up of:

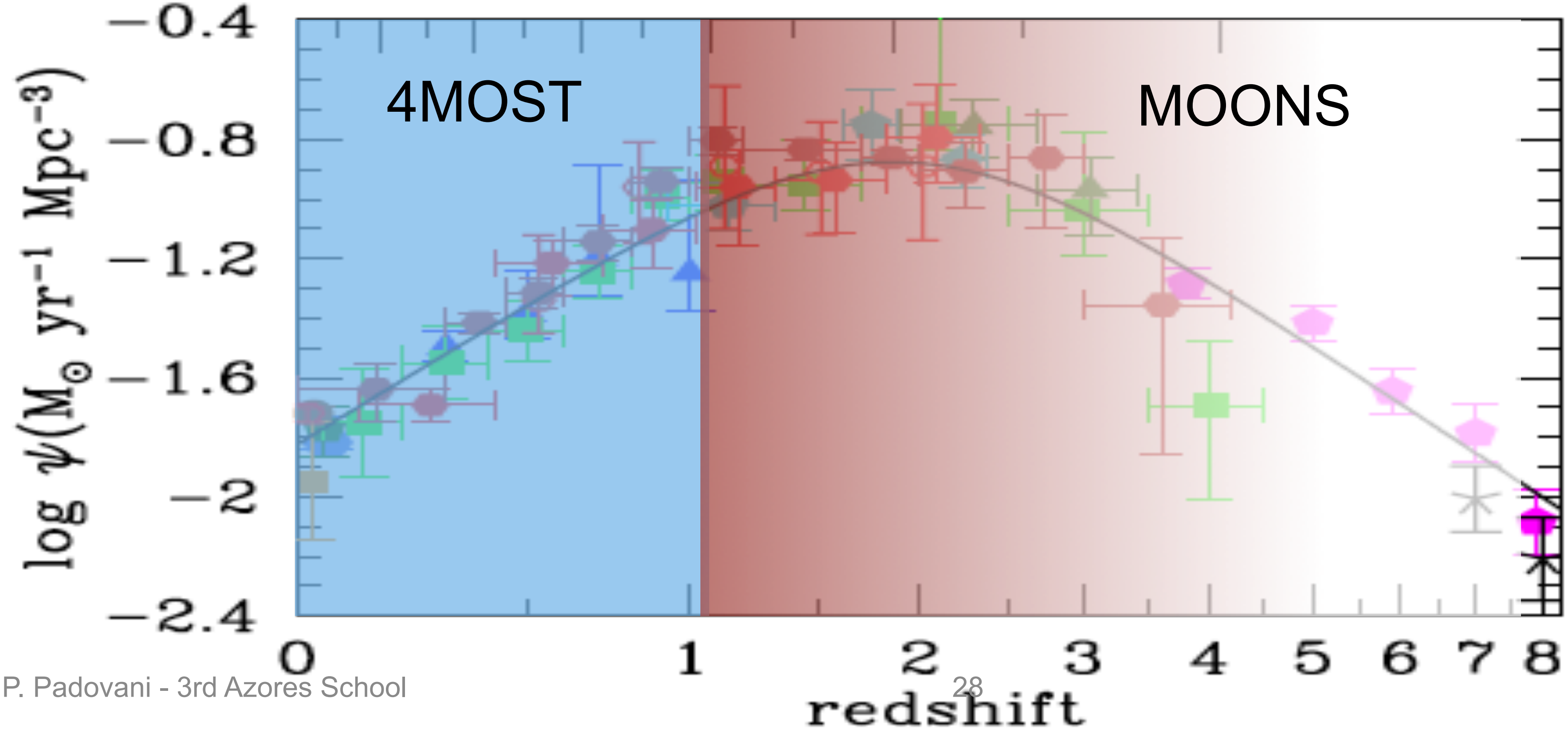
- Gaia (astrometry)
- e-ROSITA (X-ray)
- Euclid (optical-NIR), LSST (optical [time domain]), SKA (radio)

4MOST + MOONS

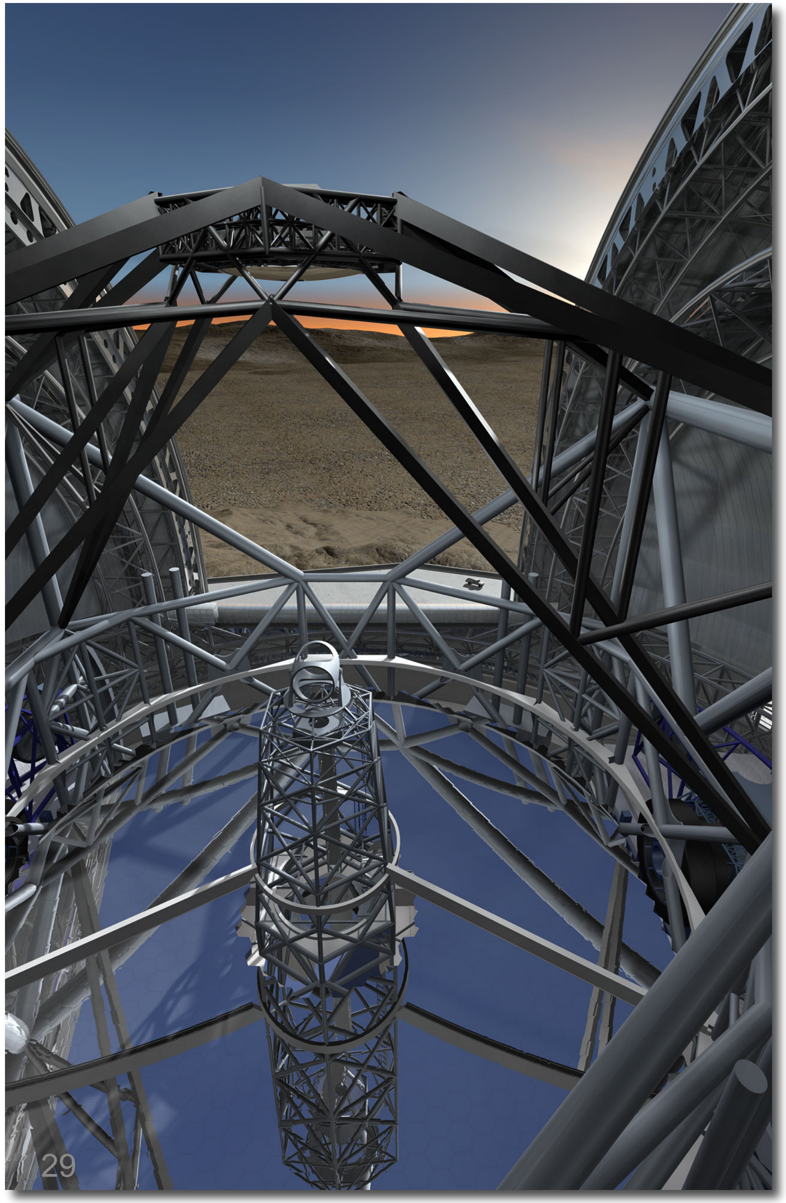
Extragalactic Surveys

4m telescope
Large FoV
Optical λ-coverage
Dedicated facility

8m telescope
Deep optical and
near-IR λ-coverage



The ELT



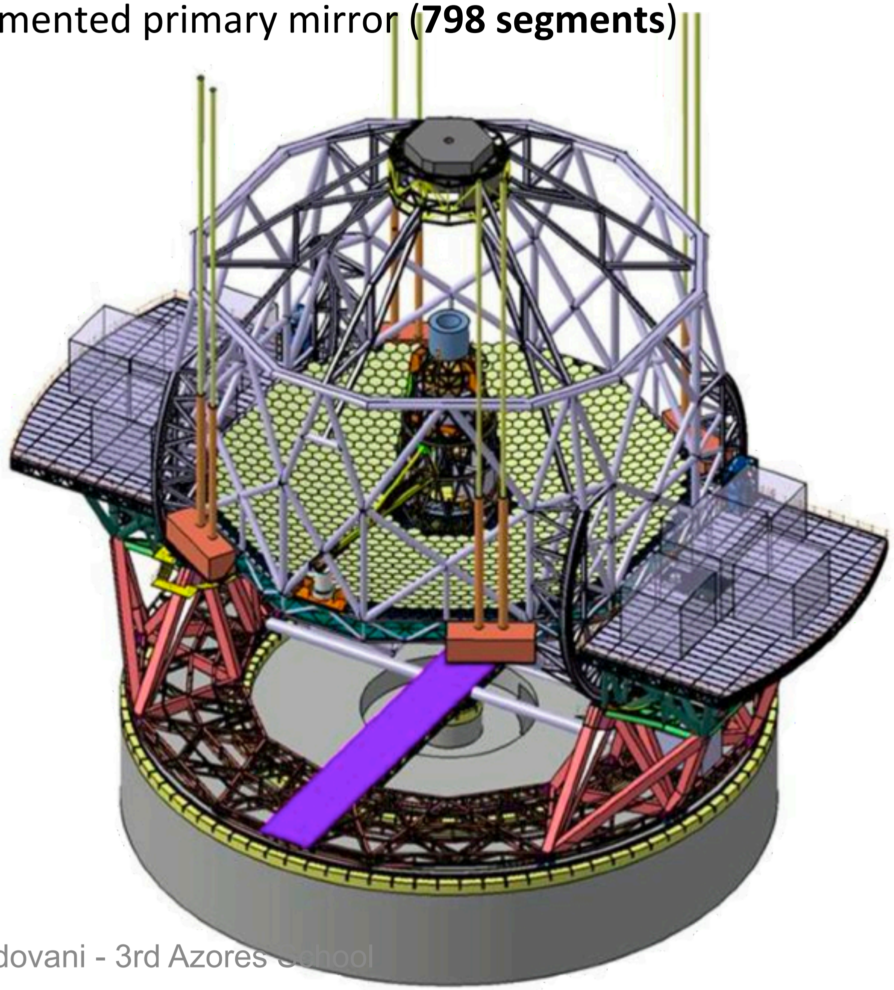
39-m class telescope

the largest optical/near-IR telescope

- Adaptive optics built in to deliver diffraction limited performance
- Mid-latitude southern site (Armazones in Chile)
- First light planned for 2024 (work well underway)
- Construction costs: 1.1 B€ (including first-light instrumentation and contingency)
- Operation costs: ~ 50 M€ per year

The ELT: overview

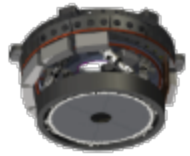
- Novel 5 mirror design to include adaptive optics in the telescope (classical 3-mirror anastigmat + 2 flat fold mirrors [M4, M5])
- Diffraction limited over full **10' FoV**
- Segmented primary mirror (**798 segments**)



M1 Unit
39-m
Concave – Aspheric f/0.9
Segmented (798 Segments)
Active + Segment shape Control

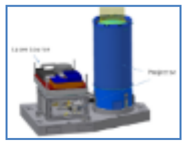
M2 Unit
4-m
Convex Aspheric f/1.1
Passive + Position Control

M3 Unit
4-m – Concave – Aspheric f/2.6
Active + Position Control



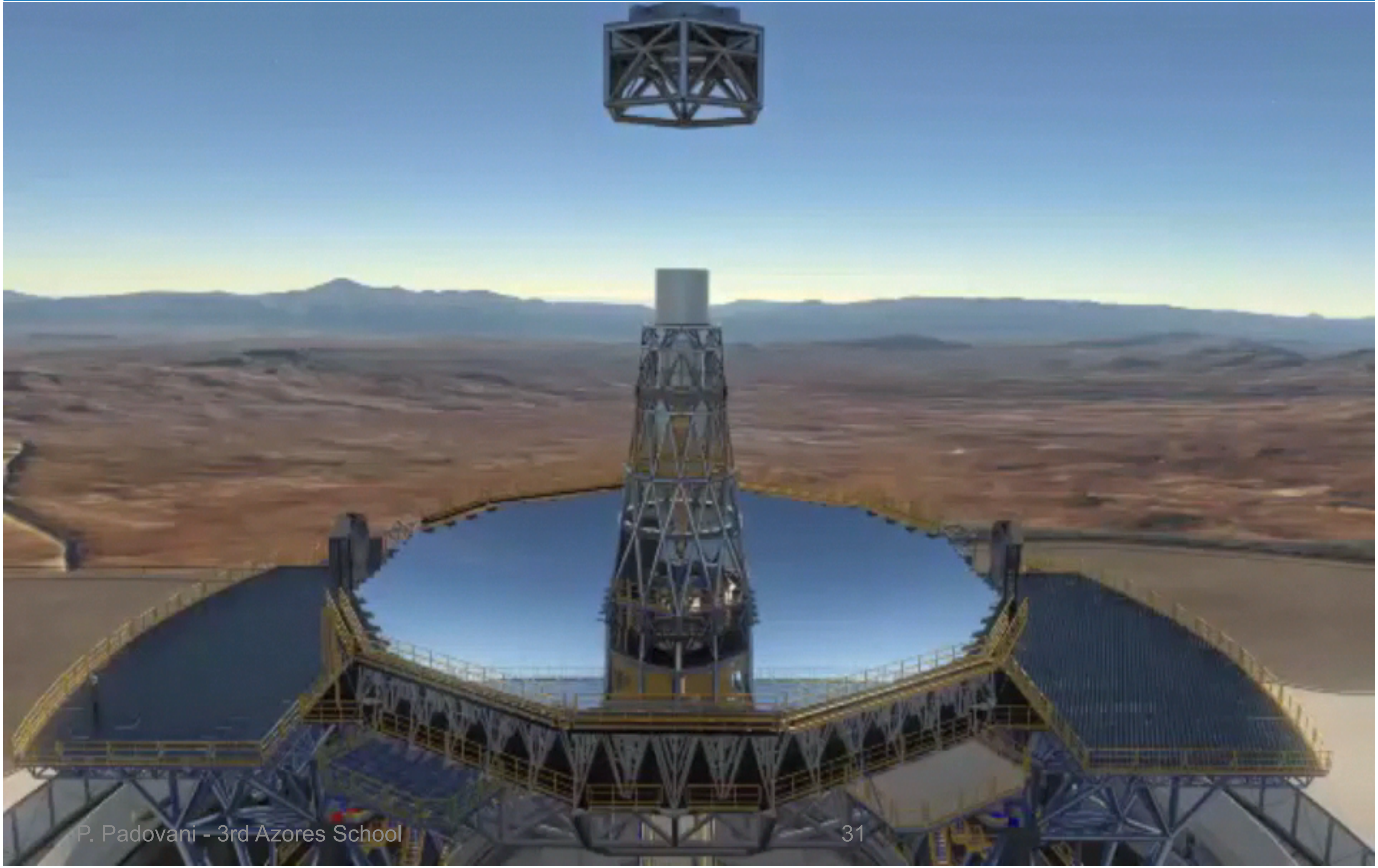
M4 Unit
2.4-m
Flat
Segmented (6 petals)
Adaptive + Position Control

M5 Unit
2.7x2.1-m
Flat
Passive + Fast Tip/Tilt

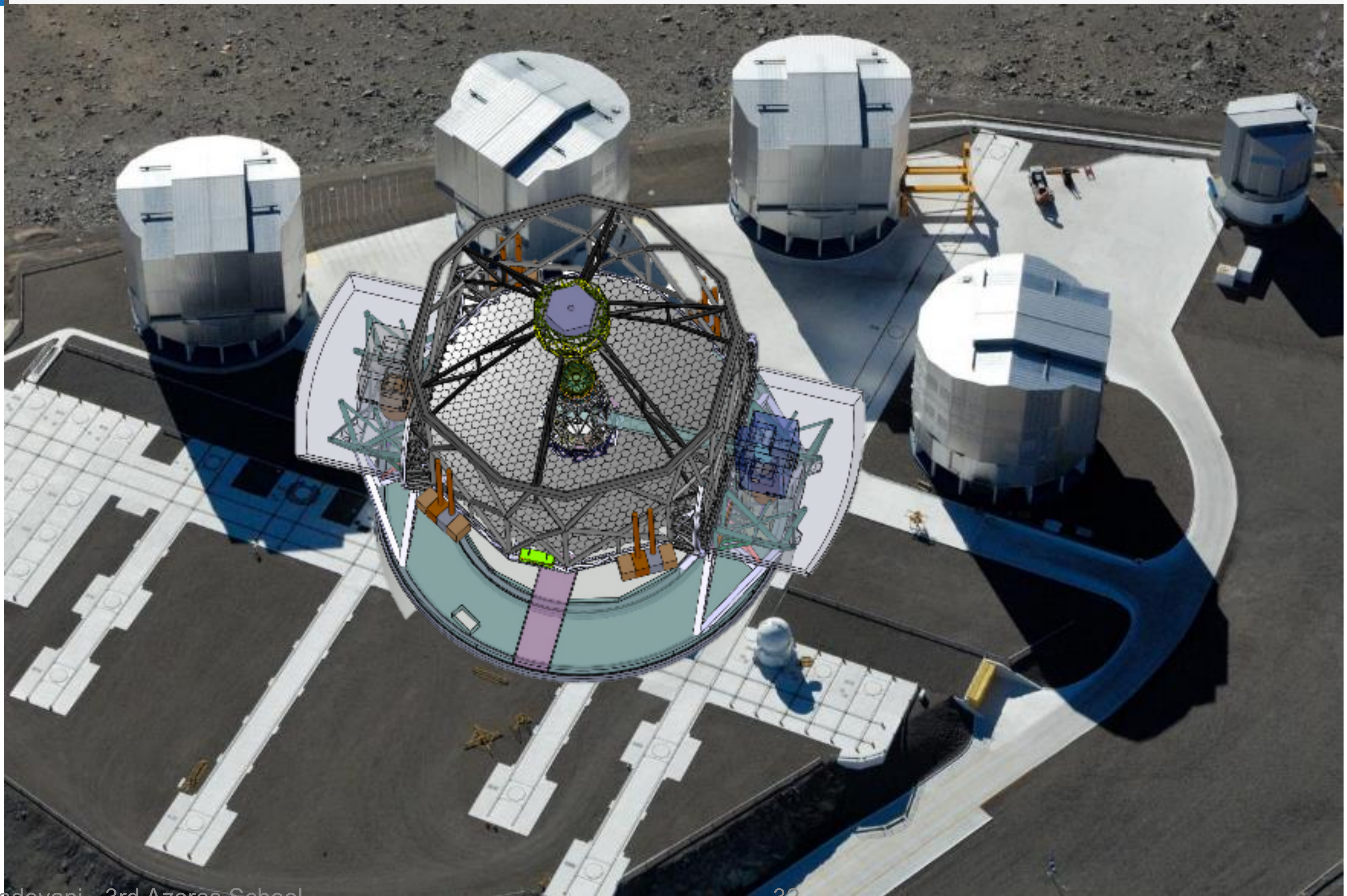


LGSU
(Laser Guide Star Units)
Laser Sources + Laser Beacons shaping and emitting

ELT Optomechanics



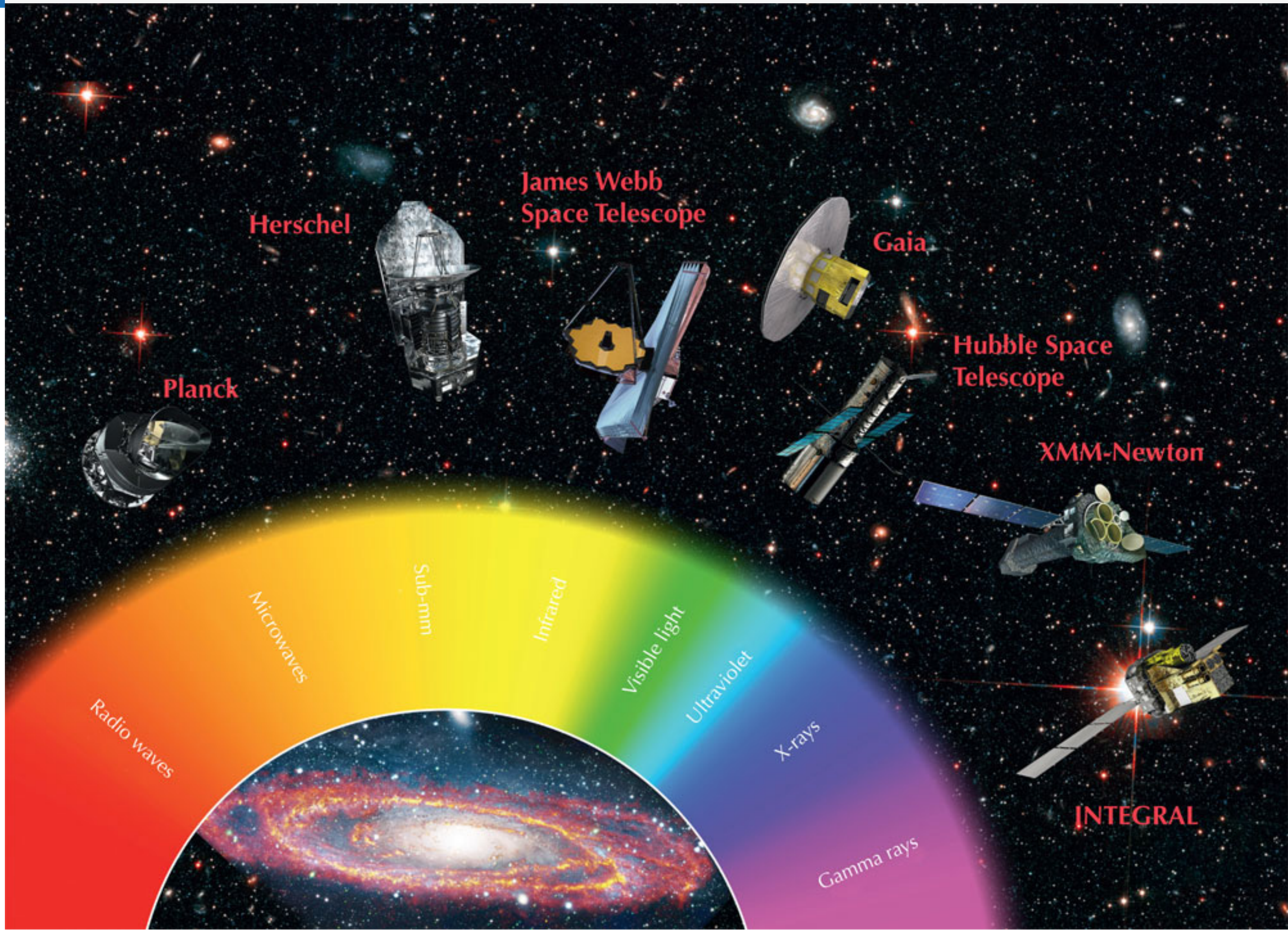
The ELT in perspective



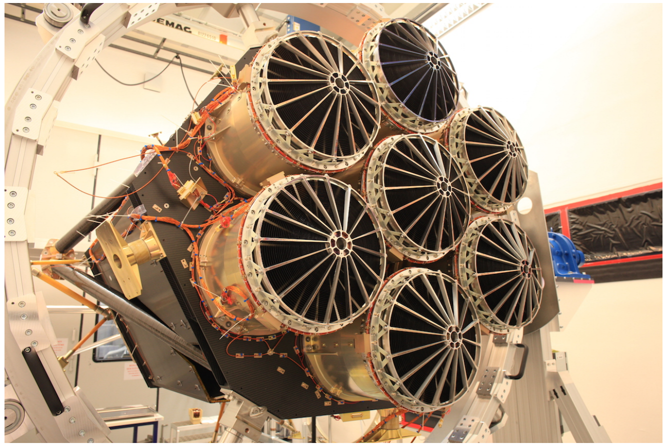
Why do we need an ELT?

- Making real progress in Astronomy requires:
  - Opening up new parameter space: a new wavelength range?

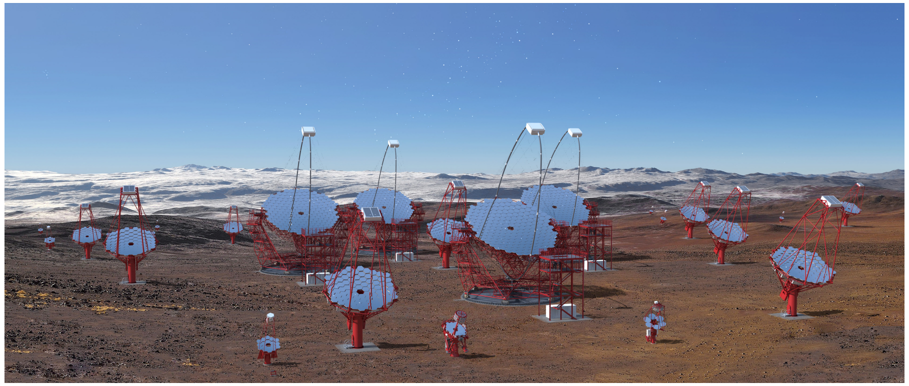
Multi-wavelength coverage



Multi-wavelength coverage

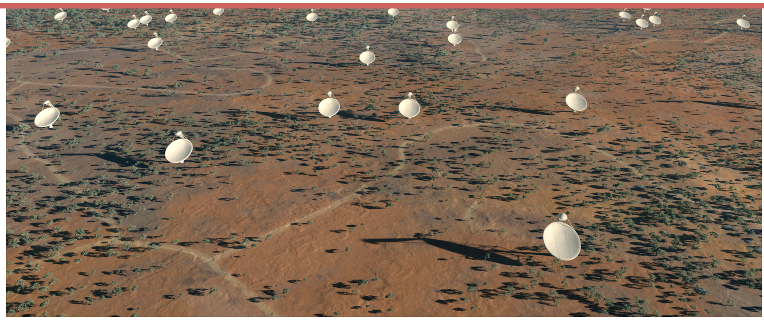


eROSITA (X-ray: 2018)

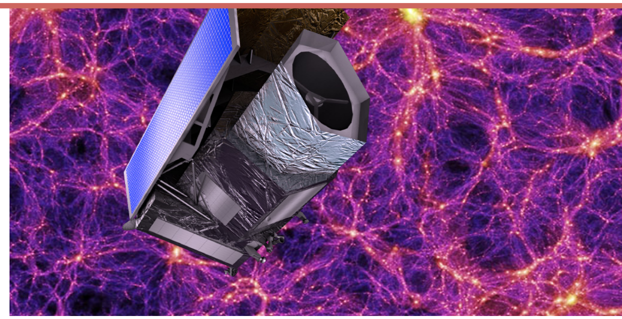


Cherenkov Telescope Array (CTA, γ-ray: 2018+)

A very small selection of future facilities!



Square Kilometre Array
(radio: 2020+)



Euclid (optical/NIR: 2020)

The case for an ELT

- Making real progress in Astronomy requires:
  - Opening up new parameter space: a new wavelength range?
  - Field of view: surveys!
    - Imaging: VISTA, VST, CFHT, UKIRT, PANSTARRS, SDSS, etc.
    - Spectroscopic: MOONS, 4MOST, etc.

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    - Spectroscopic: MOONS, 4MOST, etc.
  - Temporal information: LSST

The transient Universe

- The Large Synoptic Survey Telescope (LSST)
- Science operations to start in 2023
- An 8.4-m telescope to survey the visible sky every 3 nights for 10 years
- Millions of alerts to follow up

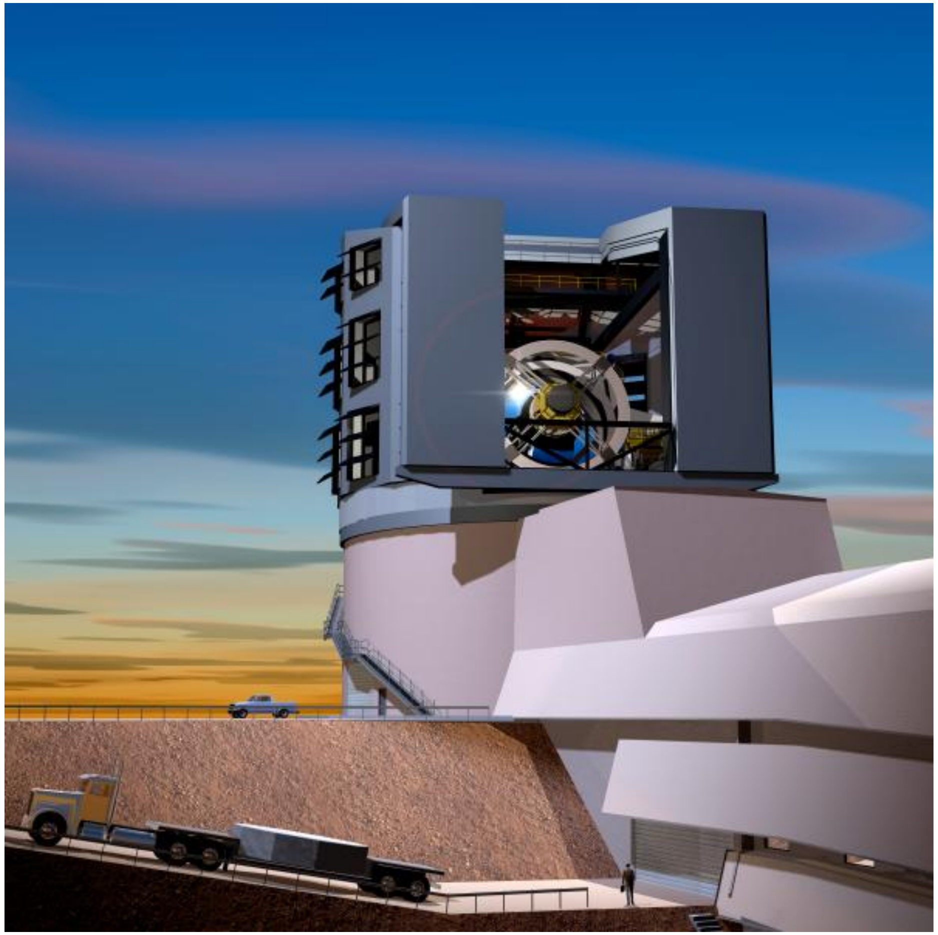

Image credit: LSST

The case for an ELT

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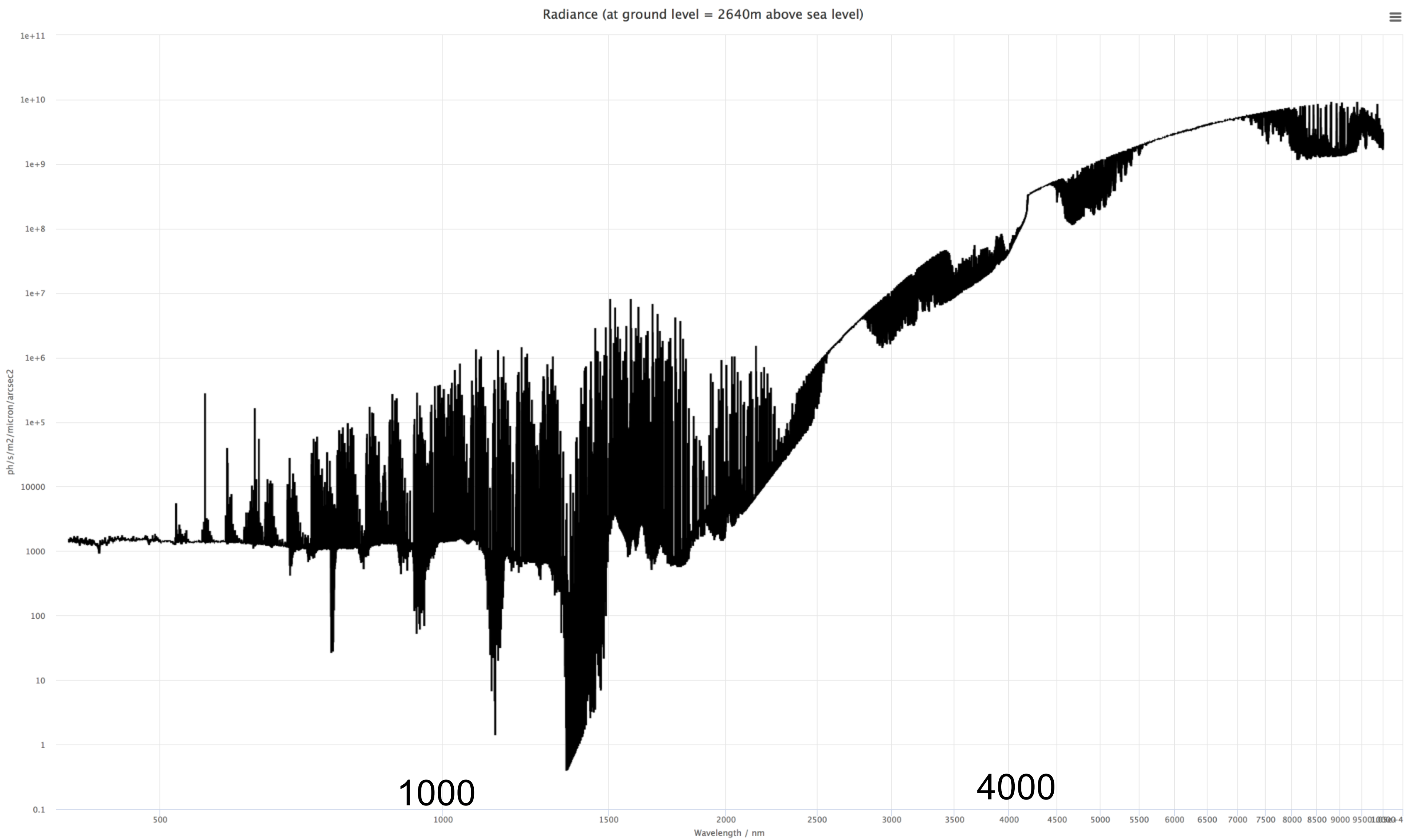
  - Temporal information: LSST
  - Sensitivity

James Webb Space Telescope



The case for an ELT

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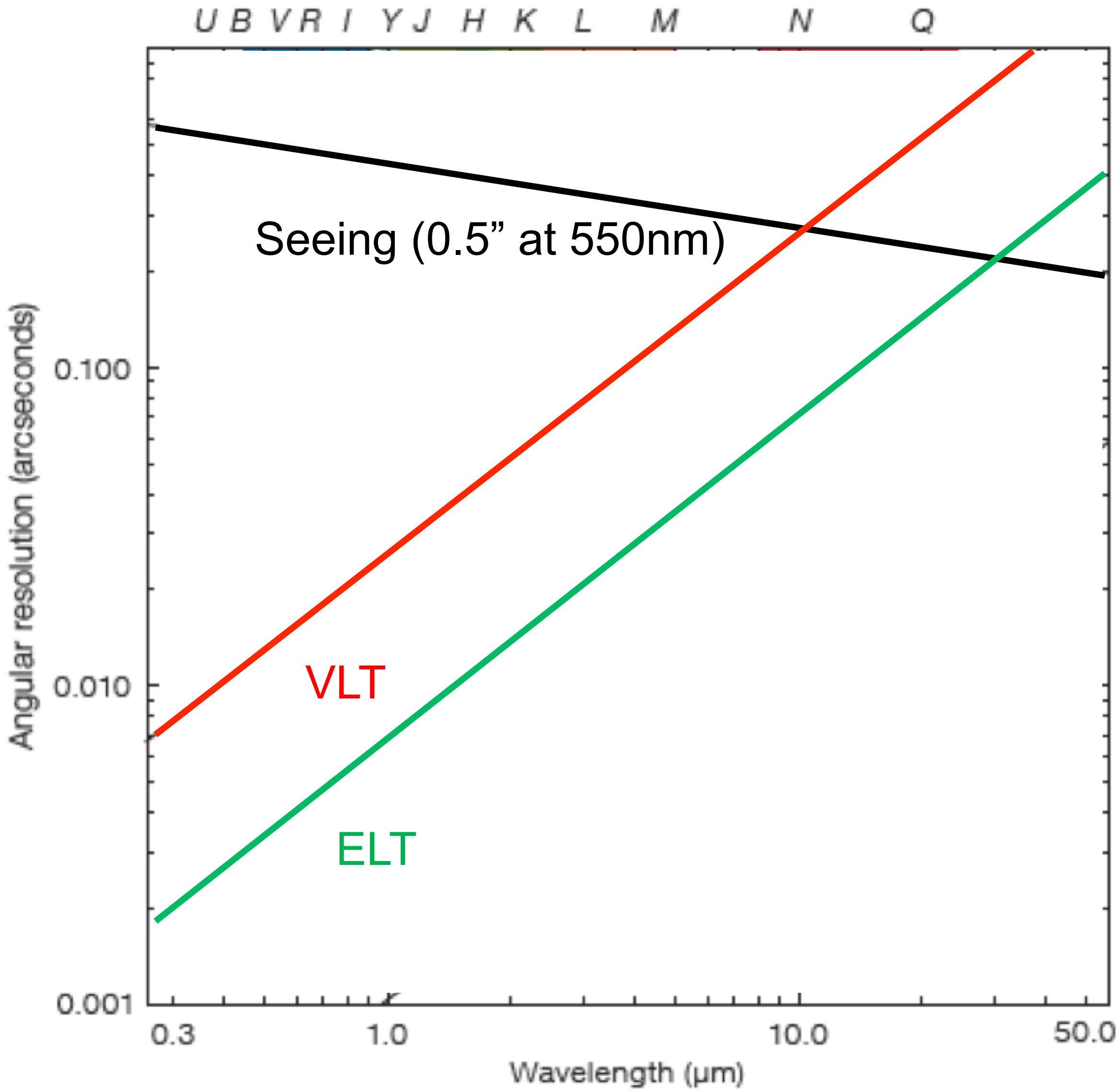
    - Spectroscopic: MOONS, 4MOST, etc.
  - Temporal information: LSST
  - Sensitivity
  - Angular resolution

The ELT in perspective

- ELT collecting area = 978 m^2 → ~ 18 x VLT
- ELT resolution = 0.006” @ 1,000 nm → 4.8 x VLT
- The ELT will be an AO telescope: the atmosphere will be “removed” by default (weather permitting) → will reach its diffraction limit

Resolution and seeing



ELT Discovery Potential

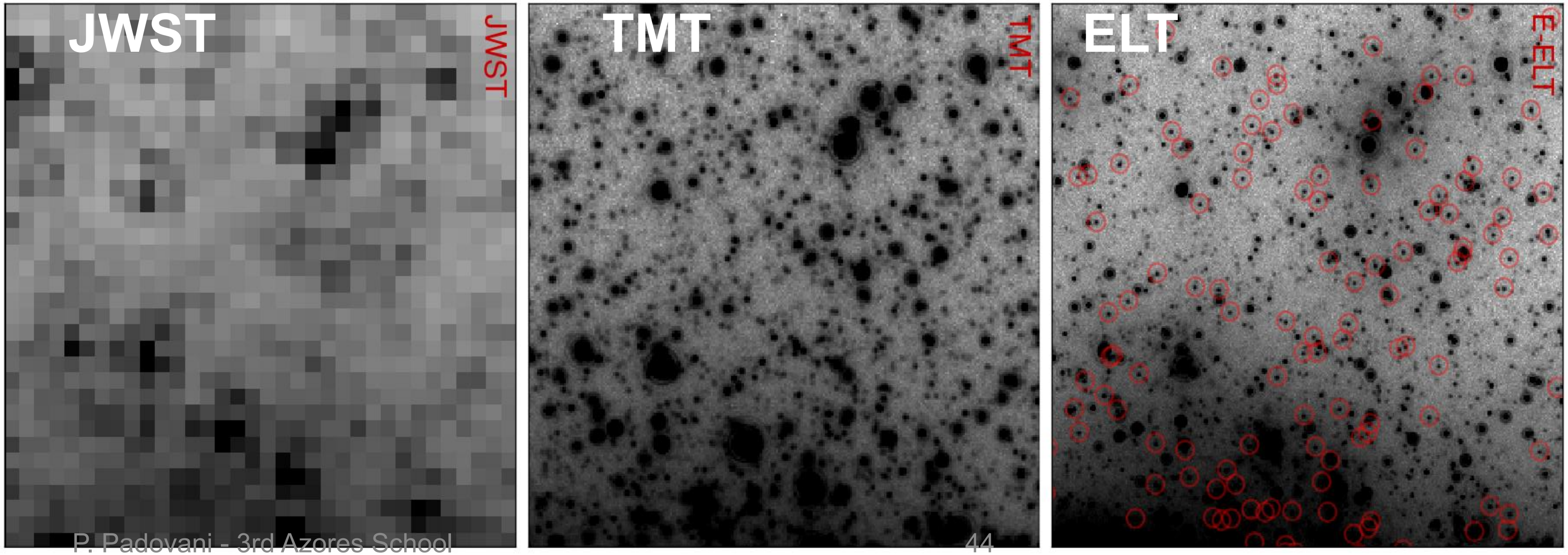
ELT excels in collecting power *and* angular resolution

Compared to existing 8m telescopes, 39m telescope with Adaptive Optics will deliver

5x better angular resolution ($\propto$ D)

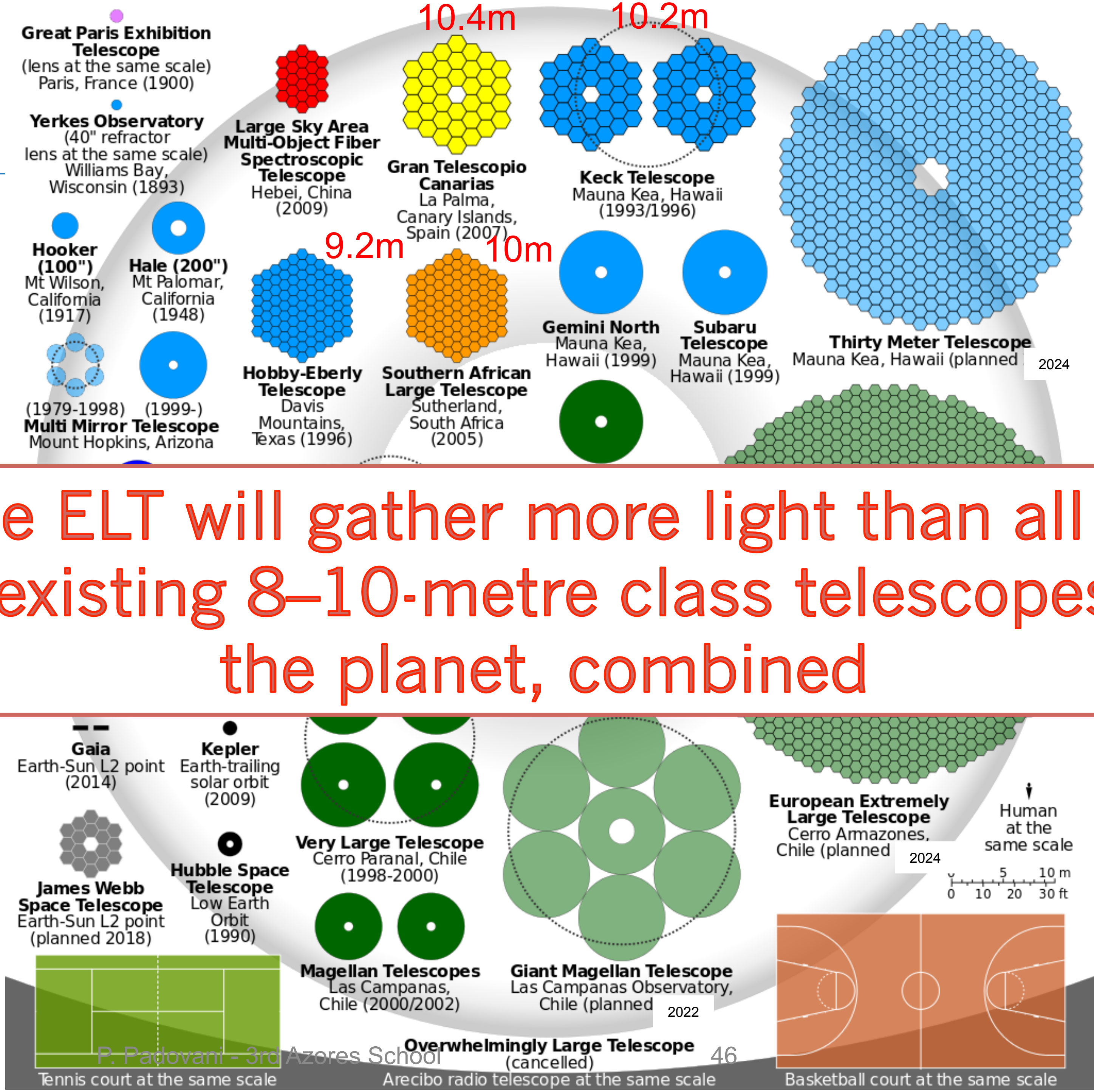
18x better collecting area ($\propto D^2$)

500x faster exposure time [point sources] ($\propto D^4$)



Gullieuszik et al 2014.

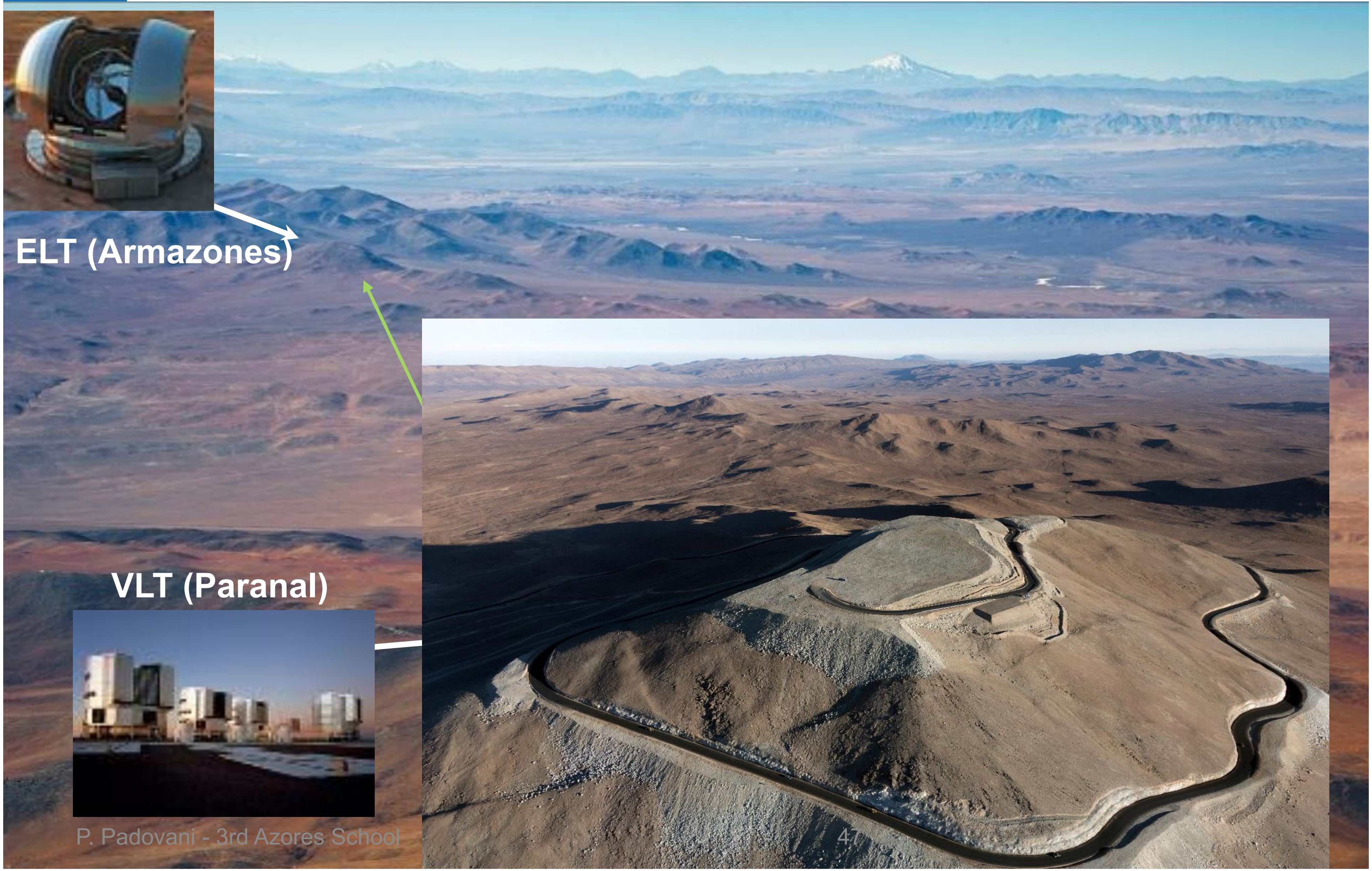
The ELT in perspective



The ELT will gather more light than all of the existing 8–10-metre class telescopes on the planet, combined

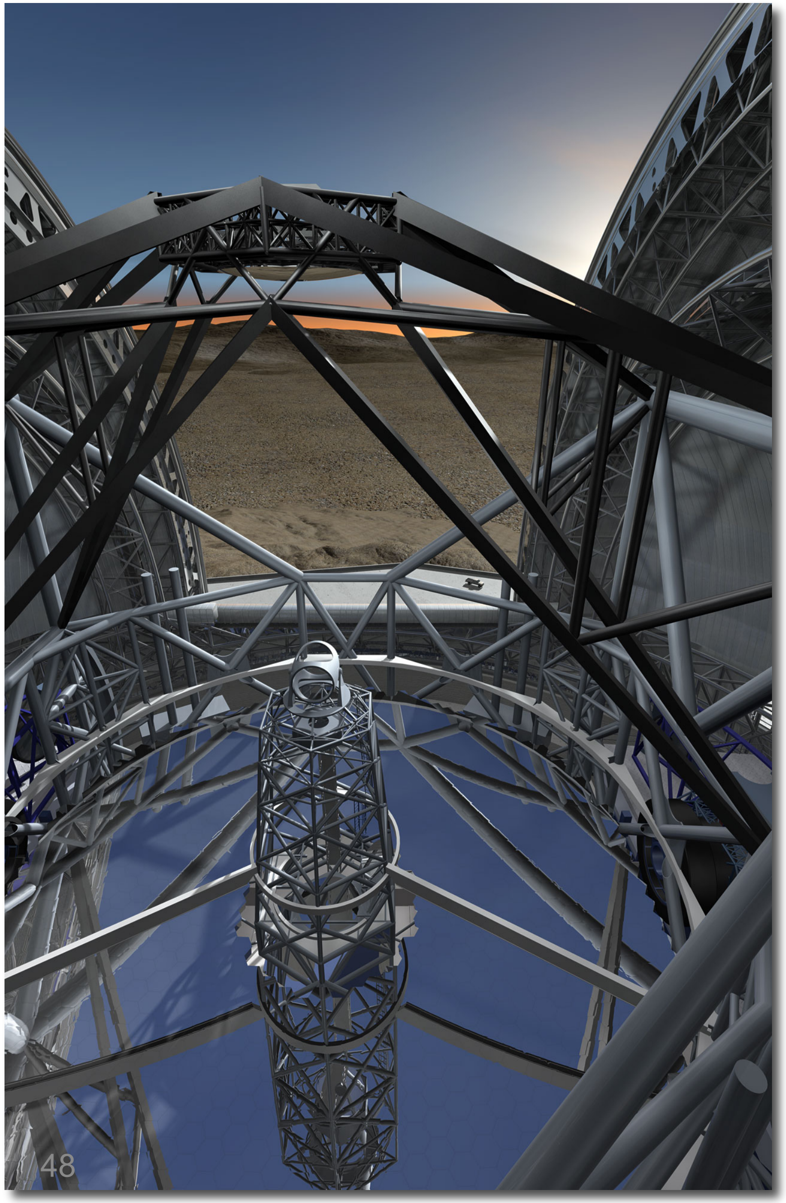
Credit: Wikipedia

Armazones and Paranal



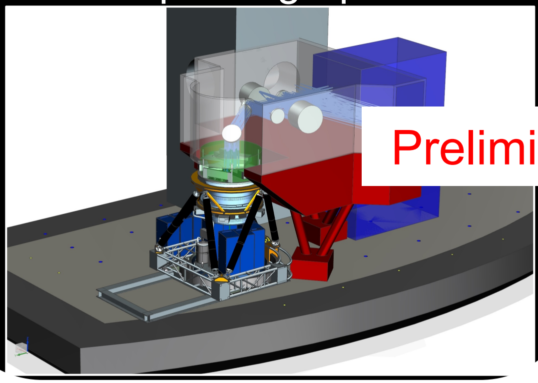
The ELT: recent developments

- Dec 2014: ESO Council gave green light for ELT construction in two phases
  - Funding approved for Phase I (90% of the costs)
  - Still expected that both phases will be completed
  - Comprehensive suit of state-of-the art instrumentation
- May 25 2016: signed the Dome and Main structure contract with the ACe consortium (Italy; *largest contract ever in ground-based astronomy*)
- June 2016: Council approved first light in 2024 (was 2026)
- May 26 2017: first stone ceremony
- Many other major contracts have started (e.g., primary mirror, secondary and tertiary mirrors): ~ 85% of the total amount available already awarded

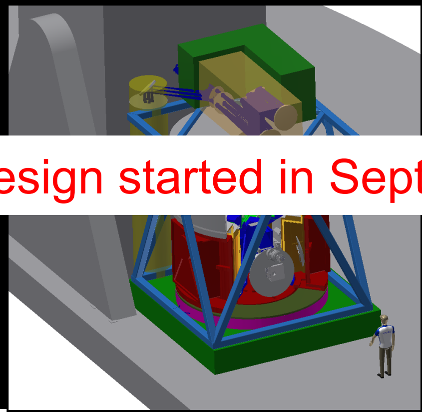


ELT Instrumentation Programme

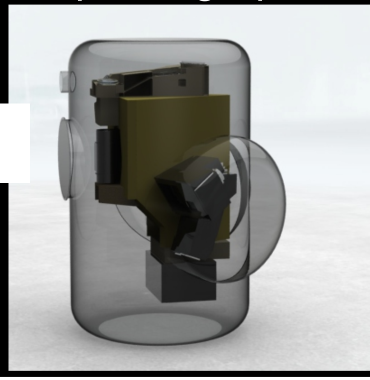
MICADO+MAORY
Imager and single slit spectrograph



HARMONI
Integral Field Spectrograph

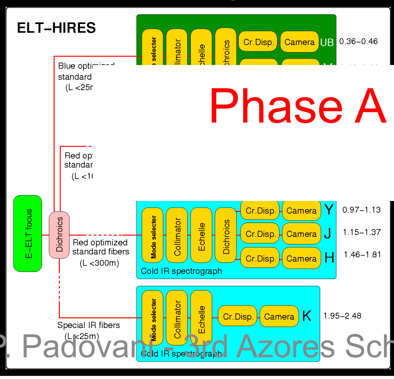


METIS
Mid-IR imager and spectrograph

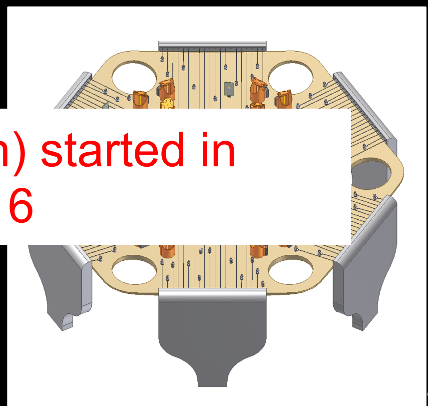


Preliminary design started in September 2015

HIRES
High resolution spectrograph



MOSAIC
Multi-object spectrograph



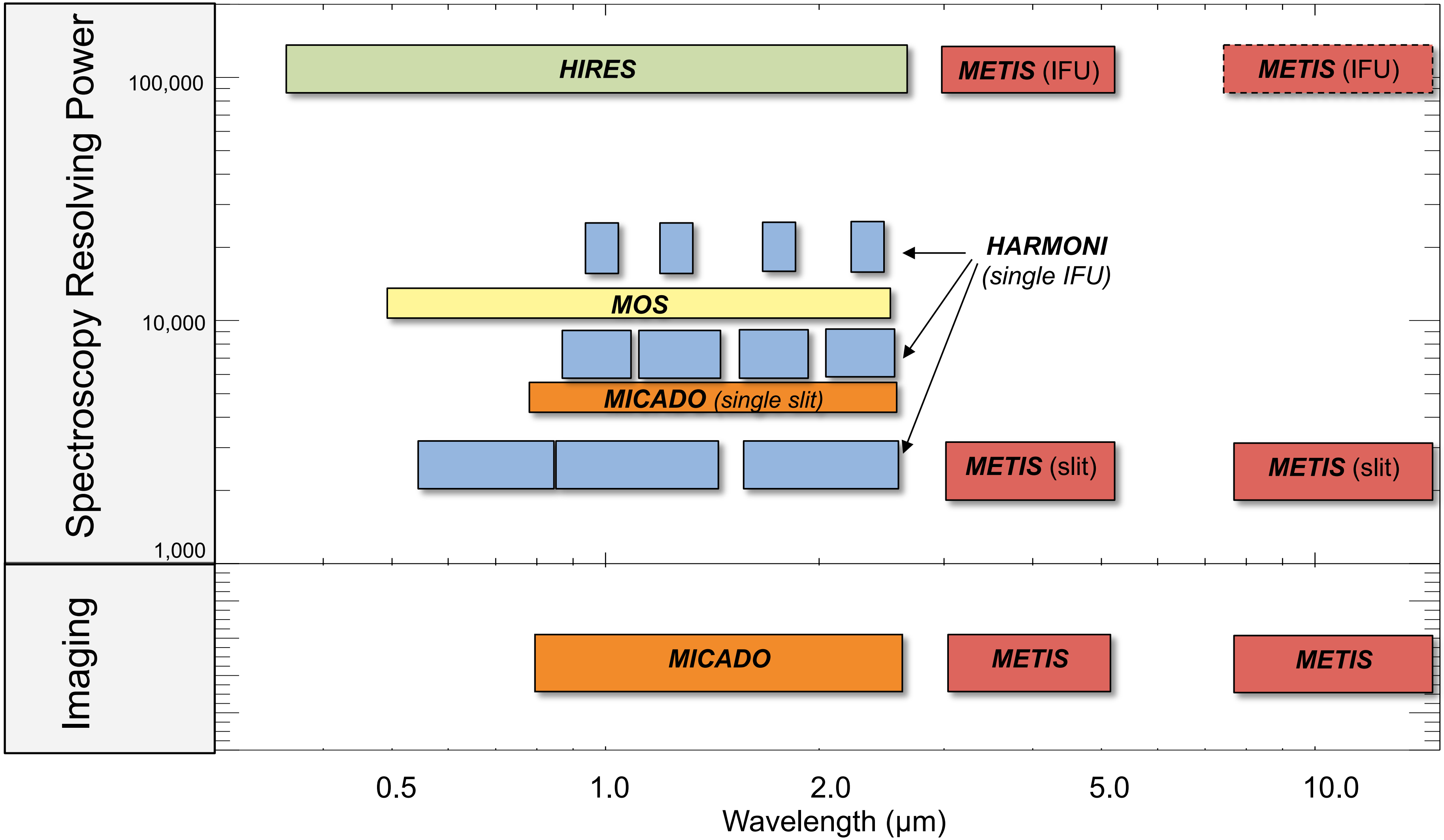
PCS
Extreme AO imager and spectrograph

Phase A (pre-design) started in March 2016

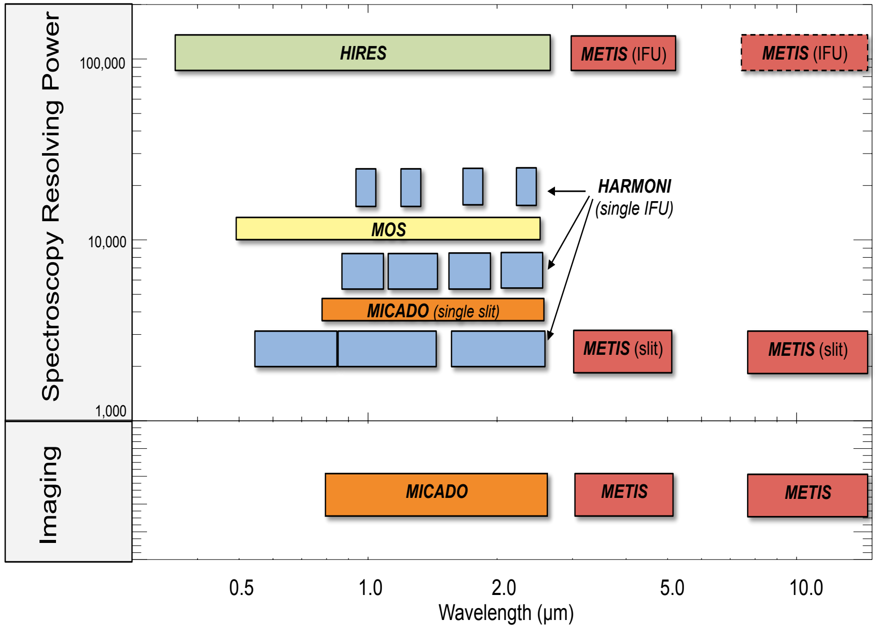
Establishing an instrument suite

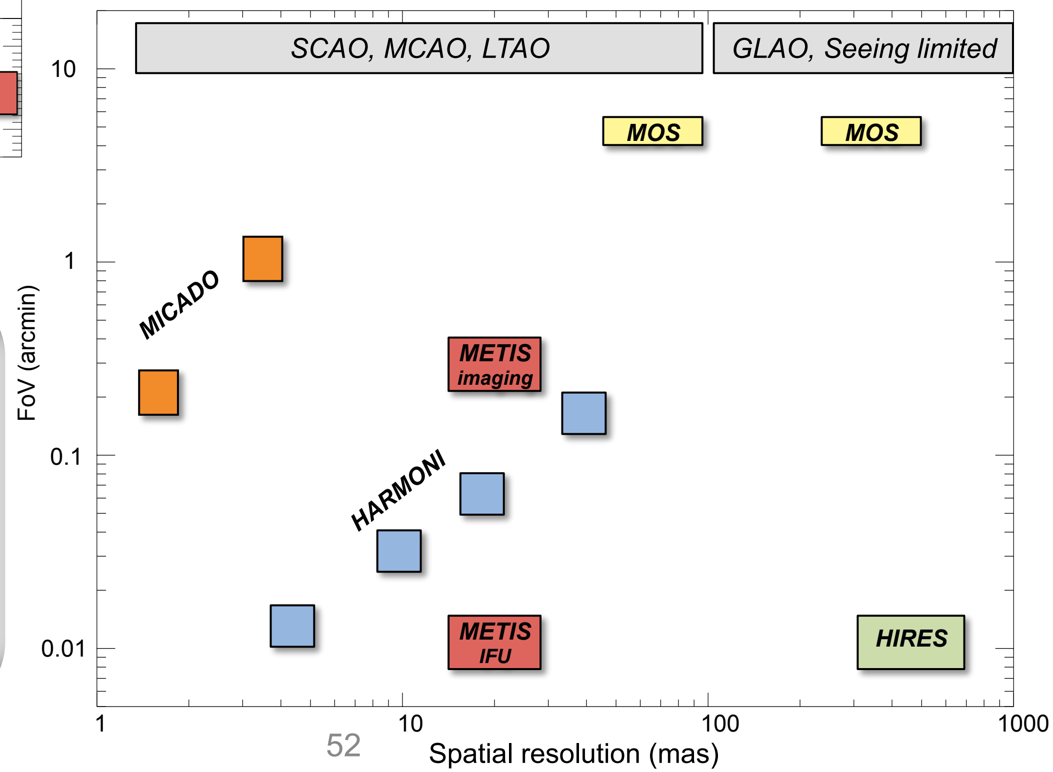
- Top Level (Science) Requirements have been developed for each E-ELT instrument
- Involvement of the community at large through workshops organized by the community and/or ESO, as well as through white papers
- Involvement of the phase A study teams through their science cases and their participation to these workshops
- The ELT Project Science Team collaborates with the ELT Science Office to author the Top Level Requirements
- The ELT Programme Scientist reviews the requirements and presents them to the ESO Scientific Technical Committee (STC) for consultation
- Once the requirements are “blessed” the E-ELT construction project will proceed with a normal instrument procurement
- Changes to the requirements based on technical, managerial or scientific grounds are possible but proceed through the normal change request review process

ELT capabilities



ELT capabilities





- Near-diffraction limit performance
- Multiple plate scales
- 50μas precision astrometry (MICADO)
- High-contrast/Coronograph
- Non-siderial tracking

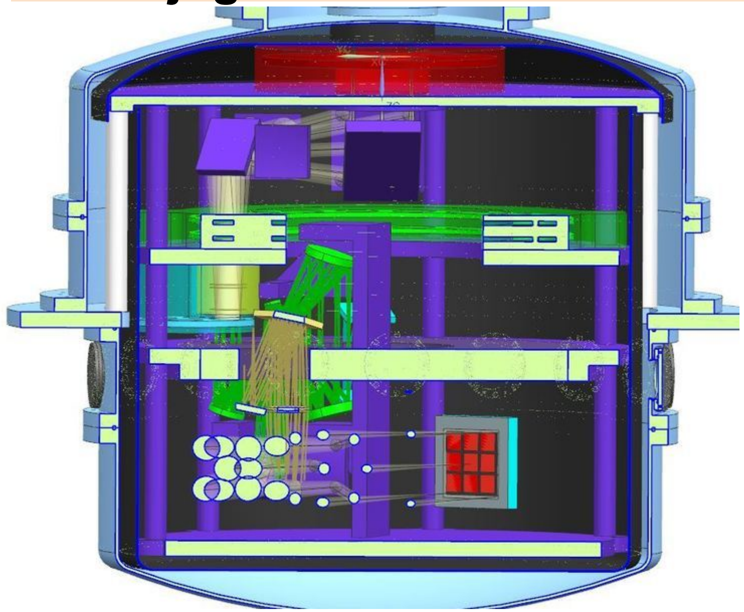
MICADO+MAORY

MICADO
(Multi-Adaptive Optics Imaging Camera for Deep Observations)
PI: R. Davies, MPE, Germany

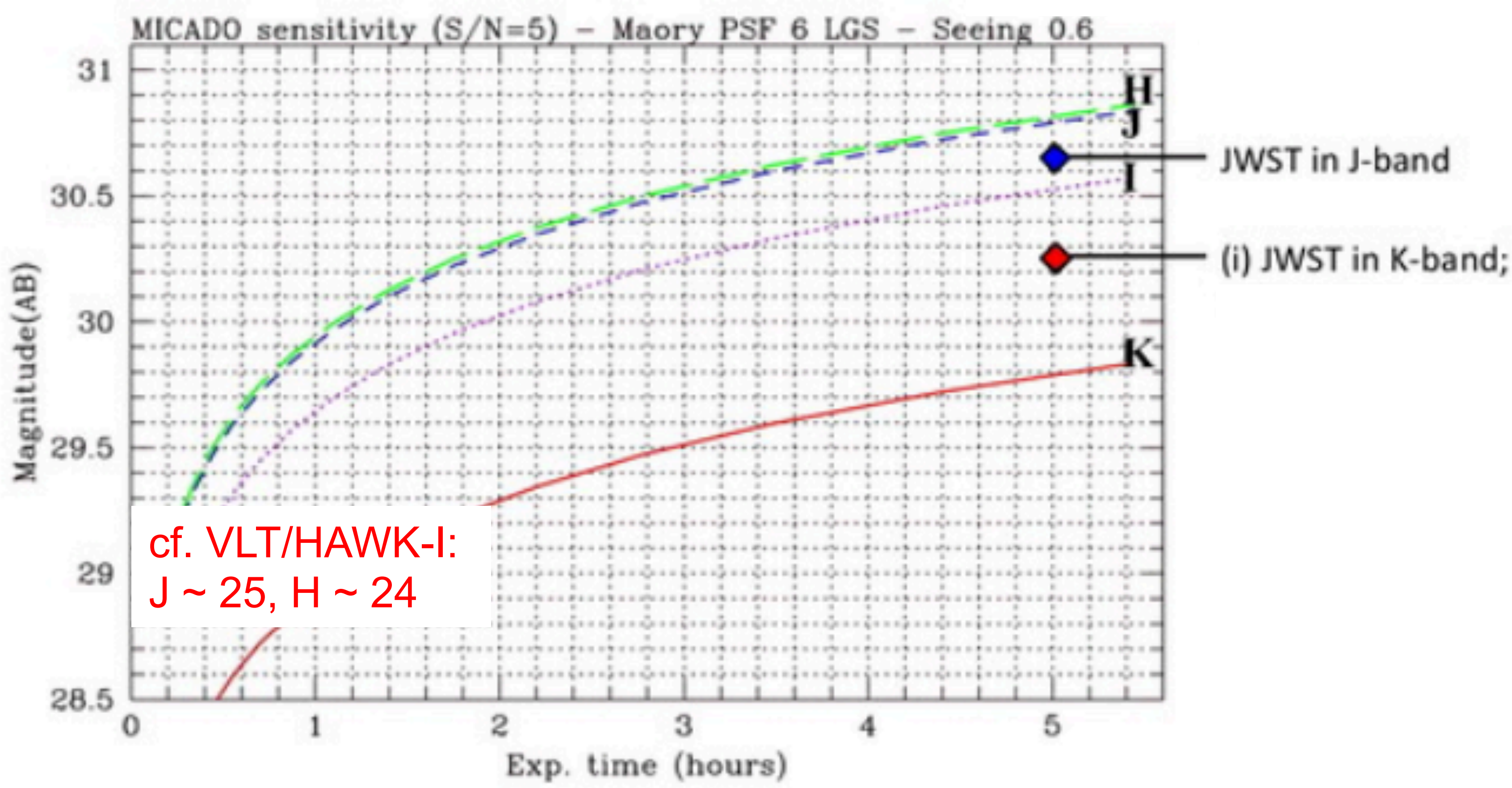
- **Imaging** 0.8-2.4µm, pixel scales of
  - 4mas (FoV ~53")
  - 1.5mas (FoV ~20")
- **Astrometric imaging** with 50µas precision
- **Spectroscopy for single slit** R~8000.
- **Coronagraphic** imaging
- Time Resolved Astronomy (goal)

MAORY
(Multi-conjugate Adaptive Optics RelaY)
PI: E. Diolaiti, INAF, Italy

- **Single Conjugate Adaptive Optics (SCAO) and Multi-conjugate AO**



MICADO+MAORY



Broadband imaging sensitivity of MICADO as a function of integration time

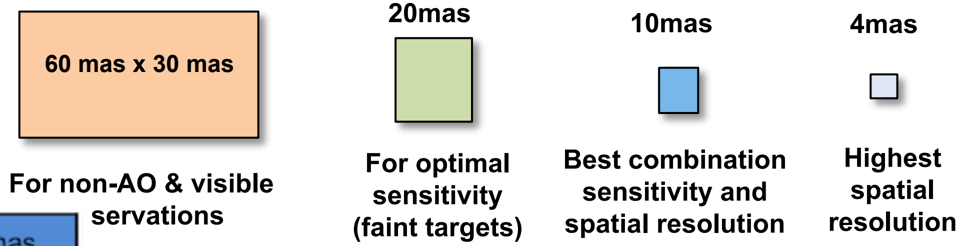
HARMONI

HARMONI
(High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph)
PI: N. Thatte, University of Oxford, UK

- **3D spectrograph** (Integral Field Unit)
- Covering **optical** (0.47 µm) to **near-IR** (2.45 µm)
- From **seeing limited** down to the **diffraction limit** with SCAO and Laser Tomography Adaptive Optics (LTAO)
- Range of **resolving powers** from R=3500 to 20000
- Range of **spatial scales** with field of views from 9”x6” to 0.8”x0.6”

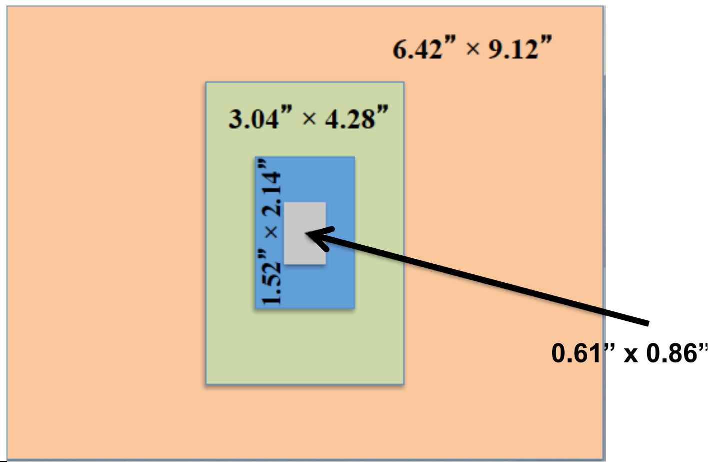
HARMONI

Diffraction-limited, single field NIR IFU



Spectral	4 mas		10 mas		20 mas		30x60 mas	
Resolution	R_{AB}	H_{AB}	R_{AB}	H_{AB}	R_{AB}	H_{AB}	R_{AB}	H_{AB}
	Point source (AB mag)							
500		27.42		[illegible]		[illegible]		26.02
3500	22.93	26.64	[illegible]	[illegible]	[illegible]	[illegible]	25.64	26.98
7500		25.82	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	26.43
20000		24.76		25.63		25.87		25.63

cf. VLT/SINFONI:
H ~ 20 (100 mas)



S/N=5, point sources, 0.7"seeing, LTAO

Large wavelength range & resolution combinations:

Bands	Wavelengths (µm)	R
"V+R" or "I+z+J" or "H+K"	0.45-0.8, 0.8-1.35, 1.45-2.45	~3000
"I+z" or "J" or "H" or "K"	0.8-1.0, 1.1-1.35, 1.45-1.85, 1.95-2.45	~7500
"Z" or "J_high" or "H_high" or "K_high"	0.9, 1.2, 1.65, 2.2 (TBD)	~20000

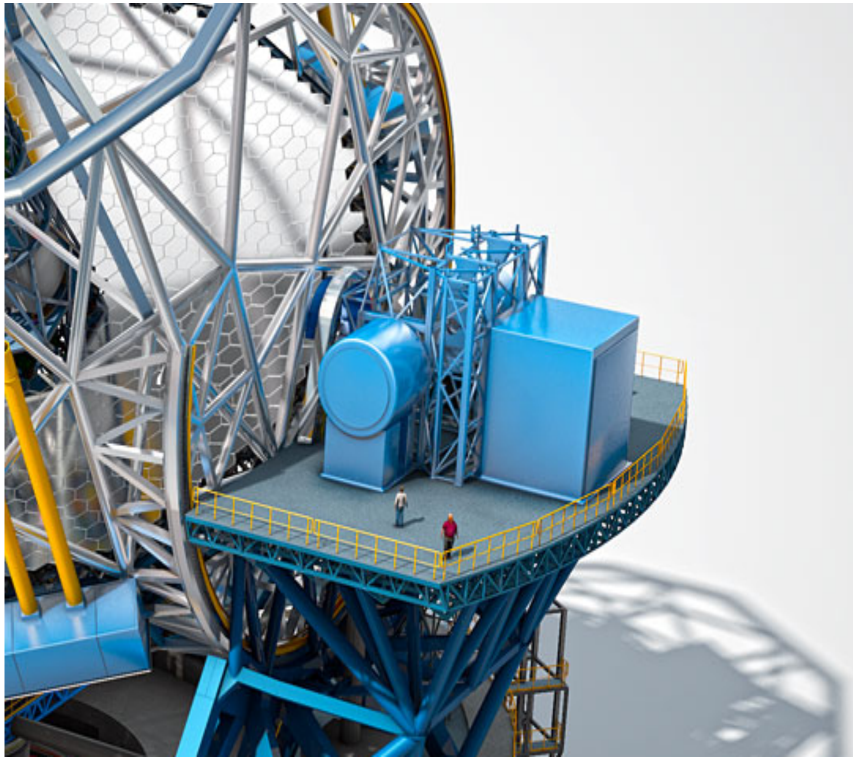
METIS

METIS
(Mid-infrared ELT Imager and Spectrograph)
PI: B. Brandl, NOVA, Leiden, The Netherlands

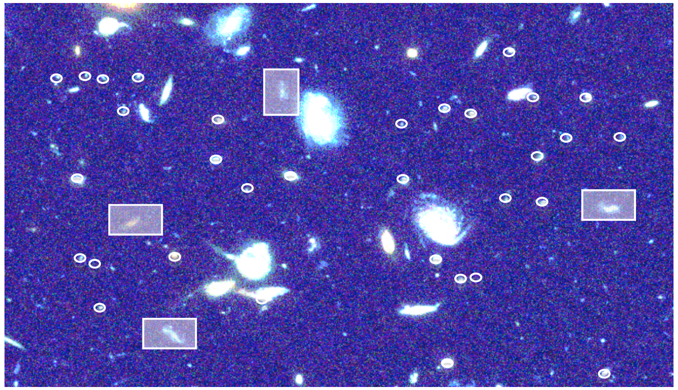
- **Imaging at L, M, N, Q**-bands (~ 3 – 20 μm)
- **Coronagraphy for high contrast imaging** at L, M and N-band
  (goal: coronagraphy for IFU spectroscopy)
- Low/medium resolution **slit spectroscopy** at L, M, and N-band
- **High resolution R~100,000 IFU spectroscopy** at L and M band
  (goal: high resolution IFU spectroscopy at N band)

Second generation instruments

Selected in 2015
Phase A started in March 2016



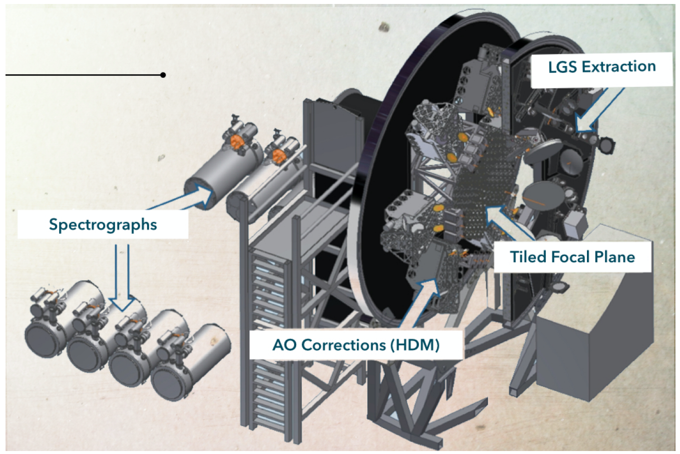
ELT-MOSAIC



Multi-object spectrograph (MOSAIC)

PI: Francois Hammer (GEPI, France)

- Wavelength range: **0.4 – 2.45 µm**
- **High definition** (HDM, 80 mas/pix) with **≥10 MOAO IFUs**
- **High multiplex (HMM, 100-250**), GLAO/seeing resolution
- R=5000-20,000

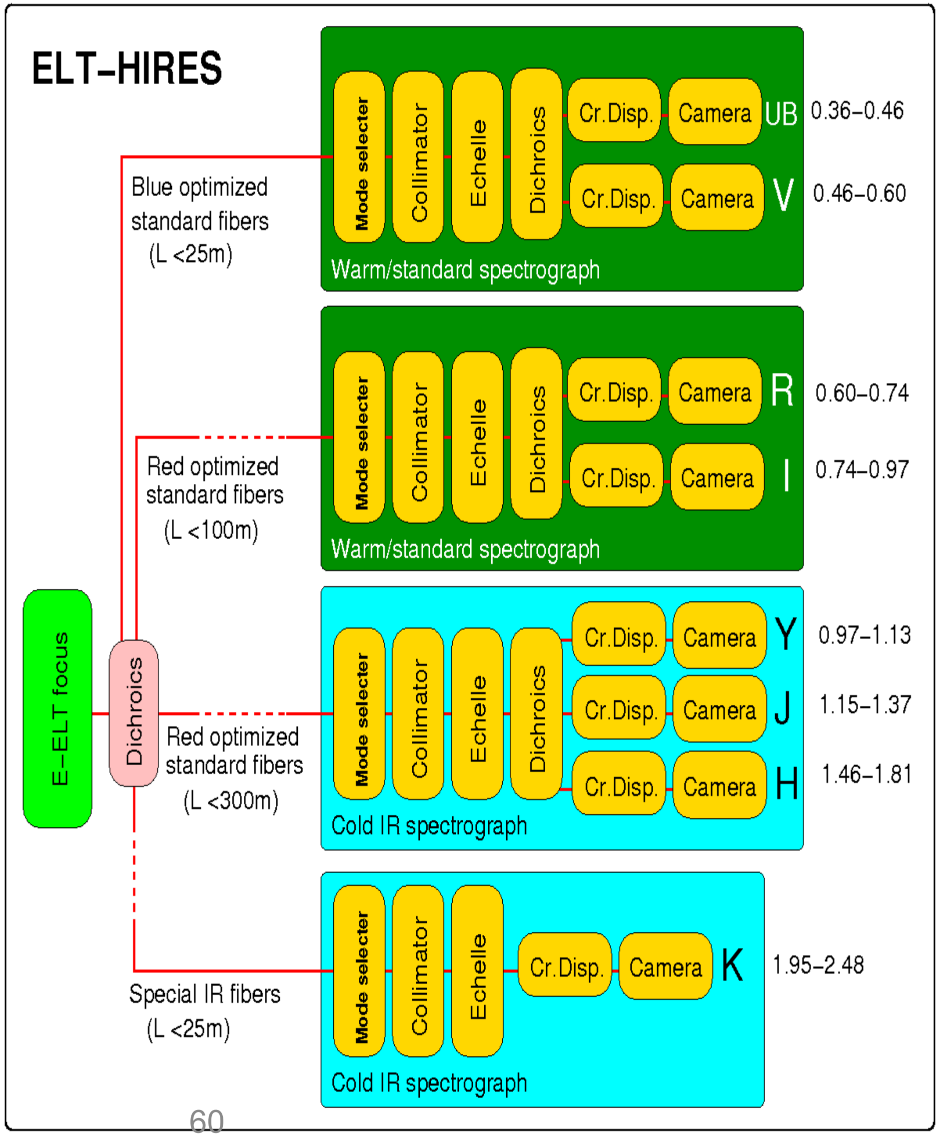


ELT-HIRES

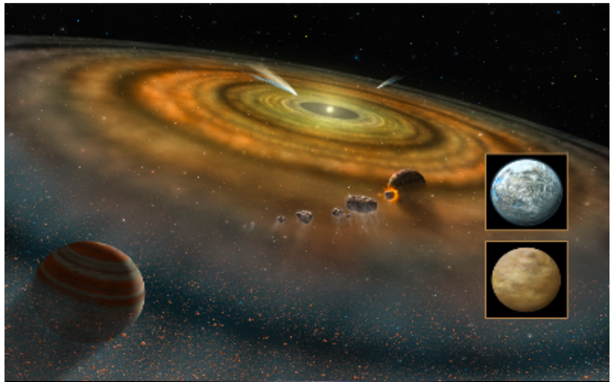
High-resolution spectrograph

PI: Alessandro Marconi (INAF, Italy)

- Spectral resolution: **R > 100,000**
- Wavelength range: **0.37 – 2.4 µm**
- Accuracy: <10cm/s



Pioneering science

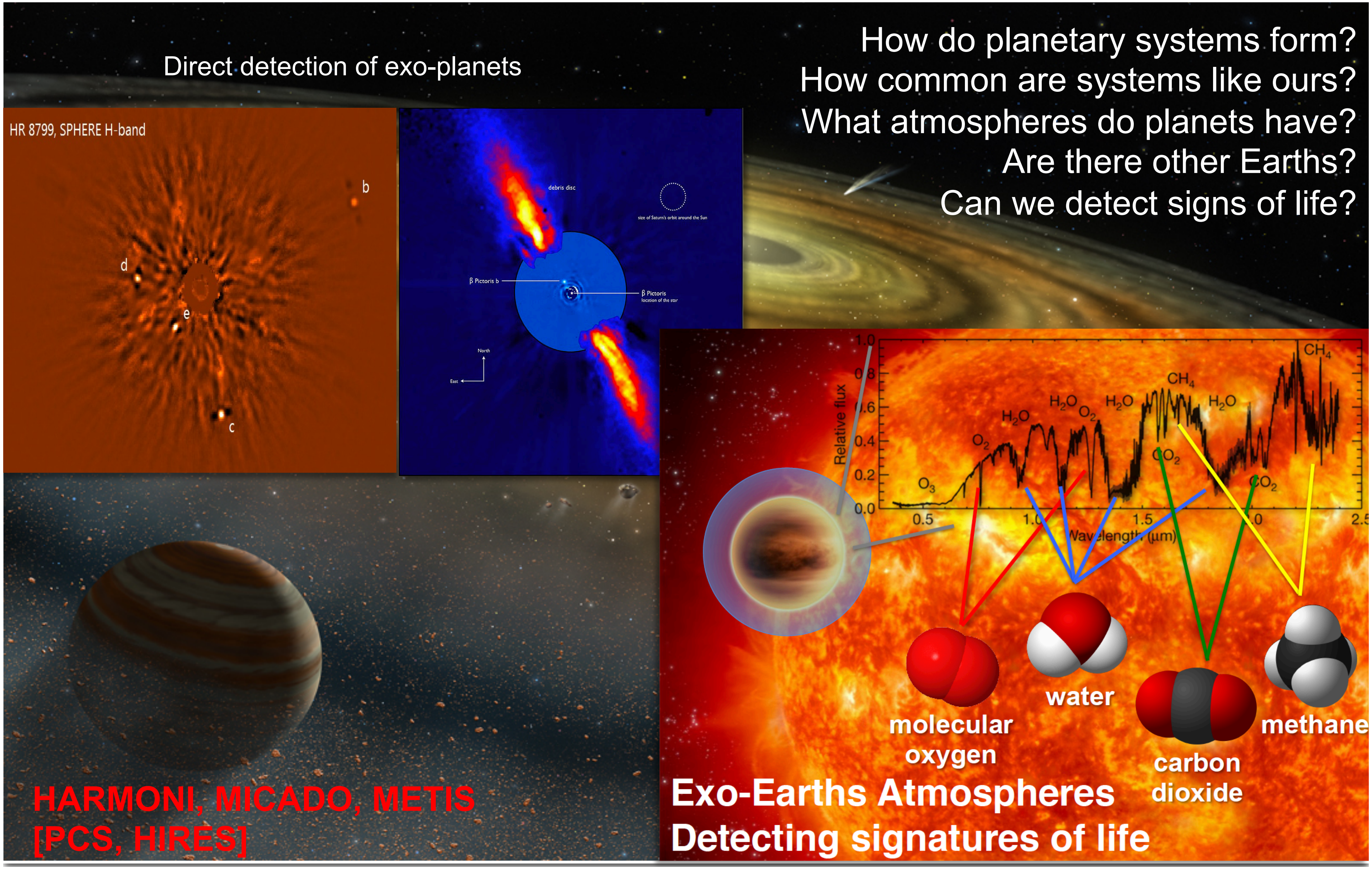


Planets & Stars

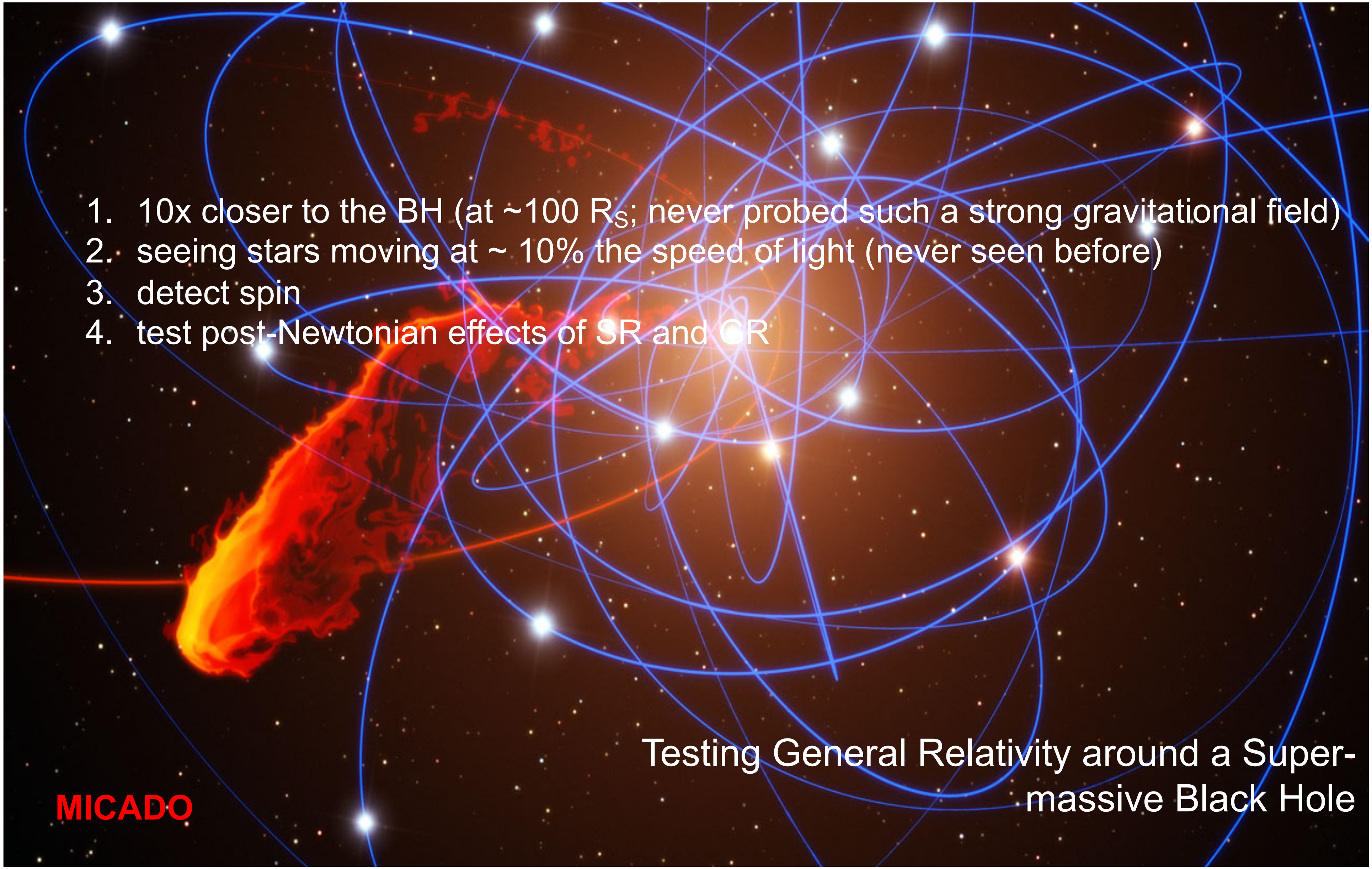
Stars & Galaxies

Galaxies & Cosmology

Exo-planets and proto-planetary disks



The Galactic centre



1. 10x closer to the BH (at ~100 R_S; never probed such a strong gravitational field)
2. seeing stars moving at ~ 10% the speed of light (never seen before)
3. detect spin
4. test post-Newtonian effects of SR and GR

Testing General Relativity around a Super-massive Black Hole

MICADO

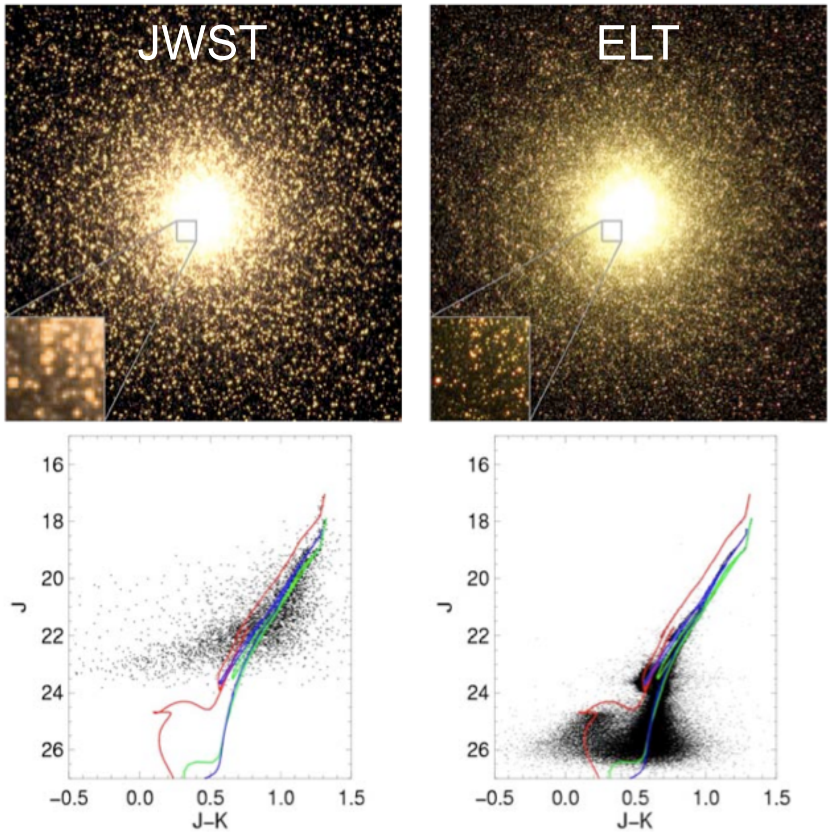
Black Holes

- Intermediate Mass BHs in Galactic Clusters
- MW-type BHs (10^6 M_o) out to Virgo
- M87-type BHs (10^9 M_o) out to z ~ 0.2

HARMONI, MICADO

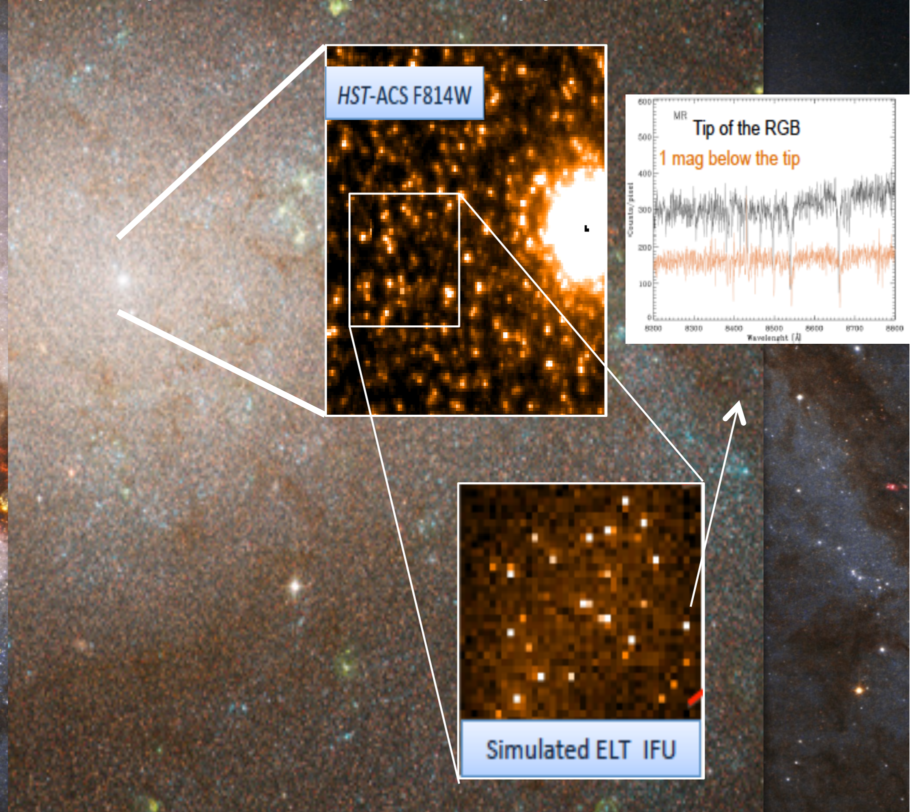
Resolved stellar population

Colour-magnitude diagrams



Simulated observations of M32

Spatially resolved spectroscopy of NGC 205

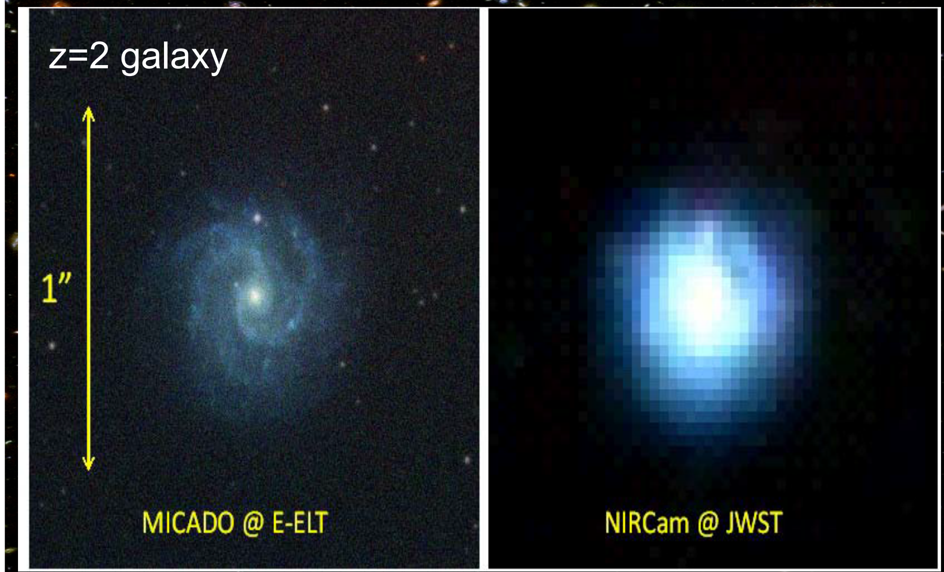


HARMONI, MICADO [MOS, HIRES]

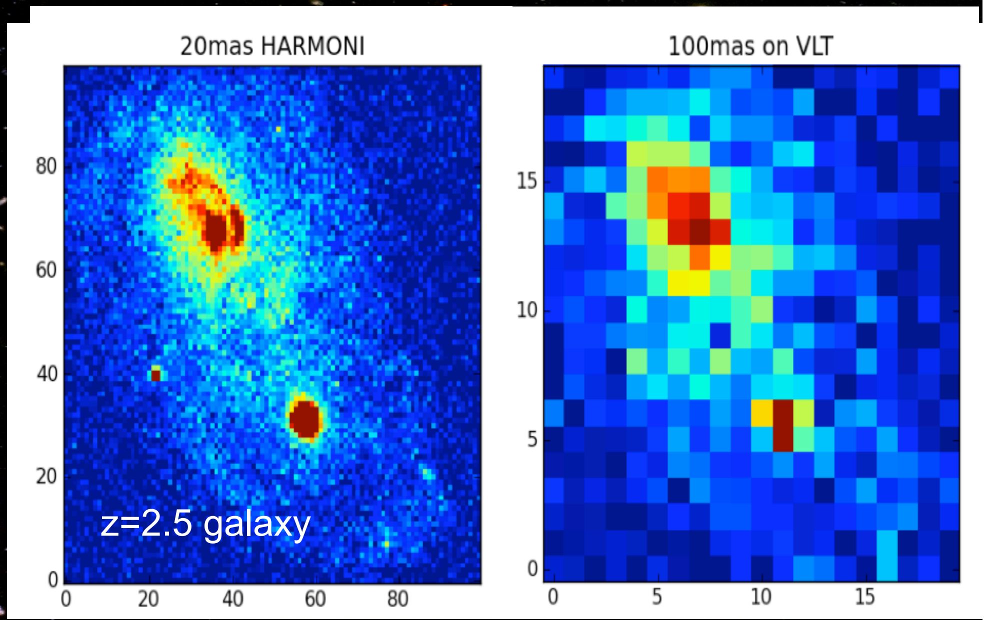
What is the evolution and merger history the Milky Way?

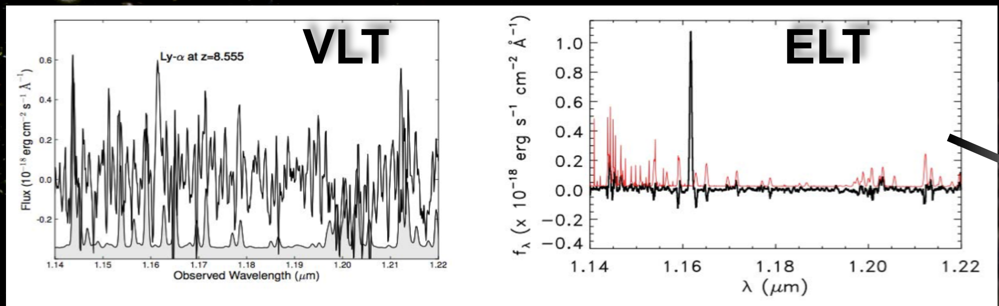
High redshift Universe

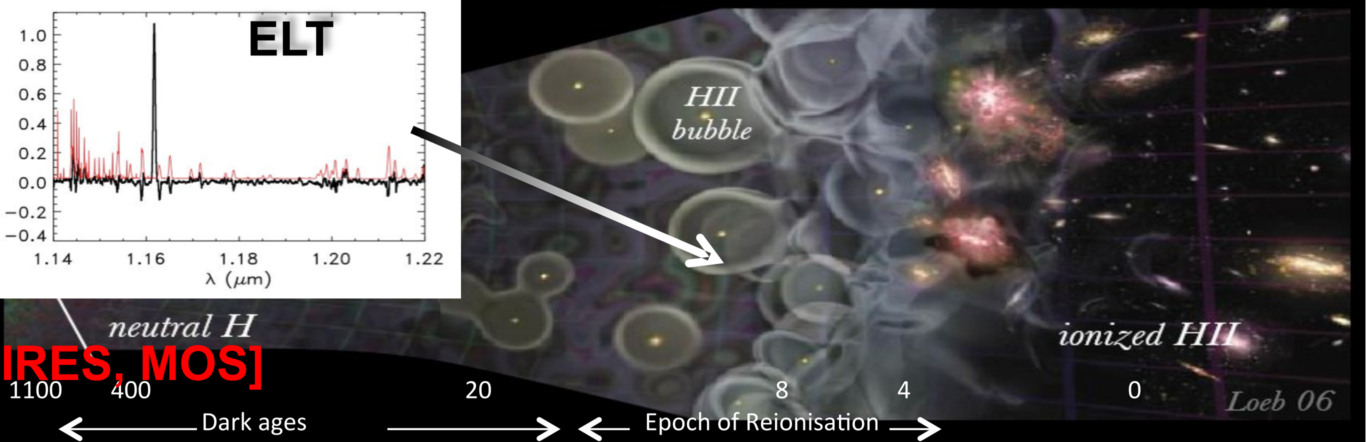
Structure and morphology of galaxies



Dynamics and physics from spatially resolved spectroscopy



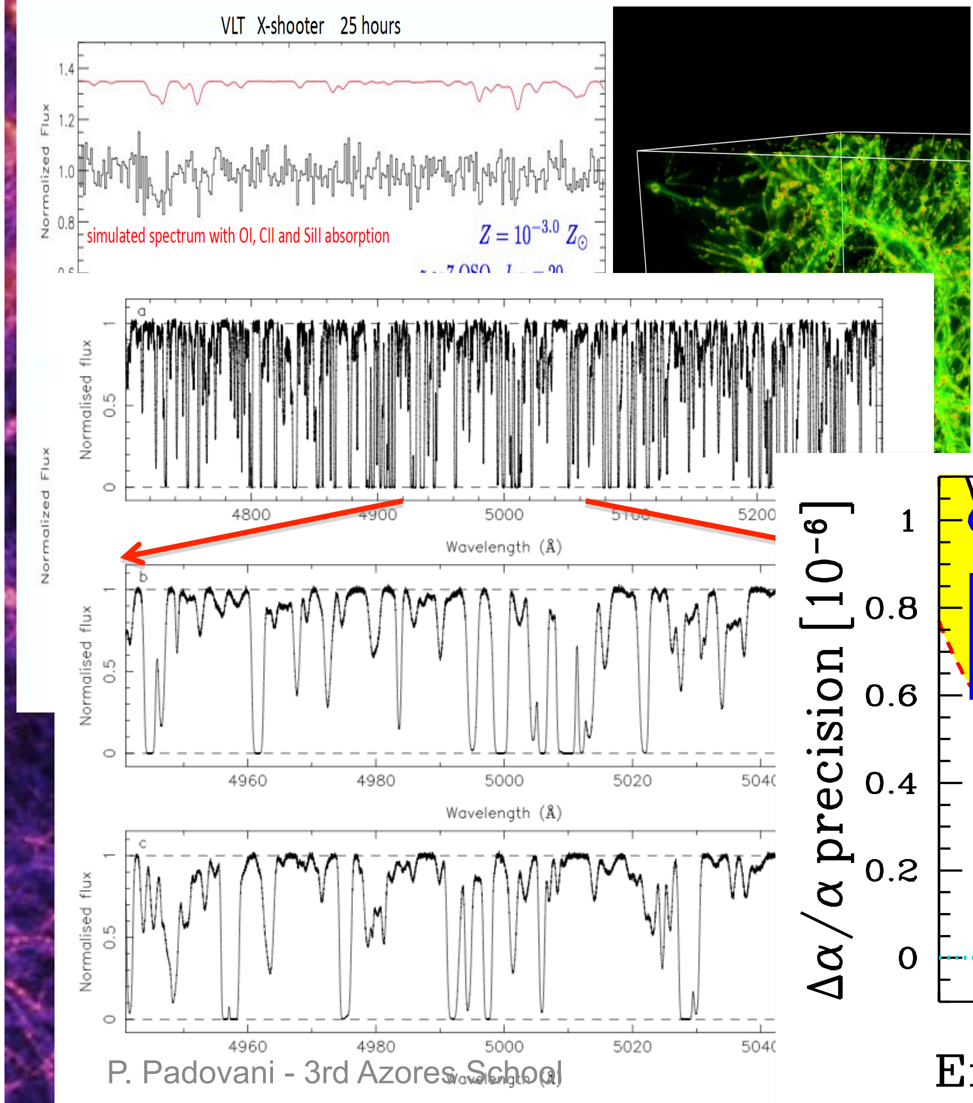


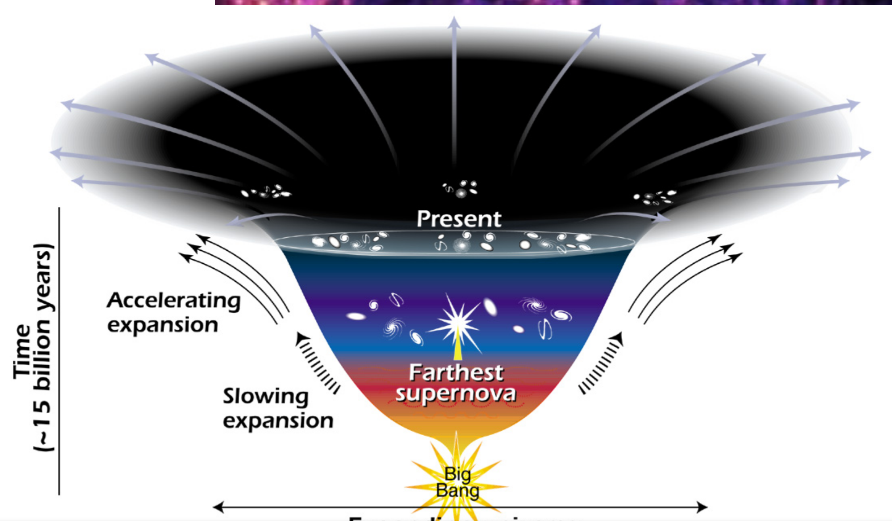


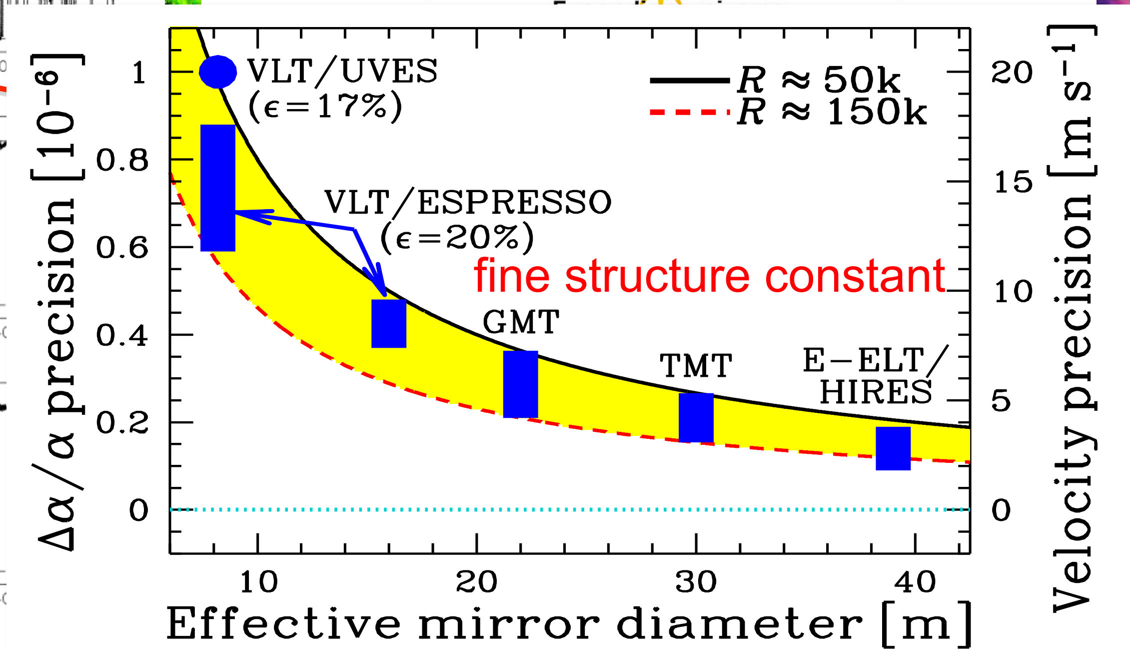
HARMONI, MICADO [HIRES, MOS]

Cosmology and Fundamental Physics

Chemical enrichment of the IGM





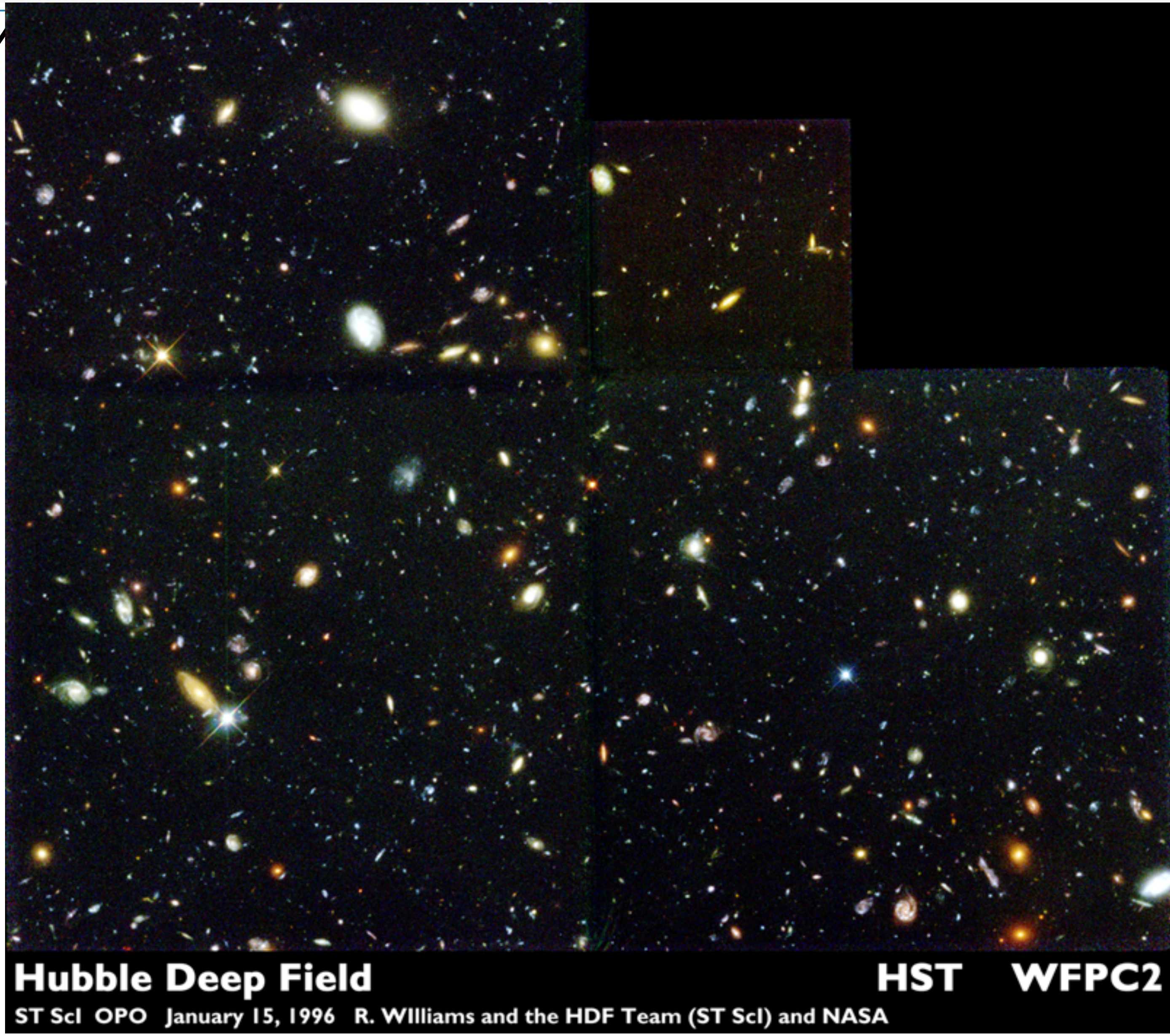


So do we already know what the ELT (and other facilities) will discover?

- Yes and no!
  - We need to plan ahead and build our instruments based on "real" science cases
  - But we cannot predict what the astronomical landscape is going to be in 10 years or so
    - HST was launched in 1990; one of its major goals was to measure the Hubble constant (H_0)
    - In 1999 the HST Key Project Team announced that H_0 was 72 km/sec/Mpc
    - In December 1995 HST looked at one spot of the sky for about 10 days: the era of "deep fields" was born

So do we already know what the ELT (and other facilities) will discover?

- Y



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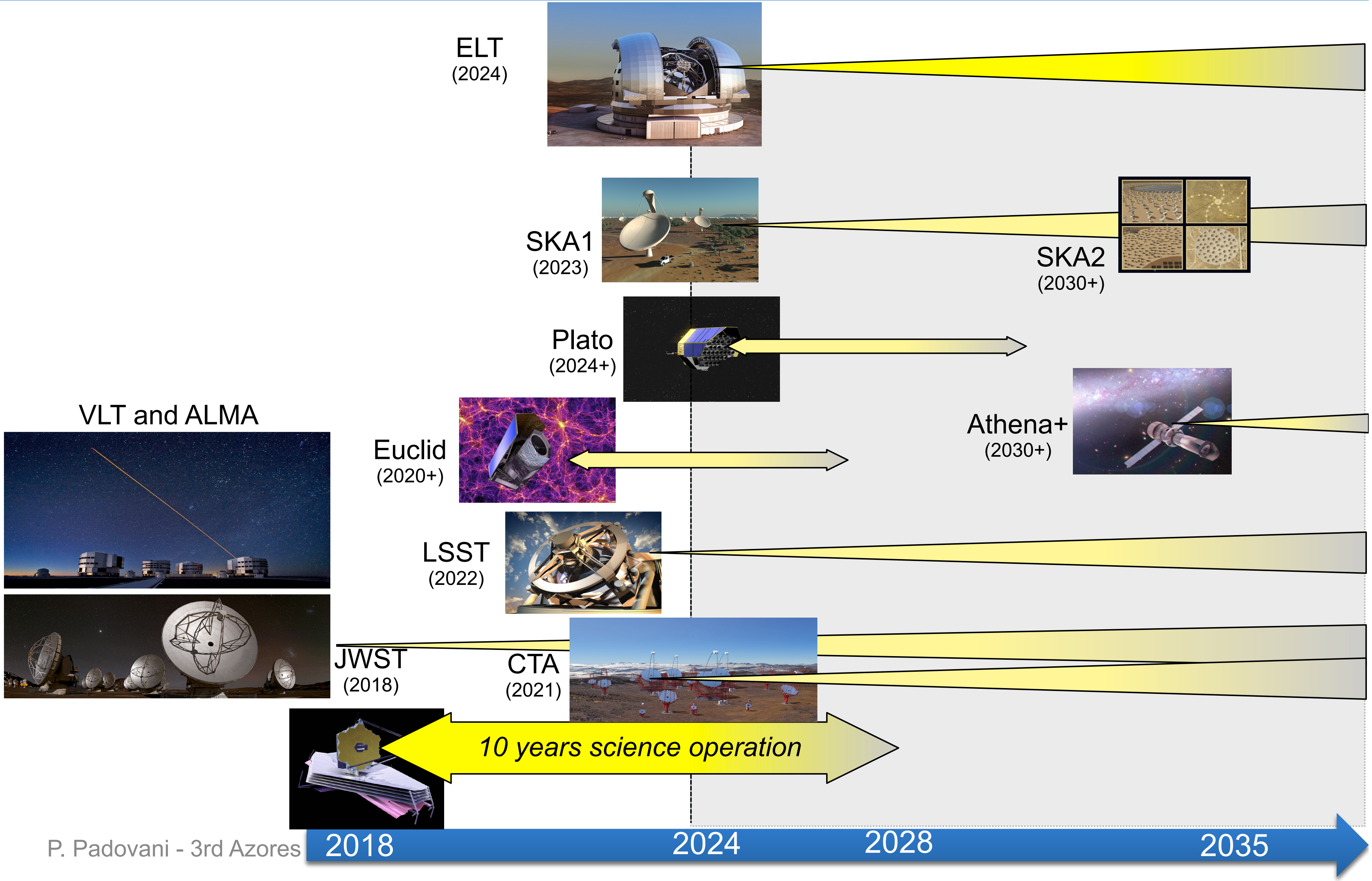
So do we already know what the ELT (and other facilities) will discover?

- The ESO 3.6m telescope was commissioned in 1977
- The first extra-solar planet was discovered in 1995
- HARPS @3.6m was commissioned in 2003; since then it has discovered hundreds of exo-planets and revolutionised the field!
  - Nobody even dreamt about exo-planets in 1977!!!!
- The ELT (and other future facilities) is going to make amazing discoveries thanks to the instruments we are planning for now; but we don't have the faintest idea what many of them are going to be

Astronomical synergies



Summary

The E-ELT will be the largest optical/near-IR telescope excelling in **collecting power** and **angular resolution**

- Good momentum across the ELT Programme
- Preliminary Designs of instruments progressing well
- Exciting scientific capabilities
- Planned first light in 2024
- CTA, MOONS and 4MOST will also add to the (already large) ESO suit of facilities