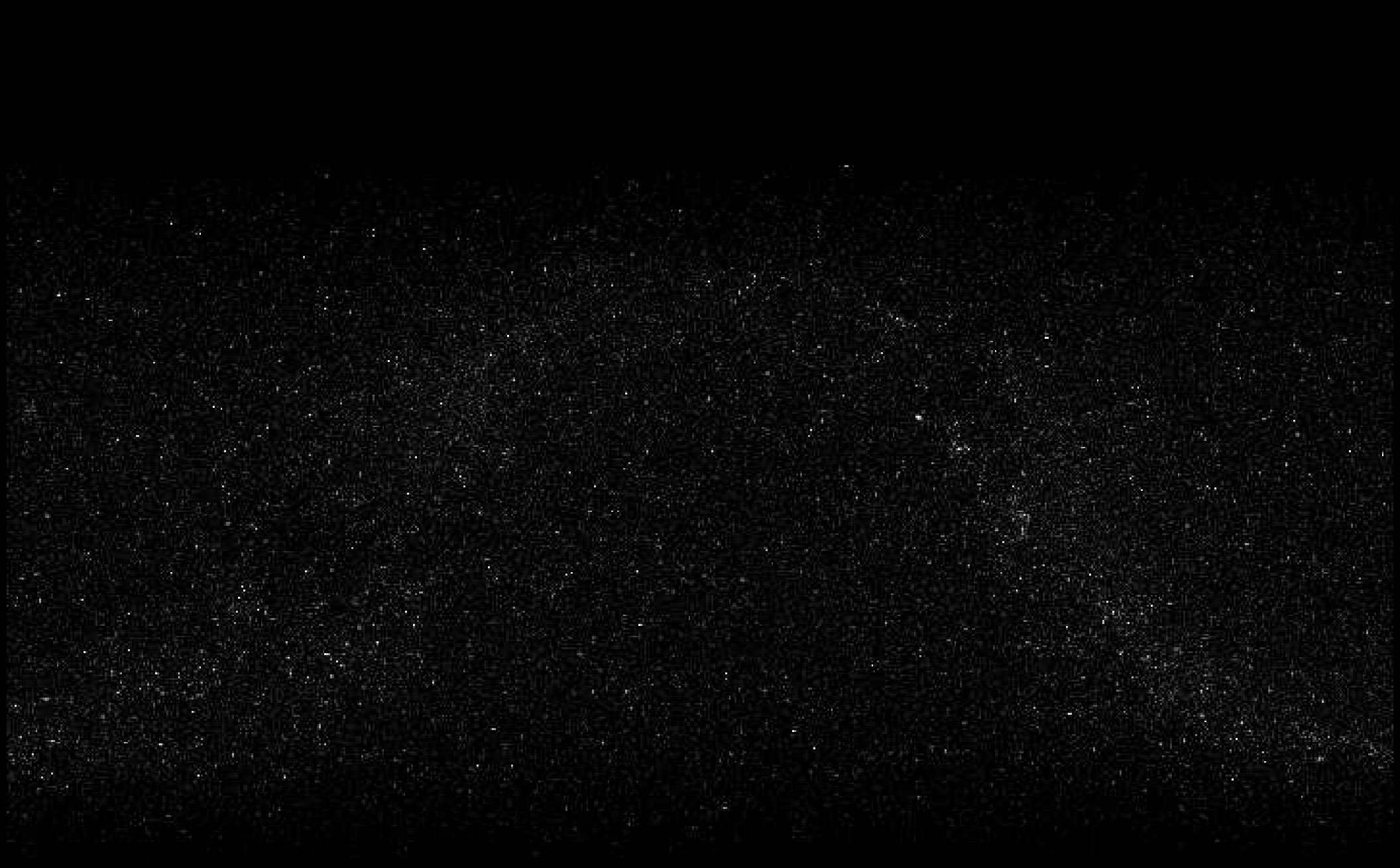


# *The Galactic Center*

D.Seal/JPL

The Yale Bright Star Catalogue (9110 brightest stars)



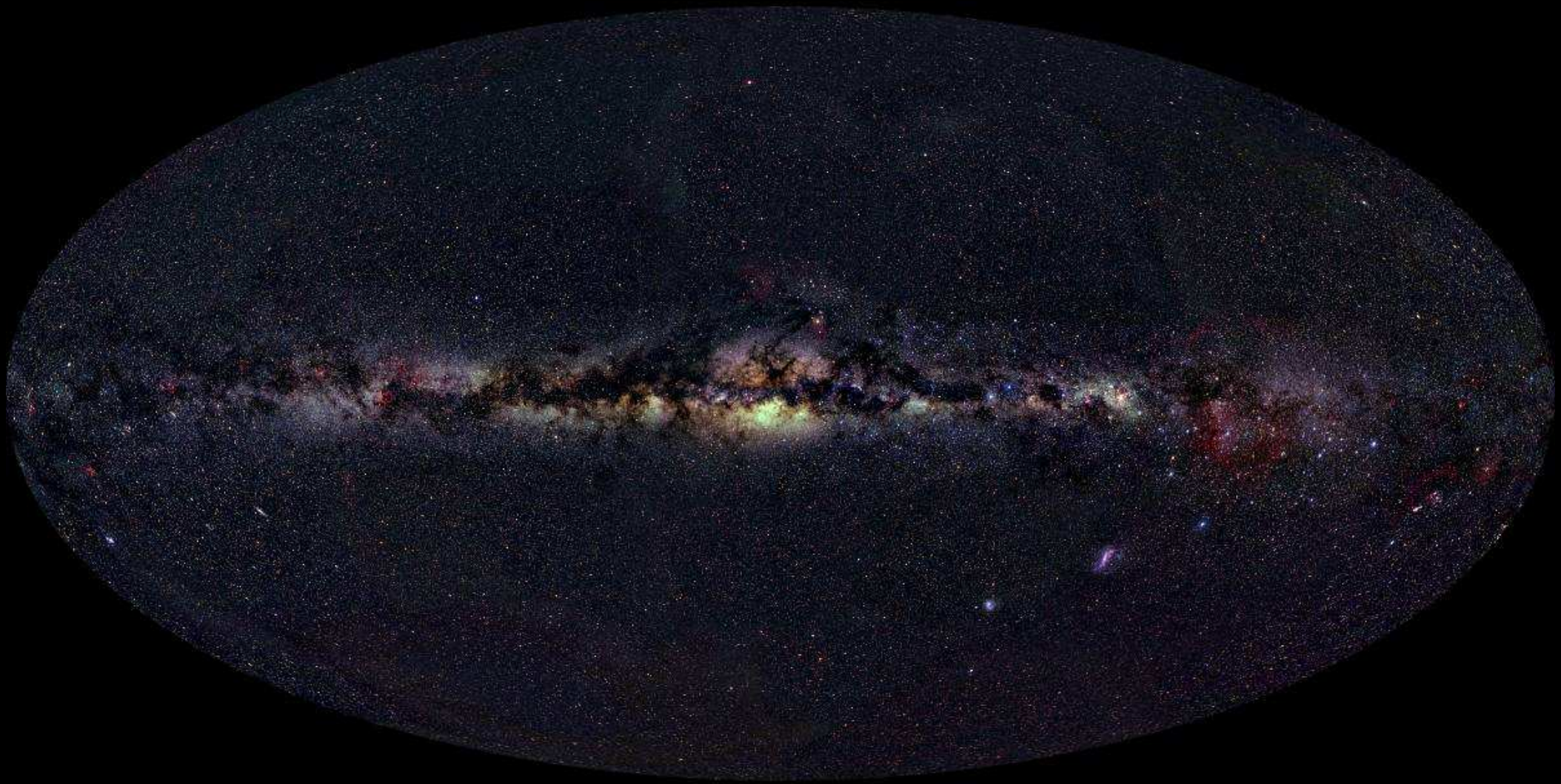
D.Seal/JPL

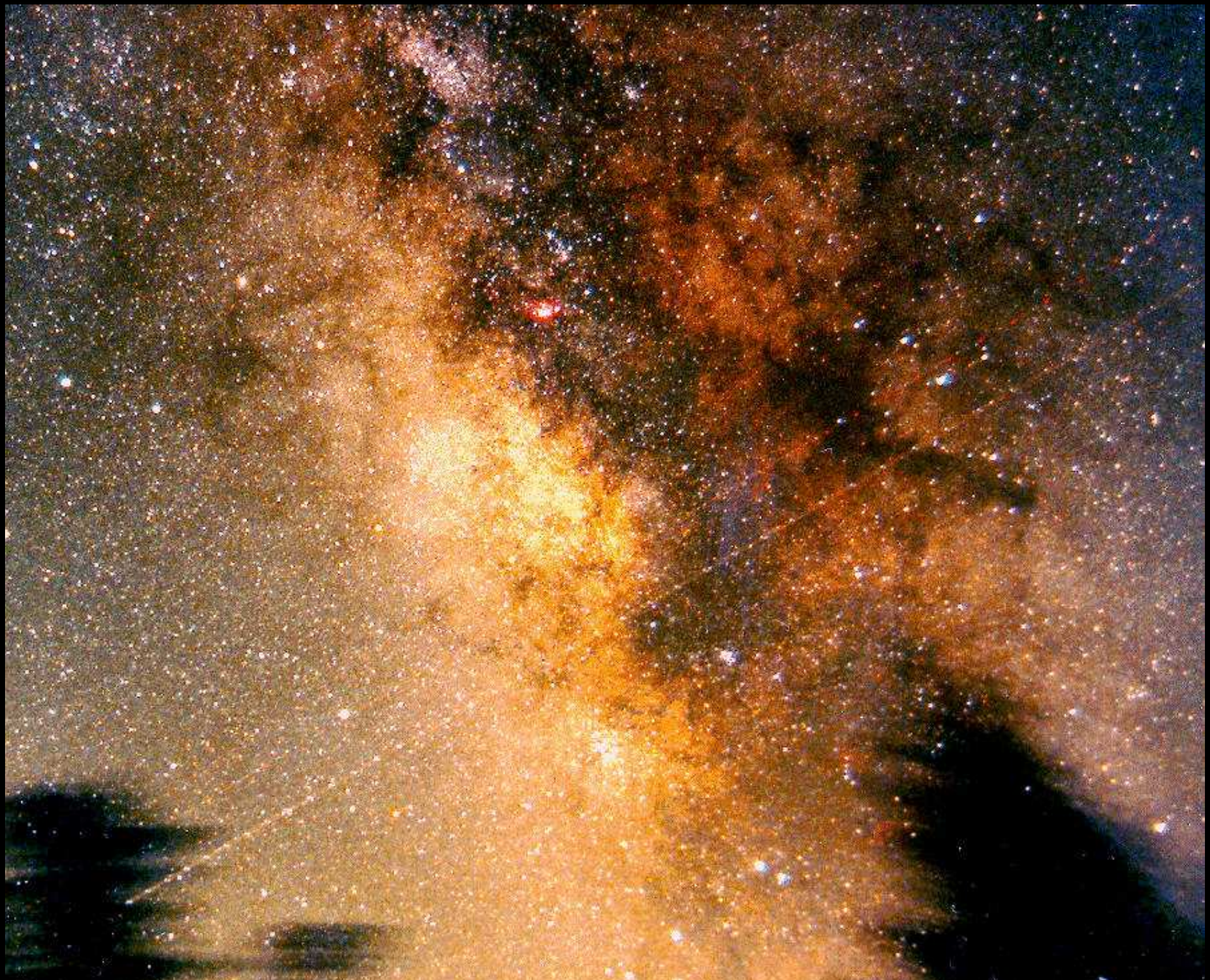
The Hipparcos Catalogue (118000 stars)

D.Seal/JPL

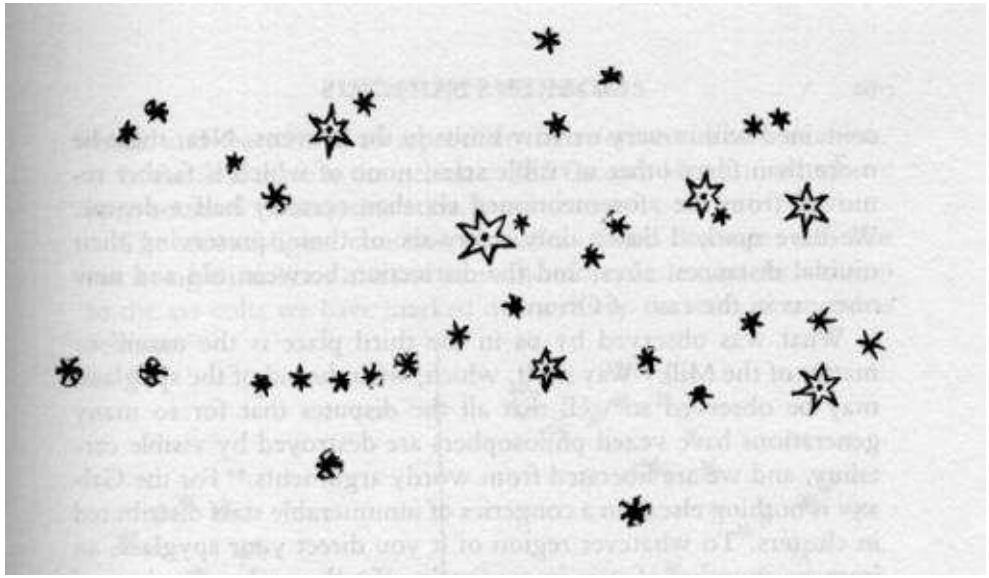
The second Tycho Catalogue (2.5 million stars)

# The Deep Sky



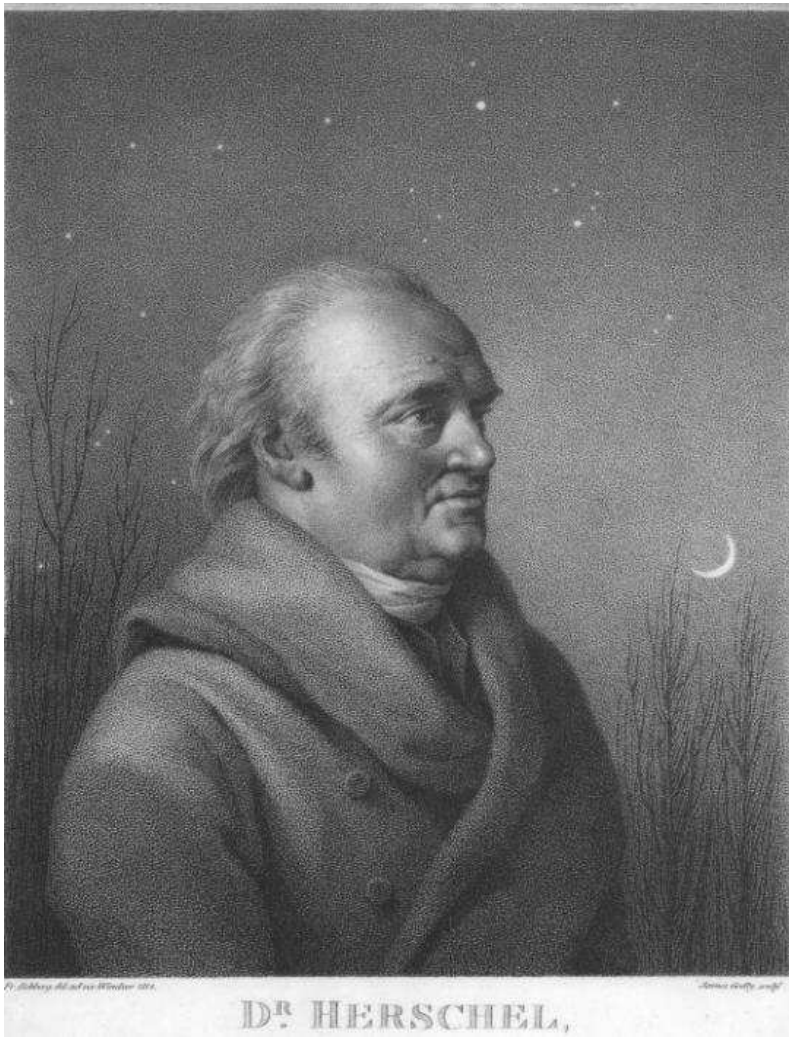


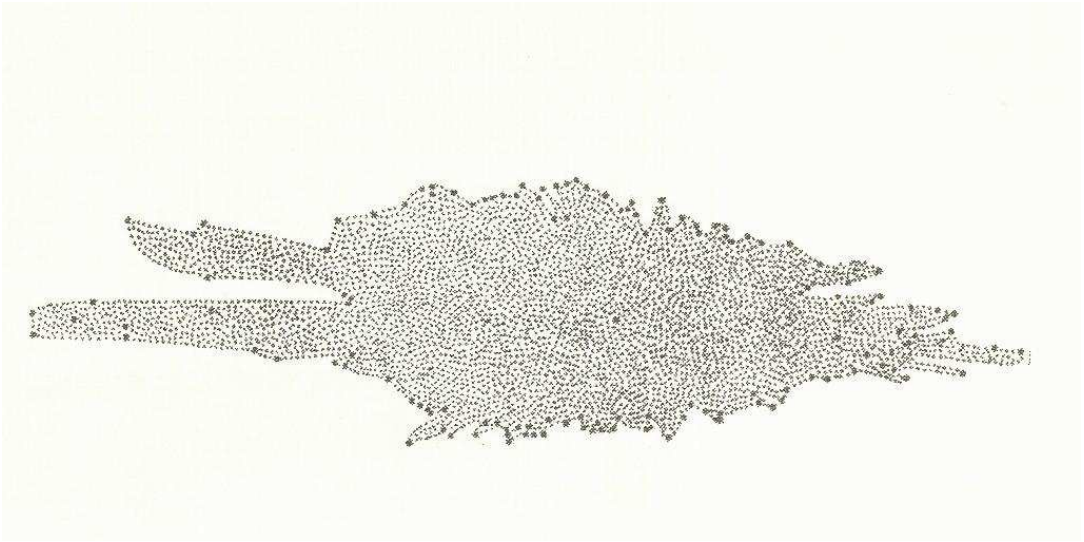
# The Night Sky, VI

Galileo Galilei (1564–1642; Sidereus Nuncius): Telescope resolves (part of) the milky way in stars, discovers new stars $\Longrightarrow$ Milky way is not “milky”!

# The Night Sky, VII

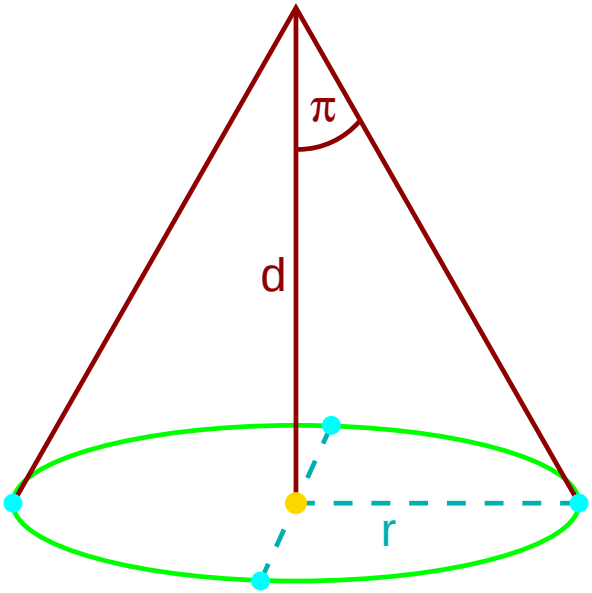


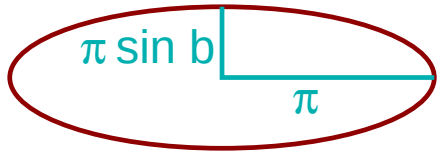



William Herschel (1738–1822): First attempts to determine morphology of the Galaxy.

*Note:* heliocentric!

# The Night Sky, VIII



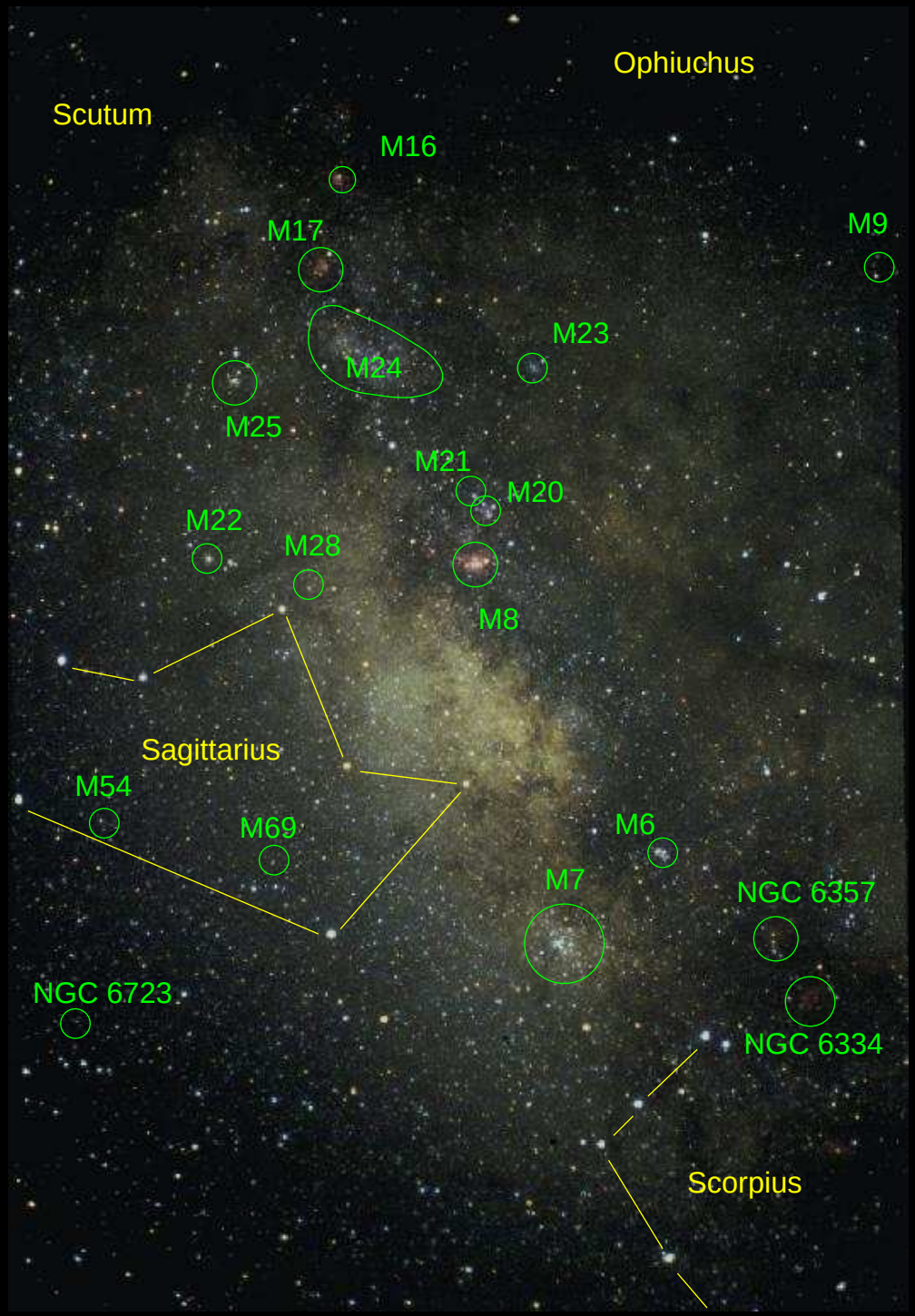

Wilhelm Bessel (1784–1846): First determination of a stellar parallax

*reminder:*

$1\,\text{parsec} = 3.26\,\text{Lj} = 3 \times 10^{13}\,\text{km}$

Milky way in Sagittarius
$27^\circ \times 40^\circ$

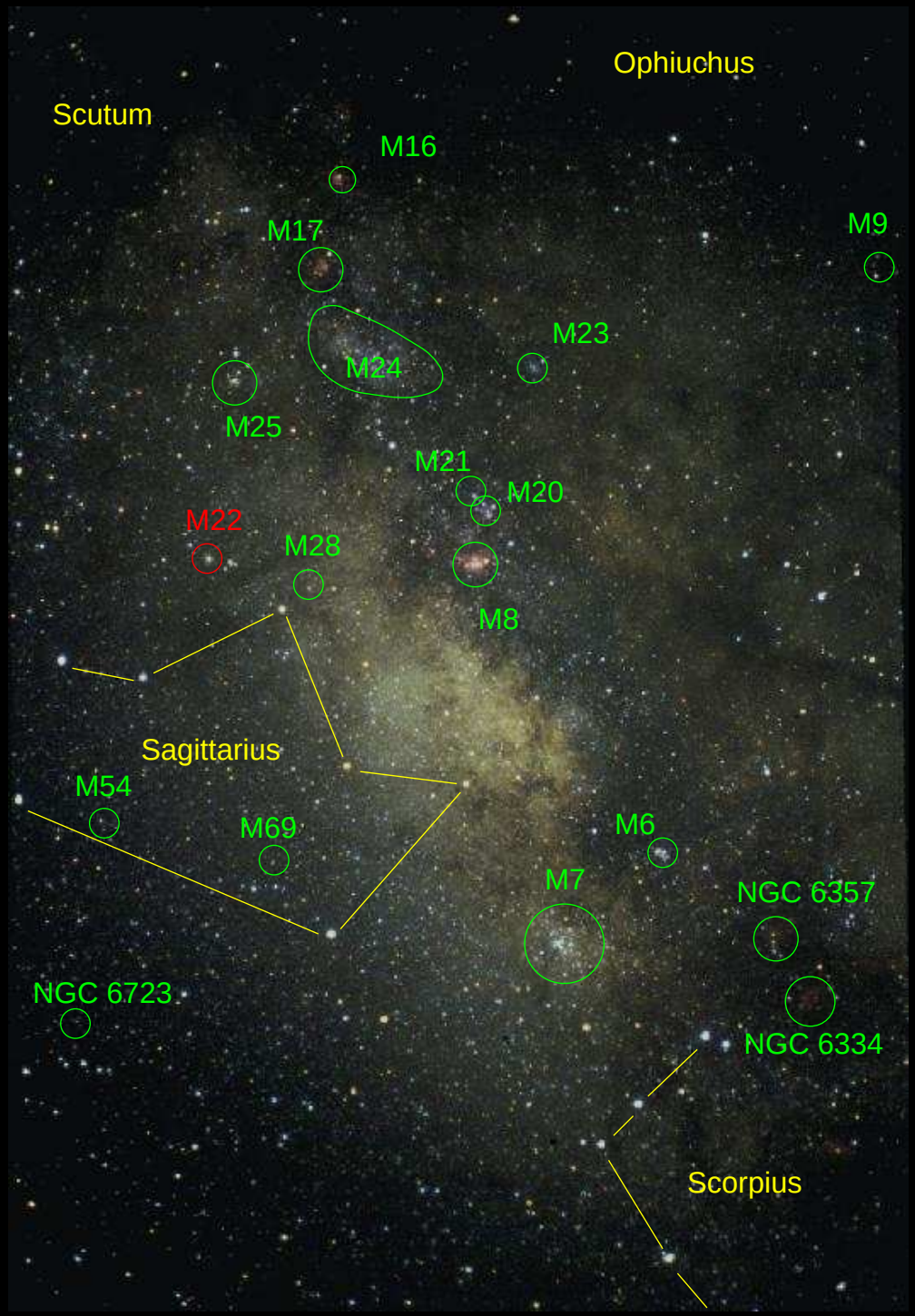
W. Keel (U Alabama)




Milky way in Sagittarius

$27^\circ \times 40^\circ$

W. Keel (U Alabama)

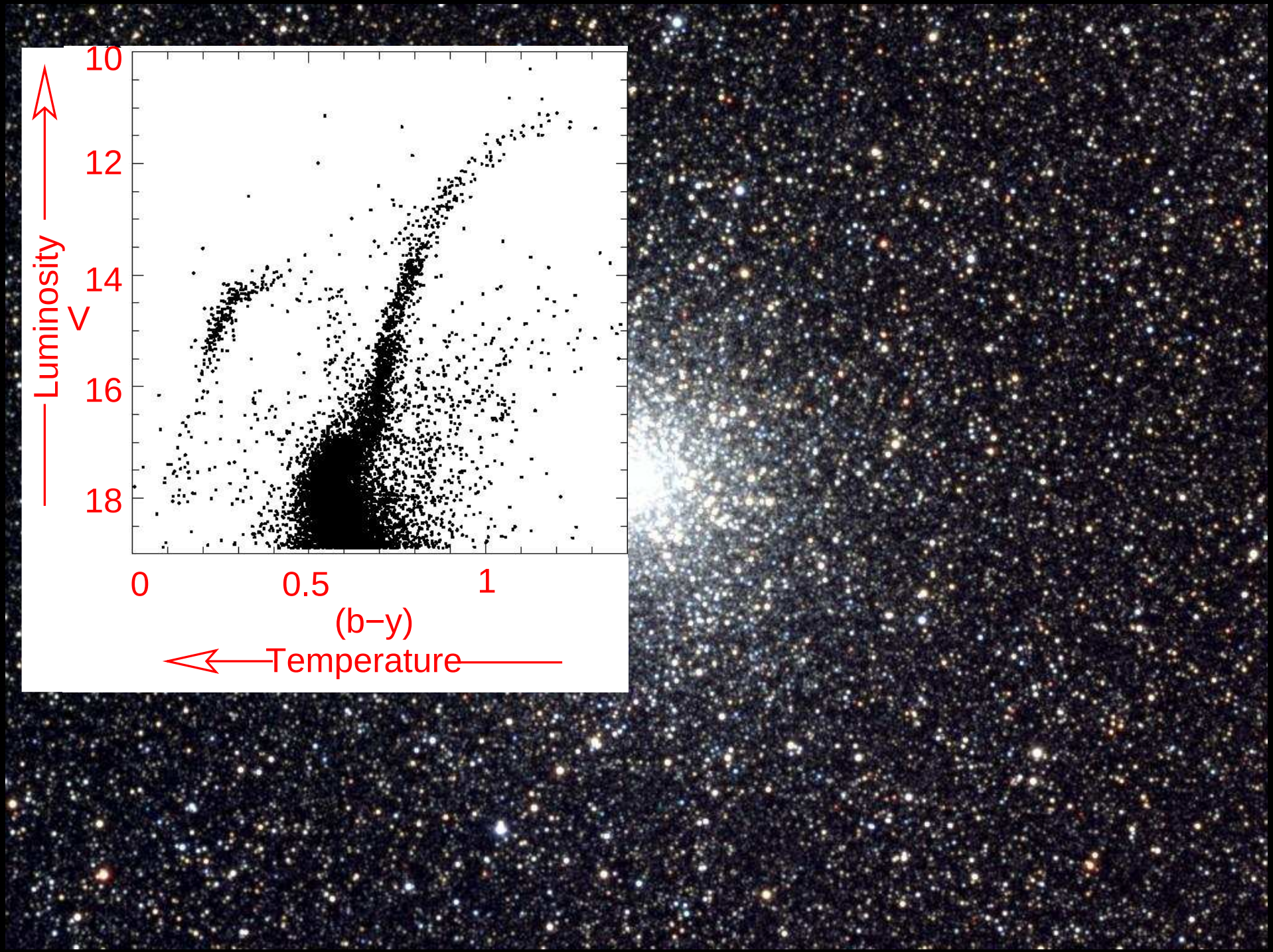



Milky way in Sagittarius

$27^\circ \times 40^\circ$

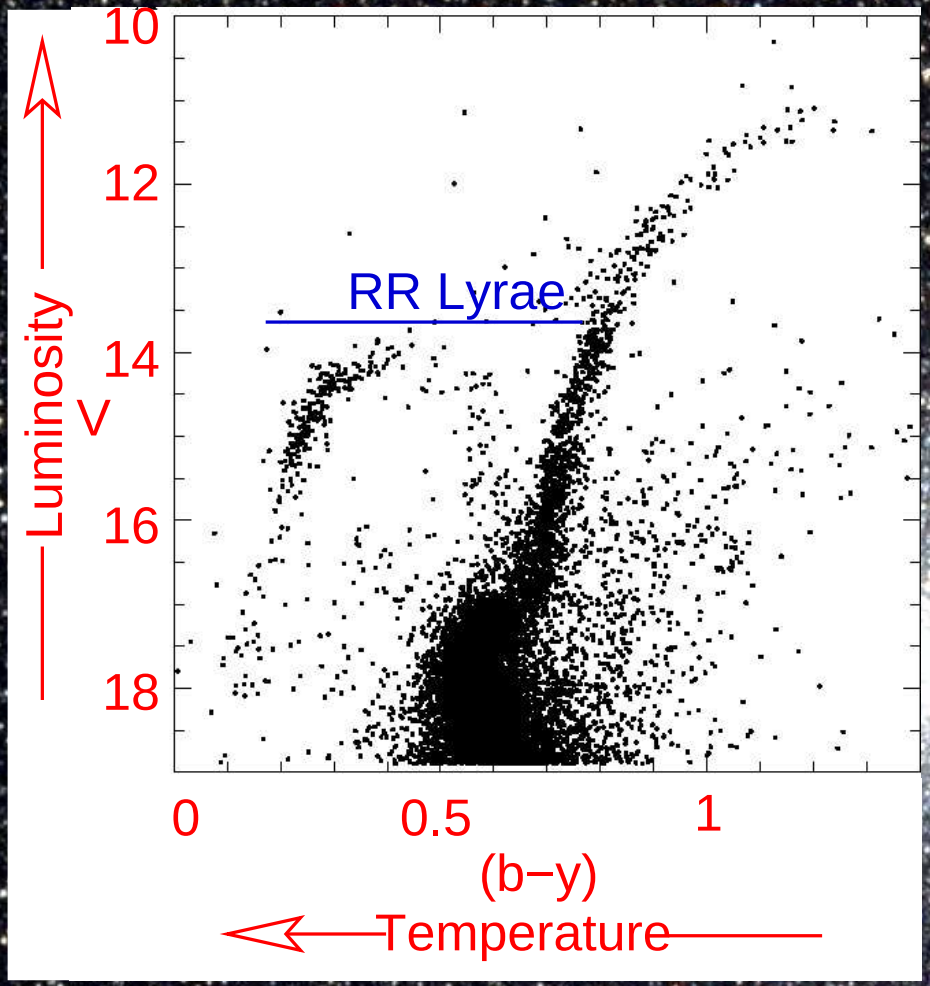
W. Keel (U Alabama)

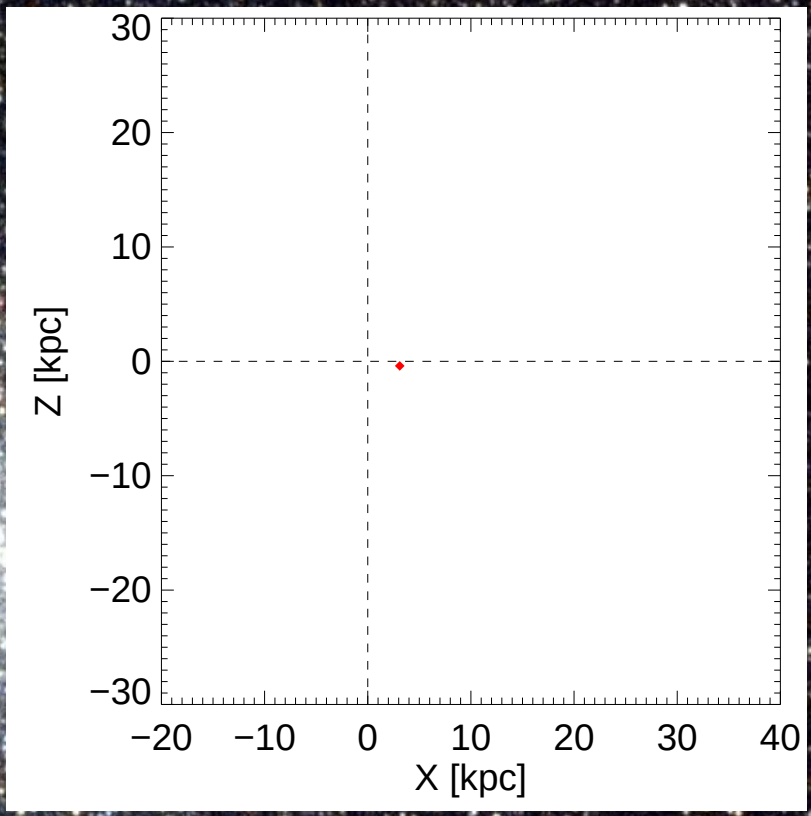
M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)




Richter et al., 1999, A&A 350, 476

M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)

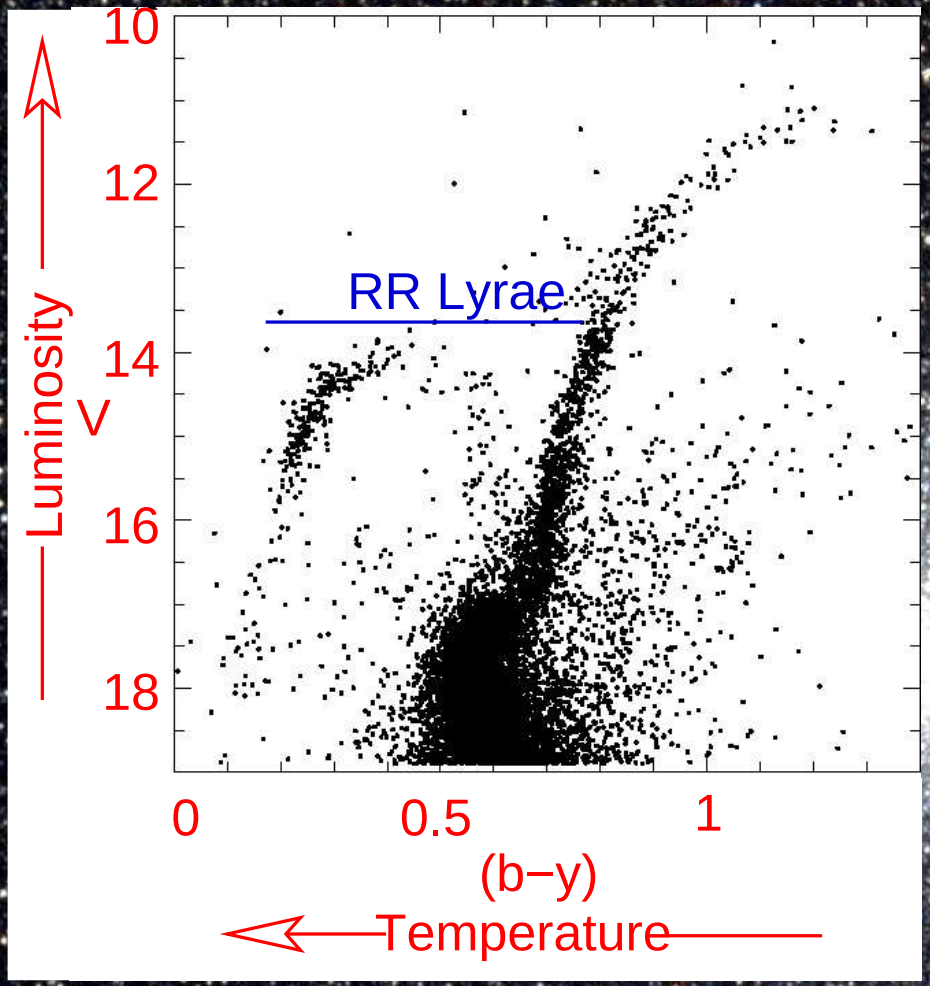


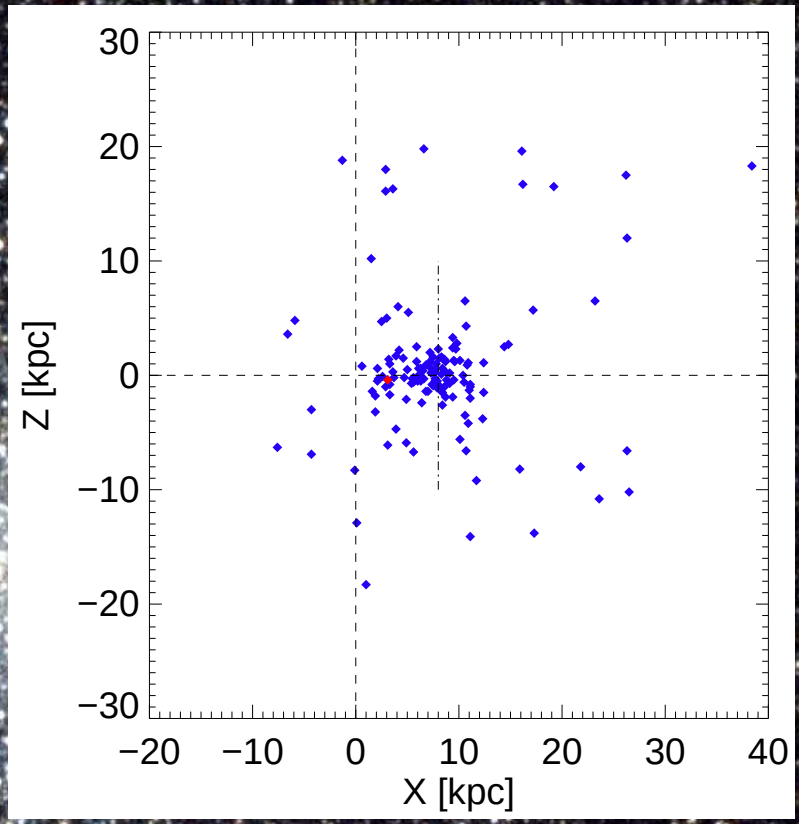




M22 has a distance of 3.2kpc

Richter et al., 1999, A&A 350, 476

M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)

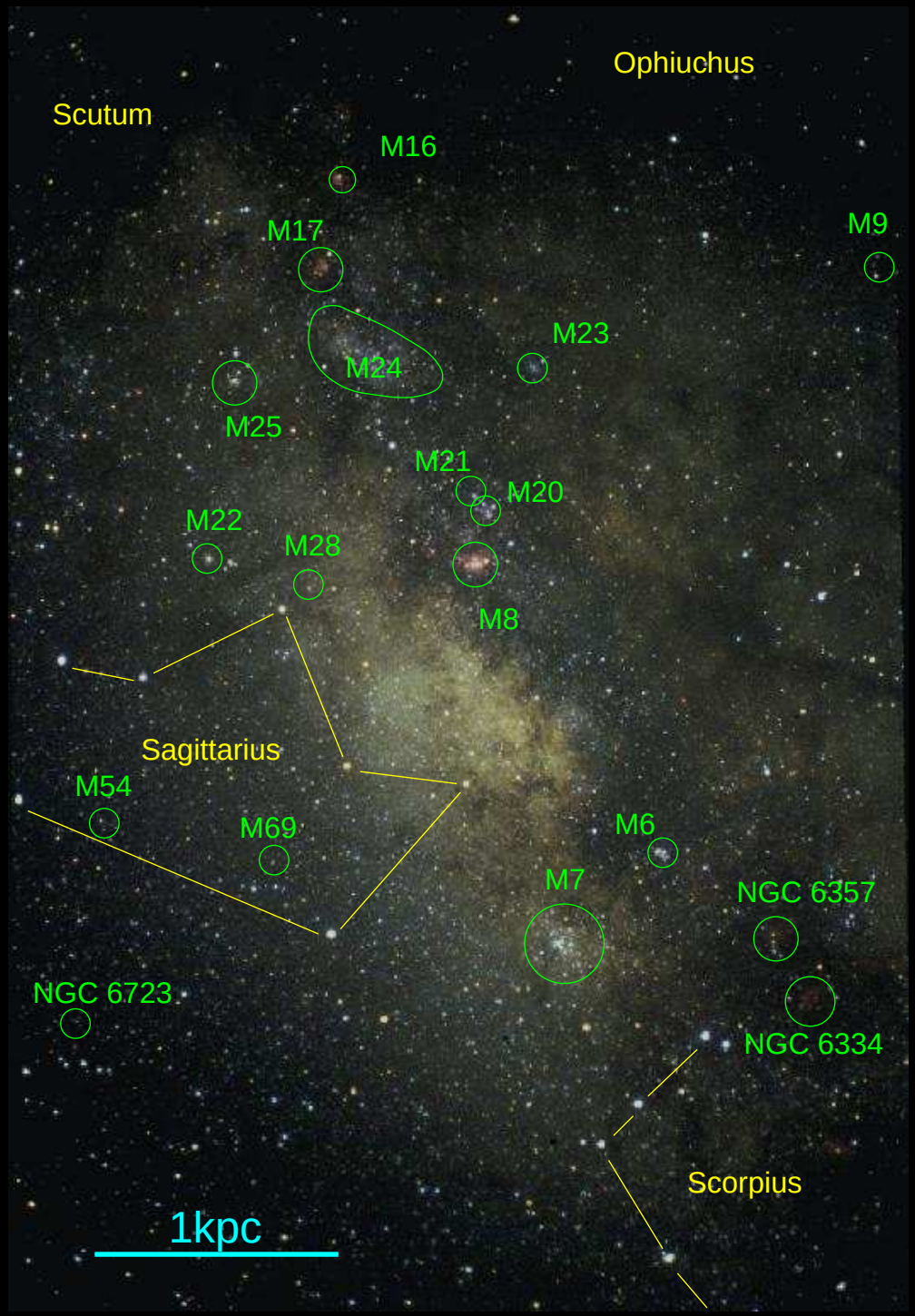



Galactic center has a distance of 8kpc

Richter et al., 1999, A&A 350, 476

M22, KPNO (N.A.Sharp, REU program/NOAO/AURA/NSF)




W. Keel (U Alabama)

Milky way in Saggitarius

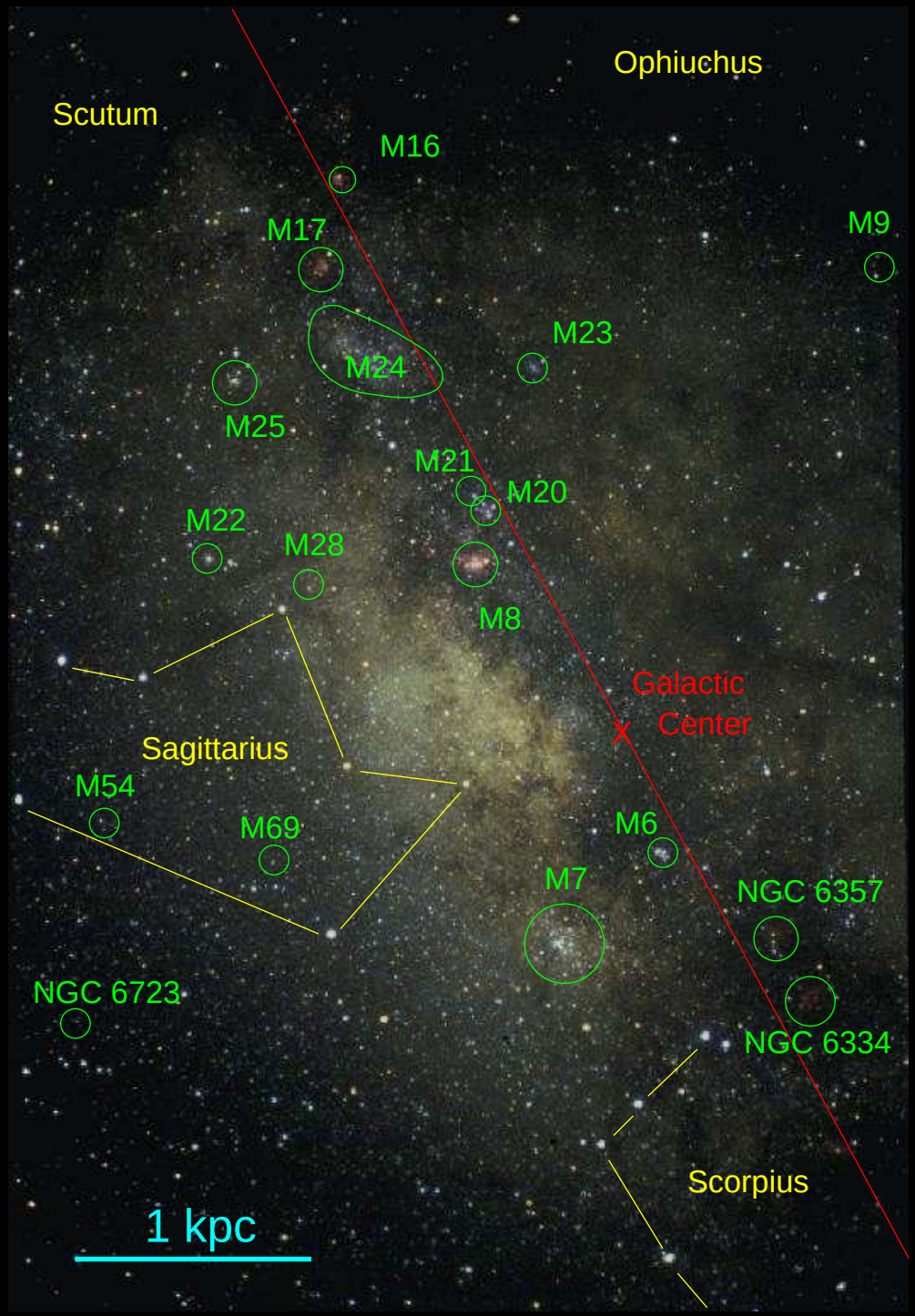
$27^\circ \times 40^\circ$

Distance: 8 kpc

$\Longrightarrow 1^\circ \sim 140\,\mathrm{pc}$

$\Longrightarrow 1' \sim 2\,\mathrm{pc}$

$\Longrightarrow 1'' \sim 0.03\,\mathrm{pc}$




W. Keel (U Alabama)

Milky way in Saggitarius

$27^\circ \times 40^\circ$

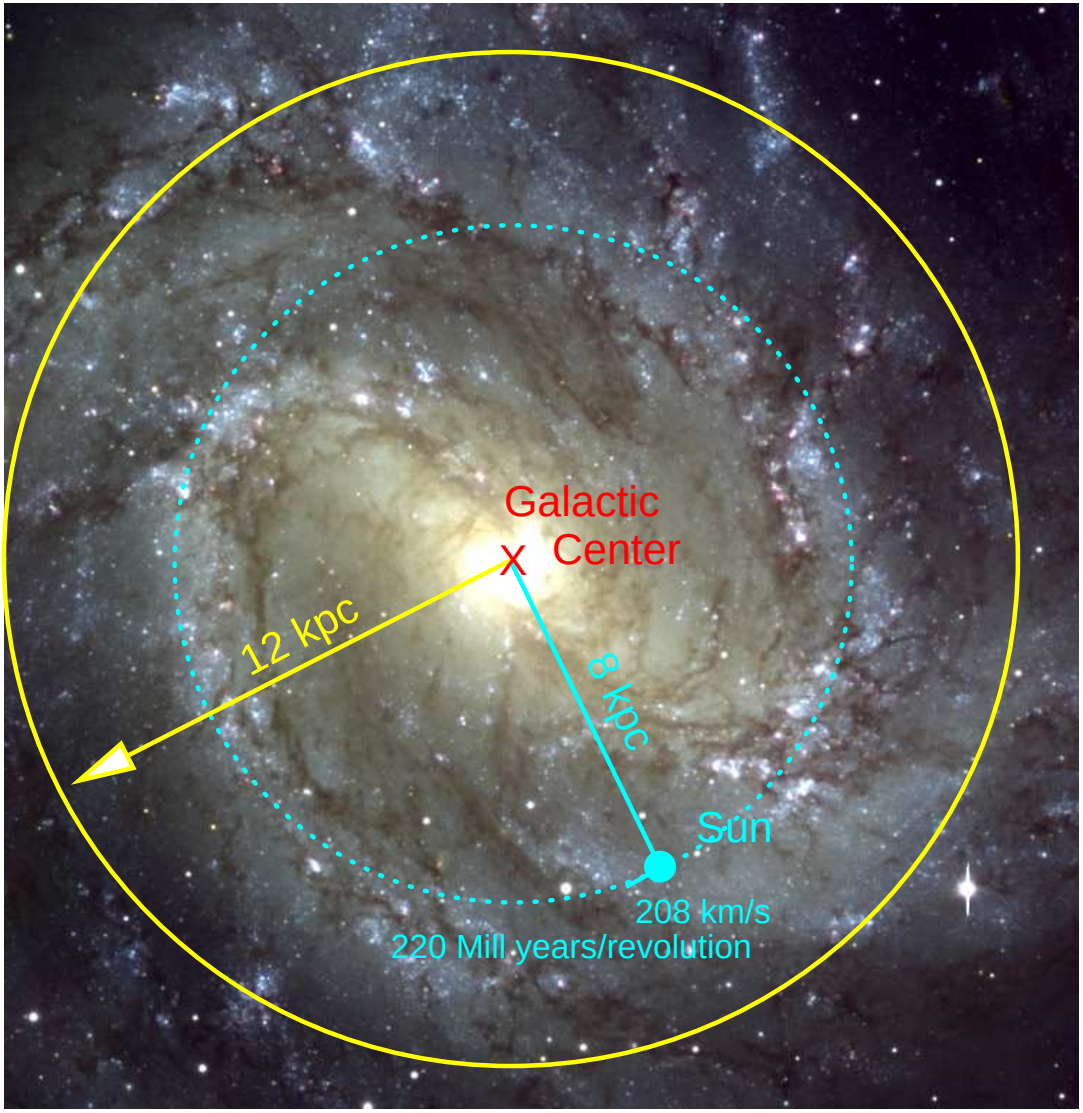
Distance: 8 kpc

$\Longrightarrow 1^\circ \sim 140\,\mathrm{pc}$

$\Longrightarrow 1' \sim 2\,\mathrm{pc}$

$\Longrightarrow 1'' \sim 0.03\,\mathrm{pc}$

# Milky Way as a Galaxy




M83: ESO [VLT ANTU+FORS1]

Luminosity: $\sim 2 \times 10^{10}\, L_\odot$

Mass: $\sim 10^{11}\, M_\odot$ (radiating)

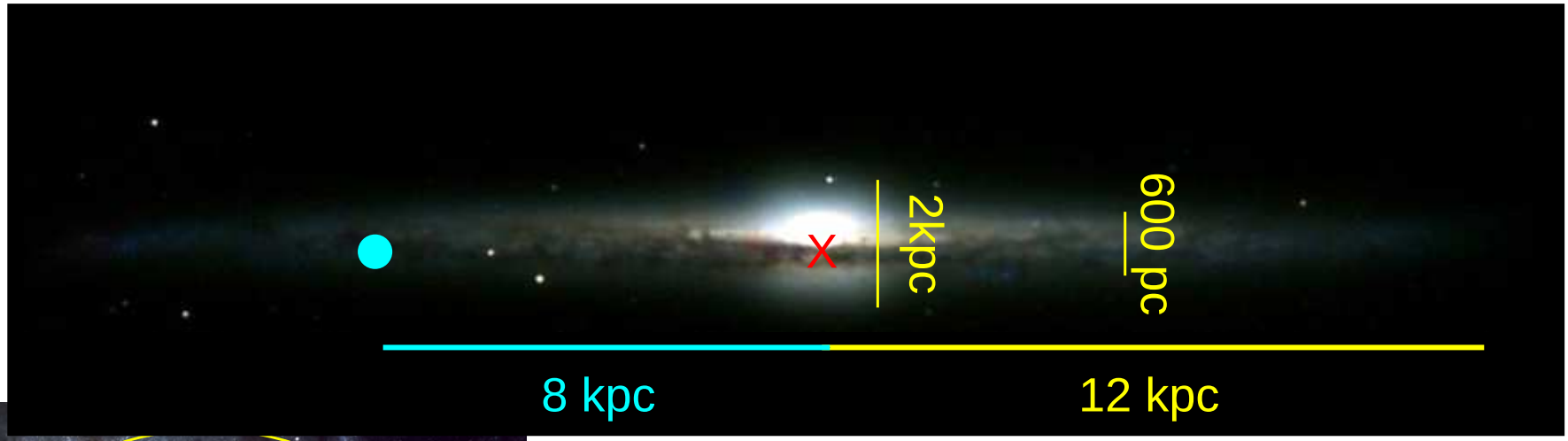
$\sim 10^{12}\, M_\odot$ (total)

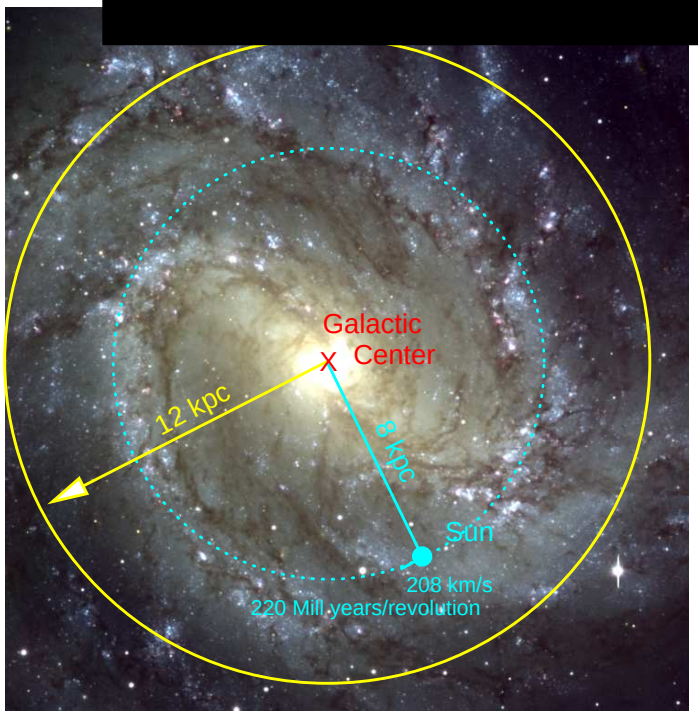
Stellar density:

$\sim 0.3\, M_\odot\, \mathrm{pc}^{-3}$

$1\, M_\odot = 2 \times 10^{33}\, \mathrm{g} = 2 \times 10^{30}\, \mathrm{kg}$,
$1\, L_\odot = 4 \times 10^{33}\, \mathrm{erg\, s}^{-1} = 4 \times 10^{26}\, \mathrm{W}$

# Milky Way as a Galaxy




NGC 4565: W. McLaughlin

Luminosity: $\sim 2 \times 10^{10}\, L_\odot$

Mass: $\sim 10^{11}\, M_\odot$ (radiating)

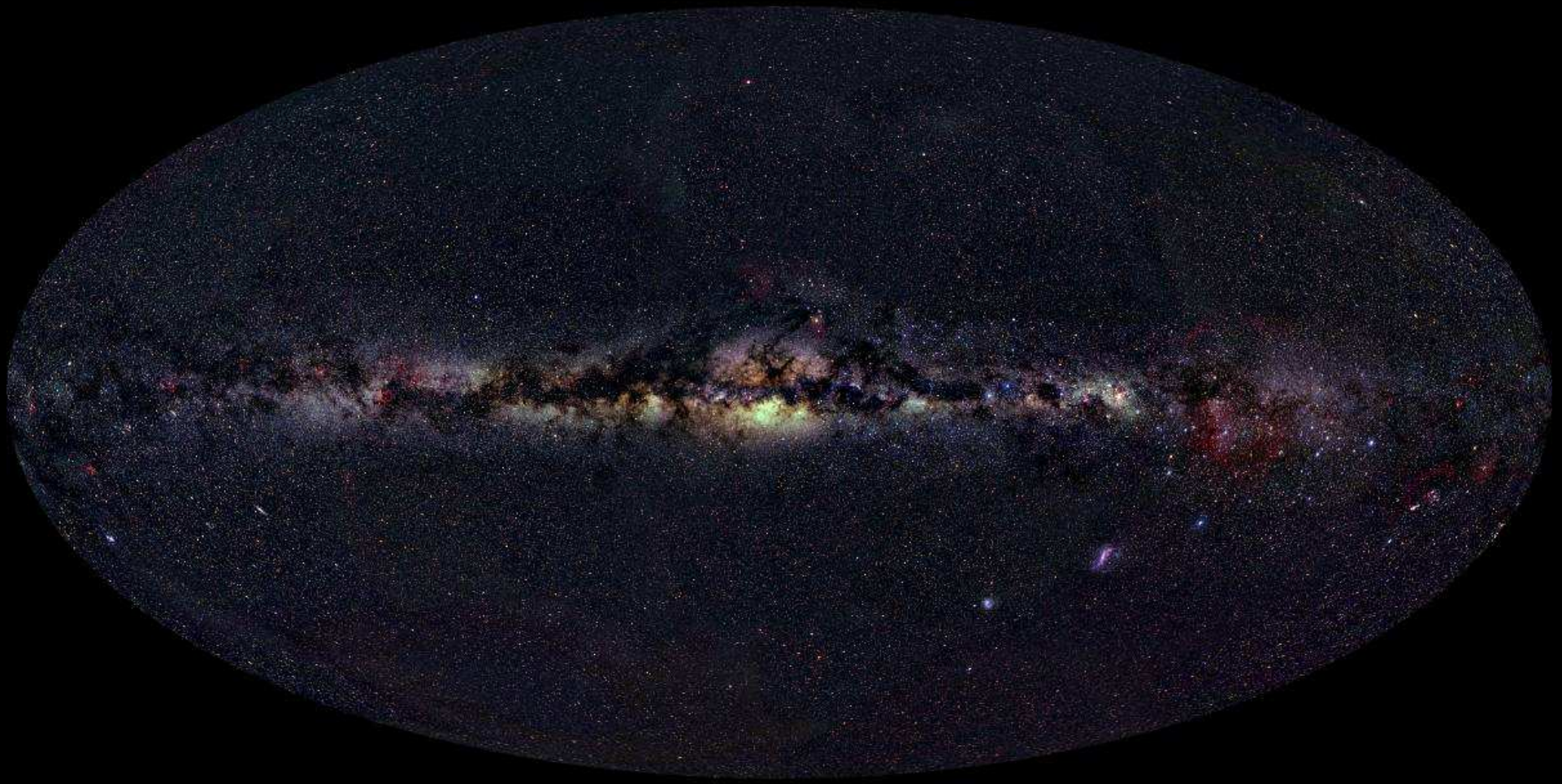
$\sim 10^{12}\, M_\odot$ (total)

Stellar density:

$\sim 0.3\, M_\odot\, \mathrm{pc}^{-3}$

$1\, M_\odot = 2 \times 10^{33}\, \mathrm{g} = 2 \times 10^{30}\, \mathrm{kg}$,
$1\, L_\odot = 4 \times 10^{33}\, \mathrm{erg\, s}^{-1} = 4 \times 10^{26}\, \mathrm{W}$

# The Deep Sky

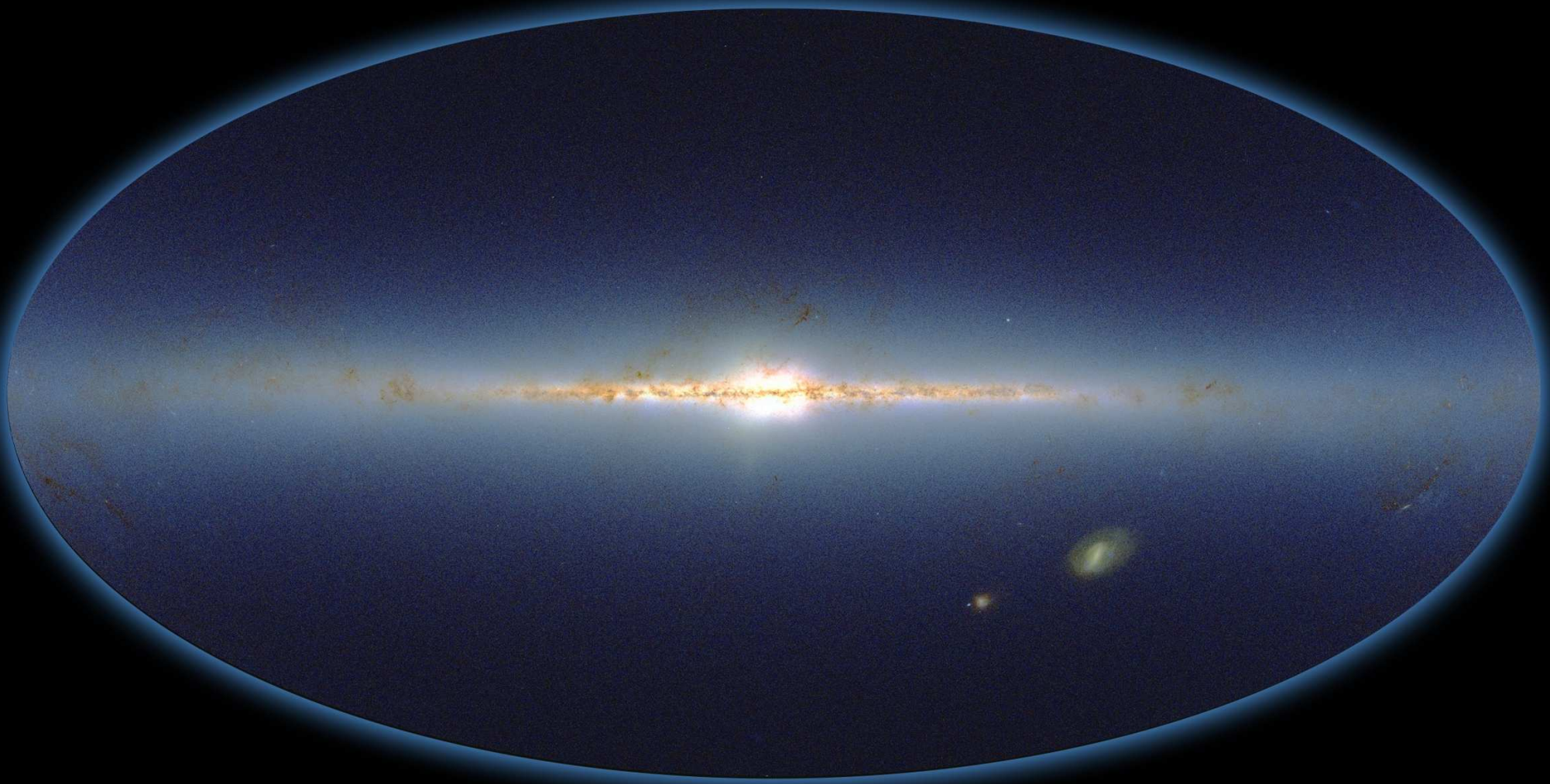



Problem: strong extinction due to dust

($A_V \sim 30$ mag: $10^{12}$ times reduction in the optical!)

$\Longrightarrow$ Multiwavelength astronomy!

# 2MASS Covers the Sky

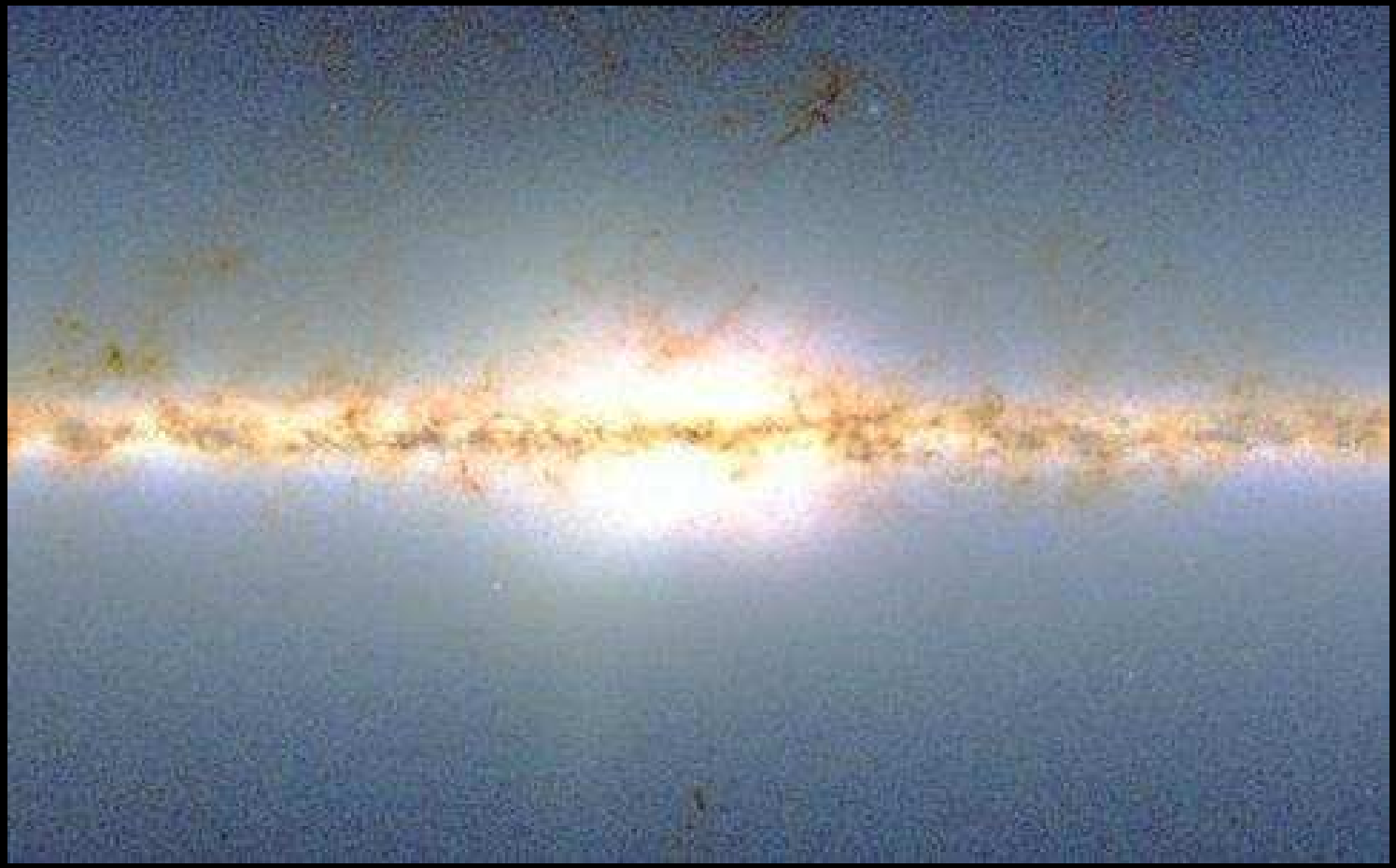


The Two Micron All Sky Survey

Infrared Processing and Analysis Center/Caltech & Univ. of Massachusetts

Infra red: Dust becomes transparent!

2MASS: 3 IR Bänder: J (1.25 $\mu$m), H (1.65 $\mu$m), $K_s$ (2.17$\mu$m)



2MASS: inner $60^\circ \times 45^\circ$

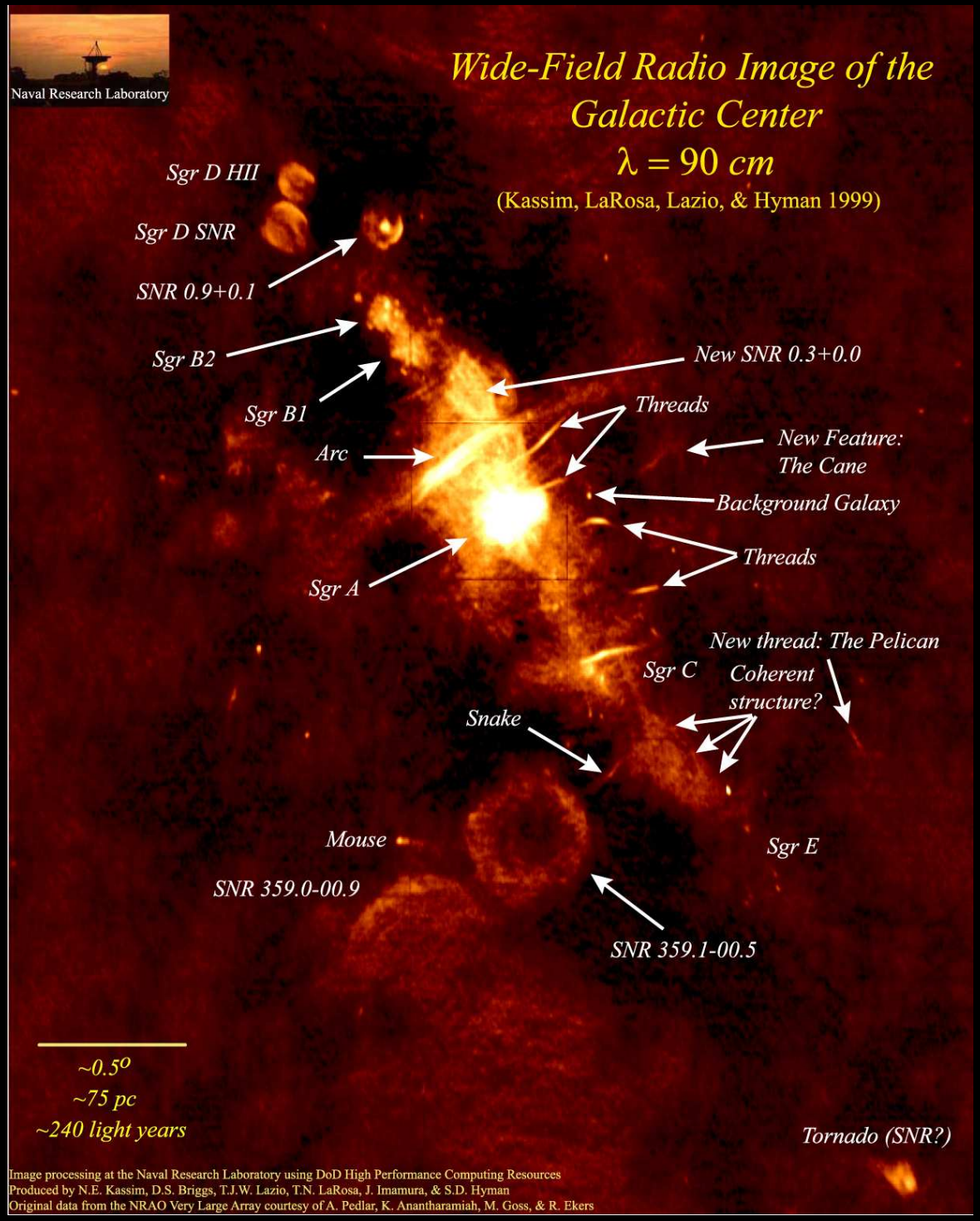
# Combined 2MASS–MSX View of the Galactic Center

Two Micron All Sky Survey
– Southern Facility –
2MASS Atlas Image Mosaic
Infrared Processing and Analysis Center & University of Massachusetts

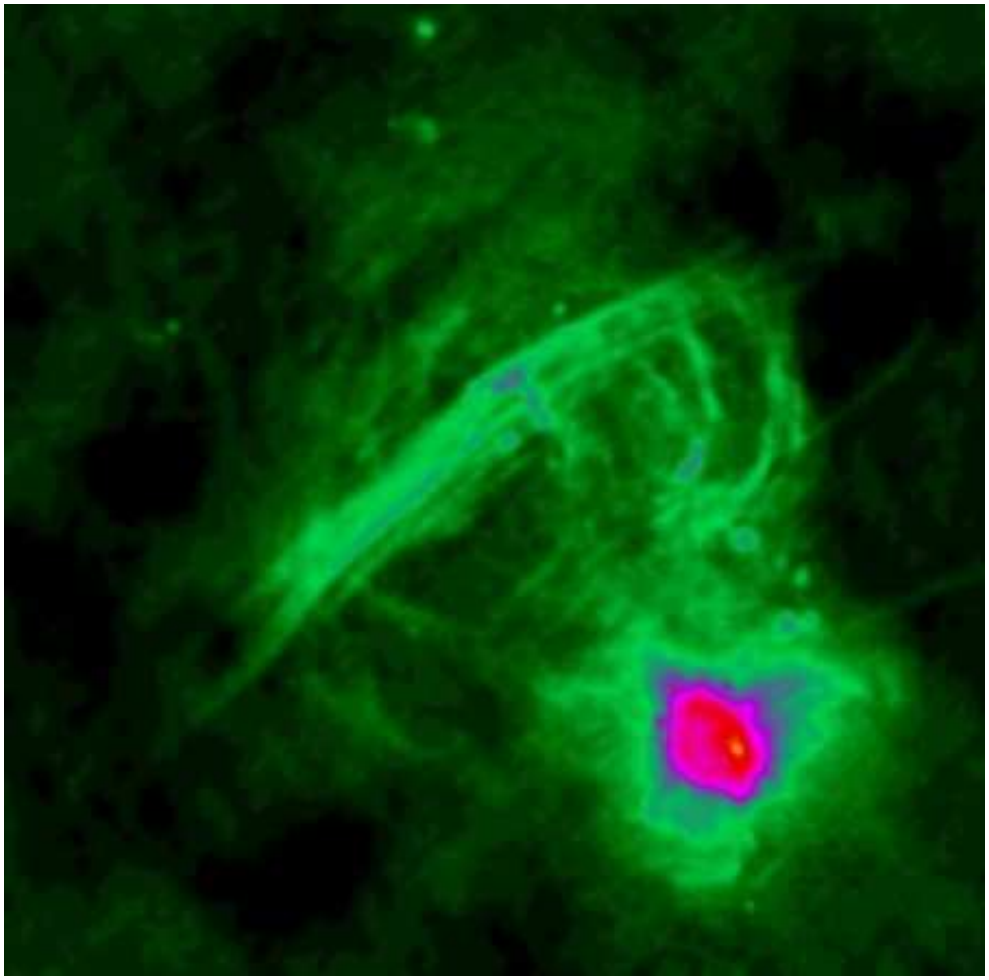
Midcourse Space Experiment
SPIRIT III

## 2MASS/MSX: Inner $4^\circ \times 2^\circ$

2MASS (J [1.25 $\mu$m], red), (K [2.17 $\mu$m], green), MSX (A [6–11 $\mu$m], blue)


Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature: The Cane
Arc
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

# The Inner kpc

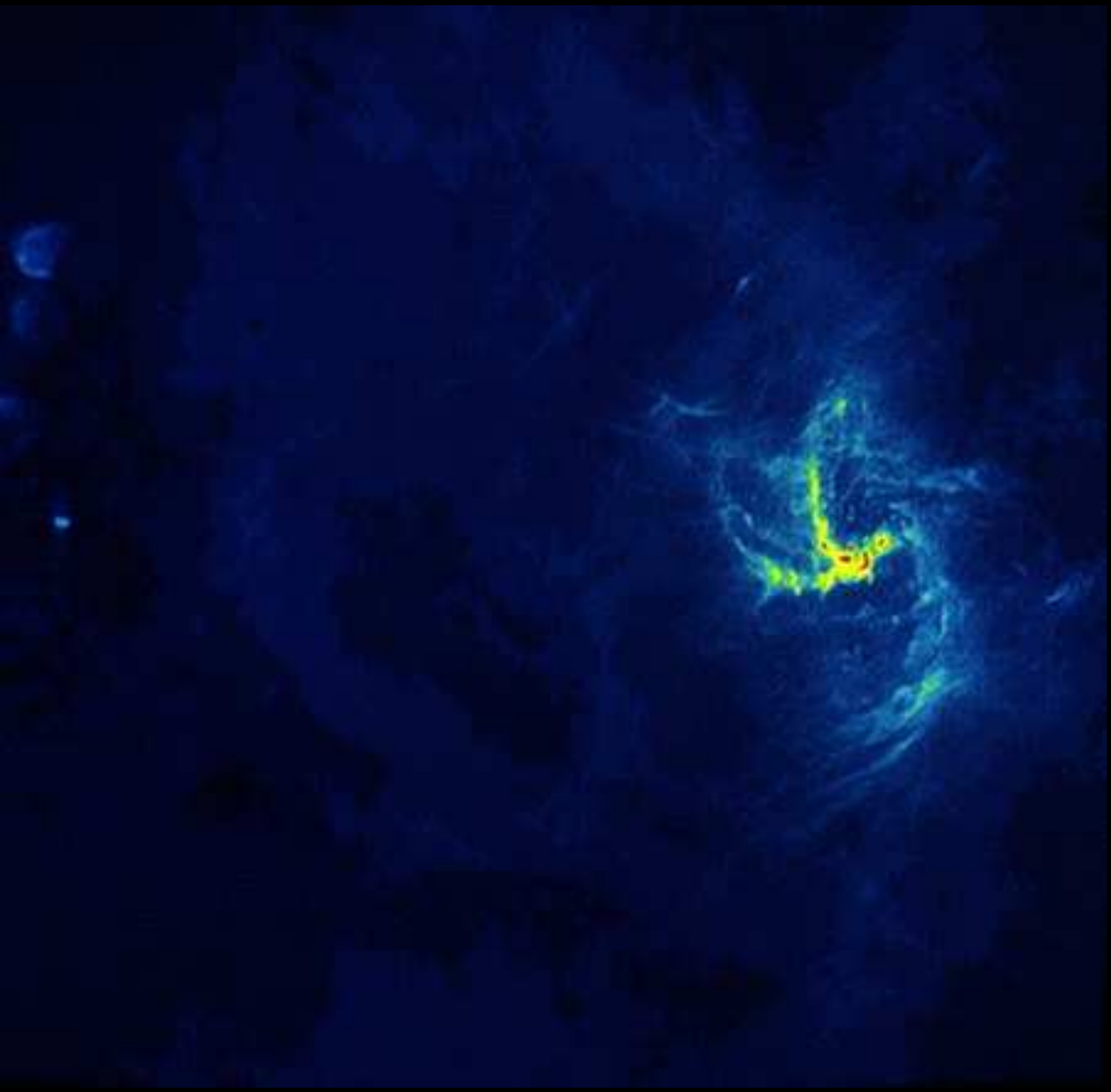


70 pc $\times$ 70 pc, VLA (F. Yusef-Zadeh et al., 1982–1984)


Radio source Sgr A:
Sgr A (West) (Arc): $5''$ (=0.2 pc) broad radio filaments, part of a much larger $\Omega$-shaped structure $\perp$ galactic plane.

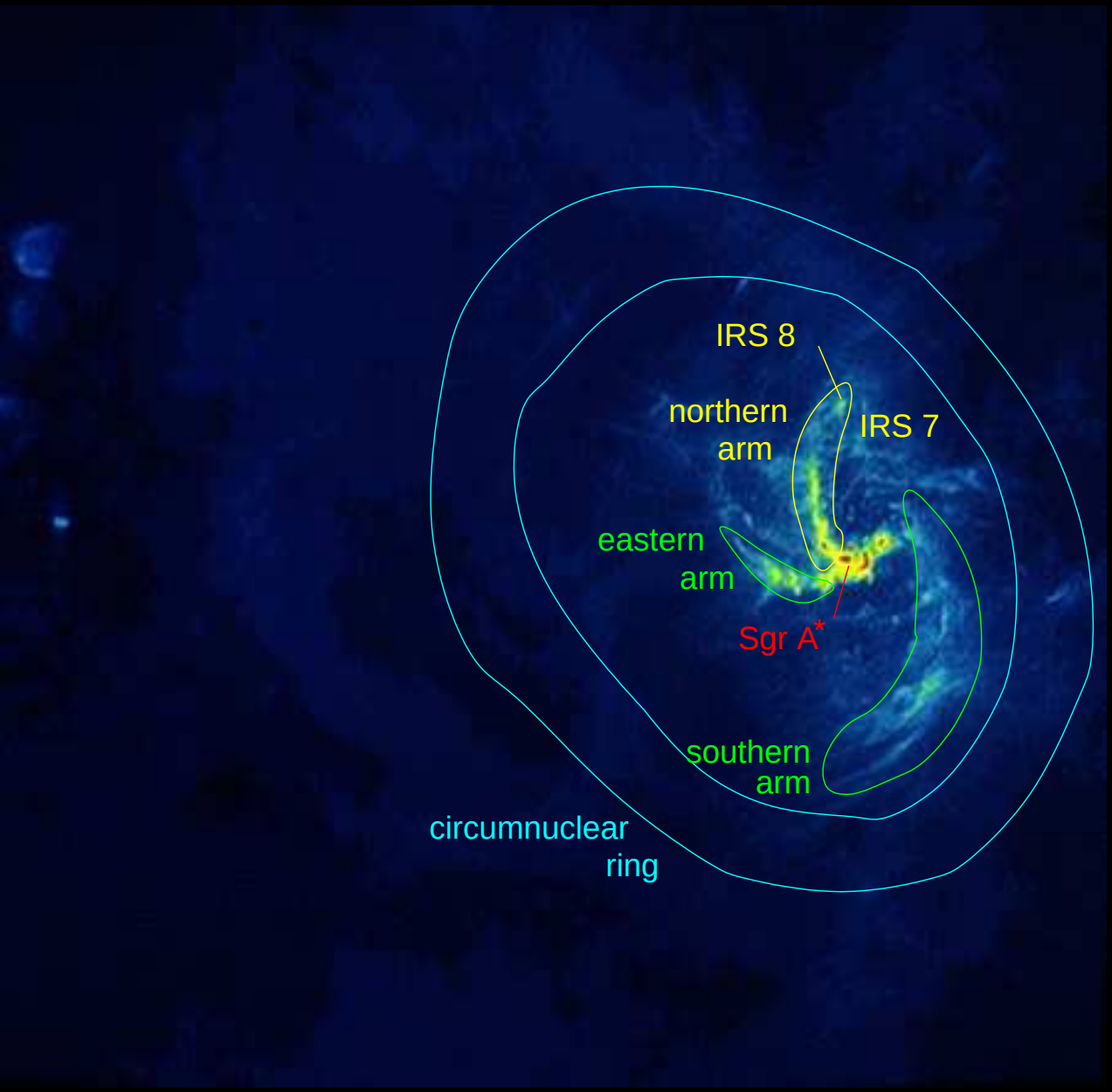
polarized, steep radio spectrum $\Longrightarrow$ synchrotron radiation (nonthermal electrons; $n_e(E) \propto E^{-p}$)!

caused by shocks from supernovae?



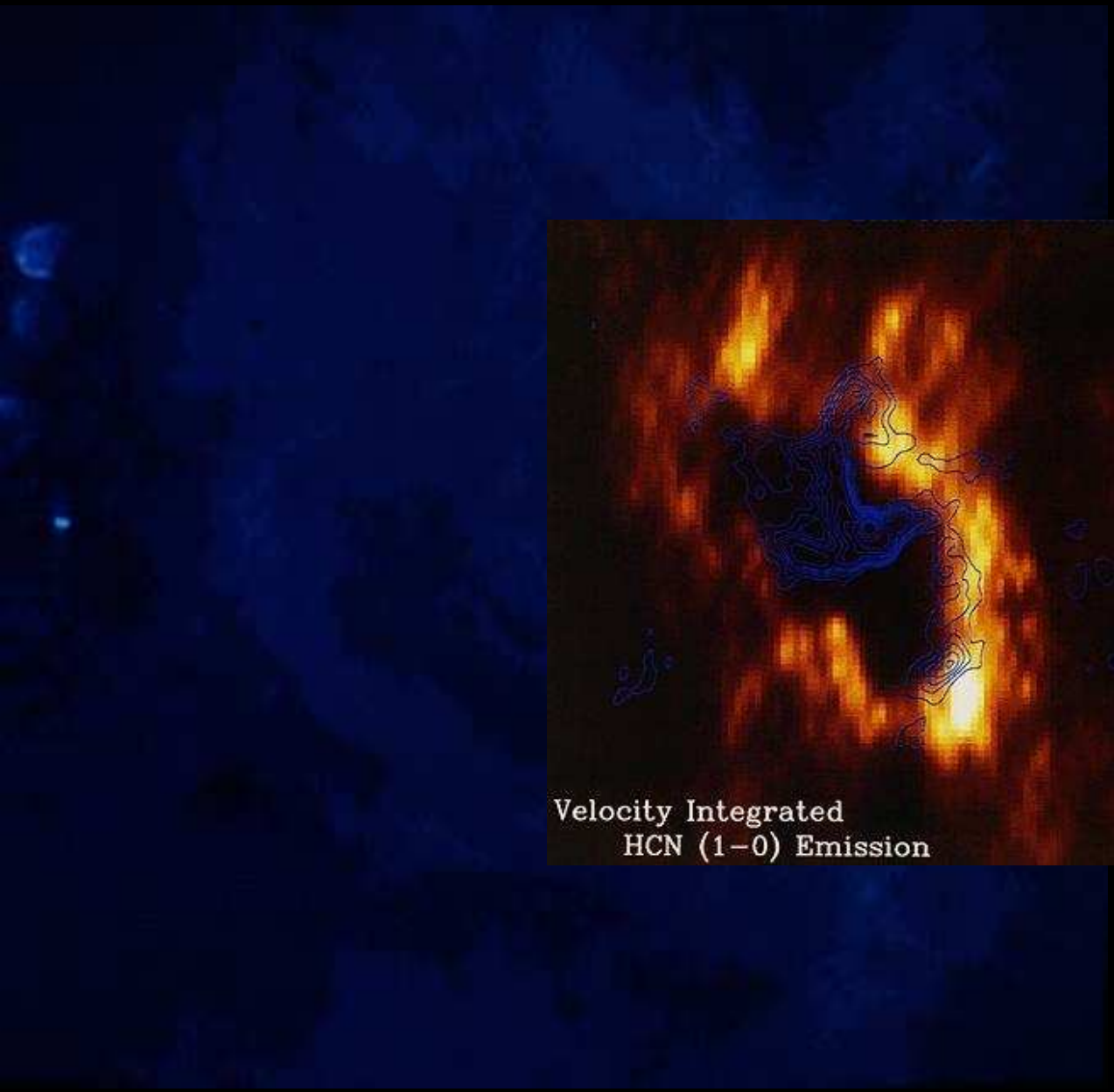
Sgr A (3.6 cm, courtesy K.Y. Lo/NRAO/AUI)

Sgr A West (“spiral”):
2 pc diameter,
$\sim$ 60 $M_\odot$ ionized gas, shaped by tidal forces
(probably influence of mG B-field),
northern arm falls on center, east and south arms rotate.
around Sgr A West: circumnuclear disk of molecular gas, ($r \sim 2$ pc).
total mass accretion rate onto Sgr A$^*$:
$\sim 3 \times 10^{-6}\, M_\odot\, \mathrm{yr}^{-1}$




Sgr A (3.6 cm, courtesy K.Y. Lo/NRAO/AUI)

Sgr A West (“spiral”):
2 pc diameter,
$\sim$ 60 $M_\odot$ ionized gas, shaped by tidal forces
(probably influence of mG B-field),
northern arm falls on center, east and south arms rotate.
around Sgr A West: circumnuclear disk of molecular gas, ($r \sim 2$ pc).
total mass accretion rate onto Sgr A$^*$:
$\sim 3 \times 10^{-6}\, M_\odot\, \mathrm{yr}^{-1}$




Sgr A (3.6 cm, courtesy K.Y. Lo/NRAO/AUI)

Sgr A West (“spiral”):
2 pc diameter,
$\sim$ 60 $M_\odot$ ionized gas, shaped by tidal forces
(probably influence of mG B-field),
northern arm falls on center, east and south arms rotate.
around Sgr A West: circumnuclear disk of molecular gas, ($r \sim 2$ pc).
total mass accretion rate onto Sgr A$^*$:
$\sim 3 \times 10^{-6}\, M_\odot\, \mathrm{yr}^{-1}$

# The Inner Parsec: Central Cluster, I

Center of Sgr A contains massive and dense cluster
($> 10^6\, M_\odot\, \mathrm{pc}^{-3}$, compare solar neighborhood: $0.1\, M_\odot\, \mathrm{pc}^{-3}$)
*Spectroscopy:* Stars are rich in Helium, early type (=massive), strong winds
($v_{\mathrm{Wind}} \sim 1000\, \mathrm{km\, s}^{-1}$).

# The Inner Parsec: Central Cluster, II

Gemini North/AURA

Observations are difficult because of astronomical seeing ($\sim 0.7''$=0.2 pc)

# The Inner Parsec: Central Cluster, III

Gemini North/AURA

Observations are difficult because of astronomical seeing ($\sim 0.7''$=0.2 pc)

. . . which can be corrected by adaptive optics

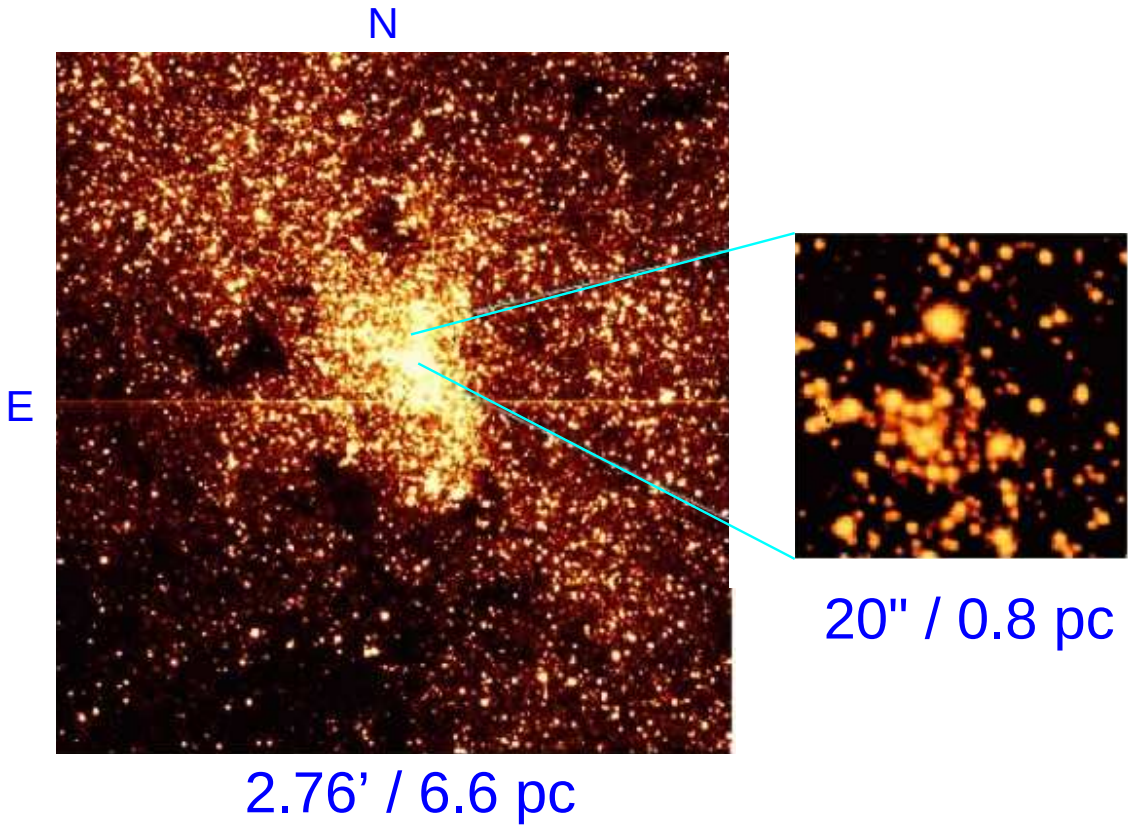
$\Longrightarrow$ resolution: diffraction limit!

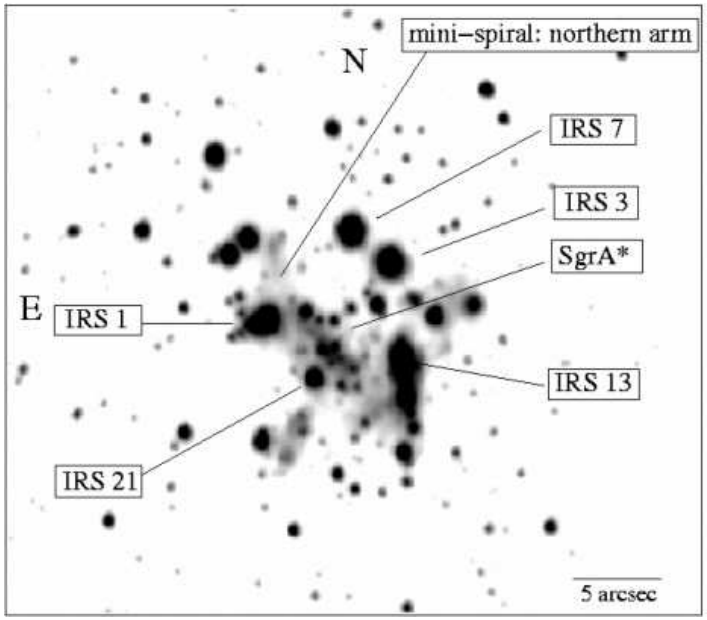
$$\theta = 1.22\,\text{rad} \cdot \lambda/d \sim 1\,\text{mas}$$

(for $d = 8$ m, $\lambda = 2.2\,\mu$m)

$\Longrightarrow$ 140 AU for gal. center!

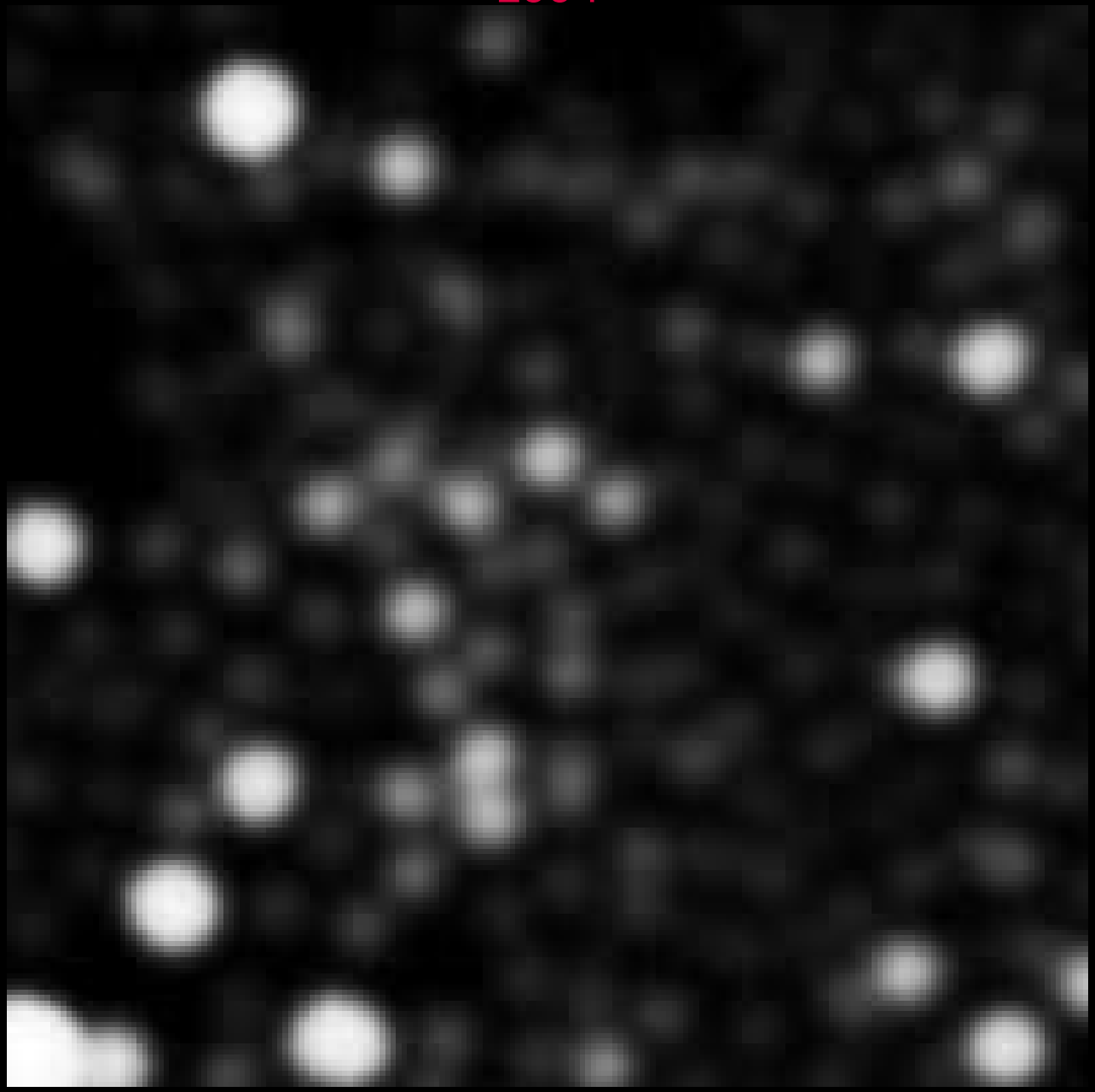
# The Inner Parsec: Central Cluster, IV



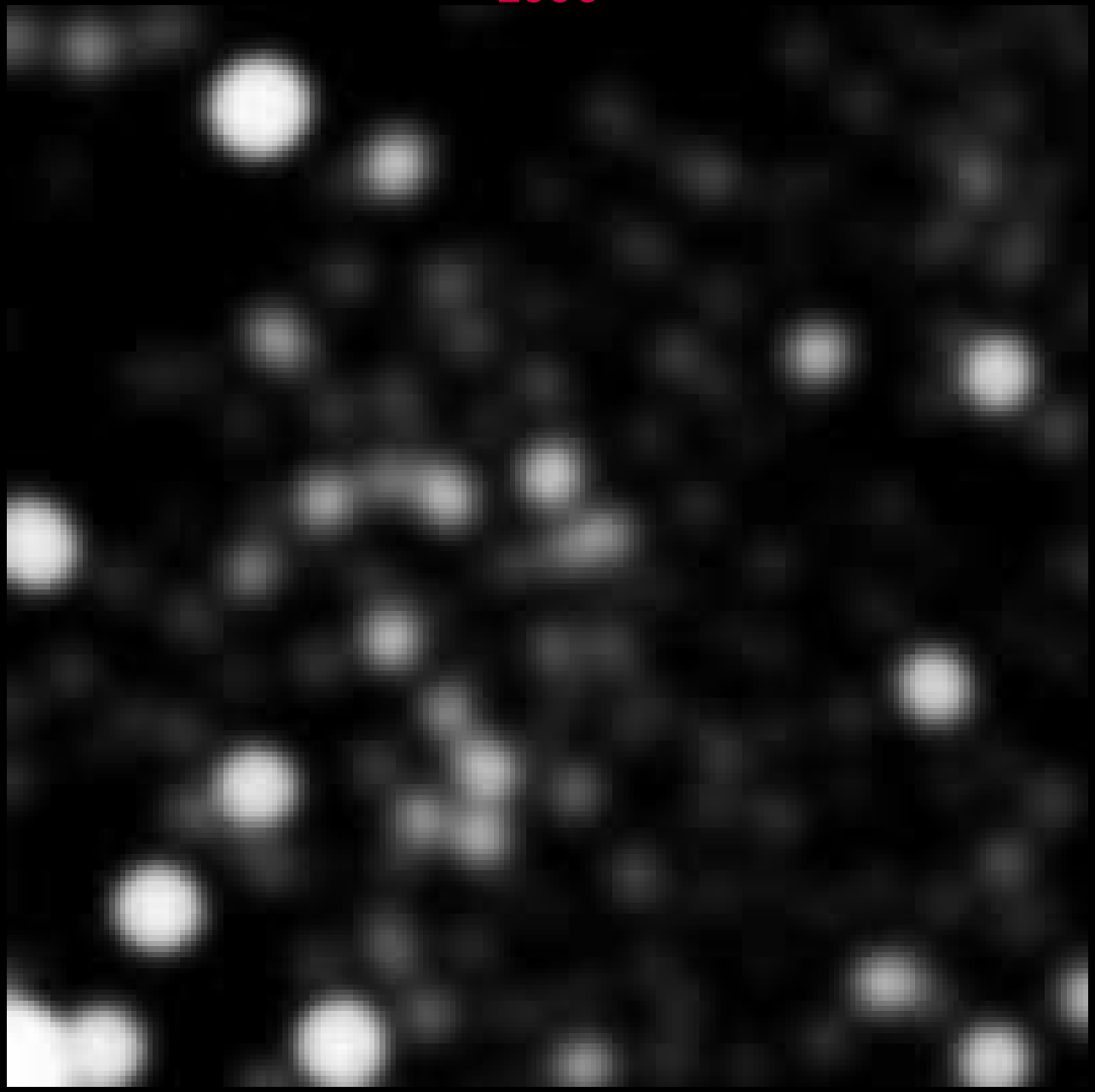

VLT ISAAC K-Band (2.2 $\mu$m) (Genzel/Eckart)

1994



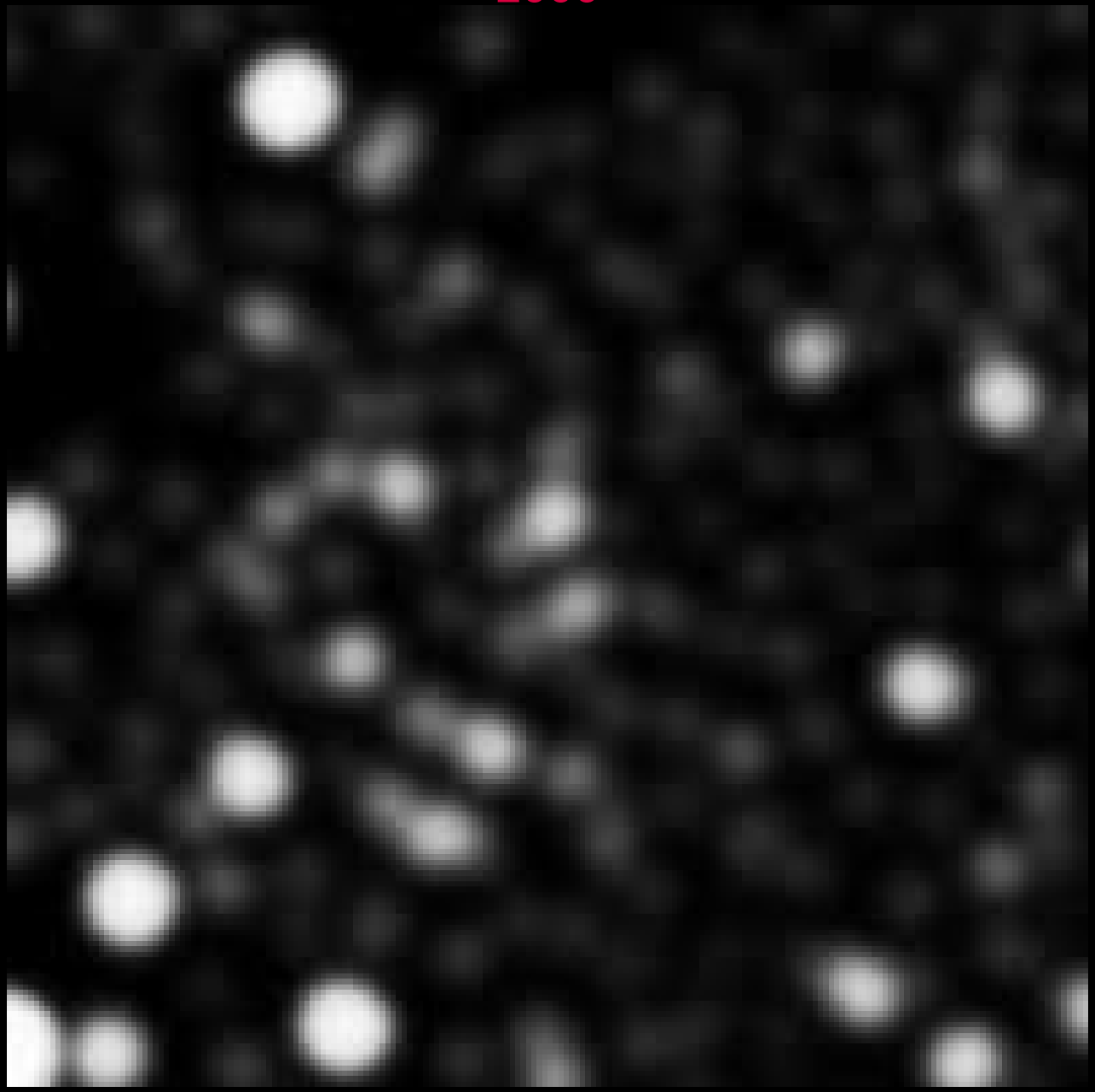
Genzel/Eckart

1996

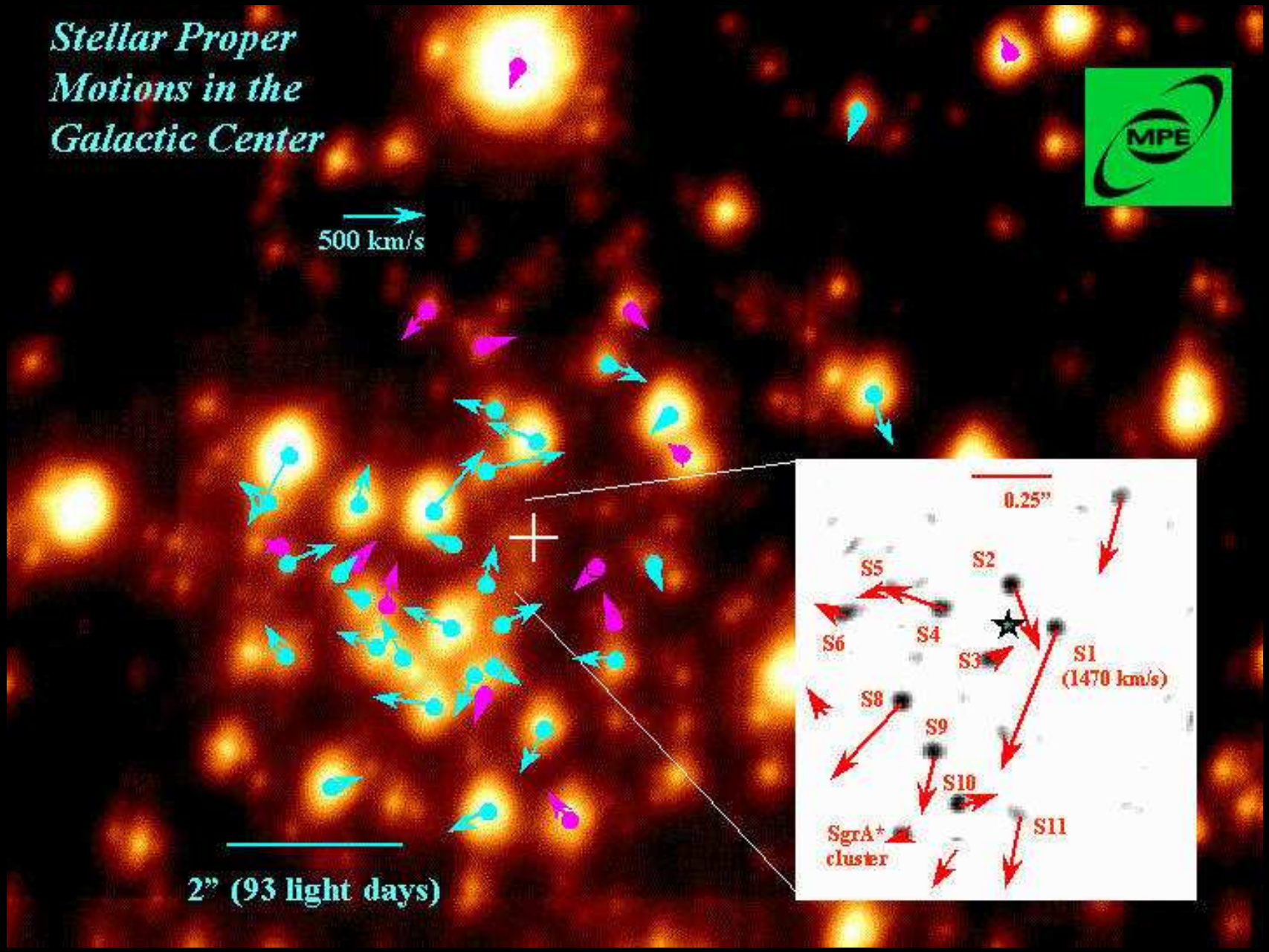


Genzel/Eckart

2000

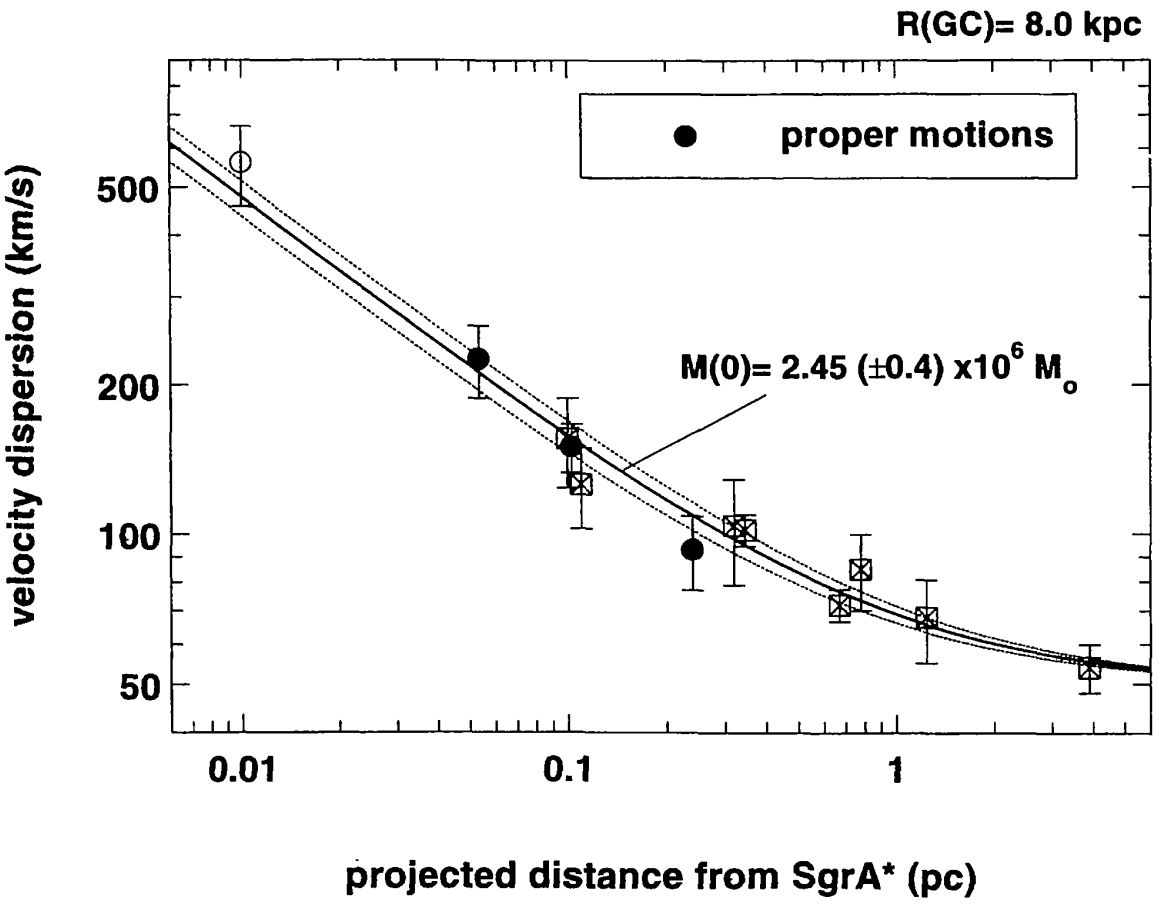


Genzel/Eckart




Genzel et al. (MPE)/Ghez et al. (UCLA): dynamical mass determination by measuring the proper motion of $\sim$ 40 stars of the central cluster (Fig.: MPE results 1991–2000).

# The inner parsec: mass determination

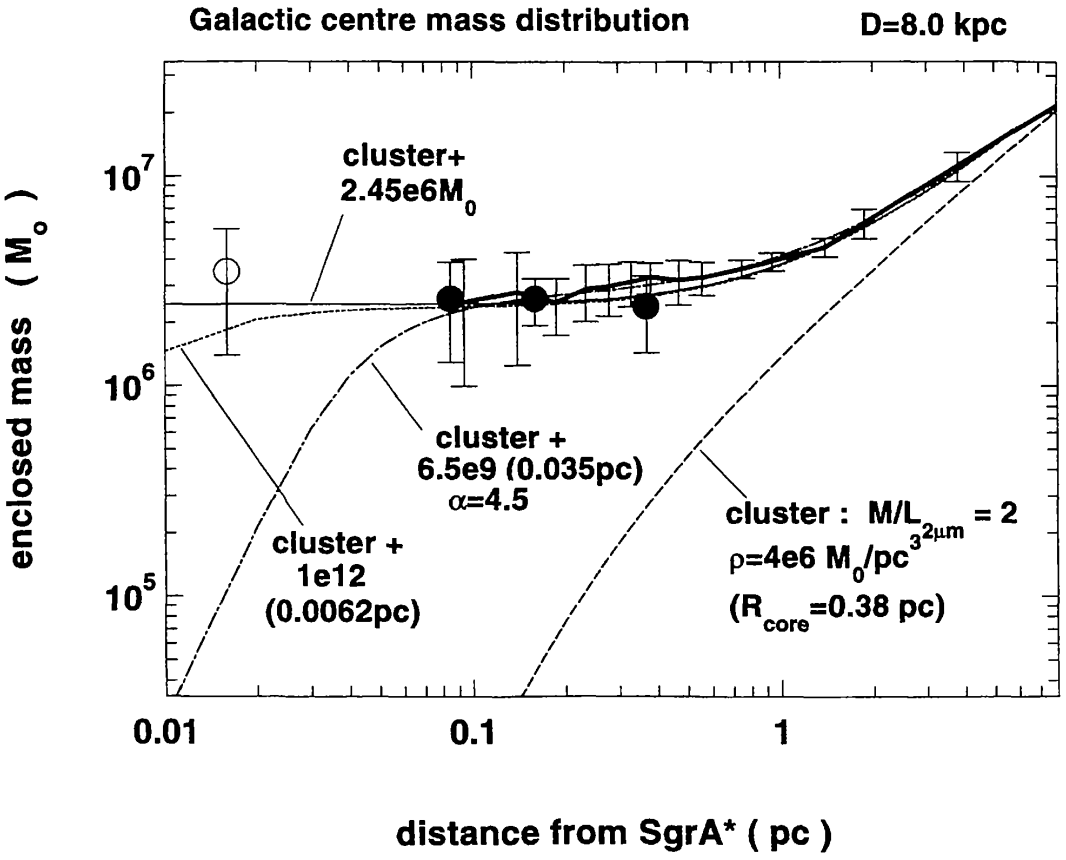



Eckart & Genzel, 1997, MNRAS, 284, 576

Velocity dispersion in the center

For $r \geq 0.057$ pc: Keplerian velocity profile ($\sigma_v \propto v^{-1/2}$), influenced by cluster at smaller distances

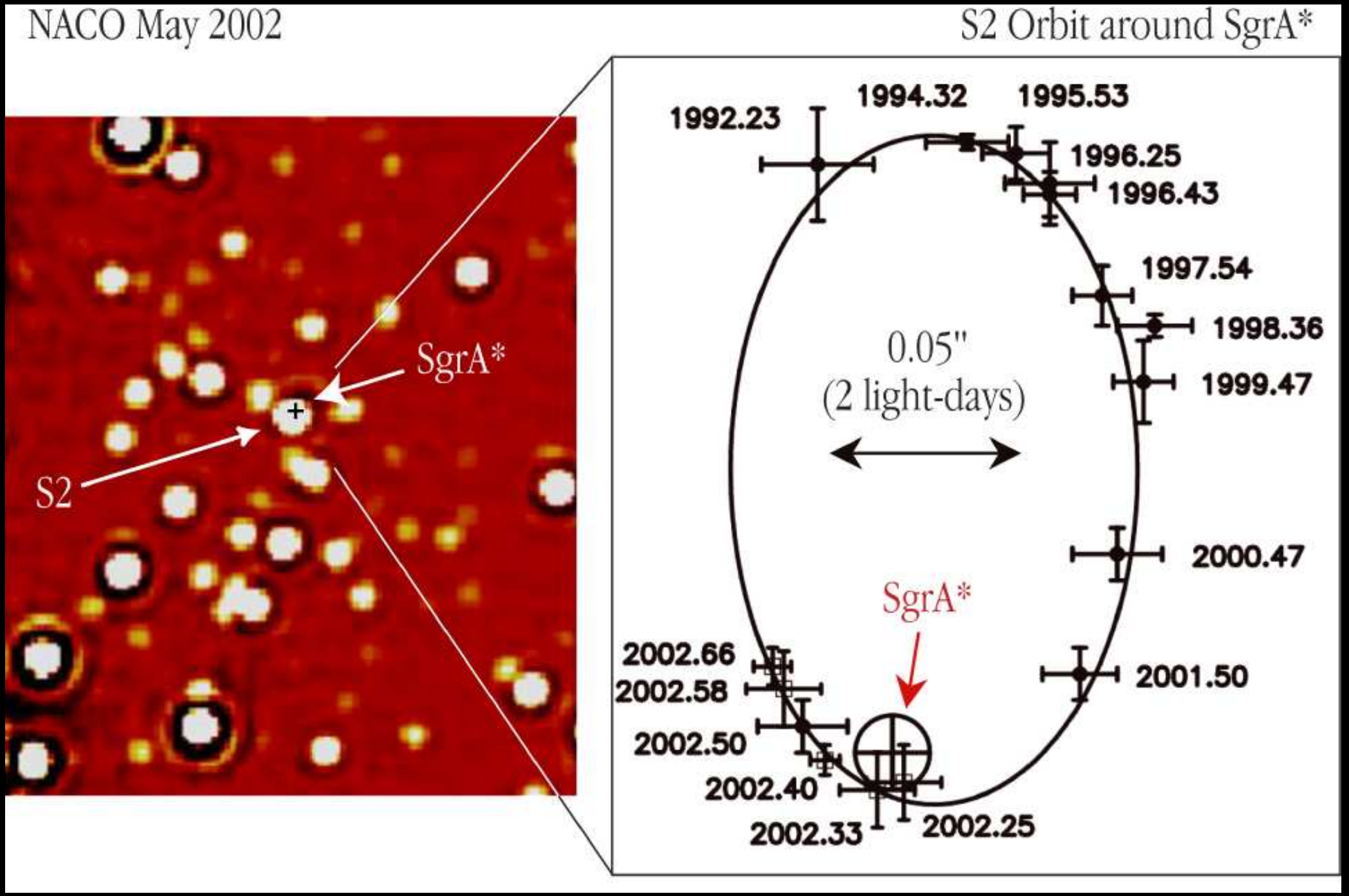
# The inner parsec: mass determination



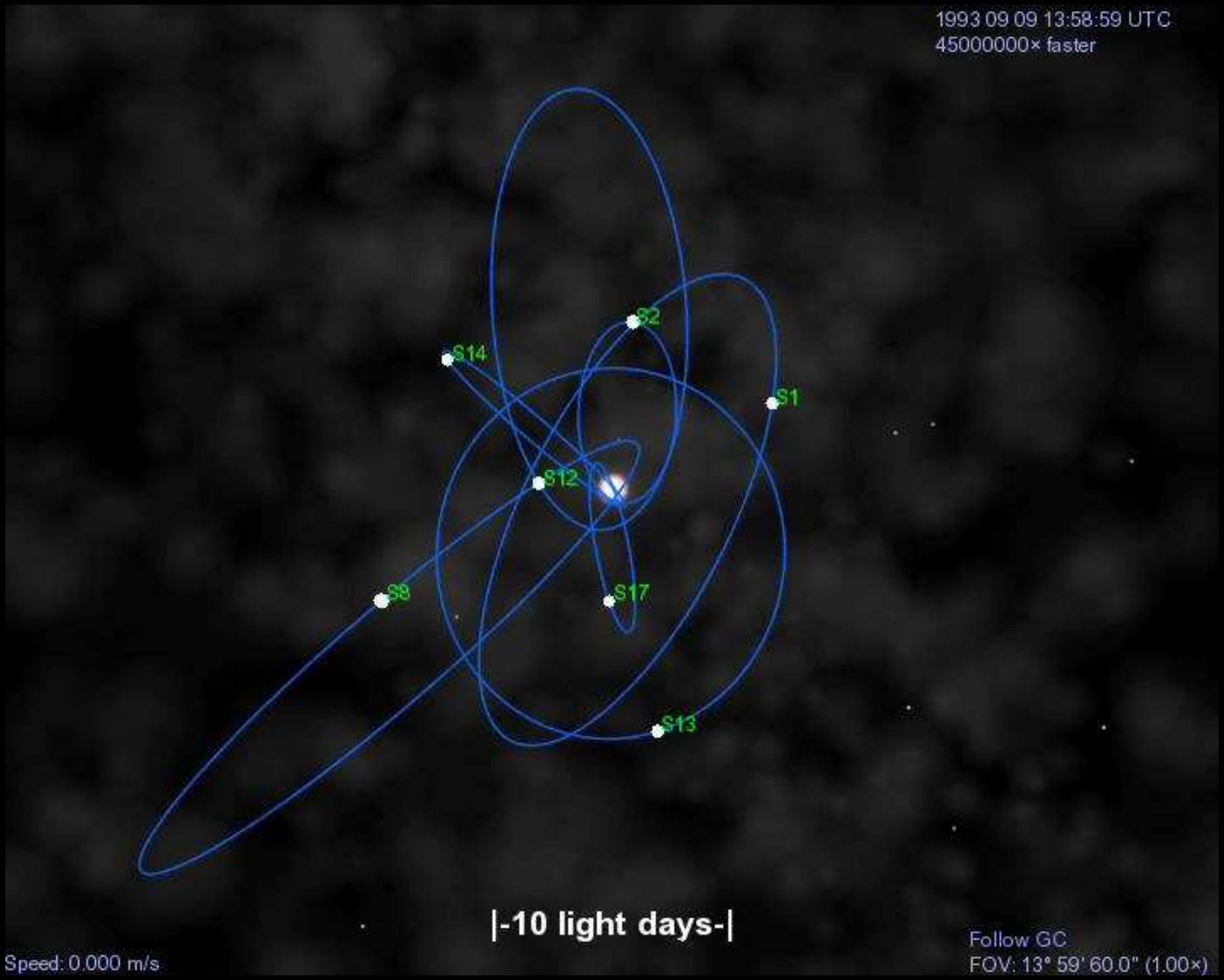

Eckart & Genzel, 1997, MNRAS, 284, 576

*Model:* point source plus cluster with a velocity dispersion of 50 km s$^{-1}$ $\Longrightarrow$ central mass: $2.4 \times 10^6\, M_\odot$.

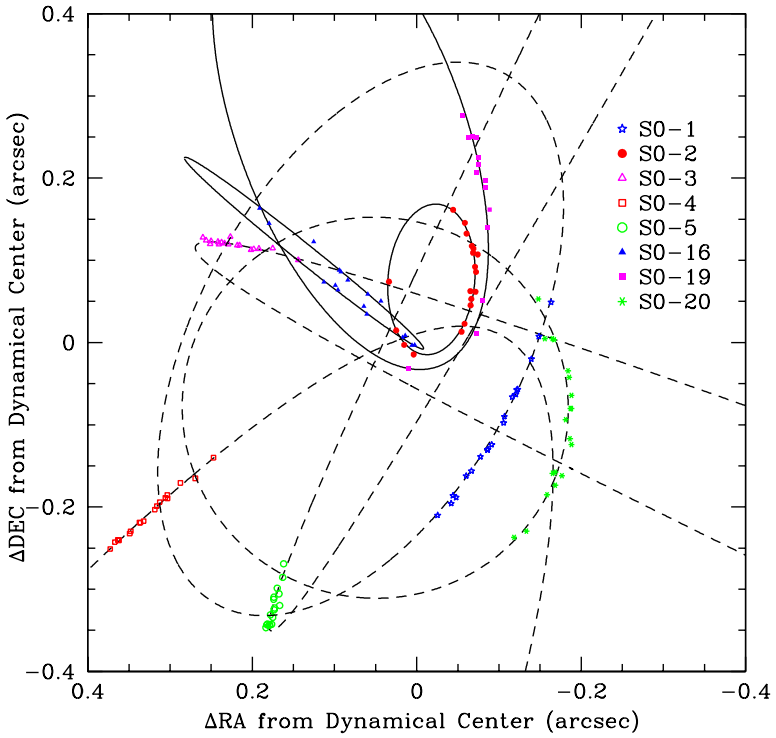
Evidence for a very massive compact object in the Galactic center $\Longrightarrow$ Black Hole?


NACO May 2002
S2 Orbit around SgrA*
SgrA*
S2
1992.23
1994.32
1995.53
1996.25
1996.43
1997.54
1998.36
1999.47
0.05"
(2 light-days)
2000.47
SgrA*
2001.50
2002.66
2002.58
2002.50
2002.40
2002.33
2002.25

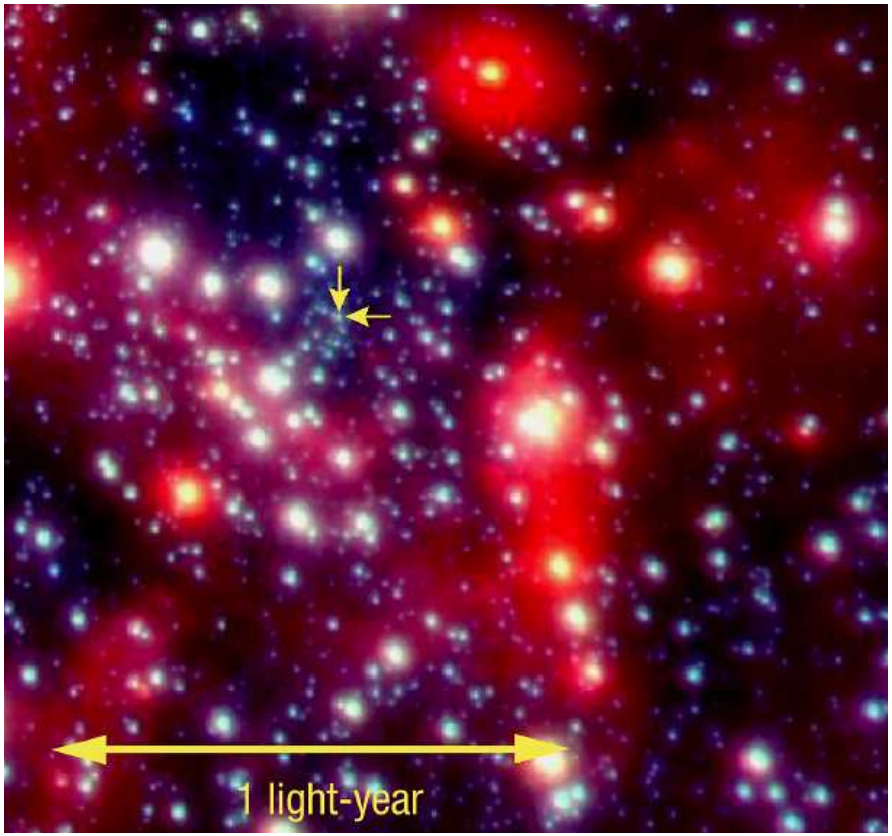
ESO, Oct 2002


1993 09 09 13:58:59 UTC
45000000× faster
S2
S14
S1
S12
S8
S17
S13
|-10 light days-|
Speed: 0.000 m/s
Follow GC
FOV: 13° 59' 60.0" (1.00×)

# The inner parsec: mass determination

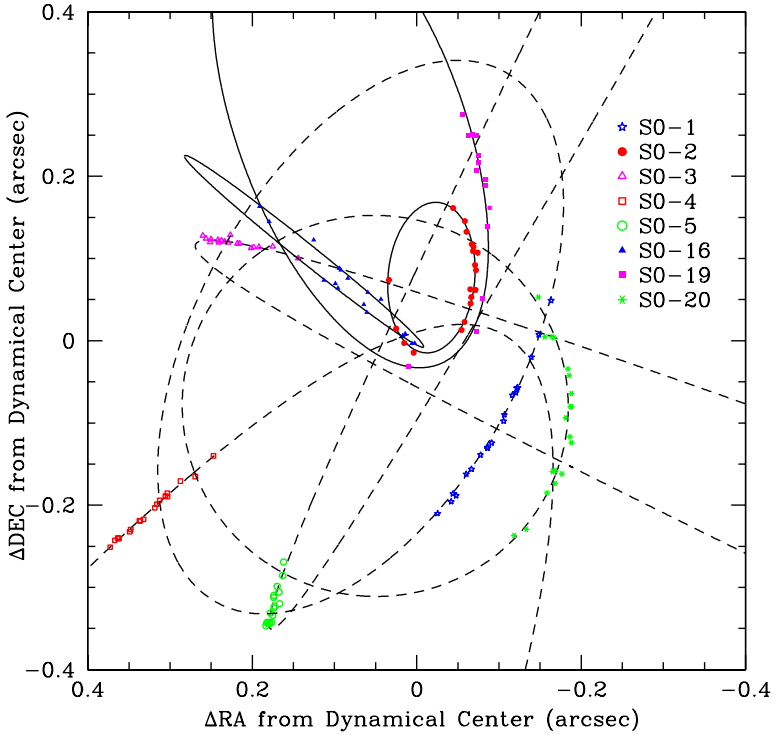



Ghez et al. (2003)

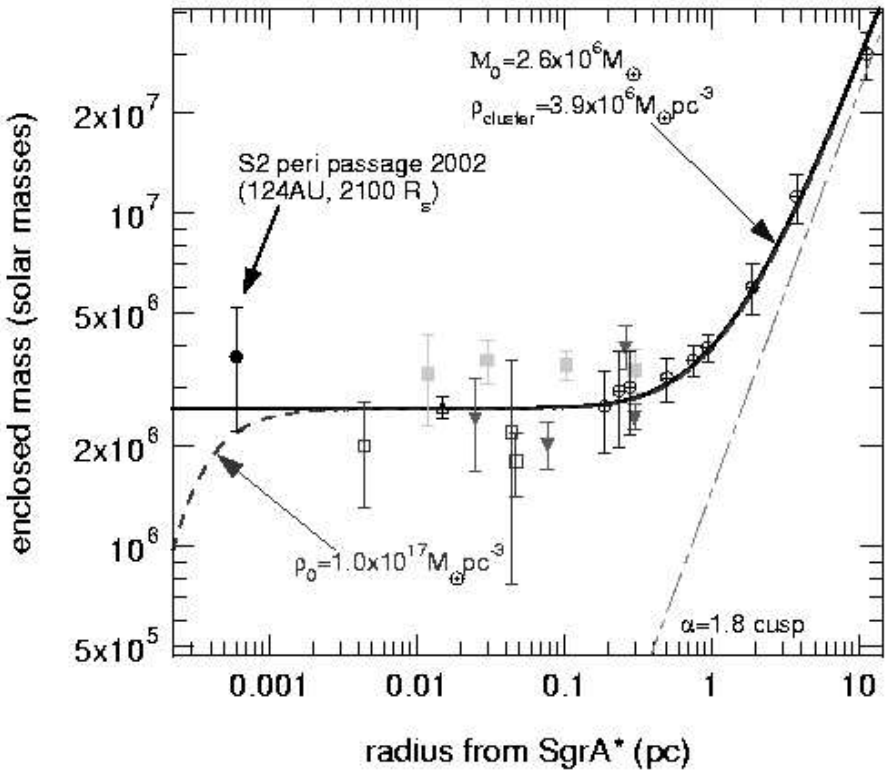



ESO

# The inner parsec: mass determination




Ghez et al. (2003)

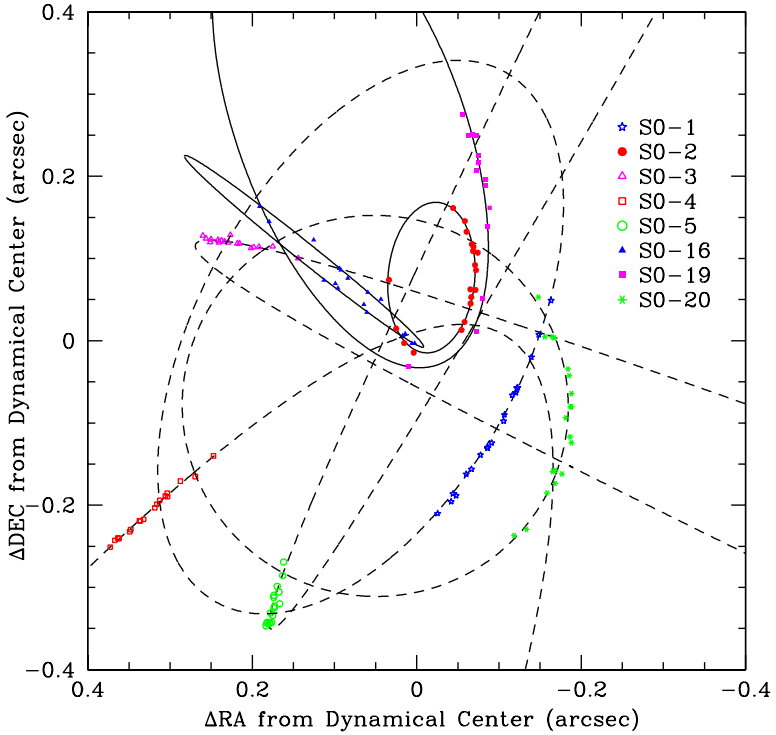



Schödel et al. (2002)

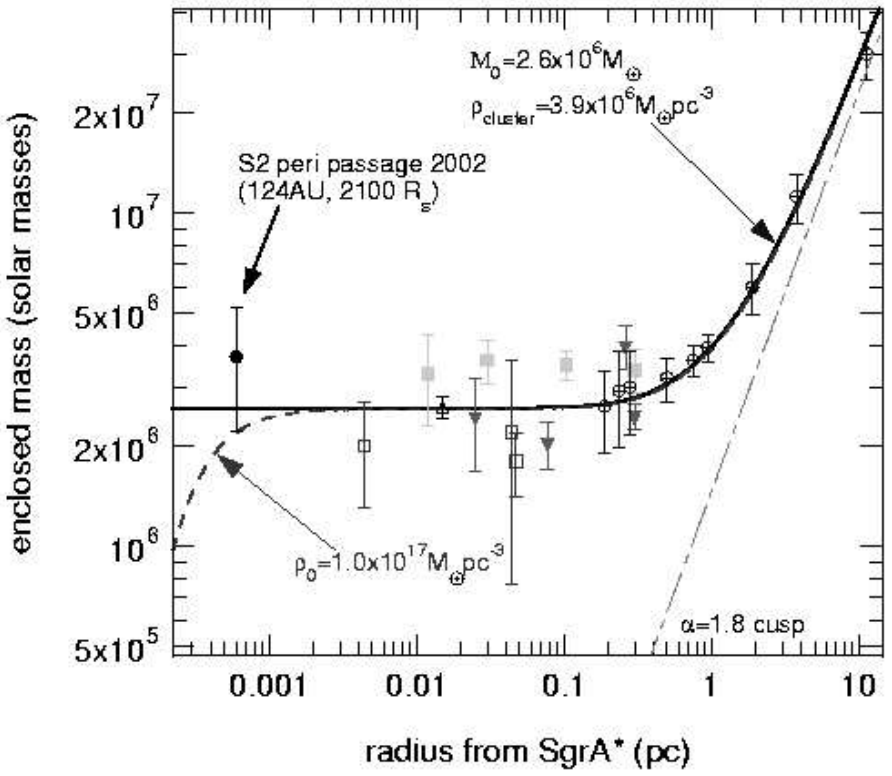
Mass determination: 3. Kepler

$$a = 5.5\,\text{light days}$$
$$P = 15.2\,\text{years}$$
$$\Longrightarrow \quad \frac{P^2}{a^3} = \frac{4\pi^2}{G(m_* + M_{\text{BH}})}$$

# The inner parsec: mass determination




Ghez et al. (2003)




Schödel et al. (2002)

The center of the Galaxy harbors a black hole with

$$M_{\mathrm{BH}} = (3.7 \pm 1.0) \times 10^6\, M_\odot$$



# *Galaxies: Classification*