Supermassive Black Holes

Across Cosmic Time

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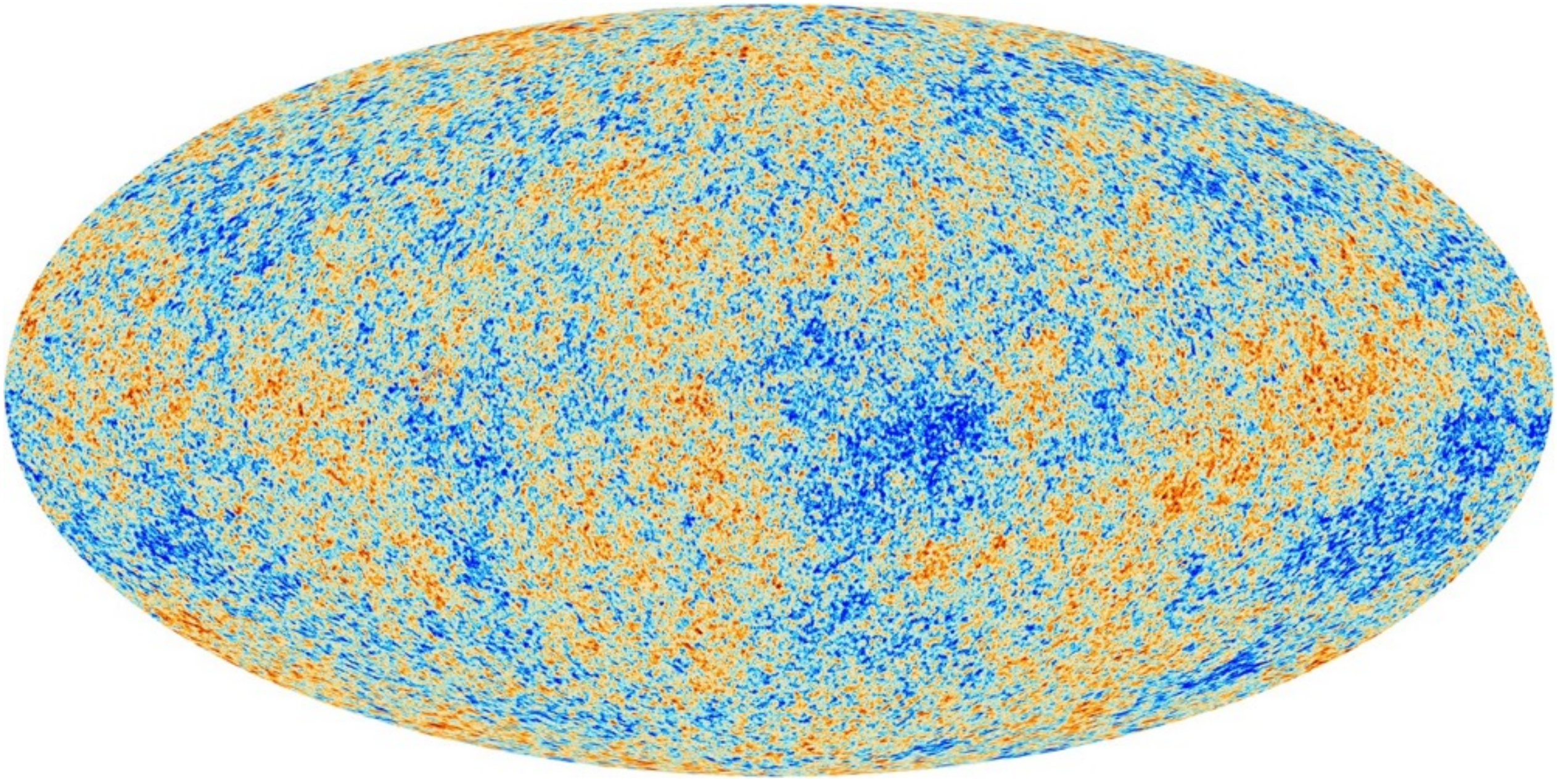
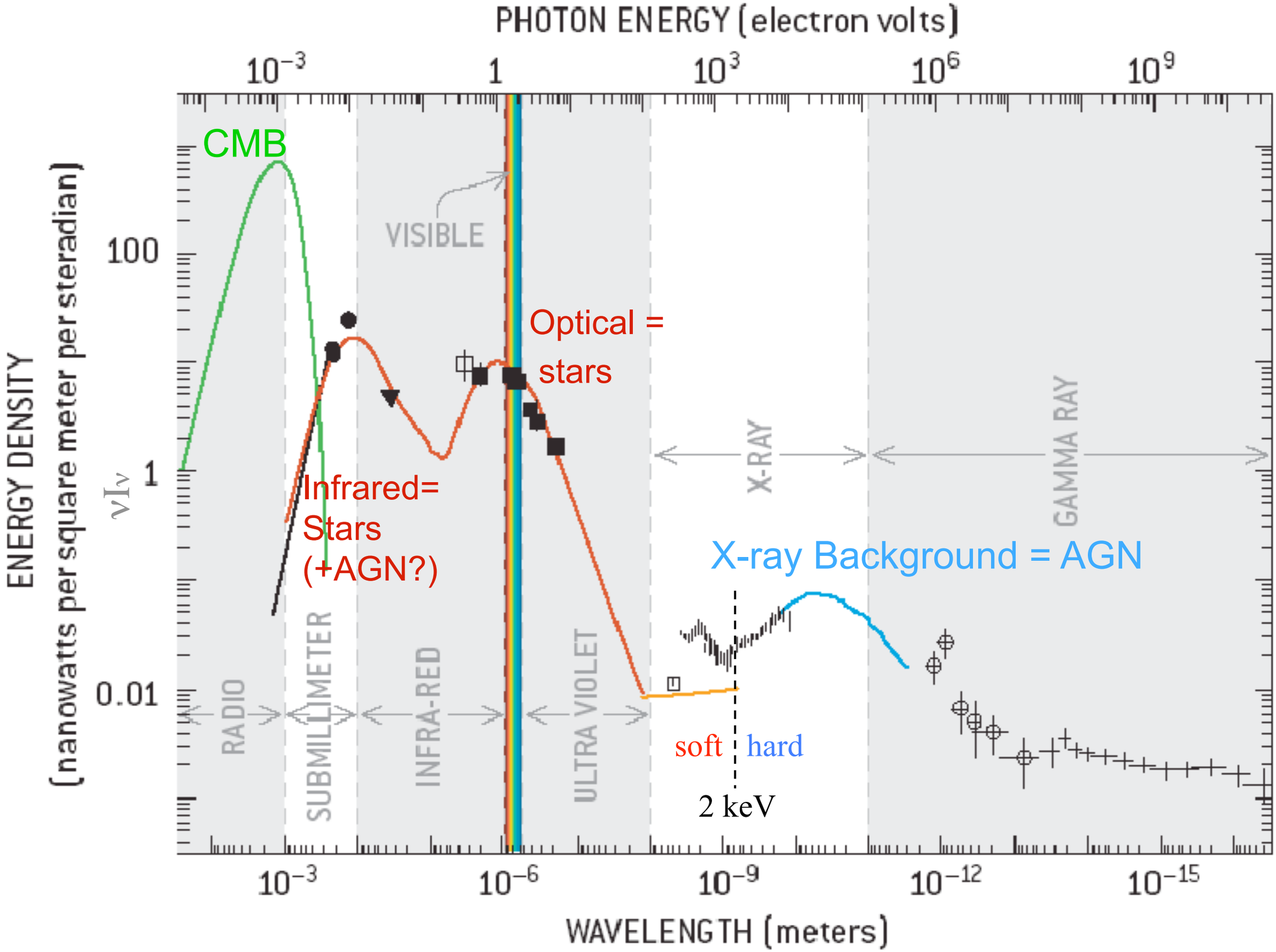
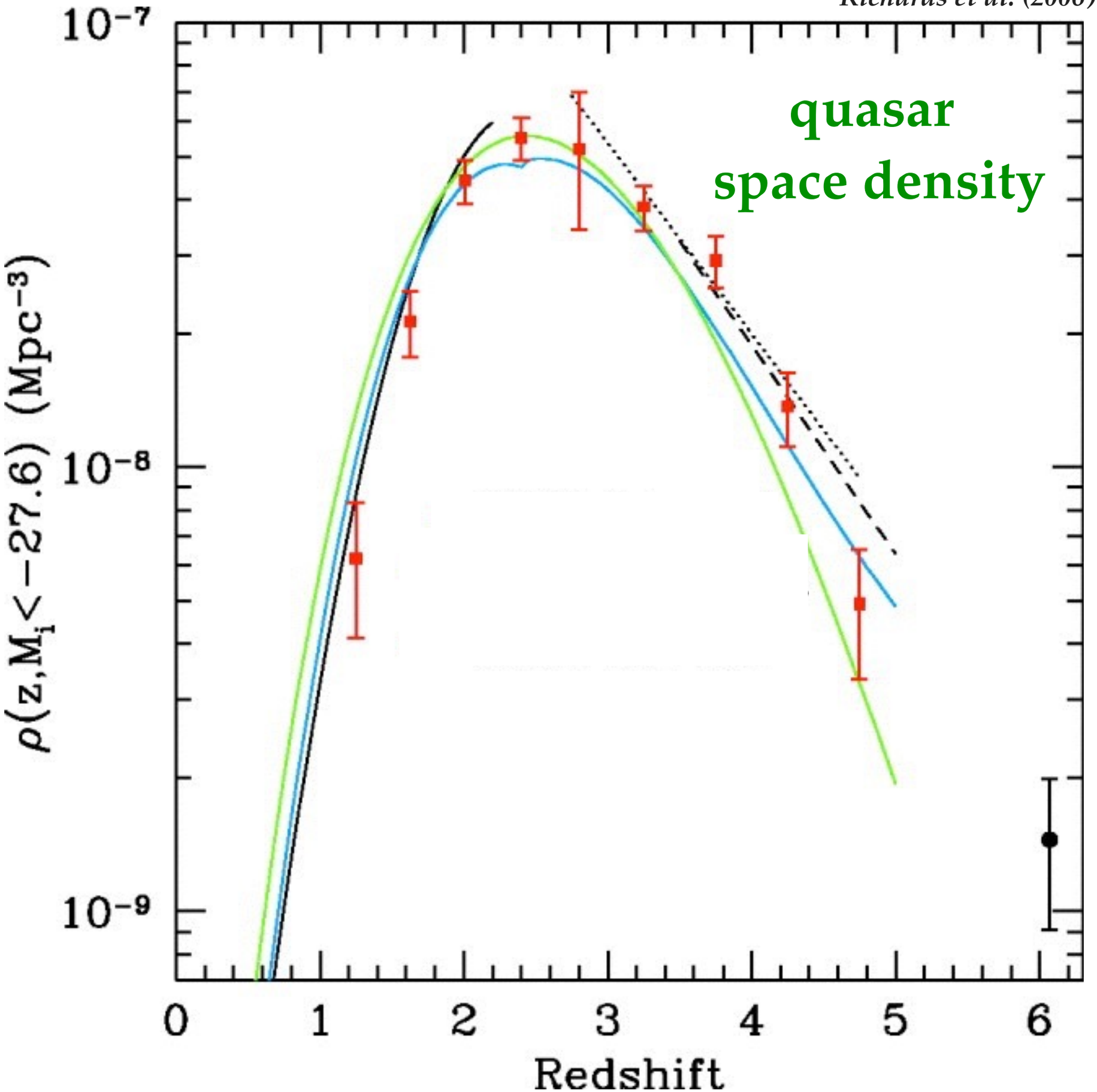
Kavli Institute for Astronomy and Astrophysics
Peking University


UMHLANGA
PLAZA
BOSTON
HOOTERS

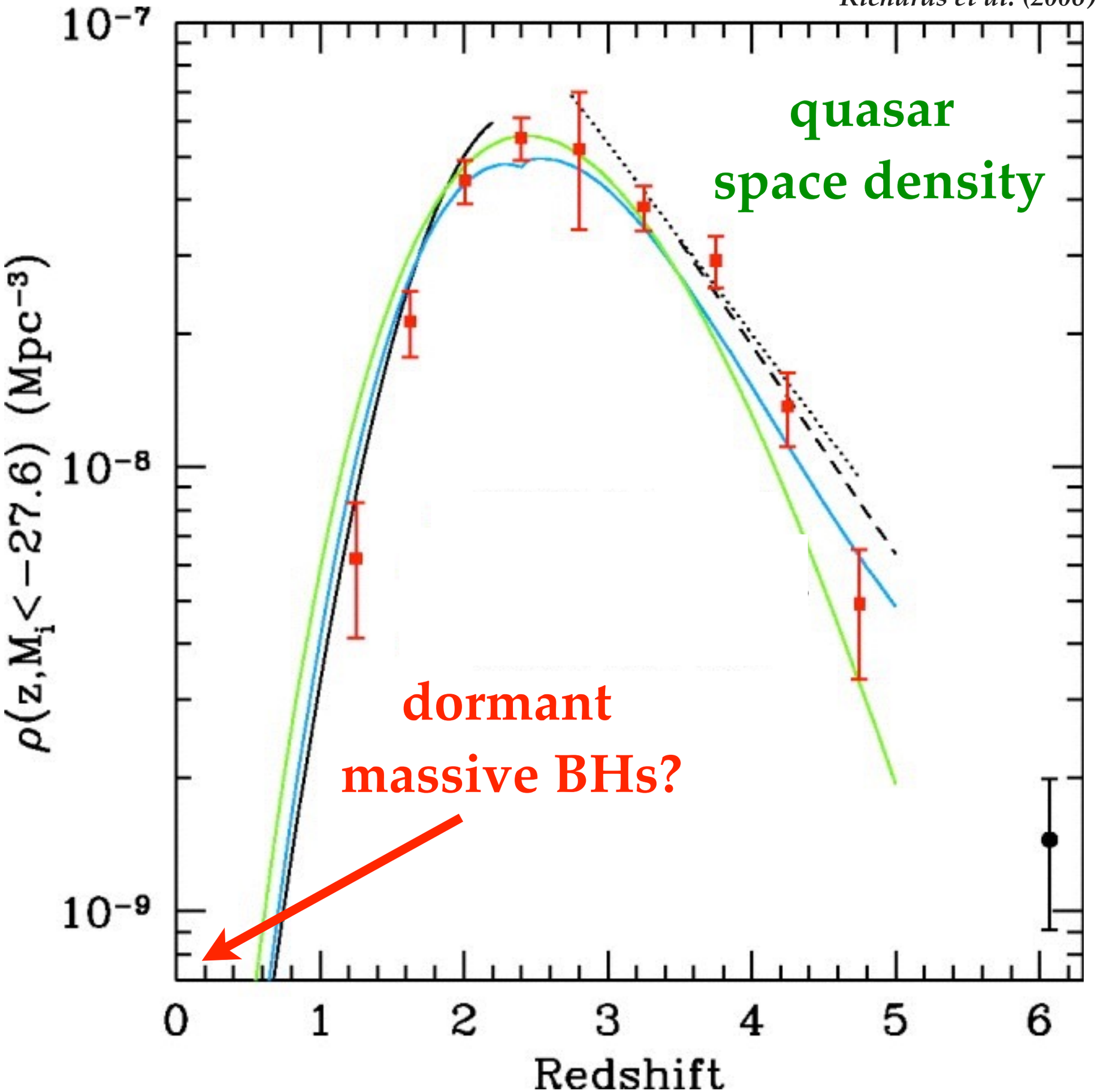


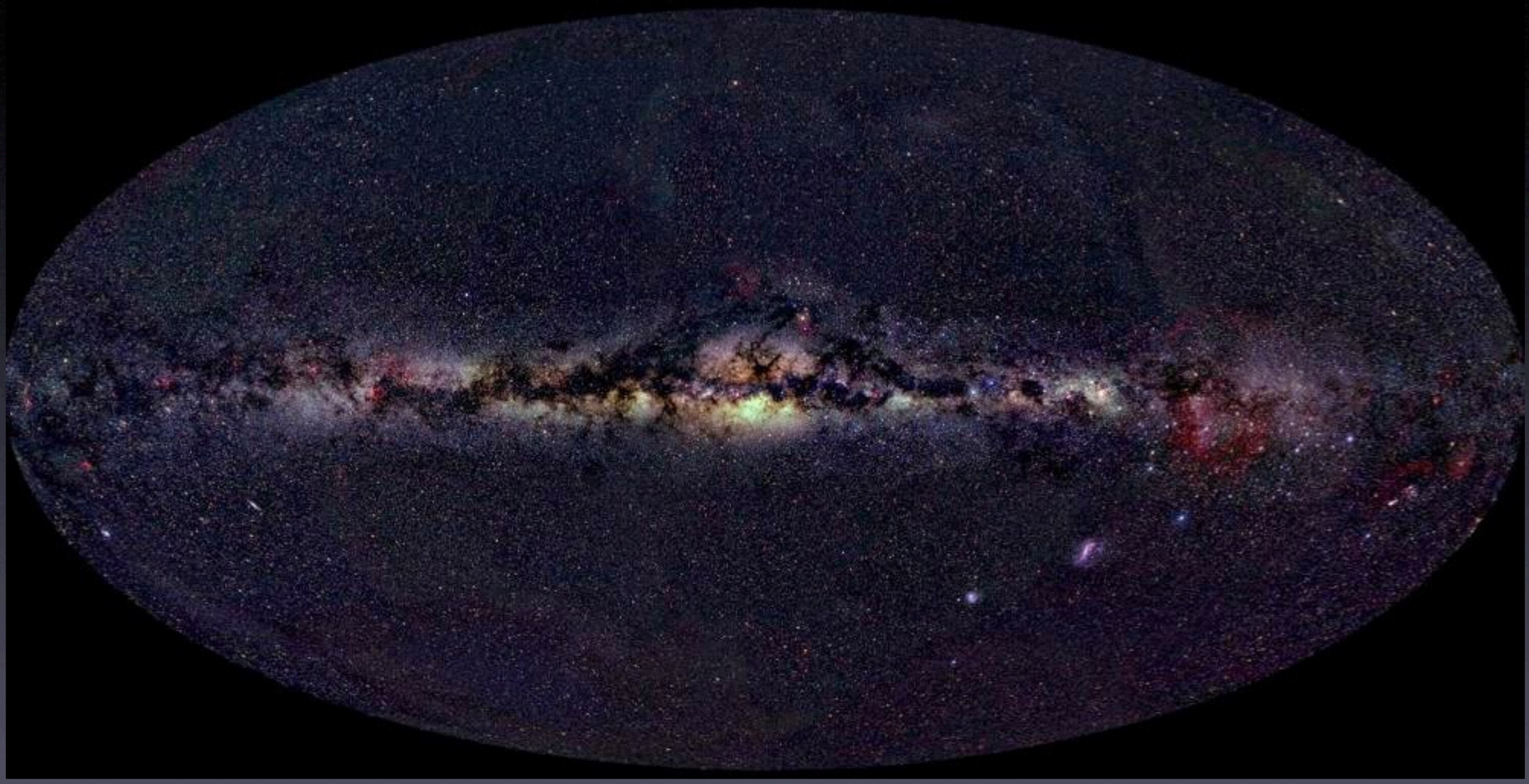

PHOTON ENERGY (electron volts)
10^{-3}
1
10^{3}
10^{6}
10^{9}
CMB
VISIBLE
Optical =
stars
Infrared=
Stars
(+AGN?)
X-RAY
GAMMA RAY
X-ray Background = AGN
soft
hard
2 keV
100
1
0.01
νI_ν
ENERGY DENSITY
(nanowatts per square meter per steradian)
RADIO
SUBMILLIMETER
INFRA-RED
ULTRA VIOLET
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
WAVELENGTH (meters)

Richards et al. (2006)

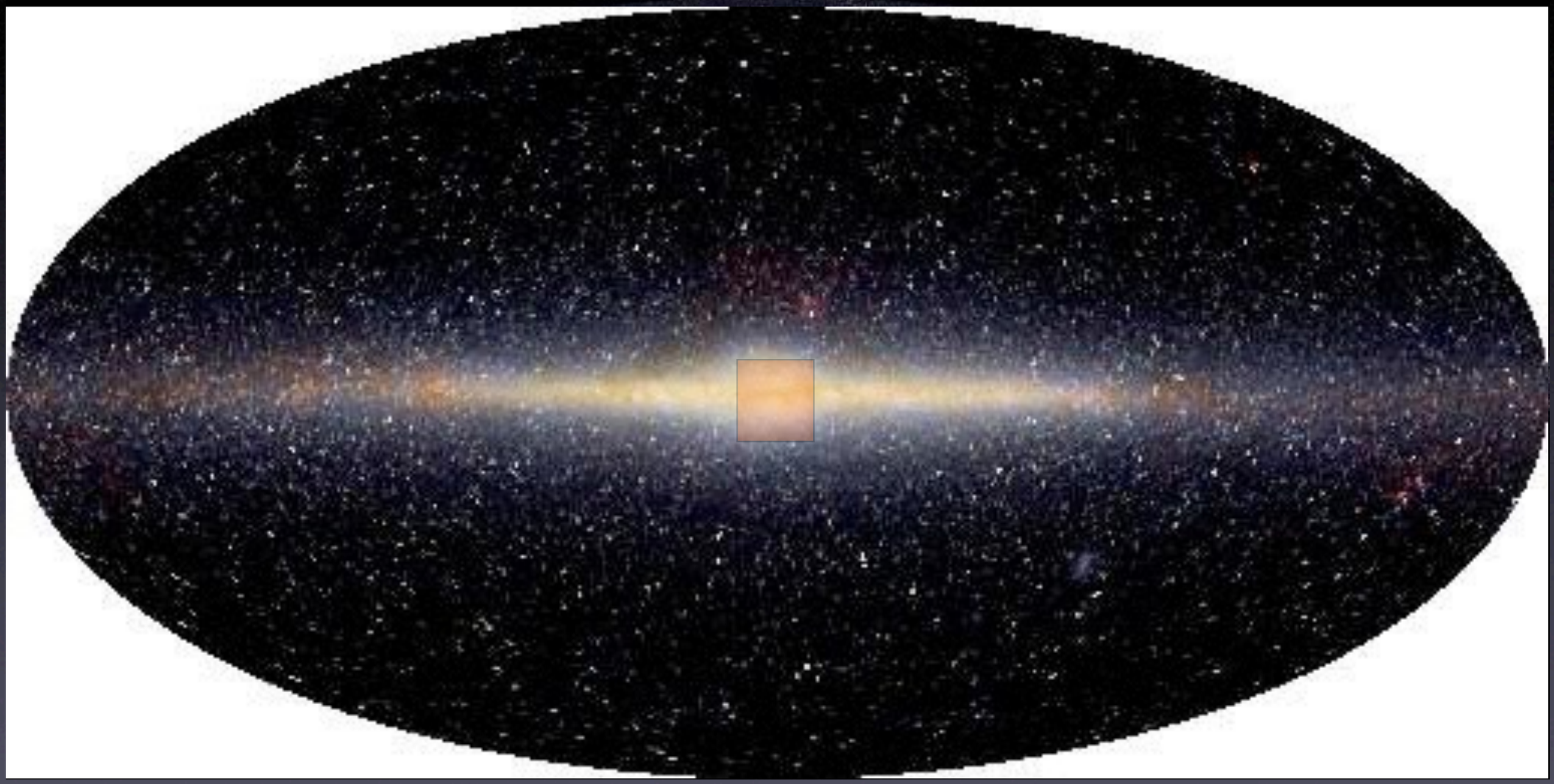


Richards et al. (2006)

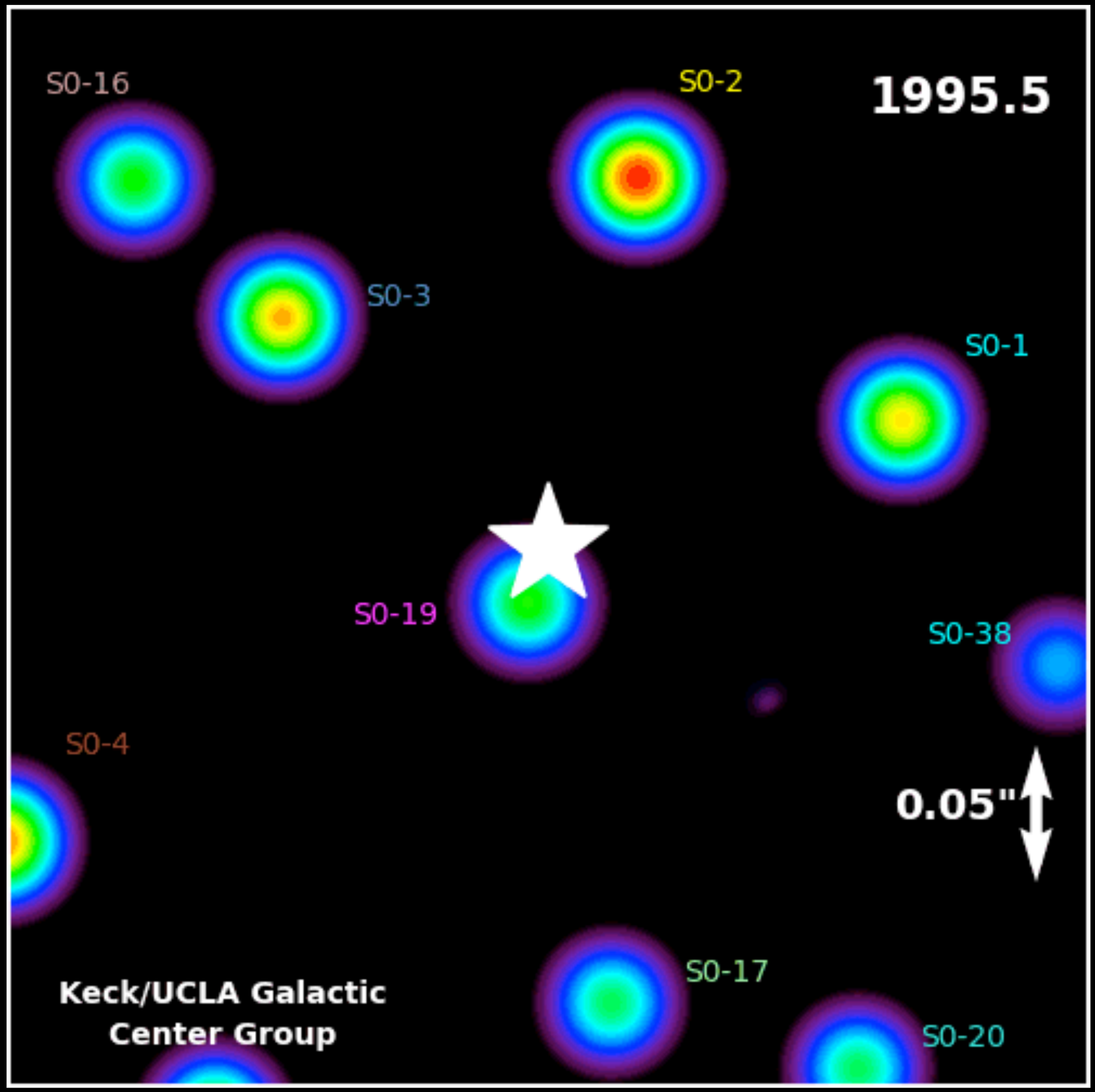


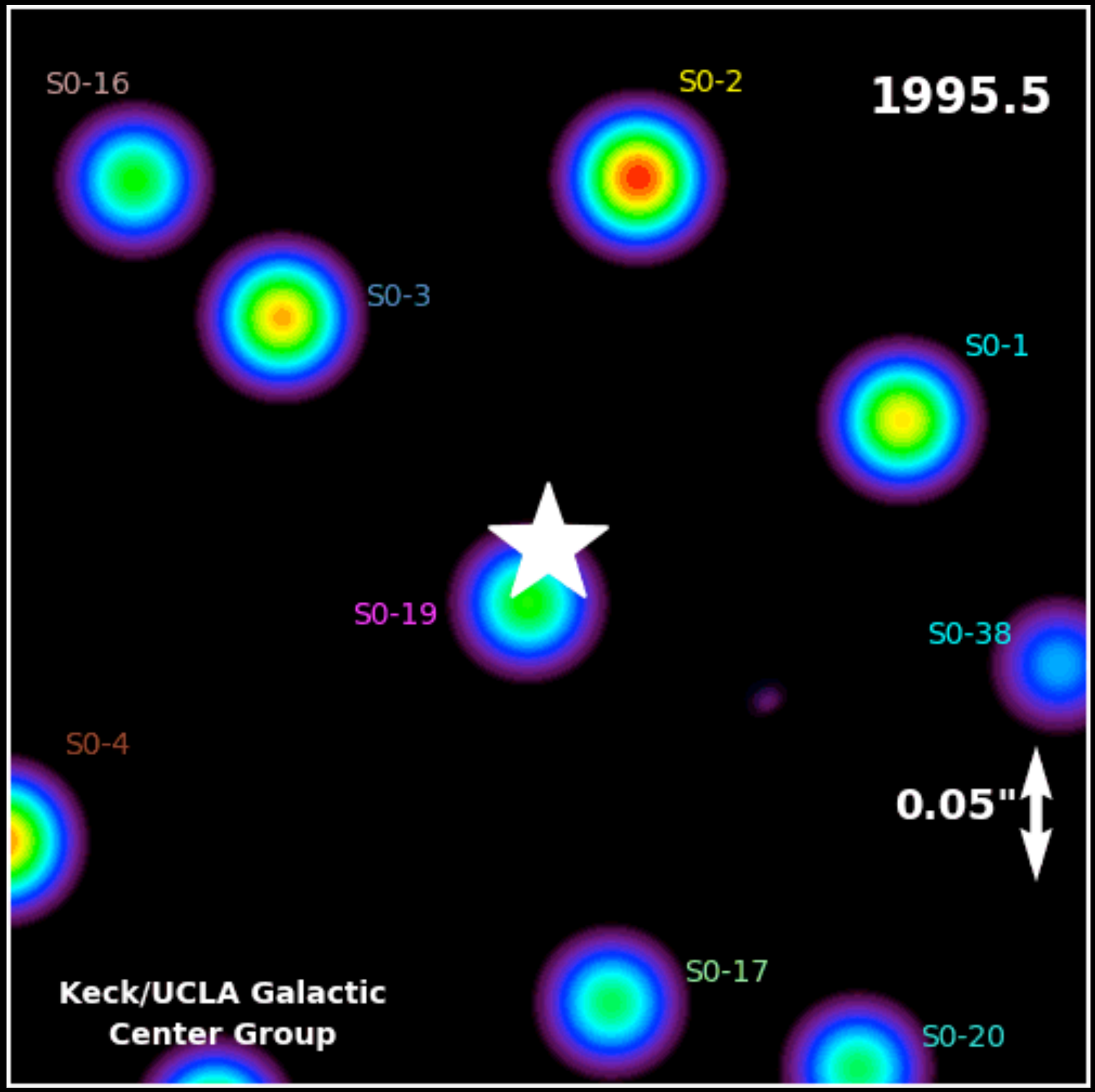


100,000 light years



100,000 light years


S0-16
S0-2
1995.5
S0-3
S0-1
S0-19
S0-38
S0-4
0.05"
S0-17
S0-20
Keck/UCLA Galactic
Center Group


S0-16
S0-2
1995.5
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S0-1
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0.05"
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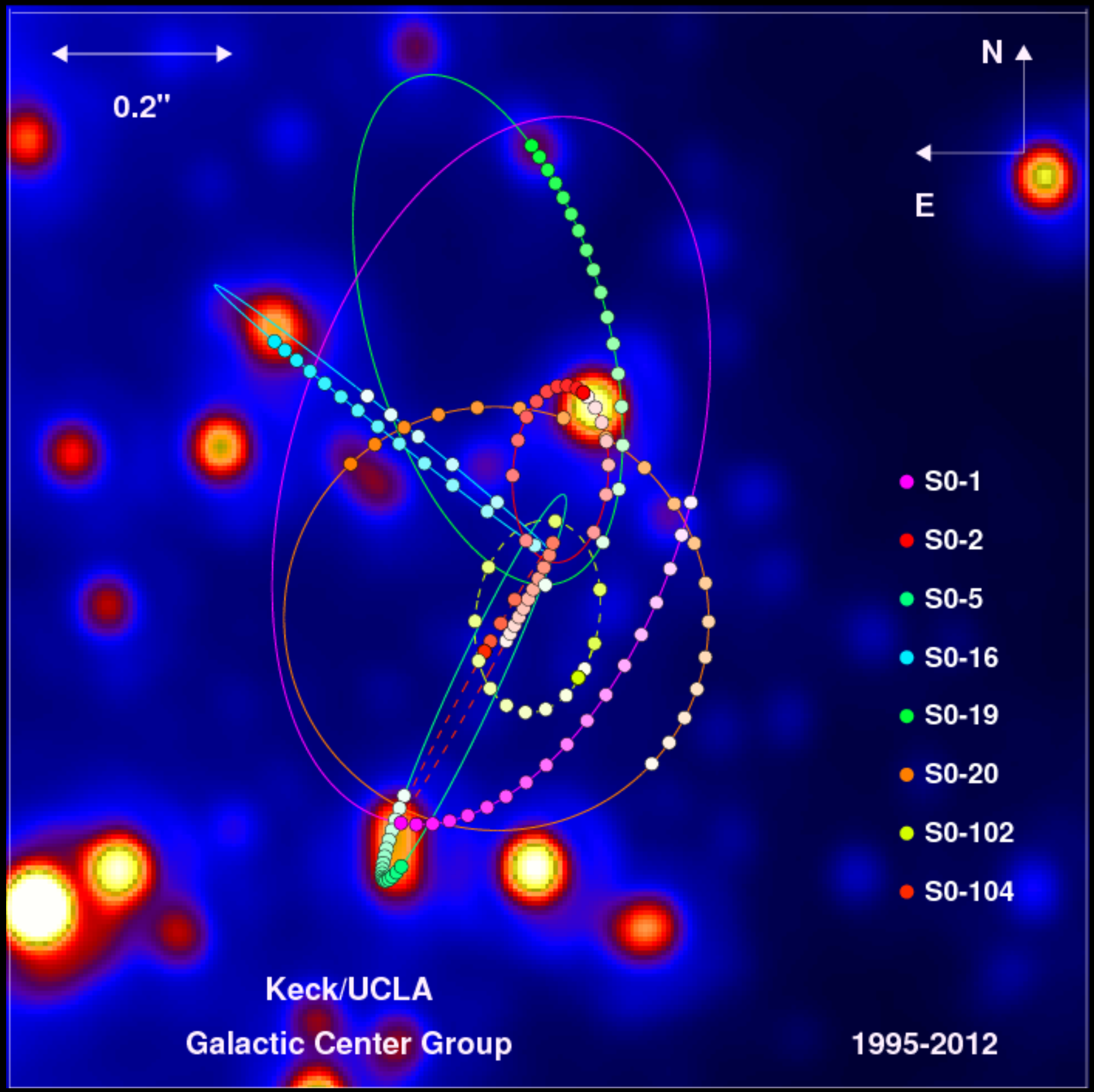
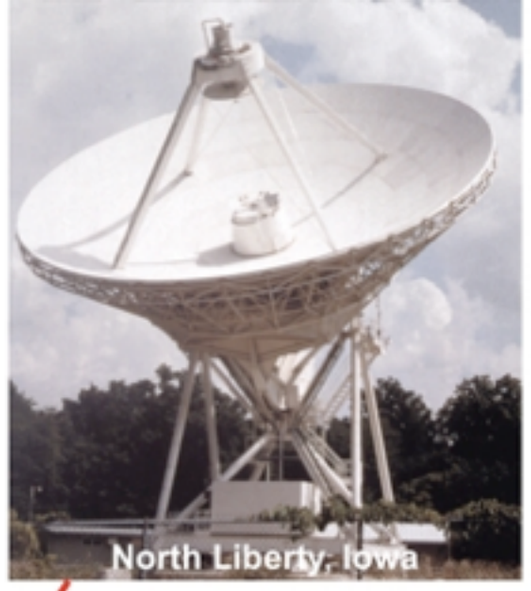
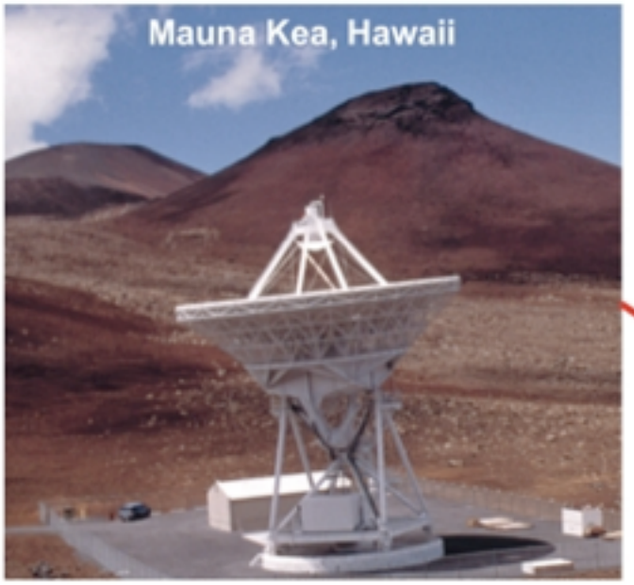

0.2"
N
E
S0-1
S0-2
S0-5
S0-16
S0-19
S0-20
S0-102
S0-104
Keck/UCLA
Galactic Center Group
1995-2012

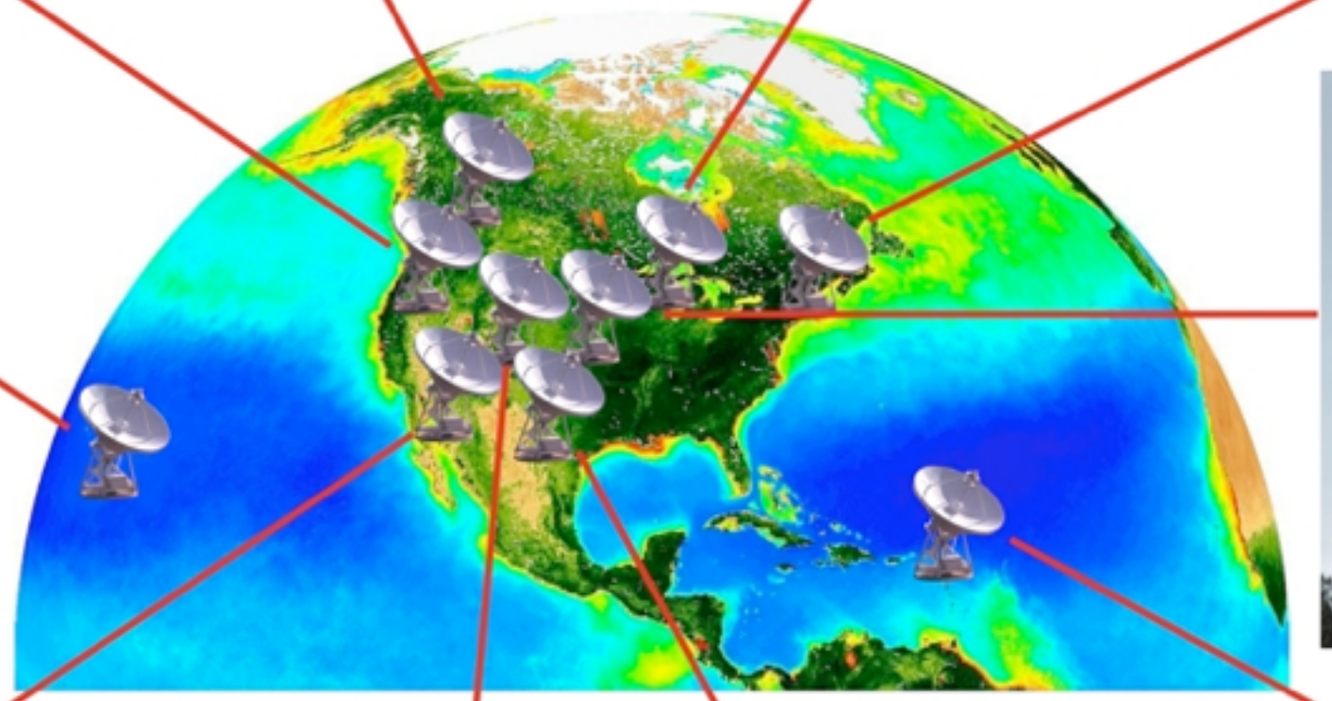

Owens Valley, California


Brewster, Washington

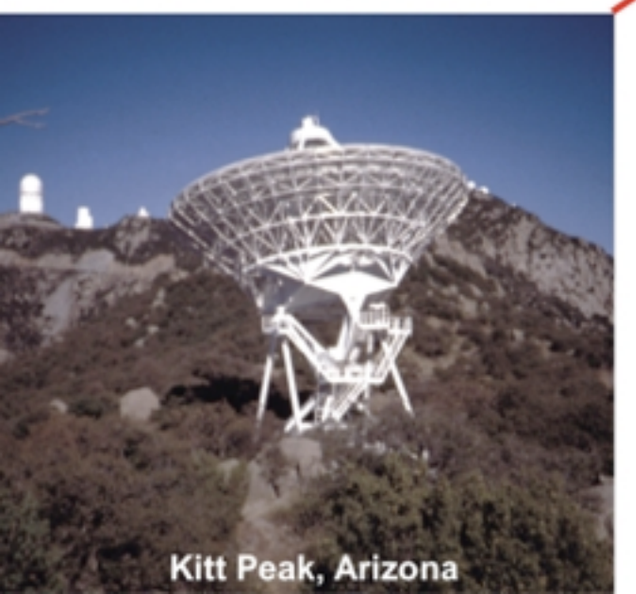

North Liberty, Iowa


Hancock, New Hampshire

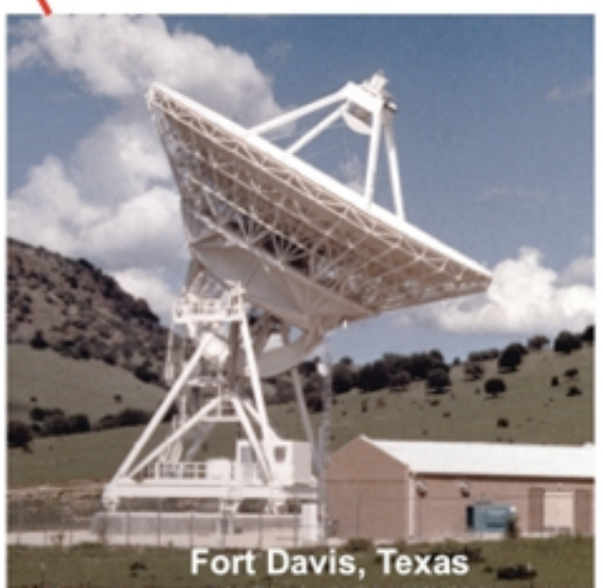

Mauna Kea, Hawaii

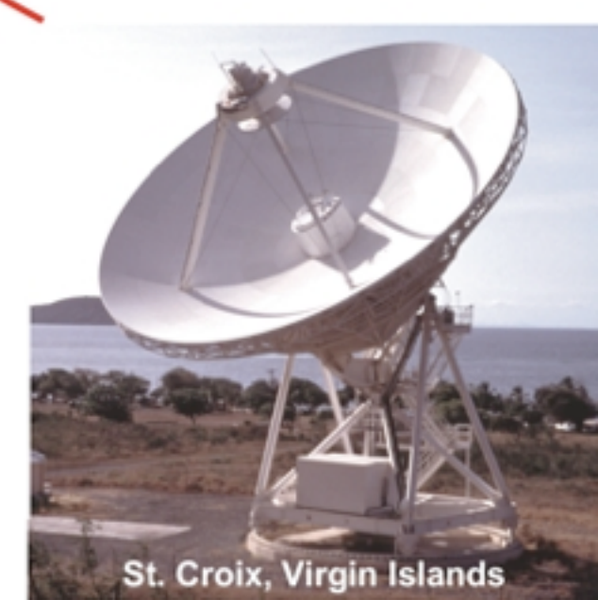


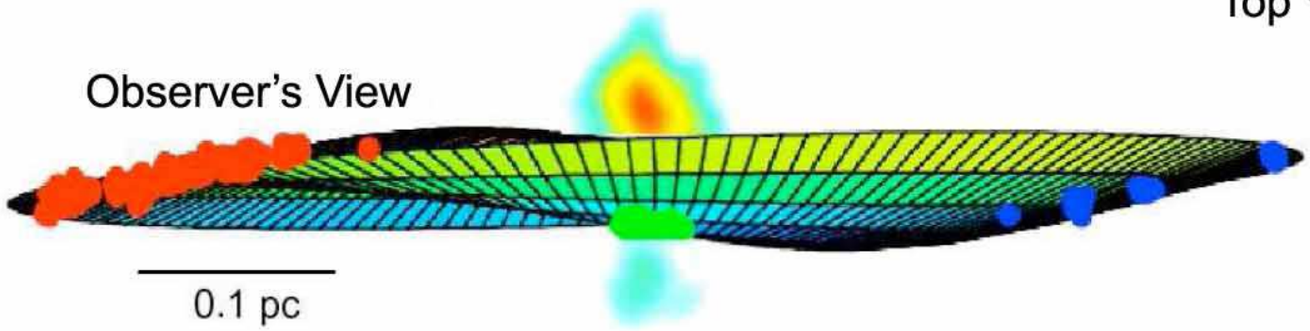

Los Alamos, New Mexico

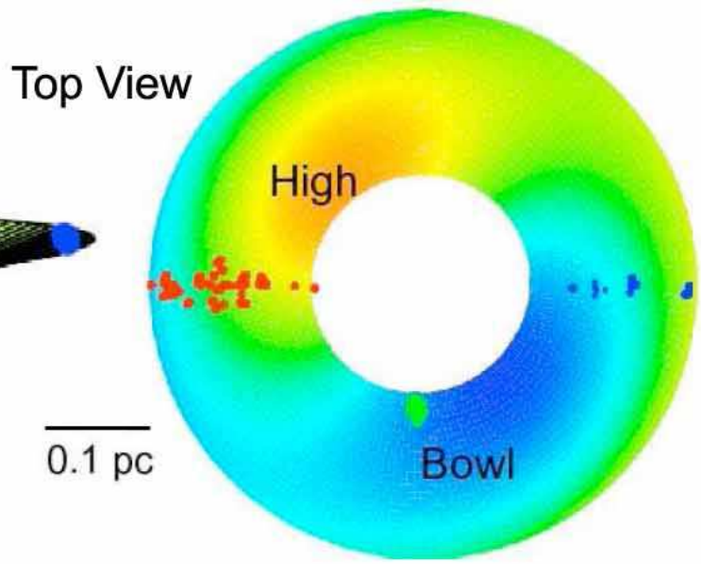

Kitt Peak, Arizona

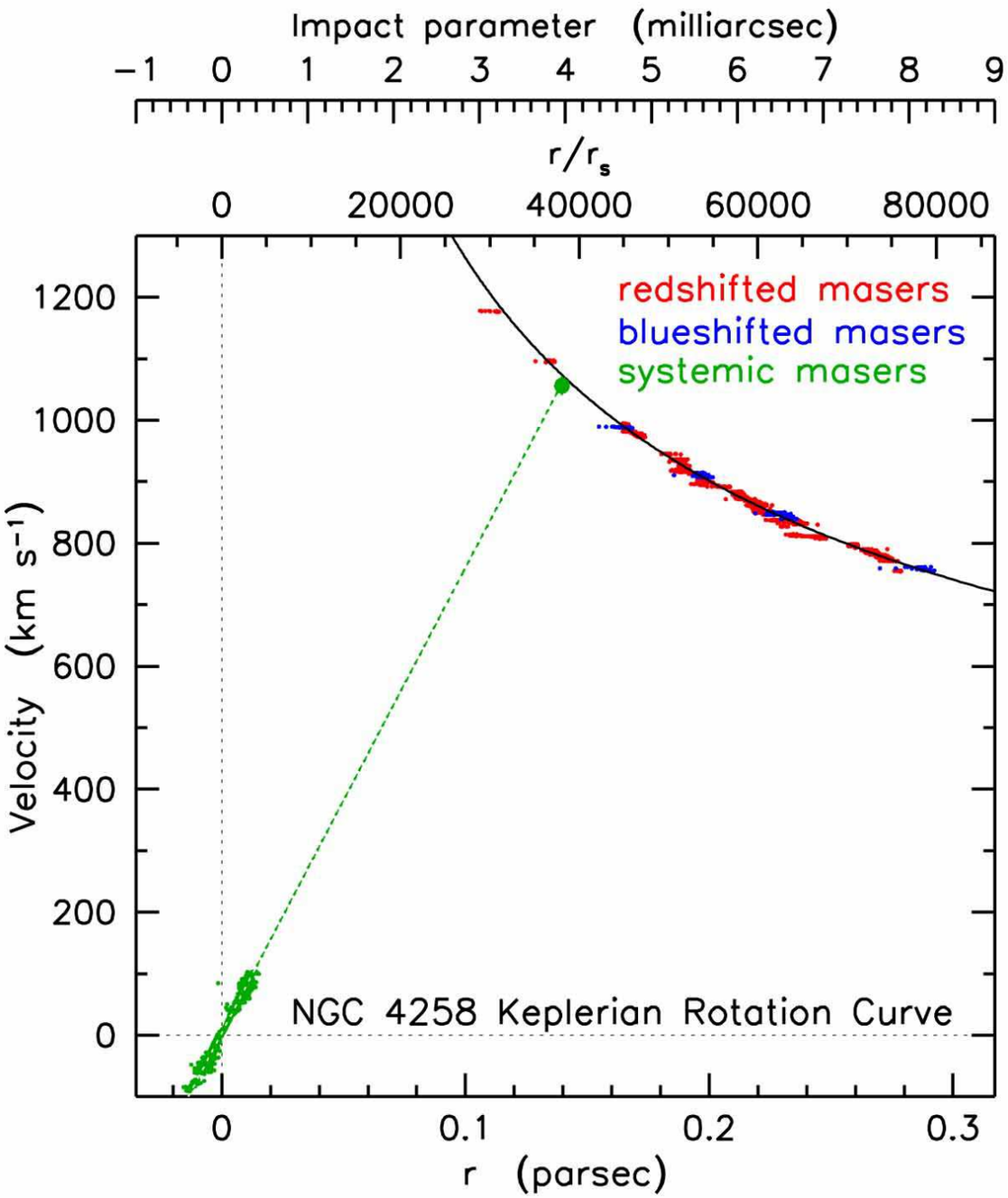

Pie Town, New Mexico


Fort Davis, Texas

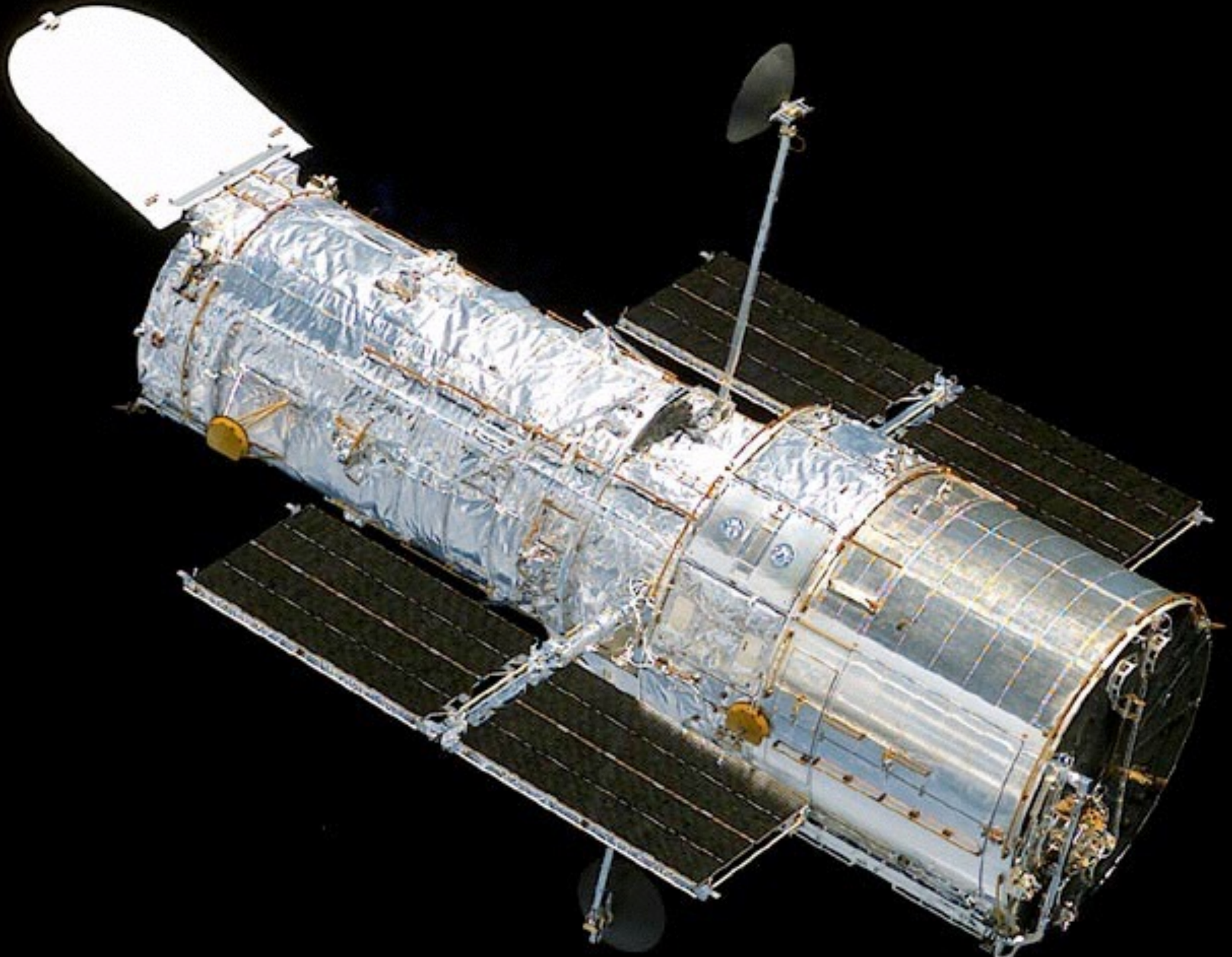

St. Croix, Virgin Islands



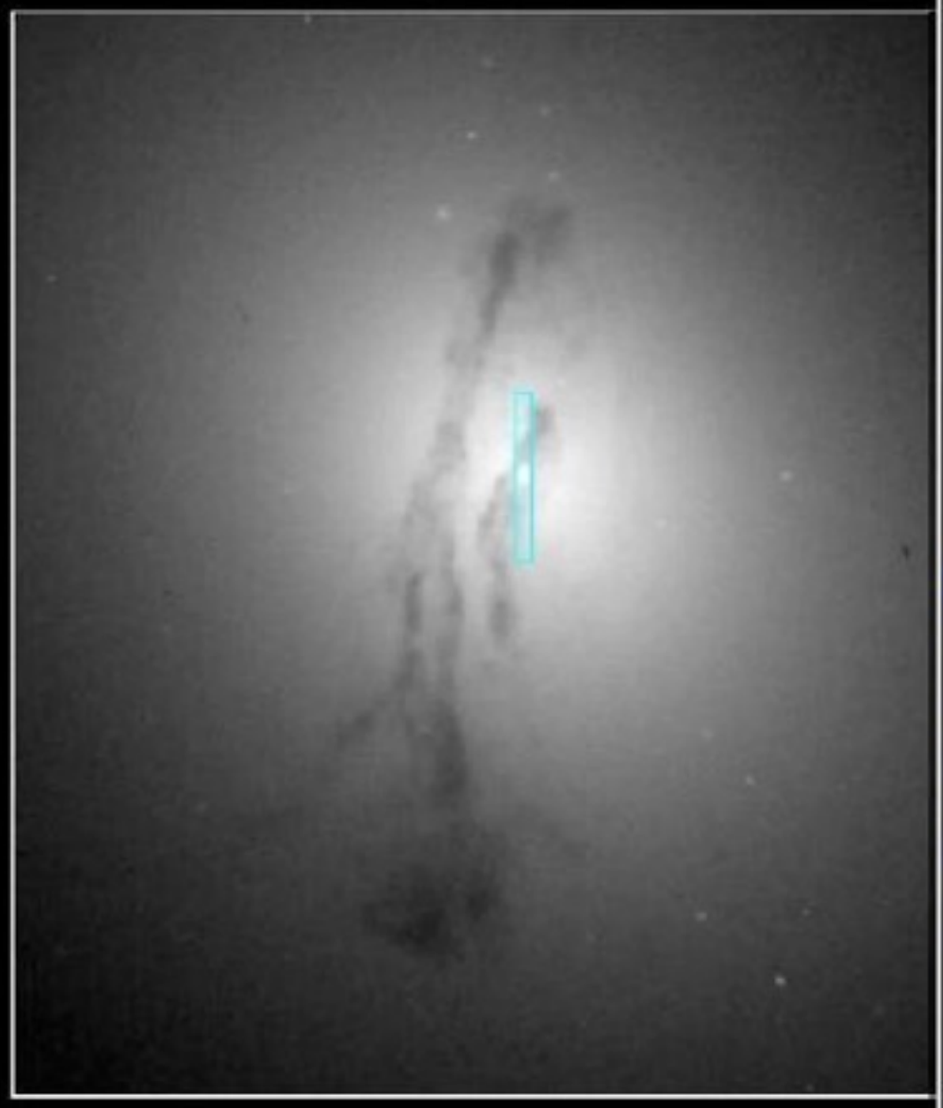




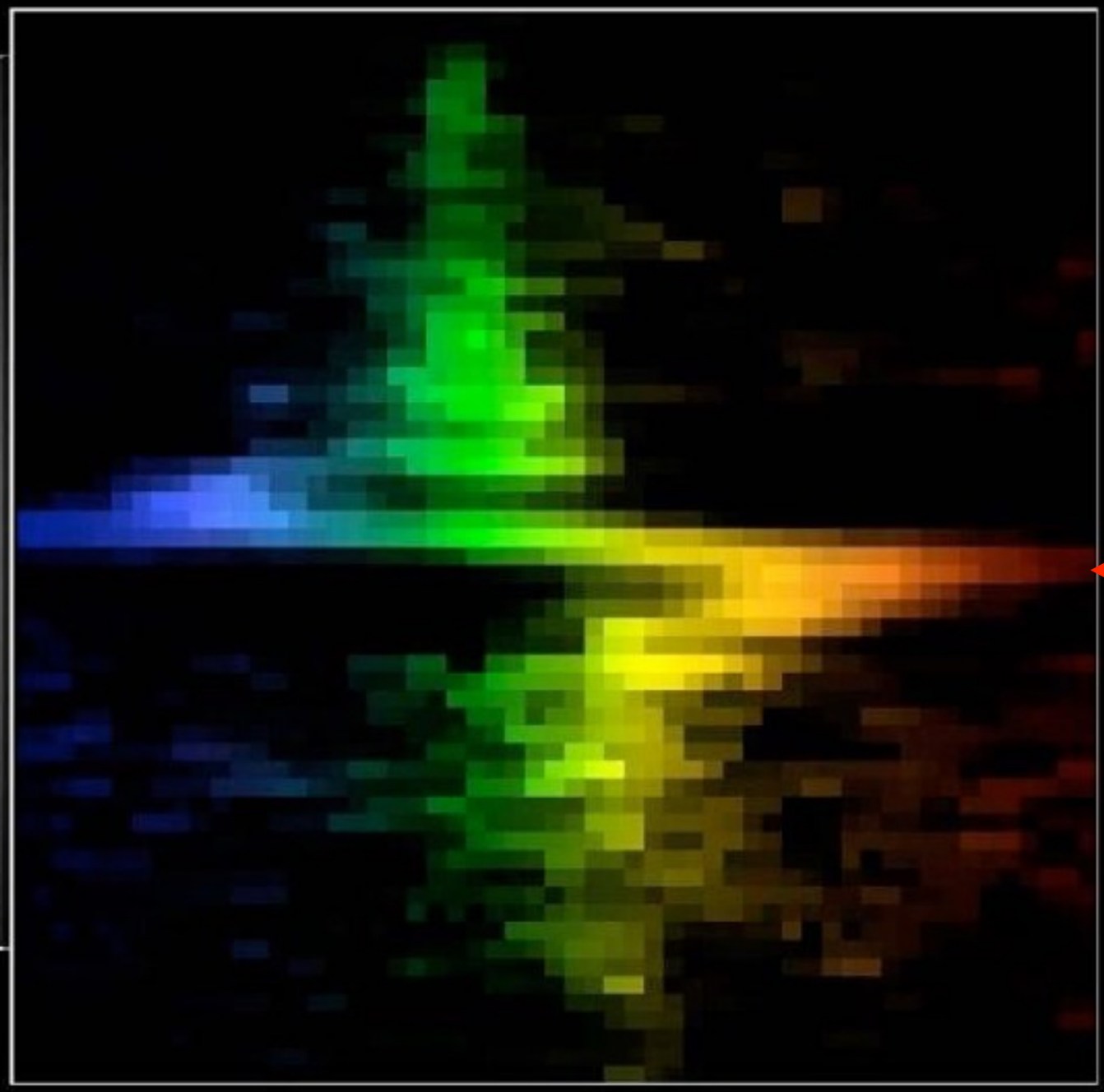
Miyoshi et al. (1995)
Herrnstein et al. (2005)



M84



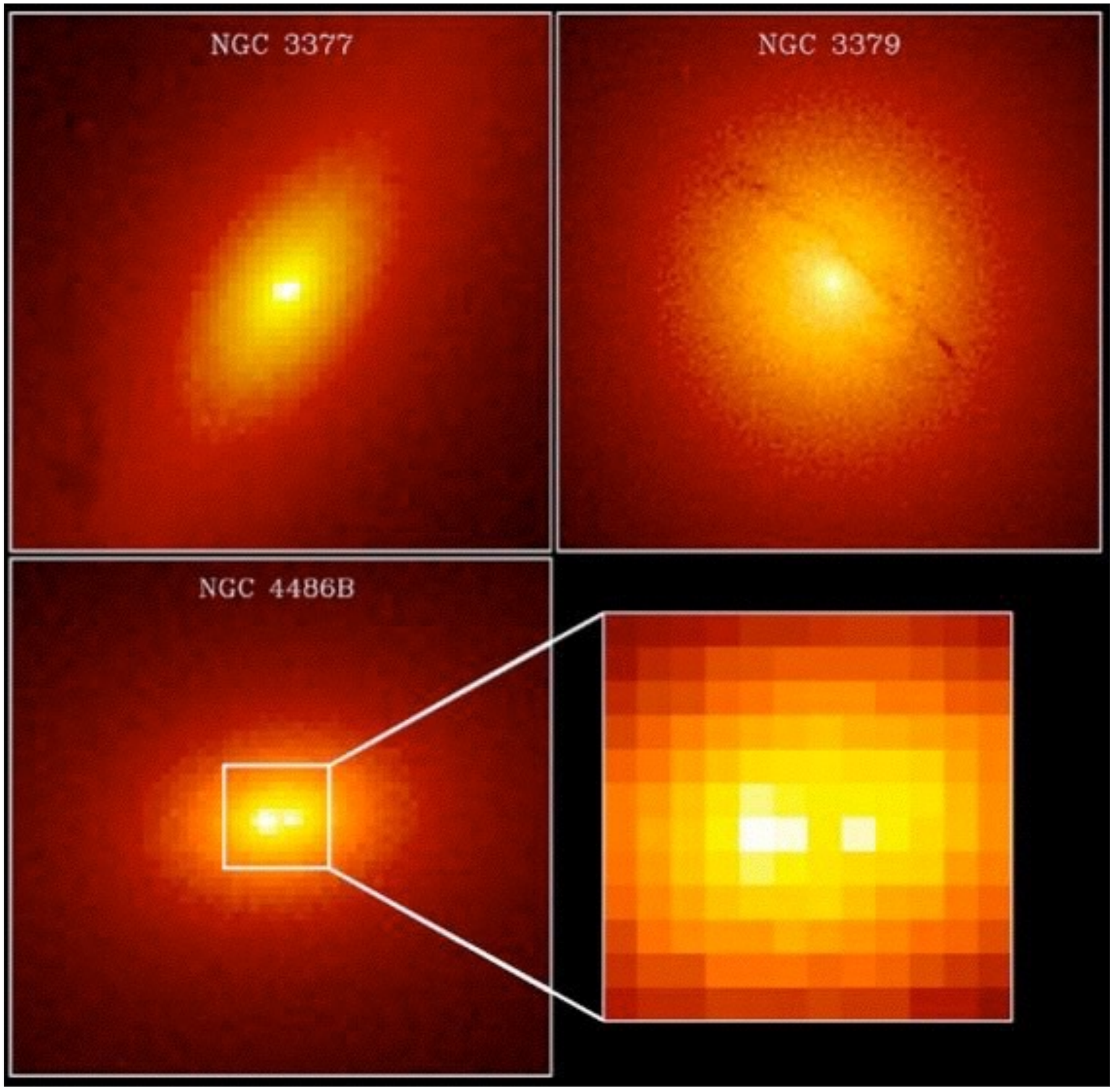
Bower et al. (1998)



distance from the center

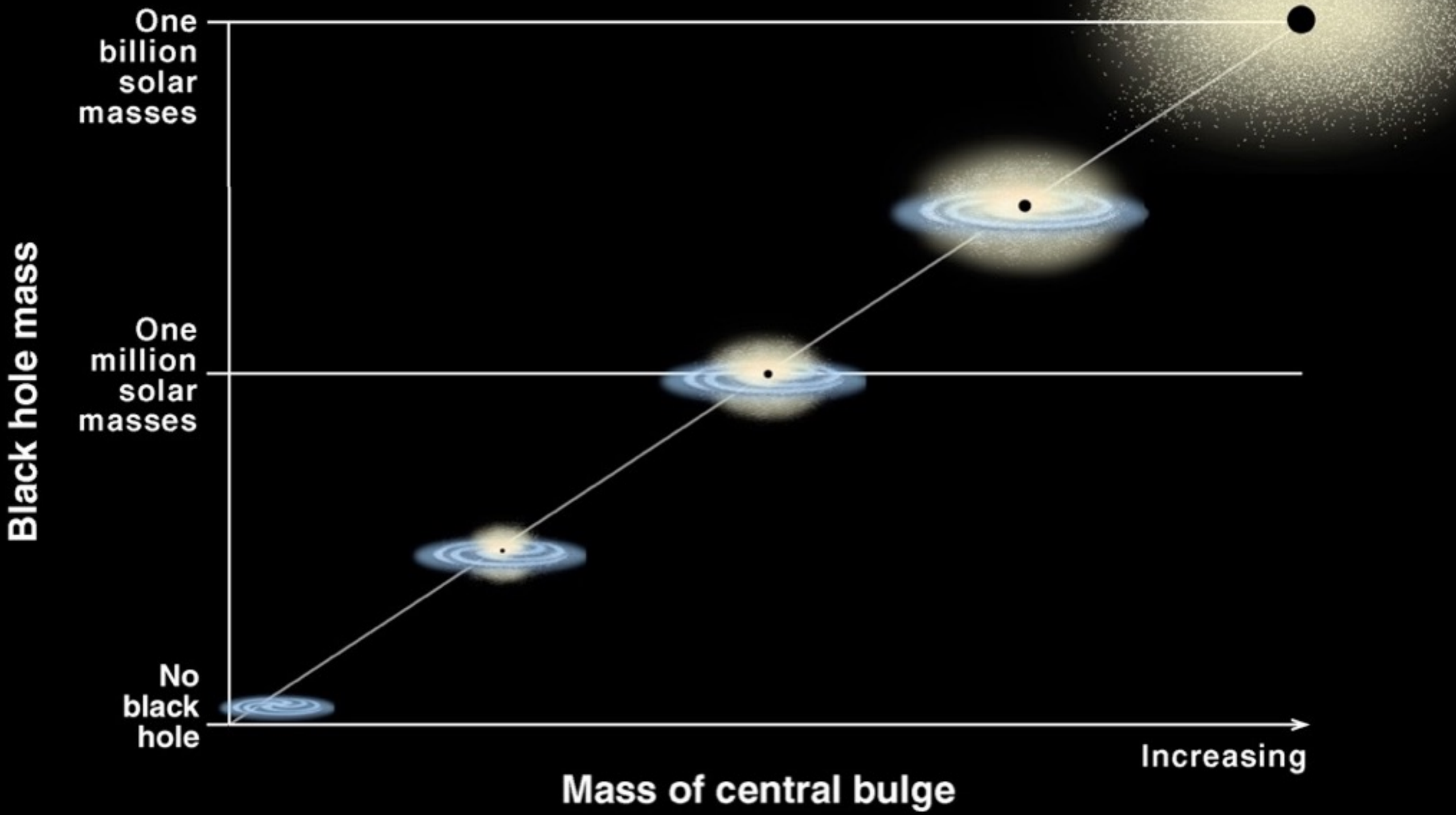
approaching **speed of gas clouds** receding

SMBH ubiquitous in bulges



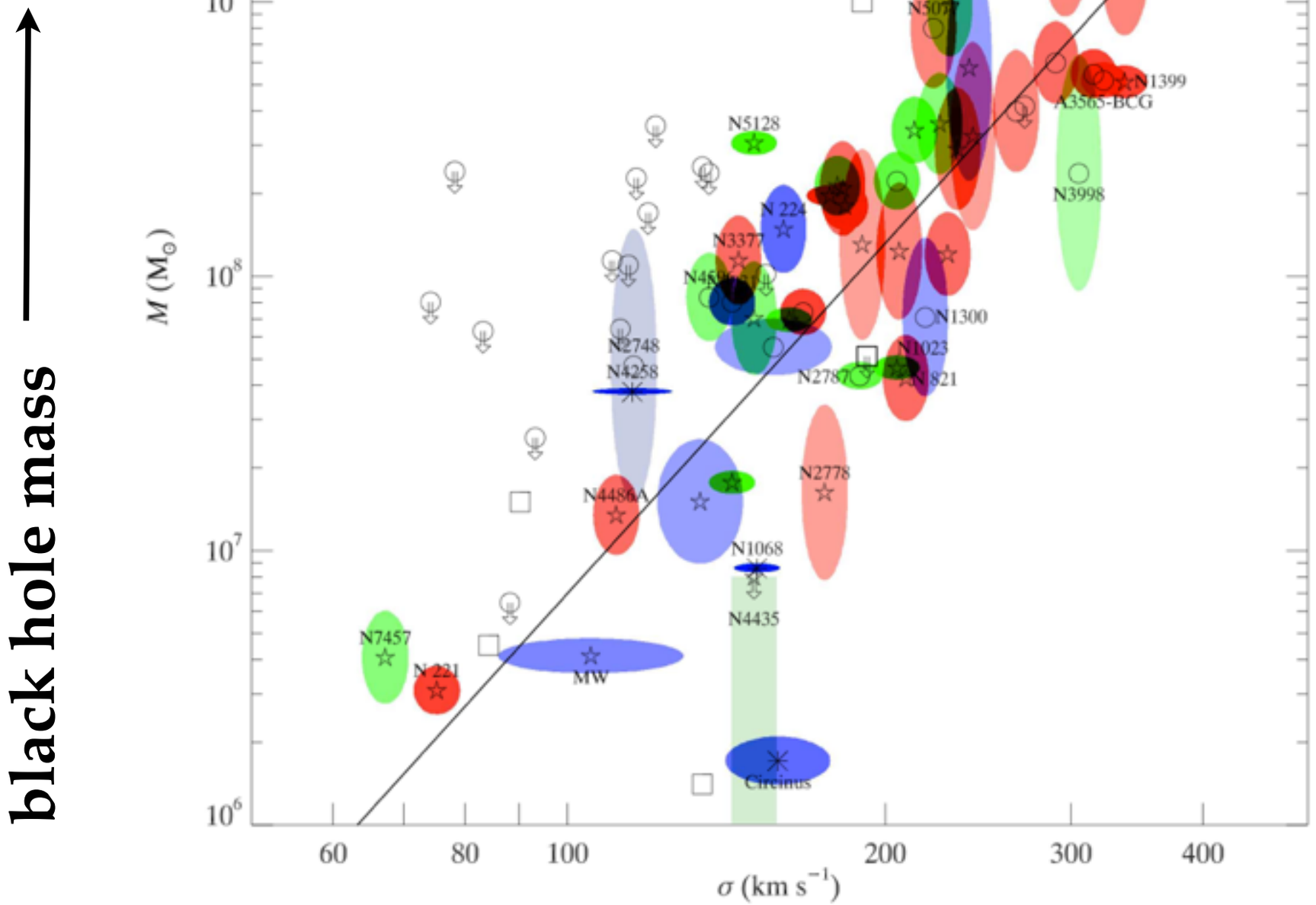
Nuker Team

Correlation Between Black Hole Mass and Bulge Mass



Magorrian et al. (1998)

Gebhardt et al. (2000); Ferrarese & Merritt (2000); Gültekin et al. (2009)

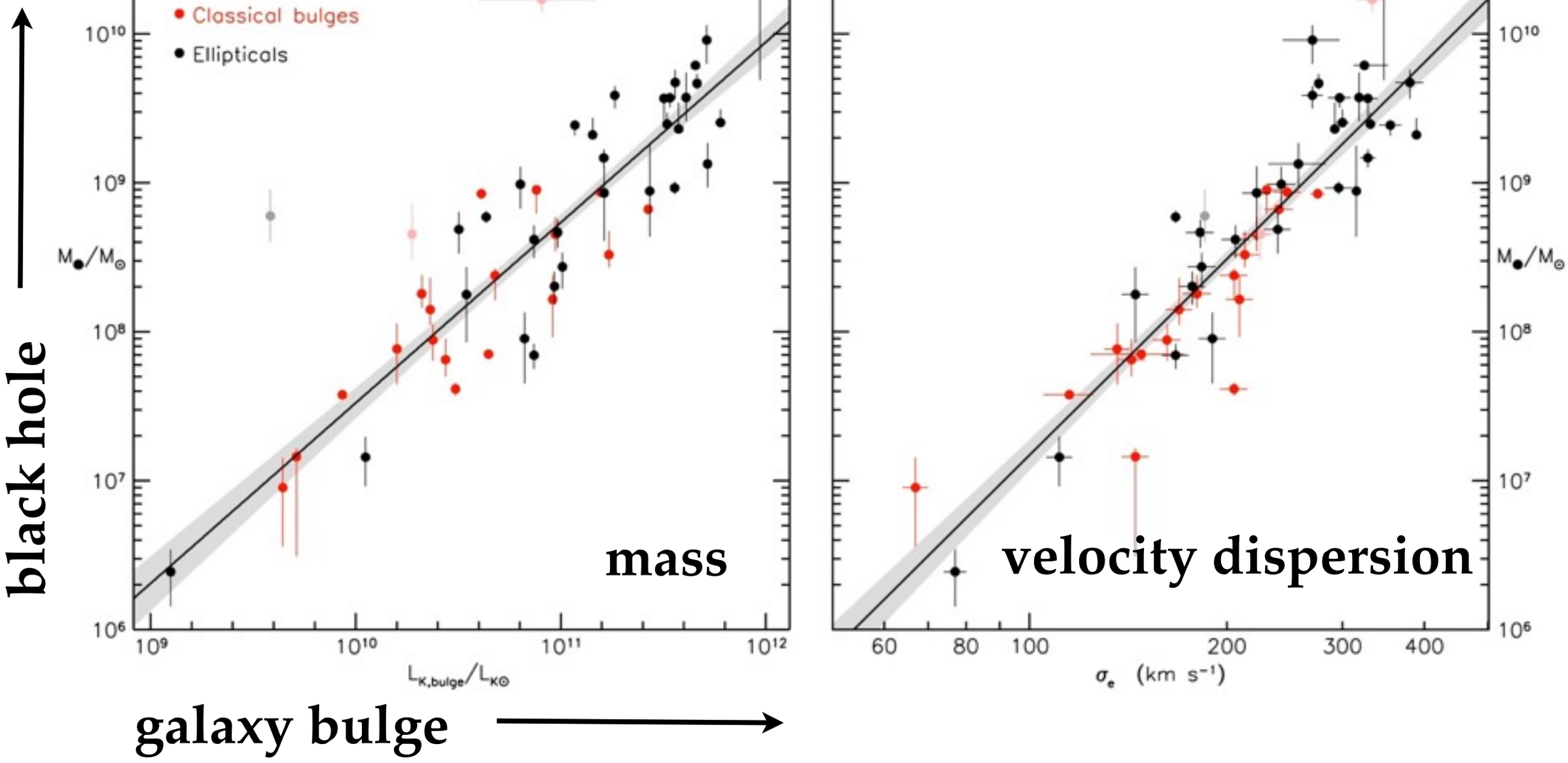


black hole mass

bulge velocity dispersion ⟶

Black Hole - Host Galaxy Scaling Relations

Kormendy & Ho (2013, ARA&A)



$M_\bullet - M_{\rm bulge}$ Relation

$$\frac{M_\bullet}{10^9\ M_\odot} = \left(0.49^{+0.06}_{-0.05}\right)\ \left(\frac{M_{\rm bulge}}{10^{11}\ M_\odot}\right)^{1.16\pm0.08}\ ;\ \text{intrinsic scatter} = 0.29\ \text{dex}.$$

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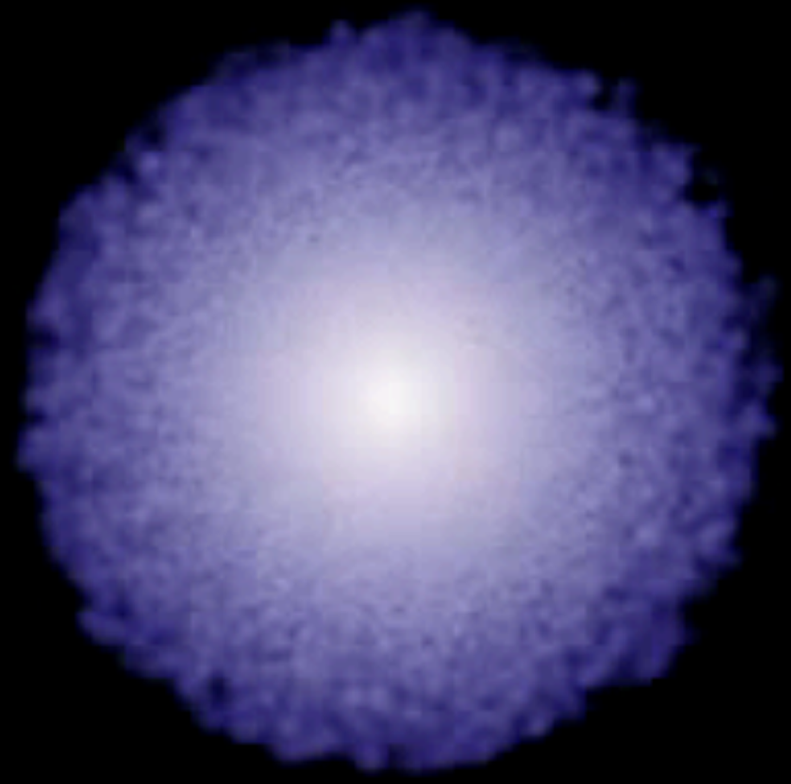
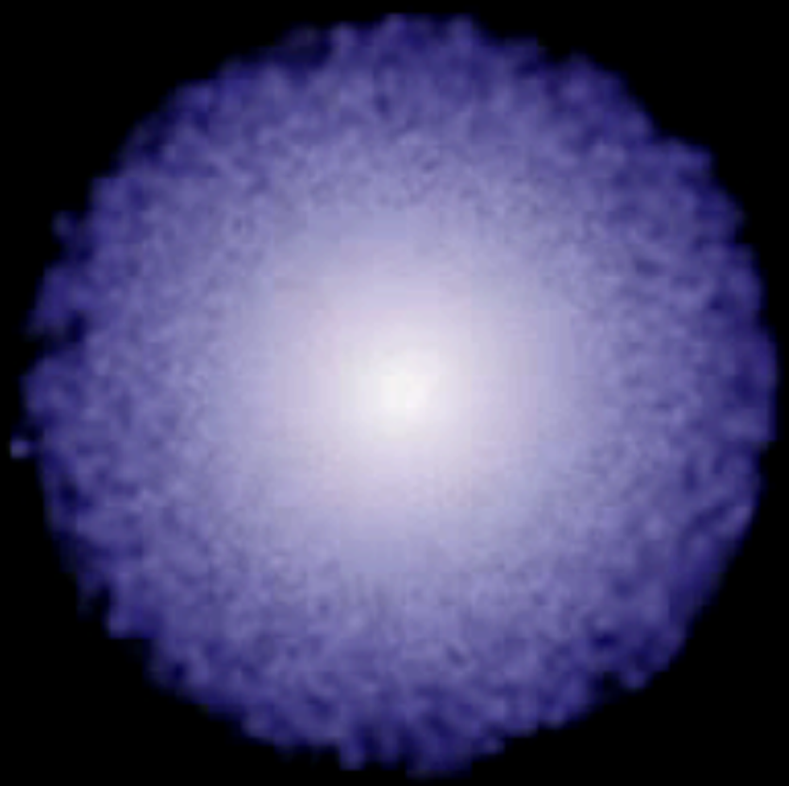
$M_\bullet - \sigma$ Relation

$$\frac{M_\bullet}{10^9\ M_\odot} = \left(0.309^{+0.037}_{-0.033}\right)\ \left(\frac{\sigma}{200\ \text{km s}^{-1}}\right)^{4.38\pm0.29} \text{intrinsic scatter} = 0.28$$

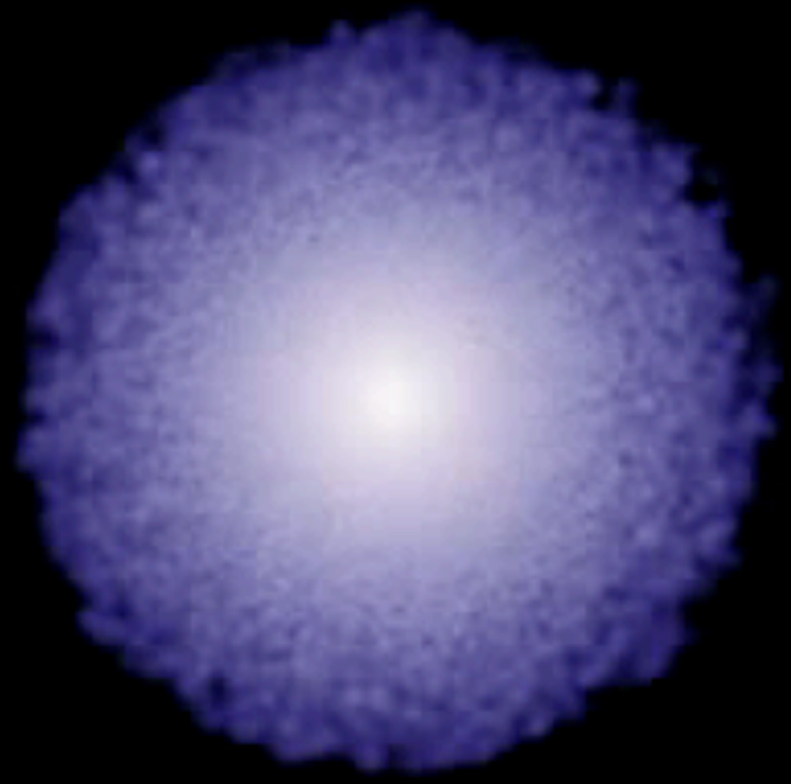
T = 0 Myr

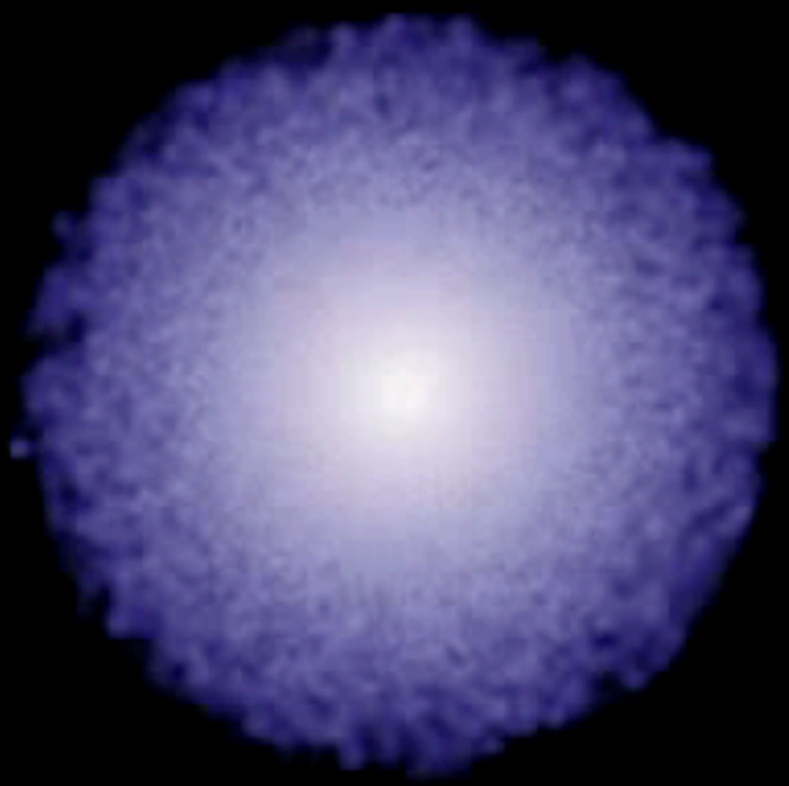




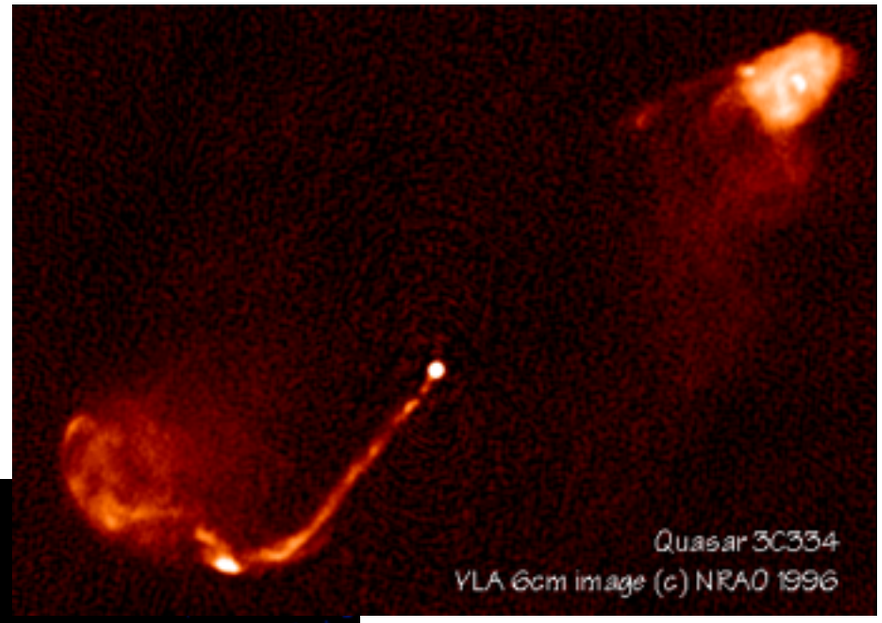
10 kpc/h

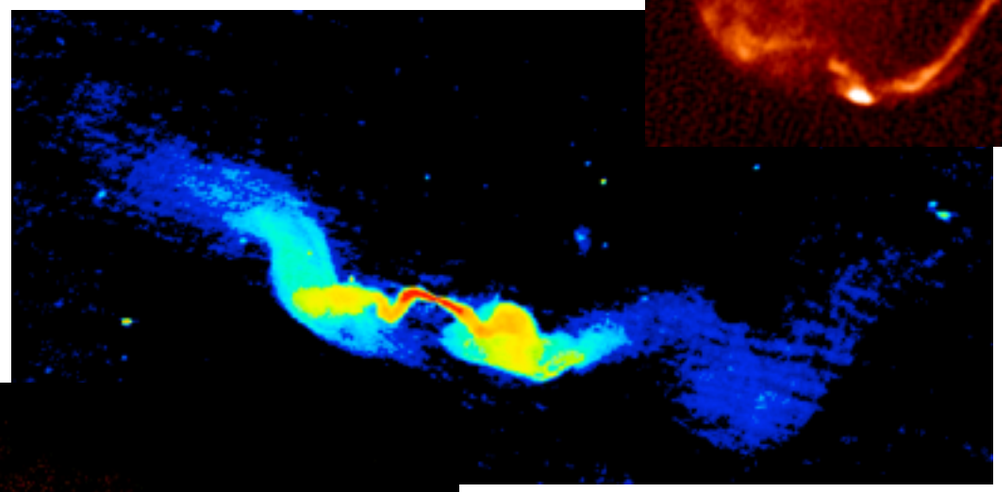
T = 0 Myr

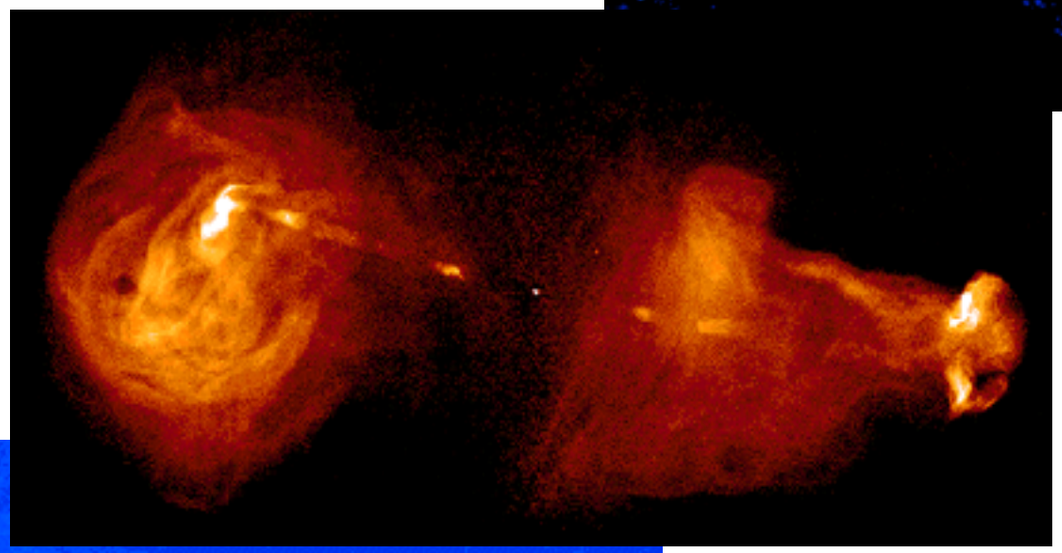


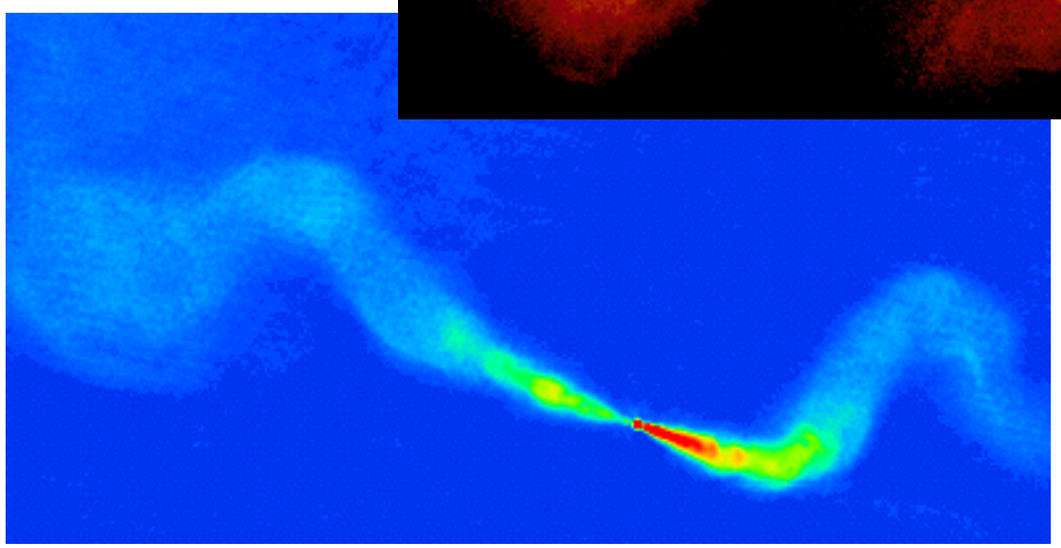


10 kpc/h


Quasar 3C334
VLA 6cm image (c) NRAO 1996







Courtesy of S. Heinz

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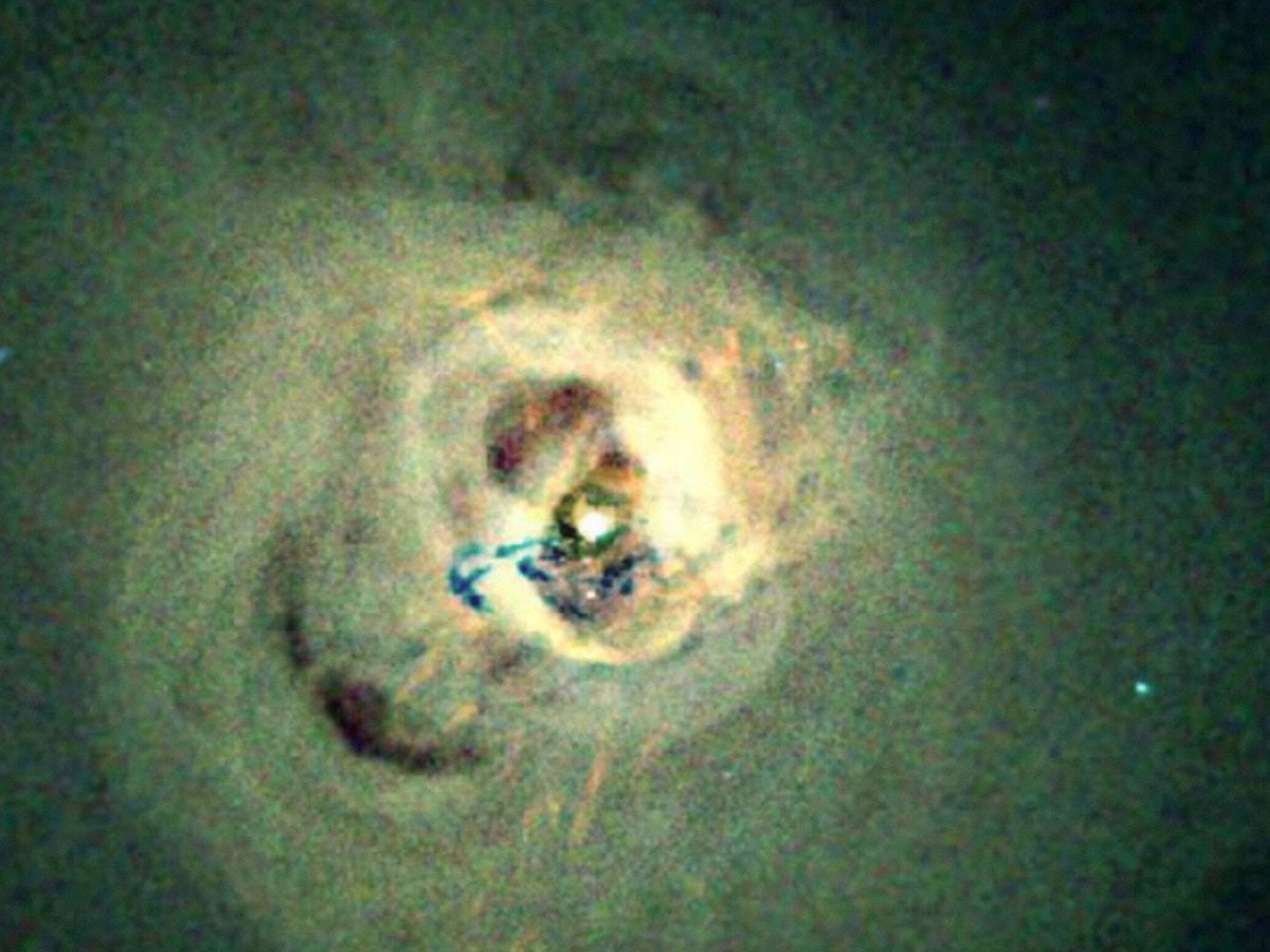
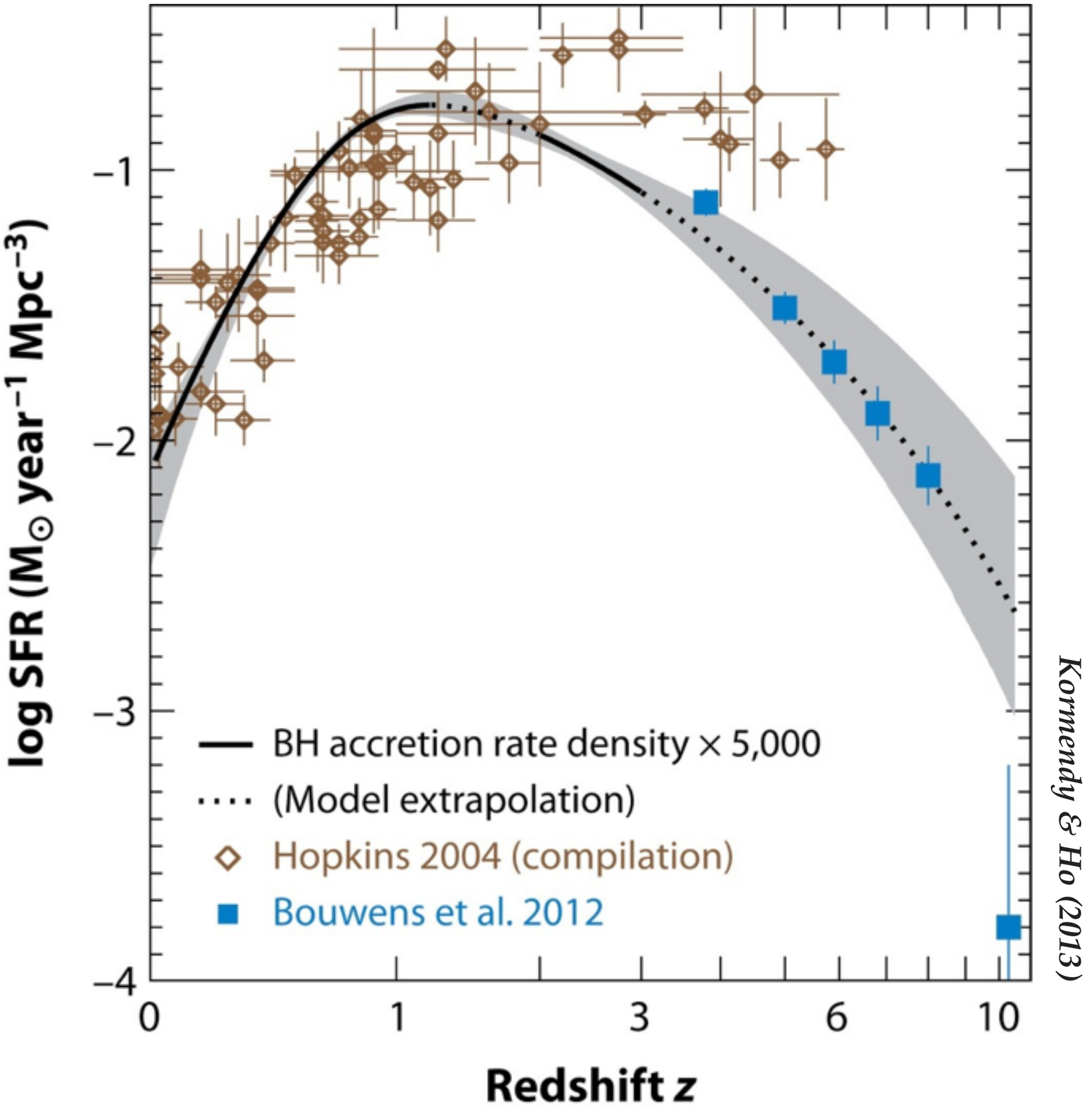
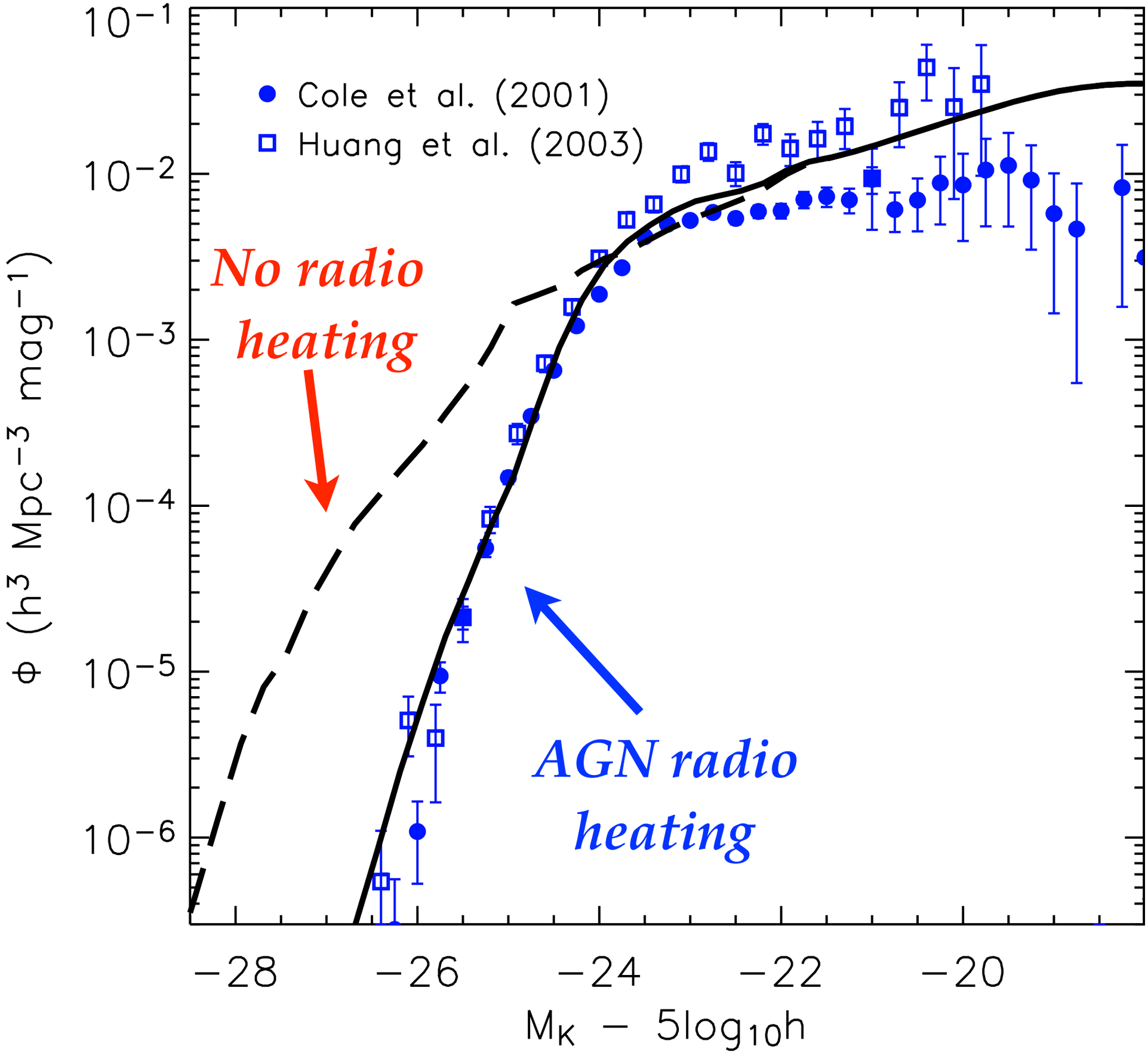


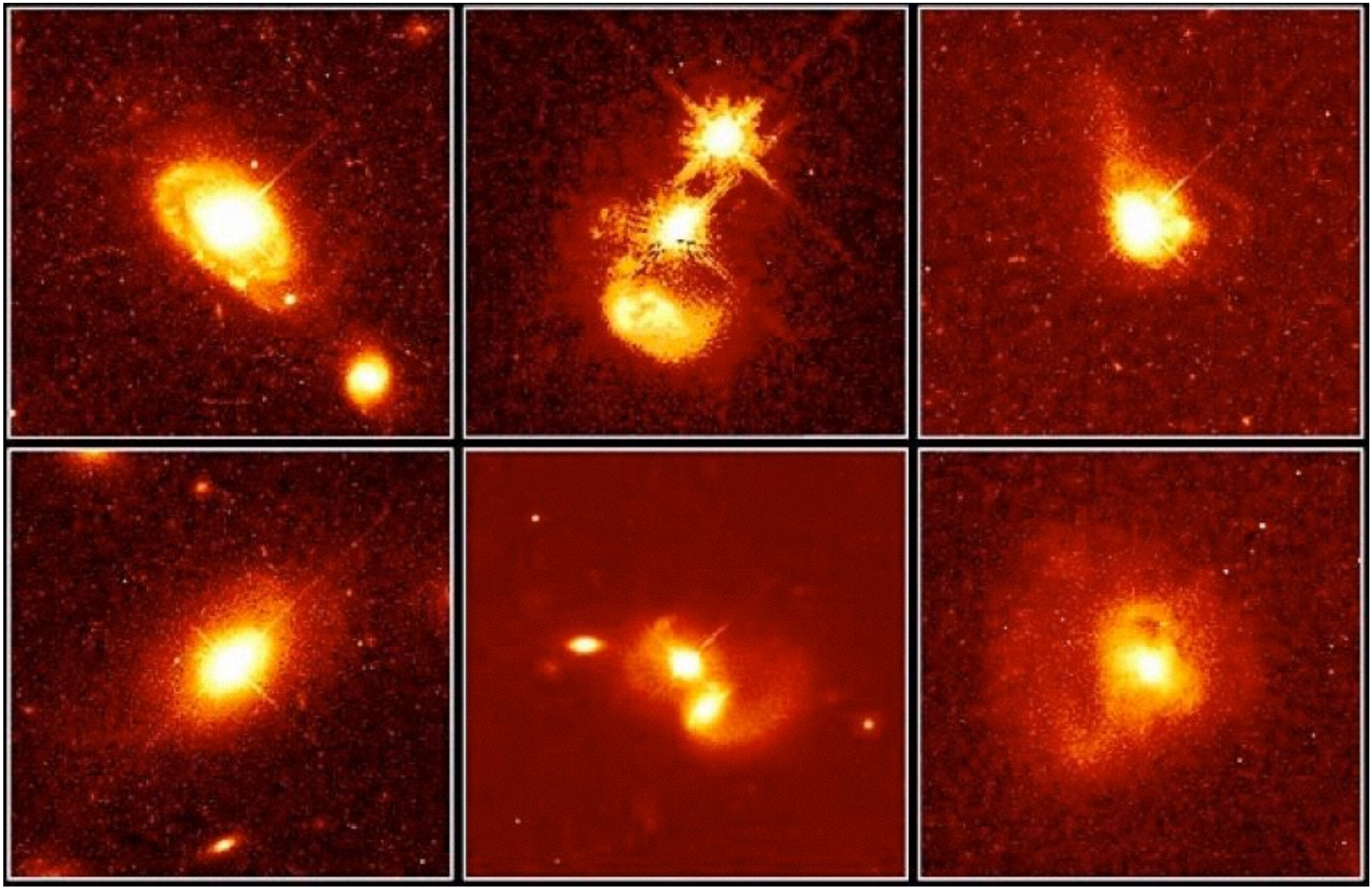


Kormendy & Ho (2013)

Crotton et al. (2006)



When were BH-galaxy scaling relations established?
How evolved?



Virial BH Masses for Type 1 AGNs

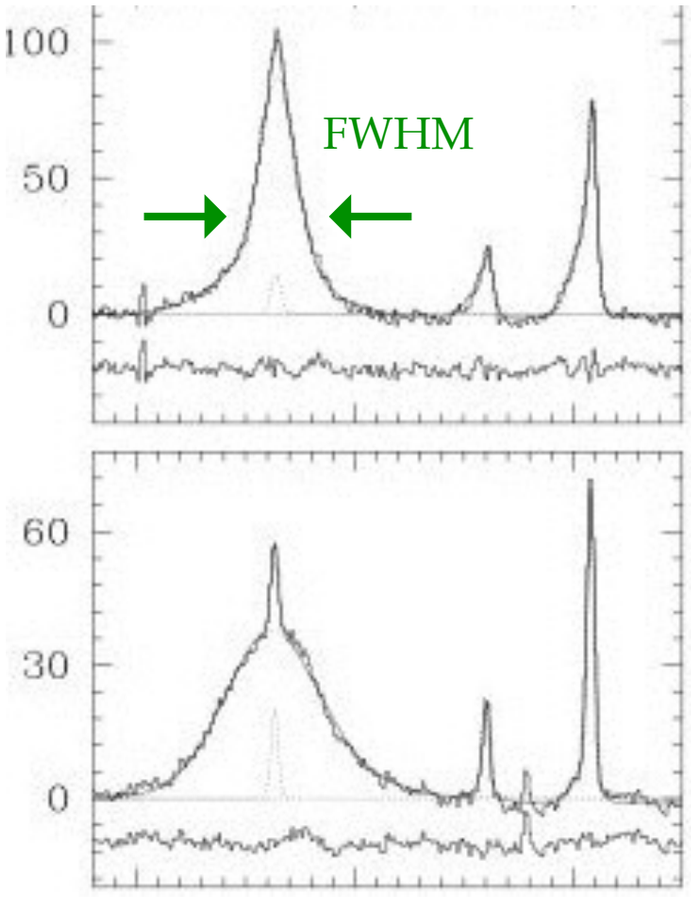
$$M_{\rm virial} = f\,RV^2/G$$

f geometric fudge factor

R BLR radius

V BLR velocity dispersion

Virial BH Masses for Type 1 AGNs



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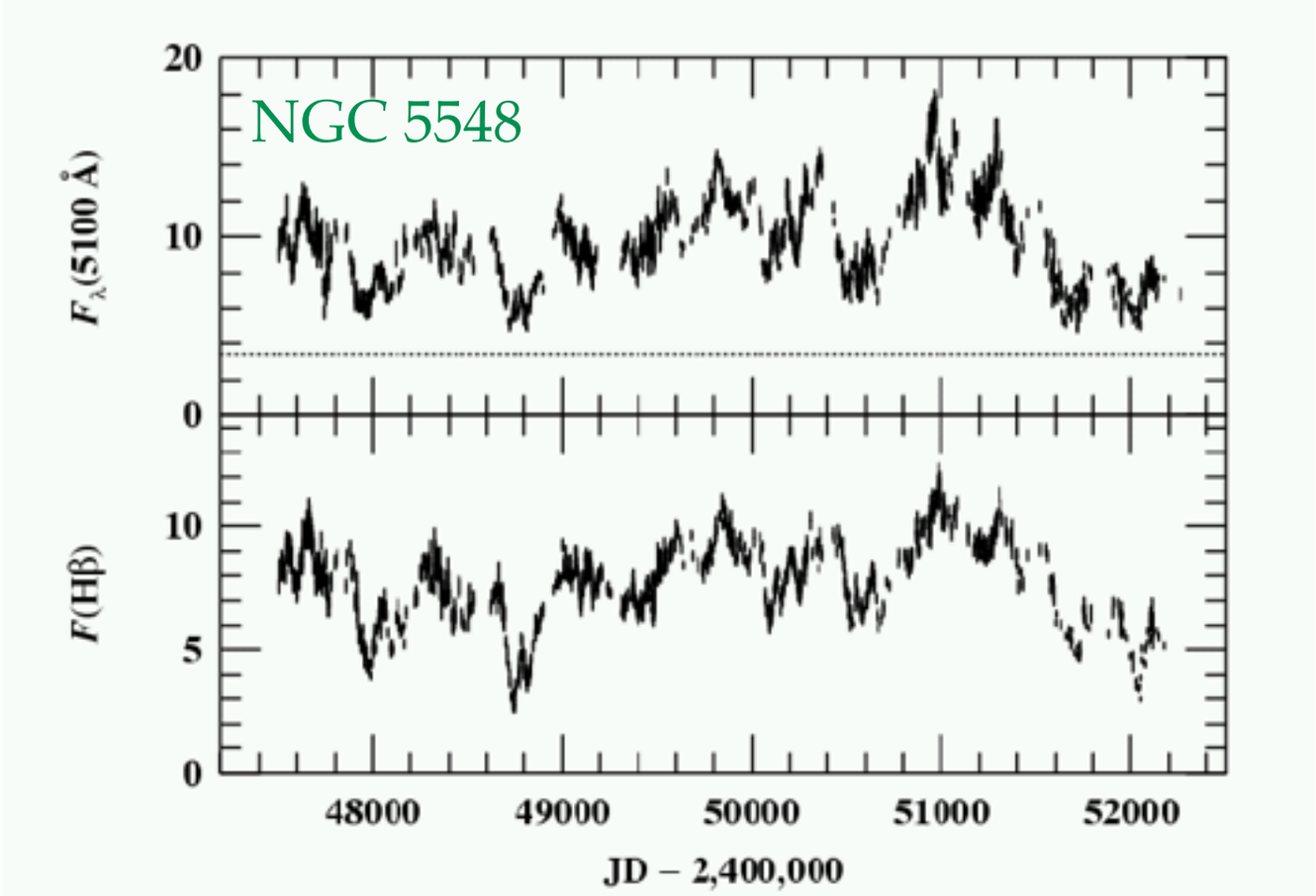
Virial BH Masses for Type 1 AGNs



Peterson et al. (2002)

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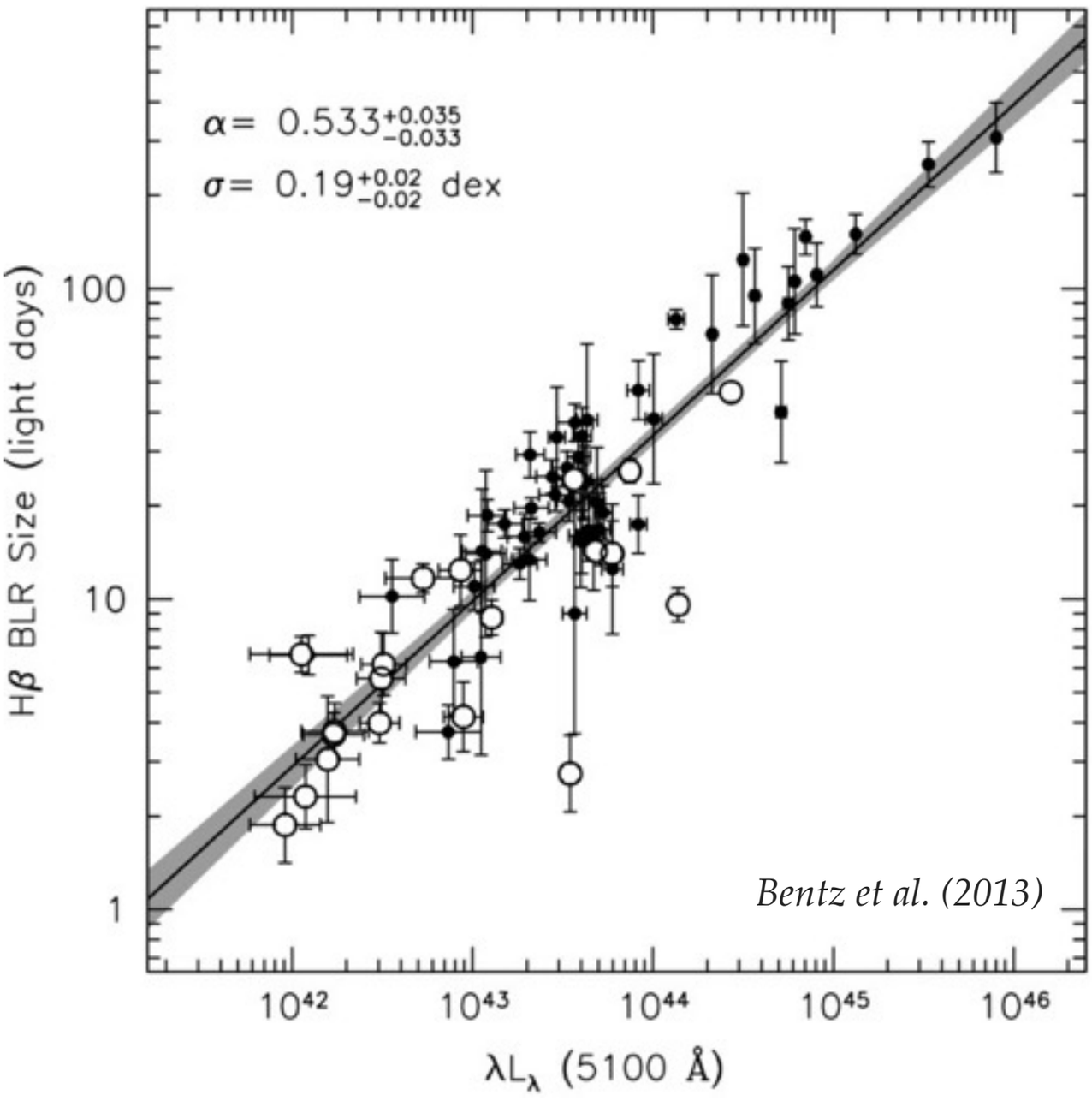
Virial BH Masses for Type 1 AGNs



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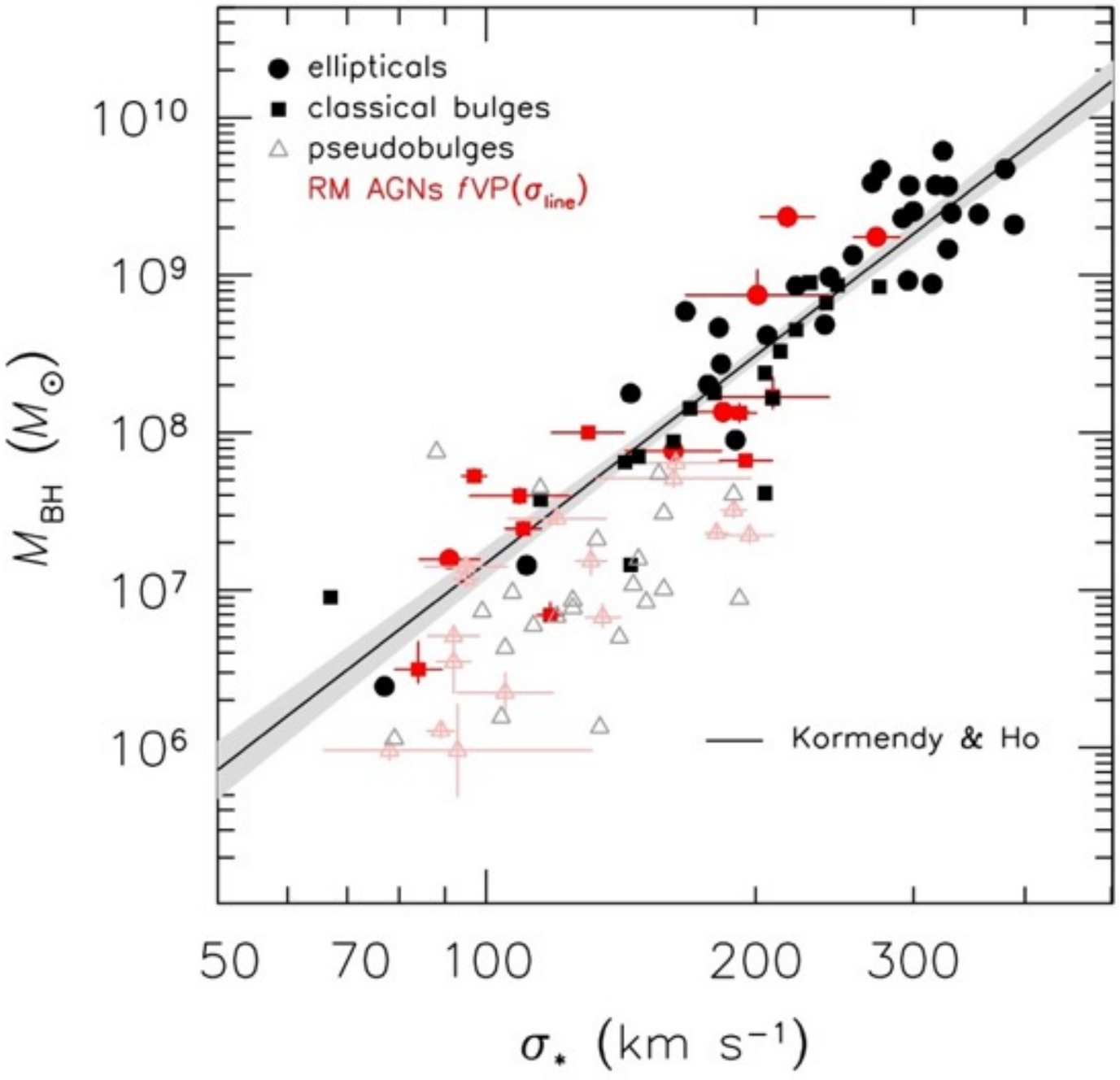
Ho & Kim (2014, 2015)



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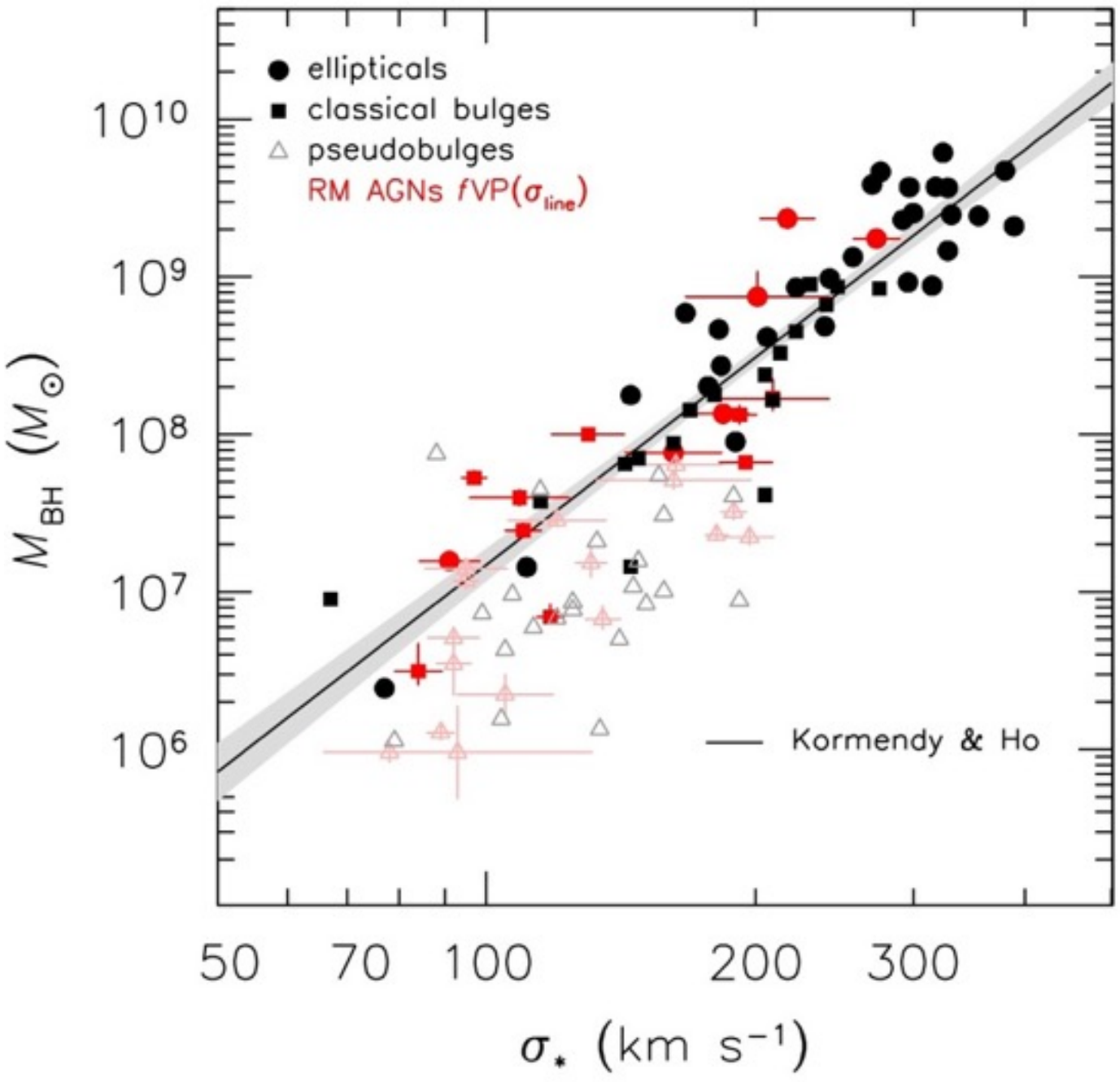

Virial BH Masses for Type 1 AGNs

$$M_{\rm virial} = f\,RV^2/G$$

- f geometric fudge factor
- R BLR radius
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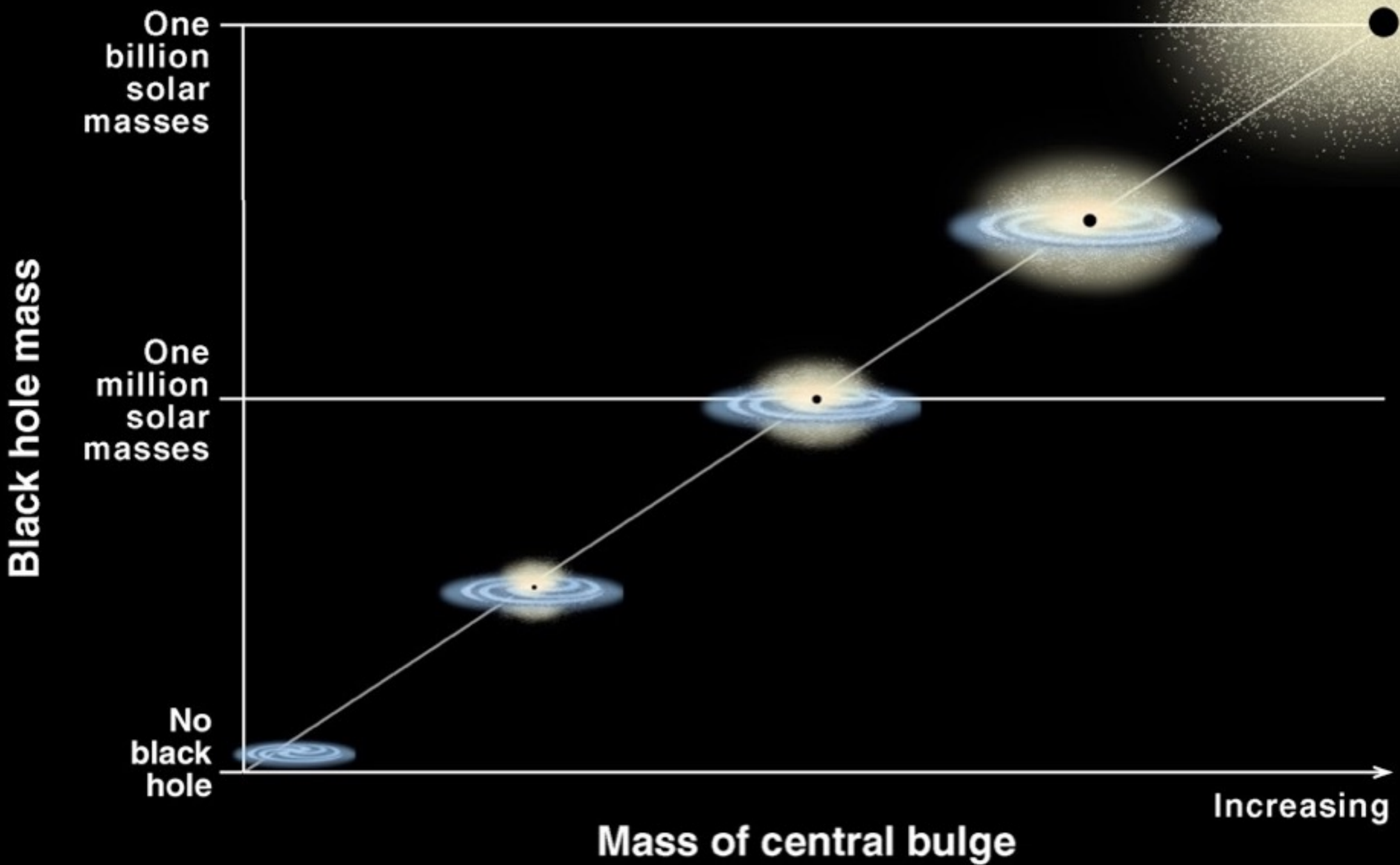
$M_\bullet$ can be estimated to an accuracy of ~0.3 – 0.5 dex for $z \approx 0 - 6$

Correlation Between Black Hole Mass and Bulge Mass



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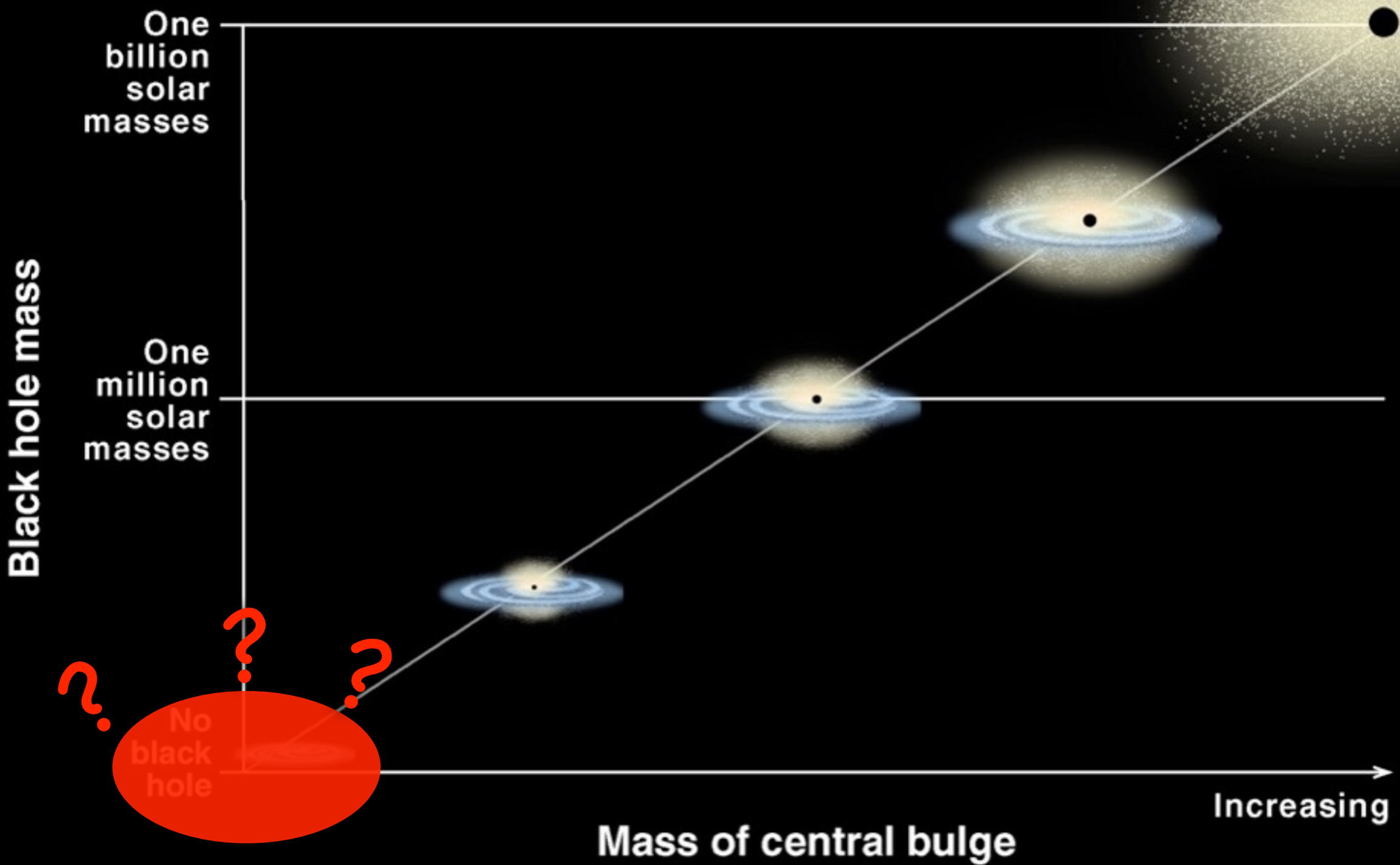
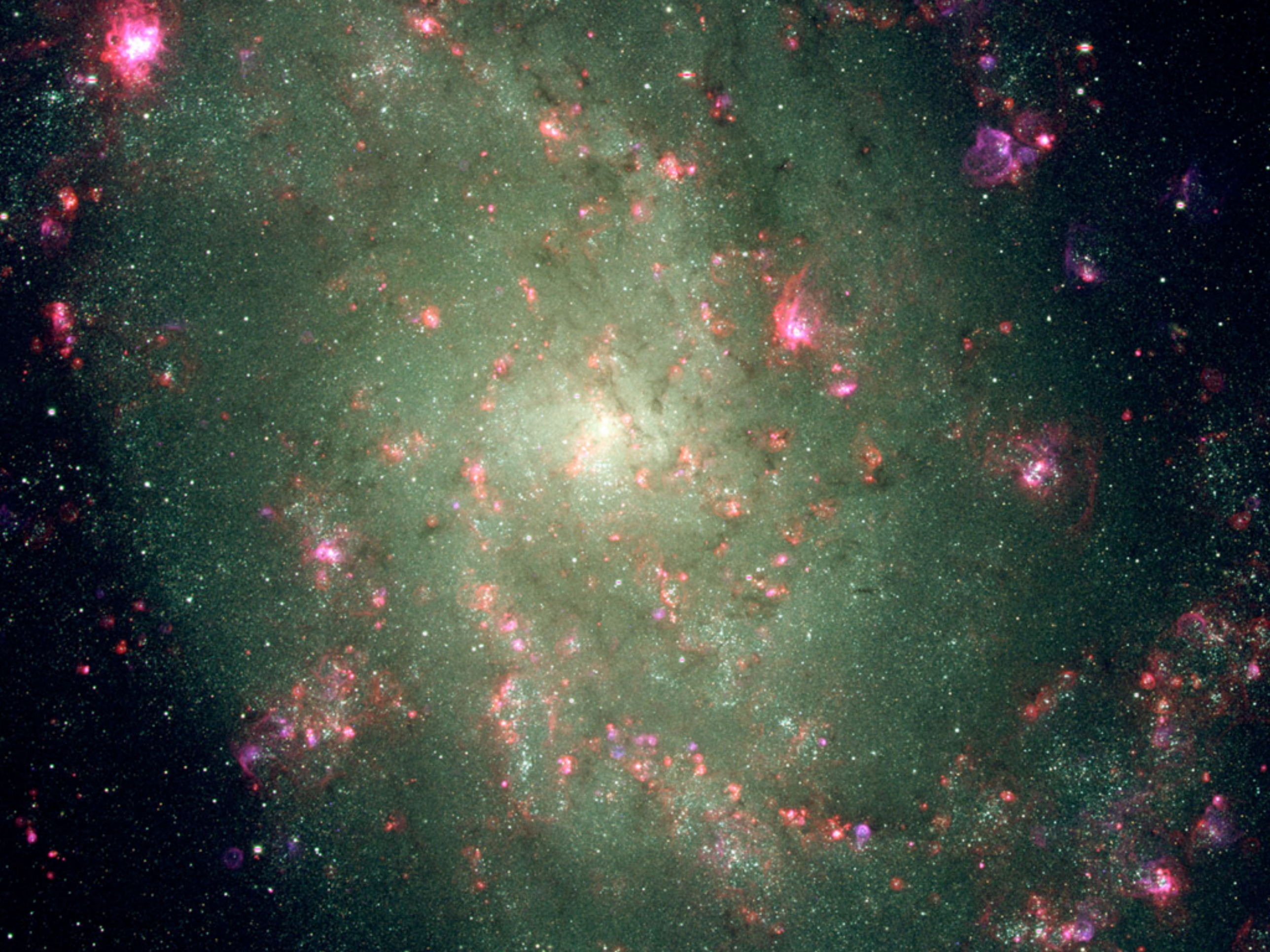
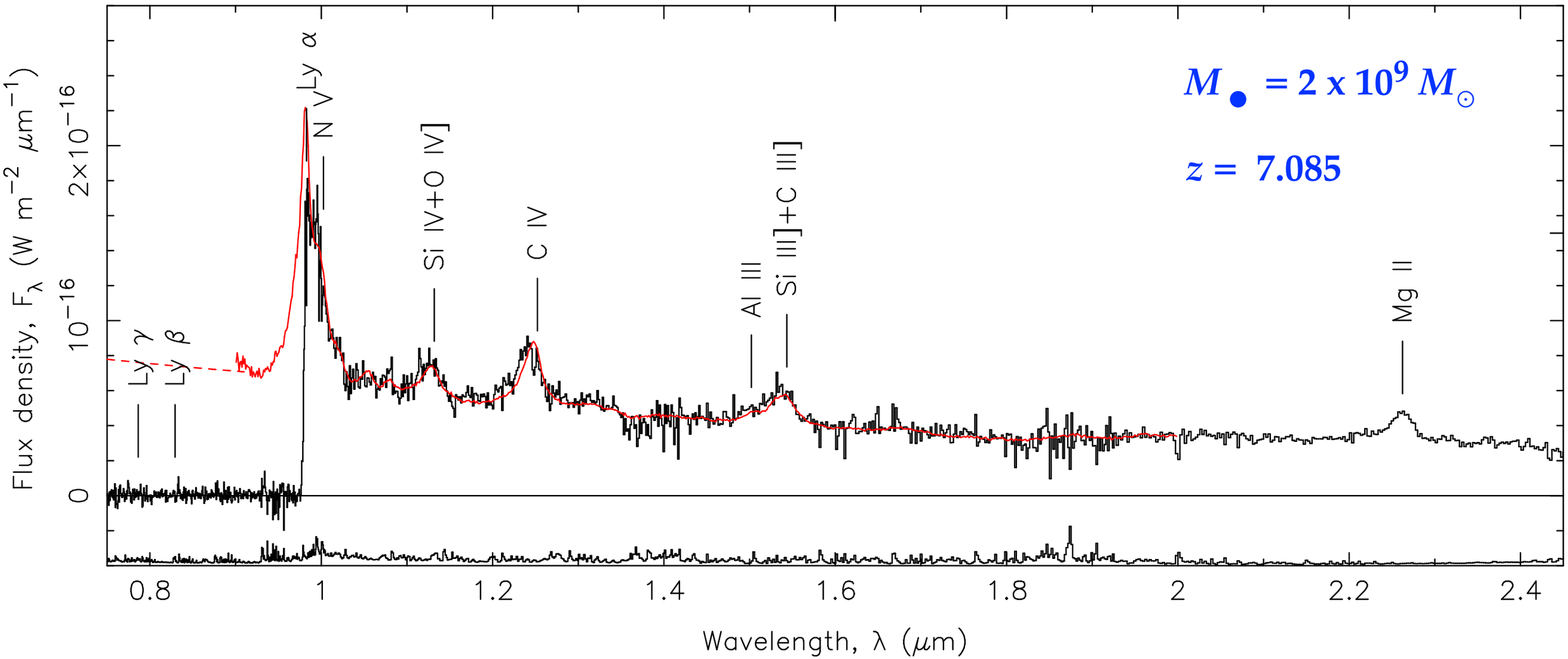


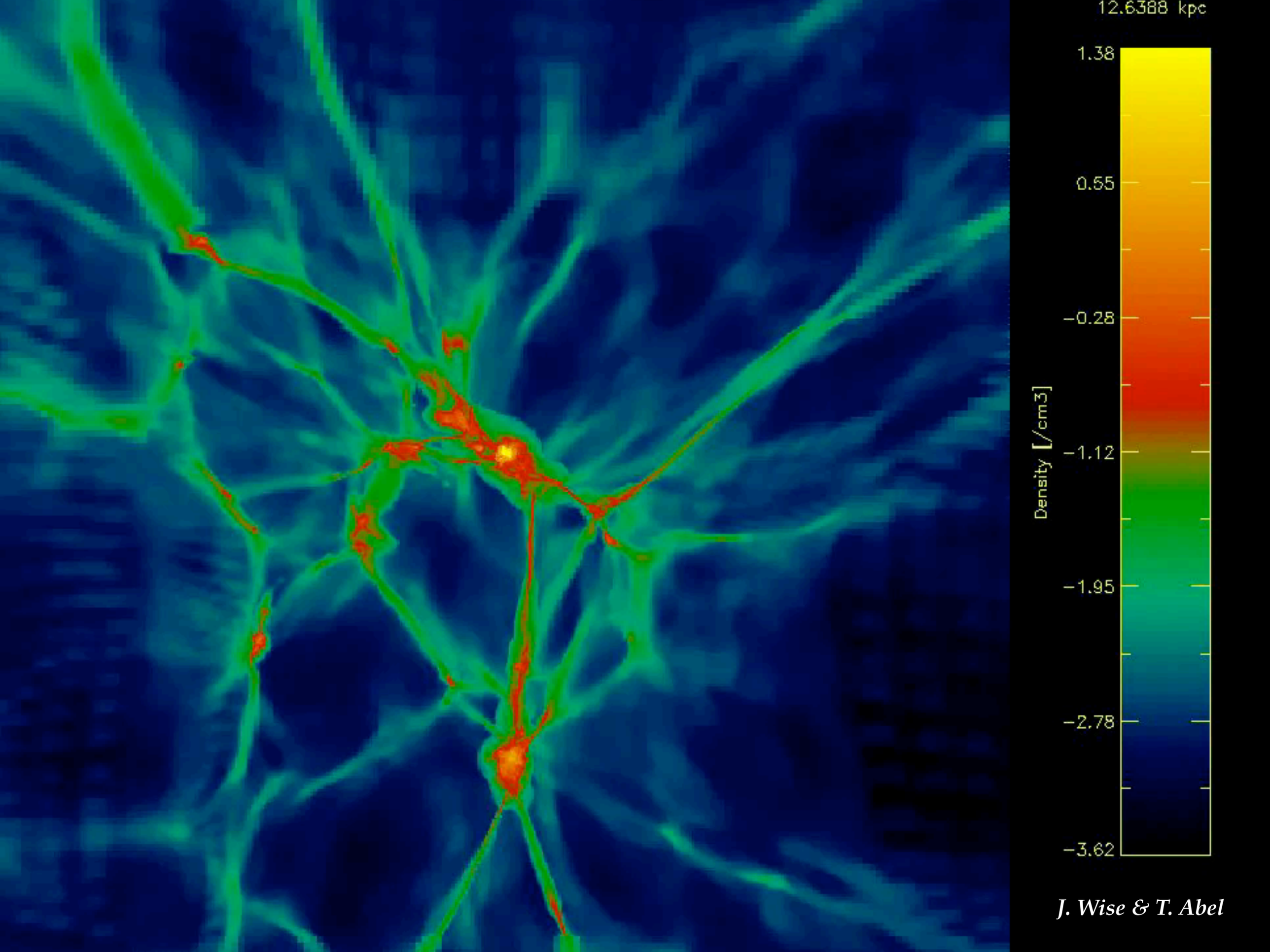


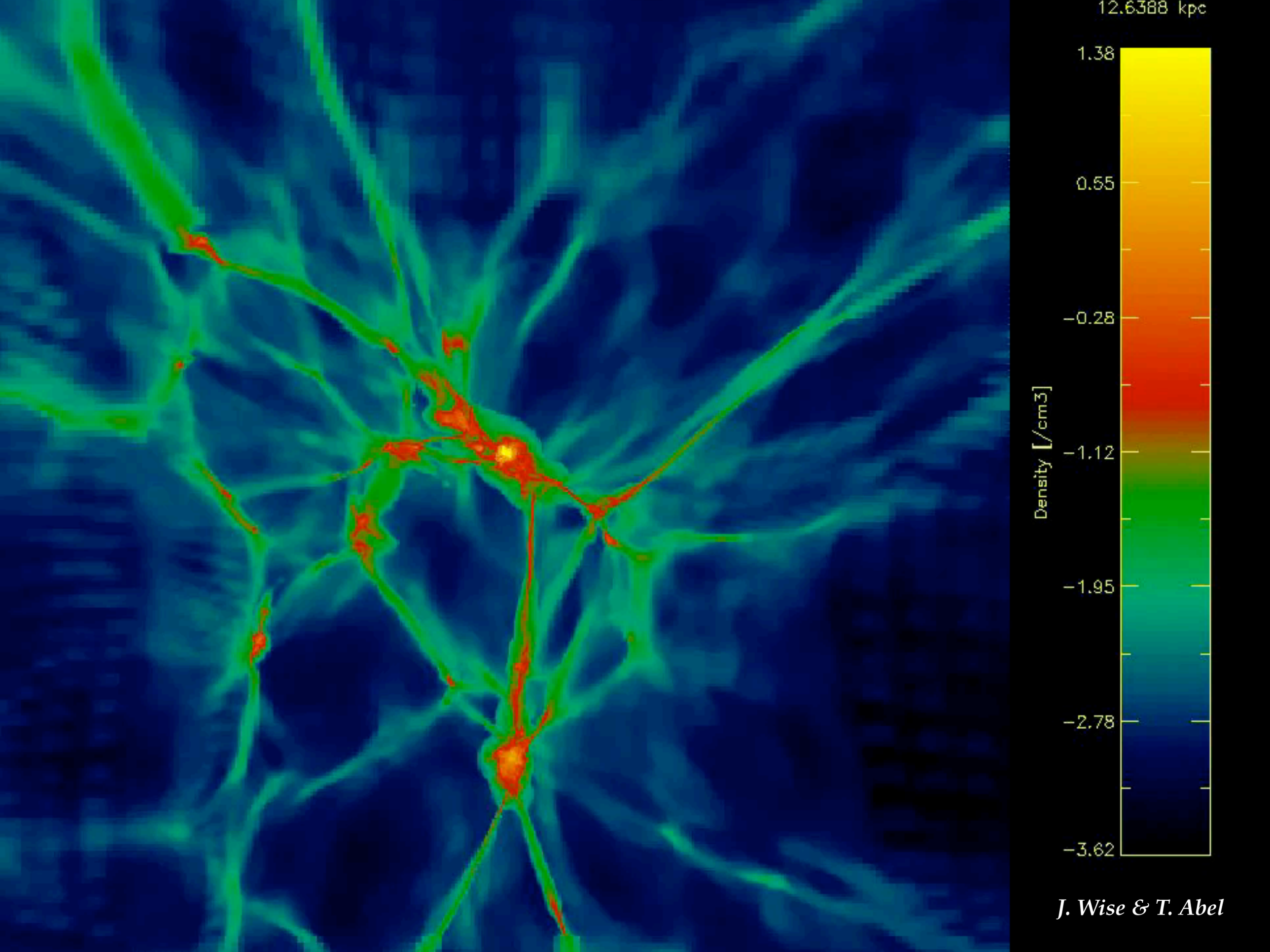

M33: $M_\bullet < 1500\ M_\odot$


M33: $M_\bullet < 1500\ M_\odot$

Mortlock et al. (2011)




12.6388 kpc
1.38
0.55
−0.28
−1.12
−1.95
−2.78
−3.62
Density [/cm3]
J. Wise & T. Abel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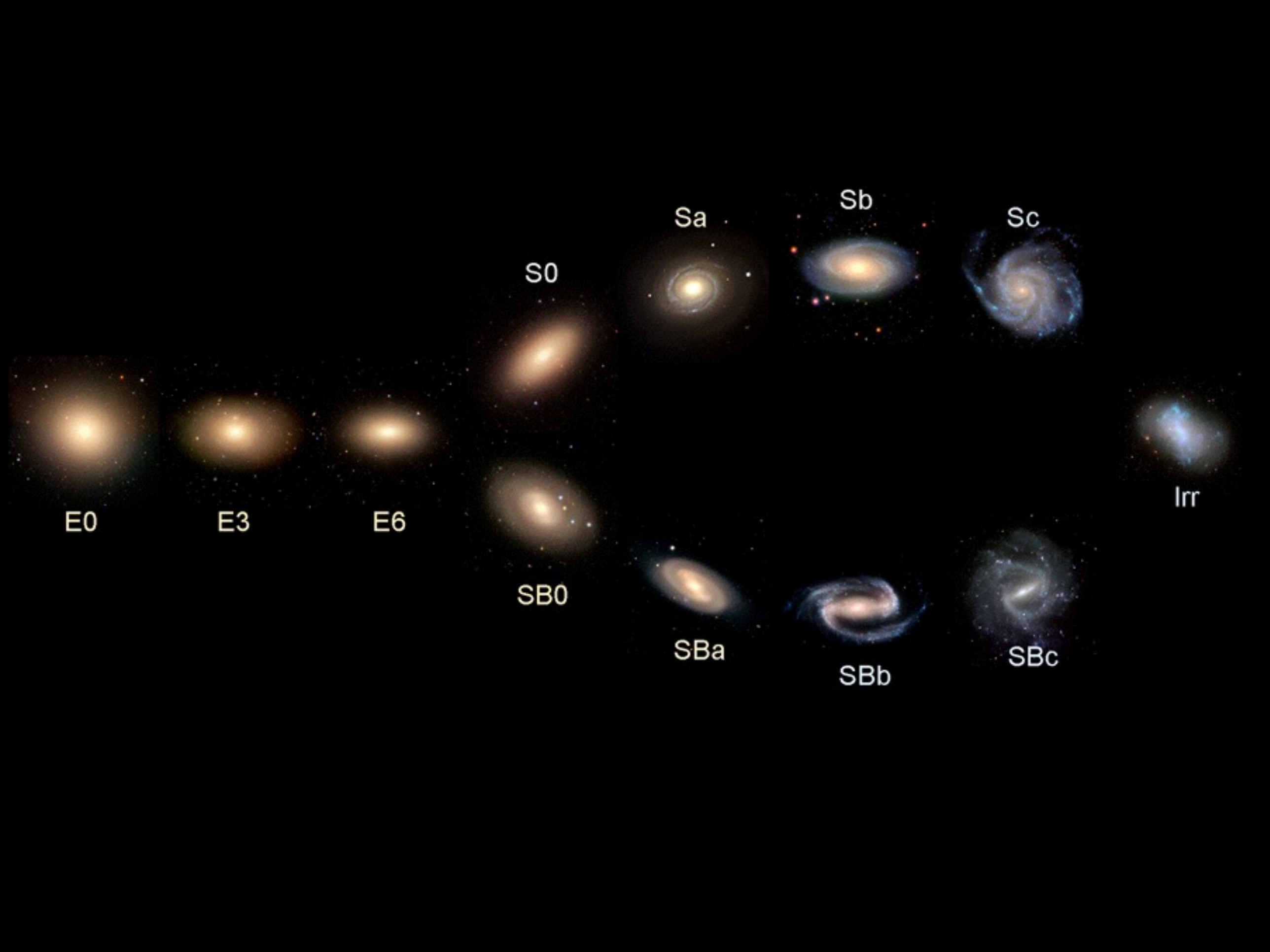
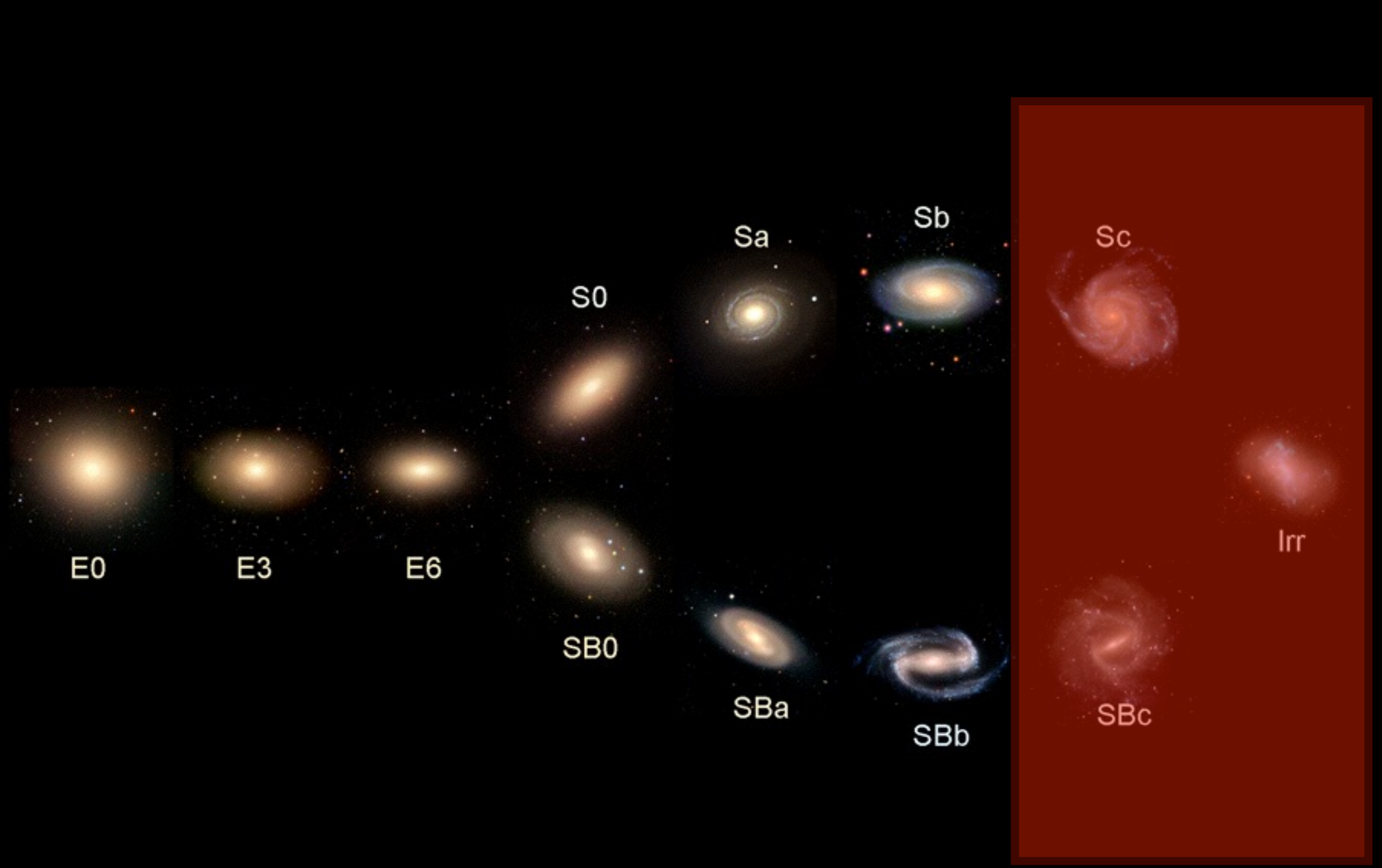
Density [/cm3]
J. Wise & T. Abel


S0
Sa
Sb
Sc
E0
E3
E6
Irr
SB0
SBa
SBb
SBc


S0
Sa
Sb
Sc
E0
E3
E6
SB0
SBa
SBb
Irr
SBc





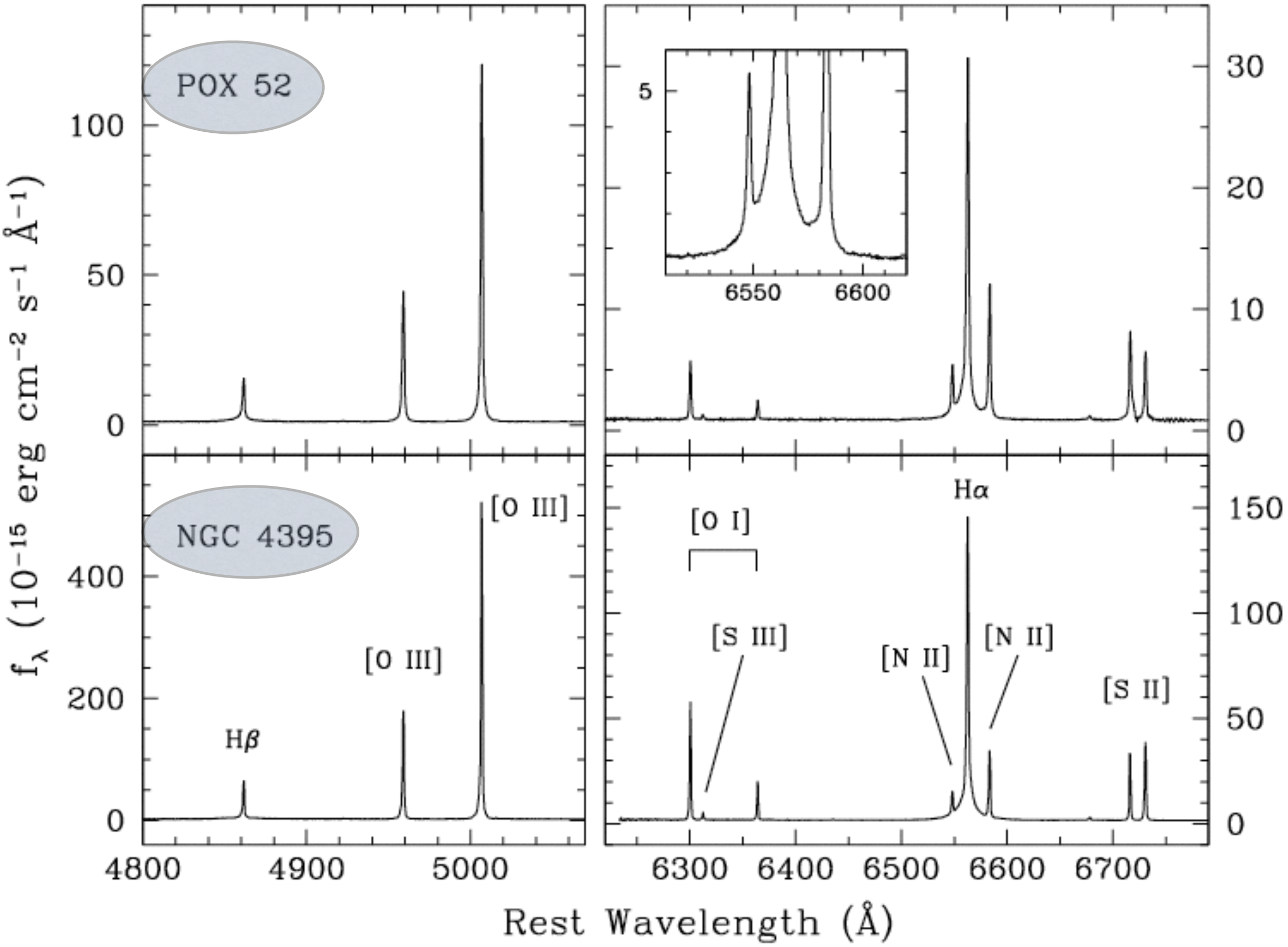




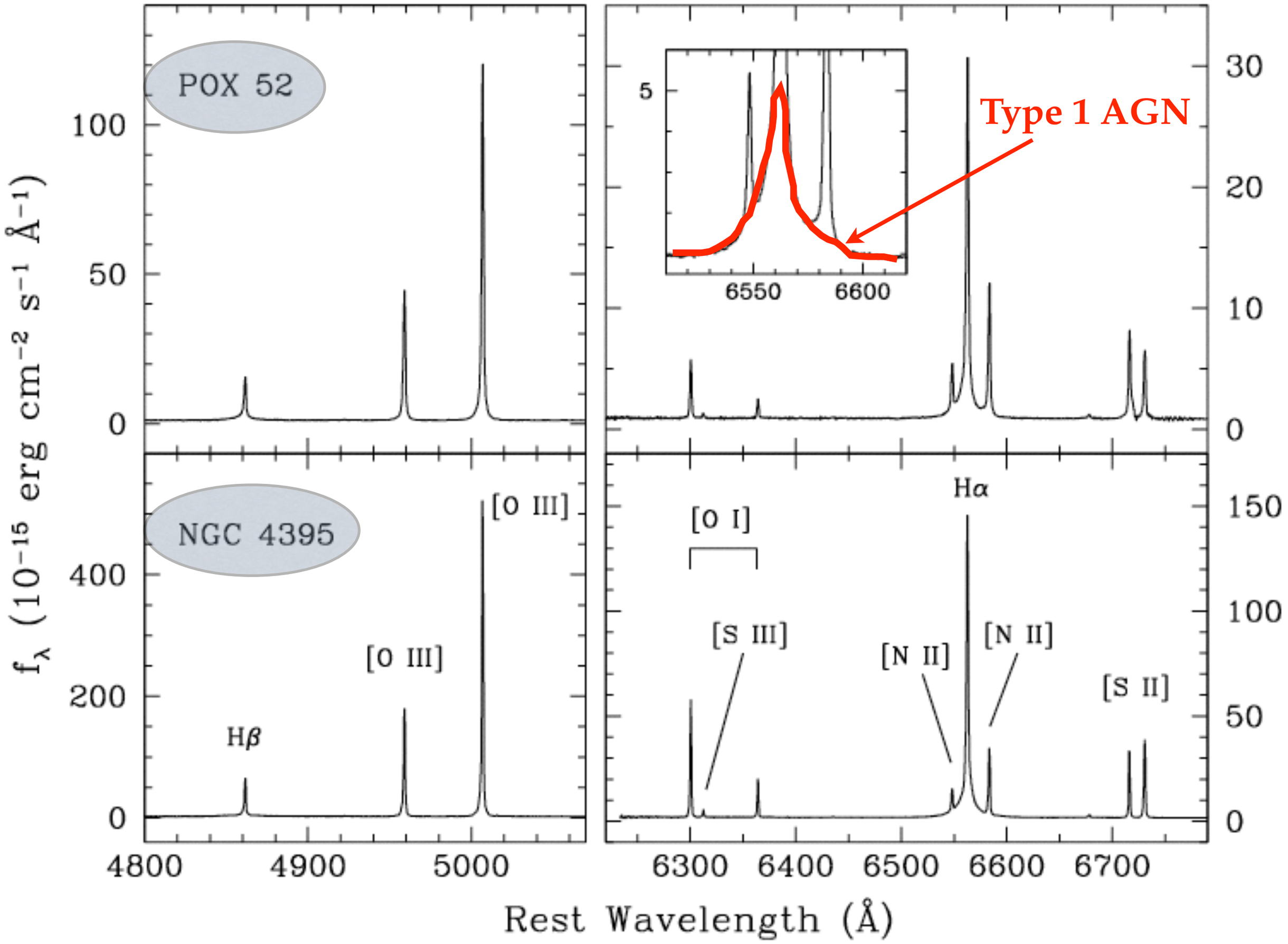



Are there mini-quasars in these "simpler" galaxies?

Filippenko & Ho (2003); Barth et al. (2004); Ho (2008, ARA&A)

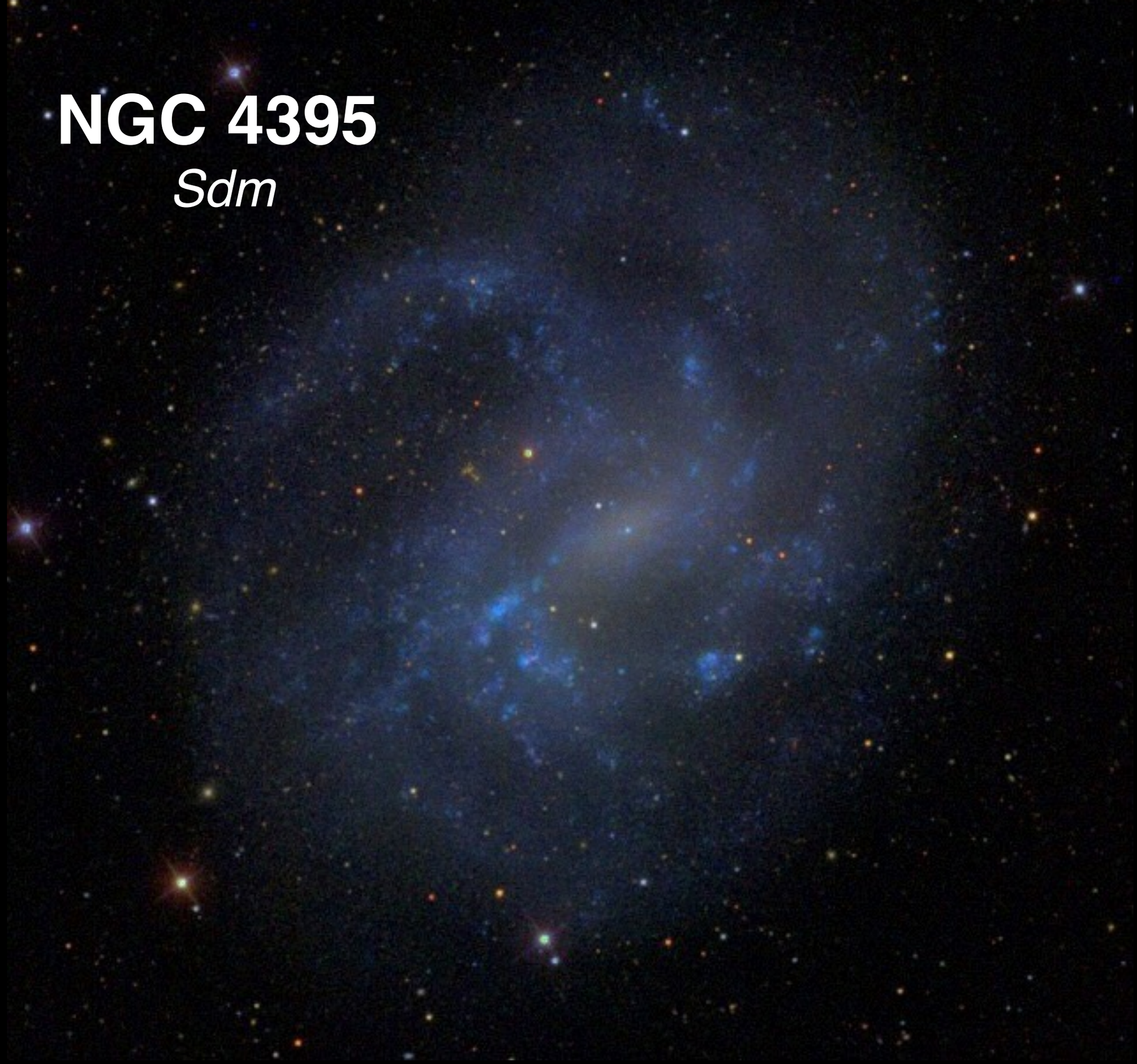


Filippenko & Ho (2003); Barth et al. (2004); Ho (2008, ARA&A)



NGC 4395

Sdm



NGC 4395

Sdm

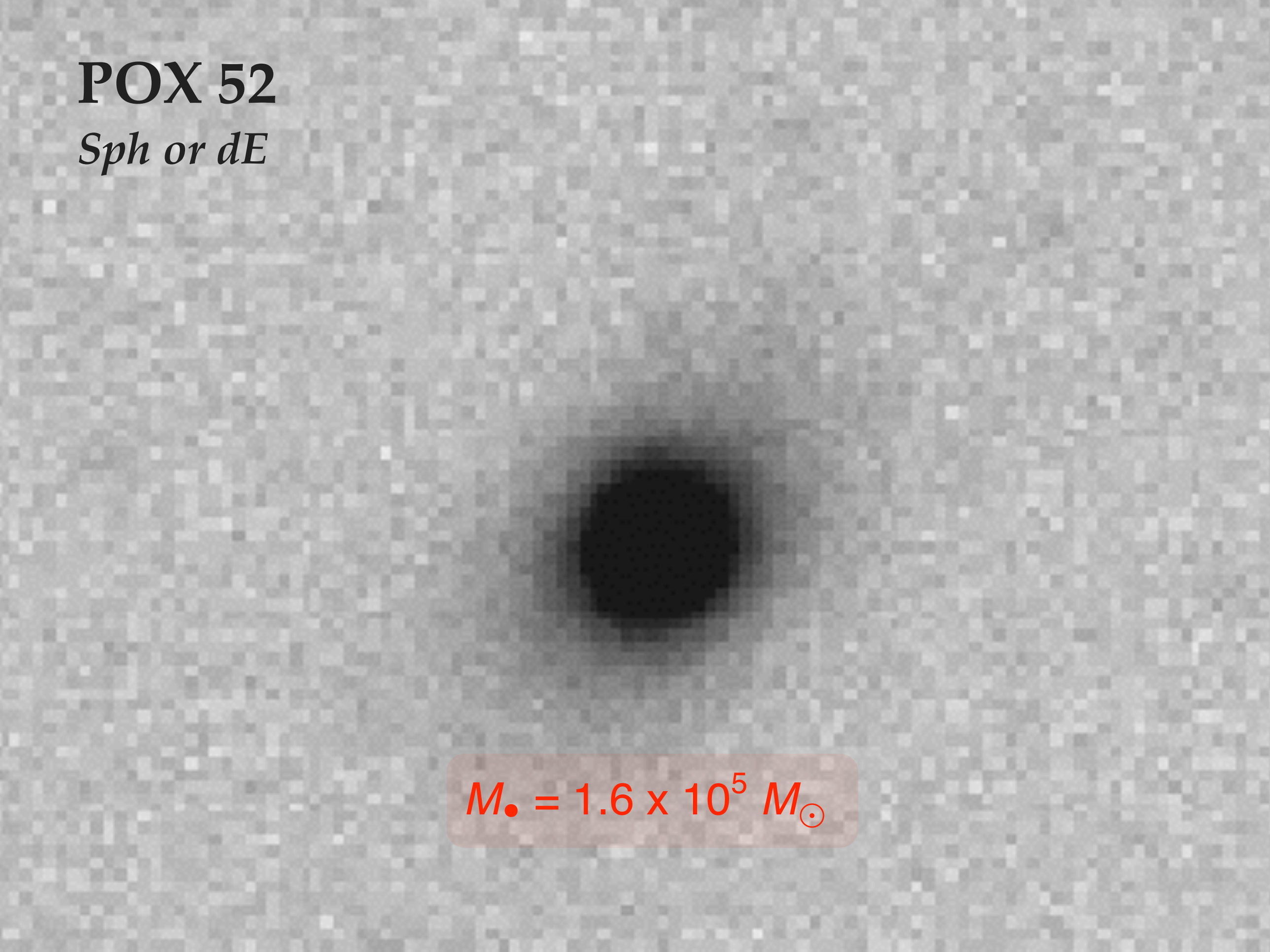
$M_\bullet = 10^4 - 10^5\ M_\odot$

POX 52

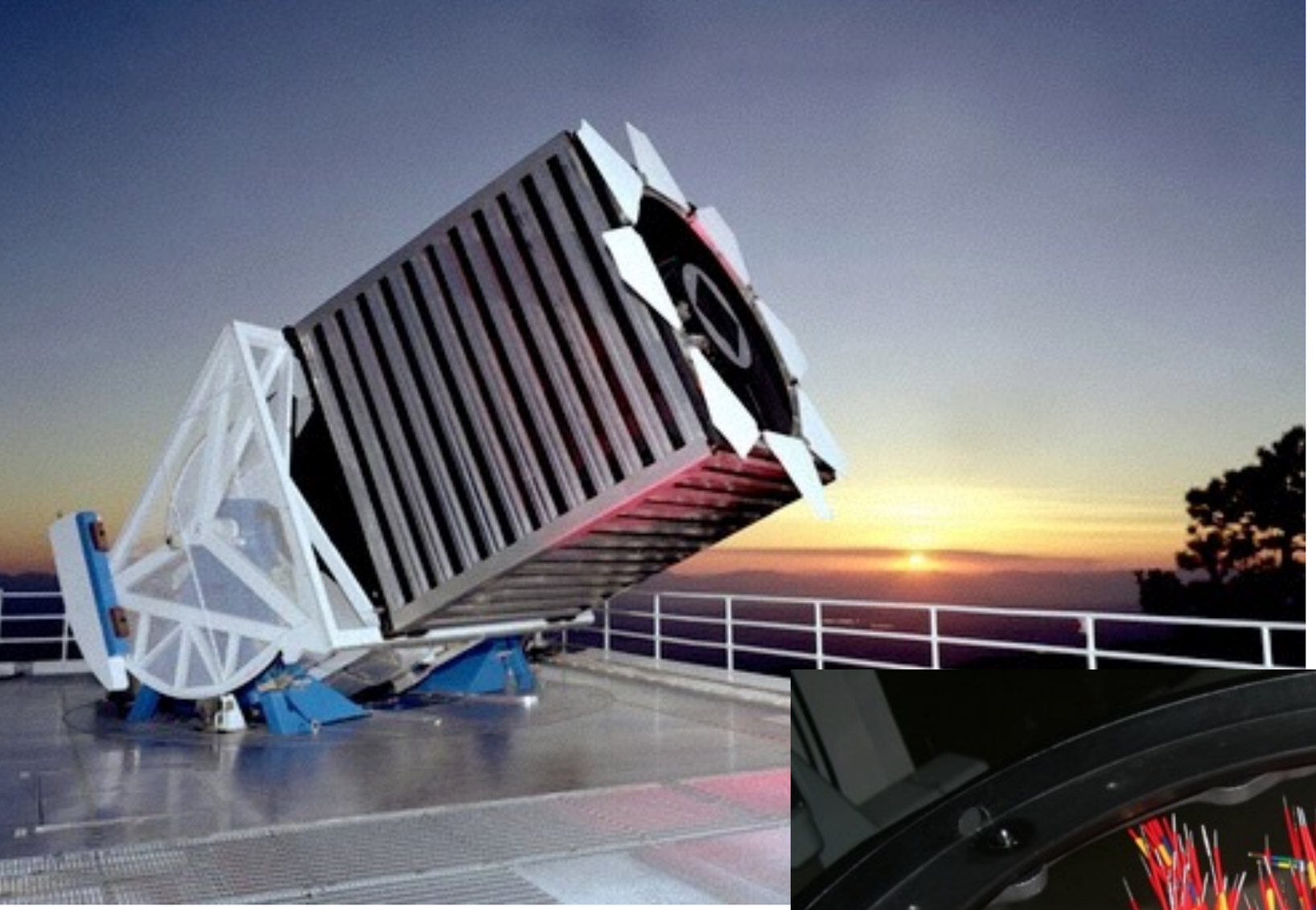
Sph or dE

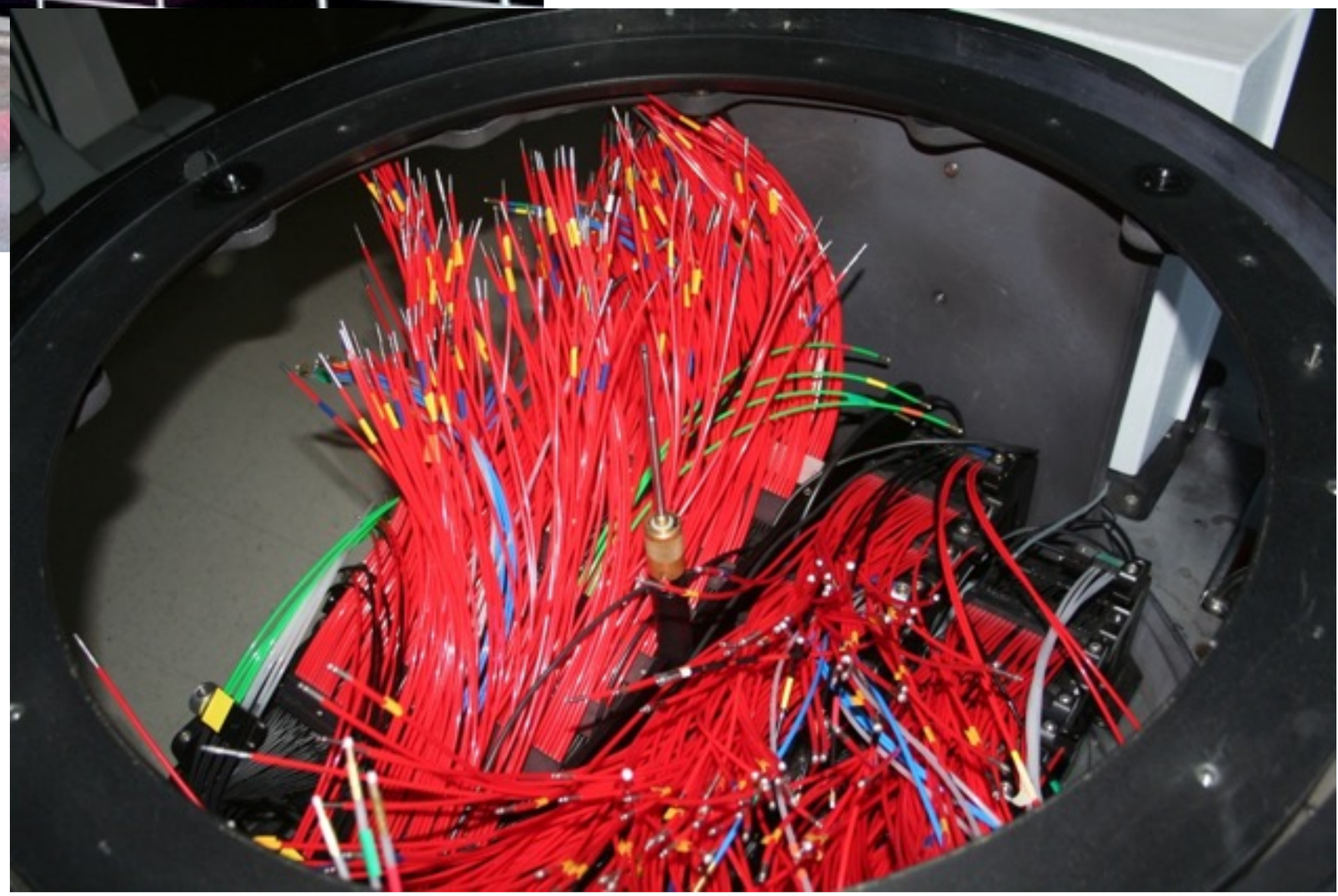
POX 52

Sph or dE

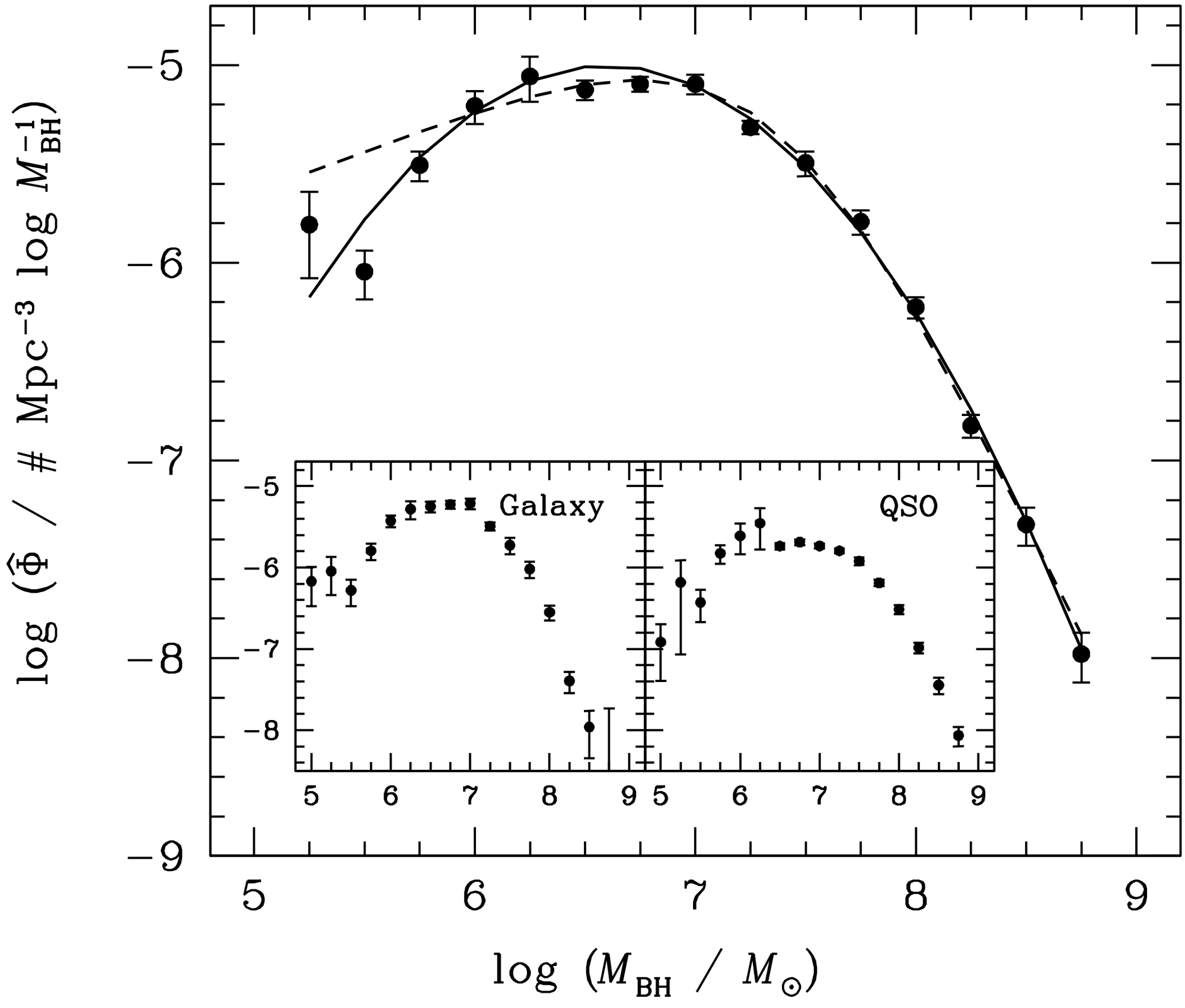


$M_\bullet = 1.6 \times 10^5\ M_\odot$

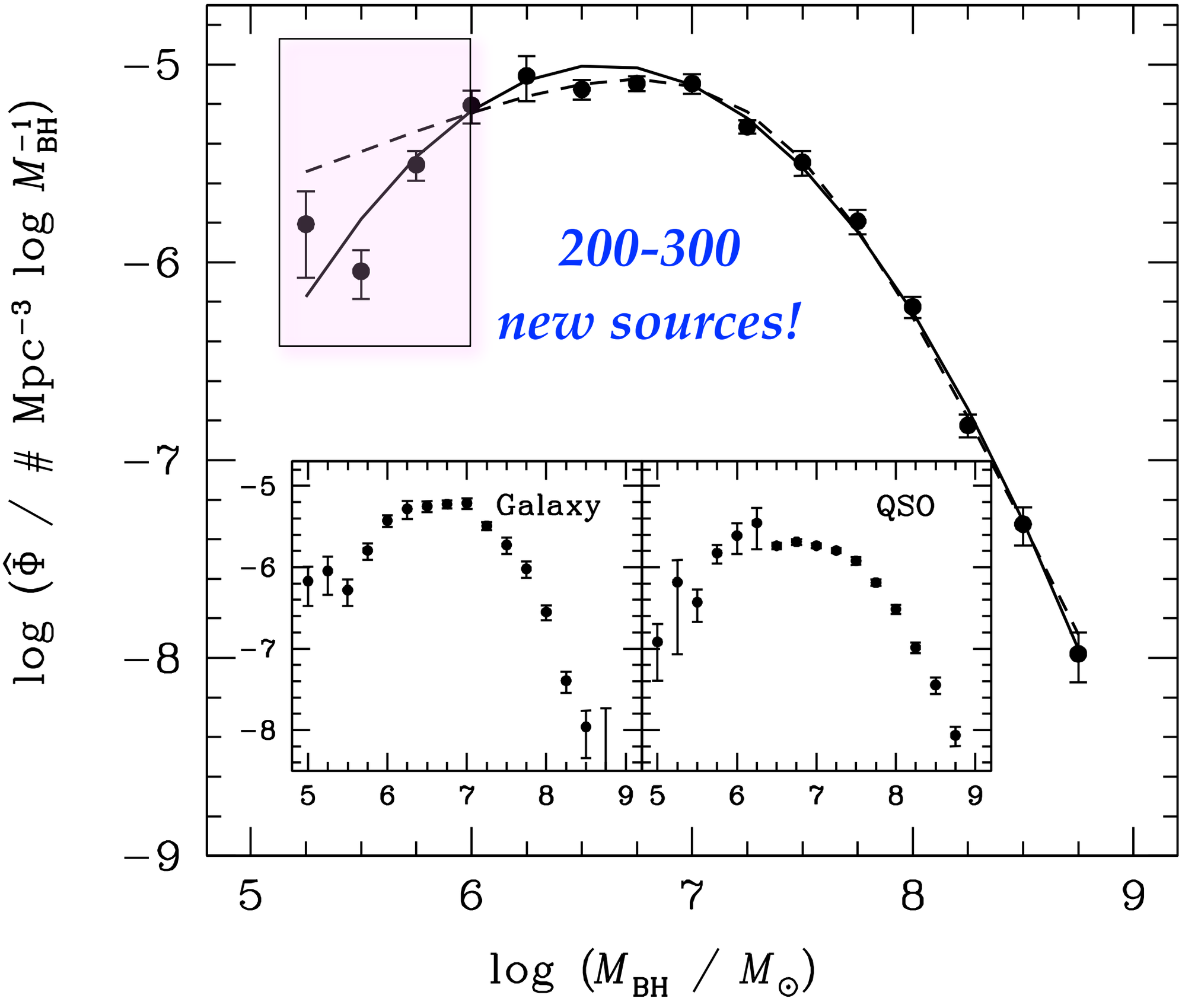




Greene & Ho (2004, 2007a,b); Dong, Ho et al. (2012)

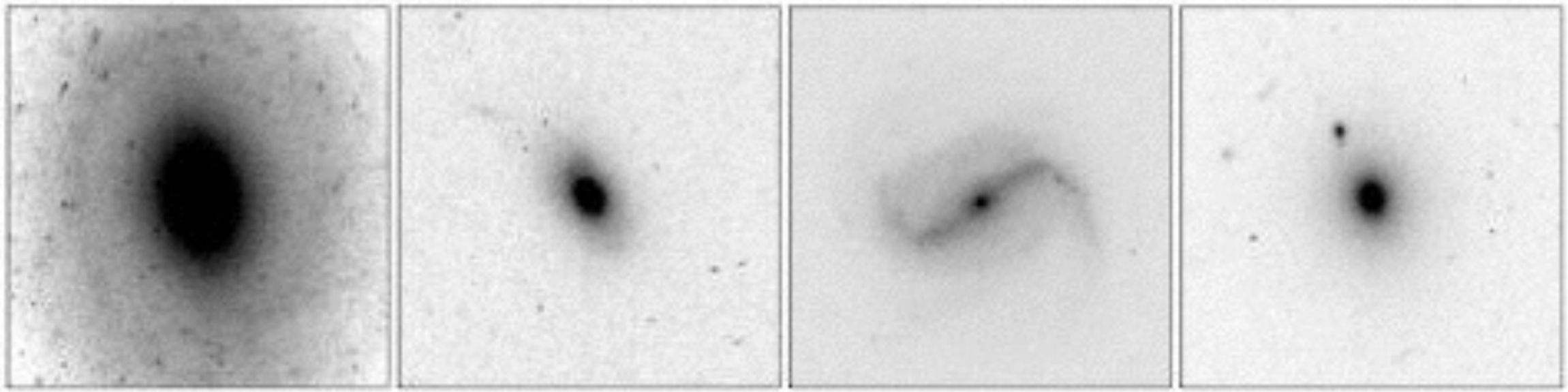


Greene & Ho (2004, 2007a,b); Dong, Ho et al. (2012)



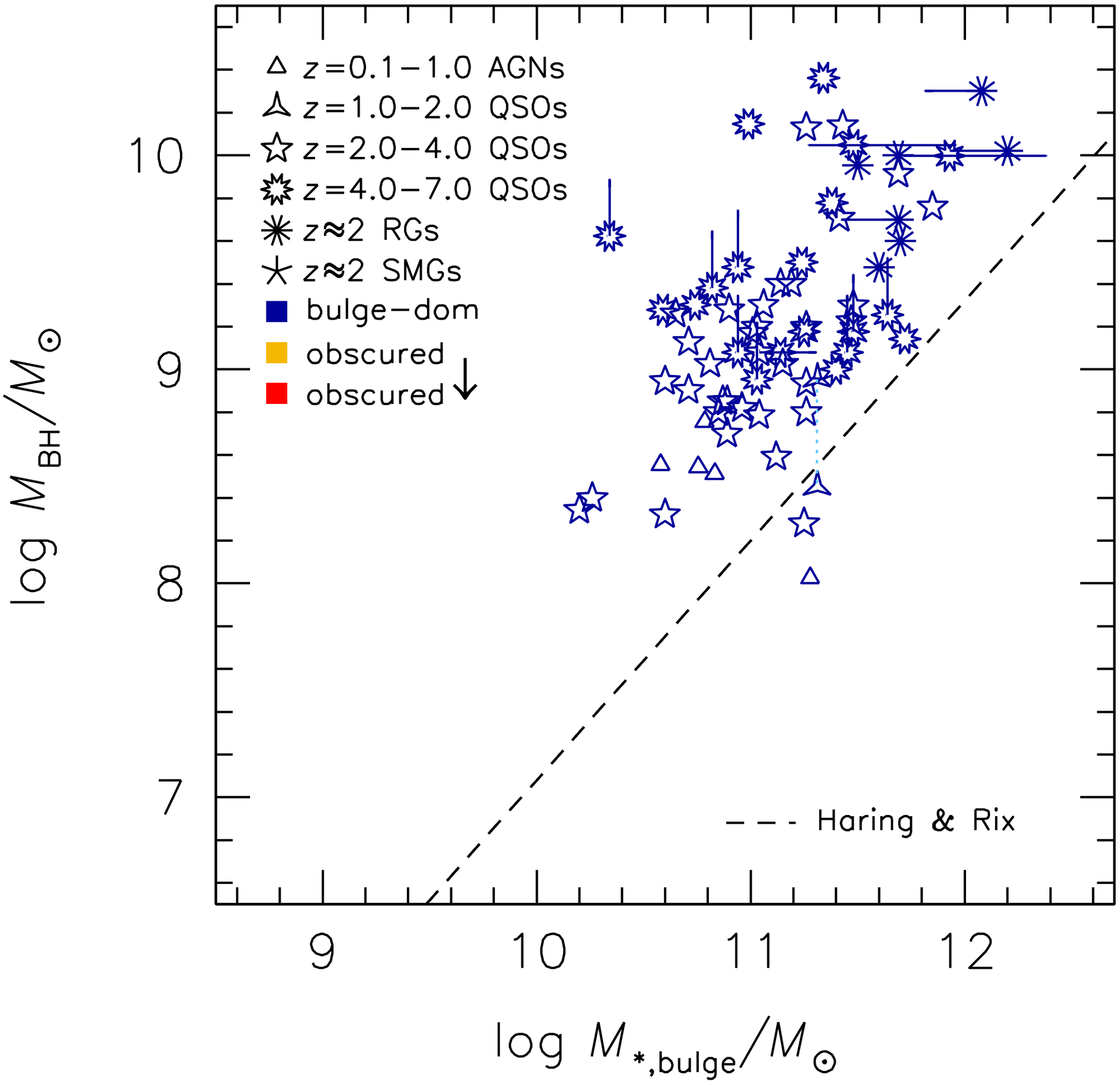
HST/ACS

Greene, Ho & Barth (2008); Jiang, Greene & Ho (2011a, b)



Baby BHs in baby galaxies.

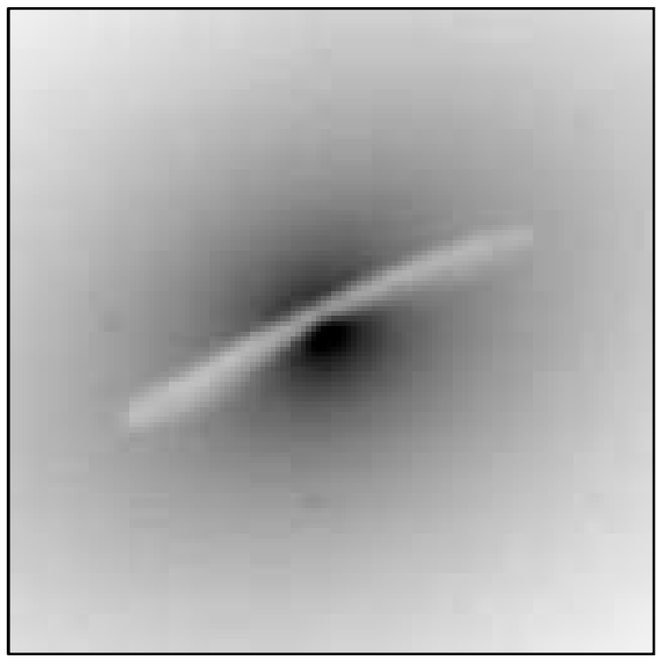
Ho (2016)

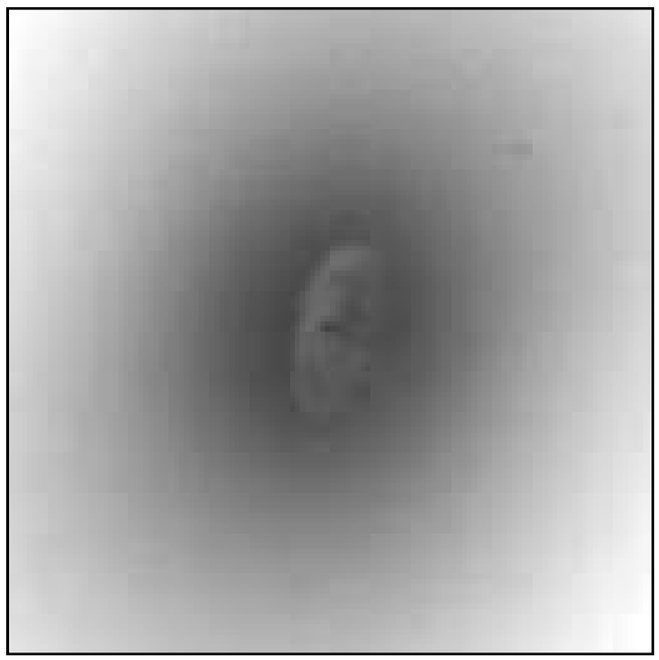

z=0.1−1.0 AGNs
z=1.0−2.0 QSOs
z=2.0−4.0 QSOs
z=4.0−7.0 QSOs
z≈2 RGs
z≈2 SMGs
bulge−dom
obscured
obscured
Haring & Rix
log M_BH/M⊙
log M_*,bulge/M⊙
10
9
8
7
9
10
11
12

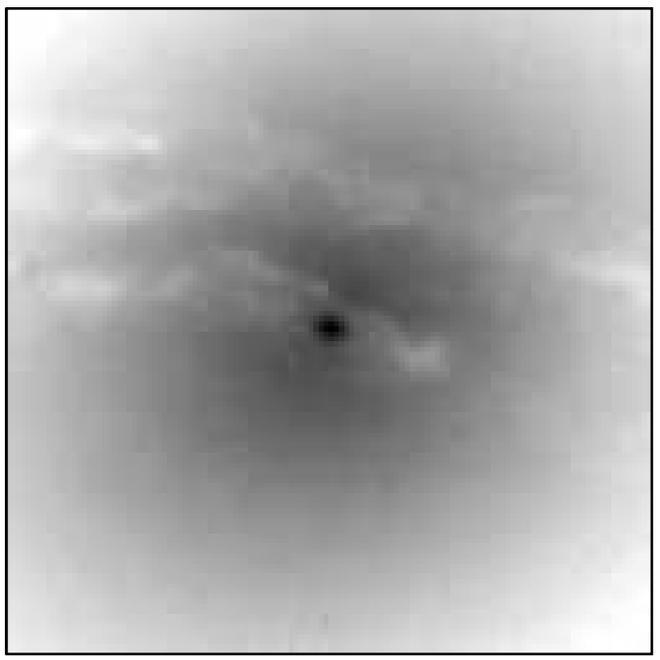
Summary

- Central BHs detected from 10^4 – $10^{10}\ M_\odot$
- All bulges contain BHs, but not all BHs live in bulges
- $M_\bullet \sim M_{\rm bulge}^{1.2}$ $\qquad$ $\langle M_\bullet / M_{\rm bulge} \rangle \sim 0.5\%$
- $M_\bullet \propto \sigma^{4.4}$
- $M_\bullet - \sigma$ and $M_\bullet - M_{\rm bulge}$ suggest BH-galaxy coevolution
- Scaling relations already in place for high-z QSOs
- Mild evolution for most massive BHs

Opportunities with ALMA





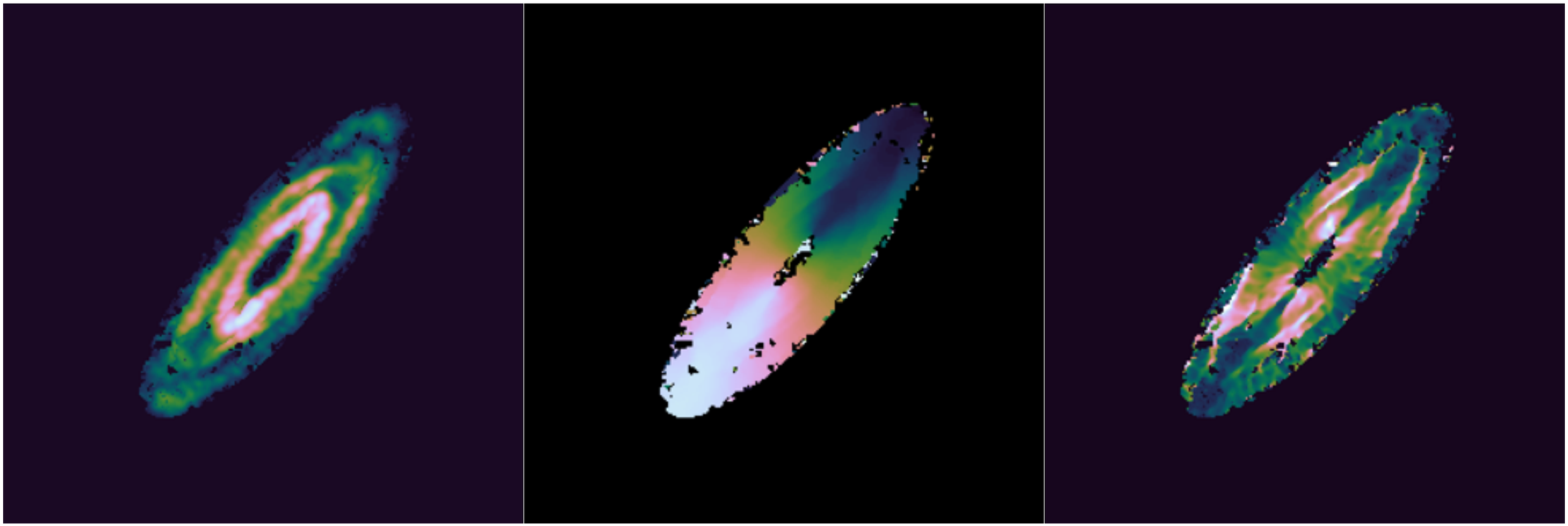


Barth, Ho, Baker, Darling

- **BH masses using nuclear (cold) gas disks**
- **ISM content of quasars at all redshifts**
- **Dynamical masses of quasar host galaxies (CO ladder, [C II])**
  Gas distribution and kinematics

MEASUREMENT OF THE BLACK HOLE MASS IN NGC 1332 FROM ALMA OBSERVATIONS AT 0.044 ARCSECOND RESOLUTION

AARON J. BARTH[1], BENJAMIN D. BOIZELLE[1], JEREMY DARLING[2], ANDREW J. BAKER[3], DAVID A. BUOTE[1], LUIS C. HO[4], JONELLE L. WALSH[5]



Data

Model

f(CO)

Synthesized Beam

v_{LOS}

σ_{LOS}

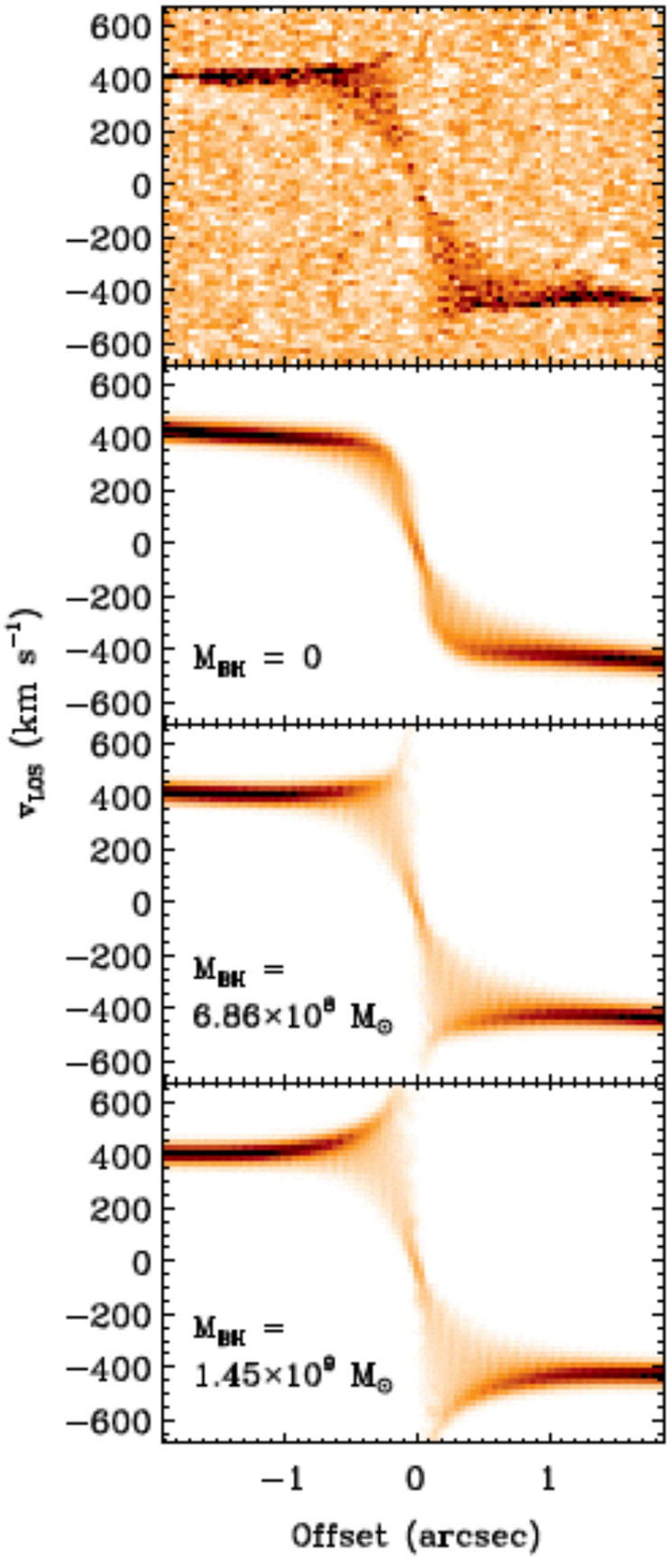
Jy beam^{-1} km s^{-1}

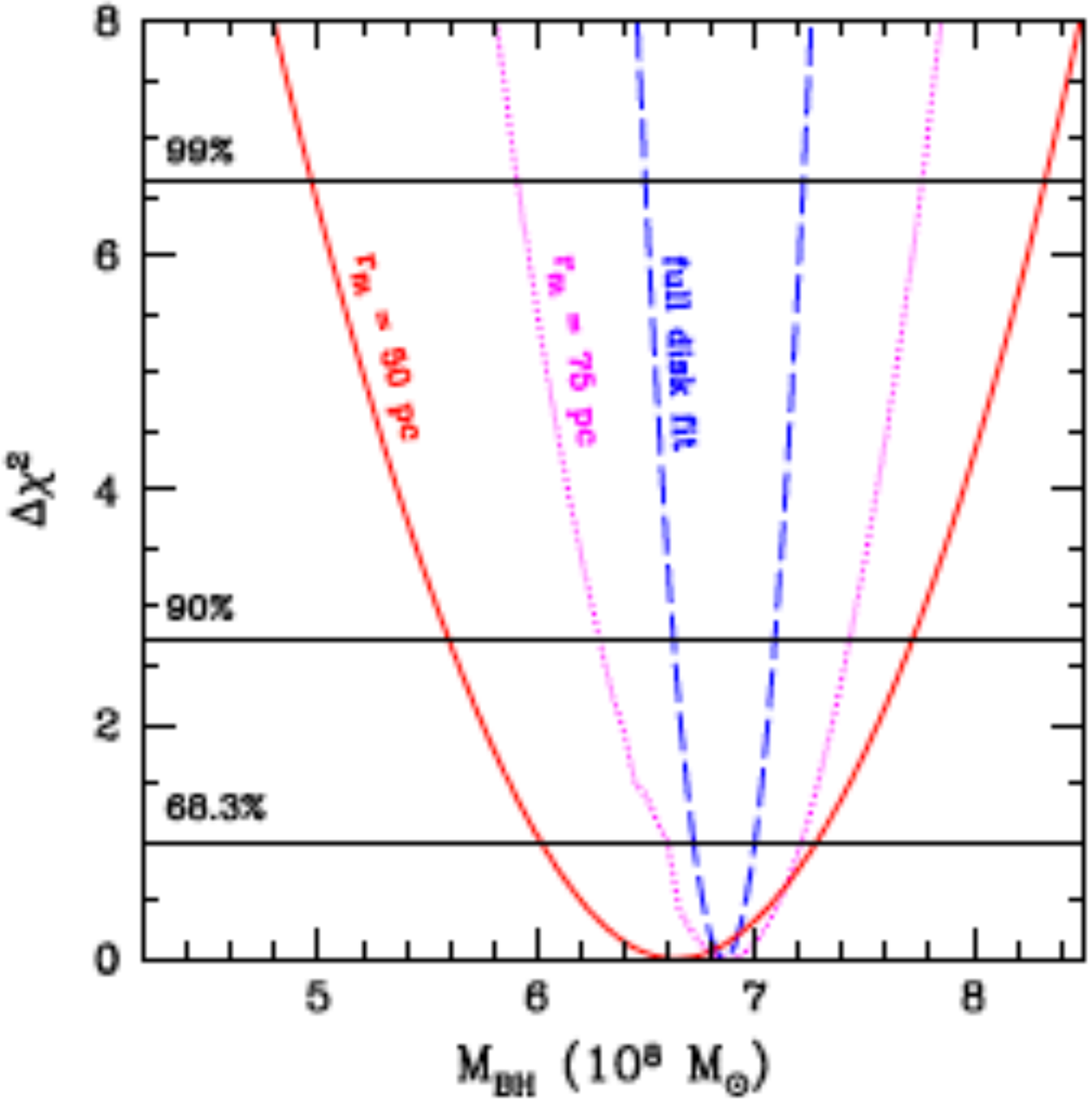
km s^{-1}

km s^{-1}

ΔDec (arcsec)

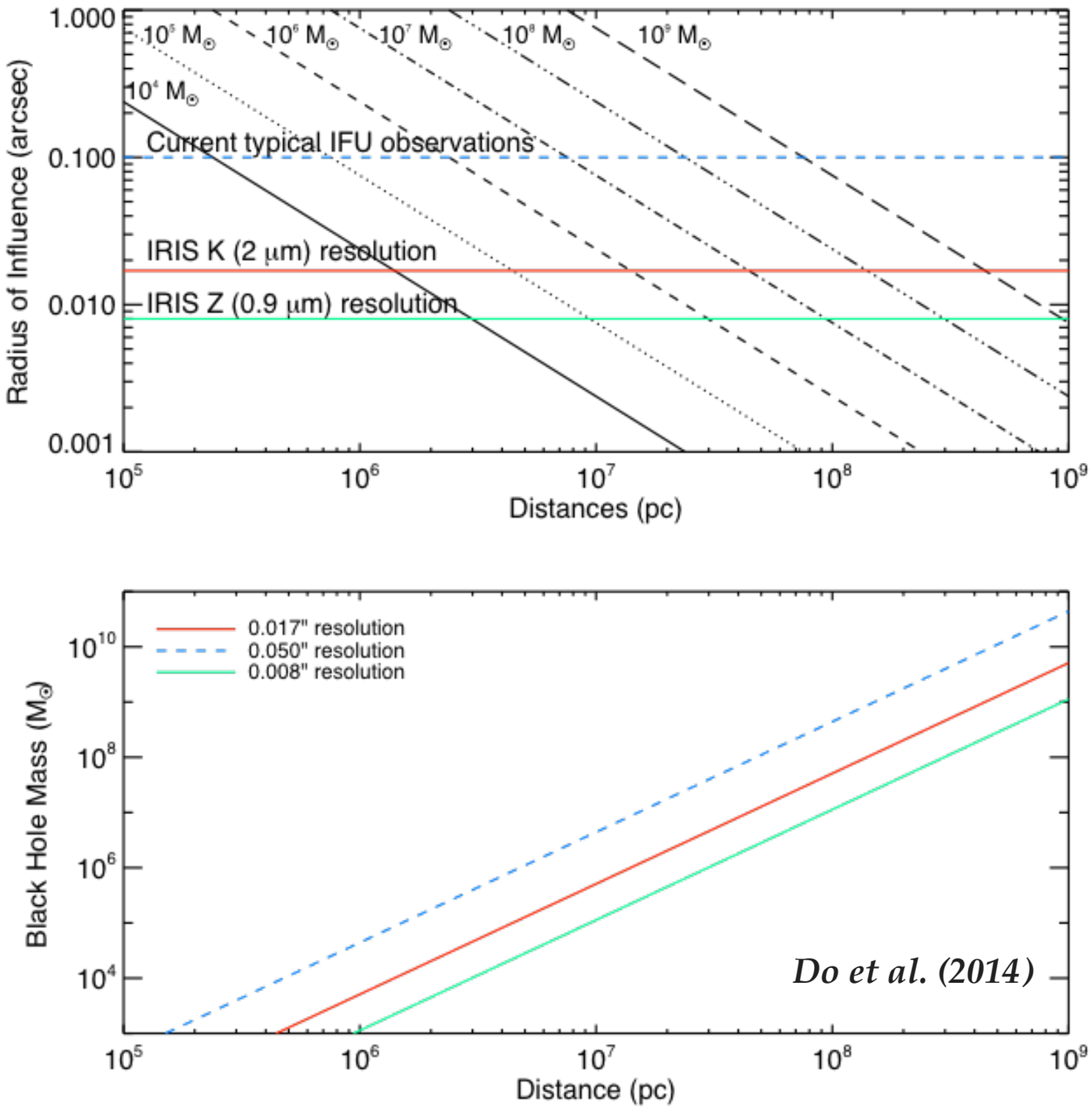
ΔRA (arcsec)


600
400
200
0
−200
−400
−600
M_{BH} = 0
M_{BH} = 6.86×10⁸ $M_\odot$
M_{BH} = 1.45×10⁹ $M_\odot$
v_{LOS} (km s⁻¹)
−1
0
1
Offset (arcsec)


8
6
4
2
0
99%
90%
68.3%
r_m = 90 pc
r_m = 75 pc
full disk fit
$\Delta\chi^2$
5
6
7
8
M_{BH} (10^8 $M_\odot$)

Thirty-Meter Telescope (TMT)

Future Directions with TMT



LIGO, NSF, Illustration: A. Simonnet (SSU)

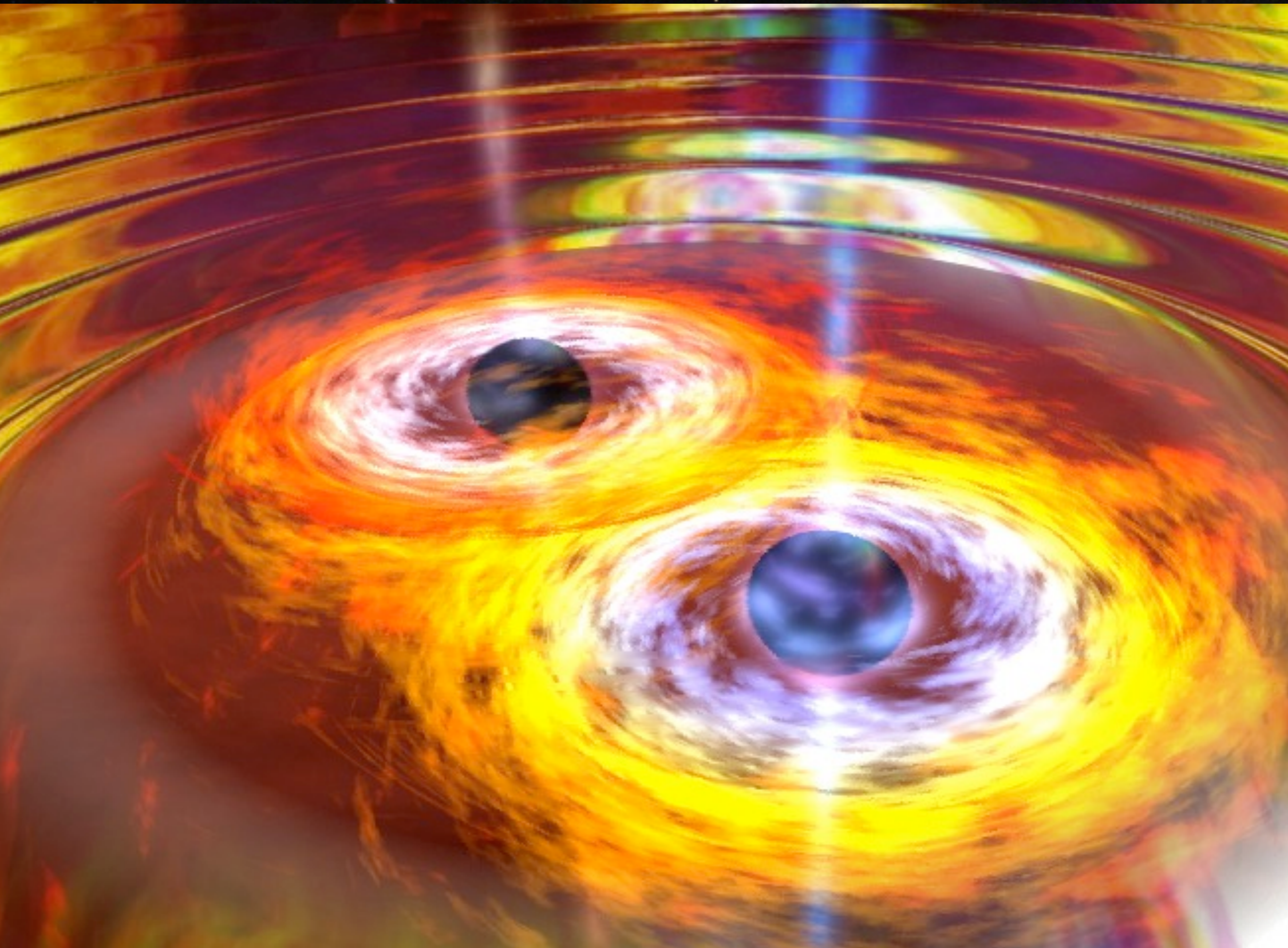
INSPIRAL

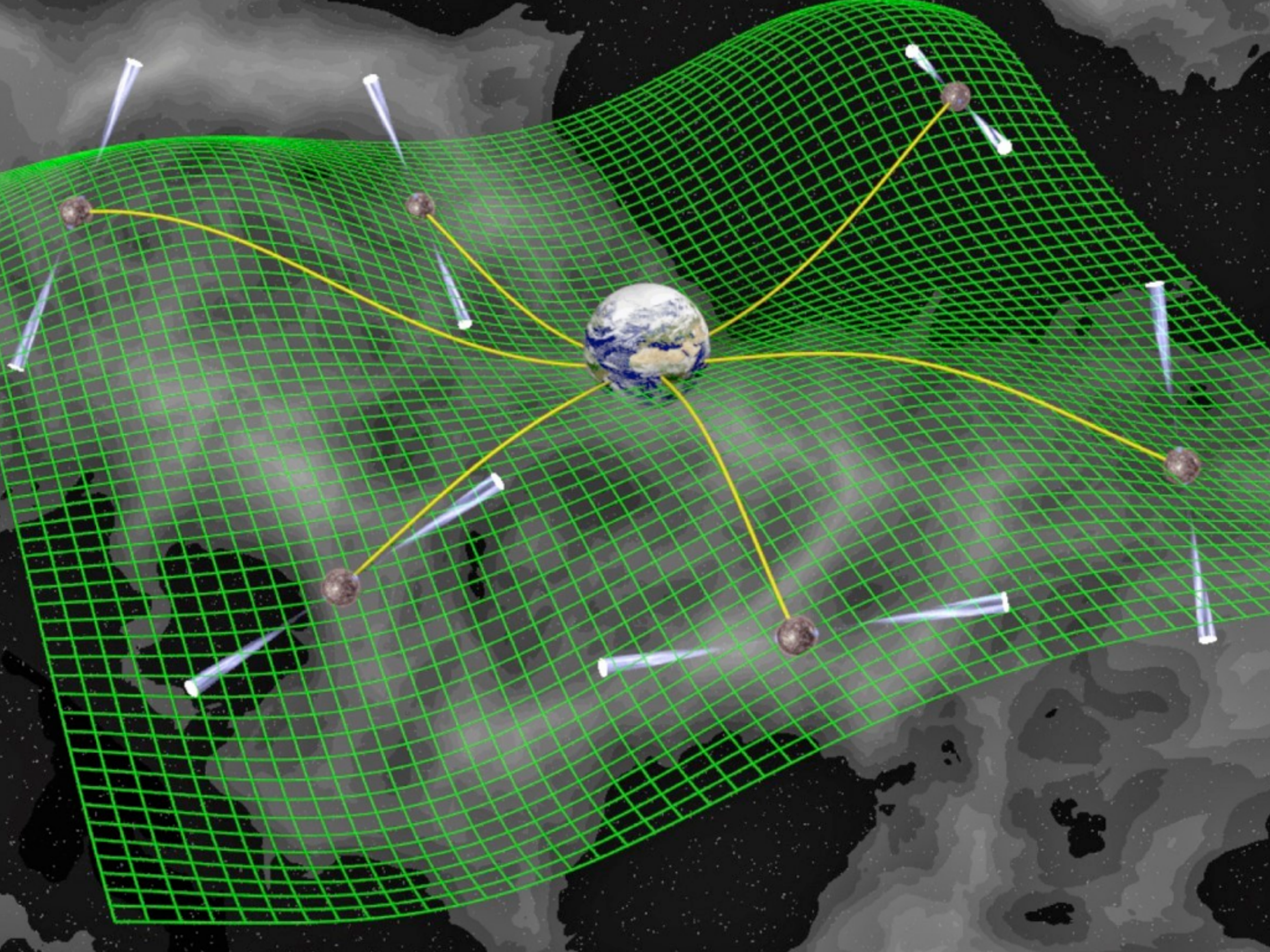
MERGER

RINGDOWN

HANFORD, WASHINGTON

LIVINGSTON, LOUISIANA





Future Directions with TMT

- Direct measurement of low-mass BHs in dwarf galaxies
- Direct measurement of BH masses in high-z inactive galaxies
- Direct measurement of BH-host scaling relations at high-z
- Calibration of BH masses in reverberation-mapped AGNs
- Stellar orbital structure of centers of BCGs, constrain growth mechanism of most massive BHs

Kavli Institute for Astronomy and Astrophysics (KIAA)

北京大学科维理天文与天体物理研究所

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Greene & Ho (2004-2011, ApJ): *Intermediate-mass BHs in Late-type Galaxies*

Huang & Ho (2013a,b; 2016, ApJ): *Two-Phase Formation of Massive Galaxies*

Ho & Kim (2014, ApJ): *The Black Hole Mass Scale of Classical and Pseudo Bulges in Active Galaxies*

Ho & Kim (2015, ApJ): *A Revised Calibration of the Virial Mass Estimator for Black Holes in Active Galaxies Based on Single-epoch Hβ Spectra*

Ho (2016, ApJ): *Joint Evolution of High-redshift Quasars and Massive Galaxies*

Barth et al. (2016a, ApJ): *Toward Precision Black Hole Masses with ALMA: NGC 1332 as a Case Study in Molecular Disk Dynamics*

Barth et al. (2016b, ApJ): *Measurement of the Black Hole Mass in NGC 1332 from ALMA Observations at 0.044 Arcsecond Resolution*