MEASURING BH MASSES AND SPINS

Lecture 8, Introduction to Black Hole Astrophysics (PHYS480)

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ANNOUNCEMENTS

- HW4 will be posted on iLMS and course website today. Due date: 4/27/2021
- Please search for black hole news for the oral presentation and paste the news link here:

https://docs.google.com/spreadsheets/d/1_aYyMj1wf_uGheZ7zp_hvthmy4mdmPwIxFDdZOMG-nc/edit?usp=sharing

- For the oral presentations, I will compile the scores and comments from the audience and send to you after the presentation
- Please start forming a team of 3 people for the final report. Choose a team leader and enter your names on iLMS -> 小組專區

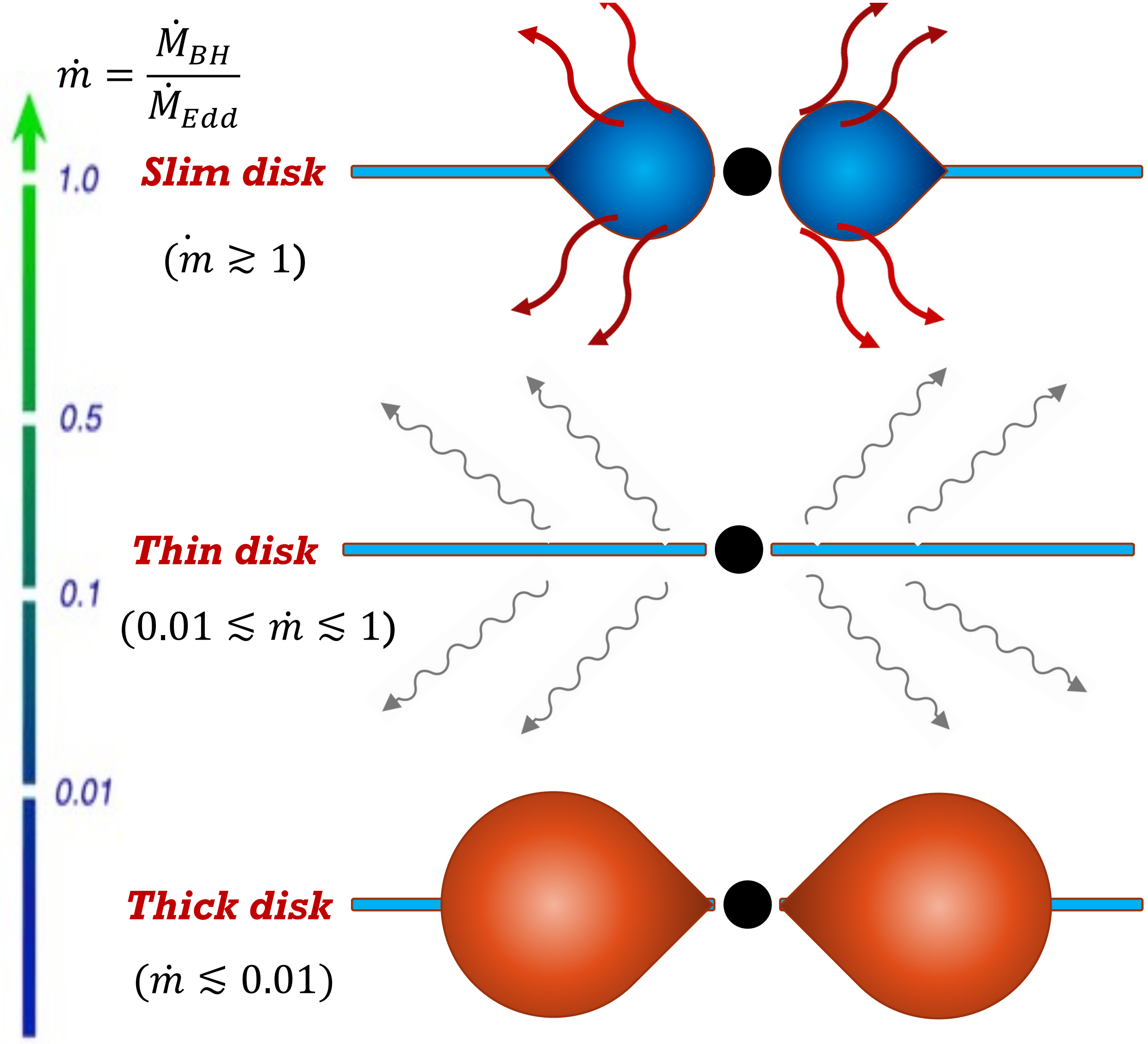
PLEASE PROVIDE YOUR FEEDBACK!

- Your feedback and comments would be valuable for improvements of this course!
- Link to the course evaluation form:

  https://qrgo.page.link/9f6cE
- Or scan the QR code here:

PREVIOUS LECTURE…

- The ***Eddington limit*** – the maximum luminosity a body can achieve due to the competition between radiation pressure force and gravity
- Accretion properties depend on ***angular momentum*** and ***mass accretion rates***
- When no angular momentum -> spherical ***Bondi accretion***; when there is angular momentum -> accretion disks
- Solution of the angular momentum problem: ***outward angular momentum transport due to viscosity*** in shear flows, which allows mass to flow inward
- ***Three types (slim, thin, and thick) of accretion disks*** depending on the mass accretion rate
- X-ray binaries exhibit ***state transitions*** between X-ray hard and soft spectra, corresponding to transitions between thin and thick accretion disks due to varying accretion rates



- Radiatively less efficient than thin disks
- Radiation pressure driven winds
- Only occur in rare cases

- Radiatively efficient
- Spectrum well described by superposition of black-body radiation
- Quasars, disk-dominated X-ray binaries

- Radiatively inefficient
- Accretion is hot – corona
- Spectrum described by nonthermal processes
- Sgr A*, low-luminosity AGN, corona-dominated X-ray binaries

THIS LECTURE

- Measuring BH ***masses***
  - Four methods
  - Mass distribution of BHs
  - Open questions and future prospects

- Measuring BH ***spins***
  - Three methods
  - Spin distribution of BHs
  - Open questions and future prospects

MEASURING BH MASSES

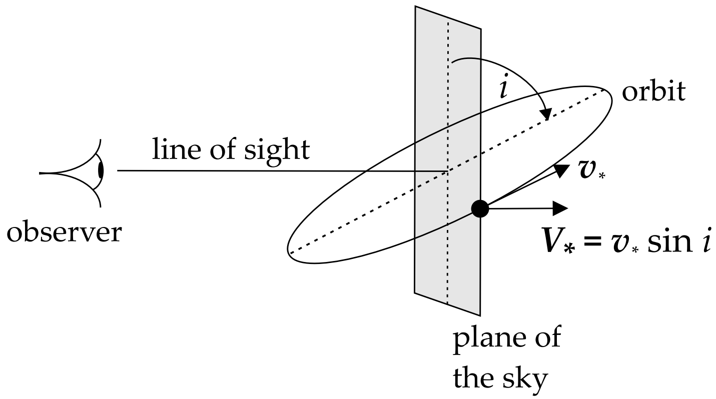
(I) DYNAMICAL MASS FROM STELLAR MOTIONS

- Use the orbital parameters of stars to determine the mass of the central object
- Newtonian gravity:

$$M = \frac{v^2 r}{G} = \frac{v^3 P}{2\pi G}$$

- Complications that need to be taken into account:
  - Mass of the companion star (due to orbits around the center of mass; important for smbhs)
  - Inclination of orbits (because Doppler's effect only traces velocities along the line of sight)
  - The mass function (Week 5):

$$f(M) = \frac{V_*^3 P_{\rm orb}}{2\pi G} = \frac{M^3 \sin^3 i}{(M + M_*)^2} = \frac{M \sin^3 i}{(1+q)^2}.$$

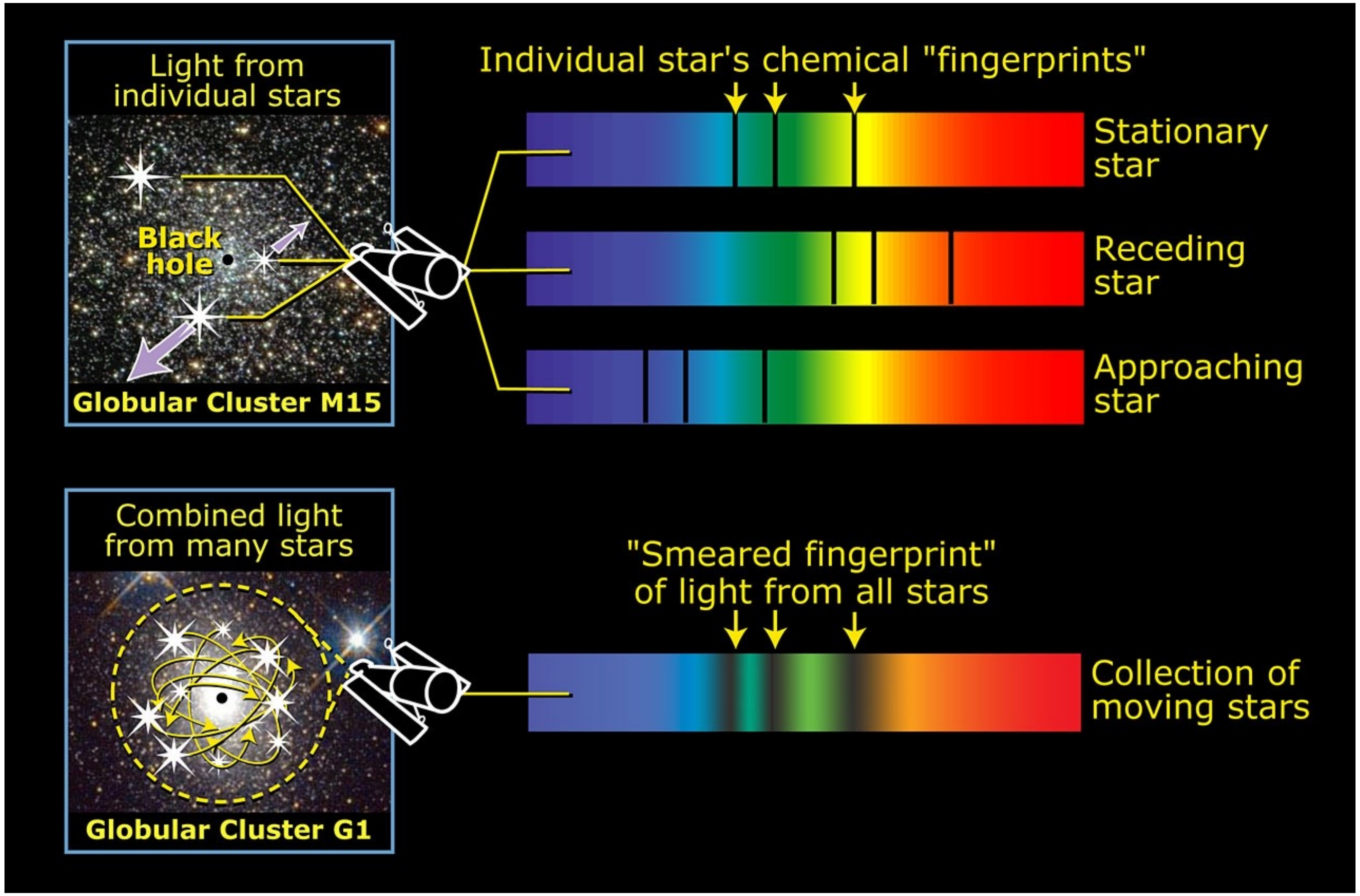


(I) DYNAMICAL MASS FROM STELLAR MOTIONS

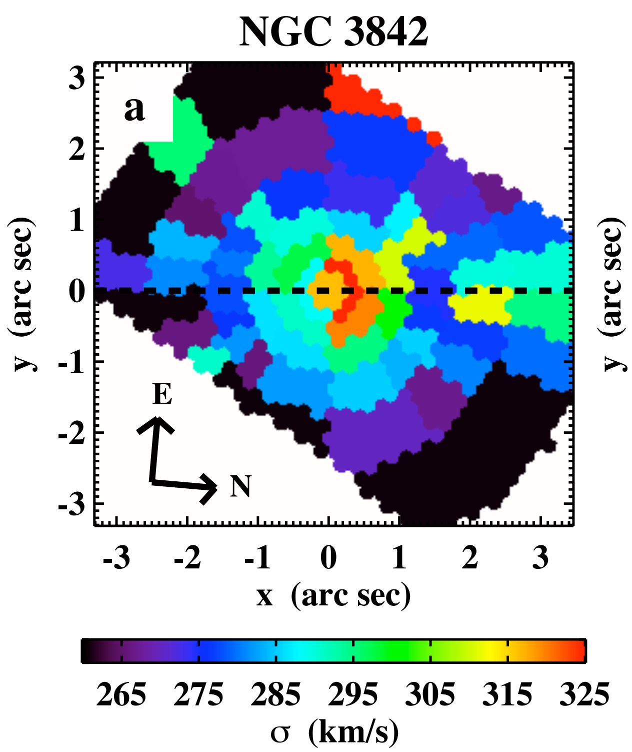
- This is how we knew Cygnus X-1 and Sgr A* are BHs
- This method provides the most precise mass measurements, but it can only be applied to really nearby systems
  - smbhs: dozens in the Milky Way Galaxy + a few in nearby galaxies
  - SMBHs: one in the Milky Way and <~20 nearby galaxies

(II) USING STELLAR/GAS DYNAMICS NEAR THE CENTER OF GALAXIES

- For SMBHs in other galaxies, it is impossible to resolve motions of individual stars
- But for relatively nearby galaxies where the ***sphere of influence*** (the region where BH's gravity is dominant) can be resolved, motions of stars/gas can be measured by the ***smearing of spectral lines due to Doppler's effect***
- ***Velocity dispersion (σ)*** = standard deviation of the velocity distribution



(II) USING STELLAR/GAS DYNAMICS NEAR THE CENTER OF GALAXIES



- One could then obtain the map of velocity dispersions near the center of nearby galaxies
- The mass of the central SMBH can then be derived using:

$$M = \frac{\sigma^2 r}{G}$$

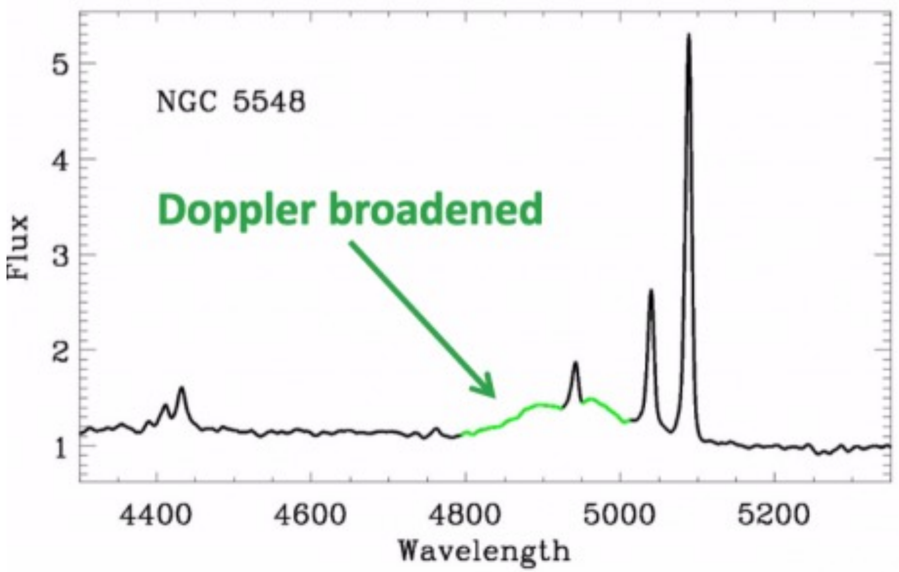
- Complication: stellar motions are not only affected by the BH but also the galaxy itself. Need to model this effect to isolate the mass of the BH

(III) REVERBERATION MAPPING

- This method is used to measure masses of SMBHs for even more distant galaxies, again using

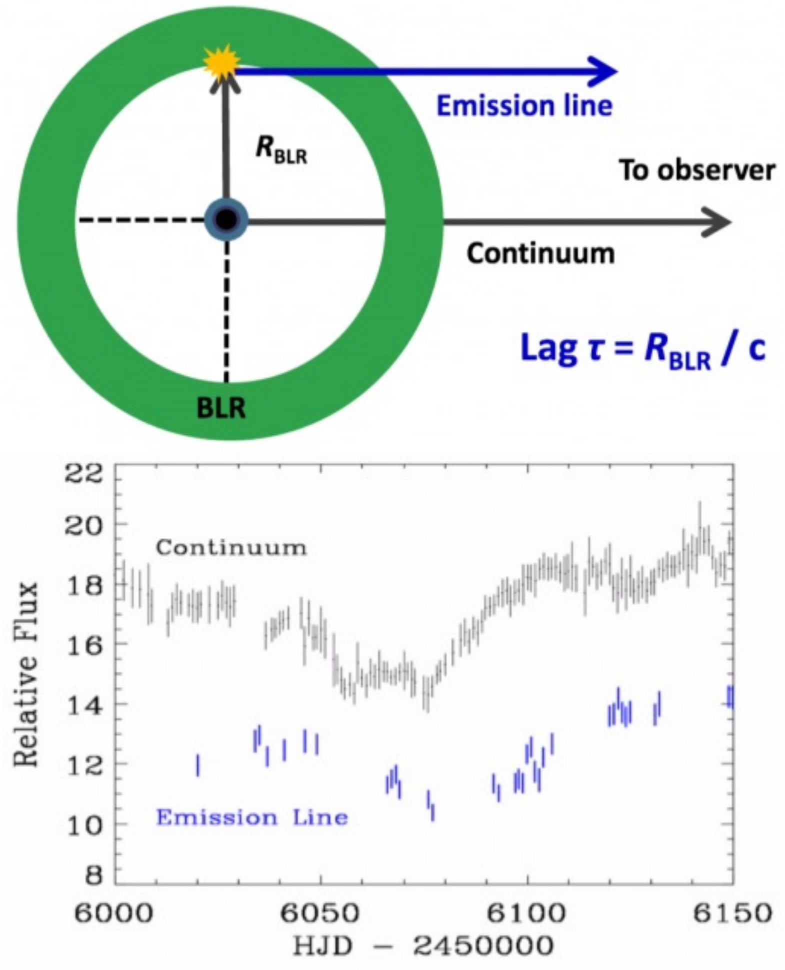
$$M = \frac{\sigma^2 R_{BLR}}{G}$$

- In the spectrum of many AGNs, some spectral lines are broadened due to gas clouds orbiting the central SMBH with high speeds (Week 9)
- This is called the "***broad line region (BLR)***"
- σ = velocity dispersion of the broad lines



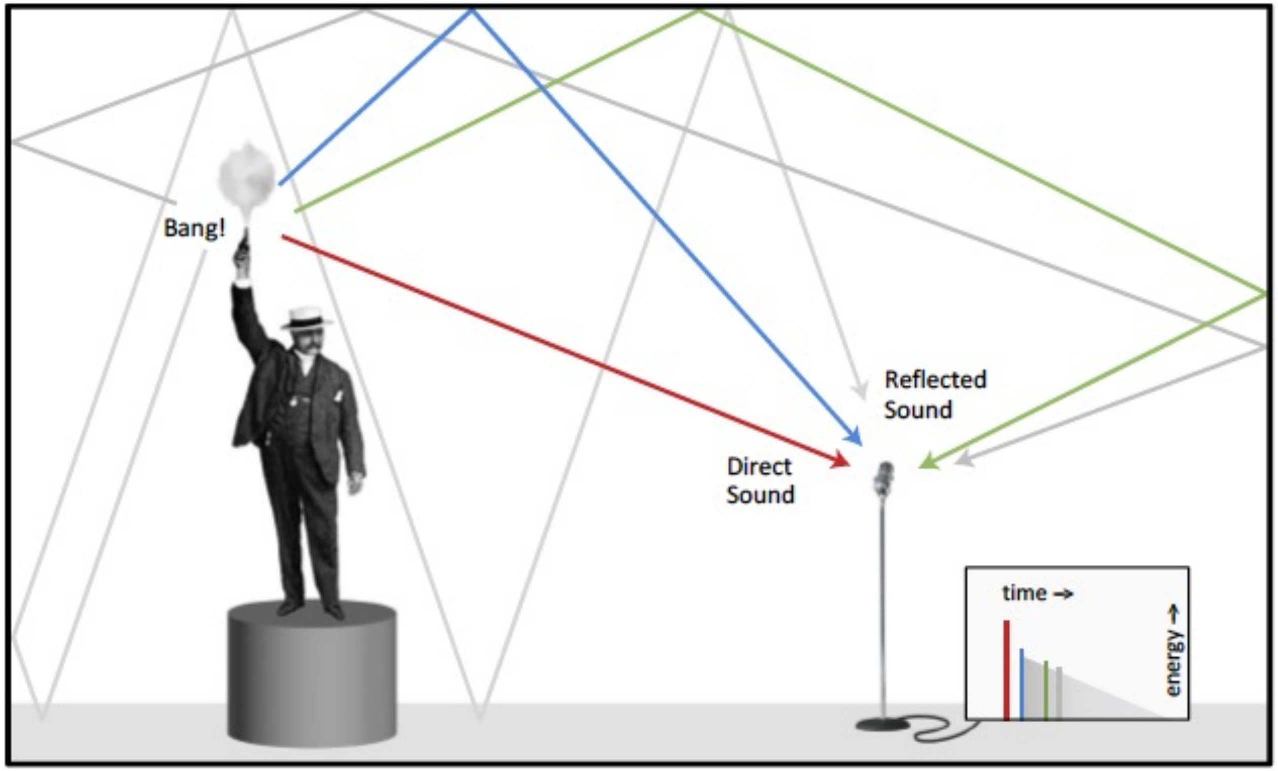
(III) REVERBERATION MAPPING

- The radius of the BLR is not resolved, but can be inferred using the ***time delay effect***
- Emission from the BLR is from electrons in elements being excited by radiation from the central SMBH
- Because AGN is often variable, the fluxes of the broad lines will vary with the central source
- There is a time delay between their variations, $\tau = R_{BLR}/c$
- By measuring τ, we could infer R_{BLR} and derive the BH mass



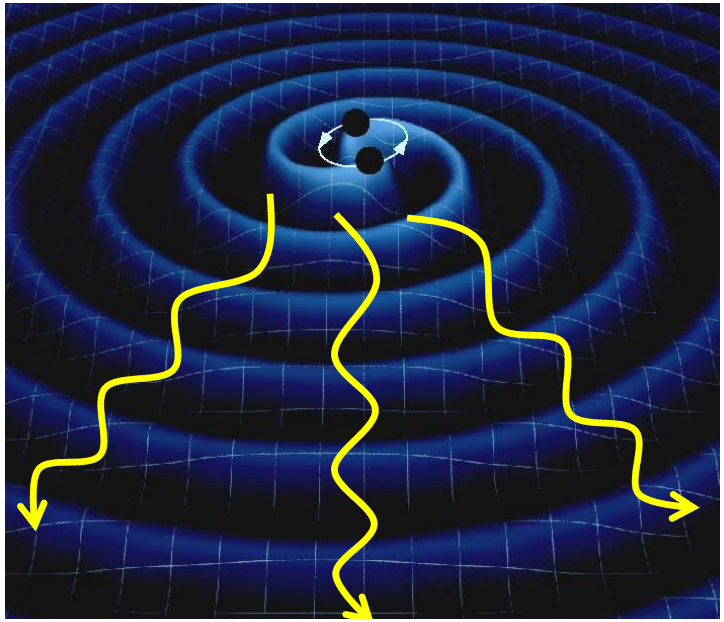
(III) REVERBERATION MAPPING

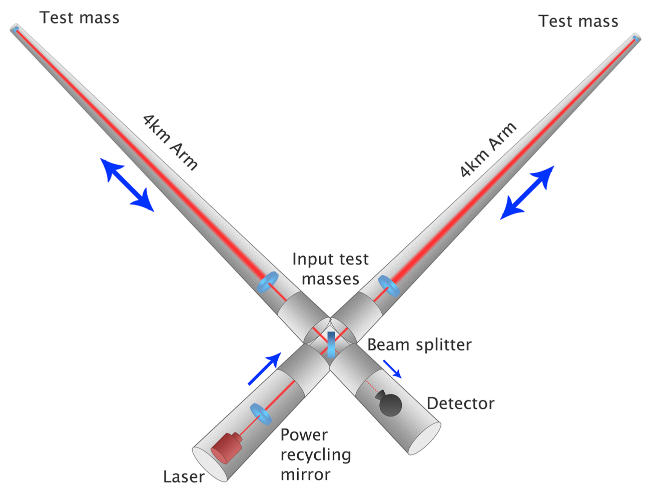
- ***Reverberation (残響／混響)*** = remaining sounds from reflections after the source is stopped



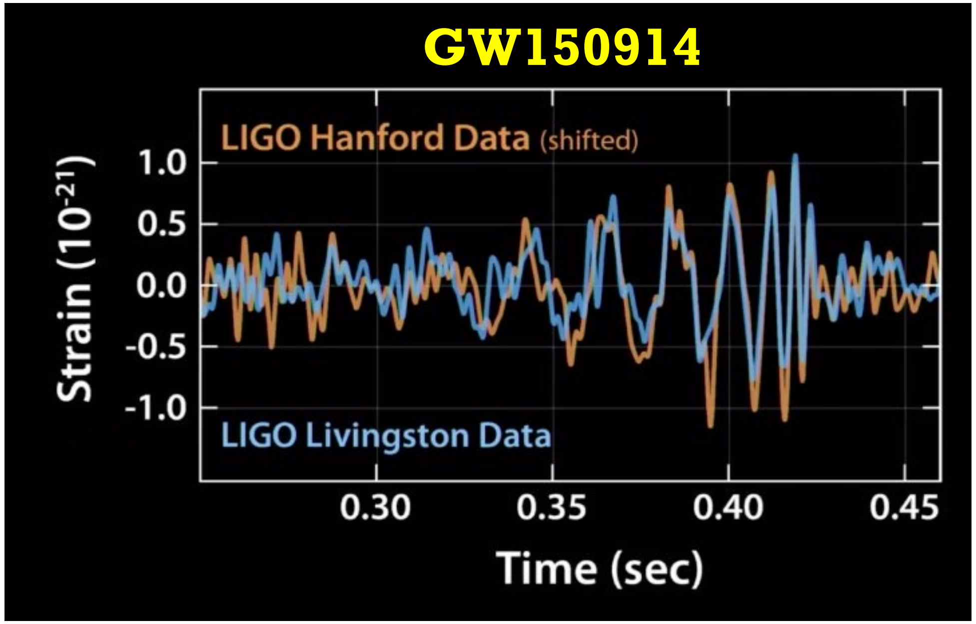
(IV) GRAVITATIONAL WAVES

- Gravitational waves (GWs) are ripples in spacetime
- LIGO = Laser Interferometer Gravitational-wave Observatory
- LIGO can measure spacetime distortions to the level of 10^{-21}!!
- LIGO has detected 50 GW events to date
- LIGO's sensitivity and frequency range (~10-1000 Hz) allow us to detect GWs from mergers of stellar-mass BHs and NSs



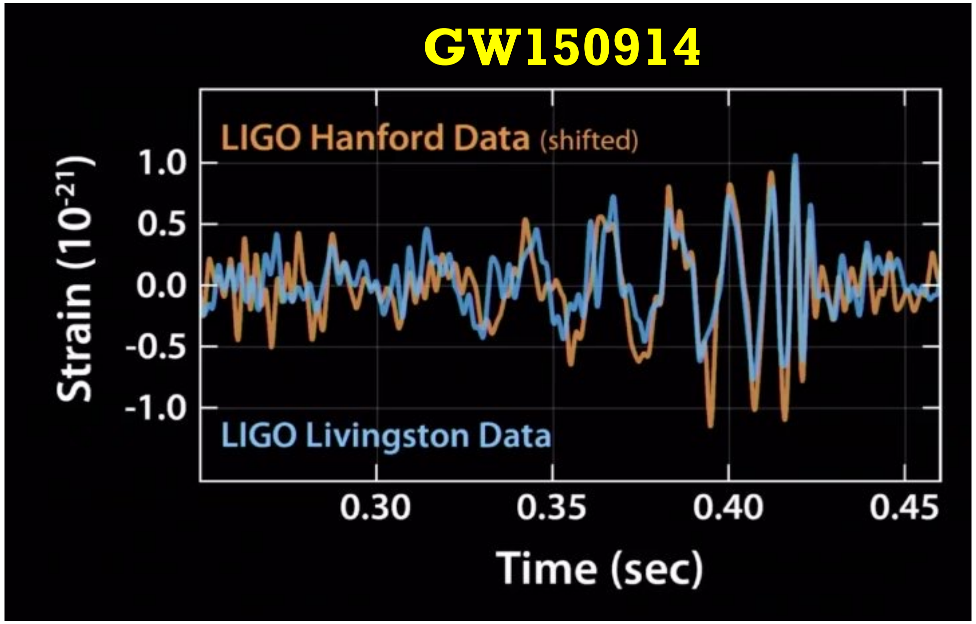


WAVEFORM OF THE FIRST GW DETECTION



- Generated by merger of two BHs with 36 and 29 M_{sun} -> 62 M_{sun}
  - Some energy is carried away by the GWs
- Frequency: 35 -> 250 Hz
  - Hear a "***chirp***"
- The waveform can be used to determine parameters including masses, spins, distance, etc

MASS CONSTRAINTS FROM GW WAVEFORMS



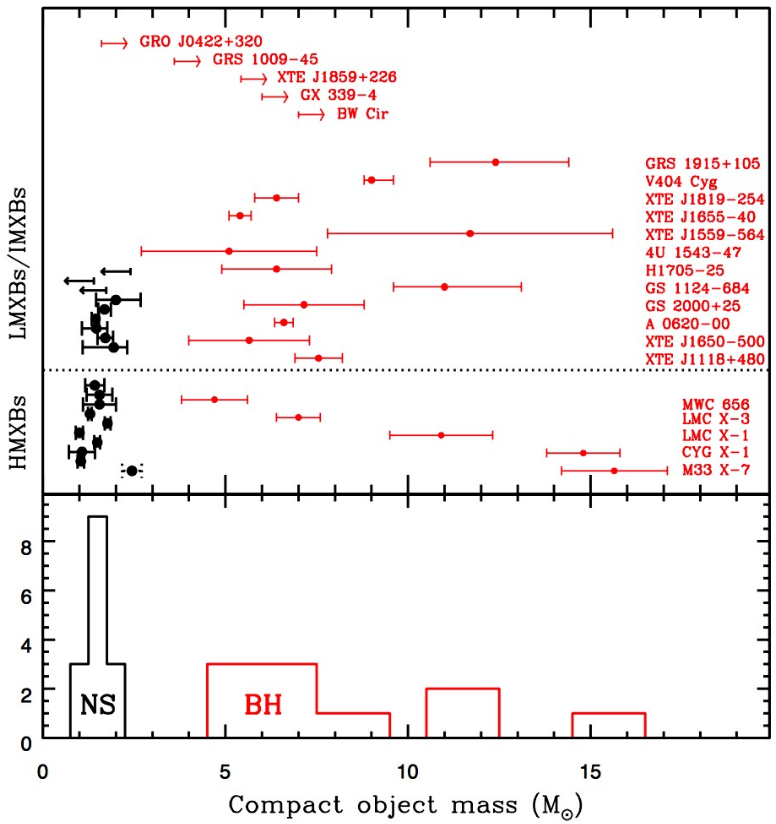
- To 1st order, frequency (f) and frequency change (df/dt) can constrain the "***chirp mass***":

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

- To 2nd order, ***mass ratios*** and ***spins*** can be fit from the waveform, enabling constraints on individual masses
- This is why the chirp mass, or total mass (M), can be measured with higher precision, but mass ratios and spins have higher uncertainties

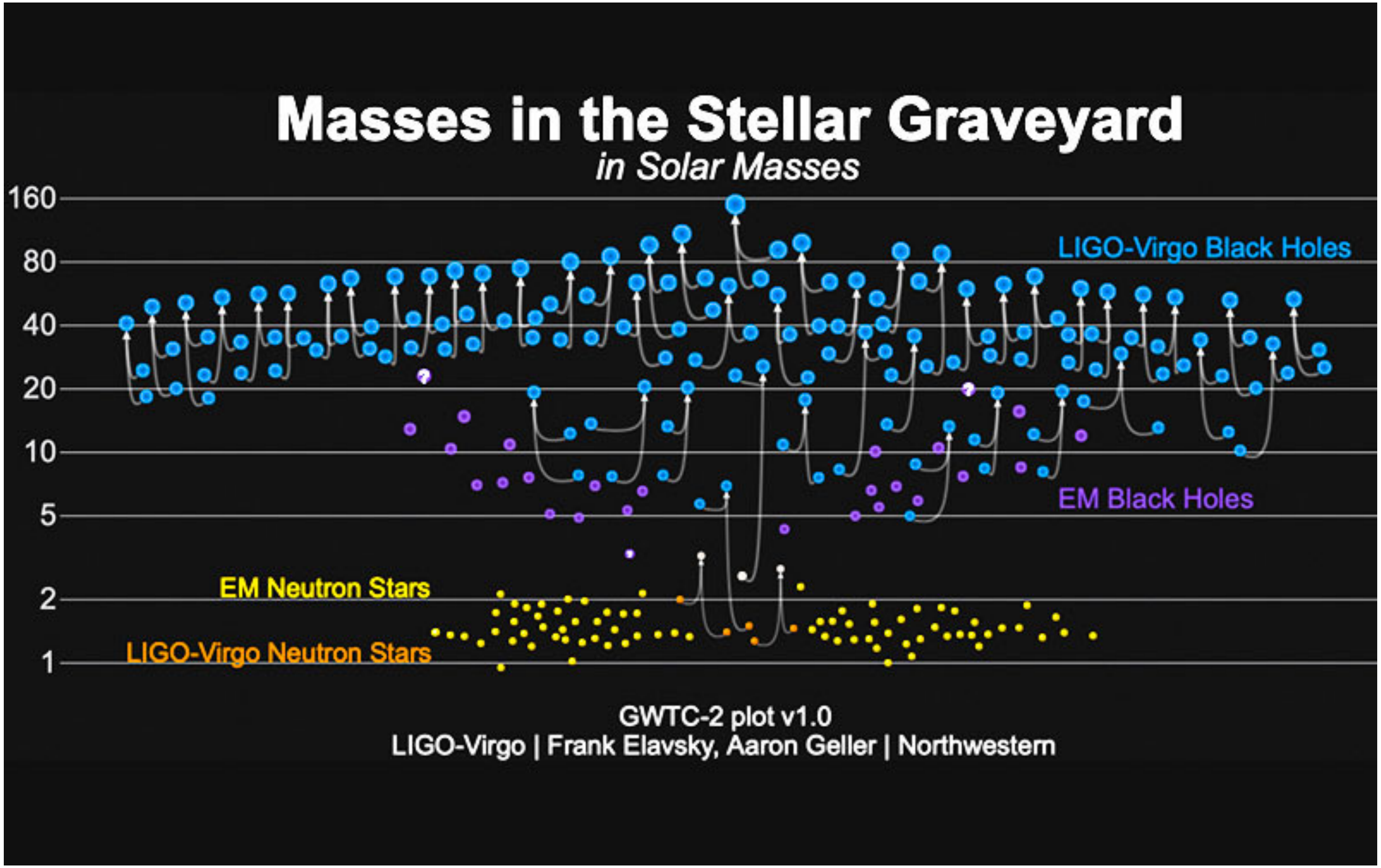
STELLAR-MASS BHS FOUND IN X-RAY BINARIES

Mass distribution of X-ray binaries

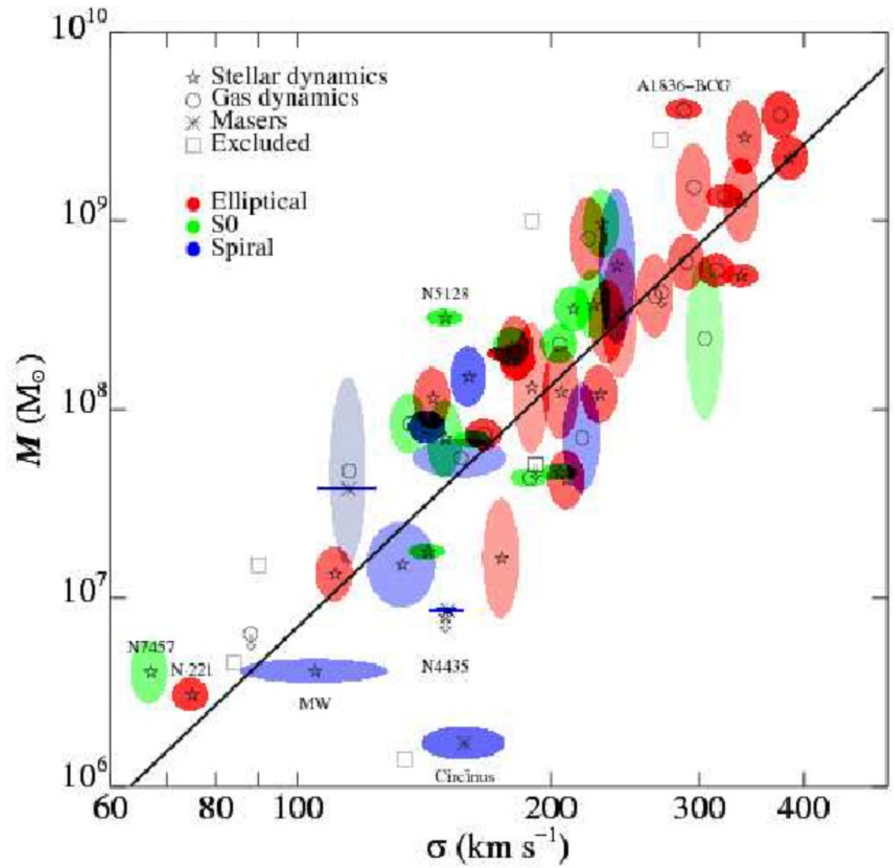


- These are the so-called "EM black holes" which emits electromagnetic radiation due to accretion
- A few dozens have been detected

STELLAR-MASS BH FOUND BY EM WAVES & GWS



SMBHS DETECTED AT CENTERS OF GALAXIES



Stellar velocity dispersion within galaxy bulges

- Every massive galaxy hosts a SMBH
- Larger galaxies host larger SMBHs
- This ***M-σ relation*** hints co-evolution of SMBHs and their host galaxies

CURRENT RECORD HOLDERS

- Stellar-mass black holes:
  - The smallest: ~3.3 M_{sun} (**check out this news**)
  - The most massive: 142 M_{sun} (**check out this news**)

- Supermassive black holes:
  - (One of) the smallest: NGC 4395 – 3.6 x 10^5 M_{sun} (using reverberation mapping)
  - The most massive: quasar TON 618 --66 billion M_{sun} (**check out this news**)

***The fact that many of these are news within 2 years means that this is a quickly evolving field!!!

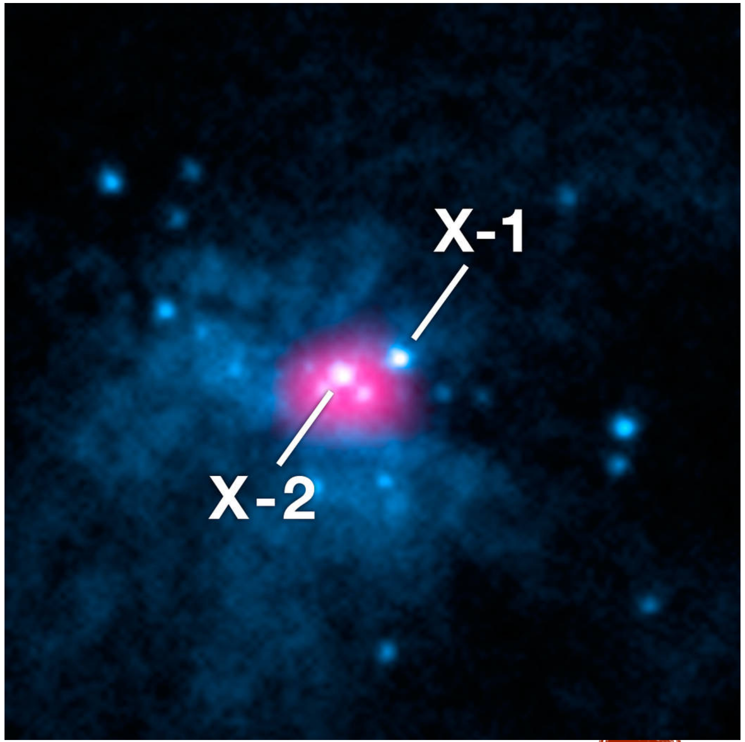
THE BIG QUESTION: ARE THERE BLACK HOLES BETWEEN 100-100000 MSUN?

- BHs within the range $\sim 10^2 - 10^5\ M_{sun}$ are called "***intermediate-mass black holes (IMBHs)***"
  - Note that the definition is not very exact. There is no clear dividing line between a smbh and an IMBH, or an IMBH and a SMBH
- If one defines the mass range of IMBHs to be exactly $10^2 - 10^5\ M_{sun}$, then the smbhs of 142 M_{sun} detected by LIGO is qualified as an IMBH
- In general, they are hard to find observationally!
  - For small IMBHs $\sim 10^2\ M_{sun}$, they are rare so few of them could be detected using EM waves -> GWs are probably the best bet
  - For large IMBHs $\sim 10^5\ M_{sun}$, many are "***candidates***" as it is hard to definitively confirm they are indeed BHs
    - They live in dwarf galaxies so emission is faint
    - Their small masses make it hard to rule out alternative models

ULTRA-LUMINOUS X-RAY SOURCES (ULXS)

- The ***ultra-luminous X-ray sources (ULXs)*** are often suspected to be accreting IMBHs
- They are similar to X-ray binaries, but have very high luminosities ($L > 10^{32}$ W or 10^{39} erg/s)
  - Typical luminosities of X-ray binaries ~ 10^{28-32} W
- The MW does not have a ULX, but other galaxies typically have one ULX on average, some can have many

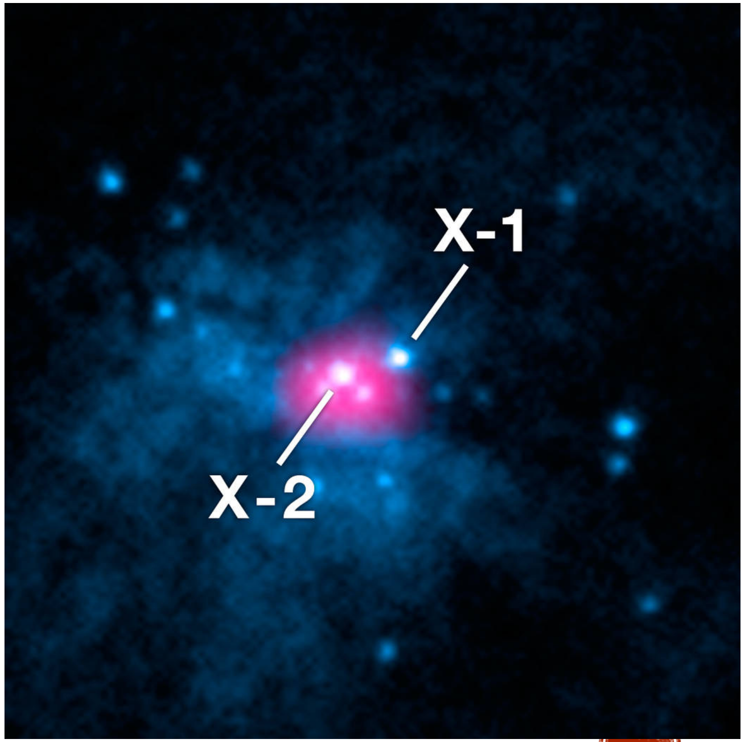
Two ULXs in the M82 galaxy



ULTRA-LUMINOUS X-RAY SOURCES (ULXS)

- Their origin is still debated. Possible explanations:
  - ***Beamed emission*** of stellar mass objects (NSs or BHs)
  - ***Accreting IMBHs***
  - ***Super-Eddington accretion*** of stellar mass objects (NSs or BHs)
- There could be more than one answer!
  - For example, M82 X-1 may be an accreting IMBH (with ~400 M_{sun}), but M82 X-2 has found to be a pulsar!

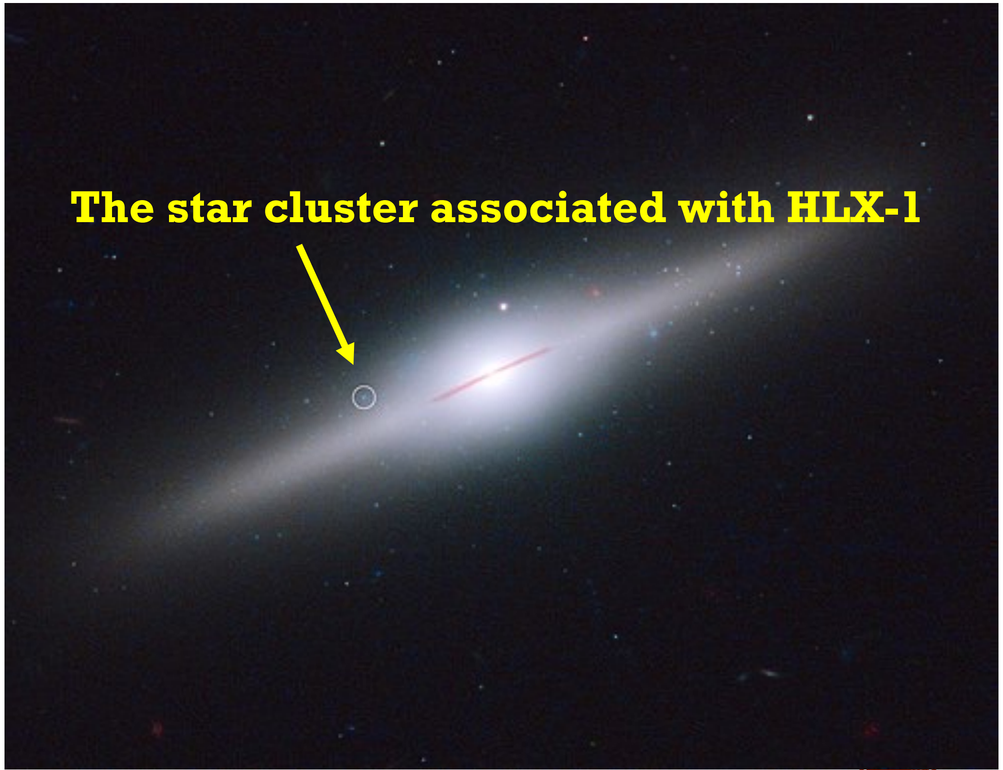
Two ULXs in the M82 galaxy



ONE OF THE BEST CANDIDATE OF IMBHS – HLX-1

- HLX-1, or Hyper-Luminous X-ray source 1, is an IMBH candidate located in galaxy ESO 243-49 ~290 million lyrs away
- Its luminosity is ultra high: $L_X \sim 10^{35}$ W
- If it is an IMBH, its mass is estimated to be $\sim 10^4\ M_{sun}$
- Follow-up observations showed that it is surrounded by a young star cluster, suggesting that it was at the center of a dwarf galaxy, which was stripped when it fell into the more massive galaxy
- News about another IMBH candidate

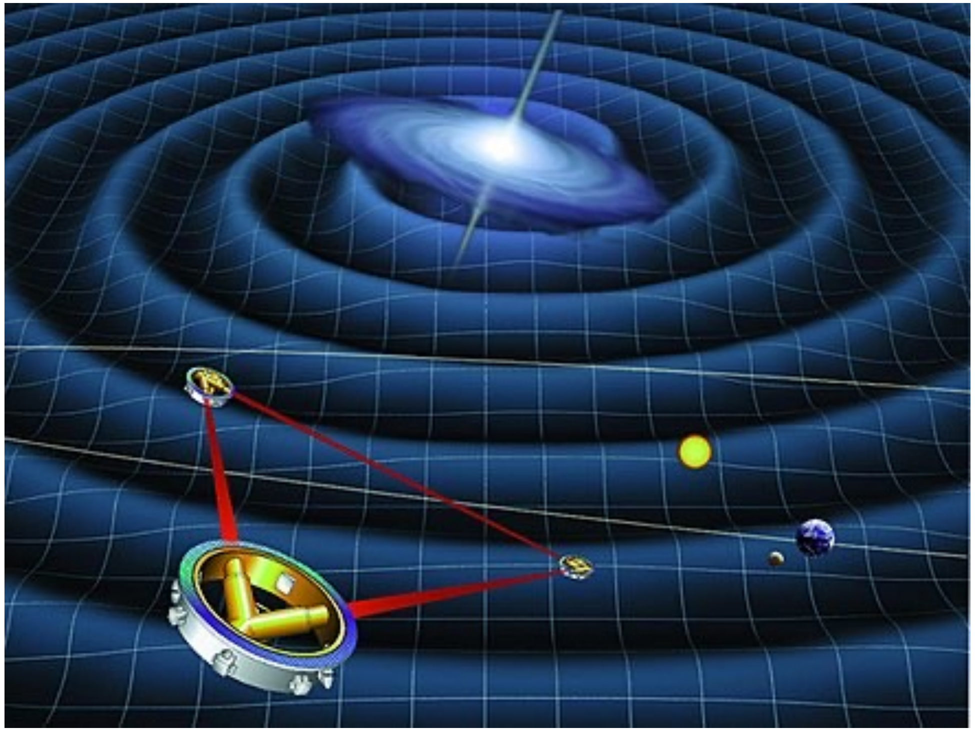
HST image of galaxy ESO 243-49



FUTURE PROSPECTS

- X-ray/optical/infrared missions with higher sensitivities will continue to increase number of sources to probe lower-mass galaxies and to larger distances
- LIGO will continue to find more and more massive smbhs or small IMBHs
- LISA (Laser Interferometer Space Antenna) is a space-based GW observatory
  - Frequency range: 0.1 mHz ~ 1 Hz
  - Capable of detecting mergers of IMBHs/SMBHs with chirp mass of $10^3 – 10^7\ M_{sun}$

Conception of LISA



MEASURING BH SPINS

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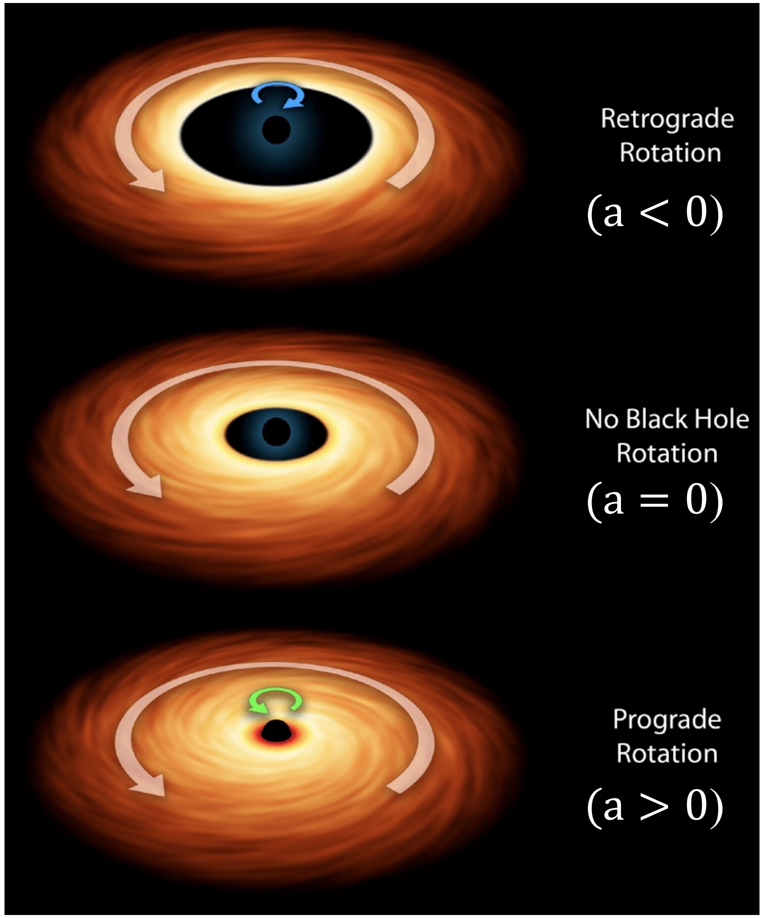
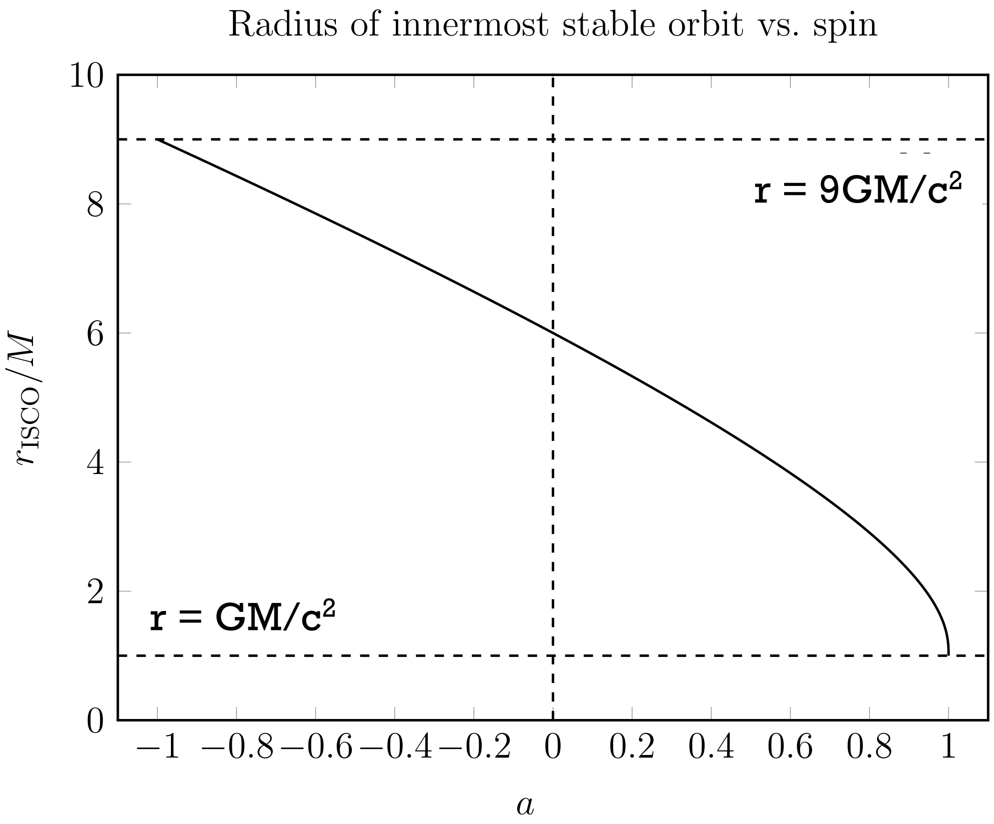
(I) THERMAL CONTINUUM FITTING METHOD





(I) THERMAL CONTINUUM FITTING METHOD

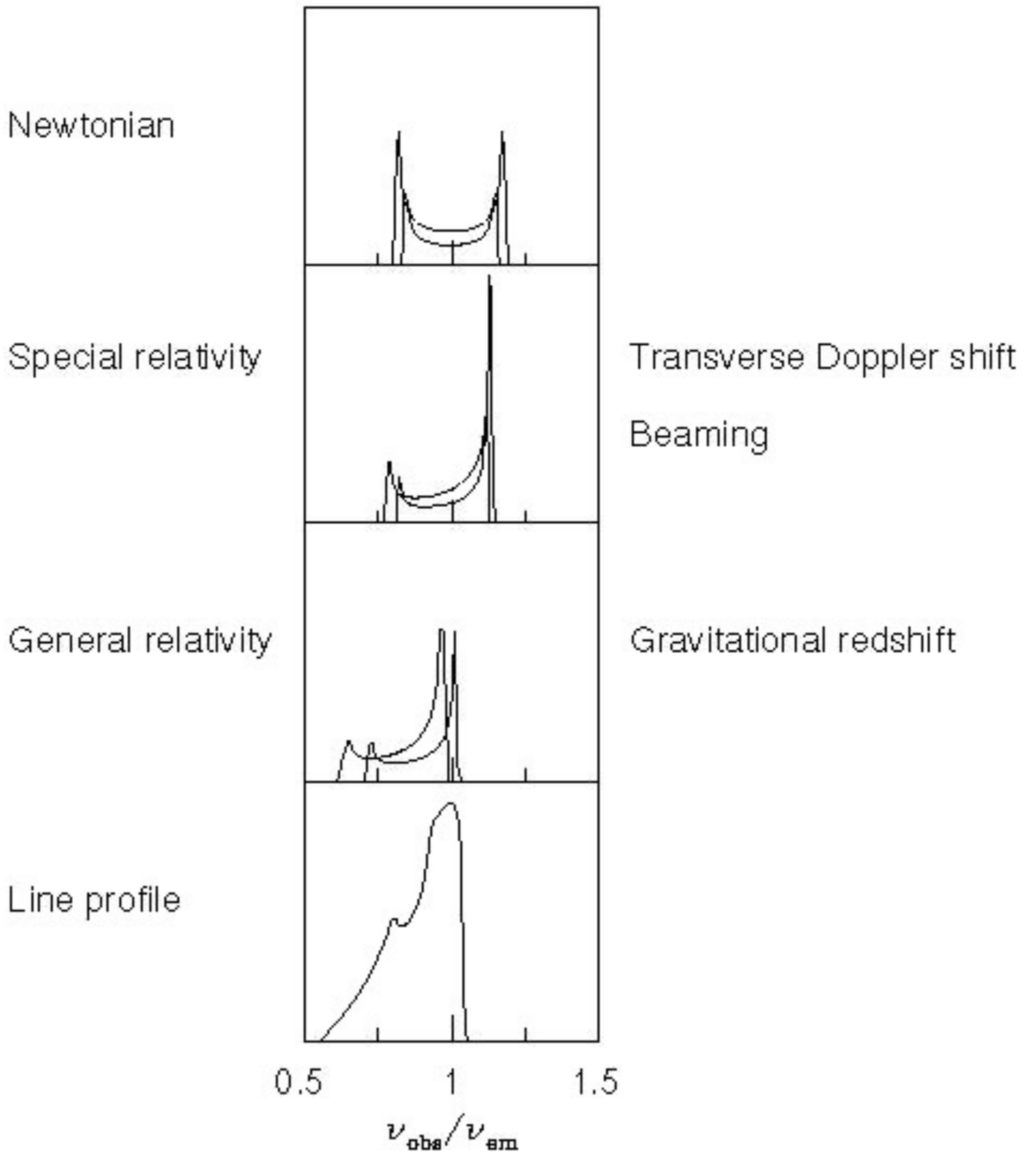
- This method for measuring BH spins can be used for systems with ***thin accretion disks,*** i.e., ***highly accreting systems*** such as quasars and disk-dominated X-ray binaries
- For thin disks, their spectra is a continuum with ***superposition of thermal black-body radiation***
- The highest energy part of the spectrum is sensitive to the hottest gas at the ***ISCO***
- By fitting the thermal continuum, the ISCO can be determined, thus the spin

COMPLICATIONS

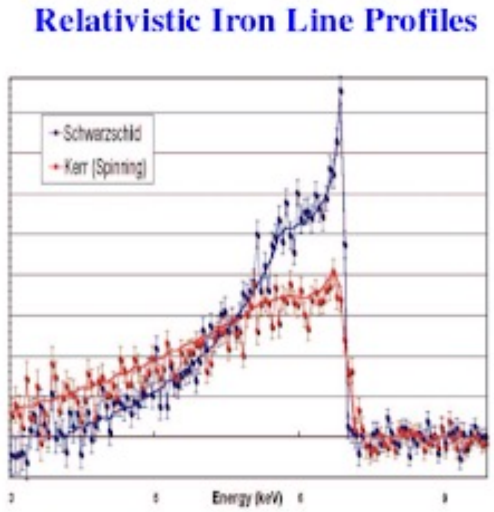
- This method requires accurate measurement of BH ***masses***
  - Uncertainties are larger for SMBHs than smbhs
- Modeling the observed spectrum of the disk also needs to include Doppler's effect and gravitational redshift effect, so disk ***inclination*** needs to be determined
  - For X-ray binaries, this can be inferred using the companion star; for AGNs it is more difficult
- For thin disks, the characteristic temperature $T_0 \sim M_{BH}^{-1/4}$
  - This method is more easily applied to X-ray binaries since the spectrum peaks in ***X-ray***
  - For some AGNs, the spectrum peaks in ***UV***, which cannot be observed because of strong absorption by gas and dust in the Milky Way Galaxy

(II) X-RAY LINE FITTING METHOD

- In the ***X-ray*** spectrum of many X-ray binaries and AGNs, there is a ***Fe line at 6.4 keV***
- It is often explained by iron within the (thin) accretion disk excited by a hot corona (with unknown origin)
- The shape of the Fe line is broadened and skewed due to
  - ***(Relativistic) Doppler's effect***
  - ***Relativistic beaming***
  - ***Gravitational redshift***
- This indicates that the Fe line is emitted close to the BH and thus can be used to measure the BH spin!

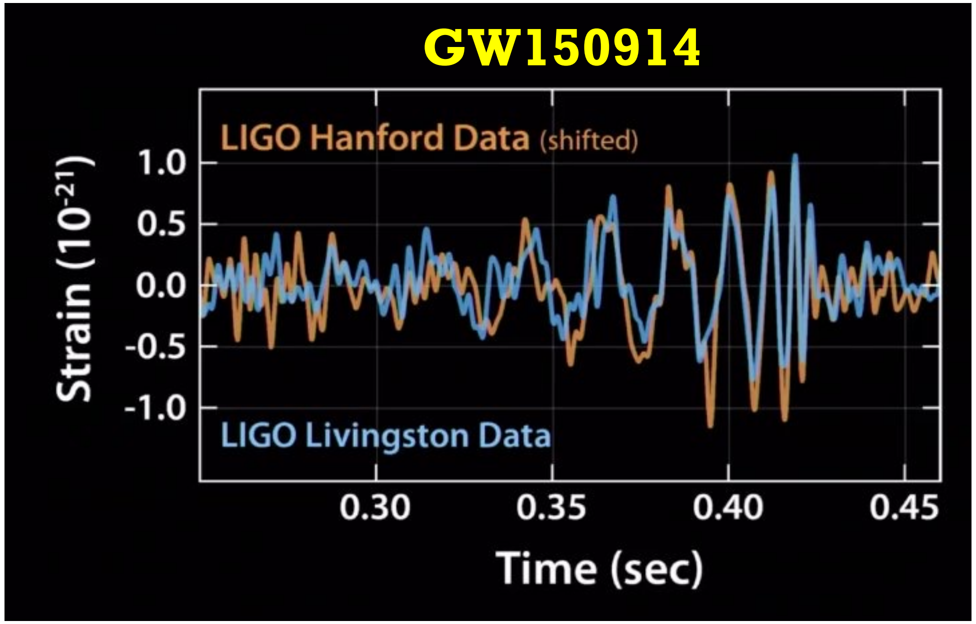


(II) X-RAY LINE FITTING METHOD



- For BHs with higher spin, R_{ISCO} is smaller, so the ***gravitational redshift effect*** is stronger
- By fitting the shape of the Fe line, one could determine the BH spin
- This method does not require the knowledge of BH masses, so could give more precise spin measurements for SMBHs

(III) GRAVITATIONAL WAVES



- Waveform of GWs not only contain information about BH masses, but also BH spins
- What it is sensitive to is the "***effective spin*** (χ_{eff})", i.e., mass-weighted average of spins projected onto the axis of rotation
- The spins projected onto the orbital plane could cause precession of the plane, called "***precession spin*** (χ_p)". This also affects the waveform in a subtle way
- Note that this method only probes ***merging BHs***, and thus the spin distribution may not reflect that of the whole population

SPIN MEASUREMENTS OF STELLAR-MASS BLACK HOLES

- To date, ~10 smbhs have spin measurements using method I, and ~15 smbhs have spin measurements using method II
- 6 of these objects have both measurements and have consistent results (except for one object, 4U1543-47)
- The distribution of spins for smbhs have a wide range, from slowly rotating (a=0.3-0.4) to rapidly rotating (a > 0.95)

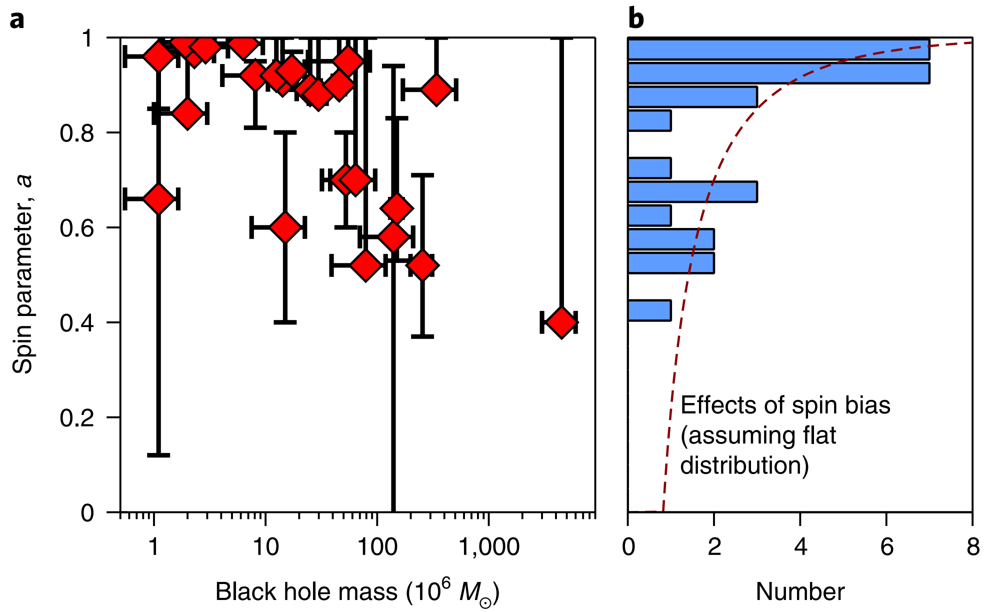
SPIN MEASUREMENTS OF STELLAR-MASS BLACK HOLES

- Within the next few years, improved soft X-ray data from NICER and distance measurement from Gaia will provide more reliable spin measurements
- ***Gaia*** is a space observatory launched in 2013 to precisely measure the 3D positions of ~ 1 billion objects (mostly stars) within the Milky Way Galaxy and other galaxies
- Maybe Gaia will really find "black" black holes!

The Gaia space observatory

SPIN MEASUREMENTS OF SMBHS

- To date, ~two dozen SMBHs have robust spin measurements using method II
- There appears to be more rapidly spinning SMBHs
  - But be careful! It could be due to selection effects because rapidly spinning BHs have smaller ISCO and tend to be brighter and easier to detect
  - The true distribution could be uniform
- There seems to be a trend for lower-mass SMBHs to have higher spins
  - More data is needed to confirm this trend



SOME OPEN QUESTIONS

- What are the true distributions of BH spins?
- Do the BH spins depend on other parameters (e.g., BH masses, environments, etc)?
- Are there other ways to measure BH spins? Do all the methods give consistent results?
- What can we learn from the BH spins?
- …

BH SPINS COULD TELL US ABOUT HOW THEY FORMED/GROW!

- The observed BH spin encodes its formation and evolution history!
  - $\boldsymbol{J}_{\mathrm{final}} = \boldsymbol{J}_{\mathrm{form}} + \boldsymbol{J}_{\mathrm{accretion}} + \boldsymbol{J}_{\mathrm{merger}}$
- For smbhs in binary systems, it could tell us through which binary-evolution channel they are formed
  - Recall the "chemically-homogeneous scenario" for forming massive smbhs in HW3, the predicted spin could be used to validate/invalidate the model
- For SMBHs, in general
  - A ***higher spin*** would suggest that the BH growth is dominated by ***disk accretion or major mergers***, for which the accreted materials tend to have more coherent directions
  - A ***lower spin*** would suggest ***chaotic accretion or minor mergers***, for which the accreted materials have more random directions

**Major/minor mergers refers to galaxy mergers with mass ratios >1:3 or <1:3

SUMMARY

- Measuring BH masses
  - Four methods: (1) dynamical mass from stellar motions, (2) using stellar/gas motions (velocity dispersions) near the center of galaxies, (3) ***reverberation mapping***, (4) gravitational waves
  - Big open question – whether ***IMBHs of 10^2 – 10^5 M_{sun}*** exist or not and what is their distribution? The origin of ***ULXs***?
- Measuring BH spins
  - Three methods: (1) ***continuum fitting method*** (use thermal black-body spectrum to fit for the ISCO and obtain spin), (2) ***X-ray line fitting method*** (use skewed Fe line in X-ray to measure the gravitational redshift effect and determine ISCO and spin), (3) gravitational waves
  - Open question – what are the spin distributions for smbhs and SMBHs and what can we learn about BH formation/growth?

PRESENTATIONS 4/20

- Astronomers image magnetic fields at the edge of M87's black hole by Hsiao, Tiger 蕭予揚

https://qrgo.page.link/9u3iq

- The environment around the supermassive black hole that changes drastically -The site of interstellar molecule destruction captured by the ALMA telescope by Wu, Jie-Ru 吳婕如

https://qrgo.page.link/xLuvQ

- Black hole caught spewing jets into space at nearly the speed of light by Cheng, Ming-Chien 鄭銘健

https://qrgo.page.link/5aiGg