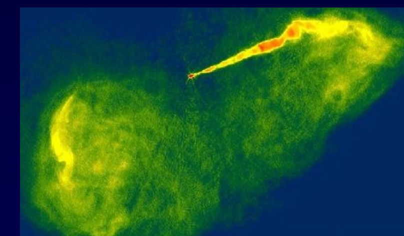
Electromagnetic Signatures of Strong Field Gravity Around Black Holes in Galactic Nuclei

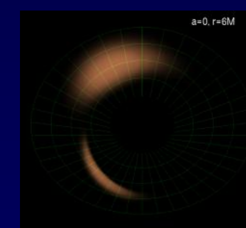
- **<u>esting theory of gas accretion:</u>**

  disks, jets



- **<u>esting . eneral \elativity:</u>**

  strong field gravity



Avi Loeb

Institute for Theory & Computation

Harvard University

S-Stars Orbits Around SgrA*

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

$$d_{\mathrm{GC}} = 8.4 \pm 0.4\mathrm{kpc}$$

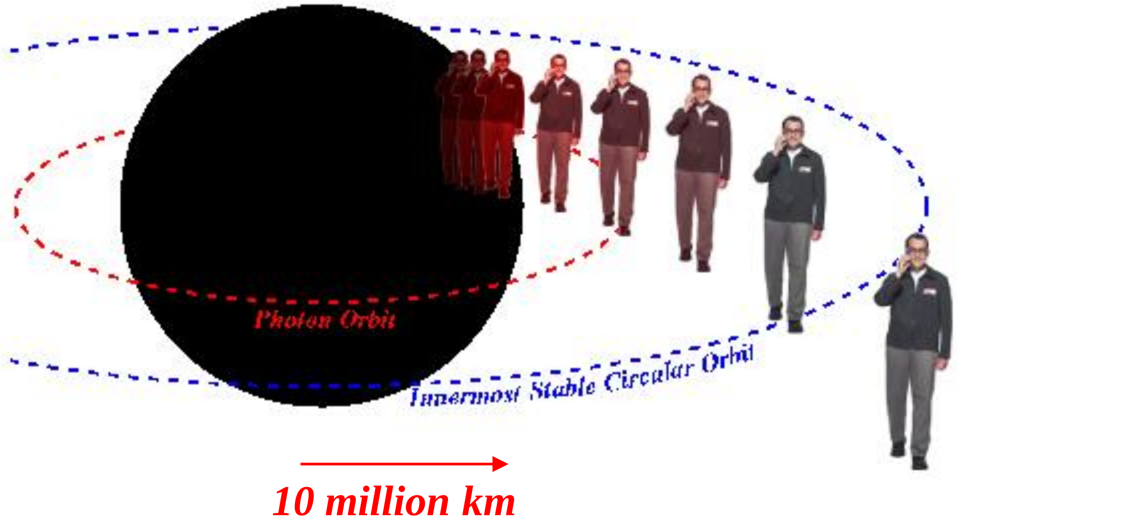
(BH at rest in GC)

Ghez et al. 2008; Genzel et al. 2008

SgrA is the largest black hole on the sky*

Can you hear me now?

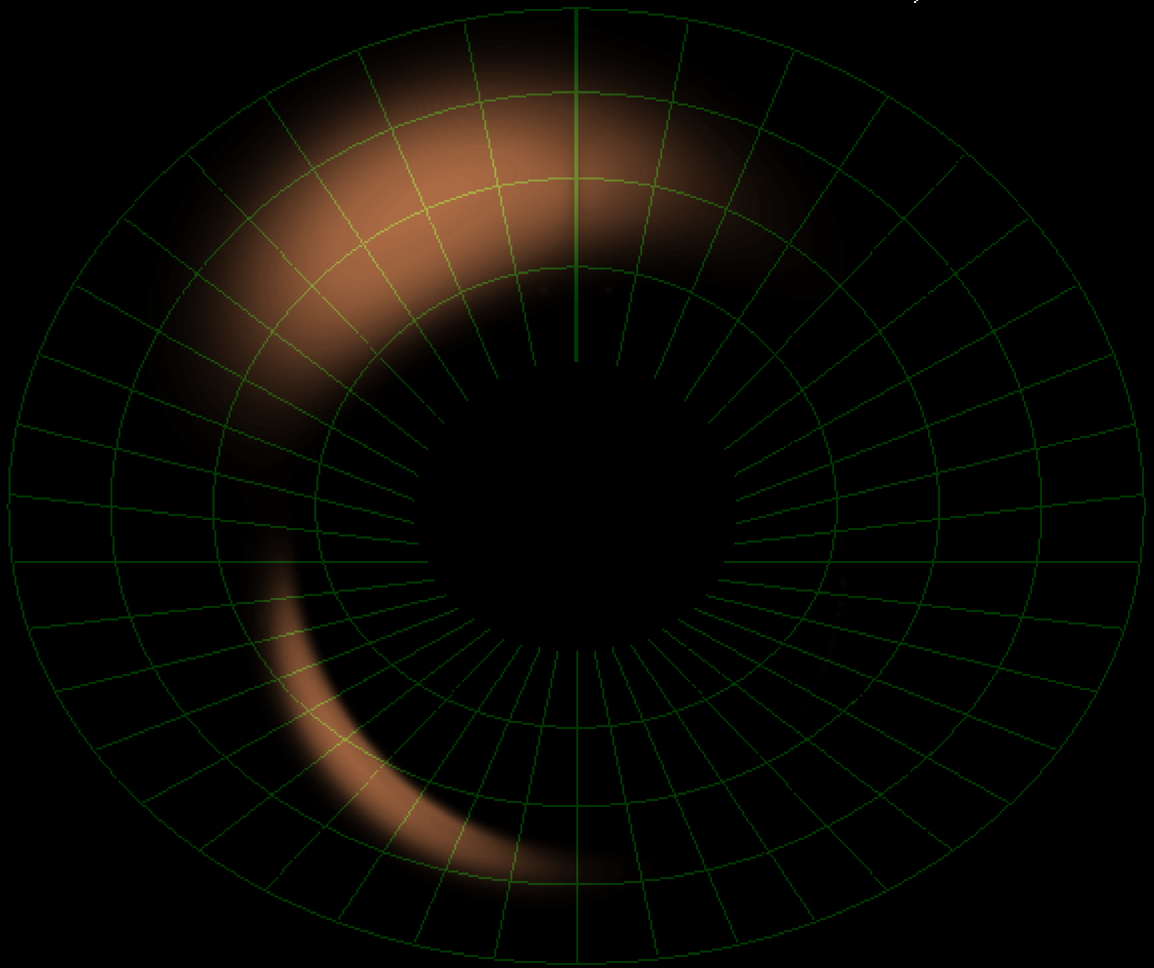
$$\left(\frac{GM_{\mathrm{BH}}}{R^2_{\mathrm{Sch}}}\right) \sim 5 \times 10^5 g$$

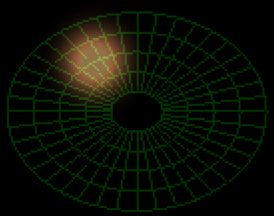


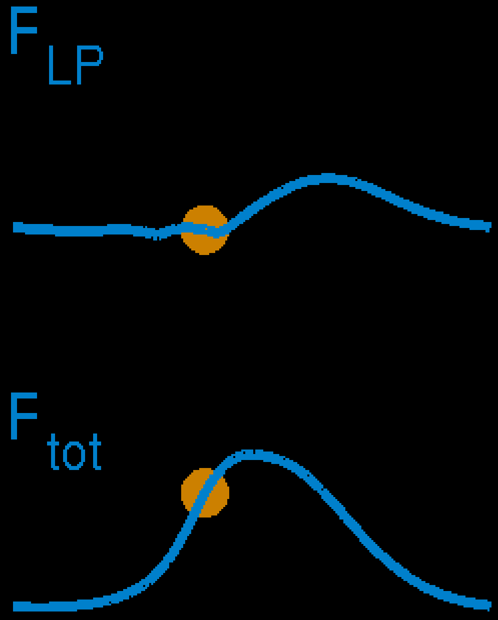
No, but no worries - you will be able to hear us for ~10 minutes until you reach the singularity…

Is general relativity a valid description of strong gravity?

a=0, r=6M





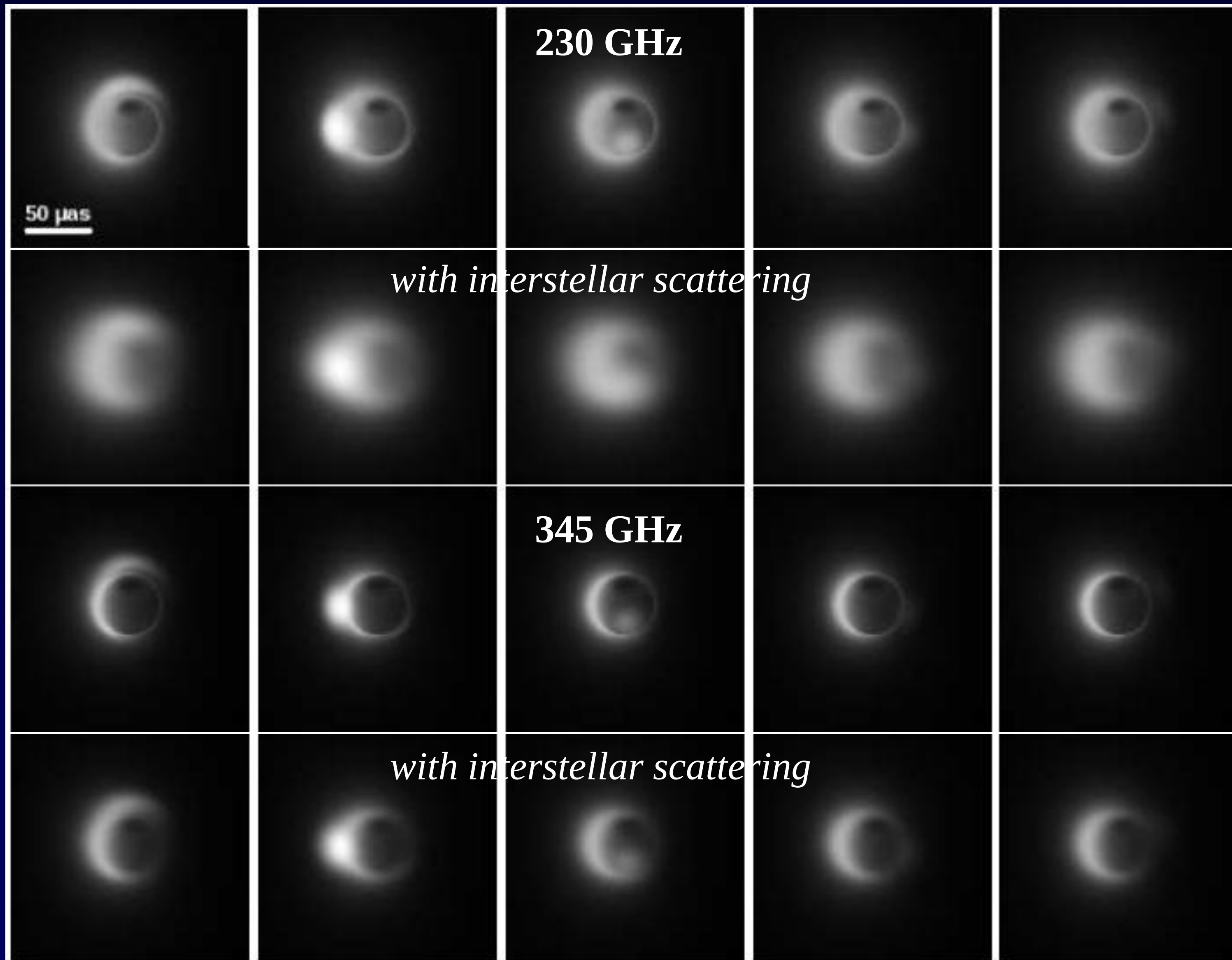


Broderick & Loeb, 2006, MNRAS, 367, 905

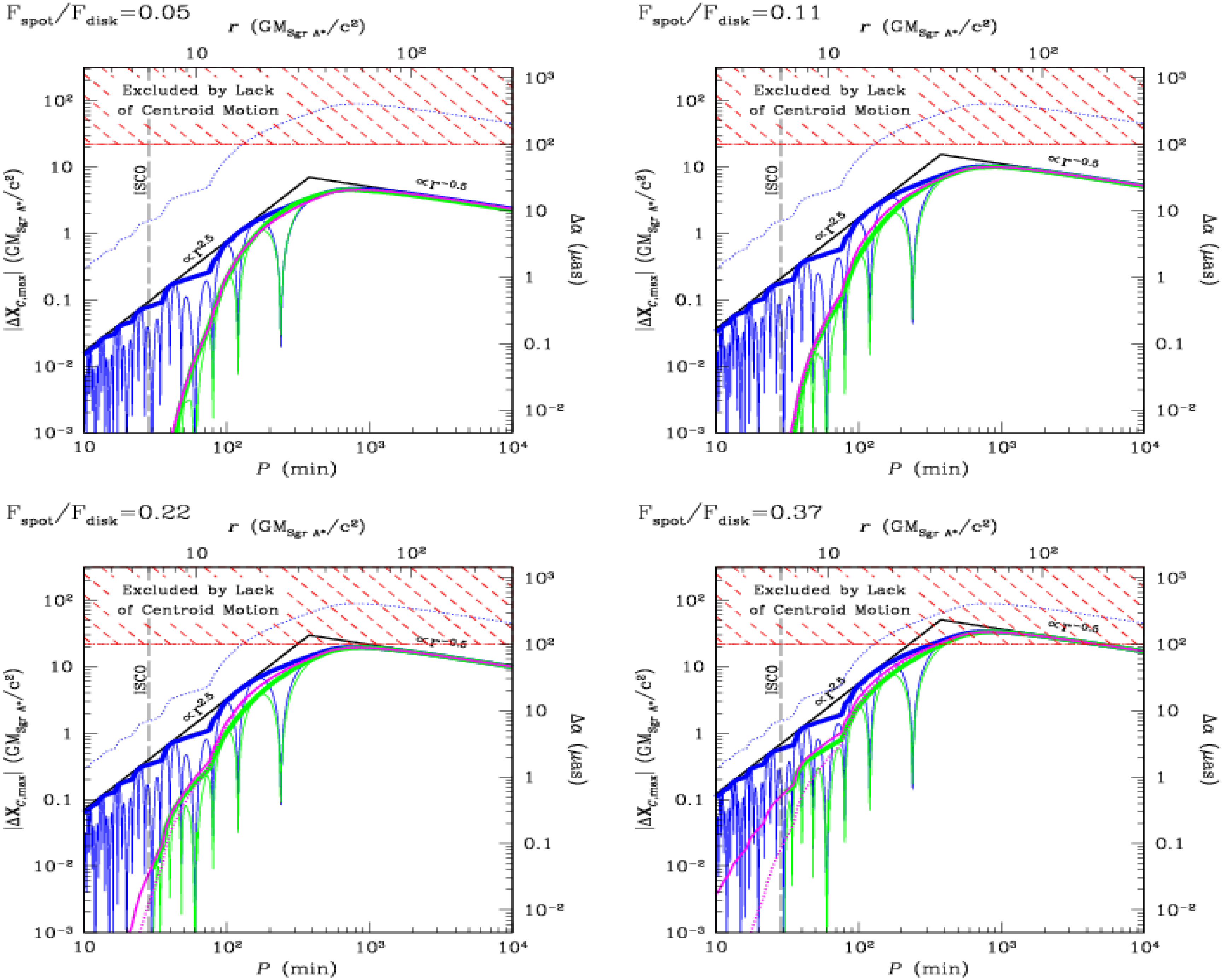
Three Fortunate Coincidences

- 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 →



F_{spot}/F_{disk}=0.05
F_{spot}/F_{disk}=0.11
F_{spot}/F_{disk}=0.22
F_{spot}/F_{disk}=0.37
r ($GM_{Sgr A*}/c^2$)
Excluded by Lack of Centroid Motion
ISCO
$\propto P^{2.5}$
$\propto P^{-0.5}$
$|\Delta X_{c,max}|$ ($GM_{Sgr A*}/c^2$)
$\Delta\alpha$ (μas)
P (min)

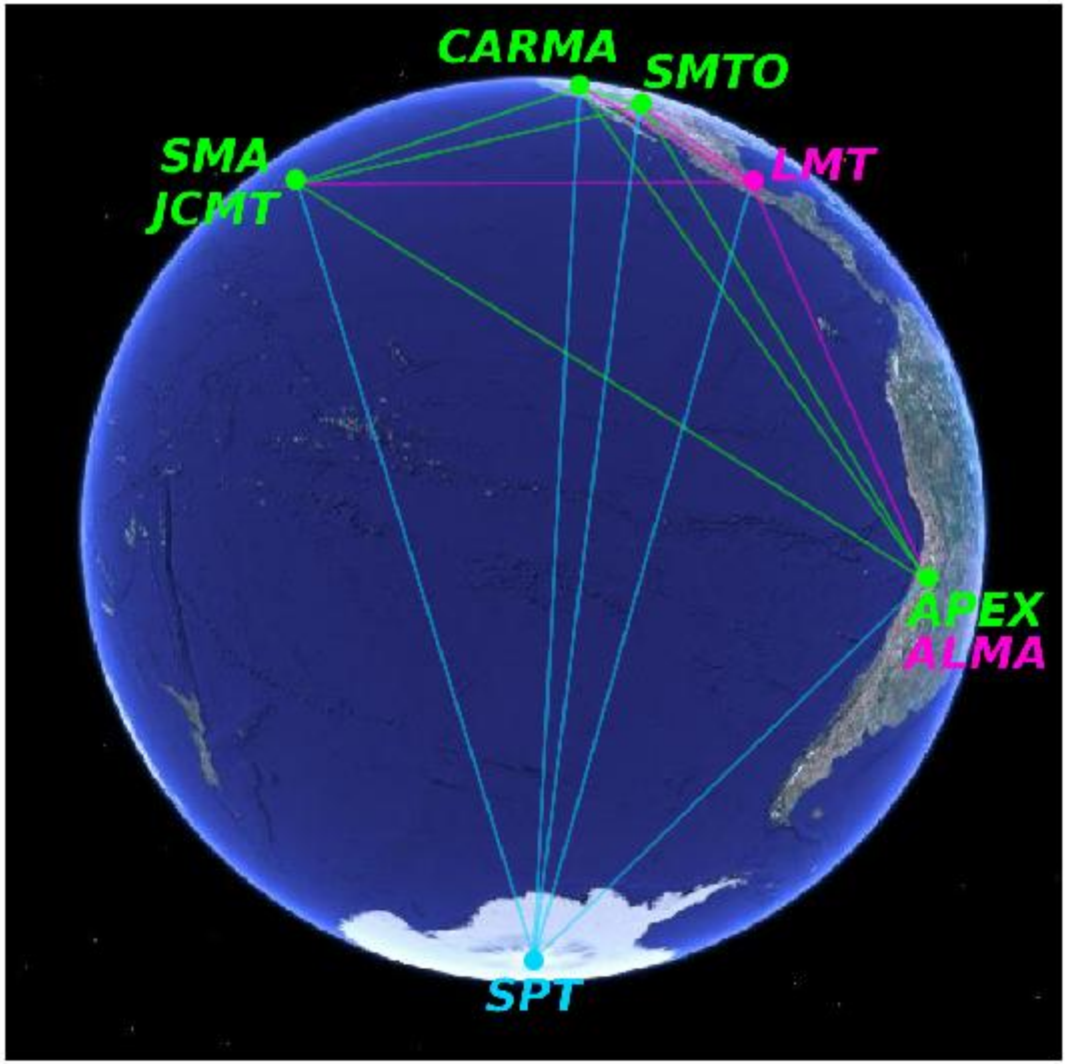


Figure 3: Existing and upcoming sub-millimeter radio telescopes in the Western hemisphere as seen from Sgr A*. Green telescopes already exist and are ready to be phased into a small array. The *Large Millimeter Telescope* (LMT) will begin operations at sub-millimeter wavelengths sometime next year. The *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 pro-

1.3mm VLBI (Doeleman et al. 2008)

ARO/SMT (Arizona); CARMA(California); JCMT (Hawaii)

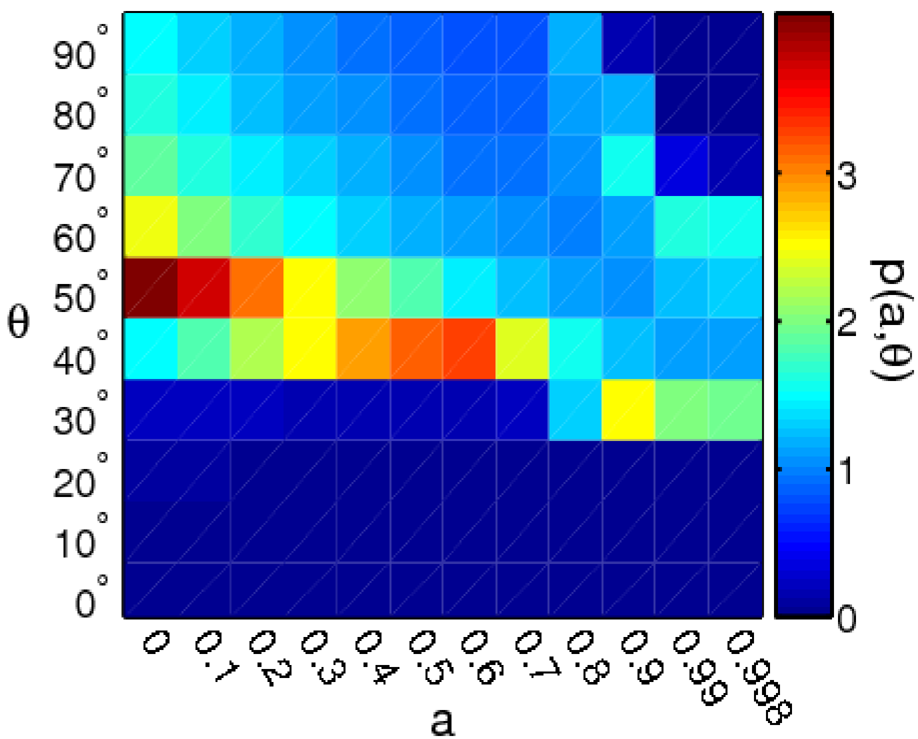
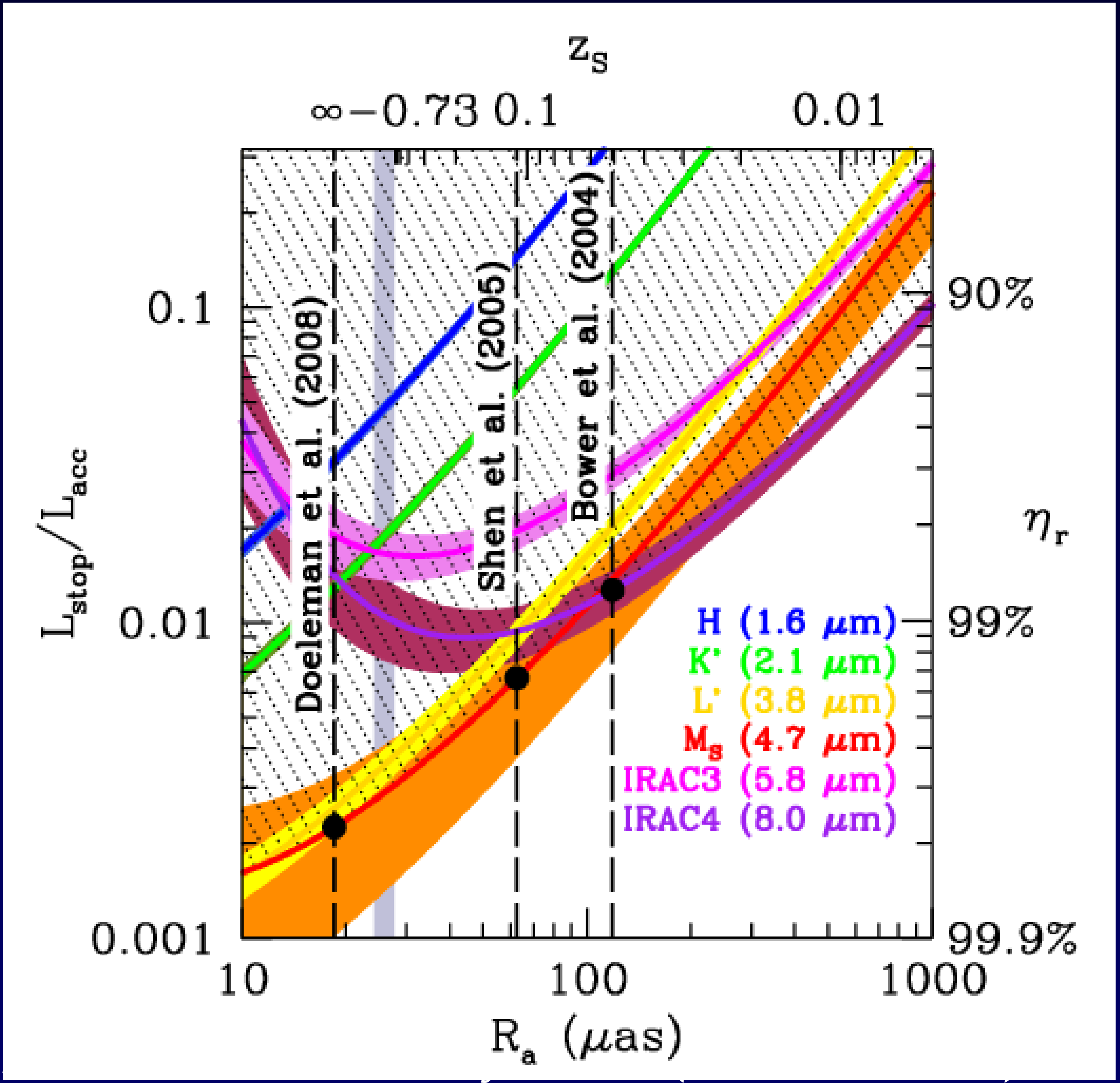


Figure 4: Probability density implied by recent millimeter VLBI detections of Sgr A* as a function of inclination and black hole spin. $p(a,\theta)$ is normalized such that the average is unity, providing a clear sense of the significance of the variations in probability. Generally, it appears that these observations strongly favor moderate inclinations and relatively low black hole spins. However, such statements are predicated upon the correctness of the RIAF model employed. (From BRODERICK ETAL.)

An Event Horizon vs a Surface



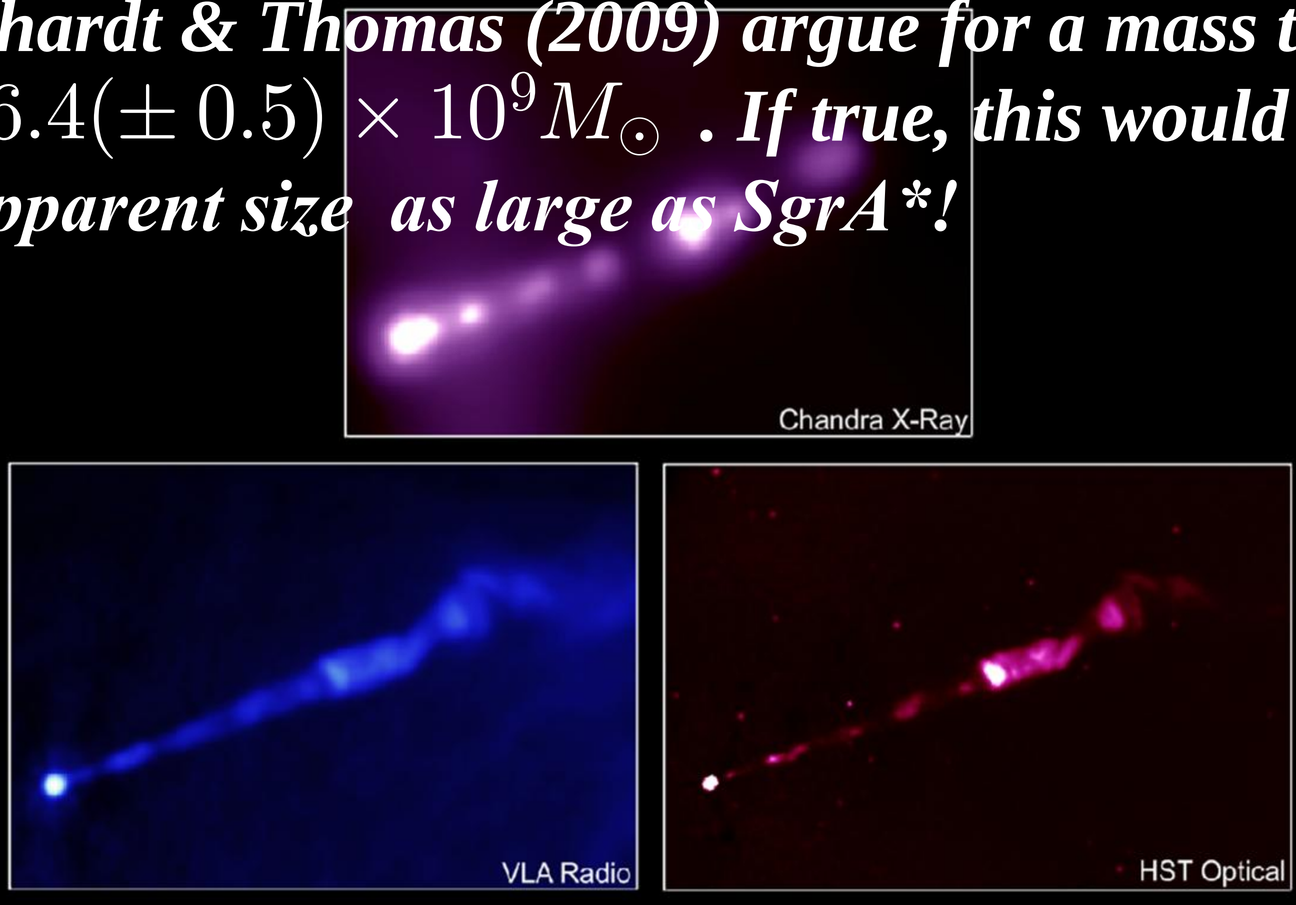
Radiative Efficiency of accreting gas

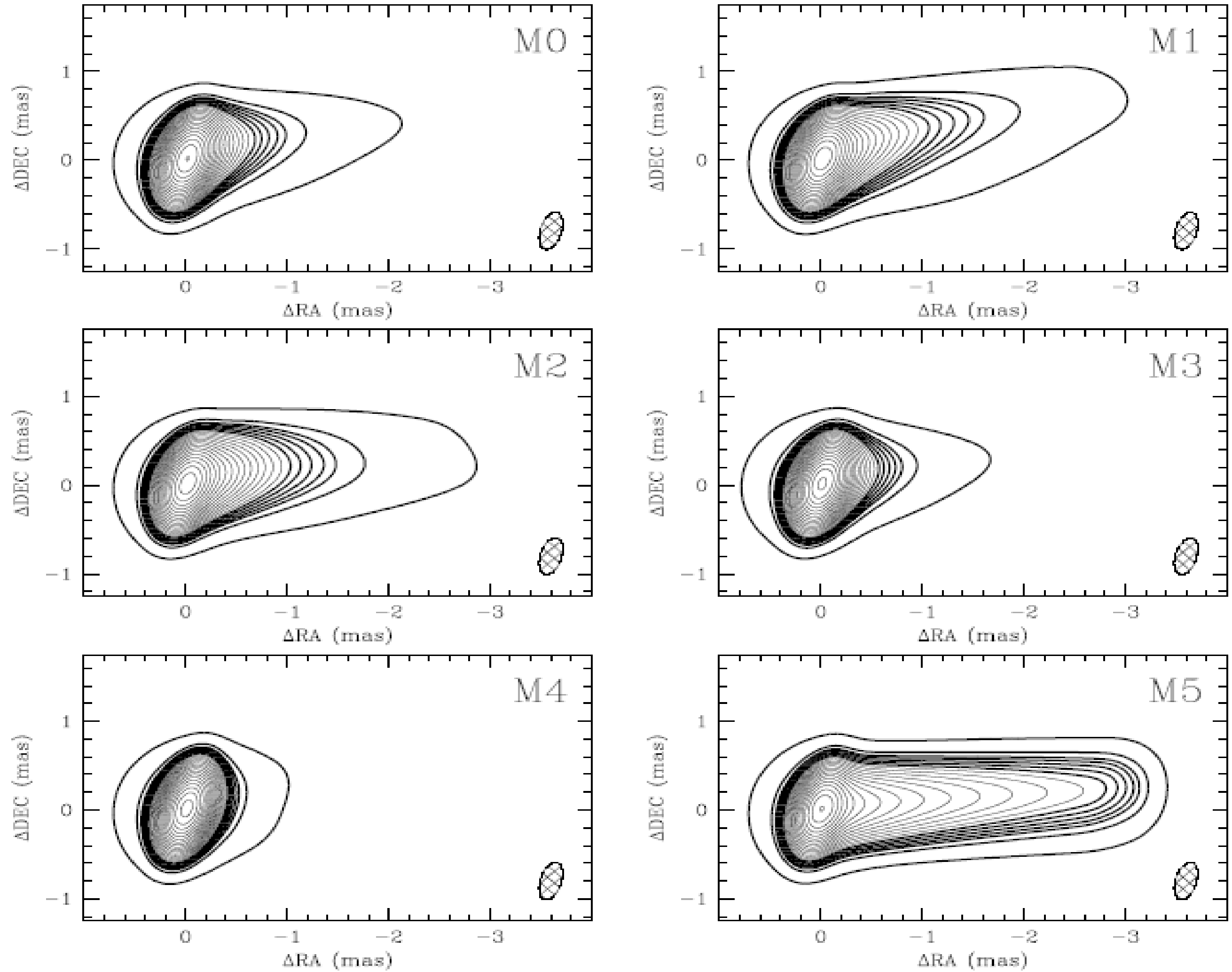
M87

$$M_{\rm BH} = 3 \times 10^9 M_\odot$$ *(~700 times more massive than SgrA*)*

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

But Gebhardt & Thomas (2009) argue for a mass twice as large, $6.4(\pm 0.5) \times 10^9 M_\odot$ ***. If true, this would make M87's apparent size as large as SgrA*!***





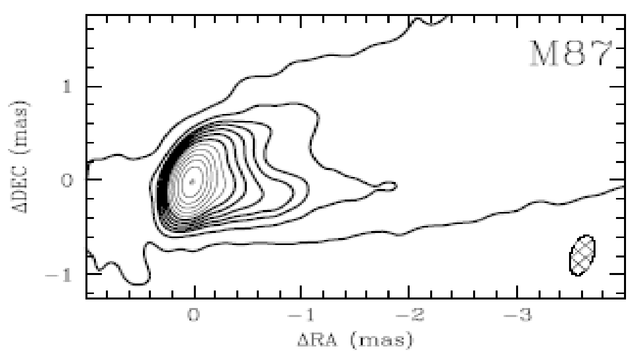
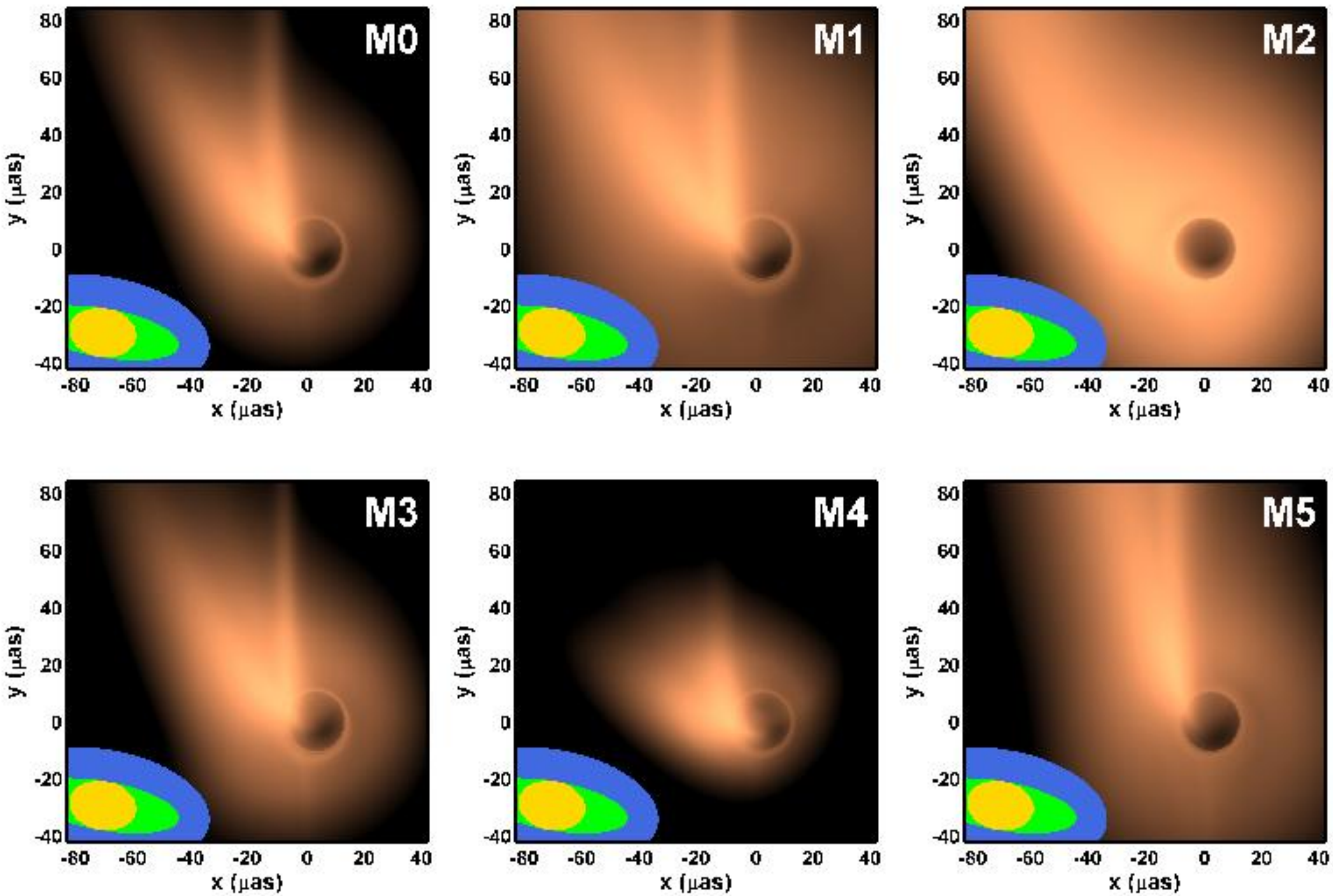


FIG. 3.— Above: 7 mm images for the models listed in Table 1 and described in §3.4, convolved with the beam described in Walker et al. (2008) (shown in the lower-right). The contours are at 0.1, 1, 2, 2.8, 4, 5.7 and 8 mJy/beam (thick lines), and spaced in factors of $\sqrt{2}$ thereafter (thin lines). 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)

1.3 mm Images

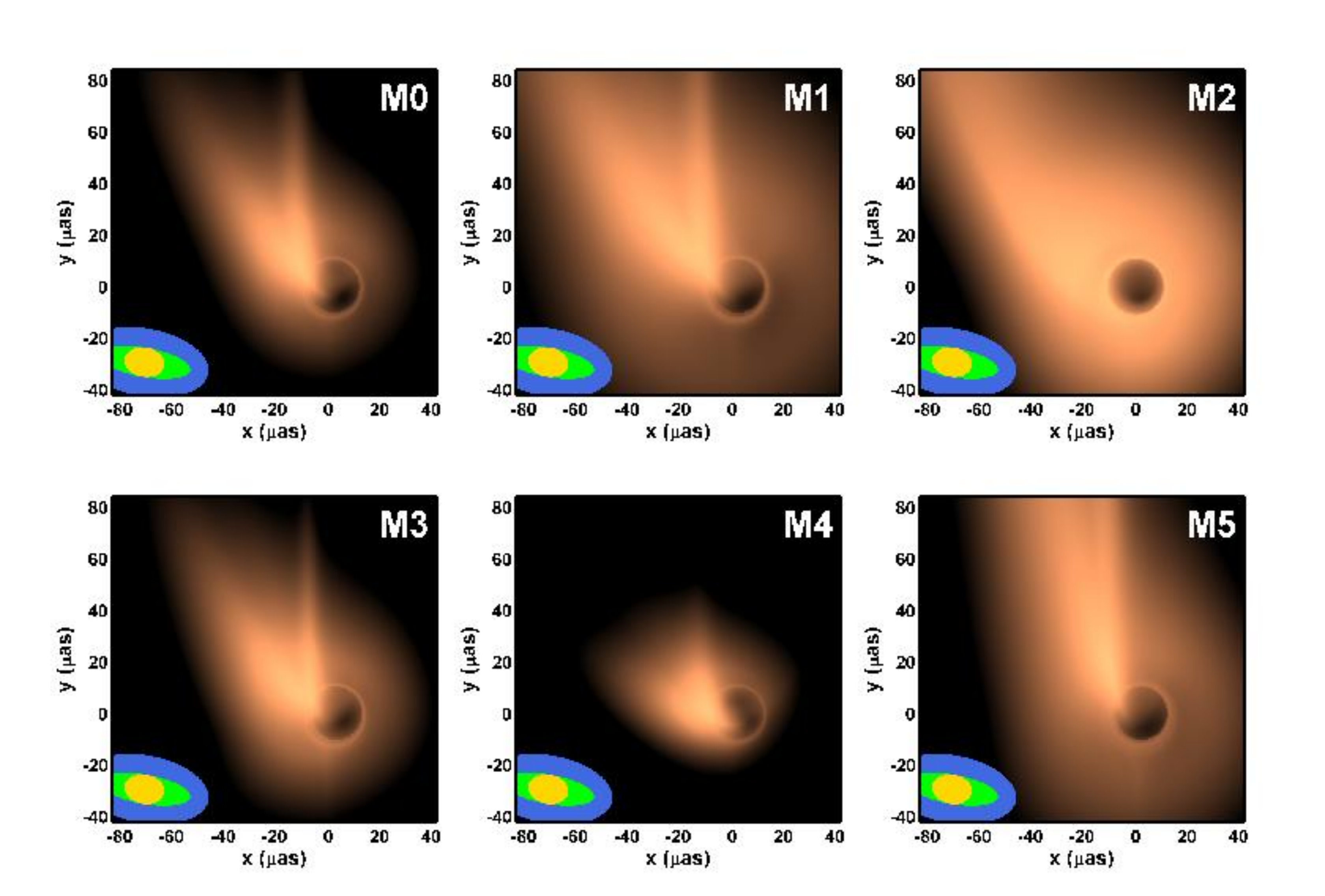


US

+EU

+LMT

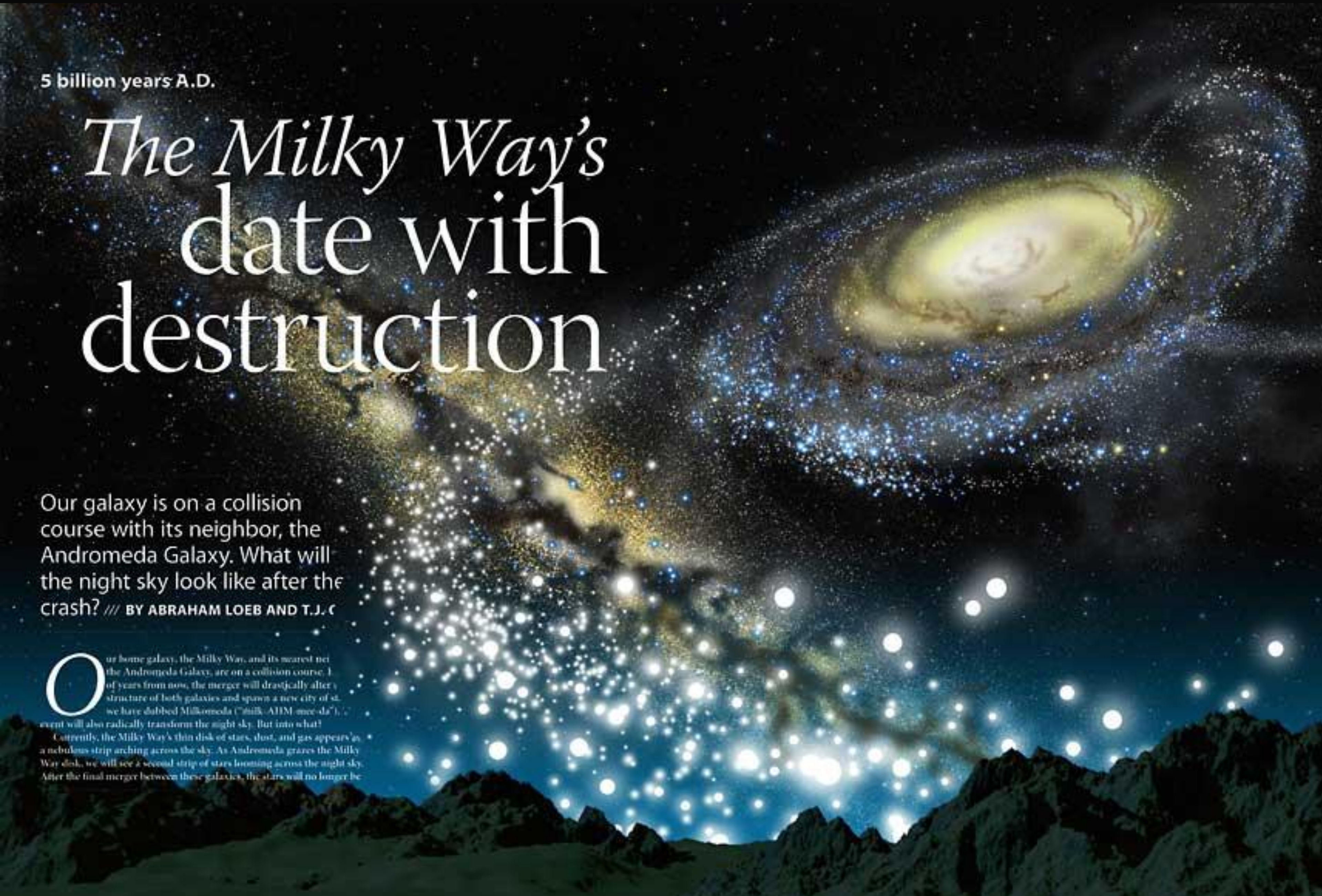
0.87 mm Images



US

+EU

+LMT



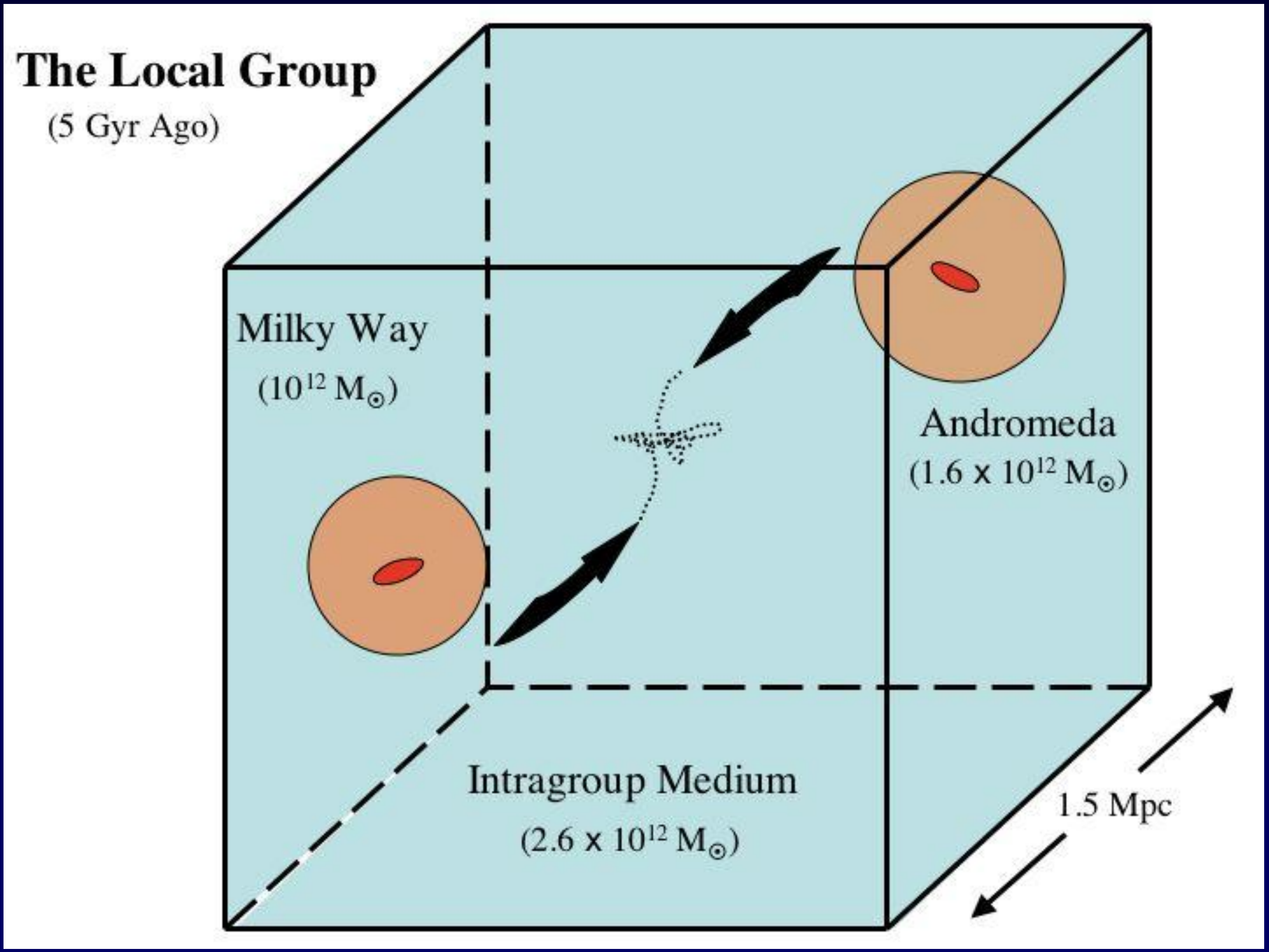
5 billion years A.D.

The Milky Way's date with destruction

Our galaxy is on a collision course with its neighbor, the Andromeda Galaxy. What will the night sky look like after the crash? /// BY ABRAHAM LOEB AND T.J.

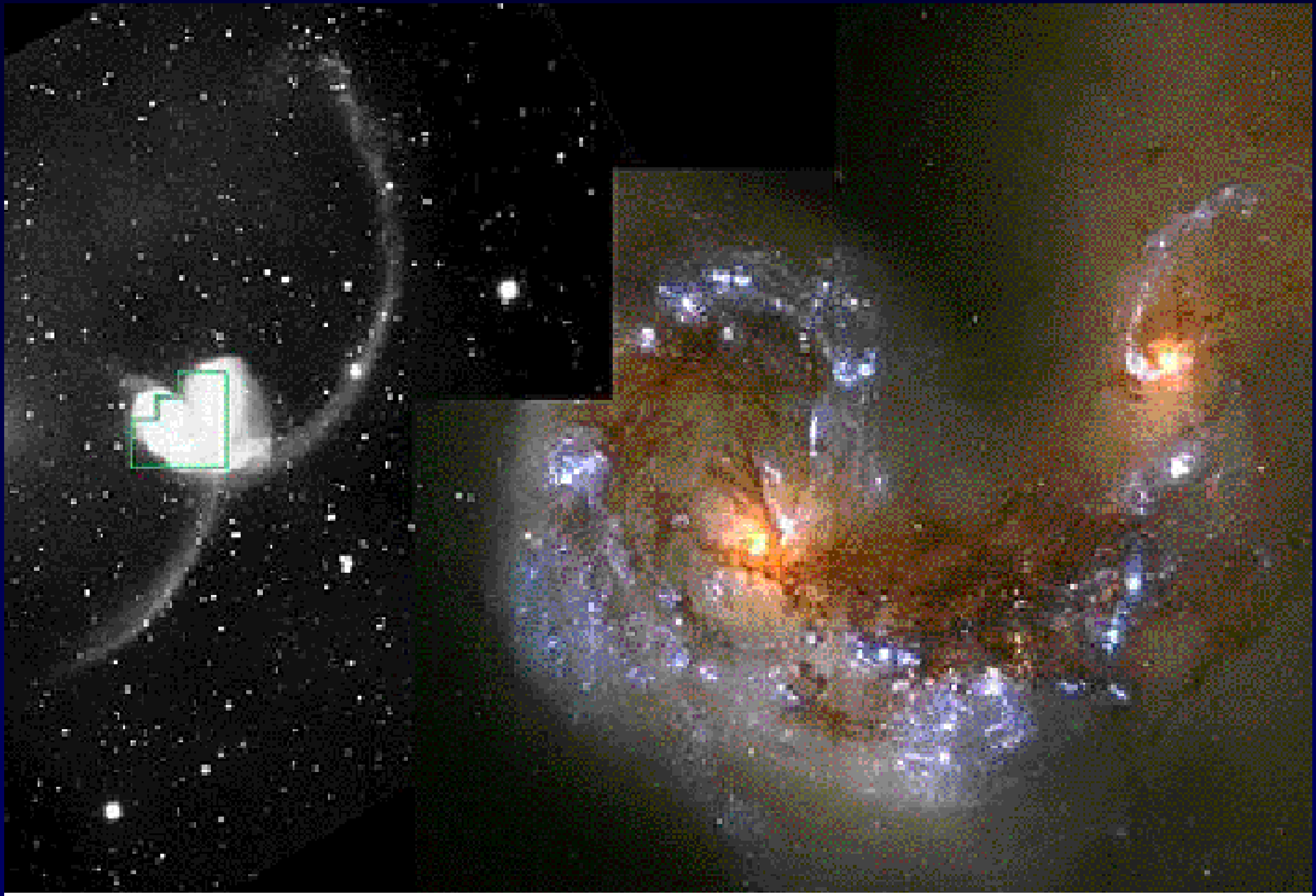
Our home galaxy, the Milky Way, and its nearest nei the Andromeda Galaxy, are on a collision course. I of years from now, the merger will drastically alter structure of both galaxies and spawn a new city of st we have dubbed Milkomeda ("milk-AHM-mee-da"). event will also radically transform the night sky. But into what?

Currently, the Milky Way's thin disk of stars, dust, and gas appears as a nebulous strip arching across the sky. As Andromeda grazes the Milky Way disk, we will see a second strip of stars looming across the night sky. After the final merger between these galaxies, the stars will no longer be


The Local Group
(5 Gyr Ago)
Milky Way
(10^12 M⊙)
Andromeda
(1.6 x 10^12 M⊙)
Intragroup Medium
(2.6 x 10^12 M⊙)
1.5 Mpc

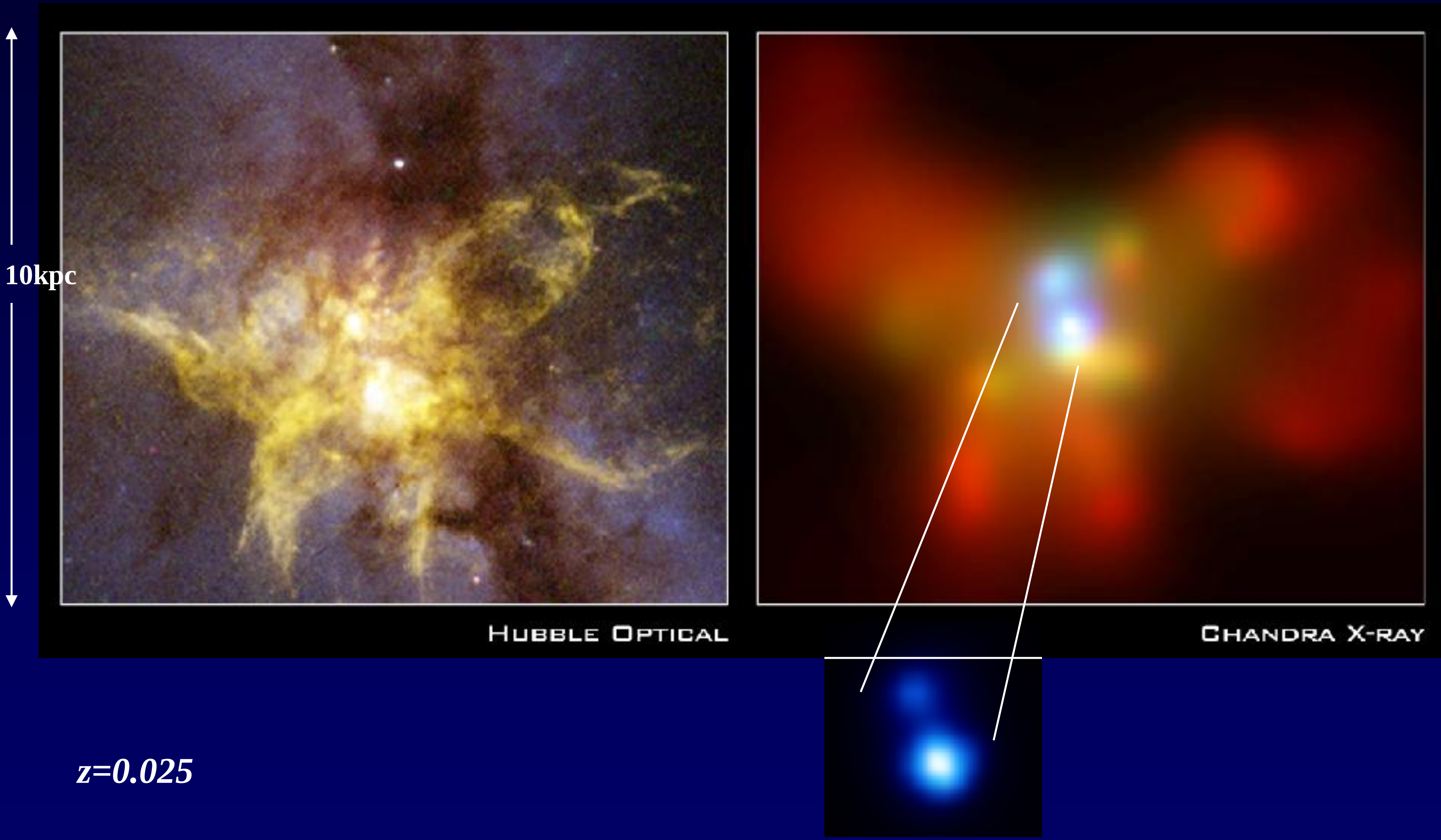
The Future Collision between the Milky Way and Andromeda Galaxies

Black Hole Binaries due to Galaxy Mergers



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

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



z=0.025

Komossa et al. 2002

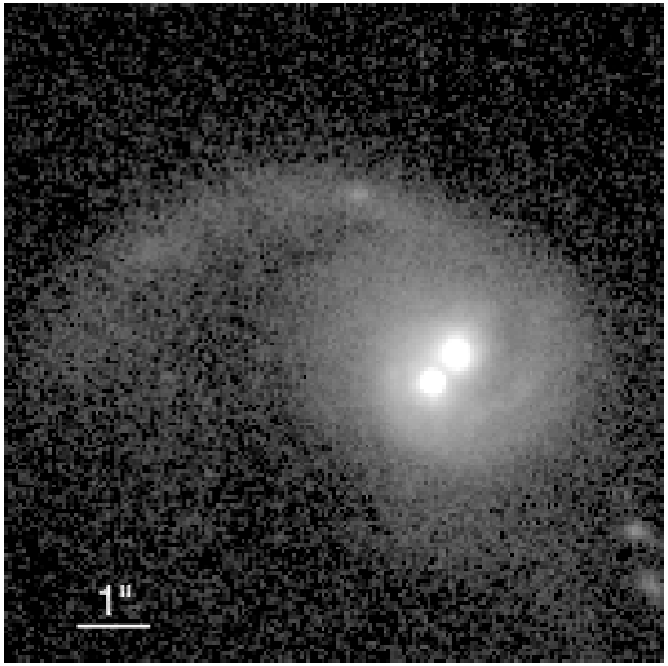


FIG. 1.— *HST* F814W ACS image of COSMOS J100043.15+020637.2, where North is up and East is to the left. The galaxy's tidal tail strongly suggests it has recently undergone a merger, and the two bright nuclei near the galaxy center appear to both be AGN. The nuclei are separated by $0.''497 \pm 0.''009$, or $1.75 \pm 0.03\ h^{-1}$ kpc.

spatial offset: ~2.5 kpc
velocity offset: ~150 km/s
z=0.36

Comerford et al. 2009

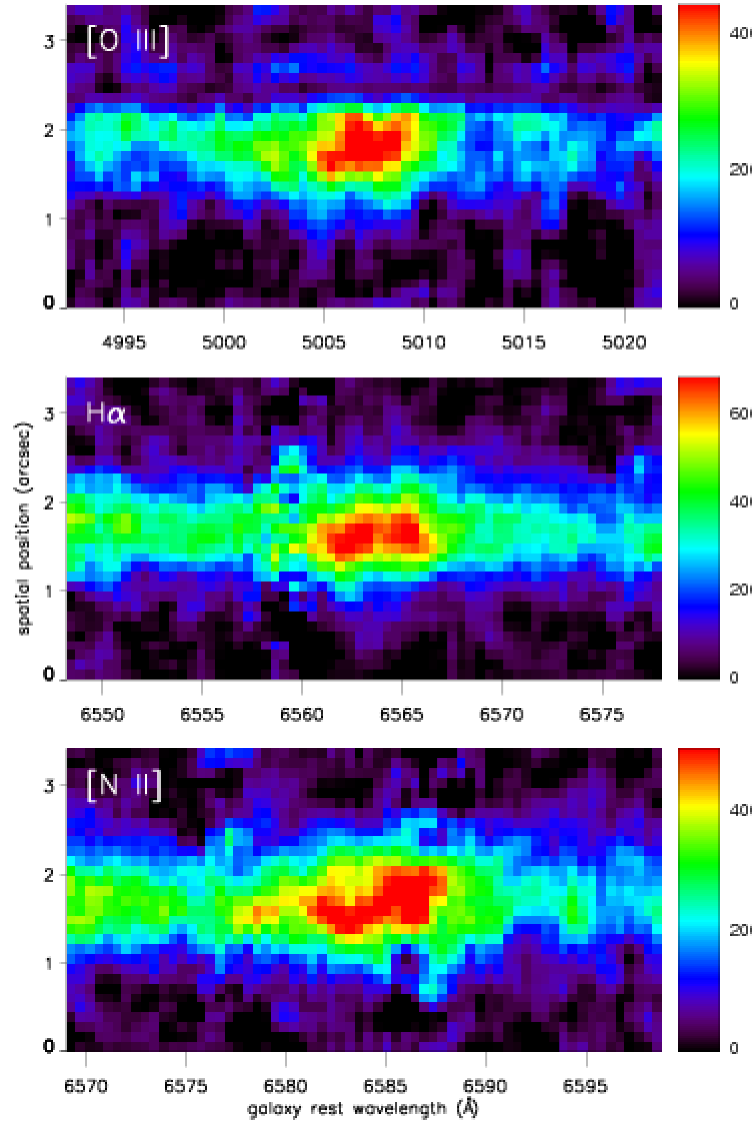
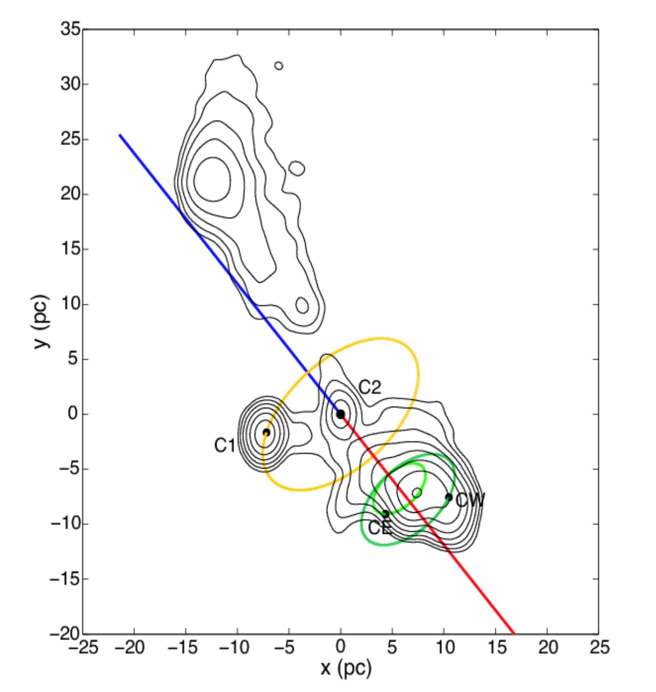
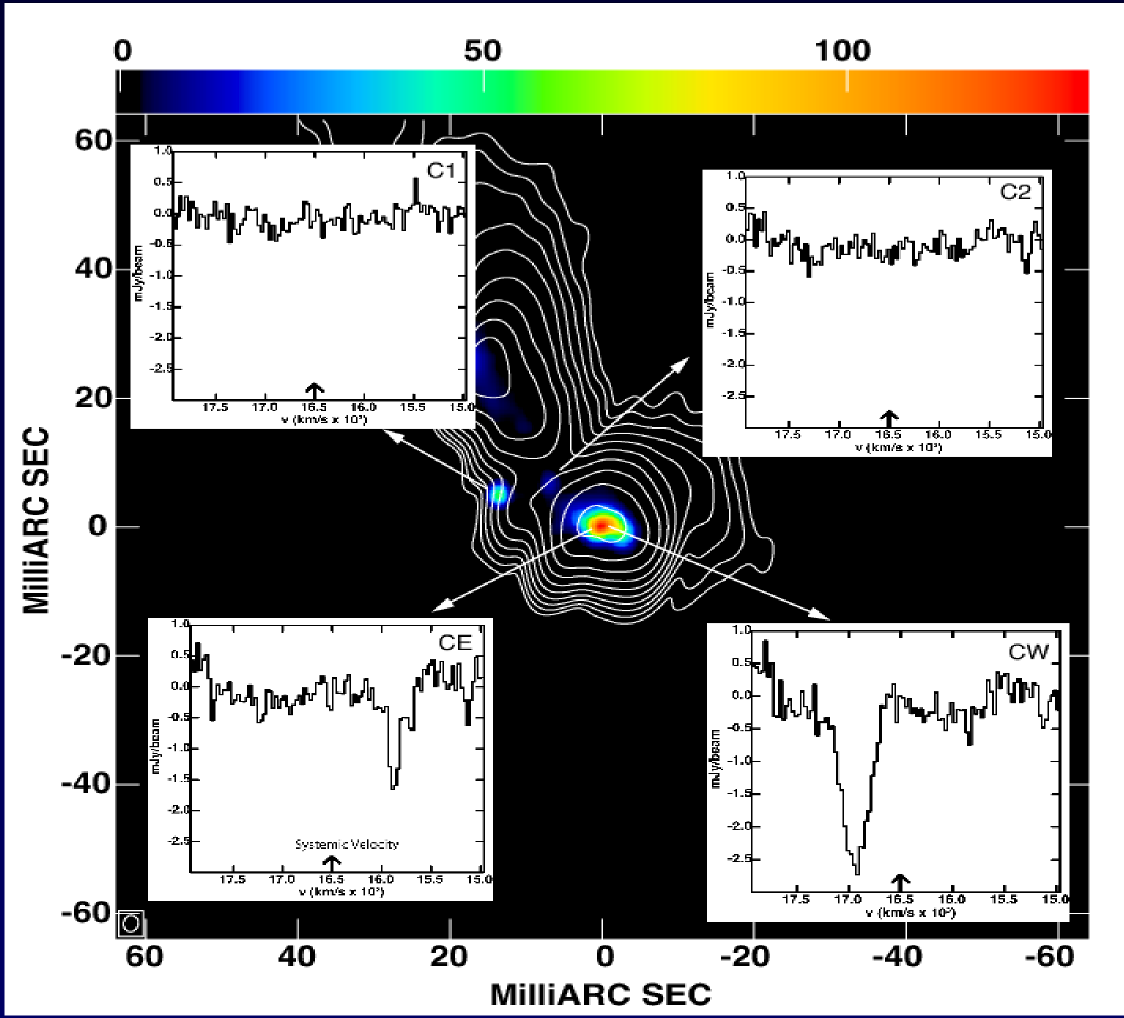


FIG. 2.— Two-dimensional DEIMOS spectrum of J100043.15+020637.2 with night-sky emission features subtracted. The spectrum has been smoothed by a smoothing length of 2 pixels, and AGN line emission at [O III] λ5007 (top), Hα (middle), and [N II] λ6584 (bottom) is shown. In each panel, the vertical axis spans $3.''41$ ($12.0\ h^{-1}$ kpc at the $z = 0.36$ redshift of the galaxy) in

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

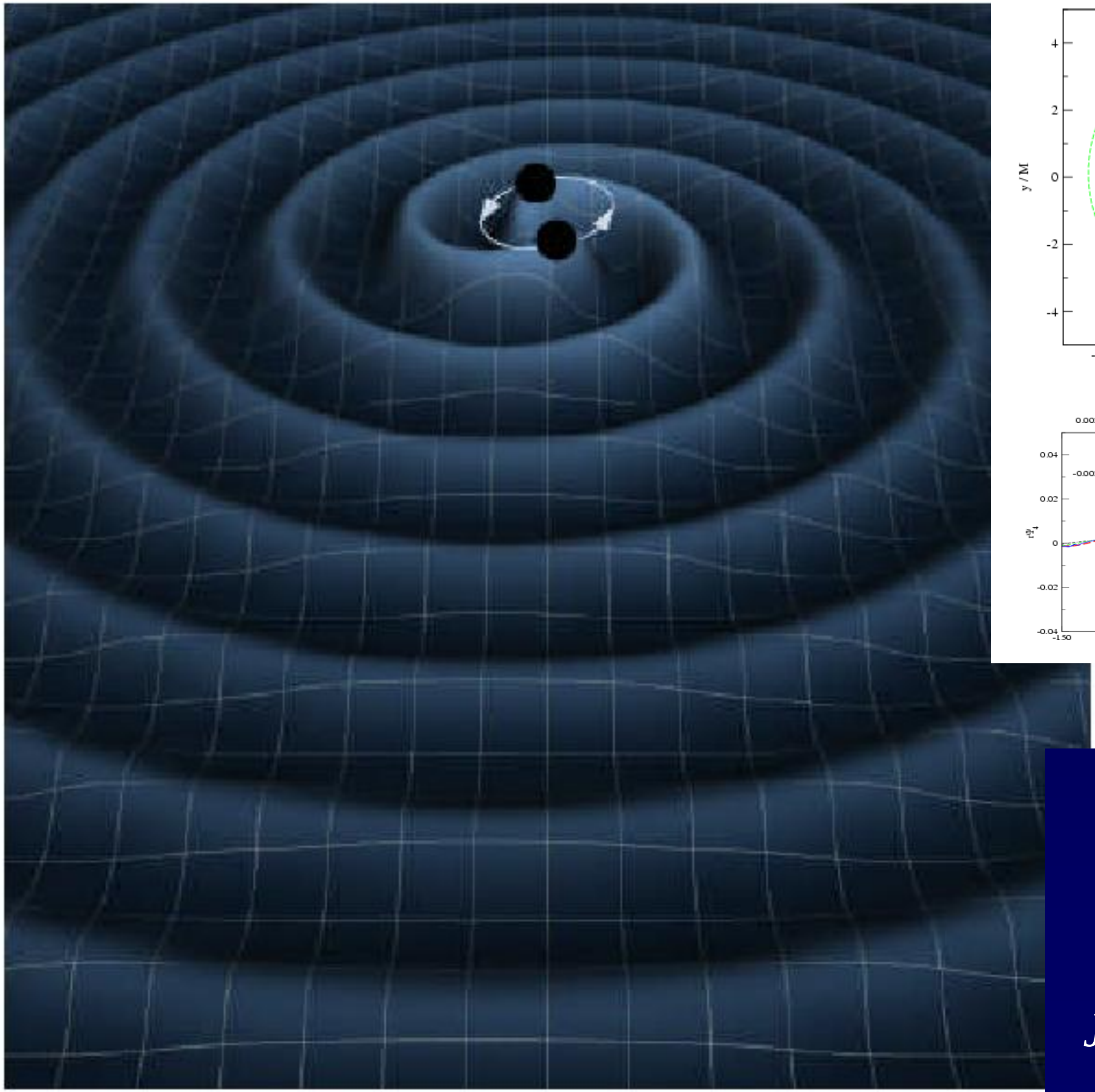


VLBI at 1.35 GHz

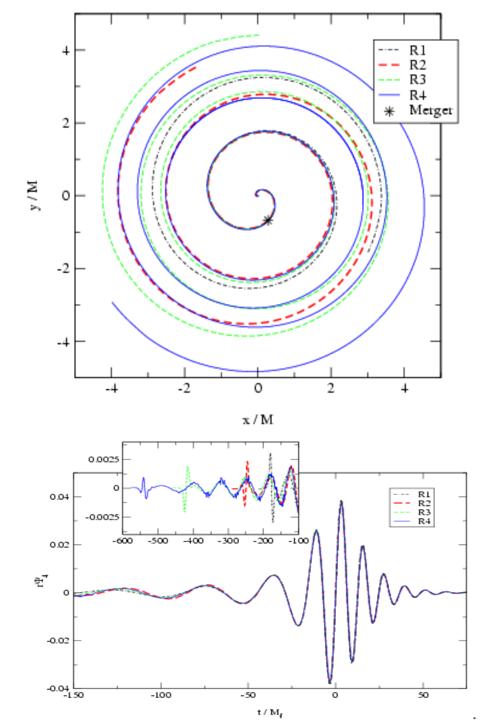


- Projected separation: 7.3 pc,
- Estimated total mass: $\sim 10^9 M_\odot$

Gravitational Waves



K. Thorne (Caltech) , T. Carnahan

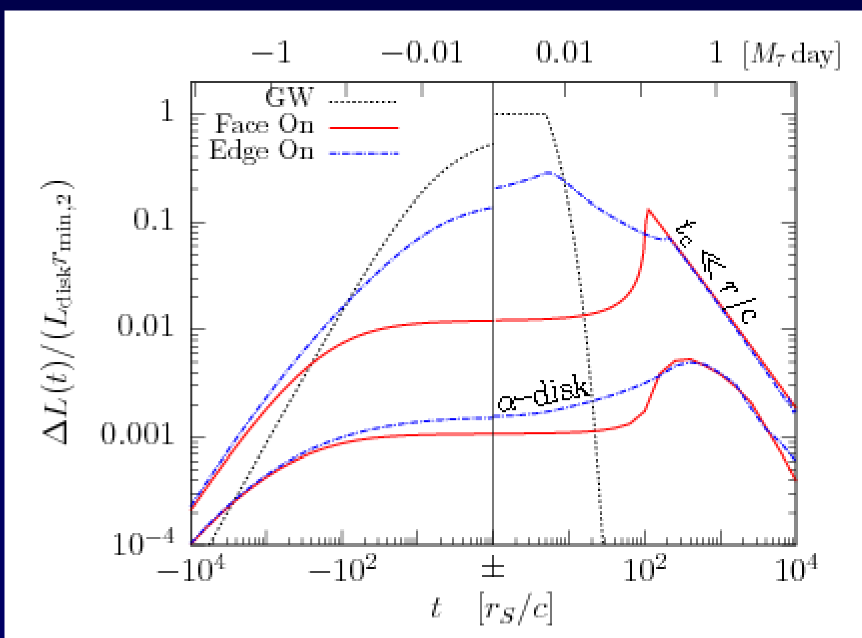


J.Centrella et al. 2007

Viscous Dissipation of Gravitational Waves in a Thin Accretion Disk

$$T_{\mu\nu} = -2\eta\sigma_{\mu\nu} \qquad \sigma_{\mu\nu} = \frac{1}{2}\dot{h}_{\mu\nu}$$

$$c^5/G = 3.6 \times 10^{59} \mathrm{erg/s} \qquad \Box h_{\mu\nu} = -16\pi G\eta\dot{h}_{\mu\nu}/c^4$$

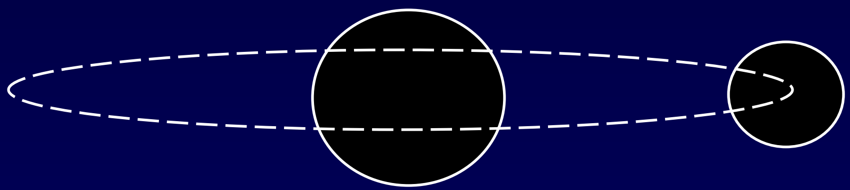


$$H\dot{e}_{\rm heat} = \frac{8G}{3c^3} Y(\theta)\dot{M}\frac{L_{\rm GW}(t_{\rm ret})}{4\pi r^2}$$

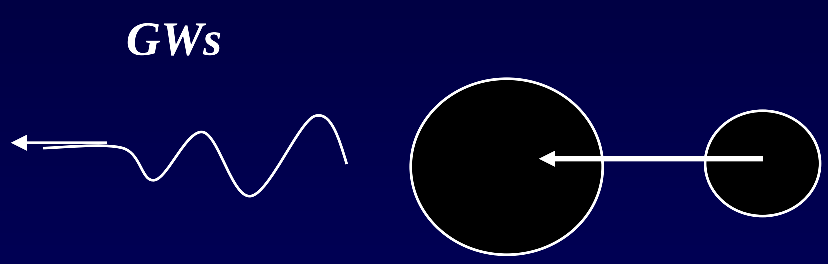
→ Equal heating per log radius

Kocsis & Loeb, Arxiv:0803.0003 (2008)

Gravitational Wave Recoil

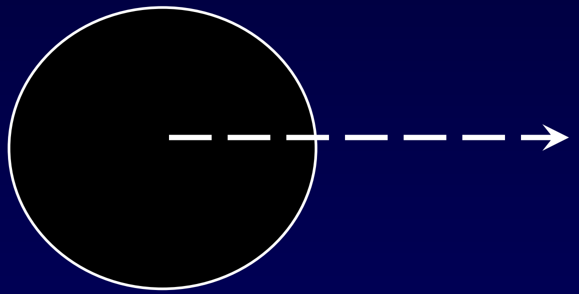


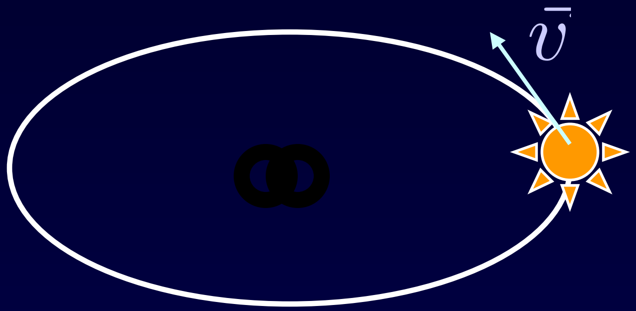
Gravitational Wave Recoil



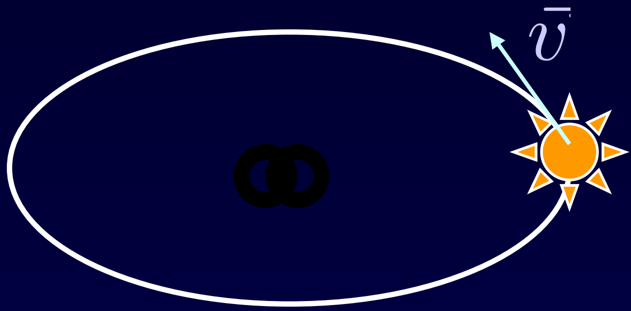
Anisotropic emission of gravitational waves → momentum recoil

Gravitational Wave Recoil

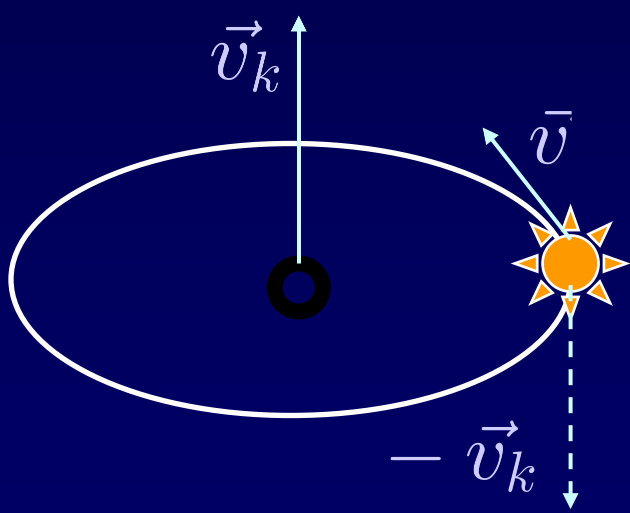




$$E = \frac{1}{2}v^2 - \frac{GM}{r} = -\frac{1}{2}v^2$$

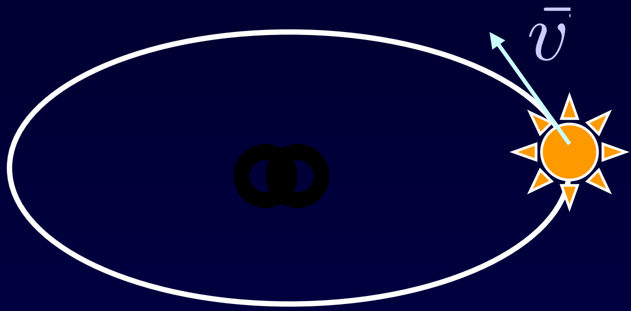


$$E = \frac{1}{2}v^2 - \frac{GM}{r} = -\frac{1}{2}v^2$$

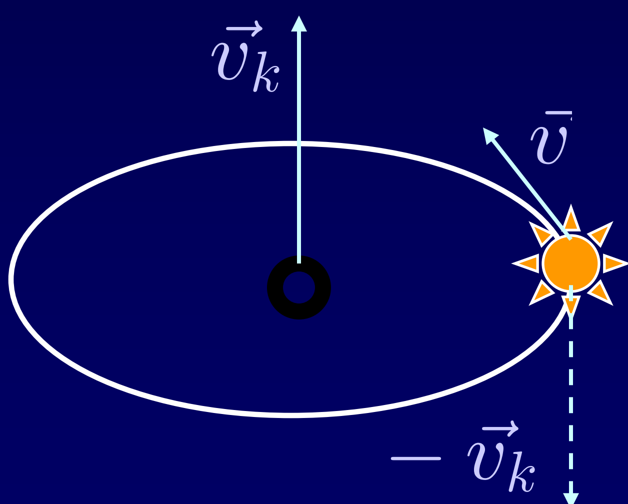


$$E = \frac{1}{2}(\vec{v} - \vec{v}_k)^2 - \frac{GM}{r}$$

$$= \vec{v} \cdot \vec{v}_k + \frac{1}{2}(v_k^2 - v^2)$$



$$E = \frac{1}{2}v^2 - \frac{GM}{r} = -\frac{1}{2}v^2$$

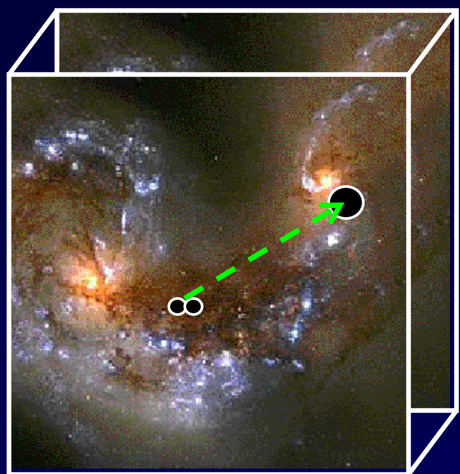


$$E = \frac{1}{2}(\vec{v} - \vec{v}_k)^2 - \frac{GM}{r}$$

$$= \vec{v} \cdot \vec{v}_k + \frac{1}{2}(v_k^2 - v^2)$$

→ ***test particles with*** $v \gg v_k$ ***remain bound***

Galaxies as “Bubble Chambers” *for BHs ejected by gravitational wave recoil*



- - - - *Ionization trail*

$$t_{\rm disk} \sim 10^7 {\rm yr}$$

$$d \sim v_{\rm ej} t_{\rm disk} \sim 10 {\rm kpc}$$

Bonning, Shields & Salviander 2007

Quasar Velocity Offset

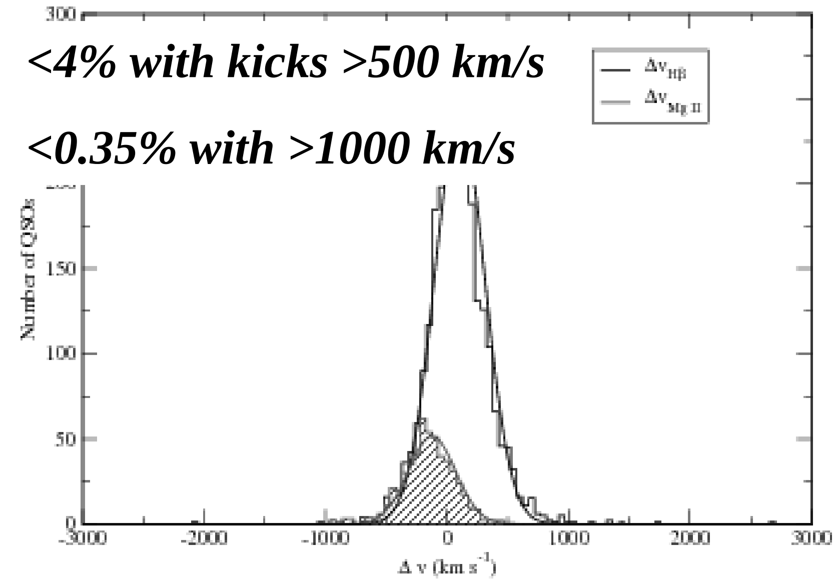


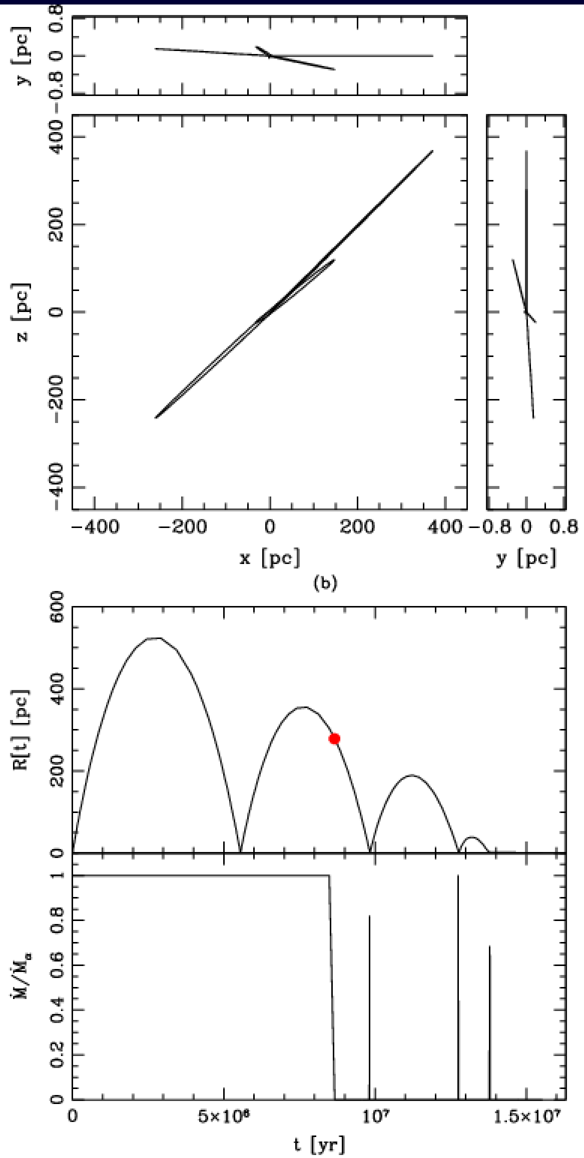
FIG. 1.— Histogram of $\Delta v_{H\beta}$ and Δv_{Mg} along with Gaussian fits to the data. The distribution is somewhat broader than a Gaussian, with small but significant numbers of outliers with $|\Delta v| > 1000$ km s^{-1}.

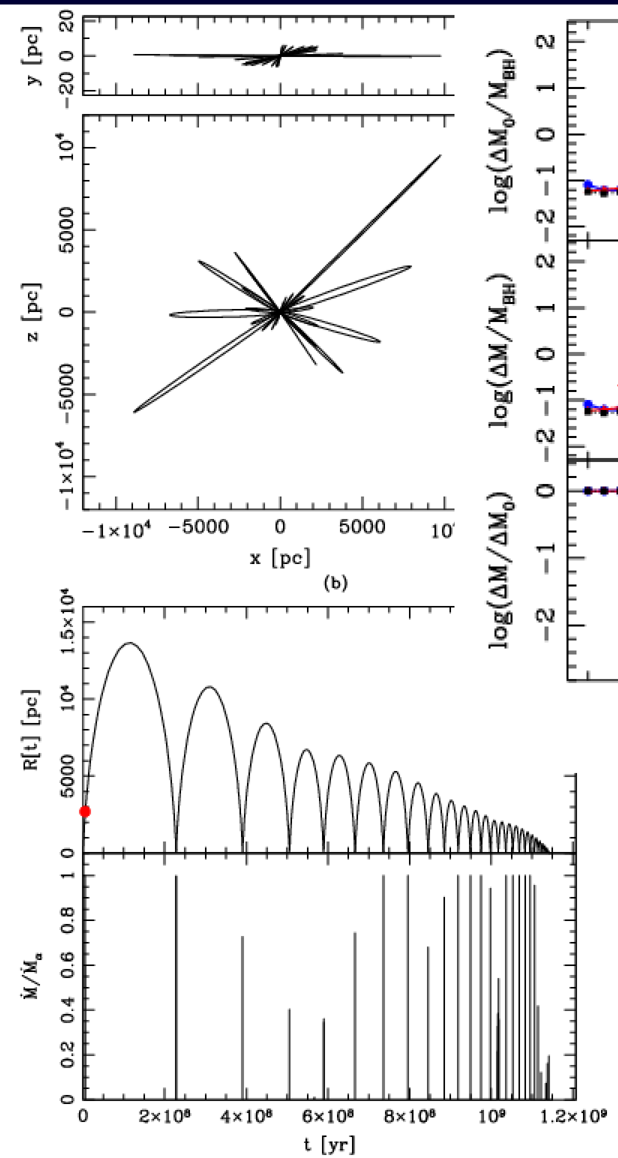
Loeb, PRL, 2007; astro-ph/0703722

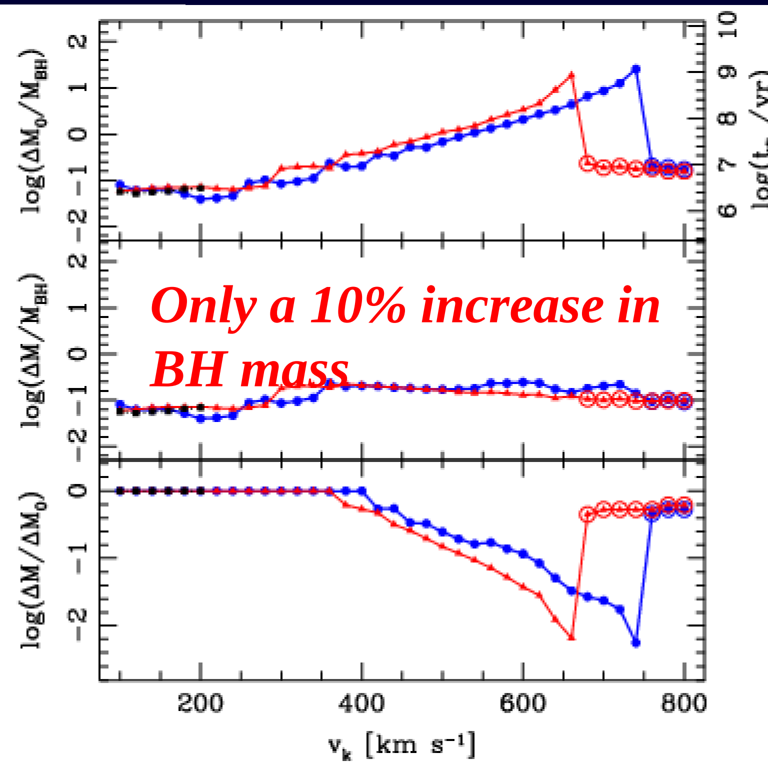
Effect of Recoil on BH Growth and Feedback

440 km/s

740 km/s







Only a 10% increase in BH mass

Blecha & Loeb
arXiv:0805.1420

Star Clusters Around Recoiled Black Holes in the Milky Way Halo

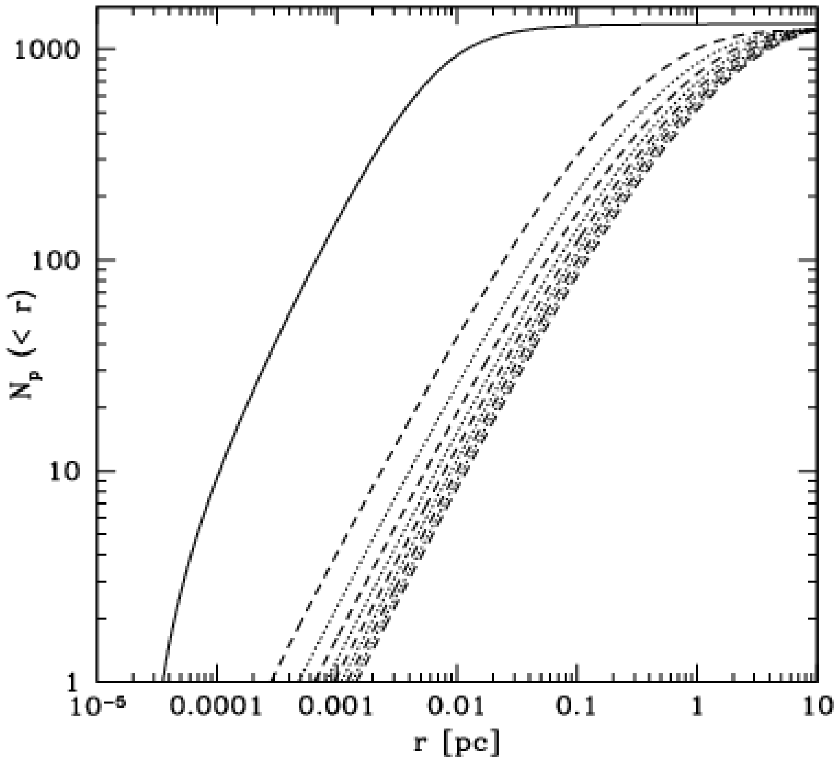


Figure 2. The total number of projected stars interior to r, $N_p(<r)$, for $M_\bullet = 10^5 \mathrm{M}_\odot$ and $\alpha = 1.75$. The solid line corresponds to the cluster immediately after being ejected from its parent galaxy with $v_k = 5.8\sigma_*$. The alternating dashed and dotted lines correspond to the projected number of stars after every $10 t_r \approx 650$ Myr. Immediately after ejection, the cluster rapidly expands until its relaxation time becomes comparable to the age of the Universe, with very little mass loss. In the case of $\alpha = 1$, the cluster evolves similarly, but only with ~ 100 stars in the cluster. For a $10^5\,\mathrm{M}_\odot$ BH, the circular velocity of the stars is $\approx 66\,\mathrm{km\,s^{-1}}(r/0.1\,\mathrm{pc})^{-1/2}$.

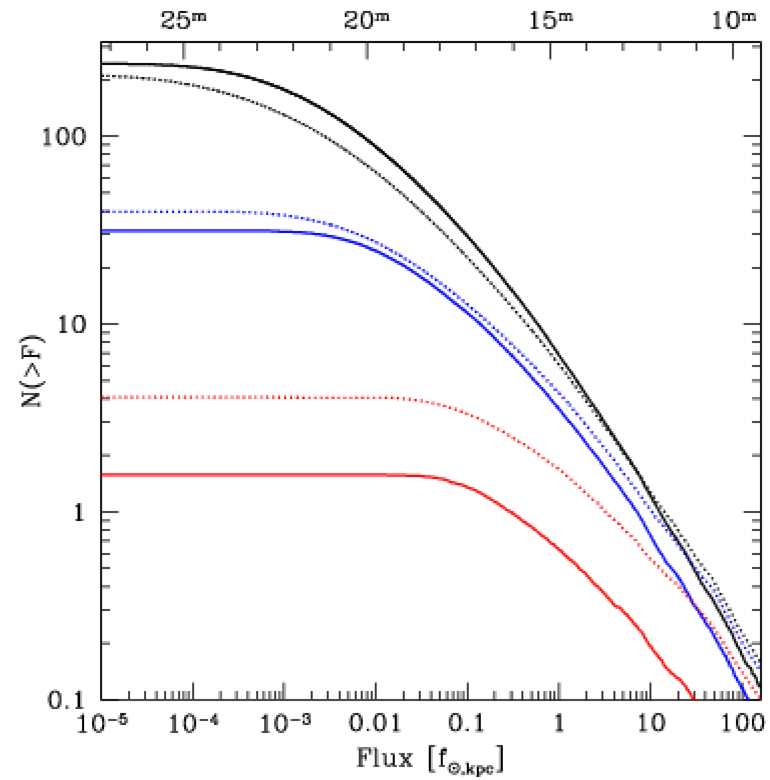


Figure 1. The cumulative distribution of ejected star clusters in the MW Halo. Plotted is the flux distribution associated with BHs masses greater than $10^3\,\mathrm{M}_\odot$ (black), $10^4\,\mathrm{M}_\odot$ (blue), and $10^5\,\mathrm{M}_\odot$ (red), in our models with BH spin $a = 0.9$ (solid) and $a = 0.1$ (dashed) lines, plotted in units of the flux of the Sun at a distance of 1 kpc ($f_{\odot,\mathrm{kpc}}$). The top axis is labeled with the apparent bolometric magnitude of the clusters. Nearly all BHs with $M_\bullet \gtrsim 2\times10^3\,\mathrm{M}_\odot$ have apparent magnitudes greater than 21, the rough magnitude limit of SDSS. The mass distribution of the ejected BHs has approximately equal mass per $\log M_\bullet$ interval, with $\mathrm{d}N_{\mathrm{BH}}/\mathrm{d}M_\bullet \propto M_\bullet^{-1}$.

Highlights

- ***Direct imaging of the nearest supermassive black holes (SgrA*, M87) is feasible in the next few years***
- ***GW-recoiled black holes have observable signatures: offset quasars, floating star clusters in the Milky-Way, electromagnetic counterparts to LISA sources***