Science with Large-Aperture Infrared Interferometry

–

KI-ASTRA: A new tool to study the Galactic center

Workshop: Astrometry and Imaging with the VLTI

Keszthely, Jun 4, 2008

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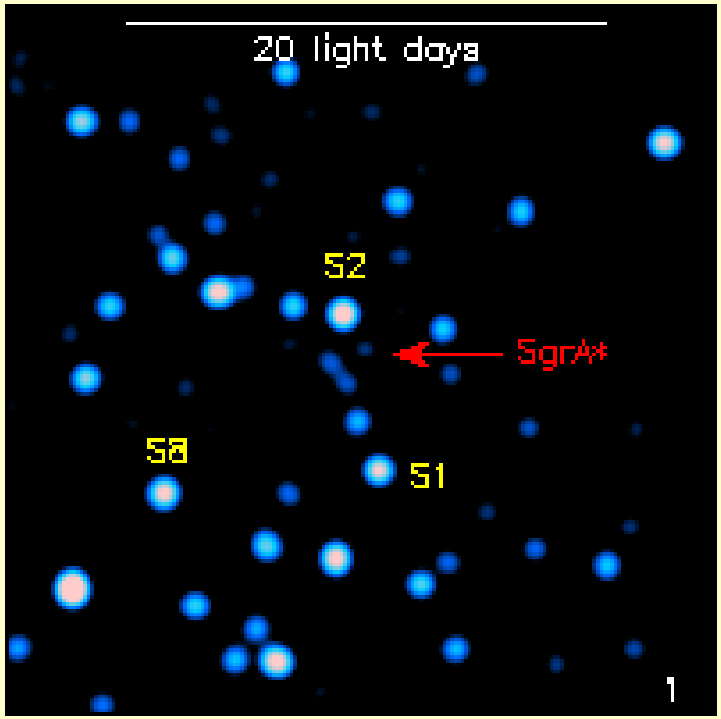
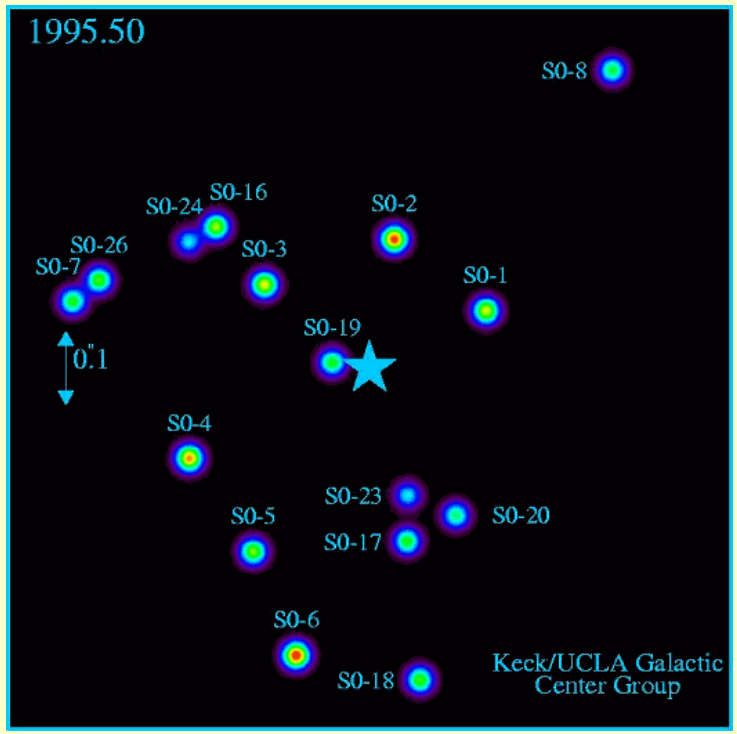
W.M. Keck Observatory

UCLA

- Galactic center research around MBH SgrA* has been driven by technology
  - IR detectors
  - large apertures
  - Speckle / AO to achieve diffraction limit
  - Interferometry is next…

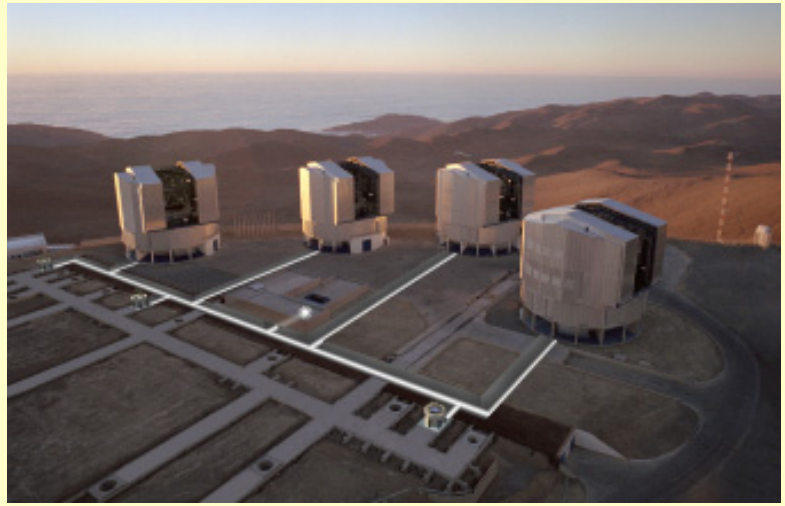




work by R. Genzel, A. Ghez, A. Eckart et al.

- Outline of this presentation
  - Modern large-aperture (8-10m) optical-long-baseline interferometry (LA-OLBI, B~100m, Θ_{FWHM}~ 5mas)
    - Keck Interferometer (NASA) and VLTI: Why large apertures?
    - What they measure and what they don't measure
    - Some 'new IF-science' highlights from LA-OLBI
  - Galactic center science – astrophysics in an extreme environment
    - GC facts
    - Focus: Interstellar matter and dust formation
  - Near future – Phase-referencing, ASTRA/Keck-IF
    - Basic ingredients
    - The prospects for GC science
    - Other science cases: from planets to AGN

ESO's VLT-I, Paranal, Chile

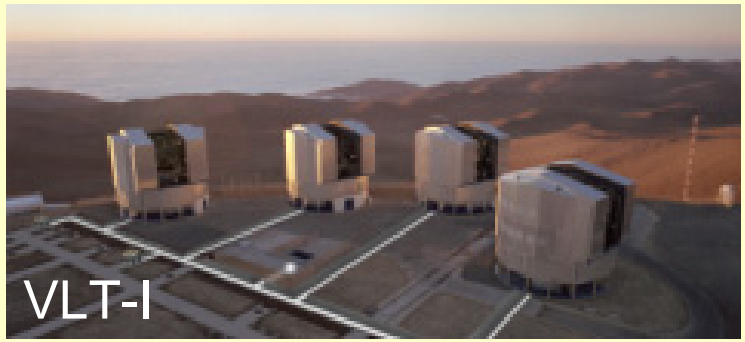


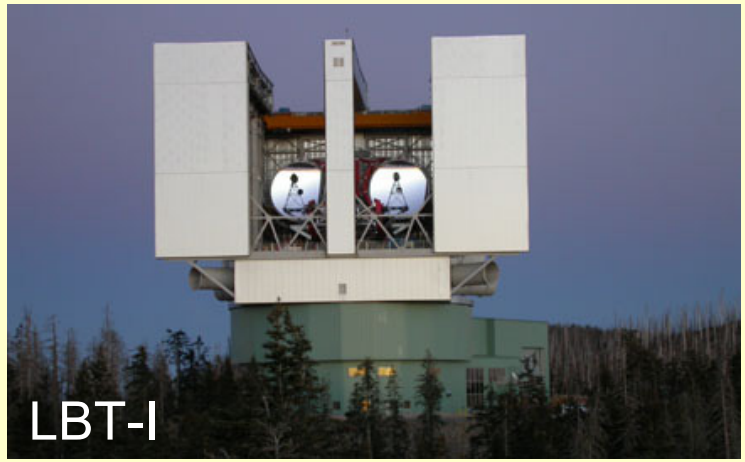
Keck Interferometer, MK, HI

- Why LargeAperture-OLBI?
  - Small apertures (e.g. ISI & CHARA on Mount Wilson)
    - Same angular resolution, smaller phase-variance, but …
    - Same atmospheric coherence time -> less sensitive!
    - Limited to nearby and very bright targets -> limited science
  - Galactic center and AGN?

Today:

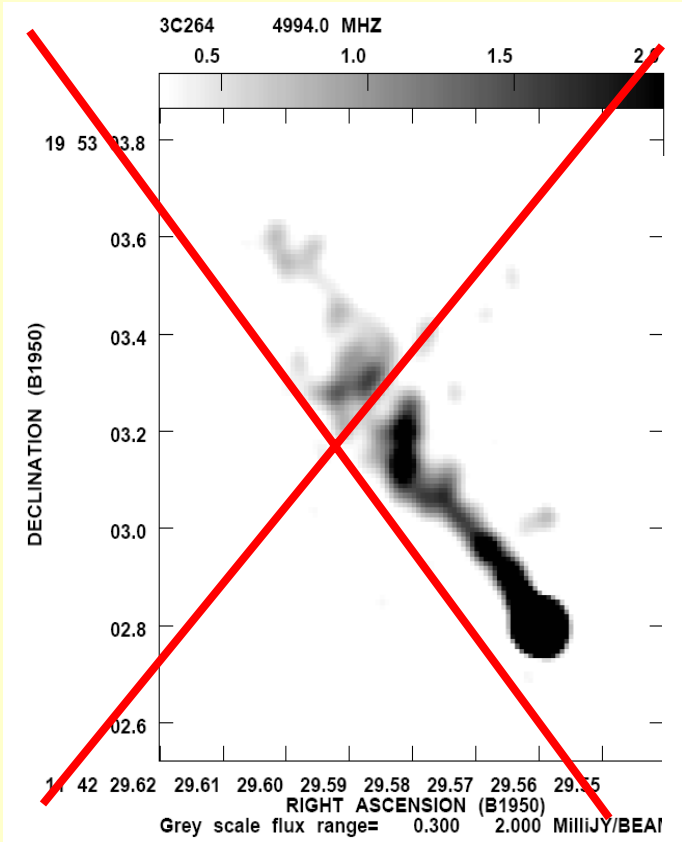
- VLT- and Keck-Interferometer (access: UC/Caltech/NASA/NOAO)
- Future: LBT-I
  - Limited angular resolution but
  - Wide FOV and better PSF
- Future: 'OHANA
  - Fibre link for Mauna Kea





- Today's LargeAperture–OLB-IF instrumentation and sensitivity
  - NIR (J/H/K, 1-2.4 μm)
    - Continuum down to K ~10mag with KI
    - Spectroscopy up to R ~10,000, at K~6-7mag with ext. fringe tracking)
    - Angular resolution up to θ_{FWHM}~ 5mas
  - MIR (N, 10 μm)
    - Continuum down to about 0.5 Jy
    - Spectroscopy up to R ~200 at > 3 Jy
    - Angular resolution up to θ_{FWHM}~ 20mas
  - Special instrumentation
    - Keck Nuller for coronography
    - 3-Telescope closure phases with AMBER/VLTI at 2 μm
  - Interferometric imaging?
    - No model-independent imaging
    - But powerful model-constraints

$\mathcal{O}(10)$ telescopes needed:



Radio-Jet with VLBI: Baum+97

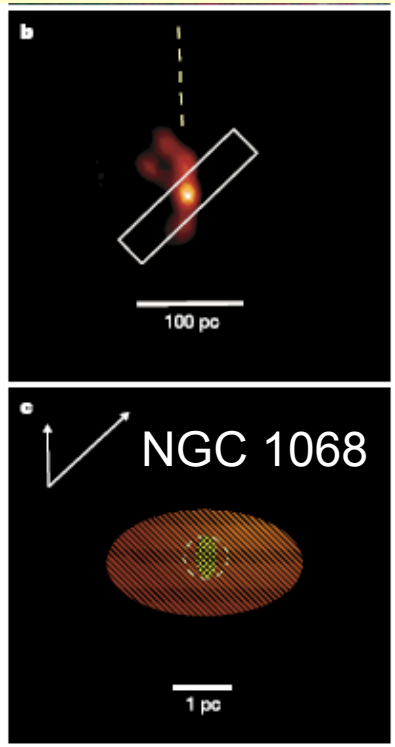
Examples for 'New IF-science'-highlights:

– First spatially resolved experimental data on AGN dust tori: much smaller than expected
  - NGC 4151(NIR, KI): Swain+03ApJ596L.163,
    NGC1068(MIR,VLTI): Jaffe+04Nature429.47

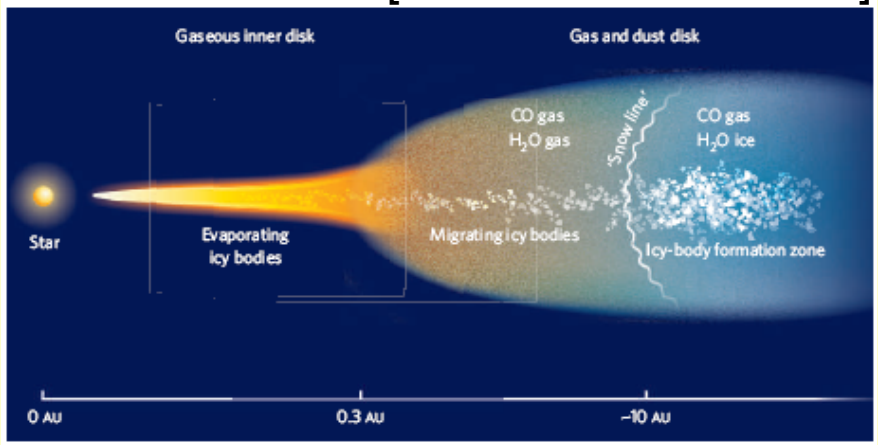
– Resolving protoplanetary discs: tracing the dust chemistry, detection of water and H in the 1AU-terrestrial zone
  - van Boekel+04Nature432.479, Eisner'07Nature447.562

– Finding, and scrutinizing discs, shells, winds, and binary interaction in evolved star systems
  - Meilland+07A&A464.59, Perrin'07A&A474.599, Weigelt+07A&A464.87 etc.

-> talks by Malbet, Chesneau, Jaffe

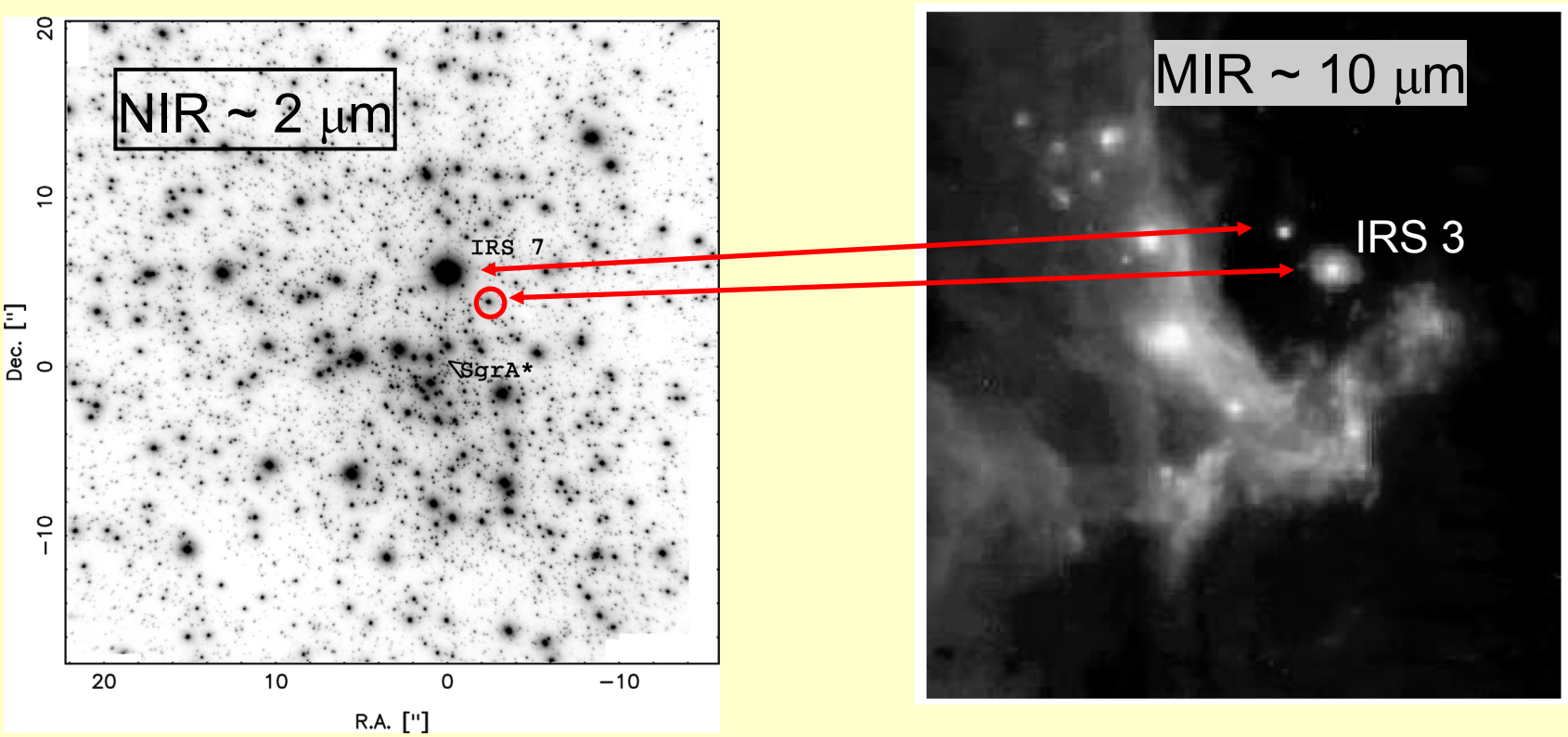


[Jaffe'04Nature429.47]



[van Boekel'07Nature447.535]

- The central parsec (~ 25”) around SgrA* as accessible to VLT- and Keck-Interferometers
  - Two different wavelengths regimes: two different worlds
  - HK is dominated by stars and their hot environs
  - N is thermal infrared: cooler dust appears, partly w/o stars

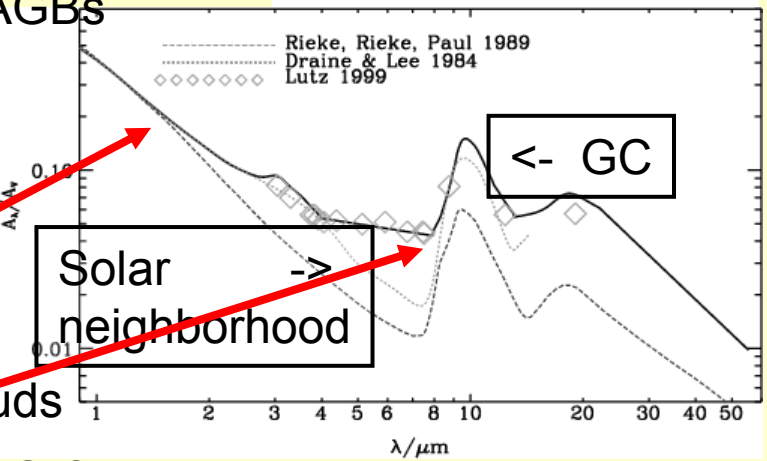


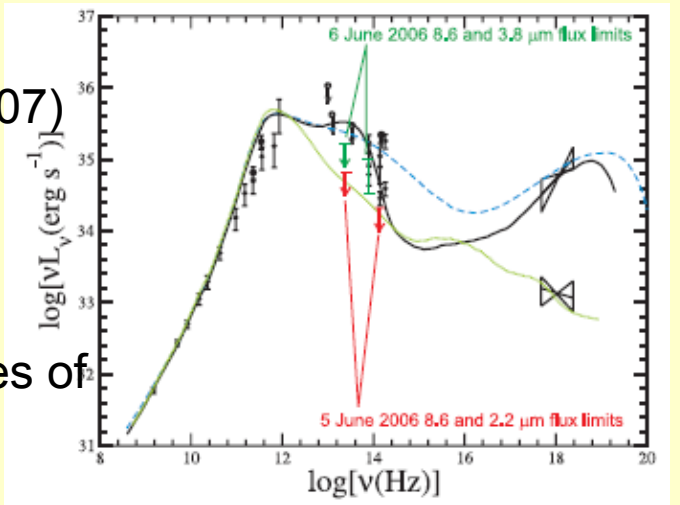
- The center of the Milky Way is the nearest galactic nucleus
  - Investigating the Galactic center (GC: nuclear cluster, star and dust formation, ...) provides seminal knowledge to understand spatially unresolved extra-galactic observations
- Harsh environment
  - Harbors closest massive BH (MBH, $3.6*10^6 M_\odot$) at only 7.6 kpc distance (1" ~ 40mpc, or 1mas ~ 8AU: a uniquely small linear scale); next similar galactic nucleus (Andromeda) is 100x farther
  - GC is ideal to study MBH-ho eraction
    - Star formation in an extreme tidal field: BH-induced top-heavy IMF?
    - Stellar evolution and interstellar GC cluster dust
    - The GC stellar cluster is the densest star cluster in the Galaxy
    - ~$3*10^6 M_\odot/pc^3$, i.e. 10 times denser than cores of Arches and NGC 3603
    - Properties known from galactic disc might not apply
    - Ideal to study unique *N*-body phenomena, e.g. hyper-velocity stars

Focus #1:

- Focus #1: interstellar GC dust chemistry
  - History of dust formation -> history of star formation
    - Silicate-to-graphite ratio -> O-rich/C-rich AGBs
    - Amorphous to crystalline silicate
    - PAH emission features
  - ISM extinction changes with the environment
    - More pronounced $\tau_{9.8}$-silicate absorption wrt. NIR-extinction
      -> GC shows opposite trend of dense clouds
    - -> Correlation betw. τ_{NIR} and $\tau_{9.8}$ is *not* always linear, but depends on the efficiency of grain coagulation (Chiar+'07)
    - nuclear abundances depend on IMF (Cunha '07)
  - Only correctly known extinction leads to correct intrinsic fluxes and physics
    - Explanation for failure to detect accretion-flares of SgrA* in the MIR

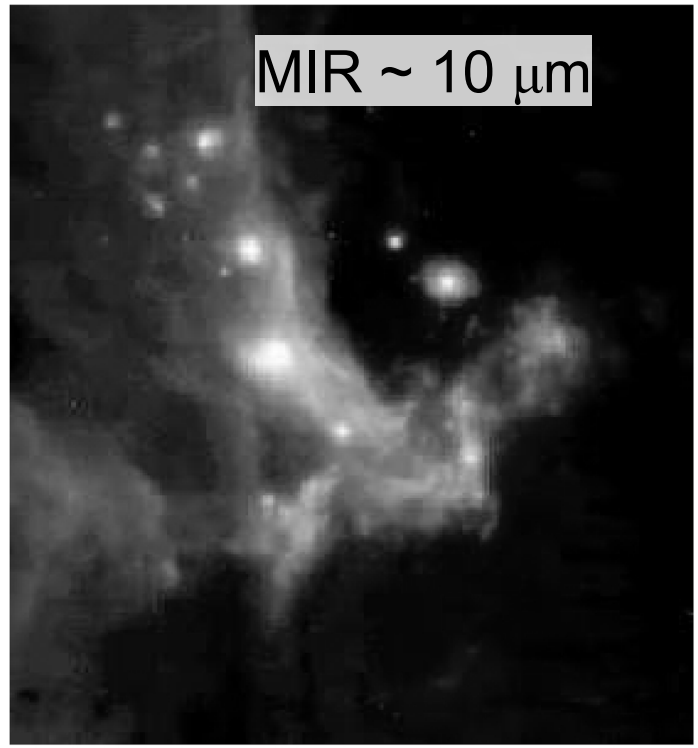
LOS Extinction law



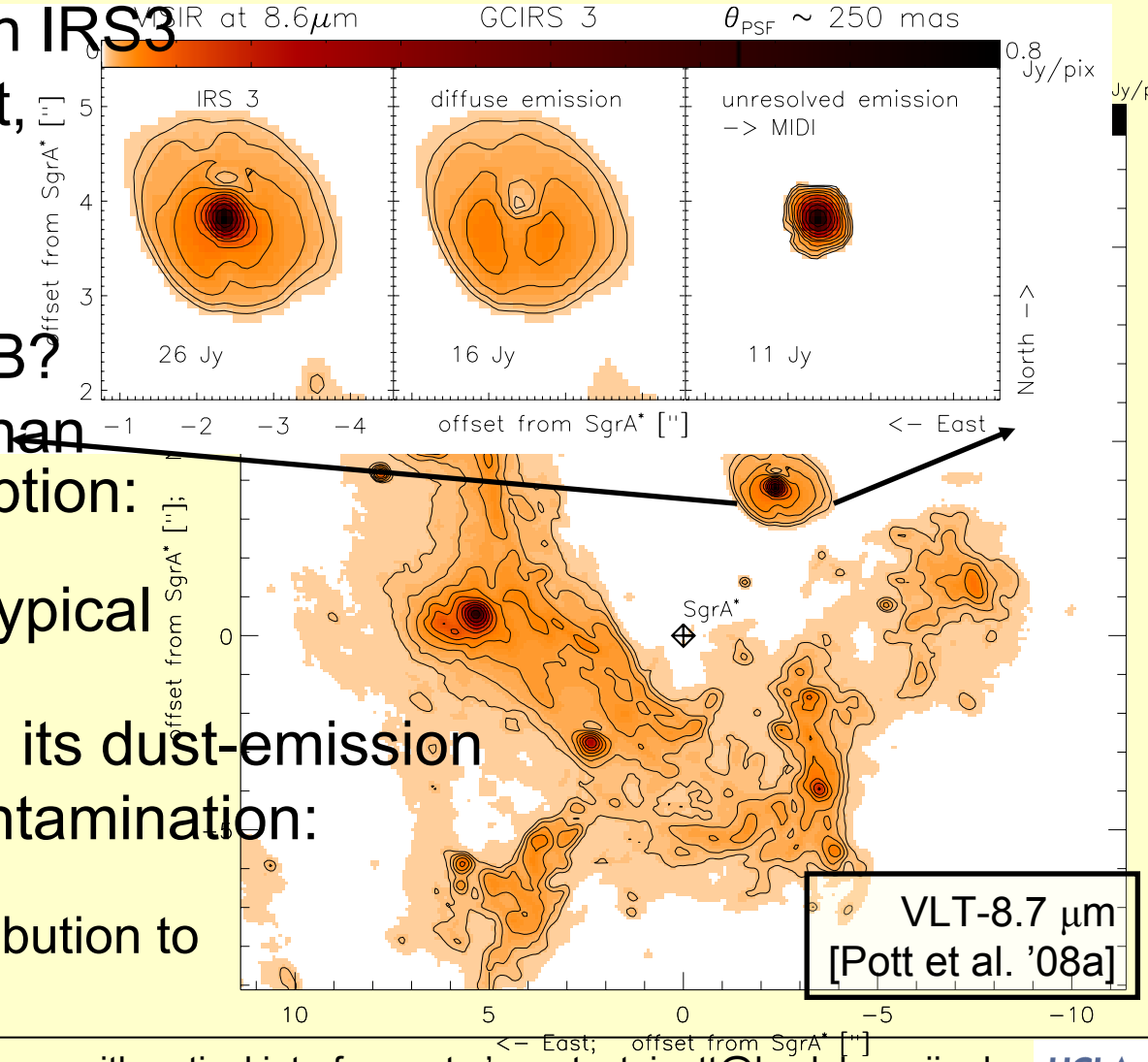


(Schodel'07)

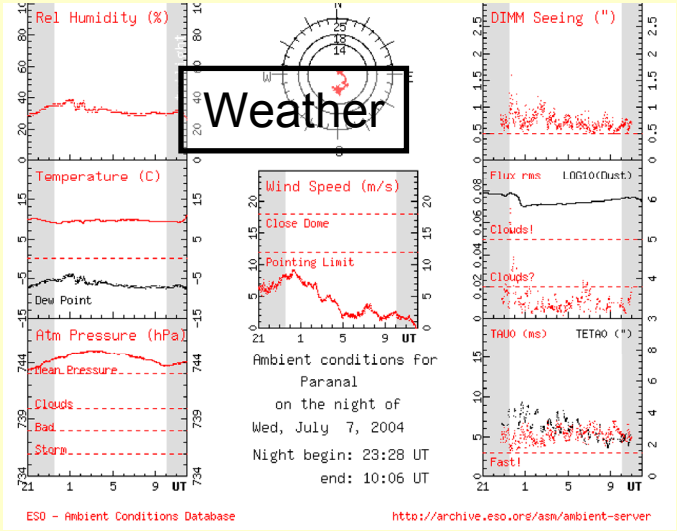
- How do you measure the interstellar dust extinction profile?
  - Spectroscopy on stars with known SED, at best without circumstellar dust
  - You will need 8-10m class telescopes to separate the stars
  - Problem: Sources need to be bright for spectroscopy, but the brightest MIR sources are all surrounded and dominated by their circumstellar dust
  - Use the high angular resolution of the interferometer to analyse the star+dust-shell SED in detail, and derive the chemistry from the interstellar dust
  - Compare the results with reference regions outside of the inner pc, and mediate about if you see the results of strongly favoured massive-star formation due to the MBH



- First choice for a reference star in the central 0.5pc: GCIRS 3
- Bright enough but local contamination due to intrinsic dust formation?
- Problems & Issues with IRS3
  - Red, isolated, bright, but unknown origin
  - Is it actively forming O-rich dust? Hot WR or cool AGB?
  - It shows a deeper than usual silicate absorption: Is the local GC dust surrounding IRS 3 typical for GC-region?
  - Need to understand its dust-emission
- Avoid circumstellar contamination:
  - Use IF to probe its circumstellar dust contribution to the LOS-GC extinction



- OLB-IF@GC: Application of a new technique
  - Time-consuming but eventually exciting when successful:



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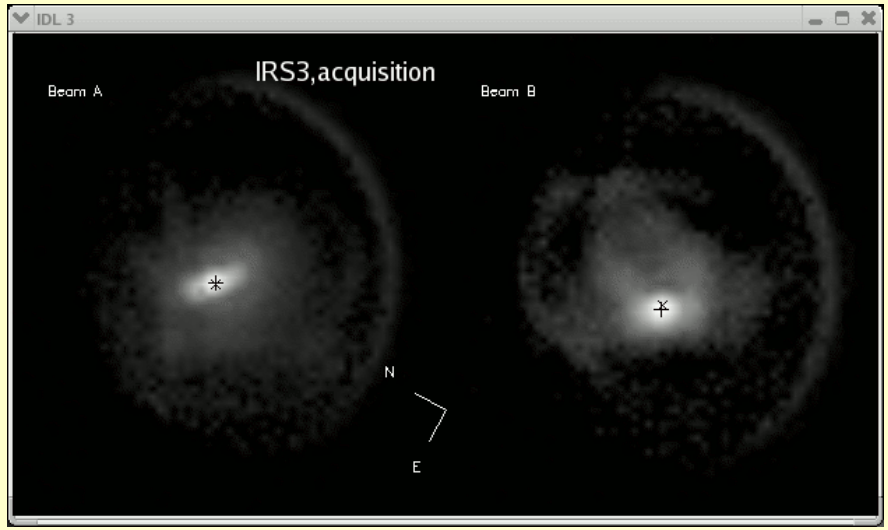

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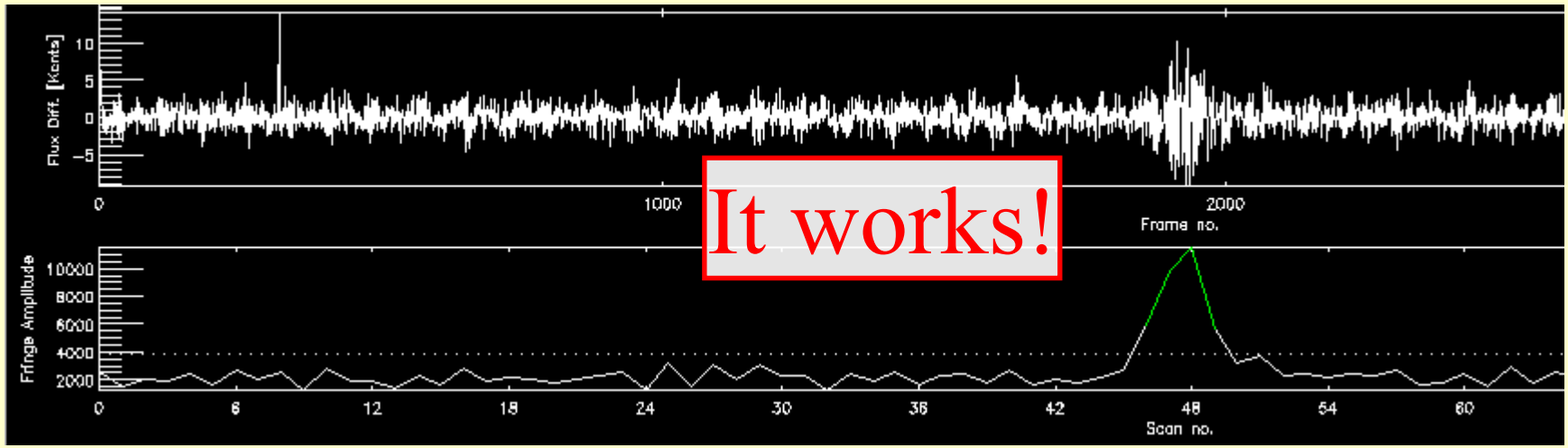
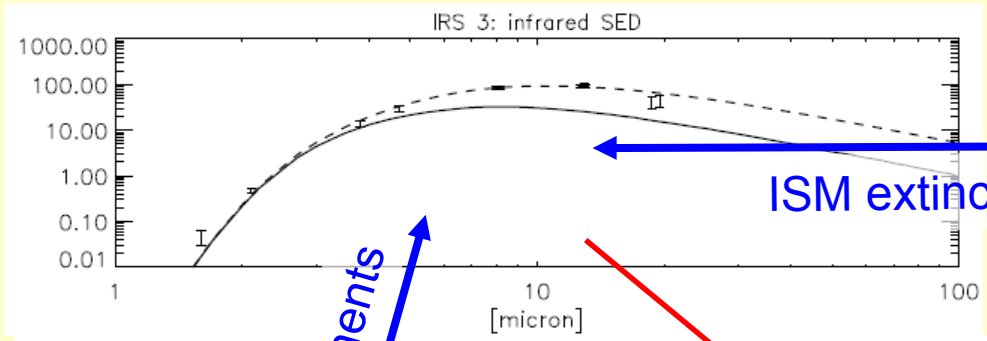
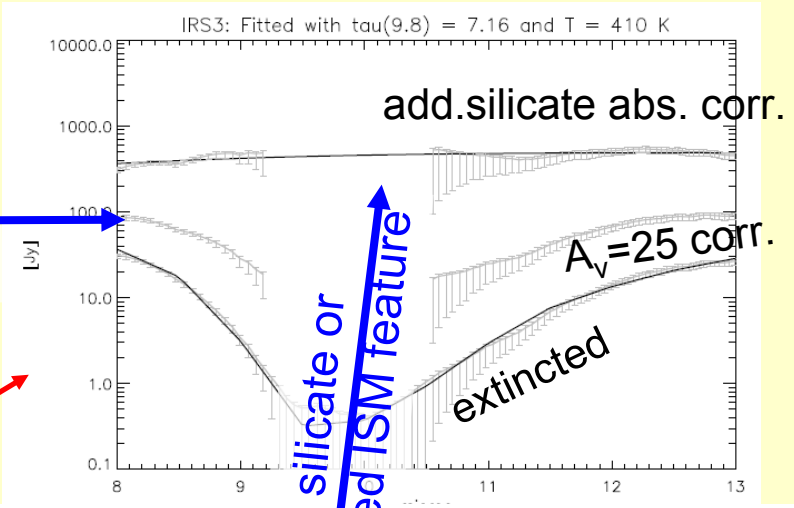


First MIR-fringes on IRS3 in July'04 (Pott et al. 05)

GCIRS3!



1. IR-SED constrains temp. and dust chemistry

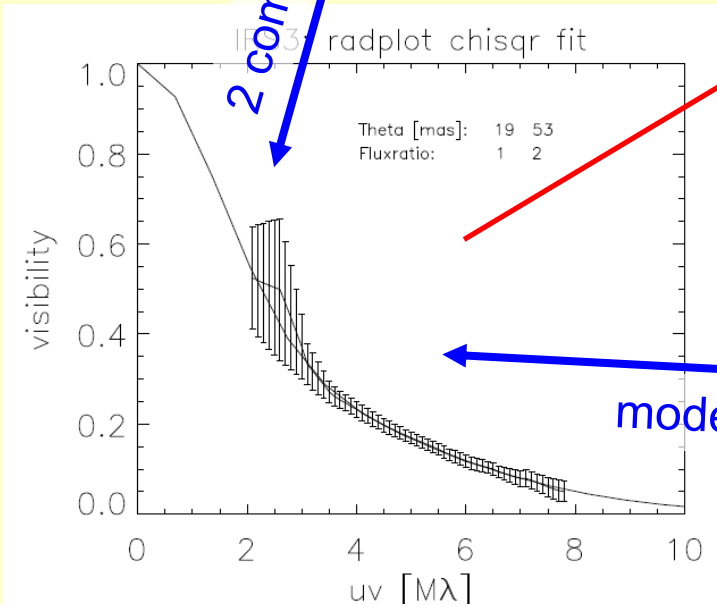


2. Spectrum shows strong silicate abs.

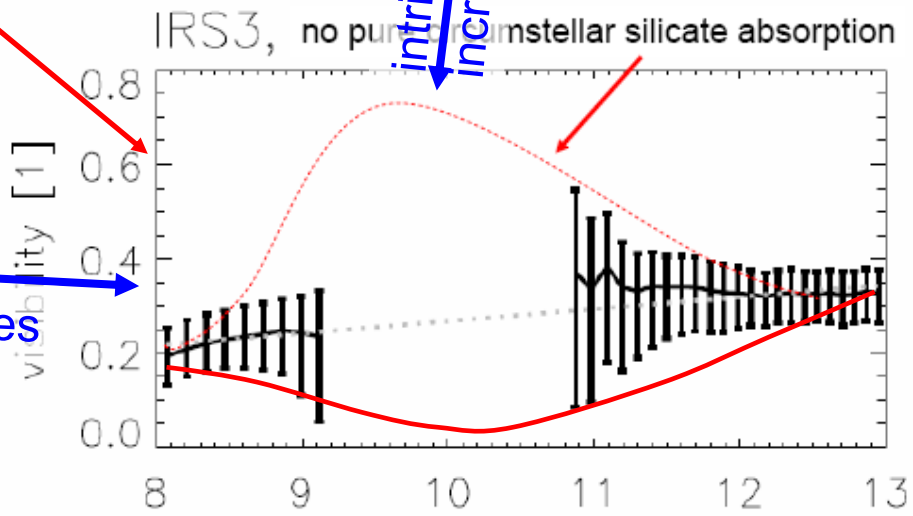
ISM extinction

2 components

intrinsic silicate or increased ISM feature



model visibilities

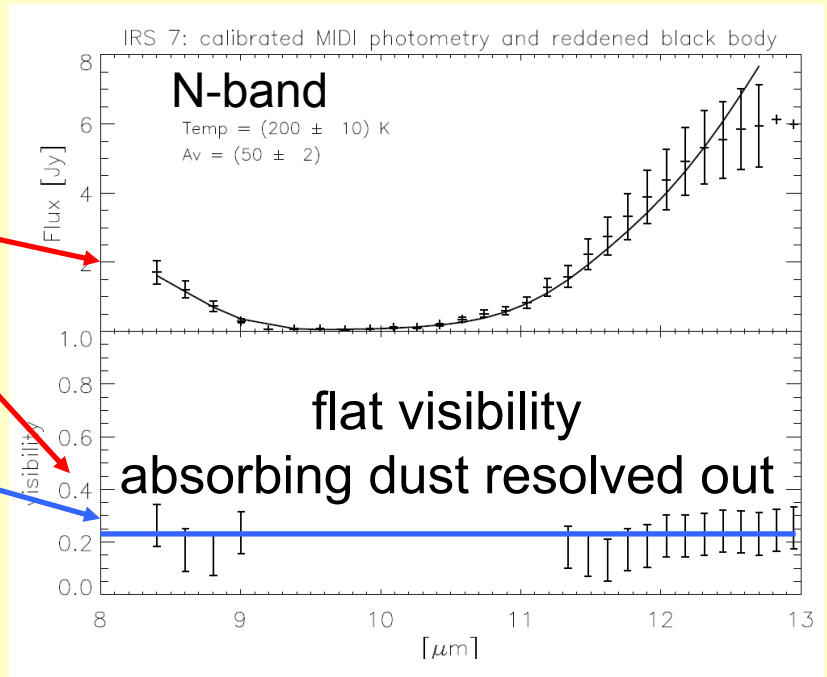


3. Mean visibility constrains overall geometry: two shells (20 & 50mas)

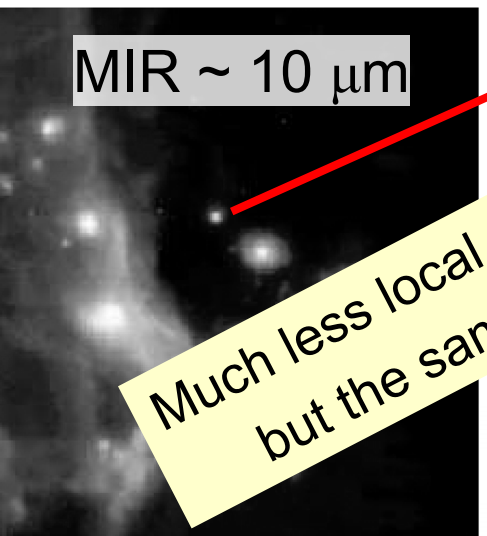
4. Visibility spectrum localizes the silicate

- New results on IRS 3:
  - RT-modelling of IRS3 suggests the embedded star to be a cool carbon-rich dust forming giant
  - No strong intrinsic (!) silicate absorption:
    IRS 3 *is* the prime candidate to study the GC local MIR-ISM properties
  - Silicate absorption excess towards IRS3 shows the GC ISM extinction, and indicates that GC dust composition (and the resulting) has to be reviewed at high angular resolution for $\lambda \geq 8\mu m$ to understand the energetics in this region, be careful with spatial confusion of silicate emitting dust.
  - More work to be done to confirm the new GC-ISM properties.
    (see Pott et al. 2008a, A&A for details)

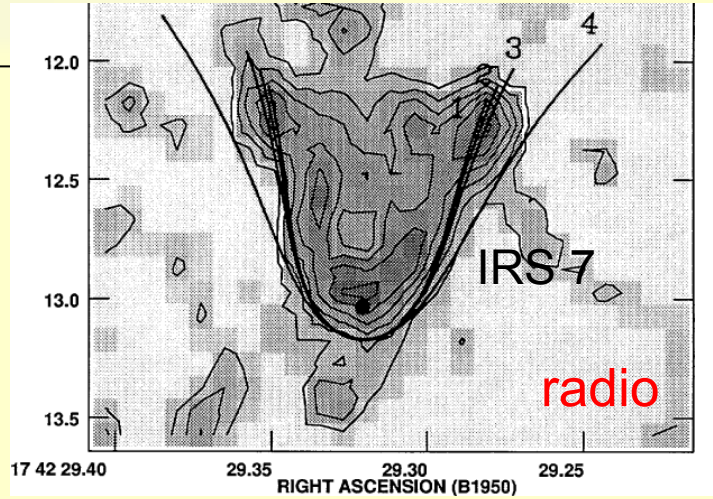
- First confirmation of new GC extinction law from other stars:
  - Supergiant GCIRS 7
  - LA-OLBI: Strongly resolved in N: cold extended dust
  - Same deep $\tau_{9.8}$ like IRS 3: confirmation of local GC-ISM theory
  - Again, deep silicate-dust absorption does not (!) happen in the resolved dust close to the star
  - ISM-Dust in the central pc *is* special

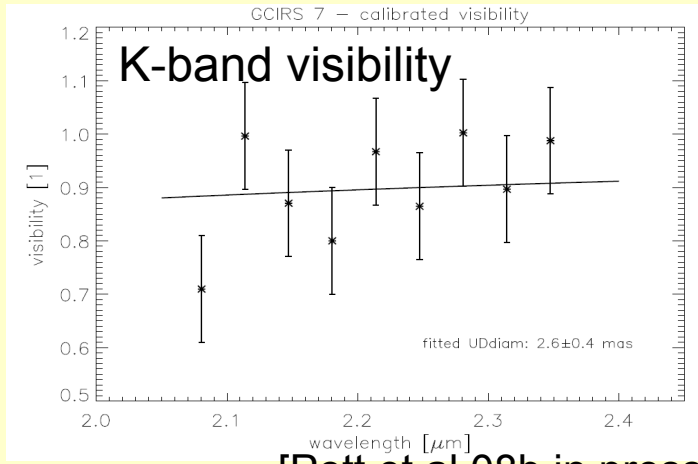


Pott et al. 2008b, in press



- Other GC science cases:
  IRS 7, a red supergiant
  - (M1I, T_{eff} ~ 3600 K), interests for two very distinct reasons, connected by LA-OLBI
  - Radio data from the VLA revealed bow-shock of ionized gas, probably heated and shaped by external radiation (Yusef-Zadeh & Melia '92, 0.4" resolution, λ = 2cm)
  - Detailed IR-IF-analysis of the morphology of this bowshock might reveal the location of the origin of the external heat source: the blue IRS 16 cluster or Sgr A* itself (note: the physical entity of the radio-bow does not have to coincide with extended IR structure)
  - High precision requires phase-referencing LA-OLBI





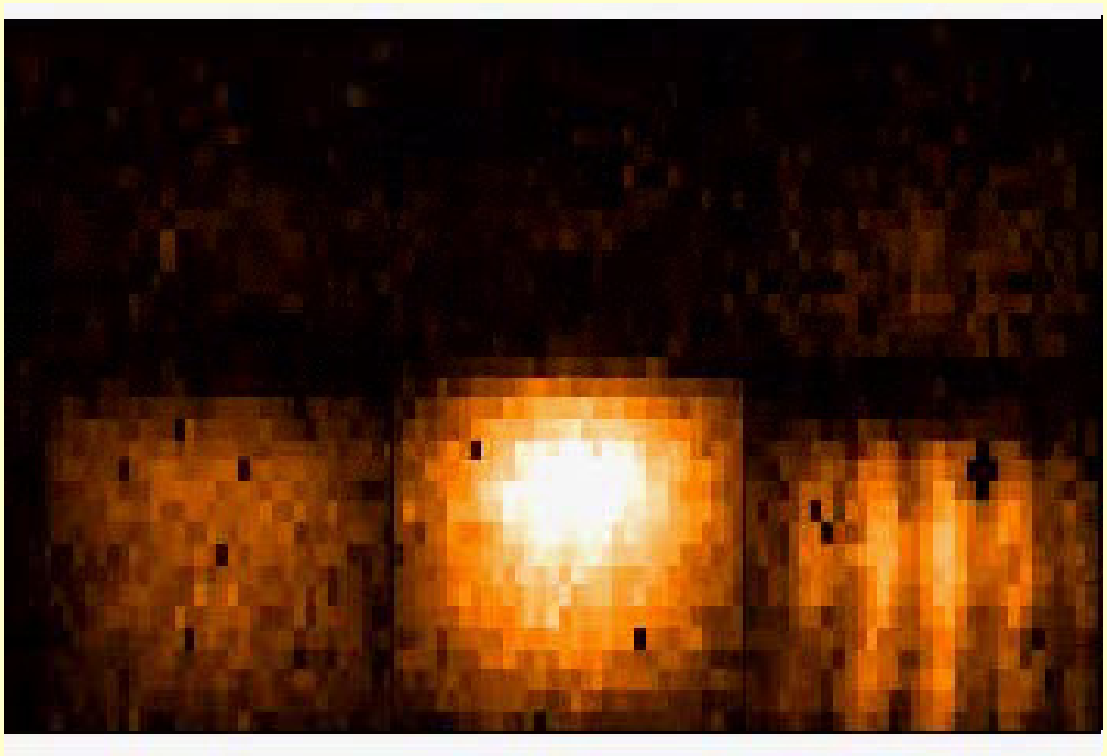
[Pott et al.08b in press.]

Slightly resolved in K: probably a warm MOLsphere like alf Ori -> phase-referencing should work!

IRS 16 Sgr A*

- Focus #2: Phase-referencing to go deeper
- What is it about?
  - NGS-AO-like atmosphere-correction
  - Avoid loss of fringe contrast at long integrations
  - Get about five magnitudes deeper, goal: K~15mag

NIR two telescope fringes



from VLTI/AMBER

VLTI/PRIMA

&

KECK-IF/ASTRA

Near future: Keck-IF ASTRA-
ASTrometric and phase-**R**eferenced **A**stronomy

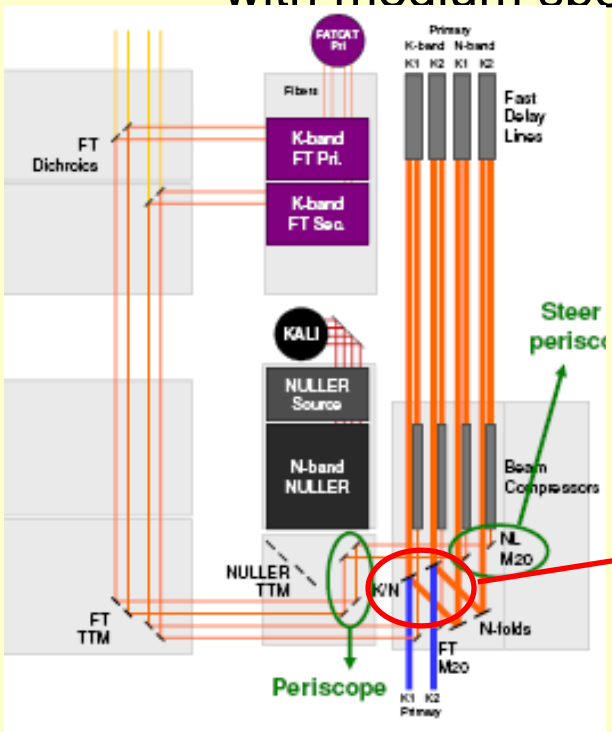
- NSF-funded sensitivity and versatility upgrade
  -> accessible to you thru NOAO !
- Pushing IF to K ~ 15 mag science with phase-referencing
- Project-collaborators:

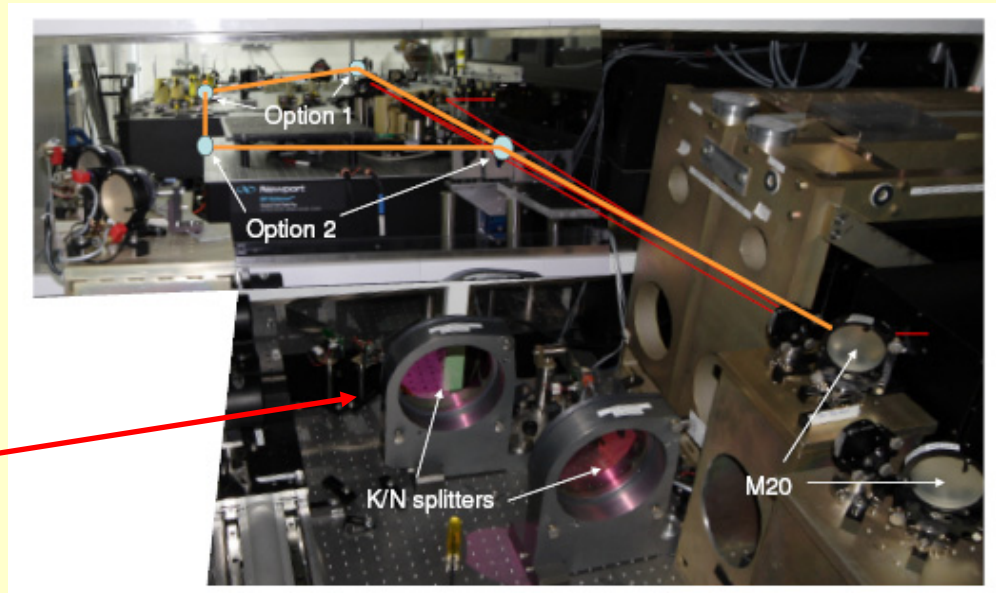
  SA: J. Woillez, PI: P. Wizinowich and the IF-team at WMKO

  M. Colavita, and the IF-team at JPL, R. Akeson, R. Millan-Gabet (MSC)

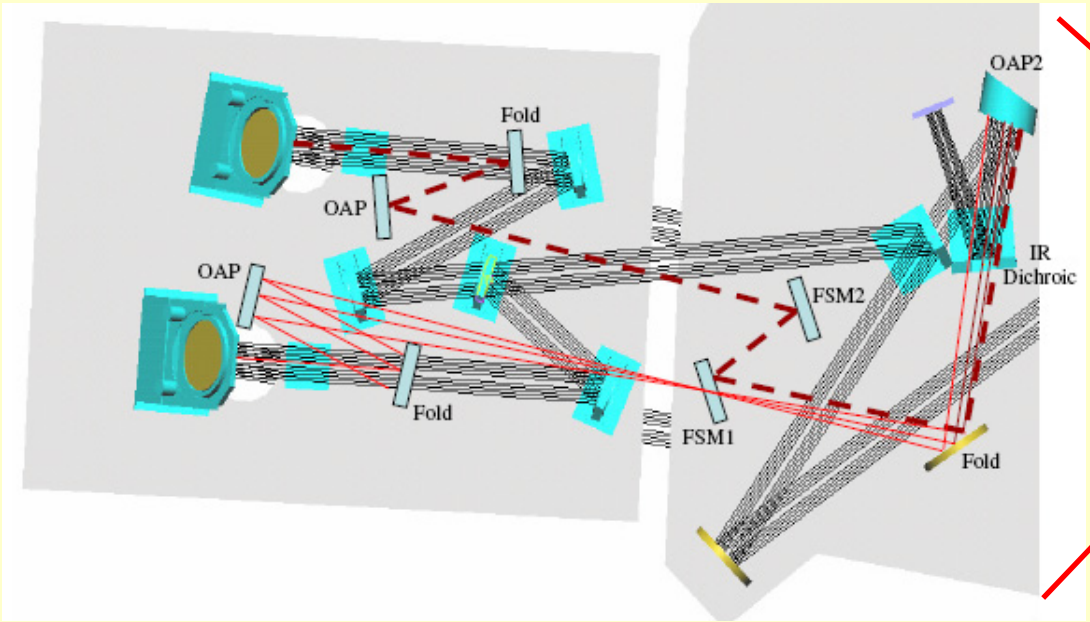
  Core science team:
  PS: J. Graham, J. Eisner (UCB),
  A. Ghez (UCLA),
  L. Hillenbrand (Caltech),
  J. Monnier (UoMichigan)

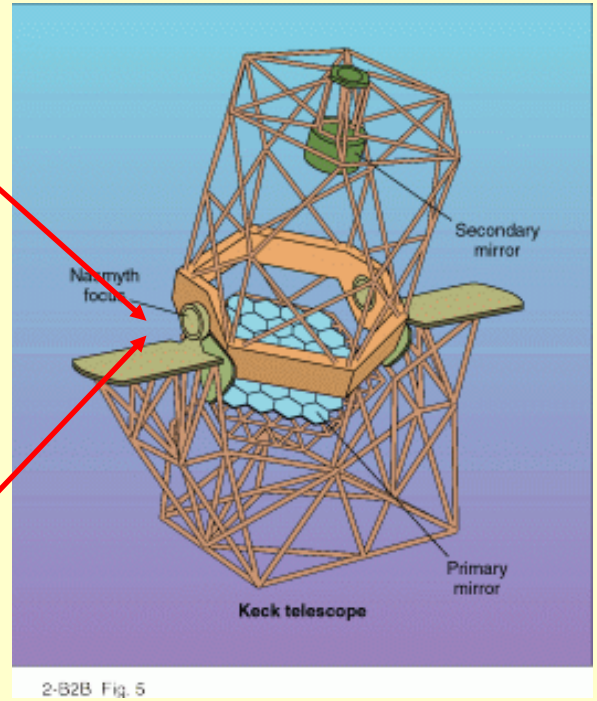
- Keck-IF ASTRA – first step – Self-referencing
  - Atm. turbulence sets the coherence time -> correction loop of ~ 20 Hz at NIR needed -> input 10x faster -> limits sensitivity or spectral resolution
  - Solution: split the light, track fast on one half, and see the spectroscopic details of other half with 2nd slow fringe camera
  - It works and will be offered this fall to the community to do IF with medium spectral resolution (R~1000) at K~8-9





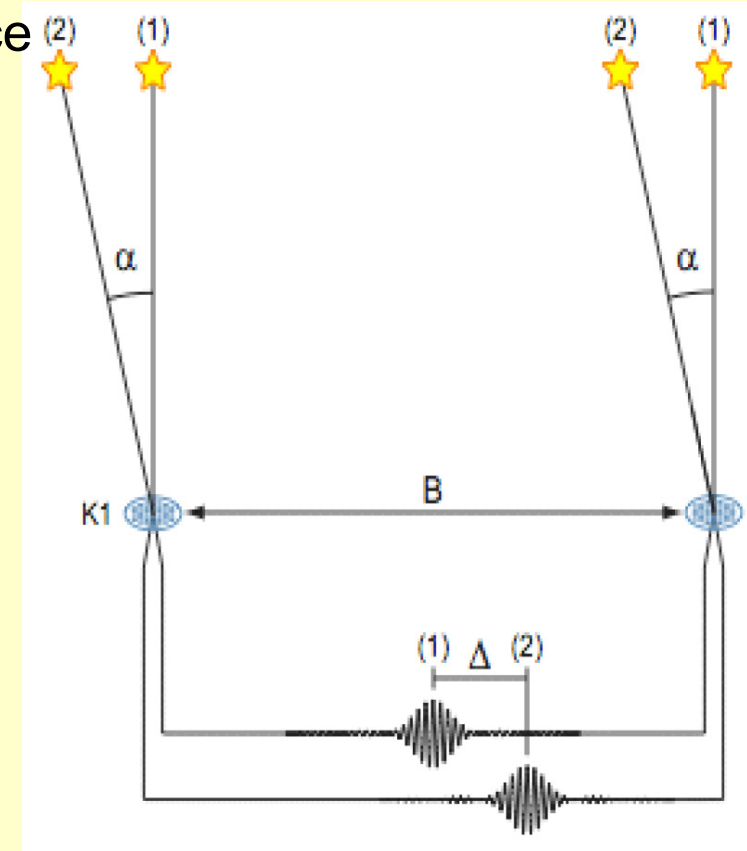
- Keck-IF ASTRA – second step - Off-axis phase-referencing
  A key technology is ‘star separation’
  - Split the light already in the telescope foci to get maximum FOV
  - Apply the gain of a stabilized fringe and a second camera to another (faint or red) star in the iso-planatic patch
  - Never been done before with large apertures!



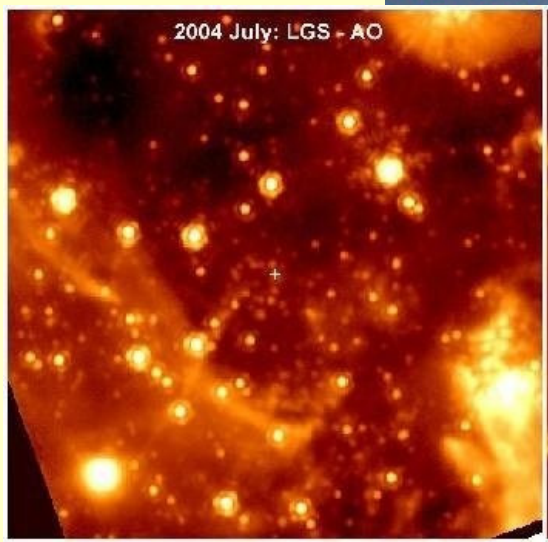


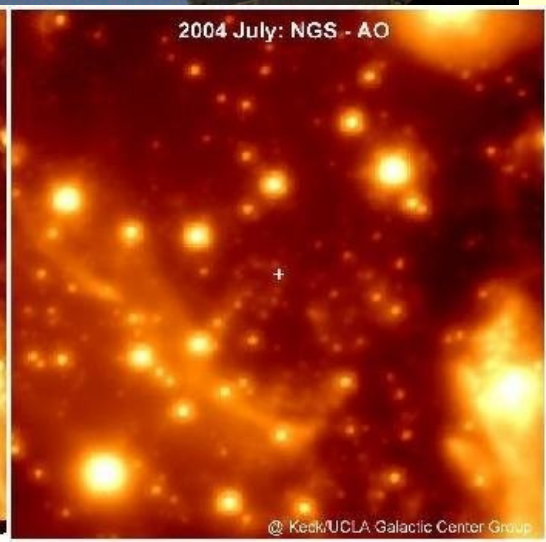
- Keck-IF ASTRA Future:
  Dual-star phase-referencing facilities will also enable:
  narrow angle precision astrometry down to ~50uas
  - IF-astrometry is orthogonal to imaging-like visibility-interferometry
  - Measure is the angular distance between two stars via intrinsic geometric-delay difference
  - Usually limited by atmosphere
  - 50μ“ require control of delay to ~ 20nm and the baseline to ~ 150μm
  - Repeated measurement can reach even higher precision
  - Laser metrology needed to probe the complete internal path at the 20nm level of precision

-> talk by Colavita for some more KI-technology

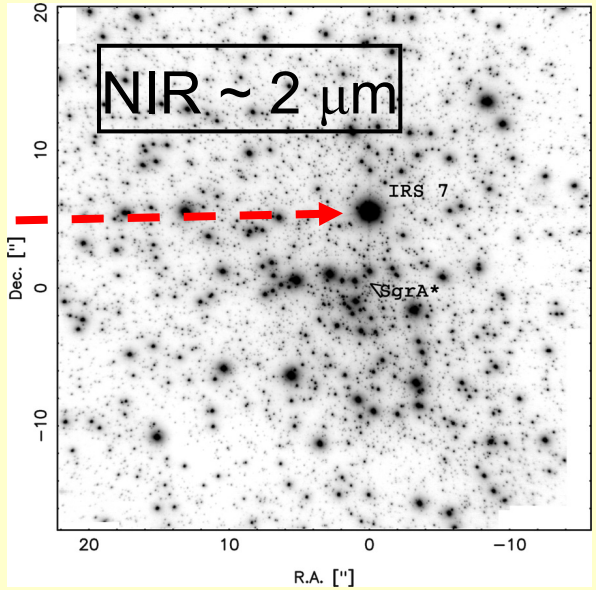


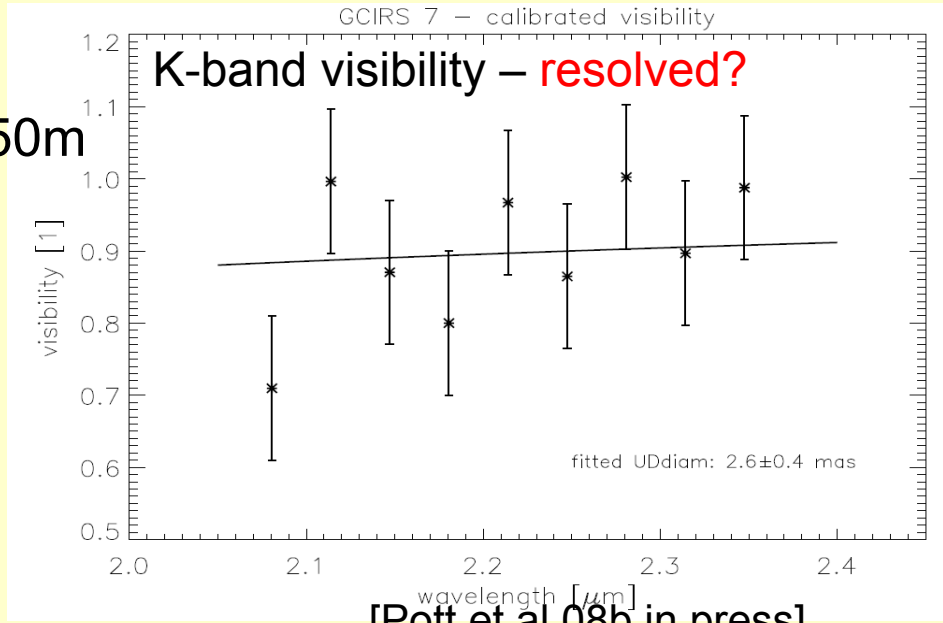
- Keck-IF ASTRA for the GC:
  Key properties
  - 10m diameter of primaries
  - Visible AO will be extended by two LaserGuideStars
  - Fringe tracking in K, and angle-tracking in H
    -> GC stars are very red
  - star-separator fully exploits the iso-pistonic angle of ~25”
    -> covers the complete central pc





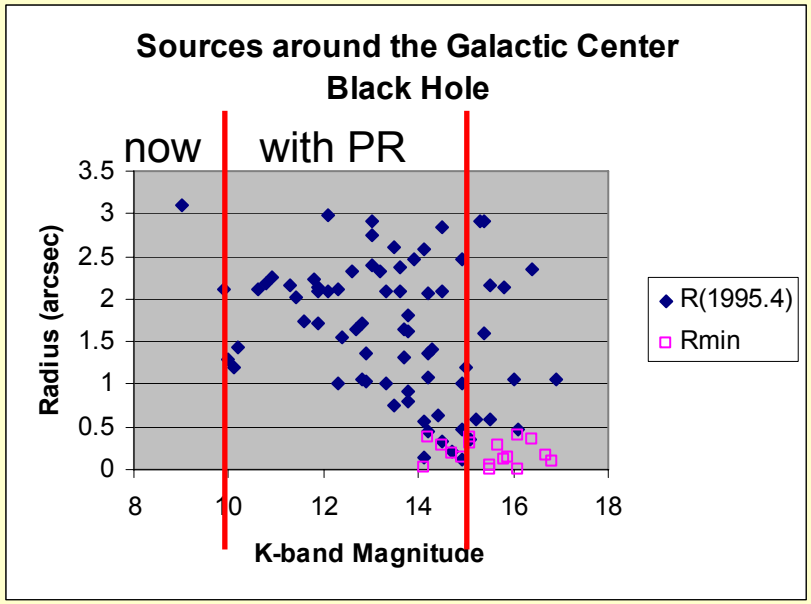
- Off-axis phase-referencing at the GC: appears to be possible
  - GCIRS7 is the prime candidate
  - First data raise some concerns:
    - Supergiant's molecular shell?
    - Dust formation and / or shocked environment
    - Variability(, proper motion)
    - Stable visibility at 100m baselines?
  - Requires some monitoring at high data quality, but interferometric response on 50m baselines is strong enough!





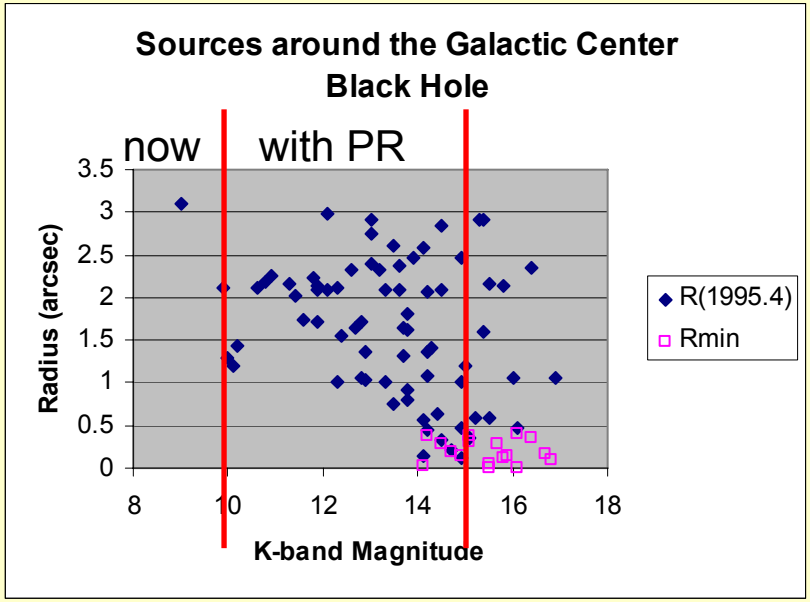
[Pott et al.08b in press]

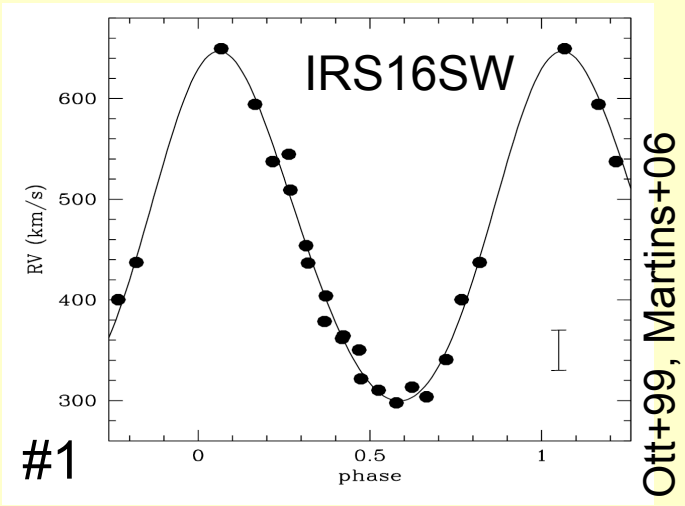
- Off-axis phase-referencing in the GC: potential sources
  - Current limit: K_{lim}~9-10mag with Keck-IF



[data: Ghez+'98,'05]

  - Off-axis phase-referencing with VLTI/PRIMA and KI/ASTRA will dramatically increase No. of targets



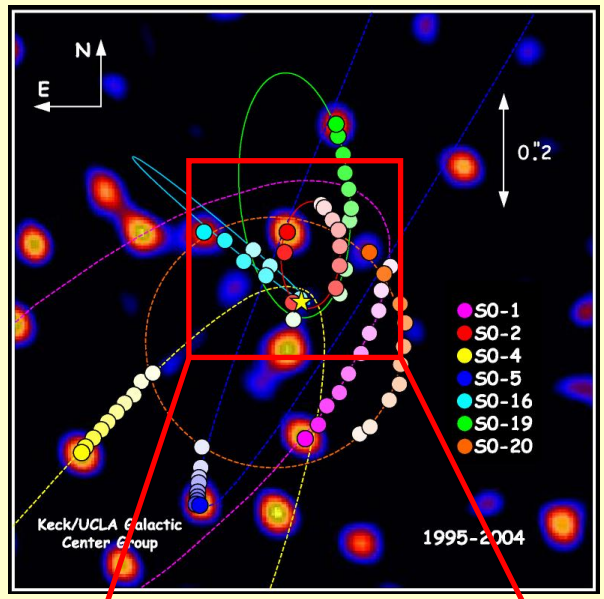


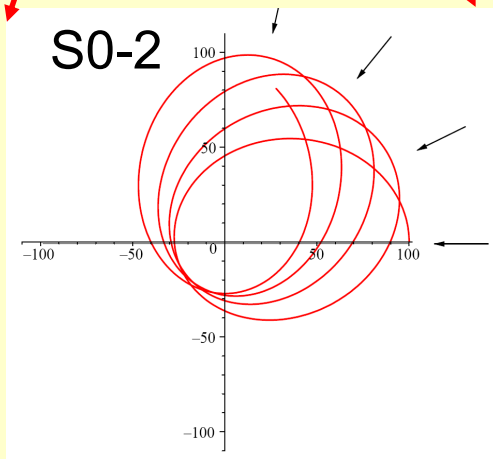
#2, #3…where ???

- GC-paradigm:
  Every star can be interesting!
  - E.g. the binary science case:
    - Binary fraction probes the SF
    - Binaries are believed to be the origin of the enigmatic hyper-velocity stars
    - Evolved binary system can result in many stellar phenomena (rejuvenation, X-ray sources, dust formation ...)
  - Today we know of one binary system only!
  - Need for higher angular resolution and differential astrometry
  - Off-axis phase-referencing will lead to new data to investigate the binary question –> ASTRA

Astrometry-GC science:

- Current single-telescope astrometry result in precise Keplerian orbit measurements of K~ 14-15 mag stars in the central 0.5”
  > evidence for MBH ($4 \cdot 10^6 M_\odot$, work by Ghez, Genzel, Eckart, Schodel…)
  > in combination with RV: distance to SgrA*: 7.6kpc (Eisenhauer+‘05)
- Single-telescope is confusion limited in the central 0.5arcsec, 0.1uas can hardly be achieved with single telescopes very close to the MBH -> Interferometry
- Deviations from Keplerian orbits
- General relativity: S0-2 expected apoapse shift: ~0.4mas/rev. (Rubilar&Eckart01, Weinstein05)
- Probing GR and extended central mass distribution
- Origin of hypervelocity stars, and comoving groups / IMBHs



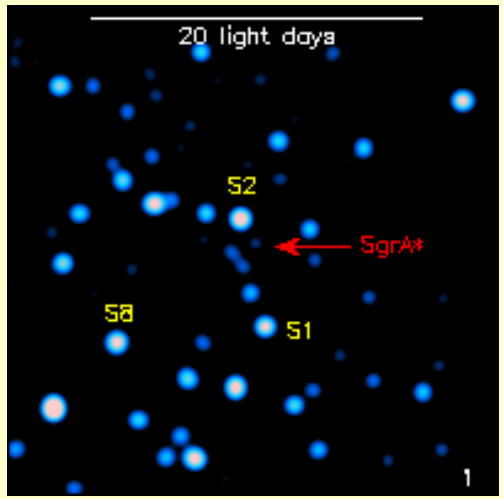


A dream of IF-GC science: the flares

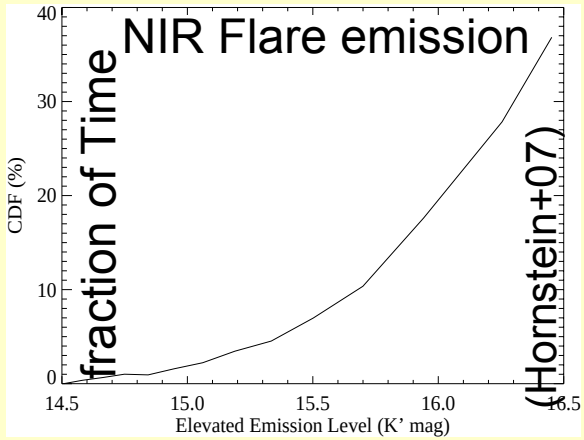
- Current single-telescope AO sees spatially unresolved IR-flares, the short time-scales of minutes to hours point to emission zones of a few $R_{Schwarz}$ close to the event horizon

- Observing the IR-flares of the BH-accretion
  - Challenge synchrotron and hot-spot models with spatial information; use IF-PSF to better characterize the spectrum

KI/ASTRA & VLTI/PRIMA break new grounds, leading to GRAVITY (2nd gen. VLTI instr.)?
-> talk by Bartko

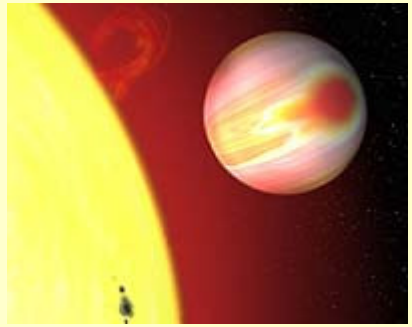


Genzel+'03

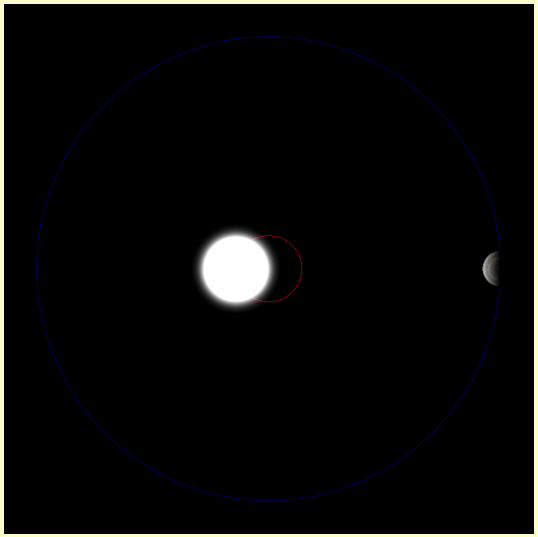


ASTRA – science cases: Planets

- The astrometry reaches accuracy levels required to measure the on-sky reflex motion, in particular of multi-planet systems



Artist's view of HD189733



Demonstration of stellar reflex motion (P. Weise, ESPRI project)

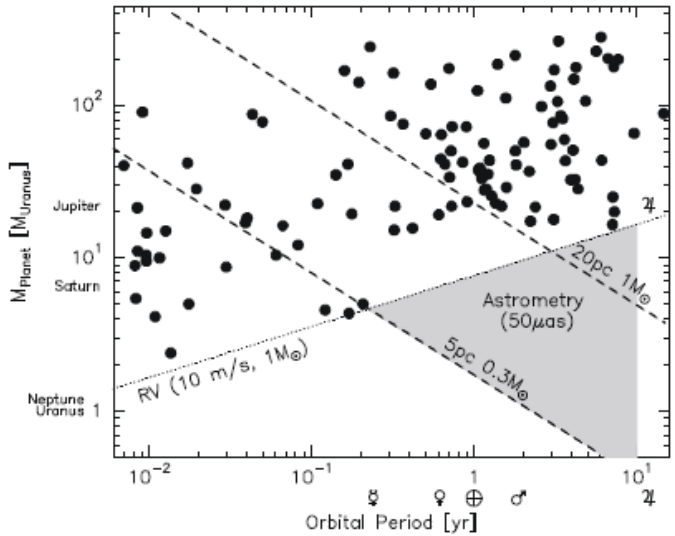
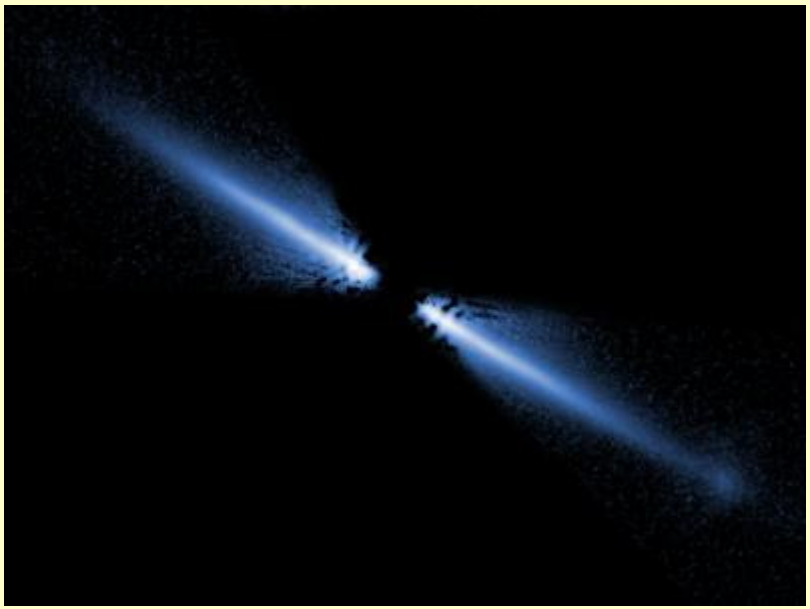


Figure 1 – detection domain for 50 μas astrometric measurements, highlighting the region which is not accessible to the radial velocity technique.

by R. Tubbs (MPIA)

ASTRA – science cases: YSO

- Self-referencing spectroscopy will enable to spatially and spectrally resolve gaseous and dusty components of YSO environs at AU-distance scales, where planets form



A visible-light HST image of a debris disk around the red dwarf star AU Microscopii. (400 AU across, J.E. Krist; STScI/JPL)

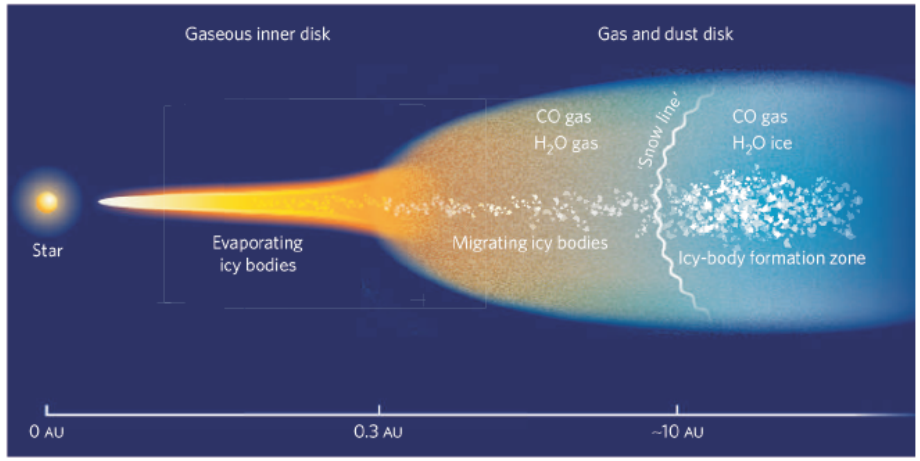
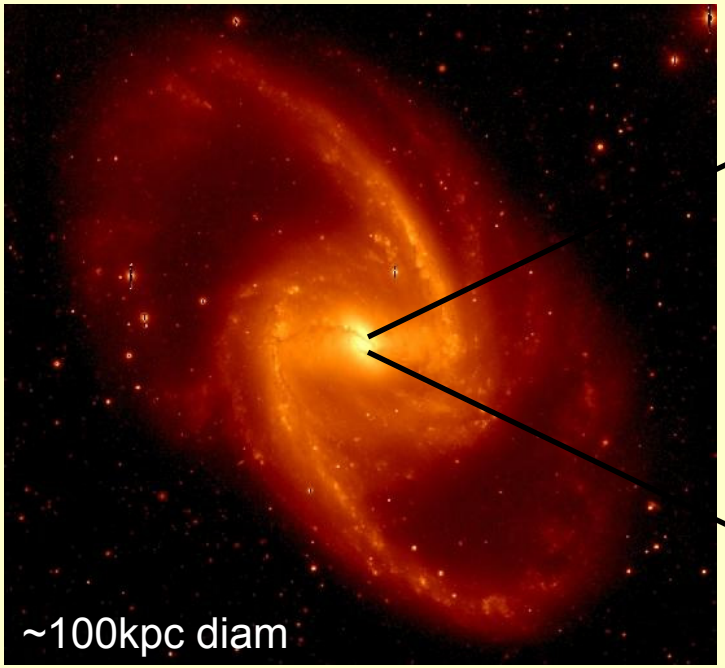


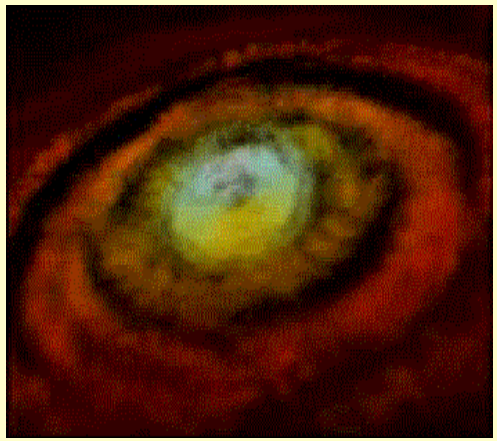
Fig.2: Current informative disc model of a YSO[3] showing the different zones (not to scale). Since 1AU equals ~15mas in the nearest starforming regions, only infrared OLBI can spatially resolve emission lines originating in stellar winds or discs, and determine outflow properties depending on the actual line-of-sight in planet-forming systems. Eisner et al. have found imprints of water in the inner disc around MWC 480, using the KI in dispersed V^2-mode[8].

van Boekel '07

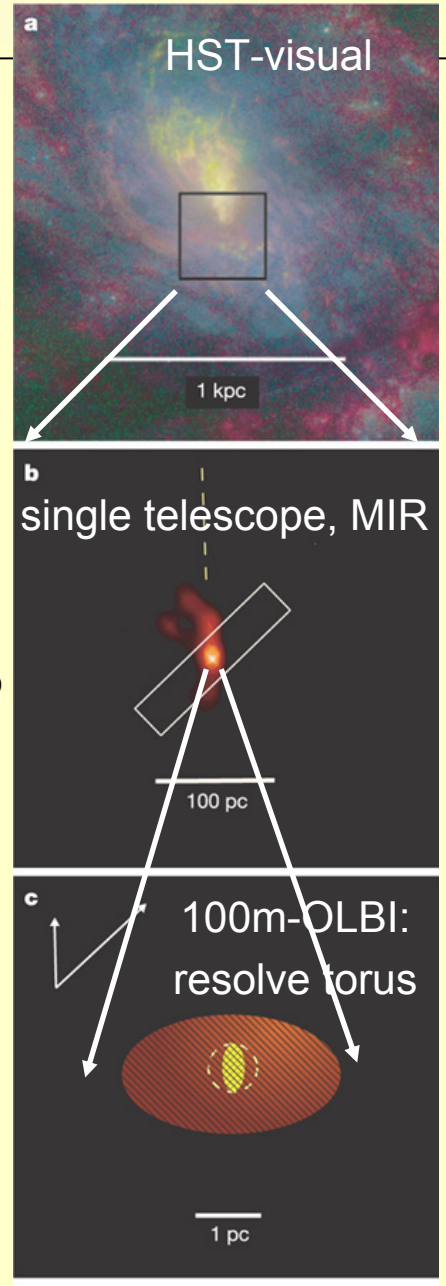
ASTRA – the science cases: AGN

- Dual-field and self-referenced observations will increase the sample of observable AGN, scrutinize the innermost dust morphology, and surrounding host-properties
- Interferometric PSF will give unique opportunities to study the nuclear SED (AGN evolution, reverberation-mapping)





NGC 1365, animation of infalling / accreted gas from Hayden Planetarium



NGC 1068, first MIR fringes, from W. Jaffe et al. '04

- There is a lot to do, and a lot to discover!
- Few-baseline interferometry is like high-resolution spectroscopy: specialized, requires some modeling but can add powerful constraints to Your science
- Write proposals, and challenge the current instrumentation!
- Grad- and postdoc projects available
- **Köszönöm**!
  Questions?