THE FUTURE OF GROUND-BASED EXTRAGALACTIC MID-IR ASTRONOMY – OR

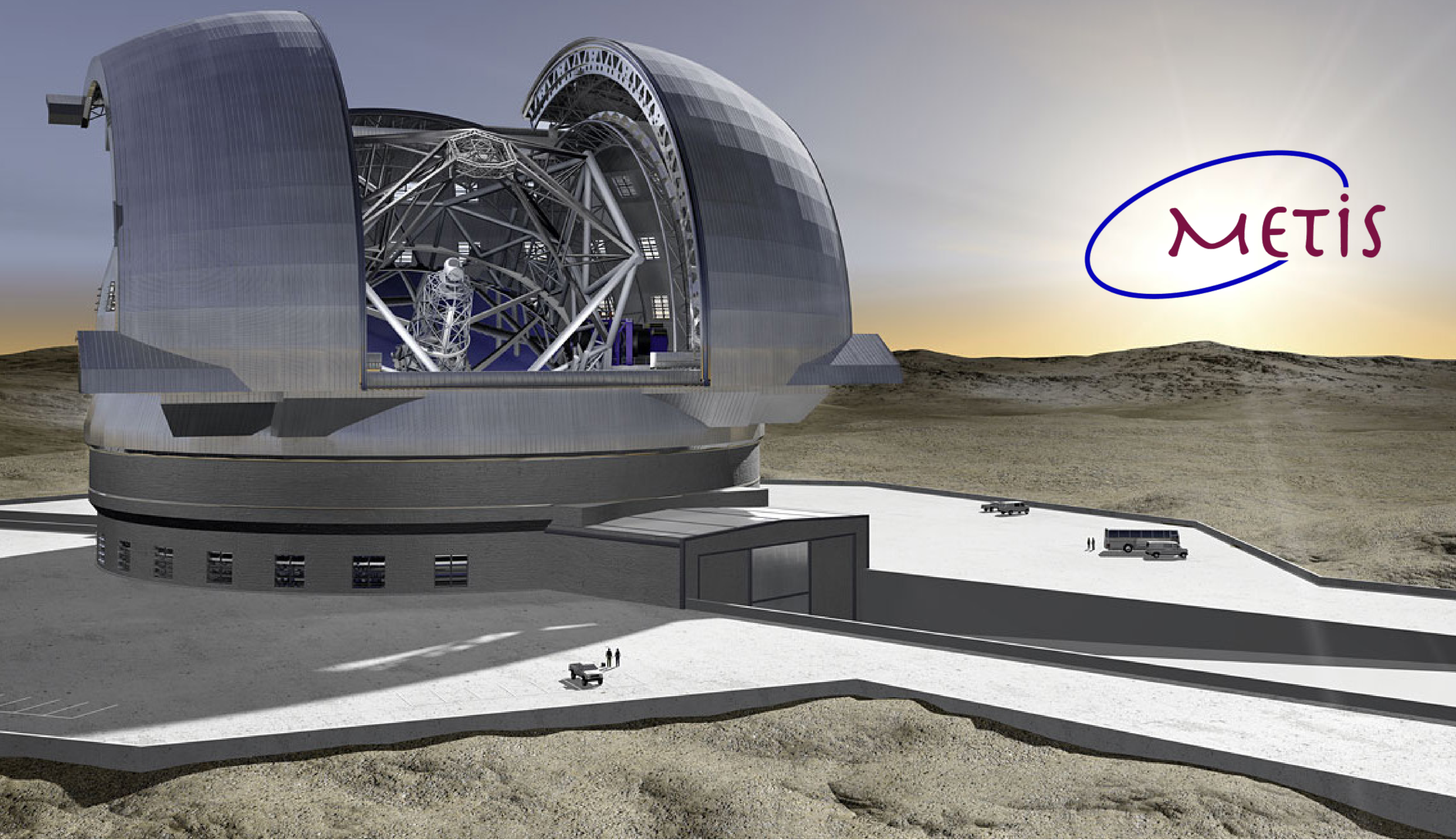
EXTRAGALACTIC SCIENCE WITH METIS ON THE E-ELT

1. Introduction
2. Angular Resolution
3. Point-source Sensitivity
4. Point Sources and extended Sources
5. METIS extragalactic Science

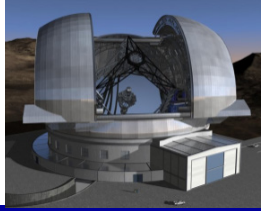
Bernhard Brandl, Leiden University & TU Delft

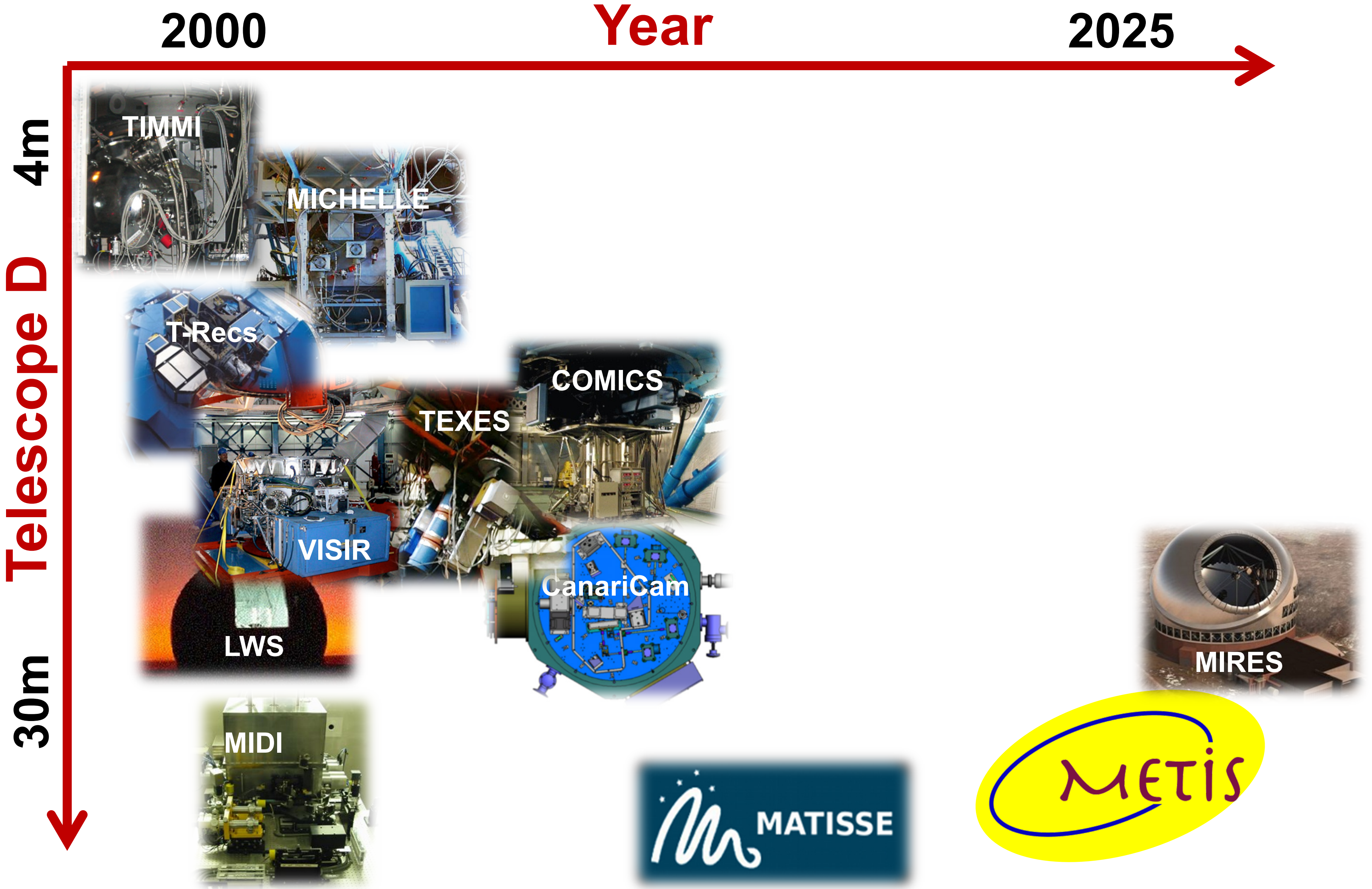
Emeric Le Floc'h, Sascha Quanz, Walter Jaffe, Paul van der Werf, Maarten Baes, Helmut Dannerbauer, Rubina Kotak, Roy van Boekel

I. INTRODUCTION

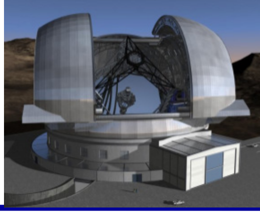


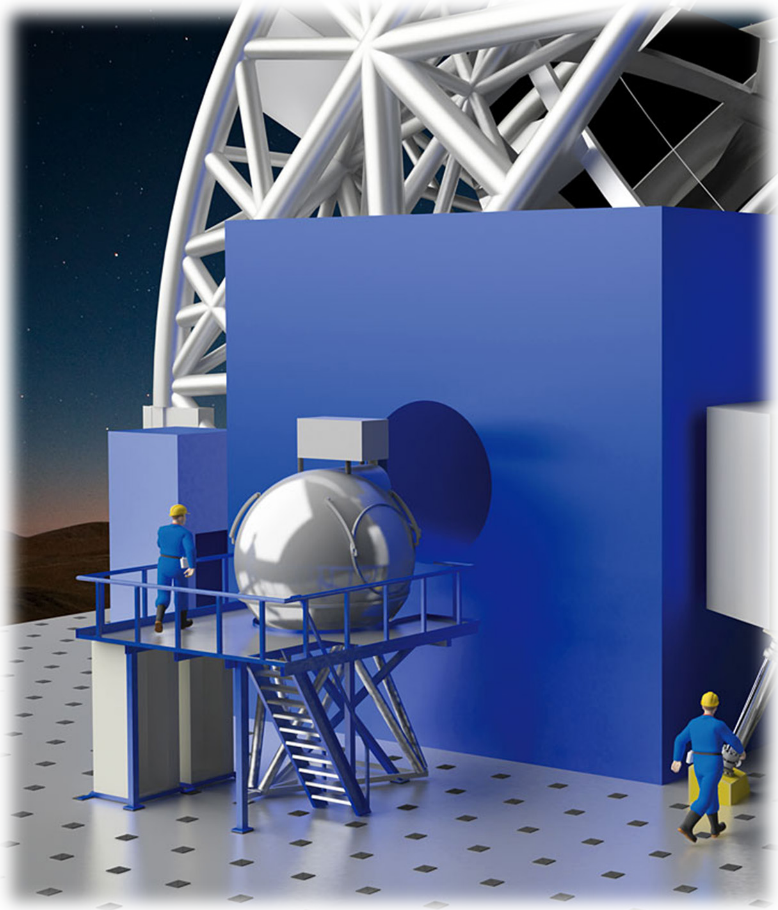
Mid-IR Ground-based Instruments





METIS



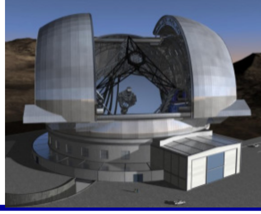


METIS

Mid-infrared E-ELT Imager and Spectrograph

…one of the first three science instruments on the E-ELT

Instrument Baseline

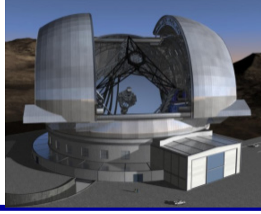


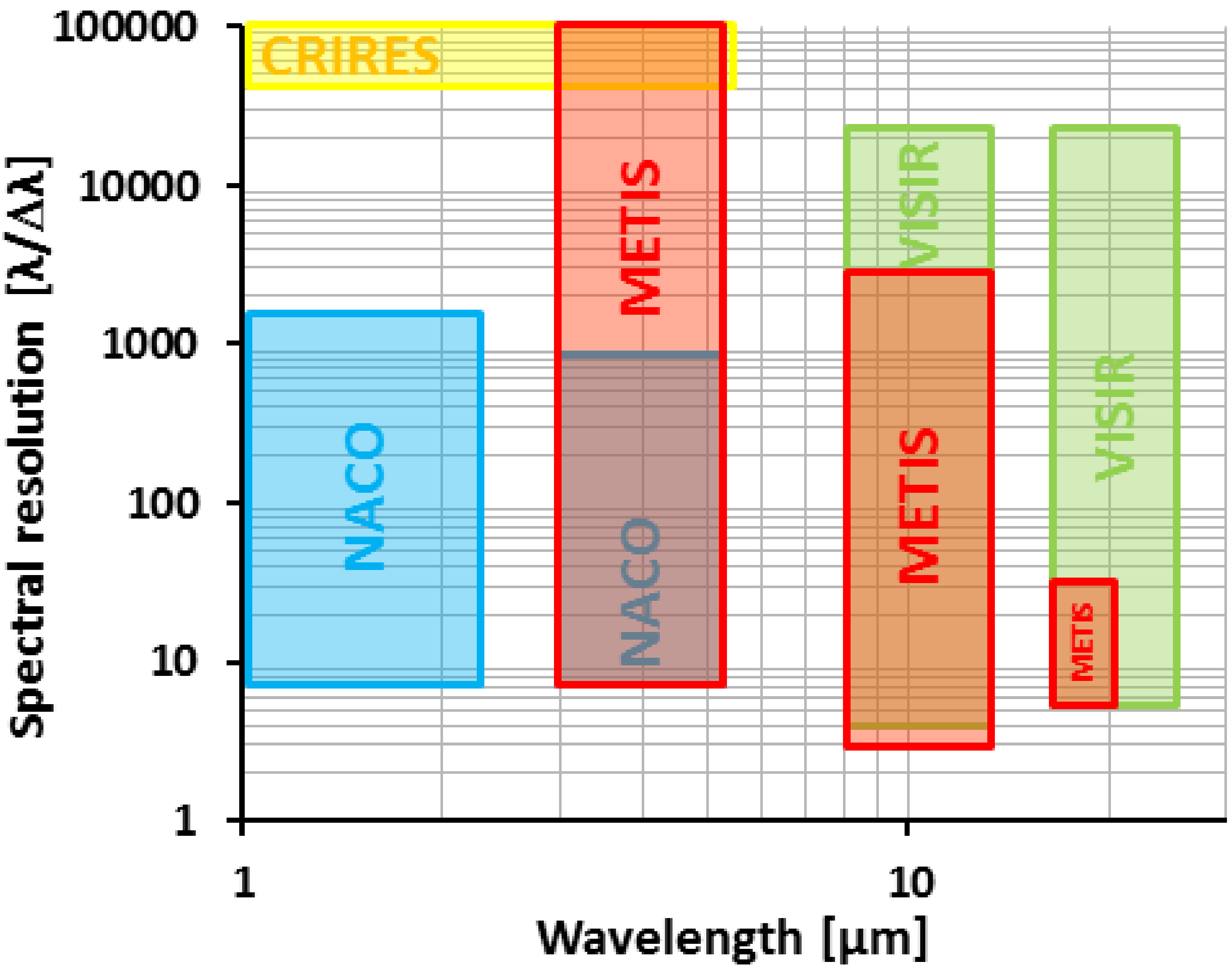
METIS will include the following observing capabilities:

- **Imaging at 3 – 19 µm.** The imager shall include low/medium resolution slit spectroscopy as well as coronagraphy for high contrast imaging.
- **High resolution (R ~ 100,000) IFU spectroscopy at 3 – 5 µm,** including a mode with extended instantaneous wavelength coverage.

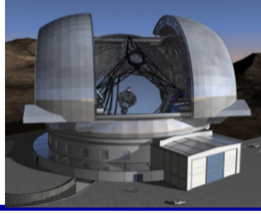
➢ All observing modes work at the **diffraction limit** with single conjugate (SC) and eventually assisted by a laser tomography adaptive optics (LTAO) system.

E-ELT/METIS⇔VLT Instr.





METIS Project Overview

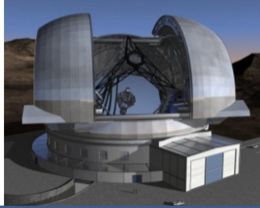


B. Brandl (PI) | **M. Feldt** | **E. Pantin** | **A. Glasse** | **C. Waelkens** | **M. Meyer** | **M. Guedel**

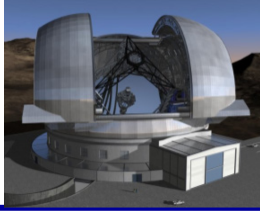
NOVA | Max-Planck-Institut für Astronomie Heidelberg | cea | Science & Technology Facilities Council UK Astronomy Technology Centre | KATHOLIEKE UNIVERSITEIT LEUVEN | ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich | universität wien

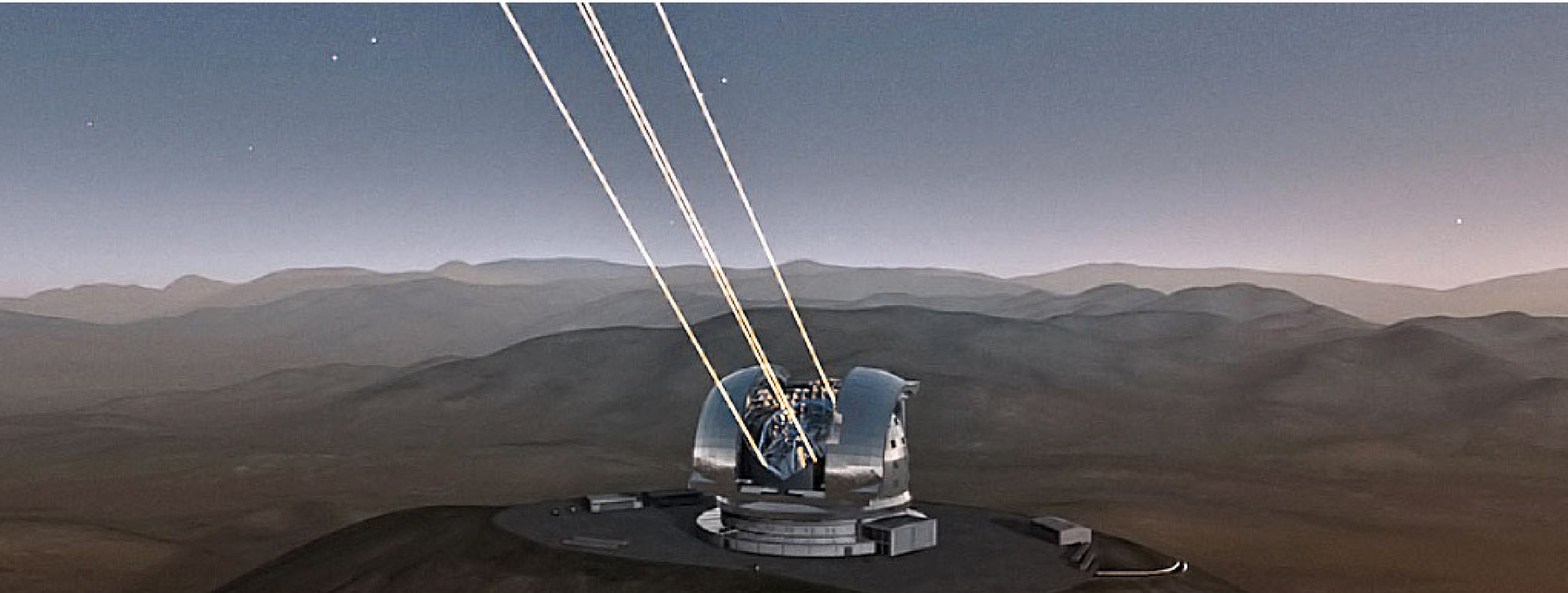
- start phase B Sep 2015
- PDR 2017
- FDR 2019
- Start AIV 2021
- E-ELT 1st light 2024
- METIS 1st light 2025

Main Science Areas



METIS AO – but no LGS@1st Light



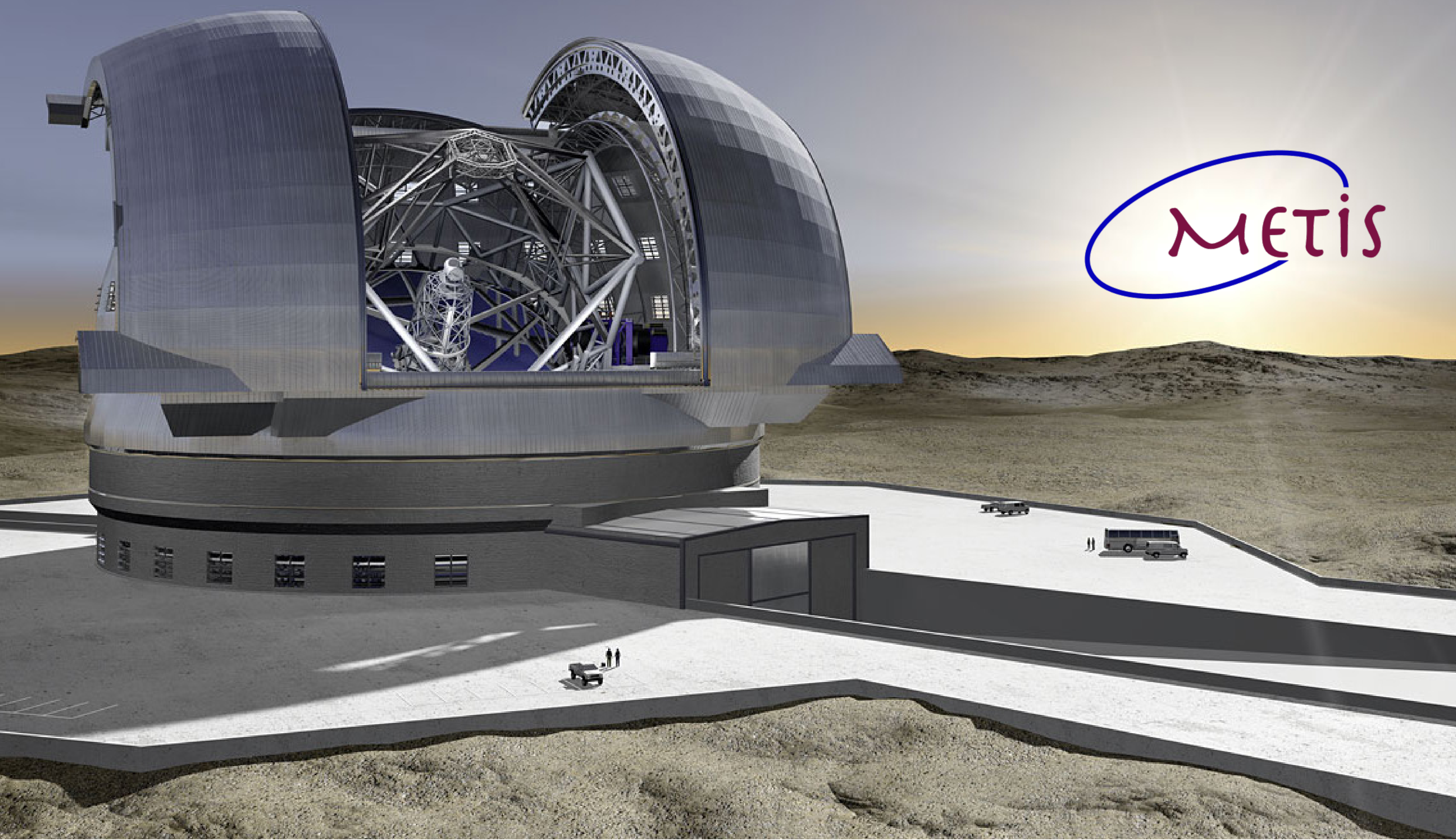


METIS has two flavors of Adaptive Optics:

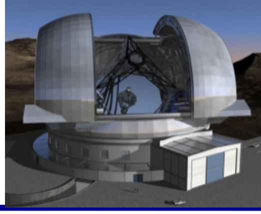
A. SCAO: internal WFS & E-ELT M4/5 → large fraction of Galactic science

B. LTAO: laser guide stars → extragalactic science & faint Galactic targets

II. ANGULAR RESOLUTION



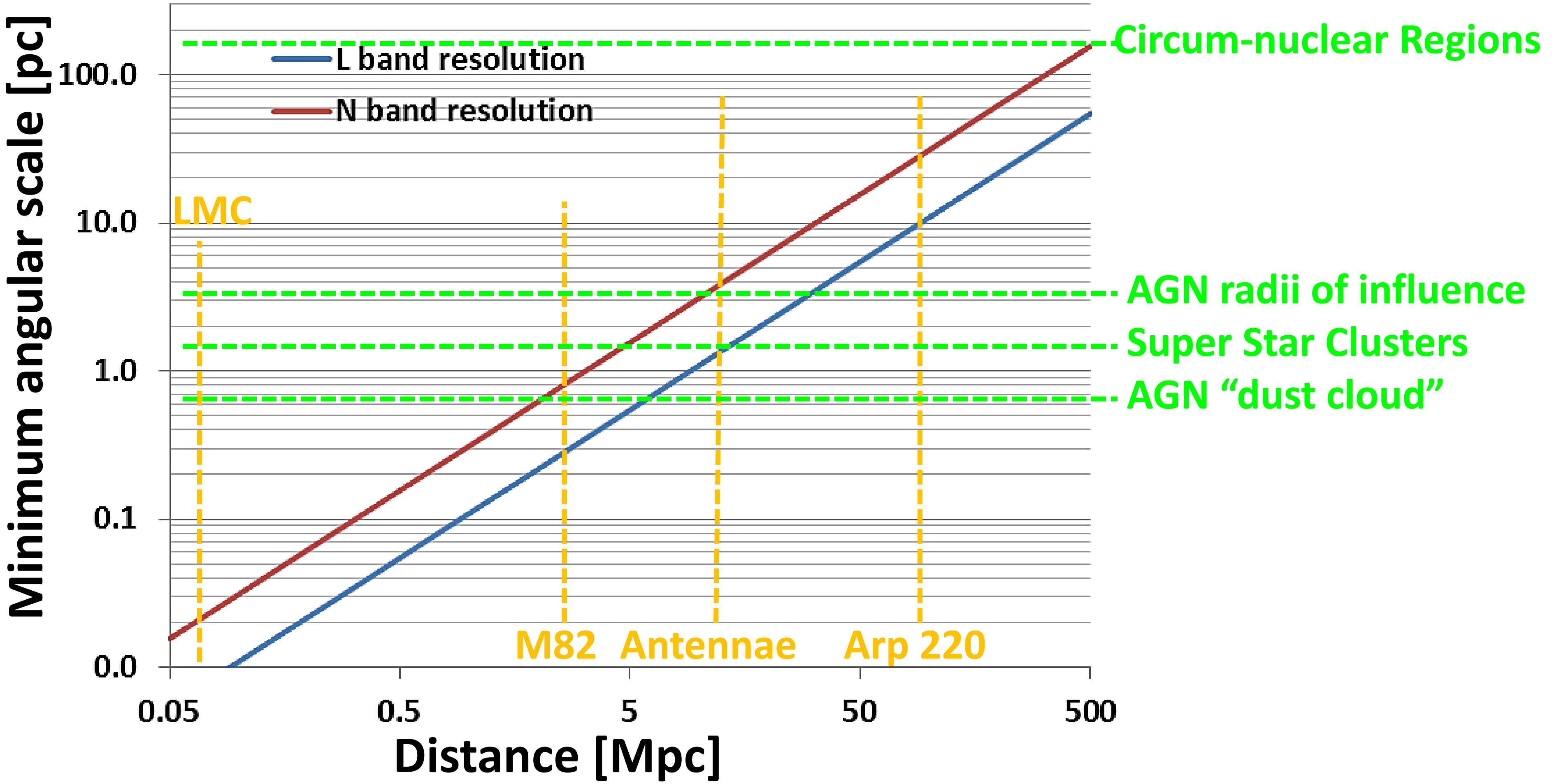
METIS E-ELT Resolution ("local")



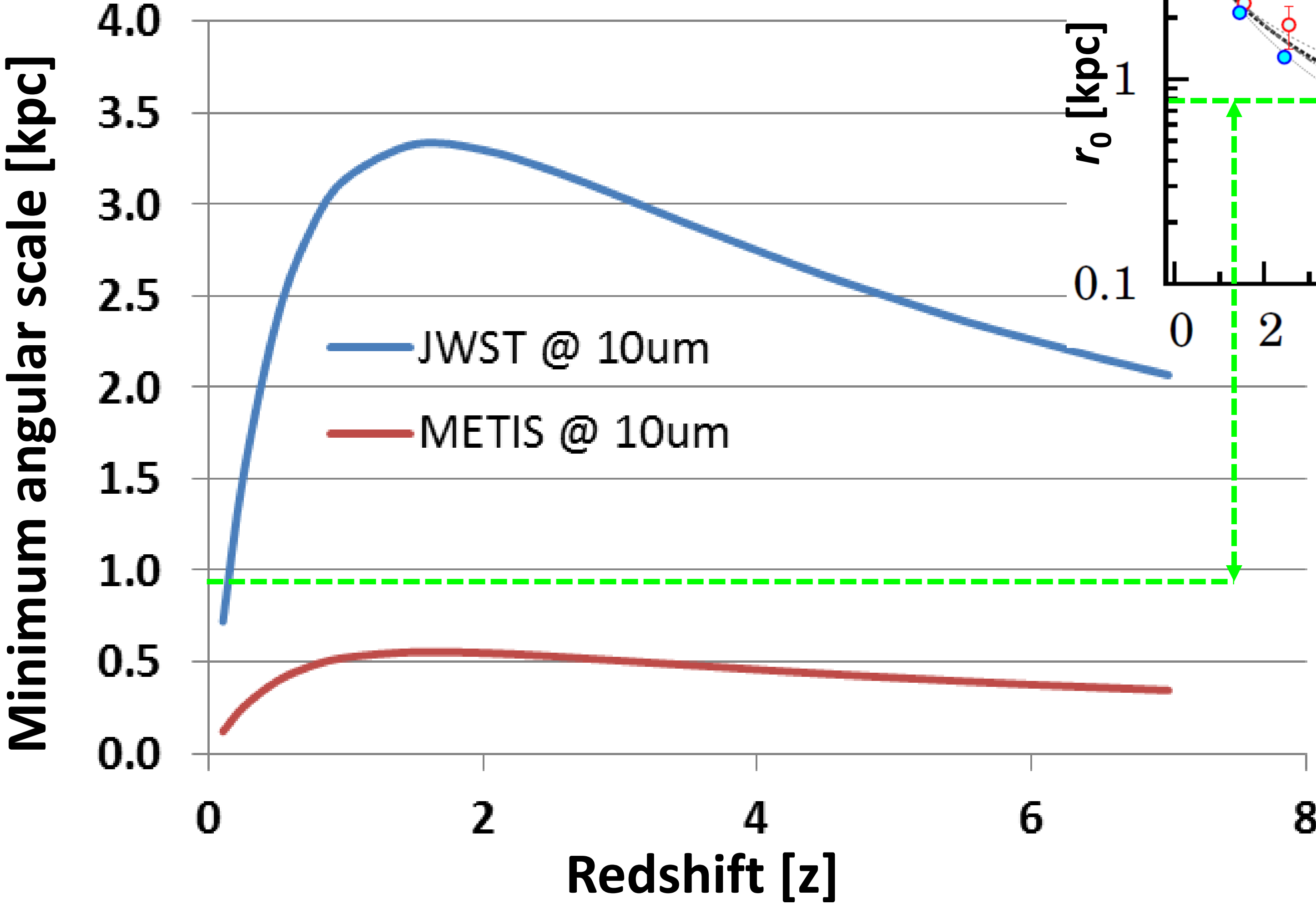
$$\theta_{\min} = 1.22\frac{\lambda}{D}$$

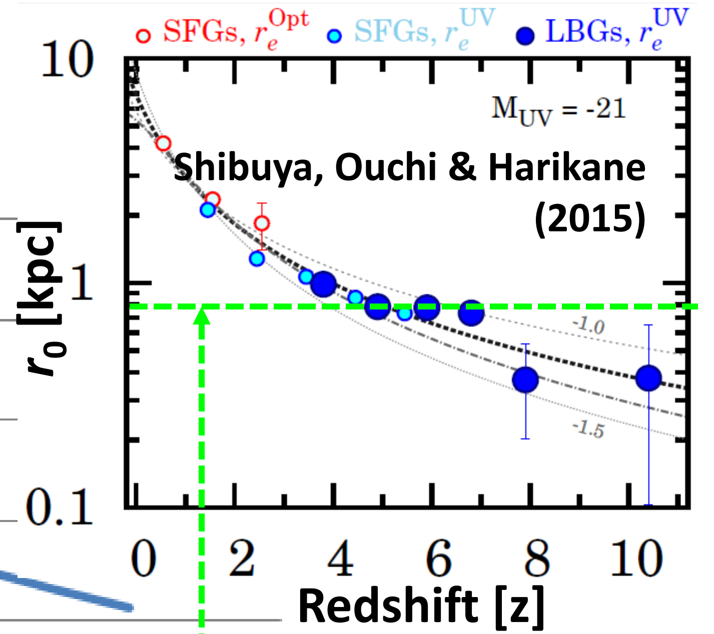
← bad! 10μm

← good! 39m

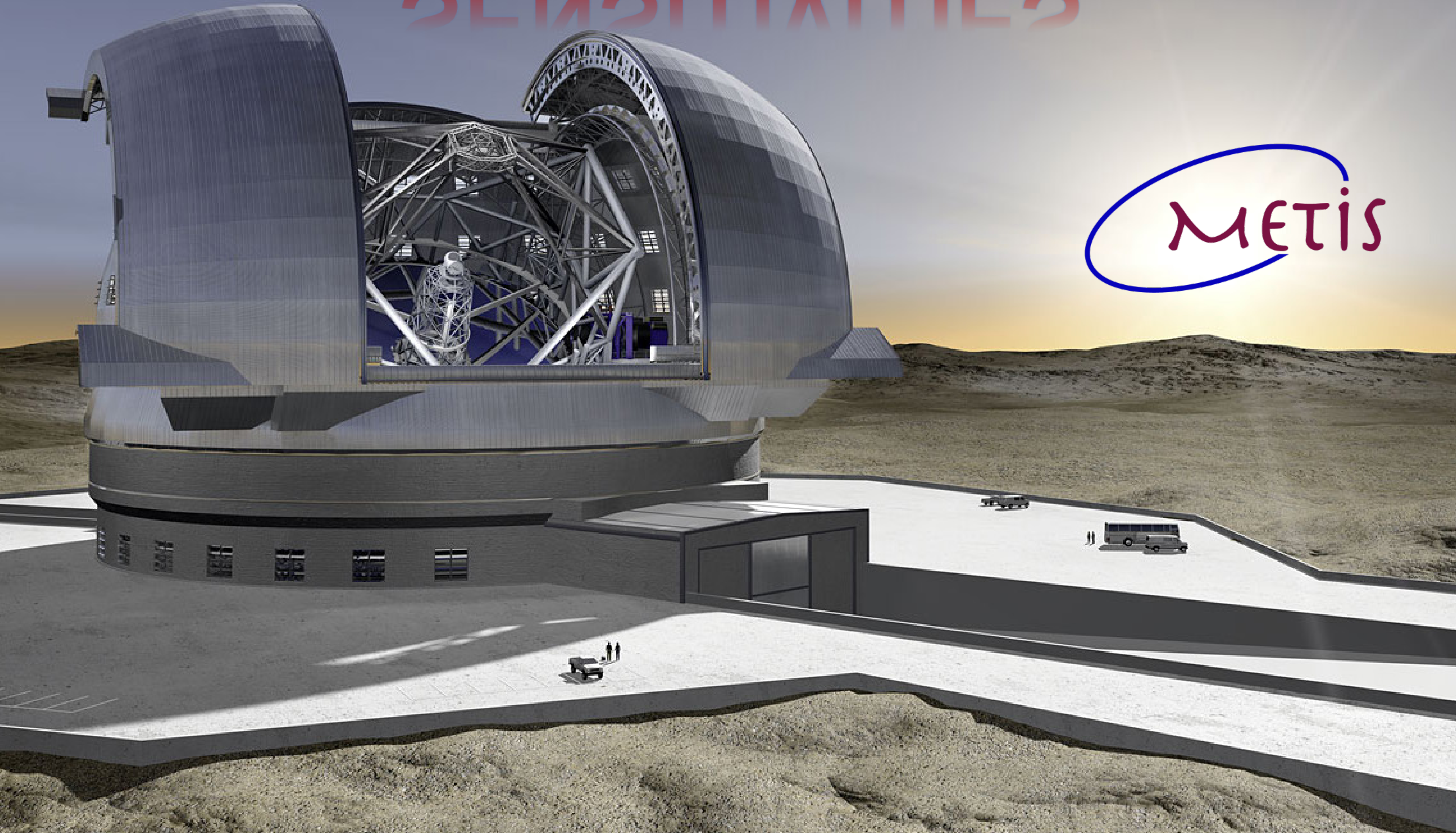


E-ELT Resolution (high z)



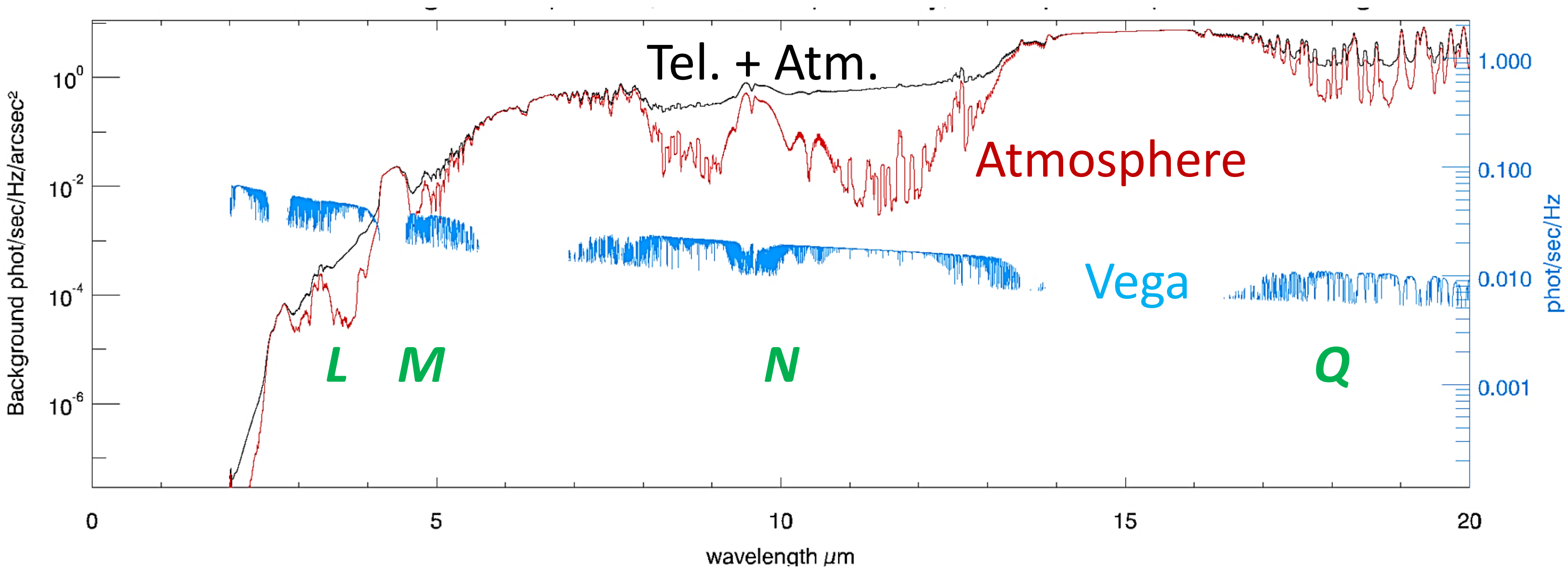


III. POINT SOURCE SENSITIVITIES



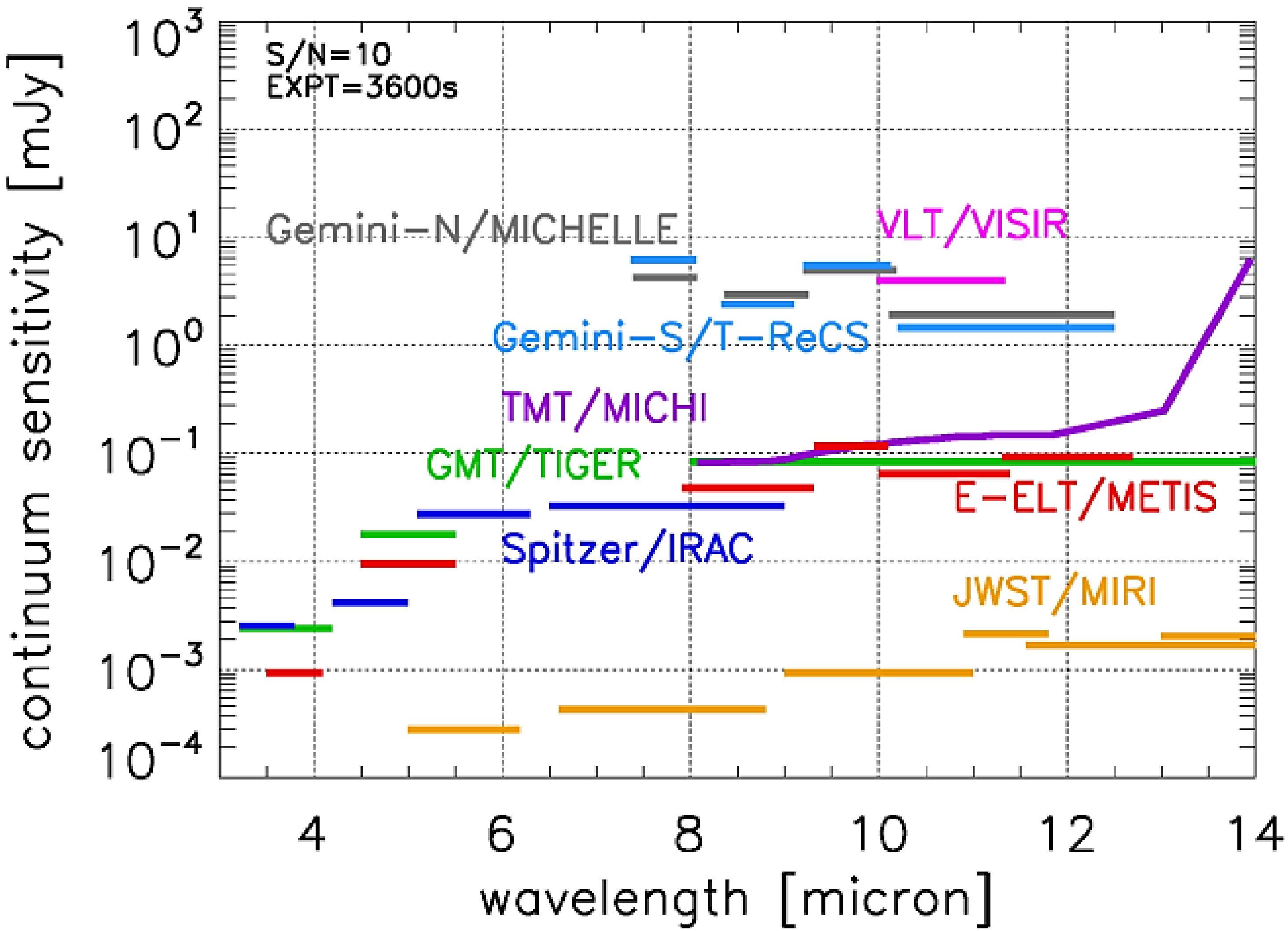
Battle against Background

Thermal background is orders of magnitude stronger than most astronomical sources – even a very bright star like Vega (0^{th} mag)

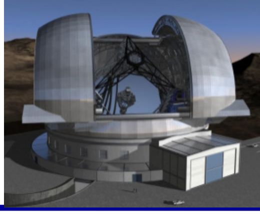


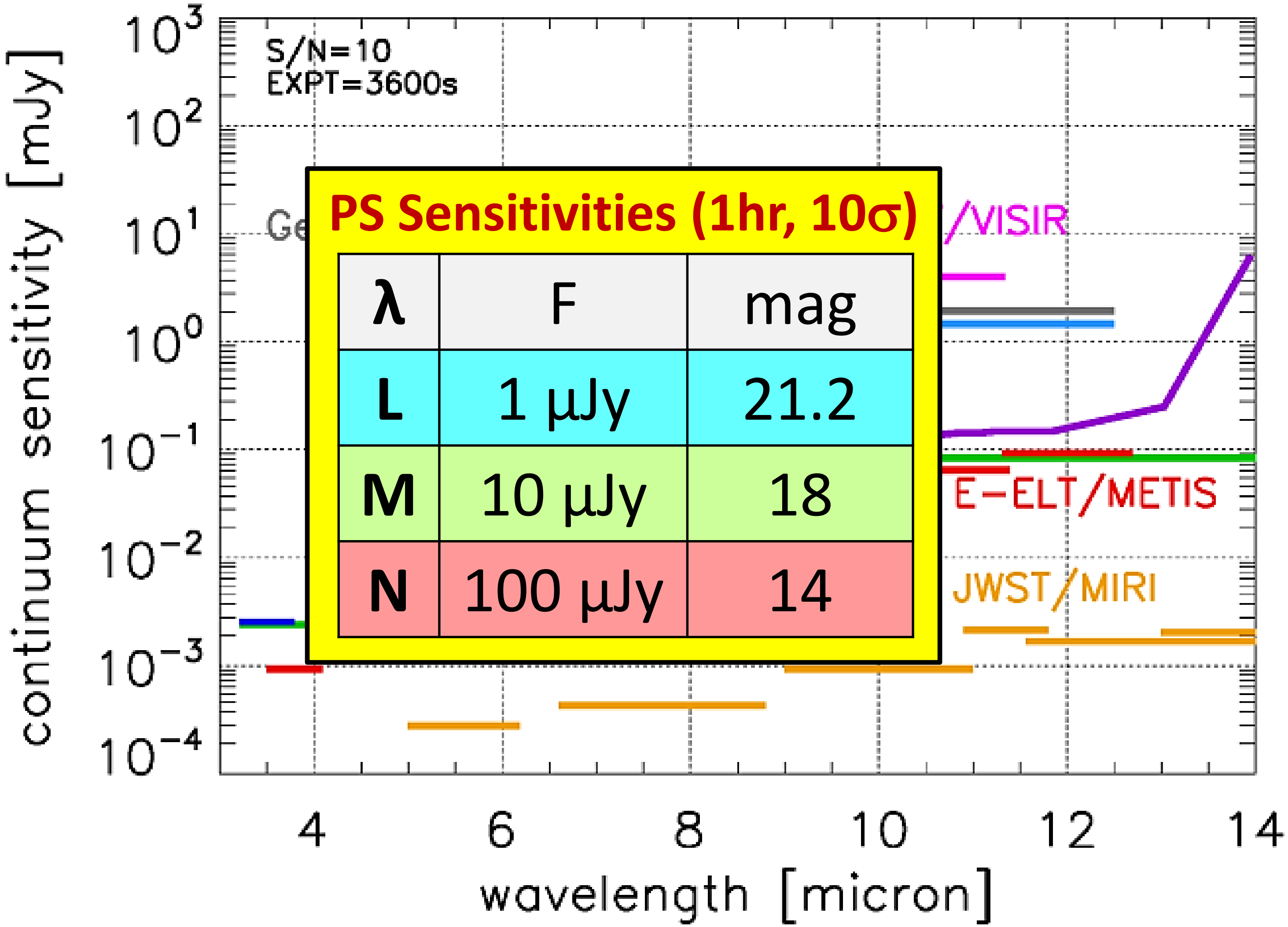
The best we can do is to get to the photon shot noise limit = $\sqrt{(n_\gamma)}$

Imaging PS Sensitivity



METIS Imaging PS Sensitivity

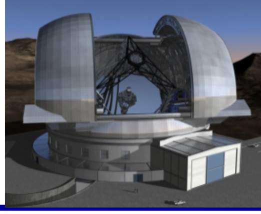


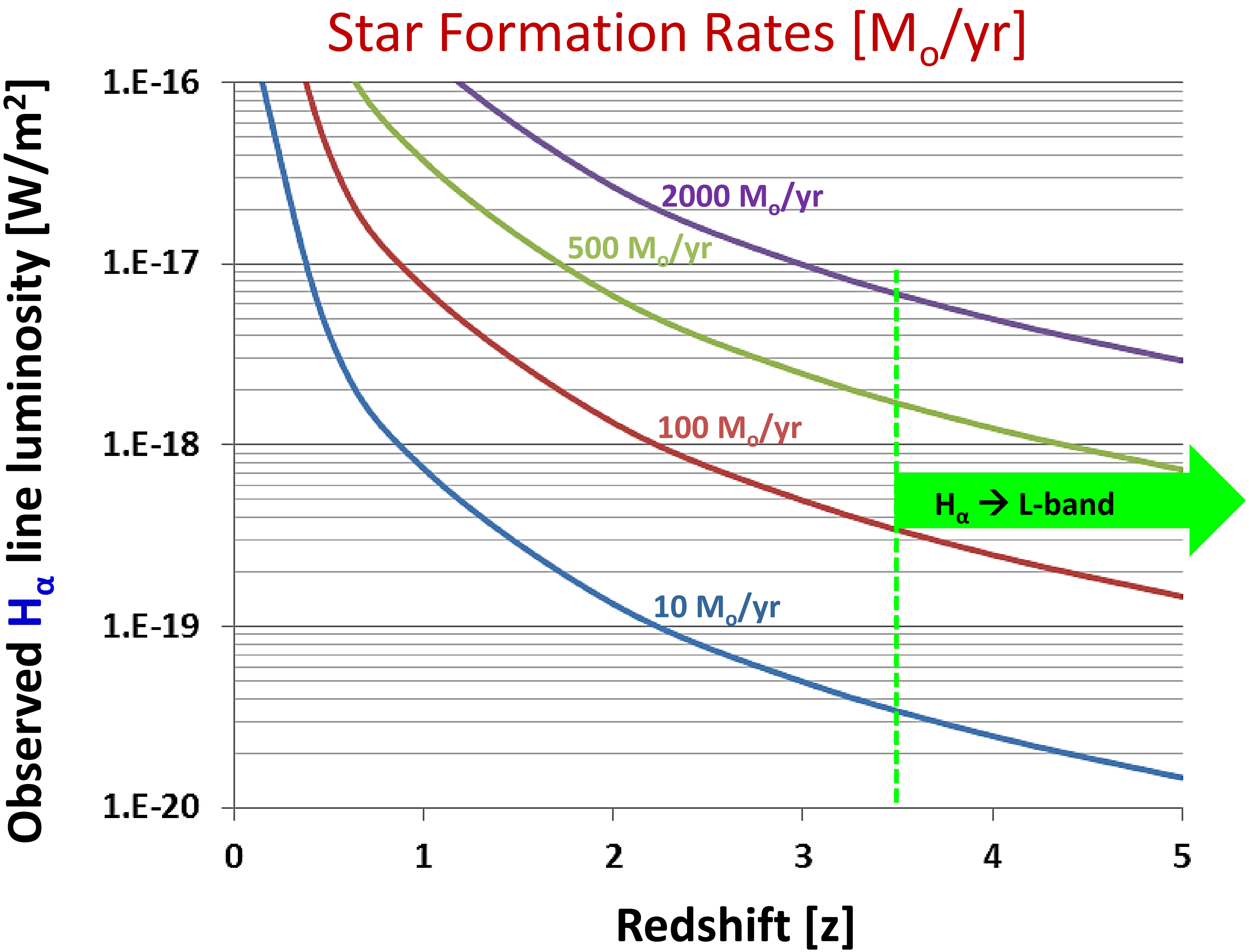


PS Sensitivities (1hr, 10σ)

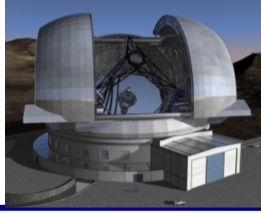
λ	F	mag
L	1 μJy	21.2
M	10 μJy	18
N	100 μJy	14

H_α as a SFR Tracer

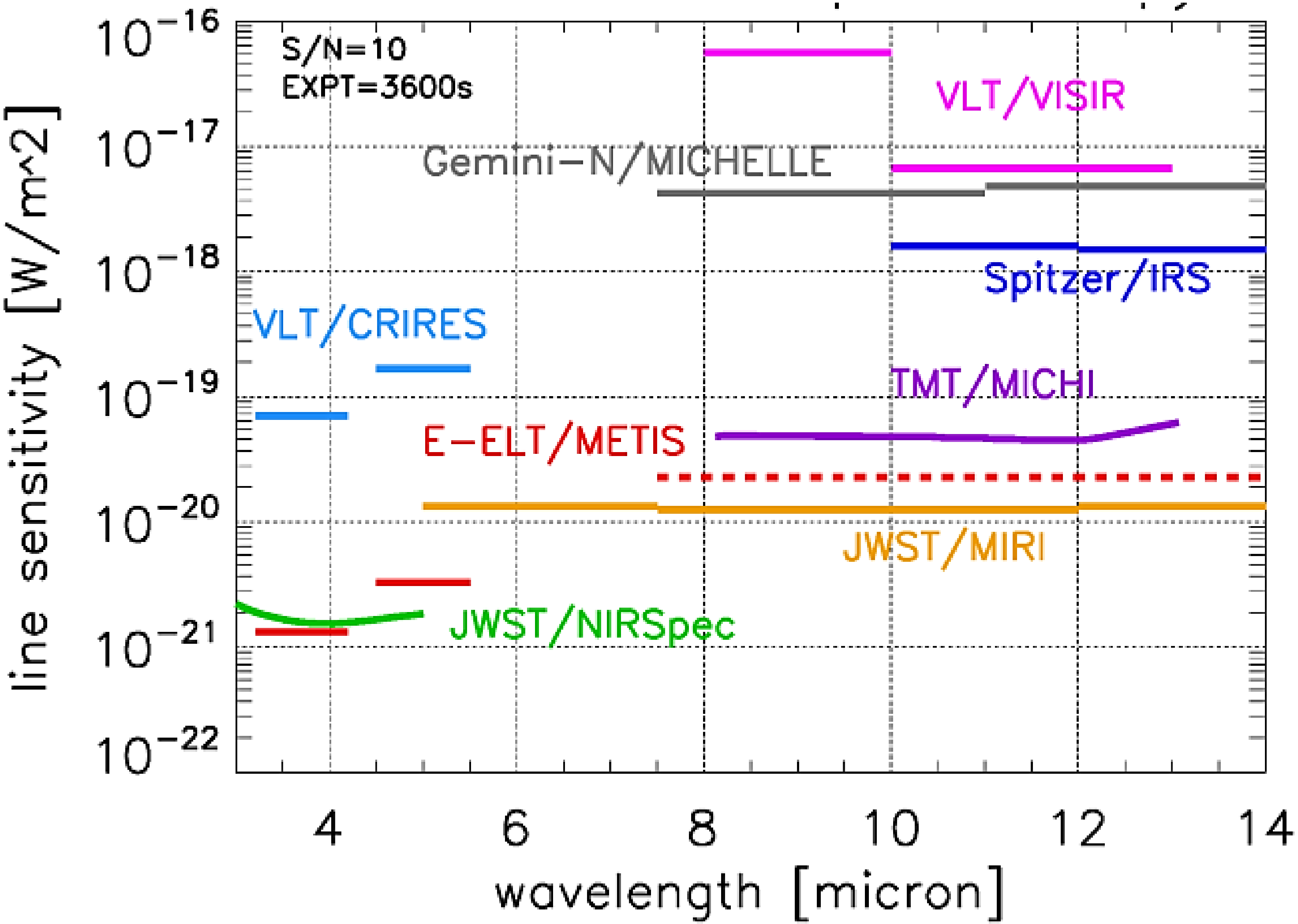




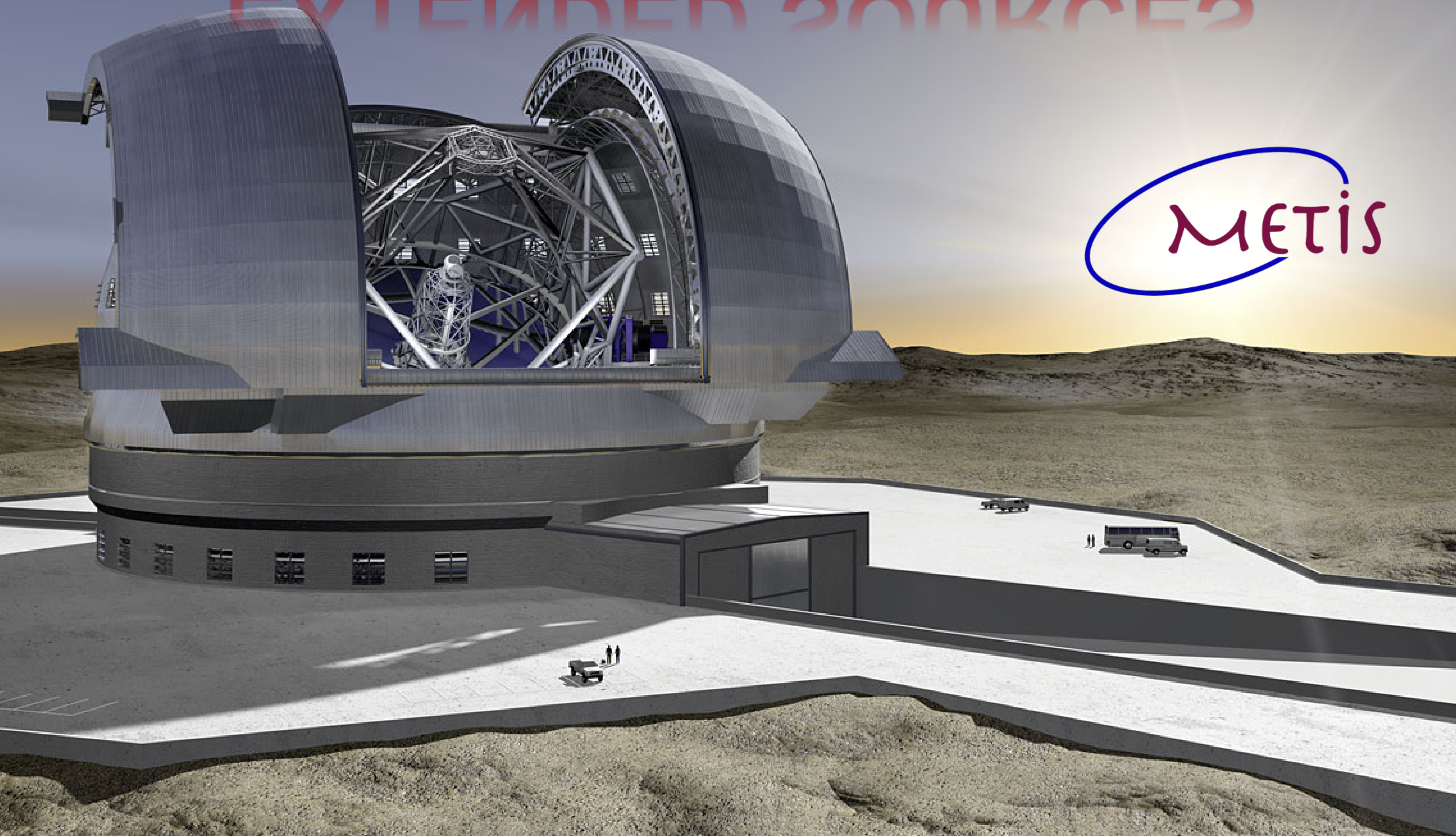
METIS Spectroscopic Sensitivity



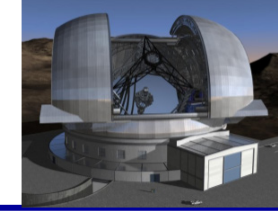
IFU *R=100,000* spectroscopy (PS, unresolved lines)



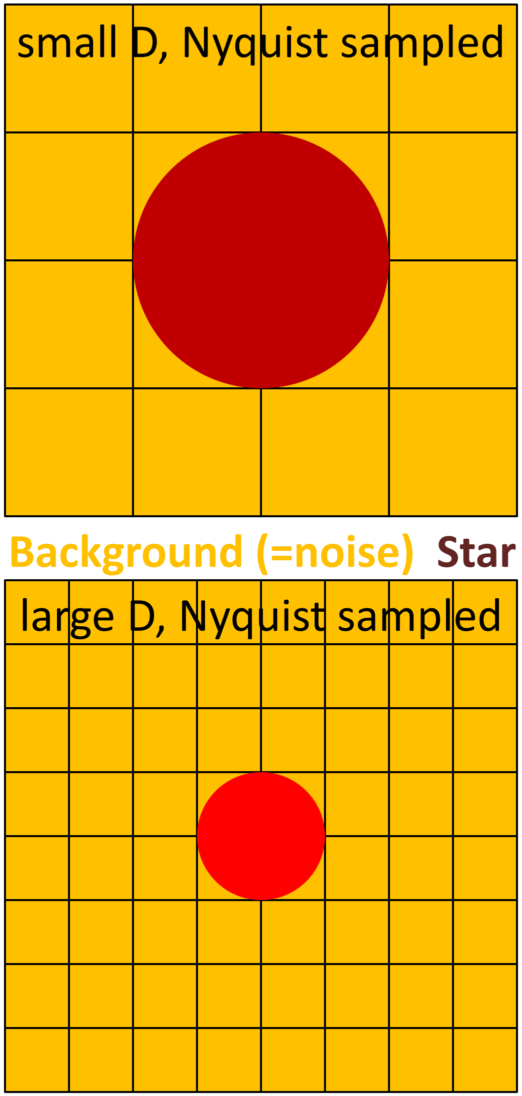
IV. POINT SOURCES AND EXTENDED SOURCES



Point Sources



Signal = S; Background = B; Noise = N; Telescope diameter = D



How does the Signal-to-Noise scale?

- Effect of telescope aperture:

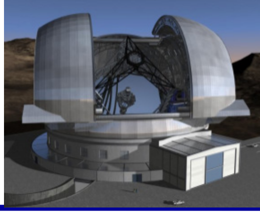
  $S \propto D^2$ and $B \propto D^2 \rightarrow N \propto D \rightarrow S/N \propto D$

- Effect of pixel FOV (if Nyquist sampled):

  $S \propto \text{const}$ and $B \propto D^{-2} \rightarrow N \propto D^{-1} \rightarrow S/N \propto D$

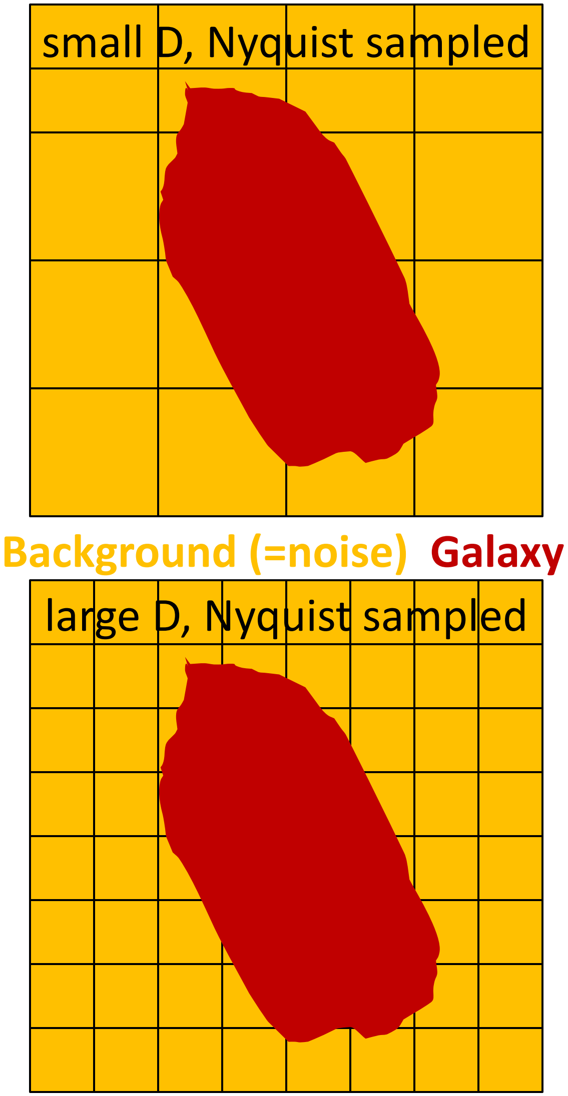
Both telescope and pixel sizes combined:

$$S/N \propto D^2 \rightarrow t_{int} \propto D^{-4}$$



Extended Sources

Signal = S; Background = B; Noise = N; Telescope diameter = D



- Effect of <u>telescope aperture</u>:

  $S \propto D^2$ and $B \propto D^2 \rightarrow N \propto D \rightarrow S/N \propto D$

- Effect of <u>pixel FOV</u> (if Nyquist sampled):

  $S \propto D^{-2}$ and $B \propto D^{-2} \rightarrow N \propto D^{-1} \rightarrow S/N \propto D^{-1}$

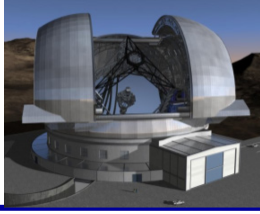
Both telescope and pixel sizes combined:

$S/N \propto const(D) \rightarrow t_{int} \propto const(D)$

Sensitivity *per pixel* on an ELT is the same as for a 4m tel.
→ insensitive to low surface brightness
→ need *compact* sources.

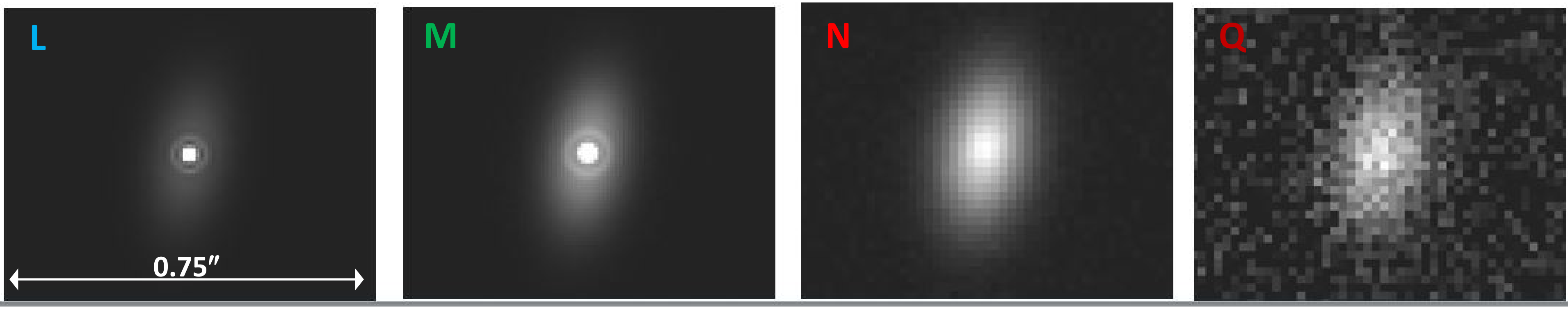
Resampling would gain sensitivity by √n but is usually not an option if angular resolution is the driver for an ELT.

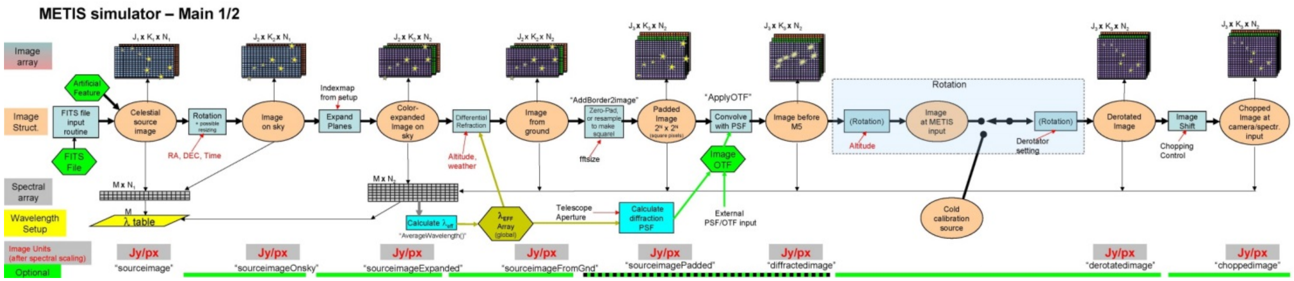
METIS Instrument Simulator

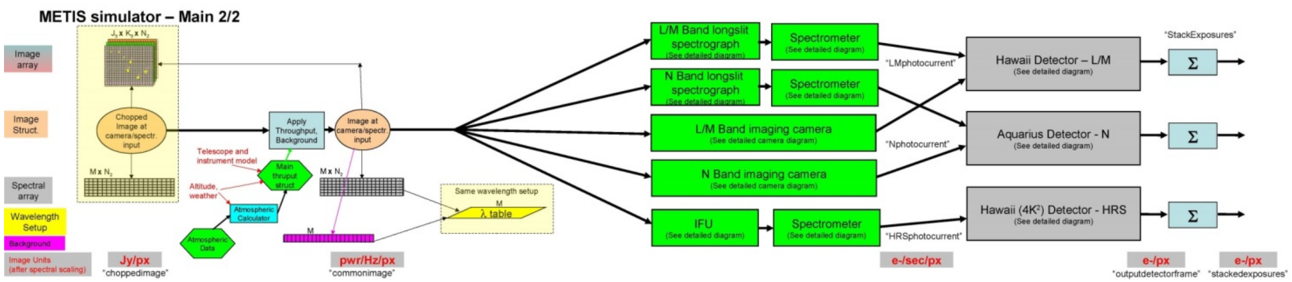


End-to-end science simulations are *essential* to assess the feasibility of observations of resolved objects.

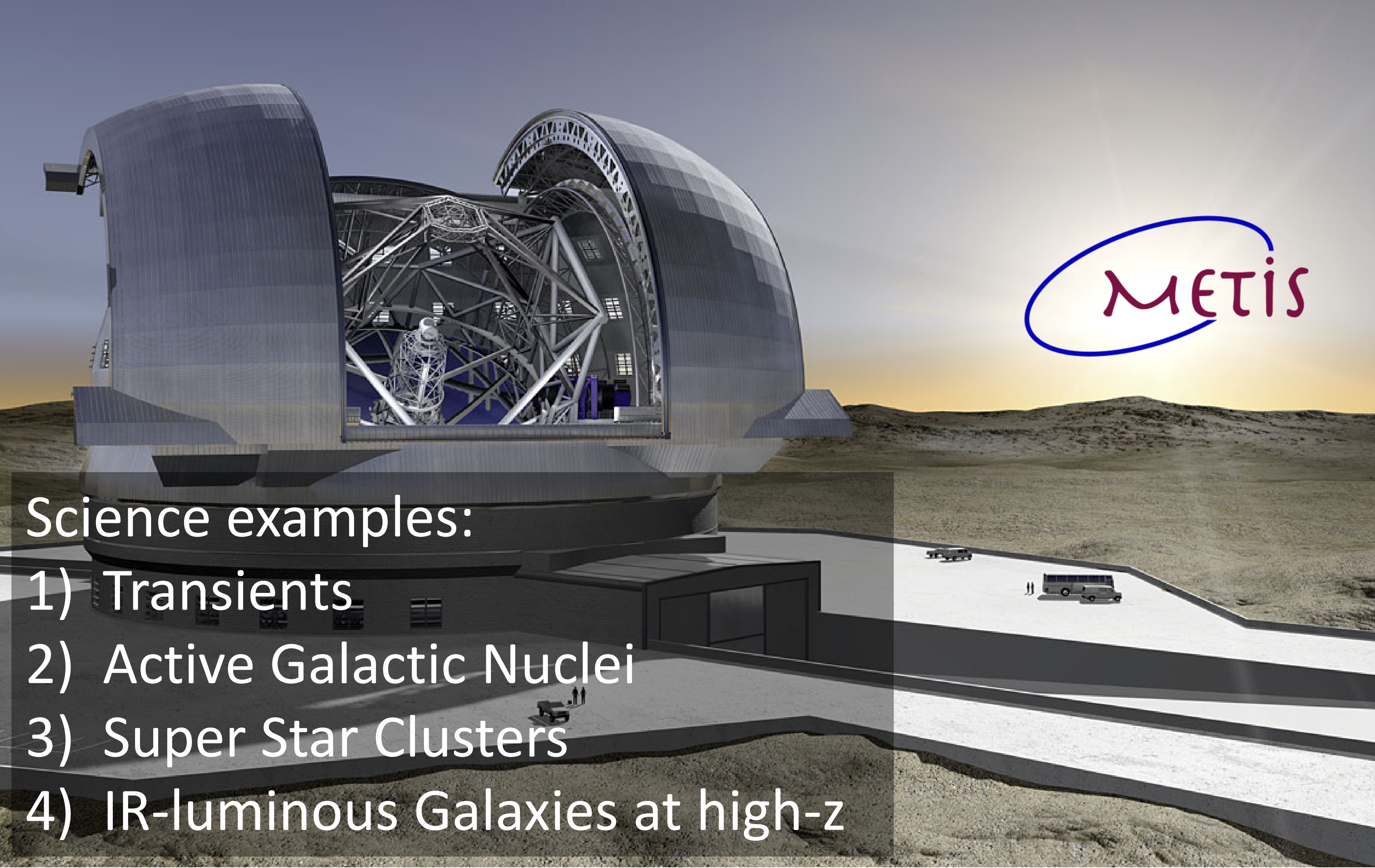
t_{int} = 1 min; star ~10mJy; nebula ~50mJy @ 4μm







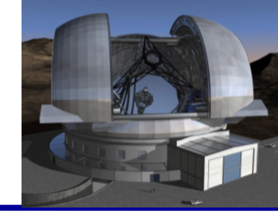
V. EXTRAGALACTIC SCIENCE



Science examples:

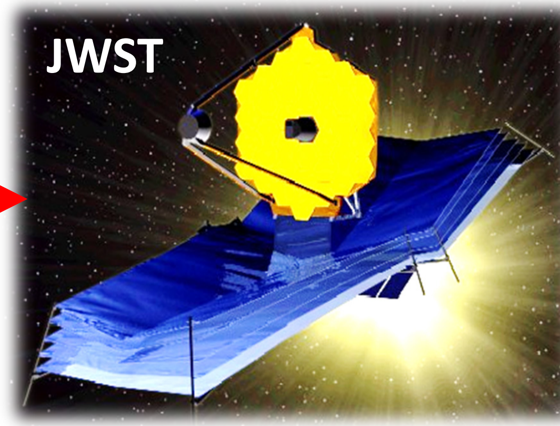
1) Transients
2) Active Galactic Nuclei
3) Super Star Clusters
4) IR-luminous Galaxies at high-z

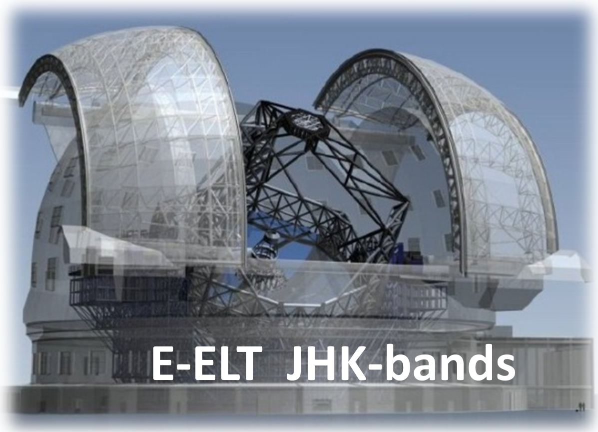
Focus on *unique* Science



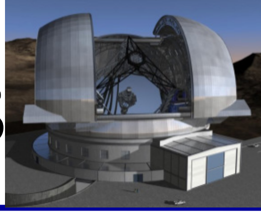
- Strong competitors will be in operation
- Only one ELT for the entire European astronomical community

ALMA

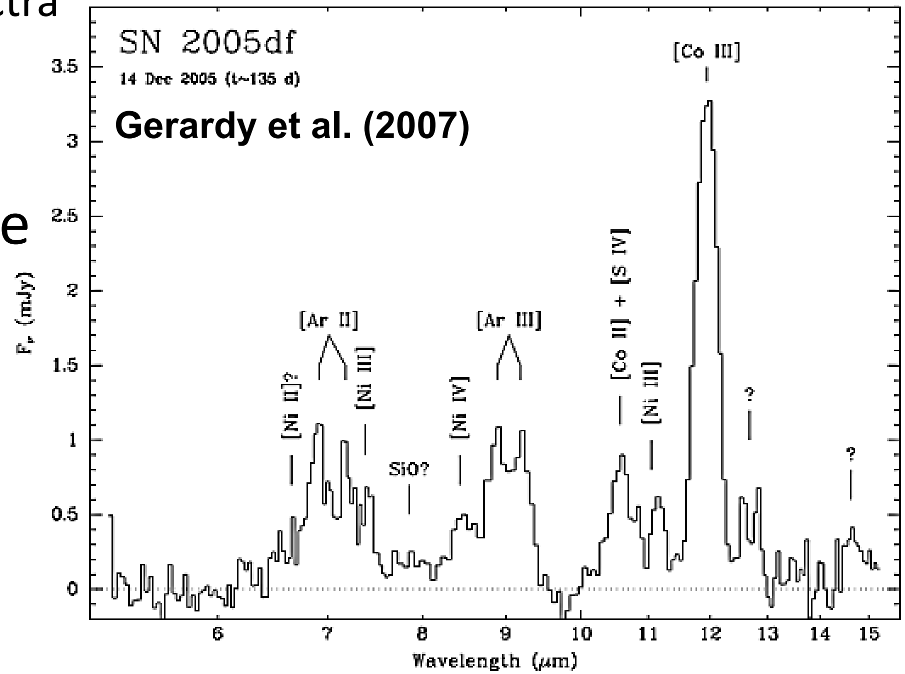




Transients – Key Questions



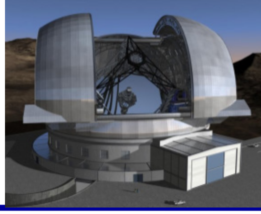
- How does the physics of the explosion work?
  - wealth of optically thin spectral diagnostics ⇔ explosion models
  - currently only 5 objects with mid-IR spectra



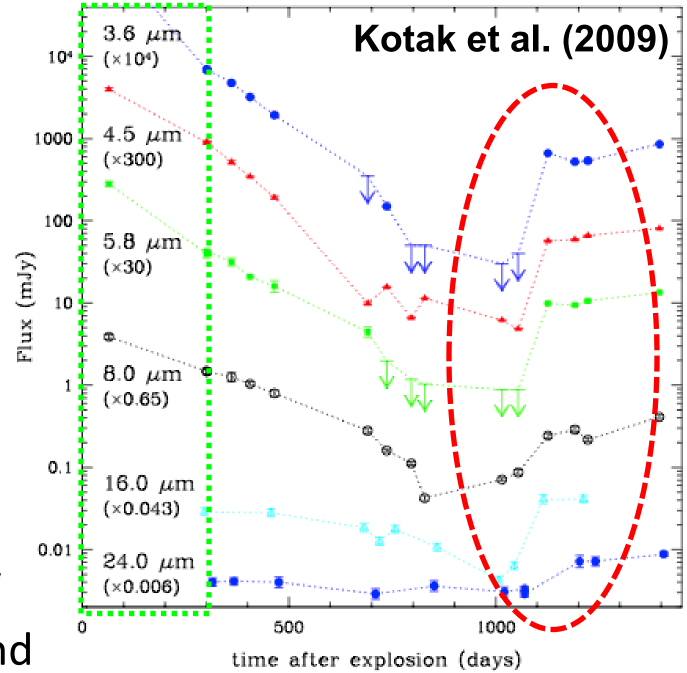
- Are core-collapse supernovae the primary sources of dust in the early Universe?
  - follow the condensation of dust grains

- What are the properties of the progenitors of the first SNe explosions?

Transients – Observations

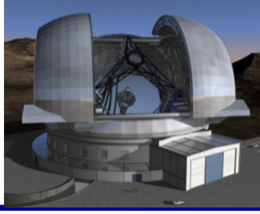


- Requires quick response times of a few minutes
- METIS needed for SNe in particularly crowded regions or close to the nuclei of their host galaxies
- Follow cooling of the ejecta → grain growth
  - requires monitoring over several years
  - re-brightening due to collision between supernova ejecta and pre-existing material



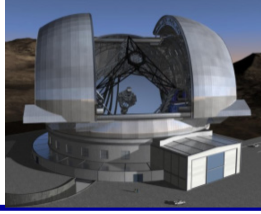
- Beyond z=4, trusted rest-frame optical line-diagnostics shift into METIS window
  - Spectroscopic follow-up of high-z SNe and GRBs, and the nature of their host galaxies
  - Study of intervening intergalactic medium

AGN – Key Questions



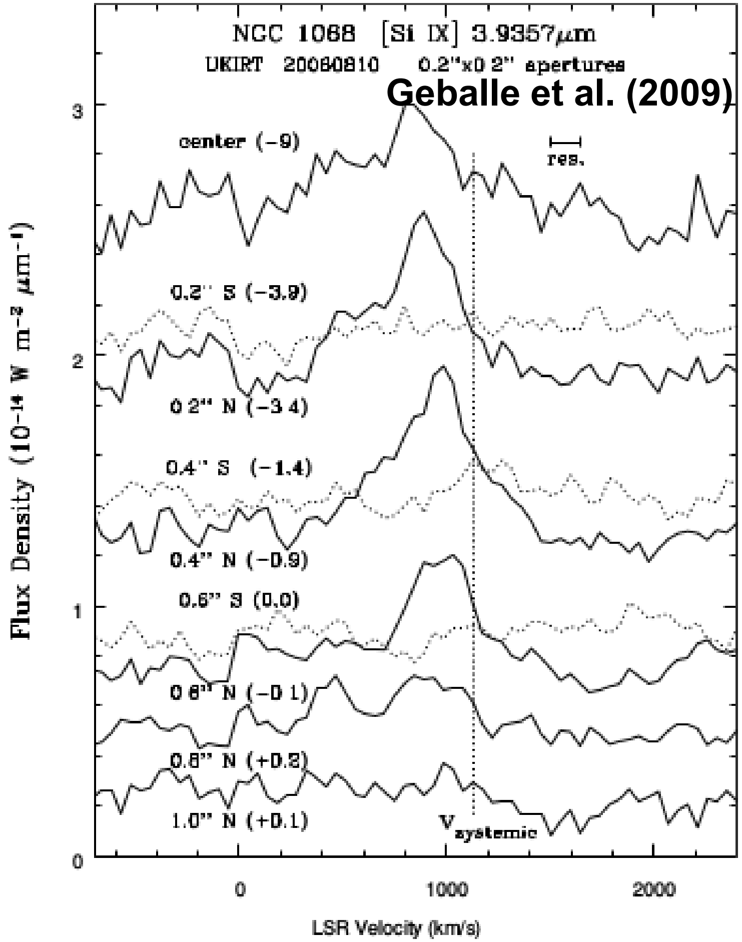
- What is the physical nature of the accreting dust systems that surround AGN at ~1 pc radius?
  - dust not collapsed into thin disk, not perpendicular to radio axes
  - origin of warm dust *along* the radio axis (Sy I ⇔ Sy II)
  - unusually low gas/dust ratio
- How is the energy fed back from AGN inner region to the surrounding galaxy?
  - radio jets ⇔ wind induced shocks
- How do the uncertainties in BLR structures affect black hole mass estimates?
  - accurate spatial and reverberation measurements → kinematics → BH masses
- Where do the huge amounts of dusty material come from?
  - from **circum-nuclear star clusters**, 100 pc away?
  - inflow → angular momentum dump (star formation ⇔ turbulence)?

AGN – Observations

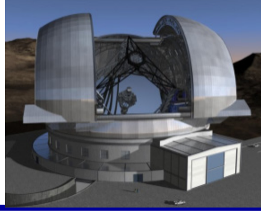


- Nearby Sy galaxies are relatively bright, $F_\nu \approx 0.1 - 5$ Jy
- Well resolved: warm dust regions ≈ 0.03″; circum-nuclear stellar disks 10× larger
- MIDI & MATISSE ≤ 20 objects
  – limited by sensitivity → METIS

Velocity profiles of the [Si IX]
→ kinematics

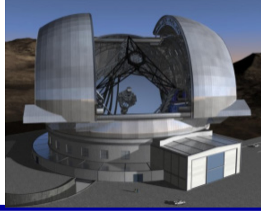


SSCs – Key Questions

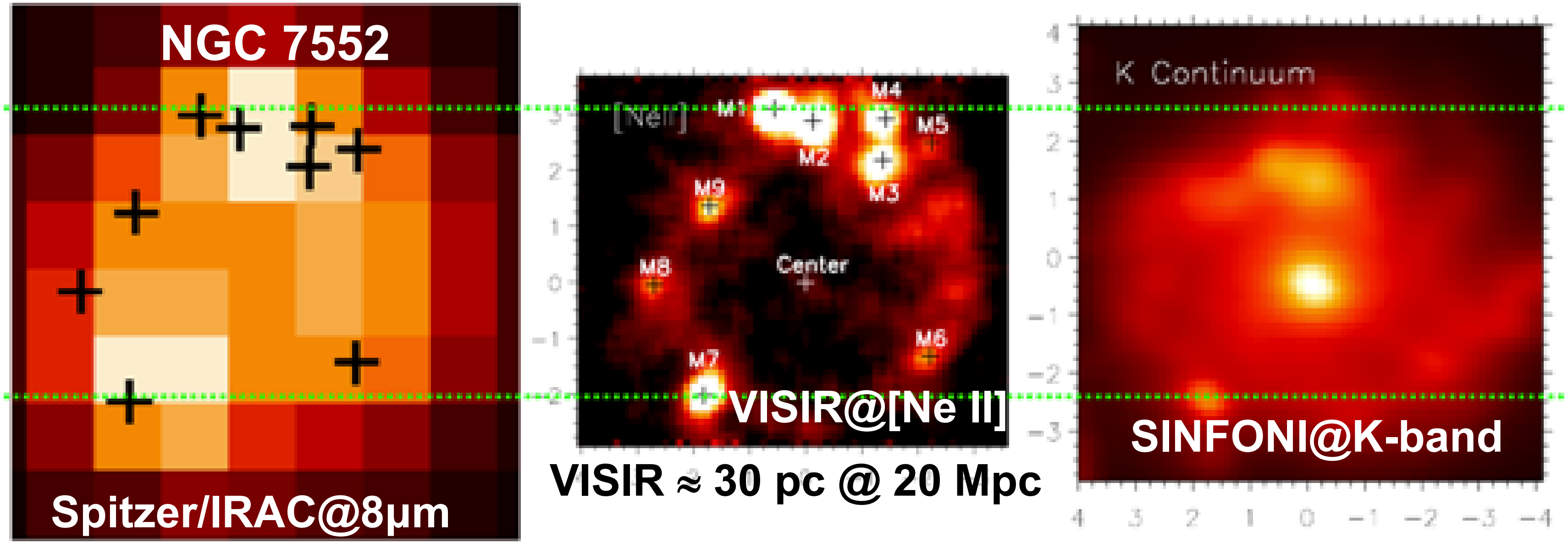


- What are the processes which form the most massive super star clusters?
  - M > 10^{6-7} M_{o}
  - ages $\leq$ 10 Myr
  - L $\approx$ 10^{8-10} L_{o}
  - $A_V \approx 5 - 20$ mag
- Where did they form wrt galactic inflows, bars, resonances, …?
- What does the spatially resolved SF history tell us?
  - continuous or episodic? Feedback?
- What is their role in galactic scale "super winds"?

SSCs – Observations



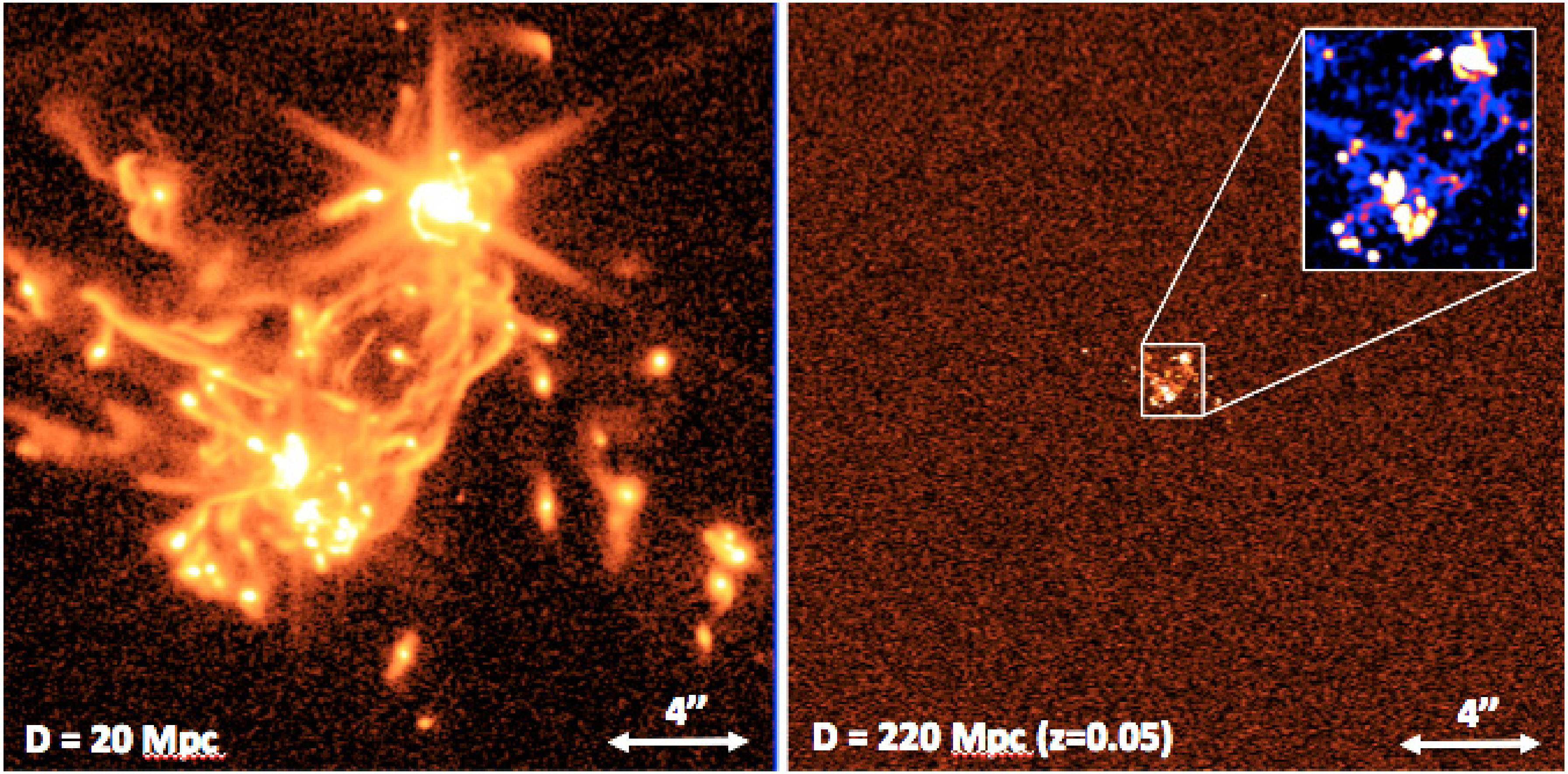
- Imaging and spectroscopy → local conditions (T, ρ, lines: EWs and shapes) → relative ages, masses, environments



- METIS will have 5× better resolution → access to hundreds of "starburst nuclei" ≤ 100 Mpc
- Systematic studies @ LMN band, PAH, Br-α, [Ne II], …

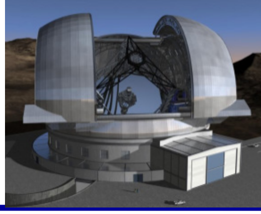
SSCs in Galaxy Mergers

- Simulation of merger @ N-band by Renaud et al. (2014)
- <u>Left:</u> *D* (20 Mpc) and total F_ν (2 Jy) of the Antennae galaxies
- <u>Right:</u> object moved to *D* = 220 Mpc (*z* = 0.05)



METIS

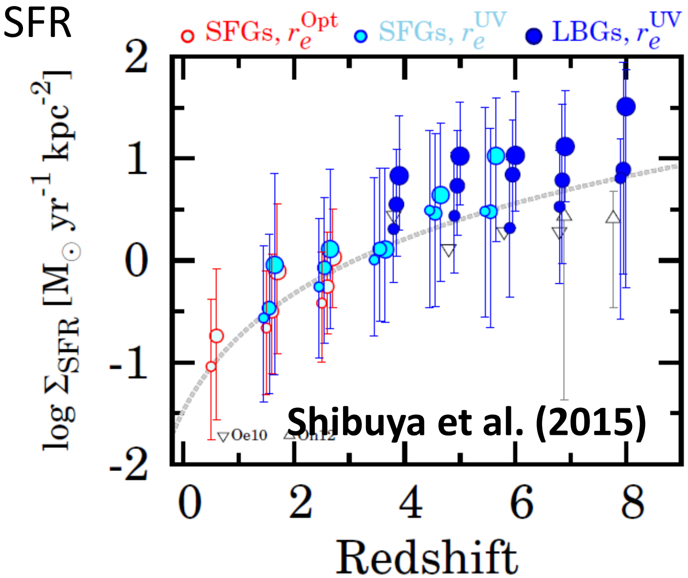
High-z – Key Questions



Dust + Redshift = Problem → METIS L/M ideal for dusty IR galaxies

- How did massive ellipticals build up their mass at 2 < z < 6?
  – in place ~ 10 Gyr ago → rapid growth → very high SFR

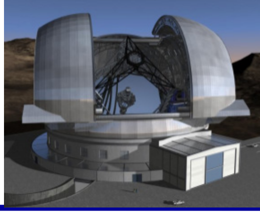
higher SFR-density at higher z
→ increased compactness



- Did disk instabilities or mergers drive the stellar growth?
  – requires ionized gas (Hα) kinematics)

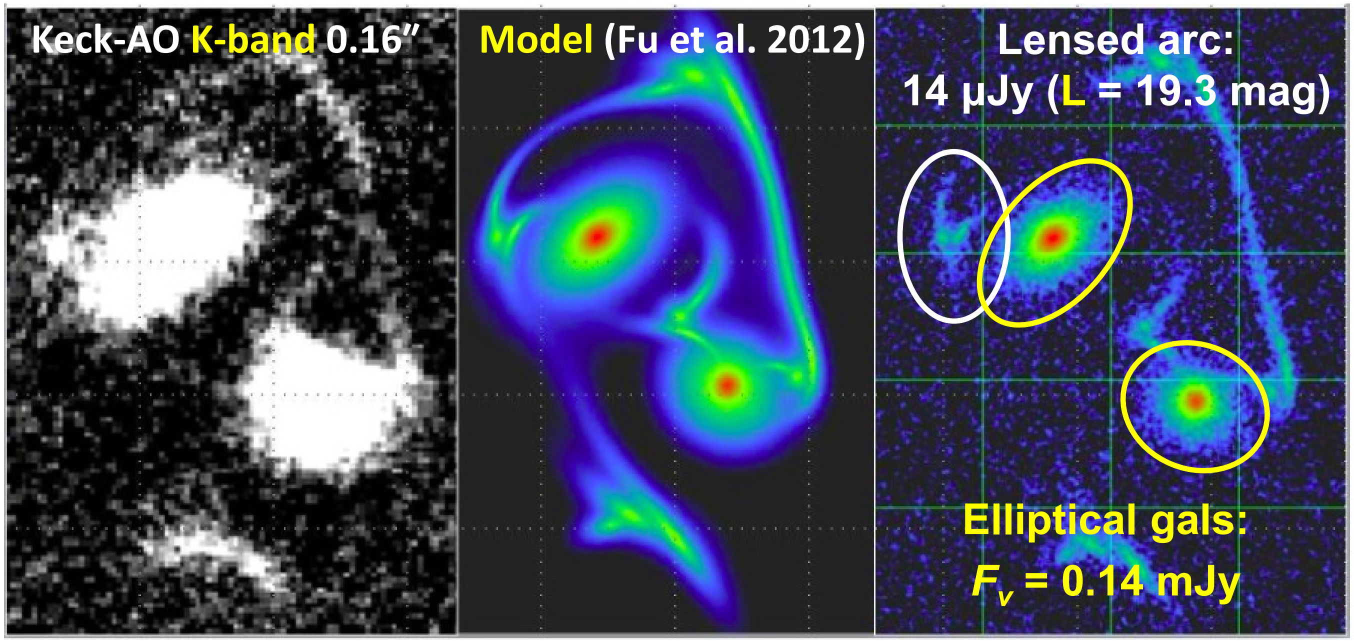
- How important is stellar feedback?
  – compare velocity dispersions: ionized gas ⇔ cold gas ← ALMA

High-z – Observations

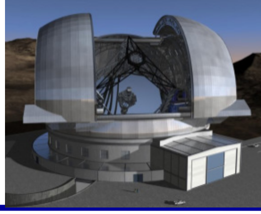


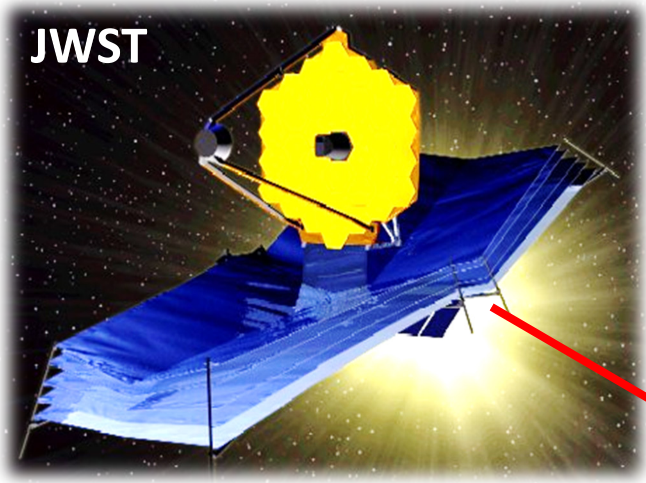
- Follow-up of strongly-lensed, dusty SF galaxies
  - Herschel/Planck: 5 sources / deg^2
- Constrain morphology and stellar mass distribution down to 100 pc scale,
  - uses trusted rest-frame optical line-diagnostics shift into METIS window

Simulation based on real system:
Two ellipticals @ z=1
&
a lensed sub-mm galaxy @ z = 3.3

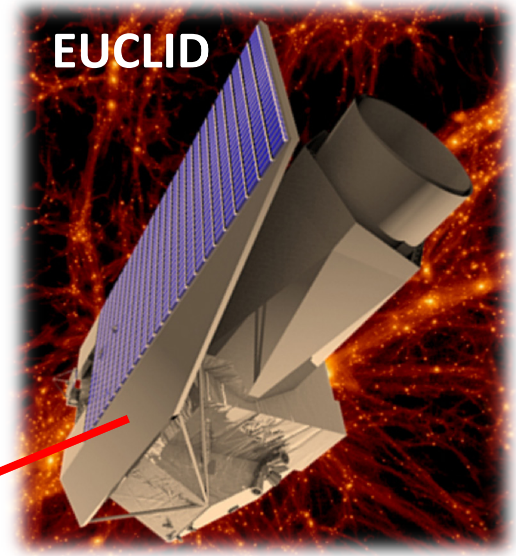


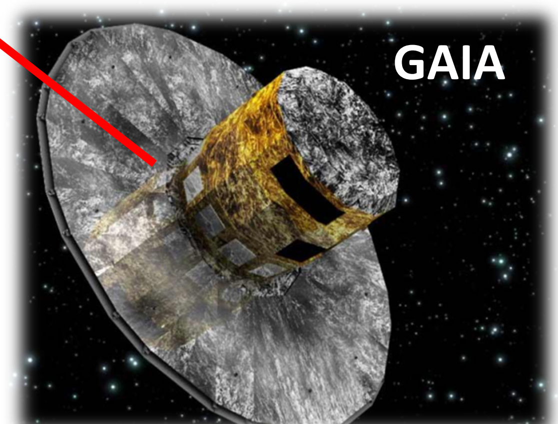
Source Follow-ups





10 years from now, our catalogs will be full of peculiar sources for follow-up studies.






THE END OF MY TALK
IS JUST THE BEGINNING
METIS