Physics of stars … thanks to interferometric observations

A. Quirrenbach and J. Surdej

(on behalf of the European Interferometry Initiative consortium)

The VLT Interferometer

EII – European Interferometric Initiatives (OPTICON, FP6)

Universität Vienna, Wien (Austria)
Université de Liège (Belgium)
Astronomical Institute, Ondrejov (Czech Republic, Prague)
Universitè de Grenoble, INSU (France)
Max-Planck-Institut für Astronomie, Heidelberg (Germany)
Konkoly Observatory, Budapest (Hungary)
TRDF Technion, Haifa (Israel)
INAF, Rome (Italy)
Nederlandse Onderzoekschool Voor Astronomie, NOVA/NEVEC (The Netherlands)
Copernicus University, Torun (Poland)
Porto University, Porto (Portugal)
Universita Autonoma Madrid, Madrid (Spain)
Observatoire de Genève, Geneva (Switzerland)
Cambridge University, MRAO (United Kingdom)
European Space Agency, Paris
European Southern Observatory, Munchen

OPTICON

WP3- NA5

Developing the vision for a next-generation interferometric facility

NA Committee : Eric Bakker, Andrzej Niedzielski, Romain Petrov, Andreas Quirrenbach and Jean Surdej

See the links :
http://www.strw.leidenuniv.nl/~eurinterf/Activities/OPTICON-NA/index.html
http://www.strw.leidenuniv.nl/~eurinterf/

Science Cases for Next Generation Optical/Infrared Interferometric Facilities (the post VLTI era)

Proceedings of the 37th Liège International Astrophysical Colloquium

23 - 26 August 2004

Edited by

J. Surdej

D. Caro

A. Detal

24/1/2007

Technology Roadmap for Future Interferometric Facilities

Proceedings of the European Interferometry Initiatives Workshop organized in Liège, in the context of the 2005 Joint European and National Astronomy Meeting “Distant Worlds”

6 - 8 July 2005

Edited by

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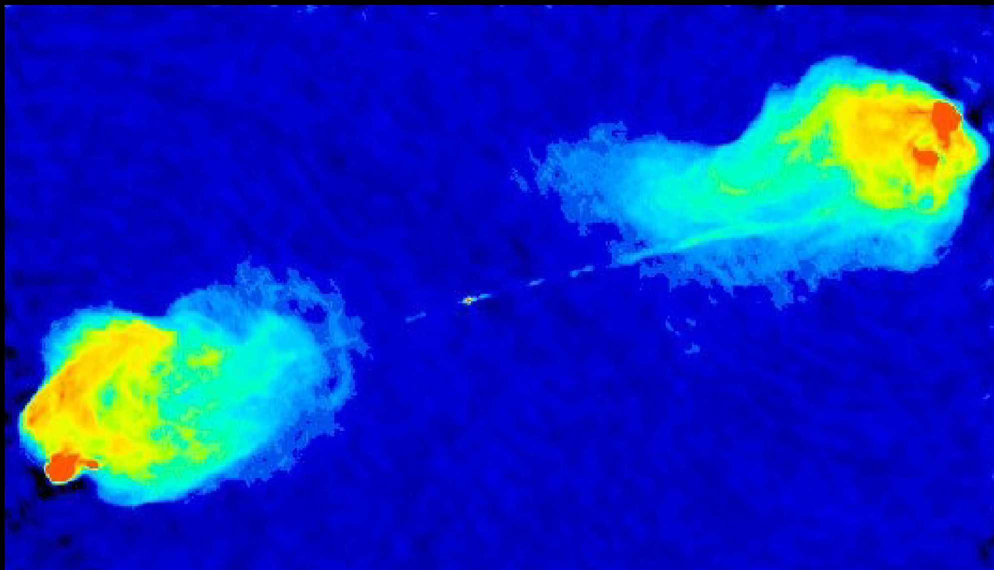
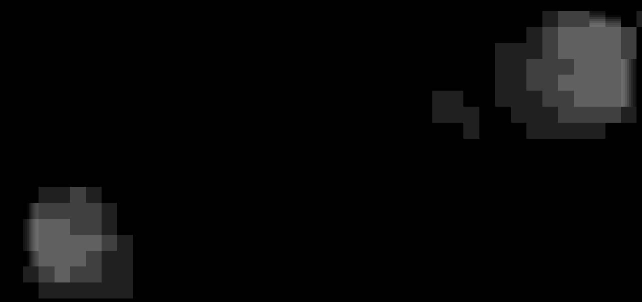
24/1/2007

Example of radiastronomy : from large, single dish to the VLA, VLBA … observations





Key Topics in Stellar Astrophysics

- Fundamental parameters of stars
- Stellar oscillations / asteroseismology
- Structure of stellar atmospheres
- Stellar activity / stellar surface imaging
- Rotation and differential rotation
- Variable stars / Baade-Wesselink distances
- T Tauri / Herbig disks
- Stellar winds
- Formation of multiple systems
- Interacting binary stars
- Stellar explosions (e.g., novae)
- Micro-lensing

The Potential of Interferometry

- Optical / IR interferometry can make truly transformational contributions to all of these topics
- In addition, interferometry is expected to revolutionize extragalactic astronomy (not covered here)
- The same applies to the detection and characterization of exo-planets … also considering nulling interferometry techniques from Dome C in Antarctica (ARENA)

Fundamental stellar parameters I

- Mass M, luminosity L, and radius R are fundamental parameters of any star.
- In addition: (initial) chemical composition, and age.

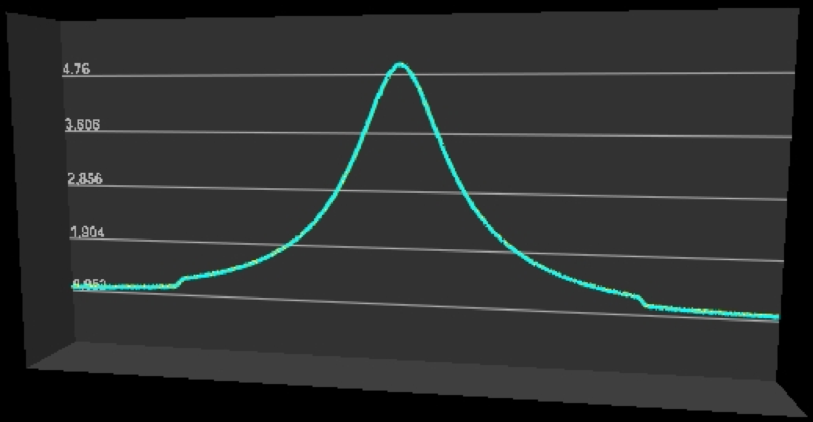
For stars in certain evolutionary stages, the following parameters can be of fundamental importance :

- (initial) angular momentum
- Magnetic field
- Pulsation period P
- Mass-loss rate
- Circumstellar environment

Fundamental stellar parameters - Purpose

- Tests of stellar evolutionary theory as well as of stellar atmosphere theory for stars in all evolutionary stages across the HR-diagram.
- Tests of different available material tables such as opacity tables, nuclear reaction rates, etc.
- Improved physical description of key phenomena such as convection, mass-loss, magnetic activity, etc.

Microlensing



Param1 = R_{min} / R_E

Param2 = V / R_E

Many simultaneous baseline measurements will provide R_E

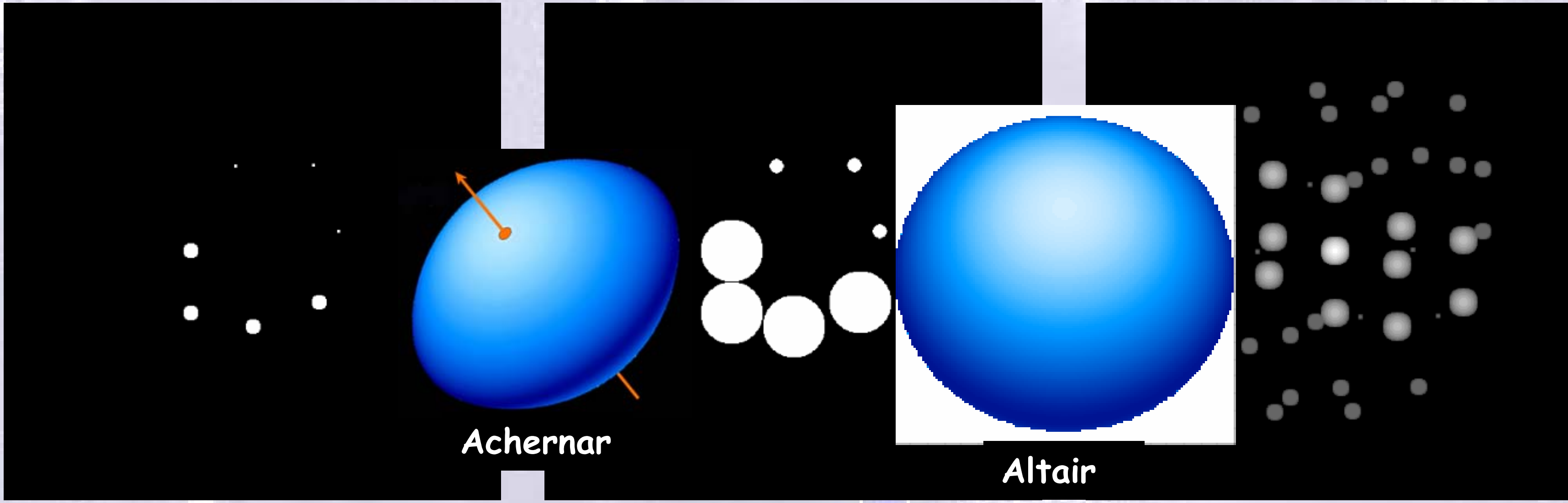
Stars, the Sun, and Planetary Systems

- Do details known from Sun (low-level activity, magnetic cycles, …) carry over to other stars?
- Stellar properties influence planet search strategies
- Future topics: habitability and life
- Need context for planets
  - System age (asteroseismology + interferometry)
  - Parent star properties (fundamental parameters, activity)
- New urgency for detailed studies of nearby stars

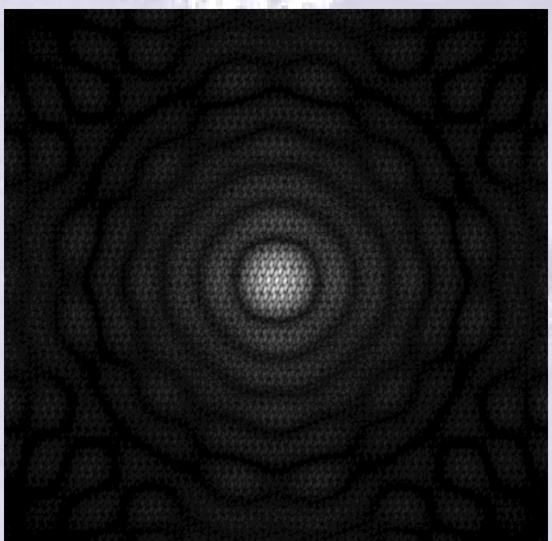
VLTI/Vitruv

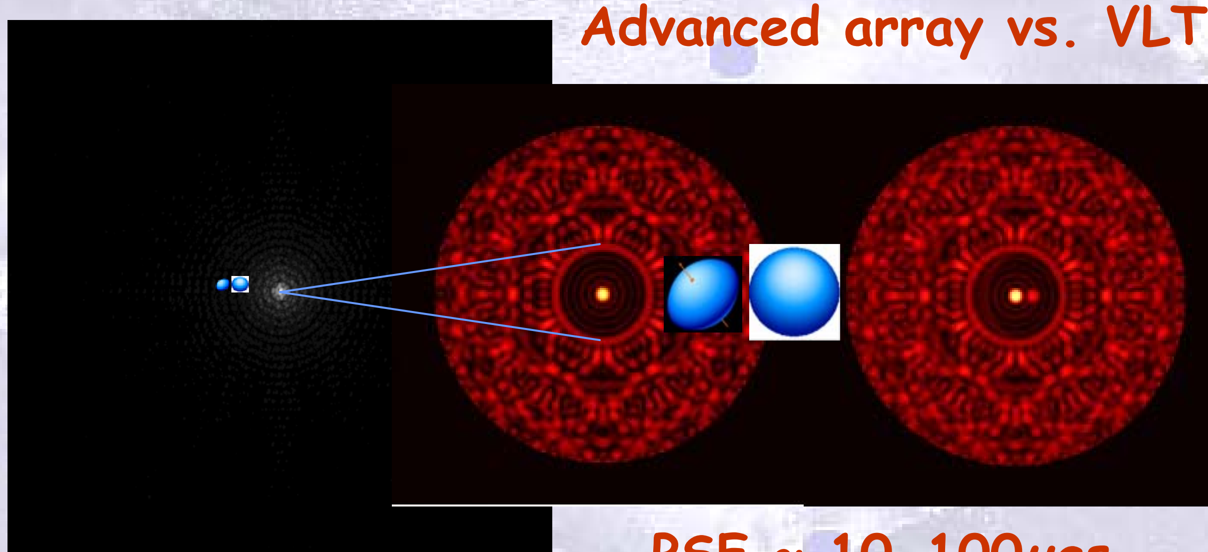
VIDA

Instantaneous u,v plane



Advanced array vs. VLTI

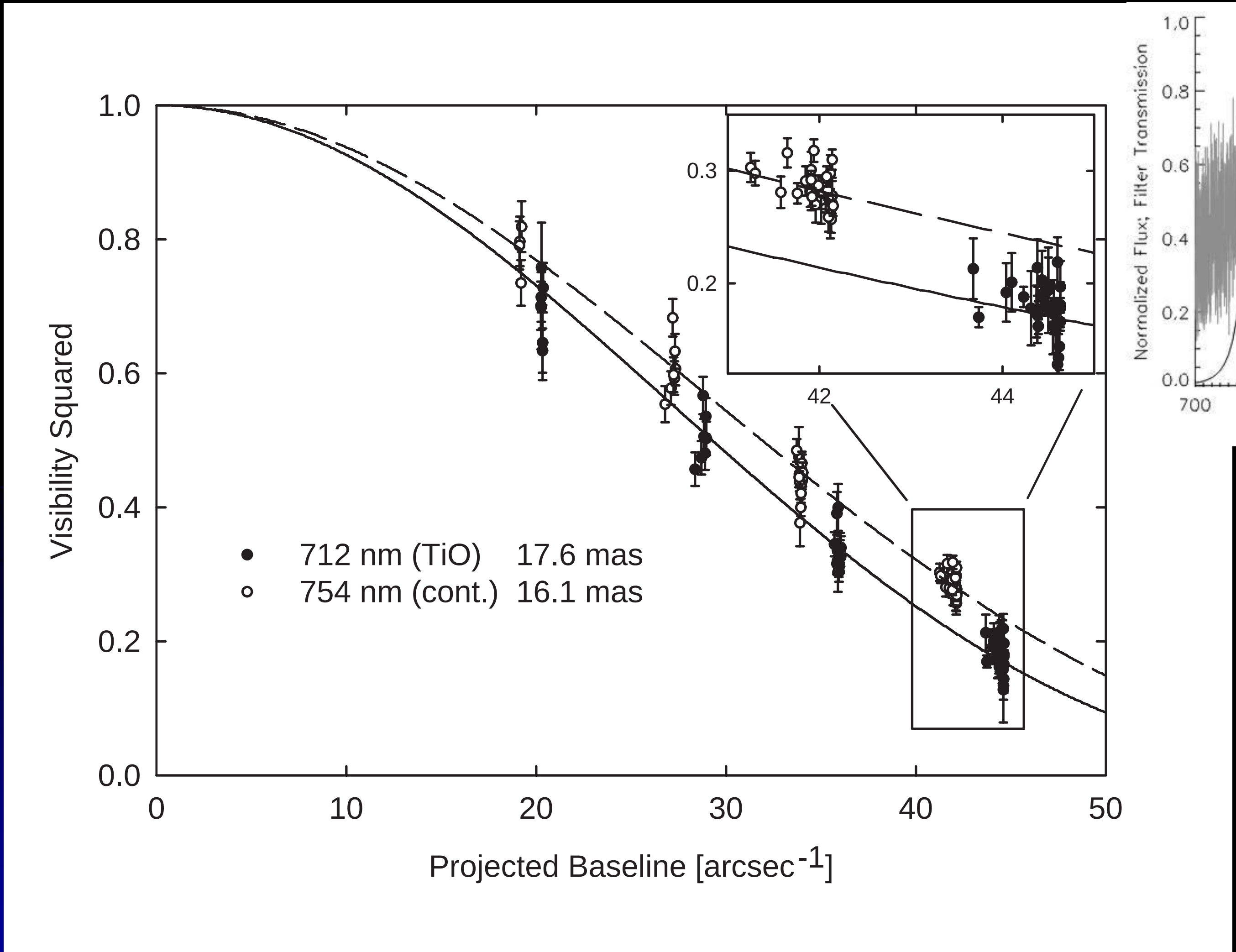


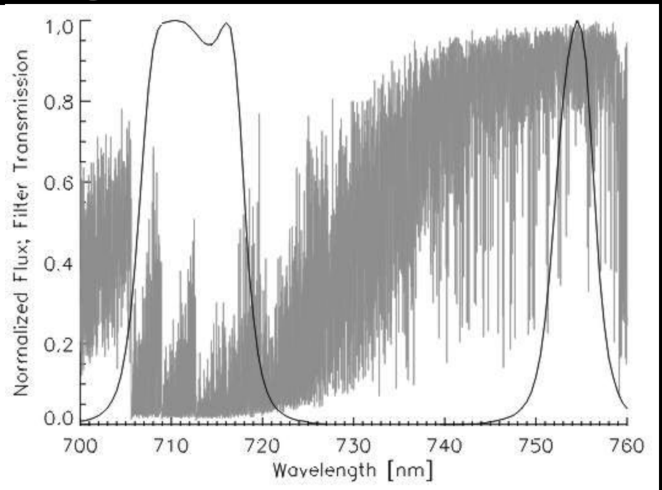


PSF ~ 10-100μas

Dumont d'Urville (F)

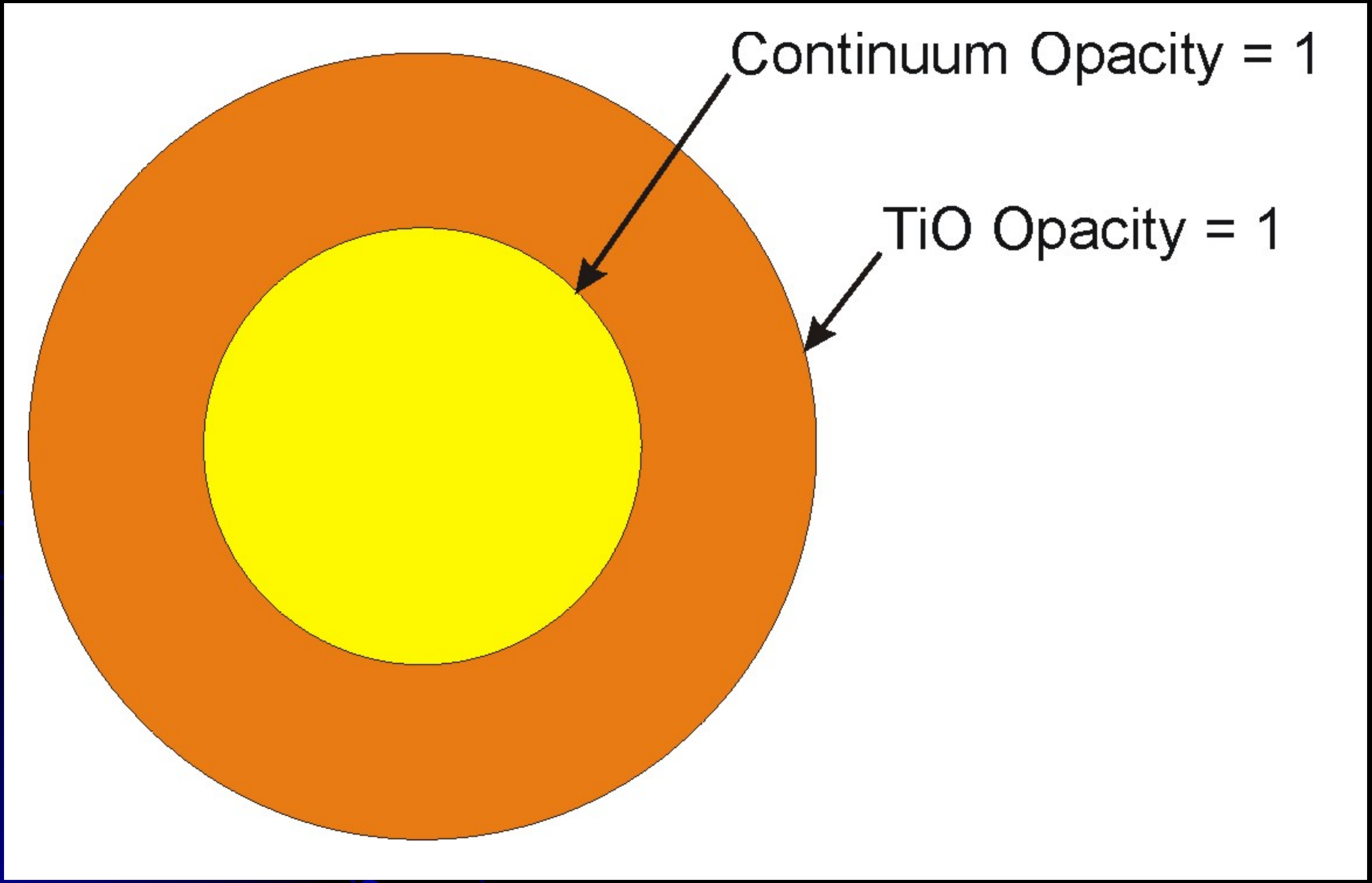
Mk III Diameter Measurements of the Giant Star β Pegasi



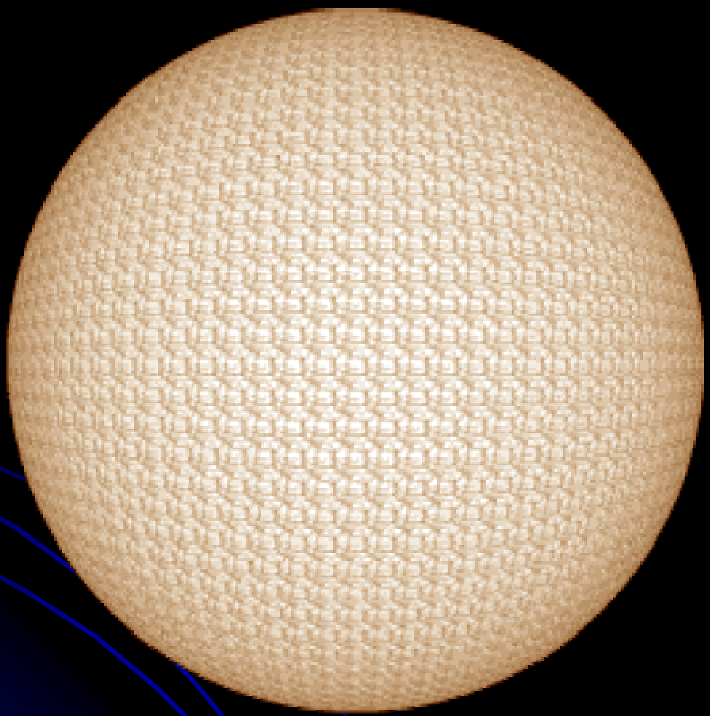


Quirrenbach et al. (1993, 2000)

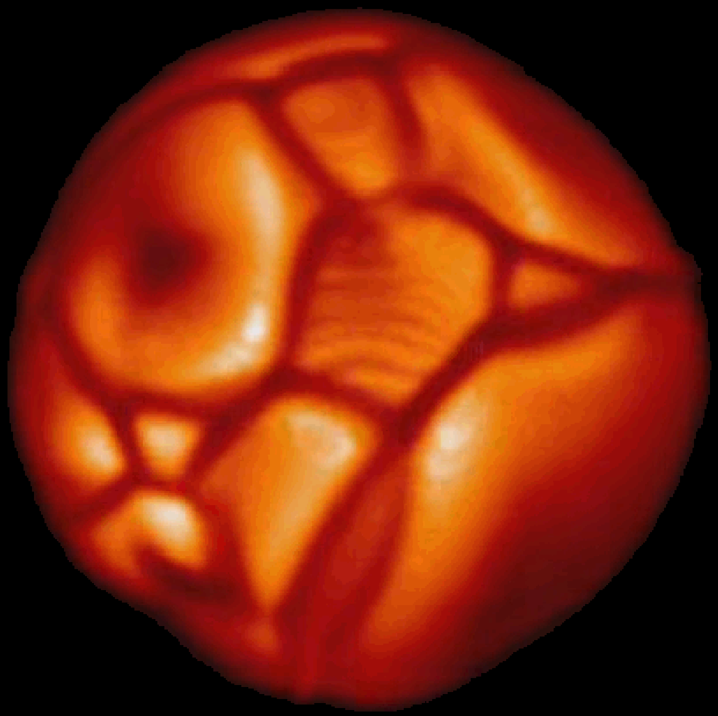
Schematic Model of Extended Stellar Atmosphere



Stellar Convection - Giants

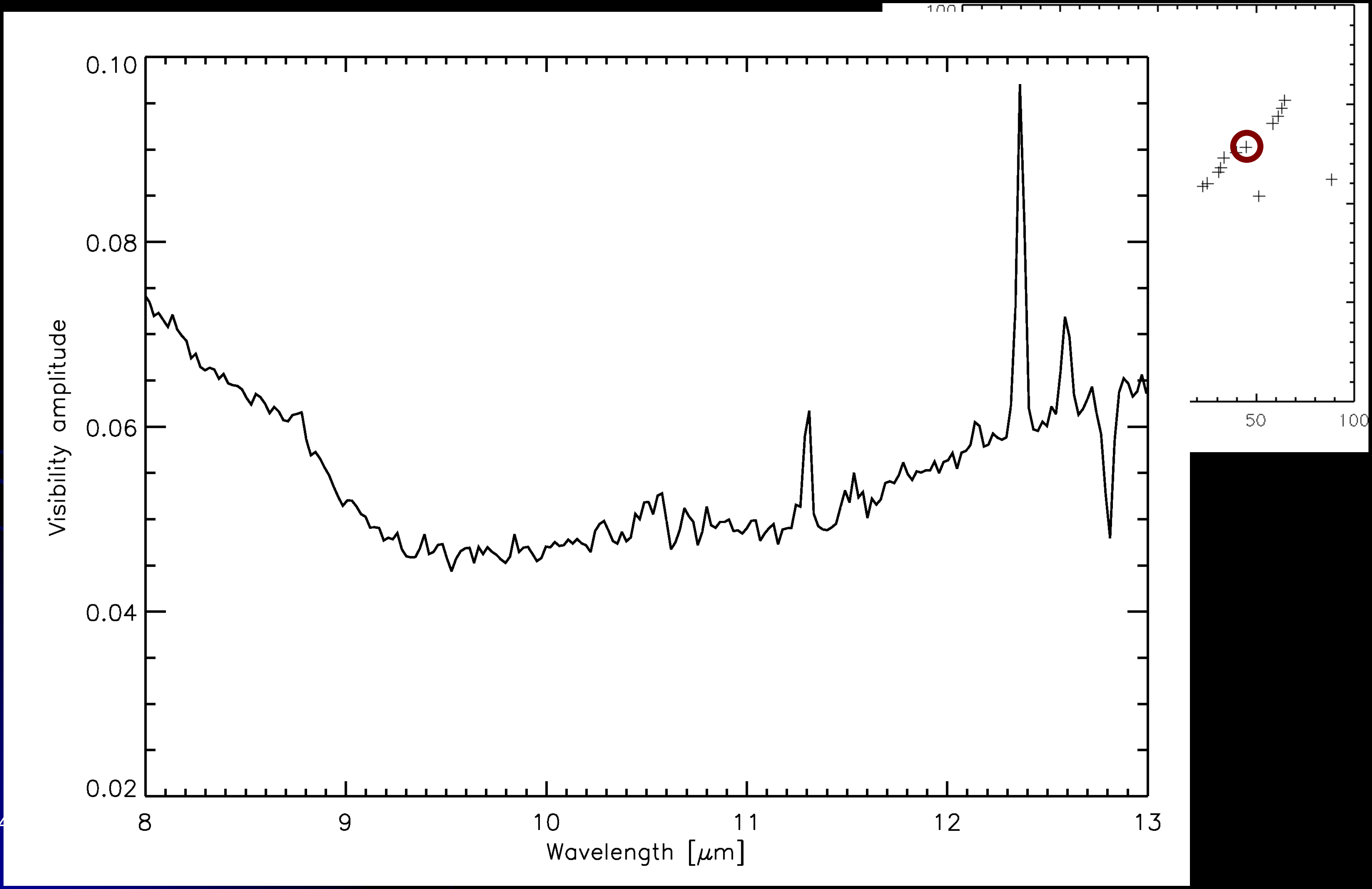


K III giant, R = 25 R_{sun}, HD simulation courtesy H.-G. Ludwig, Lund University

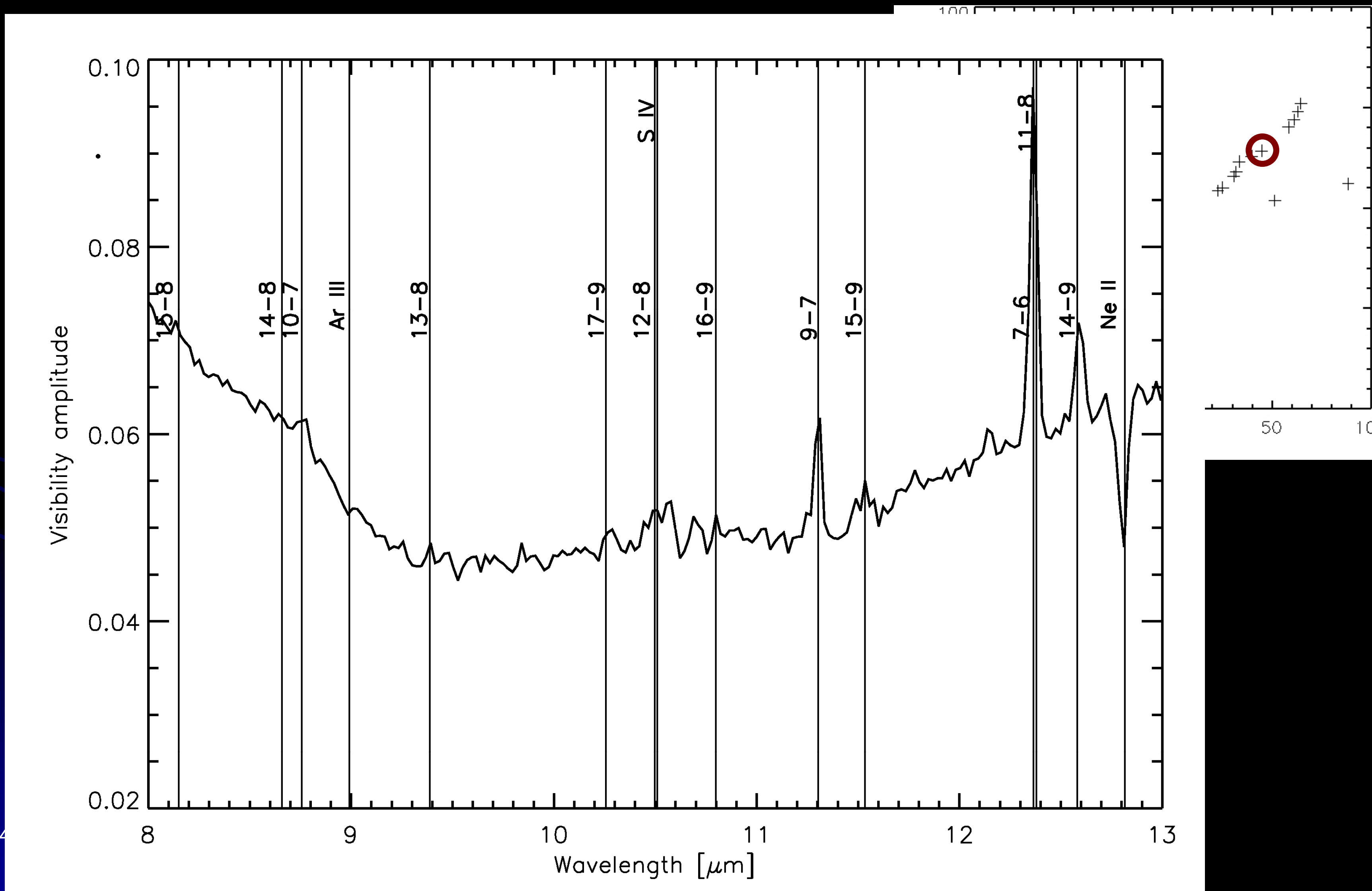


M I supergiant (Betelgeuse), HD simulation courtesy B. Freytag, Uppsala University

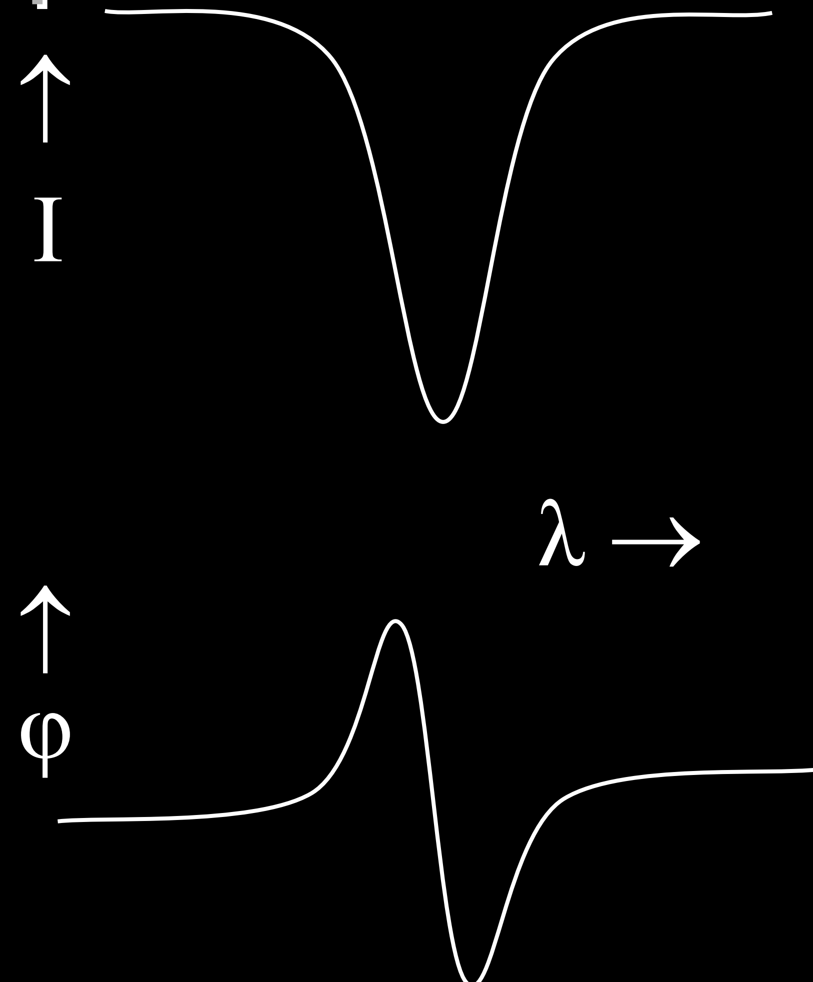
MWC 349A: Visibility Amplitude from one MIDI Observation



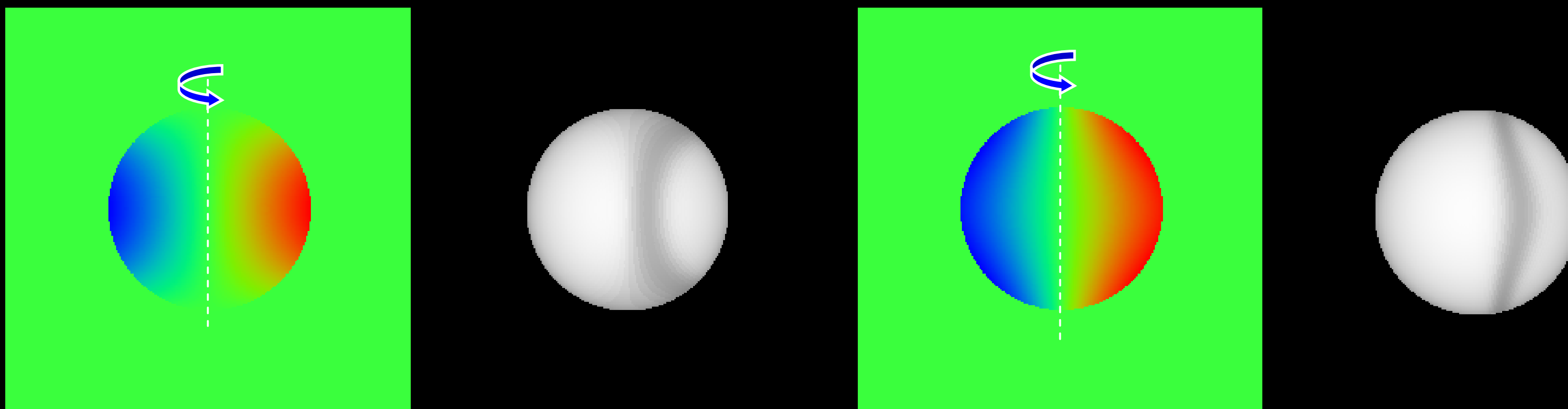
Visibility Amplitude from One Observation



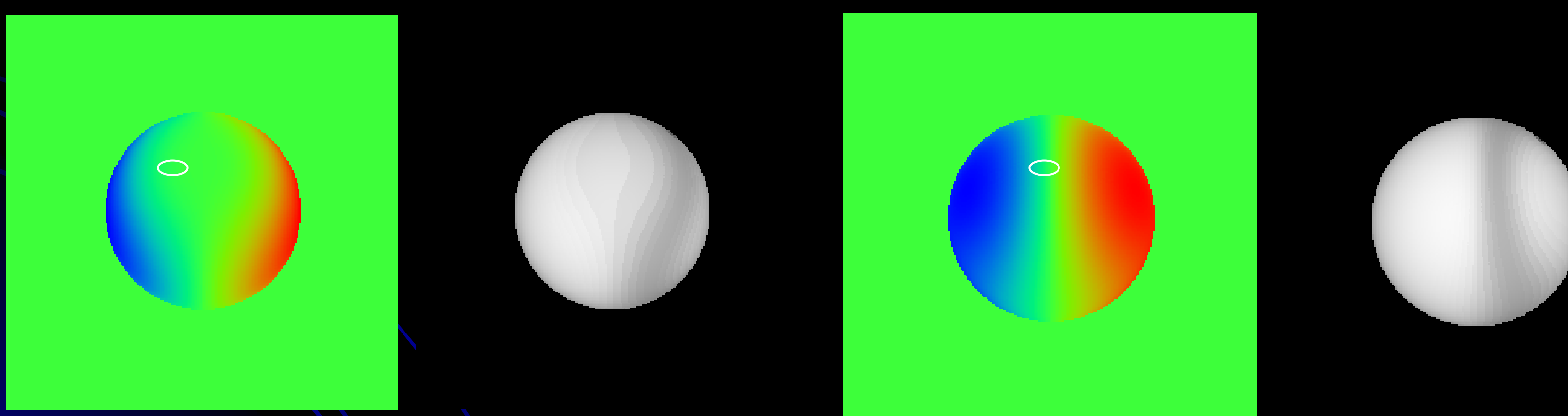
Interferometer Phase across Stellar Absorption Line



Velocity and monochromatic maps of differentially rotating stars



Inclination angle 90°



Inclination angle 30°

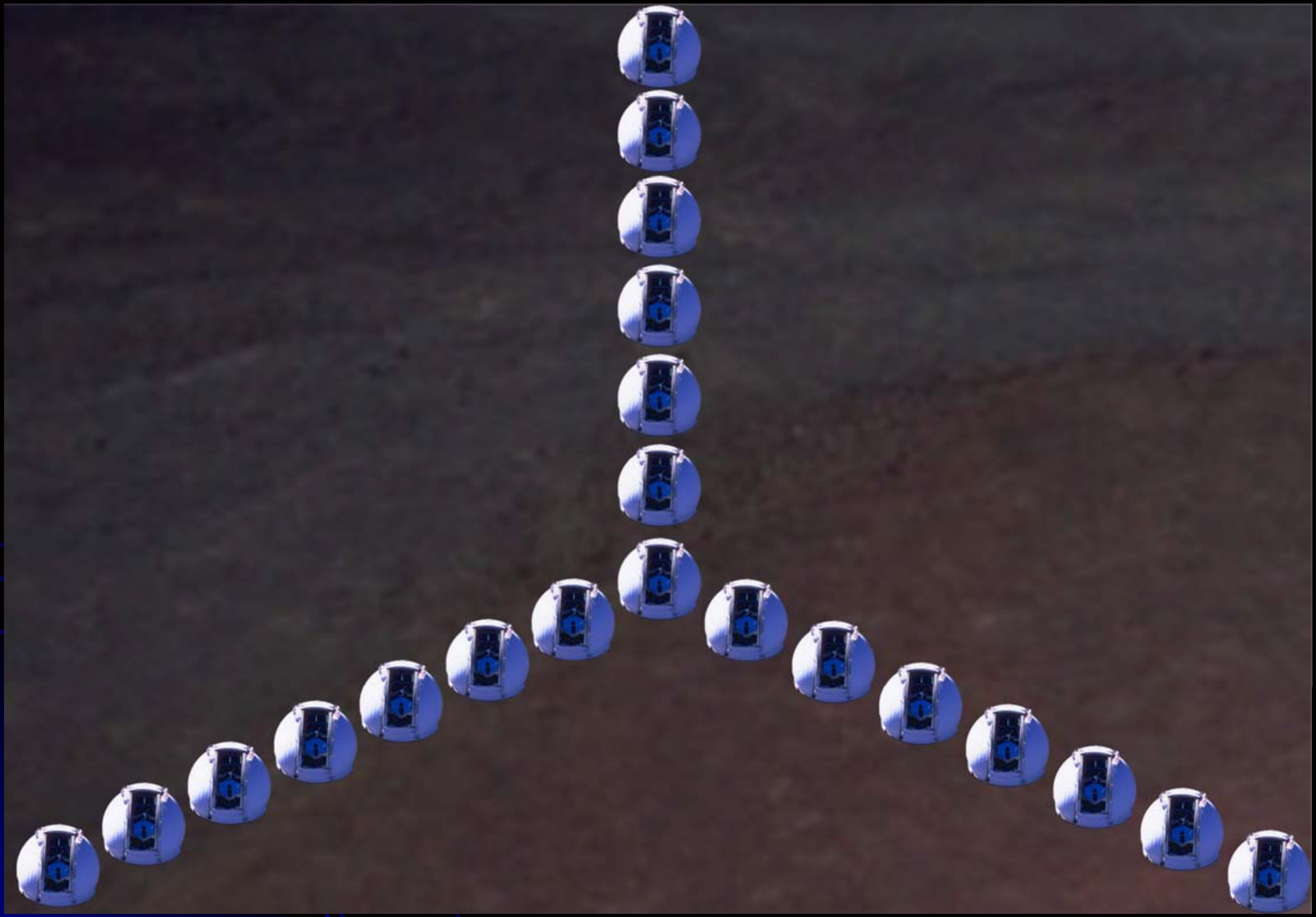
Ordinary differential rotation

Inverse differential rotation

Desirable Capabilities of a Next-Generation Interferometer

- Address wide range of scientific topics $\Rightarrow$ flexibility
- Observe faint objects $\Rightarrow$ high sensitivity and dynamic range
- Complex objects / limited prior knowledge $\Rightarrow$ imaging capability
- Access "famous" archetypical and rare objects $\Rightarrow$ good sky coverage
- Observe time-variable phenomena $\Rightarrow$ good snap-shot capability

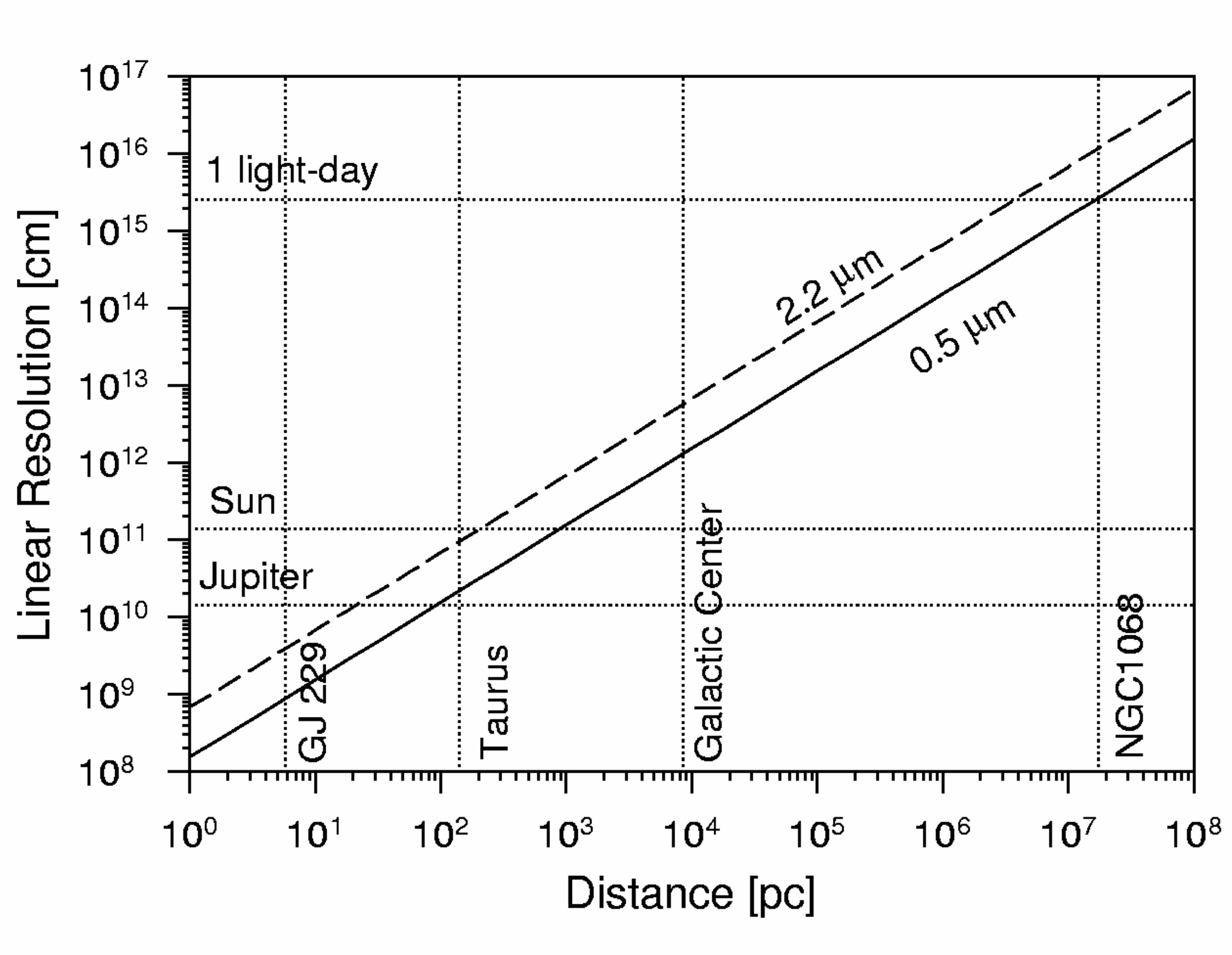
A Next-Generation Facility?

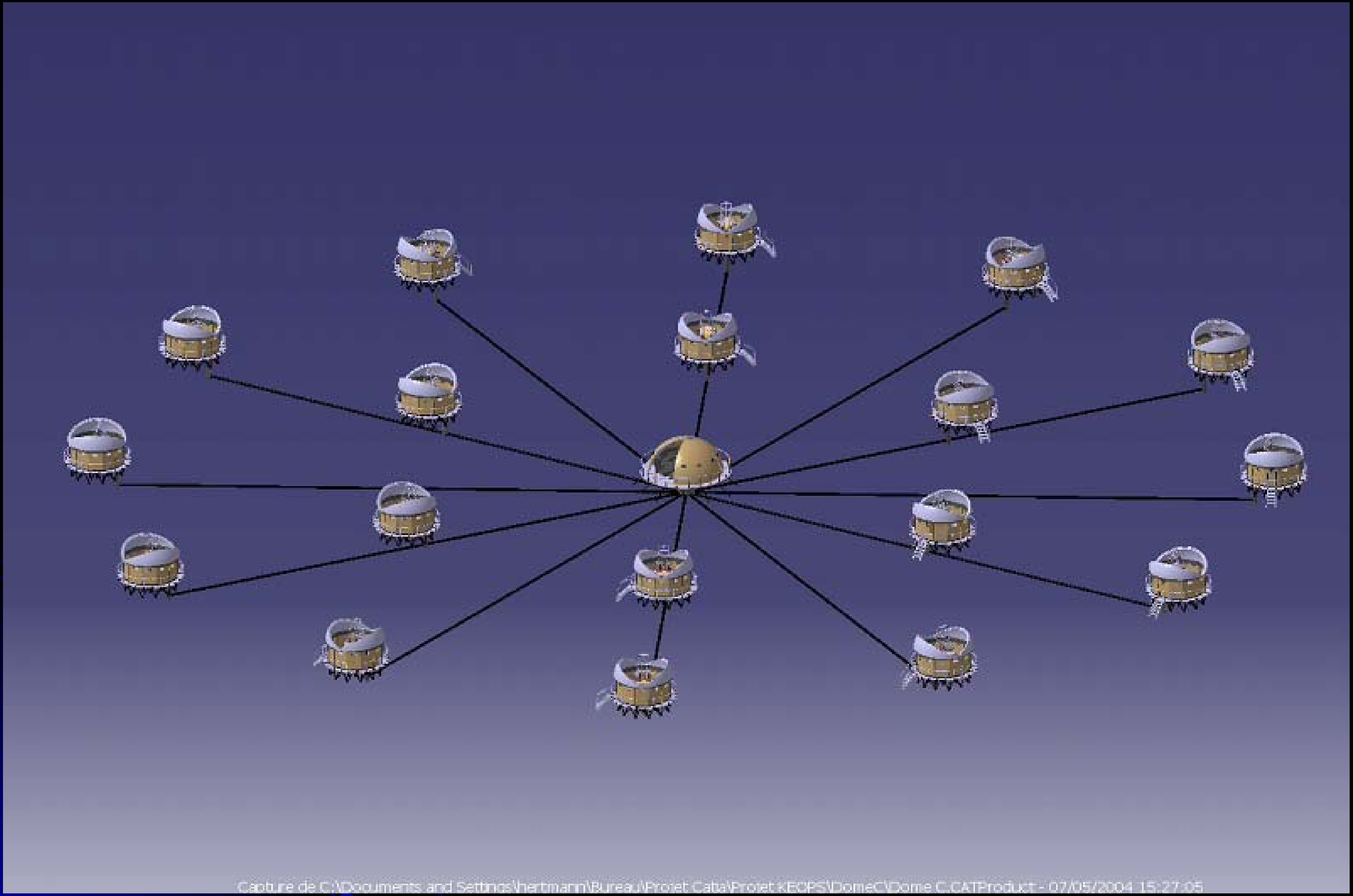


The ELSA Concept – a Strawman Interferometric Facility

- Number of telescopes: 27
- Telescope diameter: 8 m
- Maximum baseline: 10 km
- Wavelength range: 500 nm … 20 μm (?)
- Beam transport: Single-mode fiber bundles
- Beam combination: Michelson
- Sky coverage at 600 nm: & 10%
- Cost: ≈ 400 M€ (?)

Linear Resolution of ELSA in the Local Universe

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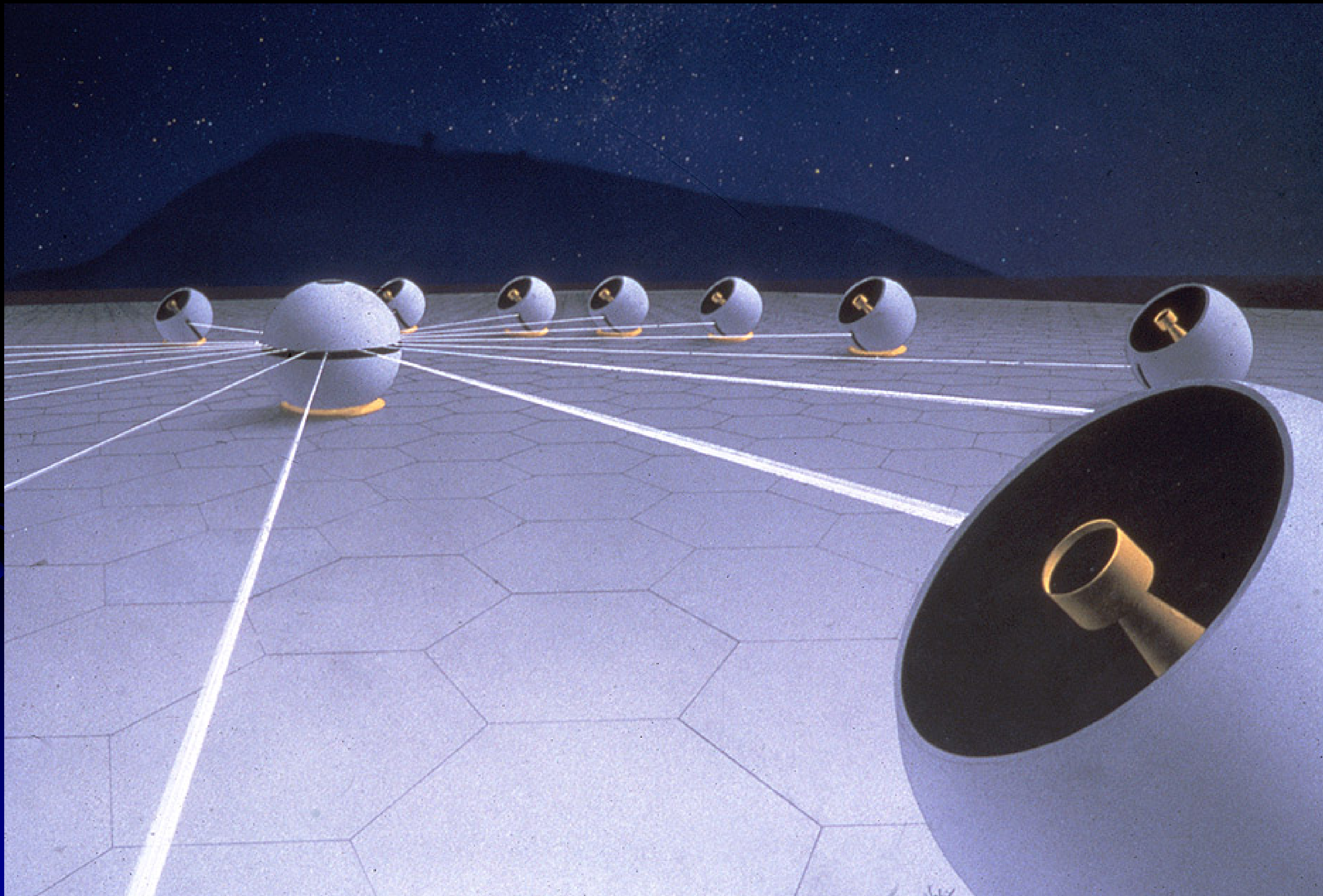
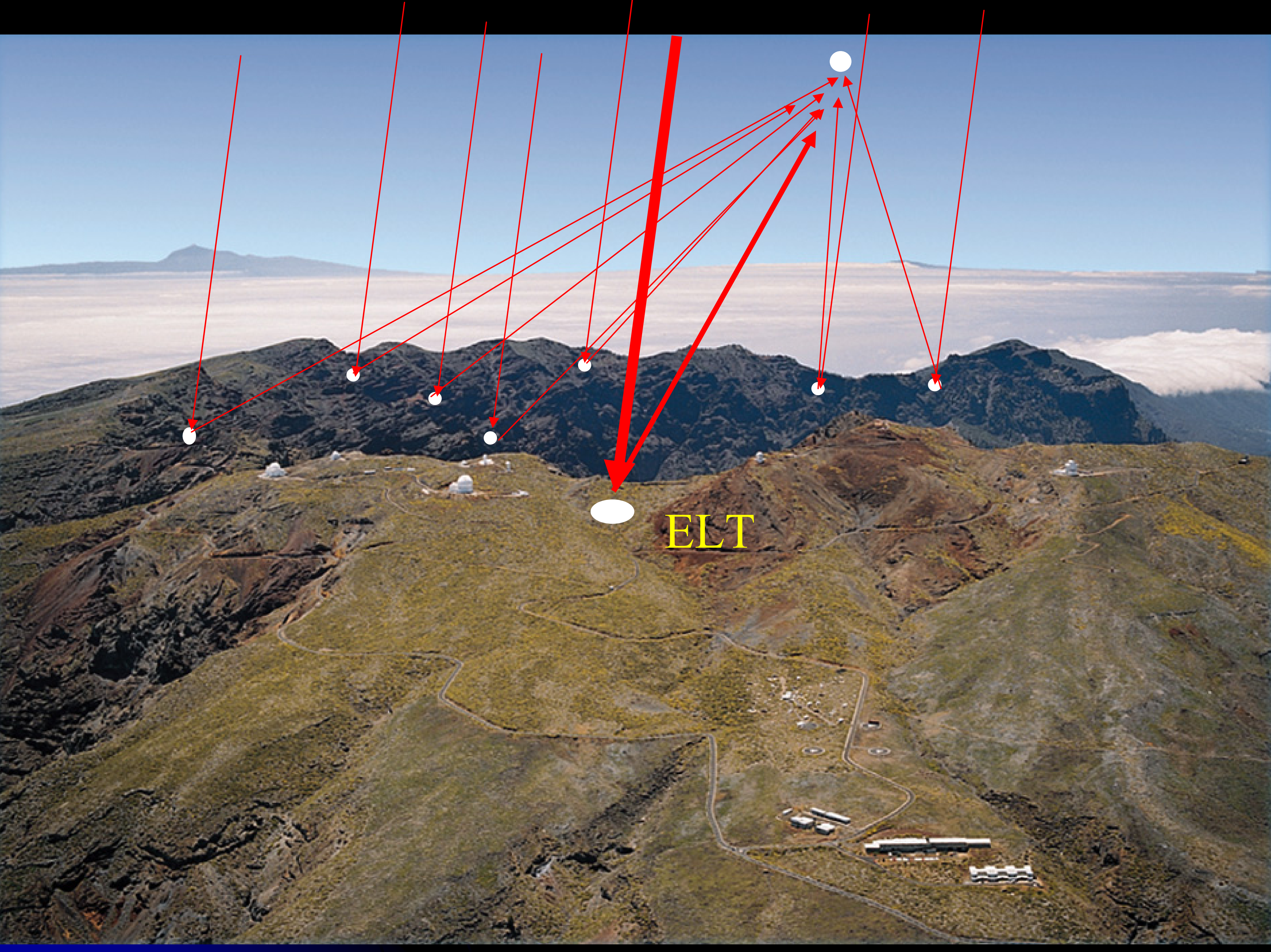



ELT

Strategic Considerations

- Interferometry enables truly transformational science – but needs patience and stable funding
- Europe (VLTI) has taken lead in interferometry
- Continued investments needed for optimum exploitation and further development
- Balance between ground and space is essential
- Global cooperation is highly desirable

Roadmap for Optical / Infrared Interferometry

- Further development of the VLTI
  - Second-generation instrumentation (near/mid-IR)
  - Visible-light instrumentation (imaging/spectroscopy)
  - Additional 1.8m telescopes, delay lines
- Enabling technology R&D
  - Telescopes $\rightarrow$ synergies with E-ELT
  - Beam transport and beam combination
- Conceptual design of next-generation facility
  - Iteration concepts $\leftrightarrow$ science case
  - Evaluation of potential sites
- Implementation plan
  - Detailed design, site selection
  - Financial constraints

Comments on Recommendations in Draft Vision Document

- “Few mas” is not good enough for many purposes – sub-mas needed
- Need complementary ground-based and space-borne facilities
  - Start with km baselines on ground, “Stellar Imager” later
- Darwin (high-contrast) is complementary to interferometers optimized for imaging

Conclusions

- Many important topics in stellar astrophysics need (sub-) milliarcsecond resolution
- VLTI can and should be made much more powerful than it is today
  - High-resolution spectroscopy
  - Visible-light interferometry
  - 8-telescope imaging
- Next-generation array with km baselines will provide absolutely unique capabilities
- Strategic planning and community support are required $\rightarrow$ input to Astronet

ELSA Astrometry

- Astrometric error due to Kolmogorov atmosphere scales with $B^{-2/3}$
- ELSA could reach 1 μas over 15″ arc
  - Sufficient to detect terrestrial planets around nearby stars
- Even better precision expected due to outer scale of atmospheric turbulence
- Precision requirements less stringent than for Keck / VLTI

ELSA Resolution: 10 μas at 500 nm, 40 μas at 2 μm

- 15,000 km at 10 pc
  - 8 pixels across Jupiter-size object
  - 80 pixels across Solar-type star
- 0.1 AU at 10 kpc
  - GR effects on stars very close to the Galactic Center
- 200 AU (1 light-day) at 20 Mpc
  - Images of AGN Broad-line regions
  - Expansion and light echoes of supernovae

ELSA Science Case (Galactic)

- Weather on brown dwarfs
- Stellar surface images (spots, flares, convection, differential rotation, oscillations, …)
- Images of interacting and accreting binaries
- Gaps and inner edge of YSO disks, jet formation
- Cores of globular clusters
- AGB stars: dust formation, winds
- Movies of novae
- Gravitational micro-lenses
- General relativity near Galactic Center

ELSA Science Case (Extragalactic)

- Stellar populations in external galaxies
  - Crowding important even on ELT scale
- Expansion and light echoes of supernovae
- Imaging of Active Galactic Nuclei
  - Dynamics of broad line regions
  - Jet formation
  - Black hole masses from stellar orbits
- Resolving gamma-ray afterglows
  - Asymmetries, relativistic beaming

ELSA Critical Technologies

- Telescopes
- Array co-phasing
- Beam transport
- Beam combination
- Delay compensation

ELSA Telescopes

- Need to produce twenty-seven 8m telescopes for ≈ 200 M€
- Moveable for array reconfiguration if possible
- Small field-of-view
- No scientific instruments (acquisition and fiber-feeds only)
- Take advantage of ELT development
  - Mass production of mirror segments
  - Standardized structural elements

Projected Cost of Telescopes

- Typical scaling of telescope cost with diameter is € _ $D^{2.7}$
- Scaling applies at any given time (for similar maturity of technology), not to future projection
- Example: scaling holds for Keck (10m) versus CHARA (1m) telescopes
- Apply scaling to ELT (e.g., European E-ELT concept): 42m for 700 M€ $\Rightarrow$ 8m for 8 M€

ELSA Beam Transport

- Fibers are much cheaper than beam tunnels $\Rightarrow D_{\text{opt}} = k \times \sqrt{\lambda L} + m\theta L$
  - Diffraction + field
- Need advances in fiber technology
  - No significant light loss over 10 km
  - Low dispersion, polarization preserving
  - Fibers for infrared wavelength range
- Need metrology to monitor fiber lengths
- Fiber bundles can handle field-of-view larger than Airy disk

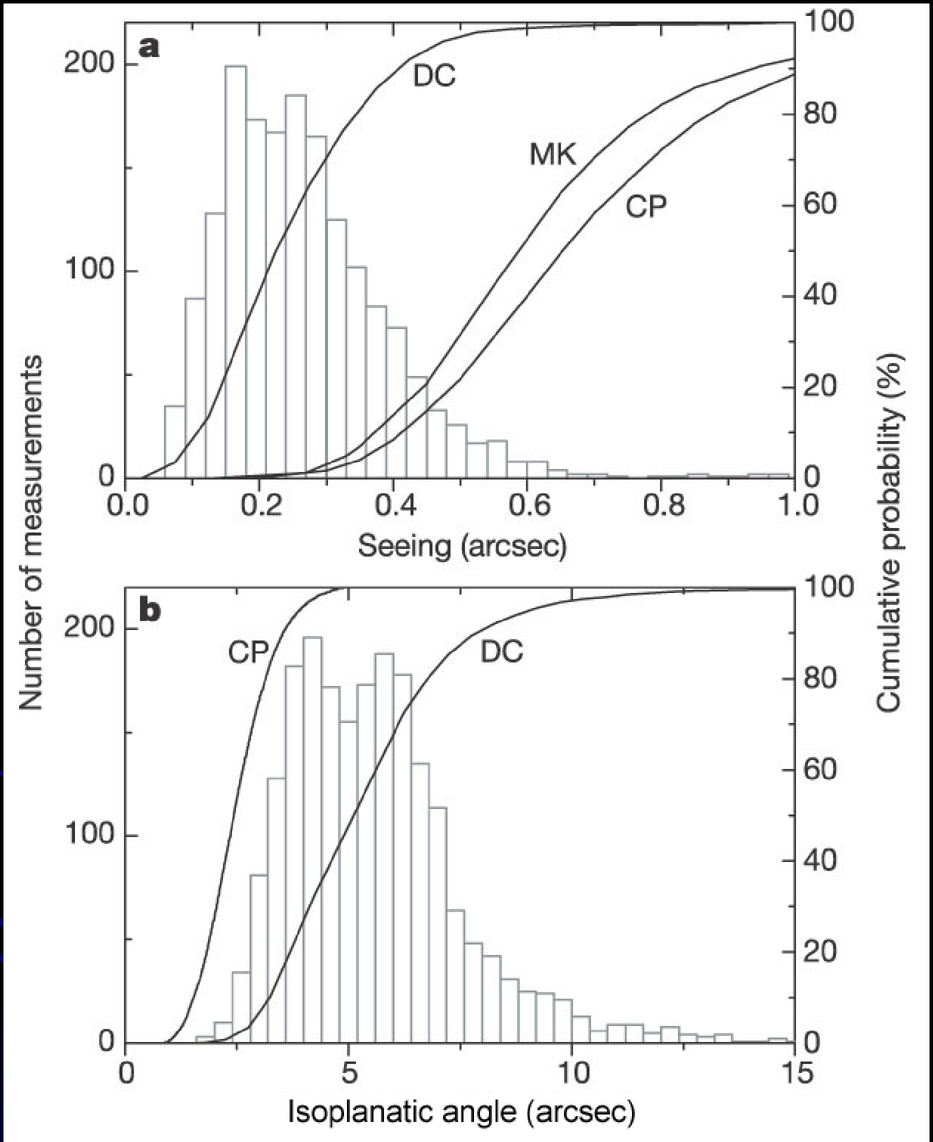
ELSA Delay Compensation

- Switch between fiber segments for bulk delay compensation
  - Add appropriate fibers from set of (1m, 2m, 4m, …)
  - Dispersion is a potential show-stopper
  - Need low-loss fiber-fiber couplers
- Fiber stretching for fine adjustment (sidereal rate plus atmosphere)
  - Fall-back is short classical delay line

ELSA Site

- Need flat ≈ 10 km plateau
- Good seeing (r_0, τ_0, θ_0) important criterion
- Southern hemisphere preferred
- Requirements different from ELT criteria
- ALMA site probably (marginally) ok

Exceptional Astronomical Seeing at Dome C in Antarctica (?)



Potential Advantages of Dome C

- Larger $r_0 \Rightarrow$ simpler adaptive optics
- Longer $\tau_0 \Rightarrow$ better sensitivity
- Larger $\theta_0 \Rightarrow$ better sky coverage
- Lower temperature $\Rightarrow$ lower IR background
- Or same performance with smaller telescopes
  - 2m at Dome C $\Leftrightarrow$ 8m at traditional sites?

VLTI, ALMA, ELTs, and ELSA

- ELSA has 50 times better resolution than any other facility $\Rightarrow$ completely new science
- ELSA draws on VLTI / ALMA / ELT heritage
  - VLTI: Interferometric techniques, beam combination, …
  - ALMA: Moveable telescopes, site (?)
  - ELTs: Cheap telescopes through mass production of optics and standardized structural elements

Conclusions (1): What we Know Already

- There is a large parameter space of first-class science beyond the ELT resolution limit
- Baseline length of ≈10 km required
- Large telescopes or superb site (Antarctica?) needed to get sensitivity and good sky coverage
- A powerful facility could become feasible and affordable in a decade

Conclusions (2): What we Don't Know Yet

- Can fibers be used for beam transport and delay compensation?
- Which site offers the best trade-off between quality and cost?
- Is the science case powerful enough to make it happen?

Key Technology Needs for Roadmap

- Beam transport with optical fibers
  - Dispersion is a potential show stopper
  - Cost driver $\Rightarrow$ top priority on my list
- Beam combination concepts and integrated optics beam combiners
- Telescopes
  - Main issue is cost $\Rightarrow$ link to ELT projects
- Site
  - Evaluate Antarctica
  - Look for good “traditional” sites

Thank You!

What Needs to be Done?

- Currently there is no formal “Future Large Interferometer” project
- Planning is beginning now
  - Detailed science case
  - Technology development roadmap
  - Site evaluation
- Need to get into “official” facility planning
  - US: Decadal Review
  - Europe: ESO, EU, Astronet
  - Others: ??

Spectroscopy – a Blurred View of Stellar Astrophysics

- Model atmospheres: T, ρ, etc. are calculated as a function of depth
  - Stellar surface provides this information (limb darkening, variations of lines strengths across disk)
  - Spectroscopy blurs it all together!
- Stellar (differential) rotation: characteristic pattern of surface motion
  - Spectroscopy blurs it all together!
- Pulsations, oscillations, spots, convection, etc.: detailed information in surface structure

Combination of Astrometry with Spectro-Interferometry