ESO in the 2020s, 20 January 2015, Garching, Germany

# The Centre of the Milky Way

An easy one, for today: stars and star formation, ISM, galaxy evolution, accretion, supermassive black holes, fundamental physics
A difficult one, in general: technically, observationally, theoretically
A highly competitive one, worldwide, but rewarding

- The last decade(s) – an overview
- The basis for success – telescopes and instruments
- The topics for the coming decade(s) – an educated guess
- ESO's role and how it can best contribute

Frank Eisenhauer (Max-Planck-Institute for extraterrestrial Physics)

# The Center of the Milky Way

Courtesy ESO

# The Galactic Center harbors a black hole

Massive

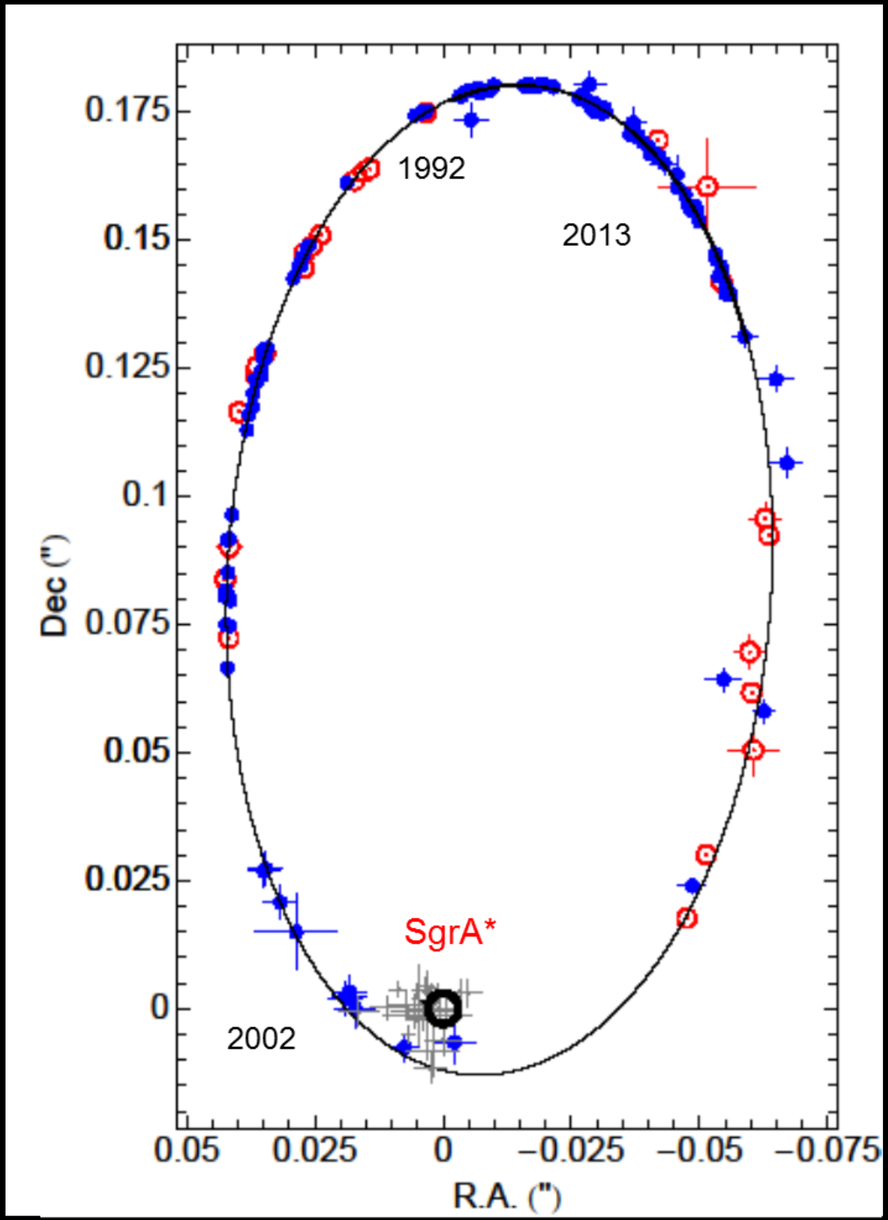
Small

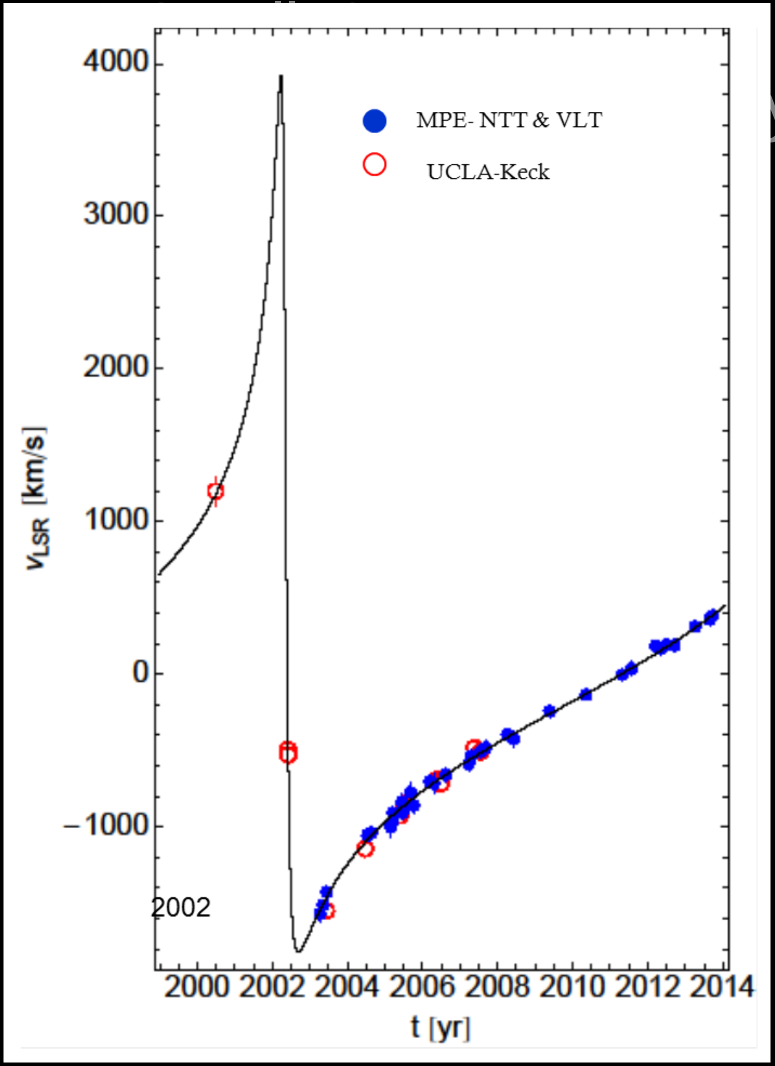
The Small is the Heavy

Faint

# The Galactic Center harbors a black hole

Massive: $4.3 \times 10^6\ M_{Sun}$




Schödel et al. 2003, Eisenhauer et al. 2005, Ghez et al. 2008, Gillessen et al. 2009

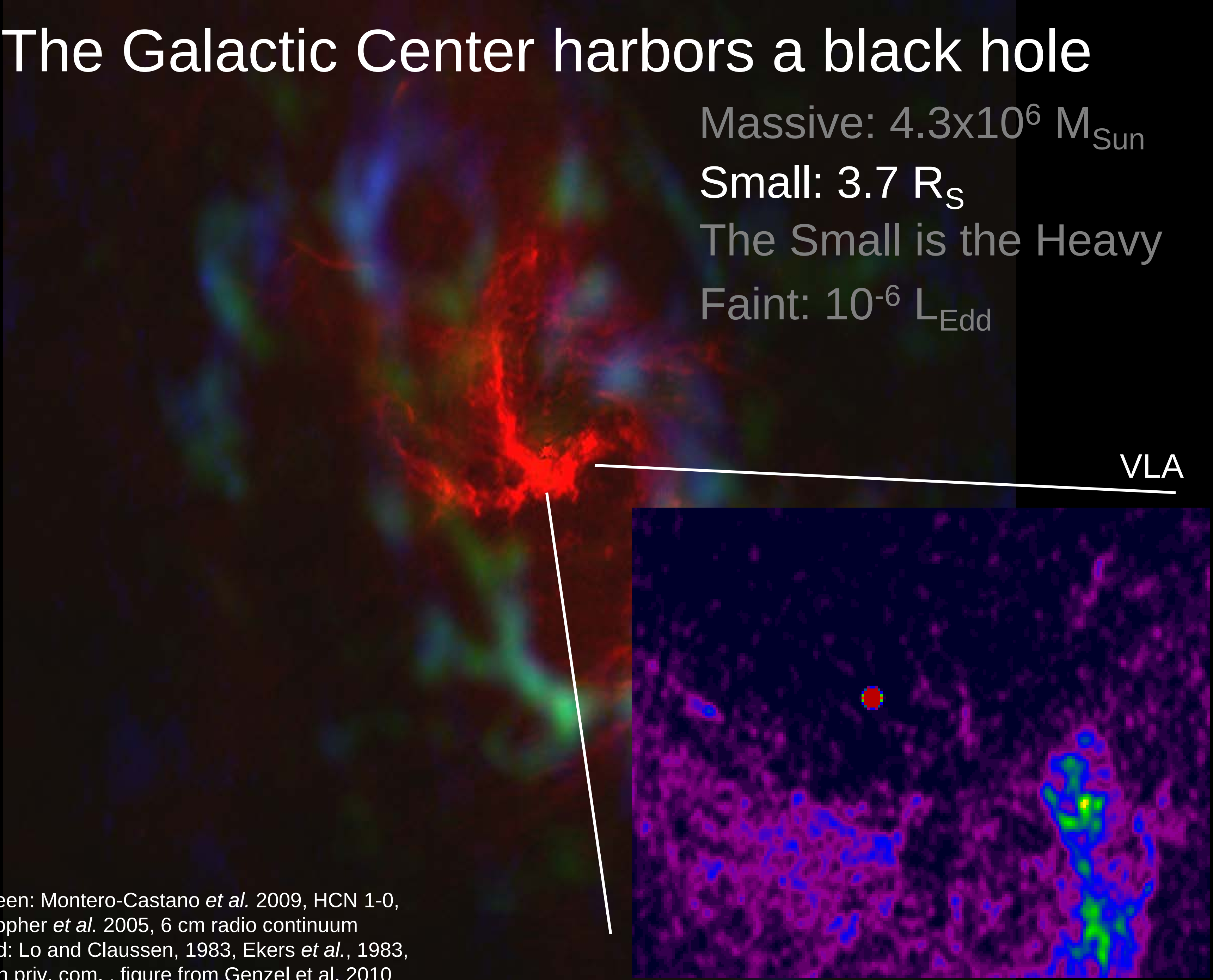
# The Galactic Center harbors a black hole

Massive: $4.3 \times 10^6 \, M_{Sun}$

Small: $3.7 \, R_S$

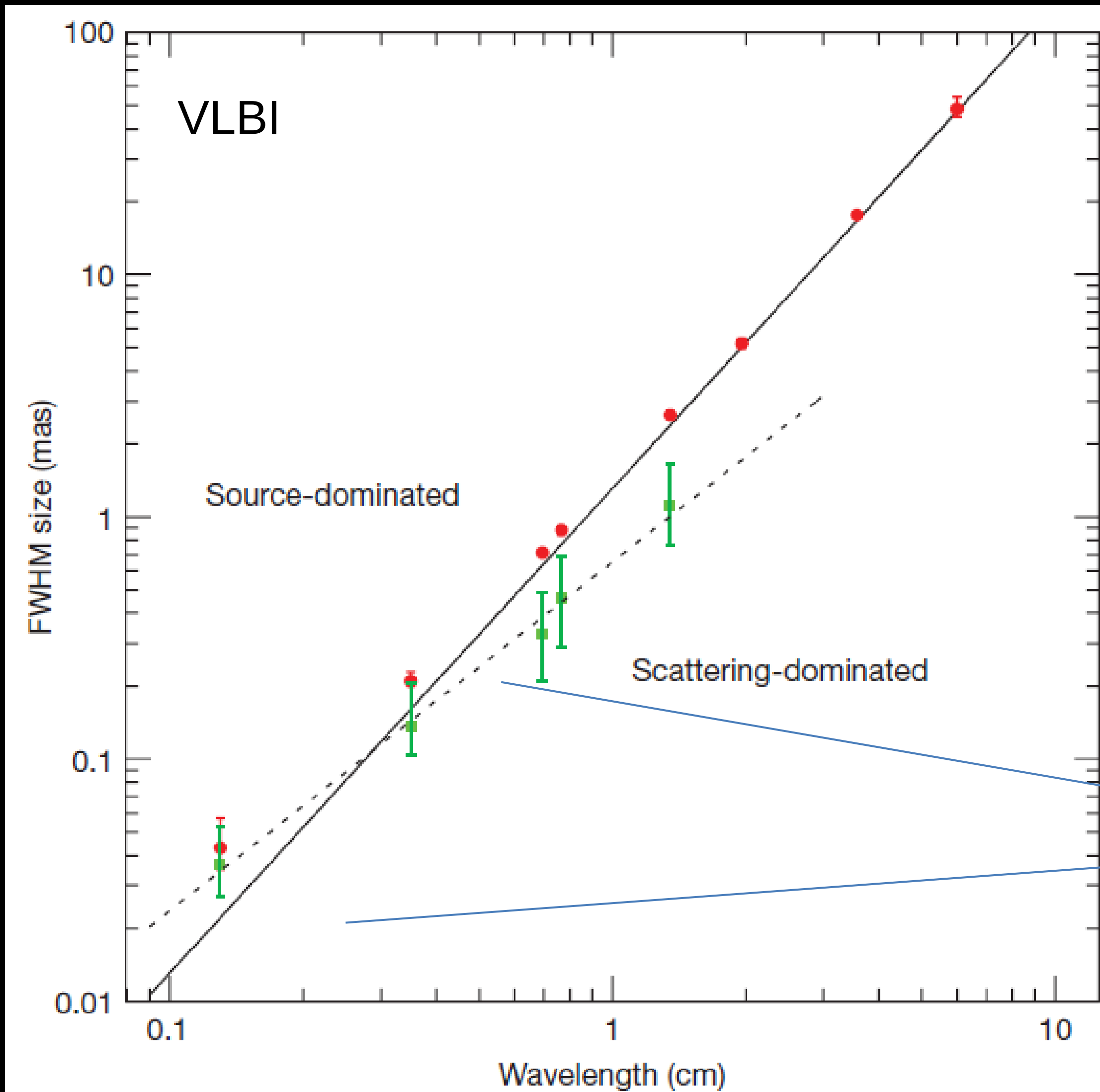
The Small is the Heavy

Faint: $10^{-6} \, L_{Edd}$




HCN 4-3 green: Montero-Castano *et al.* 2009, HCN 1-0, blue: Christopher *et al.* 2005, 6 cm radio continuum emission red: Lo and Claussen, 1983, Ekers *et al.*, 1983, Yusef-Zadeh priv. com. , figure from Genzel et al. 2010

# The Galactic Center harbors a black hole

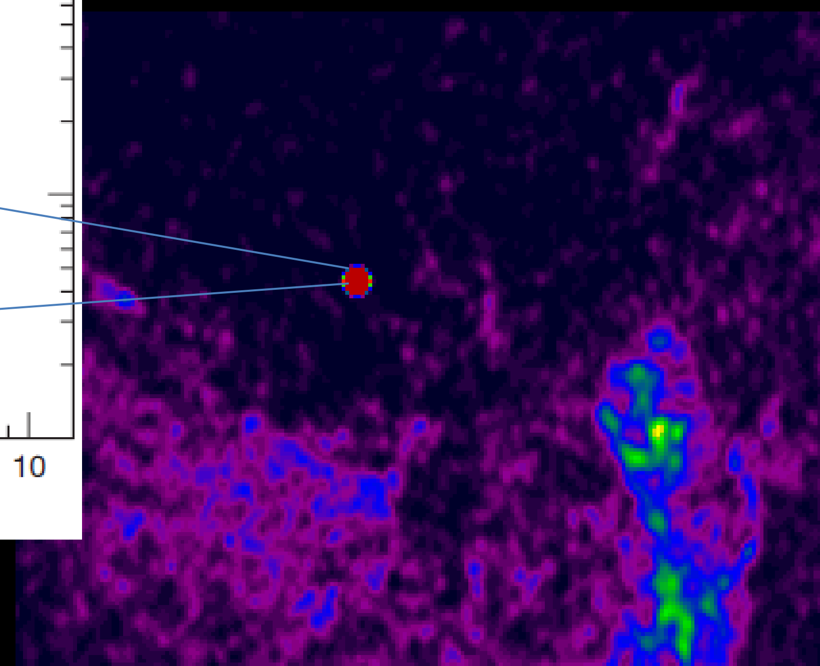



Massive: $4.3 \times 10^6$ $M_{Sun}$

Small: 3.7 $R_S$

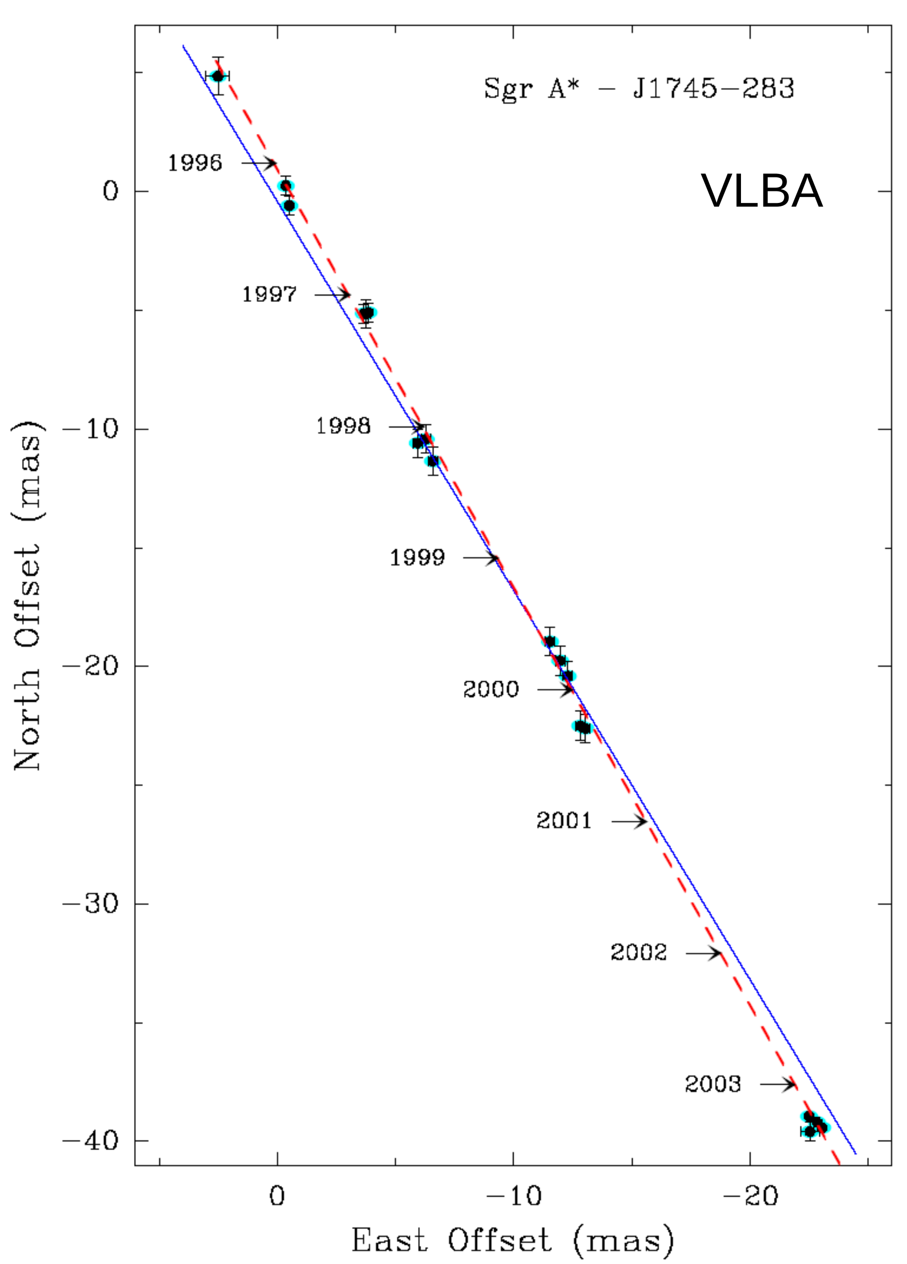
The Small is the Heavy

Faint: $10^{-6}$ $L_{Edd}$



Fish et al. 2011, Doelman et al. 2008
Bower et al. 2006, 2004, Shen et al. 2005,
Krichbaum et al. 1998

# The Galactic Center harbors a black hole




Massive: $4.3 \times 10^6$ $M_{Sun}$

Small: 3.7 $R_S$

The Small is the Heavy

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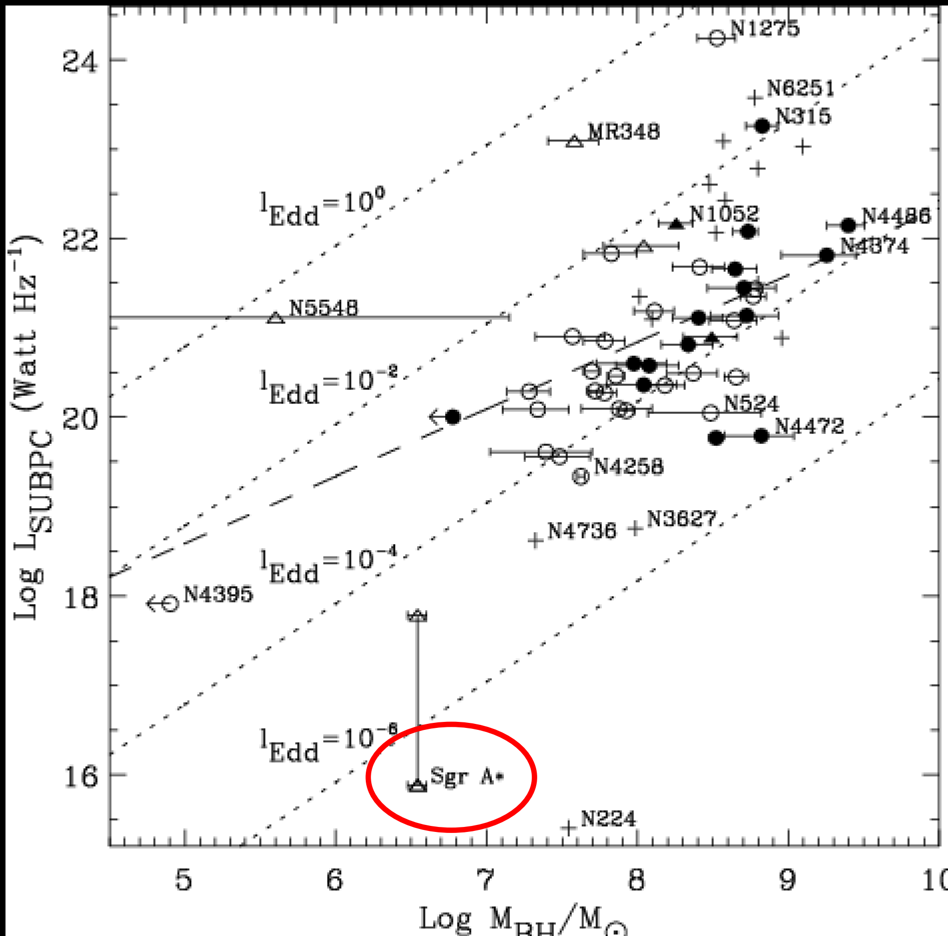
Reid & Brunthaler et al. 2004
Reid et al. 2008

# The Galactic Center harbors a black hole



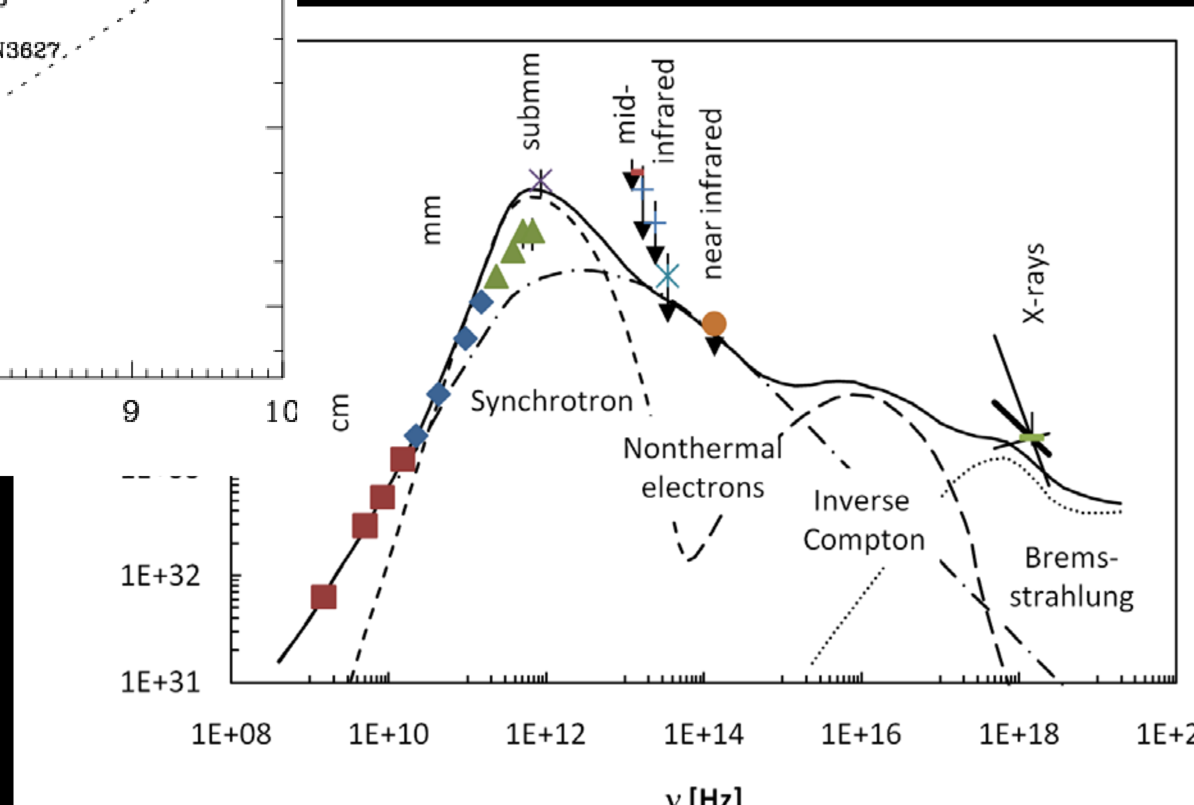

Massive: $4.3 \times 10^6$ $M_{Sun}$

Small: 3.7 $R_S$

The Small is the Heavy

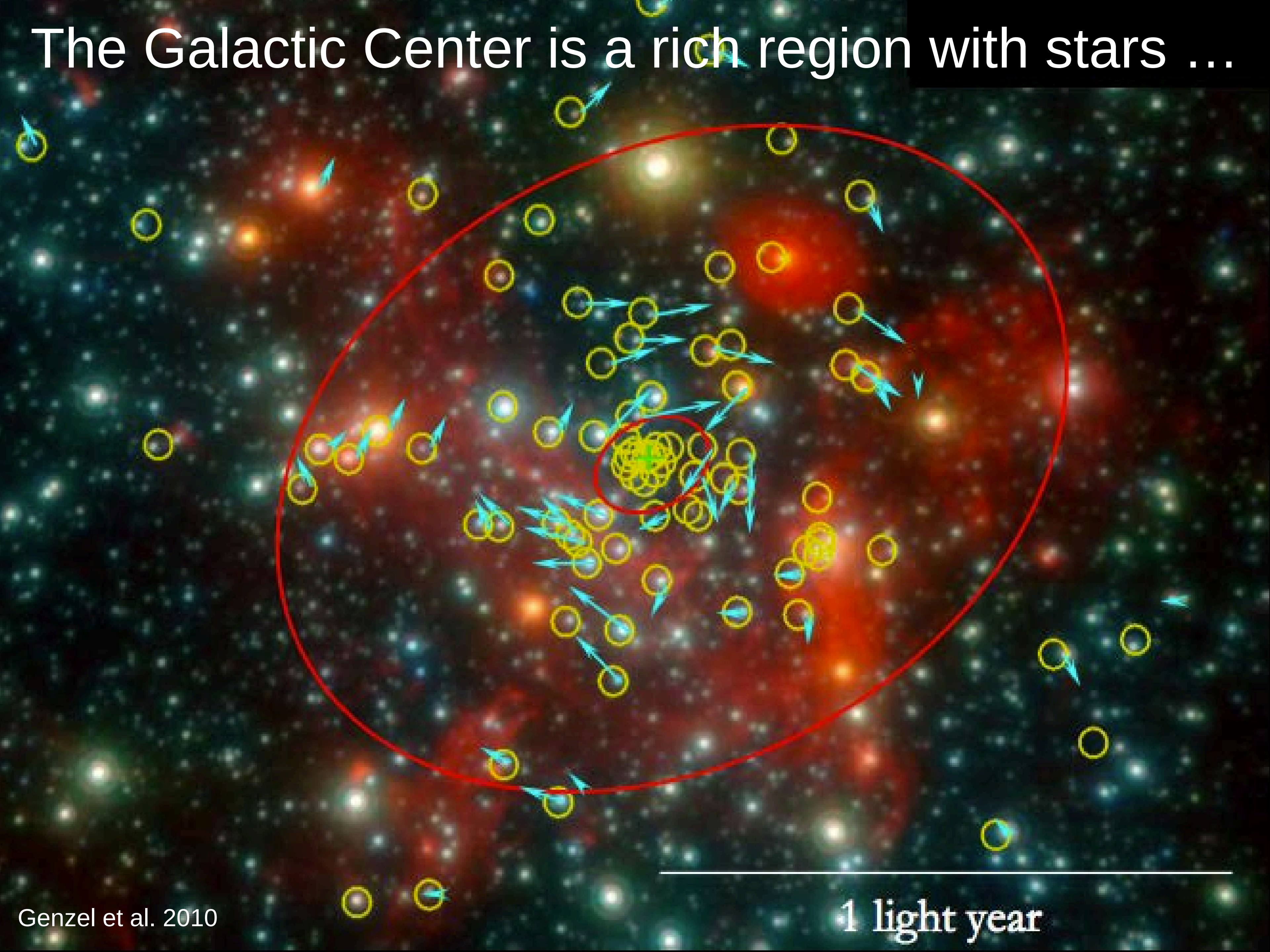
Faint: $10^{-6}$ $L_{Edd}$

Nagar et al. 2005



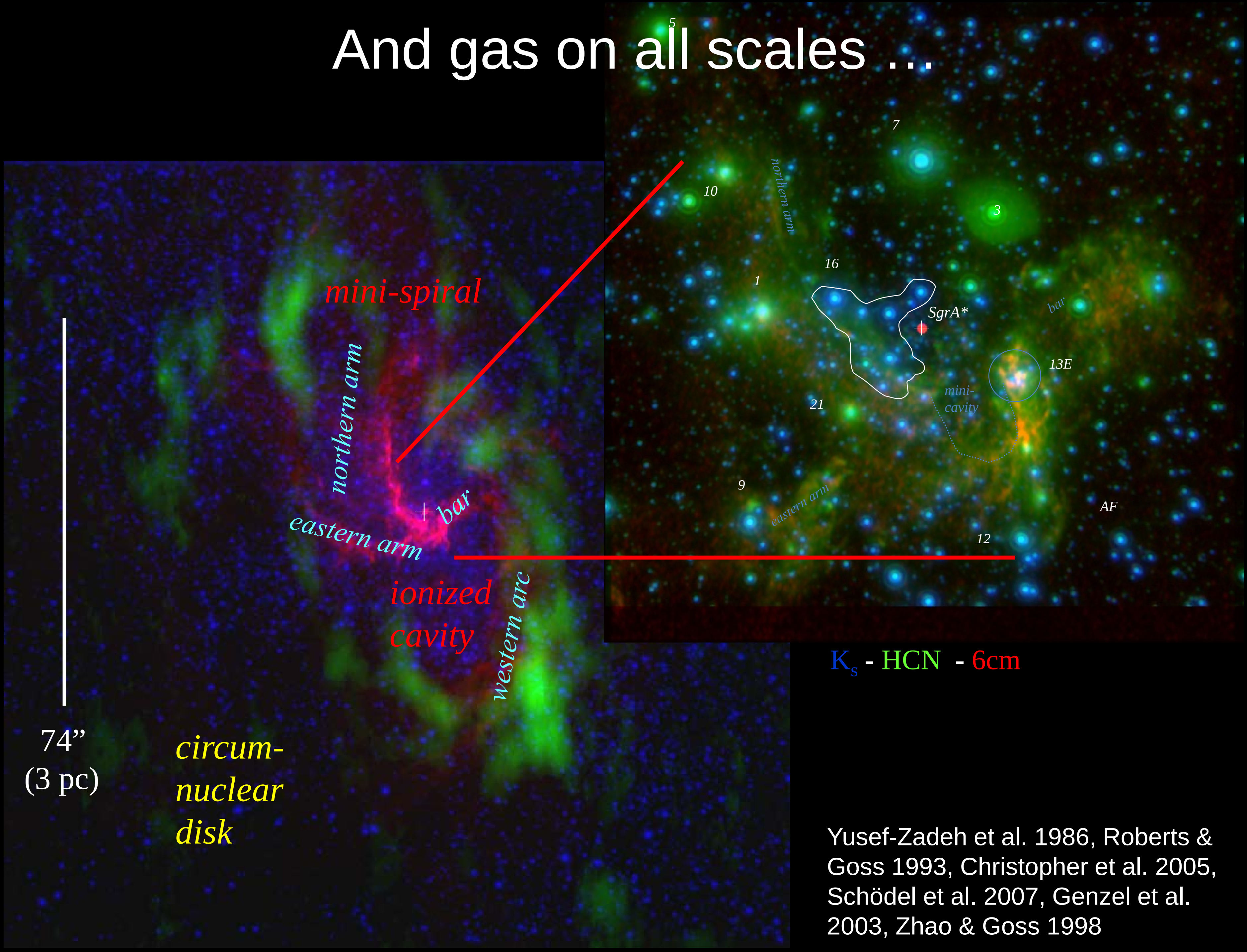

Zhao *et al.* 2001, Falcke *et al.* 1998, Zylka *et al.* 1995, Serabyn *et al.* 1997, Cotera *et al.* 1999, Gezari 1999, Schödel *et al.* 2007, Hornstein *et al.* 2002, Baganoff *et al.* 2003, Yuan *et al.* 2003, figure from Genzel et al. 2010

# The Galactic Center is a rich region with stars …




Genzel et al. 2010

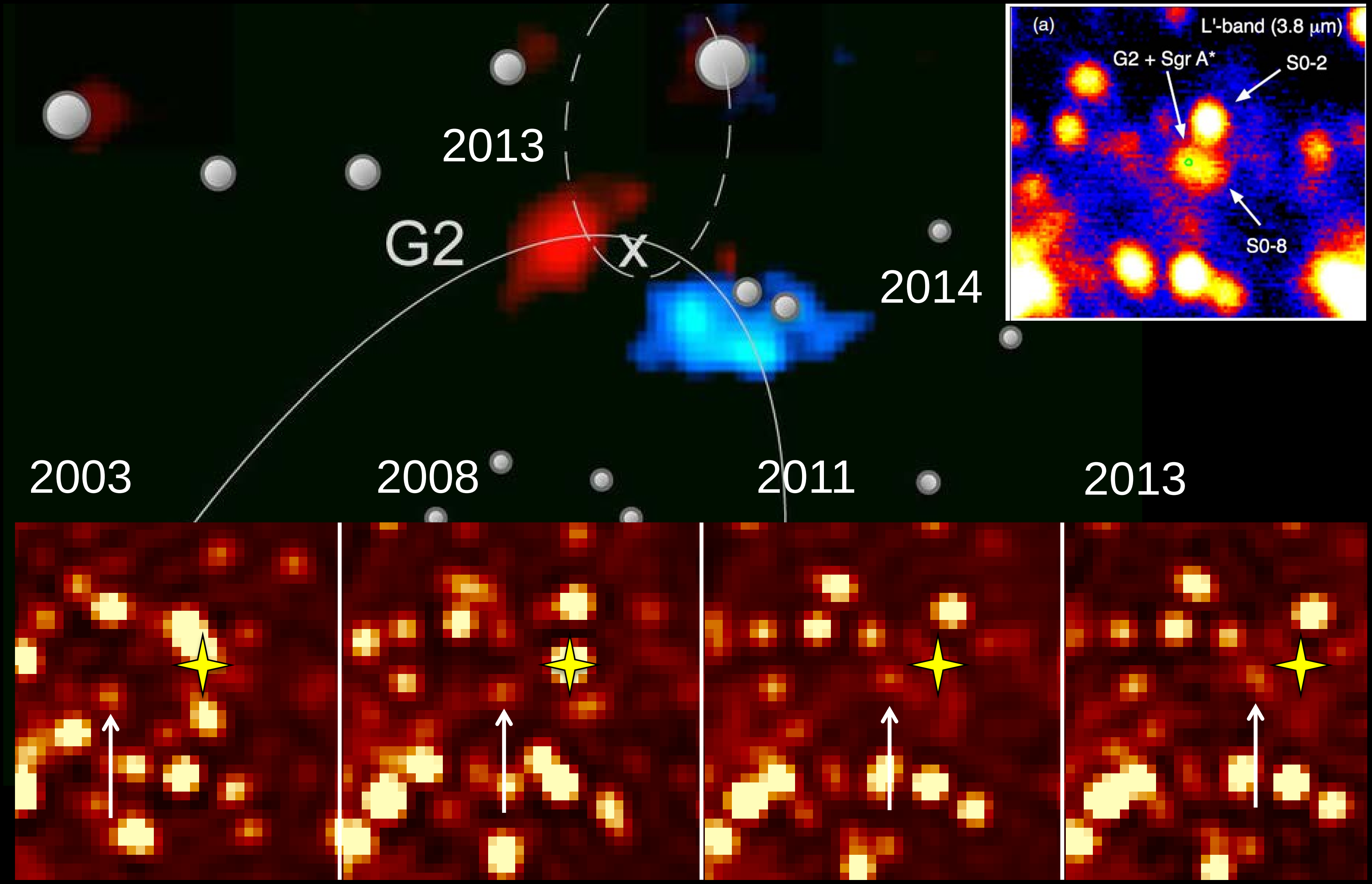
# And gas on all scales …




$K_s$ - HCN - 6cm

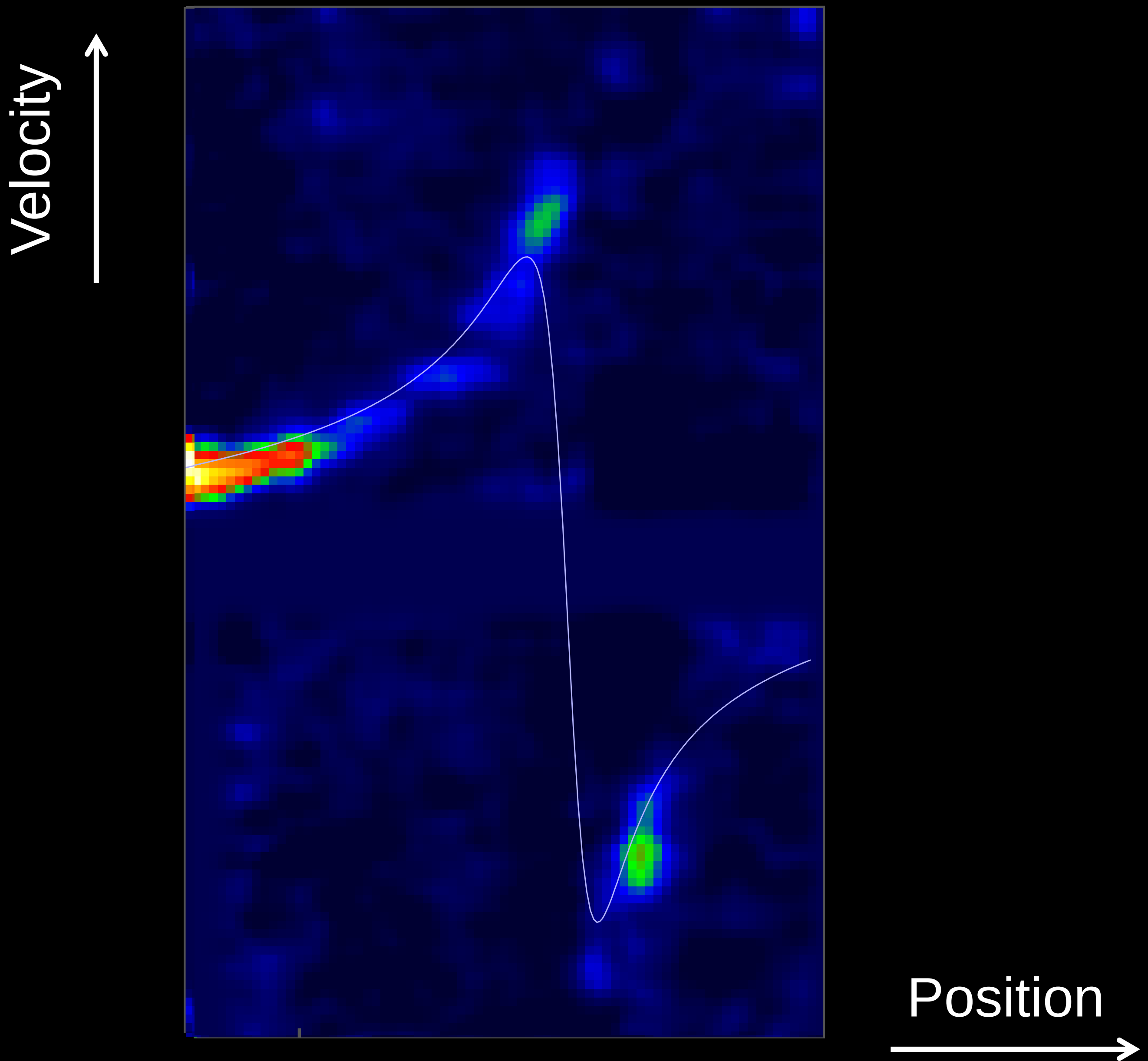
Yusef-Zadeh et al. 1986, Roberts & Goss 1993, Christopher et al. 2005, Schödel et al. 2007, Genzel et al. 2003, Zhao & Goss 1998

# Down towards the very center



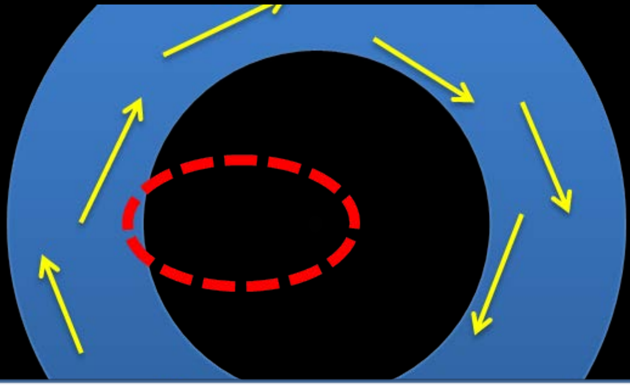

Gillessen et al. 2011, 2013+, Eckhart et al. 2013, Phifer et al. 2013, Witzel et al. 2014, Pfuhl et al. 2015, …

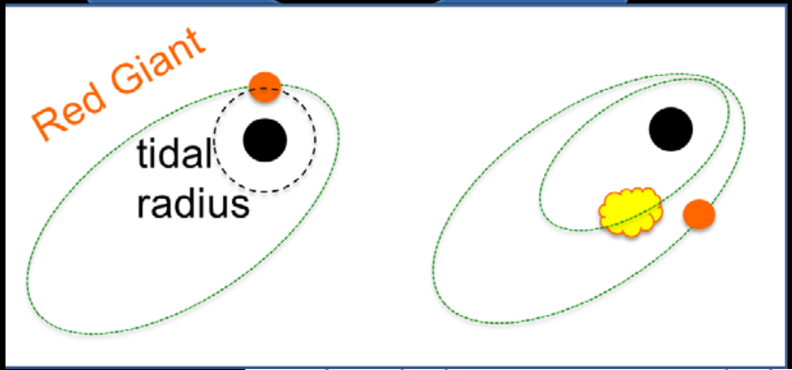
# Gas developing tidal shear in front of our eyes

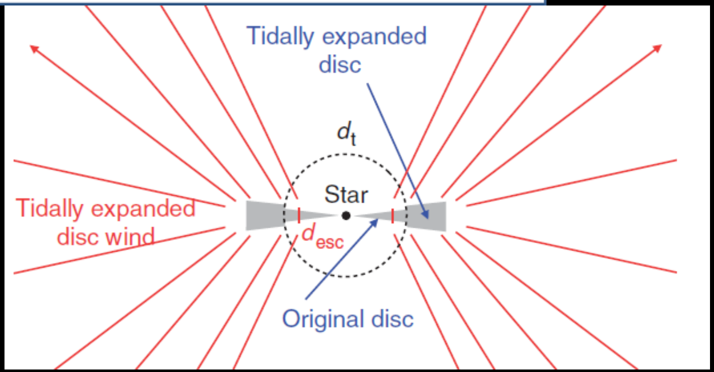



Gillessen et al. 2011, 2013+, Pfuhl et al. 2015

# What is it? Where does it come from?






Gillessen et al. 2011,13+, Murray-Clay & Loeb 2012, Miralda-Escude 2012, Phifer et al. 2013, Scoville & Burkert 2013, Prodan et al. 2014, Witzel et al. 2014, Ballone et al. 2014, De Colle et al. 2014

## We can’t tell, but we know …

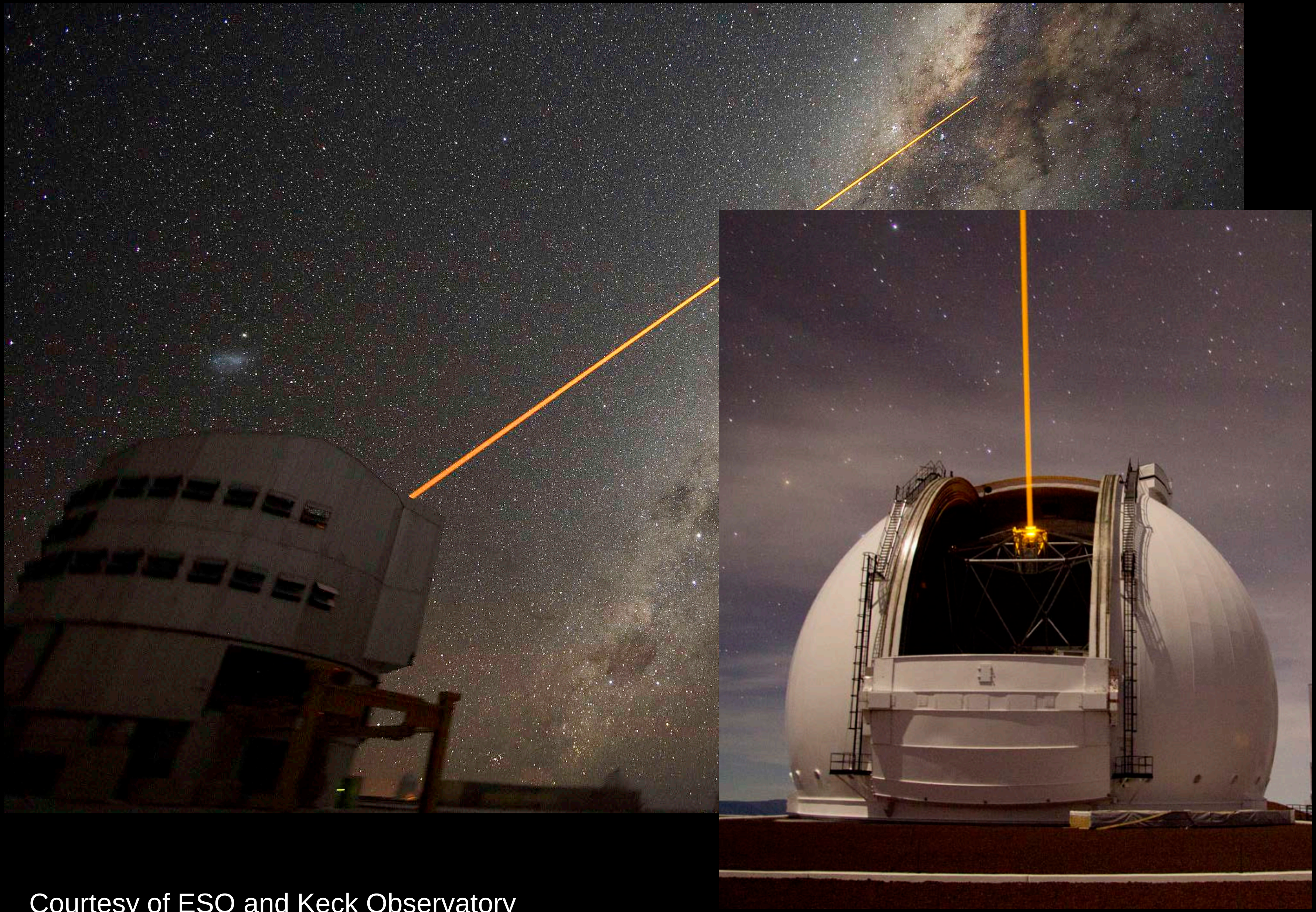
### Object

- Ionized gas slightly extended and tidally disrupted
- Not detected at 2 μm
- Point-like 3.5 μm emission, not disrupted

### Orbit

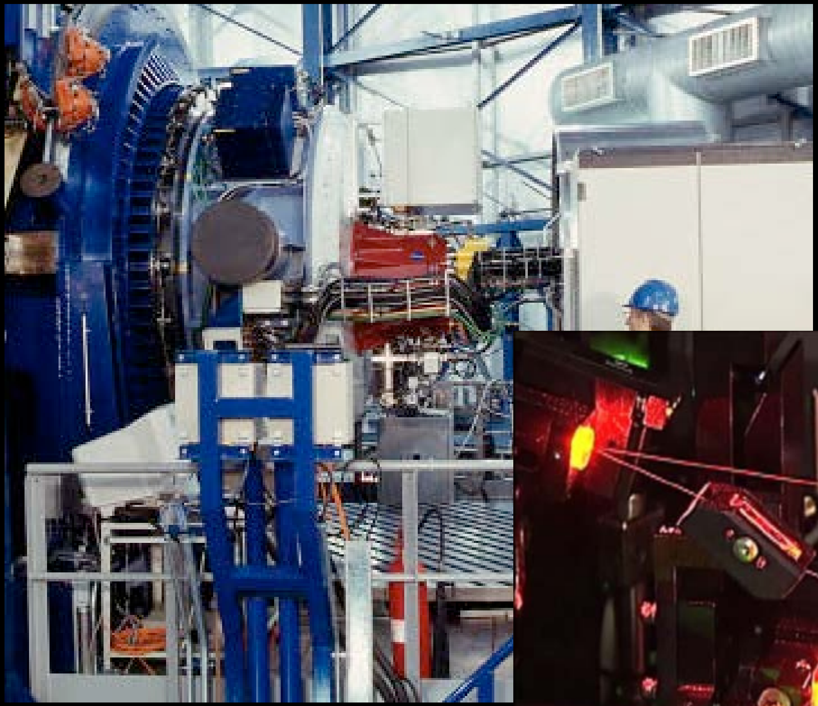
- Orbital plane coincides with disk plane
- Apocenter in the disk
- Orbit with large eccentricity $e \geq 0.966$

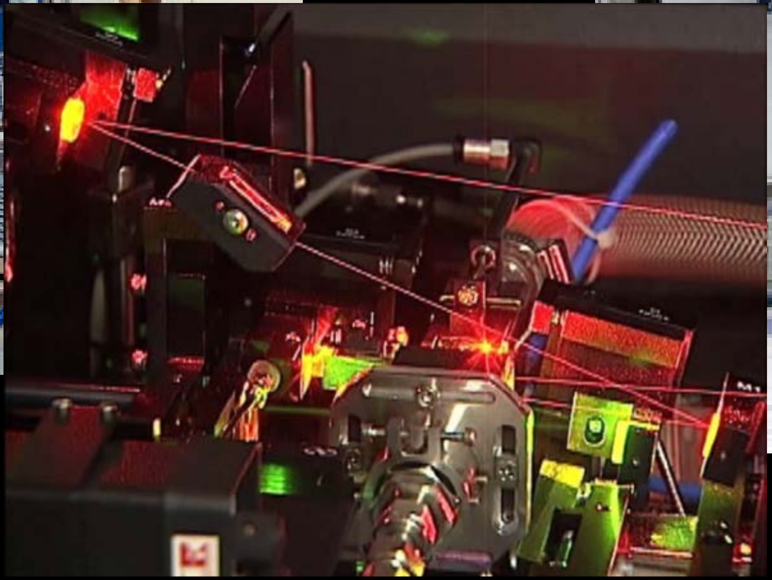
# Basis for success I: large optical / IR telescopes

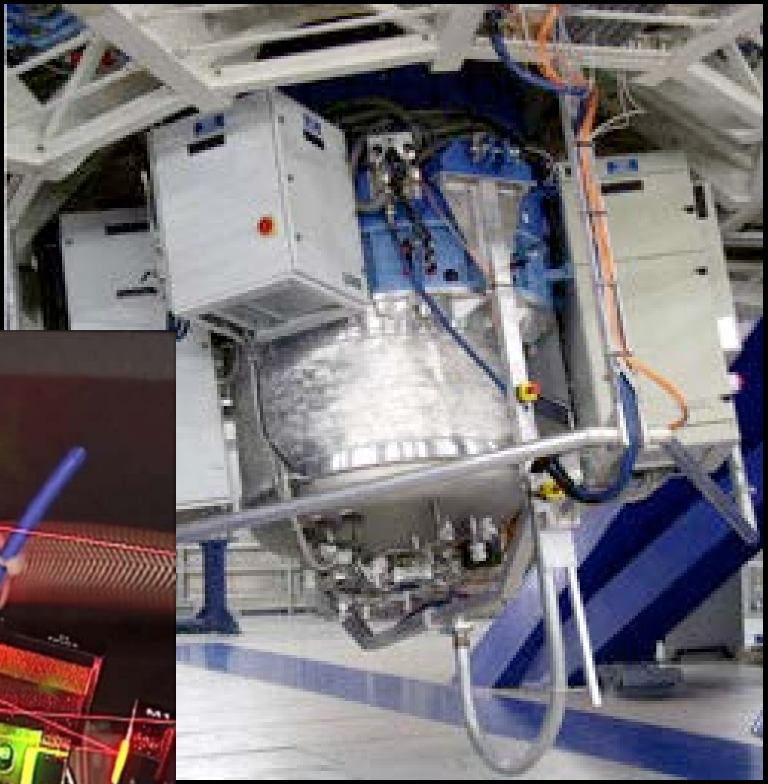


Courtesy of ESO and Keck Observatory

# Basis for success II: adaptive optics and integral field spectroscopy







NACO, Keck AO: Astrometry with 300 µas

Rousset et al. 2003
Lenzen et al. 2003
Matthews et al.
Wizinowich, Max et al.

Laser guide stars

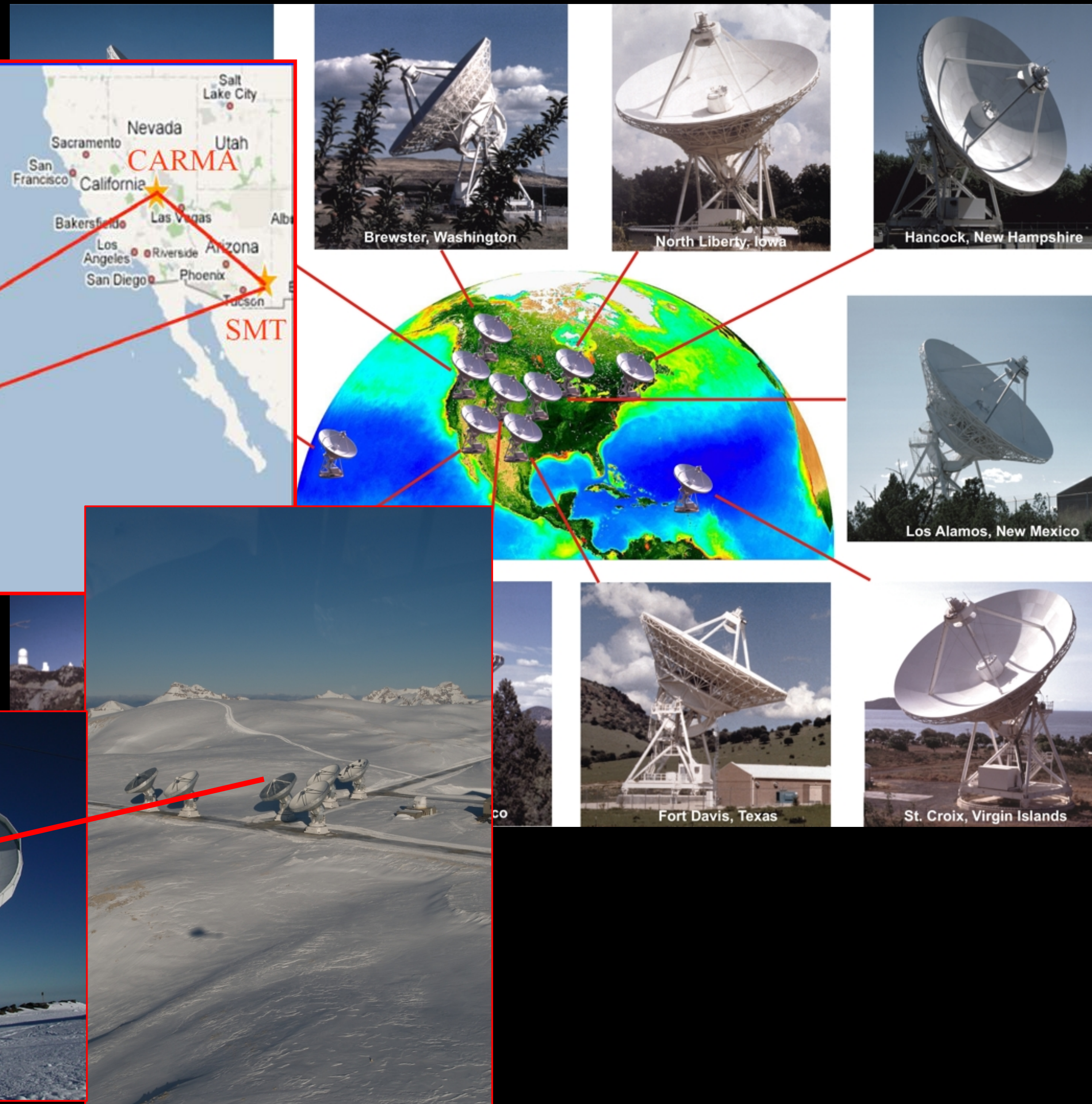
Bonnaccini et al.
Rabien et al.
Wizinowich, Max et al.

SINFONI, OSIRIS: Spectroscopy with 15 km/s

Eisenhauer et al. 2004
Bonnet et al. 2003
Larkin et al. 2006

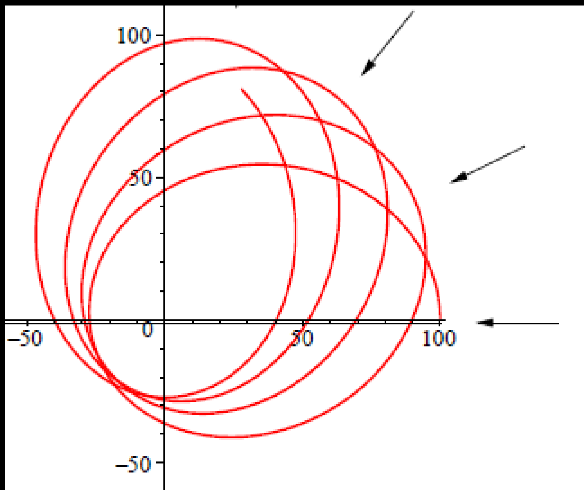
# Basis for success III: radio, VLBA and VLBI

North American


Europe

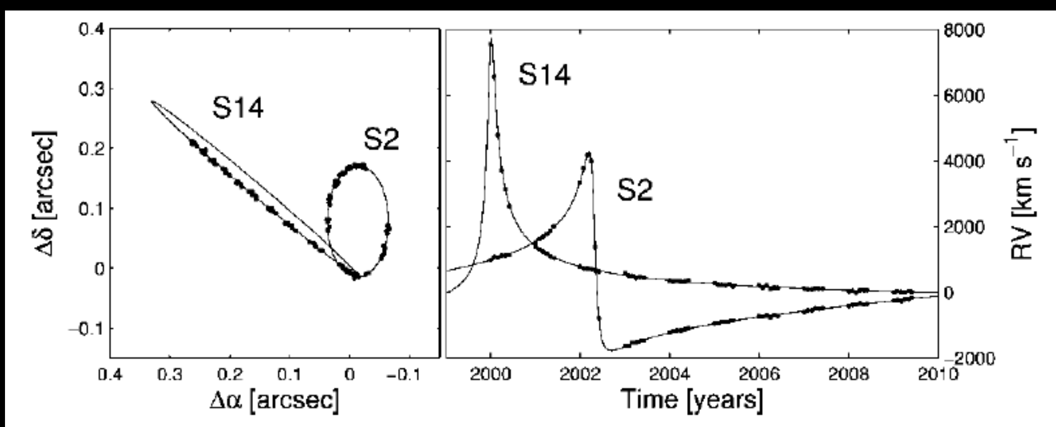
# Topics for the next decade(s) I: relativistic physics

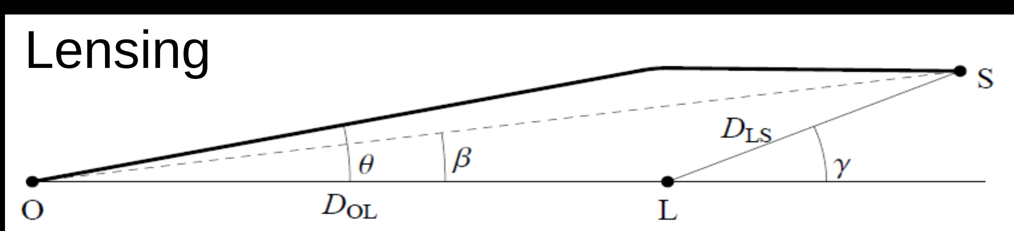



$\beta^2$ effects

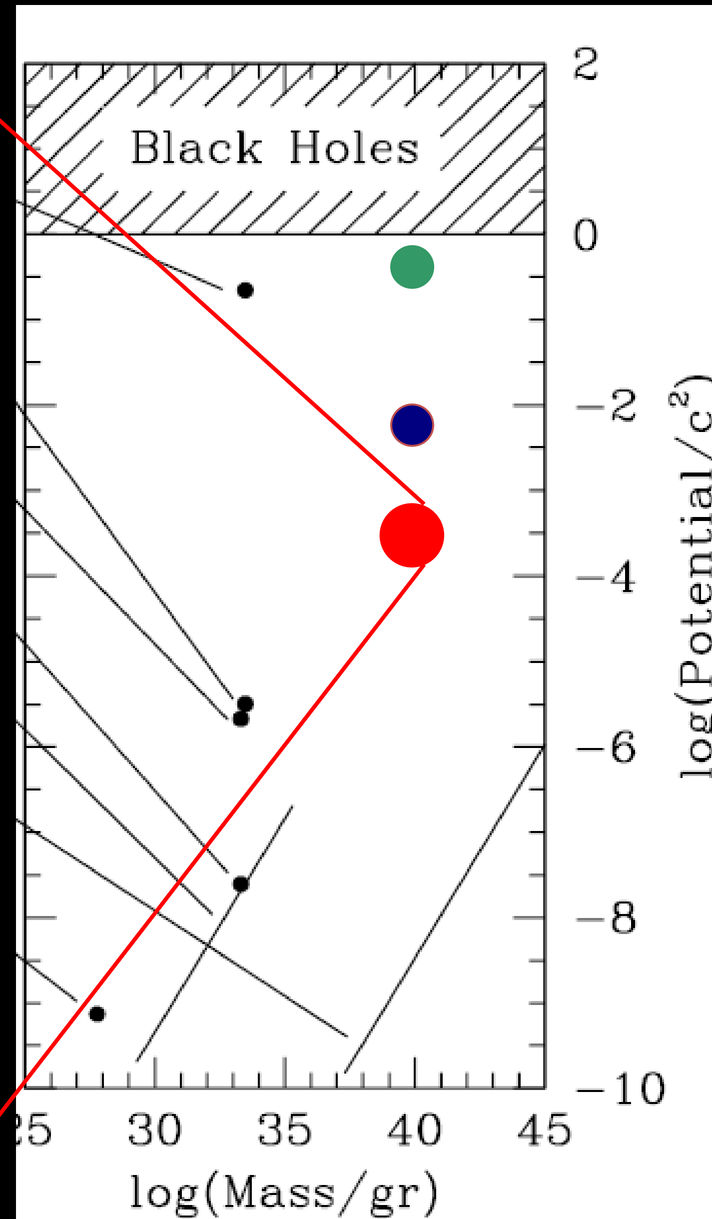
Jaroszynski 1998

Zucker et al. 2006




Bozza & Mancini 2012

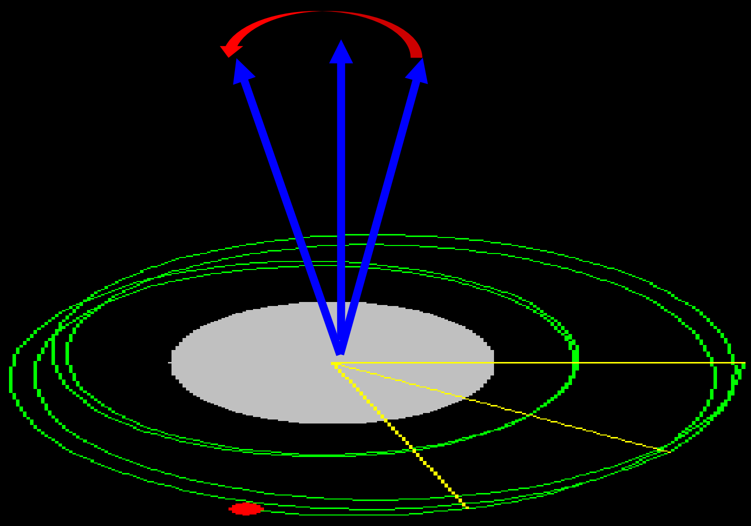



Psaltis 2004

# Topics for the next decade(s) I: relativistic physics

Spin

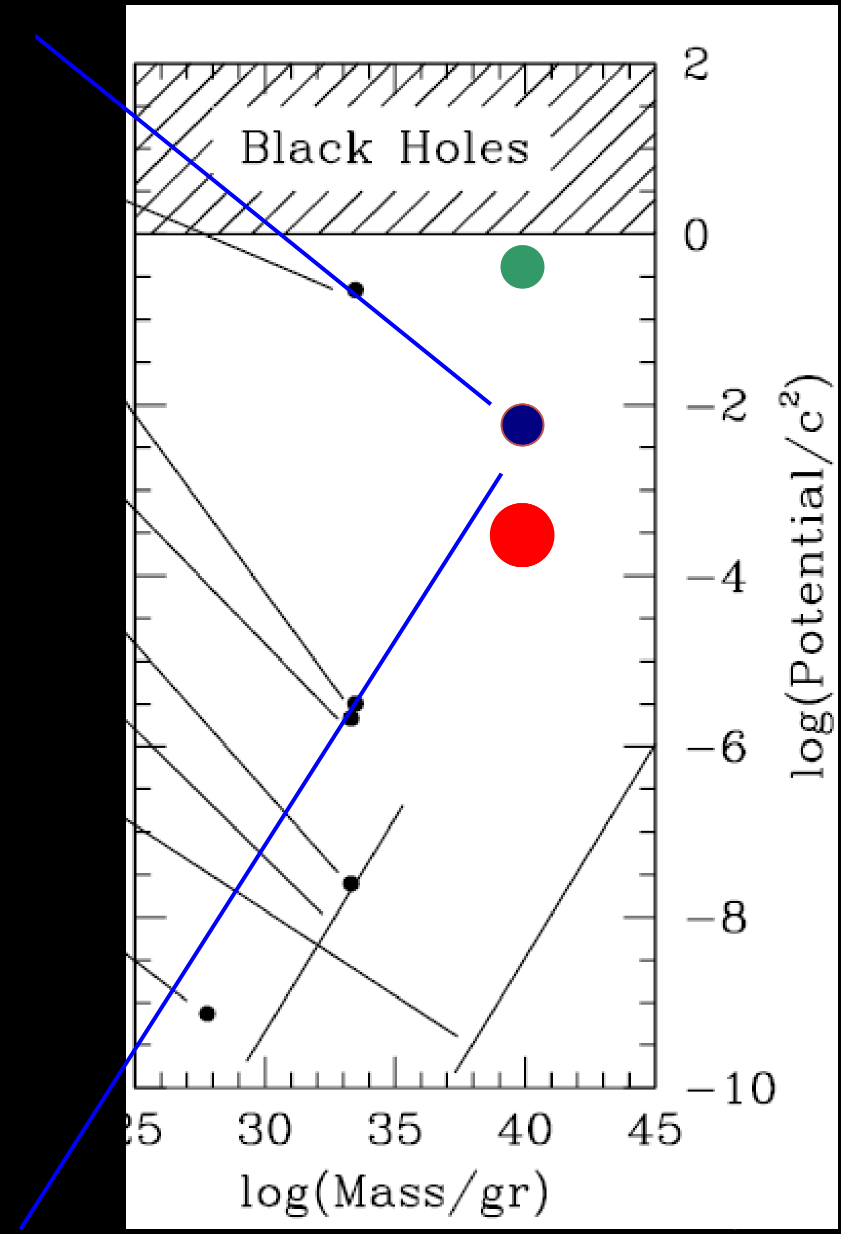
$$\dot{\Theta}_J \approx 0.847\,\chi P^{-4/3}(1-e^2)^{-3/2}\,,$$



Quadrupole moment

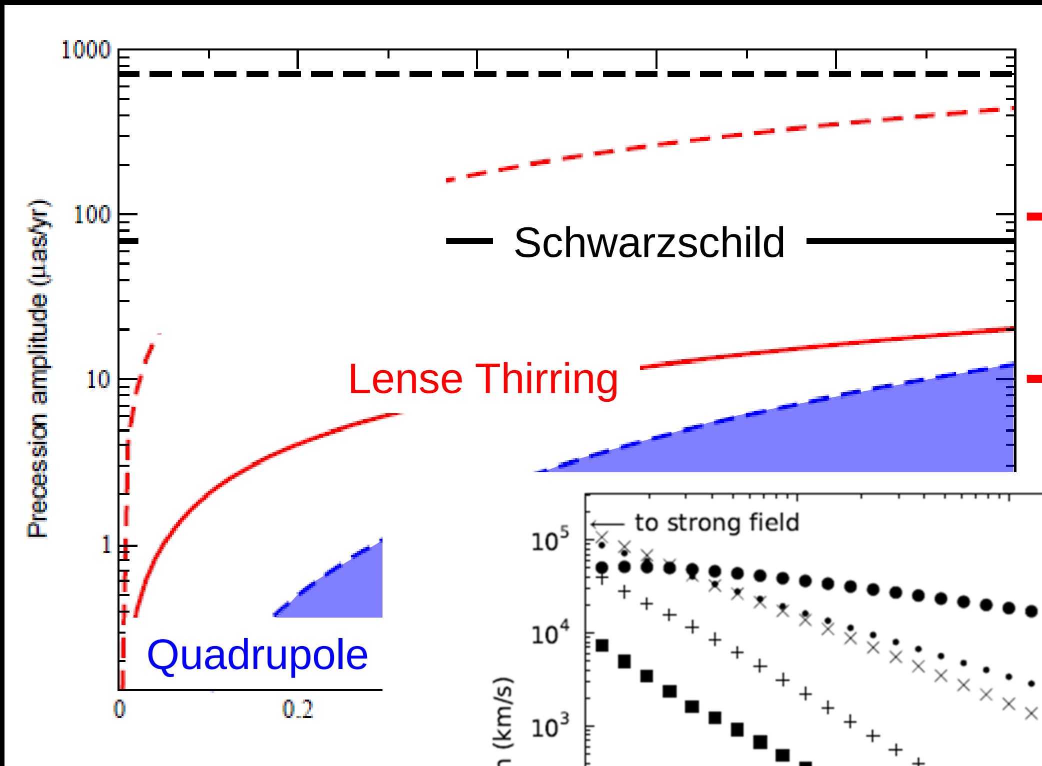
$$\dot{\Theta}_{Q_2} \approx 9.68\times 10^{-3}\,\chi^2 P^{-5/3}(1-e^2)^{-2}$$

Testing the no-hair theorem




Will 2008, Merritt et al. 2009, Liu et al. 2012

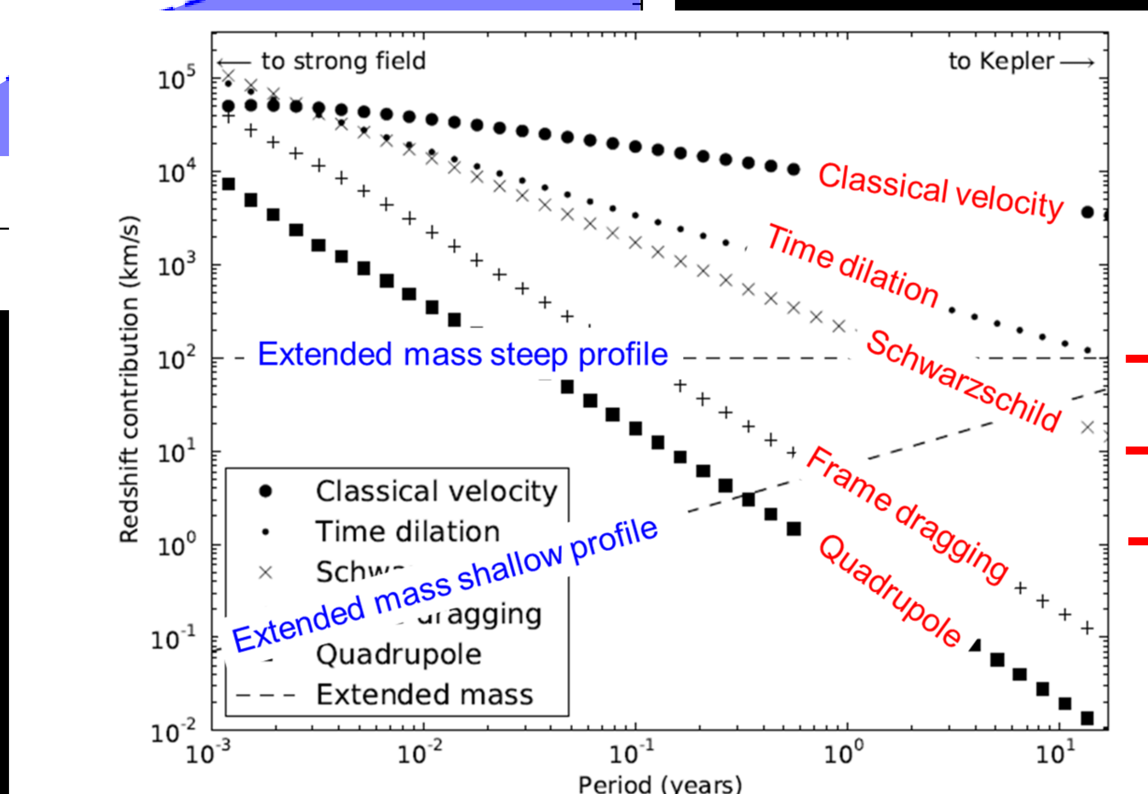
# Topics for the next decade(s) I: relativistic physics




100 μas/yr

10 μas/yr

Will 2008




100 km/s

10 km/s

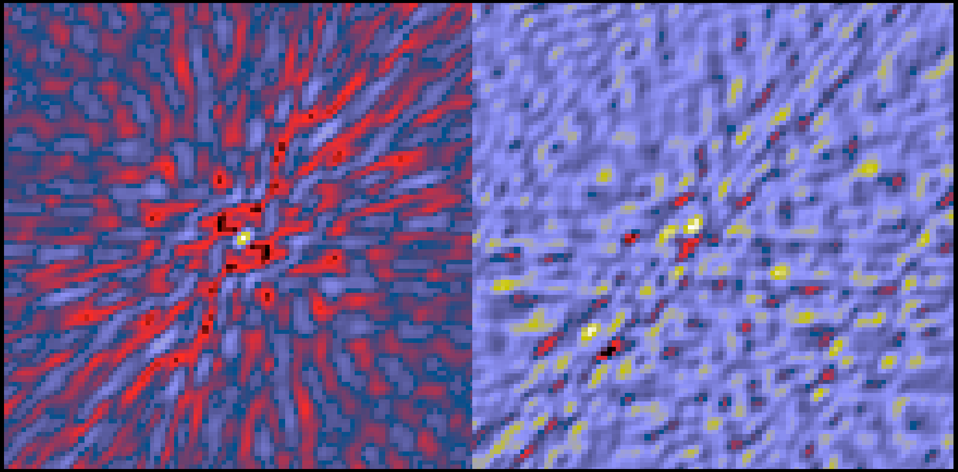
1 km/s

Angelil et al. 2010,
Iorio 2010

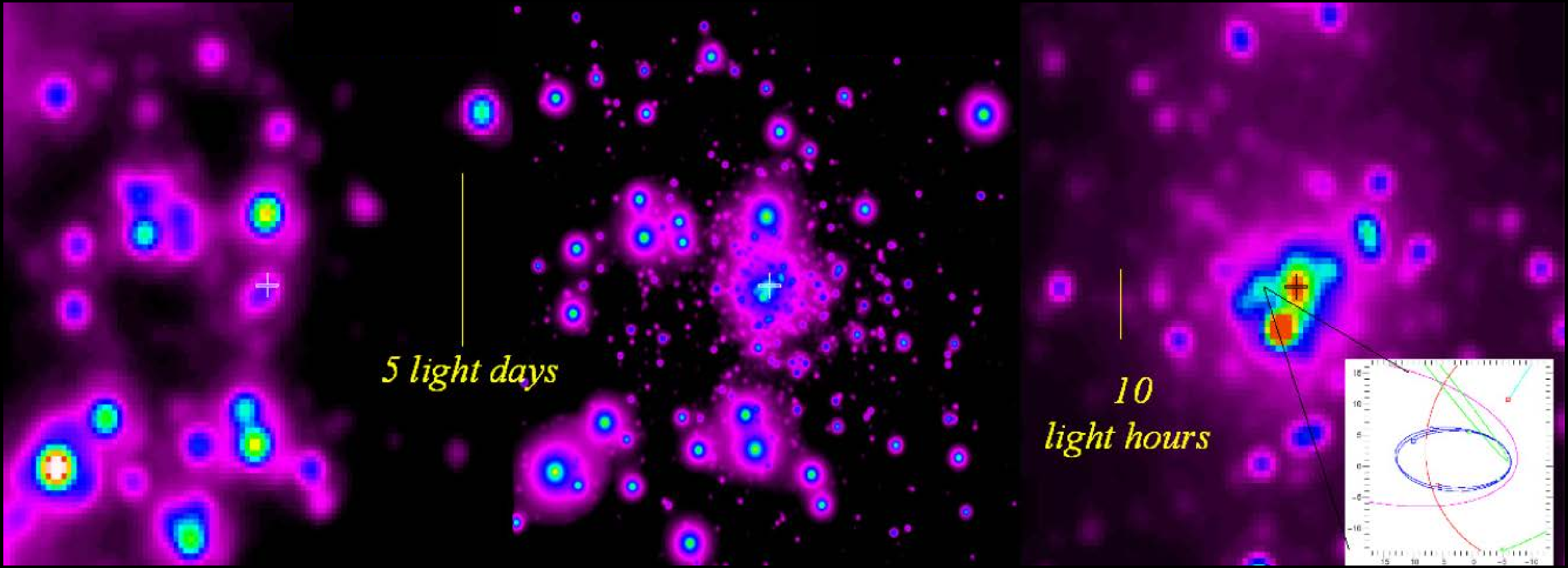
# What matters: spatial resolution and accuracy

Diffraction limit ~ D
Pointsource sensitivity ~ $D^2$
Crowding limit ~ $D^4$

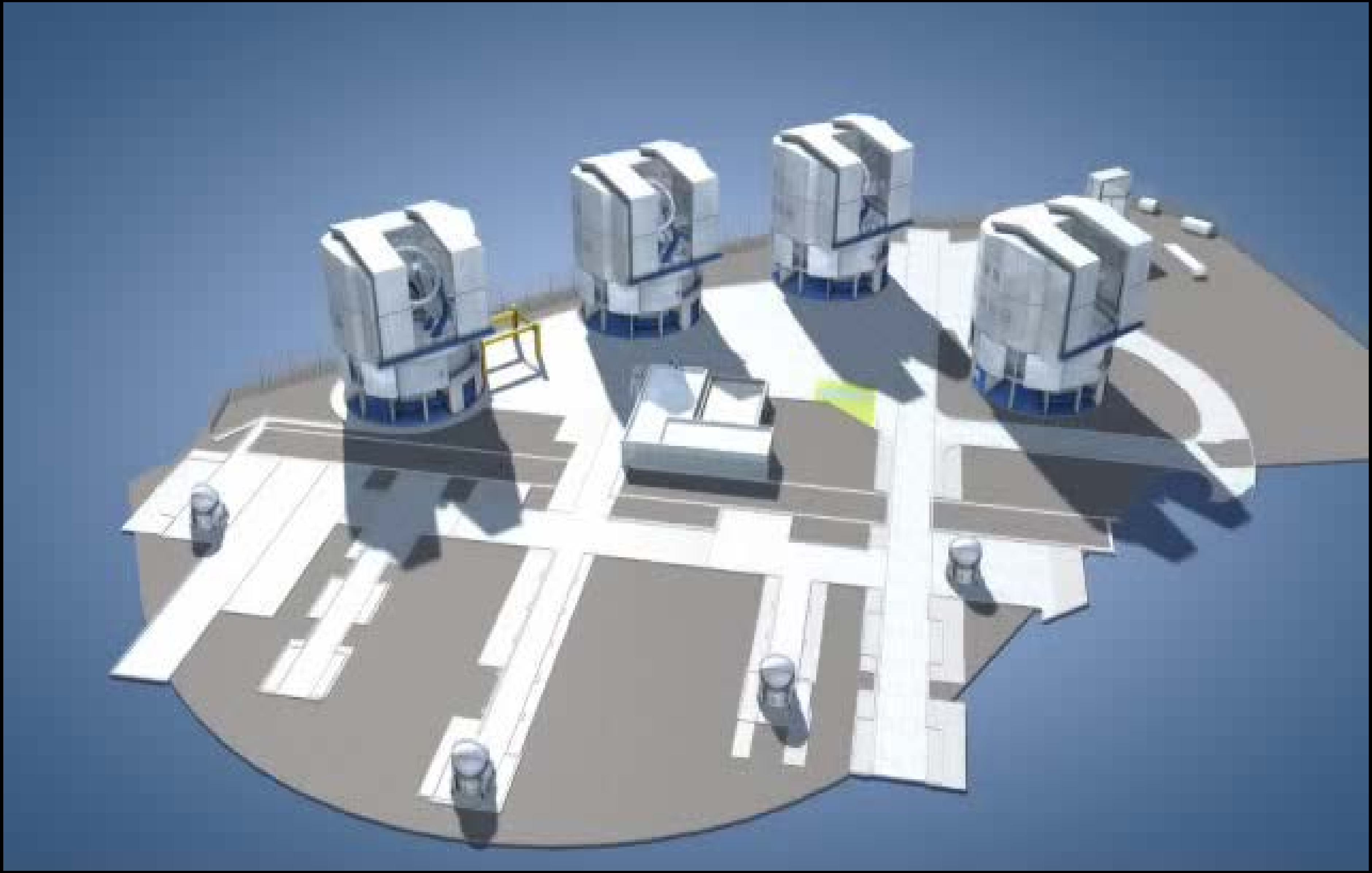
VLTI-GRAVITY



VLT-NACO/SINFONI  ELT-MICADO

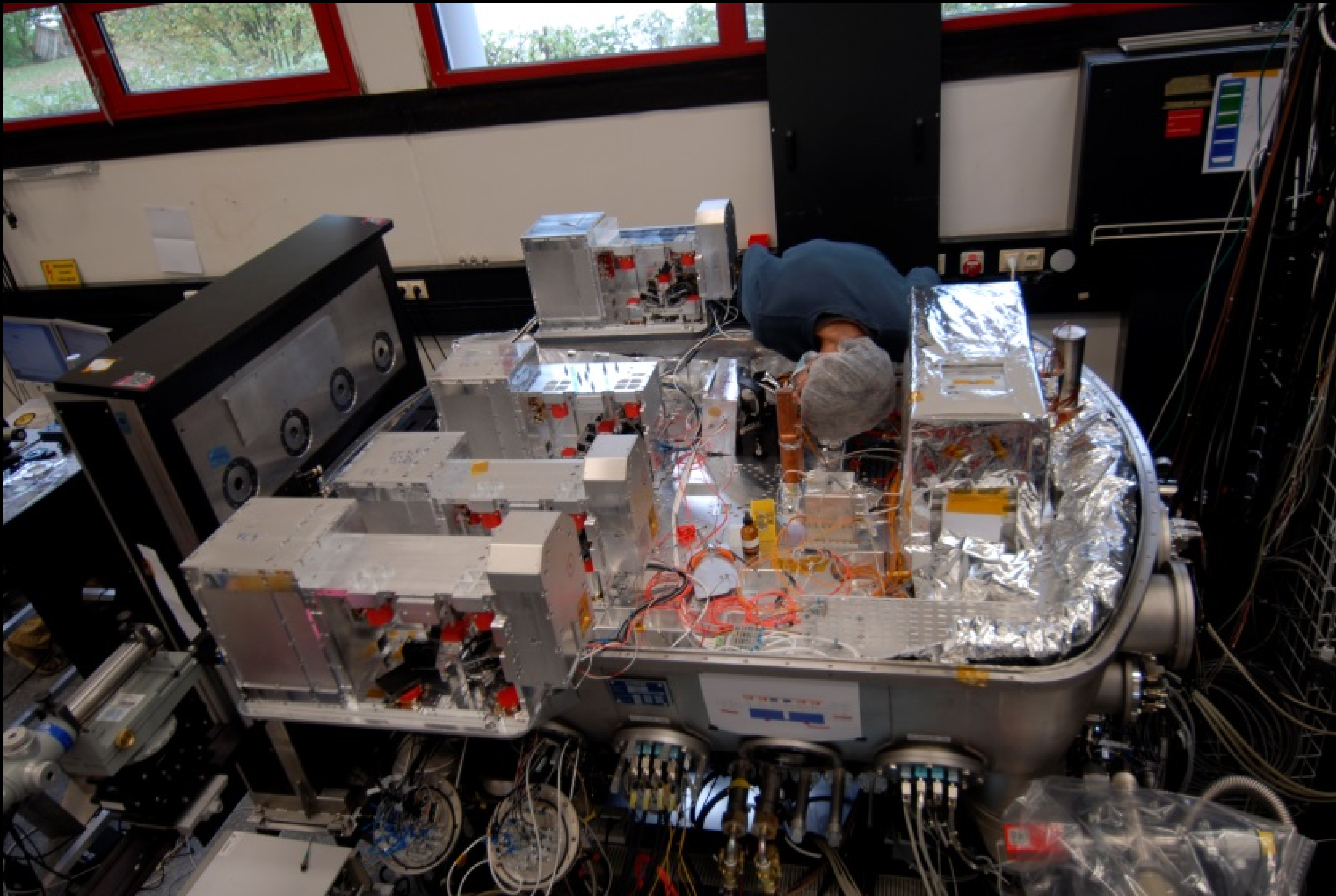


# With the help of VLT interferometry



Courtesy of ESO

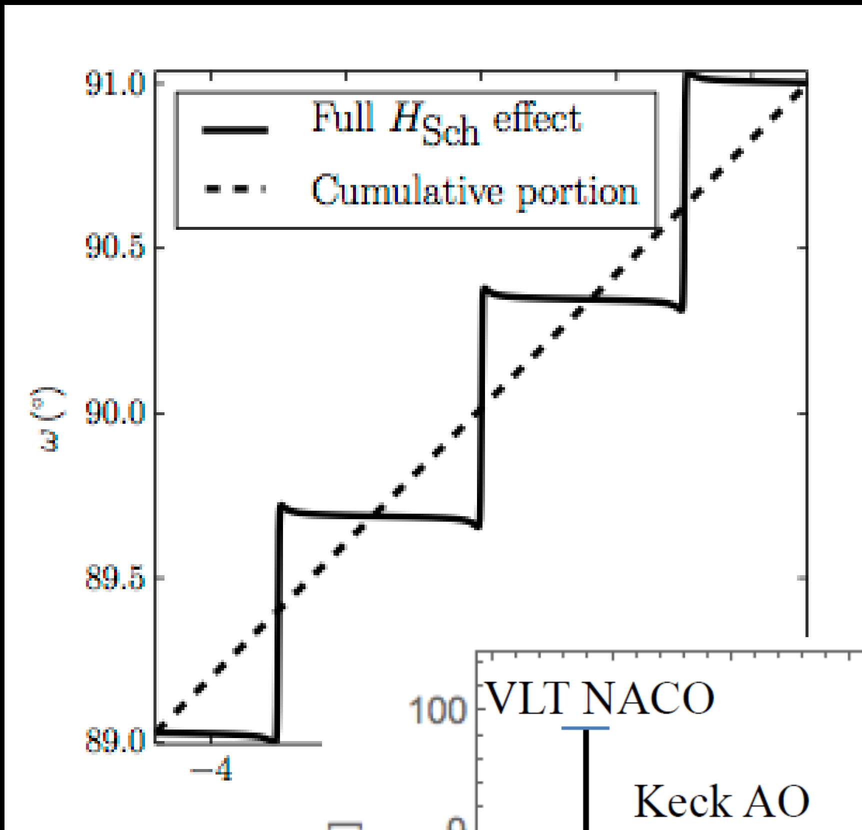
# And GRAVITY



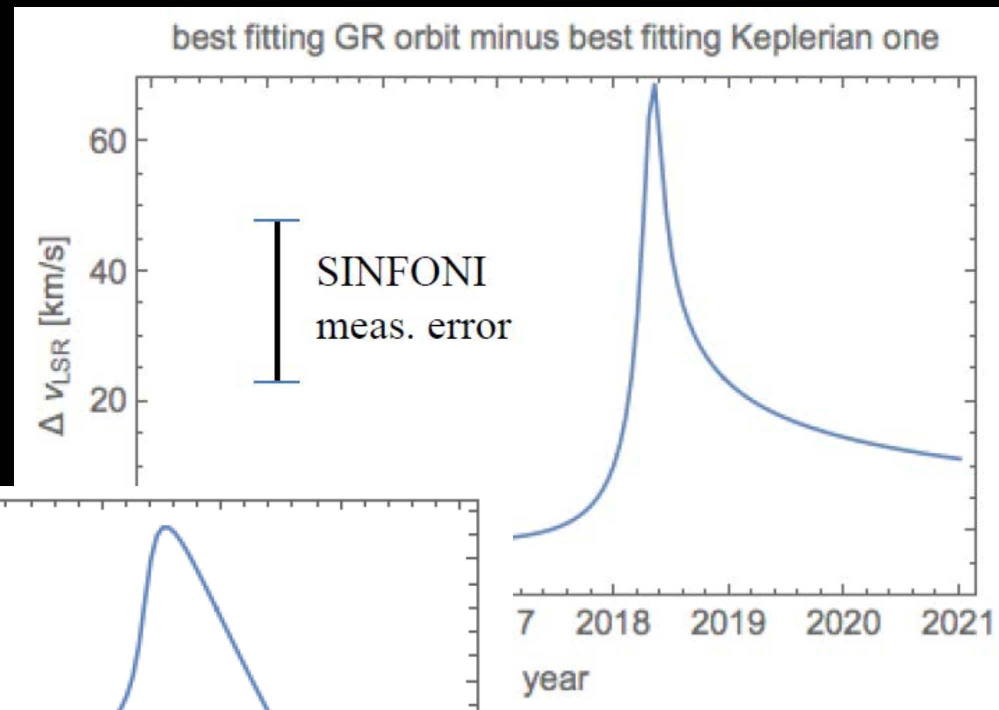
Eisenhauer et al. 2005, 2010

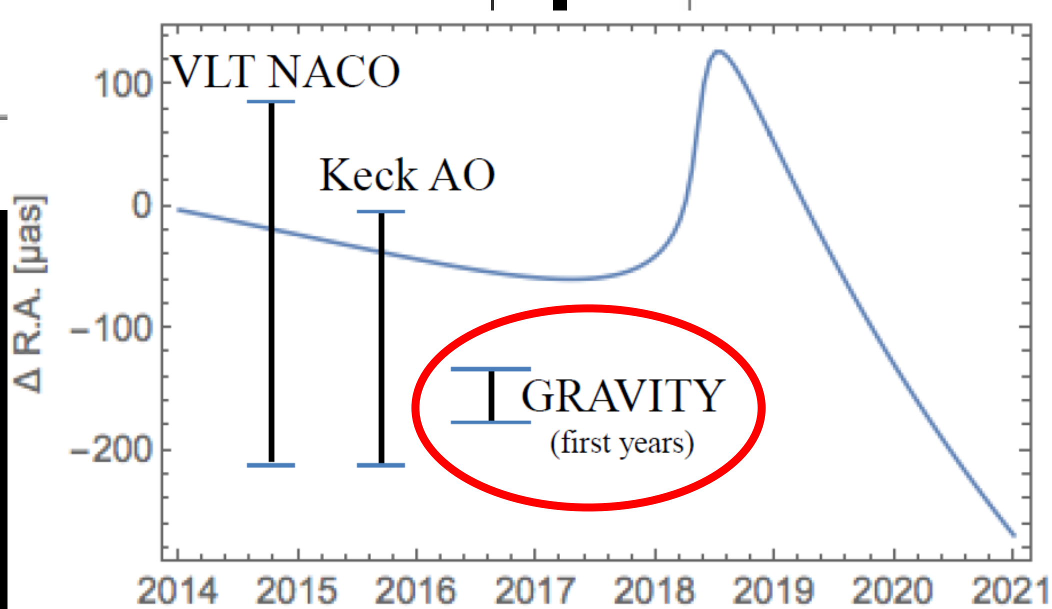
# Timing matters

Precession “ticks”
during peri-passage



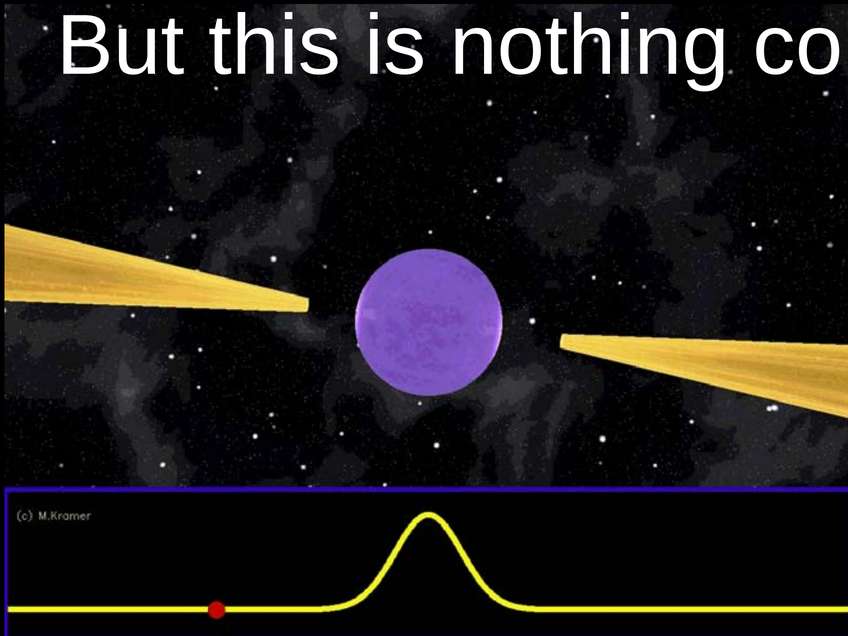

Angelil &
Saha 2014




Gillessen et al.

# But this is nothing compared to finding a pulsar




Providing exquisite precision, here "Best examples" for binary pulsar

Table from M.Kramer

| | | |
|---|---|---|
| **Masses:** | | |
| • Masses of neutron stars: $m_1$ = 1.4398(2) $M_{\odot}$ and | 1.3886(2) $M_{\odot}$ | (Weisberg et al. 2010) |
| **Orbital parameters:** | | |
| • Period: | 0.102251562479(8) day | (Kramer et al. in prep.) |
| • Eccentricity: | 3.5 (1.1) × $10^{-7}$ | (Freire et al. in 2012) |
| **Astrometry:** | | |
| • Distance: | 157(1) pc | (Verbiest et al. 2008) |
| • Proper motion: | 140.915(1) mas/yr | (Verbiest e t al. 2008) |
| **Tests of general relativity:** | | |
| • Periastron advance: | 4.226598(5) deg/yr | (Weisberg et al. 2010) |
| • Shrinkage due to GW emission: | 7.152(8) mm/day | (Kramer et al. in prep) |
| • GR validity (obs/exp): | 1.0000(5) | (Kramer et al. in prep.) |
| • Constancy of grav. Constant, dG/dt/G: | (9±12) x $10^{-13}$ $yr^{-1}$ | (Zhu et al. in prep) |

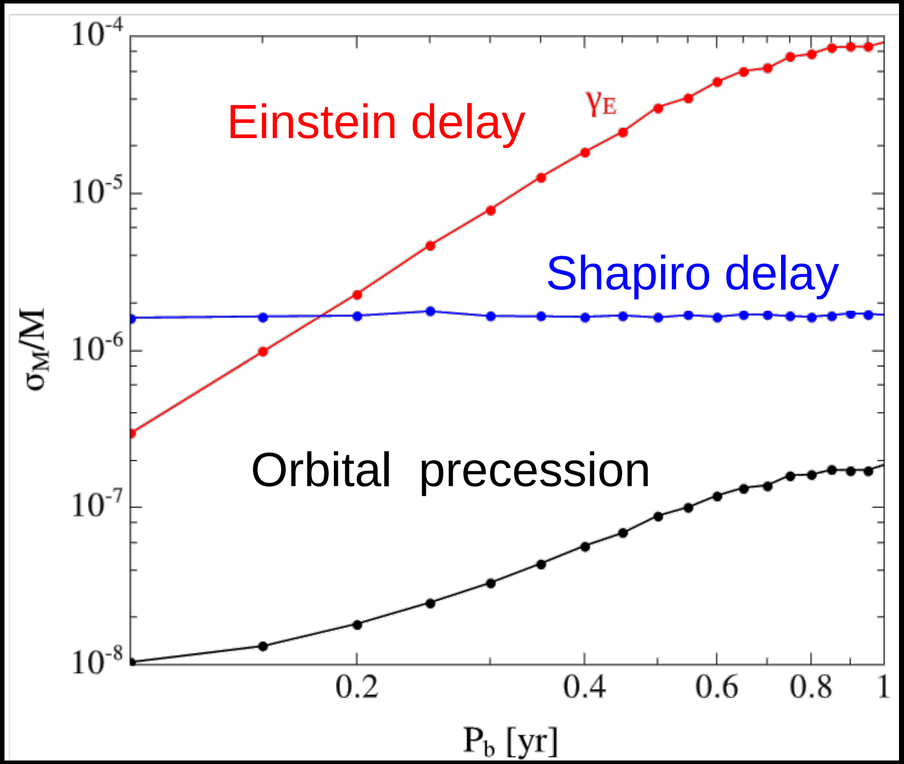
# Giving mass, spin, cosmic censorship etc.

Example: For pulsar in a 0.3 yr eccentric (e=0.5) orbit around Sgr A*

BH mass with precision < 0.1%

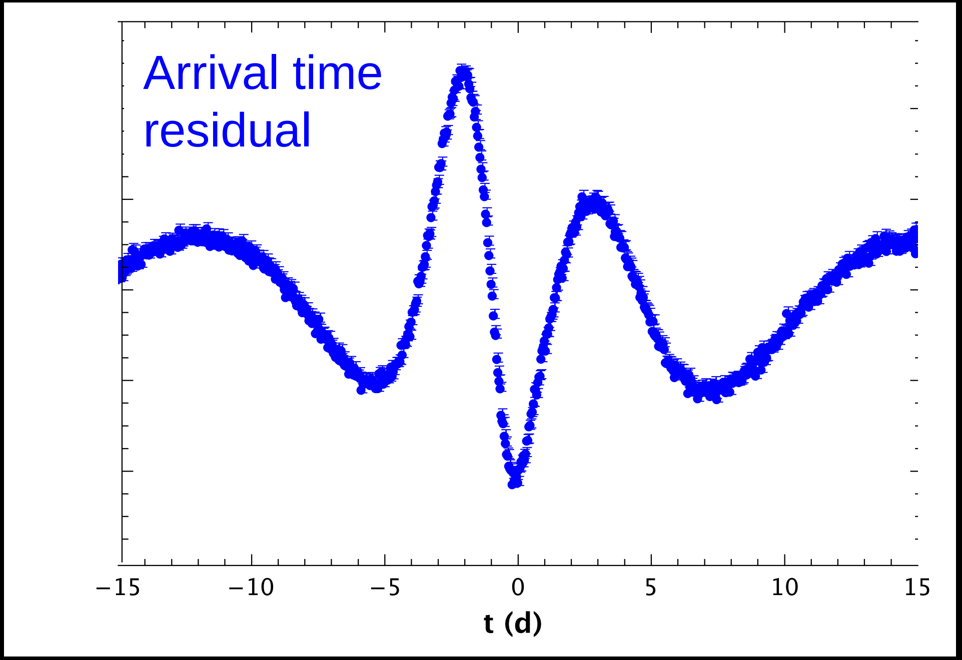
BH spin with precision < 1%

Cosmic Censorship: $S < GM^2/c$



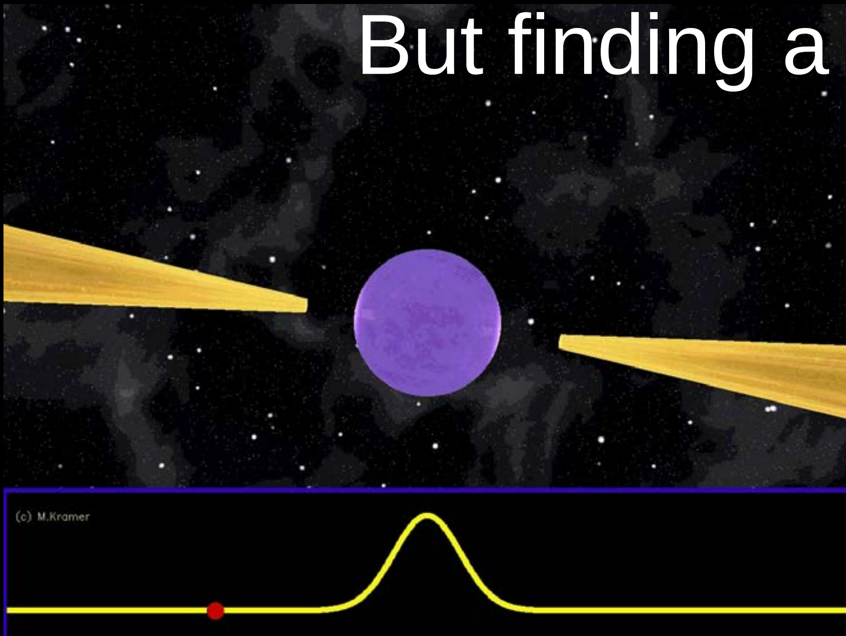

Wex & Kopeikin 1999, Liu 2012, Liu et al. 2014

And maybe even quadrupole from *characteristic periodic residuals*

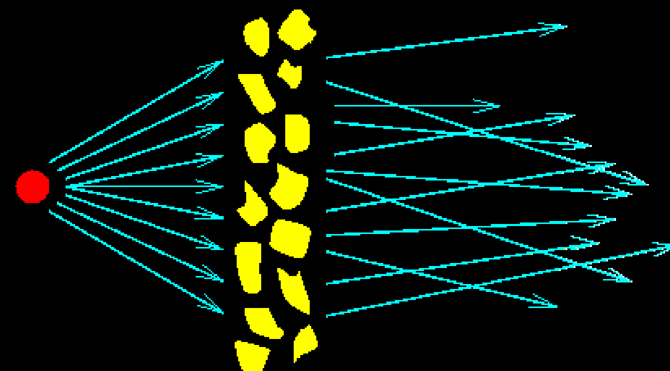



Liu 2012, Wex et al. in prep.

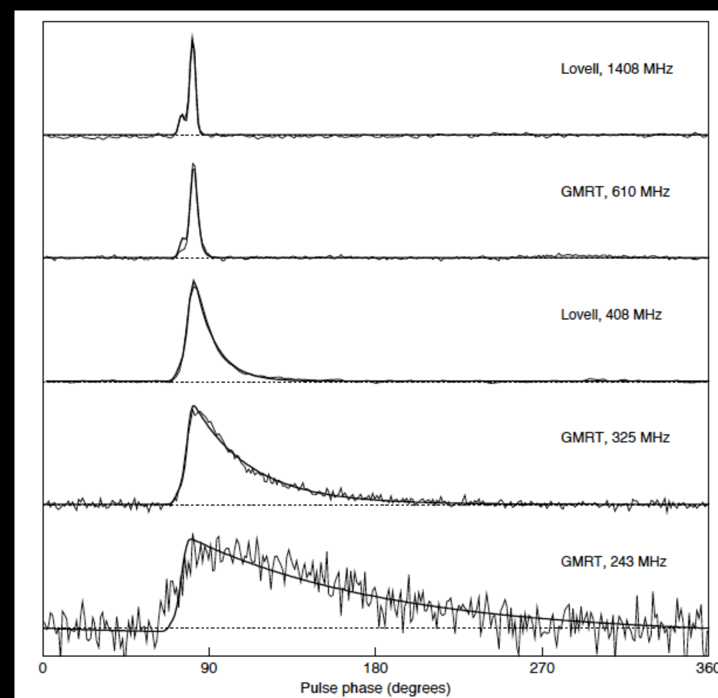
# But finding a Pulsar is not easy



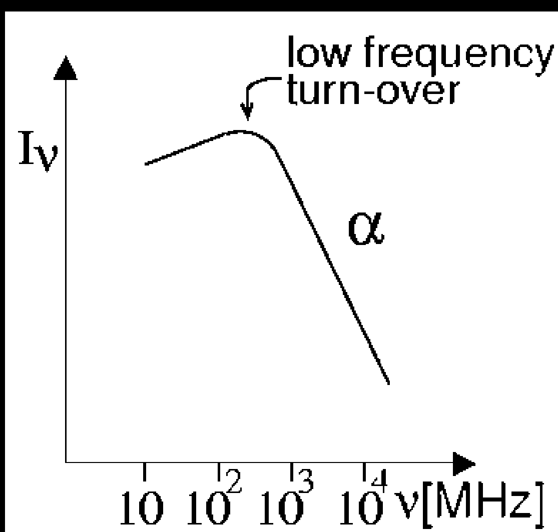

## Pulse smearing at low frequencies



Löhmer et al. (2001)

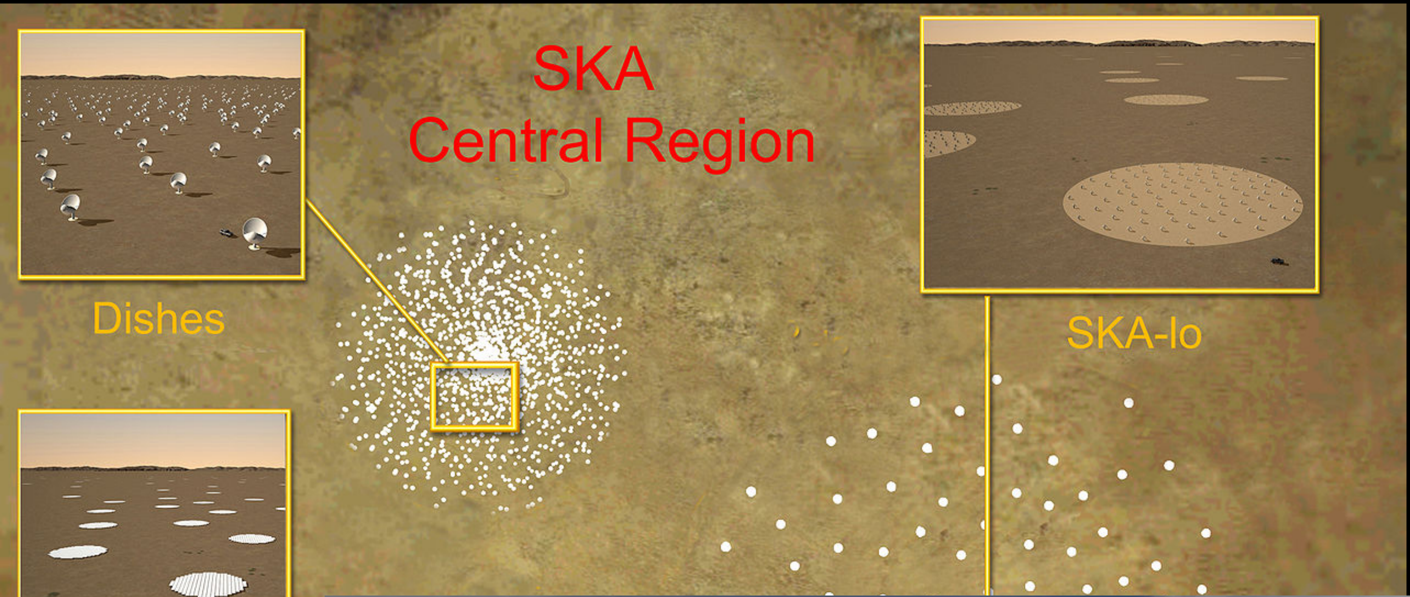



## Faint at high frequencies

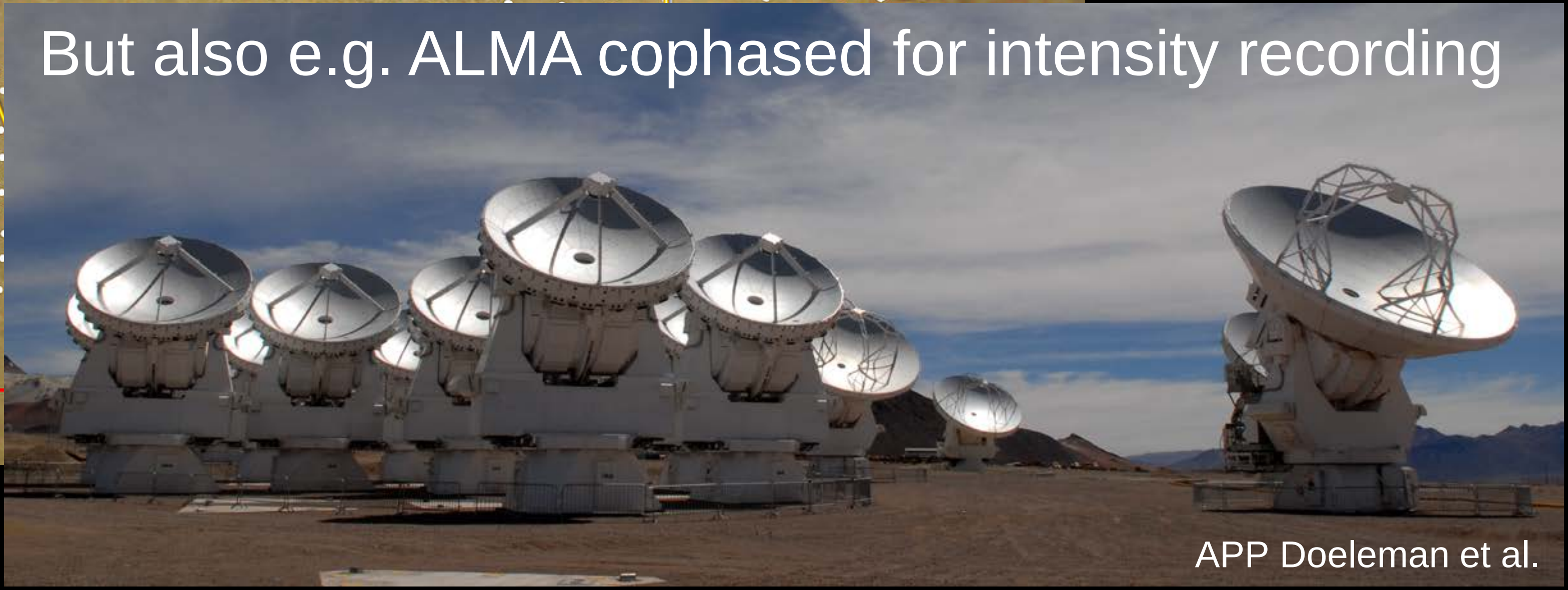


# And requires a large collecting area

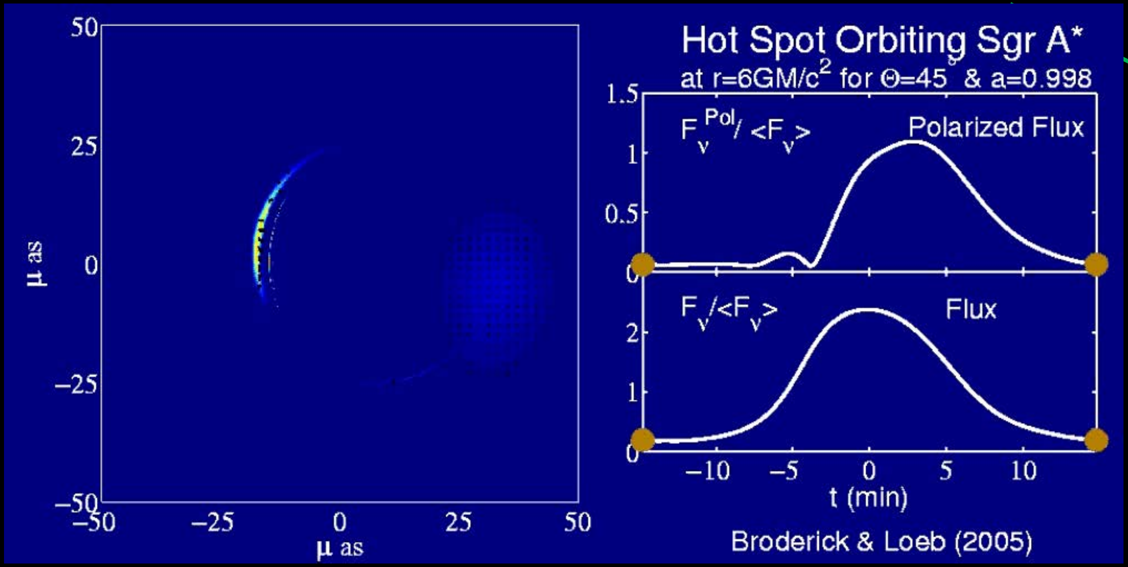
## Ideally with SKA

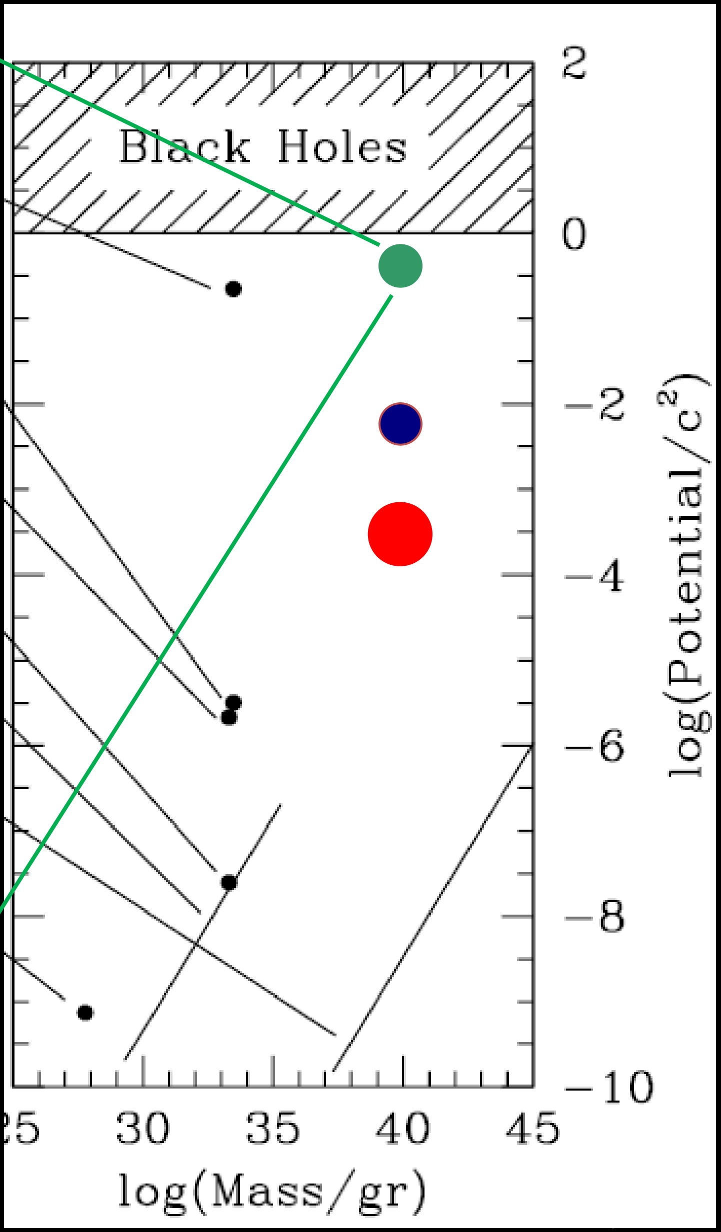



Braun, this conference

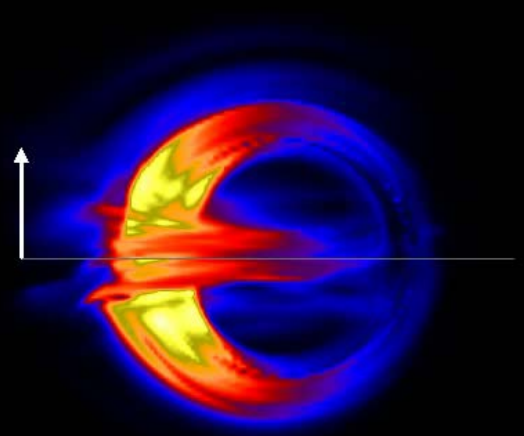


# Topics for the next decade(s) I: relativistic physics



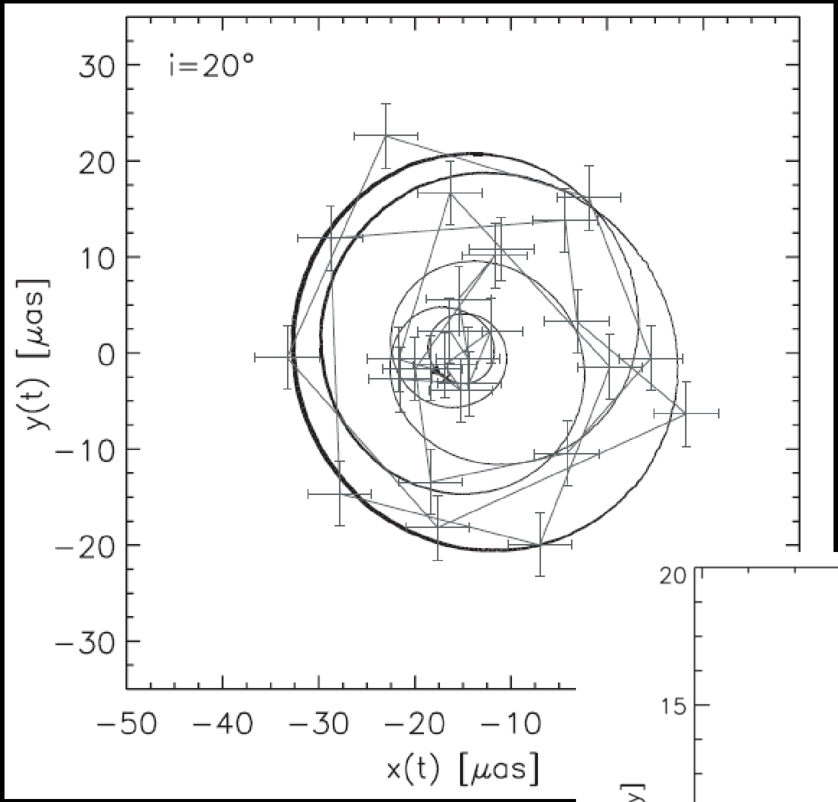




Broderick & Loeb 2005
Paumard et al. 2005

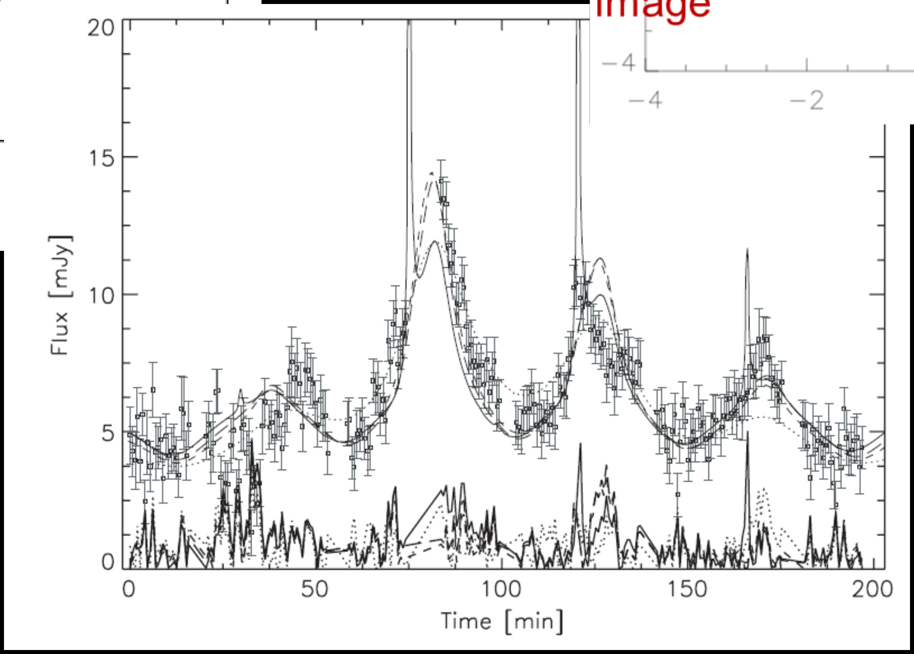


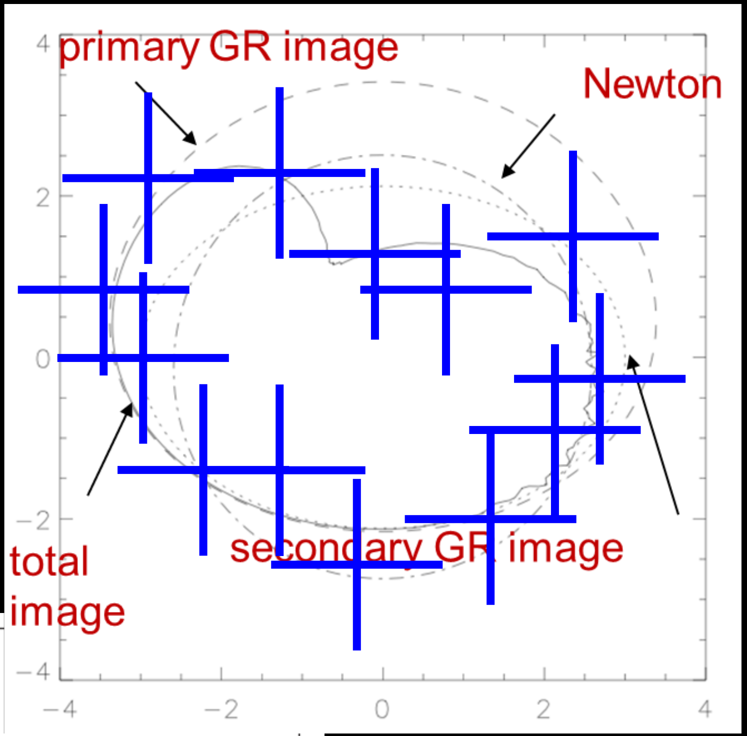
Dexter, Agol et al.,
Mościbrodzka, Gammie,
Dolence et al.,
Broderick, Loeb et al.,
Shcherbakov, Penna,
McKinney

# Infrared might offer one possibility




Hamaus et al. 2009
Mayer et al. 2010



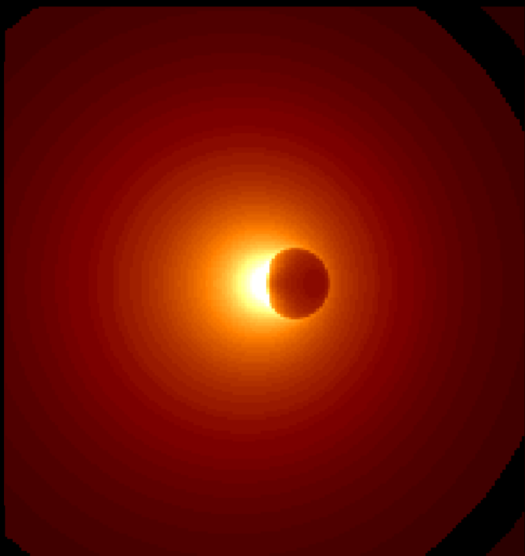

Paumard et al. 2005

# mm-Very Long Baseline Interferometry is another

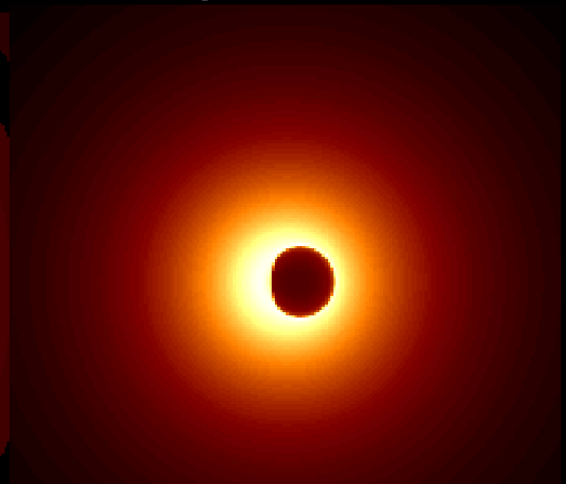
Slide by H. Falcke

# Imaging the shadow of the black hole

## Maximum spin

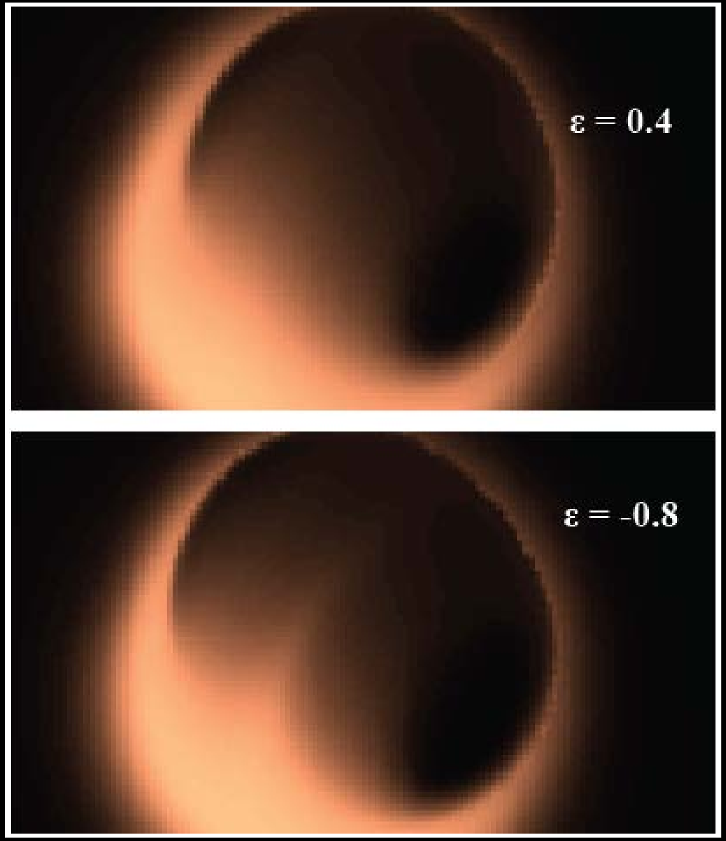


## No spin



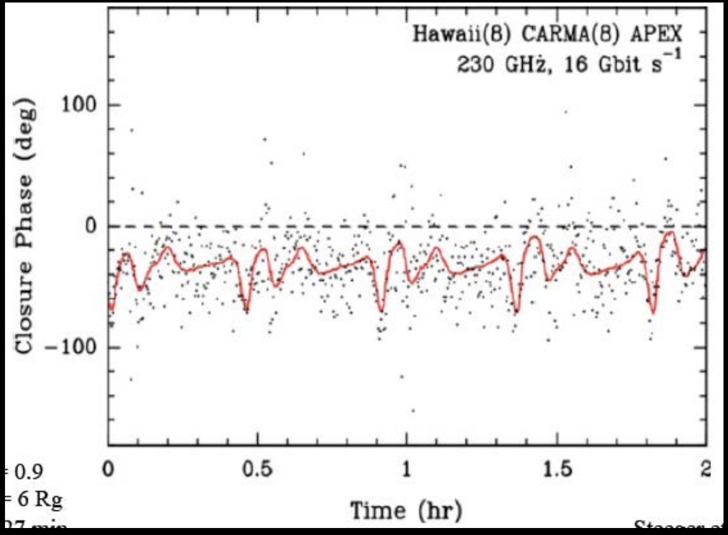
Falcke et al. 2000,
Broderick et al. 2009/11

## Quadropole effects



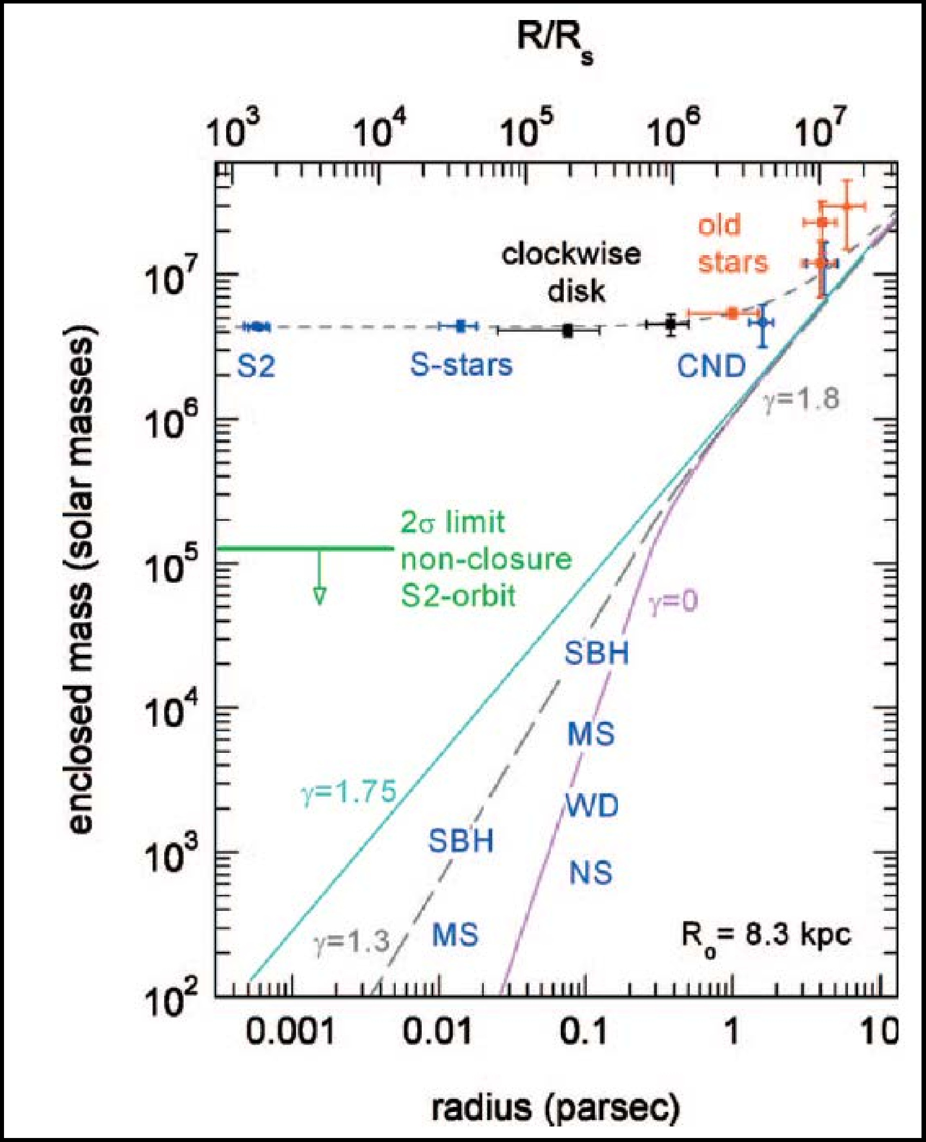

Johannsen, Psaltis 2012

## Orbiting hot spots

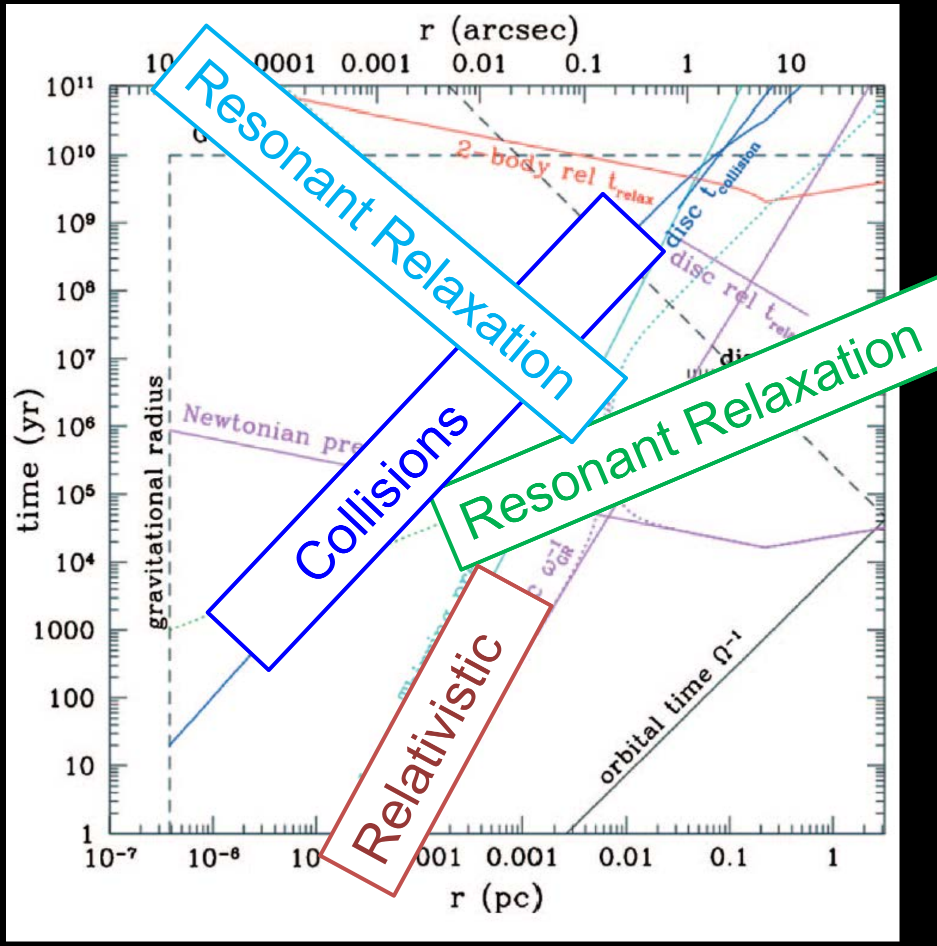



Steeger et al.

# Topics for the next decade(s) II: Complex Dynamics



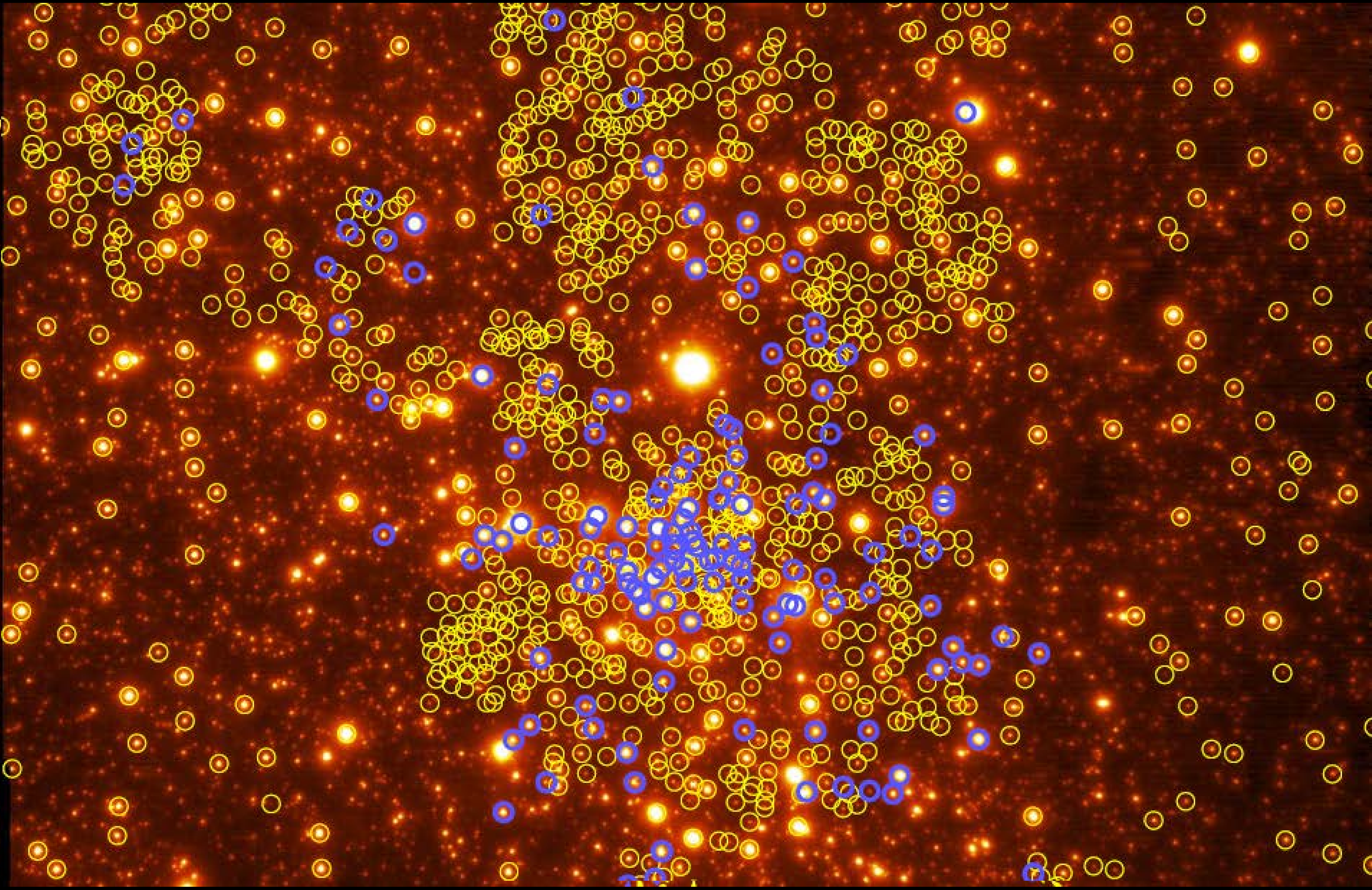

Complex, but not too complex




Kocsis & Tremaine 2010

From Genzel et al. 2010

# Large field astrometry and massive spectroscopy

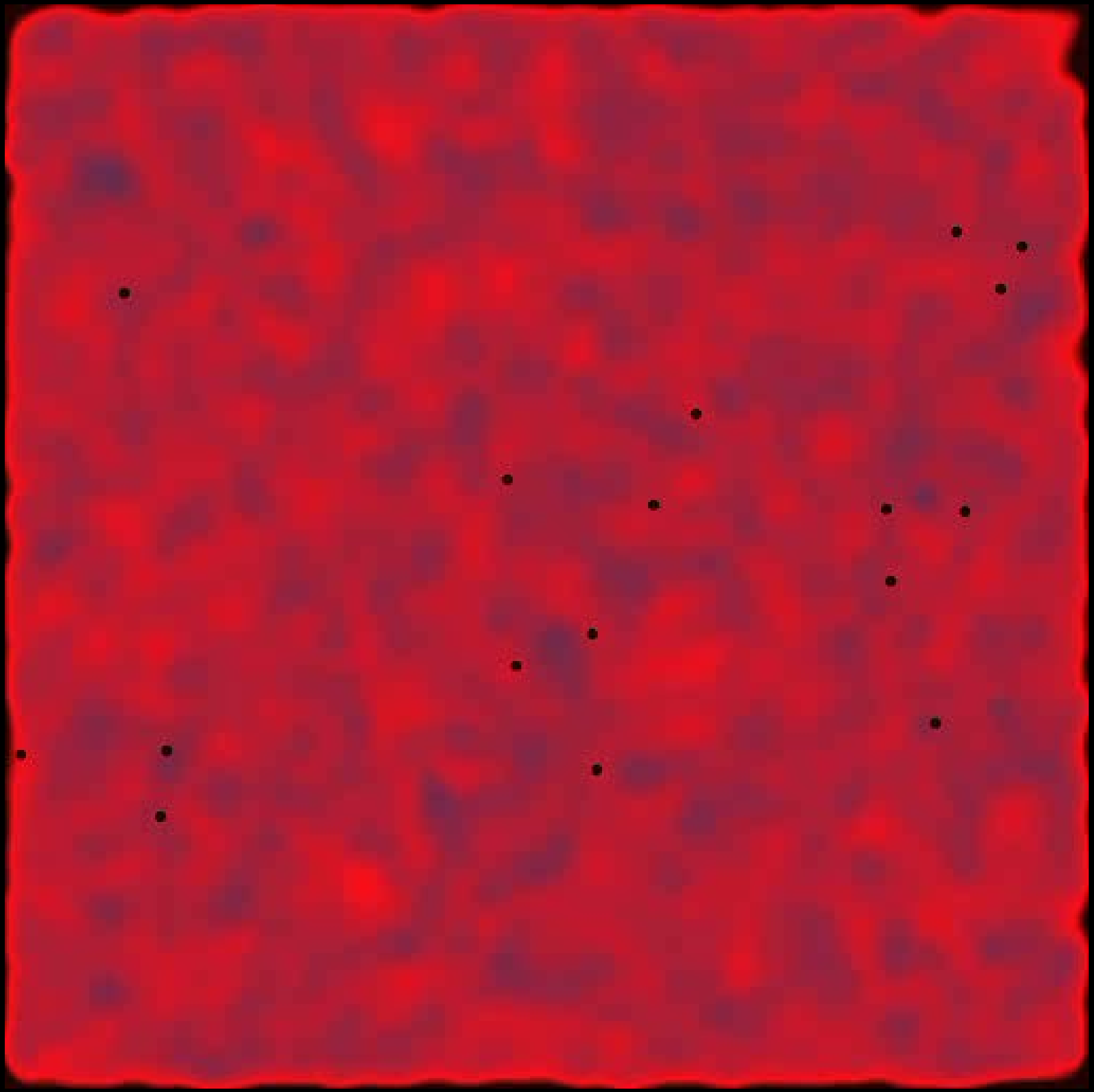


Bartko et al. Pfuhl et al. 2011, Feldmeier et al. 2014, Fritz et al. 2014,

Courtesy: P. Plewa

# Topics for the next decade(s) III: Gas dynamics

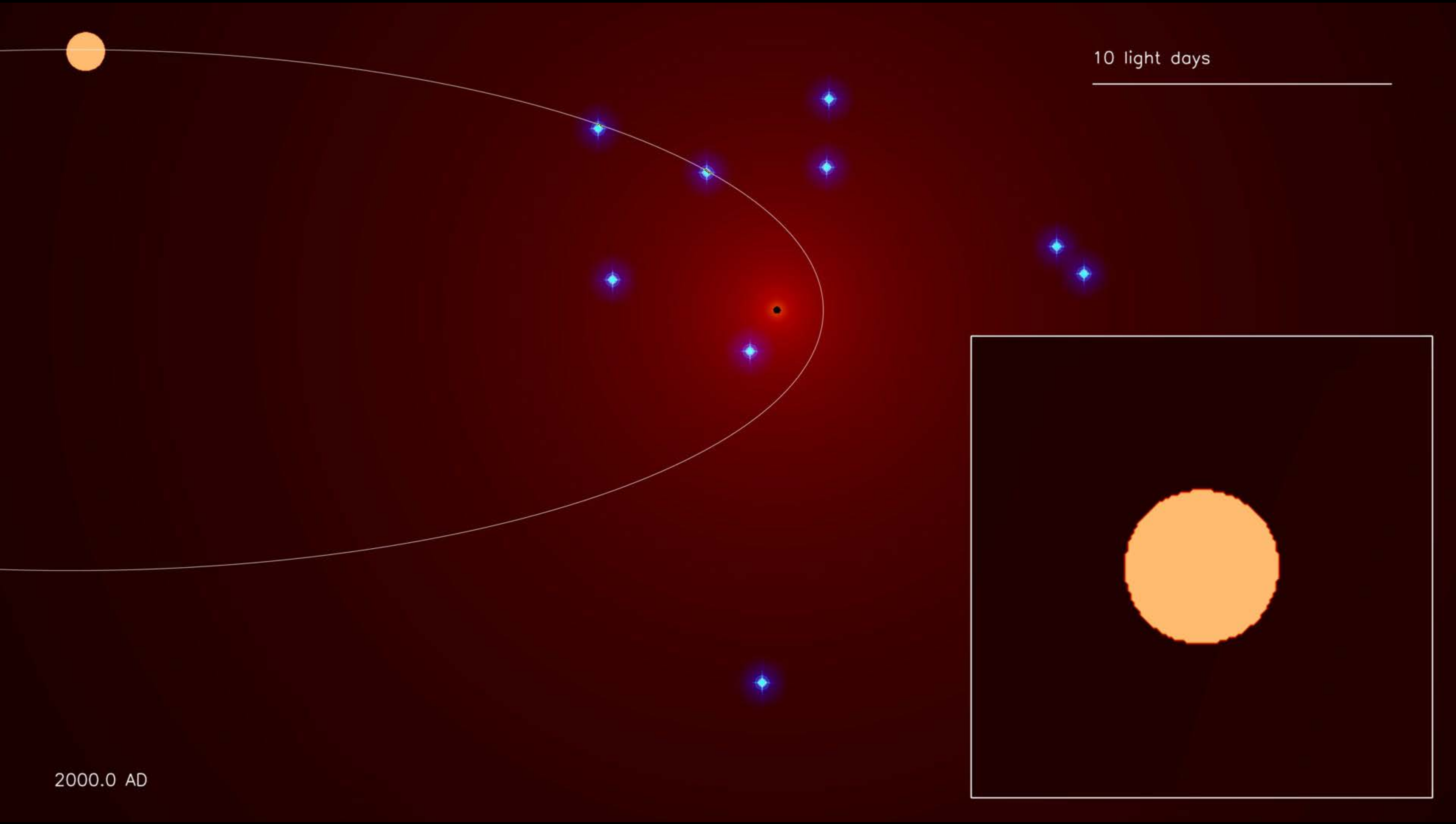
Feeding the Bondi accretion



Cuadra et al. 2006

# Topics for the next decade(s) III: Gas dynamics

## Feeding the Black Hole

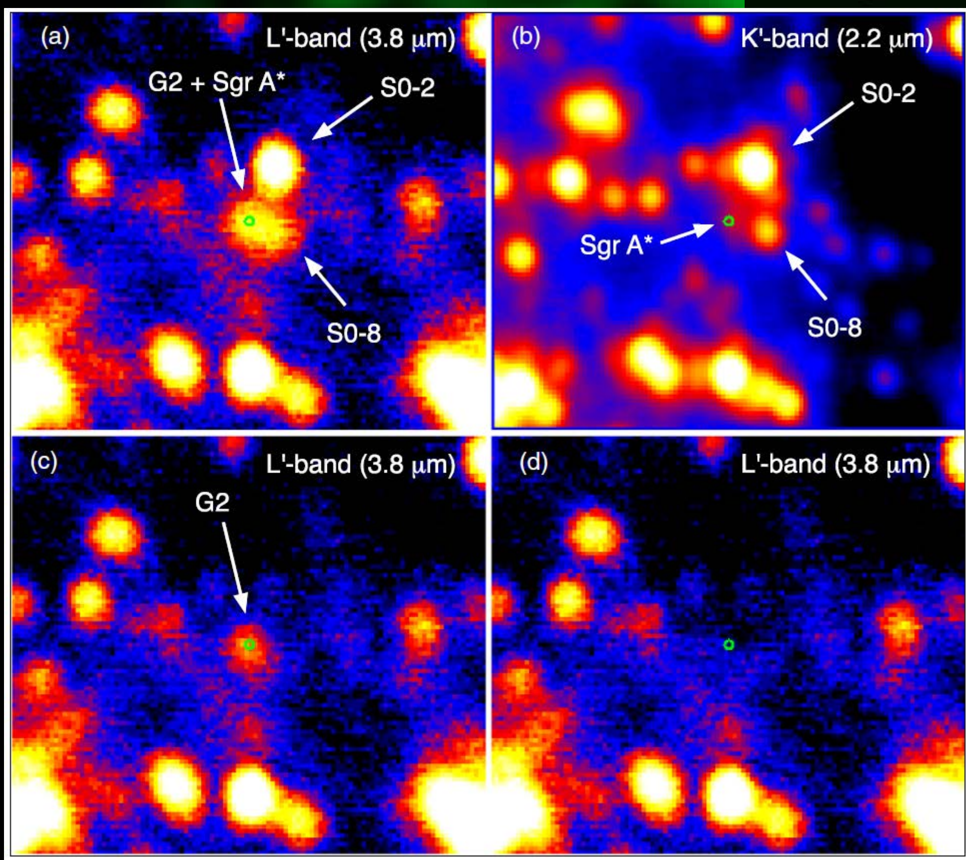



Burkert et al. 2012, Schartmann et al. 2012/13, Scoville & Burkert 2013, Ballone et al. 2014, De Colle et al. 2014, Guillochon et al. 2014

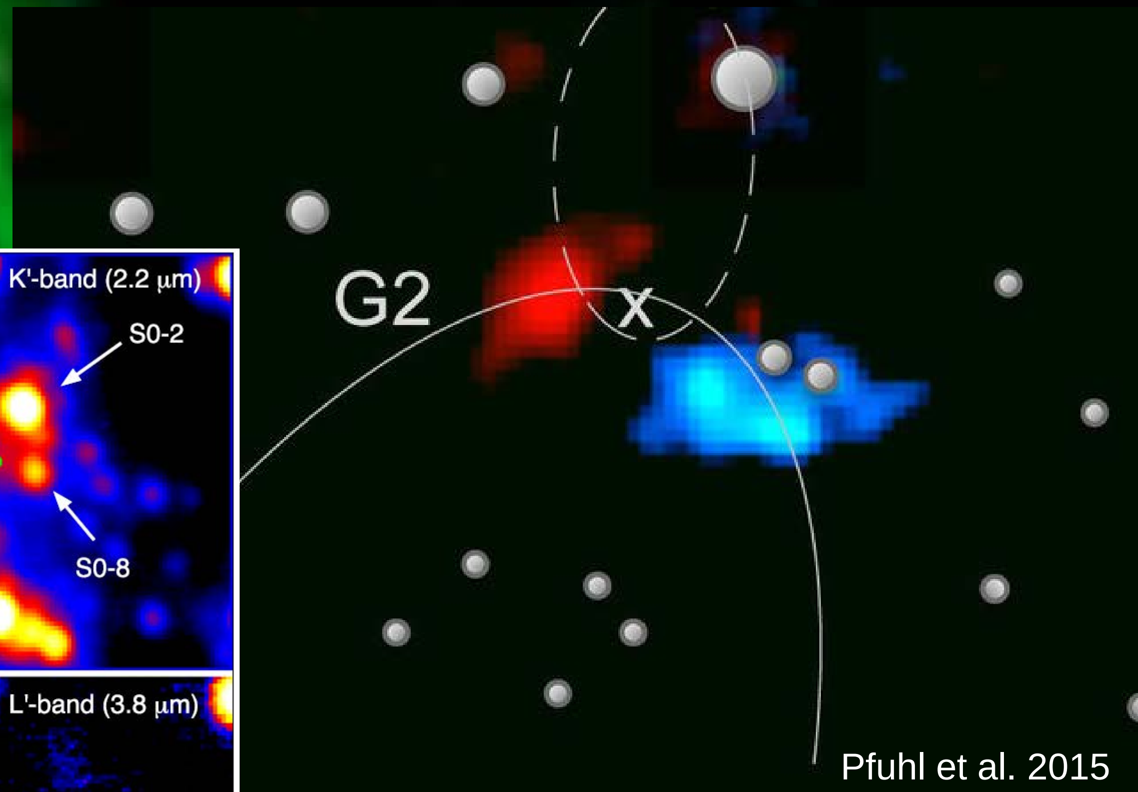
# High resolution imaging and deep spectroscopy

About 30 h of very good seeing on source

Only source removal
reveals G2 at peri



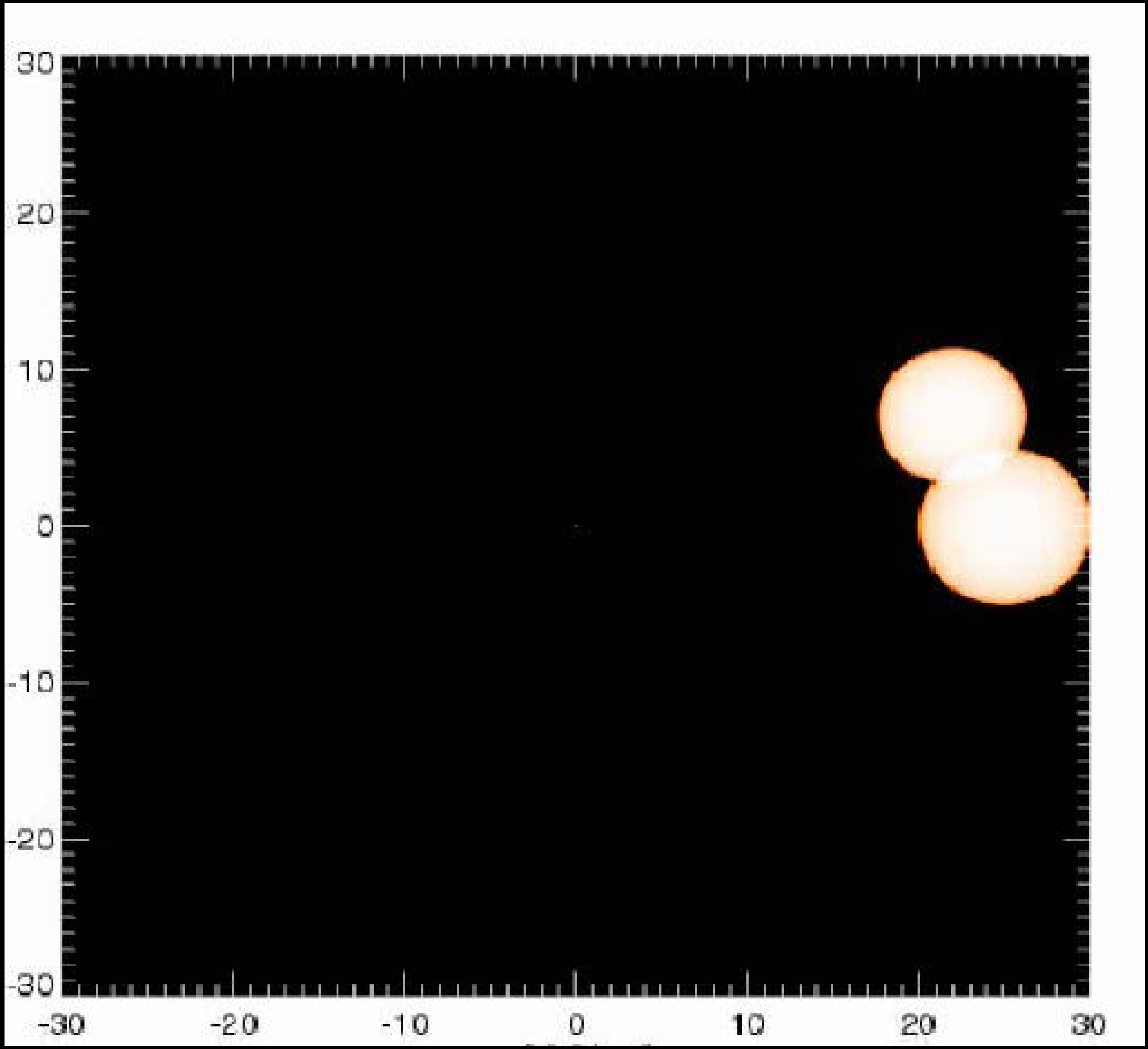

Witzel et al. 2014




Paumard et al. 2004

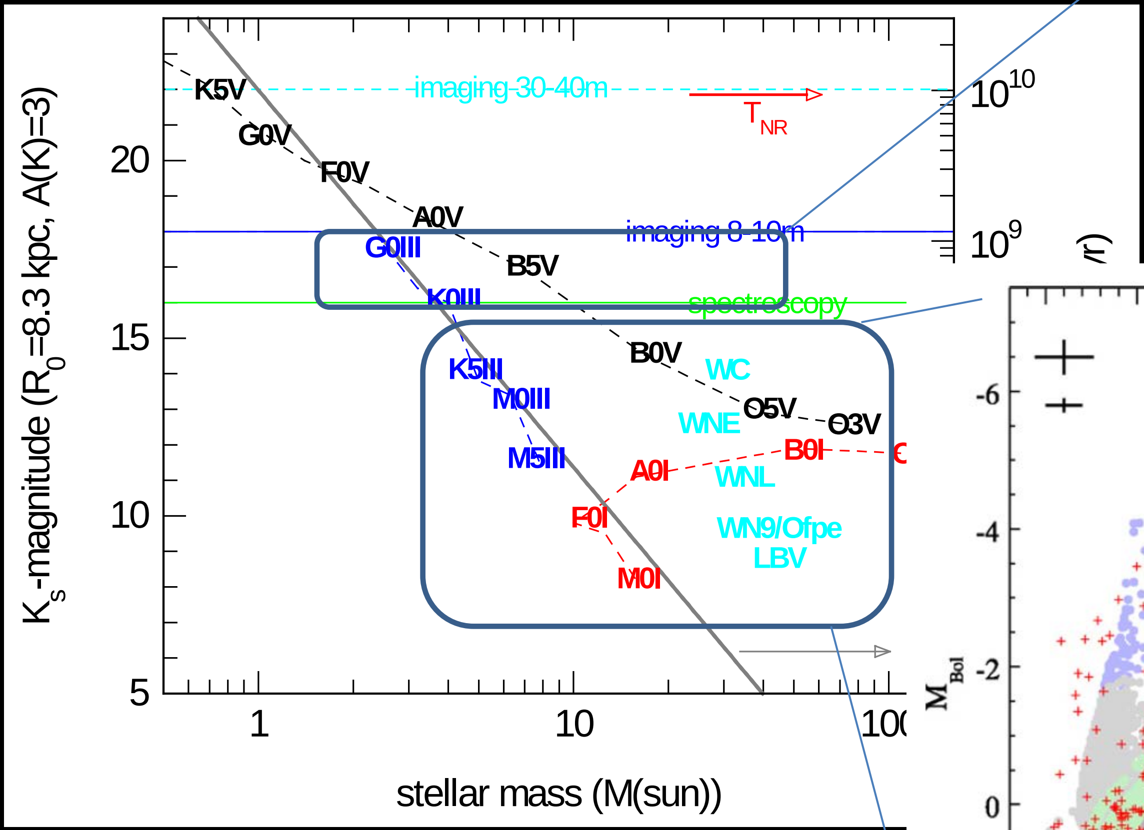
# Topics for the next decade IV: Star formation

Forming the stars

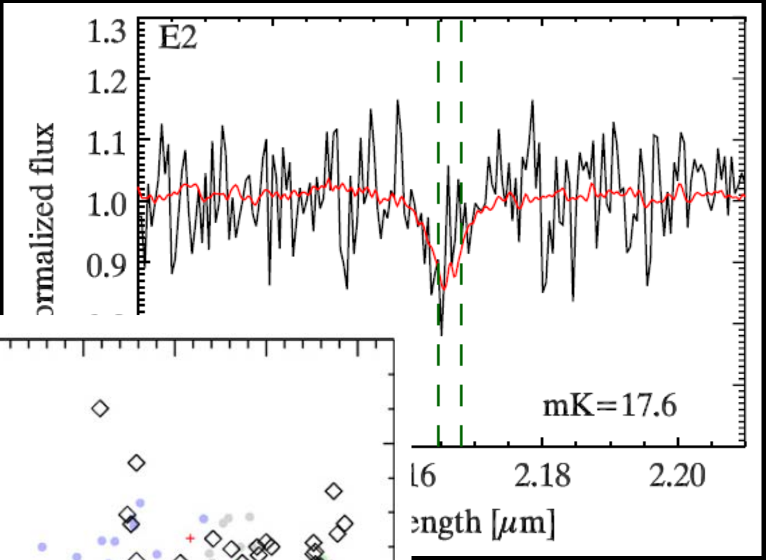


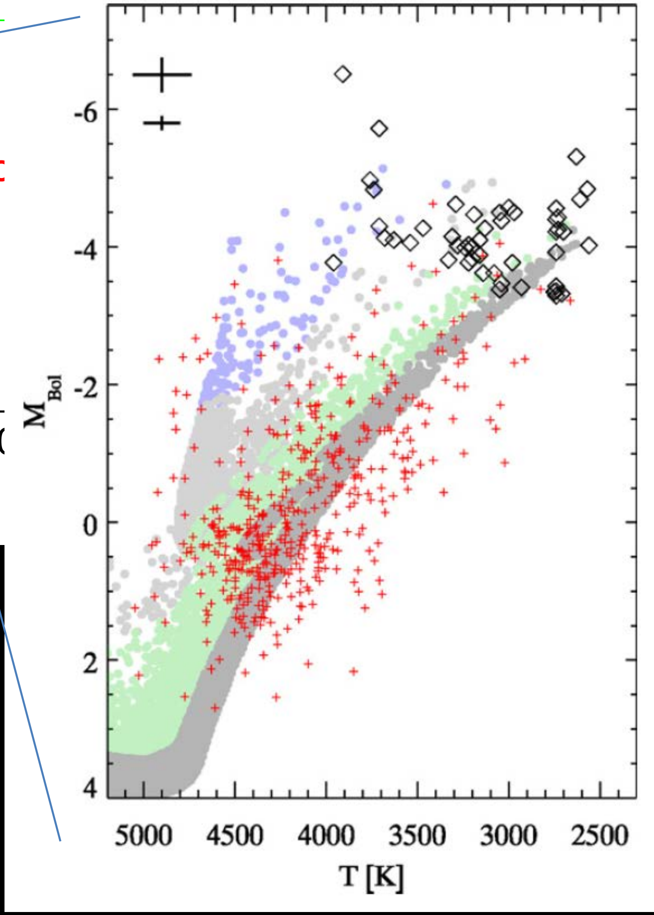

Hobbs & Nayakshin 2009

# Deep spectroscopy and high resolution imaging



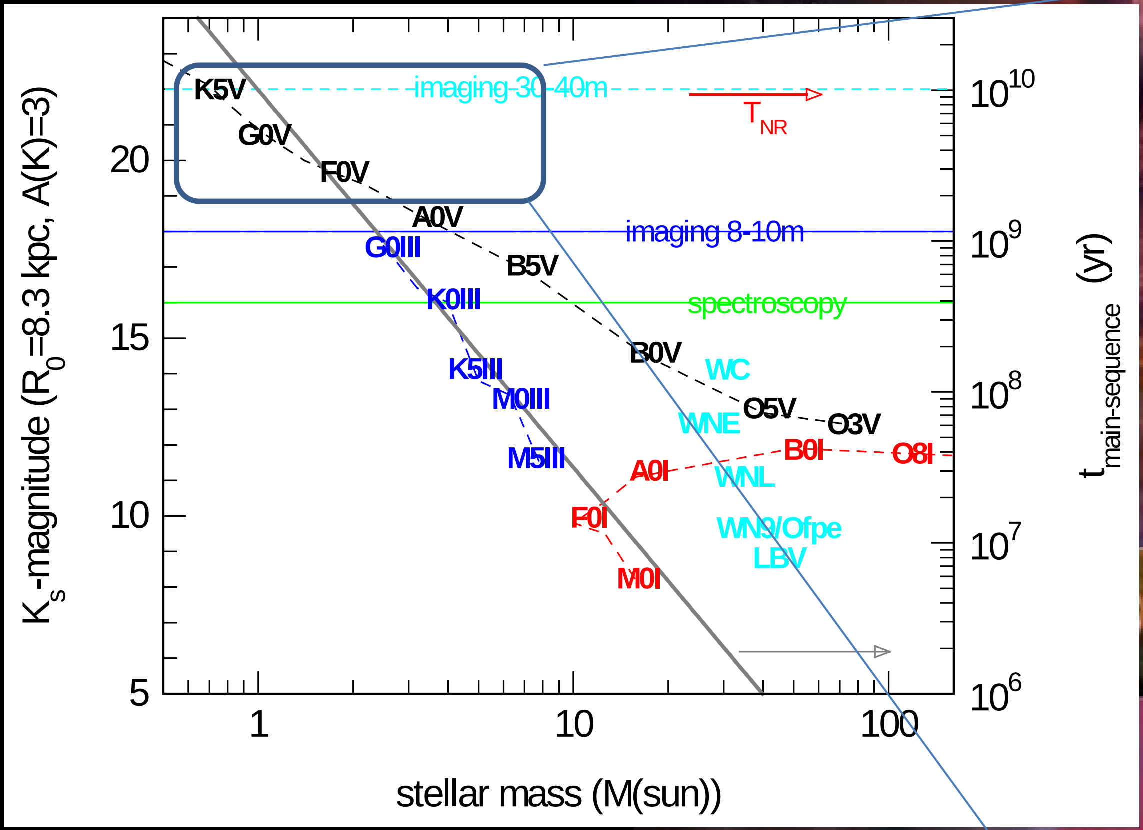

Genzel et al. 2010



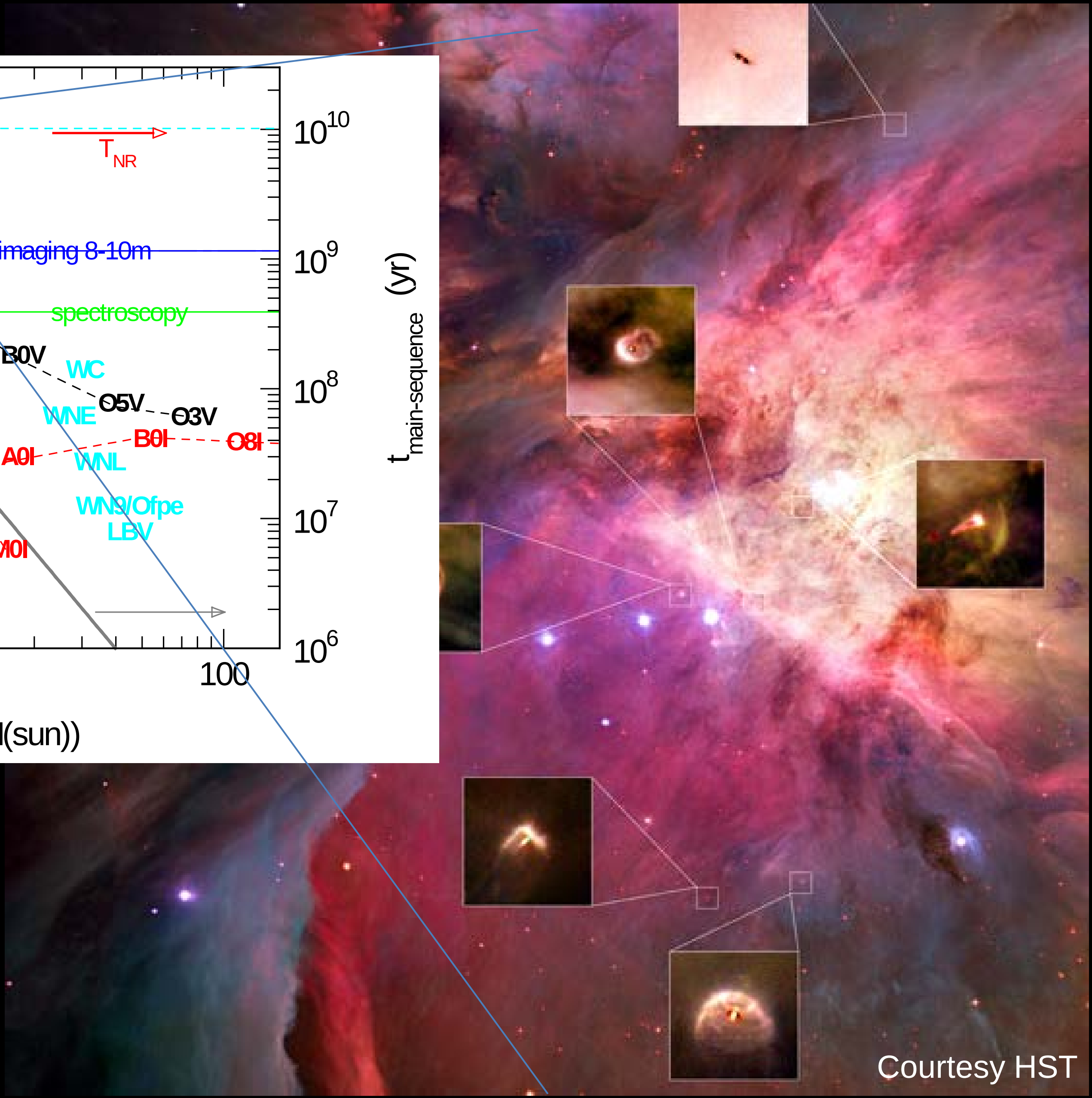




Pfuhl et al. 2011

# Deep spectroscopy and high resolution imaging




Genzel et al. 2010



Courtesy HST

# ESO's role and how it can best contribute

You have set the right directions for the next decade

VLT(I), GRAVITY

EELT, MICADO, HARMONI

Thatte et al. 2014, Davies et al. 2014

ALMA Phasing Project

Doeleman et al.

# ESO's role and how it can best contribute

But we need to stay on track and in time

VLT(I), GRAVITY

Ready and well performing before the S2 peri passage
Continued support and adequate observing model

*And keep enough margin for unexpected problems to come*

SKA, CTA etc. at ESO?

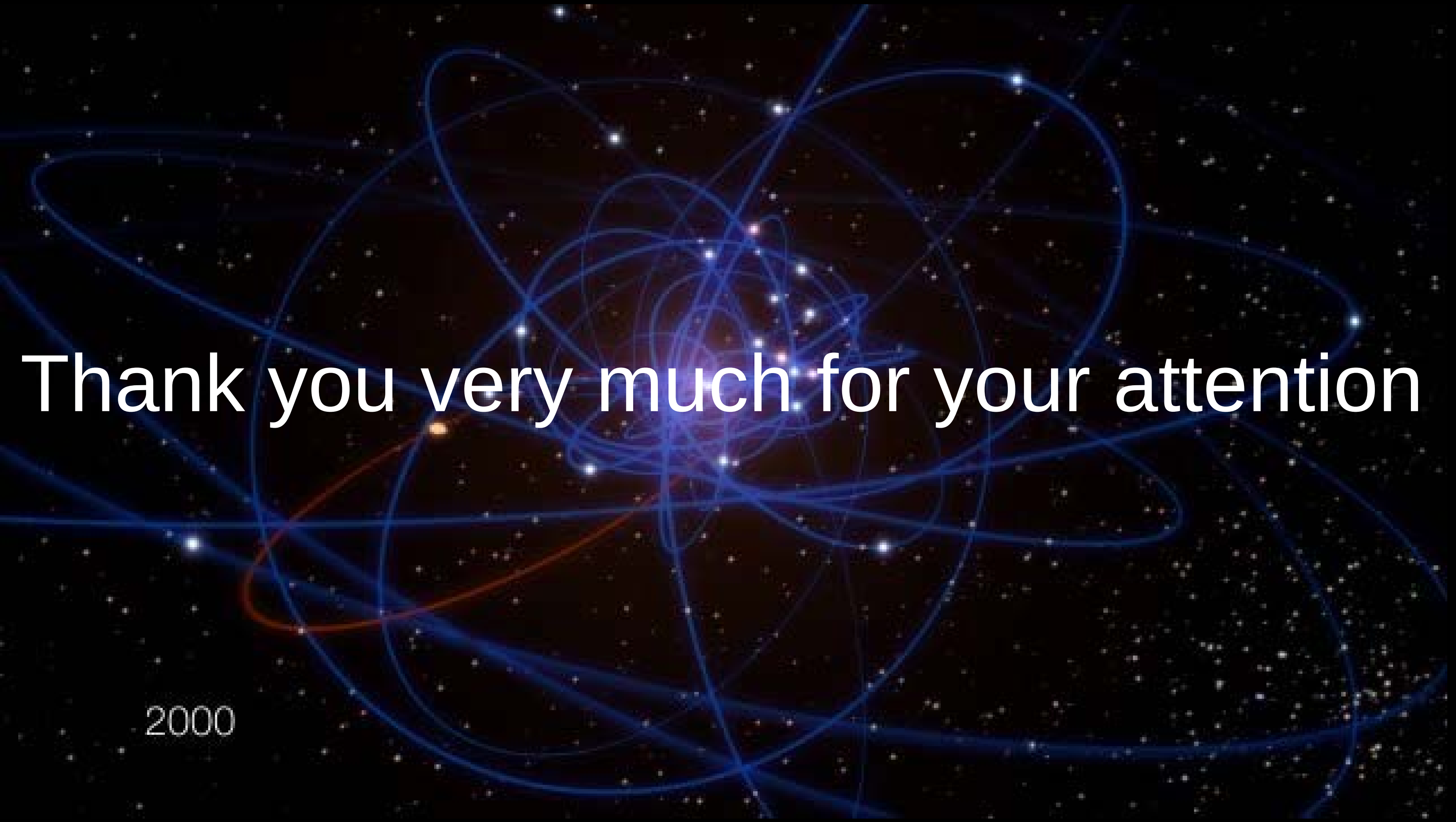
Faster than TMT
Competitive adaptive optics

EELT, MICADO, HARMONI

*I don't feel competent to advice*

ALMA Phasing Project

# In any case – exciting times to come




Thank you very much for your attention

Gillessen et al. 2012/13, Burkert et al. 2012, Schartmann et al. 2012/13, Animation ESO