Photo Credit: ESO/P. Horálek

Intermediate Black Holes: to be or not to be?

ESO Cosmic Duologue 2 - Interview

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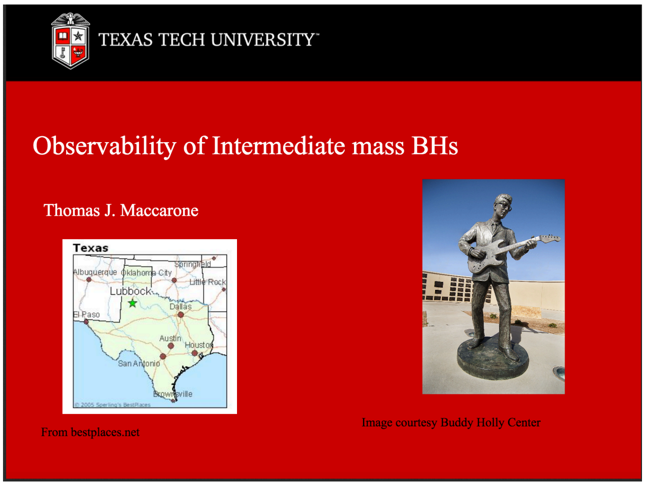
On Monday 11 May, 2020, the second ESO Cosmic Duologue took place. It consisted in a discussion between *Marta Volonteri* (IAP, France) and *Thomas Maccarone* (Texas Tech University, USA) and chaired by *Maria Diaz Trigo* (ESO), about the existence and possible detection of Intermediate Mass Black Holes. Further information on this event, including a copy of the slides, the link to the video of the duologue, as well as to some background material, is available at https://www.eso.org/sci/meetings/2020/Cosmic-Duologues/duologue2.html.

As a follow-up to this successful event, we have asked our two speakers to answer in more details some of the questions raised during the event. This is provided below, where the answers are identified by the initials of the speaker.

1. What is the importance of finding an intermediate mass black hole? What answers do you hope to get from a detection?

TM: There are several different motivations for finding intermediate mass black holes. One motivation is to develop an understanding for what the *Laser Interferometric Space Antenna* (LISA) might see in hour-to-minute frequency gravitational waves. LISA will be optimally sensitive to mergers of black holes in the 10^5 to 10^6 $M_\odot$ (solar masses) range. A combined build-up of samples from electromagnetic and gravitational wave observations will yield information about how the early growth of supermassive black holes from less massive seeds takes place.

The other things we hope to learn are issues of astronomy. From a single detection, we don't gain much there, but with a large sample of intermediate mass black holes (IMBHs), and an understanding of the environments in which they are most common, we can learn about a lot of different processes. If, for example, we find large numbers of IMBHs in the Milky Way halo, that would suggest that they can form frequently from massive stars in the Early Universe. If we find lots of them in intergalactic space, that would suggest that they are often ejected from galactic nuclei as a result of galaxy mergers. If we find them in star clusters, that could suggest a variety of routes of formation, e.g. perhaps through the mergers of stellar mass black holes that might take place in these clusters or perhaps simply direct formation from the high mass stars at low metallicity. We will have to be quite careful about how we approach the major selection biases here – it is much easier to find IMBHs in star clusters than in intergalactic space.



TEXAS TECH UNIVERSITY

Observability of Intermediate mass BHs

Thomas J. Maccarone

From bestplaces.net

Image courtesy Buddy Holly Center

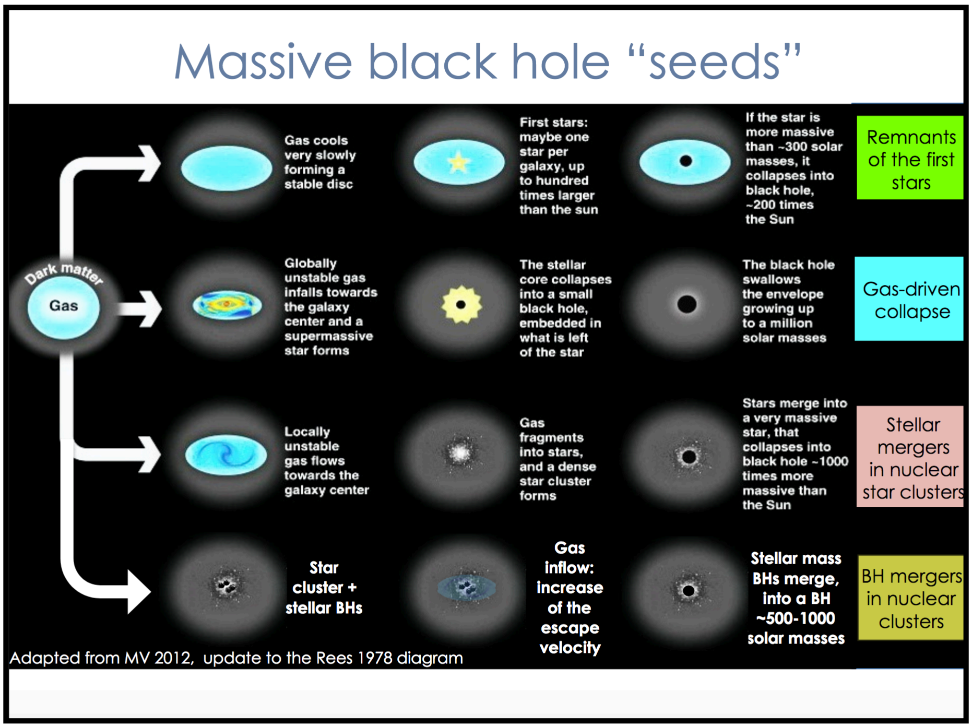
2. Why at zero metallicity do we get the largest black hole (BH) masses? Does the presence of metals prevent a massive star to form?

MV: There are three reasons why zero metallicity favors large BH masses.

The first is related to the mass of the progenitor stars: stars form from dense gas, and which in turns requires gas to cool to low temperatures. Gas generally cools through radiative processes, i.e., emission of photons via energy transitions in atoms and molecules. At zero metallicity there are fewer avenues for such transitions: only those of atomic and molecular hydrogen. Cooling is therefore slower and this favors the formation of few massive stars instead of many small stars. The extreme situation is that giving rise to supermassive stars, with mass larger than 10^4 $M_\odot$, in the so-called "direct collapse" scenario for BH formation, where almost all the gas in a zero metallicity halo participates in the formation of a single star with mass 10^4-10^5 $M_\odot$ (see Inayoshi et al. 2019 for a review and a large set of references).

The second is related to thermonuclear reactions in supermassive stars. Without CNO burning, thermonuclear reactions cannot stop collapse in stars with mass larger than 10^5 $M_\odot$, therefore the star collapses without exploding (e.g., Montero 2012 and references therein).

The third, applicable not only to supermassive stars, is related to how much mass is lost in winds during late stellar evolution. At high metallicity the opacity is larger and winds can carry away more mass than at low/zero metallicity. The mass of the star at the onset of the final collapse is similar to the initial mass of the star, and the remnant remains also more massive (e.g., Spera & Mapelli 2017 and references therein).


Massive black hole "seeds"

Gas cools very slowly forming a stable disc

First stars: maybe one star per galaxy, up to hundred times larger than the sun

If the star is more massive than ~300 solar masses, it collapses into black hole, ~200 times the Sun

Remnants of the first stars

Globally unstable gas infalls towards the galaxy center and a supermassive star forms

The stellar core collapses into a small black hole, embedded in what is left of the star

The black hole swallows the envelope growing up to a million solar masses

Gas-driven collapse

Locally unstable gas flows towards the galaxy center

Gas fragments into stars, and a dense star cluster forms

Stars merge into a very massive star, that collapses into black hole ~1000 times more massive than the Sun

Stellar mergers in nuclear star clusters

Star cluster + stellar BHs

Gas inflow: increase of the escape velocity

Stellar mass BHs merge, into a BH ~500-1000 solar masses

BH mergers in nuclear clusters

Adapted from MV 2012, update to the Rees 1978 diagram

3. Are binary (I)MBH (that is, gravitationally bound) expected, and which are the expected observational signatures? Other than GW.... (e.m. signatures)?

MV: IMBH binaries are expected in three situations: when two globular clusters containing an IMBH each merge, when two dwarf galaxies containing an IMBH each merge, and if IMBHs are born in pairs.

Whether any electromagnetic signature arises in the presence of a binary or when a binary merges is still a matter of debate. If the binary is surrounded by gas then we expect electromagnetic signatures: the binary should be embedded in a circumbinary disc, and each of the two IMBHs is embedded in a “mini-disc”: shocks should create high-temperature/high-energy features and some periodicity could be expected in the emission.

4. Which proof do we have that quasars with redshift (*z*) larger than 6 are truly SMBHs? Which observational signatures are being used to argue this?

MV: The main reason why we expect that $z>6$ quasars are powered by SMBHs is that they have spectra that are identical to those of lower redshift quasars, therefore if we are willing to accept that quasars at $z\sim1$-2 are powered by SMBHs, the same applies to z>6 quasars.

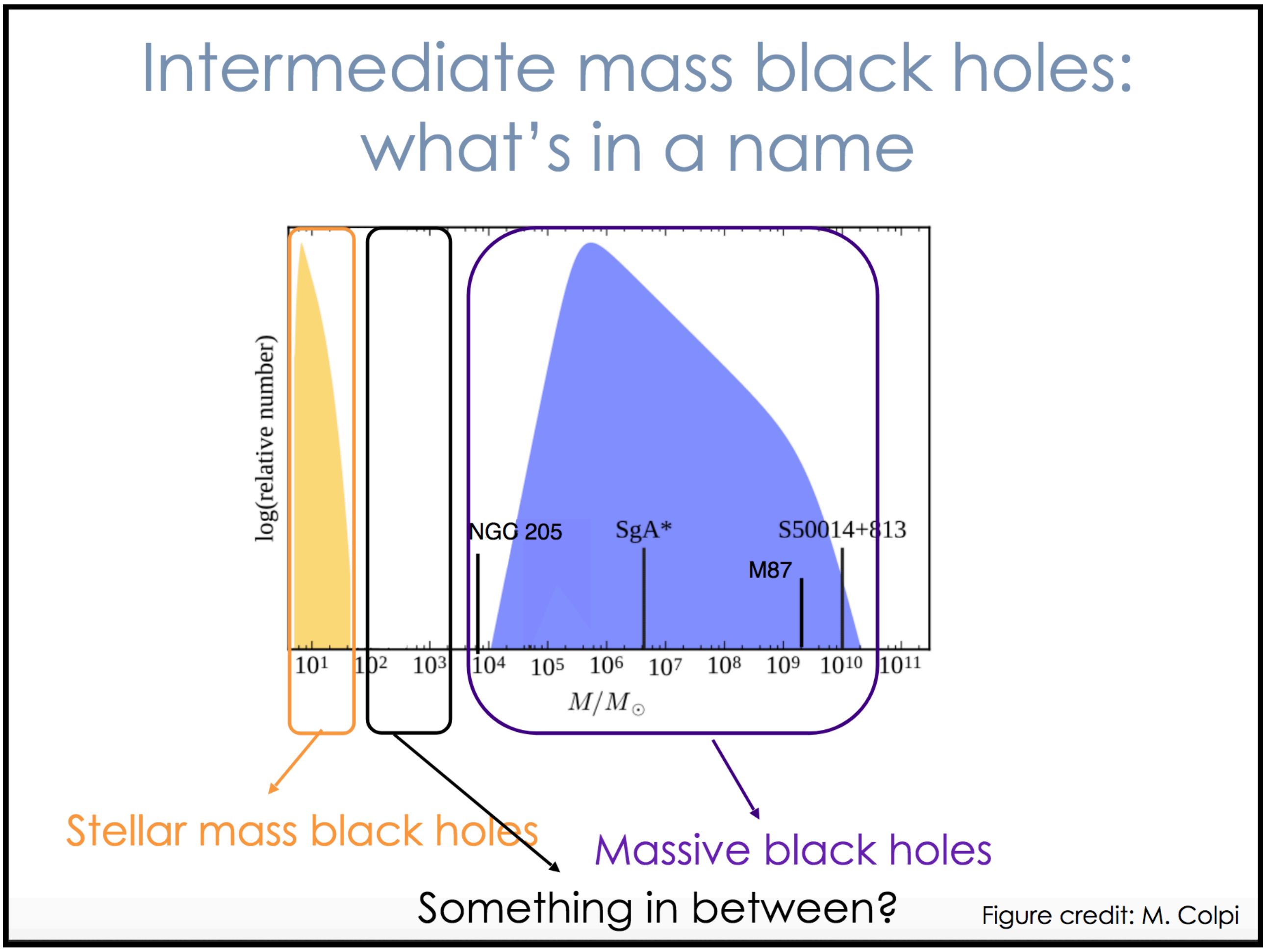
A related question would be: are the $z>6$ quasars really powered by SMBHs with mass larger than 10^9 $M_\odot$? Estimates of SMBH masses in quasars use secondary indicators, i.e., we cannot measure the masses dynamically using stellar orbits. These indicators have a statistical uncertainty of 0.5 dex, while systematic uncertainties are more difficult to assess. In principle, one could assume that masses of z>6 quasars are overestimated and in fact they’re systematically lower. This, however, would imply that $z>6$ quasars are super-Eddington accretors, which would be absolutely fine, but the same argument as before applies: since the spectra are identical to those of lower redshift quasars that are sub-Eddington, Occam’s razor suggests that the $z>6$ quasars are also sub-Eddington and thus that their masses are not underestimated.

5. Did simulations like *Illustris* produce intermediate BHs?

MV: No, a cosmological simulation like *Illustris* cannot produce IMBHs. This is because the simulation has a large volume and a low resolution. Having a low resolution means that the smallest “particle” one can resolve is $\sim10^6$ $M_\odot$. To produce IMBHs the resolution should be at least 1000 times higher, and in that case a BH with 10^4 $M_\odot$ could be simulated: for numerical stability and to avoid spurious dynamics, the mass of a BH should be ~10 times larger than the mass of all other particles. There are higher resolution cosmological simulations that can produce IMBHs, e.g., Habouzit et al. 2017 and Bellovary et al. 2019.

6. It is well known that BHs are used in the study of clusters evolution, but what is the main problem that there is not any sign of them in early universe studies. Is it theoretical or practical limit?

TM: In galaxy clusters, the black holes are likely to have relatively little impact except insofar as they affect the evolution of the individual galaxies and energy injection from SMBHs in the central galaxy prevents cooling in the cluster core. In star clusters, intermediate mass black holes may have a profound impact on the dynamical evolution, since stars in their vicinity can acquire very high speeds, and then inject energy back into the cluster through dynamical interactions. We would not expect to be able to detect IMBHs in the Early Universe with current technology. Even at the Eddington limit, a 10^4 M$_\odot$ black hole would have a luminosity of 10^{42} ergs/s, that would give a flux at z=5 of 4 10^{-18} ergs/s/cm^2. Depending on the spectral shape, this could potentially be detectable by missions like *JWST* or *Lynx* or *AXIS*, but not with existing missions.



Intermediate mass black holes: what's in a name

Stellar mass black holes

Massive black holes

Something in between?

Figure credit: M. Colpi

7. The mass function of BHs increases with decreasing mass with a peak around 10^5 M$_\odot$ it seems. There is a confirmed very significant cutoff in the BH mass function there, with IMBHs < 10^5 M$_\odot$ being extremely rare (if they even exist). Is this correct?

TM: Whether this is correct is challenging to evaluate. The figure that gives this impression that Dr. Volonteri presented (see above) was a schematic diagram, based on observations, but with some assumptions that go into correcting for the selection biases. It was not a histogram of observed masses for a volume-limited sample of galaxies. Also, the peak is much closer to 10^{46}M$_\odot$ than 10^5 M$_\odot$.

There are a few key issues that must be better understood in order to determine if the IMBHs are extremely rare or nonexistent. One issue is whether the intermediate mass black holes may be relatively common as non-nuclear objects, whether floating freely in the haloes of galaxies or being at the centers of star clusters. If even a few percent of globular clusters contain intermediate mass black holes, then they would be far more common than supermassive black holes. At the present time there is no clear evidence for this, and the evidence against intermediate mass black holes being extremely common in globular clusters is strong, but the evidence against a few percent of them containing IMBHs is not strong at all.

Another is the difficulty in estimating the masses of intermediate mass black holes. A 2003 paper by Drukier and Bailyn pointed out that using the stellar velocity dispersion-based techniques that are commonly used to estimate masses of supermassive black holes runs into a fundamental problem for lower black hole masses, in that the number of stars within the sphere of influence of the black hole is sufficiently small that stochastic motions can strongly limit the measurement power – with a thousand or so stars, and a substantial fraction of the luminosity from a small number of red giants, for example, the intrinsic velocity dispersions cannot be very well measured, even with exquisite data. This is why the use of the fastest stars is potentially a better way to go, as long as those stars can be resolved.

A related issue is the occupation fraction of black holes in the nuclei of small galaxies. About fifteen years ago, it was often suggested that bulgeless galaxies, and even galaxies with nuclear star clusters, might not contain black holes in their nuclei (or that such black holes would only be of the stellar mass variety). It has become increasingly clear in recent years that many of these lower mass galaxies do have some kind of black hole well above the stellar mass scale, but the masses of these are still not well measured. It is still not known whether these galaxies always, usually, or just occasionally have black holes, in part because of the challenges in applying the dynamical techniques to them. Generally, these galaxies are shown to have black holes when accretion-based techniques detect them.

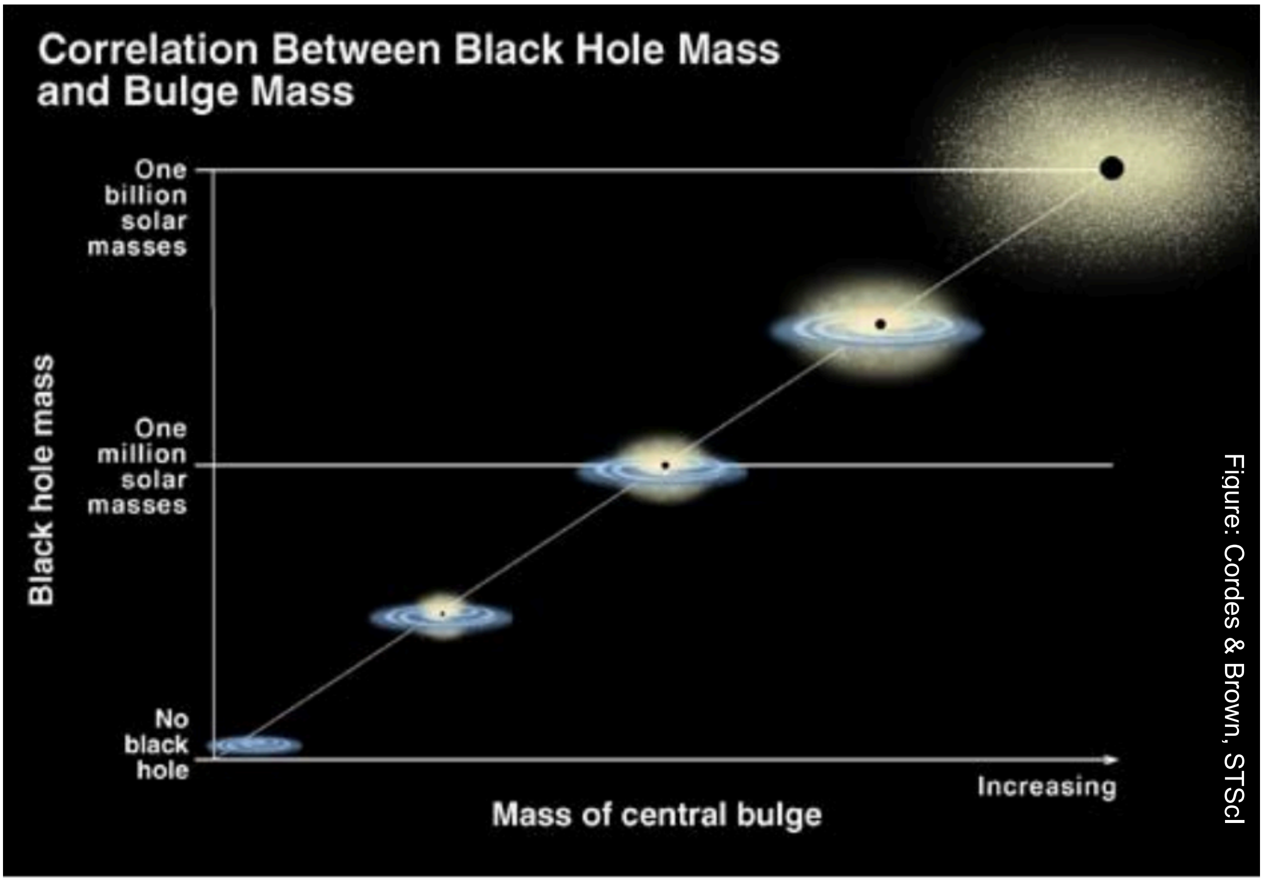


Figure: Cordes & Brown, STScI

8. The *M-sigma* relation that correlates the stellar velocity dispersion of the galaxy bulge, or sigma, with the mass of the supermassive BH at the galaxy centre is widely used to derive the mass of supermassive black holes. However, given that the measurement of sigma is performed outside of the sphere of influence of the black hole, how is it possible that there is a relation at all?

MV: First, as noted in the question, using a correlation to derive SMBH masses comes with some caveats: we have not fully understood the scatter in the correlation and how frequent outliers are, therefore using such an approach comes at risk.

Going to the origin of the correlation, and why it relates the SMBH mass to a measurement well beyond the region where the SMBH dictates the orbit of stars, that’s something that has puzzled astrophysicists since the discovery of the correlation in 2000 (Gebhardt et al. 2000; Ferrarese & Merritt 2000). There have been many many many papers proposing many many many explanations, but the one that stands out is “feedback” — in fact Silk & Rees predicted a relation between SMBH mass and velocity dispersion in 1998, two years before the relation was measured. One can understand this as a balance between the energy or momentum injected by the SMBH when in active phase and the binding energy of the gas in the galaxy: if the SMBH is “too” massive for its own galaxy, then the power it produces can blow away all the gas. In the absence of gas the SMBH goes back to quiescence and stops growing, but in the absence of gas stars also stop forming so neither galaxy nor SMBH can grow anymore until the galaxy regains some gas and the cycle can restart.

9. There are claims of a steeper M-sigma relation at low black hole masses. Are these results solid and if so, which are the theoretical implications?

TM: The data on the whole seem to argue that at low galaxy mass, there is a flatter, rather than steeper M-sigma relation. There are some arguments that this correlates with the merger histories of the galaxies. At the present time, with relatively small samples of black holes at low masses, and the systematics on these not fully understood, it seems wise not to speculate too much about the theoretical origins of any potential correlations.

10. Is it possible to detect black holes in the IGM/ISM at all? How would you search for them?

TM: There are a few approaches that might be used. In the cold phases of the interstellar medium within galaxies, if the black holes are moving slowly enough, the accretion rates can be sufficient to allow detection of the sources. There are some uncertainties in the expected accretion rates, given that AGN appear to accrete below the rate predicted from Bondi-Hoyle-Littleton theory, but even with those uncertainties, in the denser parts of the interstellar medium, intermediate mass black holes could be relatively bright X-ray and radio sources.

In most cases, it would be hard to distinguish these objects from background active galactic nuclei with single epoch surveys. With multi-epoch surveys, a variety of approaches could prove that the objects are within the Milky Way, the most promising of which would likely be radio proper motions, which should be possible with the *Square Kilometer Array*, and easy with the *Next Generation Very Large Array*.

In the intergalactic medium, such black holes are likely to be undetectable unless they bring some stars with them when they are ejected from their initial host galaxies. There, the search for low luminosity high velocity dispersion star clusters would potentially enable the systems to be detected. If they are located near enough to us, then they might also be detectable as high proper motion AGN-like objects using the *Next Generation Very Large Array*.

11. The ground-based third generation gravitational wave detectors will provide a relative uncertainty of <~50% in mass determination at *z*=2. Is this acceptable?

TM: That would be outstanding, comparable to all but the very best black hole masses from electromagnetic observations. Generally speaking, the stellar mass black holes with the best understood inclination angles have mass estimates better than 50%, but most do not. Sgr A* and M87* and some of the maser AGN have mass estimates better than this value, but few if any of the others do.

12. What spin distribution do you expect for BHs in the early Universe? Could this help us to distinguish between formation mechanisms?

MV: We don't really know what's the initial spin at birth, and it likely depends on the formation channel. The collapse of a supermassive star is expected to leave a spinning remnant, e.g., Shibata and Shapiro (2002) predict a spin parameter of 0.75. If IMBHs form by mergers of stars the spin should be low, although it may increase when the very massive star generated by the stellar mergers collapses into a BH, while if they form by mergers of BHs the spin should be ~0.7 — this is the asymptotic value for repeated BH mergers in a random configuration.

13. What initial mass should a BH accreting at the Eddington limit have to reach the mass of a supermassive BH at *z*~7? Could a stellar mass BH become a supermassive BH at that redshift if it were accreting at super-Eddington rates?

TM: Arguments about this come from the "Salpeter" timescale. The Salpeter timescale is the e-folding timescale for a black hole accreting at the Eddington rate. It makes assumptions about the accretion efficiency – for counter-rotating black holes, the mass could grow more quickly. The efficiency of converting gravitational energy into radiation can also be reduced by photon trapping in very high accretion rate flows – i.e. if the matter is converted to energy, but the photons take longer to diffuse through the optically thick flow than they do to flow into the black hole. If one violates the Eddington limit by a large enough factor, then arbitrary mass growth is possible. We don't presently have a good empirical handle on the maximum factor by which the Eddington limit can be violated.

With all those caveats discussed, given that there is not much evidence for highly super-Eddington active galactic nuclei or stellar mass black holes in the local Universe, taking the Salpeter timescale for a non-rotating black hole and working through the question can be enlightening. Additional uncertainty results from assumptions about when the first stars form.

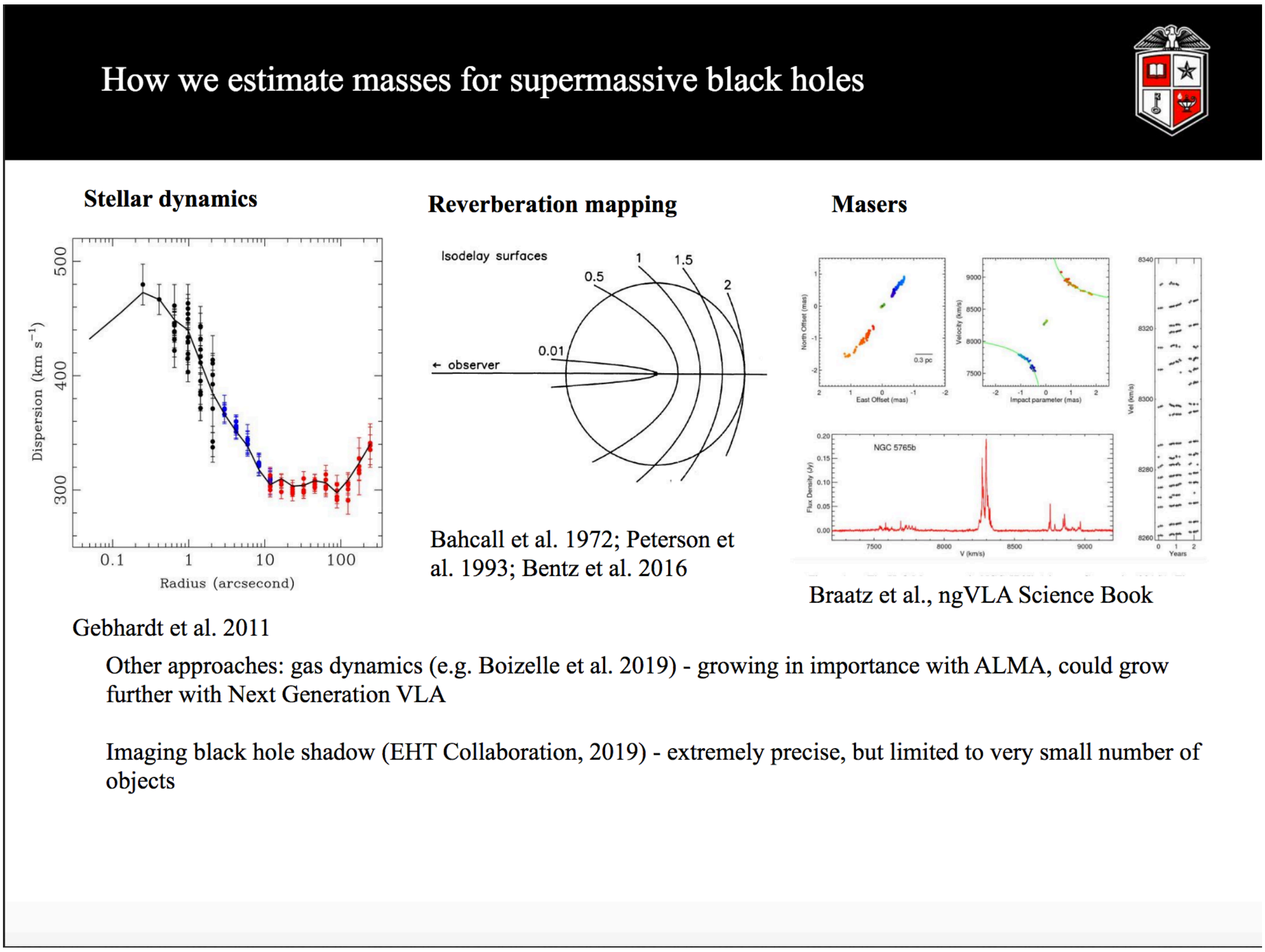
The Salpeter timescale is 45 Myrs for accretion efficiency of 10% (i.e. $L=0.1\,mc^2$). That leaves 13.1 Salpeter timescales between $z=20$ and $z=7$. Moving the epoch of the formation of the first stars backwards allows a maximum of 4 more Salpeter times. The more likely value gives above 500,000 as the multiplier of the mass of the initial black hole seed. To reach $10^9\,M_\odot$ then requires a seed of about 2,000 $M_\odot$. Taking the highly unlikely value of 17 Salpeter timescales would allow a 40 $M_\odot$ black hole seed under the rather unlikely circumstances that it was primordially formed and somehow accreted at the Eddington rate for the whole time starting from the Big Bang.

14. How do we go from having a luminosity measurement to a BH mass measurement that we can trust? Or said otherwise, how can we get a confirmation of ‘candidate’ IMBHs that are not found via GWs?

TM: Luminosity measurements alone cannot give strong evidence for intermediate mass black holes. This was most clearly illustrated when one of the brightest ultraluminous X-ray sources showed pulsations, indicating that it is actually an accreting magnetized neutron star. Many of the other bright ULXs now have also been found to pulsate. At the same time, there is no reason to believe that all intermediate mass black holes are rapidly accreting.

Mass estimates may come from (see also the below figure):

1. Stellar dynamics - this is likely to work only in the Local Group for the foreseeable future, but we may see individual stars orbiting the IMBHs.
2. Maser disks – this may allow us to take dynamical mass estimates further out.
3. X-ray spectral state transitions – these typically happen at about 2% of the Eddington luminosity, and leads to changes from thermal multi-temperature disks whose spectra are well modeled by sums of blackbodies following a standard Shakura-Sunyaev law to power law spectra.
4. X-ray timing, using the timing plane in which there is a low scatter relationship among black hole mass, accretion rate, and break frequency in the power spectrum of the X-ray emission.
5. Tidal disruption of stars that are too compact to be disrupted by black holes above the intermediate mass range. In particular tidal disruption and potentially tidal detonation of white dwarfs can be done by black holes less than about 105 $M_\odot$, but black holes more massive than this limit will swallow white dwarfs whole.



How we estimate masses for supermassive black holes

Stellar dynamics

Reverberation mapping

Masers

Bahcall et al. 1972; Peterson et al. 1993; Bentz et al. 2016

Braatz et al., ngVLA Science Book

Gebhardt et al. 2011

Other approaches: gas dynamics (e.g. Boizelle et al. 2019) - growing in importance with ALMA, could grow further with Next Generation VLA

Imaging black hole shadow (EHT Collaboration, 2019) - extremely precise, but limited to very small number of objects

15. To which extent can we extrapolate what we learn from IMBHs in the local Universe to what happened in the Early Universe?

MV: This is a not trivial question: what we are doing is to use models in a cosmological setting to evolve the conditions in the early Universe (where "early" here means at the time of formation of the first galaxies) and see what they mean for today's observables. Depending on the specific assumptions of the models, results will differ. In general, what we expect is that dwarf galaxies today host IMBHs that have not grown much since their birth, so we can make inferences on the initial conditions.

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