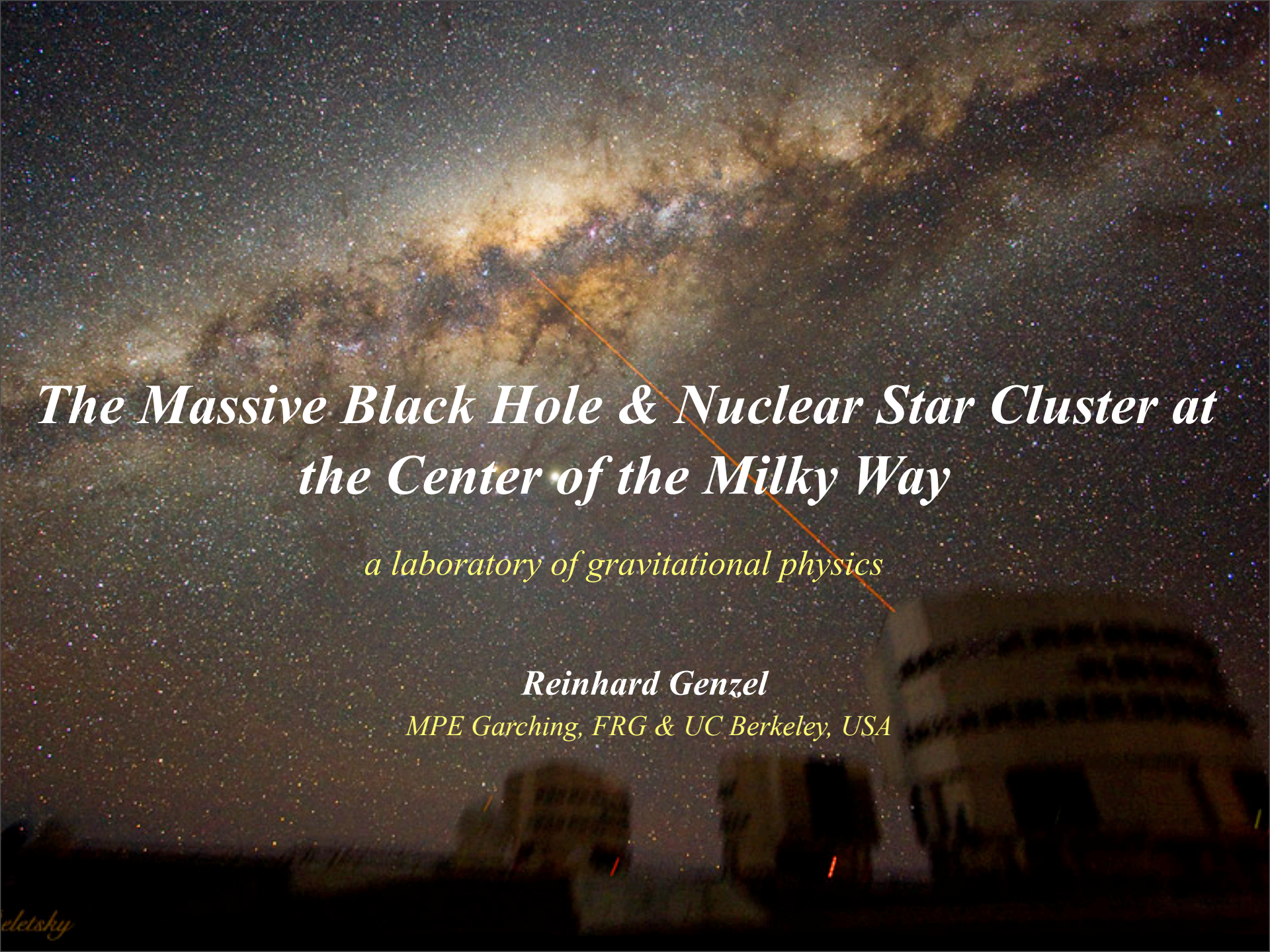

Reinhard Genzel
MPE Garching, FRG & UC Berkeley, USA



# *The Massive Black Hole & Nuclear Star Cluster at the Center of the Milky Way*

*a laboratory of gravitational physics*

**Reinhard Genzel**

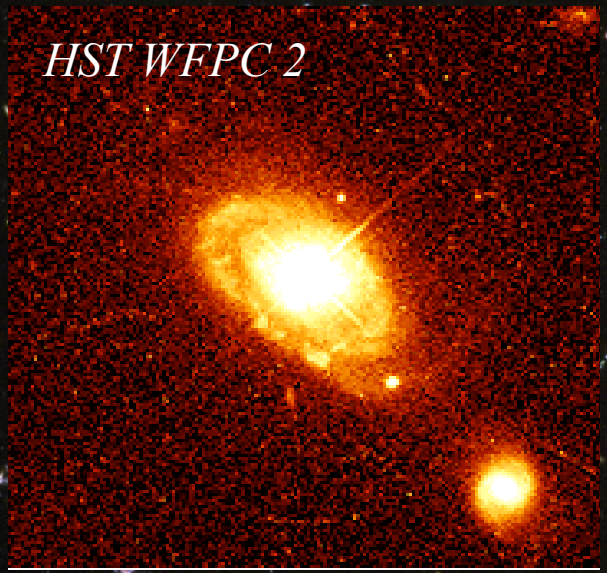
*MPE Garching, FRG & UC Berkeley, USA*


➢ star formation near a black hole:
‘paradox of youth’
➢ testing the black hole paradigm
➢ the central accretion zone


massive black holes in galactic nuclei

# *massive black holes in galactic nuclei*

**QSOs**
**variable X- & γ-rays**
**relativistic radio jets**




*Schmidt, Lynden-Bell, Rees 1963-71*

# *massive black holes in galactic nuclei*

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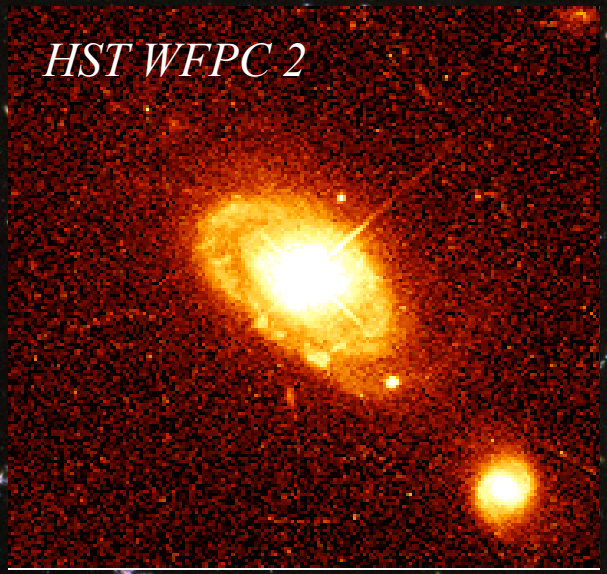
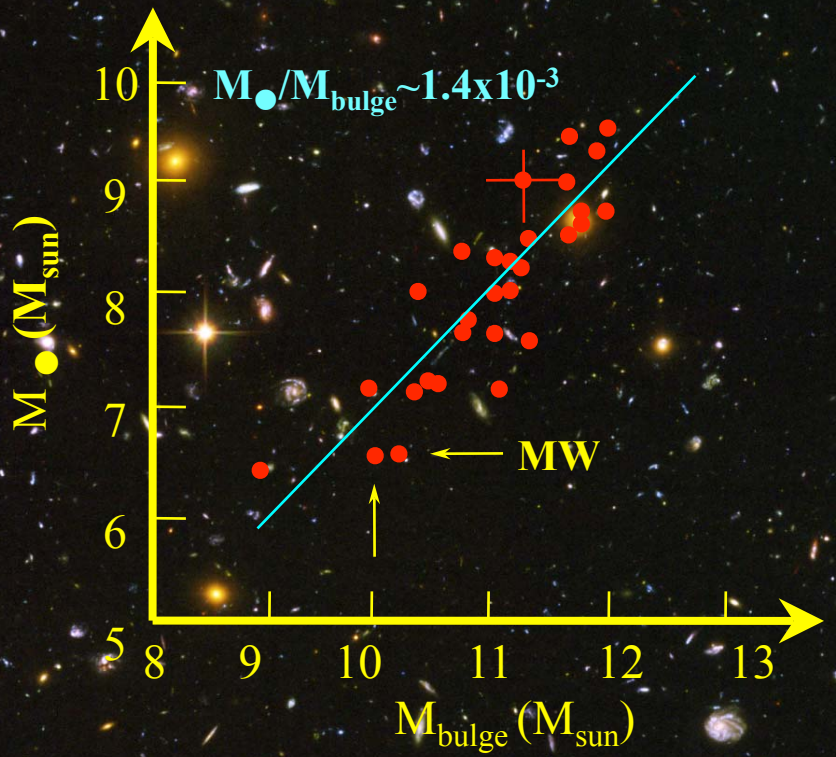
**variable X- & γ-rays**
**relativistic radio jets**



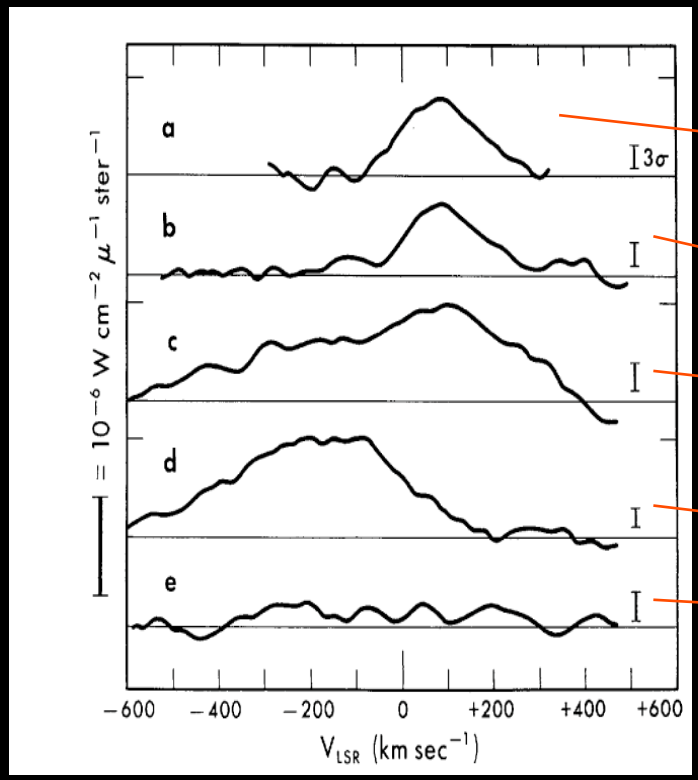

*Schmidt, Lynden-Bell, Rees 1963-71*

**dynamical evidence for dark central masses in nearby galaxy nuclei**




*Miyoshi et al. 1995, Kormendy & Richstone 1995, Gebhardt et al. 2000, Ferrarese & Merritt 2000, Tremaine et al. 2002, Bender et al. 2002, 2005*

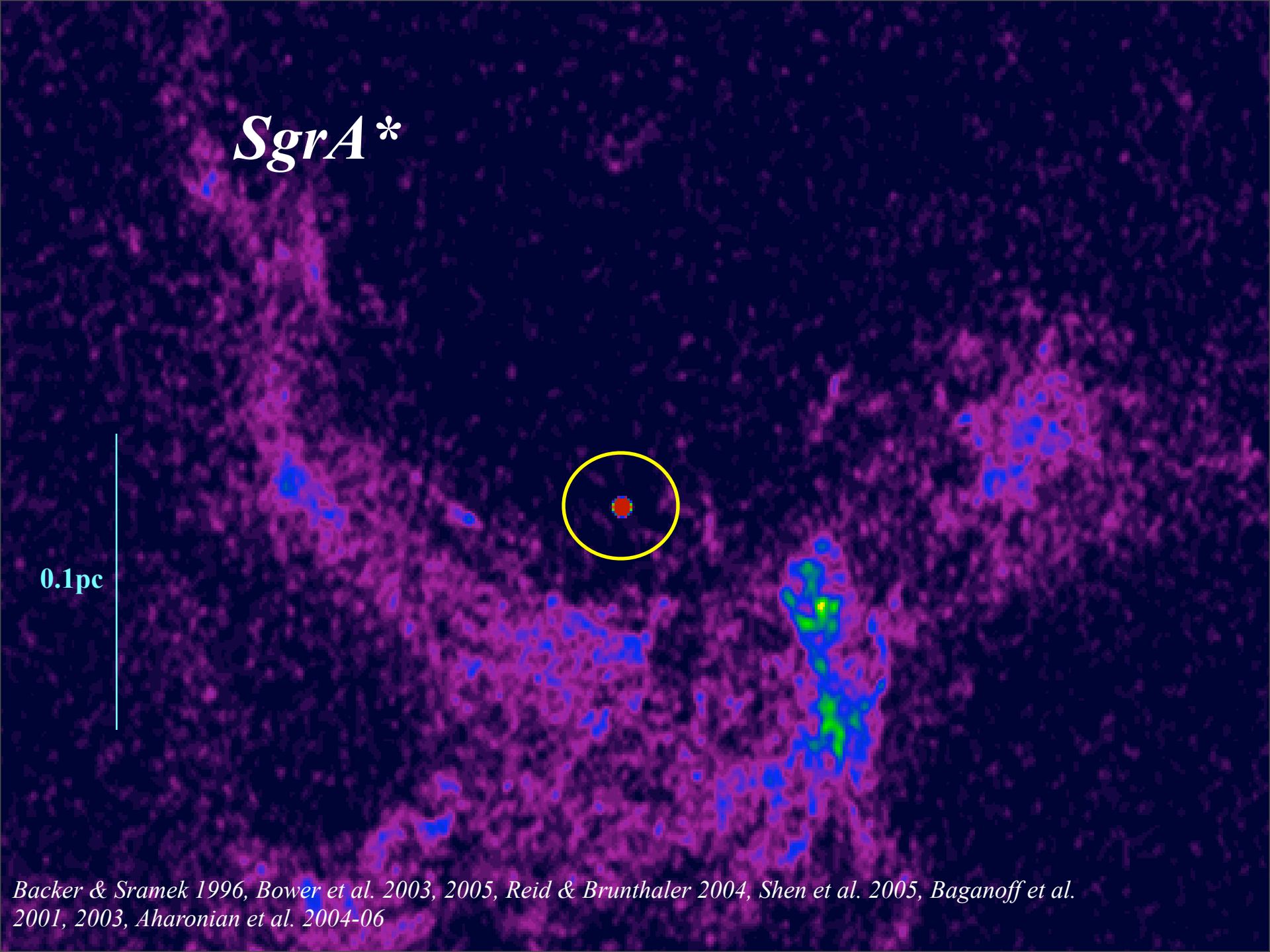
# *early evidence for a central mass concentration*



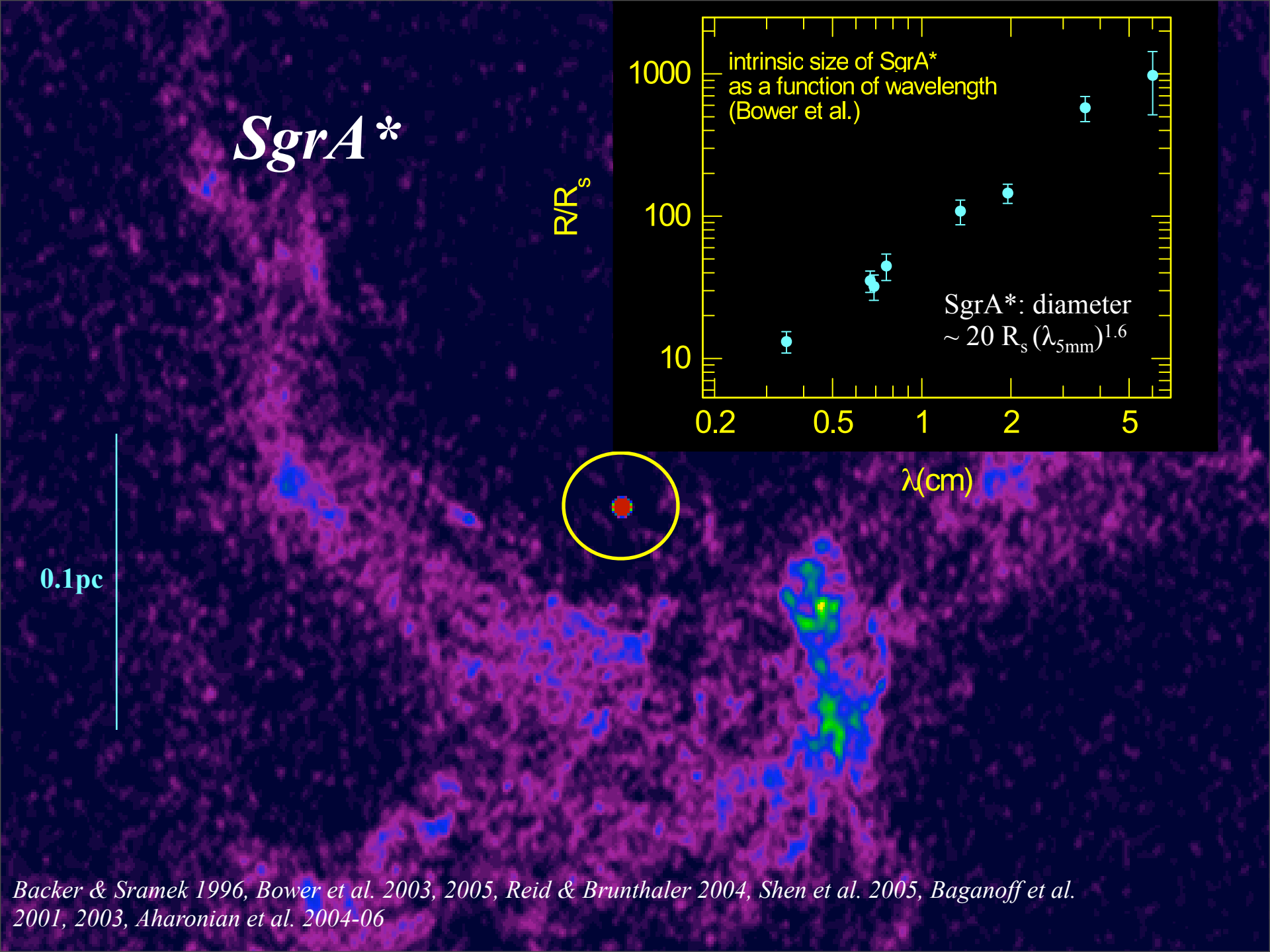

SgrA*

10” (0.39pc)

Balick & Brown 1974, Lo et al. 1975, Wollman et al. 1977, Lacy et al. 1980, 1982




*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*

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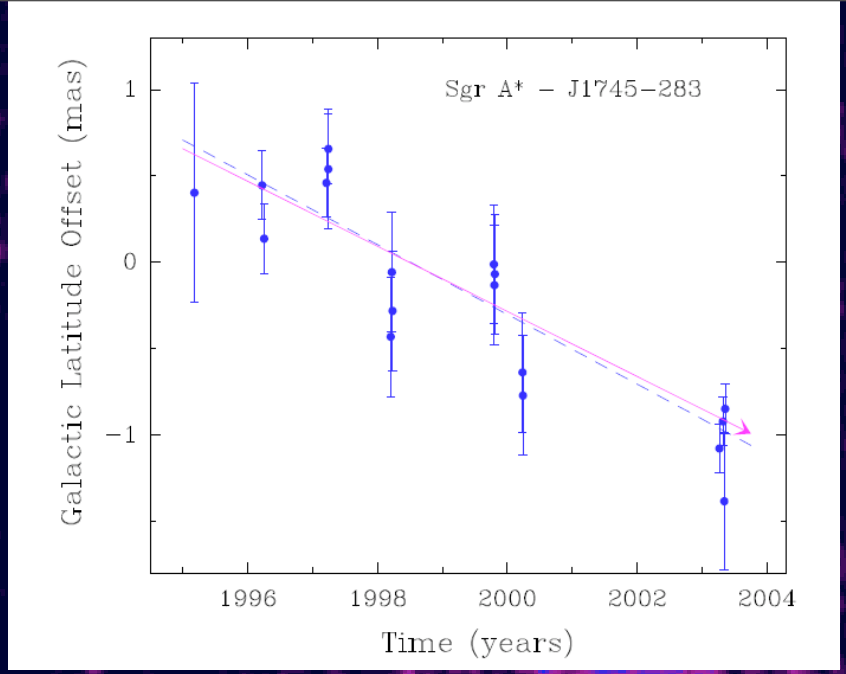
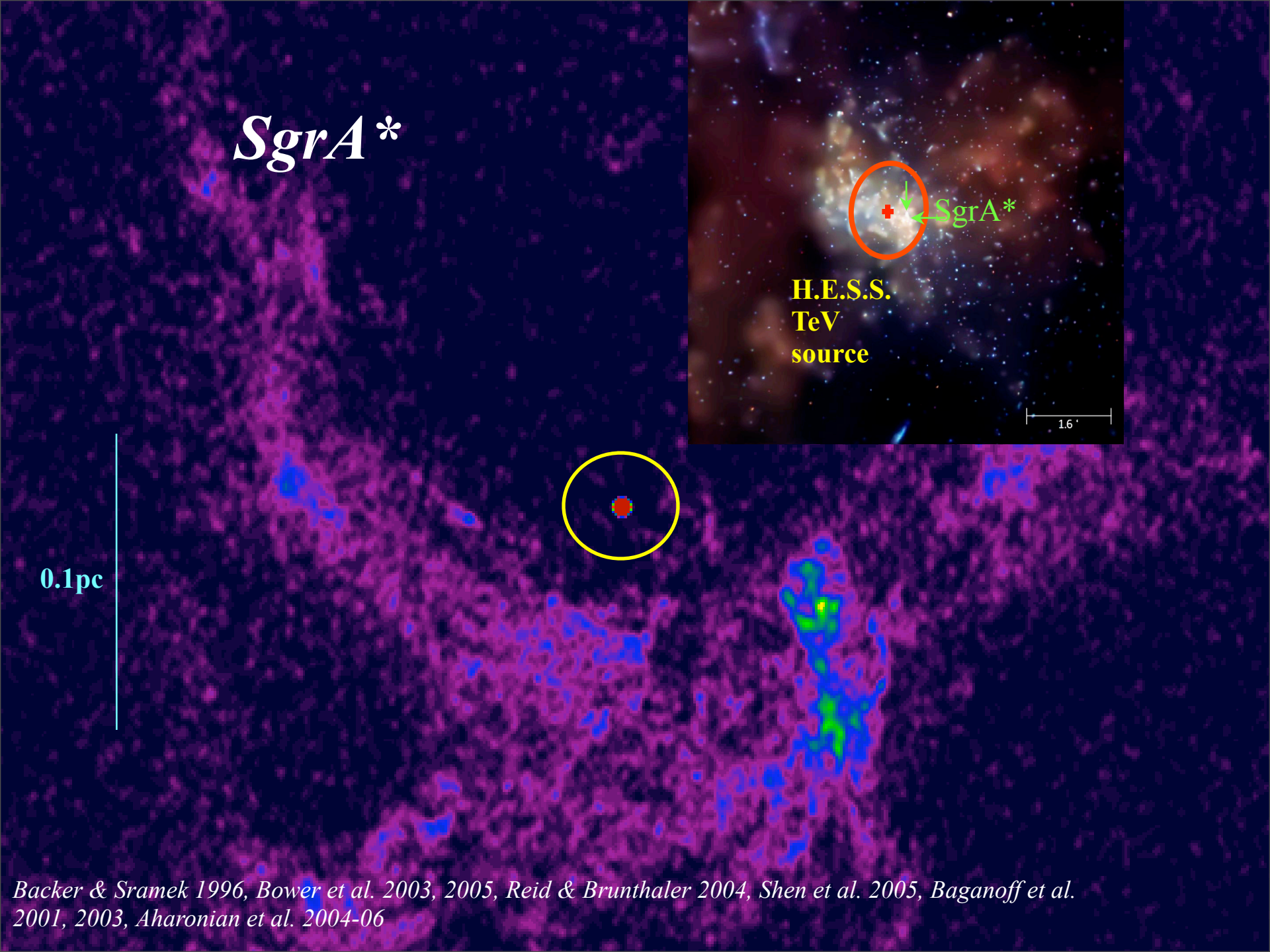



**0.1pc**

$v_{pm} \leq$ *2, 20 km/s*

*(50 μarcseconds/year !)*

*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*

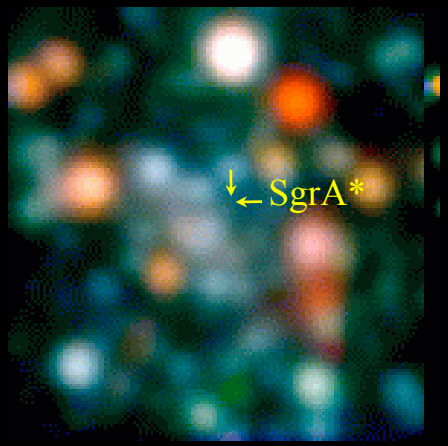



*Backer & Sramek 1996, Bower et al. 2003, 2005, Reid & Brunthaler 2004, Shen et al. 2005, Baganoff et al. 2001, 2003, Aharonian et al. 2004-06*

# *15 years progress in high resolution IR imaging*

**seeing limited (1990)**

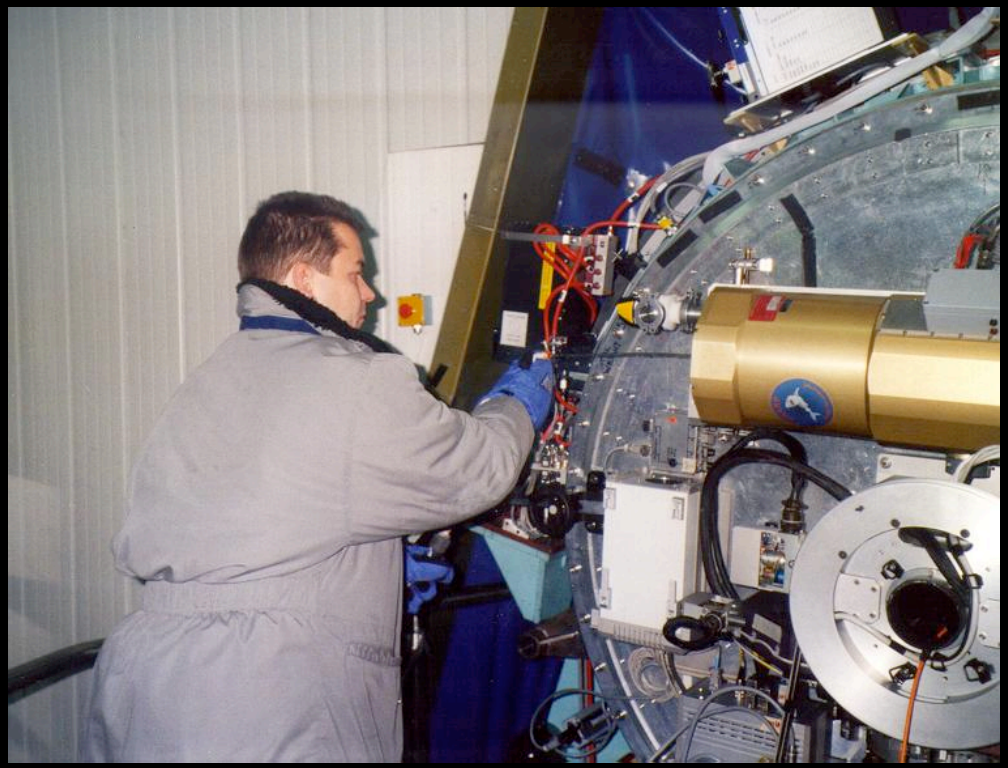
5”
(0.2
pc)



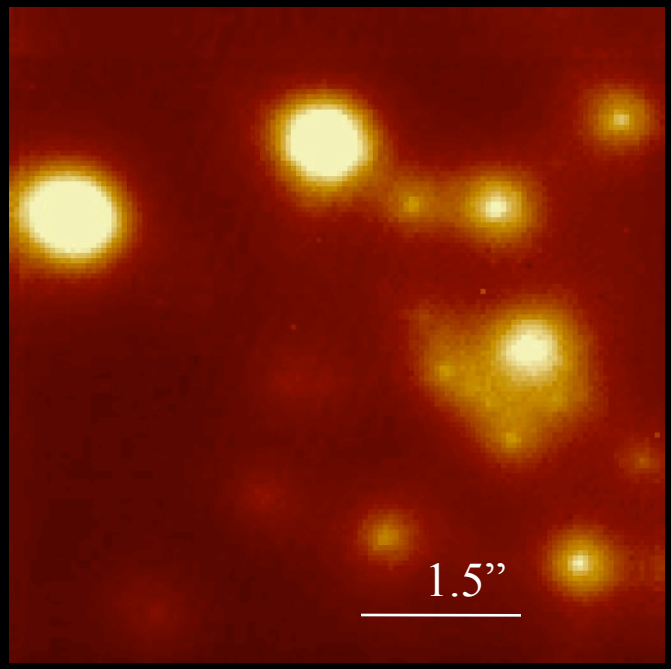

DePoy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2005

# *15 years progress in high resolution IR imaging*

'SHARP' at the 3.5m NTT



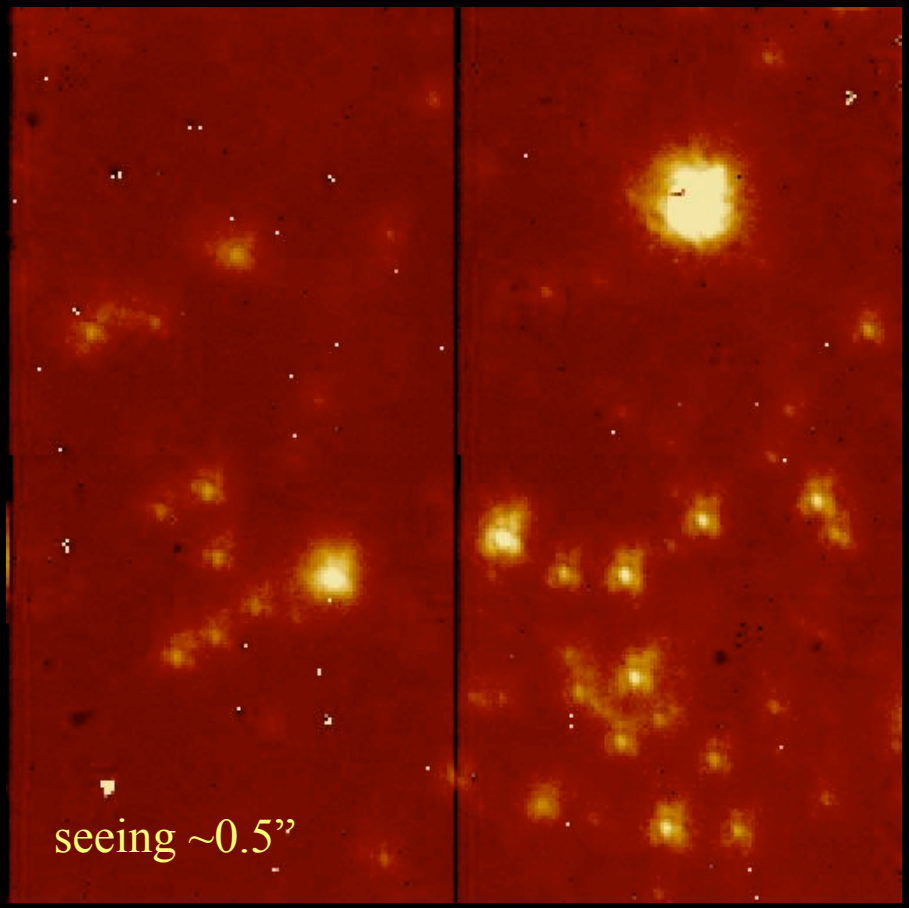
first images 1991




DePoy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2005

# *15 years progress in high resolution IR imaging*

single ‘speckle’ frame with SHARP




DePoy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2005

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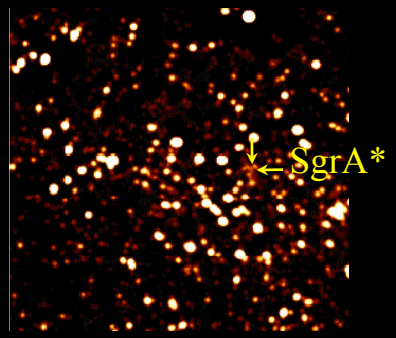


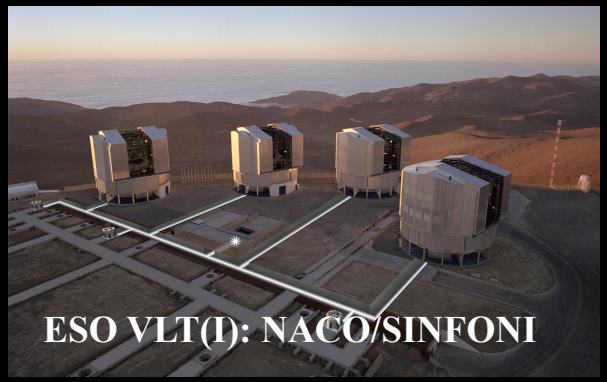

5” (0.2 pc)

**speckle imaging NTT (1992)**

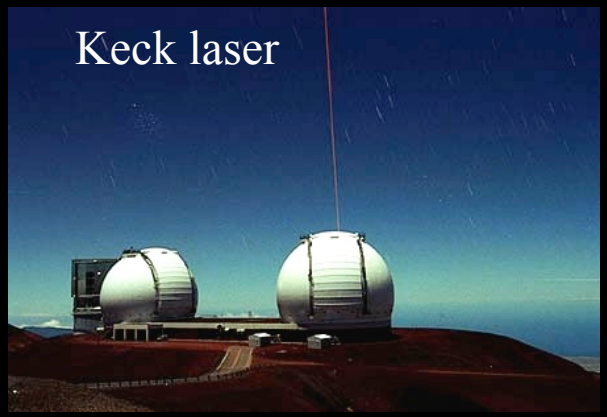
DePoy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2005

# *15 years progress in high resolution IR imaging*

## Adaptive Optics at Keck & VLT




NAOS+
CONICA


Beroy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2003

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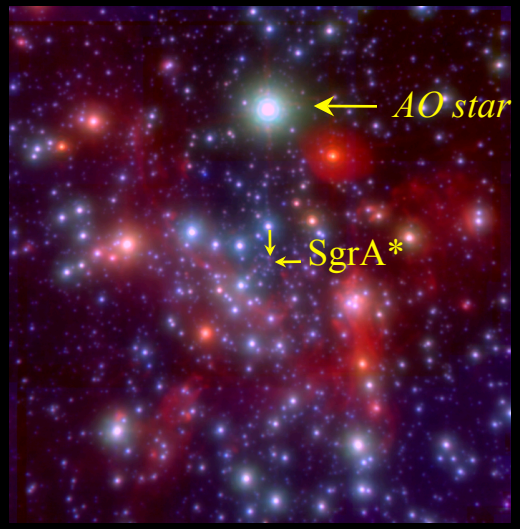
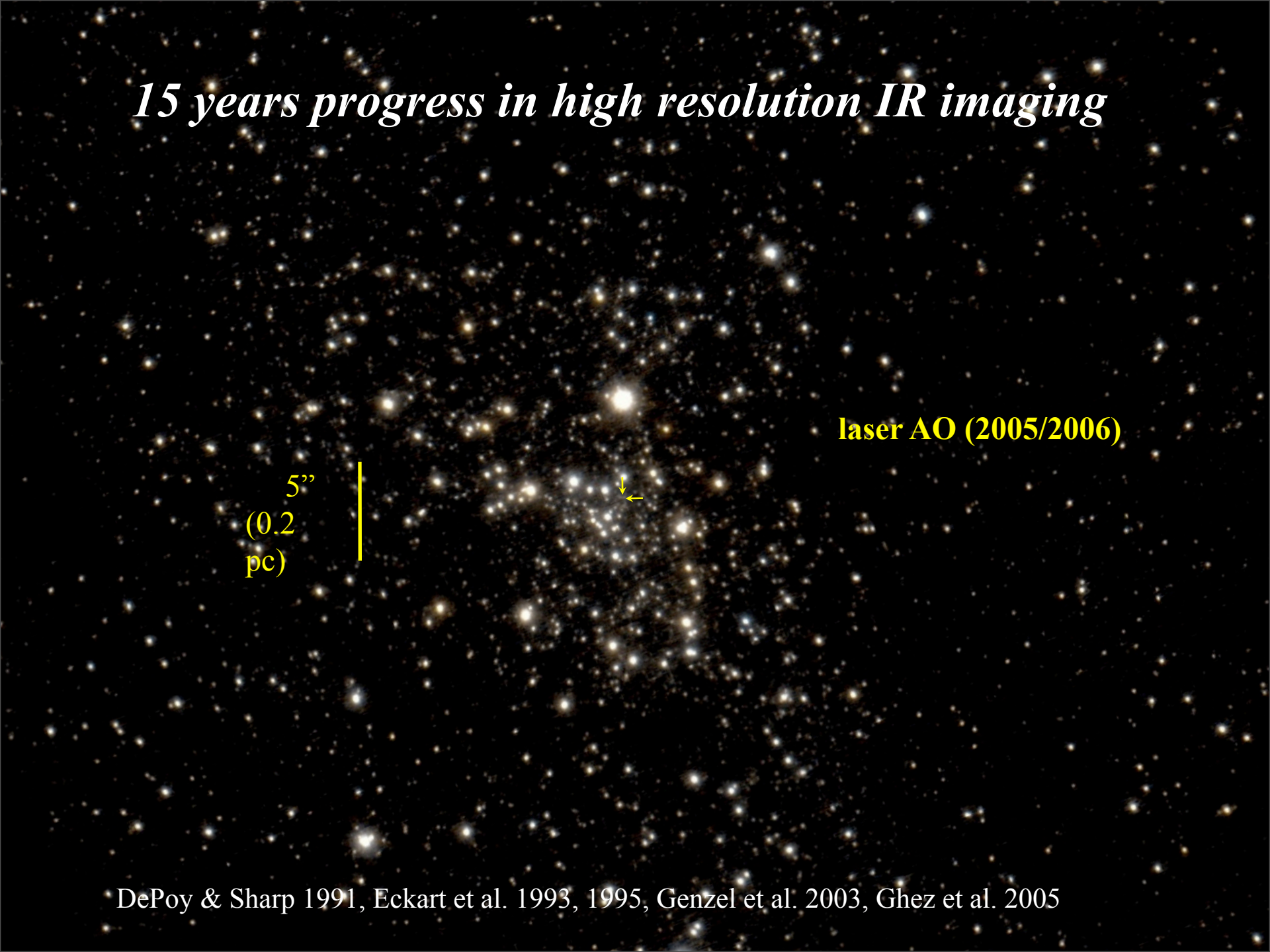
5”
(0.2
pc)




**natural star IR-AO (2003)**

DePoy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2005

# *15 years progress in high resolution IR imaging*




DePoy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2005

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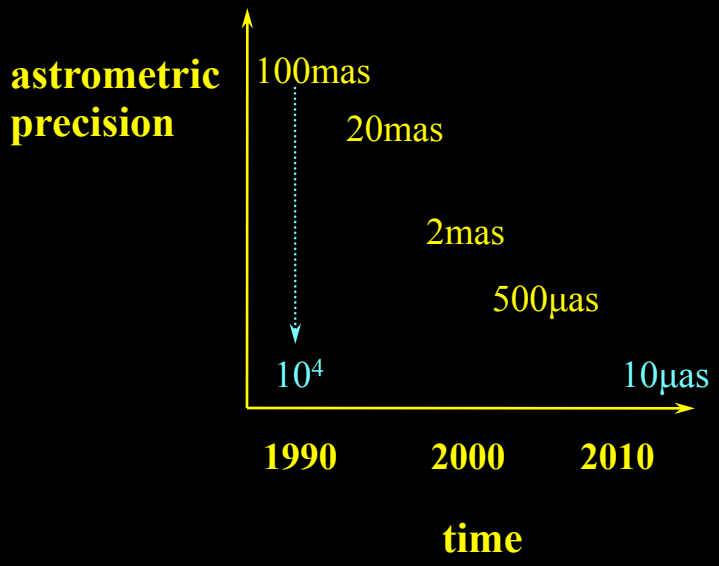


DePoy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2005

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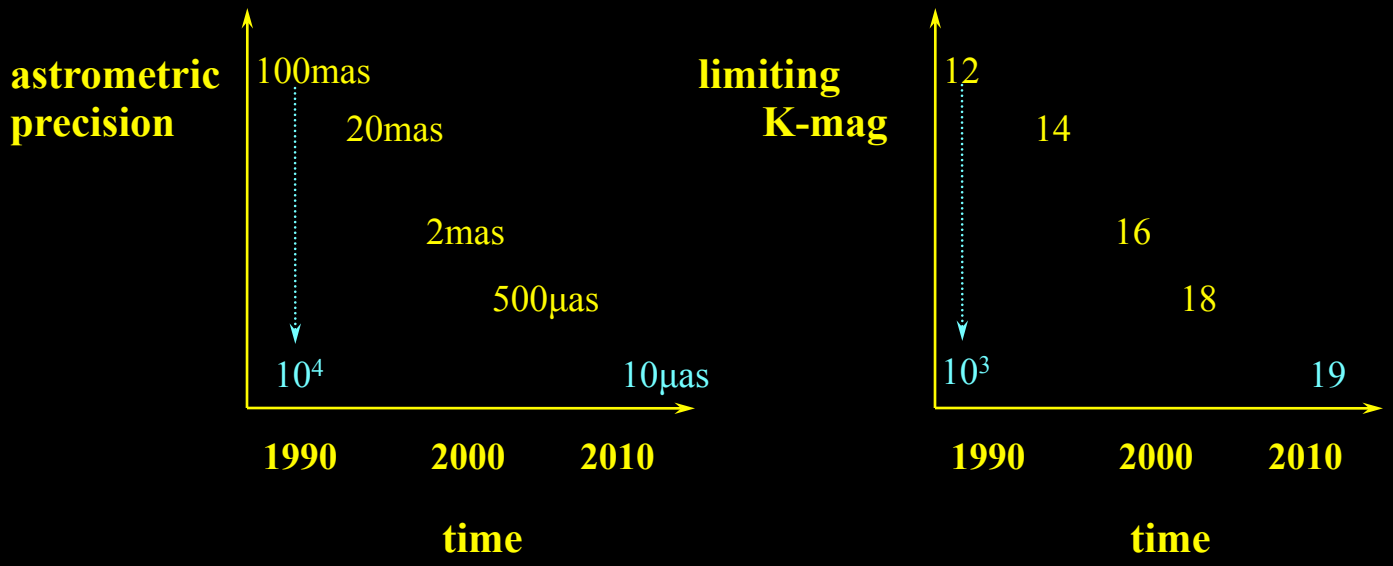
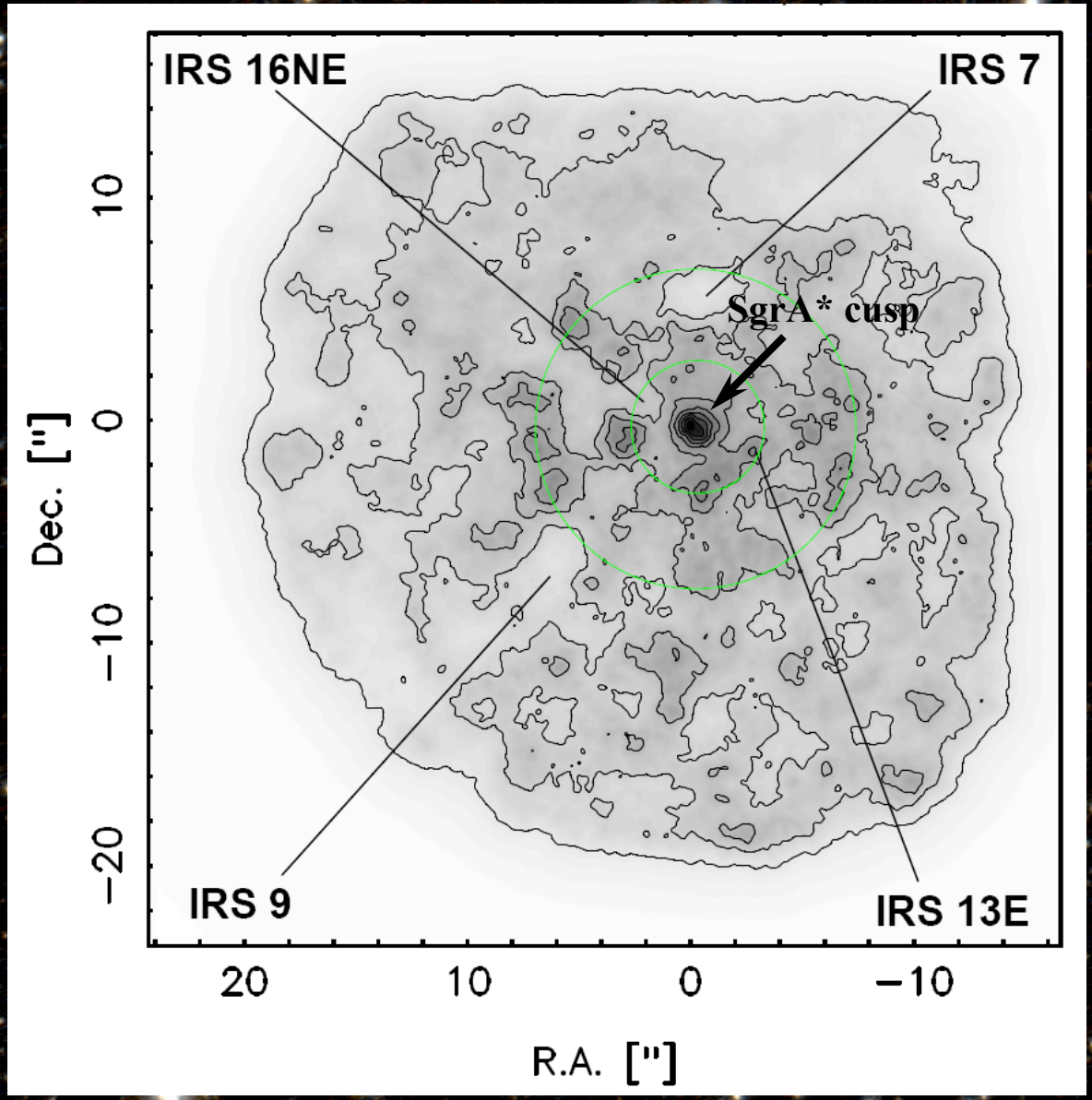



DePoy & Sharp 1991, Eckart et al. 1993, 1995, Genzel et al. 2003, Ghez et al. 2005

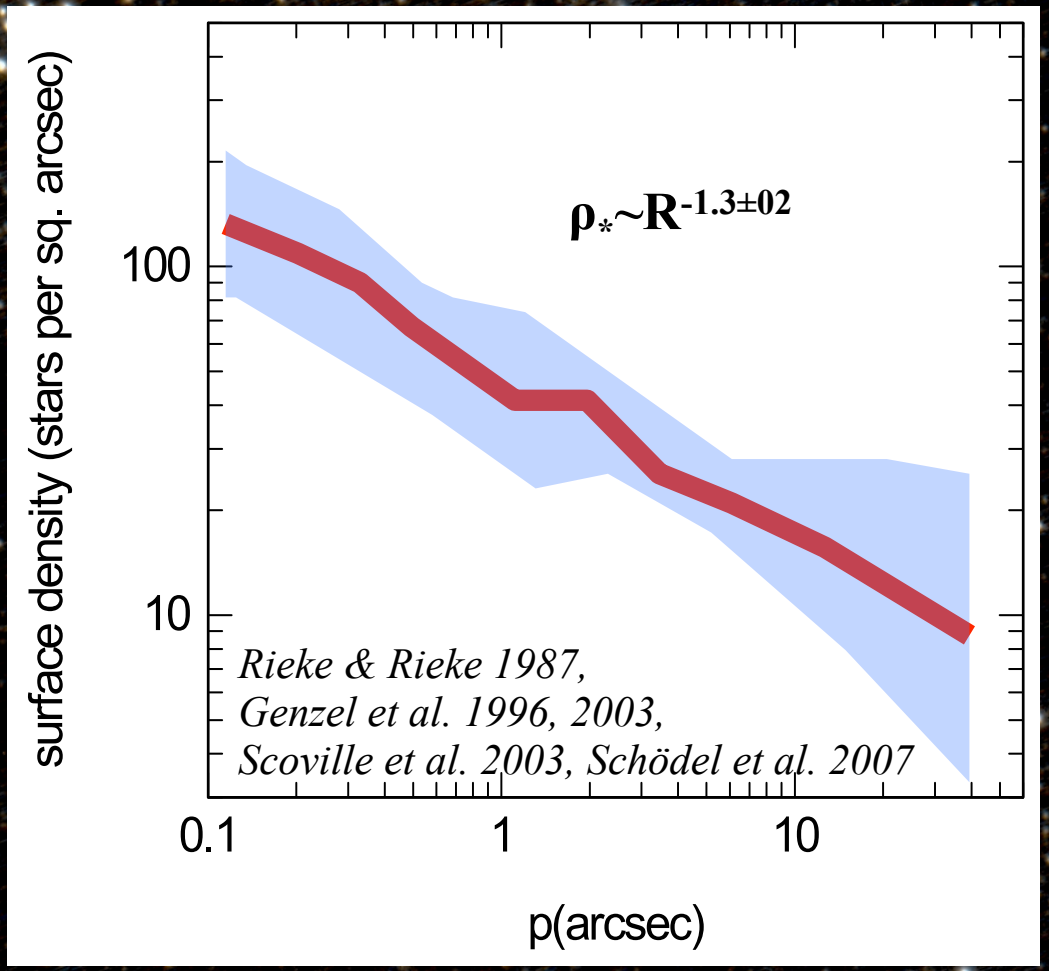

0.1 pc
SgrA*
Ghez et al. 2005, Keck laser guide star AO


***nuclear star cluster and cusp:***

*Ghez et al. 2005, Keck laser guide star AO*




*Genzel et al. 2003, Paumard et al. 2006, Ott et al. 1999, DePoy et al. 2004, Schödel et al. 2007, Martins et al. 2006*

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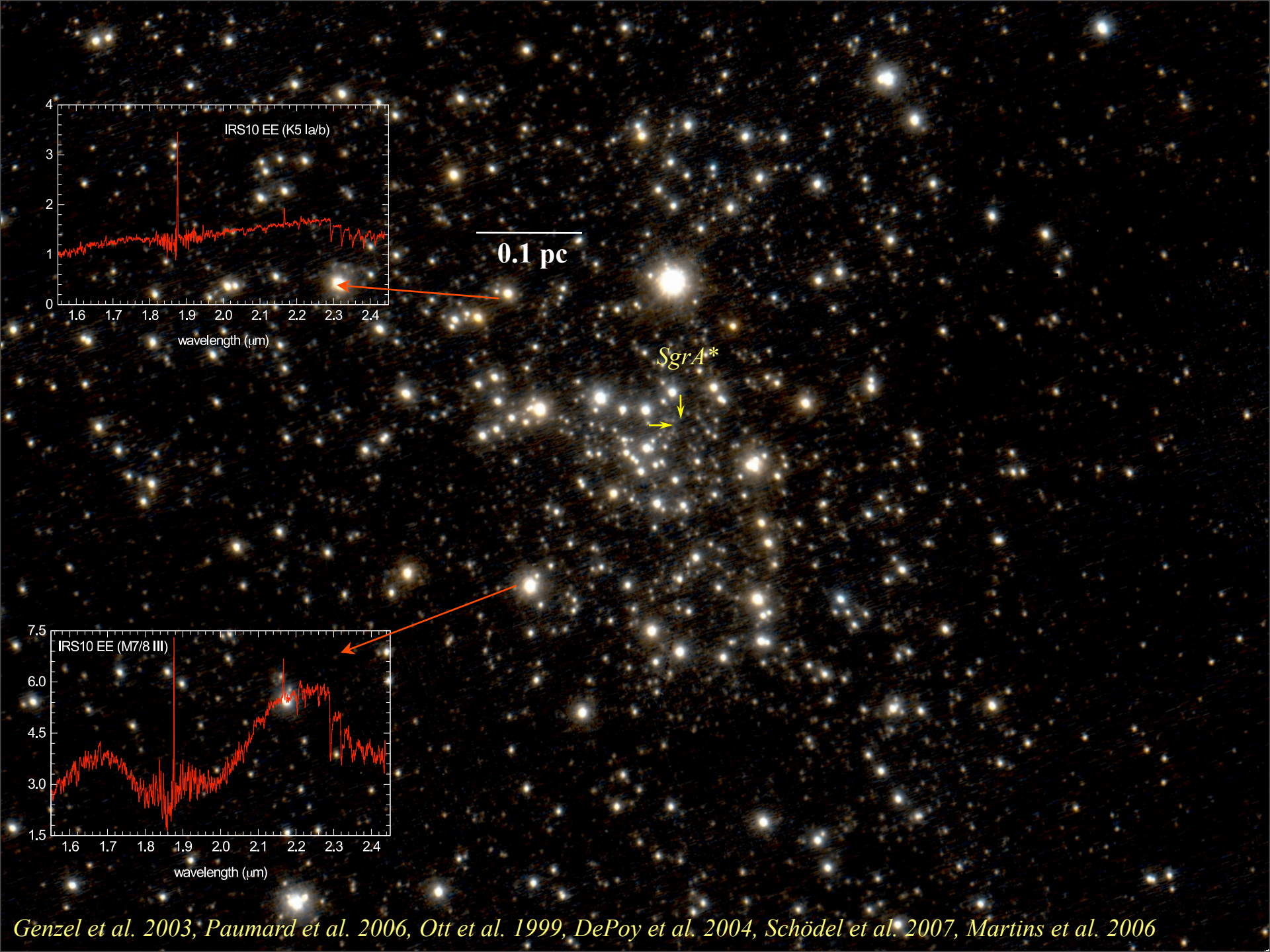


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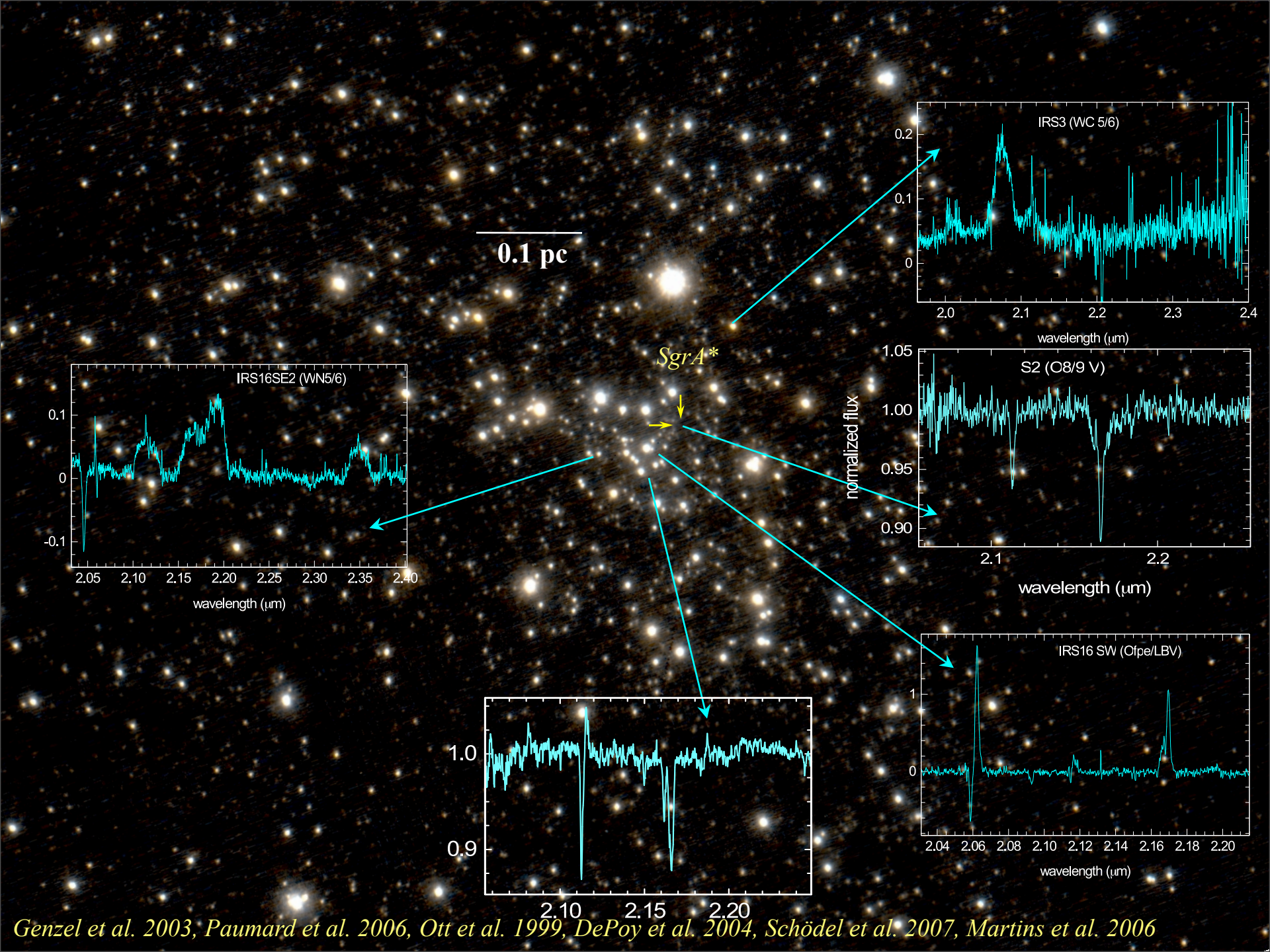


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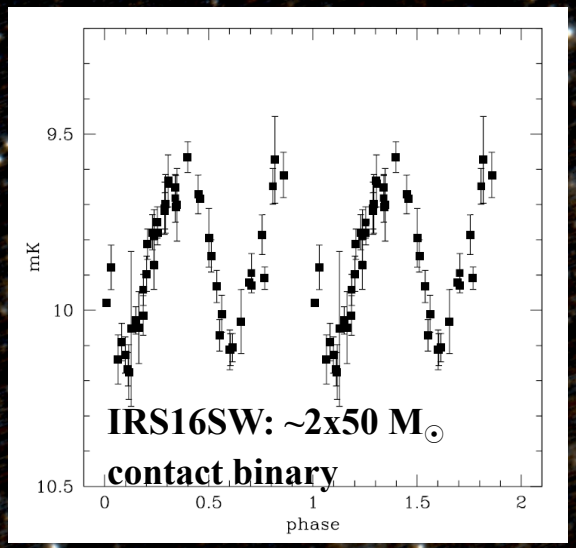
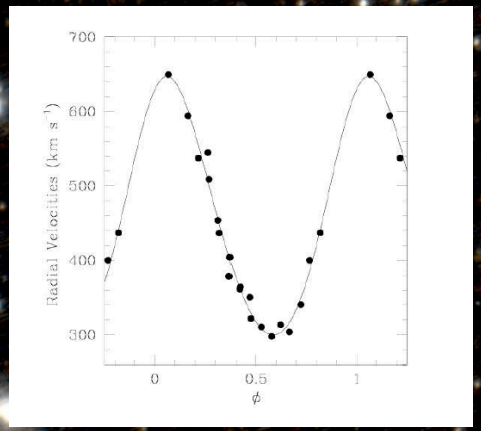


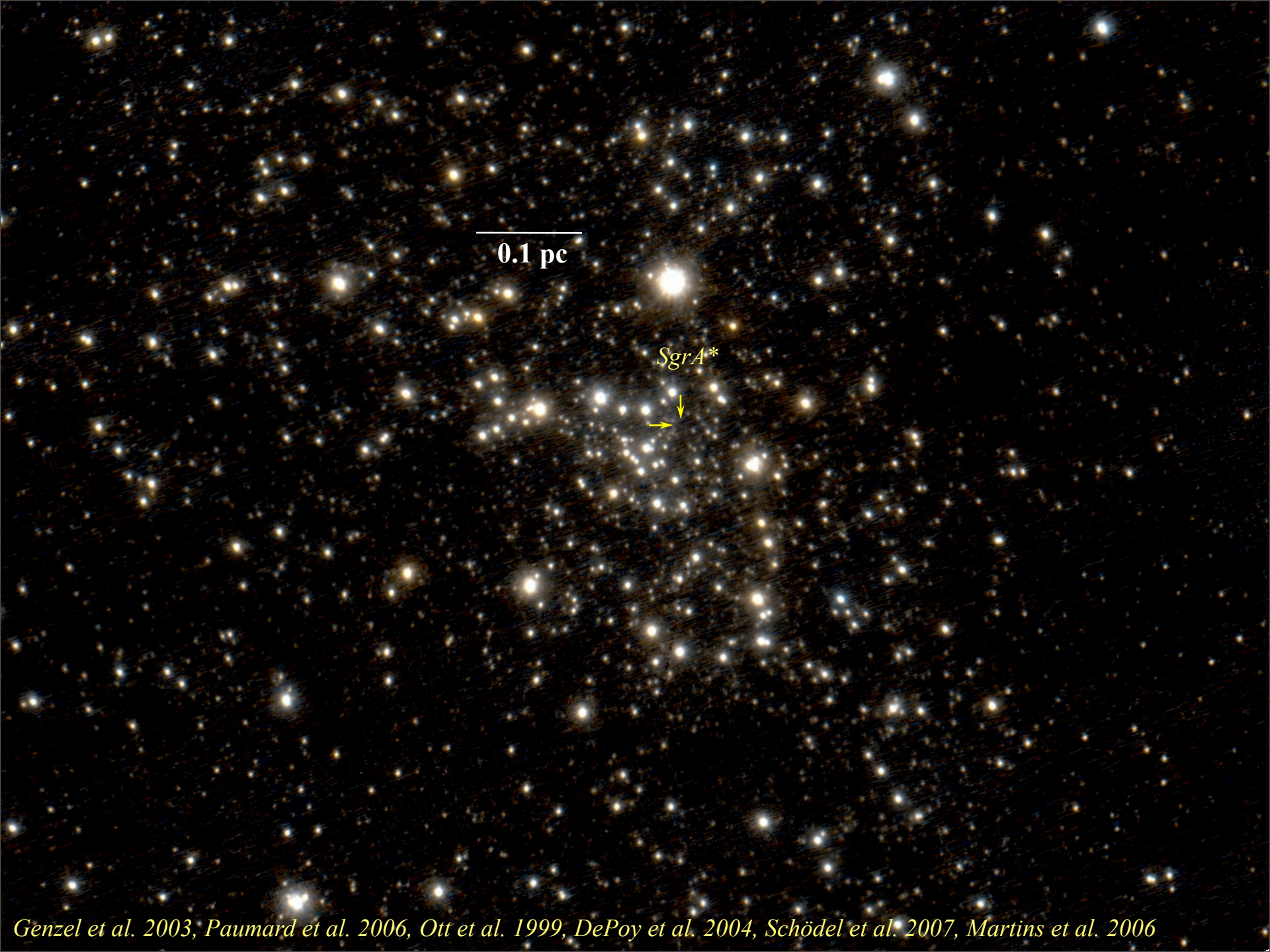

**flux variations**

*SgrA**




**radial velocity variations**

*Genzel et al. 2003, Paumard et al. 2006, Ott et al. 1999, DePoy et al. 2004, Schödel et al. 2007, Martins et al. 2006*

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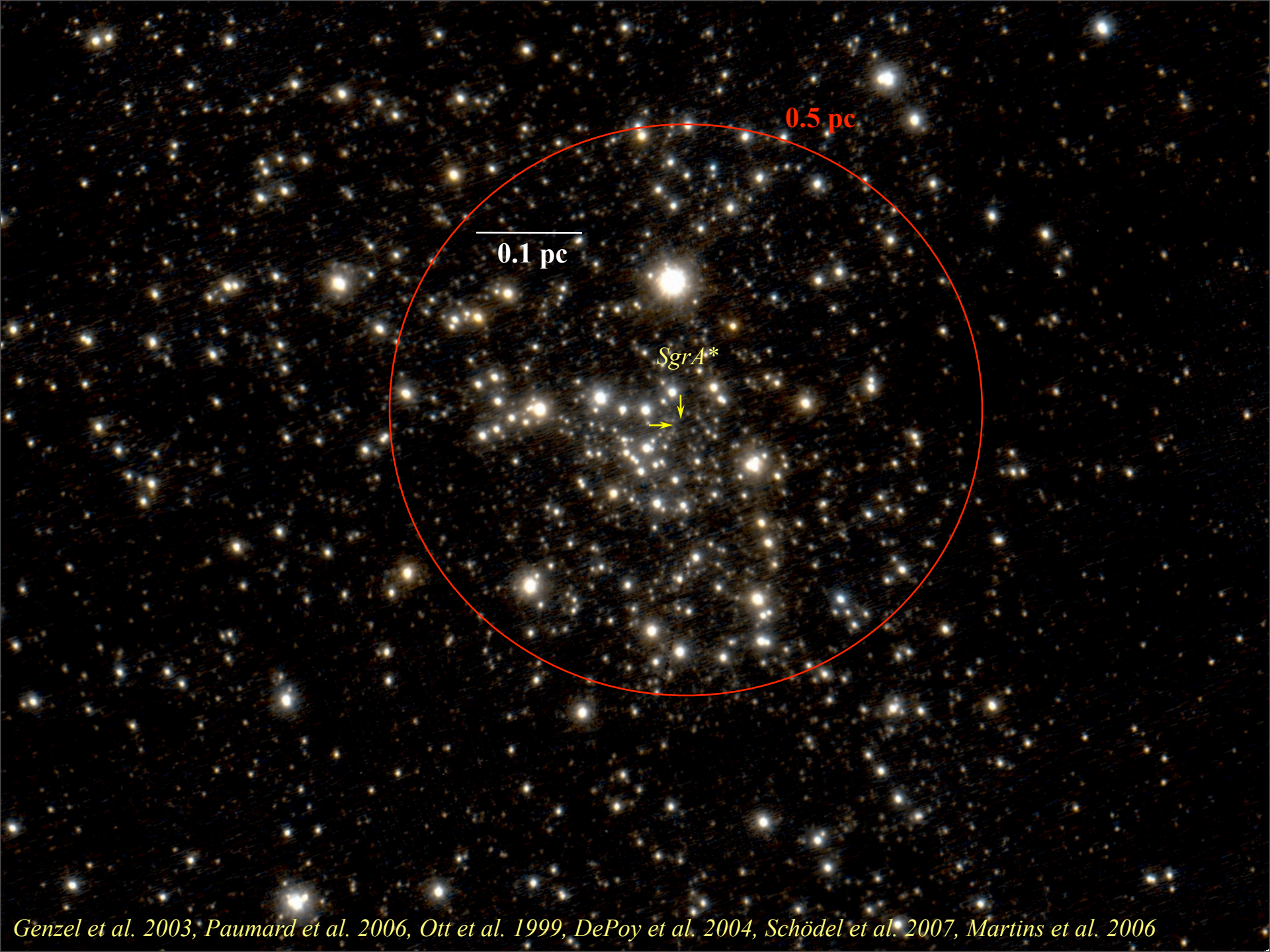


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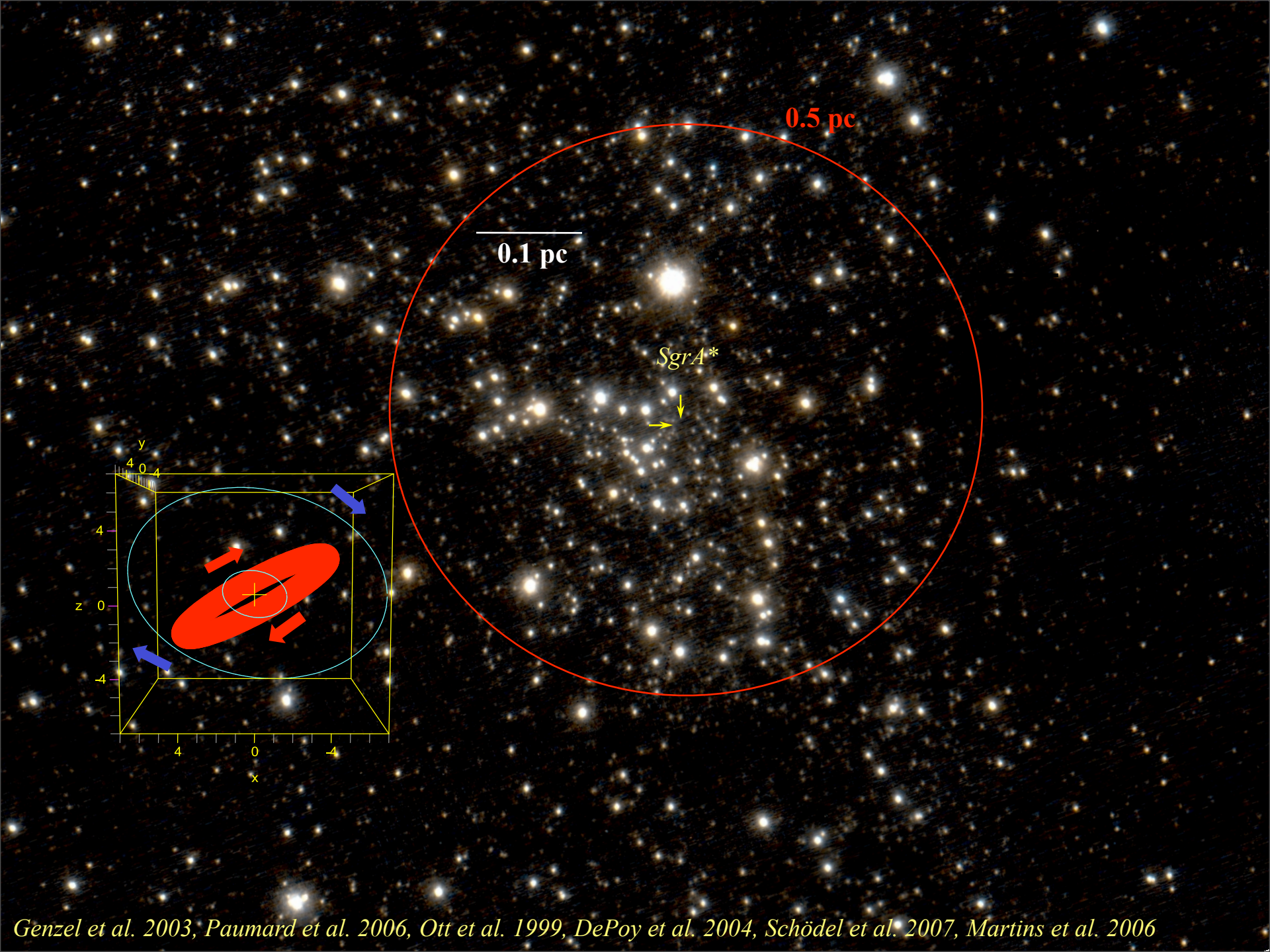



*Genzel et al. 2003, Paumard et al. 2006, Ott et al. 1999, DePoy et al. 2004, Schödel et al. 2007, Martins et al. 2006*

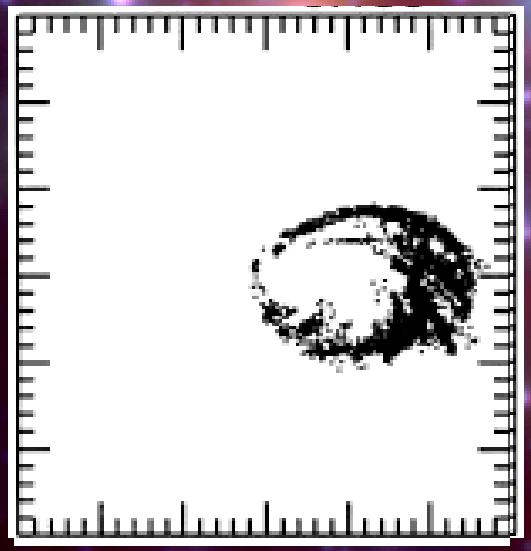
# *How did the young stars get into the central light year?*

*'normal' non-coherent, two body relaxation is too slow to allow stars with mass >2 $M_\odot$ to migrate into the central parsec*

Morris 1993, Rauch & Tremaine 1996, Sanders 1998, Levin & Beloborodov 2003, Gerhard 2001, Gould & Quillen 2003, Levin & Beloborodov 2003, Hansen & Milosavljevic 2003, Portegies Zwart et al. 2003, 2005, Kim et al. 2004, Milosavljevic & Loeb 2004, Davies & King 2005, Nayakshin & Cuadra 2005, Alexander 2005, Levin et al. 2005, Gürkan & Rasio 1005

# *How did the young stars get into the central light year?*

***local star formation:***
***tidally disrupted 'dispersion ring' evolving***
***into a star forming accretion disk:***
***problem: very high densities***



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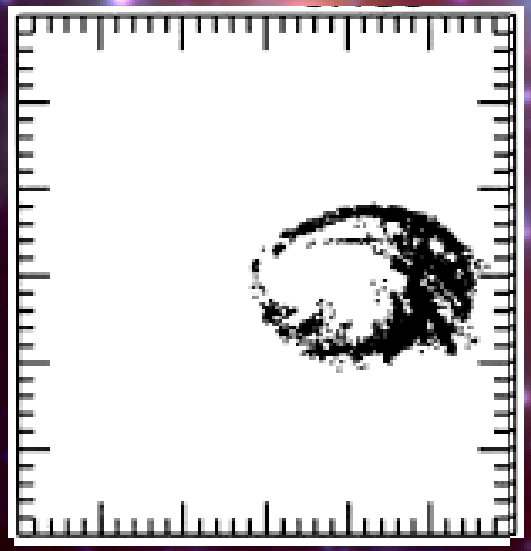

***external formation:***
***transport by in-spiraling massive cluster***
***problem: very large cluster mass and density***

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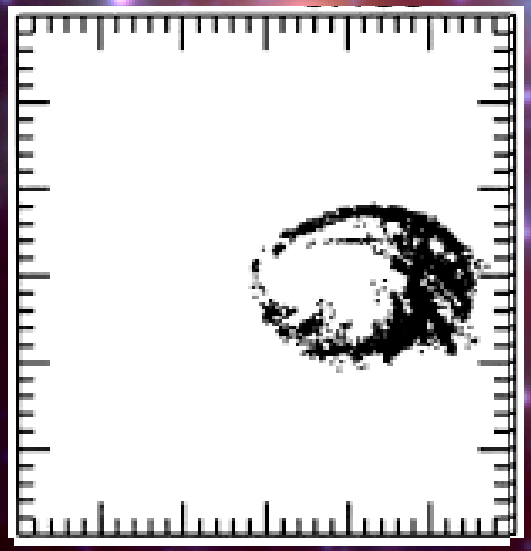

***external formation:***
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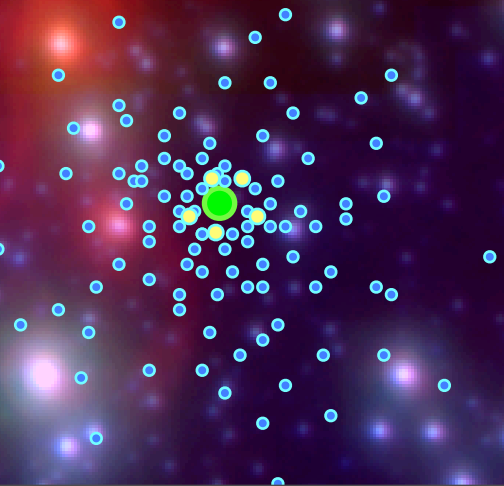
***problem: very large cluster mass and density***

***transport by scattering:***
***star-stellar BH scattering***
***stripping/re-juvenation***
***resonant relaxation***
***problem: rates and cross-sections***



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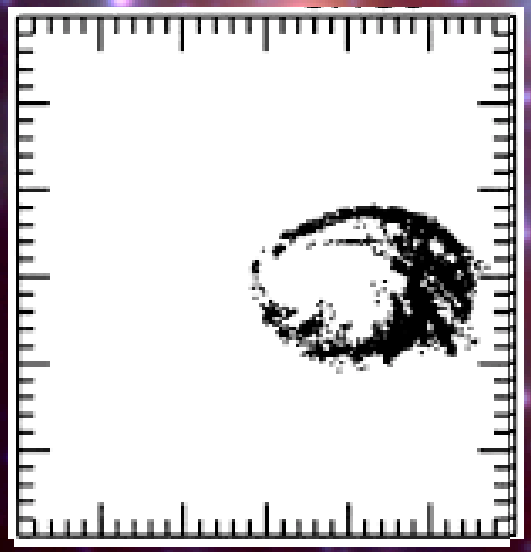

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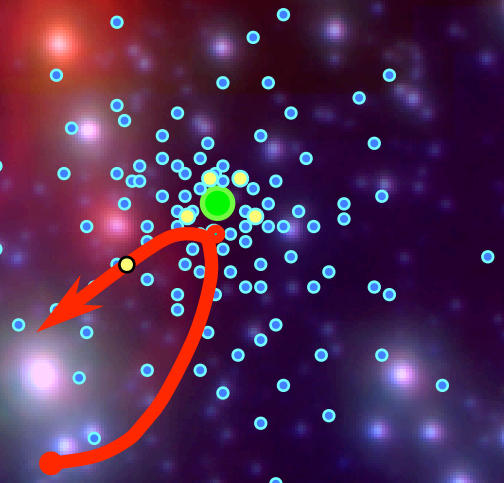

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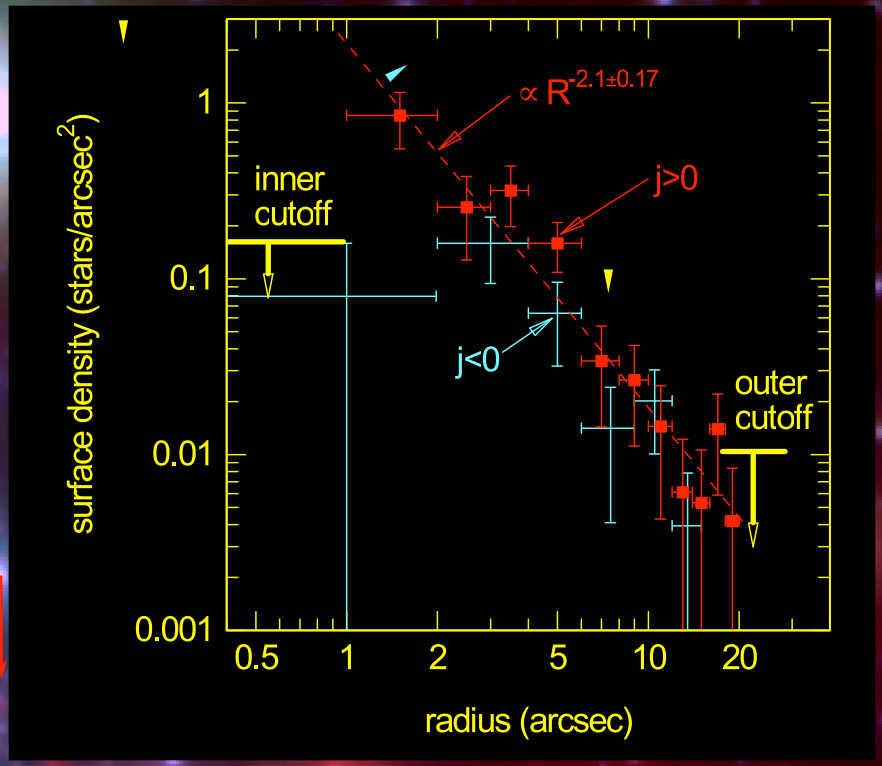
*Tamblyn & Rieke 1993, Navarro et al. 1994, 1997, Krabbe et al. 1995, Nayakshin et al. 2005, Nayakshin & Sunyaev 2005, Paumard et al. 2006, Martins et al. 2007, Berukoff & Hansen 2007*

# *surface density distribution, stellar mass*




*Tamblyn & Rieke 1993, Navarro et al. 1994, 1997, Krabbe et al. 1995, Nayakshin et al. 2005, Nayakshin & Sunyaev 2005, Paumard et al. 2006, Martins et al. 2007, Berukoff & Hansen 2007*

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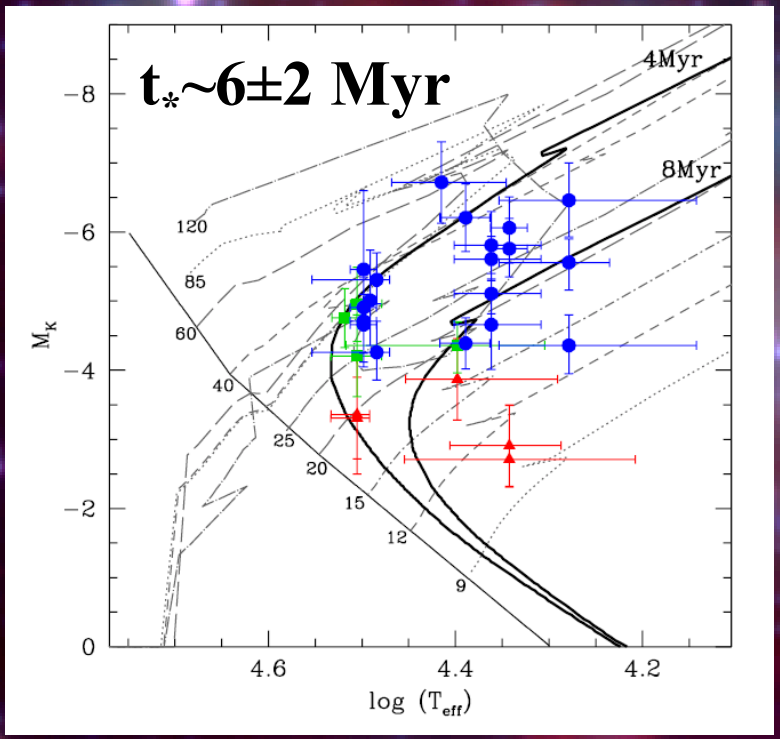


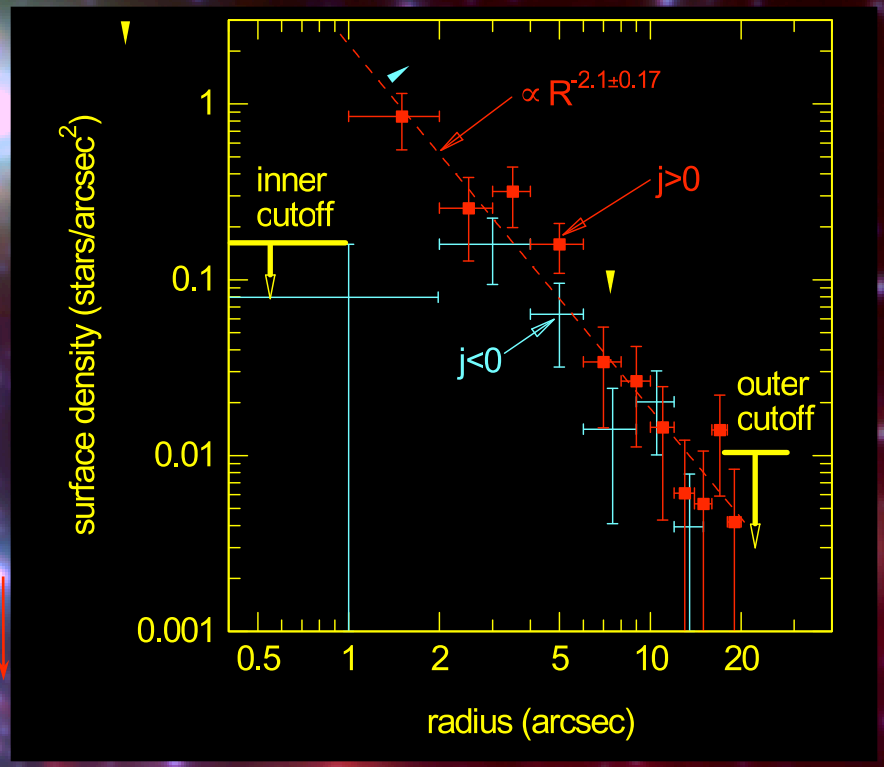


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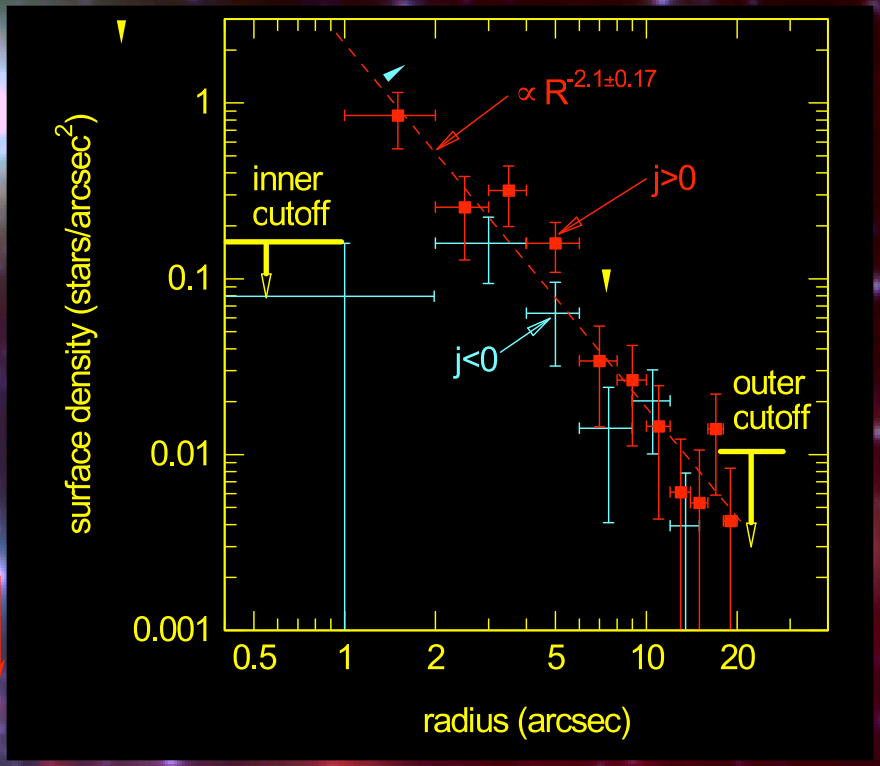
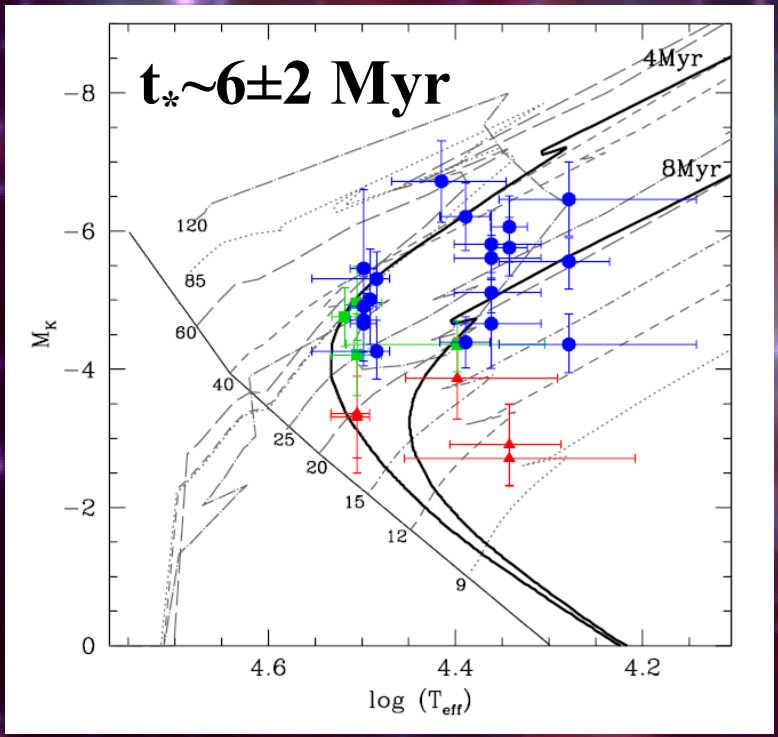



**stellar content of star disks ~$10^4$ $M_\odot$:**

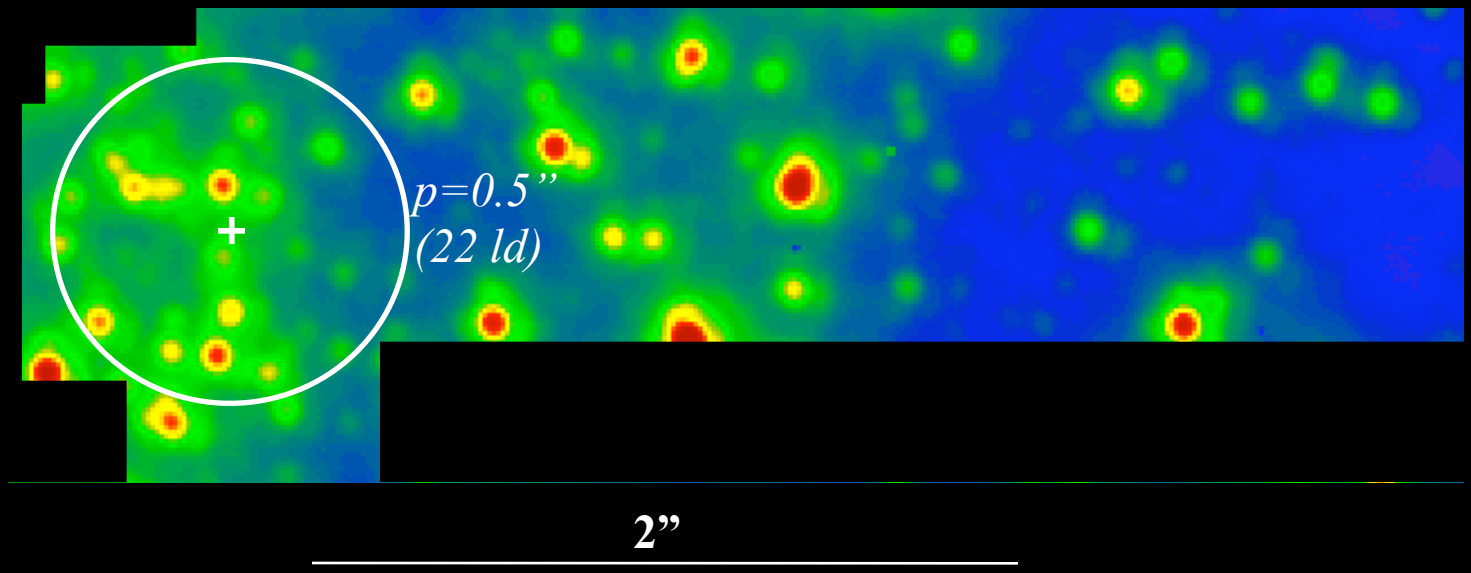
- **from K-band luminosity function and flat IMF**
- **from N-body simulations of thickness and age**
- **from limit to X-ray emission of T-Tau stars**

*Tamblyn & Rieke 1993, Navarro et al. 1994, 1997, Krabbe et al. 1995, Nayakshin et al. 2005, Nayakshin & Sunyaev 2005, Paumard et al. 2006, Martins et al. 2007, Berukoff & Hansen 2007*

**these observations make a strong case for in situ formation of the stellar disk(s), following gas inflow and formation of a dense gas disk ≥ 6 Myrs ago**

*Tamblyn & Rieke 1993, Navarro et al. 1994, 1997, Krabbe et al. 1995, Nayakshin et al. 2005, Nayakshin & Sunyaev 2005, Paumard et al. 2006, Martins et al. 2007, Berukoff & Hansen 2007*

# *'Paradox of Youth': young massive stars in the central cusp*




**SINFONI 2005**
**70 mas resolution**

Ghez et al. 2003, Eisenhauer et al. 2005, Paumard et al. 2006, **see Tal Alexander's talk**

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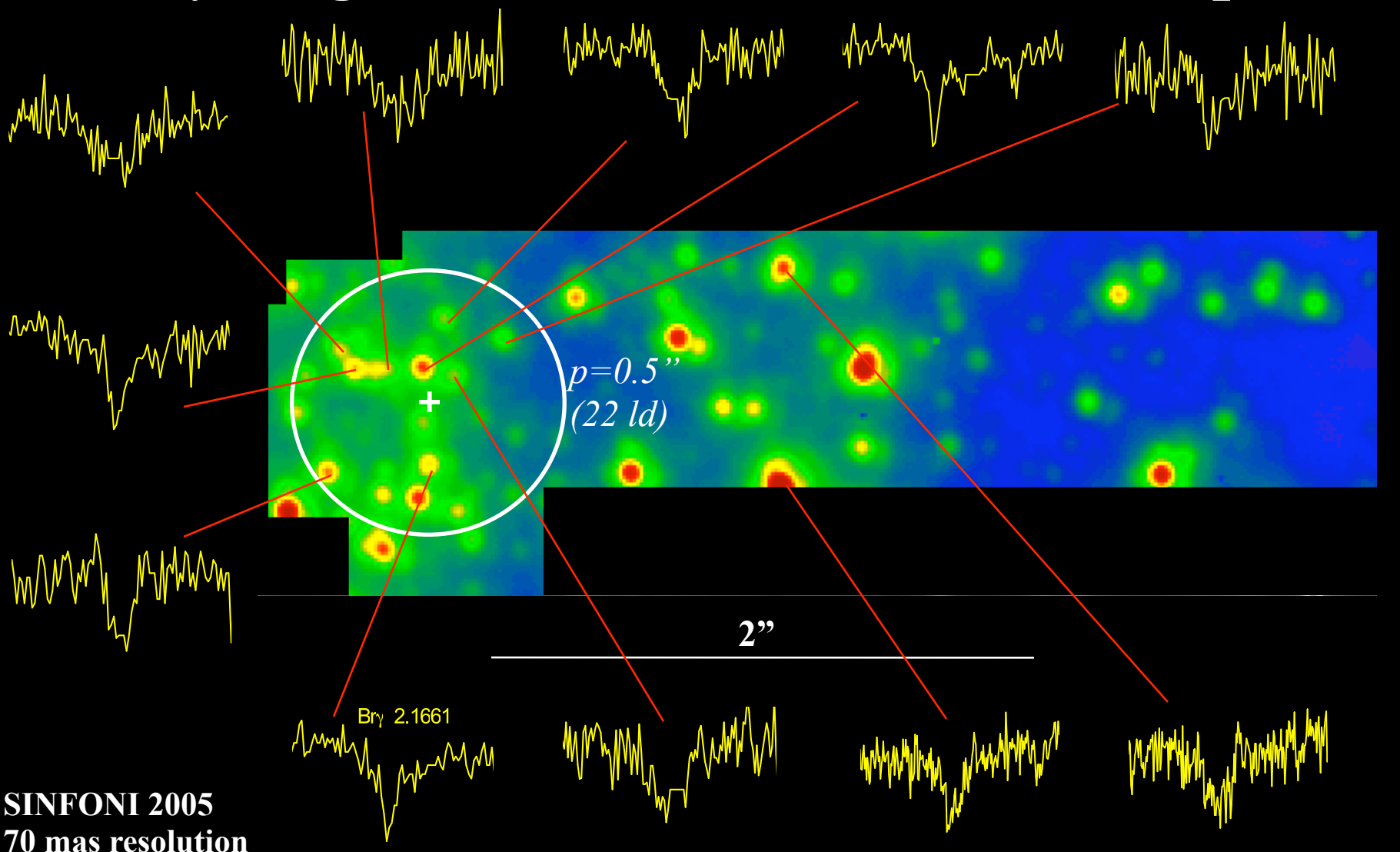


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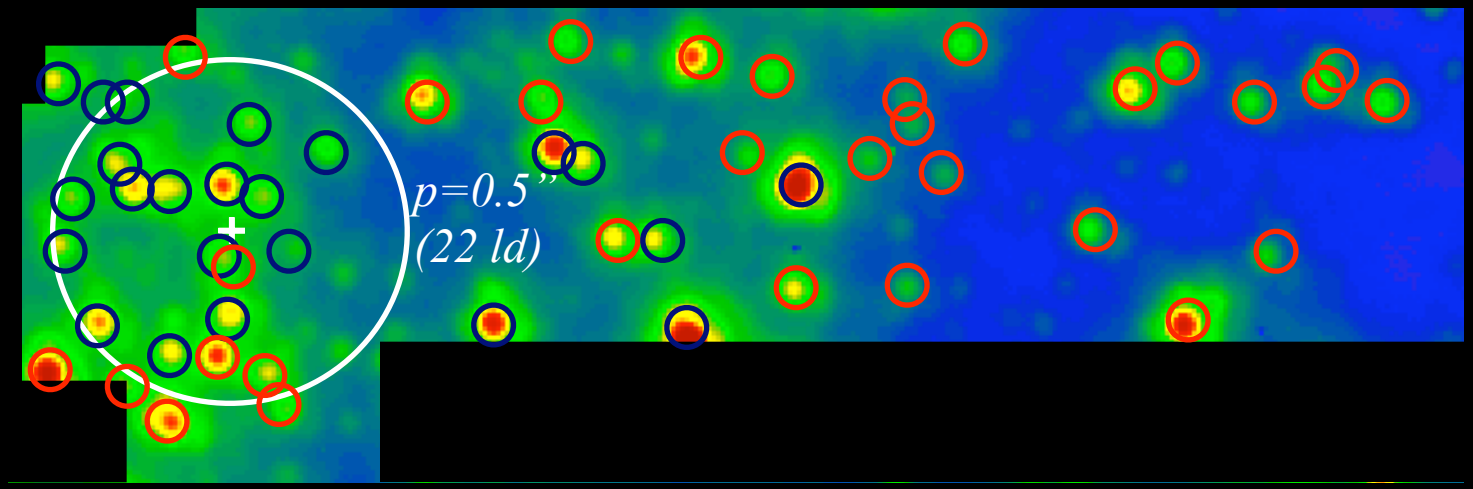
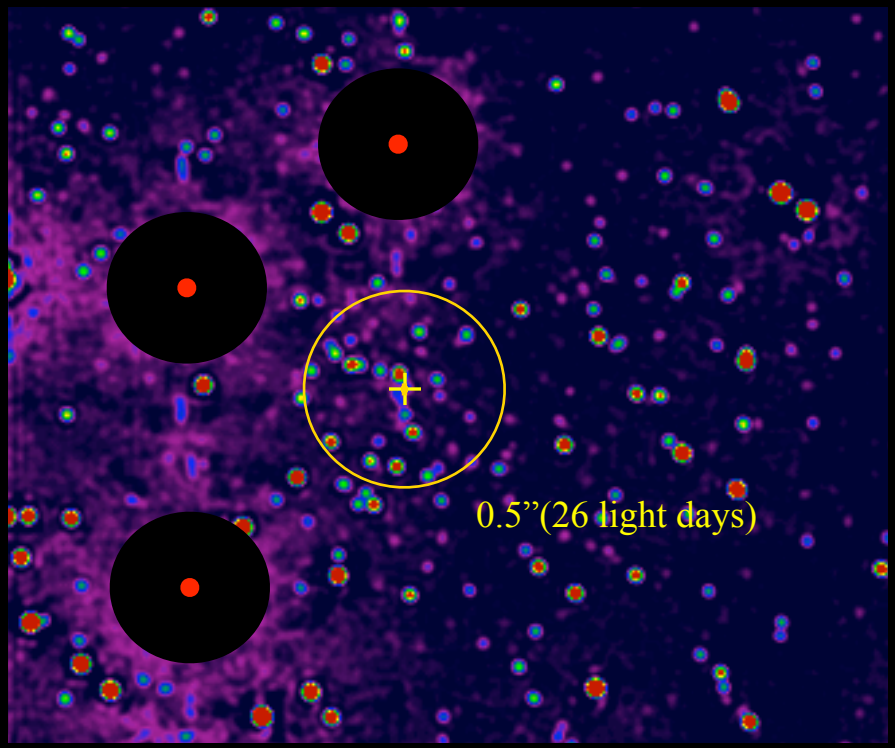



**>90% of all K<16 stars in the central light month are young main sequence B stars**

**SINFONI 2005**
**70 mas resolution**

Ghez et al. 2003, Eisenhauer et al. 2005, Paumard et al. 2006, **see Tal Alexander's talk**

# Motion of stars near SgrA*



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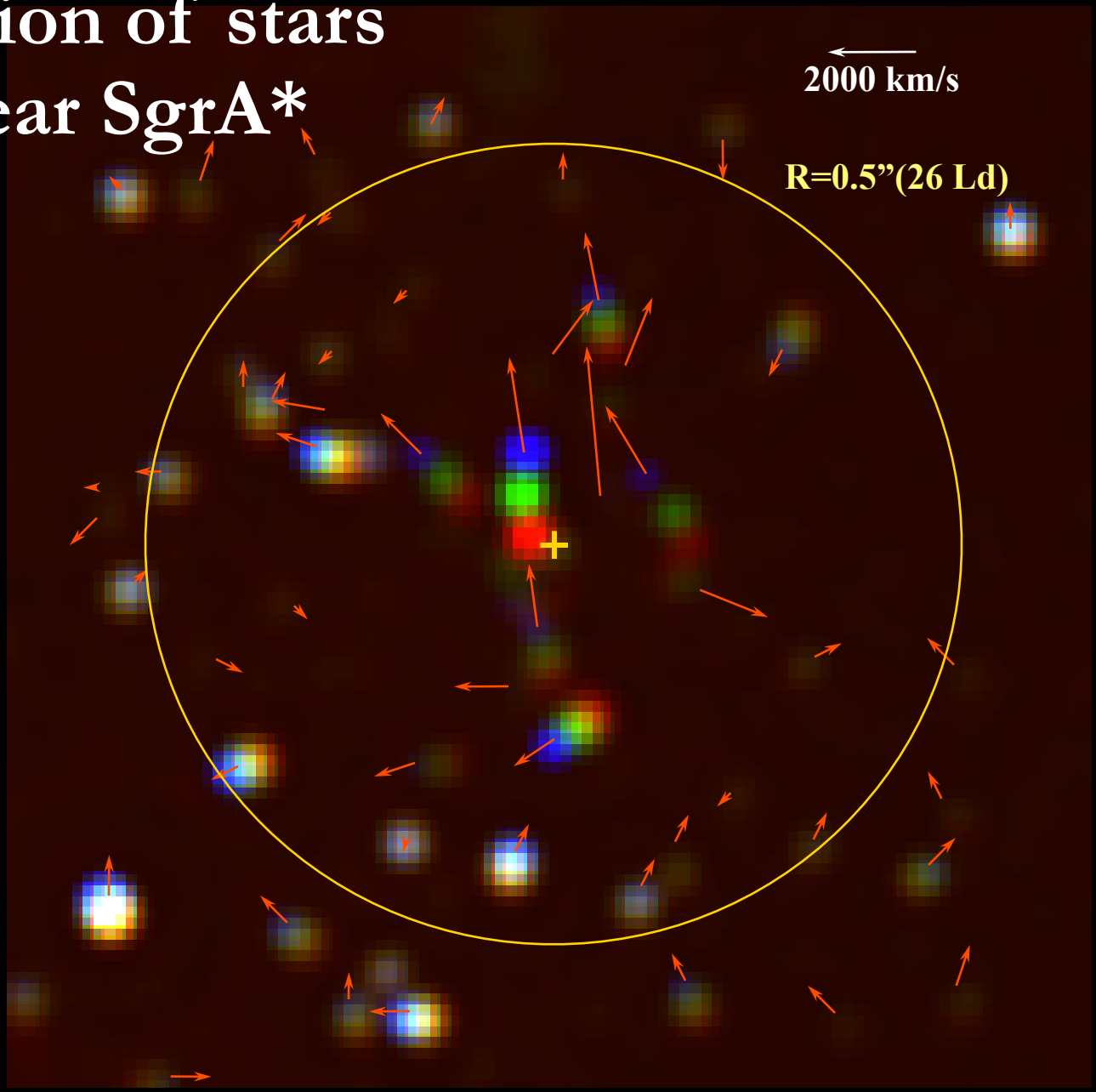

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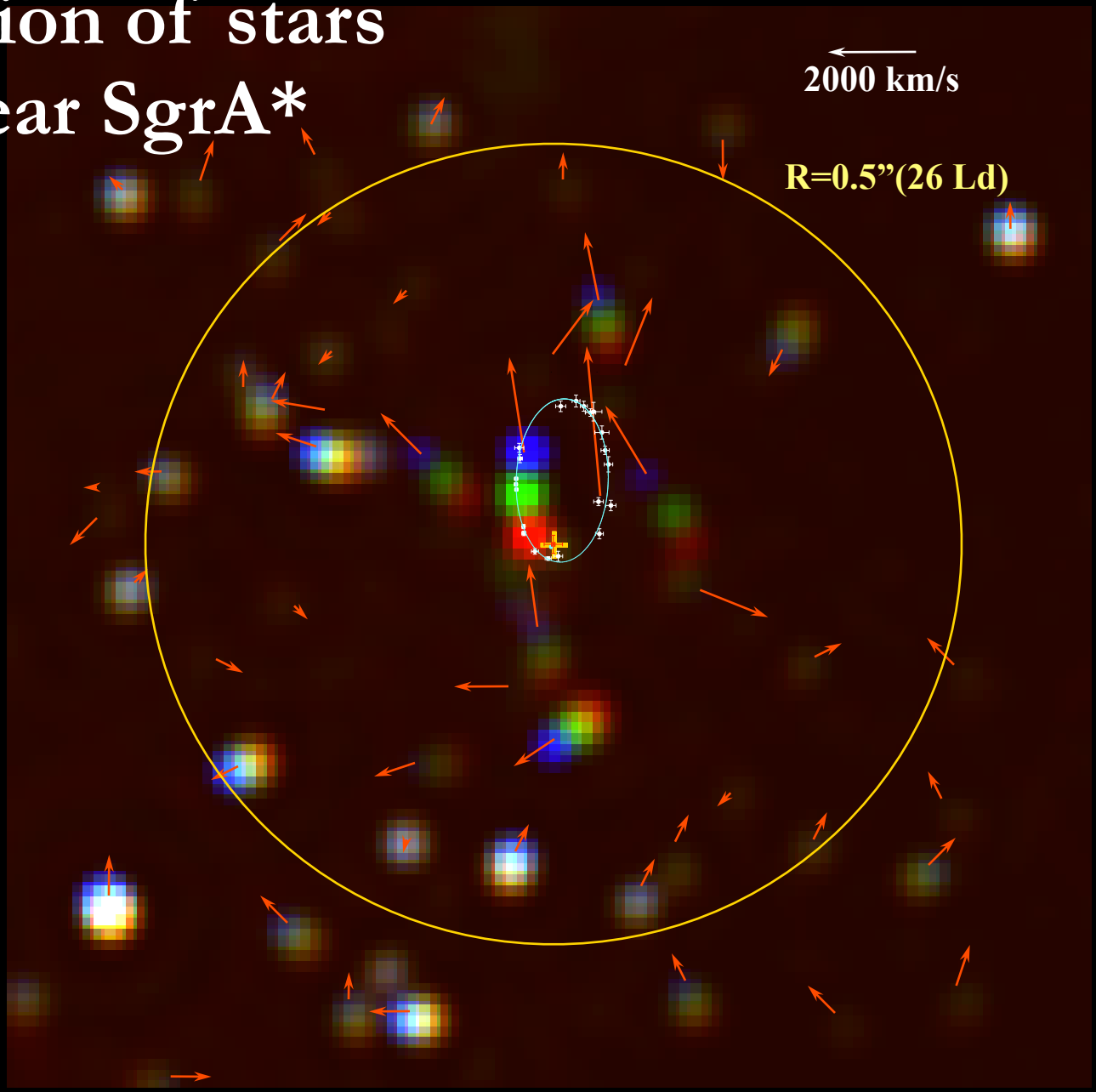
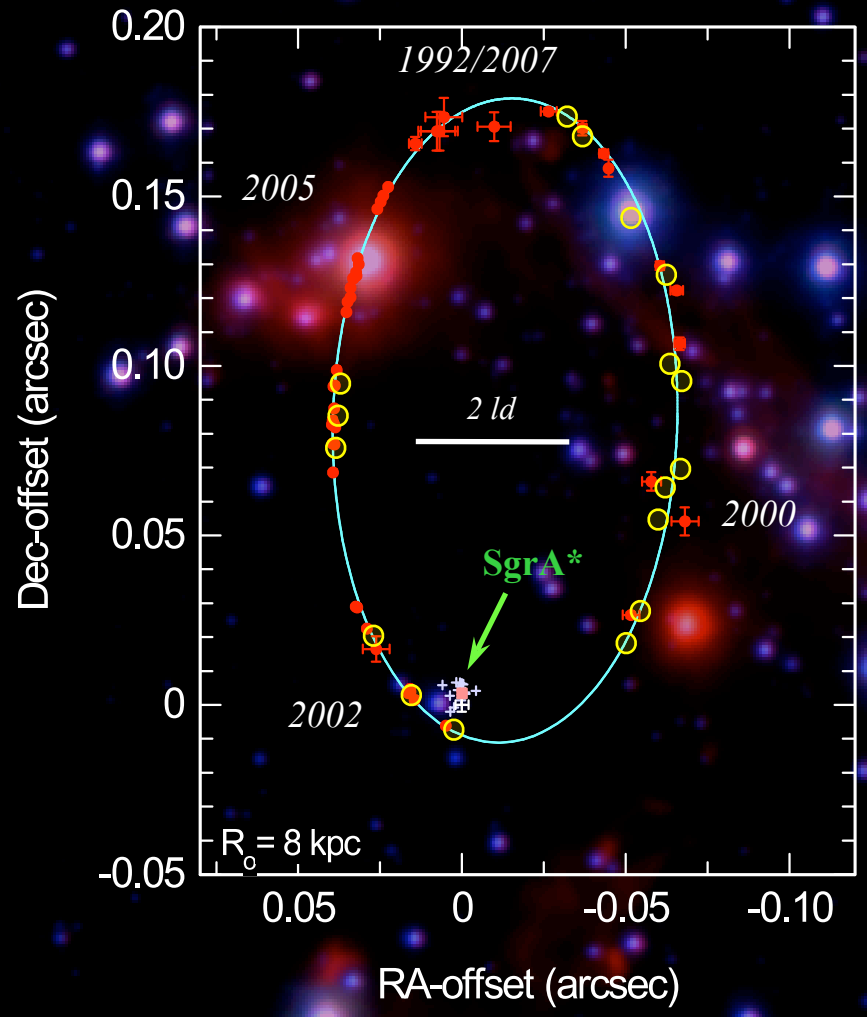
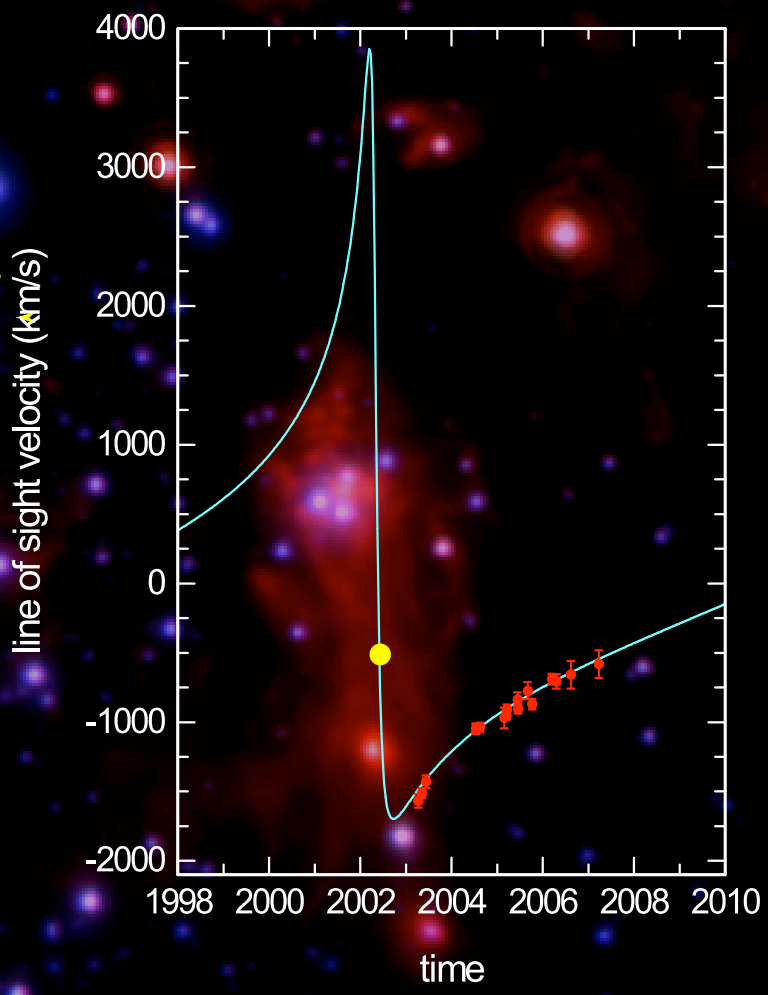


# *15 years of tracking stellar orbits*

*MPE (VLT)*
*Univ. California Los Angeles (Keck)*




Schödel et al. 2002, 2003, Ghez et al. 2003, 2005, Eisenhauer et al. 2003, 2005, Gillessen et al. 2007

# *status of BH hypothesis*

- compelling evidence for point mass hypothesis

$$M_\bullet = 3.76\ (\pm 0.05)\ (\pm\ 0.2)\ x10^6\ (R_o/8)^{2.94}\ M_\odot$$

(mass contained within a few light hours of SgrA*)

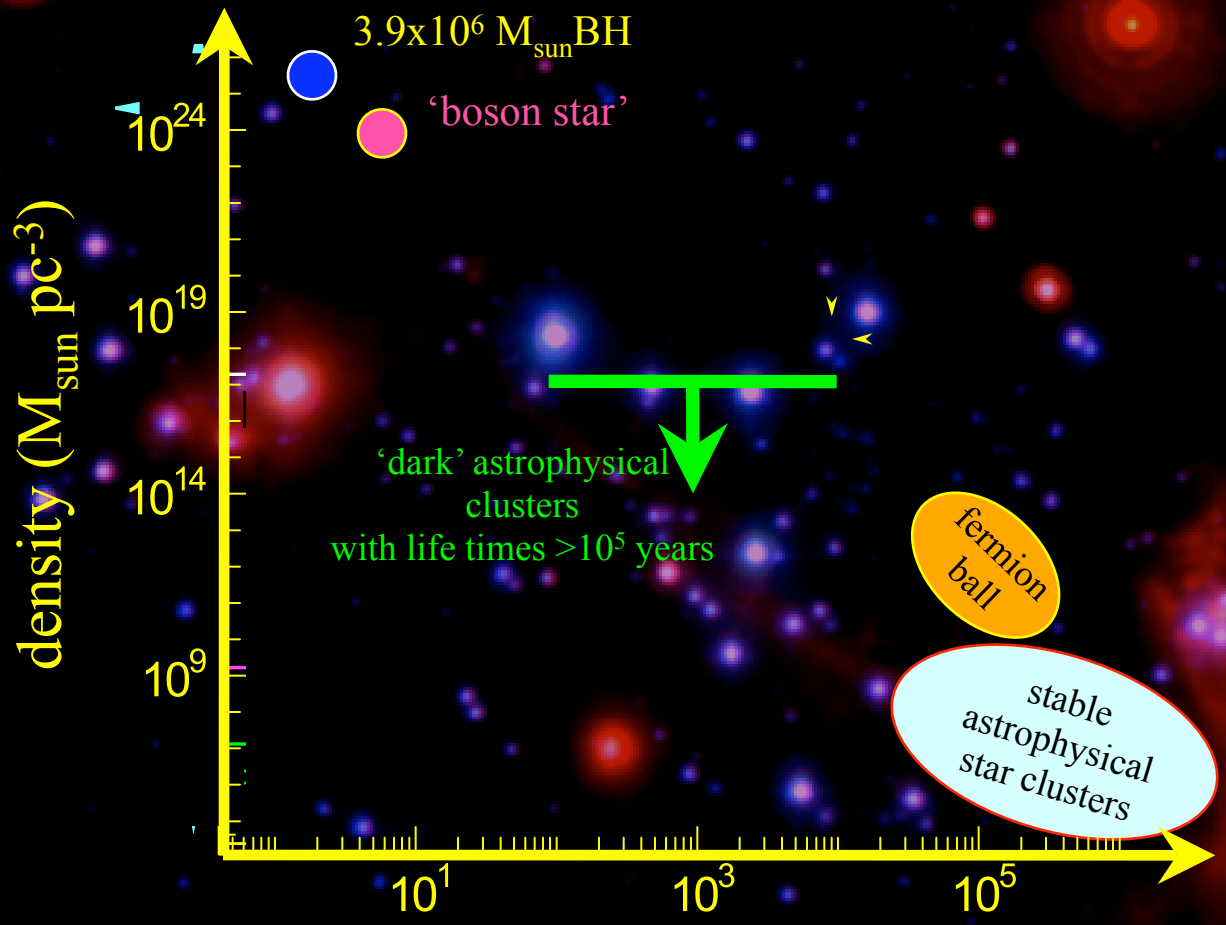
- combined with radio: $\langle\rho\rangle \geq 10^{20\text{-}22}\ M_\odot pc^{-3}$: must be BH, beyond any reasonable doubt if GR is applicable
- extended mass within S2-orbit <a few % of point mass ($<10^5\ M_\odot$)
- SR- and GR-effects can be measured within next 5-10 years: $\beta \sim 0.06$
- big next step: astrometric interferometry

Schödel et al. 2002, 2003, Ghez et al. 2003, 2005, Eisenhauer et al. 2003, 2005, Gillessen et al. 2007

# orbits of central ‘S’-star cluster


*Schödel et al. 2002, 2003, Ghez et al. 2003, 2005, Eisenhauer et al. 2005, Gillessen et al. 2007*

# *Is SgrA* a black hole ?*



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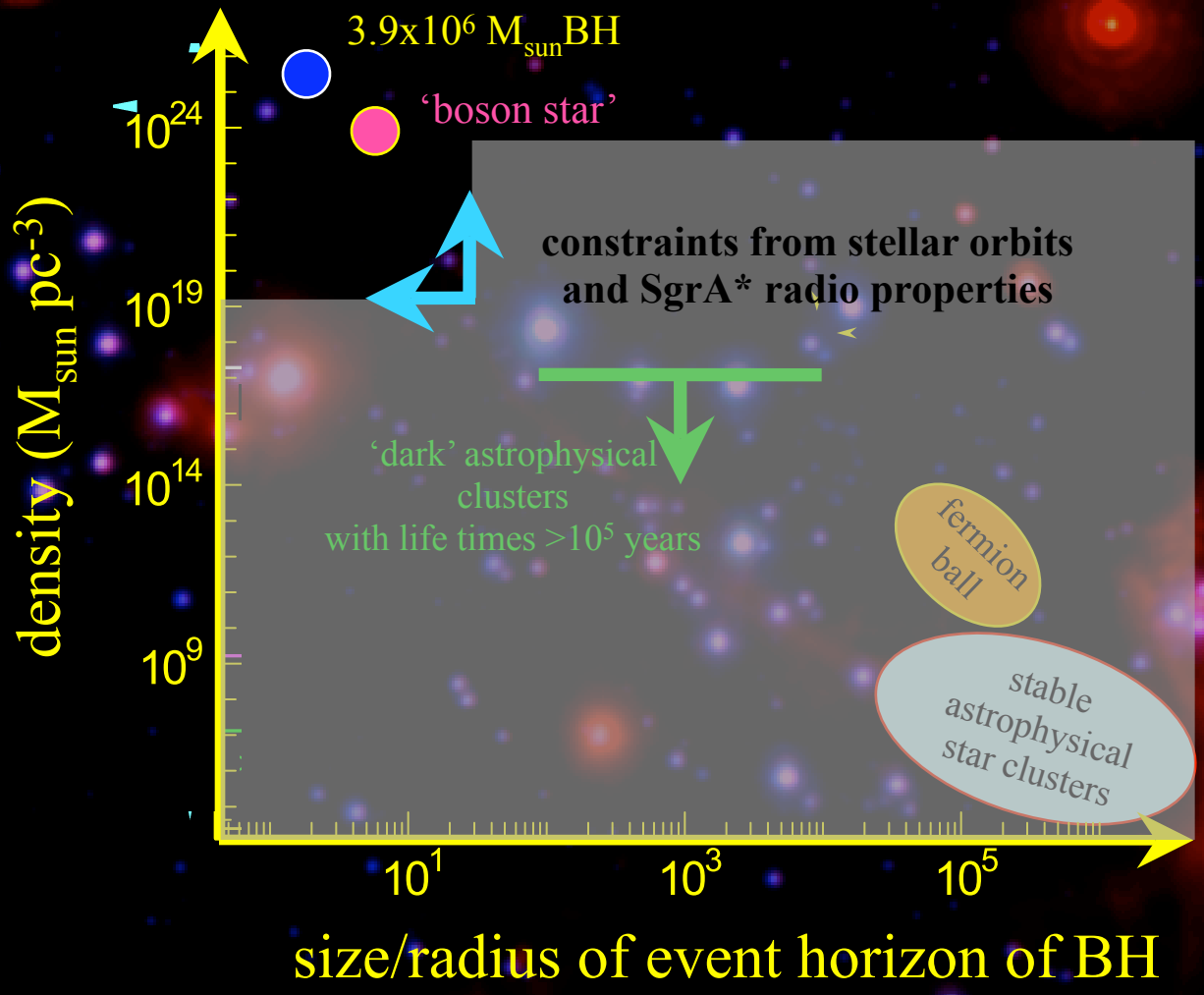
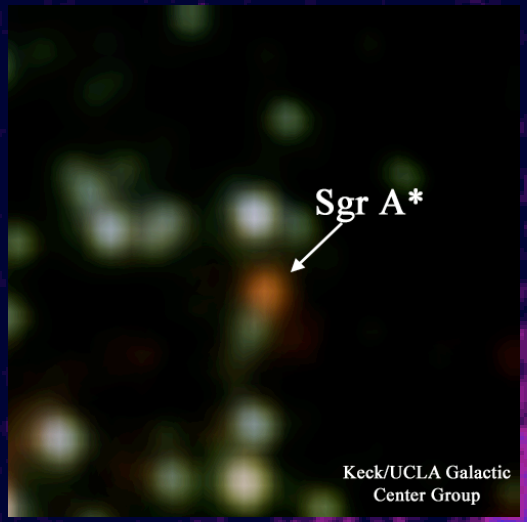


# *Is SgrA* a black hole ?*

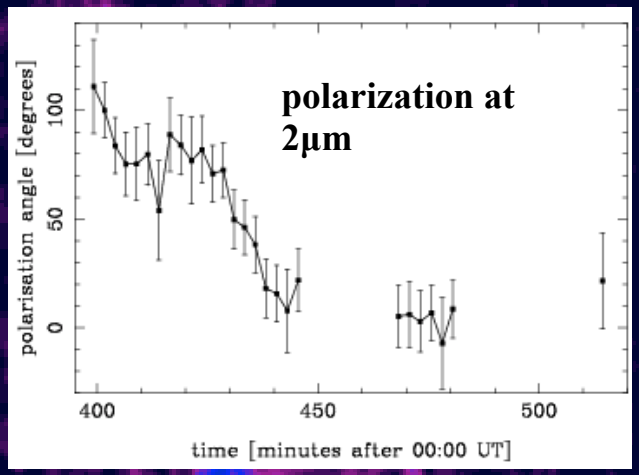
# *SgrA*:accretion onto the hole*

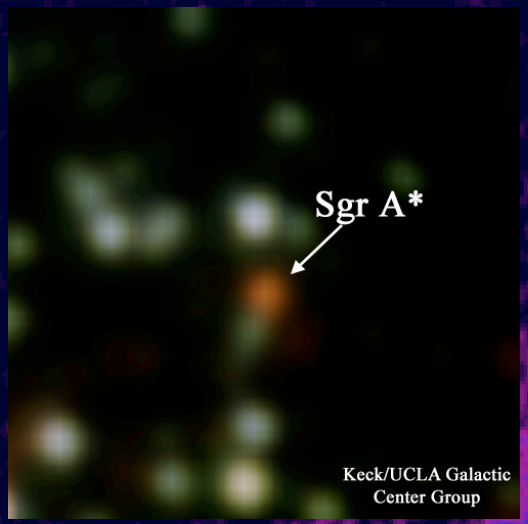
*key issue:*
*'dimness' of emission:*
$L \sim 10^{-5 \ldots 8} L_{Edd}$

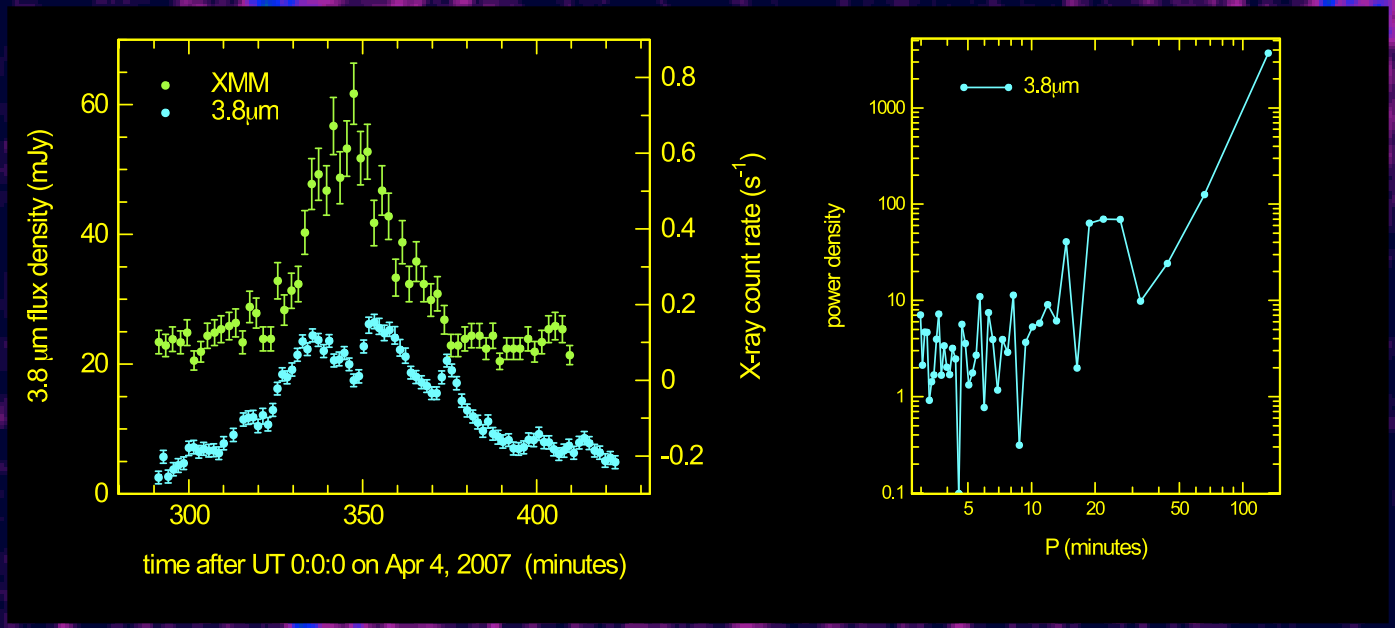



*Baganoff et al. 2001, Genzel et al. 2003,, Ghez et al. 2004, 2005, Eisenhauer et al. 2005, Gillessen et al. 2006, Eckart et al. 2005, 2006a/b, Trippe et al. 2007, Meyer et al. 2007, Porquet et al. 2007*

# *SgrA*:accretion onto the hole*

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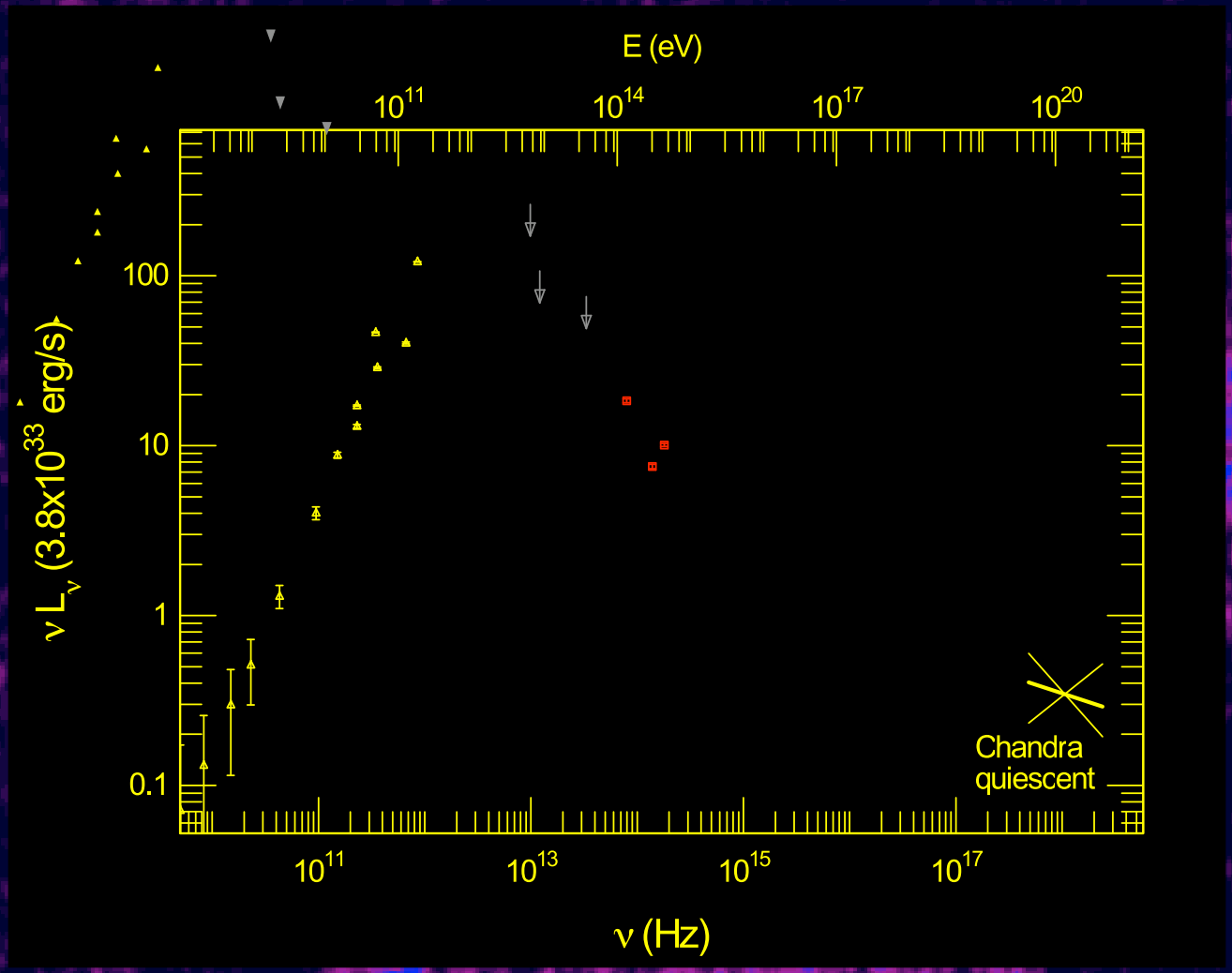
# *SgrA* spectral energy distribution*




Falcke et al. 1999, Morris et al. 2001, Zhao et al. 2004, Markoff et al. 2001, Genzel et al. 2003, Ghez et al. 2004,2005, Eisenhauer et al. 2005, Baganoff et al. 2001, 2003, Bower et al. 2003, 2004, Goldwurm et al. 2003, Porquet et al. 2003, Eckart et al. 2004, 2005, Markoff et al. 2001, Yuan et al. 2001, 2003, 2004, Liu et al. 2004,2005, Gillessen et al. 2006, Marrone et al. 2006, Krabbe et al. 2006

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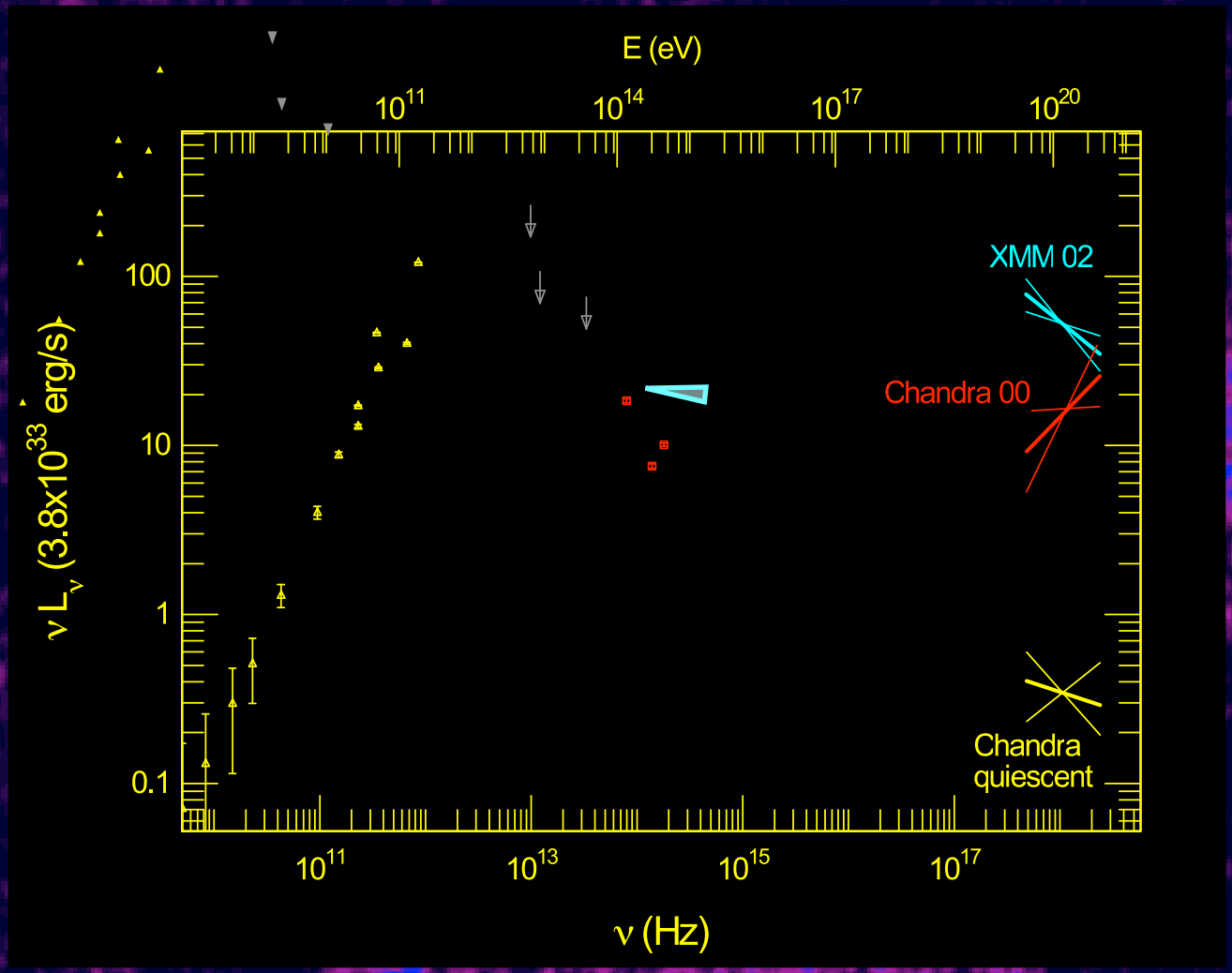


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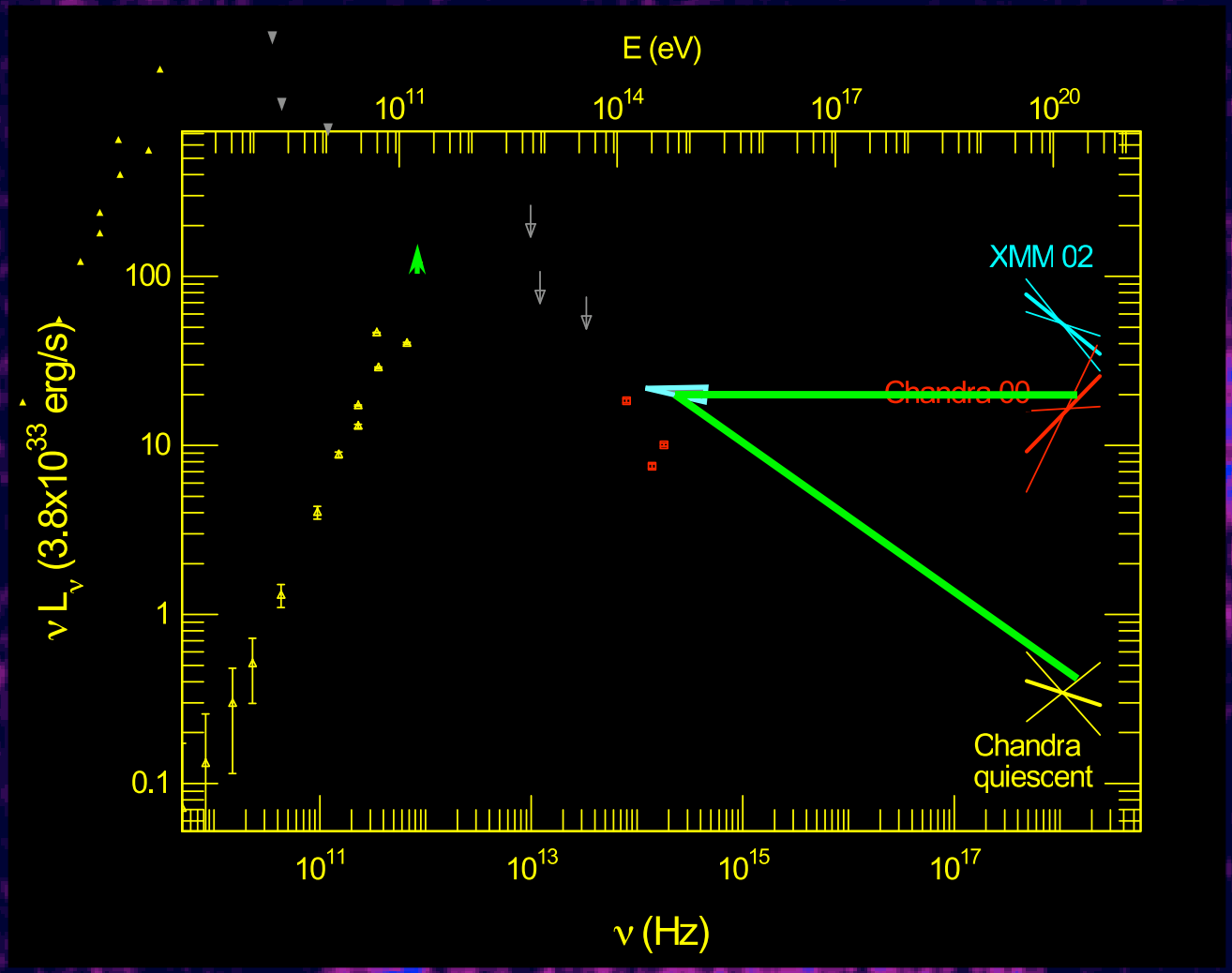


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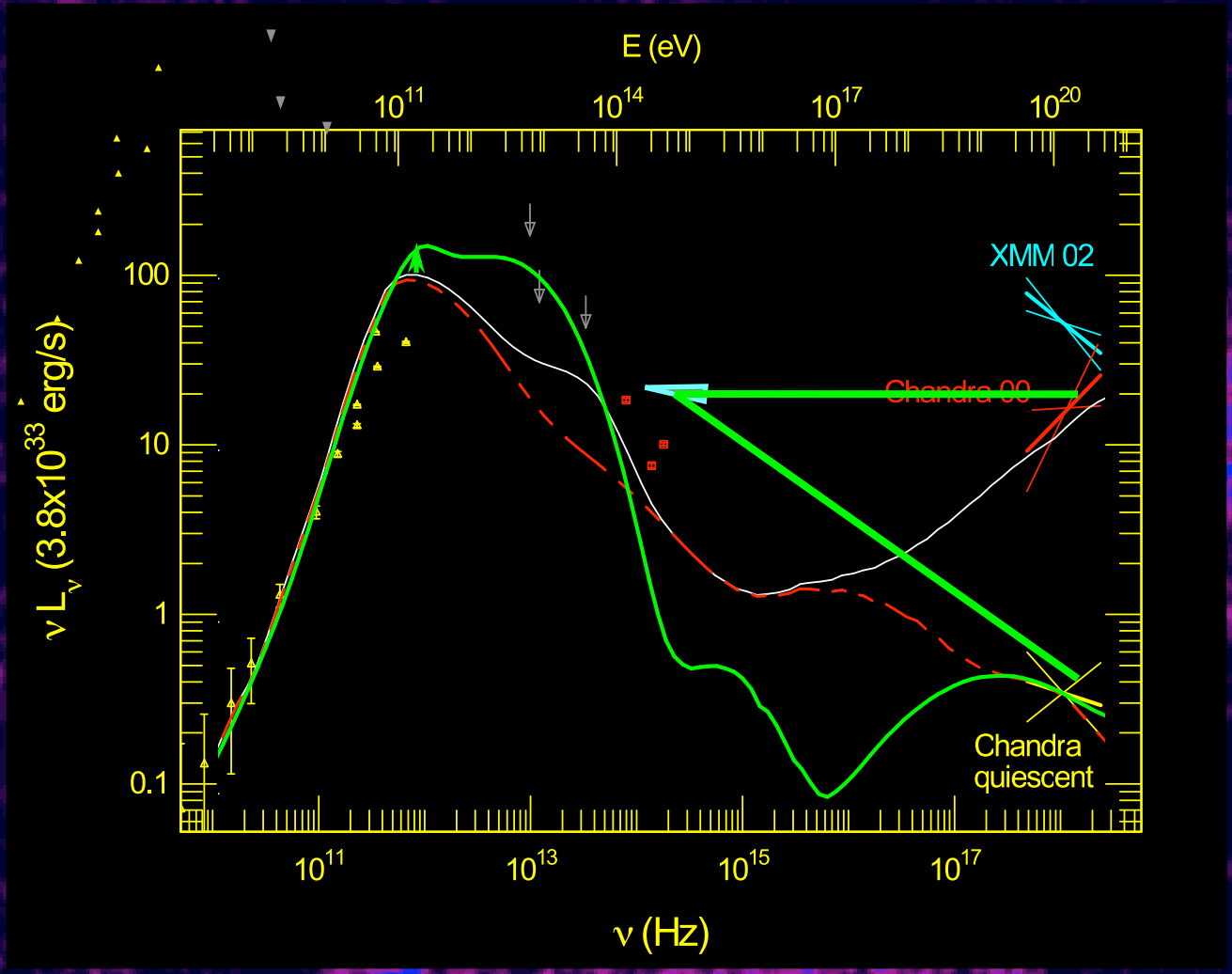


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# *SgrA* spectral energy distribution*

**most likely scenario:**

- **reconnection event transiently heats a few % of the virialized electrons to $\gamma \sim 10^3$ (NIR synchrotron emission)**
- **$\gamma \sim 10^3$ electrons upscatter photons in submm 'bump' to $\sim 10^{17....18}$ Hz (X-ray emission)**

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# *accretion onto the BH*

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

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- *dM/dt $\sim 10^{2}$ times greater $\sim 10^{2.5}$ years ago*

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- *dM/dt strongly dependent on angular momentum distribution of stars in central cusp*

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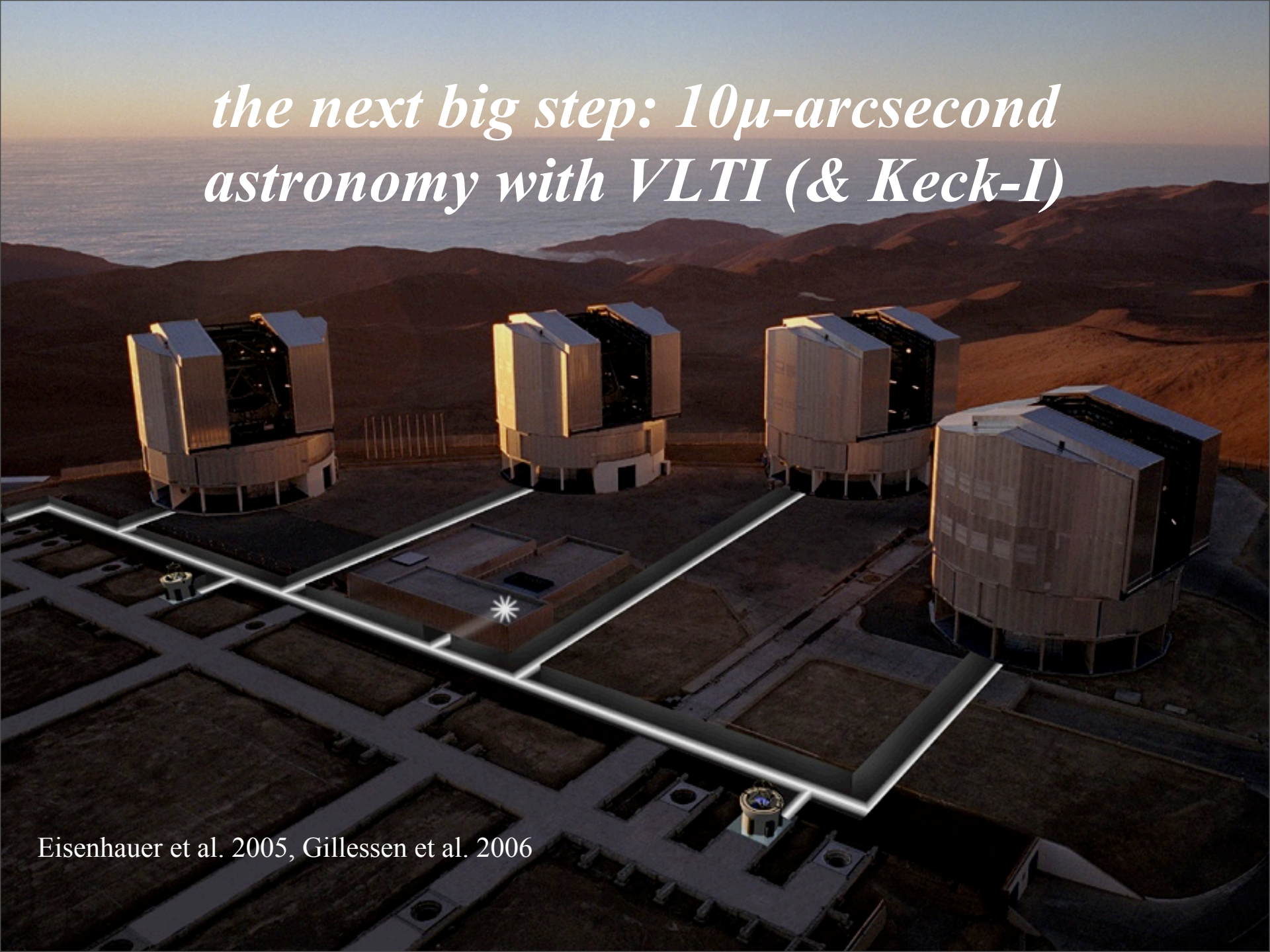
# *accretion onto the BH*

*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

# *the next big step: 10μ-arcsecond astronomy with VLTI (& Keck-I)*



Eisenhauer et al. 2005, Gillessen et al. 2006

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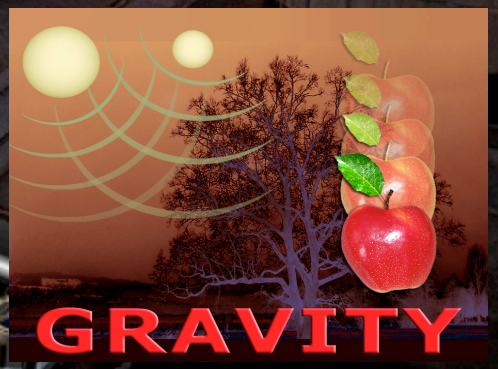


Eisenhauer et al. 2005, Gillessen et al. 2006

**MPE, Paris-LESIA, MPIA, Uni Köln**
*PI Frank Eisenhauer (MPE)*

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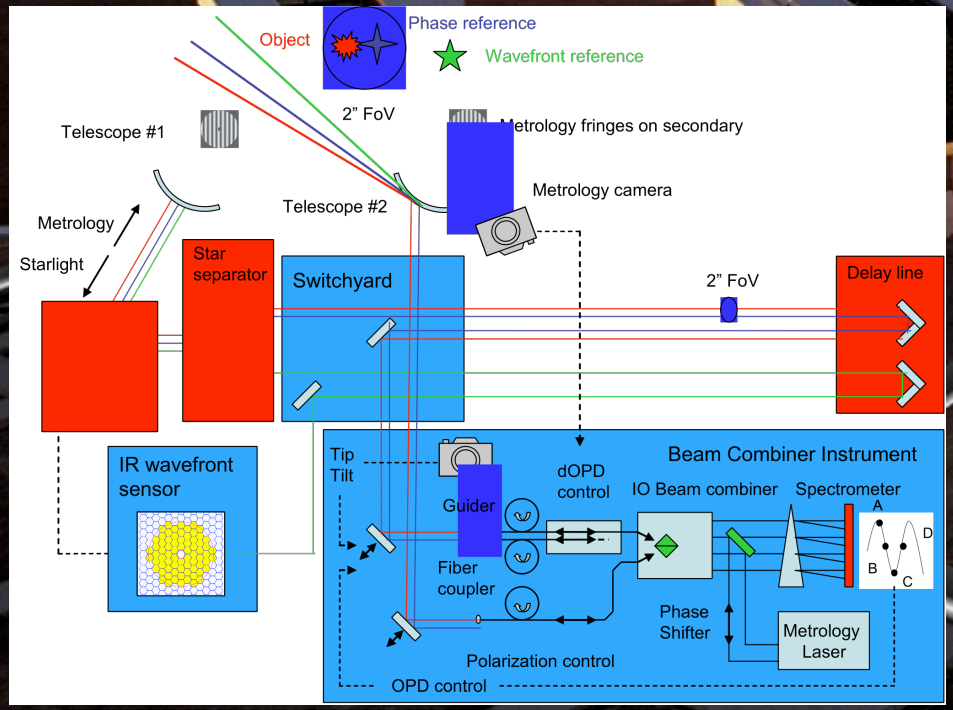
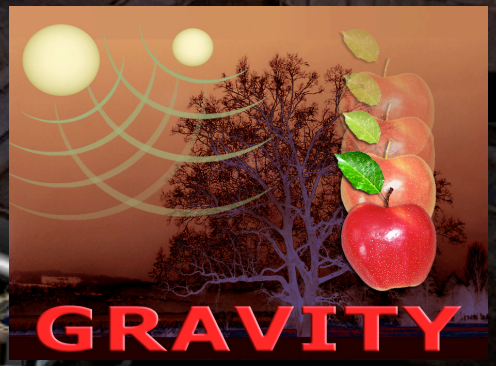



Eisenhauer et al. 2005, Gillessen et al. 2006

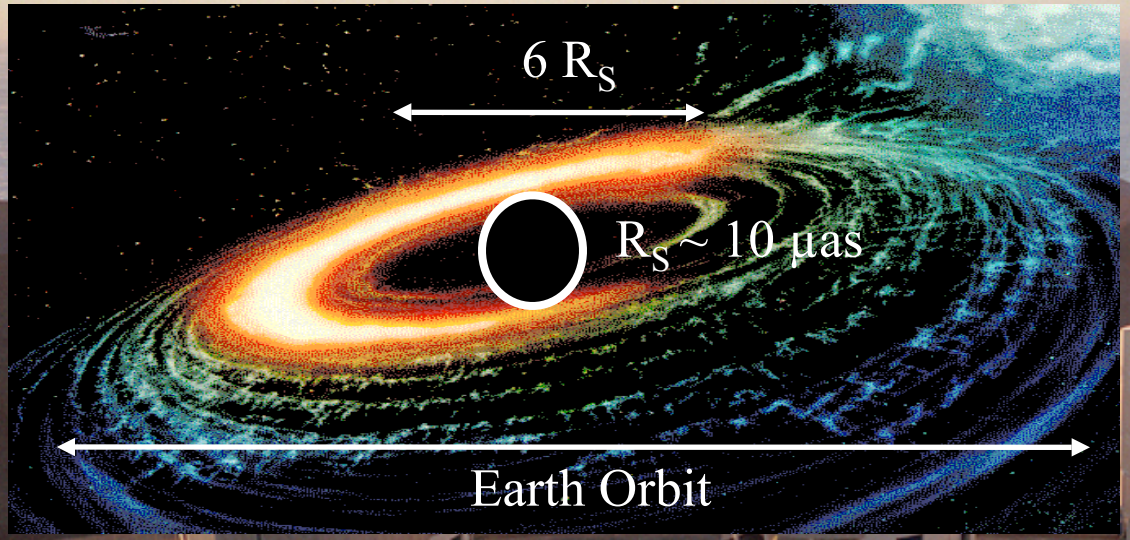
- dual beam astrometric interferometric imager
- K>19: high throughput integrated optics on 3-4 UTs, efficient IR wave front sensing, active laser metrology
- 10μarcsec astrometry: phase/fringe tracking on nearby star (< 5nm rms)




**MPE, Paris-LESIA, MPIA, Uni Köln**

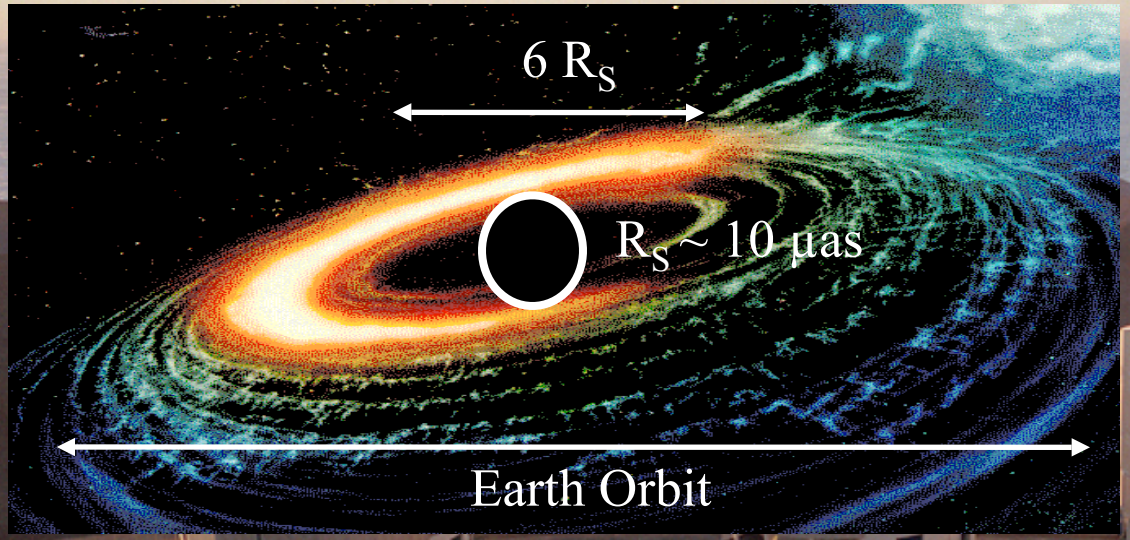
*PI Frank Eisenhauer (MPE)*

# GRAVITY and strong gravity in GC




**GRAVITY** will measure the motion of gas close to the event horizon of the Galactic Center black hole

# GRAVITY and strong gravity in GC




**GRAVITY** will measure the motion of gas close to the event horizon of the Galactic Center black hole

for a simple orbital motion **GRAVITY** may be able to probe the regime of strong gravity ($R/(GMc^{-2})$~ a few) and the Kerr metric

# *Summary*

- *The Milky Way center harbors a ~3-4 million solar mass black hole, beyond any reasonable doubt*
- *disk(s) of young massive stars formed ~6 Myrs ago: most probably cloud infall and in situ star formation in accretion disk, top-heavy IMF*
- *stellar cusp around BH: paradox of youth*
- *X-/IR-/submm flares from SgrA*: 'MHD weather' in the central accretion zone and probe of the space- time on a few $R_s$?*