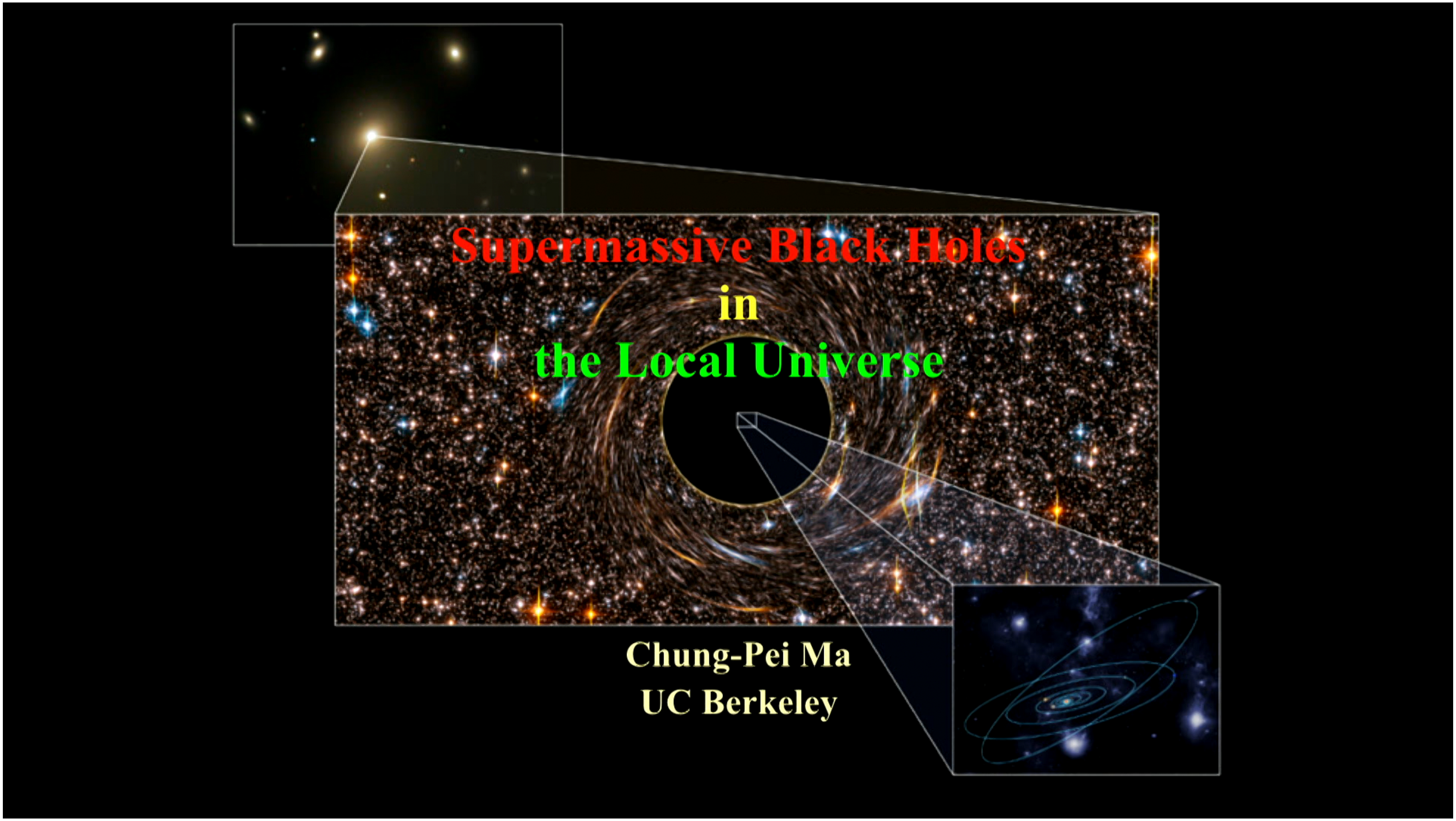
Title: Supermassive Black Holes in the Local Universe

Date: Jan 27, 2017 11:00 AM

URL: http://pirsa.org/17010081

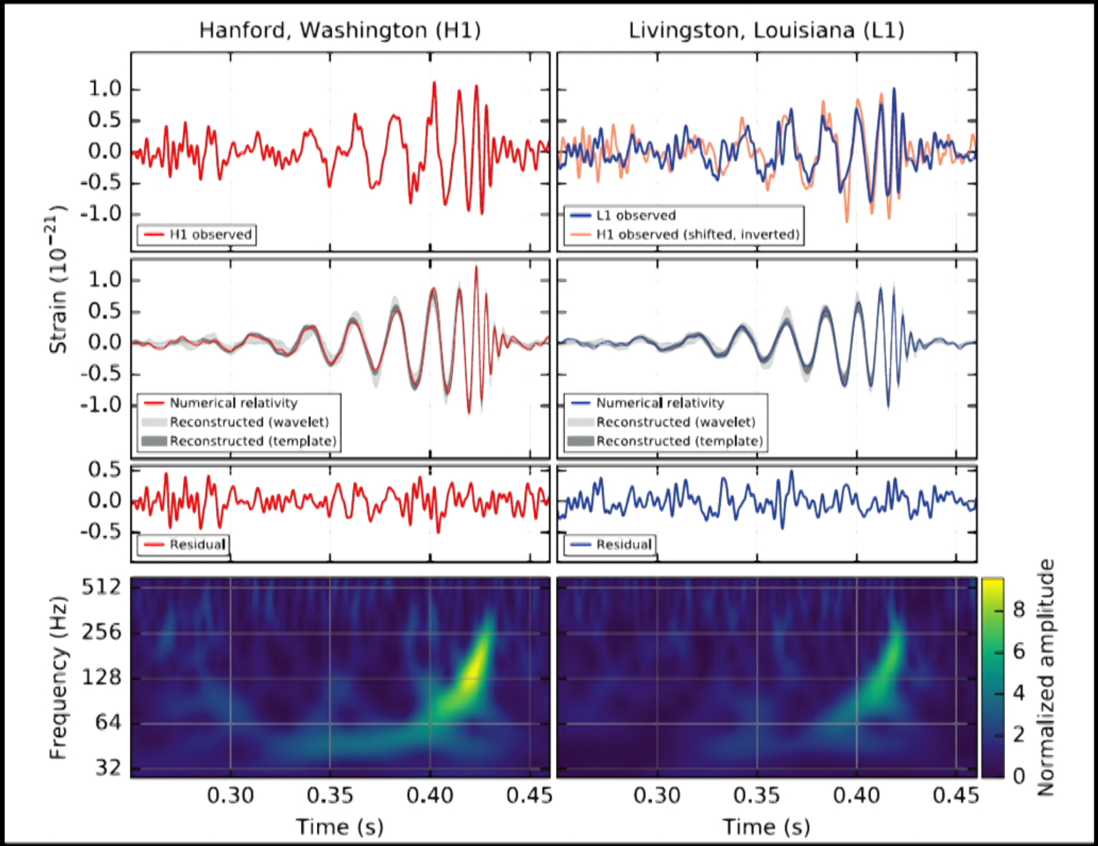
Abstract: <p>Black holes of 1 million to 20 billion solar masses have been found at the centers of galaxies.</p>

<p>New observational data and improved orbit models in the past several years have substantially expanded the sample of black holes with dynamically measured masses. I will describe recent progress in discovering a new population of ultra-massive black holes and its impact on our understanding of the symbiotic relationships between black holes and galaxies. I will discuss the implications for the ongoing pulsar timing array experiments searching for nano-Hertz gravitational waves from merging supermassive black hole binaries.</p>


Supermassive Black Holes
in
the Local Universe
Chung-Pei Ma
UC Berkeley

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?

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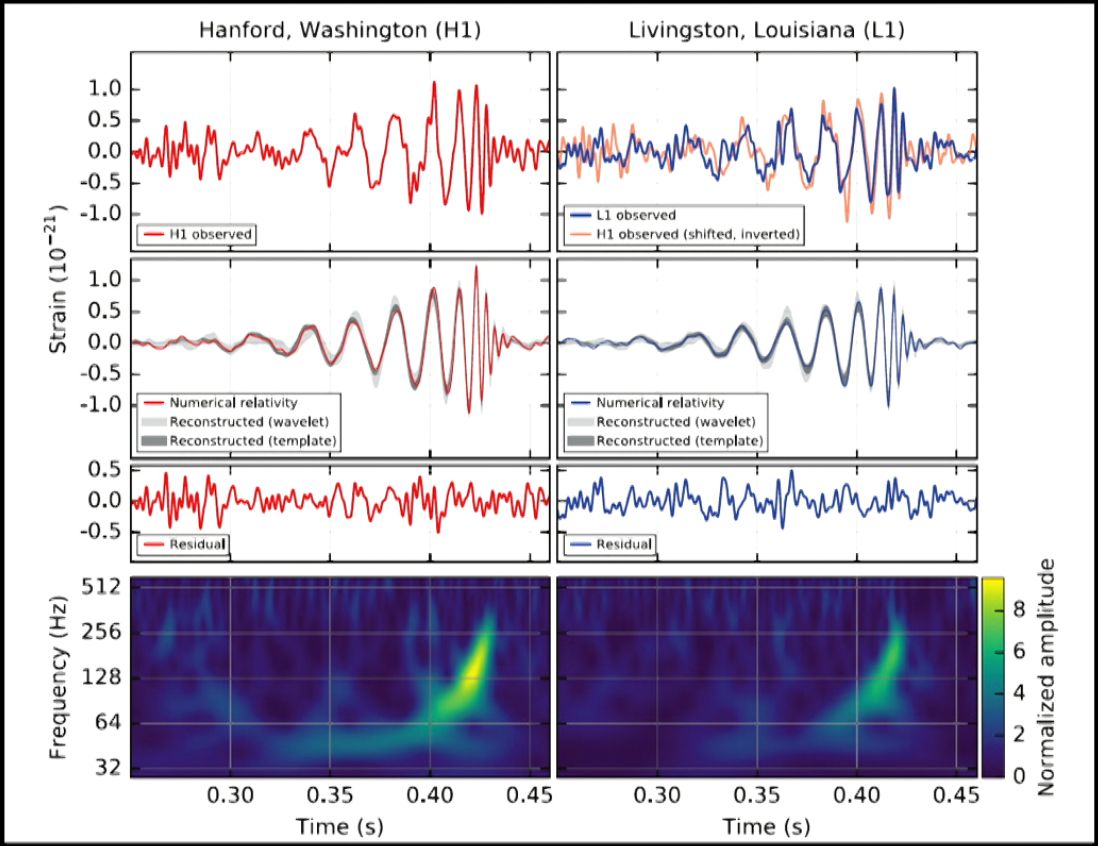


Black hole binary
36 + 29 M_{sun}

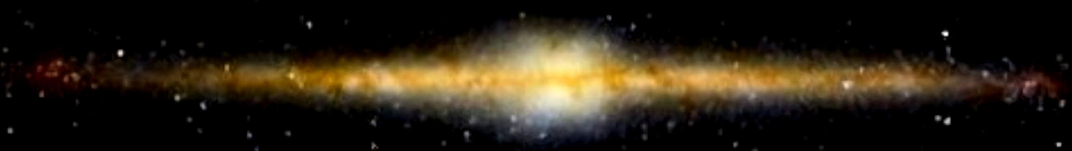
Remnant
62 M_{sun}

LIGO+Virgo (2016, *PRL*)

Where are black holes found?

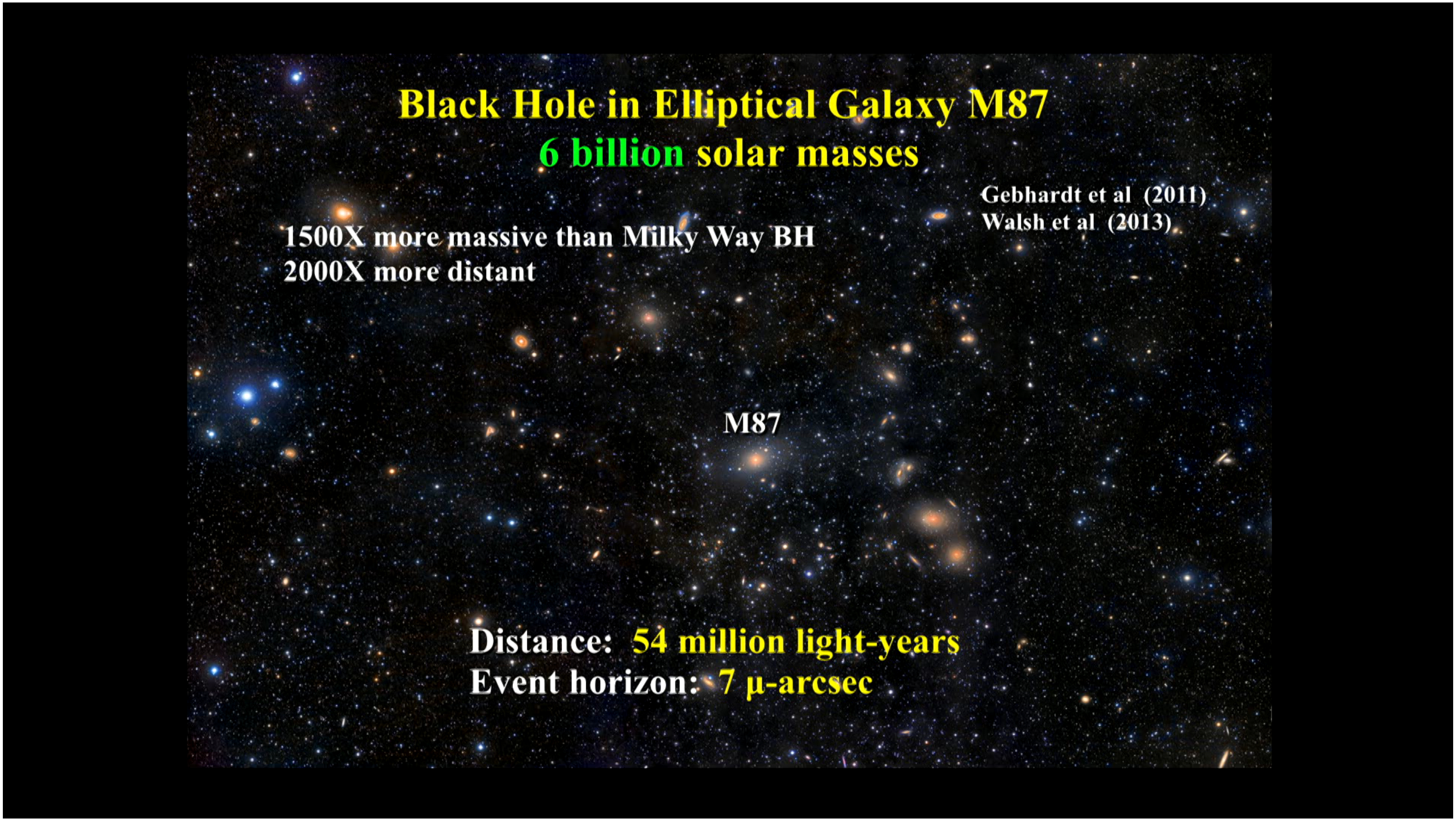
2. Centers of Galaxies

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



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

Distance: 25,000 light-years
Event horizon: 10 μ-arcsec


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
M87
Distance: 54 million light-years
Event horizon: 7 μ-arcsec

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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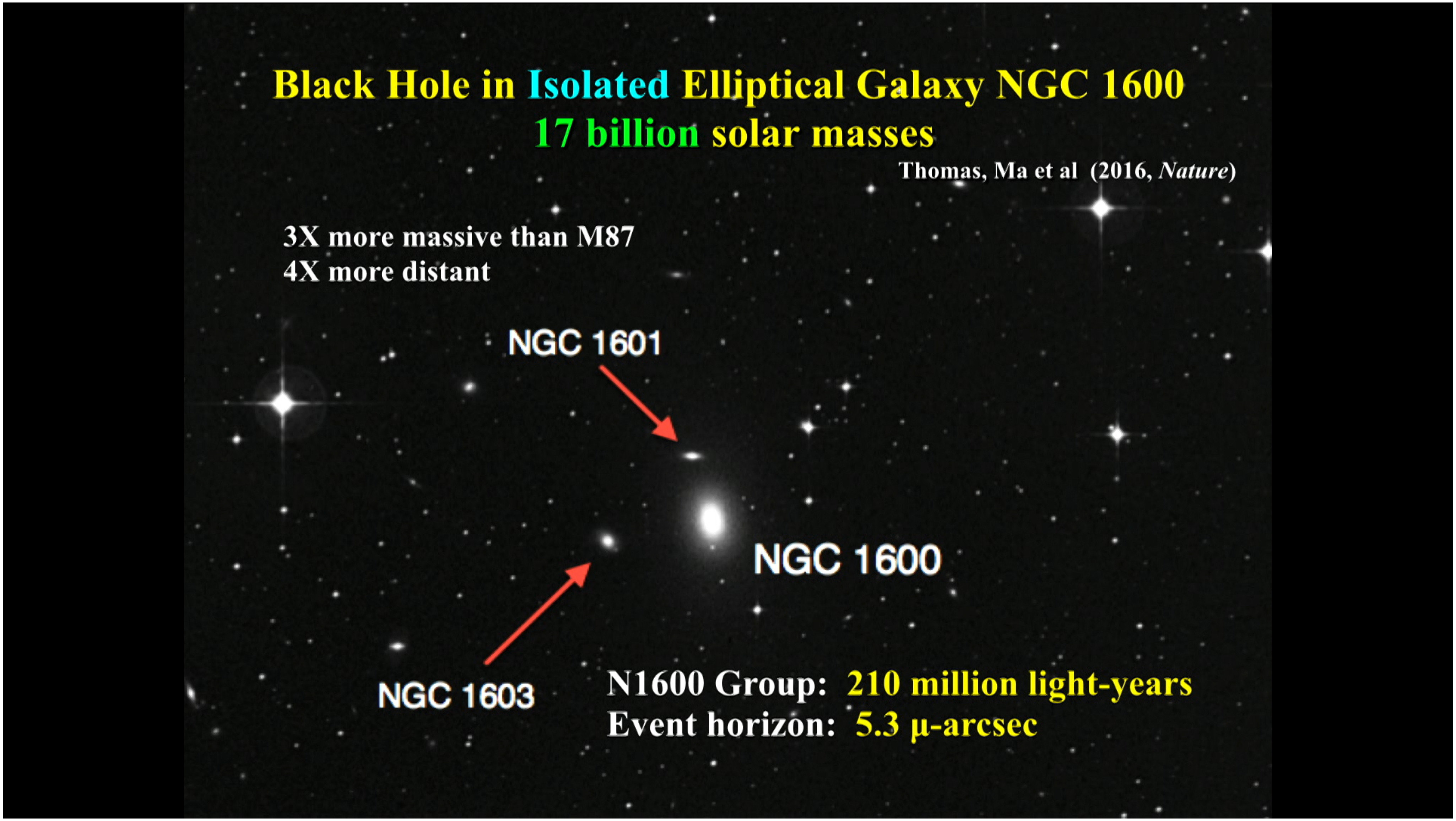
Received 1977 September 26; accepted 1977 November 1

ABSTRACT

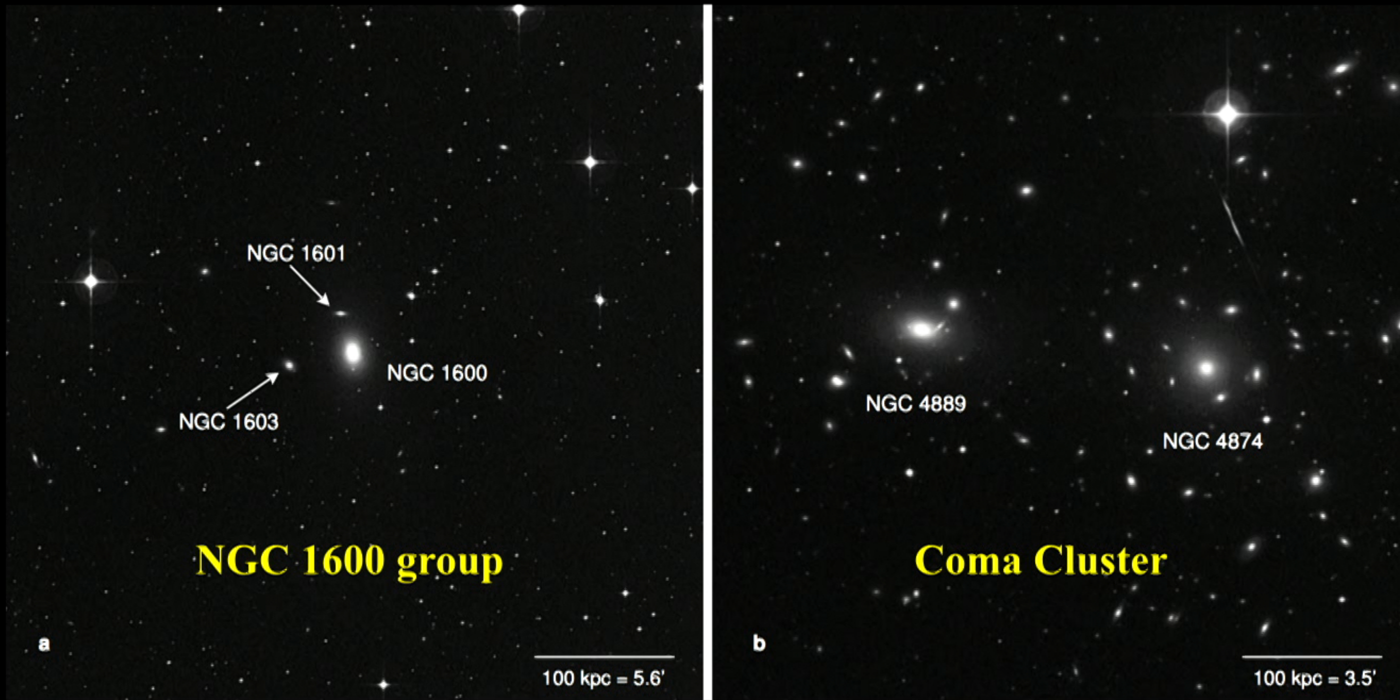
The elliptical galaxies NGC 3379 (E1) and M87 (E0) have been observed spectroscopically with the University College London Image Photon Counting System. Analysis of the redshifts and velocity dispersions as a function of radius by a Fourier method has yielded the following results: (*a*) NGC 3379 exhibits 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 ~$5 \times 10^9\ M_\odot$.

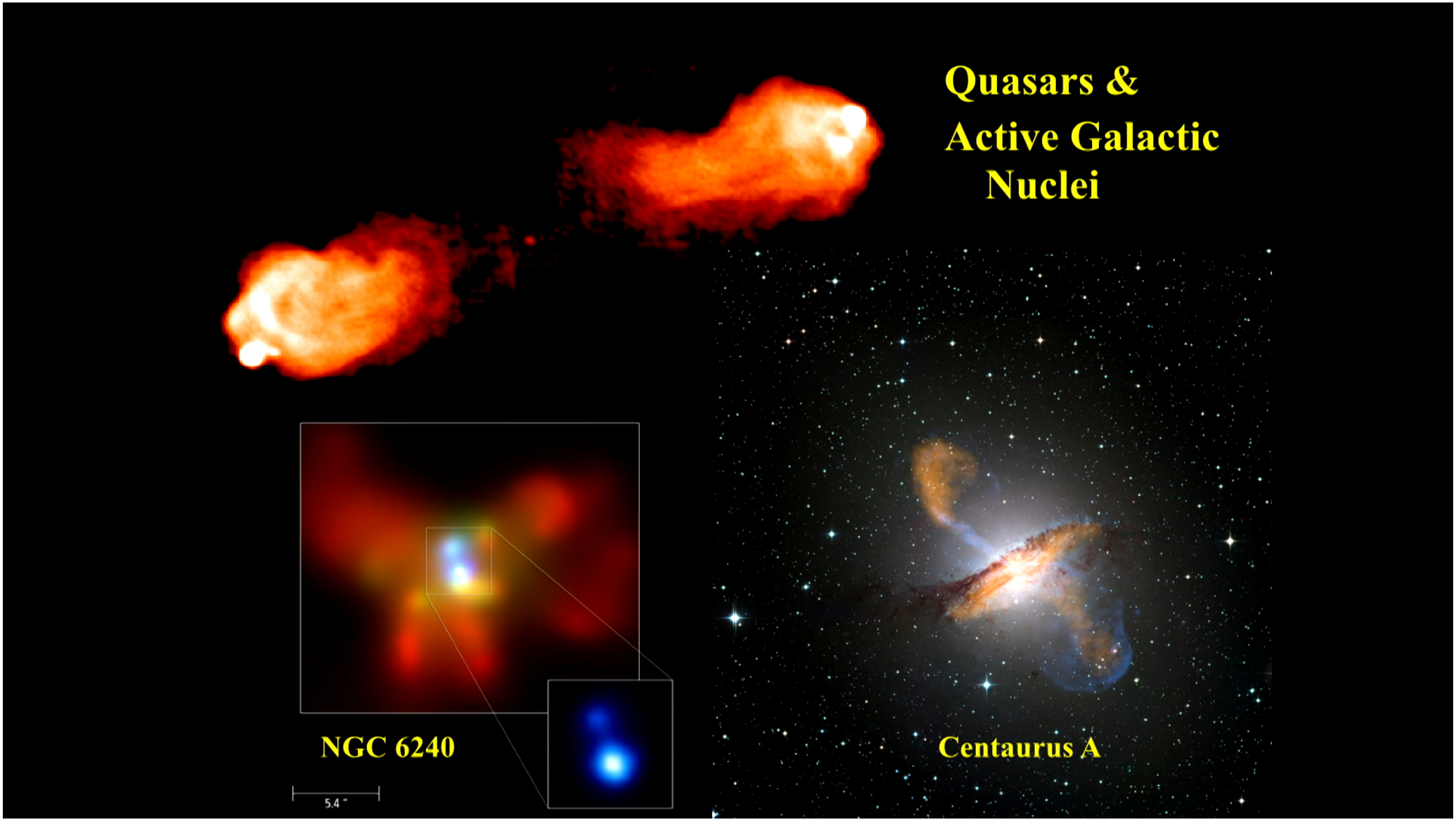

Black Hole in Elliptical Galaxy NGC 4889
15-20 billion solar masses
McConnell, Ma et al (2011, *Nature*)
~3X more massive than M87
6X more distant
NGC 4889
Coma Cluster: 330 million light-years


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
NGC 1601
NGC 1600
NGC 1603
N1600 Group: 210 million light-years
Event horizon: 5.3 μ-arcsec

The two most massive black holes reside in different environments



NGC 1600 group	Coma Cluster
$M_{vir} \sim 1.5\mathrm{x}10^{14}$ M_{sun}	$M_{vir} = (1.4\text{-}2.7)\mathrm{x}10^{15}$ M_{sun}
$L_X \sim$ 1000x lower	$L_X = 4\mathrm{x}10^{44}$ L_{sun}
Rank 2 galaxy ~3x fainter (fossil-group)	Rank 2 galaxy similar in L
D = 64 Mpc	D = 102 Mpc


Quasars &
Active Galactic
Nuclei
NGC 6240
5.4 "
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
- (Potential) 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. Supermassive 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

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

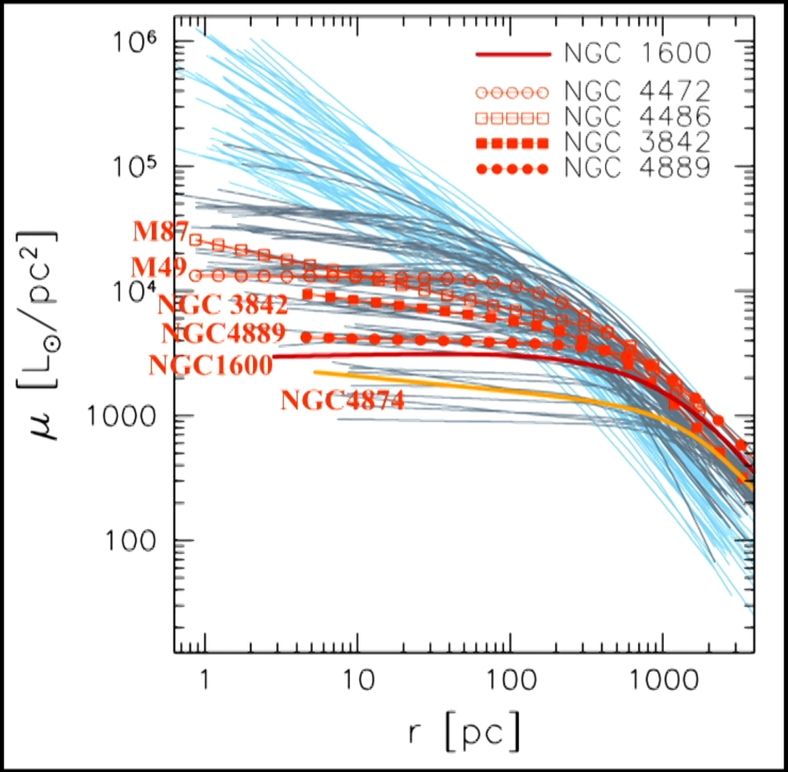
0.1 arcsec at 100 Mpc

Use Hubble Space Telescope to obtain spectra

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



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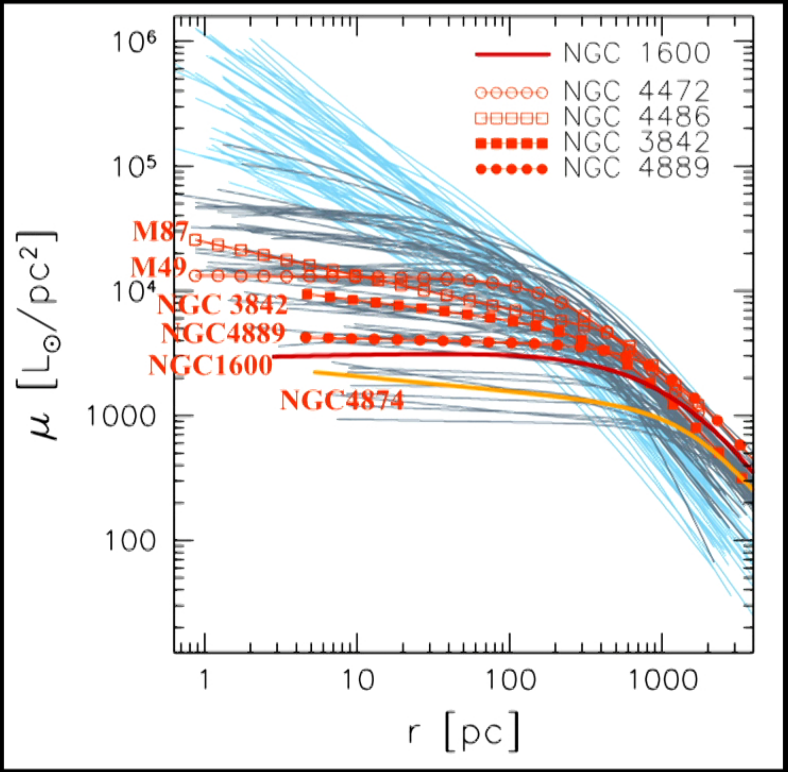
My team:
Gemini/Keck integral-field
spectrographs with
< 0.4 arcsec resolution
TMT/GMT even better



Next Step in UltraMassive Black Hole Hunt

The MASSIVE Survey

An Integral Field Unit (IFU) spectroscopic
and photometric survey
of the ~100 most massive galaxies within ~100 Mpc

MASSIVE Survey Status

Spectroscopy

Wide-field IFU (4” to 107”)

McDonald Mitchell/VIRUS-P

246 fibers each 4” 3600-5800 å

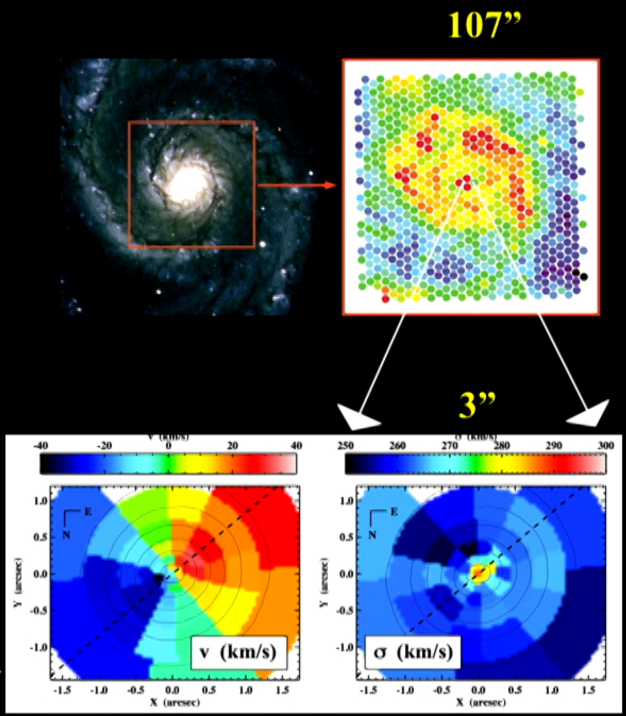
Beyond ~2 Re for >50% galaxies

In hand: Data for 85+ galaxies

Extensive tests on velocity moments

v, σ, h_3, h_4, h_5, h_6

e.g. stellar templates, spectral coverage, continuum



High-resolution IFU (~0.1” to 5”)

Gemini/Keck IFU + AO

8 MASSIVE have published M_{BH}

25+ more with GMOS/NIFS/OSIRIS data

MASSIVE Survey Status

Photometry

HST (Cycle 23+24)
Central light profiles and SBF distances for 34 galaxies
Additional ~20 with archival data

CFHT+UKIRT
Deep wide-field K-band imaging. 60+ galaxies in hand
Tidal features, outer profiles, more accurate Re & total L_k

Multi-wavelengths

IRAM+PdBI+ALMA Molecular gas survey of 66 MASSIVE galaxies
CO kinematics, molecular mass

Chandra X-ray hot halos of 33 MASSIVE galaxies in archive

VLA 5 GHz radio continuum for 90+ galaxies

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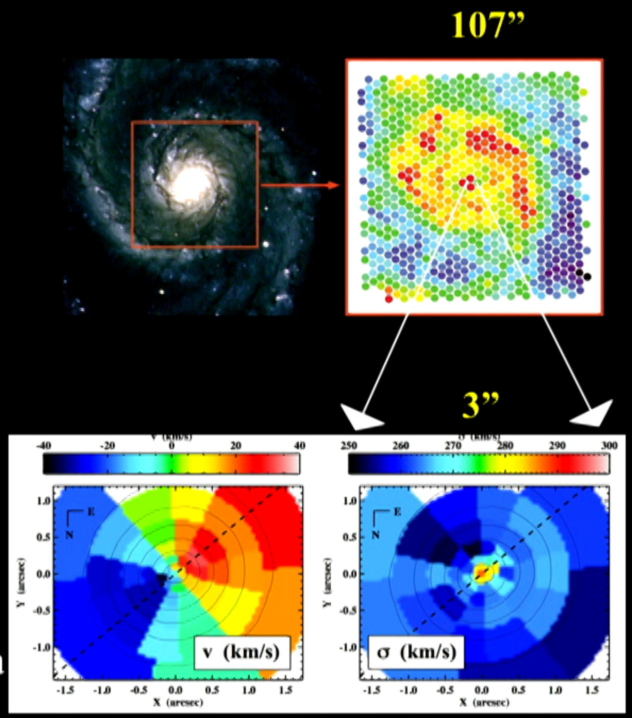

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0.1 arcsec at 100 Mpc

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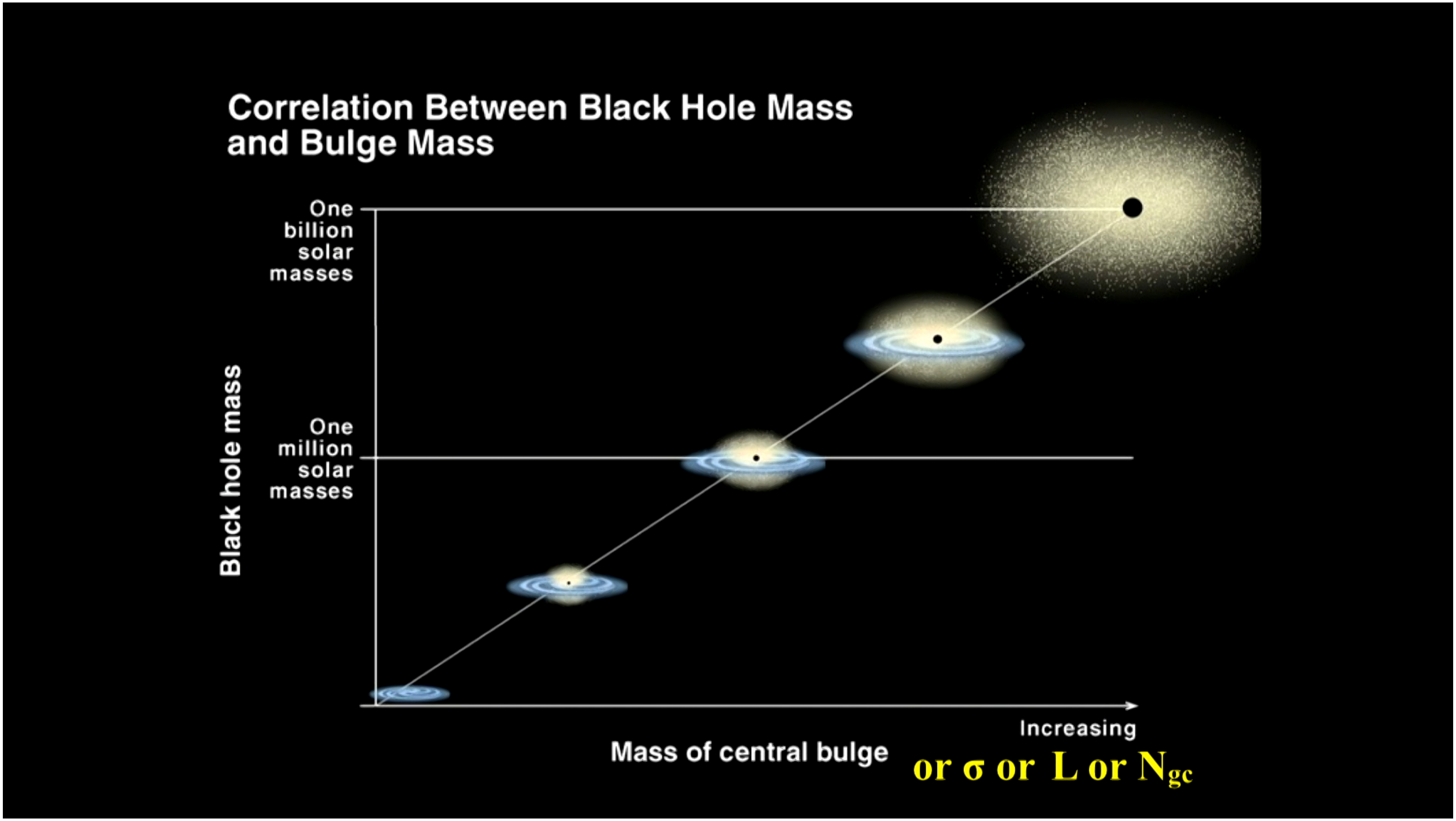
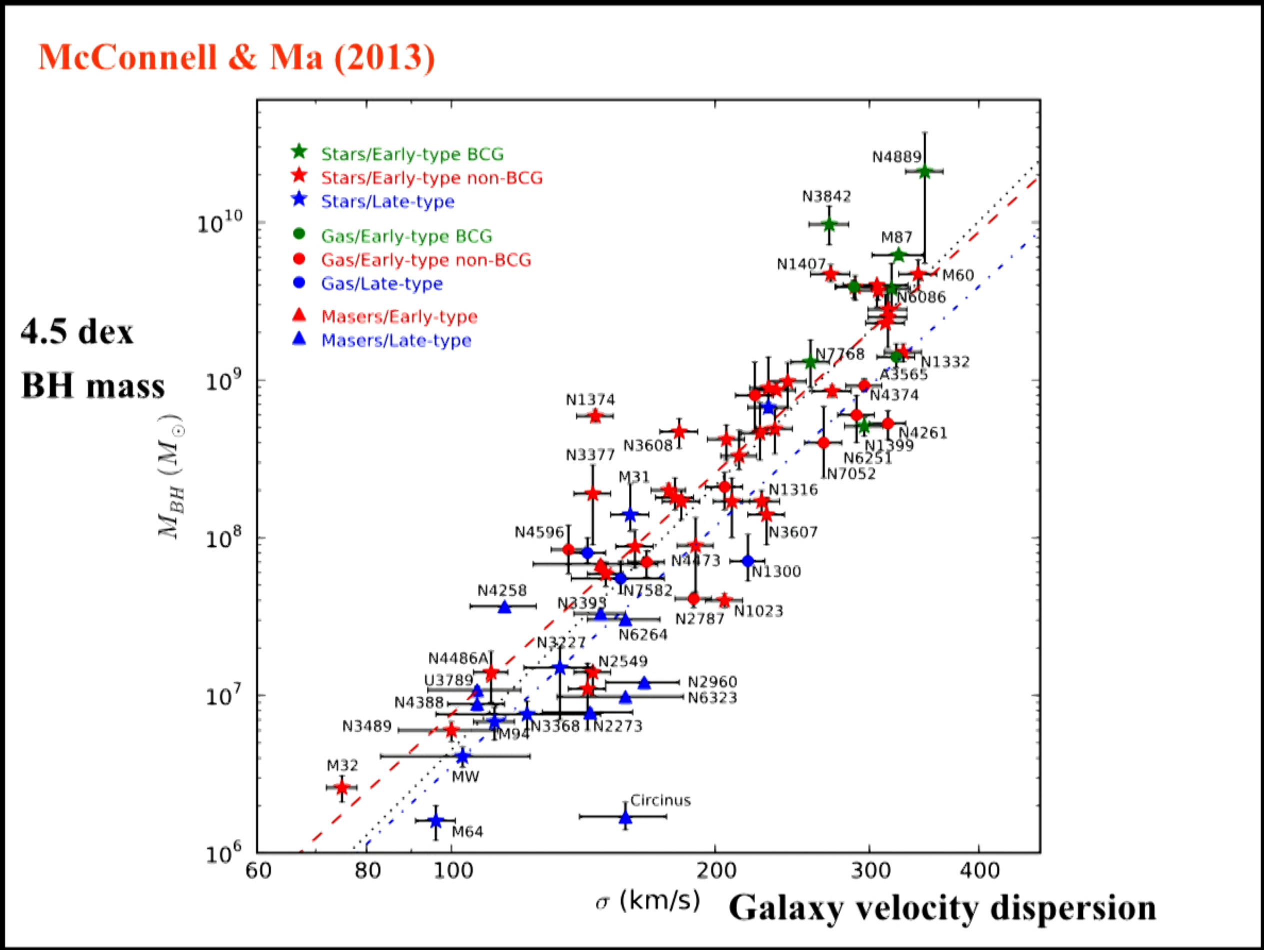

Correlation Between Black Hole Mass and Bulge Mass
One billion solar masses
One million solar masses
Black hole mass
Increasing
Mass of central bulge
or σ or L or N_{gc}

Real data are messy

M_{BH} - σ relation for 80+ Black Holes



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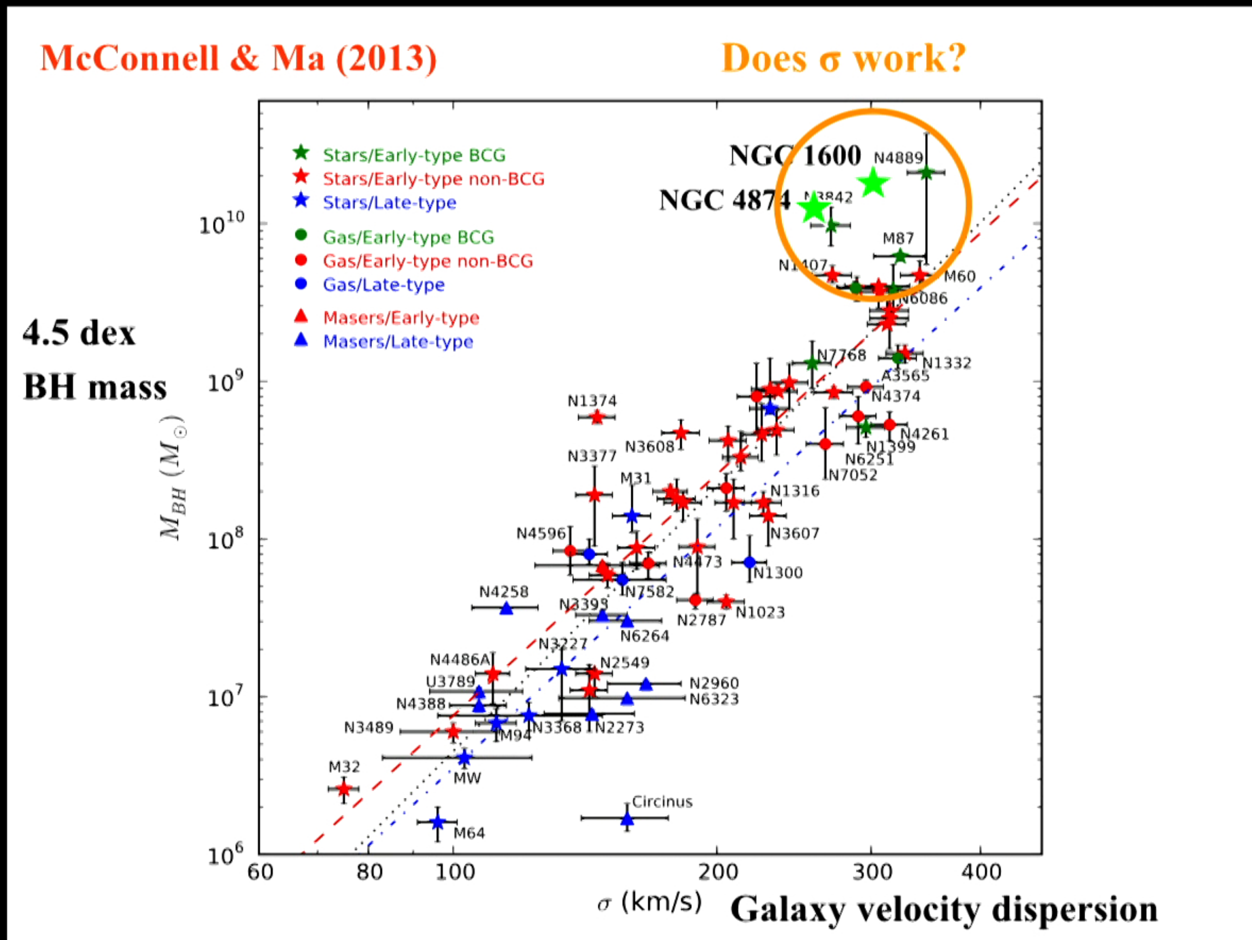
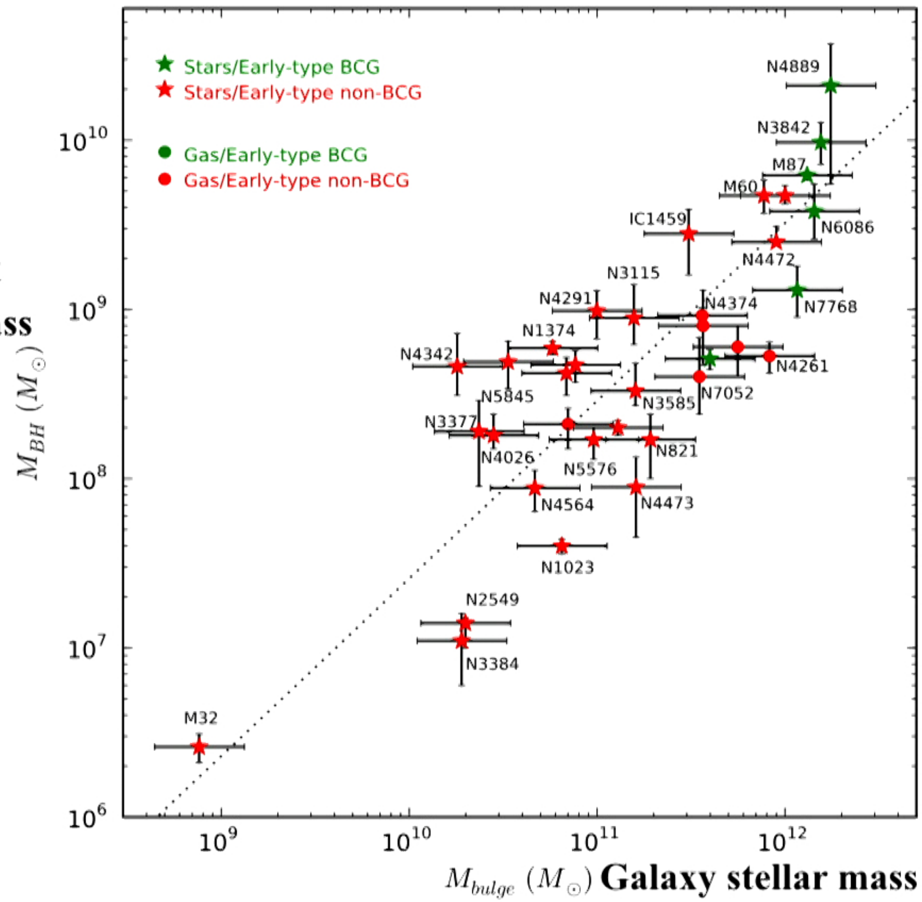


M_{BH} - M_{bulge} relation

McConnell & Ma (2013)

4.5 dex

BH mass



Galaxy stellar mass

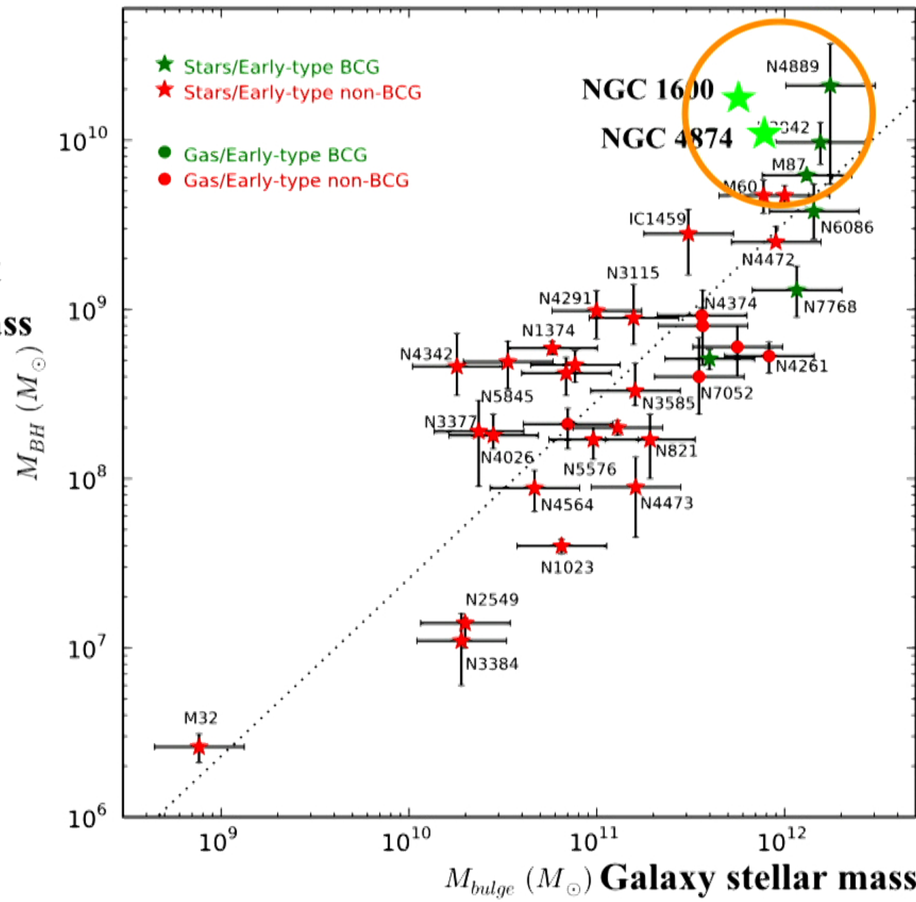
M_{BH} - M_{bulge} relation

McConnell & Ma (2013)

Does M_{bulge} work?

4.5 dex

BH mass



NGC 1600:

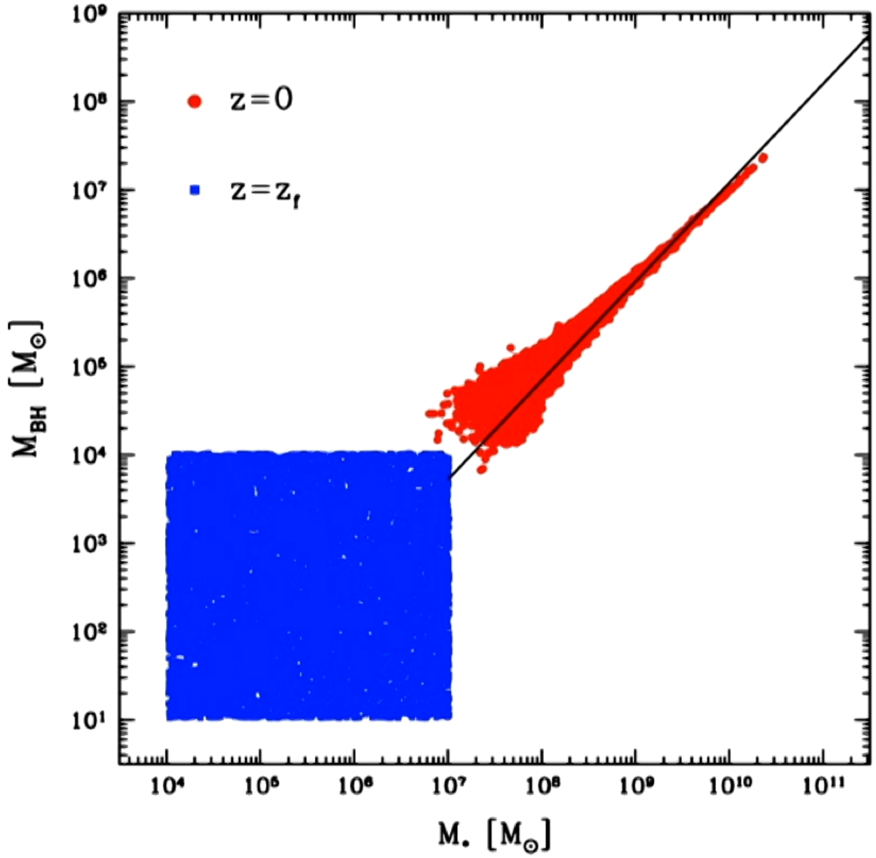
M_{BH}~2%M_{bulge}

Mean relation

M_{BH}~0.2%M_{bulg}

Theoretical models based on pure mergers

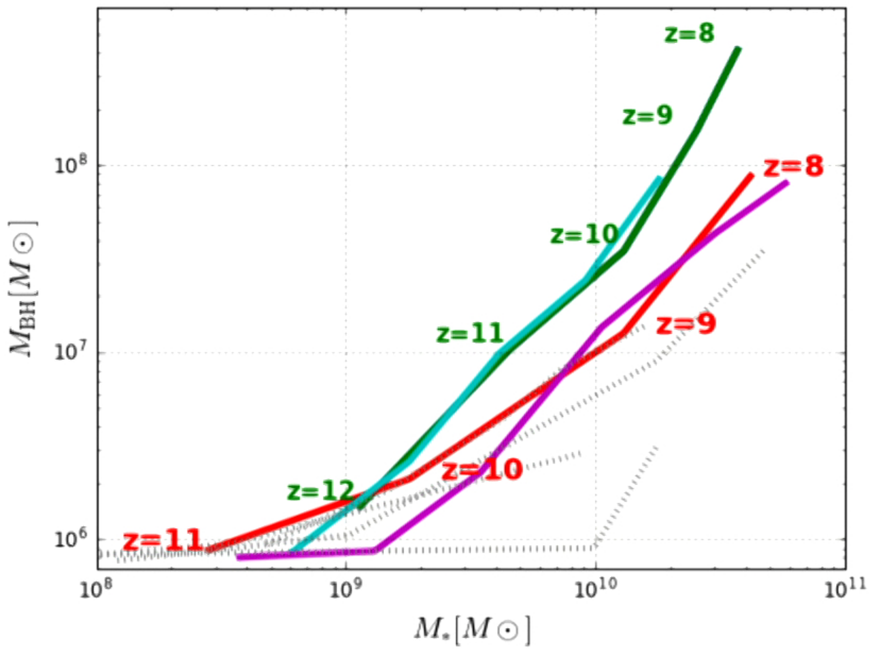
predict decreasing scatter in M_{bh}-M_{bulge} relation at high mass



While observed scatter in M_{bh}-M_{bulge} relation does not decrease at high end

Jahnke & Maccio (2011)
Hirschmann et al (2010)
Peng (2007)

BlueTides Simulation of BH growth

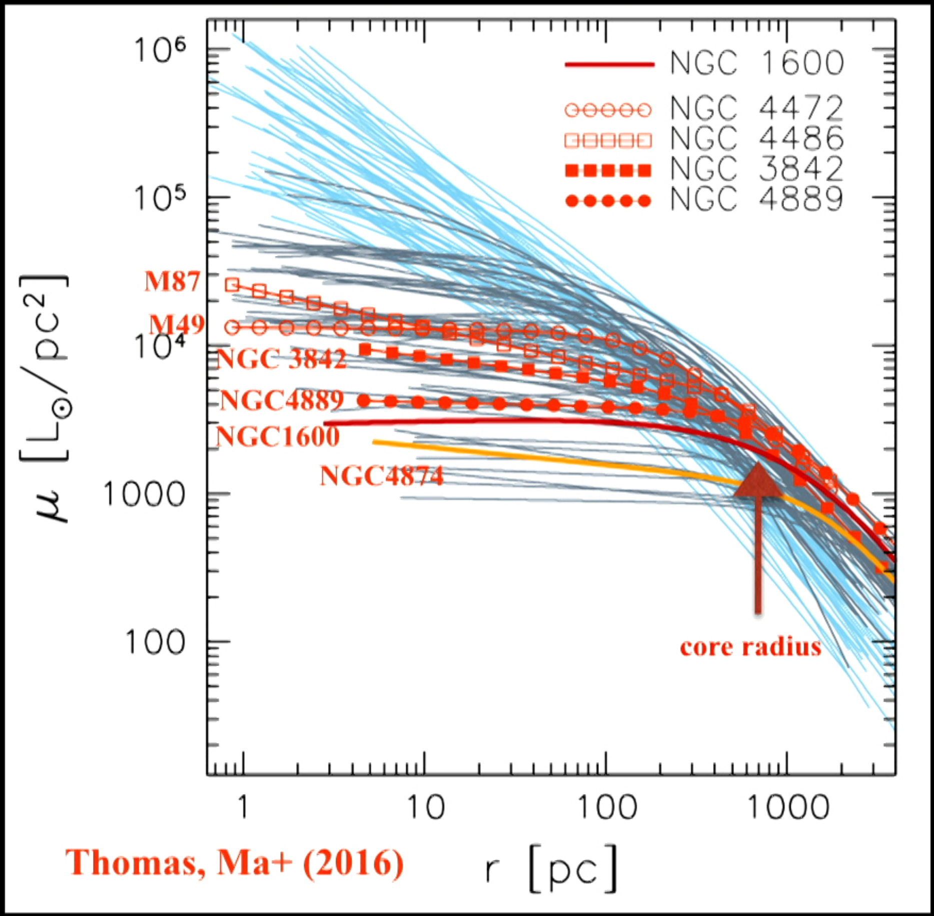


Large-scale tidal field affects angular momentum of gas accretion

Di Matteo, Croft et al (2016)

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

Massive ellipticals have large stellar cores

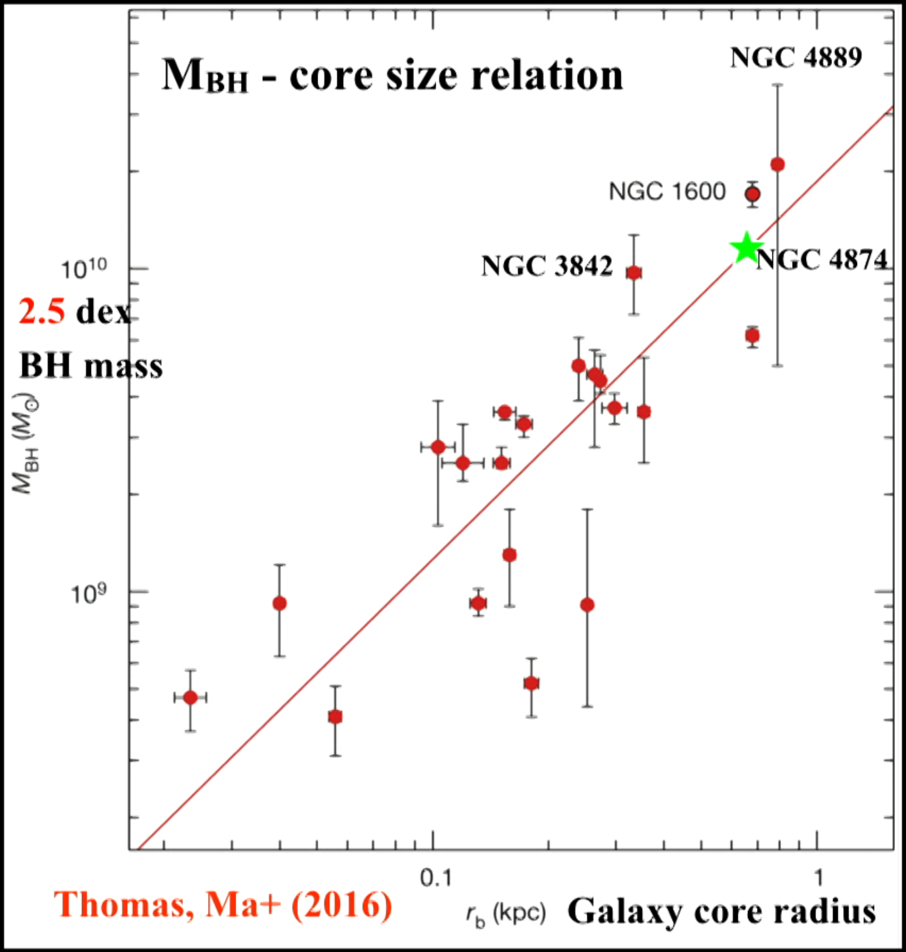


NGC 1600

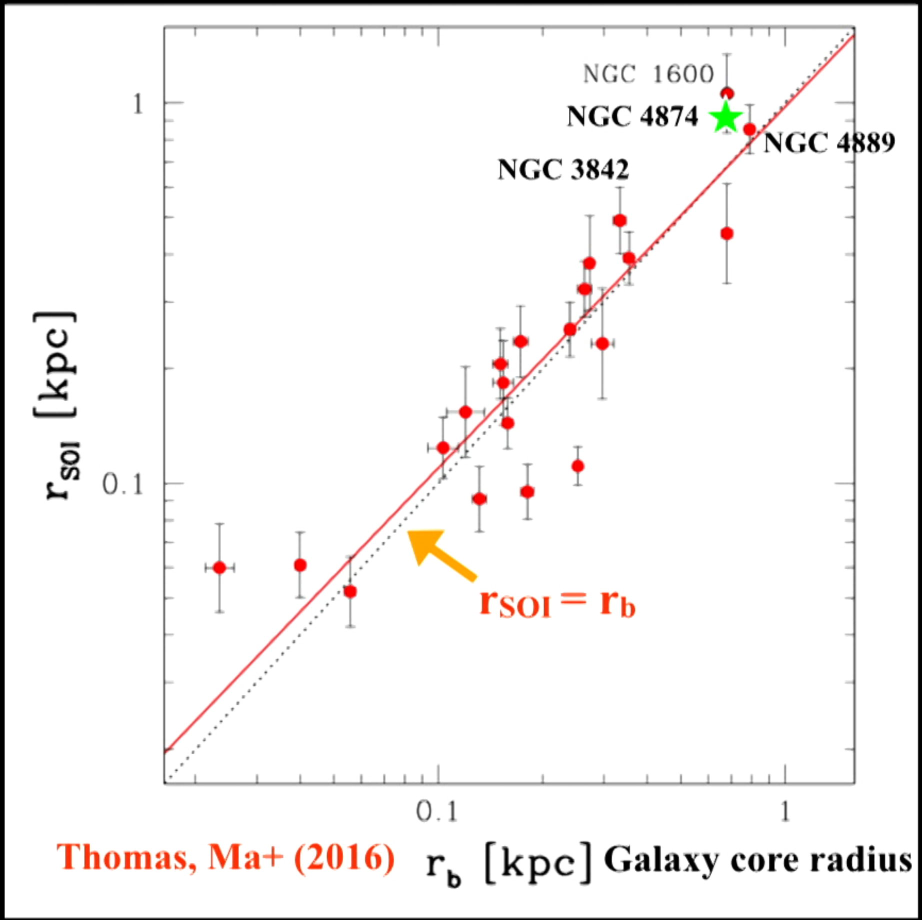
core radius

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}

How do black holes make stellar cores?

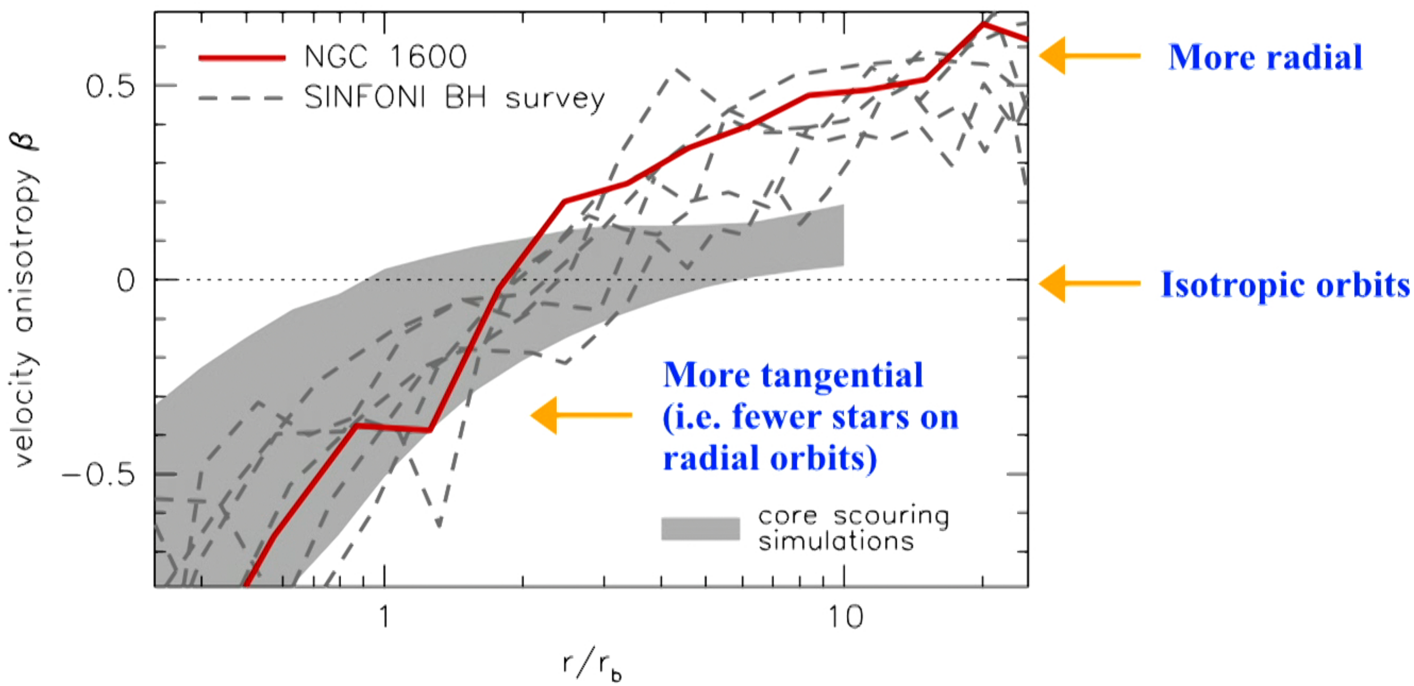
Binary black hole scouring?

Black hole recoil after merger?

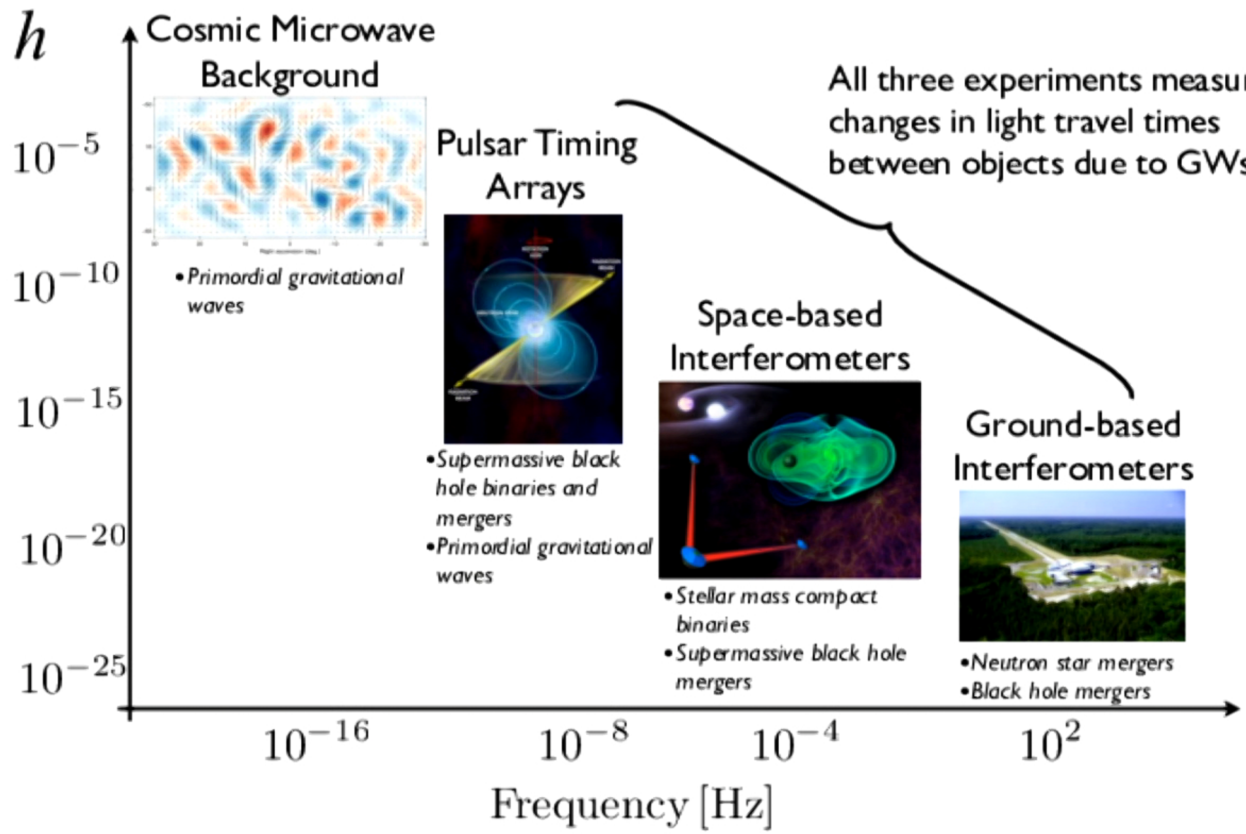
AGN feedback?

Velocity anisotropy profiles of cored ellipticals

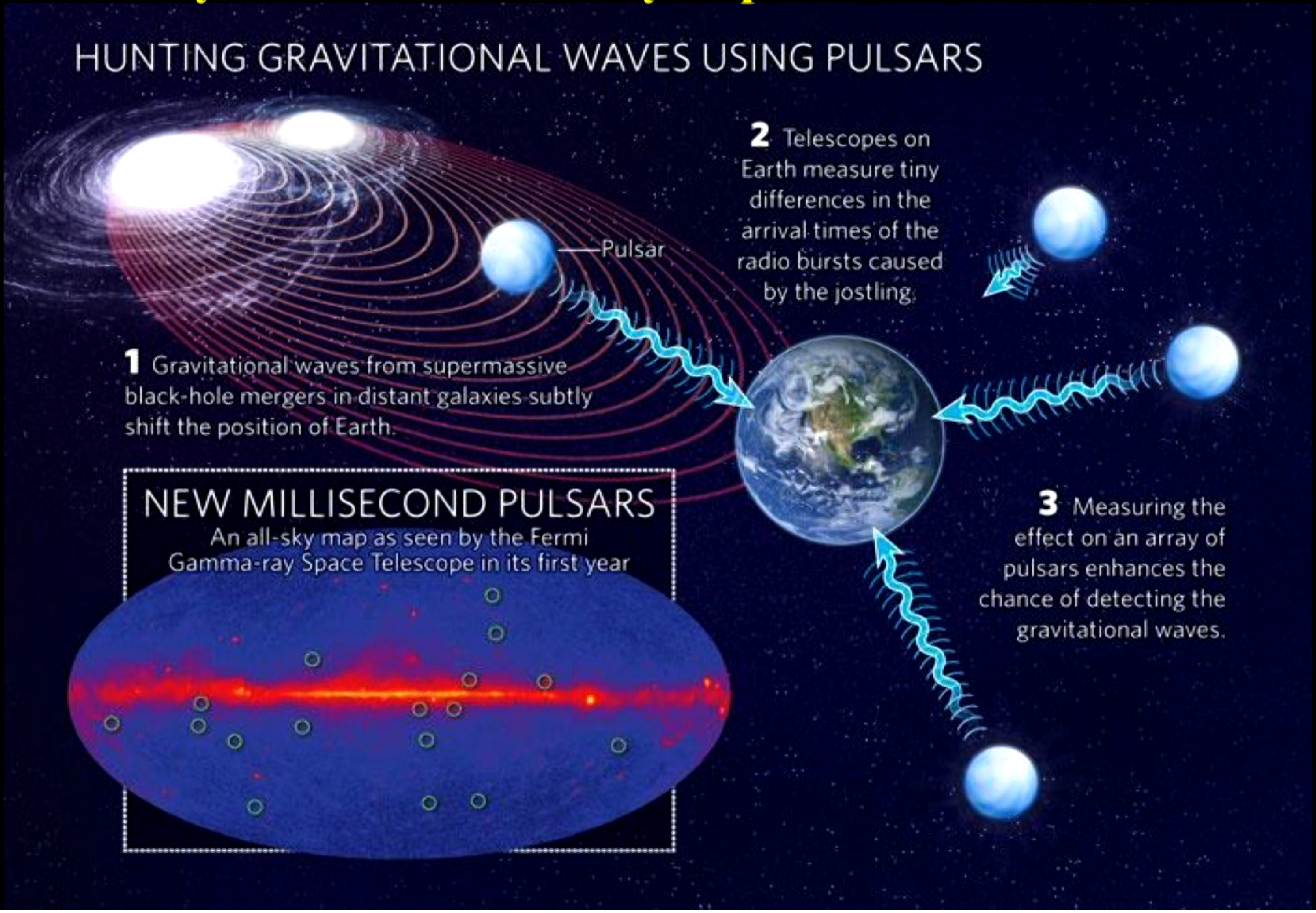
$$\beta = 1 - \sigma_t^2/\sigma_r^2 \qquad \sigma_t = [(\sigma_\vartheta^2 + \sigma_\varphi^2)/2]^{1/2}$$



The spectrum of gravitational wave astronomy

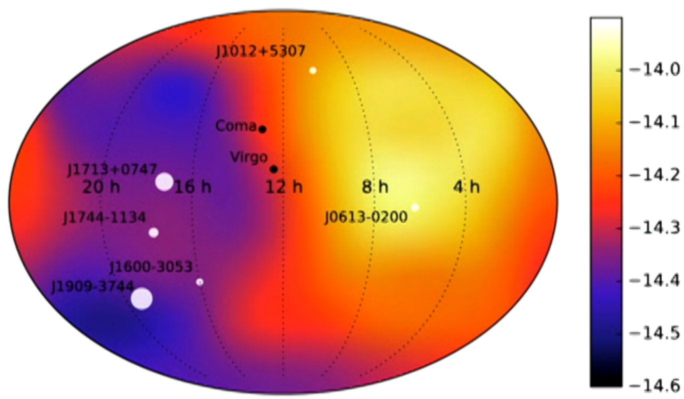


Gravity Waves from Binary Supermassive Black Holes

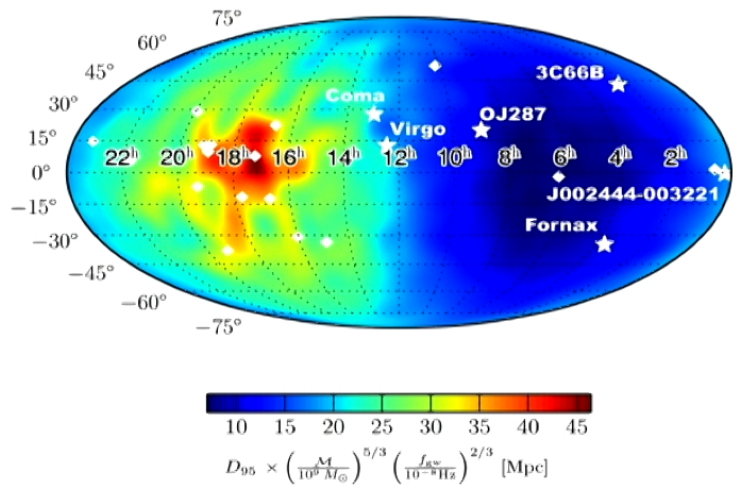


Sensitivity Sky Maps of Continuous GWs

EPTA (Babak+ 2016)



NANOGrav 5yr DR (2014)



Sky-averaged upper limit @ 10 nHz

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

$h_0 < 3.0 \times 10^{-14}$

Gravitational Wave Strain Amplitude

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

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

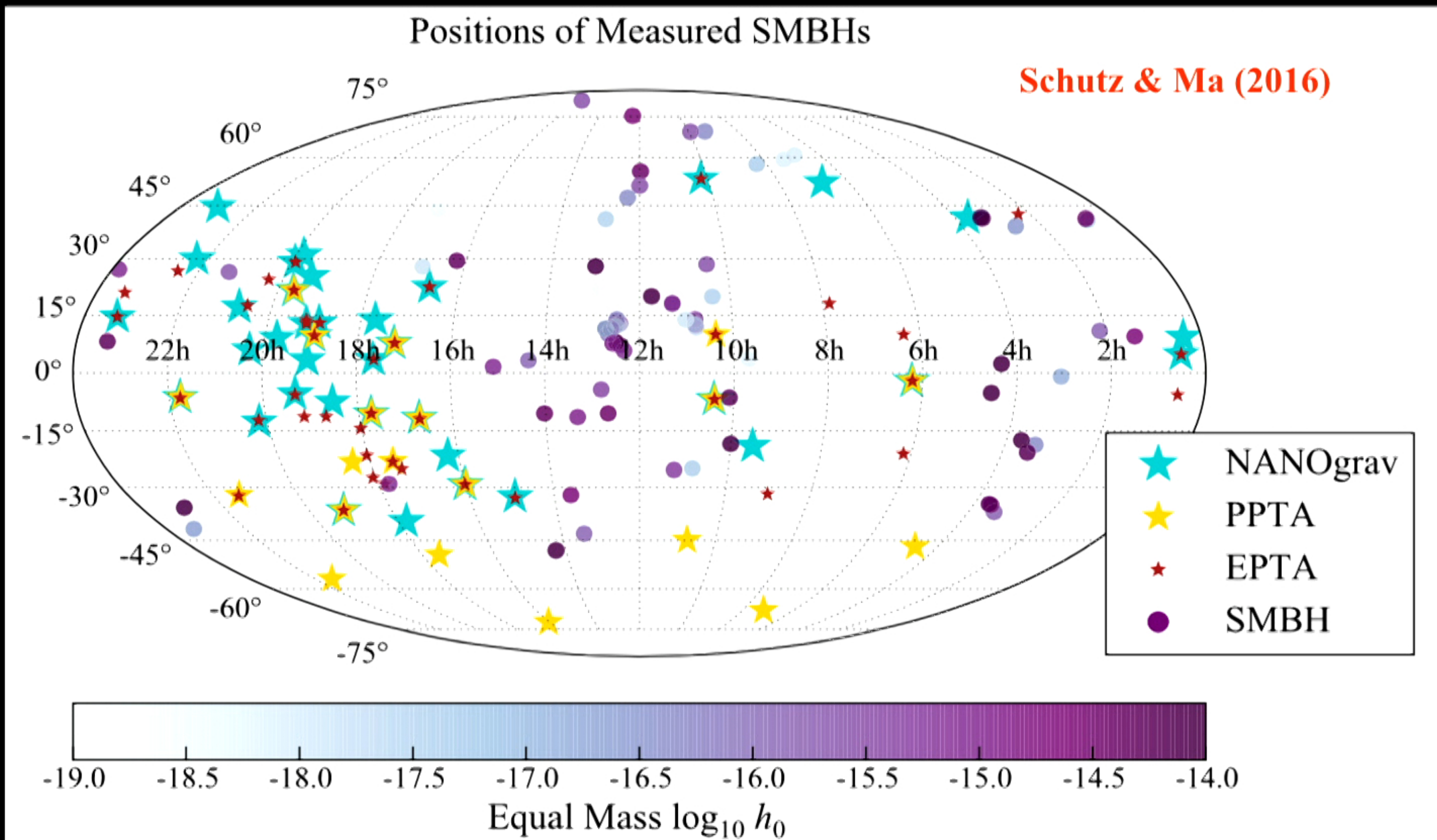
Chirp mass of black hole binary

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

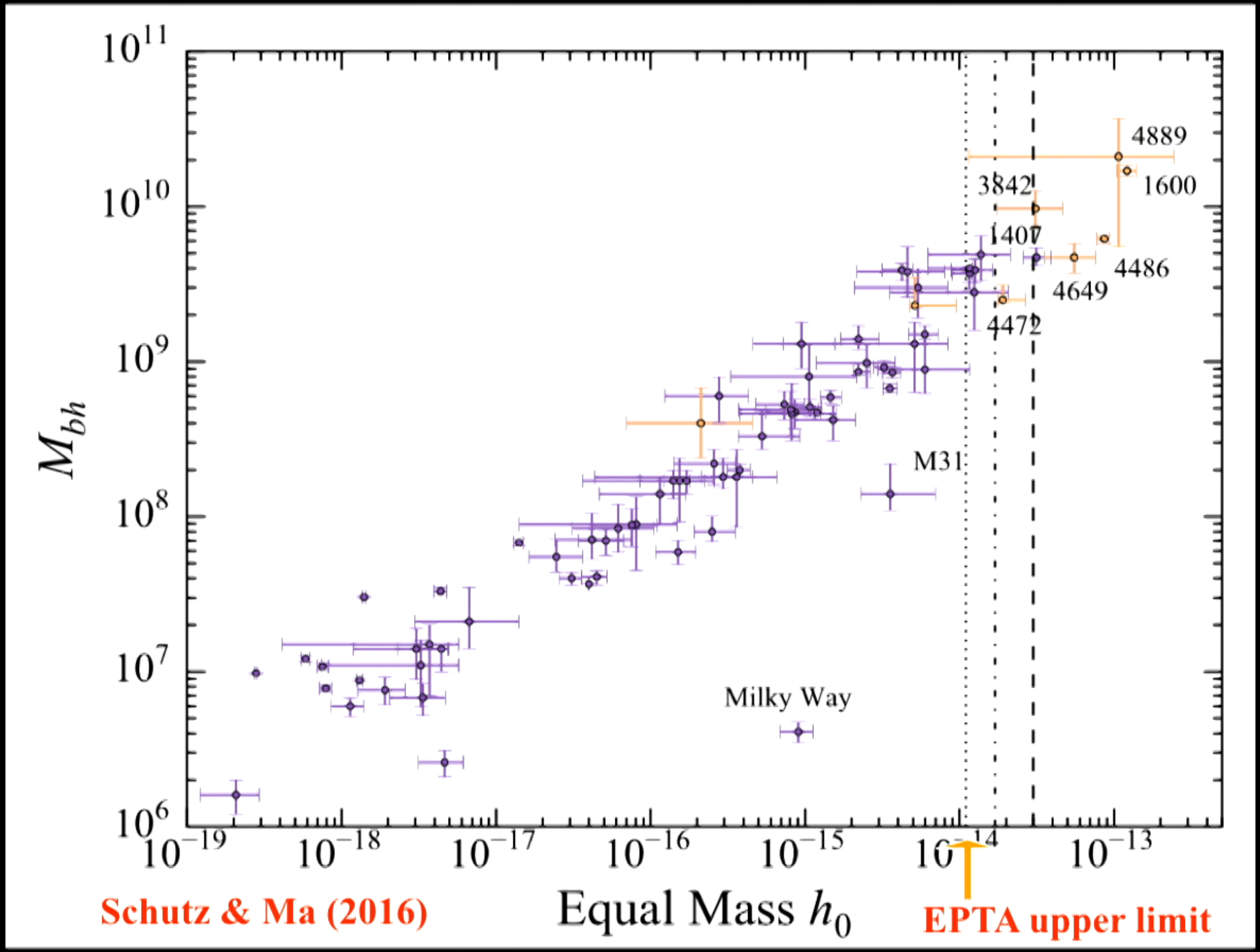
Total black hole mass from optical/IR spectroscopy of dynamical tracers (e.g. stars, gas, masers, CO)

→ **A source with known $M_\bullet$ and distance produces strongest strain h_0 if it contains an equal-mass binary black hole**

Sky Locations of Pulsars & Supermassive Black Holes



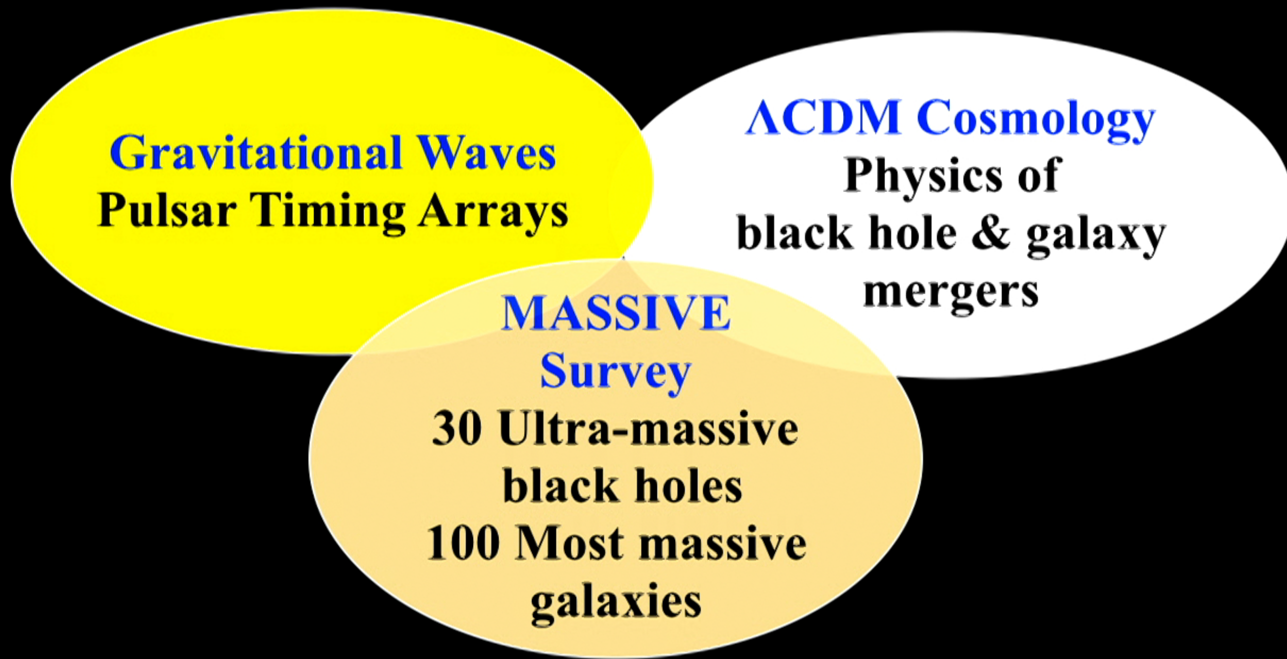
Maximum Strain from SMBHs with Measured Mass

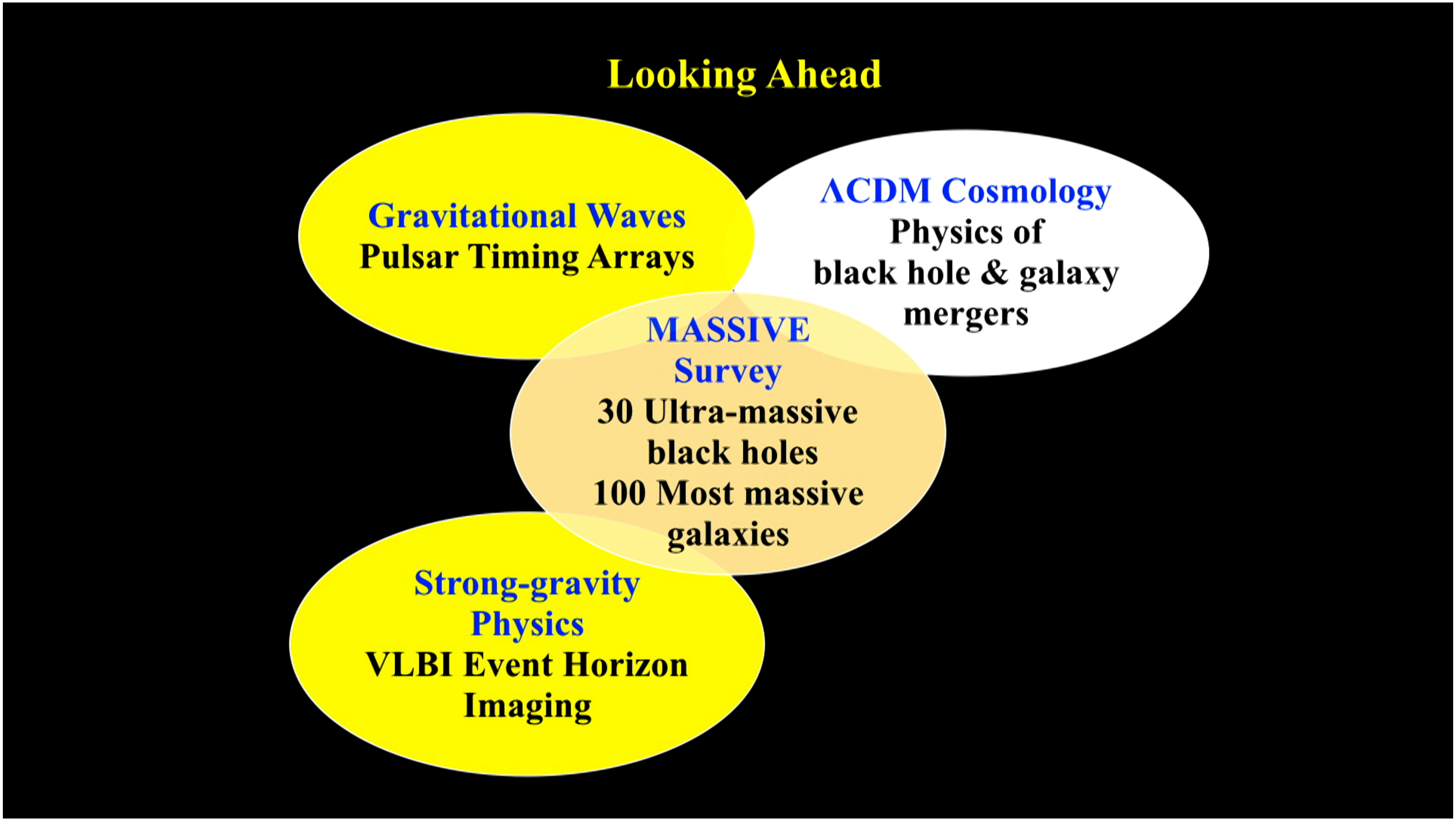


Looking Ahead

MASSIVE
Survey
30 Ultra-massive black holes
100 Most massive galaxies

Looking Ahead

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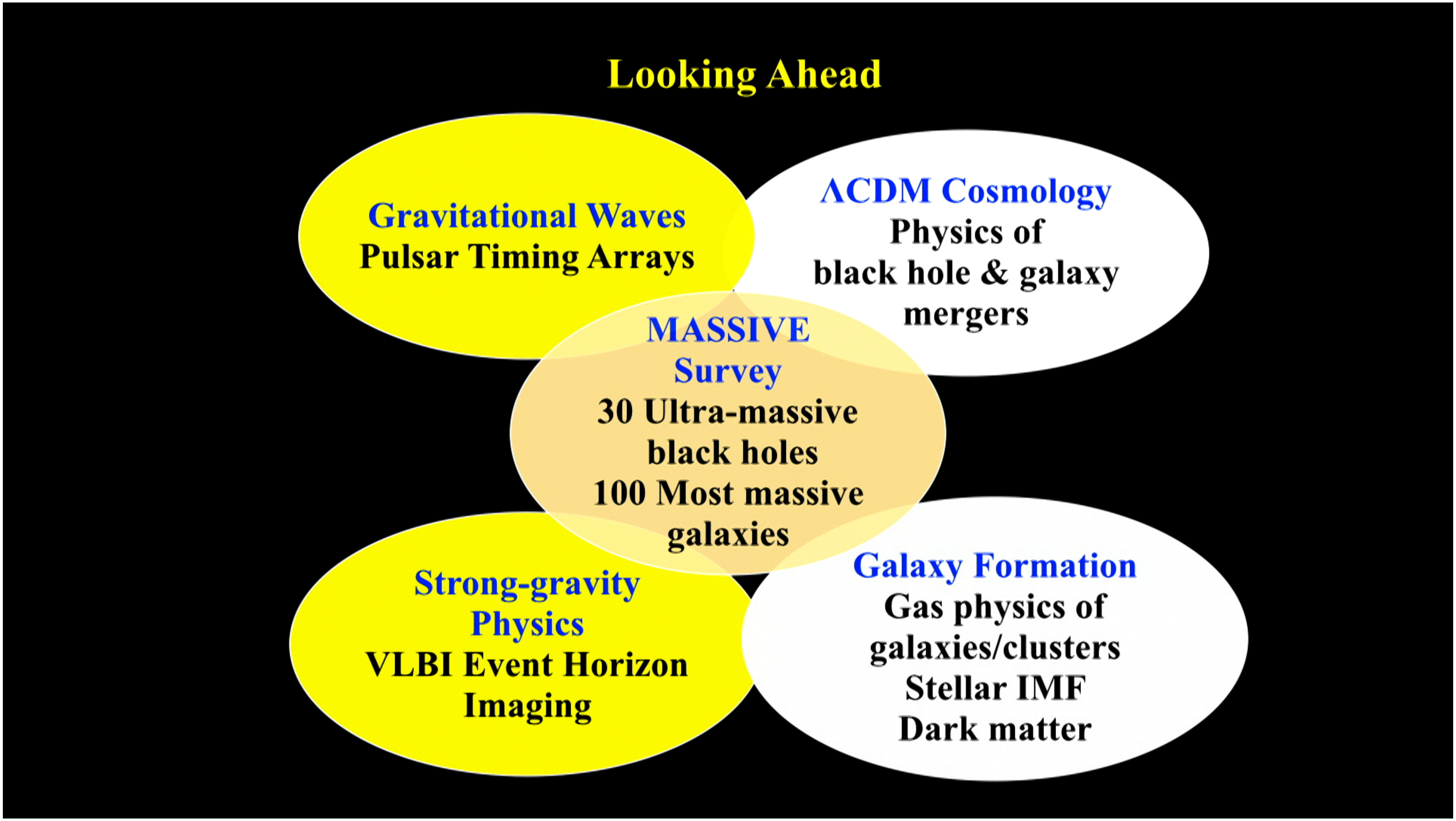
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