The VLTI

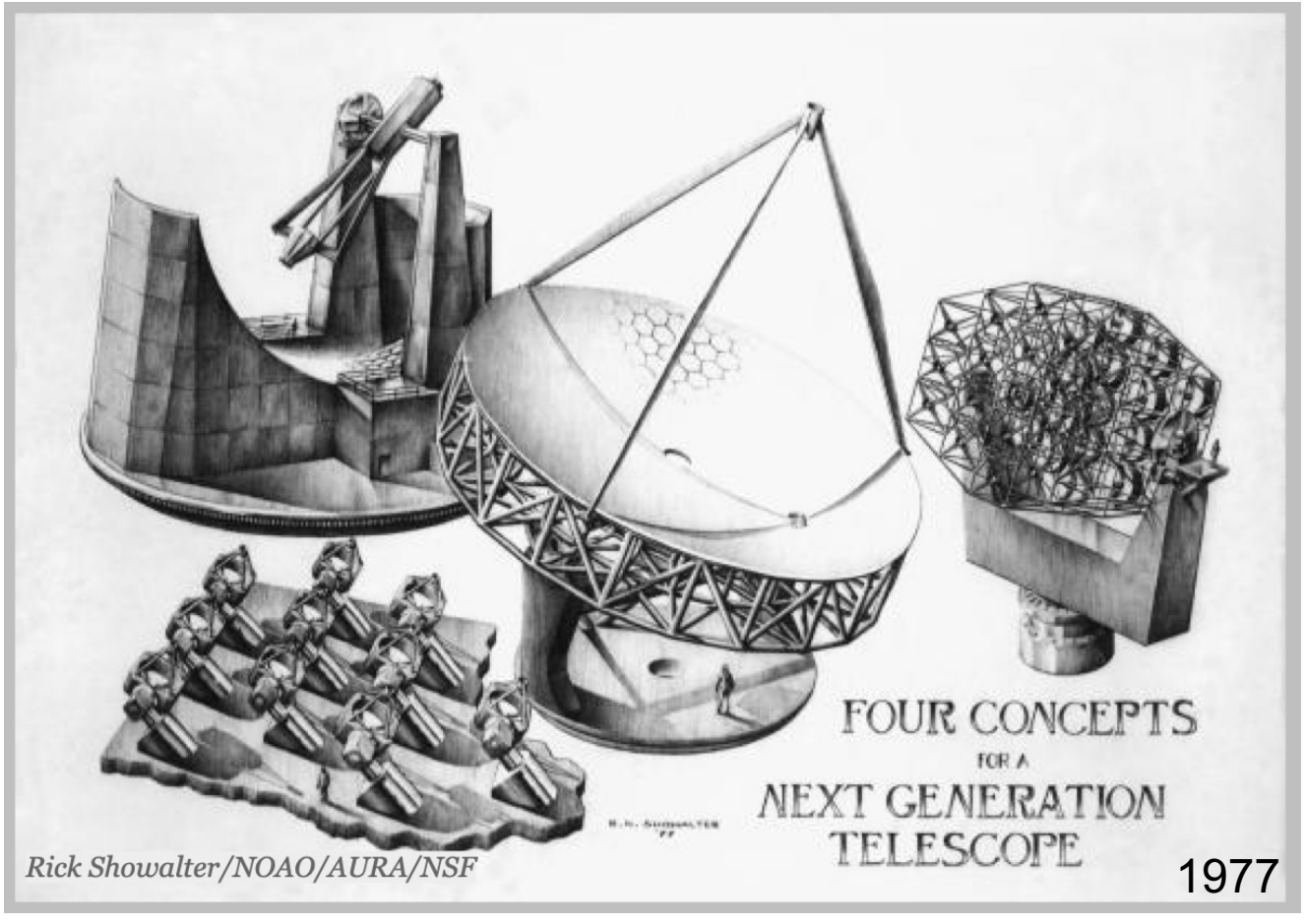
Past, Present and Future

Antoine Mérand

VLTI Programme Scientist

ESO Garching (Germany)

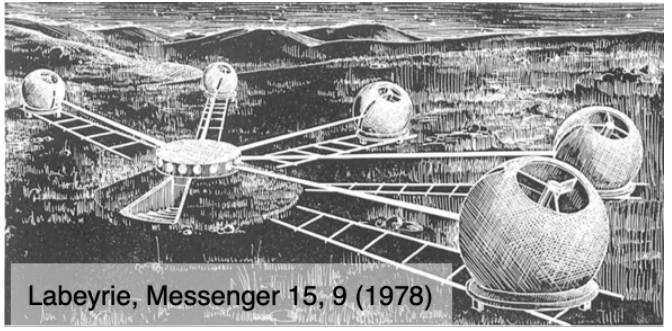
1970's: post 5m telescopes?

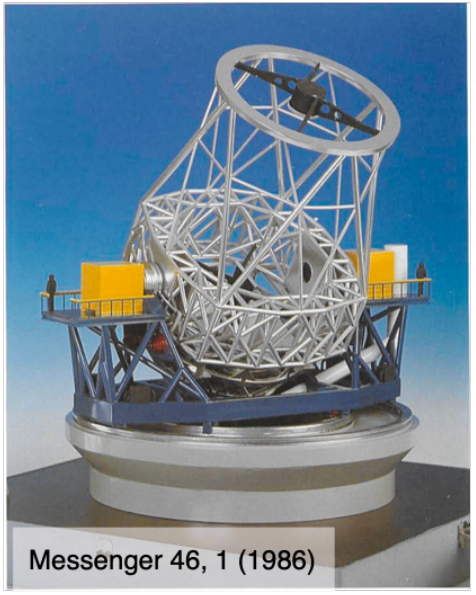


VLTI emerging as part of the VLT

- **early 1970s**: Successful coherent recombination of separate telescopes (A. Labeyrie)
- **1977**: ESO conference “Optical Telescopes of the Future”: ESO should build a 16m Telescope (or 4x8m, or 16x4m)
- **1981**: ESO conference “Scientific Importance of High Angular Resolution at Infrared and Optical Wavelengths”
- **1983, 1986**: VLT Workshops converge on 4x8m Telescopes

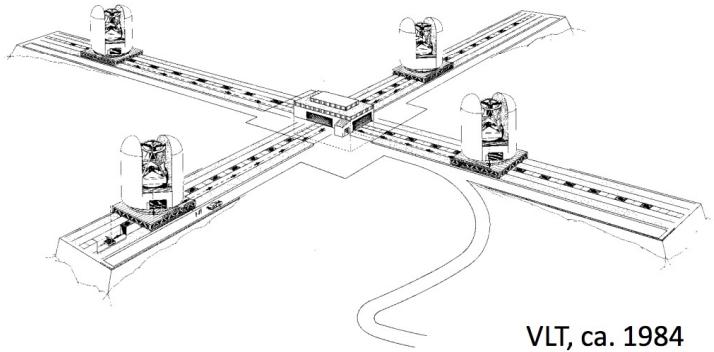
Standalone / Incoherent / Coherent


Labeyrie, Messenger 15, 9 (1978)

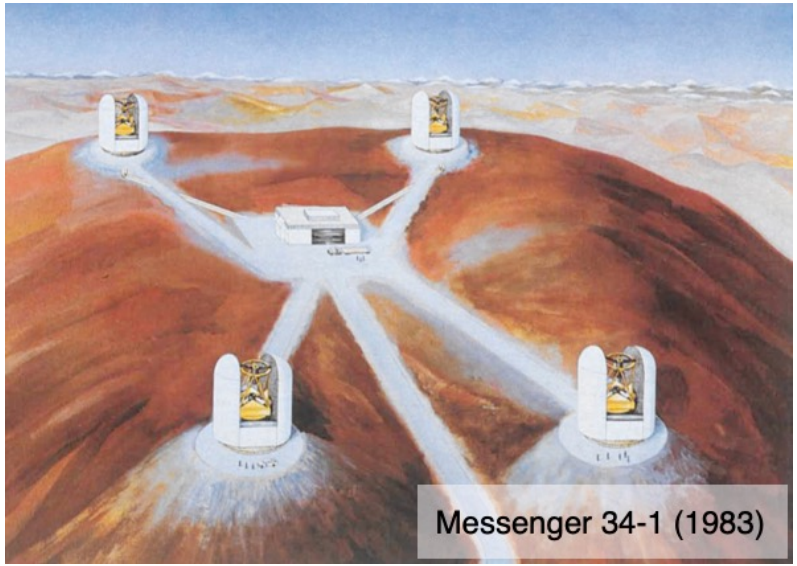

Messenger 46, 1 (1986)

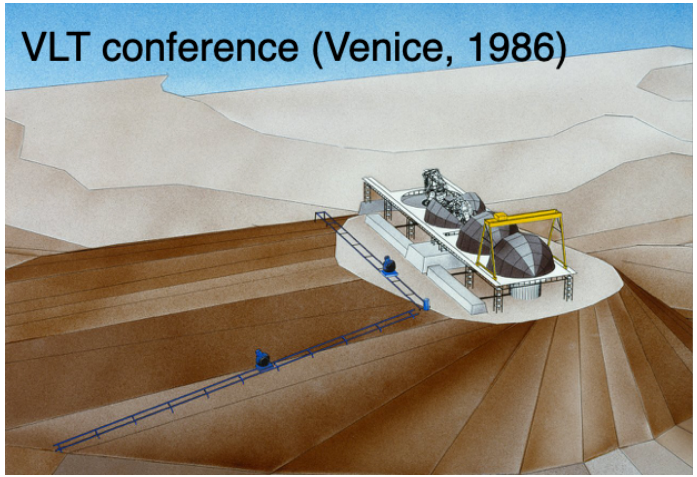
Converging on a design

- Operations and Maintenance
- u,v coverage
- Smaller moveable telescopes?

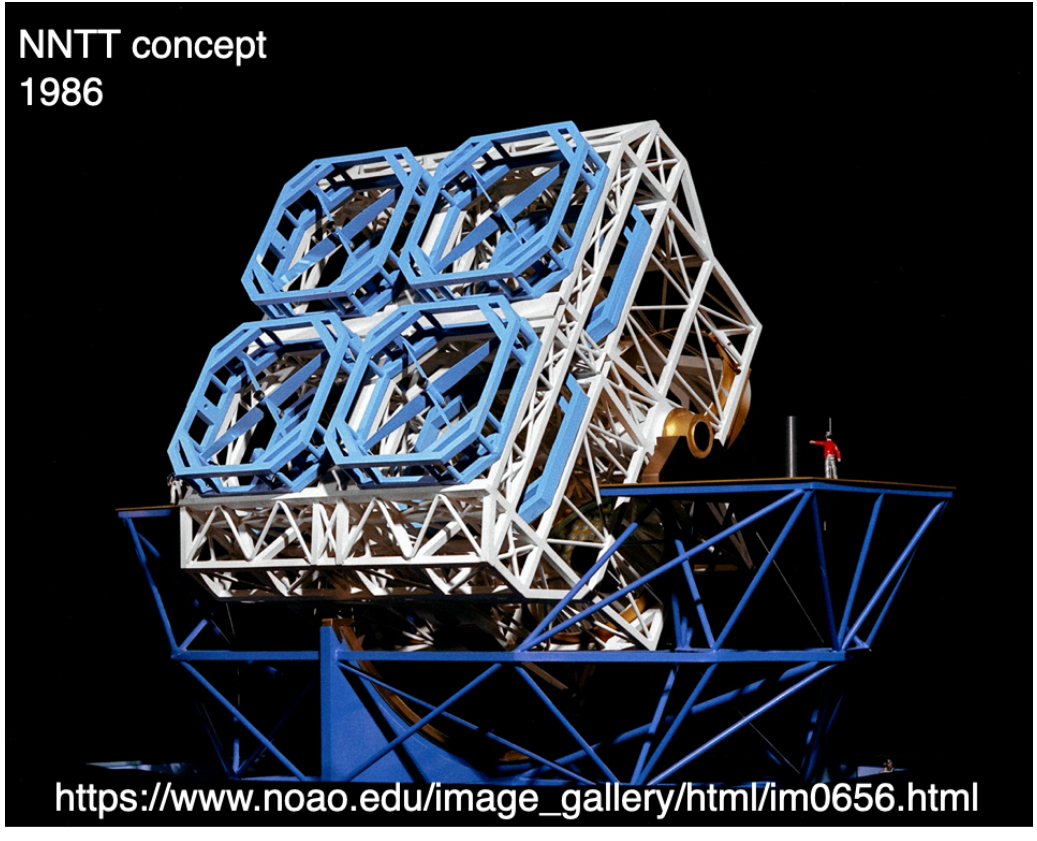


VLT, ca. 1984





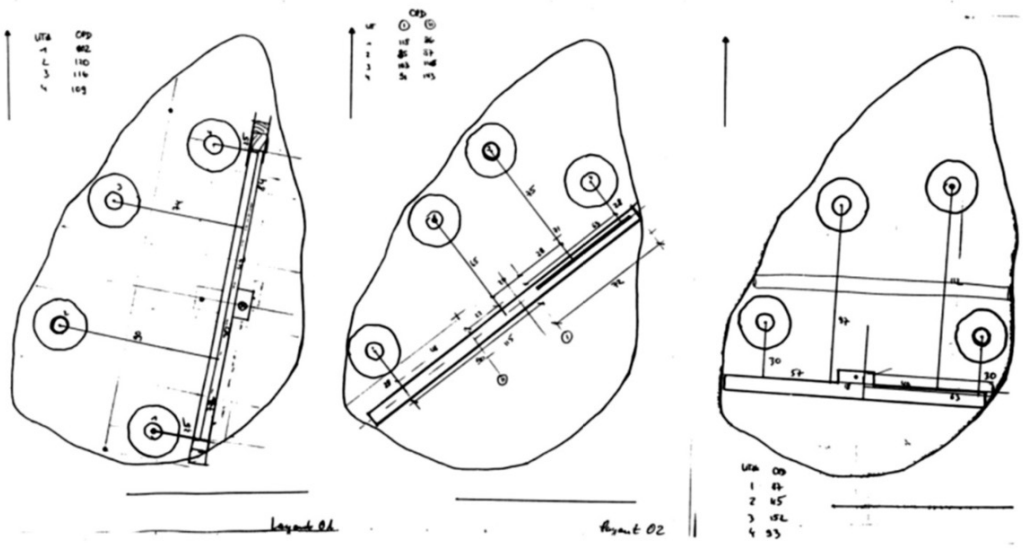
Meanwhile at NOAO in the US…



Cancelled due to lack of funds, became the twin 8m Gemini telescopes afterwards…

Converging on the layout

- 1990: Cerro Paranal selected
- 4x8m + 2 moveable ATs



"The Jewel at the Mountain Top", p246 (Claus Madsen)
https://www.eso.org/public/products/books/book_0050/

Beckers,
Messenger 66-5 (1991)

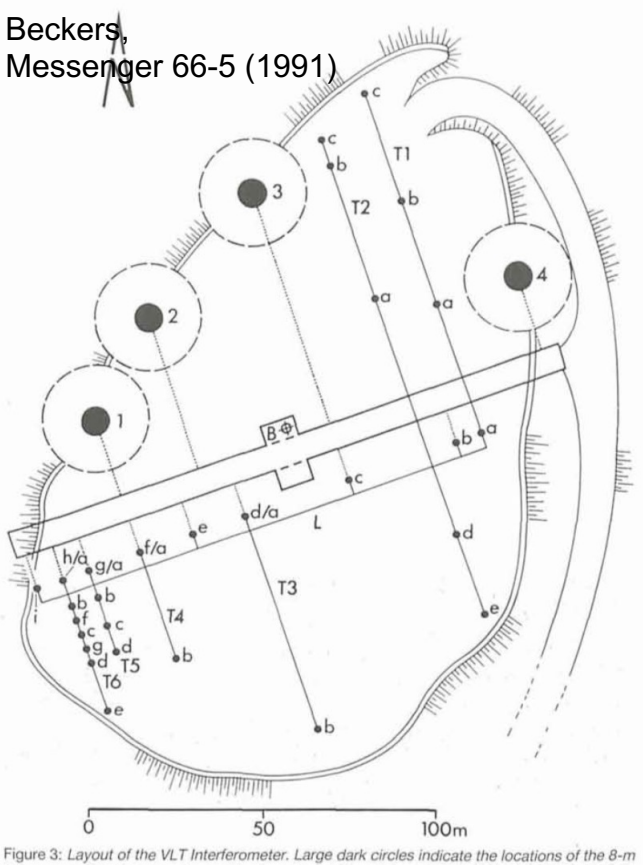


Figure 3: *Layout of the VLT Interferometer. Large dark circles indicate the locations of the 8-m telescopes. Small dark circles are the locations of the stations for the 180-cm diameter mobile auxiliary telescopes. The large rectangle is the location of the interferometric tunnel. A detailed description of the VLTI layout will appear in a future issue of the* Messenger.

Early 90's: high momentum

- **1987, 1988**: NOAO-ESO conferences "High Angular Resolution by Interferometry"
- **1991**: "High Resolution Imaging by Interferometry"
  - 200+ participants
- **1992**: "*For VLTI all preliminary work is complete, the Interferometry Panel has completed its work, its final report is in press and contracts with industry and with community institutes consortia are in preparation*" (Messenger 70-3, 1992)
- **1993**: France (CNRS) & Germany (MPG) pay for a 3rd Auxiliary Telescope

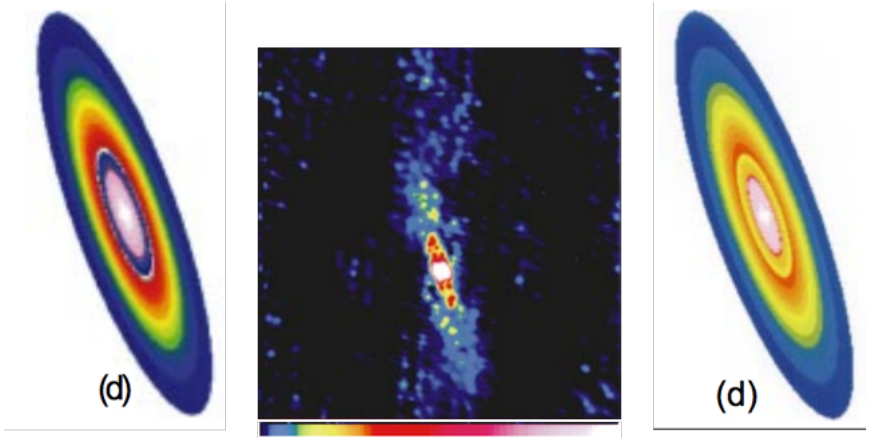
Mid-90's: low momentum

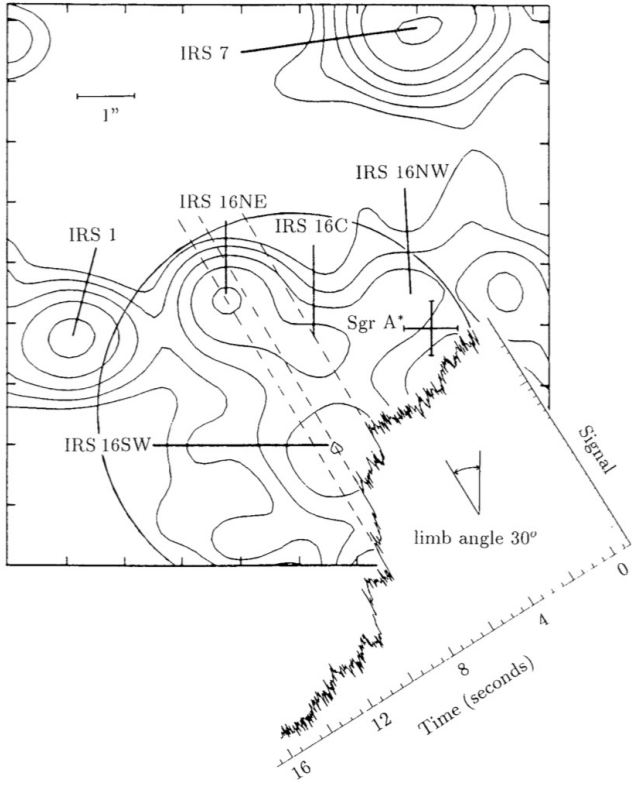
- **1993**: VLT cost re-estimated **+33%**
  - unaccounted costs: mirror handling, CCDs, interferometry…
  - "*Sensibly, but painfully, the VLT Interferometer fell victim to the hard financial realities*" (Madsen, *ibid*)
- Key VLTI people leave ESO (Jacques Beckers, Oskar von der Lühe and Fritz Merkle)
- Pierre Léna (French representative at ESO council) resigns
- VLTI postponed (not cancelled): hopes that Australia joining ESO will inject fresh cash

A Scientific Vision

"[The VLTI] will permit observations of the innermost regions of for instance star forming areas and galaxy nuclei which may have black holes near their centres" (Messenger 46-1, 1986)

Disk model, reconstructed image and fit (N. Ageorge+ 1996)

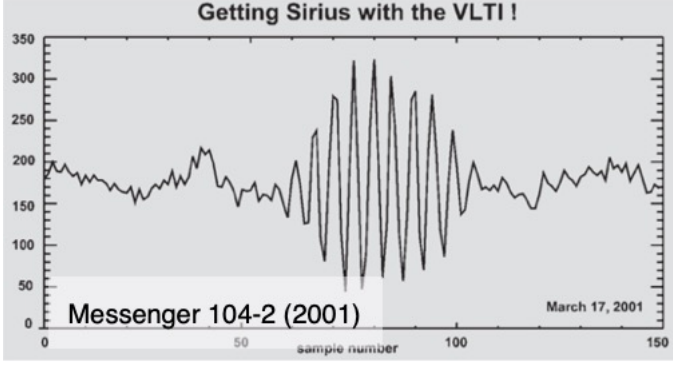




Observation of Galactic Centre using lunar occultation (J. Beckers Messenger 60-1, 1990; R. Genzel)

Late 90's: Rebirth

- **1995**: VLTI construction continues using VLT instrumentation money
- **1997**: *phased* implementation of VLTI decided.
- **1998**:
  - First light of UT1 (standalone)
  - DL, AT and AMBER contracts
- **1999**: Siderostats to commission VLTI (40cm diameter)
- **2001:** first fringes (VINCI)



2000's: a long road…

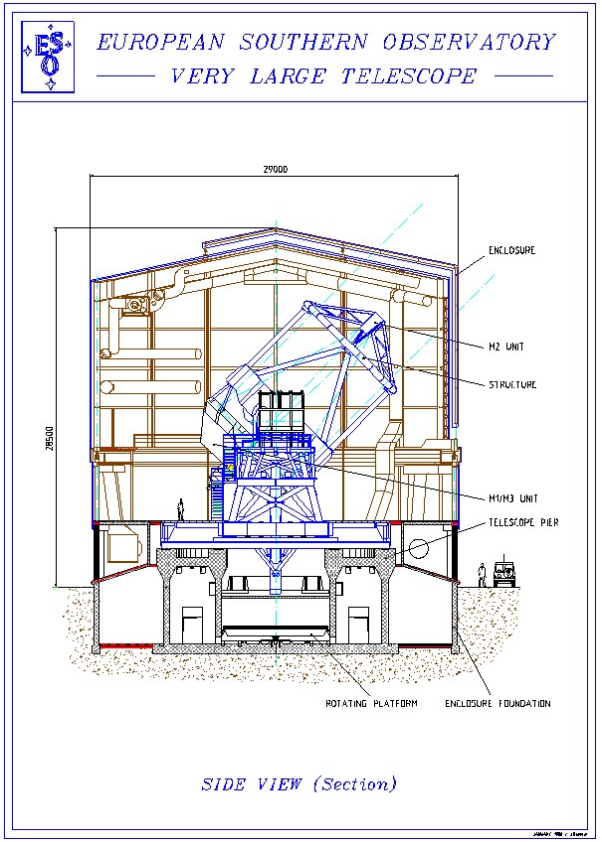
- 2001: First UT fringes (VINCI+UT1-UT3)
- 2002: AO for UTs being integrated, 4th AT
- 2003: MIDI first fringes (UTs)
- 2004: AMBER first fringes (UTs)
- 2005: First fringes with ATs
- 2005: 2G instruments selected (MATISSE, GRAVITY)
- 2006: Fringe tracking with FINITO
- 2006: Task force to address vibrations
- 2007: First results of AMBER (*A&A* special issue)
- 2008: First fringes of PRIMA (cancelled in 2014)
- 2010: First fringes with 4 Telescopes (PIONIER)

1st Gen, as of 2010

- AMBER: 3T at 1.2-2.5μm (JHK), spectroscopy (R~12000), fringe tracking
- MIDI: 2T at 8-10 μm (N)
- PIONIER: 4T at 1.4-1.7μm (H), synthetic imaging
- 4x8m (UT) with on-axis natural guide star AO in visible (MACAO)
- 4x1.8m (AT) relocatable

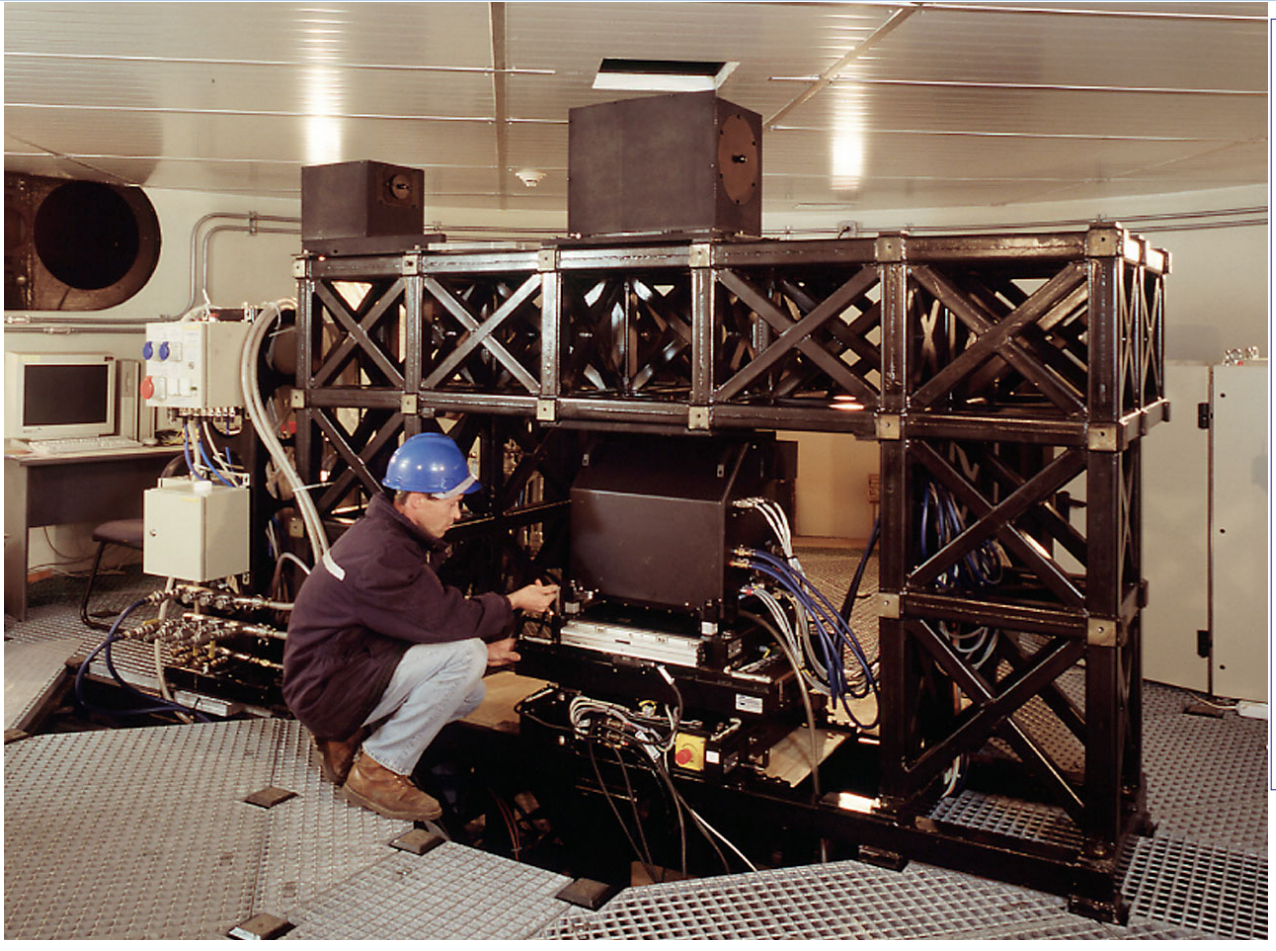
Cerro Paranal

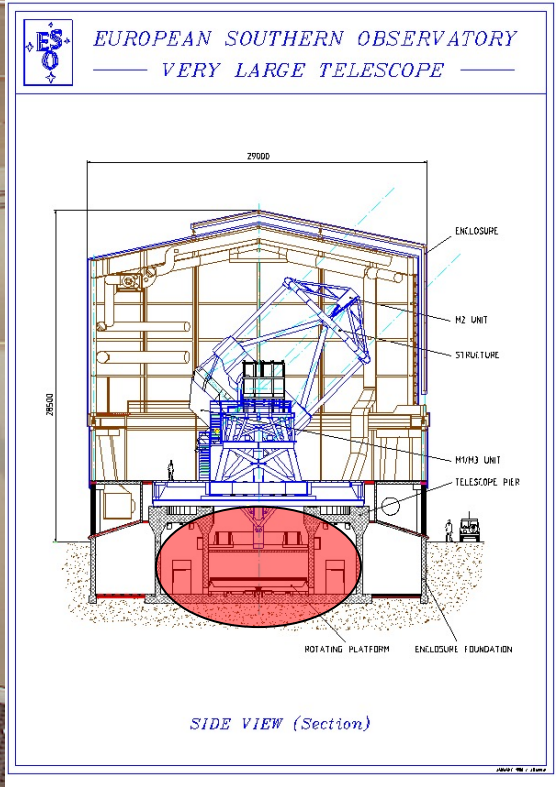
The 8m telescopes (UTs)



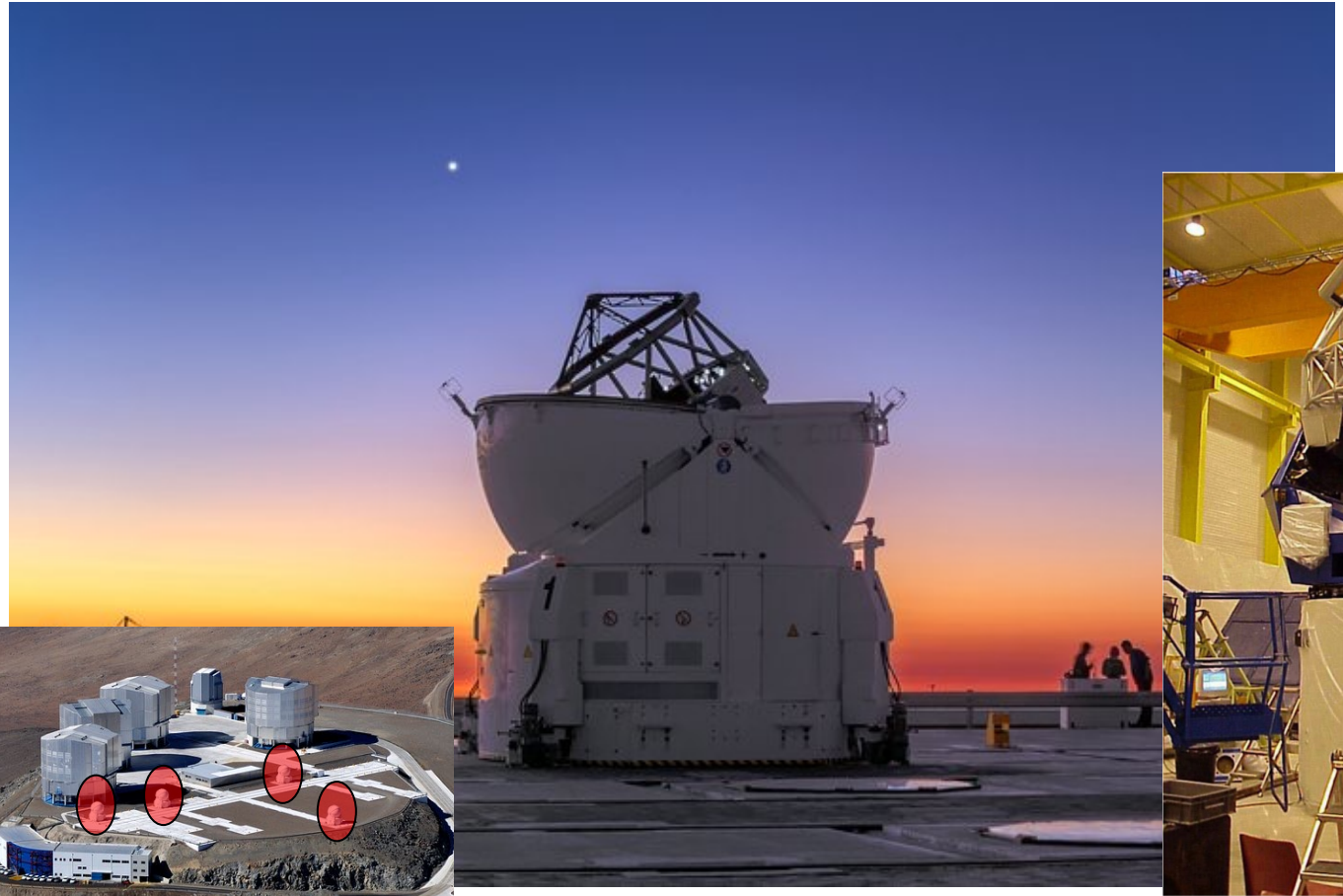
Credit: ESO

Coudé focus (AO for UTs)

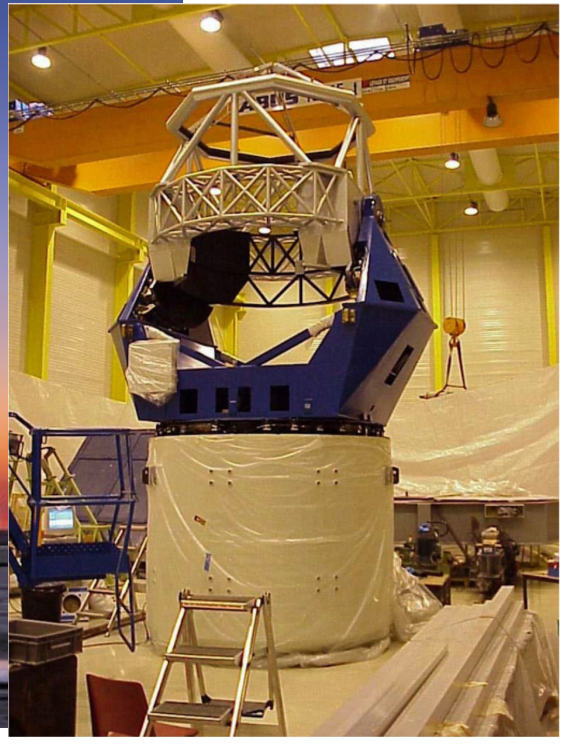




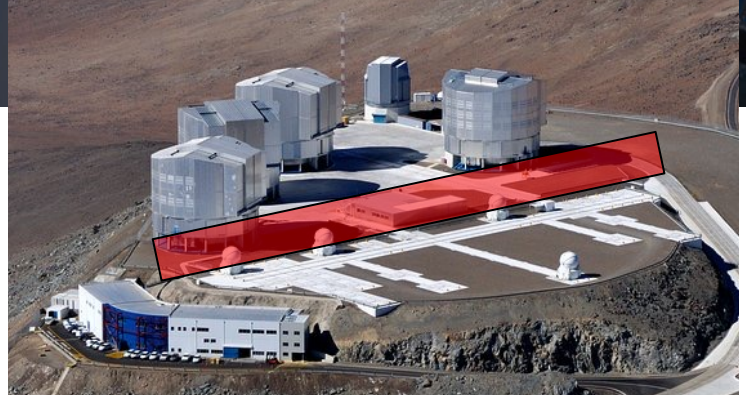
The movable 1.8m telescopes (ATs)



Credit: ESO



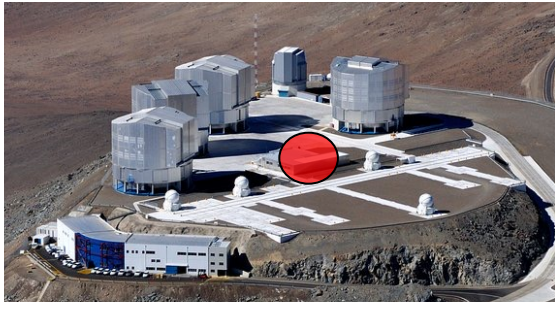
Tunnel and delay lines



Credit: ESO

Instruments (today)

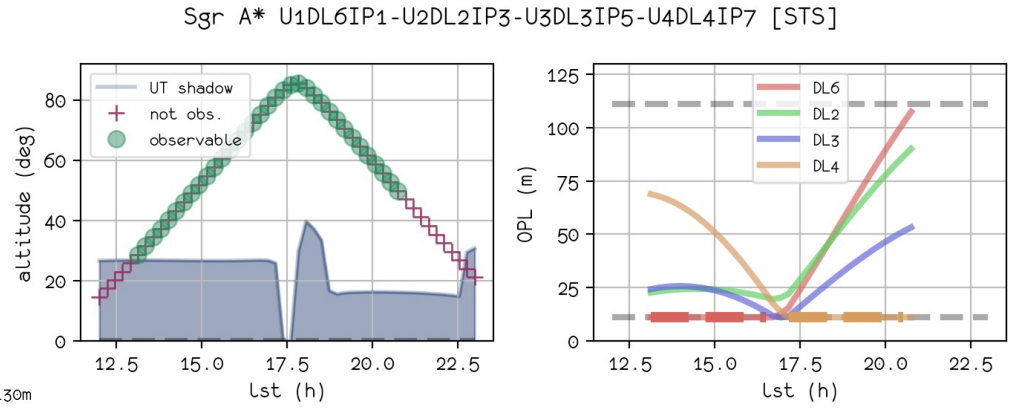
Instrument	Bands	Spec. Res.	Limiting Magnitude	FoV* (FWHM)	comment
PIONER	H	20	H<9mag	AT: 0.4” UT: 0.1”	Fast (20min)
GRAVITY	K	20, 500, 4000	K<10.mag (17.5mag)	0.6” 0.13”	Off-axis, astrometry
MATISSE	LMN	30-1000	L>0.15 Jy M>1 Jy N>1.3 Jy	0.8 - 2.8” 0.2 - 0.6”	Unique bands (LM)

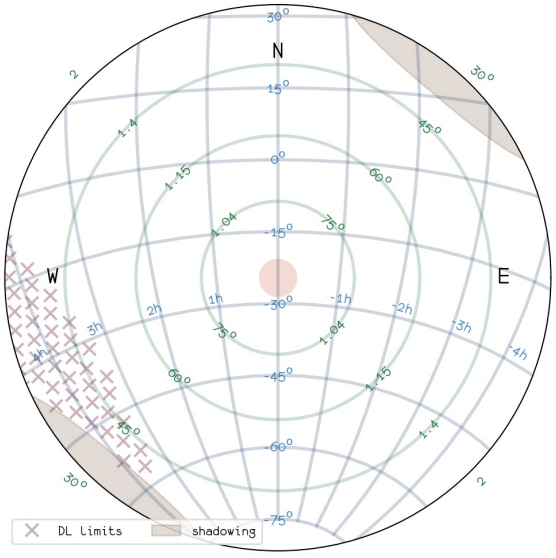


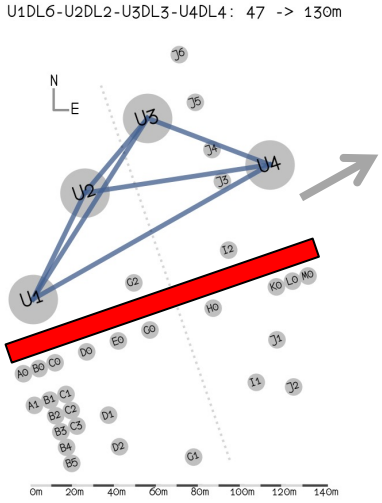
$$FoV \approx 2.44\frac{\lambda}{D}$$

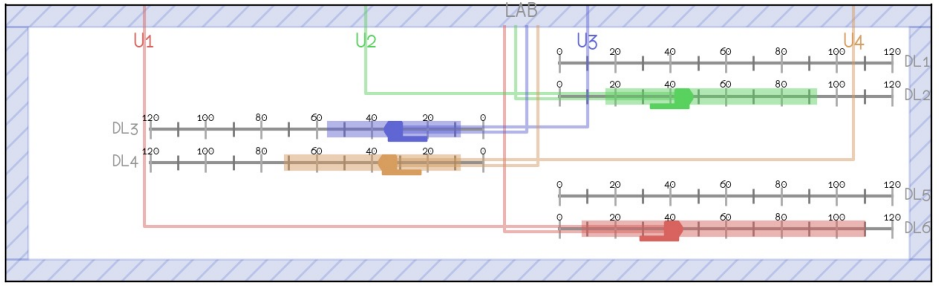
Observability

- shadowing by other telescopes' domes
- Limited length of delay lines

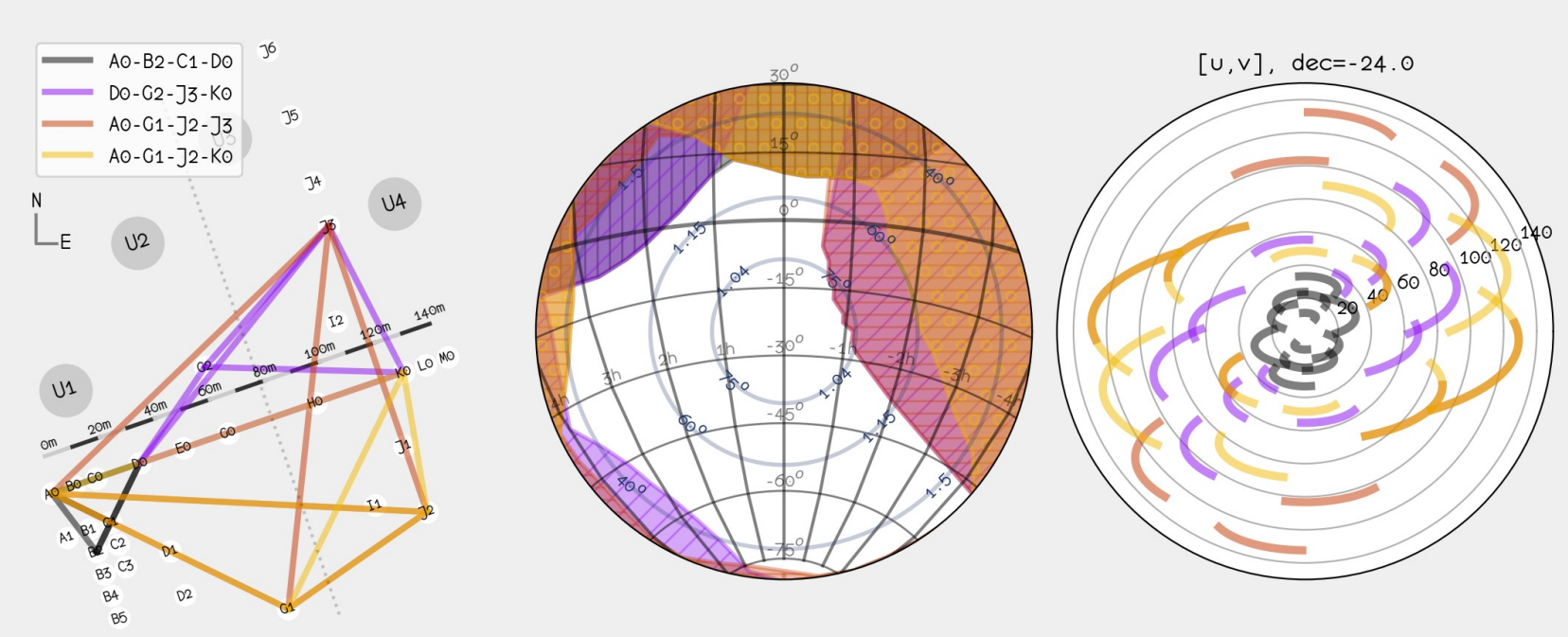








AT configurations



Small	Medium	Large	Astrometric
10-35m	40-110m	60-135m	50-130m

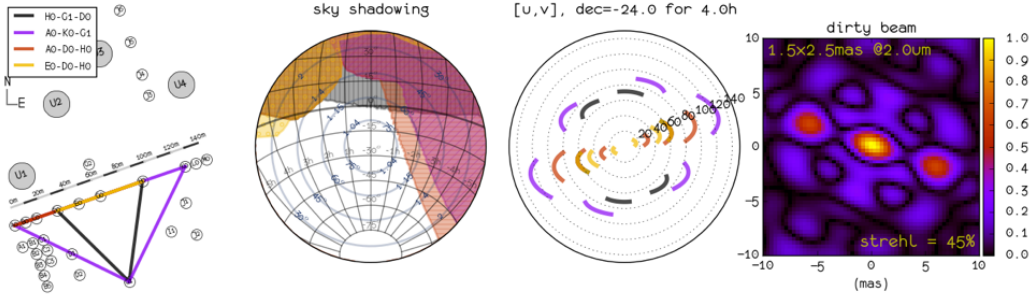
Paving the u,v plane

Spatial Frequencies	Image
Longest baseline	Smallest detail
Smallest baseline	Largest structure
Sampling B_{max}/B_{min}	N linear pixel

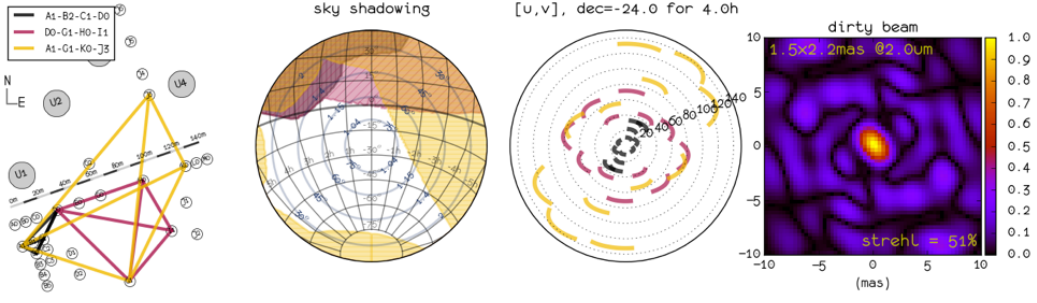
- VLTI has baselines from 8 to 200m
- It can make a “25x25” pixels images
- It requires at least 625 visibilities (u,v points)
- 4T = 6 Baselines + 3 Closure Phases
- With 4T: at least ~70 calibrated observations

Better u,v coverage

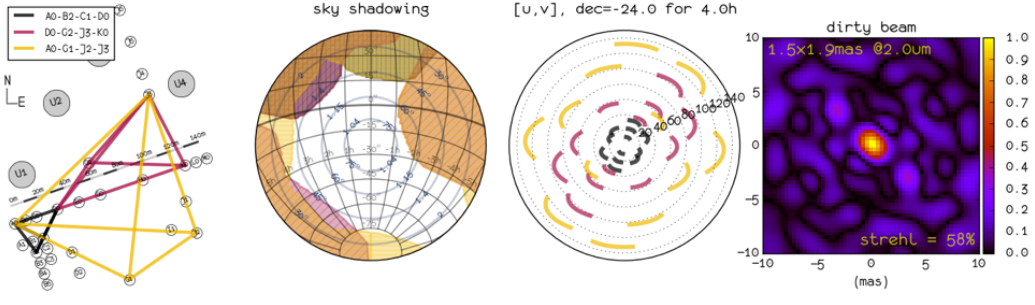
2009



2012



2015



Observational efficiency

	2006	2009	2013
science operations fraction	40%	60%	80%
calibrated observations / hour	0.5	1.0	1.5
relocation activities	20%	25%	30%
unique u,v per configurations	3	4	6
average number of obs / hour	**0.15**	**0.45**	**0.85**
unique u,v / hour	**0.5**	**1.5**	**5.0**

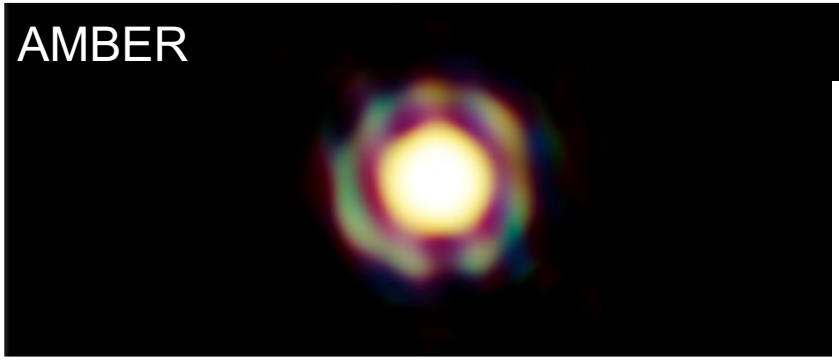
By early 2010's, we could do "10x10" images in a few nights

First images

eso0906 — Organisation Release

Hundred metre virtual telescope captures unique detailed colour image

18 February 2009

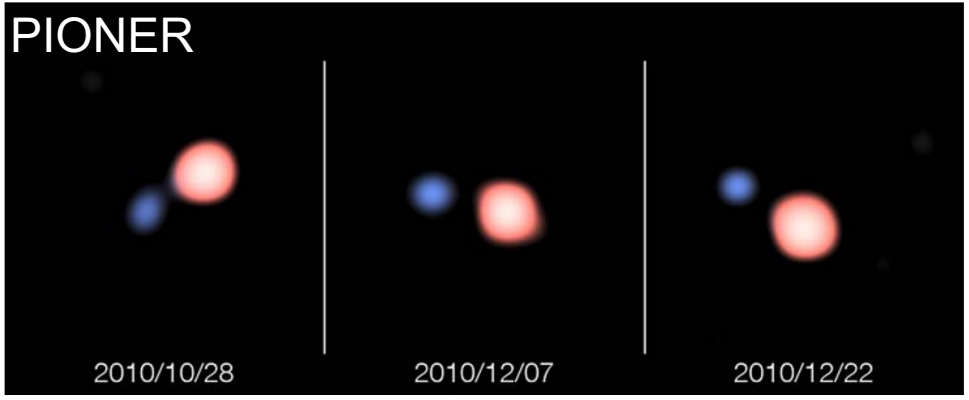


eso1148 — Science Release

SPACE SCOOP

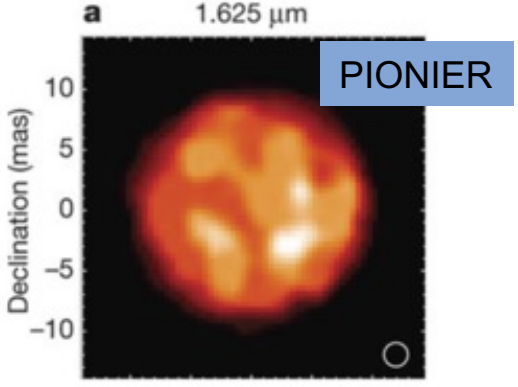
Vampire Star Reveals its Secrets

7 December 2011

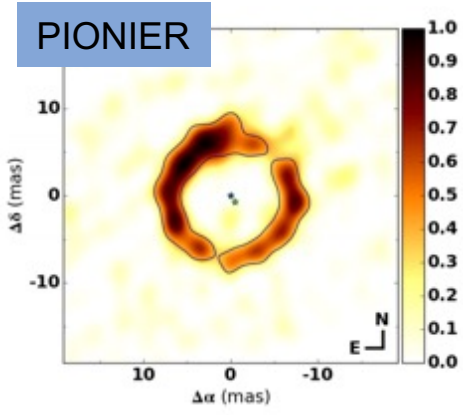


Some VLTI images

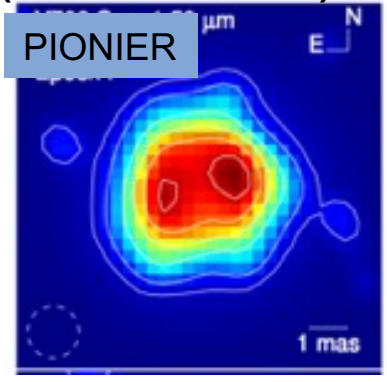
AGB pi[1] Gru (Paladini+ 2018)



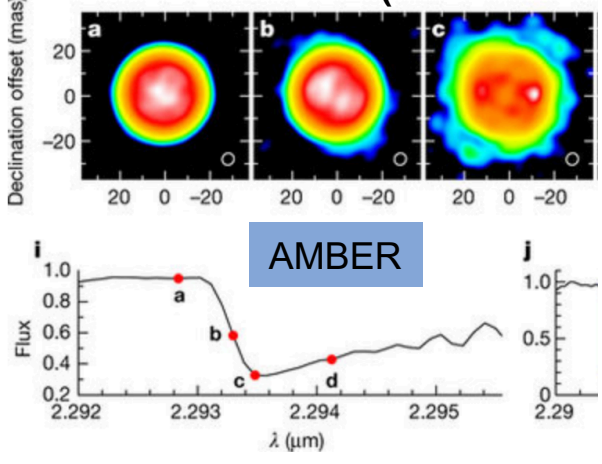
post-AGB IRAS 08544-4431 (Hillen+ 2016)

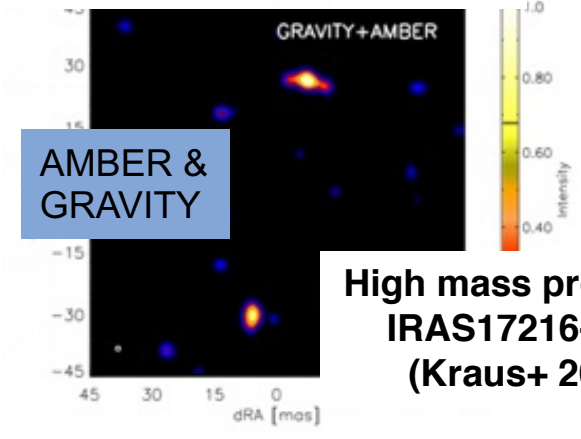


YHG V766 Cen (Wittkowski+ 2017)



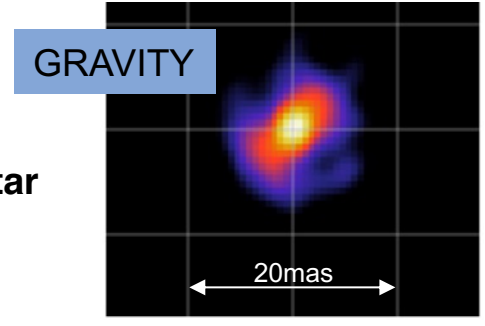
RSG Antares CO line (Ohnaka+ 2017)





High mass proto-star IRAS17216-3801 (Kraus+ 2017)

LBV Eta Car, Hel line (GRAVITY Collab 2018)



2015-2020: big upgrade

- **2015** VLTI closed for 7 months to prepare for the 2G instruments
- **2015** GRAVITY: 4T K-band, fringe tracking and dual feed
- **2017** NAOMI: AO for ATs
- **2018** MATISSE: 4T, LMN bands
- **2020** GRA4MAT: GRAVITY as a fringe tracker for MATISSE

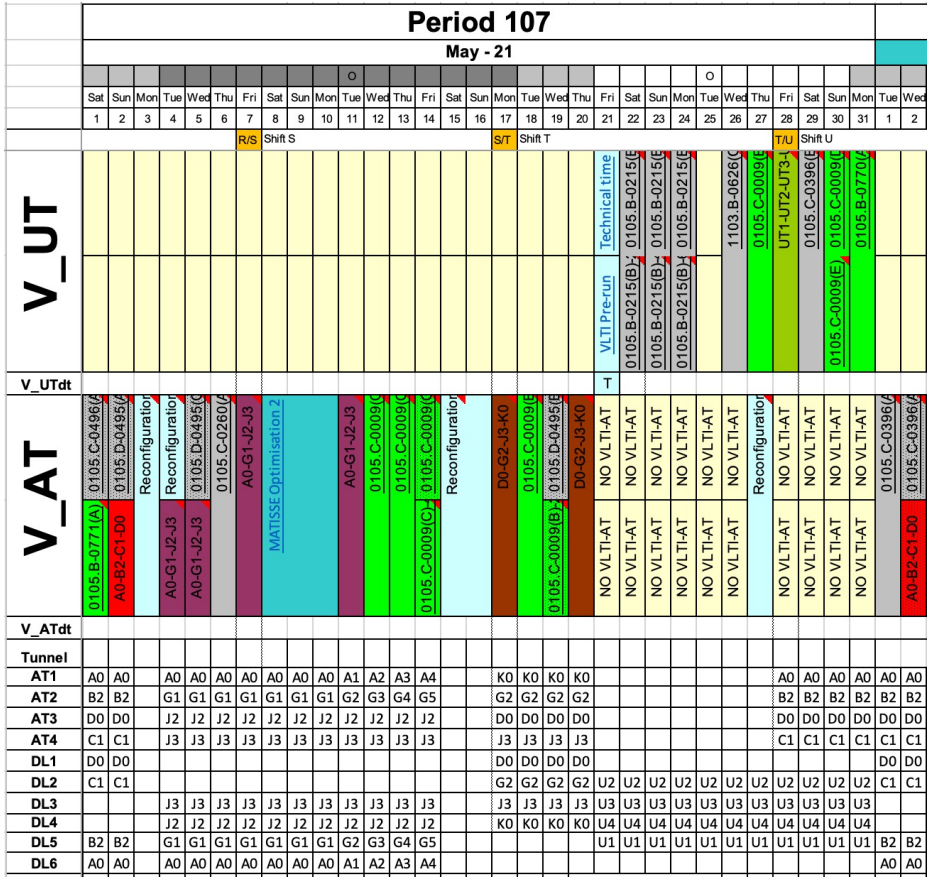
Performance jump with VLTI 2G

- By 2013, operations are 10x more efficient than in 2006 (*average u,v points / hour*)
- Fringe tracking from H~6 (FINITO) to K~10 (GRAVITY)
- Spectro-interferometry from K~7.5 (AMBER) to K~17.5 (GRAVITY)
- ATs equipped with AO (NAOMI): more reliable operations
- Mid-IR from 2T (MIDI) to 4T with FT (MATISSE)

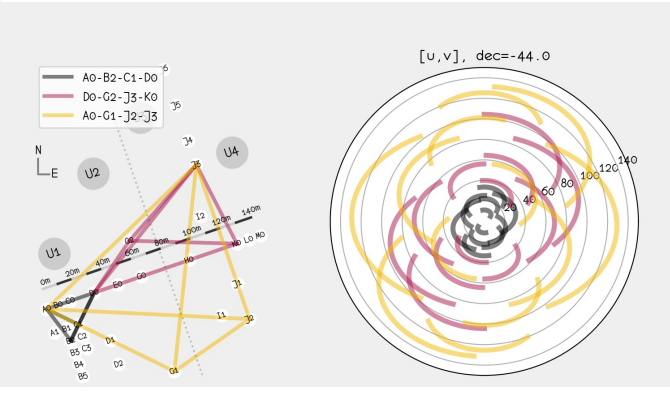
VLTI 2G: 4T instruments (better u,v coverage), Adaptive Optics, spectroscopy with fringe tracker

Observations

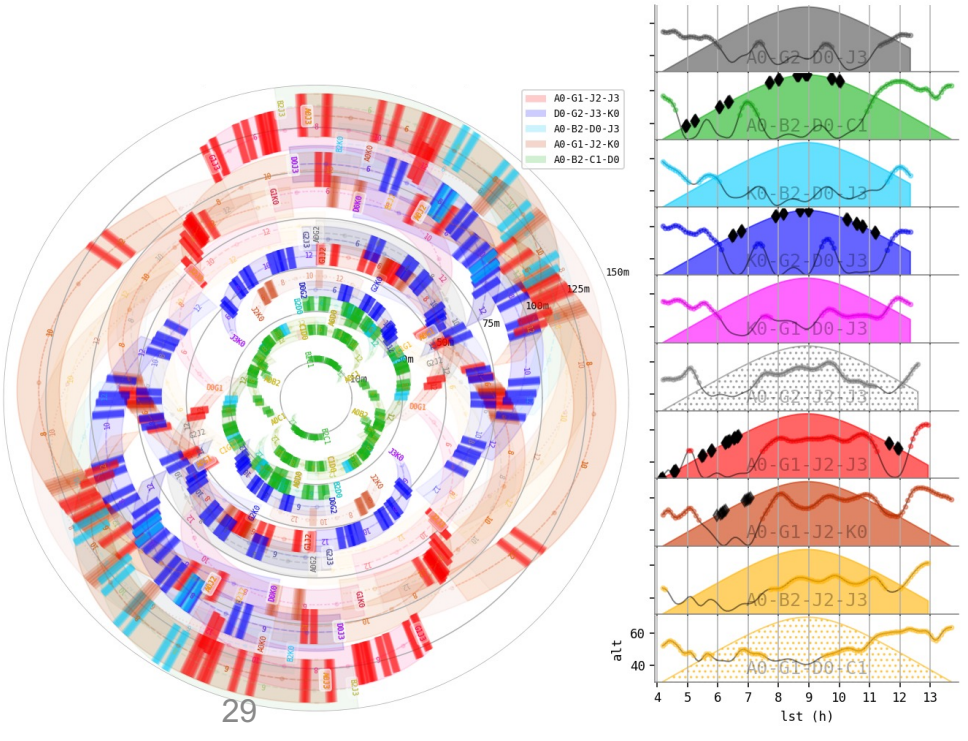
- Schedule of AT and UT is pre-determined
- Most programmes require several AT configurations (u,v coverage)
- Very sensitive to losses, both for VM and SM
- Currently lots of VM (GTO)



Filling the u,v plane

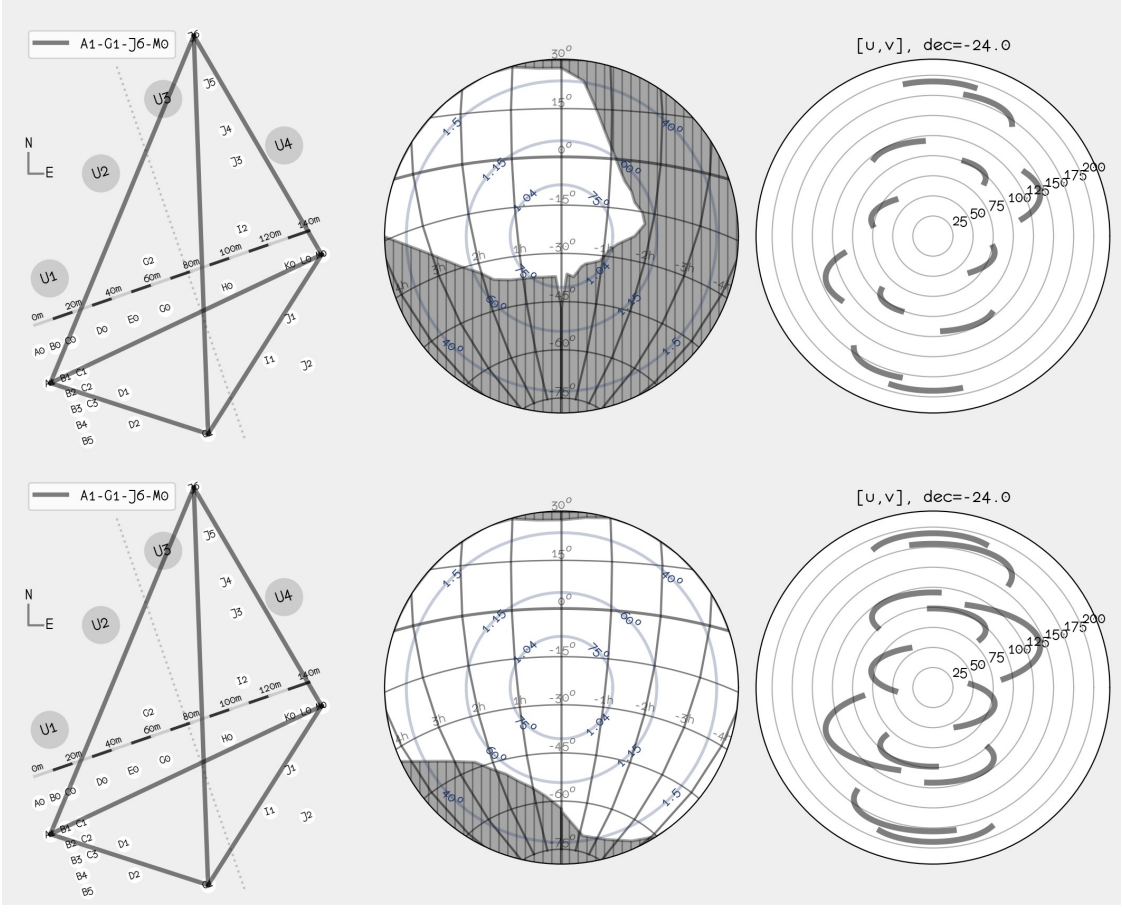


- Synthetic images
  - VLTI allows Image reconstruction require dense u,v coverage
  - multiple LST and different telescopes' configurations
- Current Optimisation of operations
  - Imaging Proposals identified as such
  - ESO to fill uniformly u,v plane (dynamic scheduling)
  - **Imaging slots** (SM only) + u,v monitoring + nested OB concatenations
- Future:
  - Full integration of imaging to operation tools
  - Include requirements in new scheduling tool



Opening longer baselines (2022?)

- 4T and 200m currently impractical
- Optical length of DL is being doubled



GRAVITY +: faint science

- Essentially same consortium as GRAVITY (Lead MPE)
- Phase A: January-July 2021

Table 1: Top-level requirements for GRAVITY+.

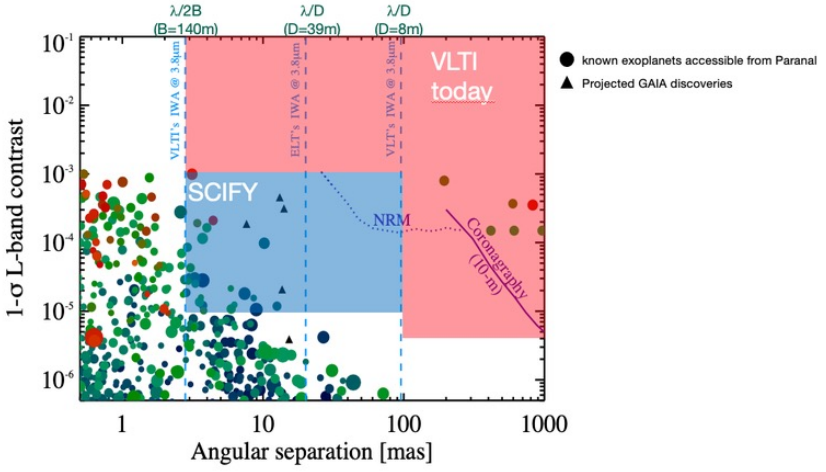
Science case	Science band	Strehl in science band	Guide star R-band magnitude	AO mode	Science K-band magnitude	Fringe trk. magnitude separation
Galactic Center	K-band	> 50%	14 (LGS)	LGS	up to 22	K = 10 at up to 30”
Extragalactic & Faint galactic	K-band	> 50%	18 (LGS) 10 (NGS)	LGS, NGS on/off-axis	up to 22	K = 13...15 at > 30”
Exoplanet & High Contrast	K-band	> 75%	10	NGS on-axis	up to 22	On-axis

NGS: natural guide star adaptive optics; LGS: laser guide star adaptive optics

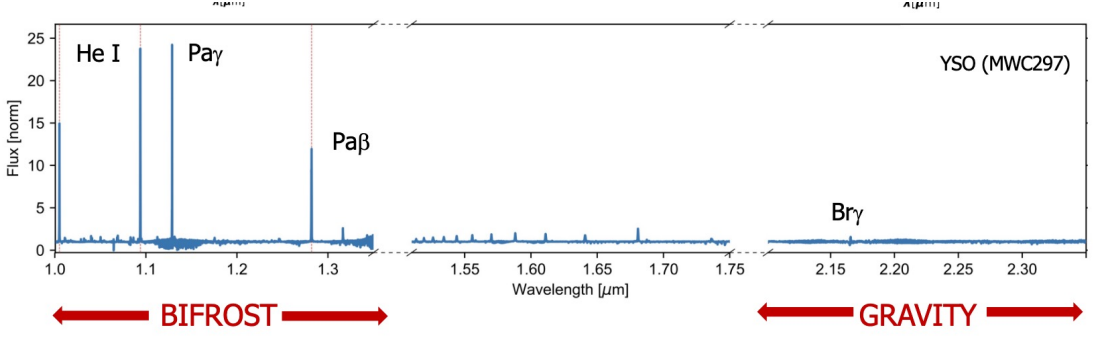
- Construction green light requires ESO Council decision (end-2021)
- https://www.mpe.mpg.de/ir/gravityplus

ERC Funded visiting instruments

- Hi-5
  - High contrast at 3-5um
  - PI: D. Defrère (KU Leuven)



- BIFROST
  - J-Band spectrograph
  - Binaries, YSOs, spin-orbit
  - PI:S. Kraus (Exeter)



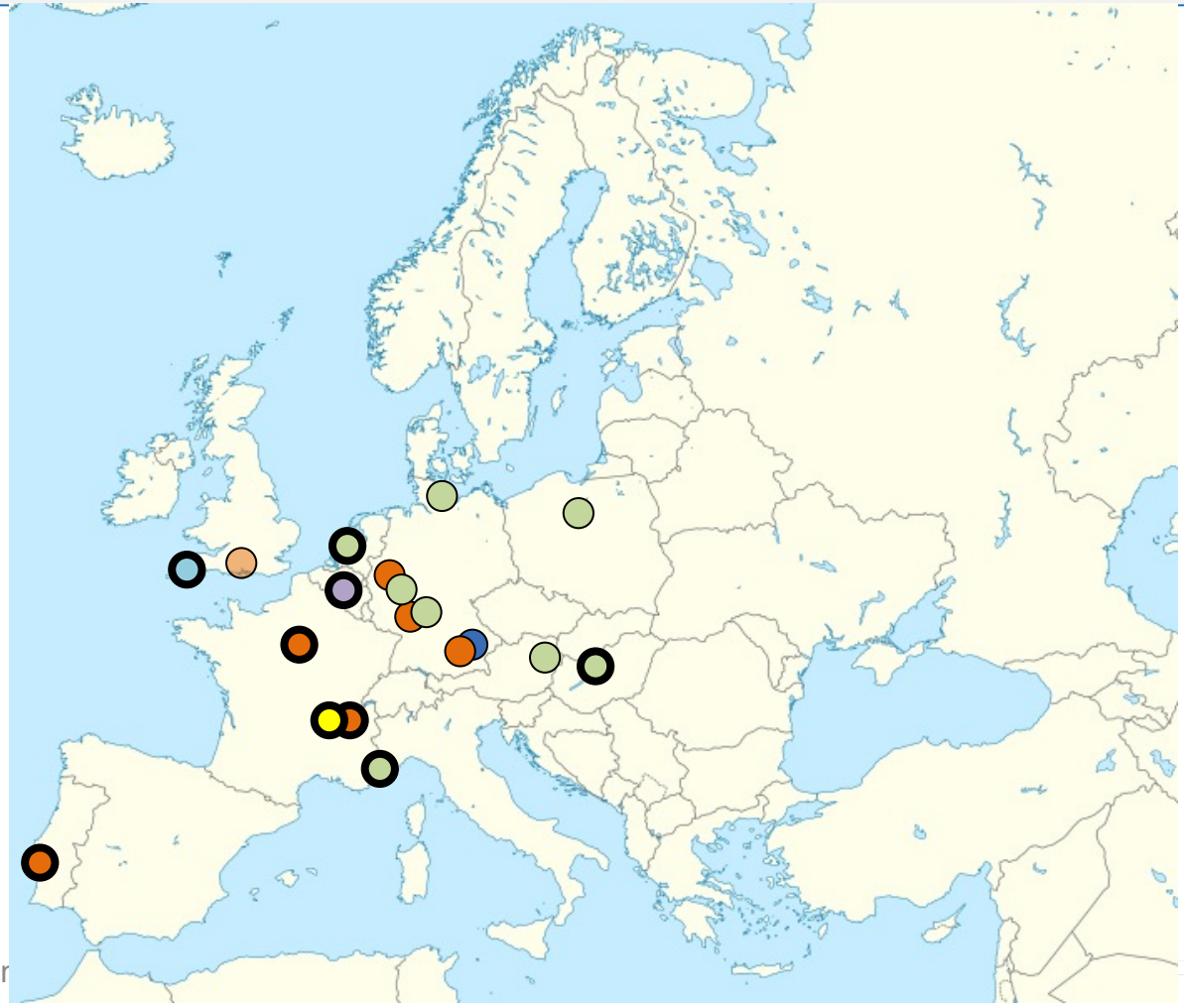
http://www.skraus.eu/presentations/kraus.GAIA-BIFROST.pdf

Consortia and Expertise Centres (EU)

ESO

PIONIER:
- IPAG

GRAVITY (+)
- MPE
- LESIA
- IPAG
- MPIA
- U Köln
- U Lisboa
- + U Southampton

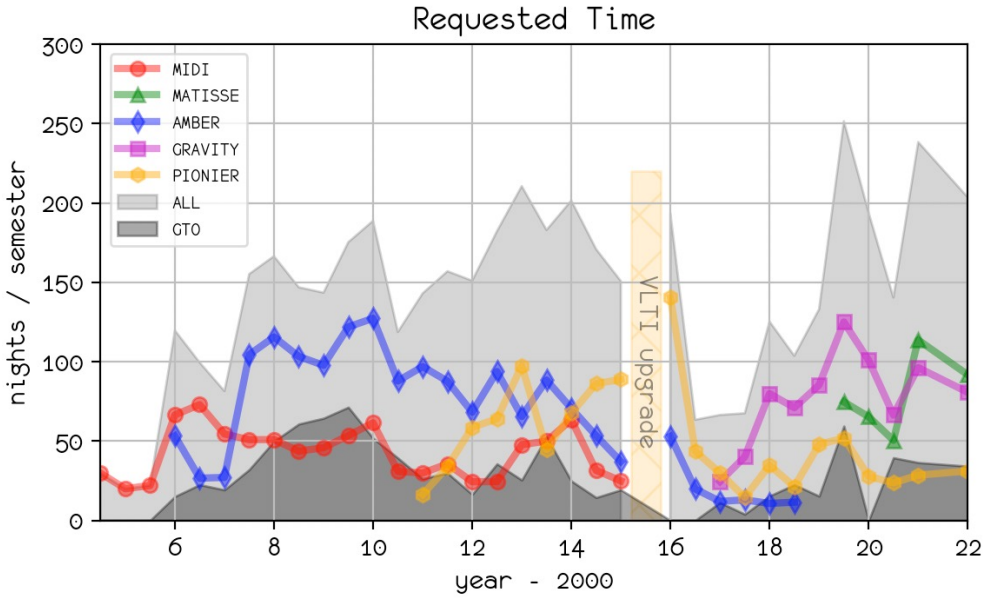


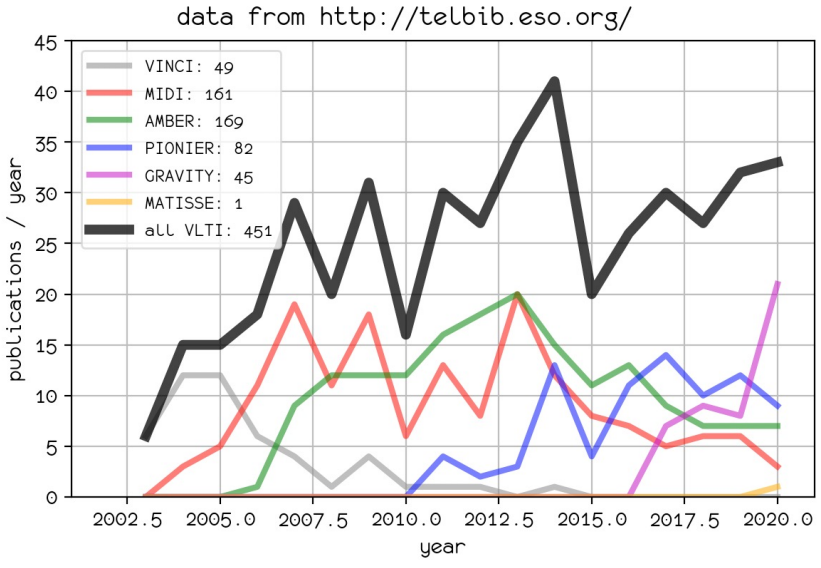
MATISSE
- OCA
- MPIA
- MPIfR
- U Leiden
- U Kiel
- U Vienna
- U Torun
- O Konkoly

Hi-5
- KU Leuven

BIFROST
- Exeter

The VLTI Community





Typical observing over-subscription to scheduled science time: 2 to 3

Community: unique PIs (Co-Is) applying for time over a given 2yr period
2010 - 2015: ~130 (450)
2018 - 2020: ~120 (600)

What are the difficulties?

- Still very much a complex technique
  - Dominated by experts
  - But many efforts to make it more accessible
- Data-poor and analysis-intense
  - Small amount of data per hour, single object
  - Still challenging u,v coverage for imaging
  - Data interpretation is complex and often the bottle neck
  - Get archival data, collaborate!
- Multi instruments / techniques
  - Difficulty to connect angular scales
  - Simultaneous spectroscopy / photometry
  - Possibility to simultaneous VLT proposals

Well supported system

- Time application alongside VLT, La Silla, APEX
- Documentation (manuals for VLTI, instruments, obs preparation, data reduction, …)
  - https://www.eso.org/sci/facilities/paranal/instruments.html
- Support from ESO's Users Support Department
  - https://www.eso.org/sci/observing/phase2/USD.html
- (Raw) data are public 1 year after observations
  - http://archive.eso.org/eso/eso_archive_main.html
- Public pipelines (from consortia), with OIFITS data format
  - https://www.eso.org/sci/software/pipelines/
- Community support:
  - http://www.jmmc.fr/ tools and reduced data archive
  - https://european-interferometry.eu/vlti-expertise-centers/
  - Fizeau Exchange Programme
  - OLBIN: https://listes.univ-grenoble-alpes.fr/sympa/subscribe/olbin

work at VLTI

- ESO studentship
  - Spend 1 or 2 years at ESO (CL or DE) to work with a local astronomer
  - Calls in May and October
- ESO Fellowship
  - 3 to 4 years in CL or DE
  - Possibilities to work directly as VLTI support
  - Calls in October
- ESO Staff
  - https://recruitment.eso.org/
- ERC funded VI, GRAVITY+ are hiring (or soon will)
- Job announcements on OLBIN email list
  - https://listes.univ-grenoble-alpes.fr/sympa/arc/olbin

Take home messages

- VLTI had slow developments in the past 20+ years, but today's performances are outstanding
- Observation pressure is still reasonable
- Some under-explored fields
- Community user-support is strong and developing
- Even more exciting developments are coming

It is a good time to use and/or get involved with VLTI

(The initial step is steep, but worth it!)