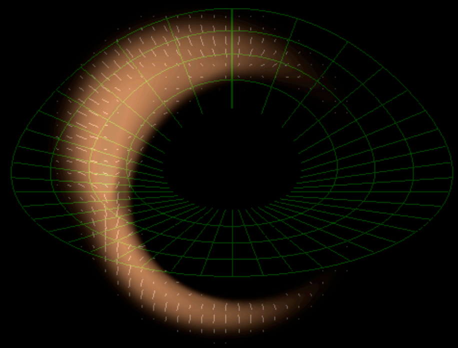
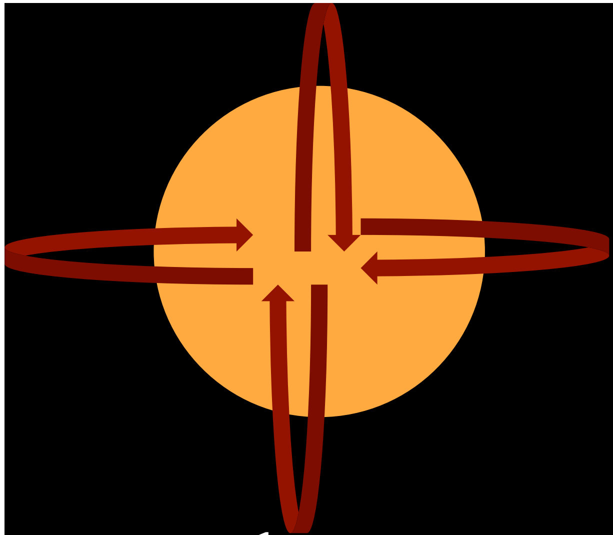
Lecture III: *A Closer Look at Black Holes*

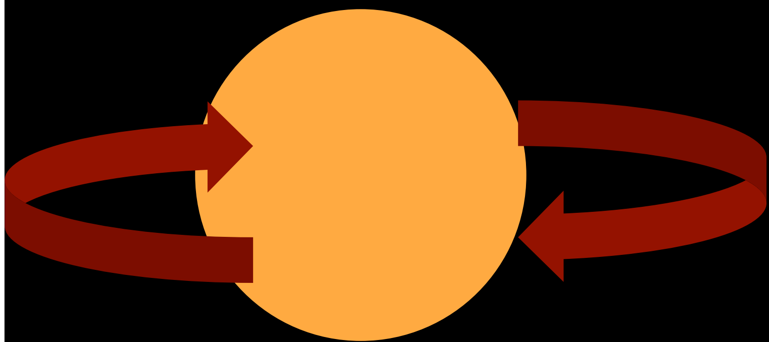


- Imaging black hole silhouettes
- Gravitational waves from black hole binaries
- Recoil of black holes
- Tidal disruption of stars by black holes



Spherical Collapse of dark matter and gas

Why are there galaxies and not just black holes in the Universe?



Tidal torque from neighboring objects near turnaround: angular momentum

$$\lambda \sim \frac{v_\perp}{\sigma} \sim 5\%$$

$$j = v_\perp r = const \Longrightarrow r_{\rm disk}/r_{\rm vir} \sim 5\%$$

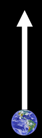
What is a black hole?

The ultimate prison. Even light cannot escape from its gravitational pull!

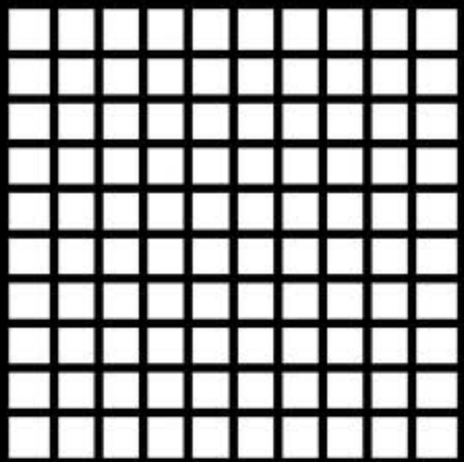
escape speed = 11 km/s

Compress the Earth to ~1cm

escape speed = 300,000 km/s = speed of light



space-time

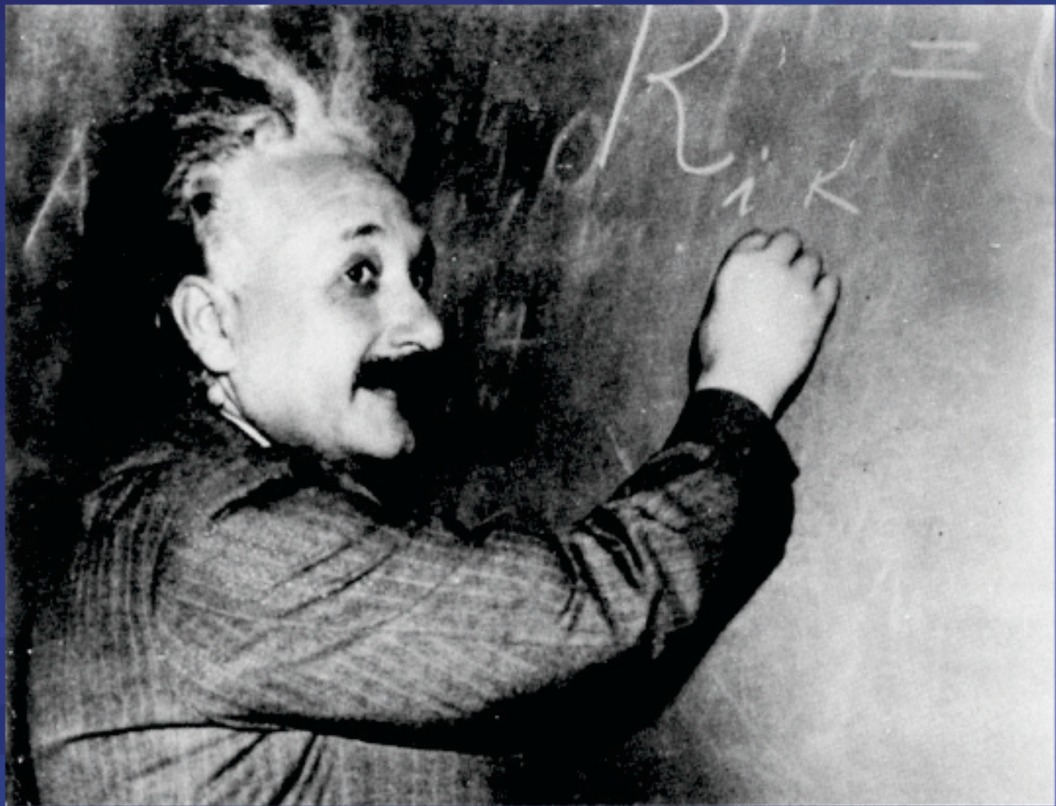


c=const

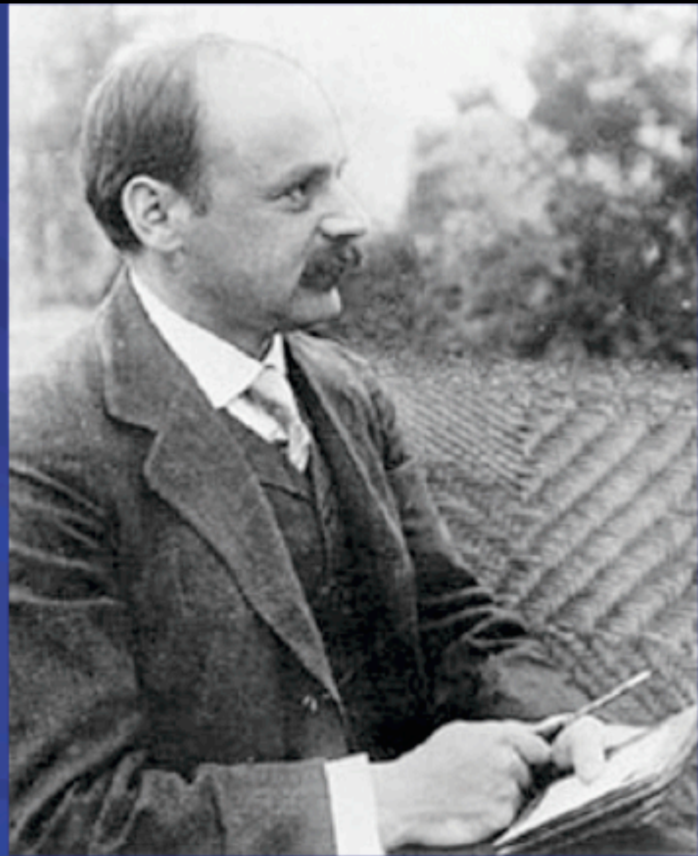
$x = c\,t$

Equivalence Principle (Galileo, Pisa)

- General relativity: matter curves spacetime
  Einstein's equations: [Matter] = [Curvature]
- Time-dependent quadrupole -> ripples in spacetime
  (gravitational waves)
- Black hole: Schwarzschild's letter in WWI



Albert Einstein



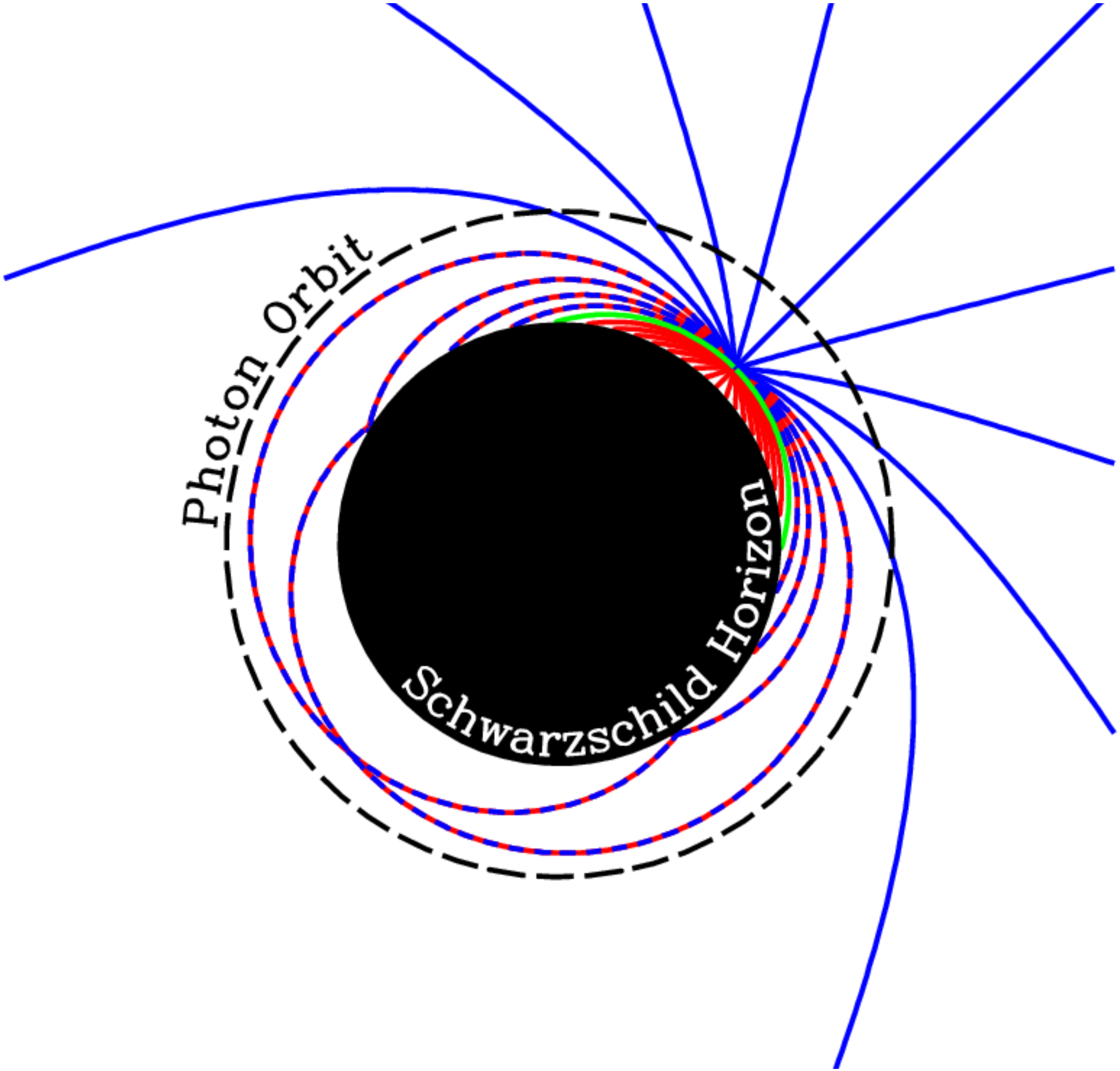
Karl Schwarzschild

How does a black hole look like?

Image of a black hole in vacuum

For a non-spinning black hole: Schwarzschild radius:

$$r_{\mathrm{Sch}} = \frac{2GM}{c^2}$$

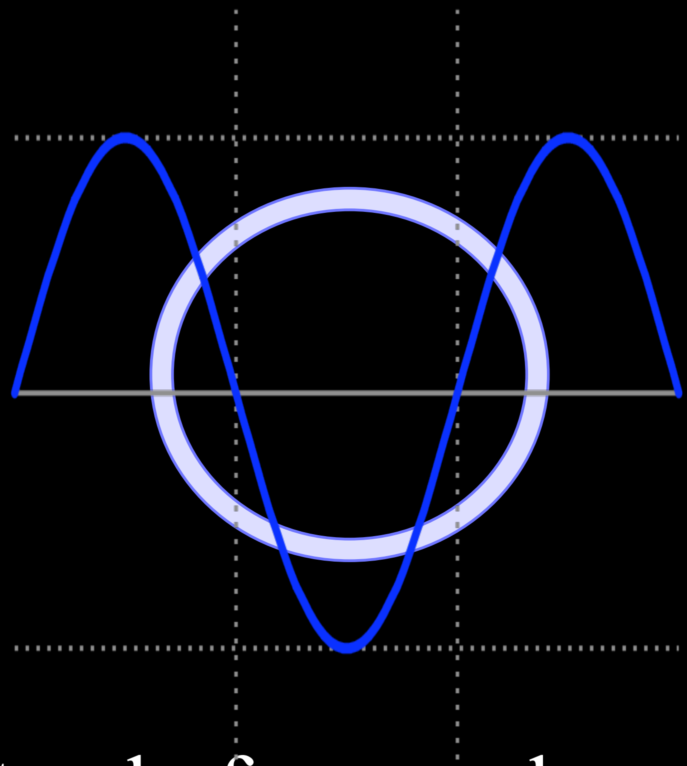


Photon Orbit
Schwarzschild Horizon

No hair Theorem: *a black hole is characterized by three numbers: its mass, spin, and charge* (N/A)

Cosmic censorship: *every singularity is surrounded by an event horizon (which protects the outside world from its influence)*

Quantum Mechanics



- Important only for wavelengths comparable to horizon size (Hawking radiation)
- Negligible importance outside the horizon of astrophysical black holes

Portrait of a BLACK HOLE

By Avery E. Broderick and Abraham Loeb

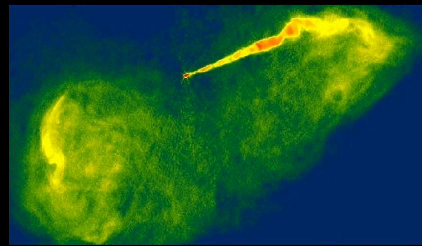
Imaging Black Holes

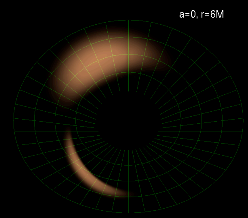
- **<u>Testing theory of gas accretion:</u>**

  disks, jets

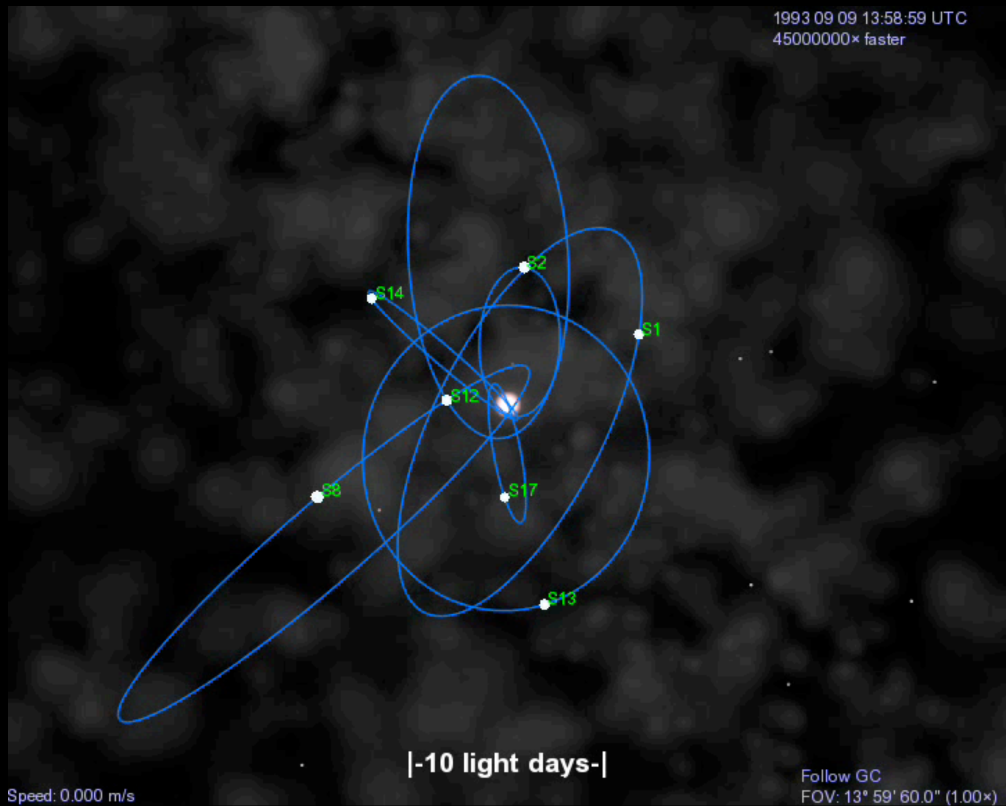
- **<u>Testing General Relativity:</u>**

  strong field gravity





Stellar Orbits Around SgrA*



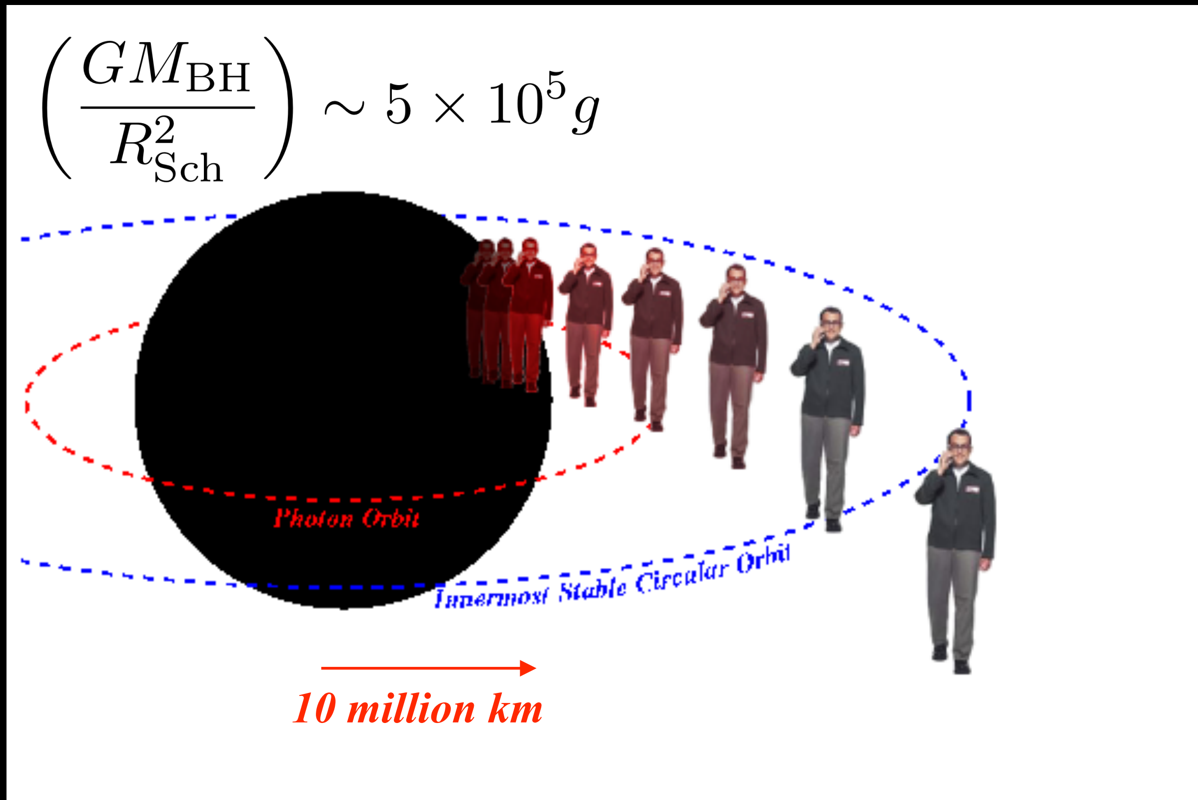
$$M_{\rm BH} = (4.5 \pm 0.4) \times 10^6 M_\odot$$

$$d_{\rm GC} = 8.4 \pm 0.4 {\rm kpc}$$ *(BH at rest in GC)*

Ghez et al. 2008; Genzel et al. 2008

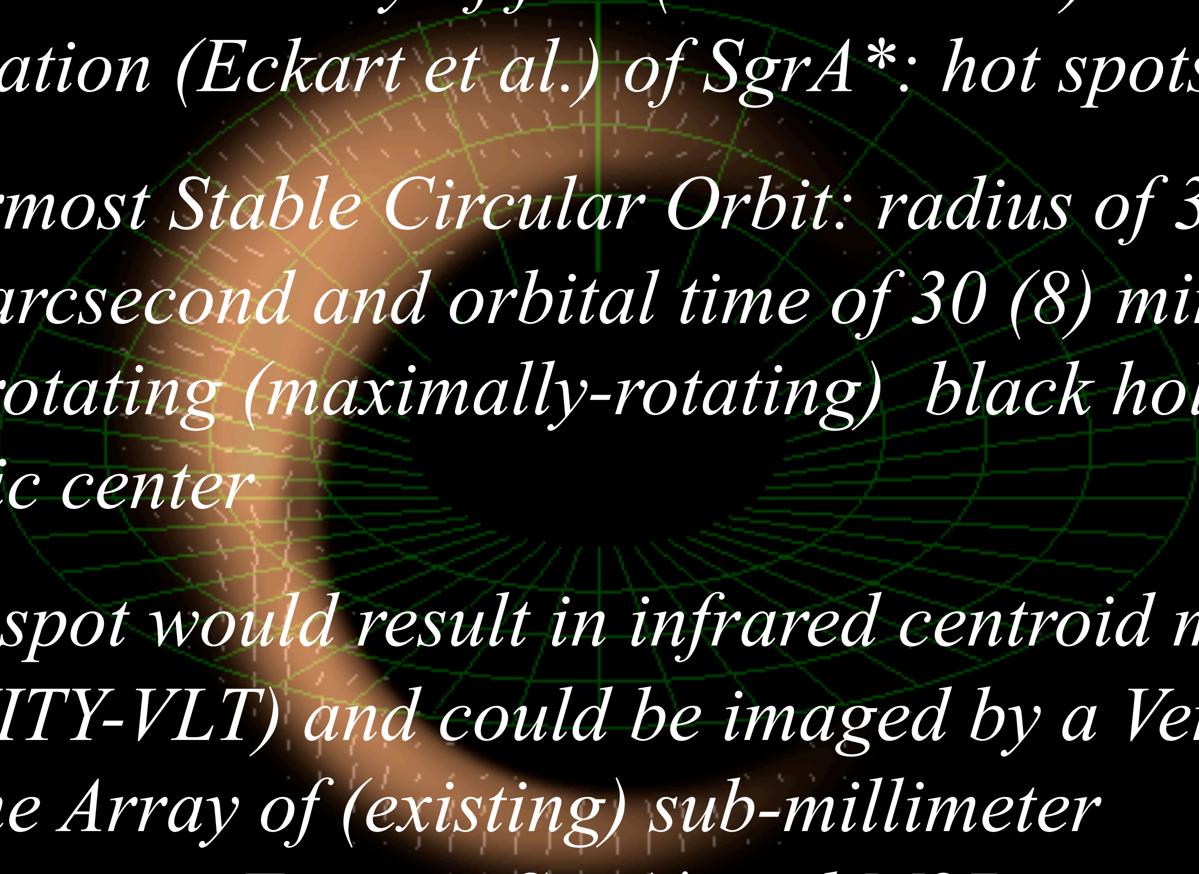
SgrA* is the largest black hole on the sky

Can you hear me now?



No, but no worries - you will be able to hear us for ~10 minutes until you reach the singularity…

Is general relativity a valid description of strong gravity?



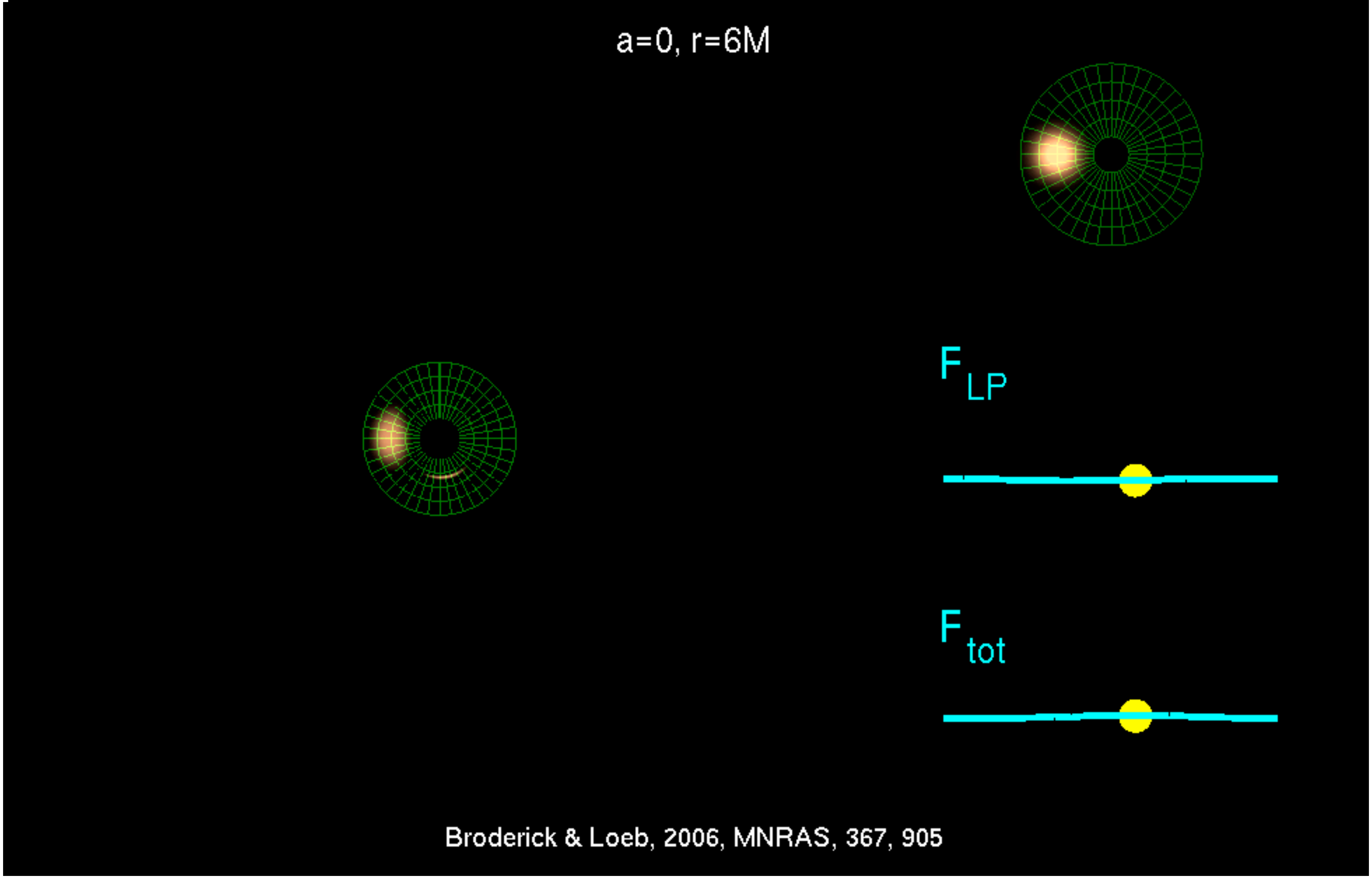
**Infrared variability of flux (Genzel et al.) and polarization (Eckart et al.) of SgrA*: hot spots.*

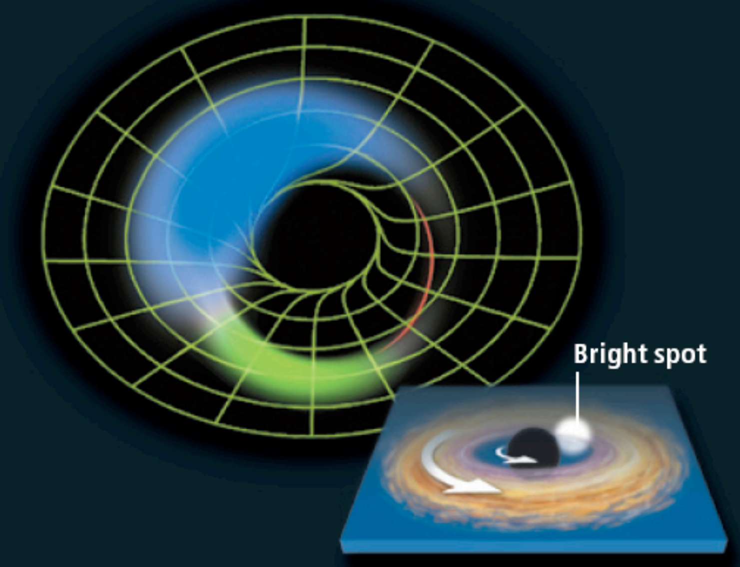
**Innermost Stable Circular Orbit: radius of 30 (10) micro-arcsecond and orbital time of 30 (8) minutes for a non-rotating (maximally-rotating) black hole at the Galactic center*

**A hot spot would result in infrared centroid motion (GRAVITY-VLT) and could be imaged by a Very Large Baseline Array of (existing) sub-millimeter observatories. Targets: SgrA* and M87*

Broderick & Loeb 2005

Physics + Astrophysics: Imaging Black Holes

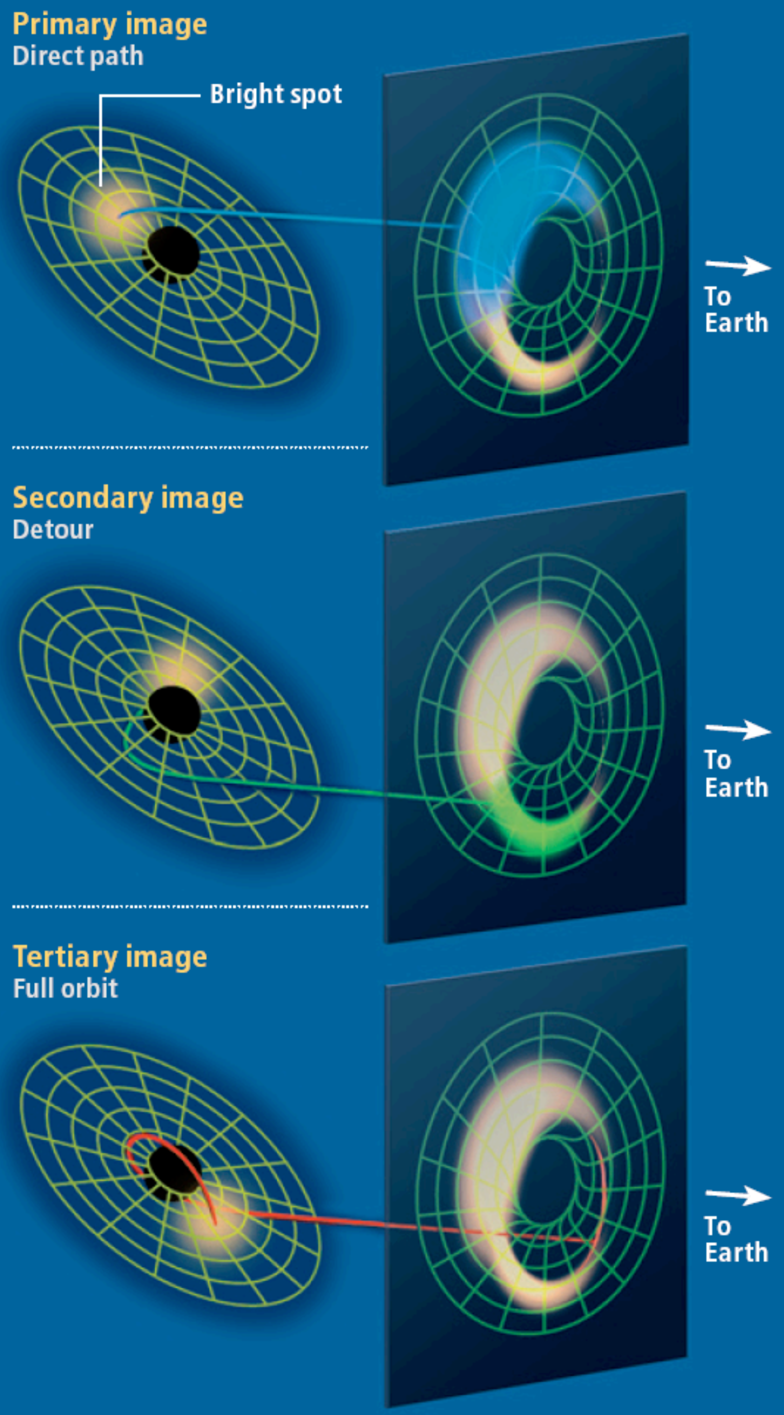


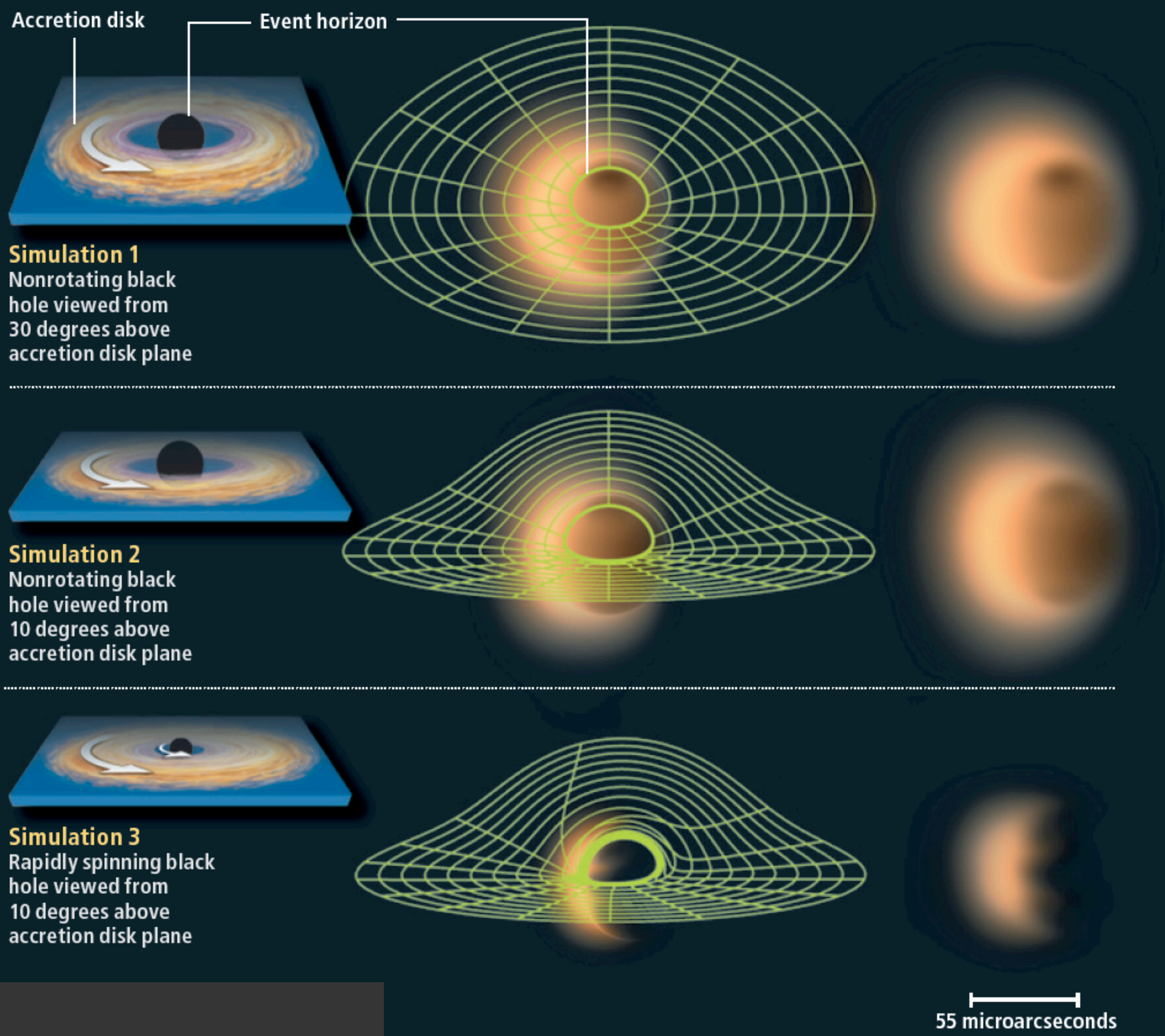


MEASURING GRAVITY WITH LENSED IMAGES

Astronomers can measure gravity very near a black hole by analyzing multiple subimages (produced by gravitational lensing) of a bright spot in an accretion disk. Shown above is a simulated image of a bright spot near a moderately rotating black hole, colored to mark its three constituent subimages, which are explained in the diagrams below.

The primary image (*blue region*) forms from radio waves that traveled from the spot along the most direct path to Earth (*blue line*). Thanks to the hole's intense gravity, some rays the spot emitted earlier take a detour around the hole (*green line*) and reach Earth at the same time, forming the secondary image (*green region*). Rays that were emitted even earlier and execute a full orbit around the black hole (*red line*) generate the barely visible tertiary image (*red region*). Because the positions and shapes of the subimages depend on how gravity bends light in a variety of locations very close to the hole, analysis of the full image can reveal if general relativity correctly describes gravity there.





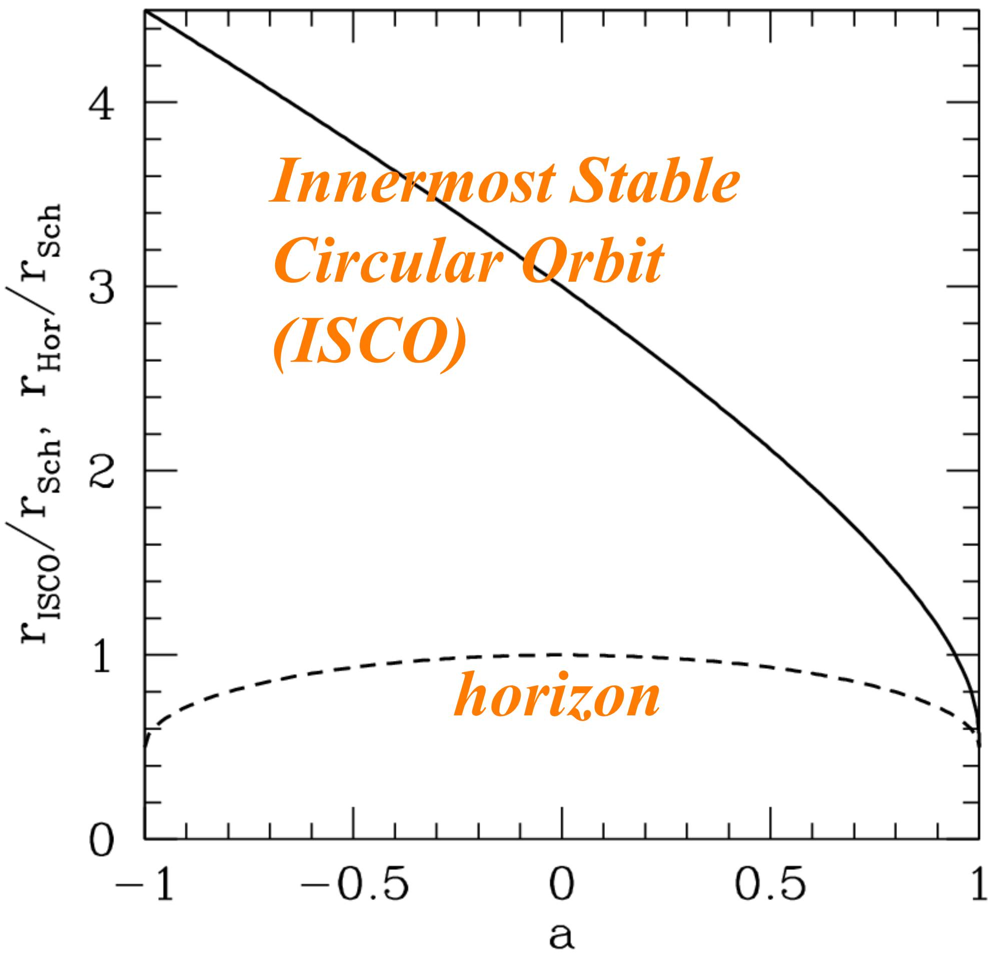
WHAT THE SILHOUETTE CAN REVEAL

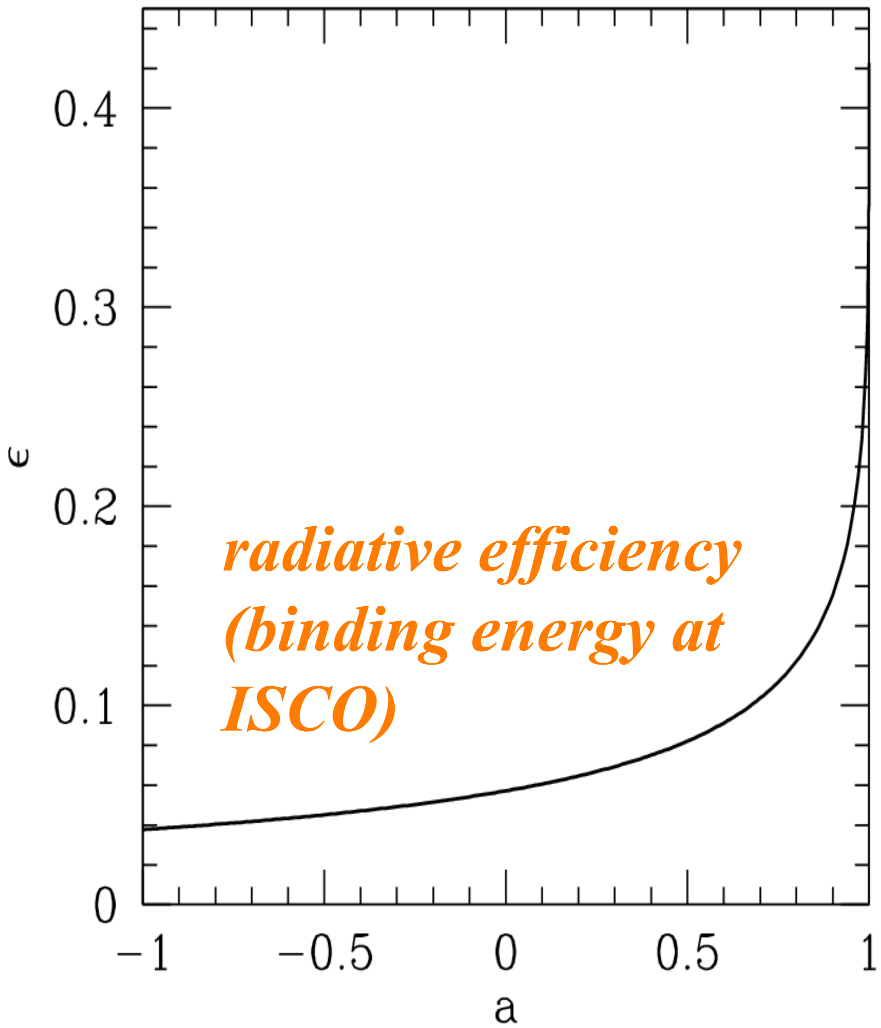
Simulations show how an accretion disk around Sgr A* would appear depending on the orientation of its accretion disk and the magnitude of its spin. The rightmost trio of images includes the blurring effects of interstellar gas.

The green coordinate grid is in the plane of the accretion disk, centered on the black hole. The grid's innermost ring is at the black hole's event horizon. Bending of light rays by the hole's gravity, known as gravitational lensing, distorts the grid's appearance and also magnifies the hole's silhouette. Because the accretion disk orbits the hole at velocities approaching the speed of light, special relativistic effects come into play, making it much brighter on the side moving toward us (*here on left side of event horizon*). In the bottom image, the black hole's large, angular momentum causes additional deflection of light, further distorting our view of the equatorial plane and dramatically changing the appearance of the accreting gas.

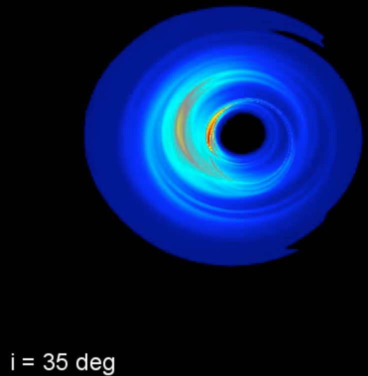
Thus, comparing images of Sgr A* with simulations can reveal the system's orientation and the black hole's spin and can also provide—from the silhouette's size—a new measurement of the hole's mass.

spin matters!

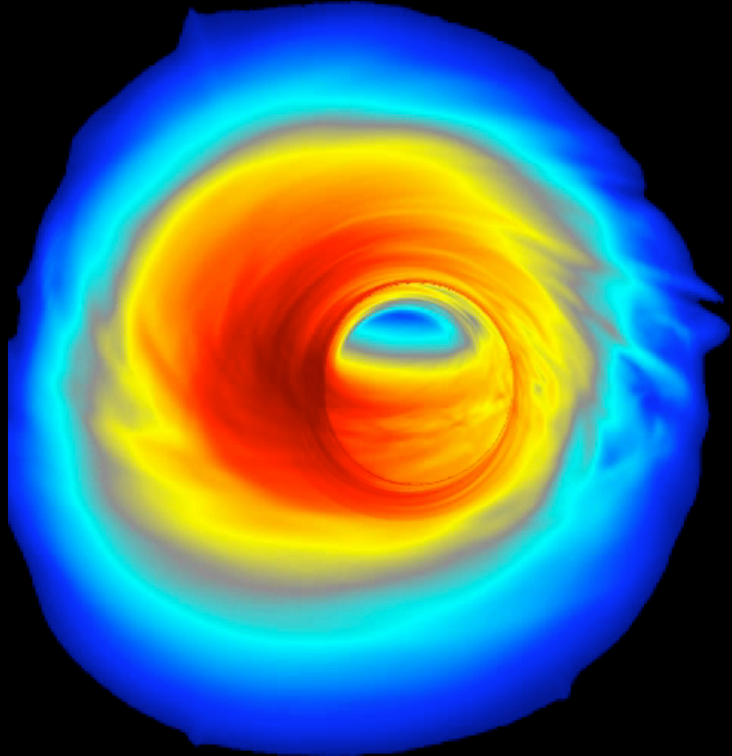


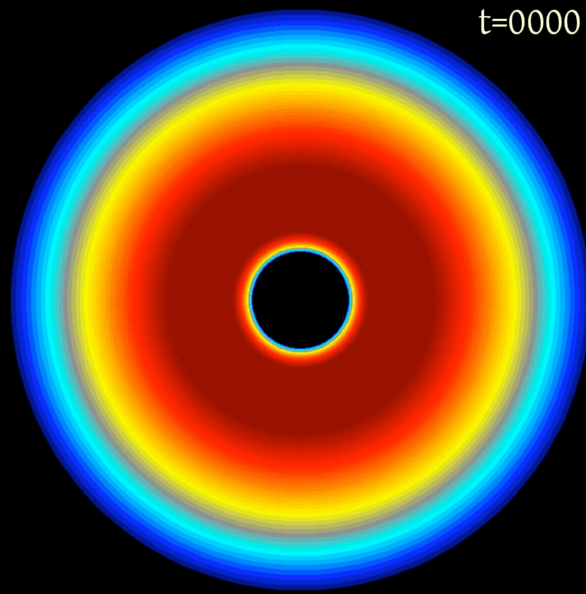


Numerical Simulations (GRMHD)

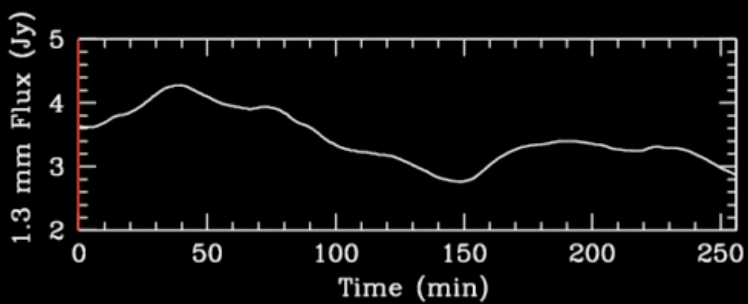


inclination





setup

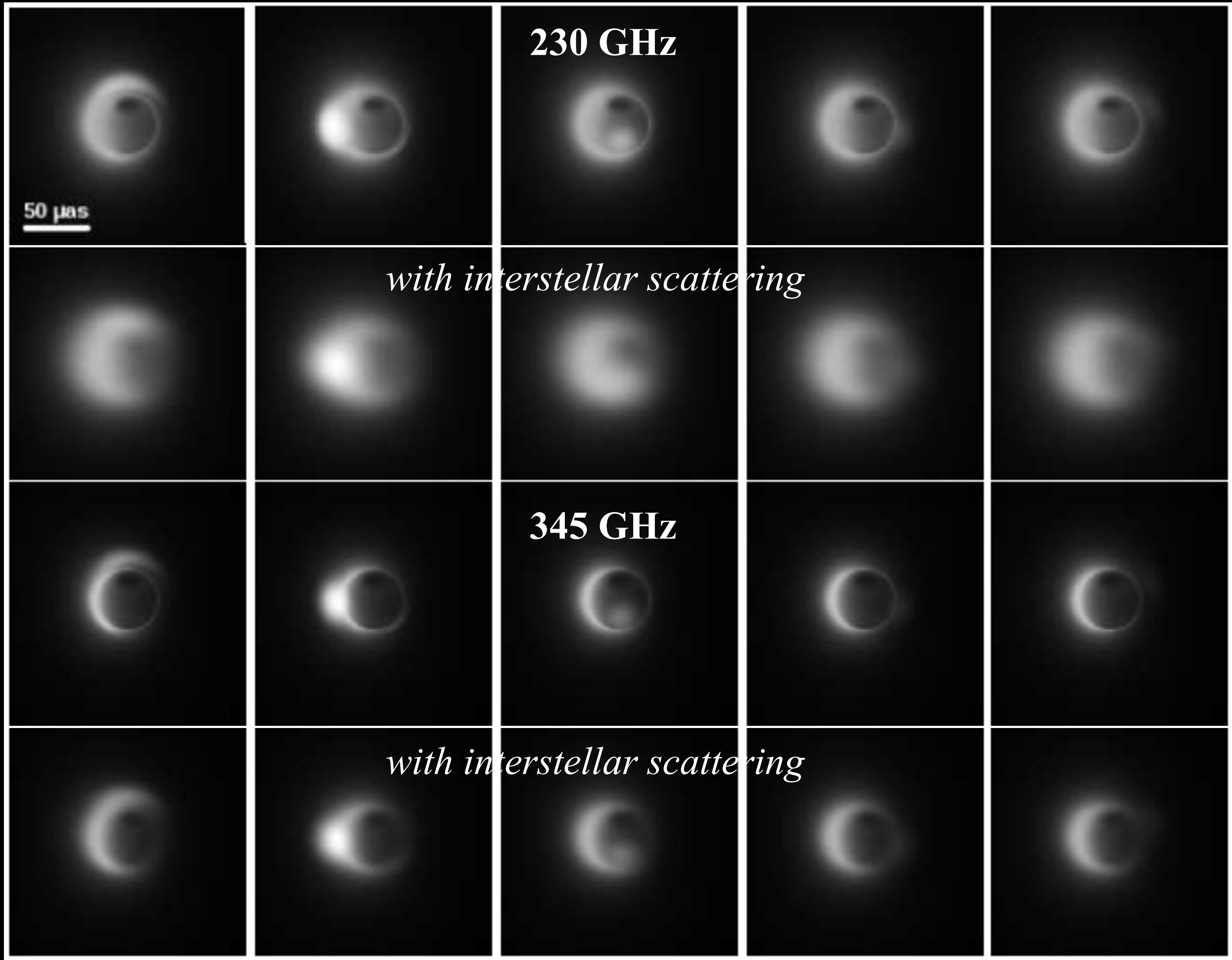


C. Gammie, J. Dolence, M. Moscibrodzka, H. Shiokawa, P. Leung (2009)

Three Fortunate Coincidences

- The accretion flow of SgrA* becomes transparent to synchrotron self-absorption *at wavelengths shorter than 1 millimeter*
- Interstellar scattering ceases to blur the image of SgrA* on horizon scales *at wavelengths shorter than 1 millimeter*
- The horizon scale of SgrA* and M87 (tens of micro-arcseconds) can be resolved by a Very Large Baseline Array across the Earth *at wavelengths shorter than 1 millimeter*

*SgrA**



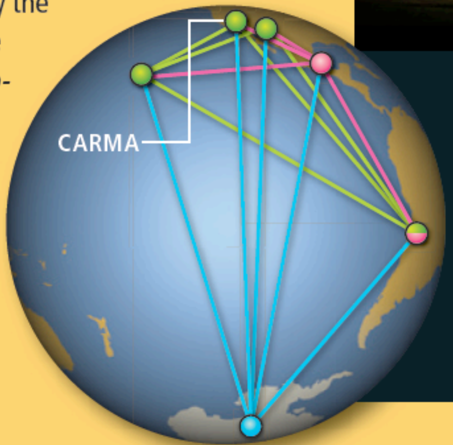
Different orbital phases of the hot spot →

[IMAGING]

Shooting the Beast

Astronomers are developing several radio telescope arrays to form a globe-spanning network of observatories (*right*) that can observe Sgr A* and its immediate surroundings at wavelengths near 0.87 and 1.3 millimeters—two "windows" that are not excessively absorbed by Earth's atmosphere or scattered by interstellar gas. The size of the network will permit observations with sufficient resolution to produce images of Sgr A*'s event horizon.

The appearance of Sgr A* should reveal information about the orientation of the black hole's accretion disk along our line of sight and how fast the black hole is spinning—two of the most basic facts to be learned about the Sgr A* system and vital for understanding whatever else is observed about it (*below*). On occasions when a bright spot flares up in the accretion disk, gravitational lensing by the black hole will form multiple subimages of the spot (*opposite page*). If these subimages can be resolved, they will provide detailed information about the gravitational field near the black hole, which will stringently test the predictions of general relativity.



COLLECTING DATA
The Combined Array for Research in Millimeter-Wave Astronomy (CARMA; *above*), located at Cedar Flat, Calif., is one of several radio telescope arrays astronomers are developing to observe Sgr A*'s event horizon. A network of such observatories (*left*) separated by baselines thousands of kilometers long (*lines*) can exploit a technique called very long baseline interferometry to produce images with resolutions as fine as those that would be possible with a radio dish the size of Earth. Four arrays (*green*) are ready to be used together, two (*pink*) are under development, and the last (*blue*) needs only to be adapted for observations at submillimeter wavelengths.

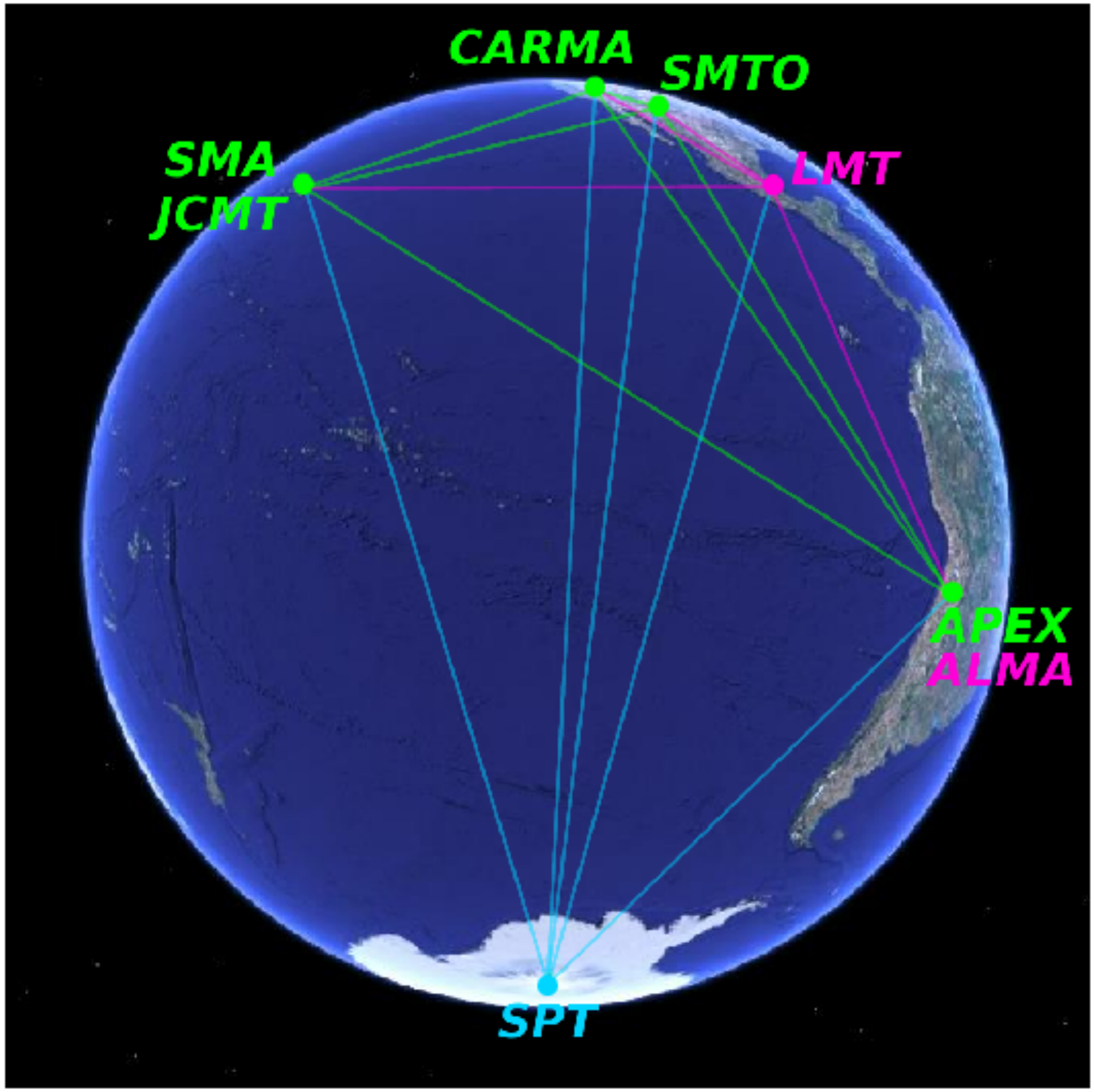
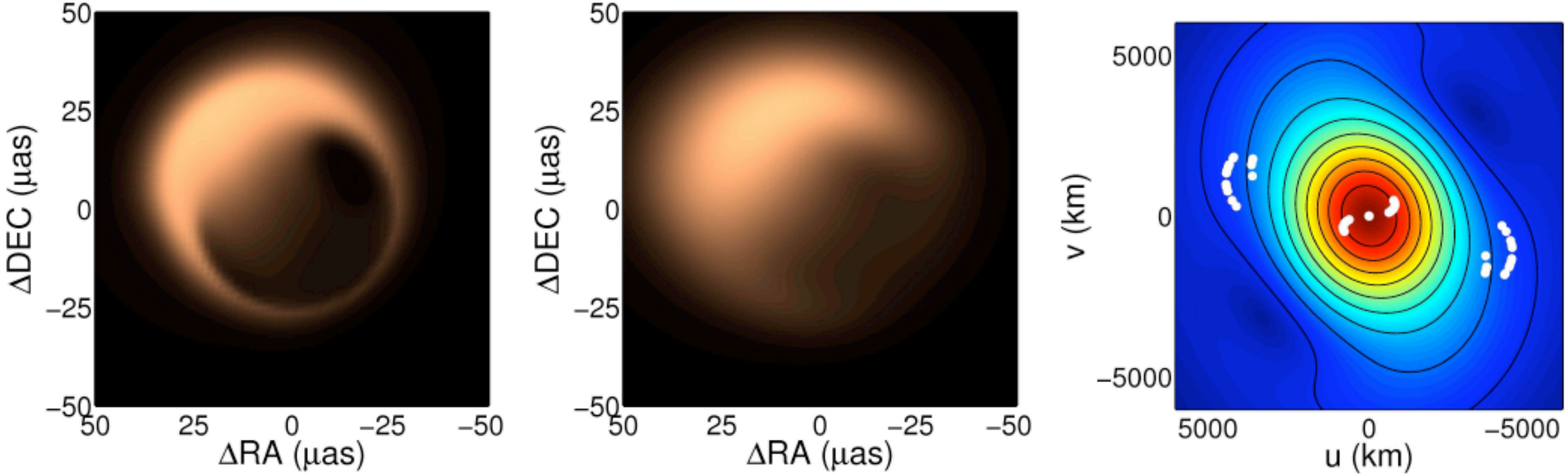
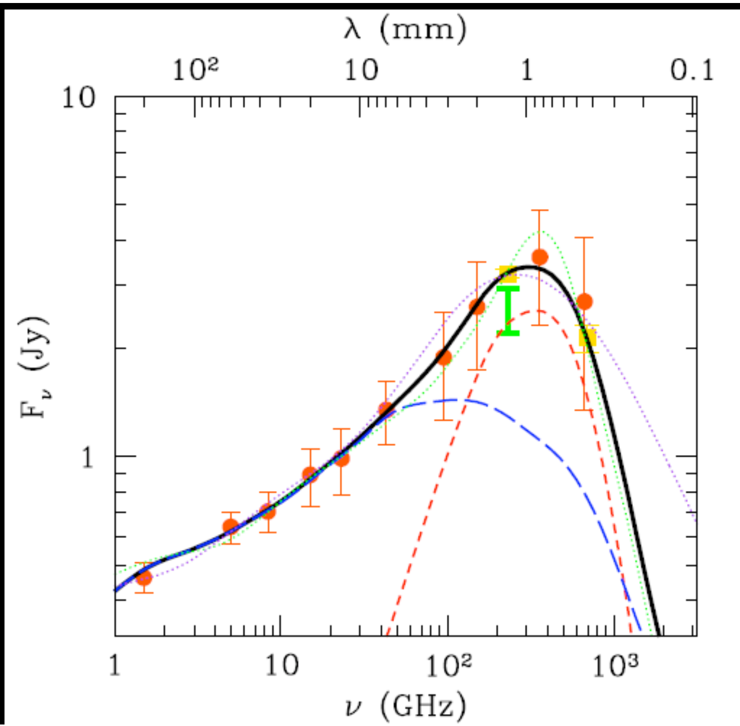


Figure 3: Existing and upcoming sub-millimeter radio telescopes in the Western hemisphere as seen from Sgr A*. Green telescopes already exist and are ready to be phased into a small array. The *Large Millimeter Telescope* (LMT) will begin operations at sub-millimeter wavelengths sometime next year. The *Atacama Large-Millimeter Array* (ALMA) is scheduled to be completed by 2012, though it will begin taking data in 2010. Already at the ALMA site, the *Atacama Pathfinder EXperiment* (APEX) is presently operating. Finally, the *South Pole Telescope* (SPT) needs only a millimeter receiver to be adapted for sub-mm VLBI. The projected baselines associated with these telescopes are shown in green for telescopes that exist, magneta for upcoming telescopes and cyan for the SPT. Note that a

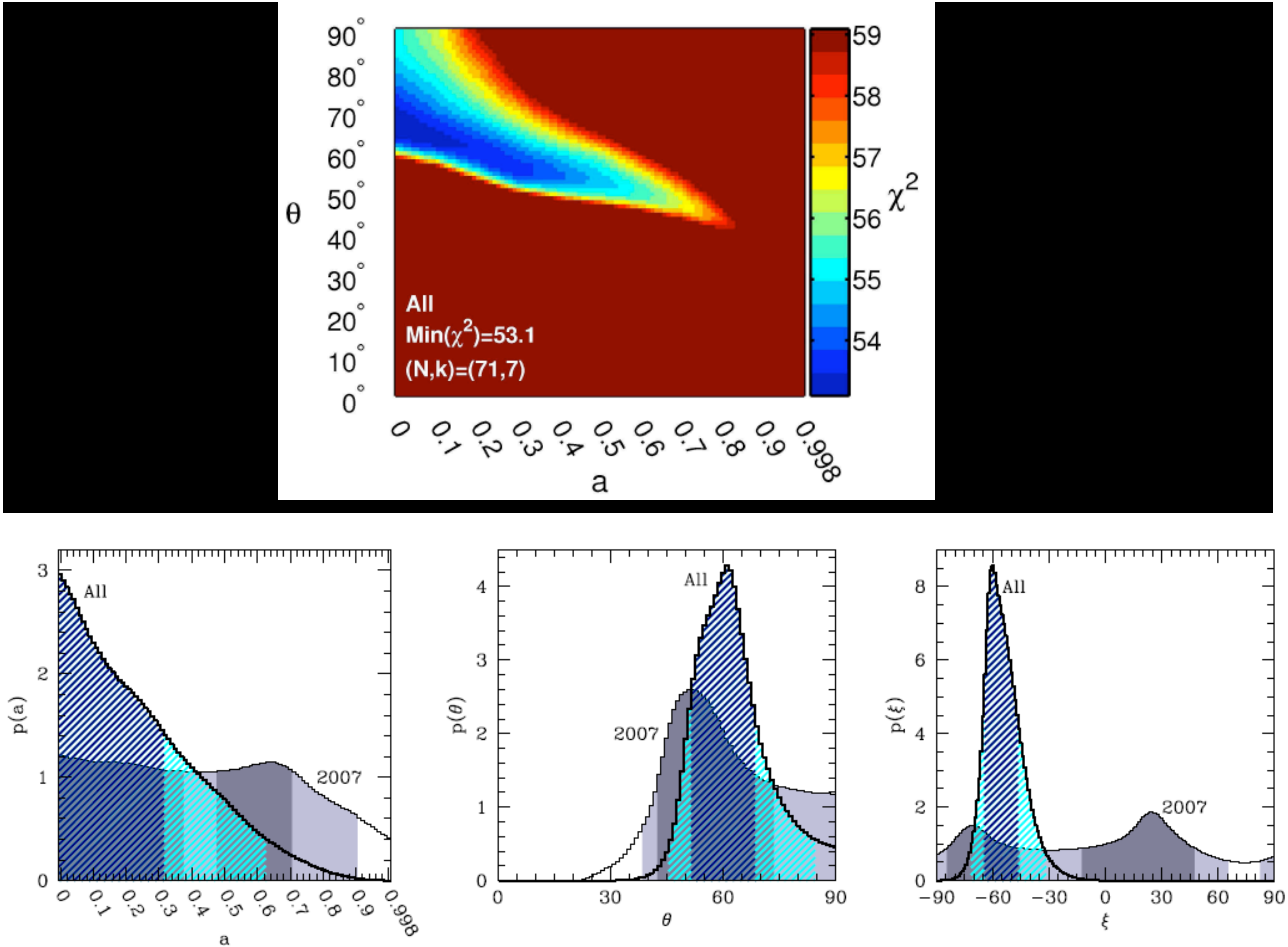
THE EVENT HORIZON TELESCOPE
2: Combined Array for Research in Millimeter wave Astronomy – California
3: Arizona Radio Observatory
1. Submillimeter Array and James Clerk Maxwell Telescope – Hawaii
2
3
1

Evidence for a Low-Spin BH in SgrA*





Broderick, Fish, Doeleman & Loeb 2010

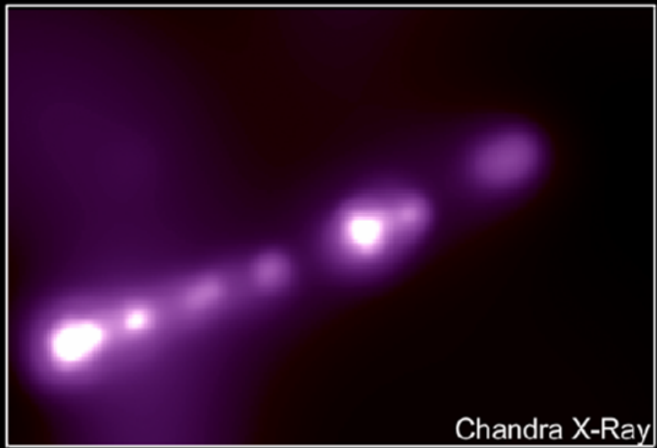


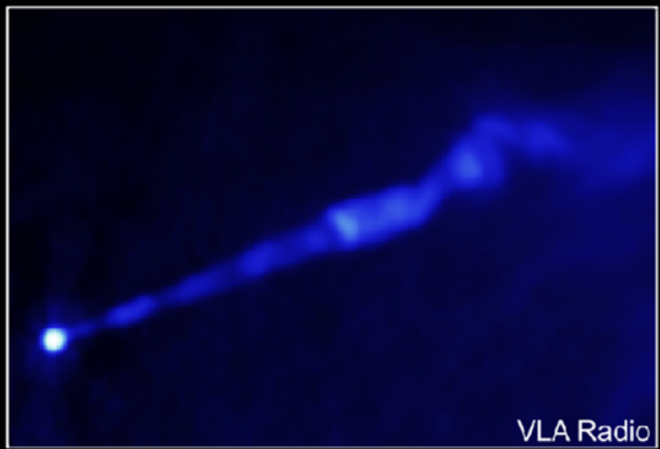
θ
90° 80° 70° 60° 50° 40° 30° 20° 10° 0°
a
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 0.998
χ²
59 58 57 56 55 54
All
Min(χ²)=53.1
(N,k)=(71,7)
p(a)
All
2007
p(θ)
All
2007
p(ξ)
All
2007
θ
ξ
0 30 60 90
−90 −60 −30 0 30 60 90

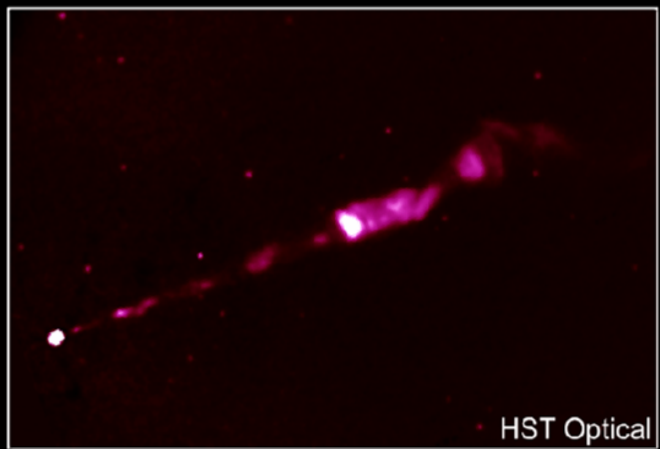
M87

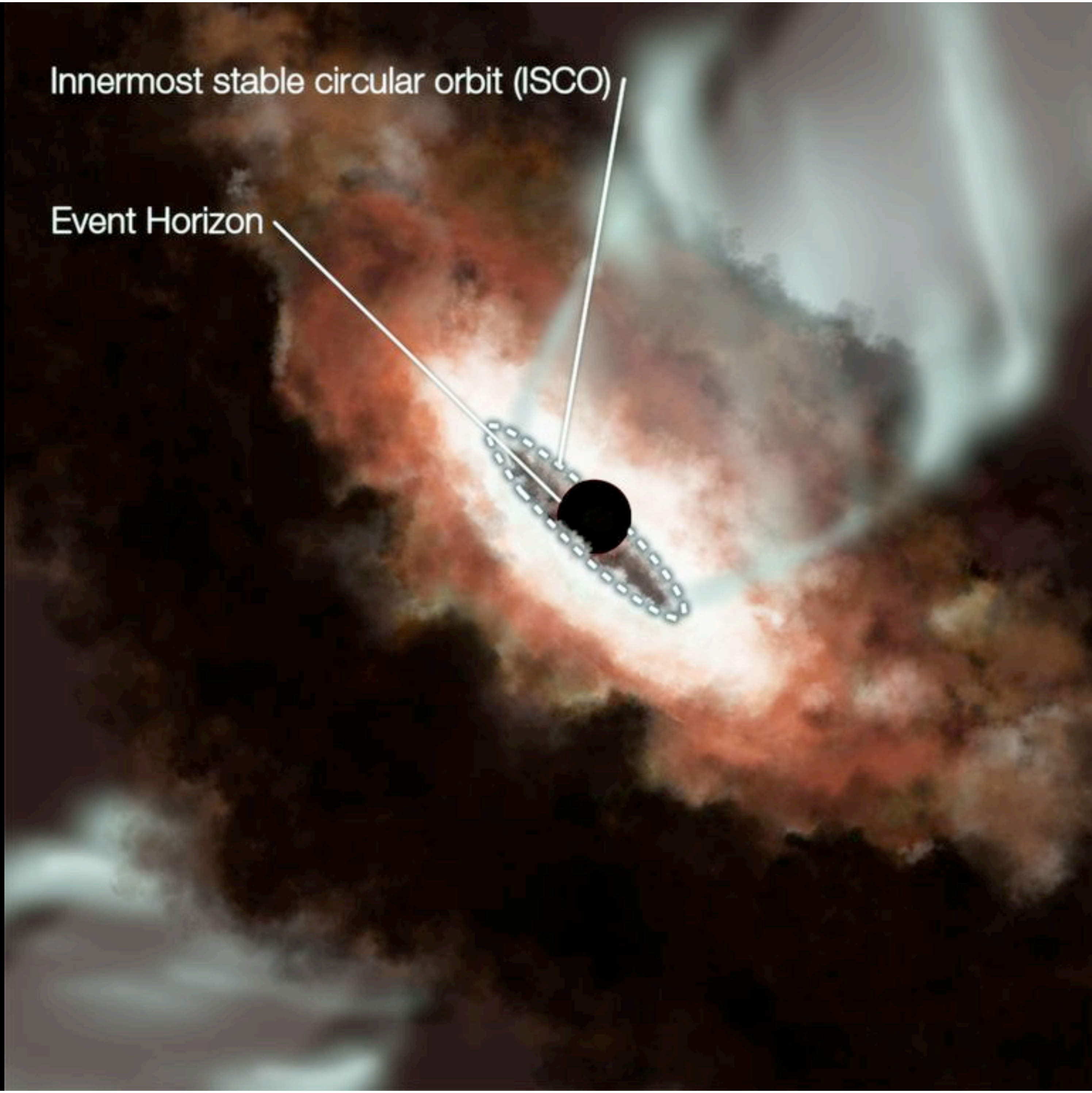
$M_{\rm BH} = 6.4 \times 10^9 M_\odot$ ***(1400 times more massive than SgrA*)***

$d_{\rm M87} = 16 \pm 1.2{\rm Mpc}$ ***(~2000 times farther than SgrA*)***

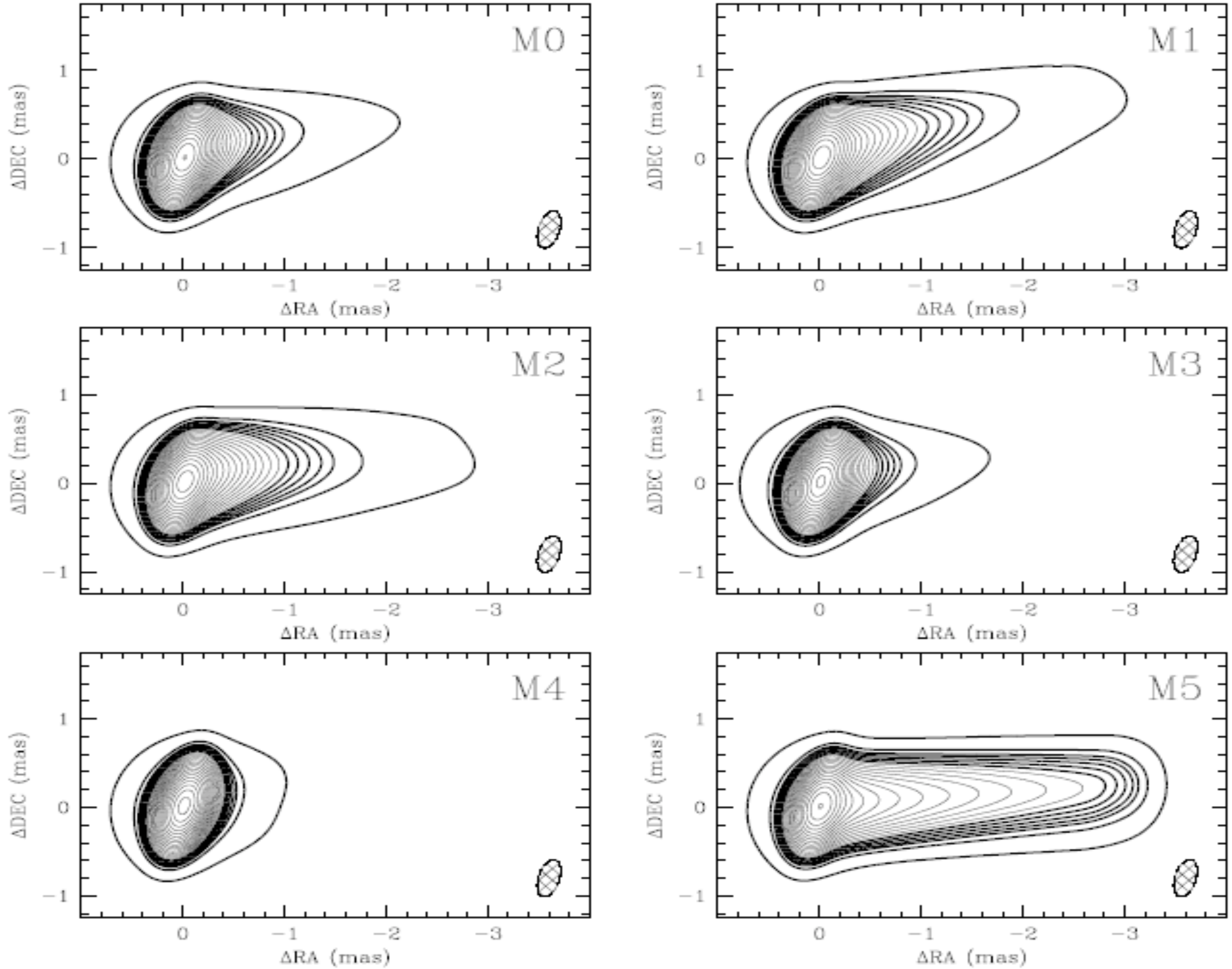








M87



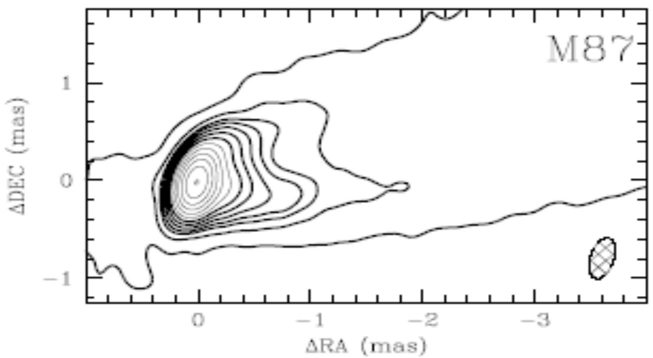
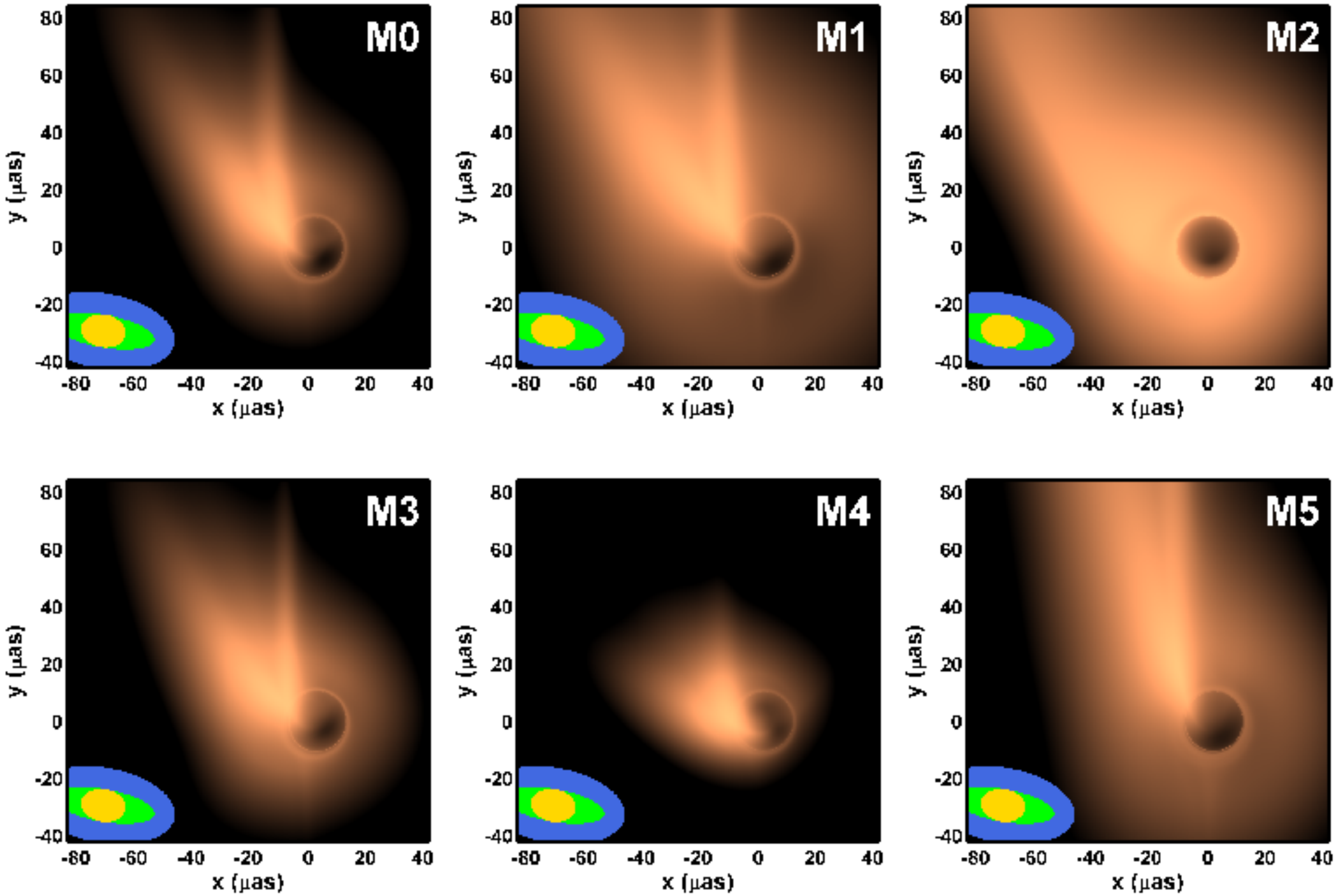


FIG. 3.— Above: 7 mm images for the models listed in Table 1 and described in §3.4, convolved with the beam described in Walker et al. (2008) (shown in the lower-right). The contours are at 0.1, 1, 2, 2.8, 4, 5.7 and 8 mJy/beam (thick lines), and spaced in factors of $\sqrt{2}$ thereafter (thin lines). In all figures, the jet is oriented along the x-axis (East-West), and the black hole is located at the origin. The counter jet is not visible in any of the images because it moves away from the observer and lacks the relativistic beaming of the forward jet. These should be compared with the 7 mm image at left, produced from the average of 10 images taken througout 2007 and described in Walker et al. (2008) (see also Ly et al. 2004)

0.87 mm Images

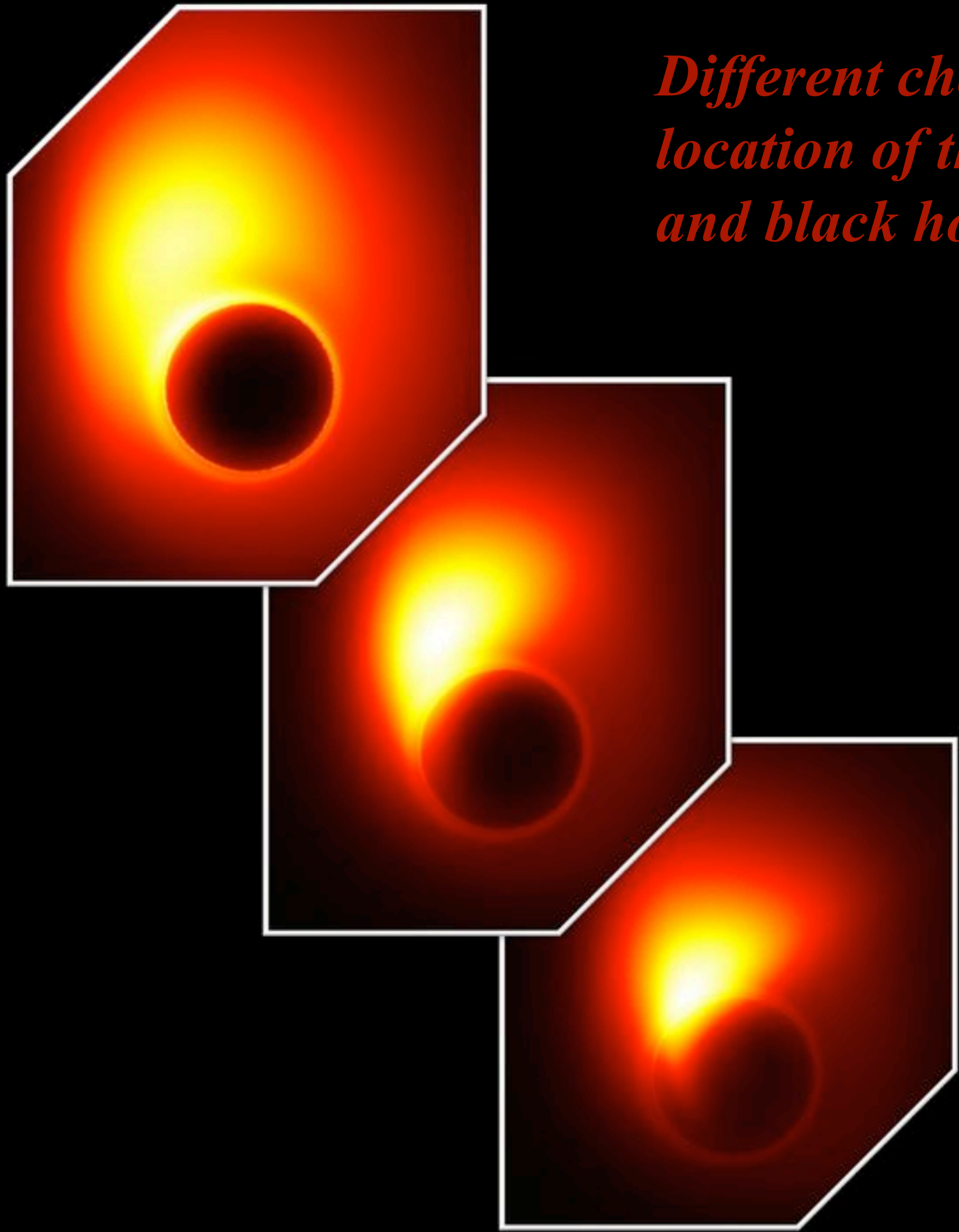


US

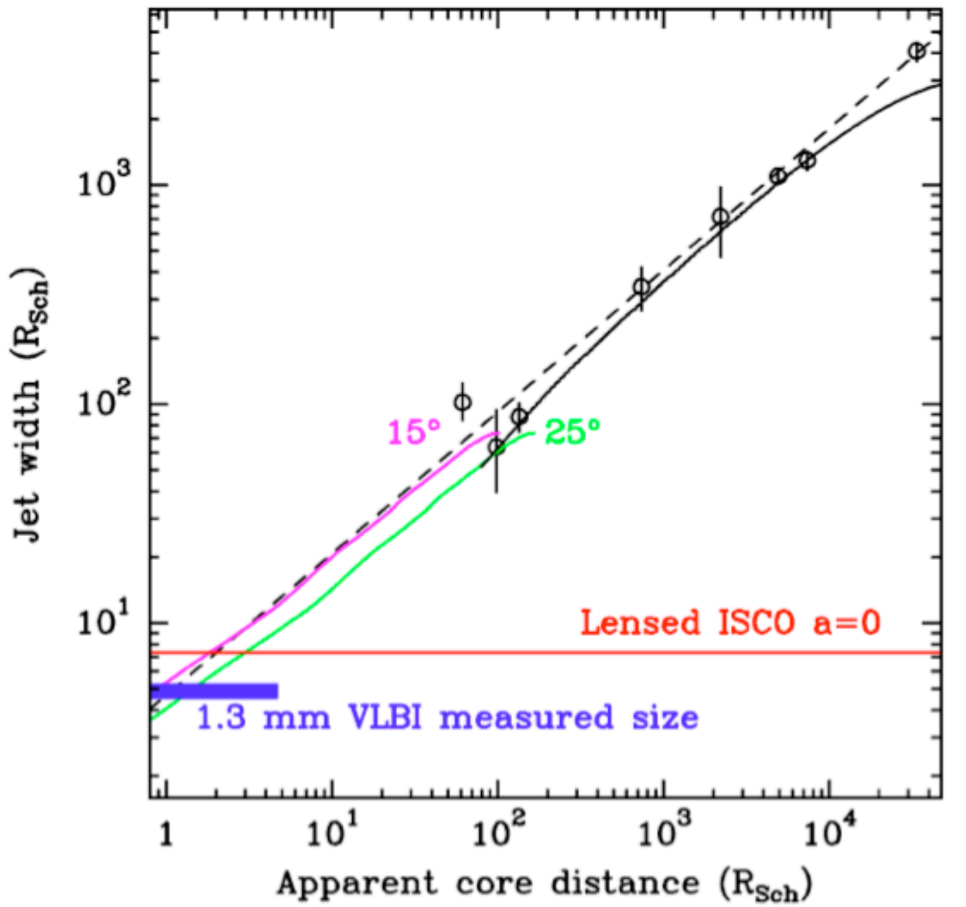
+EU

+LMT

Different choices for the location of the jet base and black hole spin



Detection of Jet Launching Structure in M87



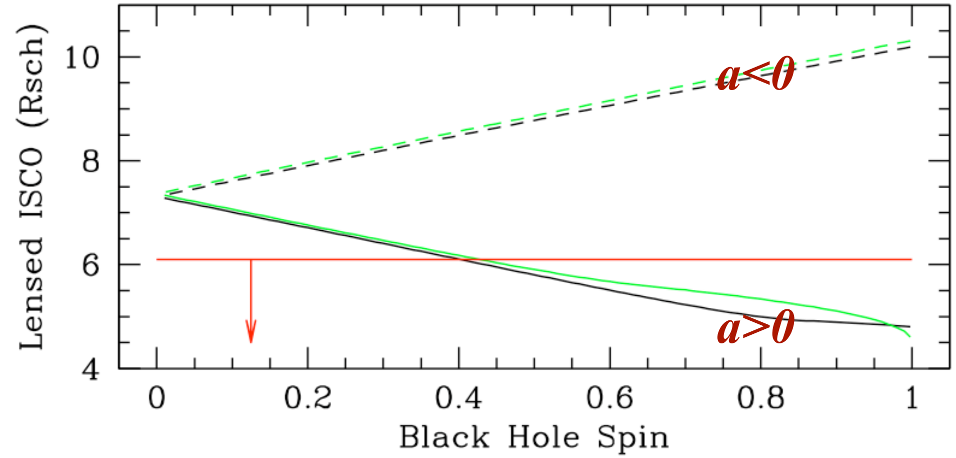


Table S1. Circular Gaussian Fits to M87. Errors are 3σ

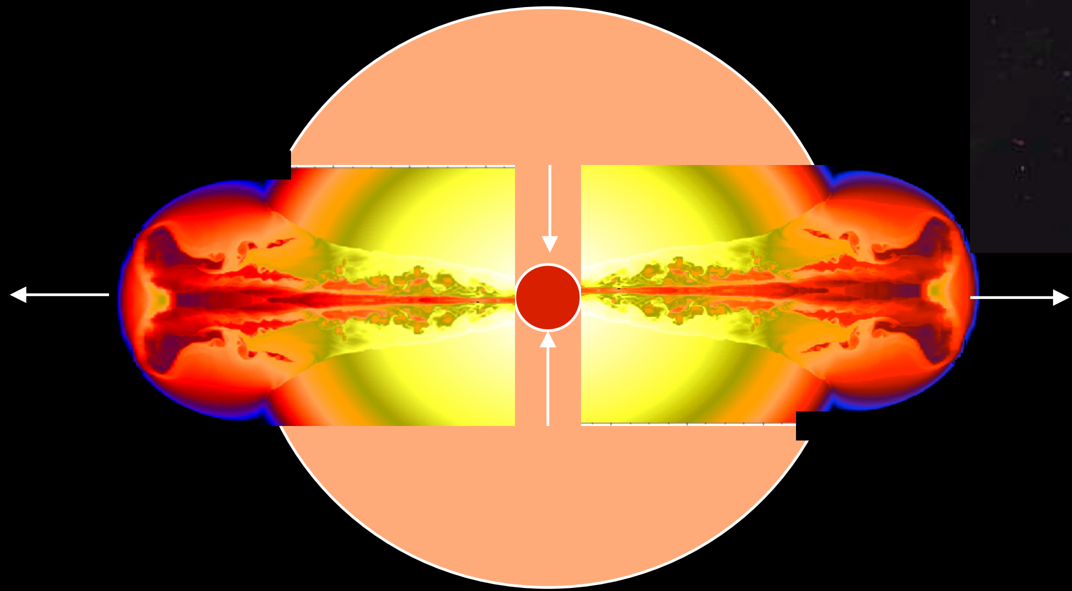
Day Number	Compact Flux Density (Jy)	Size FWHM (μas)
95	$0.95^{+0.06}_{-0.06}$	$40.3^{+2.5}_{-2.6}$
96	$0.97^{+0.07}_{-0.06}$	$39.8^{+3.8}_{-3.3}$
97	$1.03^{+0.05}_{-0.054}$	$39.1^{+3.5}_{-3.4}$
all days	$0.98^{+0.04}_{-0.04}$	$40.0^{+1.8}_{-1.8}$

Doeleman et al. (2012)

How do black holes accrete gas?

Penna et al. (2011)

Gamma-Ray Bursts: ***Observing the birth of a black hole***

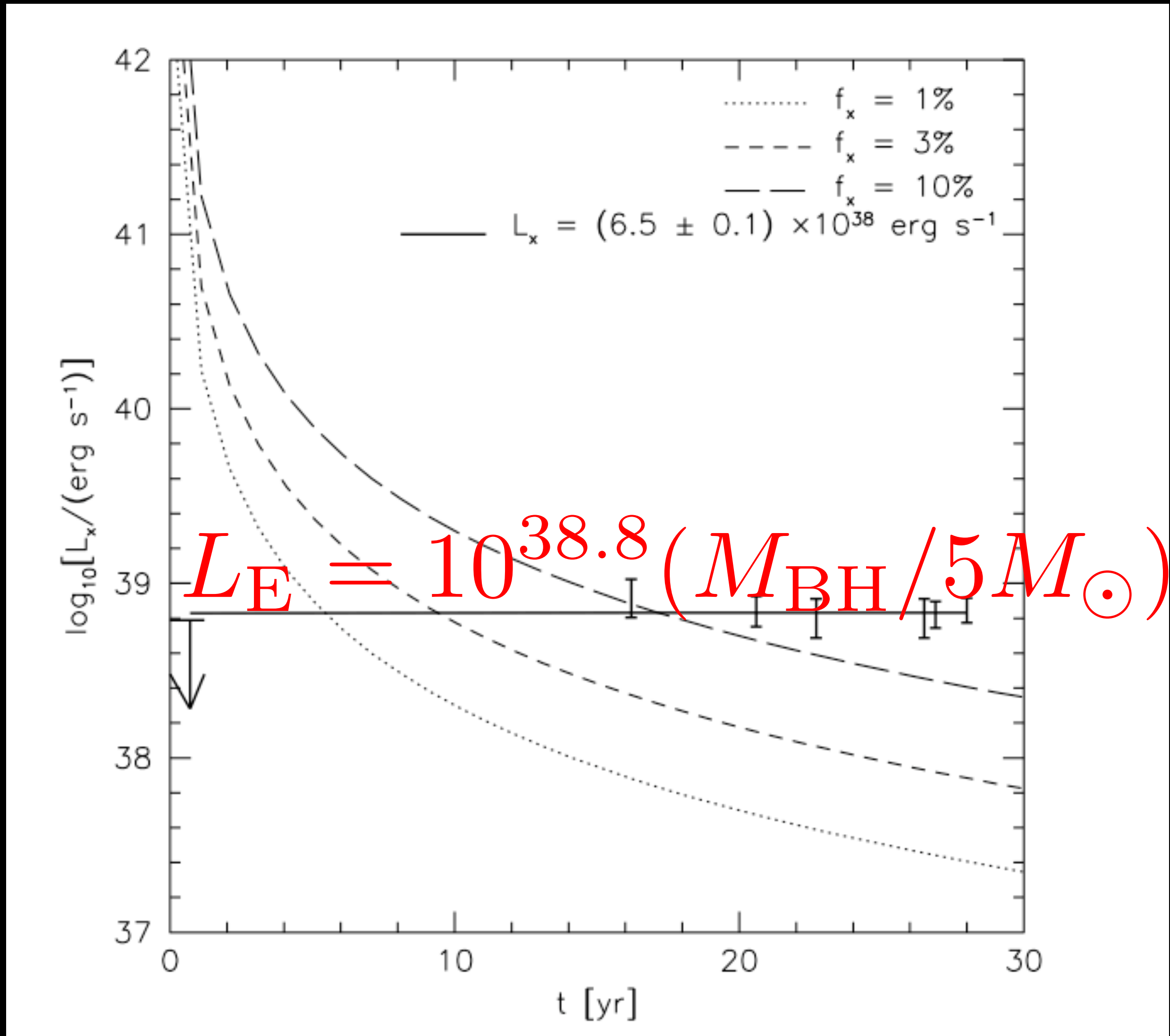


Collapse of a Massive Star

(accompanied by a supernova)

Existing finder: ***Swift;*** **Proposed:** ***JANUS, EXIST (high-z GRBs)***

EVIDENCE FOR BLACK HOLE BIRTH: persistent X-ray emission in SN1979C



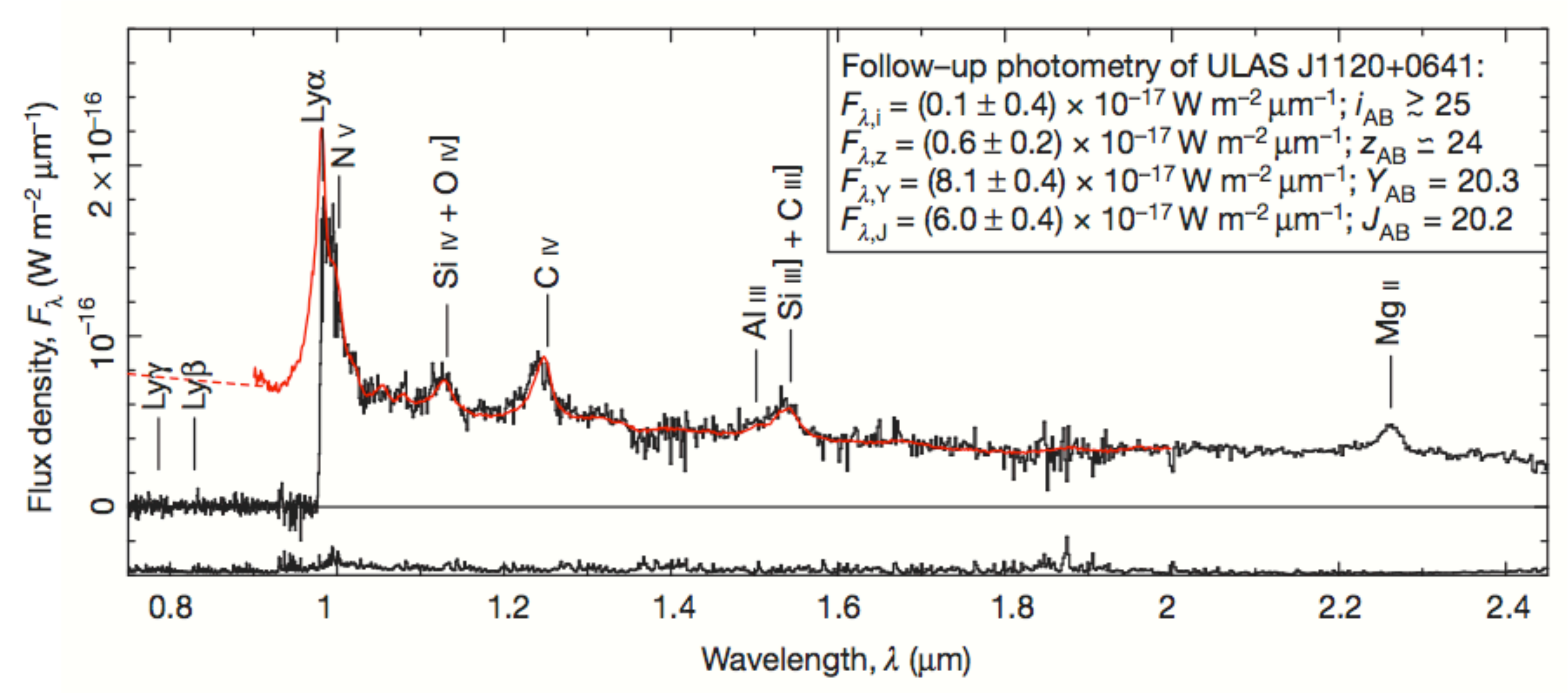
Patnaude, Loeb, Jones (2010)

…but bigger black holes form at the centers of galaxies

A luminous quasar at a redshift of $z = 7.085$

Daniel J. Mortlock[1], Stephen J. Warren[1], Bram P. Venemans[2], Mitesh Patel[1], Paul C. Hewett[3], Richard G. McMahon[3], Chris Simpson[4], Tom Theuns[5,6], Eduardo A. Gonzáles-Solares[3], Andy Adamson[7], Simon Dye[8], Nigel C. Hambly[9], Paul Hirst[10], Mike J. Irwin[3], Ernst Kuiper[11], Andy Lawrence[9] & Huub J. A. Röttgering[11]

Black Hole Mass = 2 billion solar masses



Only 0.77 billion years after the Big Bang

Nature (2011)

What is a quasar?

A supermassive black hole which accretes gas and shines brightly. Typically found in the central region of a galaxy.

The Eddington Limit

Black Hole

Outward force

$$\frac{L}{4\pi r^2 c}\sigma_T$$

Inward force

$$\frac{GMm_p}{r^2}$$

$$L_E = \frac{4\pi G M m_p c}{\sigma_T} = 1.3 \times 10^{38}\,\frac{\mathrm{erg}}{\mathrm{s}}\left(\frac{M}{M_\odot}\right).$$

Black Hole Growth

$$L = \epsilon \dot{M} c^2 = \eta L_E \propto M$$

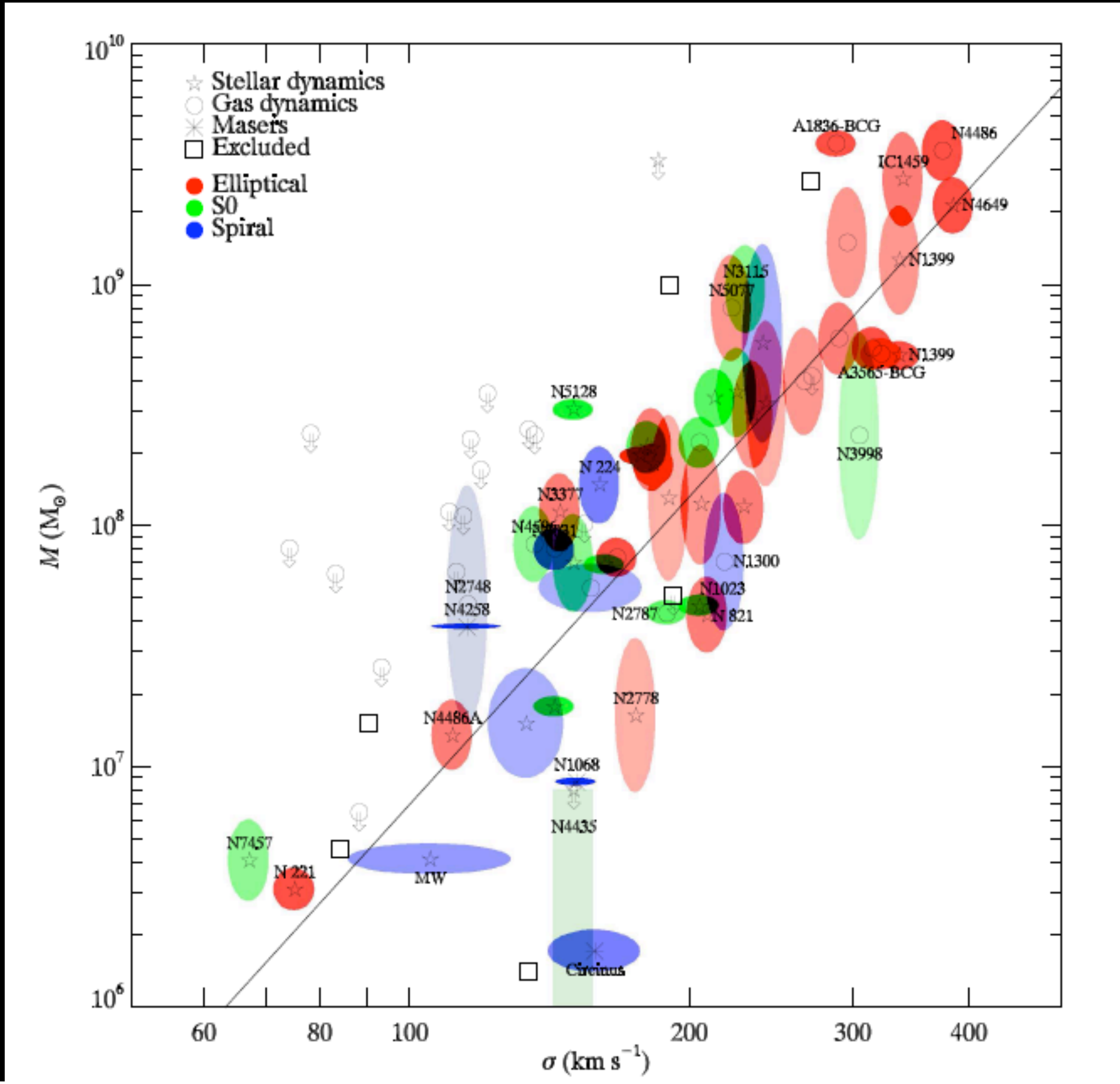
$$M = M_0 \exp\{t/t_E\}$$

$$t_E = 4 \times 10^7 \left(\frac{\epsilon/\eta}{10\%} \right) \text{years}$$

Starting from a stellar mass, there is barely enough time to grow the observed quasar black hole during the age of the Universe at z=7.1 for e=10%… but the radiative efficiency may be small due to trapping of radiation:

$$v_{\rm diff} \sim (c/\tau) \ll v_{\rm infall}$$

Correlation between black hole mass and velocity dispersion of their host spheroids



$$(N_{\rm quasars}/N_{\rm galaxies}) < 10^{-2}\ ;\ (M_{\rm BH}/M_{\rm galaxy}) < 10^{-3}$$

Why Are Quasars Short Lived?

Because they are suicidal!

<u>**Principle of Self Regulation:**</u> *supermassive black holes grow until they release sufficient energy/momentum to unbind the gas that feeds them from their host galaxy*

→*Implies a correlation between black hole mass and the depth of the gravitational potential well of its host galaxy*

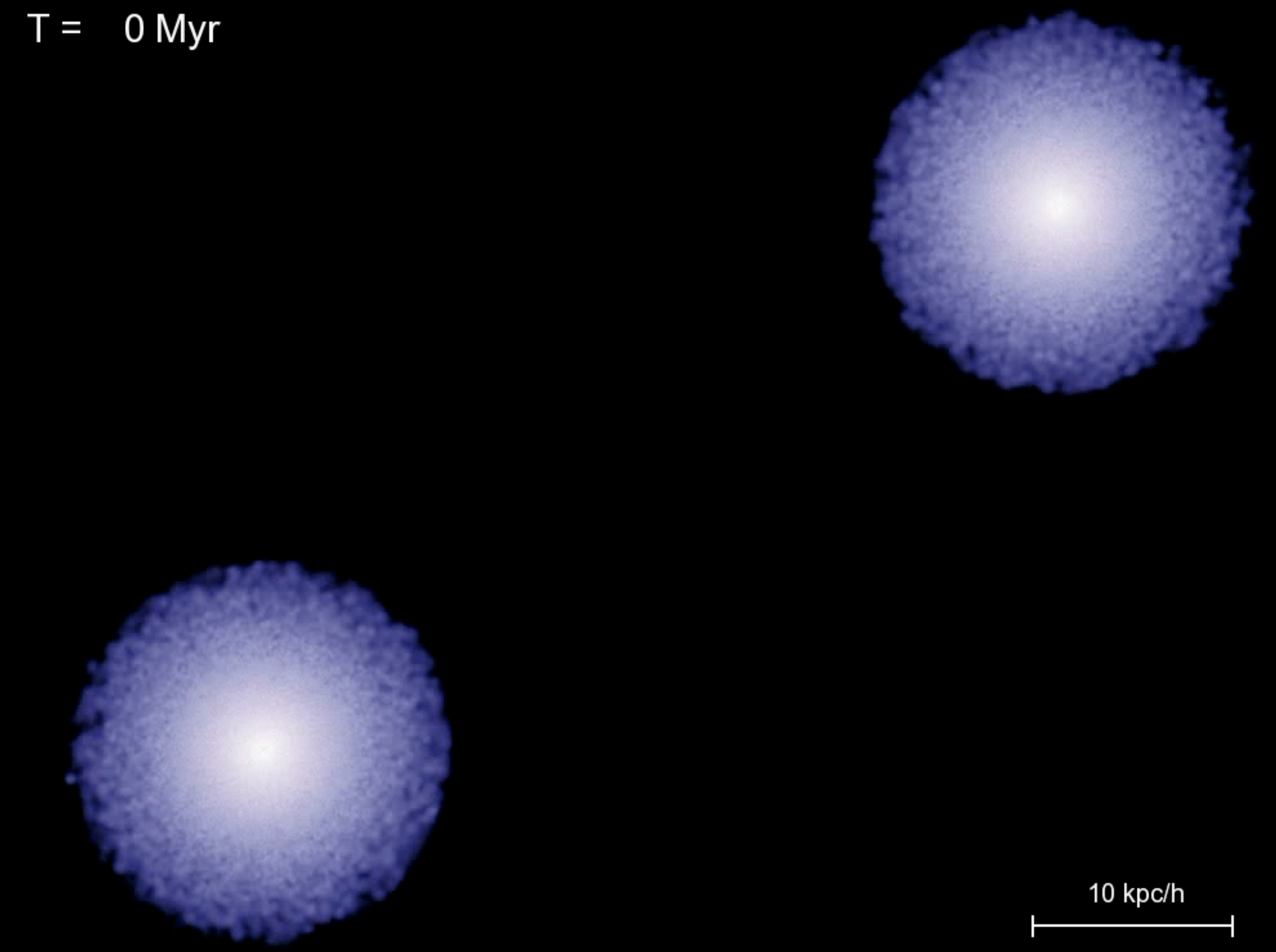
Unbinding the gas in a galaxy:

$$\epsilon_{\rm gal} M_{\rm BH} c^2 \sim M_{\rm gas} \sigma^2$$

$$\frac{\sigma}{c} \sim 10^{-4} - 10^{-3}$$

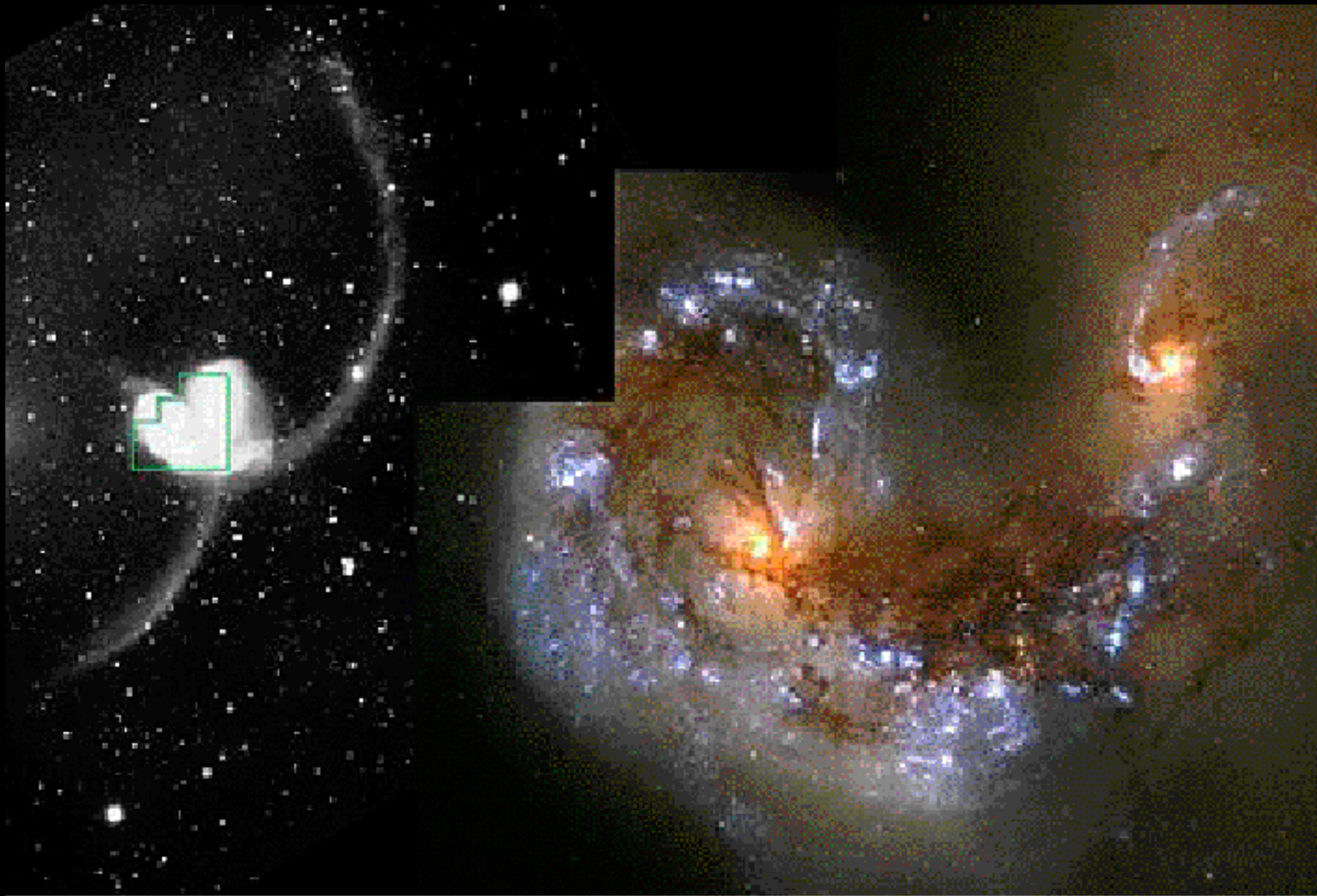
$$\frac{M_{\rm BH}}{M_{\rm gas}} \sim \frac{1}{\epsilon_{\rm gal}} \left(\frac{\sigma}{c}\right)^2 \sim 10^{-5}$$

Computer Simulations of Quasar Feedback



Springel, Hernquist, Di Matteo et al. 2005

Black Hole Binaries due to Galaxy Mergers



B. Whitmore (STScI), F. Schweizer (Carnegie Institute),

Binary AGN with 1-10kpc separation at z<0.3

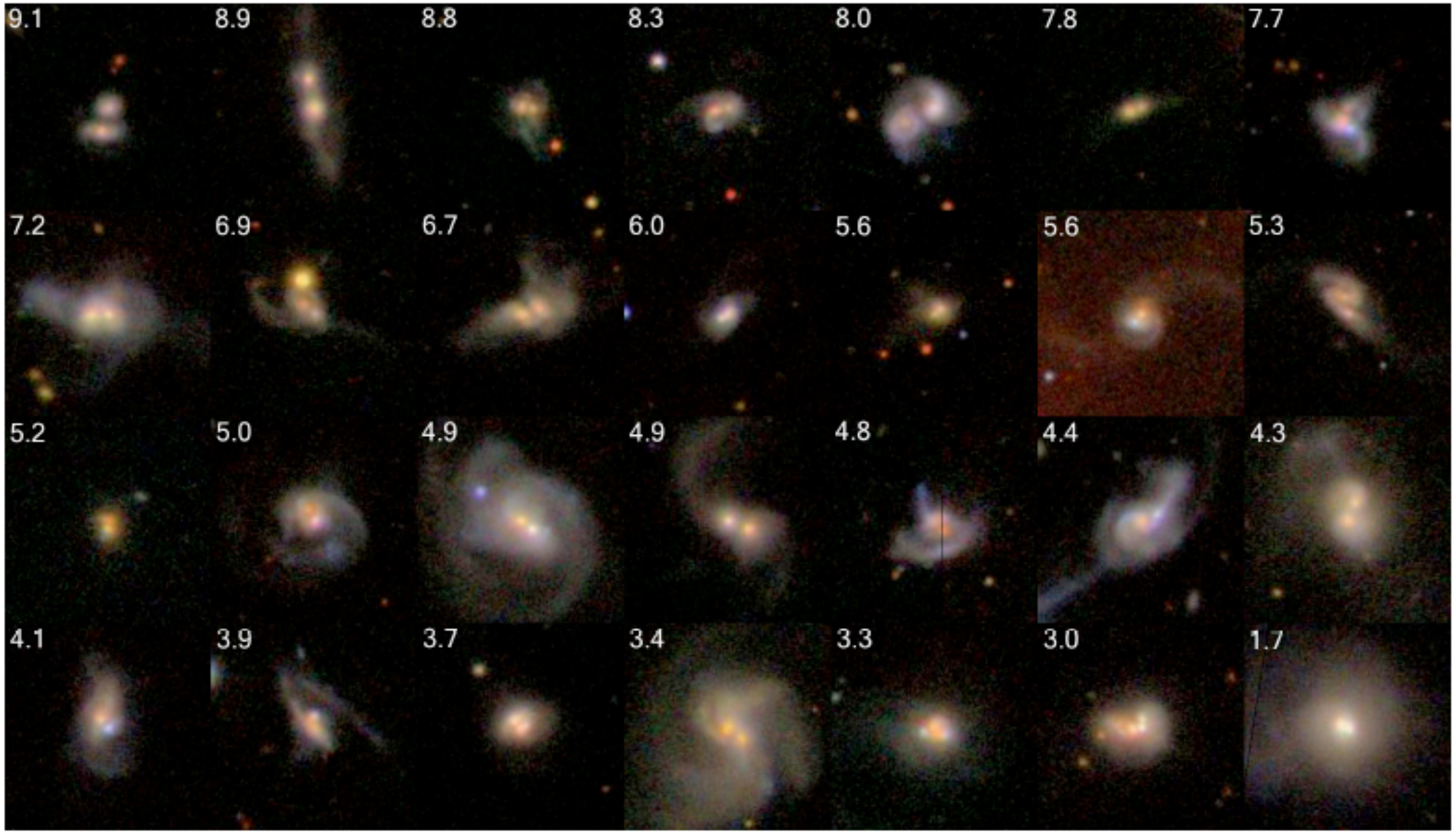
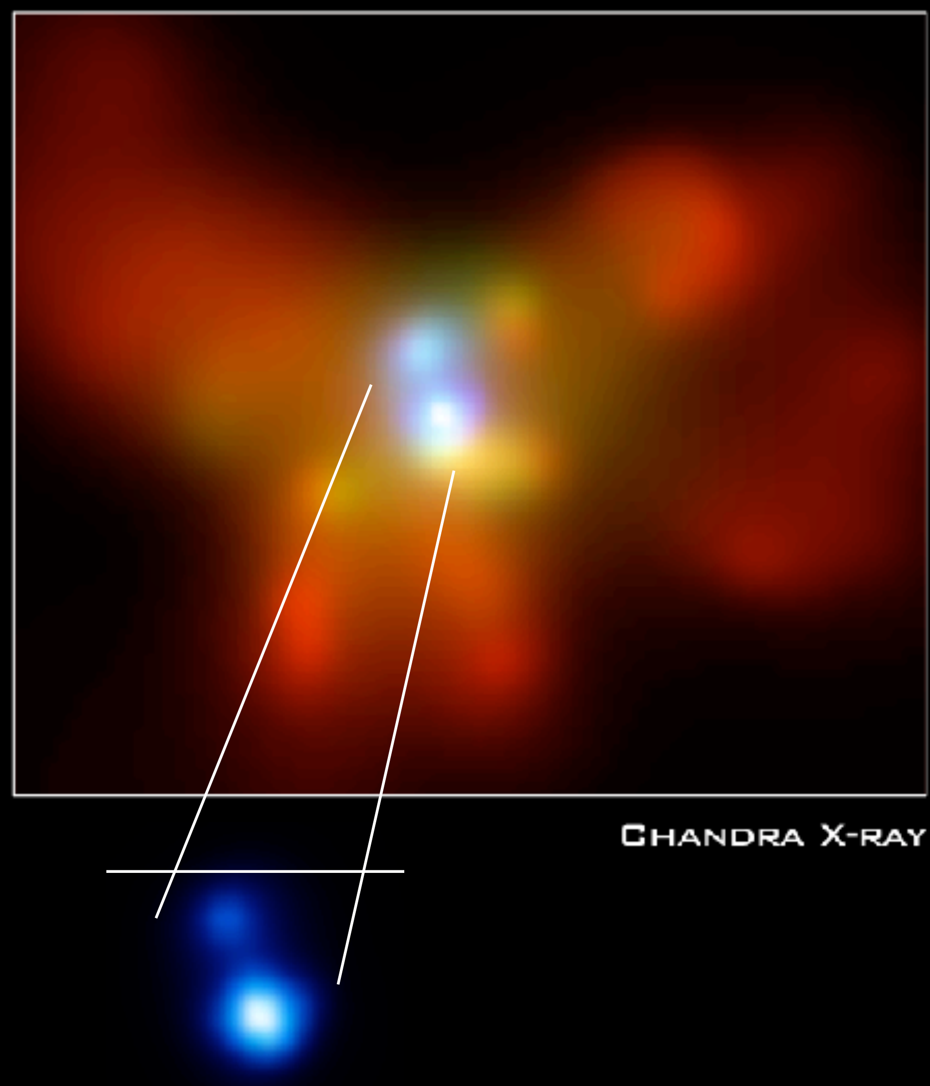


Figure 1: SDSS *gri*-color composite images of some binary AGNs selected from SDSS. North is up and east is to the left. Each panel is 50 × 50". We order the targets with decreasing projected separation r_p, ranging from $r_p = 9.1$ kpc to 1.7 kpc as labeled on each panel.

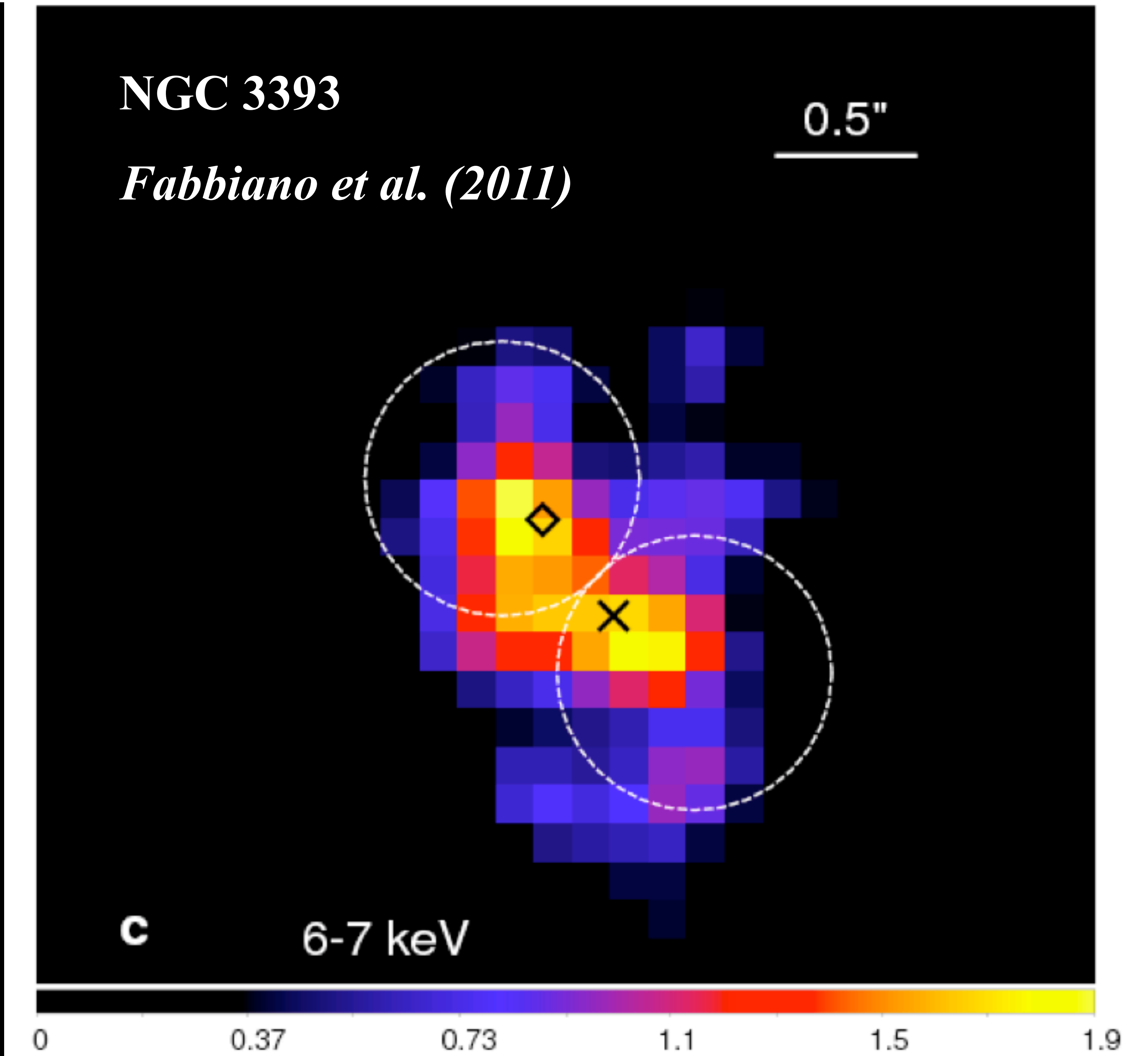
Shen et al. (2011)

X-ray Image of a binary black hole system in NGC 6240

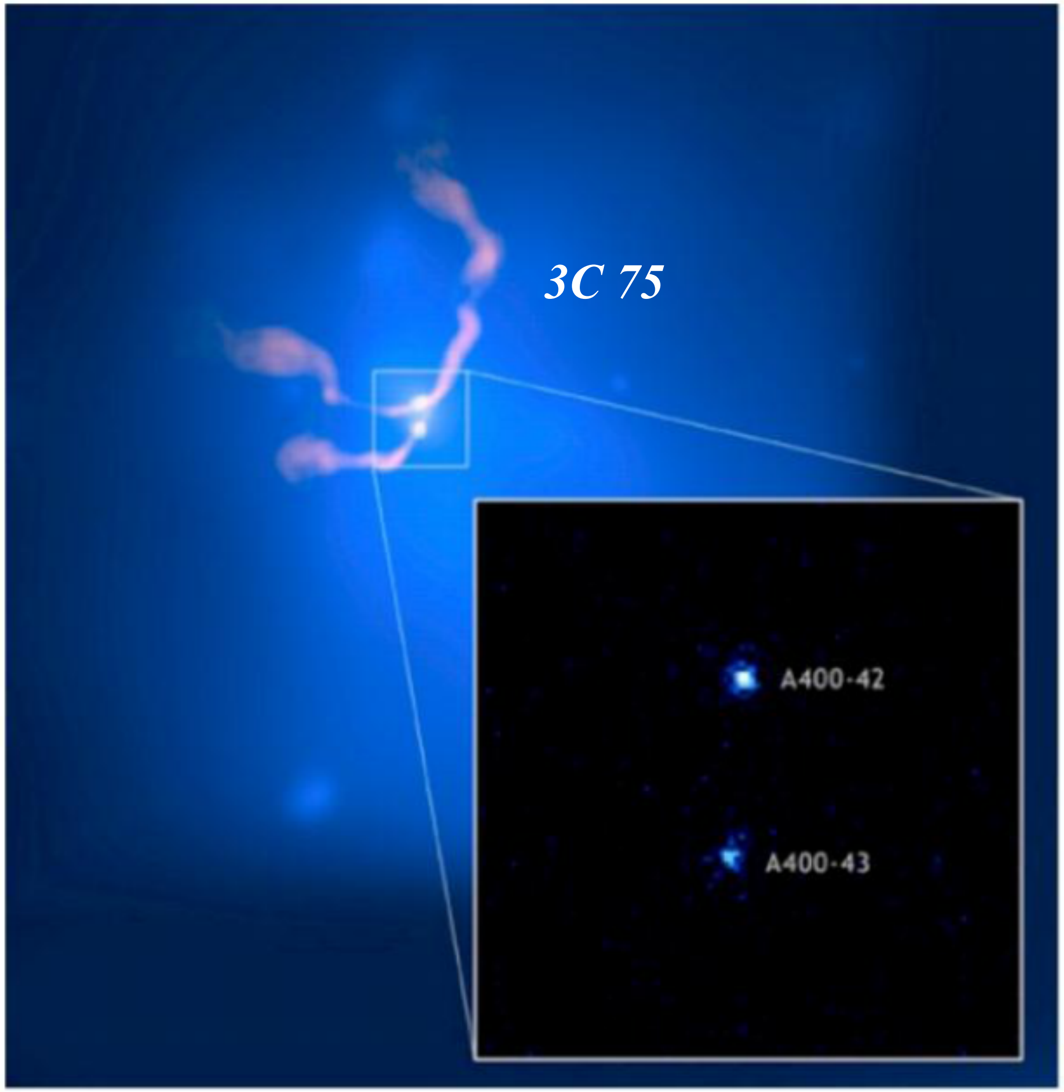


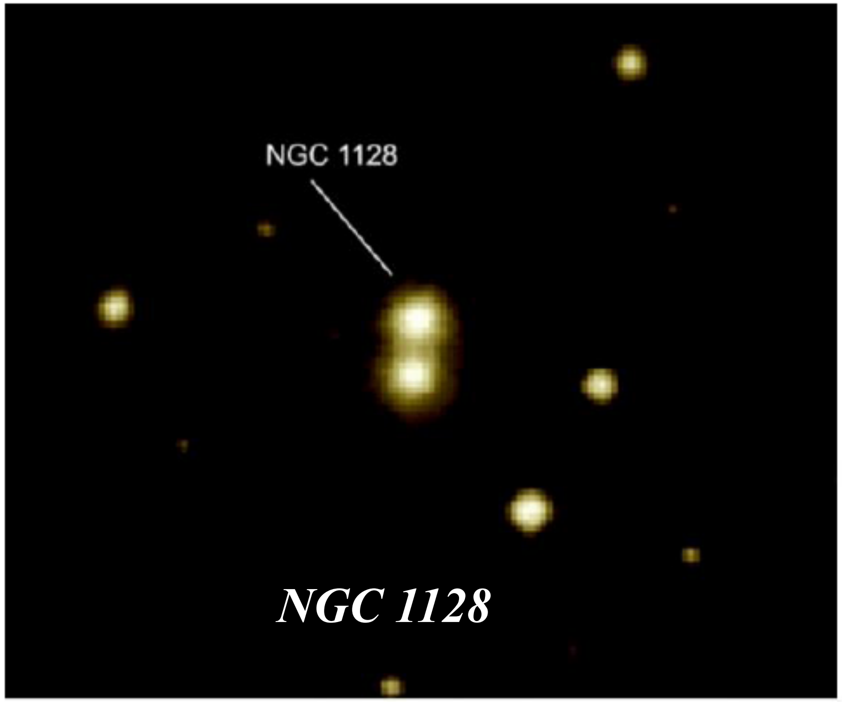
z=0.025

Komossa et al. 2002

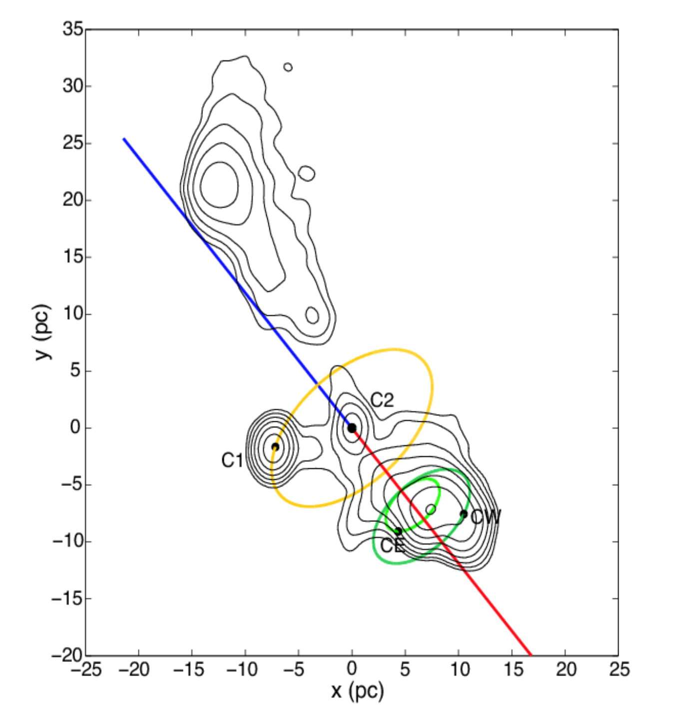

NGC 3393
Fabbiano et al. (2011)
0.5"
c
6-7 keV
0
0.37
0.73
1.1
1.5
1.9

X-ray Cluster Abell 400

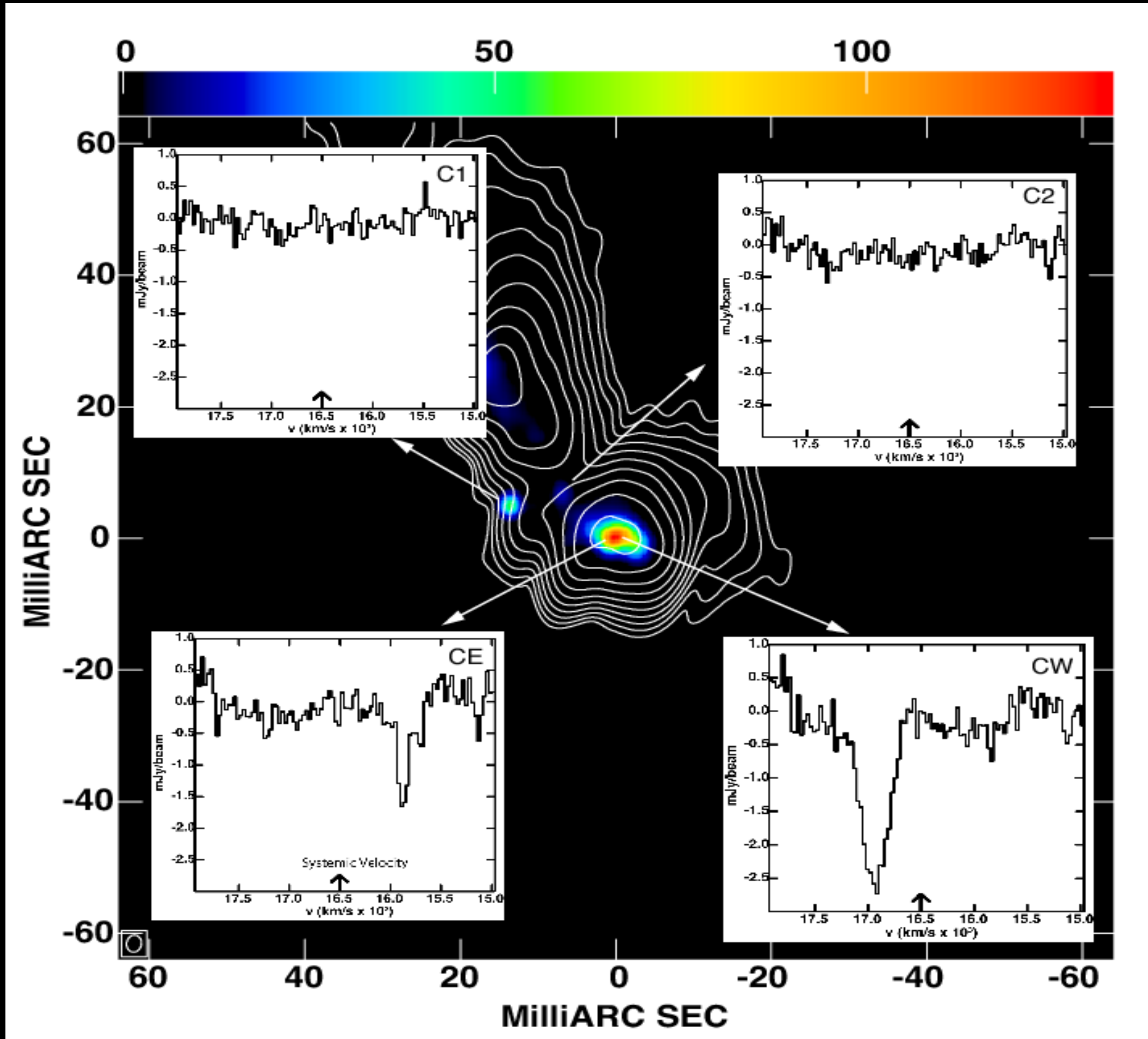




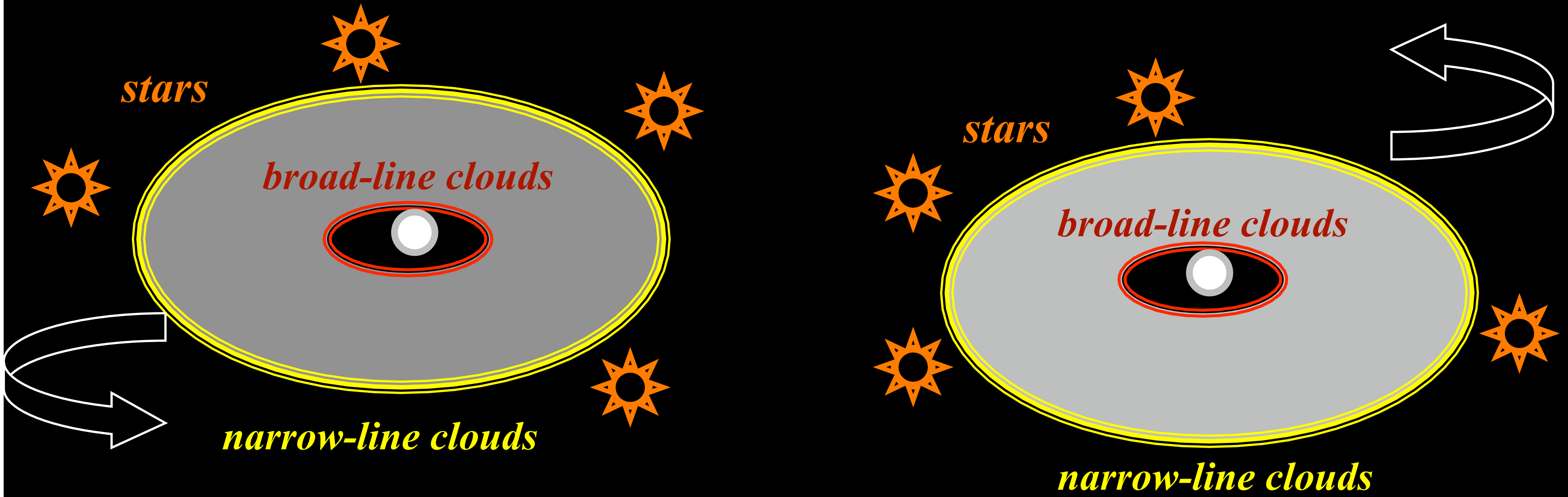
0402+379 (Rodriguez et al. 2006-9)

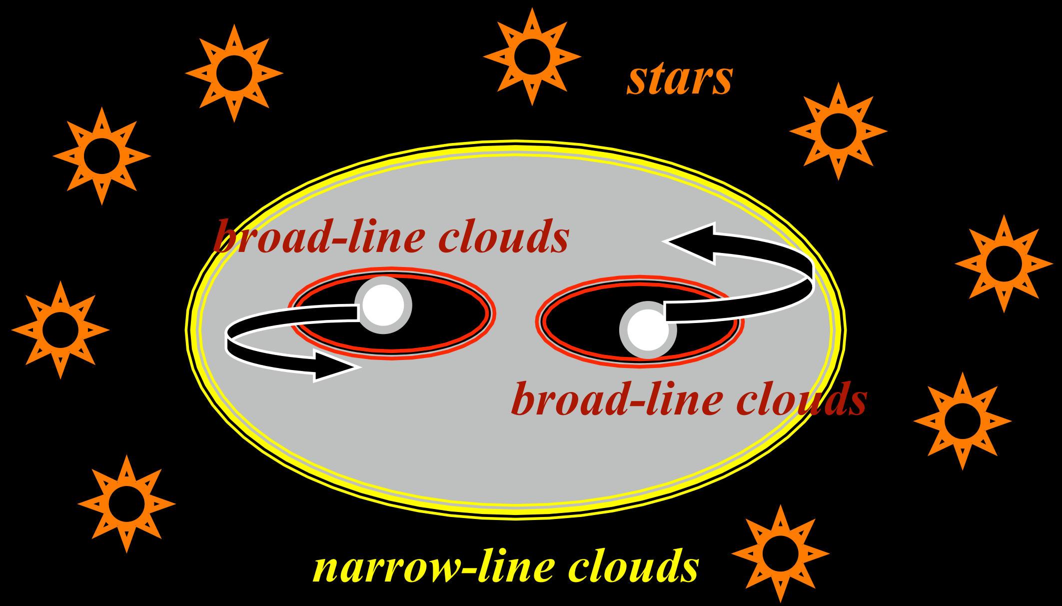


VLBI at 1.35 GHz



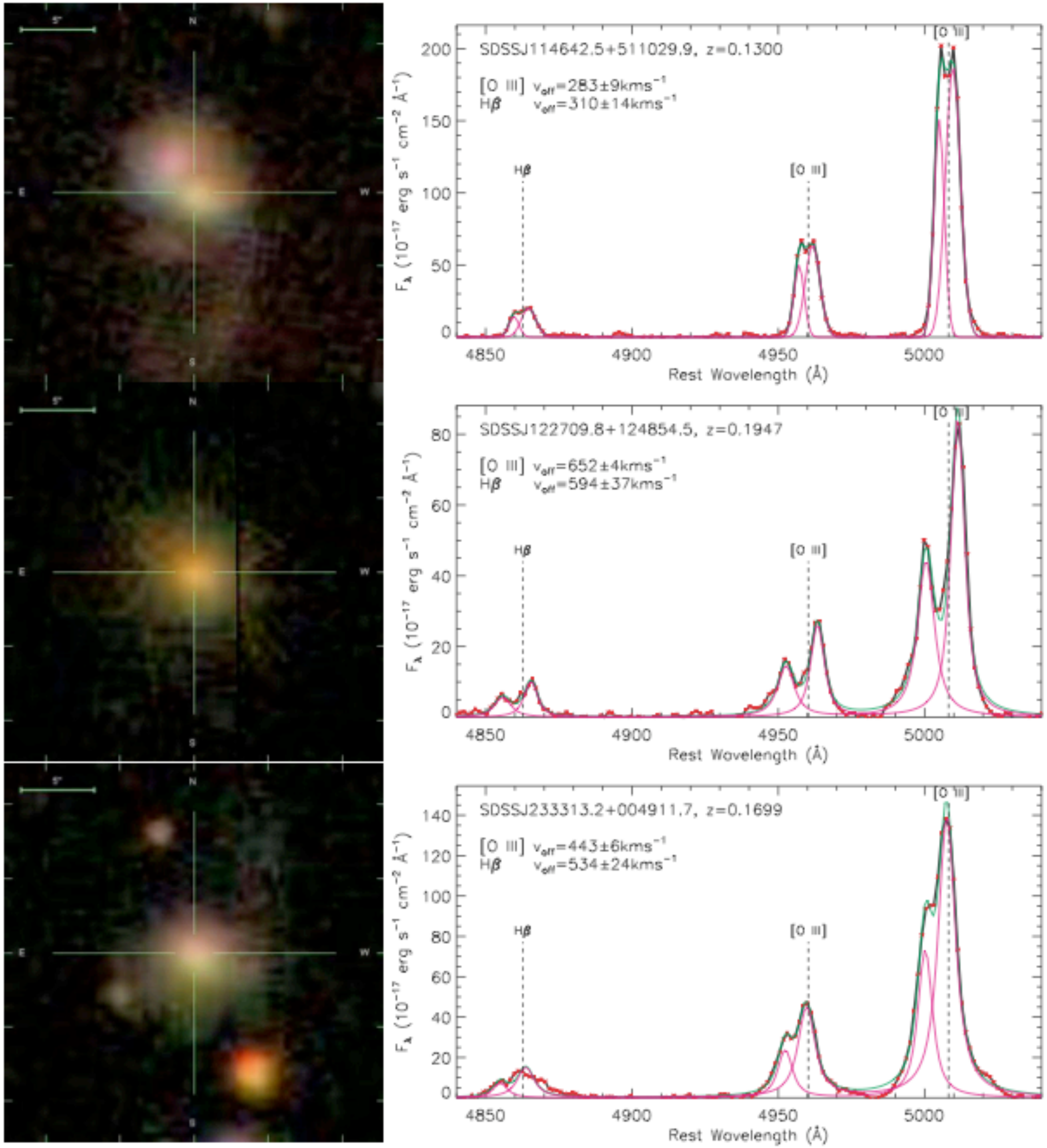
- Projected separation: 7.3 pc,
- Estimated total mass: $\sim 10^9 M_\odot$


stars
broad-line clouds
narrow-line clouds
stars
broad-line clouds
narrow-line clouds

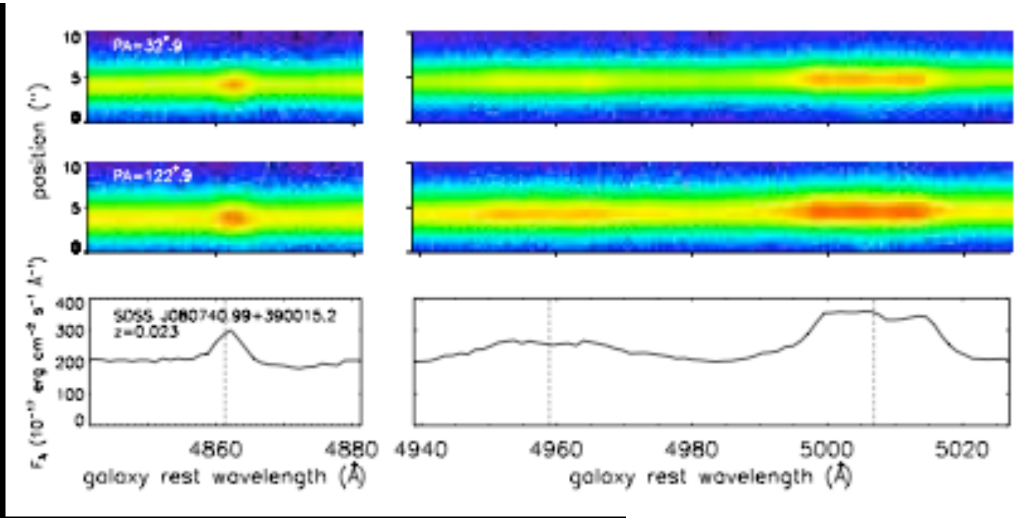


stars
broad-line clouds
broad-line clouds
narrow-line clouds

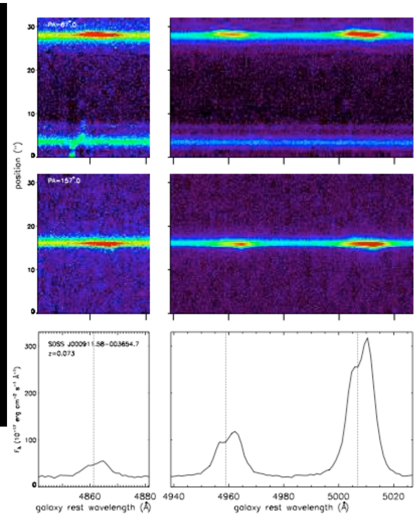
SDSS images & spectra of selected double narrow -line quasars

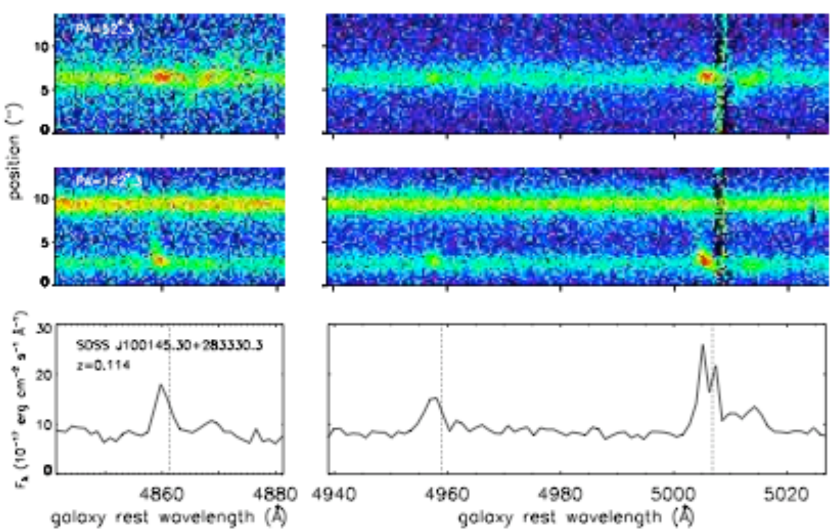


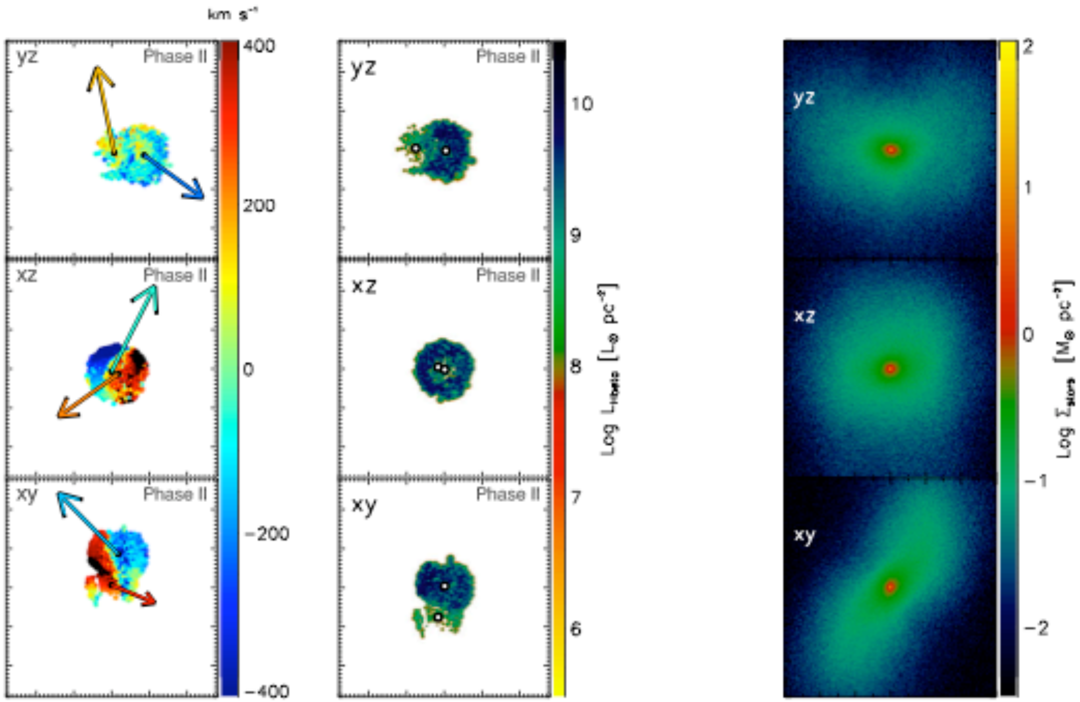
(Liu et al. 2009)



Comerford et al. (2012)

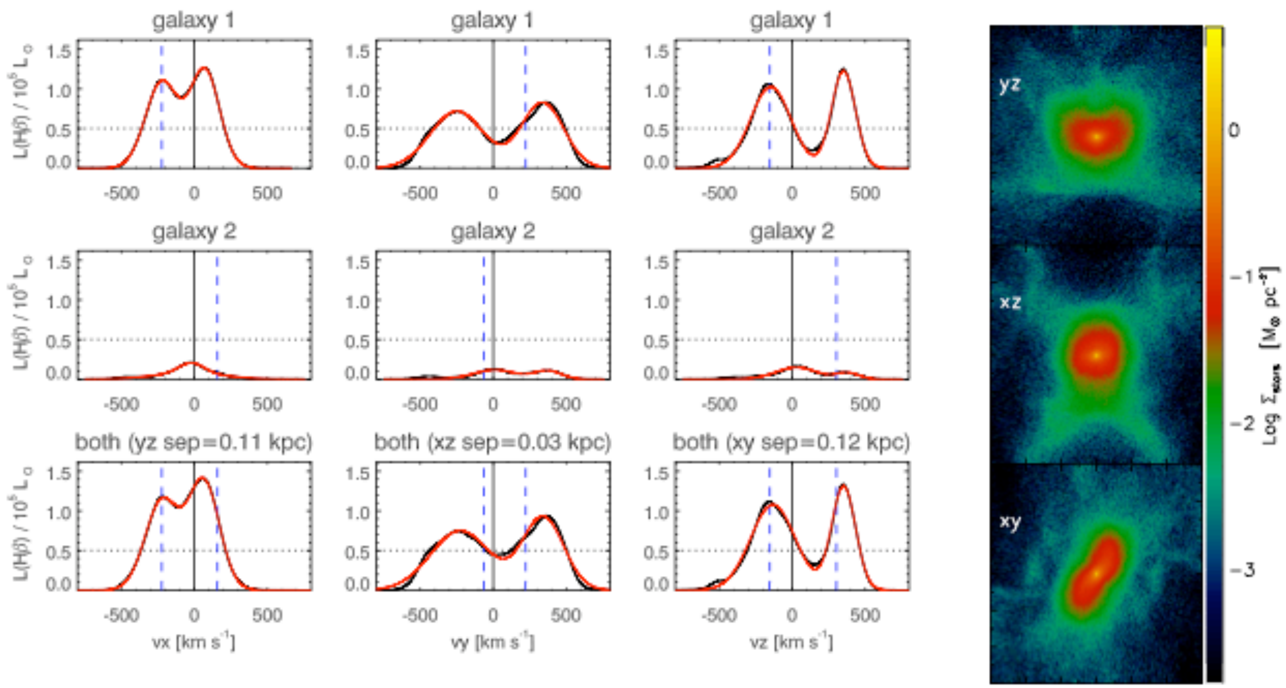






(d)

(e)



Double-peaked Narrow-Line Signatures of Dual Supermassive Black Holes in Galaxy Merger Simulations

Blecha, Loeb, & Narayan (2012)

Double Broad Lines: Reverberation

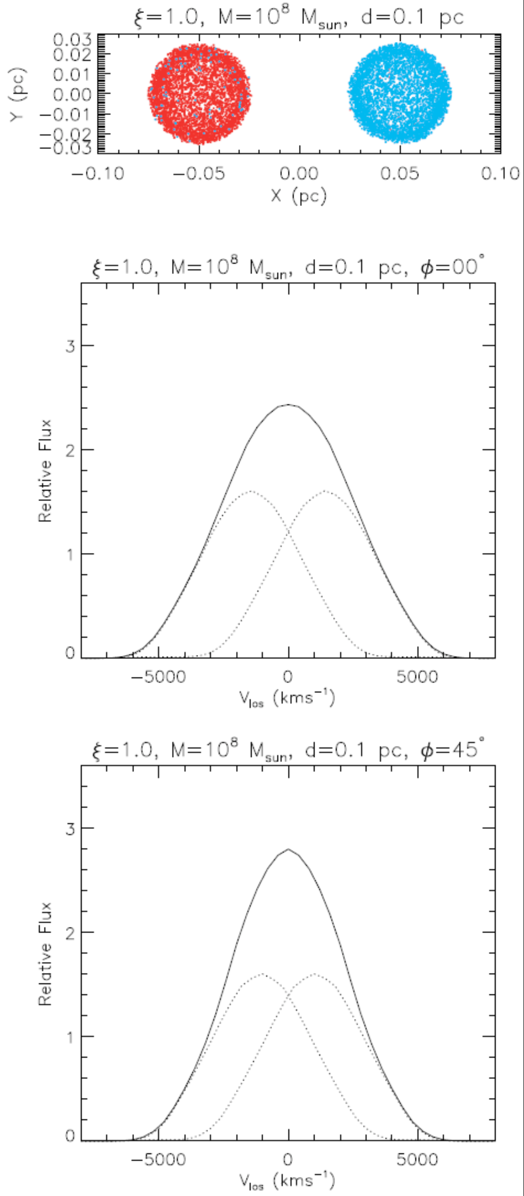


Figure 1. *Top*: Distributions of BLR clouds (projected on to the binary orbital plane) for a binary of two 10^8 $M_\odot$ BHs with a separation $d = 0.1$ pc. For clarity we only show a small fraction of randomly selected test particles. Different colors indicate BLR clouds initially associated with individual BHs. The rotation of the binary is counterclockwise. The observer is in the xy plane and at $y = +\infty$, and the radial velocities of the two BHs are maximal at this phase. *Middle*: Line profile when the radial velocities of the two BHs are maximal (orbital phase angle $\phi = 0°$). The dotted lines are contributions from the two BHs respectively. *Bottom*: Line profile after 1/8 of the orbital period ($\phi = 45°$).

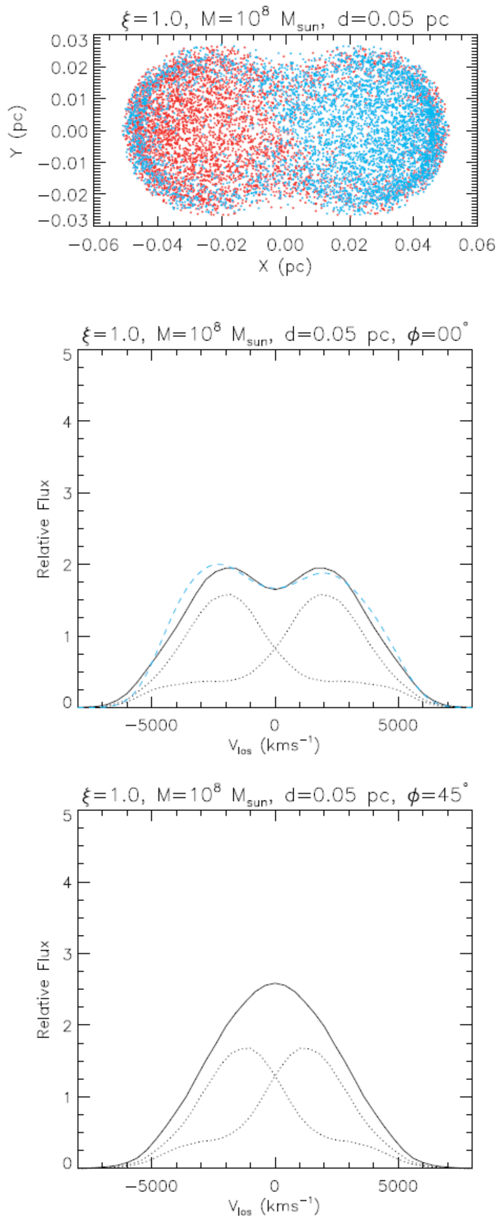
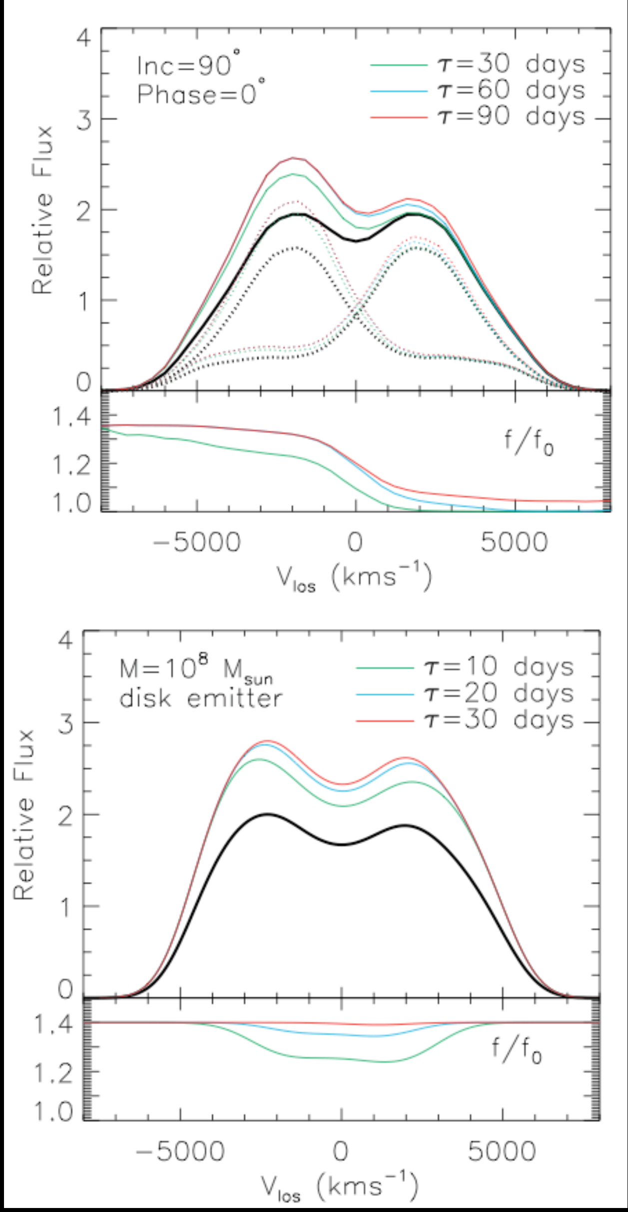
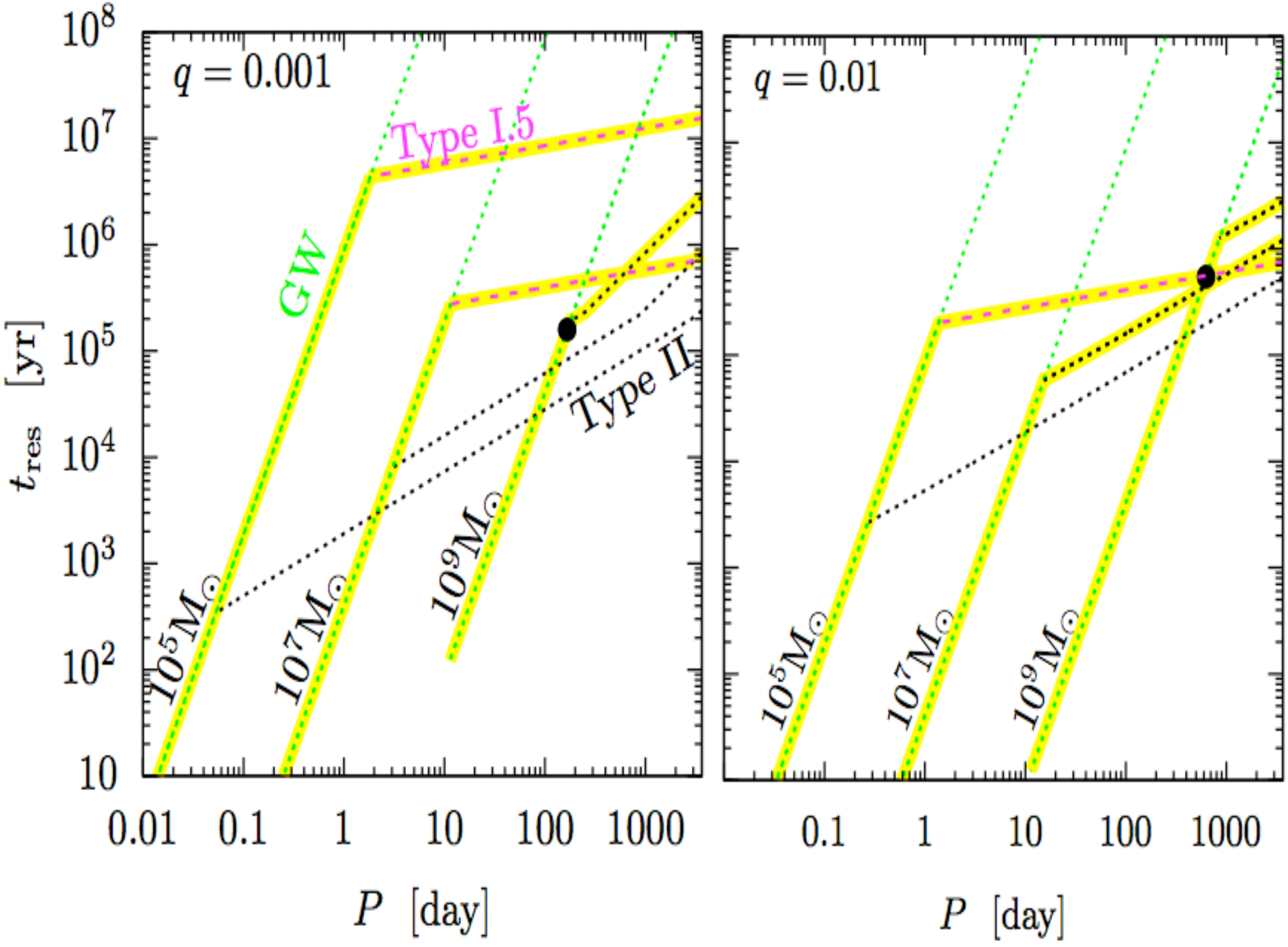


Figure 2. Distributions of BLR clouds and line profiles for a binary of two 10^8 $M_\odot$ BHs with a separation $d = 0.05$ pc. Notations are the same as in Fig. 1. The cyan dashed line in the middle panel shows a disk emitter model (see the text for details).

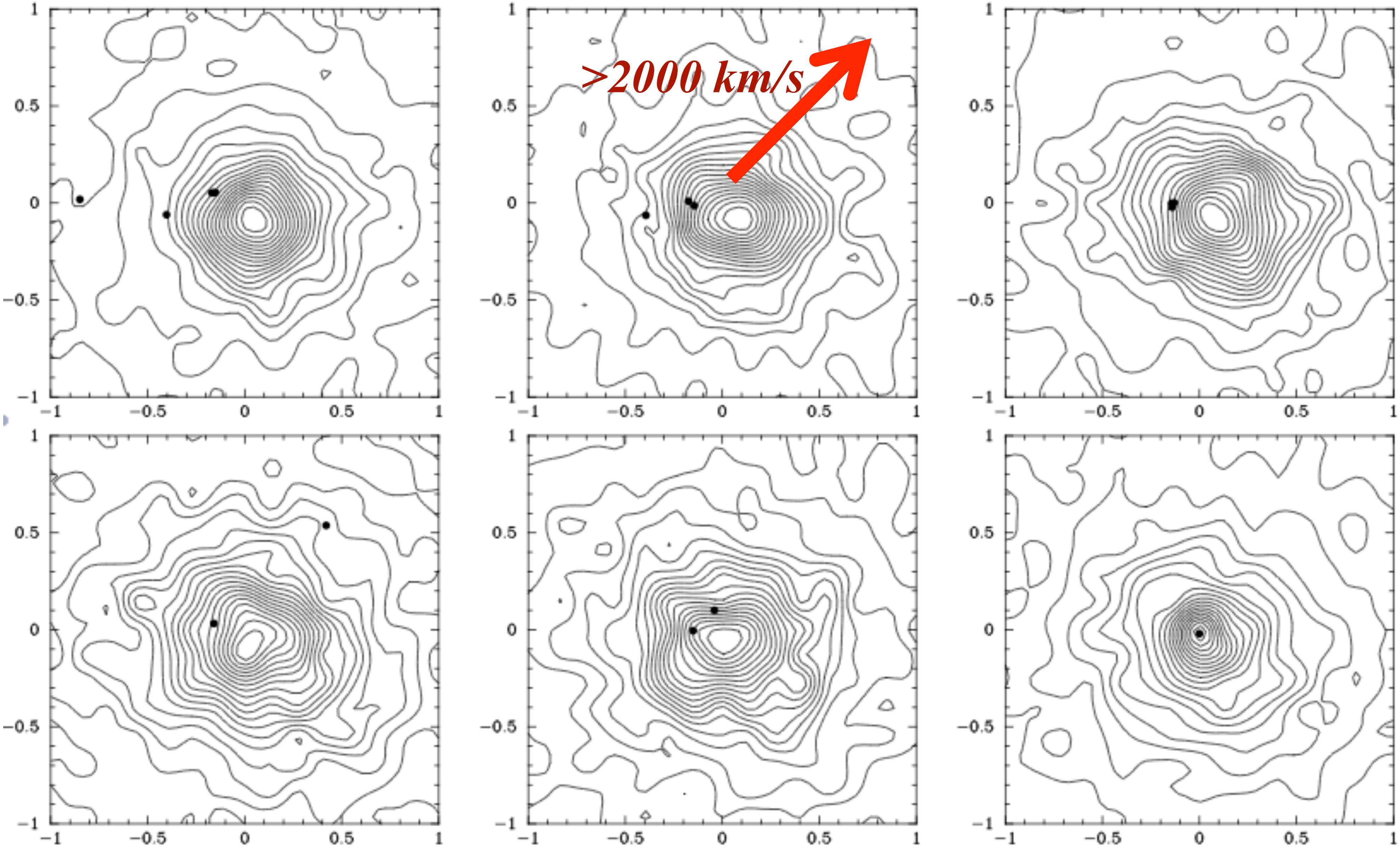


Shen & Loeb (2010)



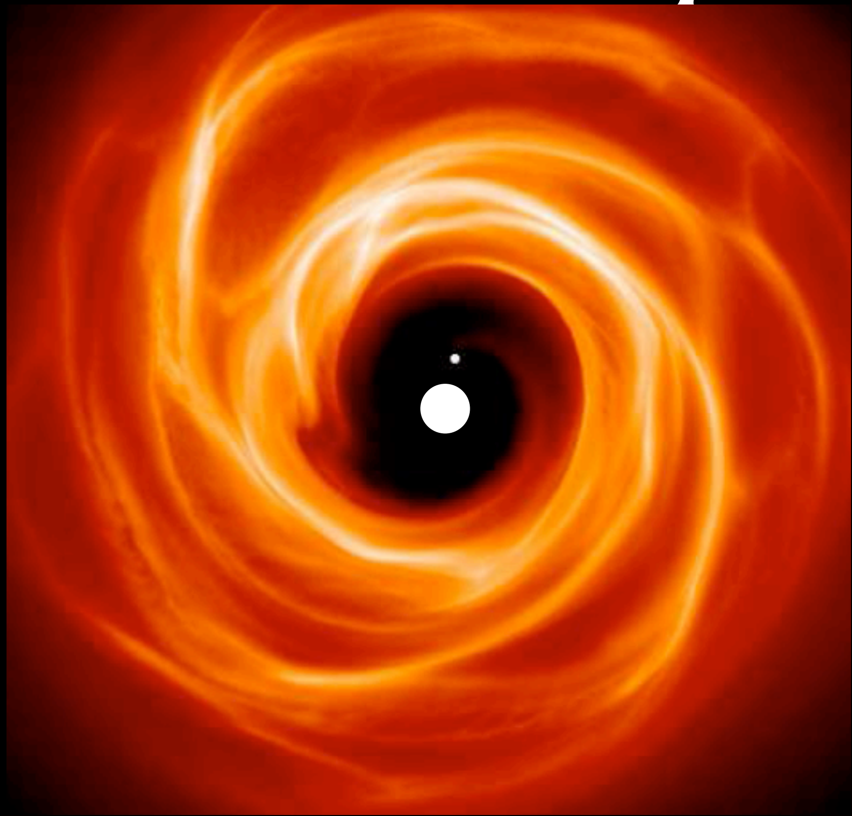
$q = 0.001$
$q = 0.01$
Type I.5
GW
Type II
$10^5 M_\odot$
$10^7 M_\odot$
$10^9 M_\odot$
$t_{\rm res}$ [yr]
P [day]

Multiple Black Holes



Kulkarni & Loeb 2011; Hoffman & Loeb 2007

Extreme Mass Ratio Inspirals (EMRIs)



- Stellar mass BH or NS in an orbits around SMBH
- Many orbital times in the eLISA/NGO band, allowing a precise determination of GR or astrophysical perturbations
- The compact object may have formed or been trapped inside the accretion disk.

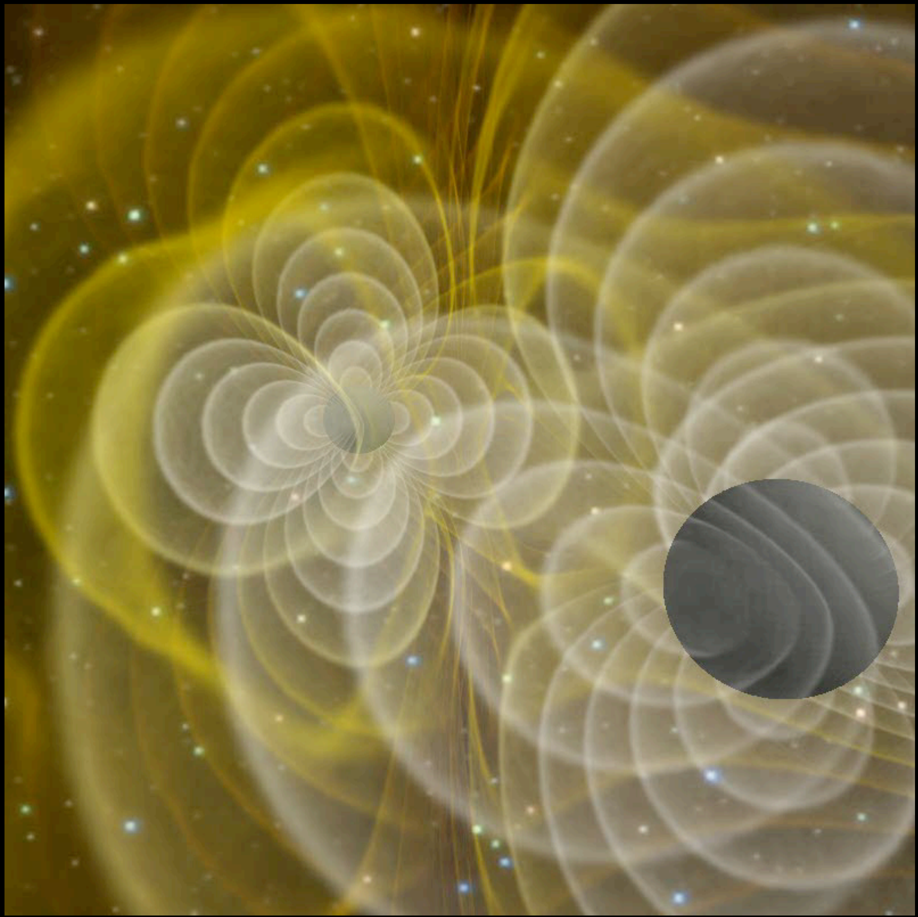
Gravitational Waves

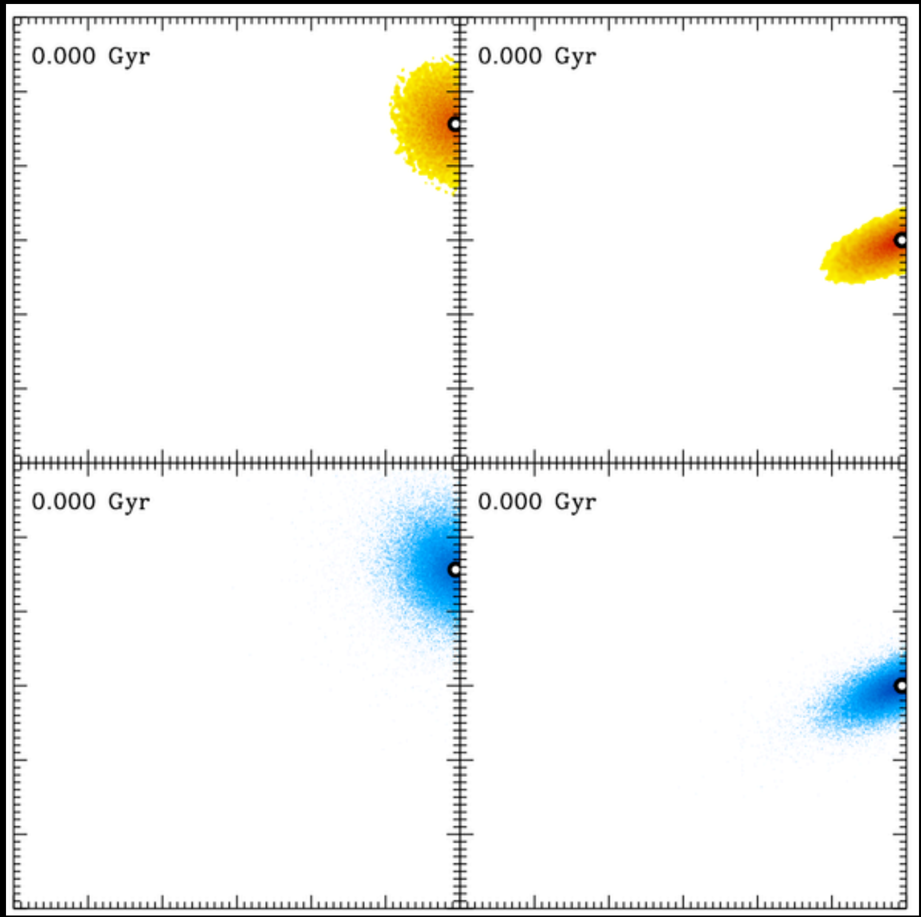
source: ***BH/NS binaries***

detector: ***laser interferometer (such as LIGO or eLISA)***

- Precision: one thousandth the diameter of a proton

Black Hole Recoil

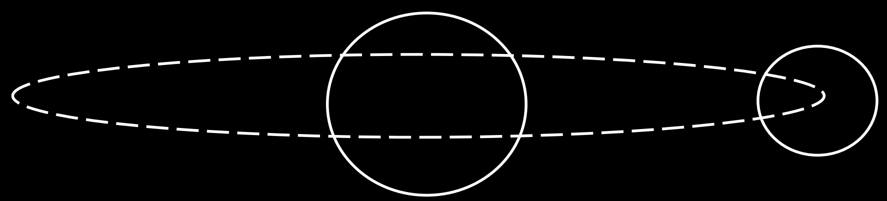




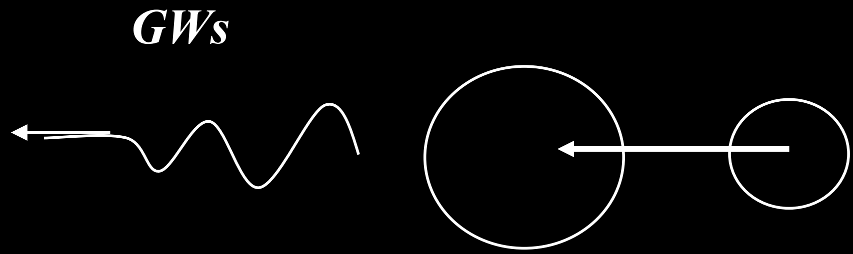
(Centrella et al.   2007)

(Blecha & Loeb 2009)

Gravitational Wave Recoil

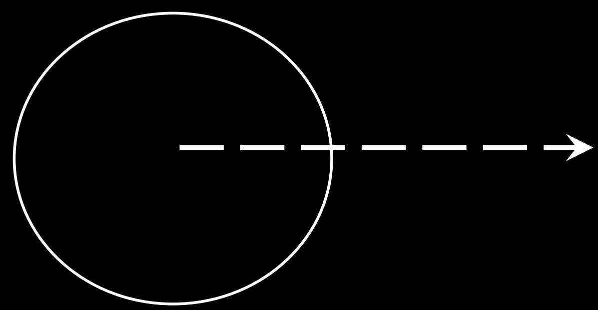


Gravitational Wave Recoil

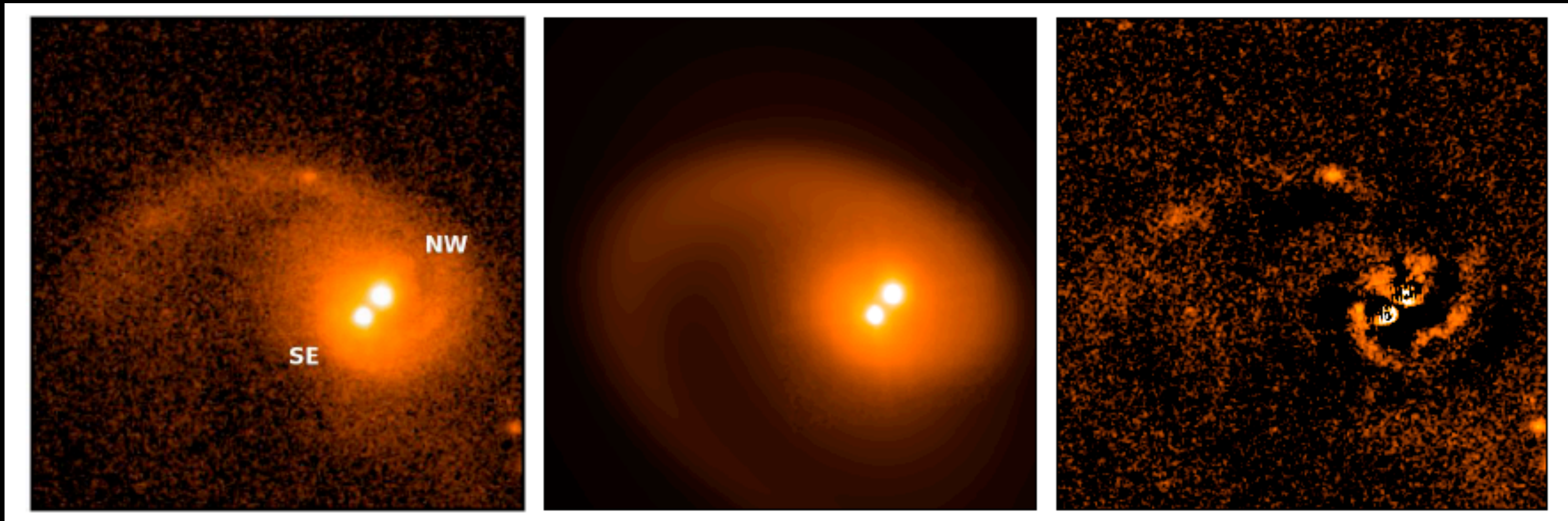


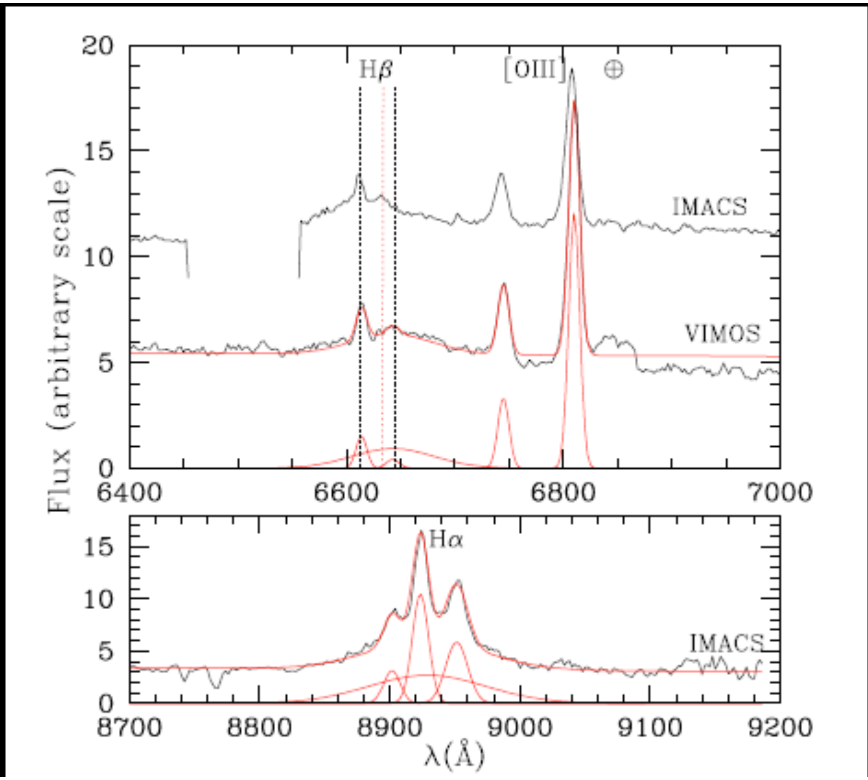
Anisotropic emission of gravitational waves → recoil

Gravitational Wave Recoil



A recoil candidate: CID-42

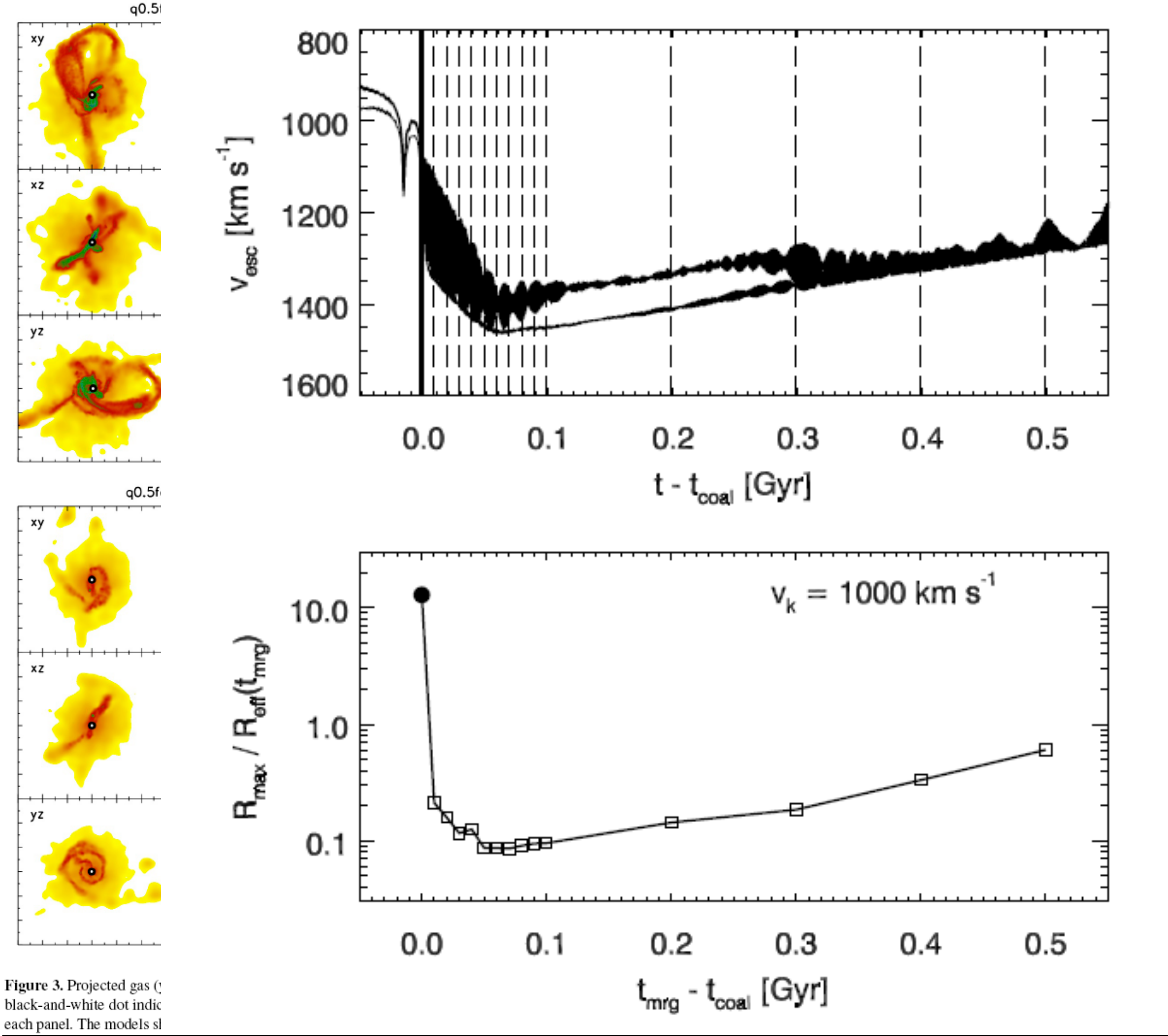


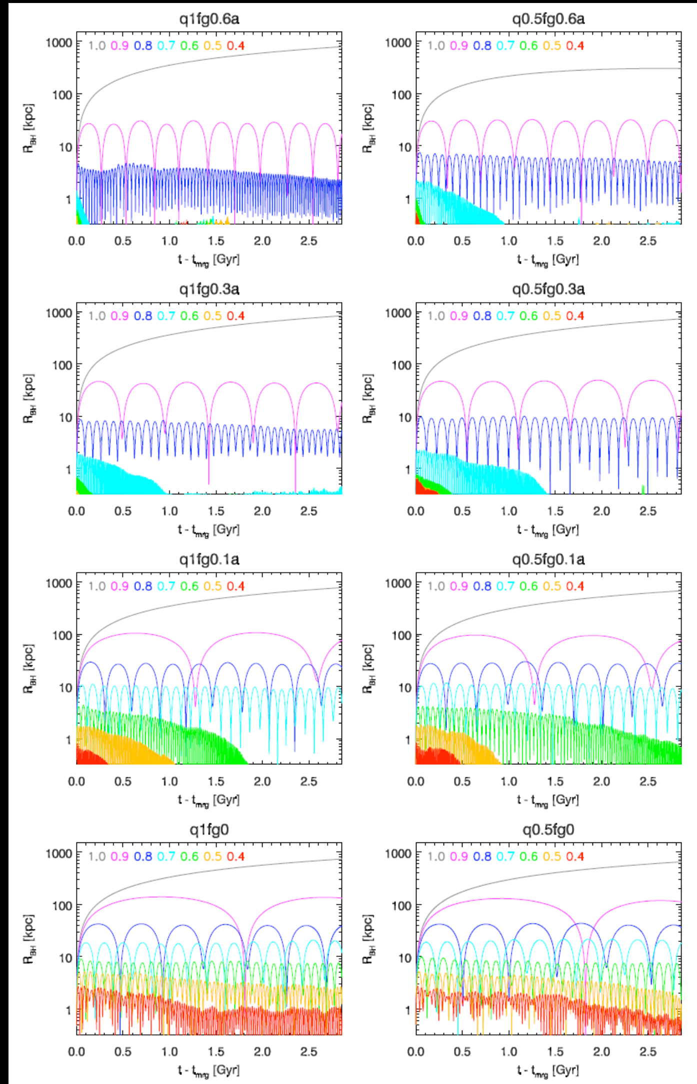


***spatial offset: ~2.5 kpc**
***velocity offset in NLR/BLR of H-beta: ~1,200 km/s**
***z=0.36**

Civano et al. (2010)

Effect of Recoil on Black Hole Growth





Blecha, Cox , Loeb, & Hernquist 2010

Star Clusters Around Recoiled Black Holes

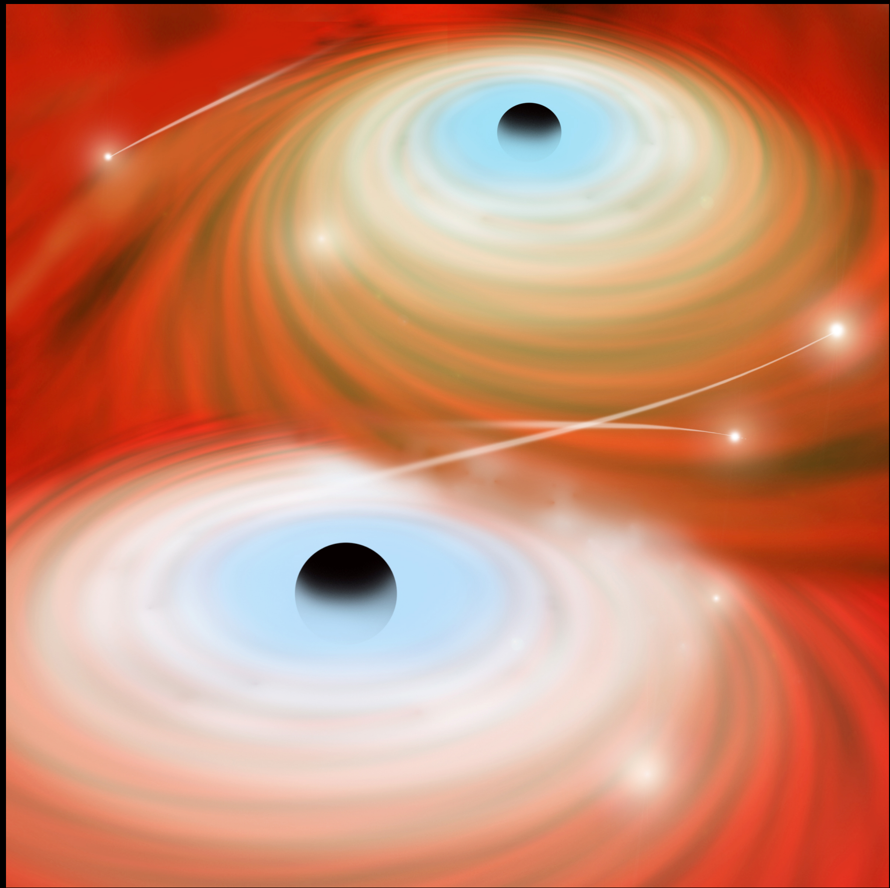
Figure 10. Thumbnails of a diverse selection of candidates. From left to right and top to bottom these are SDSS J114607.52+135233.1, SDSS J130154.22-031323.3, SDSS J052222.65-013302.9, SDSS J084034.69+162319.5, SDSS J084822.47+355630.4, SDSS J093815.82+231234.8, SDSS J121414.73+161215.4, and SDSS J123544.93+193016.9. The scale is the same for all images, with the photometric object located at the center.

O'Leary & Loeb 2008, 2010

arXiv:0809.4262 ; arXiv:1102.3695

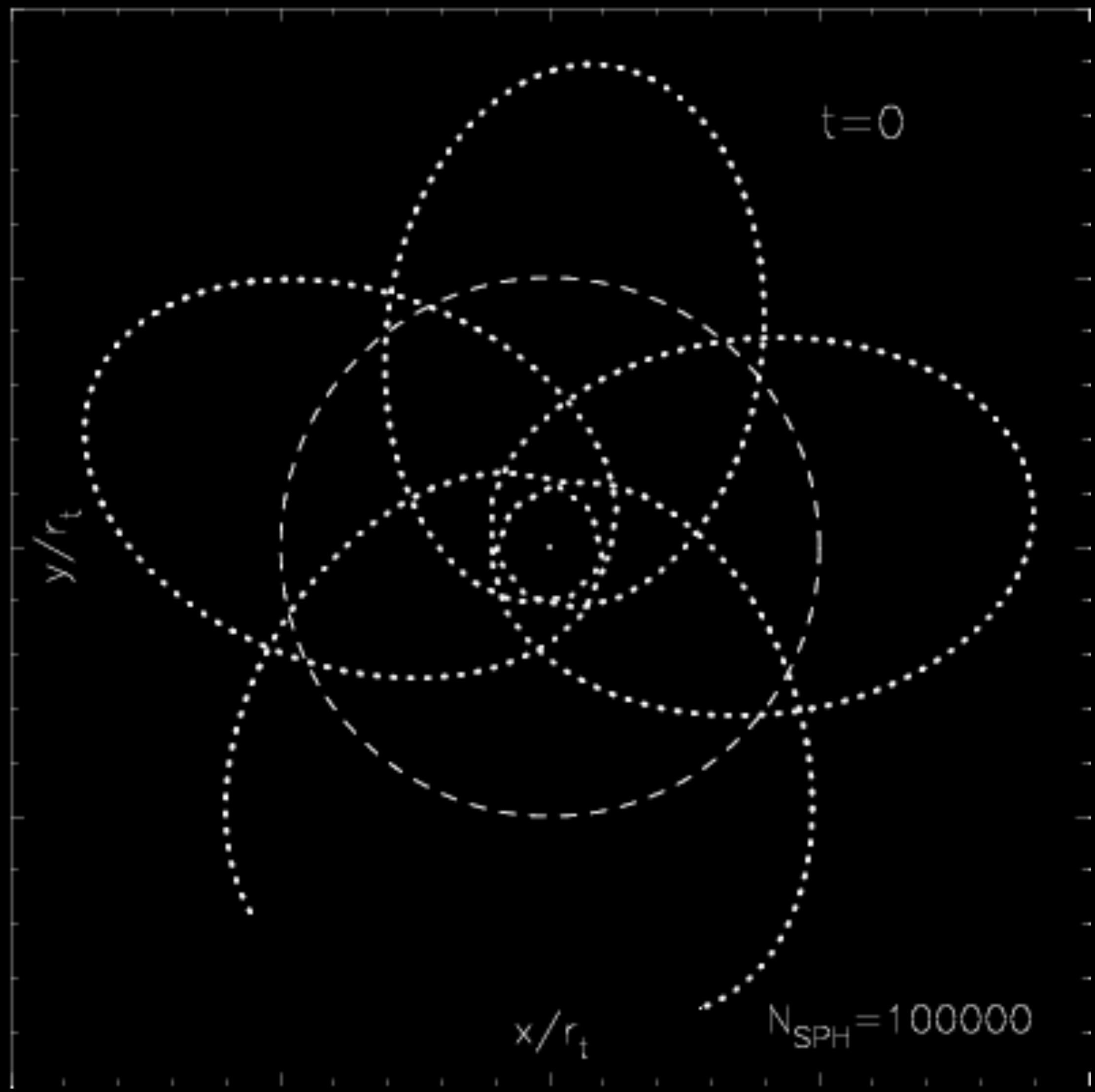
Tidal Disruption of a Star by a Supermassive Black Hole

Tidal Disruption of Stars



- Single BH rate $\sim 10^{-5}\mathrm{yr}^{-1}$ per MW galaxy due to empty loss cone
- BHs with $M_{\rm BH} > 10^8 M_\odot$ swallow the star whole
- Super-Eddington initial feeding rate: $\sim 0.3 m_\star / t_{\rm pericenter}$

Bound Star in a Pseudo-Newtonian Potential (e=0.8,beta=5)

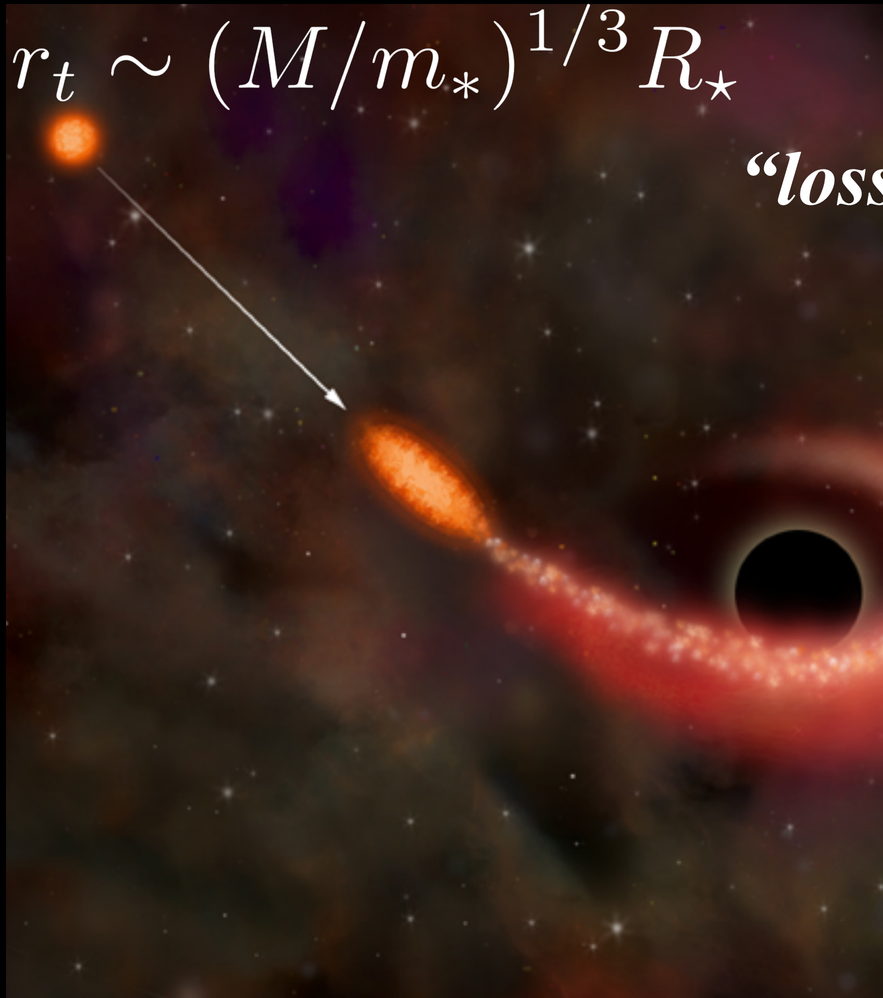


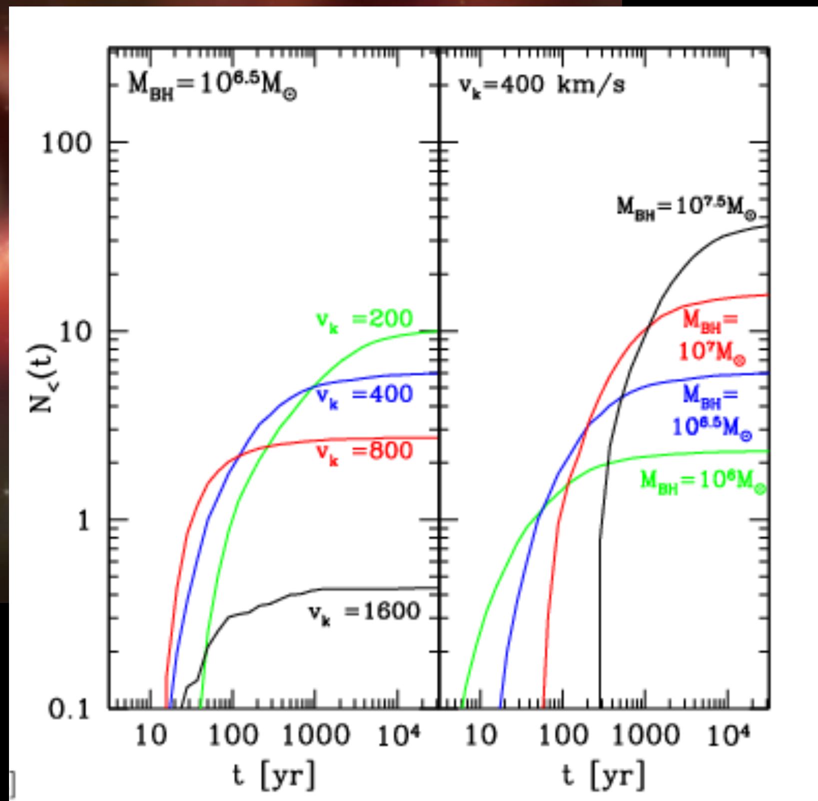
Hayasaki, Stone, and Loeb 2012

EM Counterpart of LISA Sources: Tidal Disruption of Stars

$$r_t \sim (M/m_*)^{1/3} R_\star$$

"loss cone" filled by GW recoil

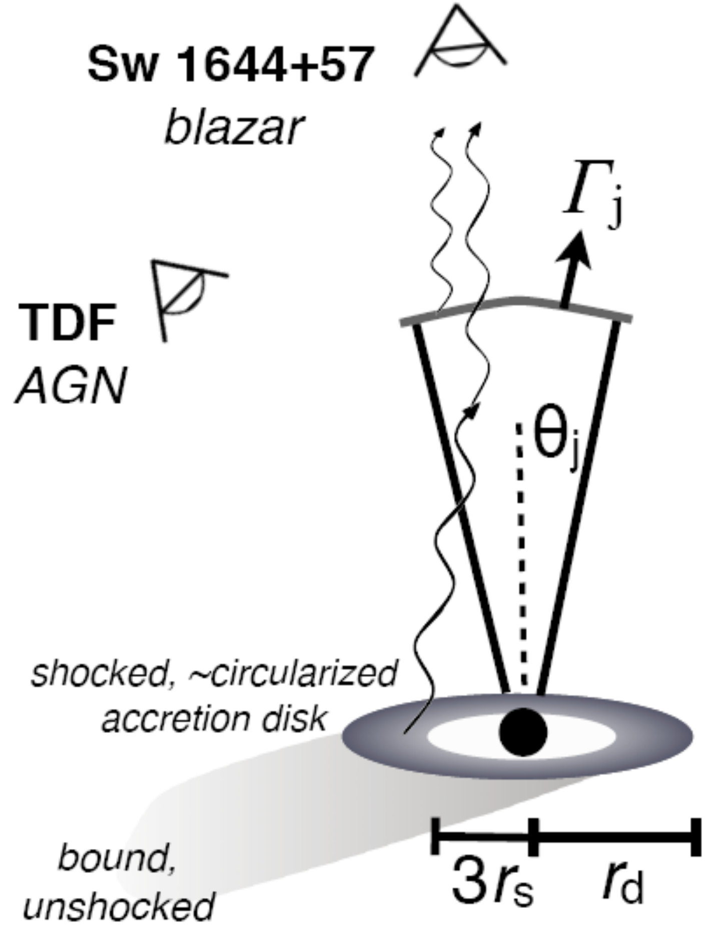


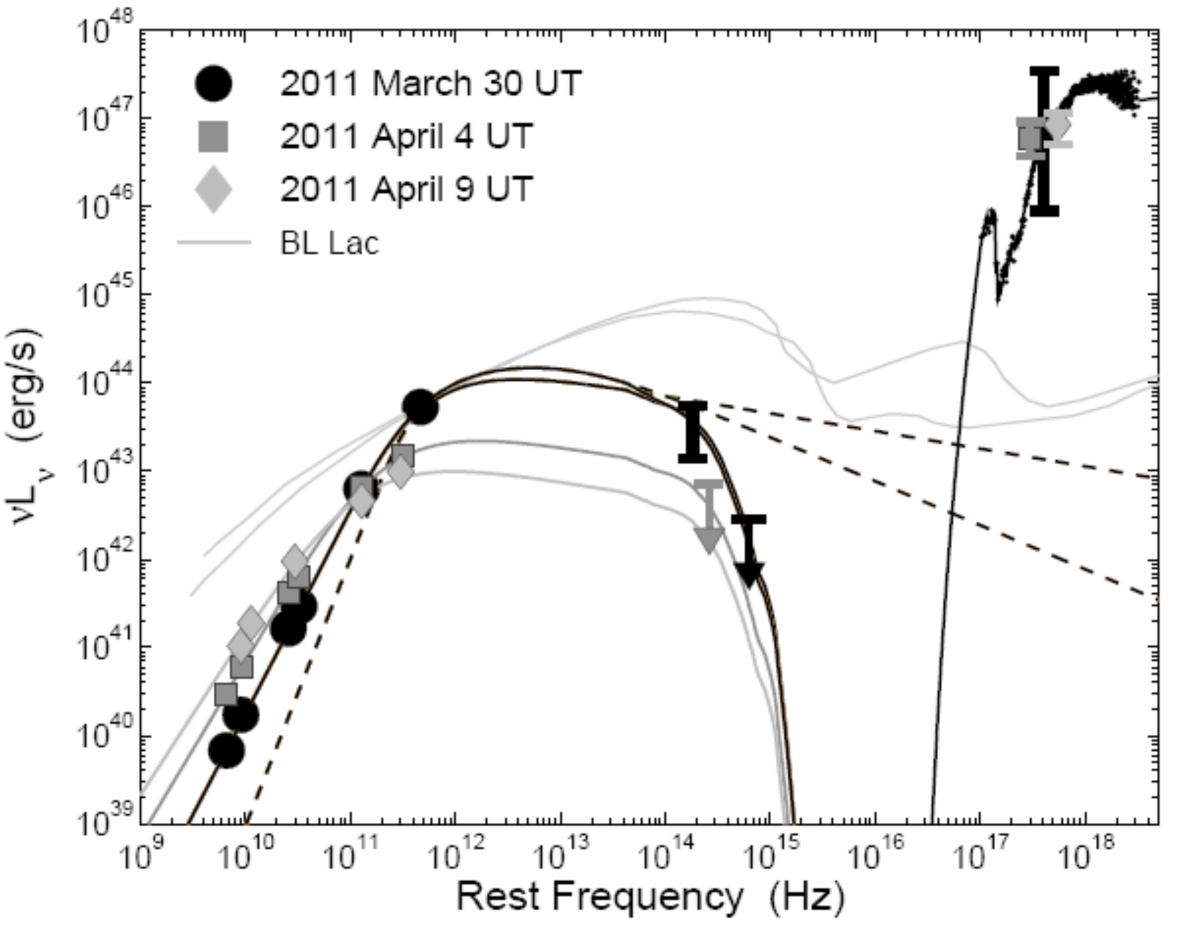


(Stone & Loeb 2010)

A Relativistic Jet from a TDE: Swift 164449.3+573451 (GRB110328A)

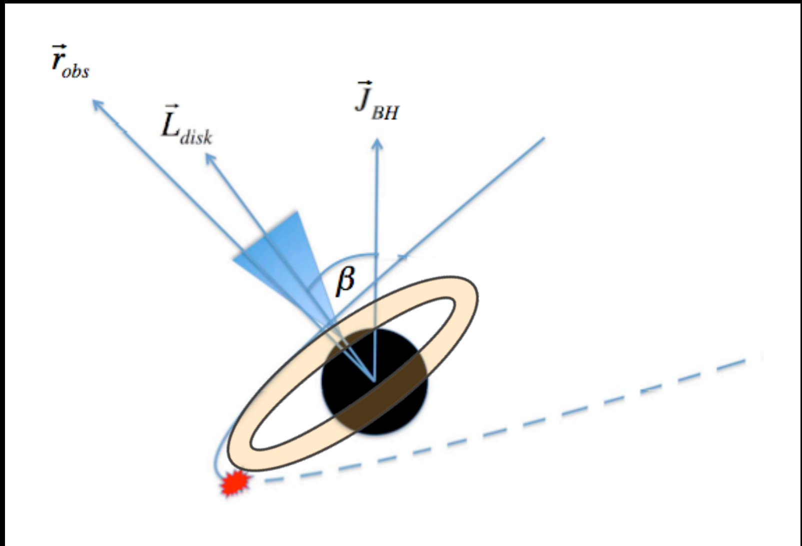
Bloom et al. 2011 ***Zauderer et al. 2011***

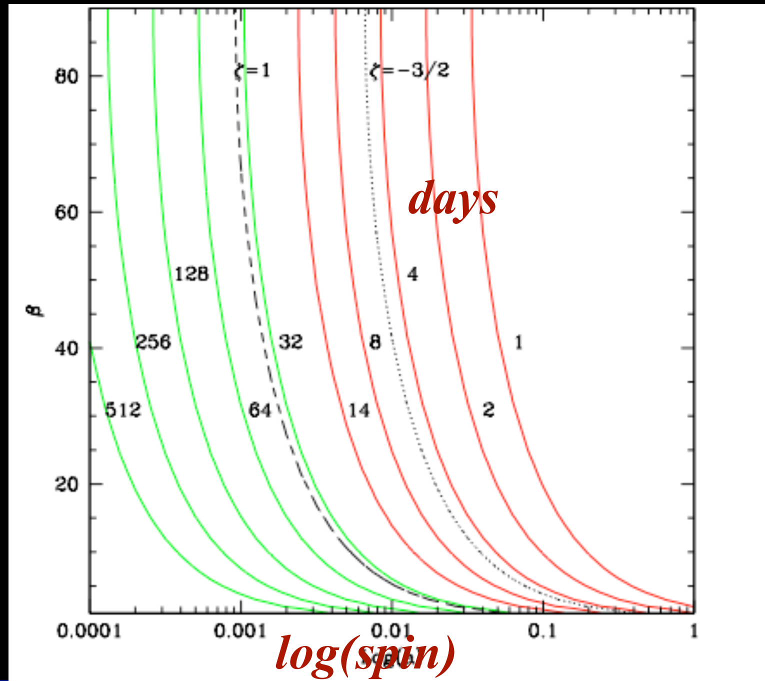




Synchrotron and X-ray peaks are emitted from different regions; bulk Lorentz factor~2-3

Observing Lense-Thirring Precession in Tidal Disruption Flares

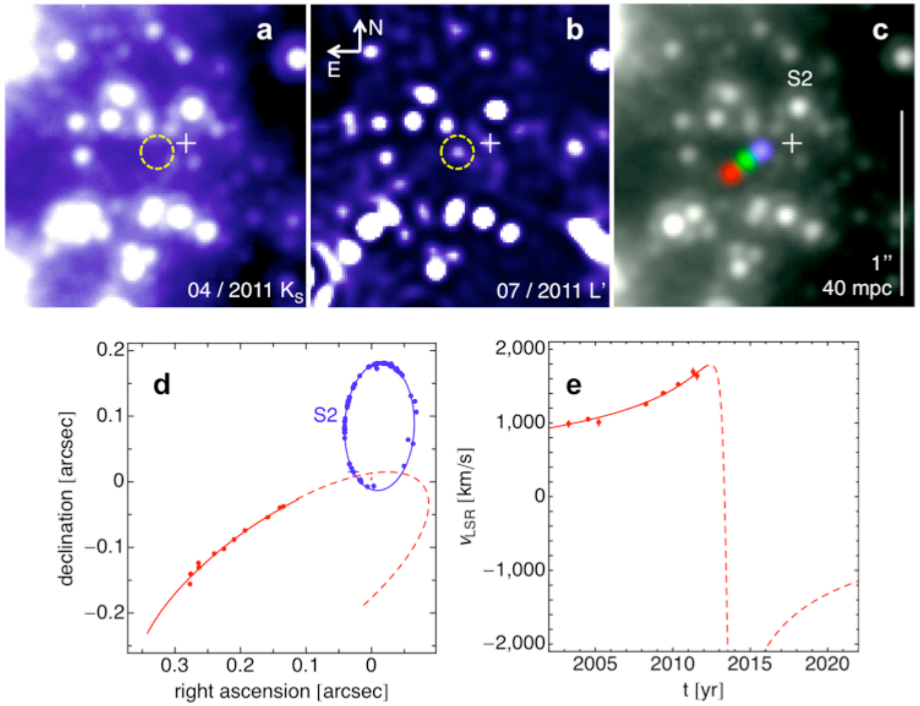


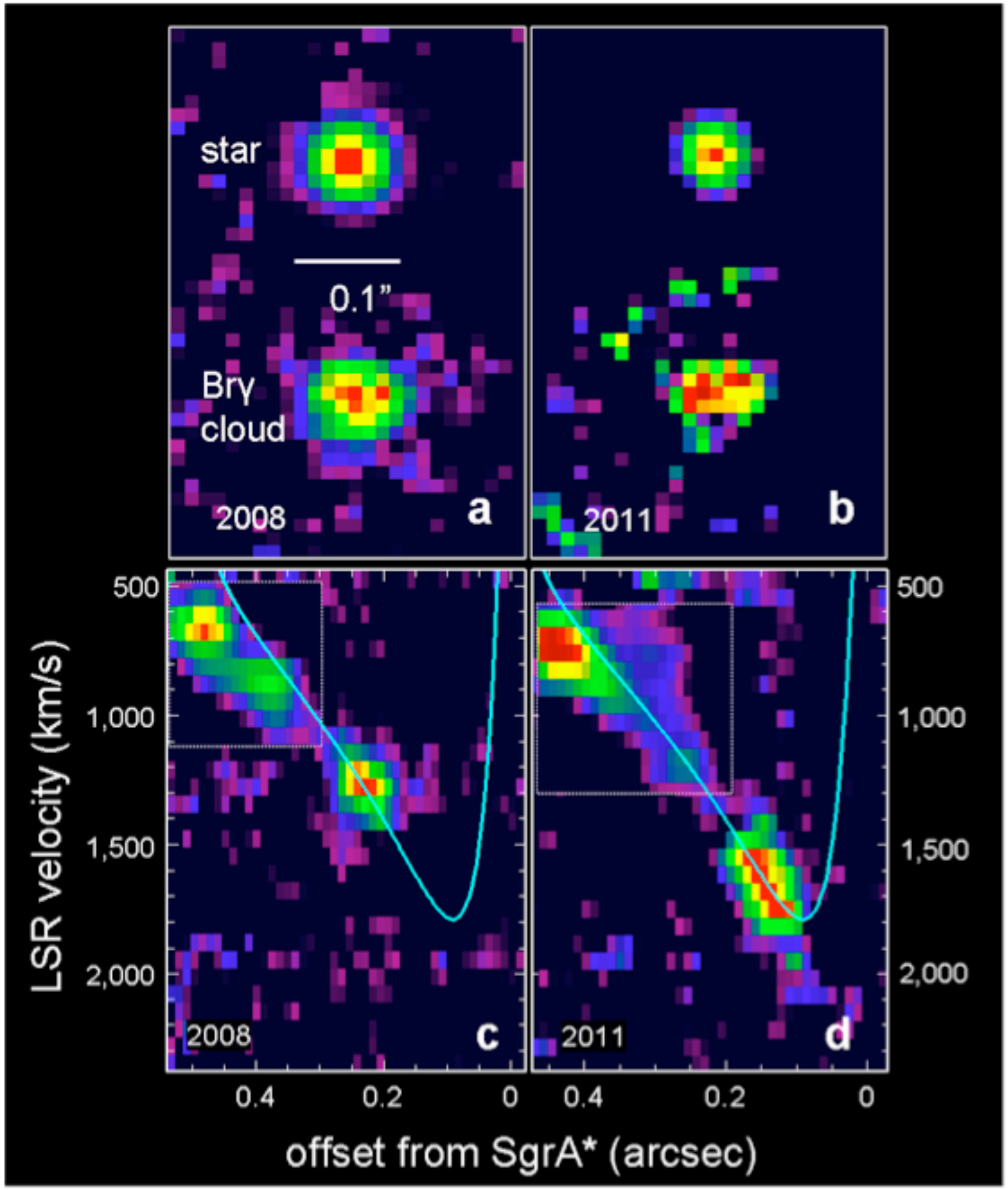


- The value of $a_{\rm BH}$ is extremely low - at most 10^{-2}.
- The initial orbit of the disrupted star was tightly aligned with the black hole equatorial plane, to within $\sim 1°$.
- The jet emission in Swift J164449.3+573451 was not aligned with the disk spin axis.

Stone & Loeb (2011)

A gas cloud on its way towards the super-massive black hole in the Galactic Centre





**Ionized cloud, ~3x10^5 cm^{-3}, ~100AU, electrons at 10^4K, dust at 550K, 3 Earth masses*

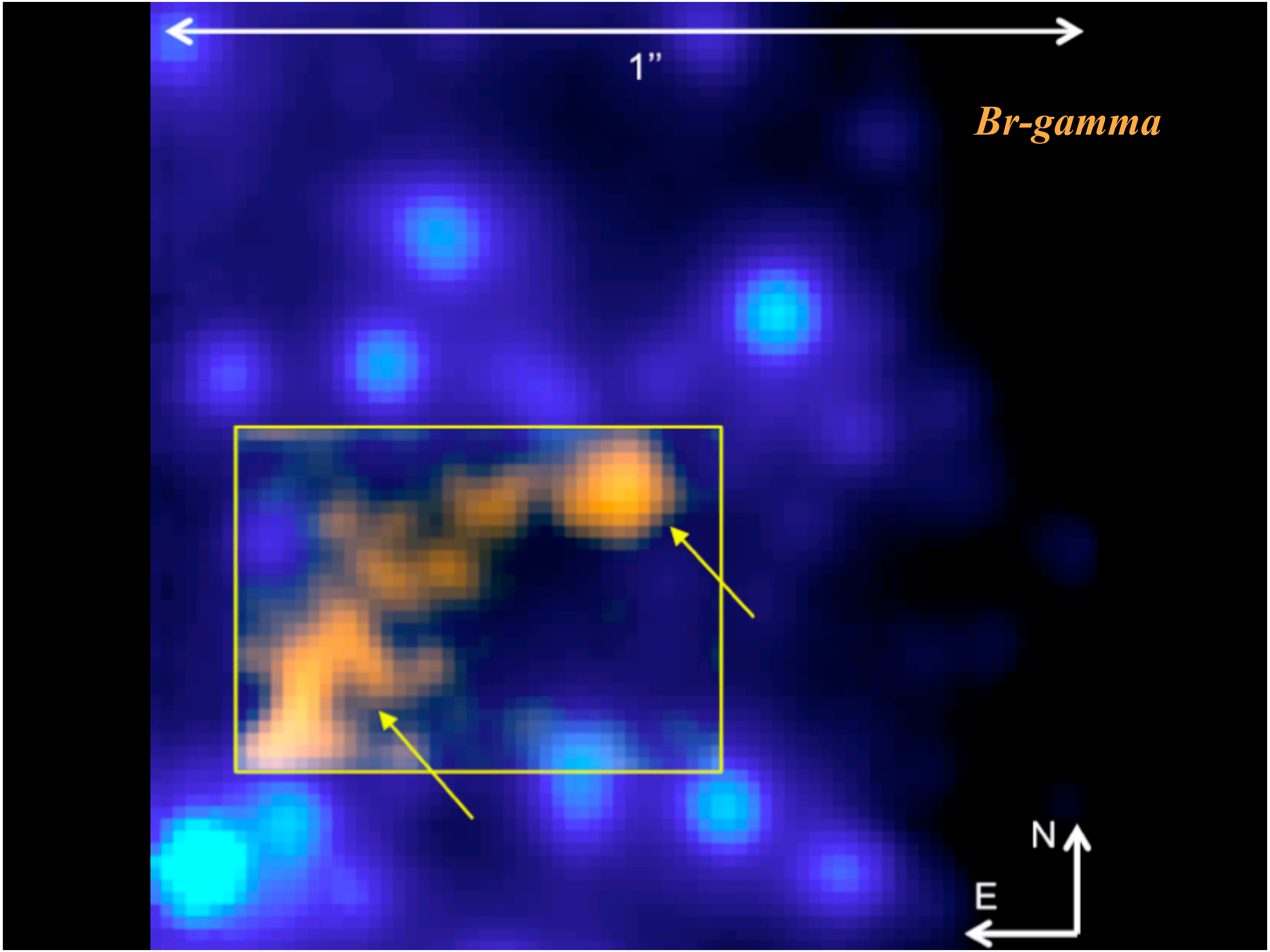
Gillessen et al., Nature (2012)

Latest Data

	Gillessen et al. 2012	Updated fit
semi major axis (mas)	521 ± 28	666 ± 39
eccentricity	0.9384 ± 0.0066	0.9664 ± 0.0026
inclination [°]	106.55 ± 0.88	109.48 ± 0.81
position angle of ascending node [°]	101.5 ± 1.1	95.8 ± 1.1
longitude of periastron [°]	109.59 ± 0.78	108.50 ± 0.74
epoch of periastron [yr]	2013.51 ± 0.04	2013.69 ± 0.04
orbital period [yr]	137 ± 11	198 ± 18

- We confirm that G2 moves on a highly elliptical orbit in the plane of the clockwise stellar disk.
- Our new observations confirm the prediction of accelerated tidal disruption of a diffuse gas cloud inferred from data between 2004 and 2011; the speed and degree of tidal disruption is larger than predicted from these earlier data, however, because the eccentricity of the orbit of G2 is larger (e = 0.966).
- The predicted epoch of pericenter passage has shifted to early September 2013, and the nominal pericenter distance has decreased to 2200 R_S only.
- G2 consists of a comparably compact head (with a velocity shear of 600 km/s by now) and a more widespread tail of at least 400 mas length.
- The observed dynamics is fully consistent with purely Keplerian motion, i.e. we don't detect any hydrodynamic effects.

Gillessen et al. , submitted (2012)

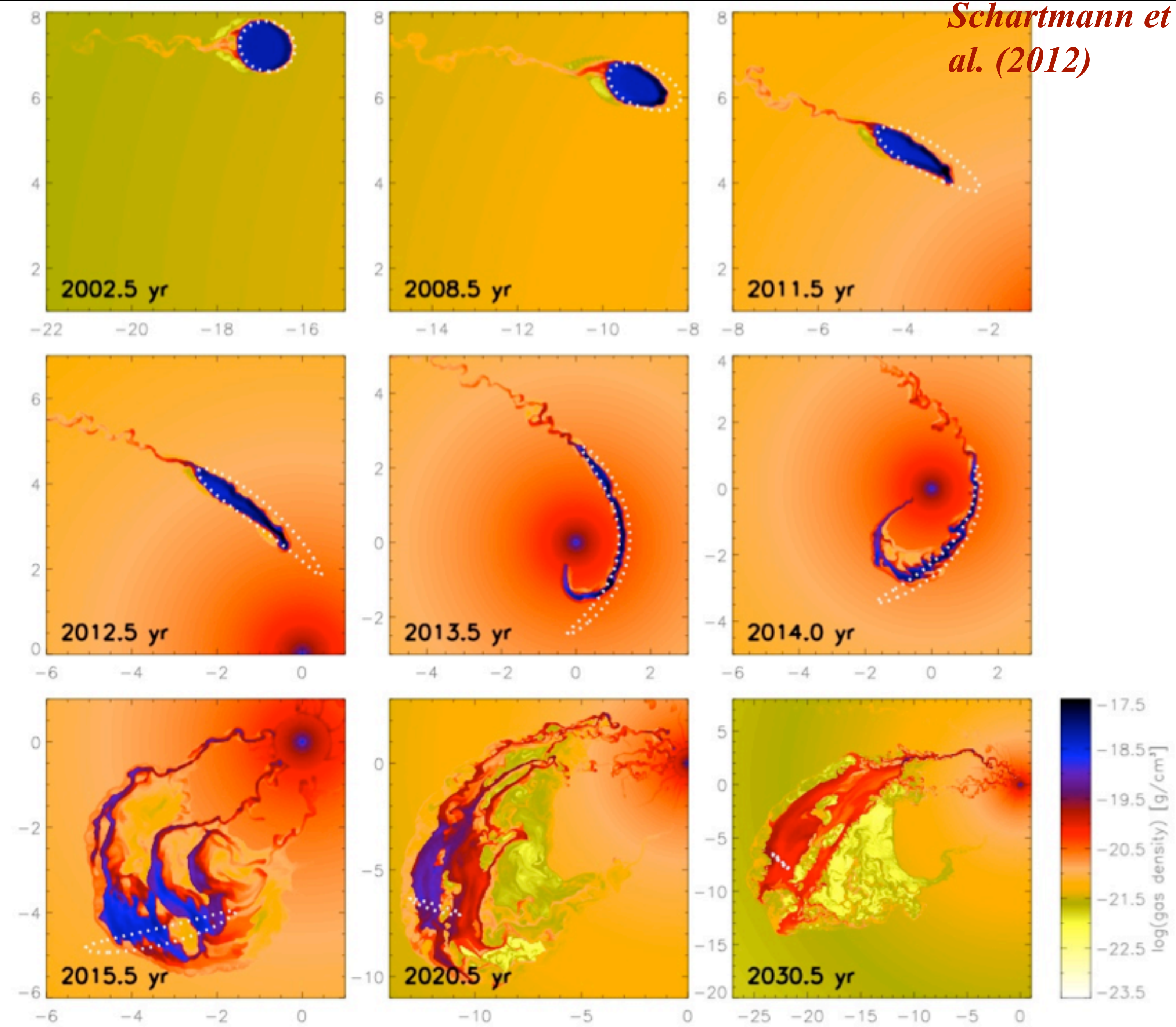

1"
Br-gamma
N
E

www.eso.org

Burkert et al. (2012)

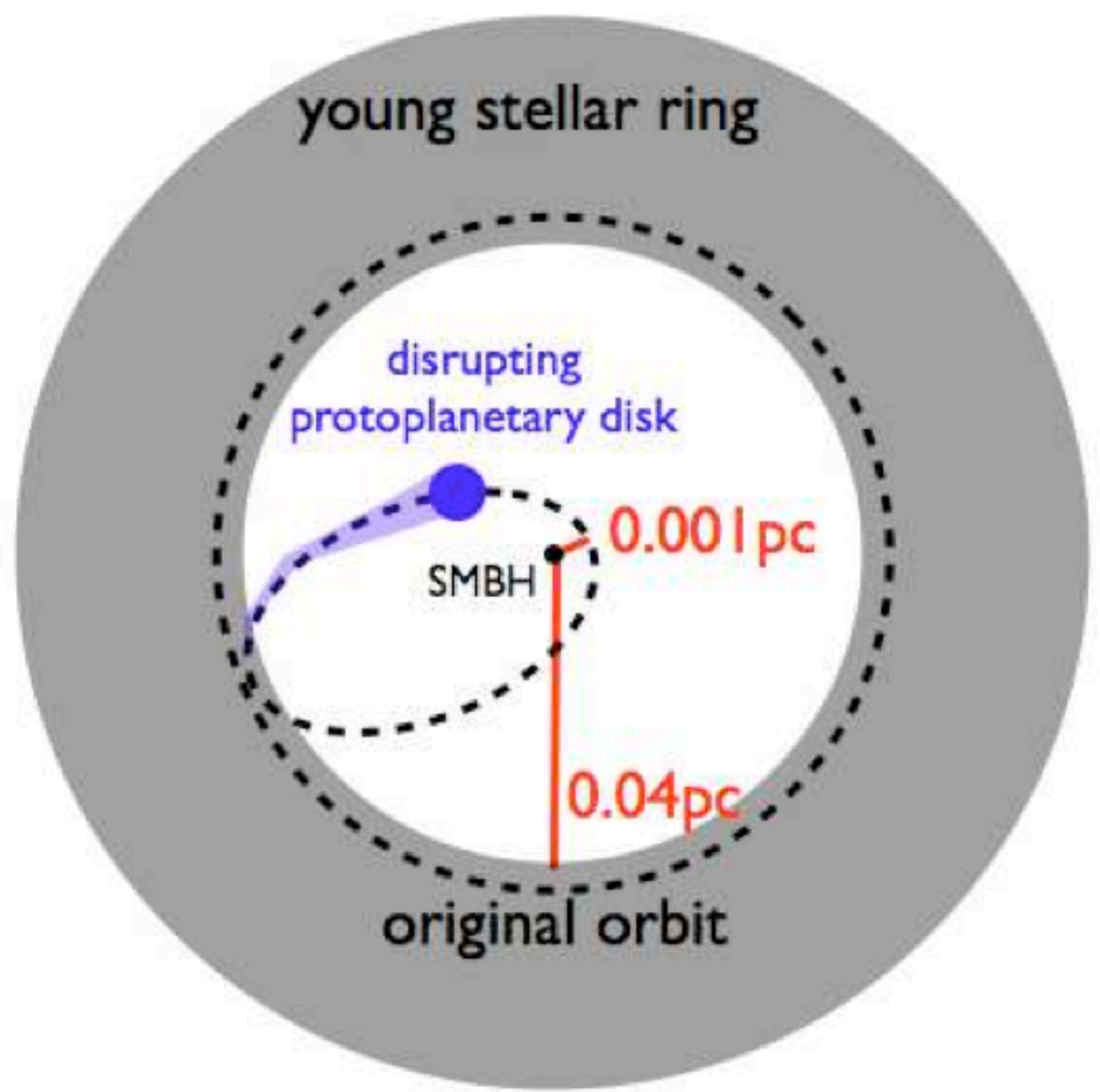
"Pressure-Confined Cloud" Model

Schartmann et al. (2012)



Problem: *why is the head moving on a ballistic orbit with no evidence for ambient ram-pressure?*

Tidal Disruption of a Proto-Planetary Disk Around a Low-Mass Star



Planets form near SgrA

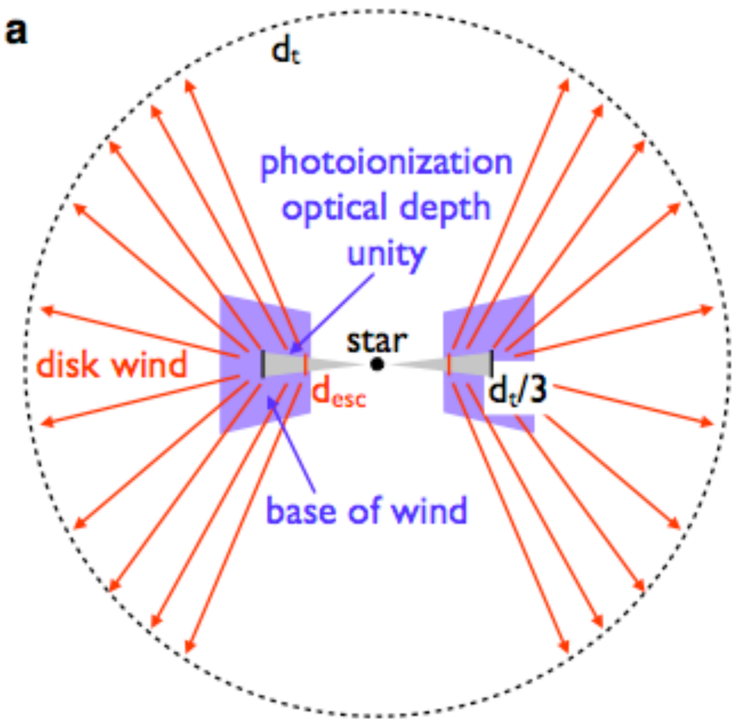
**Flags low-mass stars*

Murray-Clay & Loeb (2012)

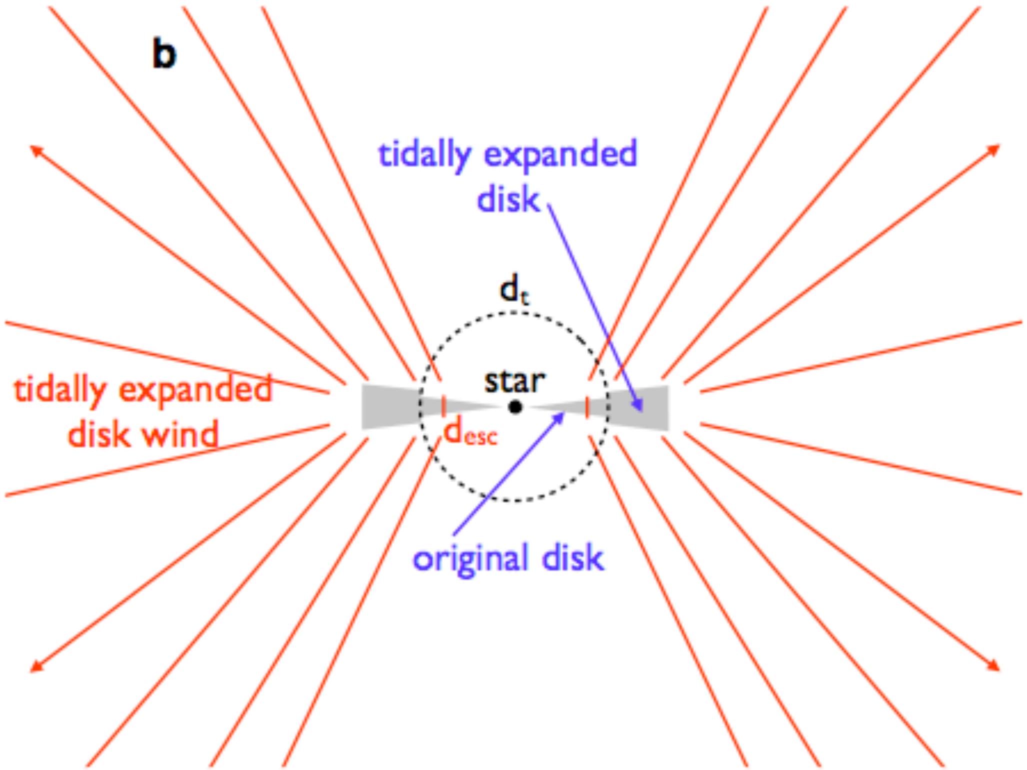
Physical Parameters

- Low-mass star, born in circum-nuclear ring at ~0.04pc, and scattered into orbit a few Myrs ago.

Original

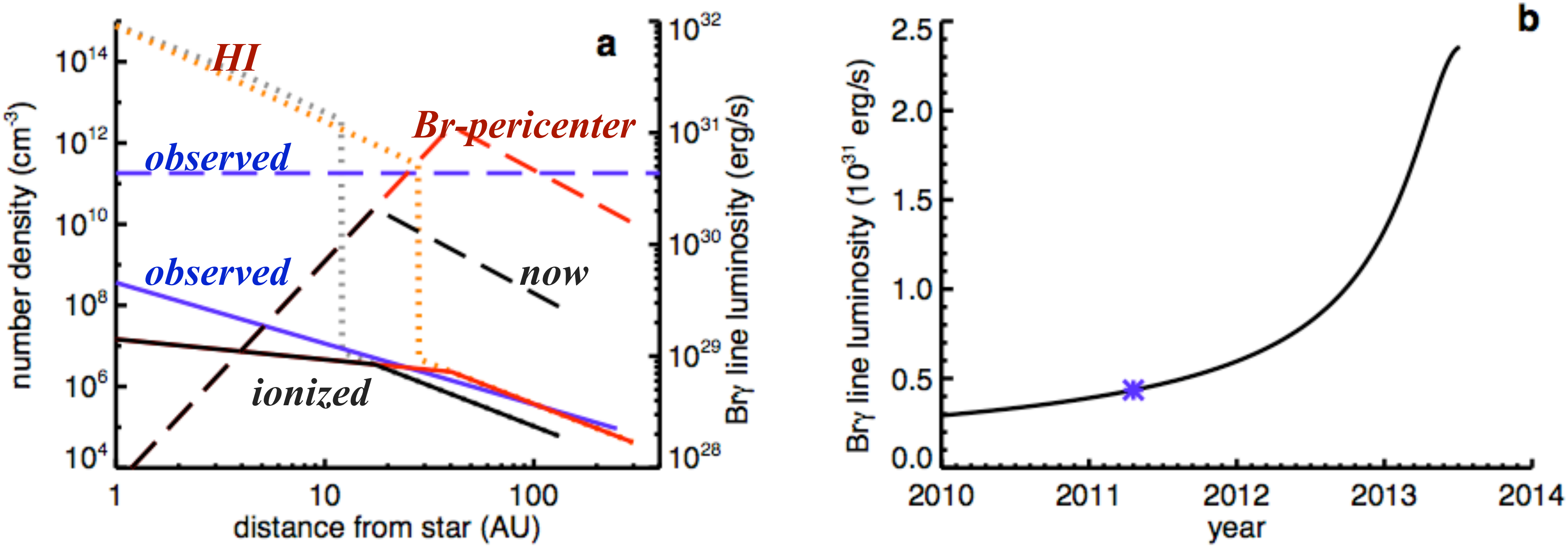


Current



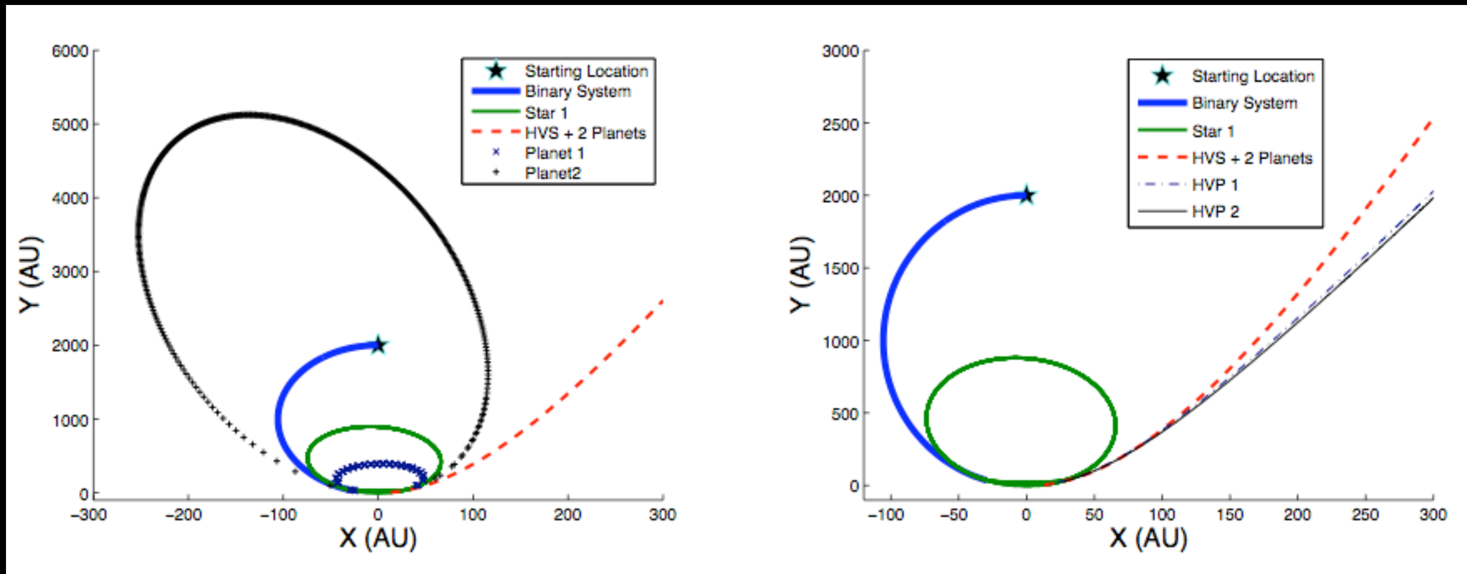
- Low probability for scattering if this represents the first passage, but high probability for multiple passages in which the gas cloud is rejuvinated every pericenter passage (from ~1AU).
- Ionizing background from surrounding O-stars generates a ~10 km/s outflow from tidally-truncated disk of 1-10AU around M-dwarf (too faint to be observable).
- Photoevaporation yields a wind mass loss rate:

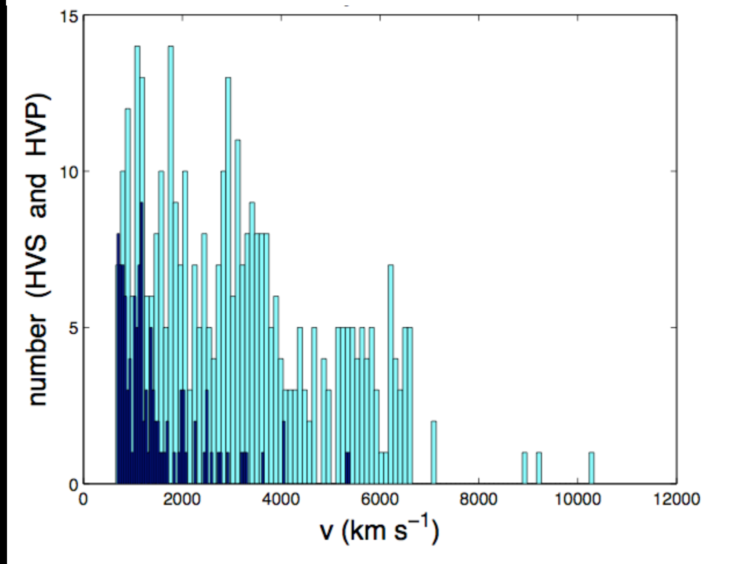
$$\dot{M}_w \sim 10^{-8} M_\odot \ \mathrm{yr}^{-1} (d_{\mathrm{out}}/10\mathrm{AU})^{3/2}$$

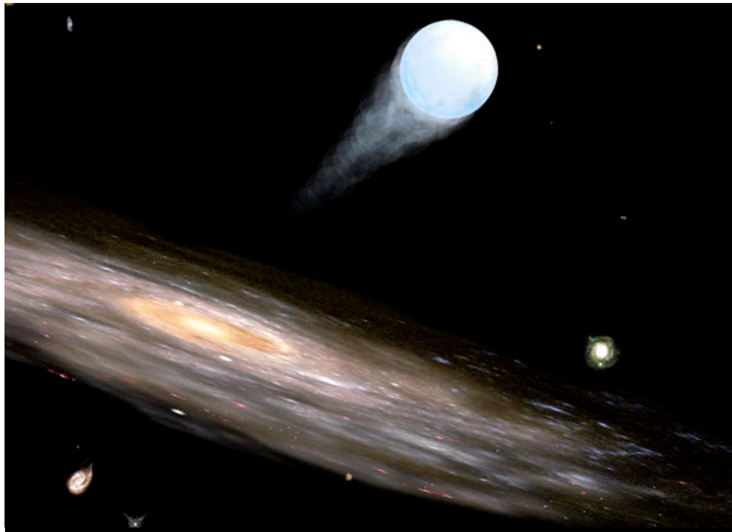


Finally, Muzic et al. reported another star complex IRS 13N at a similar projected separation from SgrA*.[36] This complex has a radius of ∼2000 AU and includes extremely red sources with colors of either dust-embedded stars older than a few Myr or extremely young stars with ages $\lesssim 1$ Myr. The latter interpretation is supported by the fact that six of the sources are close in projection and show very similar proper motion whose coherence is not expected to survive over an orbital time. Such young stellar objects could naturally host proto-planetary disks of the type required to explain the infalling cloud considered here.

*Hypervelocity Planets from Tidal Disruption of Stellar Binaries by SgrA**

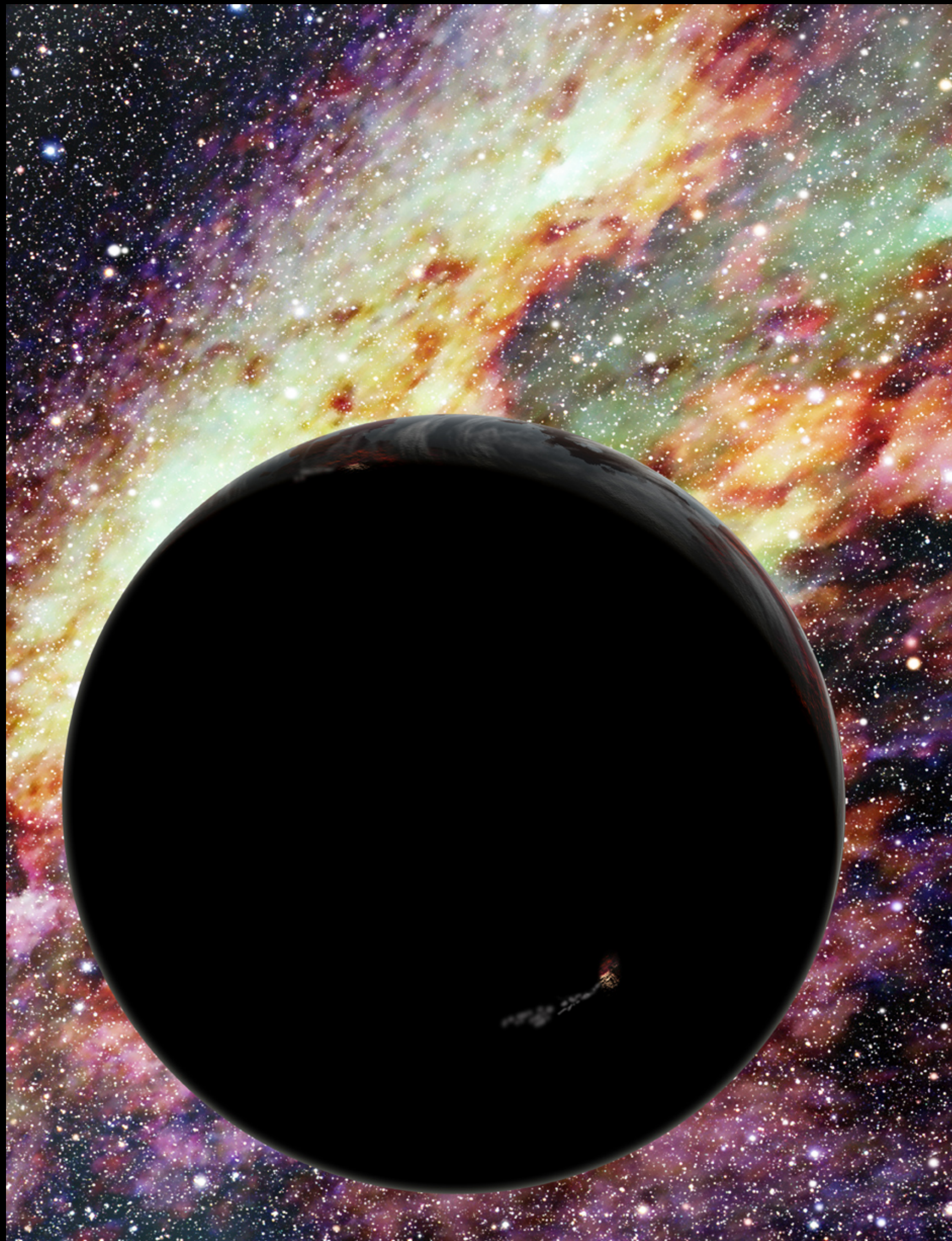




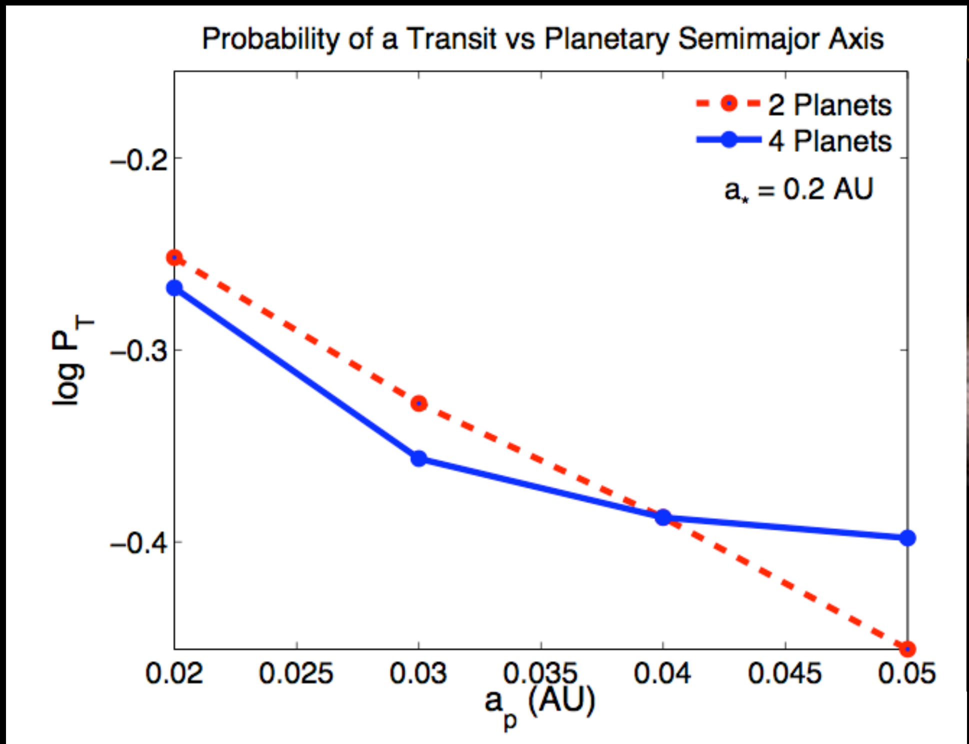


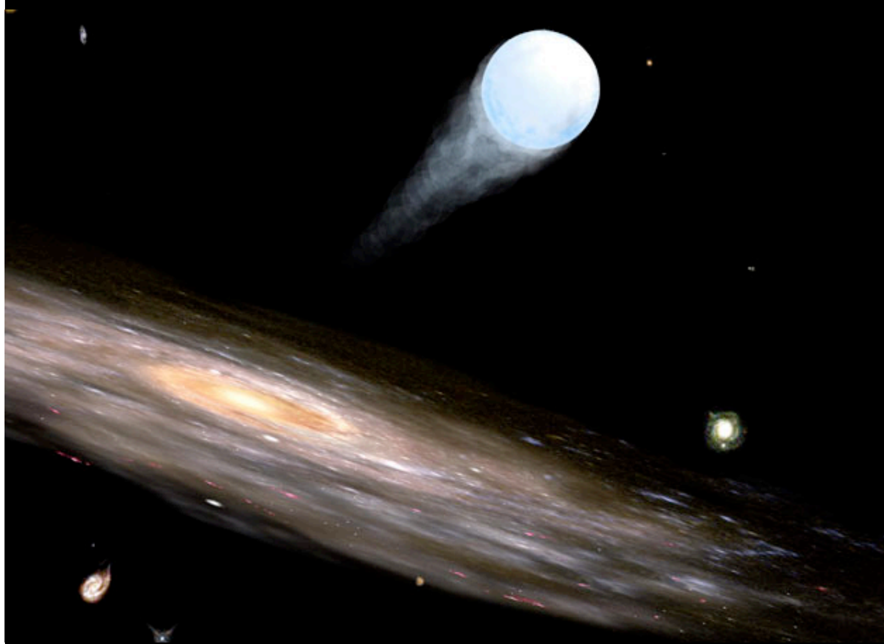
Ginsburg, Loeb, & Wegner (2012)

Possible Outcome: Free Hypervelocity Planets



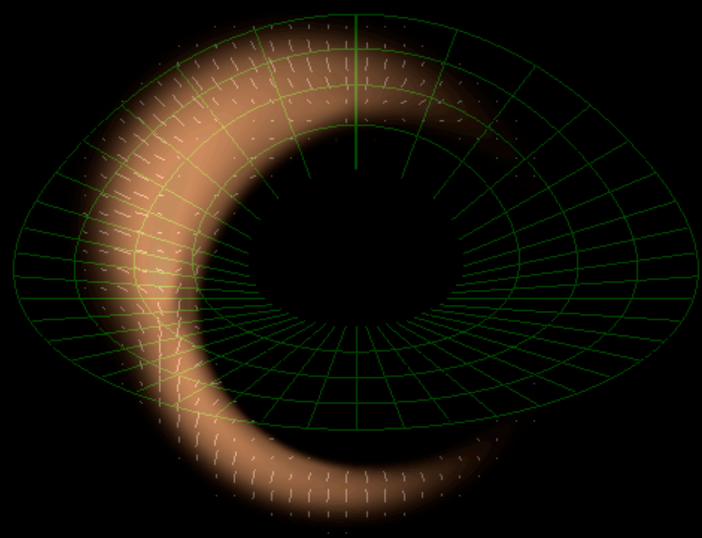
Transits of Hypervelocity Stars





Summary:

1. Direct imaging of the largest silhouettes of black holes (SgrA, M87) will be achievable with upcoming radio telescopes within the next decade.*



Summary:

2. Black hole binaries form in galaxy mergers and produce detectable gravitational waves

3. Coalescence of black hole binaries results in recoils and consequently: offset quasars, floating star clusters in the Milky-Way halo, enhanced rate for tidal disruption of stars