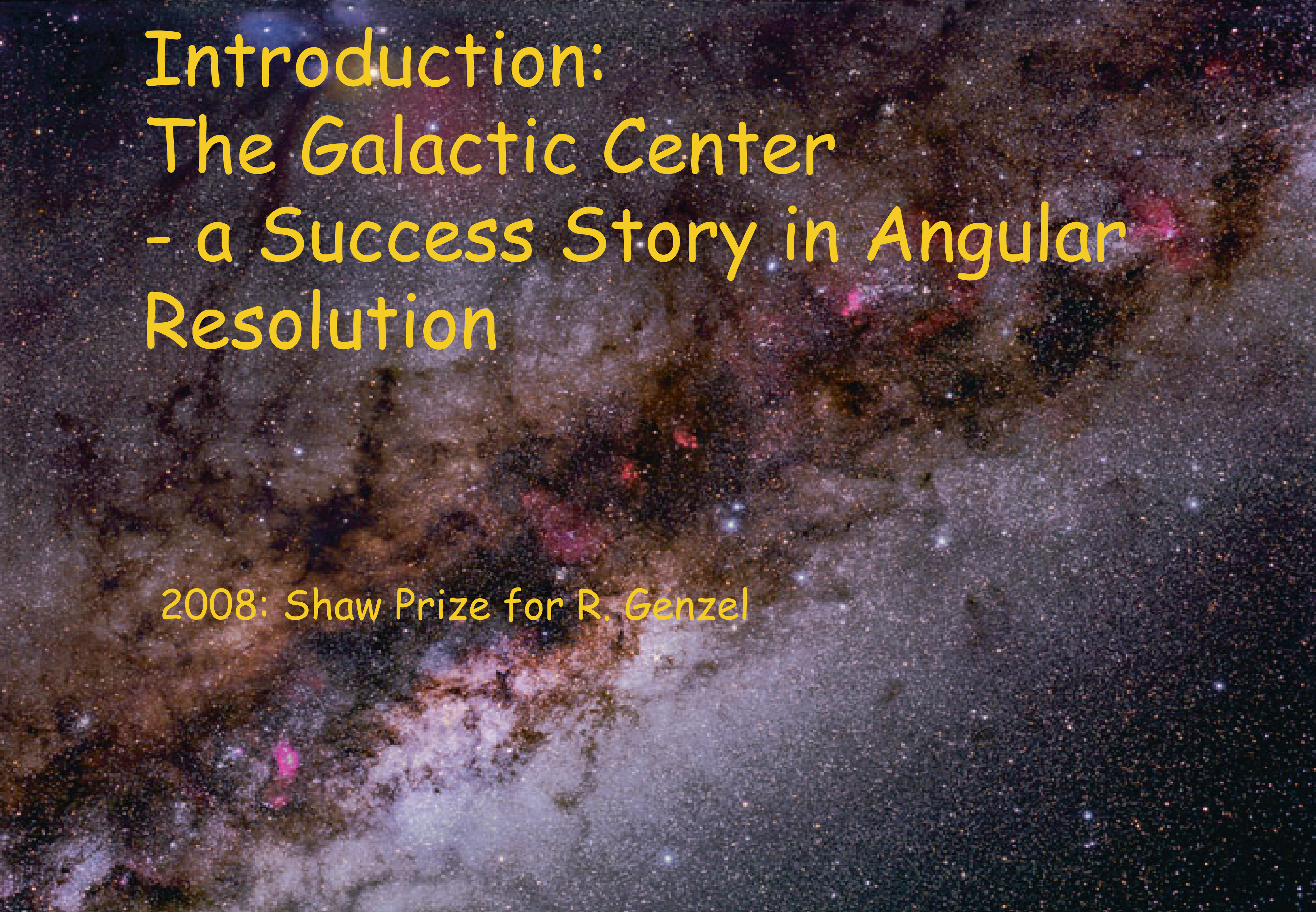
GRAVITY: Microarcsecond Astrometry and Deep Interferometric Imaging with the VLT

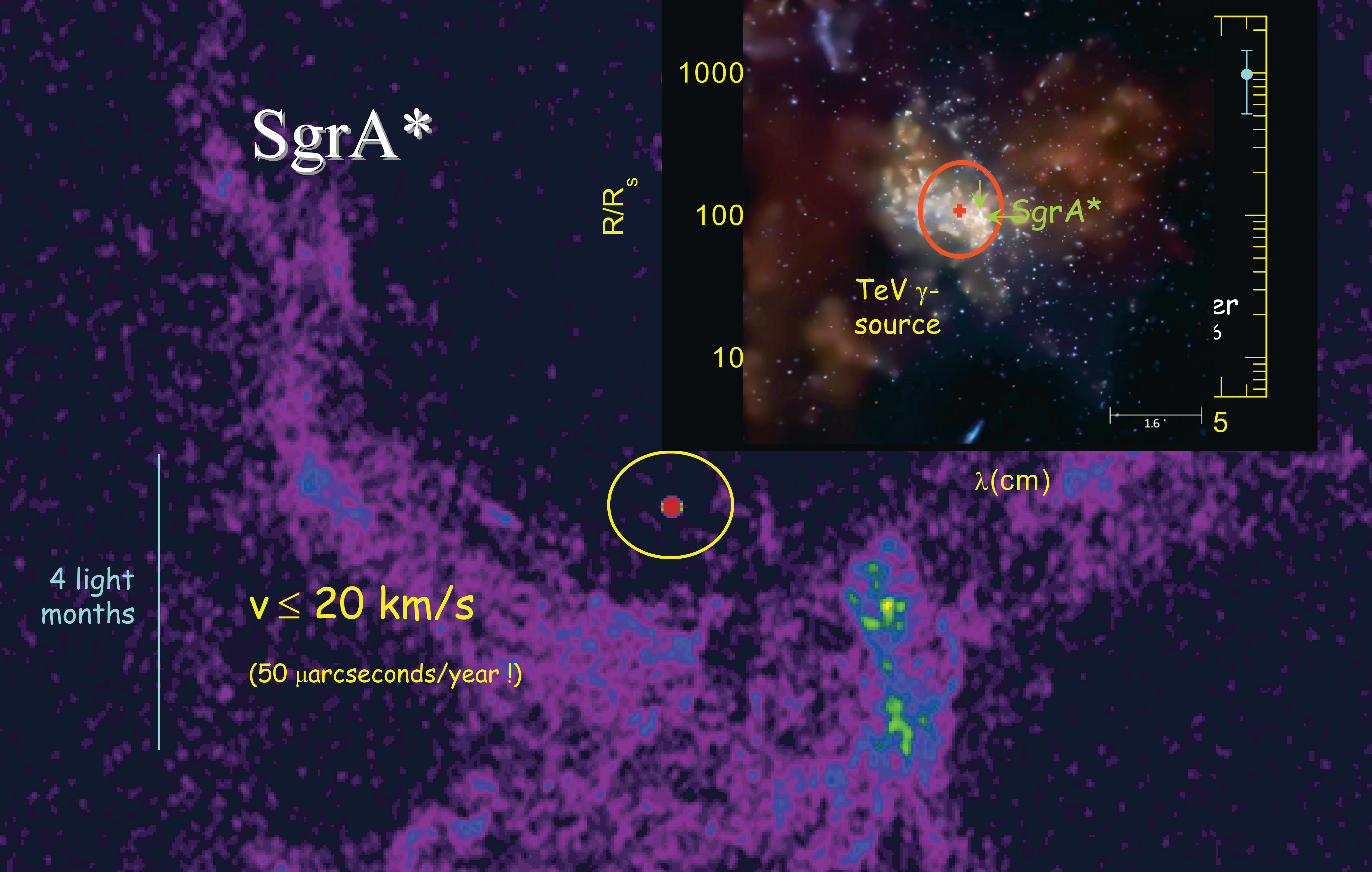
- Introduction: The supermassive black hole at the GC

- Observe supermassive black hole with dedicated VLTI Instrument: GRAVITY
- Instrument concept
- Schedule

Introduction:
The Galactic Center
- a Success Story in Angular Resolution

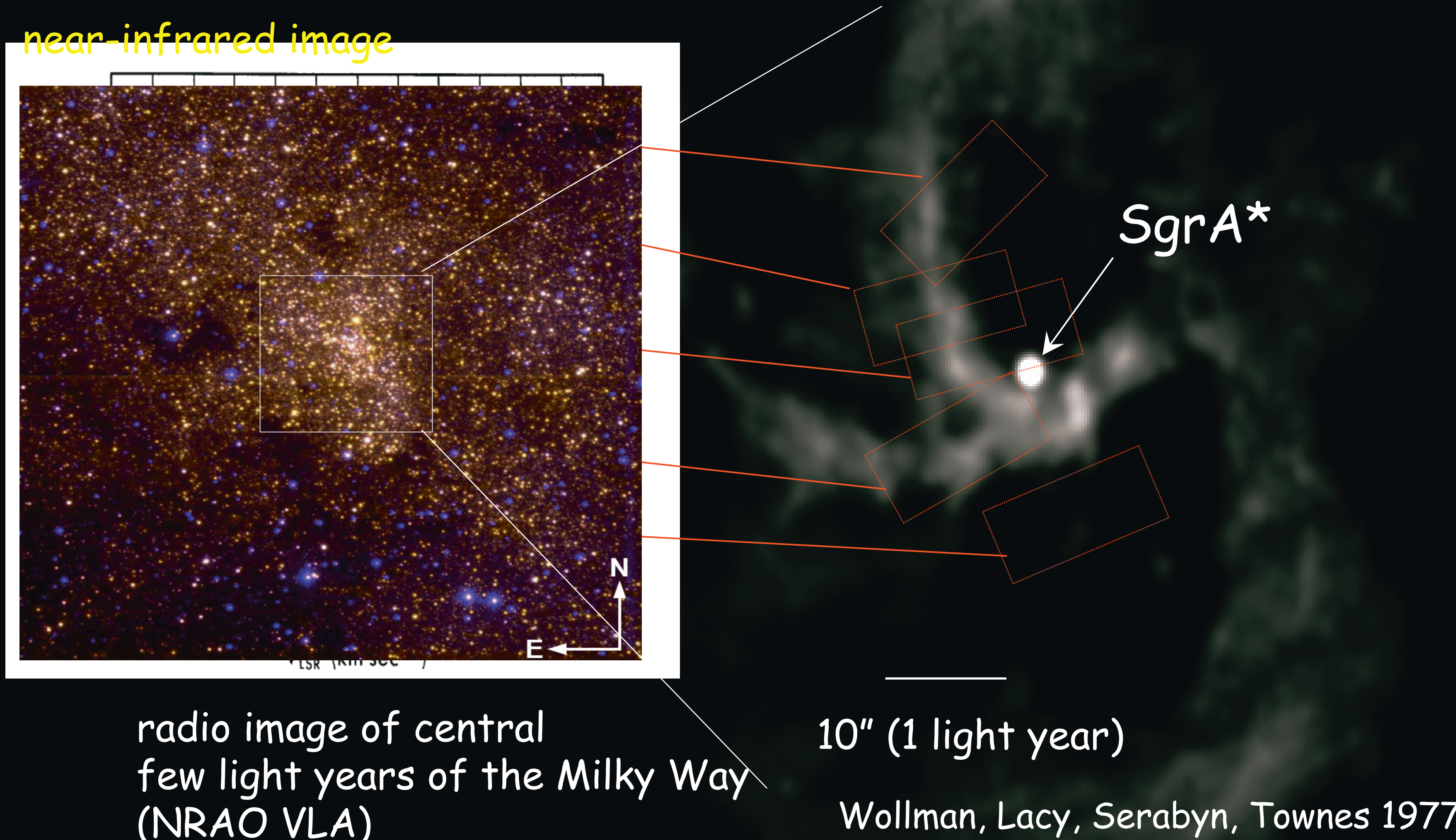


2008: Shaw Prize for R. Genzel



Backer & Sramek 1996, Bower et al. 2003, 2005, Reid & Brunthaler 2004, Shen et al. 2005, Baganoff et al. 2001, 2003, Aharonian et al. 2004-06, Bartko et al. 2007

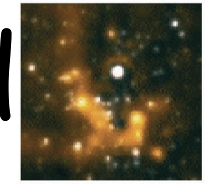
Early Evidence for a Central Mass Concentration in the Galactic Center

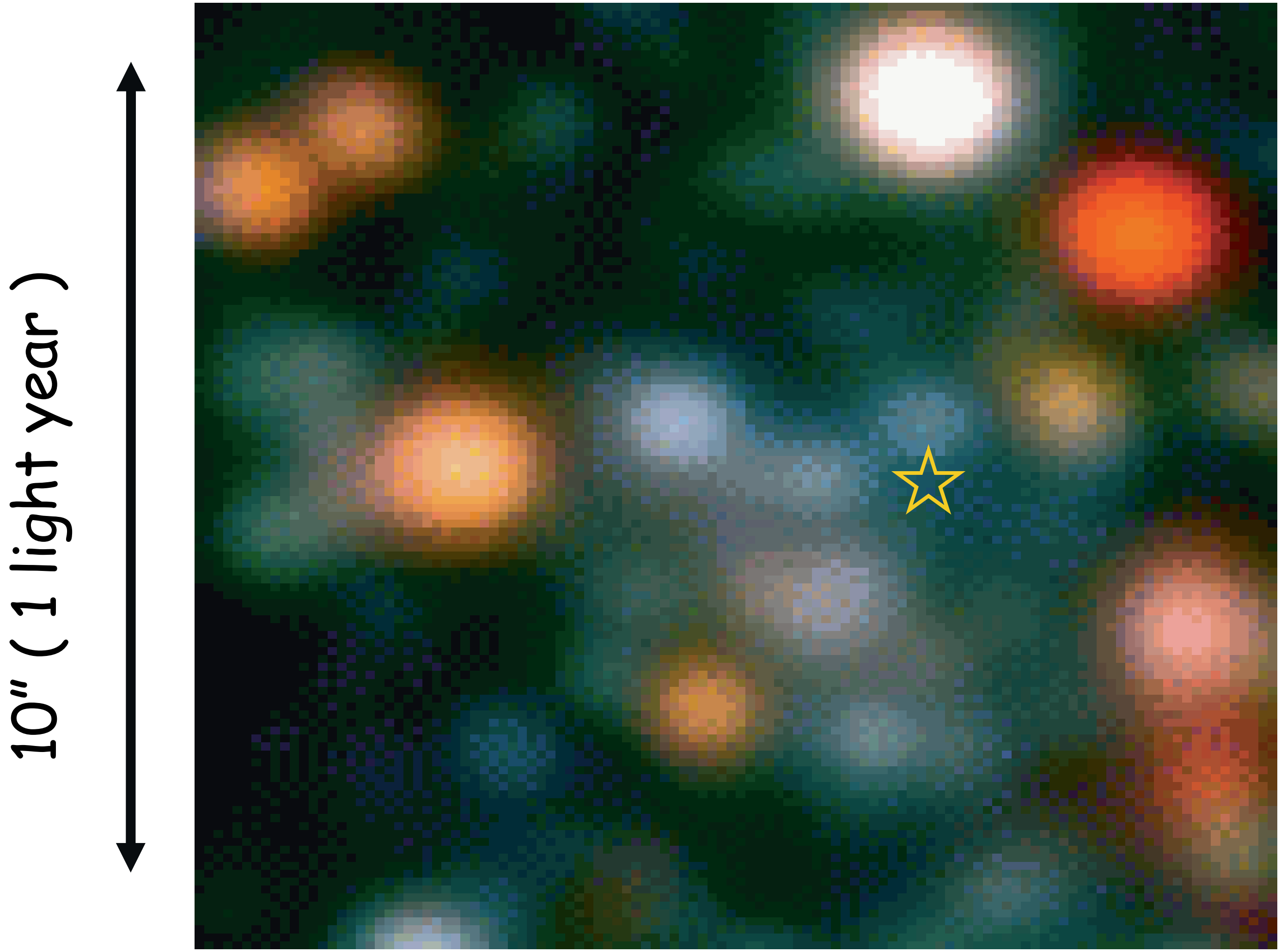


radio image of central few light years of the Milky Way (NRAO VLA)

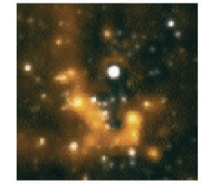
Wollman, Lacy, Serabyn, Townes 1977-1988

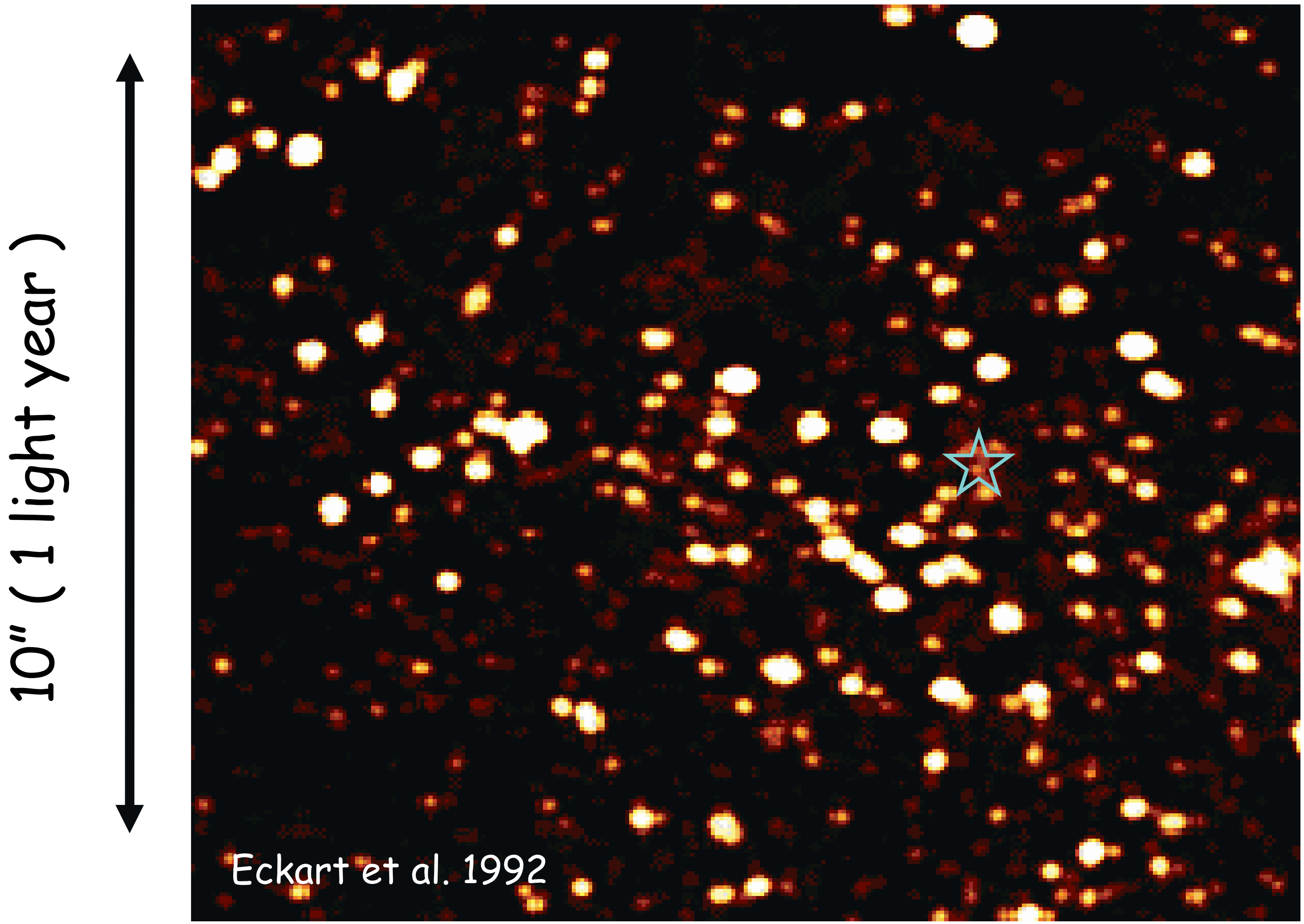
Pre 1992: IR Seeing limited



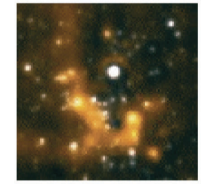


1992: IR Speckle Imaging

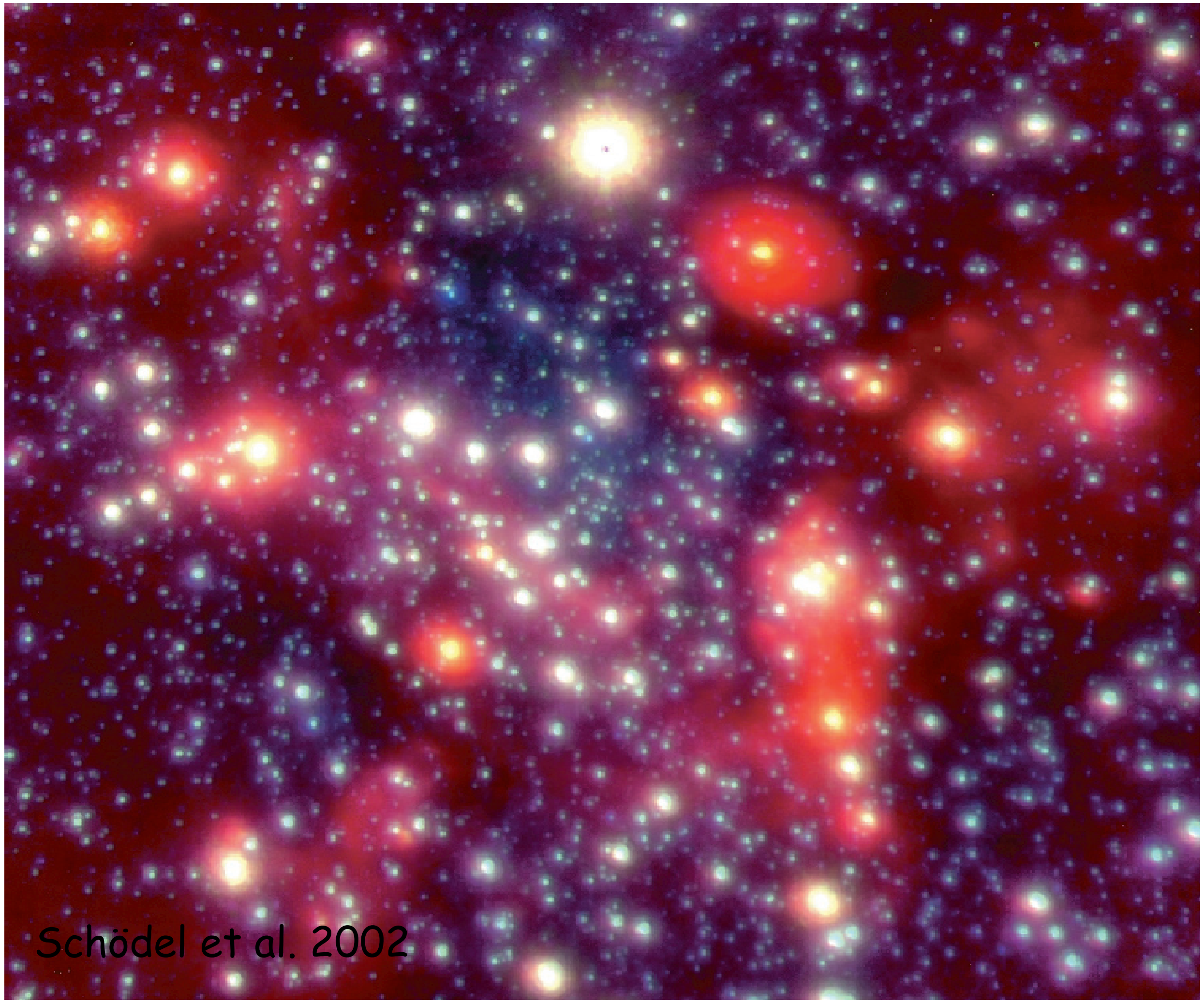




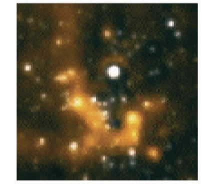
2002: AO Imaging (NACO)

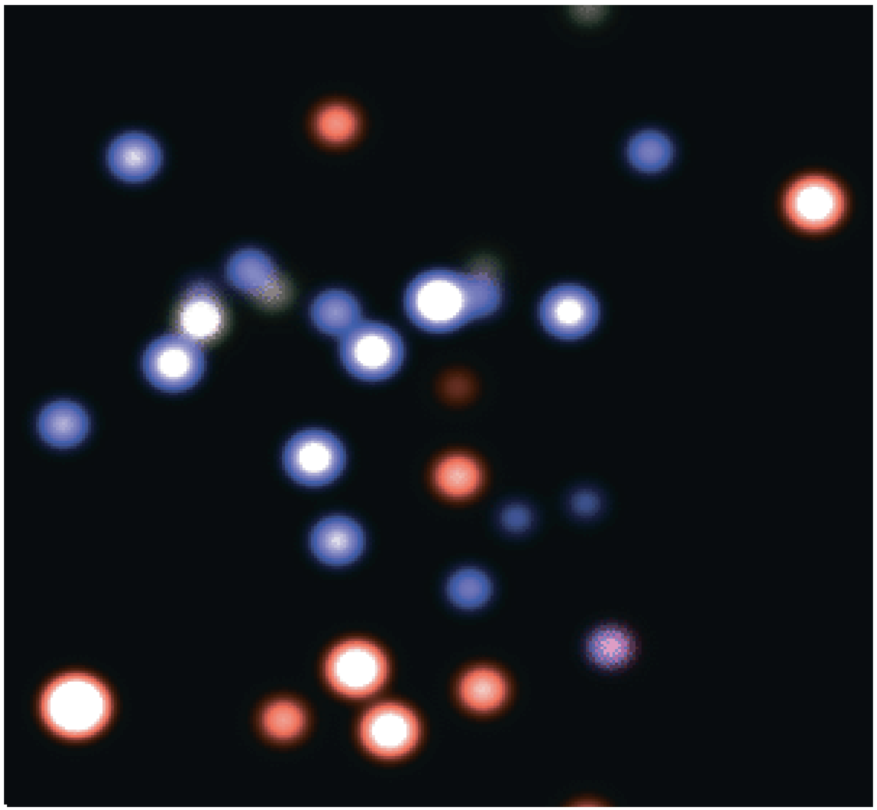


10" (1 light year)



Stellar Orbits Suggest Massive Black Hole

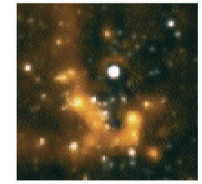




- 1996 High proper motions
  - Eckart & Genzel 1996,1997
  - Genzel et al. 1997
- 2000 First Accelerations
  - Ghez et al. 2000
- 2002 1 Stellar Orbit
  - Schödel et al. 2002
- 2005 6 Full 3D Orbits
  - Eisenhauer et al. 2005
- 2008 >25 Full 3D Orbits

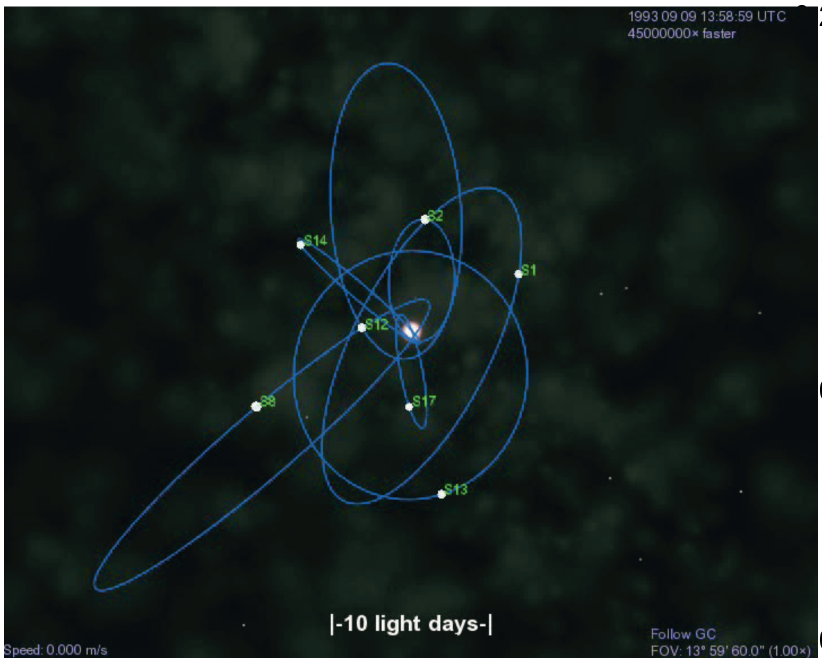
$M \sim 4*10^6\ M_\odot$, $R \sim 8$ kpc

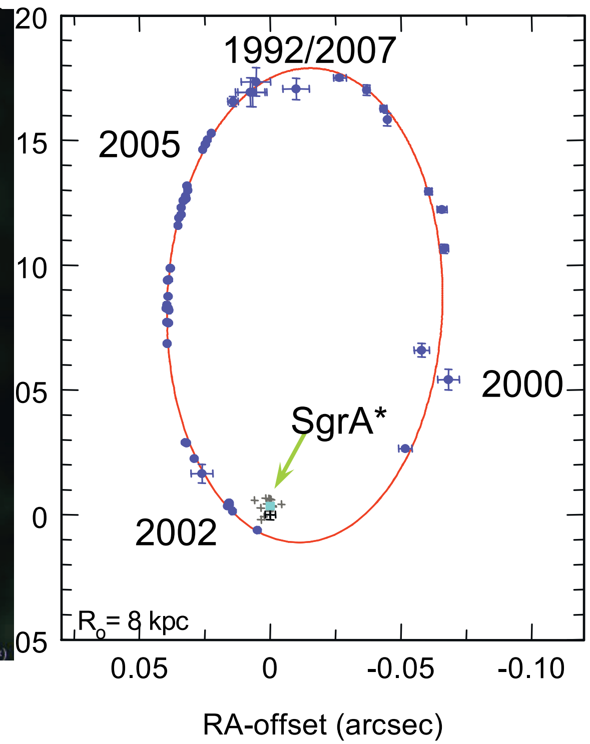
3D Orbits from Spectra

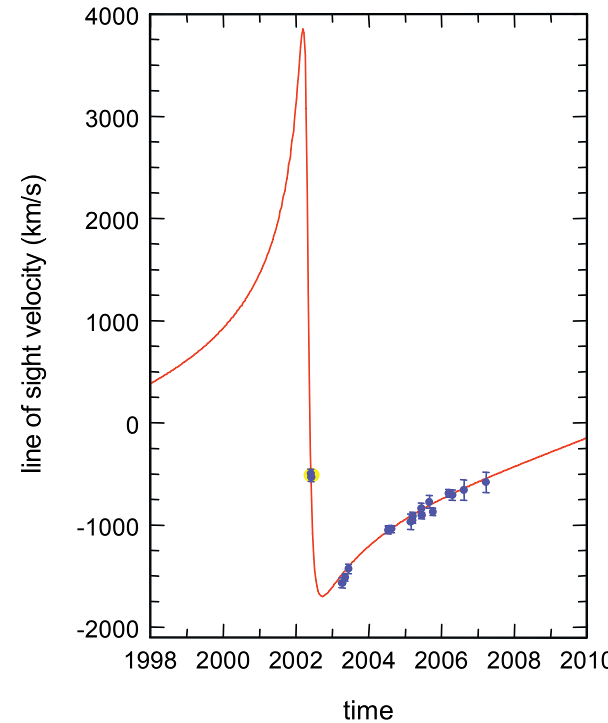


15 years of precision measurements: first full orbit

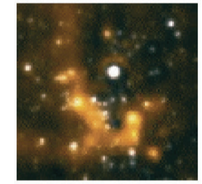
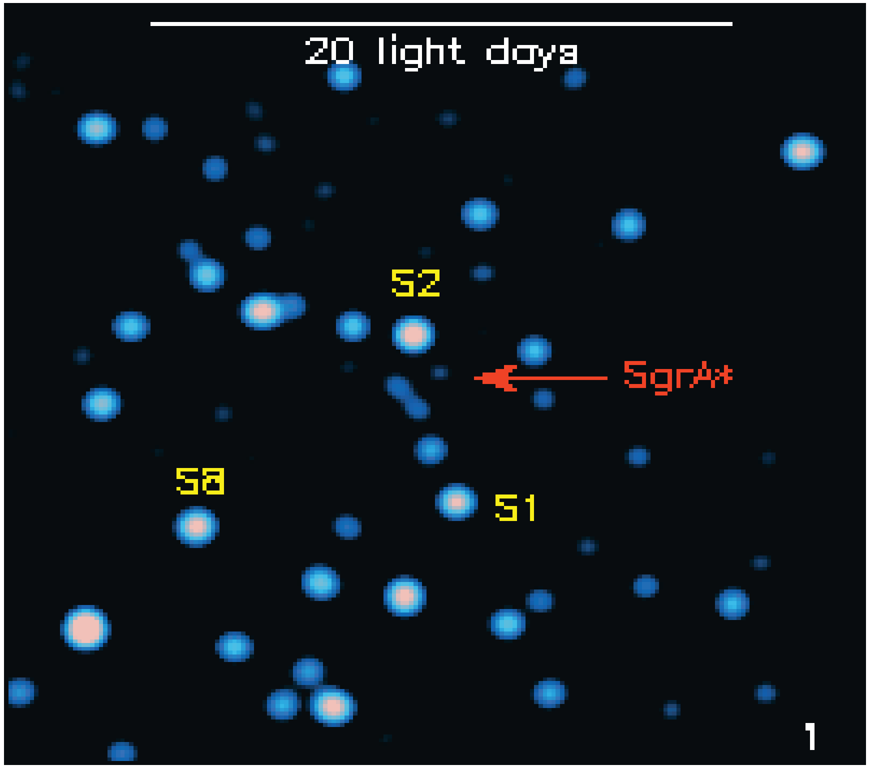
- active telescopes + adaptive optics + integral field spectroscopy
- gravitational potential dominated by 4×10^6 $M_\odot$ central point mass

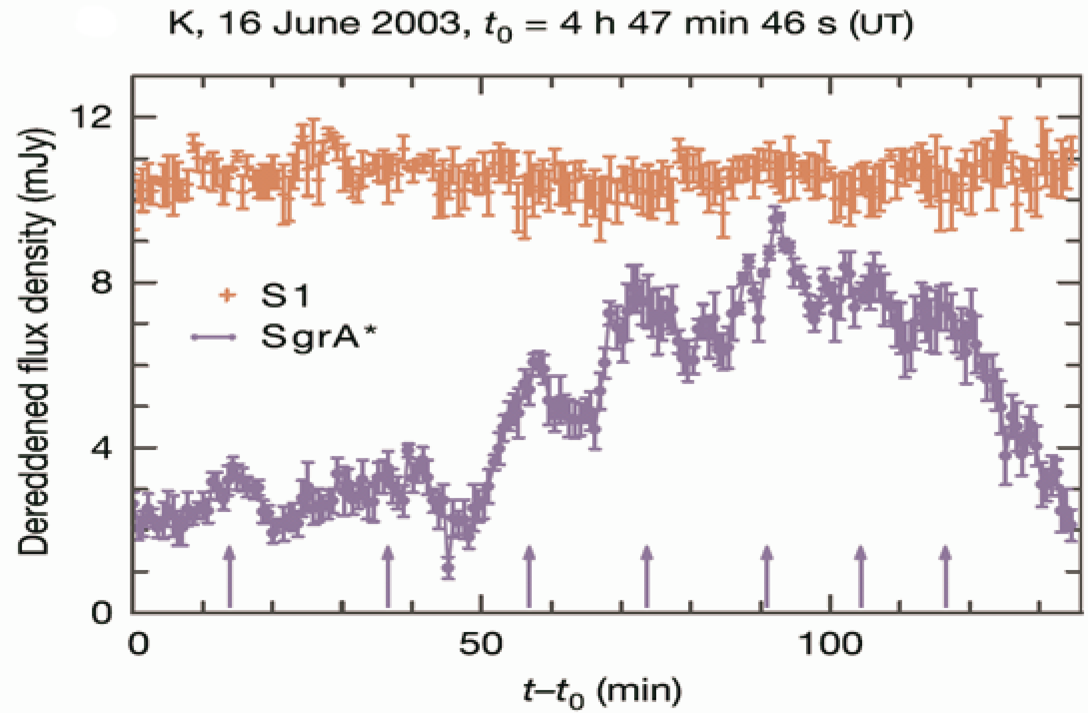






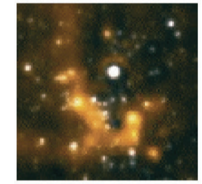
2003: Infrared Flares



~20 min quasi-periodicity: emission region <= 20 light minutes (few R_s)

Argument for a Black Hole



Distance | Mass | Radius

↑ Velocities and orbits of stars

Mass → $4 \times 10^6\ M_{Sun}$

Radius → Few thousand R_S

Non-motion of radio source vs. speed of stars

→ Few ten R_S

Size of radio source

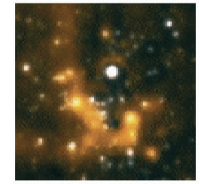
Brightness and SED variations

→ Few R_S

Faintness, SED, rotation measure

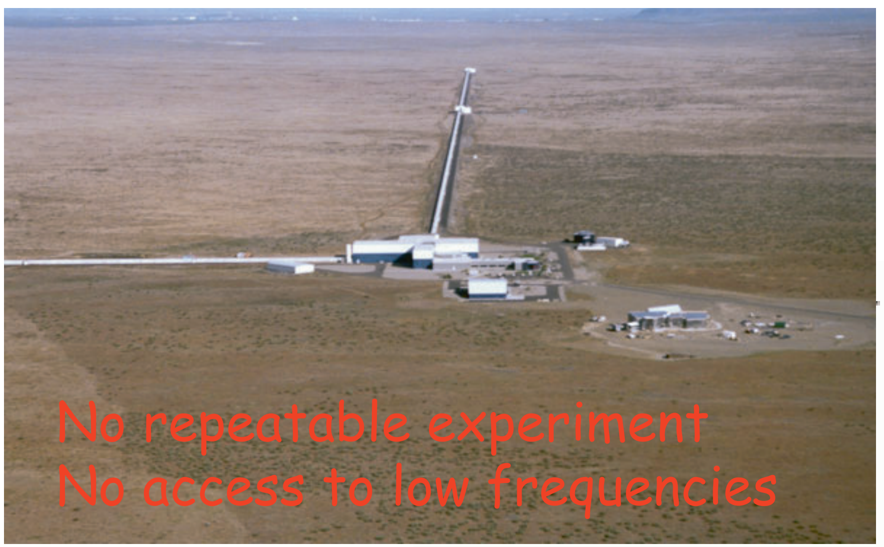
→ Event horizon

Major Next Step: Experimental Test of GR

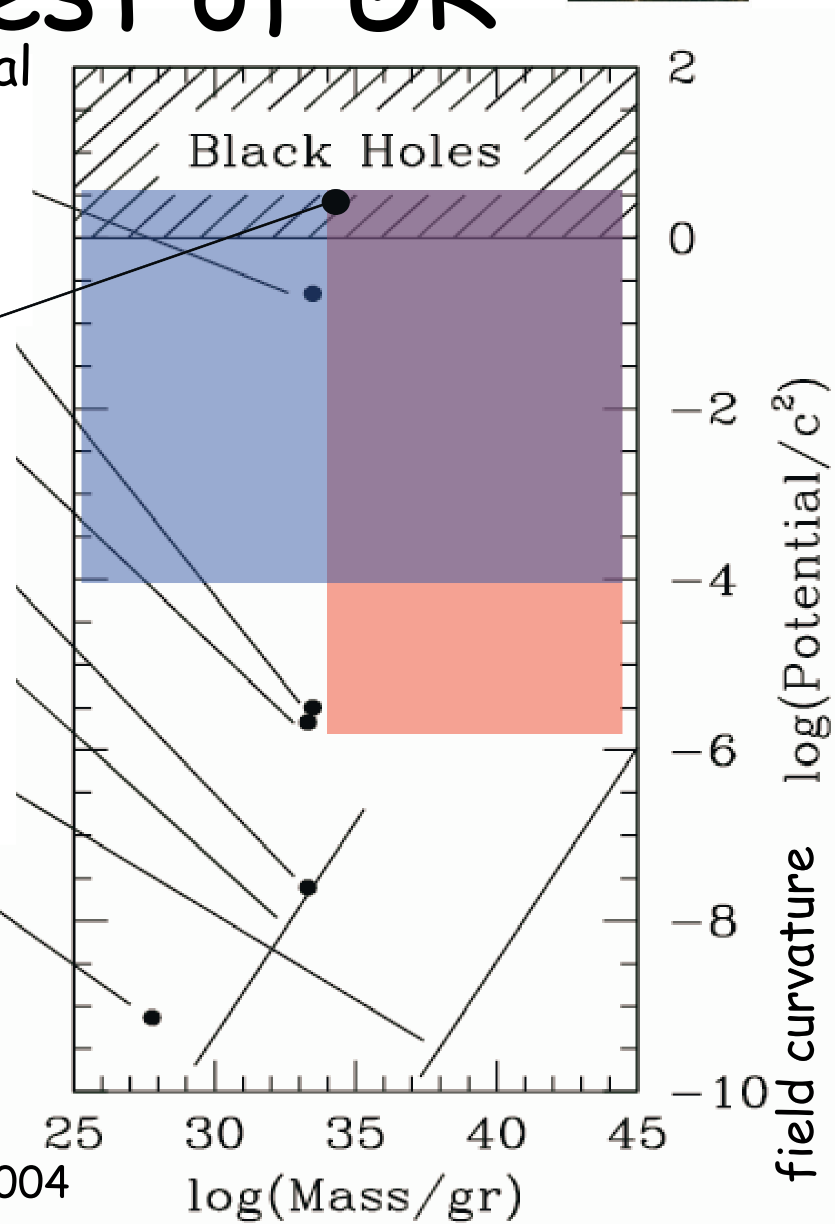


No experimental tests for
- high field curvature
- high mass

Possibility for stellar mass regime:
Observing gravitation wave pattern from Supernovae



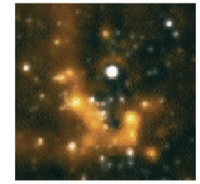
LIGO



Psaltis 2004

2008/06/12

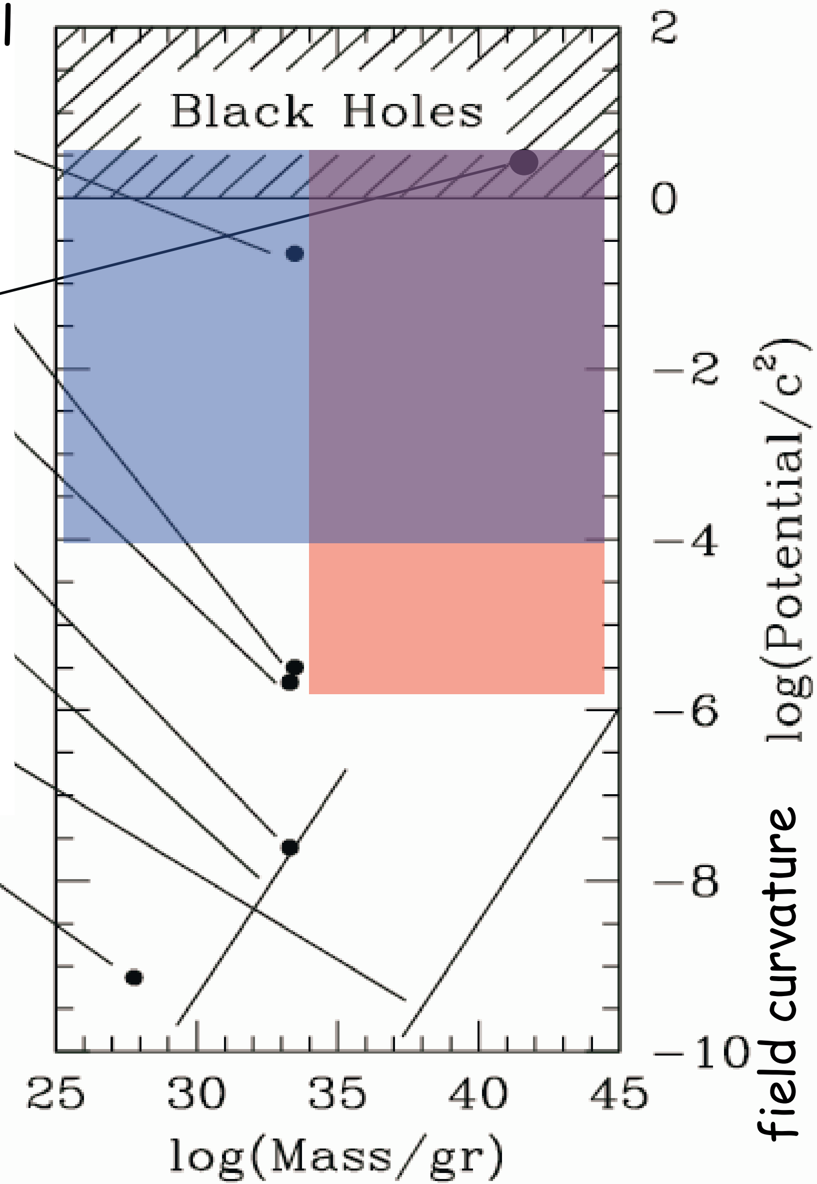
Major Next Step: Experimental Test of GR



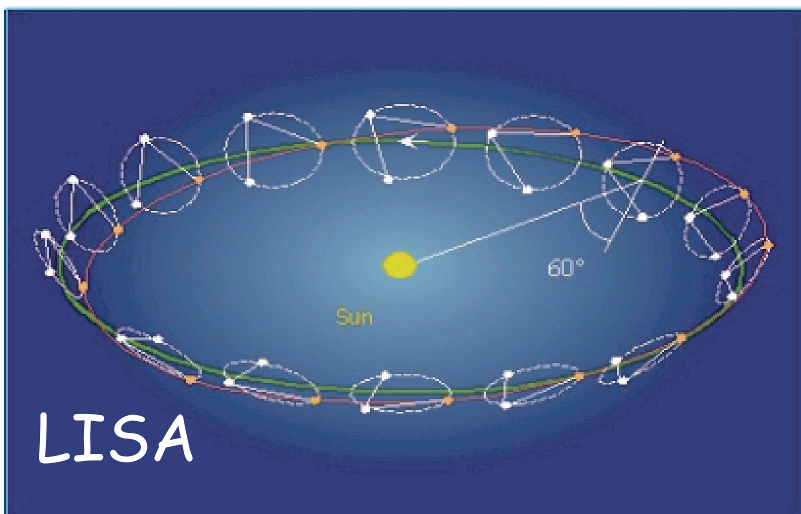
No experimental tests for
- high field curvature
- high mass

no dynamical test

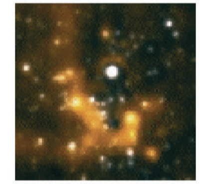
One possible route for supermassive black holes:
Observing gravitation wave pattern from BH merger



Technically extremely challenging



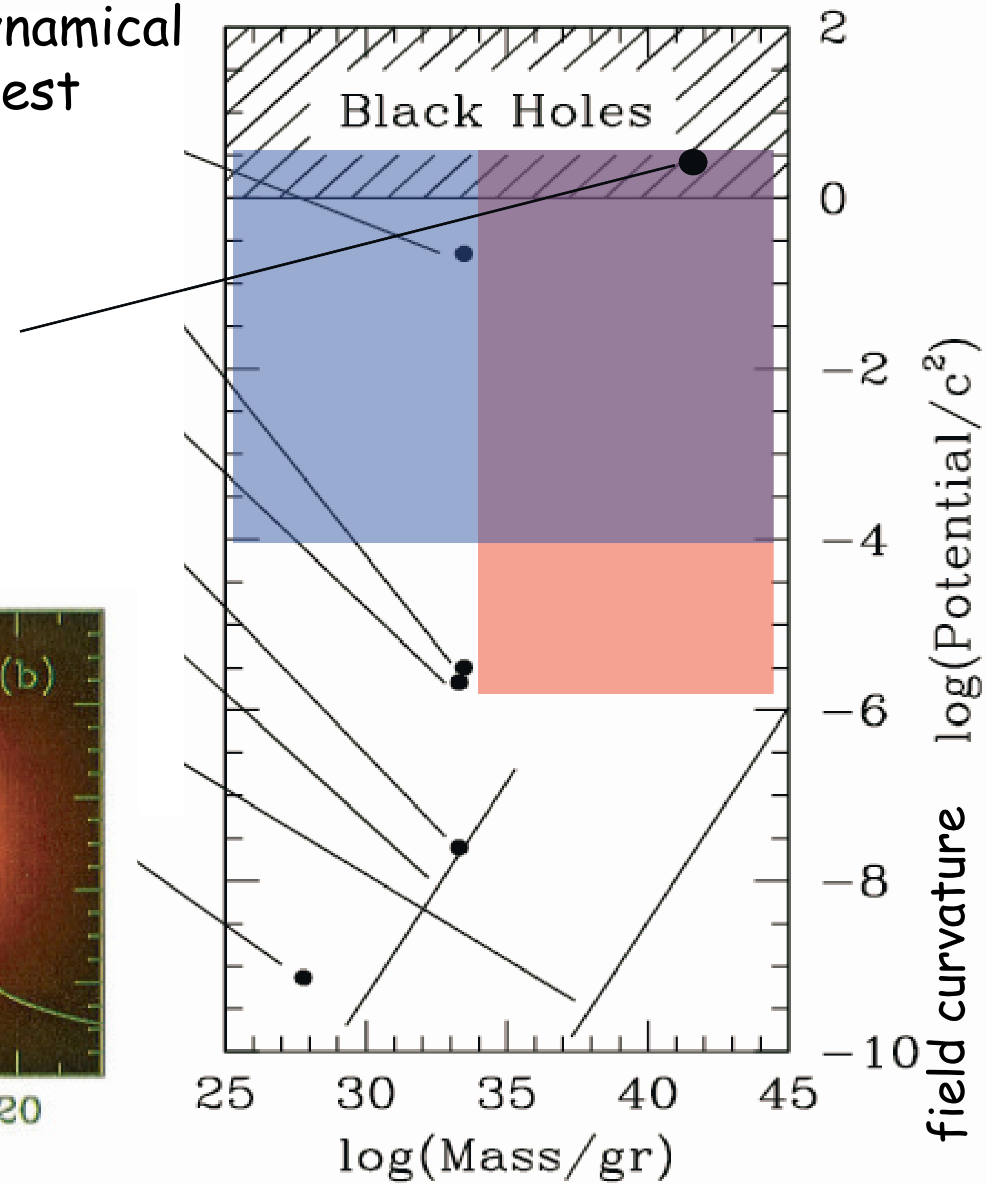
Major Next Step: Experimental Test of GR



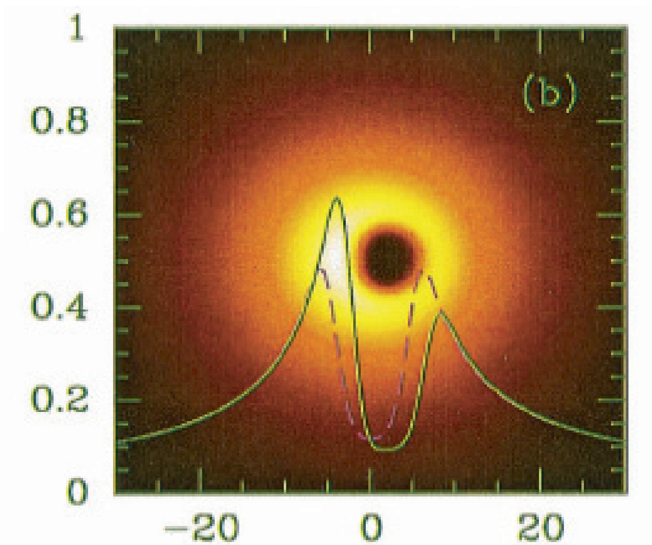
No experimental tests for
- high field curvature
- high mass

no dynamical test

Annother possible route for supermassive black holes: Submm VLBI



Fuzzy laboratory
Difficult to get to dynamics

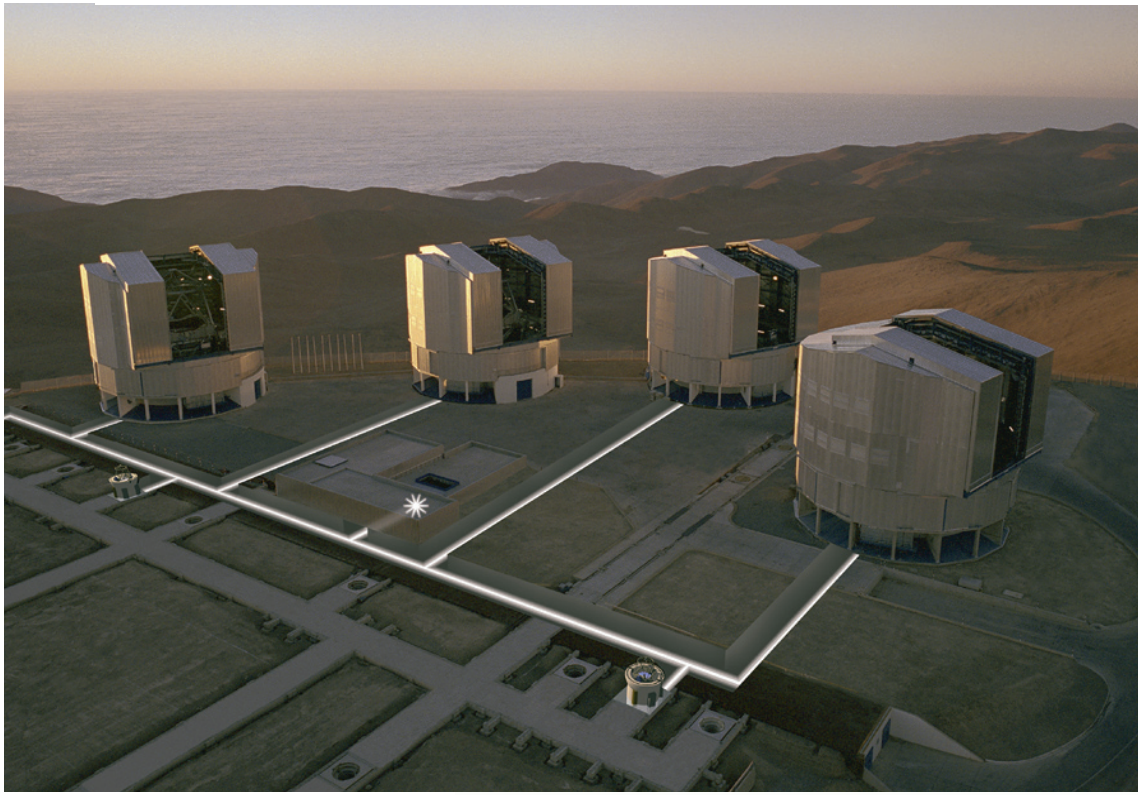


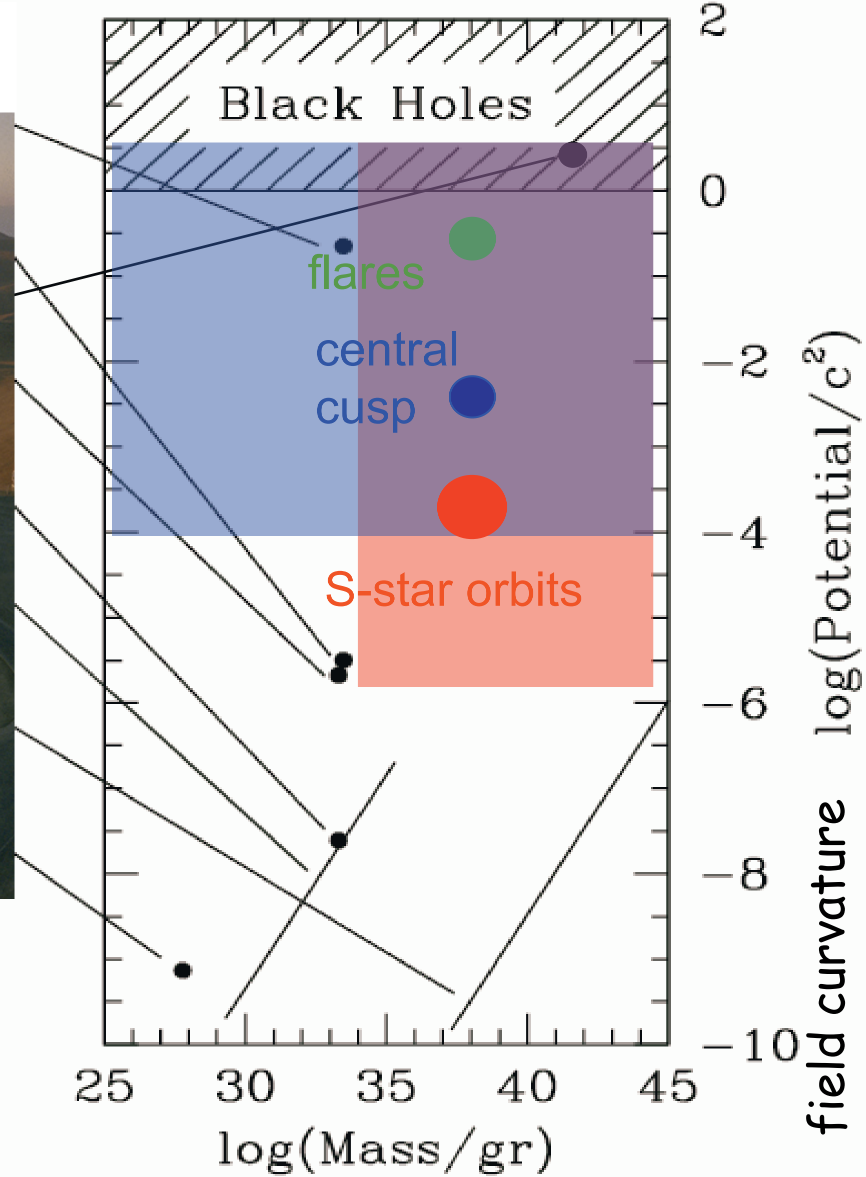
Falcke, Melia, & Agol 2000
Doeleman et al.

2008/06/12

Time-Resolved Astrometry at the VLTI: 10 μas in 5min

VLTI & GRAVITY

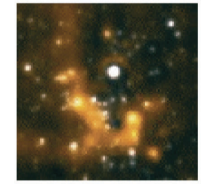




- 200 m² collecting area
- 130 m equivalent resolution

2008/06/12

The GRAVITY Consortium



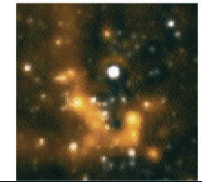
H. Bartko, H. Baumeister, A. Boehm, W. Brandner, F. Cassaing, Y. Clenet, K. Dodds-Eden, A. Eckart, F. Eisenhauer, E. Gendron, R. Genzel, S. Gillessen, A. Gräter, C. Gueriau, N. Hamaus, X. Haubois, M. Haug, T. Henning, S. Hippler, R. Hofmann, F. Hormuth, K. Houairi, S. Kellner, P. Kervella, R. Klein, J. Kolmeder, W. Laun, P. Lena, R. Lenzen, M. Marteaud, V. Naranjo, U. Neumann, T. Paumard, G. Perrin, O. Pfuhl, S. Rabien, J.R. Ramos, J.M. Rees, D. Rouan, R.-R. Rohloff, G. Rousset, B. Ruyet, A. Sévin, C. Straubmeier, M. Thiel, J. Ziegleder, D. Ziegler

= 47 physicists, engineers, technicians

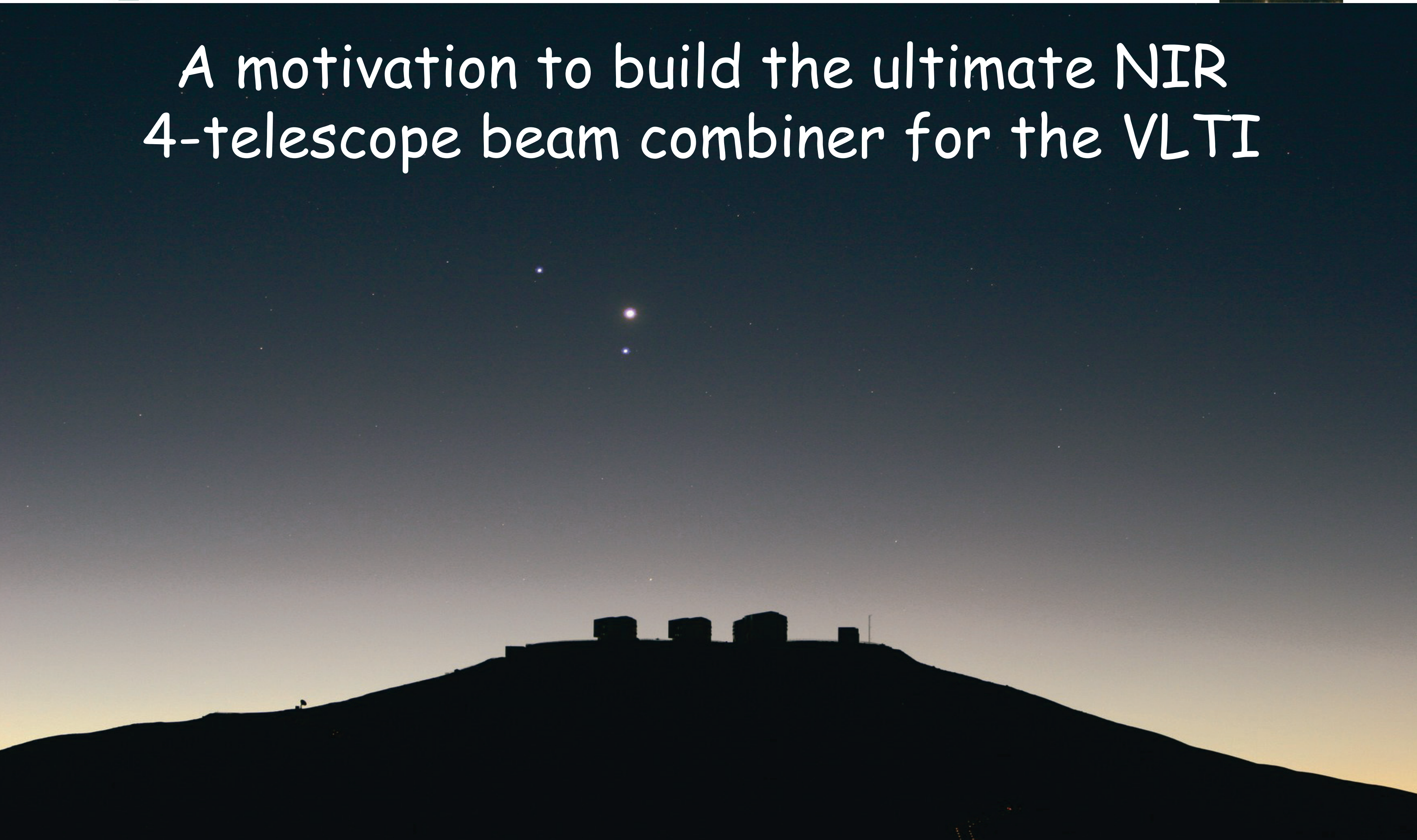
MPE Munich, Observatoire de Paris Meudon, MPIA Heidelberg, Uni Köln

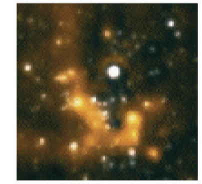
Partenariat Haute résolution Angulaire Sol-Espace

GRAVITY - Science Cases



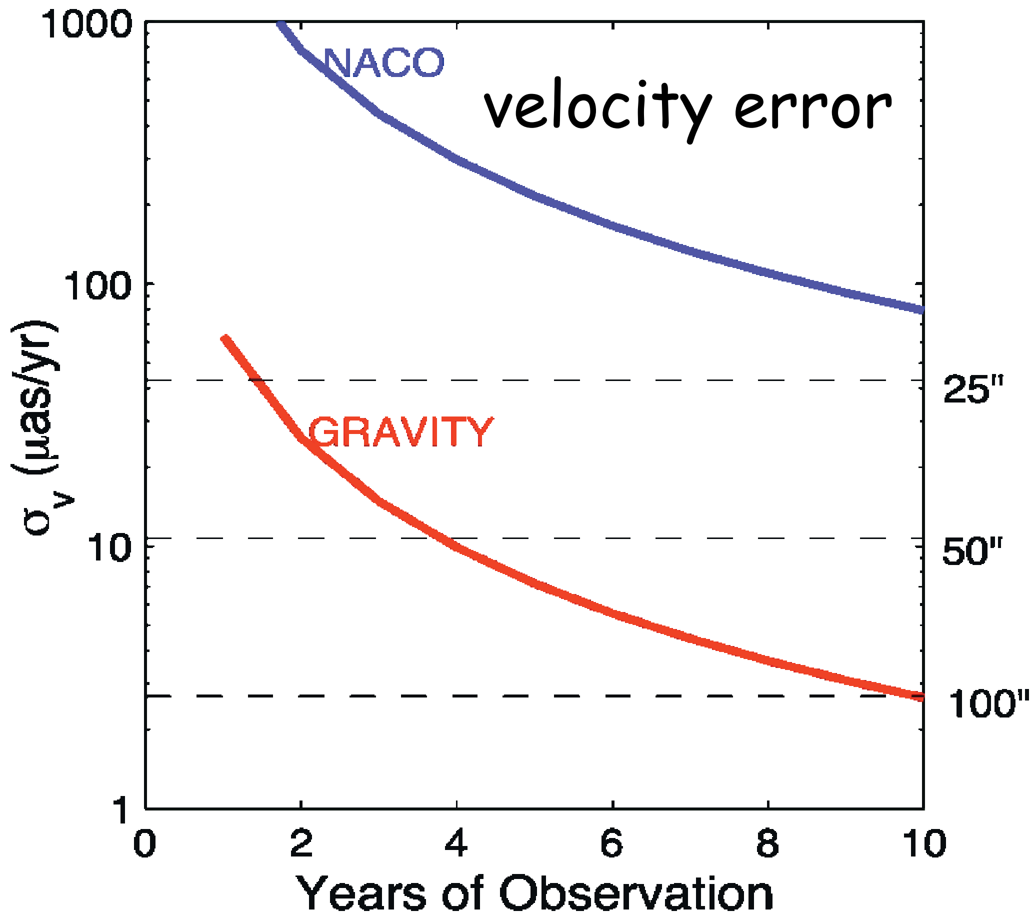
A motivation to build the ultimate NIR 4-telescope beam combiner for the VLTI

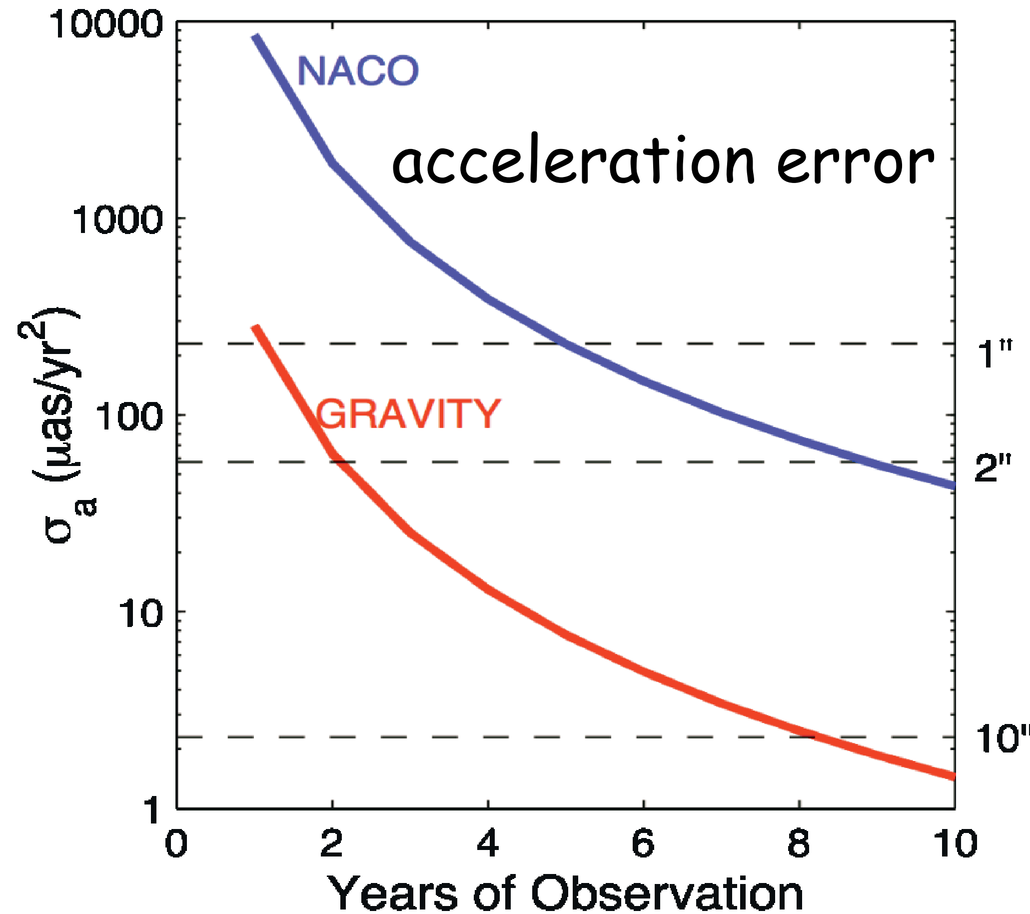




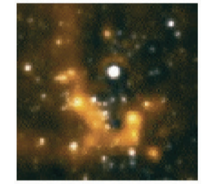
The VLTI can do 10 µas Astrometry

10 µas: better than NACO by a Factor 15

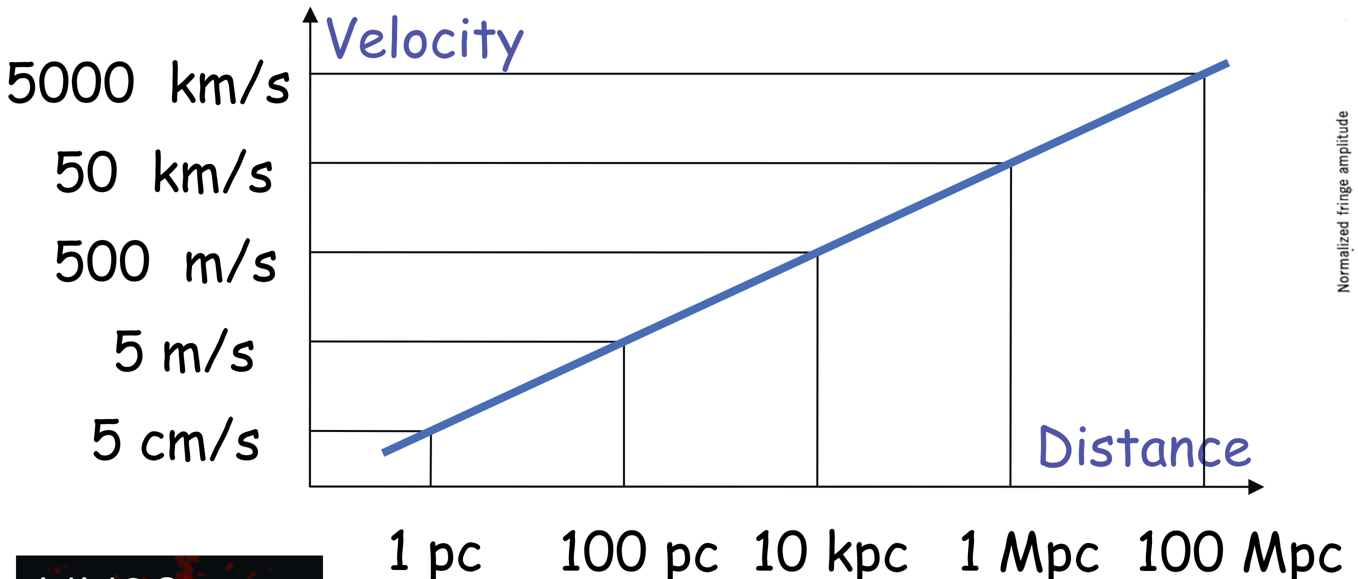


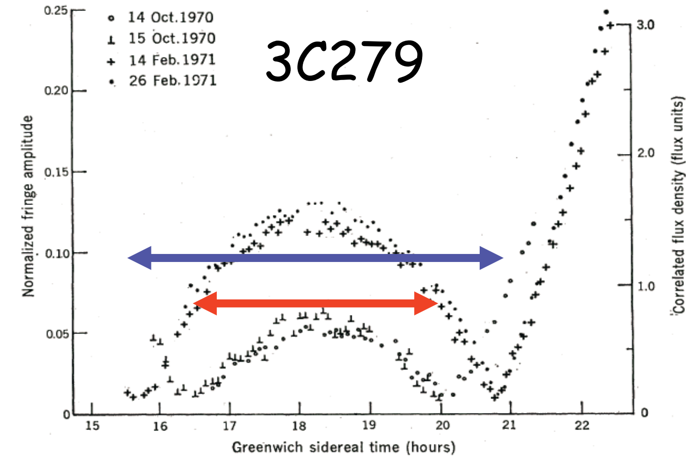


Watch Objects Move in the Local Universe



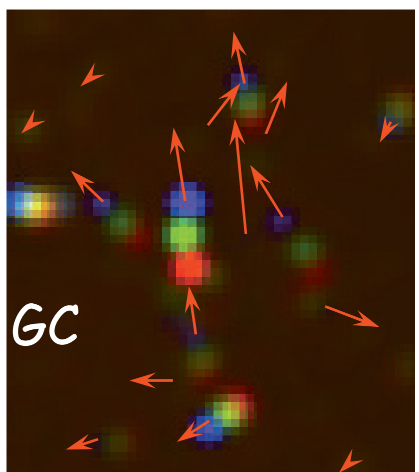
10 μas/yr corresponds to ~ 50 m/s @ 1kpc



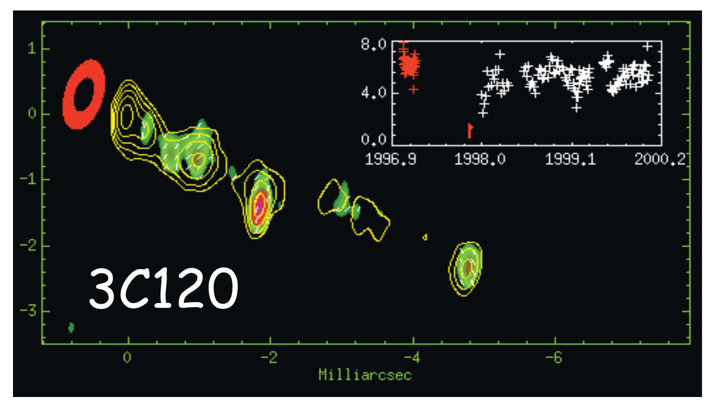


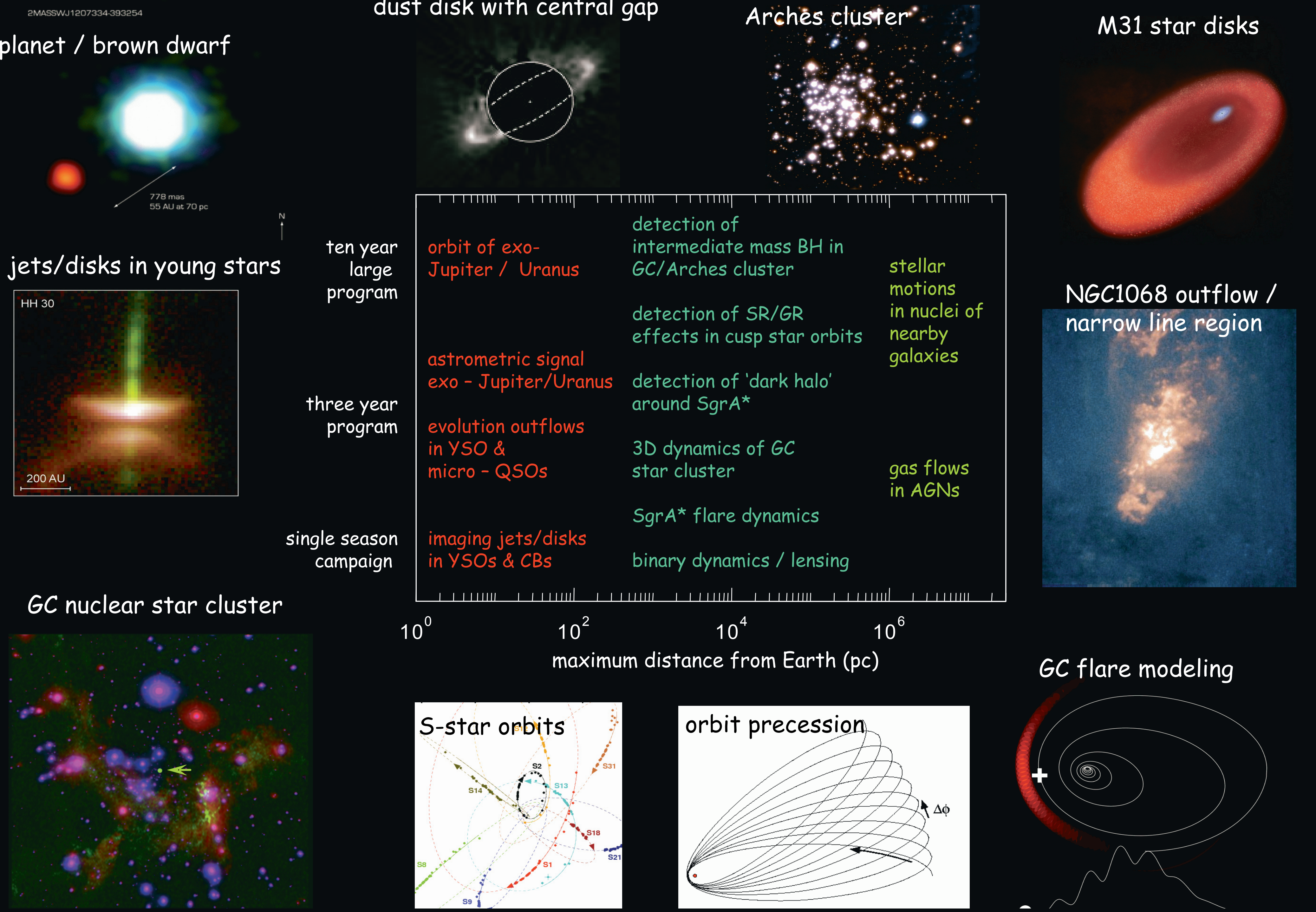
Whitney et al. 1971

Krist et al.

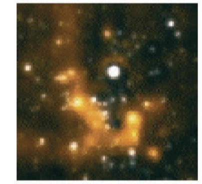


Gomez et al. 2000



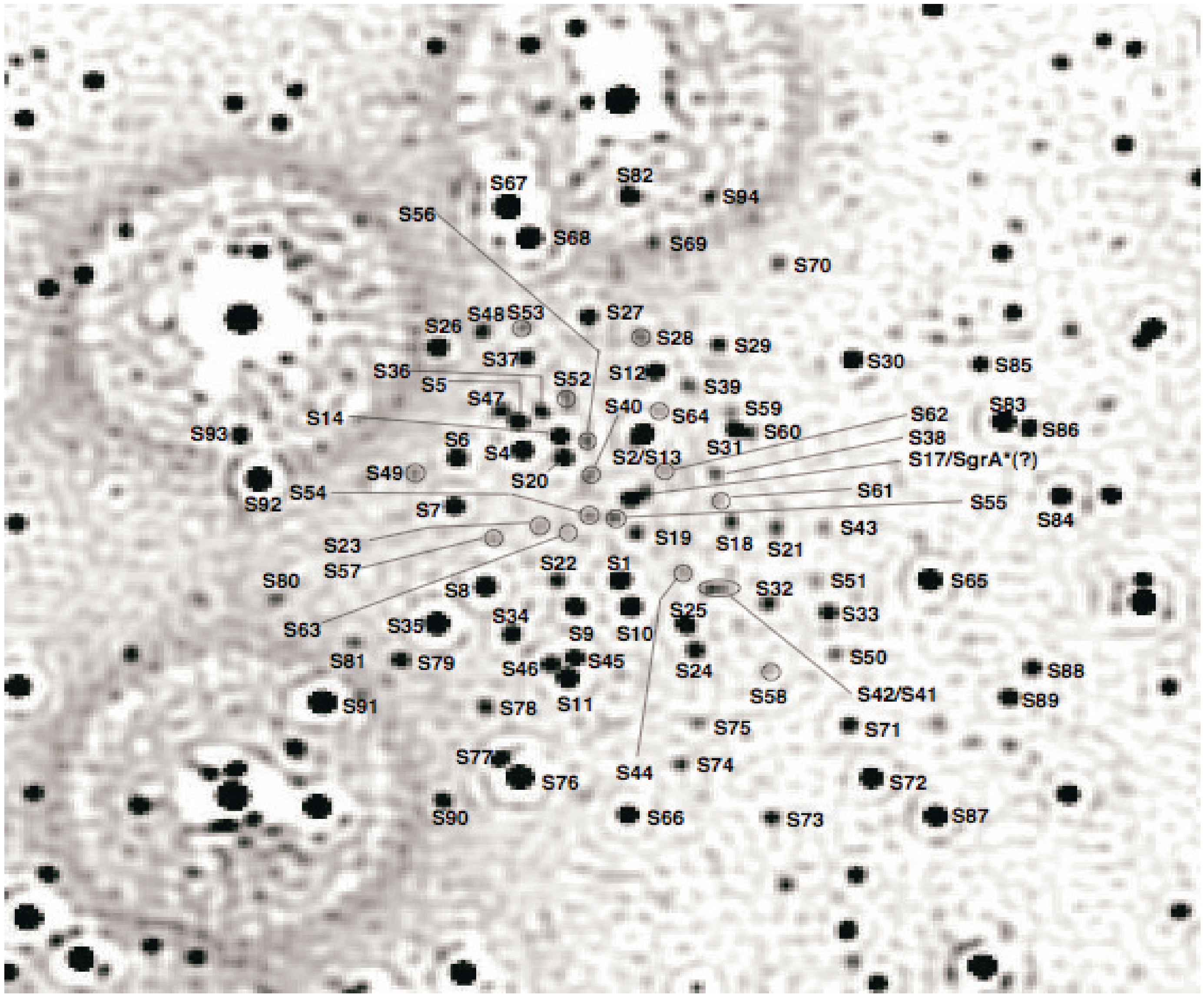

2MASSWJ1207334-393254
planet / brown dwarf
778 mas
55 AU at 70 pc
N
dust disk with central gap
Arches cluster
M31 star disks
jets/disks in young stars
HH 30
200 AU
ten year large program
three year program
single season campaign
orbit of exo-Jupiter / Uranus
astrometric signal exo - Jupiter/Uranus
evolution outflows in YSO & micro - QSOs
imaging jets/disks in YSOs & CBs
detection of intermediate mass BH in GC/Arches cluster
detection of SR/GR effects in cusp star orbits
detection of 'dark halo' around SgrA*
3D dynamics of GC star cluster
SgrA* flare dynamics
binary dynamics / lensing
stellar motions in nuclei of nearby galaxies
gas flows in AGNs
10^0
10^2
10^4
10^6
maximum distance from Earth (pc)
NGC1068 outflow / narrow line region
GC nuclear star cluster
S-star orbits
S2
S13
S14
S31
S18
S21
S1
S8
S9
orbit precession
Δϕ
GC flare modeling

Key Science Case 1 - Relativistic Orbits in the GC

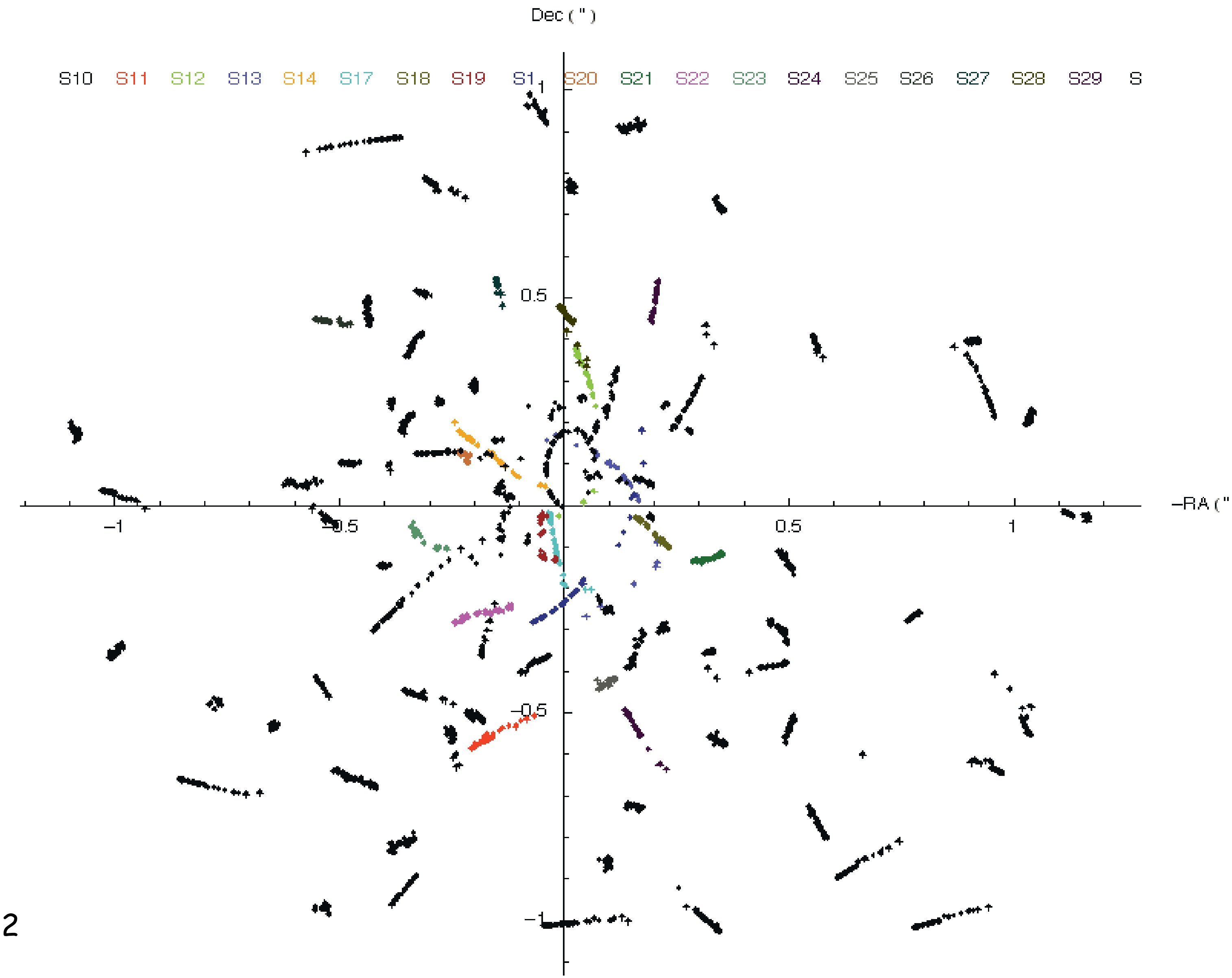


Extremely dense central cusp

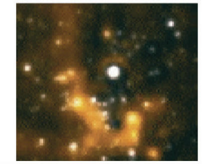
(confusion!)



NACO: Orbits out to 1"

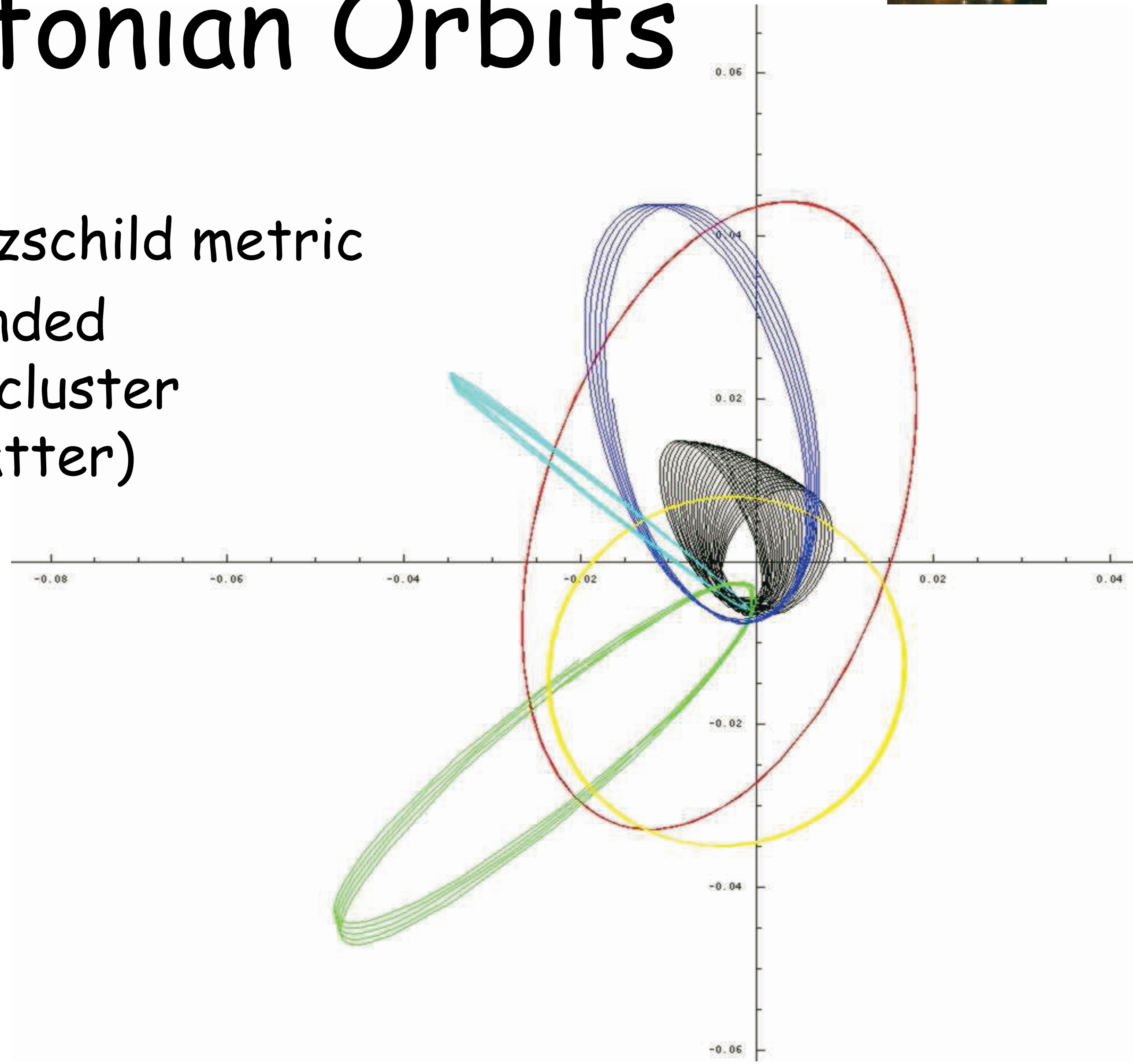


Black Hole: Post-Newtonian Orbits

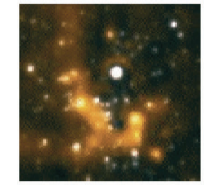


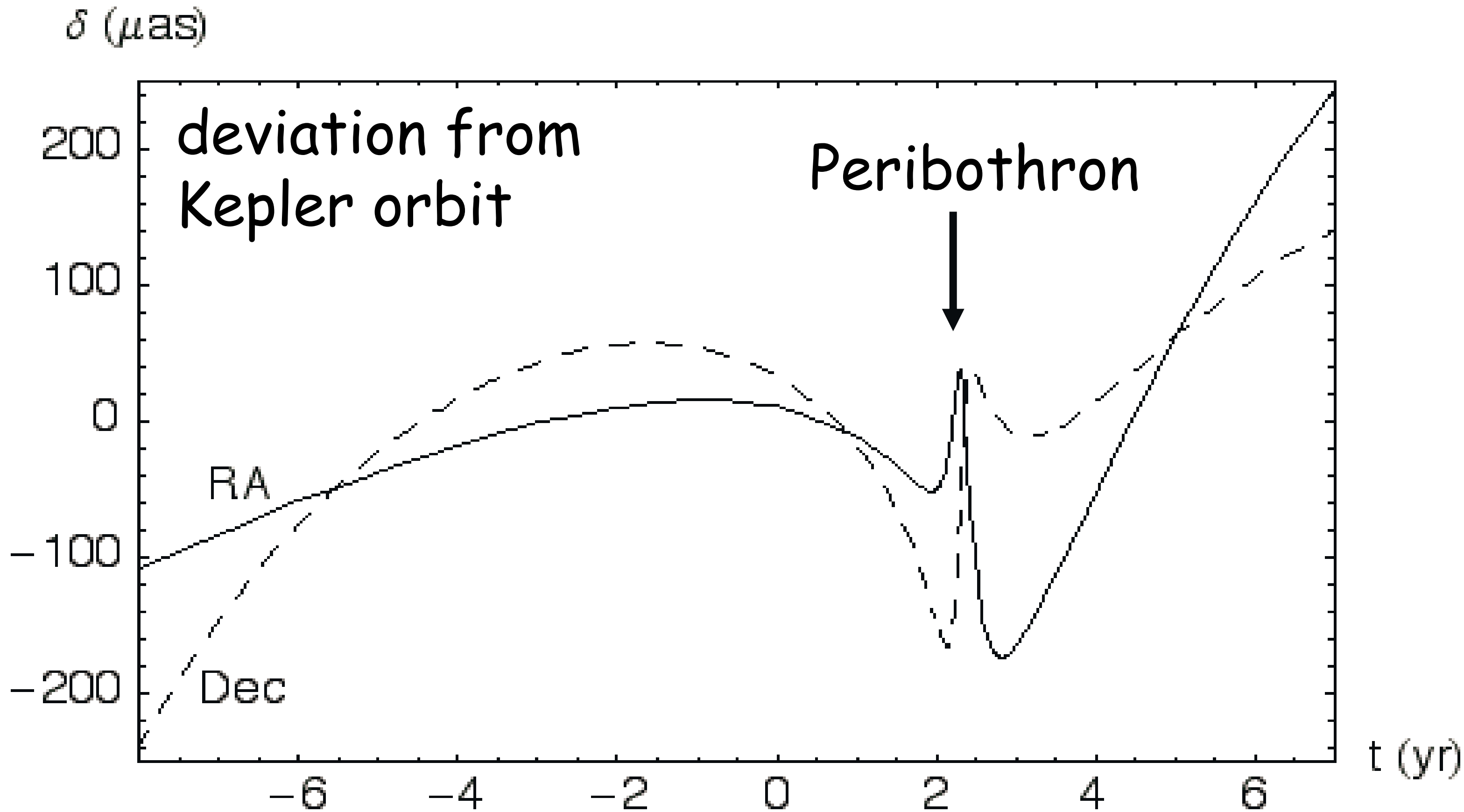
Periastron precession

- Prograde from Schwarzschild metric
- Retrograde from extended mass distribution (e.g. cluster of black holes, dark matter)

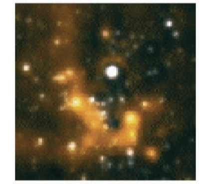


Relativistic Effects in S2: well Measurable at 10μas Accuracy





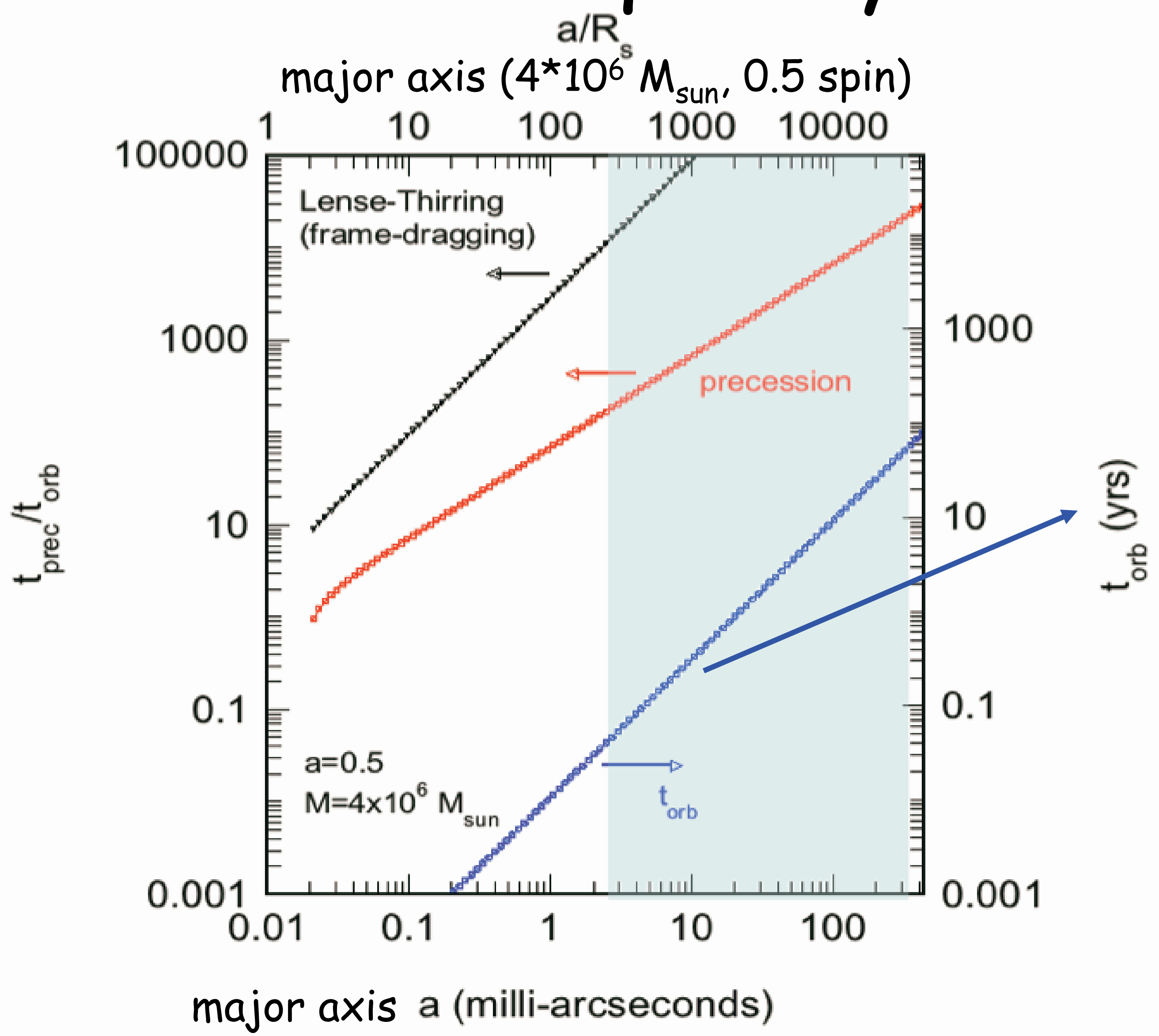
Further in: Relativistic Effects Visible more quickly



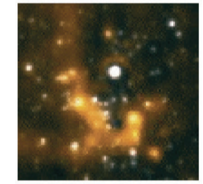
ratio of Schwarzschild precession time scale (red) and Lense-Thirring time scale (black) relative to the orbital time scale (blue)

inverse ratio: precession during a single revolution.

white shaded region: parameter space probed by GRAVITY stellar orbits in the GC.



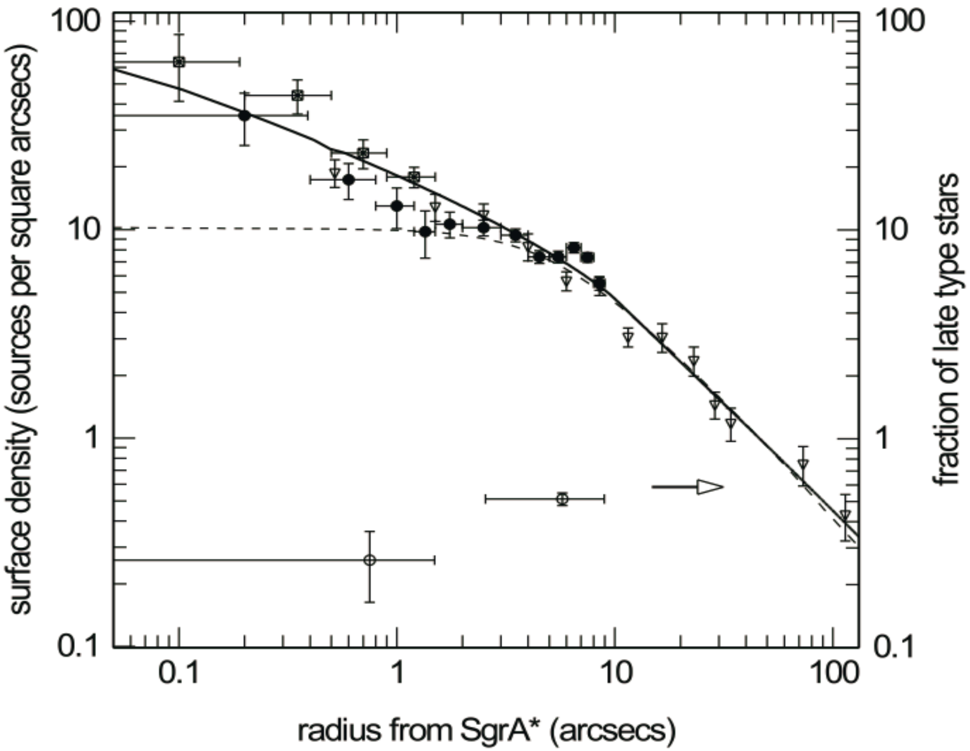
Stars in the Central 0.1"



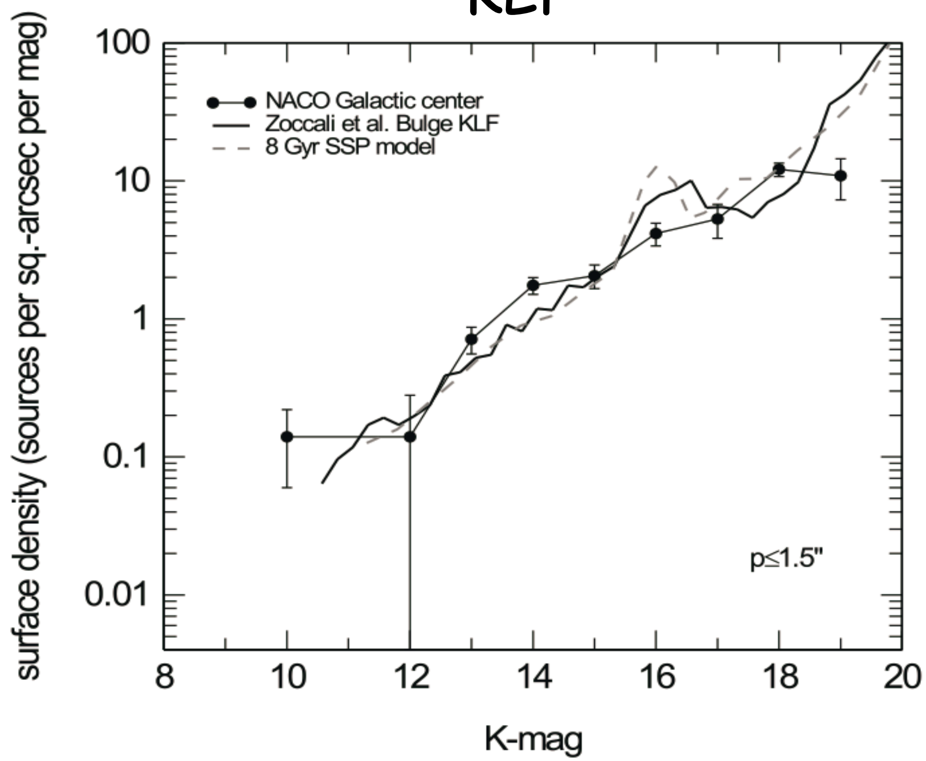
central star cluster is well characterized:

In central 100 mas should reside 2 - 10 observable stars with mK = 17…19 at any time, not yet observed due to confusion

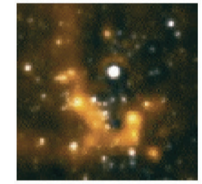
Density profile



KLF

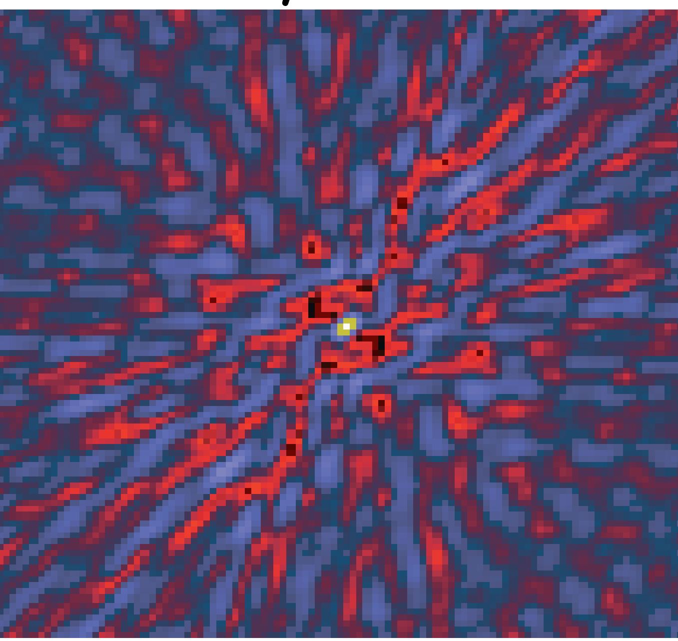


Simulation of VLTI Observations

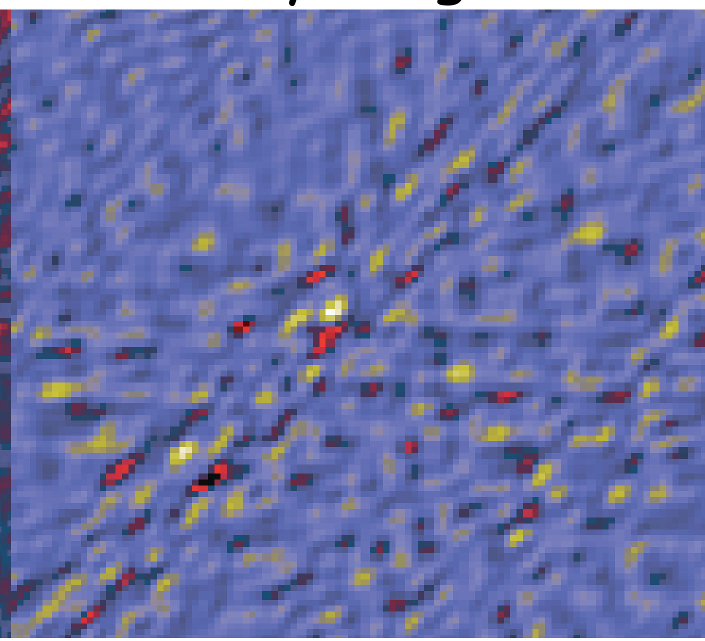


simulated 6 point sources in central 0.1", mK = 17 … 19, observation time = 1 night

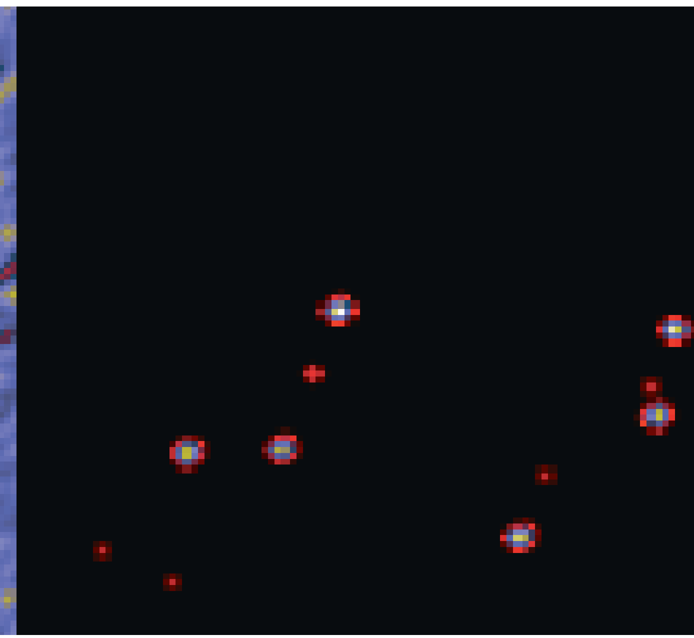
"dirty beam"



"dirty image"



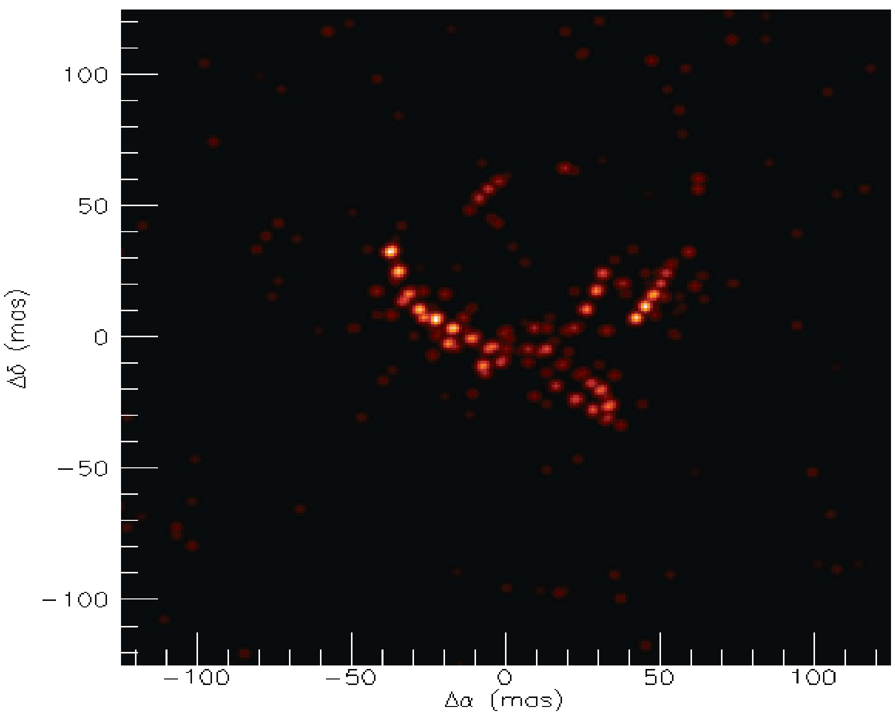
"deconvolved image" (CLEAN)



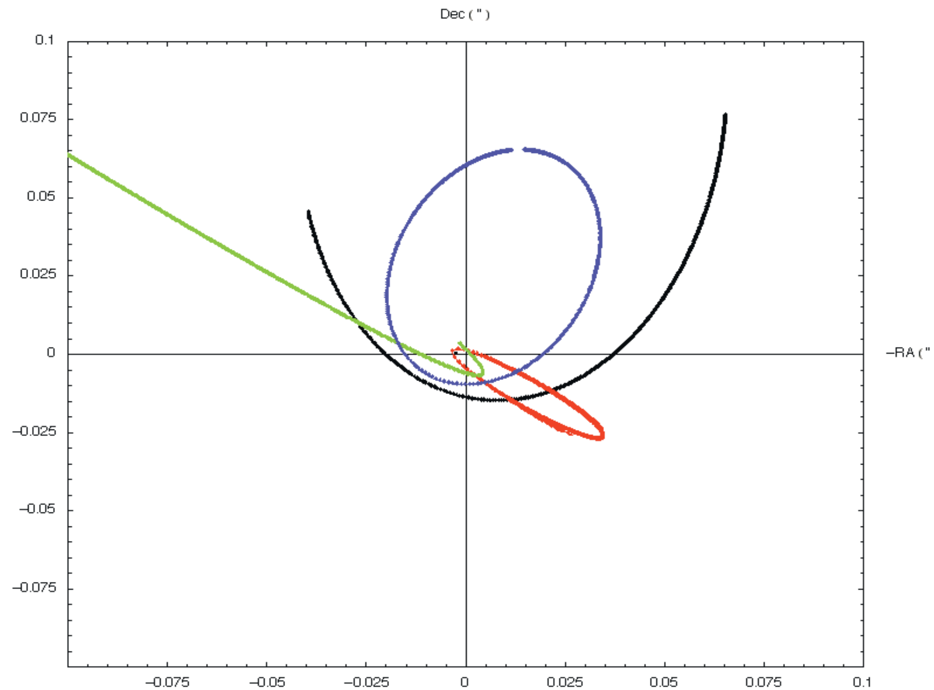
Orbit Reconstruction

sampling a few times per year: confusion can be beaten
individual stellar orbits reconstructed

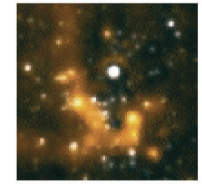
coadded observations



reconstructed orbits

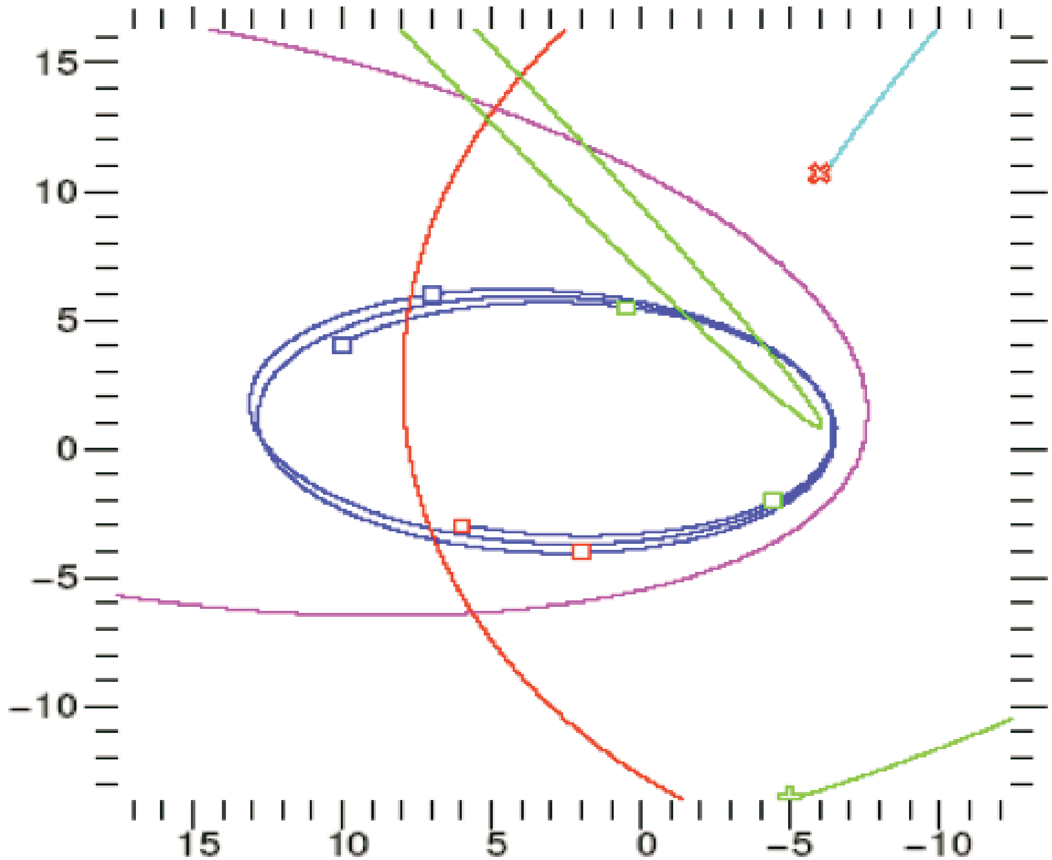


Relativistic Precession

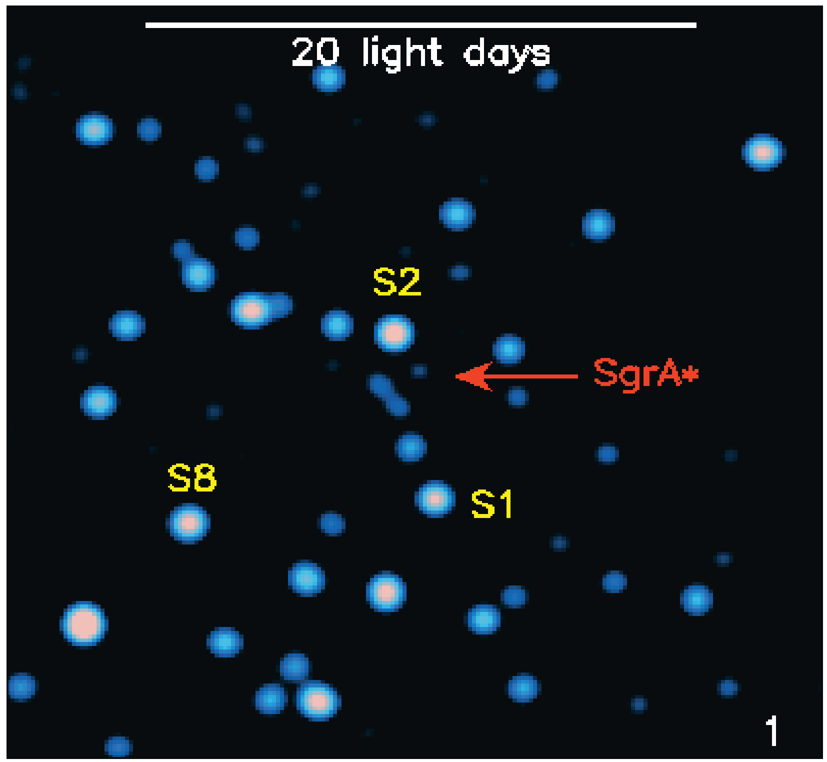


becomes visible after few revolutions

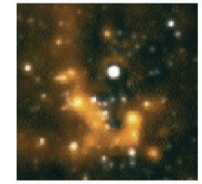
Simulation:
2 years * 3 nights * 9 hours * 4 UTs

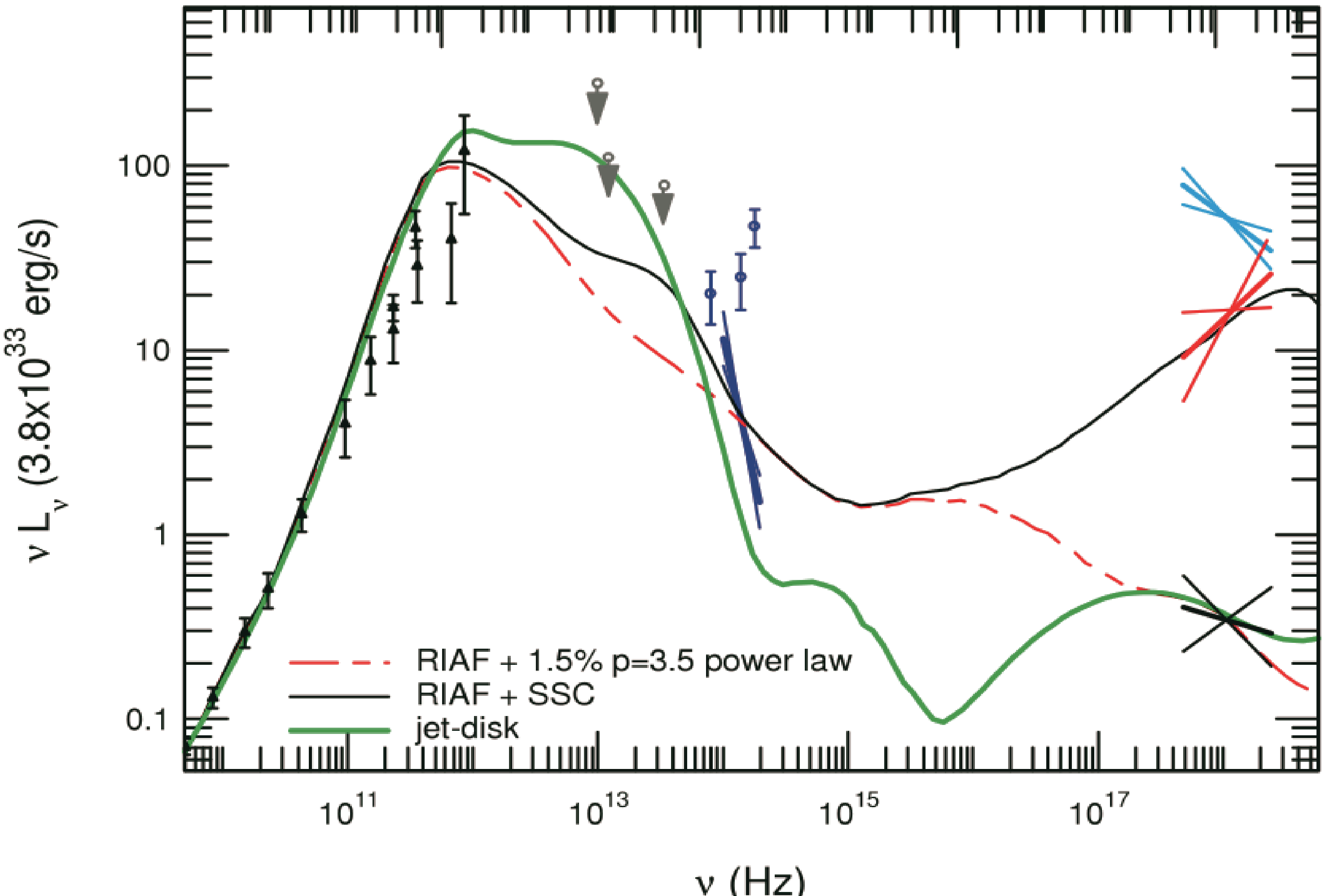


Key Science Case 2 - NIR-Flares of Sgr A*



Sgr A*: Quiet in NIR





NIR-Flares

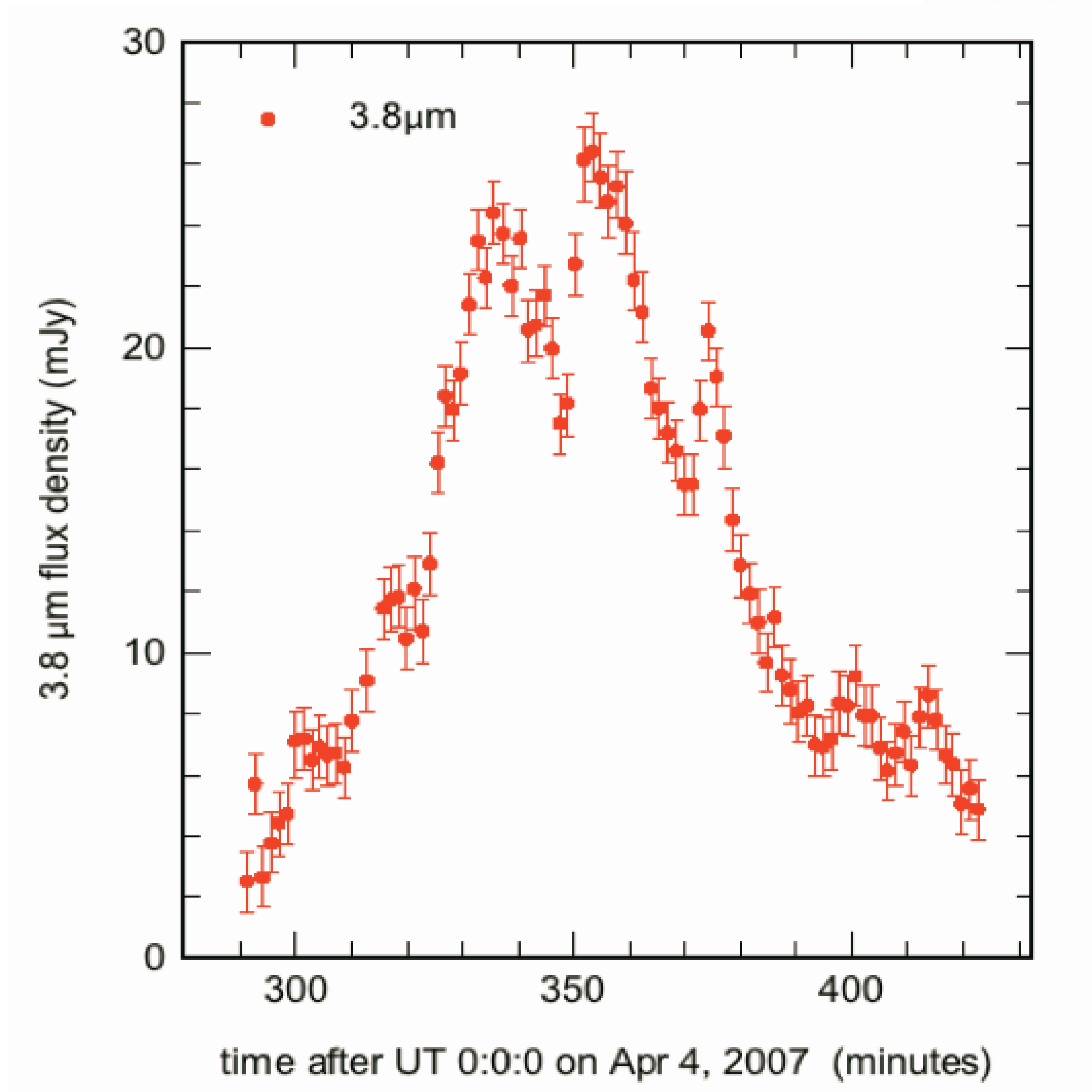
Typically once per night Sgr A* shines up in the NIR for ~1 hour

~20 min substructures

IR flare emission strongly polarized

simultaneous X-ray flares:

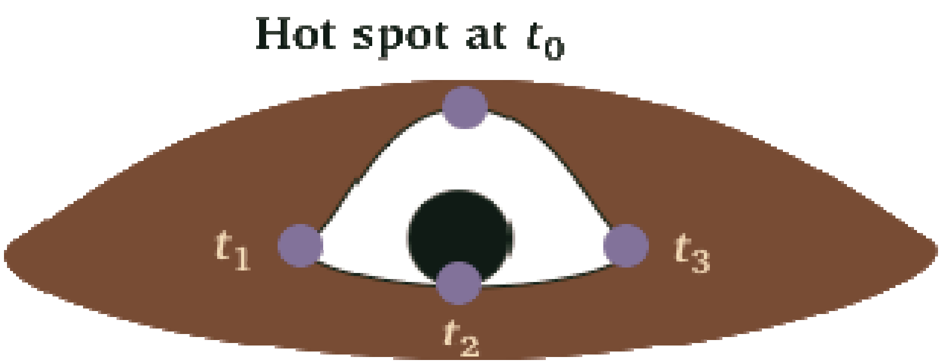
IR: synchrotron
X-ray: IC/SSC emission



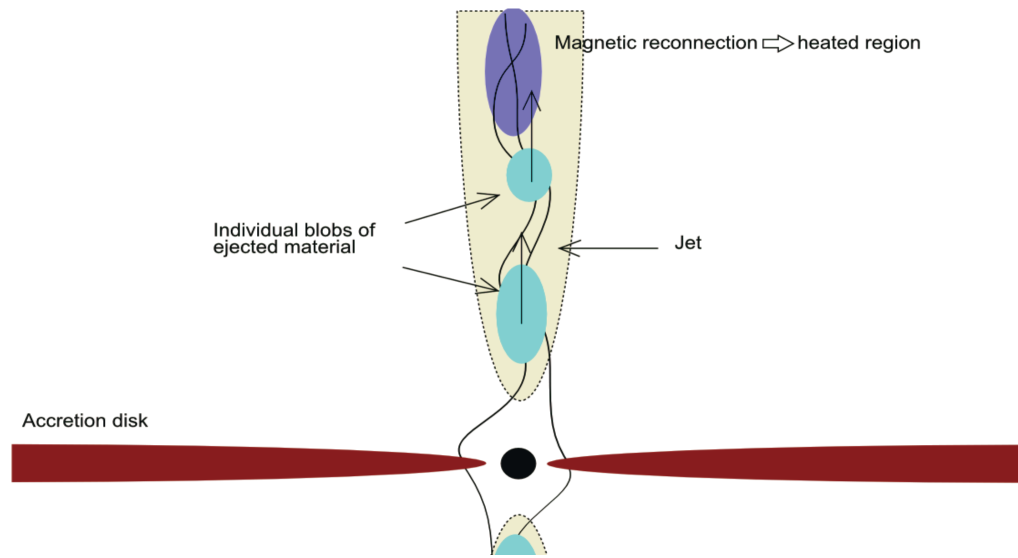
Origin of Flares

hot spots, e.g. due to magnetic reconnection in:

accretion disks

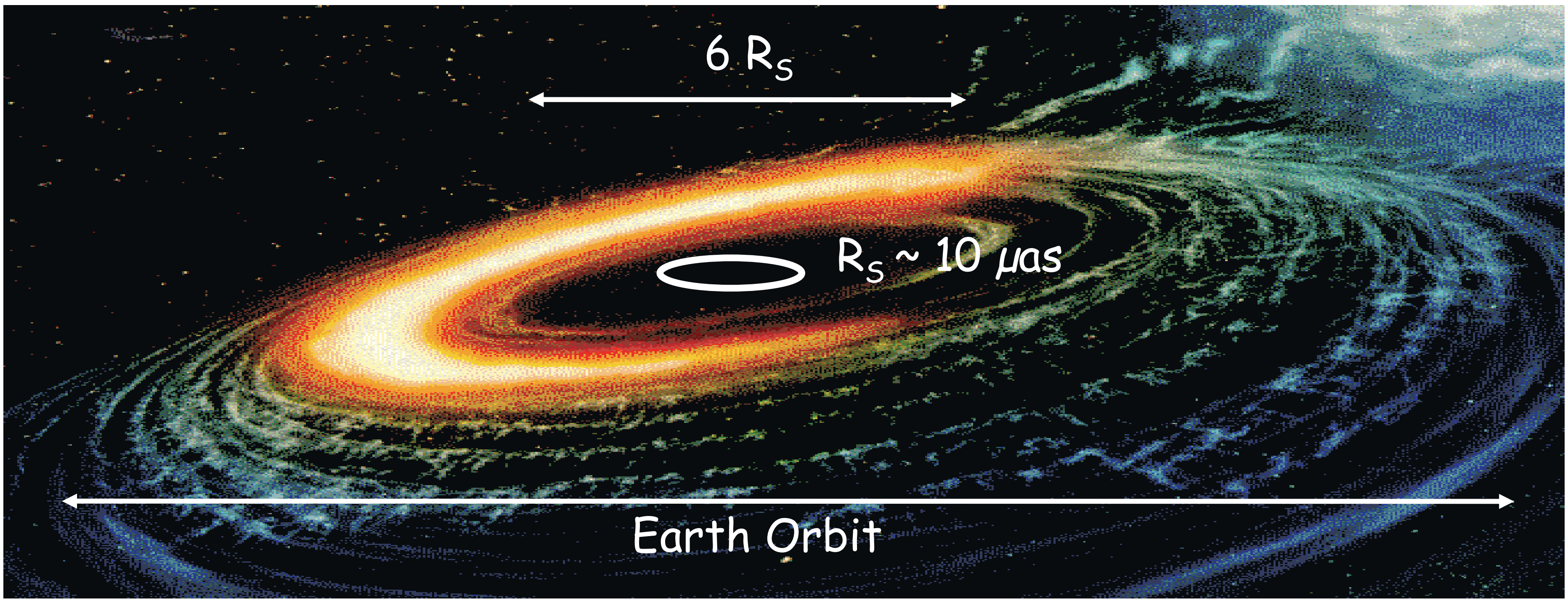


jets



20 min Quasi-Periodicity: Small Emission Region

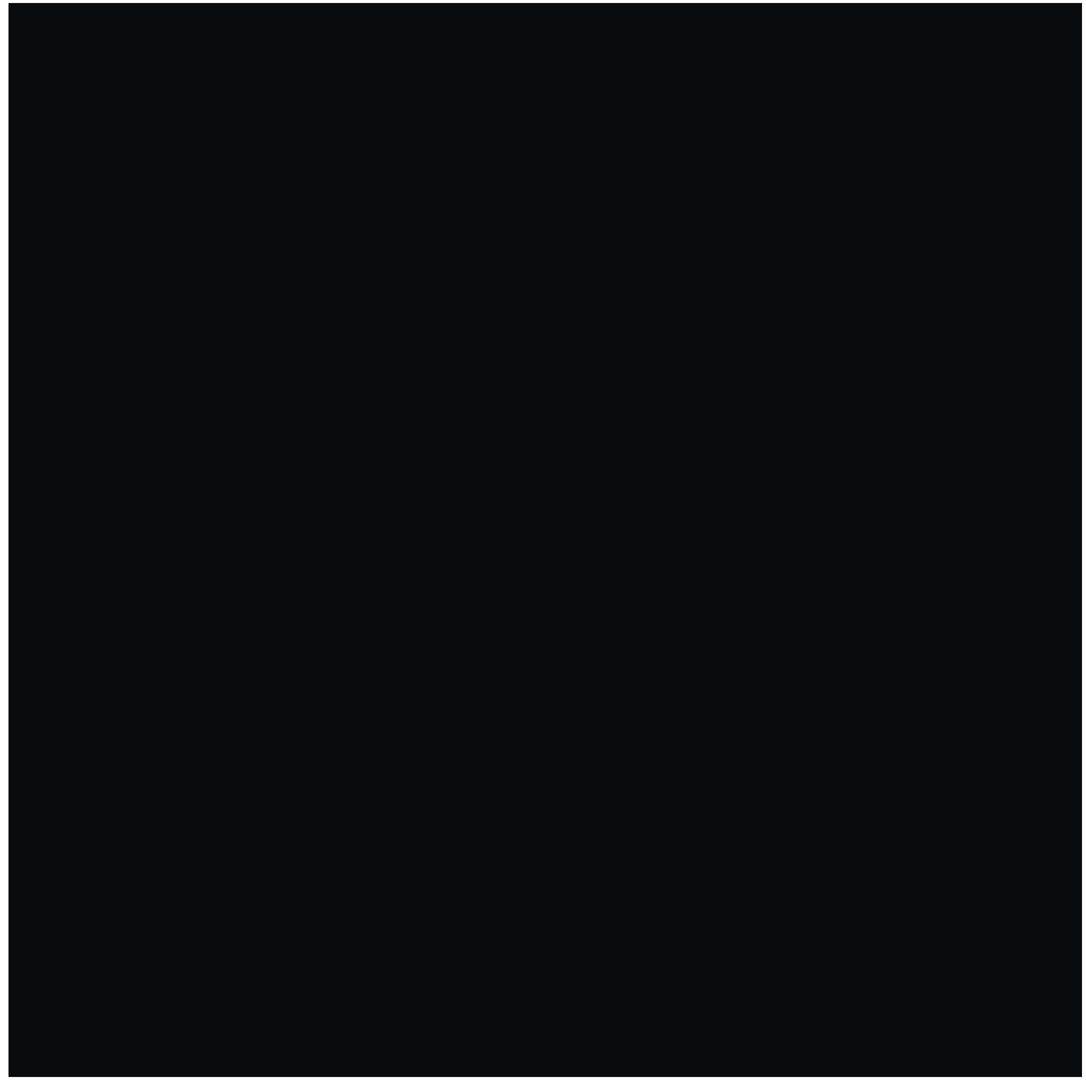
emission originates from very close to the event horizon
velocities of 10% - 90% of the speed of light (15 μas/min)
traveled path during one hour: several hundred μas



GR Simulation of Flares

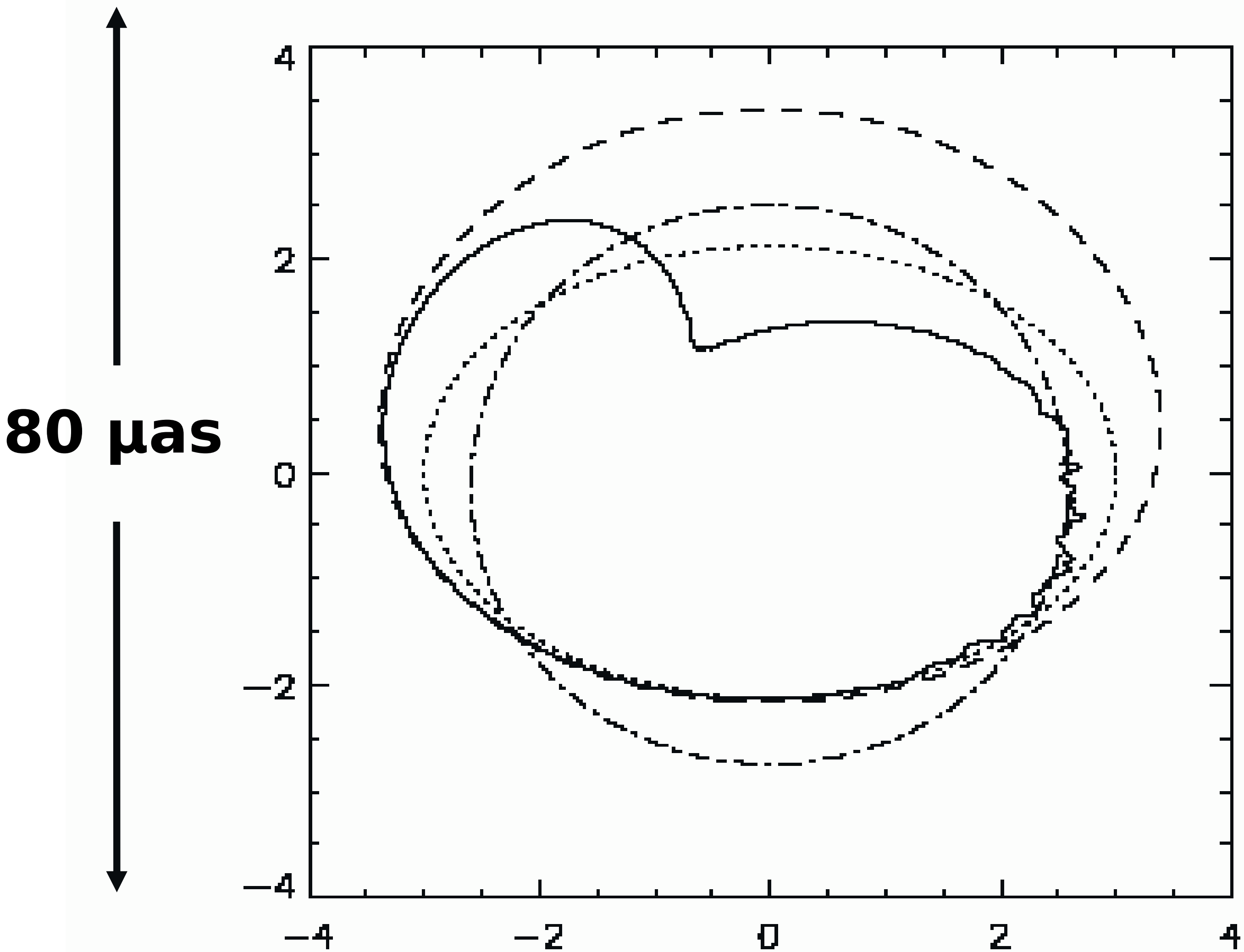
full GR simulation:

black hole spin 0.7,
inclination = 20deg
hot spot + shear



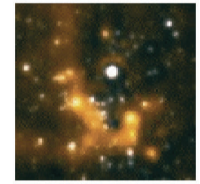
Simulated Centroid Track

hot spots: unresolved – but centroid motion can be measured



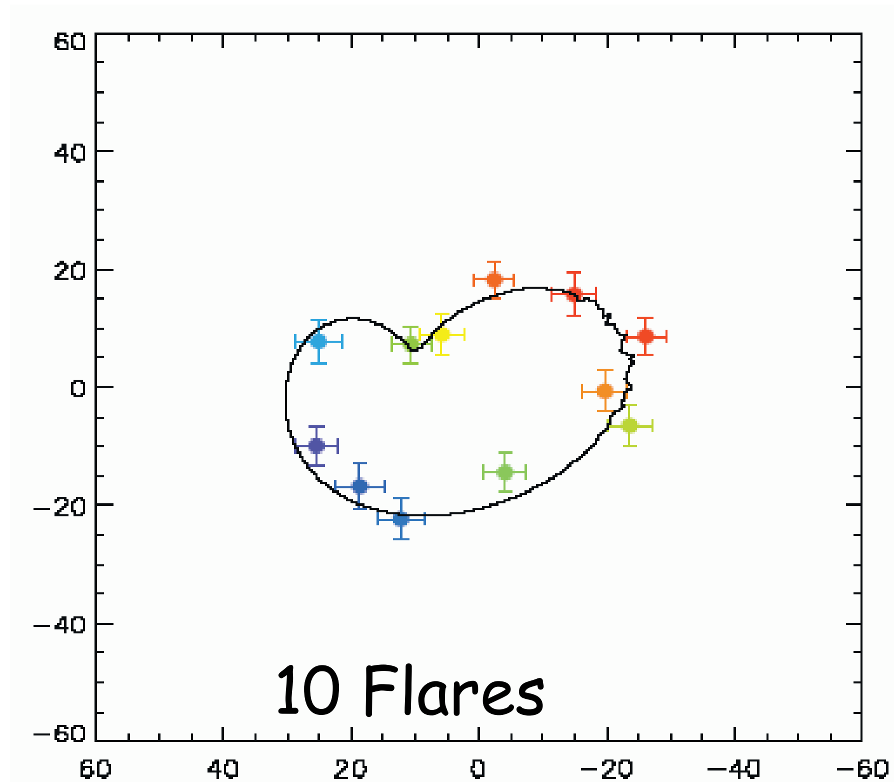
- Multiple images (lensing)
- Beaming
- Doppler effect
- Kerr metric

Feasible with VLTI



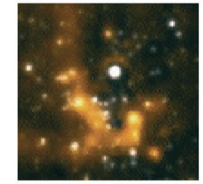
- simulation of measurements (optimistic performance):
  10 μas accuracy in 2 min
  12 positions per flare
- proves or disproves the orbital nature

1 Flare



10 Flares

Determination of Model Parameters



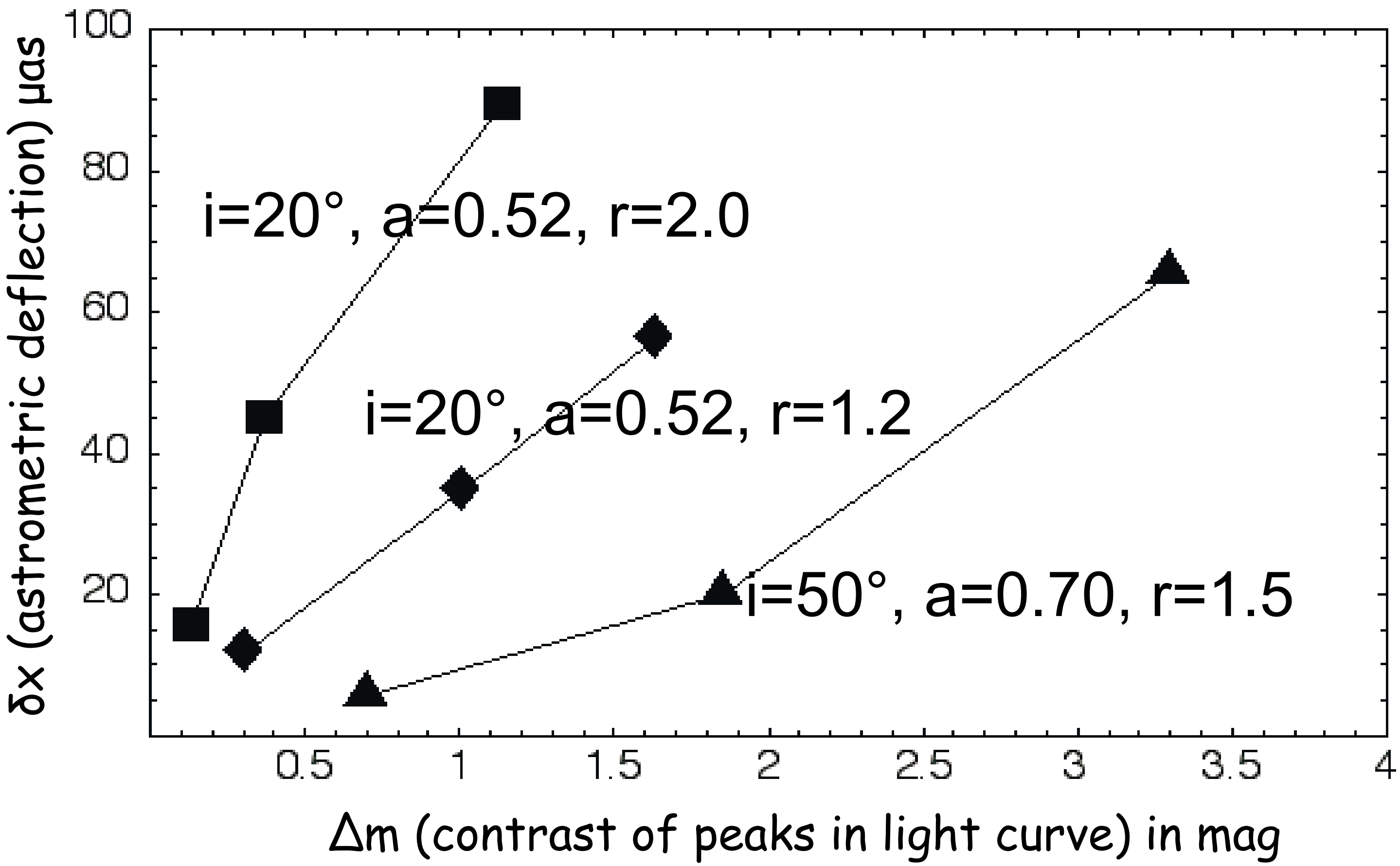
Measuring lightcurves + astrometry allows to disentangle inclination, spin & radius

Δm: magnitude difference between peak + following minimum.

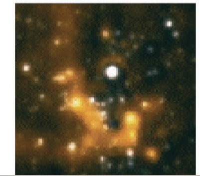
δx respective astrometric deflection of observable centroid

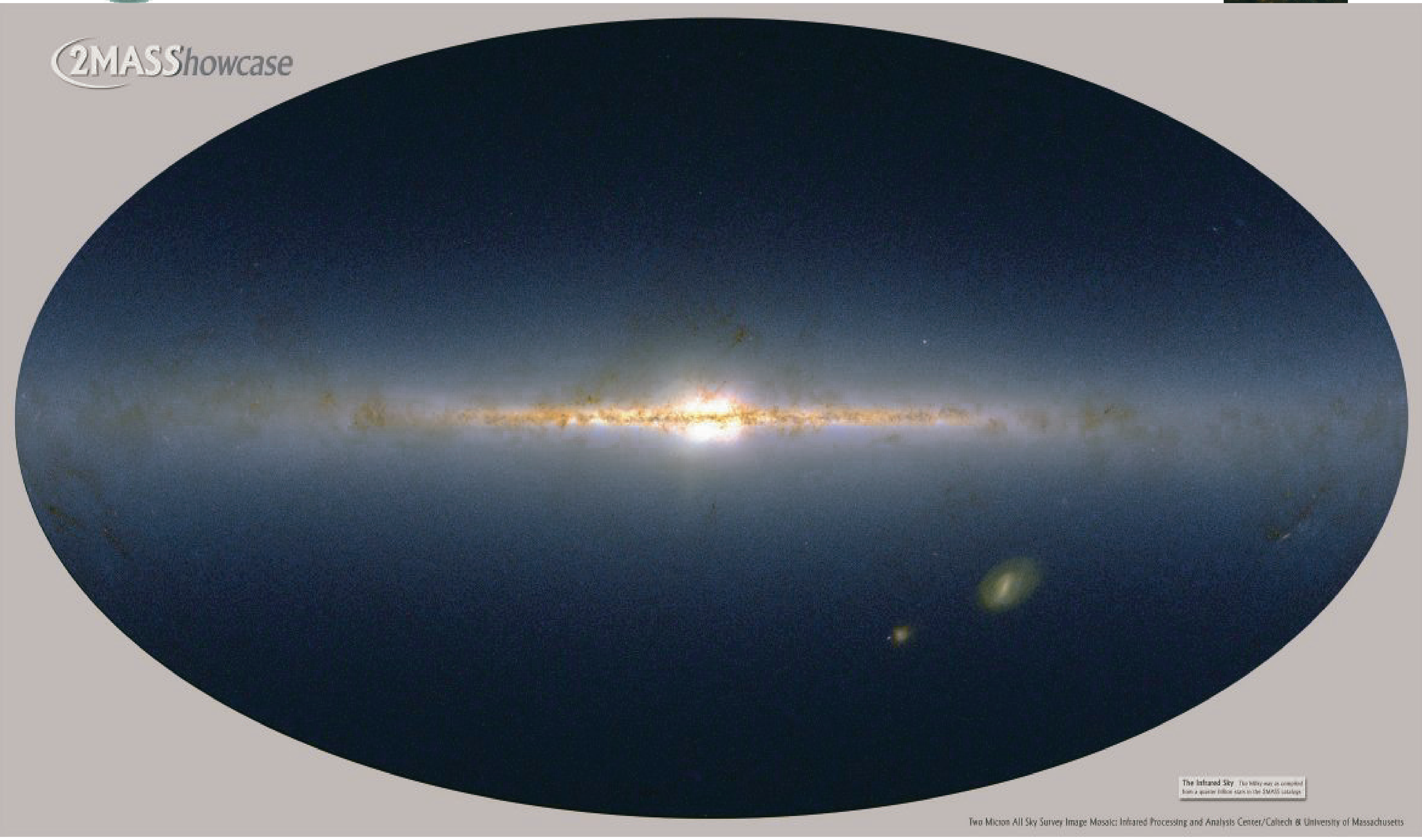
Each model starts with high deflection and high contrast, and both values decrease during the flare.

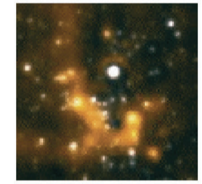
models sufficiently different, can be discriminated



Key Science beyond the GC

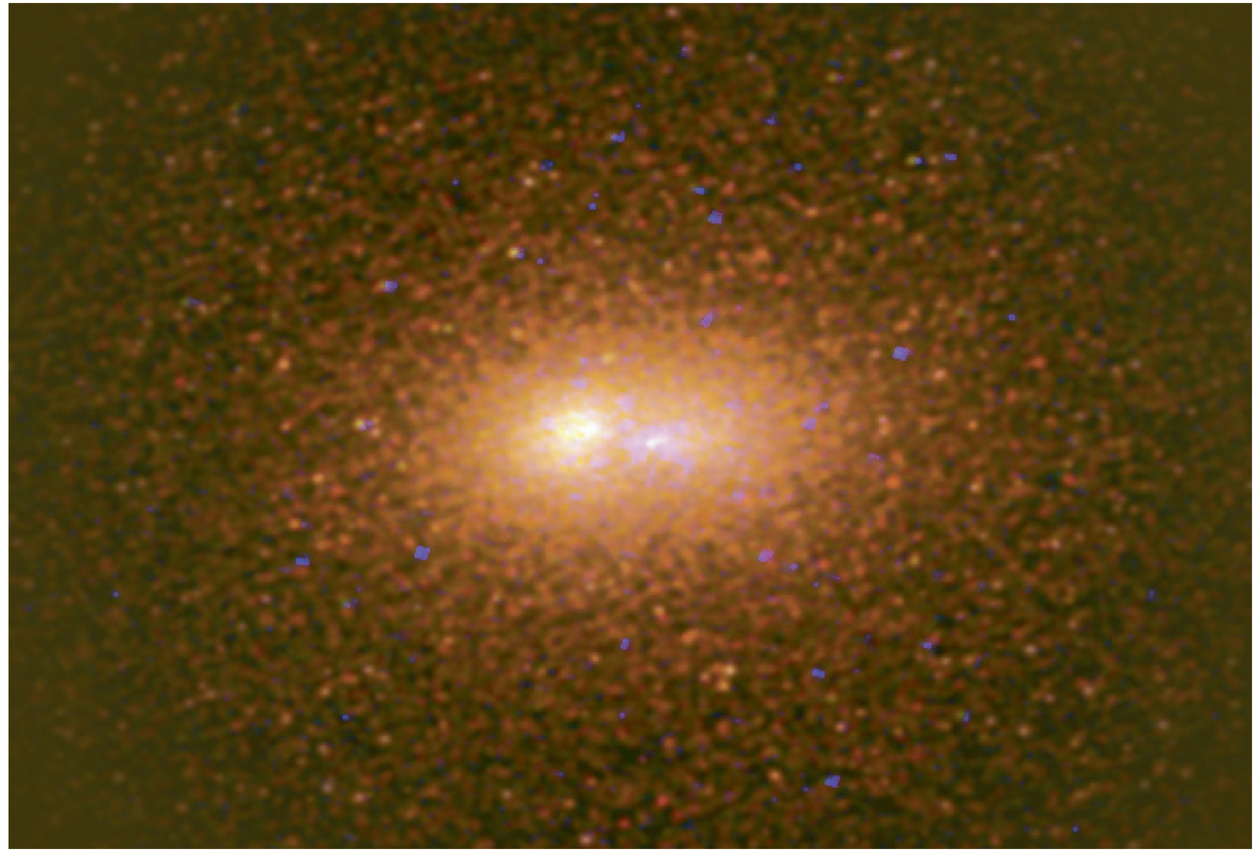






Repeat GC Experiment with other SMBH

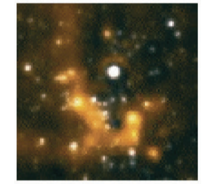
- M31 (northern sky)
  - 1.4 x 10^8 M_{sun} SMBH
  - disk of young stars
  - 10 in reach of VLTI



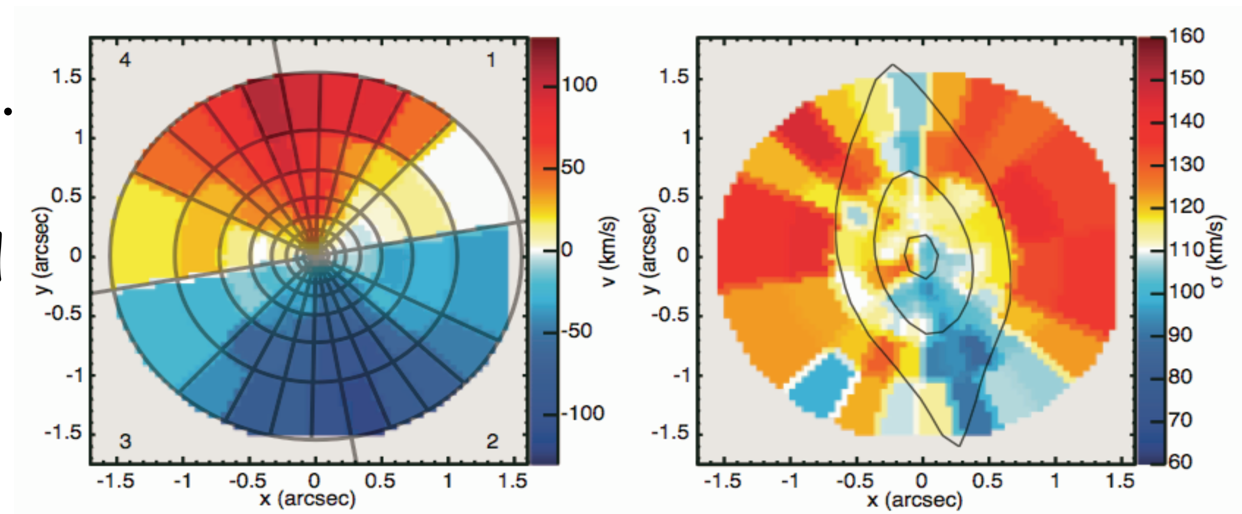
- Few years of VLTI
  - 10^7 M_{sun} @ 10 Mpc
  - 10^8 M_{sun} @ 30 Mpc

- use interferometric gain to probe higher mass further out

Black Hole Masses from Stellar Dynamics

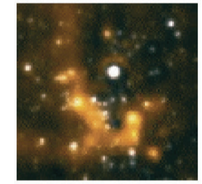


- Spatially resolved spectroscopy with GRAVITY: Similar to work with SINFONI: spatially resolved rotation patterns
- 10^7 M_{sun} black hole: sphere of influence of 4 pc.
- with 4 mas resolution: resolved out to 200 Mpc.
- Less biased by extended mass components due to higher resolution

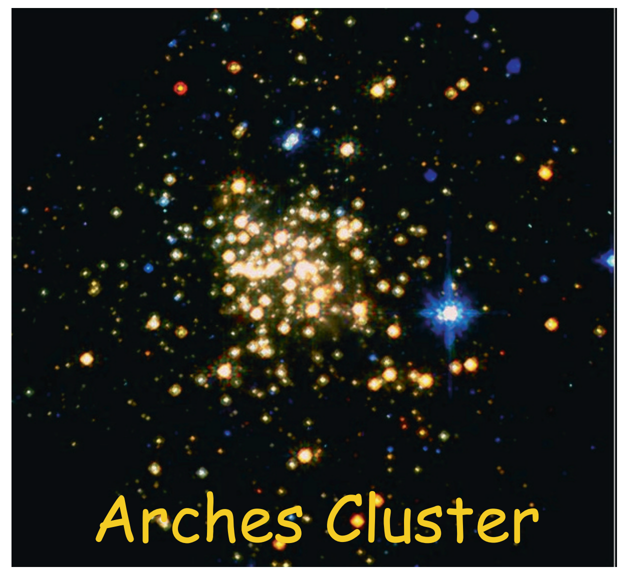


NGC 4486 Nowak et al.

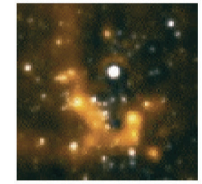
Intermediate Mass Black Holes



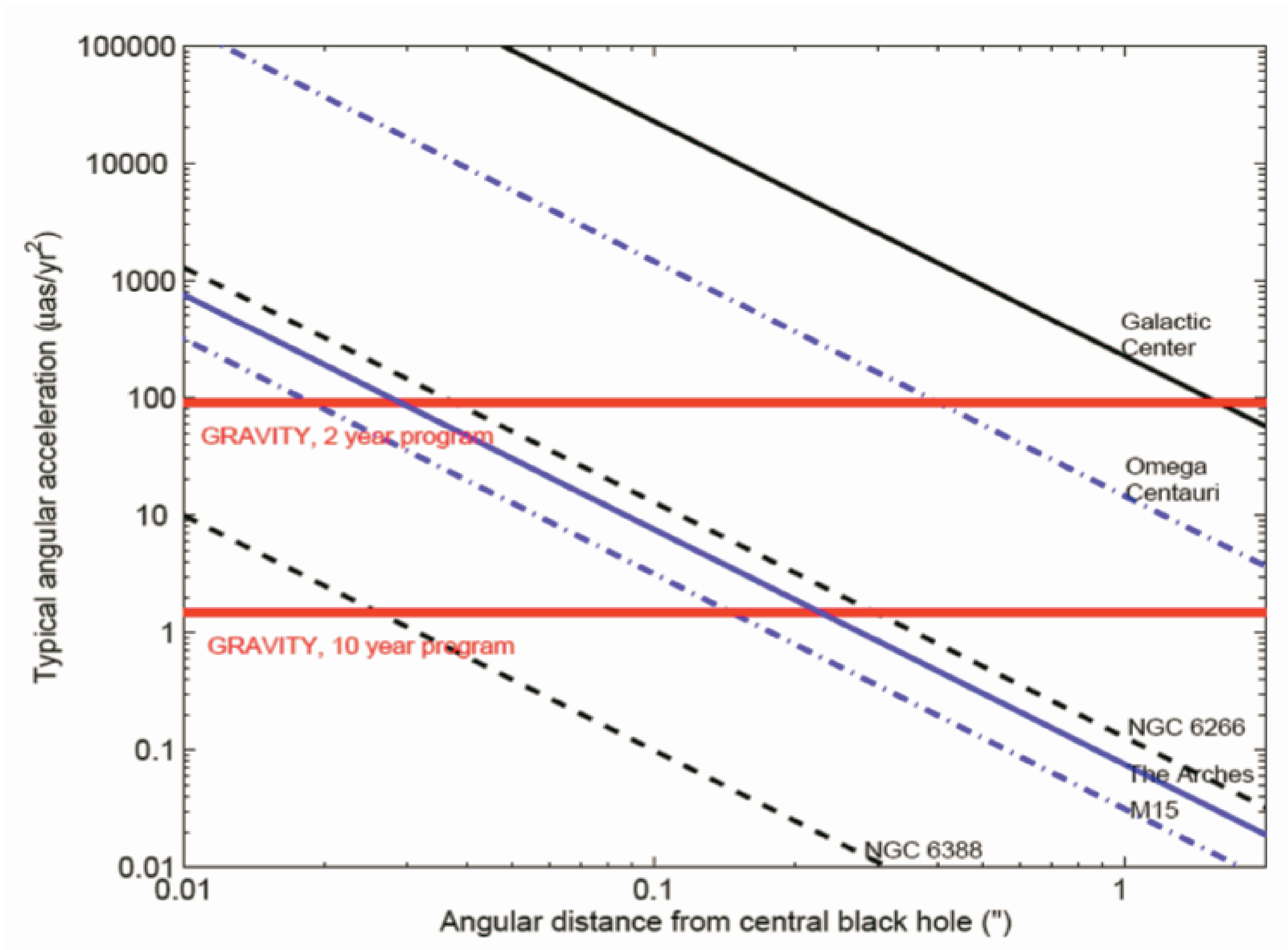
- Seeds for SMBHs ?
- formed through core collapse of Pop III stars at z = 10?
- Compelling cases: Globular Clusters, IRS 13 (close to GC)
- Use interferometric gain to see lower masses in Galaxy from unambiguous stellar orbits rather than velocity dispersion within sphere of influence



Observation Time

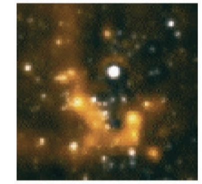


need several years of observations

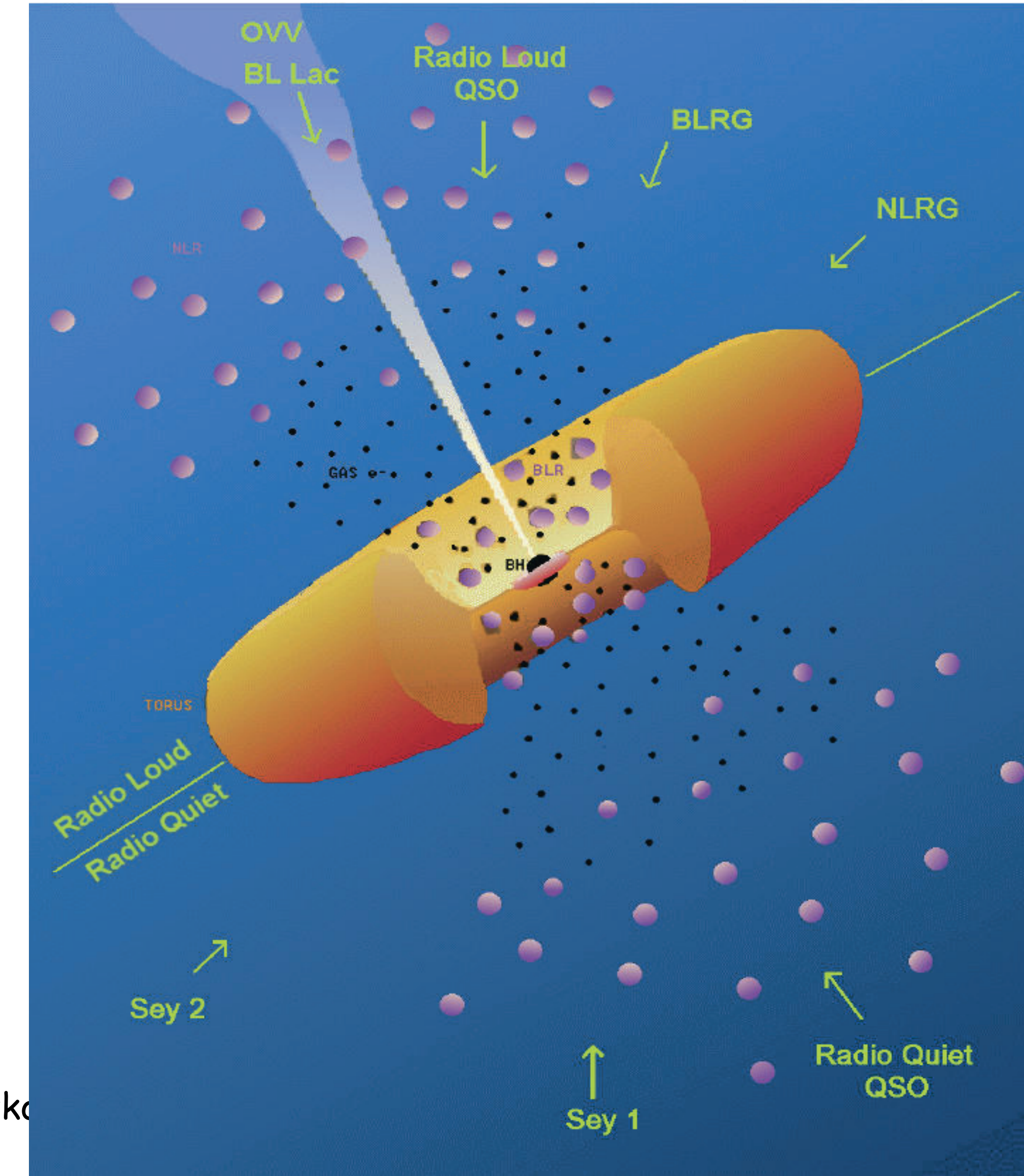


2008/06/12

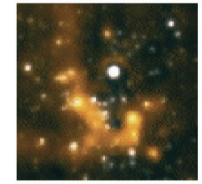
AGN with GRAVITY



- close AGN (< 20 Mpc): spatial scales accessible similar to seeing limited observations of the GC
- questions:
  dust emission: torus or NLR?
  maser disk, AGN jet and BH accretion
  BLR sizes, nuclear star cluster, gas motions

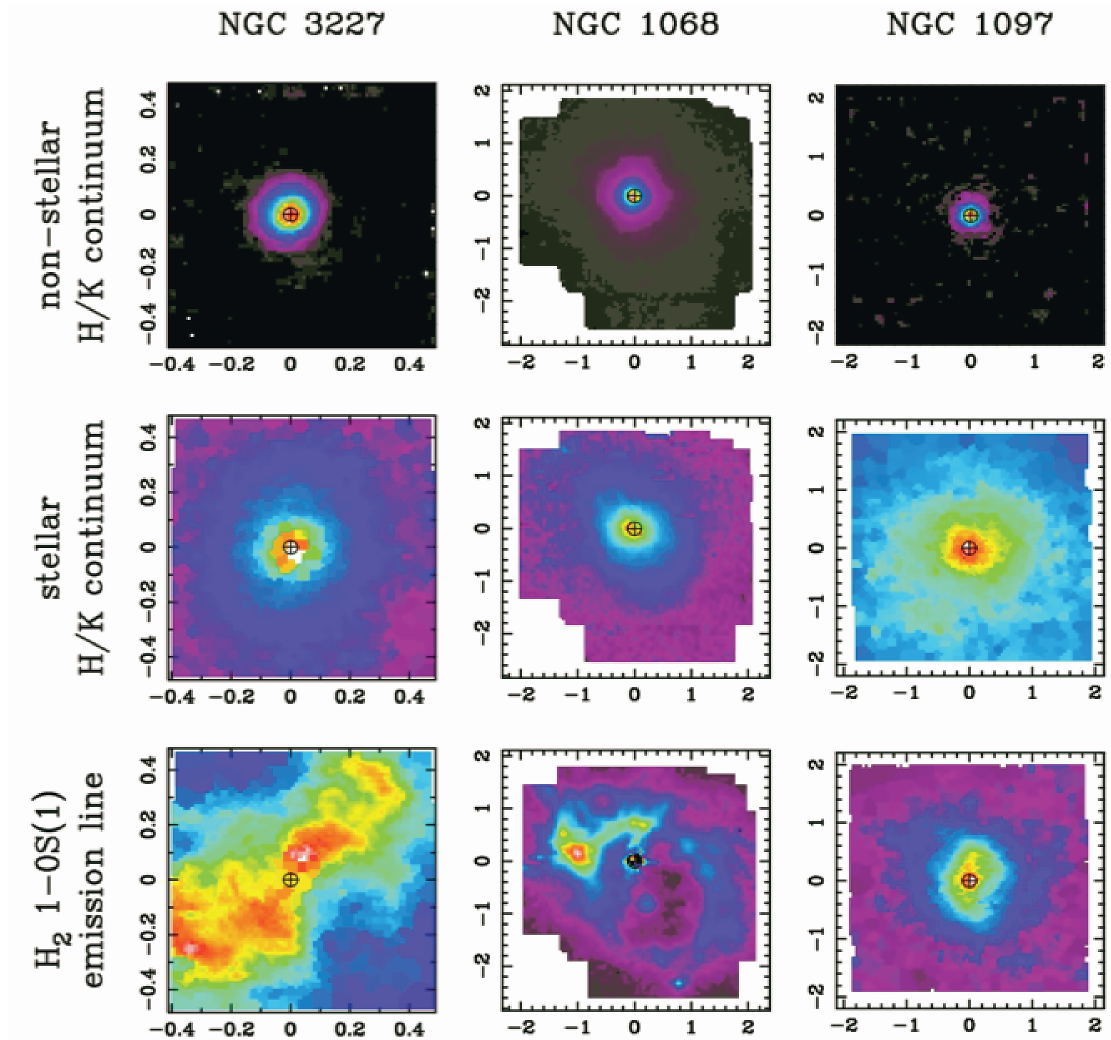


Star Formation in AGN



GRAVITY probes star formation in AGN on 1 pc scales

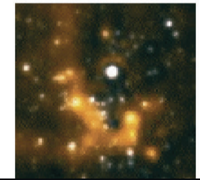
- How close in can stars still exist?
- What is LF(r) for very small r?
- Do stars exits inside the torus?

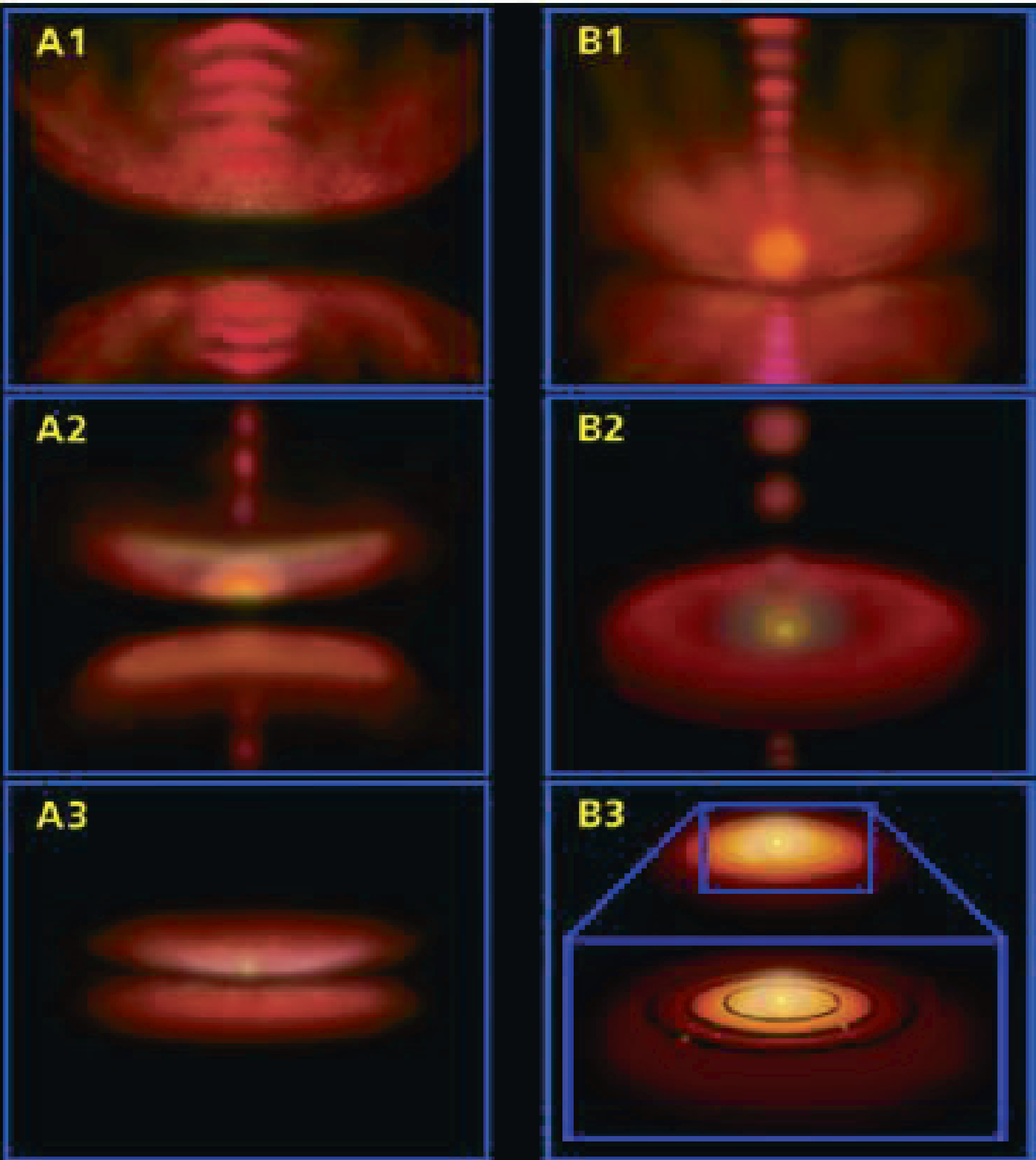


SINFONI
Davies et al.

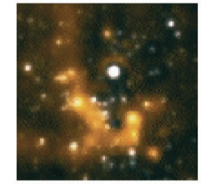
2008/06/12

Stellar Size Systems





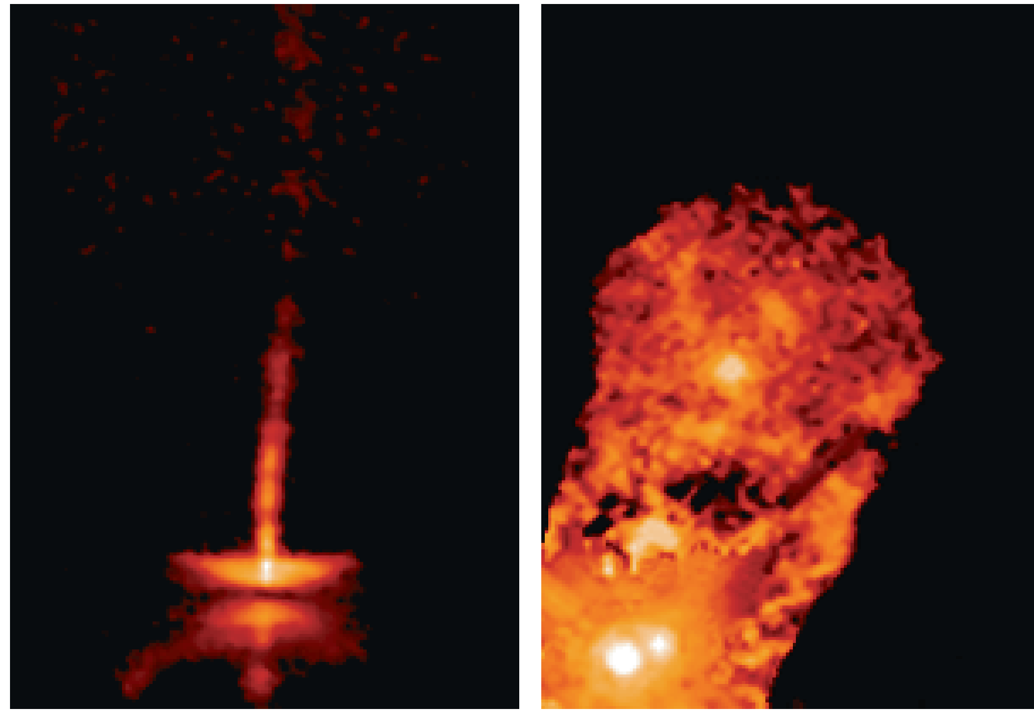
The Jet Engine in T Tauri Stars



Most young stars have disks and bipolar outflows.

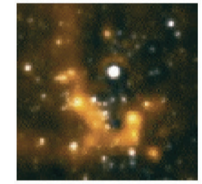
distance of Taurus (150 pc):
4 mas correspond to 0.6 A.U.

GRAVITY: trace jets from T Tauri stars in real time (i.e. on the time frame of ~weeks)

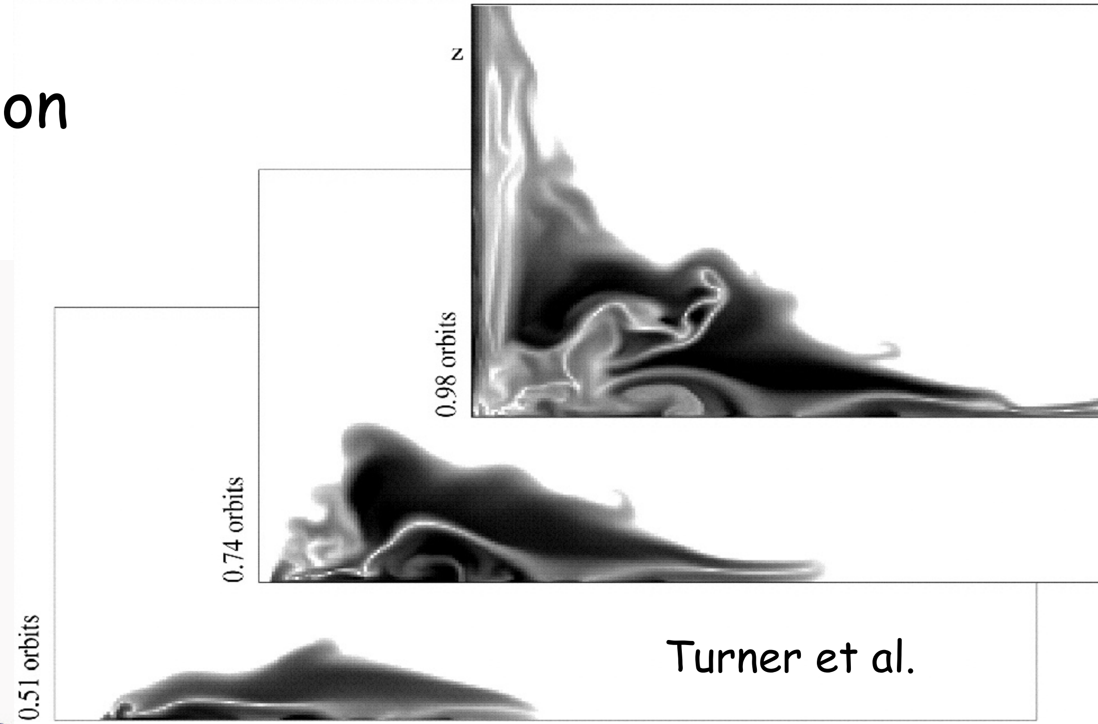


HST monitoring of HH30 and XZ Tau (Krist et al.)
FoV: 3" x 6" (300 A.U. x 600 A.U.)
Time base: 5 yr

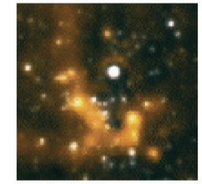
The Jet Engine in T Tauri Stars



MHD simulation of jet formation (time sequence)



GRAVITY will address the question if jets originate in disk winds, or are driven by a central engine
-> test models of jet formation and the role of magnetic fields

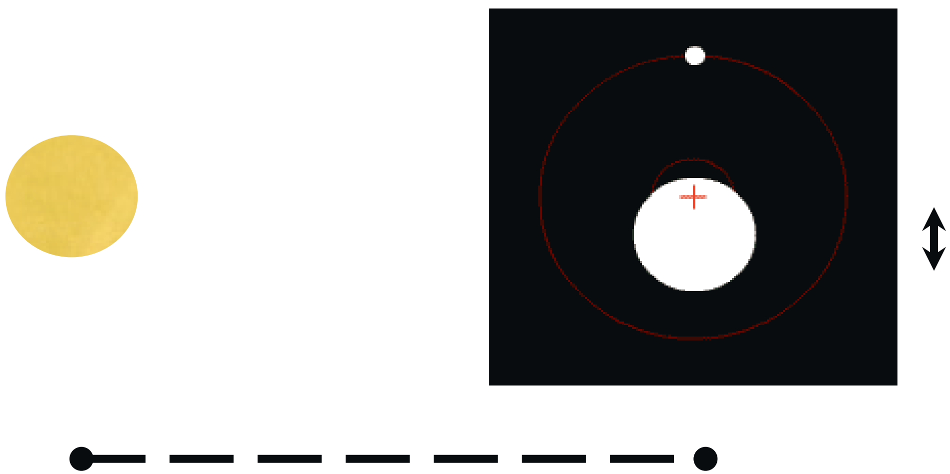


Exo-Jupiters & -Neptunes in Binary Systems

Example:

astrometric signal of Neptune-mass exoplanet in 2 A.U. orbit around M5V star (m_*/m_{pl} = 4000) at distance of 10 pc:

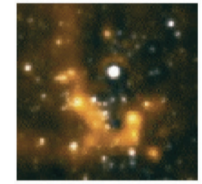
astrometric-wobble: ±50 μas, orbital period: 6.3 yr



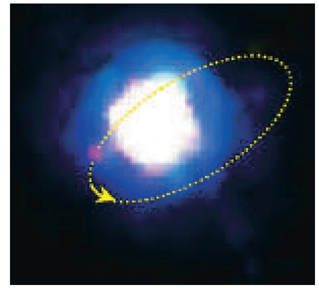
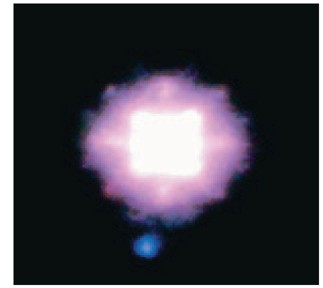
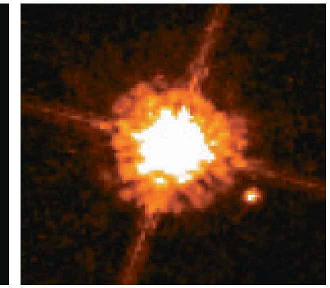
astrometric signal ≥ 10μas

binary separation ≤1.5"

Exo-Jupiters & -Neptunes in Binary Systems

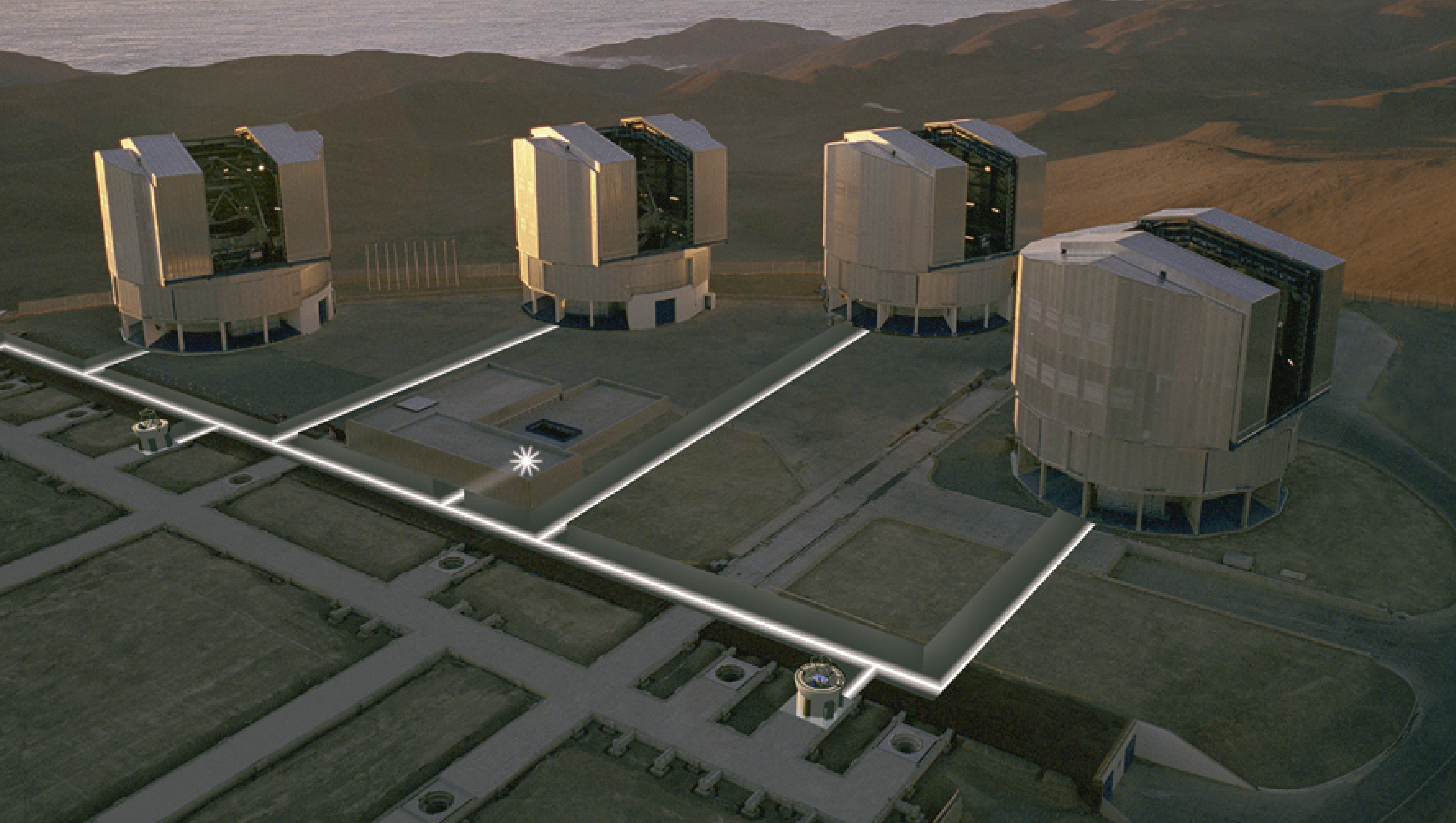


GRAVITY discovery space :

Host star	max dist (mK=10 mag)	planet mass
G2V (sun)	200 pc	Exo-Jupiter
M5V	25 pc	Exo-Neptunes

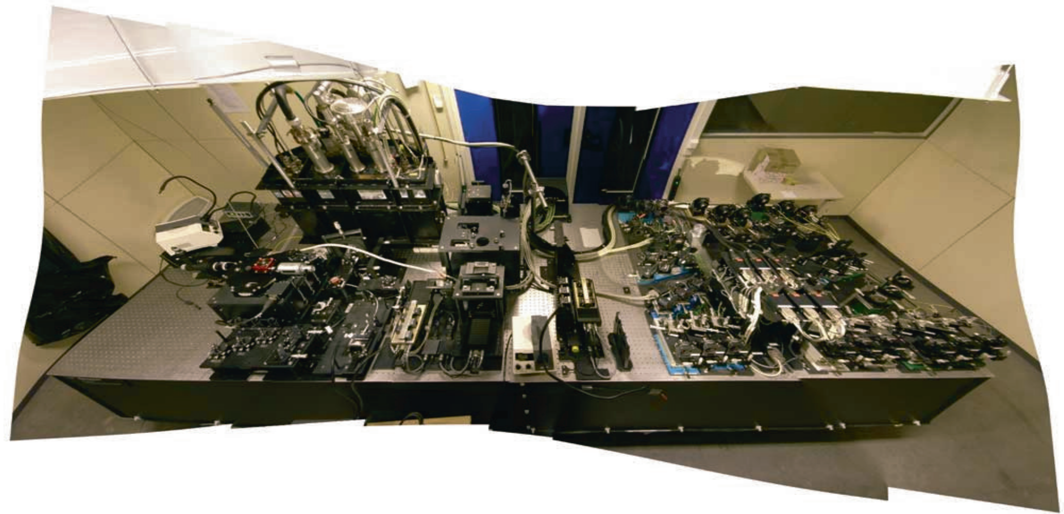
μas Astrometry with GRAVITY - in the GC and elsewhere



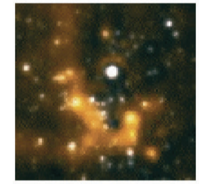
1^{st} VLTI Generation

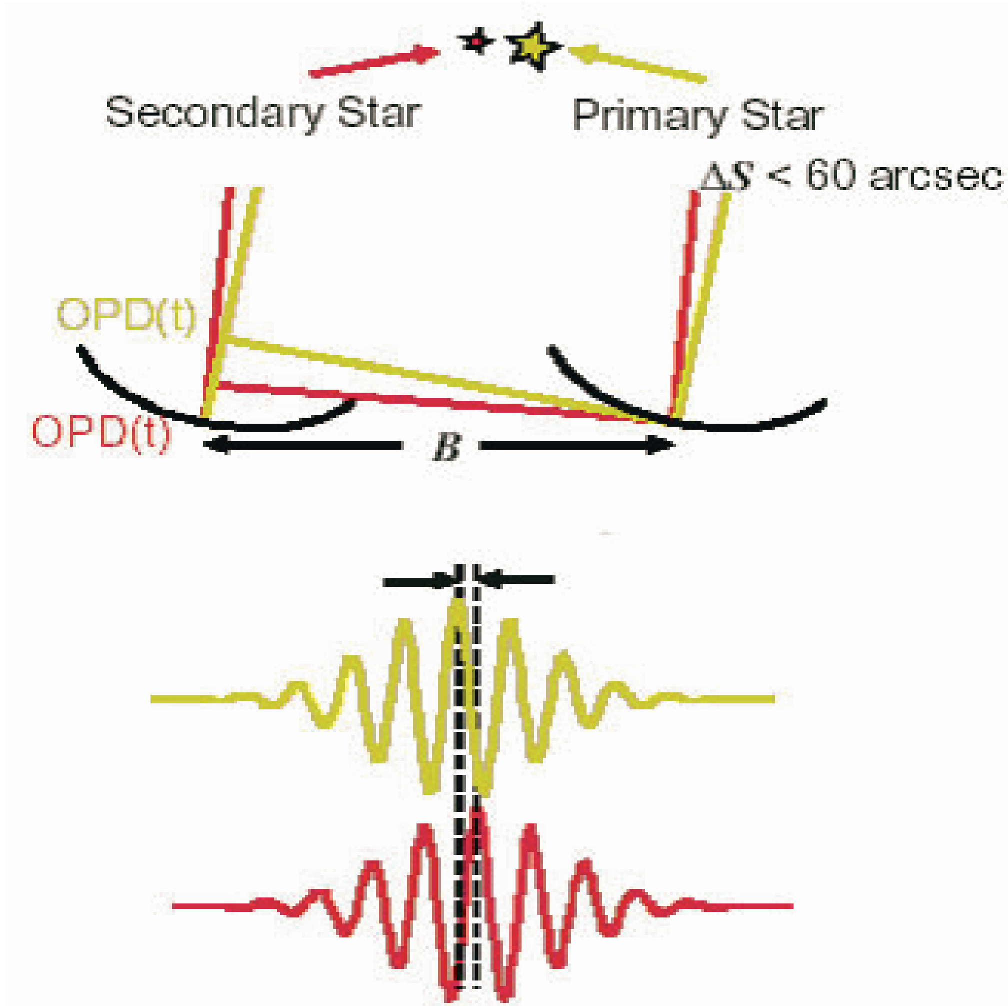
Optimized for different science

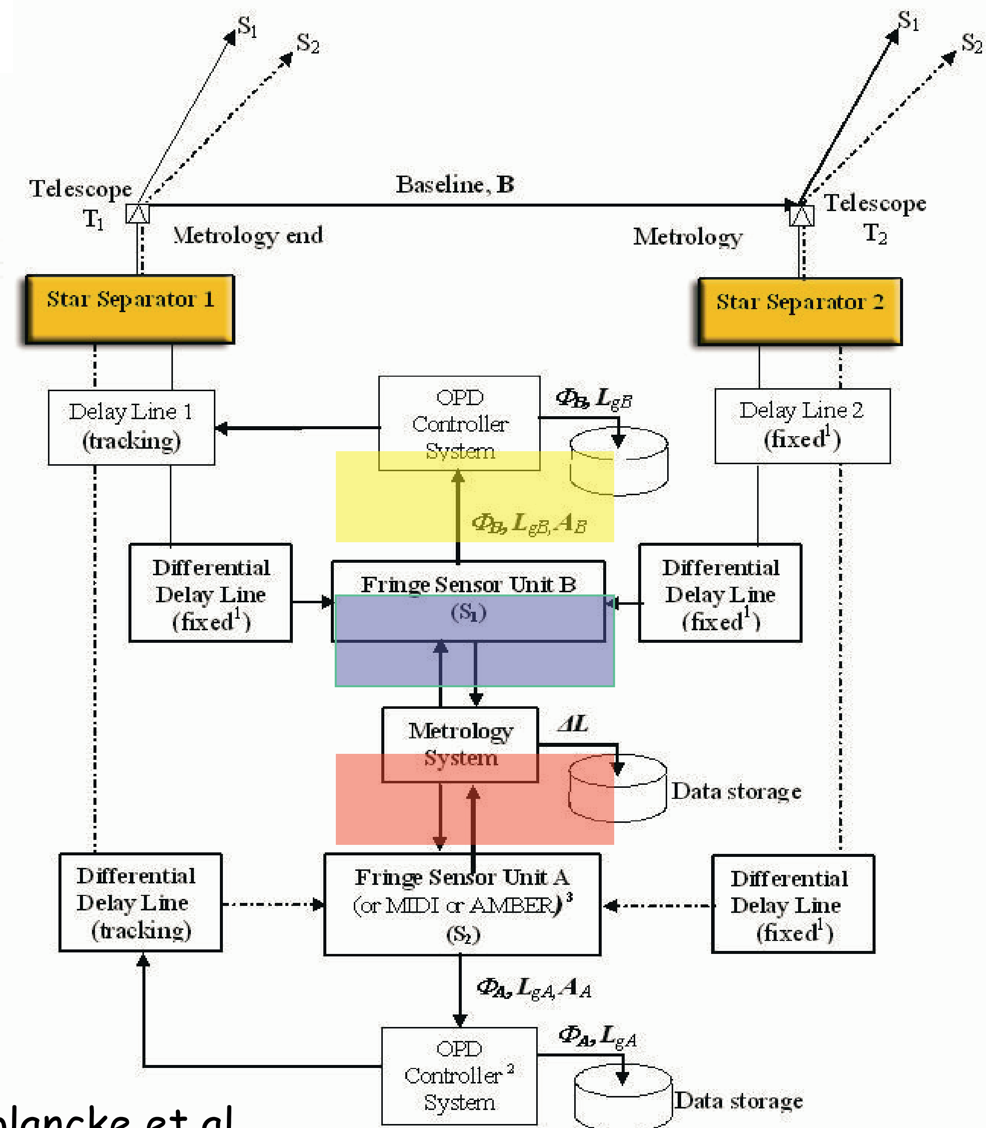
- not sensitive enough
- at most 3 UTs
- no IR-WFS



Key to μas Astrometry: Phase Referencing



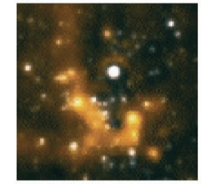




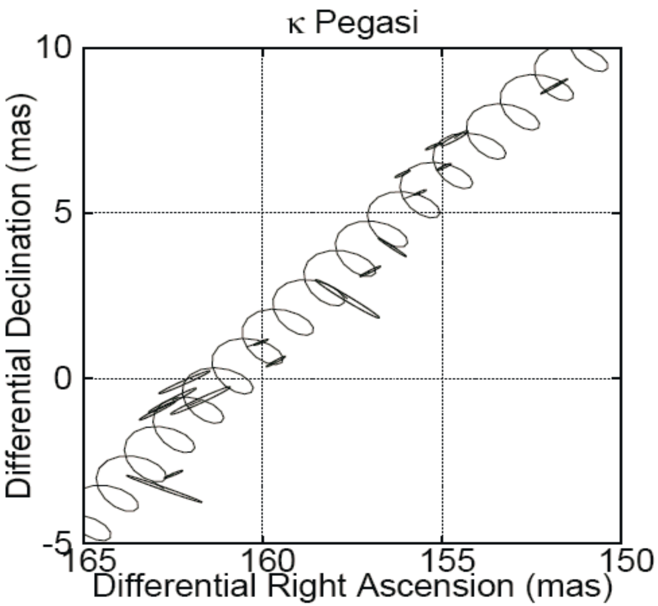
Measure relative phase

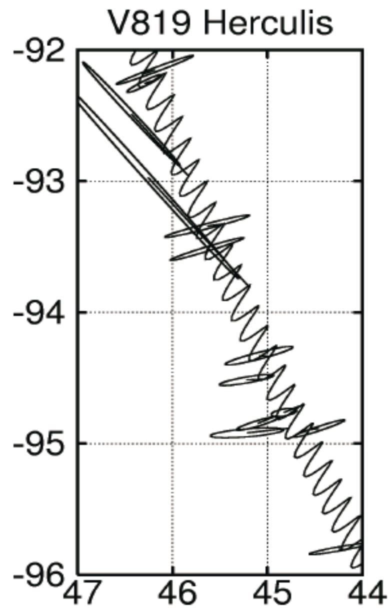
PRIMA: Delplancke et al.

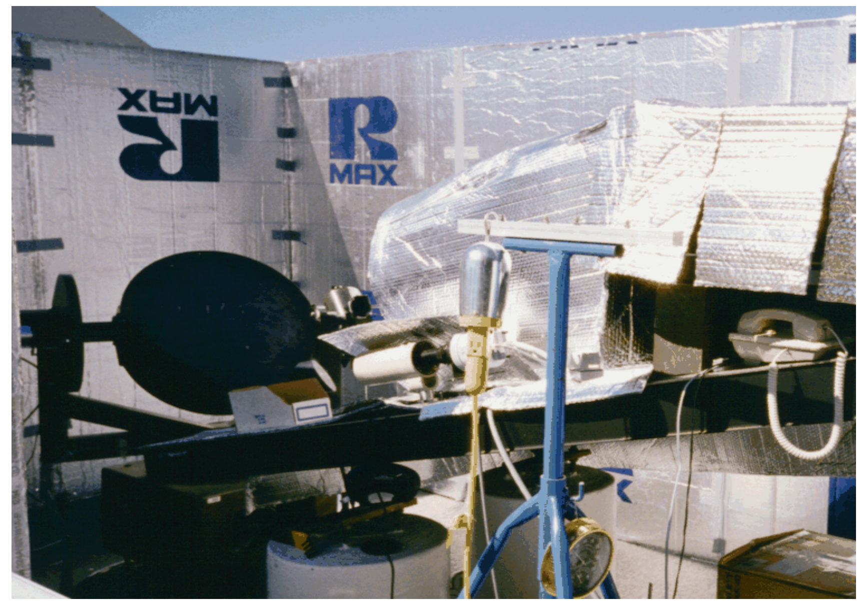
PTI: Ten μas Astrometry



Search for giant planets orbiting in binary systems







Muterspaugh et al. 2006: "… at the 20μas level has been demonstrated …"

V819 Herculis

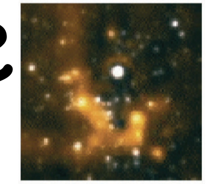
$K_{Primary/Secondary}$ = 4.4 / 5.8 mag

Palomar Testbed Interferometer

110 m / 87 m baseline

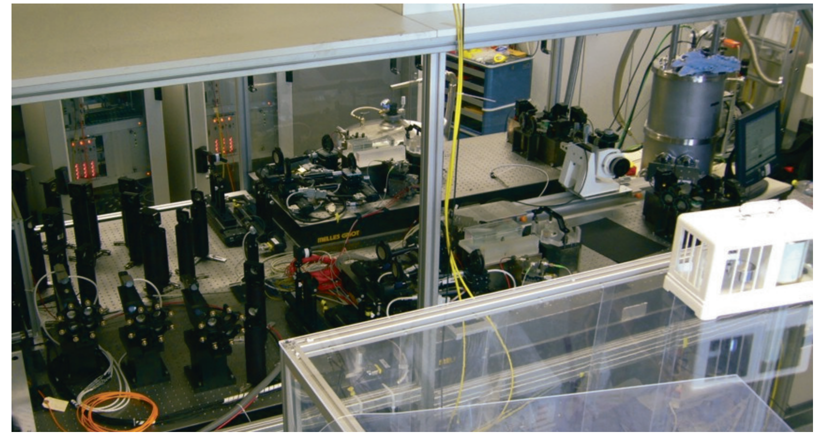
40 cm Aperture

Interferometry with Large Telescopes



PRIMA @ VLTI

- Up to 200 m baseline
- 2 telescopes
- 10-100 μas astrometry
- Installation 2008/9

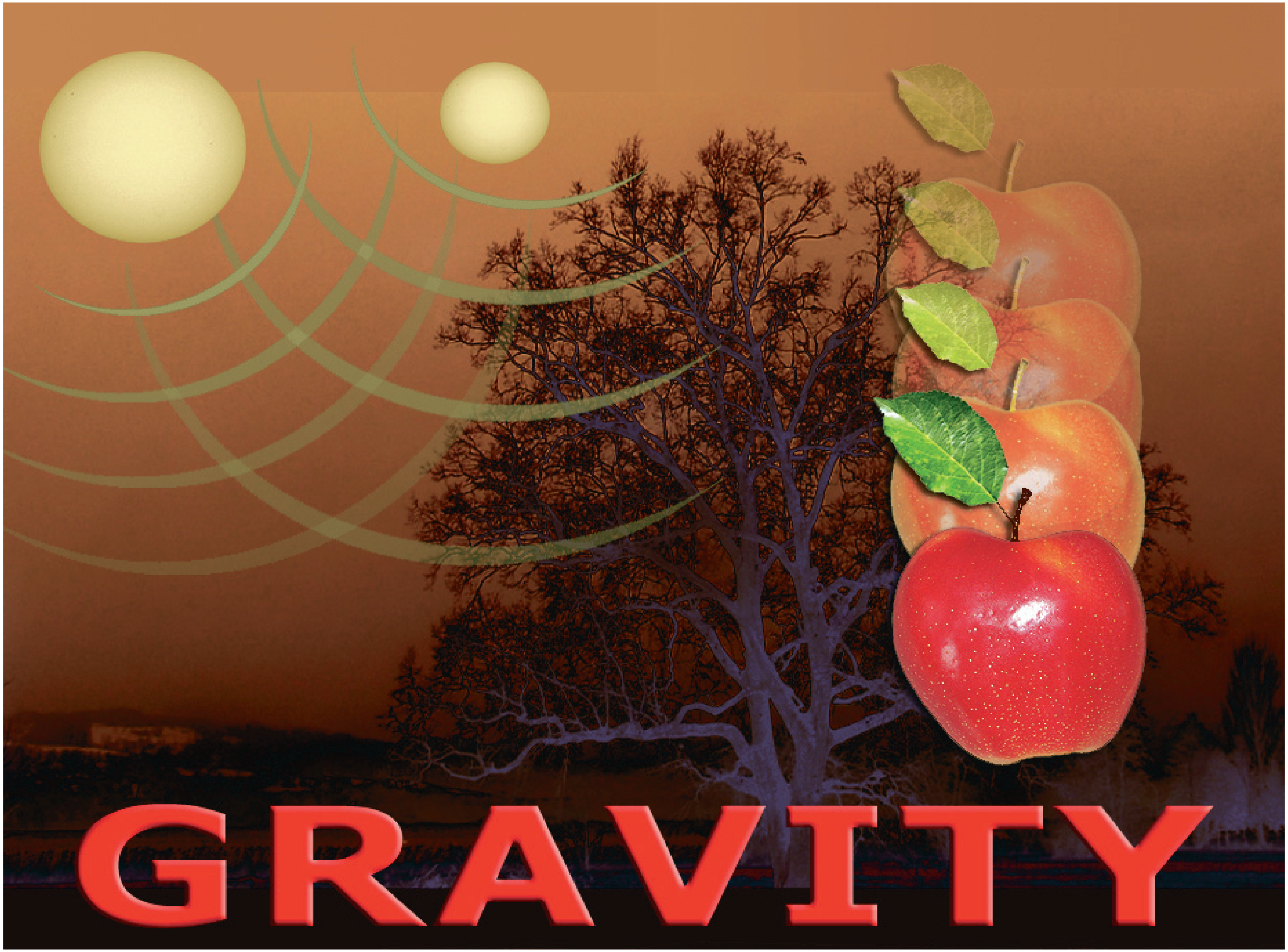


PRIMA Testbed at MPE

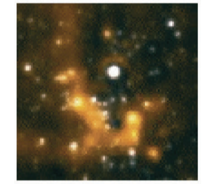
Keck interferometer upgrade

- 85 m baseline
- 30 μas astrometry
- Installation 2008-10

The GRAVITY Instrument



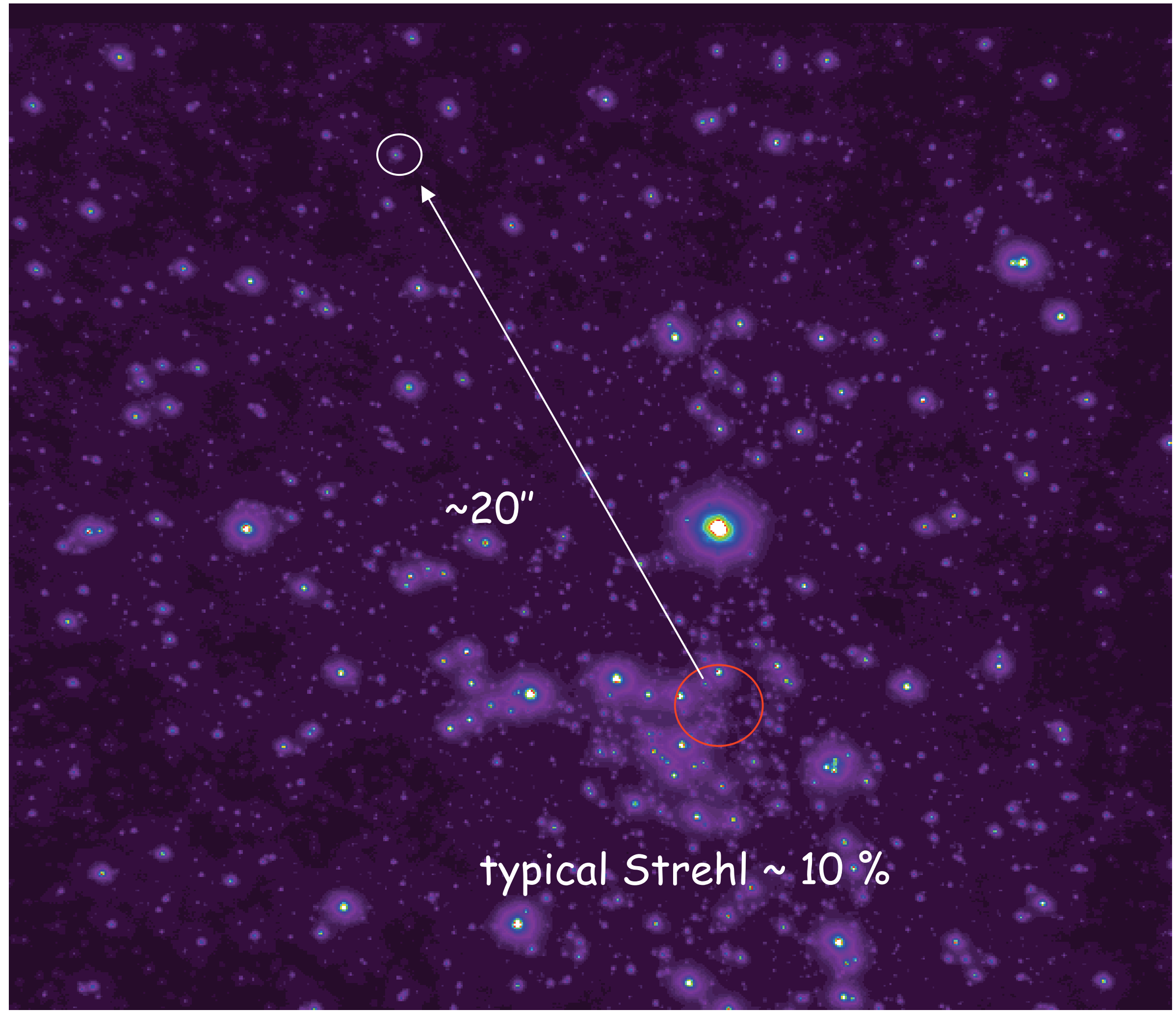
IR Wavefront Sensing: Key to GC



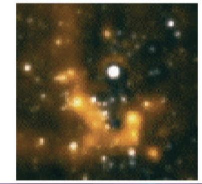
Optical AO guide star 20″ away (> isoplanatic angle)

Strehl ratio loss factor 5

But: Bright IR source 6″ North



AO Star ≠ Fringe Tracking Star

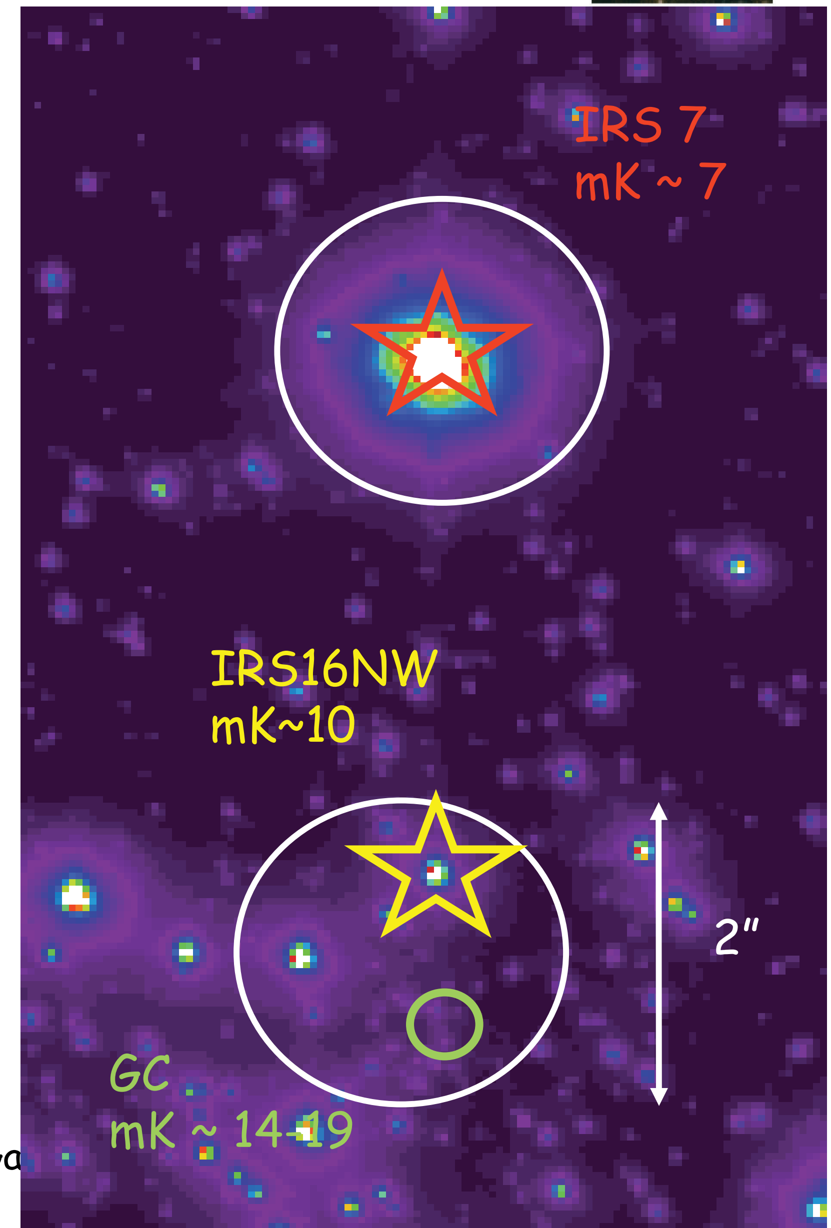


'Standard' case:
AO star = fringe tracking star
WFS on phase reference

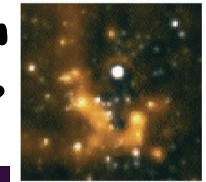
Galactic Center case:
FoV: 2" < distance to AO star

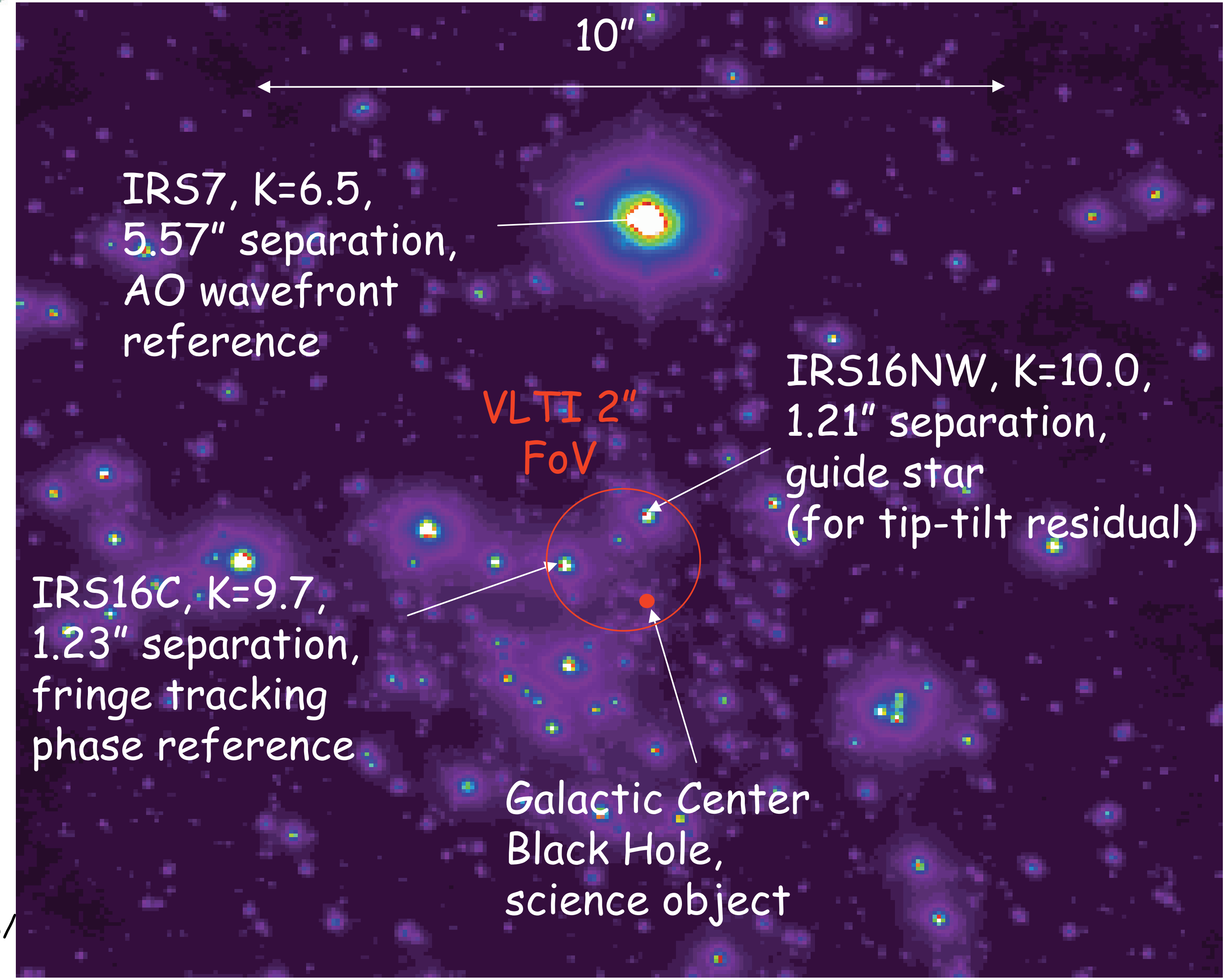
2 Beams:
a) Object / Phase Reference
b) AO / WFS

Note: Suitable stars exist!
a) IRS 16 NW: fringe-tracking
b) IRS 7: WFS

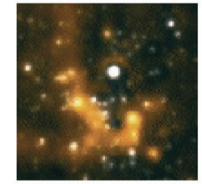


GRAVITY: Optimized for GC





Top Level Requirements

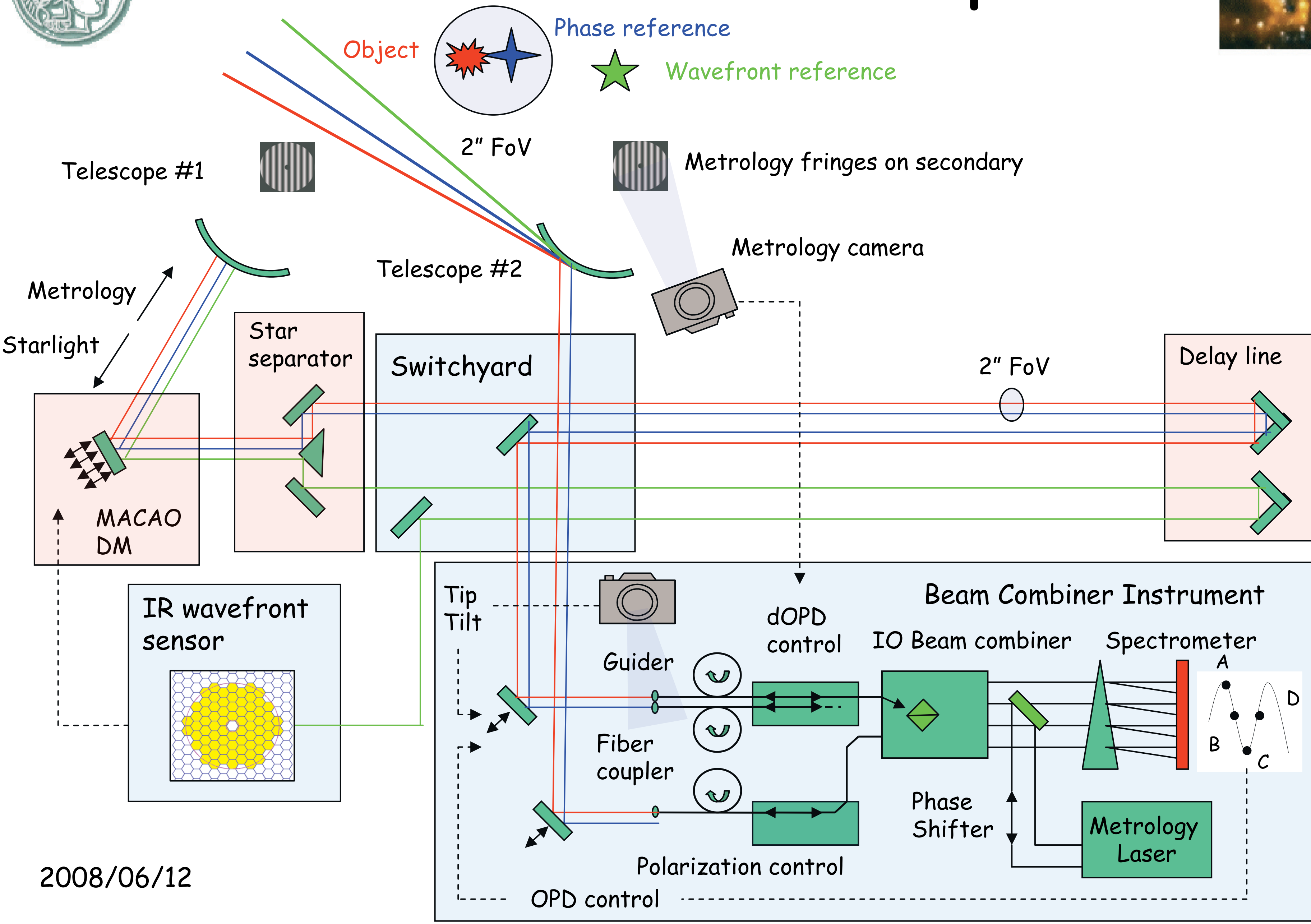


Science Requirements:
- 4 UTs, 6 baselines
- K-band, low spectral resolution (up to 500)
- 50% Strehl ratio for mK~6, 6" away
- on-axis (<2") phase referencing on mK<=10 star
- 10 µas in 5 min for mK>=15
- imaging to K~19

IR wavefront sensing down to mK~10
- off axis (e.g. GC)
- on axis (e.g. stars)

high stability: integrated (fiber) optics beam combiner-operation in cryostat

GRAVITY Concept



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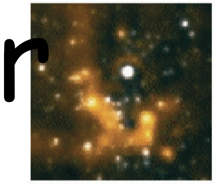
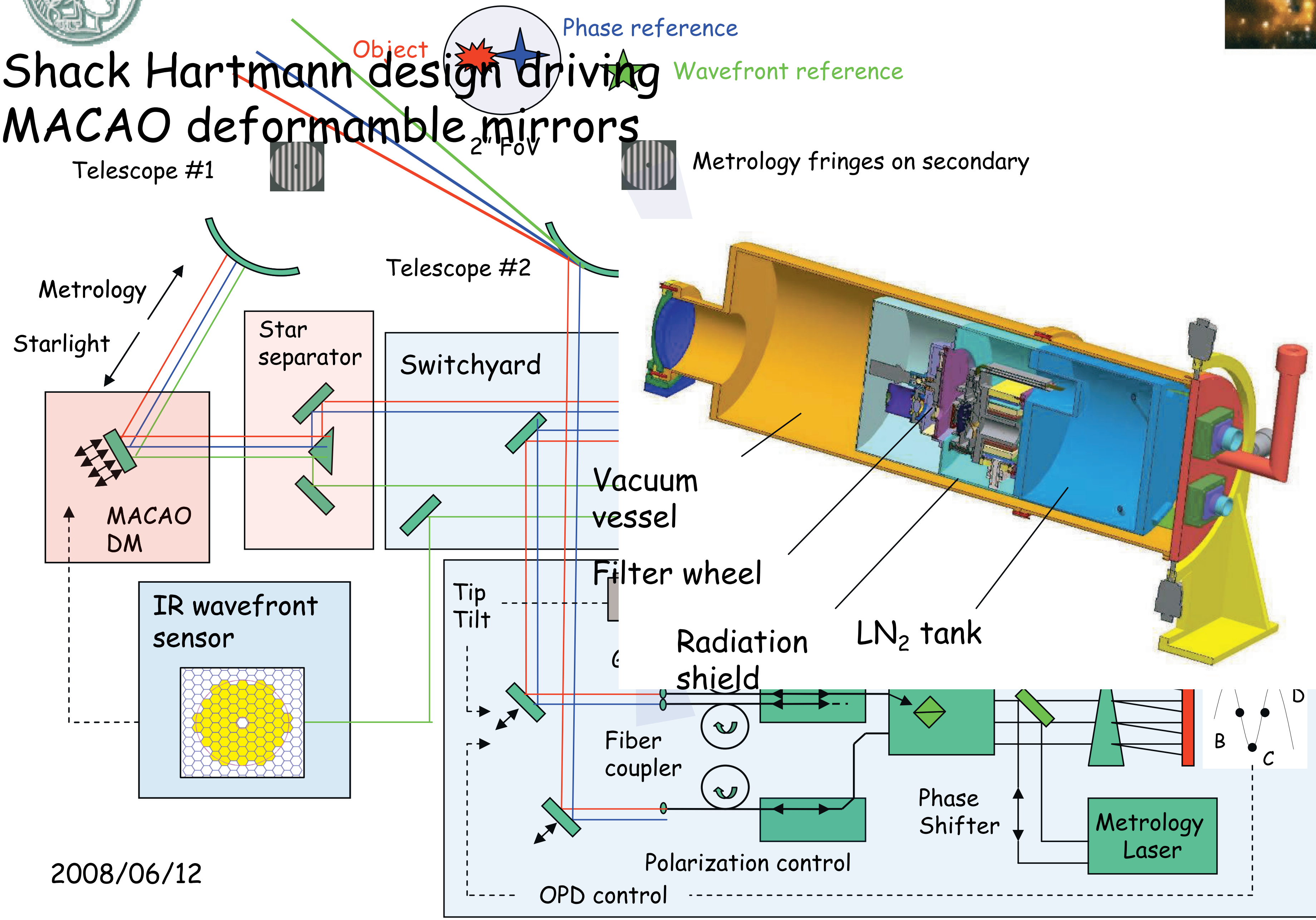
Infrared Wavefront Sensor



Shack Hartmann design driving
MACAO deformamble mirrors



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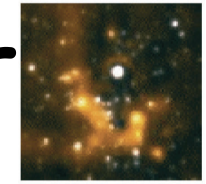
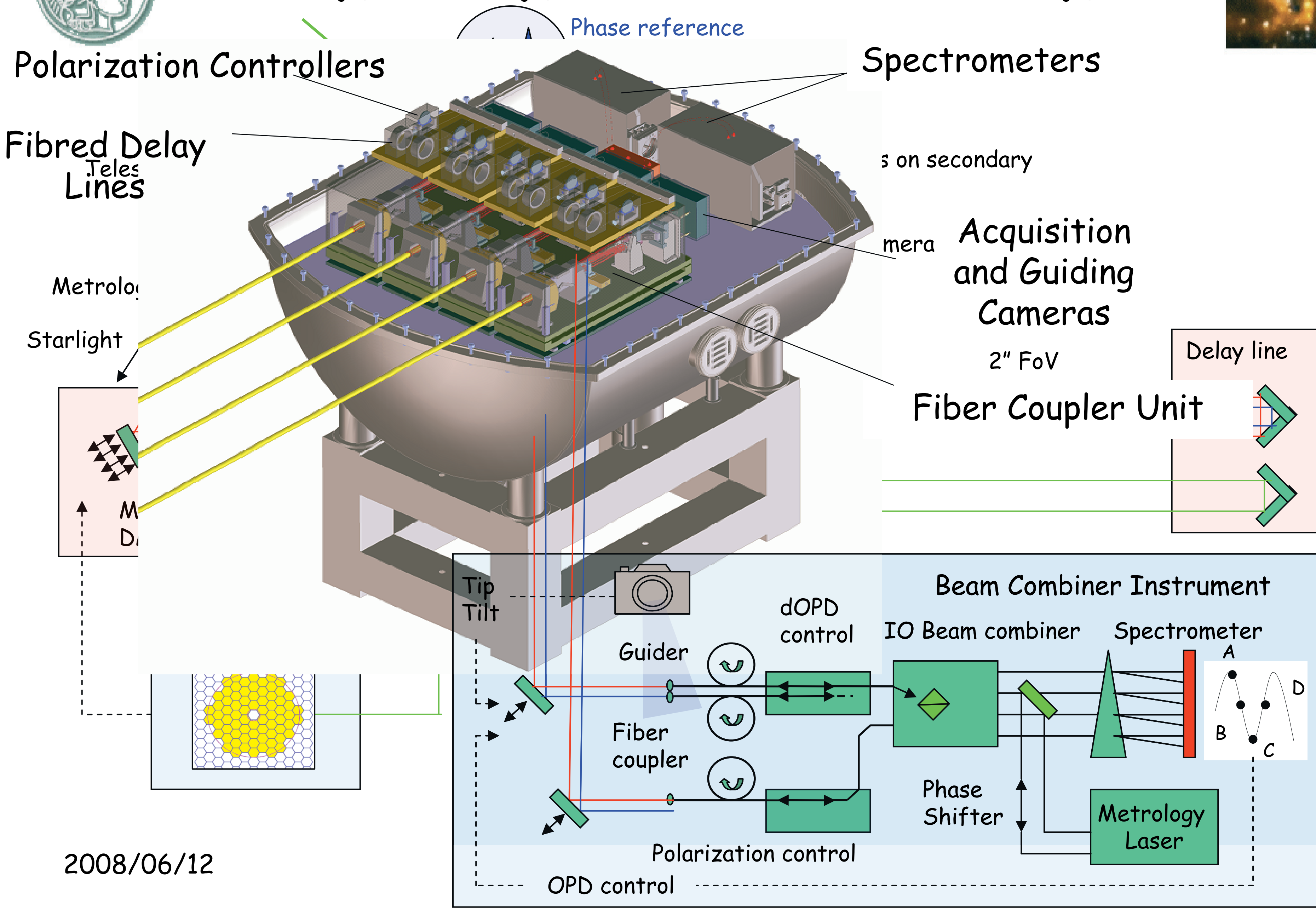
Beam Combiner Instrument





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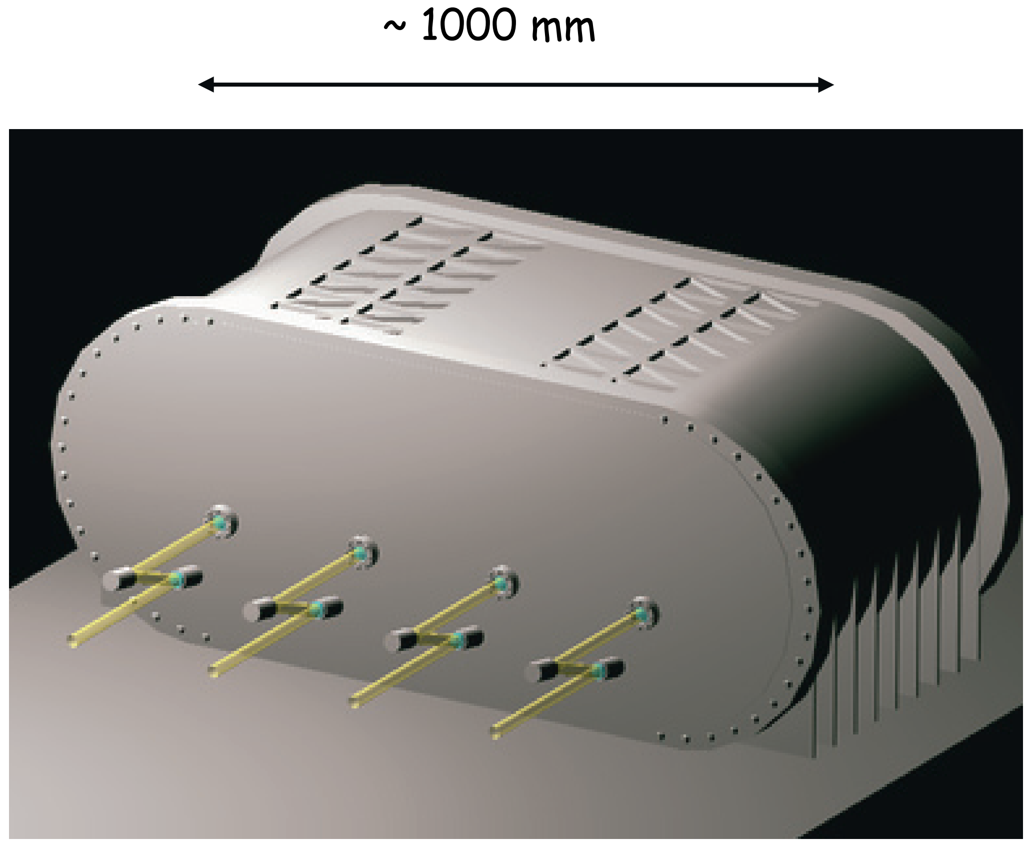
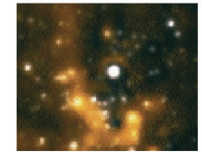
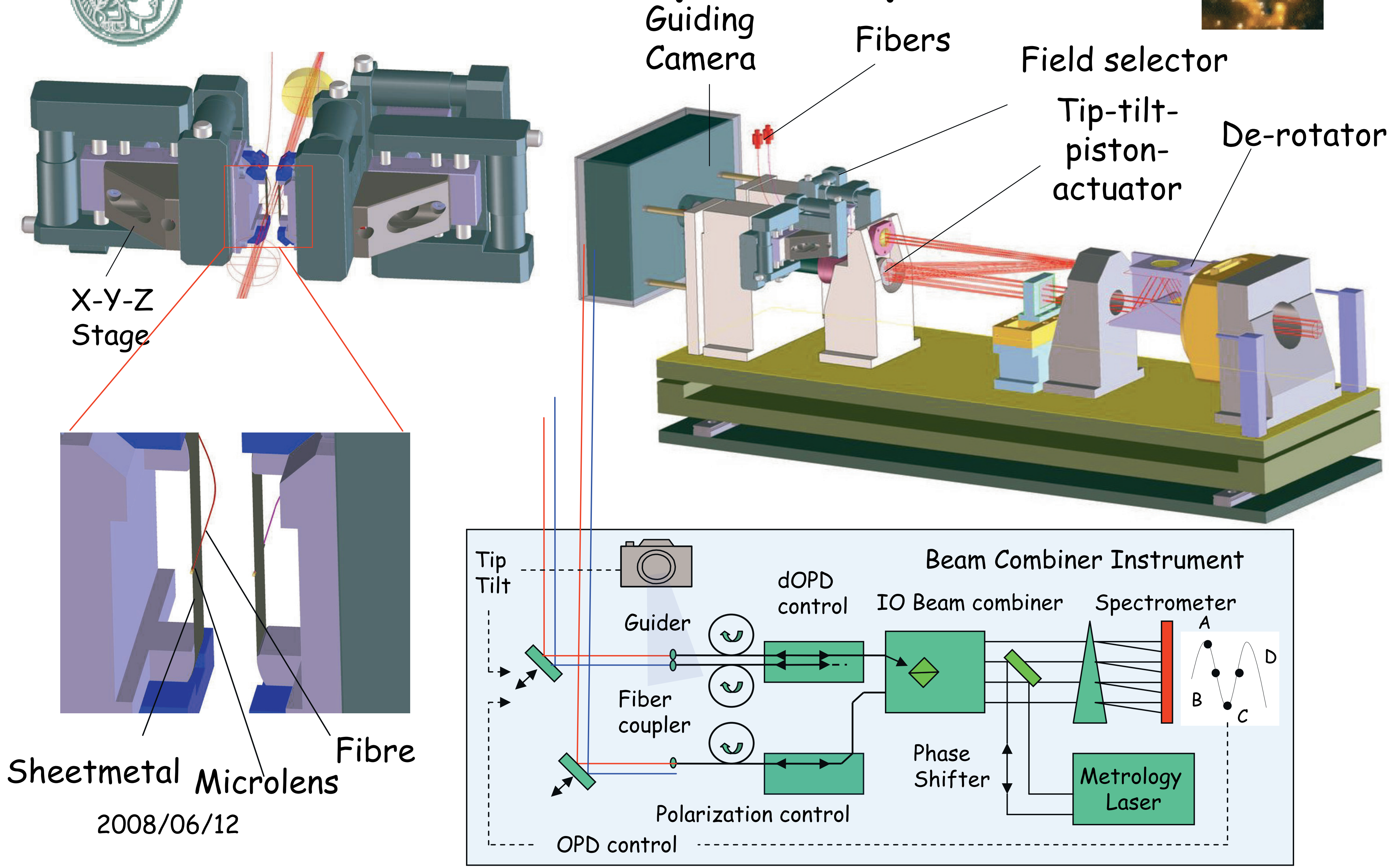
Cryogenic Instrument

- long term stability
  - mechanical
  - thermal
- no turbulence (vacuum)
- High transmission (dust is the main reason for light loss after some time)
- suppression of instrument thermal background
- technology well established

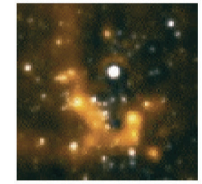


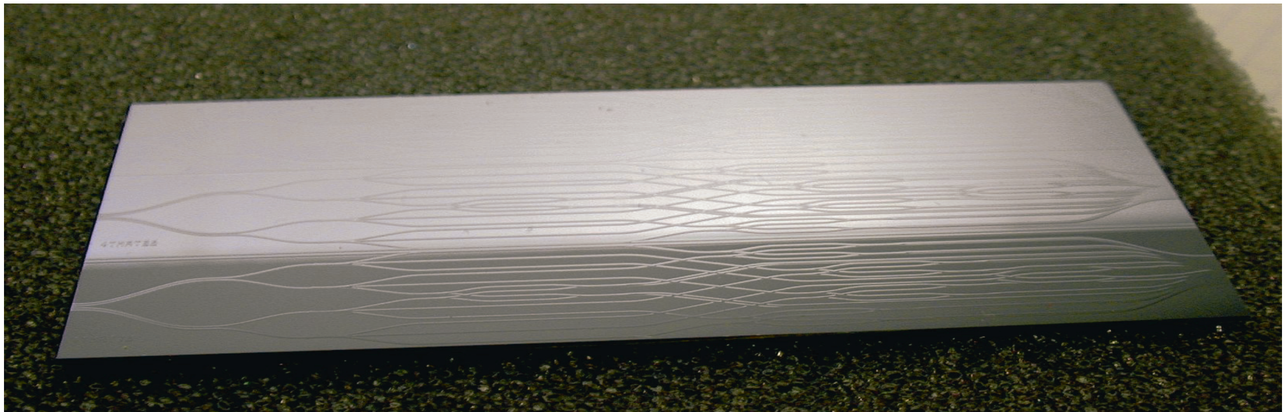
Fiber Coupler Optics

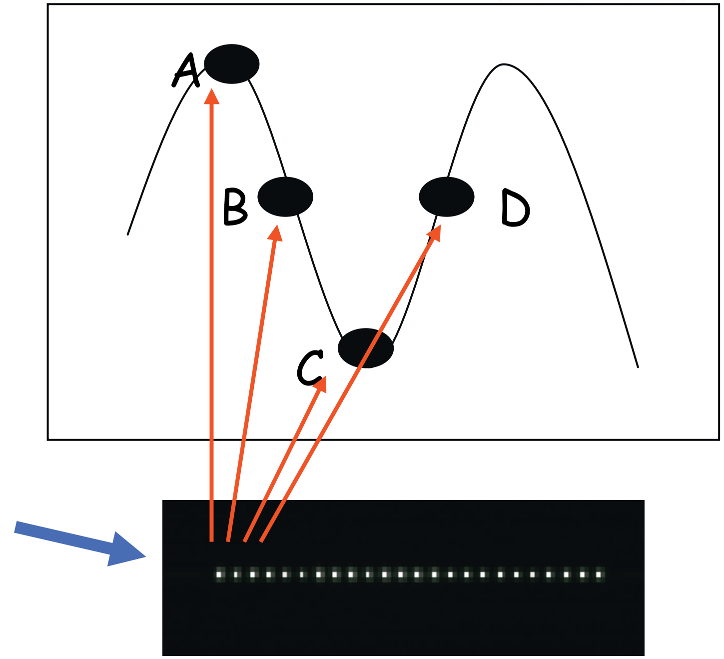




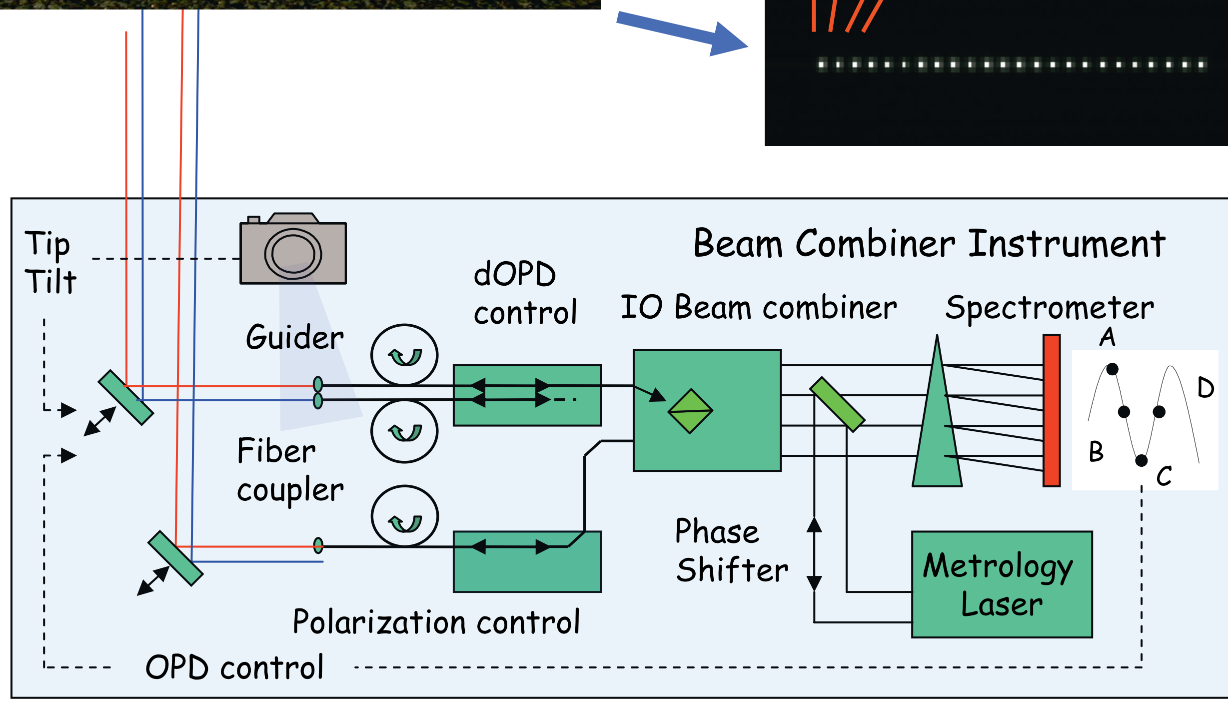
Integrated Optics Beam Combiner







Fed by single-mode fibers via polarization rotators and fibered differential delay lines



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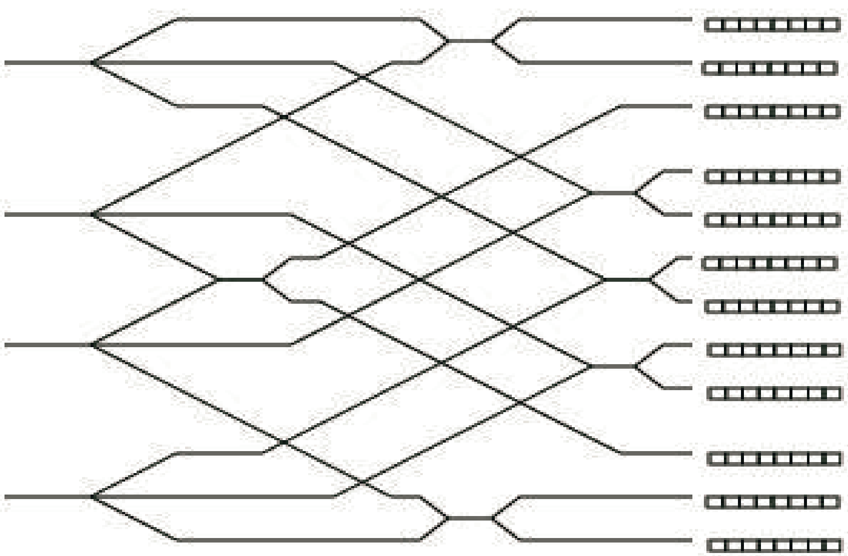
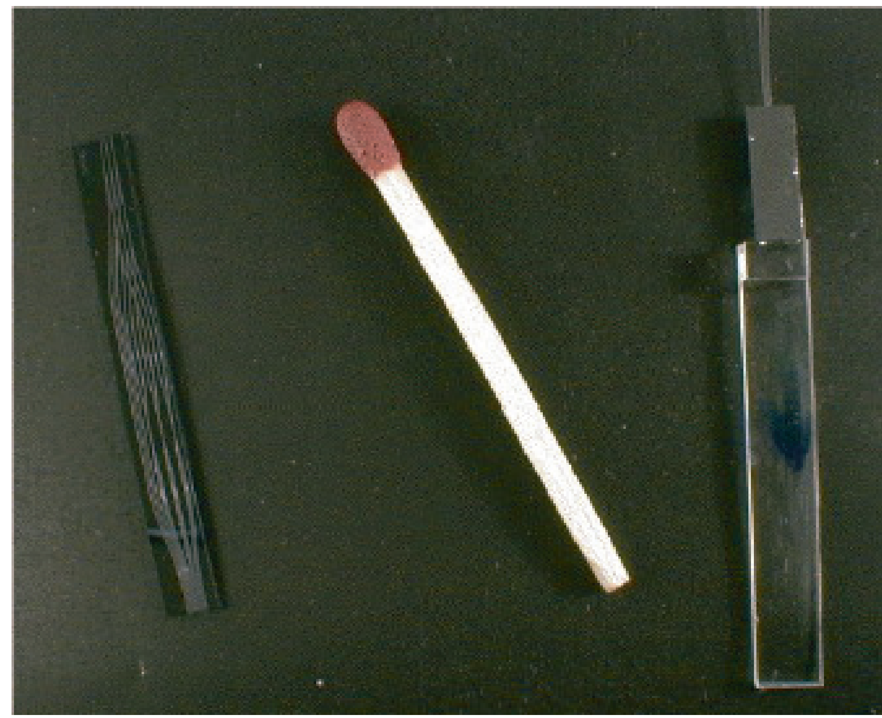
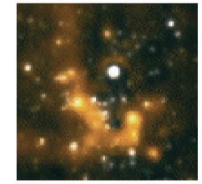
Fibre Optics & Integrated Beam Combiner

- Fluoride glass fiber
  (e.g. O'HANA, Perrin et al. 2004)

- For our application: T = 100%
  (attenuation ~ 3 dB/km)



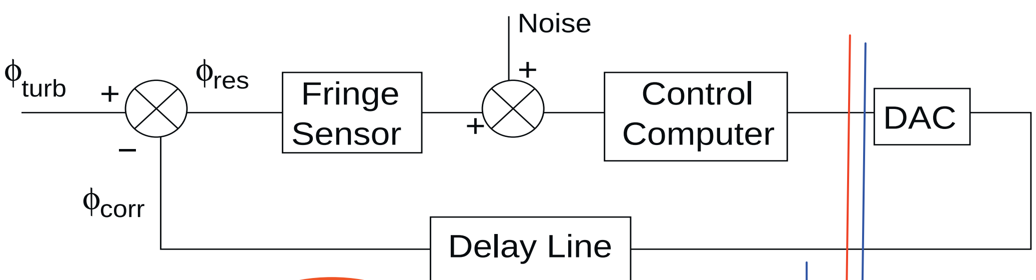


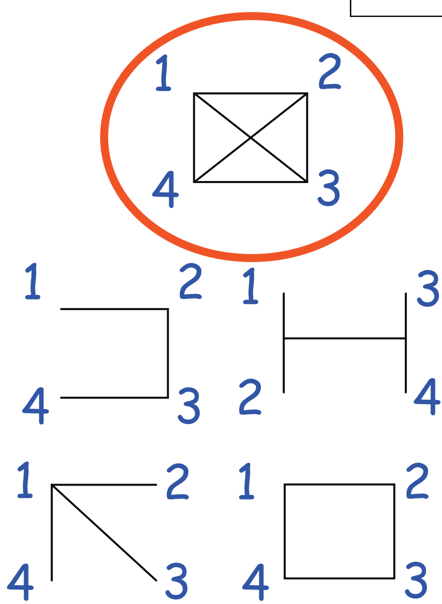


Fringe Tracker

Matricial pairwise combination

RMS OPD ~ 270 nm for K=10





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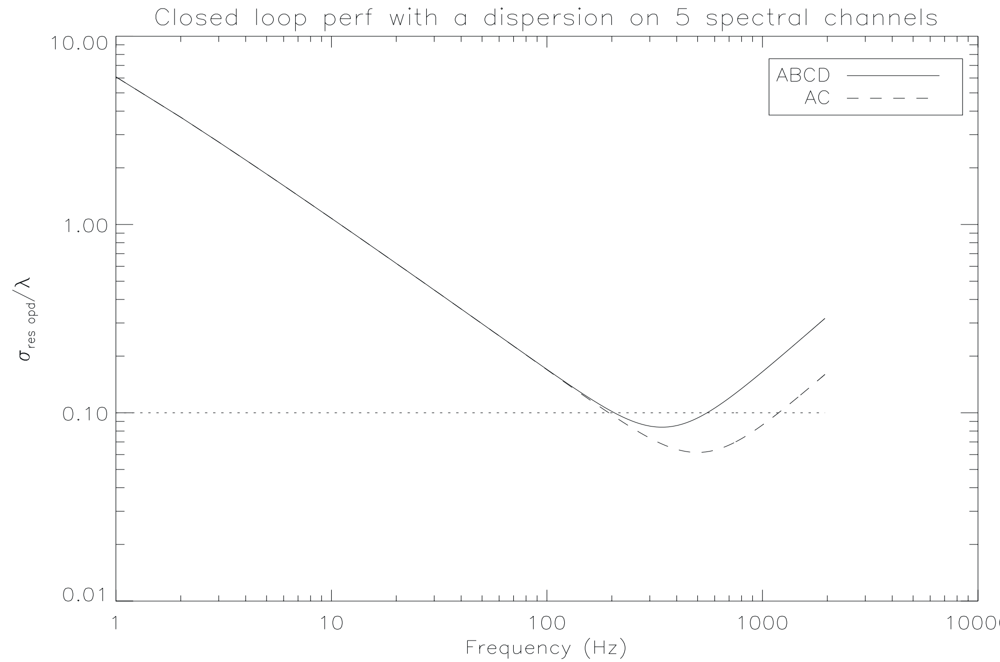
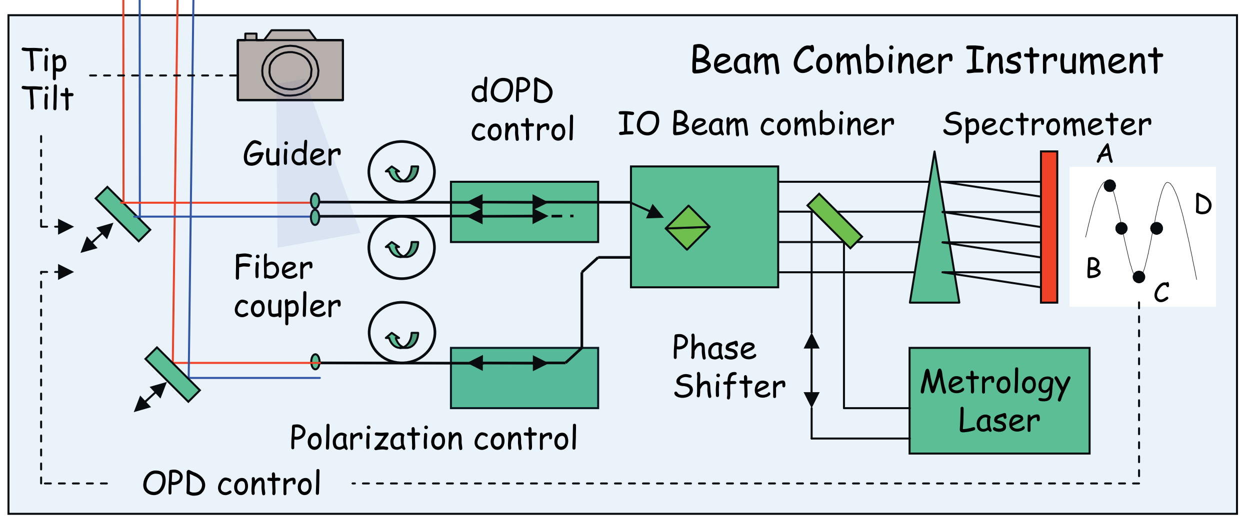
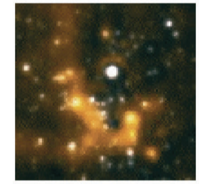
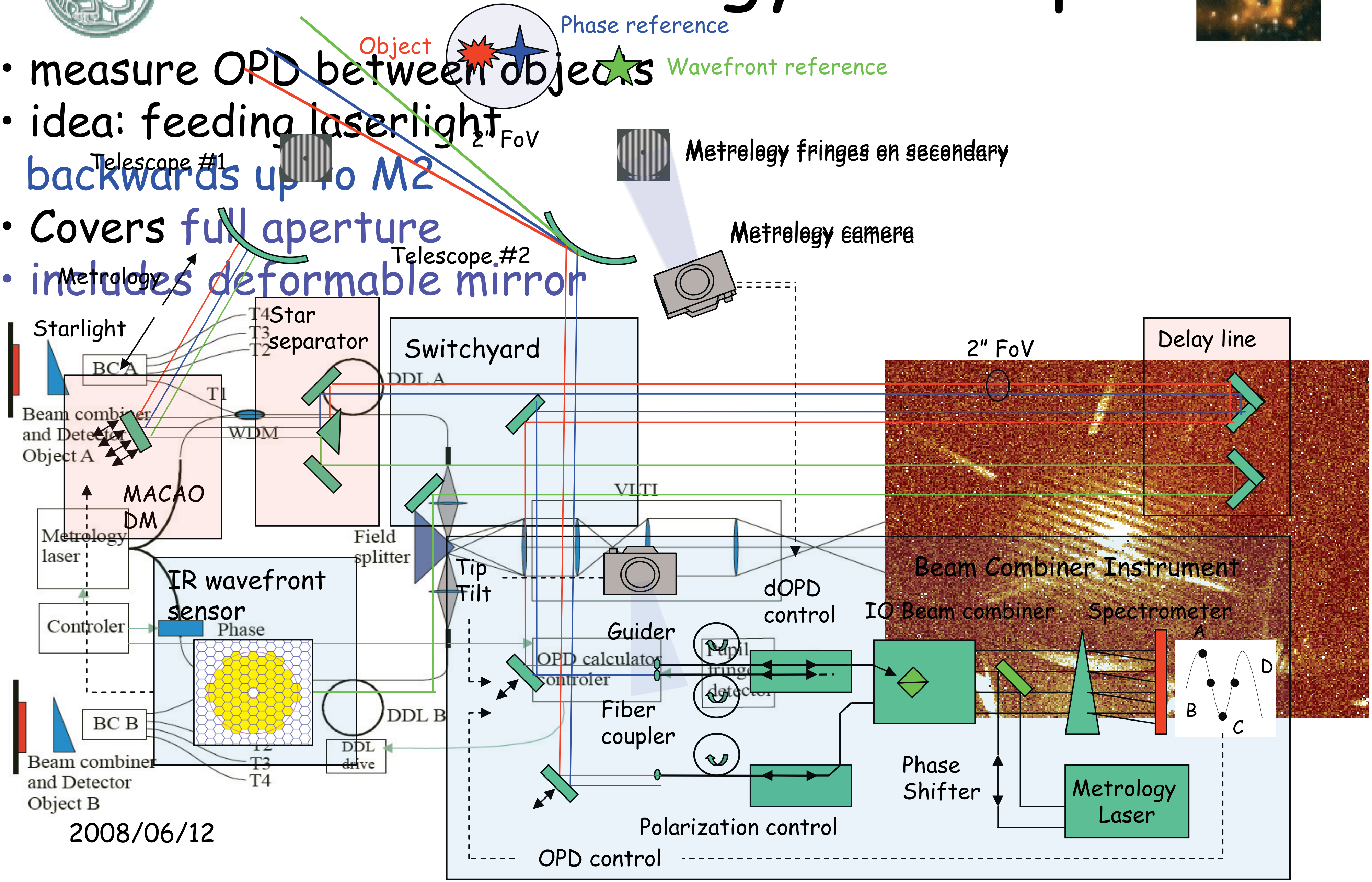




New Metrology Concept



- measure OPD between objects
- idea: feeding laserlight backwards up to M2
- Covers full aperture
- includes deformable mirror



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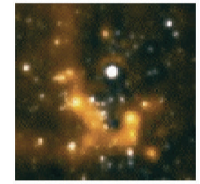
Status of GRAVITY



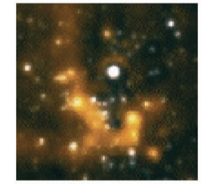
- March 2006: STC recommended a phase-A study
- December 2007: Recommendation by ESO advisory committee and approval by ESO Council
- Currently: interface definition and contract negotiations
- >=2012: Installation at the telescope

Cost

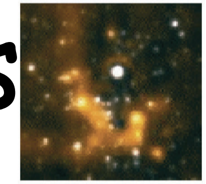
Hardware: approx. 4 Mio. Euro

Manpower: approx. 100 FTE

Backup



Guaranteed to be a success

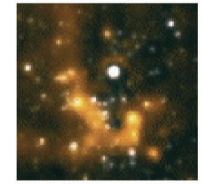


- Unclear how most massive stars form
- Mismatch between luminosity and atmosphere models
  - Physics of stellar atmospheres complex
  - Mass estimates difficult from spectra

- Needs dynamical masses

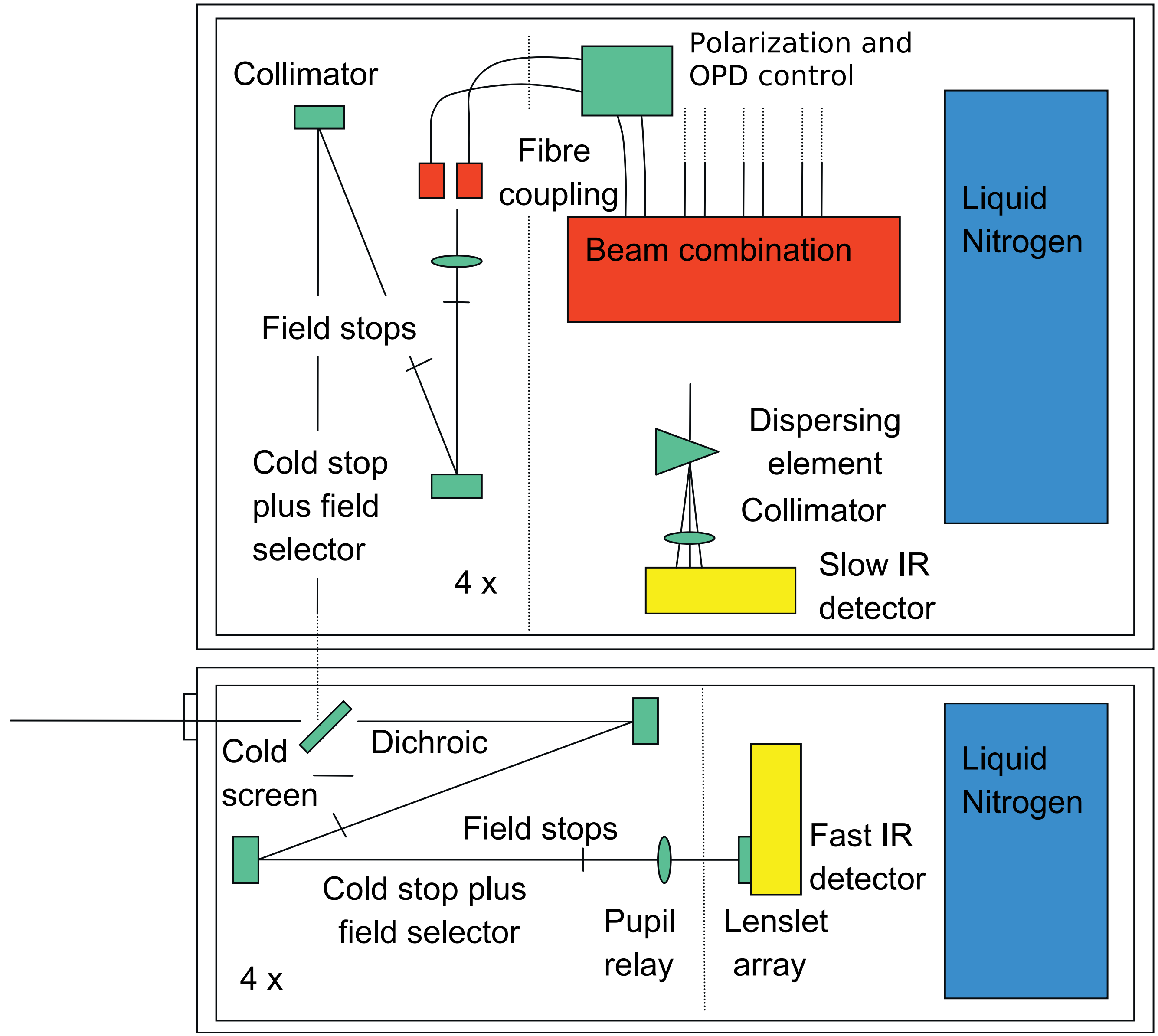
- Spectroscopic binaries are known
- Astrometric information will determine masses

Dedicated Instrument for GC



- high (40%) transmission
- 4 UTs
- 6 baselines

- single mode instrument
  - K-band
  - low spectral resolution
  - cryogenic



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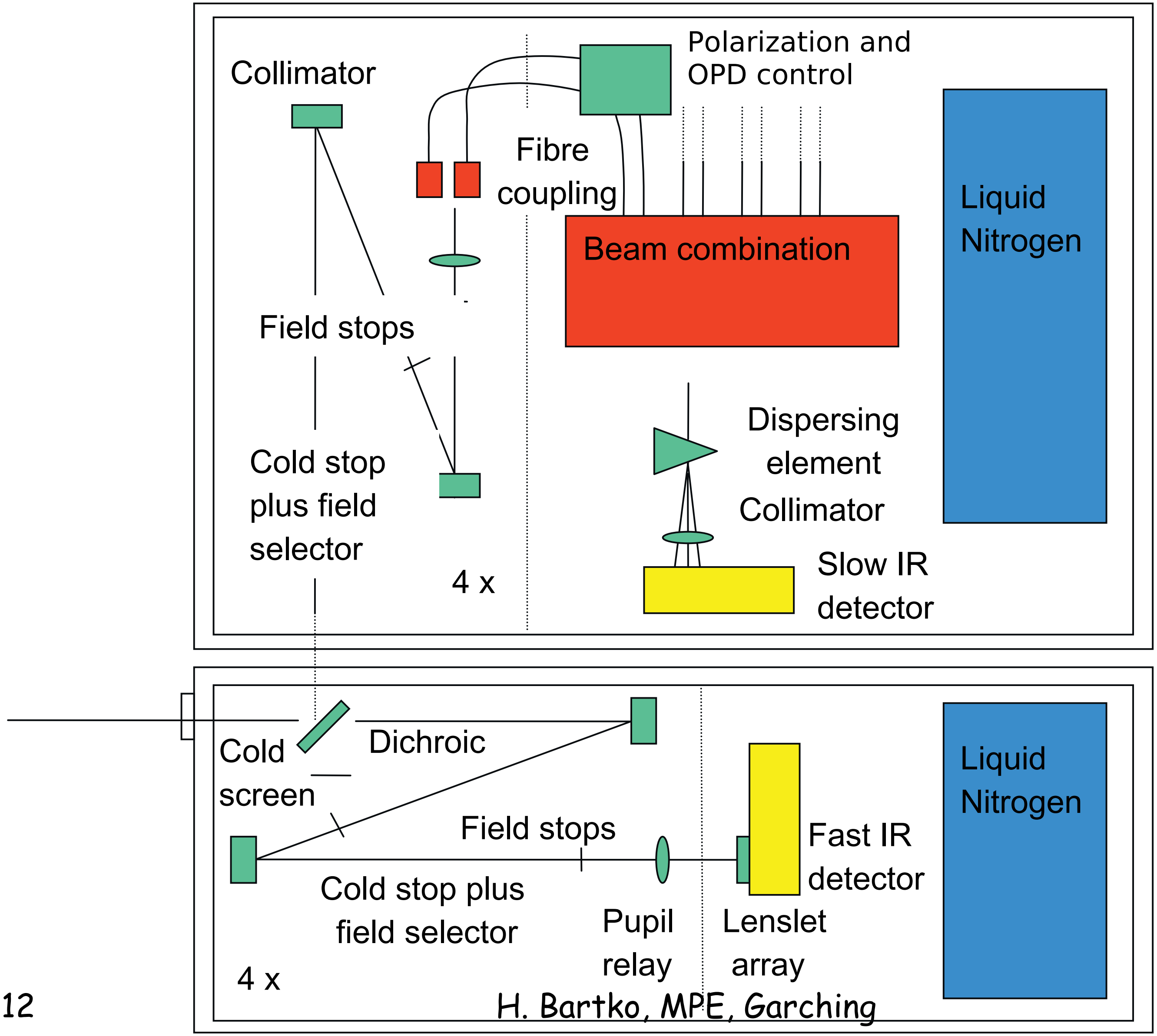
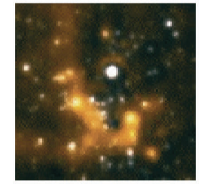
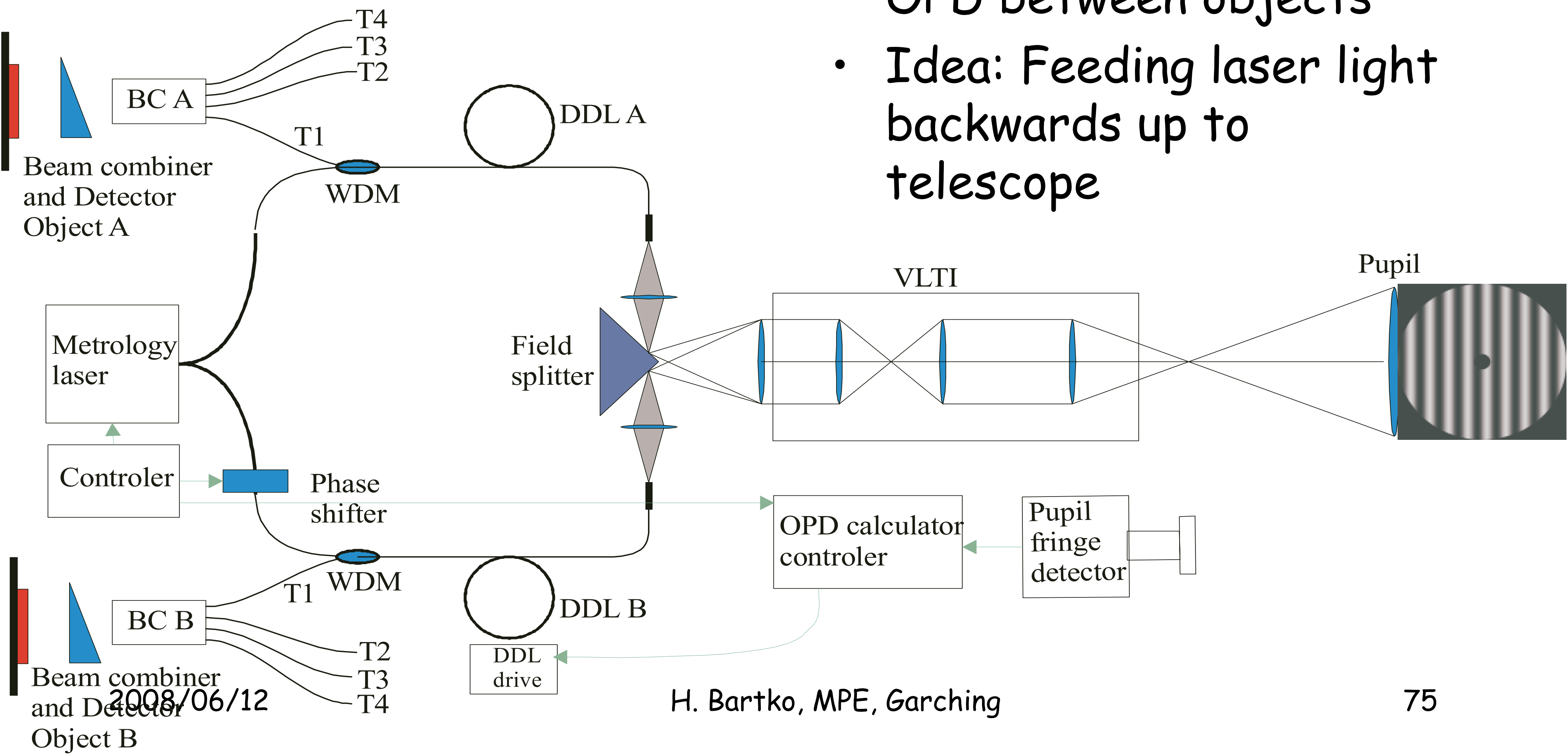
Instrument Concept



New Metrology Concept



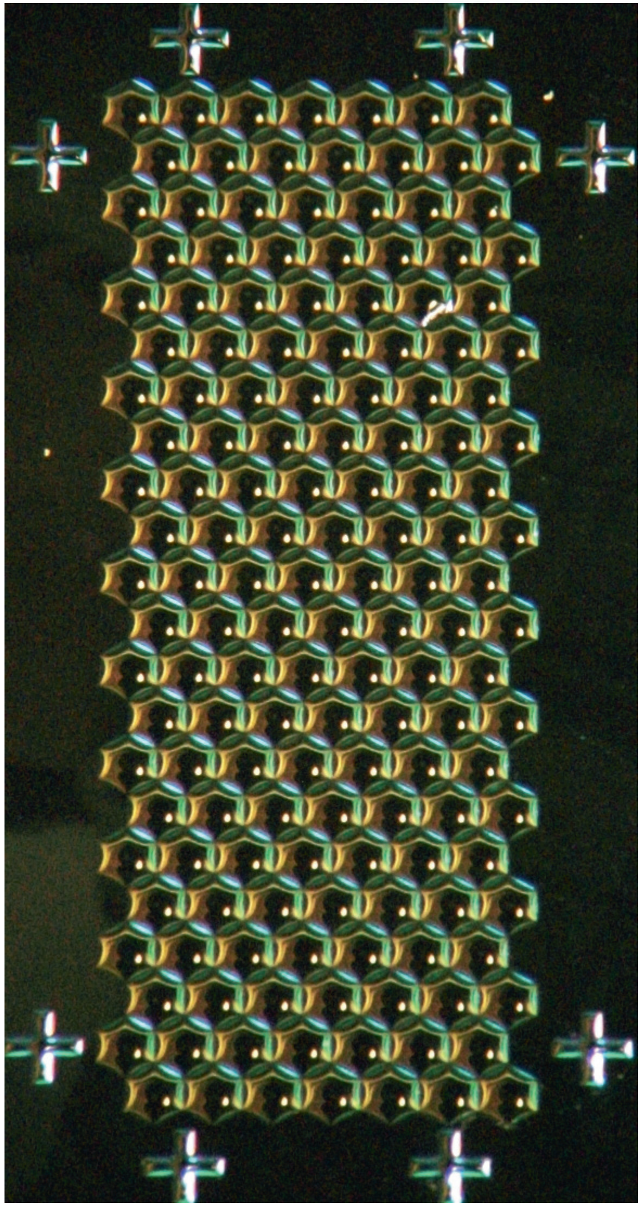
- Metrology needed to measure/compensate OPD between objects
- Idea: Feeding laser light backwards up to telescope



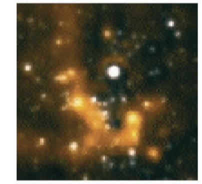
IR Wavefront Sensors Exists

Possible options:

- Shack-Hartmann
  (e.g. NAOS, Rousset et al. 2002)
- Curvature
  (2 detectors, one in front and one behind pupil)

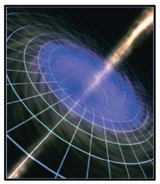


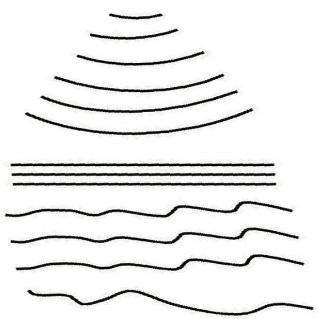
Sensitivity and Accuracy

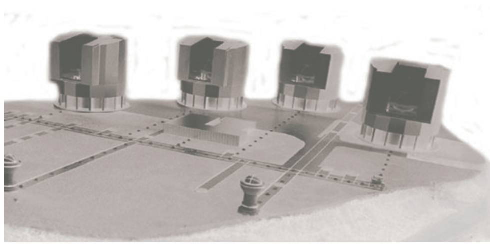


Input definition

Compiling results from subsystems



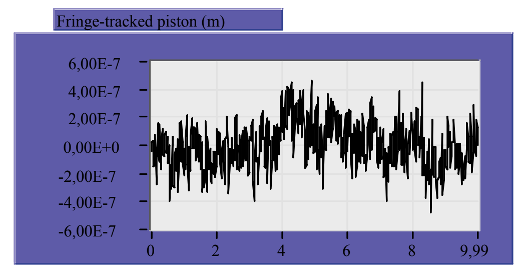




Analytic model

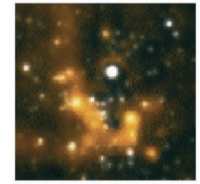
Numeric model

Astrometry



Conclusions

Sensitivity and Accuracy



For K=16 unresolved object in 100 s

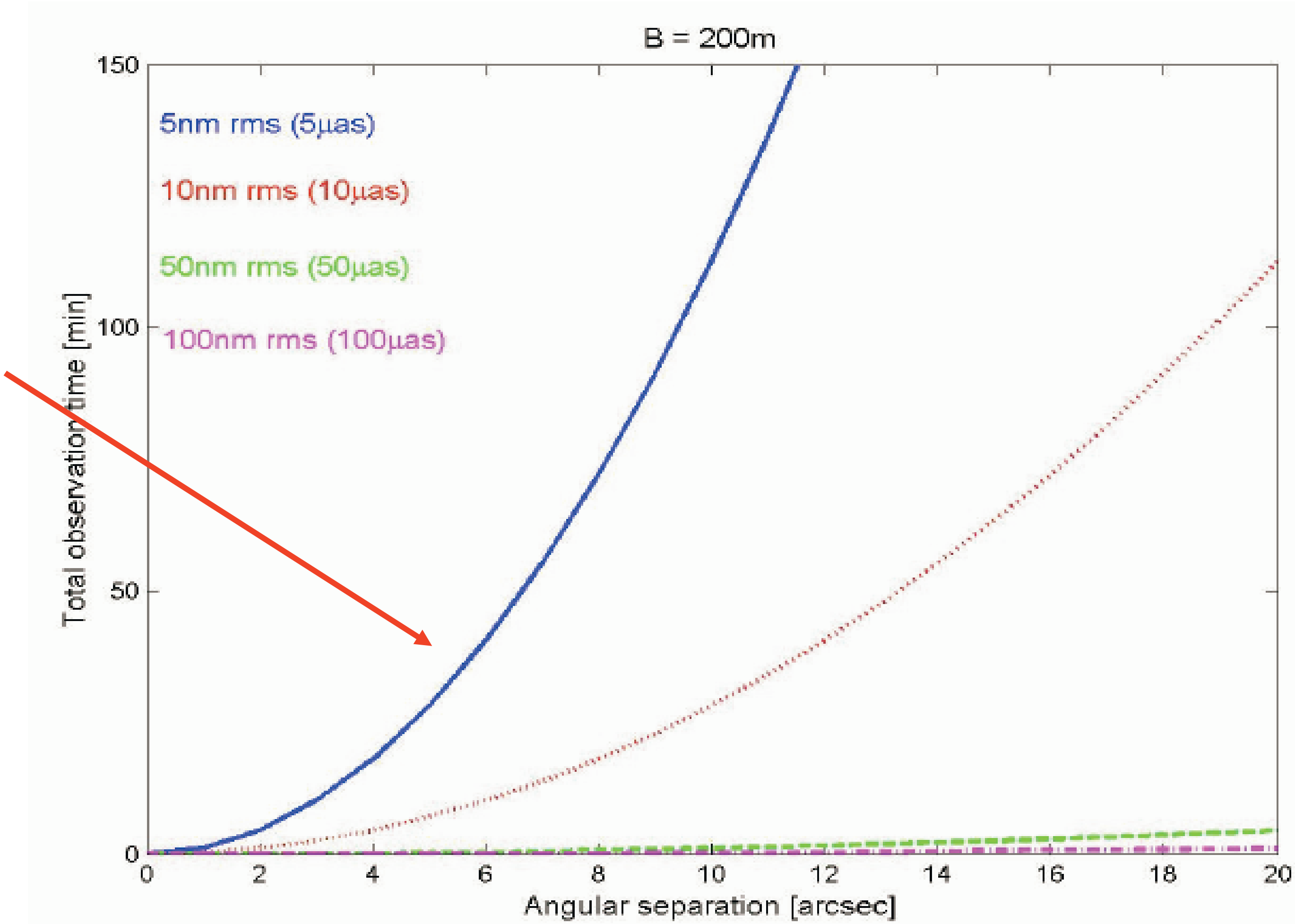
- S/N Visibility = 11
- s_f = 0.06 rad
- Dynamic range > 3 mag

For a K=10 primary and K=15 secondary star with 1″ separation:

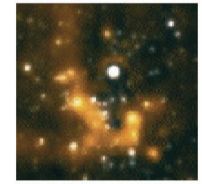
- 10 μas in 5 minutes

Sensitivity and Accuracy

Atmosphere allows for 10μas astrometry in 5 minutes

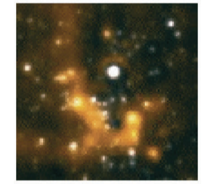


Frank



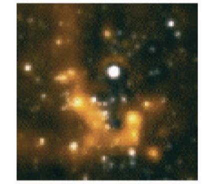

Thank you
Credit: Thomas Lucas Production

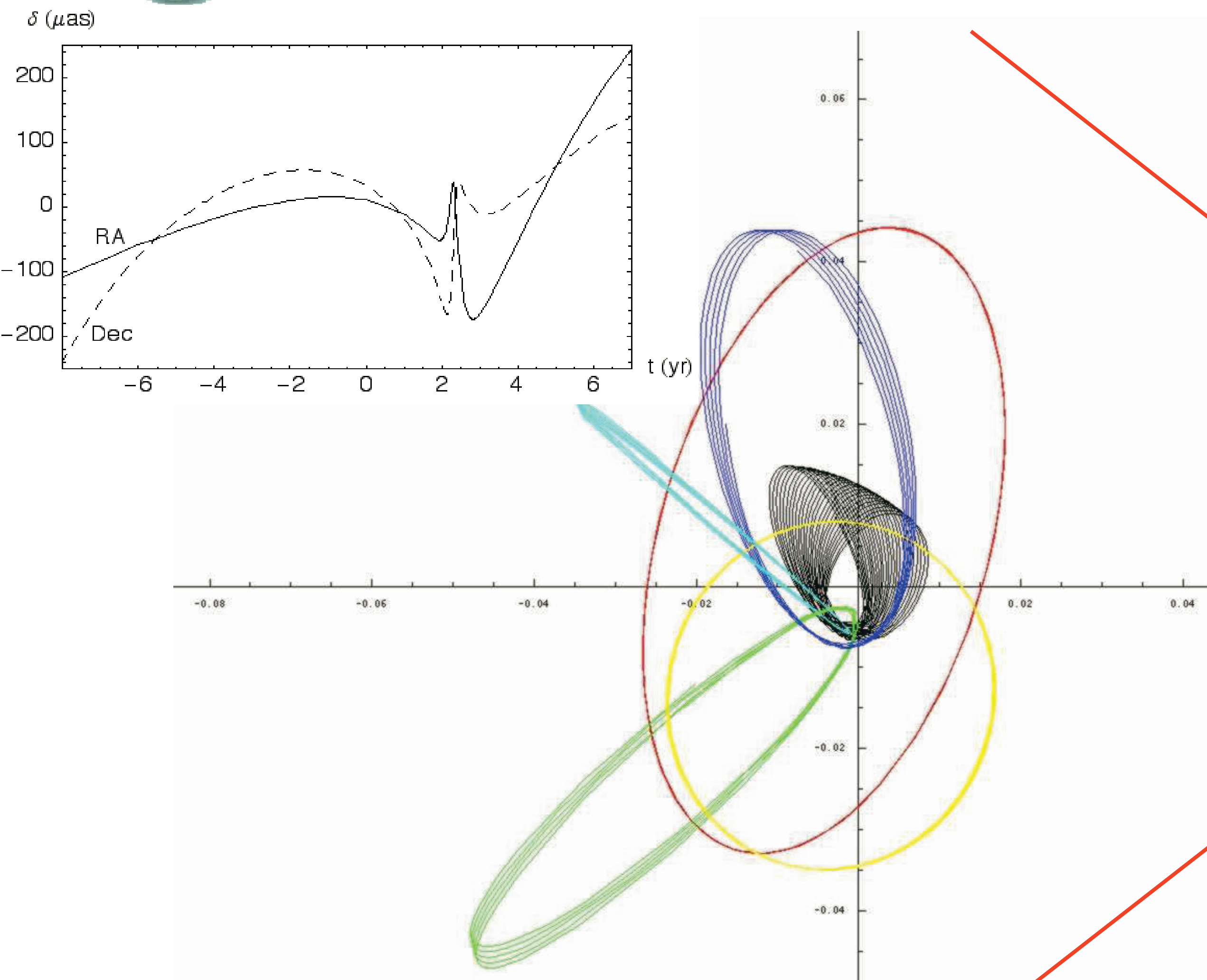
The VLTI can do 10 μas Astrometry

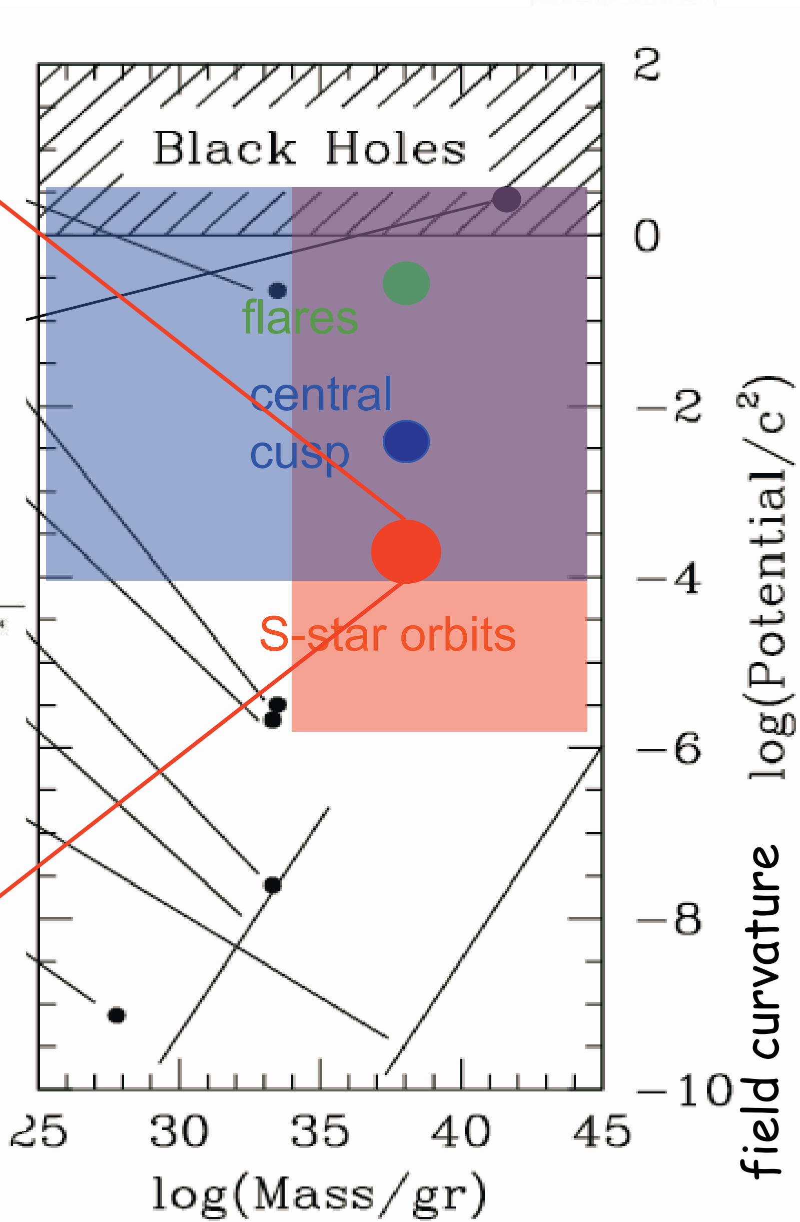


At 10 μas astrometric accuracy the Universe starts moving

Non-Keplerian Orbits







β² general relativistic effects in S-star orbits

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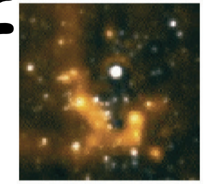
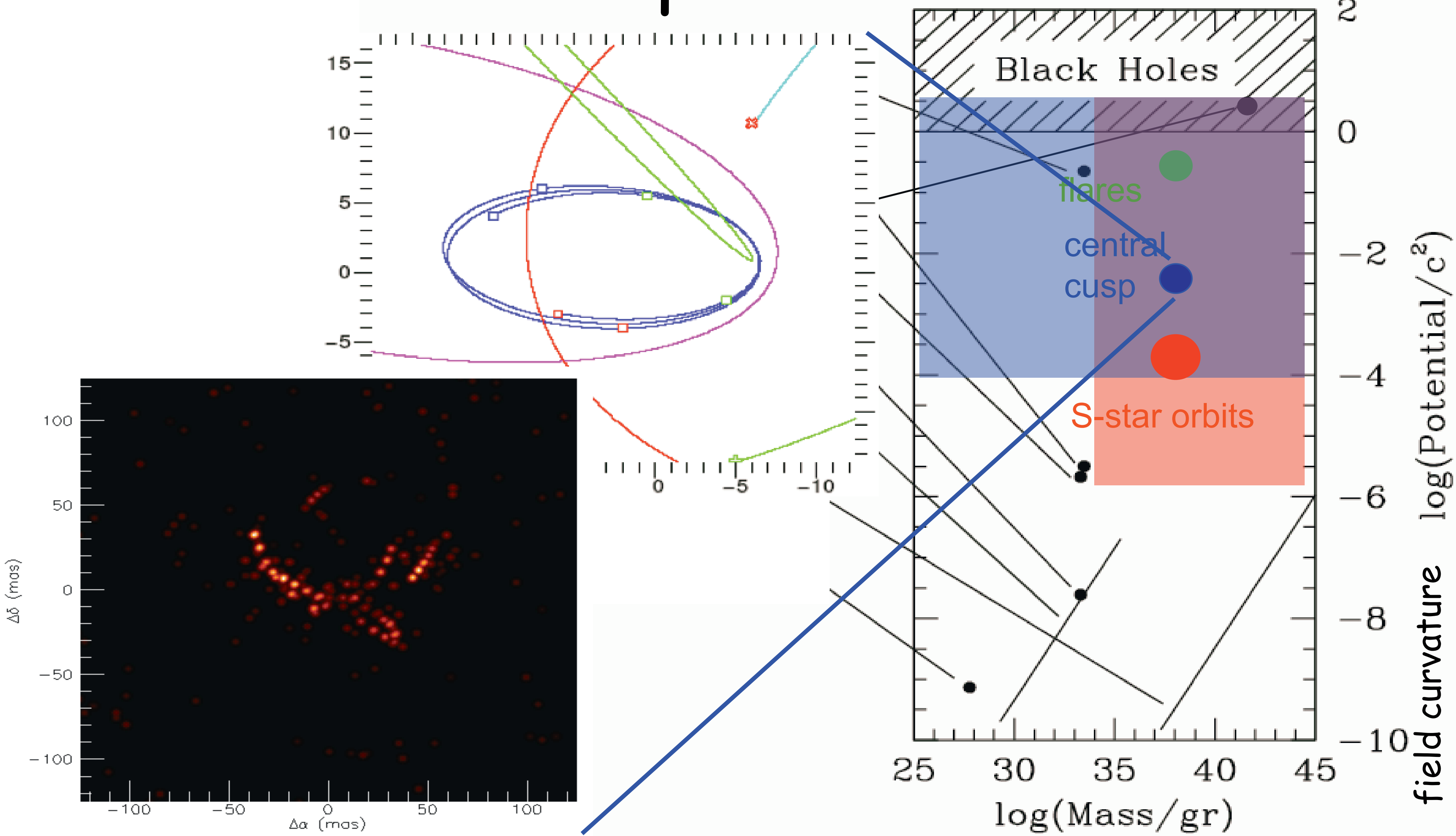
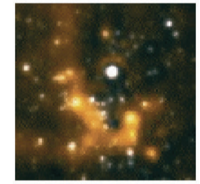
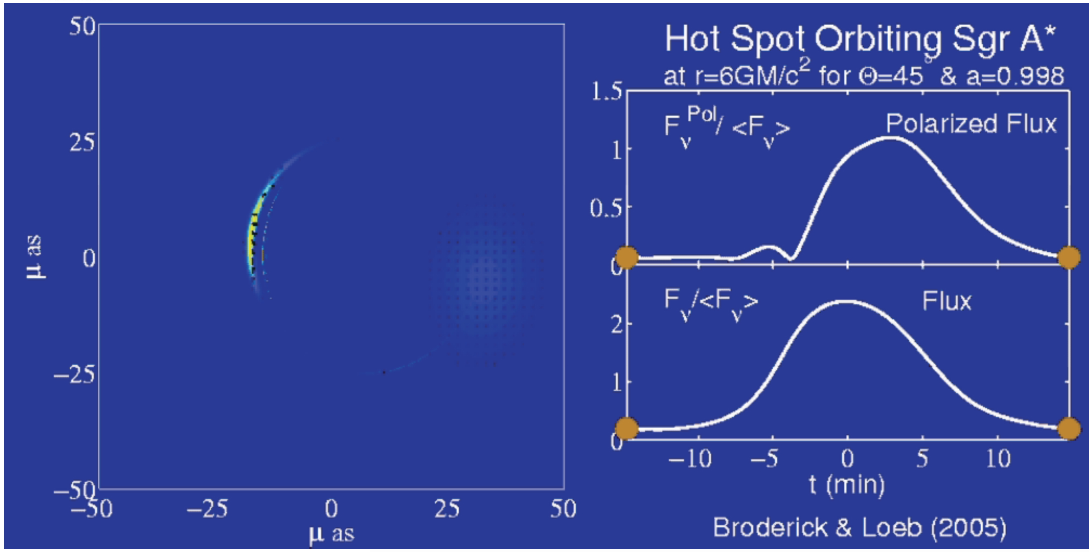
Lens Thirring Precession of Cusp Stars

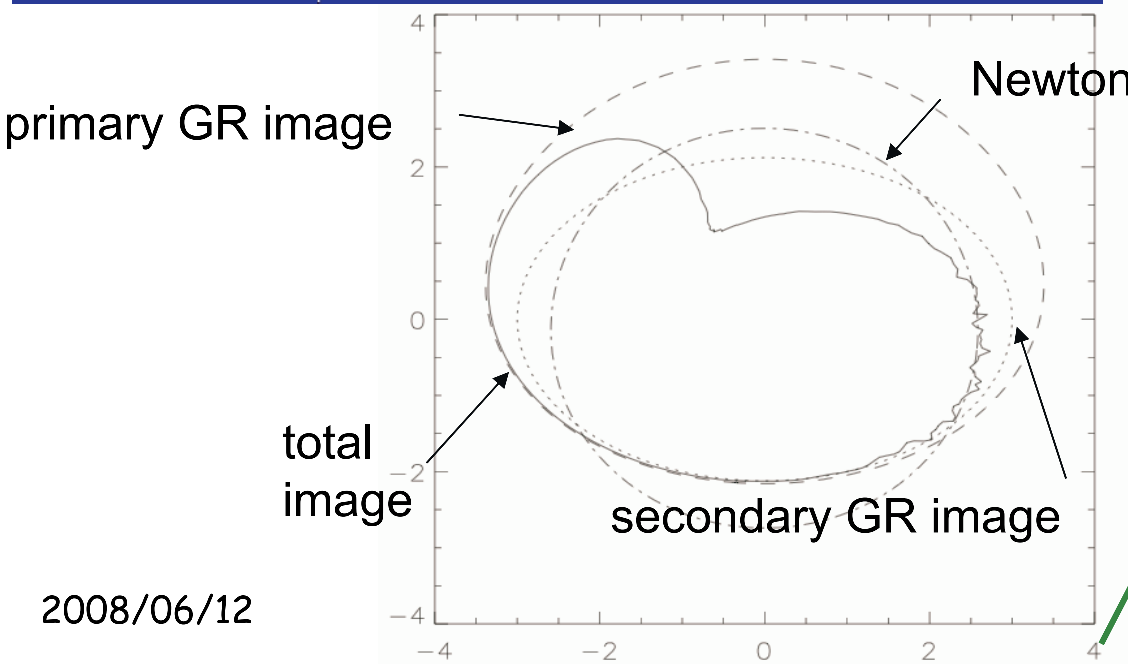


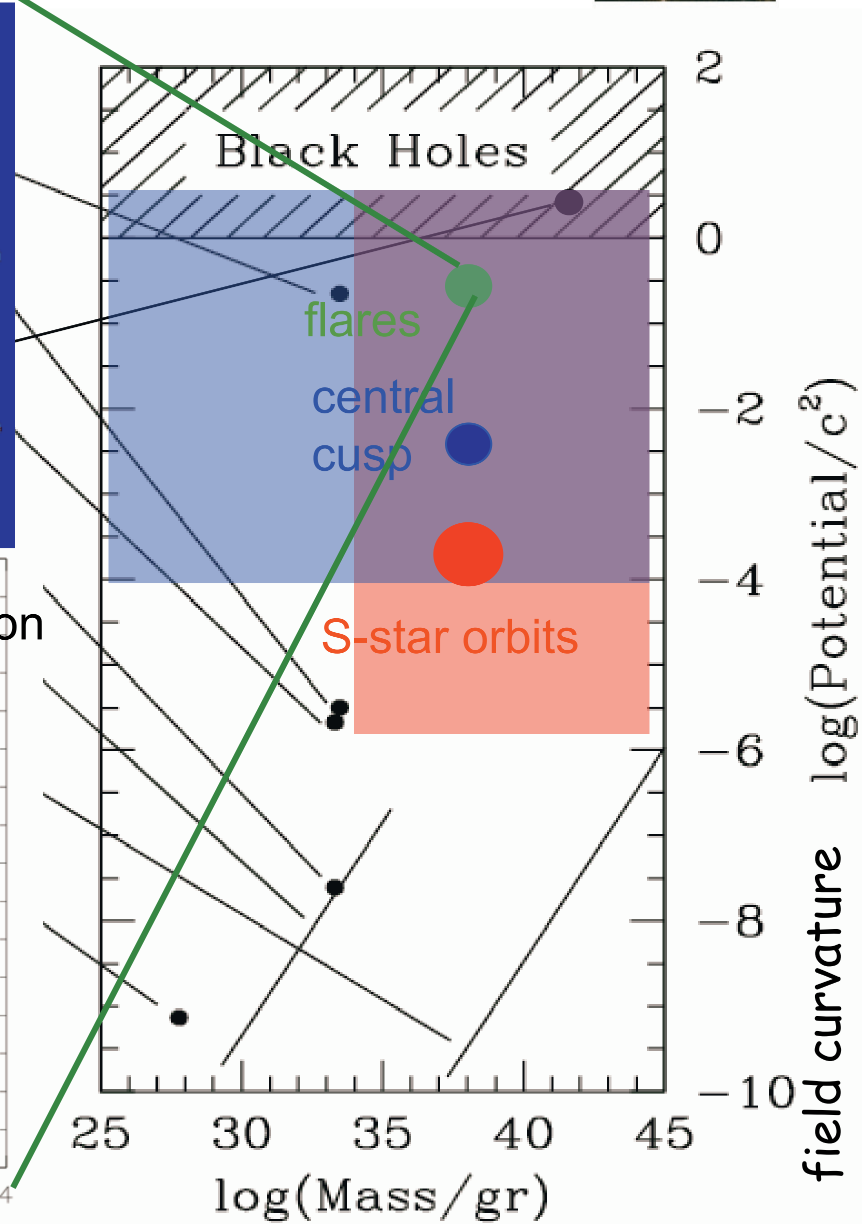


Flares - Last Stable Orbit









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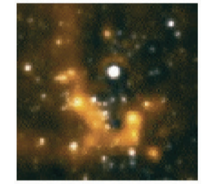
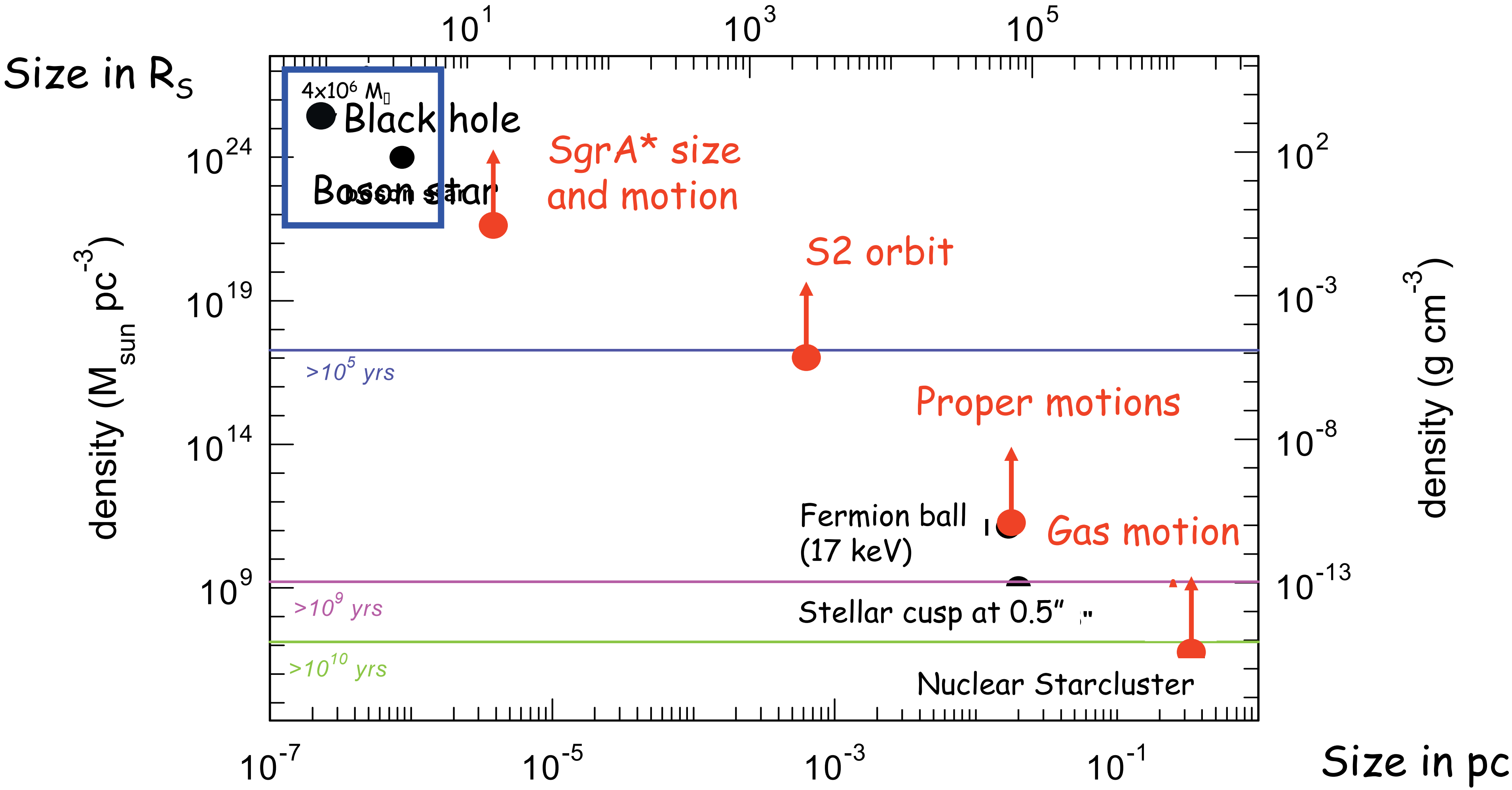
Best case for a Black Hole

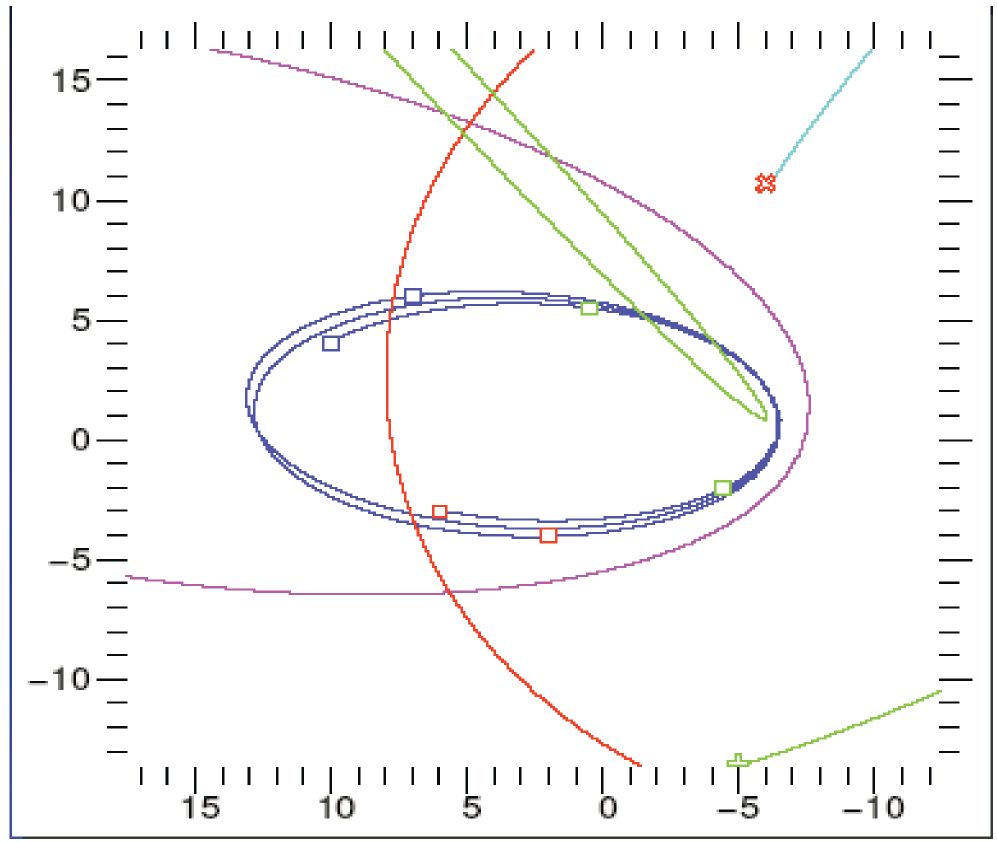




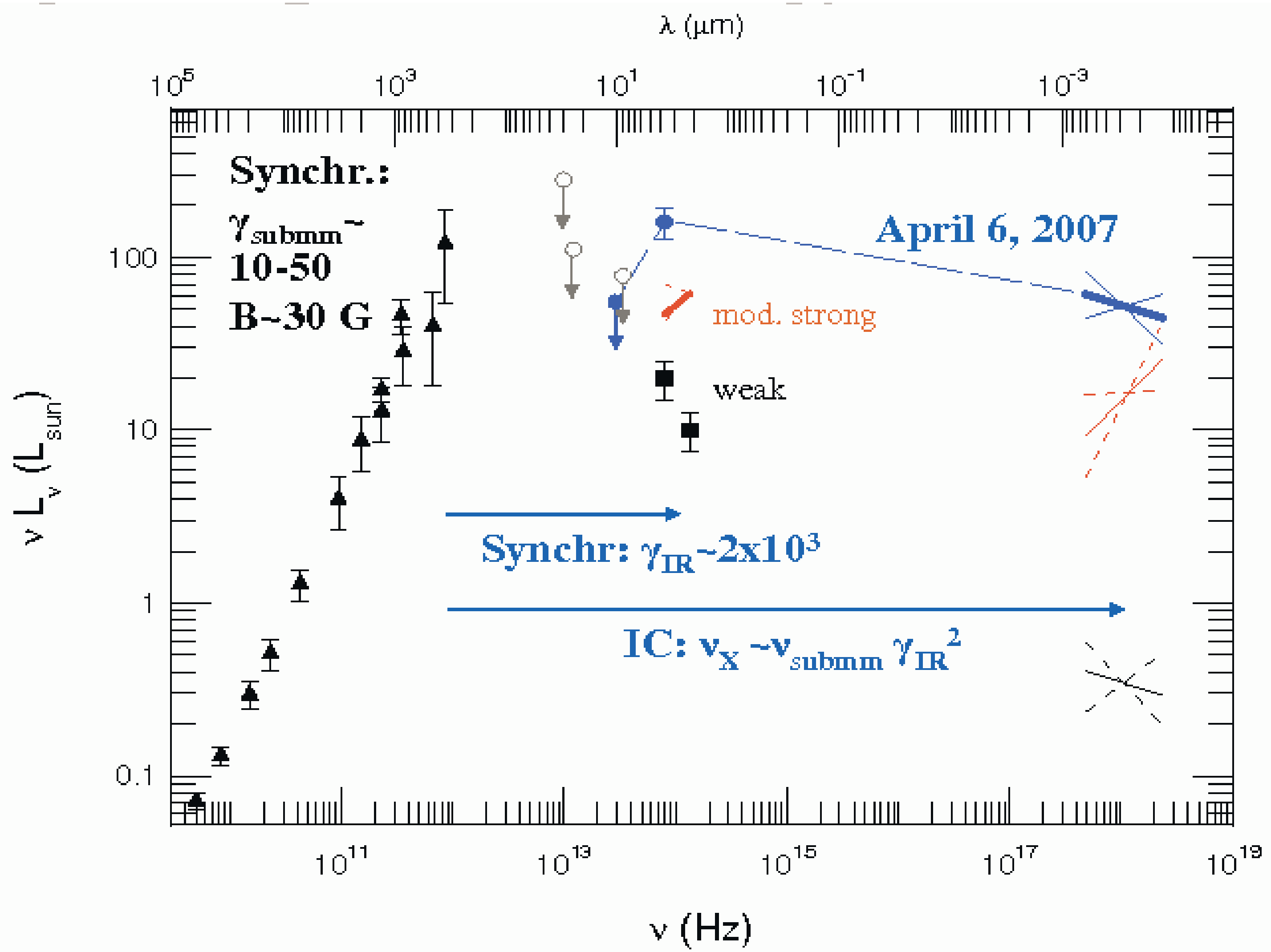
Well within reach of VLTI

Simulation:

- 2 years * 3 nights * 9 hours * 4 UTs



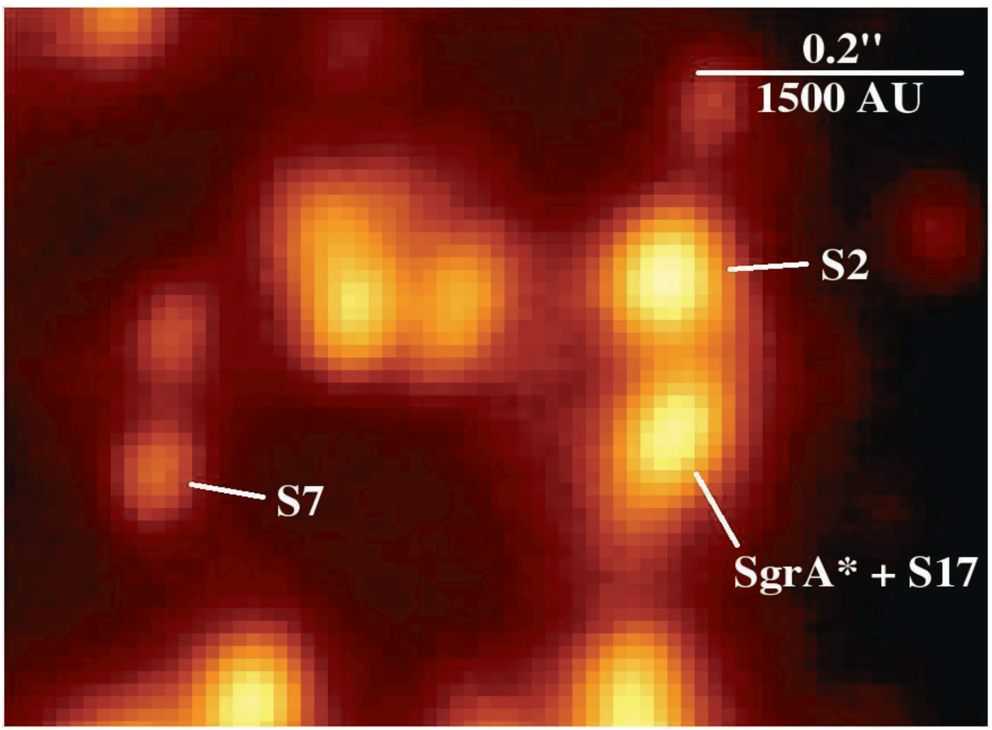
Simultaneous X-ray Flares

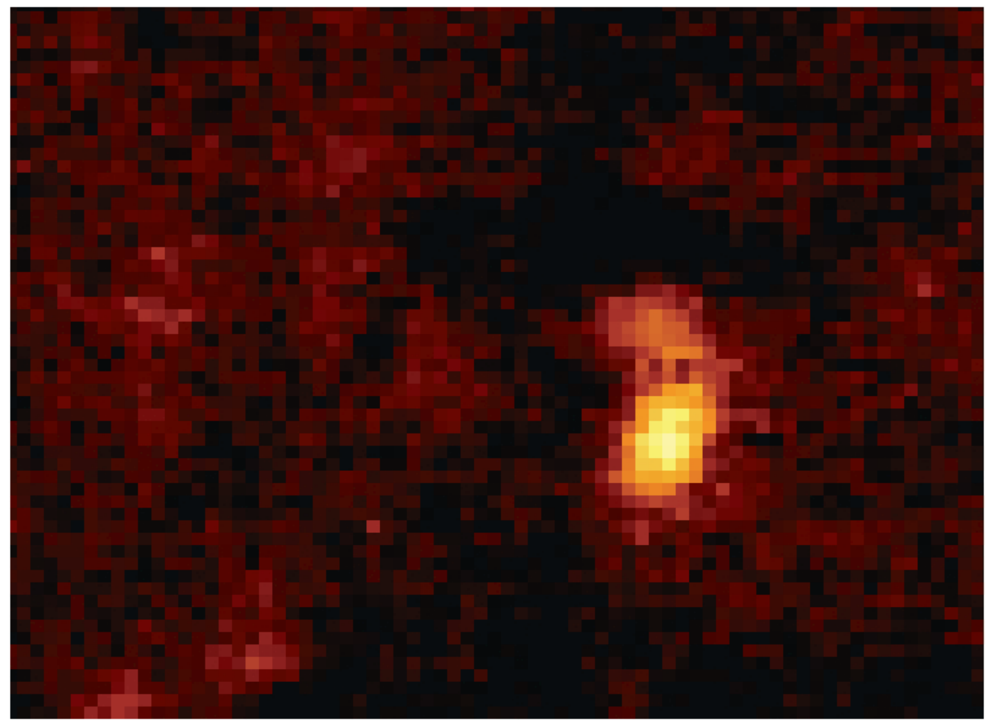


.. hot spots orbiting on the accretion disk?

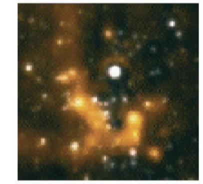
Flares Strongly Polarized (10% - 40%)

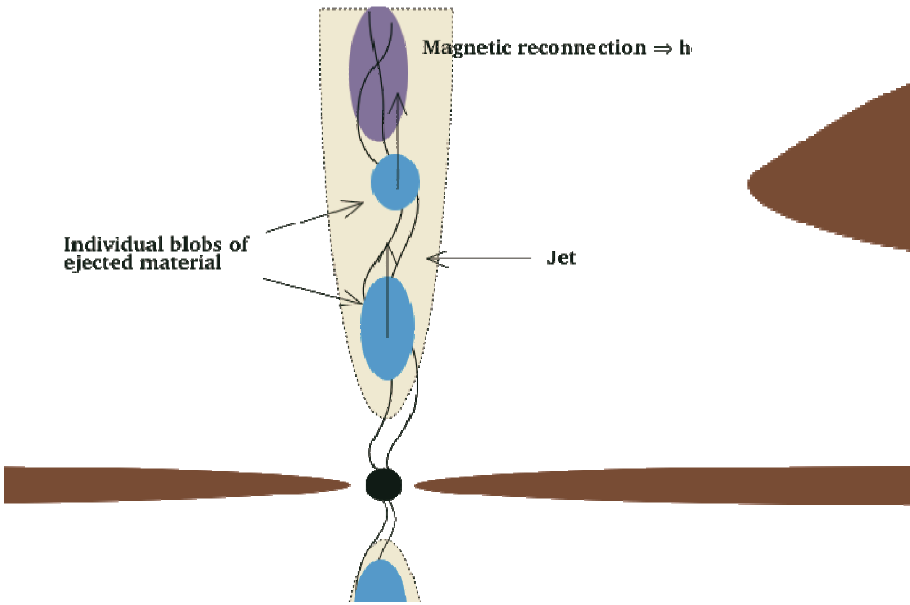
suggests synchrotron origin of the IR emission

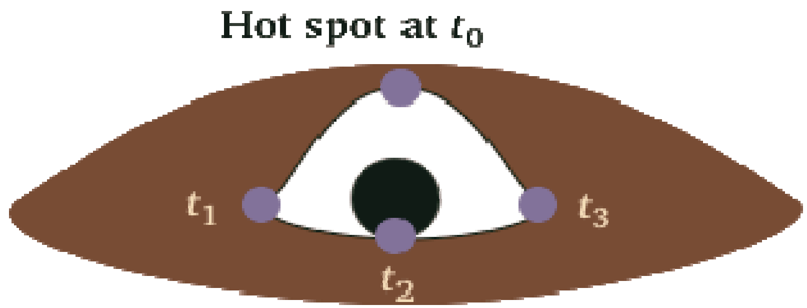


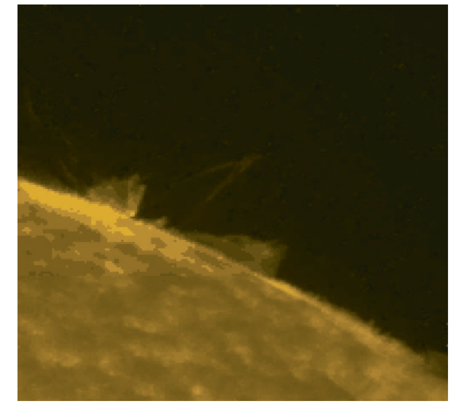


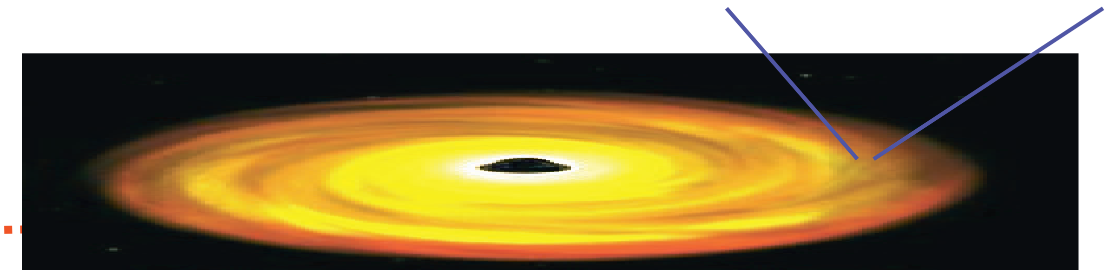
But … is the Model Right?











Brightness and SED variations

Faintness, SED, rotation measure

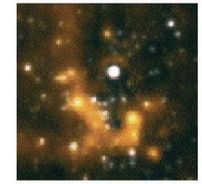
Few R_S

↓

Event horizon

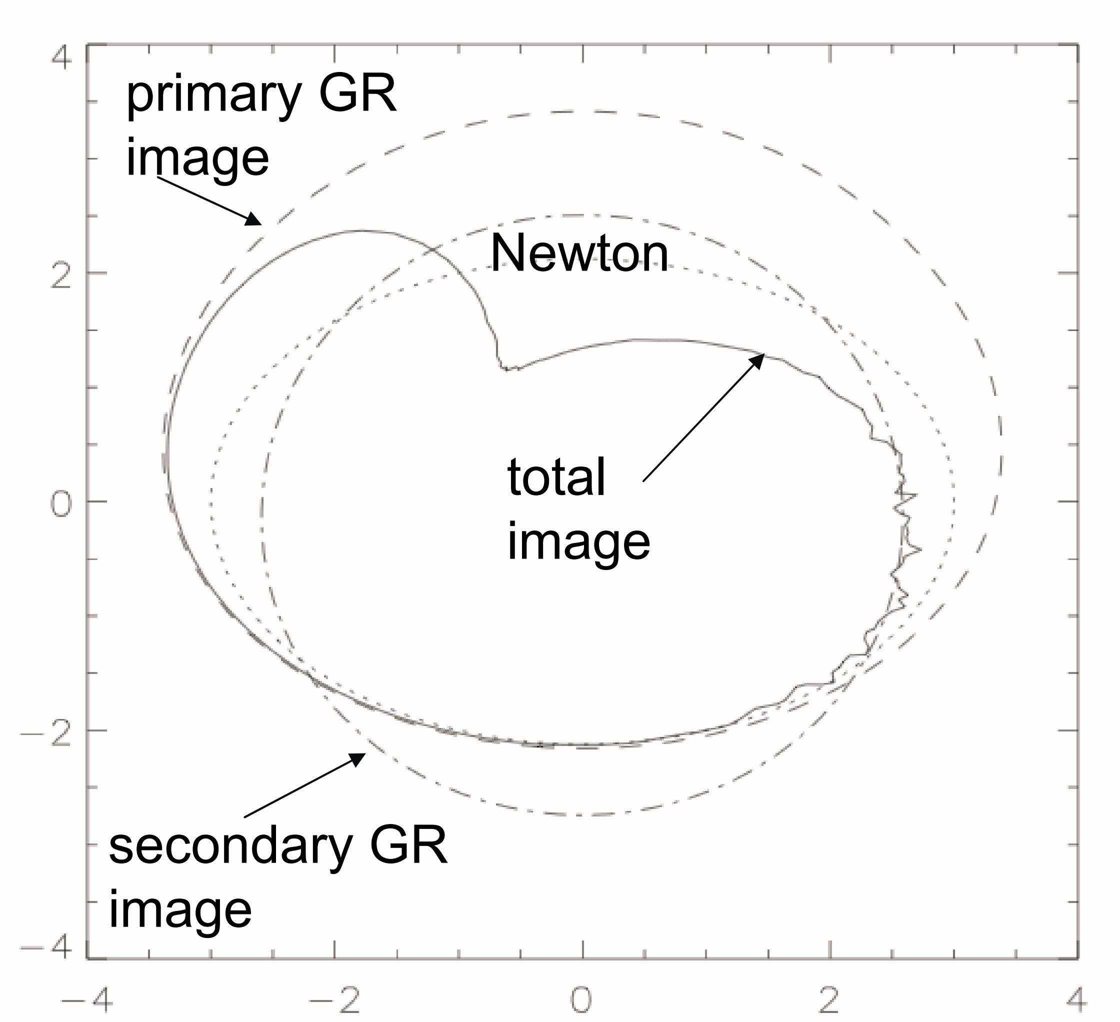
?

Flares Move at Speeds Observable with GRAVITY



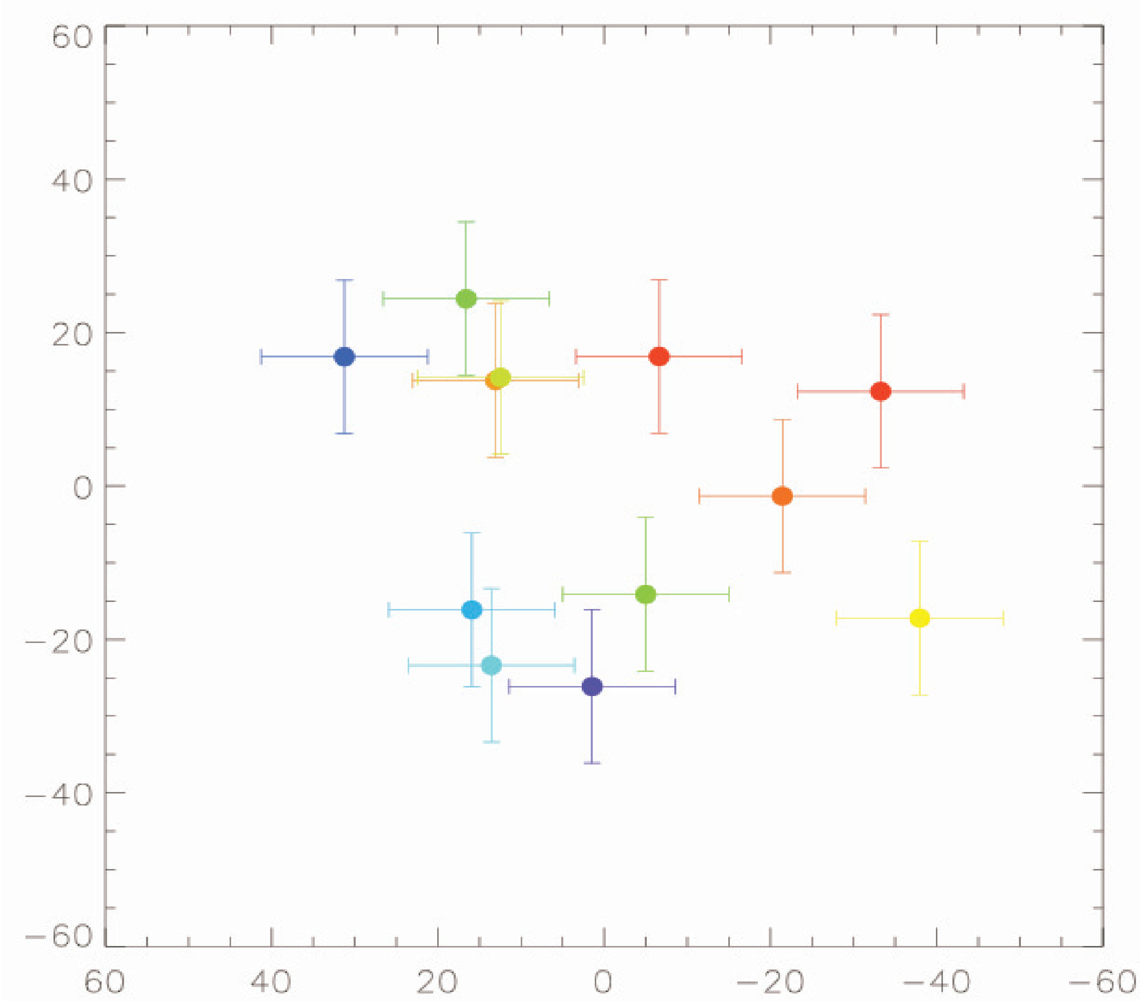
- The emission region is small
- The emission originates from very close to the event horizon
- The material has to move at 10% - 90% of the speed of light (15 μas/min)
- During one hour the travelled path is several hundred μas

The path of the centroid shows strong GR effects

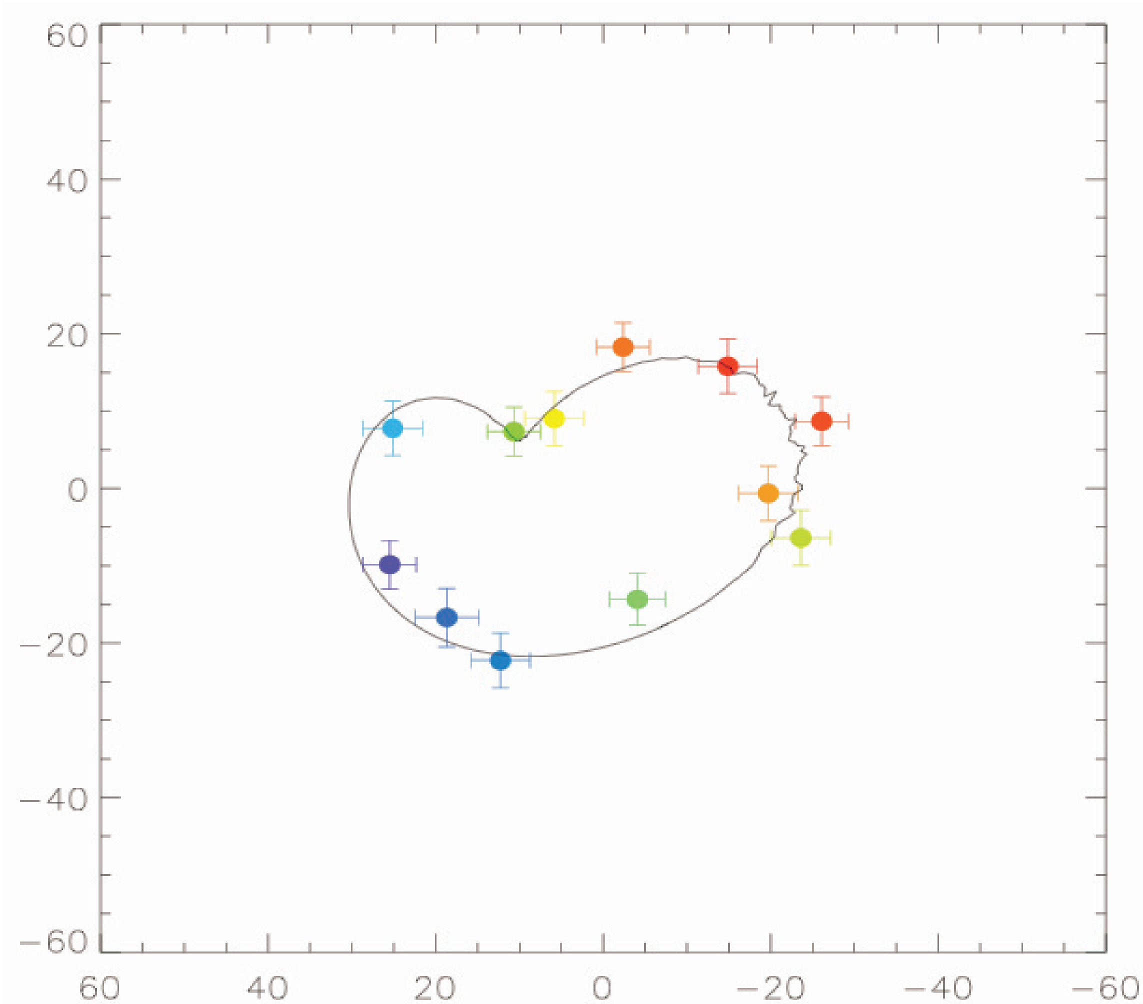


Observing one flare

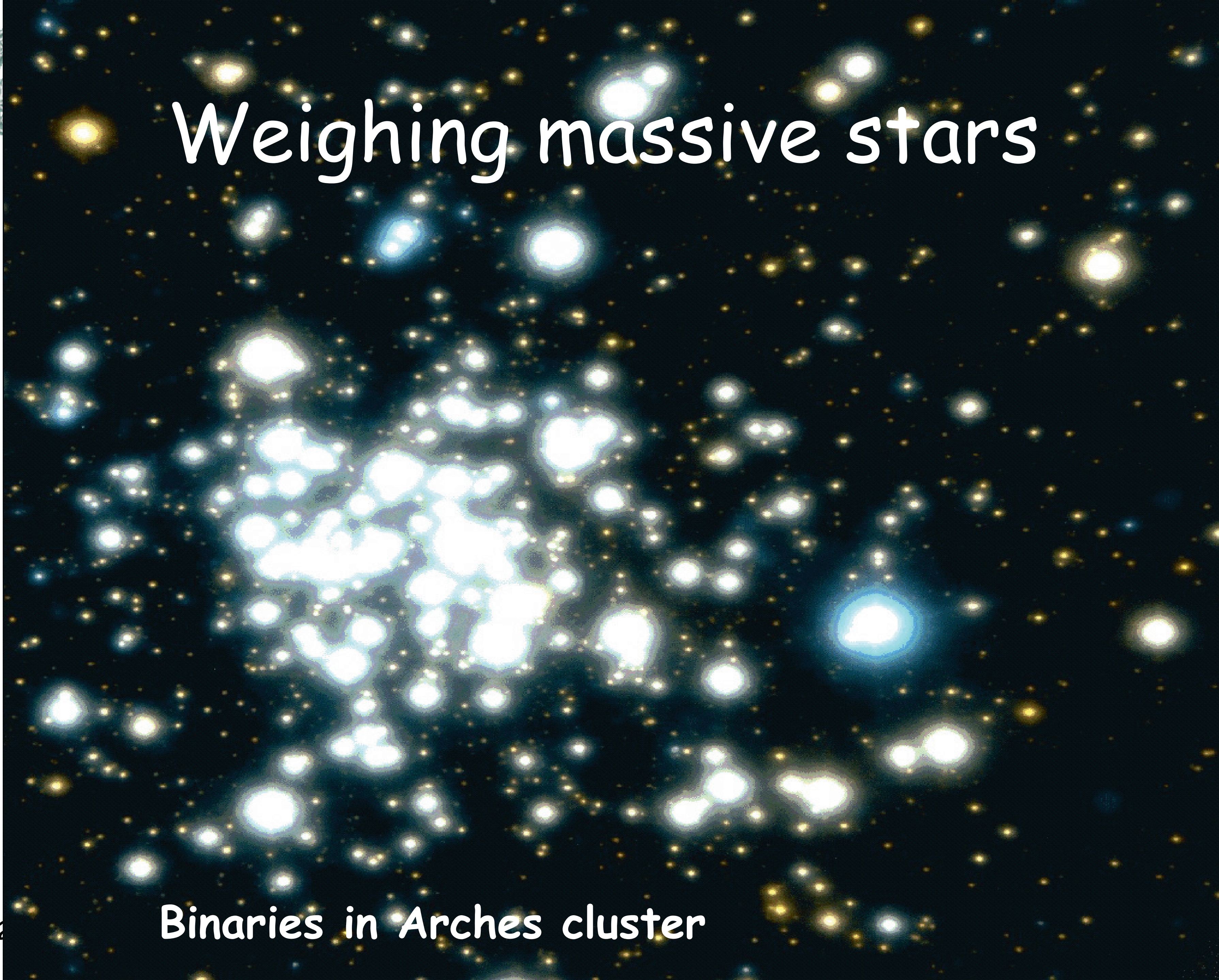
proves or disproves the orbital nature



Coadding 10 flares reveals the GR effects



Weighing massive stars

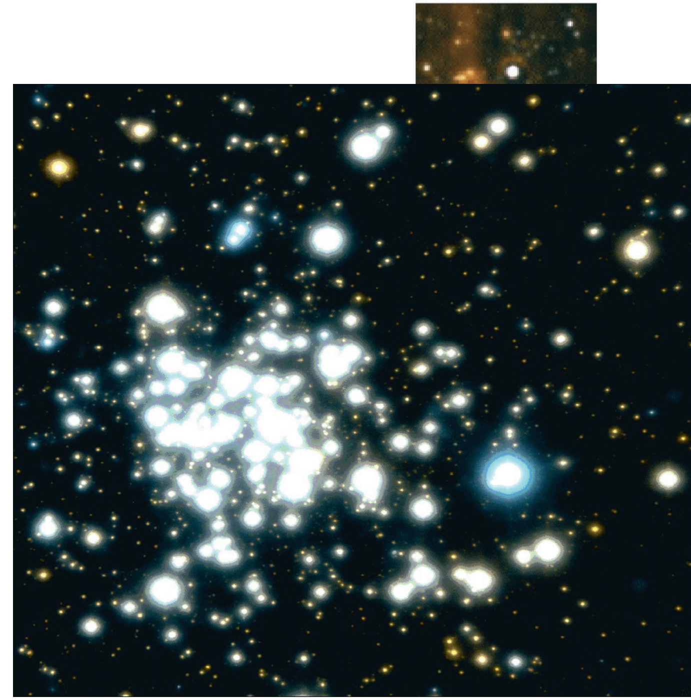


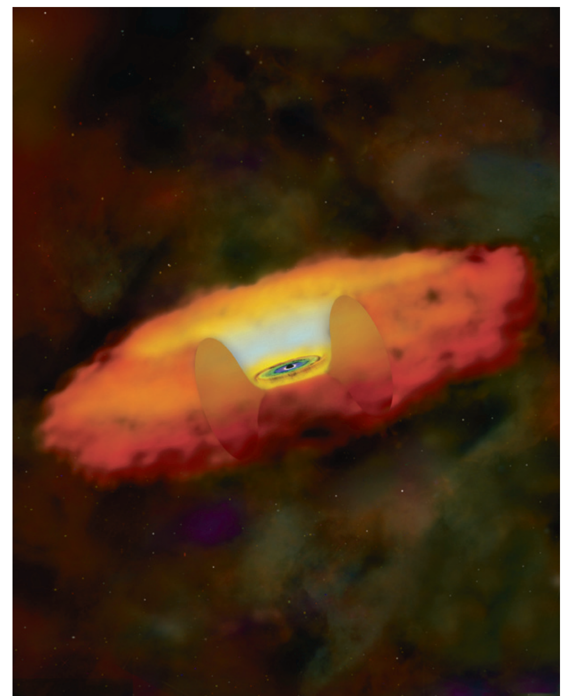
Binaries in Arches cluster

Non-BH cases

- astrometrically resolve spectroscopic binaries
  - obtain masses
  - probe upper end of stellar mass scale

- Map out AGN
  - detailed picture to be tested





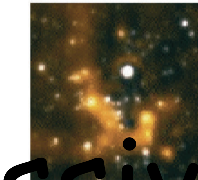
Hunt Intermediate mass BHs

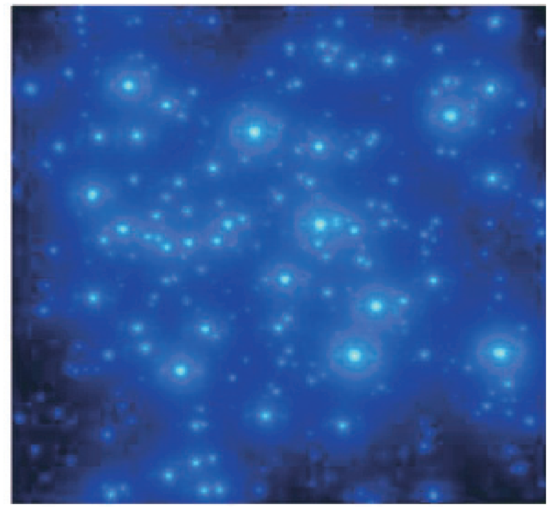
- Seeds for SMBHs ?
  - formed through core collapse of Pop III stars at $z = 10$

- Compelling case IRS 13 (close to GC)
- Globular Clusters

- Use interferometric gain to see lower masses in Galaxy

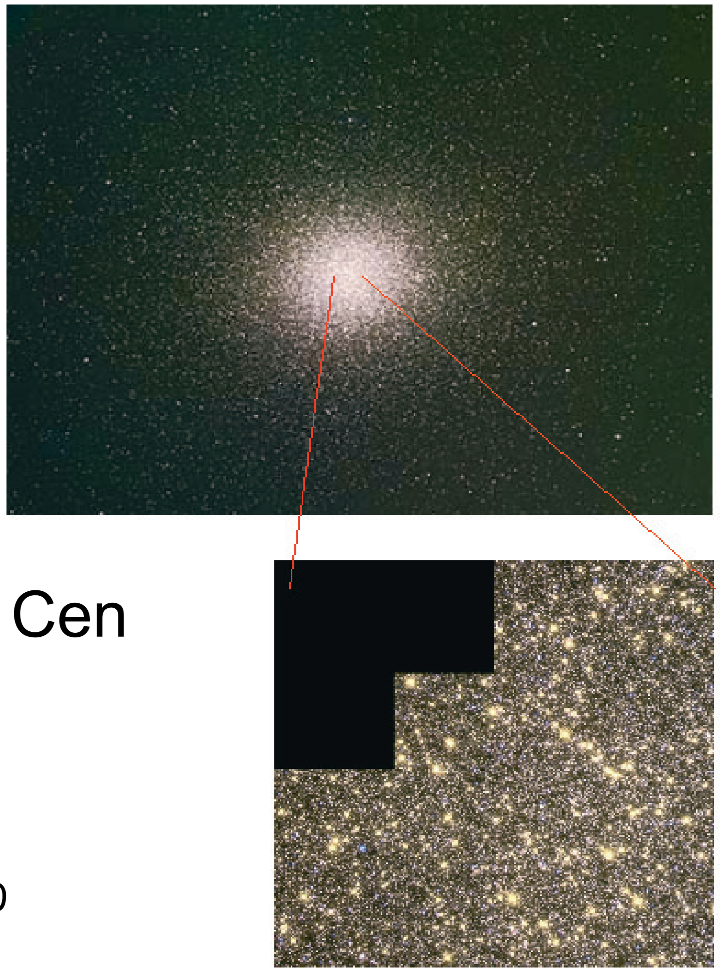
For a few stellar systems intermediate or moderately massive black holes can be probed

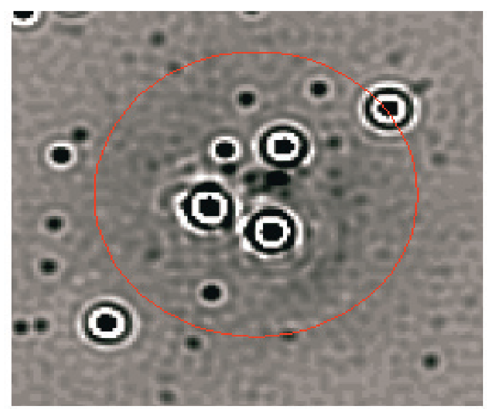




Arches

omega Cen



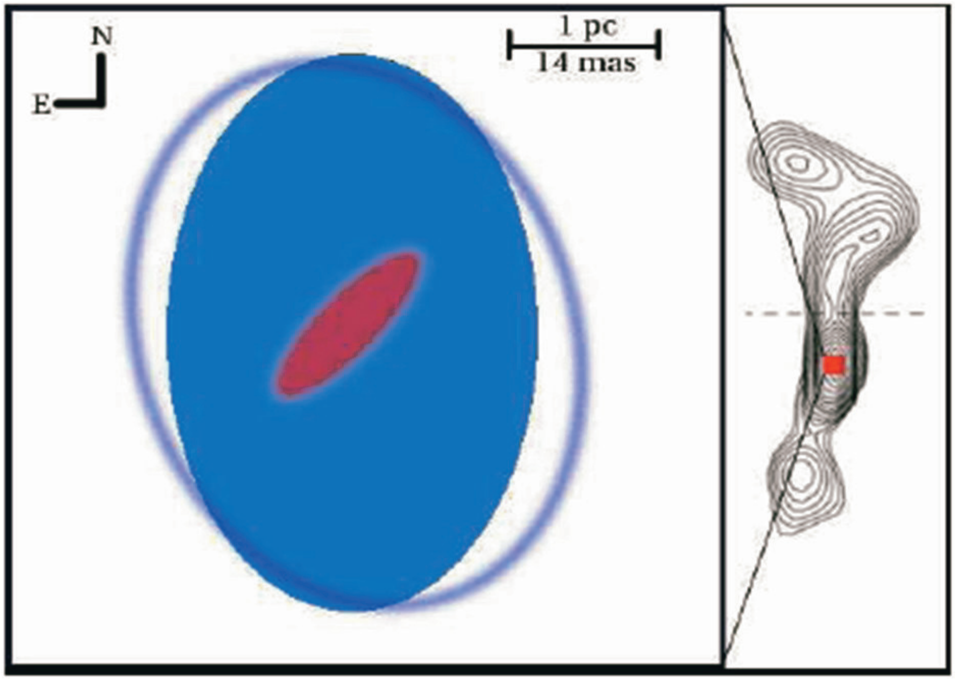


IRS 13

Active Galactic Nuclei

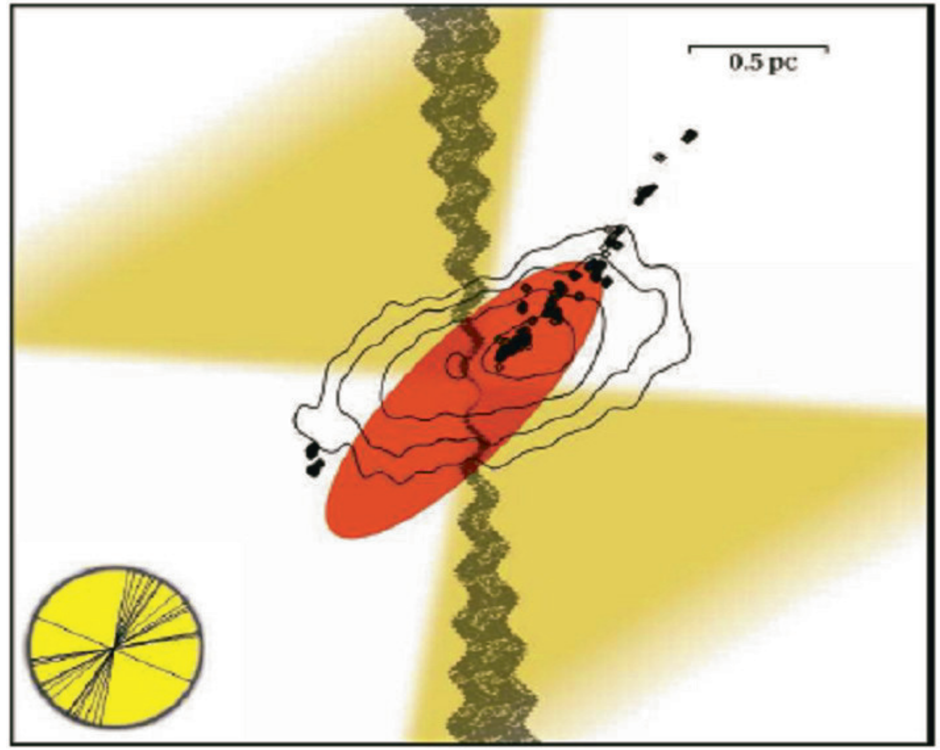
3. Active Galactic Nuclei

NGC 1068



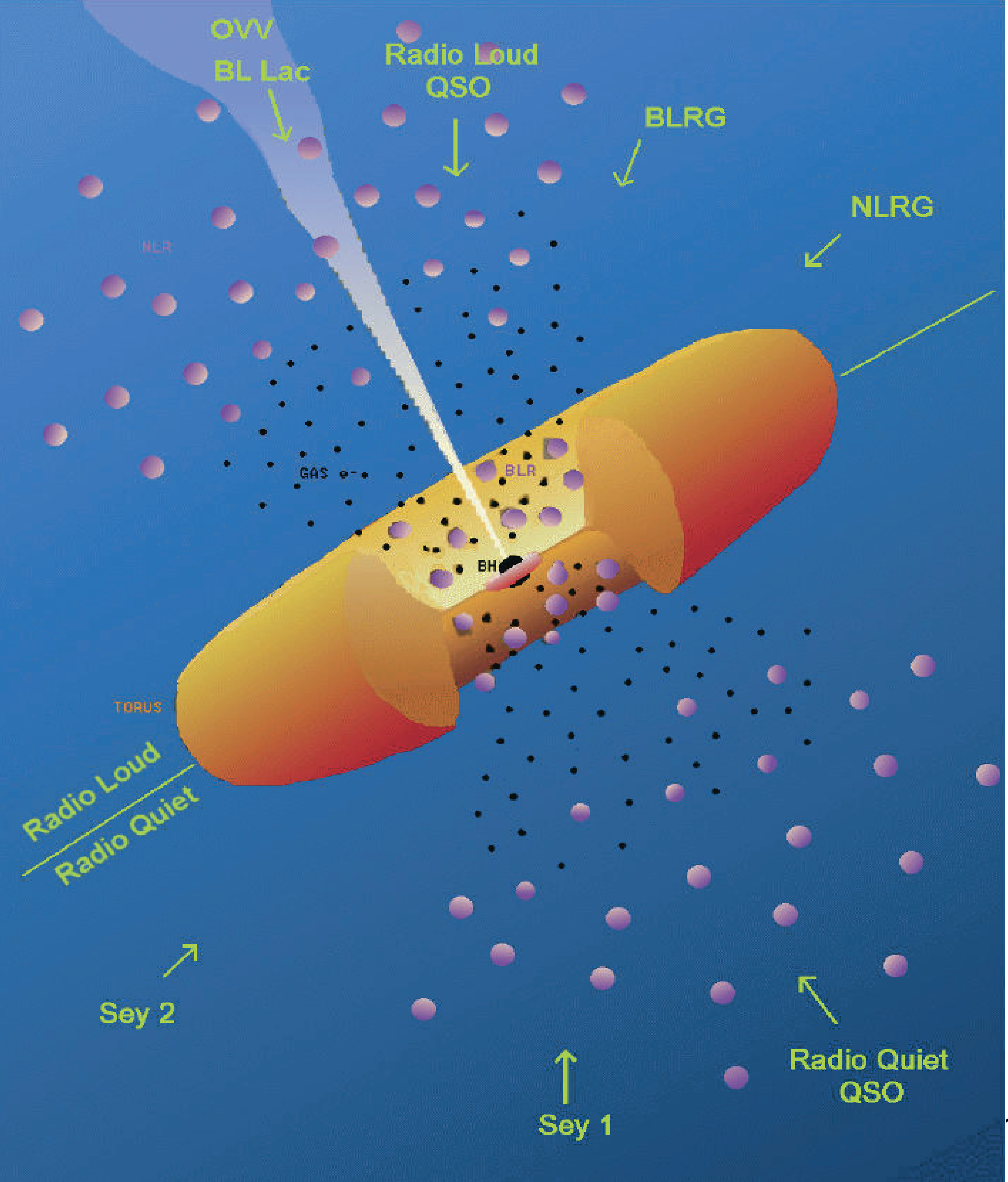
dust emission: torus or NLR?

See Walter Jaffe's talk

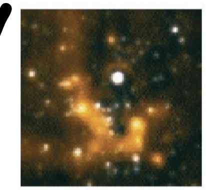


maser disk, AGN jet and BH accretion

BLR sizes, nuclear star cluster, gas motions



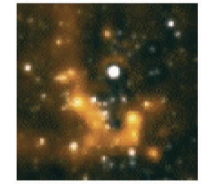
GRAVITY can measure the Dynamics of the BLR



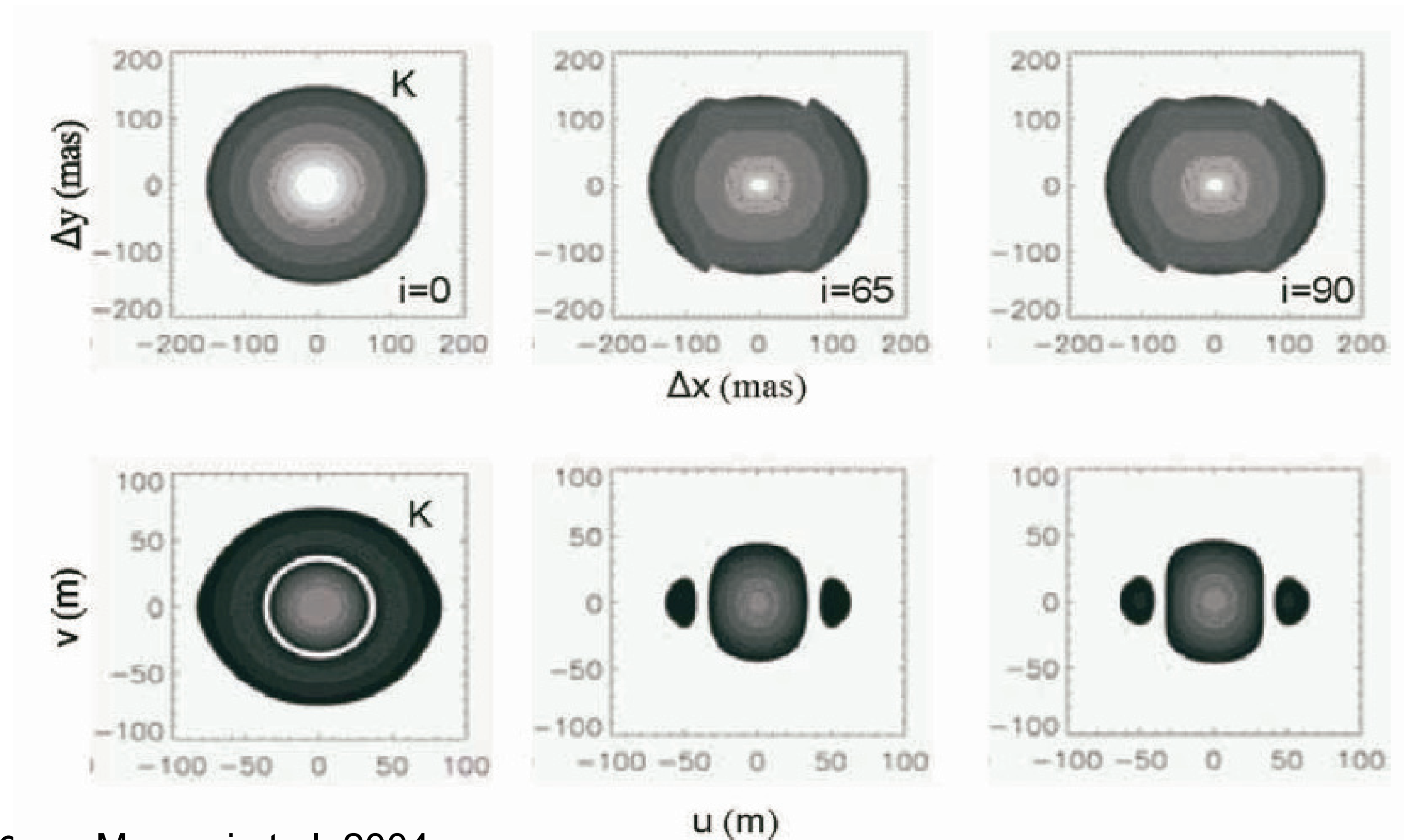
Search for rotation pattern:

Radial velocity from Br-gamma or Pa-alpha as function of position

Dust Torus Structure

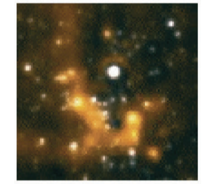


GRAVITY allows one to access the structure and composition of the clumpy dust torus

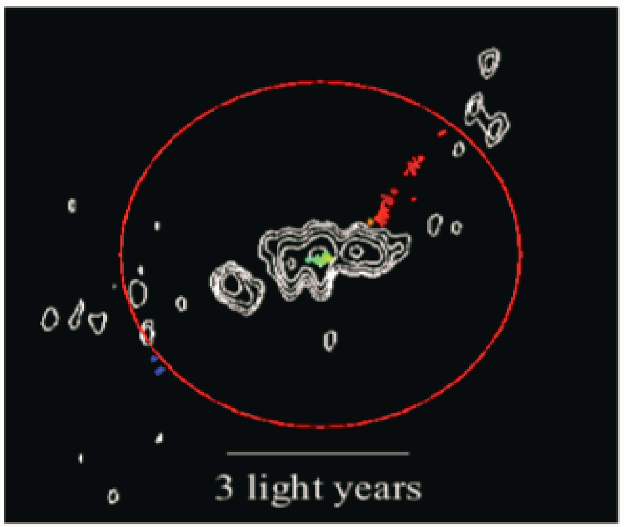


Marconi et al. 2004

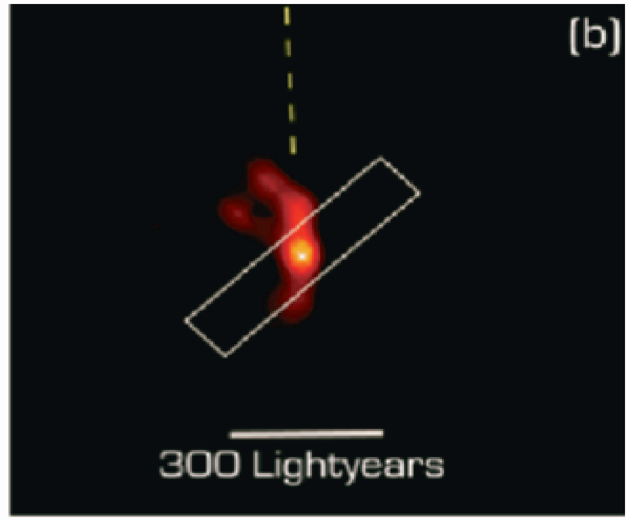
NGC 1068:
Already a VLTI Target



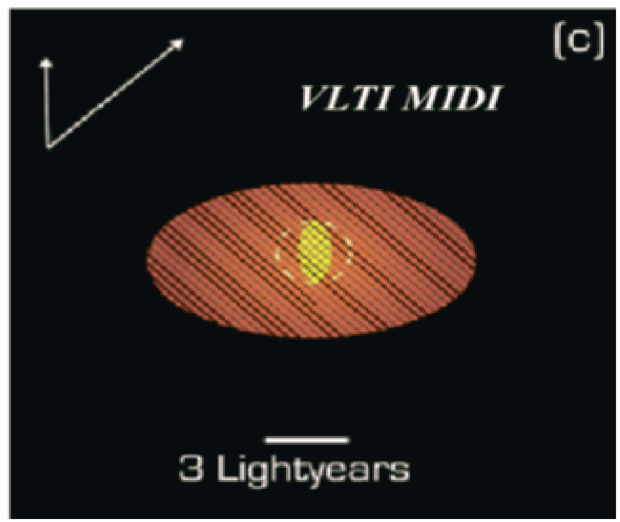
VLBA,
cont. + water masers



Greenhill et al. 1998,
Gallimore et al. 2004



VLT 10μm

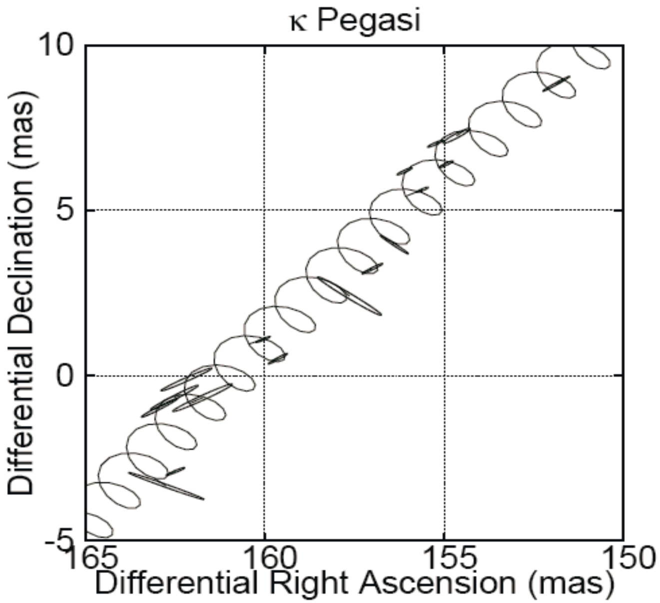


VLTI MIDI

Jaffe et al. 2004

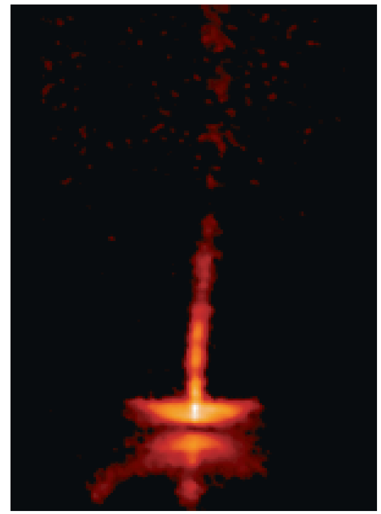
Star and Planet Formation

Do jets originate in disk winds, or are they driven by a central engine?

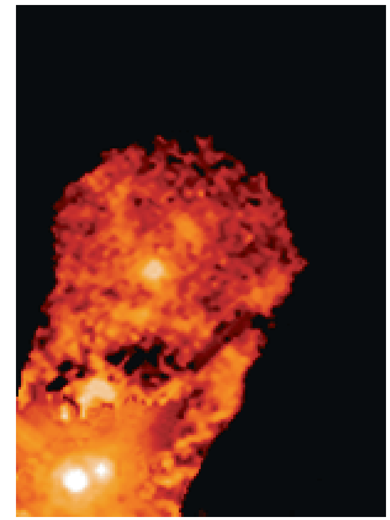


Muterspaugh et al. 2006

HH30



XZTau



FoV: 3″ x 6″ (300 AU x 600 AU) over 5 yr

(Krist et al.)

Giant planets in close binary system:
Probing the parameter space missed by PRIMA (close and faint systems)