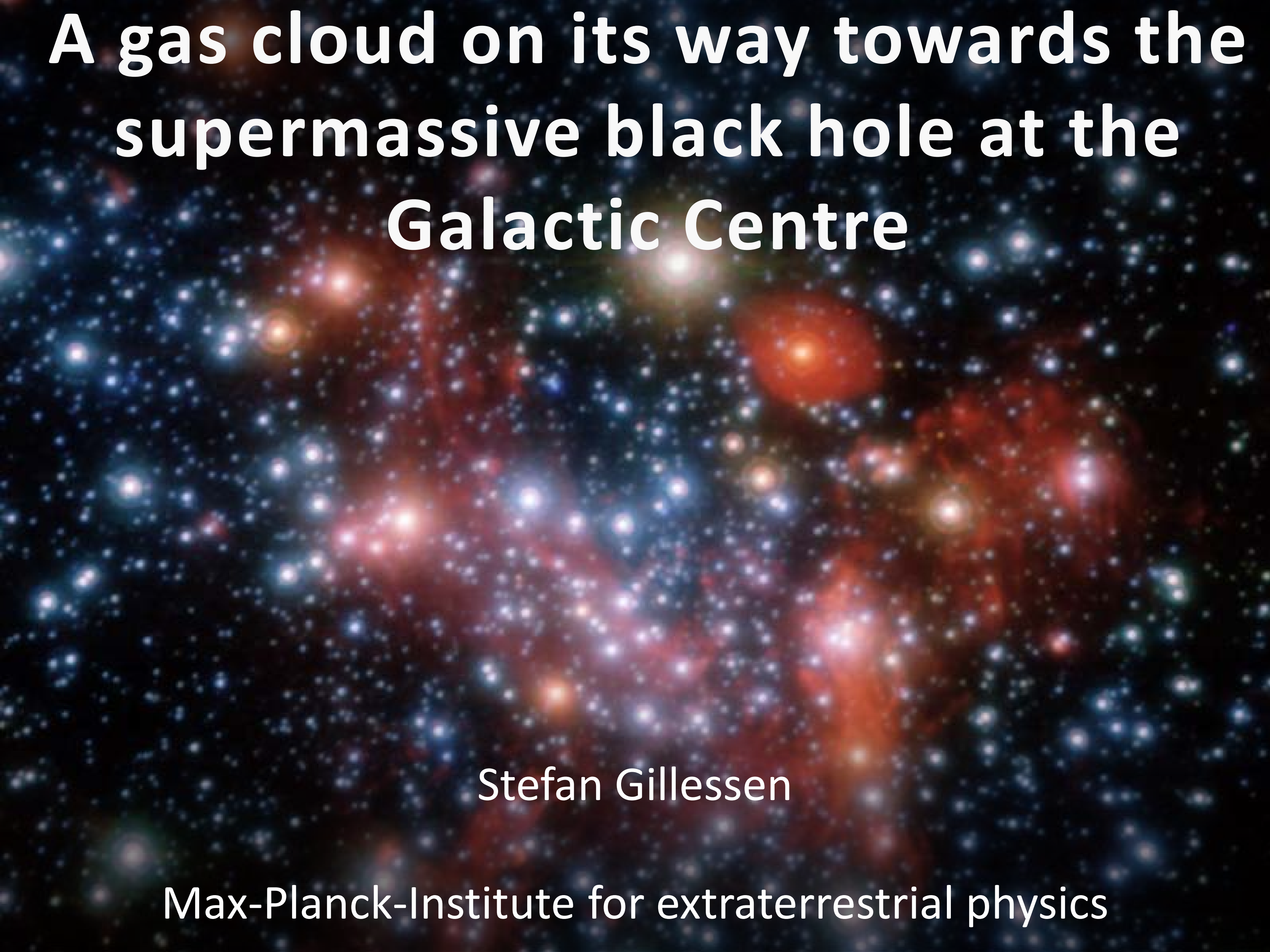


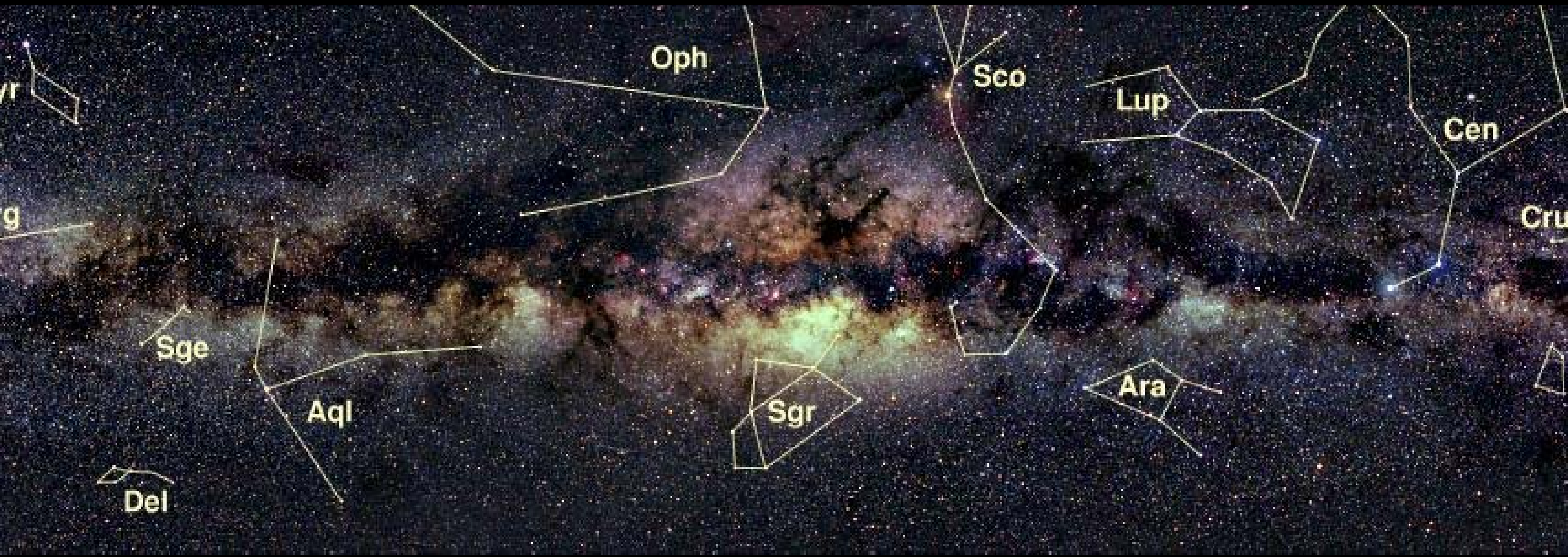
A gas cloud on its way towards the supermassive black hole at the Galactic Centre

Stefan Gillessen

Max-Planck-Institute for extraterrestrial physics

S. Gillessen, R. Genzel, T. Fritz, E. Quataert, C. Alig, A. Burkert, J. Cuadra, F. Eisenhauer, O. Pfuhl, K. Dodds-Eden, C. Gammie & T. Ott,

2012 Nature 481, 51


Oph
Sco
Lup
Cen
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Aql
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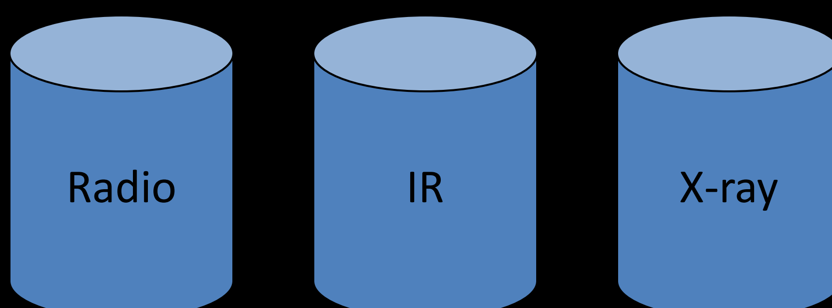
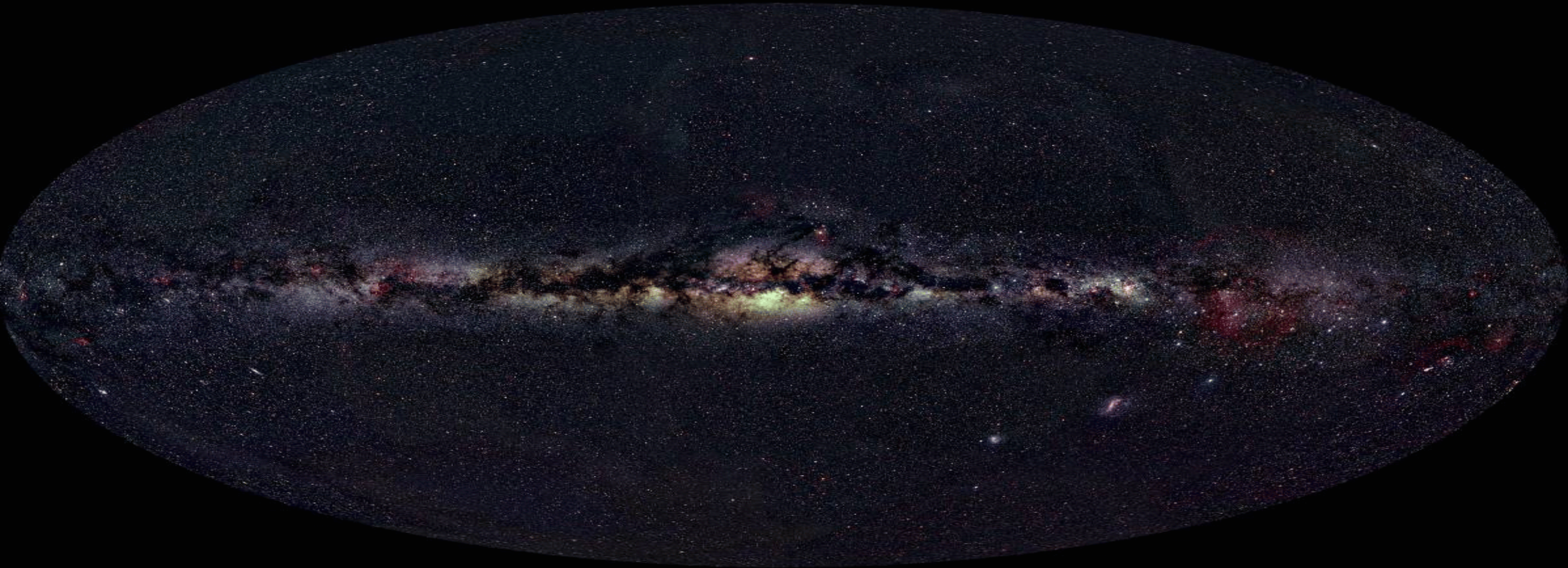
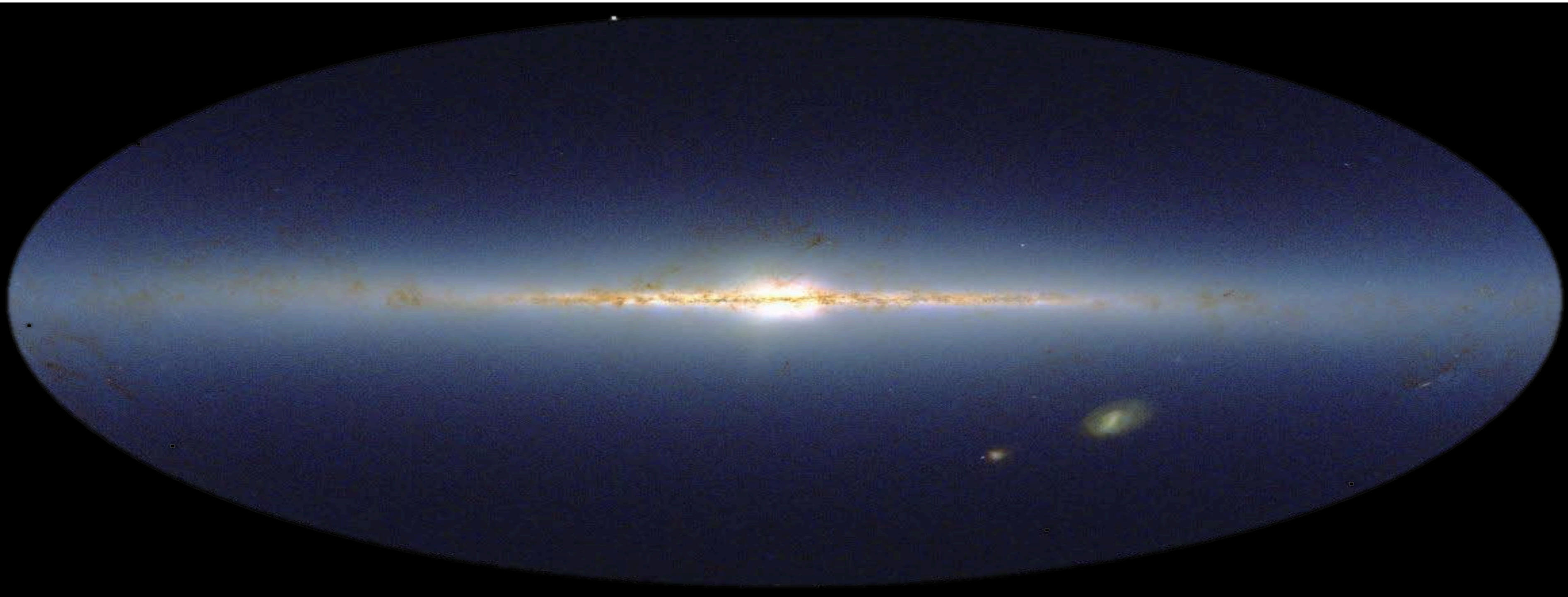
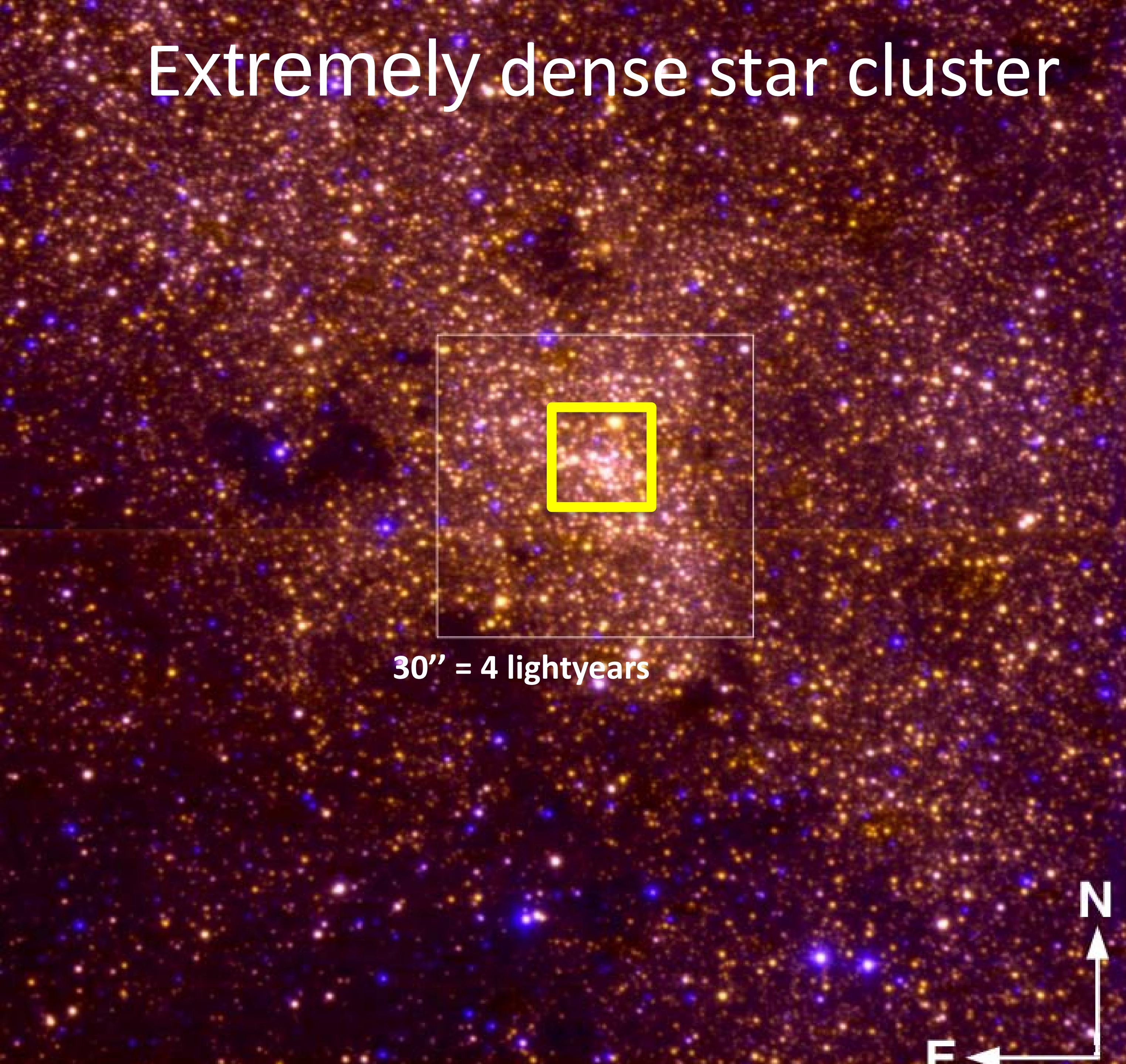
Del


Radio
IR
X-ray



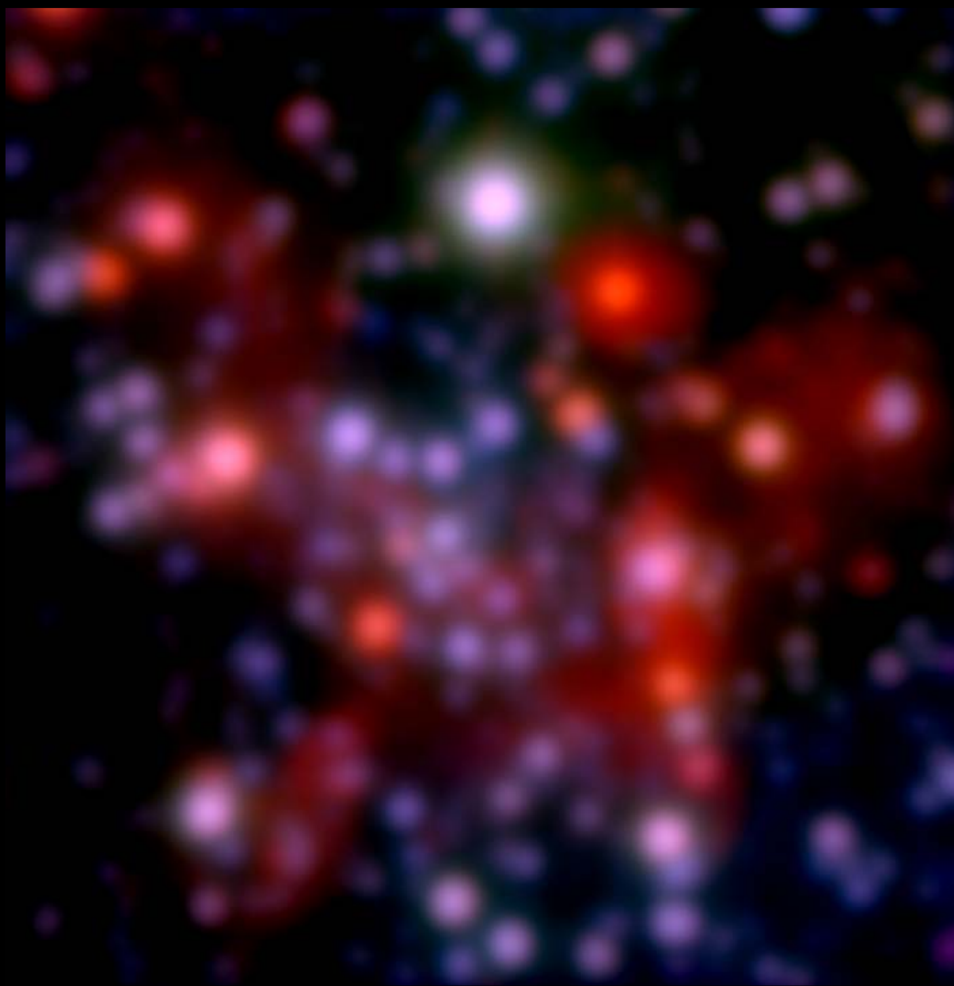


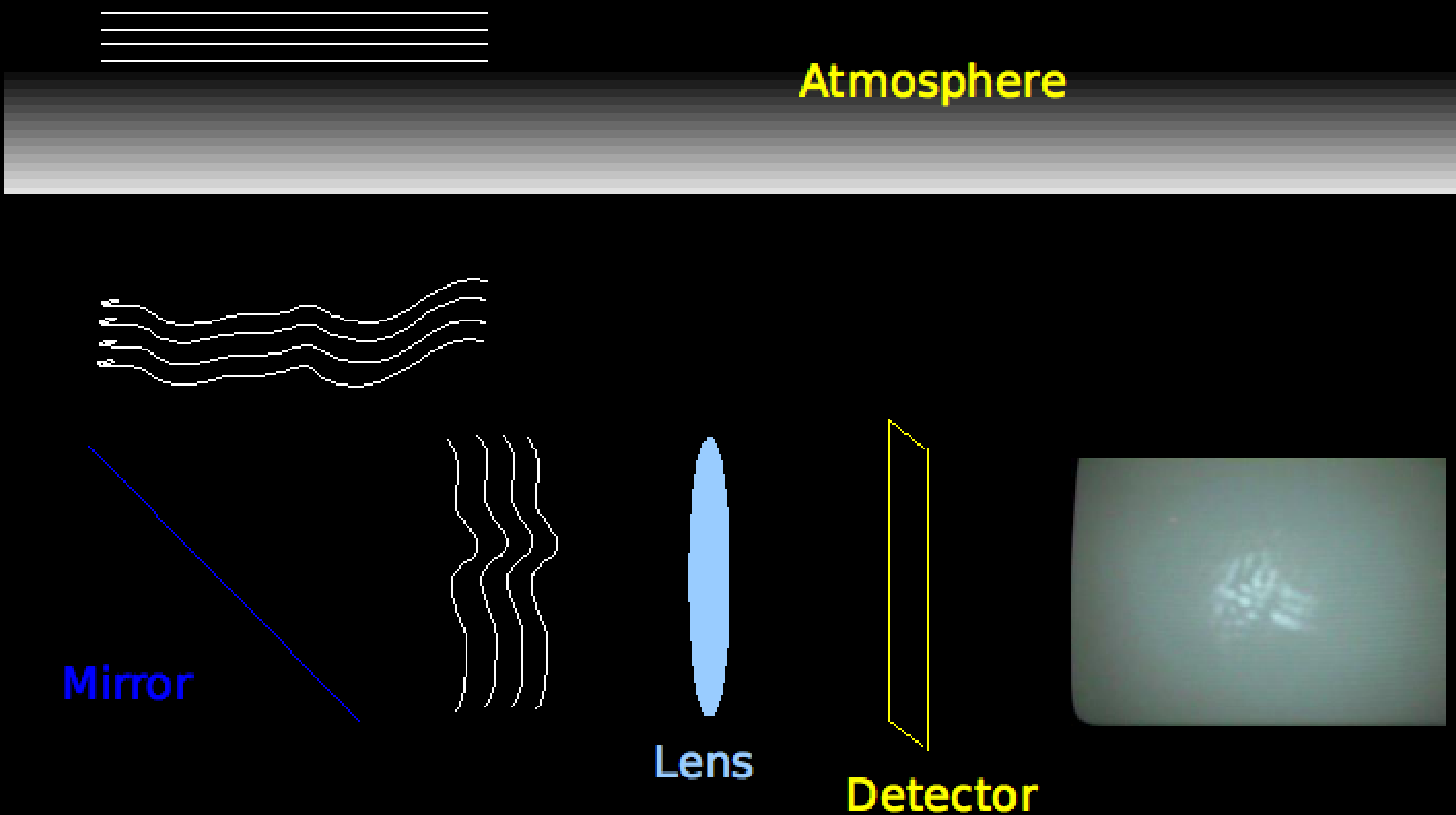
Extremely dense star cluster

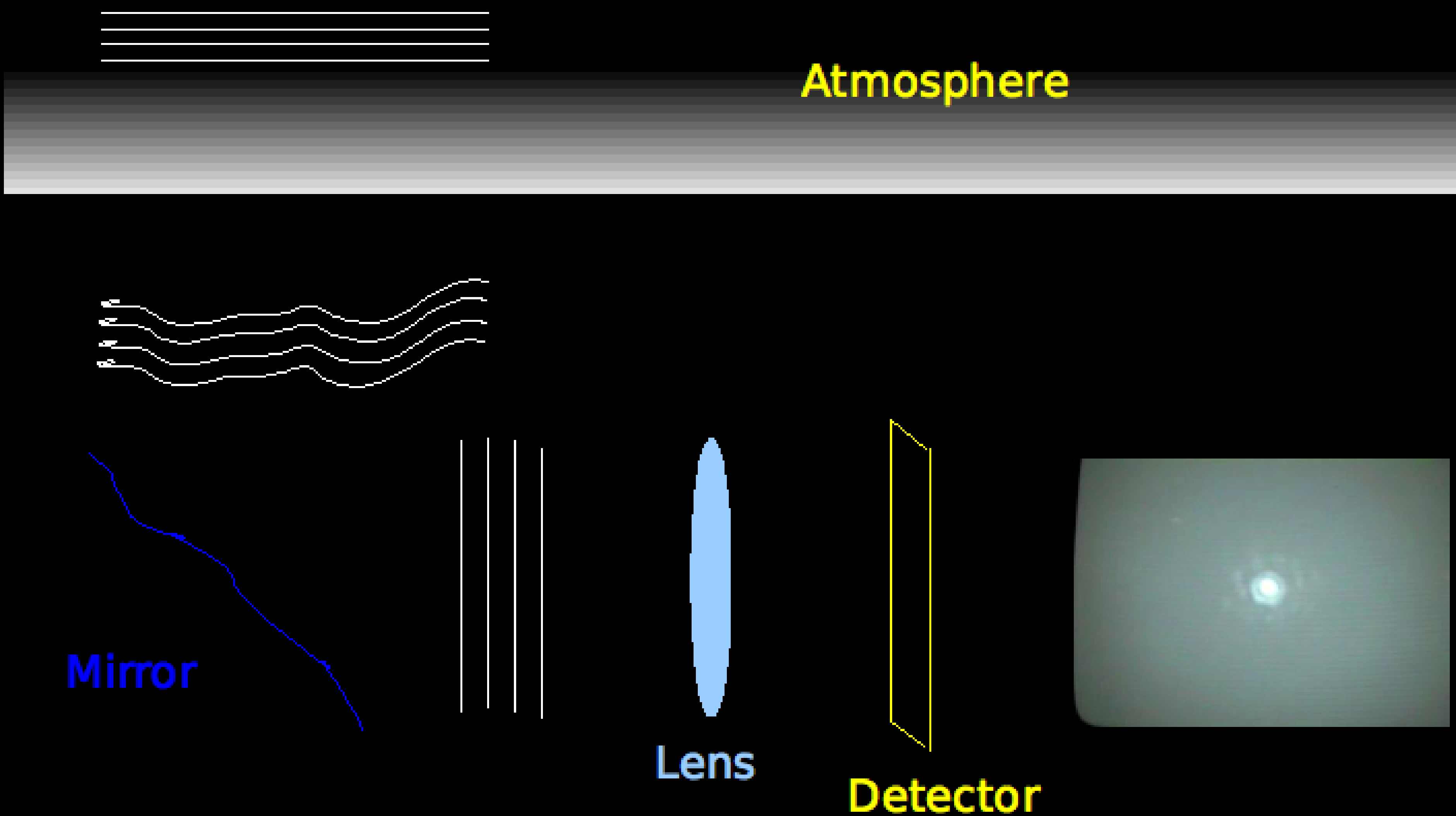


Schödel+ 2006
(ISAAC, VLT)

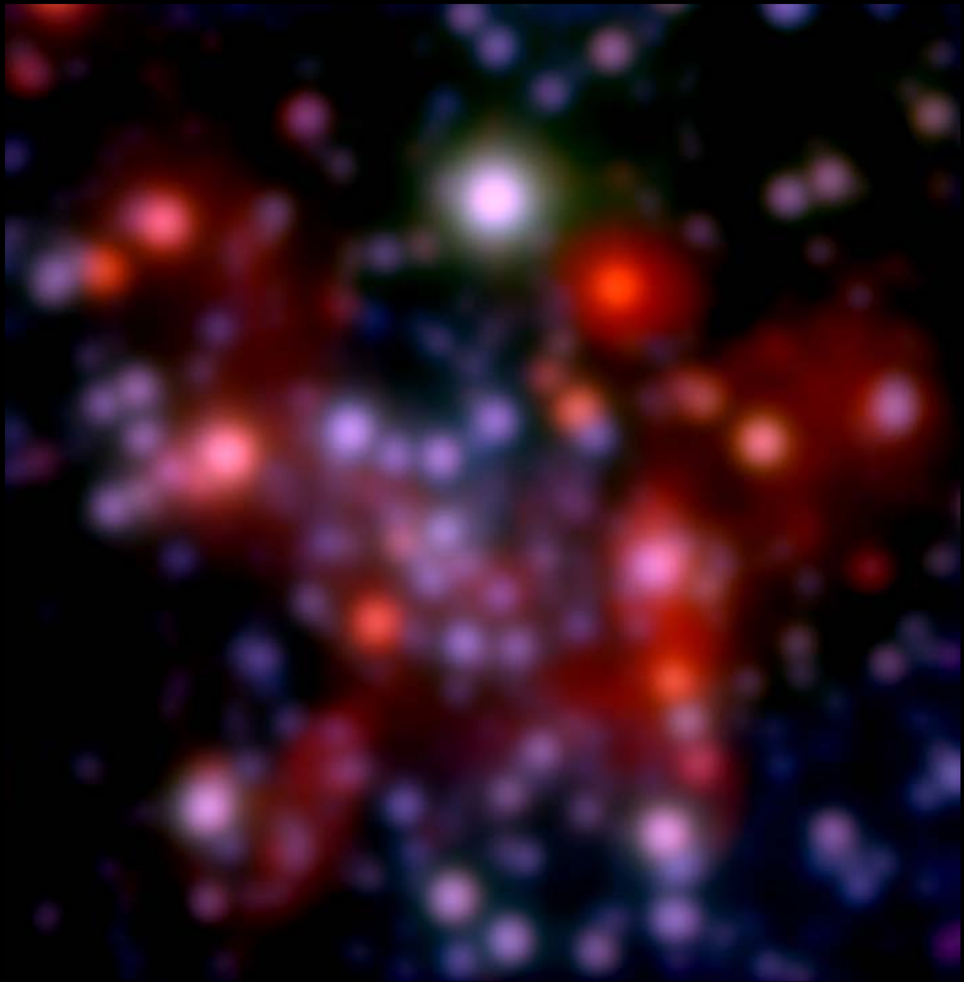
The central 20'': Seeing limited

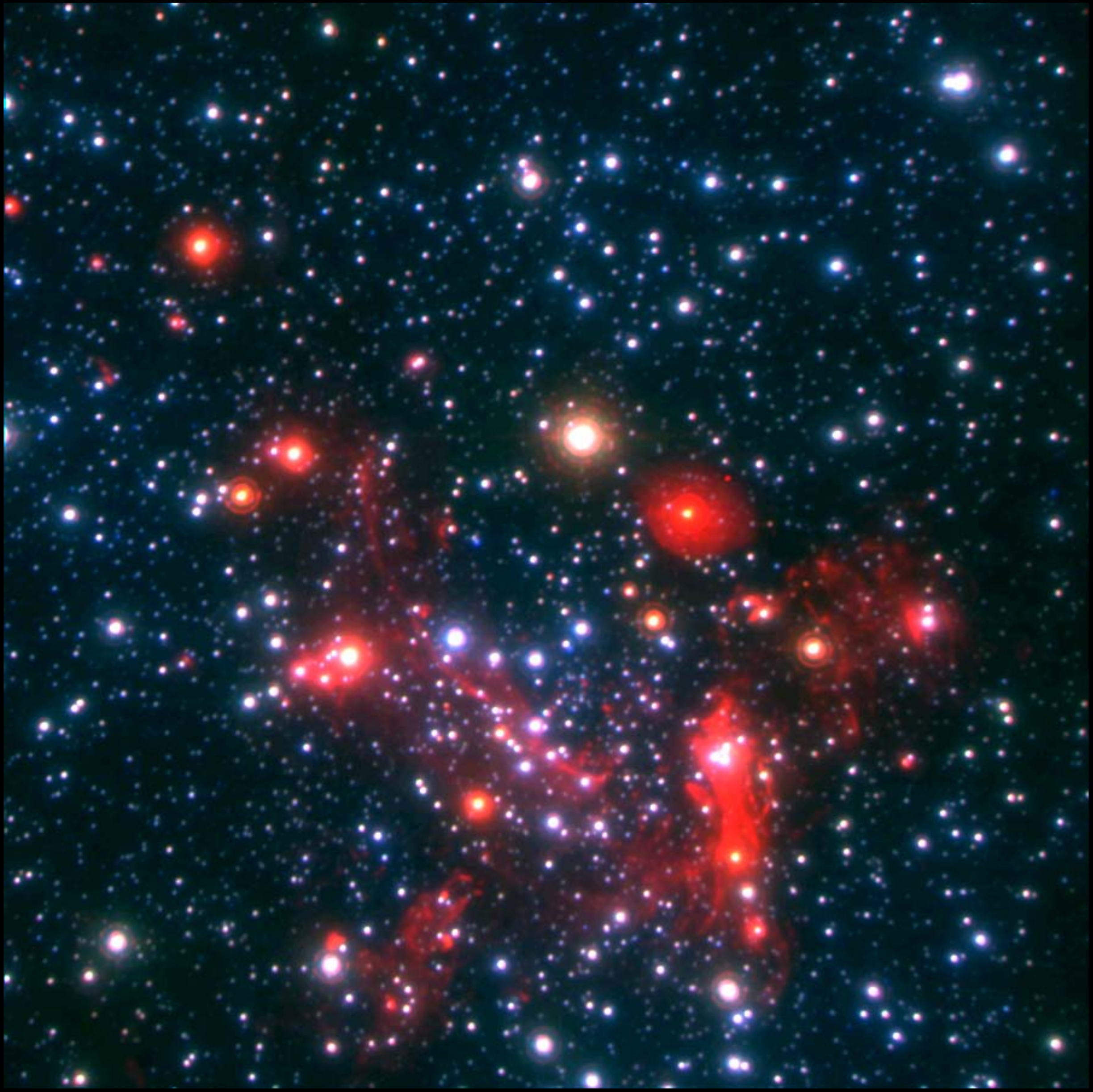



Atmosphere
Mirror
Lens
Detector


Atmosphere
Mirror
Lens
Detector

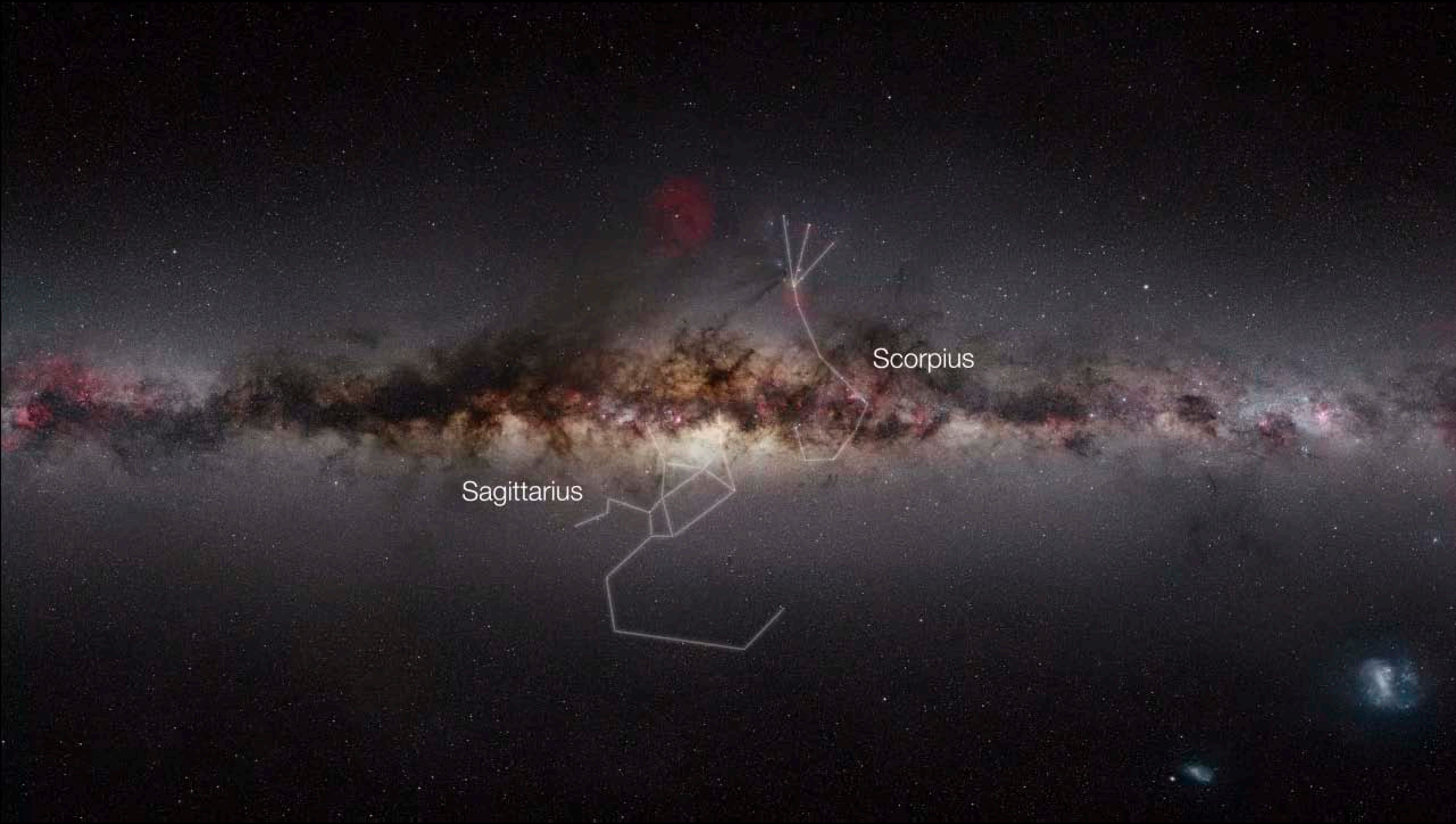
Really a big step forward: AO



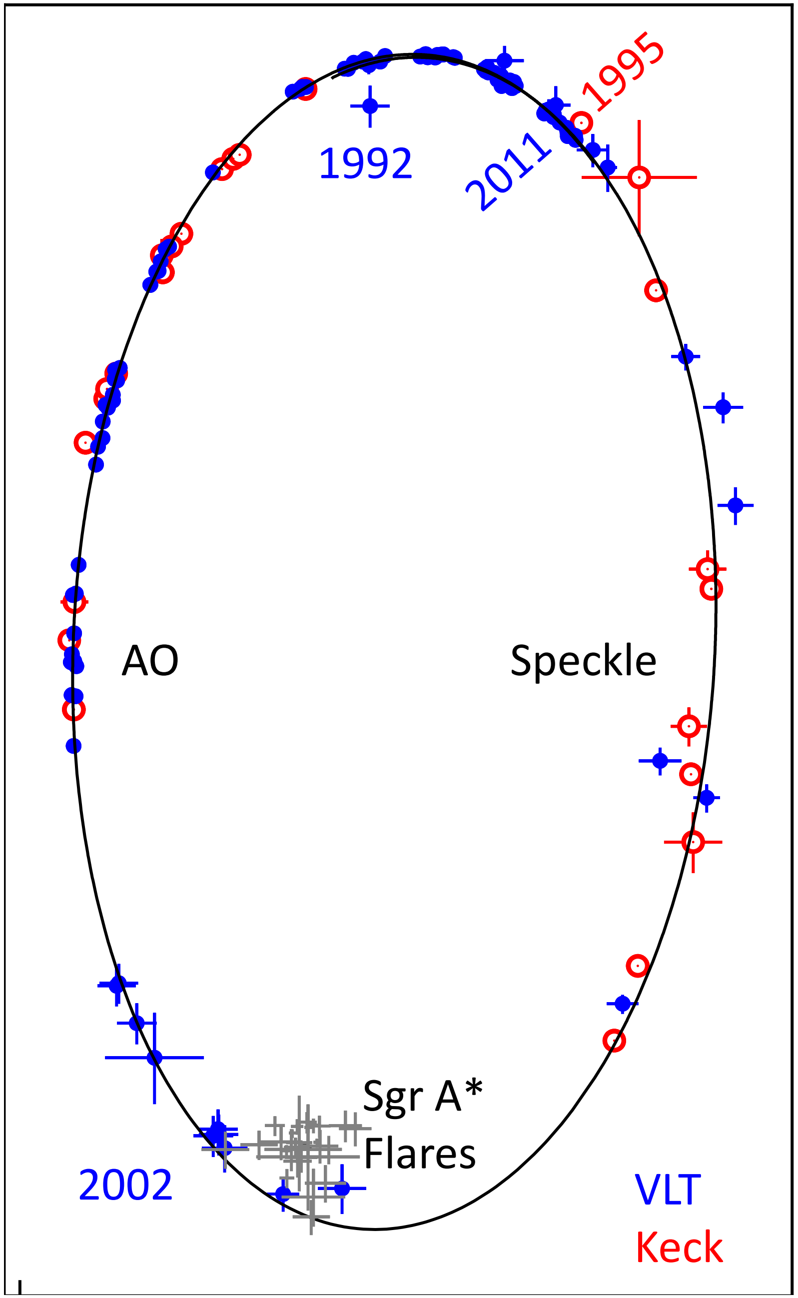


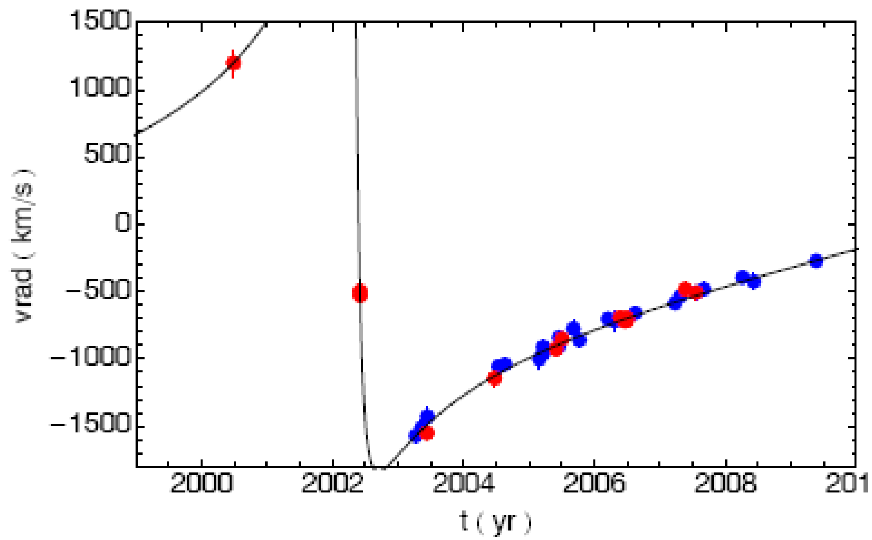
Strehl ratio 40%

NACO,
HKL color composite


Scorpius
Sagittarius

Keplerian Orbits





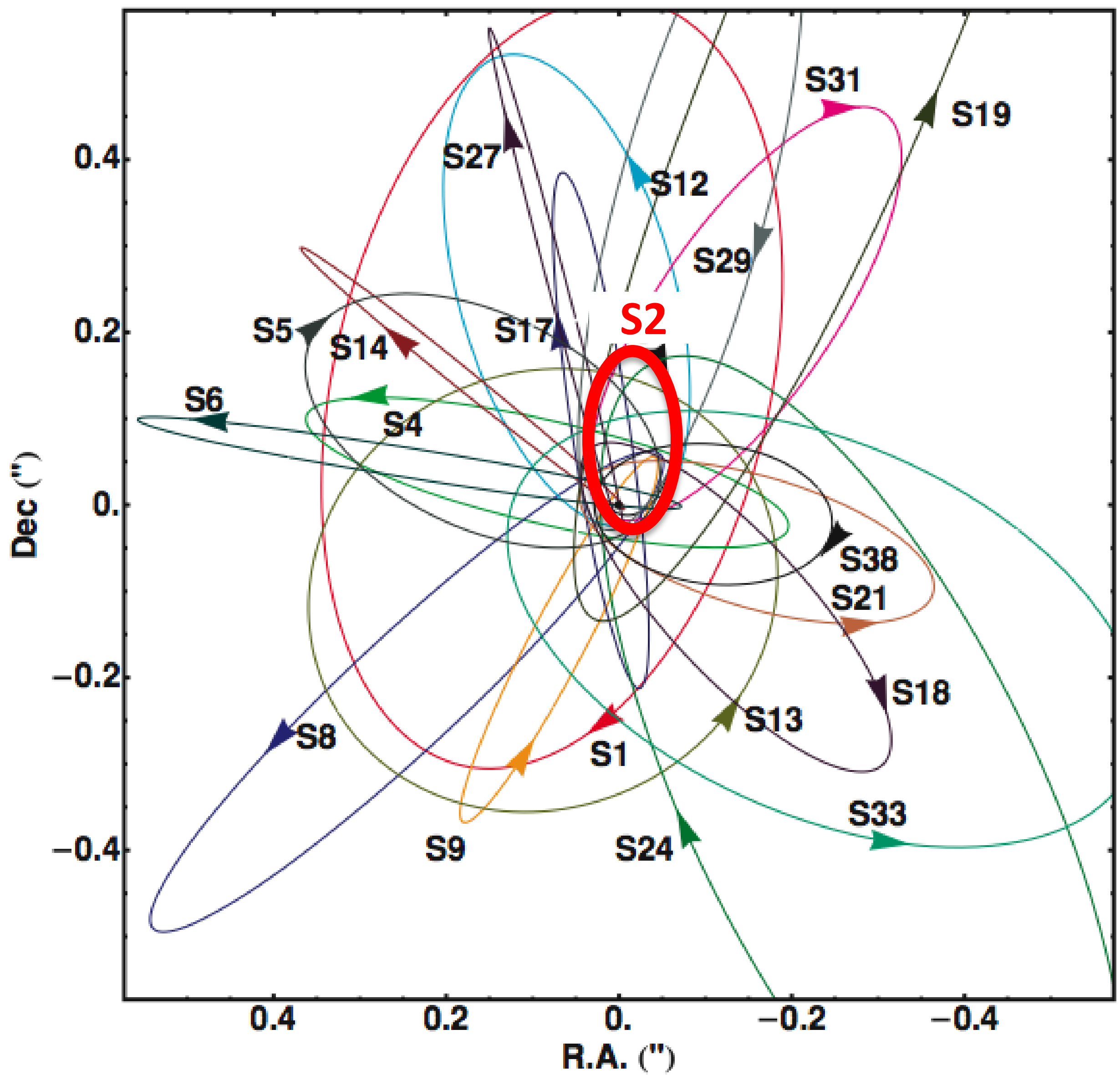
$R_0 = 8.28\ (\pm 0.15)_{stat}\ (\pm 0.29)_{sys}$ kpc

$M_\bullet = 4.30\ (\pm 0.06)_{R0}\ (\pm 0.35)_{sys} \times 10^6\ M_\odot$

$M_{ext}(S2)\ /\ M_\bullet <$ a few %

Schödel et al. 2002, 2003, Ghez et al. 2003, 2005, 2008, Gillessen et al. 2009a,b, Genzel et al. 2010

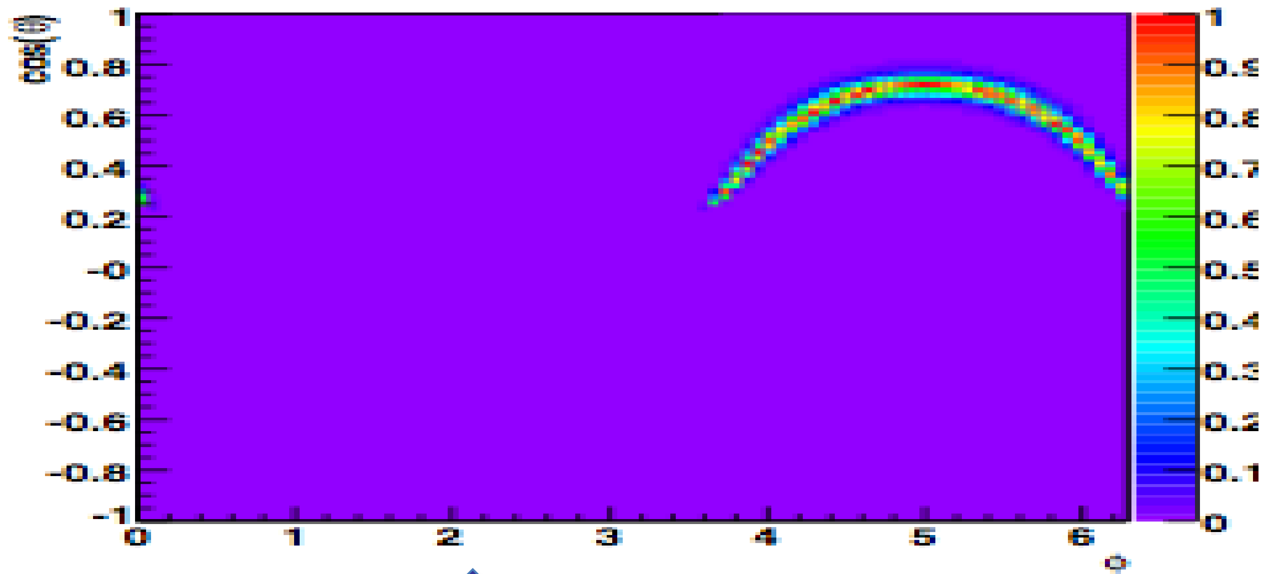
Currently: ≈ 30 orbits known



20 stars shown,
Gillessen+ 2009

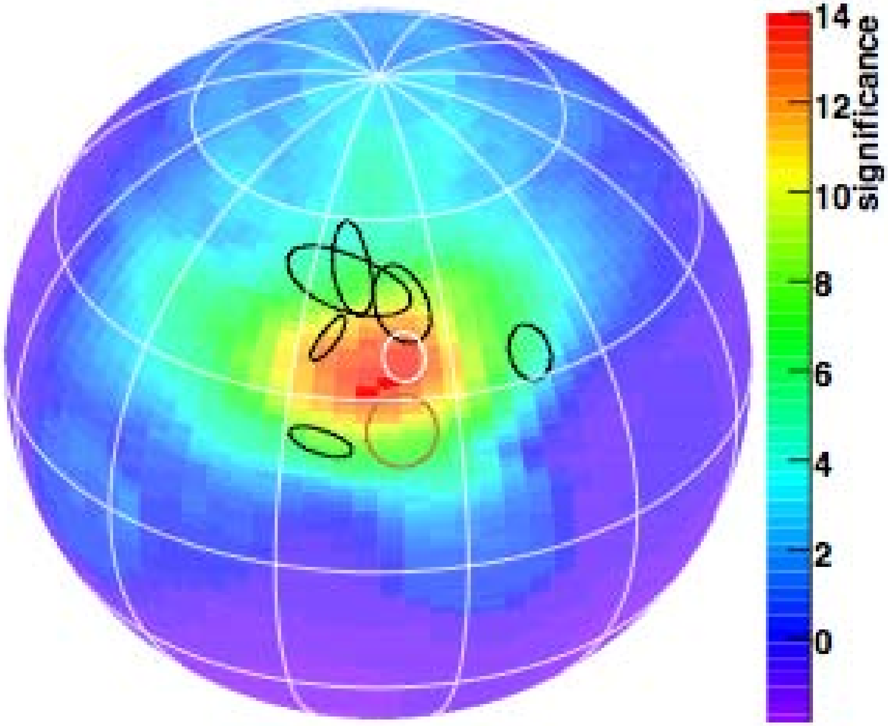
For r > 1'':
Hard to measure accelerations

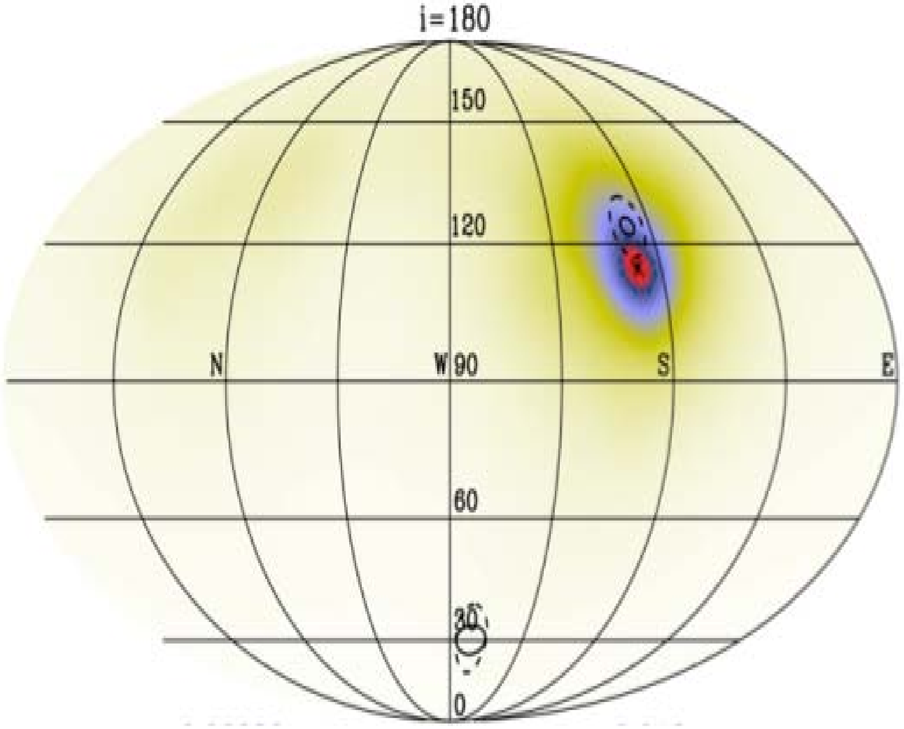
	r < 1''	r > 1''
x	✔	✔
y	✔	✔
vx	✔	✔
vy	✔	✔
vz	✔	✔
a_{2D}	✔	✖



(a, e, i, ω, Ω, t)

The traces for the young, clockwise moving stars intersect in one point



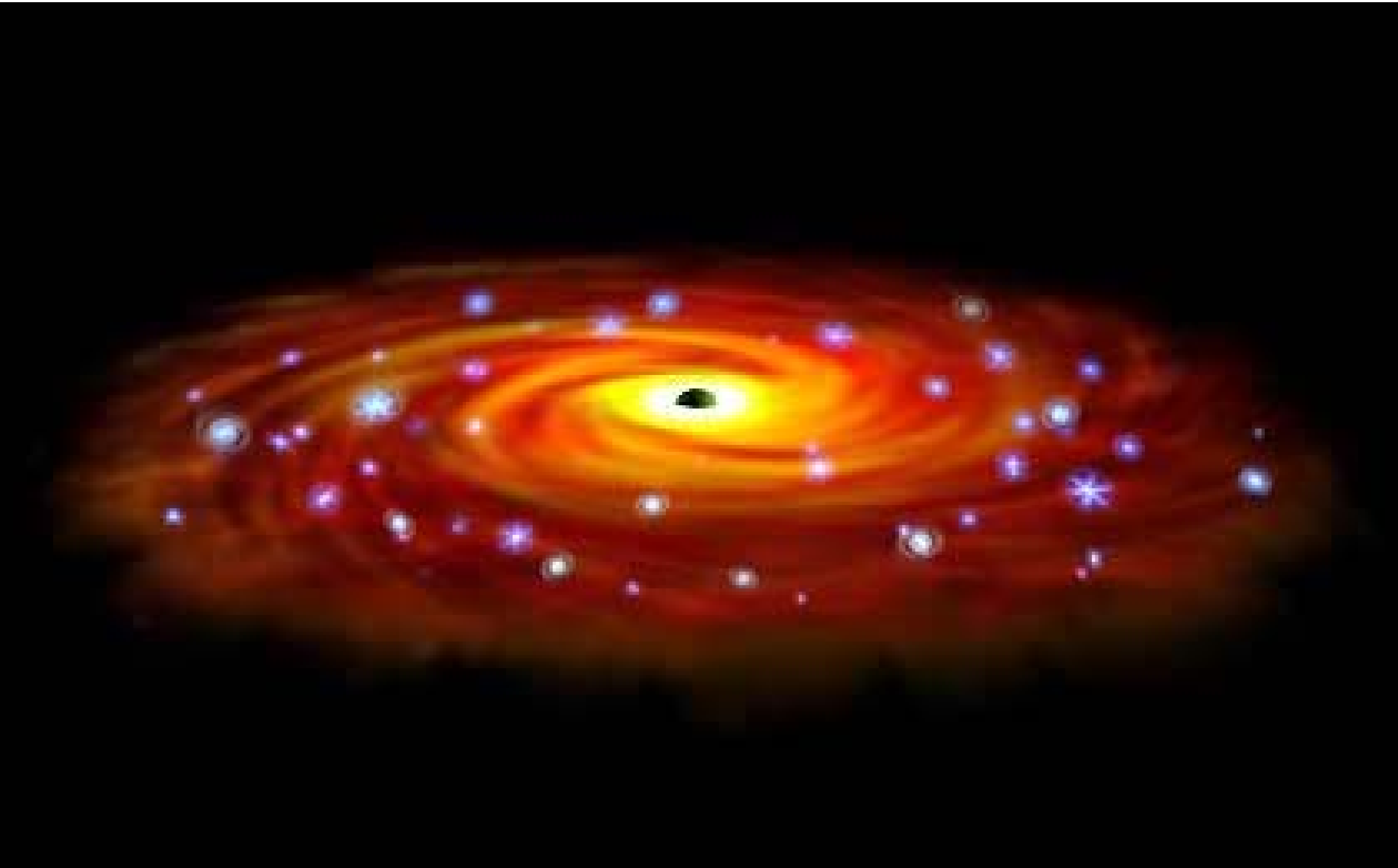


orientation of orbital angular momentum

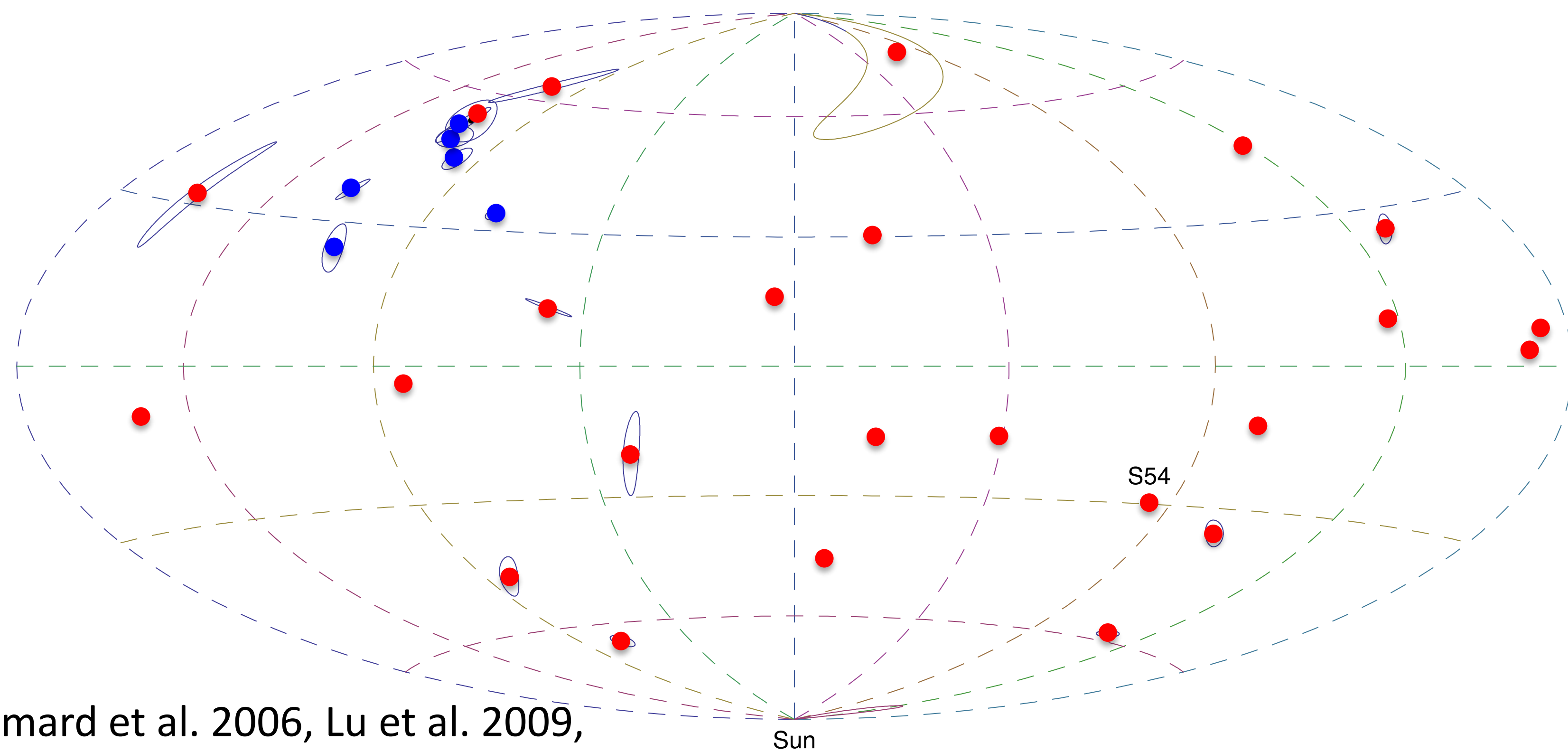
Bartko et al. 2009

Lu et al. 2009

(Most of) the CW moving O/WR-stars revolve in a disk

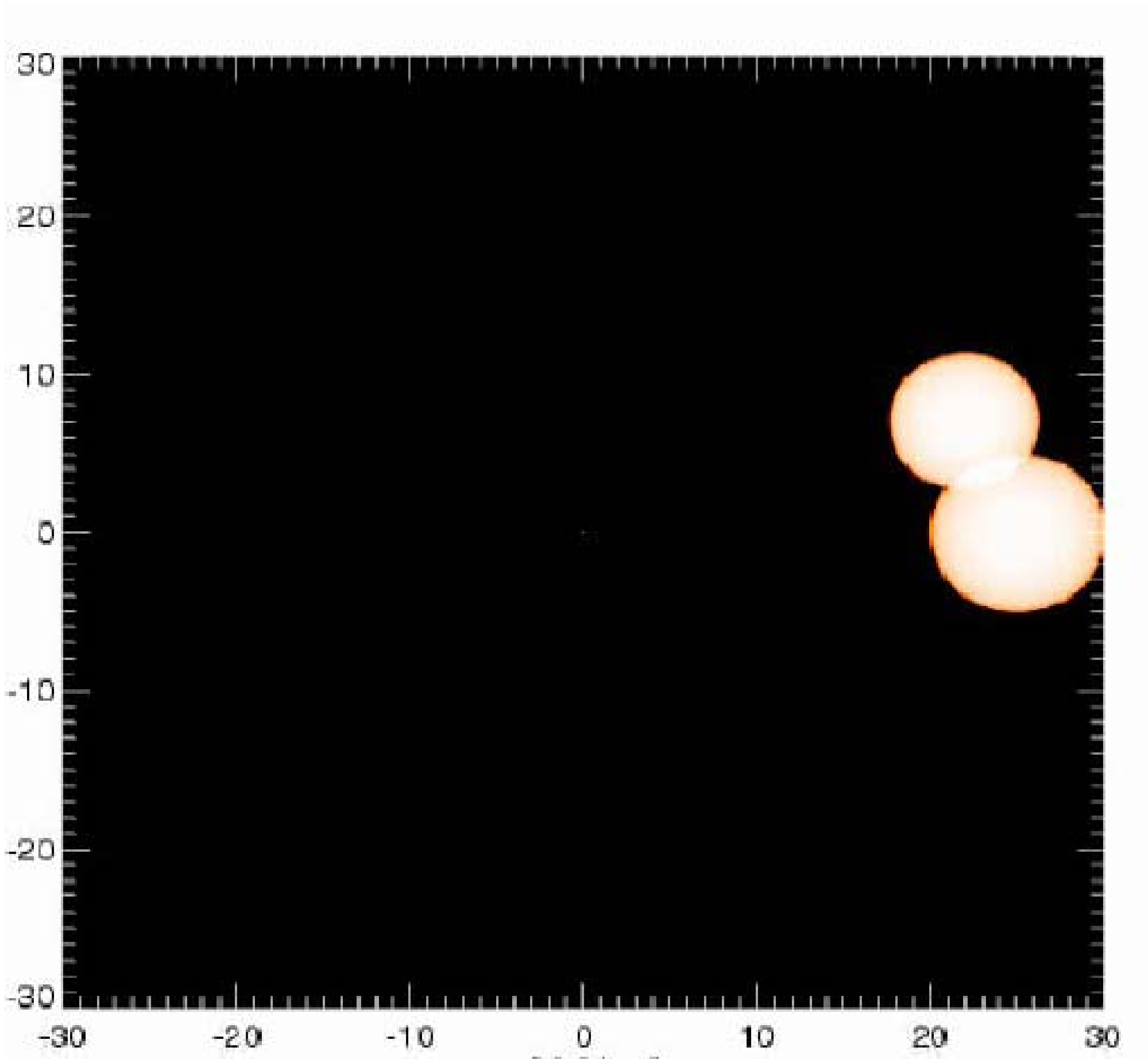


A few disk stars have full orbits now
Orbital planes: S-stars ≠ disk stars



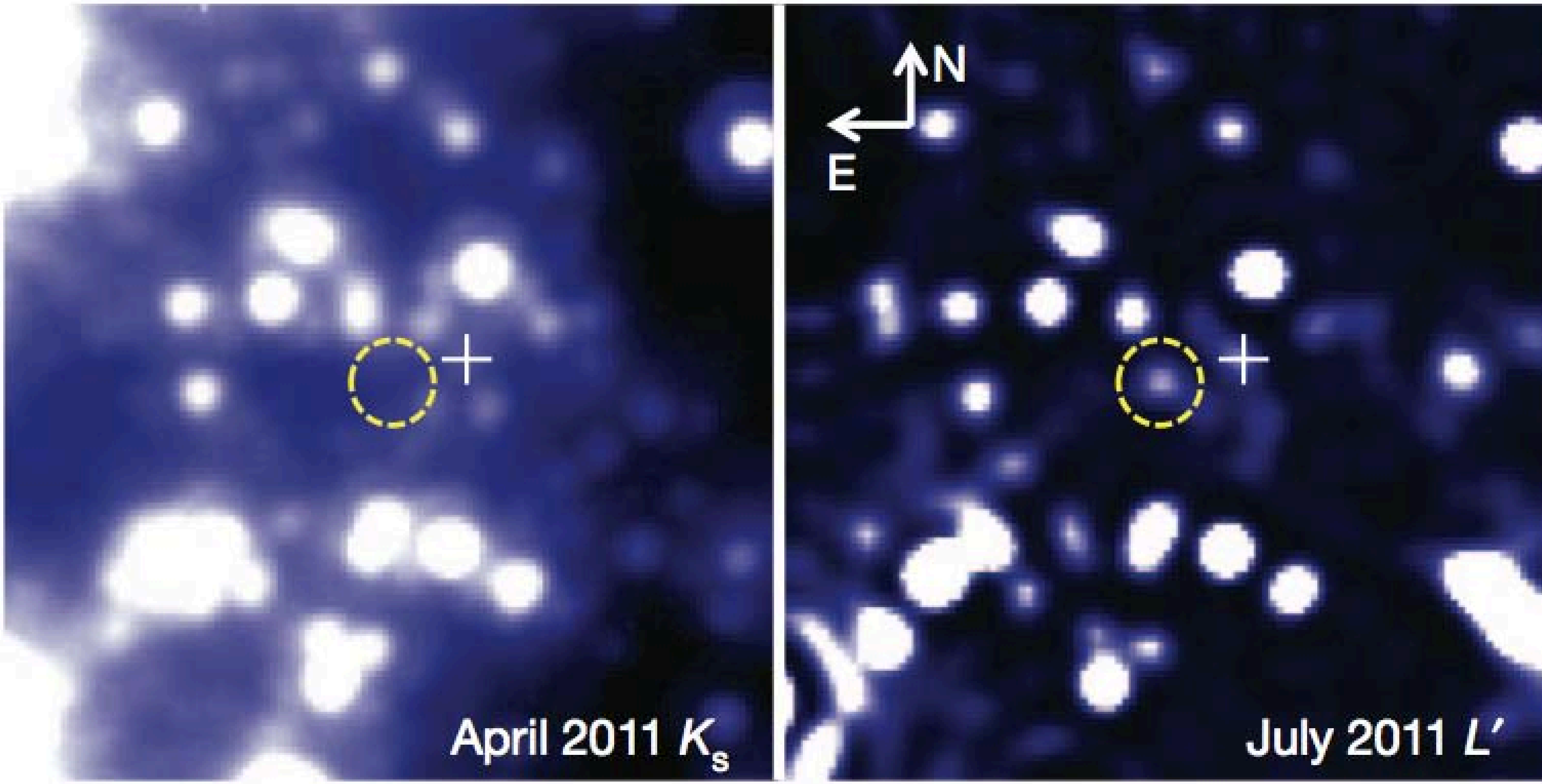
Paumard et al. 2006, Lu et al. 2009,
Bartko et al. 2009, Gillessen et al. 2009

The disk is the result of a recent (6Myr) star formation event



Hobbs & Nayakshin 2009

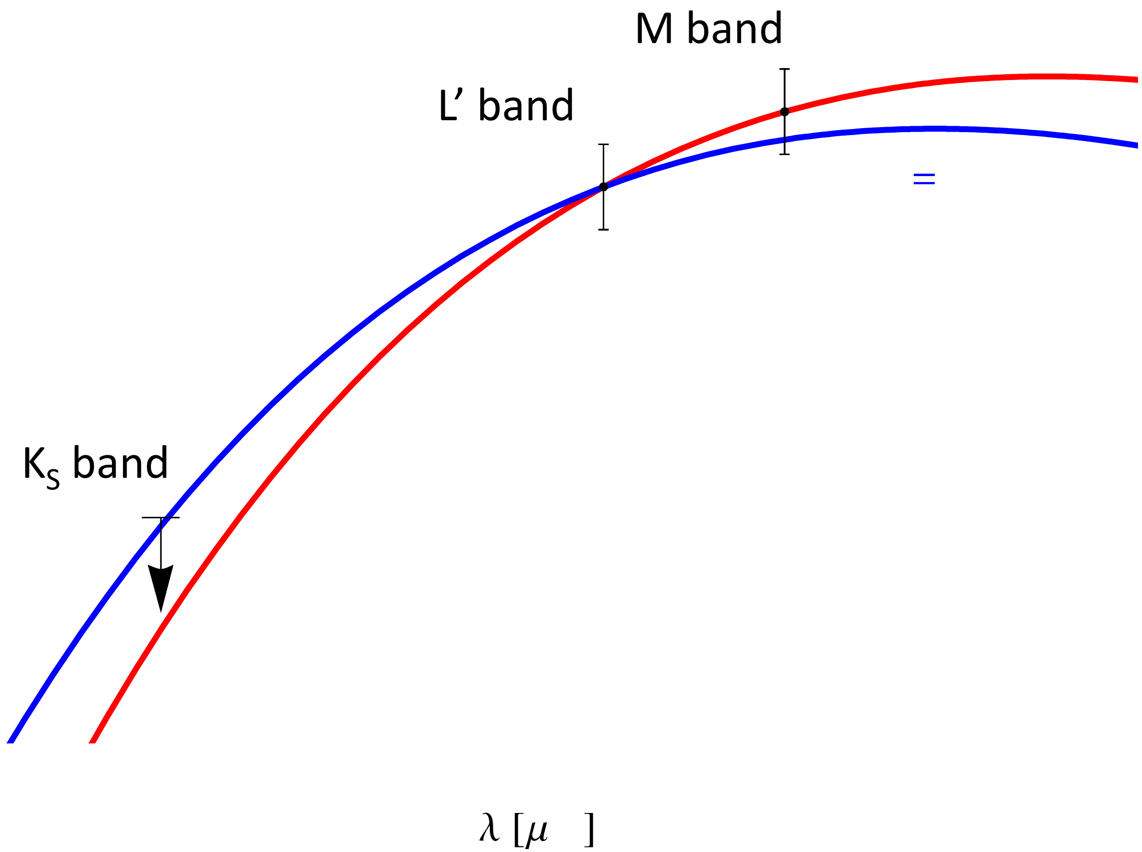
Not all objects are stars



2.15 μm

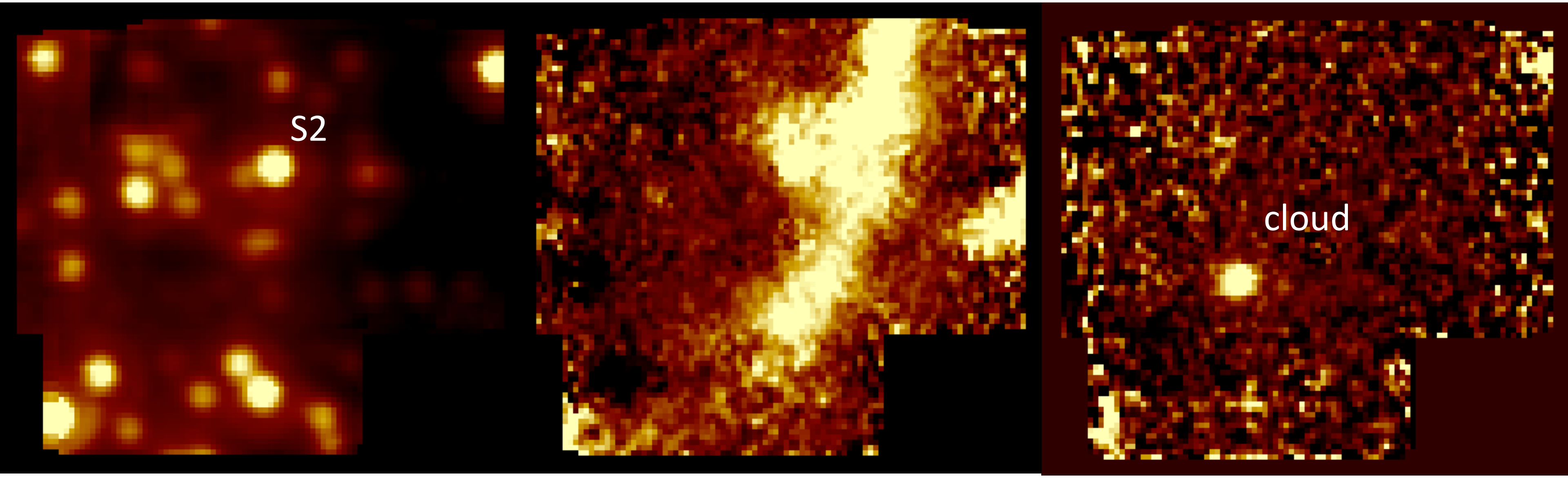
3.8 μm

The object only has T = 600K



The object is a dusty, ionized gas cloud

SINFONI data, April 2008

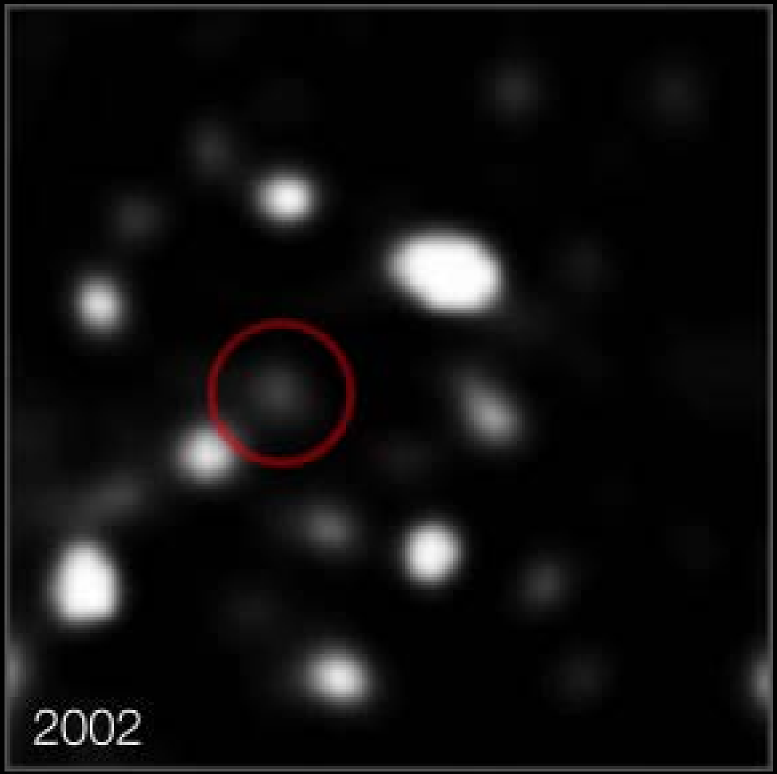


integrated K-band

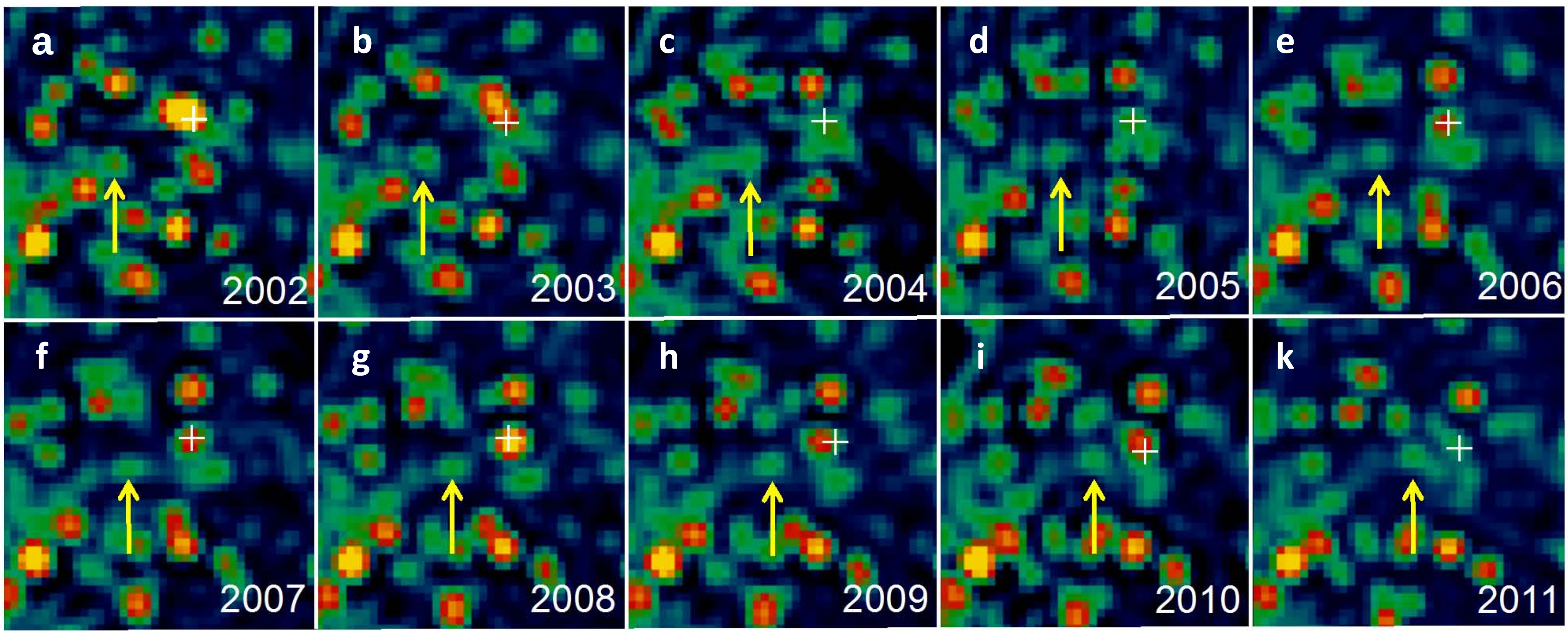
channel map at Br-γ (2.166 μm)

channel map at Br-γ + 1300 km/s (2.175 μm)

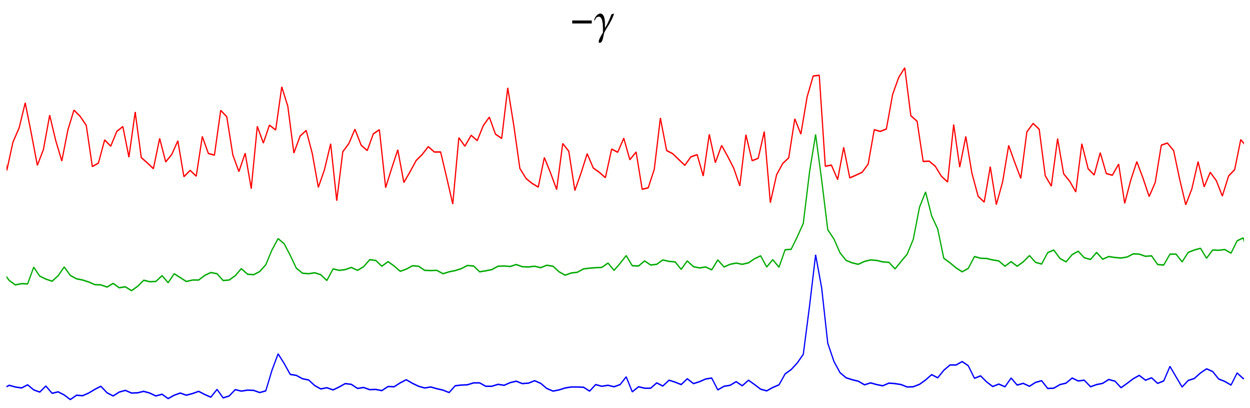
The cloud can be traced back to 2002



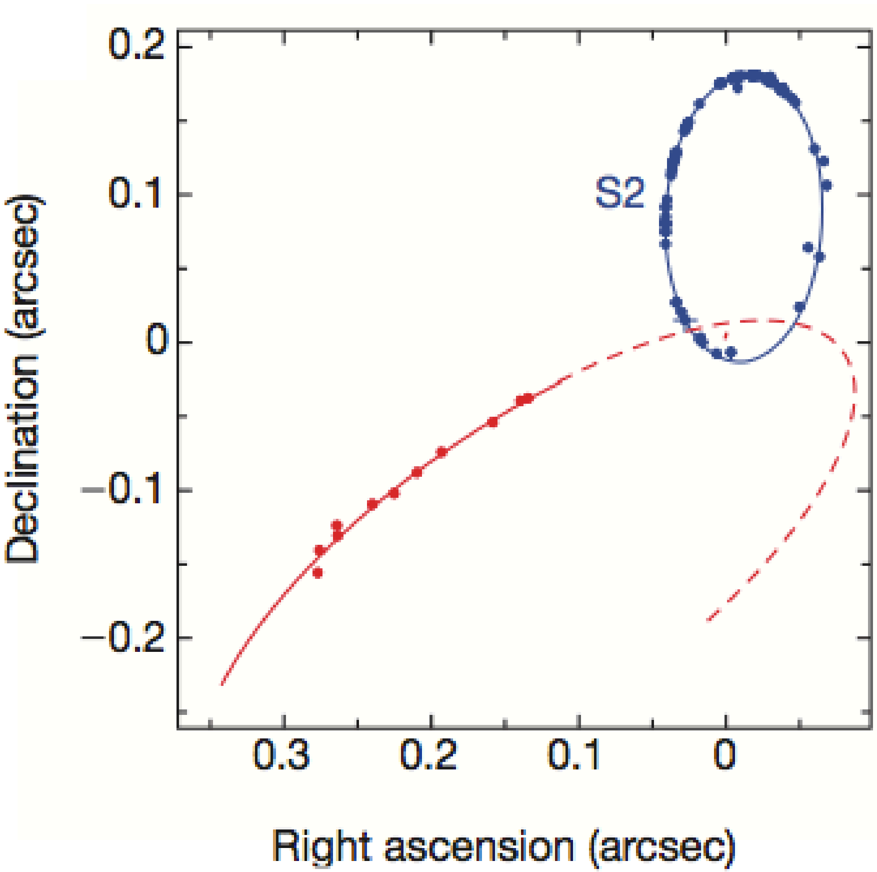
The cloud moves as fast as the fastest stars

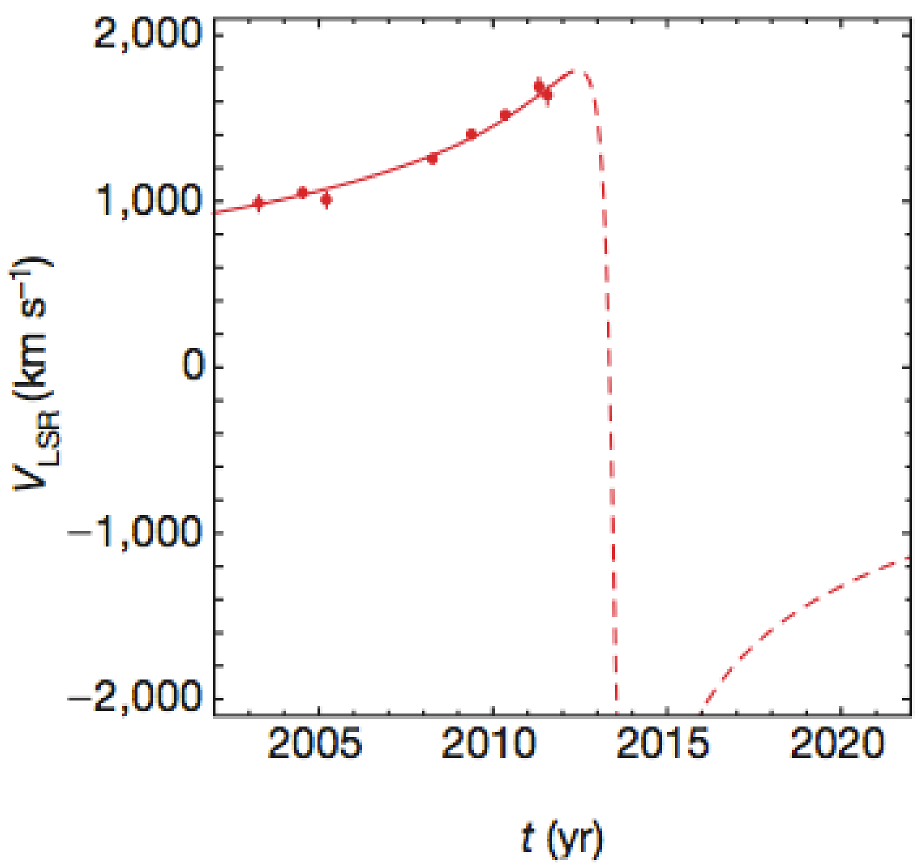


Also the radial velocity changes



The cloud’s orbit is well-constrained





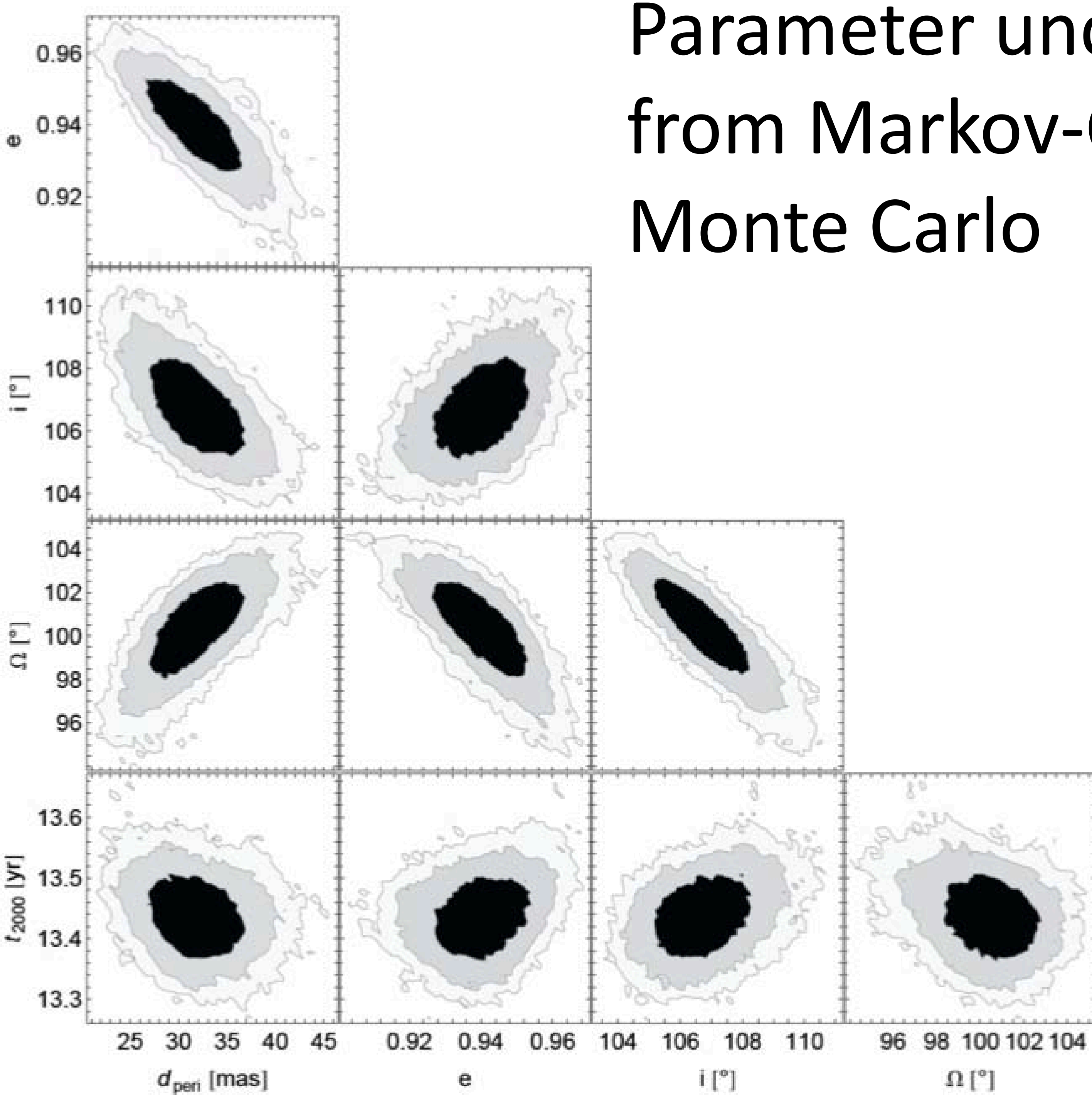
Pericentre passage: Soon and close

Parameters of Keplerian orbit around the $4.31 \times 10^6 M_\odot$ black hole at $R_0 = 8.33$ kpc	Best-fitting value
Semi-major axis, a	521 ± 28 mas
Eccentricity, e	0.9384 ± 0.0066
Inclination of ascending node, i	106.55 ± 0.88 deg
Position angle of ascending node, Ω	101.5 ± 1.1 deg
Longitude of pericentre, ω	109.59 ± 0.78 deg
Time of pericentre, t_{peri}	2013.51 ± 0.035
Pericentre distance from black hole, r_{peri}	$4.0 \pm 0.3 \times 10^{15}$ cm $= 3{,}140 R_S$ = 270 AU
Orbital period, t_o	137 ± 11 years

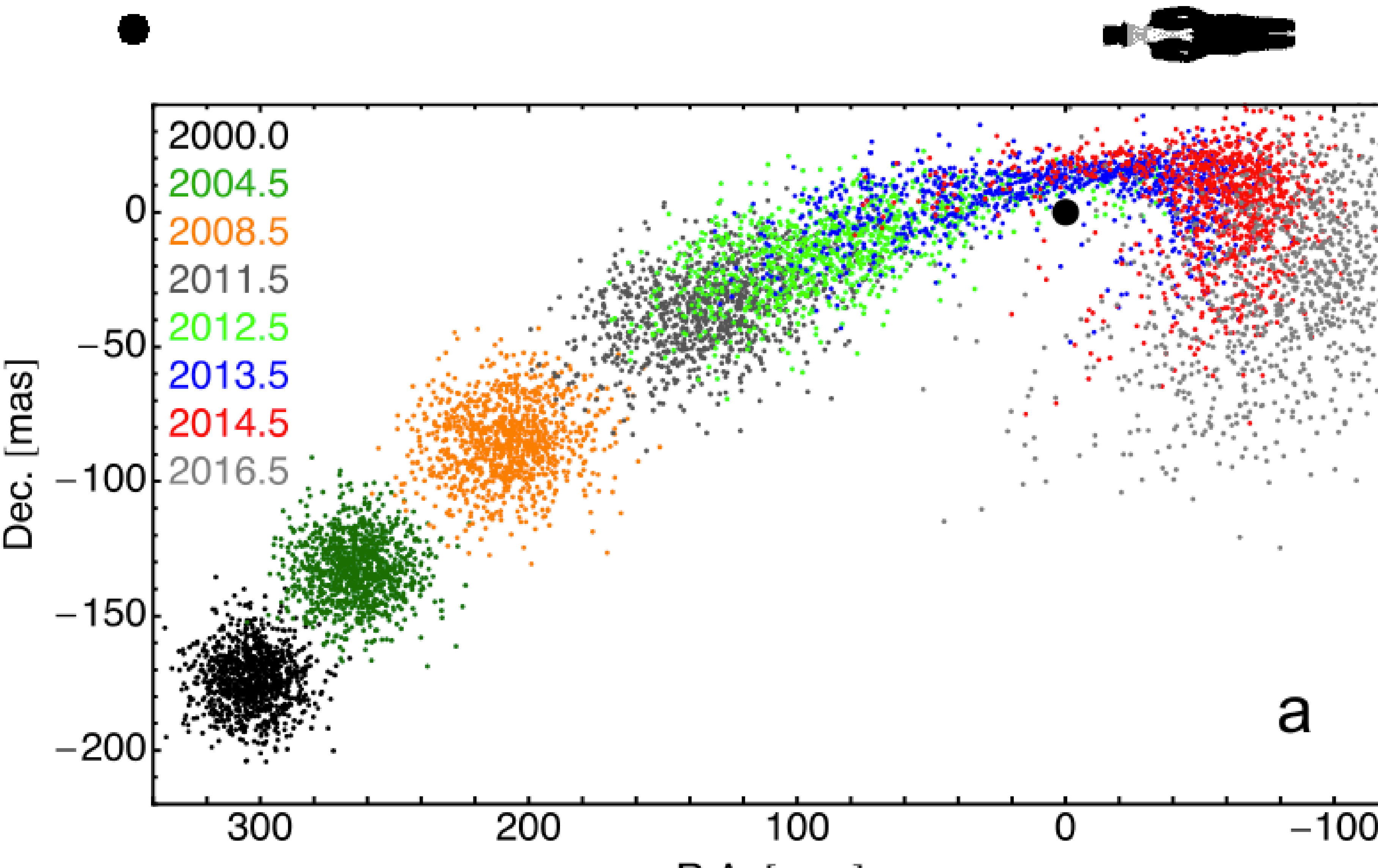
S2: 1500 R_S

S14: 1000 R_S

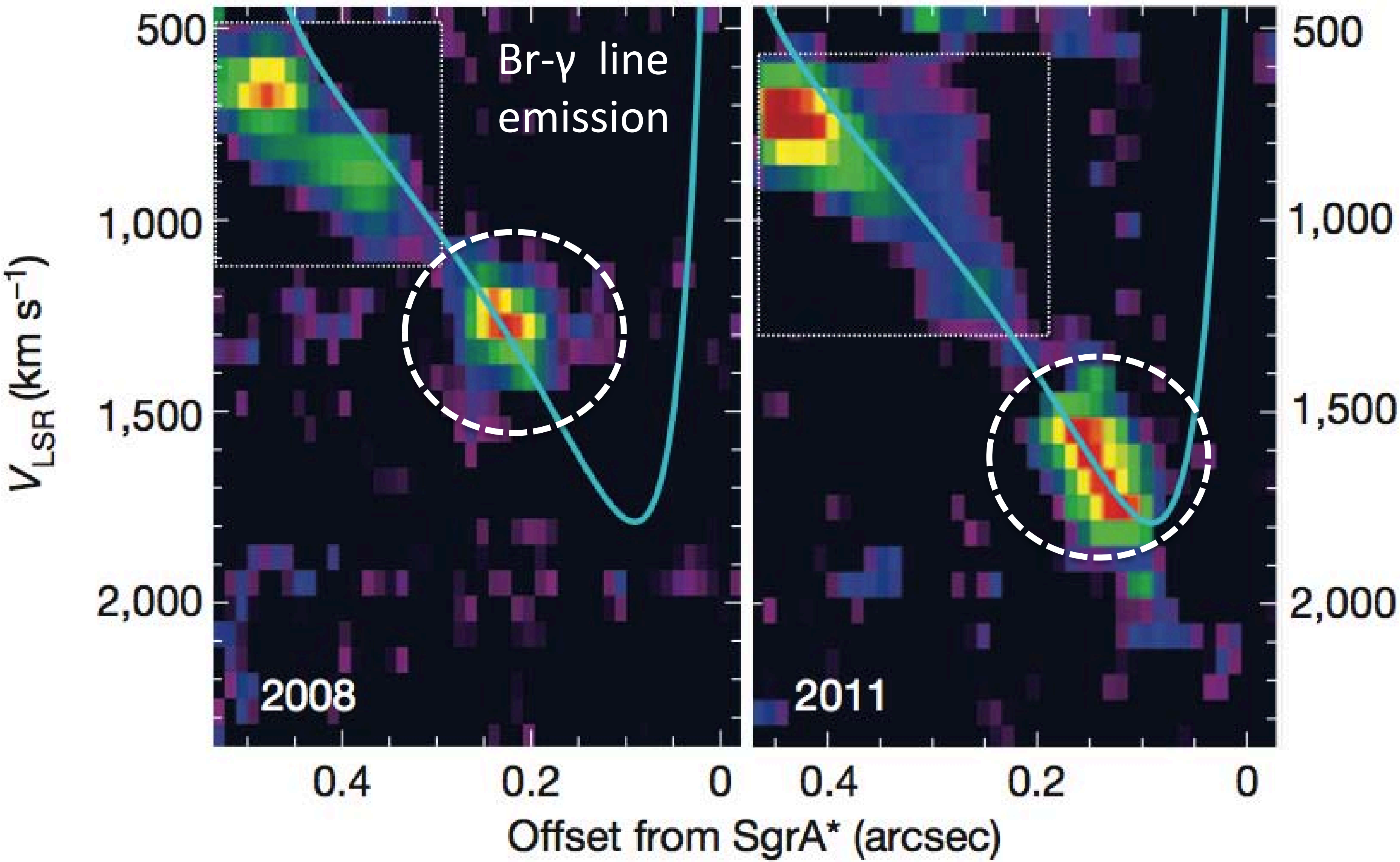
Parameter uncertainties from Markov-Chain Monte Carlo



Can a non-gravitating gas cloud survive that?



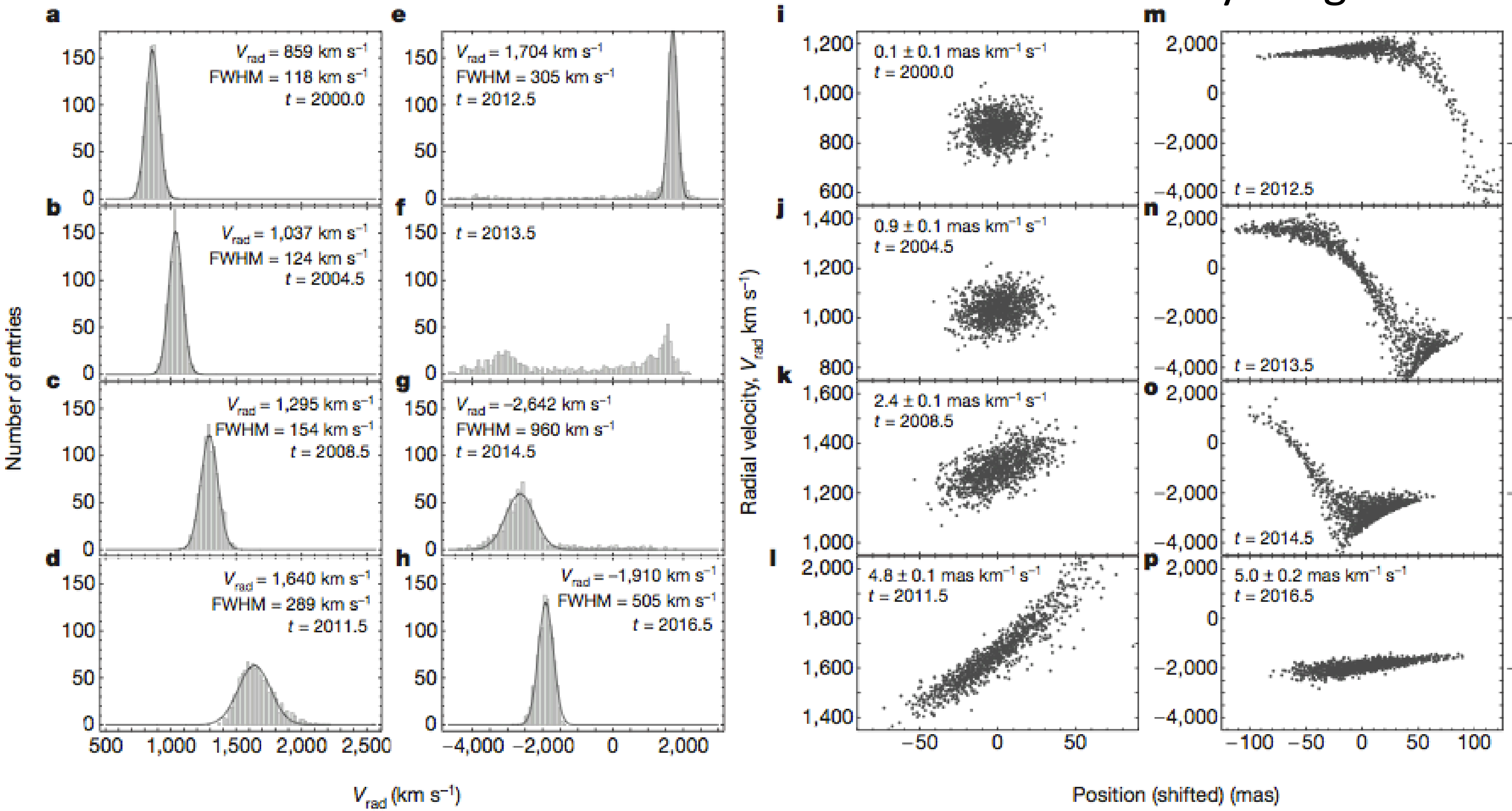
We see the tidal shear develop between 2008 and 2011



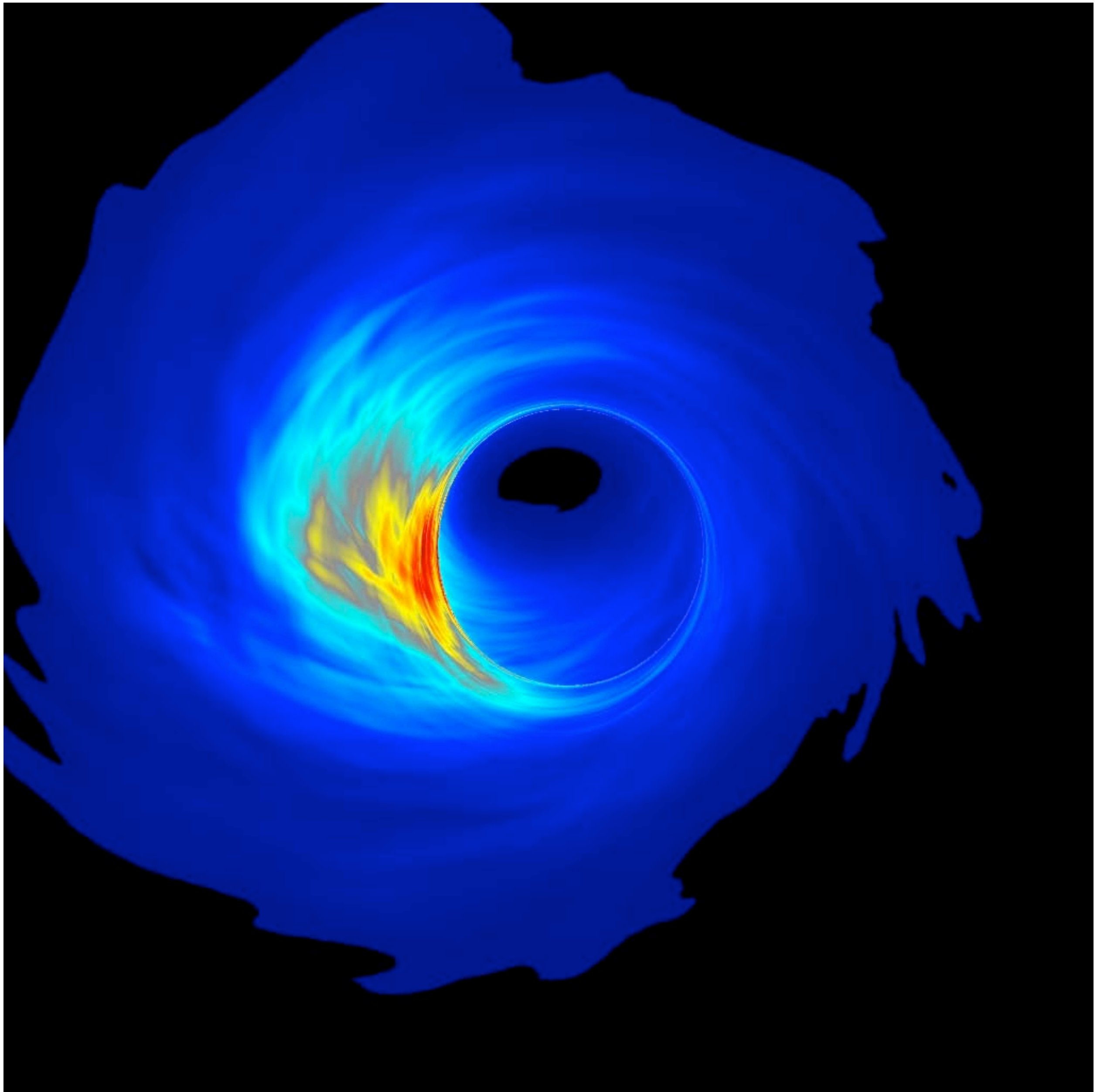
What will happen?
Test Particle simulation

Line Profile

Position-Velocity-Diagram



Missing: Interaction with Accretion Flow



Sgr A* should be bright - but is not

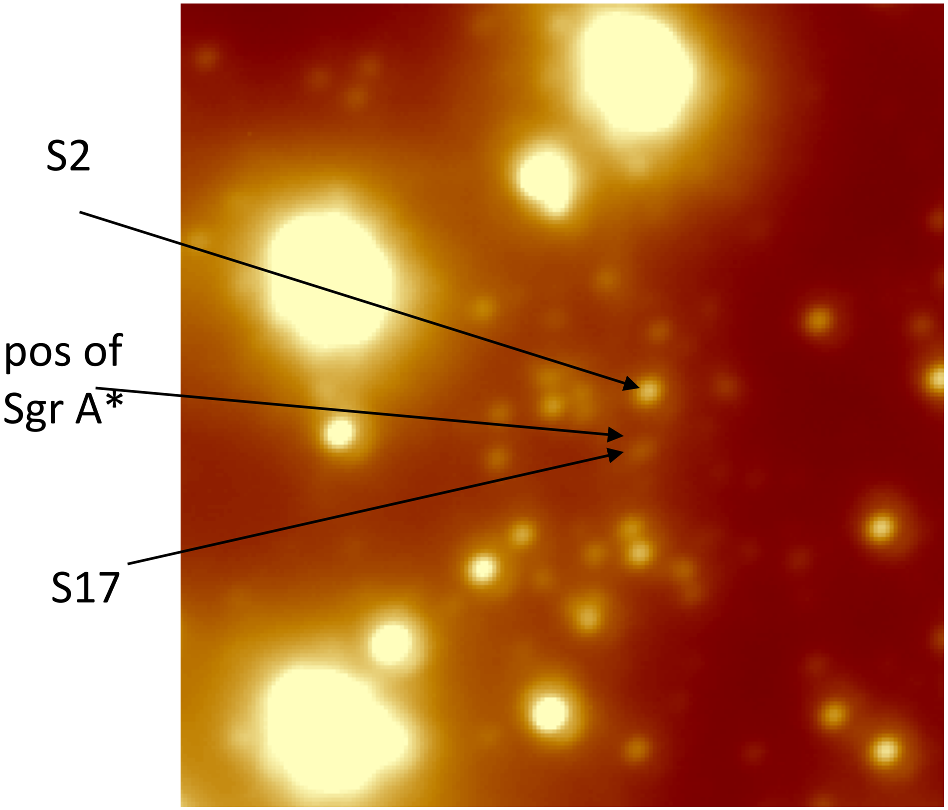
Limit: Eddington luminosity

radiation pressure = gravitation

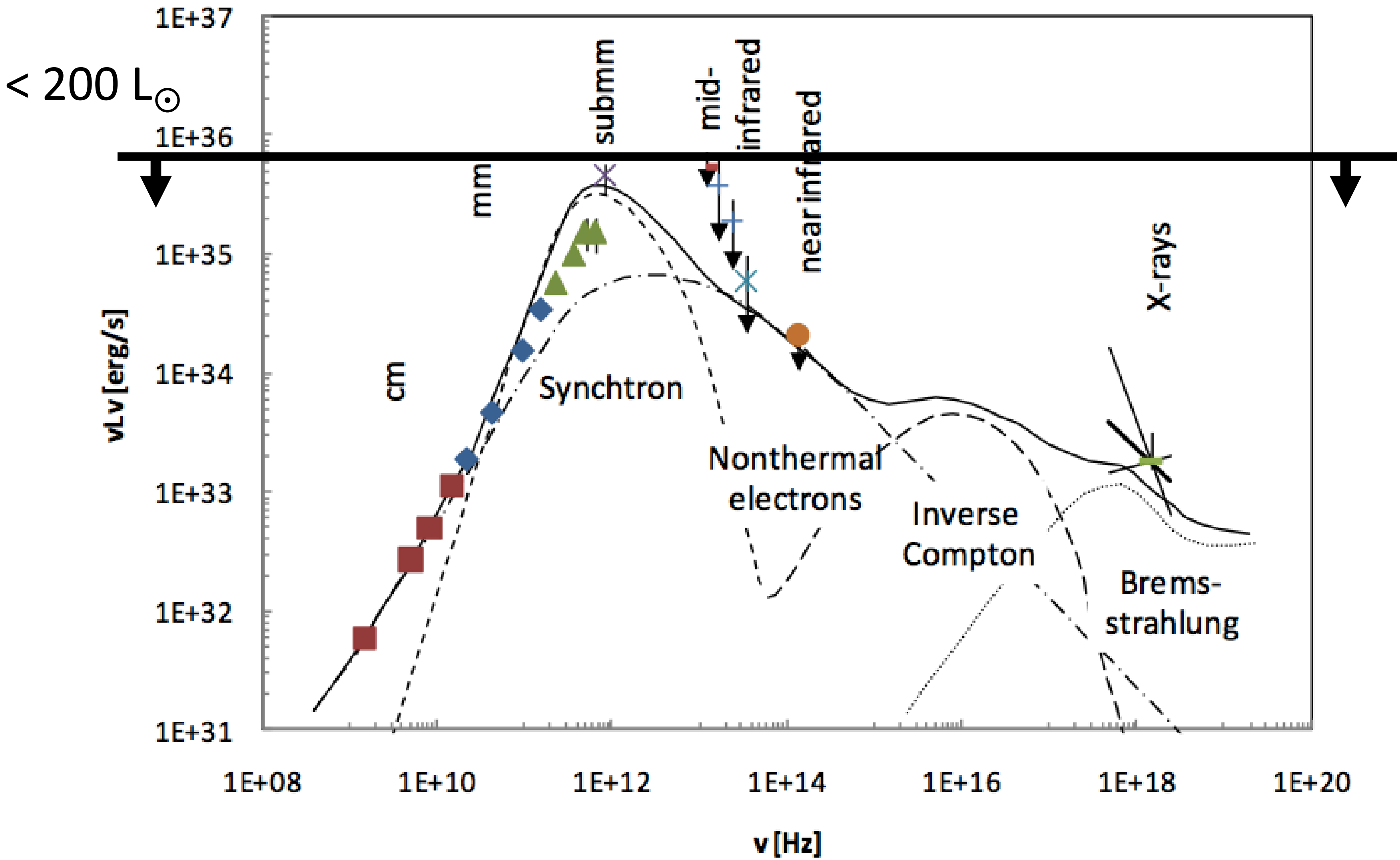
$$L_{Edd} = \frac{4\pi G m_p c}{\sigma_T} M$$

$$L = \eta \times 5 \times 10^{44} \text{ erg/s}$$

$$= \eta \times 10^{11} L_{\odot}$$



Sgr A* is dim at all wavelengths: $\eta \sim 10^{-8}$



Radiatively Inefficient Accrection Flow

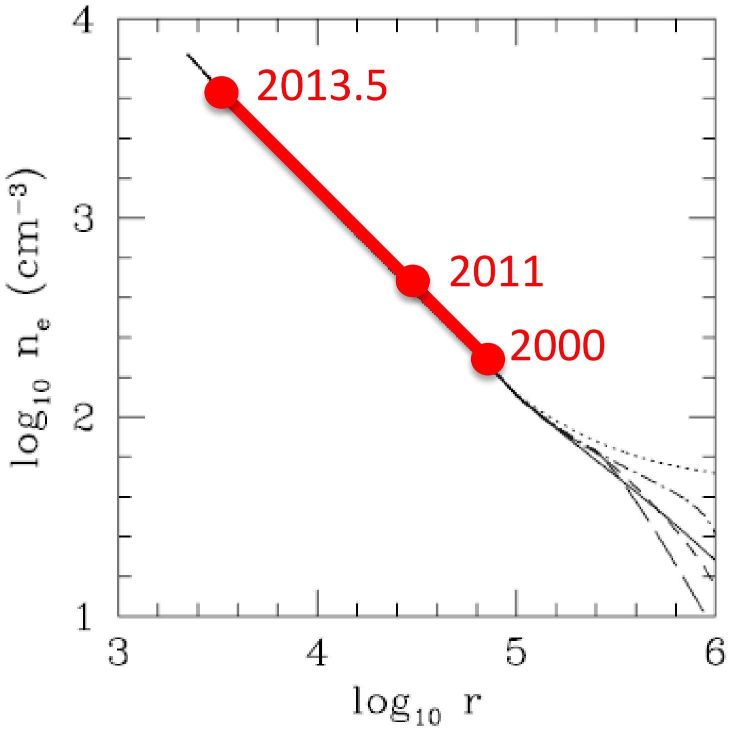
low L/L_{Edd} is a combination of:

- low accretion rate at Bondi radius
- low efficiency angular momentum transport
- low efficiency energy transfer protons to electrons
- most of the gas arriving at a few R_s ejected back out

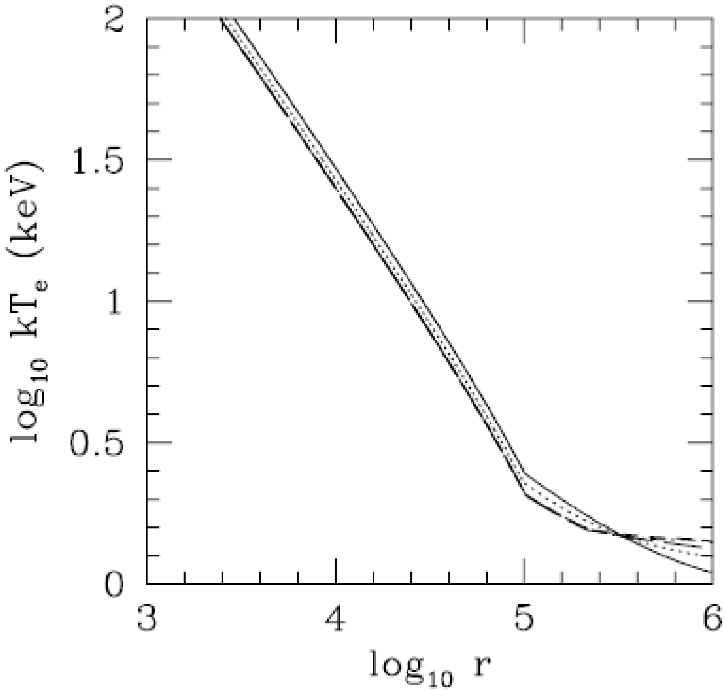
Cuadra et al. 2006, Bower et al. 2005, Marrone et al. 2006, Revnitsev et al. 2005, Begelman, Blandford, De Villers, Hawley, Krolik, Liu, Narayan, Quataert, Melia, Markoff, Rees, Stone, Yuan 1995-2006

Missing: Interaction with Accretion Flow

Density



Temperature



Yuan et al. 2003, Xu et al. 2006

The cloud is optically thin

- If it were a optically dense blackbody:
  (given T and L)
  $R \approx 100\ R_{\odot} \approx 0.5$ AU

- Marginally spatially resolved in Br-γ:
  $R \approx 15$ mas ≈ 120 AU

Mass: From Br-γ: 3 × Earth

- Br-γ luminosity: $1.7 \times 10^3\ L_\odot$
- Case B recombination theory:

$$L_{\mathrm{Br}\gamma} = \frac{4\pi}{3}\gamma_{\mathrm{Br}\gamma}\left(n_e^2\, f_V\right) R^3$$

$$n_e = 2.6 \times 10^5 \mathrm{cm}^{-3}\, f_V^{-1/2}\, R_{15\mathrm{mas}}^{-3/2}\, T_{\mathrm{e,10000K}}^{0.54}$$

$$M = \frac{4\pi}{3} R^3\, \mu\, n_e\, f_V = 1.7 \times 10^{28} \mathrm{gr}\, f_V^{1/2}\, R^{3/2} T_e^{0.54}$$

- Density 300 - 60 ≺ larger than that of accretion flow
  - motion close to Keplerian

The cloud is fully ionized

- UV radiation field of young, massive stars in GC:

$$Q_{\rm tot} = \Sigma_i \, Q_i \, \frac{\pi R^2}{4\pi r_i^2} \approx 5 \times 10^{45} {\rm s}^{-1}$$

- Needed to ionize:

$$\frac{4\pi}{3} R^3 \, f_V \, n_e^2 \, \alpha_B \approx 5 \times 10^{44} {\rm s}^{-1}$$

Interaction: cloud & accretion flow

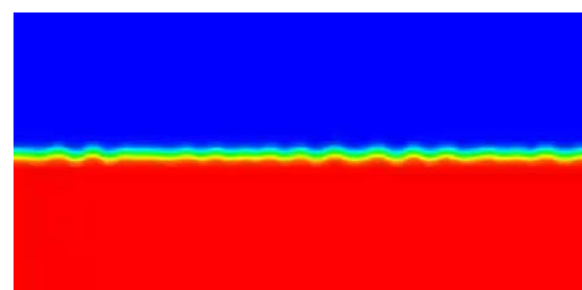
- Orbital period: 137 yr (but highly eccentric orbit)
- Compression ti
- Sound
- Insta
  - Kel
  - Rayleig

All time scales similar

complex hydrodynamics

KH

RT



Temperature-increase due to shocks

- Post-shock temperature

$$T \approx 3 \times 10^5 \mathrm{K}\, f_V^{1/2}\, R^{3/2} T_e^{-0.54} \left(\frac{r}{r_{2011}}\right)^{-2}$$

- Cooling time scale

$$t_{\mathrm{cool}} = 3 \times 10^{-3}\,\mathrm{yr}\, f_V^{0.85} R^{2.5} T_e^{-0.91}\, n_{\mathrm{e,\,post}} \left(\frac{r}{r_{2011}}\right)^{-3.4}$$

  – t_{cool} < other time scales

  – now cloud cools efficiently

  – but will get hot in 2013 (pericenter)

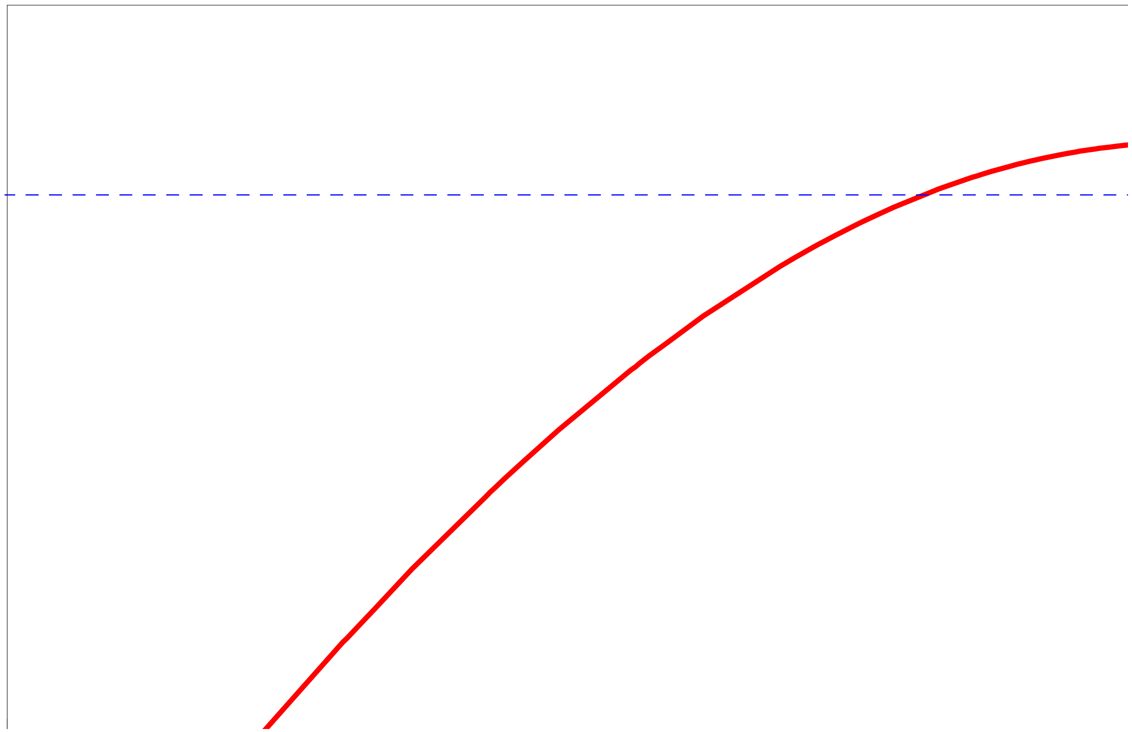
X-ray emission can be estimated

- $T \approx 10^7$ K
- $L_{cool} \approx 10^{35} - 10^{36}$ erg/s
- $L_{2-8\ keV} \approx 10^{34}$ erg/s
- Normal, quiescent state:
  $L_{quiescent} \approx 2 \times 10^{33}$ erg/s

  (Baganoff et al. 2003)

for nominal parameters

X-ray luminosity of “Sgr A*” should increase in 2013



What about feeding the black hole?

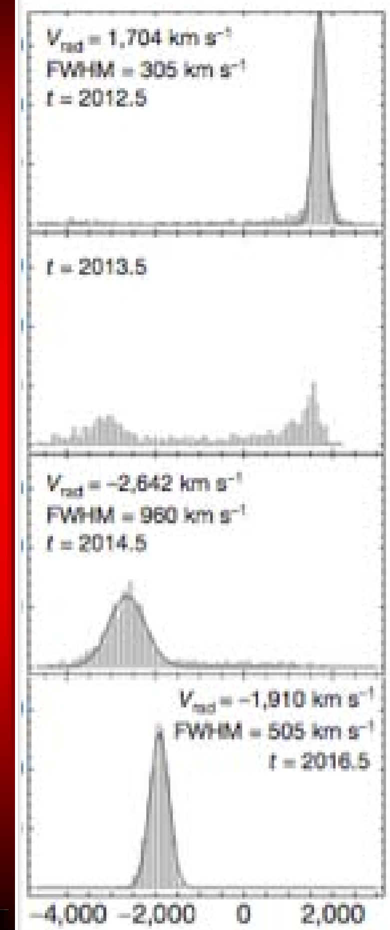
- Total energy available $\approx 10^{48}$ erg
- Mass of cloud exceeds that of accretion flow
- How much is dissipated?
  - Test particle case: 0
- Dissipation might well be efficient
  - Similarity of time scales
  - Size similar to impact parameter
  - velocity dispersion of cloud
- Main unknowns:
  - (1) volume filling factor
  - (2) radial profile of accretion flow

Unique chance: Probe accretion flow

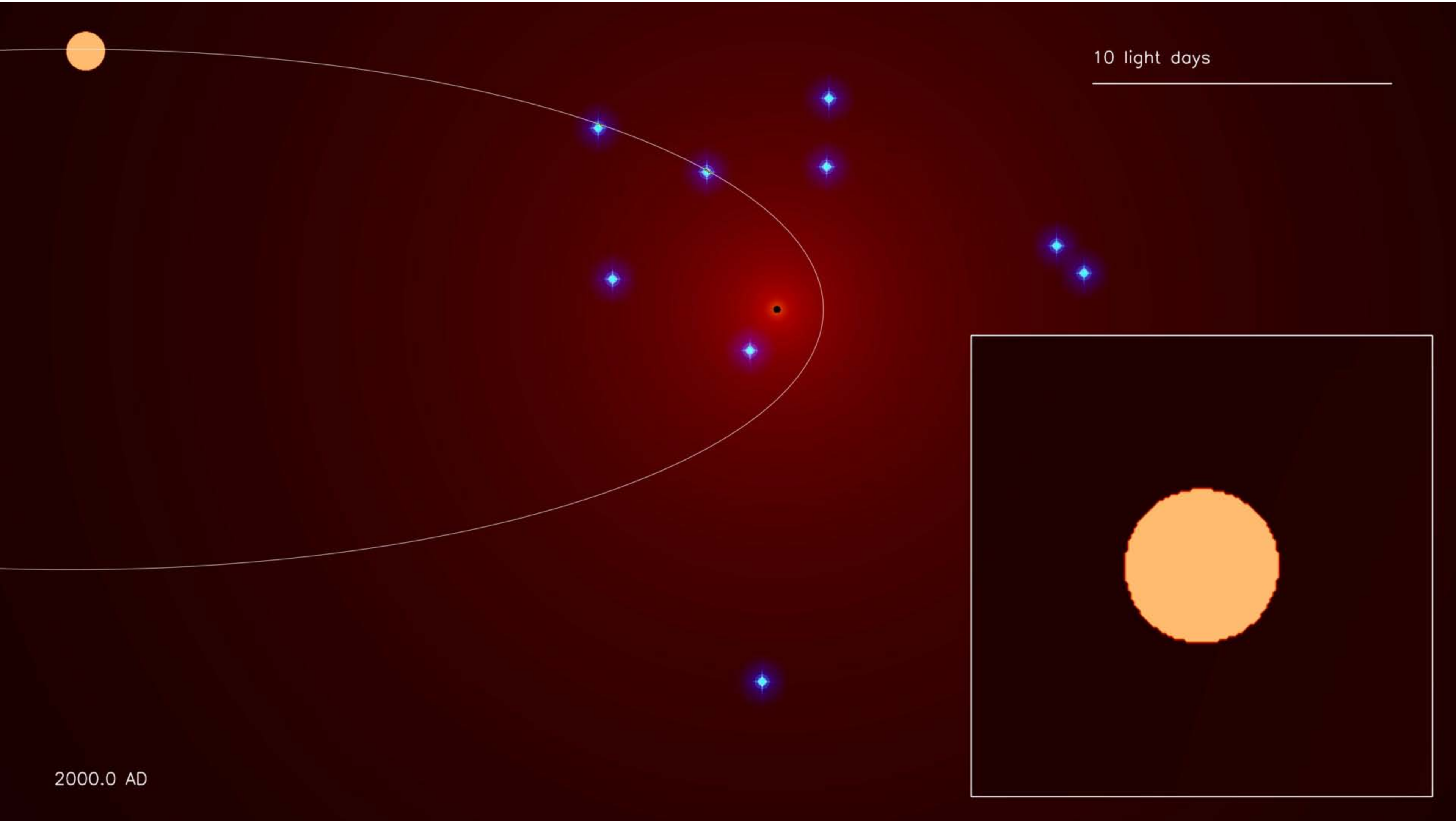
“Almost controlled experiment”

	Volume filling factor	
Density profile accretion flow	low / shallow - weak X-rays - IR line profile reassembles	high / shallow - moderate X-rays - IR line profile scrambled
	low / steep - moderate X-rays - IR line profile reassembles	high / steep - strong X-rays - IR line profile scrambled

IR line profile

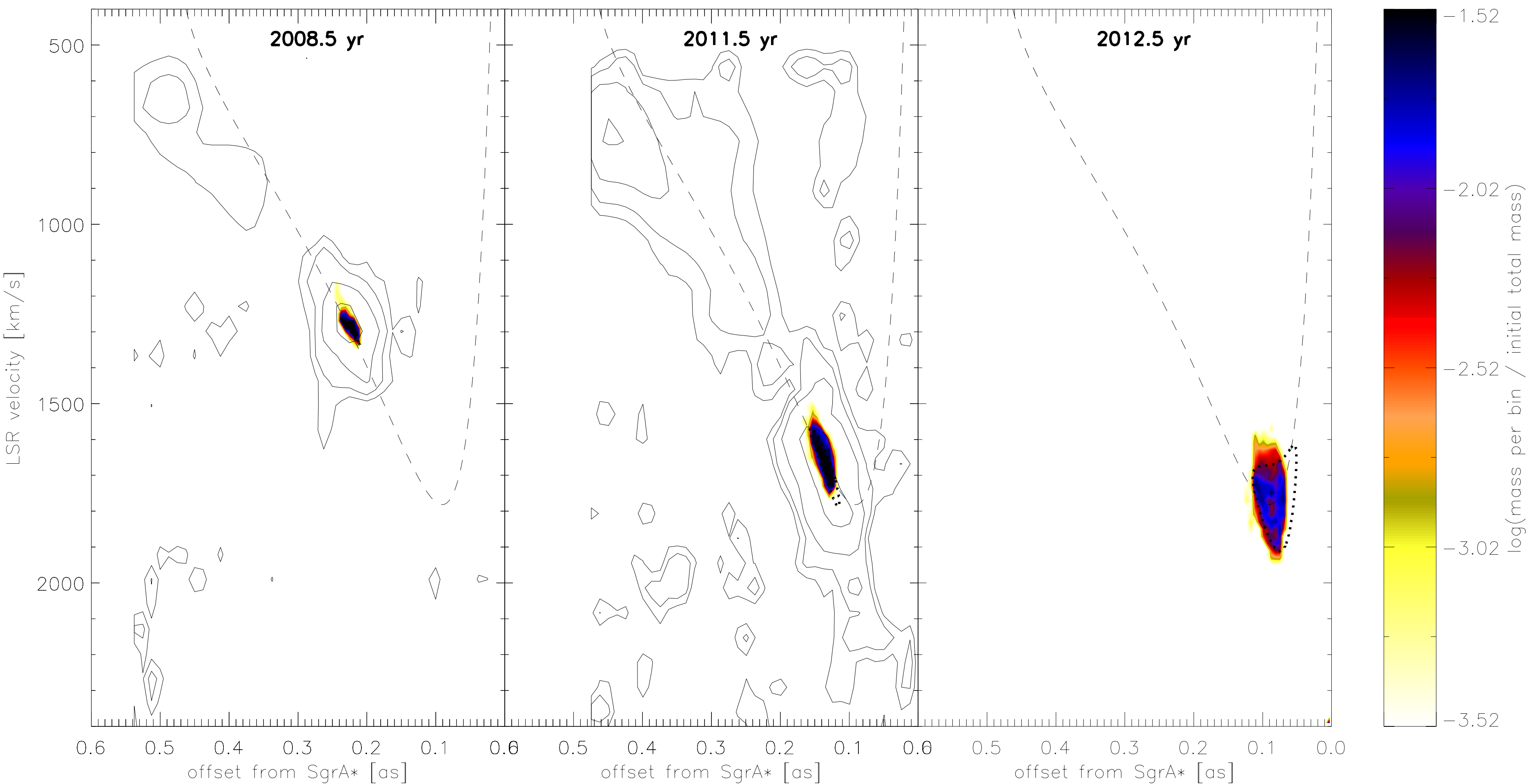


Upcoming: MHD simulations
(Marc Schartmann, Christian Alig, Andreas Burkert)



What combination of initial conditions & external medium matches data?

Schartmann et al. in prep.



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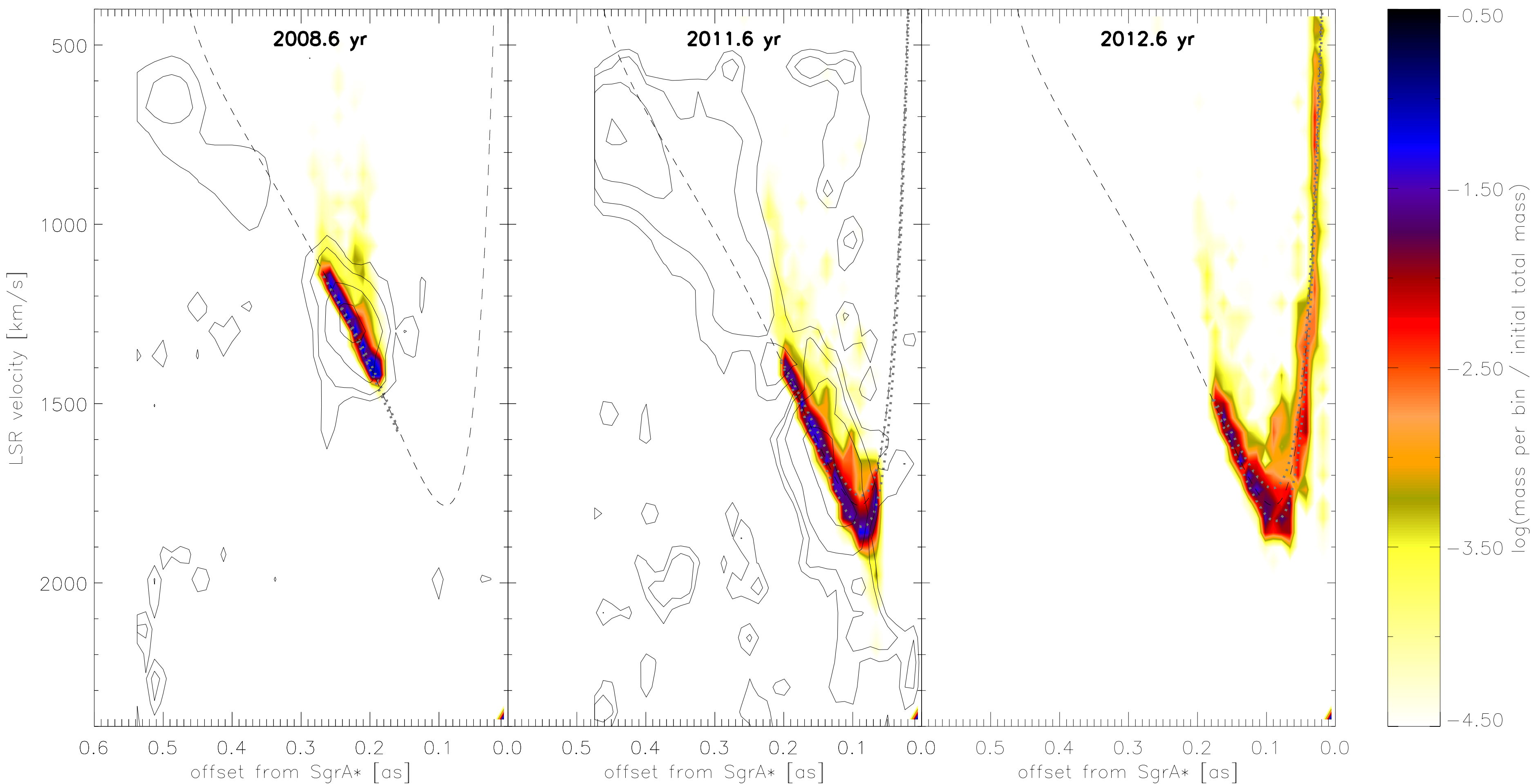
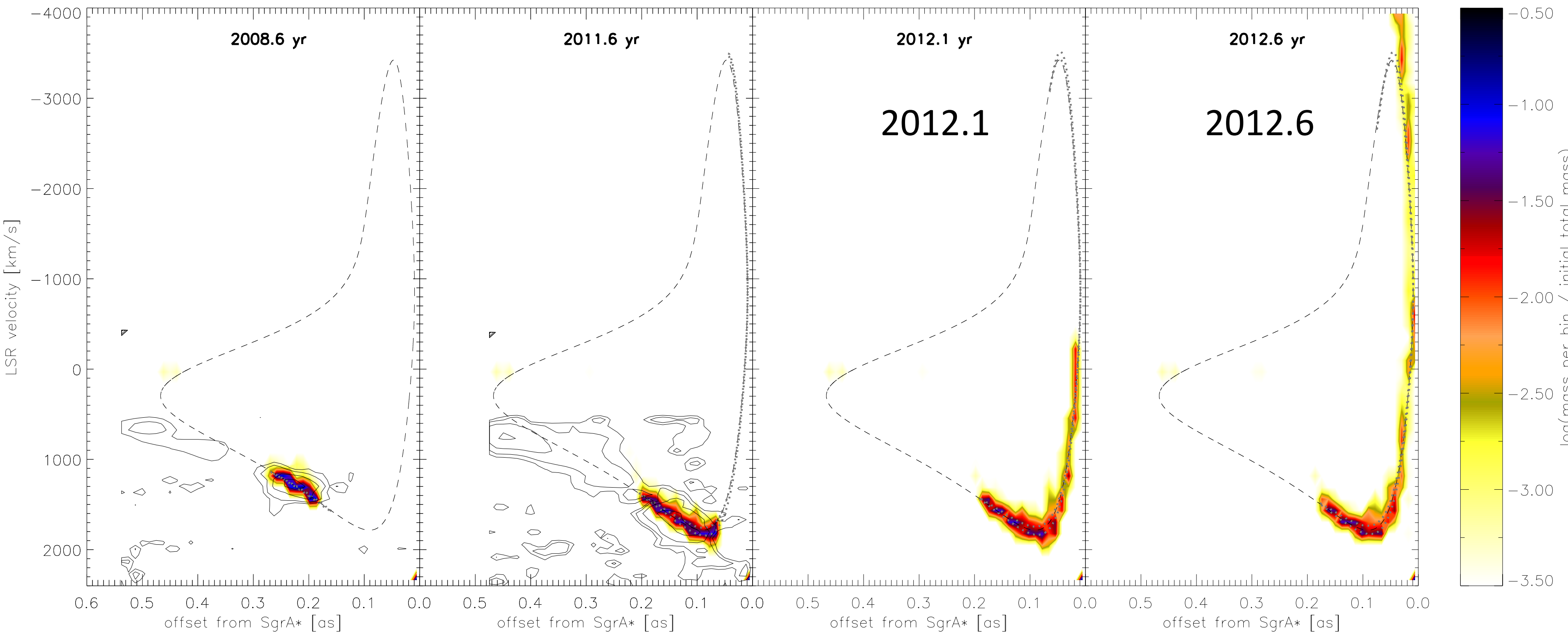
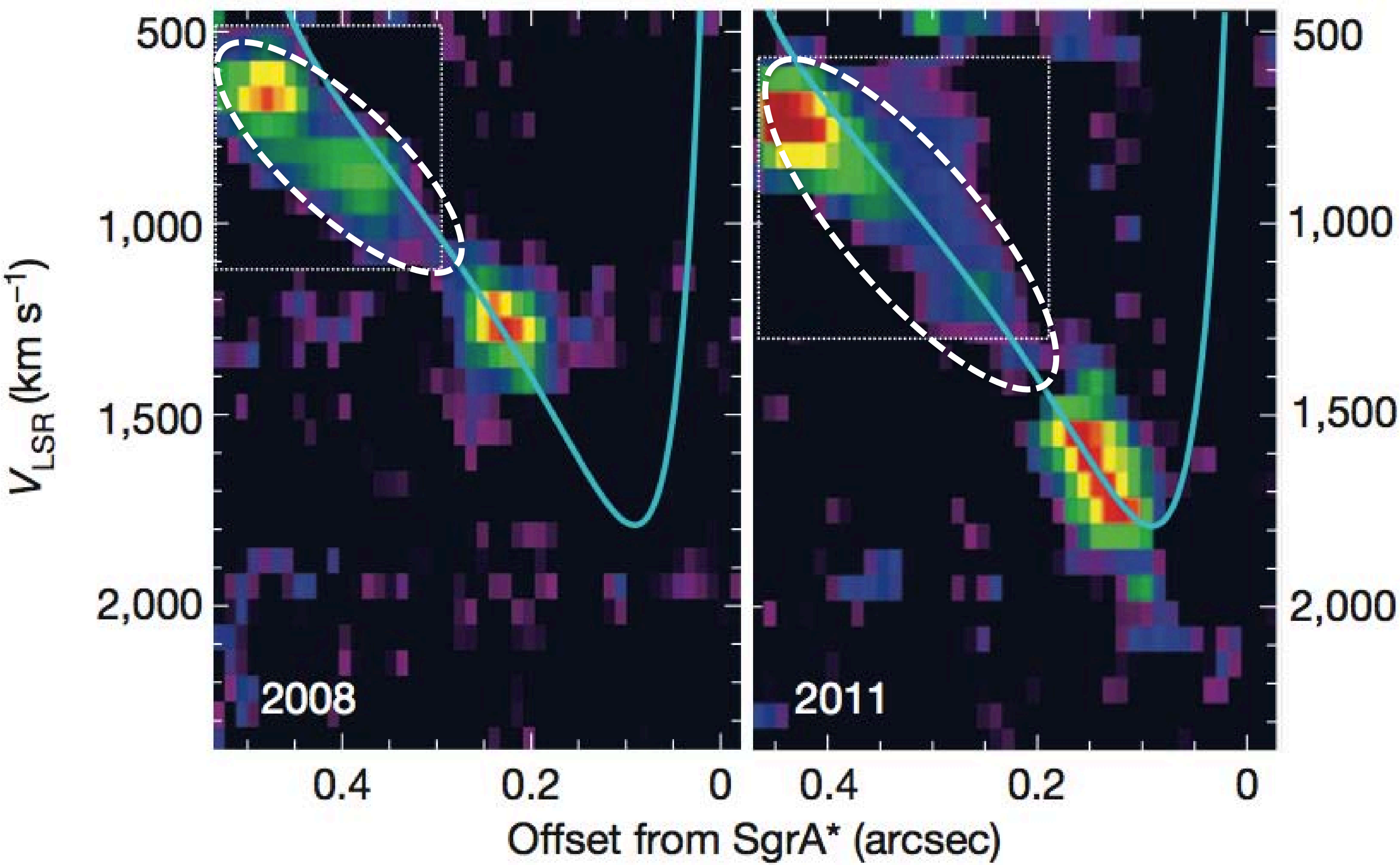


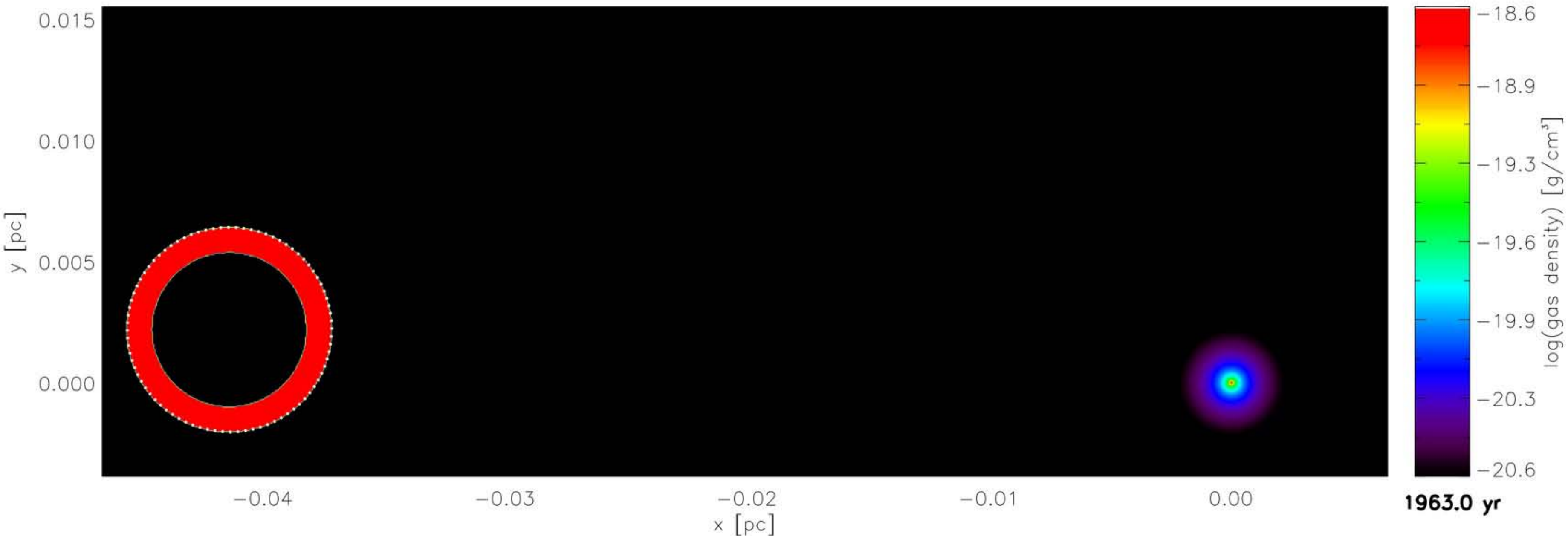
Dramatic changes in 2012



A tail of emission is seen in data

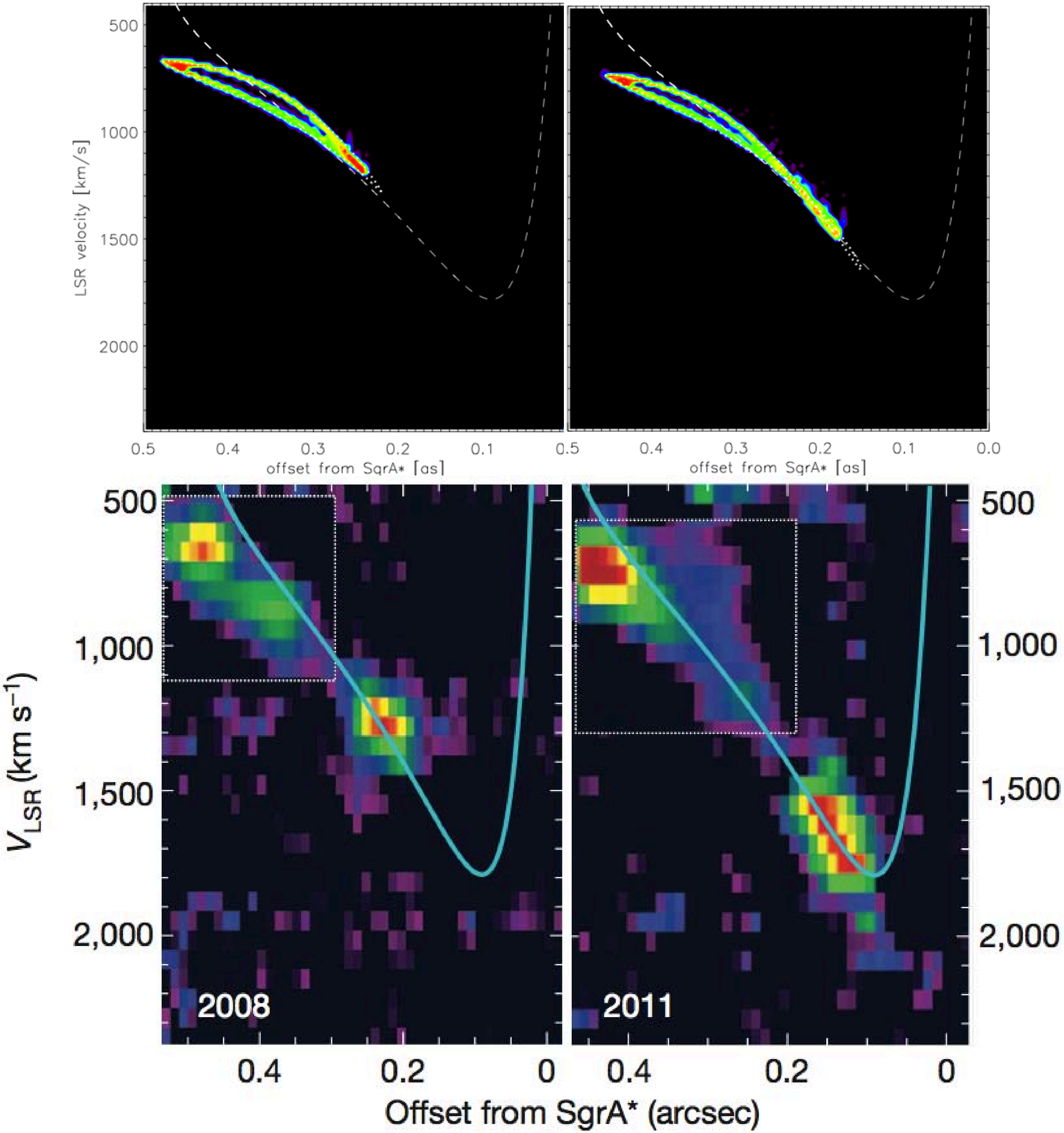


Also more difficult geometries



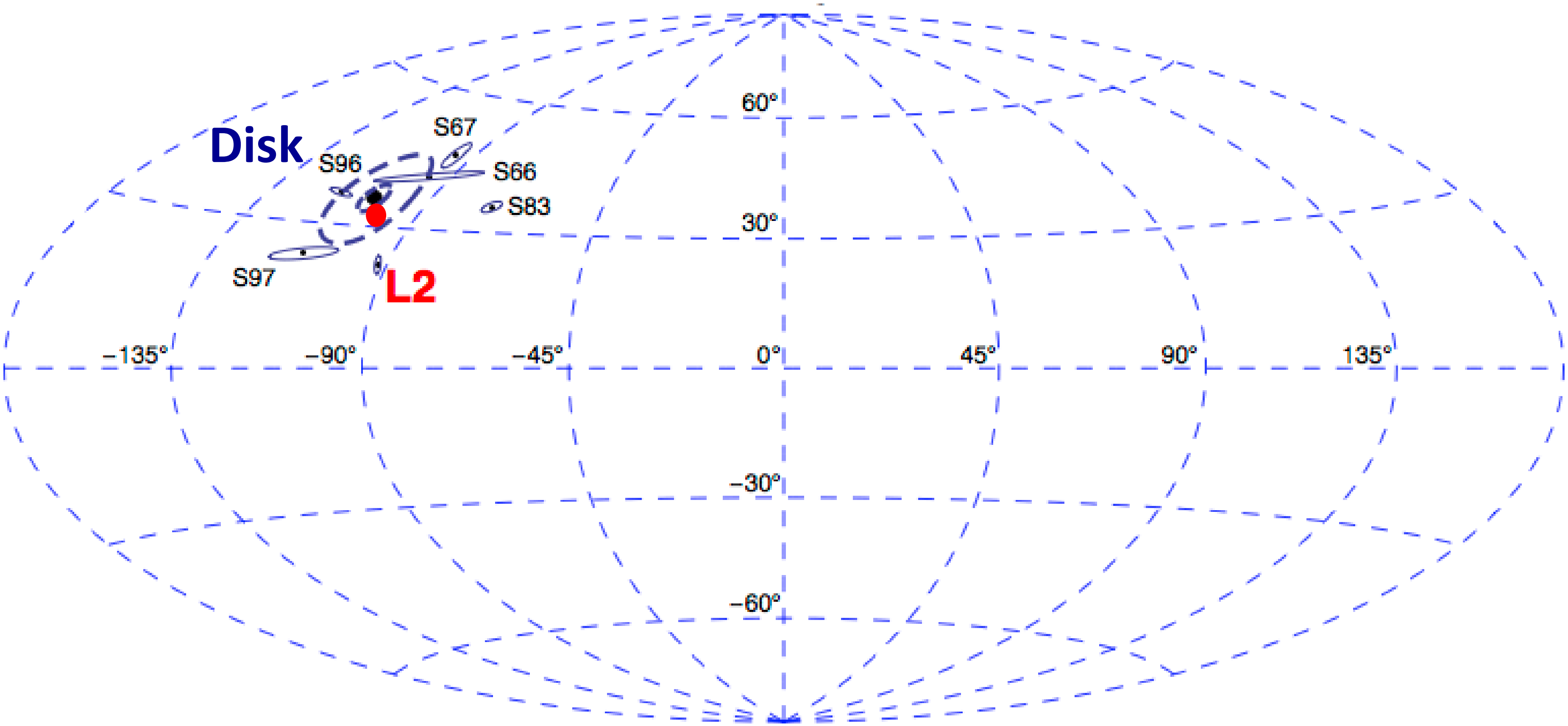
Schartmann et al. in prep.

A ring matches the morphology of the tail



What is the origin of the cloud?

- Orbital plane coincides with disk of young stars
- Apocenter of the orbit coincides with the inner edge of the disk



Two scenarios proposed

Clumplet from stellar winds / wind collisions

- Stellar winds of massive, young stars of disk
- wind speeds ≈ orbital speeds
- Creation of fragment with low angular momentum
- Ballistic infall
- First time event (but frequent events)

- Burkert et al. 2012

Evaporating disk around protostar

- Young stellar object from disk of massive, young stars
- Scattered to low-angular momentum orbit
- Disk around the star glows in UV light of hot stars
- Larger gas reservoir
- Object on similar orbit for many orbits

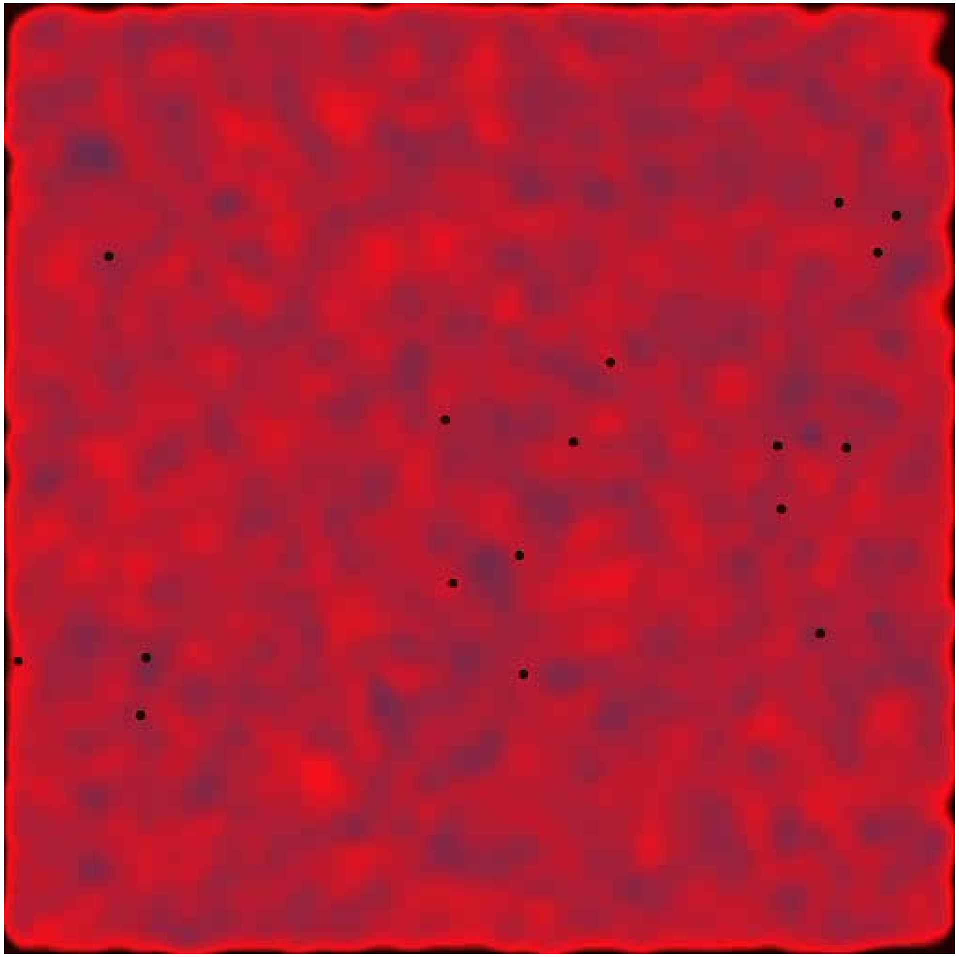
- Murray-Clay & Loeb 2012

Suitable candidate stars exist

- S91: O-star
- IRS16SW: Contact binary

Martins et al. 2006

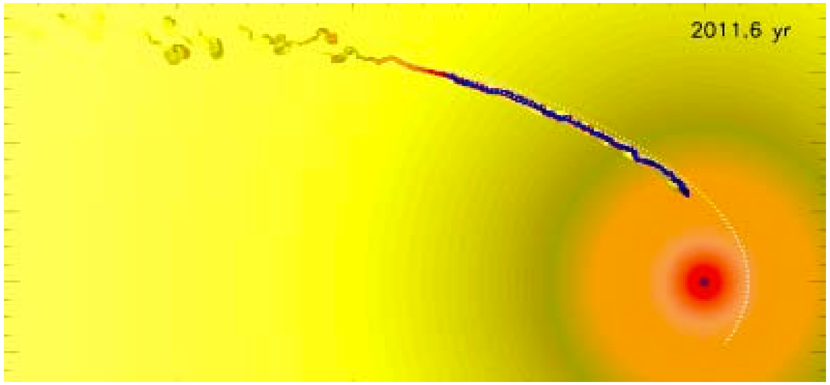
Simulations of the winds show a very clumpy structure



Cuadra et al. 2006

Problems for stellar wind origin

- Formation at apocenter (1944) is most likely
  - pressure equilibrium there
- By 2011 cloud should already be stretched much more than observed



- No reason to think cloud formed in 2000
- But: How well do we know RIAF?

Alternative: Disk around protostar

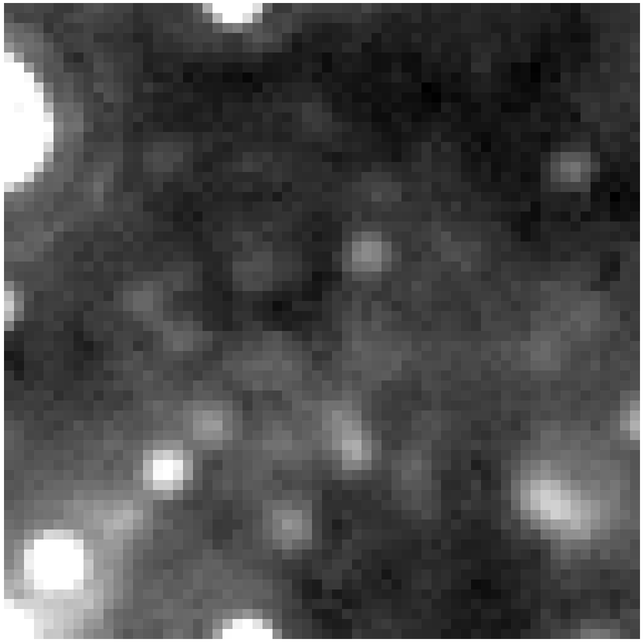
Continuous gas supply

- Protostar and its disk forms in the disk of young stars.
- Central star invisible:
  - $T > 10^{4.6}$ K and $L < 10^{3.7}$ $L_{\odot}$
- Scattering to loss-cone orbit
- Tidal forces disrupt more and more of the disk, UV radiation field illuminates gas
- density of gas cloud should increase towards pericenter

Problems for YSO origin

- Disk around protostar cannot survive strong scattering event
- If many small scattering events lead to the highly eccentric orbit, the cloud would already have been destroyed before.
- Event rate estimate in the present work is a serious over-estimate

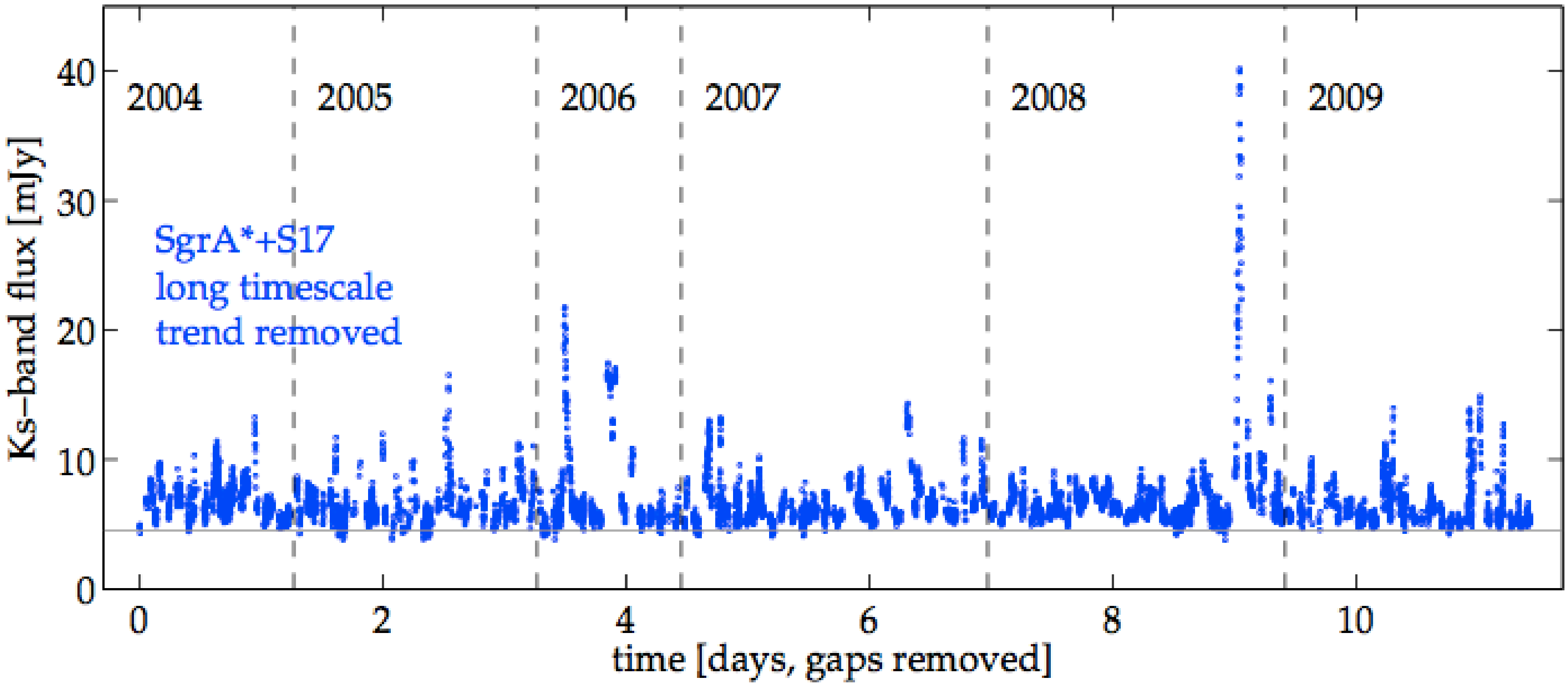
Sgr A* to date: Sometimes flares up in the NIR



- Typically one flare per night
- Lasts ~ 90 min
- Much redder than the stars

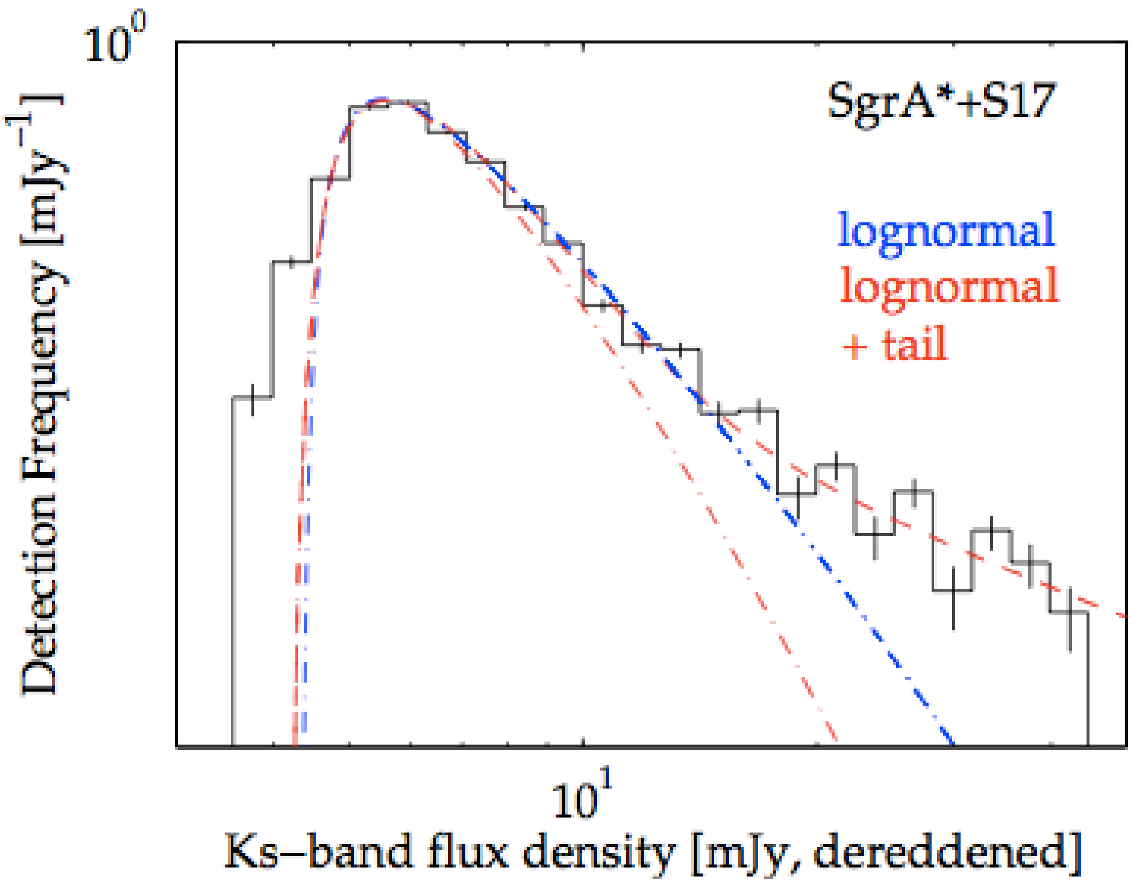
Genzel et al. 2003,
Eisenhauer et al. 2005
Gillessen et al. 2006,
Hornstein et al. 2007
Dodds-Eden et al. 2009

Sgr A* is a source that undergoes bursts



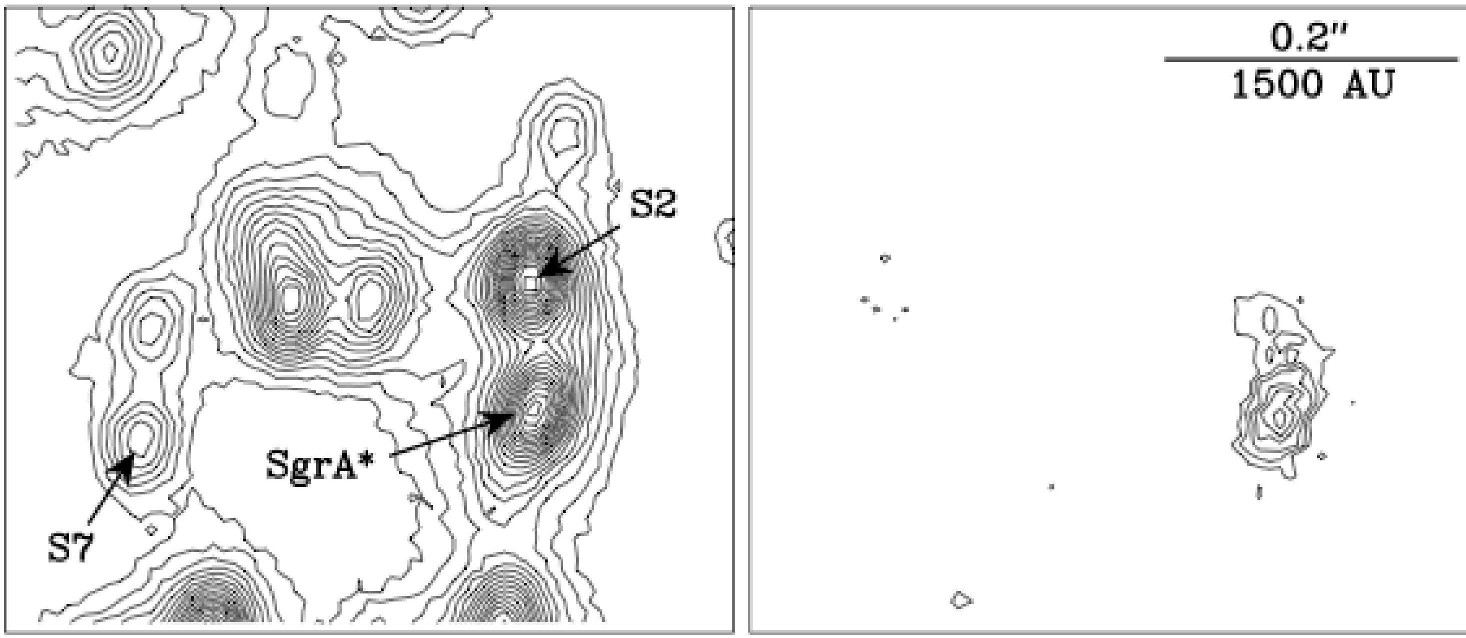
Dodds-Eden et al. 2011

Continuous variability & a tail of flares



Dodds-Eden et al. 2011

Sgr A* is the only strongly polarized source in the GC

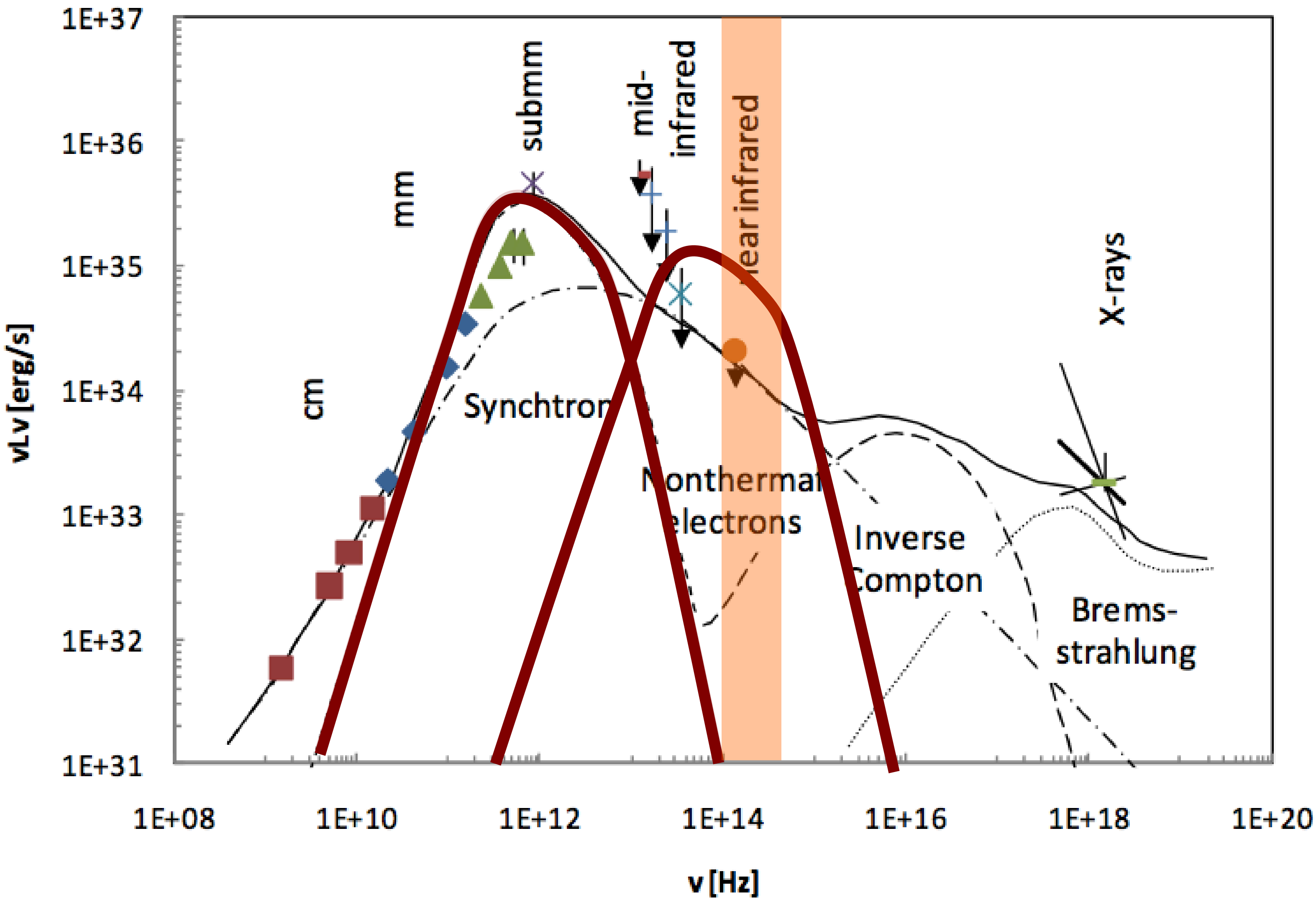


Sum of two polarizations

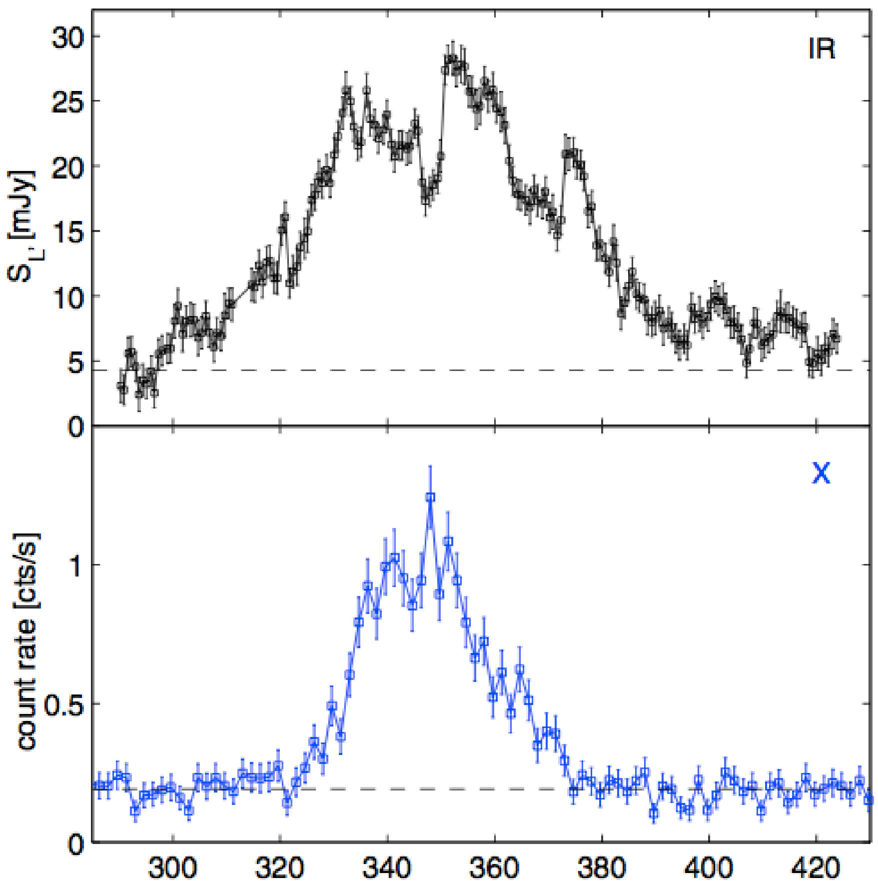
Difference of two polarizations

Trippe 2007

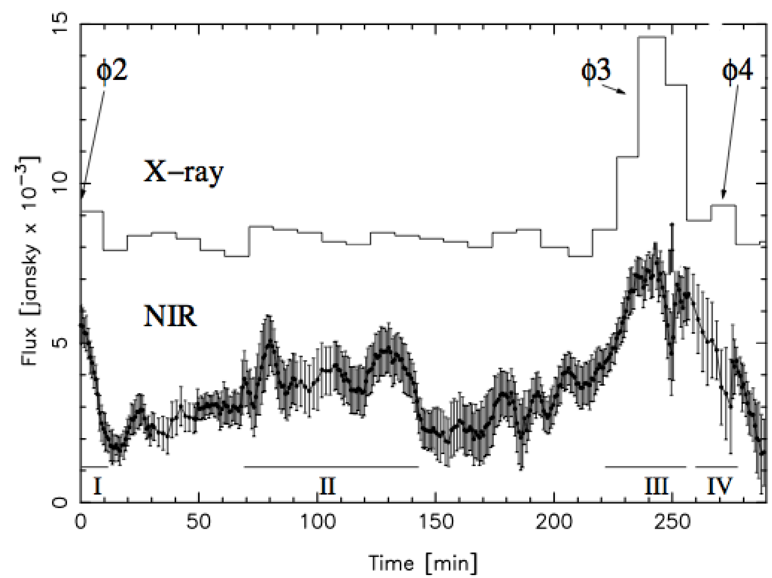
Flares are synchrotron emission of transiently heated electrons



Simultaneous X-ray flares happen on the same timescale

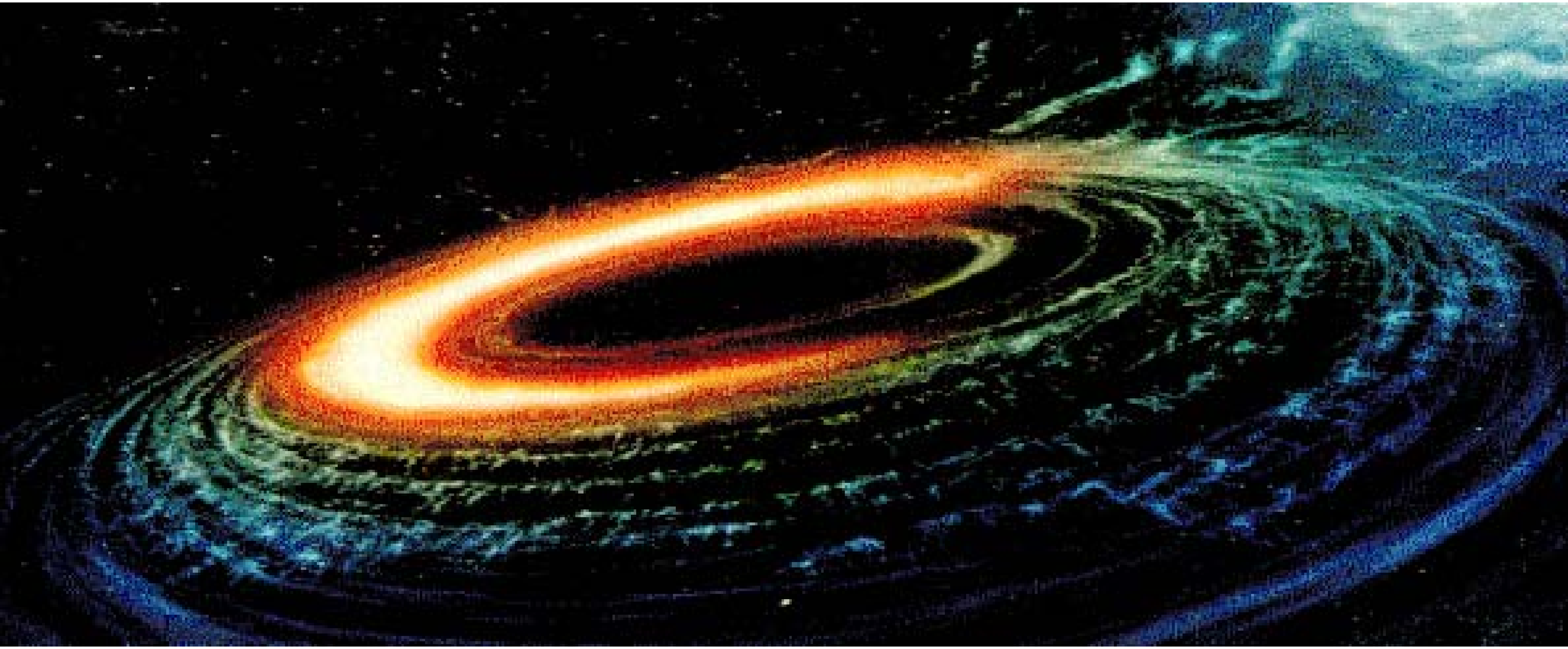


Dodds-Eden et al. 2009,
Porquet et al. 2009



Eckart et al. 2006

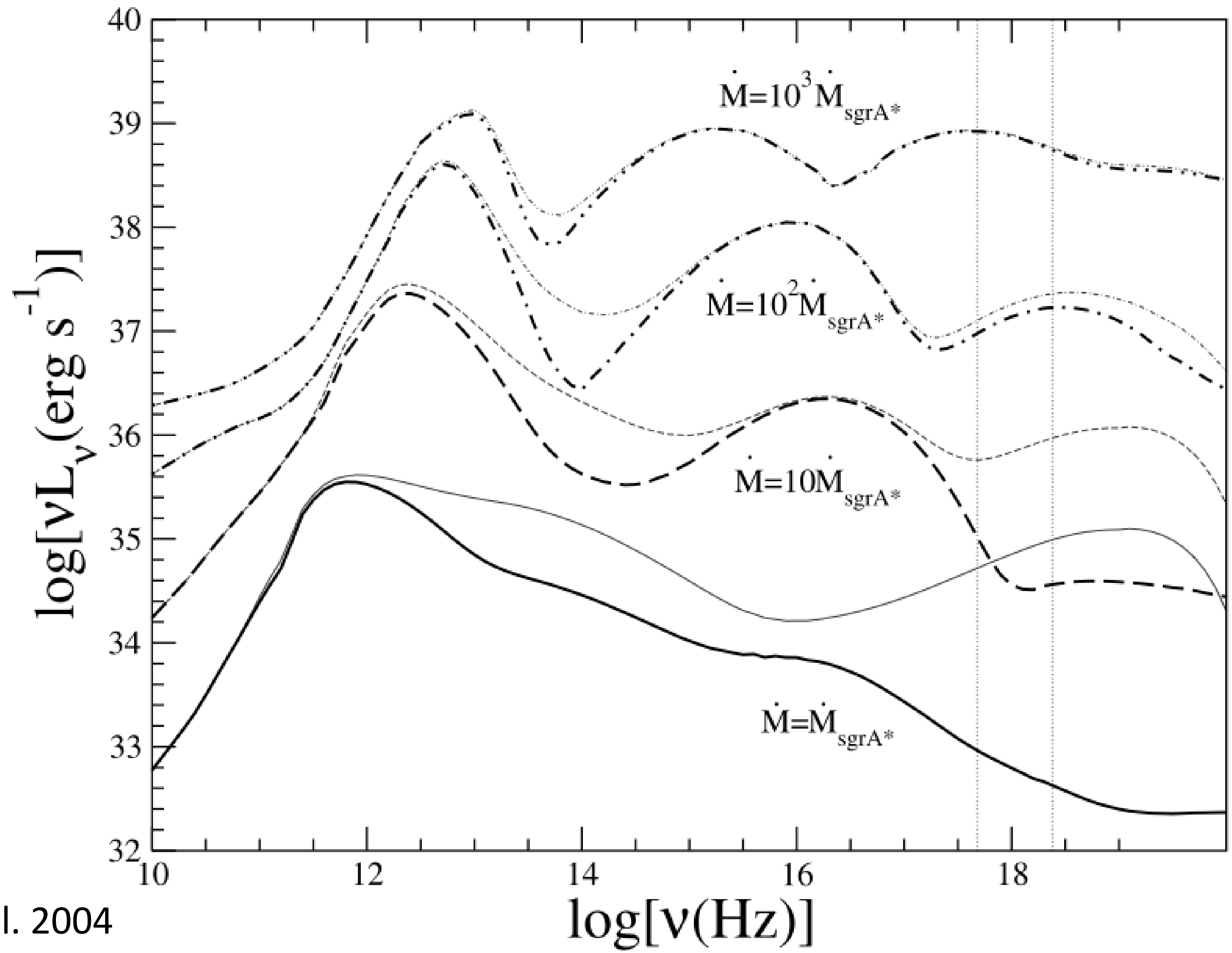
Current flares:
Magnetic weather on accretion disk



Flares are ‘ignition events’

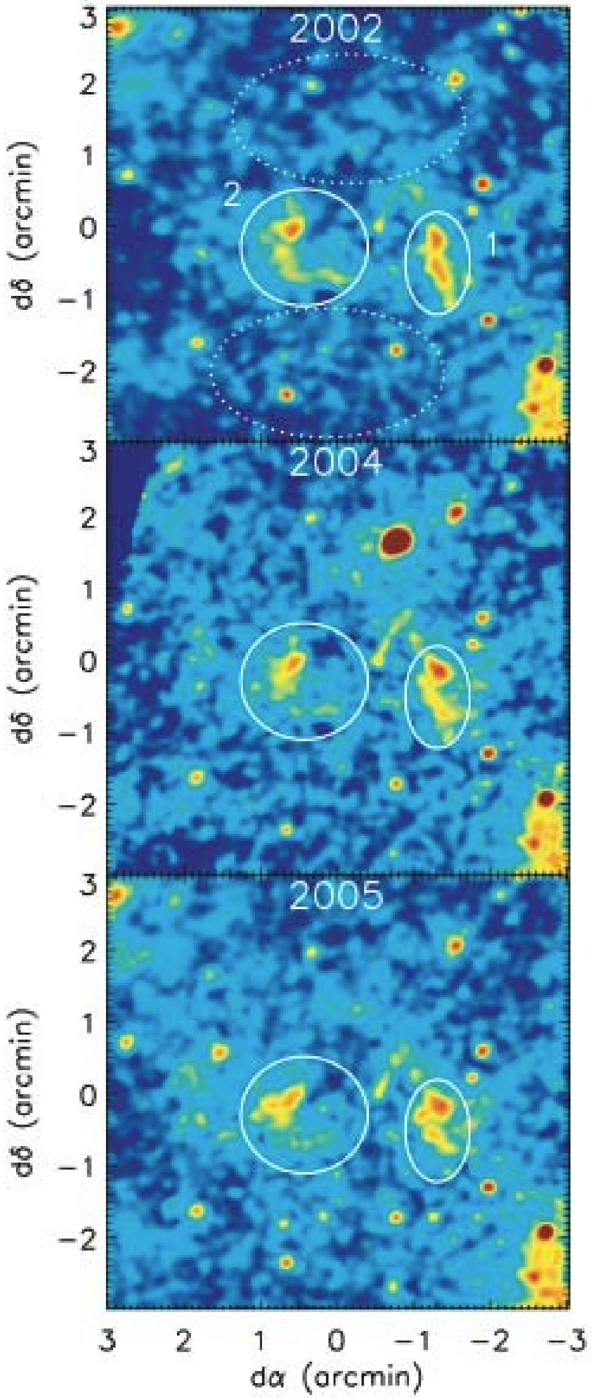
Accretion rate might increase for years

Flux will vary because of changed accrection rate – unlike for flares



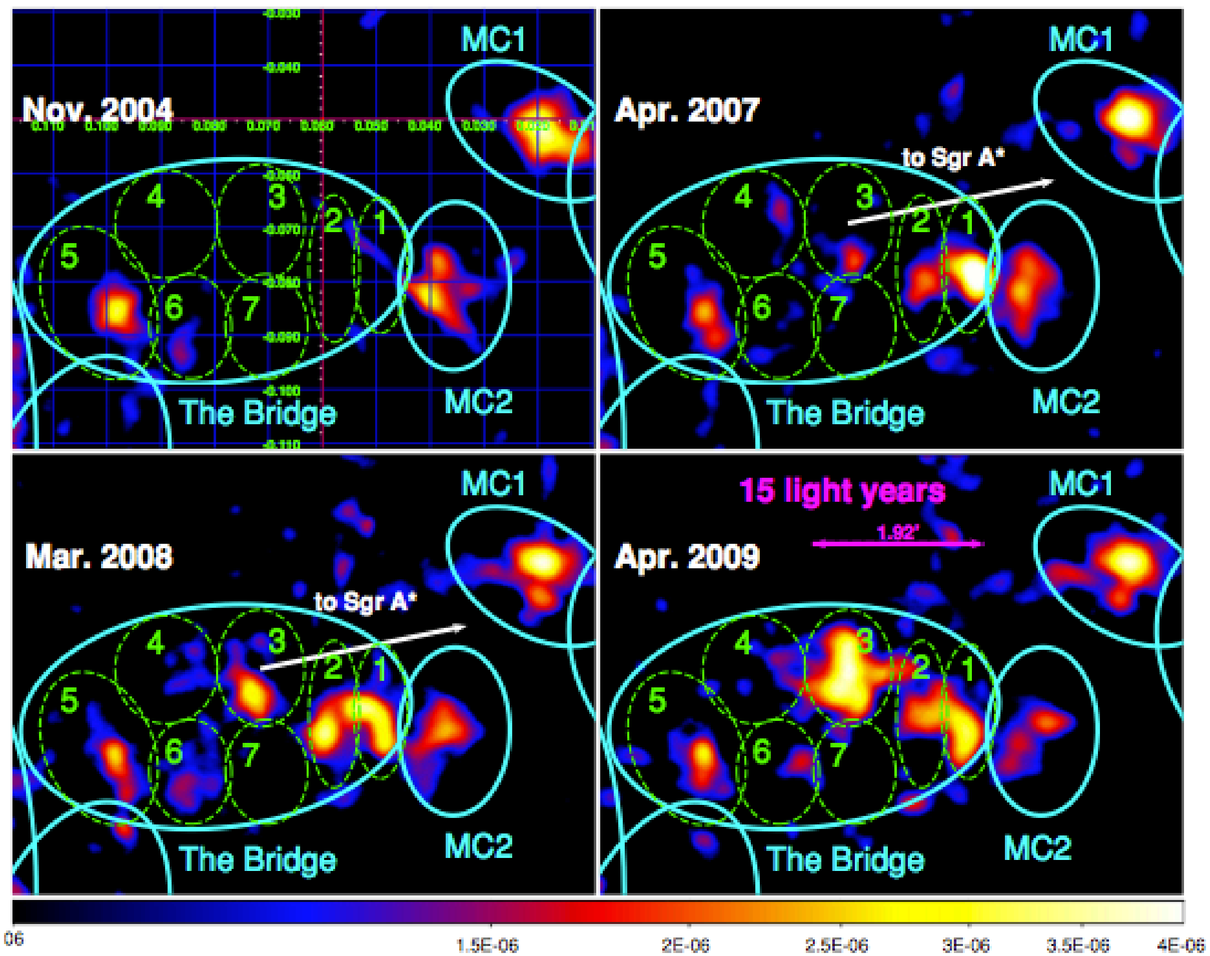
Yuan et al. 2004

X-ray echoes:
Energy release 10^{38} erg/s

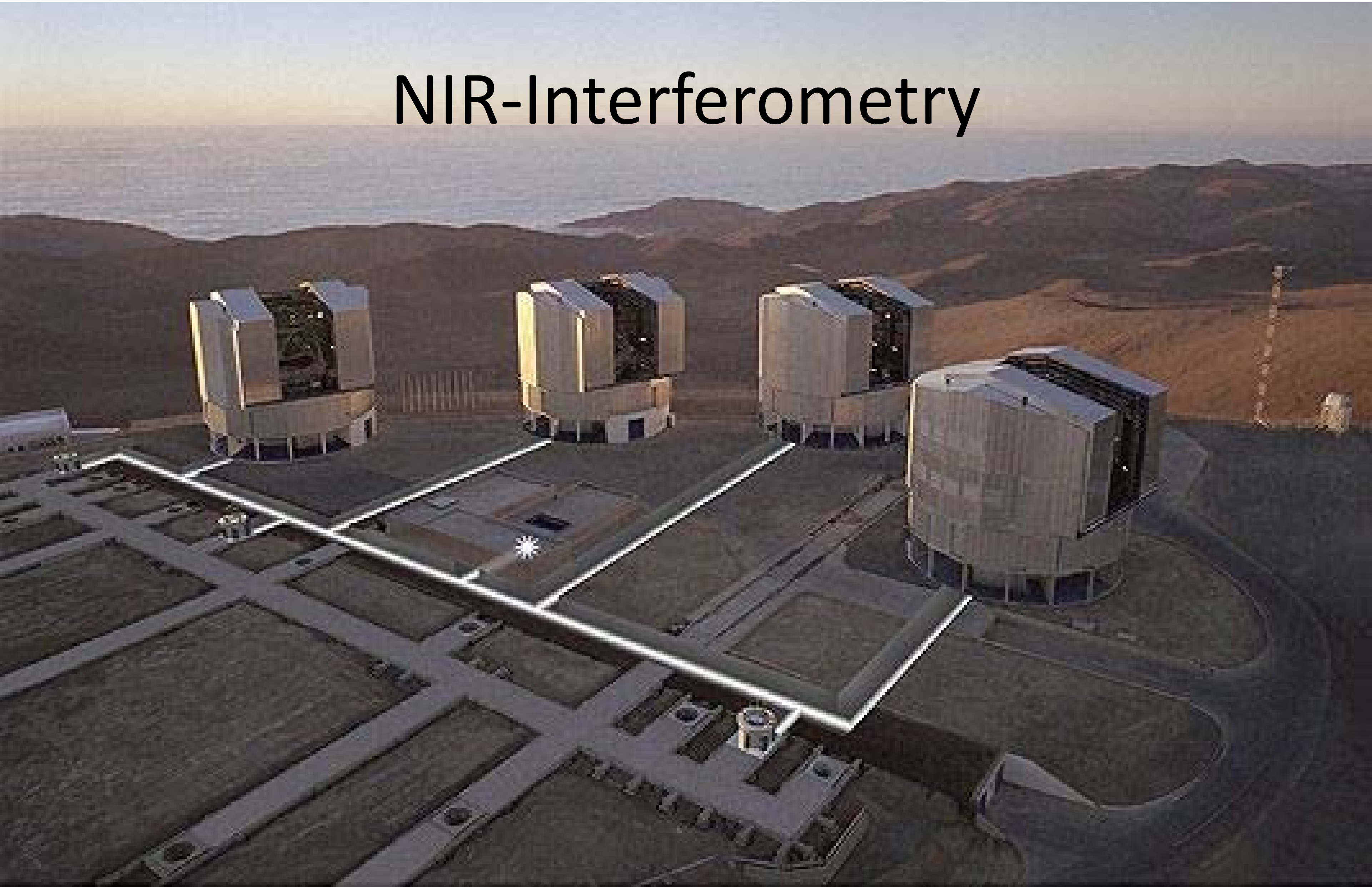


Muno et al. 2007

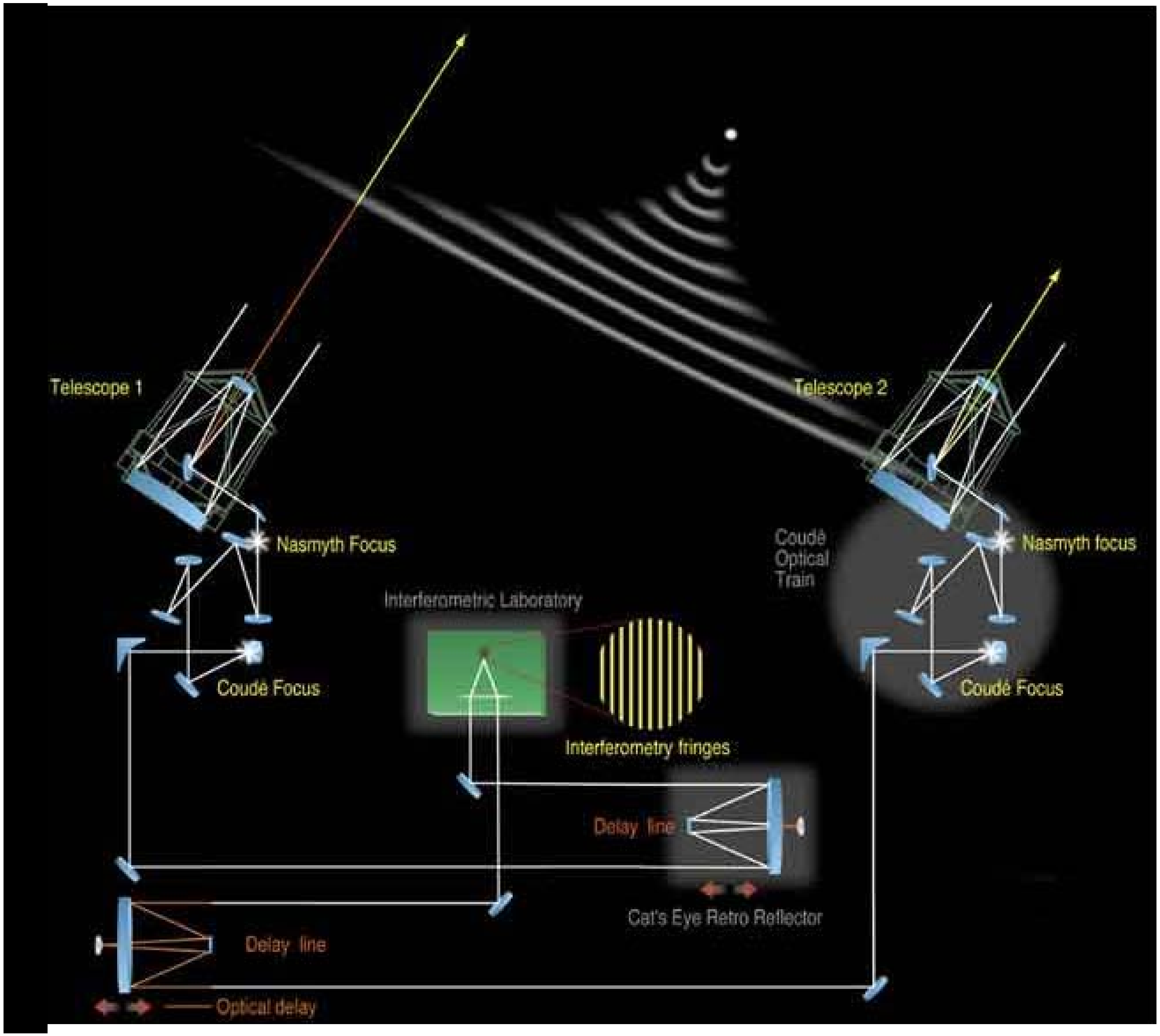
Ponti et al. 2010



The future is bright for another reason:



A factor 15 more powerful than the VLT



VLT (8m):
R = 50 mas
Δx = 150 μas

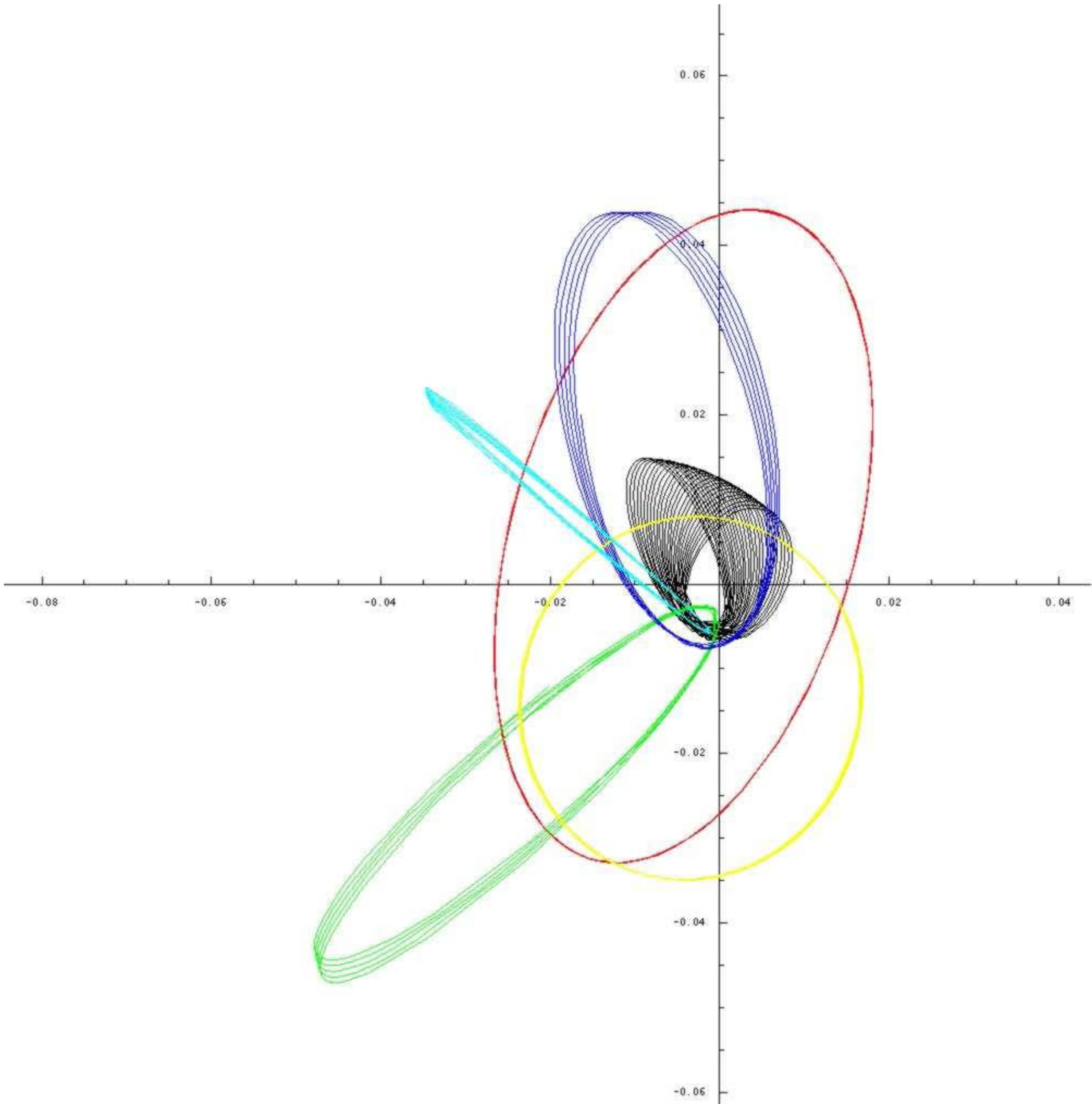
VLTI (120m):
R = 3 mas
Δx = 10 μas

Imagine we could zoom in further

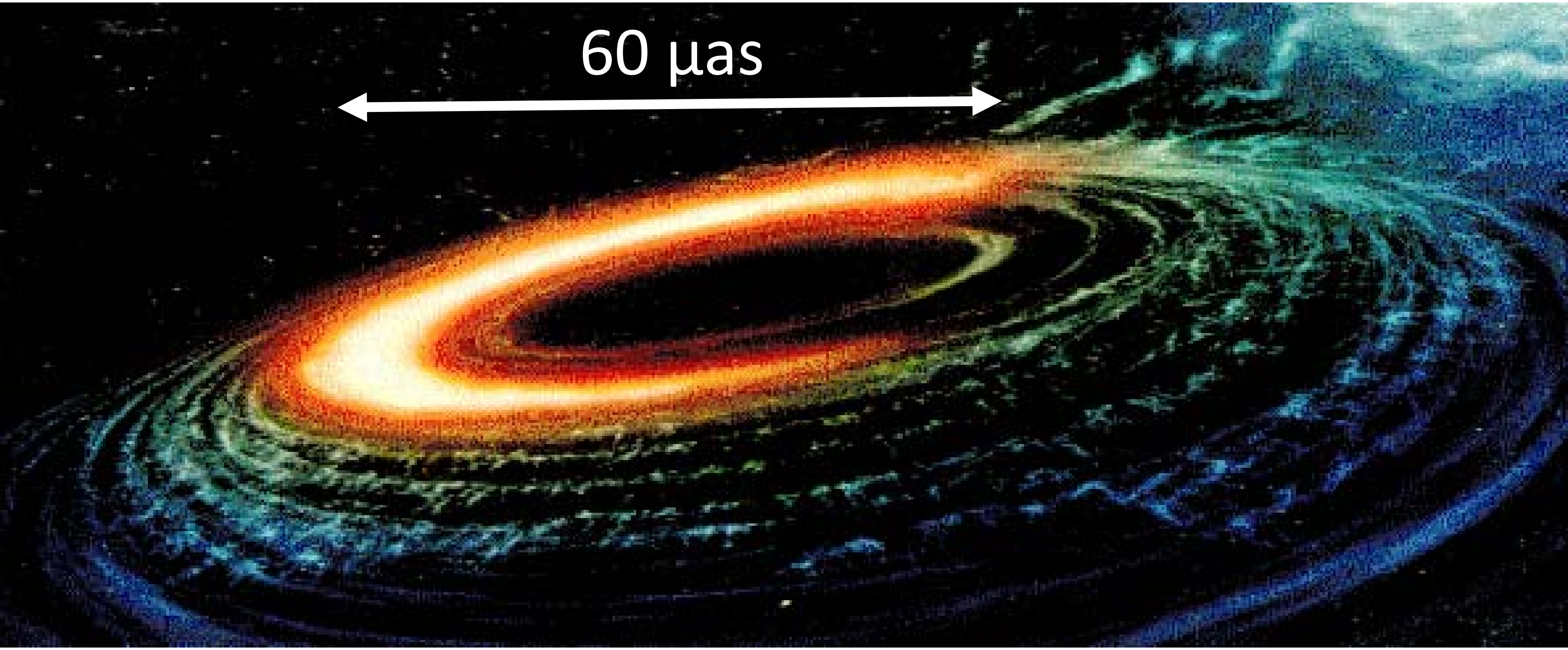
Expected in central 100 mas:
-- ~5 stars
-- K = 17..19 mag

Orbital Period:
1 year

Precession:
~ few ° per year



Flares orbit with amplitudes > 50μas



NIR interferometry has the potential to probe general relativity around Sgr A* using stars and flares

How to make it work?

- **Measure relative & narrow angle**
  - two sources, one reference & one science
- **Use UTs (8m)**
  - Sources are faint (for interferometry standards)
- **Use AO**
  - only coherent fraction of light interferes
  - stellar field is crowded, need to select correct source
  - Galactic Center: NIR wavefront sensor
- **Track the fringes**
  - need to expose minutes, stabilize wave pattern
  - atmospheric coherence time: 4ms
- **Use multiple baselines**
  - 2D positions, consistency checks
  - best choice: VLIT, 4 telescopes = 6 baselines


Dual feed, 4-telescope, adaptive optics assisted, fringe tracking beam combiner instrument
GRAVITY

GRAVITY: Observing the Universe in Motion

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+ many more

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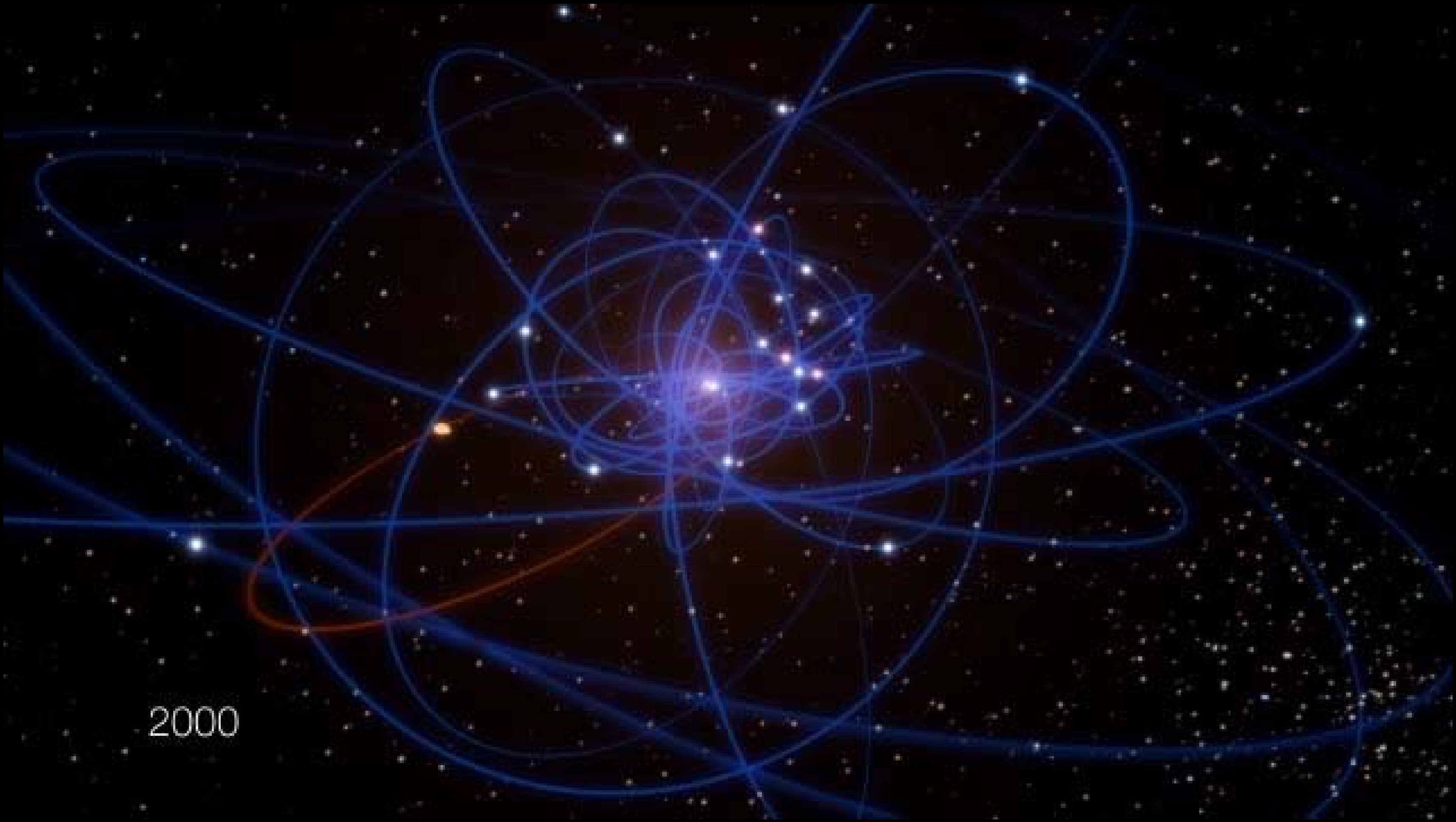
[10] Groupement d'Intérêt Scientifique PHASE (Partenariat Haute résolution Angulaire Sol Espace) between ONERA, Observatoire de Paris, CNRS and Université Paris Diderot

GRAVITY is the second generation Very Large Telescope Interferometer instrument for precision narrow-angle astrometry and interferometric imaging. With its fibre-fed integrated optics, wavefront sensors, fringe tracker, beam stabilisation and a novel metrology concept, GRAVITY will push the sensitivity and accuracy of astrometry and ...erometric imaging far beyond what ...red today. Providing precision ...metry of order 10 microarcseconds, ...naging with 4-milliarcsecond ...tion, GRAVITY will revolutionise ...nical measurements of celestial ...ts: it will probe physics close to ...ent horizon of the Galactic Centre ... hole; unambiguously detect and ...ure the masses of black holes ...ssive star clusters throughout the ...Way; uncover the details of mass ...tion and jets in young stellar ...ts and active galactic nuclei; and ... the motion of binary stars, exo...ts and young stellar discs. The ...ment capabilities of GRAVITY are ...ed and the science opportunities ...ill open up are summarised.

...mental measurements over a wide ... of fields in astrophysics

... as long-baseline radio interfer...y has tone, GRAVITY infrared (IR) ...metry, with an accuracy of order ...croarcseconds and phase-referenced ...ng with 4-milliarcsecond resolution, ...ing a number of key advances (Eisenhauer et al., 2008). GRAVITY will carry out the ultimate empirical test to show whether or not the Galactic Centre harbours a black hole (BH) of four million solar masses and will finally decide if the near-infrared flares from Sgr A* originate from individual hot spots close to the last stable orbit, from statistical fluctuations in the inner accretion zone or from a jet. If the current hot-spot interpretation of the near-infrared (NIR) flares is correct, GRAVITY has the potential to directly determine the spacetime metric around this BH. GRAVITY may even be able to test the theory of general relativity in the presently unexplored strong field limit. GRAVITY will also be able to unambiguously detect intermediate mass BHs, if they exist. It will dynamically measure the masses of supermassive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