A multi-messenger view of the first black holes in the Universe

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Université de Genève

Giant black holes …

Rev. John Michell
(25 December 1724 - 21 April 1793)

Exposition du Système du Monde
Laplace (1796, 1809)
[Ref: D. Lynden-Bell, ARAA (2010)]

VII. *On the Means of diſcovering the Diſtance, Magnitude, &c. of the Fixed Stars, in conſequence of the Diminution of the Velocity of their Light, in caſe ſuch a Diminution ſhould be found to take place in any of them, and ſuch other Data ſhould be procured from Obſervations, as would be farther neceſſary for that Purpoſe. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendiſh, *Eſq. F. R. S. and A. S.*

Read November 27, 1783.

29. If there ſhould really exiſt in nature any bodies, whoſe denſity is not leſs than that of the ſun, and whoſe diameters are more than 500 times the diameter of the ſun, ſince their light could not arrive at us; or if there ſhould exiſt any other bodies of a ſomewhat ſmaller ſize, which are not naturally luminous; of the exiſtence of bodies under either of theſe circumſtances, we could have no information from ſight: yet, if any other luminous bodies ſhould happen to revolve about them we might ſtill perhaps from the motions of theſe revolving bodies infer the exiſtence of the central ones with ſome degree of probability, as this might afford a clue to ſome of the apparent irregularities of the revolving bodies, which would not be eaſily explicable on any other hypotheſis; but as the conſequences of ſuch a ſuppoſition are very obvious, and the conſideration of them ſomewhat beſide my preſent purpoſe, I ſhall not proſecute them any farther.

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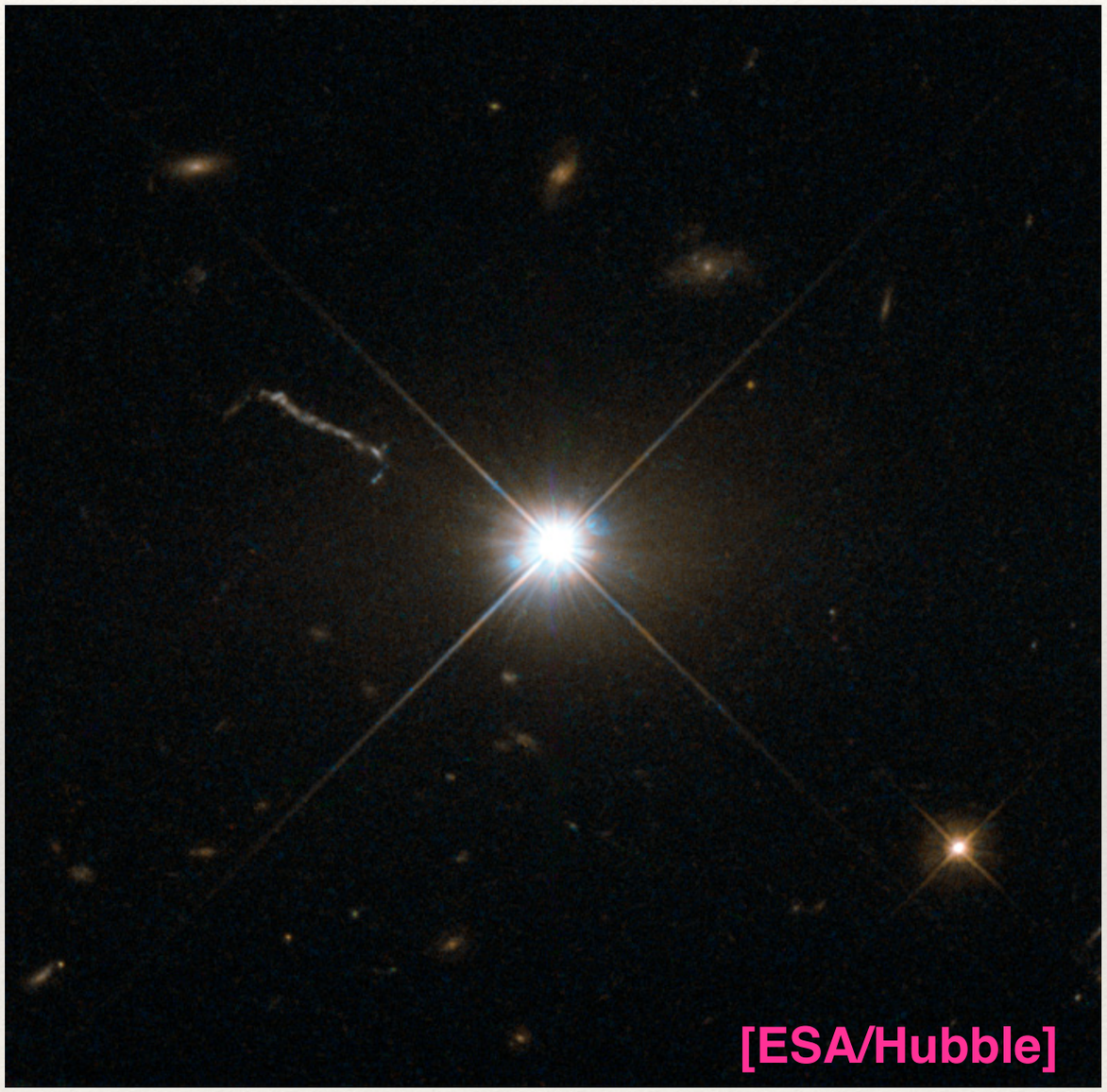
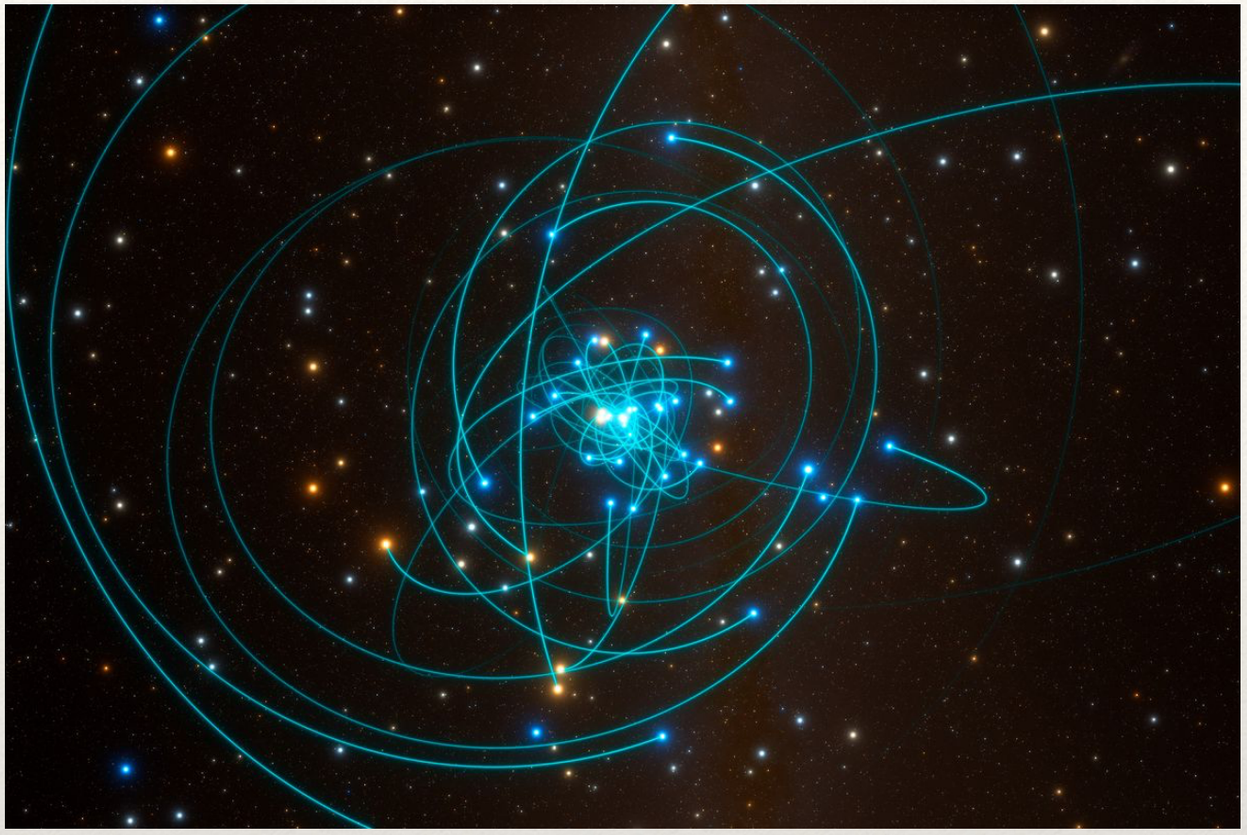
(Super)massive black holes are at the hearts of nearly all galaxies

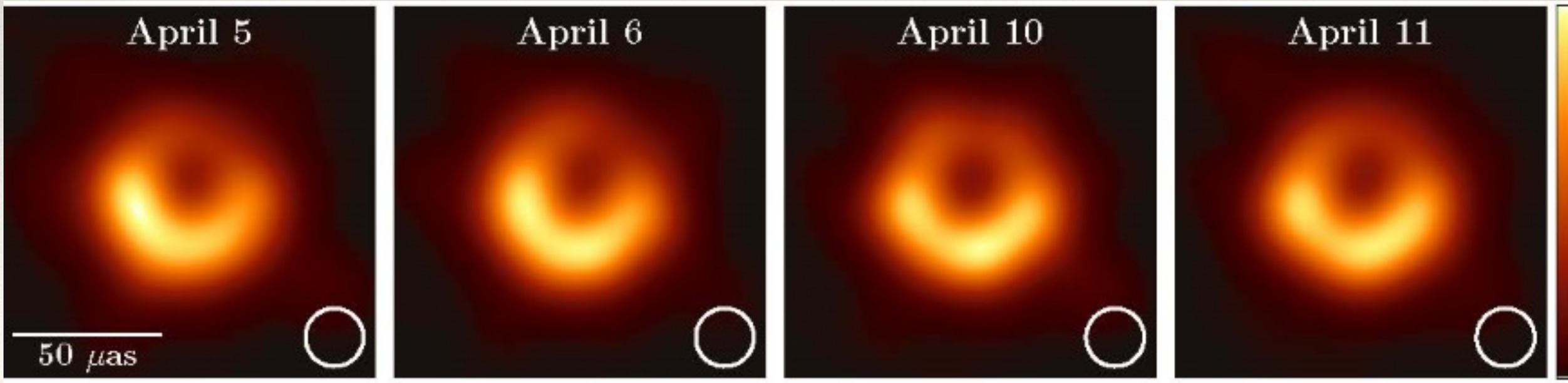


This paradigm has a long history …

Close to home …

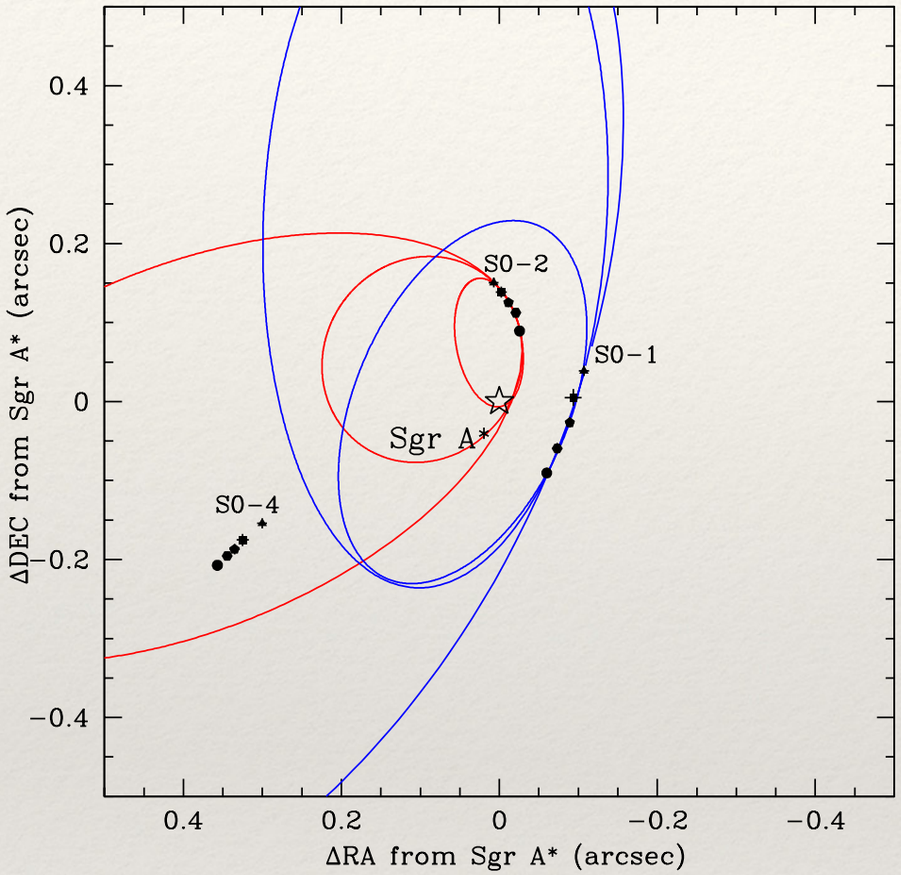


[ESO/L. Calçada]



[Shep Doeleman/ EHT collaboration (2019)]

… their masses have been measured directly, …

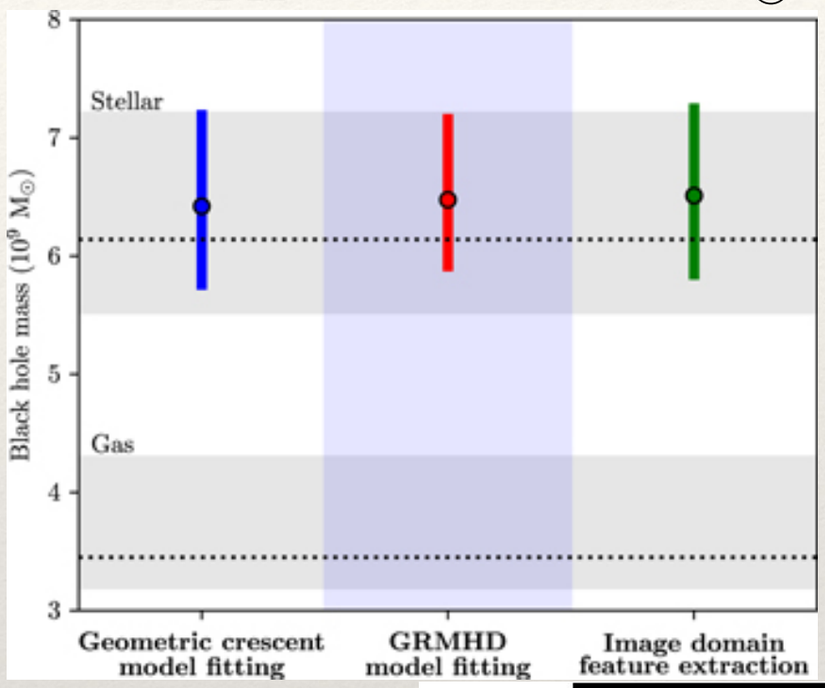


$$M_{\rm BH} = 4.1 \times 10^6 M_\odot$$

[Ghez+ (2001)]

M 87*

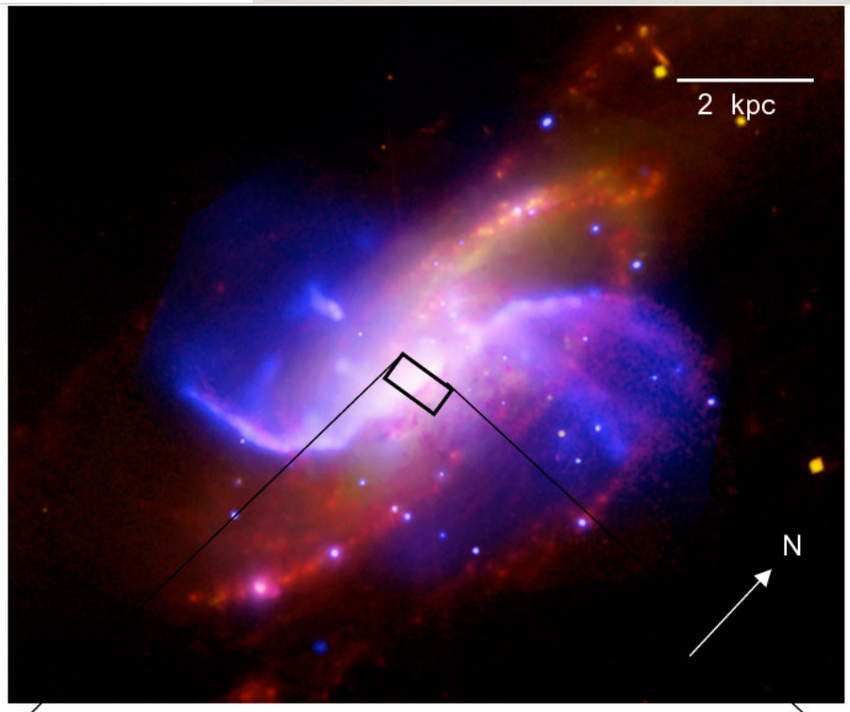
$$M_{\rm BH} = 6.5 \times 10^9 M_\odot$$



[EHT Collaboration, Akiyama+ 2019]

M 87*

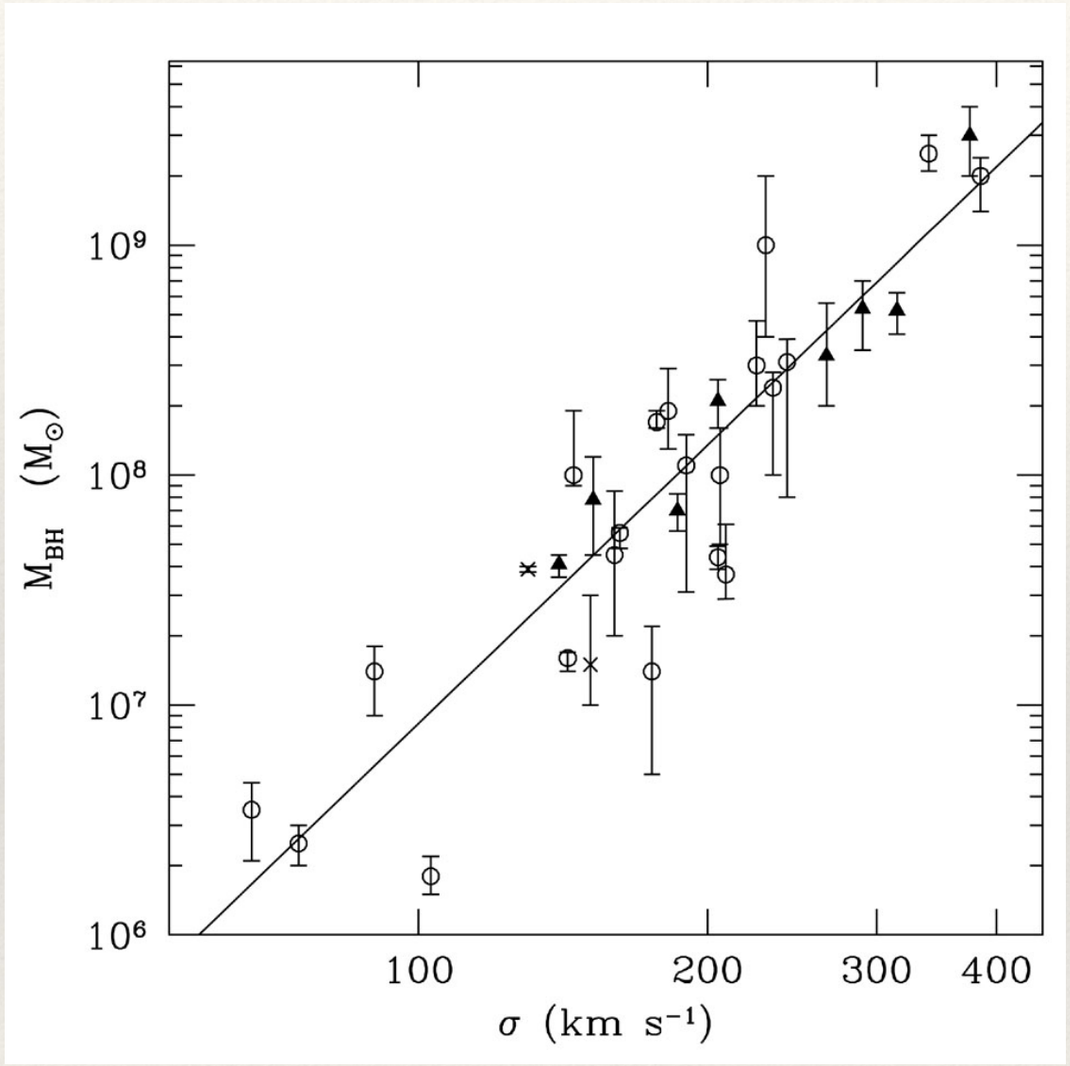
[Miyoshi+ 1995, Drehmer+ 2015, Reid+ 2019…]



Also: Woo+ 2019

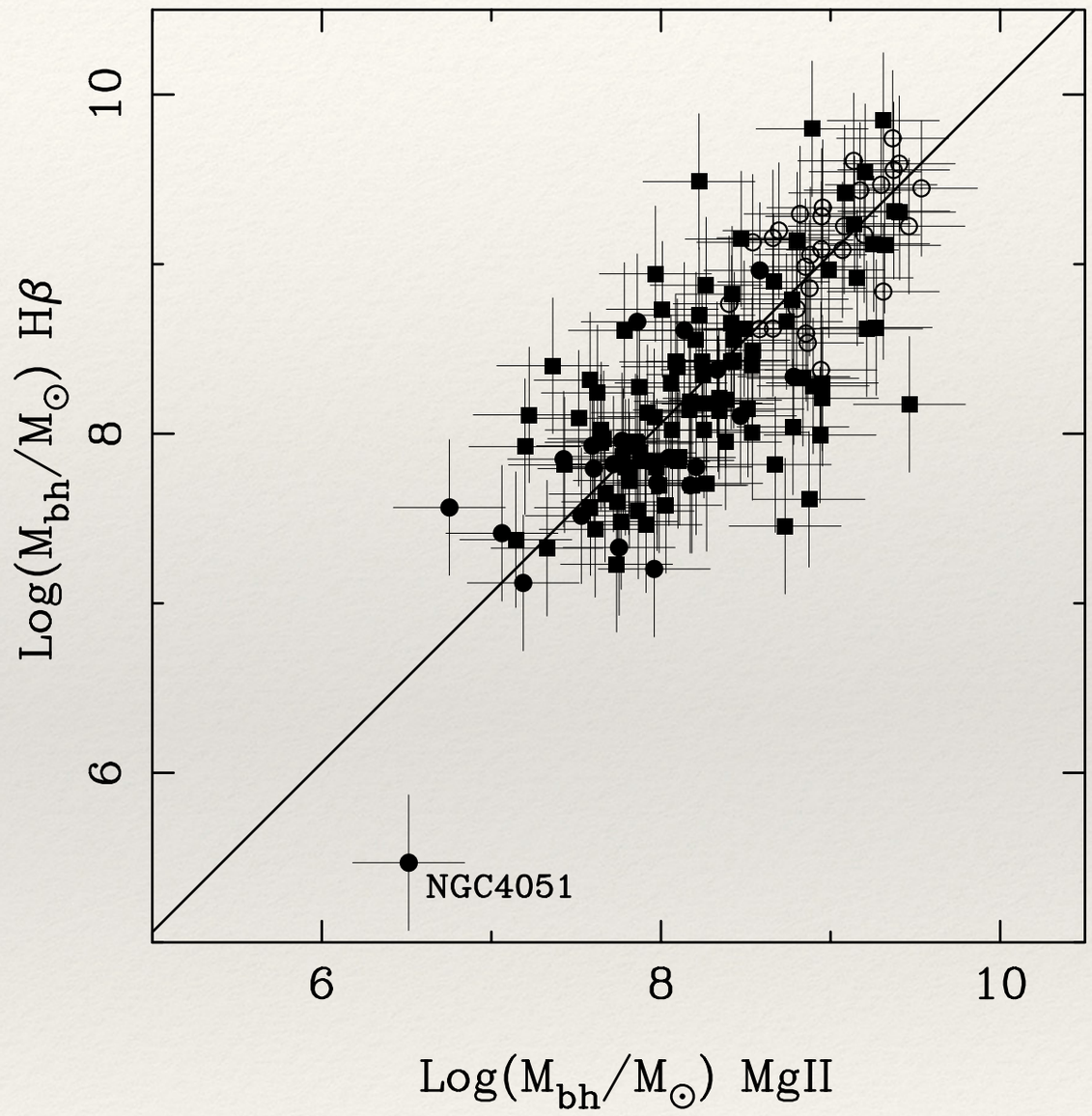
$$M_{\rm BH} = 3.6 \times 10^7 M_\odot$$

… but farther out, been calibrated to local relationships



[Ferrarese and Merritt (2000), Gebhardt et al. (2000), Tremaine+ (2002)]

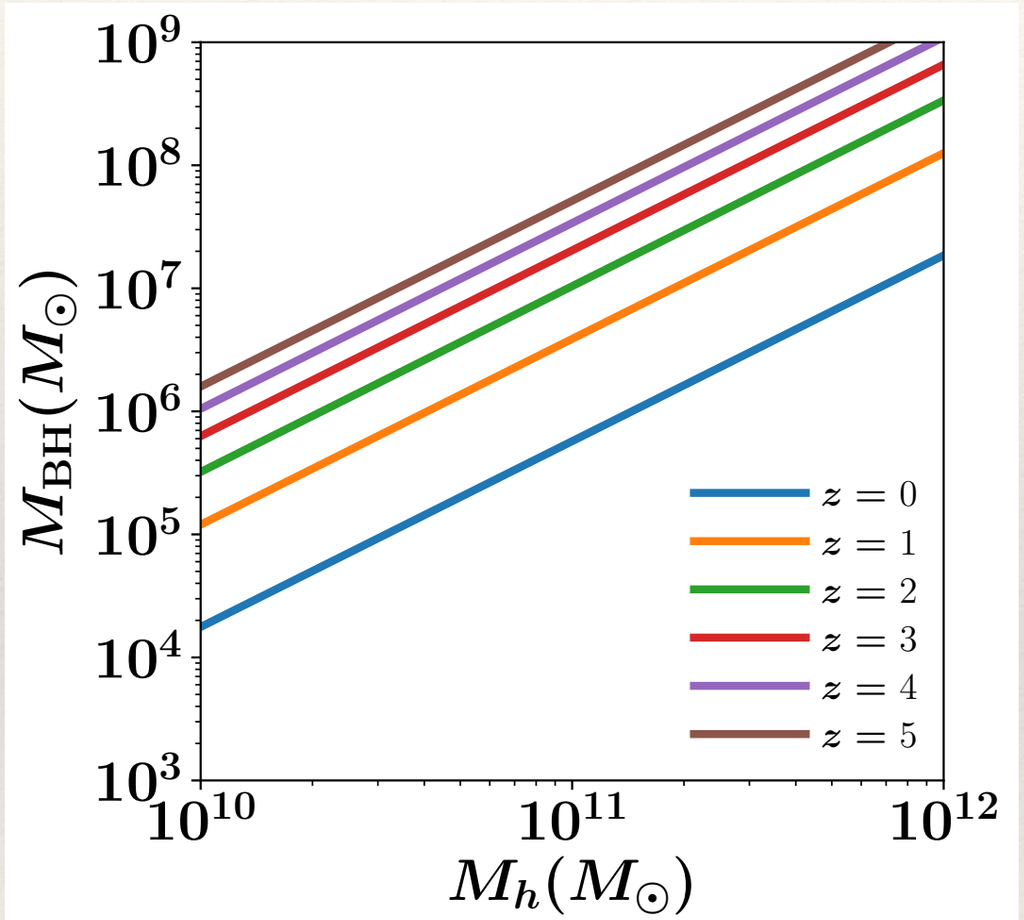
$M - \sigma$ relation



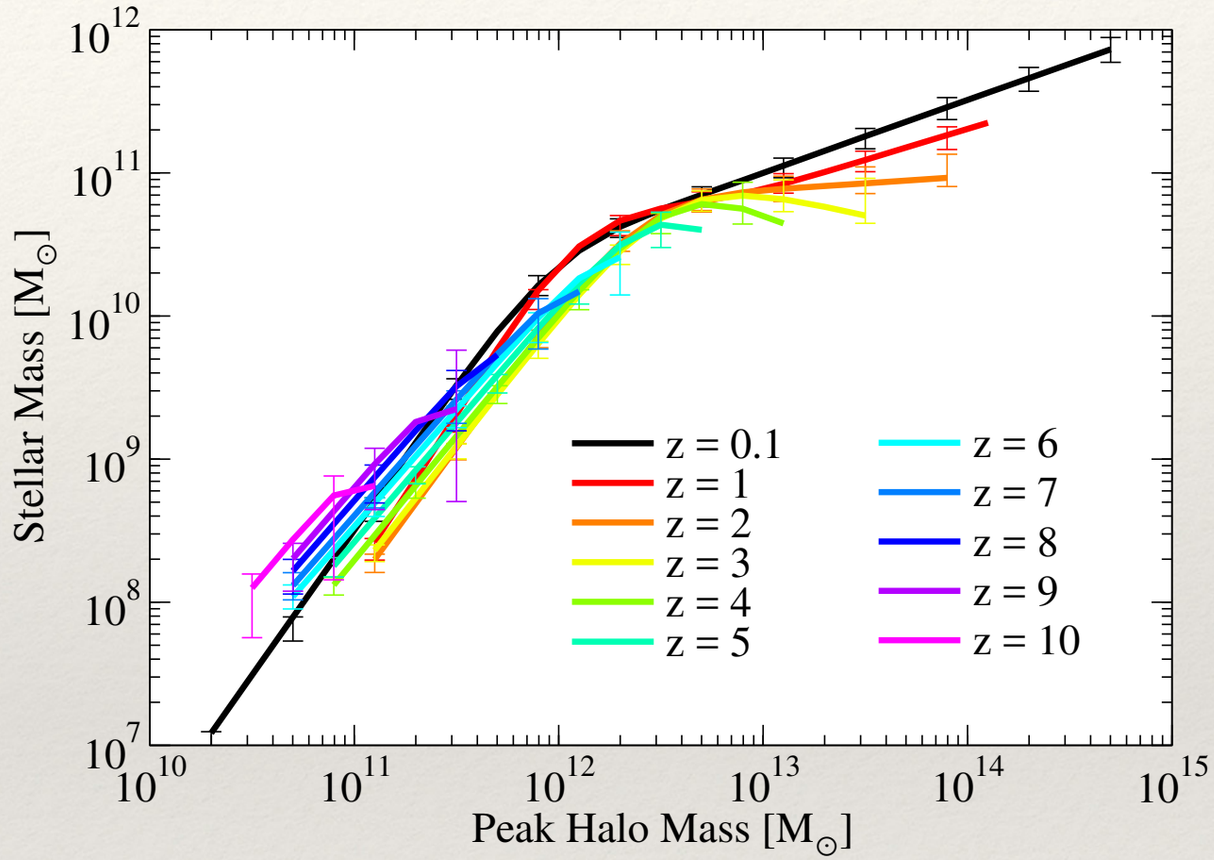
[McLure+ (2002)]

Correlation between BLR and luminosity

Empirical evidence: BH masses evolve stronger than stellar ones at high-z



[Wyithe and Loeb (2002), Ferrarese (2002), Croton+ (2009)]



[Behroozi+ (2018)]

Data:
SDSS, GAMA, ULTRAVISTA, CANDELS, ZFOURGE

*Can we **directly** measure black hole masses at high redshift?*

Look for *Keplerian* signatures at high-z

Region of influence of the black hole

$$M_{\rm BH} = M_h \epsilon_0 \left(\frac{M_h}{10^{12} M_\odot} \right)^{\gamma/3-1} \left(\frac{\Delta_v \Omega_m h^2}{18\pi^2} \right)^{\gamma/6} (1+z)^{\gamma/2}$$

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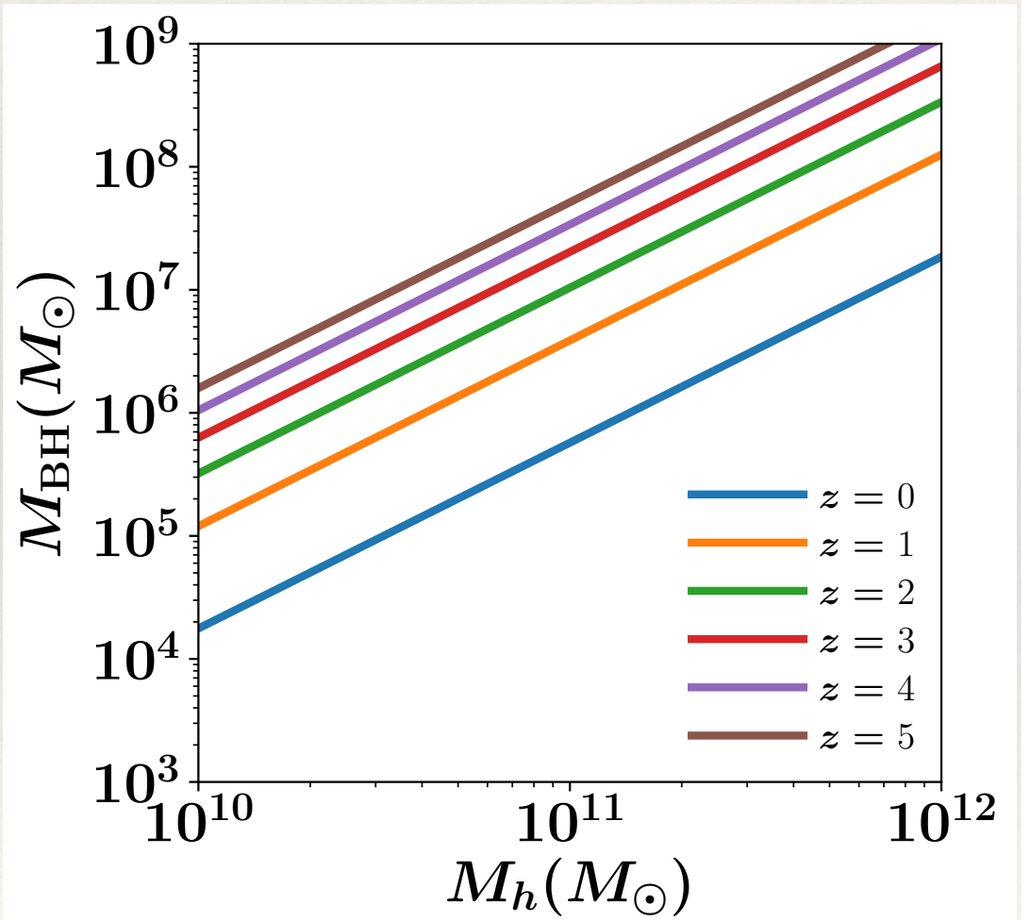

[Wyithe and Loeb (2002)]

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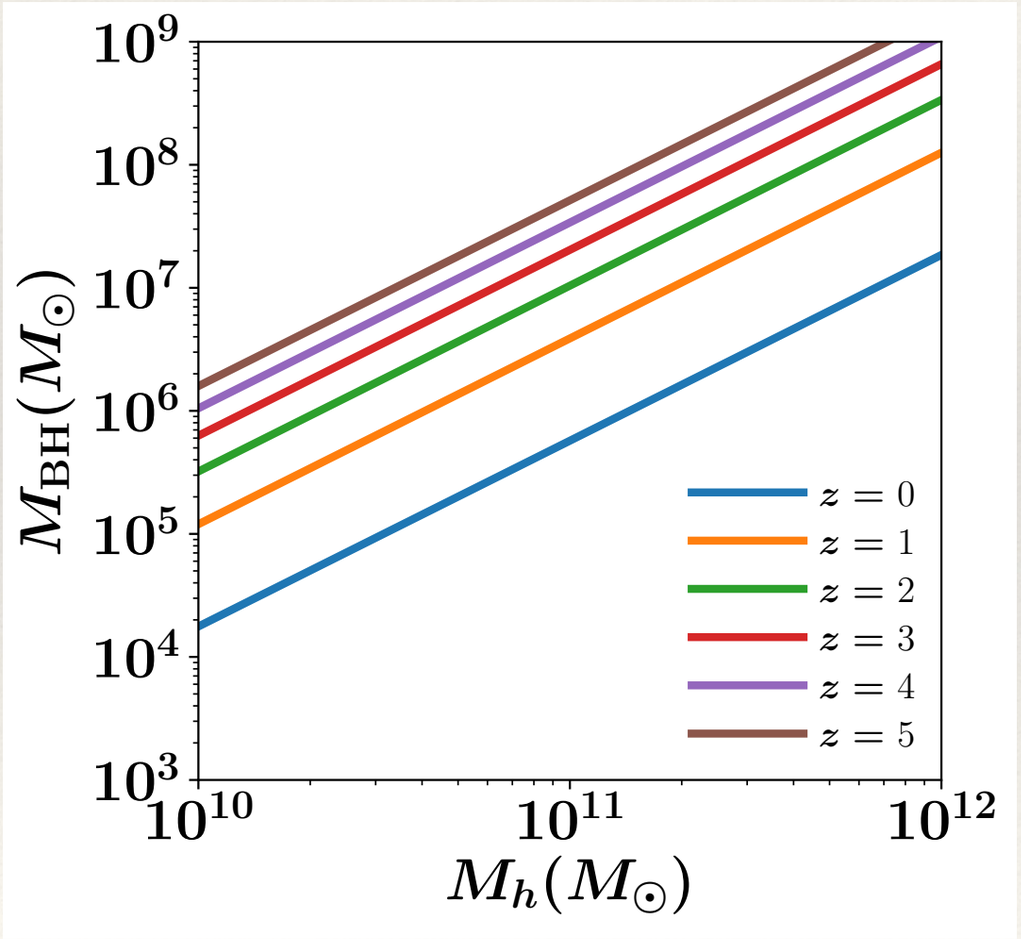
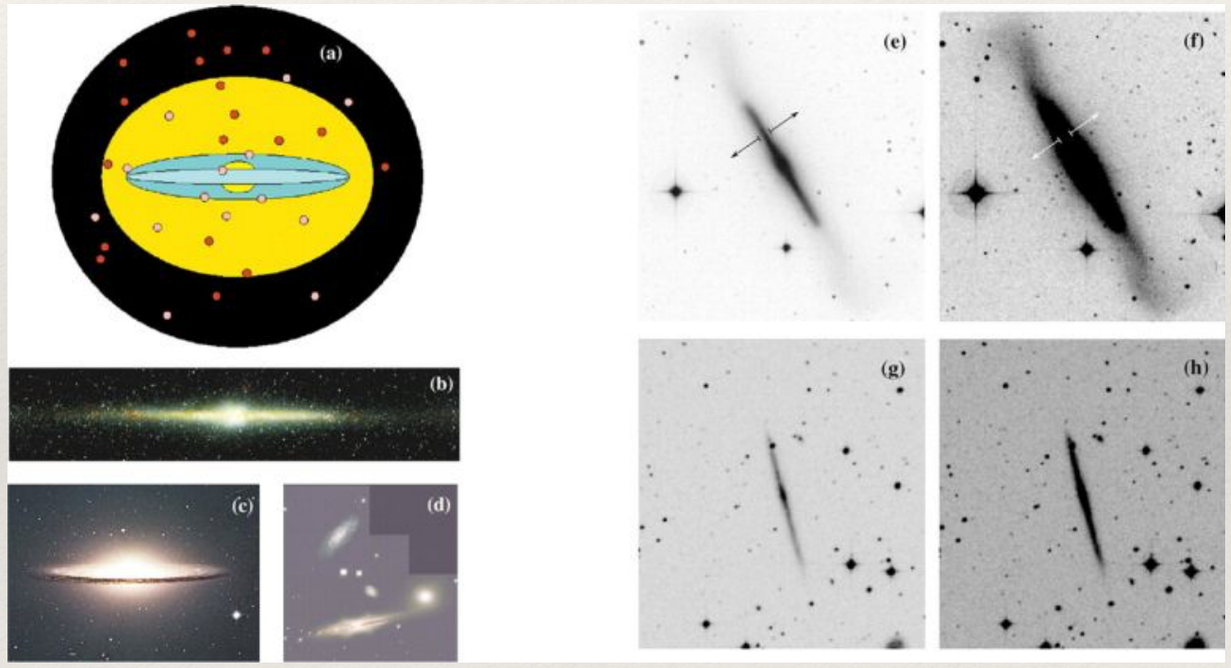


[Wyithe and Loeb (2002)]



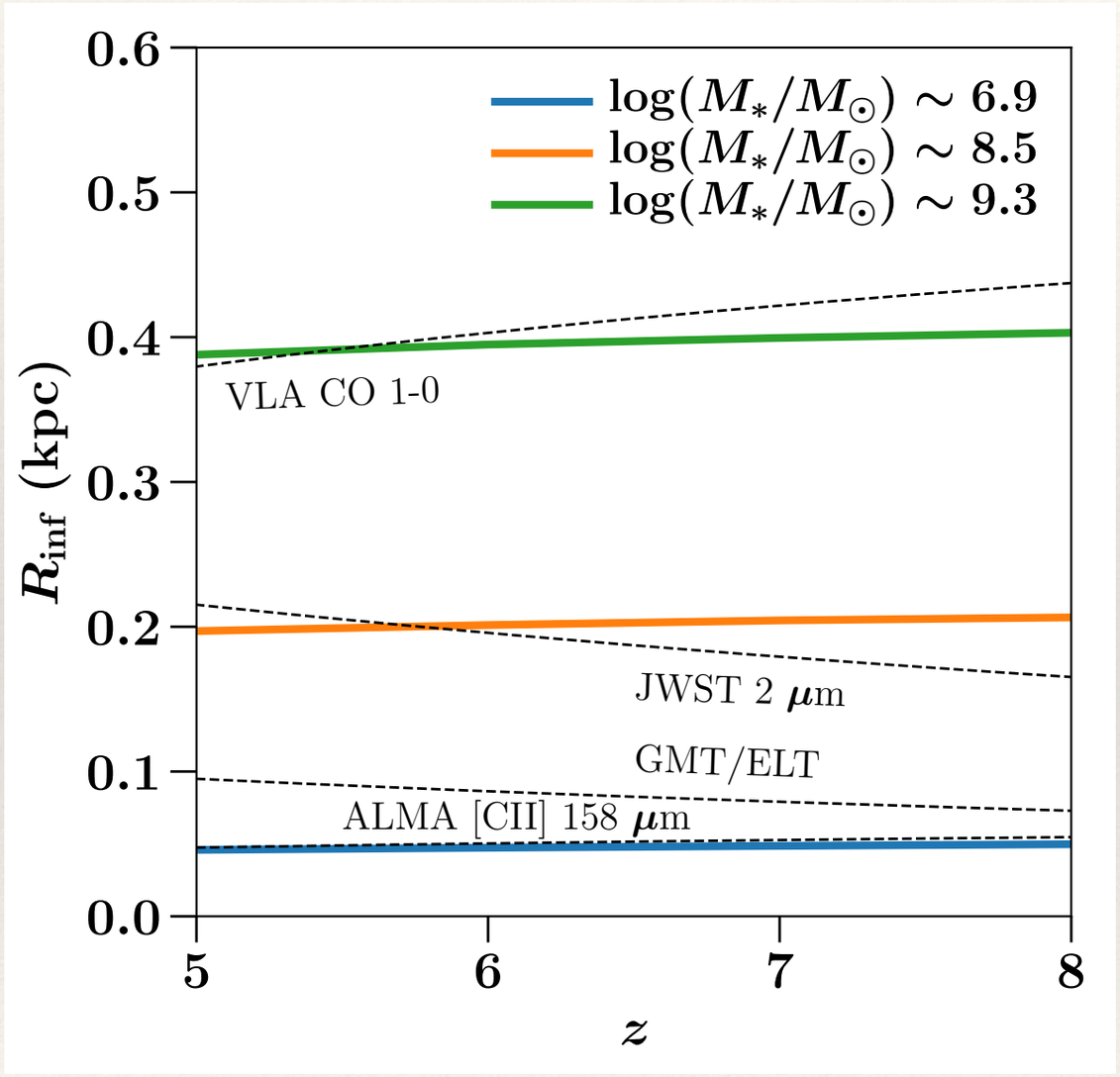
[NASA/COBE]

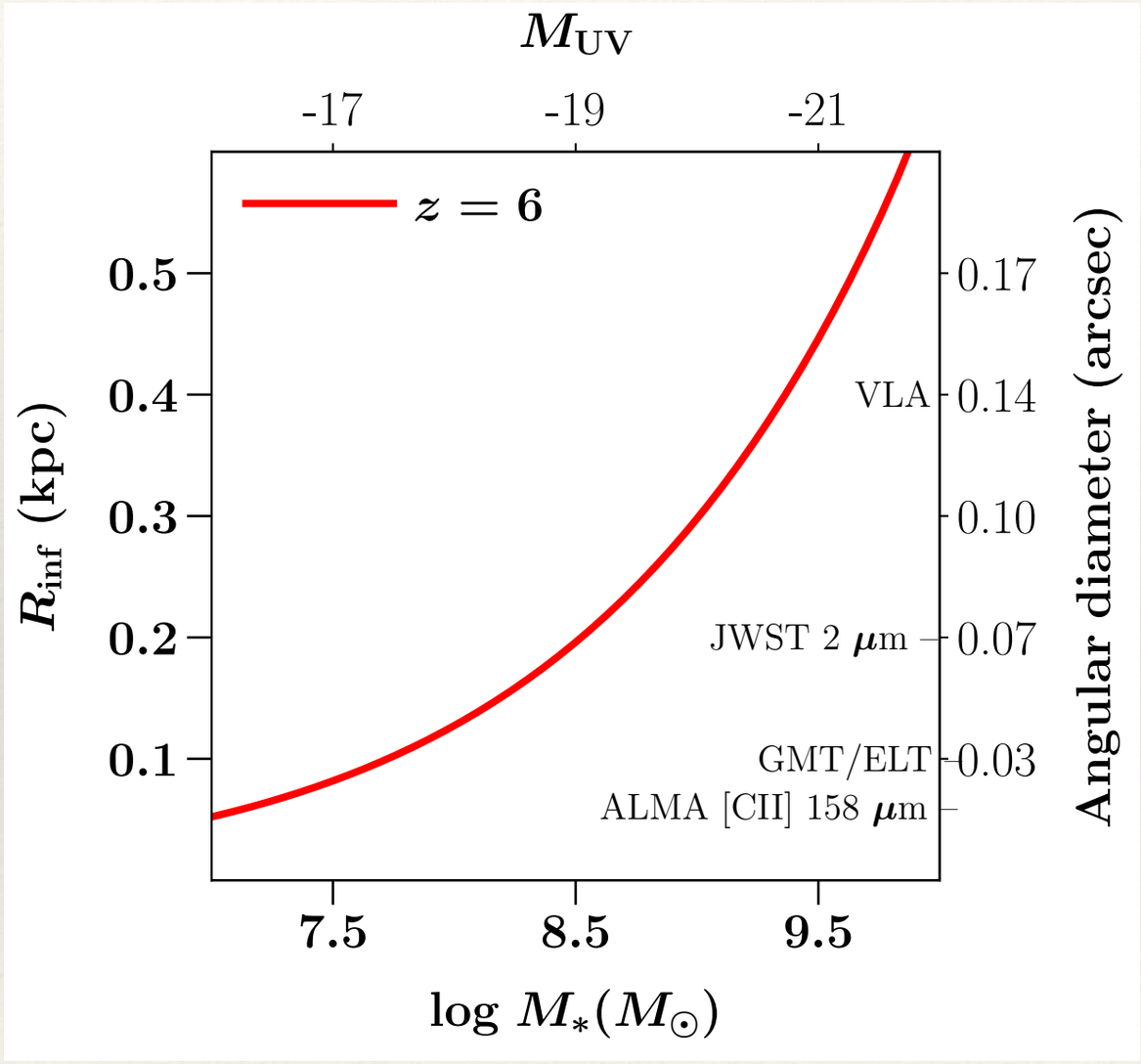
$$R_d \sim (1+z)^{-1}$$

[Shibuya+ (2019), HST/Hubble Frontier Fields]

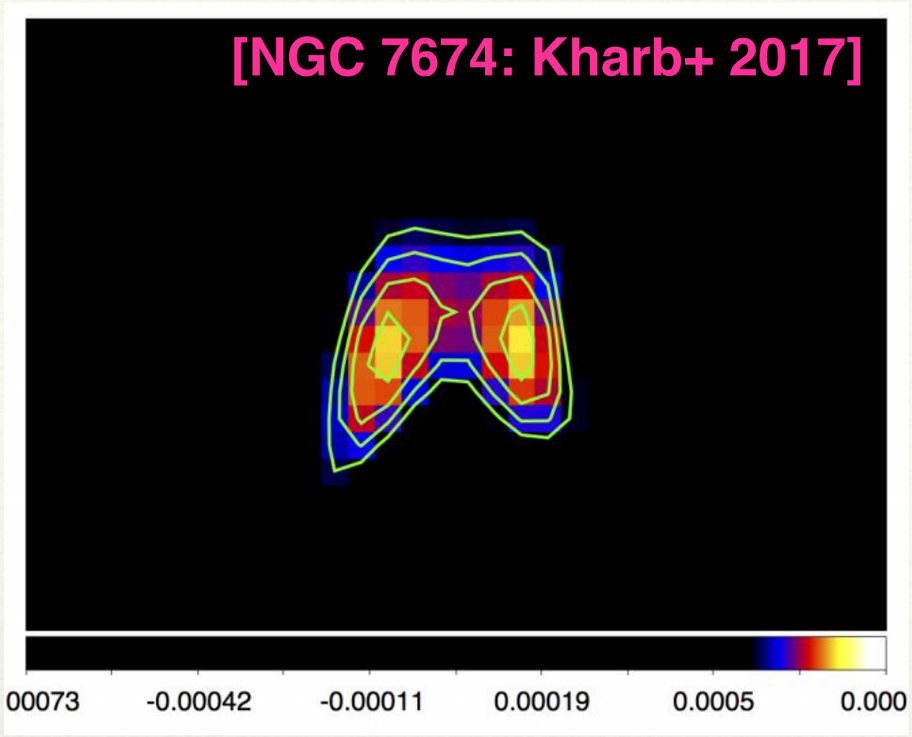
$$M_{\rm BH} = M_{\rm halo}(R_{\rm inf}) + M_{\rm d}(R_{\rm inf})$$

[Tacchella+ (2018), HUDF/Hubble Frontier Fields]



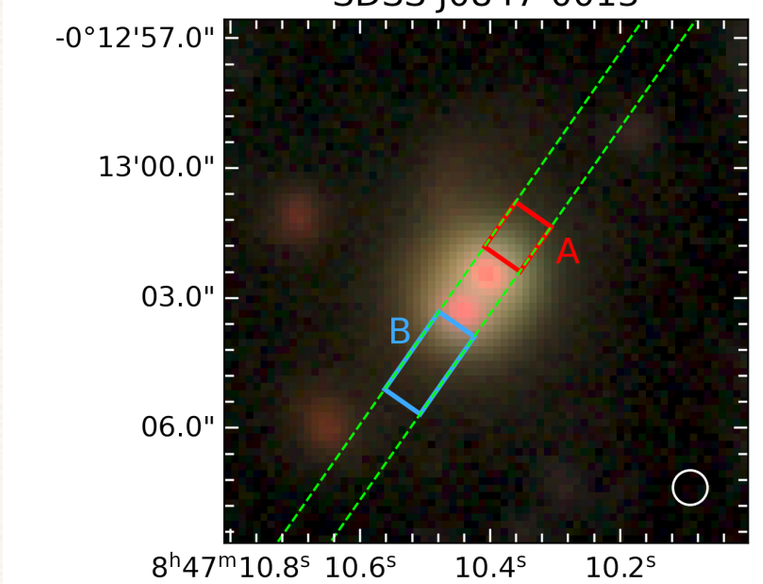


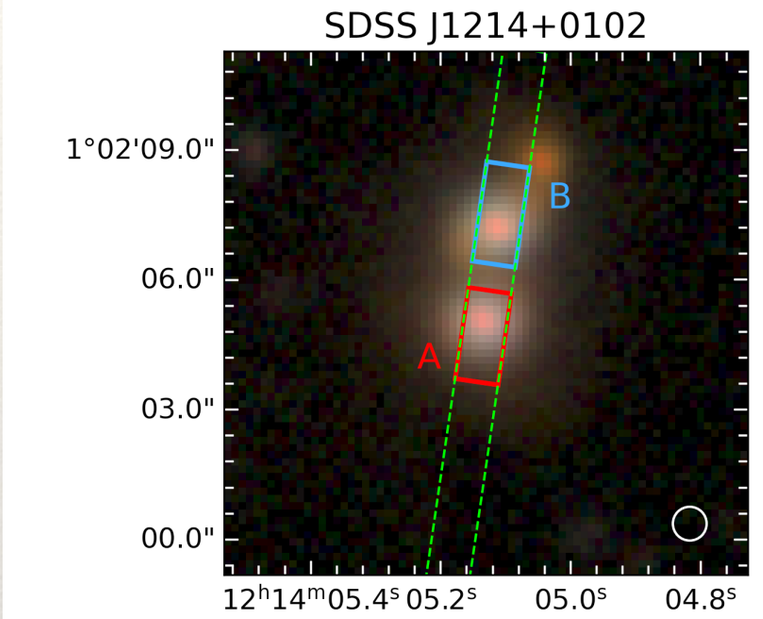
[HP and Loeb, JCAP (2020), arXiv:1912.05555]

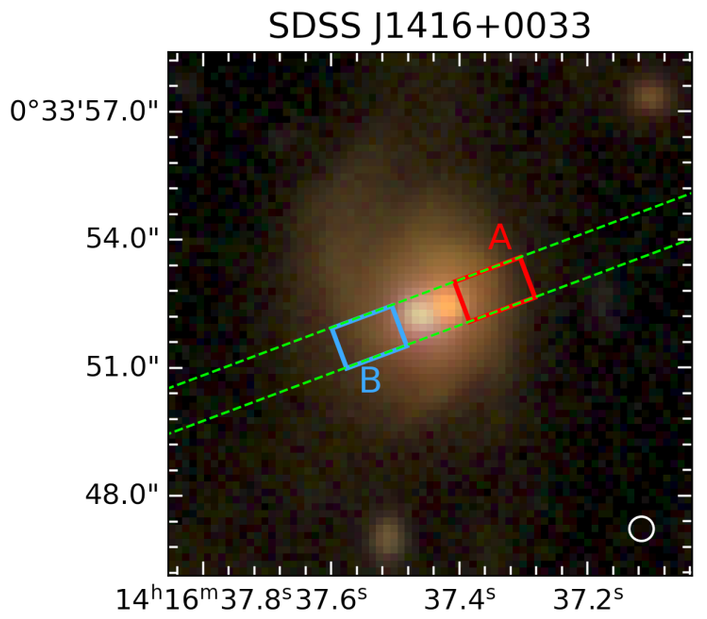


[…. but see also Breiding+ (2022), ApJ]
[Rodriguez et al. 2006]

[NGC 6240: Komossa+ 2003, Kollatschny+ 2020,
Kulkarni and Loeb 2012,
NASA/CXC/MIT/C. Canizares]



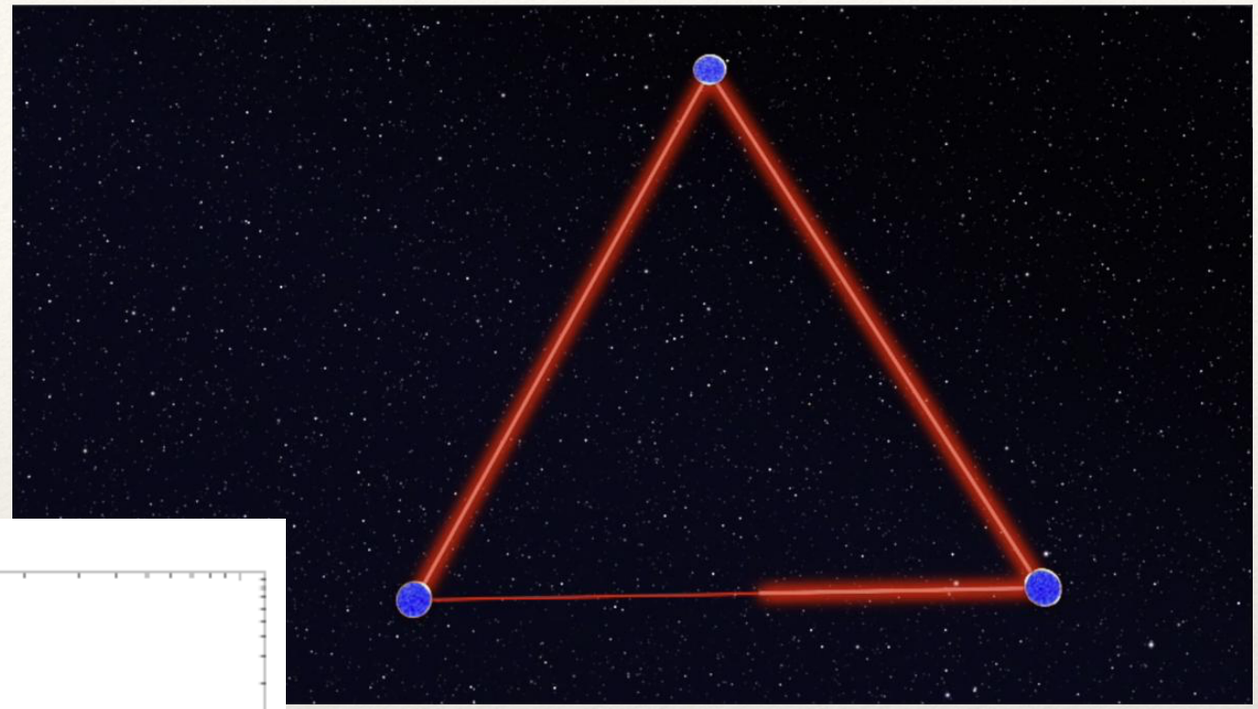


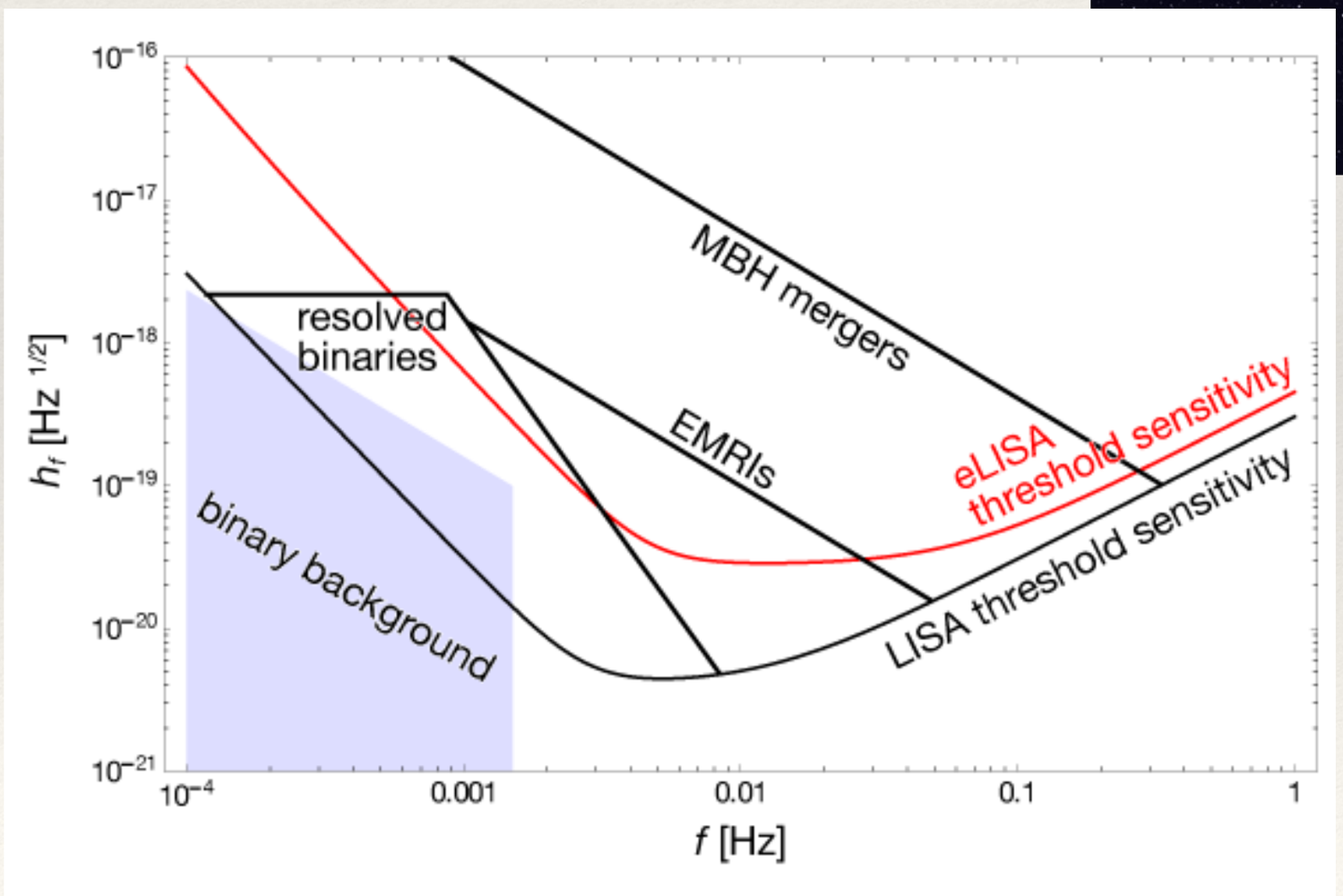


[SDSS: Silverman+ 2020]

GW emission detectable with LISA

[LISA collaboration/
AEI/Max-Planck Institute]

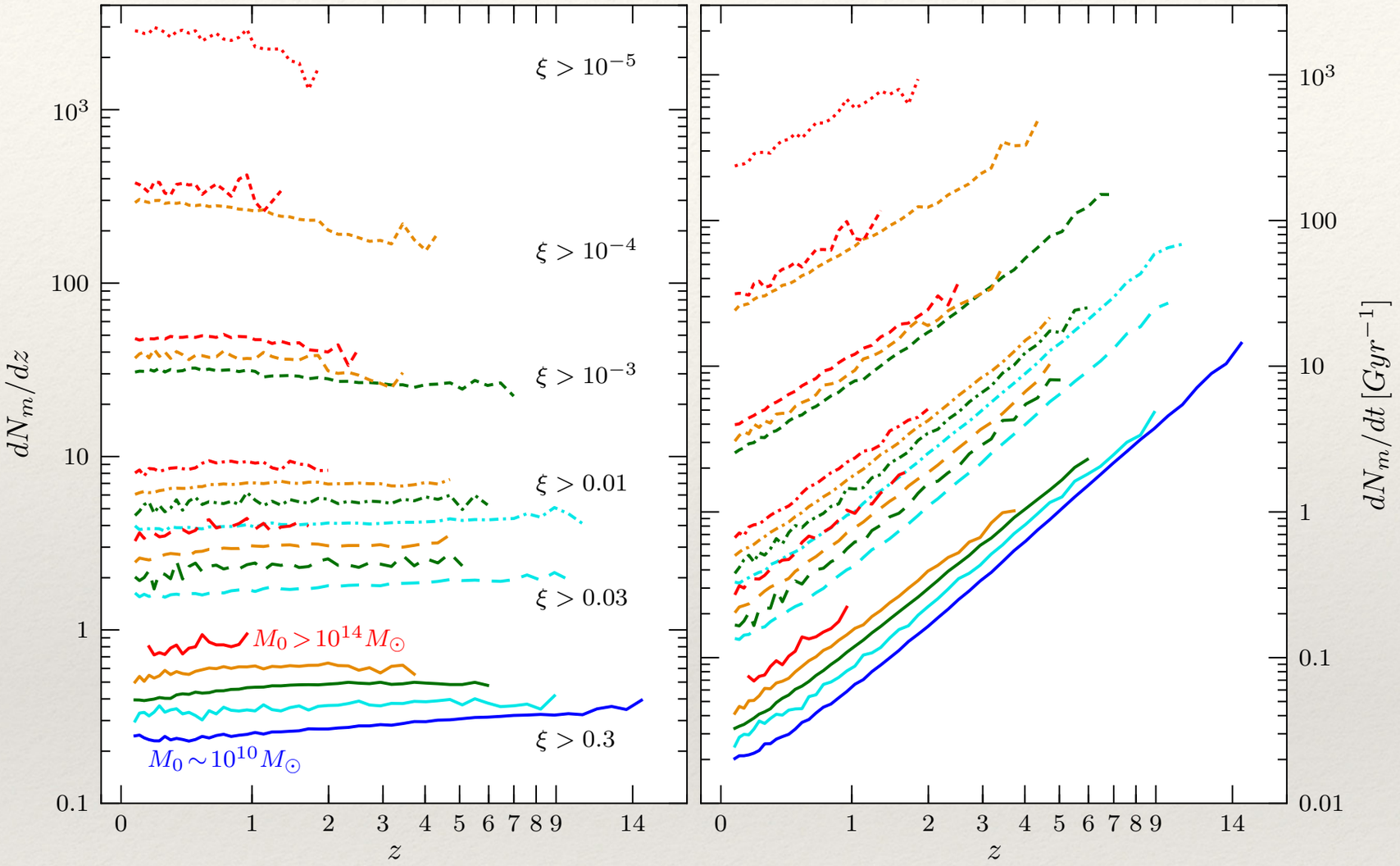




[Haehnelt (1994), Hughes+ (2001),
Wyithe and Loeb (2002)]

[Gair+ (2013)]

Merger rates of DM haloes



[Fakhouri+ 2013]

$$\frac{dn_{\rm halo}}{d\log_{10} M dz d\xi} = A\left(\frac{M}{10^{12} M_\odot}\right)^{\alpha} \xi^{\beta} \times \exp\left[\left(\frac{\xi}{\bar{\xi}}\right)^{\gamma_1}\right] (1+z)^{\eta} \frac{dn_{\rm halo}}{d\log_{10} M}$$

Parameters from the halo model

$$q, M_{\rm BH}, z, f_{\rm bh}, \epsilon_0, \gamma$$

Existing constraints

$$\Delta q/q, \Delta M_{\rm BH}/M_{\rm BH}, \Delta z/z$$

[Hughes 2002, Lang & Hughes 2006, 2010]

Parameters from the halo model

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“Known”

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“Known” **“Unknown”**

Existing constraints

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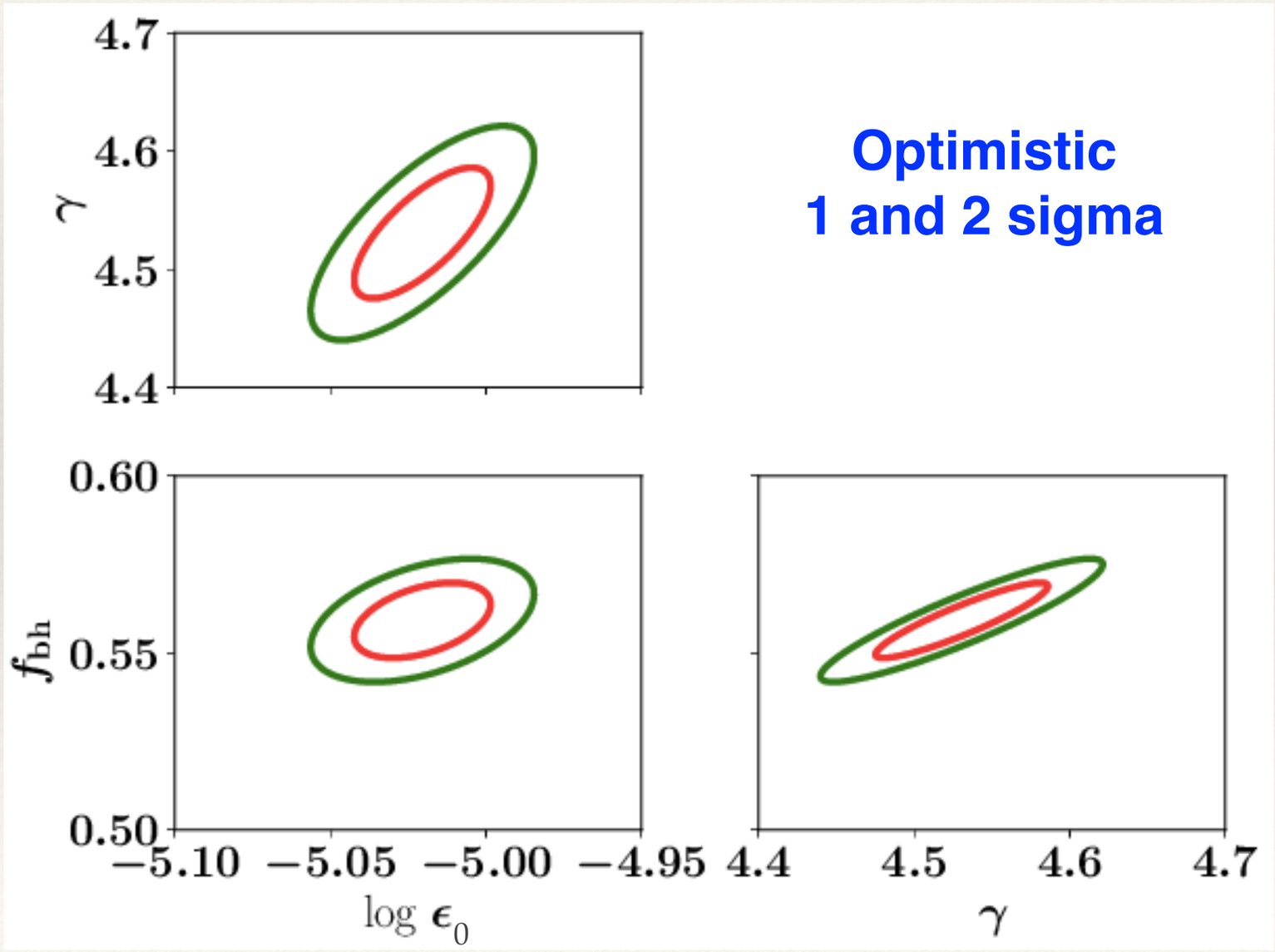
[Hughes 2002, Lang & Hughes 2006, 2010]

Forecasting: Confidence scenarios

Variance from Fisher matrix

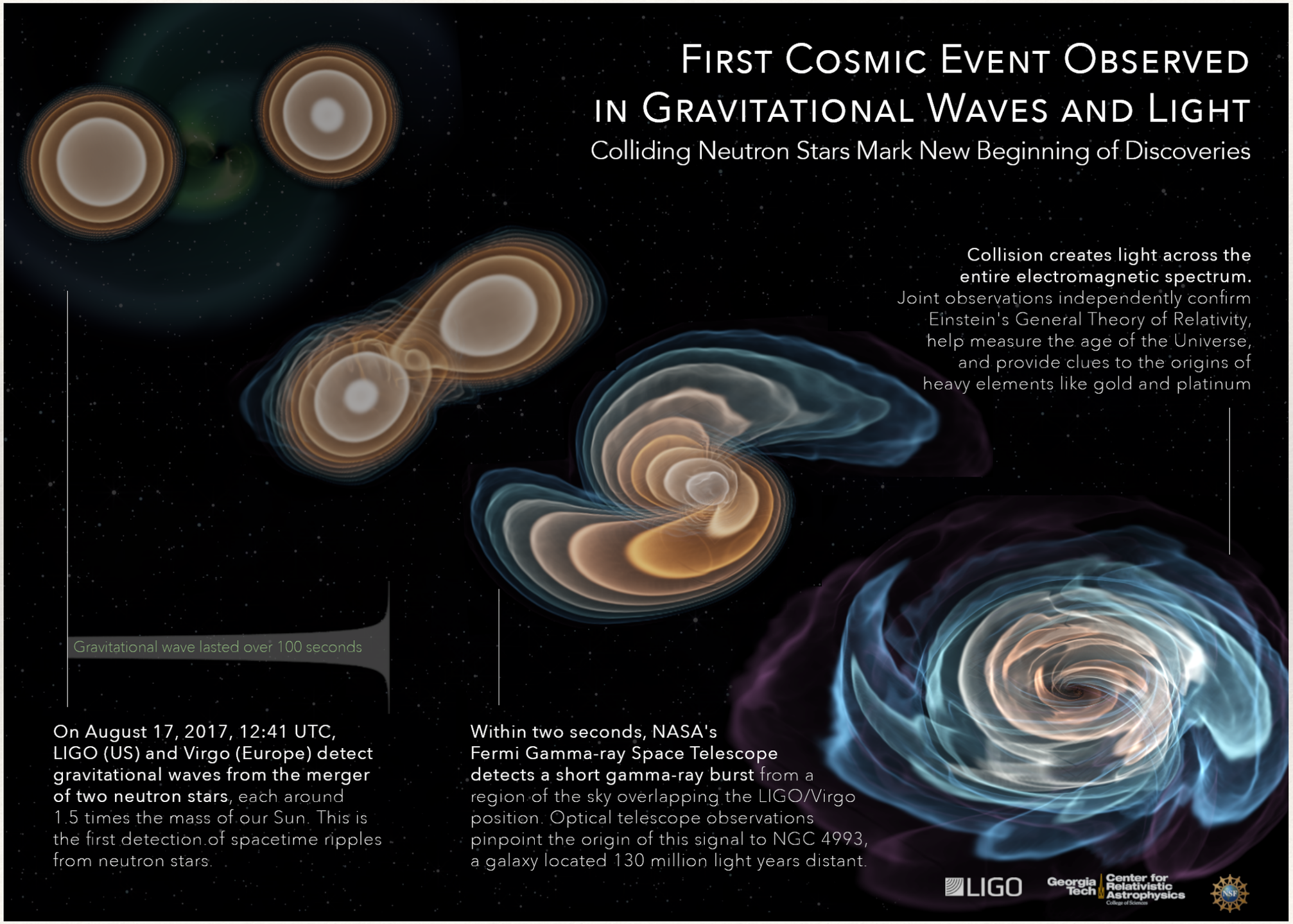
$$\sigma(p_i) = \sqrt{(\mathcal{F}^{-1})_{ii}}$$



Optimistic
1 and 2 sigma

[HP & Loeb, JCAP (2020), arXiv:2007.12710]

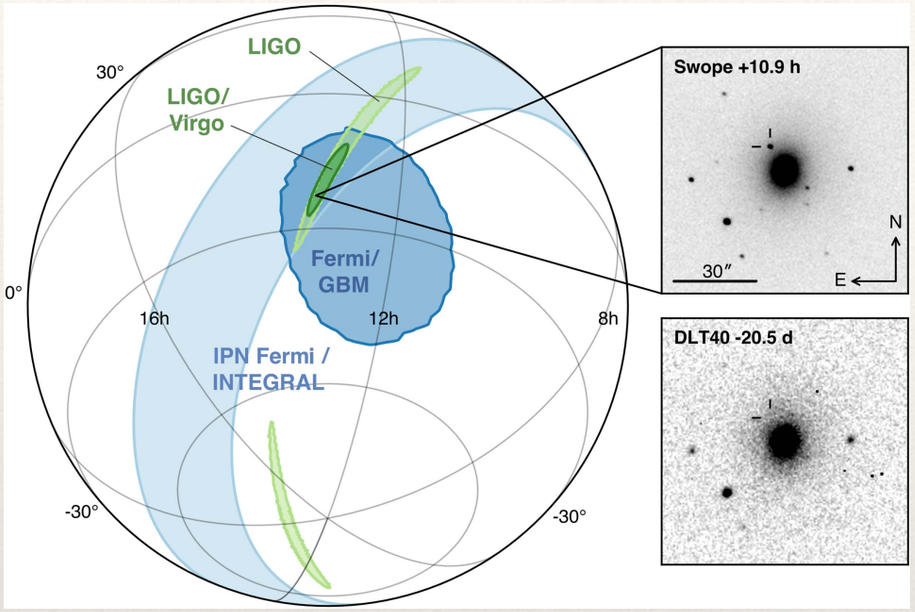
Localization; EM counterparts



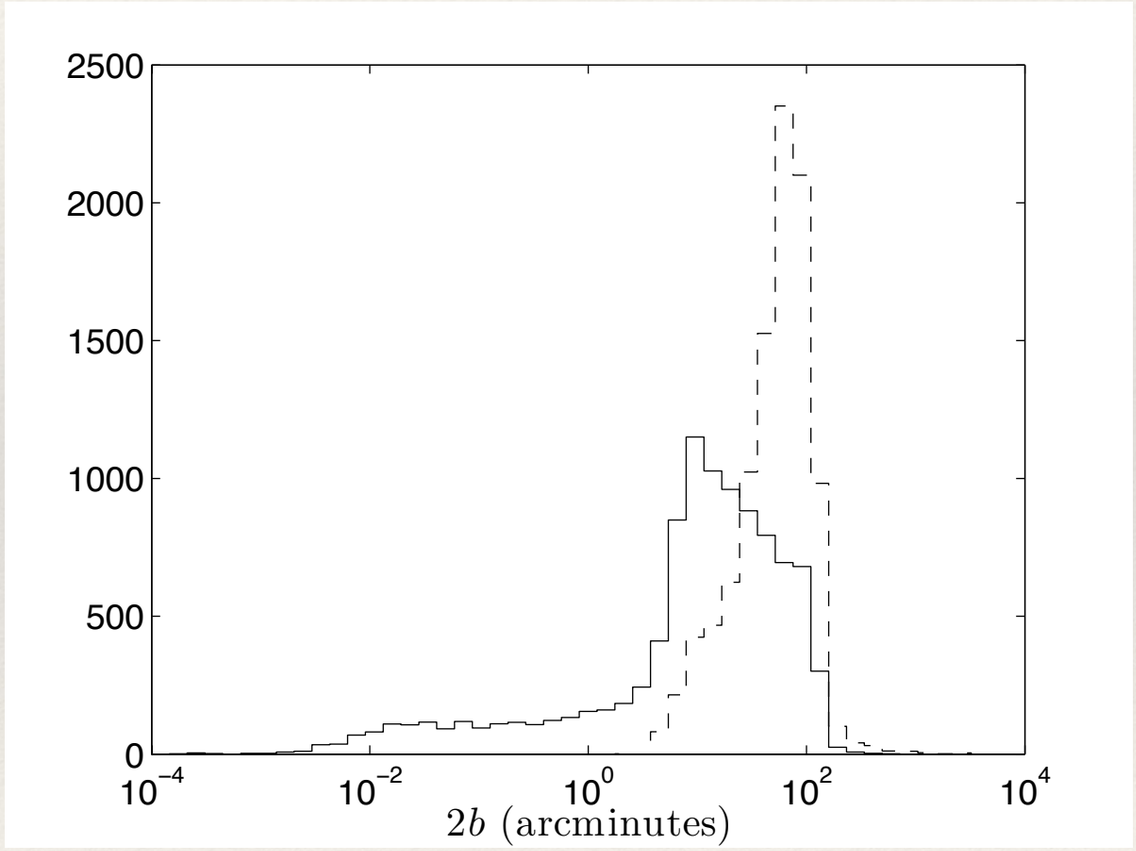
[LIGO/Georgia Tech]

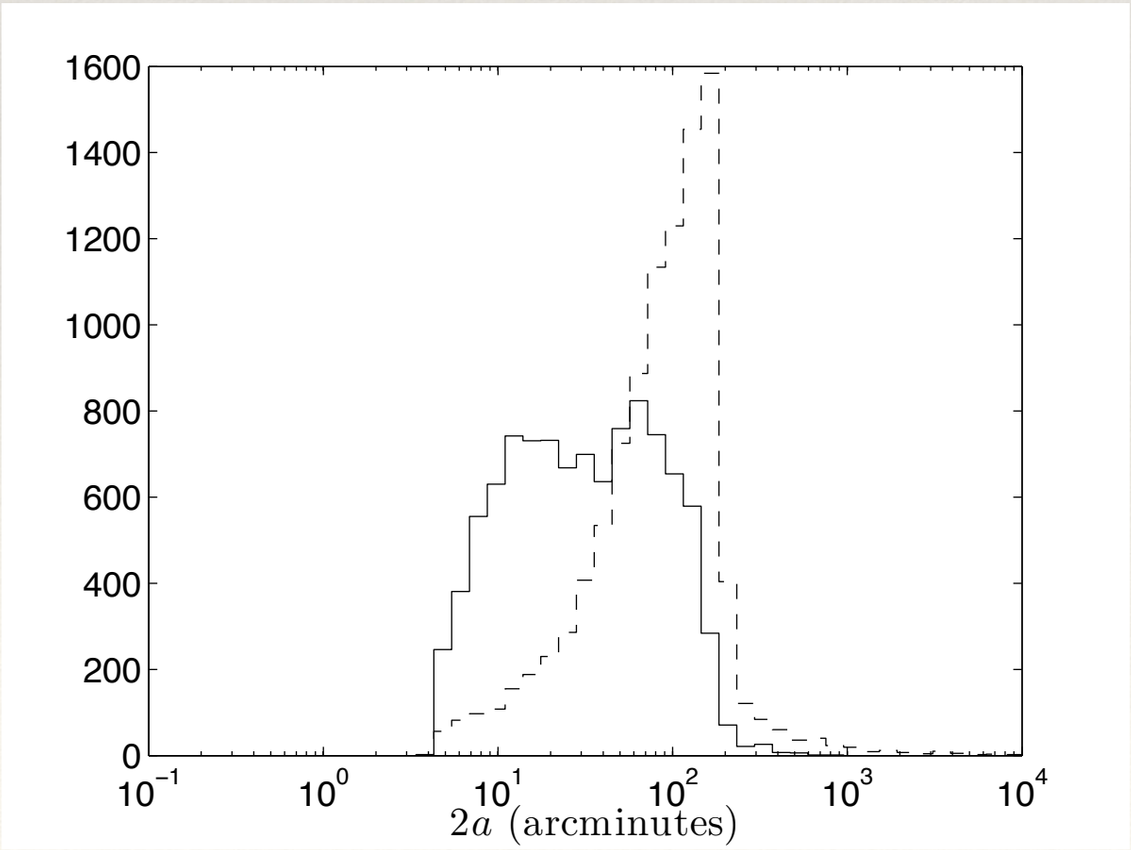
Error ellipses in SMBH localisation

[LIGO++ (2017)]



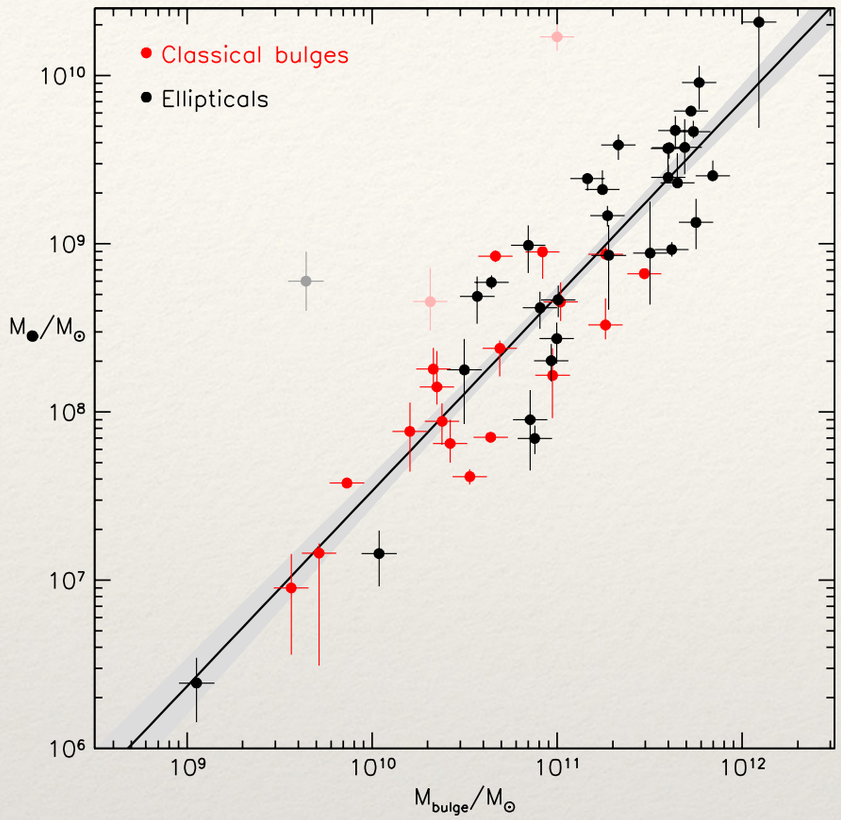
[Lang & Hughes (2006)]

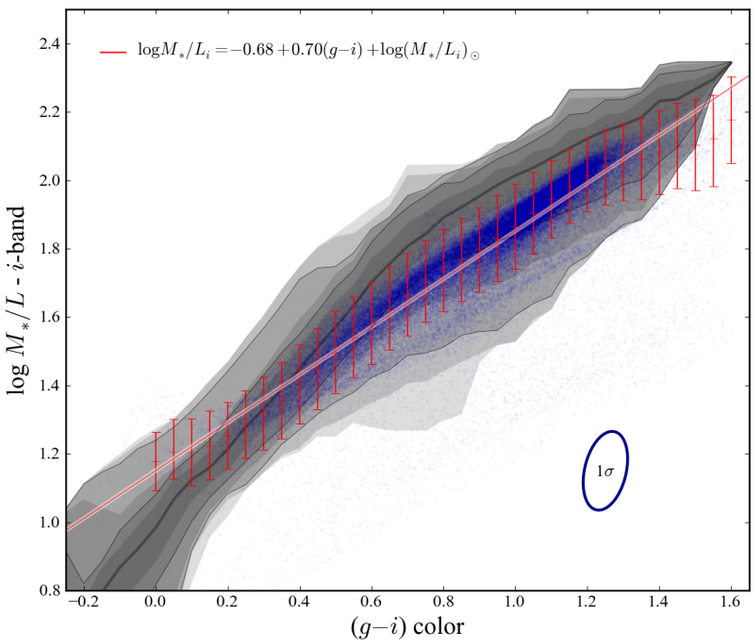




13 to 81 arcmin

High-z electromagnetic counterparts





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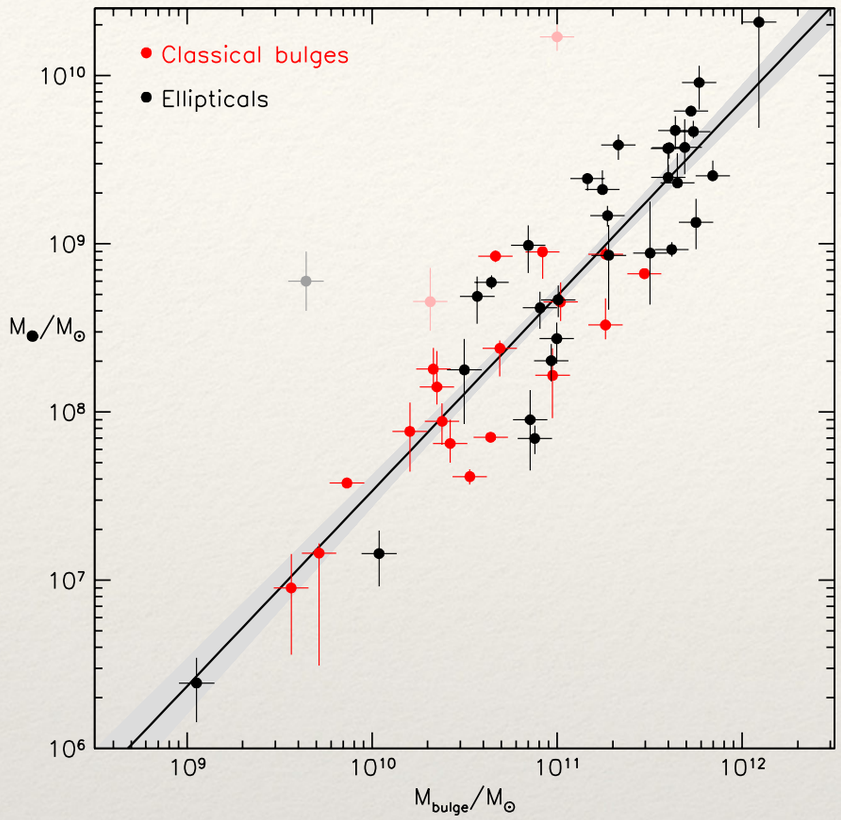
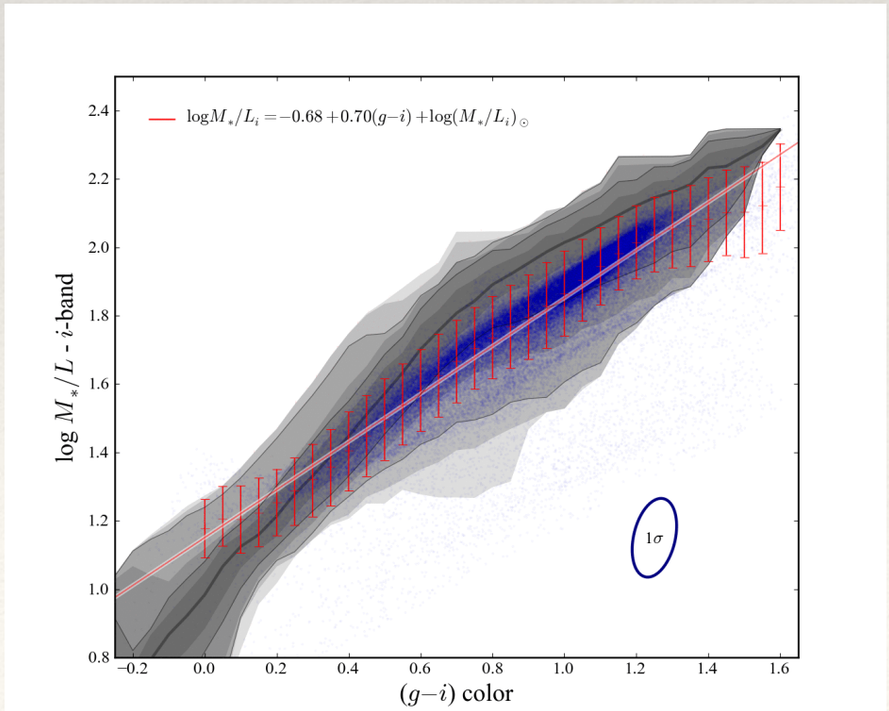
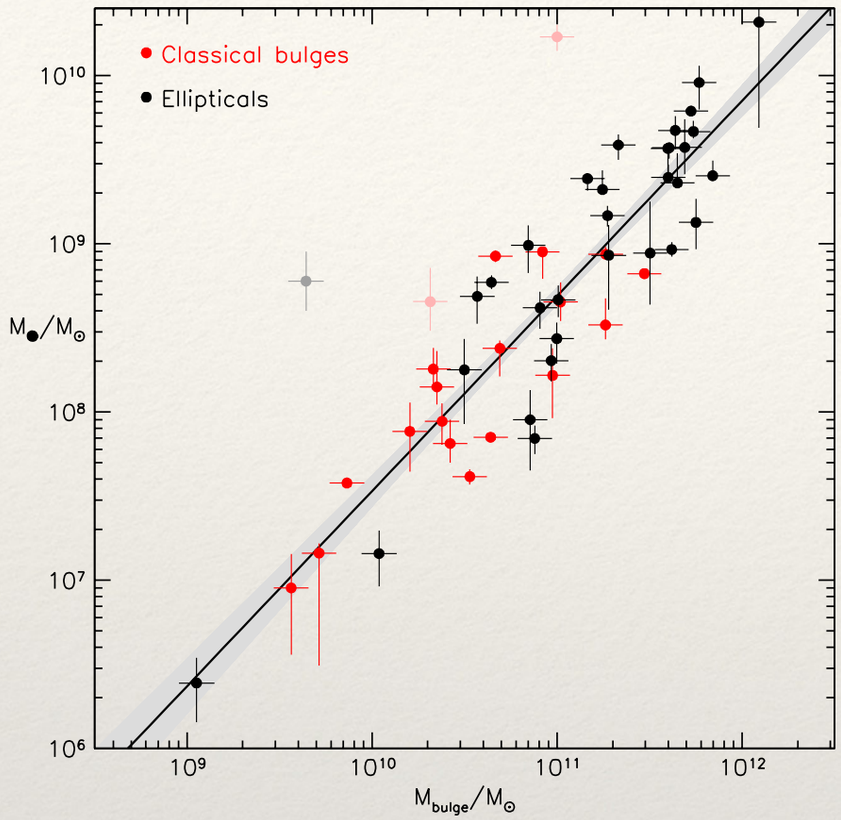


[Kormendy & Ho (2013)]



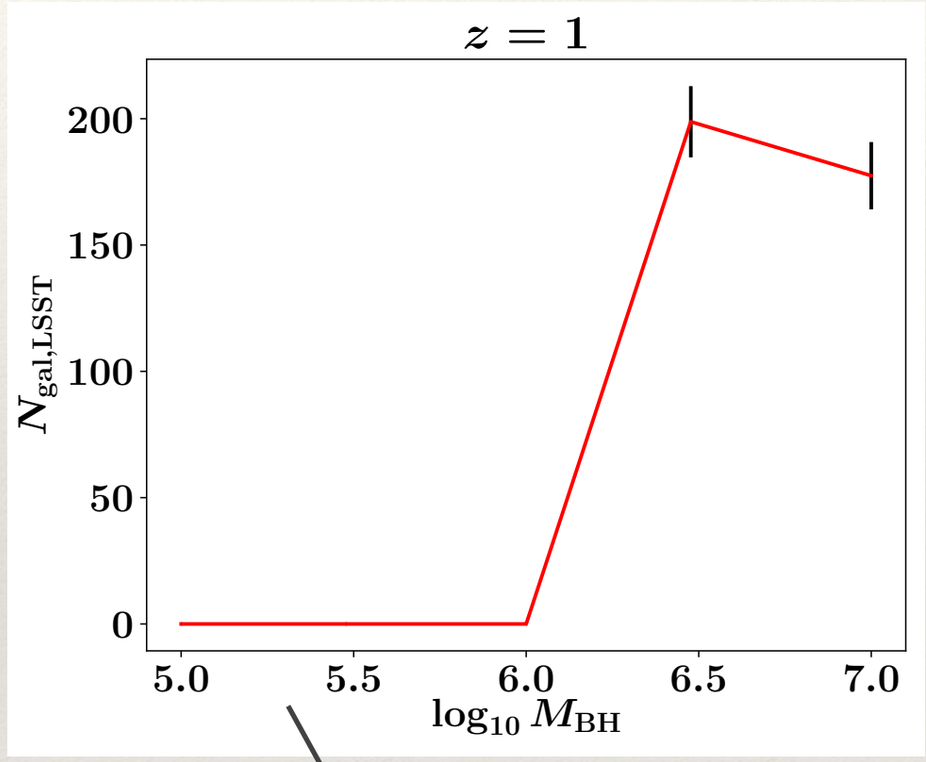
[Taylor+ (2011)]

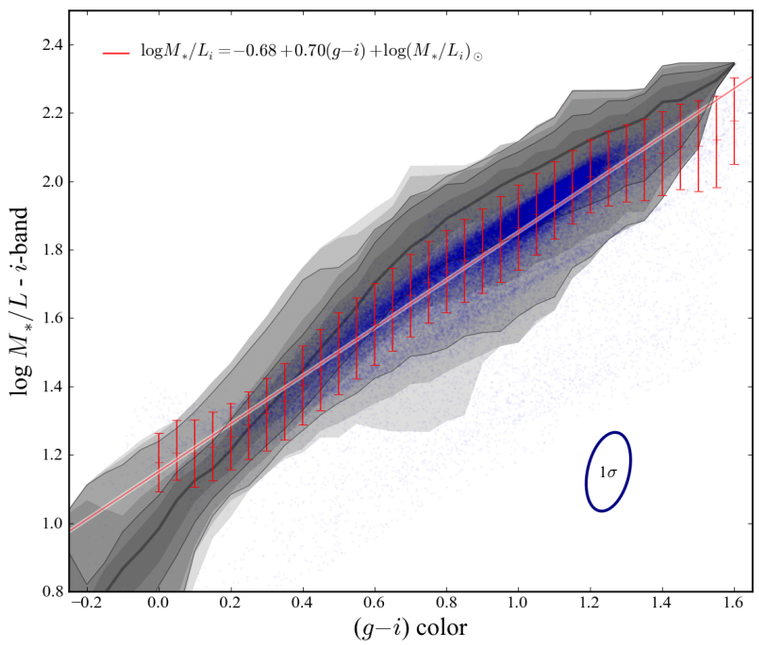
High-z electromagnetic counterparts



[Kormendy & Ho (2013)]

~ a few 100 galaxies within the error ellipse



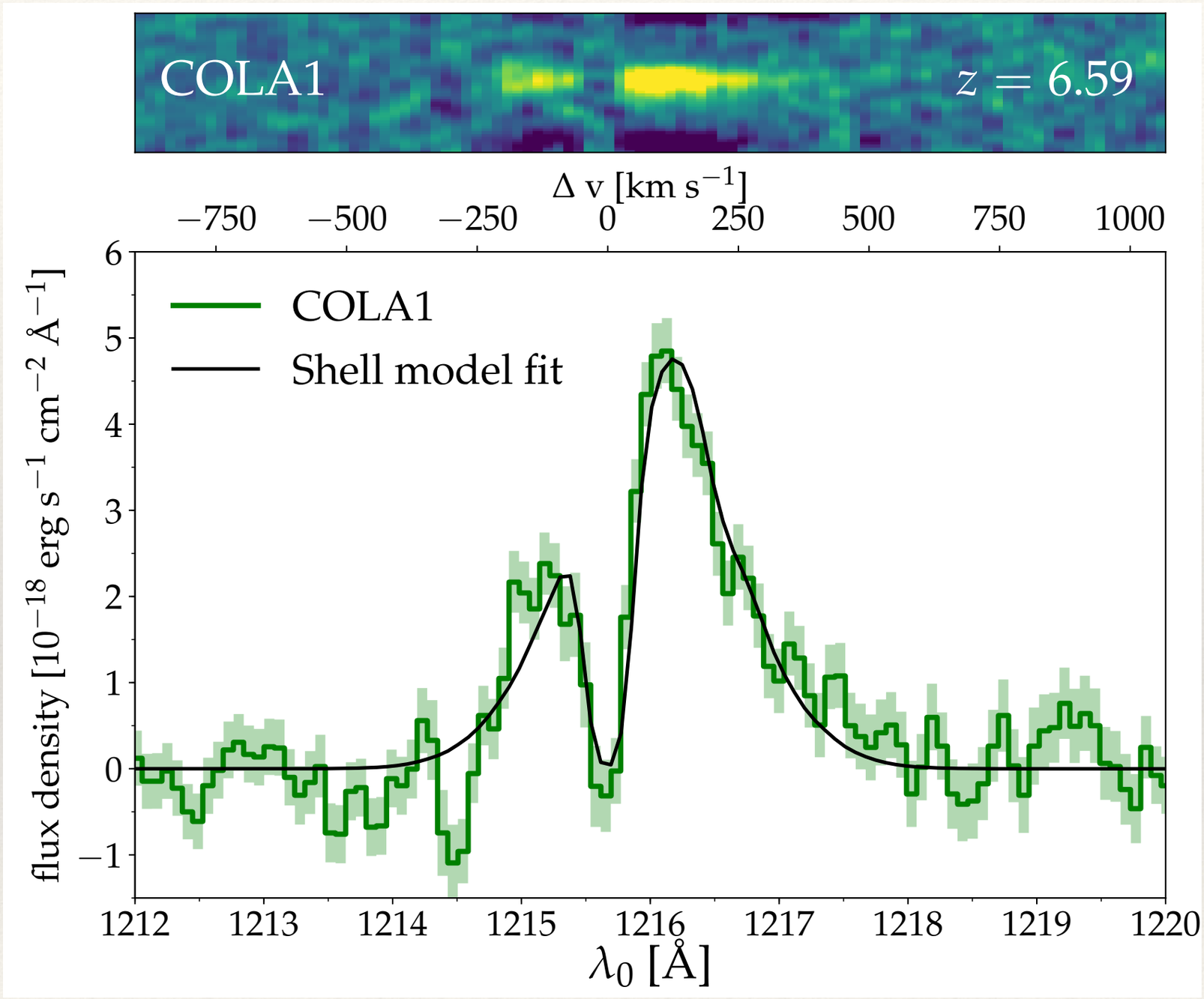


[Taylor+ (2011)]

Below LSST sensitivity limit, i < 26.5

[HP & Loeb, JCAP (2020)]

Meanwhile, in other bands …



Double peaked Lyman-alpha emitters

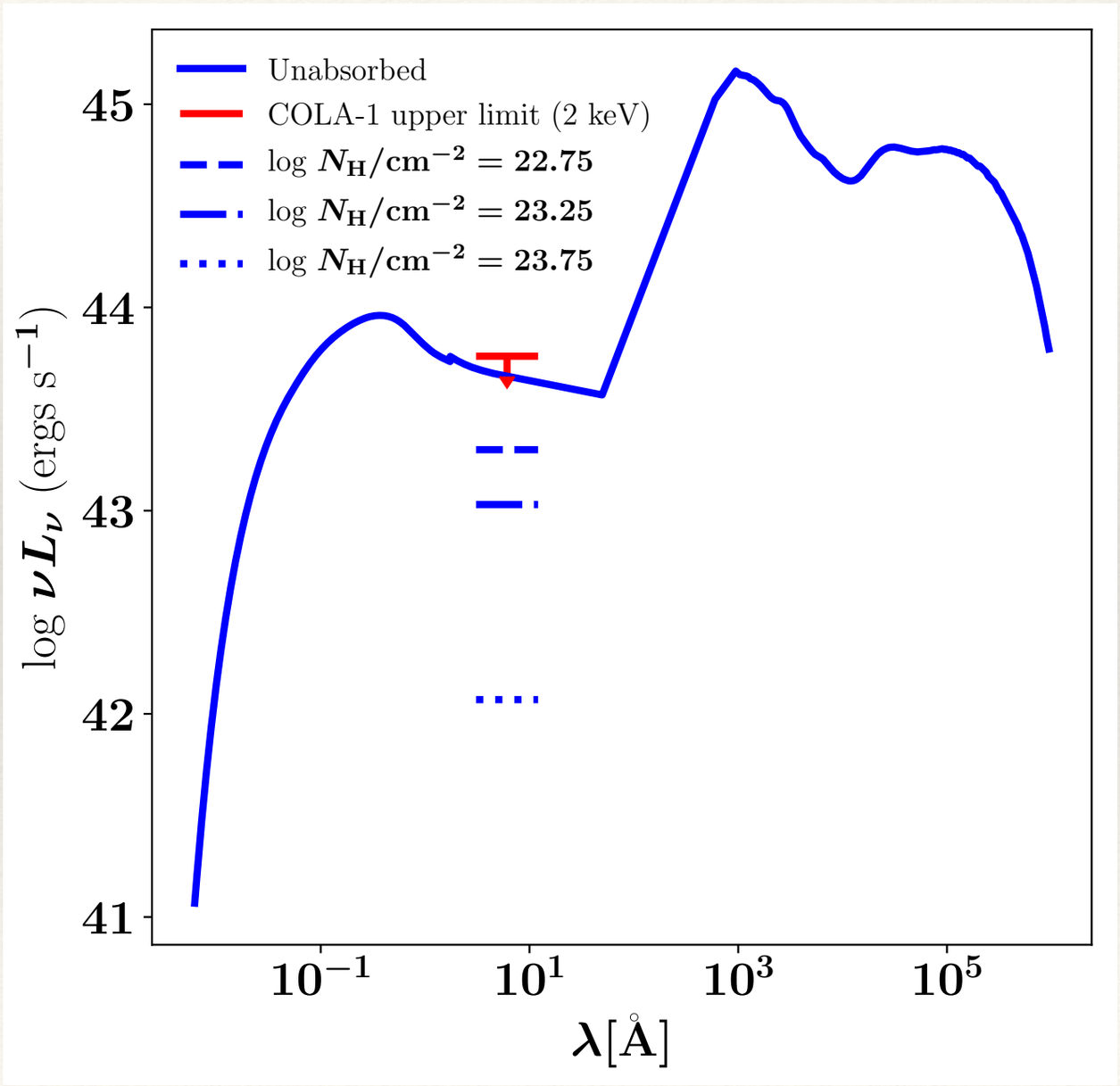
[Hu+ (2016), Matthee+ (2018), Songaila+ (2018), Meyer+ (2020), Bosman+ (2020)]

Could this be an obscured quasar?

$$R_\alpha = 3.14 \left(\frac{N_{\rm ion}}{2 \times 10^{57} s^{-1}} \right)^{1/2} \left[\frac{(\alpha_\nu)^{-1}(\alpha_\nu + 3)}{3} \right]^{-1/2} \times \left(\frac{1+z_\alpha}{7} \right)^{-9/4} {\rm Mpc}$$

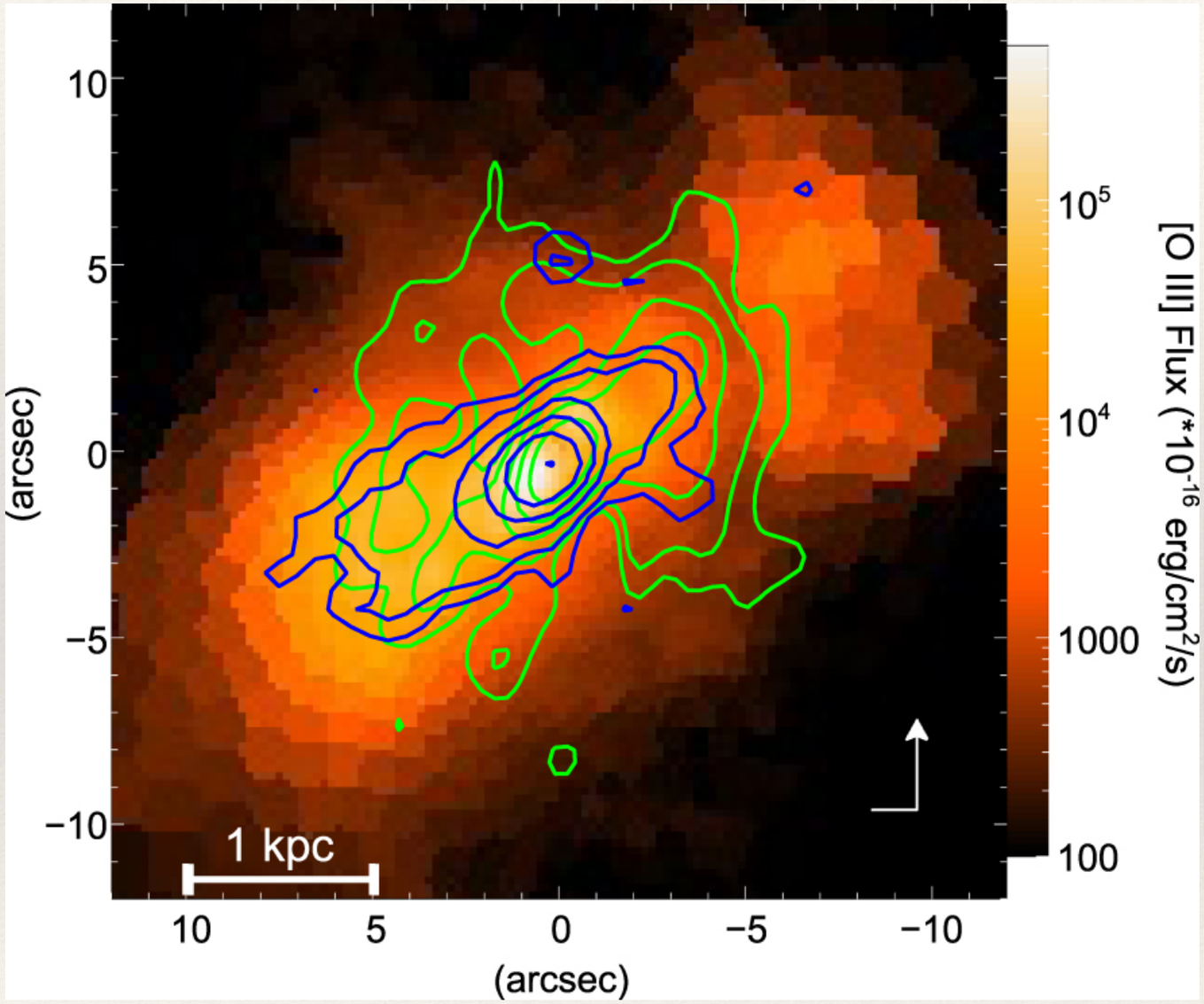
[Bolton+ (2007)]

$$N_{\rm ion,COLA-1} = 2.60 \times 10^{55}\ {\rm s}^{-1}$$

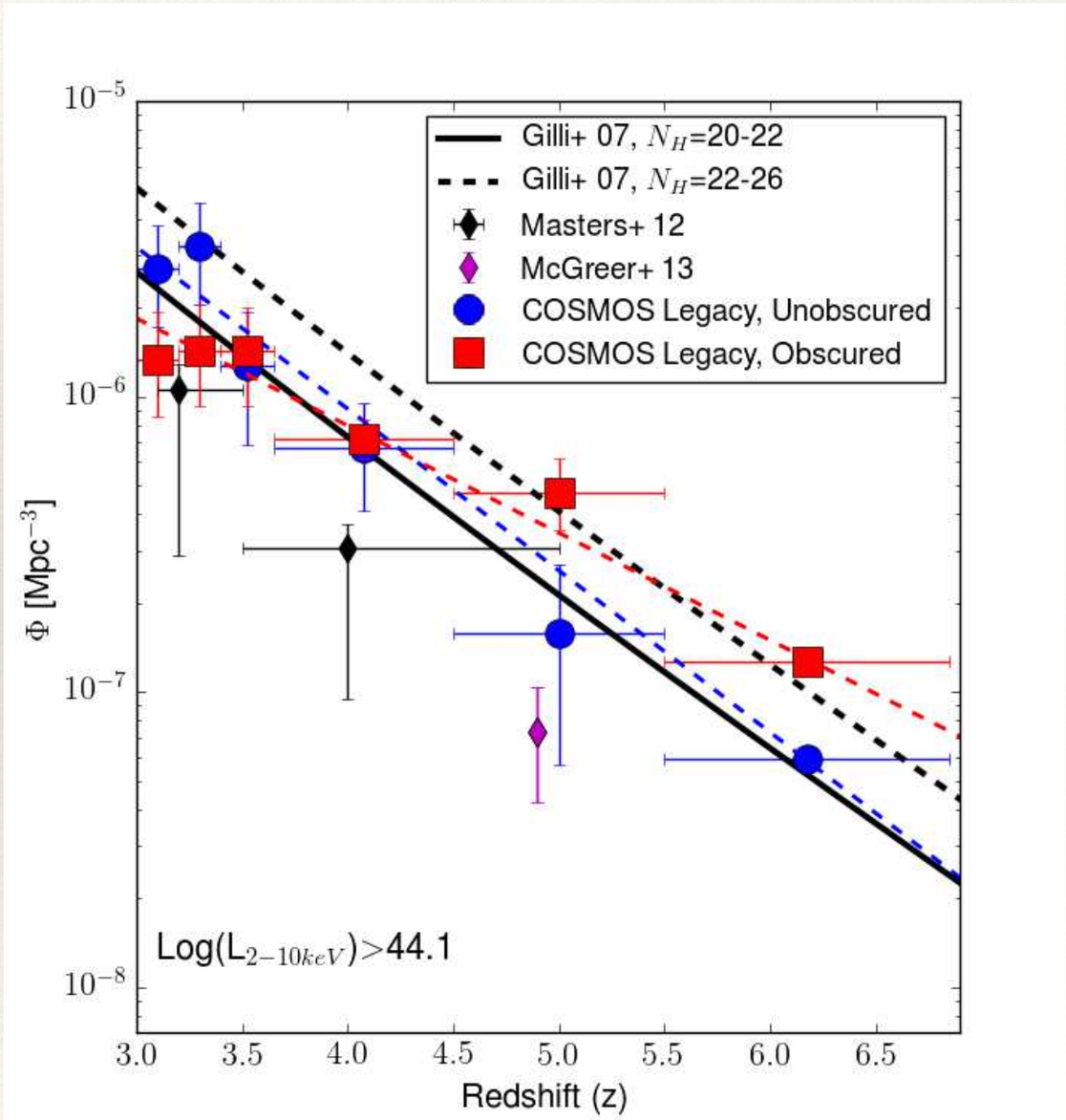


[HP & Loeb, A & A Letters, arXiv:2012.00014 (2020)]

Observational prospects



[Durré+ (2018)]



[Marchesi+ (2016)]

Contributions to reionization …

The Astrophysical Journal Letters, 813:L8 (6pp), 2015 November 1 doi:10.1088/2041-8205/813/1/L8

COSMIC REIONIZATION AFTER PLANCK: COULD QUASARS DO IT ALL?

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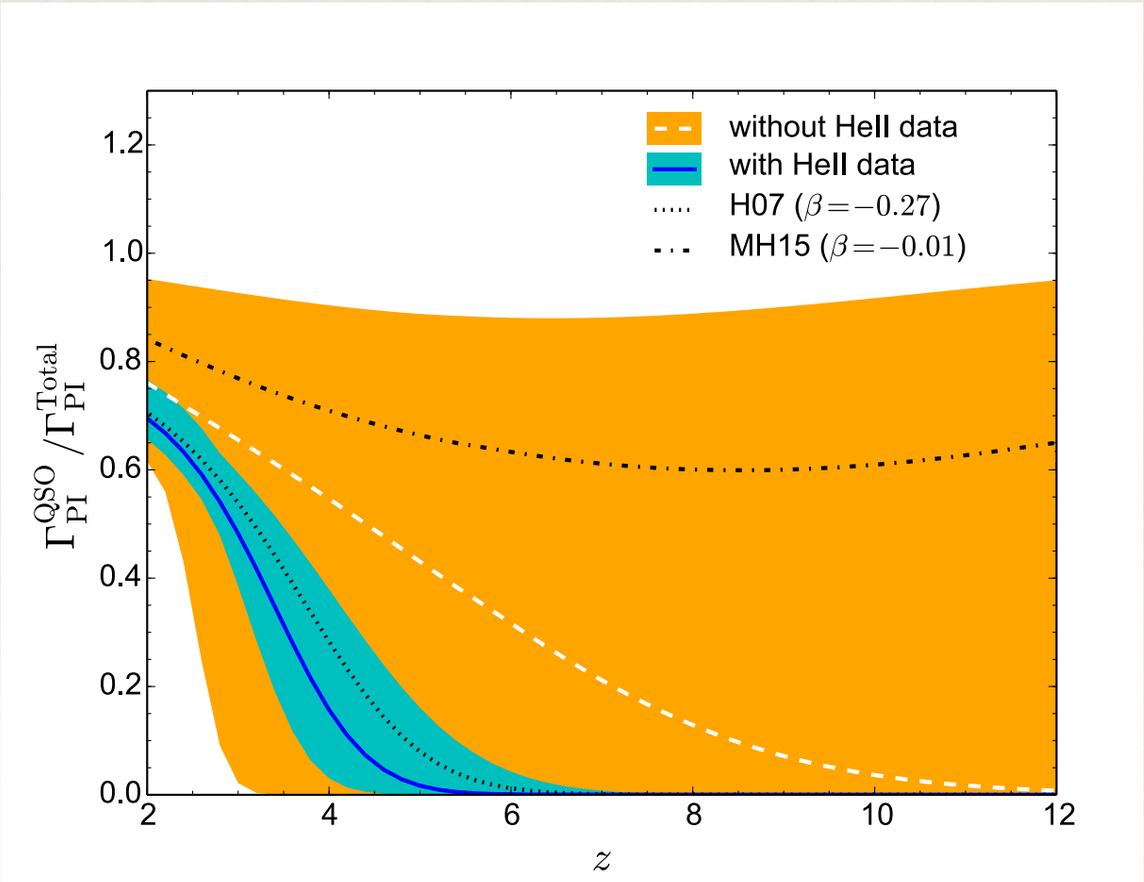
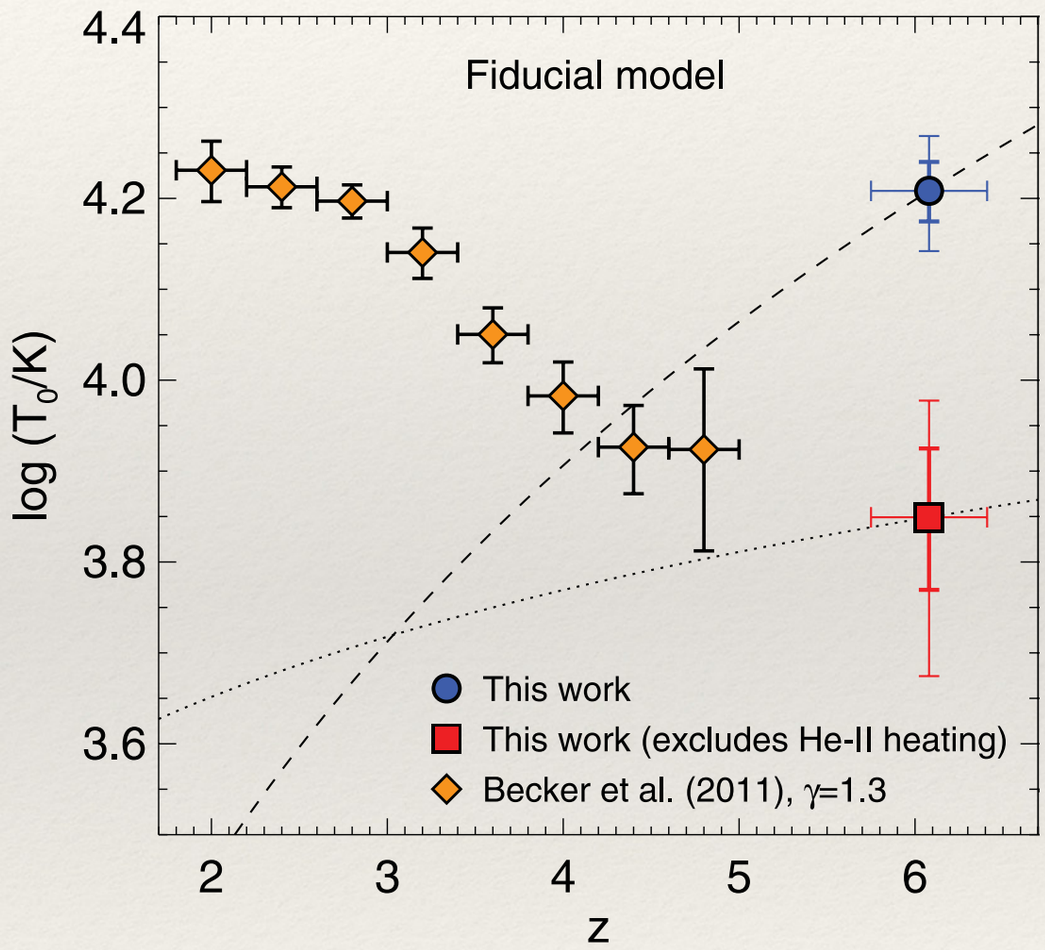
ABSTRACT

[Mitra, Choudhury & Ferrara (2018)]





Heating effects in QSO near-zones

[Bolton+ (2012), HP, Choudhury, Srianand (2014)]

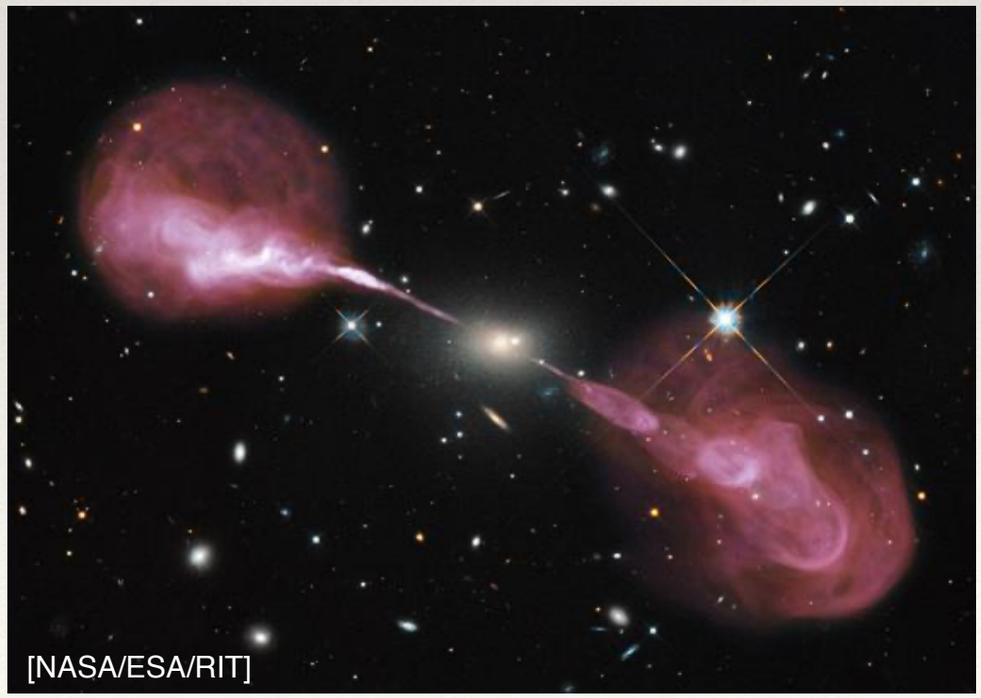
Summary

- Evidence for rapid increase in BH - halo mass relation at high redshifts
- It is feasible to make a ***direct, kinematic*** measurement of BH masses in the first galaxies **[HP and Loeb (JCAP, 2020), arXiv:1912.05555]**
- GW emission signatures from LISA constrain BH properties
- Electromagnetic counterparts from LSST/photometric surveys
- LSST expected to detect ~ 100-200 galaxies with BH masses above $10^{6.5}$ Msun **[HP & Loeb (JCAP, 2020), arXiv:2007.12710]**
- At least three times higher obscured quasars at $z > 6$
- Could be responsible for appearance of double peaked LAEs; contribute to reionization

[HP & Loeb (A & A Letters, 2021), HP, Choudhury, Srianand (MNRAS, 2014)]

In the future …

- Quasars as sources for GW [e.g., Kocsis+ (2005)]
- Priors on the ‘unknown’ parameters from astrophysics
- Modified gravity can change the luminosity distance - constraints on GR [e.g., Mastrogiovanni+ (2020)]
- Dual and binary AGN [e.g., de Rosa+ (2020)]
- Quantifying the obscured population
- Sub - mm (OIII/CII) searches [e.g., Decarli+ (2018)]



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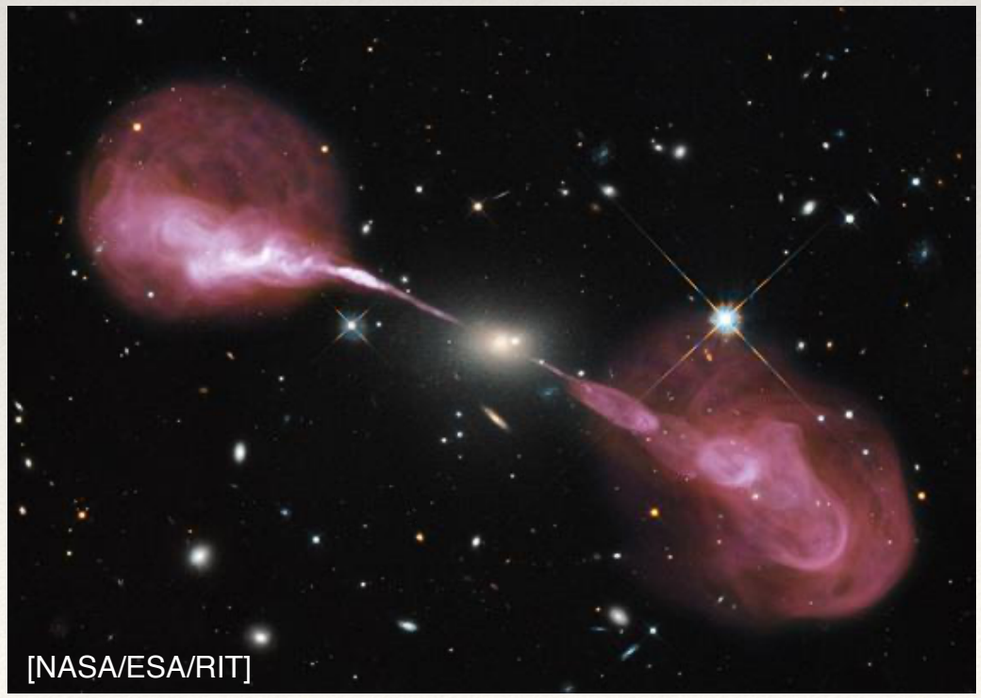
Thank you!


[NASA/ESA/RIT]