“Classical” Interferometric Arrays

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The VLT Interferometer

Optical / Infrared Interferometry Today

- Access to milliarcsecond-scale phenomena
- Perform interferometric spectroscopy
- Lots of results in stellar astrophysics
- Sensitivity sufficient for a few bright AGN

- Small number of telescopes $\Rightarrow$ parametric model fits to visibilities, no images
- Sensitivity insufficient for larger samples
- Resolution insufficient for details / more distant objects

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

What’s Next?

What’s Next?

Think BIG!

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: $\gtrsim$ 10%
- Cost: ≈ 400 M€

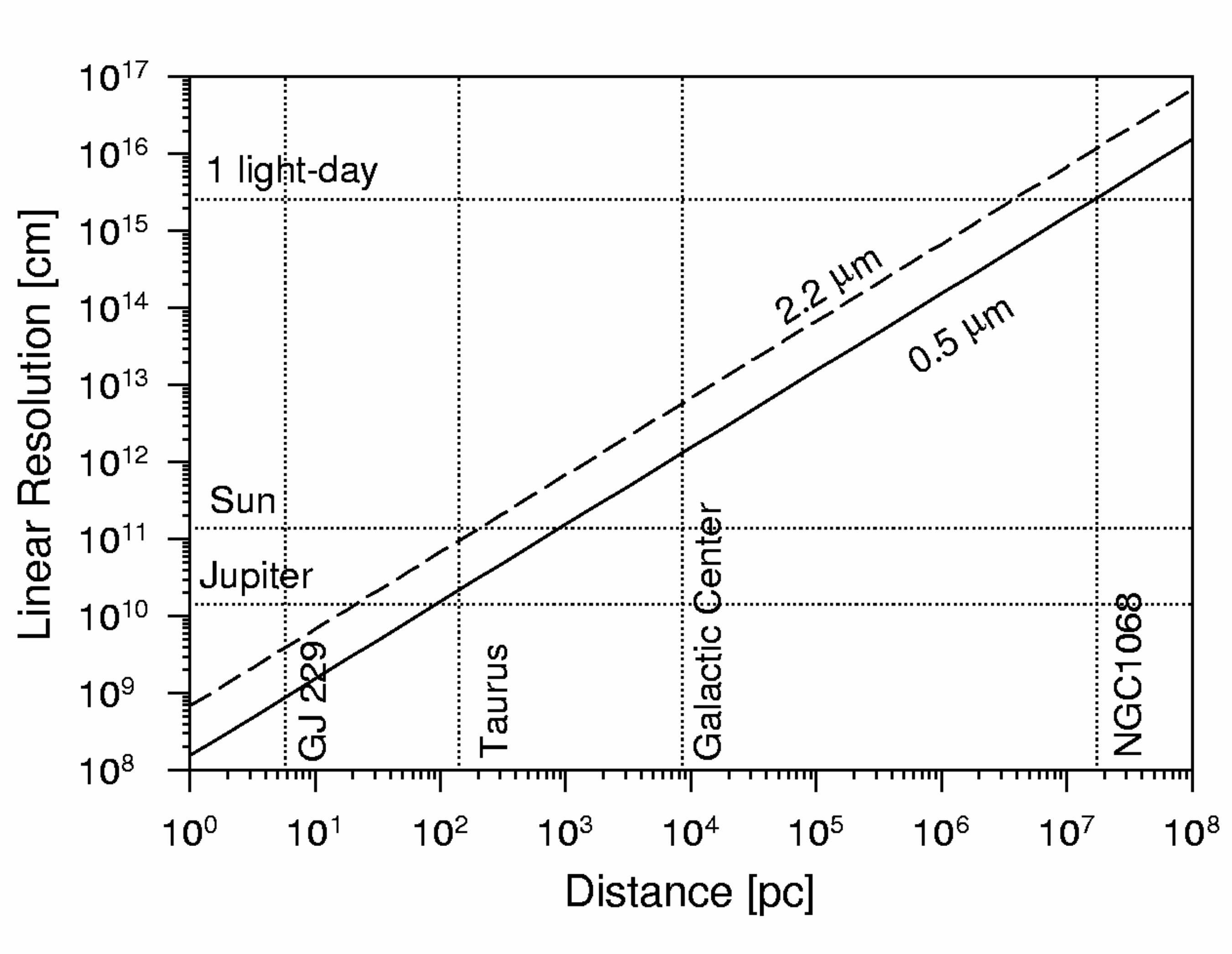
ELSA Astrometry

- 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

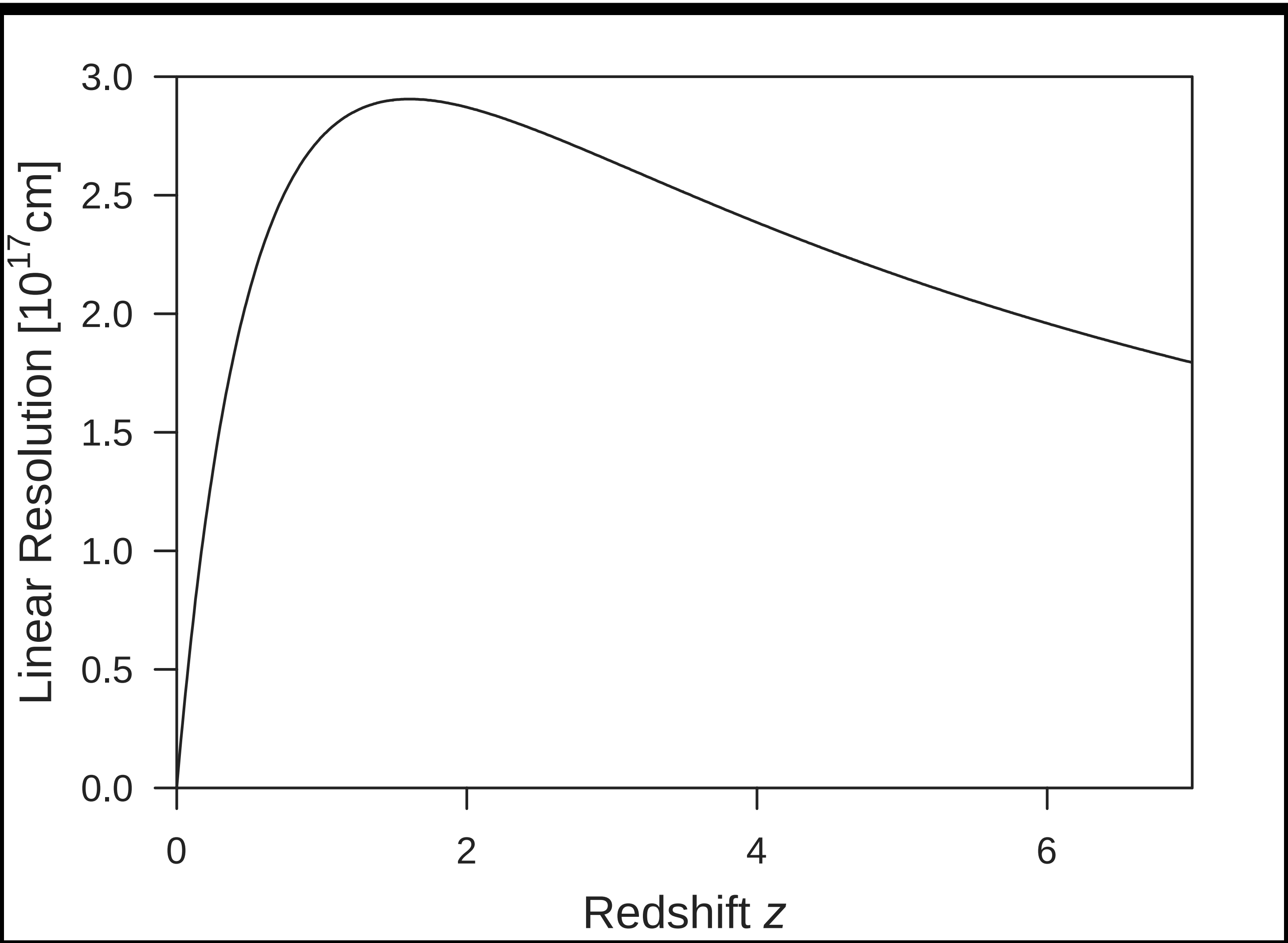
ELSA Resolution: 10 µas at 500 nm, 40 µas at 2 µm

- 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

Linear Resolution of ELSA in the Local Universe



Linear Resolution of ELSA at $\lambda = 500$ nm



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

AGN Science with ELSA

- Black-hole mass from stellar and gas dynamics
- Reverberation *mapping* (watch line response to continuum variations in movies) $\Rightarrow$ physics of BLR, geometric distances
- Optical emission from milliarcsecond jets $\Rightarrow$ jet collimation, shocks, particle acceleration, …
- Details of clumpy (?) obscuring torus $\Rightarrow$ dust properties, unification schemes
- “Mirror(s)” in HBLR objects $\Rightarrow$ AGN physics, unification schemes

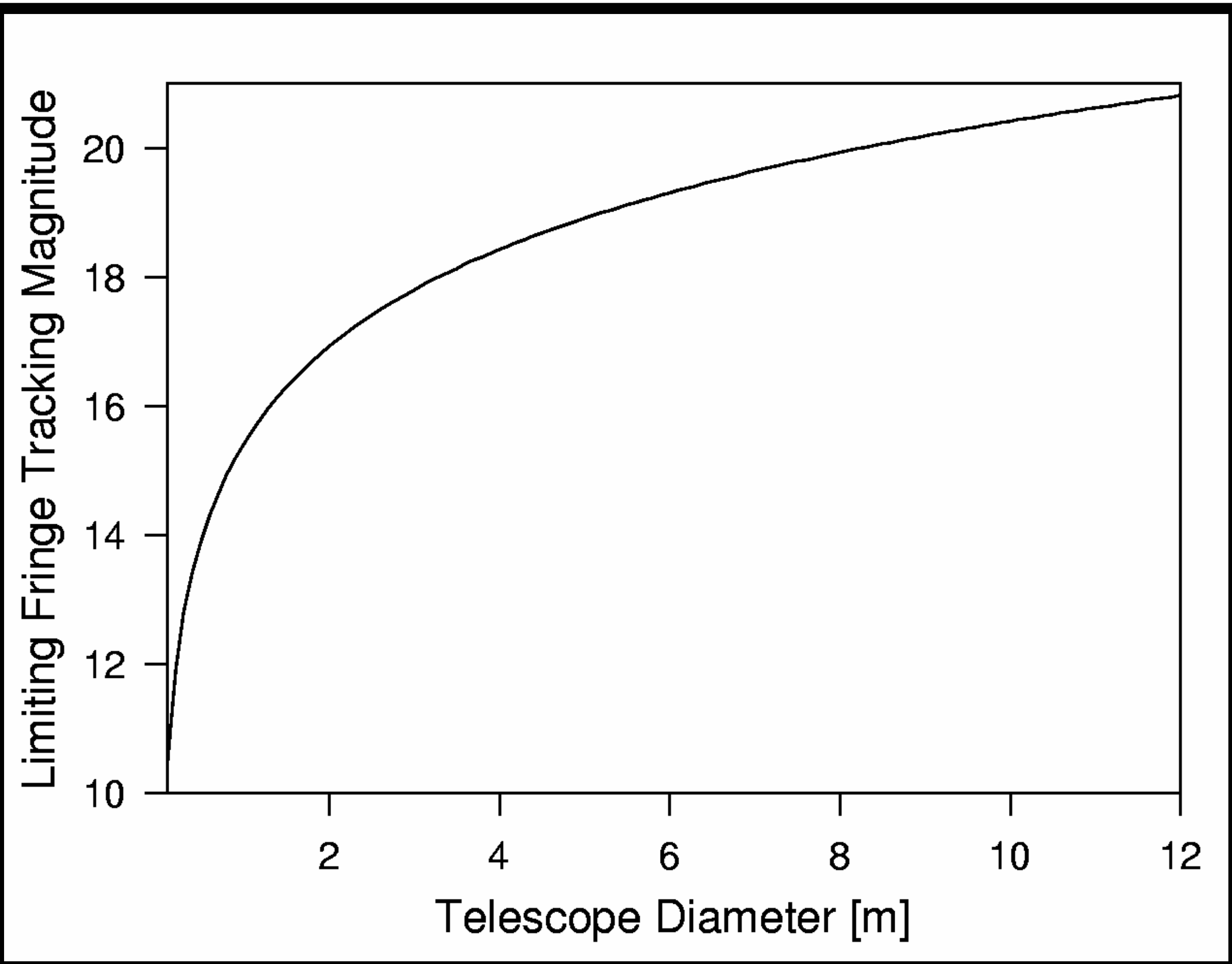
ELSA Critical Technologies

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

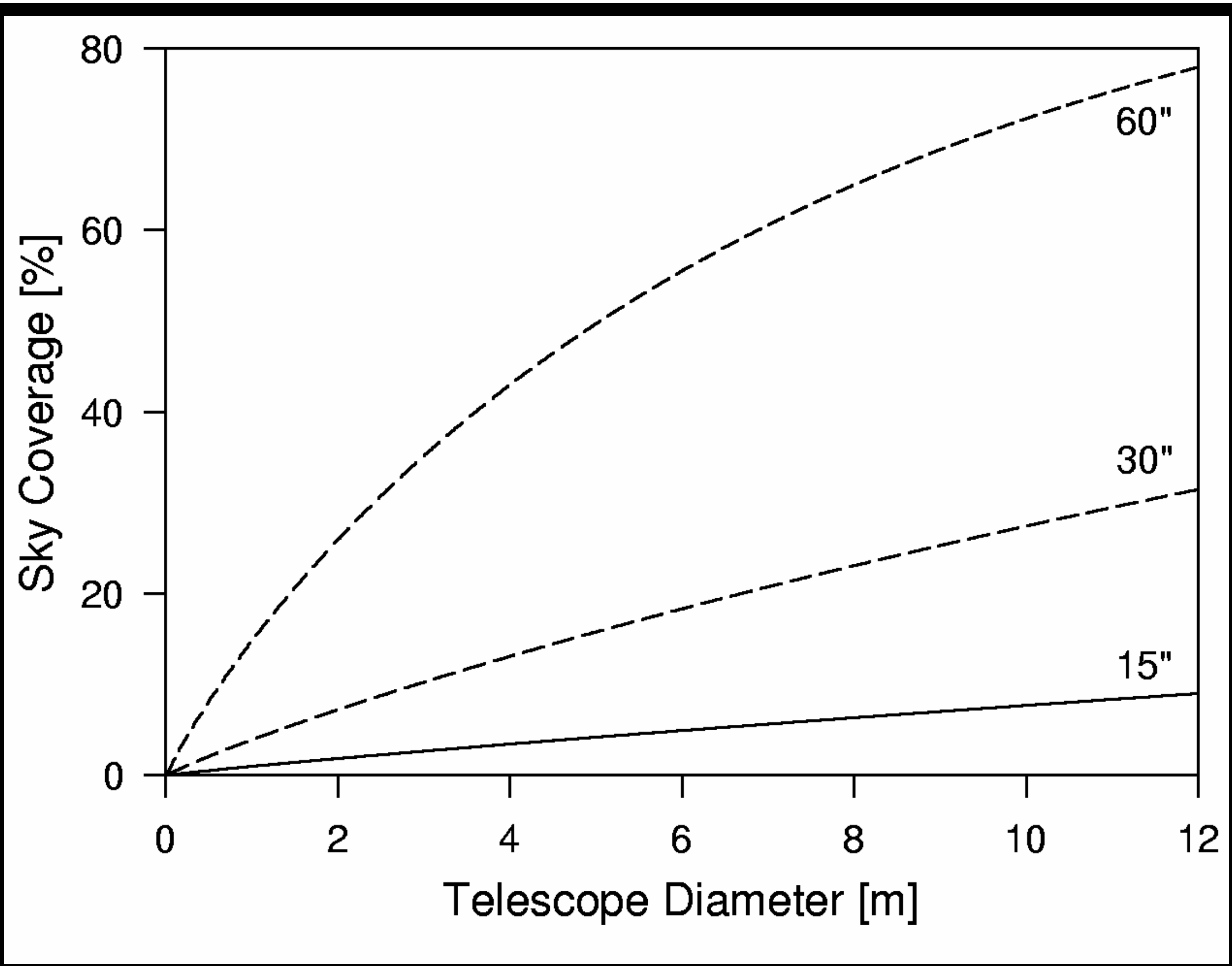
ELSA Co-Phasing Concept

- Phase individual telescopes with multiple (?) LGS adaptive optics
- Off-axis fringe tracking on “bright” star
- Large aperture $\Rightarrow$ good fringe tracking sensitivity $\Rightarrow$ near-complete sky coverage
- Requirement: fringe tracking at $K \approx 19$
  - One of the drivers for large array elements
- Fringe-tracking chain of neighboring telescopes for bright (resolved) stars
- Fringe tracking between all telescopes for faint (unresolved) stars

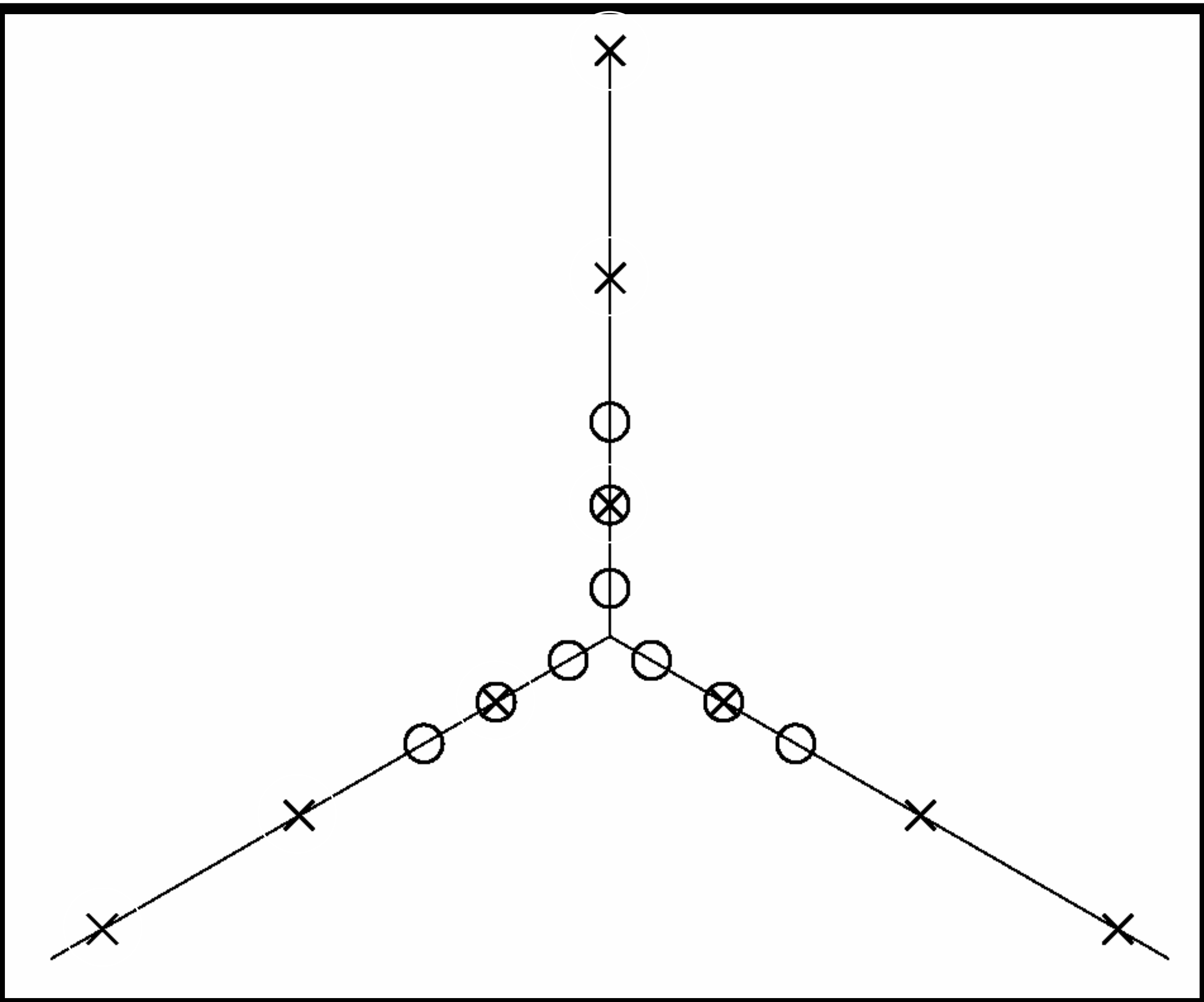
Limiting Sensitivity for Fringe Tracking in the R Band



Sky Coverage at NGP for Different Maximum Off-Axis Angles



Array Layout Optimized for Baseline Bootstrapping



A Y-Shaped Configuration (15 Telescopes)

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 € $\propto D^{2.7}$
- 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€
- Proof-of-concept for ELT?

Moving Big Telescopes around …

… is Perfectly Doable!

ELSA Beam Transport

- Fibers are much cheaper than beam tunnels
  - Diffraction + field $\Rightarrow \; D_{\text{opt}} = k \times \sqrt{\lambda L} + m\theta L$
- 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 Beam Combination

- Very diluted (B / $D \approx$ 1,000) for longest baselines $\Rightarrow$ pupil plane combination preferred
  - Field-of-view radius is $R = \lambda / \Delta\lambda$ resolution elements
- Larger field-of-view desired for more compact configurations
  - Homothetic mapping (exact or densified replica of entrance pupil) to be explored

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
- ELSA could be feasible and affordable in 2015

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