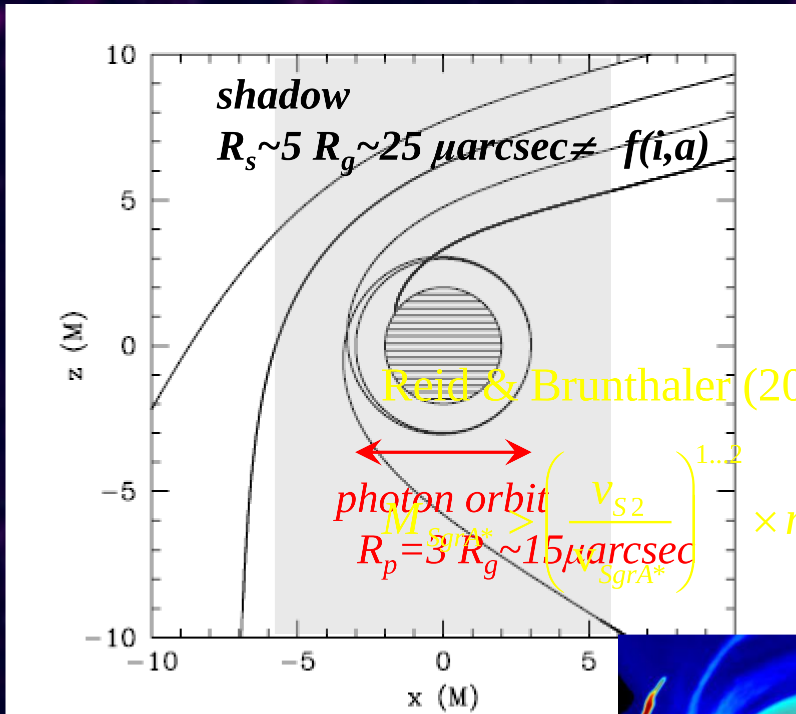
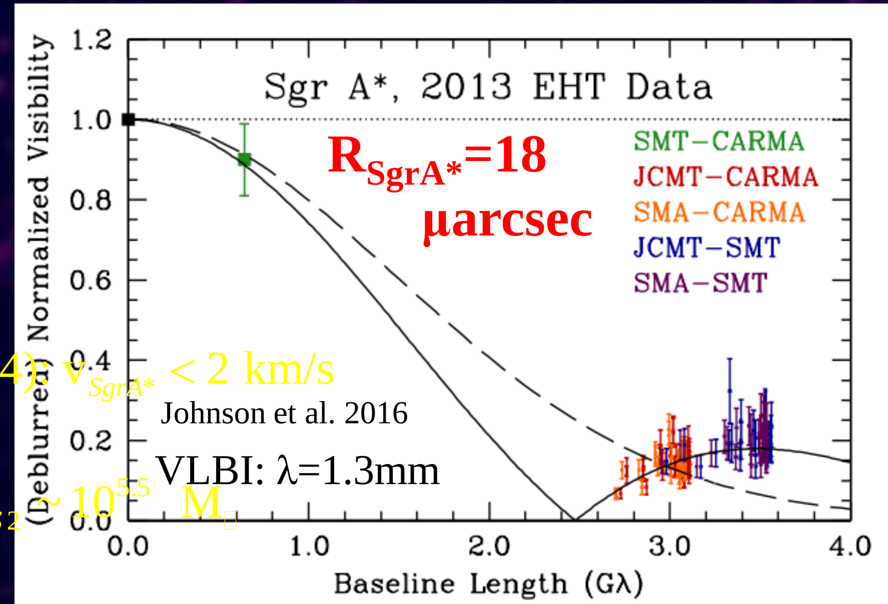
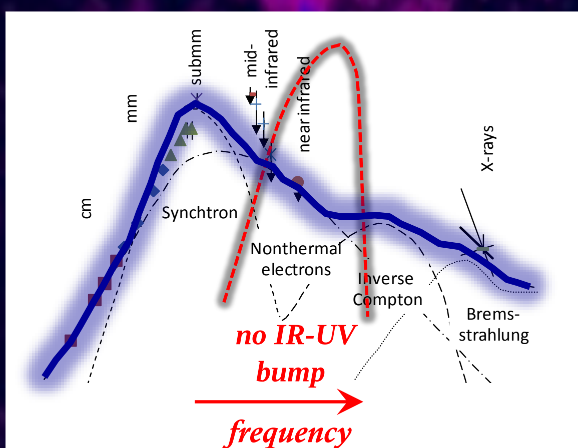
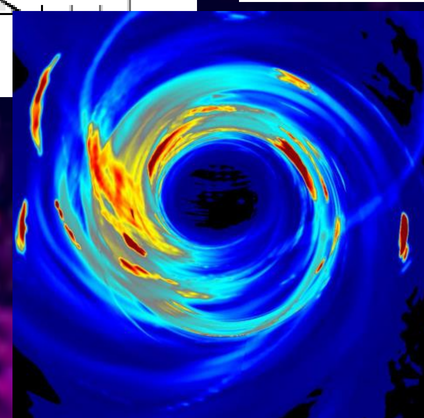




Reid & Brunthaler (2004): $v_{SgrA*} < 2$ km/s

$$M_{SgrA*} > \left(\frac{v_{S2}}{v_{SgrA*}}\right)^{1...2} \times m_{S2} \sim 10^{5.5}\ M_{\odot}$$

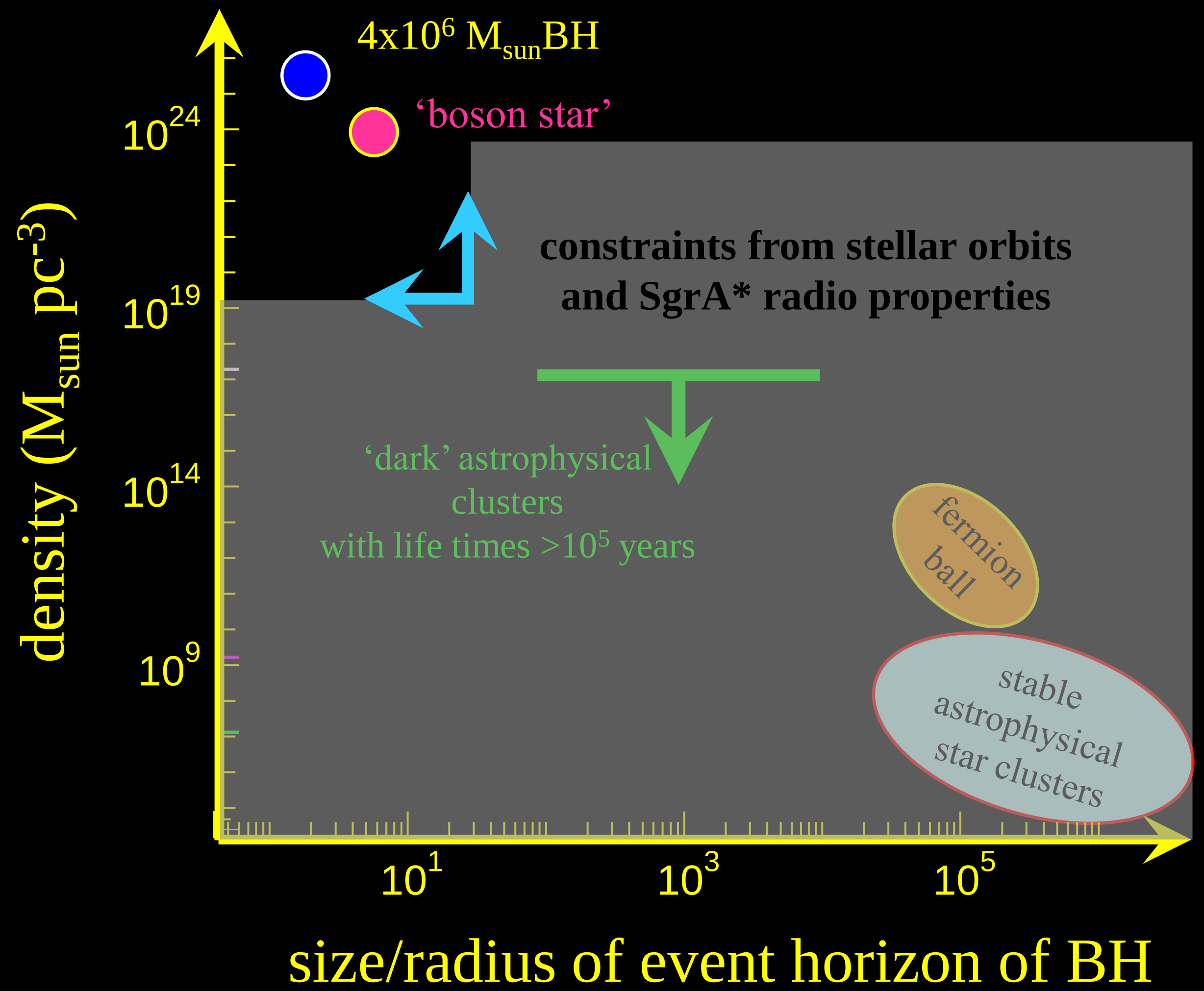




MHD simulation of SgrA*

Backer & Sramek 1996, Bower et al. 2003, 2005, Reid & Brunthaler 2004, Shen et al. 2005, Doeleman et al. 2008, 2010, Bardeen 1973, Falcke, Melia & Algol 2000, Johannsen & Psaltis 2010, Broderick et al. 2009, 2010, Dexter et al. 2012, 2013, Moscibrodzka et al. 2010, 2014, Chatterjee et al. 2007, Johnson et al. 2015, Fish et al. 2016

Is SgrA* a black hole ?



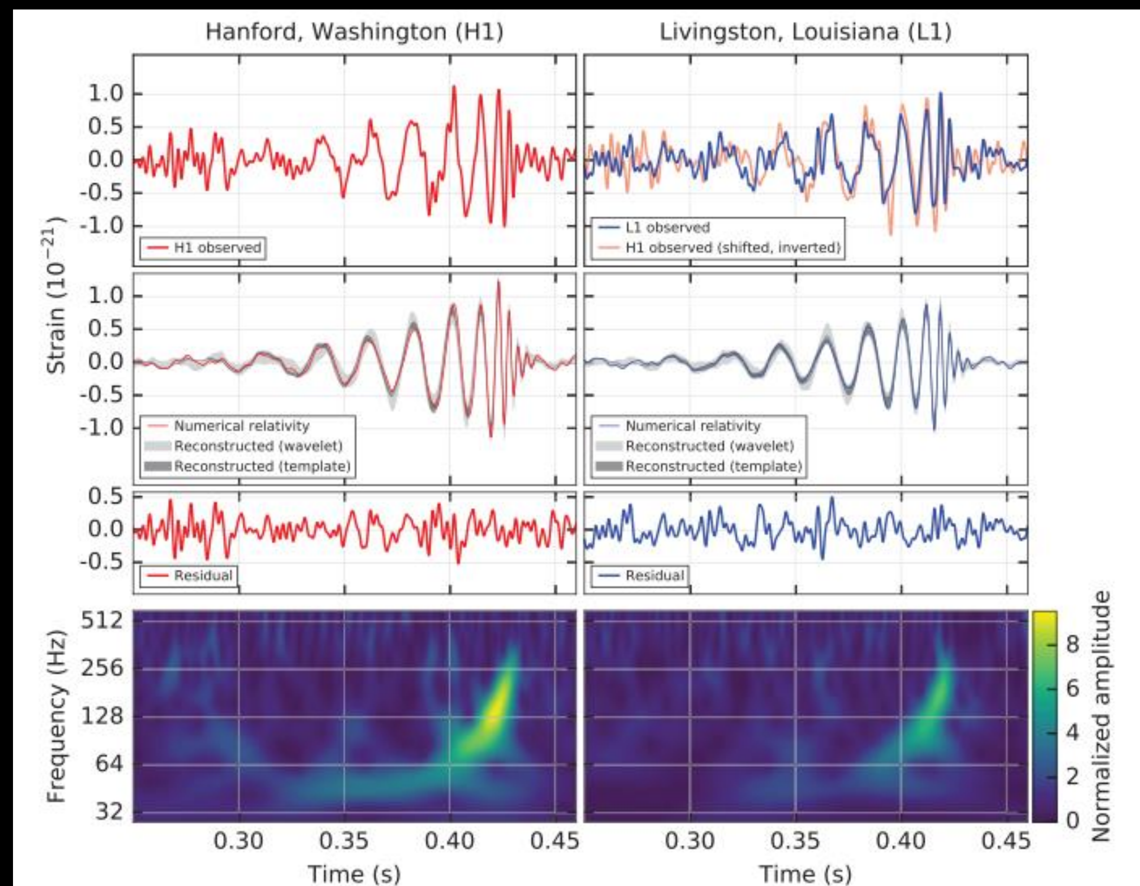
Maoz 1998, Schödel et al. 2003, Ghez et al. 2005, Coleman Miller 2006, Tsiklauri & Viollier 1998, Torres et al. 2000, Chapline et al. 2001, 2003, Mazur & Mottola 2004

A century after Einstein: direct detection of gravitational waves (from a pair of merging black holes)

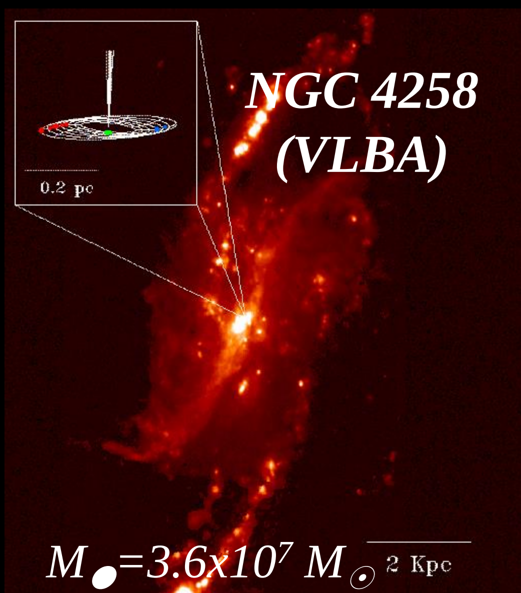
Observation of Gravitational Waves from a Binary Black Hole Merger

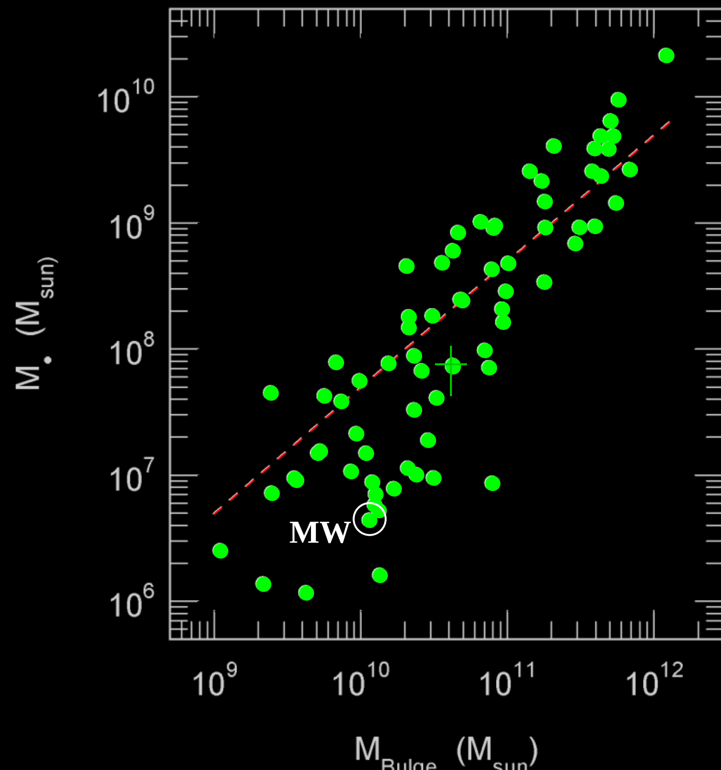
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

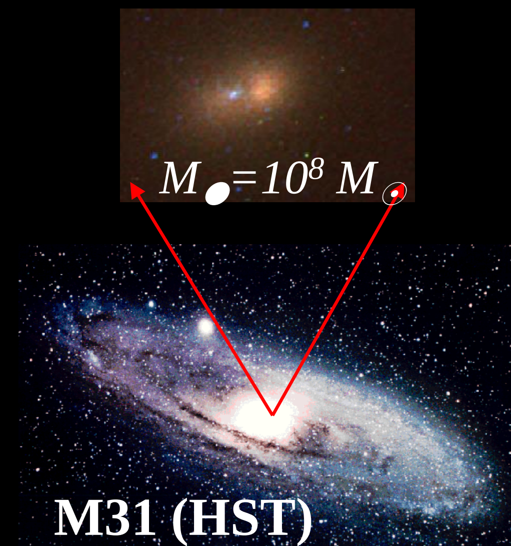
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.



Demographics of massive black holes in nearby galaxies



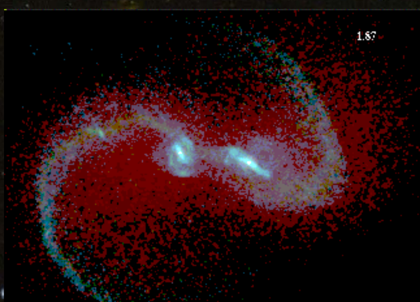




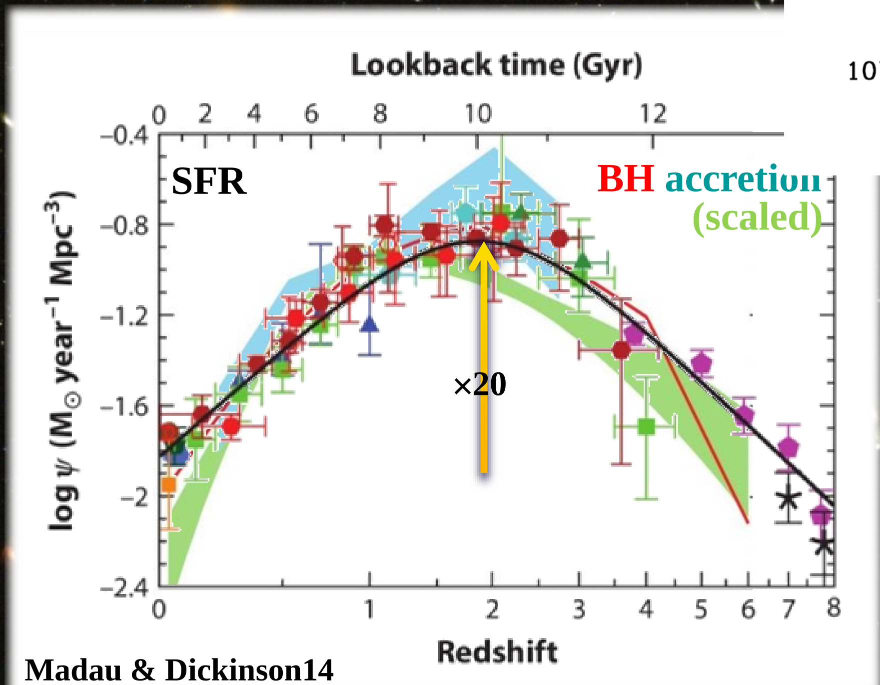
$M_\bullet / M_{bulge} \sim 2\text{-}5 \times 10^{-3}$

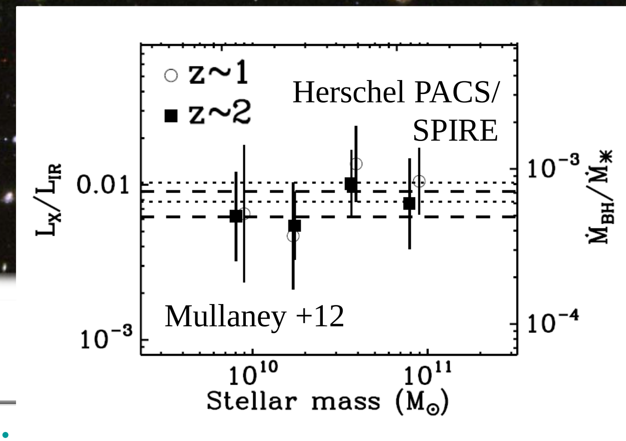
Bender, Faber, Fabian, Ferrarese, Filipppenko, Ford, Gebhardt, Greene, Greenhill, Ho, Kormendy, Nandra, Ma, McConnell, Moran, Merritt, Tanaka, Tremaine 1995-2013

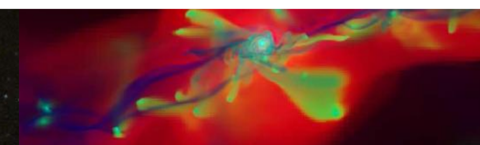
The cosmic evolution of galaxies and massive black holes



(major) mergers
& starbursts
rate ~ 20-30%





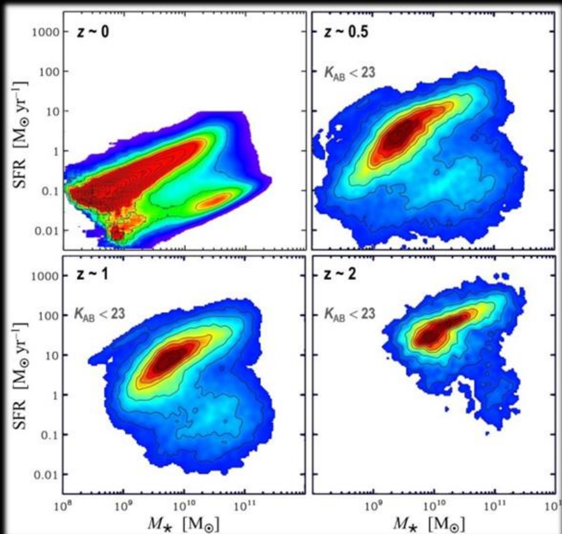


semi-continuous
accretion from halo
(including minor
mergers)
& disk instabilities
rate ~ 60-80 %

Hubble Space Telescope

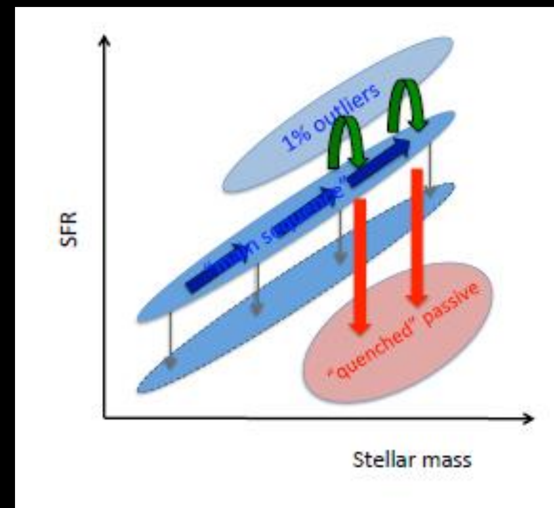
How do galaxies stop growing? quenching

Star formation rate

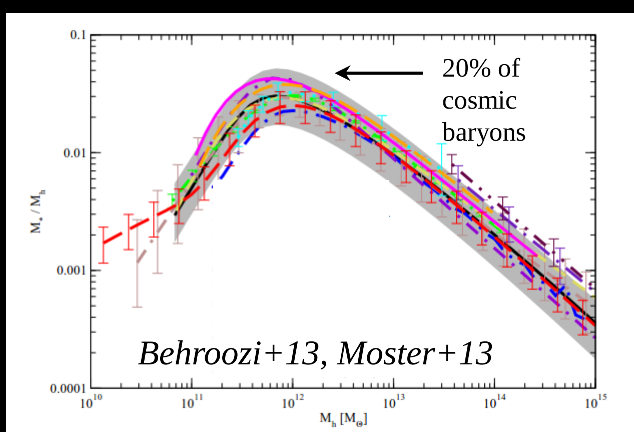


stellar mass

Peng & Renzini 2014



fraction of baryons in galaxies

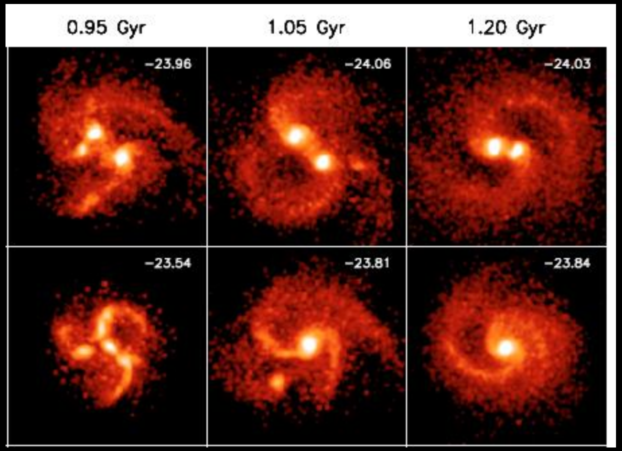


stellar mass

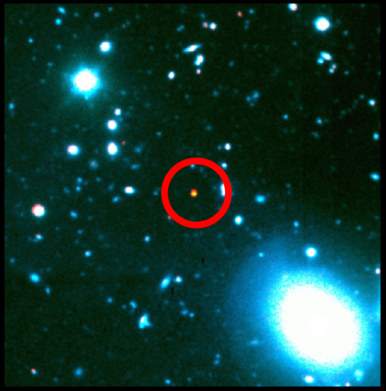
- cold/hot transition in accretion at M_{halo}~$10^{11.7..12}$ $M_\odot$ (Rees & Ostriker 1977, Dekel & Birnboim 2006, Ocvirk et al. 2008)
- major mergers/disk instabilities triggering outflows from AGN (Hopkins et al. 2006, Croton et al. 2006, Bower et al. 2007, di Matteo et al. 2005, Springel et al. 2005)

The angular momentum and early growth problems of MBH

R(galaxy)/R(BH)=15,000 ly/1AU~10^9

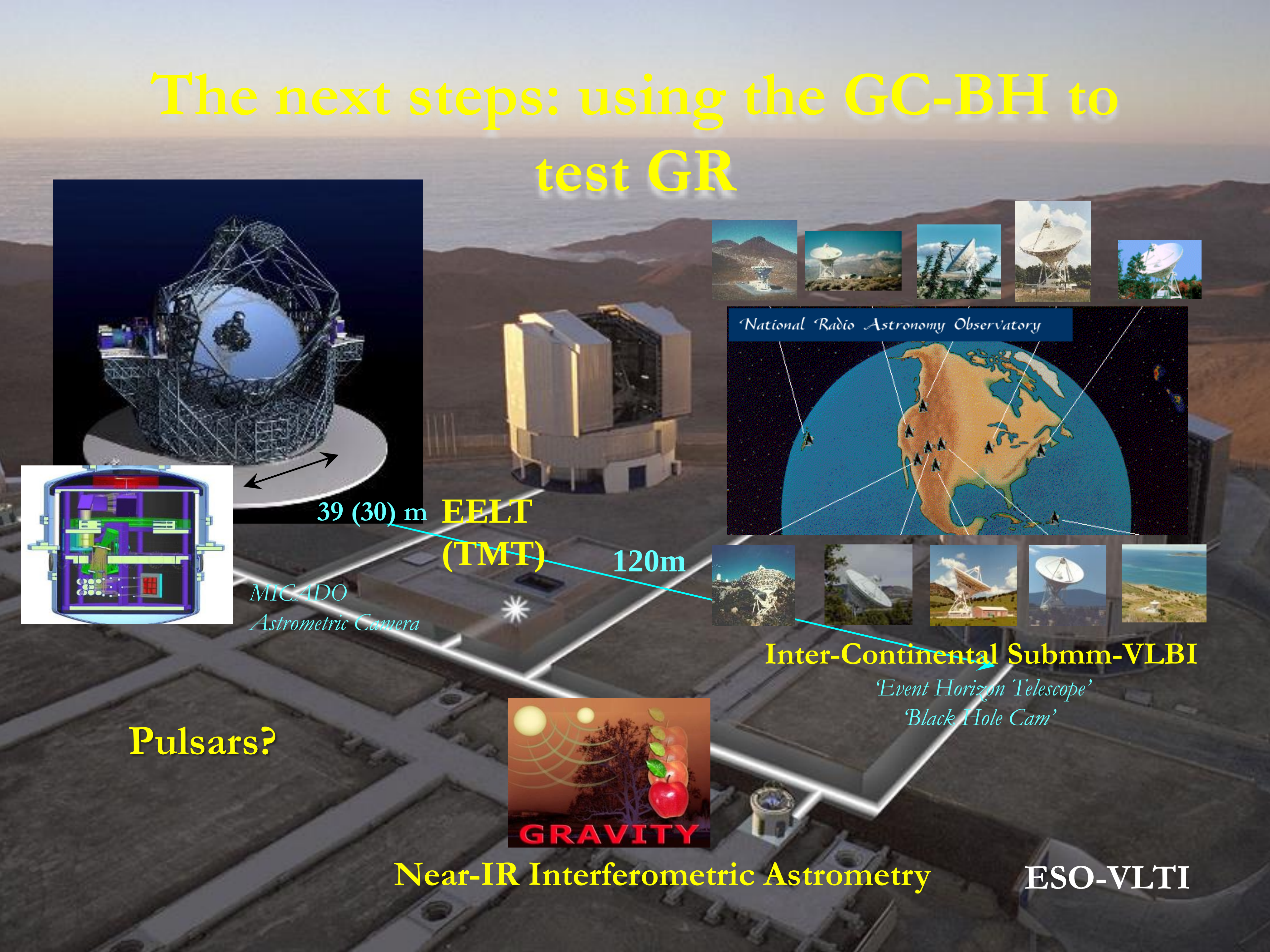


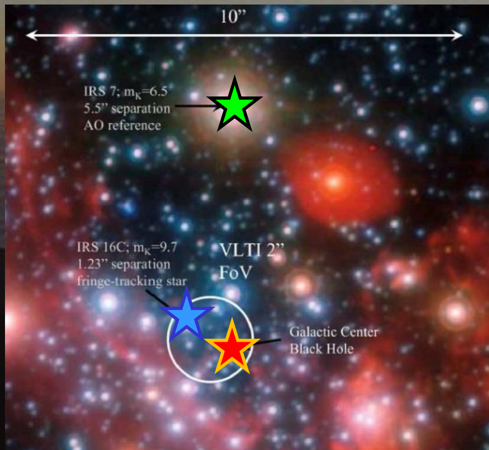
$$t_{growth} \overset{L\sim L_{Eddington}}{\approx} 2\times10^{8}\times\log\left(\frac{M_{final}}{M_{seed}}\right)\ \text{yr}$$



a 3 billion solar mass black hole 800 million years after the Big Bang!

Sanders et al. 1988, Kauffmann & Haehnelt 2000, Springel et al. 2005, Hopkins et al. 2006, Kocevski et al. 2012, Noguchi 1999, Immeli et al. 2003, Bournaud et al. 2011, Ceverino et al.2012, Rees 1984, Silk & Rees 1998,Volonteri 2010, 2012, Begelman et al. 2011

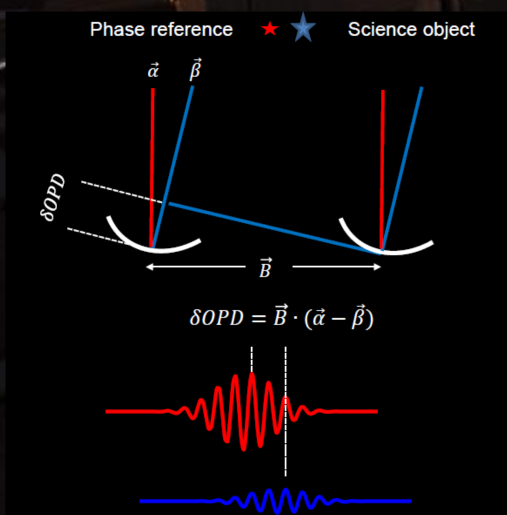

The next steps: using the GC-BH to test GR
National Radio Astronomy Observatory
39 (30) m
EELT
(TMT)
120m
MICADO
Astrometric Camera
Inter-Continental Submm-VLBI
'Event Horizon Telescope'
'Black Hole Cam'
Pulsars?
GRAVITY
Near-IR Interferometric Astrometry
ESO-VLTI



GRAVITY concept

PI
Frank Eisenhauer

- so far ground-based interferometry is restricted to observations of bright stars (K<5..9 on 2m…8m class array) since t_0(atm)~ 1ms;
  the stars near SgrA* suitable for GR tests are K>15, ~$10^{3…4}$ times fainter



GRAVITY:

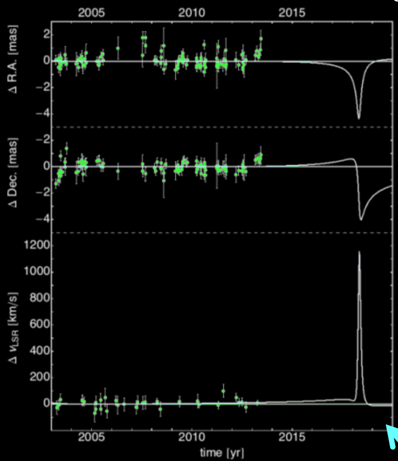
- dual beam astrometric interferometric imager
- K~17: high throughput optics, 4 UTs & AO, low noise detector
- 10µarcsec astrometry (10 mins)

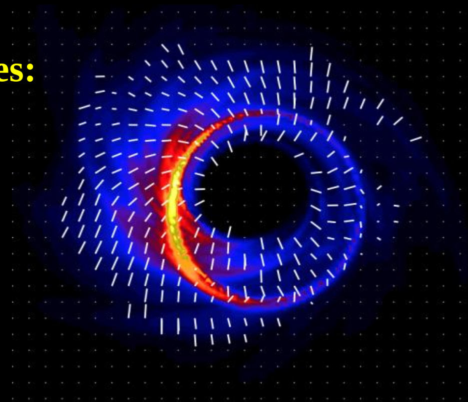
Eisenhauer et al. 2005, Gillessen et al. 2006

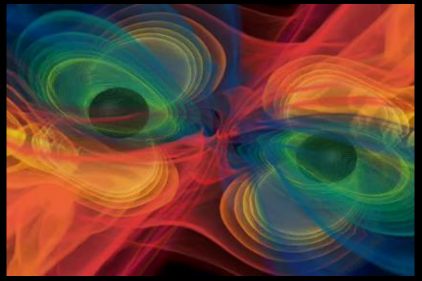
Inward bound

testing GR near massive black holes:

submm-VLBI (Event Horizon Telescope)
infrared interferometry (GRAVITY)
pulsars
30m-class telescopes
X-ray spectroscopy
gravitational waves







$$\theta_{shadow} \underset{\neq f(i,a)}{\overset{GR}{=}} (5.2 \pm 0.2) \times \frac{2GM_{\bullet}}{c^2 \times R_0}$$

1 PPN (1) in radial velocities

2 relativistic prograde precession

3 spin from L-T precession

4 Strong curvature: shadow

5 Quadrupole moment of metric, no hair & gravitational waves