The Galactic Center

Jason Dexter
MPE Garching

with slides from R. Genzel, S. Gillessen, O. Pfuhl, G. Ponti, and the MPE GC group (mpe.mpg.de/ir/GC)

ESO/Y. Beletsky

The Galactic Center

1. Evidence for a massive black hole (today)
2. A paradox of youth (16.11)
3. Sgr A* and the faintest black holes (21.11)
4. Compact objects, dark matter, and the high energy GC (23.11)

Seminar: strong gravity around Sgr A* (23.11)

About me


Born Seattle, WA
Canada
United States
Mexico
Greenland
Iceland
Hudson Bay
Gulf of Mexico
Caribbean Sea
North Atlantic Ocean
Gulf of Guinea
Cuba
Puerto Rico
Guatemala
Nicaragua
Venezuela
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Colombia
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Ukraine
Austria
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Greece
Turkey
Syria
Tunisia
Morocco
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Western Sahara
Mauritania
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Burkina Faso
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South Sudan
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Gabon
DR Congo
Kenya
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Angola
Zambia
Mozambi

About me

Born Seattle, WA

About me


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Ethiopia
Gulf of Guinea
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DR Congo
Kenya
Tanzania
Angola
Zambia
Bolivia

About me


2005
BSc Los Angeles, CA
Northwestern Passages
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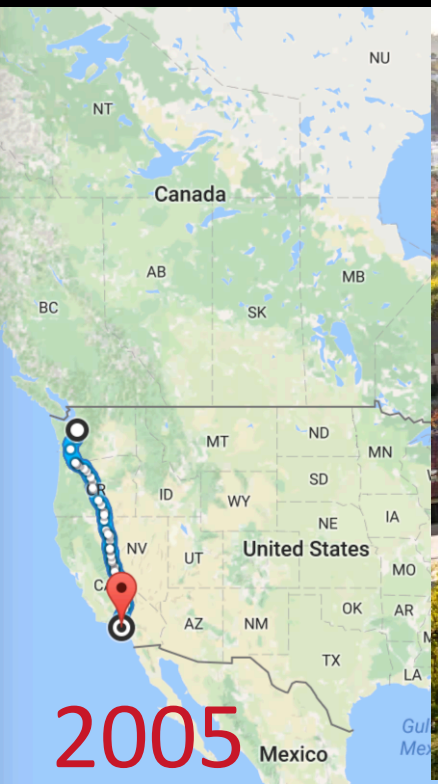
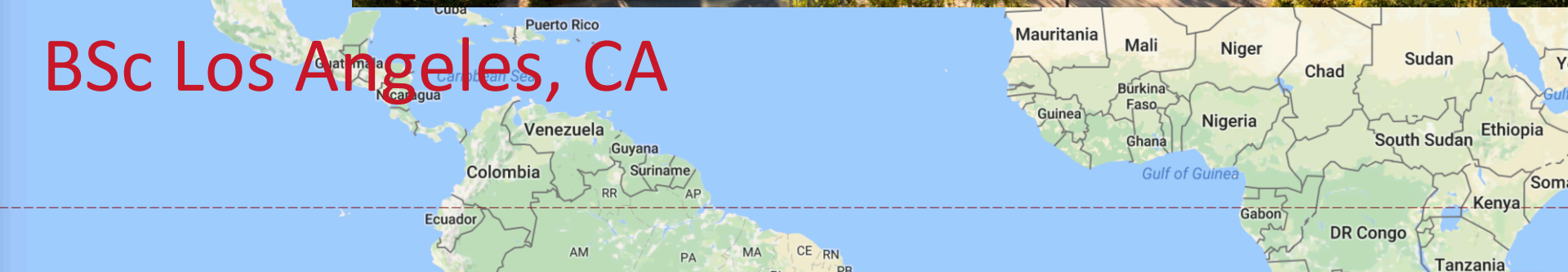
About me



Occidental College

2005 BSc Los Angeles, CA



About me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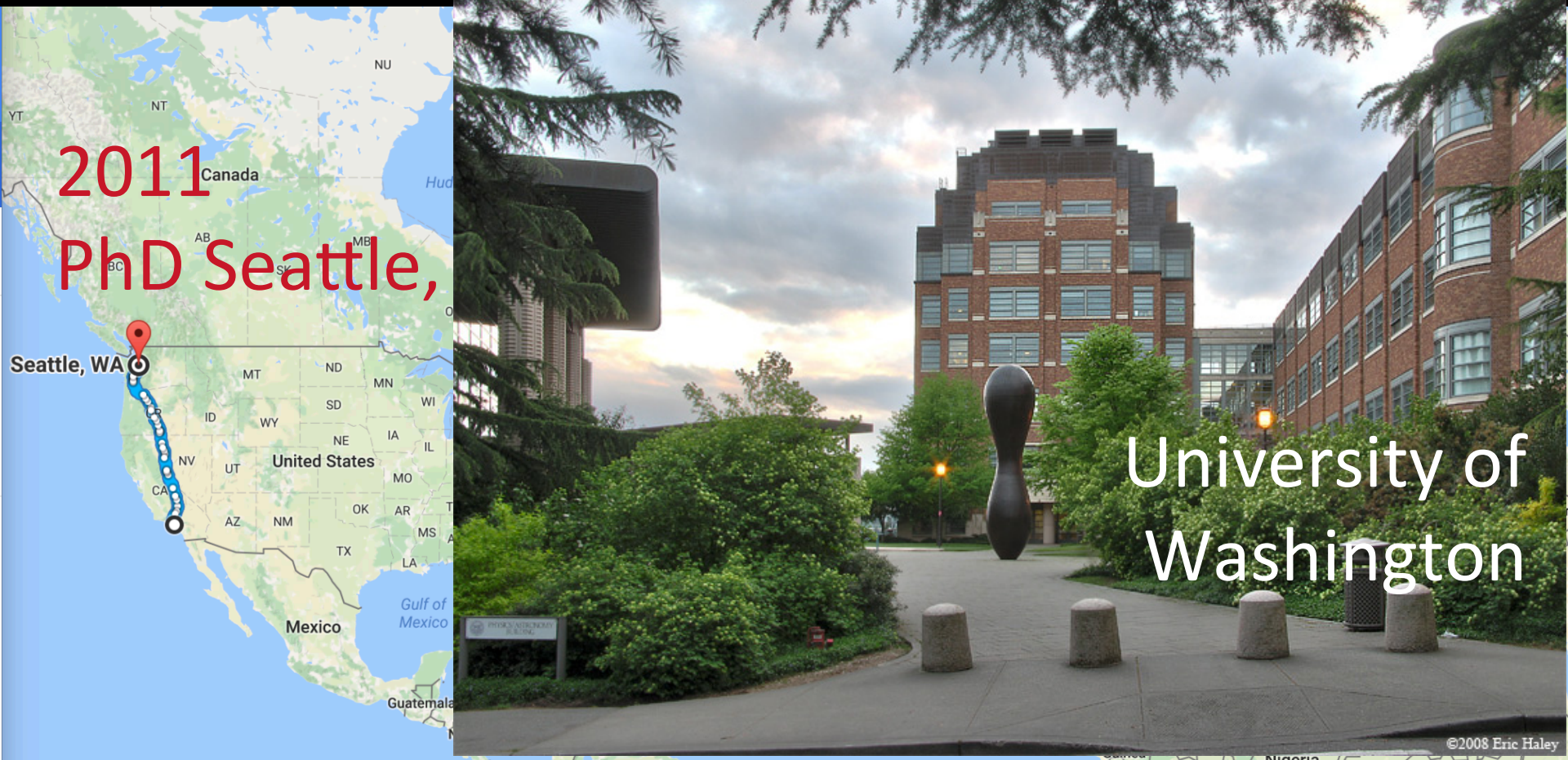

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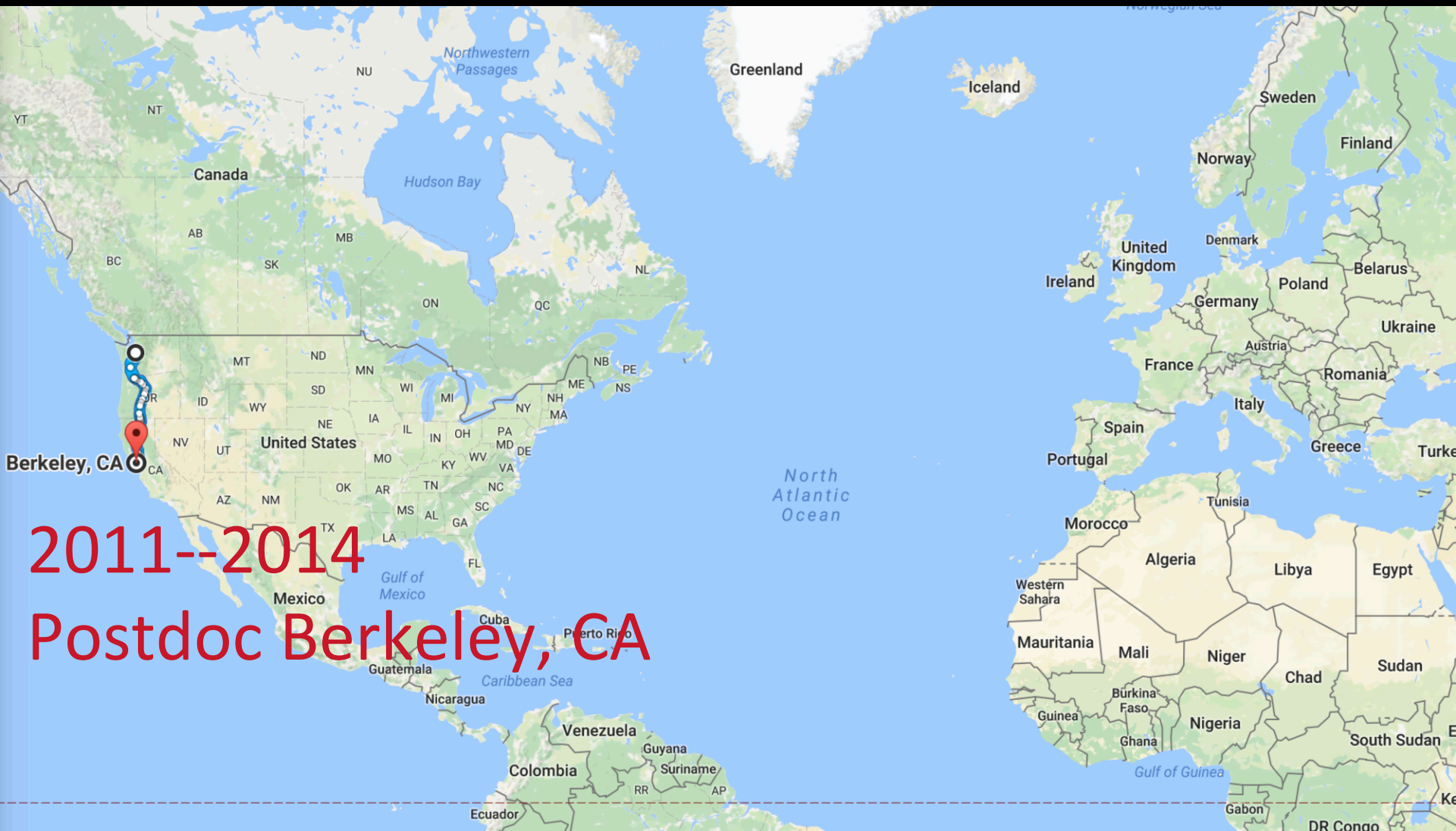
Berkeley, CA
2011--2014
Postdoc Berkeley, CA
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About me


2014--now
Garching, Germany
11 h 20 min
from €1.256
Berkeley, CA
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Brazil

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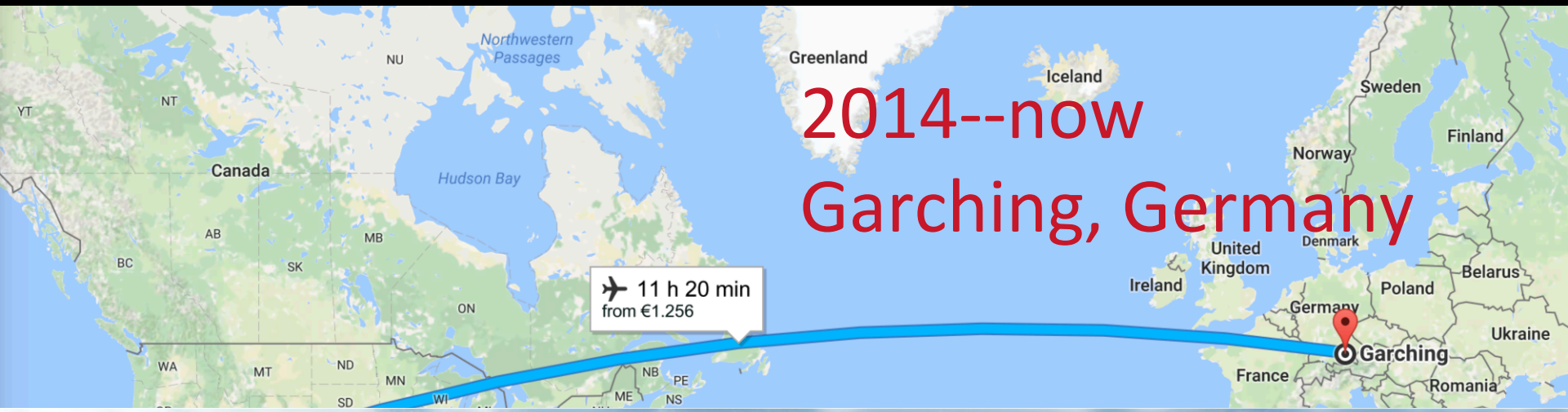


2014--now
Garching, Germany

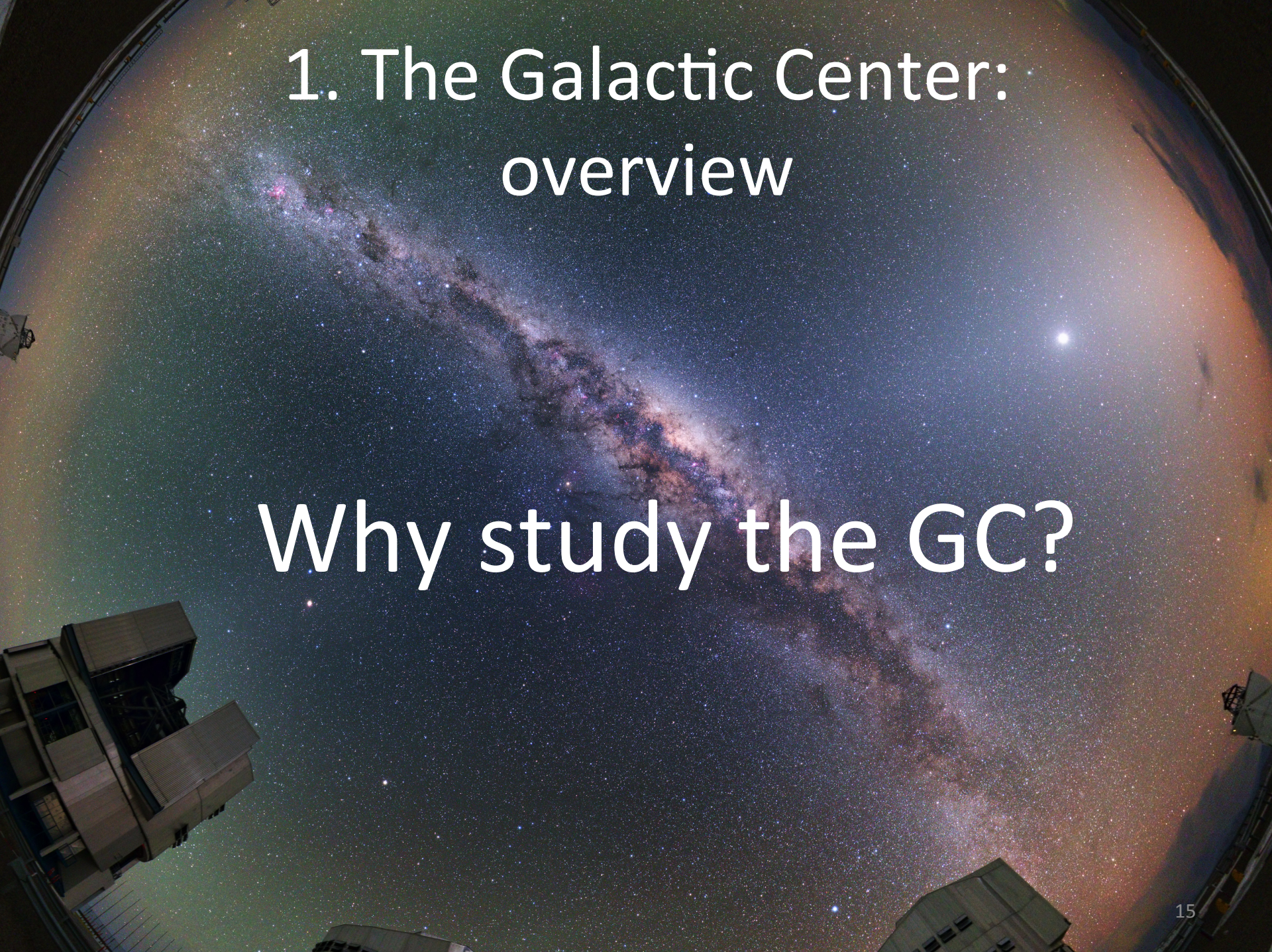
MPE Garching

About the lectures

- Selected topics: central parsec, highly biased
- Please ask questions!

- ~1 interactive Q / lecture:
  ~10 mins to think/calculate, discuss, share

- Further reading: Genzel+2010, Morris+2012, Falcke & Markoff 2013

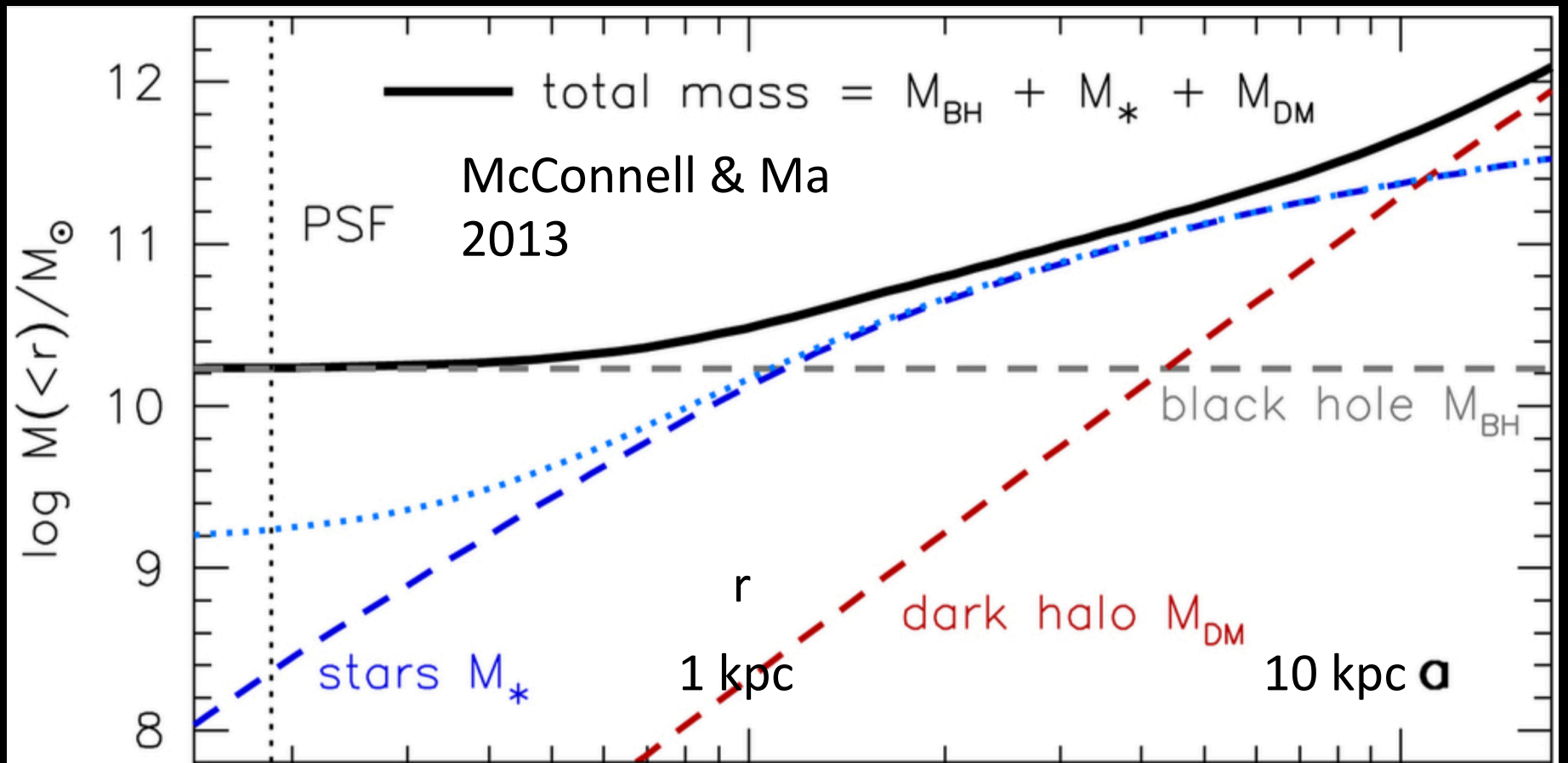


1. The Galactic Center: overview

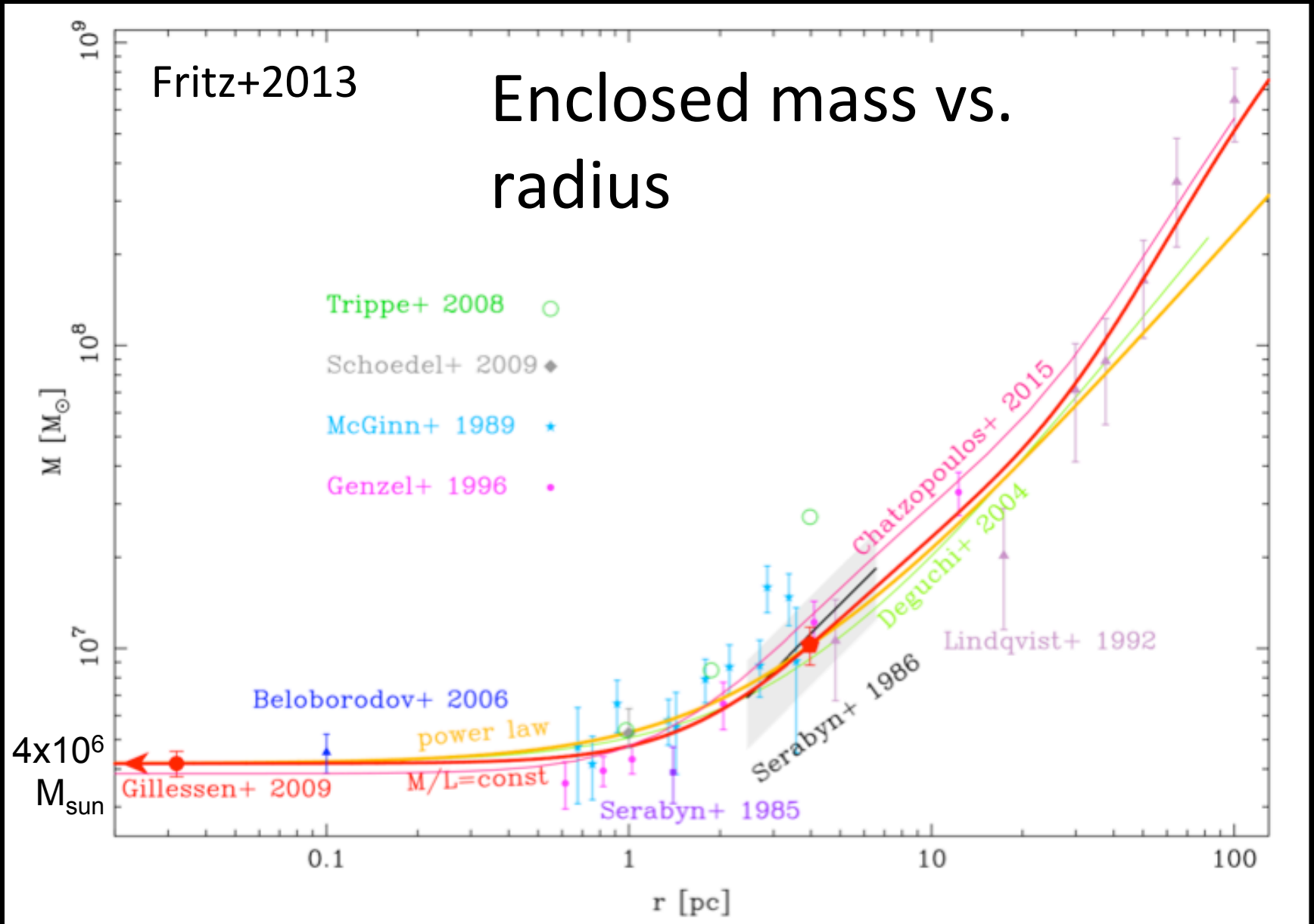
Why study the GC?

Black holes in centers of galaxies

- From modeling spatially resolved spectra
  (Bender, Kormendy, Magorrian, Richstone, Tonry, …)



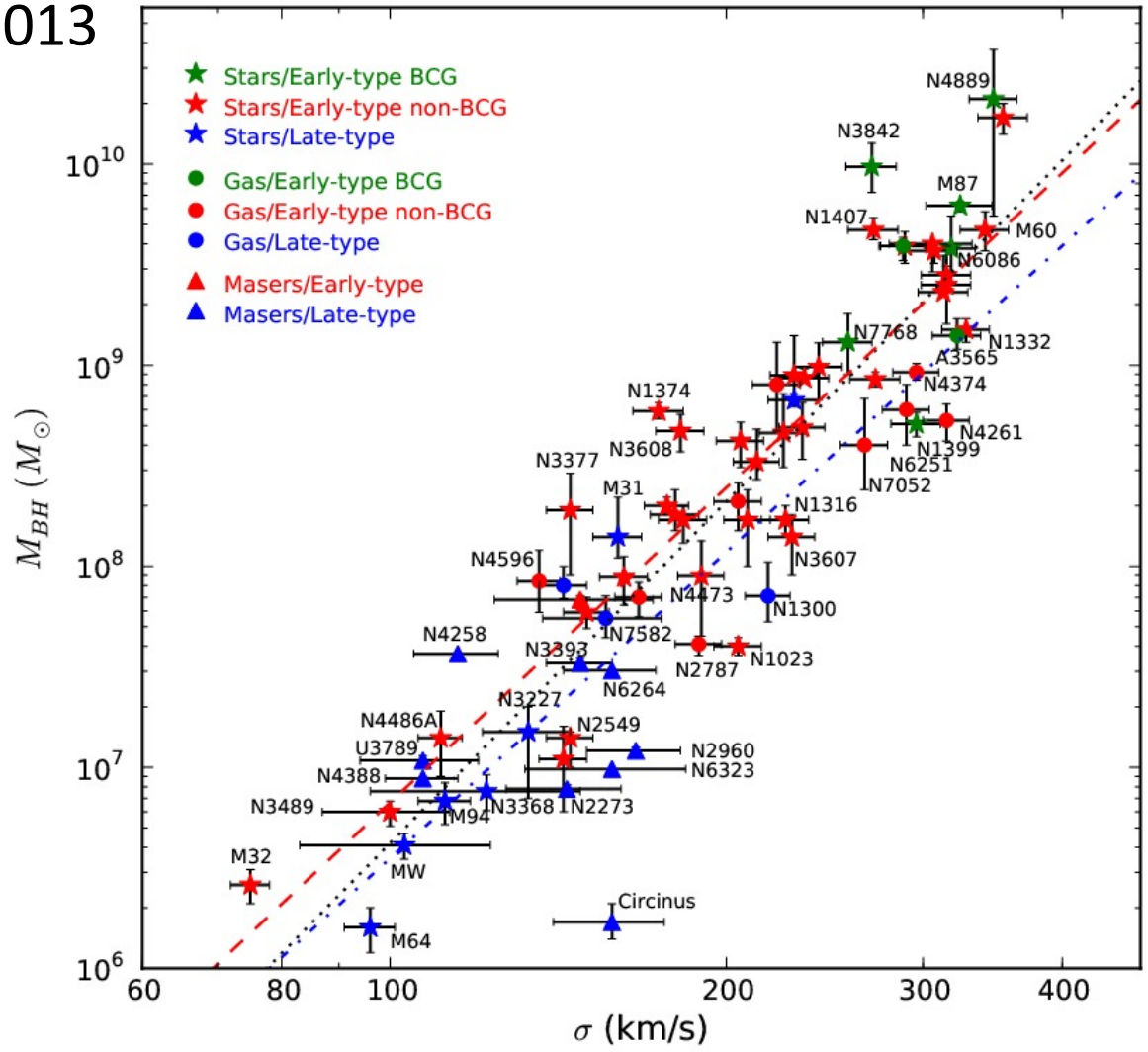
GC: best evidence for an MBH



Galaxies and black holes co-evolve

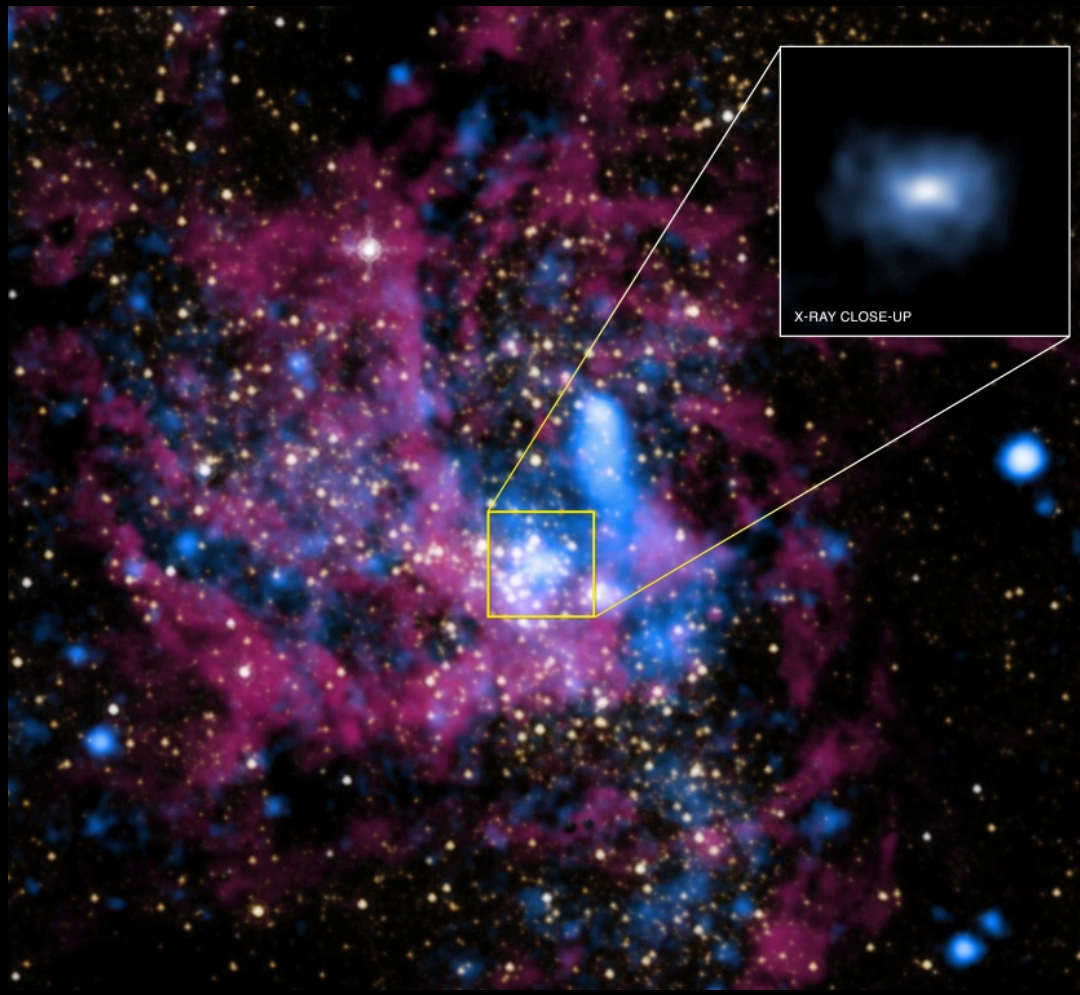
McConnell & Ma 2013

Richstone & Kormendy 1995, Magorrian+1998, Ferrarese & Merritt 2000, Kormendy+2000

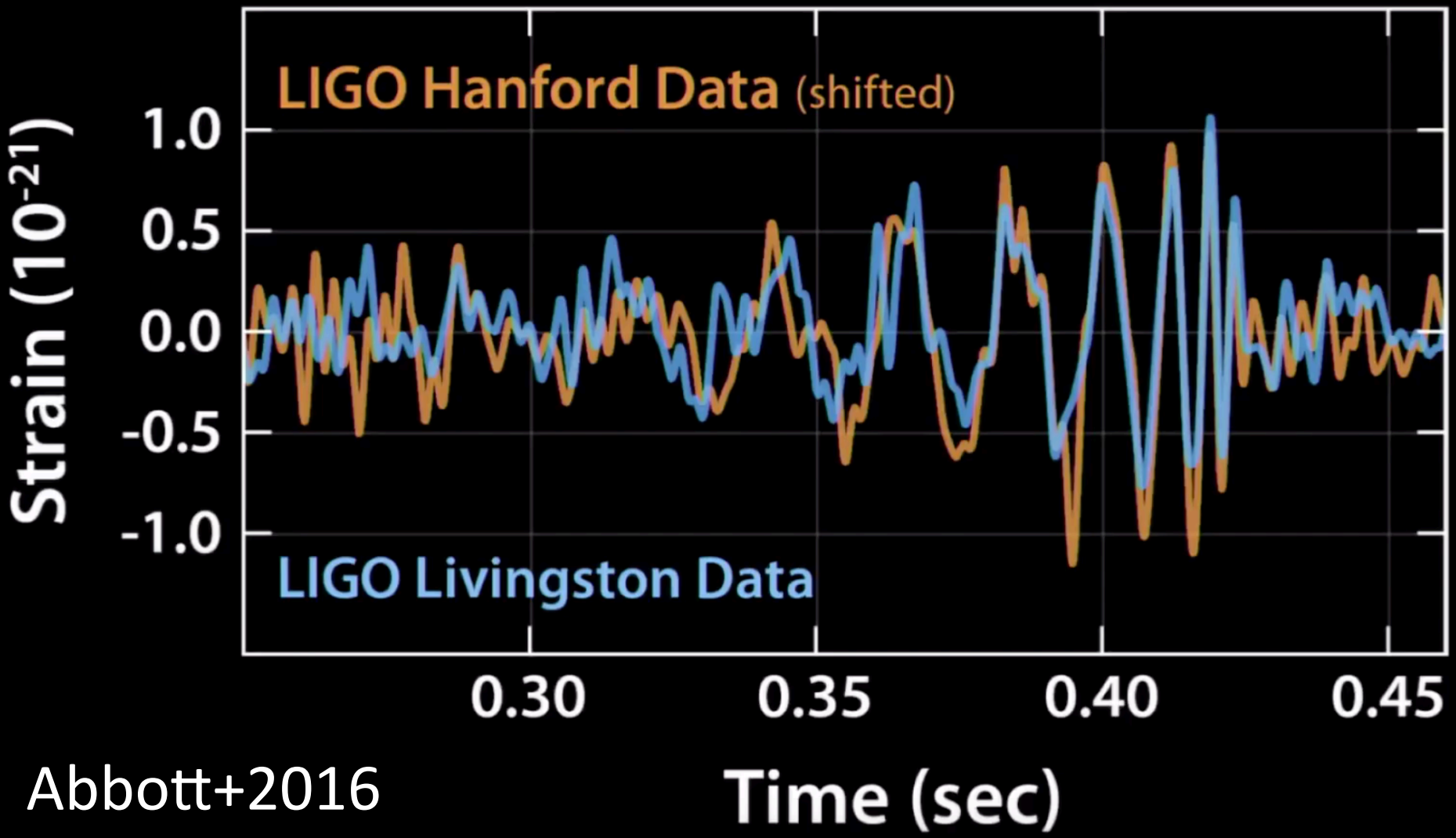


GC: feeding and feedback

- X-ray resolved inflowing gas
- > 99% of gas does not make it to center (Wang+2013)



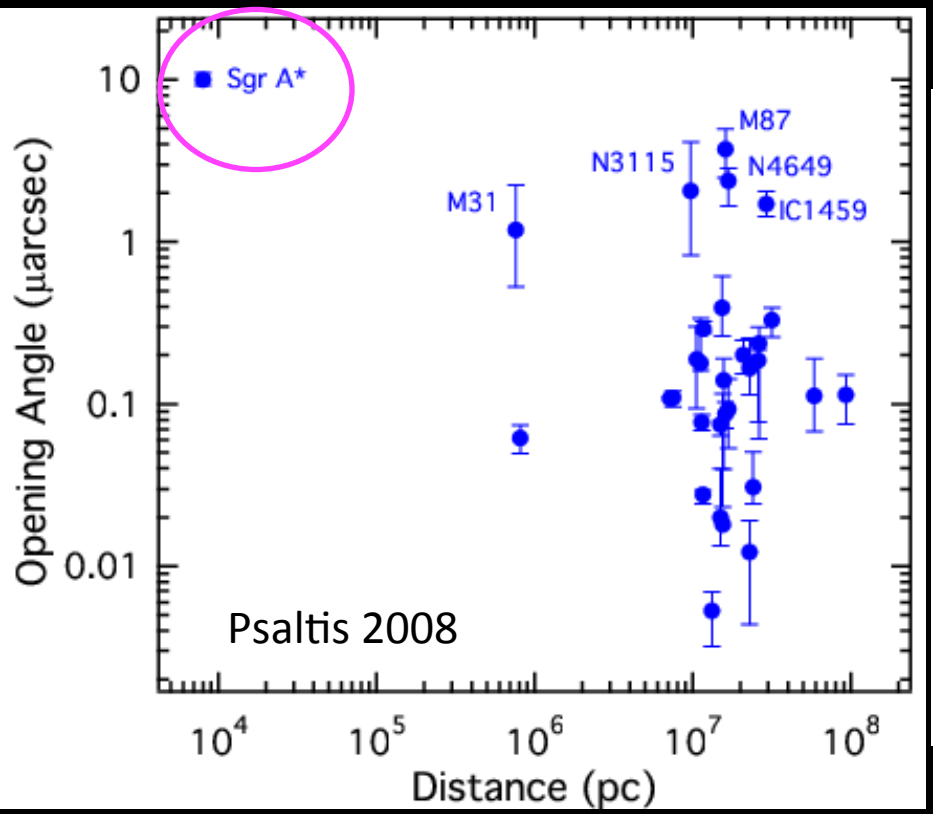
Physics frontiers of strong GR and dark matter

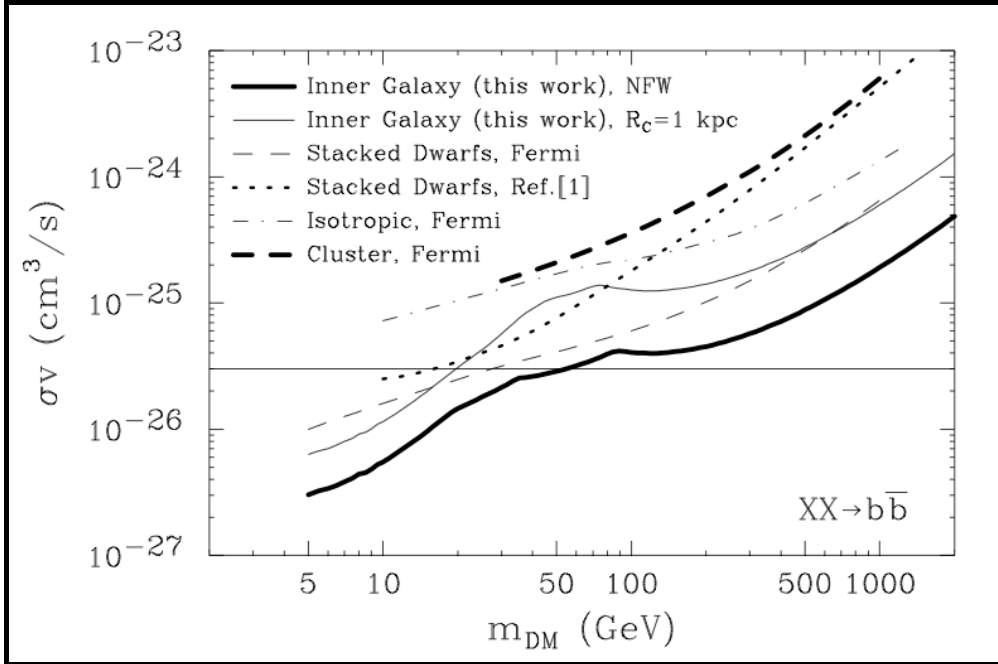


Abbott+2016

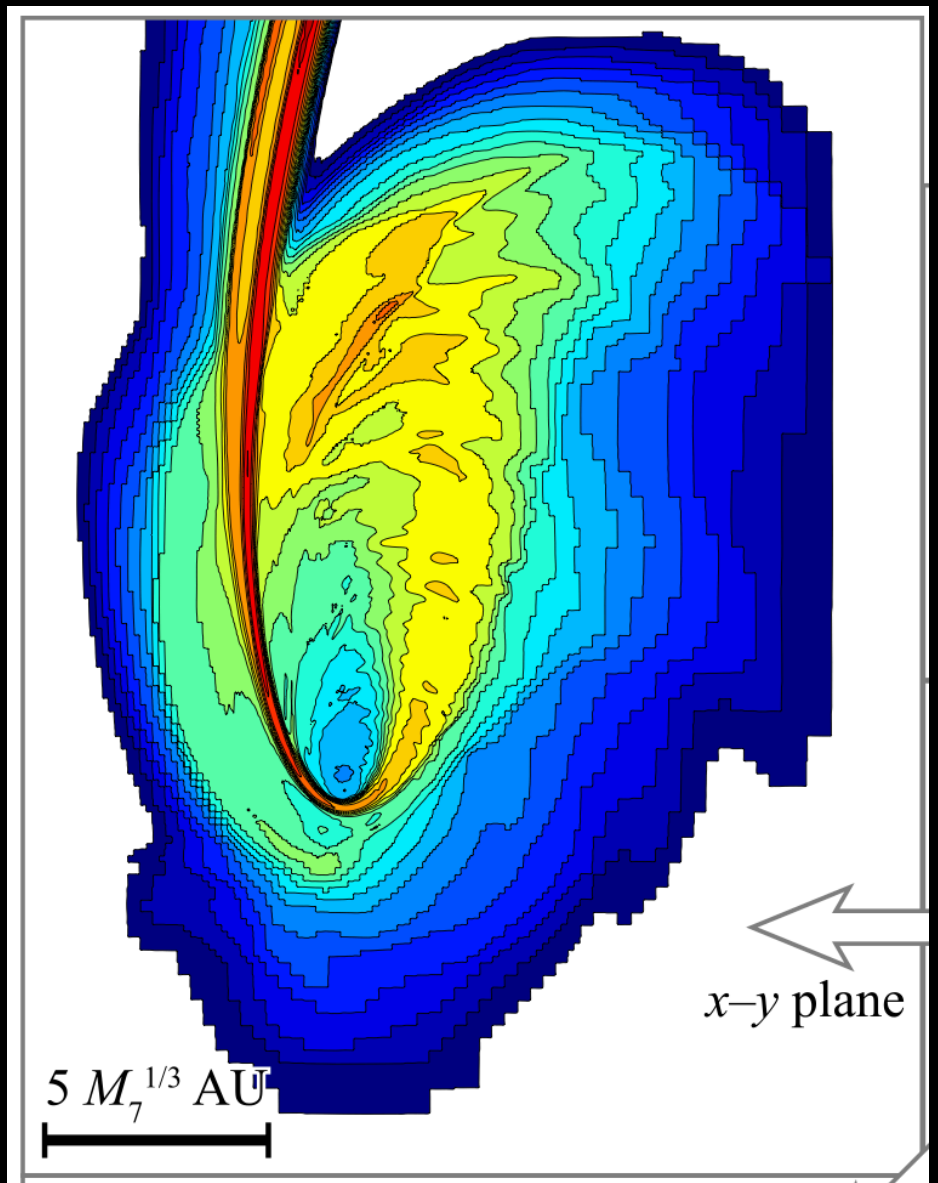
GC: physics laboratory

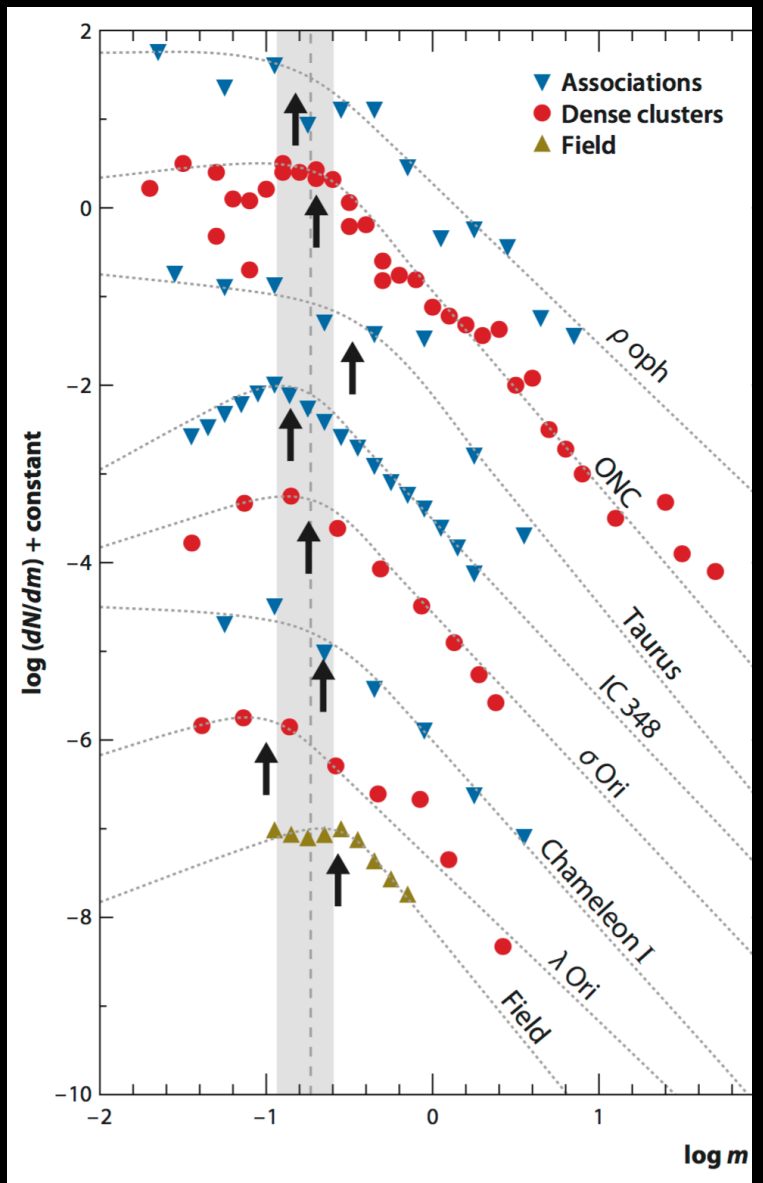
- Biggest black hole event horizon on the sky
- Limits on dark matter annihilation





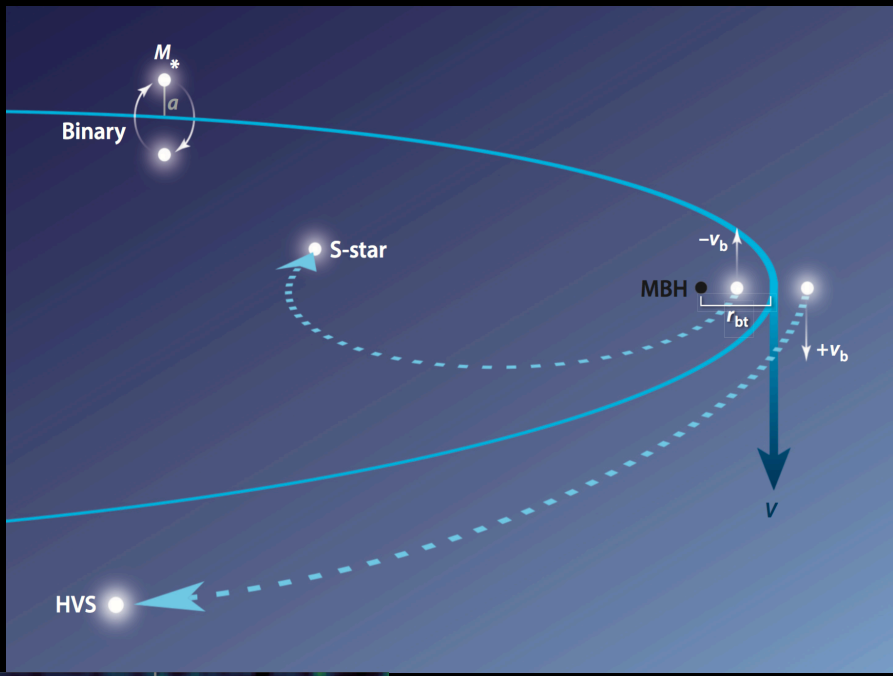
Stellar dynamics and IMF

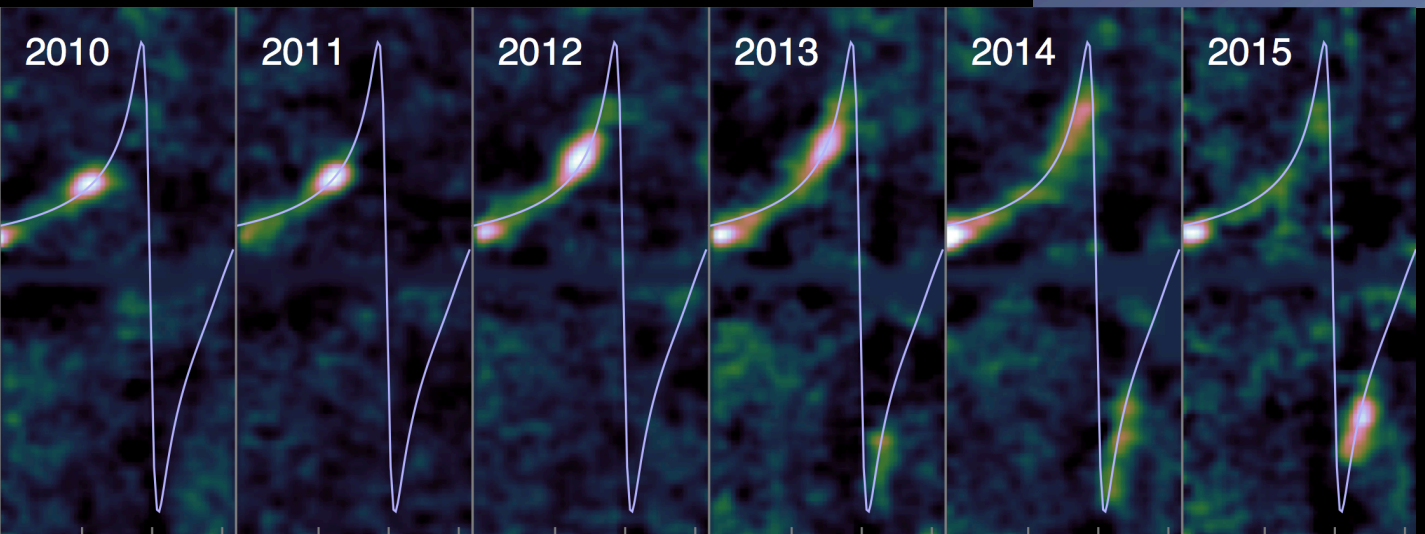




GC: stellar dynamics around a BH

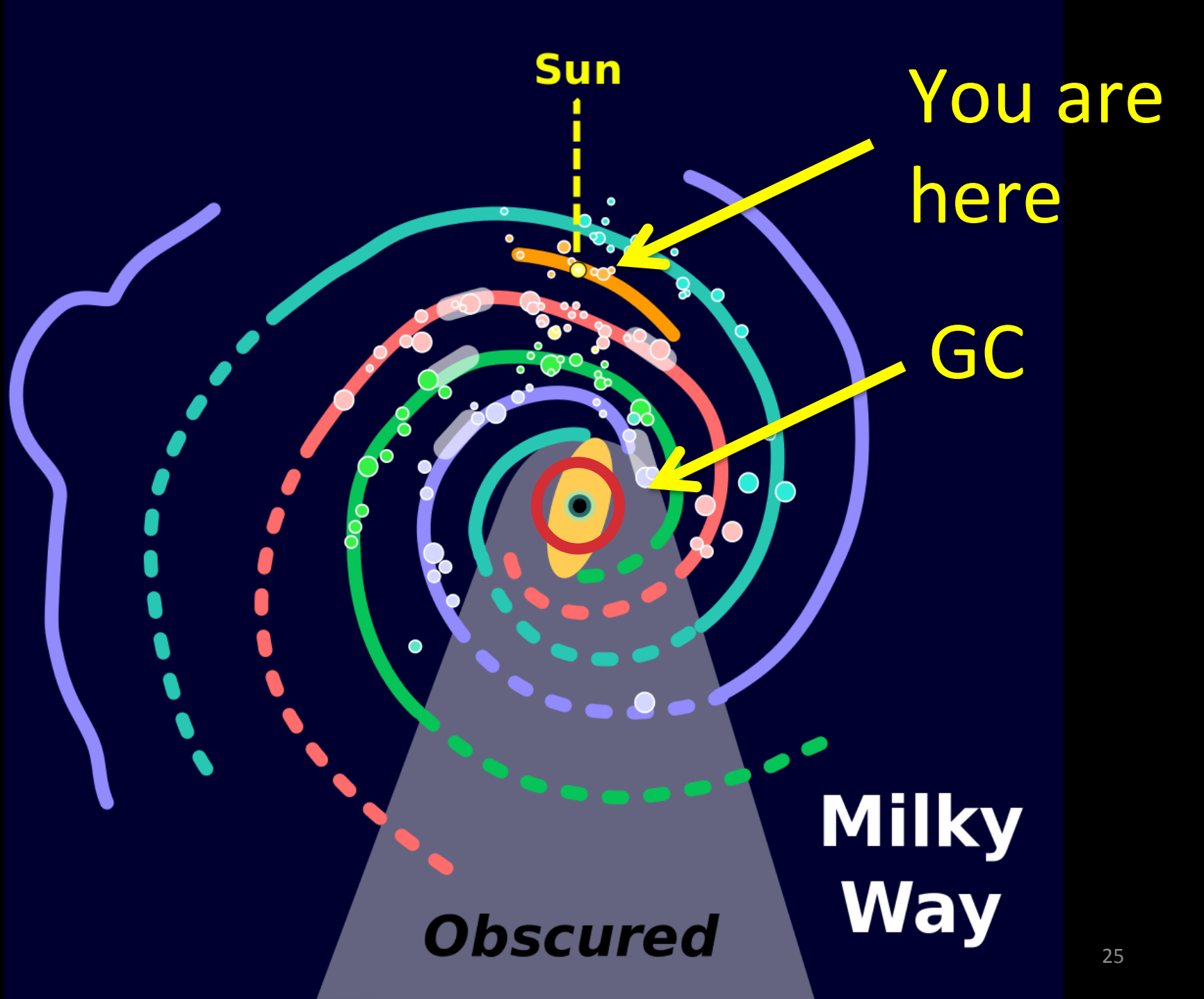
- IMF in extreme environment
- Tidal interactions between black hole and gas, stars





1. The Galactic center

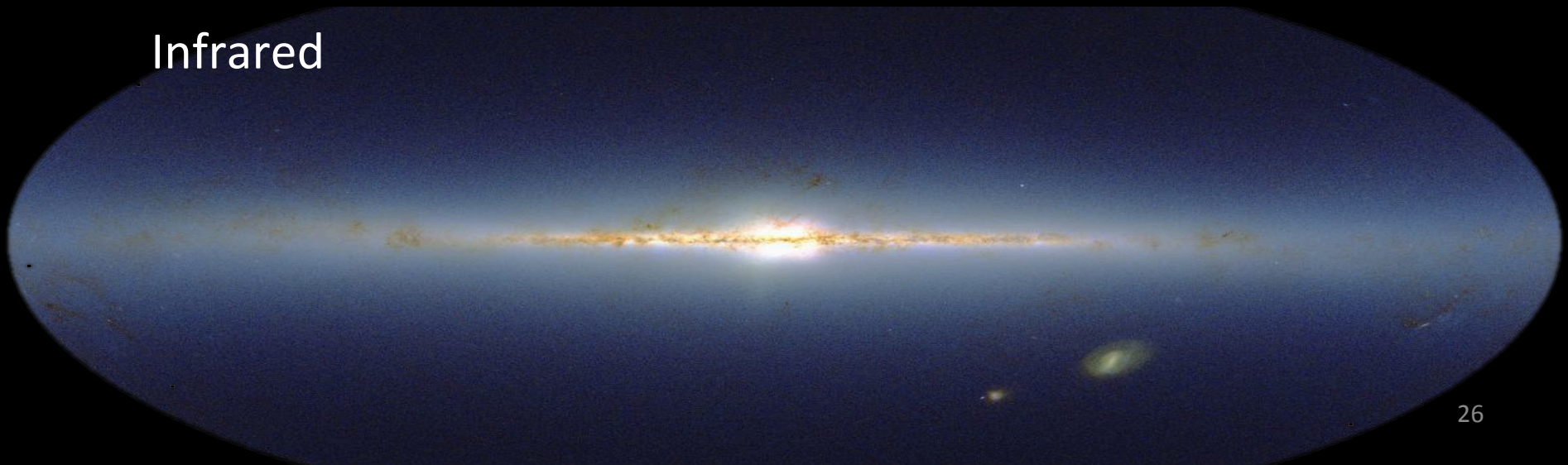
Evidence for a massive black hole


Sun
You are here
GC
Milky Way
Obscured

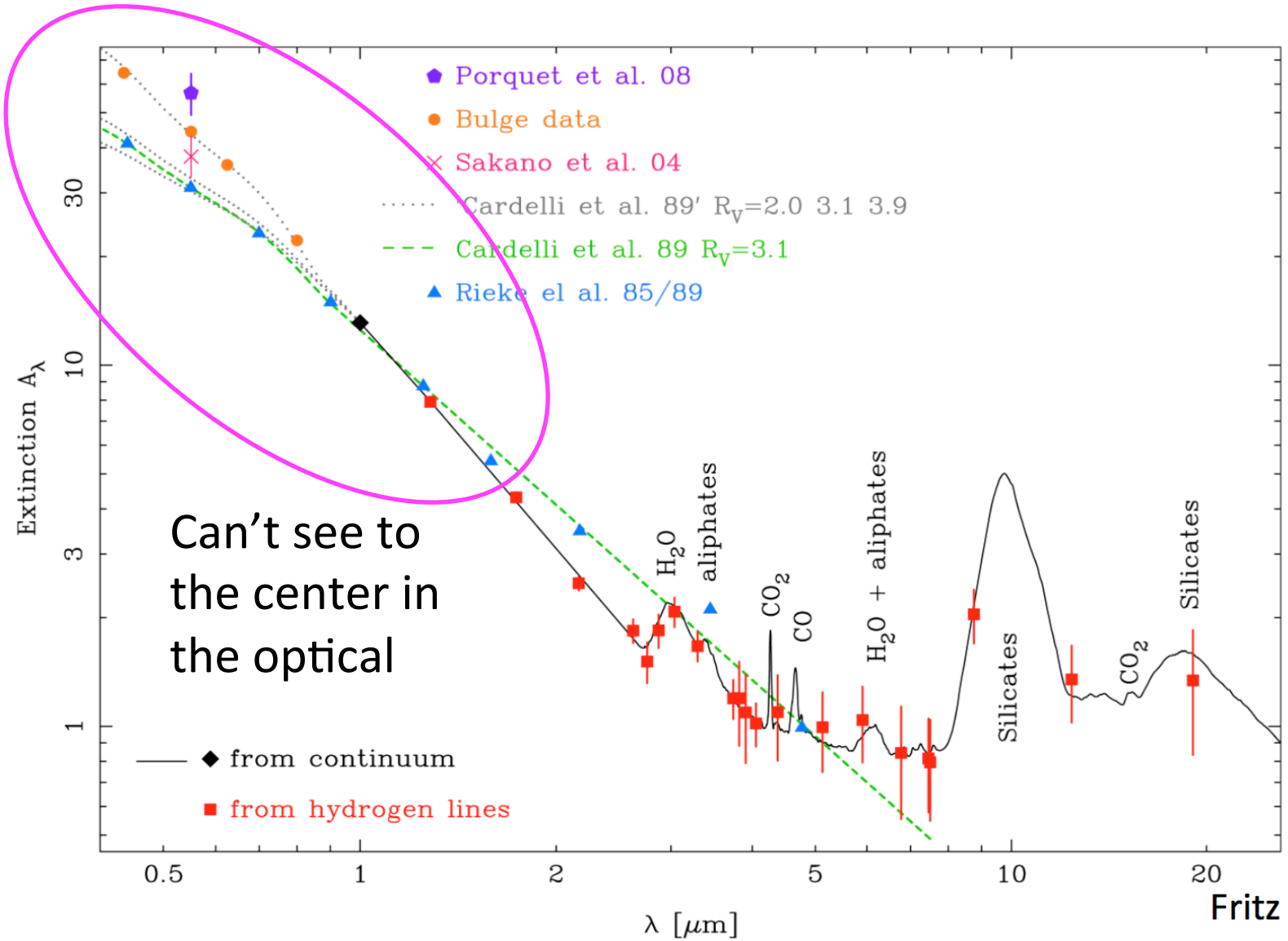
How to study the GC

Optical

Infrared

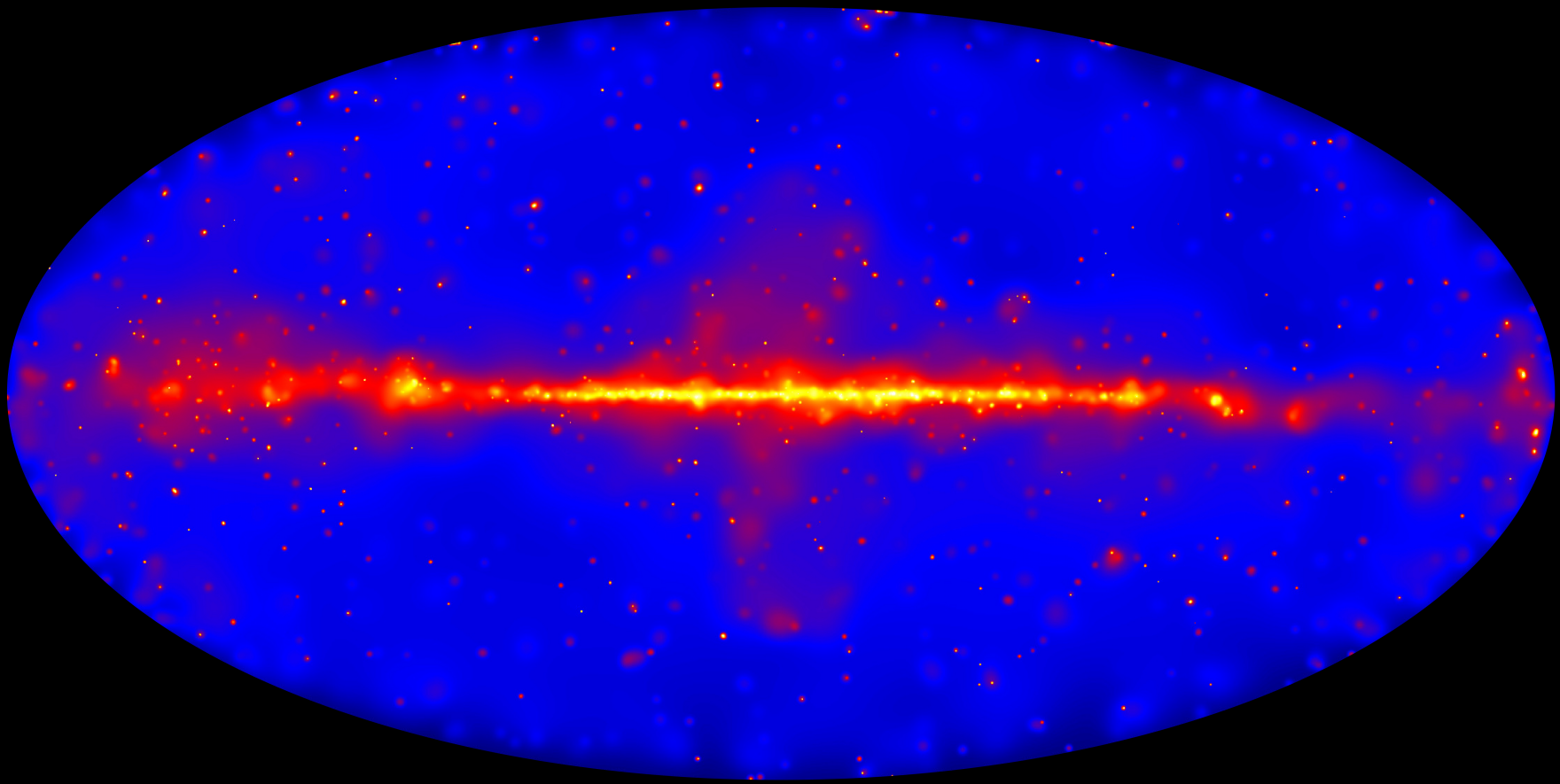


More than 30 magnitudes of extinction



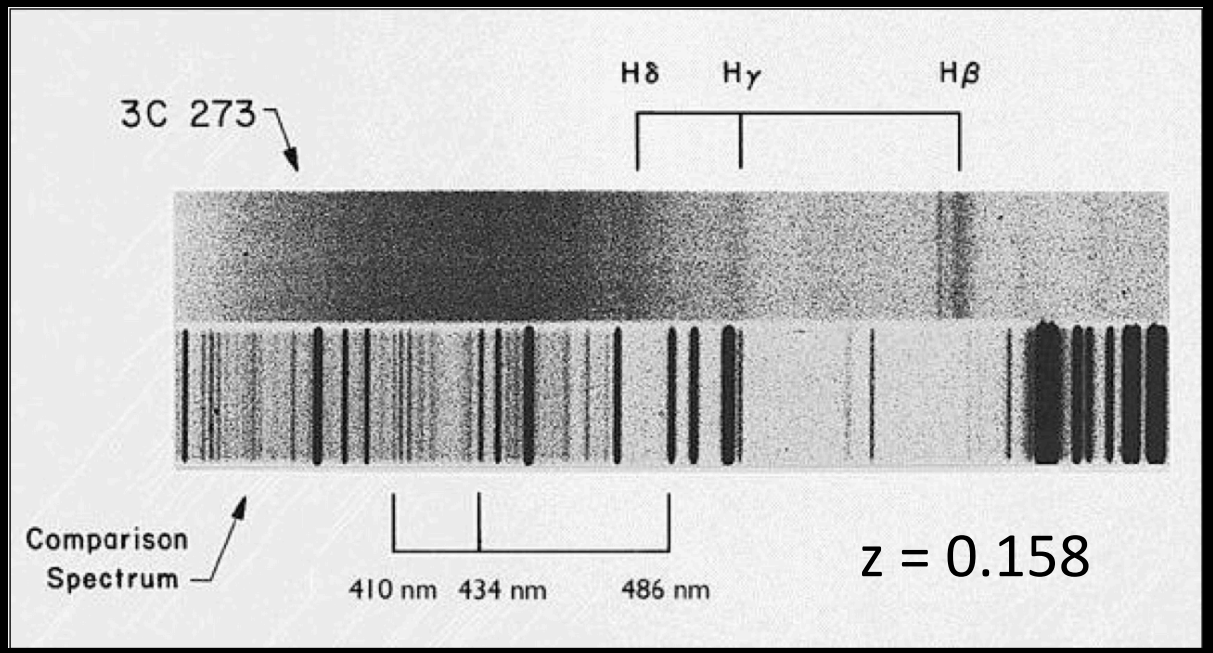
Fritz et al. 2011

The high energy Galaxy



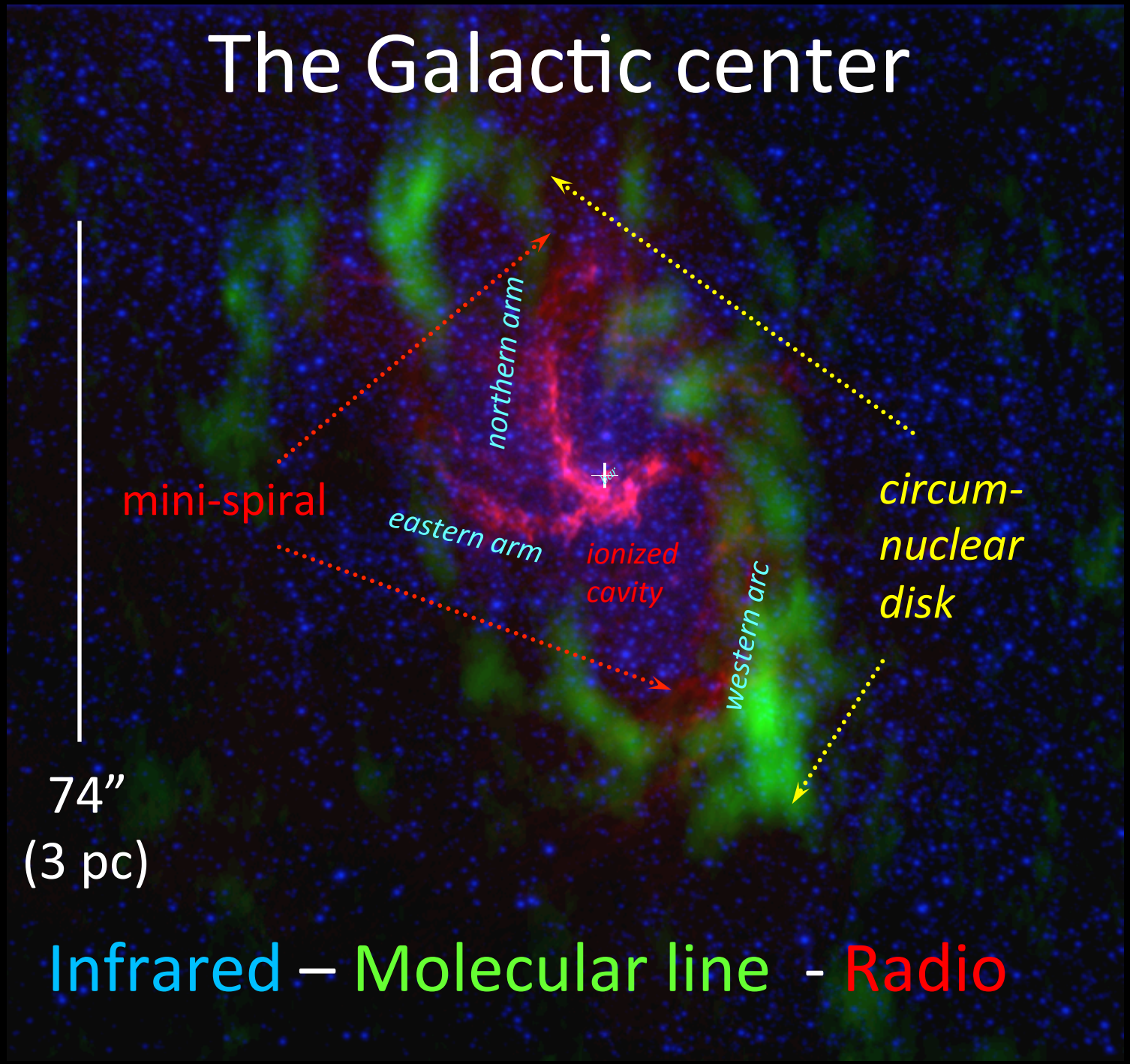
Quasi-stellar objects

- Schmidt 1963

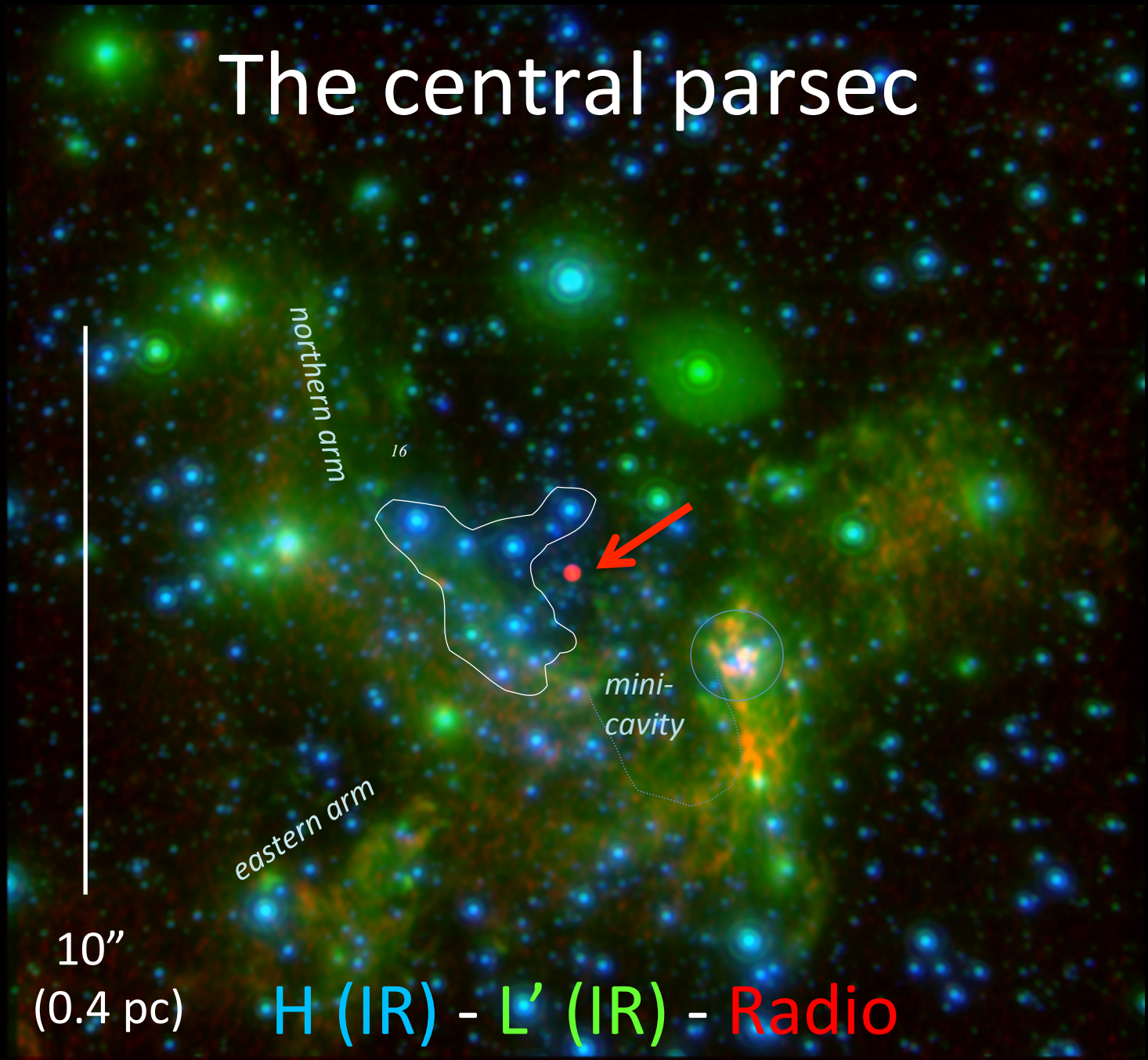


- Lynden-Bell 1969: quasars as huge black holes
- What about the center of our own Galaxy?

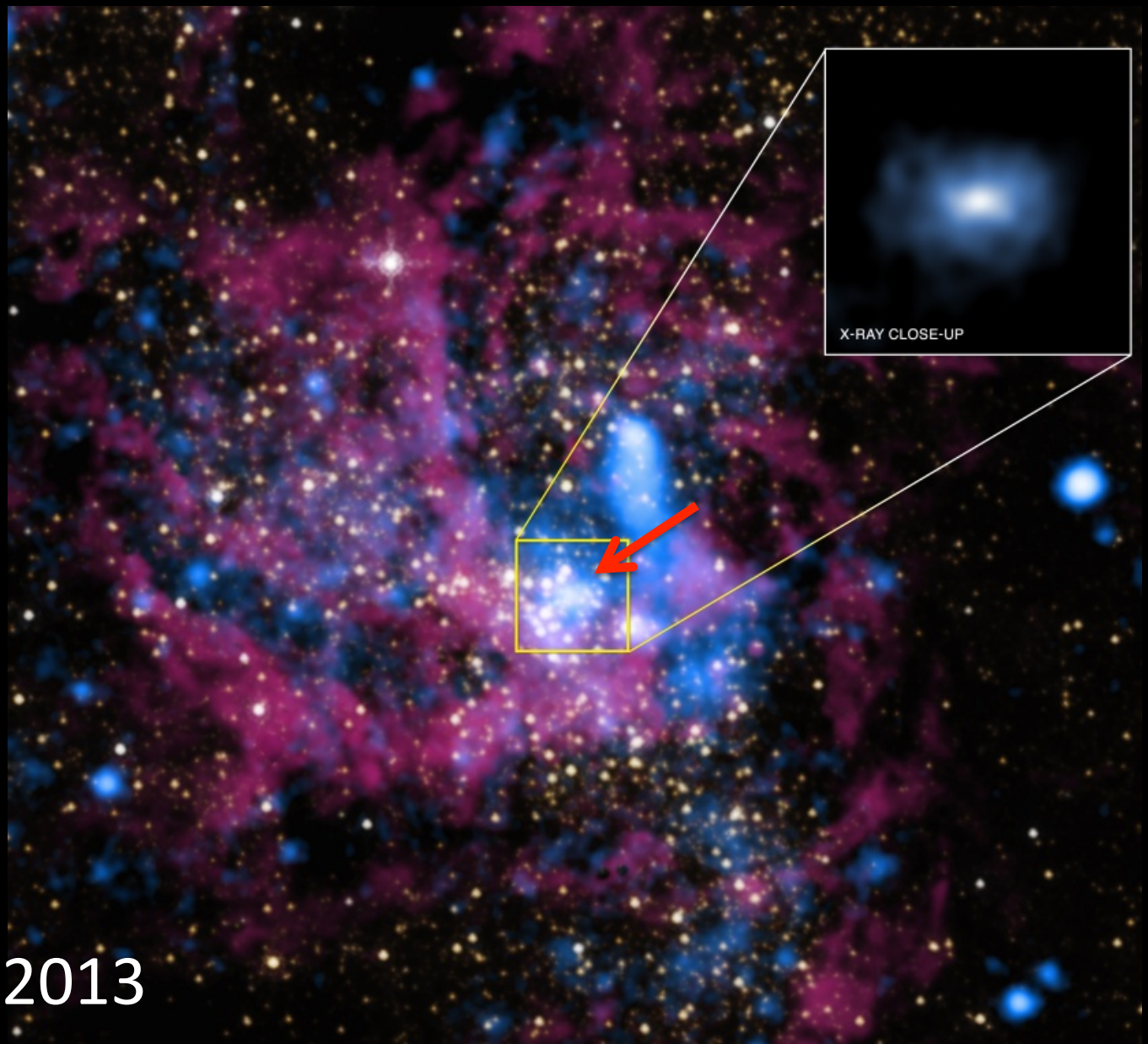
The Galactic center



The central parsec



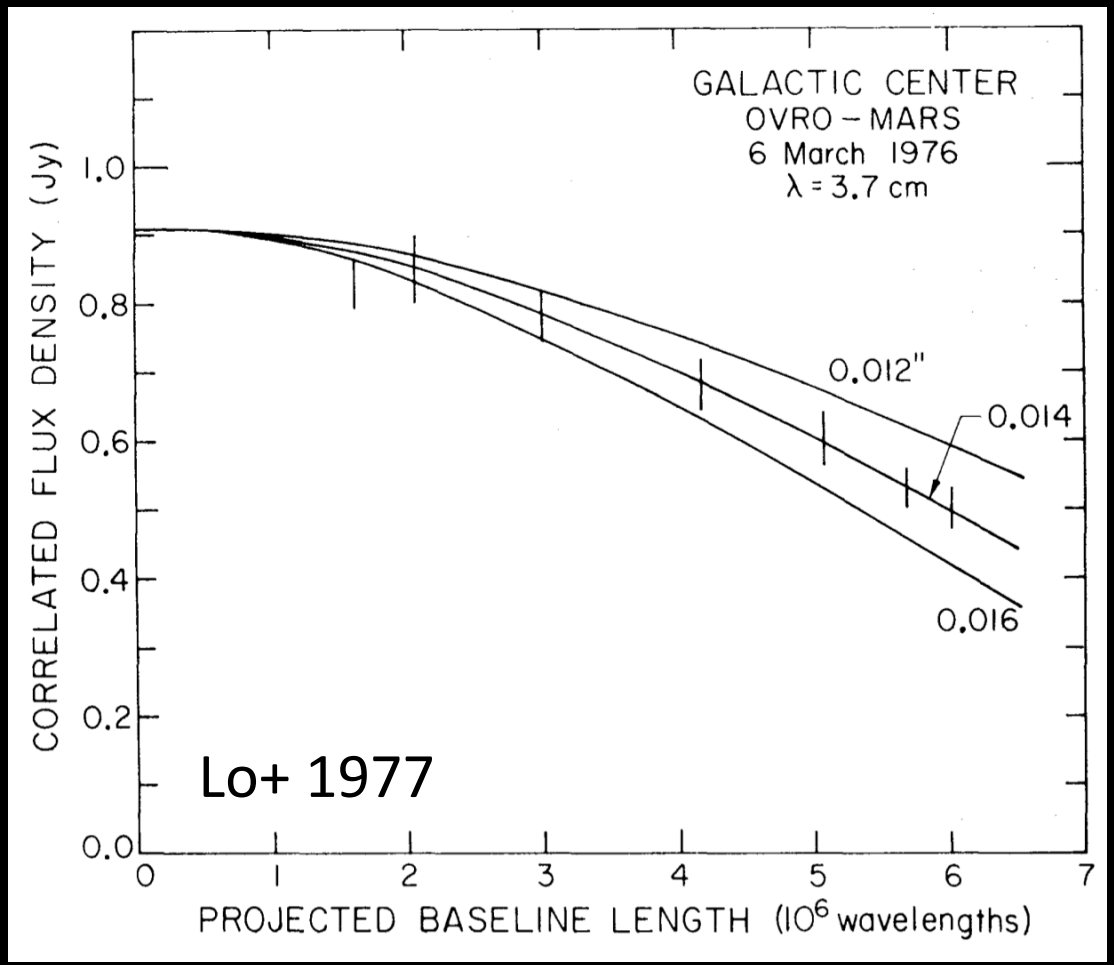
The central parsec in X-rays



Wang+2013

Sagittarius A*

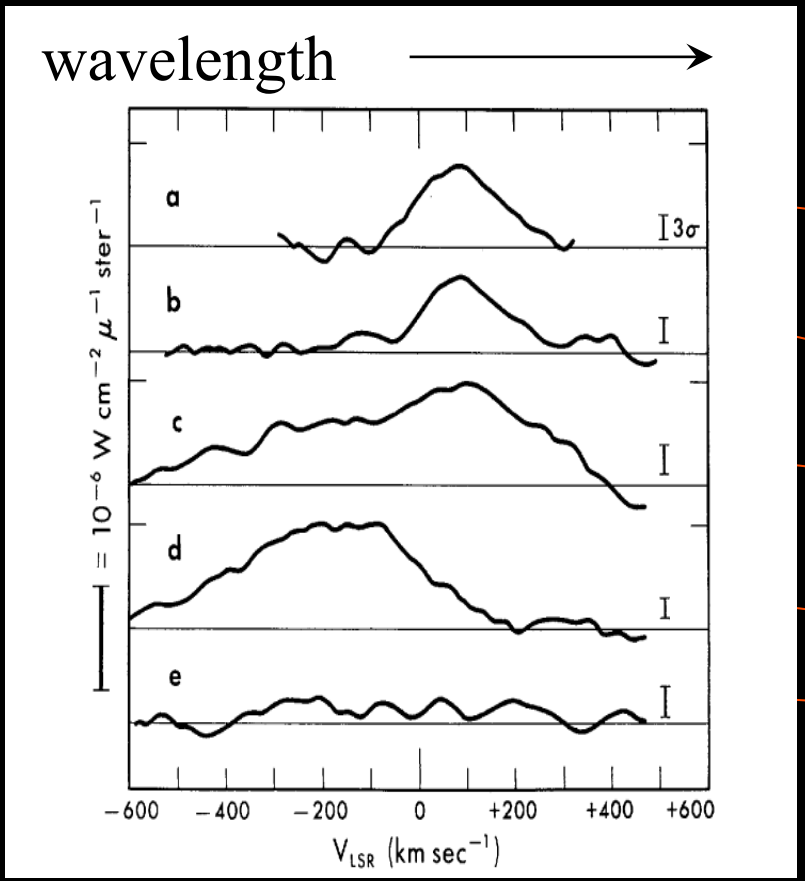
- A compact radio source at the very center
  (Balick & Brown 1974)

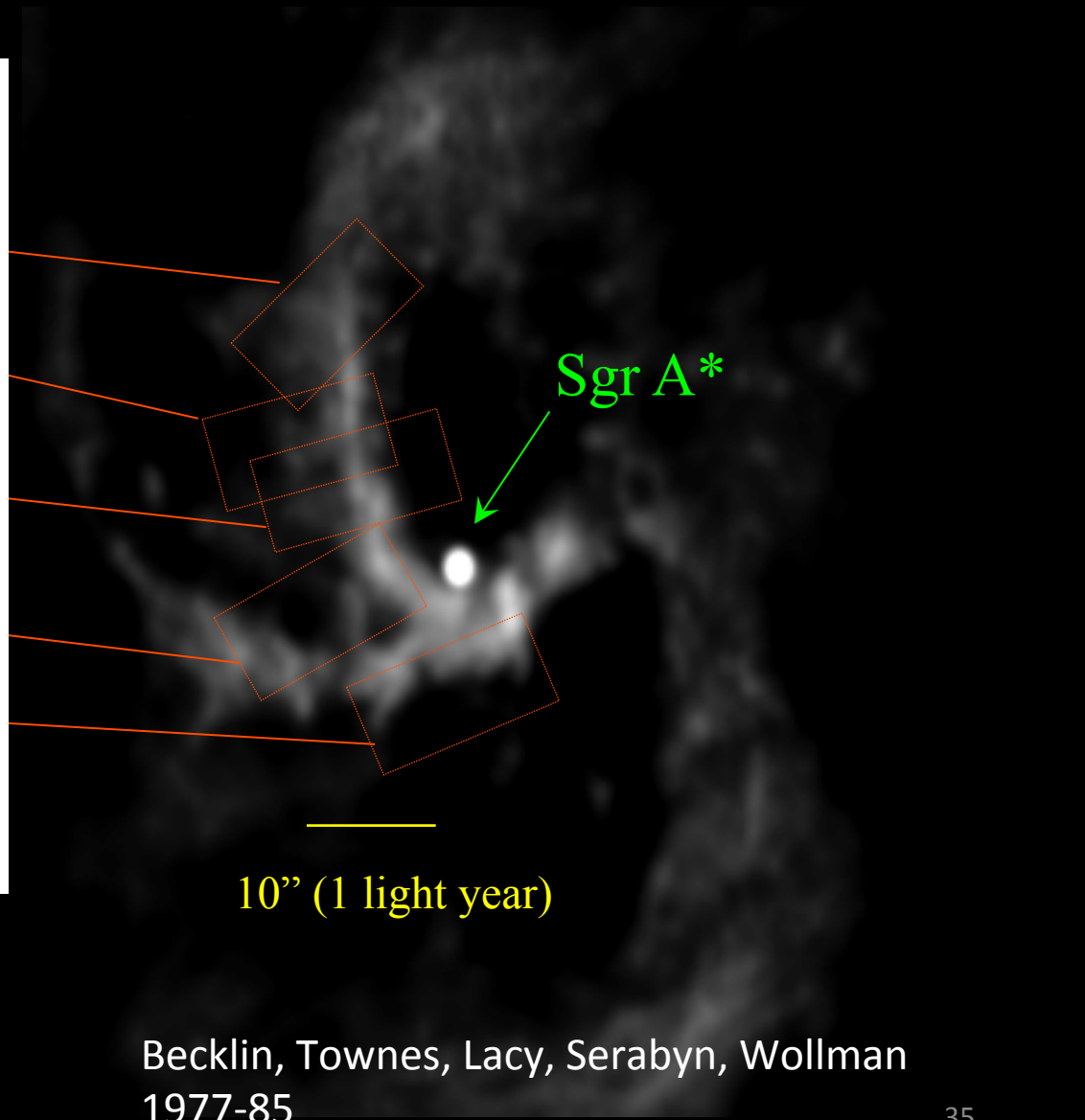


Black hole sphere of influence

- Measure: (x,y), v_z, (v_x, v_y)
- At what scale do we see effects of a black hole on stars?
- When $M_*(>r) = M_{BH}$:
  - $G M_{BH} / R > \sigma_*^2$
  - $R < GM_{BH} / \sigma_*^2$; $\sigma_* \sim 100$ km / s
    $R \sim 2$ pc ($M_{BH} / 4 \times 10^6 M_{sun}$)
- Need to go to central parsec to look!

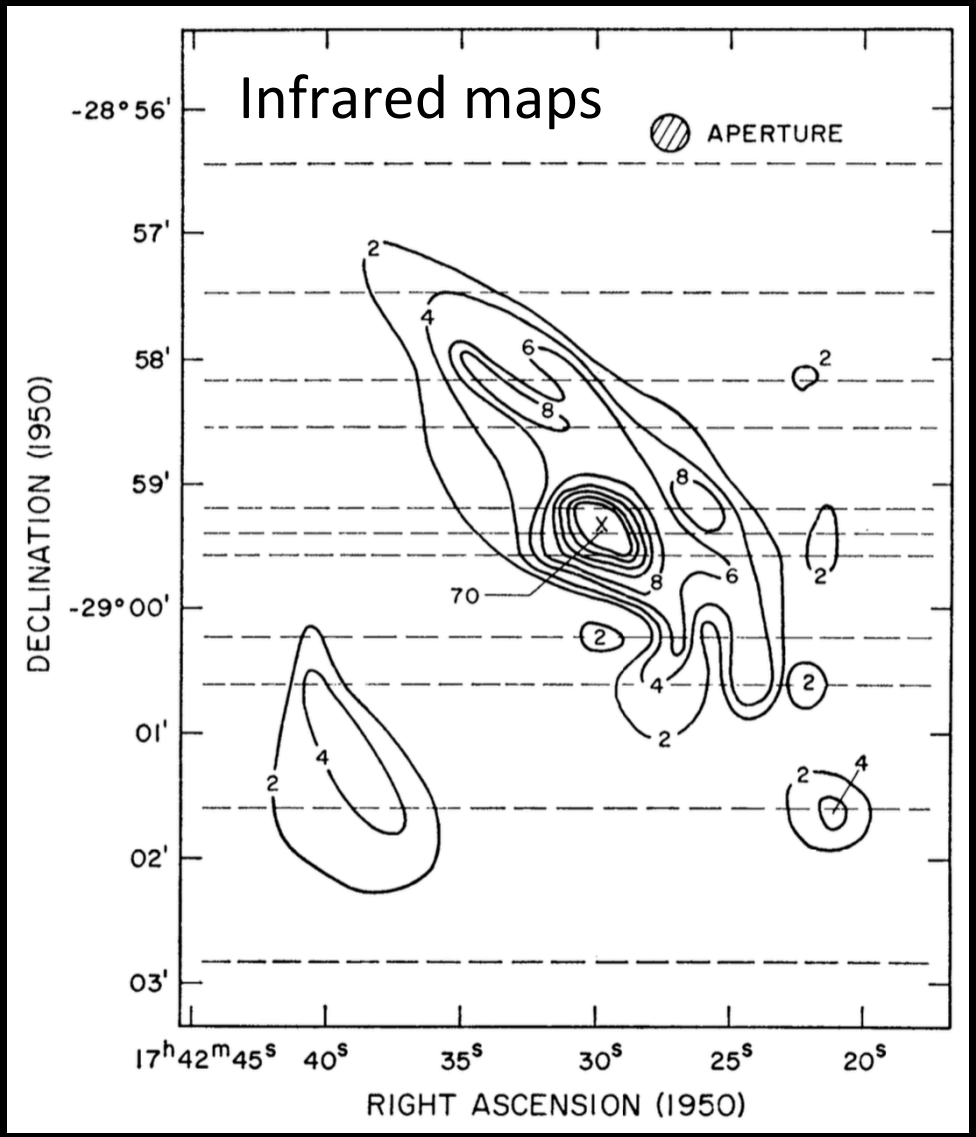
Large gas velocities around Sgr A*



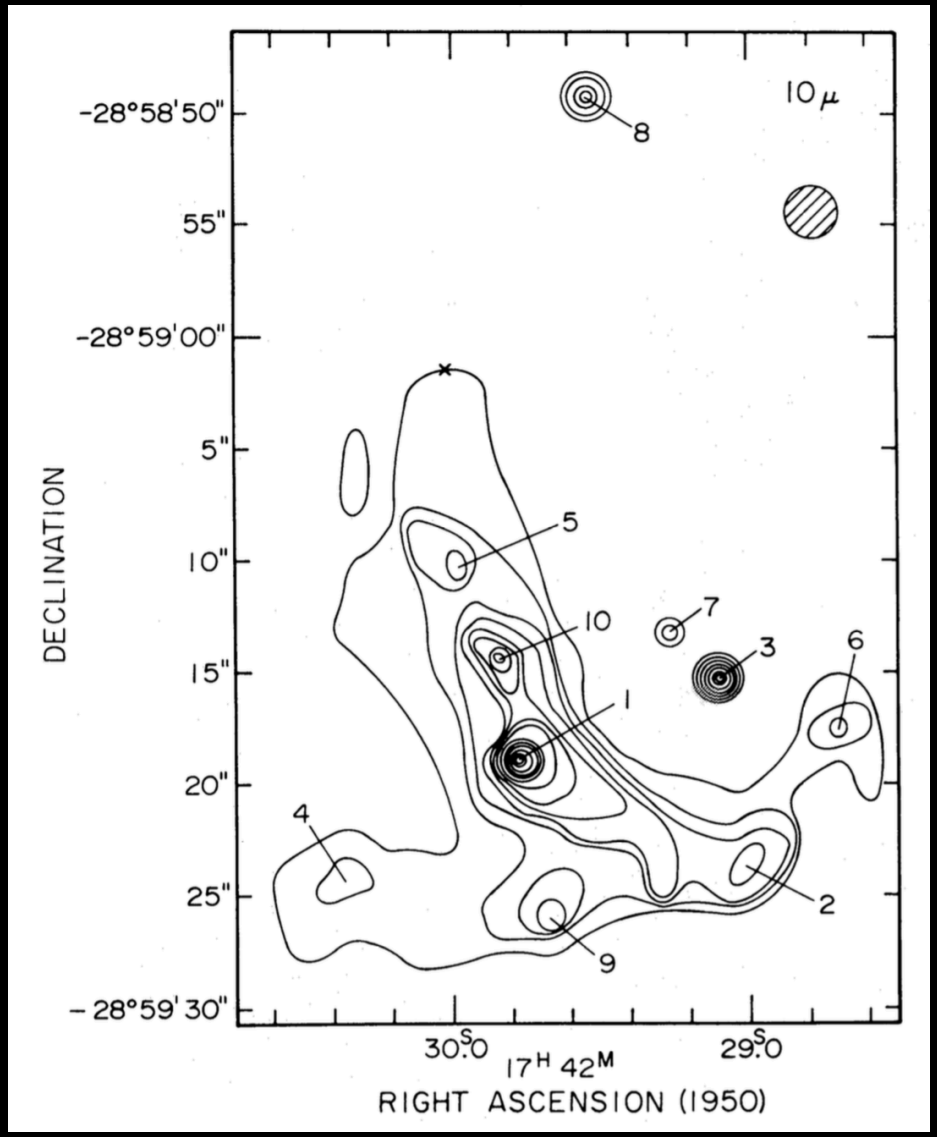


Becklin, Townes, Lacy, Serabyn, Wollman 1977-85

Stars in the Galactic center



Becklin & Neugebauer 1968

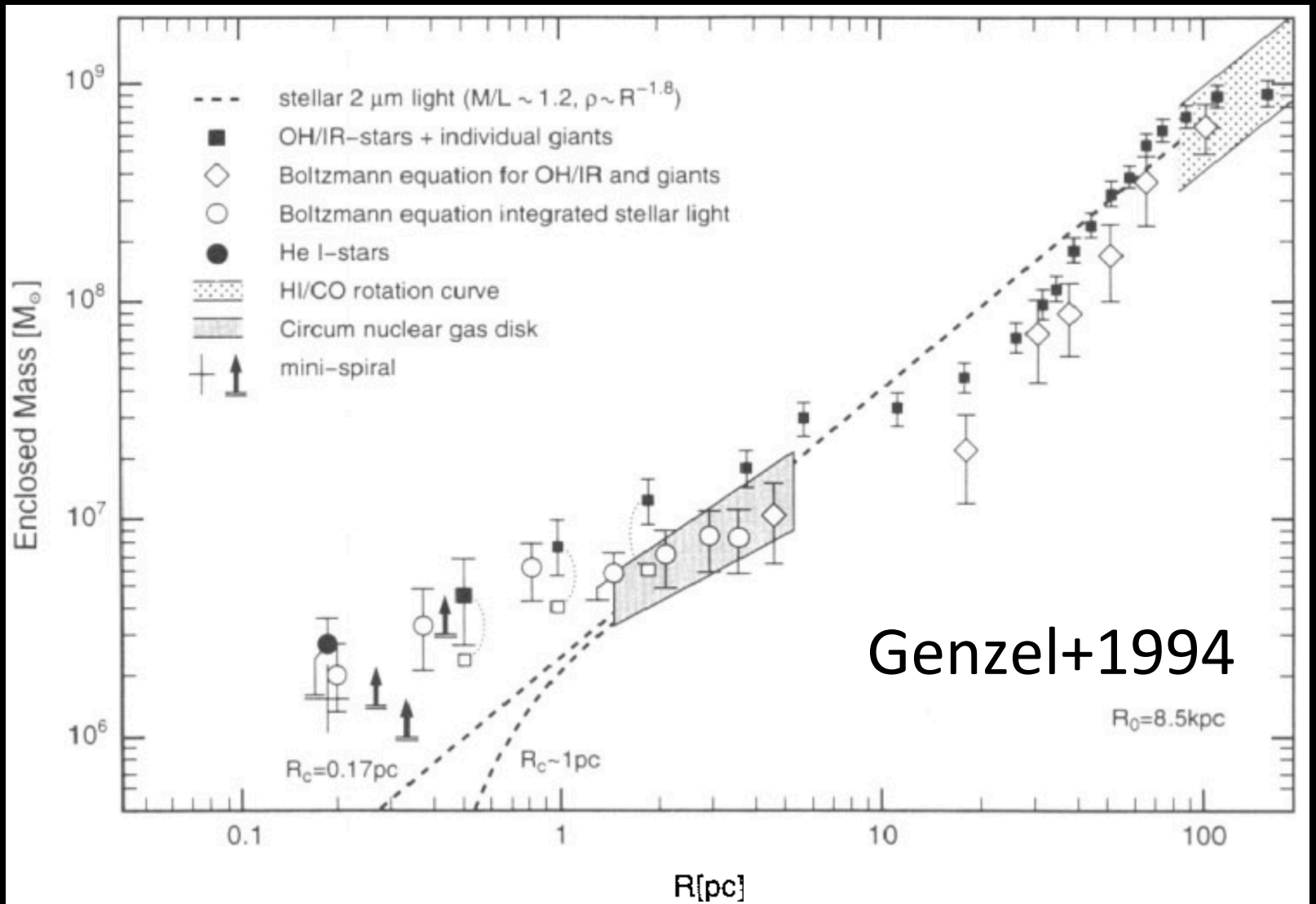


Becklin+1978

Galactic center nuclear star cluster

ESO/R. Schödel

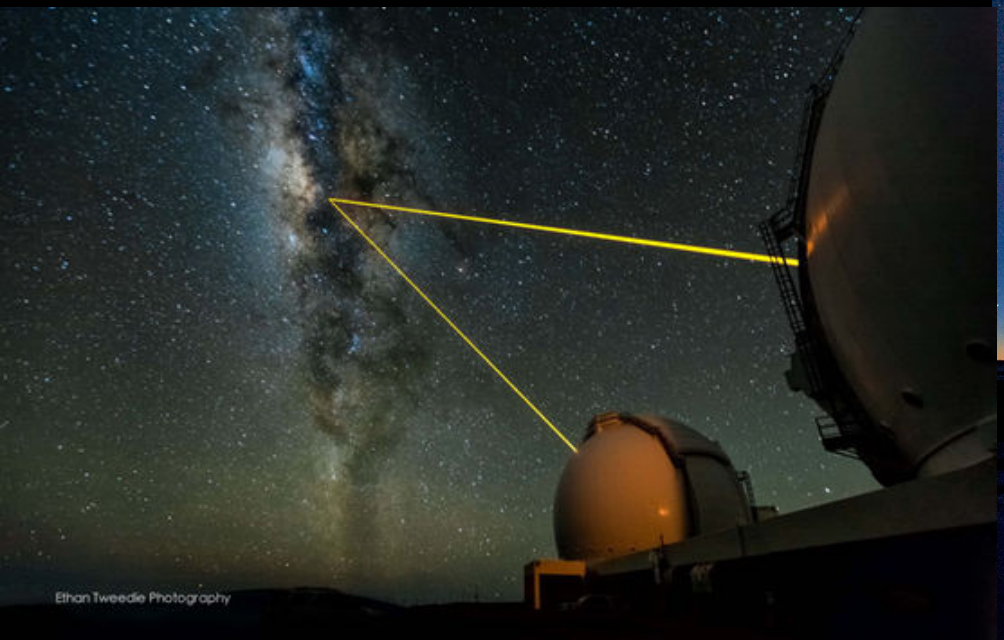
A concentrated dark mass measured from gas and stars



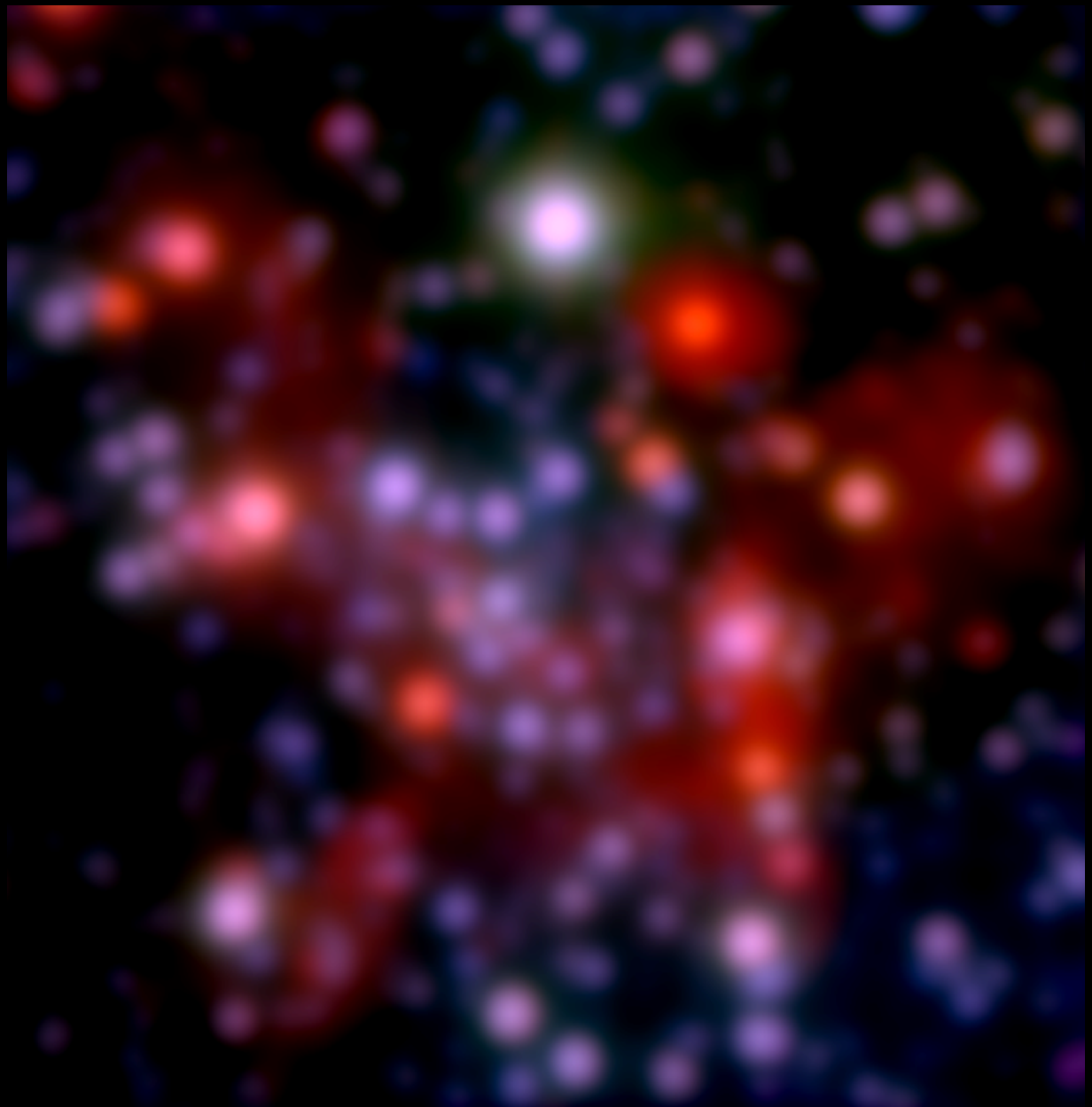
Big telescopes and adaptive optics

- Diffraction limit: $\vartheta_{min} \sim \lambda/D$
- 8-10m telescopes can resolve ~ 50 mas: in GC ~ 2 mpc!

Keck



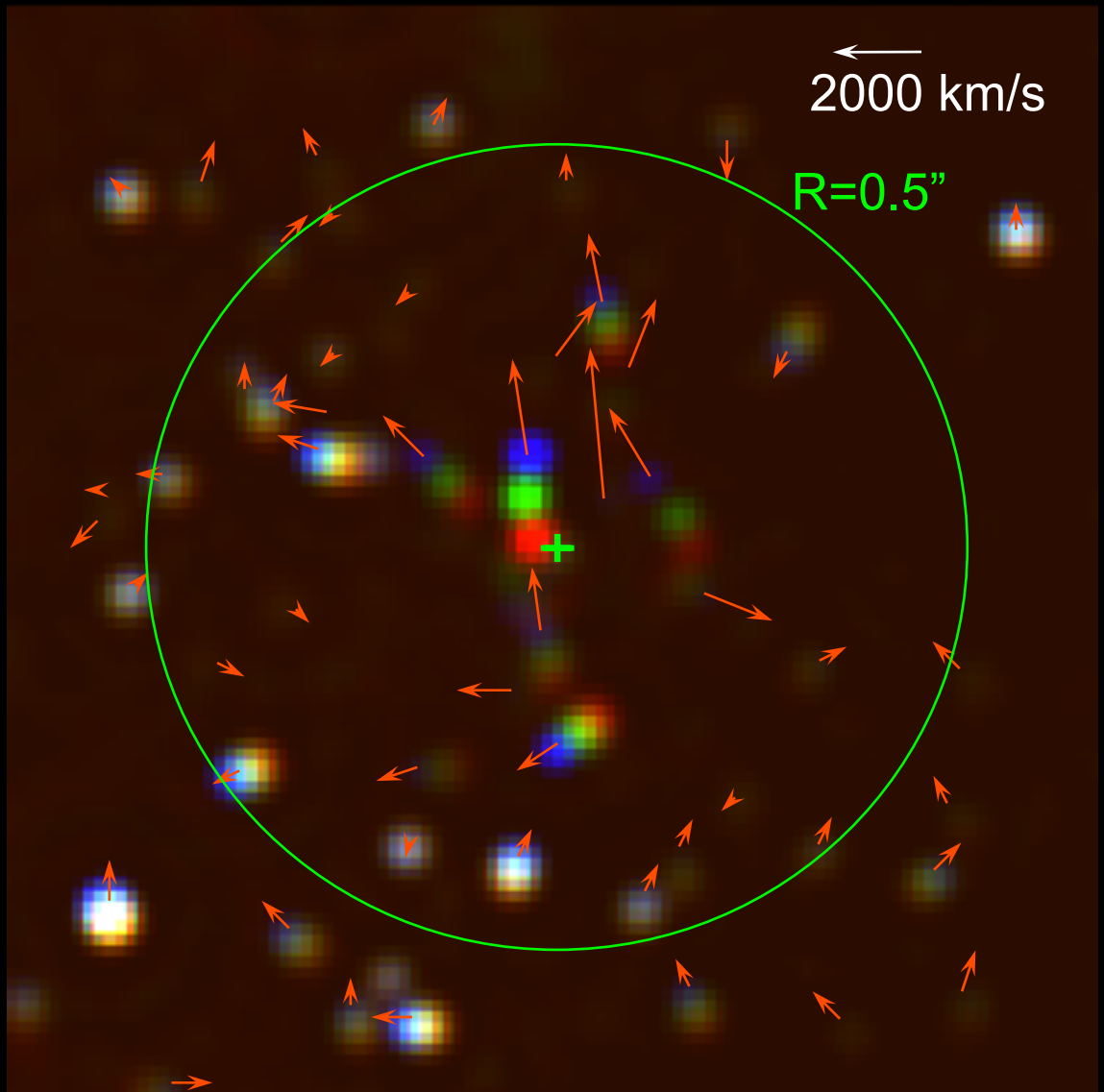
without adaptive optics



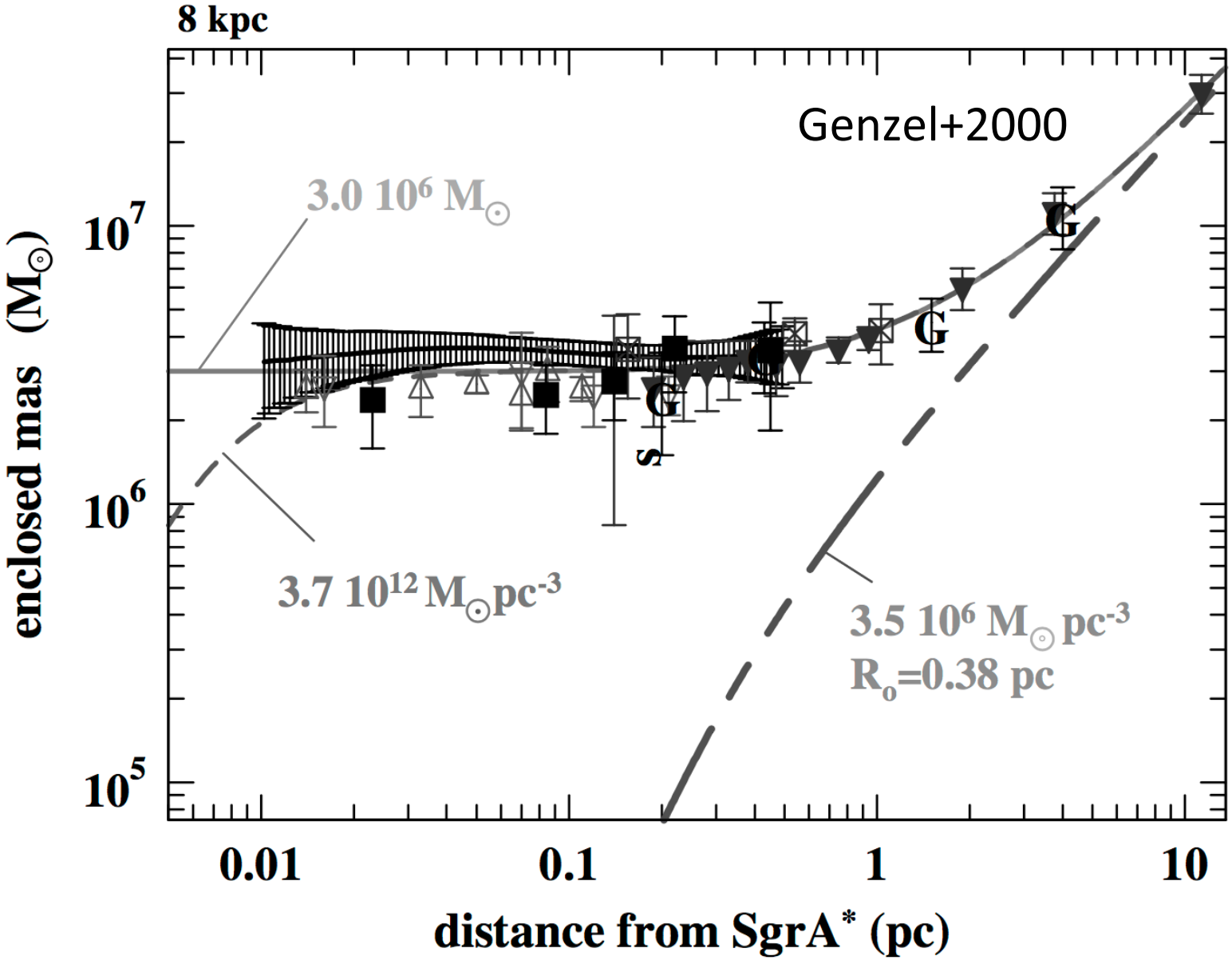
Motions of stars around Sgr A*

Eckart & Genzel 1996, 1997, Ghez et al. 1998

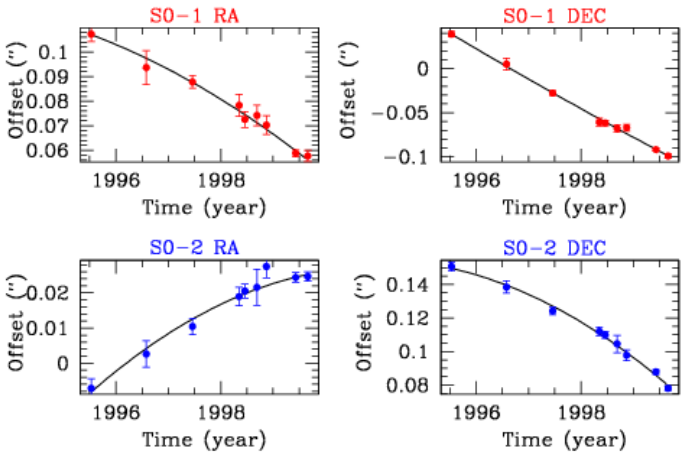
The S stars

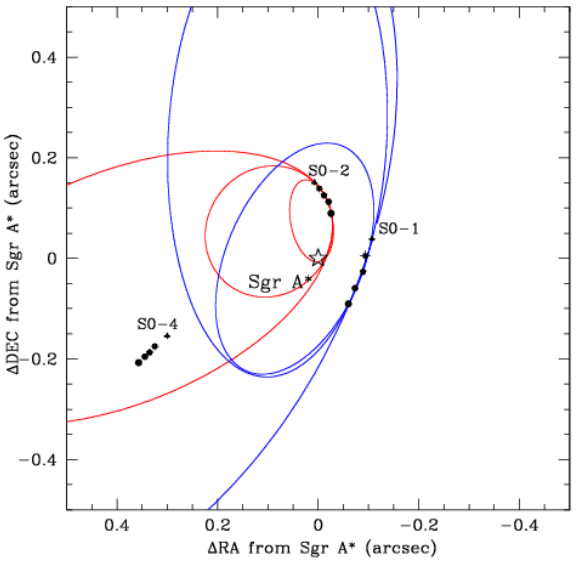


Enclosed mass from proper motions

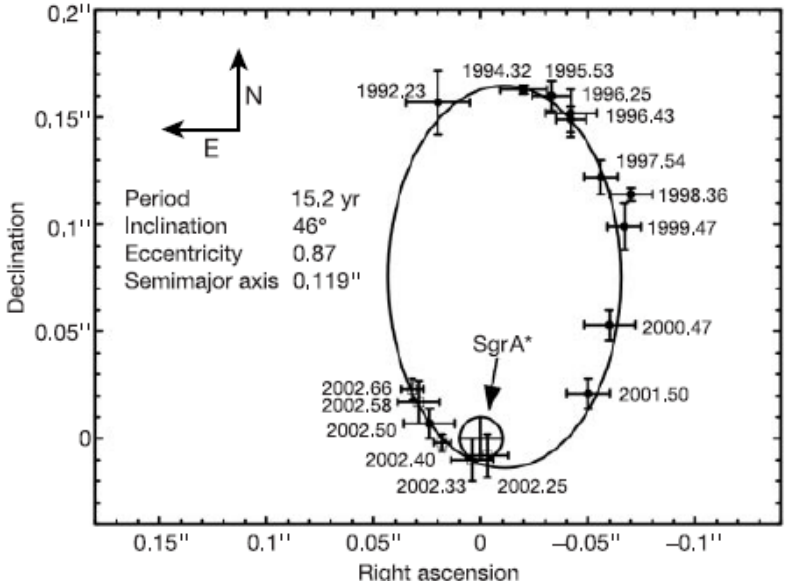


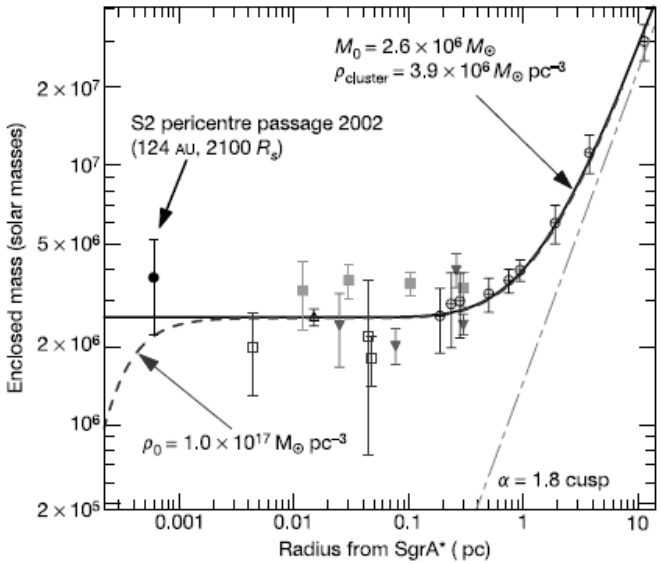
Accelerations and the first orbit





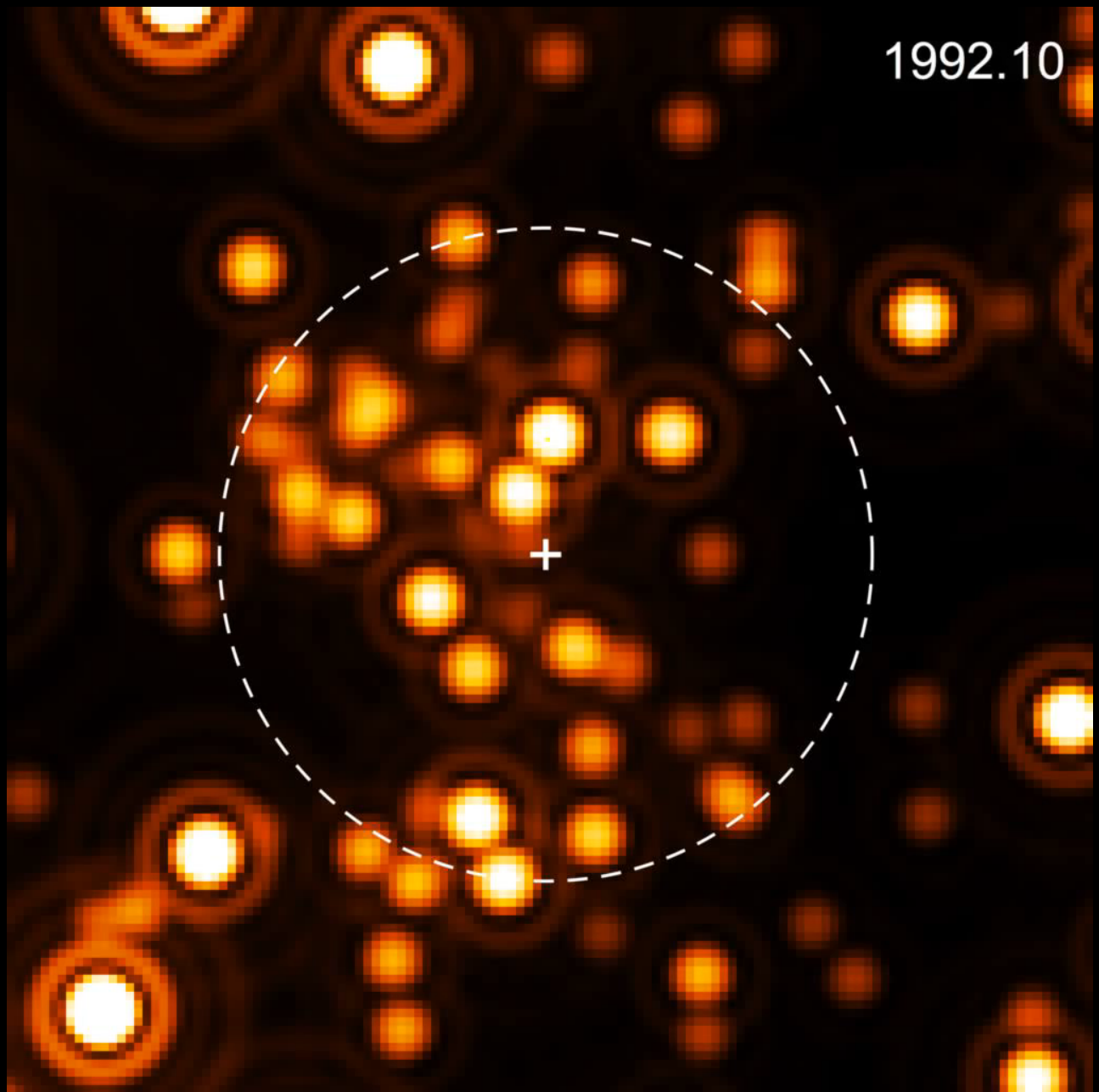
Ghez et al. 2000 (Nature): first accelerations

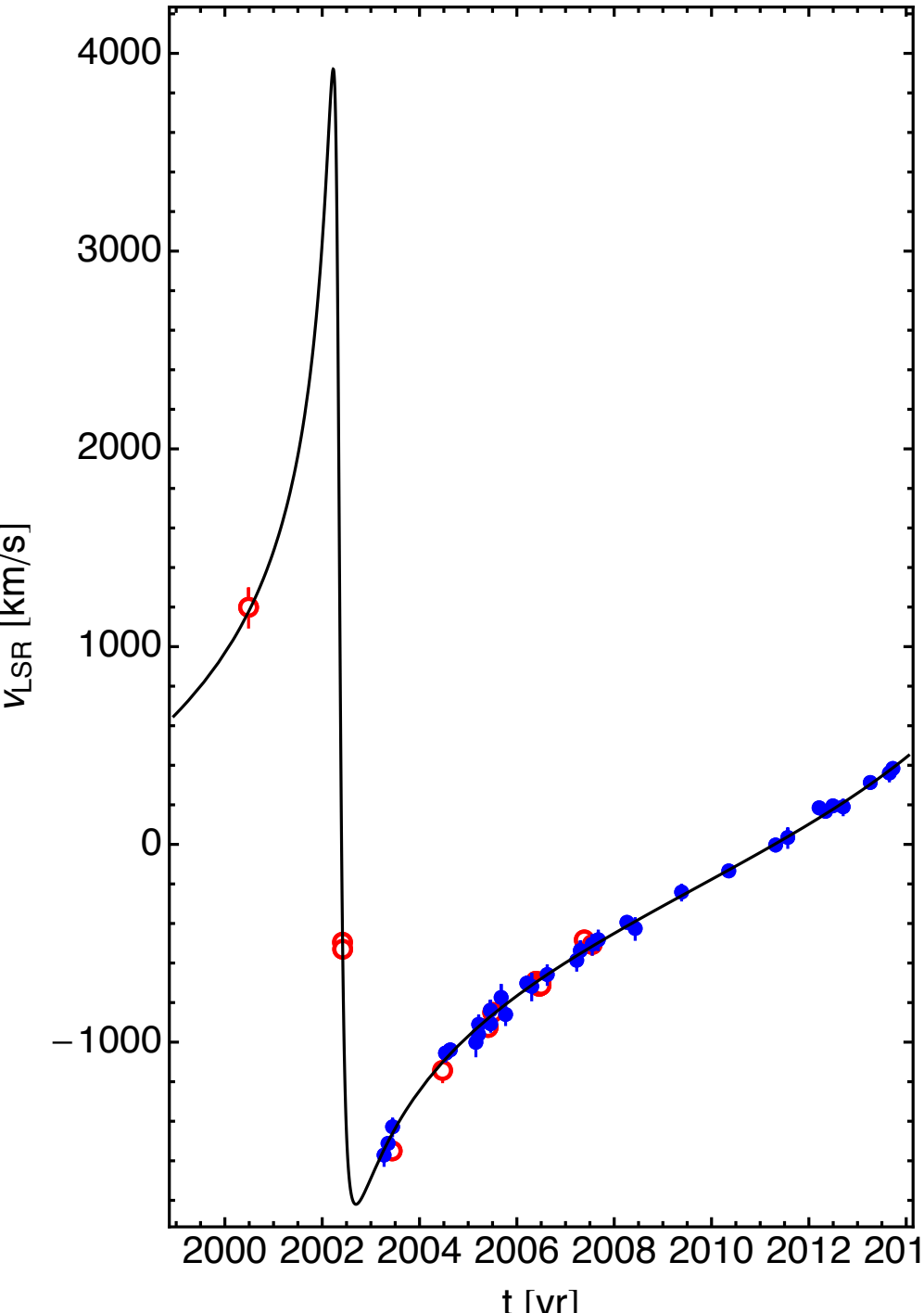




Schoedel 2002 (Nature): first orbit

The S stars 20 years later





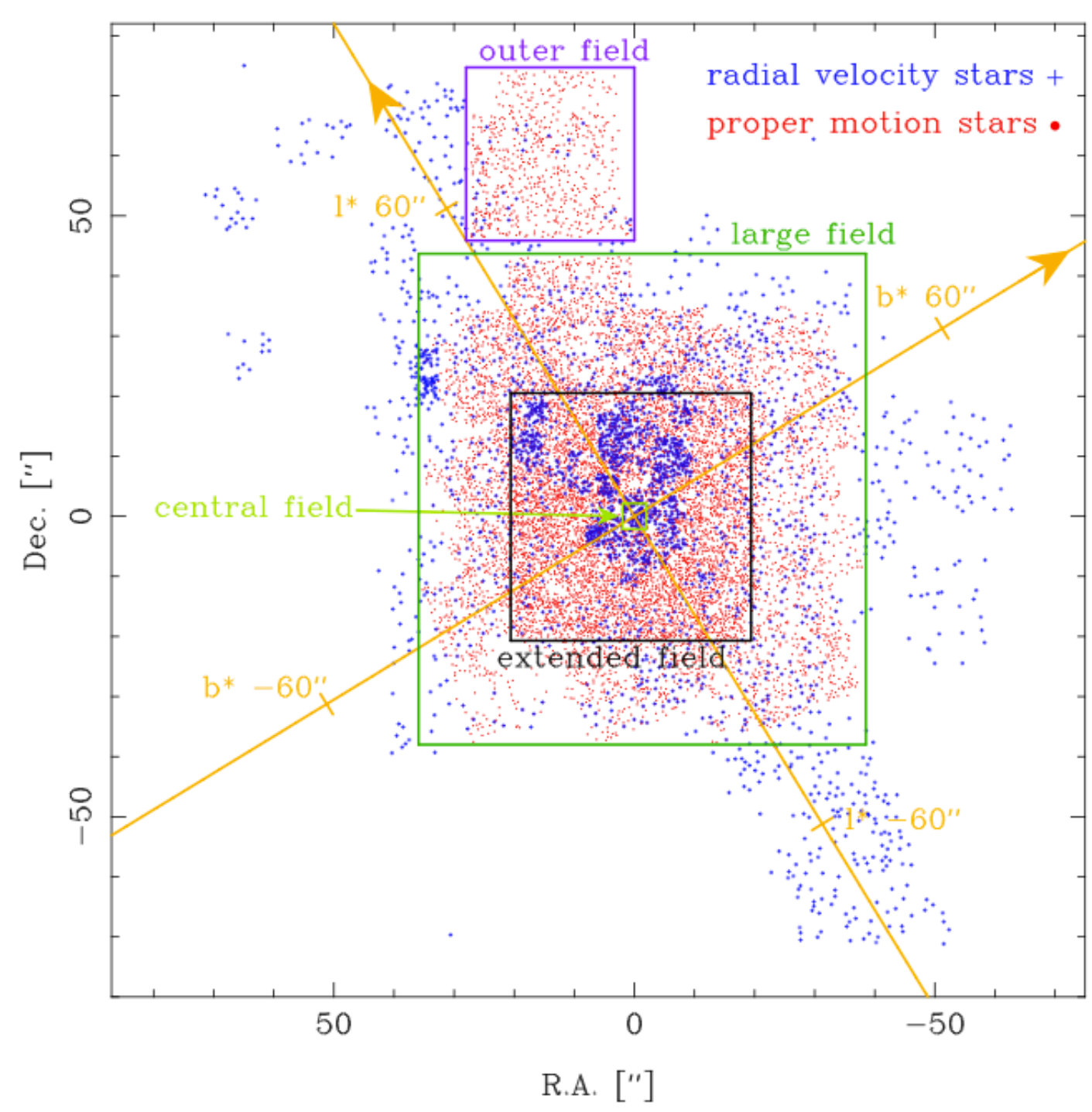
S2: the showcase star

VLT Keck

(Gillessen et al. 2009ab, Ghez et al. 2008, newer data)

- period: 15.9 years
- semi major axis: 125 mas
- eccentricity 0.88

- $M = 4.30 \pm 0.06 \pm 0.35 \times 10^6$ M,
- $R_0 = 8.28 \pm 0.15 \pm 0.30$ kpc



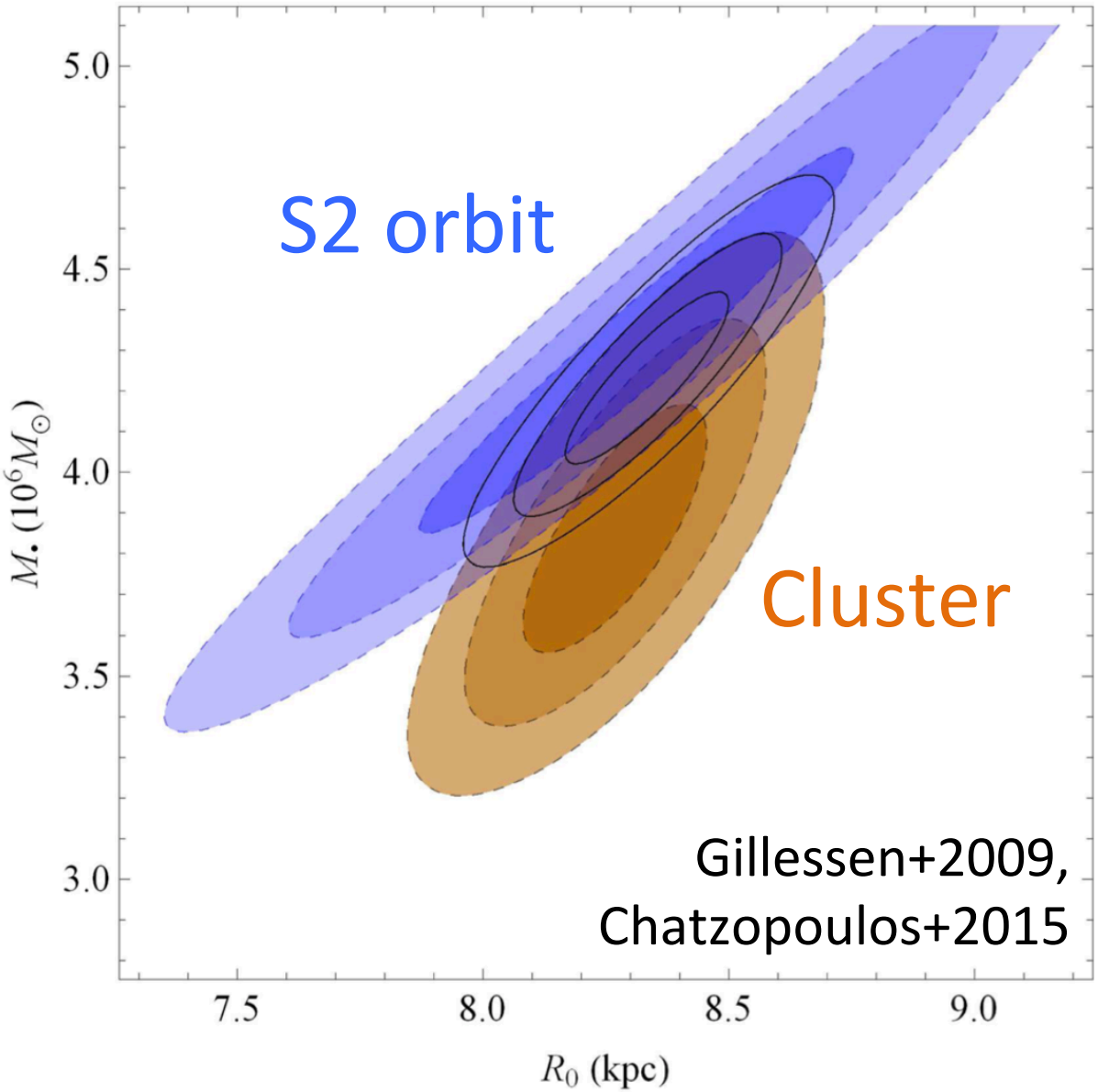
Nuclear cluster : A huge data set

> 10000
proper motions

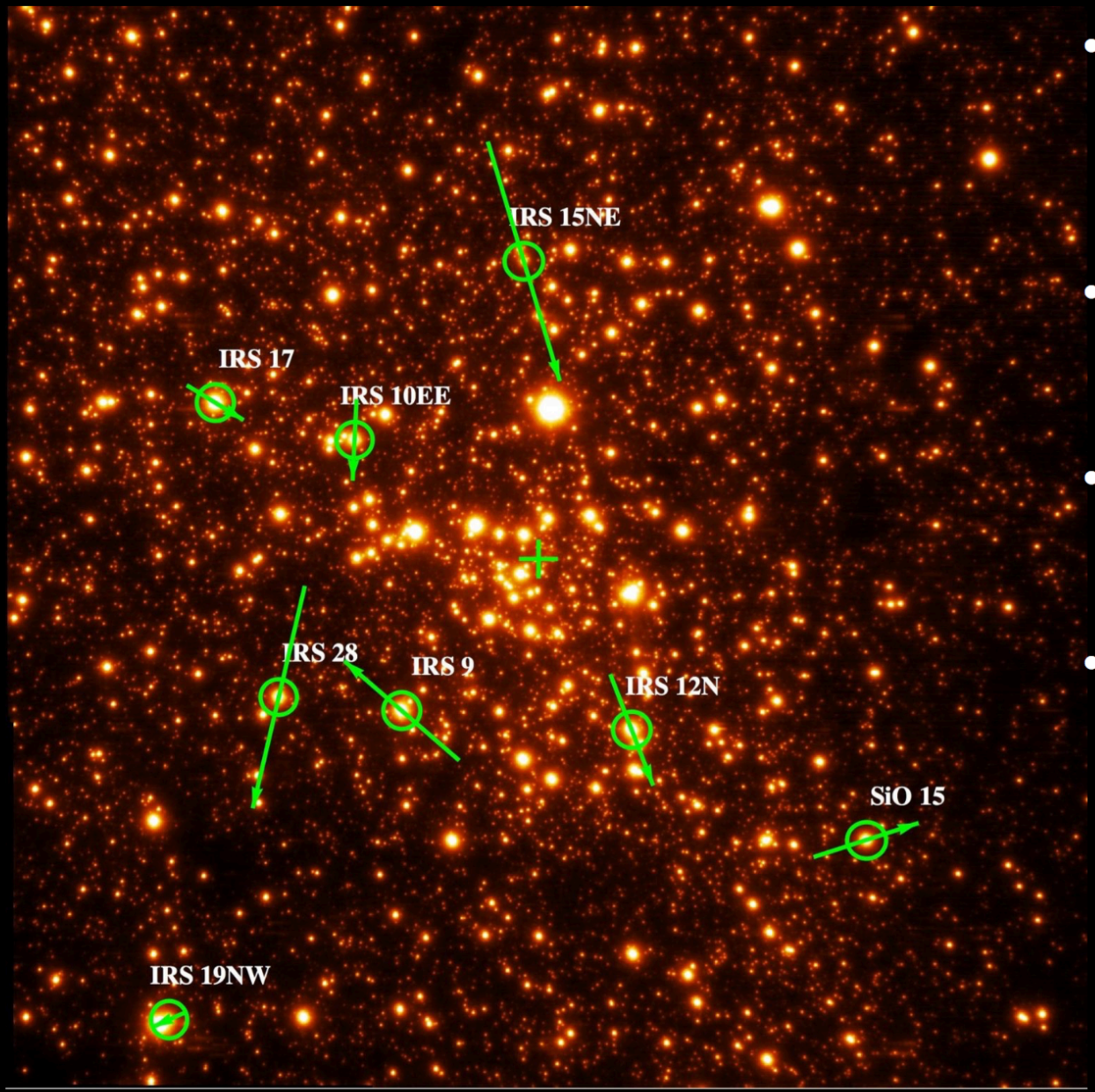
> 2500
radial velocities

Fritz+ 2014

Mass and distance to Sgr A*



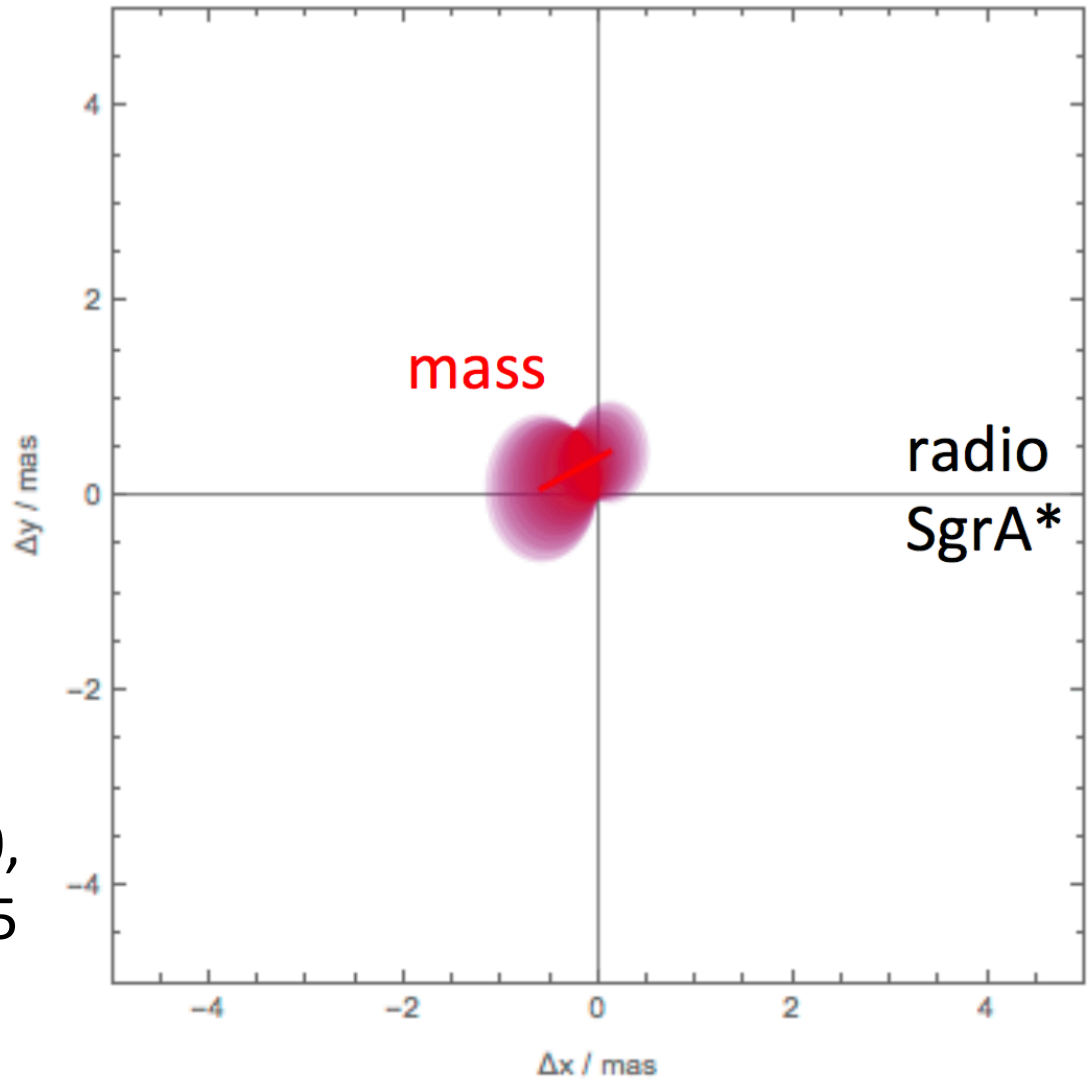
We can also locate the mass



- SiO maser stars
  - IR sources
  - radio sources
- Sgr A*
  - radio source
- Masers et "large" distances
- Positional accuracy
  - intrinsic: < mas
  - emission from outer atmosphere: up to ~mas

Reid et al. 2007

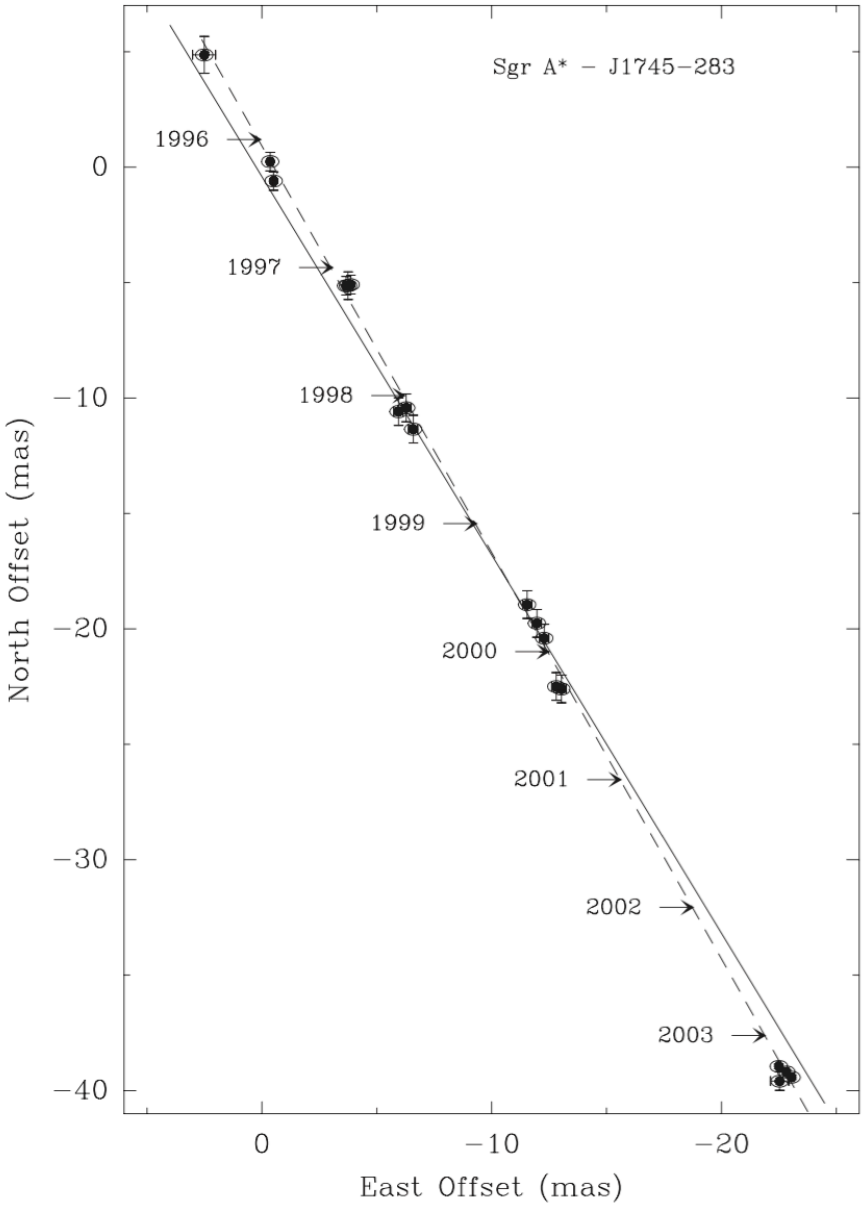
The mass is < 1 mas from Sgr A*



Yelda+2010,
Plewa+2015

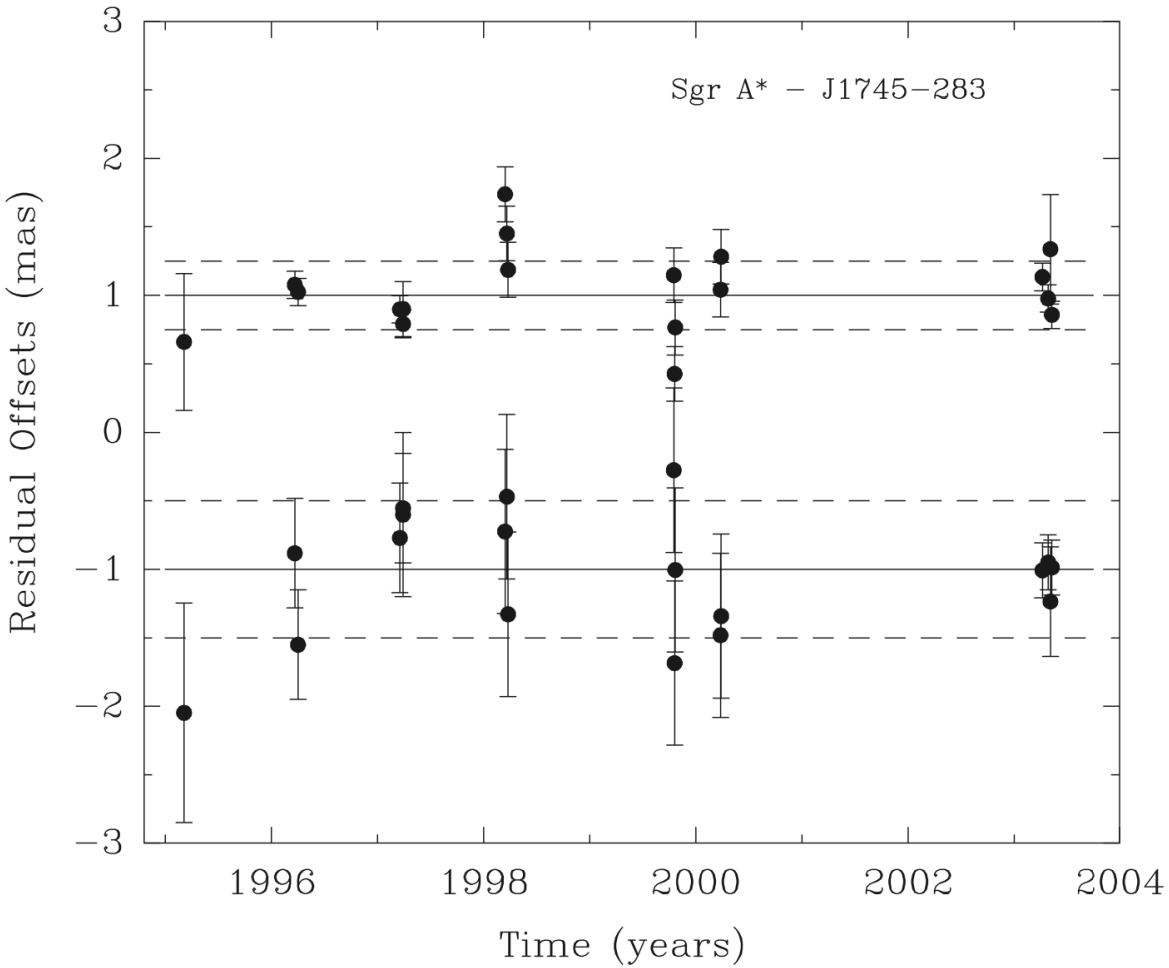
Most or all of the mass is Sgr A*

- Motion of radio Sgr A* relative to background AGN (Reid & Brunhalter 2004)
- Dashed line: motion of sun through Galaxy



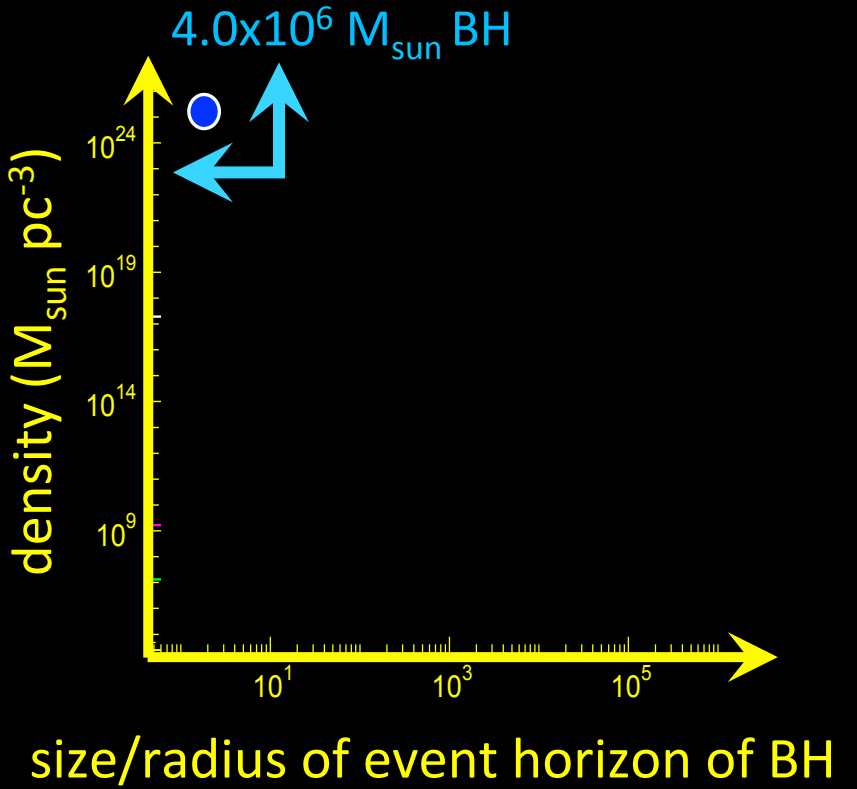
Most or all of the mass is Sgr A*

- Residual: Sgr A* is not moving!
- Radio source: > 10% of central mass



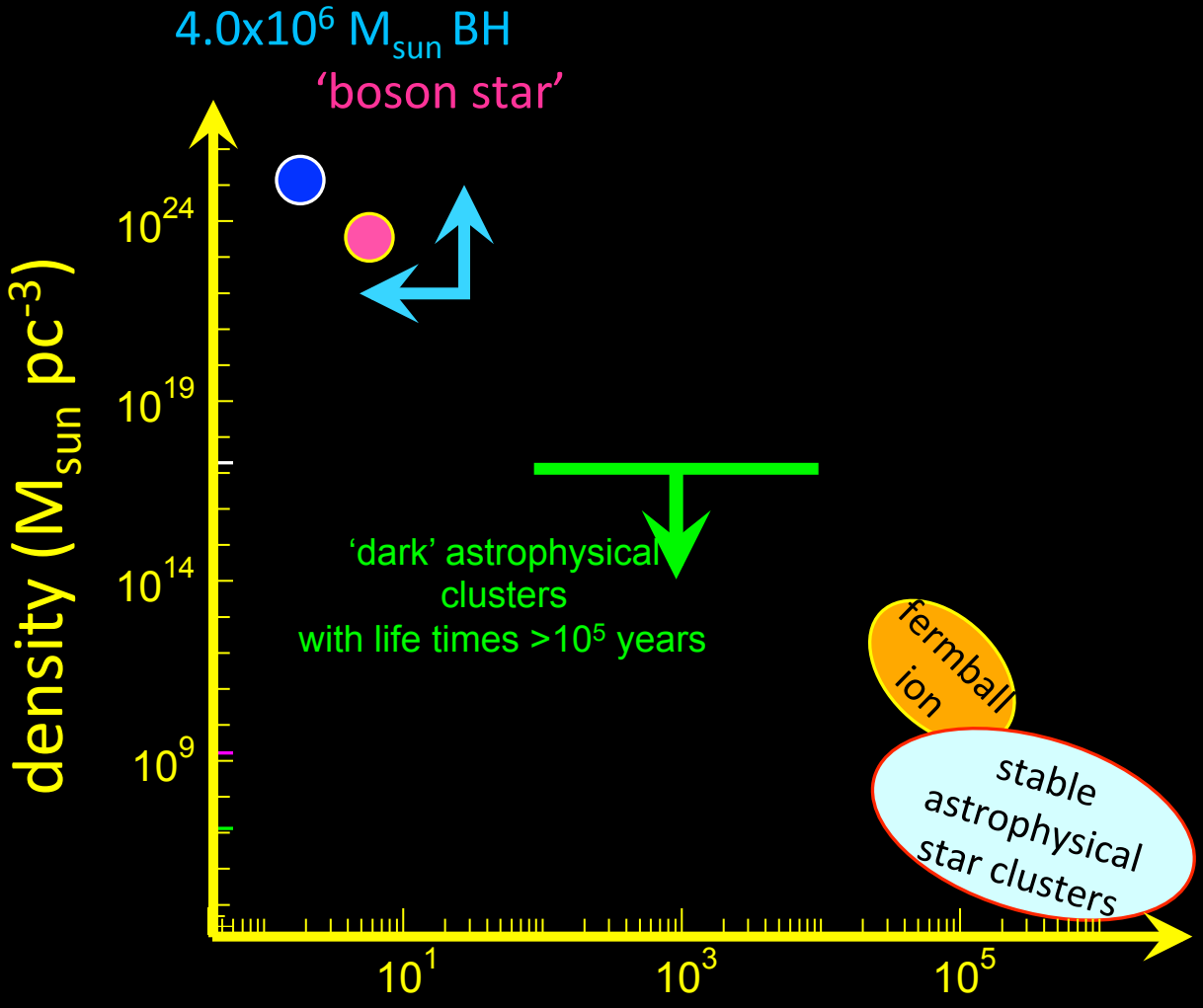
Limits on the density of Sgr A*

- 4.0×10^6 M_{sun} inside of S2
  (Schödel+ 2002, Gillessen+ 2009)
- > 10% of this is Sgr A*
  (Reid & Brunthaler 2004)
- Sgr A* radio size: ~4 R_s
  (Bower+ 2006, Doeleman+ 2008)



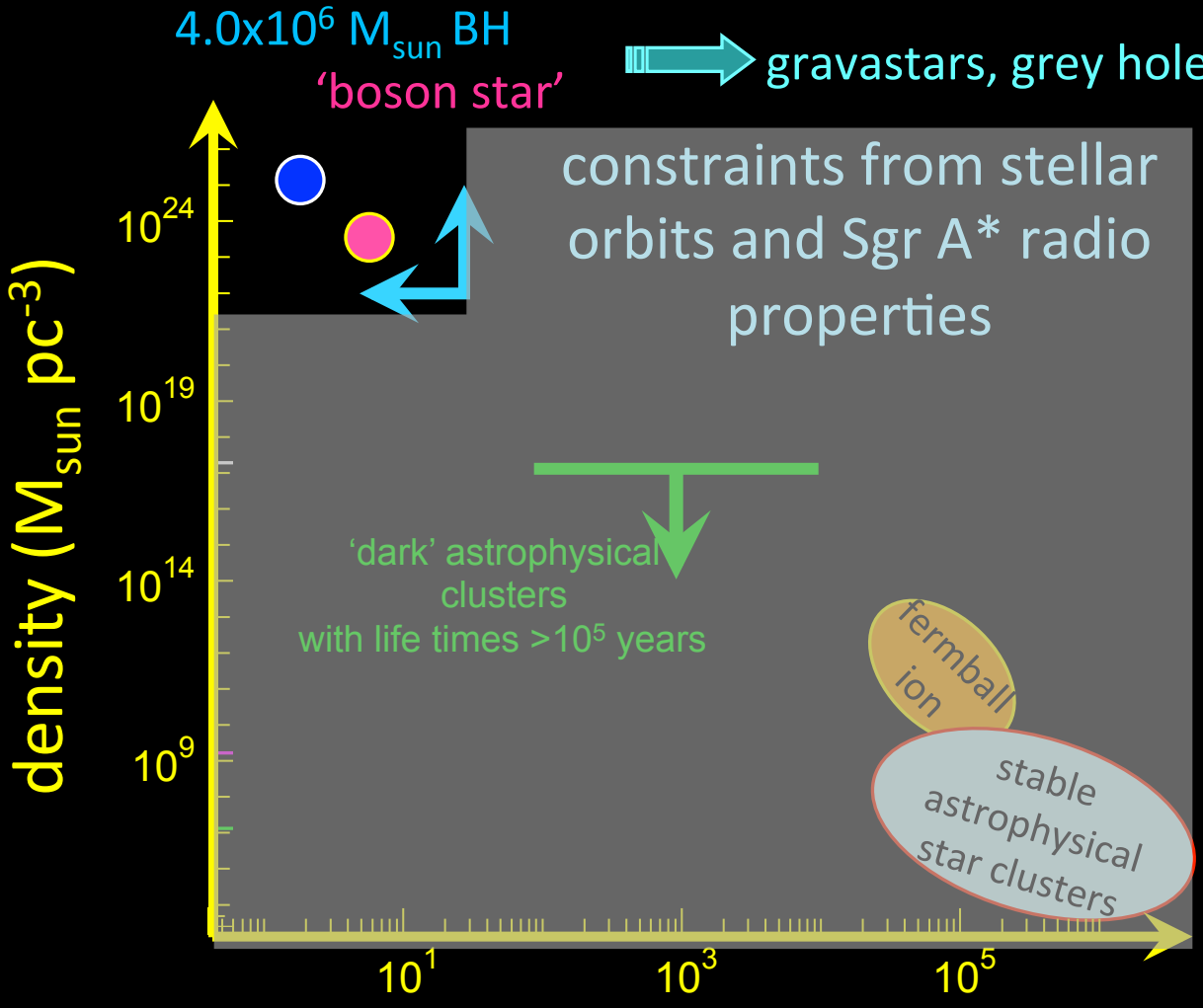
- density: ~10^{-2} of black hole

Is Sgr A* a black hole?



Schödel et al. 2003, Ghez et al. 2005, and Maoz 1998, Coleman 2005

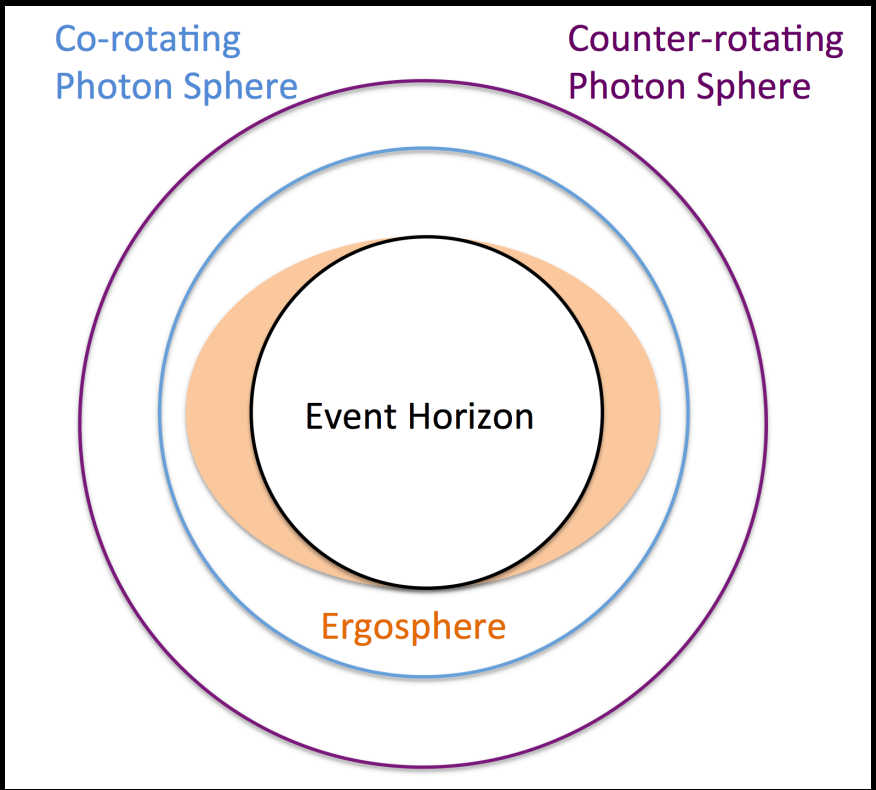
Is Sgr A* a black hole?



Schödel et al. 2003, Ghez et al. 2005, and Maoz 1998, Coleman 2005

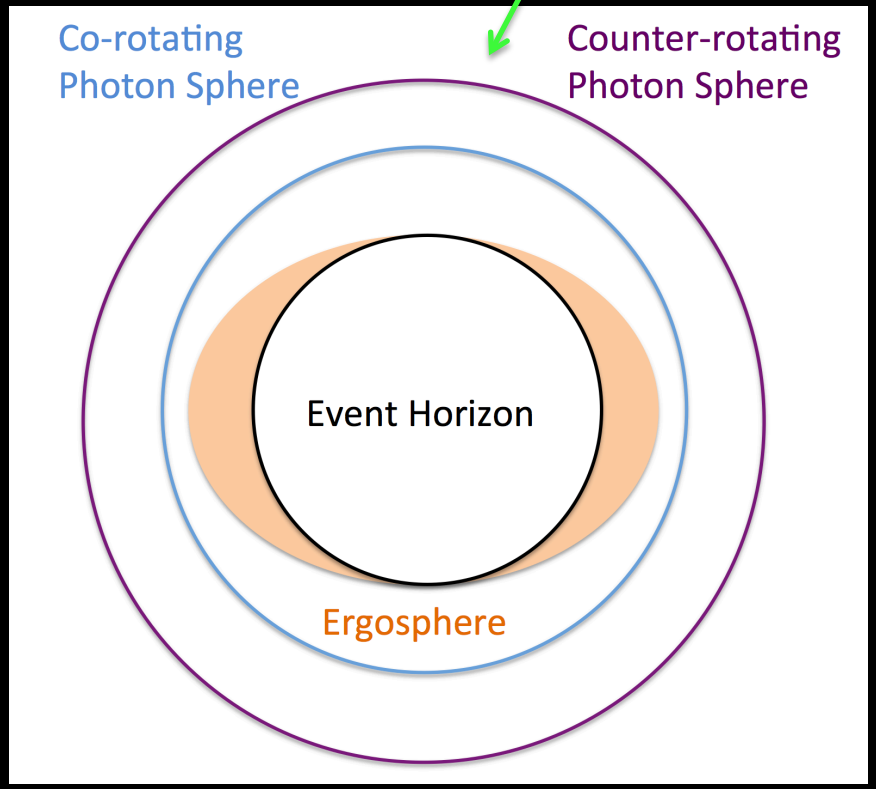
Black hole

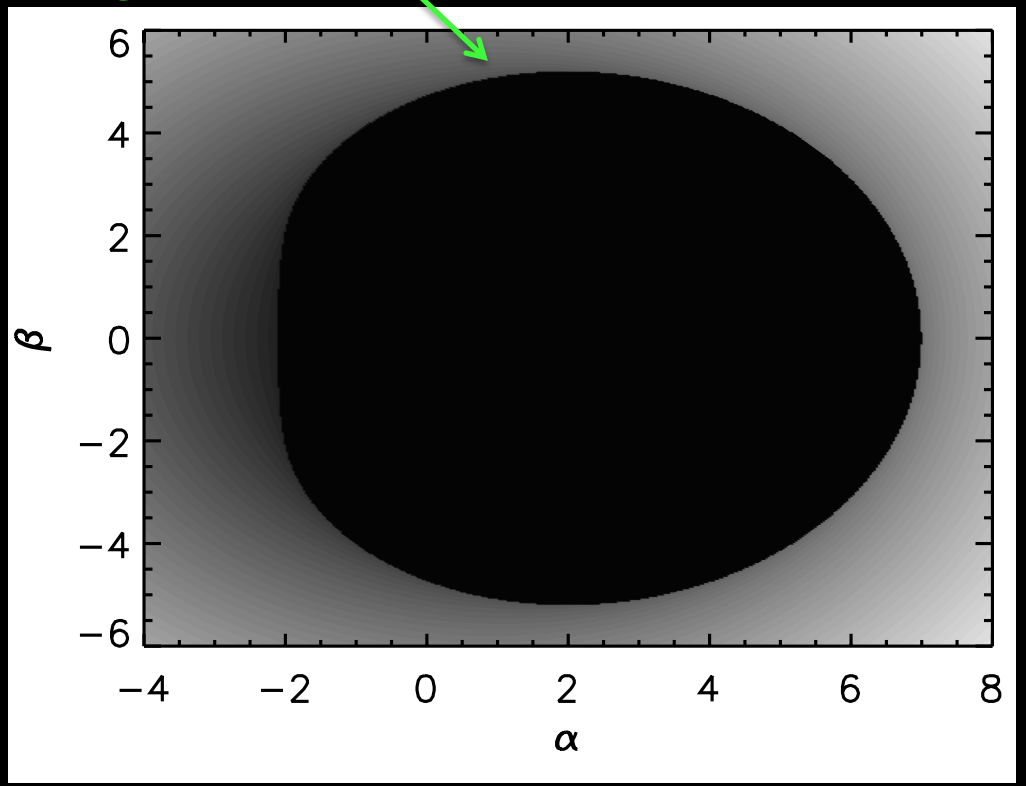
- Event horizon: $R_S = 2\,GM/c^2 = 2\,R_g$
- Innermost stable circular orbit: 1-9 R_g
- Circular photon orbit: 1-4 R_g



Black hole shadow

Shadow inside
photon spheres
Size: ~10 R_g





Bardeen (1973); Dexter & Agol (2009)

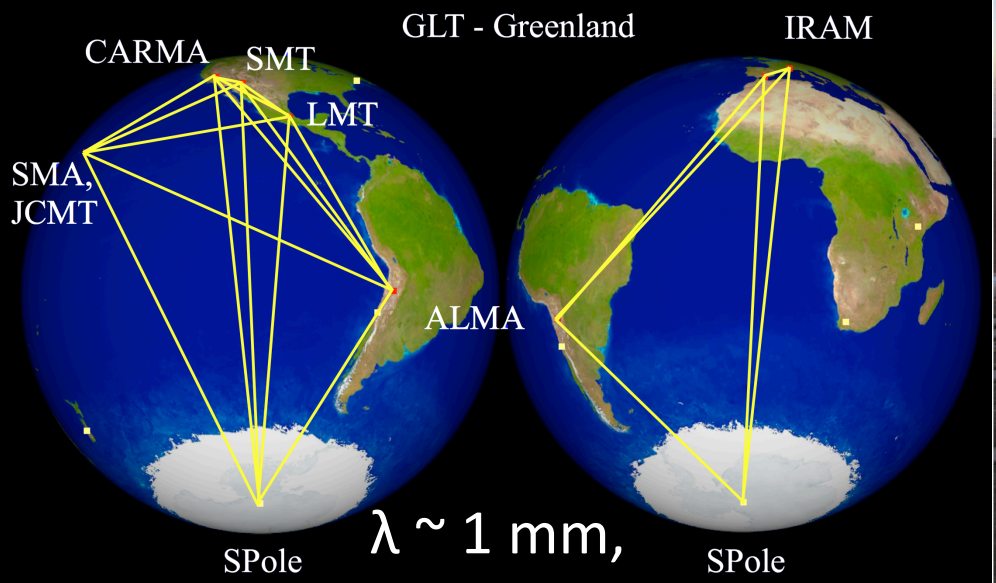
Q: resolving the BH shadow of Sgr A*

- $R_g = GM / c^2$, $M = 4 \times 10^6 M_{sun}$, D = 8 kpc
- How large is 10 R_g in angular size on sky?
- How large of a telescope do we need to resolve that size at wavelengths of:
  - 1 mm (radio)?
  - 2 micron (IR)?
  - 1 nm (X-ray)?
- Think/calculate, share, then discuss!

Imaging a black hole

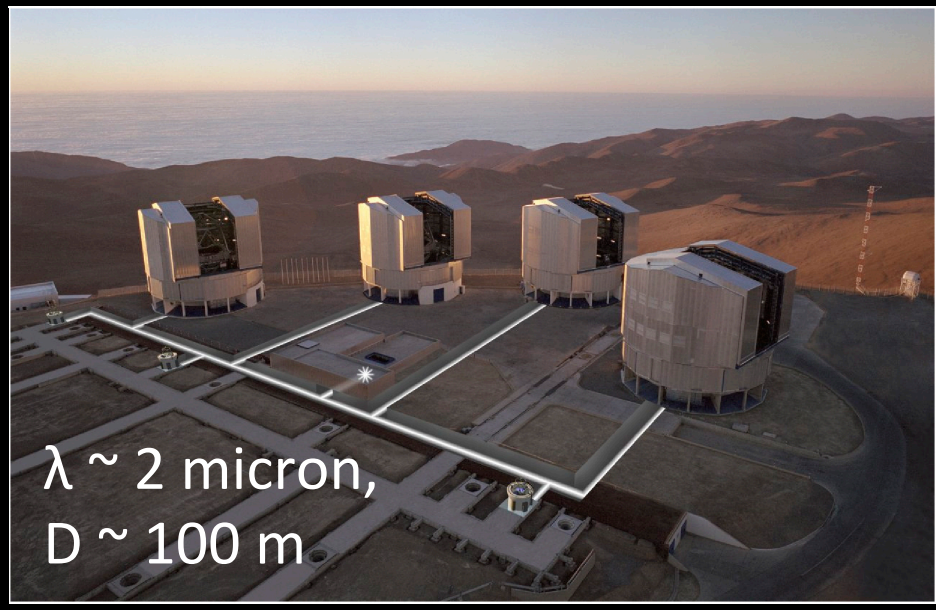
- Two new experiments to resolve gas near Sgr A*
- Resolution: 10-100 μas

Event Horizon Telescope



λ ~ 1 mm,
D ~ 5000 km

VLTI GRAVITY



λ ~ 2 micron,
D ~ 100 m

Next time: “a paradox of youth”

- How do we get clusters of young stars near a massive black hole?

- Is star formation near a massive black hole the same as elsewhere in the Universe?