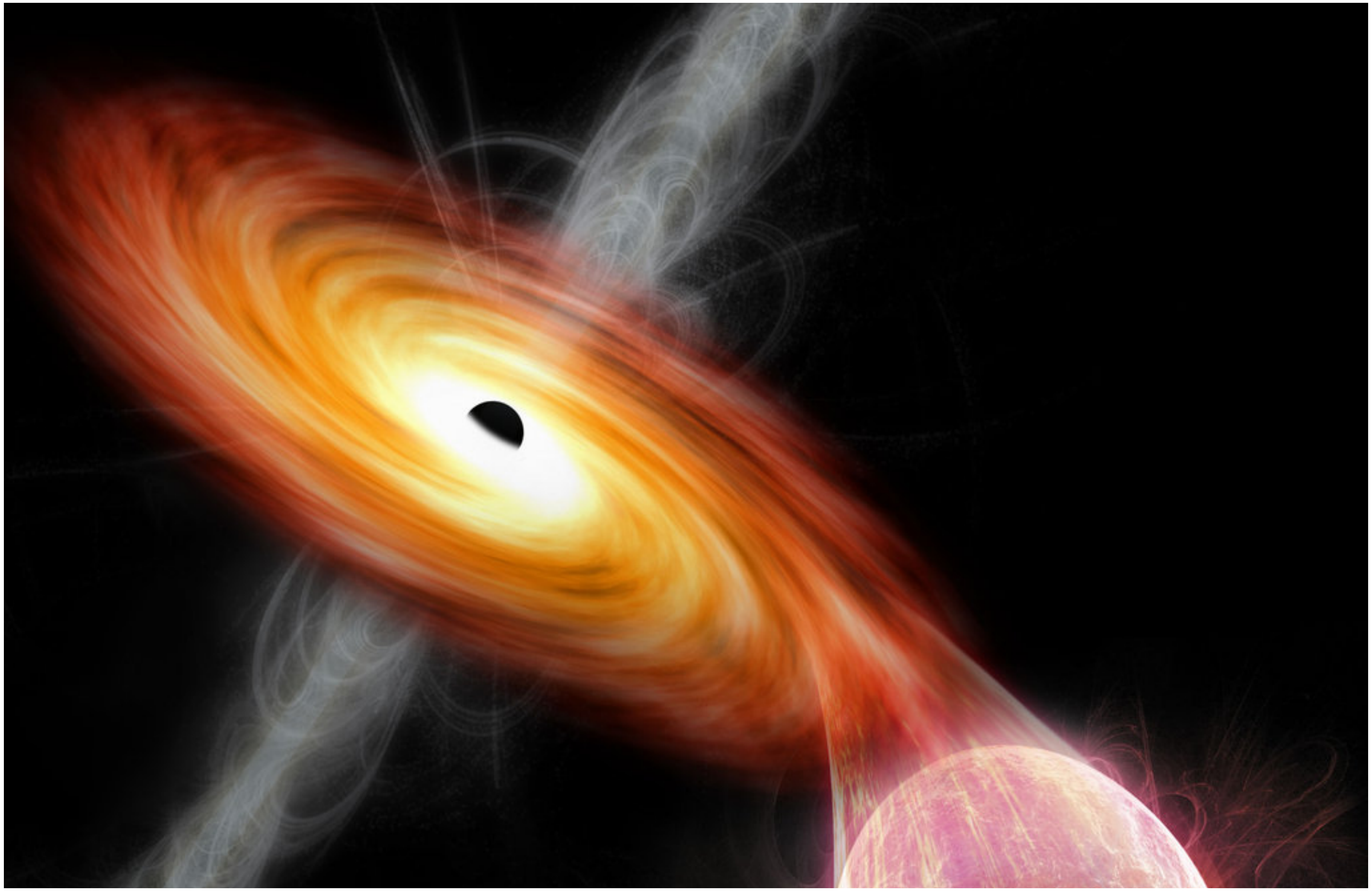
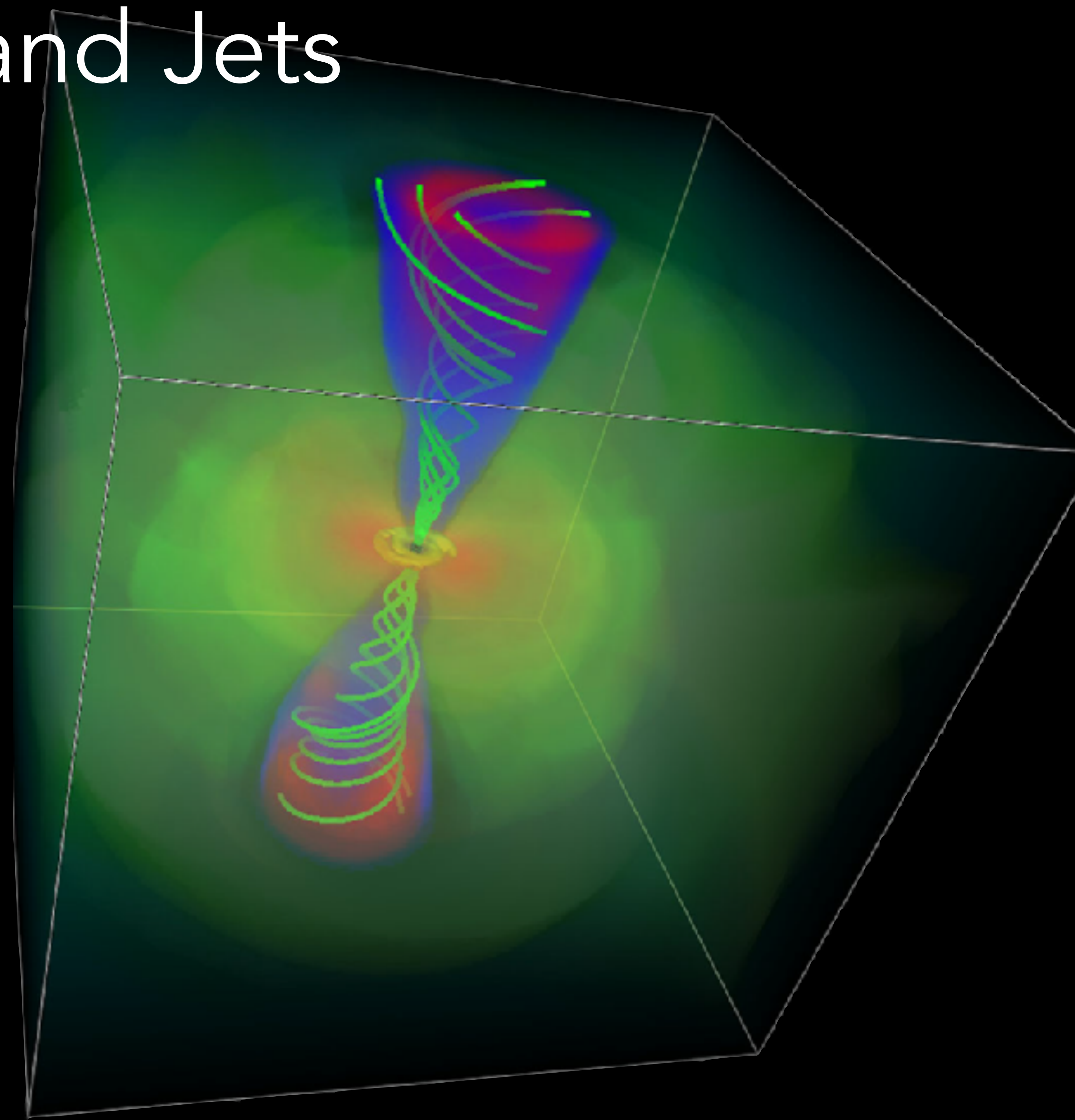
High Energy Astrophysics

Dr. Adam Ingram



Lecture 7

Black Holes and Jets

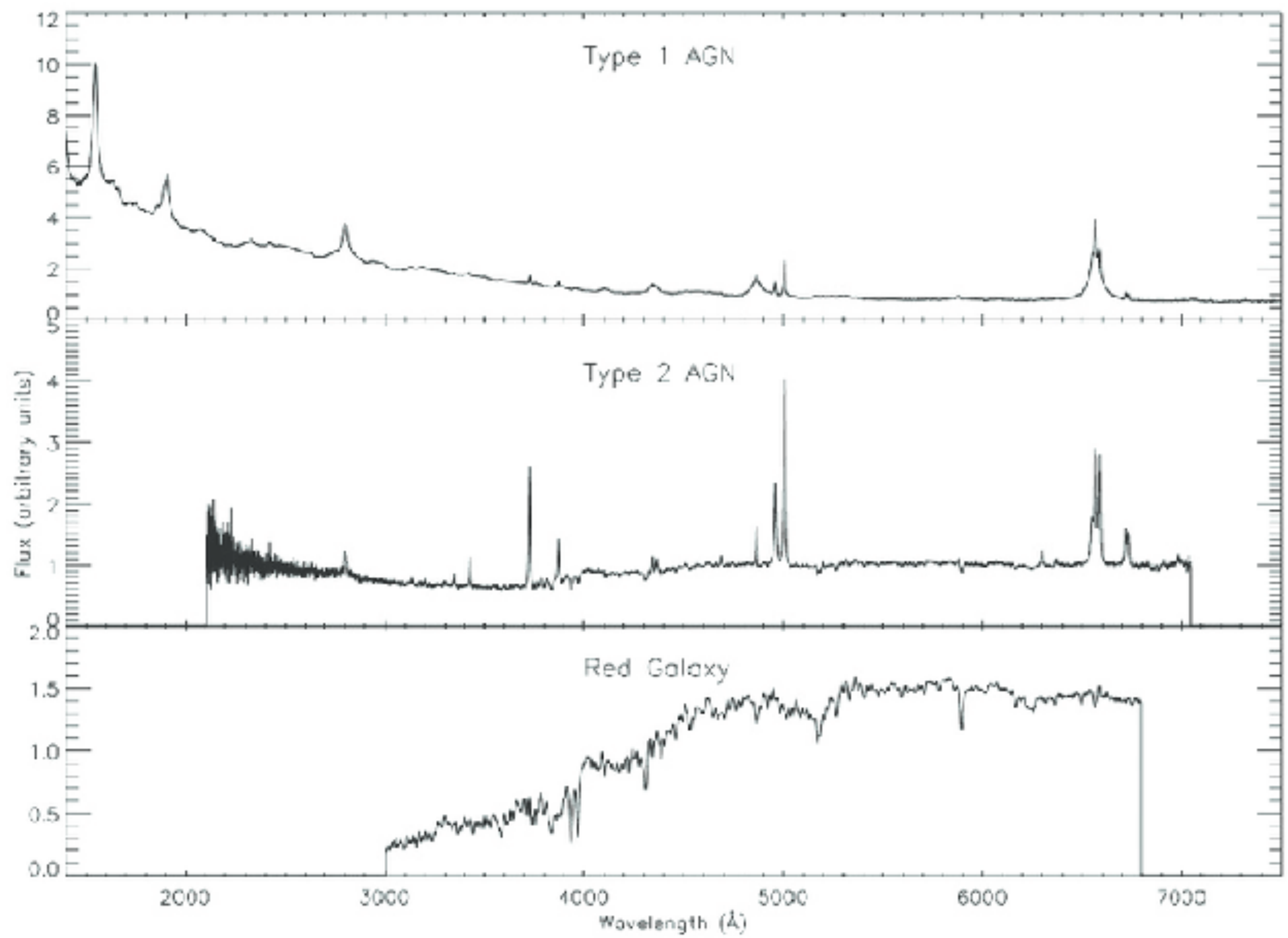


The AGN Zoo

A whole zoo of different astrophysical objects are thought to be AGN viewed from different angles, or in different accretion states (recall spectral transitions in XRBs)

The AGN Zoo

A whole zoo of different astrophysical objects are thought to be AGN viewed from different angles, or in different accretion states (recall spectral transitions in XRBs)



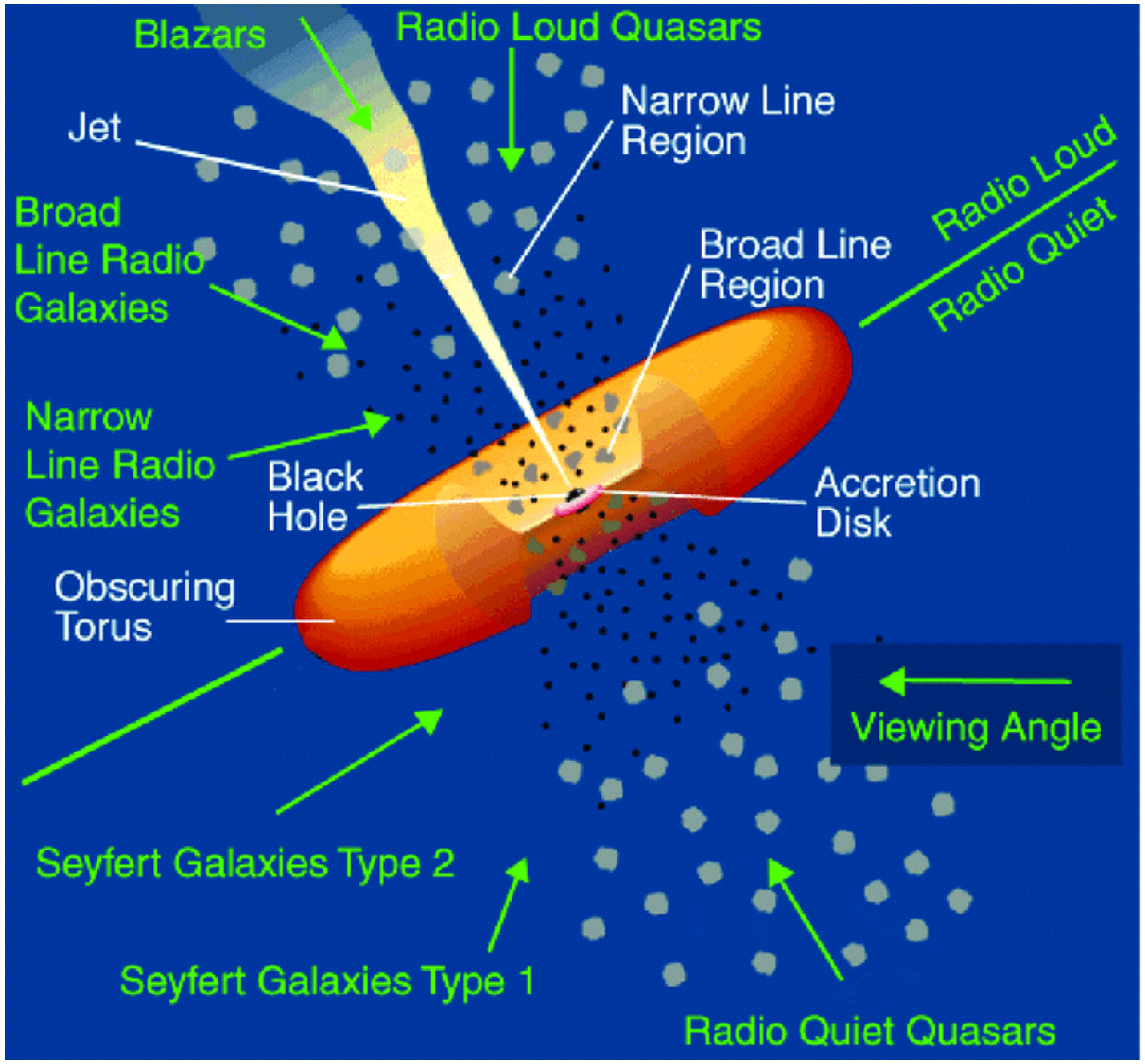
Split into Type 1 and Type 2:

Type 1: broad and narrow optical lines, unobscured X-ray spectrum.

Type 2: only narrow optical lines, obscured X-ray spectrum (i.e. don't see soft X-rays)

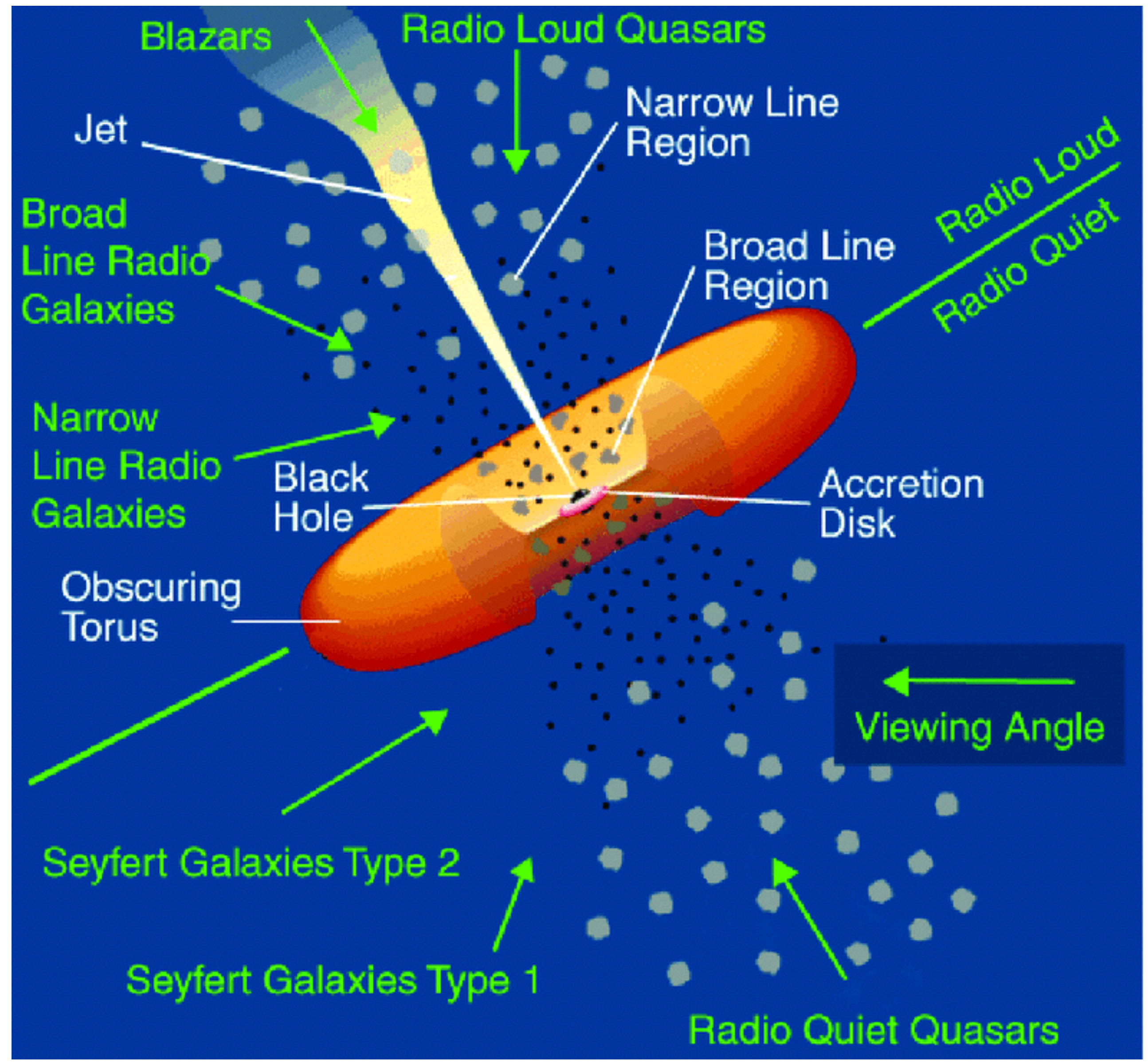
The AGN Zoo

Unification model: molecular torus ~parsecs from BH, optical lines from orbiting clouds. Broad line region closer in (faster Keplerian rotation), narrow line region further out (slower Keplerian rotation).



The AGN Zoo

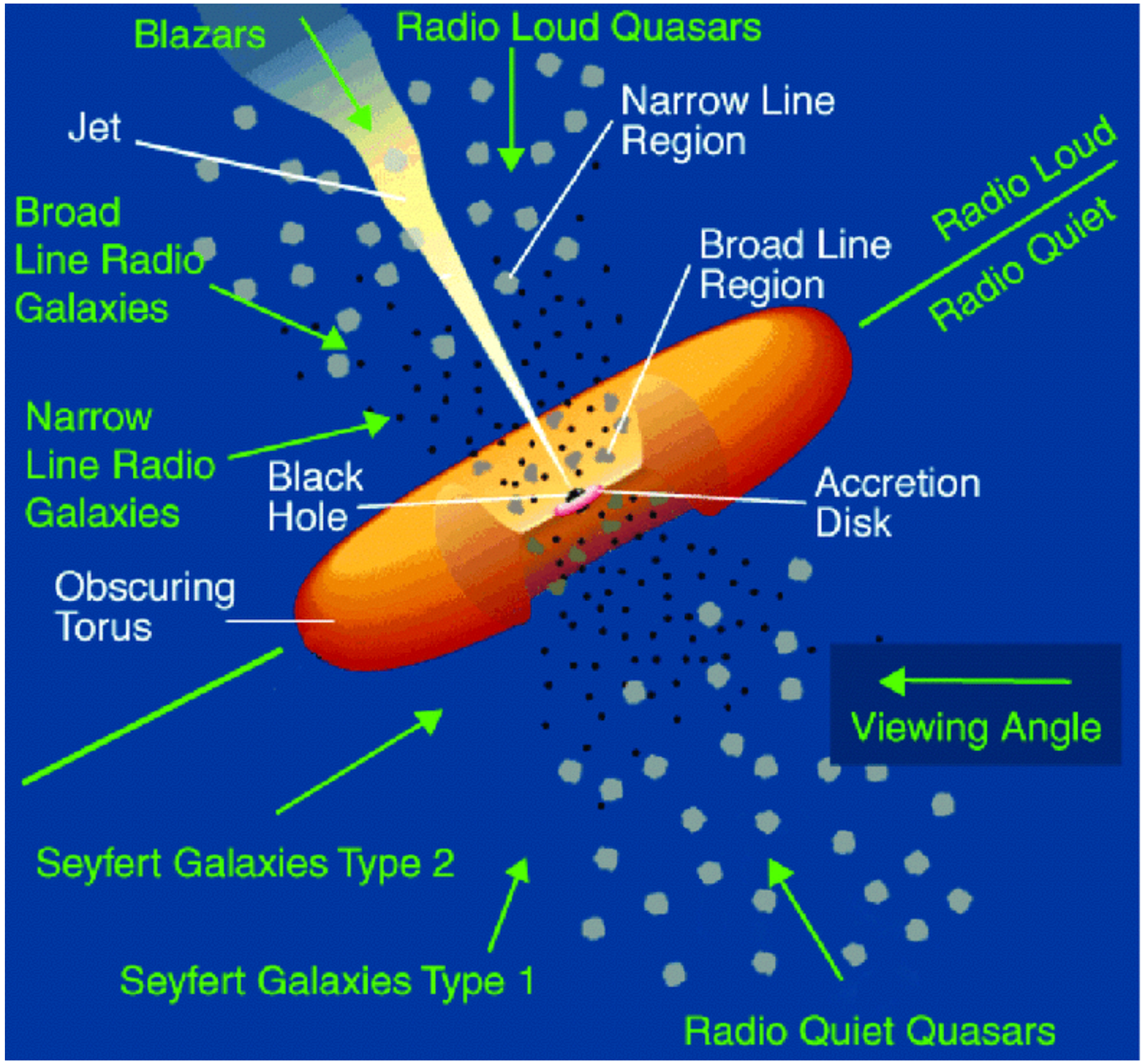
Unification model: molecular torus ~parsecs from BH, optical lines from orbiting clouds. Broad line region closer in (faster Keplerian rotation), narrow line region further out (slower Keplerian rotation).



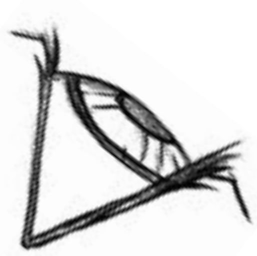
Type 1: See into heart of AGN (disc), see optical lines from BLR and NLR.

The AGN Zoo

Unification model: molecular torus ~parsecs from BH, optical lines from orbiting clouds. Broad line region closer in (faster Keplerian rotation), narrow line region further out (slower Keplerian rotation).



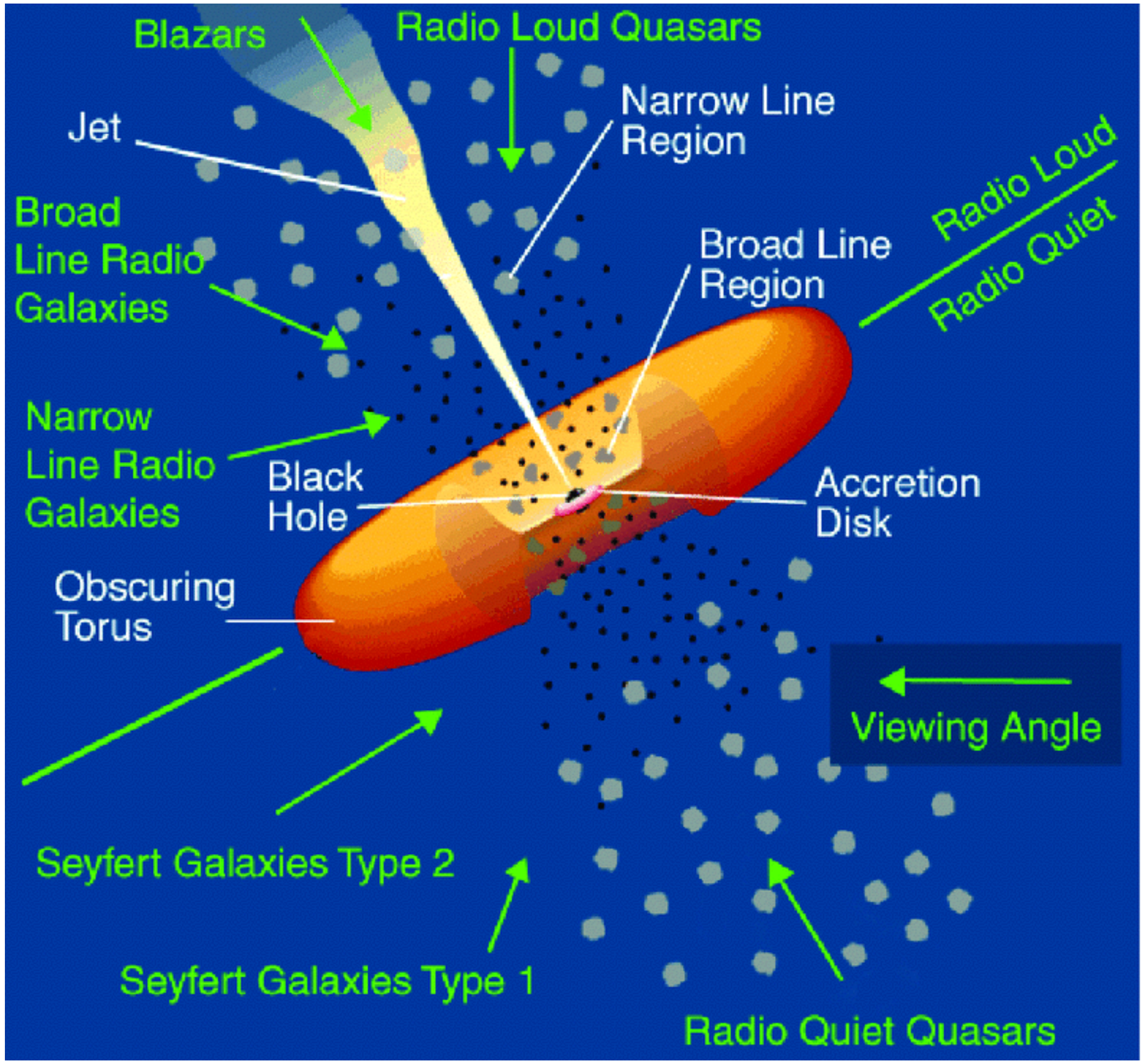
Type 2: Heart of the AGN blocked by torus, optical signature is only scattered from NLR.



Type 1: See into heart of AGN (disc), see optical lines from BLR and NLR.

The AGN Zoo

Unification model: molecular torus ~parsecs from BH, optical lines from orbiting clouds. Broad line region closer in (faster Keplerian rotation), narrow line region further out (slower Keplerian rotation).



Quasars: Originally called quasi-stellar radio sources. Strong radio sources with point-source optical counterpart (i.e. galaxy spatially unresolved).

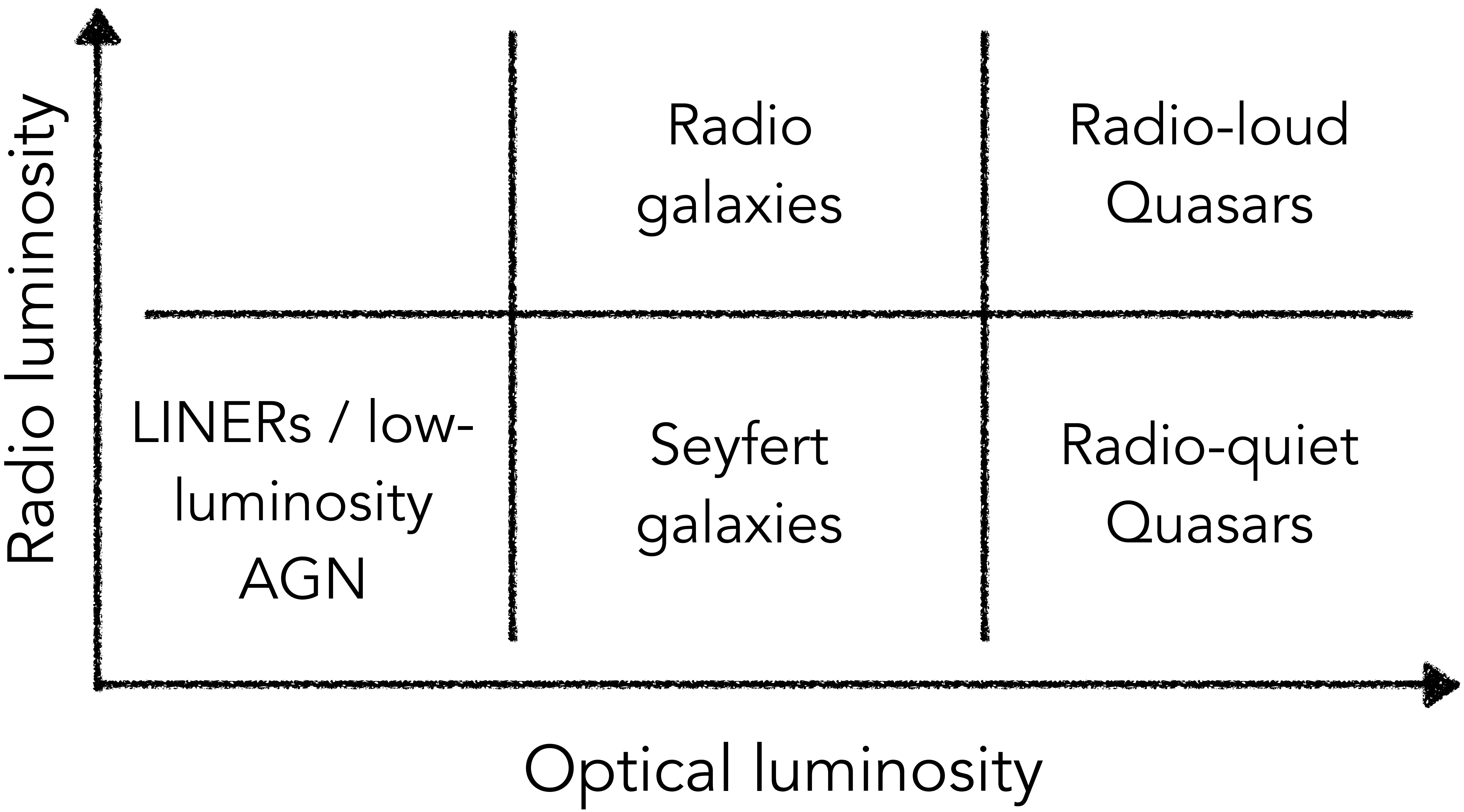
Radio galaxies: Like quasars, but the optical counterpart is less bright.

Seyfert galaxies: Galaxy is resolved, but nucleus accounts for large fraction of the light, weak radio sources.

Blazars: We see down the barrel of the jet (covered later in this lecture)

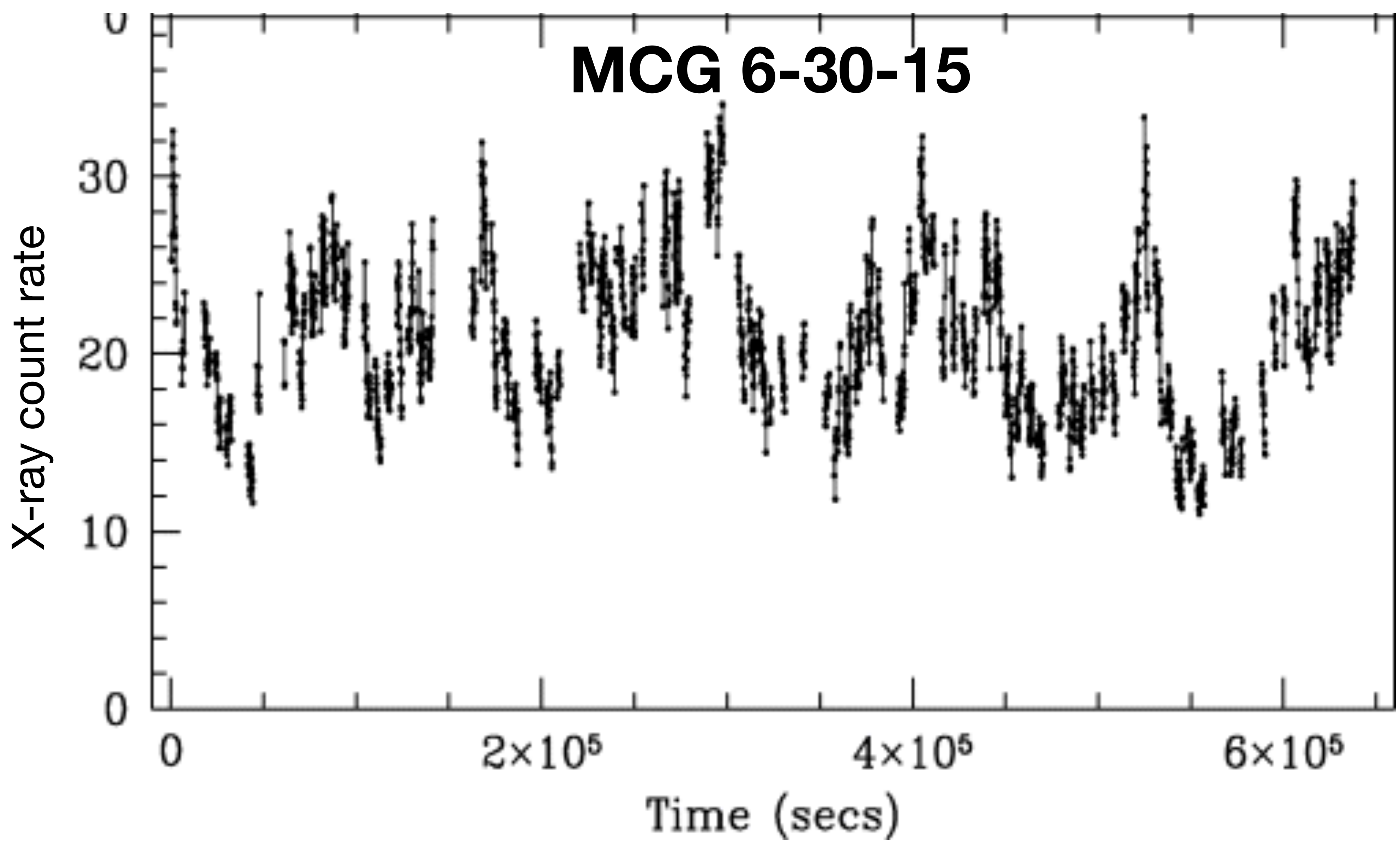
The AGN Zoo

Classification complicated, but roughly based on optical (~bolometric) and radio luminosity.



How do we know AGN are BHs?

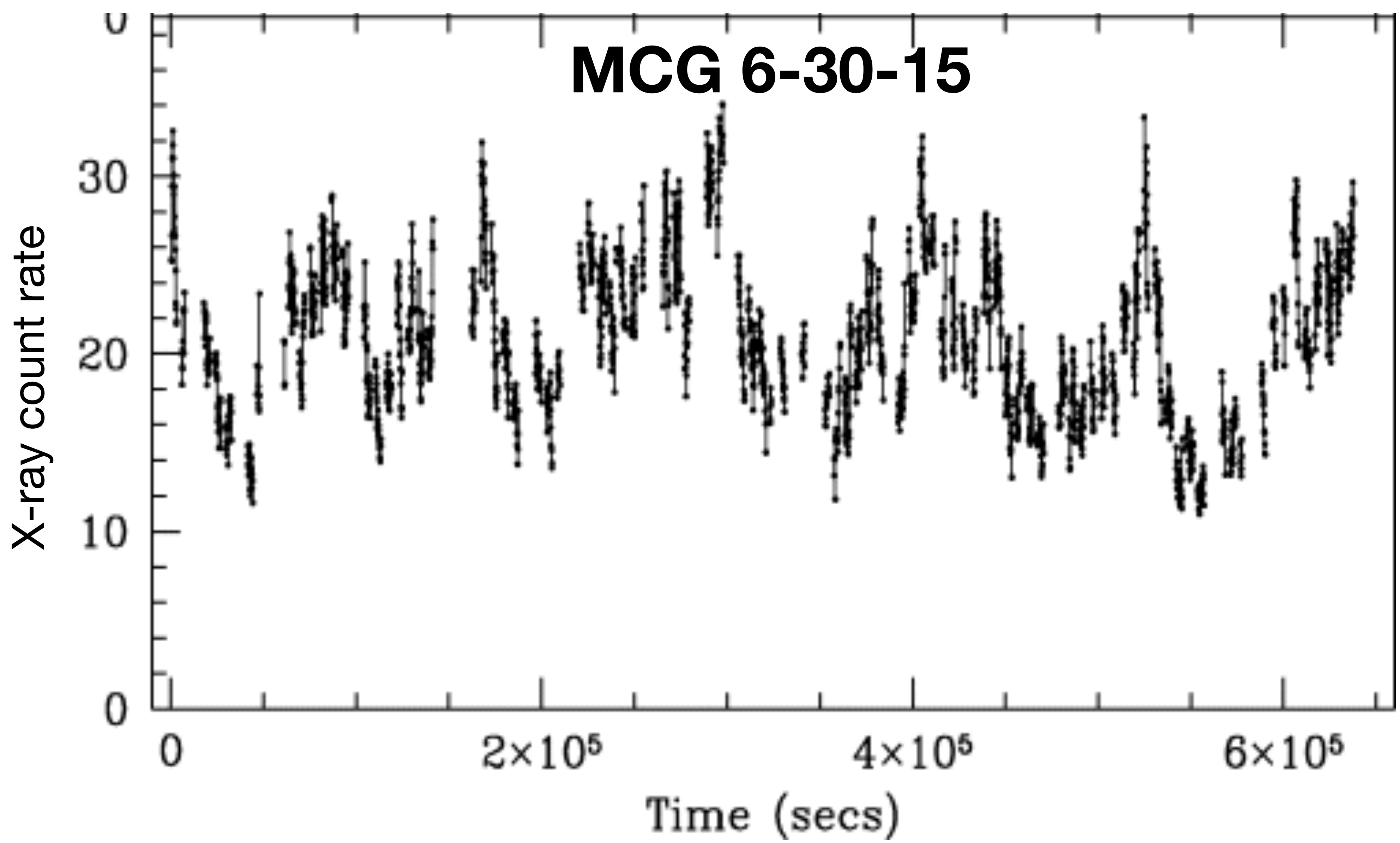
Strong multi-wavelength variability provided first evidence these are compact:



How do we know AGN are BHs?

Strong multi-wavelength variability provided first evidence these are compact:

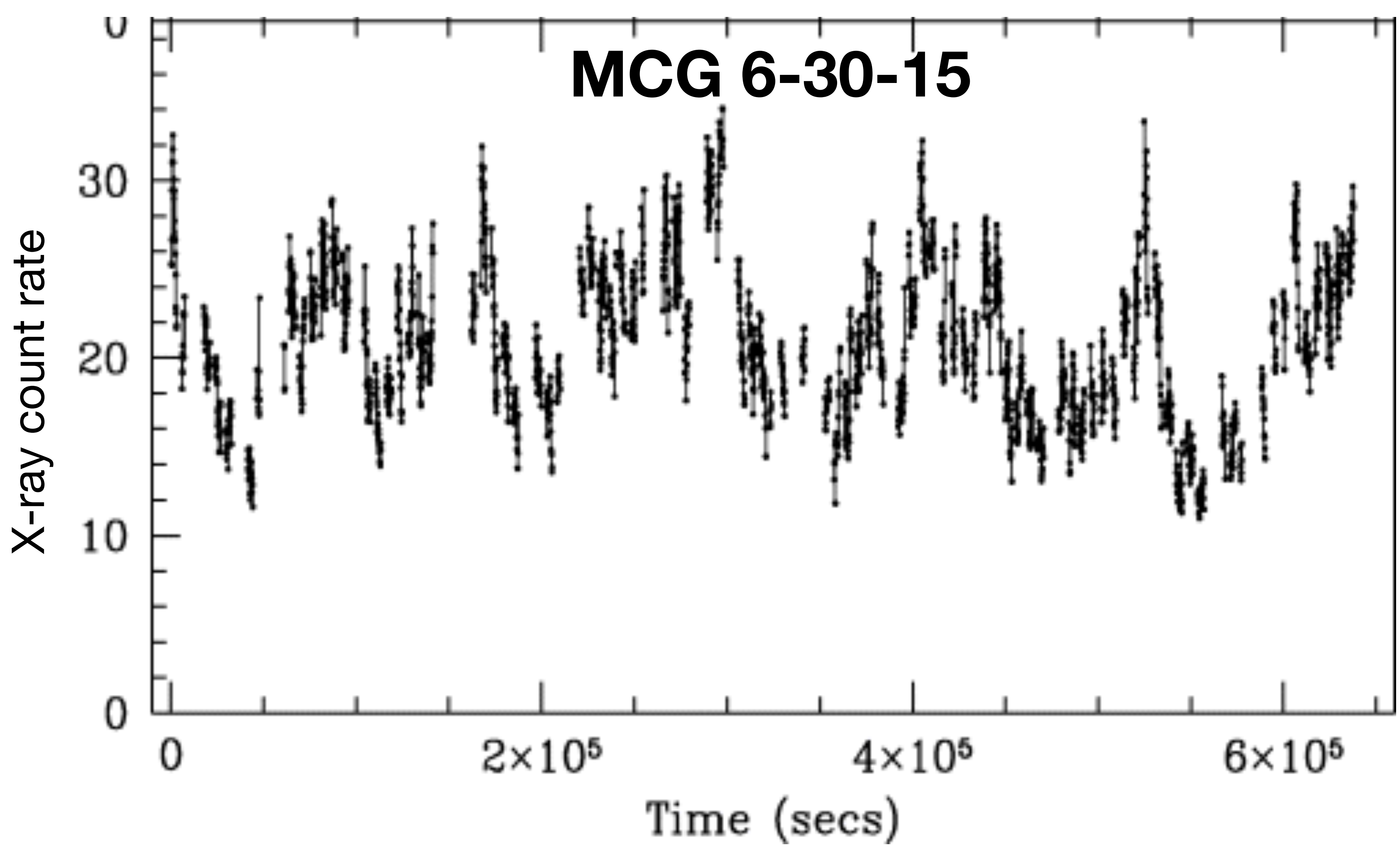
- Lower limit on mass assuming $L \lesssim L_{\rm Edd}$



How do we know AGN are BHs?

Strong multi-wavelength variability provided first evidence these are compact:

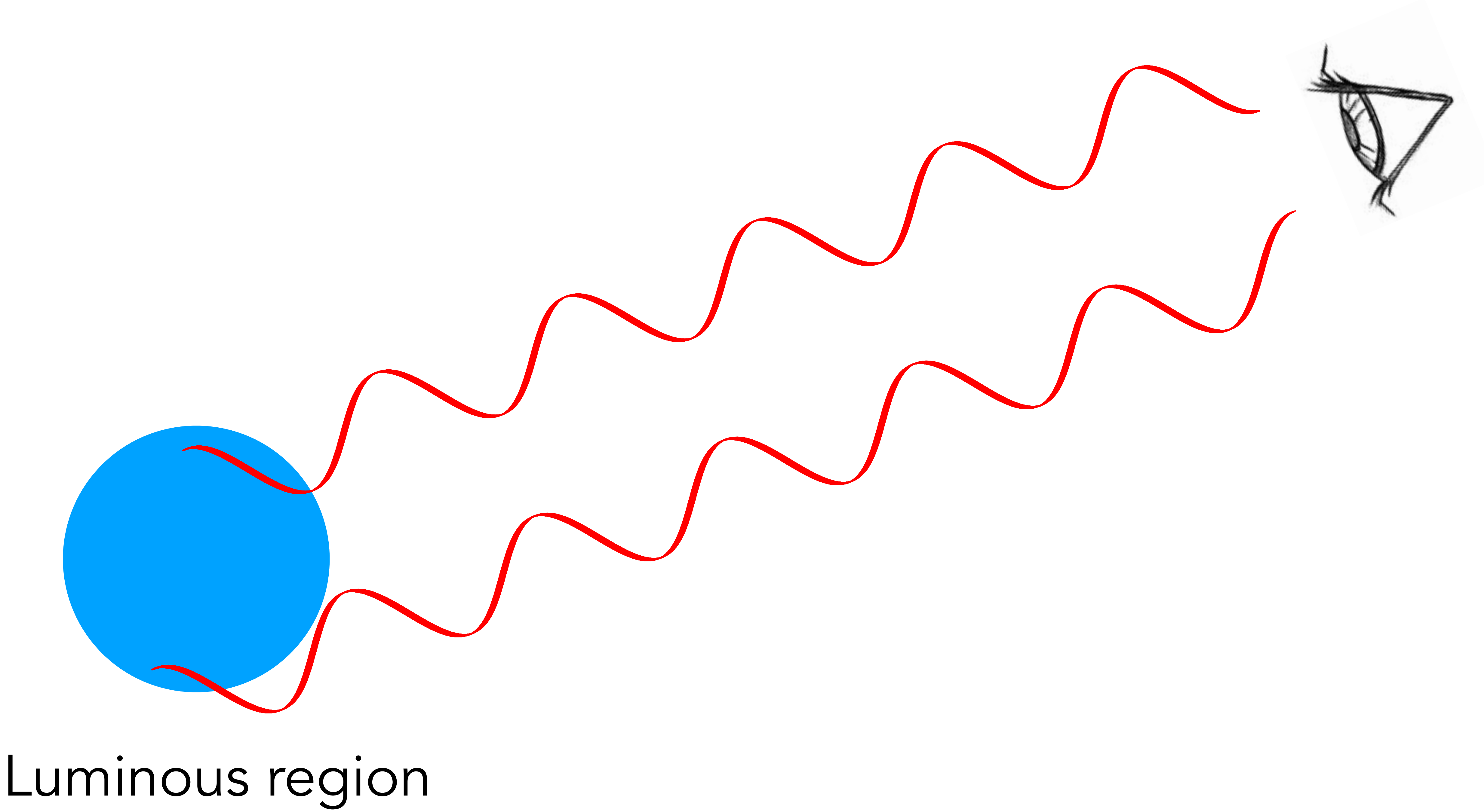
- Lower limit on mass assuming $L \lesssim L_{\rm Edd}$
- Upper limit on size from variability, since variability will be washed out on timescales $> r/c$ by destructive interference caused by light-crossing delays.



How do we know AGN are BHs?

Strong multi-wavelength variability provided first evidence these are compact:

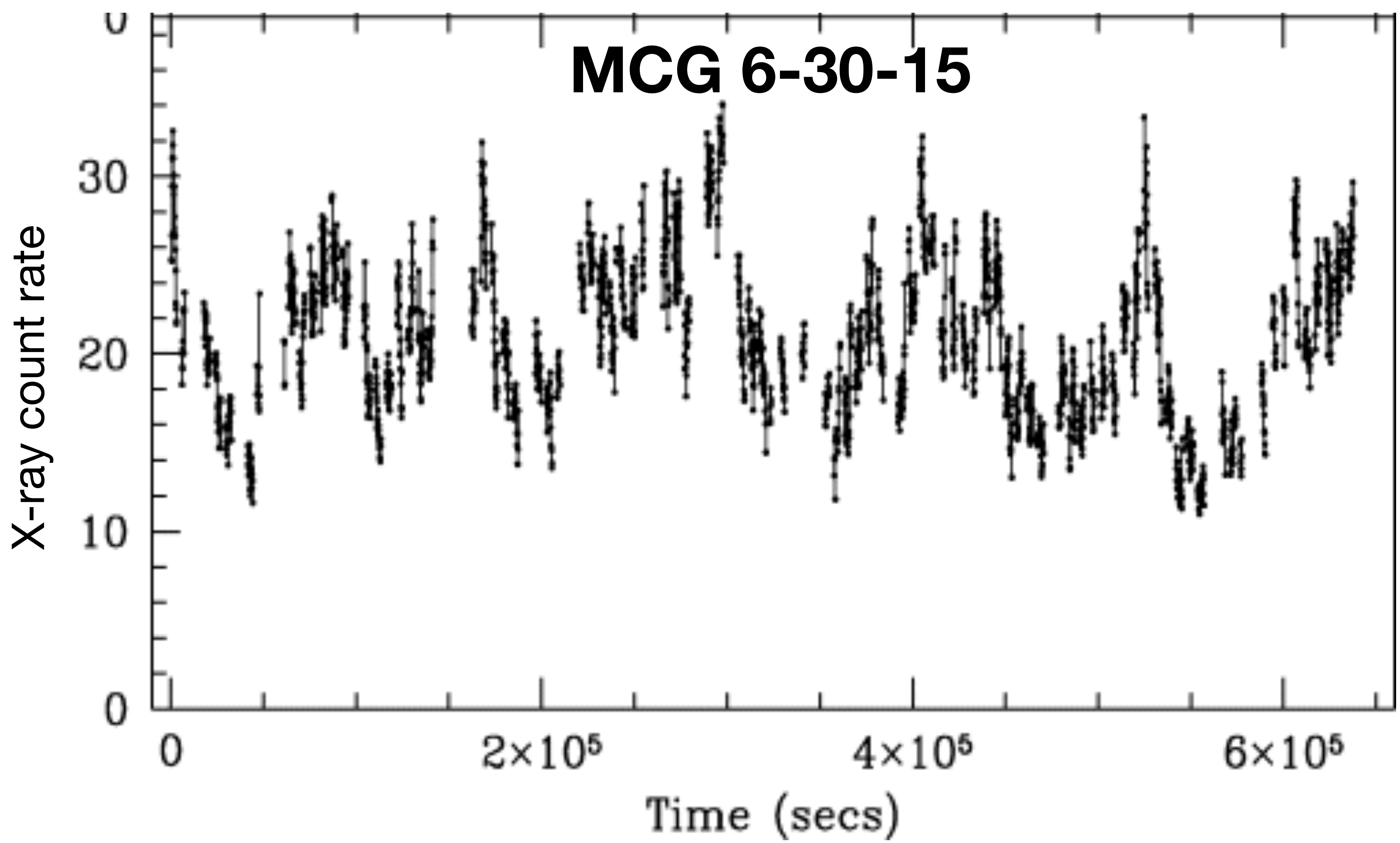
- Lower limit on mass assuming $L \lesssim L_{\rm Edd}$
- Upper limit on size from variability, since variability will be washed out on timescales $> r/c$ by destructive interference caused by light-crossing delays.



How do we know AGN are BHs?

Strong multi-wavelength variability provided first evidence these are compact:

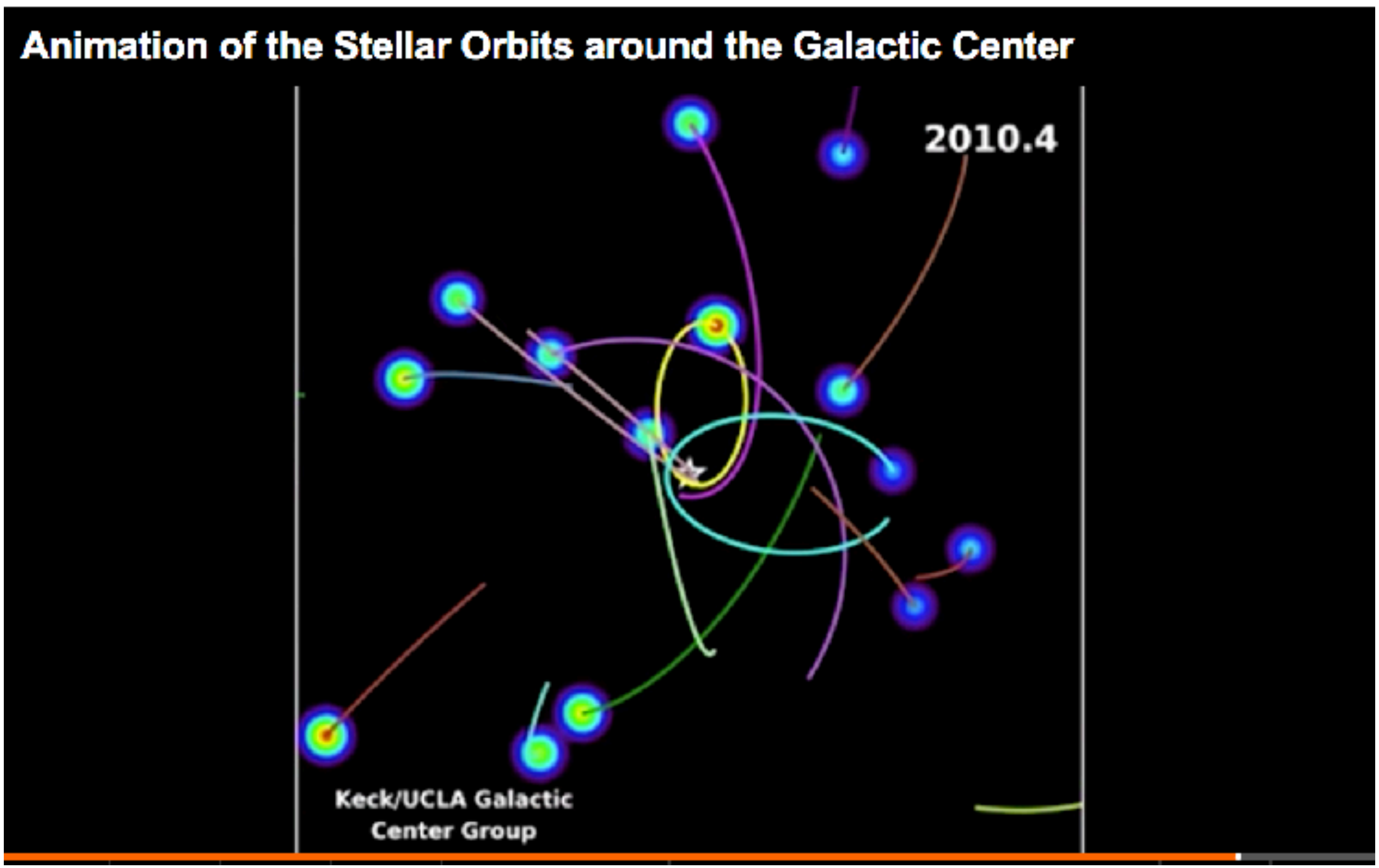
- Lower limit on mass assuming $L \lesssim L_{\rm Edd}$
- Upper limit on size from variability, since variability will be washed out on timescales $> r/c$ by destructive interference caused by light-crossing delays.
- Variability down to ~minutes + huge L => very compact!



How do we know AGN are BHs?

Stellar kinematics:

- Evidence of BH at our galaxy centre (Sgr A*) is overwhelming: decades of tracking stars' orbits confirms $M \approx 4.15 \times 10^6 M_\odot$ in compact region.
- In other nearby galaxies, can't track individual stars, but can measure velocity profiles. Compact, massive dark object inferred at galaxy centre.



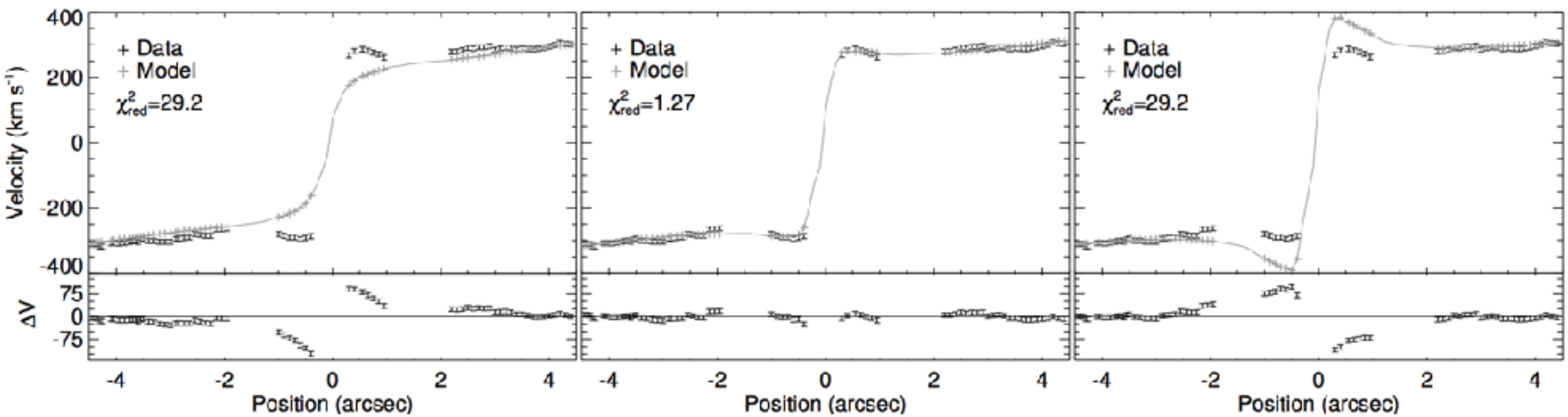
How do we know AGN are BHs?

Gas kinematics:

- Can trace velocity profile of gas using emission lines (ideally masers).

Velocity profile of CO maser emission in NGC4526

Model with no BH | Model with best-fit BH | Model with over-weight BH



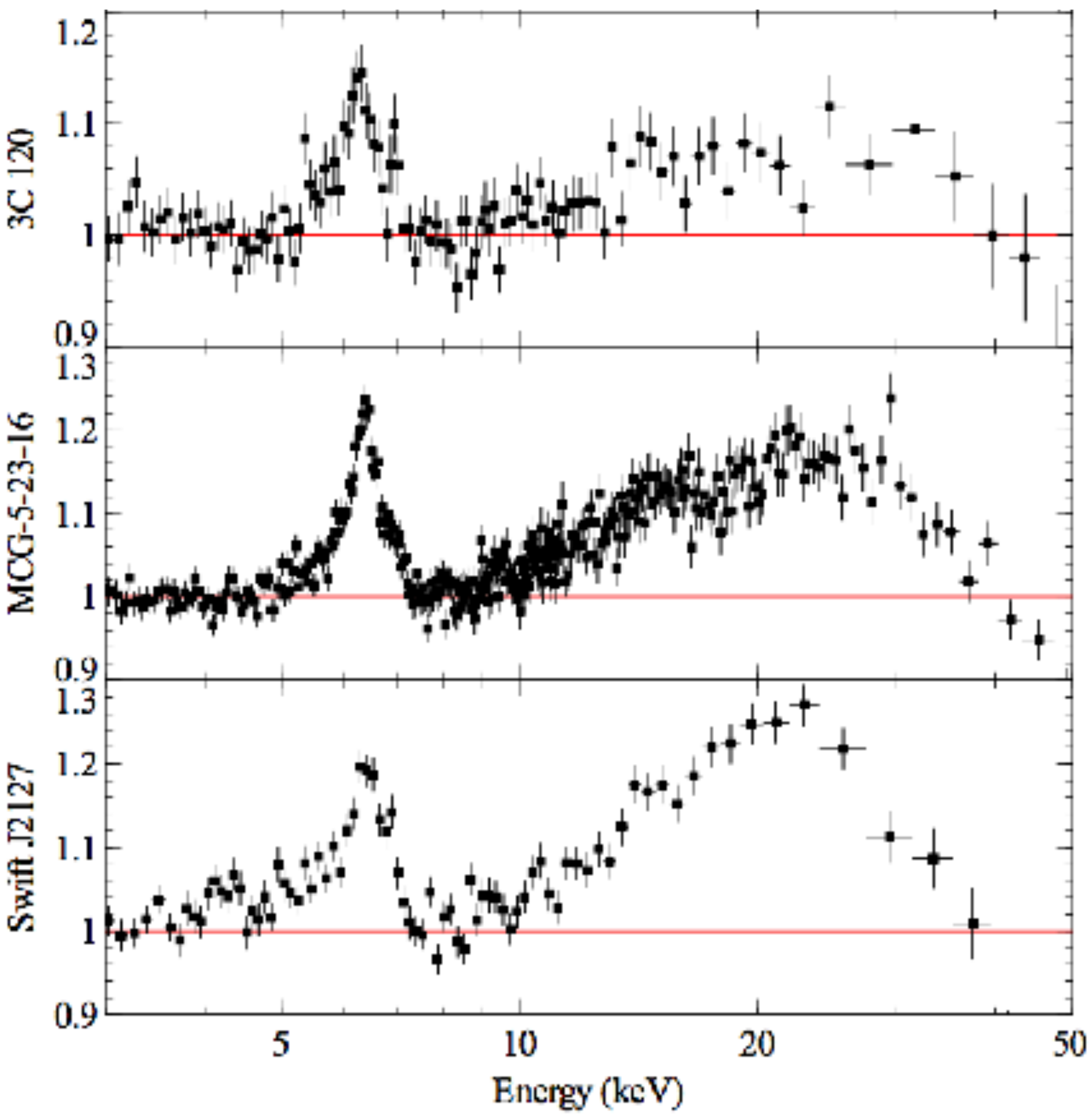
$$M \approx 4.5 \times 10^8 M_\odot$$

Plot from Davis et al (2013)

How do we know AGN are BHs?

Iron line profiles:

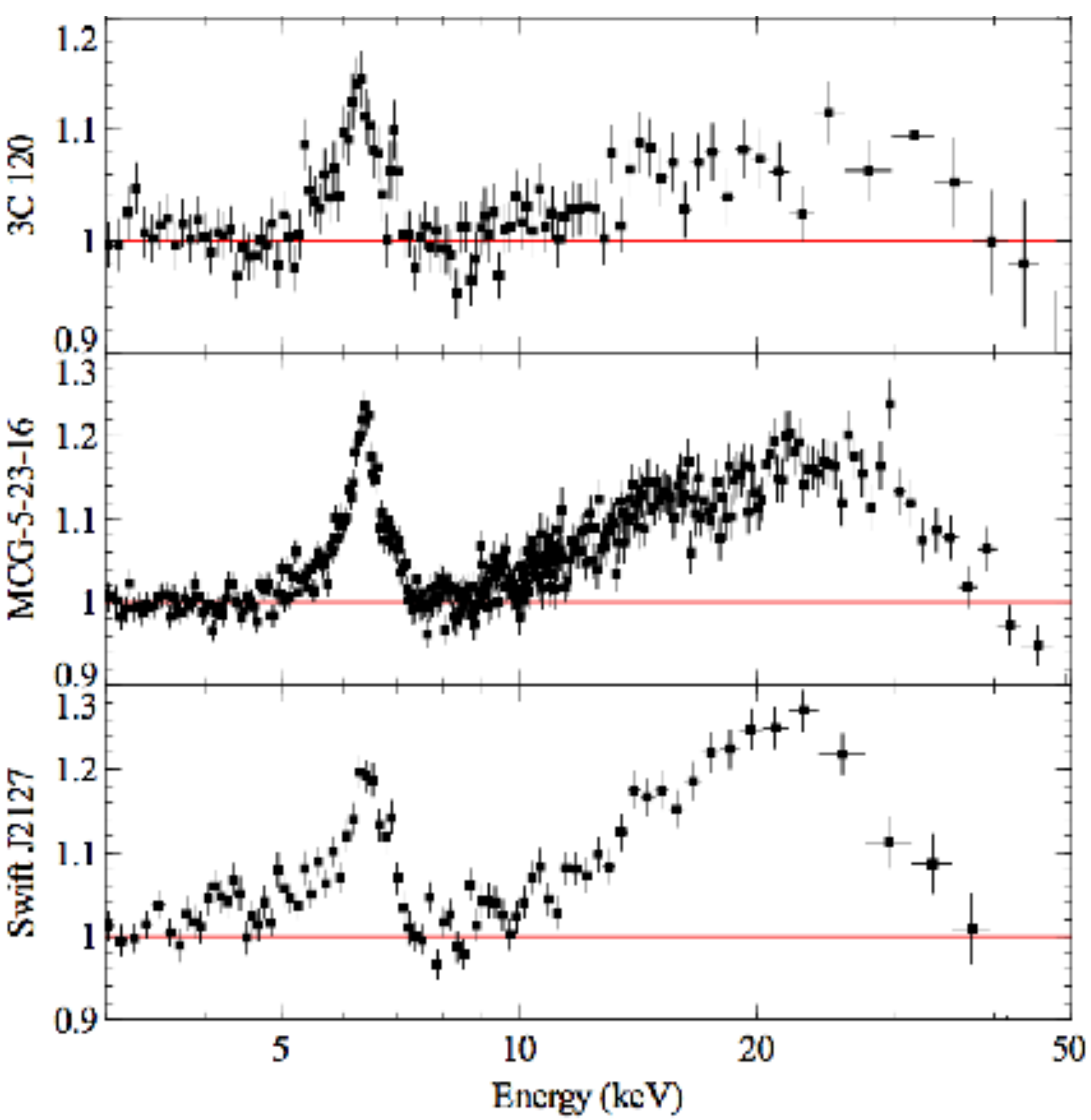
- Skewed, super-broad line profile => very compact emitting region.

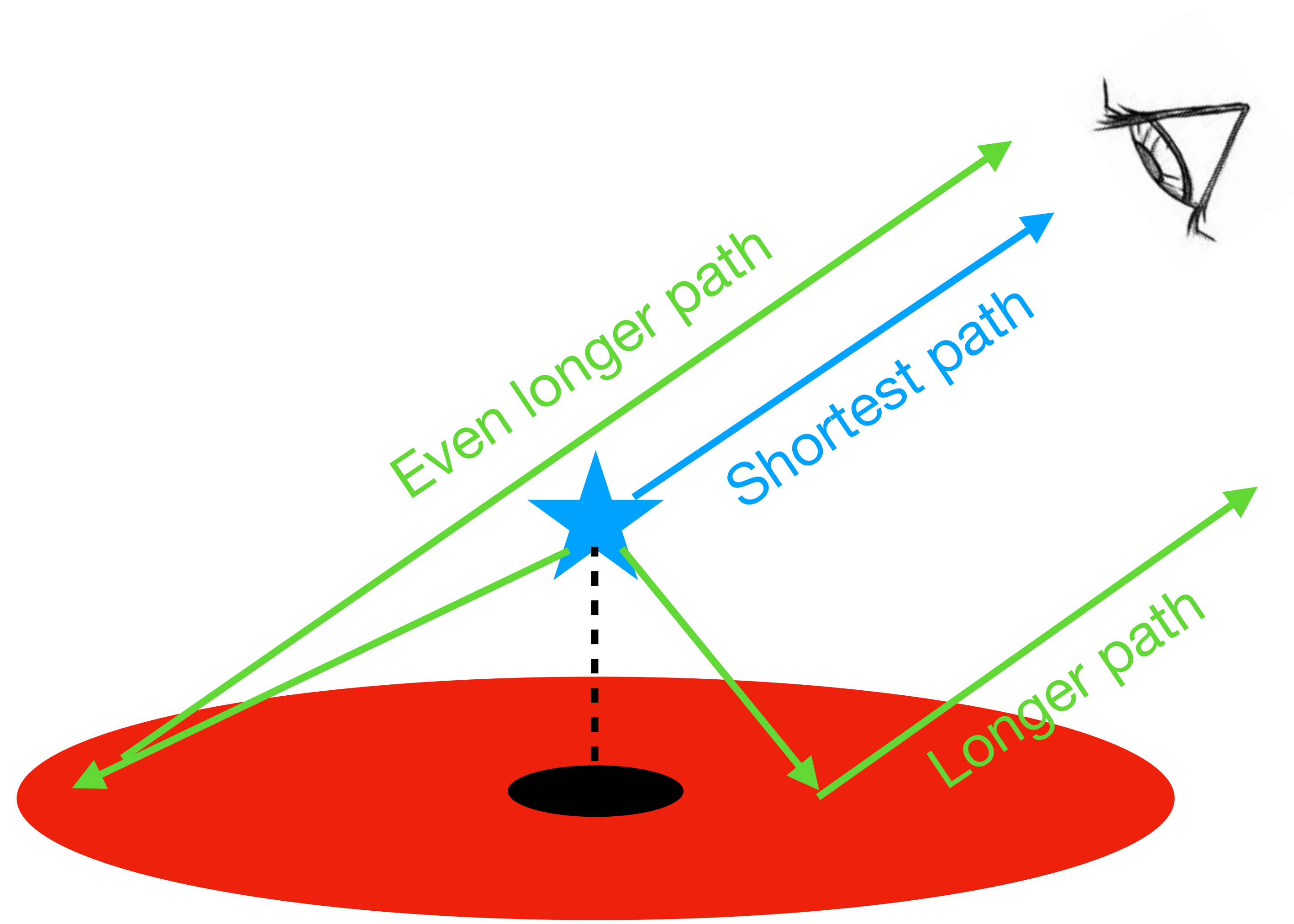


How do we know AGN are BHs?

Iron line profiles:

- Skewed, super-broad line profile => very compact emitting region.
- But not sensitive to BH mass — need to measure time lags between iron line and continuum X-rays for that (X-ray reverberation mapping).

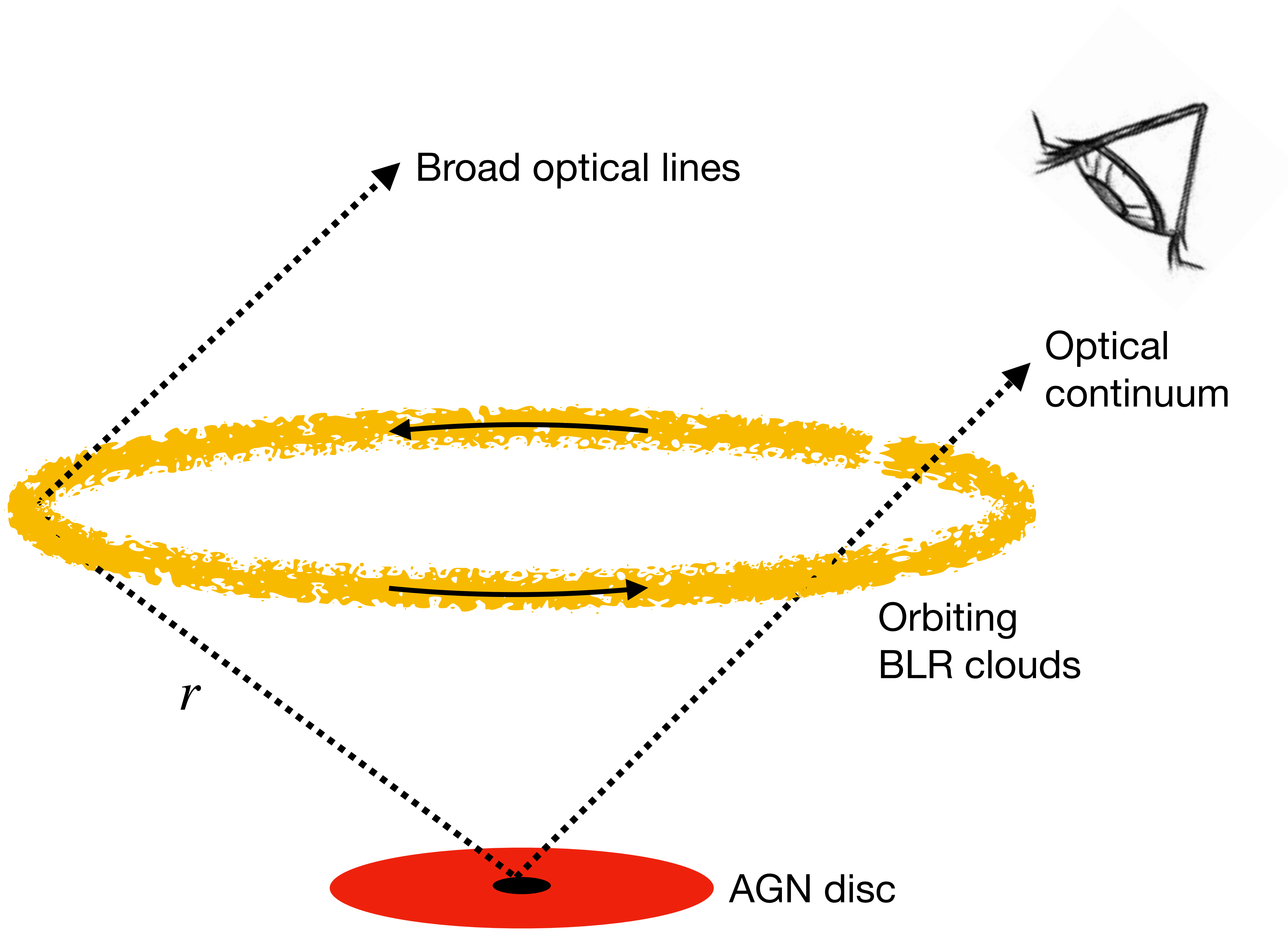




How do we know AGN are BHs?

Optical reverberation mapping:

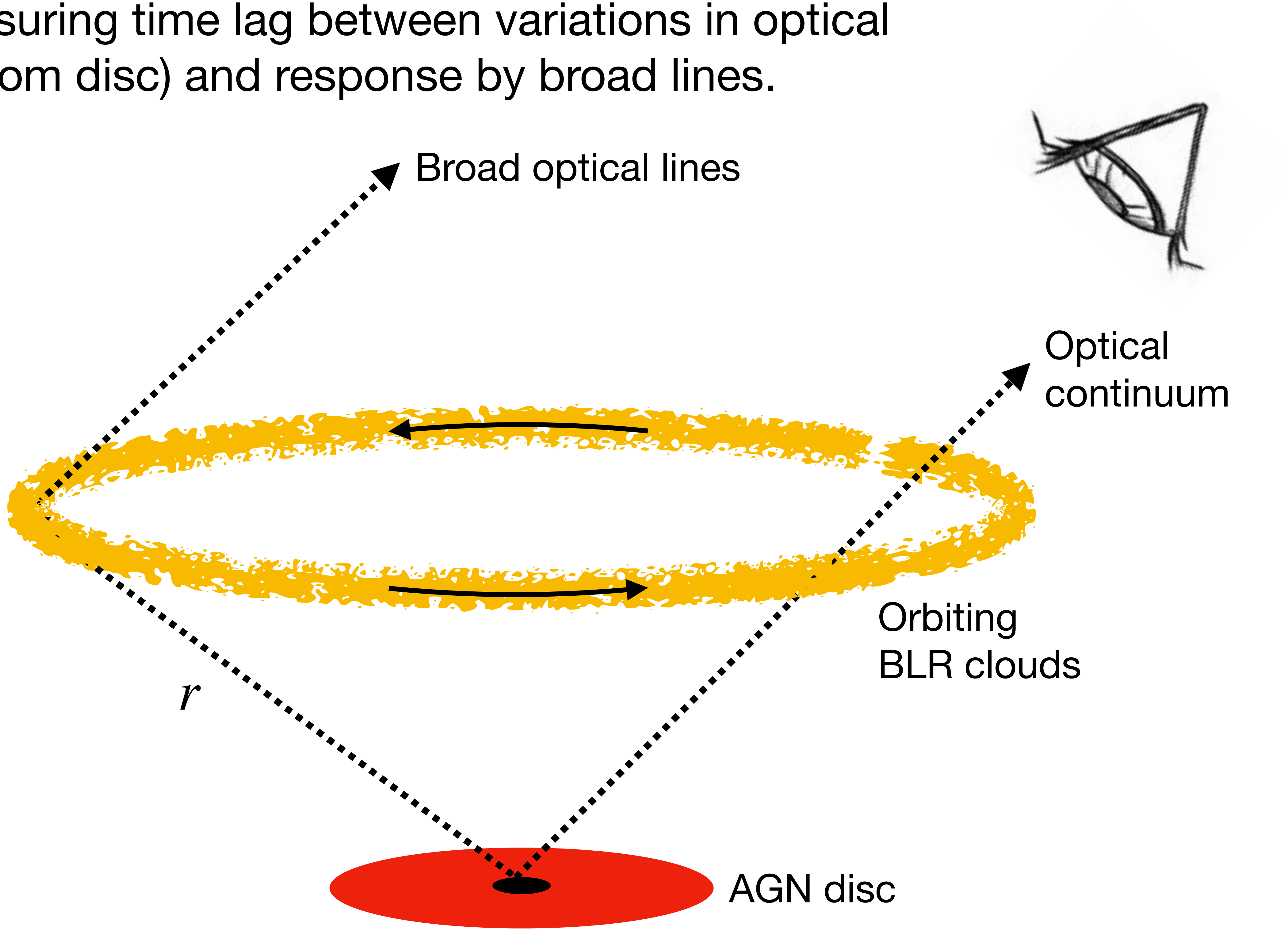
- Width of BLR lines gives velocity of BLR clouds: $v = (GM/r)^{1/2}$



How do we know AGN are BHs?

Optical reverberation mapping:

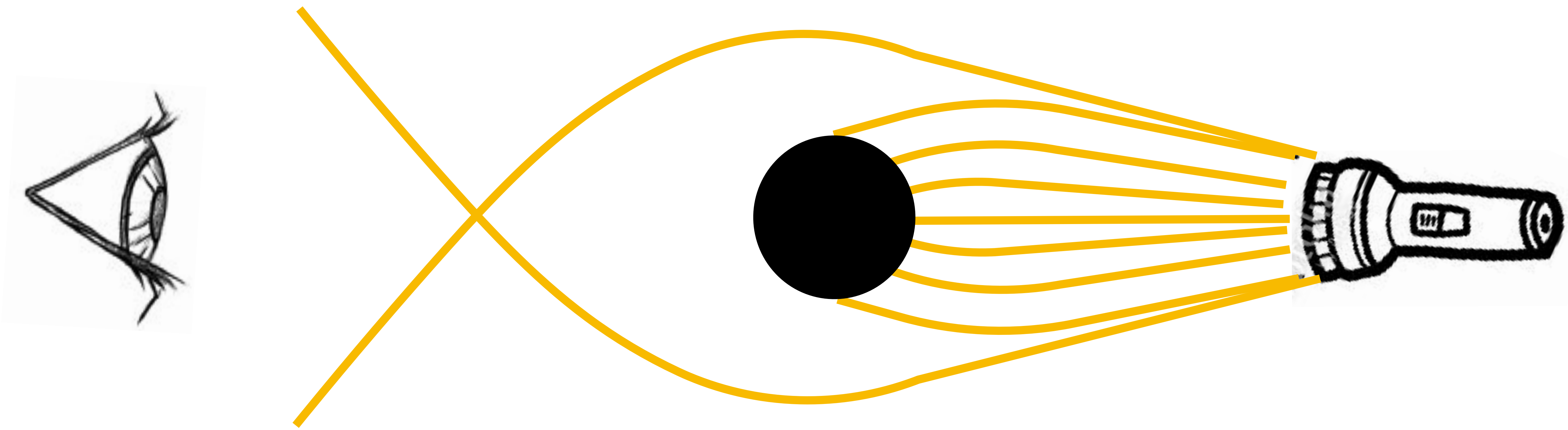
- Width of BLR lines gives velocity of BLR clouds: $v = (GM/r)^{1/2}$
- Get r by measuring time lag between variations in optical continuum (from disc) and response by broad lines.



How do we know AGN are BHs?

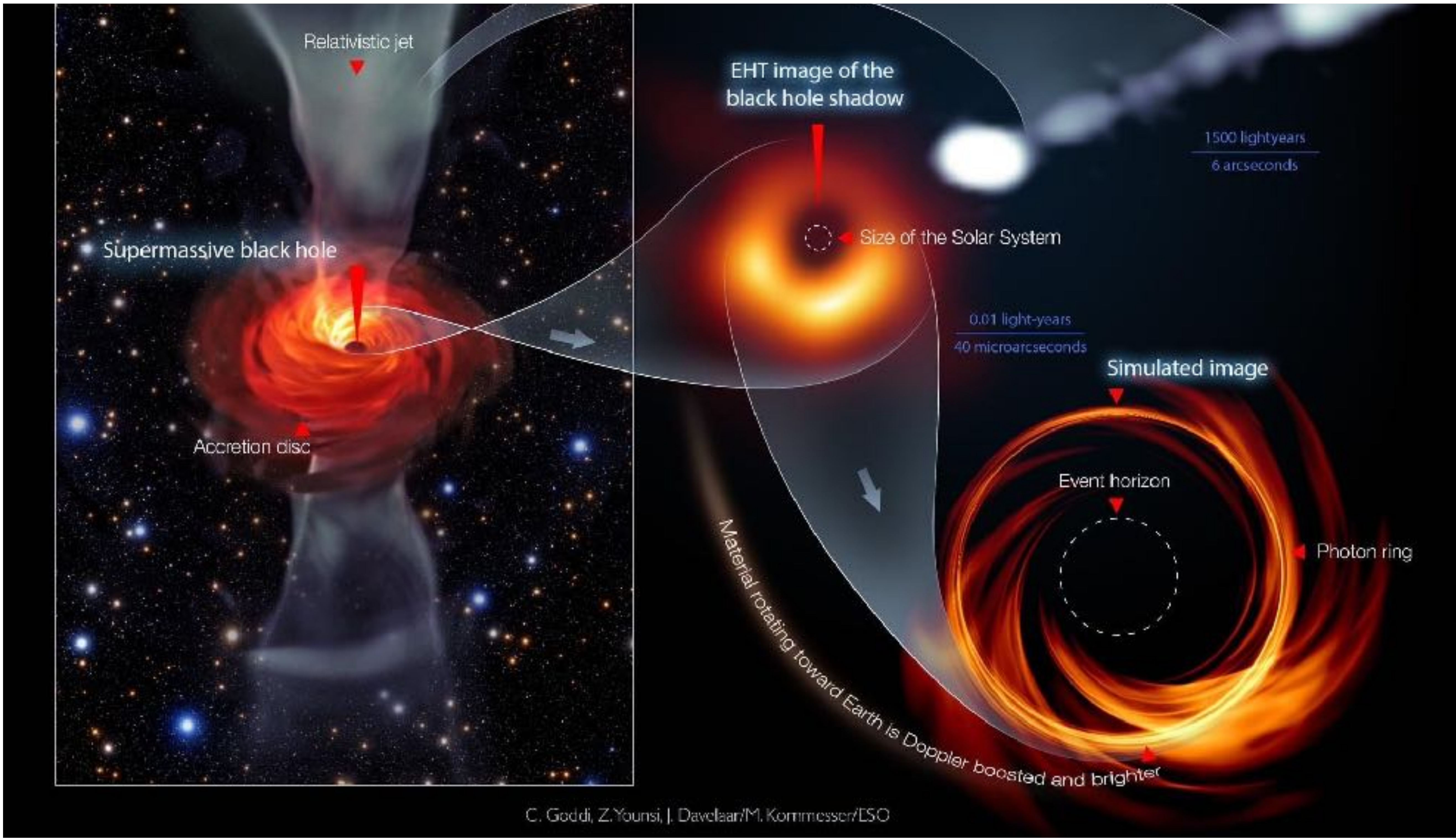
Black hole shadow of M87:

Back lit black hole has a “shadow” (really a silhouette) from light rays disappearing beneath the event horizon.



How do we know AGN are BHs?

Black hole shadow of M87: Seen for the first time by exquisite resolution of the Event Horizon Telescope — network of radio telescopes providing interferometry baseline the size of the Earth.

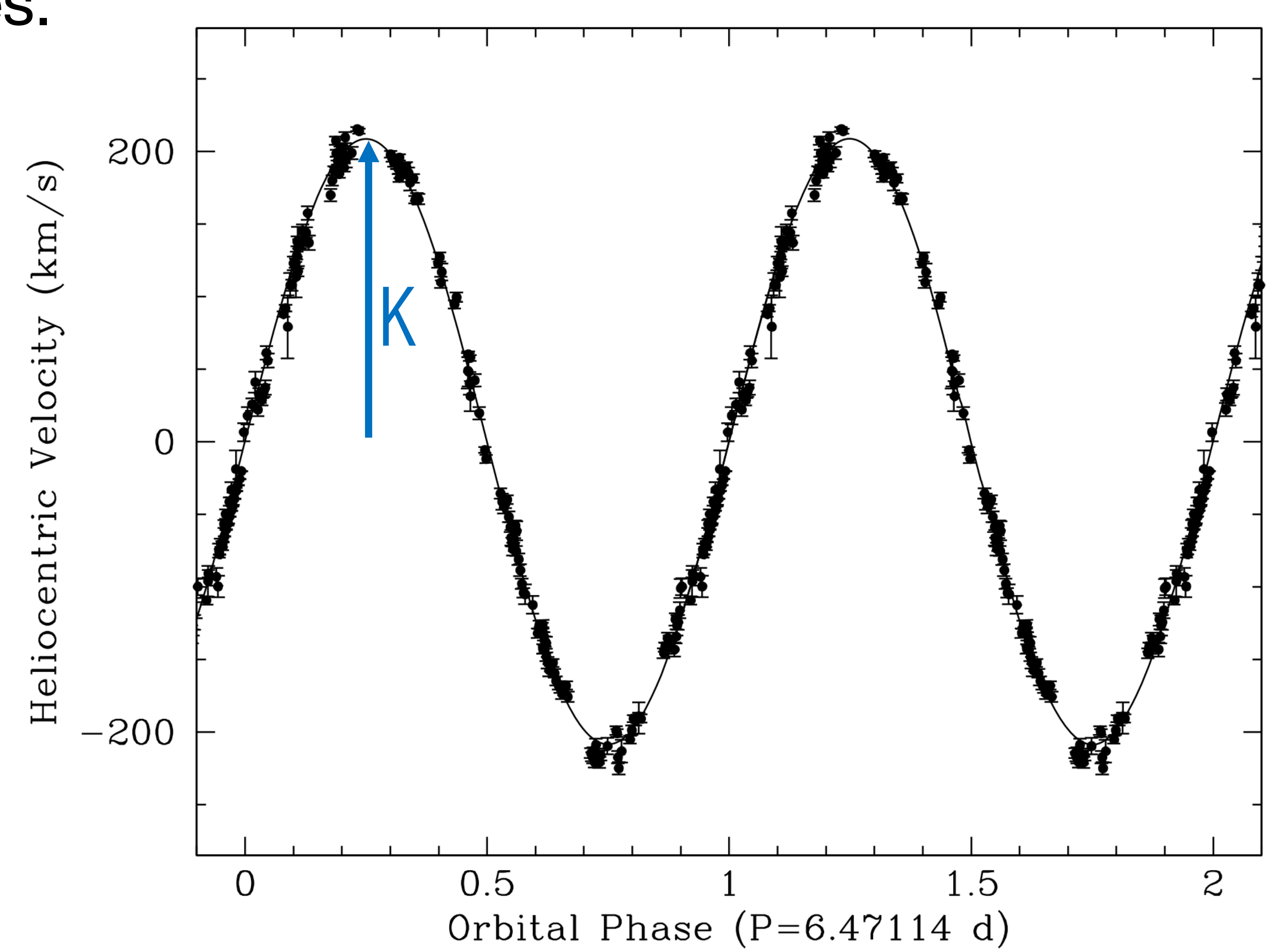


How do we know XRBs are BHs?

Same / similar arguments:

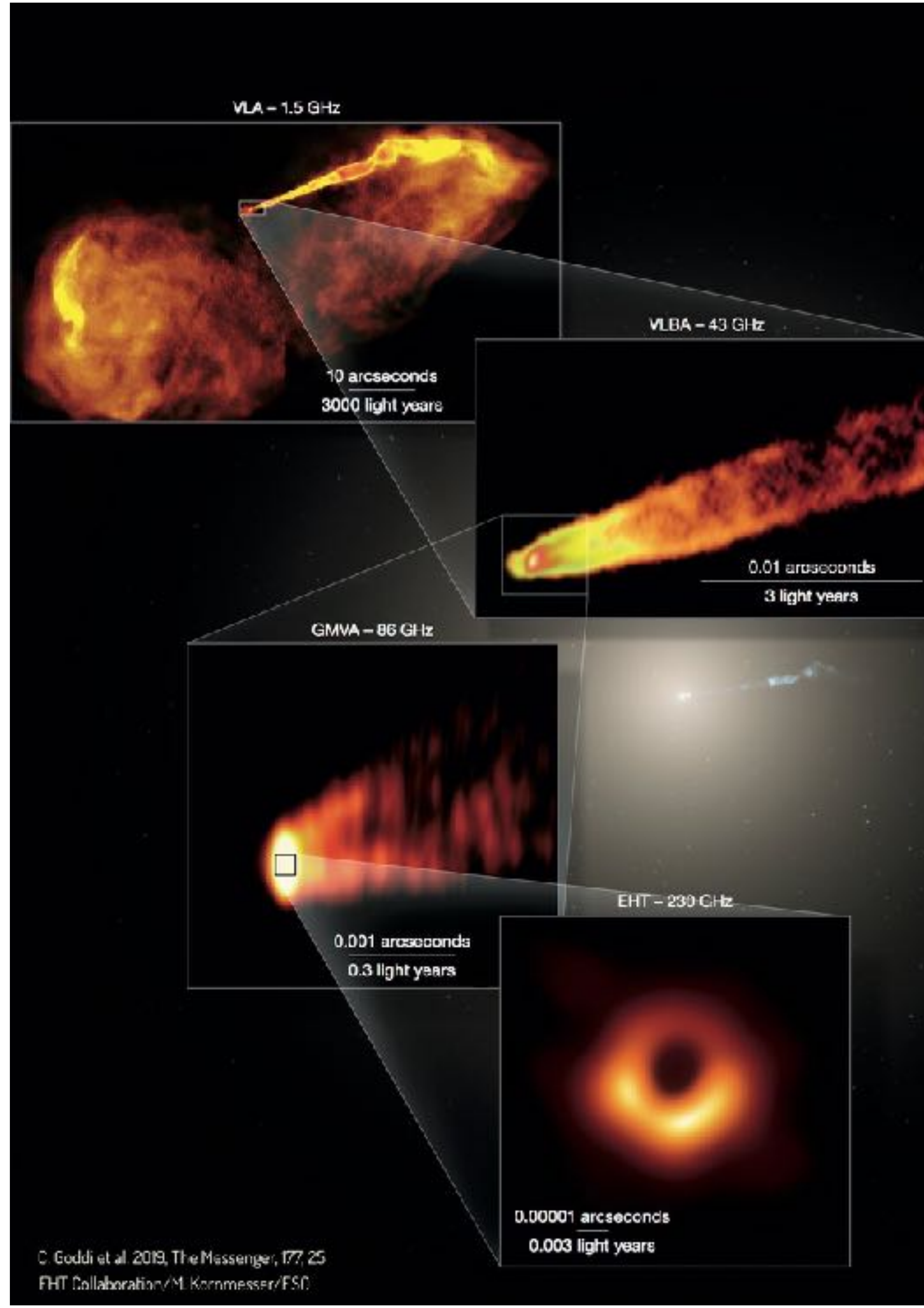
- Rapid X-ray variability (much faster) and large luminosity.
- Broad iron lines (+ can also measure BH mass with X-ray reverberation mapping).
- Dynamical mass measurement by tracing orbit of companion star by Doppler shifts of absorption lines.

  ~20 dynamically confirmed BHs in our Galaxy (~60 known “candidates”)



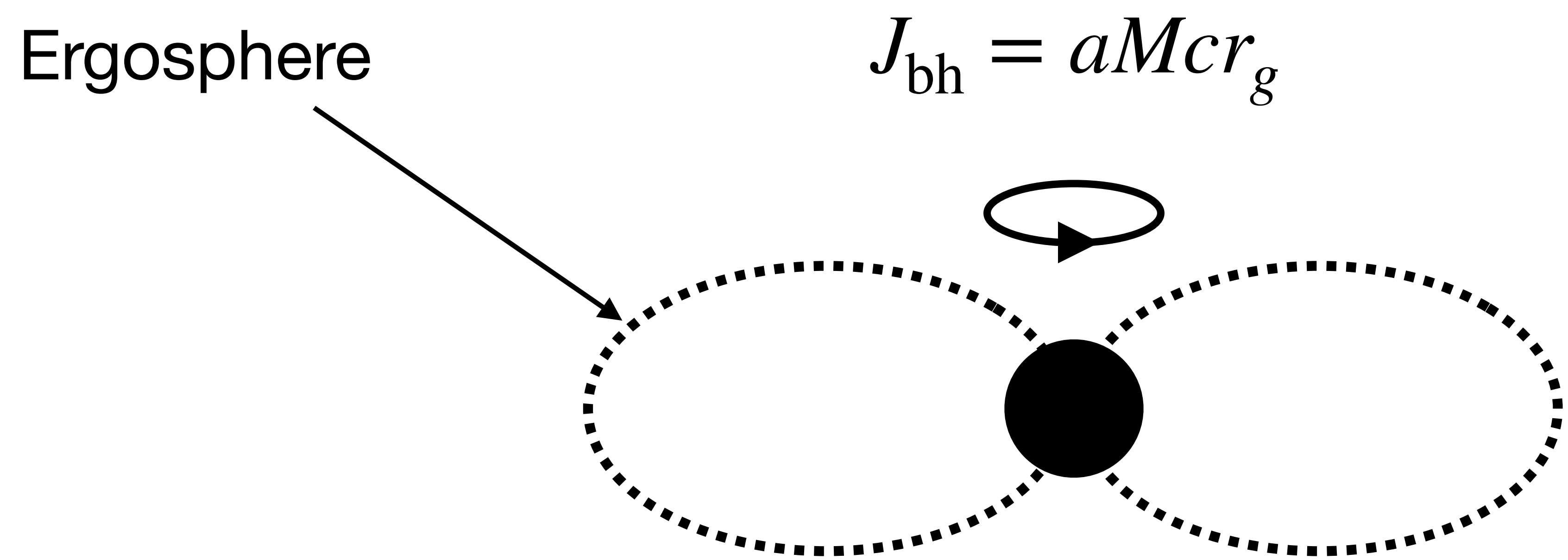
Casares & Jonker (2014)

Jets
M87 Jet


VLA – 1.5 GHz
10 arcseconds
3000 light years
VLBA – 43 GHz
0.01 arcseconds
3 light years
GMVA – 86 GHz
0.001 arcseconds
0.3 light years
EHT – 230 GHz
0.00001 arcseconds
0.003 light years
C. Goddi et al. 2019, The Messenger, 177, 25
EHT Collaboration/M. Kornmesser/ESO

Blandford-Znajek mechanism

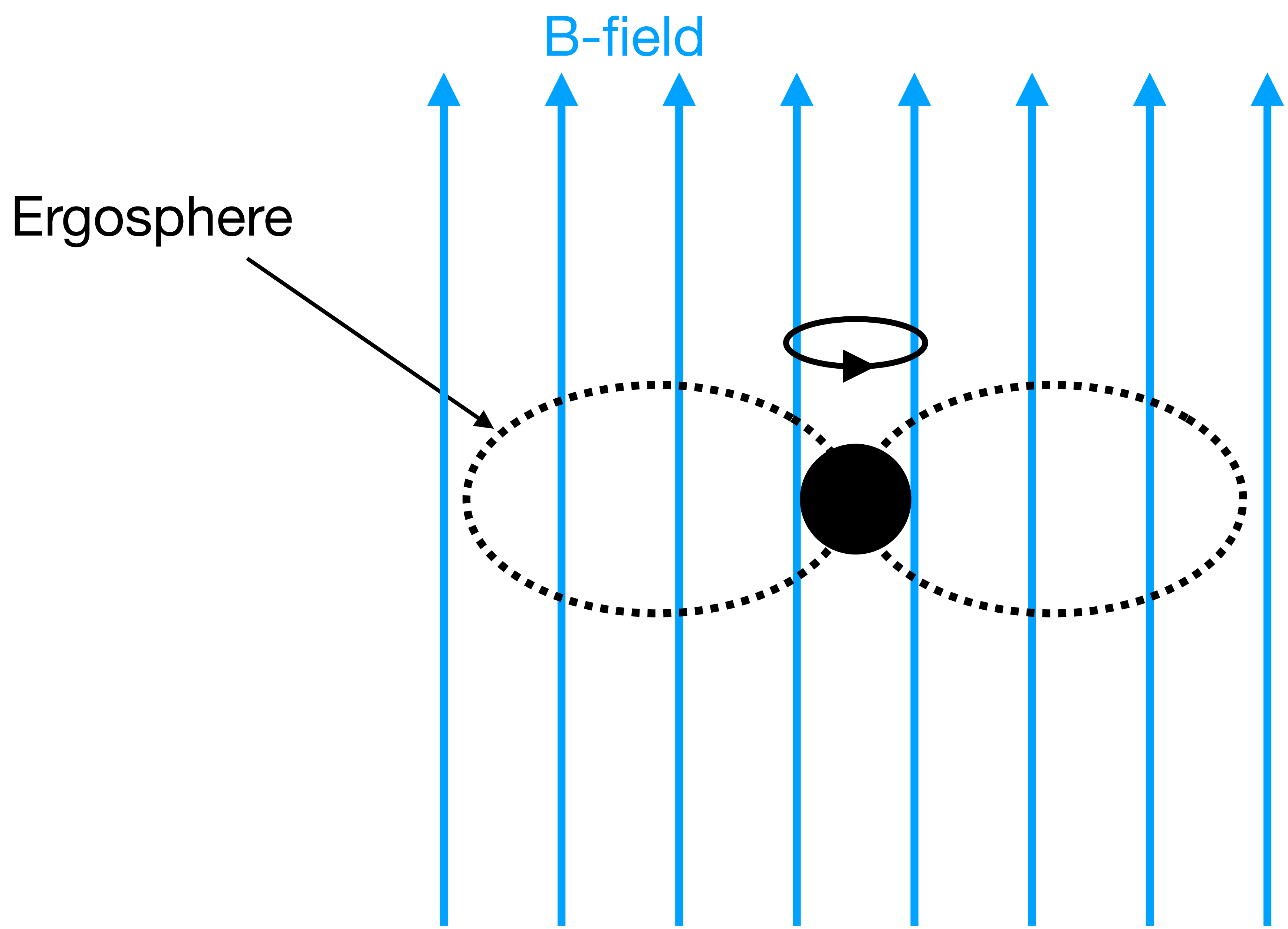
- Inside of ergosphere, it is *impossible* to not rotate with the black hole!
- BH is enormous reservoir of angular momentum and rest mass energy.



Blandford & Znajek (1977)

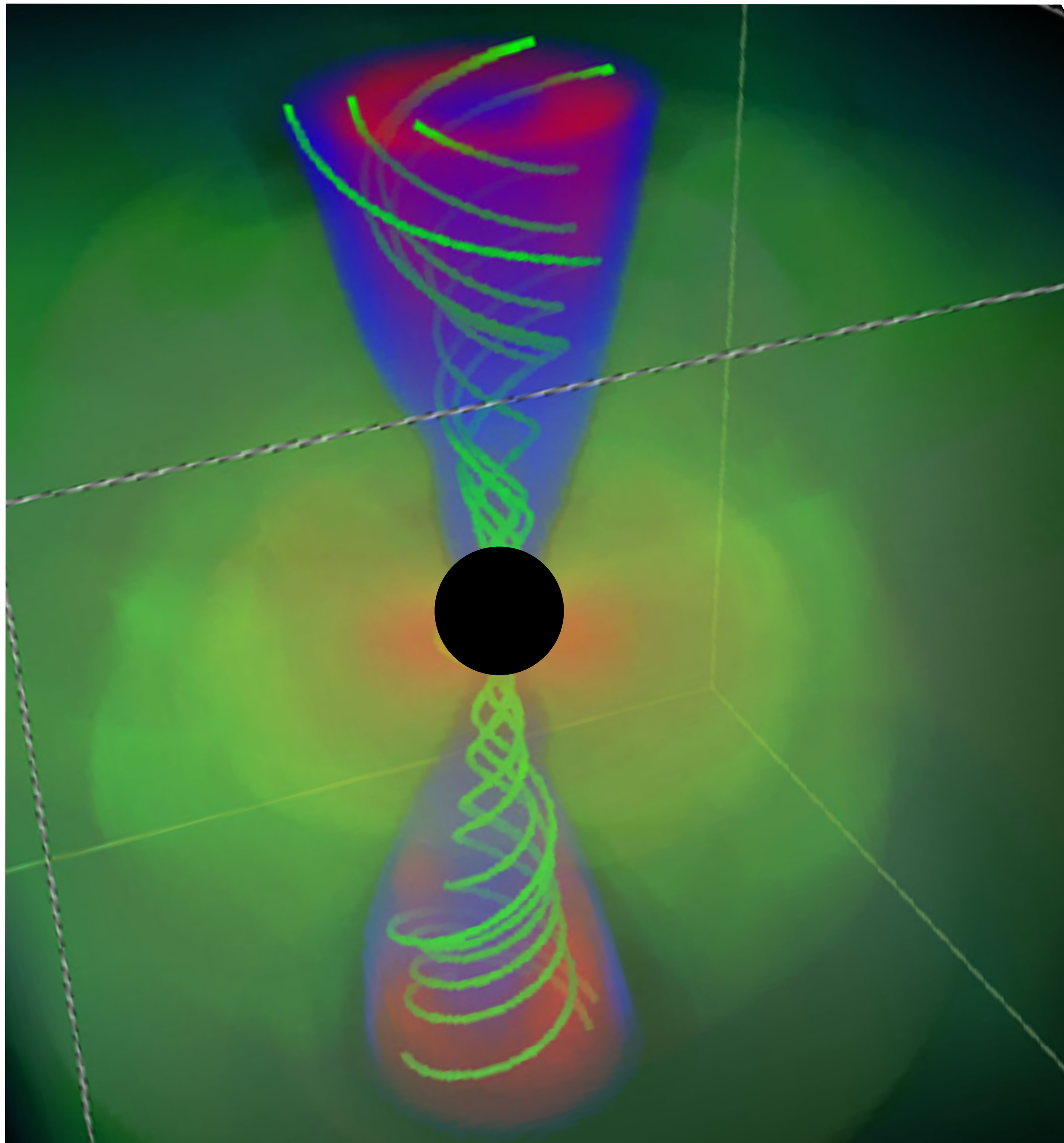
Blandford-Znajek mechanism

- Inside of ergosphere, it is *impossible* to not rotate with the black hole!
- BH is enormous reservoir of angular momentum and rest mass energy.
- So what happens if we have a vertical (toroidal) B-field close to BH?
- Fairly strong B-field expected, since in-falling material has carried and compressed B from ISM / companion.



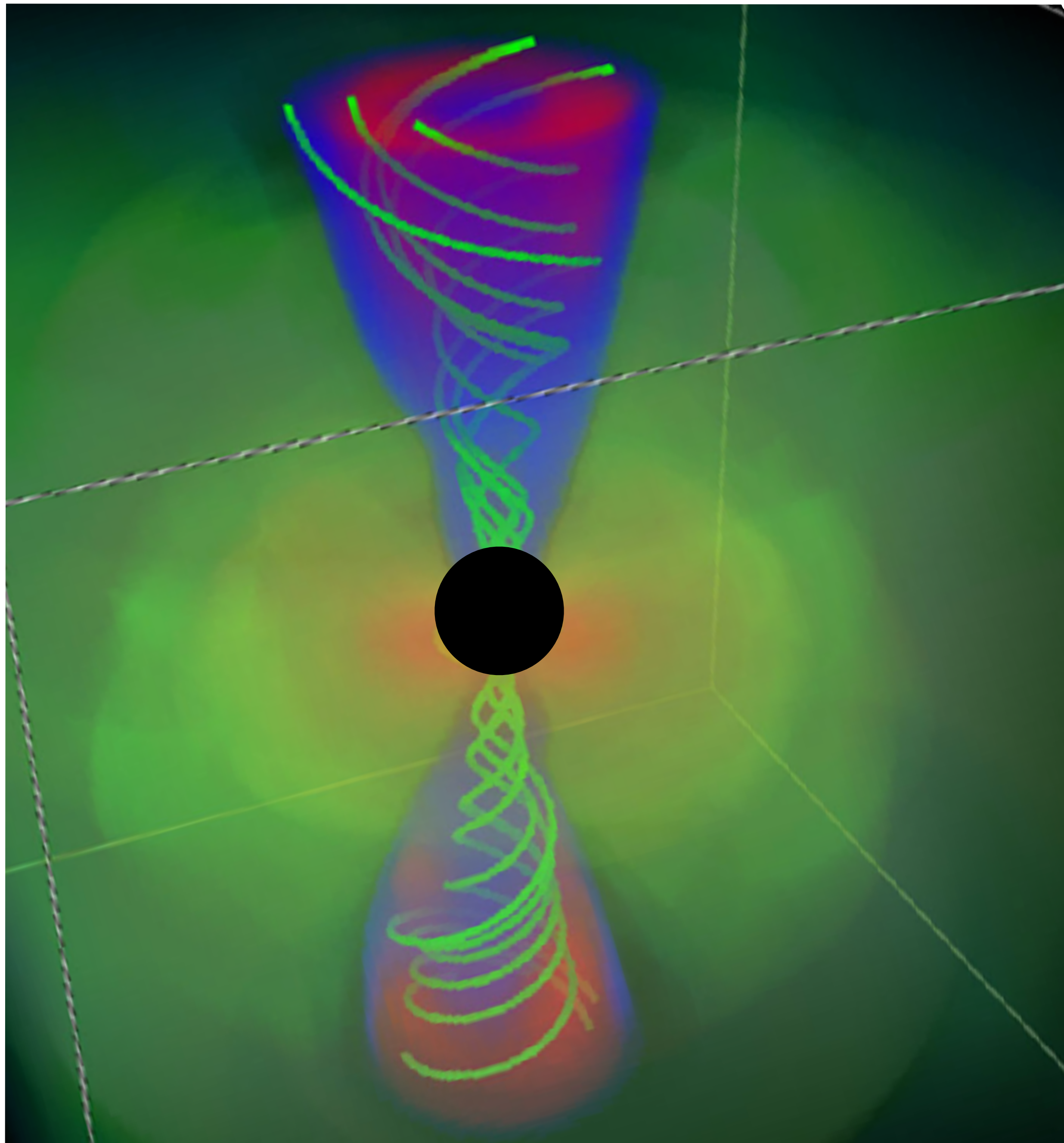
Blandford-Znajek mechanism

- Inside of ergosphere, it is *impossible* to not rotate with the black hole!
- BH is enormous reservoir of angular momentum and rest mass energy.
- So what happens if we have a vertical (toroidal) B-field close to BH?
- Fairly strong B-field expected, since in-falling material has carried and compressed B from ISM / companion.
- It creates a toroidal, twisting B-field!



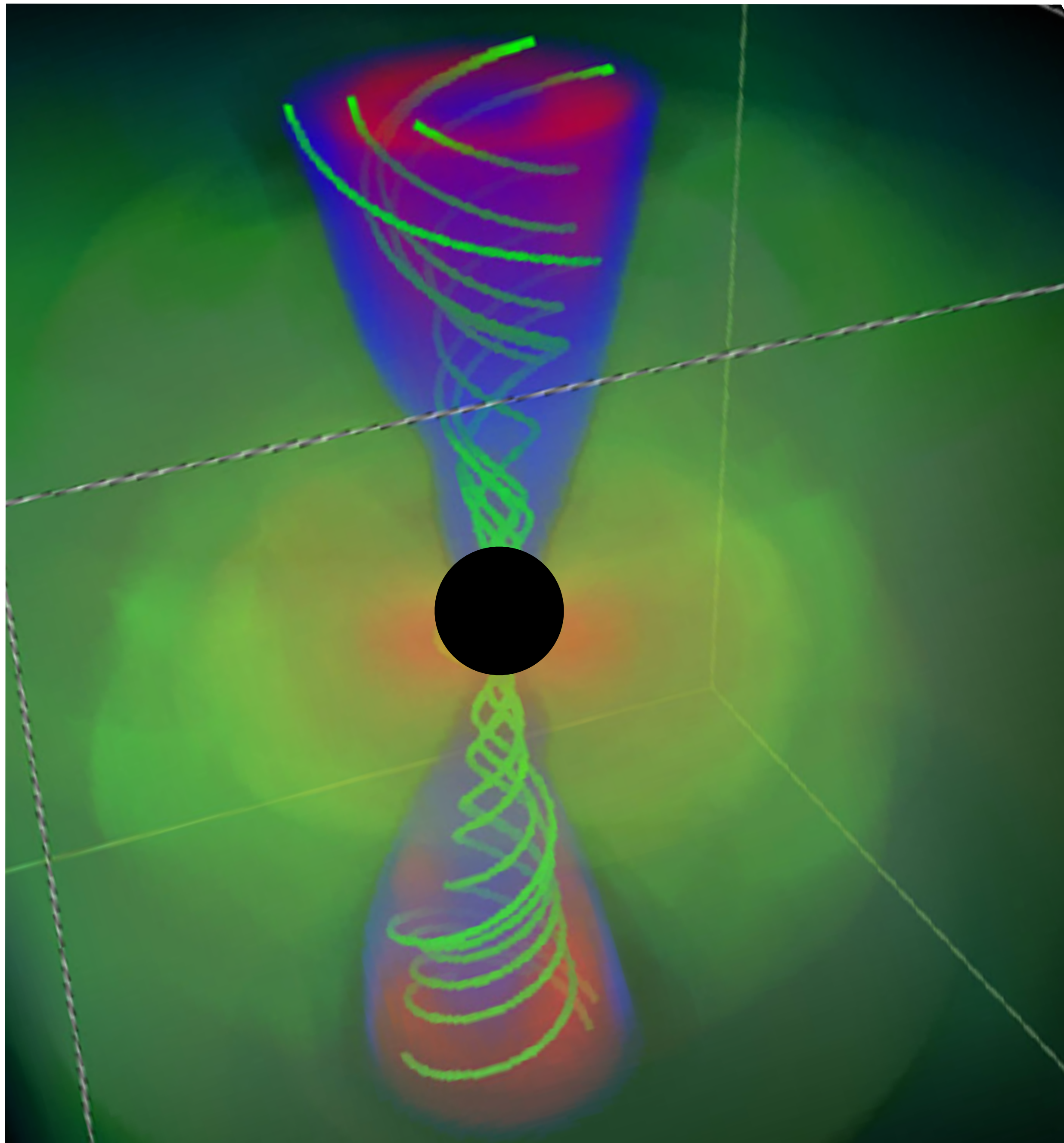
Blandford-Znajek mechanism

- Inside of ergosphere, it is *impossible* to not rotate with the black hole!
- BH is enormous reservoir of angular momentum and rest mass energy.
- So what happens if we have a vertical (toroidal) B-field close to BH?
- Fairly strong B-field expected, since in-falling material has carried and compressed B from ISM / companion.
- It creates a toroidal, twisting B-field!
- This can create collimated outflows, as material is channelled through the funnel created by the toroidal B-field.



Blandford-Znajek mechanism

Jet power estimate:

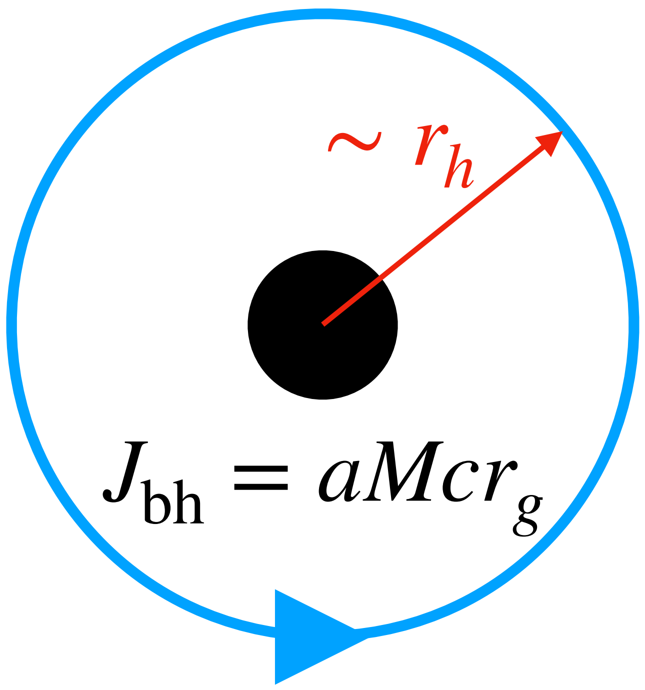


Blandford-Znajek mechanism

Jet power estimate:

- Viewed from above: B-field in circular motion, therefore induces an electric field.

Viewed from above

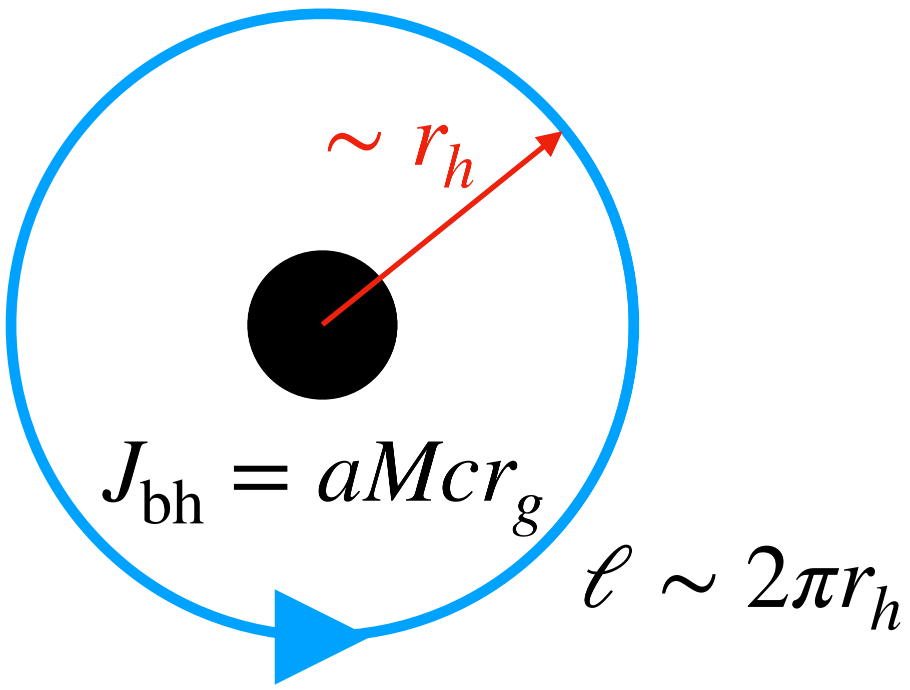


Blandford-Znajek mechanism

Jet power estimate:

- Viewed from above: B-field in circular motion, therefore induces an electric field.
- Faraday's law => voltage in loop $= \dfrac{d\Phi_B}{dt} = \displaystyle\int_A \mathbf{v} \times \mathbf{B} \cdot d\ell$

Viewed from above



Φ_B = Magnetic flux through loop

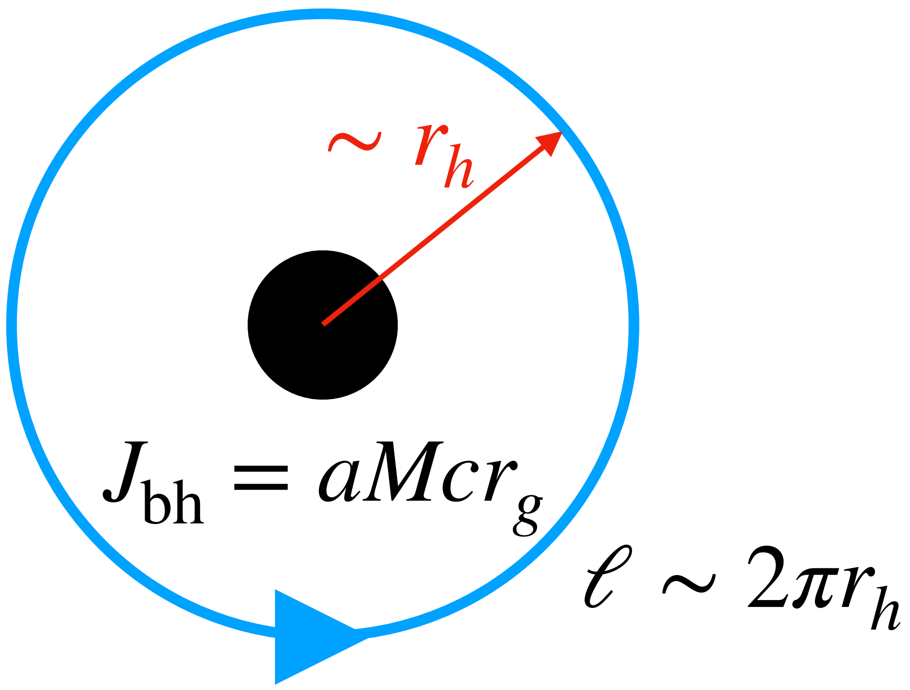
Blandford-Znajek mechanism

Jet power estimate:

- Viewed from above: B-field in circular motion, therefore induces an electric field.
- Faraday's law => voltage in loop $= \dfrac{d\Phi_B}{dt} = \displaystyle\int_A \mathbf{v} \times \mathbf{B} \cdot d\ell$
- From Ohm's law, power in the circuit = (voltage)^2/(resistance, Z)

$$\therefore P_j = \frac{1}{Z}\left[\int \mathbf{v} \times \mathbf{B} \cdot d\ell\right]^2$$

Viewed from above



Φ_B = Magnetic flux through loop

Blandford-Znajek mechanism

Jet power estimate:

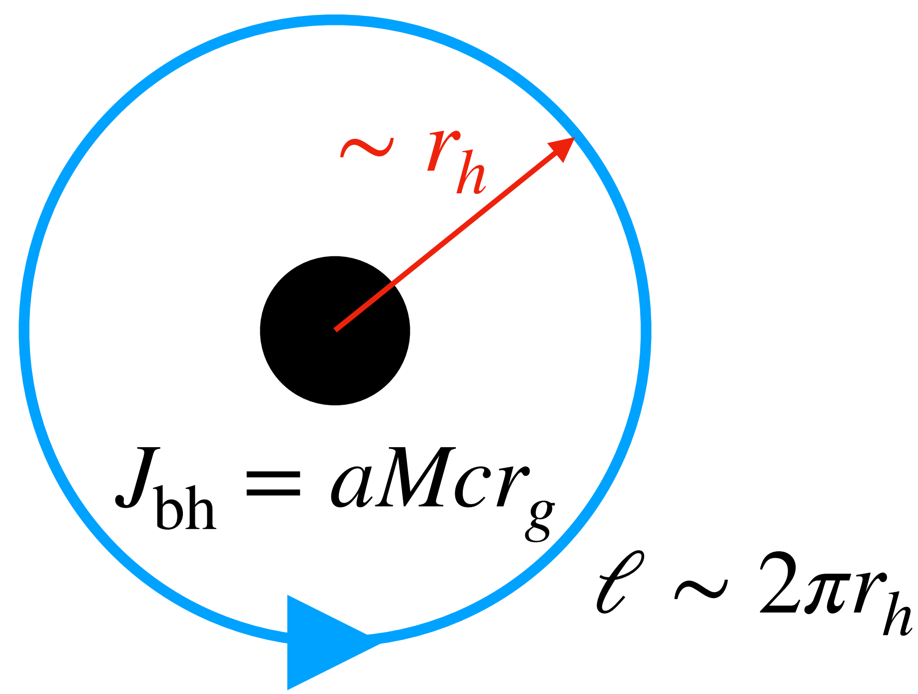
- Viewed from above: B-field in circular motion, therefore induces an electric field.
- Faraday's law => voltage in loop $= \dfrac{d\Phi_B}{dt} = \displaystyle\int_A \mathbf{v} \times \mathbf{B} \cdot d\ell$
- From Ohm's law, power in the circuit = (voltage)^2/(resistance, Z)

$$\therefore P_j = \frac{1}{Z}\left[\int \mathbf{v} \times \mathbf{B} \cdot d\ell\right]^2$$

- Field lines rotating with hole, so velocity is:

$$v \sim J_{\rm bh}/(Mr_h) = acr_g/r_h$$

Viewed from above



Φ_B = Magnetic flux through loop

Blandford-Znajek mechanism

<u>Jet power estimate:</u>

- Viewed from above: B-field in circular motion, therefore induces an electric field.
- Faraday's law => voltage in loop $= \dfrac{d\Phi_B}{dt} = \displaystyle\int_A \mathbf{v} \times \mathbf{B} \cdot d\ell$
- From Ohm's law, power in the circuit = (voltage)^2/(resistance, Z)

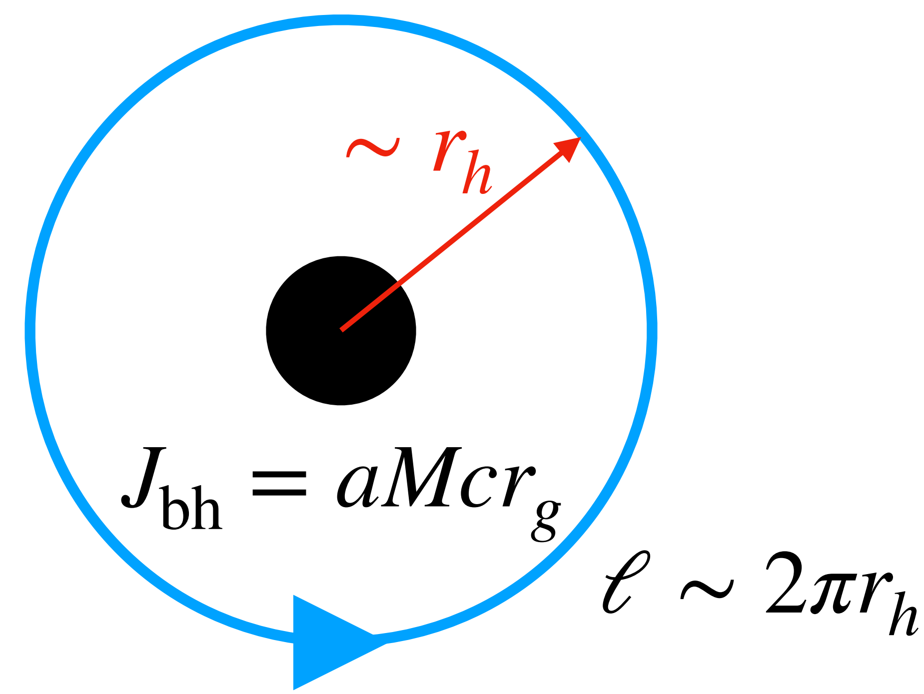
$$\therefore P_j = \frac{1}{Z}\left[\int \mathbf{v} \times \mathbf{B} \cdot d\ell\right]^2$$

- Field lines rotating with hole, so velocity is:

$$v \sim J_{\rm bh}/(Mr_h) = acr_g/r_h$$

$$\therefore \int \mathbf{v} \times \mathbf{B} \cdot d\ell \sim ac\frac{r_g}{r_h}.B.2\pi r_h = 2\pi acr_g B$$

Viewed from above



Φ_B = Magnetic flux through loop

Blandford-Znajek mechanism

Jet power estimate:

- Viewed from above: B-field in circular motion, therefore induces an electric field.
- Faraday's law => voltage in loop $= \dfrac{d\Phi_B}{dt} = \displaystyle\int_A \mathbf{v} \times \mathbf{B} \cdot d\ell$
- From Ohm's law, power in the circuit = (voltage)^2/(resistance, Z)

$$\therefore P_j = \frac{1}{Z}\left[\int \mathbf{v} \times \mathbf{B} \cdot d\ell\right]^2$$

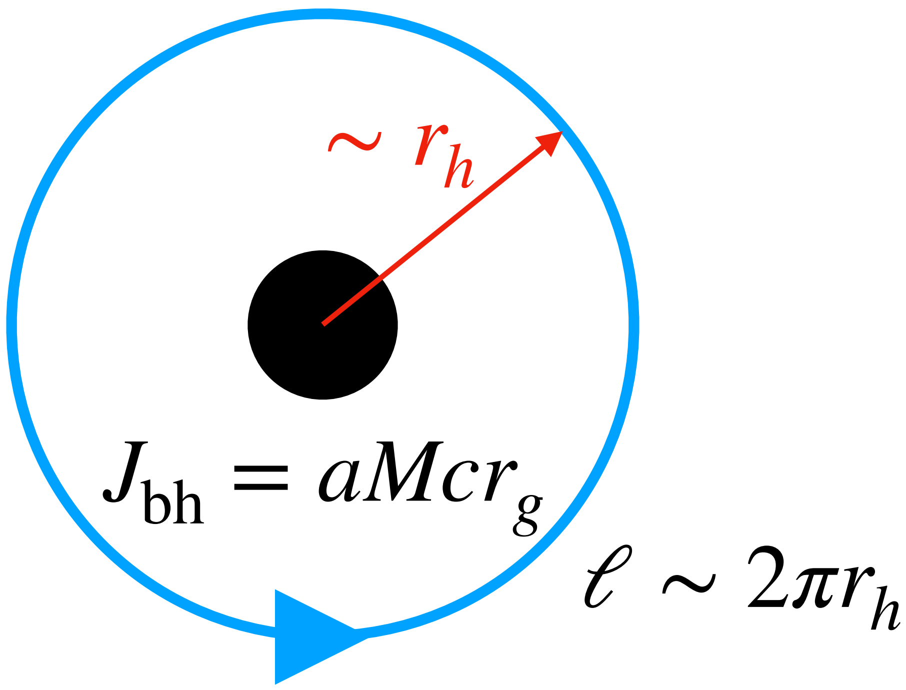
- Field lines rotating with hole, so velocity is:

$$v \sim J_{\rm bh}/(Mr_h) = acr_g/r_h$$

$$\therefore \int \mathbf{v} \times \mathbf{B} \cdot d\ell \sim ac\frac{r_g}{r_h}.B.2\pi r_h = 2\pi acr_g B$$

$$\therefore P_j \sim (2\pi acr_g B)^2/Z$$

Viewed from above



Φ_B = Magnetic flux through loop

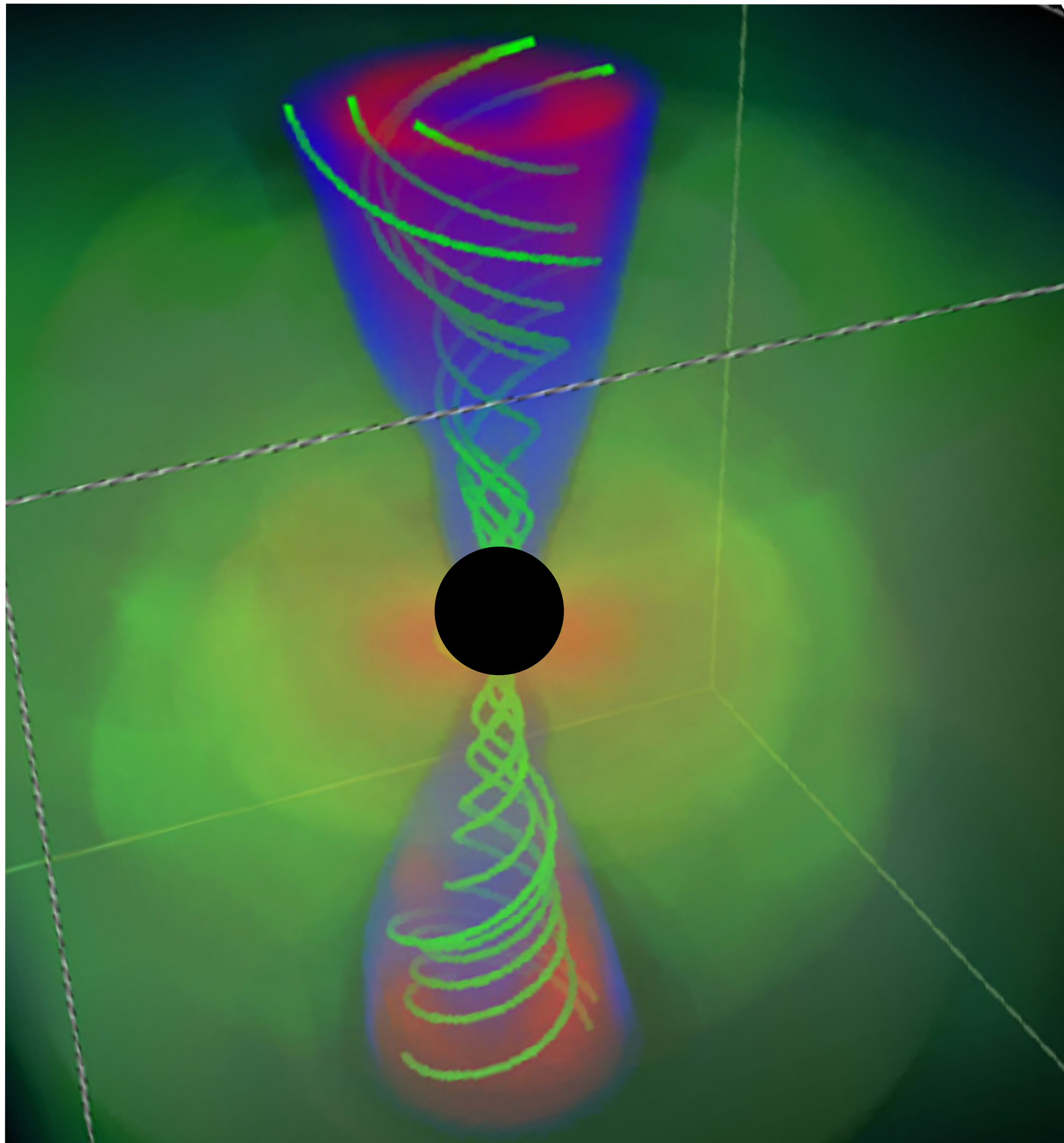
Blandford-Znajek mechanism

$$P_j \sim (2\pi a c r_g B)^2 / Z$$

- Resistance is ~impedance of free space (Z ~ 377 Ohms).
- Can estimate B from setting U_{mag} equal to gas pressure (note that energy density is a pressure).
- End up with:

$$P_j \sim 10^{38} \frac{M}{10^9 M_\odot} \mathrm{W}$$

- This is enormous! In fact, for strong B-field can end up with $P_j > \dot{M}c^2$!
- Where did the extra energy come from? From the BH!

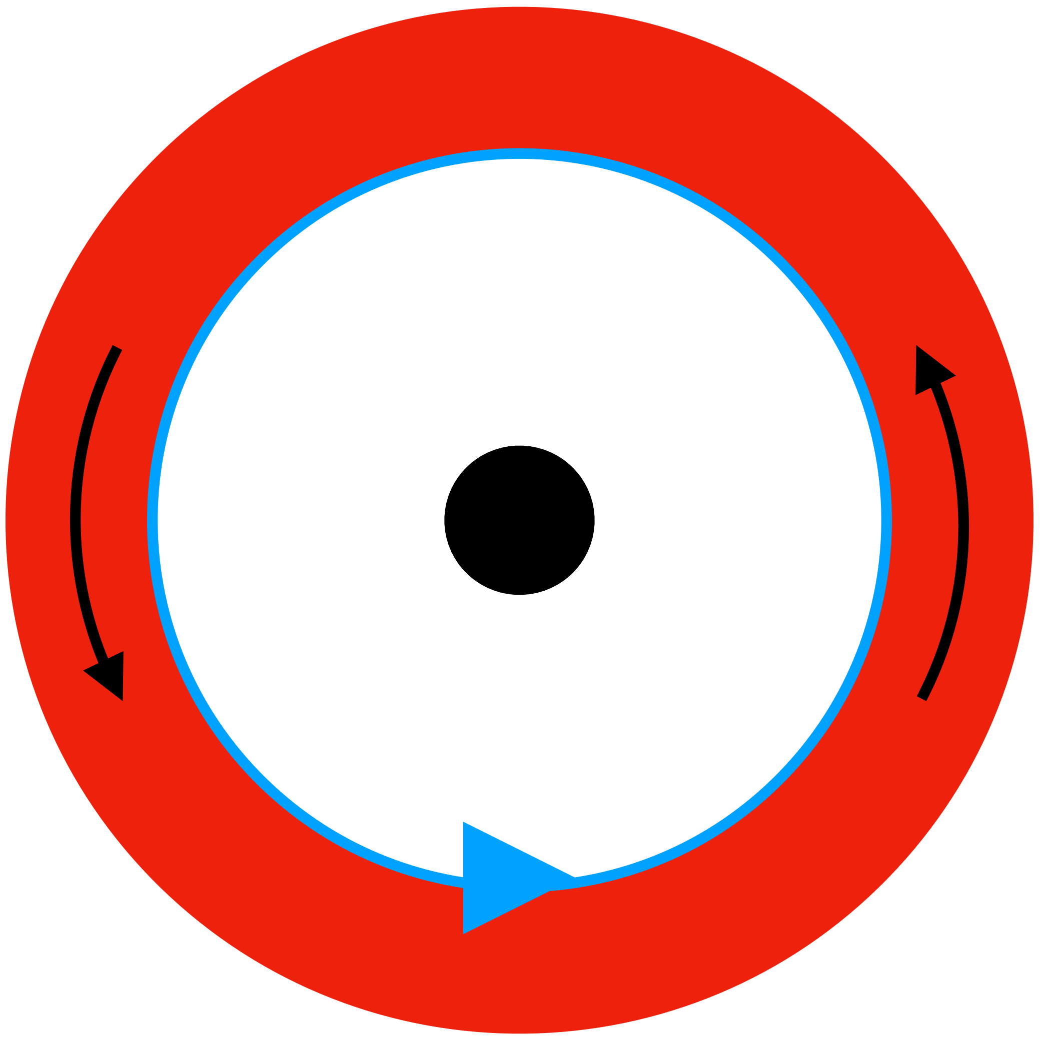


Blandford-Payne mechanism

- We don’t need a spinning BH to collimate the magnetic field though.

Blandford-Payne mechanism

- We don't need a spinning BH to collimate the magnetic field though.
- The disc can do it: field lines anchored in the differentially rotating disc.

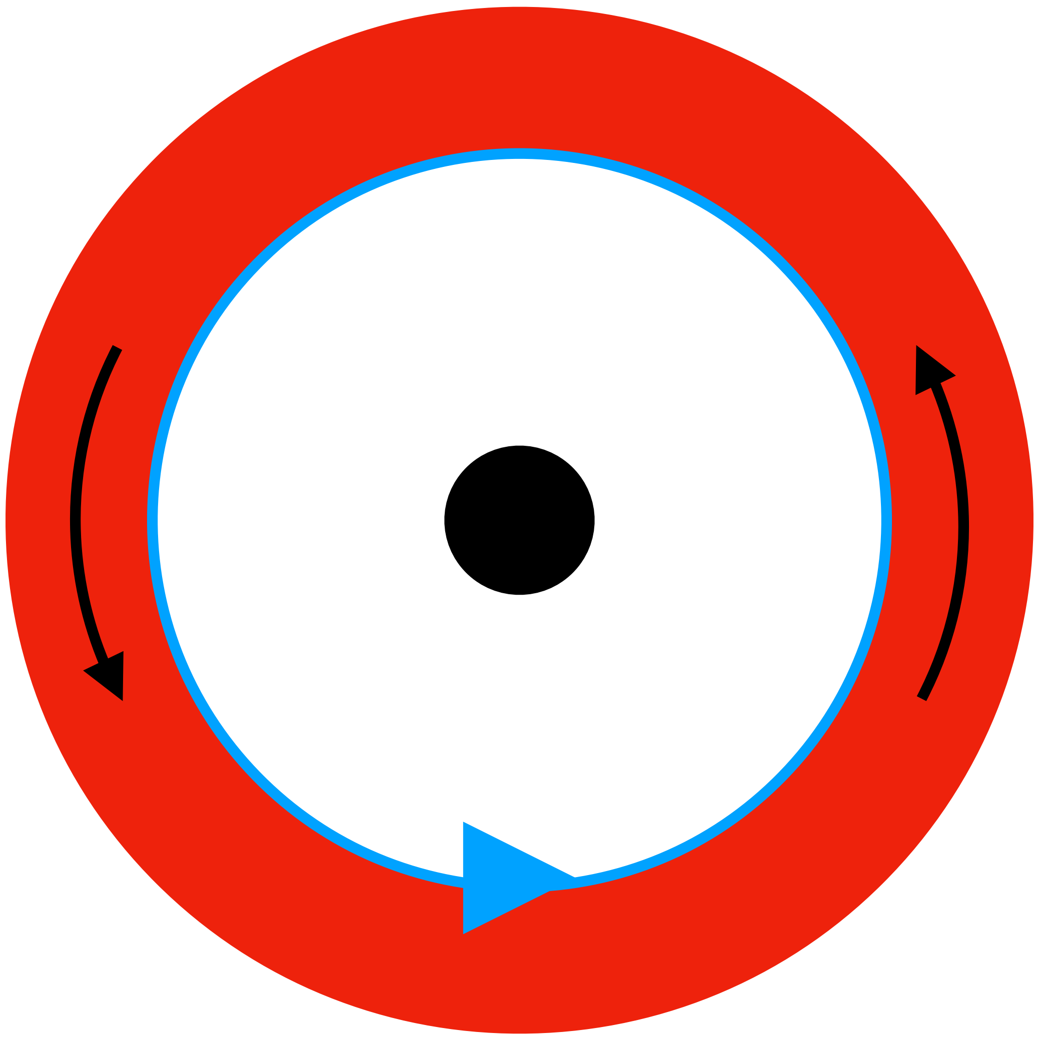


Blandford & Payne (1982)

Blandford-Payne mechanism

- We don't need a spinning BH to collimate the magnetic field though.
- The disc can do it: field lines anchored in the differentially rotating disc.
- Now the velocity is: $v \sim (GM/r_{\rm in})^{1/2}$
- Same calculation as before gives:

$$\therefore P_j \sim (2\pi c r_g B)^2 \, (r_{\rm in}/r_g) \; / \; Z$$



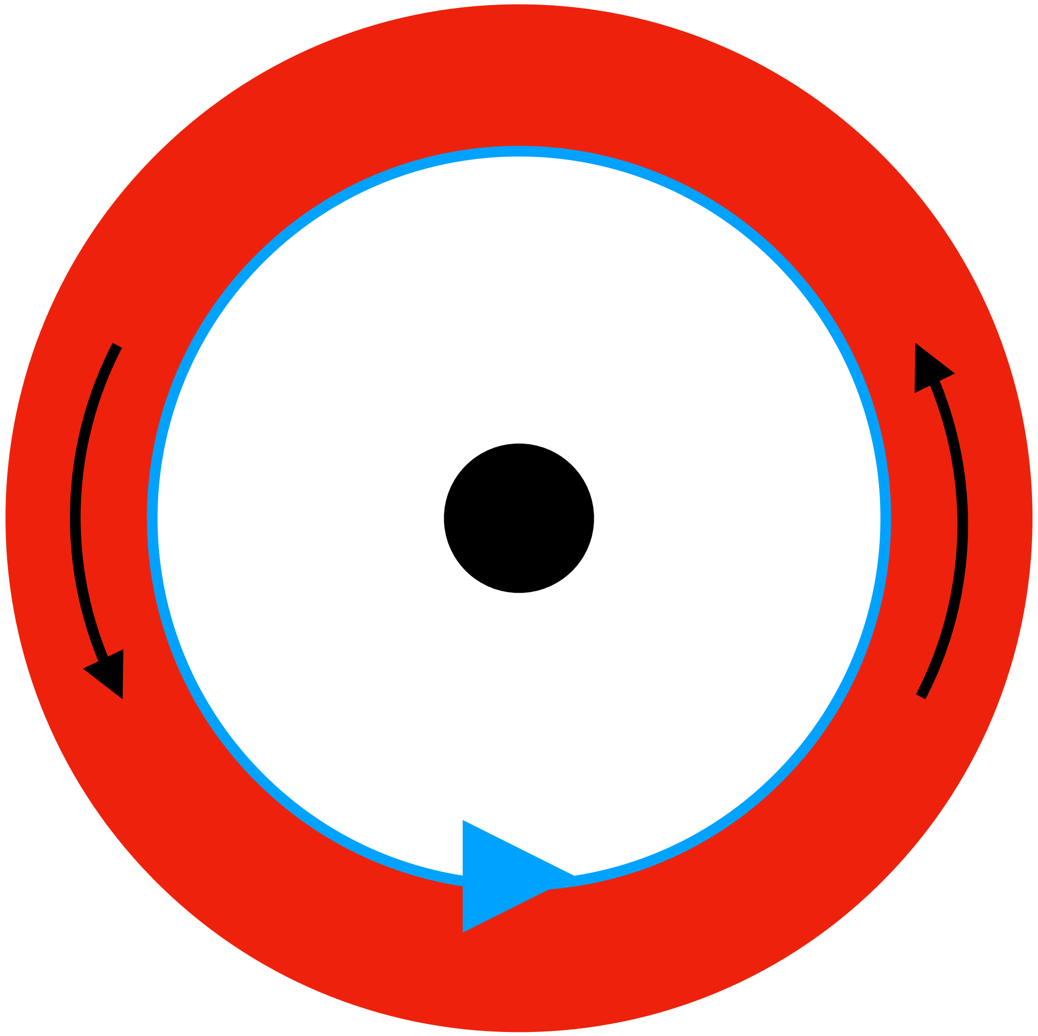
Blandford & Payne (1982)

Blandford-Payne mechanism

- We don't need a spinning BH to collimate the magnetic field though.
- The disc can do it: field lines anchored in the differentially rotating disc.
- Now the velocity is: $v \sim (GM/r_{\rm in})^{1/2}$
- Same calculation as before gives:

$$\therefore P_j \sim (2\pi c r_g B)^2 \; (r_{\rm in}/r_g) \; / \; Z$$

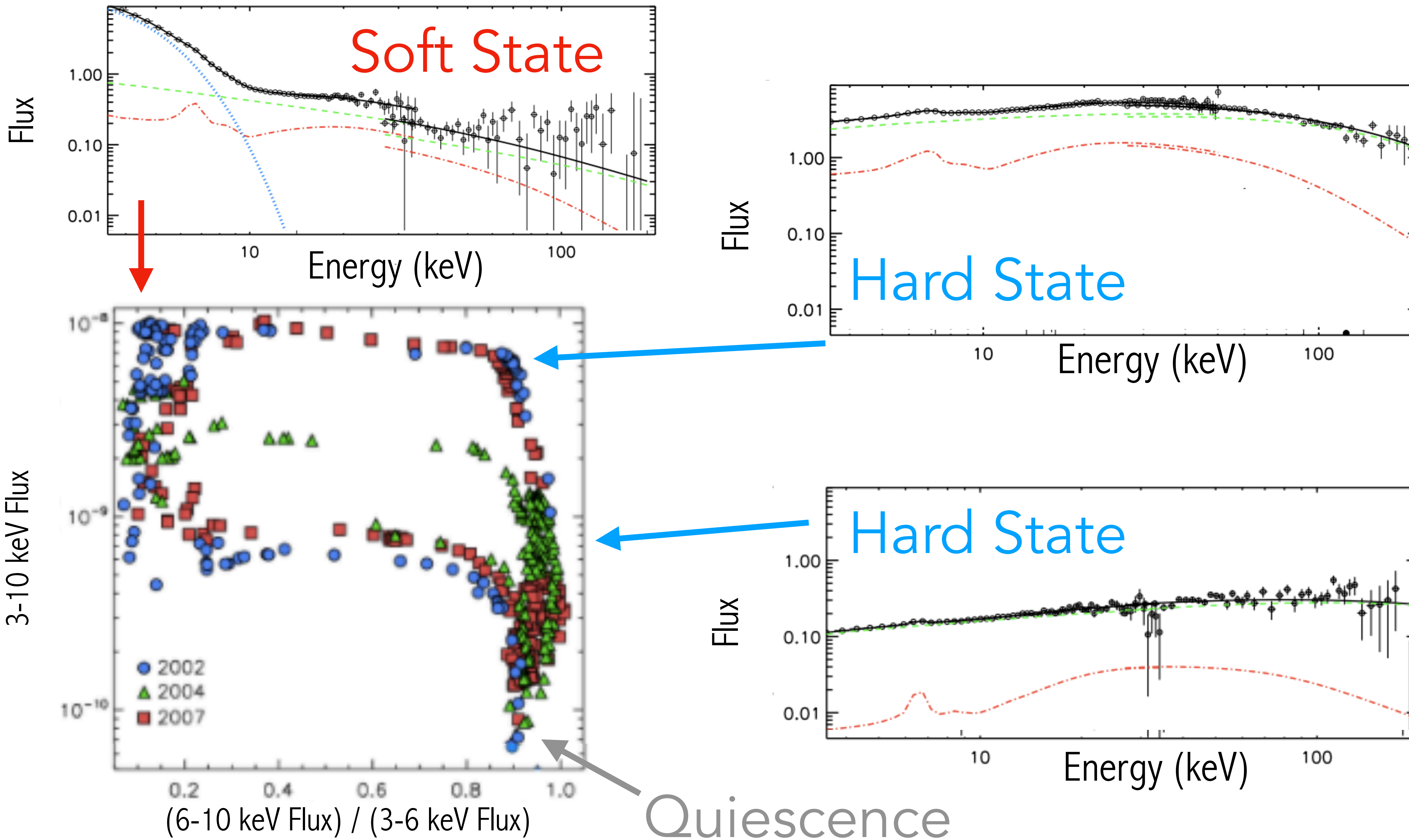
- Less power than BZ mechanism because speed is slower — but can still get a jet for a Schwarzschild BH or even for a neutron star or white dwarf.



Blandford & Payne (1982)

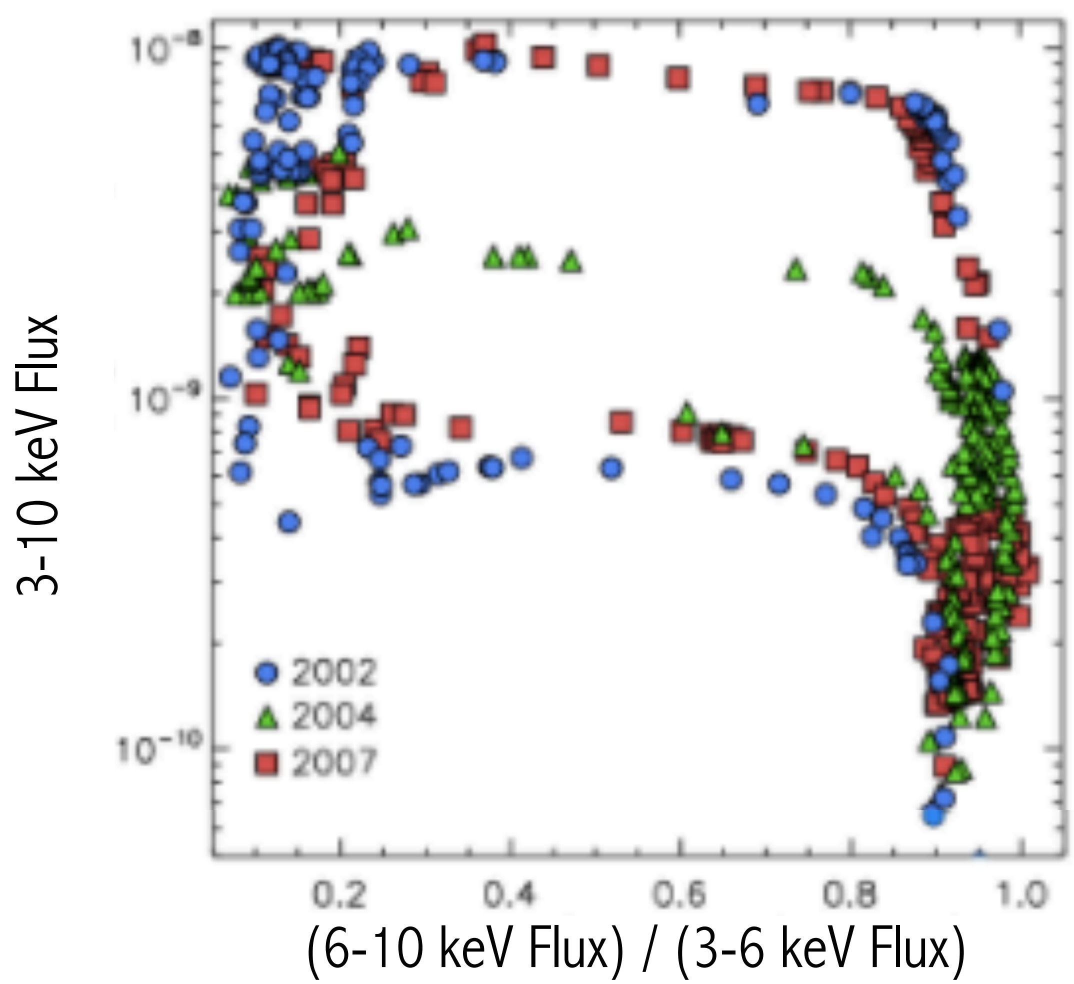
Jets in X-ray binaries

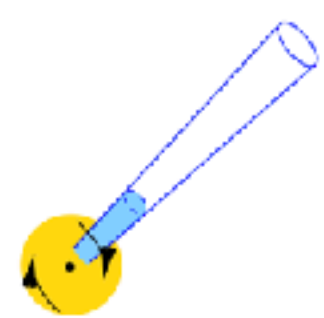
Jet properties coupled to X-ray spectral state transitions.



Jets in X-ray binaries

Jet properties coupled to X-ray spectral state transitions.

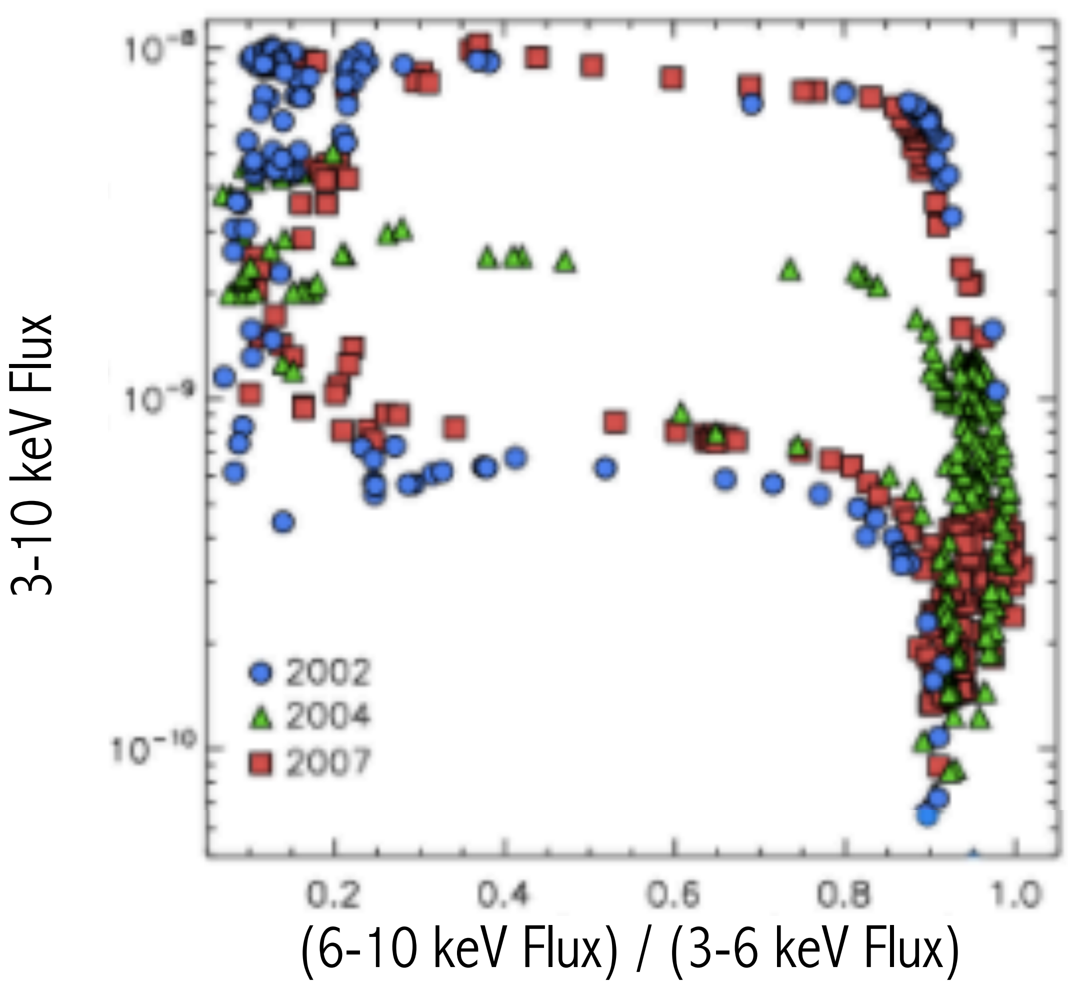




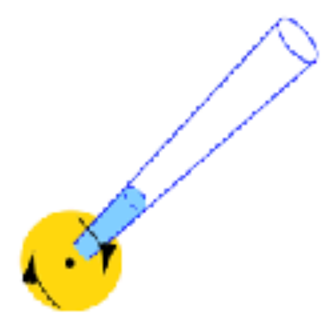
Compact jet: no lobes, only unresolved core

Jets in X-ray binaries

Jet properties coupled to X-ray spectral state transitions.



Compact jet gets brighter, still unresolved

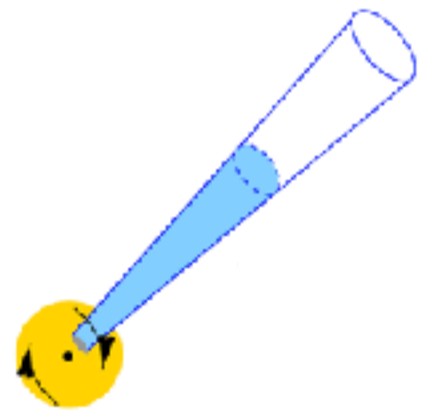


Compact jet: no lobes, only unresolved core

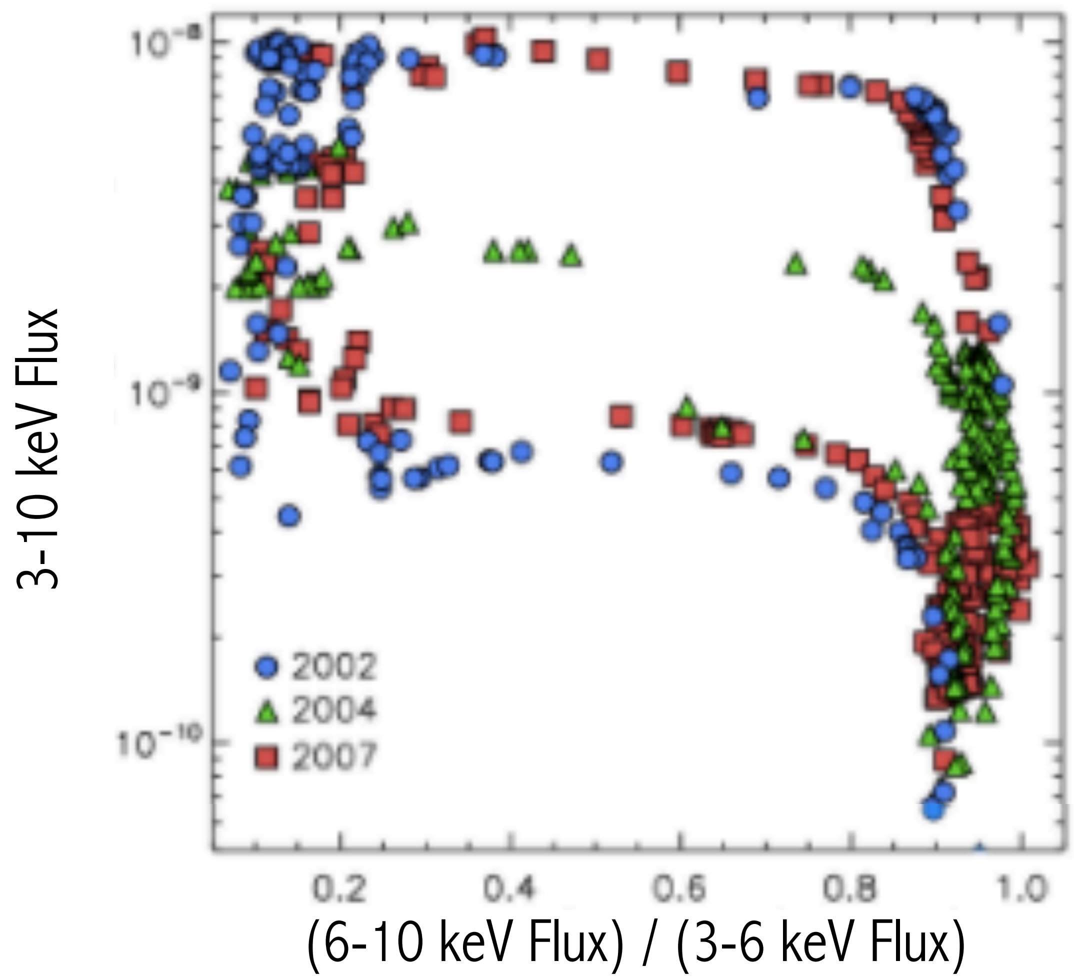
Jets in X-ray binaries

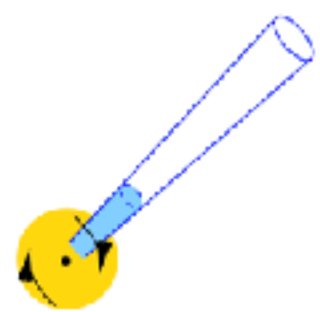
Jet properties coupled to X-ray spectral state transitions.

Discrete jet ejection: can track knots moving away from the core



Compact jet gets brighter, still unresolved





Compact jet: no lobes, only unresolved core

Jets in X-ray binaries

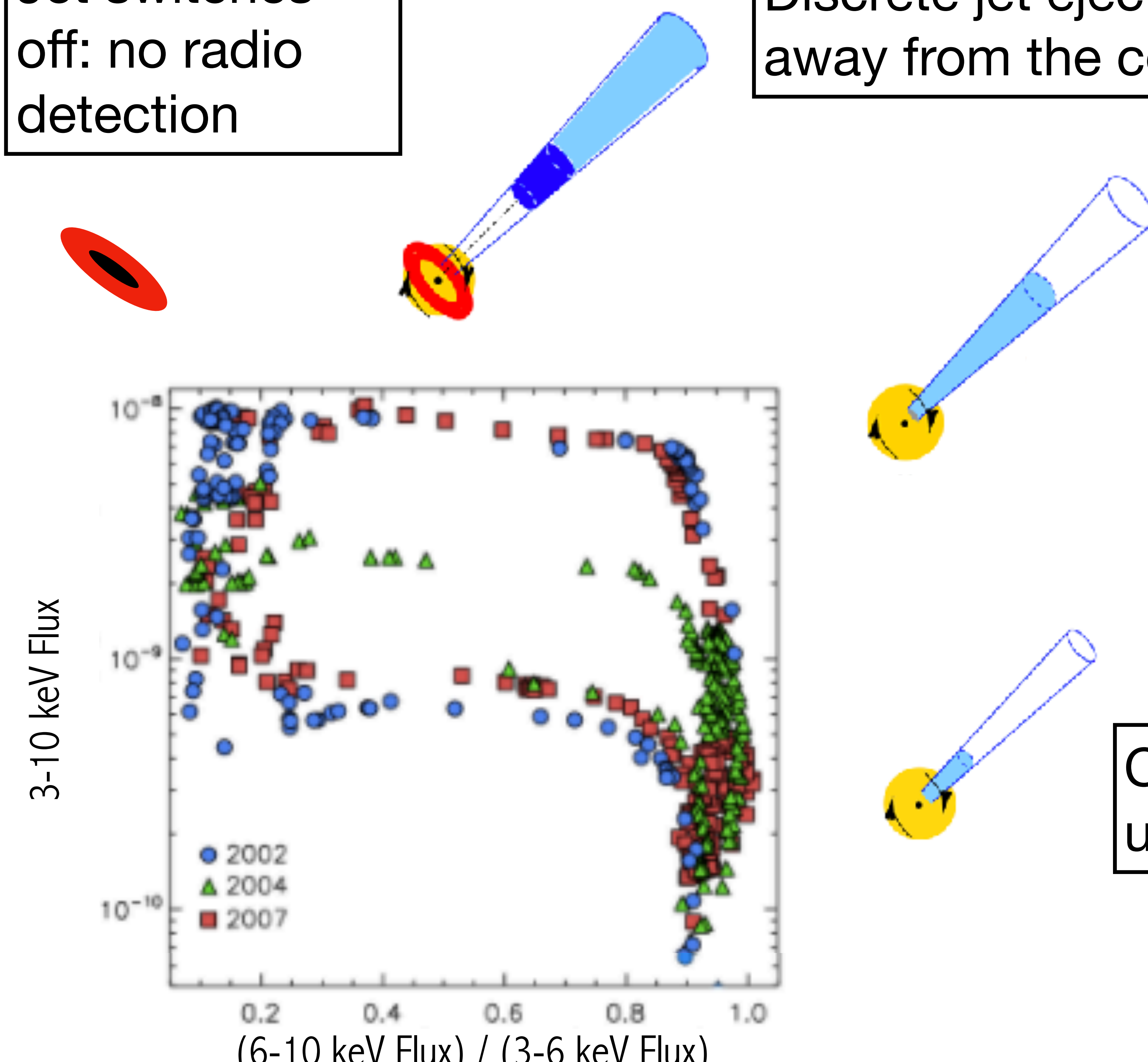
Jet properties coupled to X-ray spectral state transitions.

Jet switches off: no radio detection

Discrete jet ejection: can track knots moving away from the core

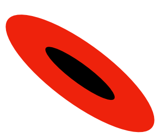
Compact jet gets brighter, still unresolved

Compact jet: no lobes, only unresolved core



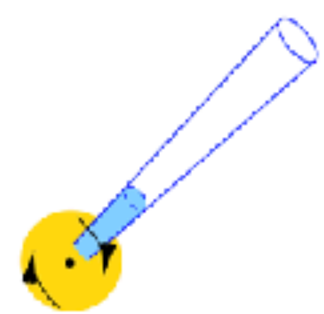
Comparison with AGN

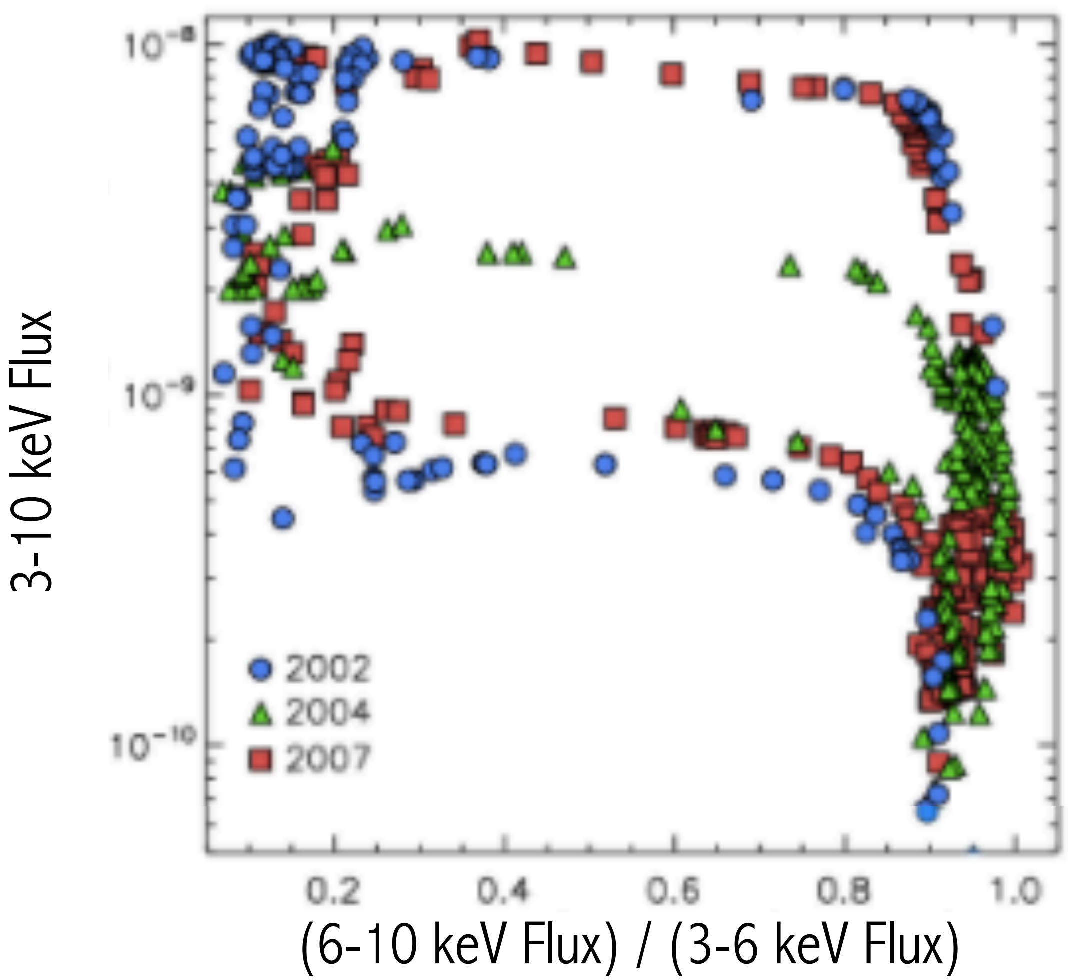
We see lots of AGN, but evolution is very slow.



Bright AGN have jet lobes: could have been ejected long ago and are still interacting with IGM

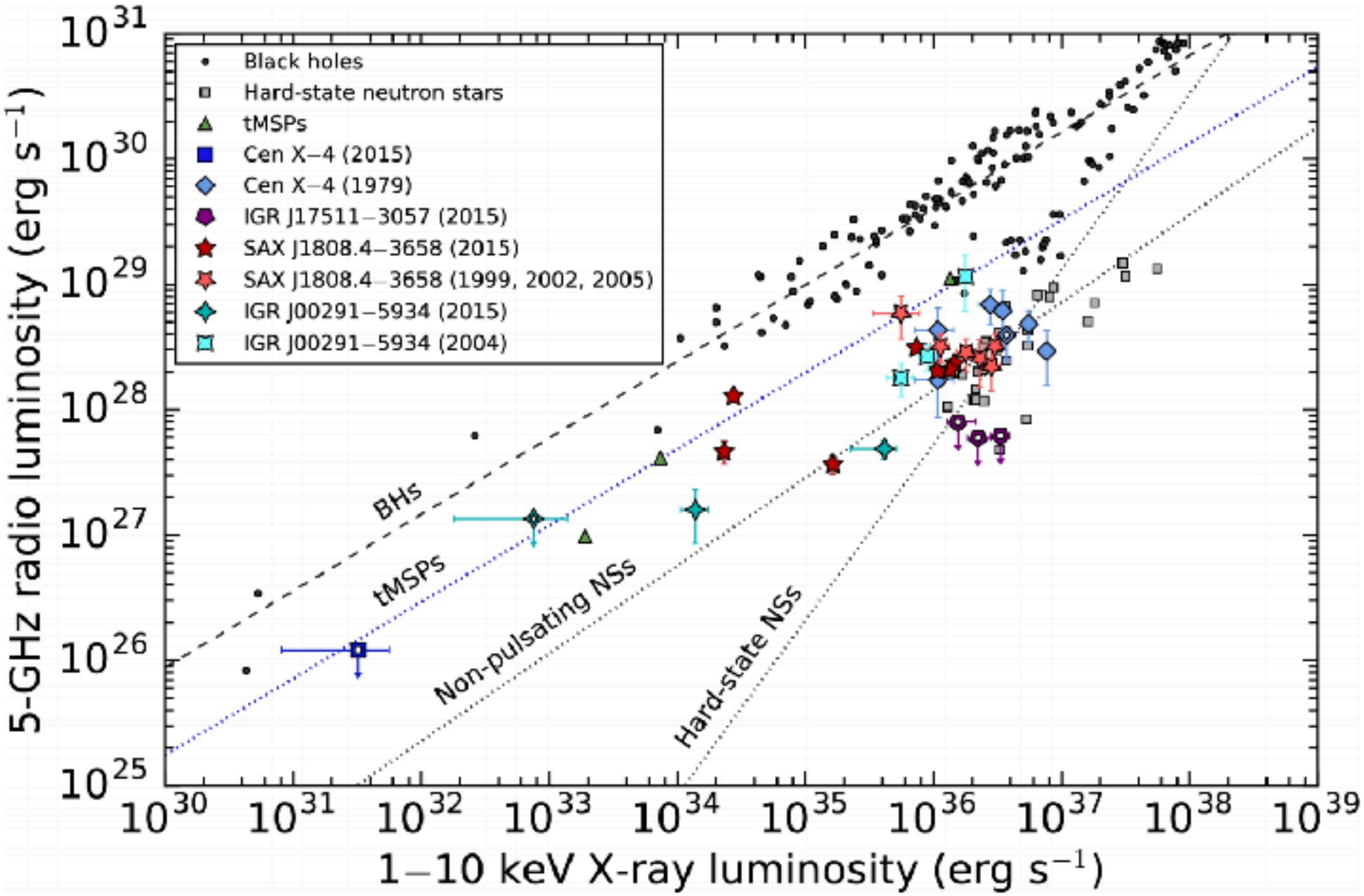
~low luminosity AGN have compact core.





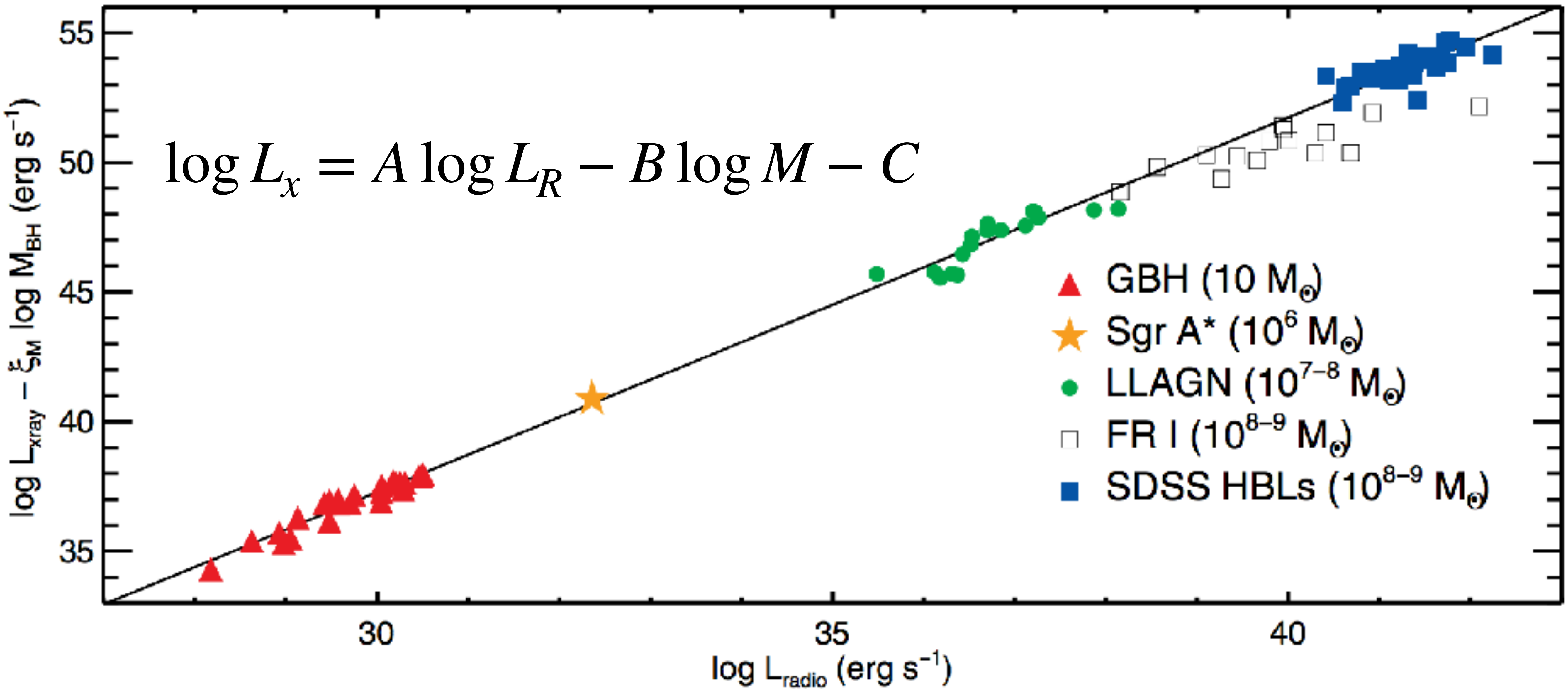
The full story is very complex though, and not fully understood.

Compact jet: X-ray/Radio correlation



- BH XRBs: radio loud and quiet tracks not understood (radiative efficiency of X-rays?)
- NSs: jets are weaker than BH jets — expected!

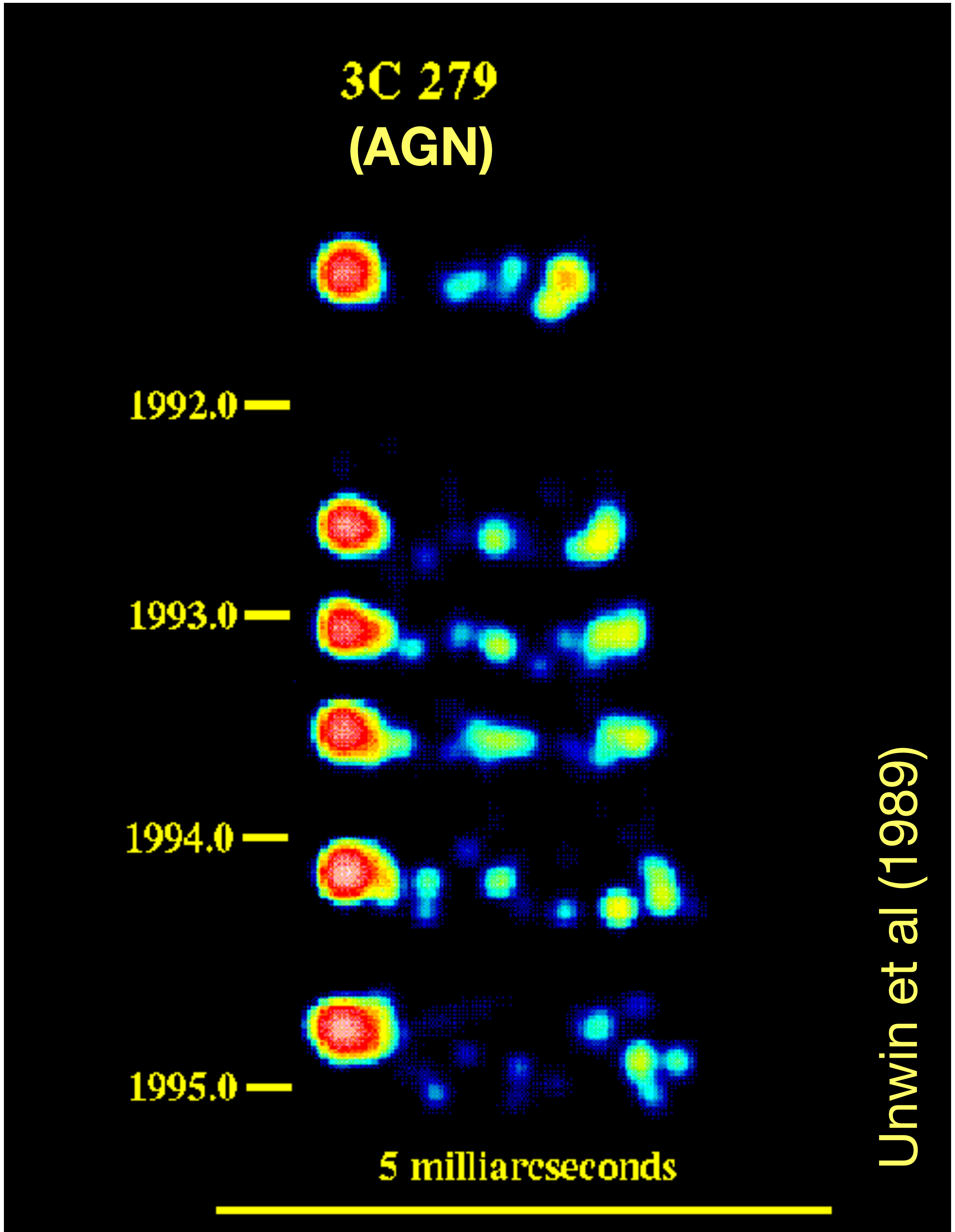
Compact jet: X-ray/Radio correlation



$$\log L_x = A \log L_R - B \log M - C$$

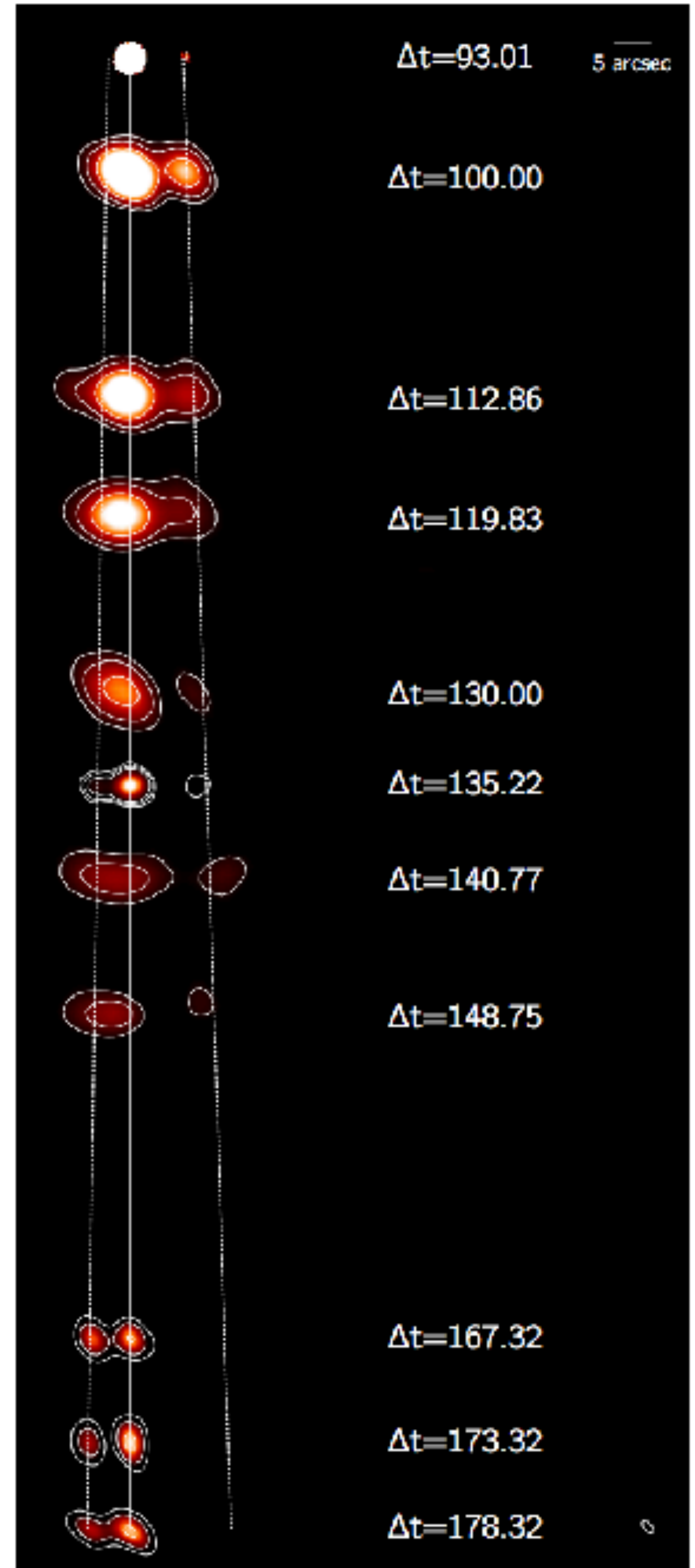
- Correlation holds for AGN too!
- “Fundamental plane of black hole accretion” holds over many orders of magnitude in black hole mass.
- Scale invariant process.

Transient jet



Unwin et al (1989)

MAXI J1820+070
(X-ray binary)

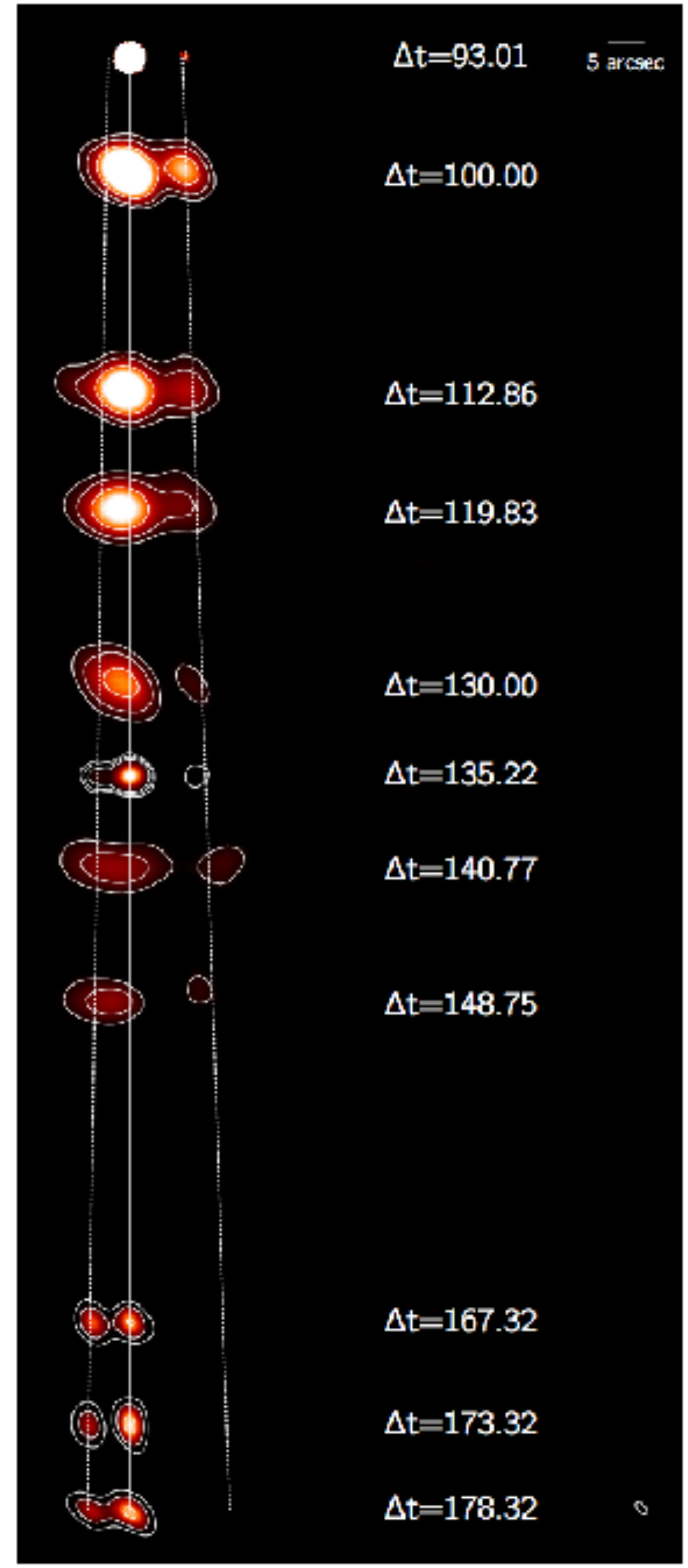


Bright et al (2020)

Transient jet

- Each blob is the jet plowing into an over density in the ISM/IGM, leading to shock heating and synchrotron emission (lectures 3 & 4).

MAXI J1820+070
(X-ray binary)



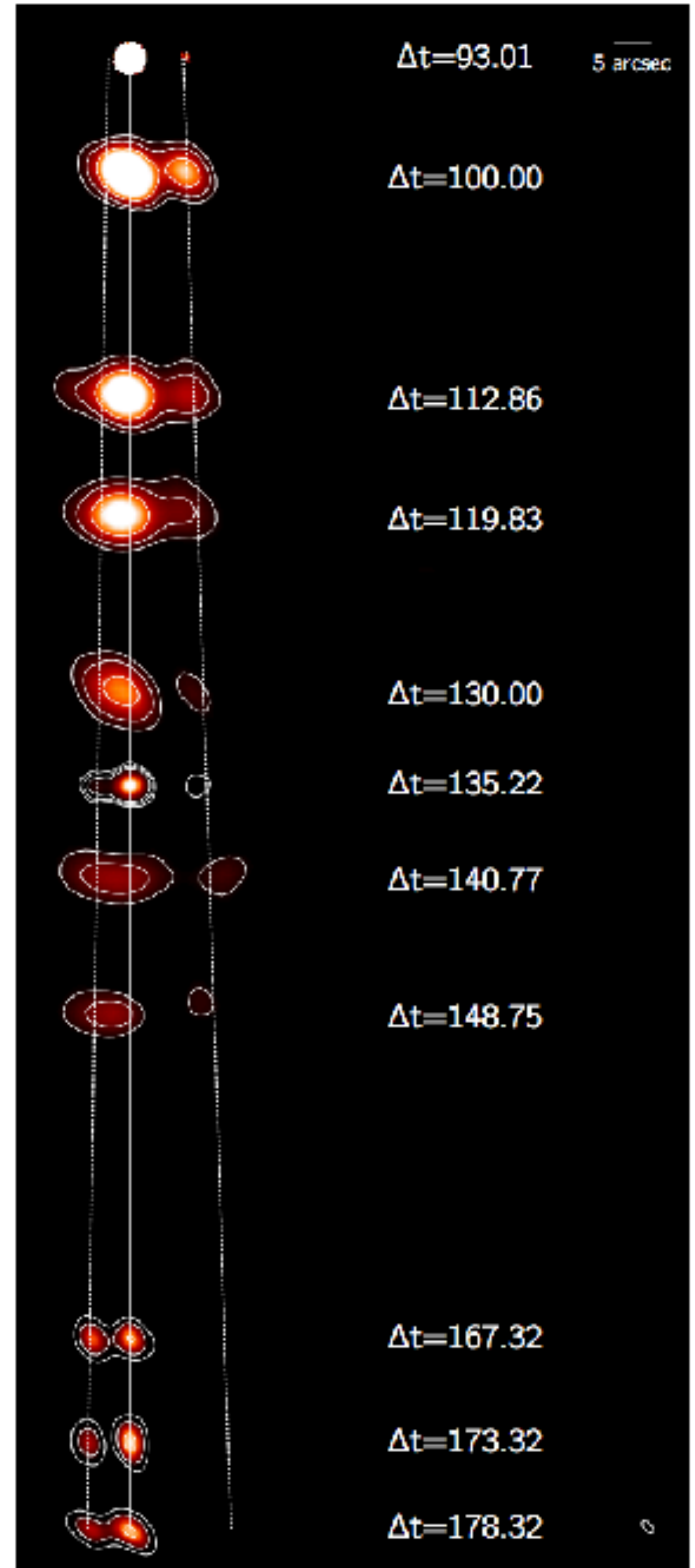
Bright et al (2020)

Transient jet

- Each blob is the jet plowing into an over density in the ISM/IGM, leading to shock heating and synchrotron emission (lectures 3 & 4).

- Blobs move away from the core (centred on the black hole) as the jet flows outwards.

MAXI J1820+070
(X-ray binary)

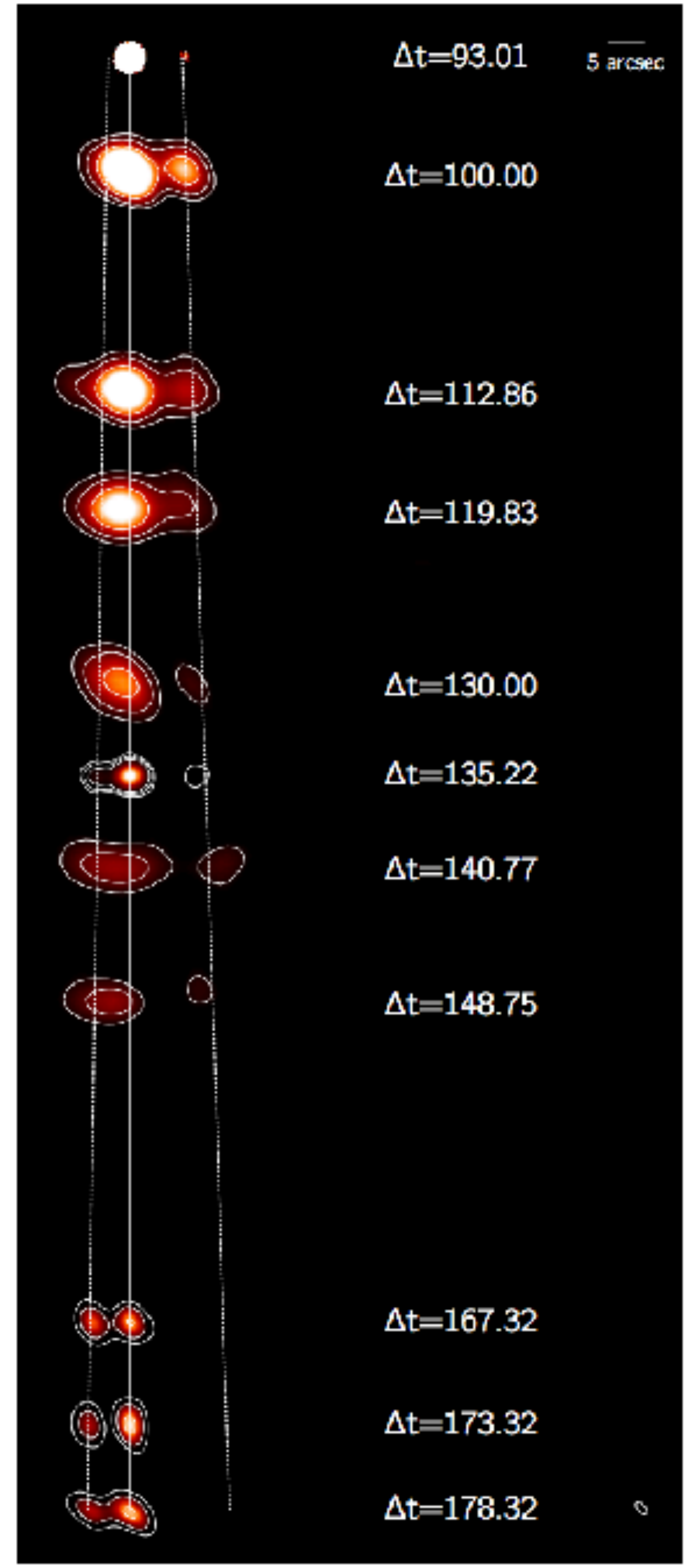


Bright et al (2020)

Transient jet

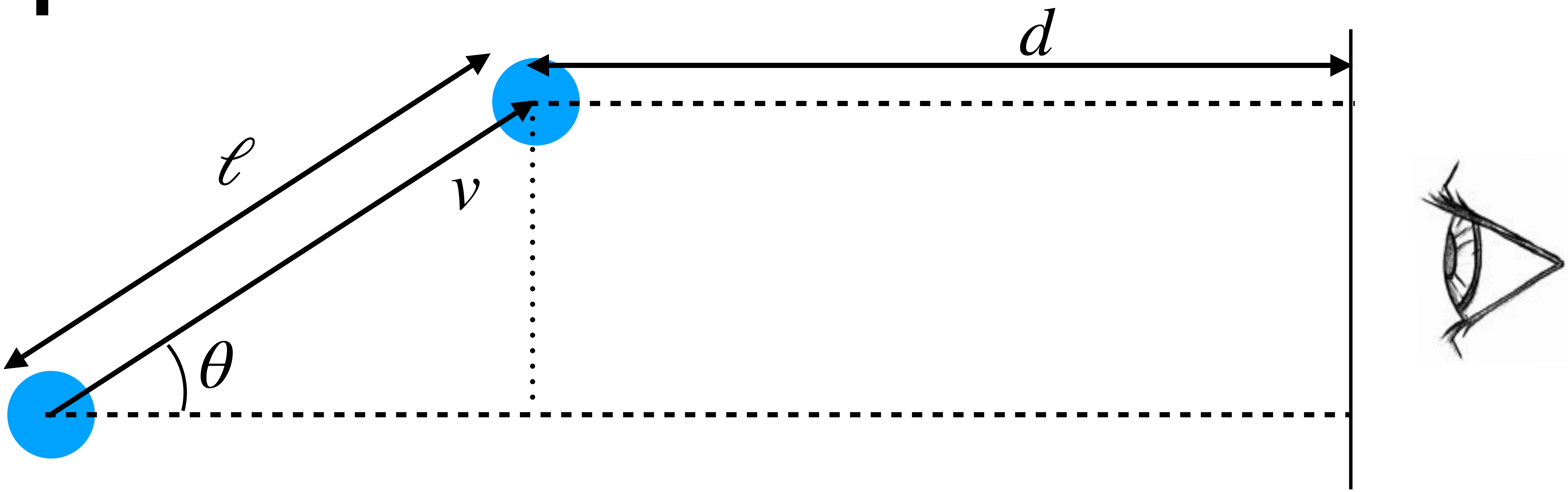
- Each blob is the jet plowing into an over density in the ISM/IGM, leading to shock heating and synchrotron emission (lectures 3 & 4).
- Blobs move away from the core (centred on the black hole) as the jet flows outwards.
- Hang on! Those blobs are moving faster than the speed of light!!

MAXI J1820+070 (X-ray binary)



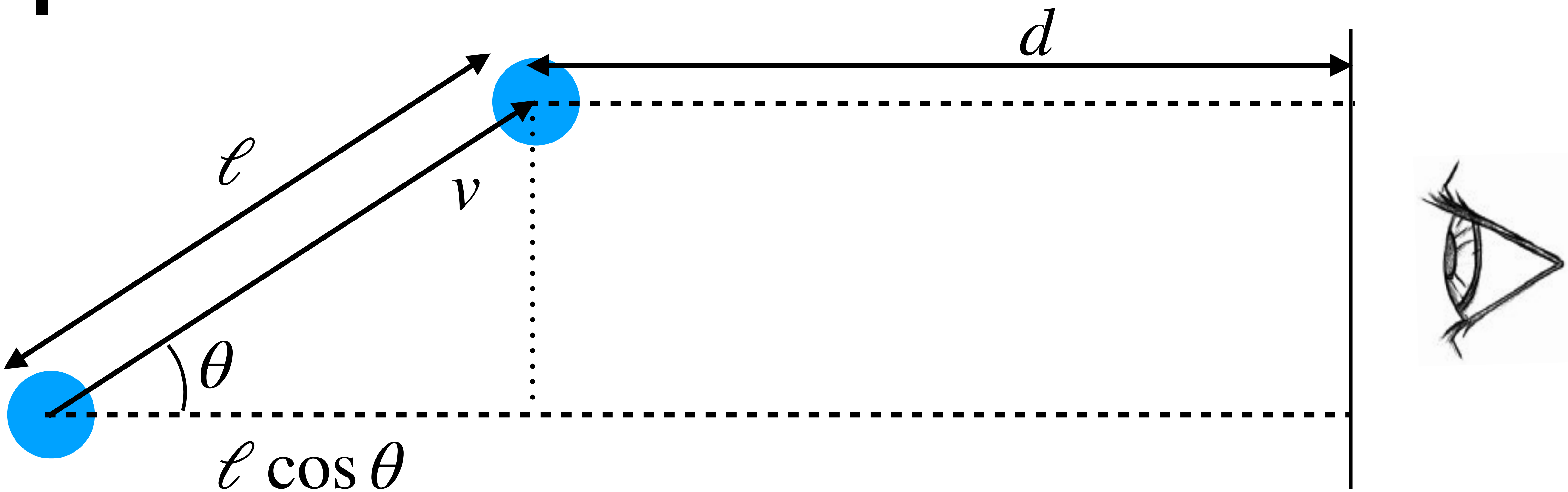
Bright et al (2020)

Superluminal motion



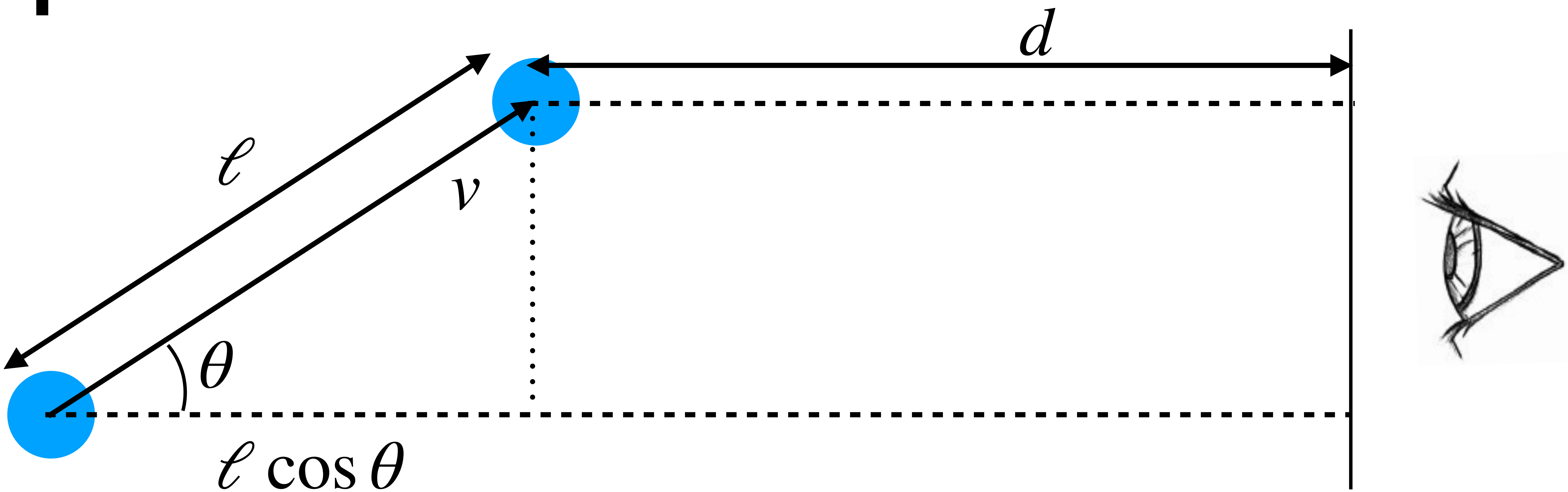
- Blob moves distance ℓ at velocity v. θ is as measured in *observer's* frame.
- Light emitted from blob in 1st position at time t=0.

Superluminal motion



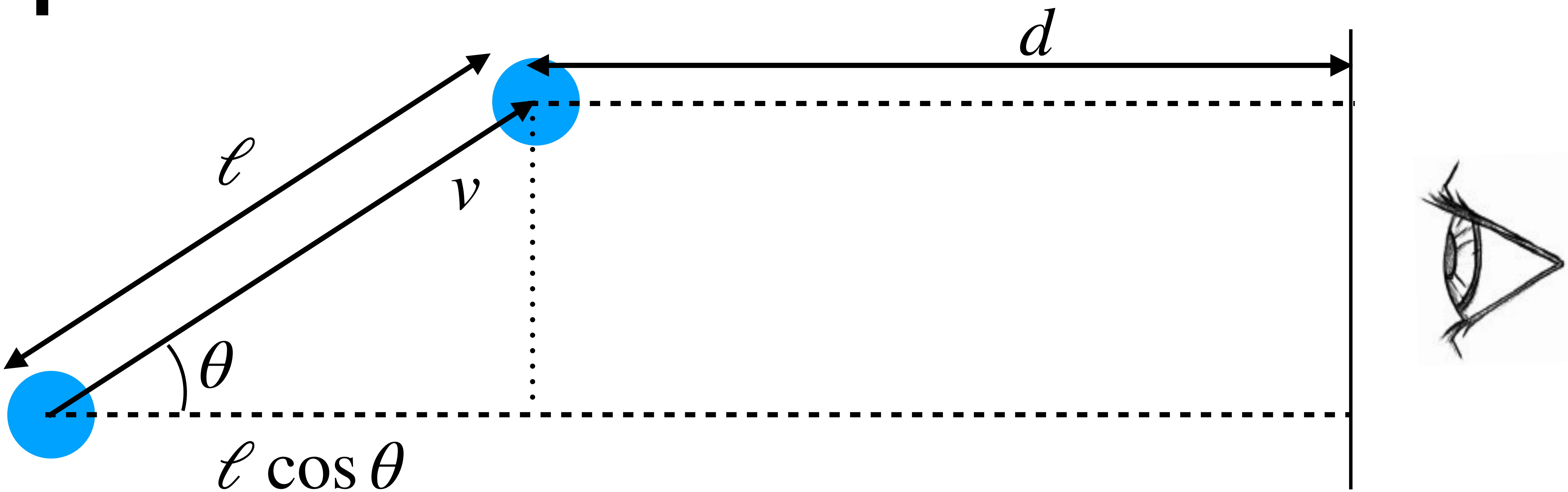
- Blob moves distance ℓ at velocity v. θ is as measured in *observer's* frame.
- Light emitted from blob in 1st position at time t=0.
- We *see* that light at time: $t_1 = \ell \cos\theta/c + d/c$

Superluminal motion



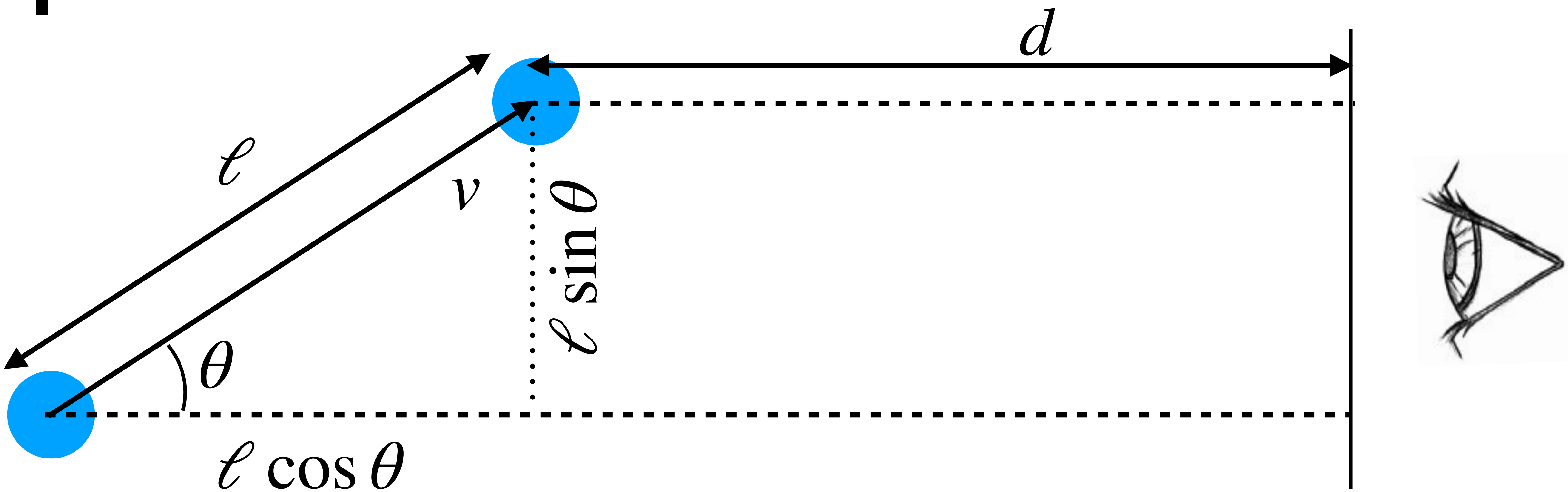
- Blob moves distance ℓ at velocity v. θ is as measured in *observer's* frame.
- Light emitted from blob in 1st position at time t=0.
- We *see* that light at time: $t_1 = \ell\cos\theta/c + d/c$
- Light emitted from blob in 2nd position at time: $t = \ell/v$
- We *see* that light at time: $t_2 = \ell/v + d/c$

Superluminal motion



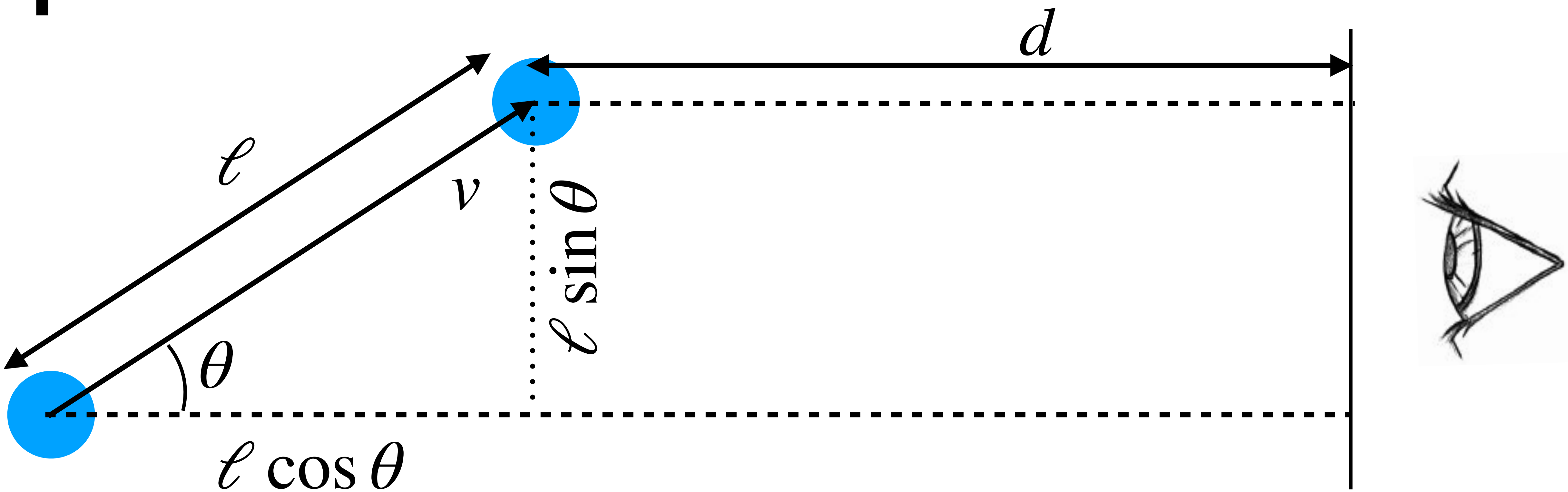
- Blob moves distance ℓ at velocity v. θ is as measured in *observer's* frame.
- Light emitted from blob in 1st position at time t=0.
- We *see* that light at time: $t_1 = \ell \cos \theta / c + d/c$
- Light emitted from blob in 2nd position at time: $t = \ell / v$
- We *see* that light at time: $t_2 = \ell / v + d/c$
- Therefore time interval: $\Delta t = t_2 - t_1 = \ell / v - \ell \cos \theta / c$

Superluminal motion



- Blob moves distance ℓ at velocity v. θ is as measured in *observer's* frame.
- Light emitted from blob in 1st position at time t=0.
- We *see* that light at time: $t_1 = \ell \cos\theta/c + d/c$
- Light emitted from blob in 2nd position at time: $t = \ell/v$
- We *see* that light at time: $t_2 = \ell/v + d/c$
- Therefore time interval: $\Delta t = t_2 - t_1 = \ell/v - \ell \cos\theta/c$
- Apparent distance travelled = $\ell \sin\theta$

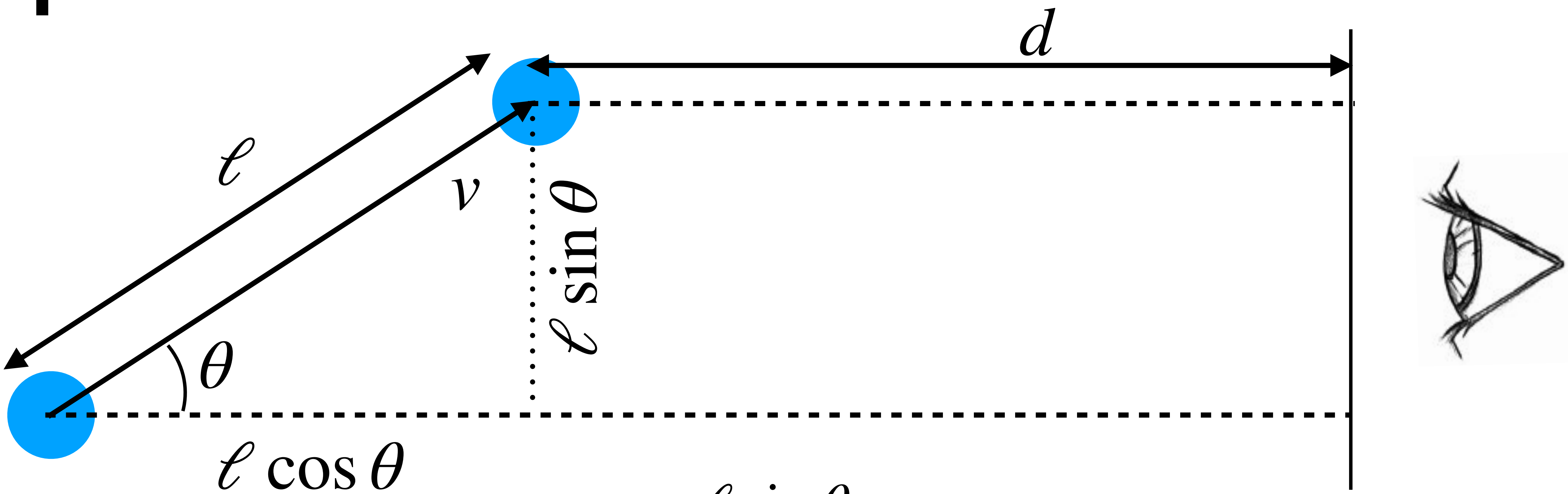
Superluminal motion



- Blob moves distance ℓ at velocity v. θ is as measured in *observer's* frame.
- Light emitted from blob in 1st position at time t=0.
- We *see* that light at time: $t_1 = \ell \cos\theta / c + d/c$
- Light emitted from blob in 2nd position at time: $t = \ell / v$
- We *see* that light at time: $t_2 = \ell / v + d/c$
- Therefore time interval: $\Delta t = t_2 - t_1 = \ell / v - \ell \cos\theta / c$
- Apparent distance travelled = $\ell \sin\theta$
- Therefore apparent velocity:

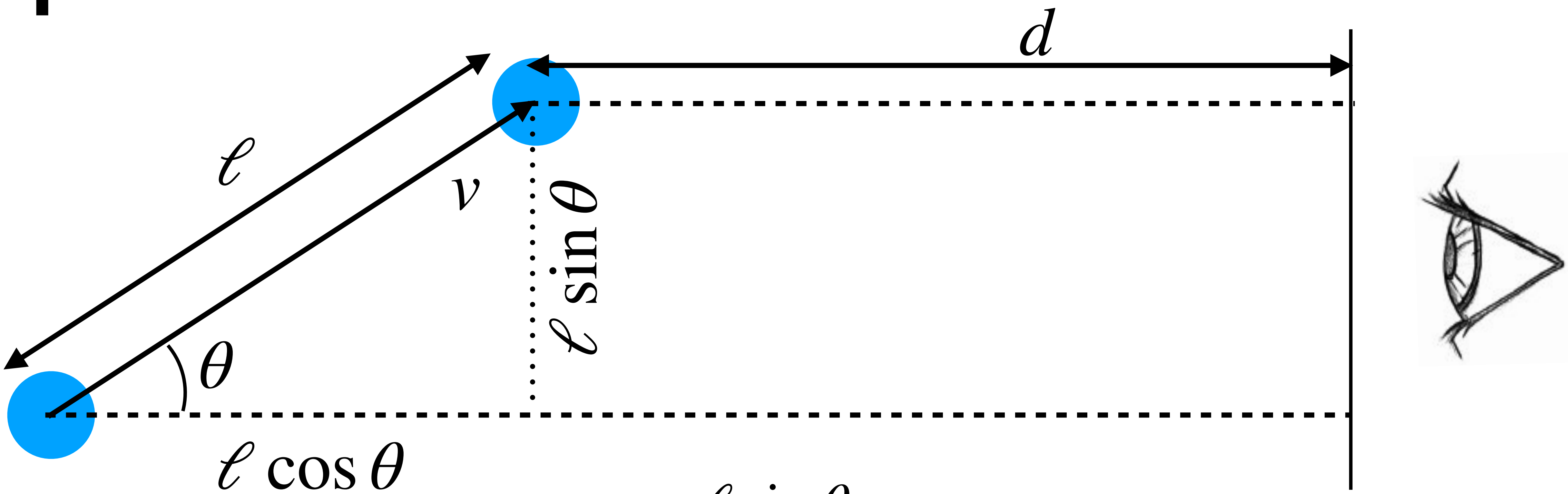
$$v_{\rm app} = \frac{\ell \sin\theta}{\ell / v - \ell \cos\theta / c}$$

Superluminal motion



$$v_{\text{app}} = \frac{\ell \sin\theta}{\ell / v - \ell \cos\theta / c}$$

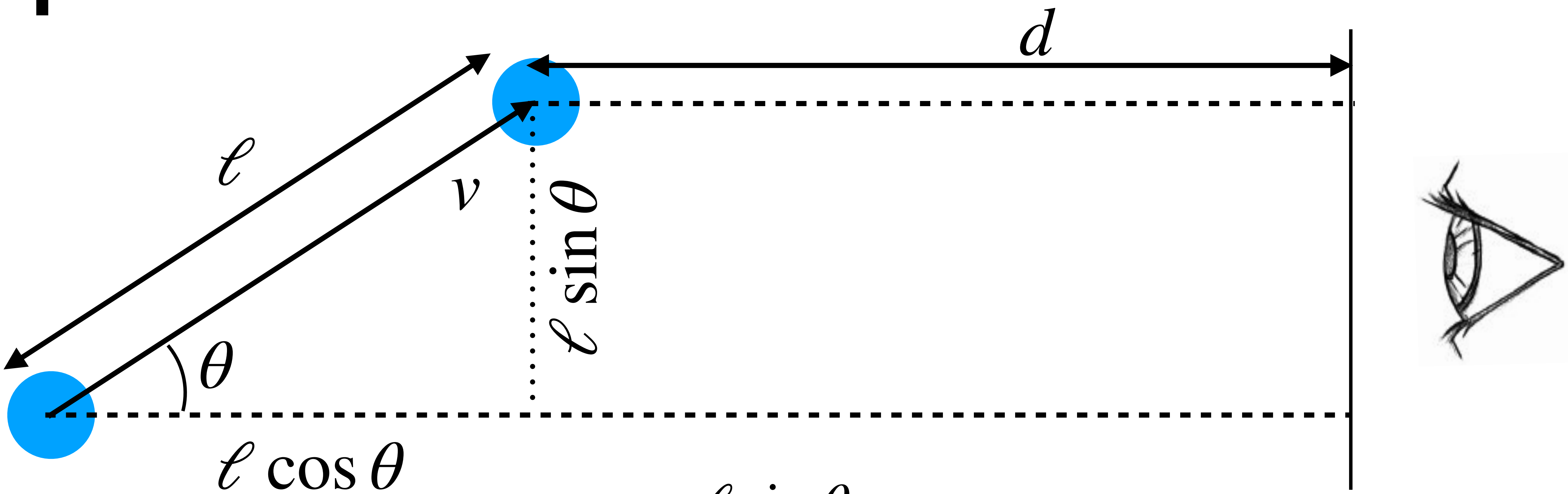
Superluminal motion



$$v_{\rm app} = \frac{\ell \sin\theta}{\ell/v - \ell\cos\theta/c}$$

$$\beta \equiv v/c \implies \boxed{\beta_{\rm app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}}$$

Superluminal motion

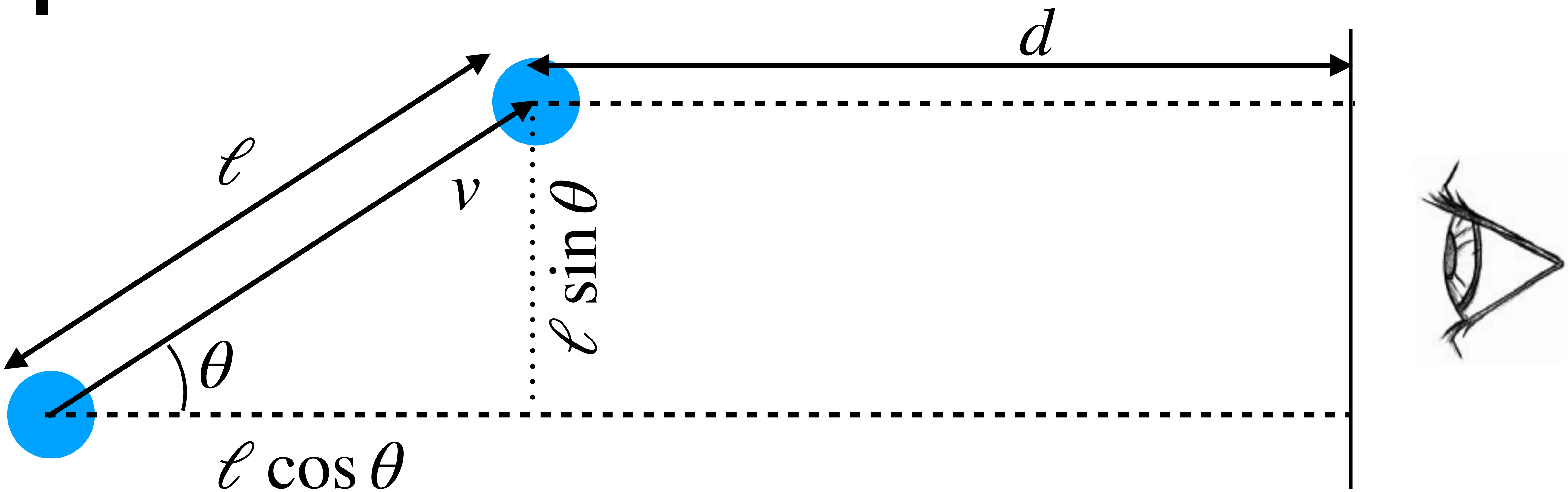


$$v_{\text{app}} = \frac{\ell \sin\theta}{\ell/v - \ell\cos\theta/c}$$

$$\beta \equiv v/c \implies \boxed{\beta_{\text{app}} = \frac{\beta\sin\theta}{1-\beta\cos\theta}}$$

Try: $\beta = 0.99;\ \theta = 15^\circ \implies \beta_{\text{app}} = 5.86!$

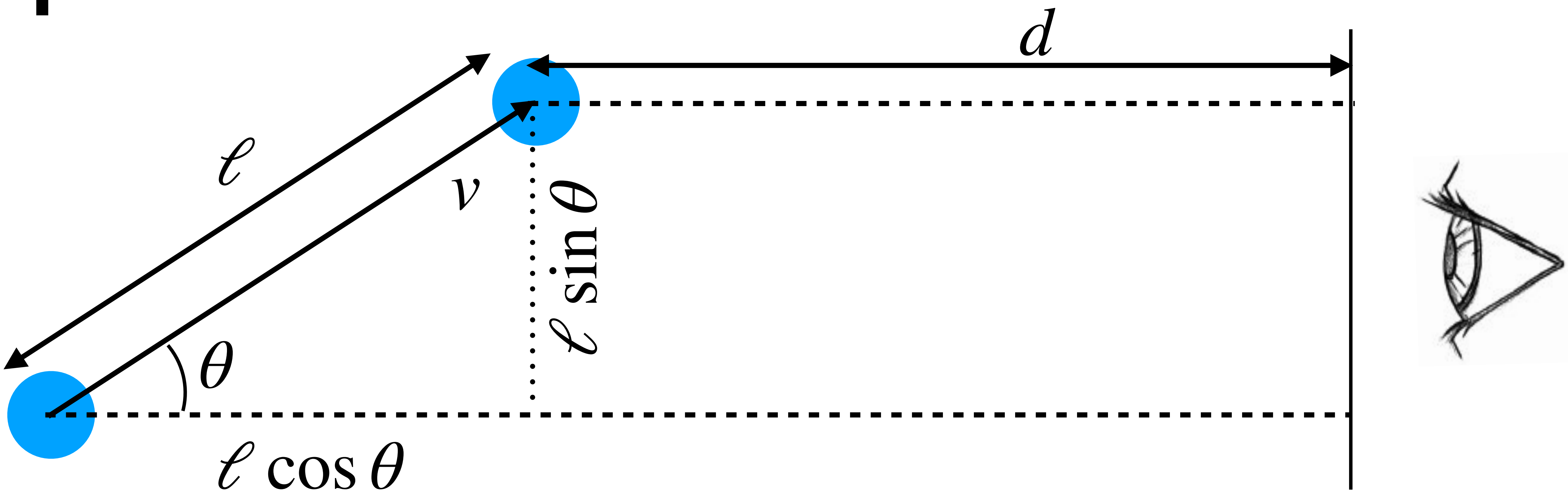
Superluminal motion



Approaching jet much brighter than receding jet:

$$I_\nu = \delta^3 I'_{\nu'}$$

Superluminal motion

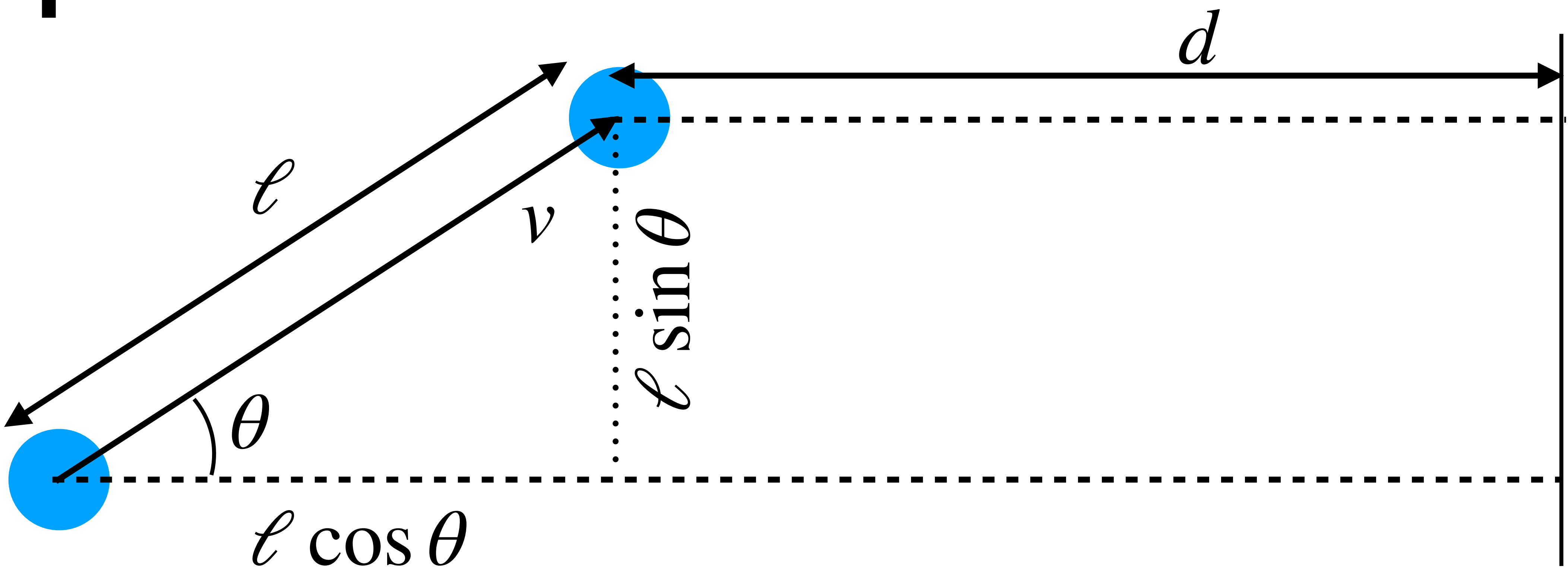


Approaching jet much brighter than receding jet:

$$I_\nu = \delta^3 I'_{\nu'}$$

$$I'_{\nu'} = A(\nu')^{-\alpha} = A(\nu/\delta)^{-\alpha}$$

Superluminal motion



Approaching jet much brighter than receding jet:

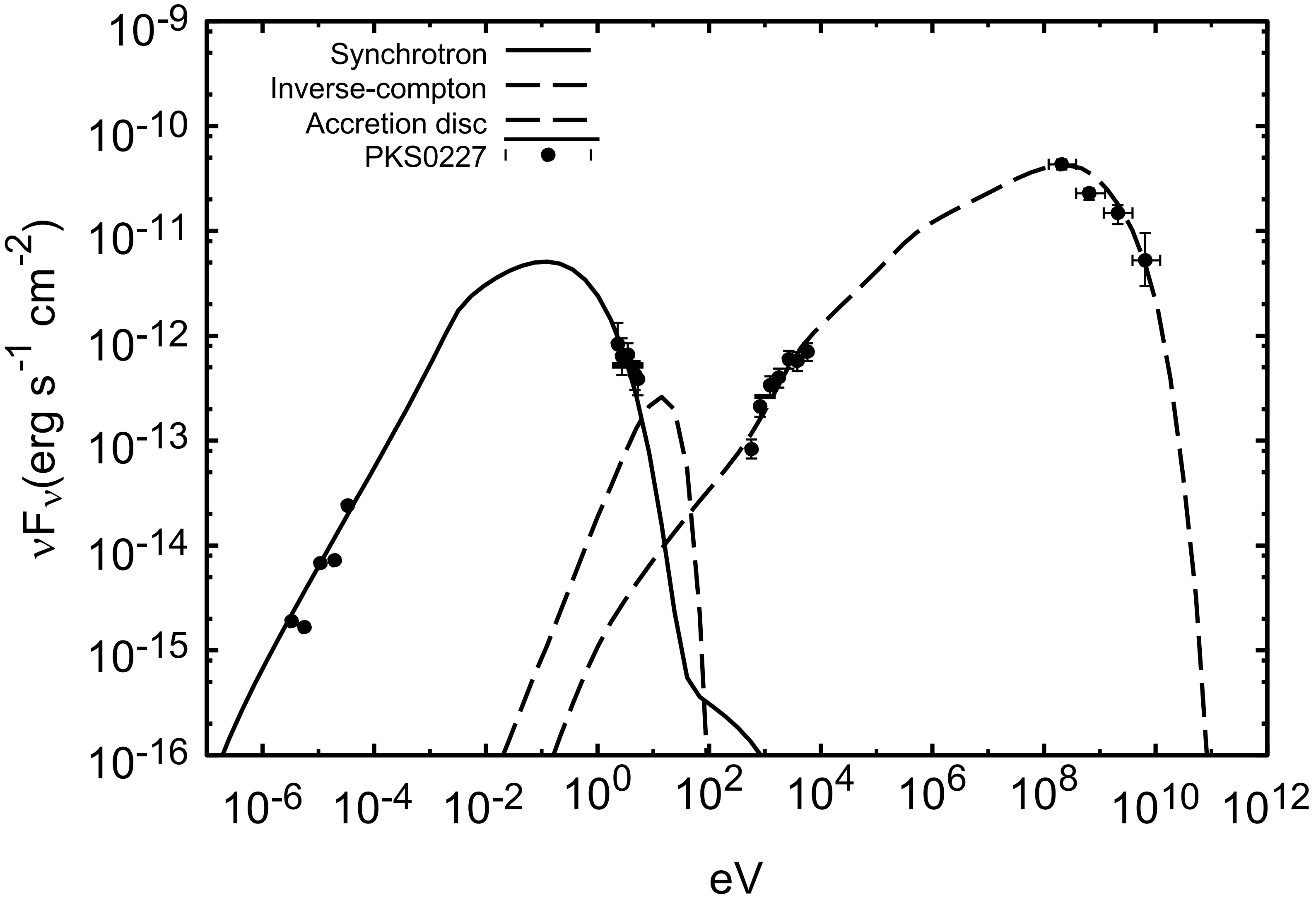
$$I_\nu = \delta^3 I'_{\nu'}$$

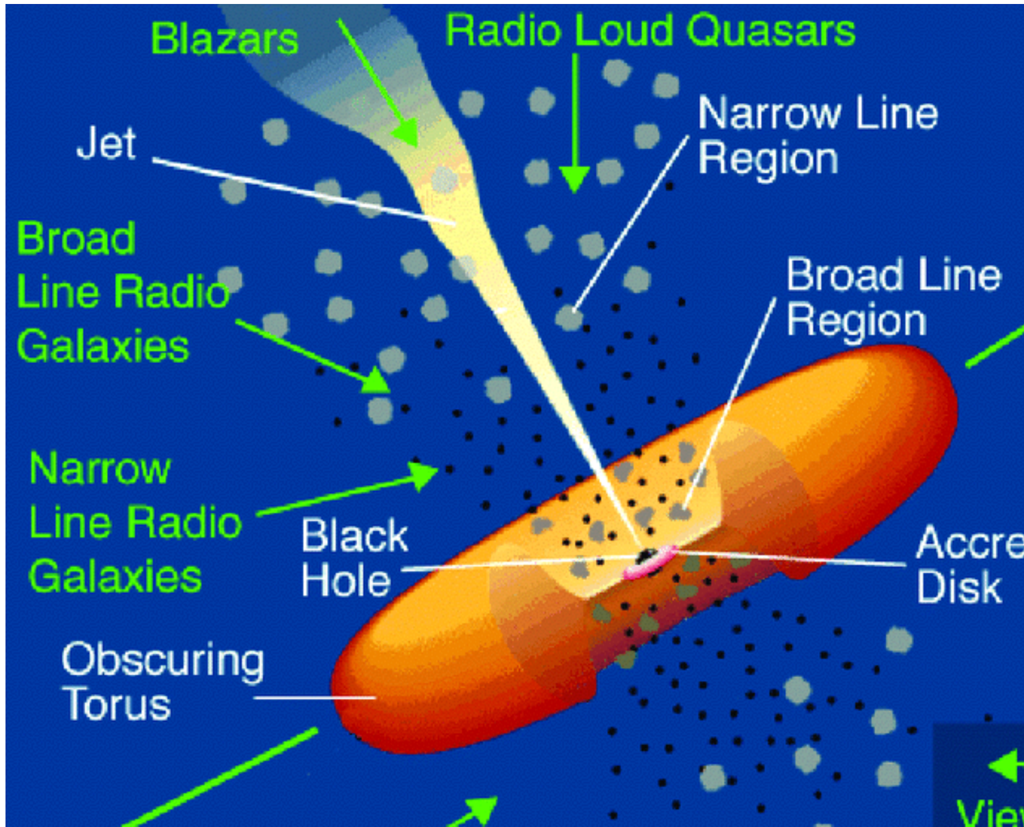
$$I'_{\nu'} = A(\nu')^{-\alpha} = A(\nu/\delta)^{-\alpha}$$

$$\therefore I_\nu = \delta^3 \delta^\alpha A \nu^{-\alpha} = \delta^{3+\alpha} I'_\nu$$

Blazars

- Blazars are AGN viewed right down the barrel of the jet.
- Radio (synchrotron) emission is strongly beamed.
- Strongly beamed X-ray - gamma-ray emission also seen from Compton up-scattering of radio photons by ultra-relativistic (shock accelerated) electrons.





Blazars

- Recall power transferred from electrons to photons is:

$$P_{\rm IC} = \frac{4}{3}\sigma_T c U_{\rm rad} \left(\frac{v}{c}\right)^2 \gamma^2$$

- Previously (lecture 6), v/c was from thermal motions, but now we have v/c~1 from shock acceleration of electrons.

Blazars

- Recall power transferred from electrons to photons is:

$$P_{\rm IC} = \frac{4}{3}\sigma_T c U_{\rm rad}\left(\frac{v}{c}\right)^2\gamma^2$$

- Previously (lecture 6), v/c was from thermal motions, but now we have v/c~1 from shock acceleration of electrons.
- Number of scatterings per second is still: $= \sigma_T(U_{\rm rad}/h\nu)c$
- Therefore mean energy transferred from electron to photon per collision is:

$$\left(\frac{\Delta\epsilon}{\epsilon}\right)_{\rm IC} = \frac{4}{3}\left(\frac{v}{c}\right)^2\gamma^2$$

Blazars

- Recall power transferred from electrons to photons is:

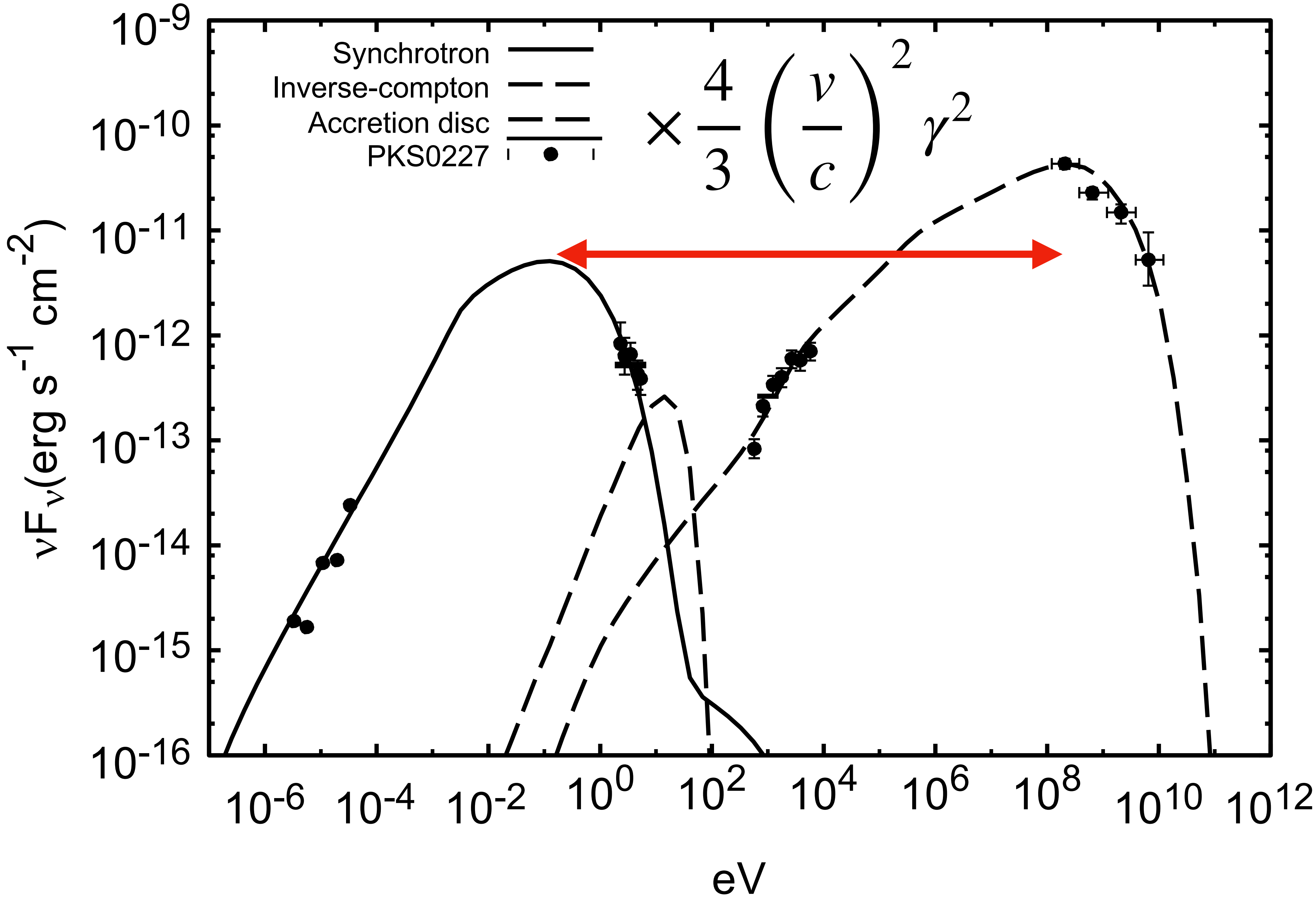
$$P_{\mathrm{IC}} = \frac{4}{3}\sigma_T c U_{\mathrm{rad}} \left(\frac{v}{c}\right)^2 \gamma^2$$

- Previously (lecture 6), v/c was from thermal motions, but now we have v/c~1 from shock acceleration of electrons.
- Number of scatterings per second is still: $= \sigma_T (U_{\mathrm{rad}}/h\nu) c$
- Therefore mean energy transferred from electron to photon per collision is:

$$\left(\frac{\Delta\epsilon}{\epsilon}\right)_{\mathrm{IC}} = \frac{4}{3}\left(\frac{v}{c}\right)^2 \gamma^2$$

- Since seed photons are radio $(h\nu \ll m_e c^2)$, can ignore recoil.
- Therefore photons gain an enormous amount of energy in a single scattering (much less in any subsequent scatterings).

Blazars



Potter & Cotter (2013)