Whittle : EXTRAGALACTIC ASTRONOMY

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14. GALAXY NUCLEI & NUCLEAR BLACK HOLES

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(1) Introduction

- Galaxies usually have a very **well defined** nucleus :
  eg, the Milky Way has a distinct region ≲ 1pc in size
  this is equivalent to an 8 micron dot at the center of an 8½"×11" page !

  The nuclear gravitational potential is **significantly deeper** than anywhere else in the galaxy
  For this reason, we find nuclei to be **highly unusual environments**

  - high star densities ≳ 10^2 - 10^7 pc^{-3}
  - high ISM densities ≳ 10^2 - 10^6 cm^{-3}
  - high ISM pressures ≳ 10^6 - 10^{10} K cm^{-3}
  - Ubiquitous star formation : mild (≈ all) → Starburst (rare)
  - Classical Activity : mild (≈ all) → AGN (rare)
  - **Many** (perhaps all) galaxy nuclei contain **massive black holes**

- The study of galaxy nuclei is currently a very active research area.
  However, the subject is still in its infancy, mainly because :
  we lack the necessary spatial resolution for external galaxies
  there are ≈30 mag of extinction to our own galaxy nucleus

- In this topic, we will focus on :
  - Nuclear black holes in non-active galaxies
  - The Milky Way nucleus as an example of a (normal?) galaxy nucleus

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(2) Finding Nuclear Black Holes

Here we outline the basic approach for finding nuclear black holes :

- We need a **tracer** of the near-nuclear velocity field
  This defines the gravitational field, dΦ / dr, which then yields M(r)

If stars alone cannot explain M(r) → infer a central dark mass
Ideally, in addition, we detect a Keplerian velocity distribution at smallest r.

- Obvious tracers include **gas** and **stars** :
  Measure velocities using Doppler and (in some cases) proper motion methods.
  As always, gravitational motions include both **rotation** and **dispersion**
  In this case, we can use the Jeans Equation (8.24a-c) to derive M(r) from the velocity field.
  Recall, this equation describes **Pressure & rotation support** modified by an anisotropy term.

- We note a few other details :
  The equations apply for a **spherical or near spherical potential** ($\simeq$ true for galaxy nuclei)
  The velocities V_c, V_{rot}, σ, σ_r, σ_θ, σ_ϕ, are all **functions of radius**, r.
  These velocities refer to the **tracer, not** the material defining the potential
  We must first **deproject** all quantities : $I(R) \rightarrow j(r)$; $\sigma_p(R) \rightarrow \sigma_r(r)$; $\Delta V(r) \rightarrow V_{rot}(r)$

- Depending on the simplicity of the velocity field, the Jeans equation takes on several forms
  Equations 14.1a-e below describe increasingly complex velocity fields :

$$
\begin{aligned}
M(<r) &= \frac{V_c^2 r}{G} \\
M(<r) &= \quad - \frac{\sigma^2 r}{G}\left[\frac{d\ln n}{d\ln r} + \frac{d\ln\sigma^2}{d\ln r}\right] \\
M(<r) &= \frac{V_{rot}^2 r}{G} - \frac{\sigma^2 r}{G}\left[\frac{d\ln n}{d\ln r} + \frac{d\ln\sigma^2}{d\ln r}\right] \\
M(<r) &= \quad - \frac{\sigma_r^2 r}{G}\left[\frac{d\ln n}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right] \\
M(<r) &= \frac{V_{rot}^2 r}{G} - \frac{\sigma_r^2 r}{G}\left[\frac{d\ln n}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]
\end{aligned}
\qquad (14.1a\text{-}e)
$$

- **14.1a** : **Pure (circular) rotation (no dispersion)**
  This is the ideal case -- unambiguous retreaval of M(r) (knowing inclination)
  Within factors $\lesssim$2 this also works for flattened potentials (even disks)

- **14.1b** : **Pure <u>isotropic</u> dispersion (no rotation)**
  This is the case for a non-rotating spherical galaxy (with stars as tracer).
  Note that since n and σ **decrease** with r, both logarithmic derivatives are **negative**
  Typically, their sum is between -1 and -2, yielding (of course) a positive M(r).

- **14.1c** : **Some rotation and some <u>isotropic</u> dispersion**
  If the galaxy is also rotating, this adds an additional (positive) contribution to M(r)
  ie the total support comes from the sum of rotation support and dispersion support.

- **14.1d** : **Pure <u>anisotropic</u> dispersion (no rotation)**
  Here, we have introduced the anisotropy parameters $\beta_\theta = 1 - \sigma_\theta^2 / \sigma_r^2$ and $\beta_\phi = 1 - \sigma_\phi^2 / \sigma_r^2$
  However, we further simplify and assume $\sigma_\theta = \sigma_\phi$ and write 2β in place of $\beta_\theta + \beta_\phi$
  Usually, β ranges from 0 (isotropic) to +1 (pure radial dispersion)
  (rarely, do we expect greater tangential dispersion $\sigma_\theta > \sigma_r$, which would give negative β)

  So : the presence of radial anisotropy (+ve β) tends to **counteract** the -ve logarithmic gradients
  The sum of the terms inside [ ] could even be **zero** !
  → pure radial orbits could, in principal, support a distribution with an almost empty central cavity
  Conclusion :

  > Knowledge of the anisotropy is needed to derive M(r) reliably from **non-rotating velocity tracers**.
  > When galaxy stars act as the tracers, the above applies to **non-rotating galaxies**

- **14.1e** : **Some rotation with some anisotropic dispersion**
  Clearly, if the system/tracer is also rotating, we gain an unambiguous contribution to M(r)
  Basically, rotation **must** have mass interior to provide the centripetal acceleration.
  Important : the more rotation dominates the velocity field, the less we need worry about anisotropy.

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(3) Difficulties

- The ambiguities introduced by anisotropy
  As described above, for non-rotating systems we must assume (or measure) the anisotropy (β).
  The reliablility of this assumption depends on the system:
  Low luminosity Ellipticals and bulges are probably fairly isotropic ($\beta \approx 0$)
  High luminosity Ellipticals are probably anisotropic, but with unknown degree
  For this reason, most BH measurements for giant Es are from **gas rotation**, although:
  Recent methods have used the h_3 and h_4 parameters of the LOSVD to help constrain β

- Using **gas** to trace the velocity field has advantages and disadvantages :
  - The motion is probably dominated by rotation, with little dispersion

  However
  - non-gravitational forces (eg winds, radiation pressure) may be important
  - the inclination may not be known

- High spatial resolution is critical
  The region influenced by the black hole is **small** (call this r_{BH}):
  for nuclear velocities V_c or σ far from the BH, we have :

  $$r_{BH} \approx GM_{BH} / V_c^2 \approx GM_{BH} / \sigma^2 \approx 1.5\ M_7\, \sigma_{200}^{-2}\ \text{pc} \qquad (14.2)$$

  where M_7 is M_{BH} in units of $10^7 M_\odot$ (similarly for σ_{200})
  this is equivalent to the radius within which there is equal mass in stars and the BH
  Note : r_{BH} is **very small** for all but the biggest black holes or the nearest galaxies
  Problems : seeing and/or finite aperture size **reduces gradients** in luminosity and velocity
  $\rightarrow$ this reduces the terms in the Jeans equation and **underestimates** M(r) at small r
  HST has made a critical contribution in this area, allowing the field to move forward quite quickly
  (though a number of legitimate BH detections had already been achieved from the ground)

- Superposed contamination may need to be subtracted
  Obviously, observing nuclei includes projected light from greater radii
  Usually, this is **not** a big problem because the steep luminosity gradient (ie bright nucleus).
  However, if one wants to observe a kinematically distinct sub-population (eg a cold stellar disk)
  then the other (possibly dominant) components need to be measured and subtracted.
  This is not always easy.

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(4) Case Studies

Most of the methods and difficulties can be illustrated by a few good cases :

(a) M87 -- Giant Elliptical

- This was the first serious attempt to detect a nuclear black hole (1978 Sargent et al; Young et al)
  The observations consisted of CCD (early days !) images and long slit (absorption line) spectra
  They developed some of the earliest methods for measuring stellar velocities and dispersions
  The light profile, rotation profile (**no rotation**) and dispersion profile yields M(r) and M/L(r) [images]

Assuming an **isotropic dispersion** → rising M/L → central black hole $M_{BH} \approx 10^9 M_\odot$

- However, introducing radial anisotropy eliminates the need for the central mass (Binney & Mamon '82)
  In this case, one can require M/L to be **constant**, and solve for β(r) [images]
  Typically, for this kind of data set :
  → **there are often many dynamically self-consistent models which match the observations**
  → some of these have BHs, and some dont.

- More detailed observations have yielded h_3 and h_4 (van der Marel '94, [images])
  these suggest the anisotropy is fairly low (though cannot rule out a higher anisotropy)
  the best fit model gives $M_{BH} \approx 5\times10^9 M_\odot$

- Finally, ionized **gas** velocities were measured on either side of the nucleus using HST
  (Harms et al 1994, [images])
  Since the HST Hα image indicates a gas disk, rotation is assumed
  A (simple) estimate yields : $M_{BH} \approx 3\times10^9 M_\odot$, which is now fairly robust

(b) M84 -- Another Giant Elliptical

- This giant elliptical has an approximately edge on gas disk: [images]
- The installing of Space Telescope Imaging Spectrograph (STIS) has helped enormously in the hunt for nuclear black holes: [images]

(c) NGC 3115 -- An Edge on S0 Galaxy

- Since the bulge dynamics is consistent with rotational flattening, the bulge is probably close to isotropic.
  Ground based observations show steep rotation and dispersion profiles (images)
  $\sigma(0)$ = 300 km/s is well off the Faber Jackson relation for a bulge with M_B = -20.2.
  isotropic models indicate $M_{BH} \approx 10^9 M_\odot$ (50% error in log)
  maximally anisotropic models still require $M_{BH} \approx 10^8 M_\odot$

- An HST image shows a central star cluster (as we expect near a BH)
  HST spectra show dispersion and rotation rising even more steeply
  The measured nuclear cluster dispersion is 440 km/s, adjusted to 600 km/s after disk light subtraction
  this is **double** V_{esc} for the cluster, which would evaporate in 2×10^4yr without additional mass
  The implied central mass is $M_{BH} \approx 10^9 M_\odot$ (25 × the estimated mass of the cluster)

(d) M31 -- Nearby Luminous Sb

- Great spatial resolution : 1 arcsec ≈ 3.5 pc
  Long slit spectra show steep rotation and dispersion gradients (images)
  Steep, high amplitude rotation ($\Delta V \approx$ 400 km/s across 3pc) → $M_{BH} \approx 4.5\times10^7 M_\odot$
  This is robust and is independent of any velocity anisotropy

- The details may be more interesting :
  An HST image shows a **double nucleus**, separation 0.5 arcsec (first seen by `stratoscope' in 1975)
  The true nucleus is probably the **fainter** bluer and more compact nucleus :
  it is found at the center of the larger scale light distribution
  the rotation and dispersion profiles are symmetric about it
  its high dispersion (≈440 km/s; FOS) is significantly greater than the other (brighter) nucleus
  This double nucleus cannot be a late-stage merger, since $t_{merge} \approx P_{rot} \approx 10^4$yr
  → the double nucleus seems to be quasi-stable
  A good model includes an eccentric disk of stars :
  → the second nucleus arises from stars lingering at their apocenters (Tremaine).

(e) M32 -- Nearby Compact Dwarf Elliptical

- As with M31, proximity combined with high resolution has been critical
  On arcsec scales, there are gentle rotation and dispersion gradients
  however, within $\lesssim$0.15 arcsec (0.5pc) there is :
  a sharp rise in dispersion : 70 $\rightarrow$ 150 km/s
  a steep rotation curve : $\Delta V \approx$ 70 km/s across 0.6pc
  A fairly robust estimate for the central mass is $M_{BH} \approx 3.9\times10^6 M_\odot$
  (Tonry 1987; van der Marel 1997; images)

(f) NGC 4258 -- Sbc Galaxy

- Truely remarkable (and quite different) observational approach (images)
  Water maser emission comes from the nucleus : inverted population is pumped by young stars
  Line emission at λ 1.35cm allows Doppler velocities to 1 km/s
  High surface brightness allows VLBI at resolution of 10^{-4} arcsec = 720 AU
  We see emission knots where long path lengths have small ΔV
  for edge on disk $\rightarrow$ L & R sides (max Doppler shift) and center (zero Doppler shift)

- Miyoshi et al (1995) observed these disk signatures, and measured :
  V_{rot} = 1080 km/s at a radius of 0.12 +/- 0.001 pc
  accurate Keplerian velocity form outside this radius
  $\rightarrow M_{BH} = 4.0\ (+/- 0.1) \times10^7 M_\odot$
  probably the best estimate of BH mass to date.

- subsequently, many other things measured :
  radius measured independently from **centrepetal acceleration** (V_c^2/r) : 9.5 +/- 1.1 km/s/yr
  $\rightarrow$ absolute measure of distance to NGC 4258 $\rightarrow$ direct estimate of H_o
  other disk details : disk warp, thickness, accretion rate, etc.

(g) Milky Way Nucleus

- Excellent spatial resolution : 1 arcsec = 0.04 pc = 8000 AU (images)
  Terrible absorption : 10^{-12} at V (30 mag); but down to 0.05 at 2.2mu (3.3 mag = workable)
  Unusual radio source Sgr A^* : 1 Jy @ 2cm, R < 1.6 AU (**not** AGN on energetic grounds)

- star cluster centered on Sgr A^* occupies central 1-3 pc
  it has an isothermal profile with core radius $r_c \approx$ 0.2-0.3 pc
  $\approx$ 600 stars with M_K < 16 yield radial velocities (spectroscopy), and proper motions (speckle camera)
  These data yield : (images, Movie-1, Movie-2)
  - for r $\lesssim$ 1pc the velocities are (statistically) **isotropic** with a **Keplerian radial dependence**
    ie, consistent with M(r) $\approx$ constant for r $\lesssim$ 1pc
    best fits yield $M_{BH} \approx 2.8\ (+/- 0.3)\times10^6 M_\odot$
  - for r $\approx$ 1-3 pc, mass increases and quickly becomes dominated by stars
  - within 0.01 pc (2000 AU) of Sgr A^* : $\sigma \approx$ 420 km/s with the fastest stars $\approx$ 1500 km/s
    Orbital timescales are $\approx$ 100 yrs $\rightarrow$ human lifetime !
  - the maximum extent for the central mass consistent with the data is 0.0042pc or 800 AU
    the central density is therefore > $2\times10^{12} M_\odot\ pc^{-3}$
    Such densities rule out many options :
    Brown Dwarfs merge;
    clusters of neutron stars or white dwarfs quickly evaporate via 2-body relaxation

  Conclusion : the case for a black hole of mass $\approx 3\times10^6$ at the galactic center is now **very strong**

- Can we pin the location of the black hole on Sgr A^* ?
  - it is located within the peaked region of maximum stellar densities and velocities
    ie it lies (within errors) at the center of the nuclear star cluster
  - accelerations for 3 stars have been measured, yielding orbit segments

the orbits are consistent with Sgr A^* at focus of an ellipse, having the mass of the black hole.
- the proper motion of Sgr A^* is **zero** in the MW frame (12 +/- 9 km/s)
  (in fact, we witness Sgr A^*'s **apparent** motion due to the **Sun's** motion around the galaxy)
  (Doppler velocity is unobtainable ↔ no detectable optical or IR emission from Sgr A^*).
- it is possible to place useful lower limits on the mass of Sgr A^*
  Since the 2-body relaxation time is short, we expect energy **equipartition** amongst all objects
  ie $M_* V_*^2$ is the same for **all** objects (including Sgr A^*)
  we can now use the **lack** of velocity of Sgr A^* to set limits on its mass
  using a Gaussian energy distribution, if Sgr A^* **were** moving at 10 km/s :
  we derive probabilities of 99.7% / 97% / 70% that $M_{Sgr\,A^*}$ is greater than 1 / 100 / 10,000 $M_\odot$
  Since Sgr A^* is moving **slower** than 10 km/s, these are **lower limits** to the mass.
  it seems highly unlikely that Sgr A^* is a star of some kind

conclusion : The evidence supports the fact that the Sgr A^* radio source is indeed the black hole.

Going a little further : the Schwarzschild radius for the MW black hole is $r_s = 0.056$ AU ($\approx 20\ R_\odot$)
Expressing the Sgr A^* apparent radio source size in terms of r_s gives $\approx 60 \times 20\ r_s$
these are **upper limits** since the measured size of Sgr A^* is set by interstellar scattering
It seems, therefore, that the radio emission originates within a region where GR effects are significant
Why Sgr A^* is such a feeble emitter (in both radio and X-ray) is still a mystery.

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(5) Influence of Black Holes on Nuclear Star Distributions

(a) In Situ Growth of Black Holes

- Crudely speaking, one expects a central black hole to draw stars towards it, creating a luminosity spike.
  The details depend on timescales as well as how the black holes form/grow
  Only a few situations are analytically tractable.

- **Before** 2-body relaxation becomes important, one can use the Jeans equations (eg Young 1980)
  Start with a King model : core radius r_c, central density n_c, central dispersion σ
  introduce a small black hole with mass << core mass (ie $M_{BH} << n_c M_* r_c^3$)
  allow it to slowly grow (eg by gas accretion) → this is called **adiabatic** growth
  The result is a **power law cusp** superimposed on the core, extending out to $r_{BH} \approx GM_{BH} / \sigma^2$
  The cusp has density law : $n(r) \approx 0.75\ n_c\ (r / r_{BH})^{-3/2}$
  Thus, one **might** see such a luminosity spike **if** the galaxy has a flat King core.

- **After** 2-body relaxation sets in, a different equilibrium power law distribution arises
  There are two competing processes :
  - evolution towards isothermality : $n(r) \propto \exp(-\Phi(r) / \sigma^2)$
    near the BH this gives the diverging density law : $n(r) \propto \exp(r_{BH} / r)$
  - eating (removing) the stars which get too close to the BH.

  Scaling arguments give a density law : $n(r) \approx n_c\ (r / r_{BH})^{-7/4}$
  this is slightly steeper than the adiabatic growth case described above

  2-body scattering **at large radii** keeps providing stars of ≈ zero angular momentum to feed the hole
  the eating rate is given by :

  $$dN/dt \approx 0.013 \text{ per year} \times M_{BH,7}^{2.33} \times n_{c,4}^{1.6} \times \sigma_{100}^{-5.76} \times M_{*,\odot}^{1.06} \times R_{*,\odot}^{1.6} \qquad (14.3)$$

  where the units are indicated by the subscripts (eg n_c is in units of 10^4 stars pc^{-3})
  Note that for main sequence stars :

for $M_{BH} \lesssim 10^8\ M_\odot$, tidal shredding occurs giving luminous accretion
for $M_{BH} \gtrsim 10^8\ M_\odot$, stars are swallowed whole, with no associated luminosity

if AGN luminosity depends on accretion of **stars**, we might expect :

- low mass spheroids (bulges + Es) : **high** nuclear densities and **low** mass black holes
  → high accretion rate ($\approx 10^{-4}$ yr^{-1}) of **shredded** stars
- high mass spheroids (bulges + Es) : **low** nuclear densities and **high** mass black holes
  → low accretion rate ($\approx 10^{-6}$ yr^{-1}) of **unshredded** stars

(b) Star Scattering and Orbit Modification

- Star orbits which pass close to the nucleus may suffer large (random) angle deflections
  A class of such orbits are called **box orbits** [image]
  These orbits are important in maintaining **triaxiality** in galaxies, eg following a merger.
  If a triaxial galaxy has a massive central black hole, over time it will destroy the box orbits
  galaxy will gradually change from triaxial to axisymmetric
  the central regions are also likely to become more spherical

- The same mechanism can operate with any steep nuclear potential :
  for example, when large amounts of gas settle into the nuclear regions

- This may lead to a natural termination of black hole growth at 1% of M_{bulge} :
  Gas settles to the nucleus efficiently in triaxial and/or barred potentials
  while this continues, a nuclear black hole can continue to grow by accretion
  early on, while the black hole mass is still small, it cannot significantly affect the galaxy shape
  When the black hole reaches ≈1 % of the bulge mass, it rapidly destroys the triaxiality
  this shuts off the gas supply to the nucleus, the AGN turns off, and the black hole ceases to grow
  As we shall see below, black holes don't seem to grow beyond ≈1 % of the bulge mass.

(c) Binary Black Holes

- Since galaxy mergers are common and nuclear black holes are common,
  → we expect to have many merger remnants which harbour **two** black holes

- in these situations, the binary black hole can dramatically affect the stellar distribution
  Initially, the black holes arrive close to the center along with their host bulges,
  (this happens quite rapidly -- see Topic 12 on mergers)
  The black holes continue to spiral together, slowed by dynamical friction
  Further orbit decay results from scattering stars out of the core region
  In this way, the decaying binary black hole **lowers** the central stellar density
  (In effect, the binary acts like a nuclear fuel in a star, causing core expansion)

- it has been suggested that :
  cuspy cores with shallow central slope form from binary black hole scattering
  power law cores with steep central slope form from adiabatic black hole growth via gas accretion.
  these suggestions are currently little more than speculations

- as the black hole orbital velocities approach c, gravitational waves are generated, causing further orbit decay
  finally, the black holes merge, with a luminosity in G-waves of $\approx c^5/G \approx 10^{60}$ erg/s, for a duration $\propto M_{BH}$
  for two $10^7 M_\odot$ black holes, the final frequency is $\approx 10^{-4}$Hz (detectable by LISA but not LIGO) [images]
  possible BH merger rates are ≈ 1 per year in the visible universe
  detection of such events would be an extraordinary scientific achievement.

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(6) Black Hole Demographics

(a) A Major New Component of Galaxies

- For almost 20 years following the (premature) announcement of a black hole in M87, progress was **slow**
  The case for black holes in a handful of galaxies was gradually strengthened
  With the installation of the STIS spectrograph on HST, things have changed dramatically
  In the last 5 years, **dozens** of black hole masses have been measured
  There are currently several HST programs targetting $\approx$ 100 additional galaxies

- Finally, nuclear black holes can be thought of as a **normal component** of many galaxies.
  As with other galaxy components (eg disks/bulges/halos) we can now ask **demographic** questions :

  What determines whether galaxies have nuclear black holes or not ?
  What do their properties (mass, spin, orientation) depend on ?
  How have they affected other components of the galaxy ?
  How were they formed and how have they grown ?
  How do they fit into the picture of the formation and evolution of galaxies ?
  How do they relate to AGN, both locally and at high redshift ?

- Answers to these questions may have a lasting impact on many branches of astronomy
  Progress has begun, but it is still very early days
  Not surprisingly, this is currently a very active area of research

(b) The Ubiquity of Nuclear Black Holes

- Kormendy's March 2001 census lists 37 measured black hole masses (census)
  a similar number can be added by combining ground based spectroscopy with HST imaging

- **All** classes of galaxy are found, with the exception of those with little or no bulge
  When detection threshold allows (see below), a black hole is found $\approx$ **95% of the time**
  $\rightarrow$ **almost all** galaxies with bulges seem to have nuclear black holes
  $\rightarrow$ **This is a remarkable result !**

- An alternative (though less direct) approach is to consider the AGN population :
  AGNs are likely to be `parents' of local (inactive) nuclear black holes
  First consider local AGNs :
  Although Seyferts are quite rare (few %),
  LINERs (weak AGNs) are **very common** (> 50%, see Topic 14)
  $\rightarrow$ since activity is currently ubiquitous then, by extension, so are nuclear black holes
  Now consider high redshifts :
  At $z \approx 2$, quasars were $\approx 10^4$ times more numerous than today (the ``Quasar Era'')
  <u>qualitatively</u> : many dead quasar black holes should be lurking in local inactive galaxies
  <u>quantitatively</u> : integrate the QSO luminosity function
  $\rightarrow$ mean photon energy density : $u \approx 1.3\times10^{-15}$ erg cm^{-3}
  for efficiency ϵ, the equivalent black hole density is : $\rho_{BH} \approx u / c^2\epsilon = 2.2\times10^4\ \epsilon^{-1}\ M_\odot\ \mathrm{Mpc}^{-3}$

  A simple comparison with the galaxy luminosity function suggests :
  $\rightarrow$ an L_* galaxy should have $M_{BH} \approx 10^{7.7} M_\odot$ (setting $\epsilon = 0.1$)
  assuming that BH mass scales with galaxy luminosity, we now expect :
  $\rightarrow$ M32 might have $M_{BH} \approx 10^6 M_\odot$ while M87 might have $M_{BH} \approx 10^{8.5} M_\odot$
  in fact, the most luminous QSOs have $L \approx 10^{47}$ erg/s, suggesting an upper limit :
  $\rightarrow$ $M_{BH} \approx 10^{9.5} M_\odot$ (setting $L \approx L_{edd}$)

  Conclusion : we expect a range of BH masses : $10^6 M_\odot$ (very common) - $10^{9.5} M_\odot$ (very rare)

(c) Ties to the Bulge

- One might expect a correlation between BH mass and **bulge luminosity** (ie bulge mass)
  The evidence for this has steadily grown, and is now very strong (image)
  There is, however, significant scatter (rms $\approx$ 0.5 in log, full range 2 in log)

- Adopting a normal bulge M/L ratio $\rightarrow M_{BH} \approx 0.13\% M_{bulge}$ with quartiles at $\approx$ 0.05% and 0.5%
  this approximately constant ratio spans a factor $\approx 10^3$ in BH mass

- The correlation is **much poorer** with total galaxy luminosity
  more specifically, there is **no** correlation with disk luminosity
  $\rightarrow$ when bulges are present, disks have little/no influence on BH formation/growth
  A slightly different approach is to look for BHs in pure disk galaxies :
  $\rightarrow$ **none have been found**
  example : for M33, $M_{BH} < 1000\ M_{\odot}$, which is $< 10^{-5}\%\ M_{disk}$ (image)

- There is also a good correlation between BH mass and **bulge velocity dispersion**, σ_e (images)
  (note : σ_e is measured on **much larger** scales than r_{BH}, ie it is not directly affected by the BH)
  The M_{BH} vs σ_e correlation is **significantly stronger** than the M_{BH} vs L_{bulge} correlation
  eg, the worst outliers in the M_{BH} vs L_{bulge} correlation fall nicely on the M_{BH} vs σ_e correlation
  for the best data, the scatter is consistent with the observational errors
  $\rightarrow$ M_{BH} is more fundamentally linked to σ_e than M_{bulge}
  Why ?

- Recall that L_{bulge} and σ_e do not correlate perfectly (the F-J relation has real scatter)
  the hidden variable is R_e, the effective radius (recall L_{bulge}, σ_e, and R_e make the fundamental plane)
  $\rightarrow$ galaxies with relatively **high** σ_e at given L_{bulge} also have relatively **small** R_e
  for their mass, they are more **compact** -- their bulges have **collapsed more** during formation
  but these are just the galaxies with relatively high M_{BH} (since M_{BH} follows σ_e closely)
  $\rightarrow$ M_{BH} seems to follow the degree of dissipative collapse experienced during bulge formation
  conclusion : BH formation may be closely related to **dissipative bulge formation**

- Speculating : Lets bring in the link to AGN, QSOs, and ULIGs :
  Bulges probably formed by dissipative collapse during a merger
  We know major mergers today result in ULIGs
  ULIGs often hide genuine AGN activity, and after blowout may reveal full fledged AGNs/QSOs
  Perhaps :
    the formation of bulges resembles local ULIGs
    this event leads to **the formation (and feeding) of nuclear BHs**
    when visible, these become QSOs
  Associating BH formation with bulge formation naturally leads us to the next section

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(7) Black Holes and Galaxy Evolution

- Exacly how and when nuclear black holes formed is still very uncertain
  (though there is no shortage of speculation)
  it is premature, therefore, to attempt to review the various possibilities.
  Instead, it is worth noting some broad themes.

- Summarizing the emerging picture :
    Nuclear black holes are common and seem to be related to bulge formation
    The space density of black holes matches that expected from QSO background light
      (ie nuclear black holes are probably the dead remnants of QSOs)
    QSOs are plausibly associated with bulge formation by analogy with ULIGs (image)
  Since ULIGs and bulge formation are intimately connected with the star formation history of galaxies :
  $\rightarrow$ compare QSO N(z) evolution with SFR(z) (images)

- Recognizing that the SFR(z) plot is far from clearcut, we nevertheless press on :
  The comoving QSO and SFR densities seem to share a similar epoch of **turn on** ($z \gtrsim 3$)
  this would be natural if both were associated with bulge formation
  However, the QSO numbers drop rapidly after $z \approx 2$ while the SFR stays reasonably high
  one might associate the QSO decline with the decline of high fueling rates :
    mergers get less frequent
    bulges become more axisymmetric as stars are scattered by the black hole
    steep central densities maintain an ILR which suppresses bar formation and gas inflow
    black hole masses grow beyond $\approx 10^8 M_\odot \rightarrow$ main sequence stars are swallowed whole

- Needless to say, the themes of this section are far from firmly established
  As more black holes are measured and the SFR history better pinned down, their connection will hopefully become clearer.

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(8) The Galactic Center as a Typical Galaxy Nucleus

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