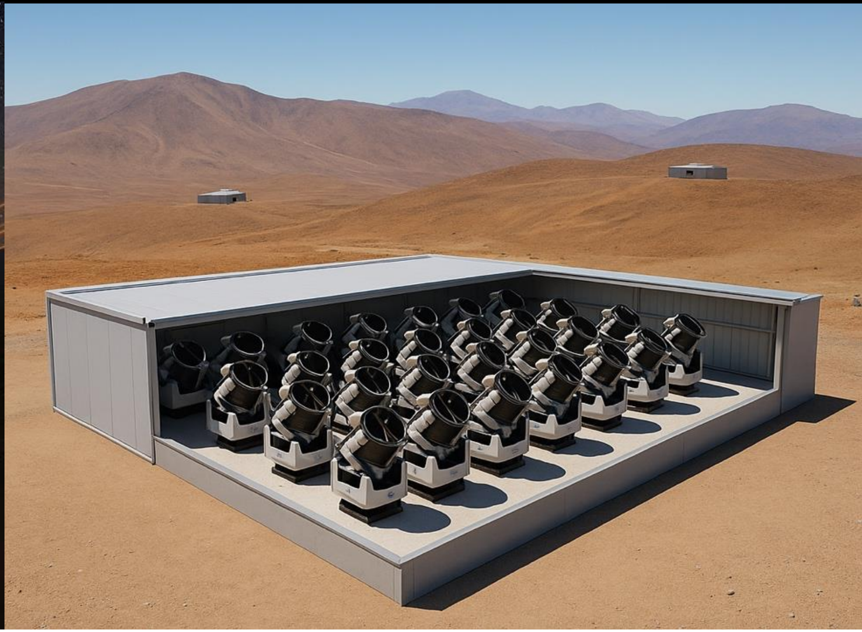
Observing the most compact binaries with the Time Domain Telescope



Thomas Kupfer

University of Hamburg / Hamburg Observatory

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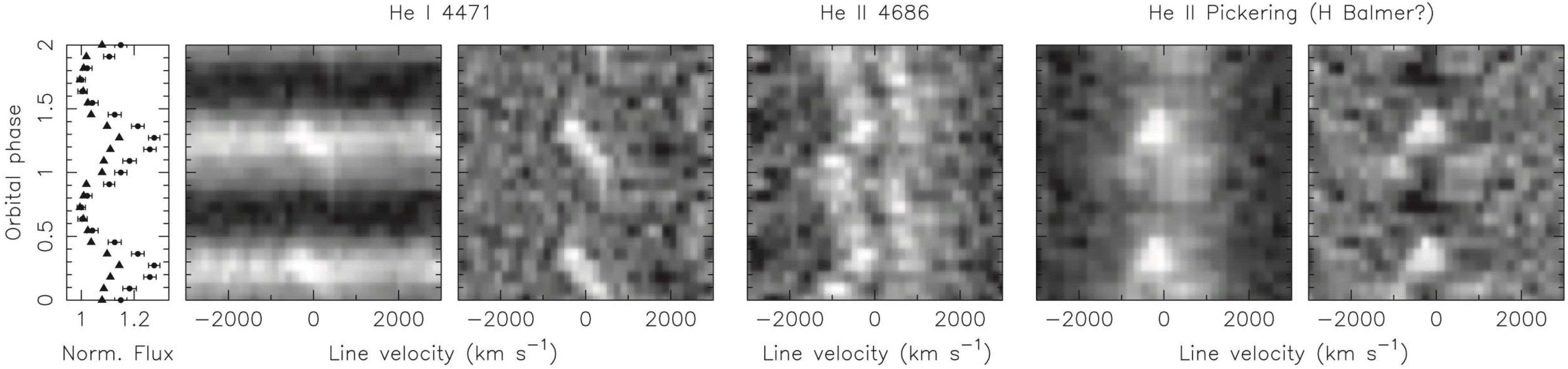
Universität Hamburg

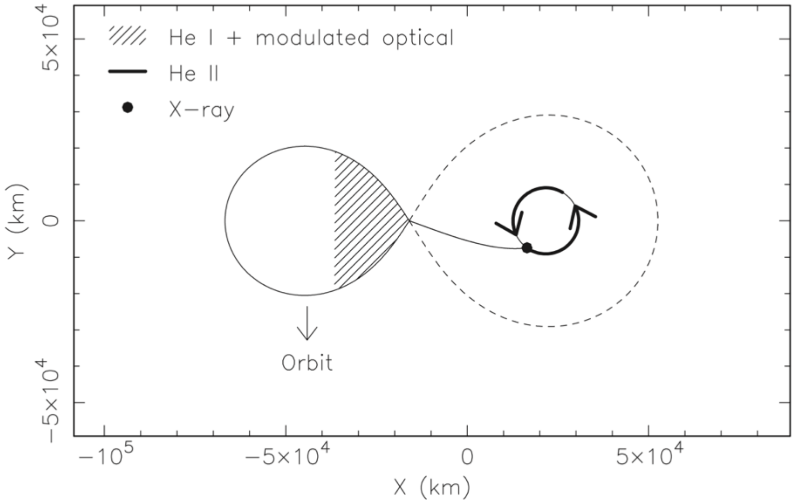
www.tdtelescope.org

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

erc
European Research Council

HM Cnc the most compact binary known





<u>HM Cnc:</u>

Orbital Period: 5.4min -> most compact binary known.

Mass transferring: Stream hits the accretor directly

Merger timescale: A few ten thousand years

Gravitational wave source: One of the loudest LISA sources known

TIME DOMAIN TELESCOPE

HM Cnc the most compact binary known

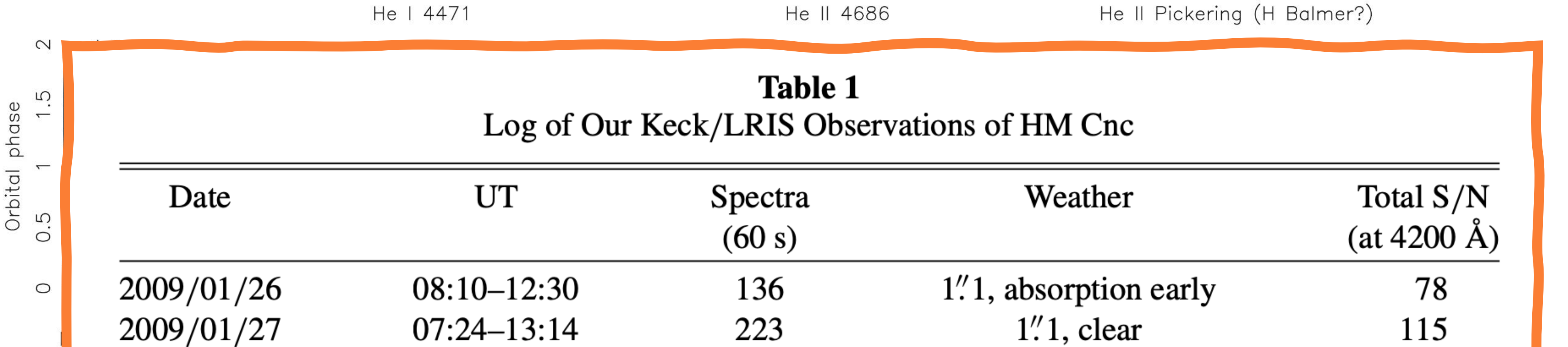
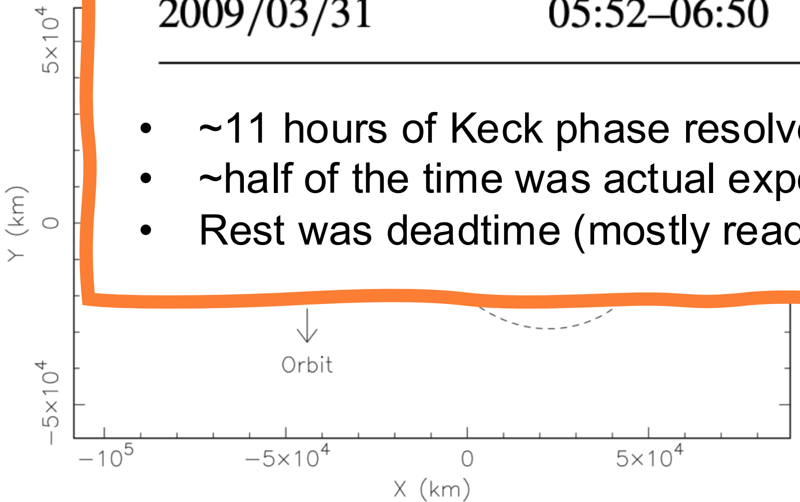


Table 1
Log of Our Keck/LRIS Observations of HM Cnc

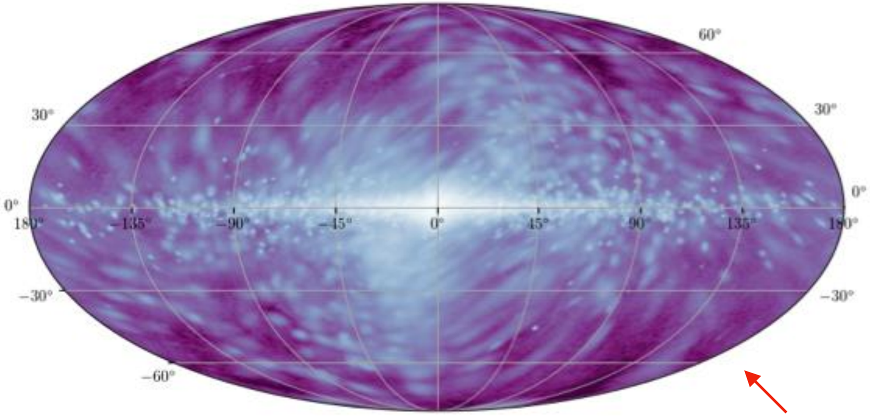
Date	UT	Spectra (60 s)	Weather	Total S/N (at 4200 Å)
2009/01/26	08:10–12:30	136	1.″1, absorption early	78
2009/01/27	07:24–13:14	223	1.″1, clear	115
2009/03/31	05:52–06:50	41	1.″3, clear	41

- ~11 hours of Keck phase resolved spectroscopy
- ~half of the time was actual exposure time
- Rest was deadtime (mostly readout) -> ***lots of lost time***



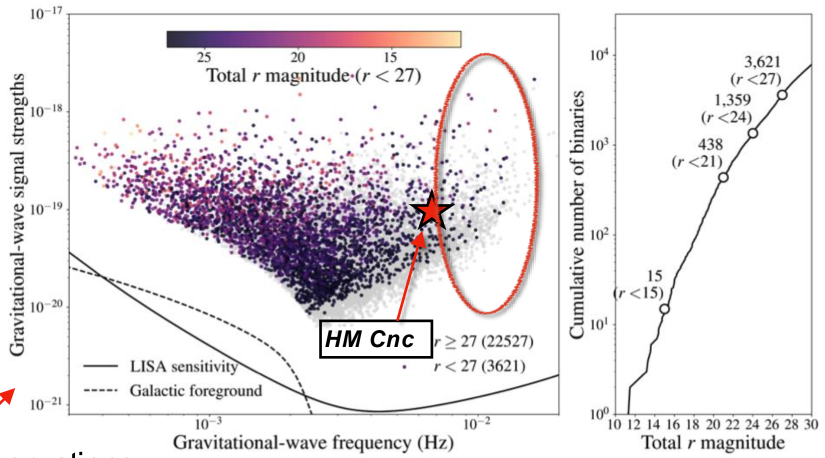
LISA binaries when LISA turns on

TIME DOMAIN TELESCOPE



Littenberg & Cornish 2023

The LISA sky after 12months of LISA observations



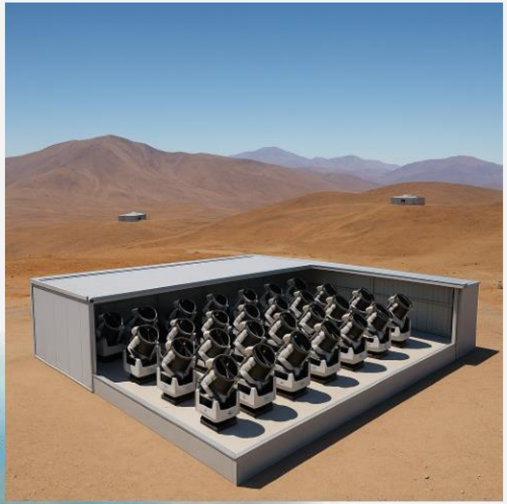
From Munday et al. 2025 (ESO Expanding Horizons white paper

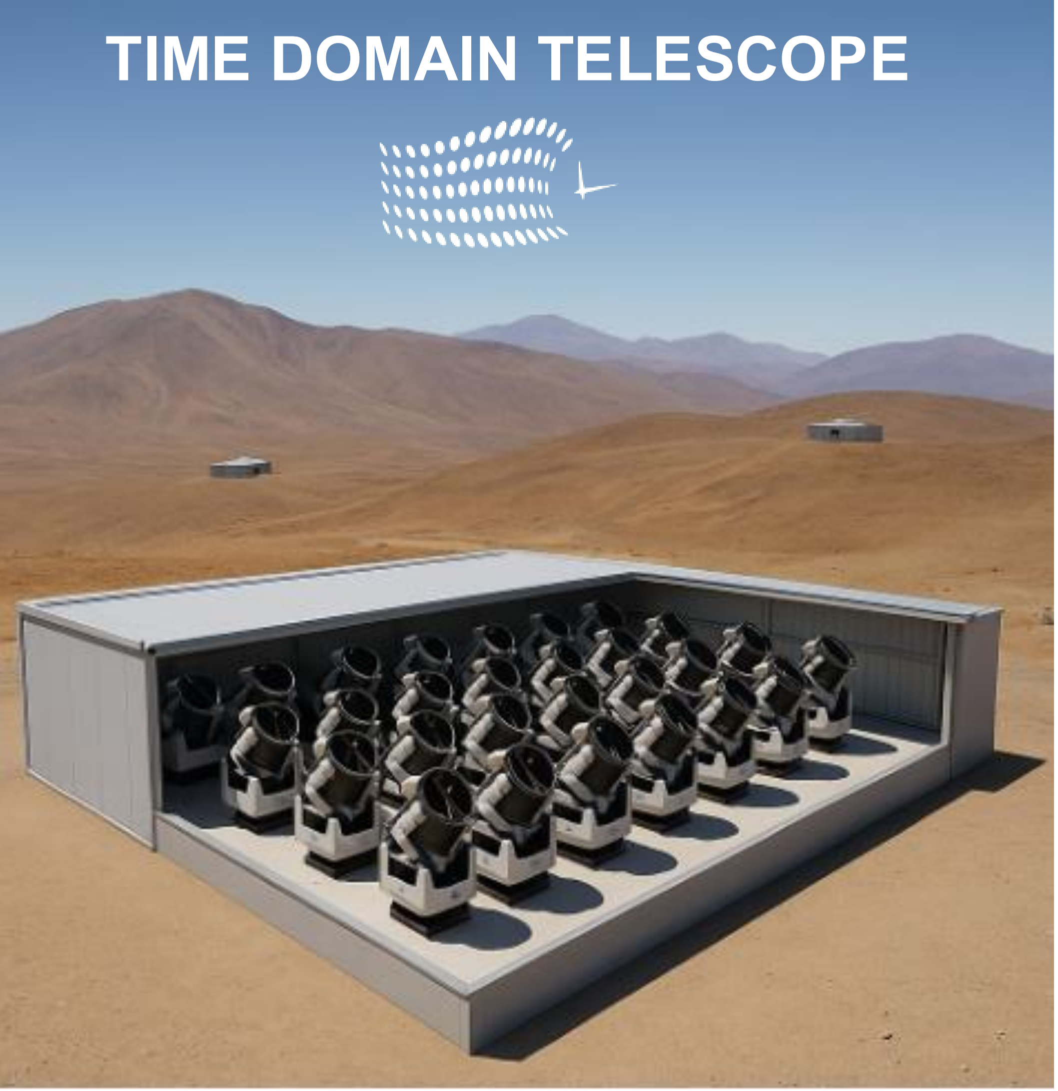
	6 mo	1 yr	2 yr	4 yr
# detected	6,590	11,142	18,281	29,059
2D mapped	104	1,065	4,138	6,304
3D mapped	19	129	1,010	2,373
$\mathcal{M}$ measured	233	737	4,432	10,770

Sky loc. < 1 sqd.
Distance < 10%

Table from
Cornish & Robson 2017

How to complement / strengthen ESO facilities
Our proposal: Time Domain Telescope
<u>Letters of Intent:</u> **December 1st 2026**
<u>Full proposal:</u> **December 1st 2027**





Robotic *spectroscopic* telescope array

Unit telescopes of size ~2 m, AO enabled – Diffraction limited

→ *a 2m@0.12" resolution equal in SNR to a 6.5m@0.8" resolution*

→ *Essential in background-limited regime (21 < m < 27)*

→ *Essential in crowding-limited regions (Bulge, Globular cluster etc.)*

Multiple units ('25') feed cluster of spectrographs

→ *e.g. R ~ 10^3, 10^4 and 10^5 per cluster): VIS-NIR: 0.35 – 2.5 μm*

Unit telescopes *individually* steerable/programmable

→ *Go big or go wide: N x 1 unit or 1 x N units or m x n units*

Proposal/PI-based observing

→ *from regular scheduled to hard-ToOs*

<u>Key technological characteristics:</u>

1) *Robotic AO in the visual*
2) *Near read-noise-free detectors → No read-noise penalty*
3) *On-the-fly scheduling (<1 min response time)*

"Spectra when you need them. Anywhere, Anytime!"

TIME DOMAIN TELESCOPE

Who are the TDT?

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

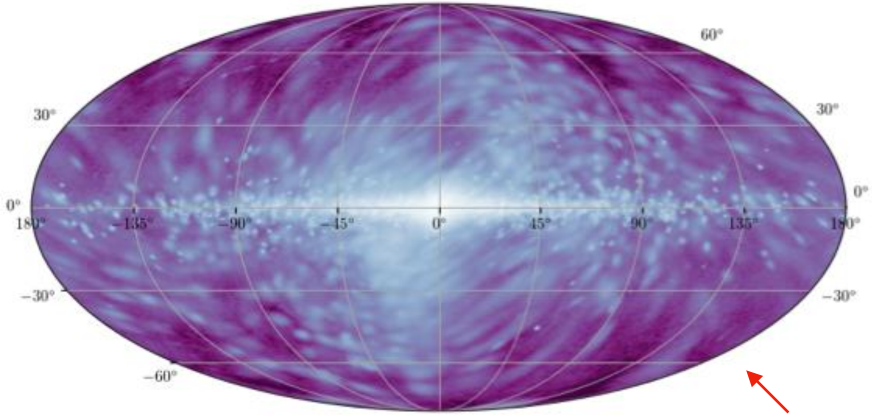
Compact Binaries &
White Dwarfs

Broader collaboration with 100+ scientists and Instrumentalists across Europe

We want you!
Sign up here

LISA binaries when LISA turns on

TIME DOMAIN TELESCOPE



Littenberg & Cornish 2023

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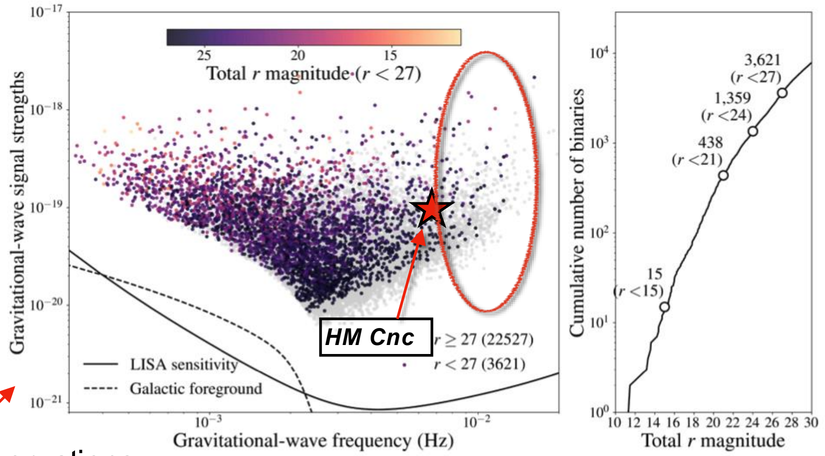

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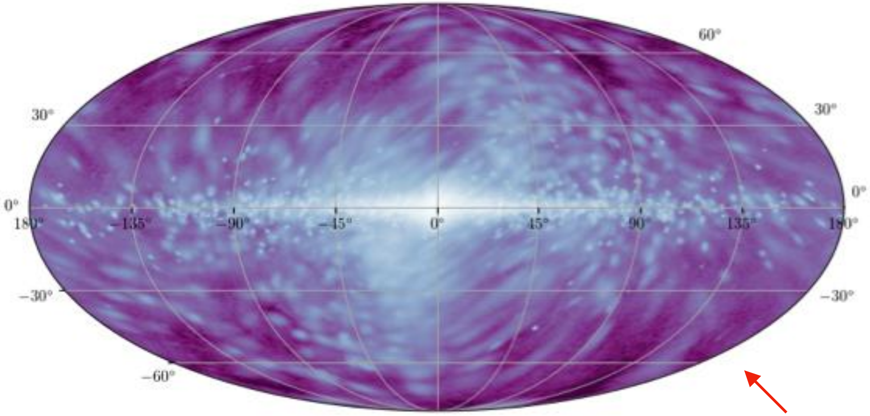
Distance < 10% → 3D mapped

Table from
Cornish & Robson 2017

LISA sources with the TDT

TIME DOMAIN TELESCOPE



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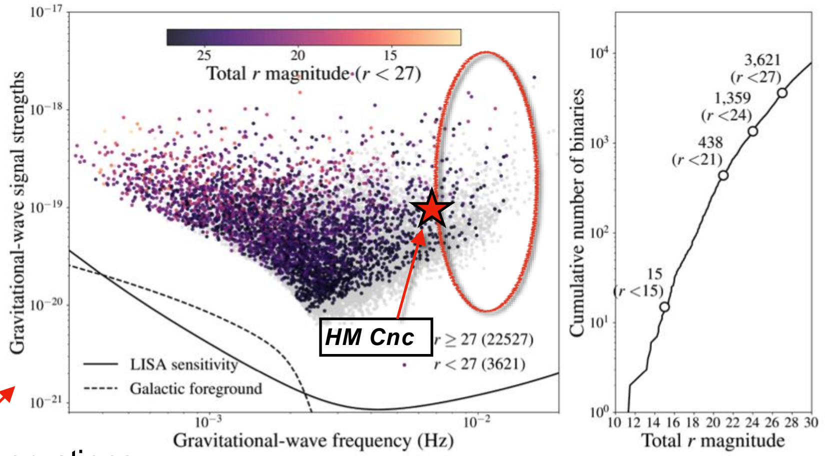

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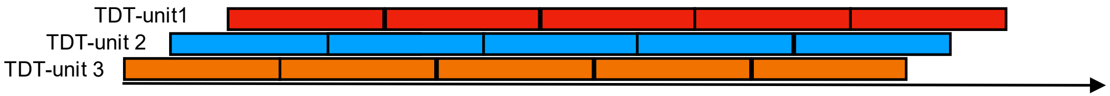
Table from
Cornish & Robson 2017

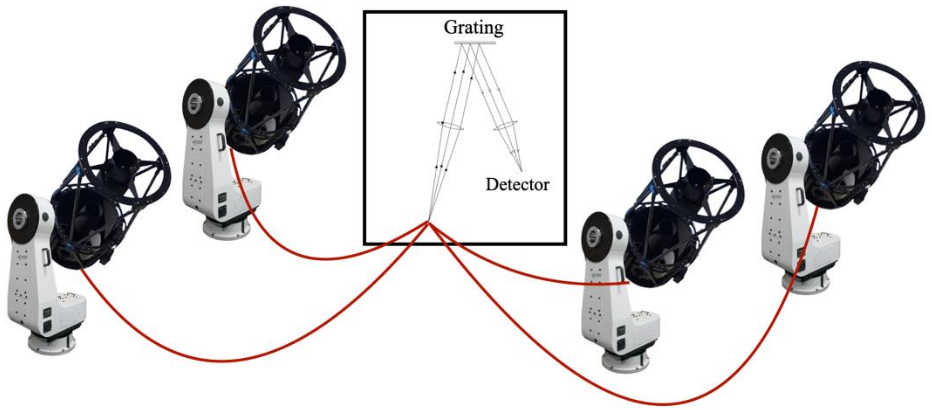
<u>Time Domain Telescope will:</u>

- Identification and spectral classification of hundreds of LISA sources
- Phase resolved follow-up of the most compact sources



The idea for a proto-TDT

PROTO-TIME DOMAIN TELESCOPE



Science demonstrator for the ESO community:

4-meter class telescope at 0.1'' spatial resolution
Basically NTT+SOXS at 0.1'' spatial resolution

MMA: LIGO follow-up / Galactic LISA sources
Monitoring or transients or variables over weeks to months
Early spectra of rare transients
Phase resolved spectra of compact binaries / pulsators
Binary solutions for massive main sequence binaries
etc…

Testing the TDT technologies – Prototype

- **4 x ~2m unit telescopes**
- **VIS + NIR**
- **(almost) noise free detectors**
- **Fiber connected to low-res spectrograph + SpecOnChip + Photonic Lantern**
- **MKID spectrograph**
- **Each telescope individually steerable**
- **Agent scheduling**
- **LGS-AO system in the visible**

Total cost ~25 MEur (incl. telescopes)
~15 MEur (excl. telescopes)

PROTO-TIME DOMAIN TELESCOPE

The idea for a proto-TDT

Testing the TDT technologies – Prototype

- 4 x ~2m unit telescopes

ctrograph +

n

erable

Kick-off meeting at Hamburg Observatory Oct. 8 / 9

Interested to join the effort?
Come talk to me or sign up here

Science demons

4-meter class tel

Basically NTT+SOXS at 0.1'' spatial resolution

MMA: LIGO follow-up / Galactic LISA sources
Monitoring or transients or variables over weeks to months
Early spectra of rare transients
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etc…

Total cost ~25 MEur (incl. telescopes)
~15 MEur (excl. telescopes)

The general path for a proto-TDT

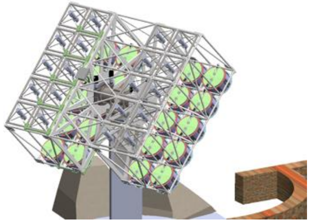
PROTO-TIME DOMAIN TELESCOPE

NOW

Precursor-TDT (no AO)

MAST, MARVEL, MINERVA, LFAST

- Synchronous, array configuration
- Scheduling, Fiber coupling



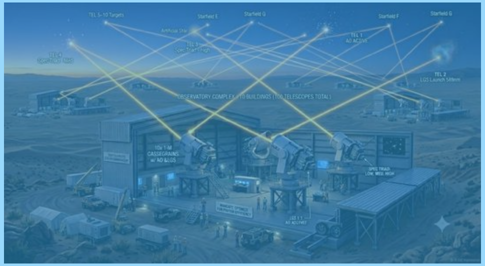
2027

-

~2036

Proto-TDT 4 x 2m, LSG-AO

- *Laser AO, Photonic Lanterns + SpecOnChip*
- *qCMOS*
- *Agent scheduling, Asynchronous operation*



Early 2030s
2040s

Start Design study full TDT
First light TDT

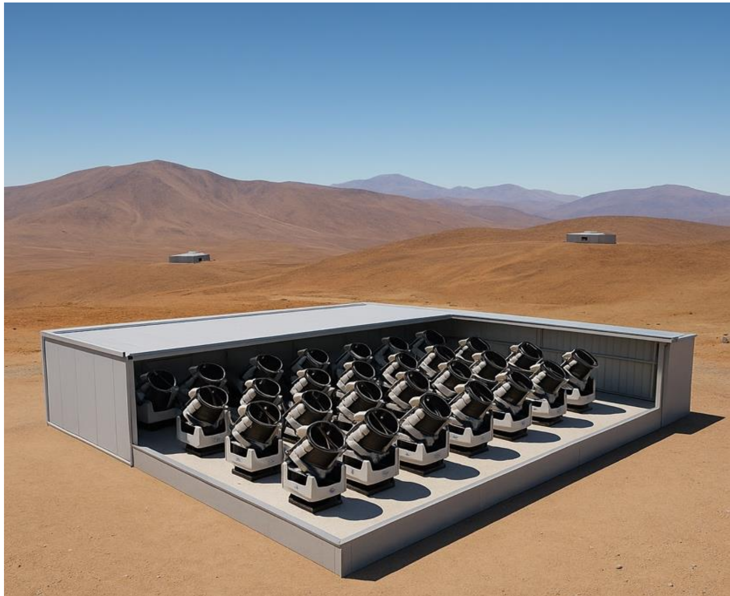
TIME DOMAIN TELESCOPE

TDT / proto-TDT Summary

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**
- **Prototype using the ATs operational in the early 2030s**

Sign up at www.tdtelescope.org



Interested to join the group as PhD student?
I am hiring! Come talk to me to learn more

Backup slides

Possible solutions for the ATs

PROTO-TIME DOMAIN TELESCOPE

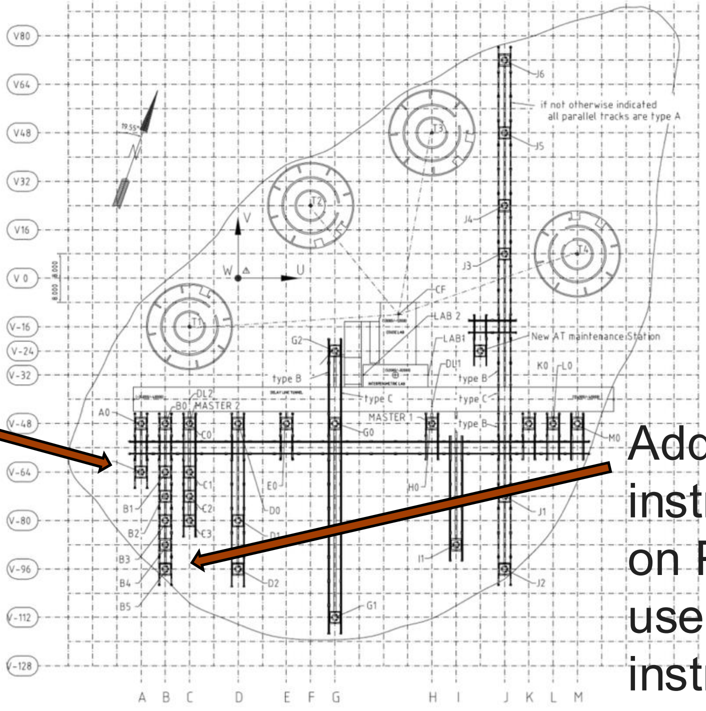
Use four dedicated PITs and set up the optics within those.

→ Design so that light passes through unimpeded when the VLTI is in use,

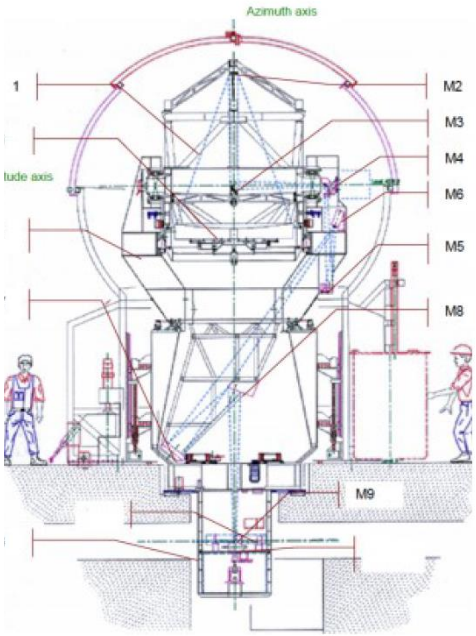
→ proto-TDT PITs wouldn't need to be removed when the ATs are used for VLTI.

Design PIT that can hold optics for proto-TDT

Maybe assign fixed stations that are not used by VLTI

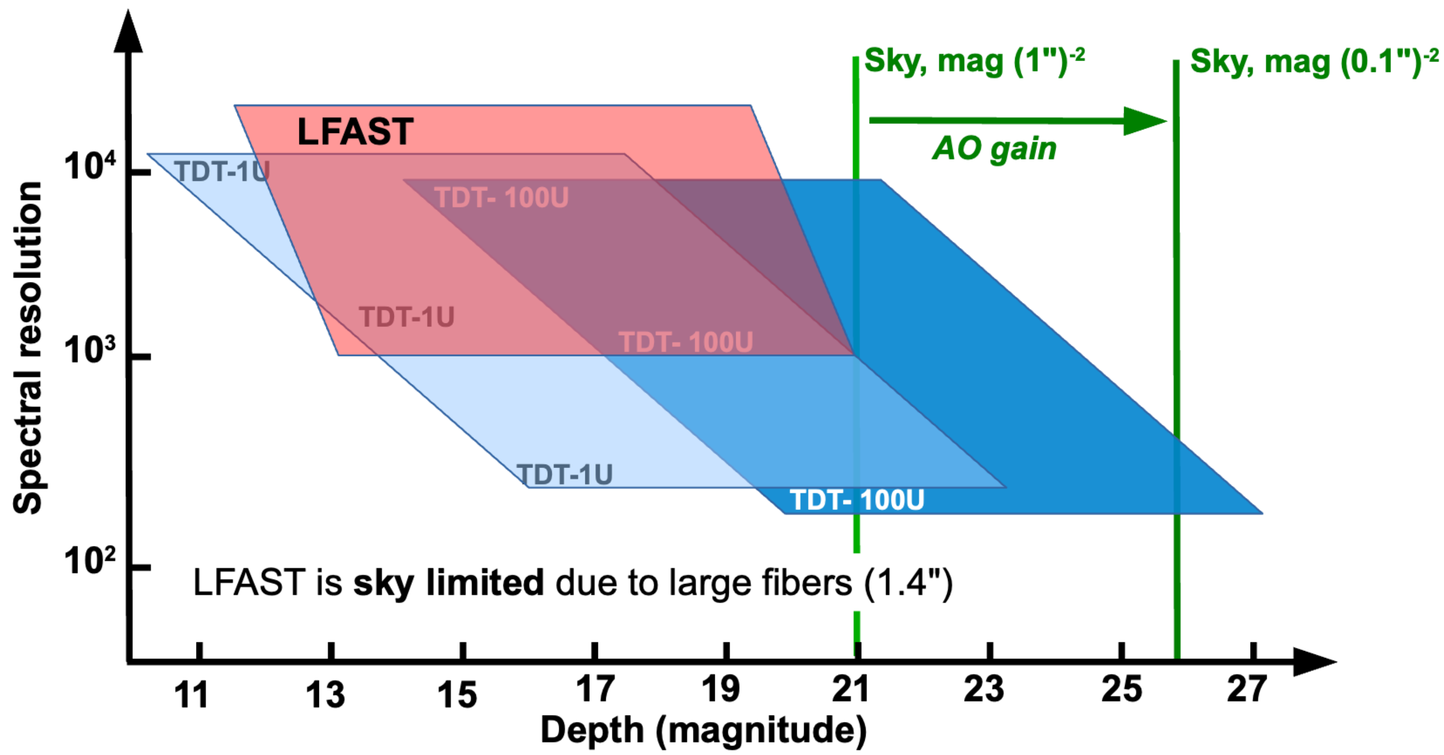


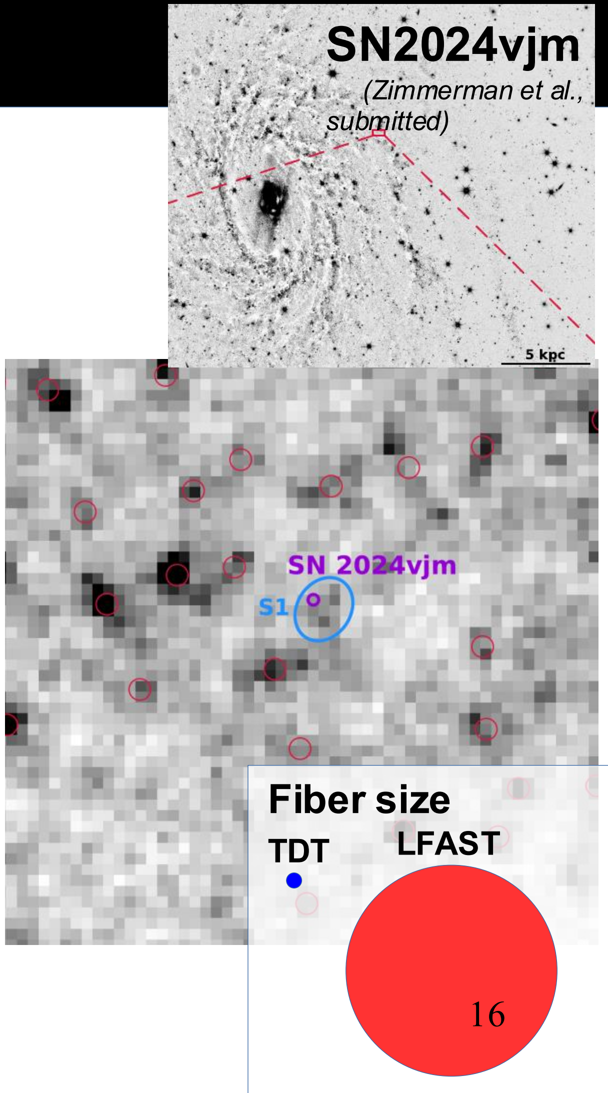
Add small instrument shelter on Platform or use dedicated instrument PIT



TDT Sensitivity vs. LFAST

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

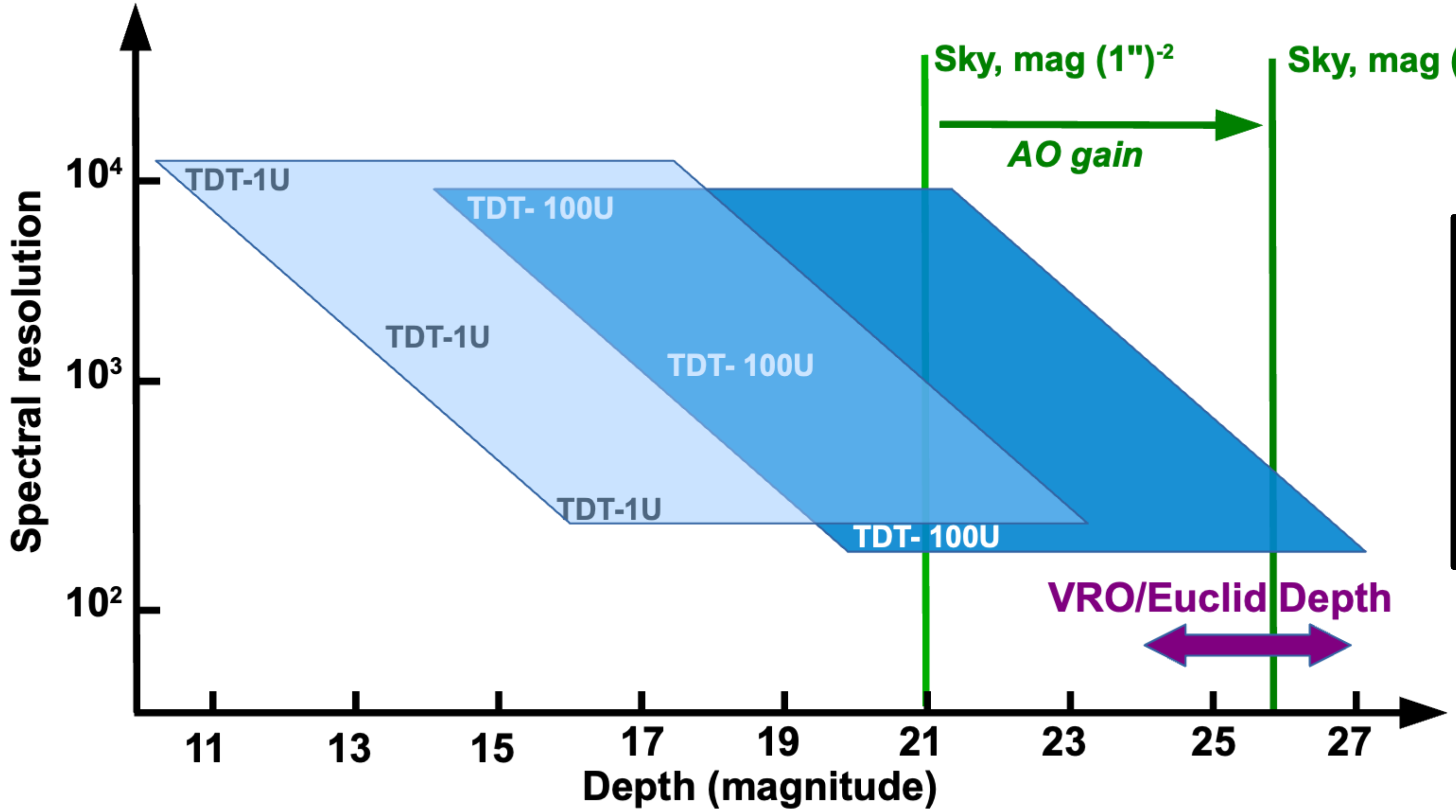




TDT Sensitivity vs. VRO/Euclid/Roman

TIME DOMAIN TELESCOPE

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



TDT is spectroscopic complement to VRO/Euclid/Roman

Counterpart to LISA, Athena and HBO

TIME DOMAIN TELESCOPE

TDT vs. LFAST - an overview

LFAST	TDT	TDT advantage
One mount for many telescopes	Each telescope works independent	***Higher flexibility***
Fiber size: 1.5 arcsec - no AO	Fiber size: 0.2 arcsec - AO	***TDT not sky limited - much deeper observations***
One high resolution spectropgrah	More spectrographs covering large resolution range	***TDT more flexible for different science cases***
US led facility	European led facility	***Time-domain facility for European based researcher***
One site	Several sites proposed	***Quicker response to transient events***

<u>TDT has significantly higher flexibility / depth crucial for time-domain spectroscopy</u>

Key Science questions

An array of telescopes for everyone

Q1: What is the origin of the elements?

→ *Gravitational wave mergers*
→ *Supernovae & Gamma-Ray Bursts*
→ *Stellar furnaces*

Q2: What powers the Universe?

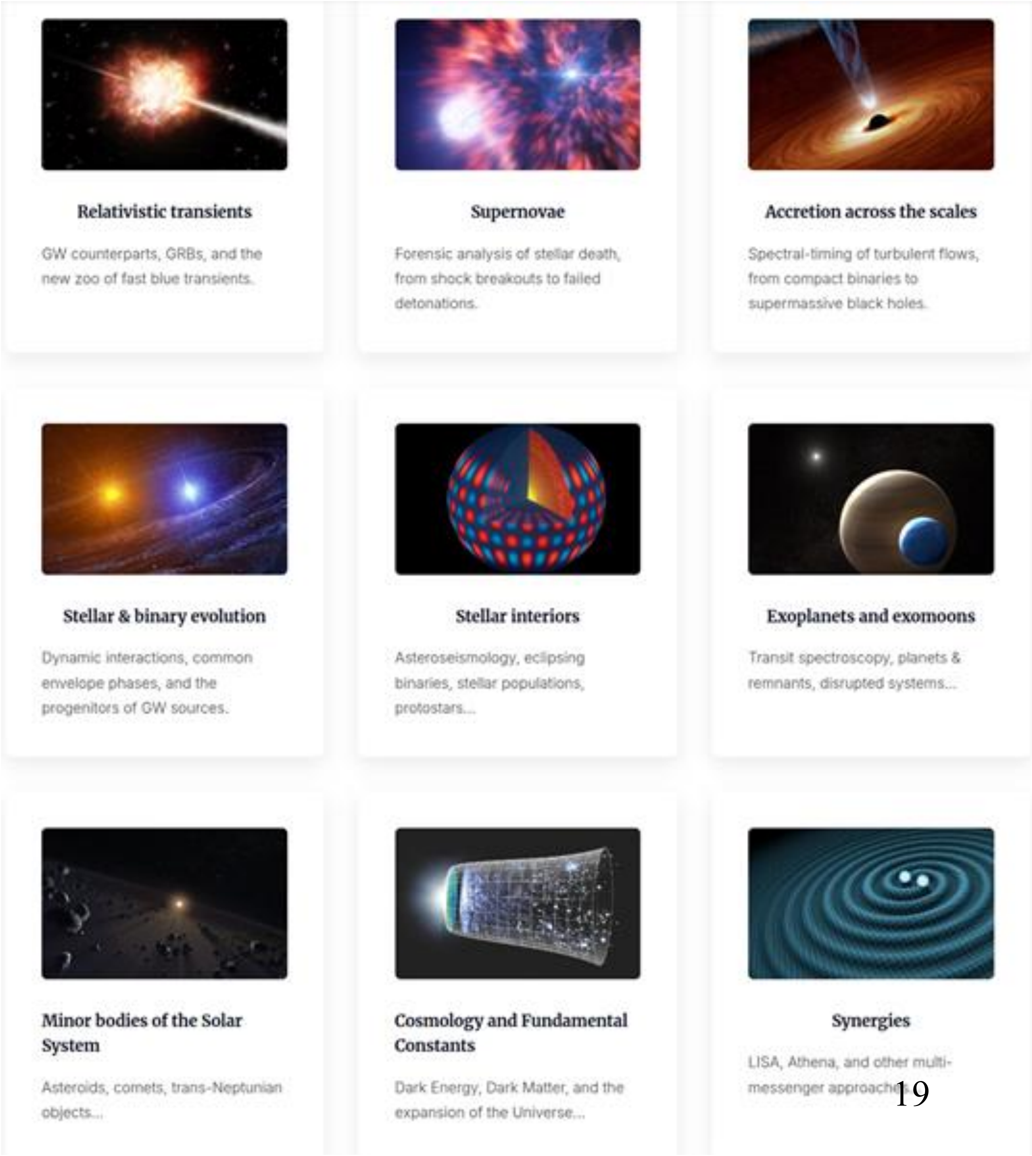
→ *Accretion physics at all scales, from YSO to QSO*
→ *Stellar mergers incl. LISA sources*
→ *Growth of supermassive black holes*

Q3: What is the expansion history of the Universe?

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

Q4: What is the structure of exoplanetary systems

→ *Host star – planet interactions/interplay*
→ *Remnants of exoplanetary systems*
→ *The outer Solar System*



TIME DOMAIN TELESCOPE

Exposure time calculator

Find the TDT ETC on www.tdtelescope.org

Example: SNR=10 on 100 x 2m @ 25mag, R=5000, t_{exp} = 36 minutes

TDT and Schmidt Observatories

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

Argus: Optical, Photometric, 'All Sky', Transients and Variables

DSA: Radio, Fast Radio Bursts, Very high time resolution

LFAST: Optical, Spectroscopic, Low Spatial Resolution, Bright

TDT: Optical – Infrared, Spectroscopic, High Spatial Resolution, Faint

TDT highly complementary to current Schmidt Science initiatives.

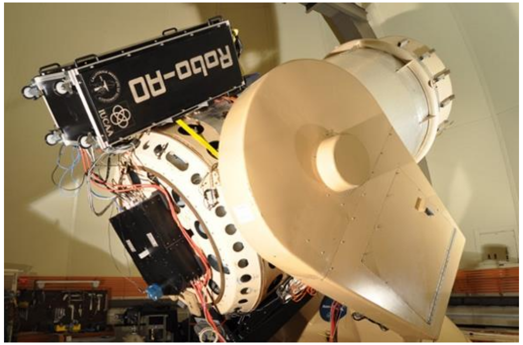
TDT Key Technologies

TIME DOMAIN TELESCOPE

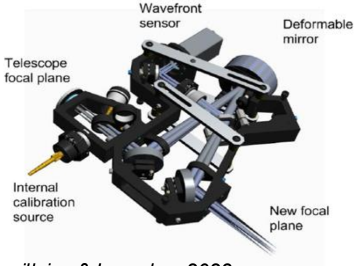
Readout noise (typ.)	Standard scan	0.43 electrons (rms), 0.39 electrons (median)
	Ultra quiet scan	0.30 electrons (rms), 0.25 electrons (median)

Hamamatsu ORCA manual

- **(Almost) Read-noise free detectors**
  - → To be photon-noise limited, not sky-background or read-noise
  - → qCMOS detectors (now at <0.3 e^-): ***further push***
  - → Organic detectors (VIS / NIR)
  - → ***MKID*** detectors? Push on routine operations, energy sensitivities
- **Robotic adaptive optics in the blue**
  - → Not yet near diffraction limit in the blue → Development needed
  - → Robotic, ‘24/7’ operations on 100-unit array → Stability, MTBF paths
- **Spectrographs**
  - → Spectrograph per cluster, fiber throughputs in blue
  - → Photonic spectrographs? One per telescope?
  - → Photonic lanterns? One per telescope?
- **Dynamic scheduling**
  - → Highly dynamic and restrictive scheduling on full array
  - → Agentic approach?



RoboAO; CalTech/IfA/IUCAA



Dovillaire & Leveder, 2023

Fig. 1. The CIAO system and its components.