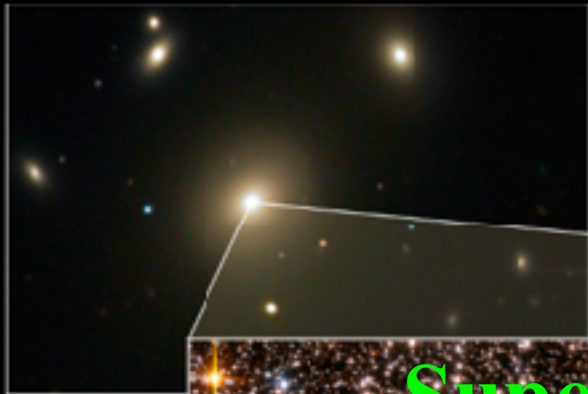
Supermassive Black Holes and Gravitational Waves



Chung-Pei Ma
University of California, Berkeley

Talk Outline

1. **Motivations for studying supermassive black holes**

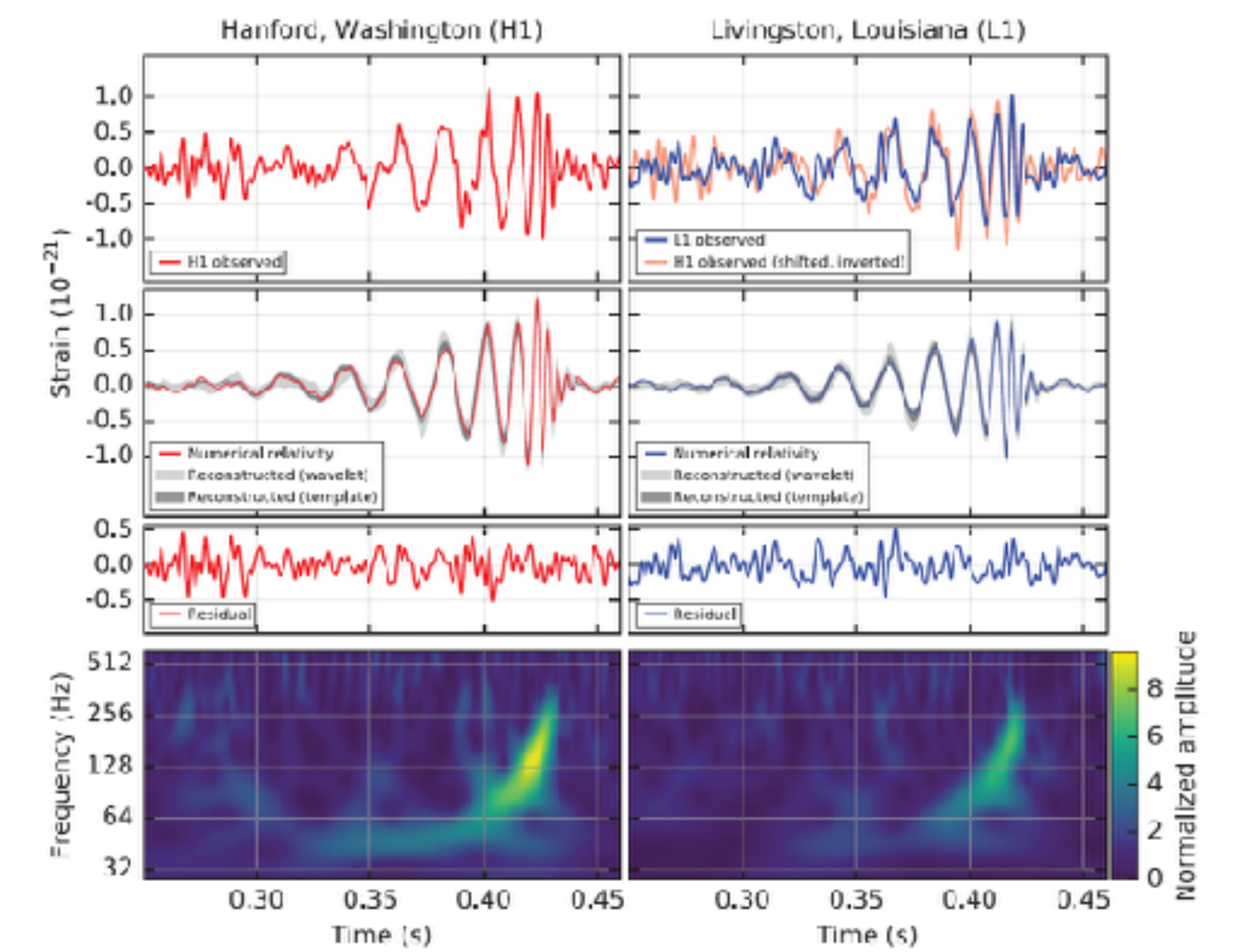
2. **Observational challenges & the MASSIVE survey**

3. **Black hole mass & galaxy scaling relations**

4. **Binary black holes & gravitational waves**

Where are black holes found?

1. Deaths of Massive Stars



Black hole binary
36 + 29 M_{sun}

Remnant
62 M_{sun}

LIGO+Virgo (2016, *PRL*)

Where are black holes found?

2. Centers of Galaxies

Boehle, Ghez et al (2016)
Genzel et al (2010)

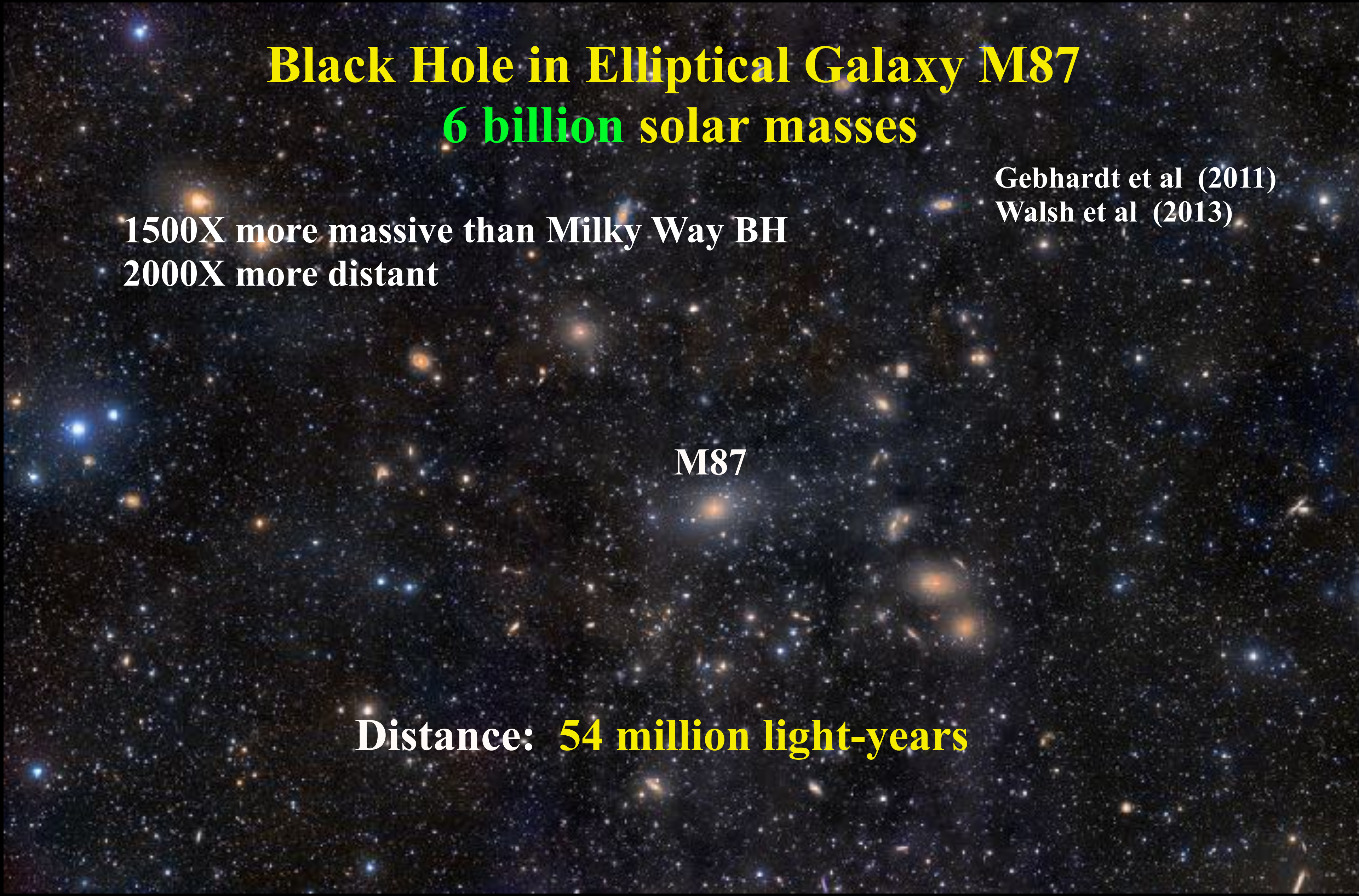
Milky Way: $M_{BH} = 4$ million M_{sun}

Distance: 25,000 light-years

Black Hole in Elliptical Galaxy M87
6 billion solar masses

Gebhardt et al (2011)
Walsh et al (2013)

1500X more massive than Milky Way BH
2000X more distant



Distance: 54 million light-years

THE ASTROPHYSICAL JOURNAL, 221:731–744, 1978 May 1

M87 was the most massive known (nearby) BH for 34 years.

DYNAMICAL EVIDENCE FOR A CENTRAL MASS CONCENTRATION IN THE GALAXY M87

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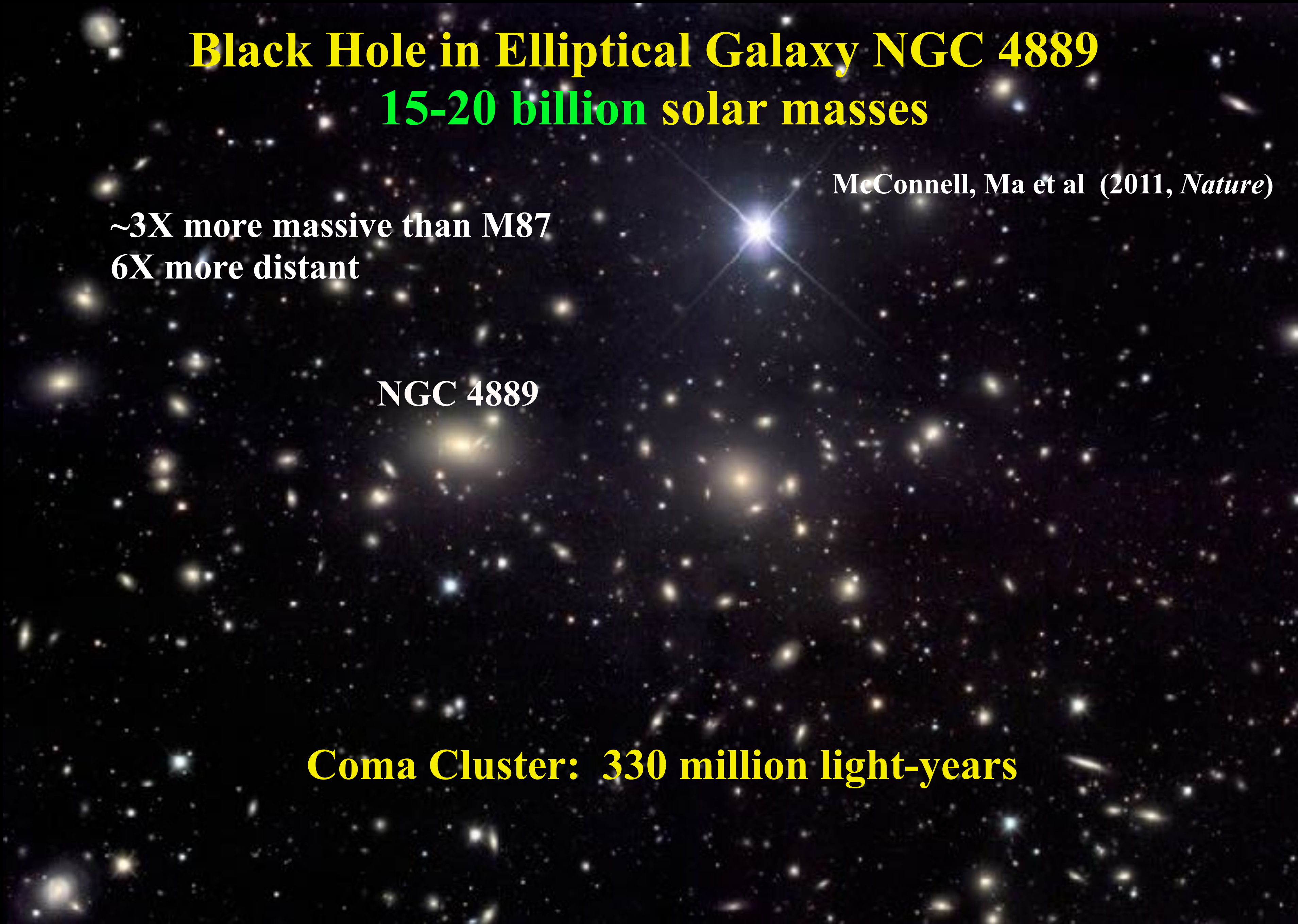
ABSTRACT

The elliptical galaxies NGC 3379 (E1) and M87 (E0) have been observed spectroscopically with the University College London Image Photon Counting System. Analysis of the redshifts and velocity dispersions as a function of radius by a Fourier method has yielded the following results: (*a*) NGC 3379 exhibits slight rotation ($v_\theta = 15$ km s^{-1} at $r = 14''$) along the N-S direction (22° from the minor axis). The velocity dispersion is 195 km s^{-1} for $r < 14''$; this shows a small decrease with increasing radius. The data, including the photometric profile, is adequately fitted by a King model with $\log r_T/r_c = 2.20$ and constant $M/\mathscr{L} = 6$ for $0'' < r < 14''$ (with $r_c = 2''.8$). (*b*) M87 shows no rotation ($v_\theta < 10$ km s^{-1}) for $r < 72''$ in the E-W direction. The velocity dispersion at the edge of the core ($r_c = 9''.6$) is 278 km s^{-1}, but decreases to 230 km s^{-1} when $r = 72''$. Inside the core a sharp increase is observed, up to 350 km s^{-1} at $r = 1''.5$. The photometric profile and velocity dispersion data outside the core are explained by a King model with $M/\mathscr{L} = 6.5$ and $\log r_T/r_c = 2.10$. The data inside the core radius can be explained by a central mass concentration $M = 5 \times 10^9 M_\odot$ contained within $r = 1''.5$ ($= 110$ pc). For $r < 1''.5$ we find $M/\mathscr{L} = 60$, a factor of 10 higher than that in the outer regions. The observed width (1500 km s^{-1} [full width at zero intensity]) of the [O II] λ3727 doublet also suggests a central mass of ~$5 \times 10^9 M_\odot$.

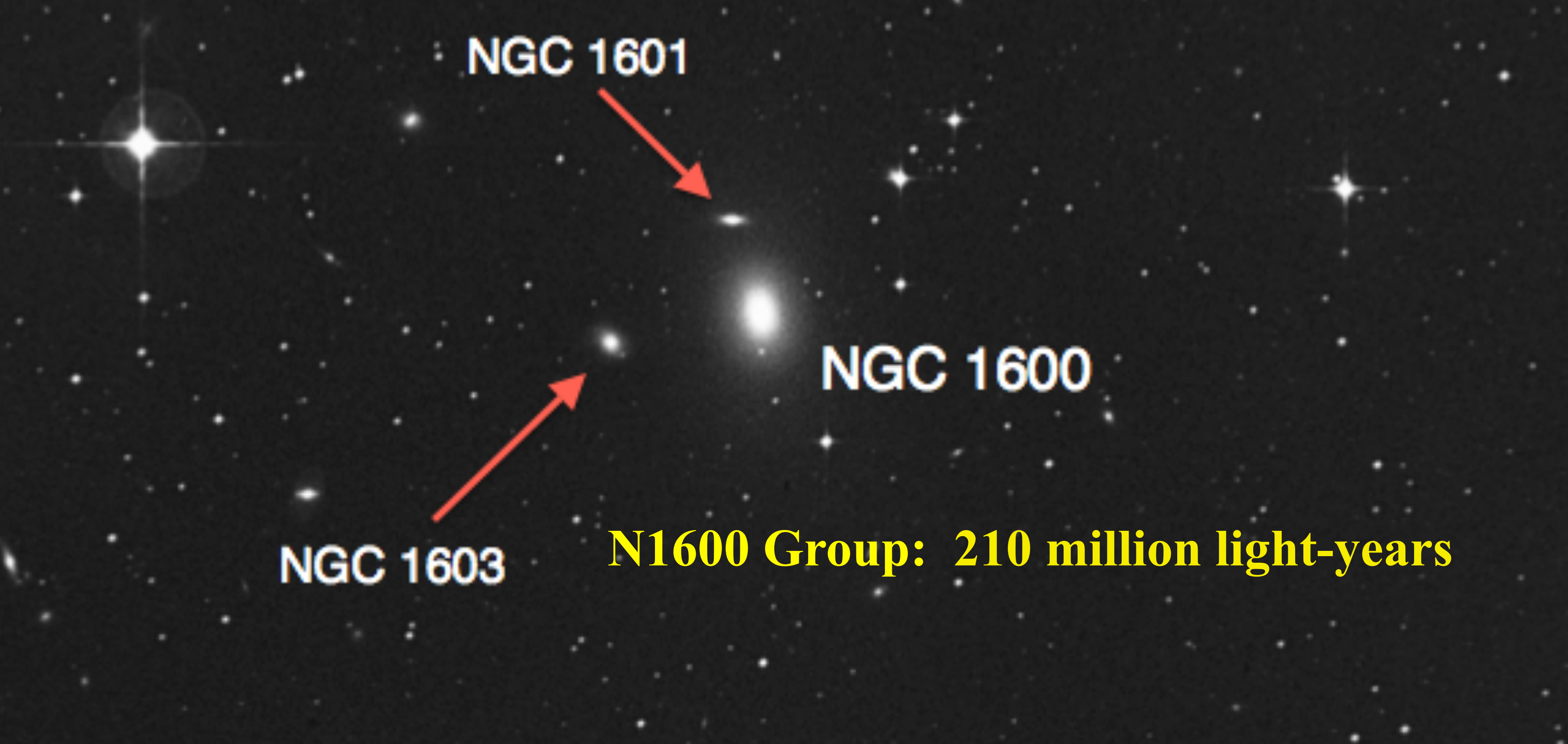
We conclude that the observations of M87 are entirely consistent with the presence of a central black hole of ~$5 \times 10^9 M_\odot$.


Black Hole in Elliptical Galaxy NGC 4889
15-20 billion solar masses
McConnell, Ma et al (2011, *Nature*)
~3X more massive than M87
6X more distant
NGC 4889
Coma Cluster: 330 million light-years

Black Hole in "Isolated" Elliptical Galaxy NGC 1600
17 billion solar masses

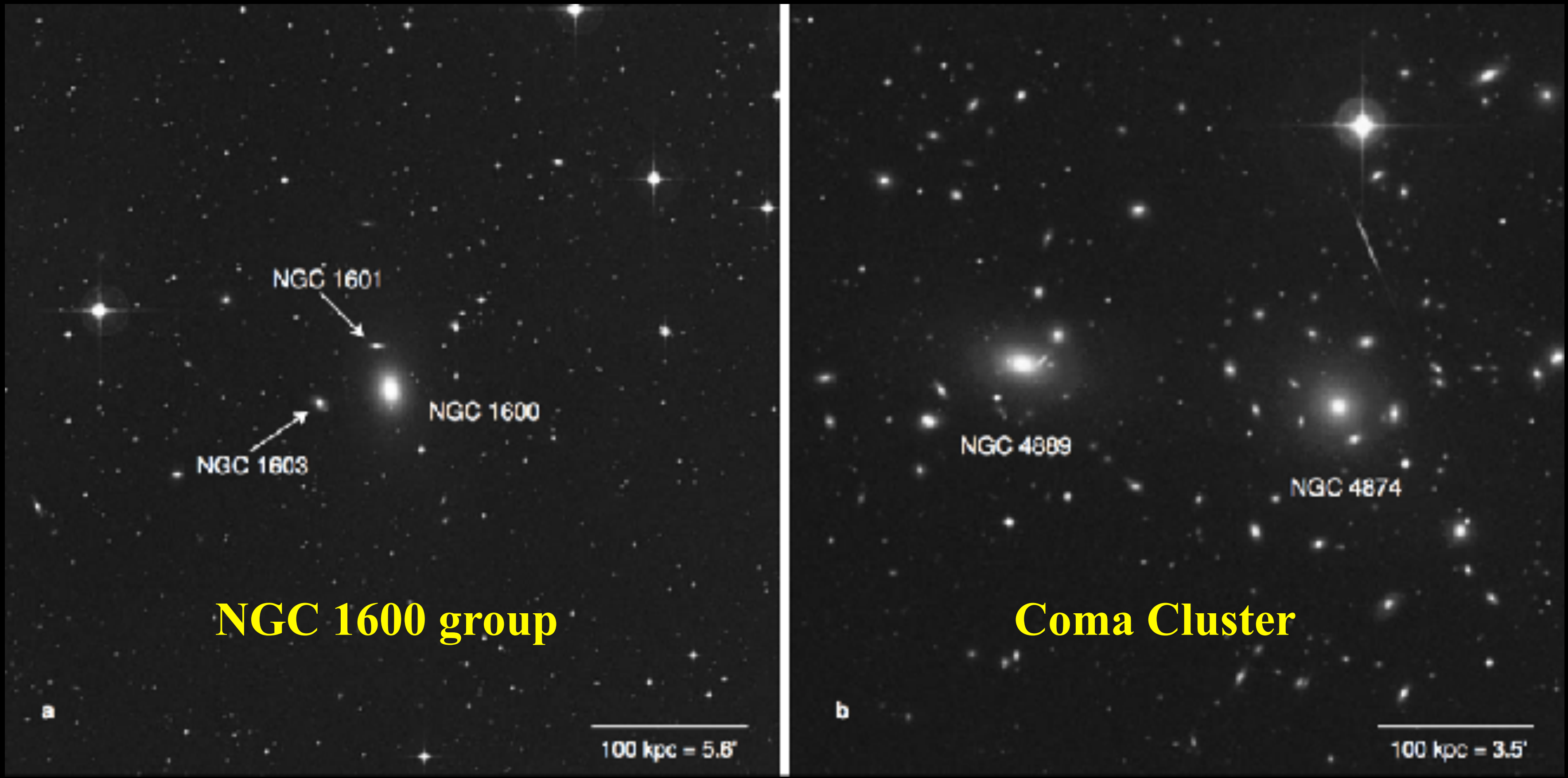
Thomas, Ma et al (2016, *Nature*)

3X more massive than M87
4X more distant



N1600 Group: 210 million light-years

The two most massive black holes reside in different environments



$M_{vir} \sim 1.5 \times 10^{14}$ M_{sun}
$L_x \sim 1000$x lower
Rank 2 galaxy ~3x fainter (fossil-group)
D = 64 Mpc

$M_{vir} = (1.4\text{-}2.7) \times 10^{15}$ M_{sun}
$L_x = 4 \times 10^{44}$ L_{sun}
Rank 2 galaxy similar in L
D = 102 Mpc

Escaping Gravity's Fatal Attraction

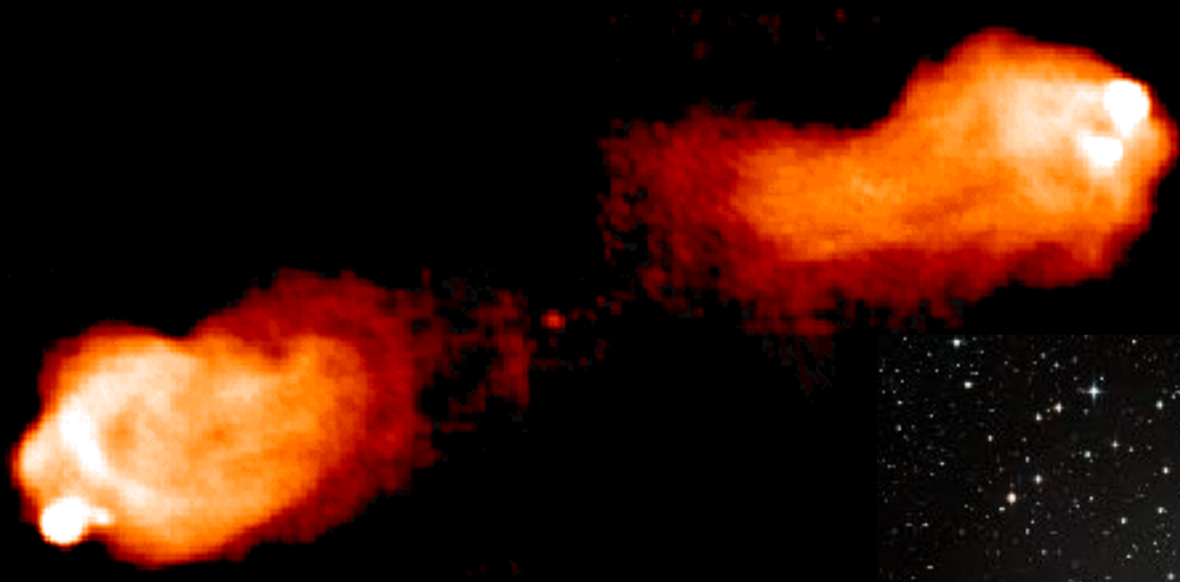
Physical radius of the event horizon

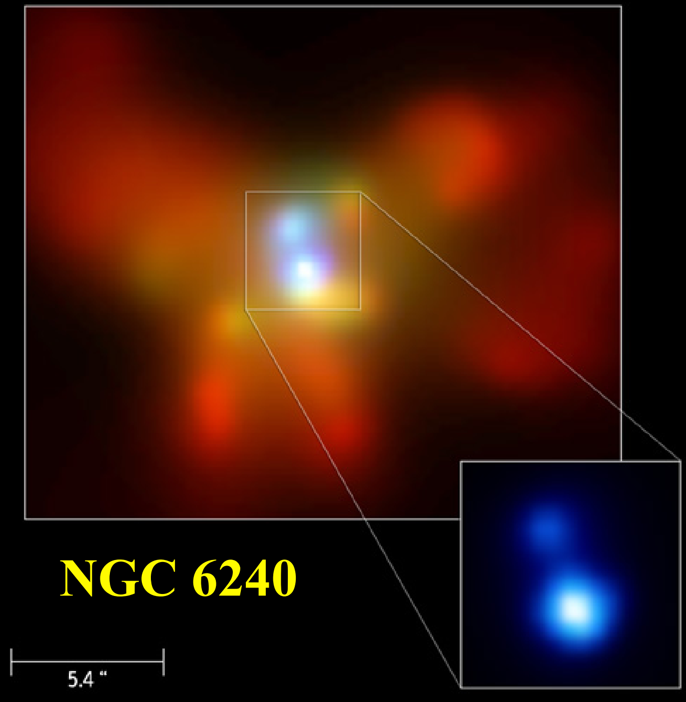
Earth mass	R_{sch} = 1 inch
Sun mass	R_{sch} = 3 km
10-billion solar mass black hole	R_{sch} = 5X the size of the Solar System

Angular size on the sky (Event Horizon Telescope)

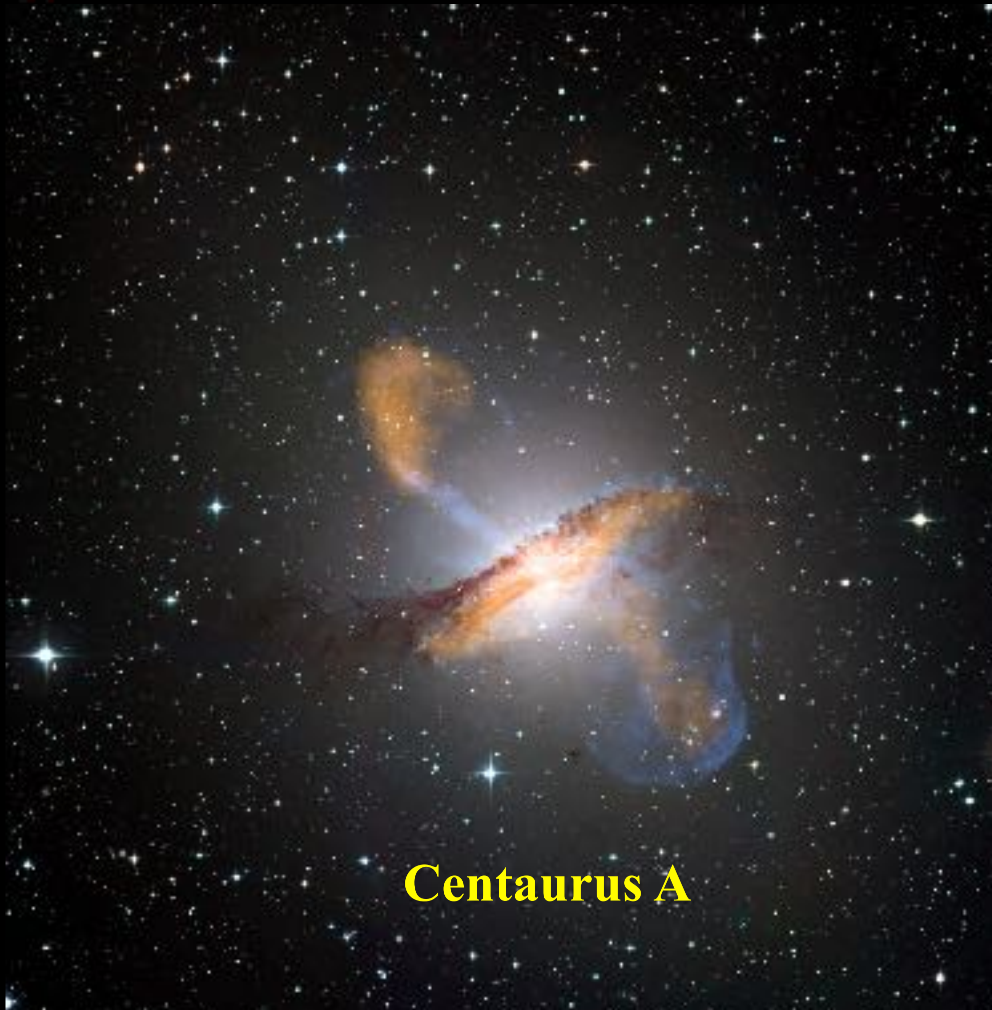
Milky Way BH	10 micro-arcsec
M87 BH	4.1-7.3 micro-arcsec
NGC 1600 BH	5.3 micro-arcsec

Quasars & Active Galactic Nuclei





NGC 6240



Centaurus A

Why study the most massive black holes?
(and their host galaxies)

They are

- Ubiquitous components of galaxies
- Most evolved systems; remnants of minor & major mergers
- Quiescent counterparts of high-redshift luminous quasars
- Sites of AGN feedback and varying IMFs
- Targets for the Event Horizon Telescope
- Sources of low-frequency gravitational waves

Talk Outline

1. **Motivations** for studying supermassive black holes

2. Observational **challenges** & the **MASSIVE** survey

3. **Black hole mass** & **galaxy** scaling relations

4. **Binary** black holes & **gravitational waves**

Why are the biggest black holes hard to find?

Challenge 1

Massive objects are rare

=> Must look farther

=> Harder to resolve stars within
black hole's sphere of influence

$$r = \frac{GM_{BH}}{\sigma^2} \approx 50\,\mathrm{pc}\,\frac{M_{BH}}{10^9 M_\odot}\left(\frac{300\,\mathrm{km\,s^{-1}}}{\sigma}\right)^2$$

0.2 arcsec at 50 Mpc

Past strategy: HST stellar or gas spectra

Why are the biggest black holes hard to find?

330 million light years

Coma Cluster

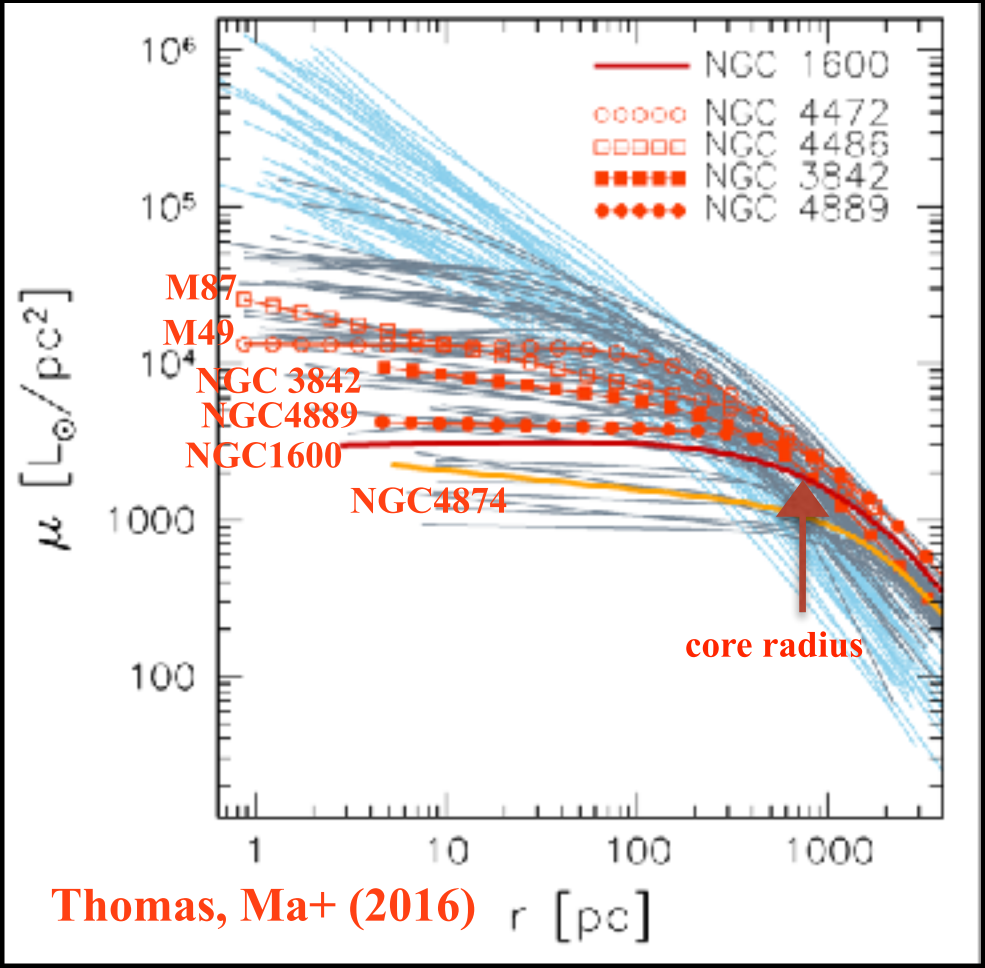
Why are the biggest black holes hard to find?

Challenge 2

Central regions of giant elliptical galaxies are faint

=> Hubble is too small for high S/N spectroscopy !
Need 8-10 meter telescopes

My team:
Gemini/Keck integral-field spectrographs with subarcsec resolution
JWST/30m even better



Ongoing Super-Duper Massive Black Hole Hunt

The MASSIVE Survey

**An integral field spectroscopic (IFS)
and photometric survey
of the ~100 most massive galaxies within ~100 Mpc**

**Volume-limited, target all galaxies (in northern sky)
with $M^* > 10^{11.5}$ Msun**

The MASSIVE Survey

I	Survey paper	Ma +	(2014) ApJ
II	Stellar pop gradient	Greene +	(2015) ApJ
III	Molecular gas	Davis +	(2016) MNRAS
IV	X-ray properties	Goulding +	(2016) ApJ
	Black hole mass	Thomas +	(2016) Nature
V	Stellar kinematics	Veale +	(2017) MNRAS
VI	Ionized gas	Pandya +	(2017) ApJ
VII	λ & environment	Veale +	(2017) MNRAS
VIII	σ radial profile	Veale +	(2018) MNRAS
IX	HST photometry	Goullaud+	(2017) submitted
X	Kinemetry	Ene+	(2017) submitted
	Core kinematics	Ene+	(2018) in prep
	Black hole masses	Ma+	(2018) in prep
	CFHT K-band photometry		
	SBF distances		
	Dynamical mass modeling		
	IMF indicators (4000-10300 å)		
	………..		

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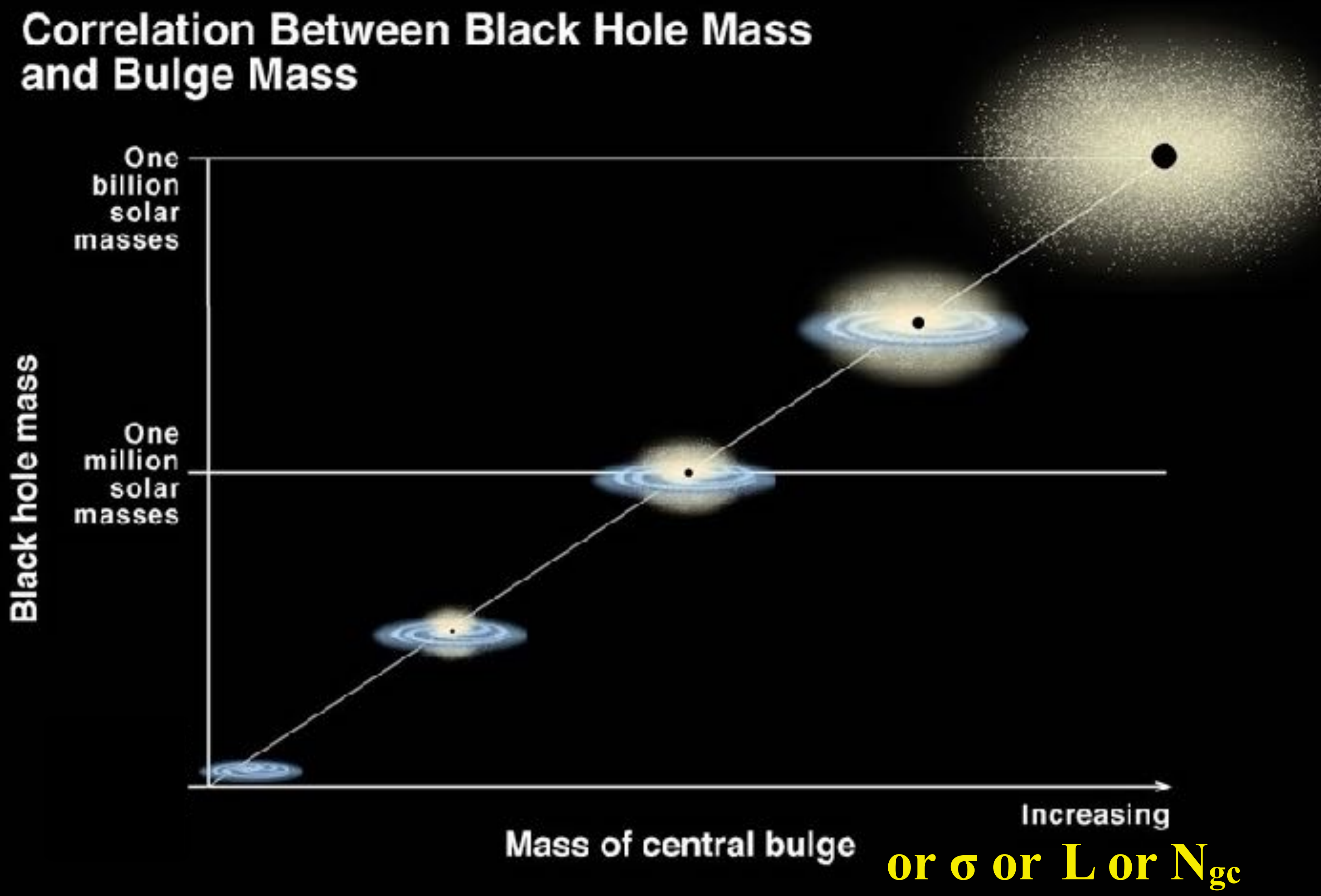


Correlation Between Black Hole Mass
and Bulge Mass
One billion solar masses
One million solar masses
Black hole mass
Increasing
Mass of central bulge
or σ or L or N_{gc}

Real data are messy

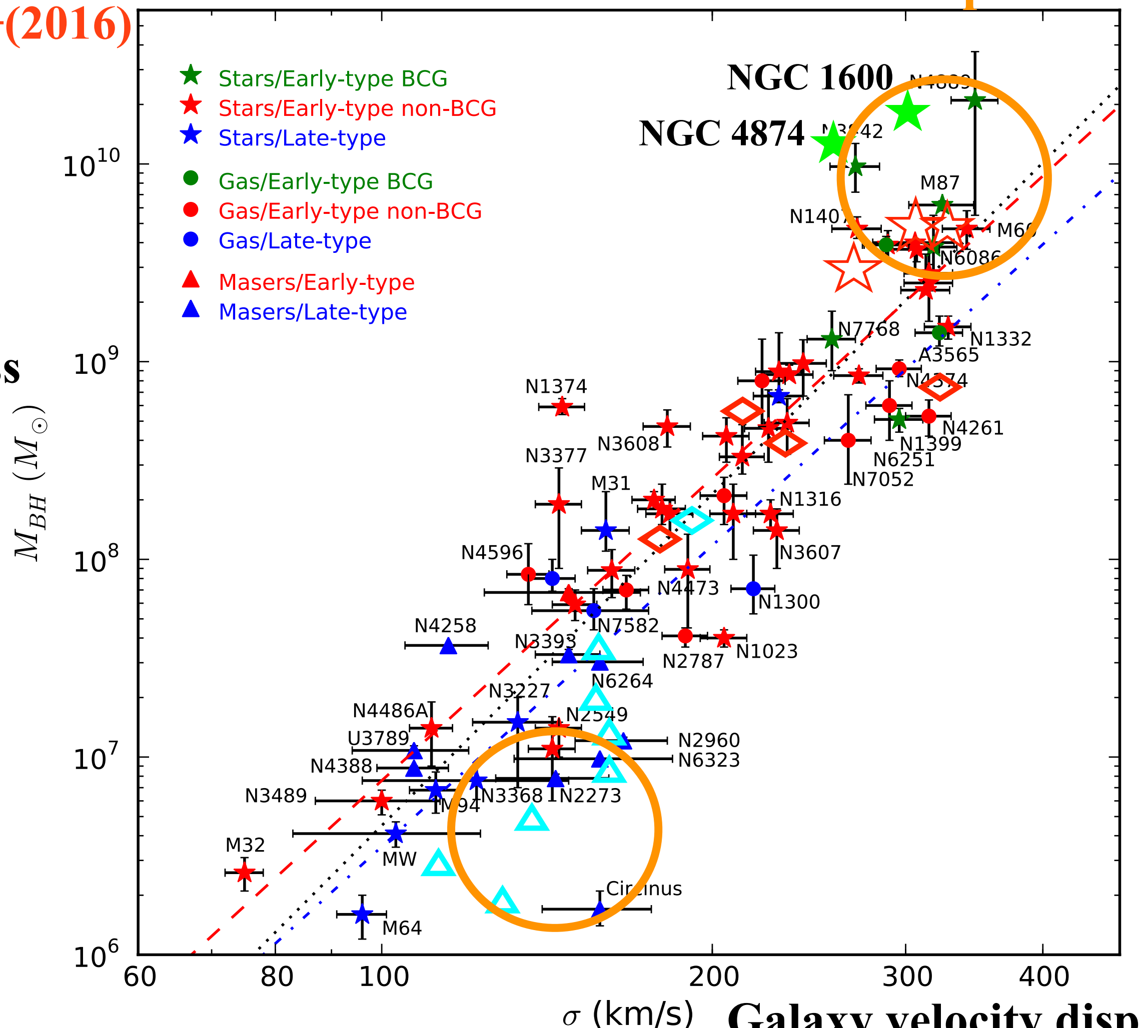
The M_{BH} - σ relation

McConnell & Ma (2013)

Saglia+(2016)

Is σ a good M_{BH} proxy for massive ellipticals?

4.5 dex BH mass



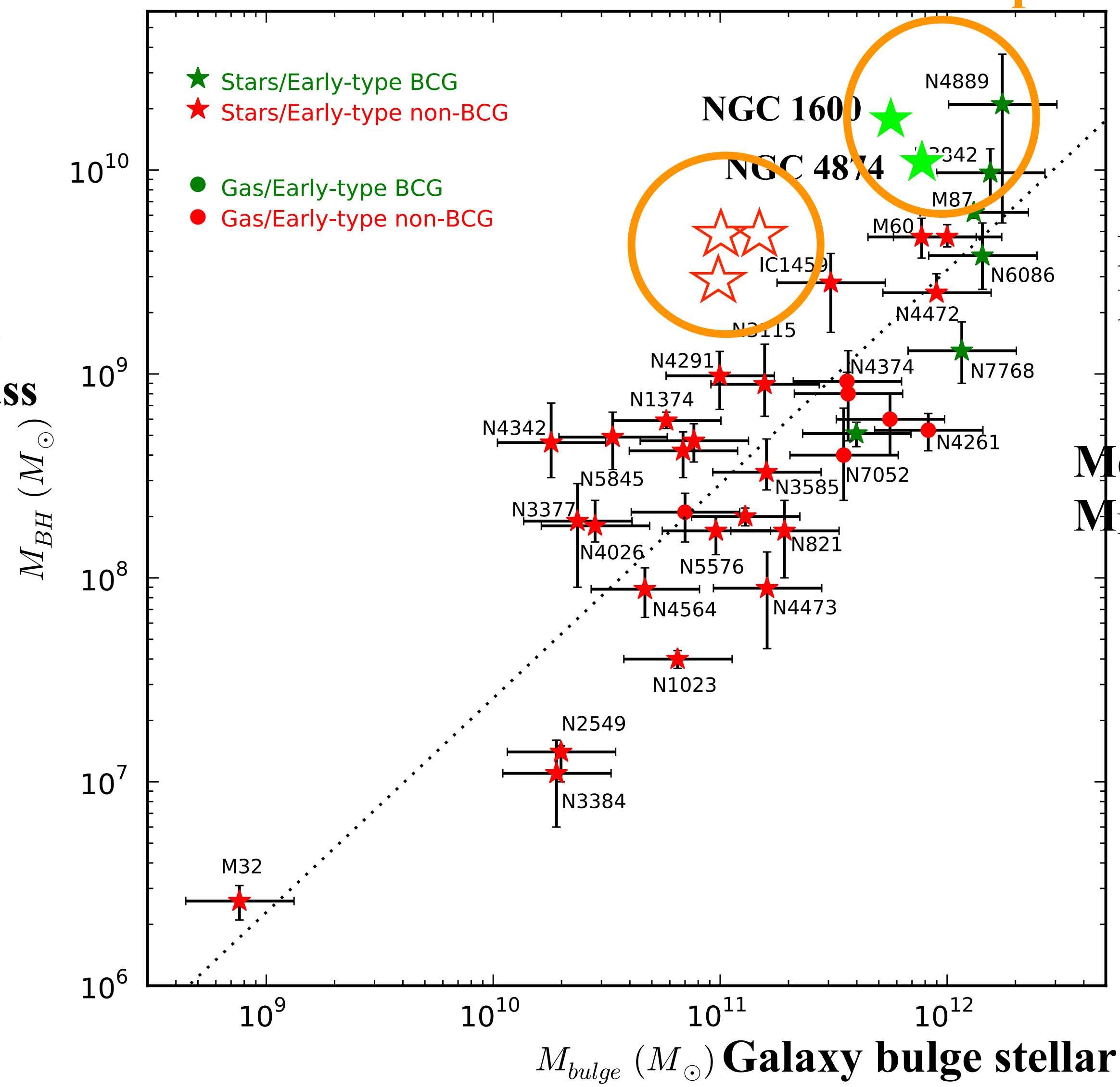
Galaxy velocity dispersion

The M_{BH} - M_{bulge} relation (early-types only)

McConnell & Ma (2013)

Does M_{bulge} work for massive or compact ellipticals?

4.5 dex BH mass



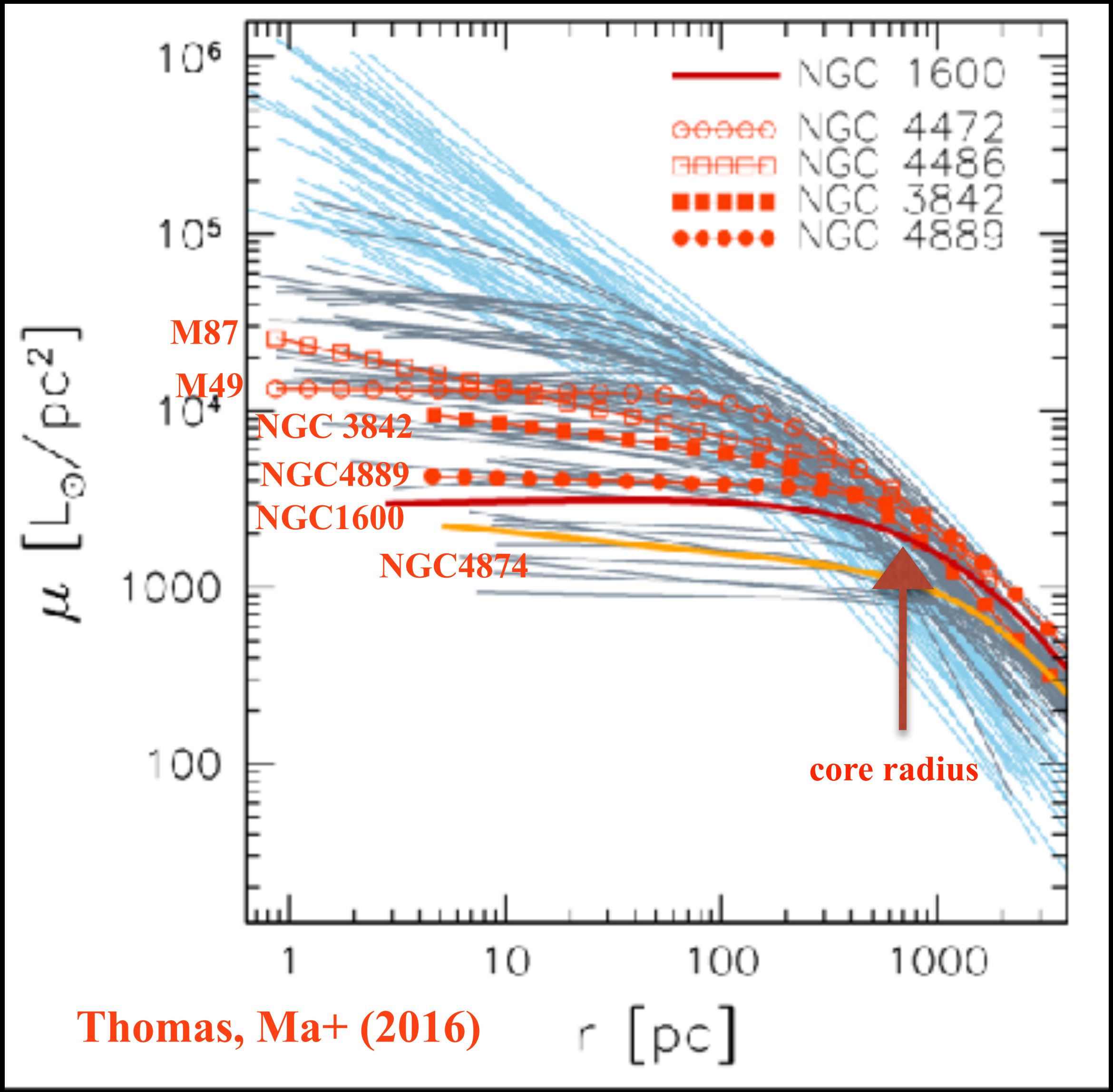
Galaxy bulge stellar mass

NGC 1600
M_{BH}~2%M_{bulge}

Mean relation
M_{BH}~0.2%M_{bulge}

Is M_{BH} correlated with any galaxy property at high mass?

Massive ellipticals have large stellar cores

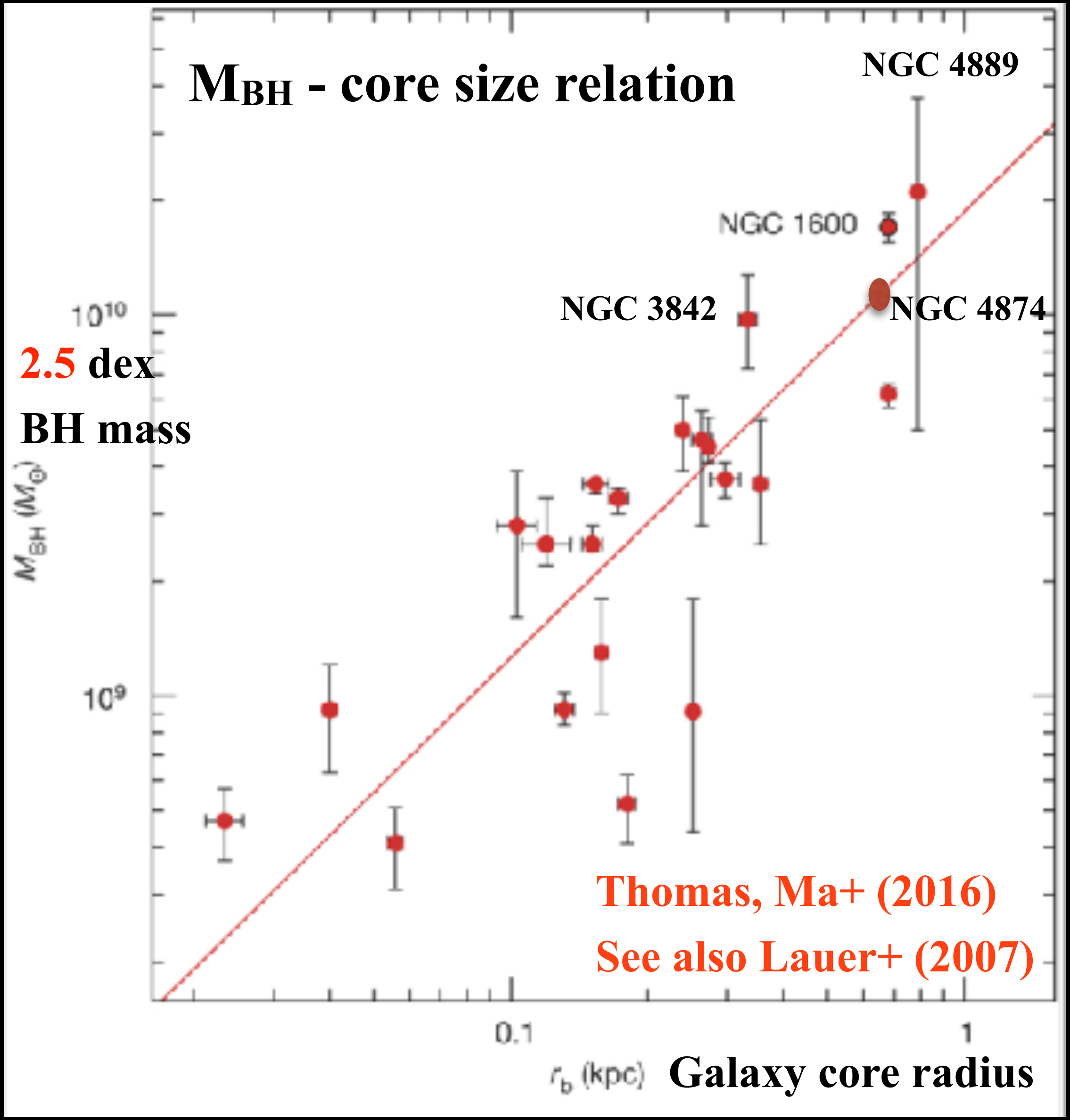


NGC 1600

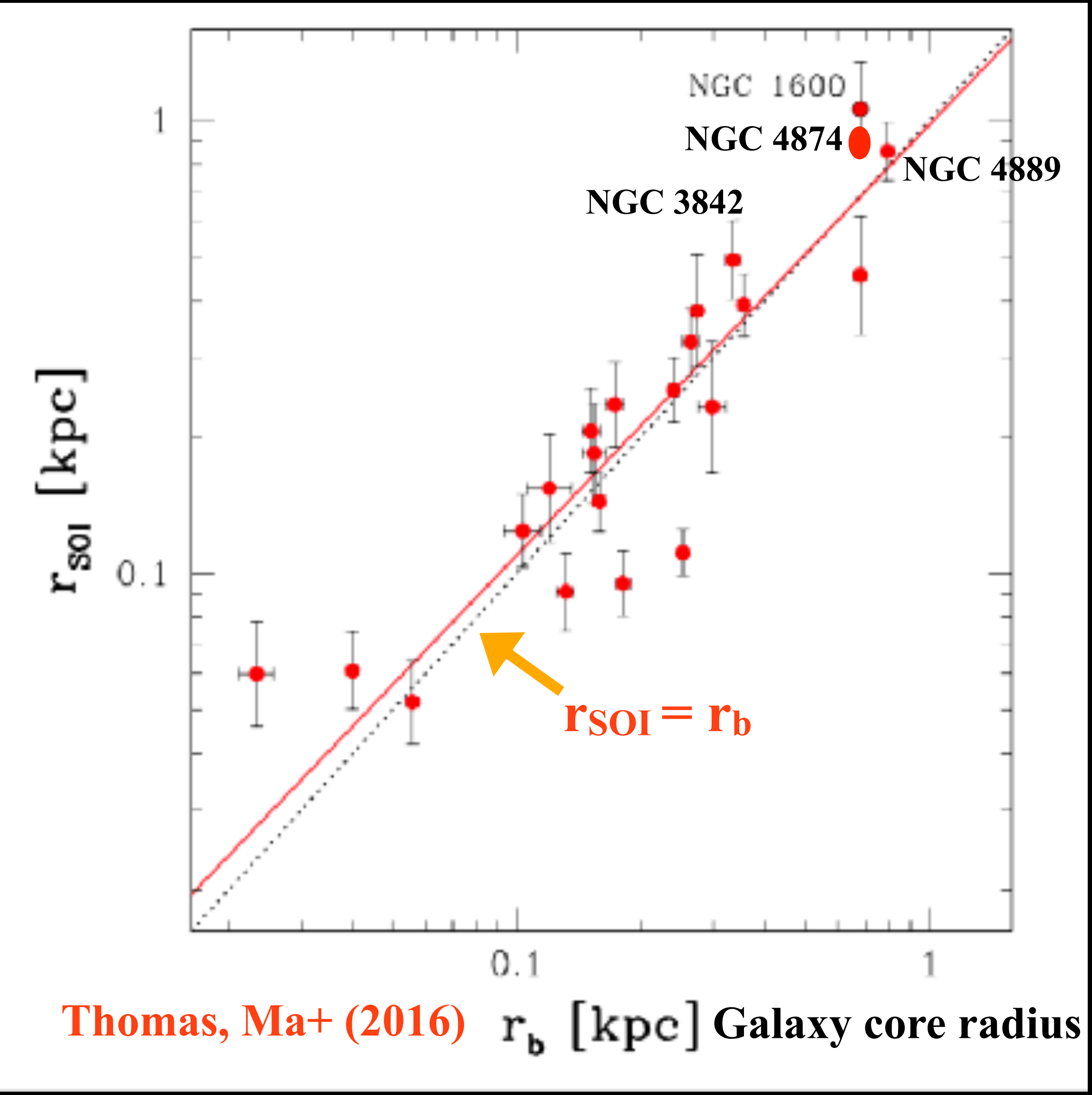
core radius

r_b = 0.7 kpc or 2.3”

M_{BH} correlates better with galaxy core size



New BH scaling relation for cored ellipticals



Black hole's gravity dominates within the sphere of influence

$$M_{BH} = M_*(< r_{SOI})$$

Best-fit is consistent with

$$r_{SOI} = r_b$$

Intrinsic scatter 0.17 dex

=> r_b is better than GM/σ^2 as a predictor for r_{SOI}

Physical Origin of Stellar Cores?

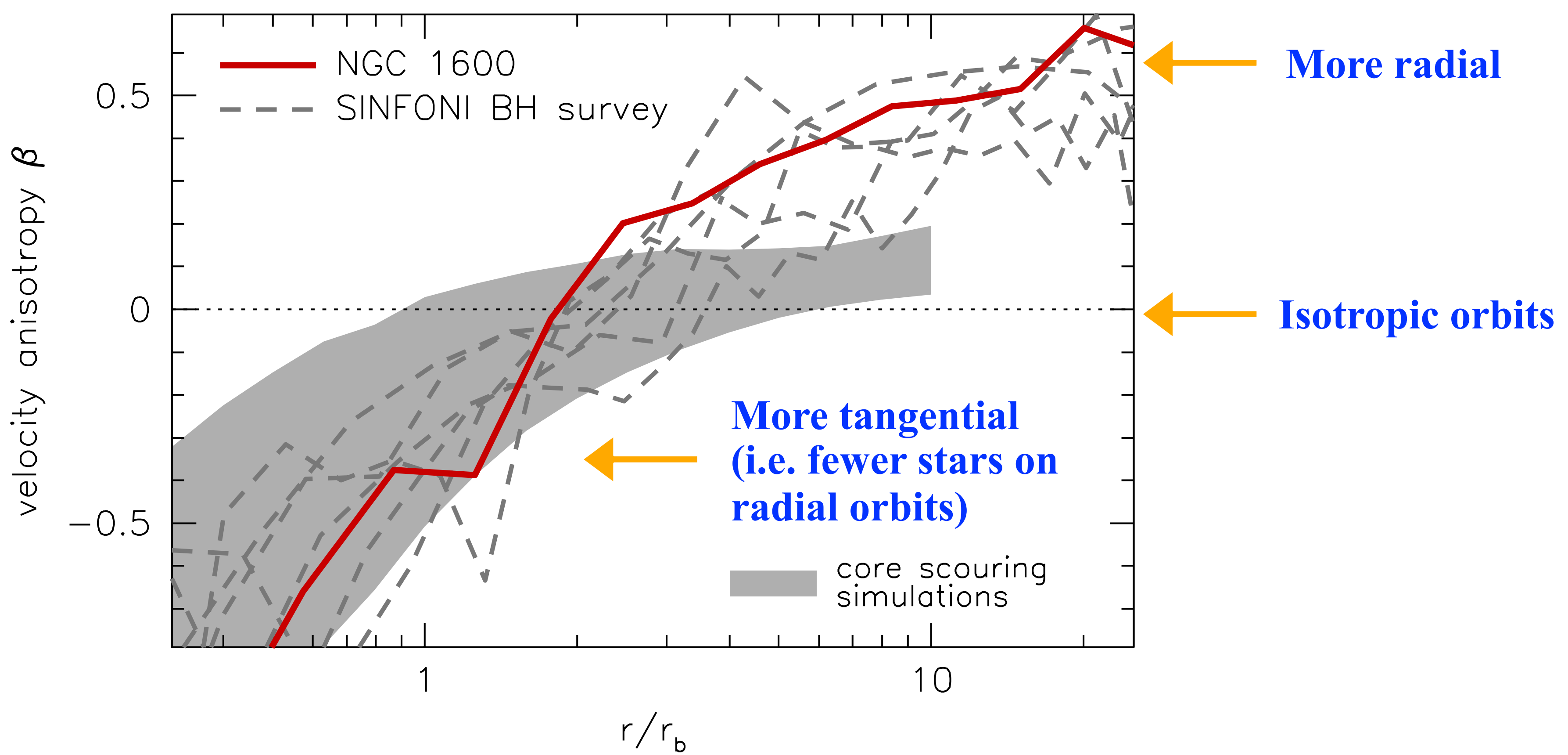
The tight SOI - core radius scaling relation
strongly suggests
black holes created stellar cores

But how?

Binary black hole scouring
Black hole recoil after merger
AGN feedback

A Possible Discriminating Factor:
Stellar orbits are tangential in core regions

$$\beta = 1 - \sigma_t^2/\sigma_r^2 \qquad \sigma_t = [(\sigma_\vartheta^2 + \sigma_\varphi^2)/2]^{1/2}$$



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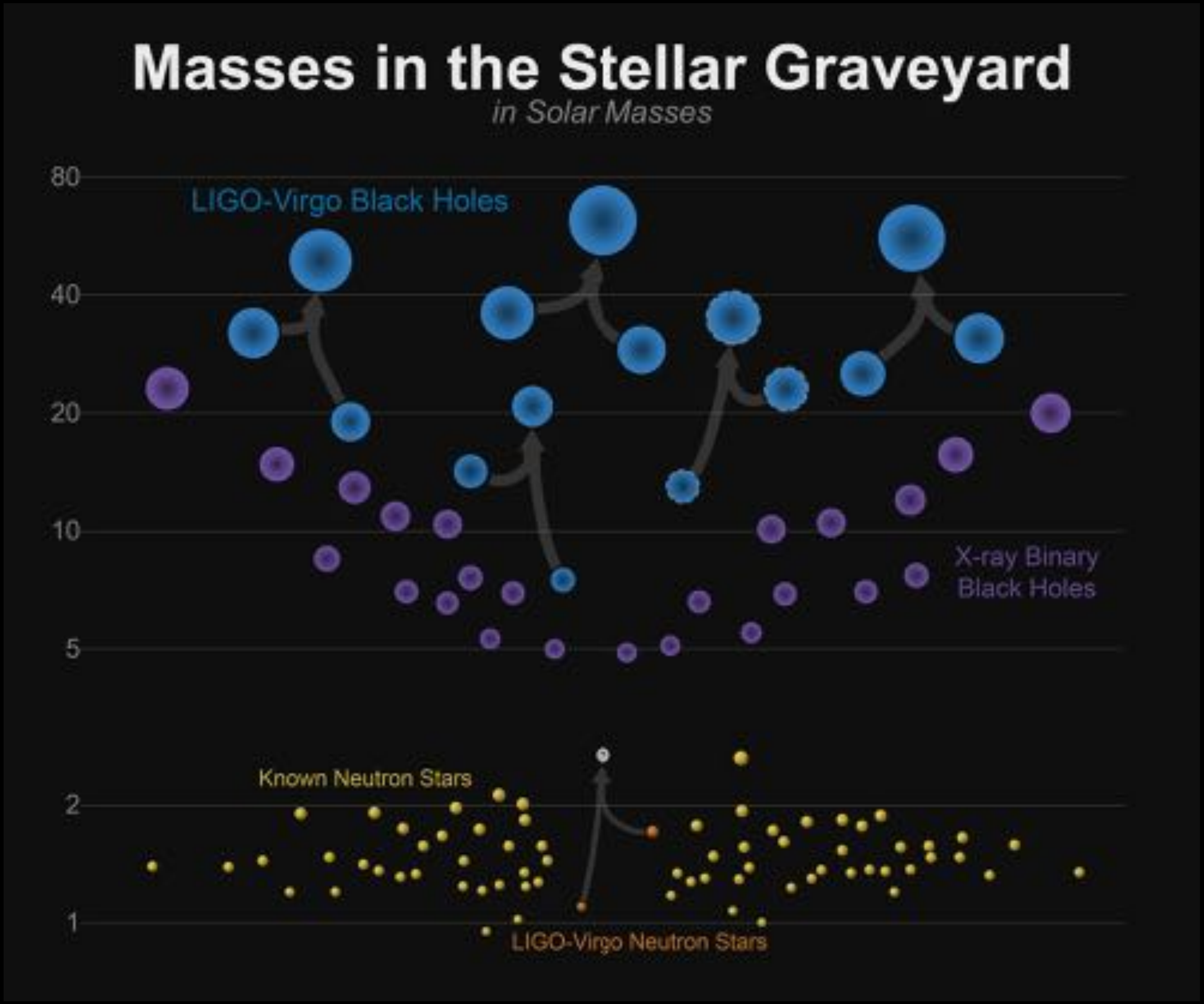
Binary Stellar Black Holes

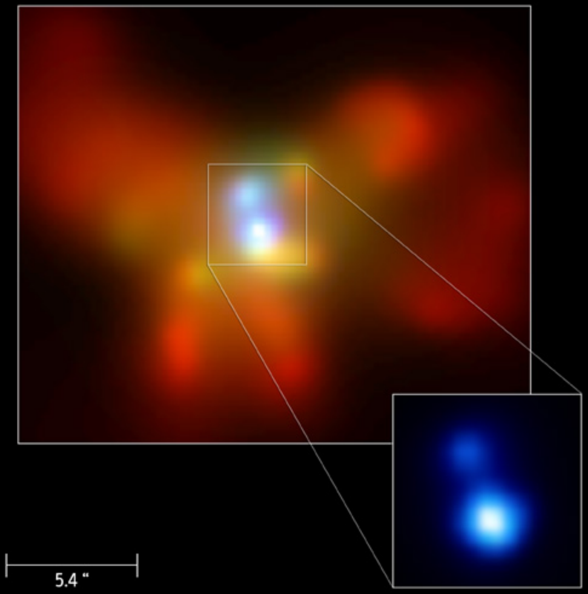
22 X-ray Binaries with dynamical BH masses



Binaries Supermassive Black Hole?

Supermassive Black Hole Binaries?

NGC 6240



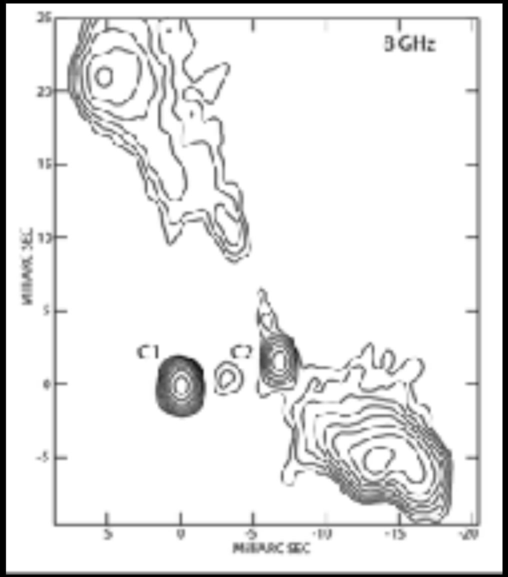
z=0.024 LIRG

Luminous hard X-ray from two cores

Separation 1.4 kpc

Komossa+ (2003)

0402+379



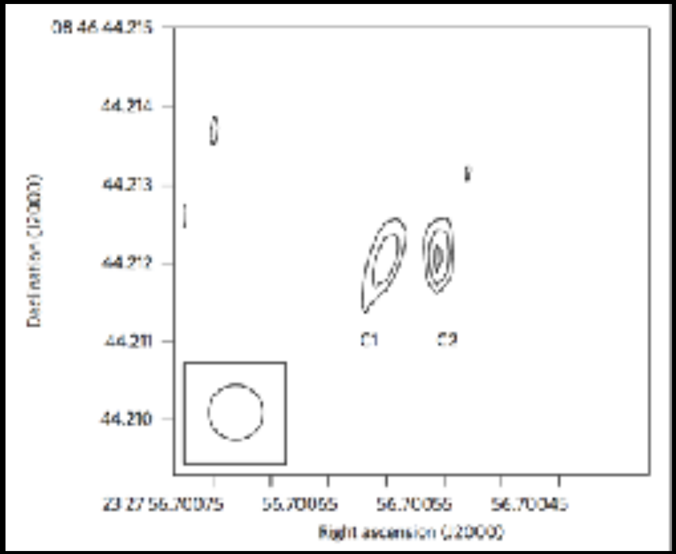
z=0.06 radio galaxy

Two compact radio cores, flat spectrum

Separation 7.3 pc

Rodriguez+ (2006)

NGC 7674



z=0.029 LIRG AGN

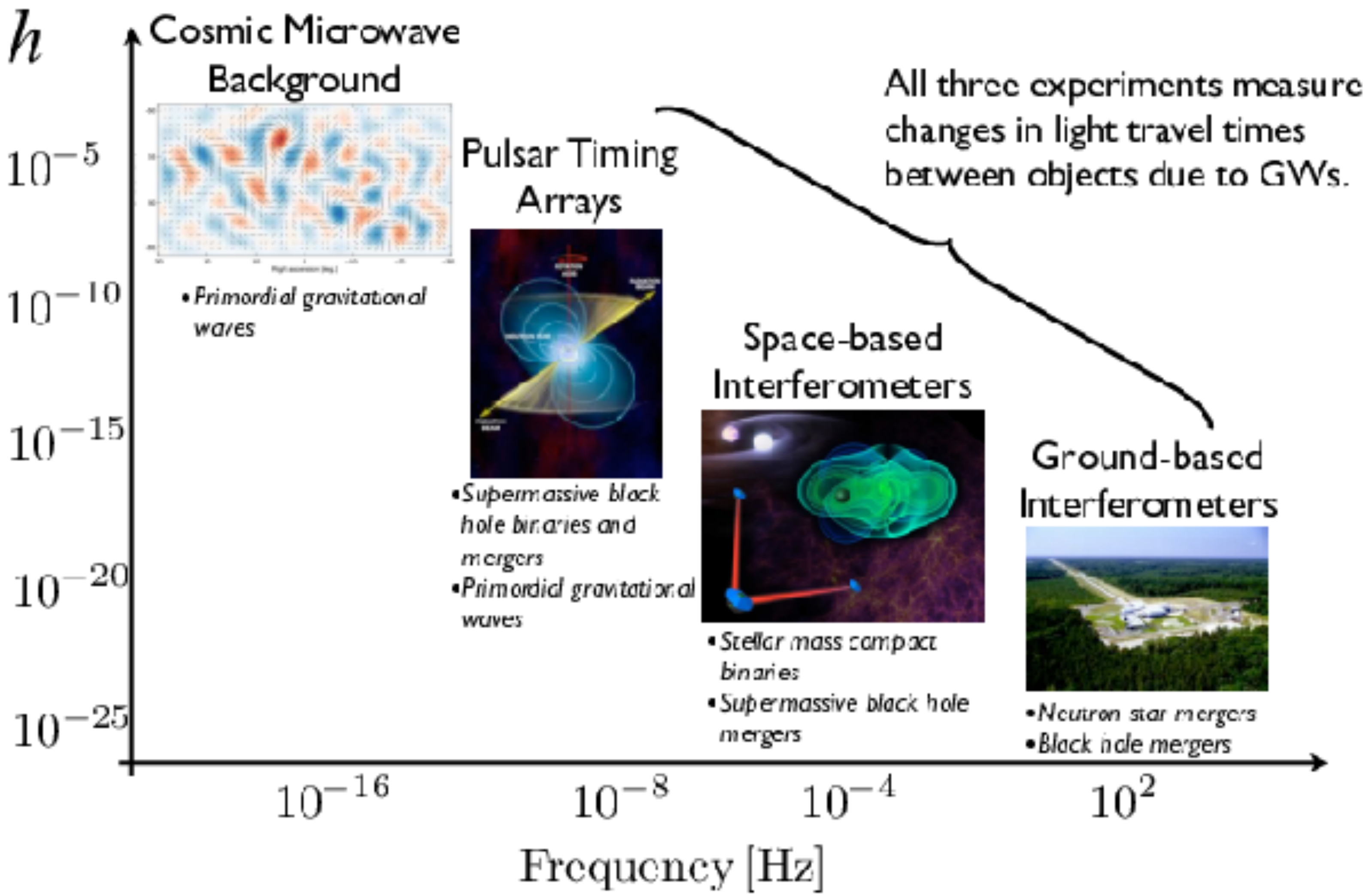
Two compact radio cores

Separation 0.35 pc

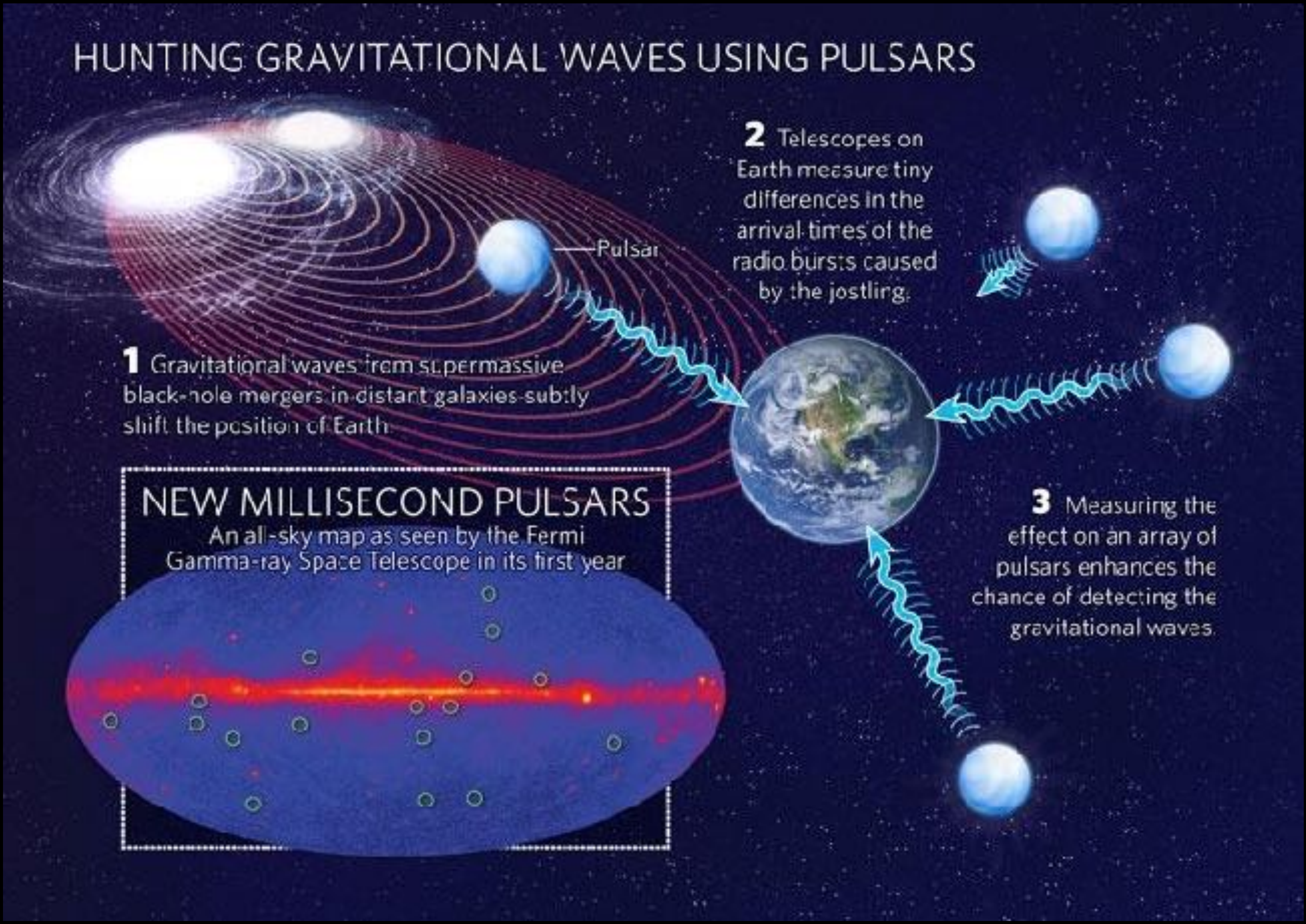
Kharb+ (2017)

NANOGrav

The spectrum of gravitational wave astronomy



Gravitational Waves from Binary Supermassive Black Holes



GW Strain Amplitude

$$h_0 = 2\,\frac{(G\mathcal{M})^{5/3}(\pi f_{gw})^{2/3}}{c^4\,d_L}$$

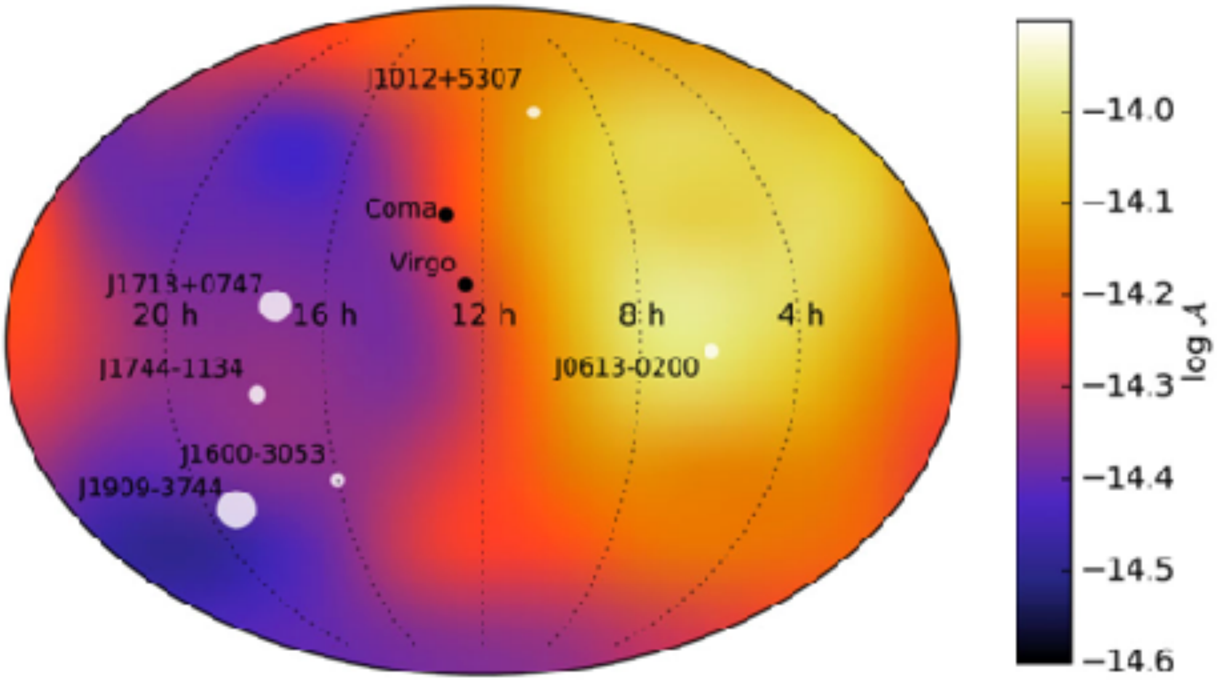
$$h_0 = 2.76\times 10^{-14}\left(\frac{\mathcal{M}}{10^9\,M_\odot}\right)^{5/3}\left(\frac{10\,\mathrm{Mpc}}{d_L}\right)\left(\frac{f}{10^{-8}\mathrm{Hz}}\right)^{2/3}$$

Chirp mass of black hole binary

$$\mathcal{M} \equiv \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = M_\bullet\,\frac{x^{3/5}}{(1+x)^{6/5}}$$

$$x \equiv m_2/m_1 \le 1$$
$$M_\bullet = m_1 + m_2$$

Sensitivity Sky Maps of Continuous GWs



Sky-averaged upper limit @ 10 nHz

$$h_0 < 1.1 \times 10^{-14}$$

EPTA (Babak+ 2016)

Summary

A new population of ultra-massive black holes beyond M87

Not all UMBHs reside at centers of rich clusters

NGC 1600: first extreme M_{BH} outside rich clusters

A rare find or the tip of an iceberg?

M_{BH} above mean $M_{BH} - \sigma$ & $M_{BH} - M_{bulge}$ relations

Why?

New black hole scaling relation:

BH sphere of influence = stellar core radius

BHs created cores. How? Binaries?

Our new hunting strategy: MASSIVE survey + galaxy cores

Looking Ahead

Gravitational Waves
Pulsar Timing Arrays

ΛCDM Cosmology
Physics of black hole & galaxy mergers

MASSIVE Survey
20+ black holes above 10^9 M_{sun}
100 most massive galaxies

Strong-gravity Physics
VLBI Event Horizon Imaging

Galaxy Formation
Gas physics of galaxies/clusters
Stellar IMF
Dark matter