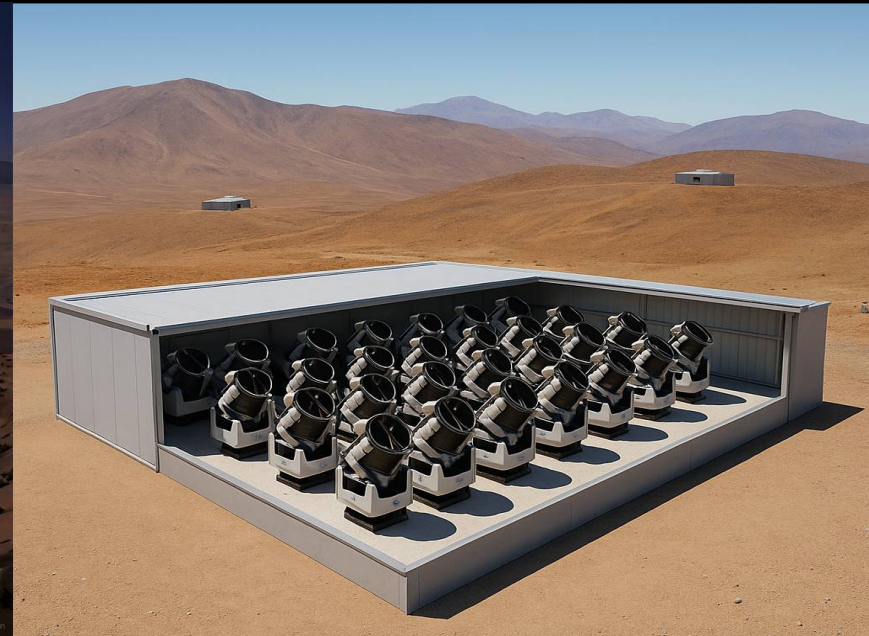
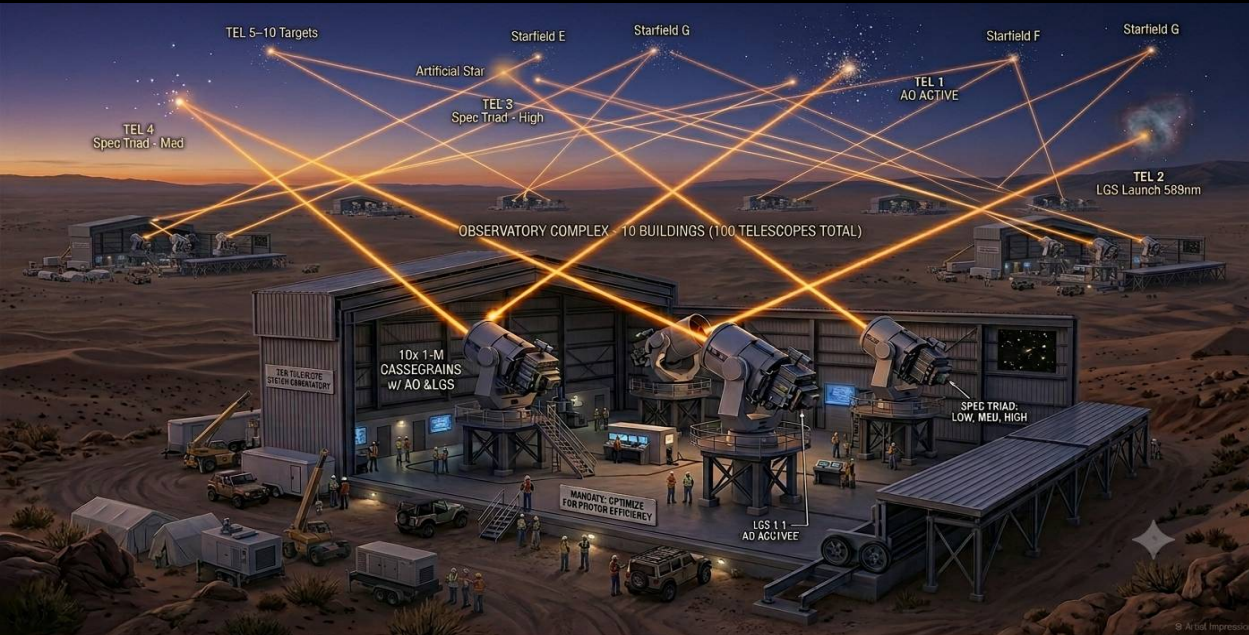




TIME DOMAIN TELESCOPE

TIME DOMAIN TELESCOPE

An ESO Expanding Horizons Initiative



“Spectra when you need them. Anywhere, Anytime!”

www.tdtelescope.org

Paul Groot

p.groot@astro.ru.nl

Radboud Universiteit

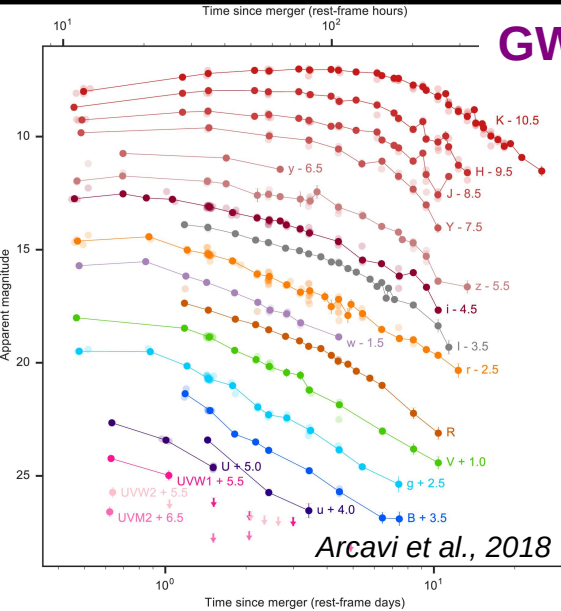


SAAO
South African
Astronomical Observatory



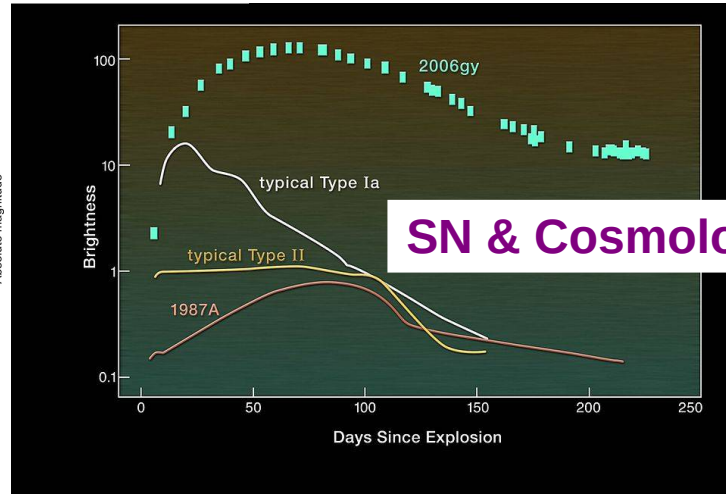
Time Domain: A tool for all astronomy

TIME DOMAIN TELESCOPE

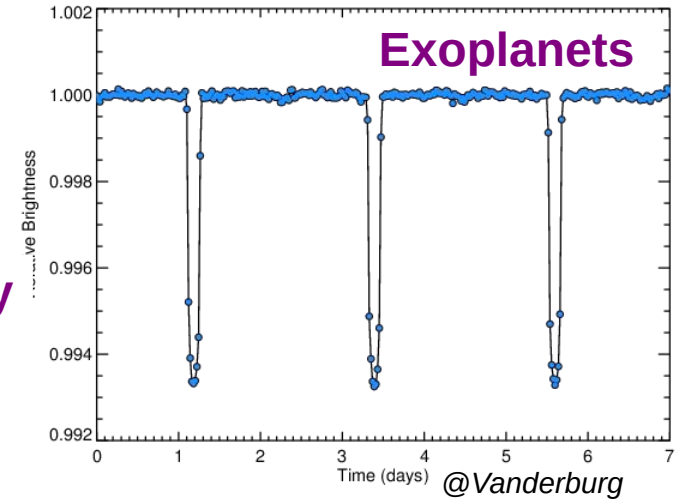


GW+Kilonovae

Arcavi et al., 2018

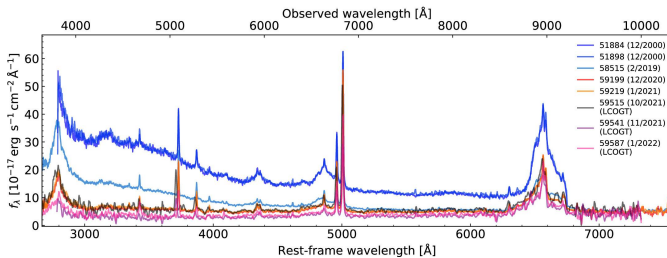


SN & Cosmology

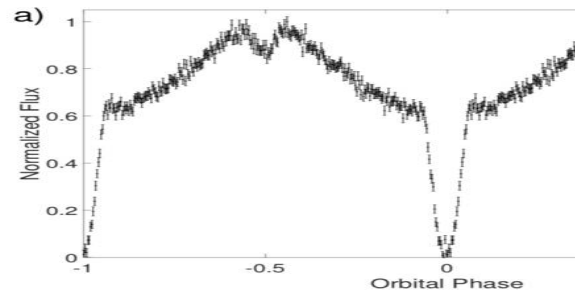


Exoplanets

Galaxy Evolution



Zeltny et al., 2024



Stellar Evolution

Burdge et al., 2020



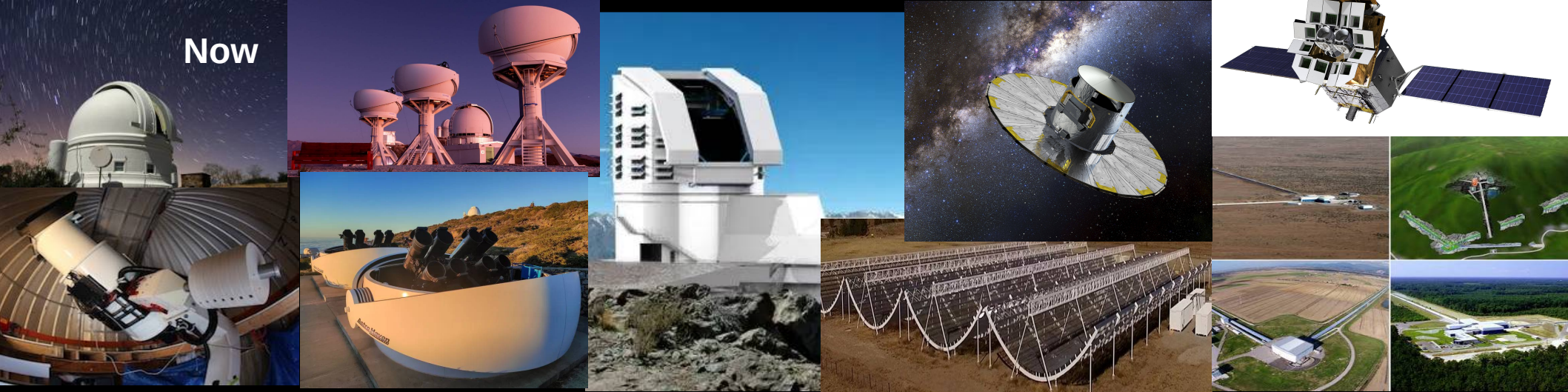
Solar System



Finding a variable/transient: Explosion

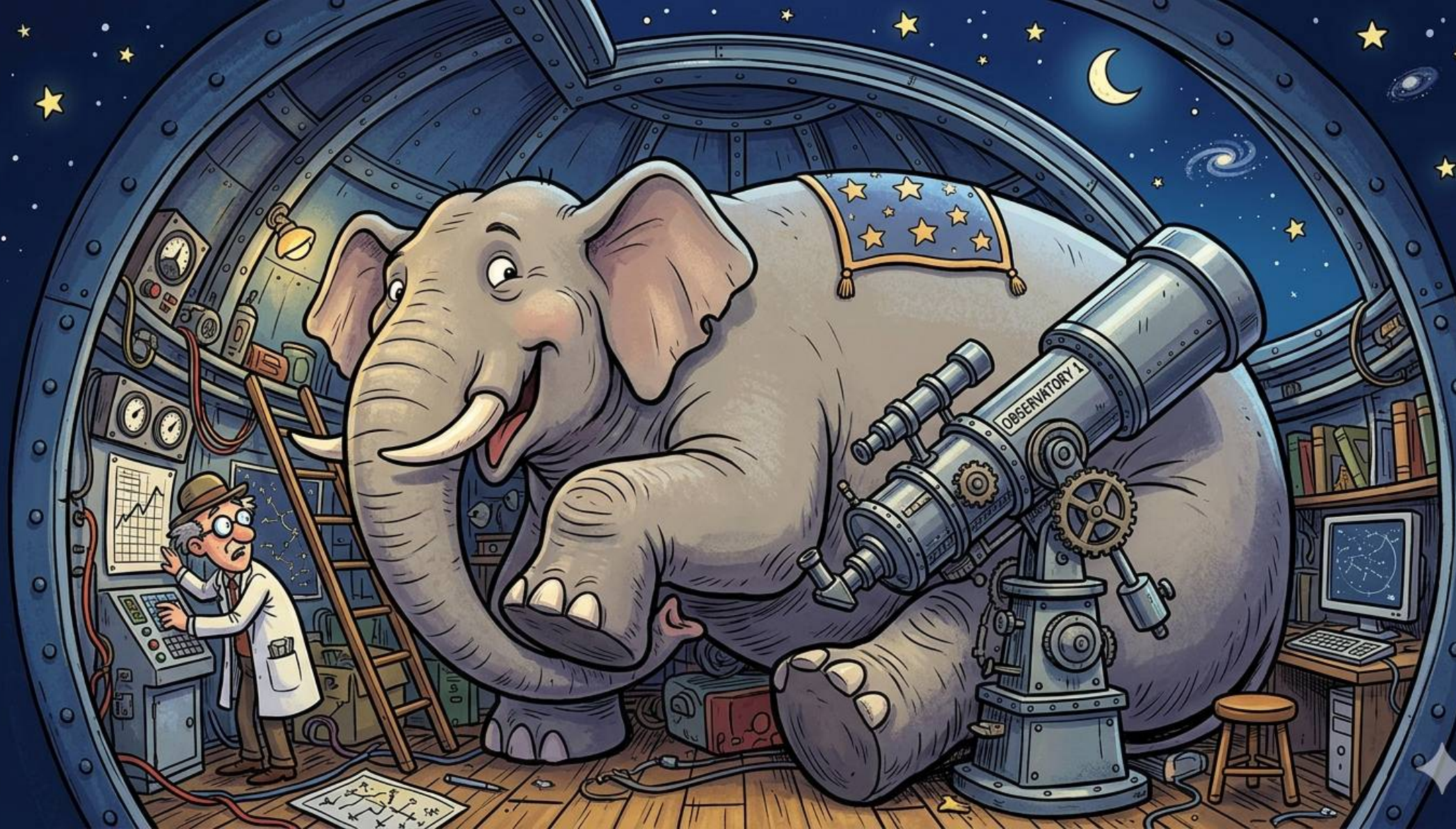
TIME DOMAIN TELESCOPE

Now



Near Future







Expanding Horizons

How to complement /
strengthen ESO facilities?

What's missing?

Time-critical spectroscopy!





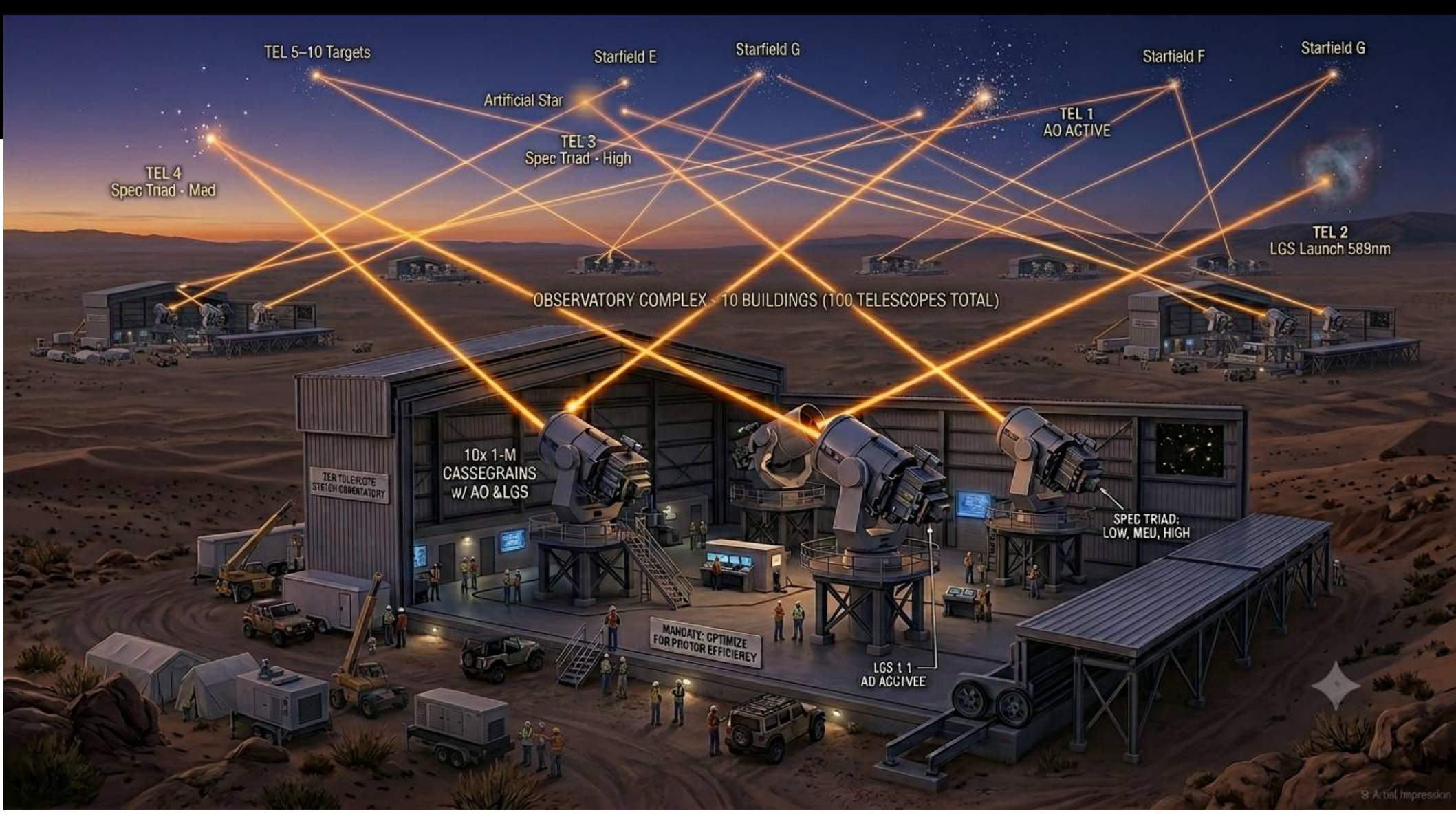
What is the Time Domain Telescope?

TIME DOMAIN TELESCOPE

- Robotic *spectroscopic* telescope array for time-domain, time-constrained observations
→ *Global coverage in 2040s*
- 100 unit telescopes of ~2 m, AO enabled → Diffraction limited : 0.12" @ 2m @ 400nm
→ *Essential in background-limited regime ($m > 21$)*
→ *Essential in crowding-limited regions*
- Unit telescopes *individually* steerable/programmable
→ *Go big or go wide: $N \times 1$ unit, or $1 \times N$ units, or $m \times n$ units*
- Multiple units ('25') feed cluster of spectrographs
(e.g. $\mathcal{R} = 10^3, 10^4$ and 10^5 per cluster): VIS-NIR: 0.35 – 1.8 μm
- Facility: Proposal/PI-based observing where 'Hard ToO' is default:
→ *Scheduling challenge*

Key technological characteristics:

- 1) Robotic AO in the visual
- 2) Near read-noise-free detectors ($\leq 0.2 \text{ e}^-$)
- 3) On-the-fly scheduling (<1 min response time)



TEL 5-10 Targets

Starfield E

Starfield G

Starfield F

Starfield G

Artificial Star

TEL 3
Spec Triad - High

TEL 1
AO ACTIVE

TEL 4
Spec Triad - Med

TEL 2
LGS Launch 589nm

OBSERVATORY COMPLEX - 10 BUILDINGS (100 TELESCOPES TOTAL)

10x 1-M
CASSEGRAINS
w/ AO & LGS

SPEC TRIAD:
LOW, MED, HIGH

LGS 11
AO ACTIVE

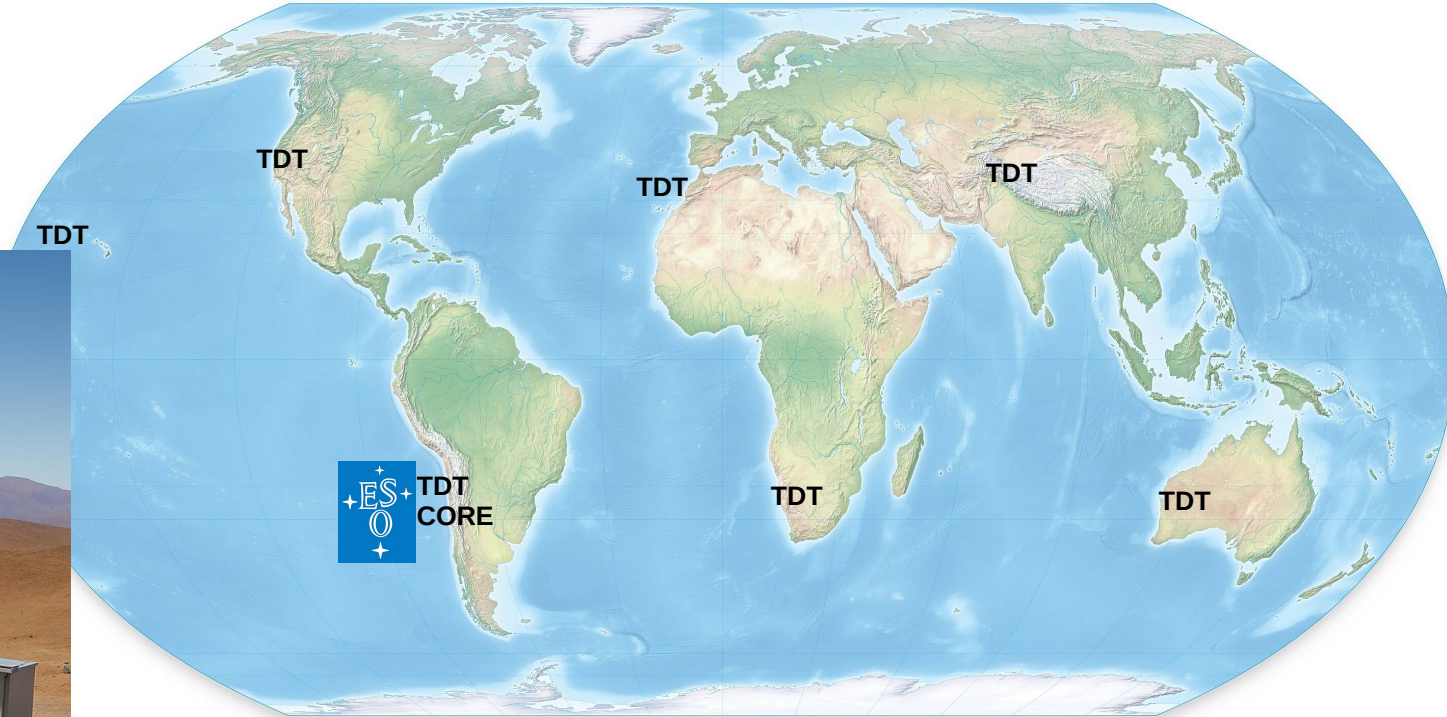
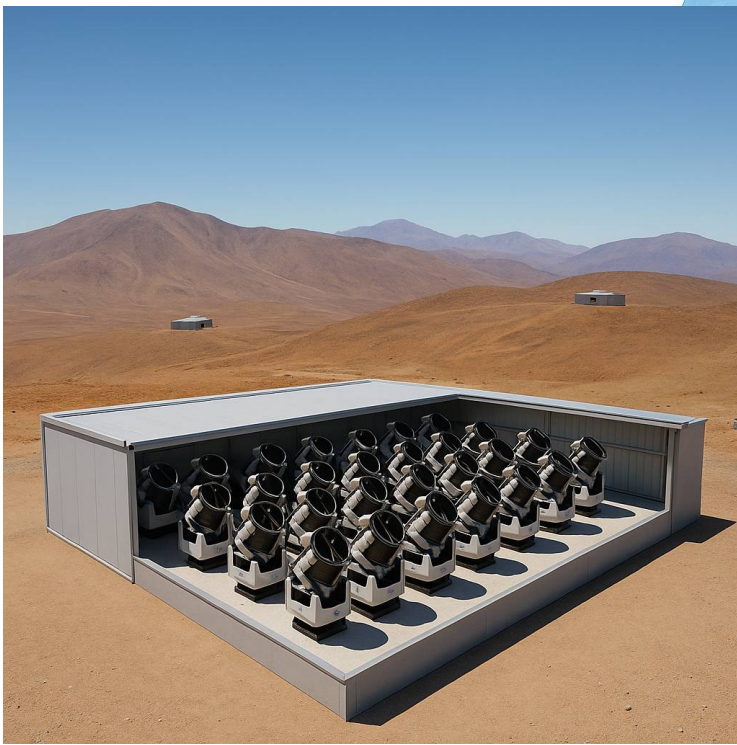
MANDATORY: OPTIMIZE
FOR PROTOR EFFICIENCY



TIME DOMAIN TELESCOPE

TDT Global: 24/7 coverage

- Core at ESO
- Global partnerships



“ Spectra when you need them. Anywhere, Anytime!”



Who are the TDT?

TIME DOMAIN TELESCOPE

Europe-based initiative, in the context of the ESO Expanding Horizons program

TDT Steering Committee



Paul Groot
Radboud & Cape Town

Transients,
Compact Binaries
Instrumentation



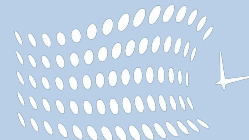
Thomas Kupfer
Hamburg Observatory

Compact Binaries &
LISA Sources



Samaya Nissanke
DESY / DZA

Multi-messenger Astronomy
Gravitational Wave Mergers



Simone Scaringi
Durham University

Accretion Physics at
All scales



Kieran O'Brien
Durham University

Instrumentation &
X-ray Binaries



Boris Gänsicke
University of Warwick

Compact Binaries &
White Dwarfs

You!
www.tdtelescope.org

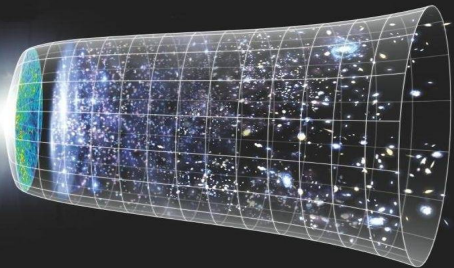
*Broad collaboration with
100+ scientists and
instrumentalists across Europe*



TDT Science Case

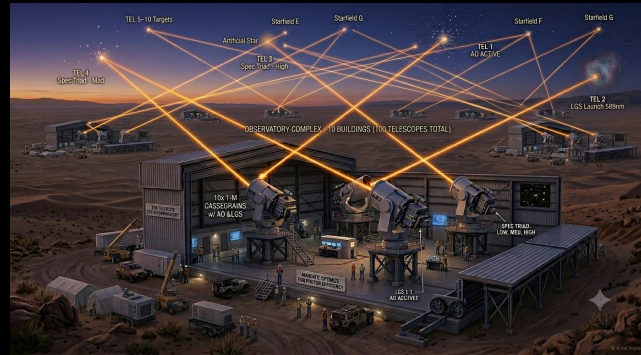
1: Origin of the elements

- Gravitational wave mergers
- Supernovae
- Gamma-Ray Bursts
- Stellar furnaces



2: What powers the Universe?

- Accretion physics
- at all scales, from YSO to QSO
- Stellar mergers incl. LISA sources
- Growth of supermassive black holes

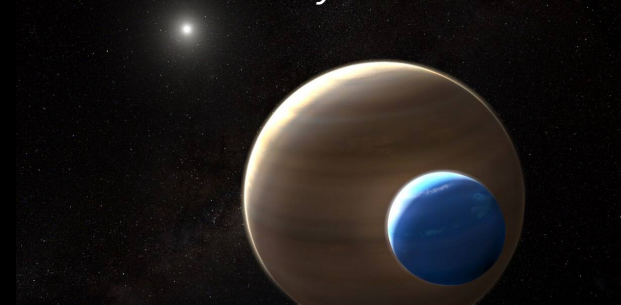


3: Expansion history of the Universe?

- *Supernovae Type Ia as tracers*
- *Gravitational wave sirens*
- *Cosmic Distance Ladder, near and far*

4: Structure of exoplanetary systems

- Host star – planet interactions
- Remnants of exoplanetary systems
- The outer Solar System



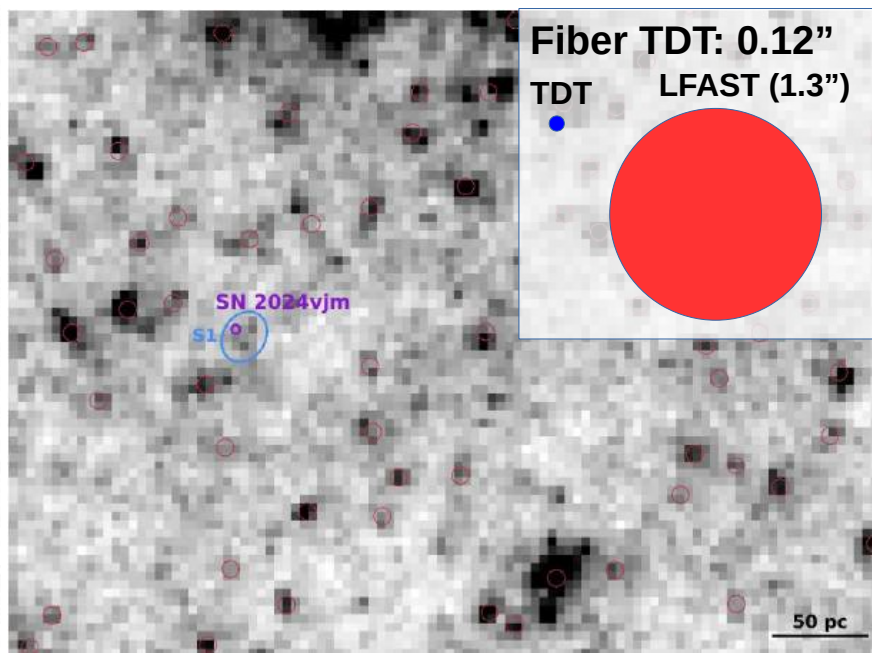
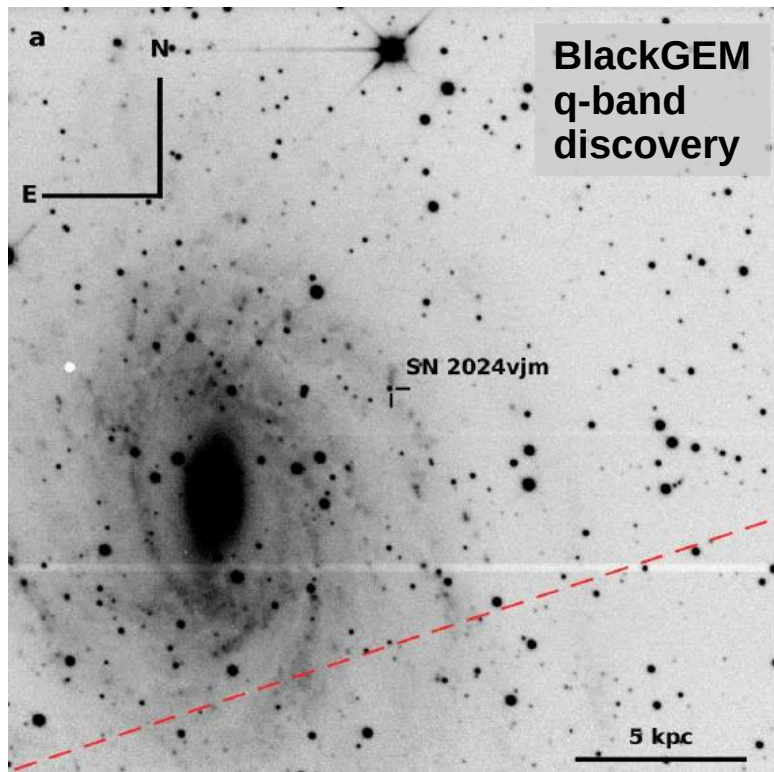


TDT Example Science

TIME DOMAIN TELESCOPE

SN2024vjm

- Discovered with BlackGEM
- In NGC6744 at 9 Mpc
- SN Type Iax: ultralow-luminosity $M_{\text{abs,peak}} = -12$
- Euclid pre-explosion image @ 0.1" resolution



TDT:

- Remnant?
- Companion?
- Cluster?
- Late phases?

(Zimmerman et al. 2026)

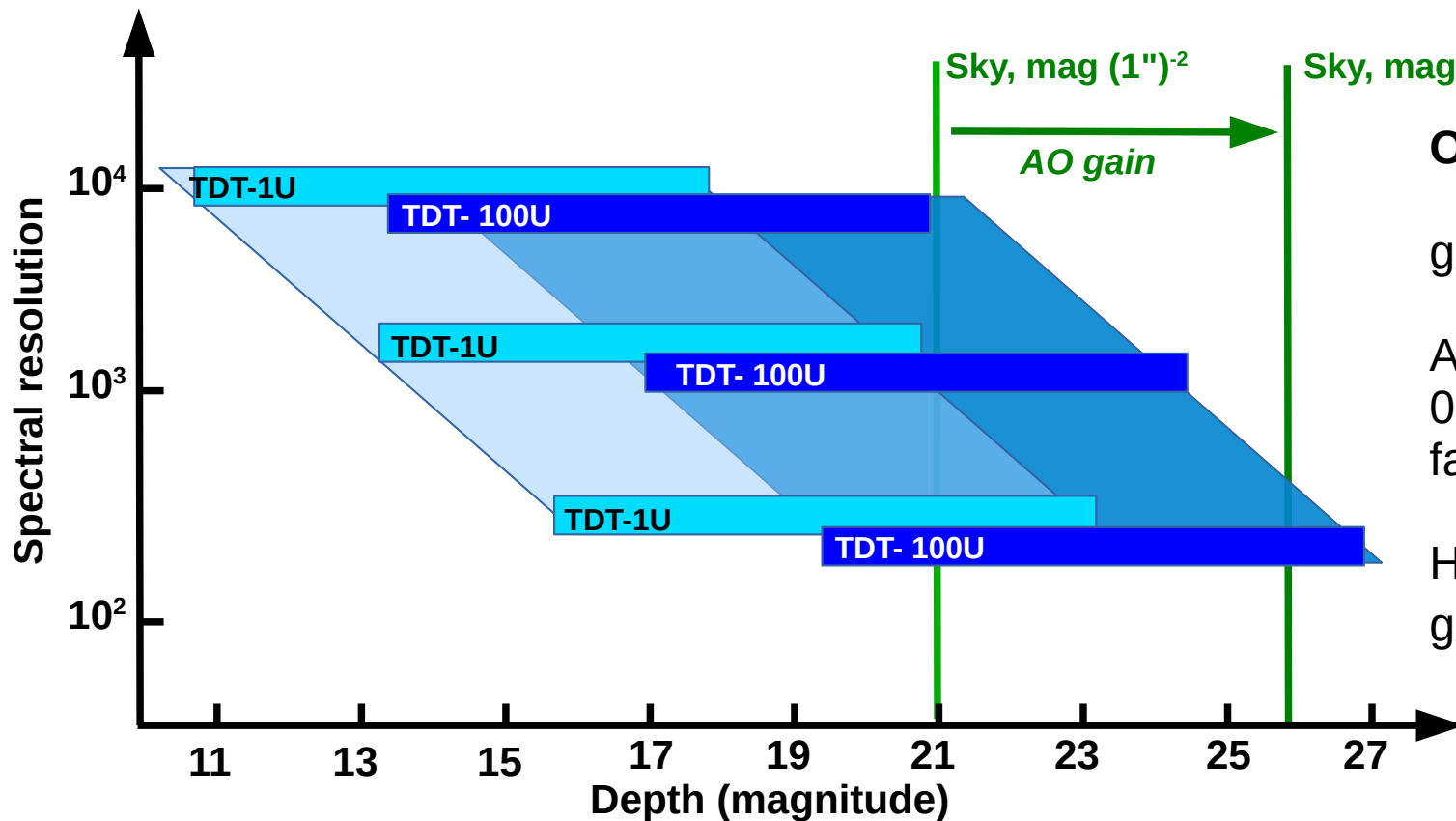
Euclid pre-explosion at 0.1" spatial resolution at VIS = 25 mag



TIME DOMAIN TELESCOPE

AO essential: Sky Background

TDT sensitivity (deepest: SNR = 5 in 900s)



Optical sky background:

$$g_{\text{sky}} \sim 21 \text{ mag arcsec}^{-2}$$

At a spatial resolution of $0.1'' \rightarrow$ sky background factor **100x lower**,

Hence:

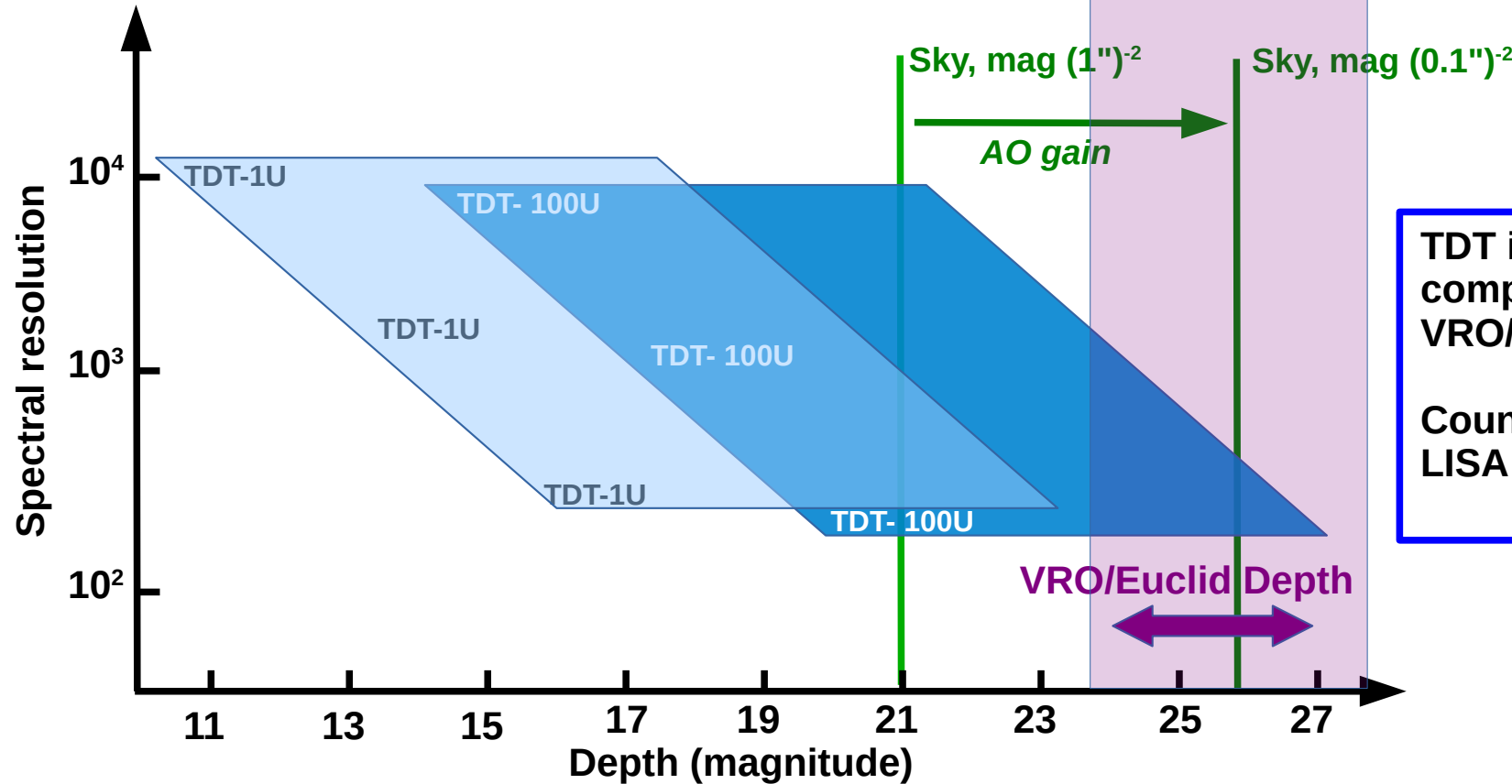
$$g_{\text{sky}} \sim 26 \text{ mag (0.1'')}^{-2}$$



TDT Sensitivity vs. VRO/Euclid/Roman

TIME DOMAIN TELESCOPE

TDT sensitivity (deepest: SNR = 5 in 900s)



TDT is spectroscopic complement to VRO/Euclid/Roman

Counterpart to LISA & ET, Athena, HWO



TDT Exposure Time Calculator

TDT ETC on www.tdtelescope.org Try out your case!!

e.g. SNR=10 on 100 x 2m @ 25 mag and R=5000: $t_{\text{int}} = 36$ minutes...

Telescope, Observation Parameters & Results

TELESCOPE CONFIGURATION

N

Number of Unit Telescopes

D

Diameter of Unit Telescope m

OBSERVATION

m

Target Magnitude g-band

texp

Exposure Time seconds

SNR

Signal-to-Noise Ratio

SPECTROGRAPH

R

Spectral Resolution

N = 100

D = 2m

g = 25

SNR=10

R=5000

100

2.0

25

10

5000

REQUIRED EXPOSURE TIME

36.3 min

(2178 seconds)

TOTAL COLLECTING AREA

314.2

m²

EQUIVALENT DIAMETER

20.00

m

FIBRE DIAMETER

0.104

arcsec

DIFFRACTION LIMIT

0.0692

arcsec

SOURCE PHOTON RATE

5.21e-4

photons/s per telescope

Parameter Space Explorer

X-AXIS

m — Magnitude (g-band)



TIME DOMAIN TELESCOPE

TDT: Why 2m?

- **Balance** between **D** and **N** → Goal of **20+ meter** combined aperture
- **Blue AO**: 80%EE in 0.1" @ 400nm → **D ≥ 1.8m**, with ~500 actuator DM
- Focal **Anisoplanatism** (cone effect) → **D ≤ 2.2m** for **SCAO@NaD** @ 0.8" median (Isoplanetic angle ~2")
- **Tip-Tilt star**: requires star $G < 17$ within ~3' diameter : **RC** design + ~2m for $\Sigma_{G=17}$

2m RC design with single LGS: close to optimal

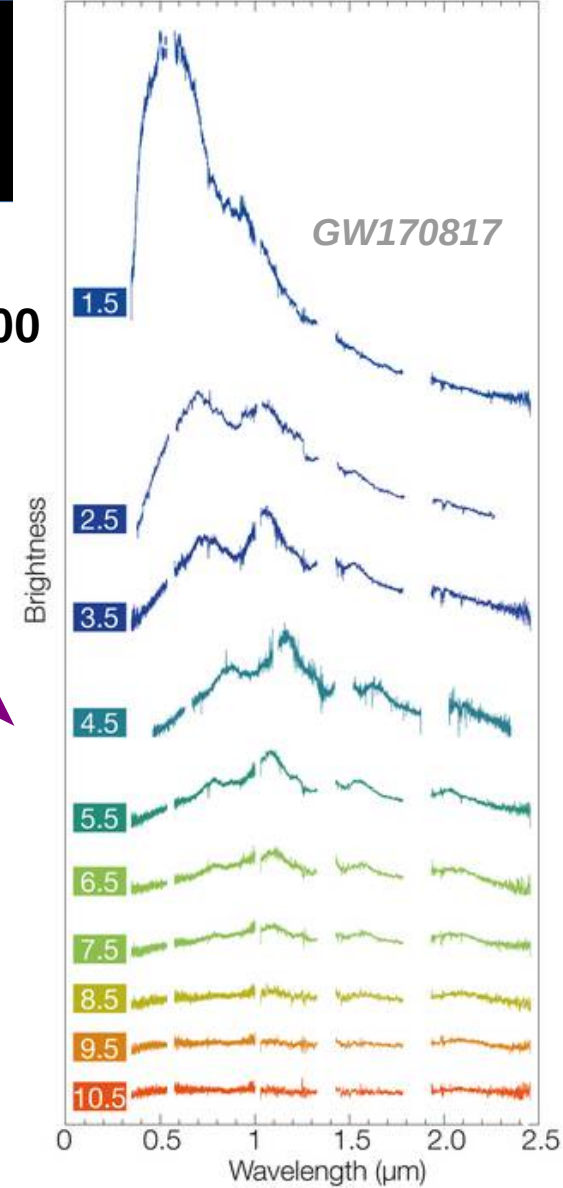
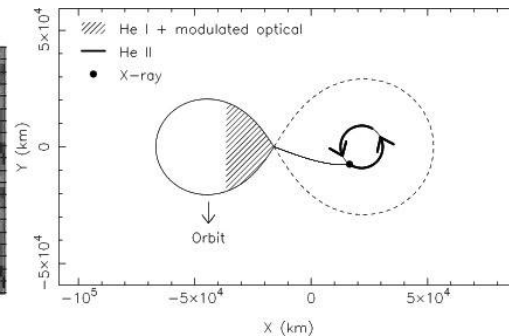
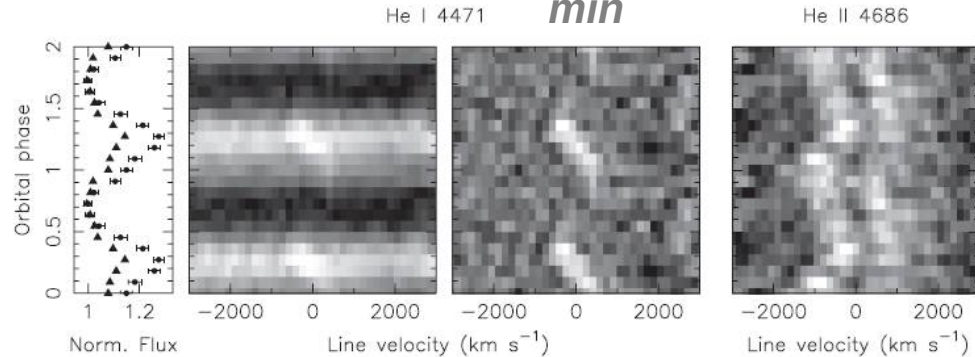


TDT: Why 100?

TIME DOMAIN TELESCOPE

- **Balance** between D and N → Goal of **20+ meter (at 0.1")** aperture
- **Sensitivity** down to $g \geq 25 \leq 1800s$ → Requires 20+ meter → **N=100**
- $R_{SN} = 42$ per sky per night @ $r = 20$ → >1000 per night @ $r=24$
 - Already now **only 10%** gets ID-spectrum and 10% of those 10% get detailed study → 99% go unstudied
 - Completely new classes: GW sources ([LISA](#) and [LIGO/Virgo/ET](#))
 - **GW170817 at 1 Gpc** → $r = 23$ @ max.

HM Cnc @ 5.4 min





TDT Key Technologies

TIME DOMAIN TELESCOPE

- **Robotic adaptive optics in the blue**

- Near-diffraction limit in the visual/blue → **Development needed**
- Laser tomography: 1 laser (beam) per telescope
- Robotic, '24/7' operations on 100 unit array → Stability, MTBF paths

- **Low read-noise detectors**

- To be photon-noise limited, not sky-background or read-noise
- qCMOS detectors (now at $<0.3 e^-$): **further push**
- **MKID** detectors? Push on routine operations, energy sensitivities

- **Spectrographs**

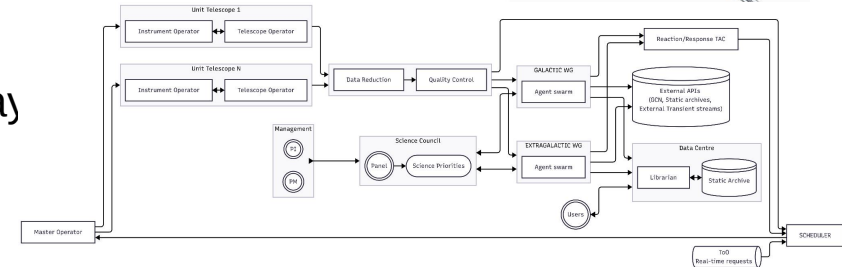
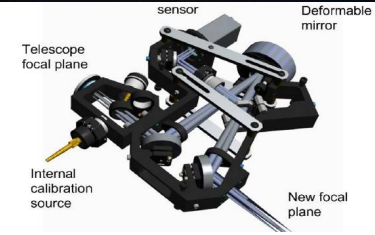
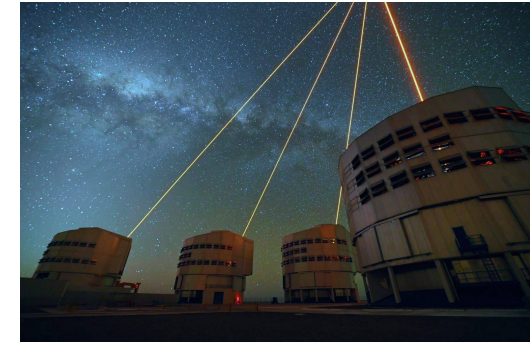
- Spectrograph per cluster, fiber throughputs in blue
- Photonic spectrographs? One set per telescope?
- Photonic lanterns with SpecOnChip?

- **Dynamic scheduling**

- Highly dynamic and restrictive scheduling on full array
- Agentic approach?

Readout noise (typ.)	Standard scan	0.43 electrons (rms), 0.39 electrons (median)
	Ultra quiet scan	0.30 electrons (rms), 0.25 electrons (median)

Hamamatsu ORCA manual





TIME DOMAIN TELESCOPE

TDT Development path

NOW



2027
-
2035



2033
2036
2041
2045
2048 ---

Precursor-TDT: *MAST, MARVELS, MINERVA* (no AO)

- Synchronous, array configuration
- Scheduling; Fiber coupling

Proto-TDT:

4 x ~2m, LSG – AO, 1 spectrograph

- Laser AO, Photonic Lantern+ SpecOnChip, qCMOS
- Mean-Time-Between-Failures
- Asynchronous operations, Agentic scheduling

TDT:

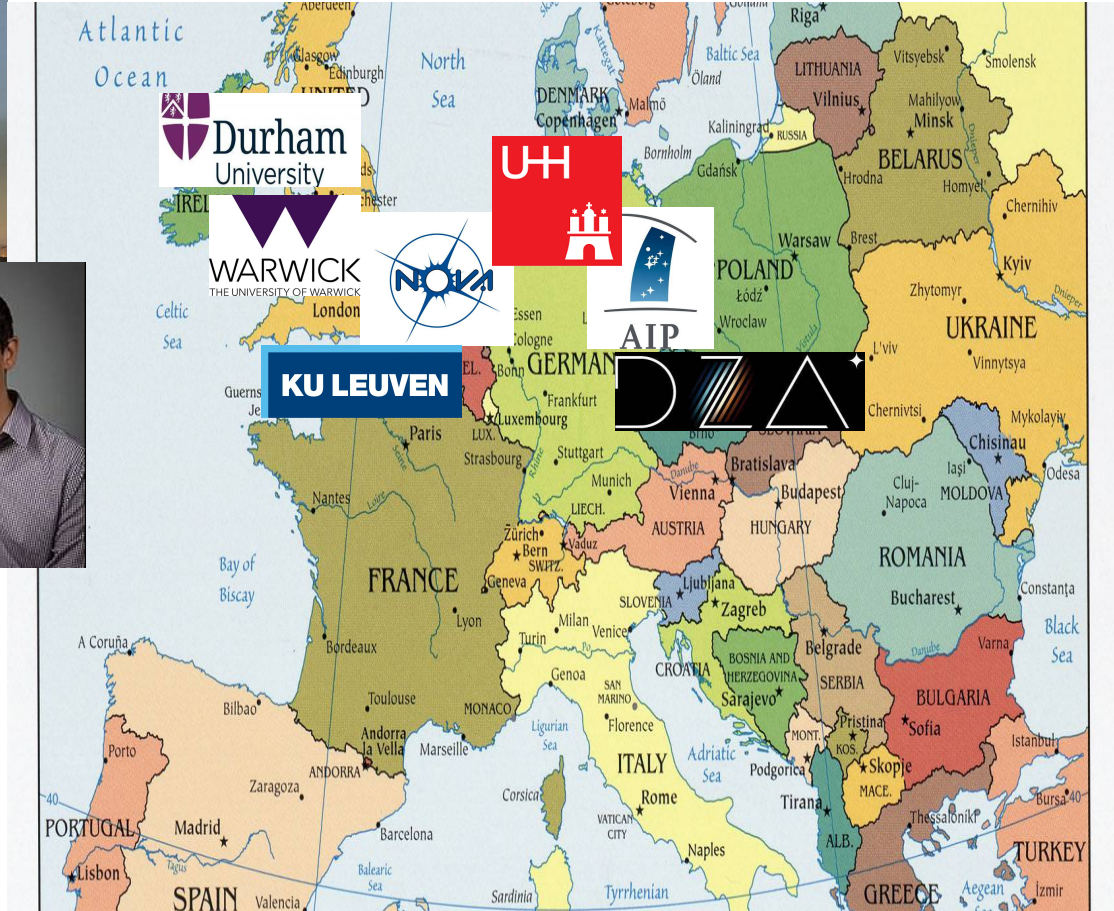
- Start full design study
- PDR
- FDR
- MAIT
- 1st Light

“ Spectra when you need them. Anywhere, Anytime!”



TDT Prototype in reality

TIME DOMAIN TELESCOPE



Work packages

- Adaptive Optics
- PM & IR Spectrograph
- Detectors
- Photonic Lanterns & SpecOnChip
- High Res. Spectrograph
- Science Consortium

*Diffraction-limited version of
NTT+SOXS*



TDT Summary

TIME DOMAIN TELESCOPE

Europe-based initiative, in the context of ESO Expanding Horizons

- Revolutionary Optical-nIR *spectroscopic* array of 100+ units
- *Designed* for time-domain, time-critical observations.
- Can be used for *any* spectroscopy science case in OIR.
- *Each* ~2m AO-enabled unit at 0.1" spatial resolution
- Core at [ESO](#), global coverage in partnerships

Sign up at www.tdtelescope.org

“ Spectra when you need them. Anywhere, Anytime!”

