Supermassive Black Holes and the Evolution of Galaxies

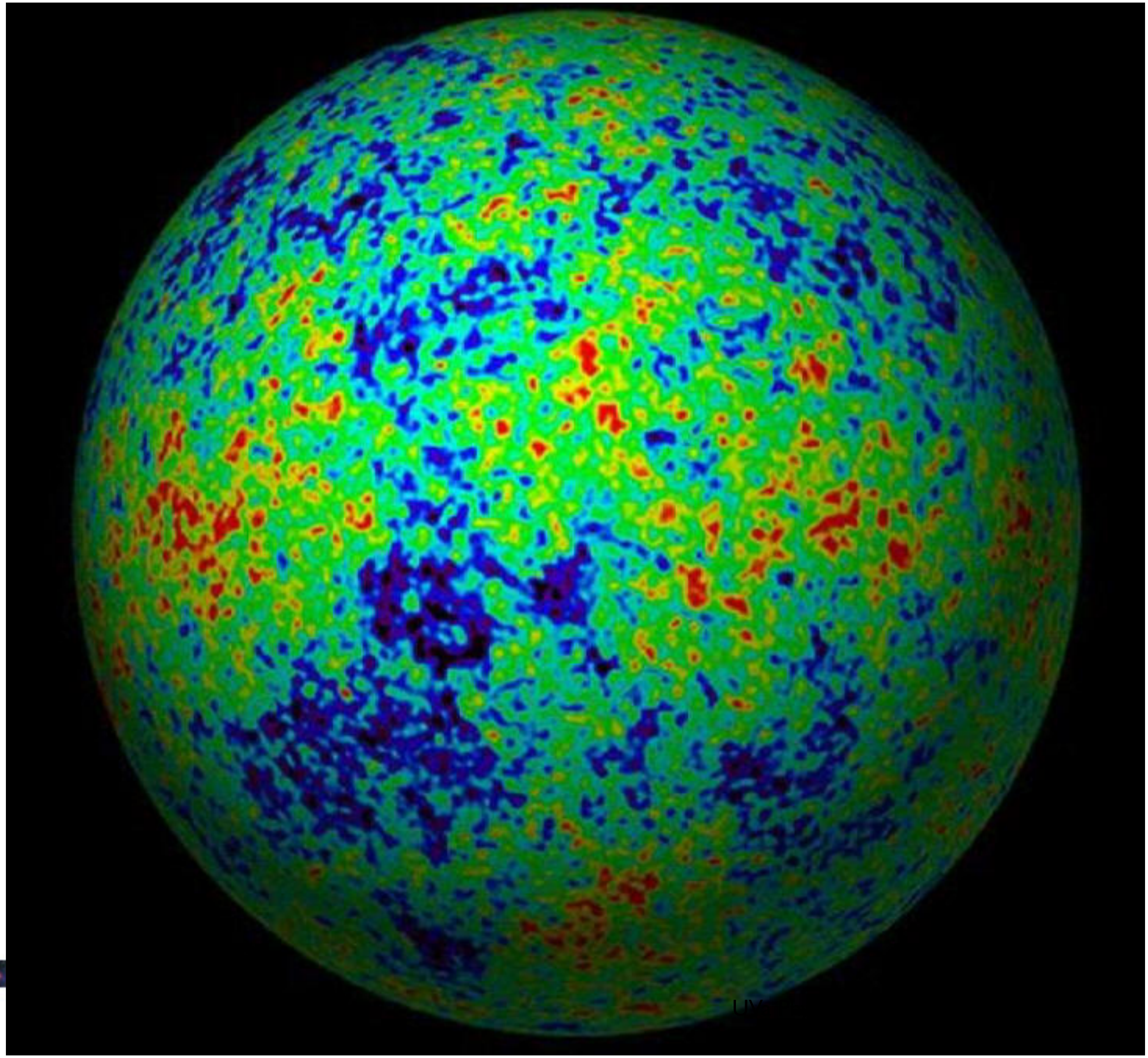
Jim Condon

NRAO, Charlottesville

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

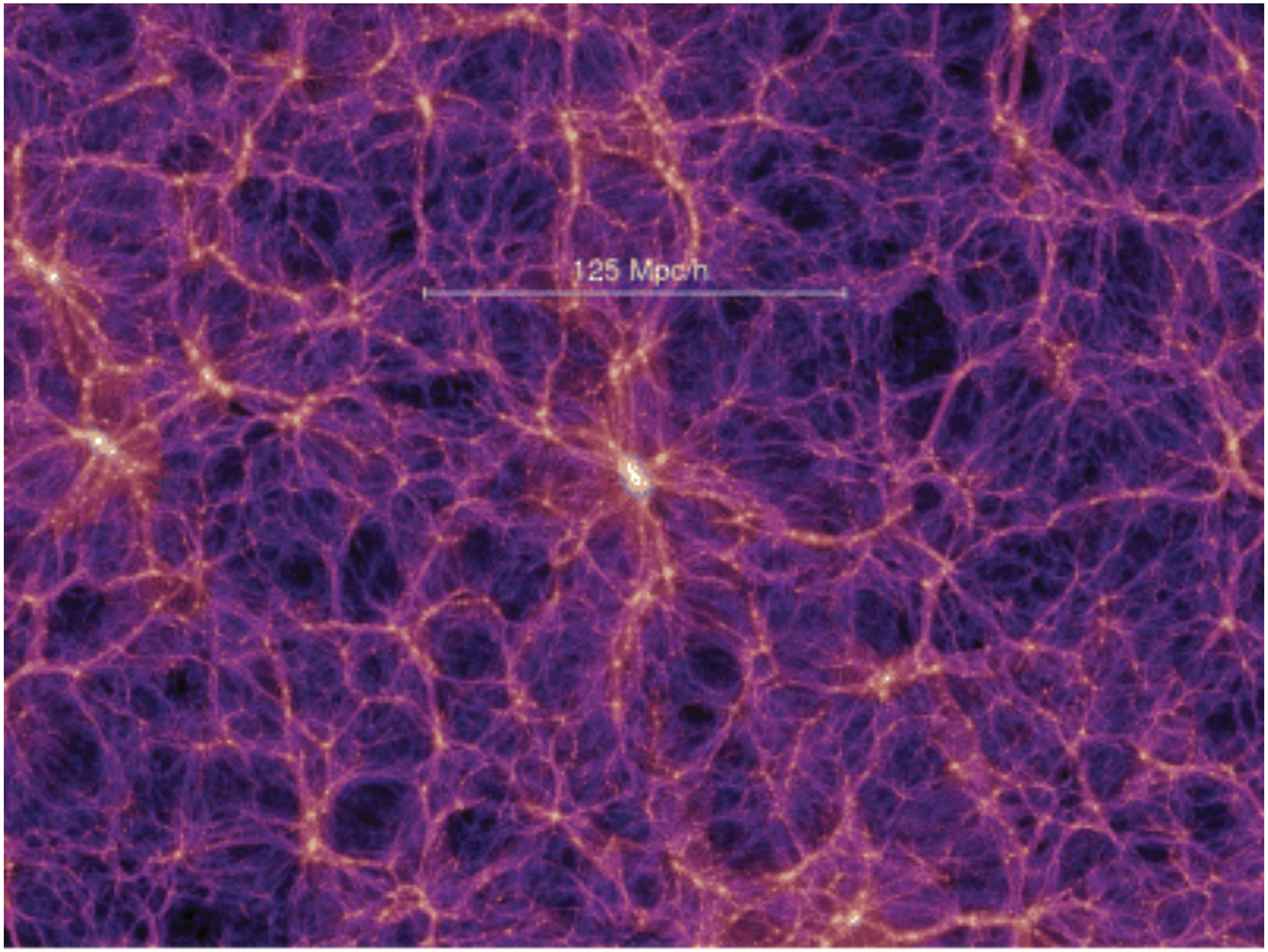
In the beginning…



Simulated dark-matter distribution today

Intensity indicates surface density,

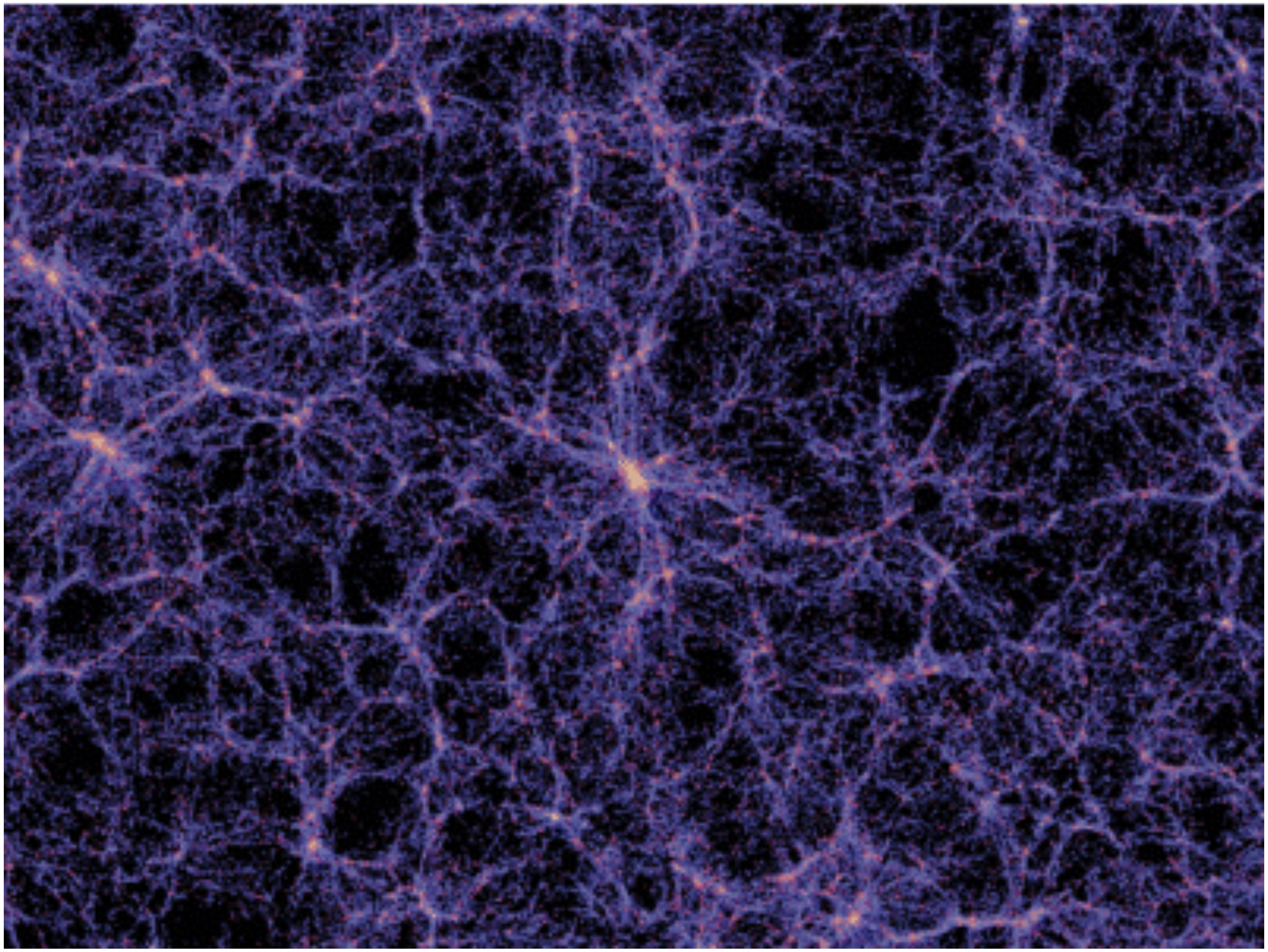
color indicates velocity dispersion.

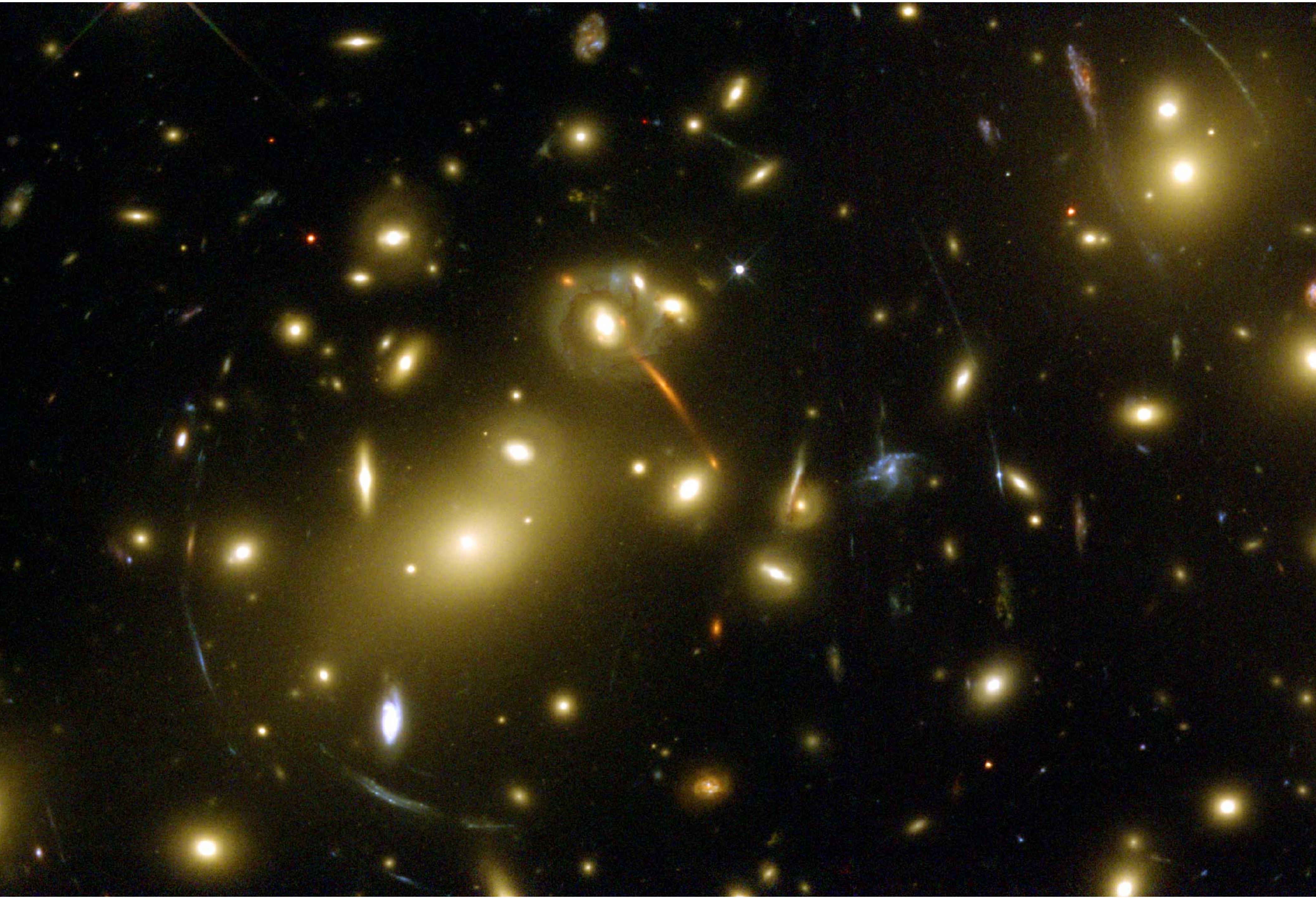


Simulated galaxy light distribution today

Intensity indicates surface brightness,

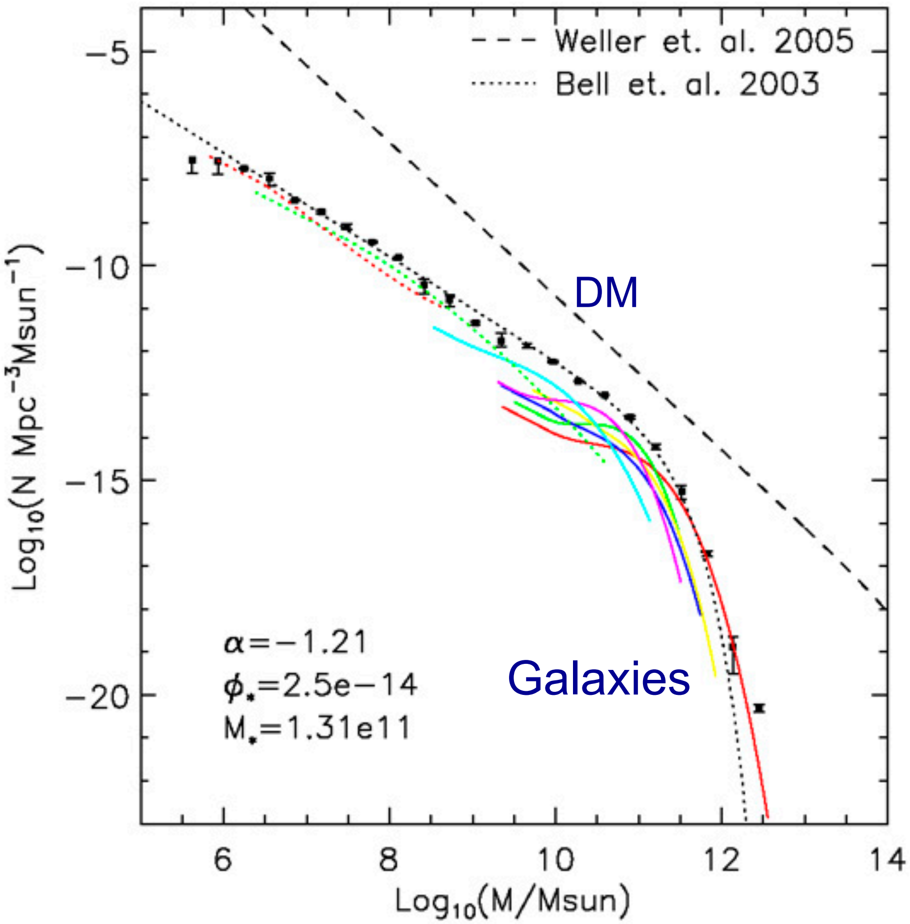
color indicates light color.



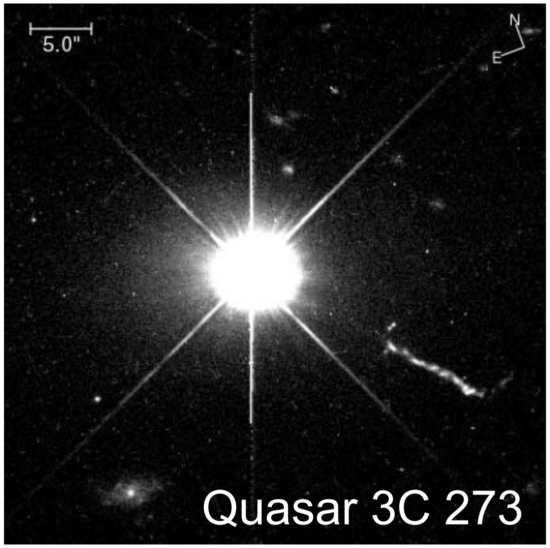


What is wrong with simple DM collapse?

1) There are no 10^{14} $M_\odot$ galaxies
2) The biggest galaxies are “red and dead”



Feedback from supermassive black holes:
1. Radiative mode



Galaxy binding energy: $E_{gal} \sim M_{gal}\, \sigma^{2}$

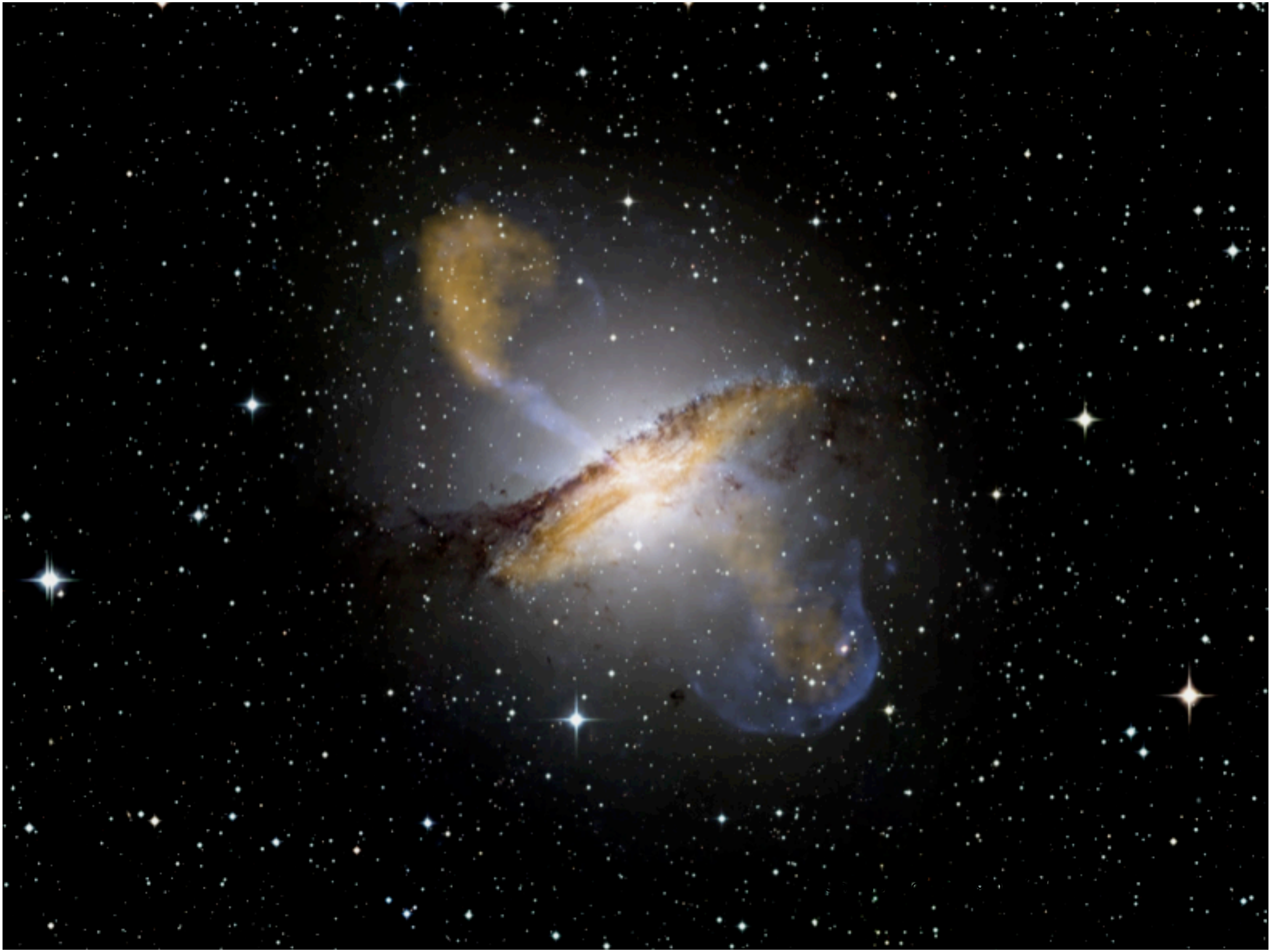
Energy released by black hole: $E_{bh} \sim 0.1\, M_{bh}\, c^{2}$

If $\sigma \sim 10^{-3}\, c$ and $M_{gal} \sim 10^{3}\, M_{bh}$, then $E_{bh} \sim 10^{2}\, E_{gal}$

Eddington's luminosity limit: radiation force on surrounding ionized gas cannot exceed gravity.

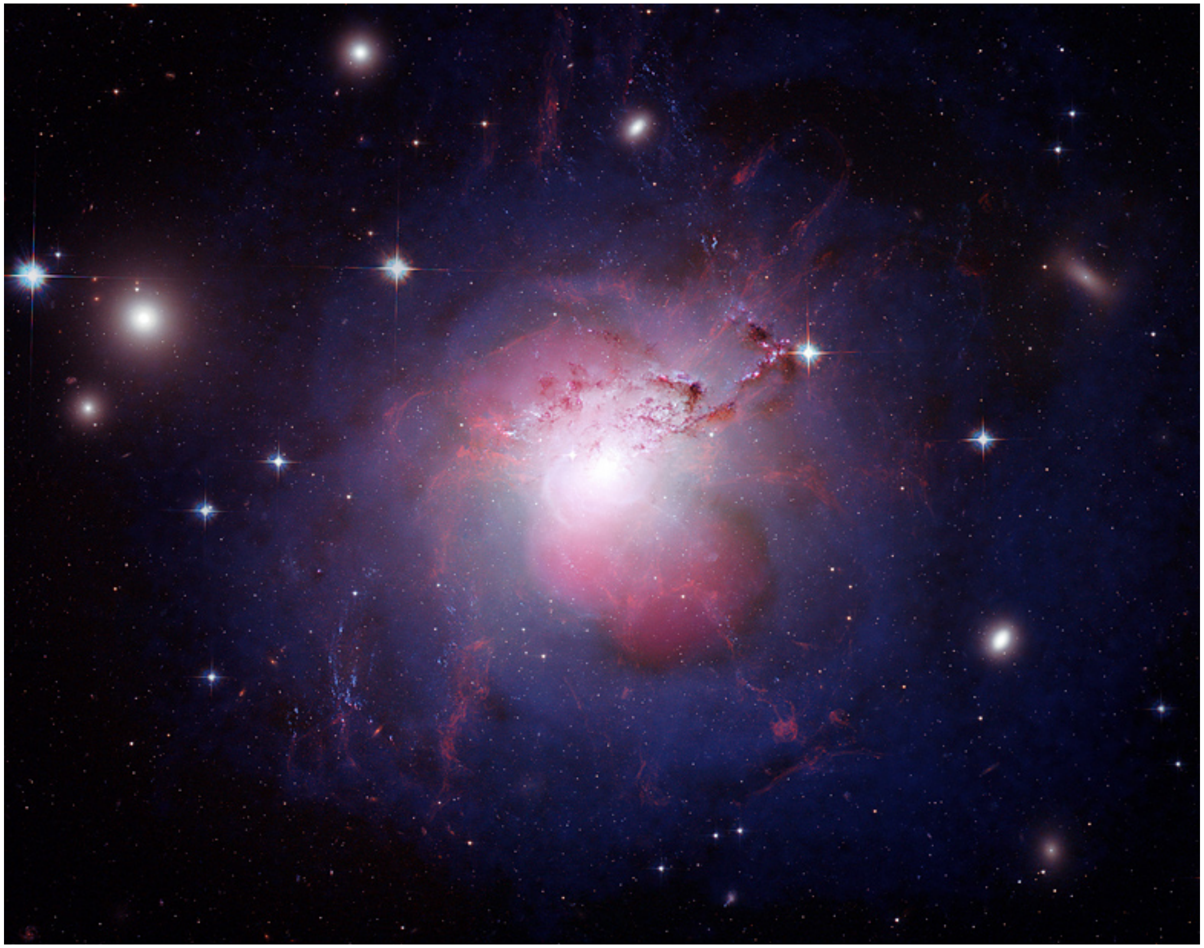
$$L_{Edd} / L_{\odot} \sim 3 \times 10^{4}\, M_{bh} / M_{\odot}$$

Dusty galaxy luminosity limit: $Lgal \sim 500\, L_{Edd}$ for typical dust/gas ratio can limit $M_{bh} \leq M_{gal} / 500$, retard growth of M_{gal} and star formation.

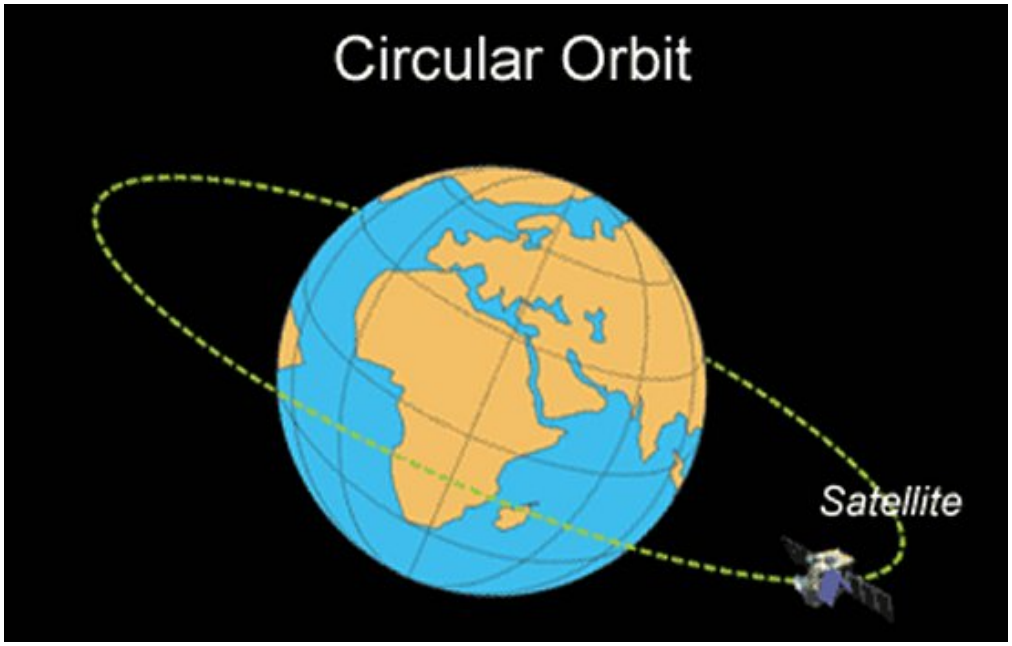


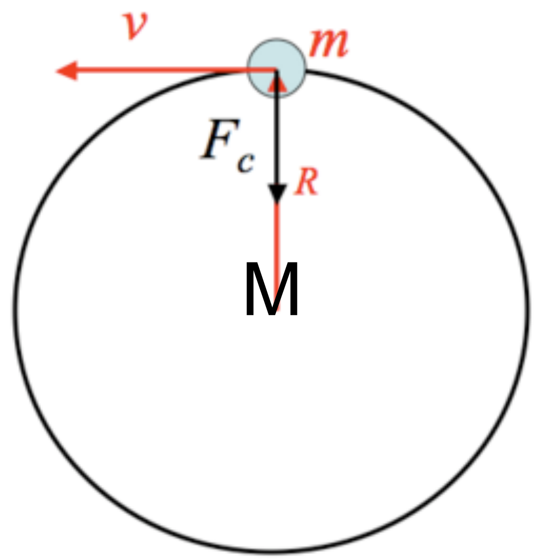
Feedback from supermassive black holes: II. Kinetic mode

Radio jets can inject $E_{\text{kin}} \sim 10^{61}$ ergs of kinetic energy into the intracluster gas in clusters of galaxies, retarding the growth of the most massive galaxies in the centers of clusters of galaxies.



How to weigh a black hole





$M = R\, v^2 / G$ is total enclosed mass

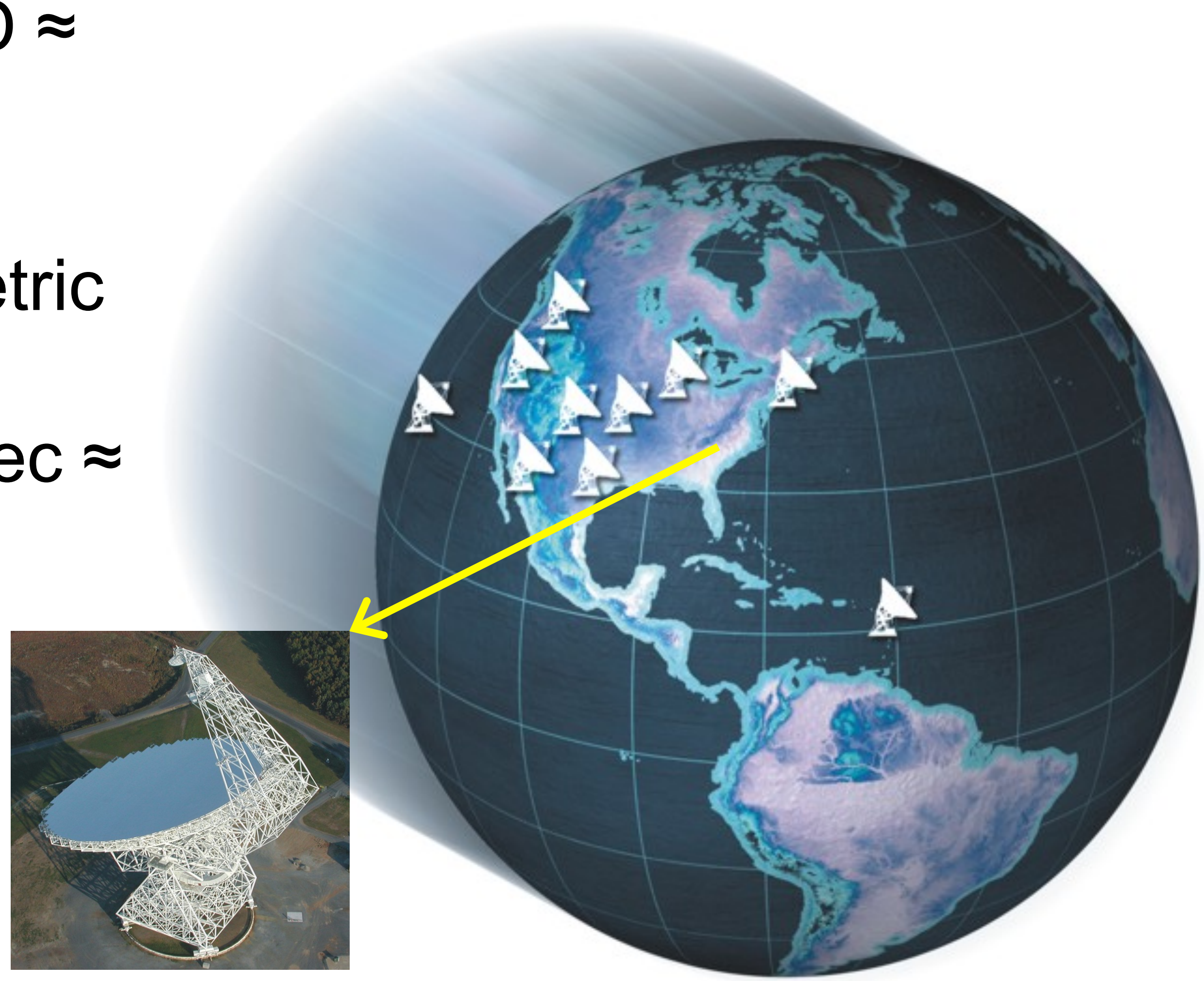
$R = \theta\, D$ *θ from VLBA, D = Hubble distance*

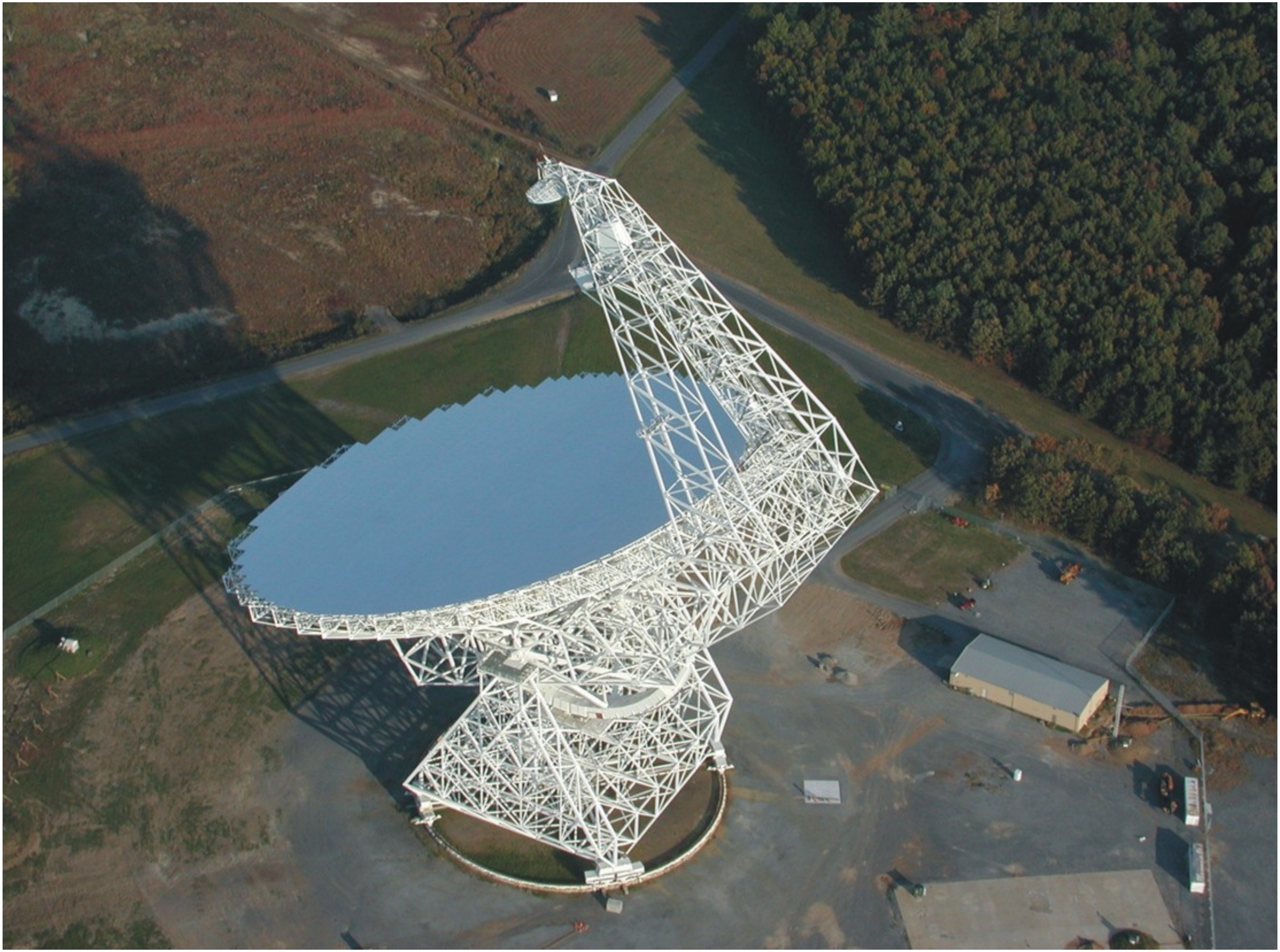
$v = v_r / \sin i$ v_r = Doppler velocity, i = inclination

λ = 1.3 cm imaging with HSA = GBT + VLBA

Resolution: λ / D ≈ 0.0003 arcsec

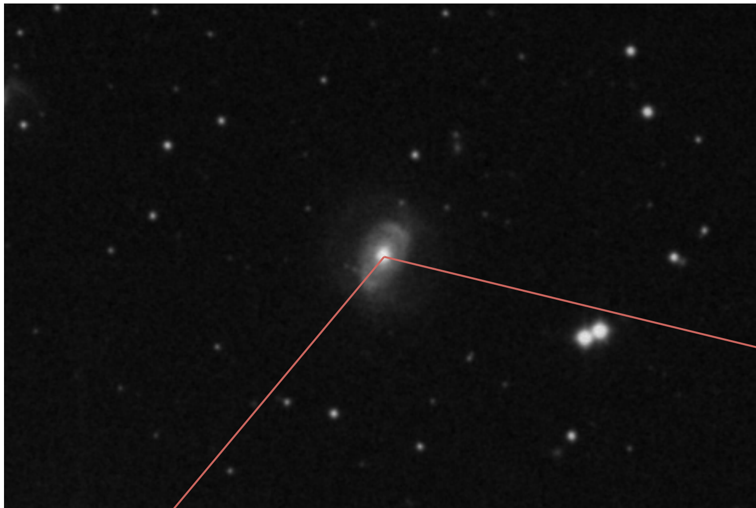
Relative astrometric accuracy:
> 0.000002 arcsec ≈ 10^{-11} radians



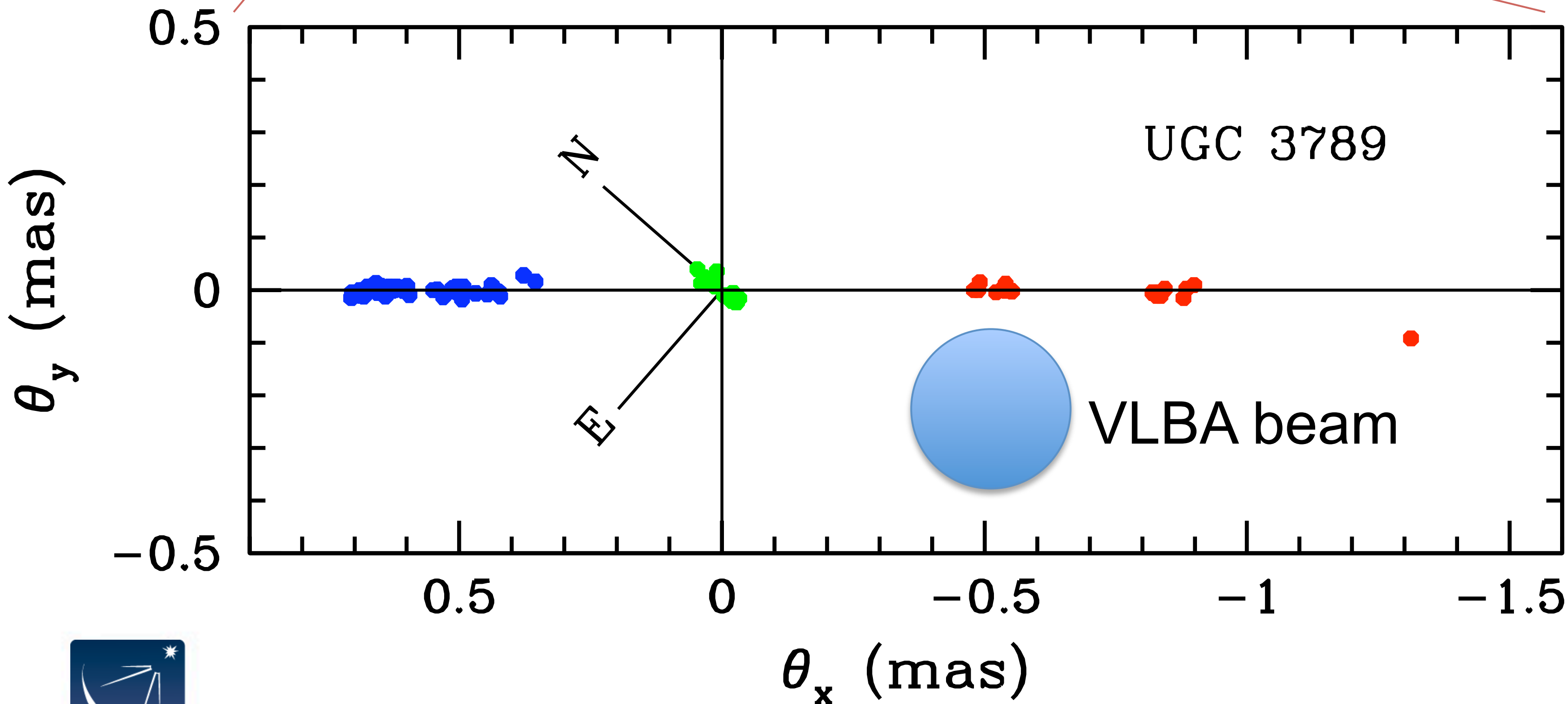


UGC 3789

D ~ 50 Mpc



Zoom 300,000 x

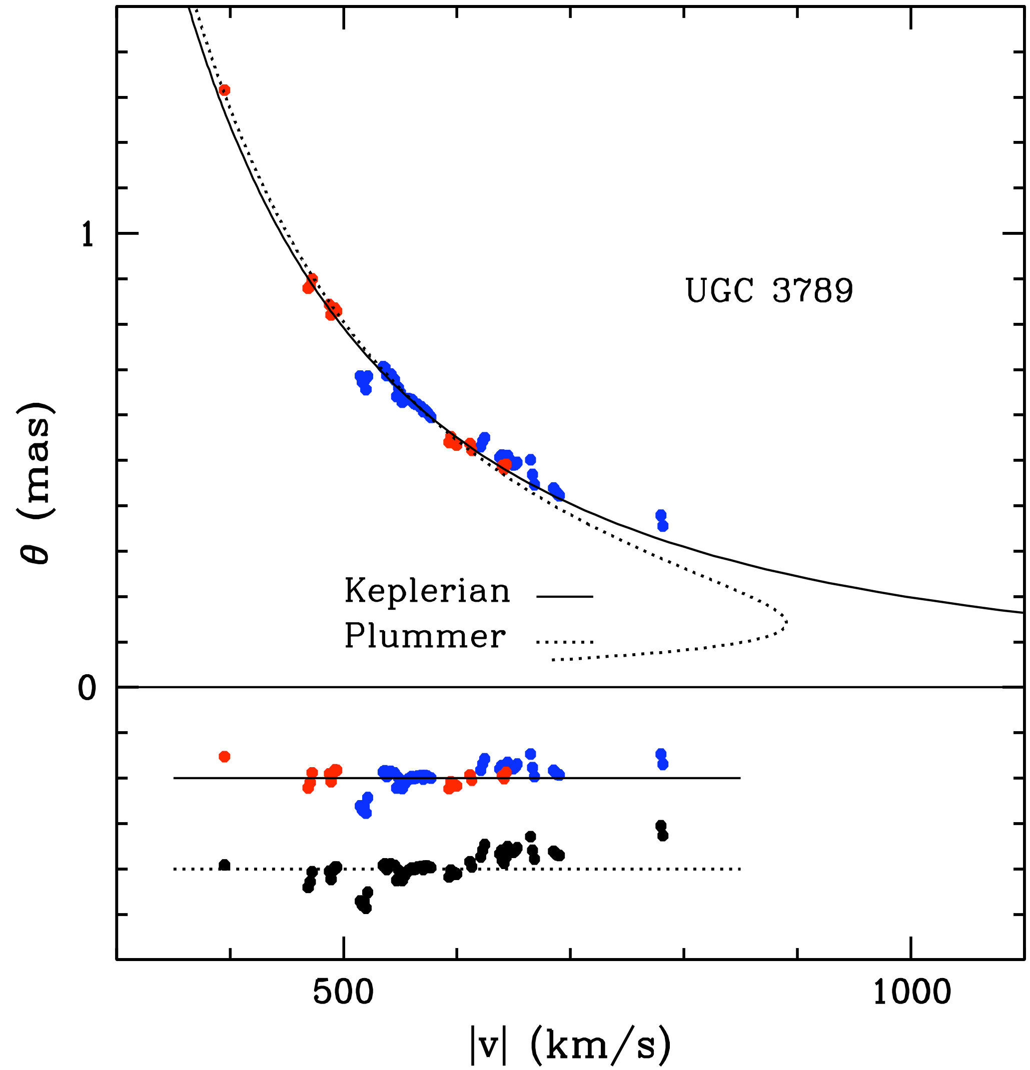


UGC 3789 maser rotation curve

D_A ~ 50 Mpc so

0.1 mas ~ 0.024 pc

$$M_\bullet = (v^2\,\theta / G)\,D_A$$
$$= 1.12 \times 10^7\,M_\odot$$
$$\times (D_A / 50\text{ Mpc})$$



Accurate SMBH masses

Galaxy	$\boldsymbol{R_{maser}}$ **(pc)**	$\boldsymbol{M_\bullet / 10^6 M_\odot}$
NGC 1194	0.58 – 1.41	66
NGC 2273	0.03 – 0.08	7.6
UGC 3789	0.08 – 0.30	11
NGC 2960	0.05 – 0.30	7.5
NGC 4388	0.24 – 0.29	8.4
NGC 6264	0.23 – 0.78	25
NGC 6323	0.11 – 0.29	10

Kuo et al. 2011, ApJ, 727, 20

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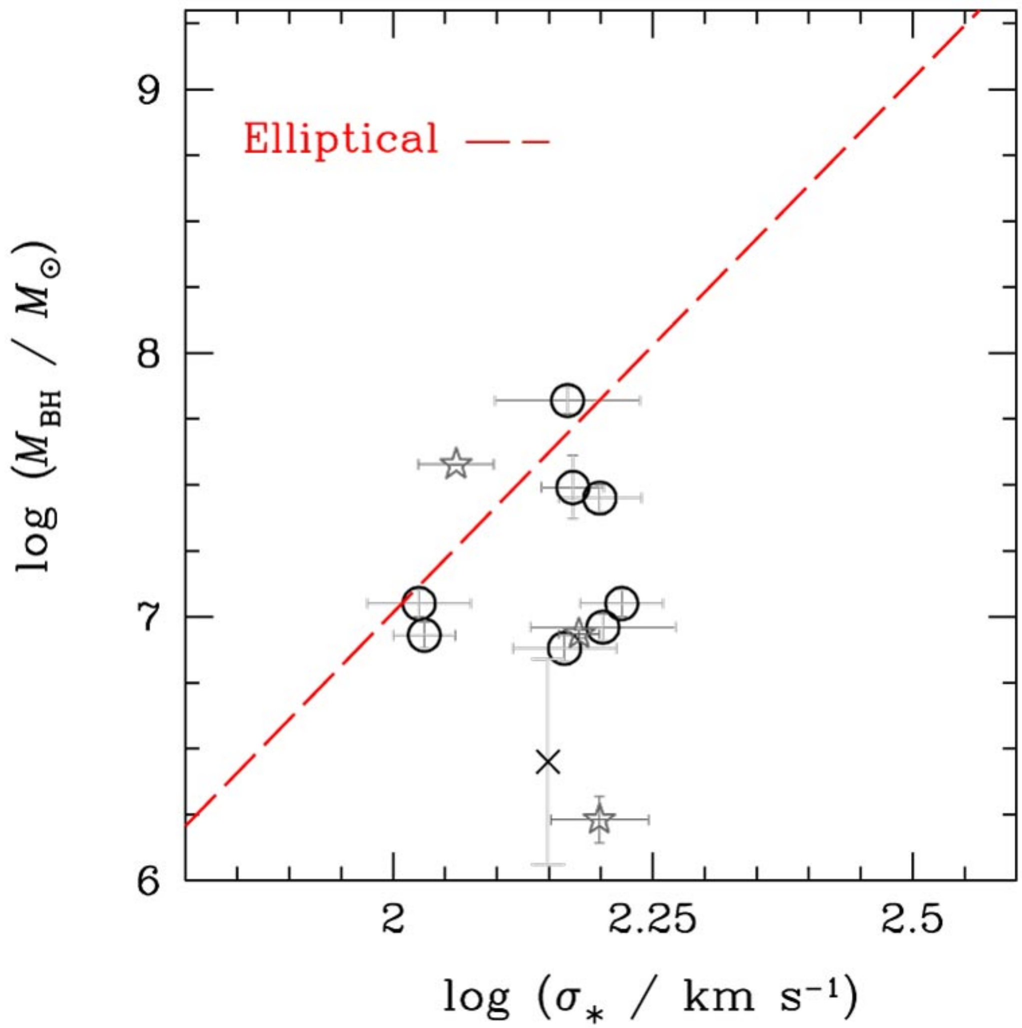
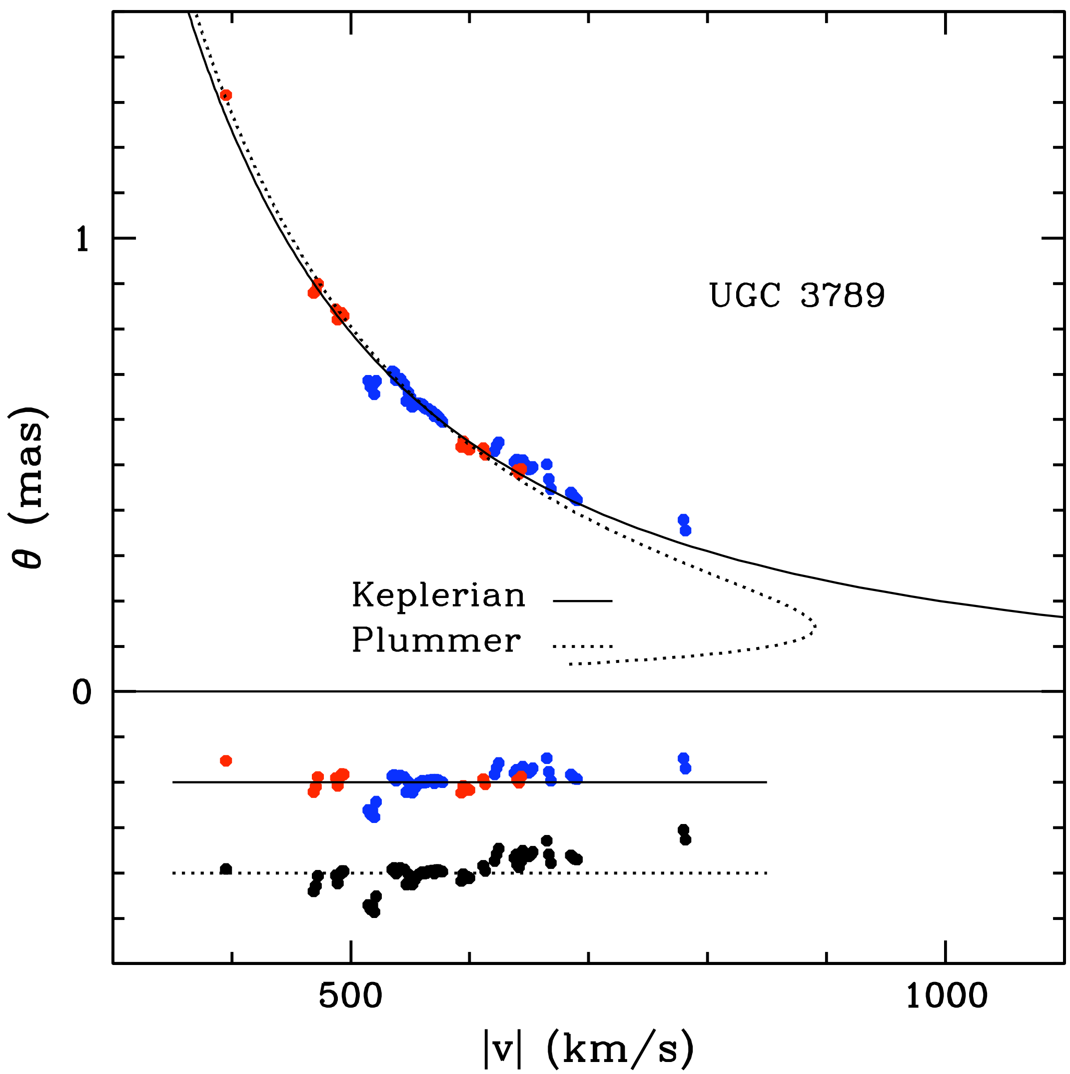
SMBH masses in Seyfert galaxies lie below the line defined by SMBH's in elliptical galaxies

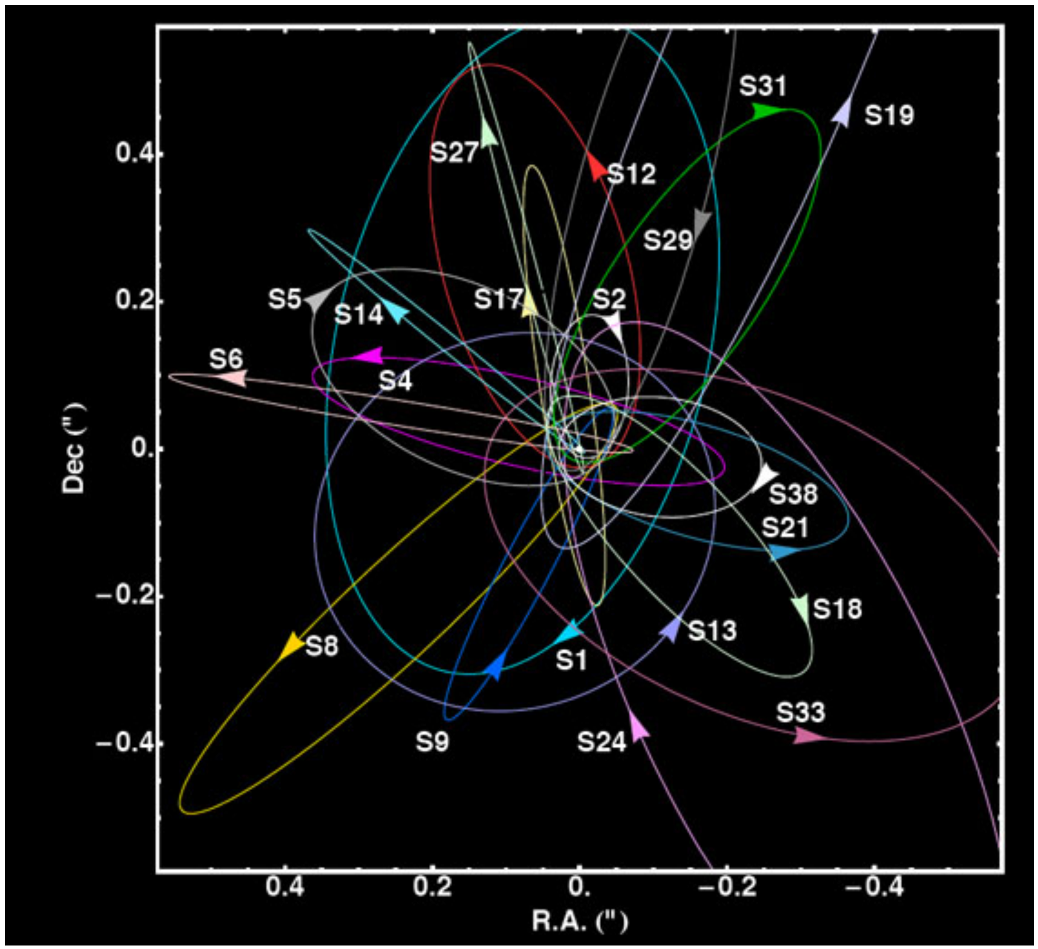


Real SMBH or just a dense star cluster?

$\rho = \rho_0(1+r^2/a^2)^{-5/2}$
$a < 0.02$ pc
$\rho_0 \geq 4\times10^{11}\ M_\odot\ \mathrm{pc}^{-3}$
$N_\star \geq 10^8$
$M_\star < 0.08\ M_\odot$
$\tau \leq 2\times10^6$ yr



Most large galaxies contain SMBHs. What happens when they merge?



Inspiraling, Binary, and Recoiling SMBHs

- Dynamical friction inspiraling time scale
  $\tau_{\mathrm{df}} \sim 1.7 r^2 \sigma_v / (G m^2 \ln \Lambda)$
  where r = distance to galaxy center, σ_v = rms stellar velocity dispersion, m = black hole mass, and $\ln \Lambda \sim 5$ is the Coulomb logarithm.
  For r = 1 kpc, σ_v = 200 km/s, and $m = 10^8\ M_\odot$, $\tau_{\mathrm{df}} \sim 10^8$ years

- Binary SMBH maximum orbit diameter
  $d_b = 3\ G\ (m_1 + m_2)\ /\ \sigma_v^2$
  where m_1 and m_2 are the black hole masses.
  For $m_1 = m_2 = 10^8\ M_\odot$, $d_b \sim 10^2$ pc

Inspiraling, Binary, and Recoiling SMBHs

The "last parsec problem"

- Binary SMBH "stalling" orbit diameter
  $d_s \sim 0.2\, d_b\, (m_1 / m_2) / (1 + m_1 / m_2)^2$
  For $m_1 = m_2 = 10^8\ M_\odot$, $d_s \sim 10$ pc

- Binary orbit diameter for gravitational coalescence within Hubble time
  $d_g = 8\, [H_0^{-1}\, G^3\, (m_1 m_2)^3\, (m_1 + m_2)^3 / (5c^5)]^{1/4}$
  where $H_0^{-1} = 13.6$ Gyr.
  For $m_1 = m_2 = 10^8\ M_\odot$, $d_g \sim 0.2$ pc

How can we find them?

Make a high-resolution 8.6 GHz VLBA search for off-nuclear and binary SMBHs in a complete sample of ~10^3 nearby (<D_A> ~ 200 Mpc) massive galaxy bulges to:

(1) discover off-nuclear inspiraling SMBHs predicted by the “merger tree” theory for massive galaxy evolution

(2) resolve “stalled” binary SMBHs in tight (d ~ 10 pc) orbits

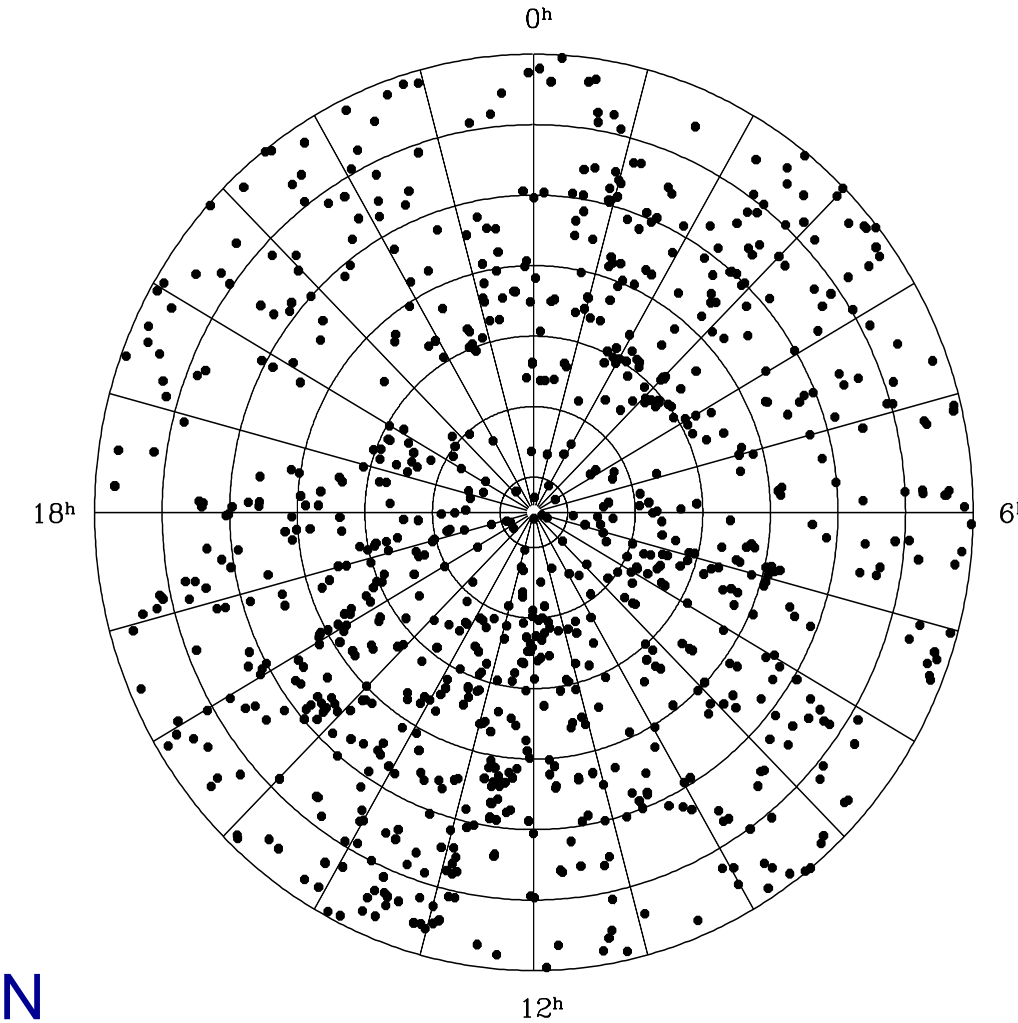
(3) discover off-nuclear recoiling SMBHs kicked out by the strong anisotropic gravitational radiation sought by LISA and NANOgrav

(4) discover currently active nearby SMBHs (no dust bias)

Nearby galaxy sample

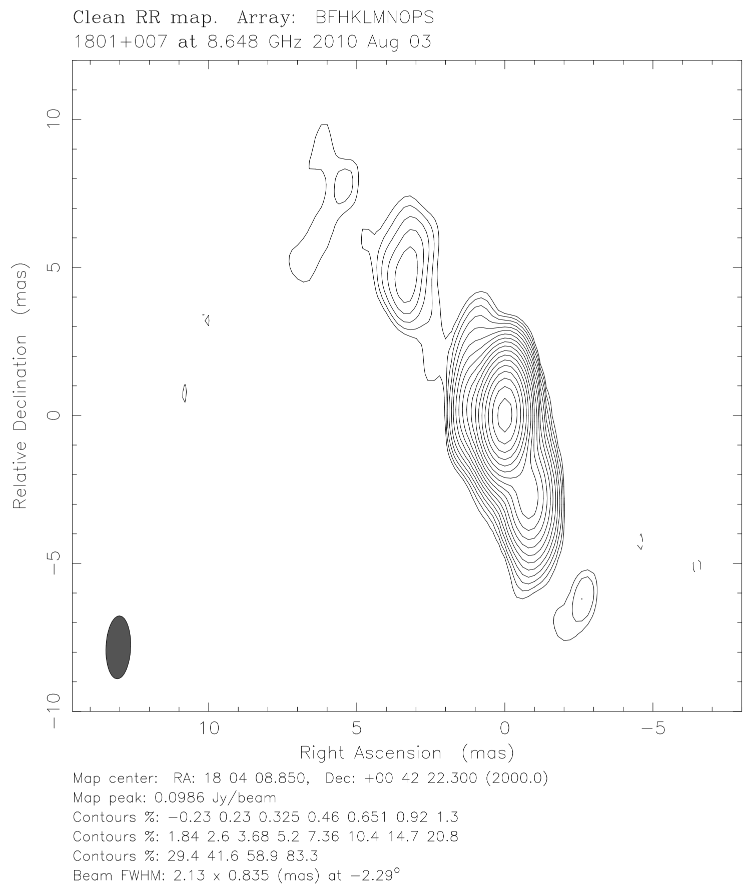
2MASS $K_{20fe} < 12.25$
NVSS $S_{1.4} > 100$ mJy
$\delta \geq -40°$, $|b| \geq 5°$
$N = 923$ galaxies

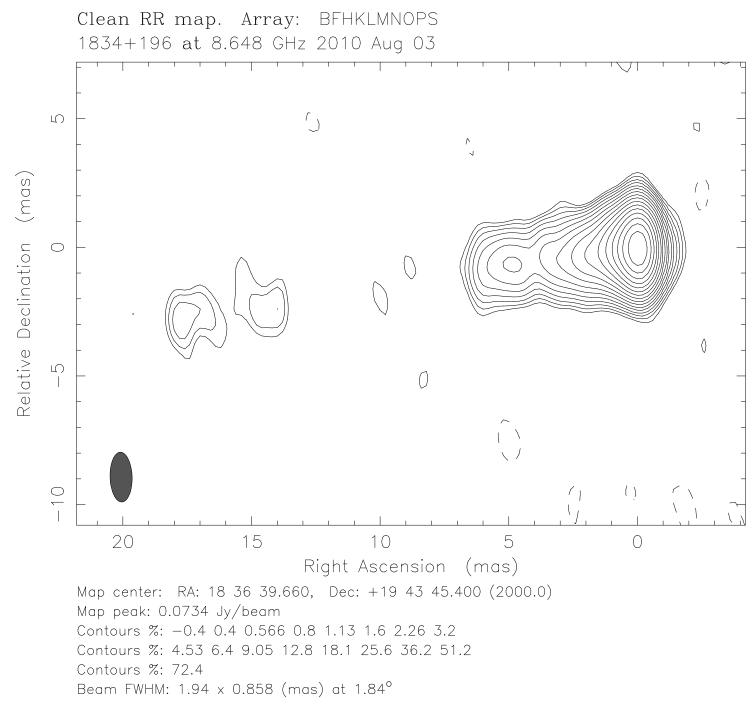
$\langle D_A \rangle \sim 200$ Mpc so
1 mas ~ 1 pc
$\langle L_{1.4} \rangle \sim 10^{24}$ W Hz^{-1}
> 90% are radio-loud AGN



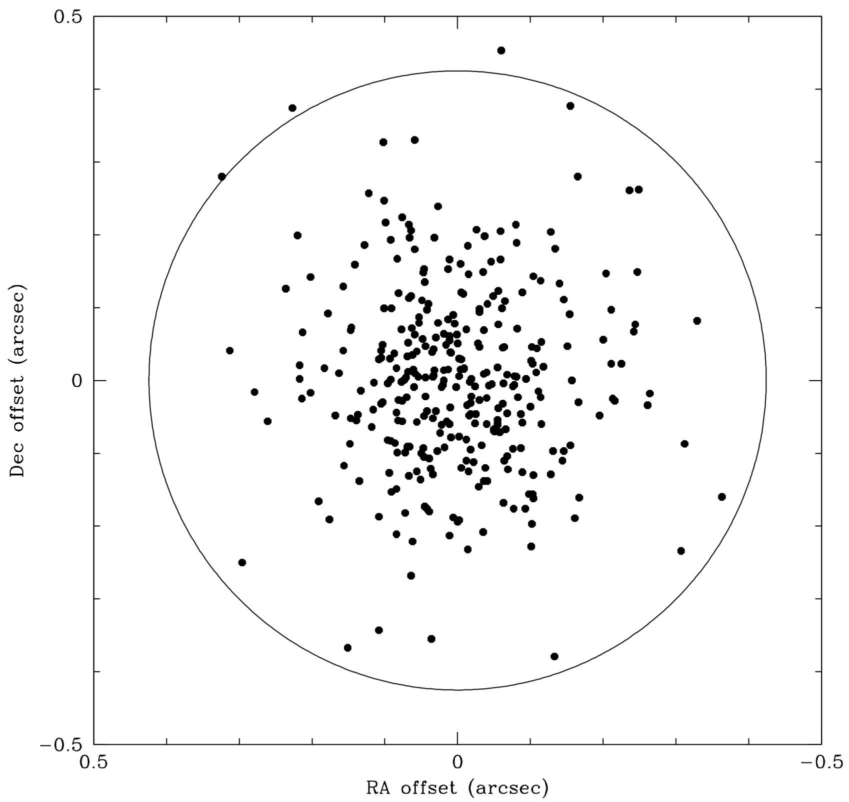
$\delta \geq -40°$, $|b| \geq 5°$

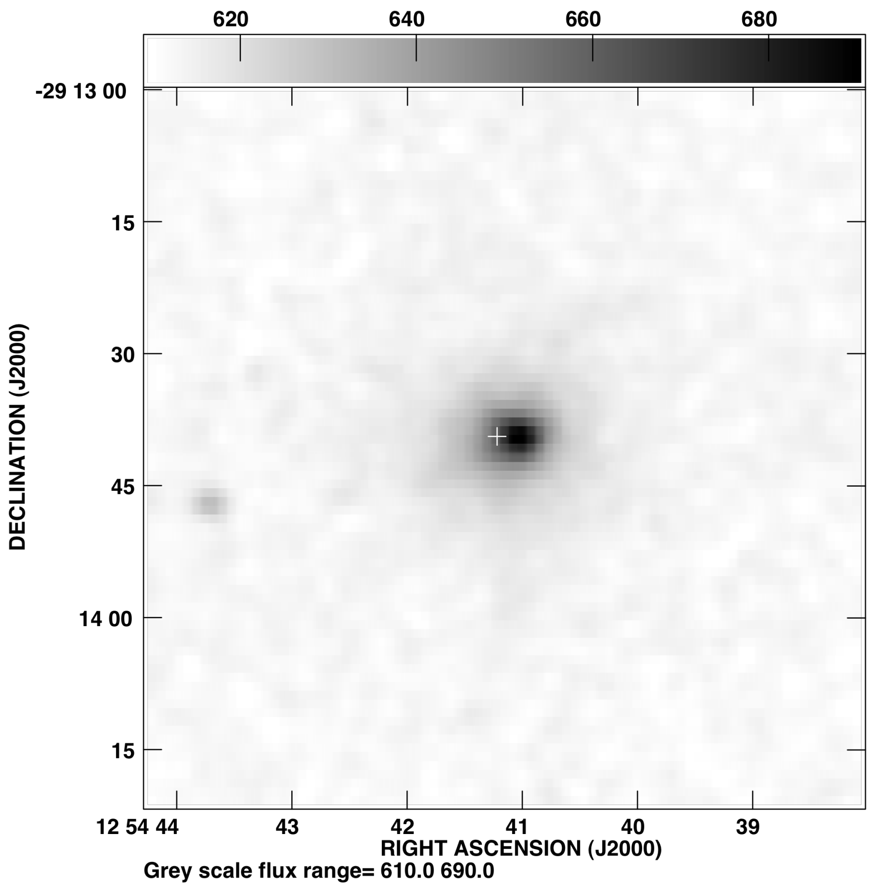
The VLBA observations





First results





Summary

Black holes regulate the growth and evolution of galaxies.

Accurate masses of black holes in disk galaxies were measured via classical physics and modern technology.

They fall below the linear black hole/bulge mass relation for massive elliptical galaxies, as expected.

The maser galaxies contain supermassive black holes, not just dense star clusters.

Galaxy mergers yield inspiraling, binary, and recoiling black holes that may be detectable in current surveys.