Lecture 2:
Astrophysical Black Holes

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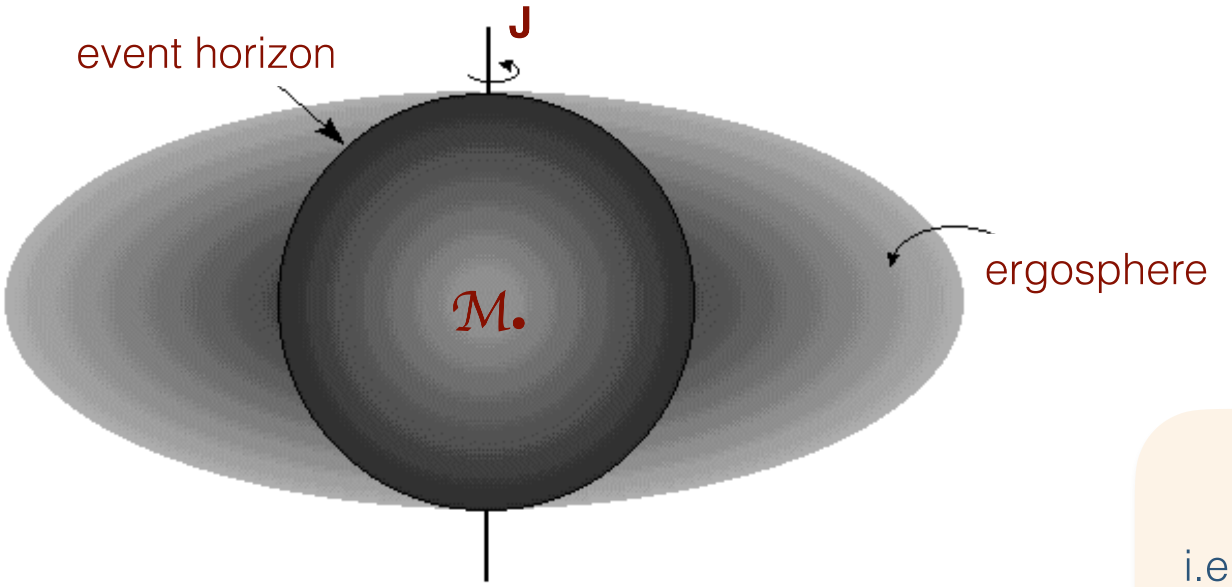
Selected Topic in High Energy Astrophysics, 2025/26

- **no-hair theorem/conjecture:** black holes can be completely characterized by only three externally observable classical parameters: **mass**, electric charge, and **angular momentum (spin)**. All other information (for which "hair" is a metaphor) about the matter which formed a black hole or is falling into it, "disappears" behind the black-hole event horizon and is therefore permanently inaccessible to external observers (J.A. Wheeler: “black holes have no hair”)

- how exactly can we *“**observe**”* black holes in the Universe? how can we measure their masses and spins?

- **this talk:** black holes as astrophysical objects, interacting with their environment (gravitational potential, but also jets/outflows), and thus ***observable***



gravitational radius,
i.e. mass expressed in length units

$$r_\mathrm{g} = \frac{G\mathcal{M}_\bullet}{c^2} \approx \left(\frac{\mathcal{M}_\bullet}{M_\odot}\right) \mathrm{km}$$

$$M_\odot = 2 \times 10^{30}\,\mathrm{kg}$$

angular momentum (spin)
expressed in length units

$$a = \frac{J}{c\,\mathcal{M}_\bullet}$$

$$J_\mathrm{max} = \frac{G\mathcal{M}_\bullet^2}{c}$$

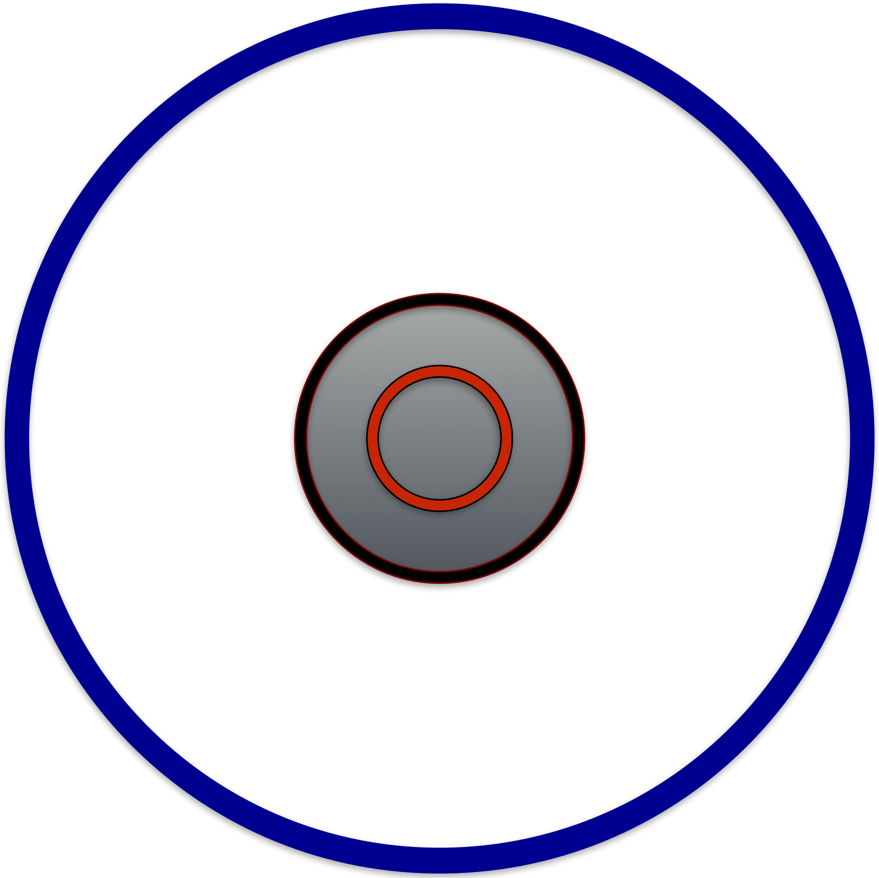
$$0 \quad \leq \quad a_\star \equiv \frac{a}{r_\mathrm{g}} \quad \leq \quad 1$$

event horizon (Schwarzchild radius) r_S
and static limit r_C

$$r_\mathrm{S} = r_\mathrm{g} + \sqrt{r_\mathrm{g}^2 - a^2}$$

$$r_\mathrm{C} = r_\mathrm{g} + \sqrt{r_\mathrm{g}^2 - a^2 \cos^2\theta}$$

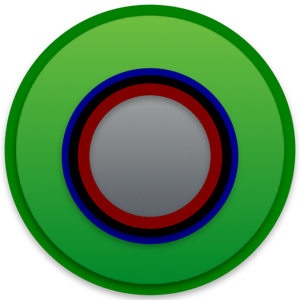
the innermost stable circular orbit: r_{ISCO}



non-spinning BH: **a=0**

$r_g = GM/c^2$
$r_S = 2\ r_g$

$r_{ISCO} = 6\ r_g$

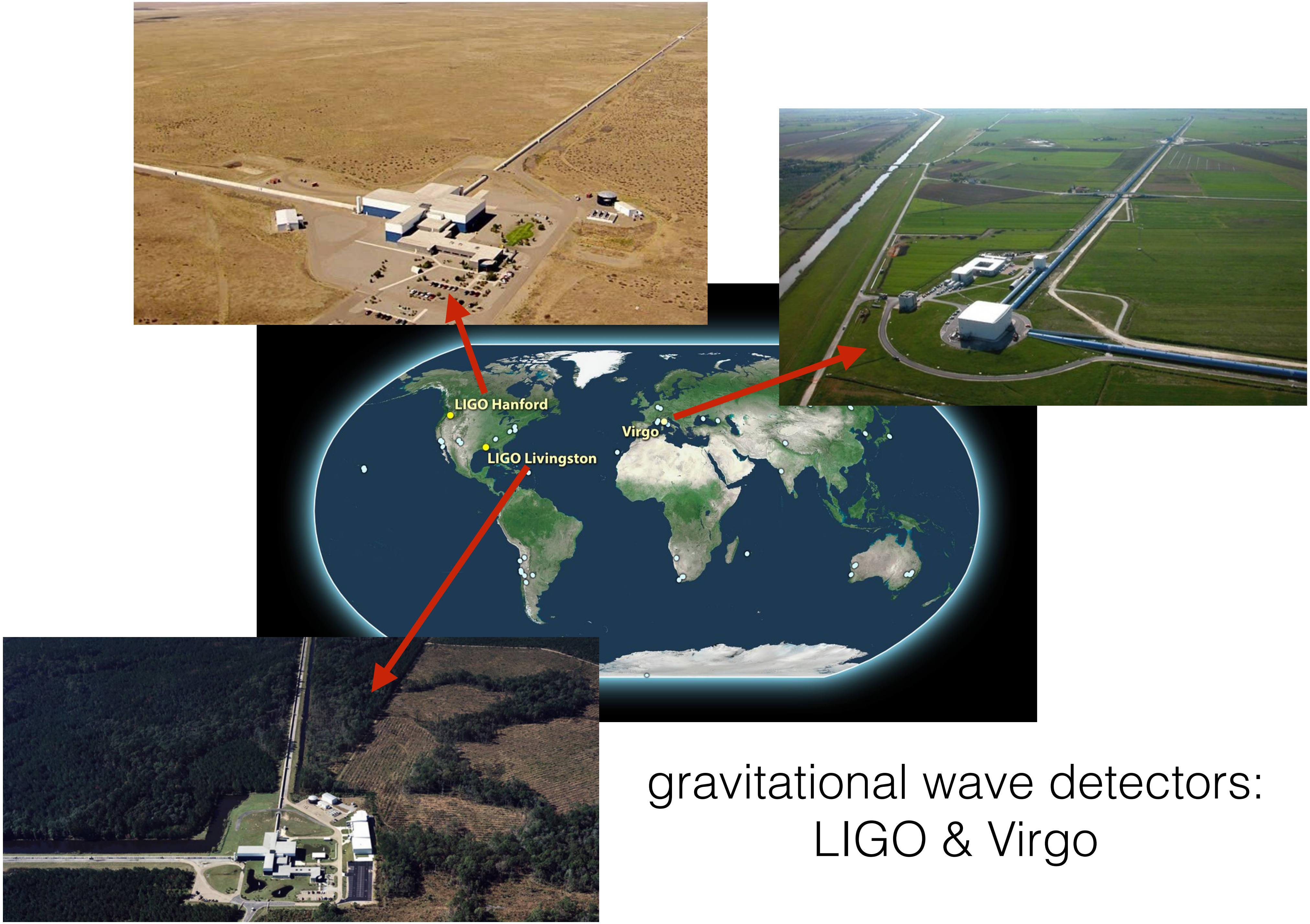


maximally-spinning BH: **a~1**

$r_g = GM/c^2$
$r_S \sim r_g$
$r_C(\pi/2) \sim 2\ r_g$
$r_{ISCO} \sim r_g$

- charged BH are expected to neutralize quickly by attracting charge of the opposite sign
- J_{max} as you cannot have a “naked singularity”, i.e. a singularity exposed to the rest of the Universe
- **Lense-Thirring/frame-dragging effect**: due to the twisting of a spacetime by rotating BH, an object within the ergosphere cannot appear stationary with respect to an outside observer
- **Penrose process**: since the ergosphere is outside the event horizon, it is still possible for an object that enters that region to escape from the gravitational pull of the BH, possibly removing the BH rotational energy (“reducible mass”, although note that the gravitational mass of the BH has to increase at the same time)
- **Blandford–Znajek process**: the BH rotational energy and angular momentum transported electromagnetically outwards (**jets!**) due to the magnetic field supported within the ergosphere by the accreting matter

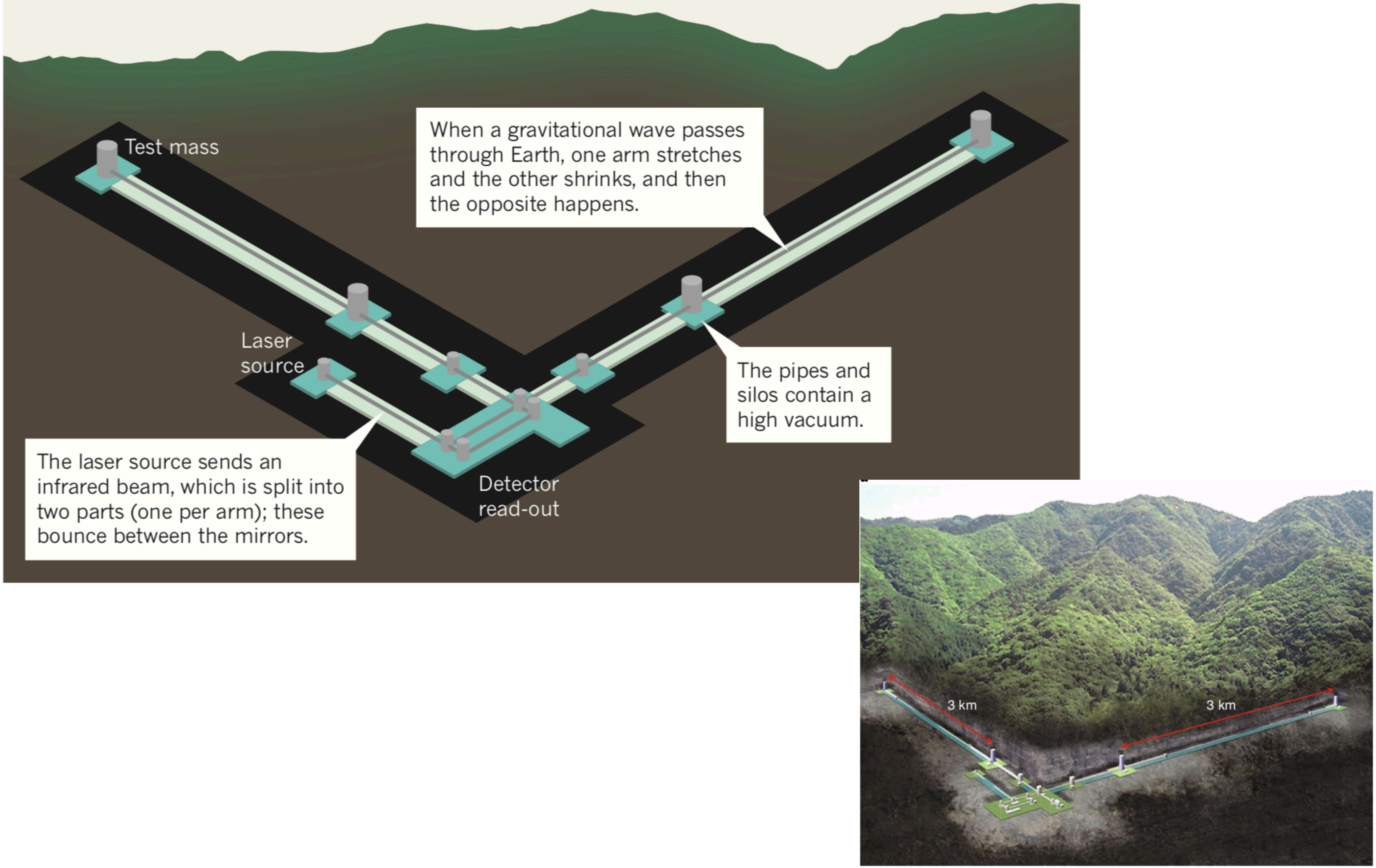
$$\frac{E_{\mathrm{rot}}}{\mathcal{M}_{\bullet}c^2} = 1 - \sqrt{\frac{1}{2} + \frac{1}{2}\sqrt{1 - \left(\frac{a}{r_{\mathrm{g}}}\right)^2}} \quad \leq 0.3$$



gravitational wave detectors:
LIGO & Virgo

JAPAN'S WAVE HUNTER

The Kamioka Gravitational Wave Detector (KAGRA) is the world's fourth major gravitational-wave detector — and Asia's first. Due to open in late 2019, it is the first one to be built underground, and to have cryogenically cooled mirrors, operating at around 20 kelvin. Both innovations should help KAGRA to separate the cosmic ripples from background noise.

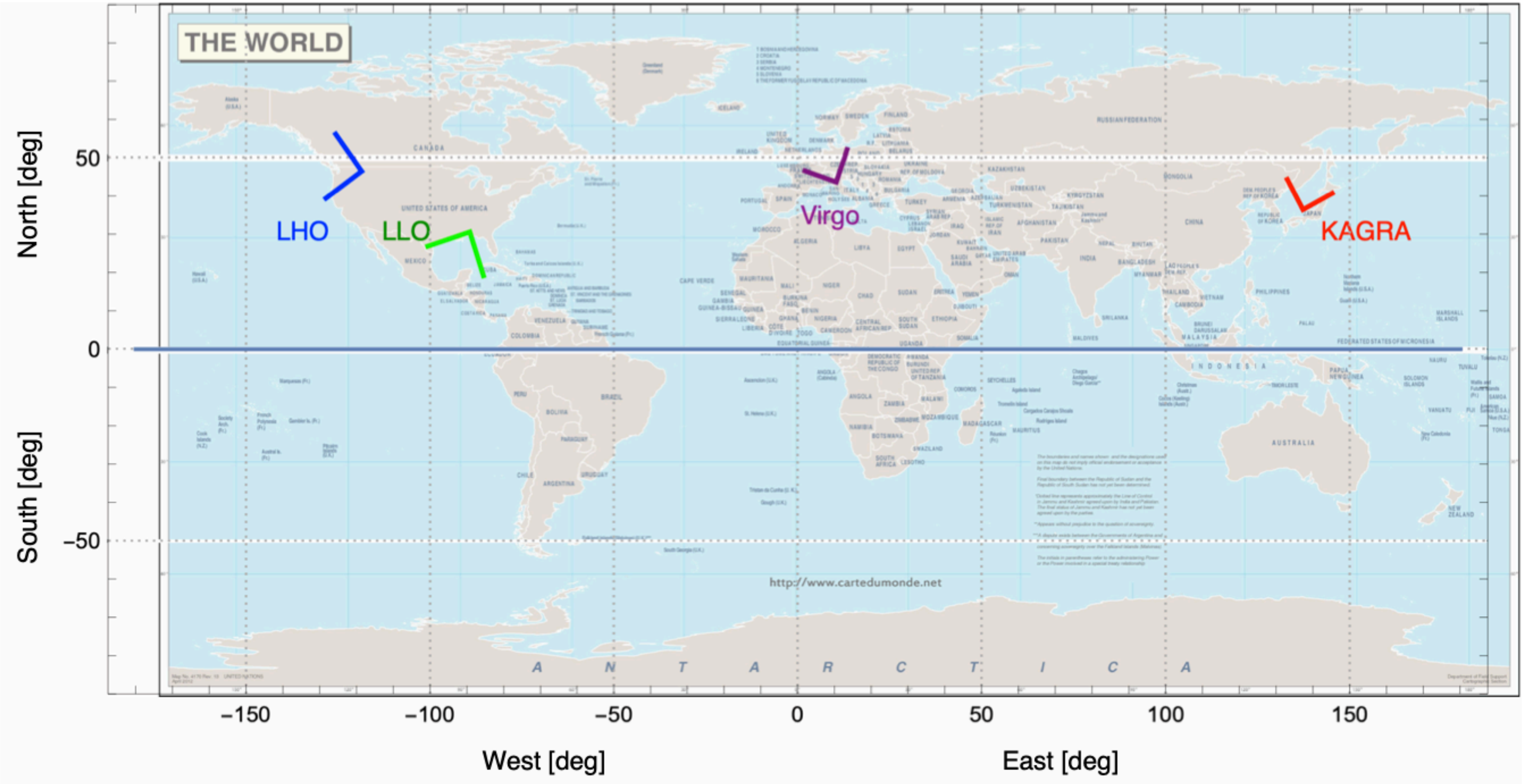


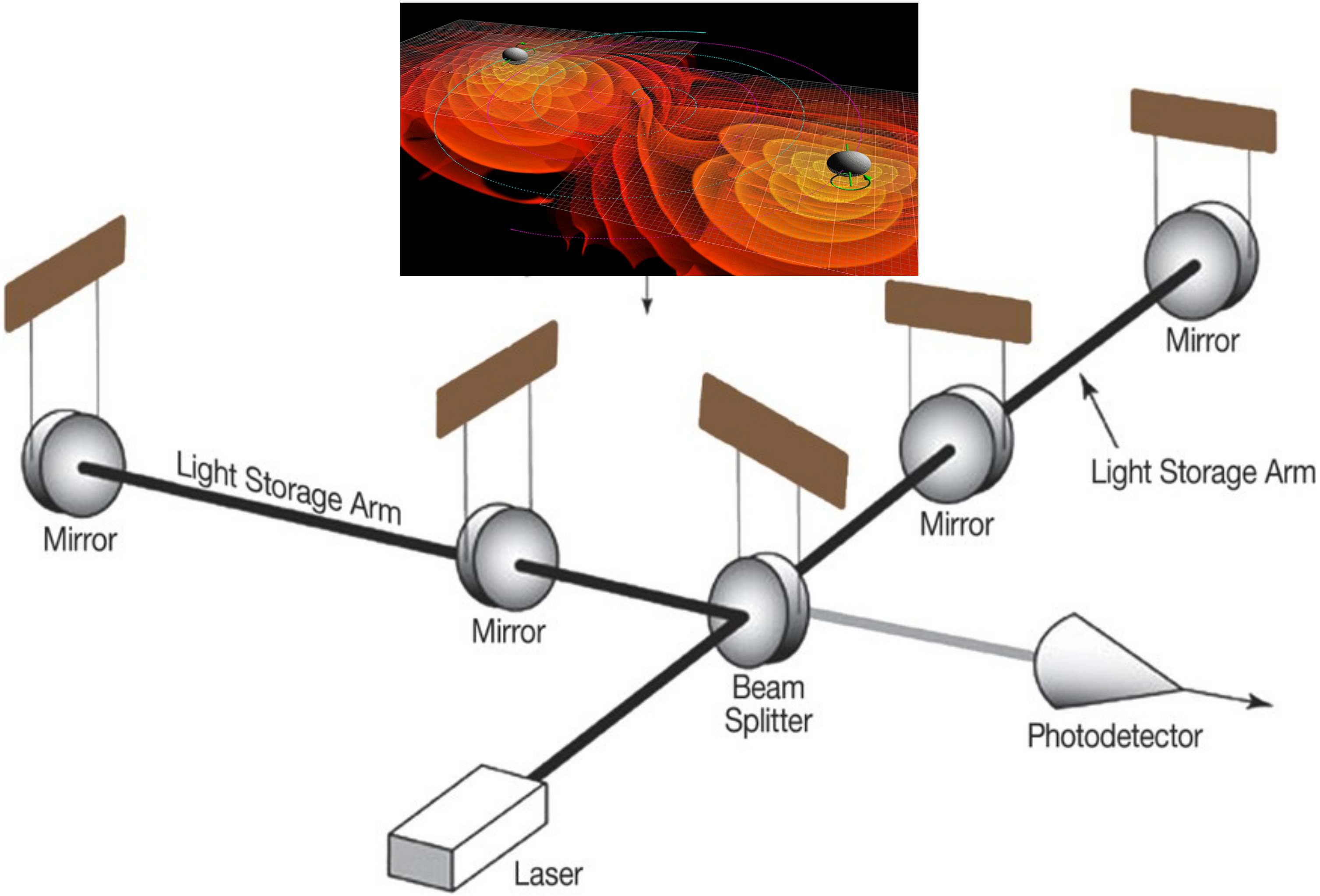
When a gravitational wave passes through Earth, one arm stretches and the other shrinks, and then the opposite happens.

The pipes and silos contain a high vacuum.

The laser source sends an infrared beam, which is split into two parts (one per arm); these bounce between the mirrors.

VIRGO + LIGO + KAGRA

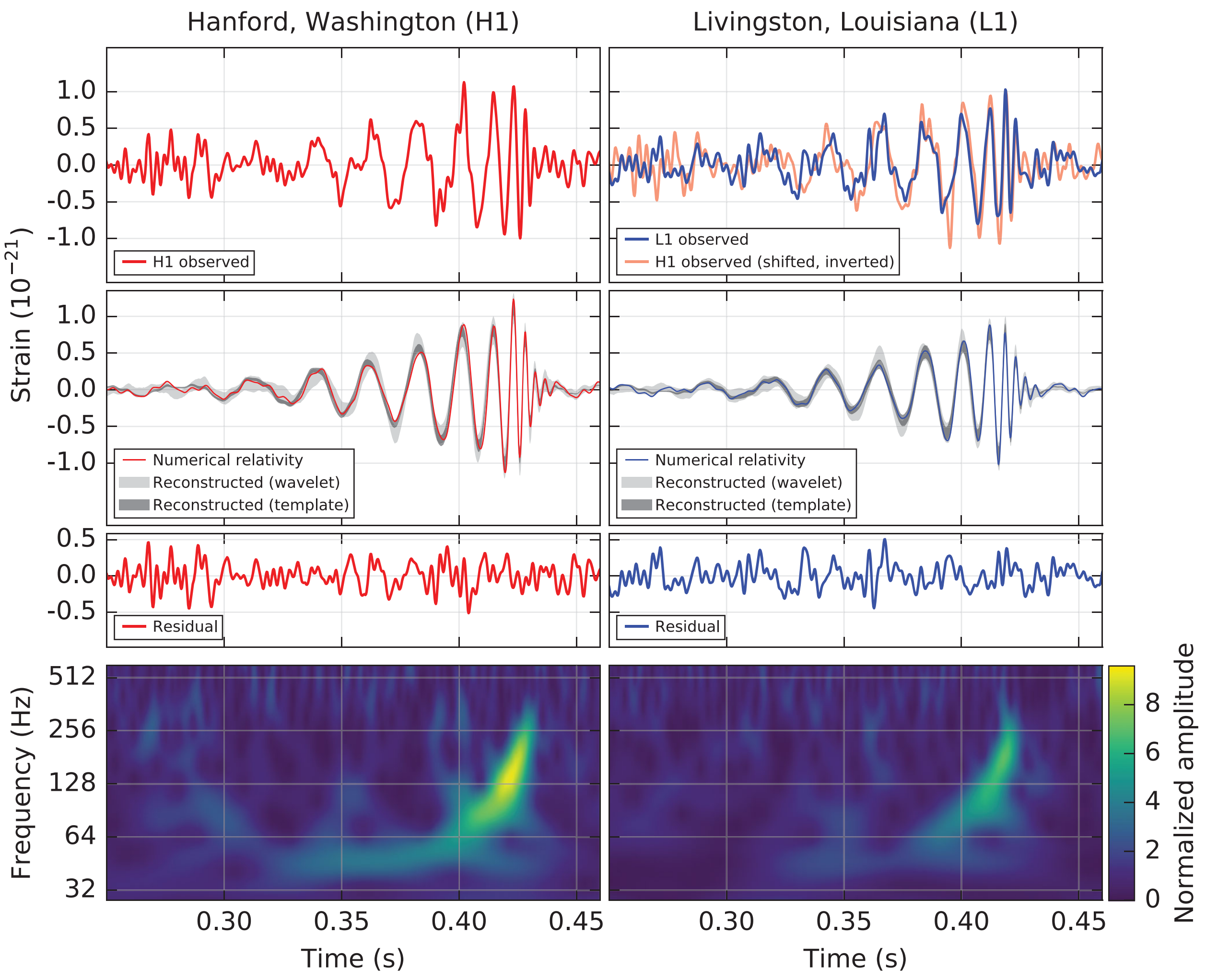


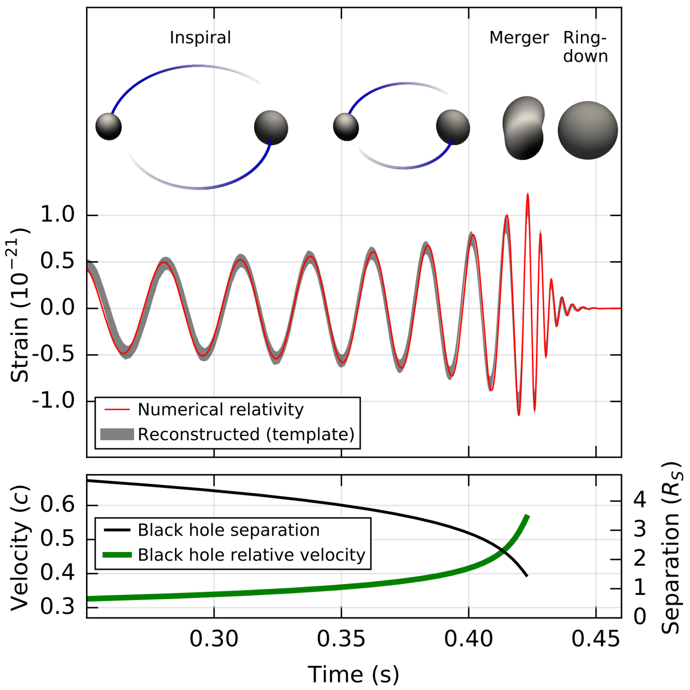


Gravitational waves cause space itself to stretch in one direction and squeeze in a perpendicular direction simultaneously. The effect on LIGO is this: as the wave passes, one arm of an interferometer lengthens while the other shrinks, then vice versa, and so on. The arms will oscillate this way for as long as it takes the wave to pass. As the length of each arm varies, the distance traveled by each laser beam also varies. Consequently, the beam in the shorter arm returns to the beam splitter before the beam in the longer arm. Arriving at different times (one before the other, then after, then before again, etc.) causes the beams to shift in and out of alignment as they merge, experiencing varying levels of destructive and constructive interference as long as the arms change lengths, which is for as long as it takes for the gravitational wave to pass.

First LIGO detection: GW150914

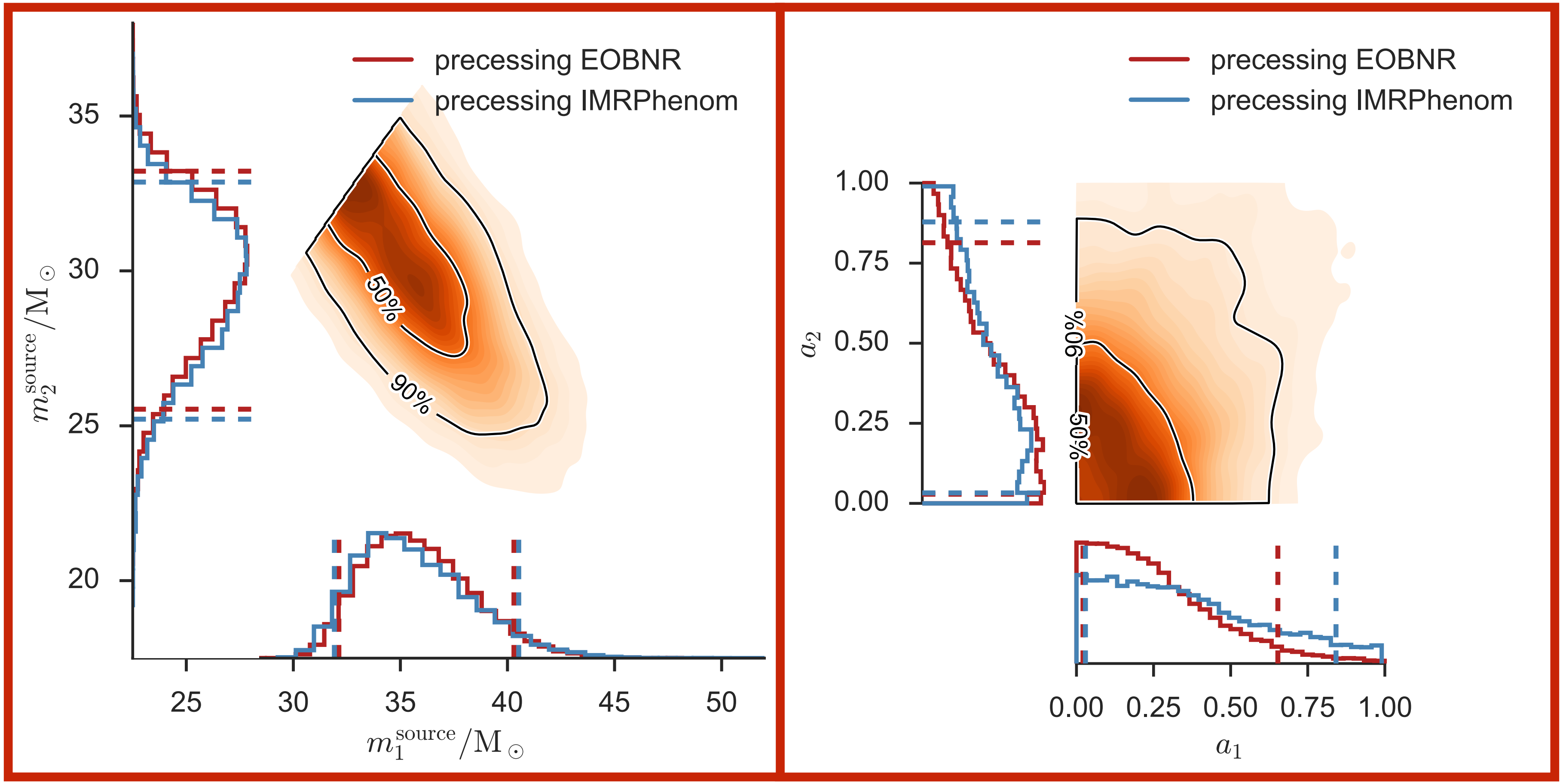
unique characteristics of the signal: direct estimates of the distance, masses, and spins of the merging black holes





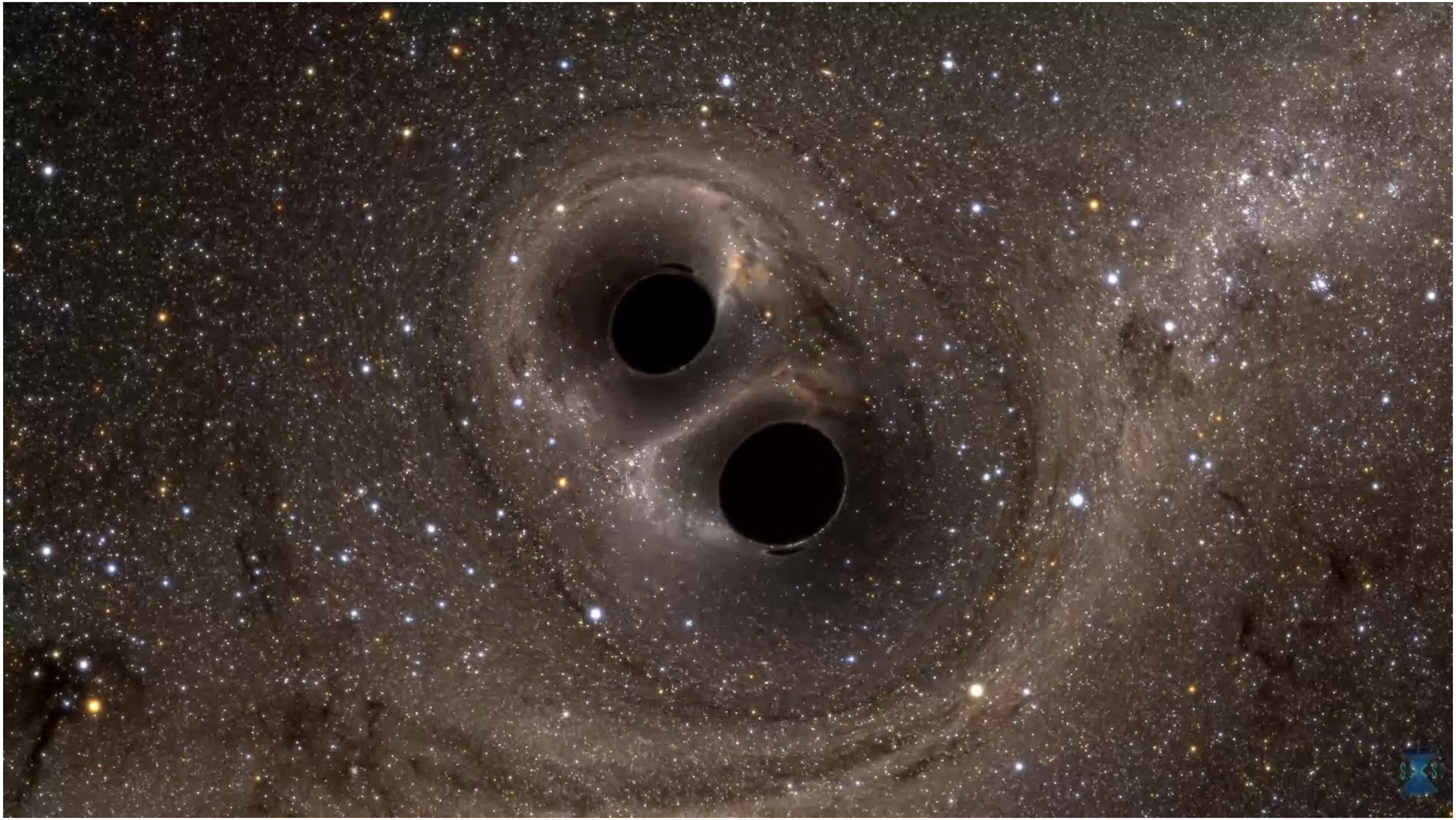
LIGO Collab., 2016

GW150914 — distance 410$^{+160}_{-180}$ Mpc

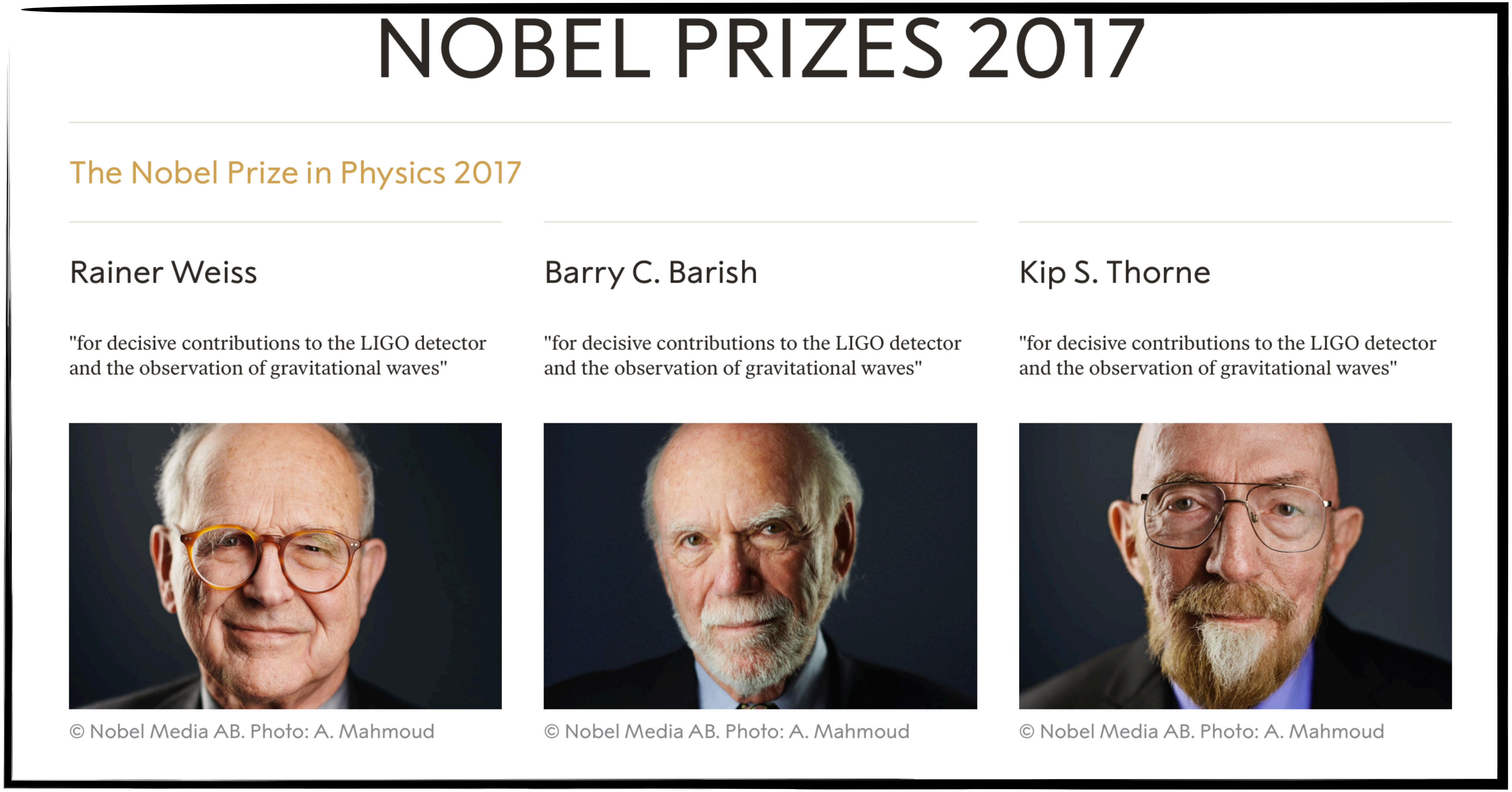


posterior probability densities

LIGO Collab., 2016



NOBEL PRIZES 2017



The Nobel Prize in Physics 2017

Rainer Weiss

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

© Nobel Media AB. Photo: A. Mahmoud

Barry C. Barish

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

© Nobel Media AB. Photo: A. Mahmoud

Kip S. Thorne

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

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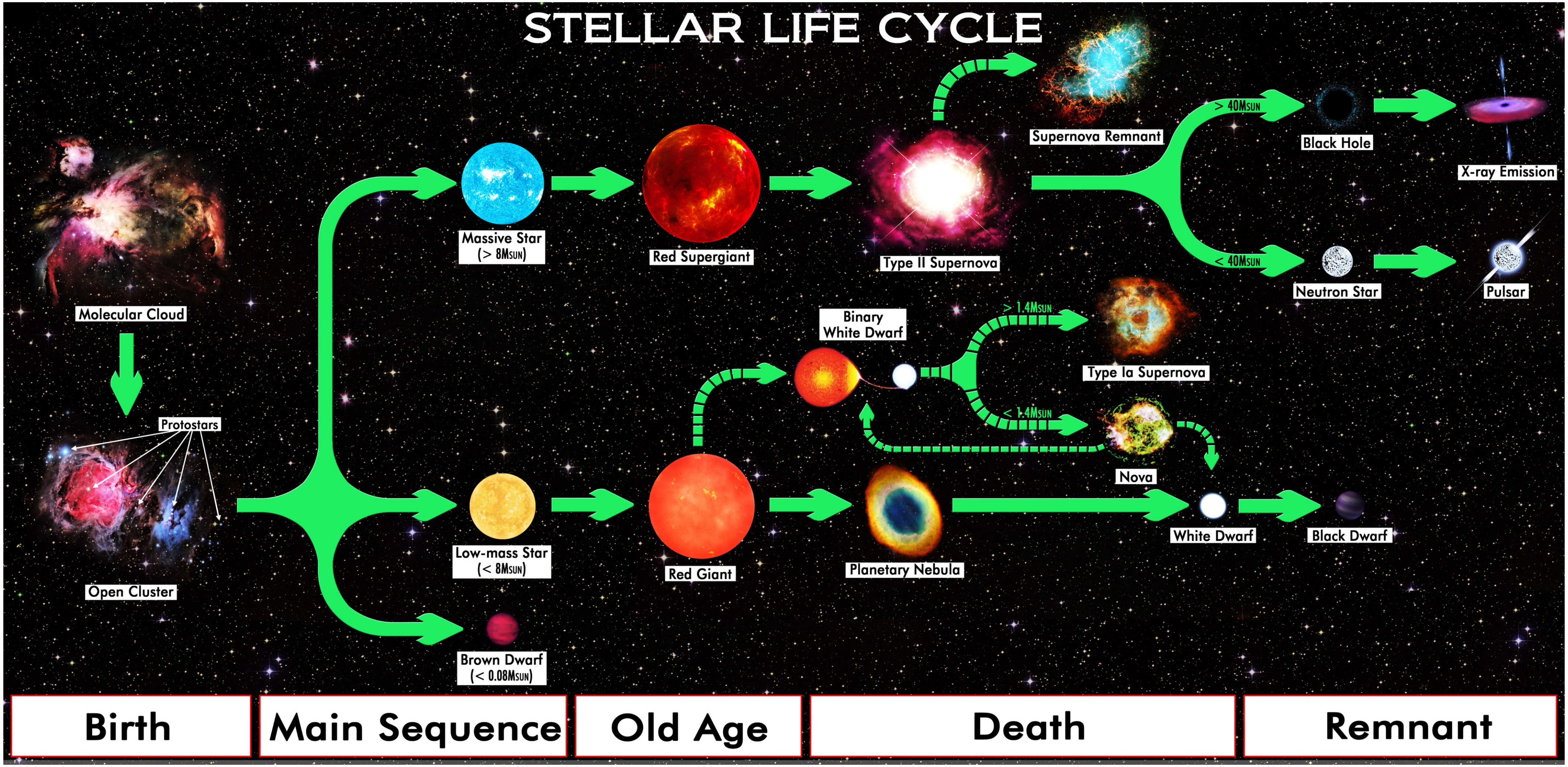
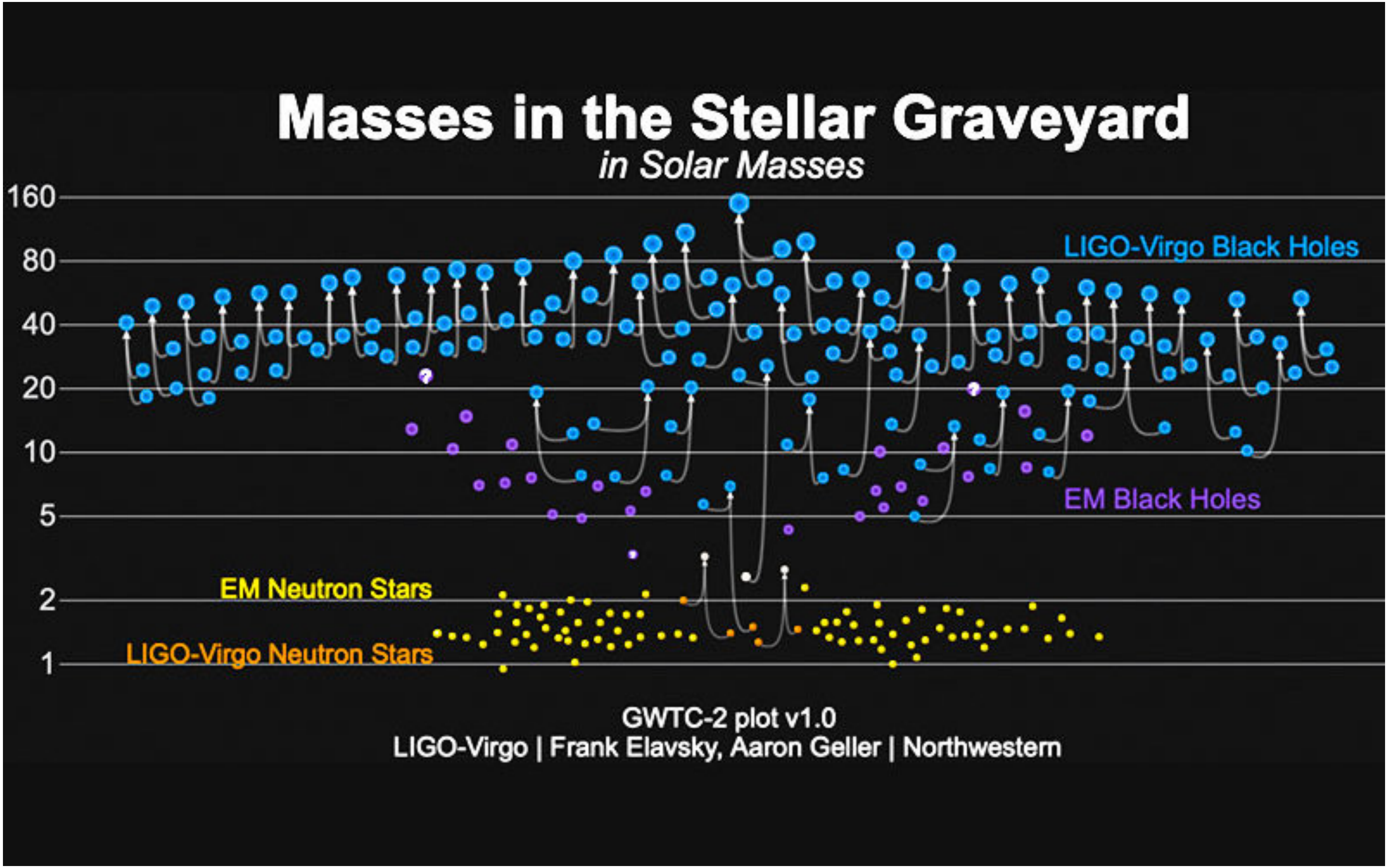
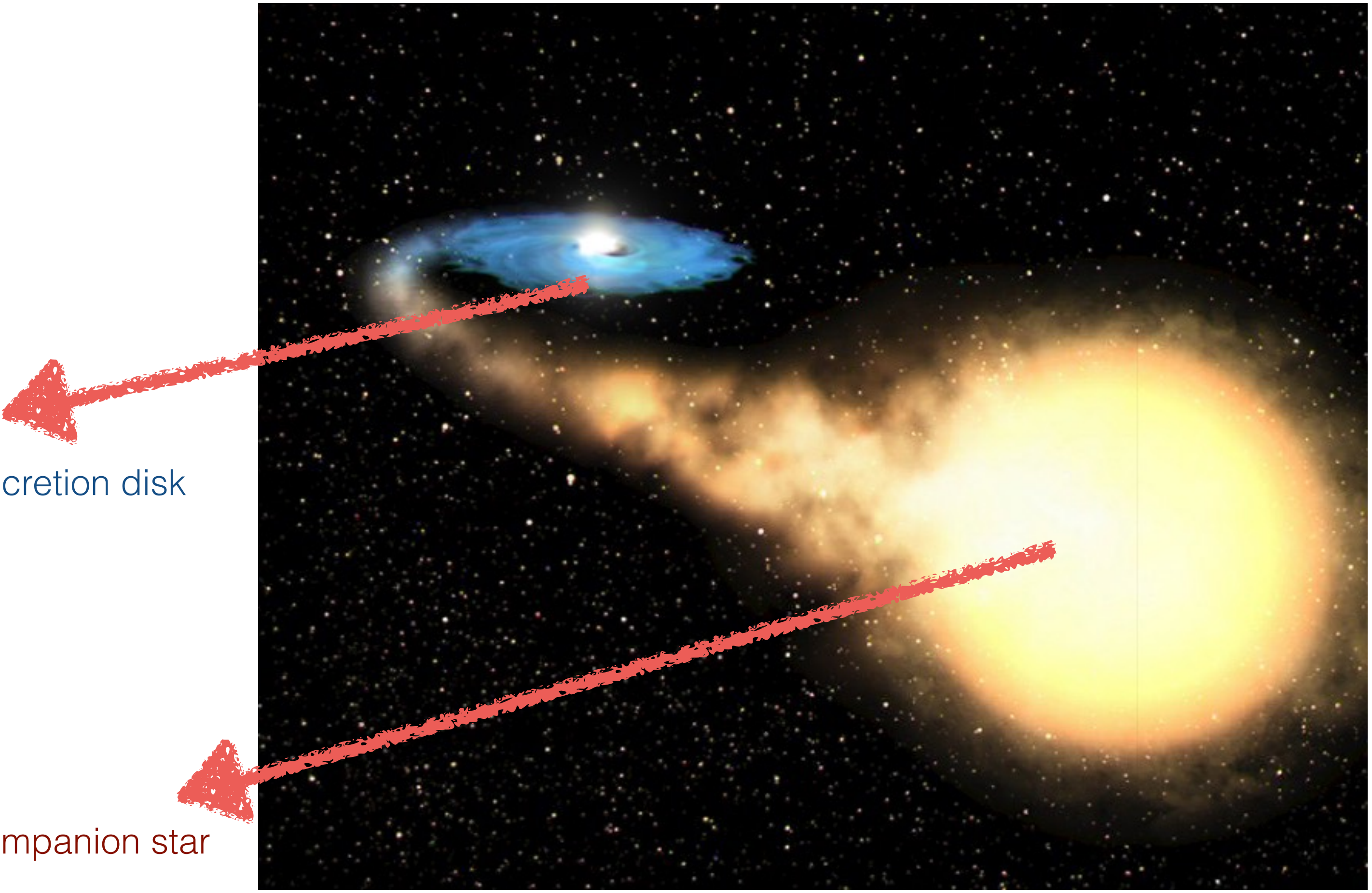
Black holes with masses **3-100 $M_\odot$** are formed (*exclusively?*) during the **gravitational collapse** of massive stars at the end of their evolution (-> supernovae!)




Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
?
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

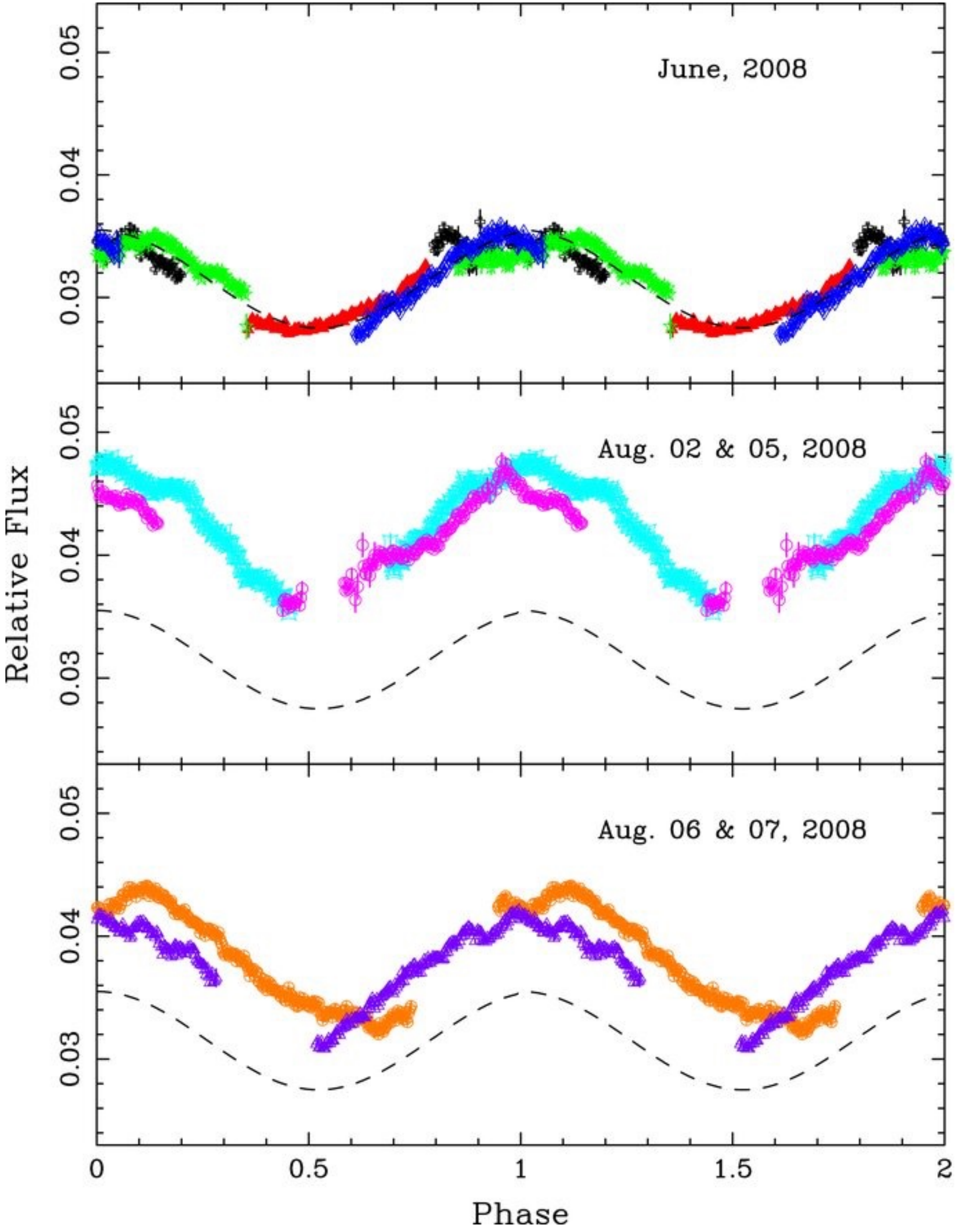
BH X-ray Binaries:
stellar-mass black holes accreting mater from the companion star



X-ray emission of the accretion disk

optical emission of the companion star

BH mass estimates in X-ray Binaries



orbital modulation of the optical emission (companion star partly eclipsed by the accretion disk)

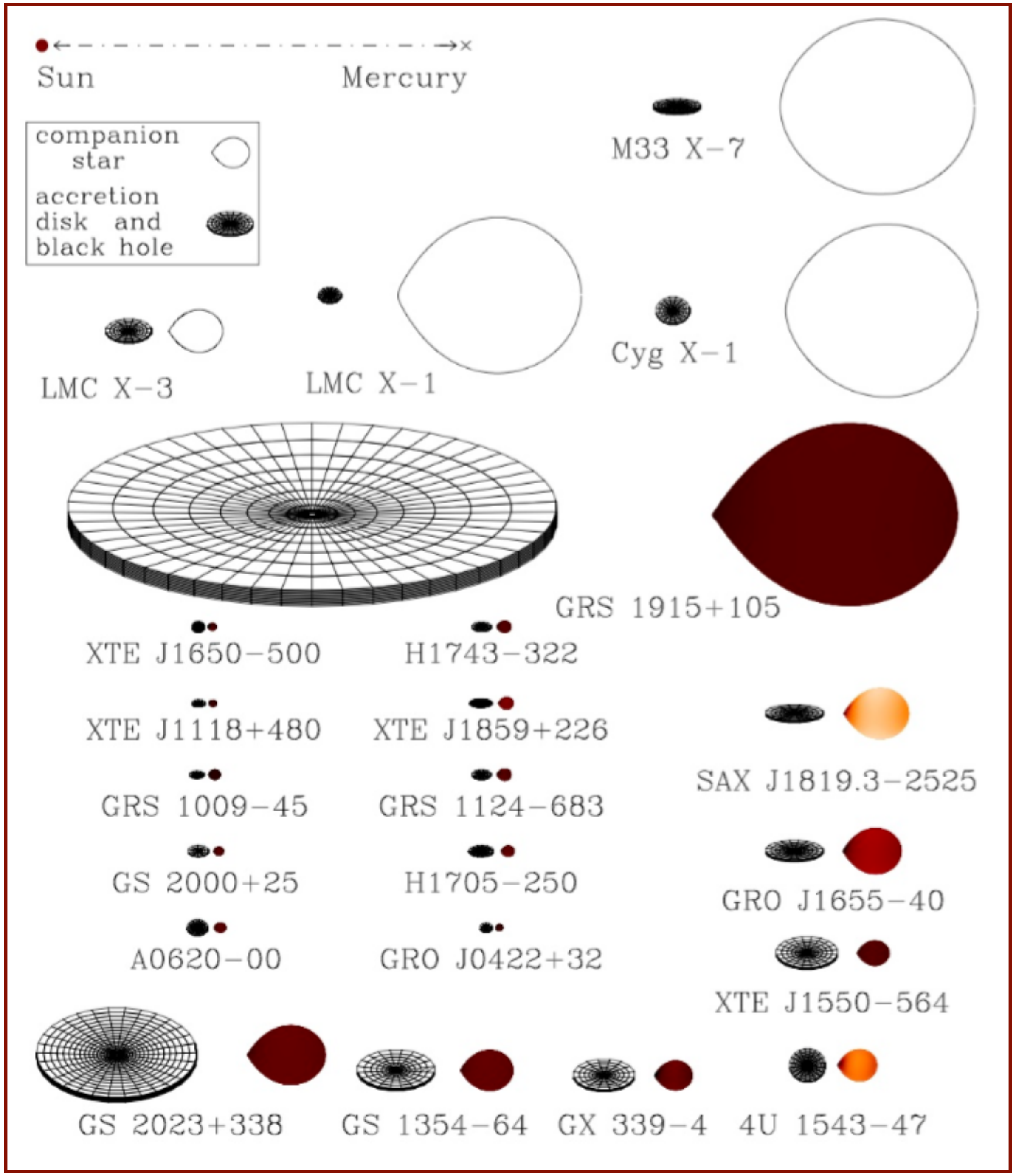
↓

given the type of the companion (main sequence) star, one may estimate the other dynamical parameters of the system, including the BH mass

V1408 AQUILAE
(Bayless et al. 2011)

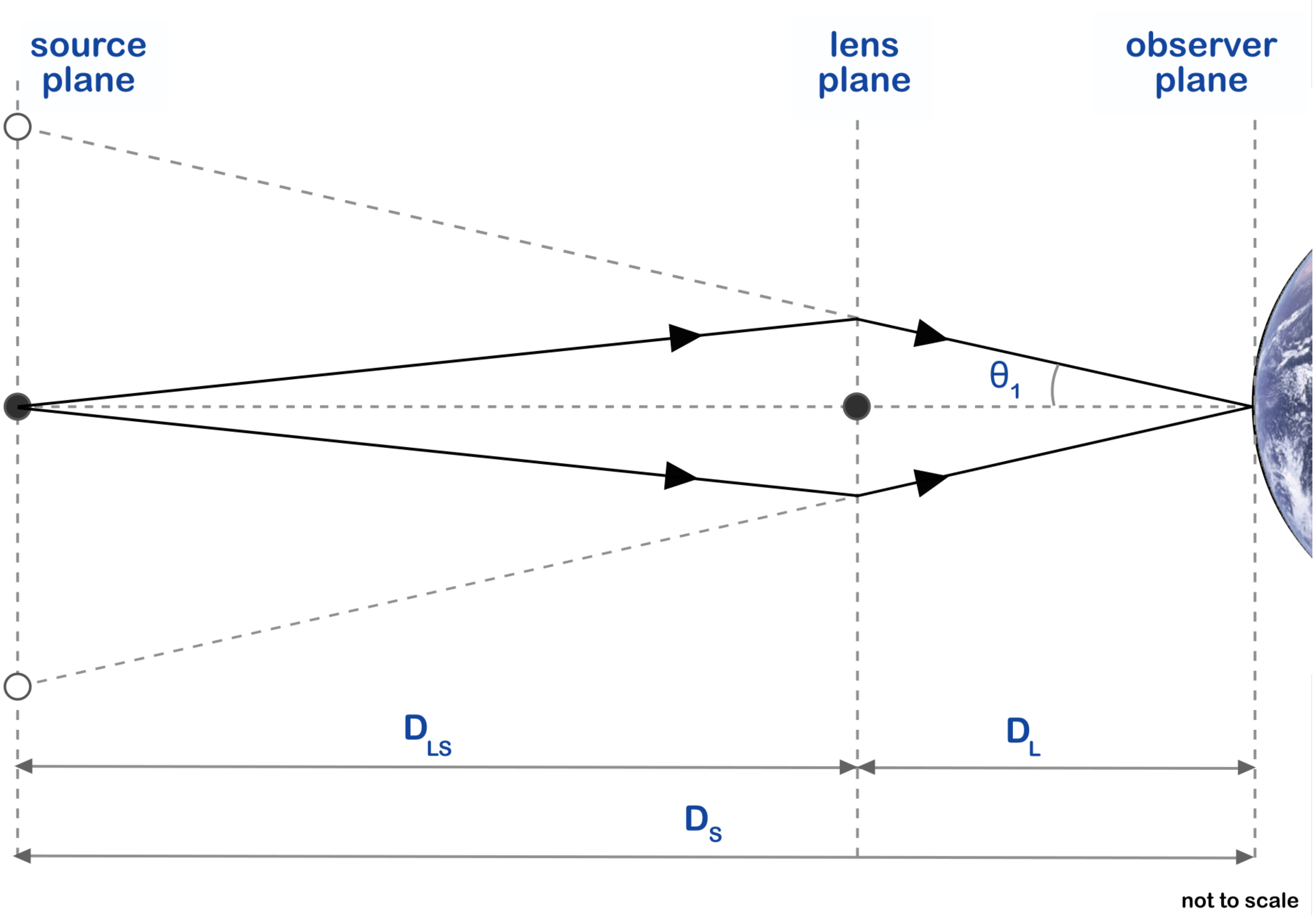
No	Name	$M_{comp}[M_\odot]^b$	Spec. type	$M_{BH}[M_\odot]$
1	XTE J1118+480	0.22 ± 0.07	K7/M1V	$6.9 \div 8.2$
2	XTE J1550-564	0.3 ± 0.07	K2/4IV	10.5 ± 1.0
3	GS 2000+25	$0.16 \div 0.47$	K3/6V	~ 6.55
4	GRO J0422+32	~ 0.45	M0/4V	~ 10.4
5	GRS 1009-45	~ 0.5	G5/K0V	~ 8.5
6	GRS 1716-249	~ 1.6	K-M	$\gtrsim 4.9$
7	GX339-4	$0.3 \div 1.1$	KIV	> 7
8	H1705-25	$0.15 \div 1.0$	K3/M0V	$4.9 \div 7.9$
9	A0620-00	0.68 ± 0.18	K2/7V	6.6 ± 0.25
10	XTEJ1650-50(0)	0.7	K4V	~ 5.1
11	XTEJ1859+226	0.7	K5V	7.7 ± 1.3
12	GS2023+338	$0.5 \div 1.0$	K0/3IV	12 ± 2
13	GRS 1124-68	$0.3 \div 2.5$	K5V	6.95 ± 0.6
14	GRS1915+105	0.8 ± 0.5	K1/5III	12.9 ± 2.4
15	GS 1354-64	1.03	G5IV	7.6 ± 0.7
16	GROJ1655-40	1.75 ± 0.25	F3/G0IV	5.31 ± 0.07
17	4U1543-47	$2.3 \div 2.6$	A2V	$2.7 \div 7.5$
18	XTEJ1819-254	$5.49 \div 8.14$	B9III	$8.73 \div 11.70$
19	CygX-1 [b]	19.2 ± 1.9	OI	14.8 ± 0.1
20	LMC X-1[c]	31.79 ± 3.48	O7/O8	10.91 ± 1.55
21	LMC X-3[cf]	3.72 ± 0.24	B5III	7.00 ± 0.32
22	IC 10 X-1[c]	> 17	WNE	> 23.1
23	NGC 300 X-1[c]	26^{+7}_{-5}	WN5	20 ± 4
24	M33 X-7[c]	70.0 ± 6.9	O7/O8 III	15.65 ± 1.45

BH XRBs



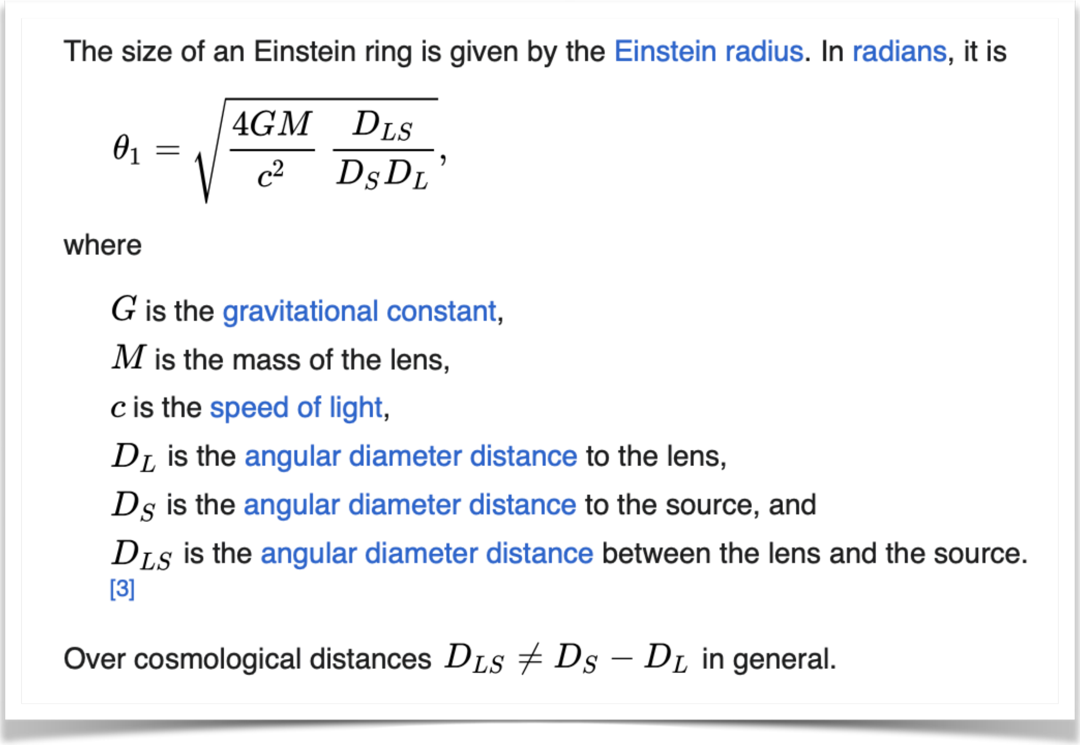
courtesy of J. Orosz

Gravitational Lensing



not to scale

Einstein Radius



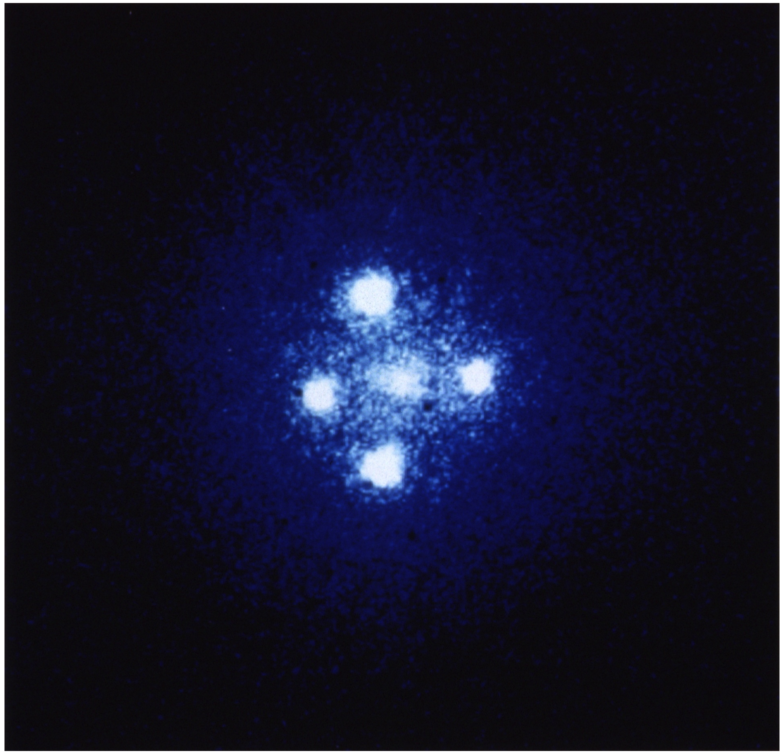
The size of an Einstein ring is given by the Einstein radius. In radians, it is

$$\theta_1 = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_S D_L}},$$

where

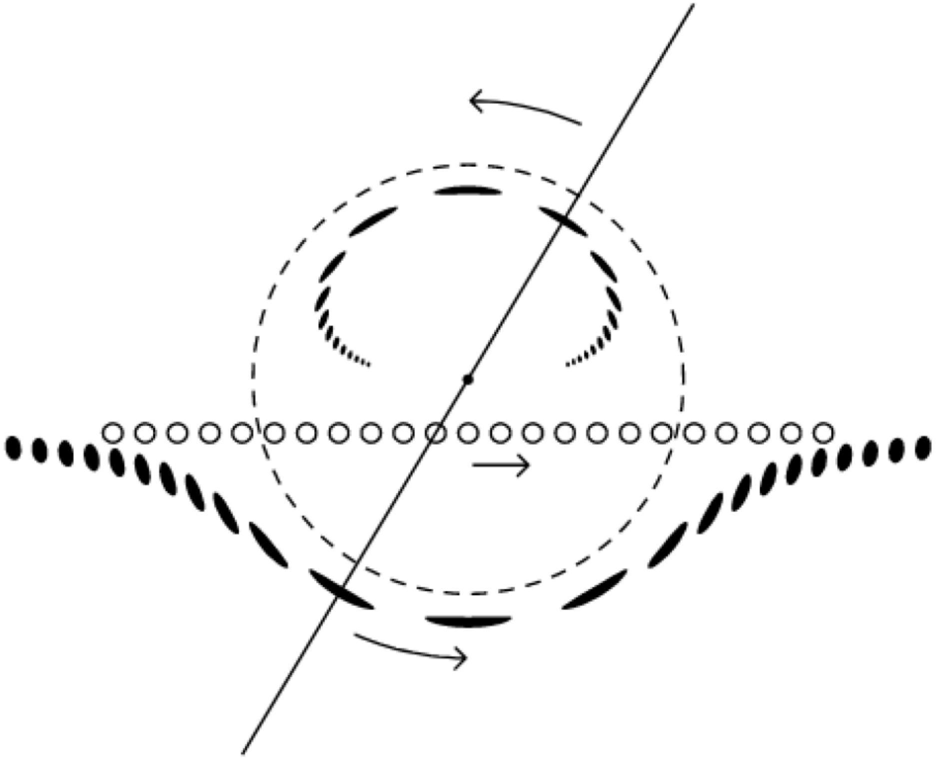
- G is the gravitational constant,
- M is the mass of the lens,
- c is the speed of light,
- D_L is the angular diameter distance to the lens,
- D_S is the angular diameter distance to the source, and
- D_{LS} is the angular diameter distance between the lens and the source.[3]

Over cosmological distances $D_{LS} \neq D_S - D_L$ in general.



In the formation known as Einstein's Cross, four images of the same distant quasar appear around a foreground galaxy due to strong gravitational lensing.

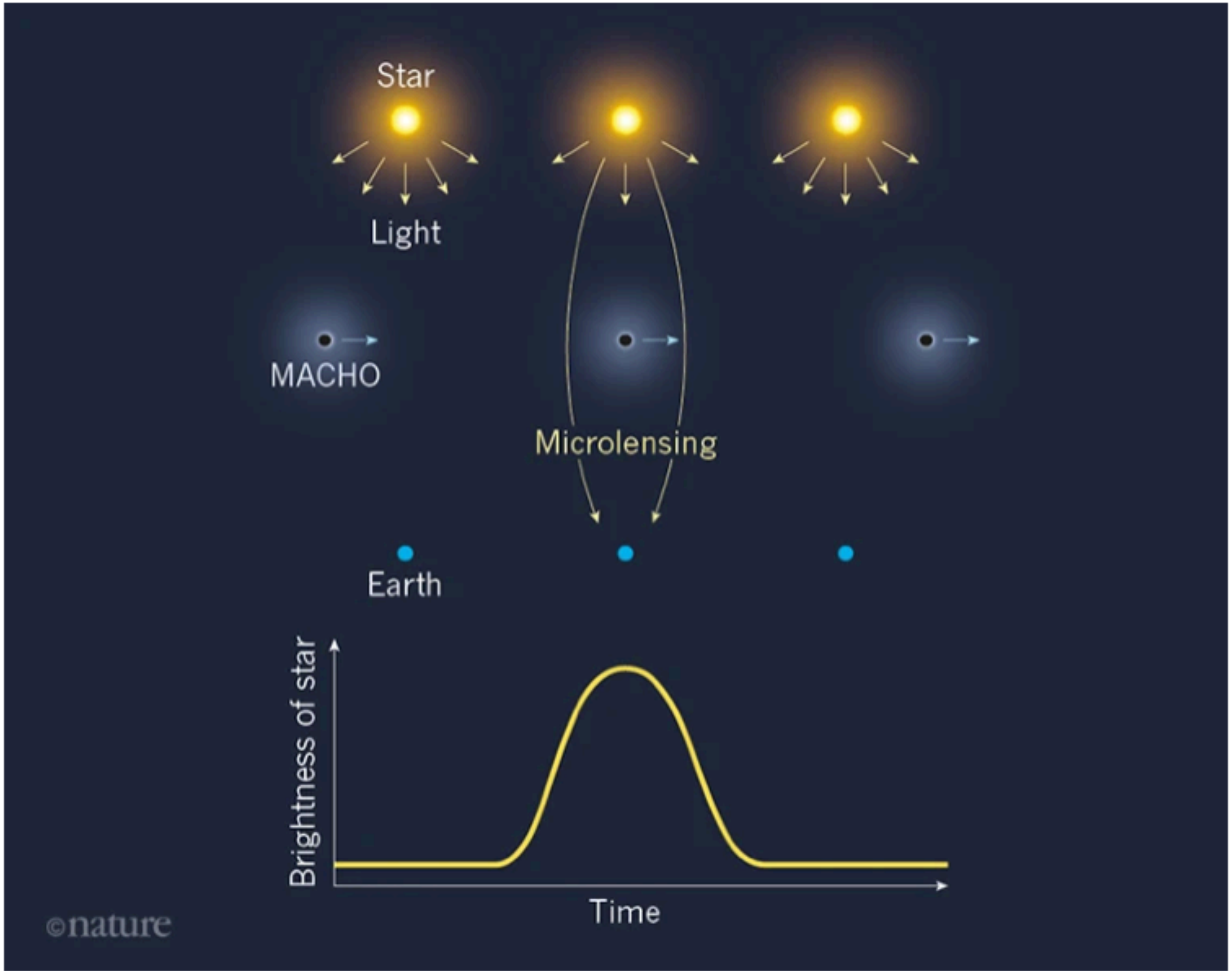
Gravitational Micro-Lensing



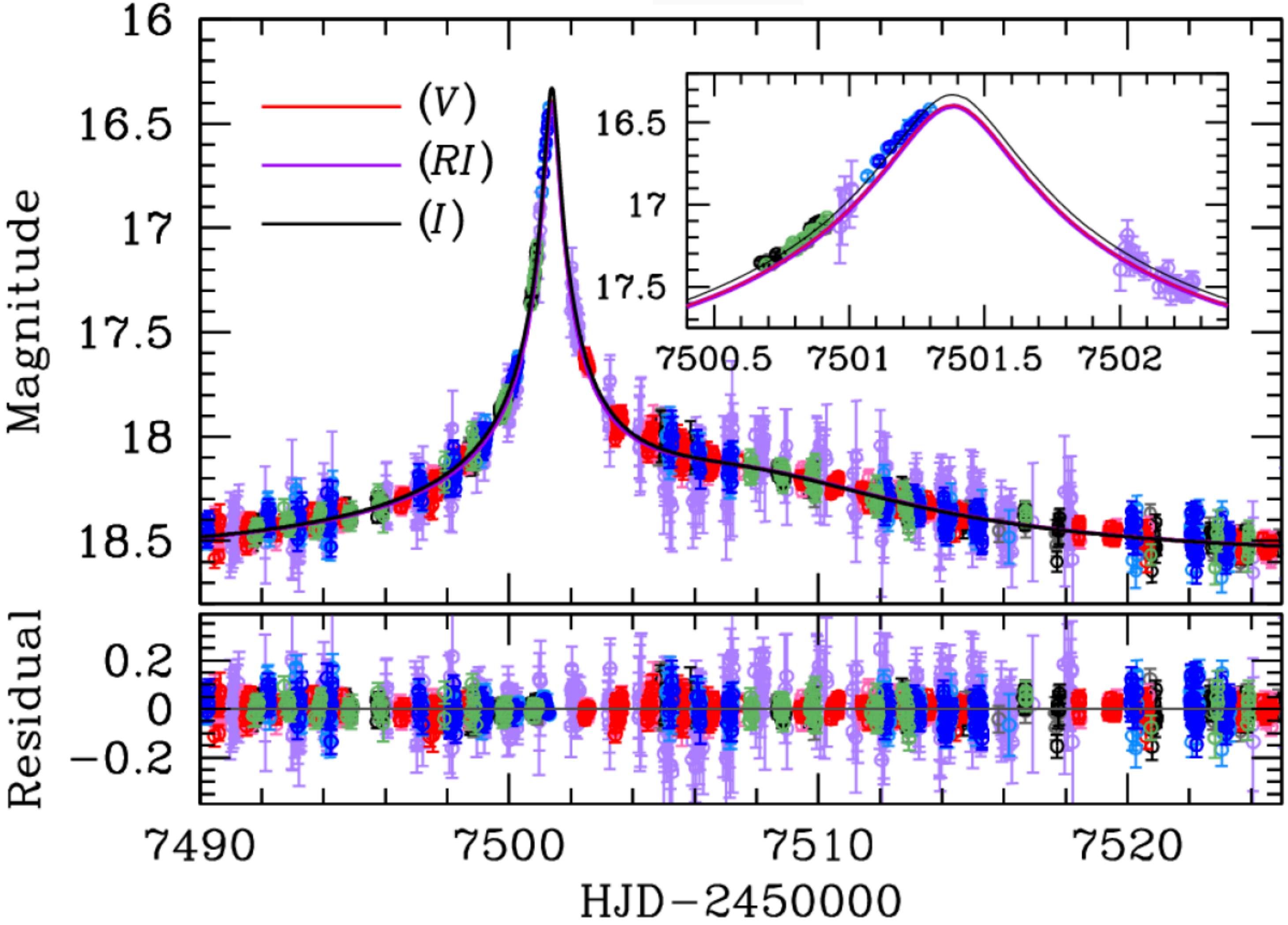
Rysunek 1.3: Geometryczne przedstawienie obrazów źródła podczas zjawiska mikrosoczewkowania. Soczewka znajduje się w środku okręgu narysowanego przerywaną linią (pierścienia Einsteina). Otwarte małe okręgi oznaczają kolejne pozycje źródła. Czarne obłe kształty to kolejne obrazy dla różnych położeń źródła. Linią prostą oznaczono źródło oraz odpowiadające mu obrazy. Strzałkami zaznaczono kierunek ruchu źródła oraz obrazów. Rysunek pochodzi z pracy Paczyński (1996).

https://commons.wikimedia.org/wiki/File:A_remote_light_source_passing_behind_a_gravitational_lens.gif#/media/File:A_remote_light_source_passing_behind_a_gravitational_lens.gif

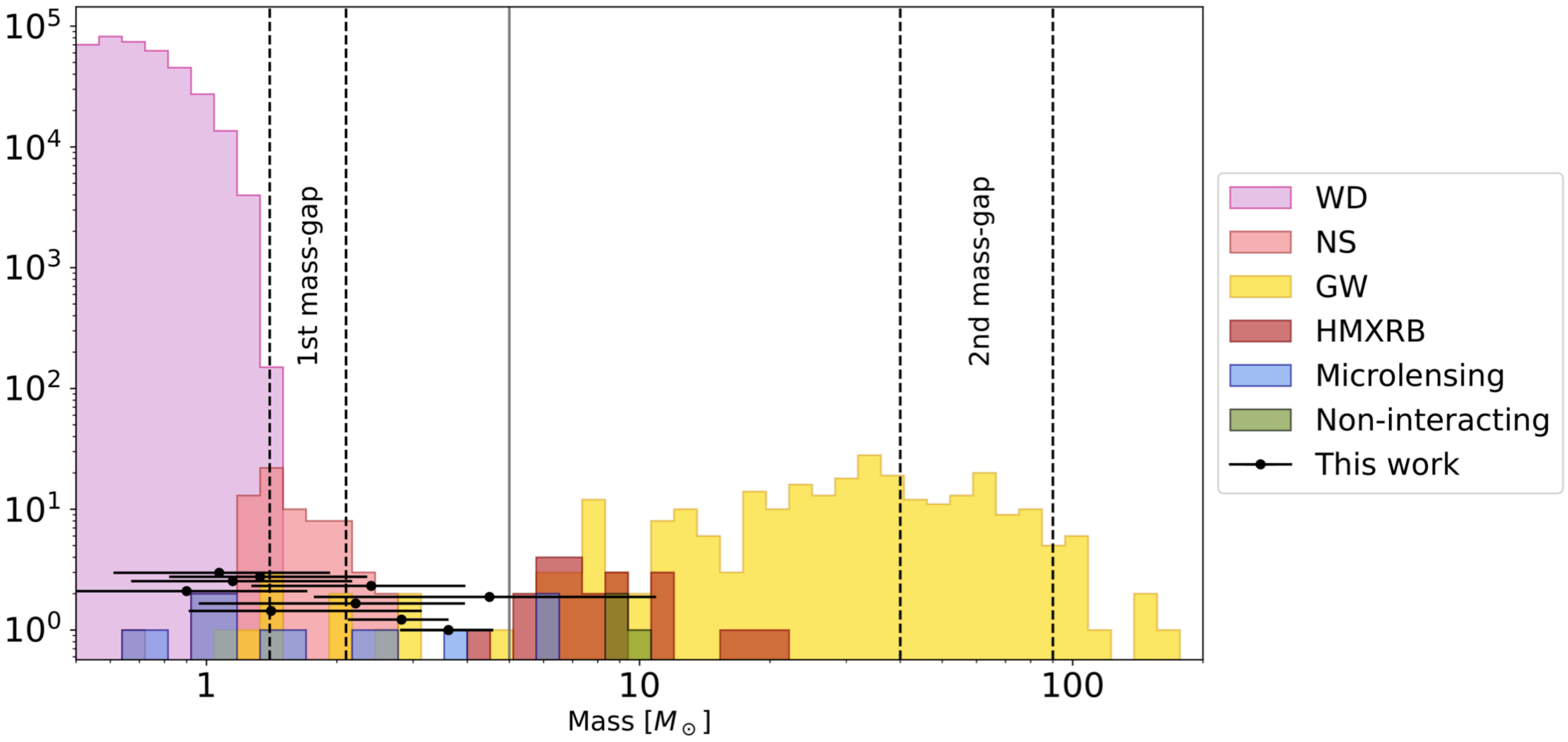
Paczyński, MACHO, and OGLE



Detections?

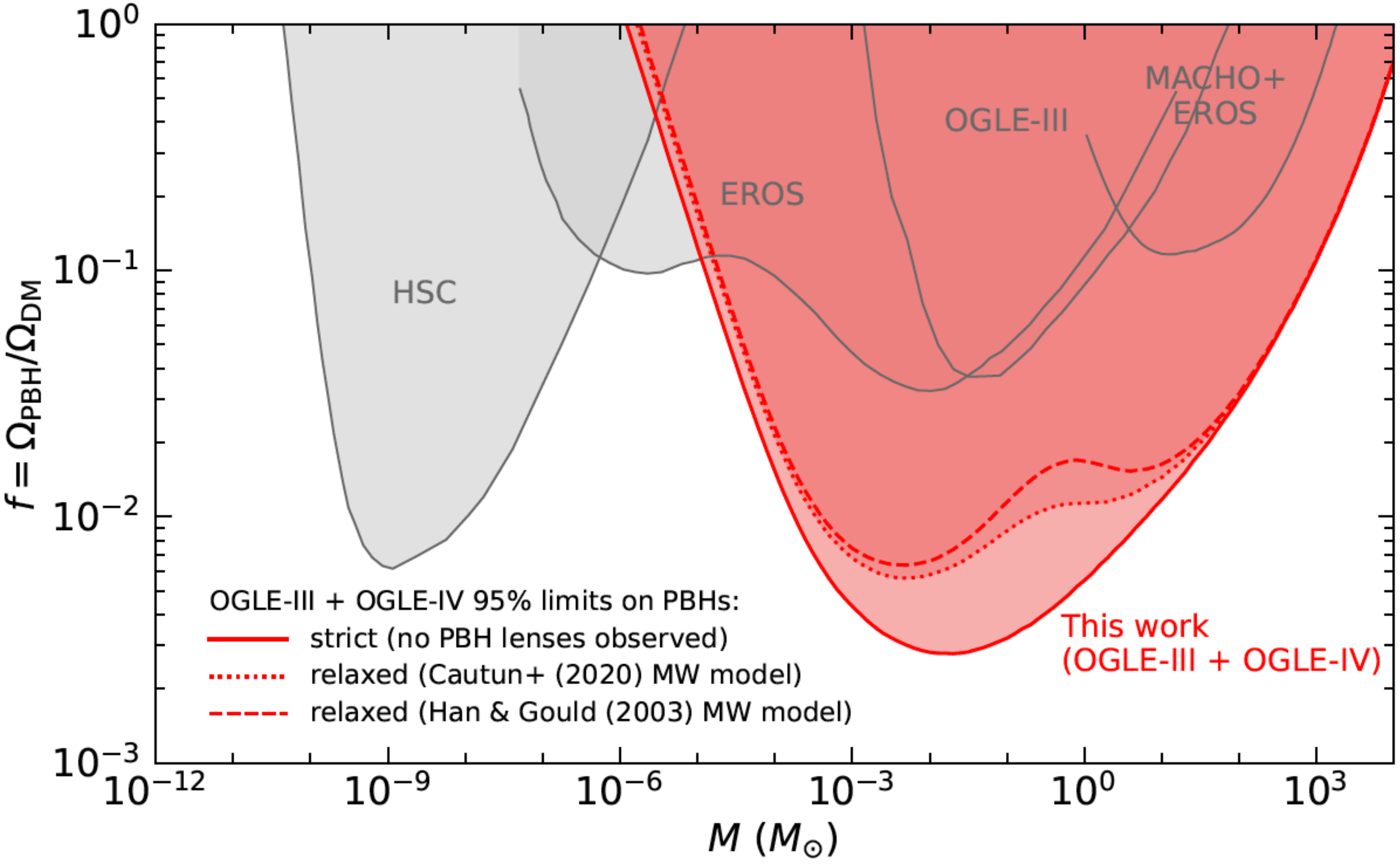

16
16.5
17
17.5
18
18.5
Magnitude
(V)
(RI)
(I)
16.5
17
17.5
7500.5
7501
7501.5
7502
Residual
0.2
0
−0.2
7490
7500
7510
7520
HJD−2450000

Detections?



Kruszyńska et al. 2024

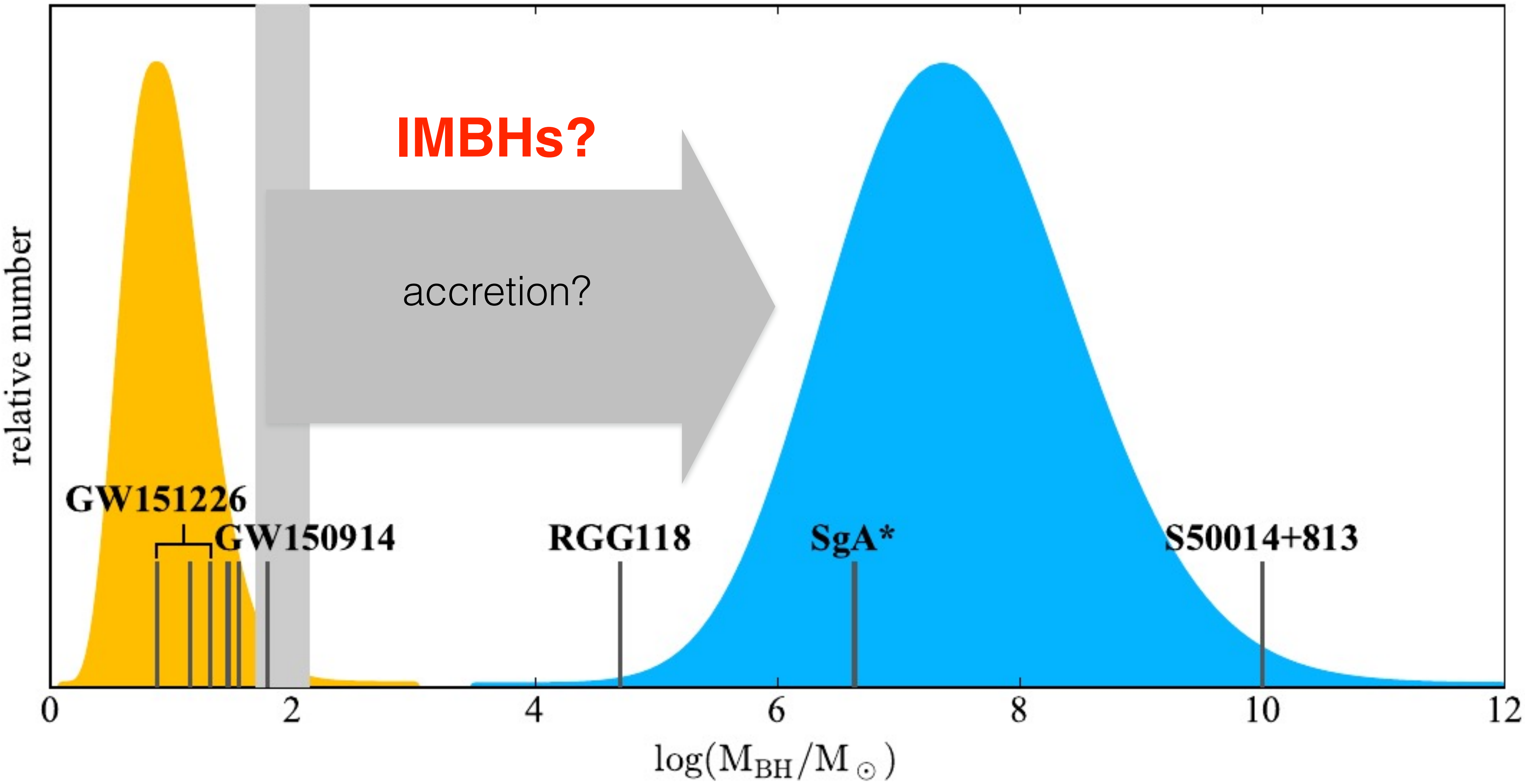
Paczyński, MACHO, and OGLE



Mróz et al. 2024

Supermassive BHs

Stellar-mass BHs



IMBHs?

accretion?

Celoria et al. 2018

Gravity versus Radiation

We wish to find the luminosity at which the gravitational force inwards balances with the radiation force outwards. The gravitational force is given simply via:

$$F_{\mathsf{grav}} = \frac{GMm}{R^2}$$

To calculate the radiation force first we need to get the *radiation pressure* at R:

$$P_{\mathsf{rad}} = \frac{L}{c}\frac{1}{4\pi R^2}$$

Then to calculate the radiation force on the cloud, we need its opacity, κ. Radiation pressure is force per unit area; opacity is the cross-sectional area per unit mass for radiation scattering.

$$F_{\mathsf{rad}} = P_{\mathsf{rad}}\kappa m$$

Opacity

Minimum force is given by the absorption due just to free electrons, such that $\kappa = \sigma_{\mathrm{T}}/m_p$ (for ionized hydrogen)

If the source is surrounded by gas with opacity κ, then in traveling a distance ds the fraction of radiation absorbed is:

$$\frac{dI}{I} = -\kappa \times \underset{\uparrow}{\rho ds}$$

column density of gas

Can therefore interpret κ as being the **fraction** of radiation absorbed by unit column density of gas. Force exerted by radiation on that gas is then:

$$f_{rad} = \frac{\kappa L}{4\pi c r^2}$$

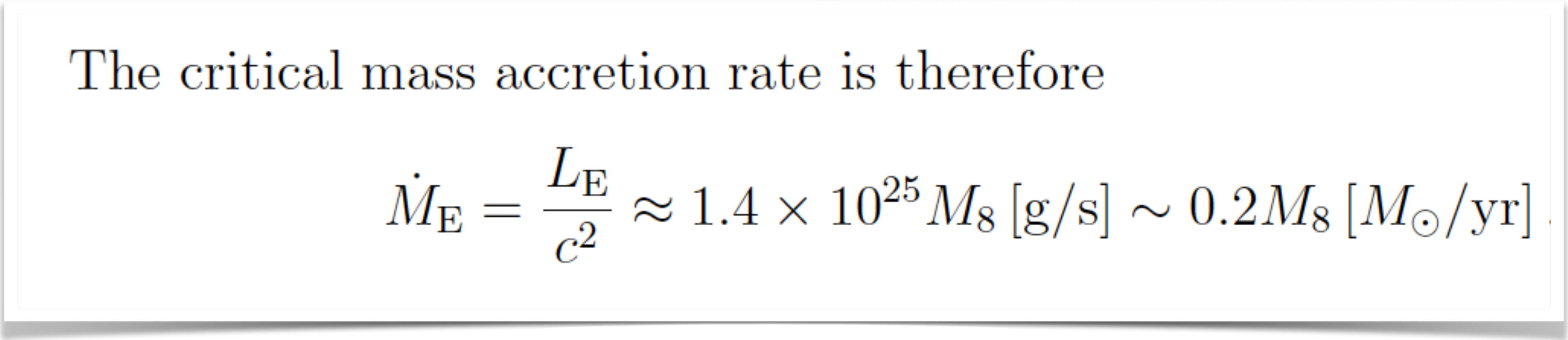
outward force

Eddington Luminosity

Radiation pressure balances gravity when $L = \frac{4\pi c G M}{\kappa}$

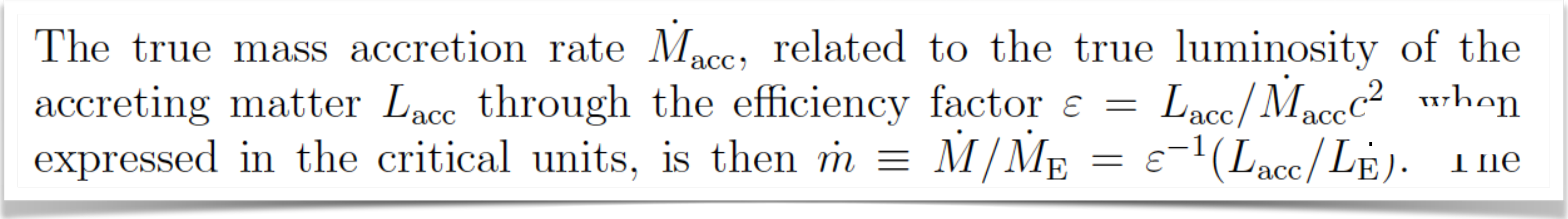
$$\boxed{L_E = \frac{4\pi G M m_p c}{\sigma_T} \approx 1.3 \times 10^{46} M_8 \; [\mathrm{erg/s}]}$$

Accretion rate



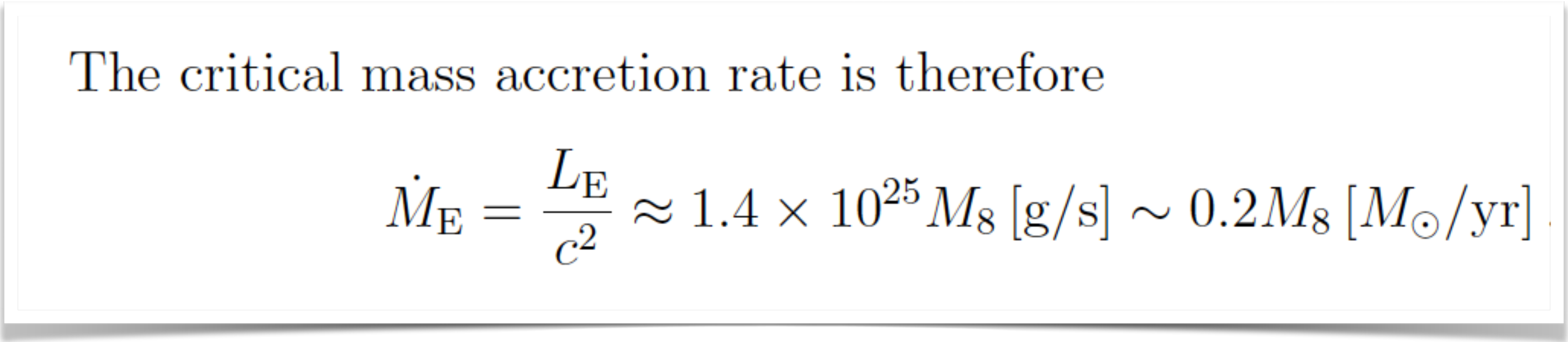
The critical mass accretion rate is therefore

$$\dot{M}_{\mathrm{E}} = \frac{L_{\mathrm{E}}}{c^2} \approx 1.4 \times 10^{25} M_8 \, [\mathrm{g/s}] \sim 0.2 M_8 \, [M_\odot/\mathrm{yr}] \, .$$



The true mass accretion rate $\dot{M}_{\mathrm{acc}}$, related to the true luminosity of the accreting matter L_{acc} through the efficiency factor $\varepsilon = L_{\mathrm{acc}}/\dot{M}_{\mathrm{acc}} c^2$ when expressed in the critical units, is then $\dot{m} \equiv \dot{M}/\dot{M}_{\mathrm{E}} = \varepsilon^{-1}(L_{\mathrm{acc}}/L_{\mathrm{E}})$. The

Accretion rate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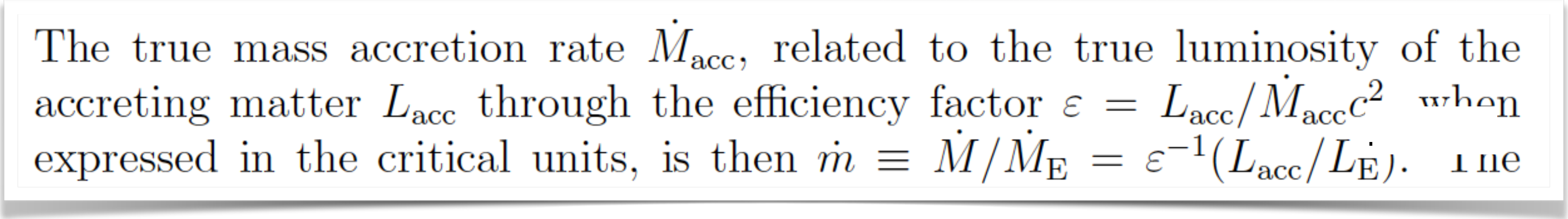
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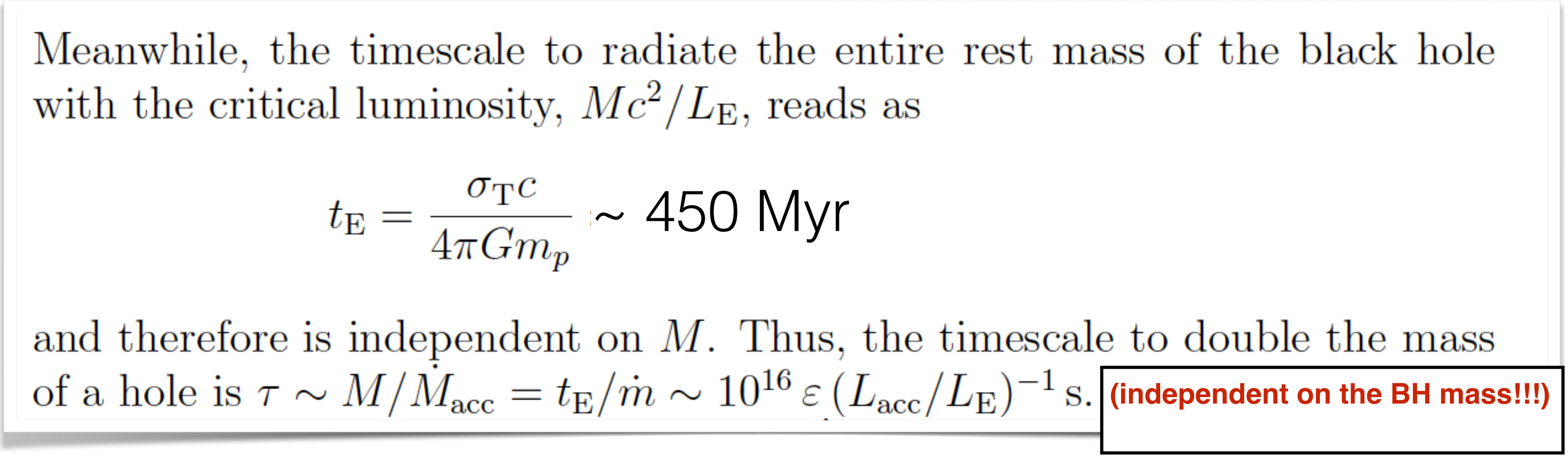

Meanwhile, the timescale to radiate the entire rest mass of the black hole with the critical luminosity, $Mc^2/L_{\rm E}$, reads as

$$t_{\rm E} = \frac{\sigma_{\rm T} c}{4\pi G m_p} \sim 450 \text{ Myr}$$

and therefore is independent on M. Thus, the timescale to double the mass of a hole is $\tau \sim M/\dot{M}_{\rm acc} = t_{\rm E}/\dot{m} \sim 10^{16} \, \varepsilon \, (L_{\rm acc}/L_{\rm E})^{-1}$ s.

(independent on the BH mass!!!)

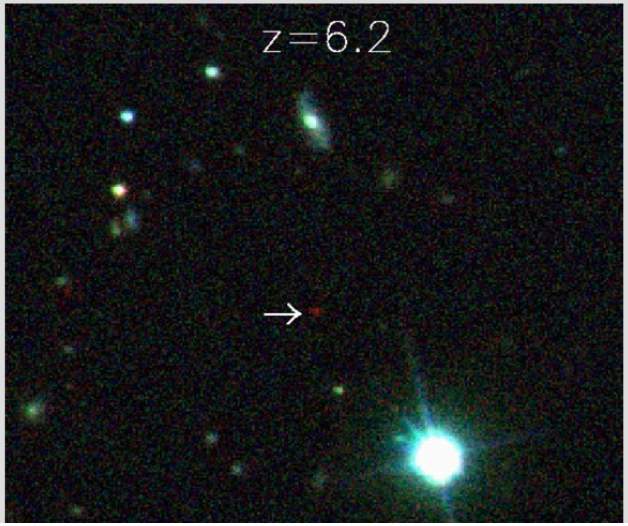
Black Hole Growth

$$M = M_0 e^{t/\tau}$$

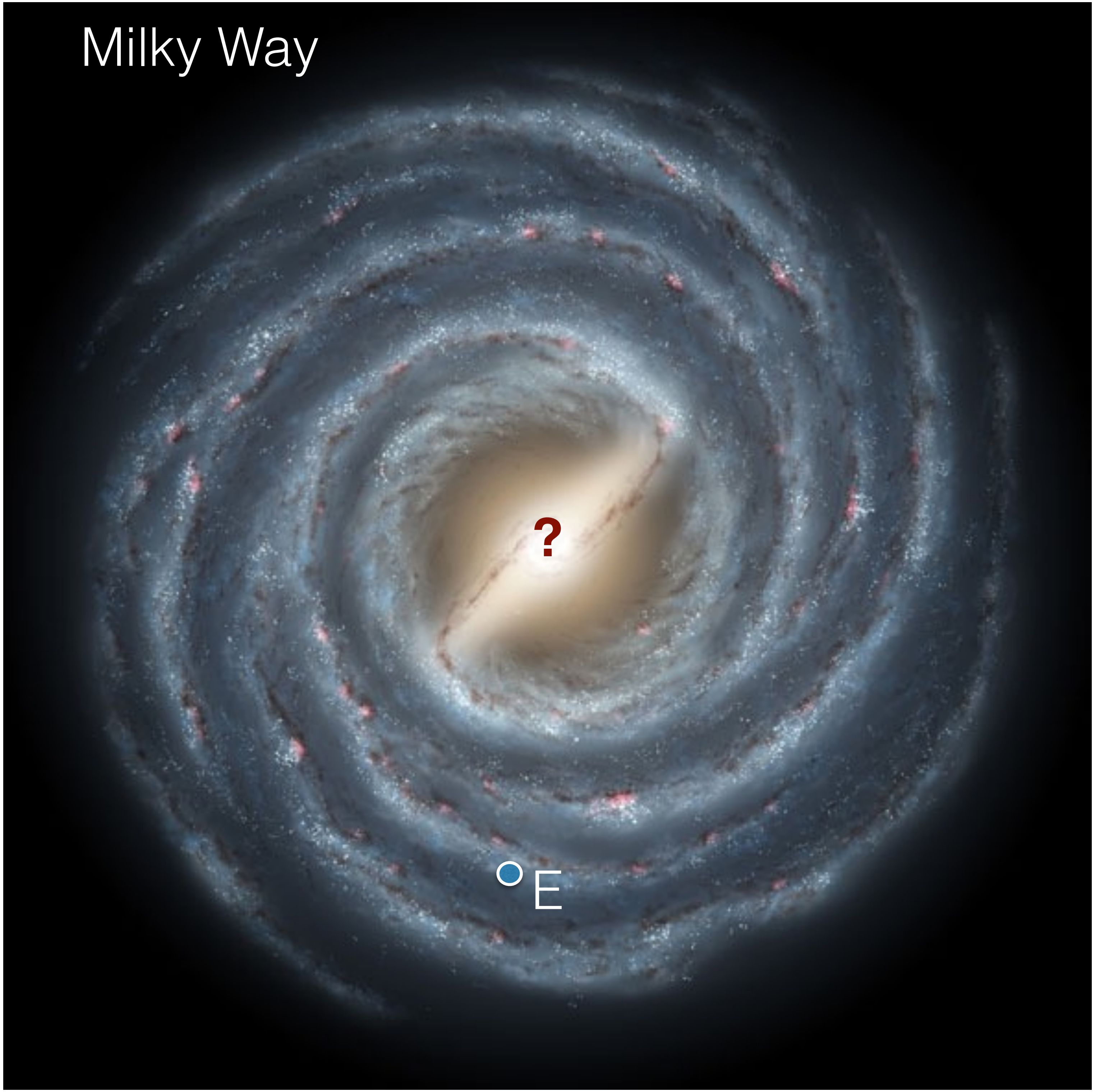
Example: how large can a black hole formed from the collapse of a massive star grow in 1 Gyr?

Initial mass M_0 = 10 Solar masses

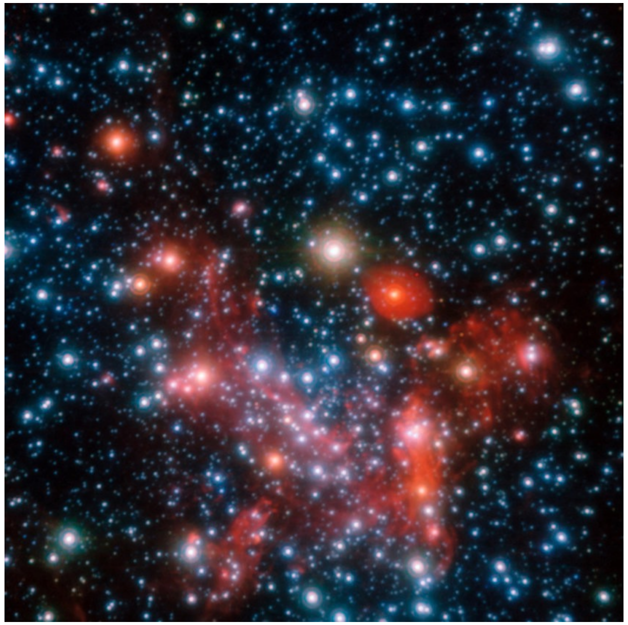
Final mass M= 10 x exp(10^9 / 4.5 x 10^7)
= 4 x 10^{10} Solar masses



Conclude: if the record breaking quasars at z > 6 have black hole masses of ~ 10^{10} Solar masses, and are being seen when the Universe was about 1 Gyr old, **just** enough time for them to have grown from small seed black holes…


Milky Way
?
E

Galactic Center



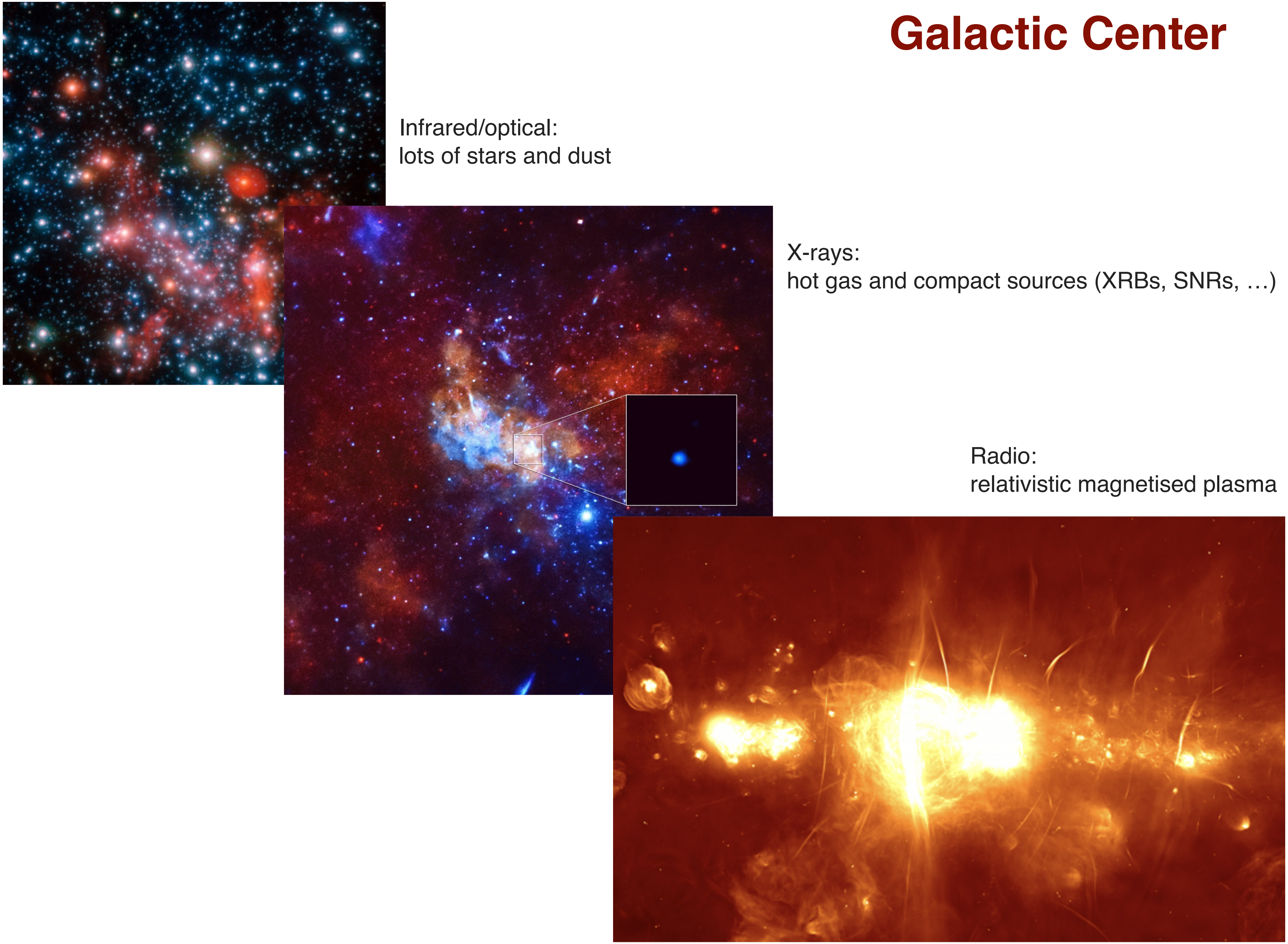
Infrared/optical:
lots of stars and dust

Galactic Center

Infrared/optical:
lots of stars and dust

X-rays:
hot gas and compact sources (XRBs, SNRs, …)

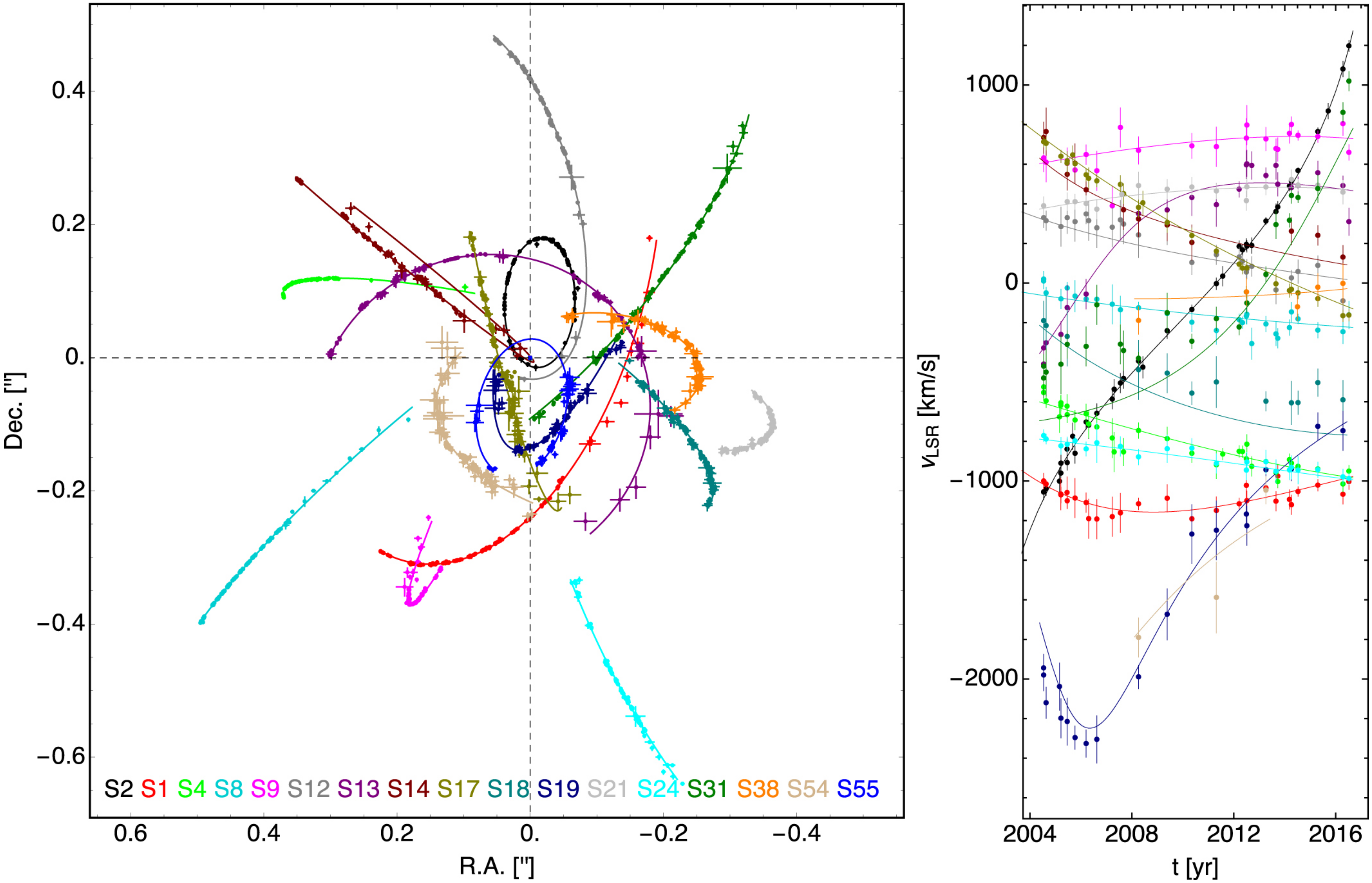
Galactic Center



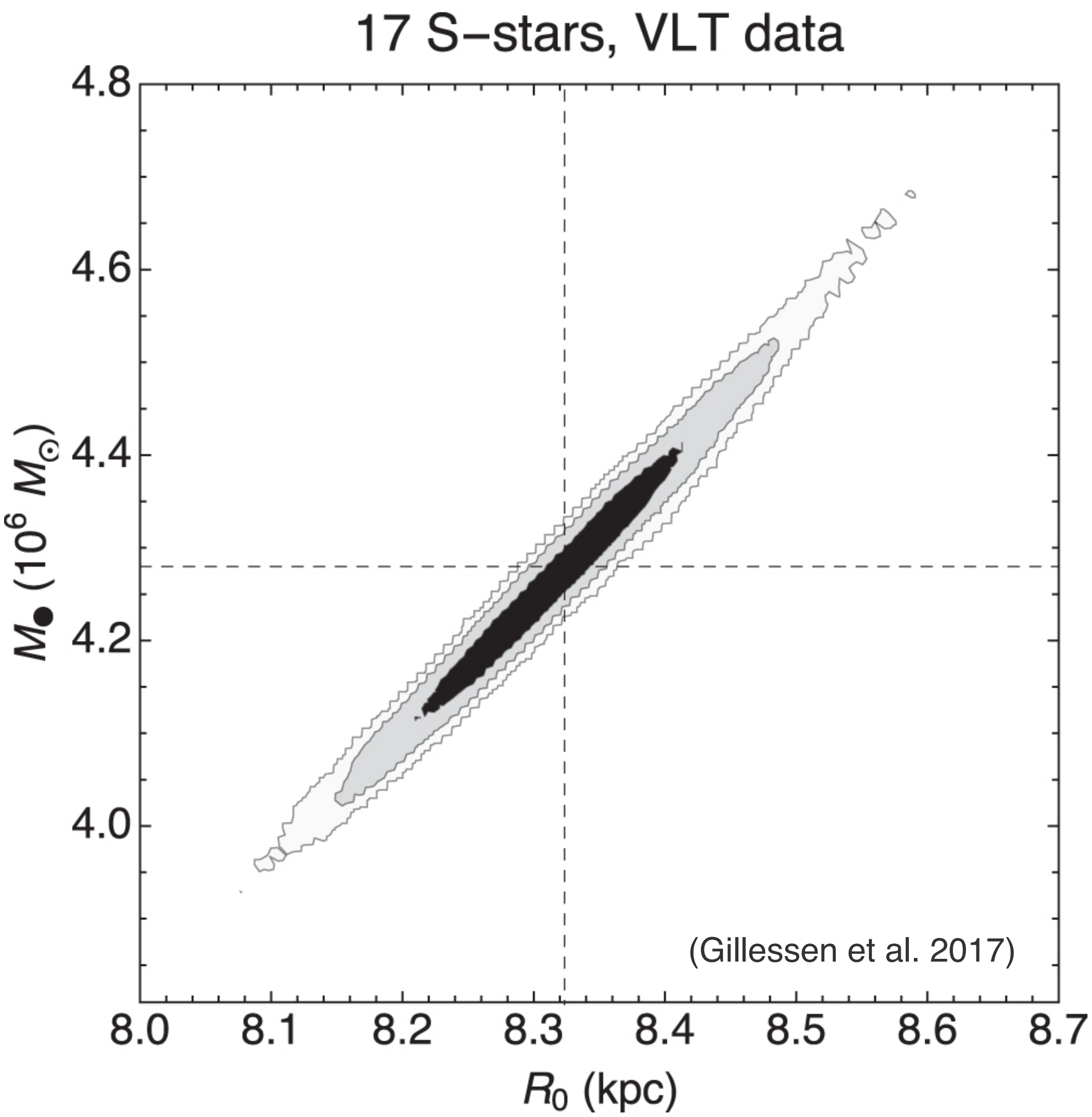
Infrared/optical:
lots of stars and dust

X-rays:
hot gas and compact sources (XRBs, SNRs, …)

Radio:
relativistic magnetised plasma



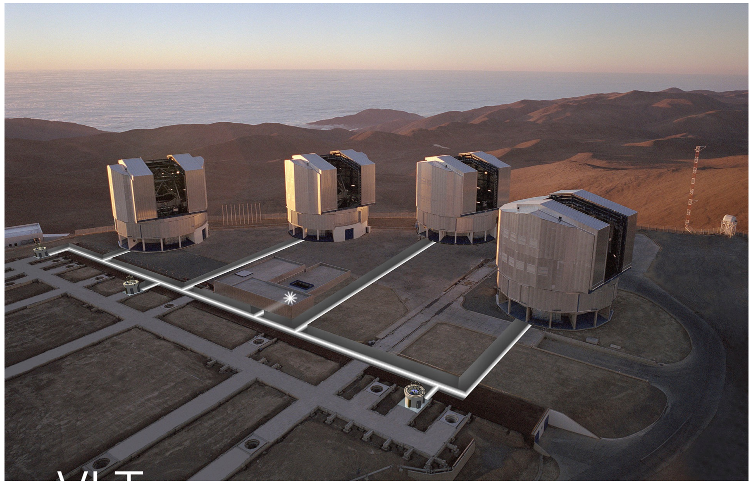
Orbits and radial velocities (along the line of sight) of 17 stars
in the closest neighbourhood of Sgr A*
(Gillessen et al. 2017)



(Gillessen et al. 2017)

1 kpc = 3 x 10^{16} km

exact measurements of the mass
and the distance of the SMBH
residing in the center of our Galaxy!



PRESS RELEASE

6 October 2020

The Nobel Prize in Physics 2020

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2020

with one half to

Roger Penrose

University of Oxford, UK

"for the discovery that black hole formation is a robust prediction of the general theory of relativity"

and the other half jointly to

Reinhard Genzel

Max Planck Institute for Extraterrestrial Physics, Garching, Germany and University of California, Berkeley, USA

Andrea Ghez

University of California, Los Angeles, USA

"for the discovery of a supermassive compact object at the centre of our galaxy"

Black holes and the Milky Way's darkest secret

Three Laureates share this year's Nobel Prize in Physics for their discoveries about one of the most exotic phenomena in the universe, the black hole. Roger Penrose showed that the general theory of relativity leads to the formation of black holes. Reinhard Genzel and Andrea Ghez discovered that an invisible and extremely heavy object governs the orbits of stars at the centre of our galaxy. A supermassive black hole is the only currently known explanation.

Roger Penrose used ingenious mathematical methods in his proof that black holes are a direct consequence of Albert Einstein's general theory of relativity. Einstein did not himself believe that black holes really exist, these super-heavyweight monsters that capture everything that enters them. Nothing can escape, not even light.

In January 1965, ten years after Einstein's death, Roger Penrose proved that black holes really can form and described them in detail; at their heart, black holes hide a singularity in which all the known laws of nature cease. His groundbreaking article is still regarded as the most important contribution to the general theory of relativity since Einstein.

Reinhard Genzel and **Andrea Ghez** each lead a group of astronomers that, since the early 1990s, has focused on a region called Sagittarius A* at the centre of our galaxy. The orbits of the brightest stars closest to the middle of the Milky Way have been mapped with increasing precision. The measurements of these two groups agree, with both finding an extremely heavy, invisible object that pulls on the jumble of stars, causing them to rush around at dizzying speeds. Around four million solar masses are packed together in a region no larger than our solar system.

Using the world's largest telescopes, Genzel and Ghez developed methods to see through the huge clouds of interstellar gas and dust to the centre of the Milky Way. Stretching the limits of technology, they refined new techniques to compensate for distortions caused by the Earth's atmosphere, building unique instruments and committing themselves to long-term research. Their pioneering work has given us the most convincing evidence yet of a supermassive black hole at the centre of the Milky Way.

"The discoveries of this year's Laureates have broken new ground in the study of compact and supermassive objects. But these exotic objects still pose many questions that beg for answers and motivate future research. Not only questions about their inner structure, but also questions about how to test our theory of gravity under the extreme conditions in the immediate vicinity of a black hole", says David Haviland, chair of the Nobel Committee for Physics.

Roger Penrose, born 1931 in Colchester, UK. Ph.D. 1957 from University of Cambridge, UK. Professor at University of Oxford, UK.

Reinhard Genzel, born 1952 in Bad Homburg vor der Höhe, Germany. Ph.D. 1978 from University of Bonn, Germany. Director at Max Planck Institute for Extraterrestrial Physics, Garching, Germany and Professor at University of California, Berkeley, USA.

Andrea Ghez, born 1965 in City of New York, USA. Ph.D. 1992 from California Institute of Technology, Pasadena, USA. Professor at University of California, Los Angeles, USA.

Prize amount: 10 million Swedish kronor, with one half to Roger Penrose and the other half jointly to Reinhard Genzel and Andrea Ghez
Further information: www.kva.se and www.nobelprize.org
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Experts: Ulf Danielsson, +46 70 314 10 86, ulf.danielsson@physics.uu.se and Ariel Goobar, +46 8 553 786 59, ariel@fysik.su.se, the Nobel Committee for Physics

The Royal Swedish Academy of Sciences, founded in 1739, is an independent organisation whose overall objective is to promote the sciences and strengthen their influence in society. The Academy takes special responsibility for the natural sciences and mathematics, but endeavours to promote the exchange of ideas between various disciplines.

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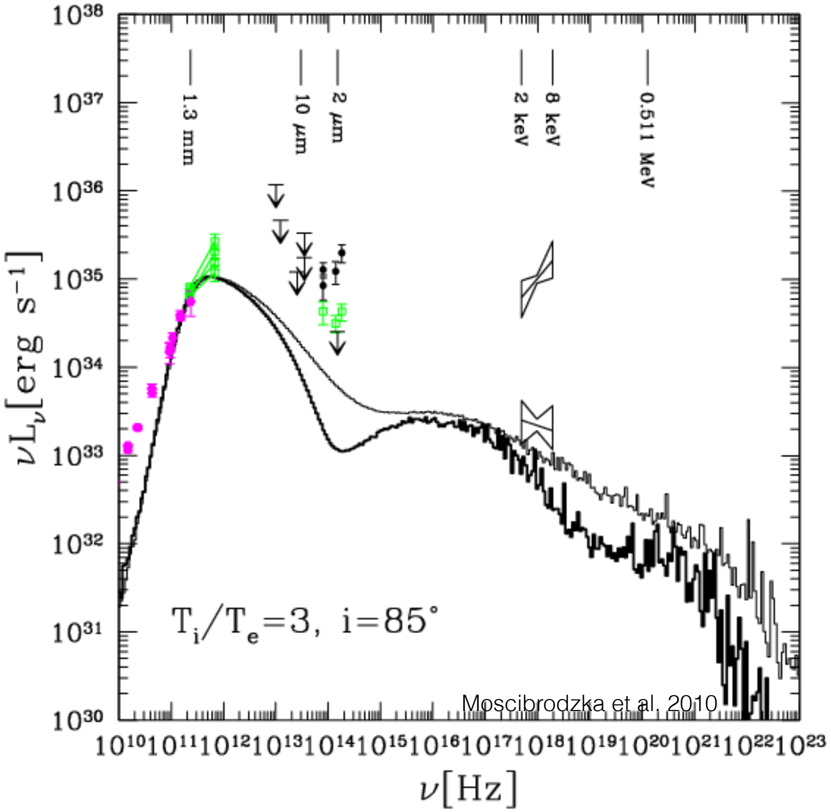
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Can we resolve the Sgr A* horizon?

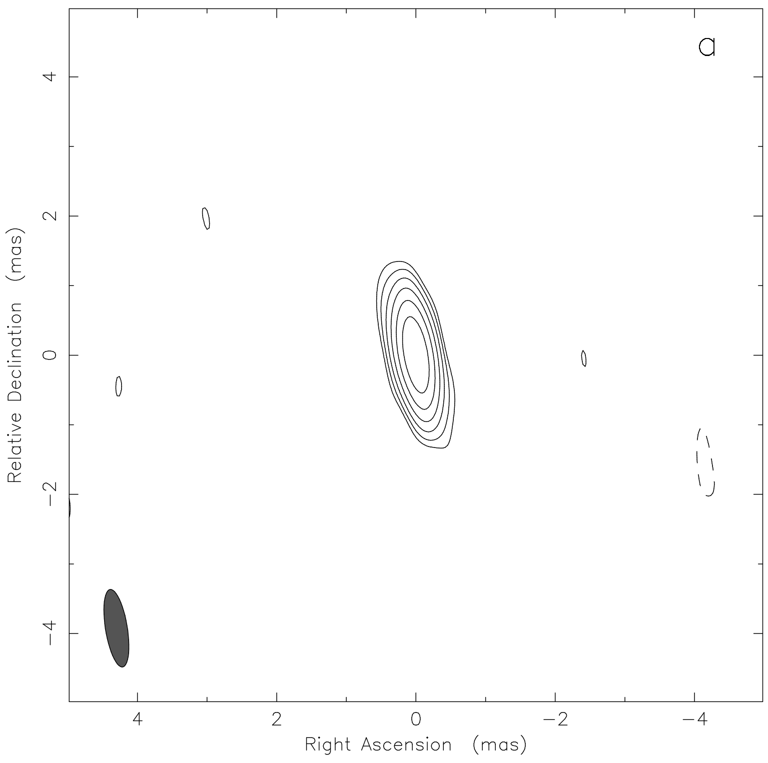


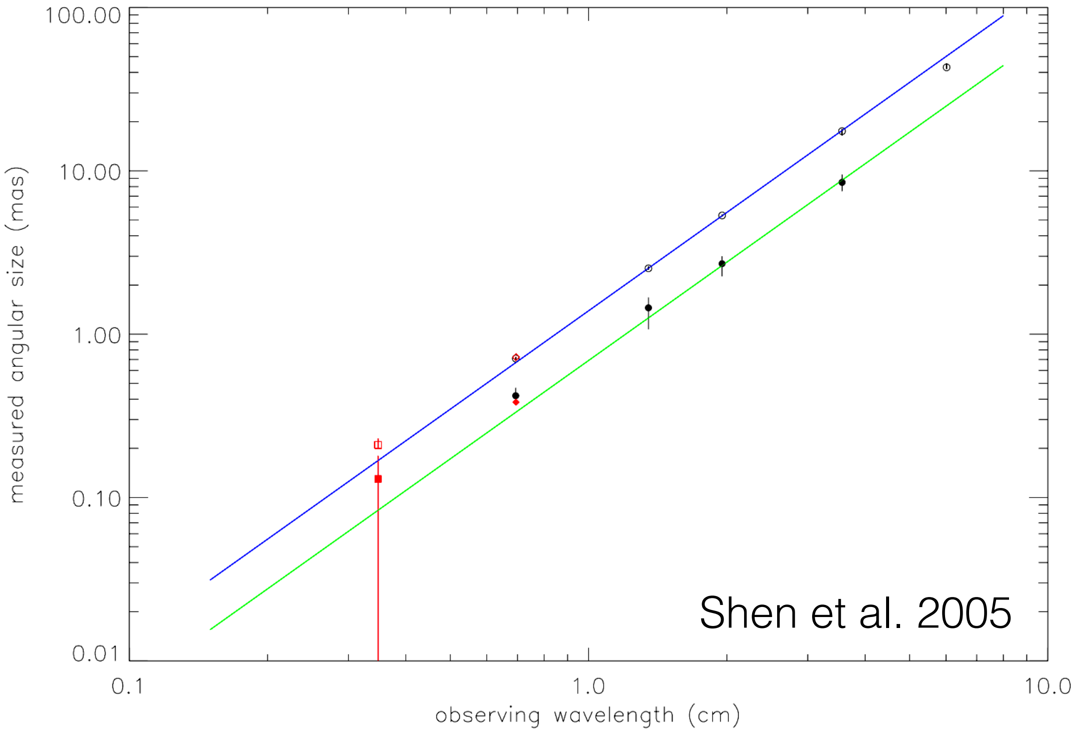
Moscibrodzka et al. 2010

due to very low accretion rate of Sgr A*, its accretion disk should be pronounced not only in X-rays, but also at radio frequencies (“Radiatively Inefficient Accretion Flow”, with de-coupled electron and proton temperatures, and hence broad-band emission continuum)

->

good news, as radio interferometers are of a much better angular resolution than the currently operating X-ray telescopes (in particular *Chandra*, with ~arcsec resolution)



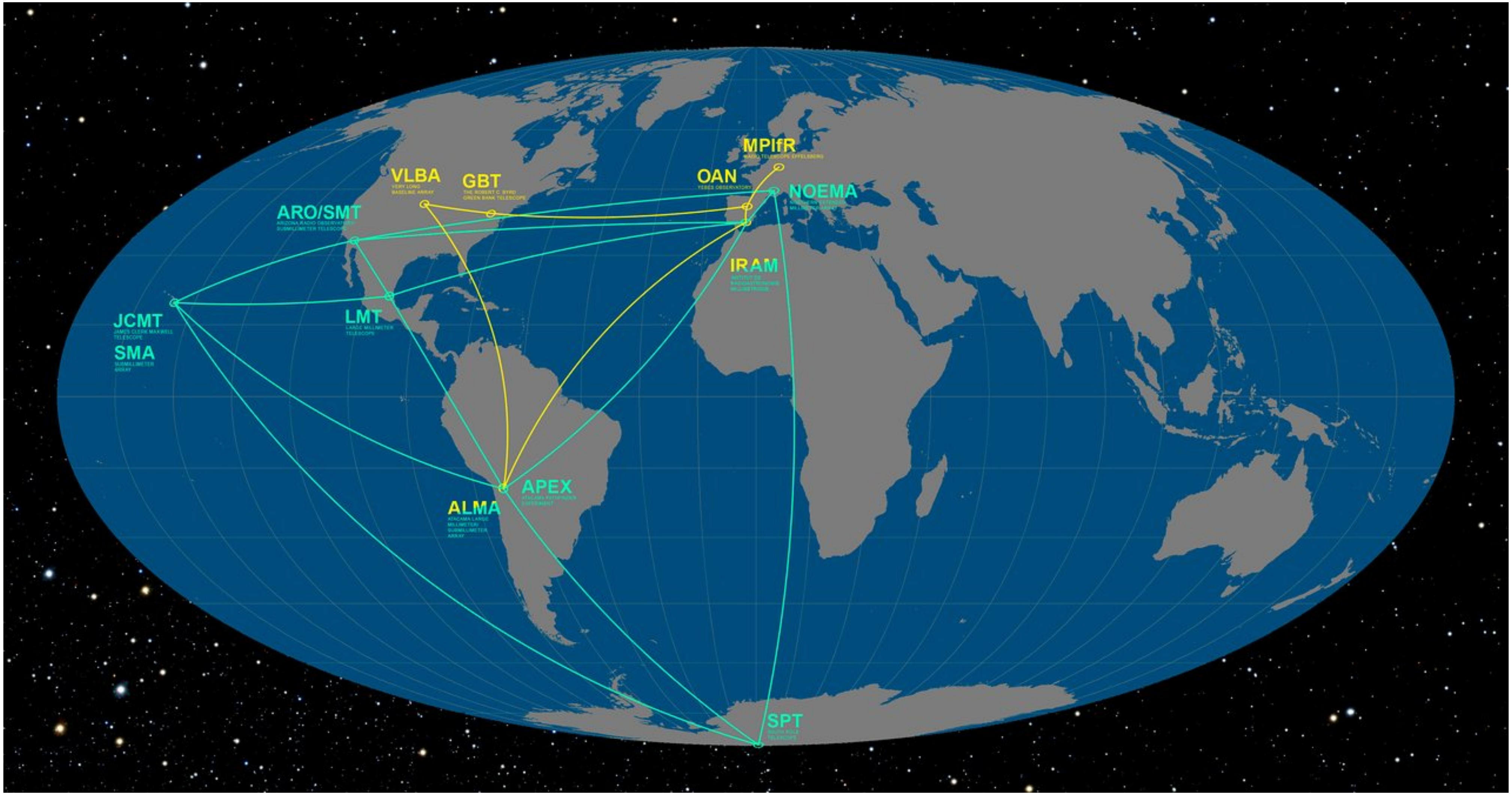


Shen et al. 2005

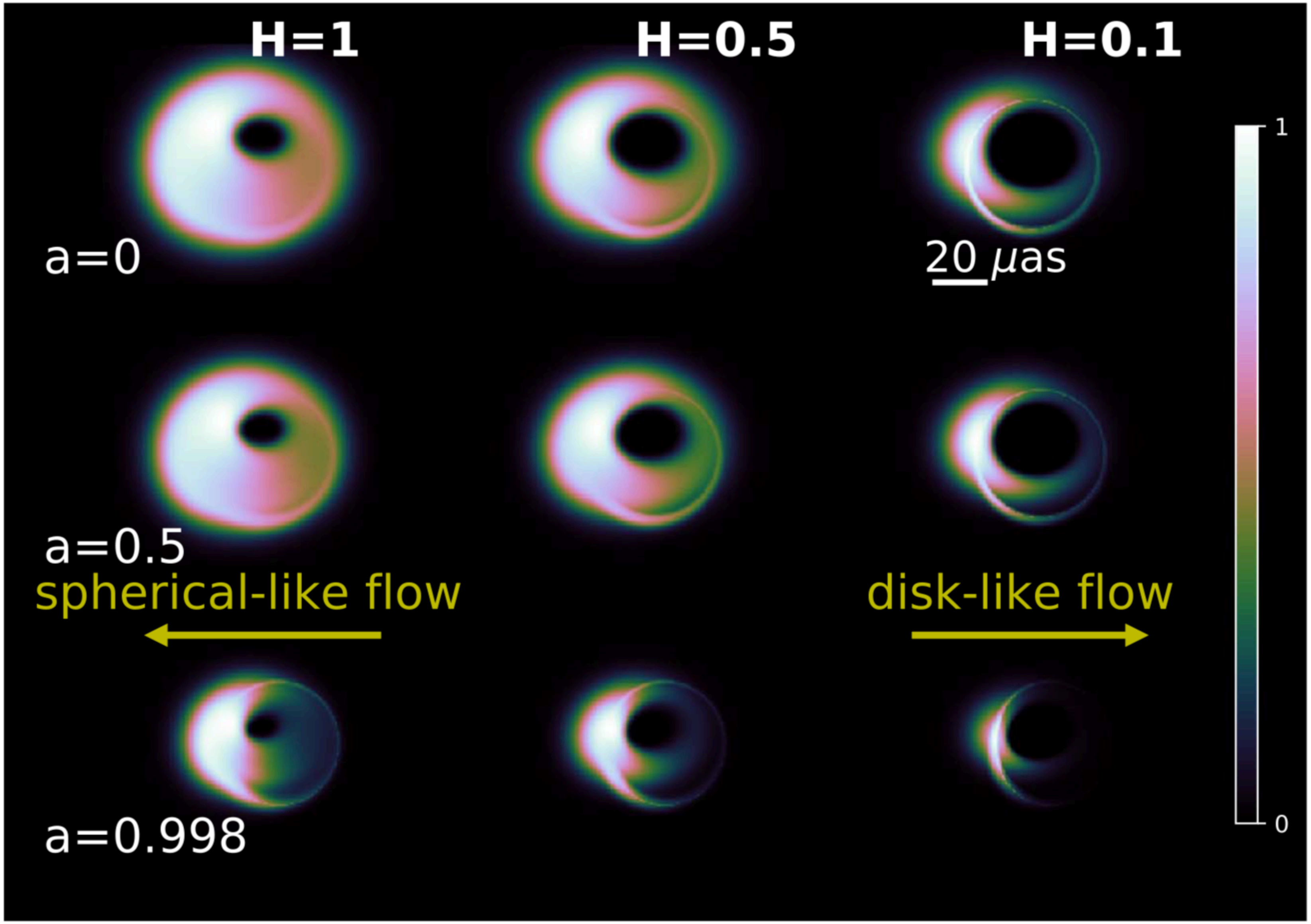
VLBA observations with very high angular resolution (~0.2mas) at 3.5mm:
upper limit for the radio size of Sgr A*
0.1 mas -> ~10^8 km ~1 AU

event horizon of Sgr A*
(assuming zero angular momentum)
r_S ~ 10^7 km ~ 0.1 AU -> 0.01 mas

The **Event Horizon Telescope** (**EHT**)
is a project to create a large telescope array consisting of a global network of radio telescopes and combining data from several very-long-baseline interferometry (VLBI) stations around the Earth



Imaging of the Sgr A* event horizon with the EHT



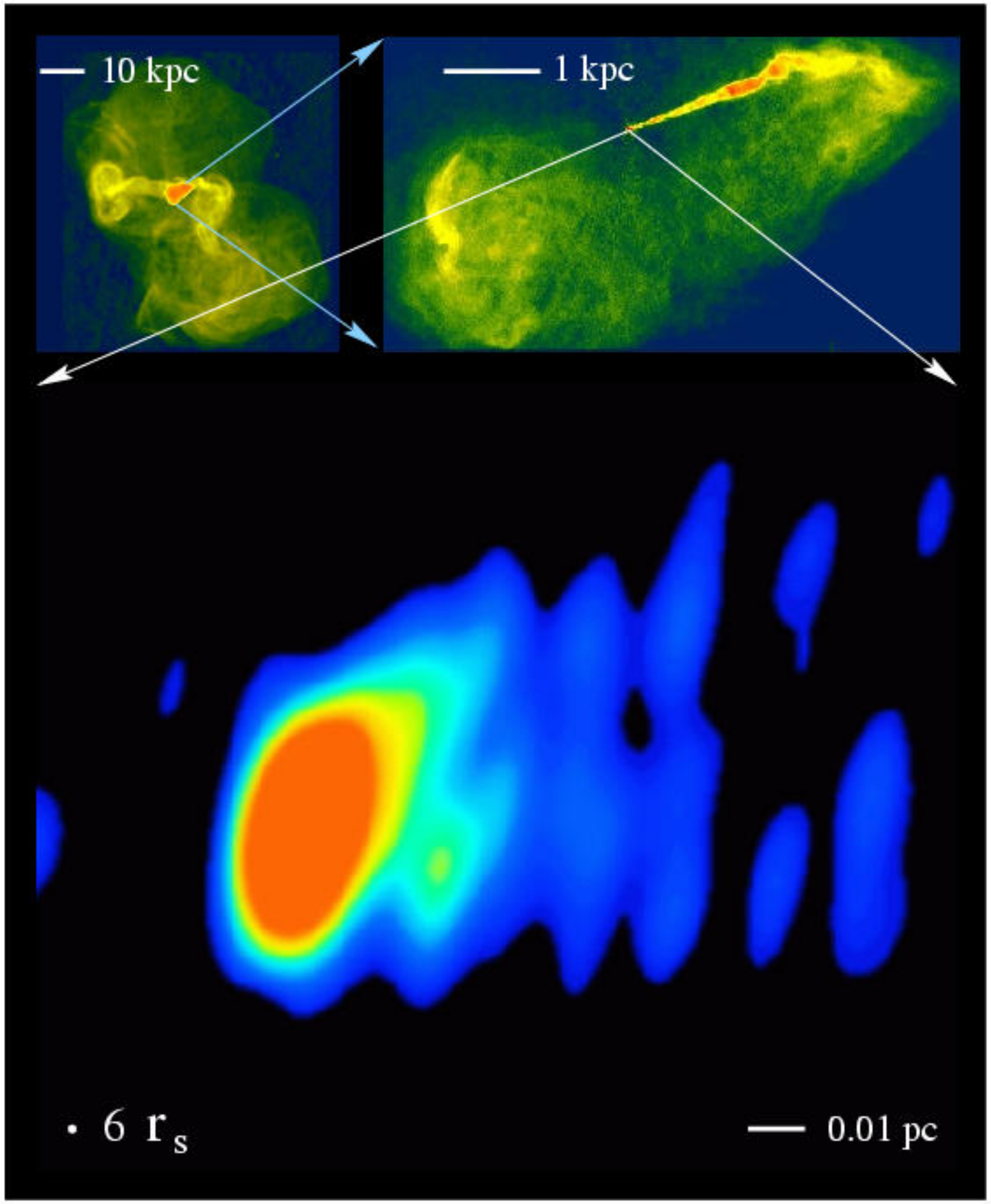
Pu & Broderick 2018

Virgo A (M87)

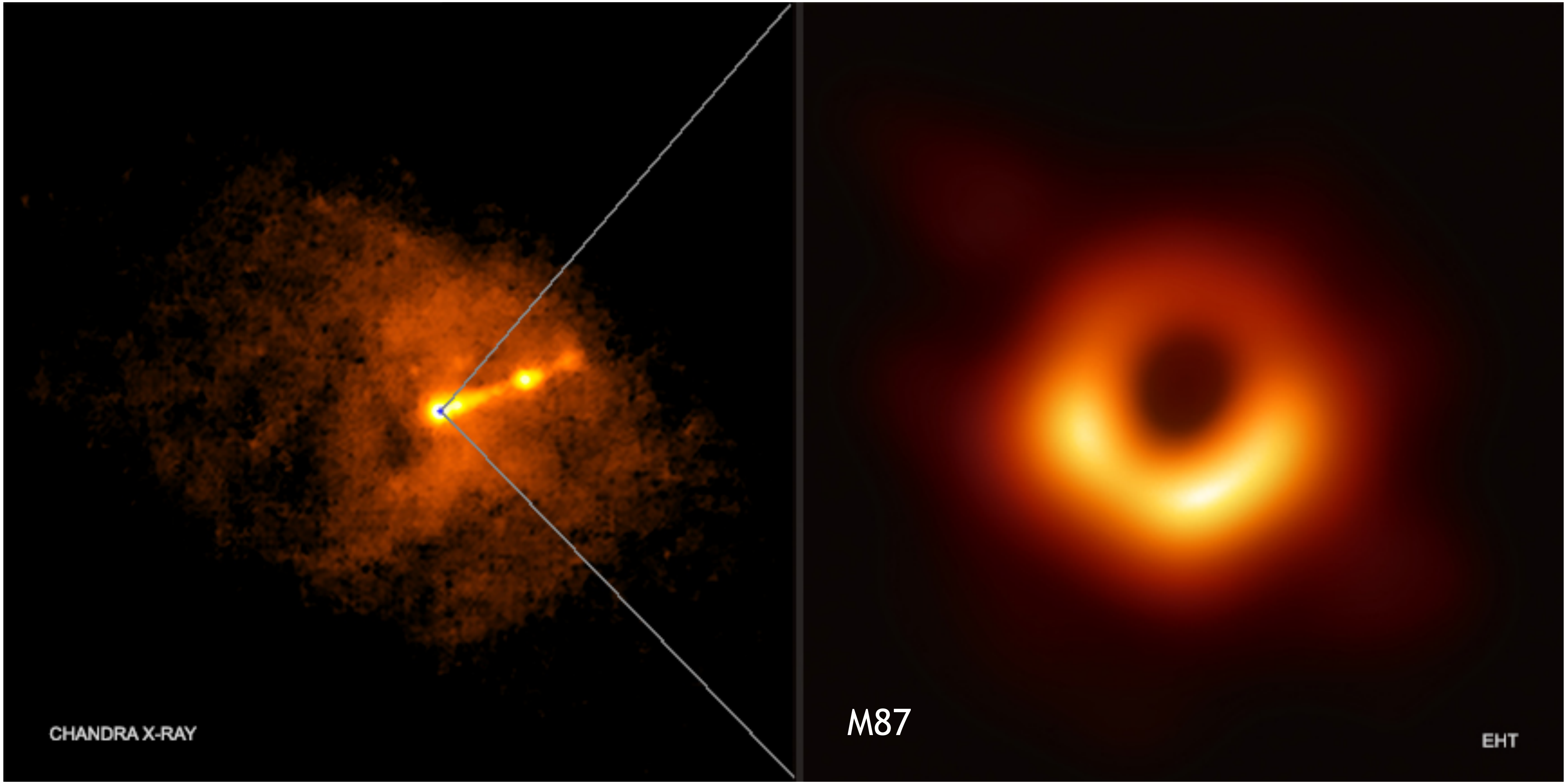
- low-power but nearby radio galaxy, hosted by the dominant galaxy in the Virgo cluster
- complex radio outflow interacting with the intracluster medium

Virgo A (M87), distance 16 Mpc

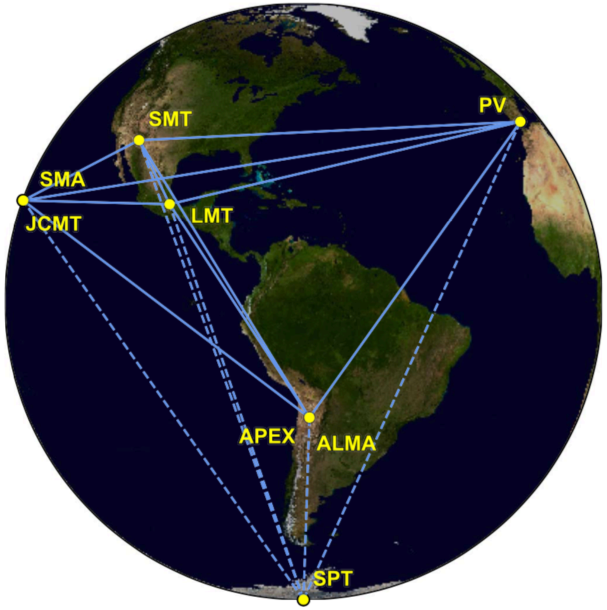
- radio outflow can be traced from kpc scale down to sub-pc scale

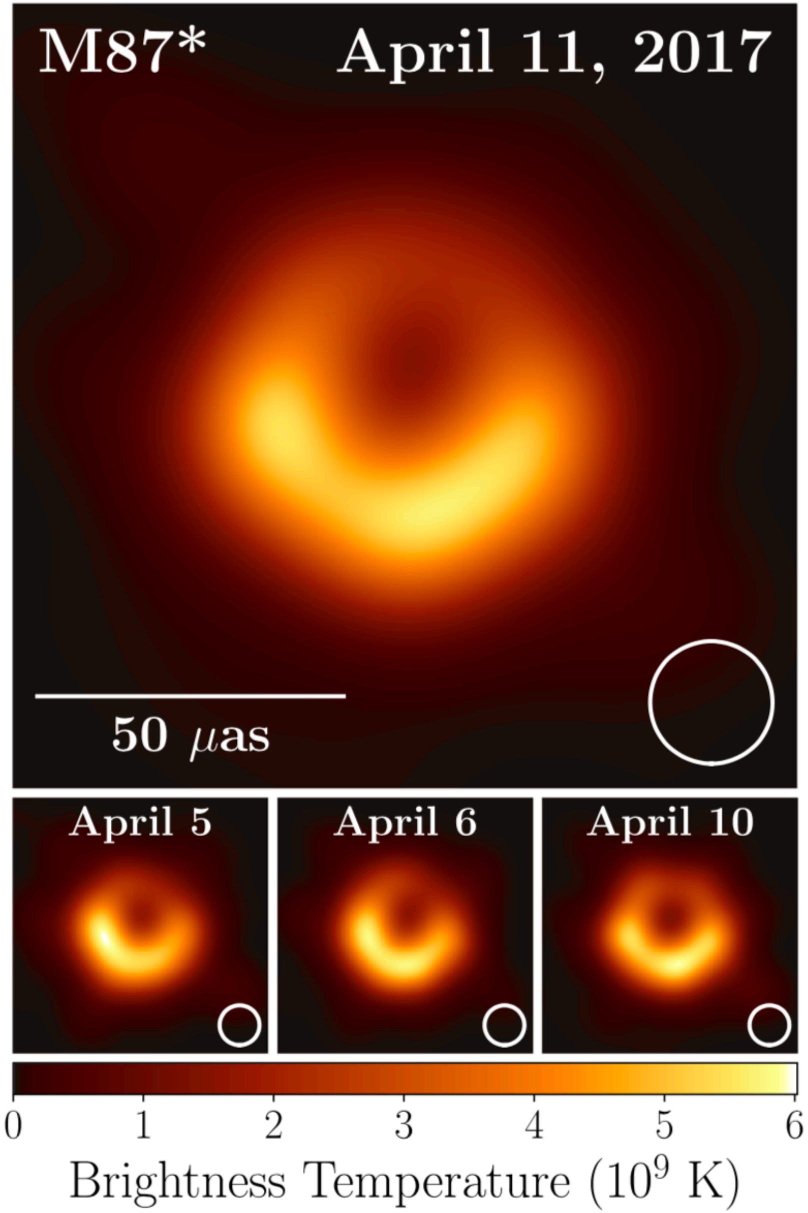


First Image of a SMBH



The EHT 2017 campaign





The EHT Collab. 2019:

“Comparing the data with an extensive library of synthetic images obtained from GRMHD simulations covering different physical scenarios and plasma conditions (…) allows us to derive an estimate for the black hole mass of

$$M_\bullet=(6.5\pm0.7)\times10^9\ M_\odot$$

Based on our modeling and information on the inclination angle, we derive the sense of rotation of the black hole to be in the clockwise direction, i.e., the spin of the black hole points away from us. The brightness excess in the south part of the emission ring is explained as relativistic beaming of material rotating in the clockwise direction as seen by the observer, i.e., the bottom part of the emission region is moving toward the observer.”

SMBH sphere of influence

event horizon (for *a=0*)

$$r_S = \frac{2G\mathcal{M}_\bullet}{c^2} \approx 10^{-8} \left(\frac{\mathcal{M}_\bullet}{10^8 M_\odot}\right) \mathrm{kpc}$$

radius of the "sphere of influence" of the SMBH, i.e. the distance at which its gravitational potential significantly affects the motion of the stars or of the interstellar medium (for the velocity dispersion **σ** of the stars within the inner parts of the galaxy, i.e. spheroidal component whose stellar dynamics is dominated by random motions, not by rotation)

$$\frac{1}{2}\sigma^2 = \frac{G\mathcal{M}_\bullet}{r_i} \longrightarrow r_i = \frac{2G\mathcal{M}_\bullet}{\sigma^2} \approx 10^{-2} \left(\frac{\mathcal{M}_\bullet}{10^8 M_\odot}\right) \left(\frac{\sigma}{200\,\mathrm{km\,s^{-1}}}\right)^{-2} \mathrm{kpc}$$

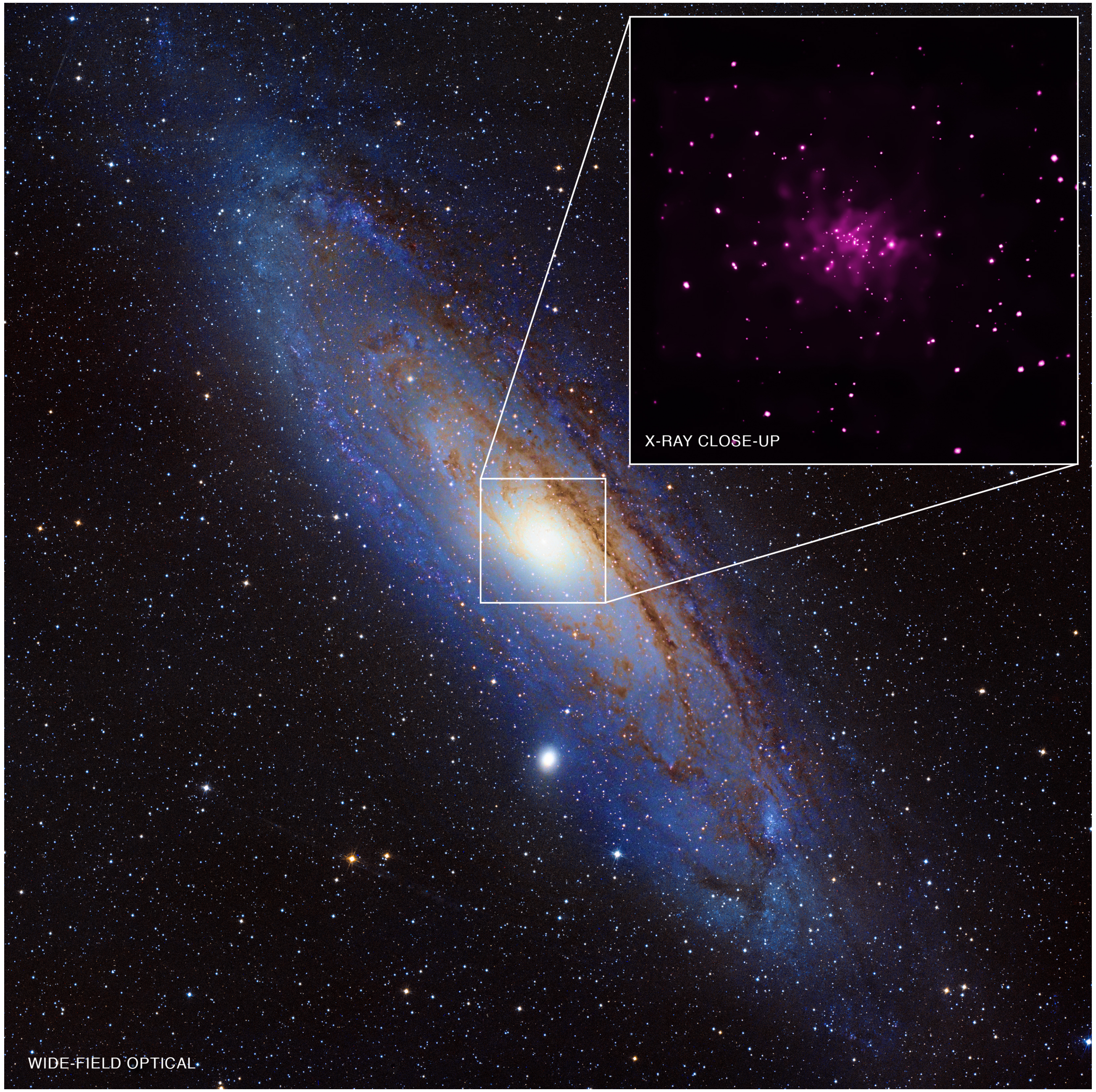
linear scale of a typical galaxy

$$r_G \sim 10 - 100\,\mathrm{kpc}$$

the direct dynamical influence of central SMBHs is relevant only in the innermost regions of the galaxies, and— due to the limited angular resolution of the optical telescopes — could be observable only in most massive galaxies located at distances <100 Mpc (effectively ~100 systems)

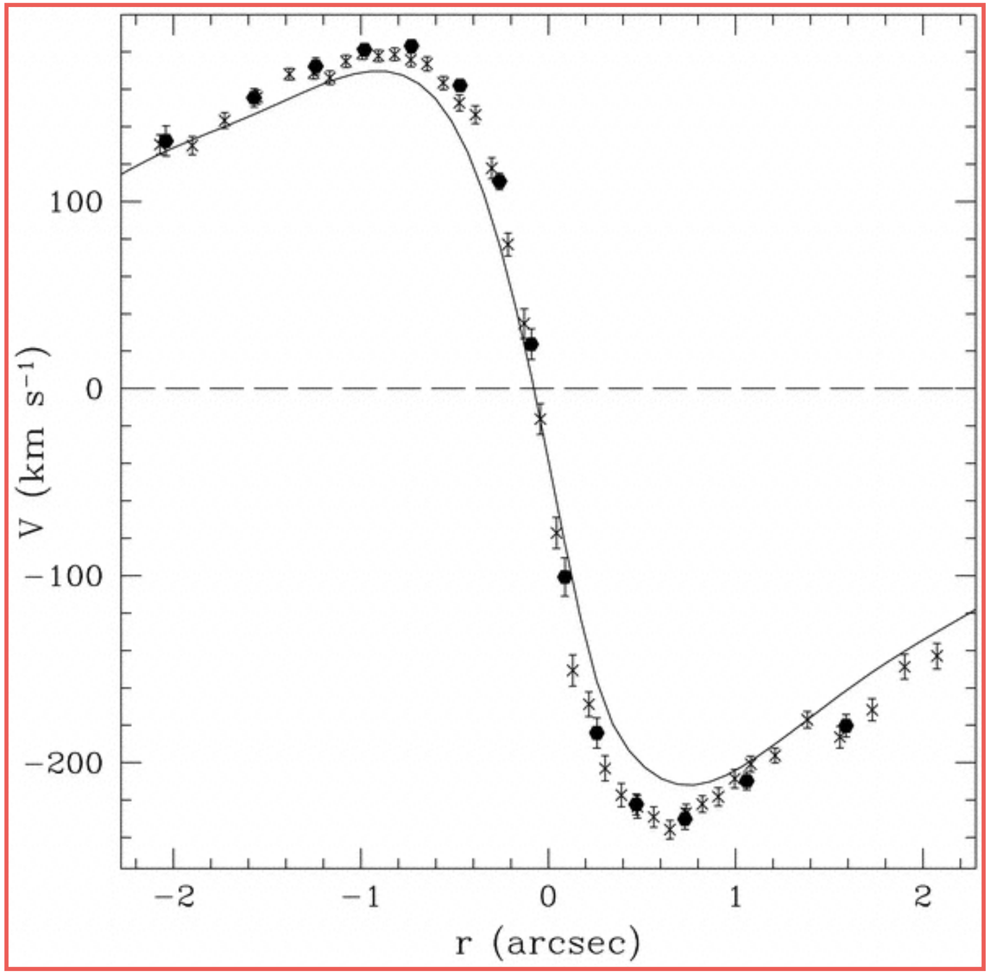
Andromeda (M31)

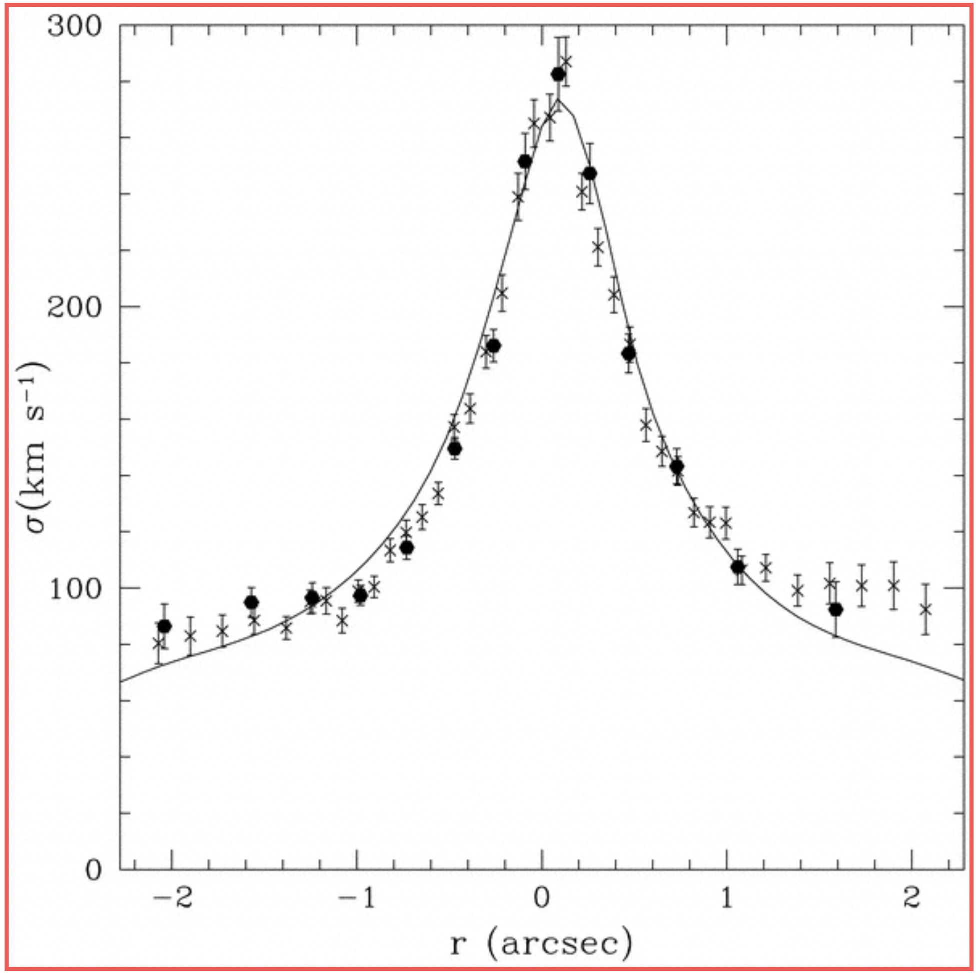
- relatively large angular size of the sphere of influence of the central SMBH
- small amount of gas, relatively young stars in the center, with older stars located at Keplerian orbits within the outer disk



Andromeda (M31), distance 0.7 Mpc

radial velocities and velocity dispersion of the stars in the central parts of the galaxy gives **$M_\bullet$ = (1.1-2.3) x 10^8 $M_\odot$**



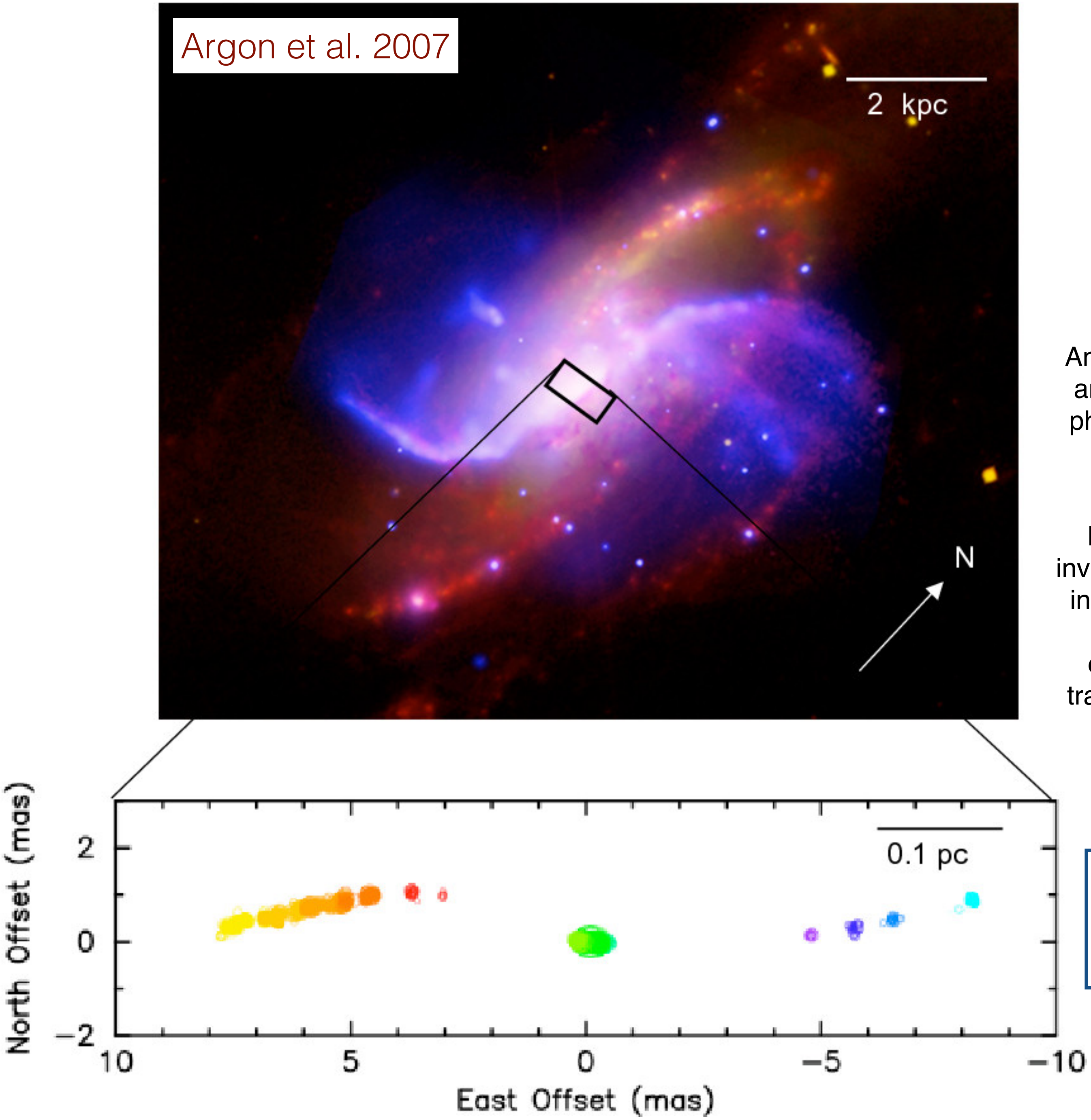


Peiris & Tremaine 2003

Bender et al. 2005

NGC 4258 (M106)

(X-ray – blue, Optical – gold, IR – red, Radio – purple)



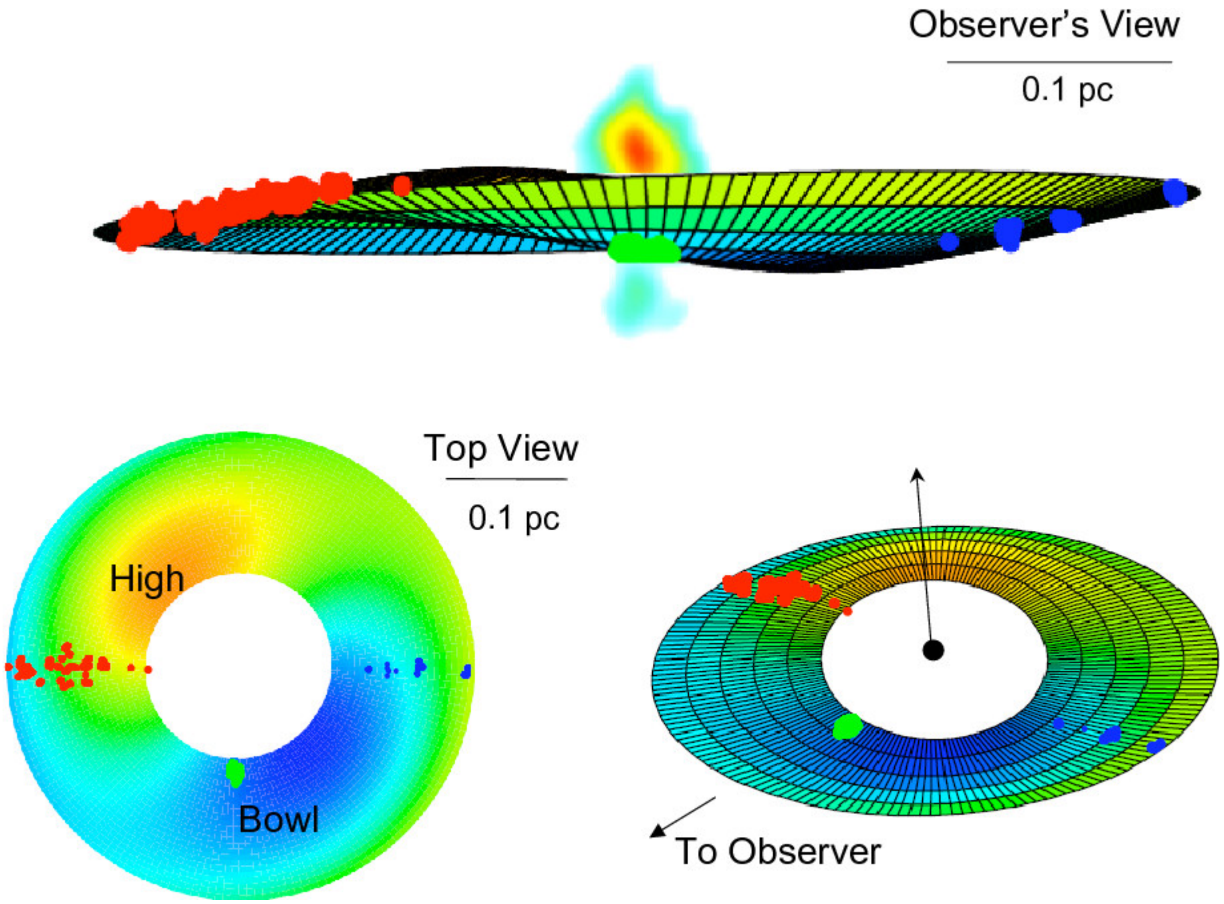
An atom or molecule may absorb a photon and move to a higher energy level, or the photon may stimulate emission of another photon of the same energy causing a transition to a lower energy level.

Producing a maser requires population inversion, i.e., a system with more members in a higher energy level relative to a lower energy level. Water maser emission is observed primarily at 22 GHz, due to a transition between rotational energy levels in the water molecule.

MASER = Microwave Amplification by Stimulated Emission of Radiation

NGC 4258, distance 7.6 Mpc

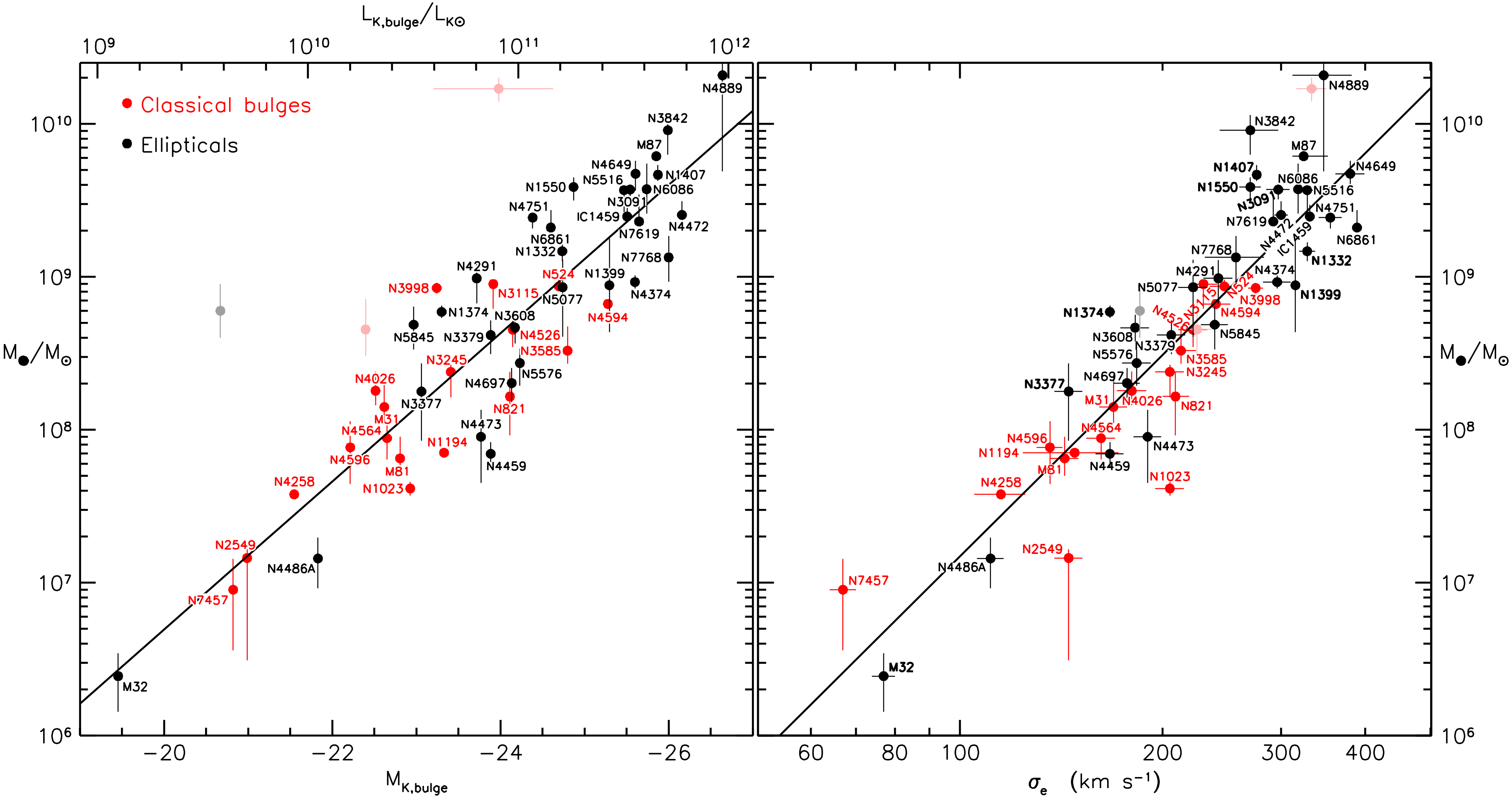
$M_\bullet=(3.9\pm0.1)\times10^{7}\,M_\odot$



The phenomenon is observed in edge disks hosting molecular clouds with water molecules. The rest frame frequency of the maser line is 22 GHz and by measuring the Doppler shift due to the Keplerian motion of the clouds, the rotation curve of the disk can be measured, allowing the estimate of the BH mass.

Maser emission occurs only along the major axes (at 90deg with respect to the observer line of sight) of the edge on disk, and the nearest semi minor axis (if a photon at 22 GHz is emitted at an angle with respect to the observer, it encounters molecules with different radial velocities along the line of sight to the observer and Doppler shifts prevent maser amplification to occur).

Empirical **correlations** between the stellar velocity dispersion or the luminosity of a galaxy bulge and the mass of the central SMBH

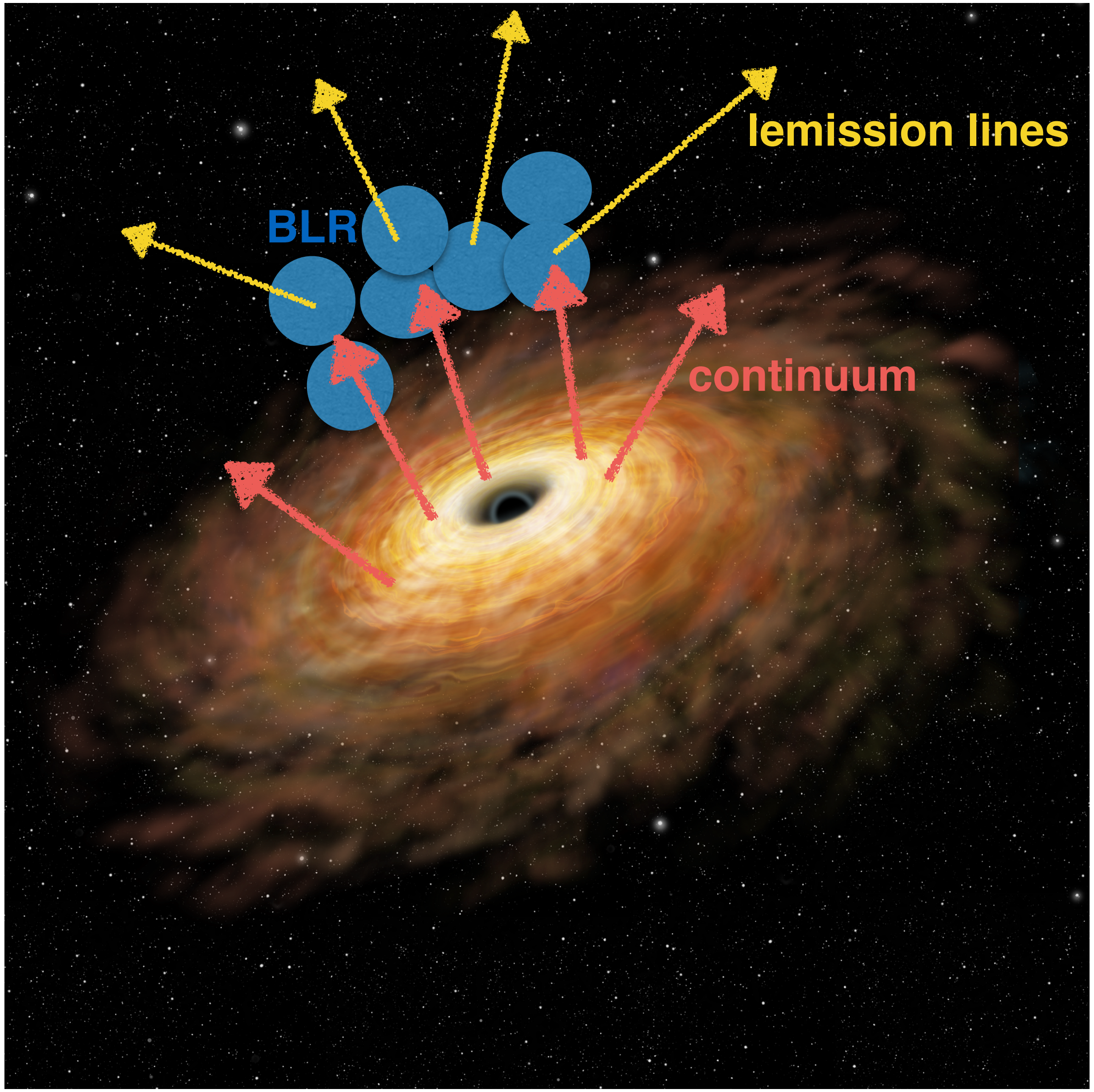


Kormendy & Ho 2013

Continuum and line emission in type I AGN

continuum: dominated by the innermost parts of the accretion disk, around the innermost stable circular orbit, i.e. a few/several r_S

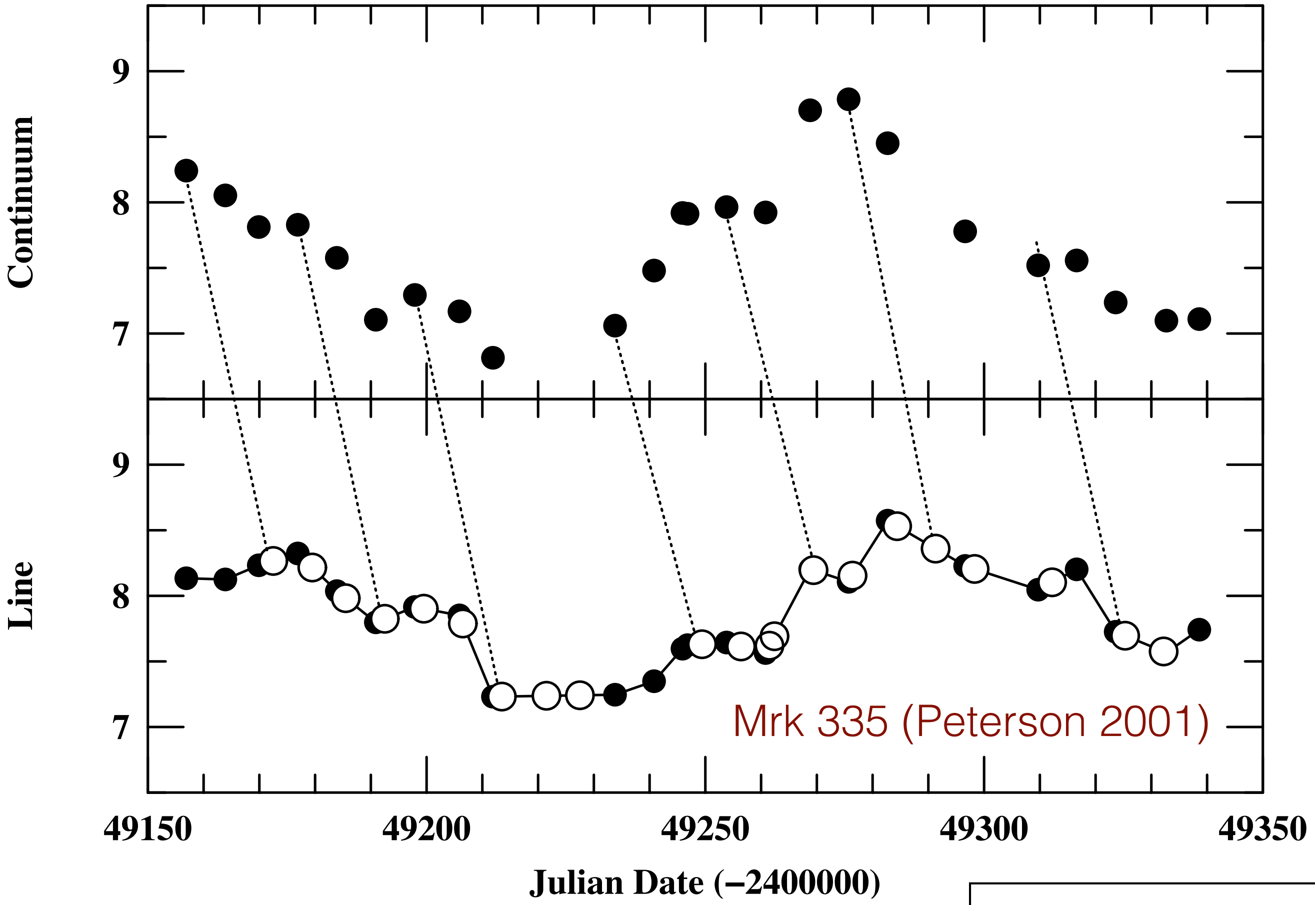
broad emission lines: emitted from atomic gas in the "broad line region" (BLR), i.e. from dense clouds located at some distance from the central engine (but within the SMBH sphere of influence), and photoionized by the disk continuum



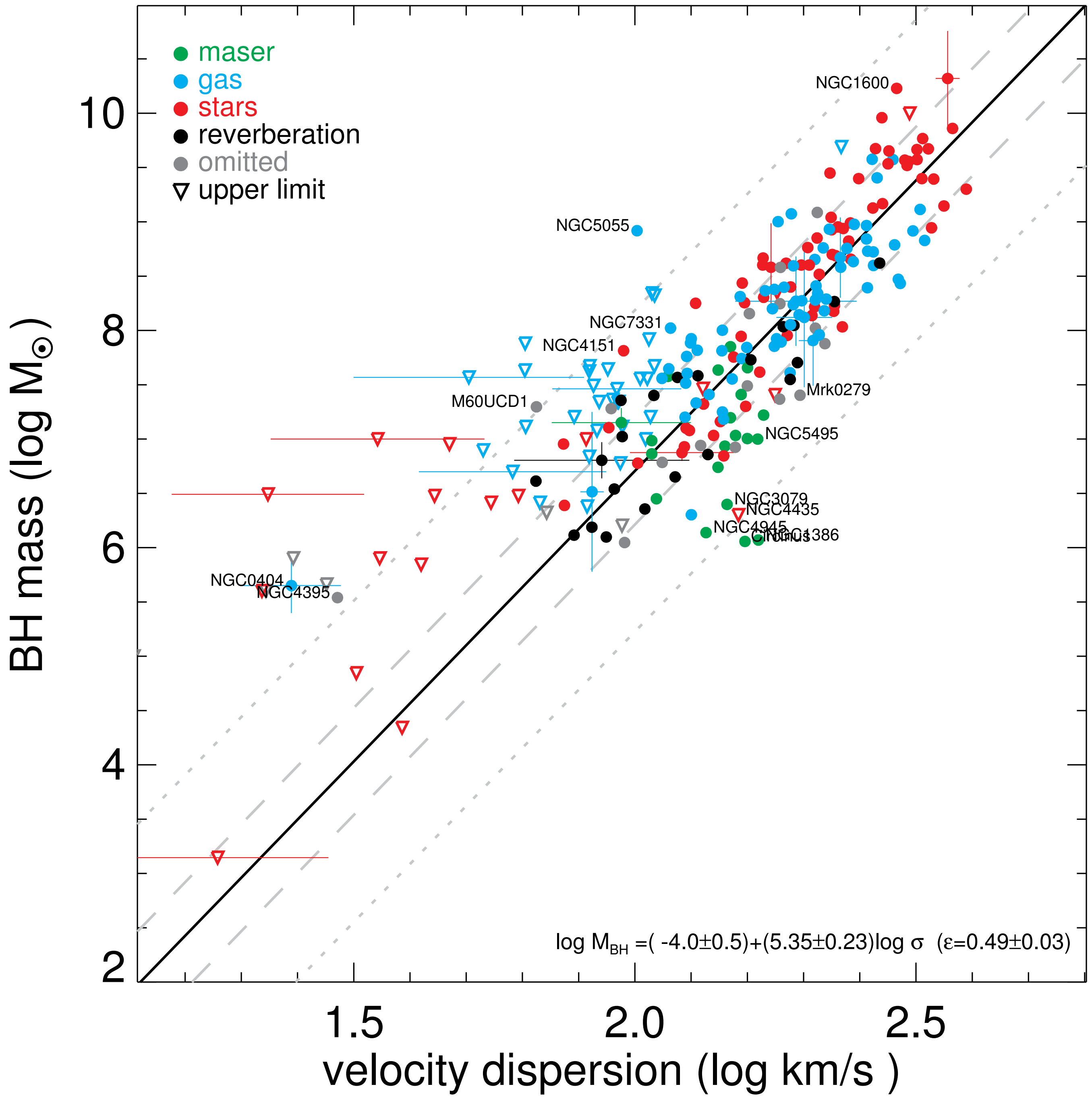
Reverberation mapping: the emission line variability shows a time lag with respect to the continuum — line intensity varies in response to the continuum variability, with a time lag Δt that can be associated to the distance of the BLR from the central engine via $R_{BLR} = c\Delta t$.

From the full width half maximum (FWHM) of the broad lines the velocity Δv of the gas can be inferred.

Main issues here: geometry and structure of the BLR!



$$G\mathcal{M}_\bullet \sim R_{\rm BLR}\,(\Delta v)^2$$

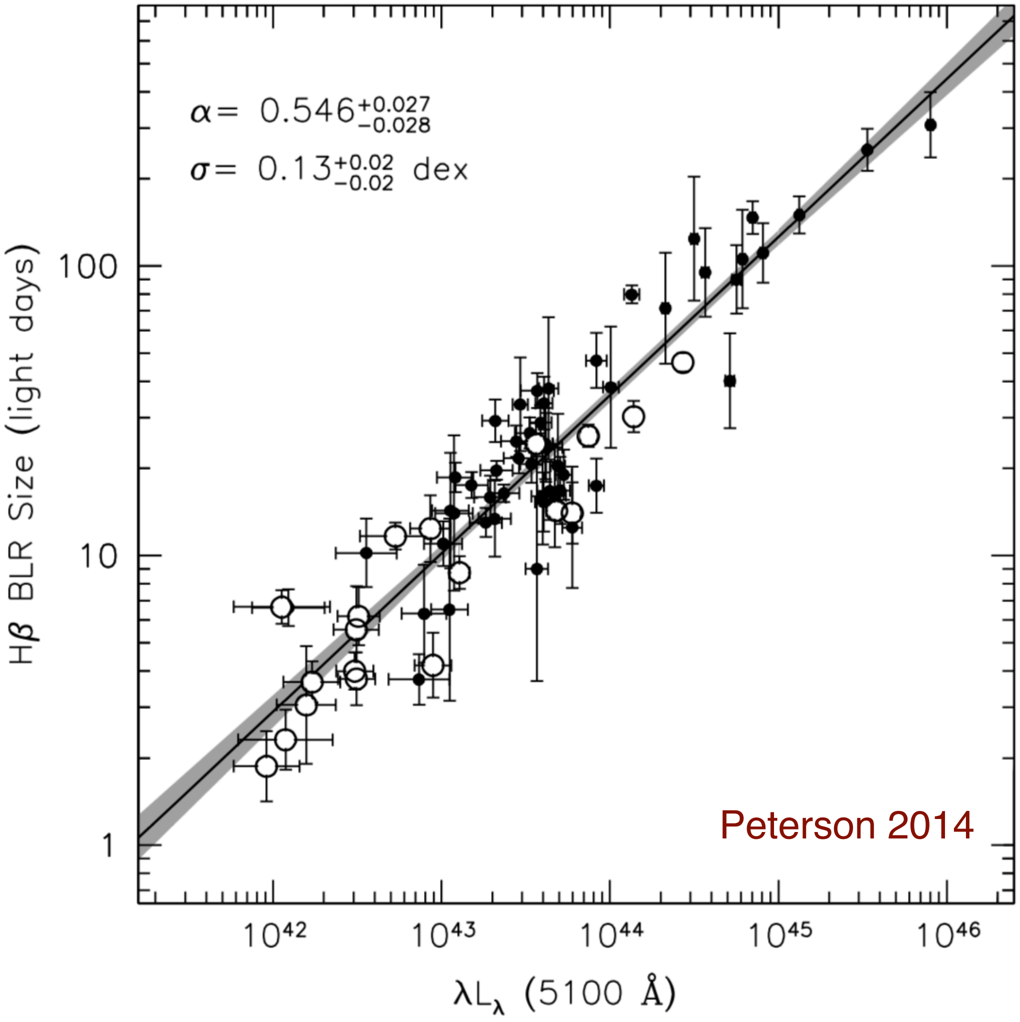


van den Bosch 2016

What if Δt cannot really be measure?

Empirical correlation between the characteristic broad-line region size R_{BLR} and the optical (continuum) AGN luminosity!

This relationship allows us to estimate R_{BLR} from the luminosity in a single AGN spectrum, thus by-passing the resource-intensive RM technique

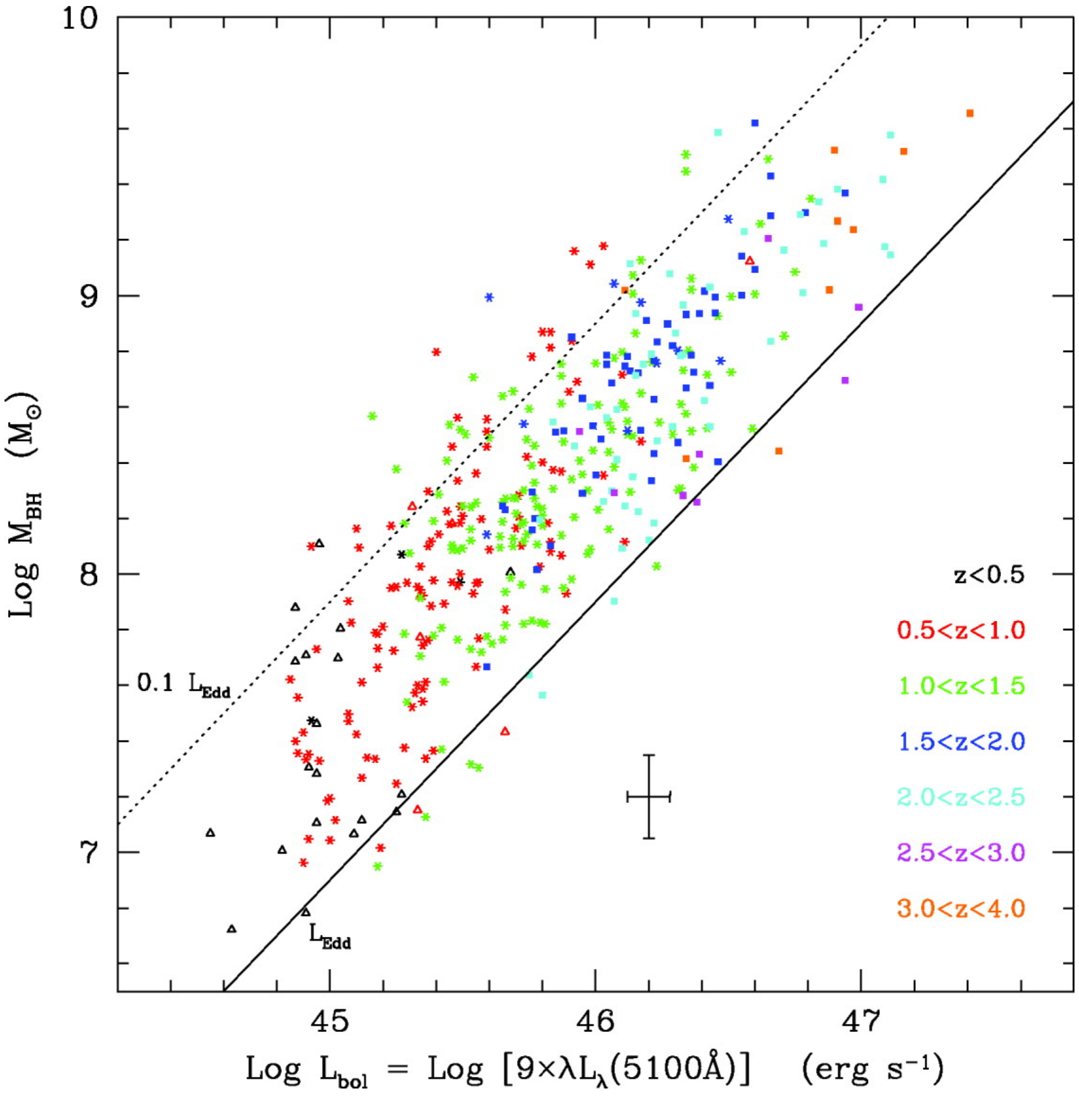


Peterson 2014

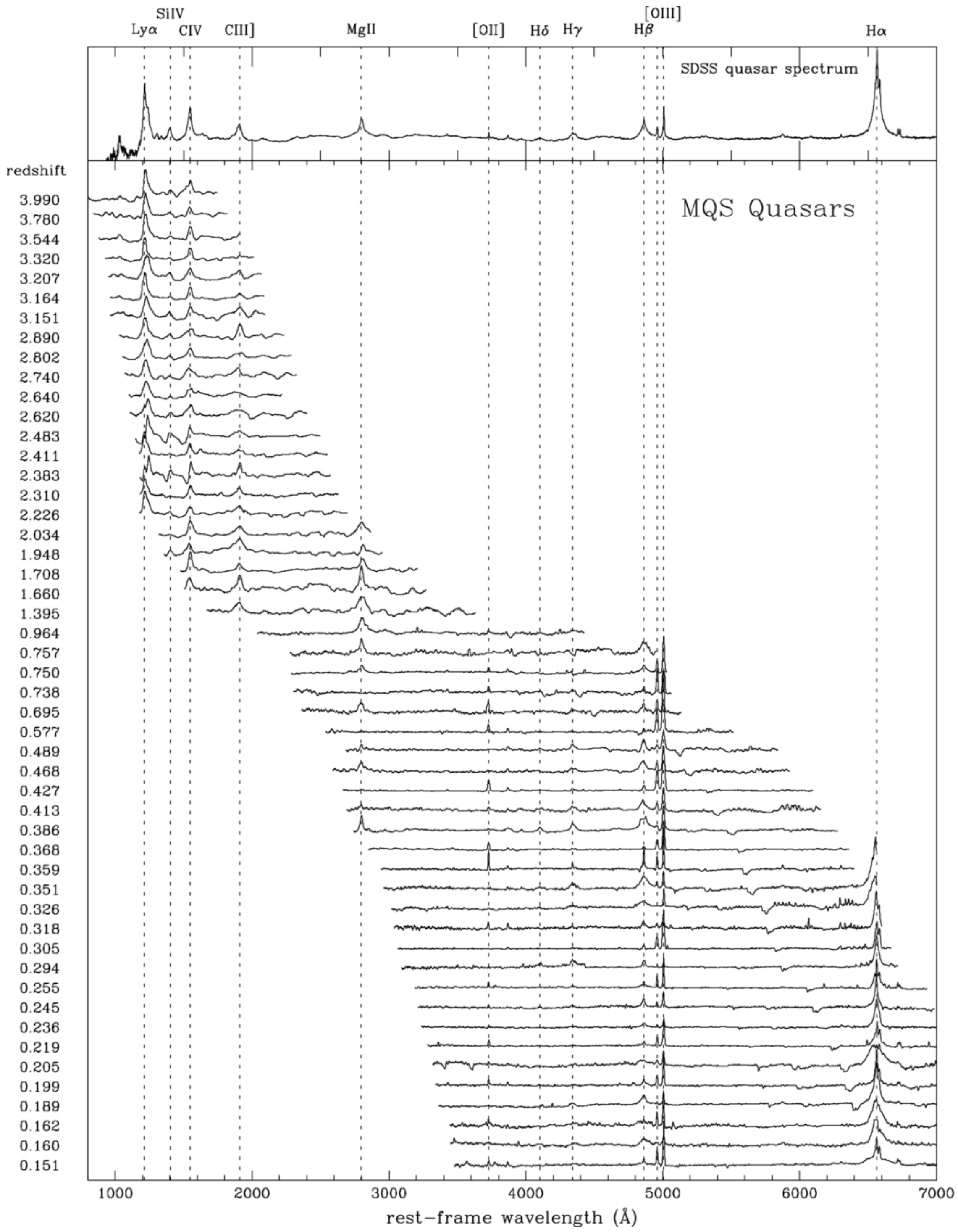
This single-epoch method is used for large samples of distant AGN using any of the prominent emission lines. The absolute mass uncertainty is evaluated statistically to be a factor ~4 to 5 on an absolute scale and a factor ~3 relative to the reverberation mapping-based mass. Individual mass estimates can be uncertain by a factor of ~10, however.

$$\log M_{\rm BH}({\rm H}\beta) = \log \left[\left(\frac{{\rm FWHM(H}\beta)}{1000 \ {\rm km \ s^{-1}}} \right)^2 \ \left(\frac{\lambda L_\lambda (5100\,\text{Å})}{10^{44} {\rm erg \ s^{-1}}} \right)^{0.50} \right] + (6.91 \pm 0.02)$$

e.g., Vestergaard & Peterson 2006

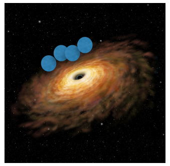


e.g., Kollmeier et al. 2006 (point types denote the emission line used for the mass measurement, with open triangles, asterisks, and filled squares corresponding to H-beta, Mg II, and C IV, respectively)

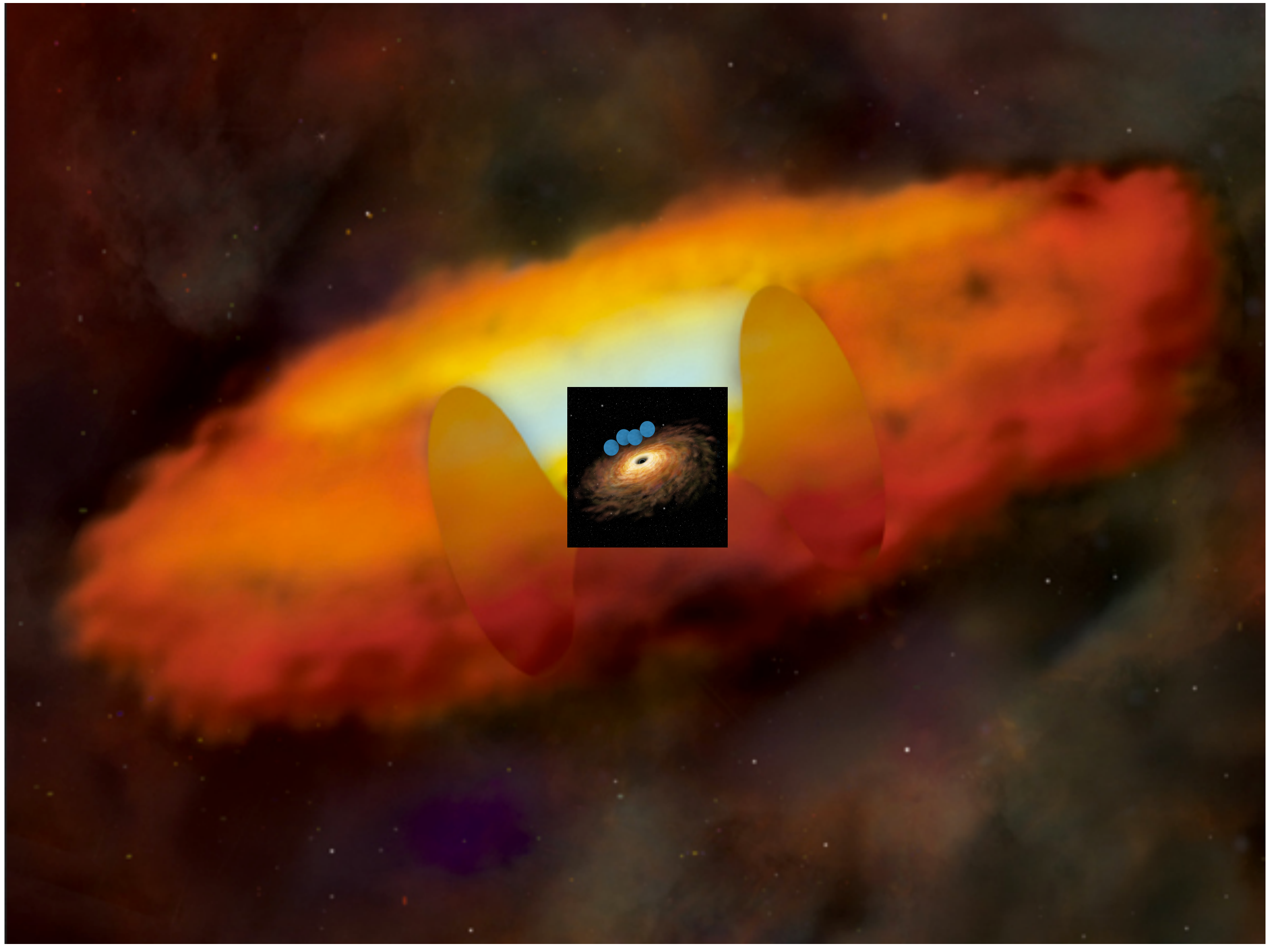


Kozlowski et al. 2013
spectroscopy of OGLE quasars

Active galaxies: accretion disks



Active galaxies: accretion disks and dusty torii

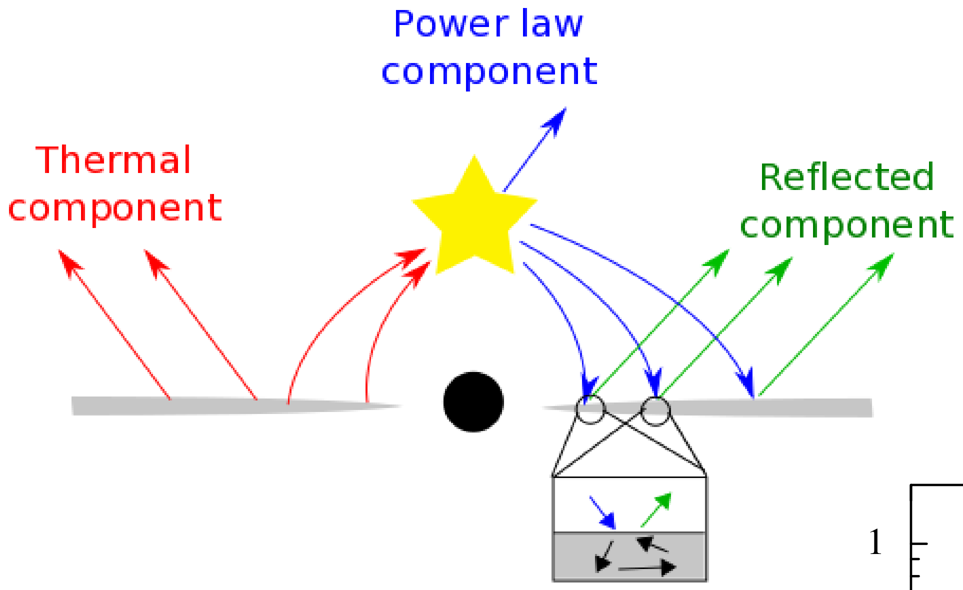


dusty torii in type 2 AGN may completely obscure central engines, i.e. accretion disks and BLRs…

“Hidden” active galactic nuclei

X-ray spectroscopy

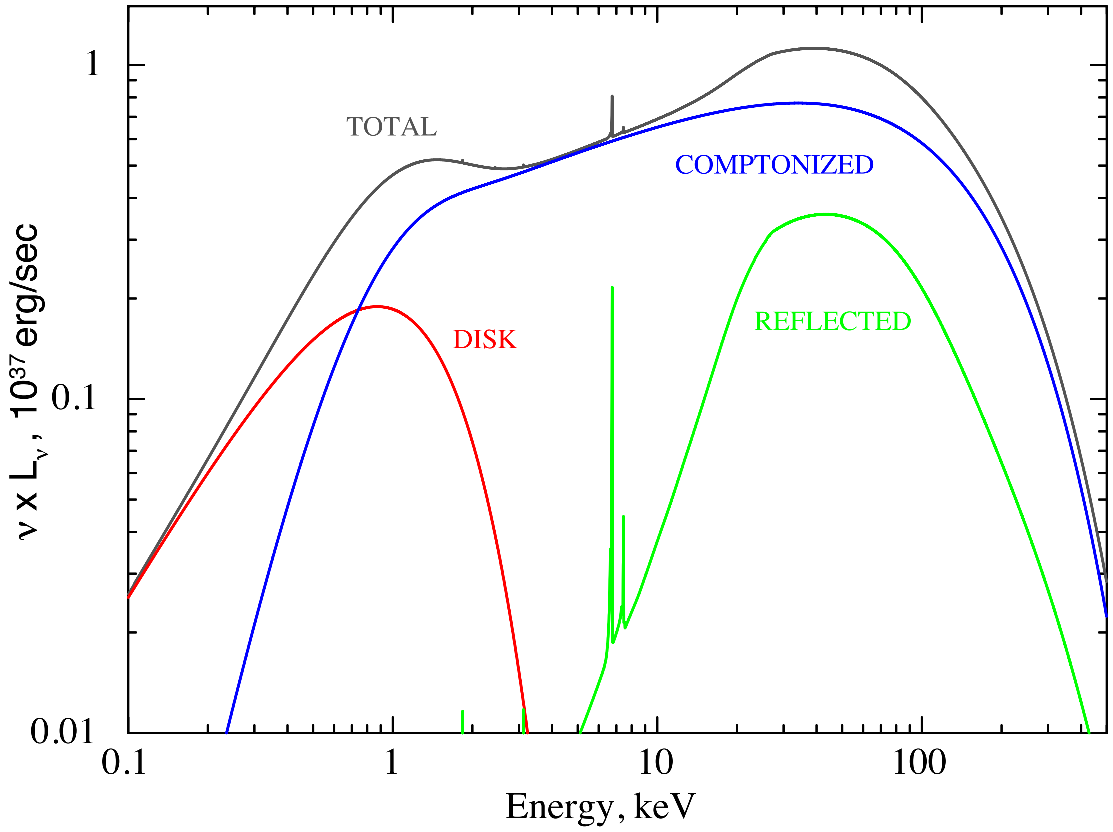
X-ray emission of accretion disk coronae



Power law component

Thermal component

Reflected component



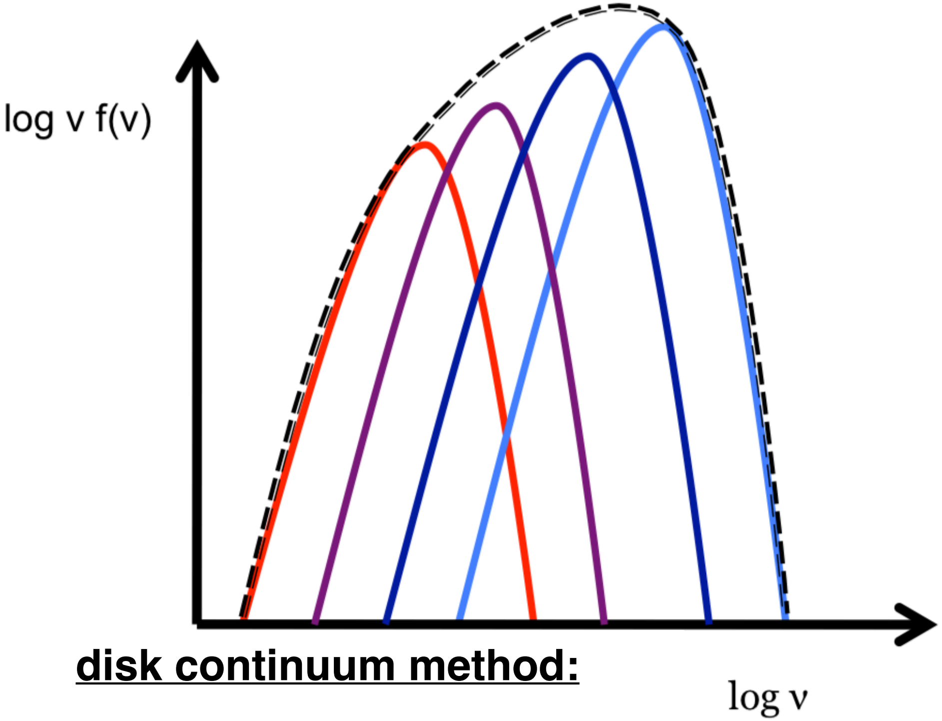
Bambi & Nampalliwar 2018

Spin measurements in BH XRBs

To date, there are three methods that have been widely applied in estimating the spins of stellar-mass BHs (Remillard & McClintock 2006), namely,

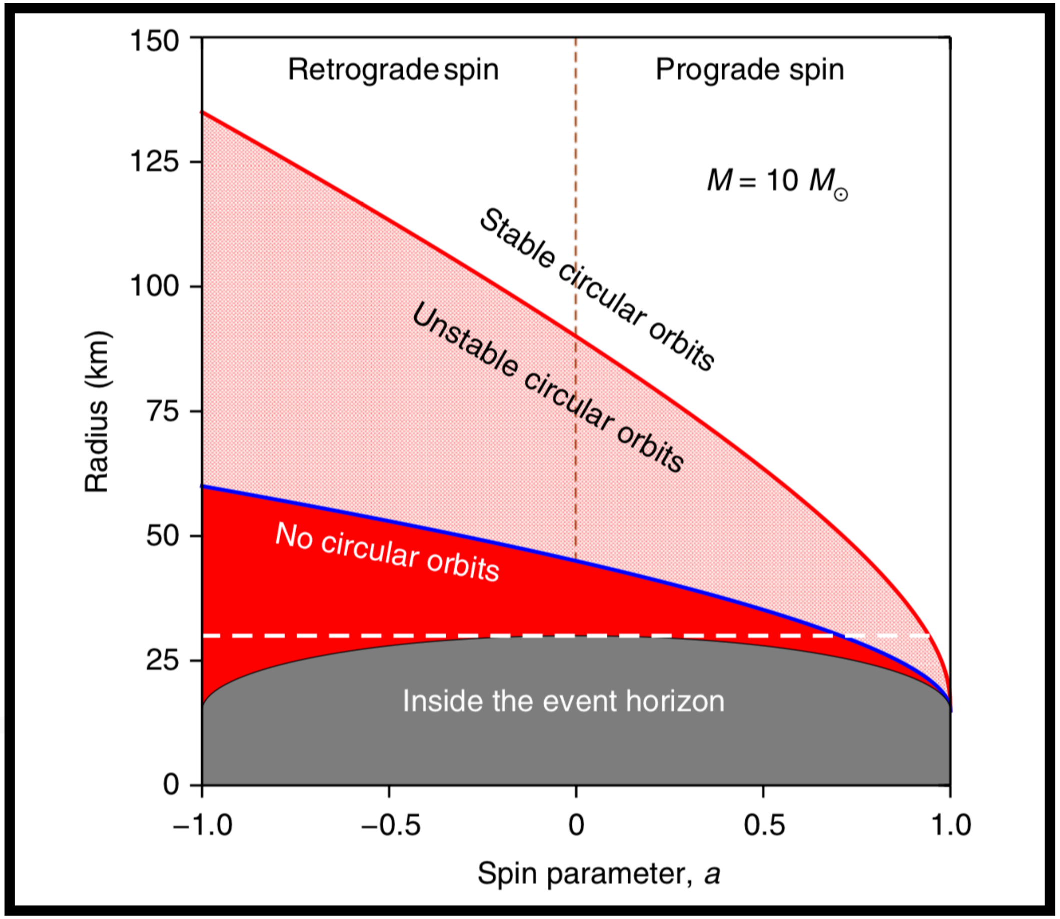
- **fitting the thermal continuum spectrum of the accretion disk,**
- **modeling the disk reflection spectrum with a focus on the Fe K line, and**
- **modeling high-frequency (~100–450 Hz) quasi-periodic oscillations (HFQPOs).**

While there are well-established models underpinning the first two methods, there is no agreed upon, or even leading, model of HFQPOs. Many classes of models have been proposed including several types of resonance models; global oscillation (“disko- seismic”) modes of the accretion disk; orbiting hot spots; tidal disruption of large inhomogeneities in the accretion flow; and the “relativistic precession” model.

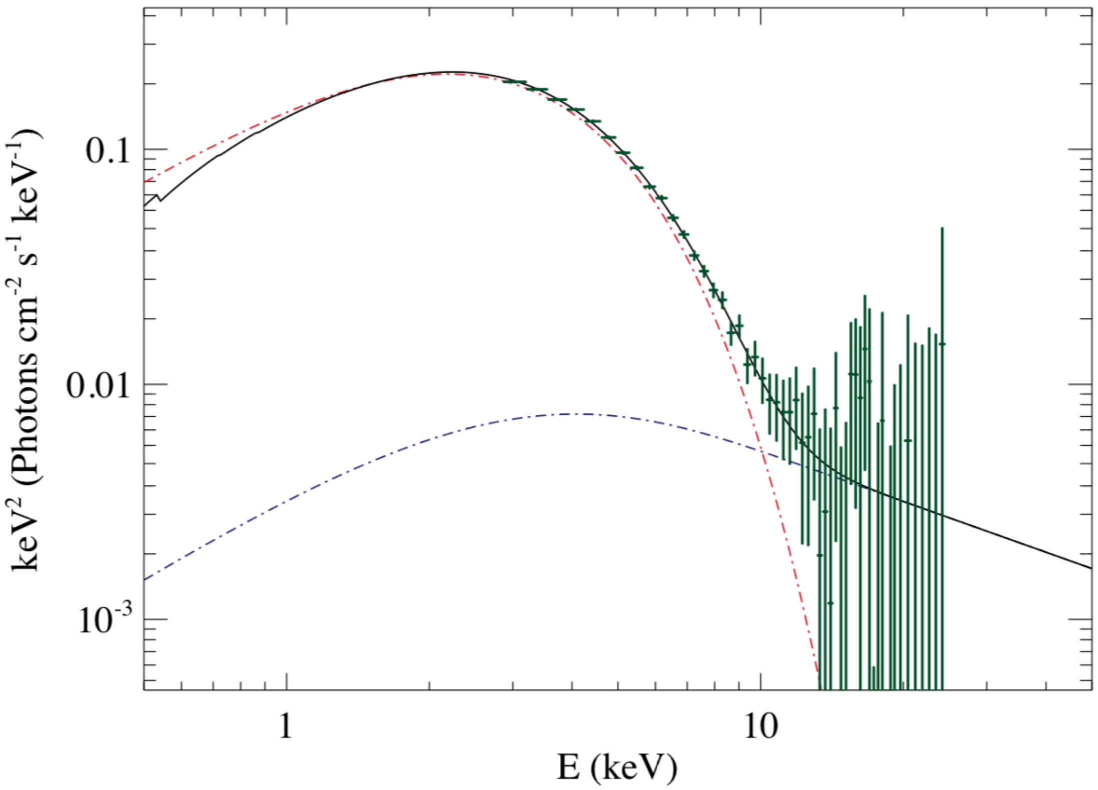


disk continuum method:

disk temperature depends on the radius, while at the same time the innermost stable circular orbit is a function of the BH spin: r_{isco} ~$6r_g$ for a=0, and ~r_g for a=1

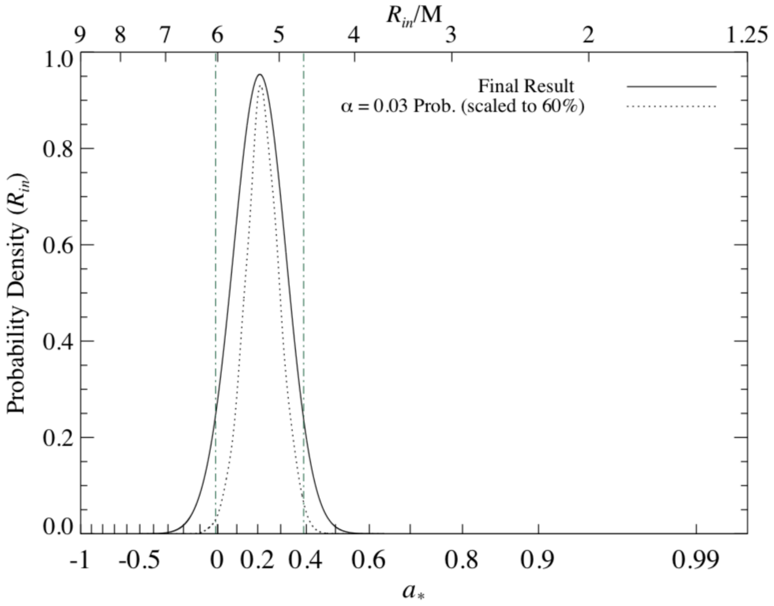


Reynolds 2019



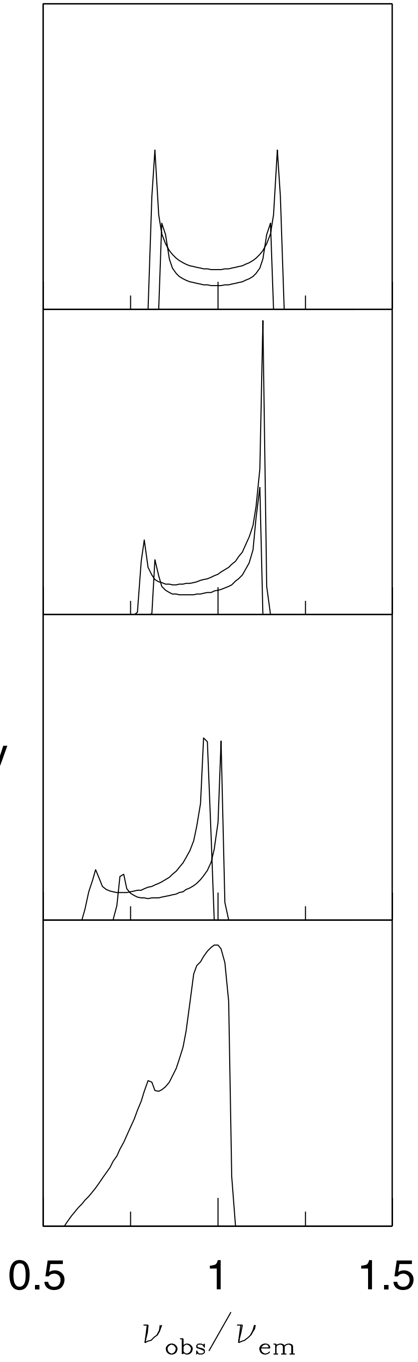
LMC X–3

Steiner et al. 2014



Method not applicable to AGN, as the BH mass estimates for AGN are much less accurate, and also the AGN disk continuum peaks at UV frequencies which are hardly accessible observationally

Fe: one of the most abundant heavy elements in the Universe, characterized in addition by a particularly high fluorescent yield (i.e. the probability that a photoelectric absorption event is followed by fluorescent line emission); the fluorescent line at ~6keV energies accessible for currently operating X-ray telescopes.



Newtonian

Special relativity

Transverse Doppler shift

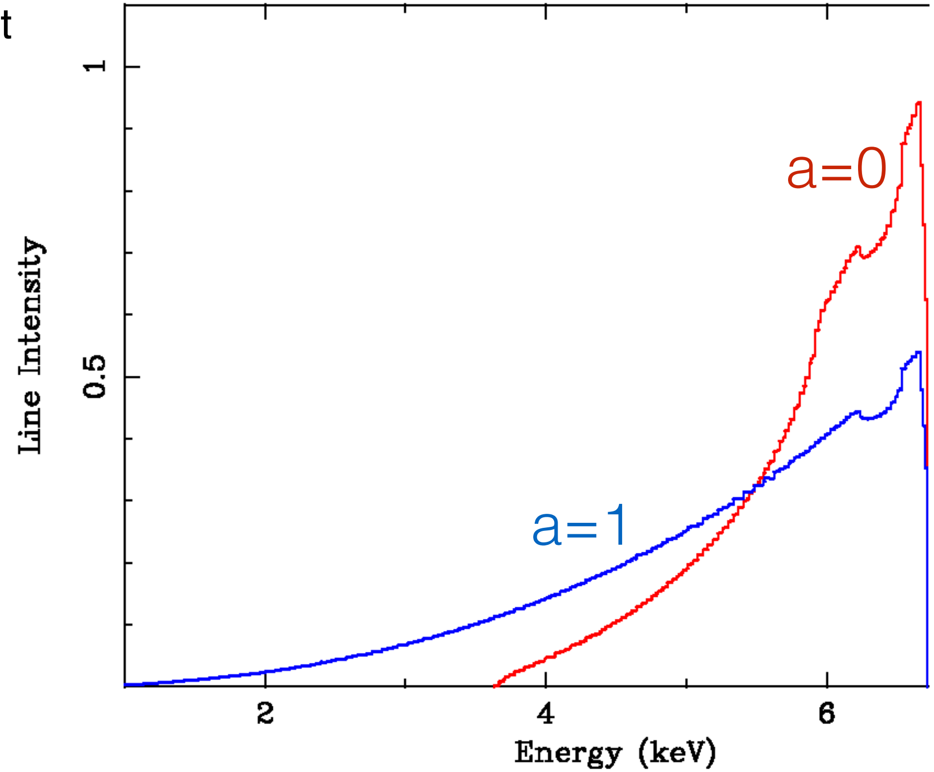
Beaming

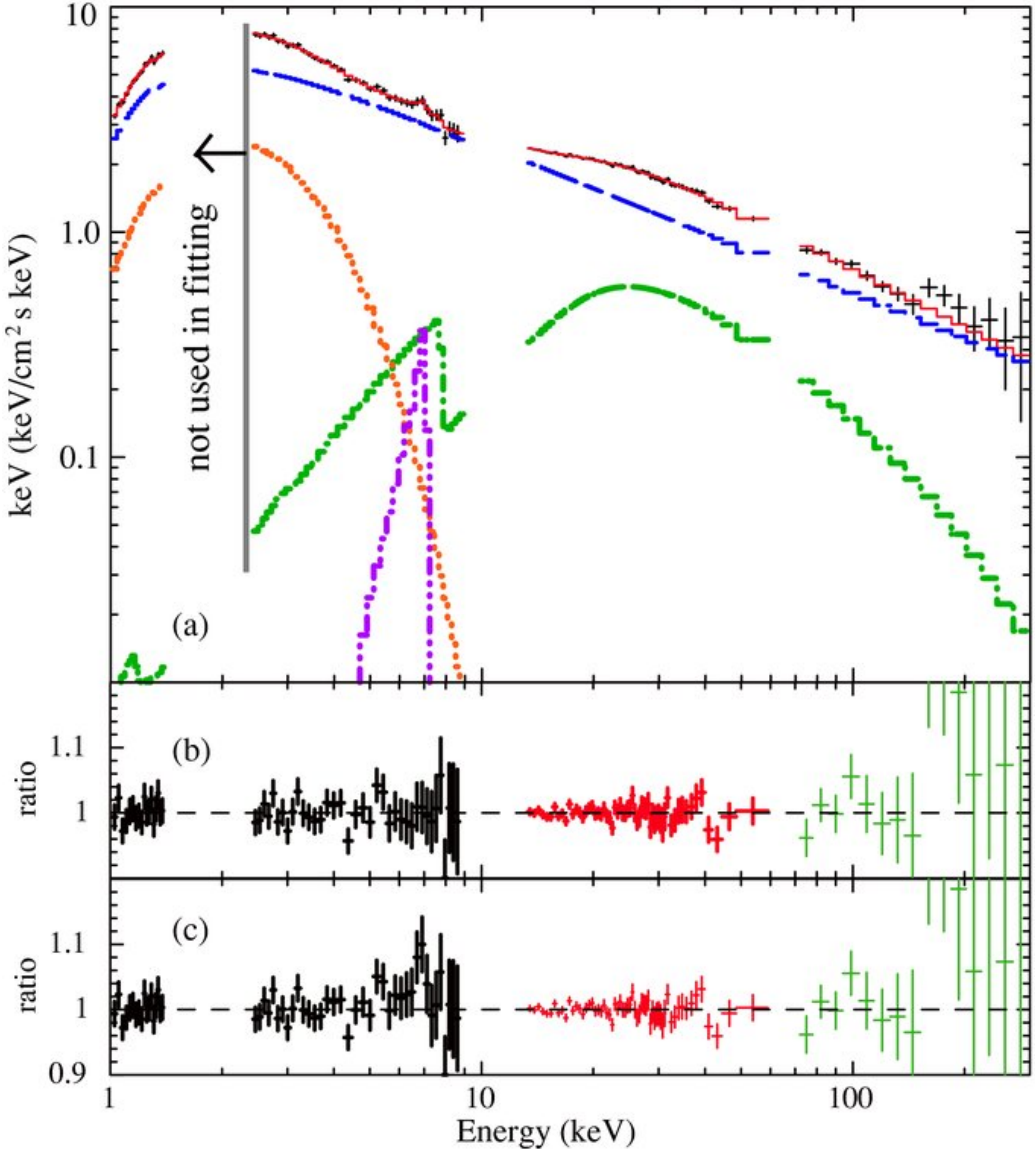
General relativity

Gravitational redshift

Line profile

Fabian 2013

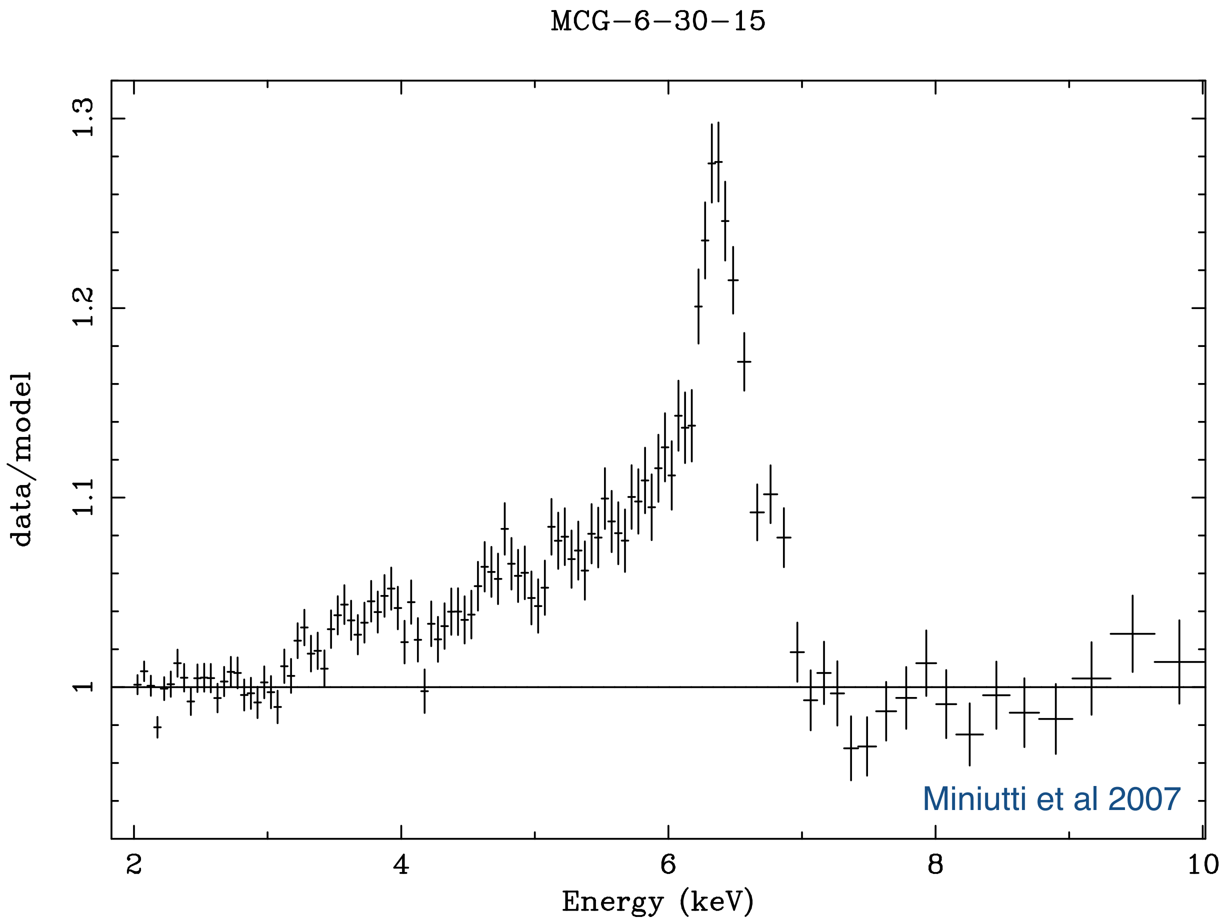




GX 339–4
Yamada et al. 2009

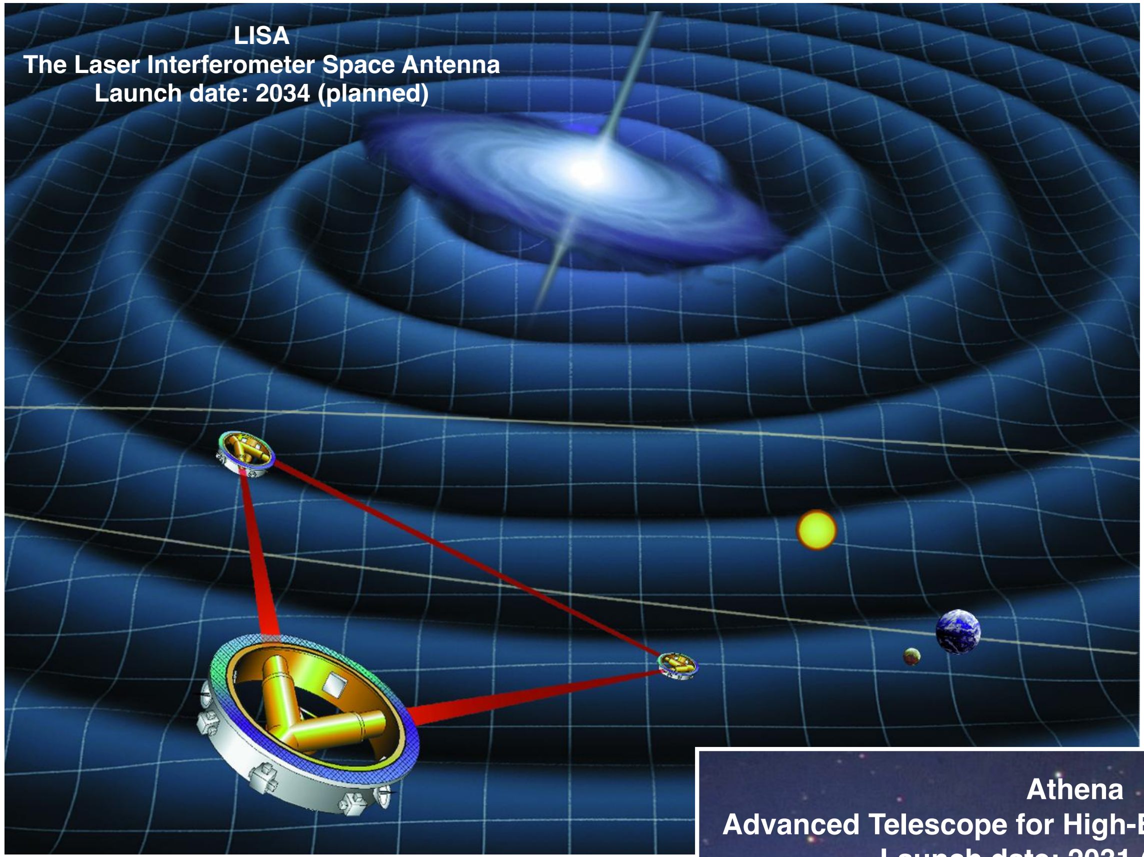
BH Binary	a_* (Continuum)	a_* (Iron)
GRS 1915+105	> 0.98	0.98 ± 0.01
Cygnus X-1	> 0.98	> 0.95
GS 1354-645	–	> 0.98
MAXI J1535-571	—	> 0.98
Swift J1658.2	—	> 0.96
LMC X-1	0.92 ± 0.06	$0.97^{+0.02}_{-0.25}$
GX 339-4	< 0.9	0.95 ± 0.03
XTE J1752-223	—	0.92 ± 0.06
MAXI J1836-194	—	0.88 ± 0.03
M33 X-7	0.84 ± 0.05	—
4U 1543-47	$0.80 \pm 0.10^{\star}$	—
IC10 X-1	$\gtrsim 0.7$	—
Swift J1753.5	—	$0.76^{+0.11}_{-0.15}$
XTE J1650-500	—	$0.84 \sim 0.98$
GRO J1655-40	$0.70 \pm 0.10^{\star}$	> 0.9
GS 1124-683	$0.63^{+0.16}_{-0.19}$	—
XTE J1652-453	—	< 0.5
XTE J1550-564	0.34 ± 0.28	$0.55^{+0.15}_{-0.22}$
LMC X-3	0.25 ± 0.15	—
H1743-322	0.2 ± 0.3	—
A0620-00	0.12 ± 0.19	—
XMMU J004243.6	< -0.2	—

AGN



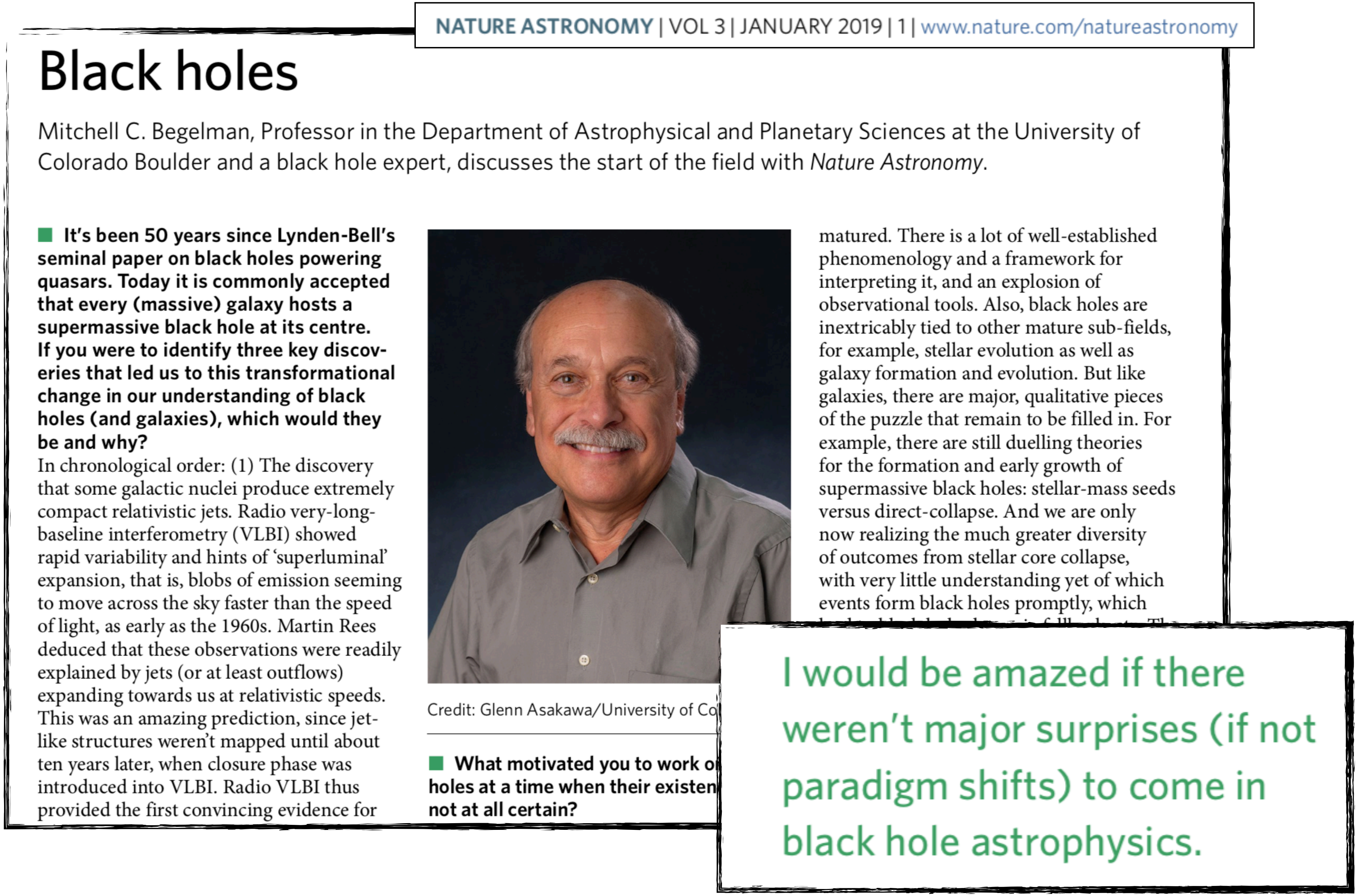
Object	a_* (Iron)
IRAS 13224-3809	> 0.99
Mrk 110	> 0.99
NGC 4051	> 0.99
1H0707-495	> 0.98
RBS 1124	> 0.98
NGC 3783	> 0.98
NGC 1365	$0.97^{+0.01}_{-0.04}$
Swift J0501-3239	> 0.96
PDS 456	> 0.96
Ark 564	$0.96^{+0.01}_{-0.06}$
3C120	> 0.95
Mrk 79	> 0.95
NGC 5506	$0.93^{+0.04}_{-0.04}$
MCG-6-30-15	$0.91^{+0.06}_{-0.07}$
Ton S180	$0.91^{+0.02}_{-0.09}$
1H0419-577	> 0.88
IRAS 00521-7054	> 0.84
Mrk 335	$0.83^{+0.10}_{-0.13}$
Ark 120	$0.81^{+0.10}_{-0.18}$
Swift J2127+5654	$0.6^{+0.2}_{-0.2}$
Mrk 841	> 0.56
Fairall 9	$0.52^{+0.19}_{-0.15}$

FUTURE



LISA
The Laser Interferometer Space Antenna
Launch date: 2034 (planned)

Athena
Advanced Telescope for High-ENergy Astrophysics
Launch date: 2031 (planned)



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Black holes

Mitchell C. Begelman, Professor in the Department of Astrophysical and Planetary Sciences at the University of Colorado Boulder and a black hole expert, discusses the start of the field with *Nature Astronomy*.

■ It's been 50 years since Lynden-Bell's seminal paper on black holes powering quasars. Today it is commonly accepted that every (massive) galaxy hosts a supermassive black hole at its centre. If you were to identify three key discoveries that led us to this transformational change in our understanding of black holes (and galaxies), which would they be and why?

In chronological order: (1) The discovery that some galactic nuclei produce extremely compact relativistic jets. Radio very-long-baseline interferometry (VLBI) showed rapid variability and hints of 'superluminal' expansion, that is, blobs of emission seeming to move across the sky faster than the speed of light, as early as the 1960s. Martin Rees deduced that these observations were readily explained by jets (or at least outflows) expanding towards us at relativistic speeds. This was an amazing prediction, since jet-like structures weren't mapped until about ten years later, when closure phase was introduced into VLBI. Radio VLBI thus provided the first convincing evidence for

Credit: Glenn Asakawa/University of Co

■ What motivated you to work o holes at a time when their existen not at all certain?

matured. There is a lot of well-established phenomenology and a framework for interpreting it, and an explosion of observational tools. Also, black holes are inextricably tied to other mature sub-fields, for example, stellar evolution as well as galaxy formation and evolution. But like galaxies, there are major, qualitative pieces of the puzzle that remain to be filled in. For example, there are still duelling theories for the formation and early growth of supermassive black holes: stellar-mass seeds versus direct-collapse. And we are only now realizing the much greater diversity of outcomes from stellar core collapse, with very little understanding yet of which events form black holes promptly, which

I would be amazed if there weren't major surprises (if not paradigm shifts) to come in black hole astrophysics.