# Science with Interferometers
## in the era of ELTs, ALMA, JWST

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"Prediction is very difficult, especially about the future."
Niels Bohr

# Three options

1. ELTs will go over budget and consume all all operations. The end of interferometry

2. ELTs will go over budget, be cancelled, and then everyone will be interested in interferometry

3. ELTs will go over budget, full operations delayed, leaving interferometry on track…

# Science with interferometers

- View from the Decadal Surveys
- Suitability of current facilities to these goals
- What is limiting current science
- Moving forward with current facilities

# New Worlds, New Horizons

## in Astronomy and Astrophysics

# *Cosmic Vision*

## *Space Science for Europe 2015-2025*

Does ESO have such a guiding document based on community input?

| Science Frontiers Panel | Science Questions and Discovery Areas (D) | GSMT | LSST | Existing Facilities | Mid-Scale Instrumentation | Interferometry |
|---|---|---|---|---|---|---|
| **Stars and Stellar Evolution (SSE)** | 1. How do rotation and magnetic fields affect stars? | | | | Sola | |
| | 2. What are the progenitors of Type Ia supernovae? | | | | AO | |
| | 3. How do the lives of massive stars end? | | | | MOS, AO | |
| | 4. What controls the mass, spin, and radius of compact stellar remnants? | | | | | |
| | D. Time-domain astronomy | | | | Solar | |

Optical Interferometers will play key role for questions of wide interest in the area of Stars and Stellar Evolution

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|---|---|---|---|---|---|---|
| **Planets and Star Formation (PSF)** | 1. How do stars form? | | | | AO | |
| | 2. How do circumstellar disks evolve and form planetary systems? | | | | AO | |
| | 3. How diverse are planetary systems? | | | | ExA , HPR | |
| | 4. Do habitable worlds exist around other Sun-like stars? | | | | | |
| **[Discovery area]** | D. Identification and characterization of nearby habitable exoplanets | | | | HPRV | |

Near-ir and mid-IR studies of planet-forming disks will remain probably the highest impact area for optical interferometry

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|---|---|---|---|---|---|---|
| **Galactic Neighborhood (GAN)** | 1. What are the flows of matter and energy in the circumgalactic medium? | | | | | |
| | 2. What controls the mass-energy-chemical cycles within galaxies? | | | | | |
| | 3. What is the fossil record of galaxy assembly from the first stars to the present? | | | | MOS | |
| | 4. What are the connections between dark and luminous matter? | | | | | |
| | D. Astrometry | | | | | |

Interferometry only obliquely affects astronomers studying galactic evolution

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|---|---|---|---|---|---|---|
| **Galaxies through Cosmic Time (GCT)** | 1. How do cosmic structures form and evolve? | | | | MOS, DWFIR | |
| | 2. How do baryons cycle in and out of galaxies and what do they do while they are there? | | | | | |
| | 3. How do black holes grow, radiate, and influence their surroundings? | | | | AO | |
| | 4. What were the first objects to light up the universe and when did they do it? | | | | MOS | |
| | D. The epoch of reionization | | | | DWFIR | |
| | | | | | | |
| **Cosmology and Fundamental Physics (CFP)** | 1. How did the universe begin? | | | | MOS | |
| | 2. Why is the universe accelerating? | | | | MOS | |
| | 3. What is dark matter? | | | | | |
| | 4. What are the properties of neutrinos? | | | | MOS | |
| | D. Gravitational wave astronomy | | | | DWFIR | |

Single greatest obstacle to future development: a large swath of high-priority science is off-limits

# Converging Trends

- Young Stellar Objects: Disks and planet formation
  - High priority for Decadal Surveys
  - ALMA
  - Extreme AO + coronagraphy
  - Spectroscopy
  - near-IR (CHARA) and mid-IR Interferometry (VLTI/MATISSE)

# Converging Trends

- Galactic Center
  - Not listed as Astro2010 priority
  - Adaptive Optics monitoring: 10m and 30m class telescopes
  - Near-IR Interferometry (VLTI/GRAVITY)
- AGN
  - Not listed as Astro2010 priority
  - Reverberation mapping
  - Near-IR, mid-IR interferometry (VLTI, MROI)

# Converging Trends

- Stars
  - Some of this work is highly-prioritized by Decadal Surveys (but not all!)
  - Asteroseismology studies (COROT, Kepler, RV)
  - Doppler imaging using large telescopes (magnetic fields)
  - Imaging spots with visible/NIR interferometers

# Diverging Trends

- Wide field imaging and spec surveys
  - DES, PANSTARRS, BIG-BOSS, JWST, WFIRST, relevant to interferometry?
  - LSST four main themes: dark energy, solar system, optical transients, galaactic structure
- Cosmology, Extragalactic, Local Group studies
  - Little overlap until far/mid-IR space interferometer
- Data mining (in general)
  - More astronomers working with large databases and survey products
  - BUT… Kepler database will be relevant

# Reality Check

Astronomers intend to spend:

- $8 billion dollars on JWST
- $3+ billion dollars on 3x30m class telescopes
- $1 billion dollars on ALMA
- $600M on LSST

"The future, according to some scientists, will be exactly like the past, only far more expensive."
John Sladek

Compare this to the $20-50 million to upgrade all the existing interferometers to next-gen instrumentation. We are cheap.

# Changing our mental picture

- 10m telescope facilities are a bad model for us
- Radio/mm interferometry is more relevant model
  - As for radio, OI will not be competitive in all interesting areas
- We have to do better than radio/mm-wave in making interferometric observing accessible to non-experts
  - See common-user panel discussion tomorrow and lesson of VLBA
  - This might be feasible with 4- (or 6-) beam combiners
- Interferometry is “mid-scale” activity for next decade
  - More diverse science and less expansive than most niche instruments in the $20-50M range
  - Comparable science impact as judged against community priorities

# How do we get there?

- Positive Developments
  - Imaging becoming more routine (MIRC, PIONIER)
  - Spectro-astrometry in near-IR (AMBER) and visible (CHARA/VEGA) extremely productive
  - PAVO on CHARA points way to use large apertures in visible
  - Fringe tracking: NIR->VIS, NIR->MIR, dual-beam!
  - CHARA phase-1 Adaptive Optics upgrade funded
  - Exciting new instruments for VLTI under development
  - New near-IR detectors on horizon
  - LBTI with do faint-source interferometry soon!

# How do we (not) get there?

- Negative Developments
  - Keck Interferometer closing; MROI work stalled
  - No space interferometry (no SIM, no TPF, no LISA)
  - Antarctica progress is frozen
  - No new facilities expected soon
  - Increasing competition for UTs at ESO/VLTI
    - UT access is crucial to continued mainstream adoption allowing for relatively faint objects (esp. mid-IR)
    - Insecurity over future access
  - Slow improvements to VLTI instruments due to higher level of bureaucracy

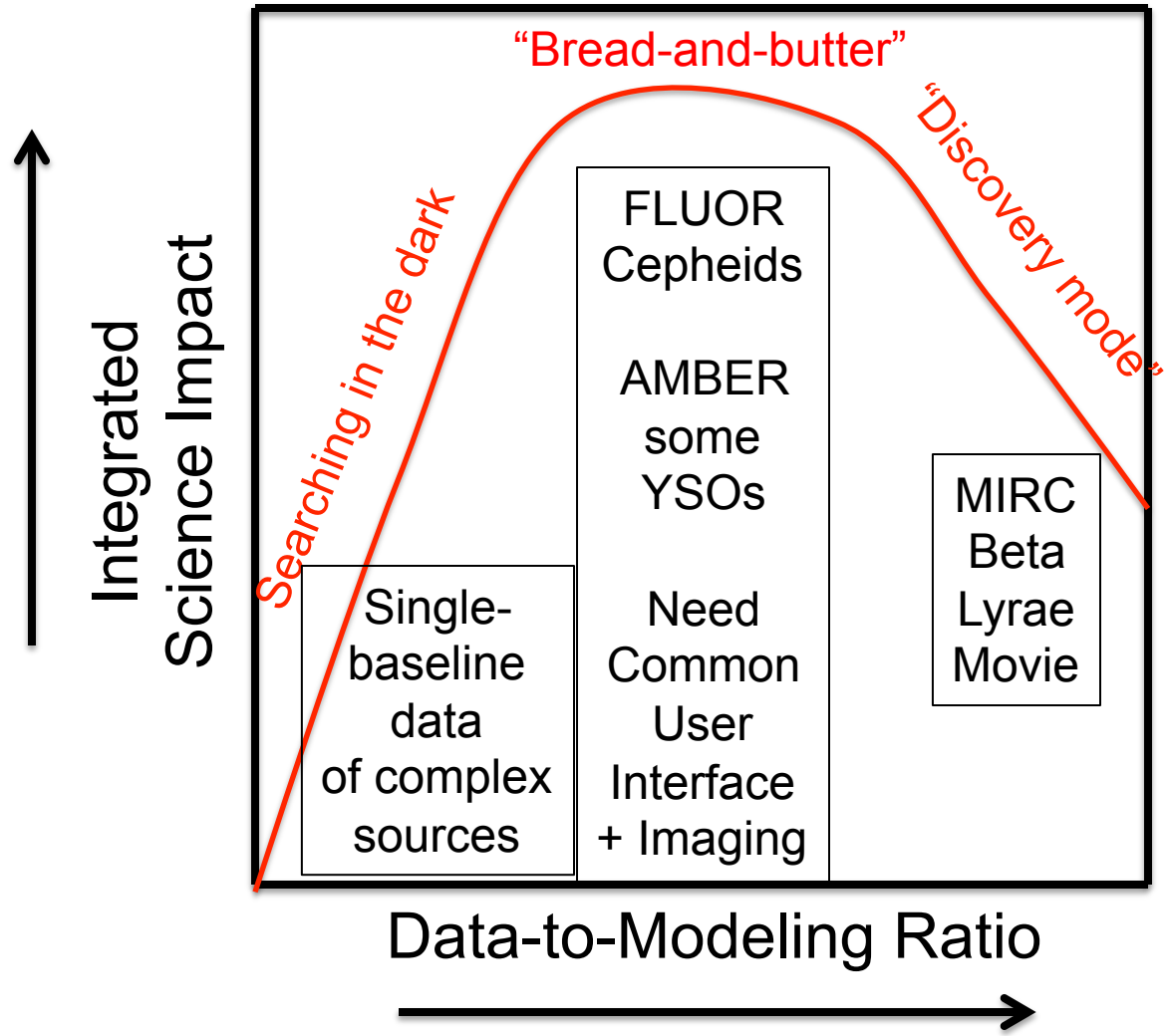
# Path to science

Experience with real facilities in the last 5-10 years have revealed the most capabilities:

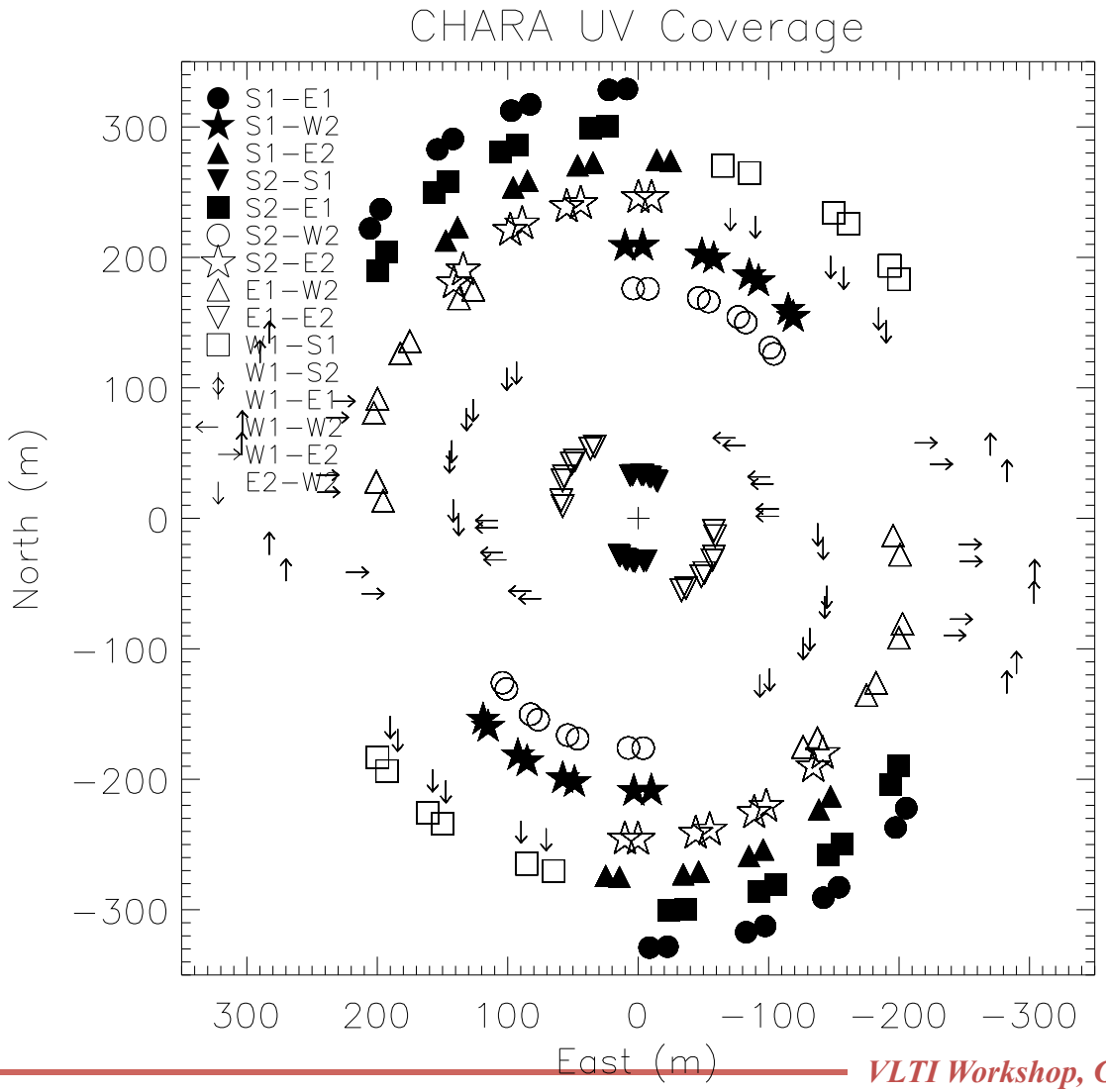
- Imaging with the right angular resolution
  - Mid-IR has the most untapped potential and will impact mainstream areas
  - Near-IR (best if baselines >300m for YSOs and imaging stars)
  - Develop visible light with PAVO-style combiner for sensitivity
- Spectro-interferometry
  - Better calibration
  - Kinematic constraints open a new frontier
  - Usually, we need imaging here too (complexity, time-changing)

# Importance of "imaging"

- Many current interferometer papers contain results that are "informative" but not "definitive"
- On sub-AU scales, changes occur too fast to combine datasets taken over months or years
  - Even AGNs change on these timescales!
- Interferometers should prioritize 4 or 6-beam combination
  - i.e., single-baseline diameters of faint targets are not well-aligned with community priorities, won't grow community
- Unappealing to community if it takes years to collect data leading to a (non-)definite result
  - Low data-to-modelling ratio

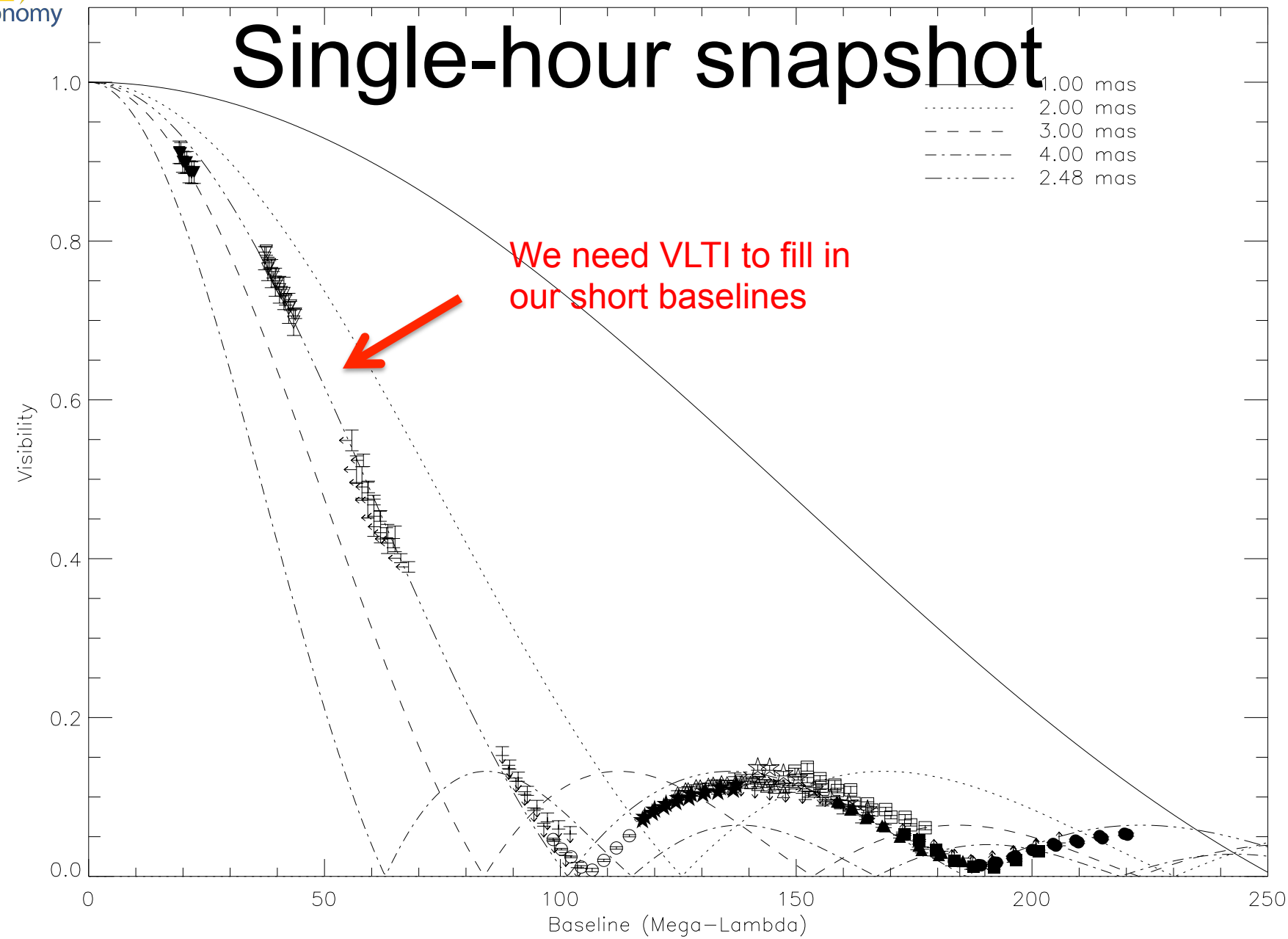

"Bread-and-butter"
"Discovery mode"
Searching in the dark
FLUOR
Cepheids
AMBER
some
YSOs
Need
Common
User
Interface
+ Imaging
Single-
baseline
data
of complex
sources
MIRC
Beta
Lyrae
Movie
Integrated
Science Impact
Data-to-Modeling Ratio

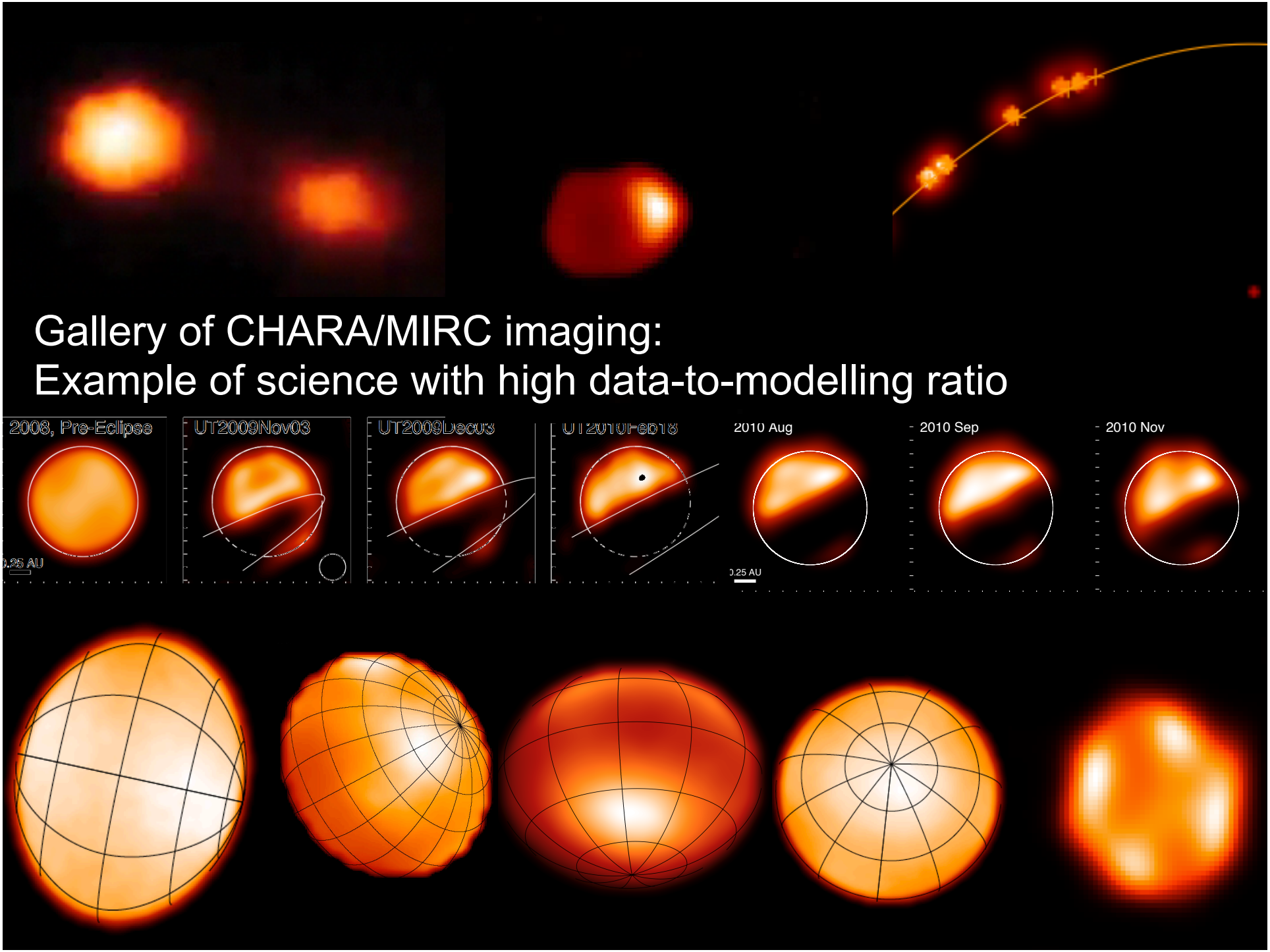
# Single night with CHARA/MIRC6




Data from Rob Parks

# Single-hour snapshot






# Gallery of CHARA/MIRC imaging: Example of science with high data-to-modelling ratio

# Predictions:

Interferometry will continue to make crucial contributions to mainstream, popular areas.

Most notably,

- Planet formation (VLTI/MATISSE)
- AGN and circumnuclear environments (VLTI/MATISSE)
- Mass-loss and massive stellar evolution (NIR, MIR)
- Specialized areas: Exoplanets, Galactic Center, Asteroids, Novae

# Predictions

Interferometers will lead the revitalization of stellar astrophysics with imaging and spectro-interferometry at milli-arcsecond scales:

- Magnetic fields and the stellar dynamo
  - Synergy with doppler imaging
- Stellar structure and evolution
  - Synergy with asteroseismology
- Interacting binaries

The best way to predict the future is to invent it.
Alan Kay

# Towards alignment of technical and scientific goals…

For ESO:

- Continue to improve existing instruments and encourage innovation
  - Allowing visiting instrument Pionier is great start! Keep going…
- Build GRAVITY and MATISSE
  - Focused well on mainstream topics, emphasizes imaging
  - Leverages the four 8-m class telescopes (UNIQUE!)
- Develop visible light interferometric imaging
  - Even VLTI has long enough baselines to do interesting things
  - Aim for PAVO-style 6-beam combiner with various spectral resolution

For USA groups:

- Improve sensitivity for NIR imaging (CHARA, MROI)
- Visible light imaging on >100m baselines (NOI, CHARA)
  - Spectro-interferometry needs imaging

"The future will be better tomorrow." Dan Quayle