Black hole phenomenology

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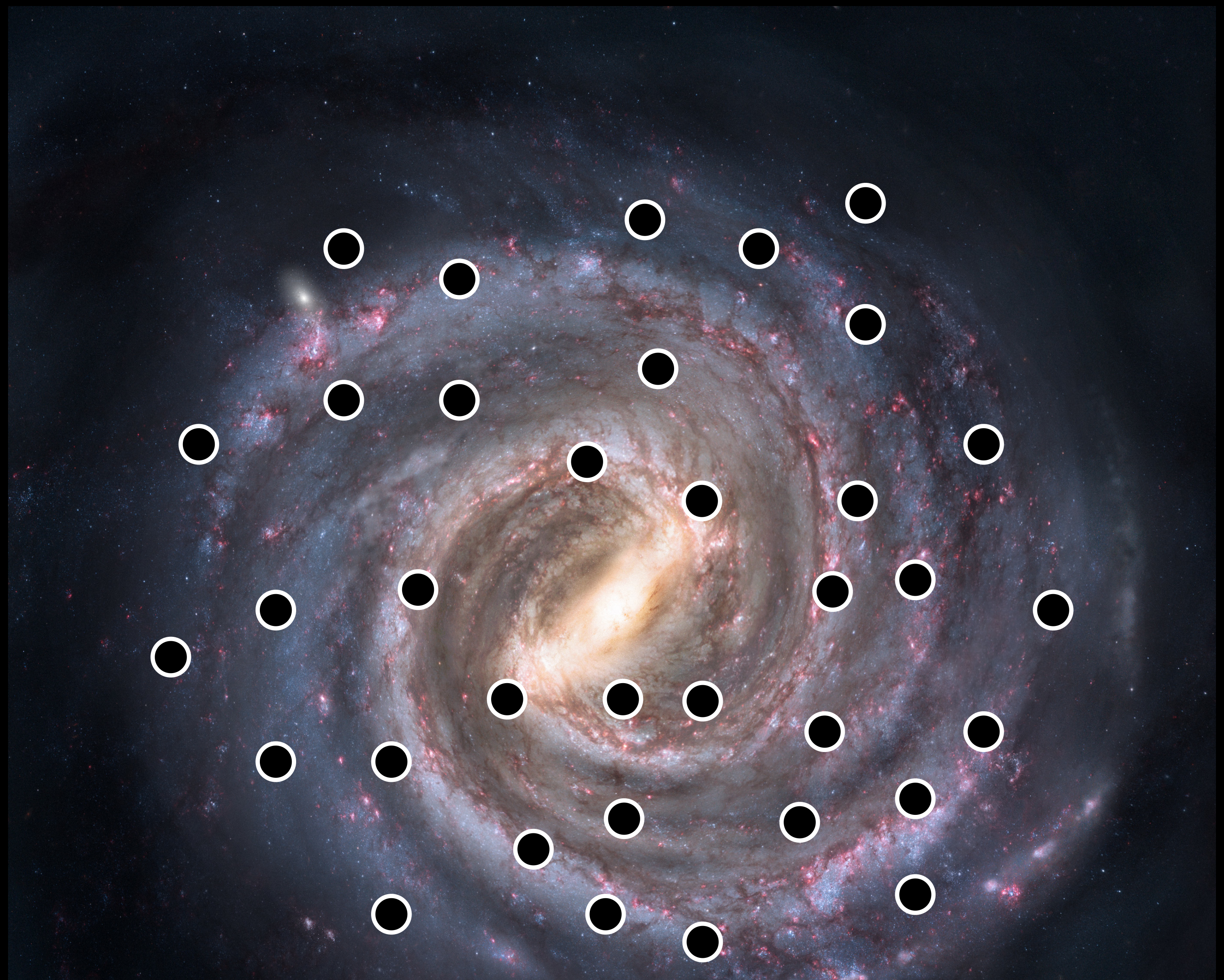
Two populations of black holes

Supermassive

10^6-10^{10} solar masses
one in every galactic nucleus

Stellar

5-60 solar masses
~10^7 per galaxy



X-ray binaries, $M \sim 5\text{-}20 M_{sun}$

10^7 XRBs per galaxy

Credit: NASA GSFC; Britannica

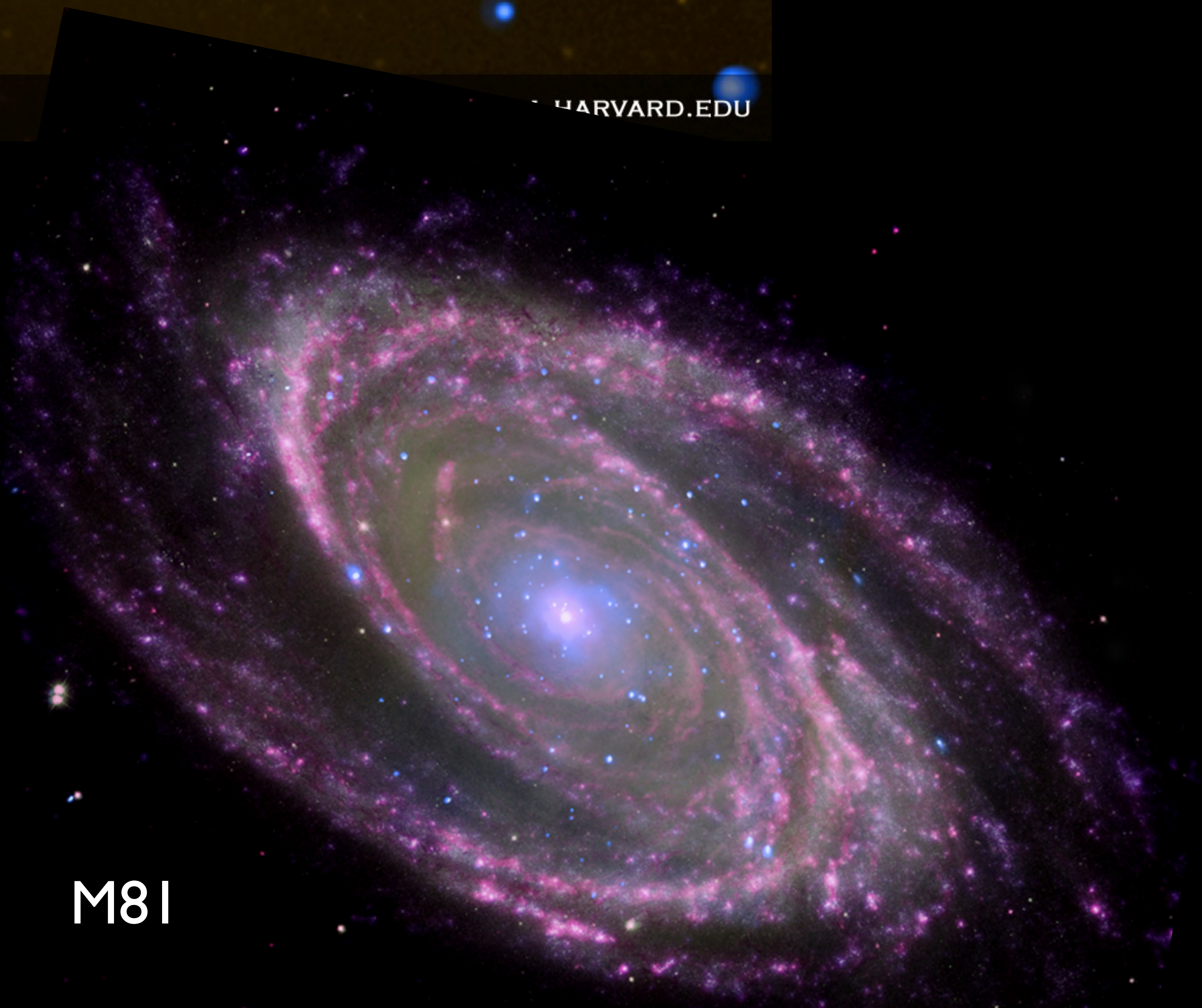
Binary BH systems: M~20-80 M_{sun}

Supermassive BHs have M~10^6-10^{10} M_{sun}, one in every galactic nuclei

M87

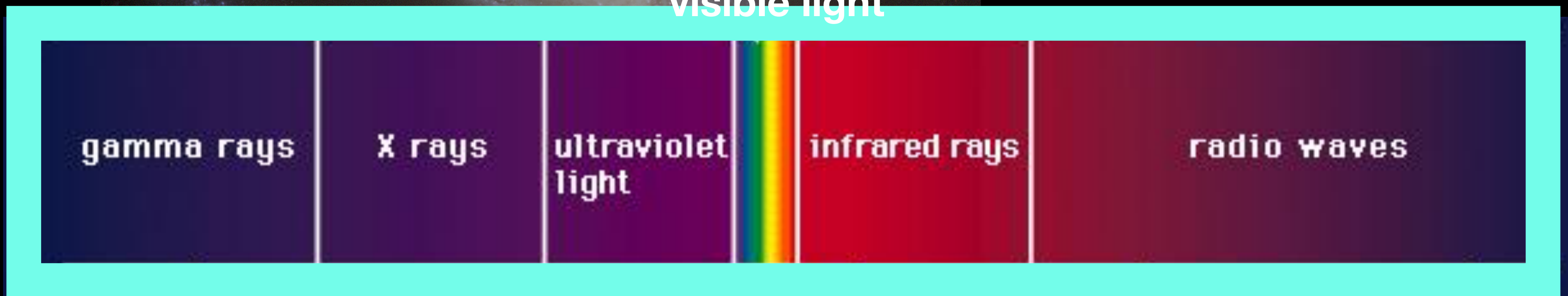
Do dwarf galaxies host supermassive BHs?

NGC 1097



M81

Credit: NASA, HST, CXC




gas loses angular momentum
feeds central black hole
~10 – 100 kpc
Sun in comparison
~10^{-7} – 10^{-3} pc
extreme spacetime curvature
accretion disk
$\frac{GM}{rc^2} \approx 0.1$
$\frac{GM}{rc^2} \gtrsim 10^{-9}$
active galactic nuclei (AGN)

The nearest supermassive black hole: Sagittarius A*


Sagitário A*
Massa = $4 \times 10^6 M_{Sun}$
Sistema Solar

Journey to Sagittarius A*: the supermassive black hole at the center of the Milky Way

Credit: ESO

Credit: ESO

Observational evidence of a black hole

Compact (r < few R_s) and too massive to be a neutron star (M > several M_{sun})

need mass and size measurements

How do we know they are black holes?

Criteria used to identify astrophysical BHs

- **Must be compact: radius < few R_s**
- **Must be massive: M > several M_{sun}, too massive to be a neutron star ($M_{ns,crit} \leq M_{sun}$)**

These are strong reasons for BH candidates

It is possible to empirically prove the existence of event horizons

Prove that BHs have event horizons (soon: Event Horizon Telescope)

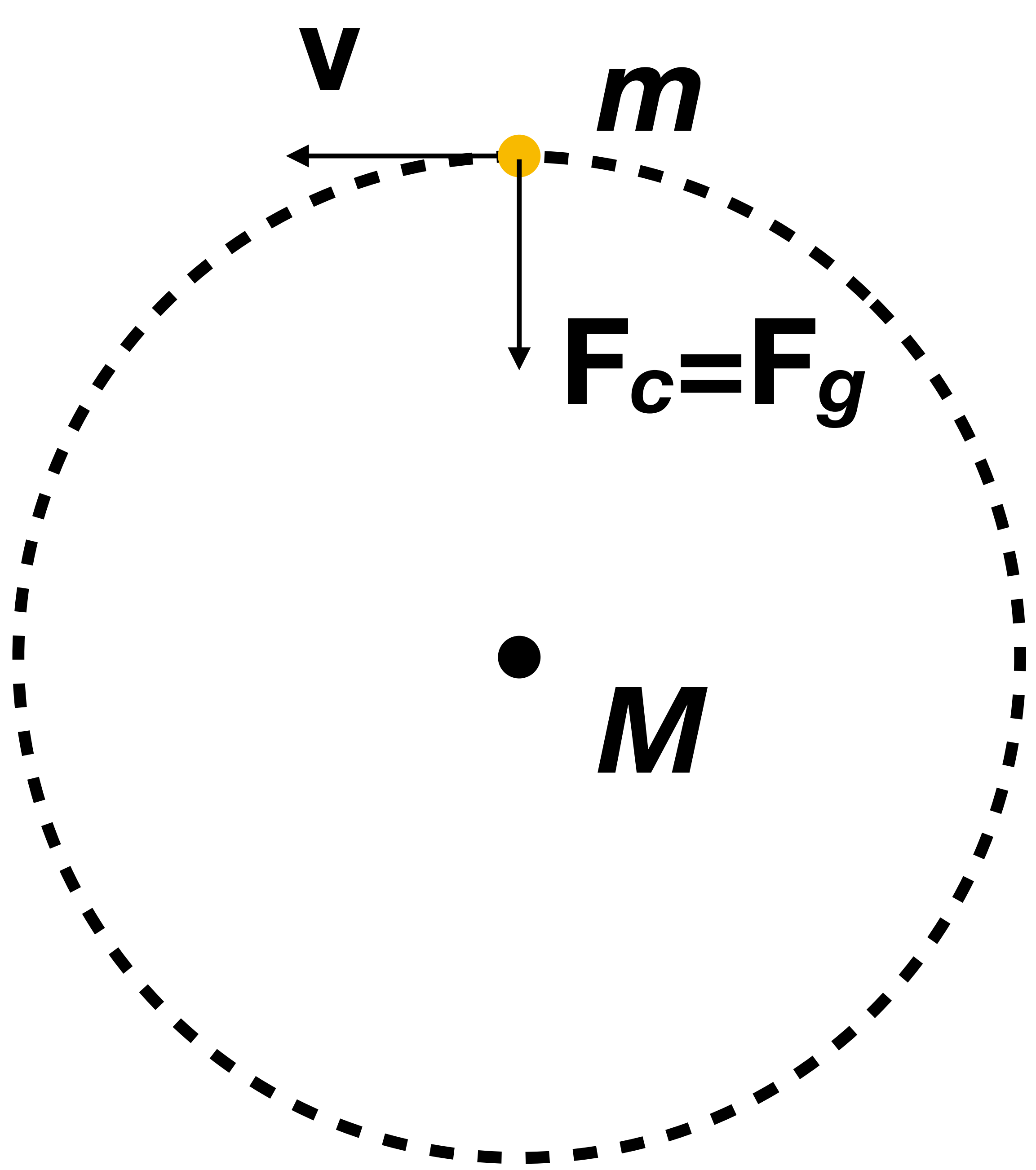
Measuring mass in astronomy

Best mass estimates are *dynamical*

Test particle in circular orbit

$$F_g = F_c \Rightarrow \frac{GMm}{r^2} = \frac{mv^2}{r}$$

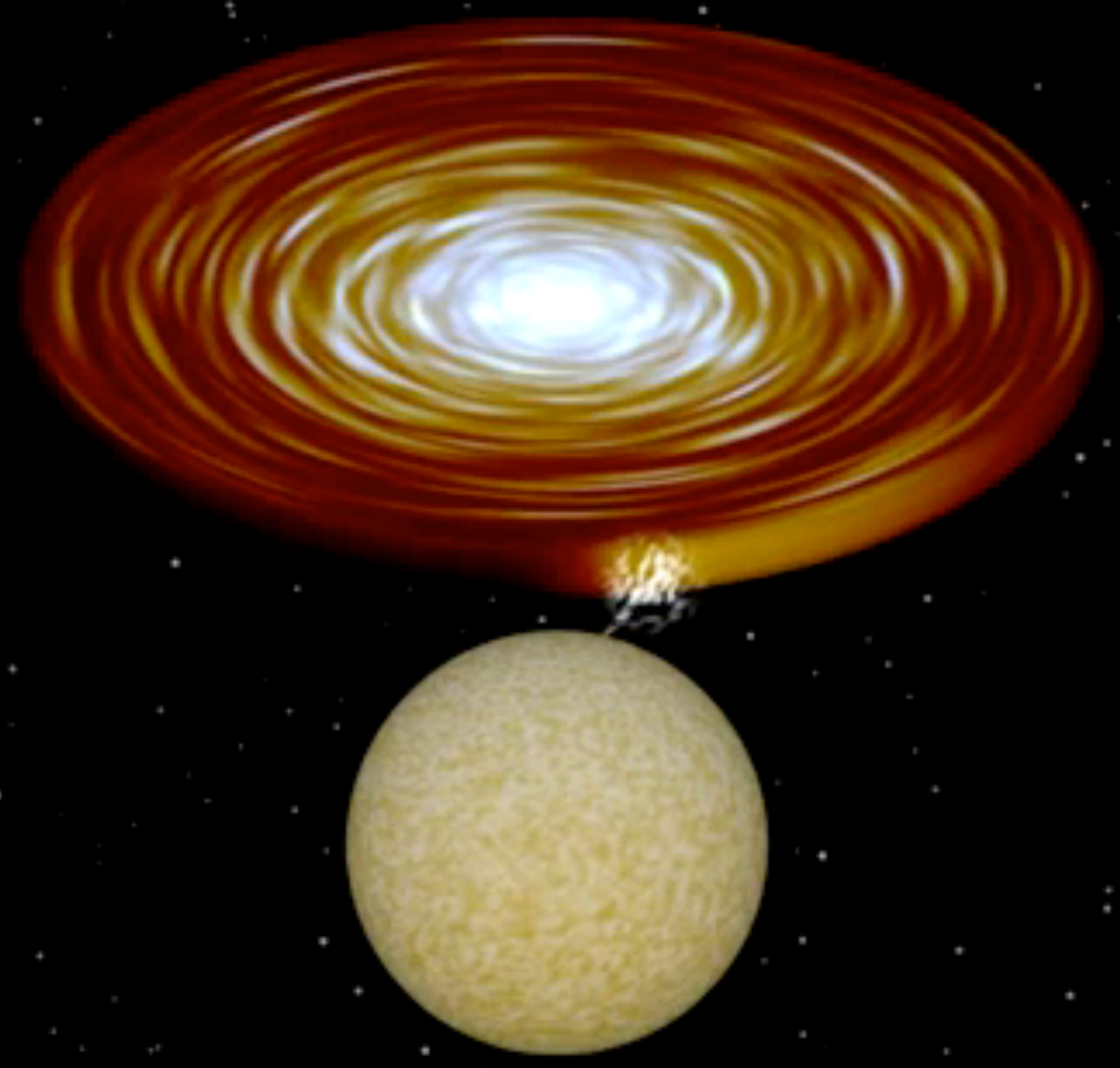
$$\Rightarrow \boxed{M = \frac{v^2 r}{G}}$$



Alternatively, Kepler's third law

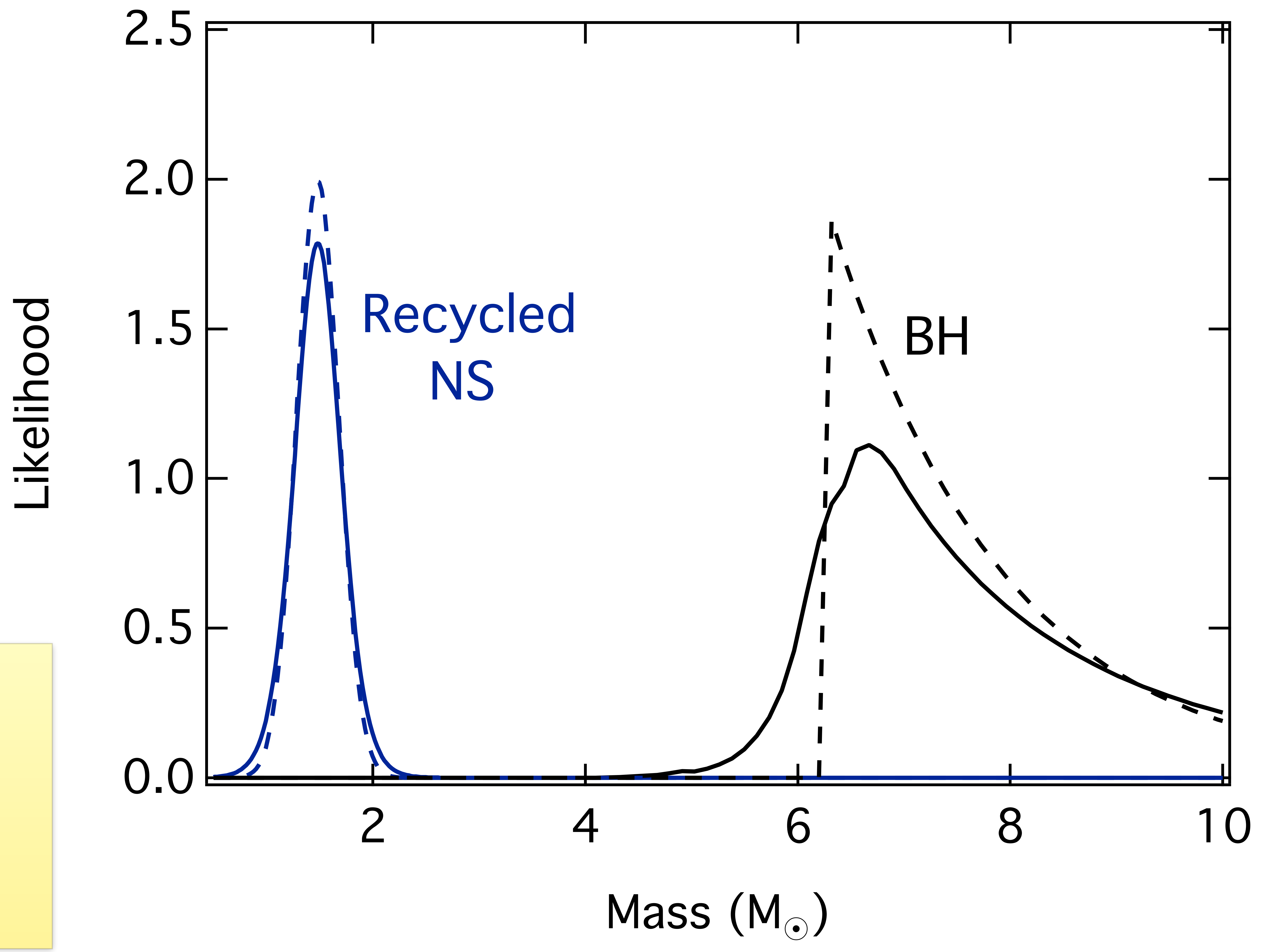
$$\frac{P^2}{r^3} = \frac{4\pi^2}{G(M+m)} \Rightarrow \boxed{M \approx \frac{4\pi^2 r^3}{GP^2}}$$

Measuring mass for a X-ray binary system with a BH



Observe modulation of secondary star

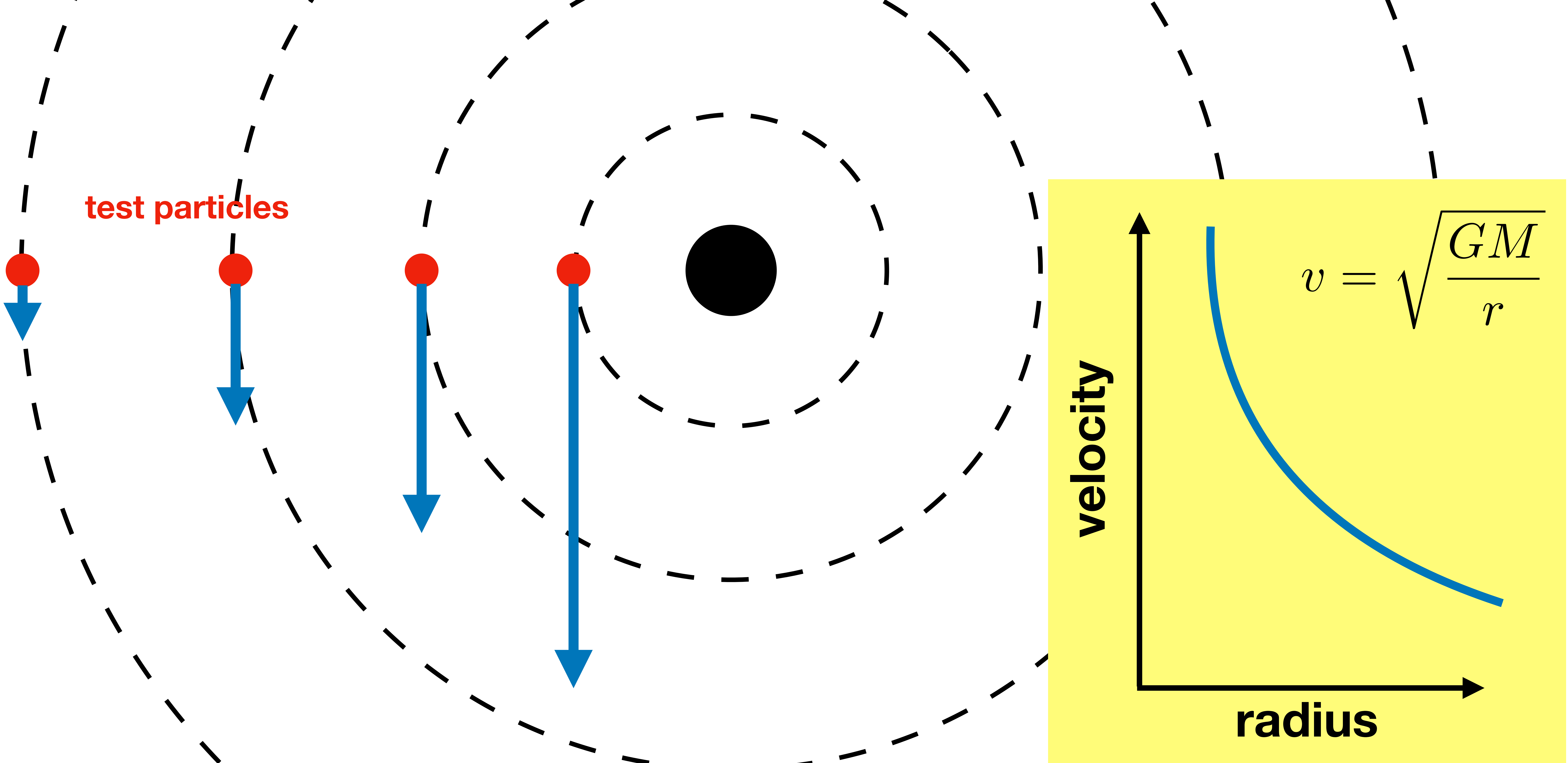
Distribution of masses of neutron stars and stellar mass black holes



FUTURE: LIGO PLOT COMPARING WITH MASSES FROM GWS

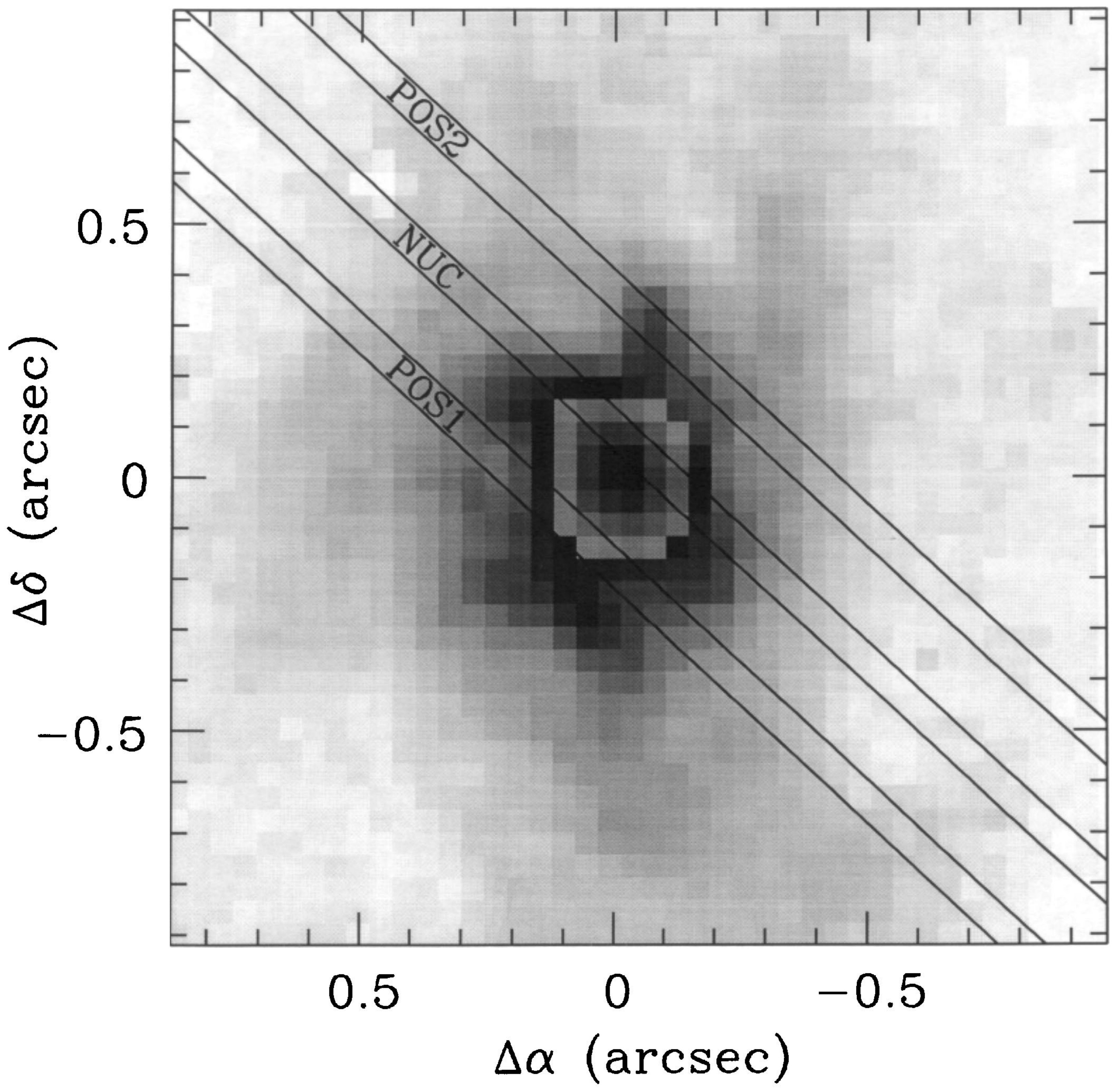
Özel+2012

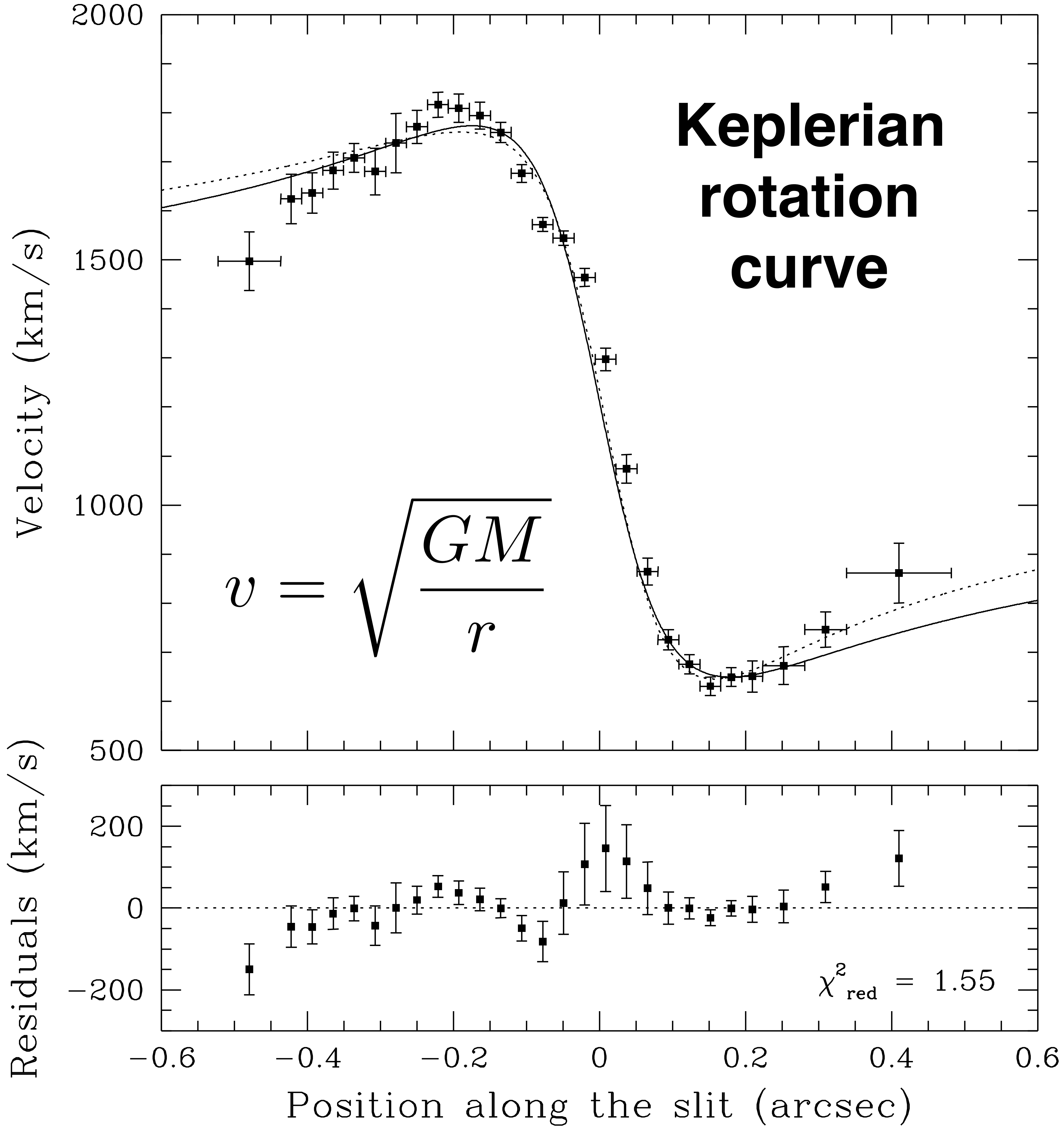
Keplerian rotation curves: signature of motion around a central mass



Example 1: Kinematics of gaseous disk in giant elliptical galaxy M87 mapped with HST

HST observation of ionized gas



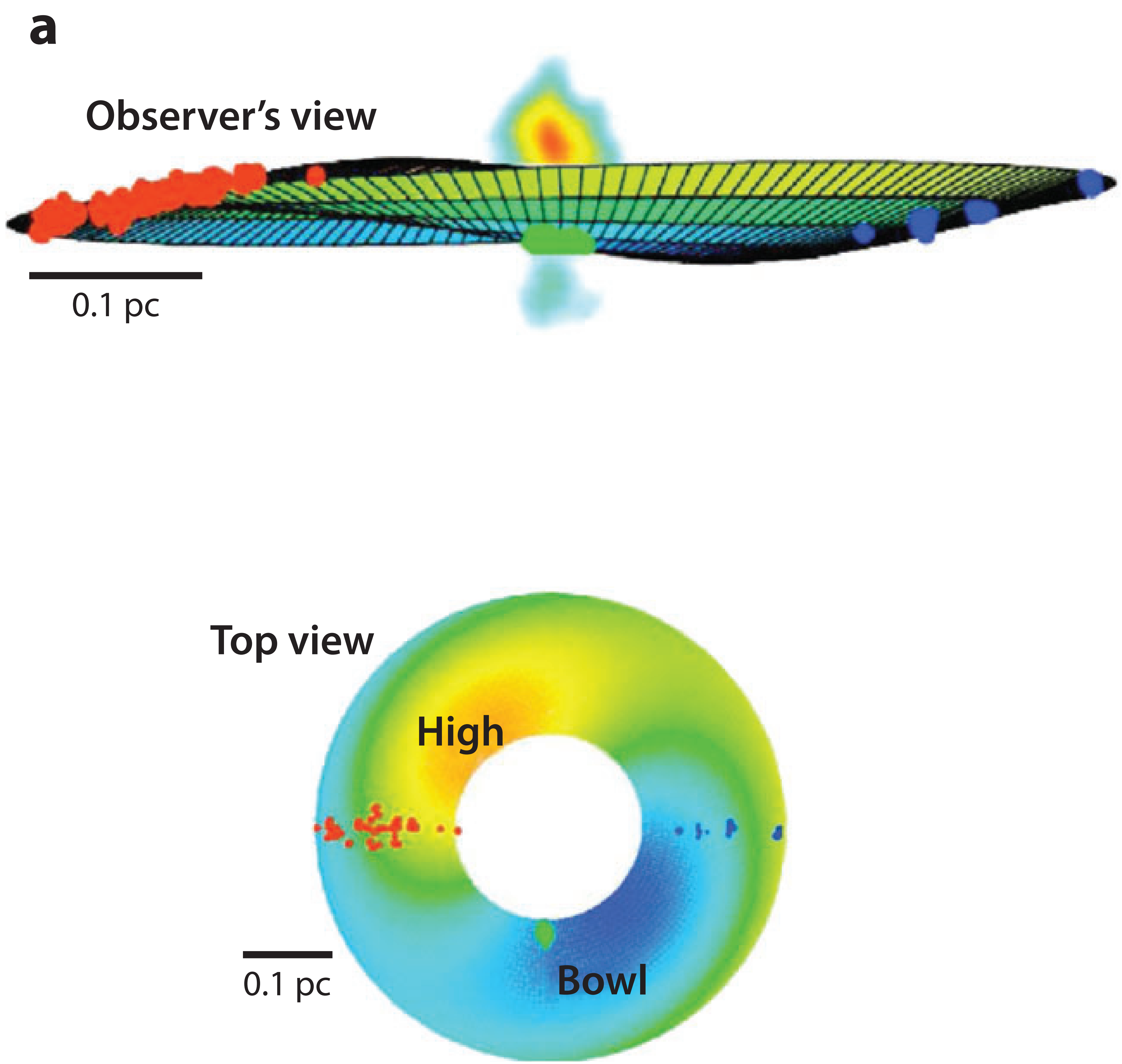


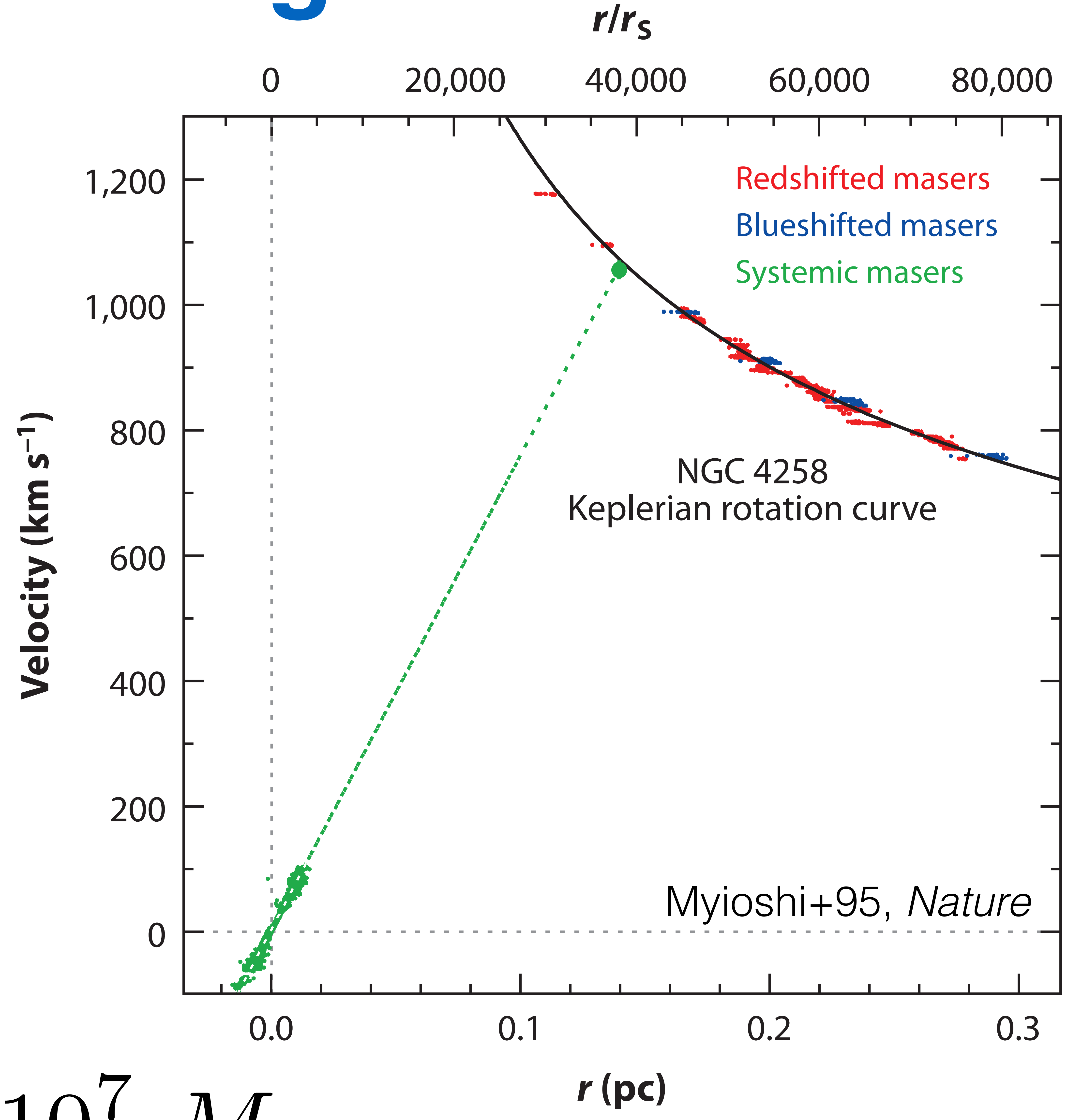
$$v = \sqrt{\frac{GM}{r}}$$

$$M = 3 \times 10^9 \ M_\odot$$

Macchetto+1997, ApJ

Example 2: VLBA radio observations of water maser in NGC 4258: Keplerian gas disk

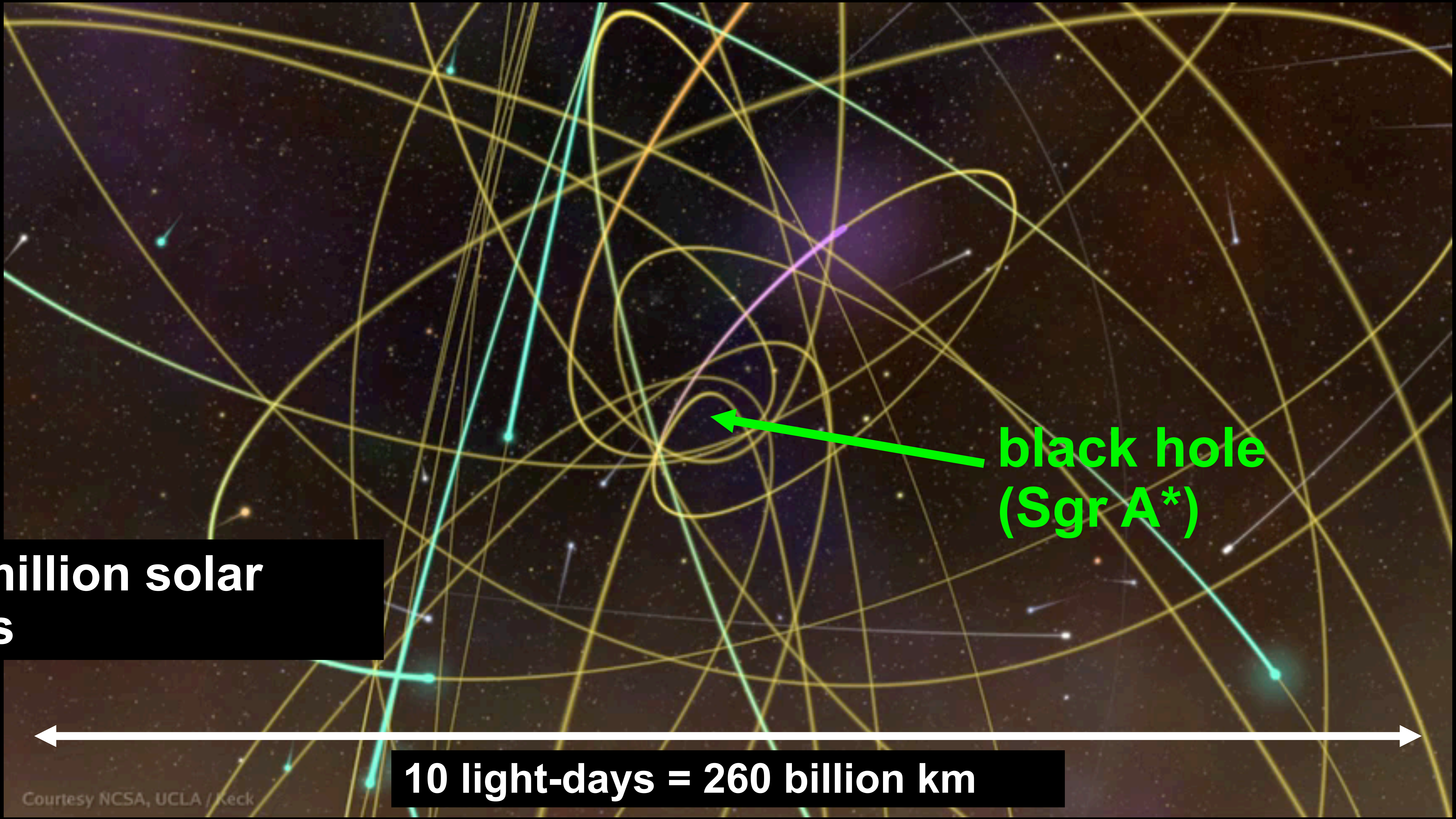




$$M = 3.6 \times 10^7\ M_\odot$$

Kormendy & Ho 2013, ARA&A

Resolved stellar dynamics around Our Galactic Center with Keck observations



M = 4 million solar masses

Ghez, Schödel, Genzel et al.

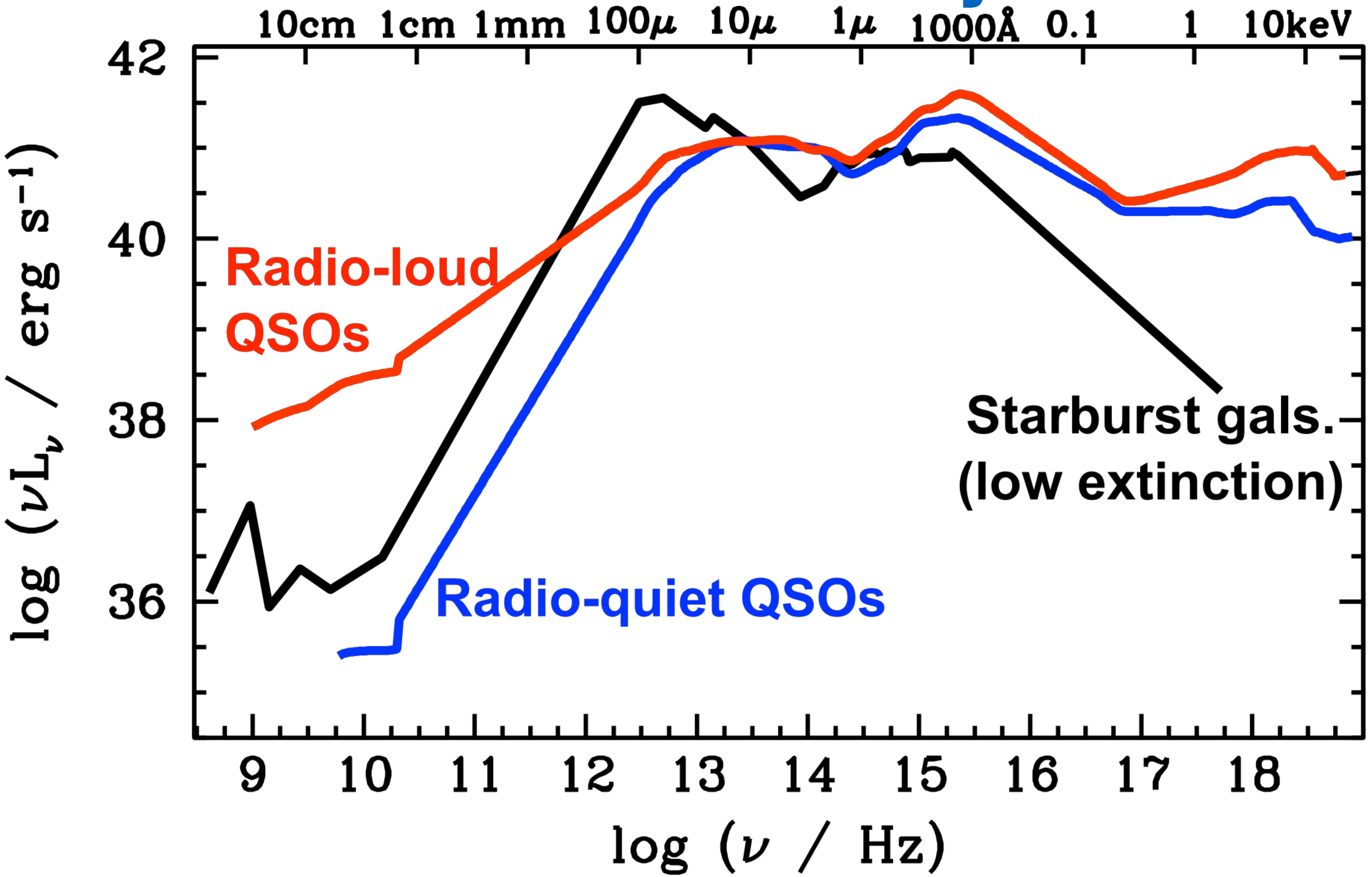
Observational evidence of a black hole

Compact (r < few R_s) and too massive to be a neutron star (M > several M_{sun})

Strong point like EM light in the radio, gamma-rays (from jet), X-rays (from disk) → nonstellar continuum

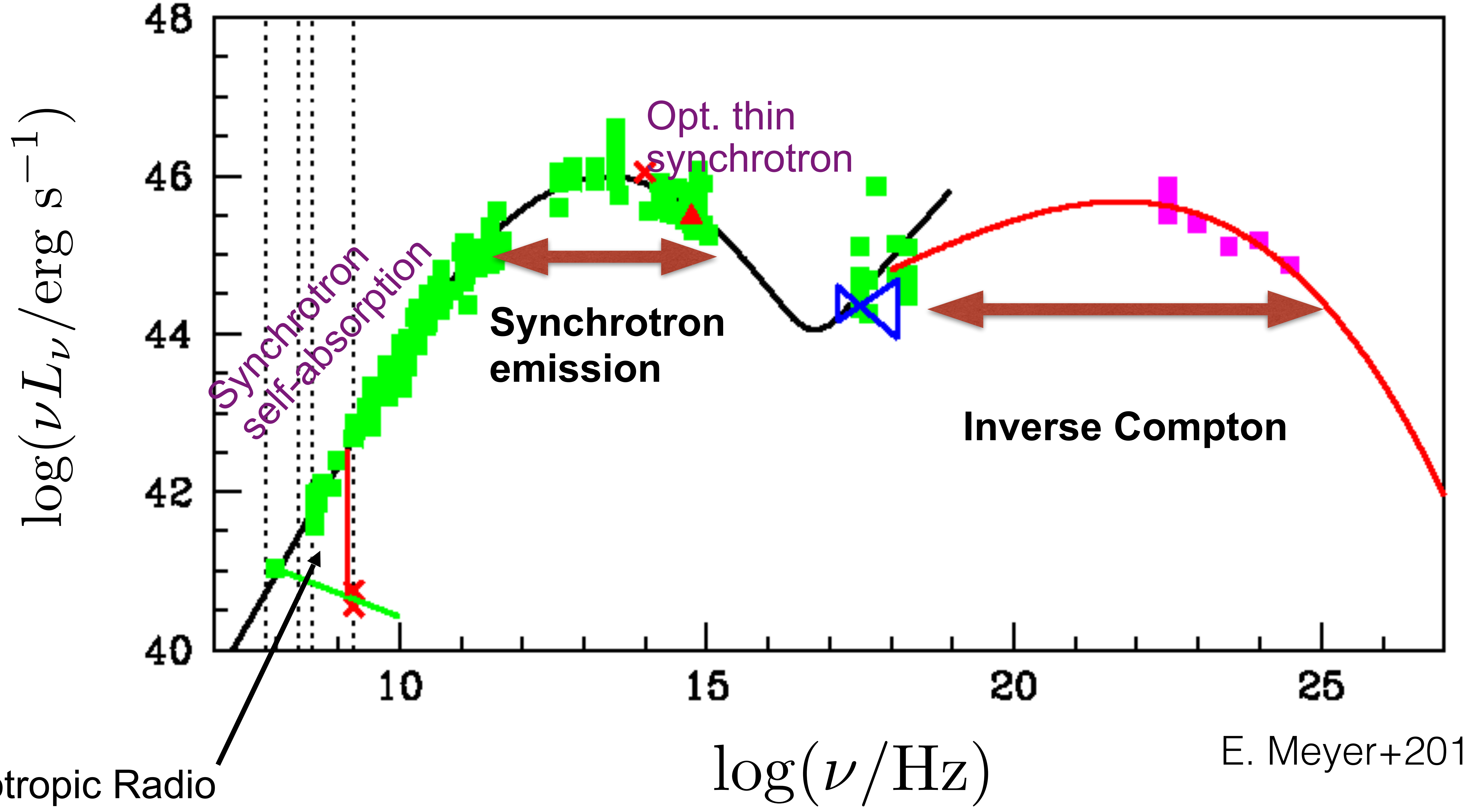
need to look at many wavelenghts

Spectral energy distributions of many galactic nuclei are decisively non-stellar



Ho 2004

Blazars: looking down the “barrel of the gun”, observe the *beamed* power of the relativistic jet



Isotropic Radio
Emission from
Slowed Plasma in the
Lobes

E. Meyer+2011

Synchrotron power:

$$P = 2\sigma_T c \gamma^2 \beta_\perp^2 \left(\frac{B^2}{8\pi}\right)$$

Observational evidence of a black hole

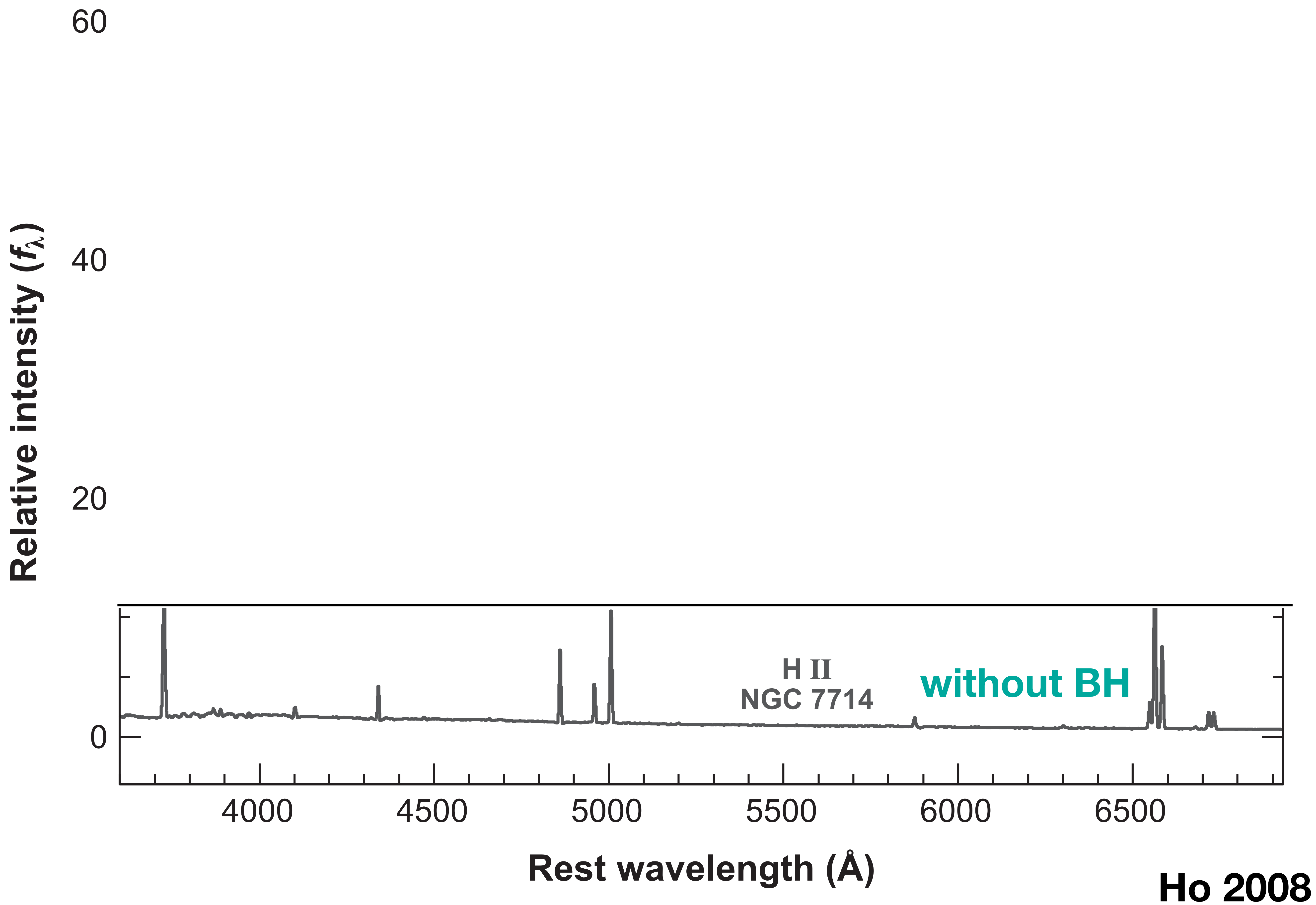
Compact (r < few R_S) and too massive to be a neutron star (M > several M_{sun})

Strong point like EM light in the radio, gamma-rays (from jet), X-rays (from disk) → nonstellar continuum

Broad emission lines (widths>few 1000 km/s)

spectroscopy is fundamental

Broad emission lines due to high velocities of gas induced by the BH



Ho 2008

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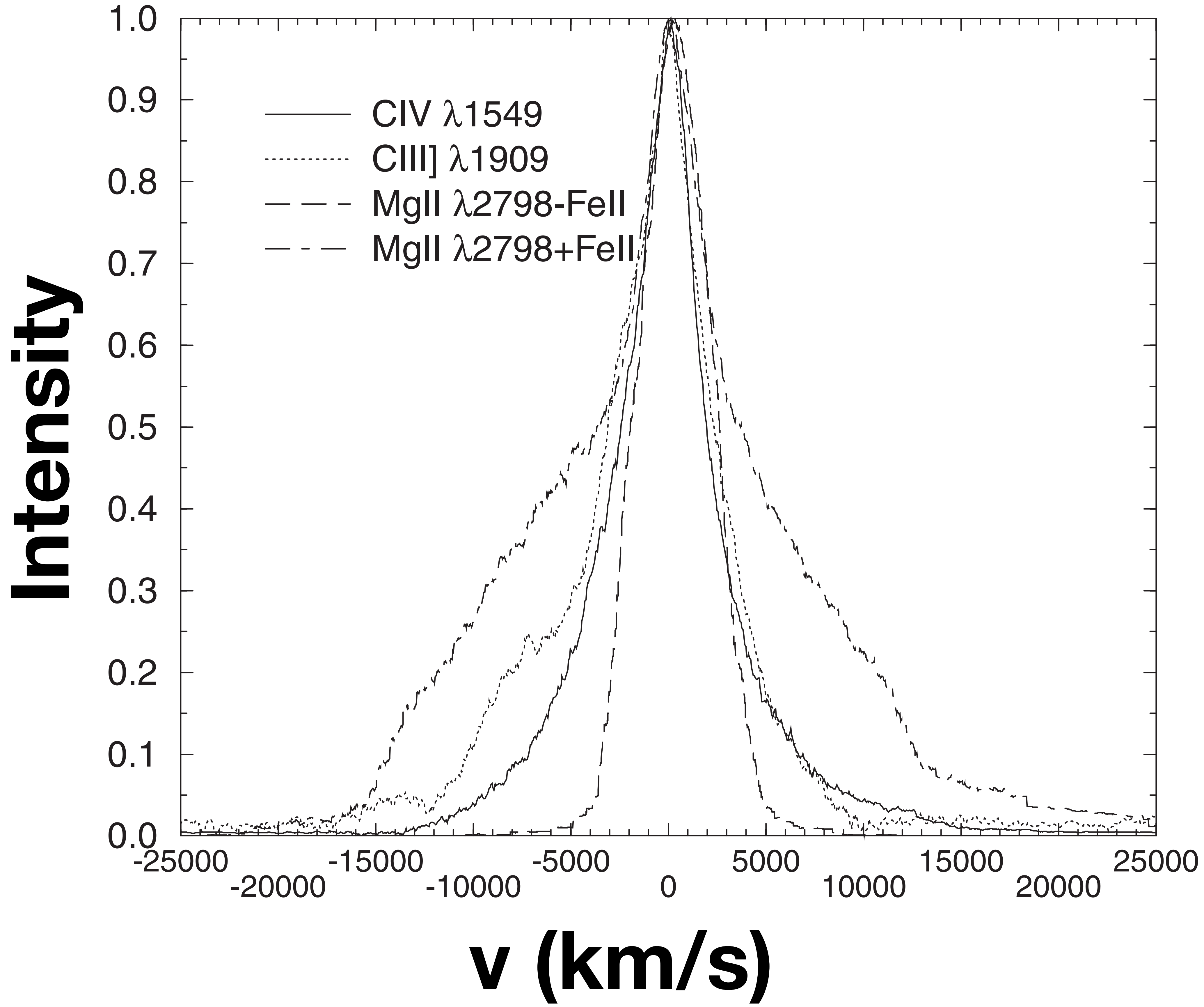
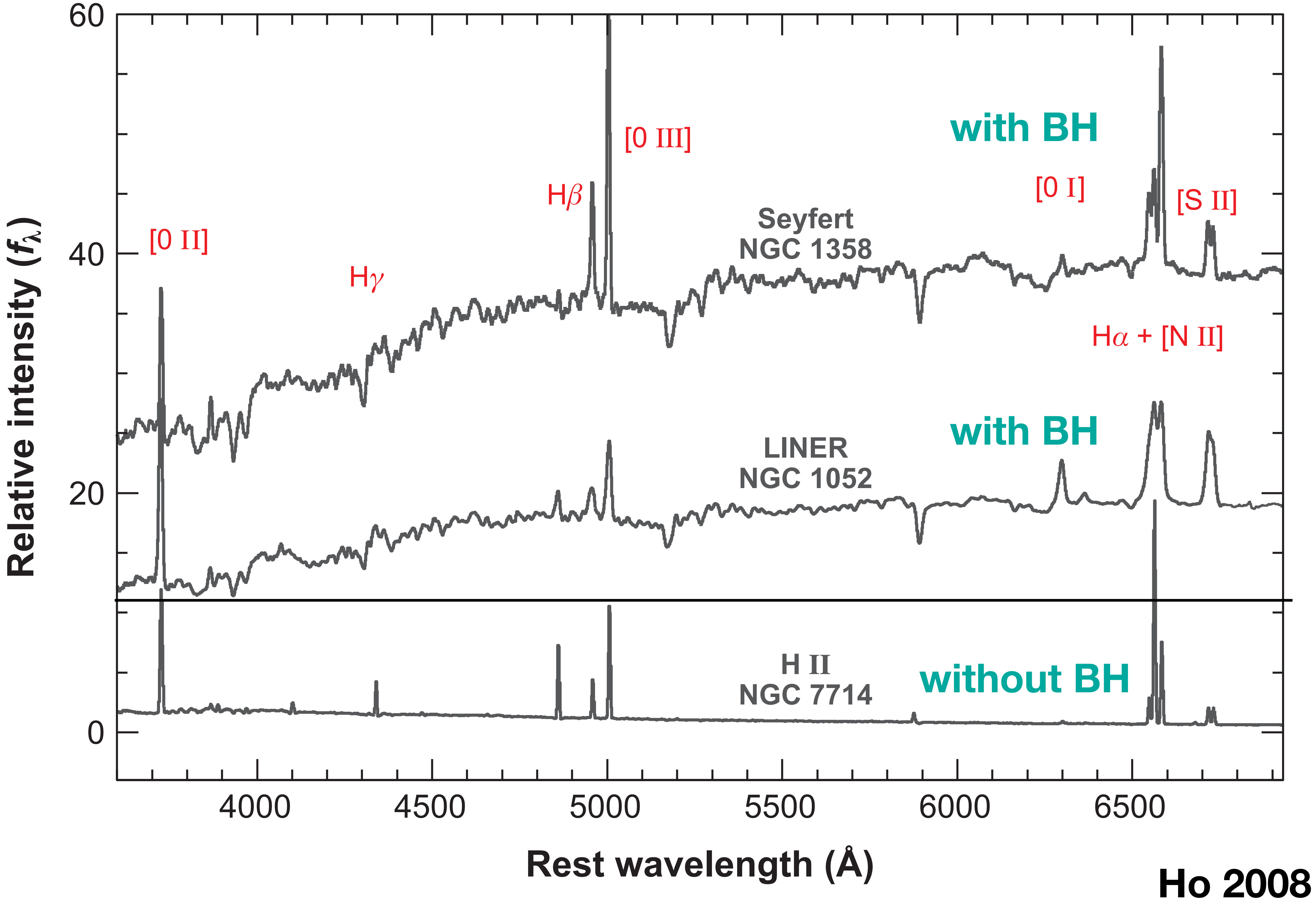


Netzer



Ho 2008

Observational evidence of a black hole

Compact (r < few R_S) and too massive to be a neutron star (M > several M_{sun}) **need mass and size measurements**

***Strong point like* EM light in the radio, gamma-rays (from jet), X-rays (from disk) → nonstellar continuum**

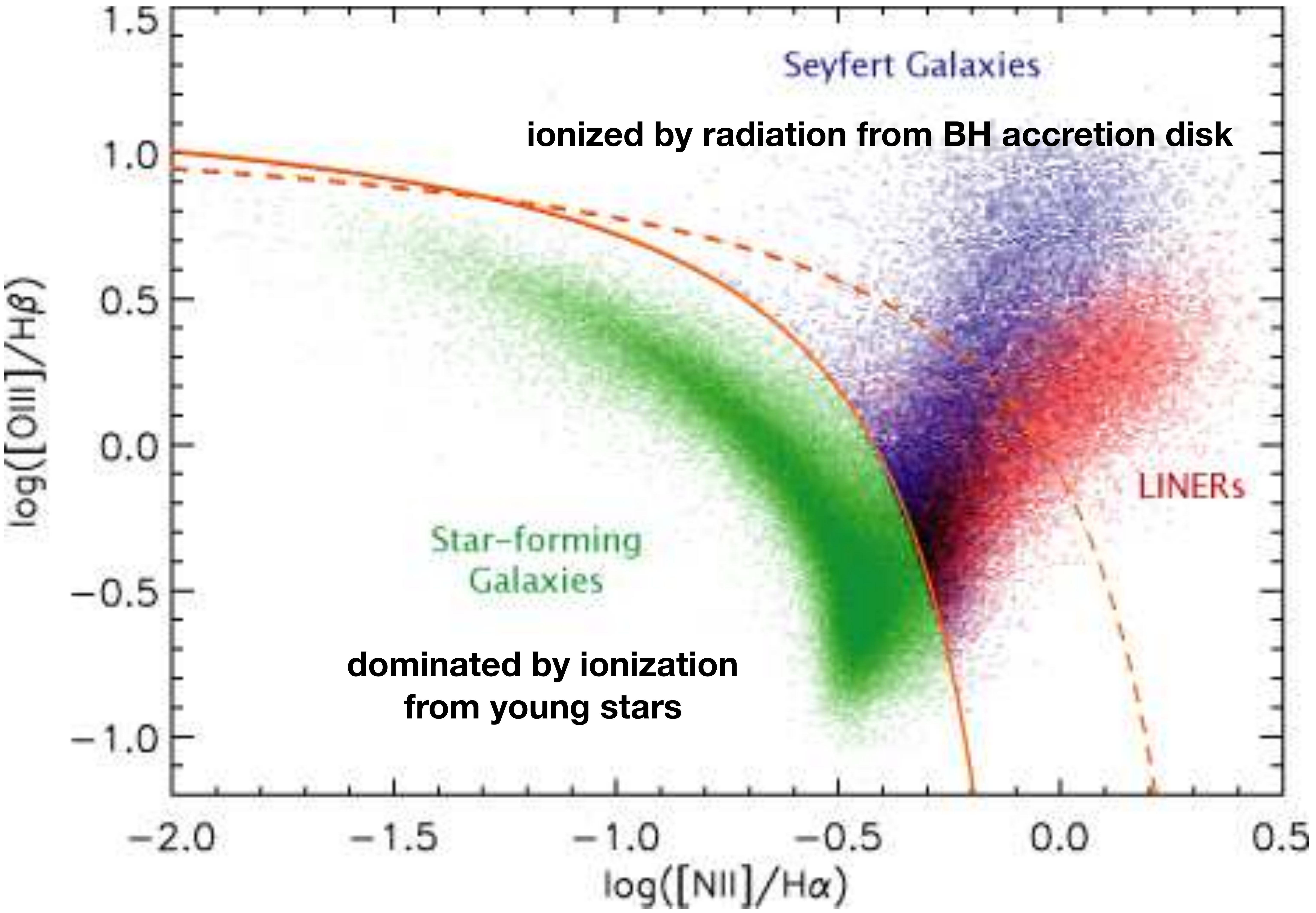
need to look at many wavelenghts

Broad emission lines (widths>few 1000 km/s)

spectroscopy is fundamental

Strong optical emission lines

Presence of strong emission lines: photoionization by BH accretion disks's radiation field



Groves+2006

Observational evidence of a black hole

Compact (r < few R_s) and too massive to be a neutron star (M > several M_{sun})

need mass and size measurements

Strong point like EM light in the radio, gamma-rays (from jet), X-rays (from disk) → nonstellar continuum

need to look at many wavelenghts

Broad emission lines (widths>few 1000 km/s)

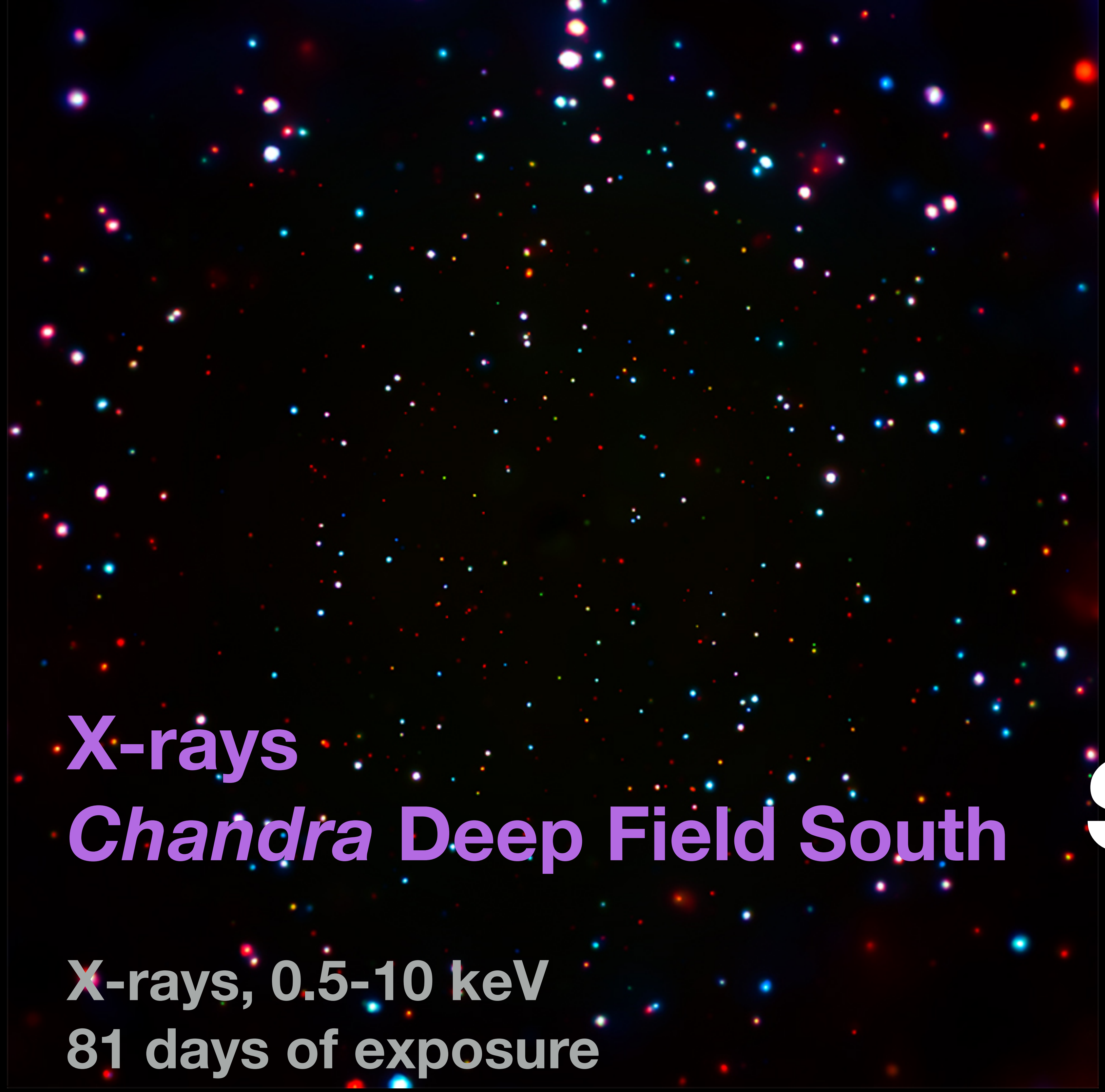
spectroscopy is fundamental

Strong optical emission lines

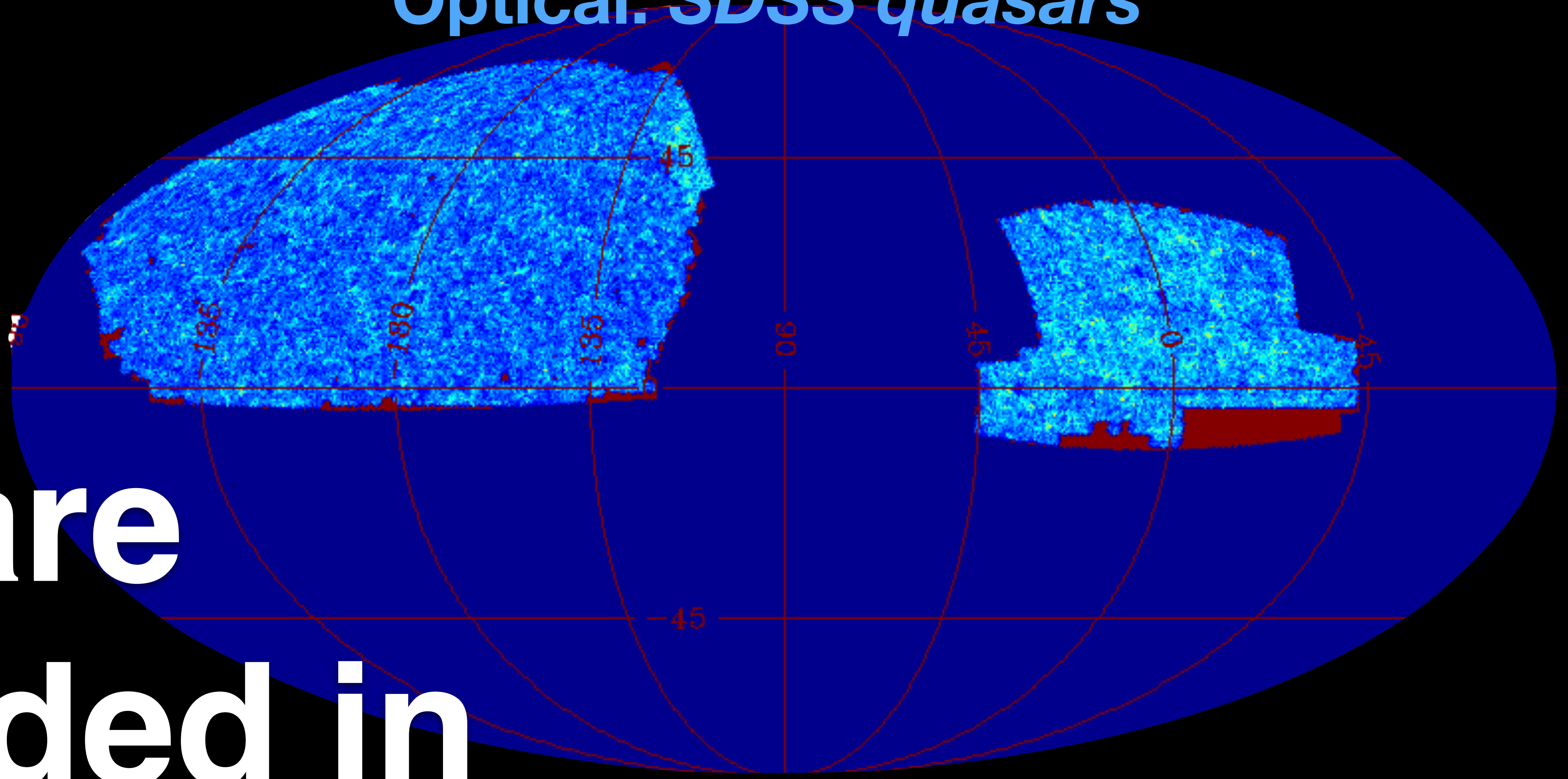
Apparent superluminal flows (relativistic blobs)

Active galactic nuclei (AGN)

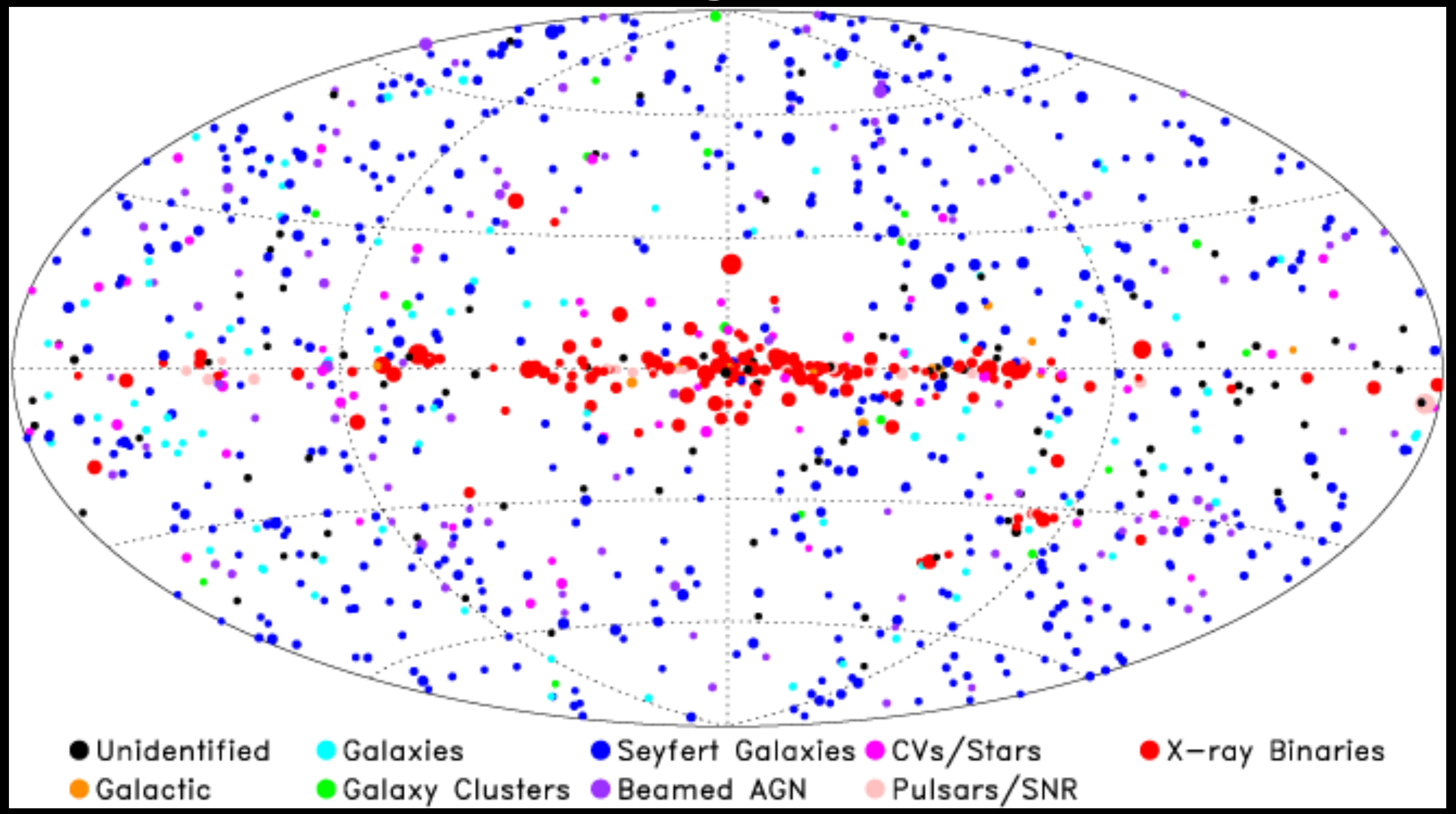
We are surrounded in all directions by AGNs



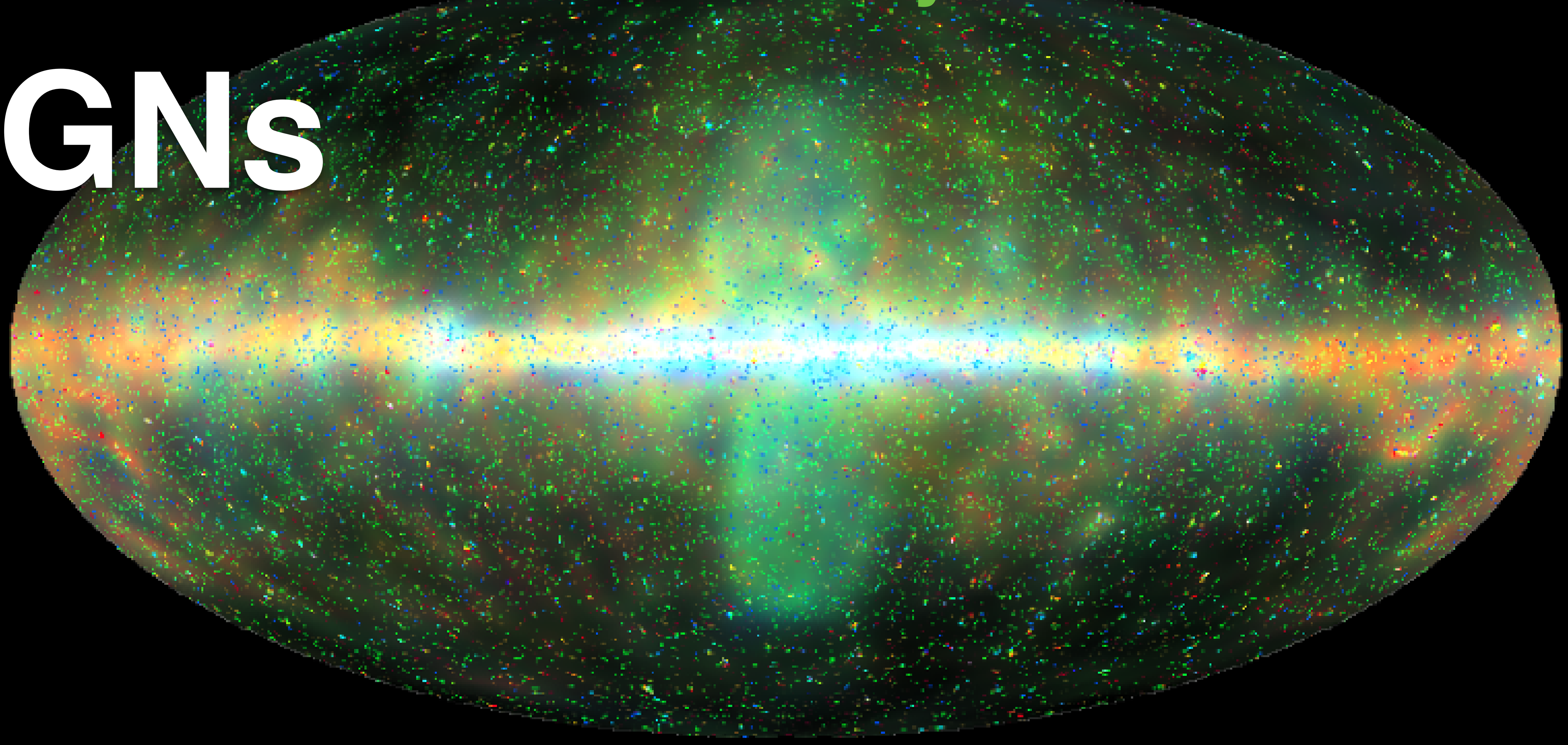
Optical: *SDSS quasars*



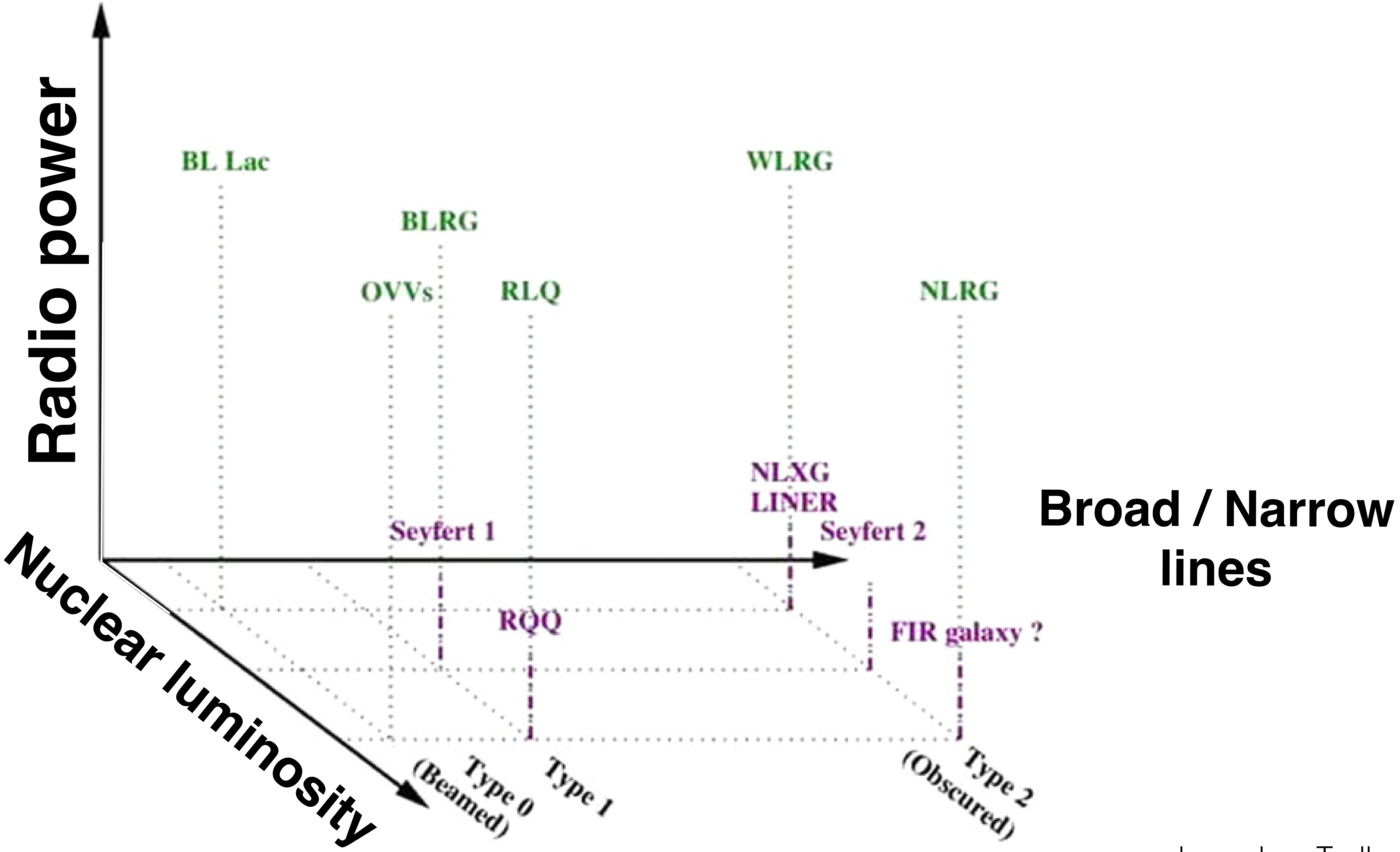
X-rays: *Swift BAT*



Gamma-rays: *Fermi LAT*

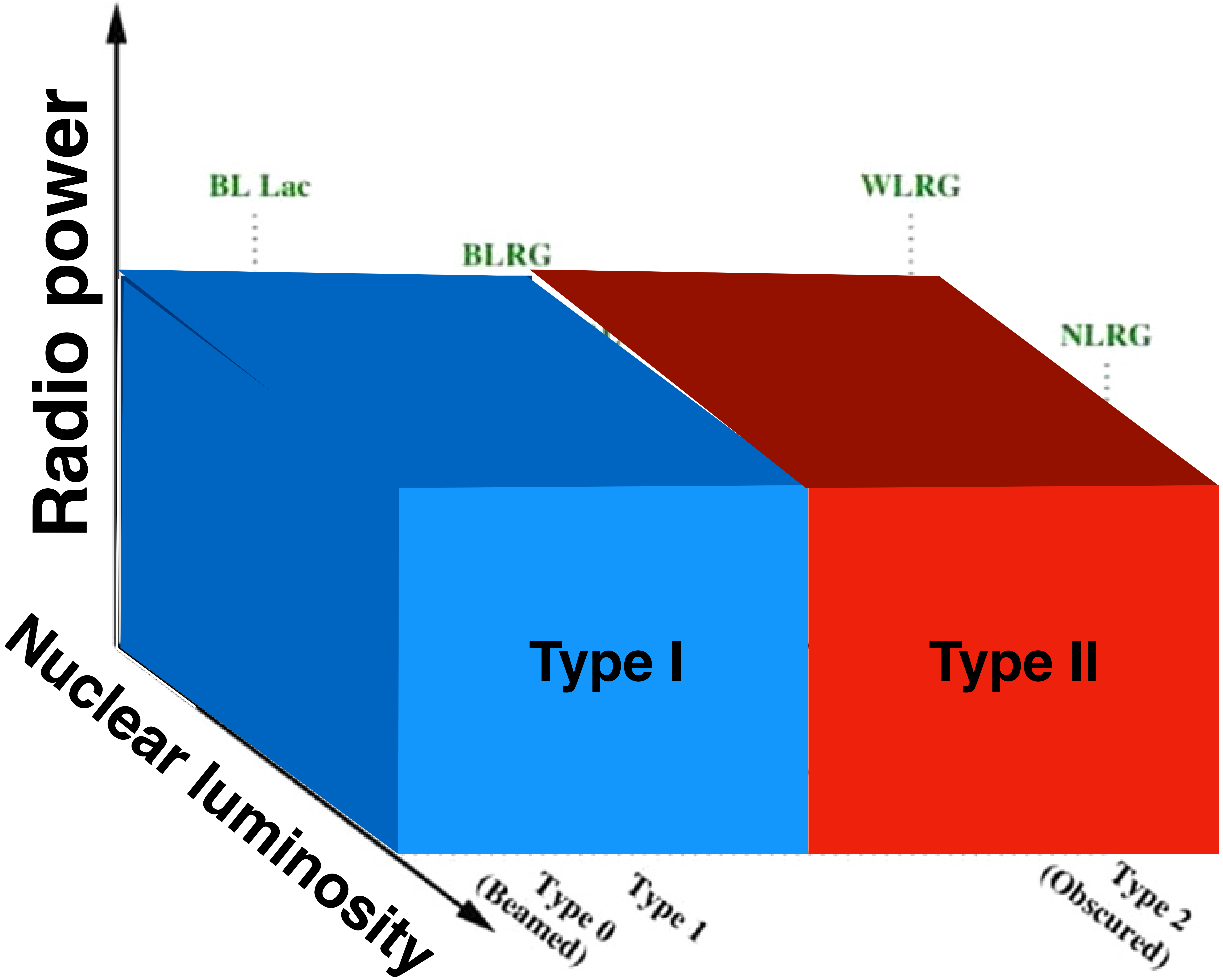


Phenomenology of active galactic nuclei



based on Tadhunter+08

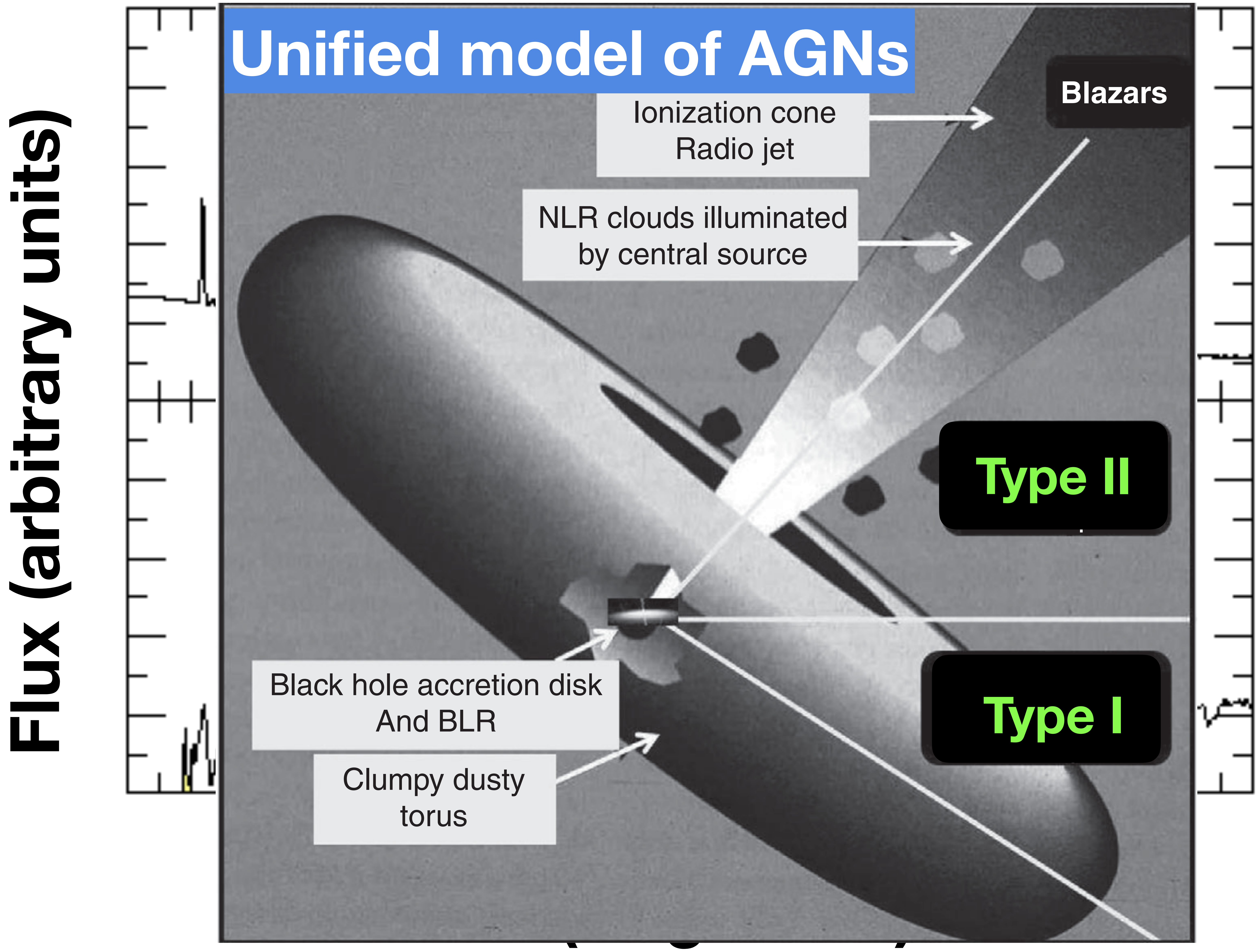
Phenomenology of active galactic nuclei



Broad / Narrow lines

based on Tadhunter+08

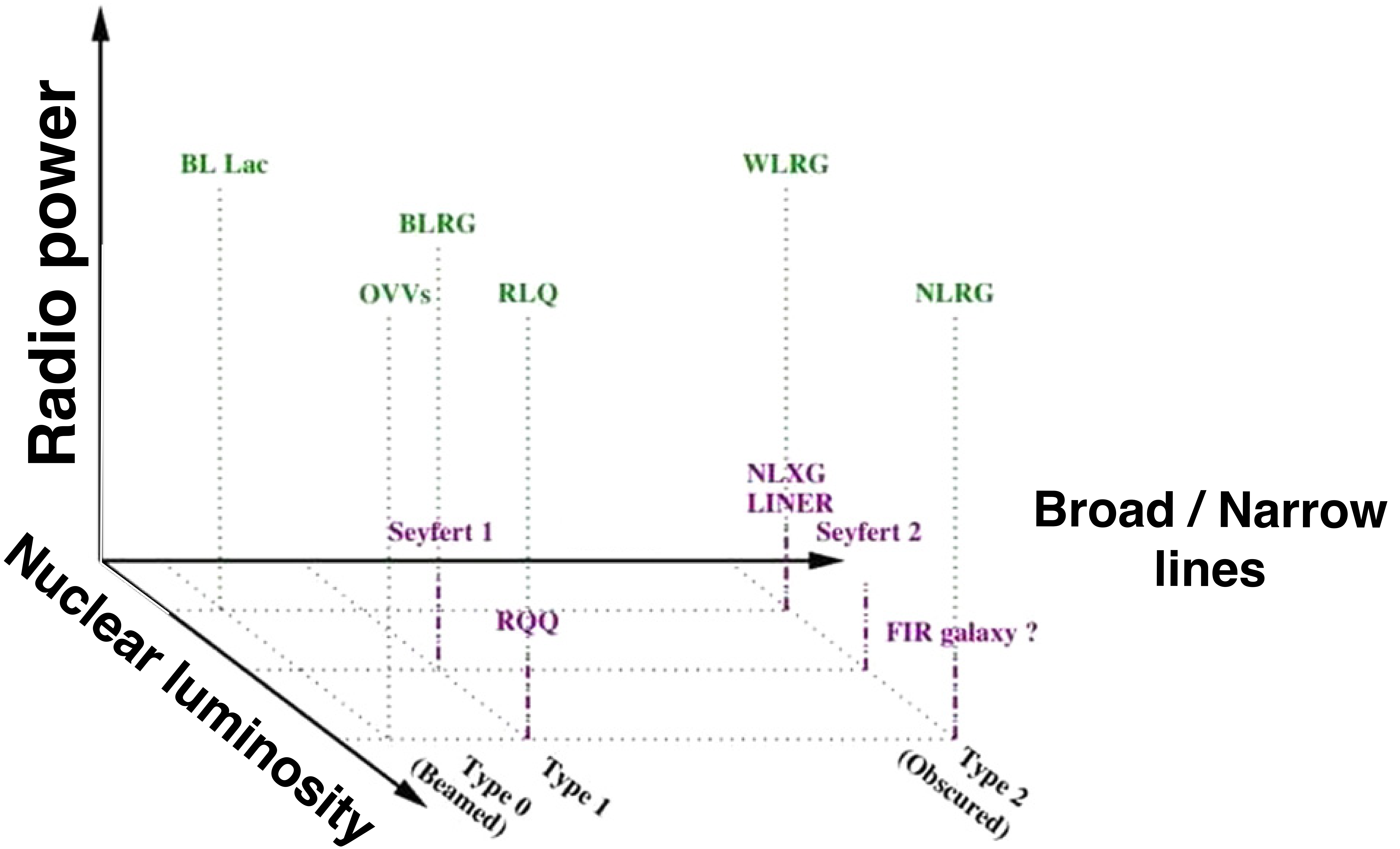
AGNs with and without broad emission lines



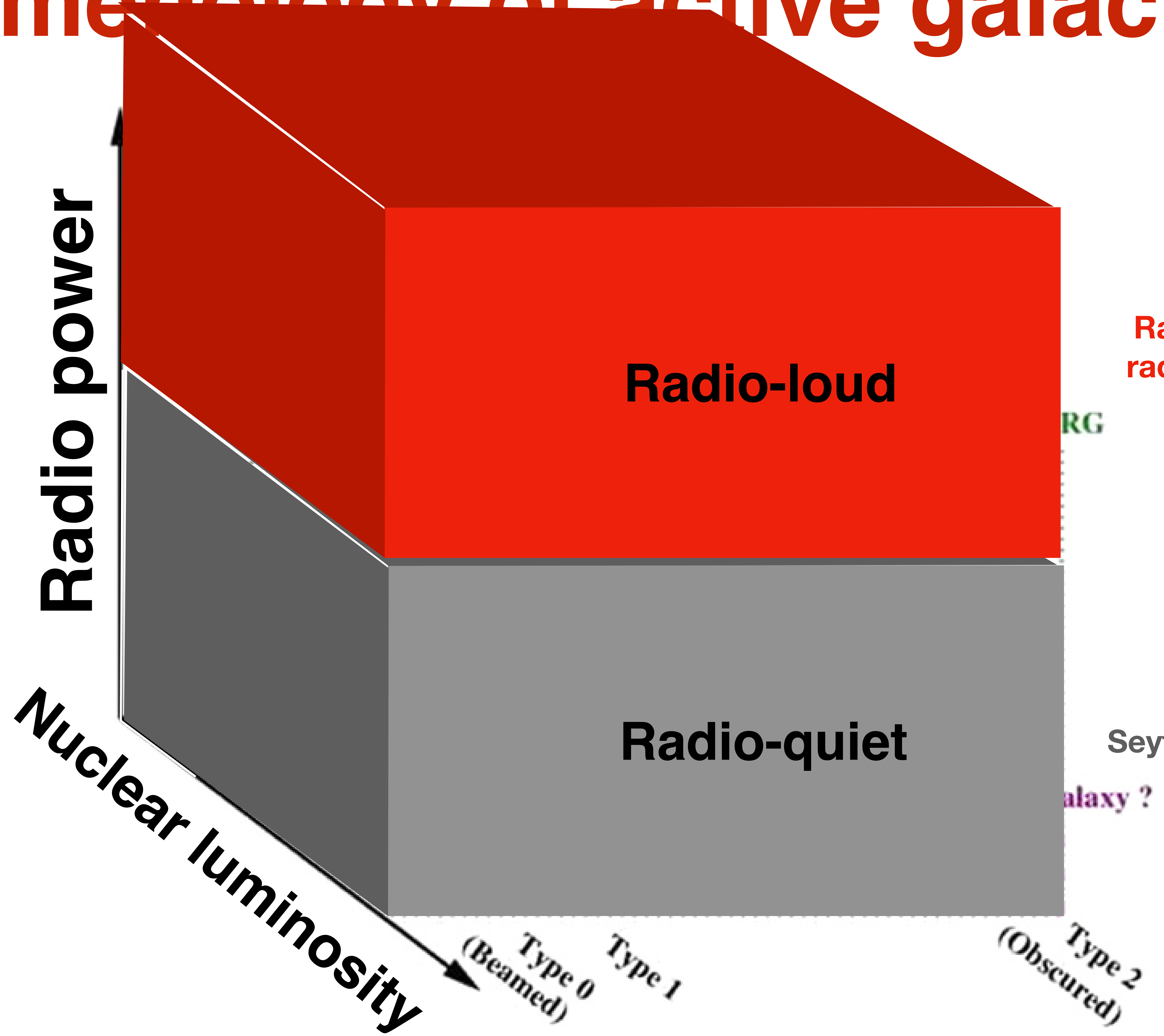
BH's gravity accelerating the gas to *v*>1000 km/s

but half of AGNs show narrower lines

Phenomenology of active galactic nuclei



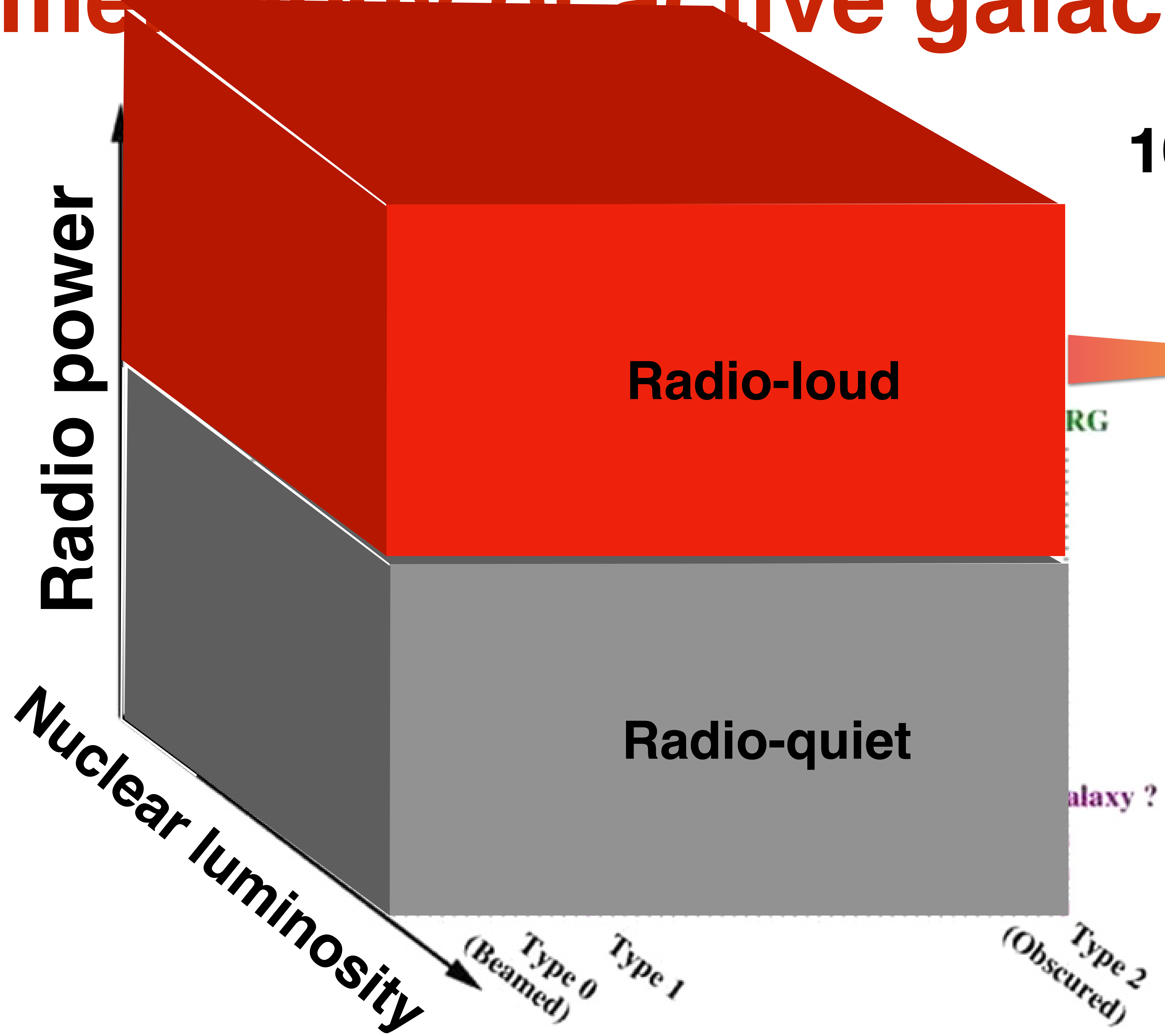
Phenomenology of active galactic nuclei



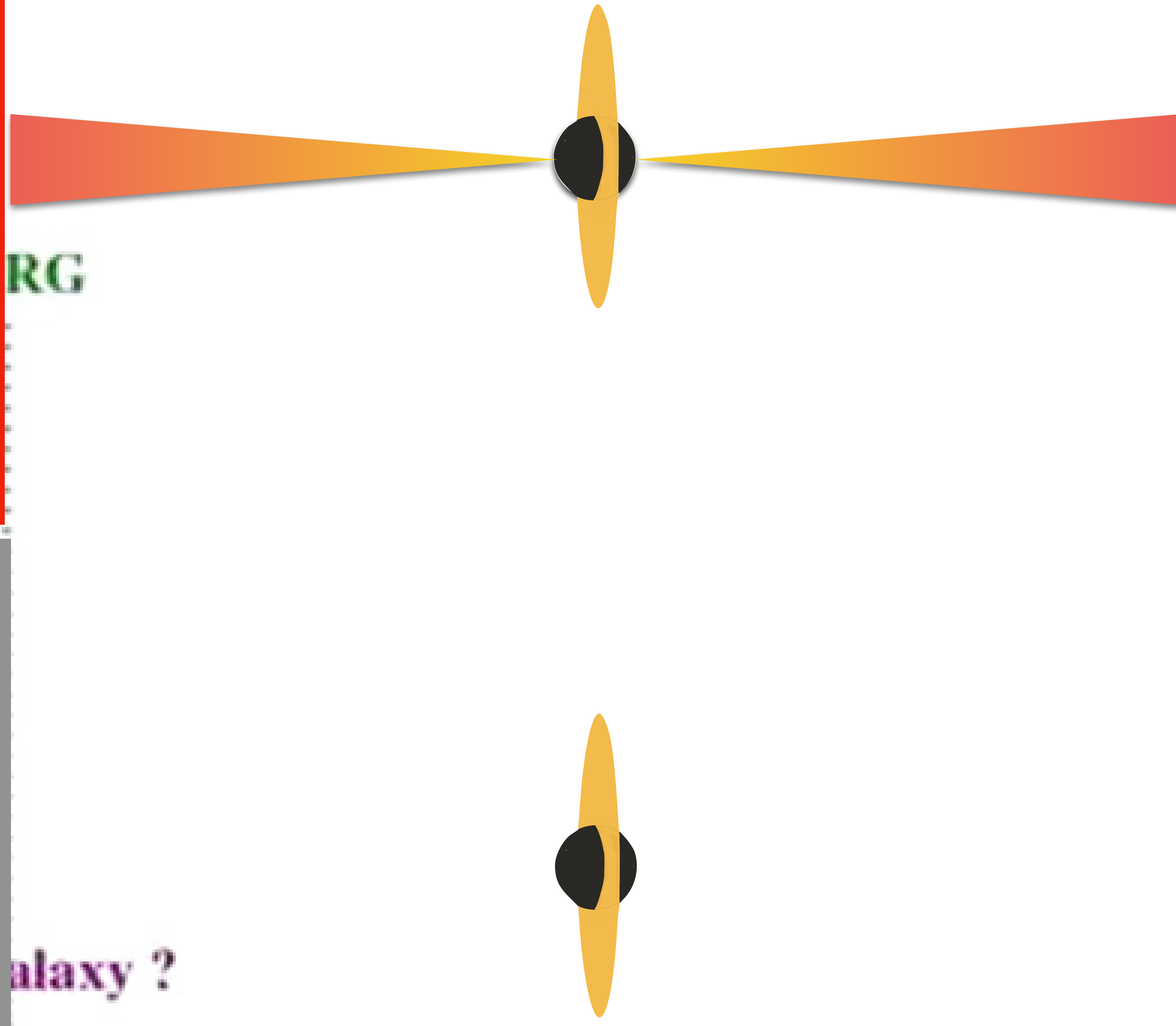
Radiogalaxies (FRI, FRII), radio-loud quasar, blazars (BL Lac, FSRQ)

Seyferts, Radio-quiet quasar

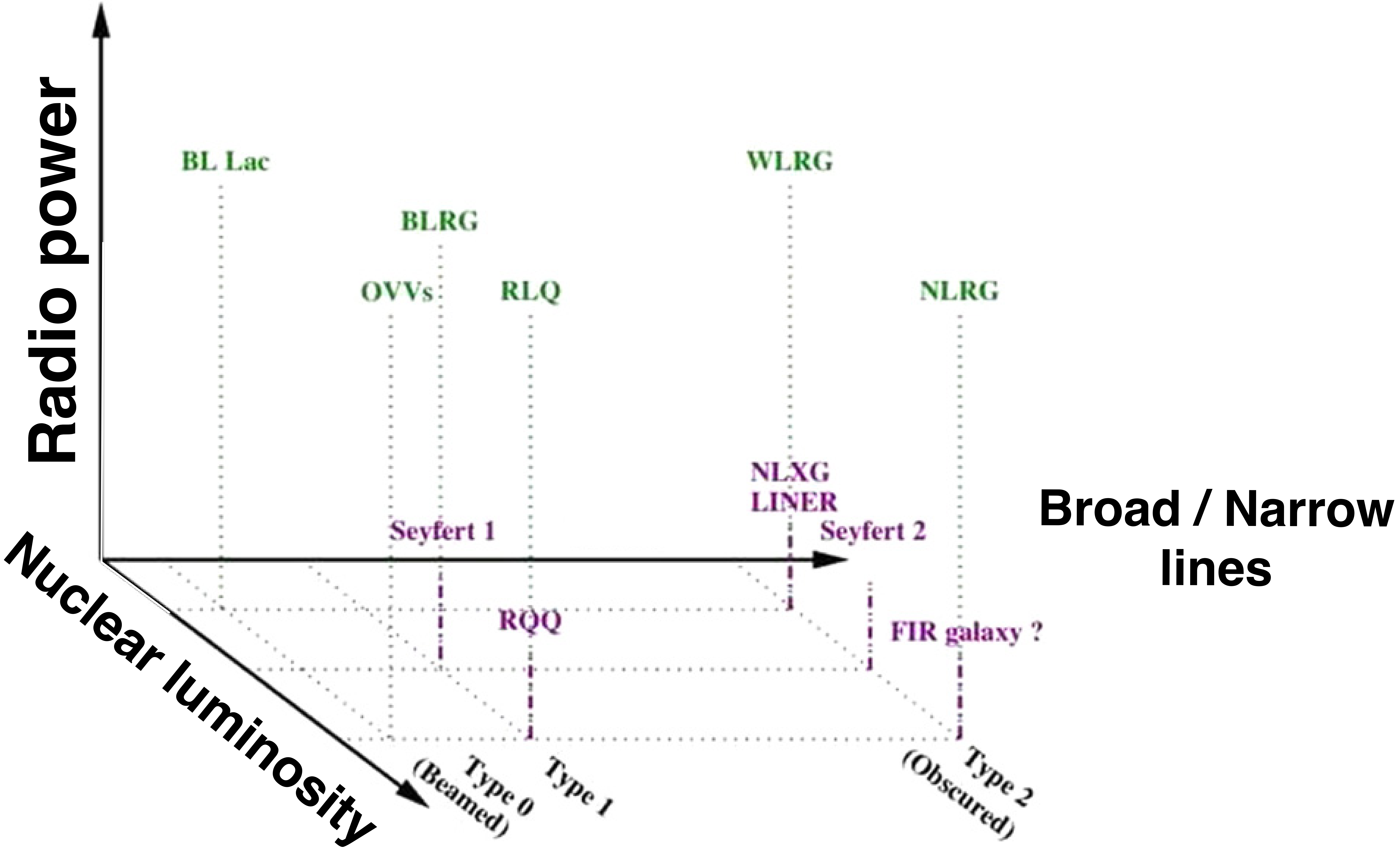
Phenomenology of active galactic nuclei



10% of AGNs are radio-loud

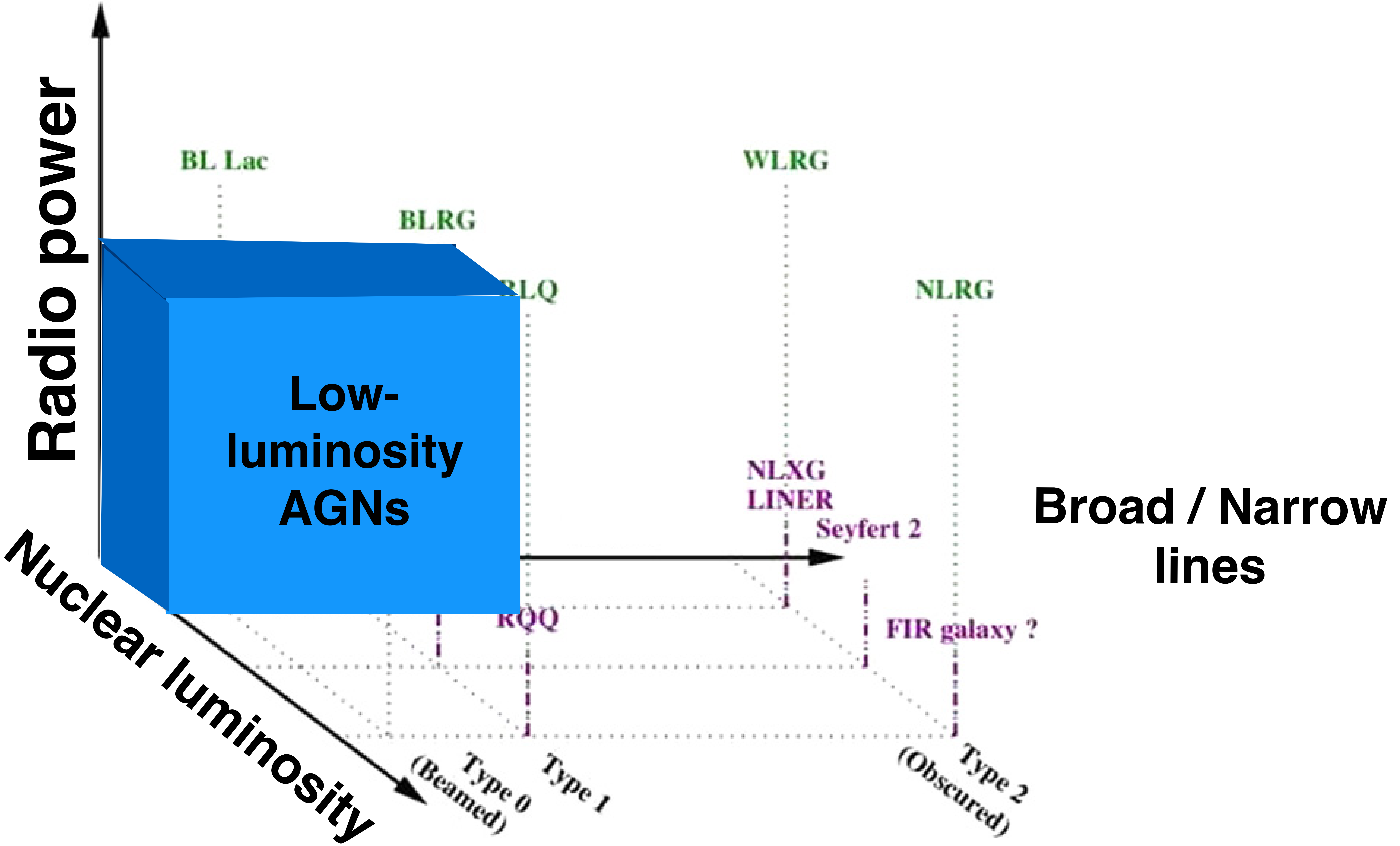


Phenomenology of active galactic nuclei



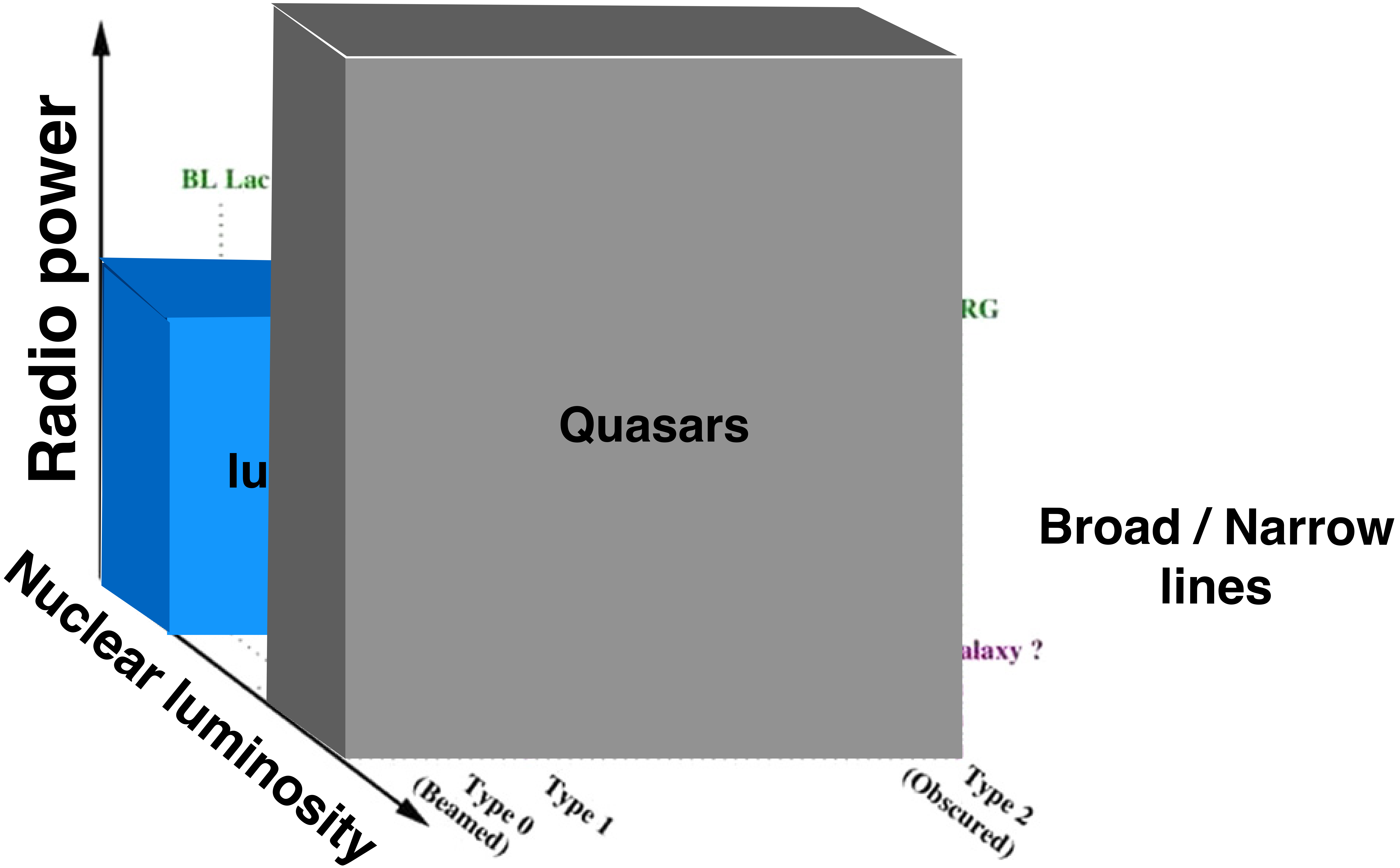
based on Tadhunter+08

Phenomenology of active galactic nuclei



based on Tadhunter+08

Phenomenology of active galactic nuclei



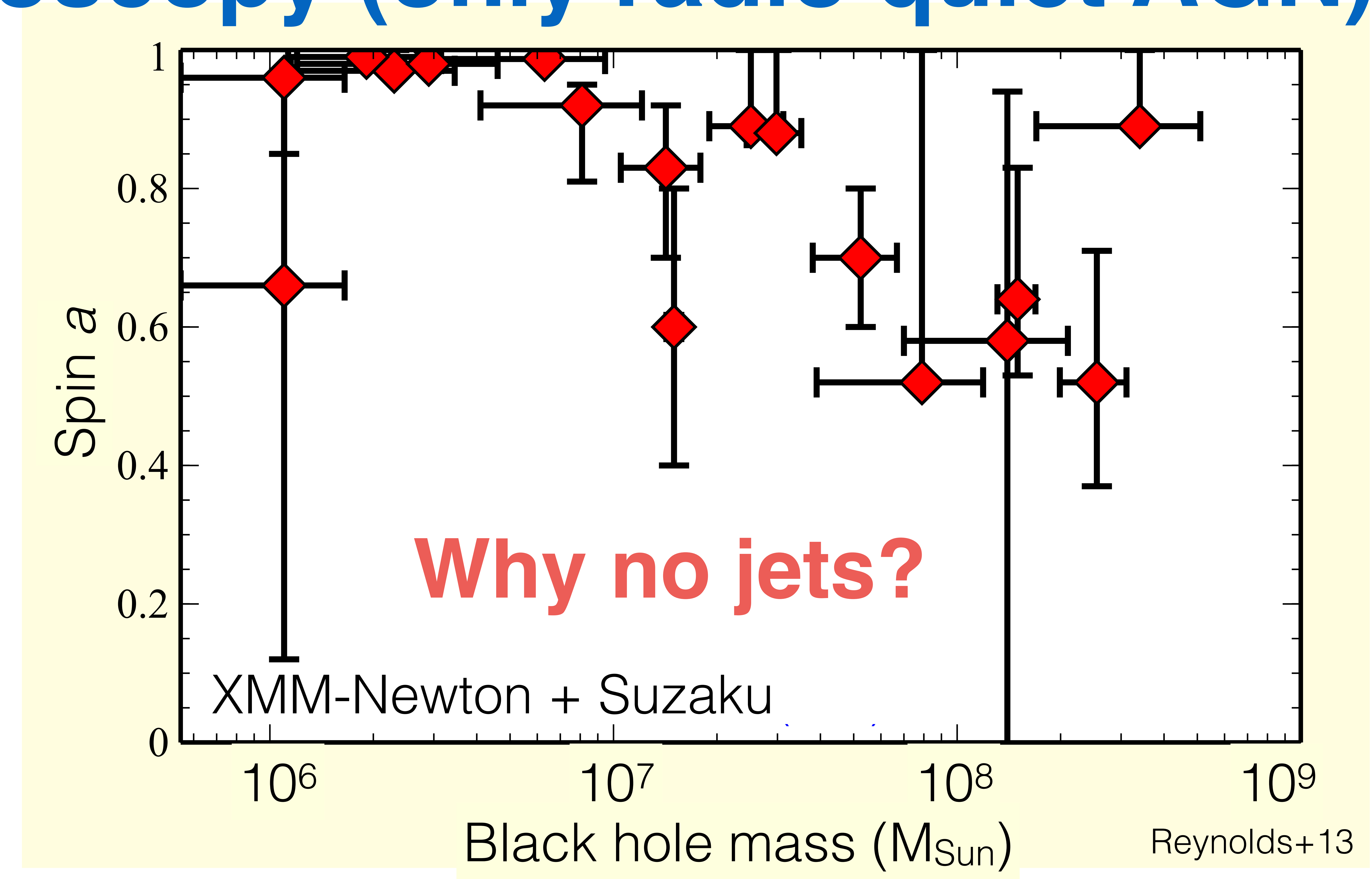
based on Tadhunter+08

Phenomenology of active galactic nuclei

based on Tadhunter+08

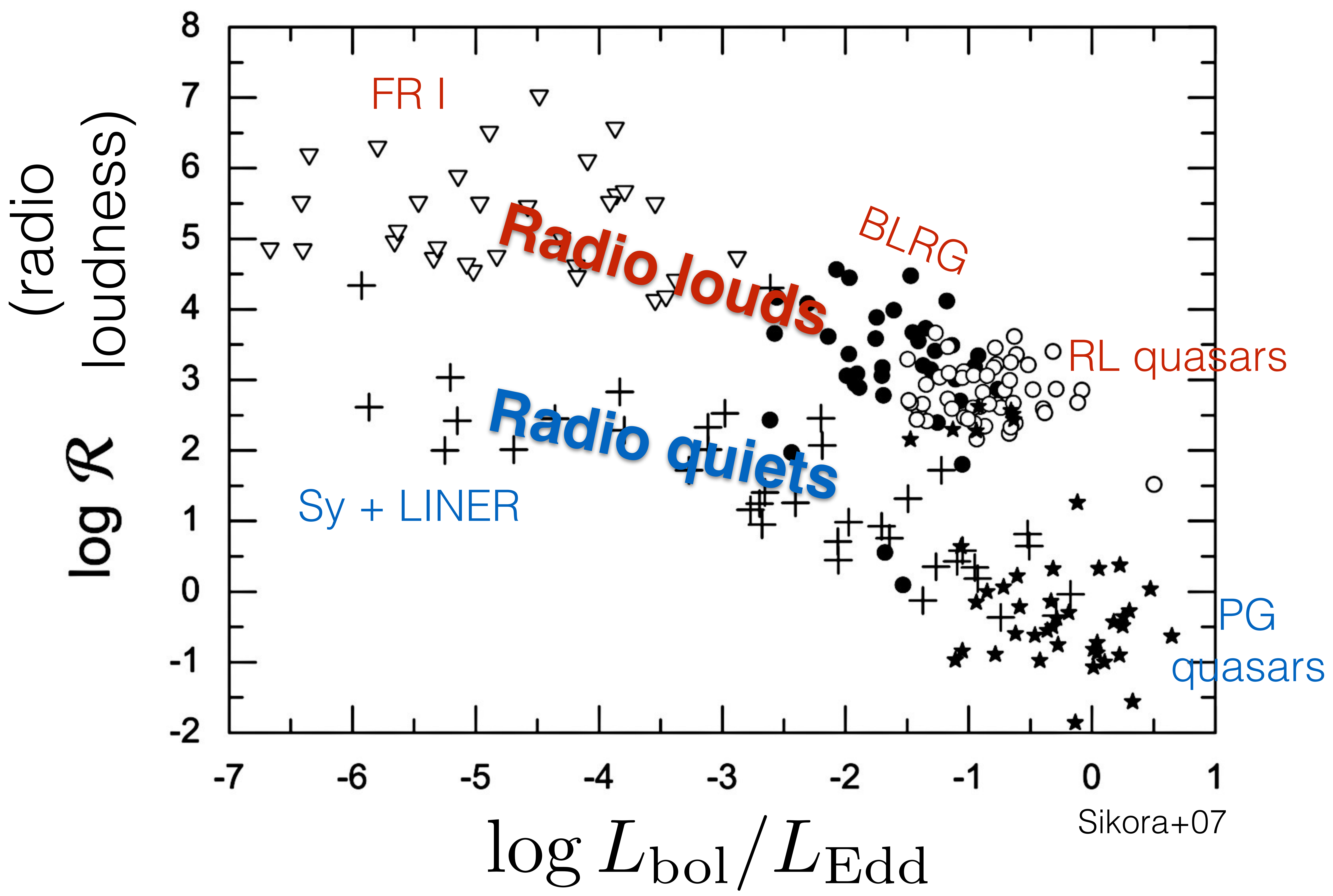
Many issues with the AGN unification proposal

Black hole spin distribution from X-ray spectroscopy (only radio quiet AGN)



cf. also Brenneman+13; King+13

Puzzle: The BH knows about its host galaxy



Sikora+07

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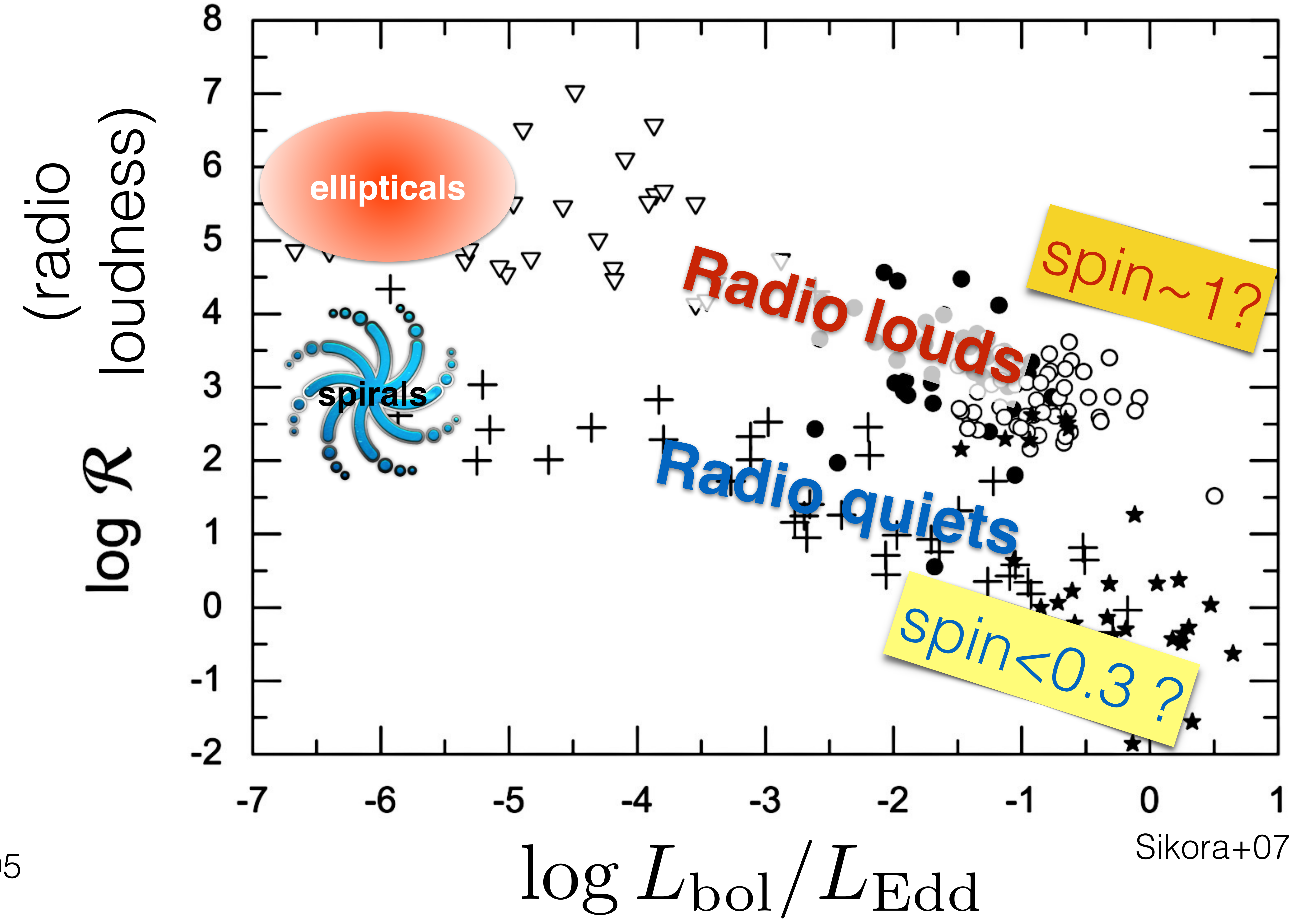
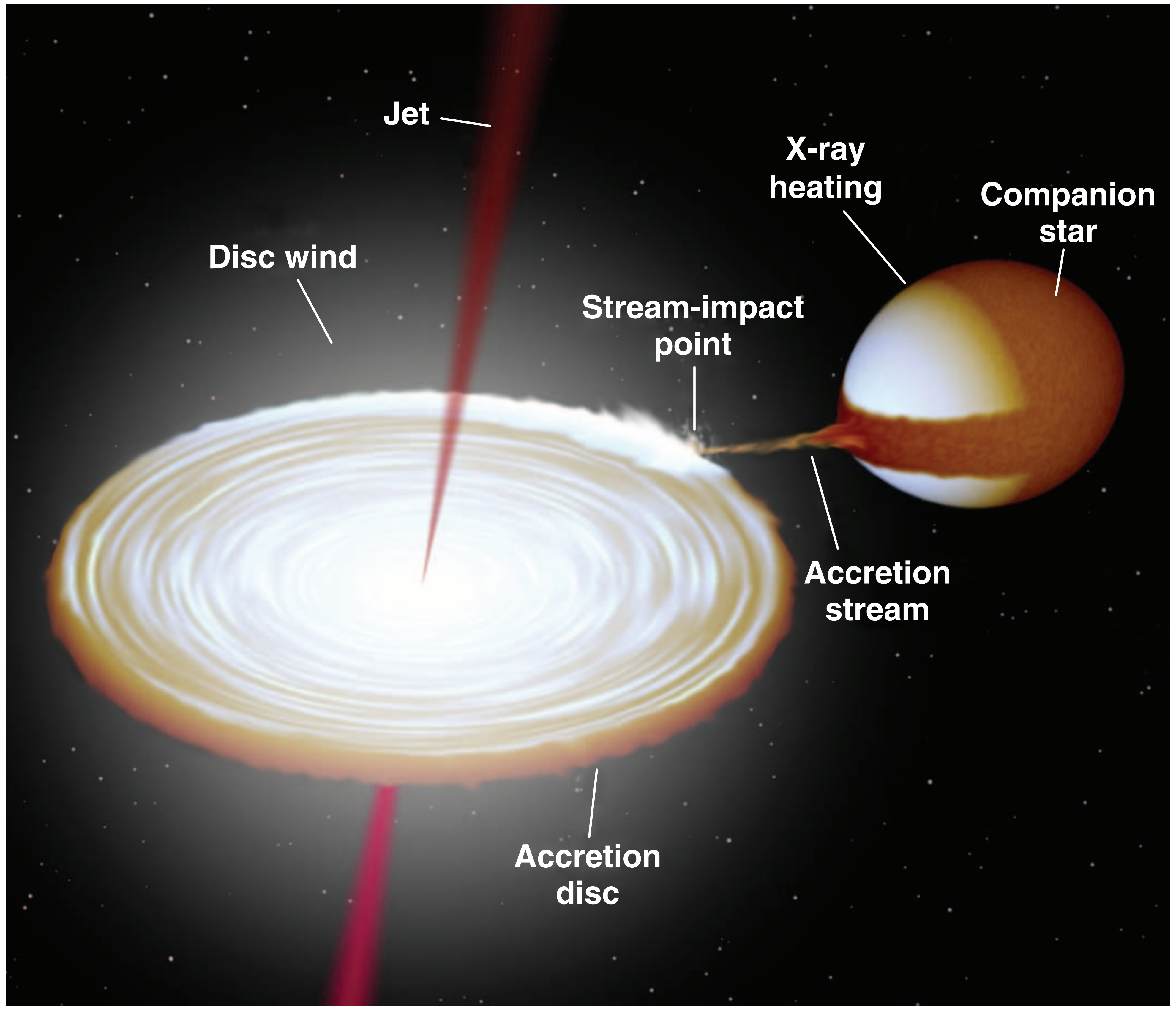


Sikora+07

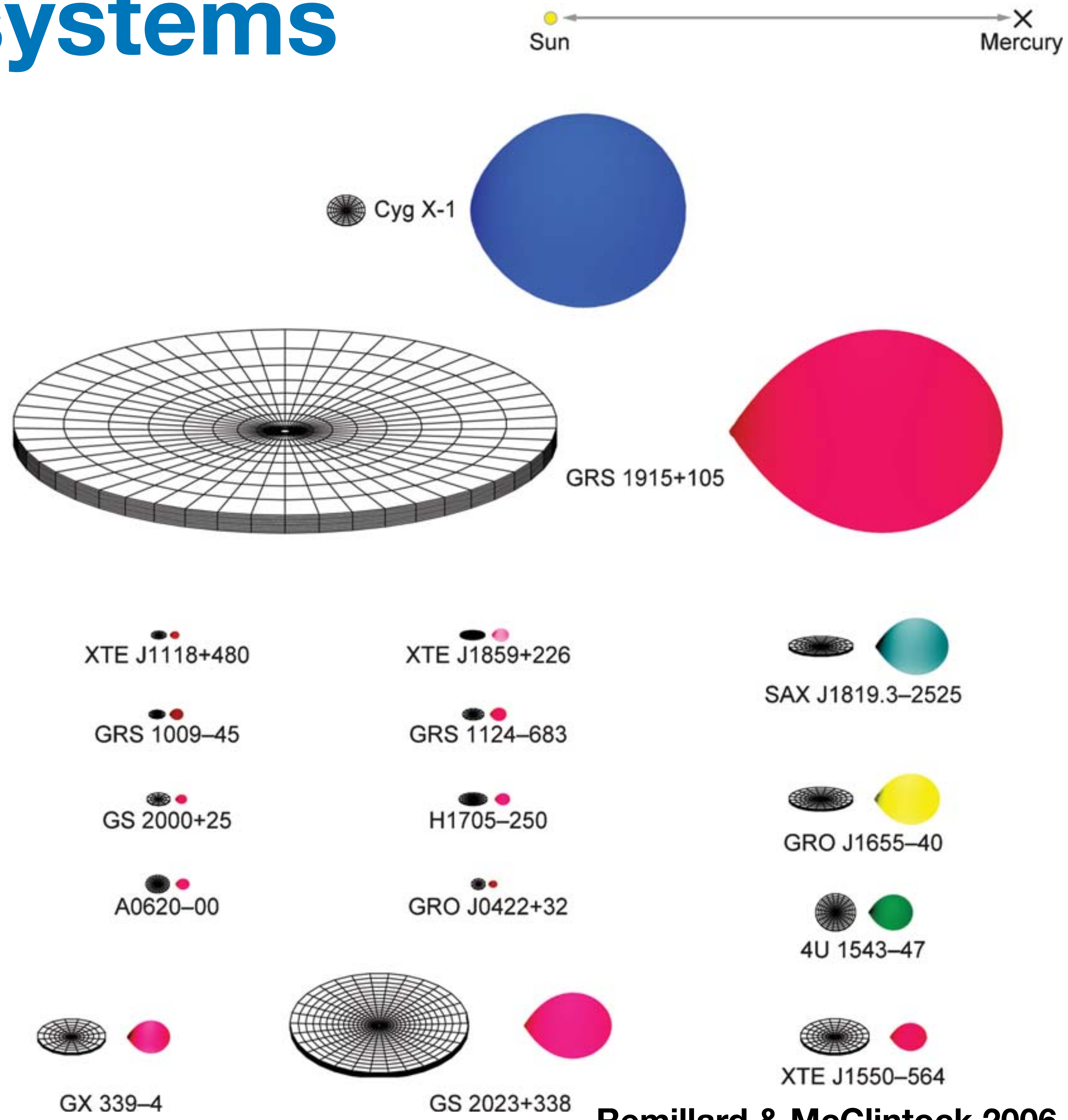
Wilson & Colbert 95
Moderski+96,98
Tchekhovskoy+10

X-ray binaries

Black holes in binary systems

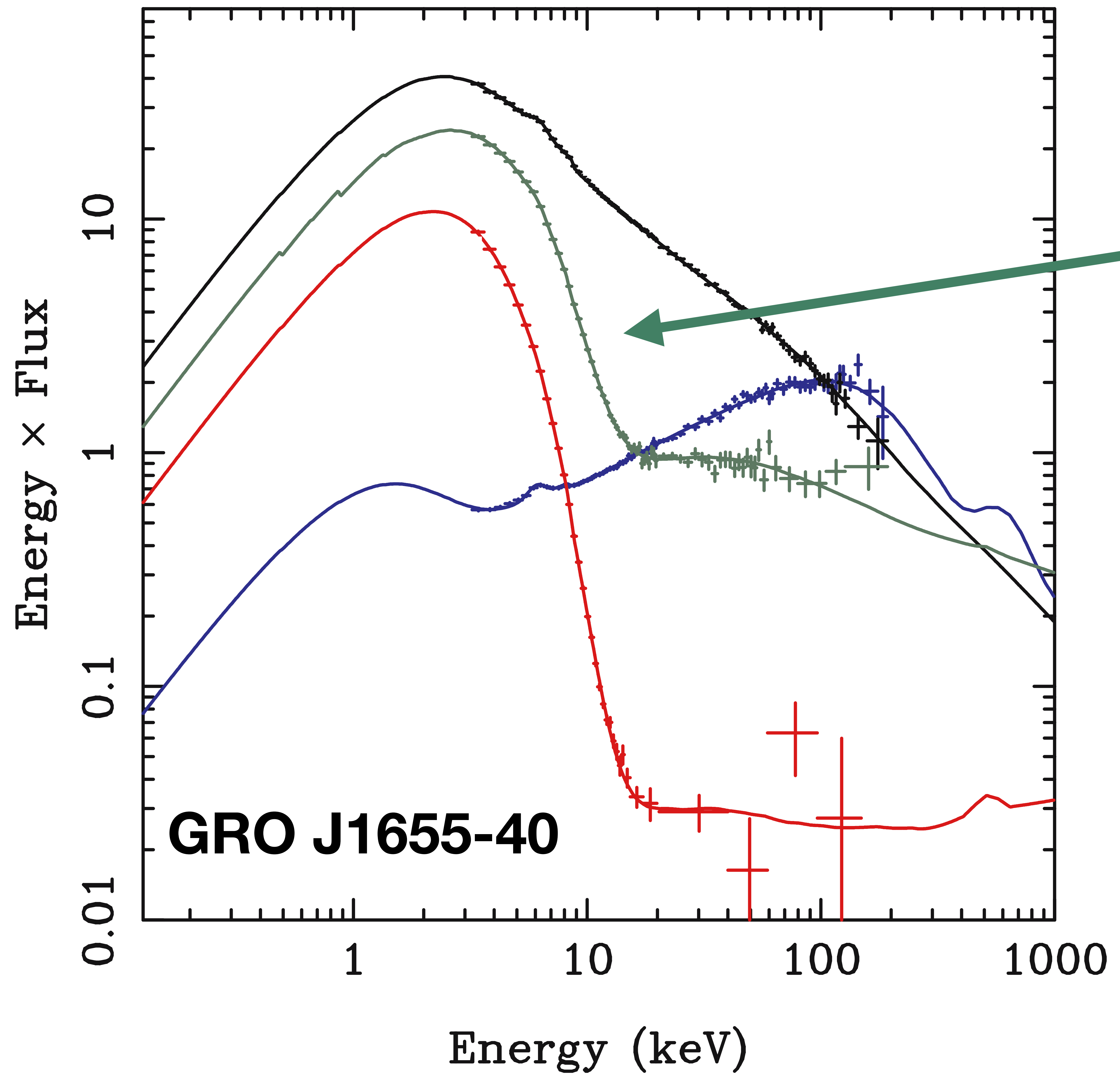


Rob Hynes

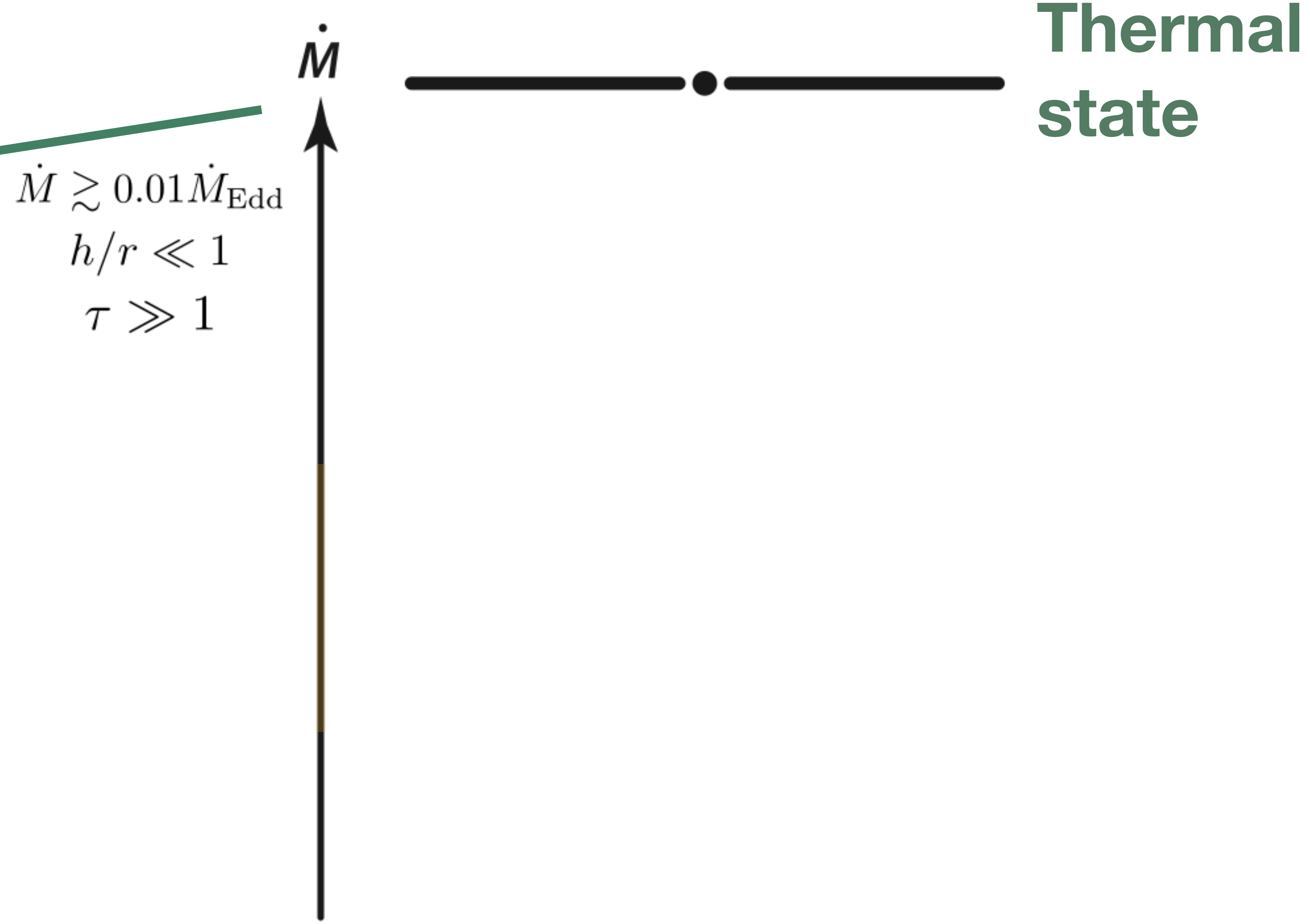


Remillard & McClintock 2006

Black holes binaries show different states

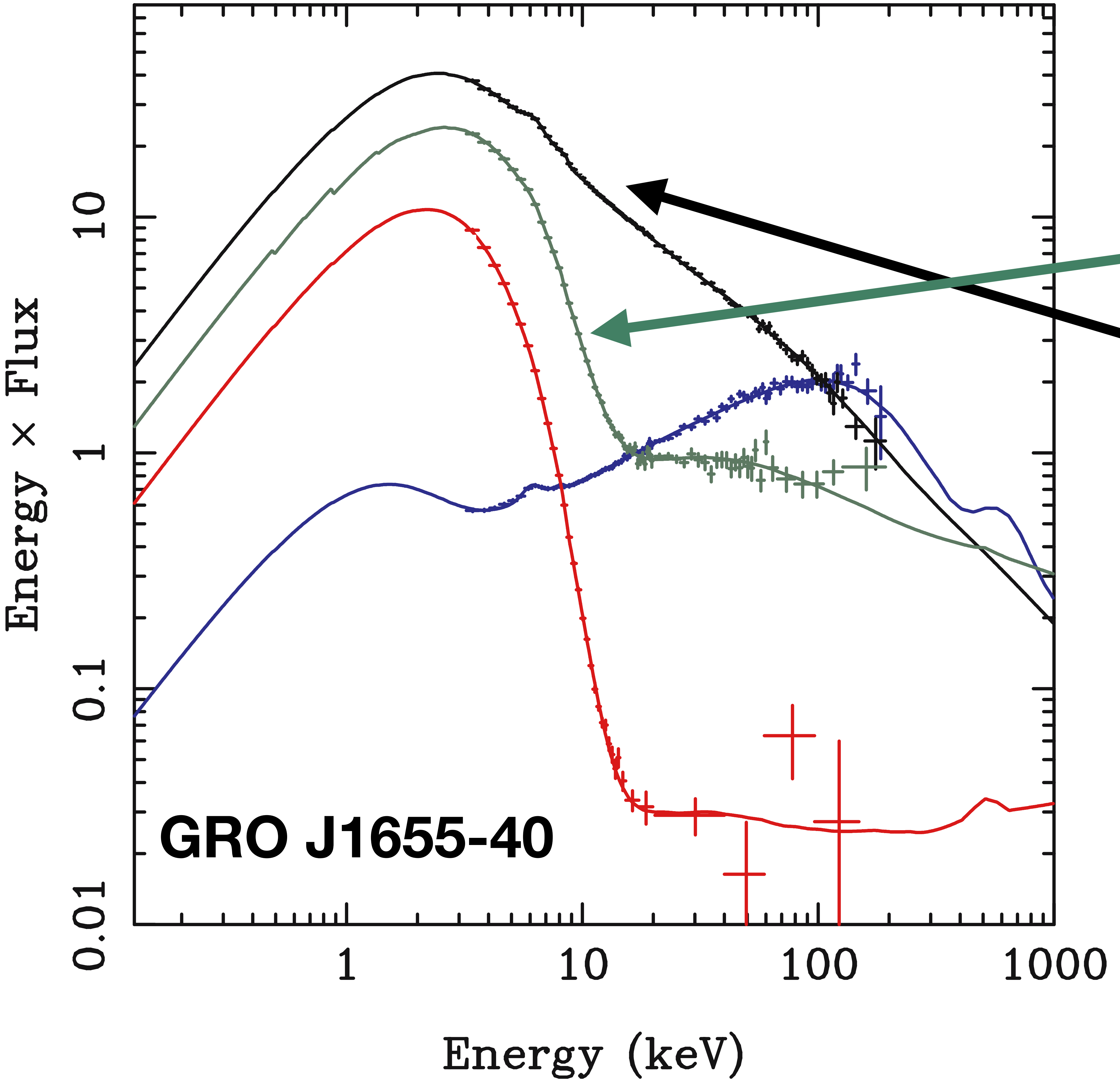


Done+2007

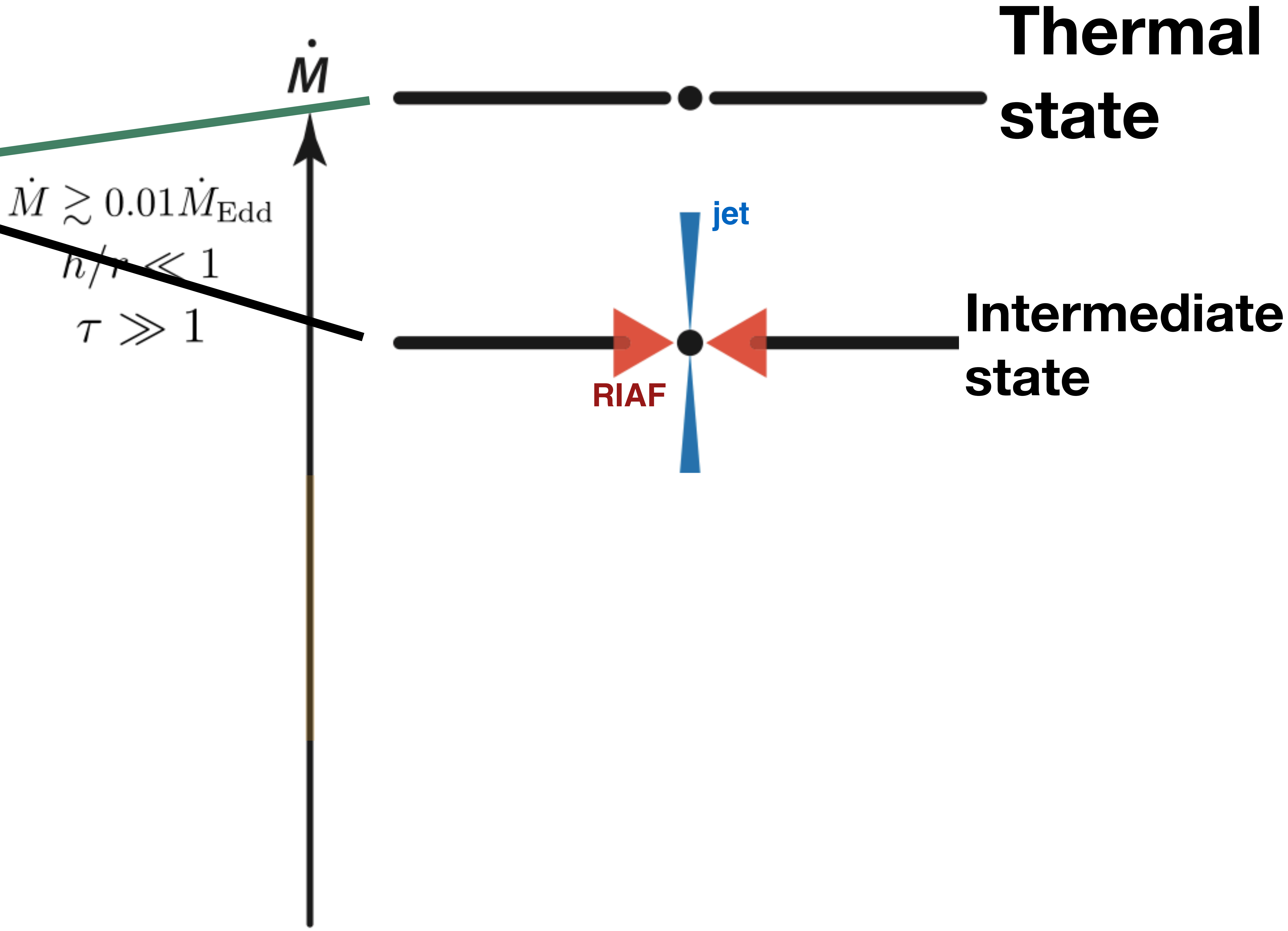


Adapted from Yuan & Narayan 2014, ARA&A

Black holes binaries show different states



Done+2007



Adapted from Yuan & Narayan 2014, ARA&A

Black holes binaries show different states

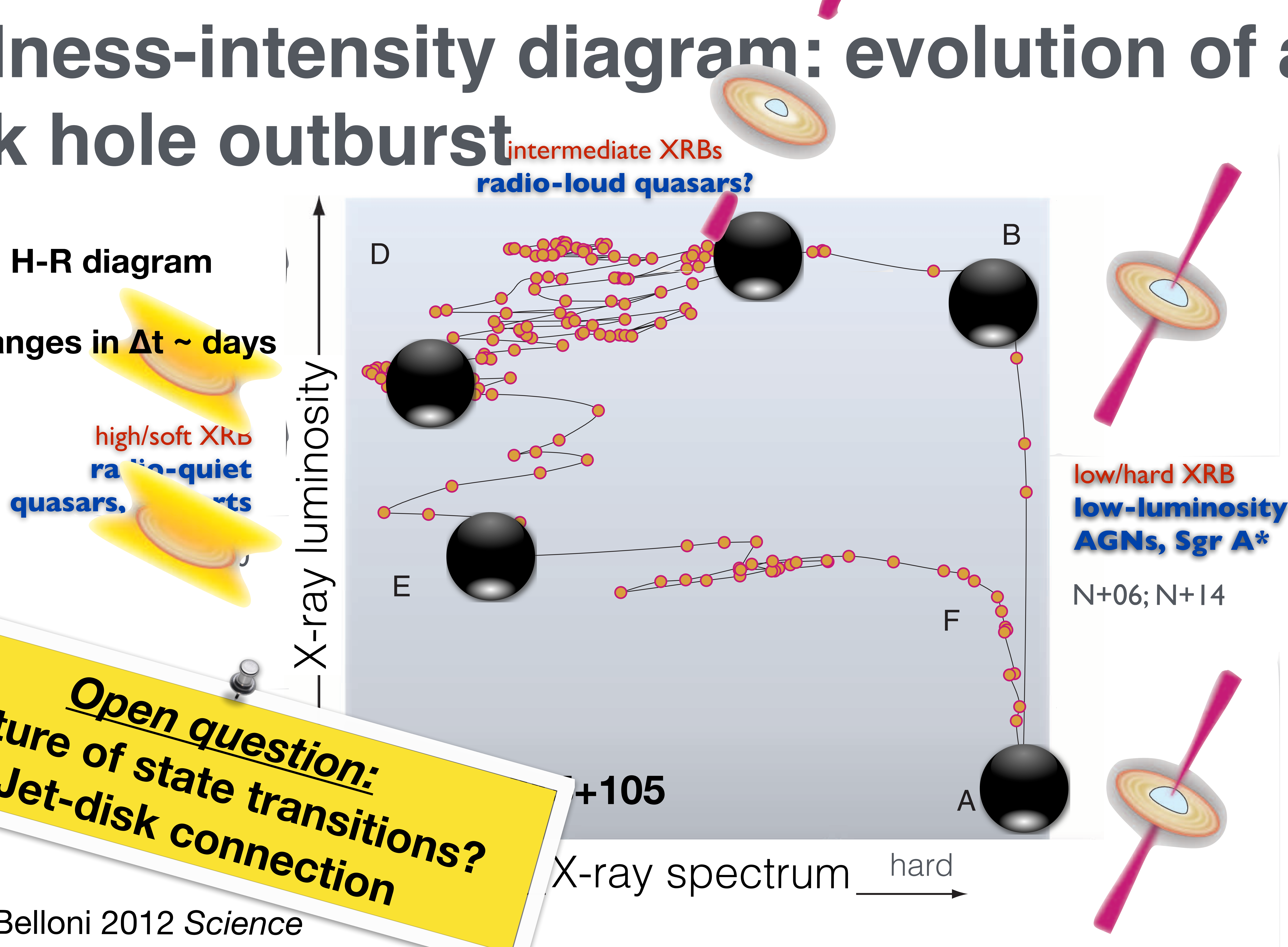
Done+2007

Adapted from Yuan & Narayan 2014, ARA&A

Hardness-intensity diagram: evolution of a black hole outburst

Similar to H-R diagram

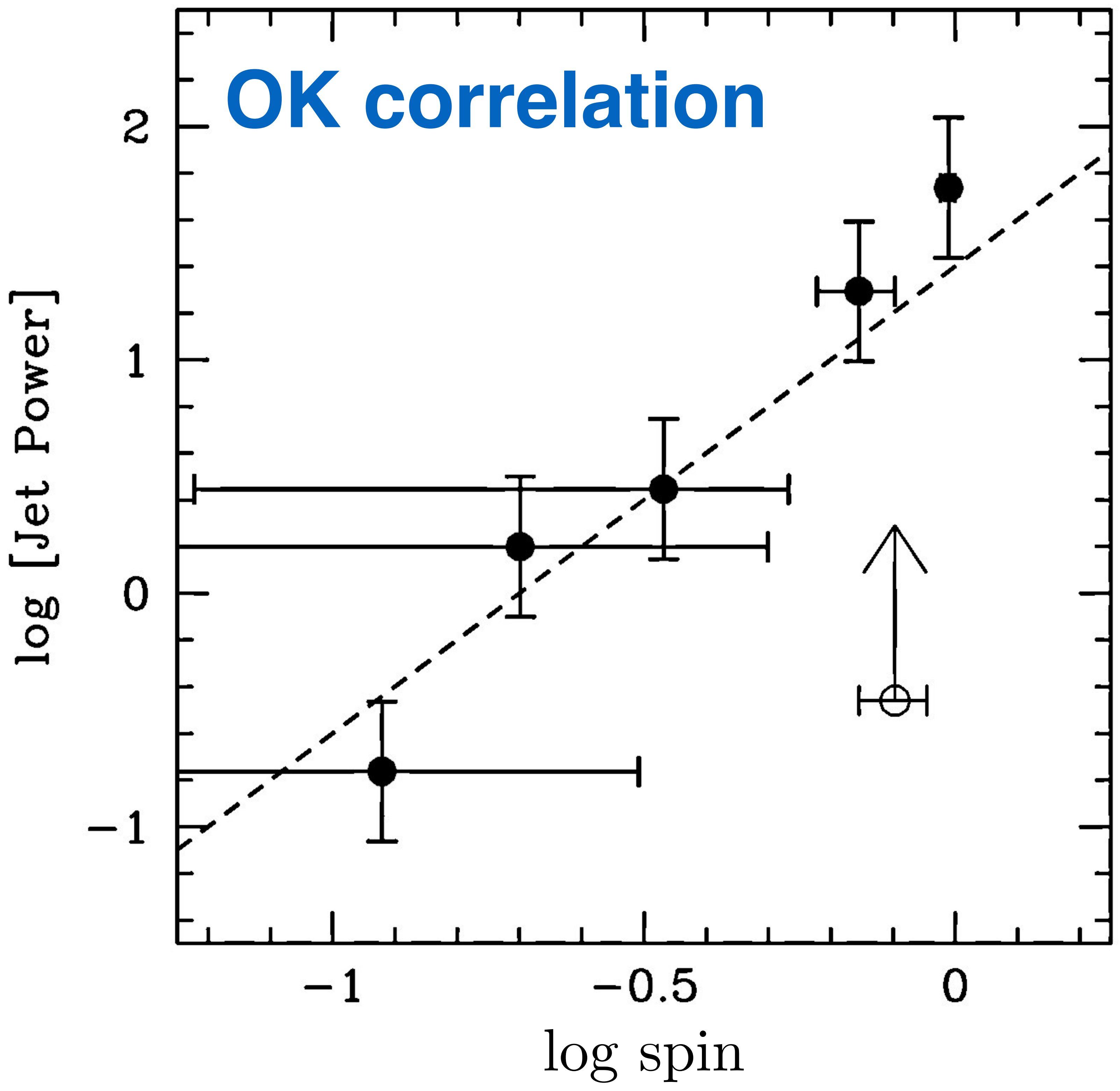
State-changes in Δt ~ days



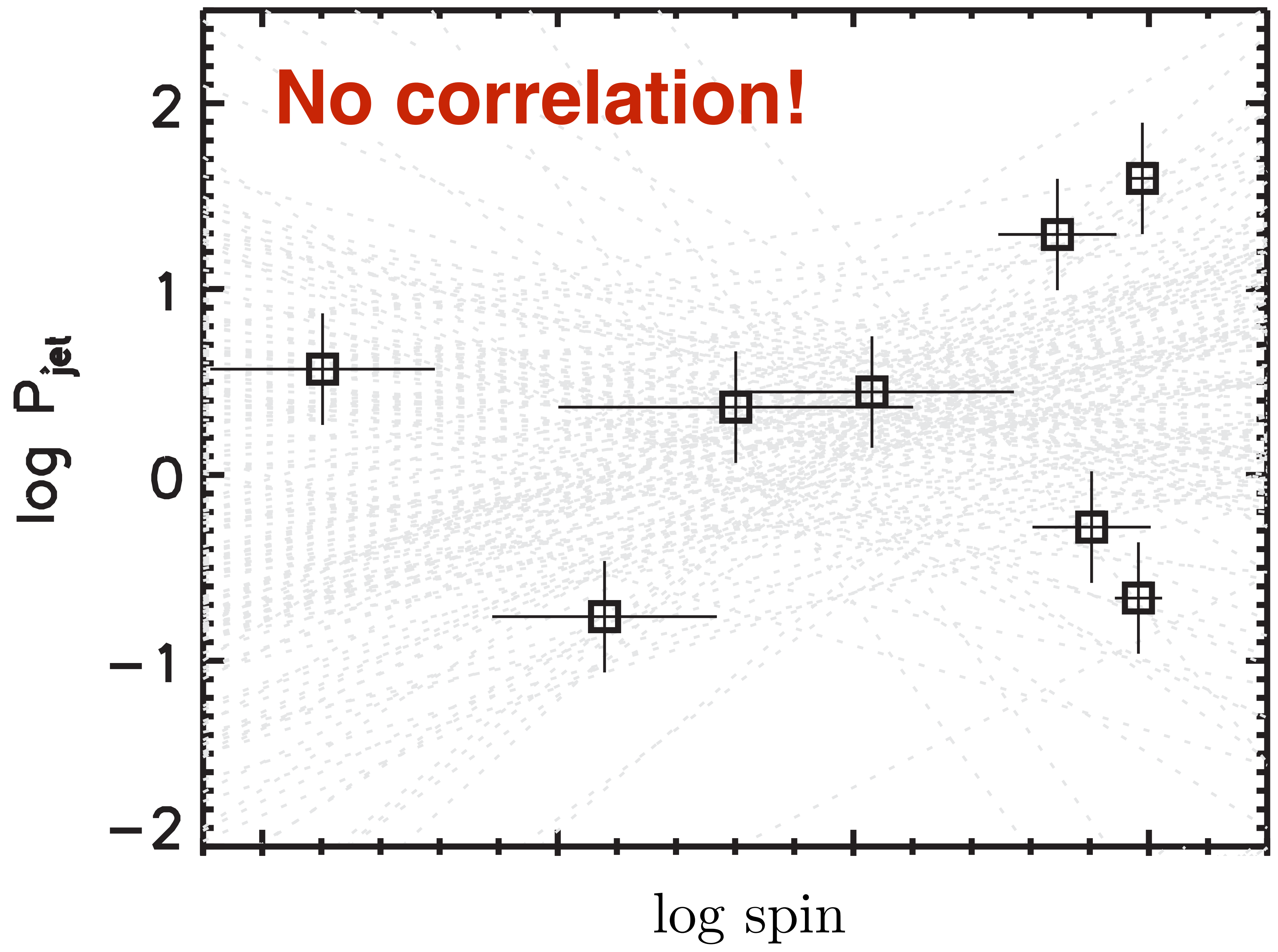
Open question:
Nature of state transitions?
Jet-disk connection

Fender & Belloni 2012 *Science*

Studies of *jet power vs spin* for stellar-mass black holes have been inconclusive so far



Narayan & McClintock 11;
Steiner+13



Russell+13; Fender+10

Spin is a necessary but not sufficient condition for jets?

Gamma-ray bursts

Stay tuned for Sylvia Zhu's lectures next week

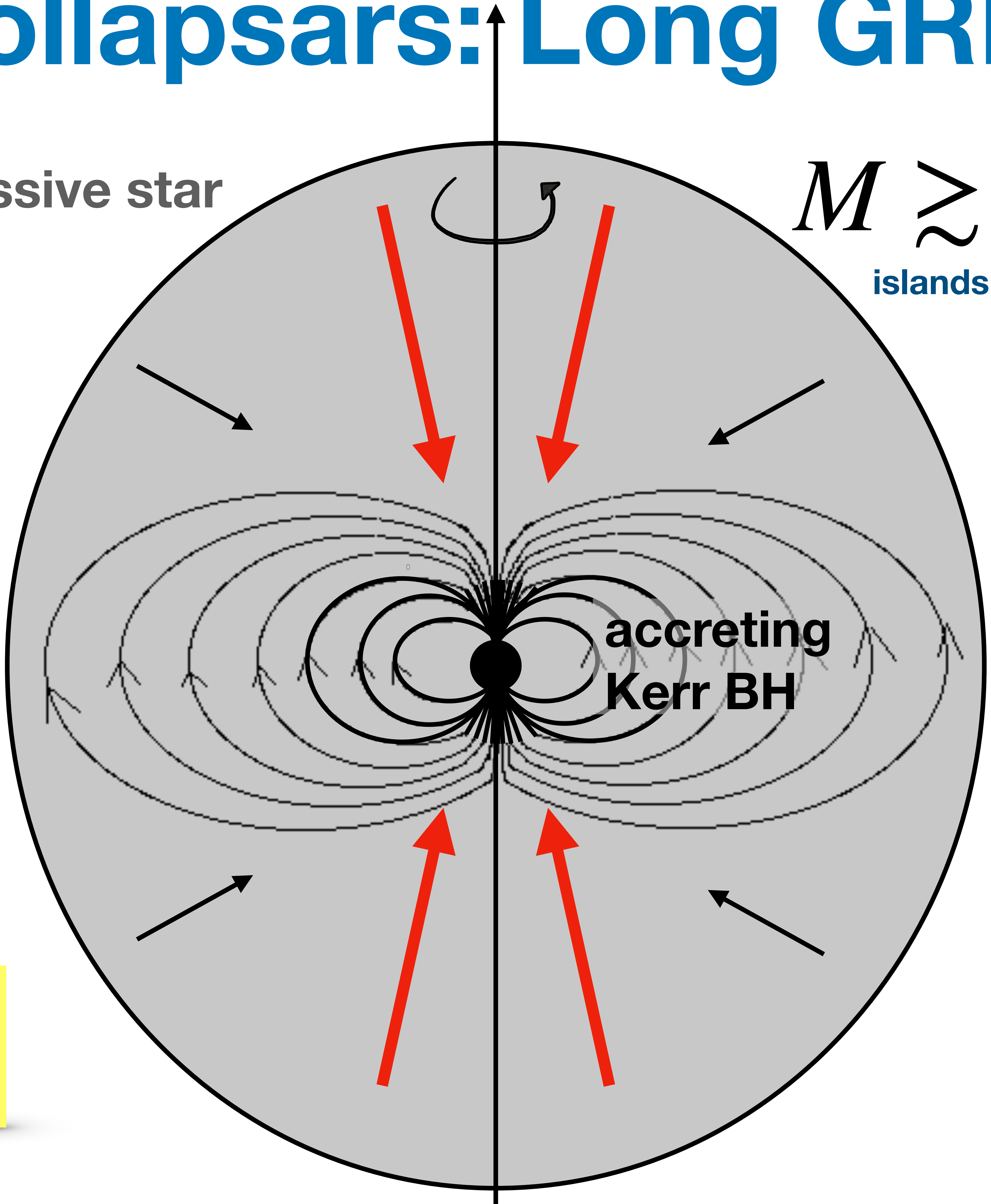
Jets from collapsars: Long GRBs

rotating massive star

$M \gtrsim 30 M_\odot$

islands of explosion? (Sukhbold's talk)

core-collapses



$\dot{M} \gg \dot{M}_{\mathrm{Edd}}$

BH accretion rate

conditions for jet production ✓

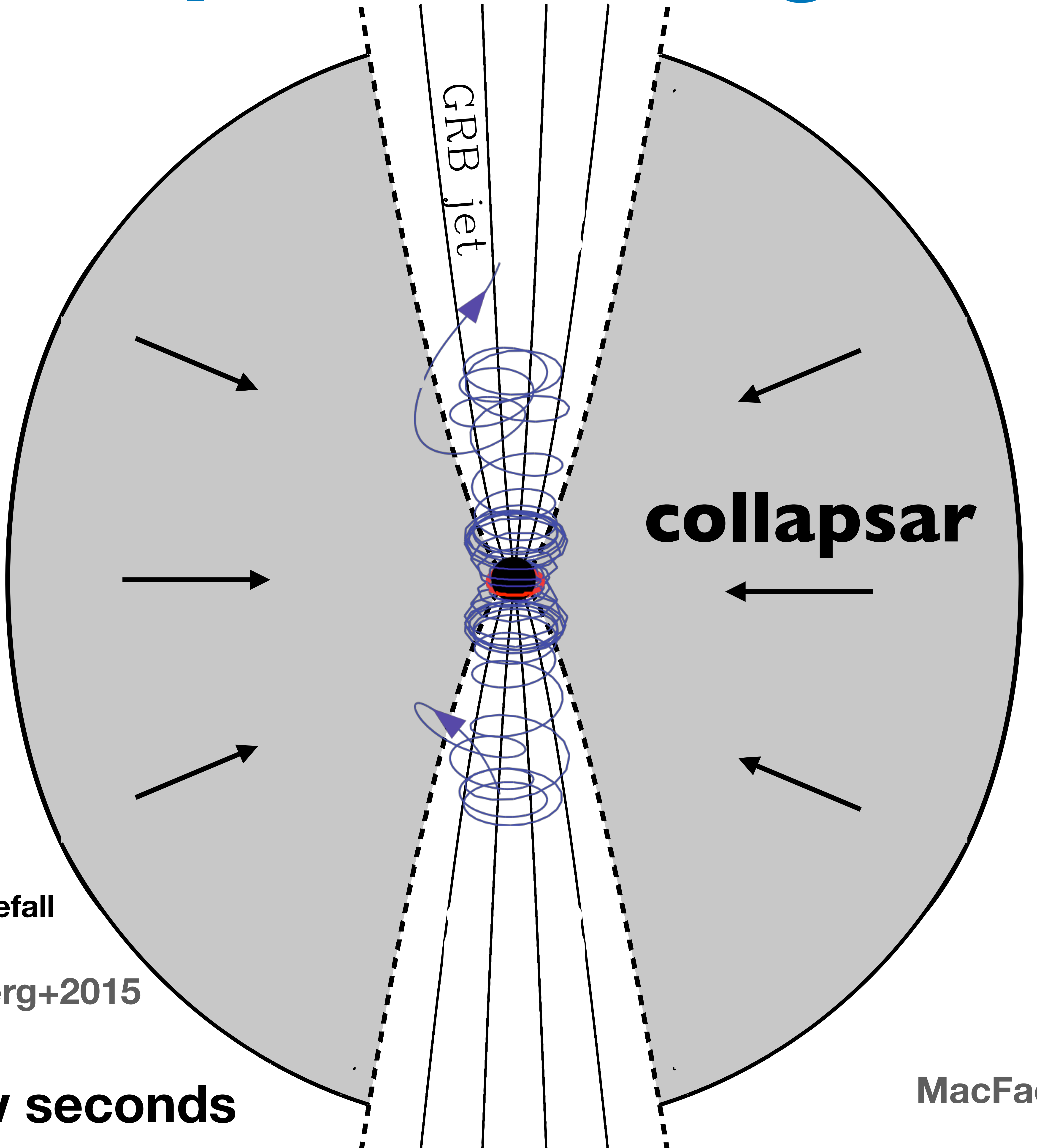
MacFadyen & Woosley 1999;
Woosley & Heger 2006;
Woosley & Bloom 2006

Jets from collapsars: Long GRBs

Relativistic jet w/:

$\gamma \gg 1$ Lorentz factor

$E_{\rm jet}^{\rm iso} \sim 10^{50} - 10^{54}$ erg



jet punctures stellar envelope → GRB along jet axis (beaming)

central engine operation ~ $t_{\rm freefall}$

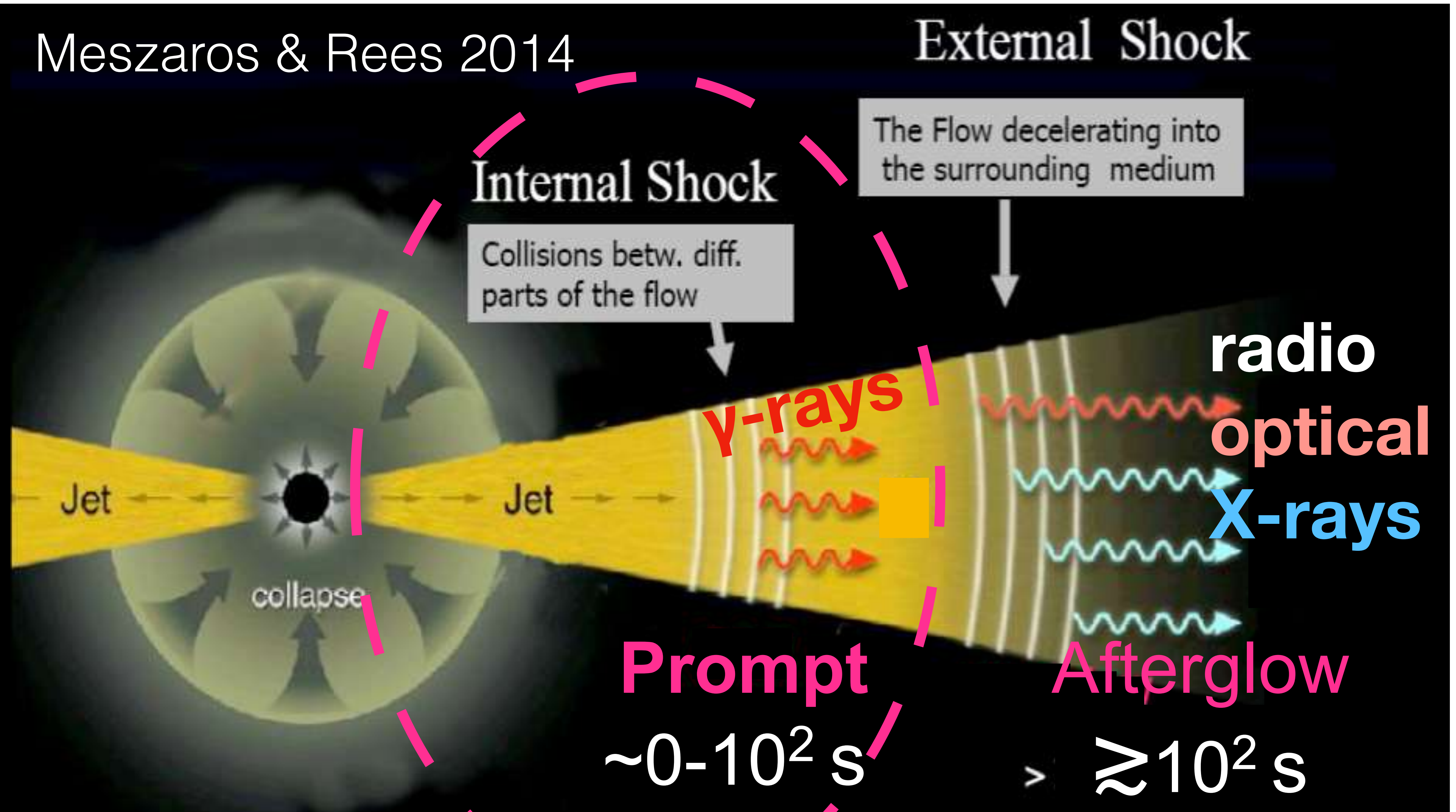
jet breakout ~ seconds Bromberg+2015

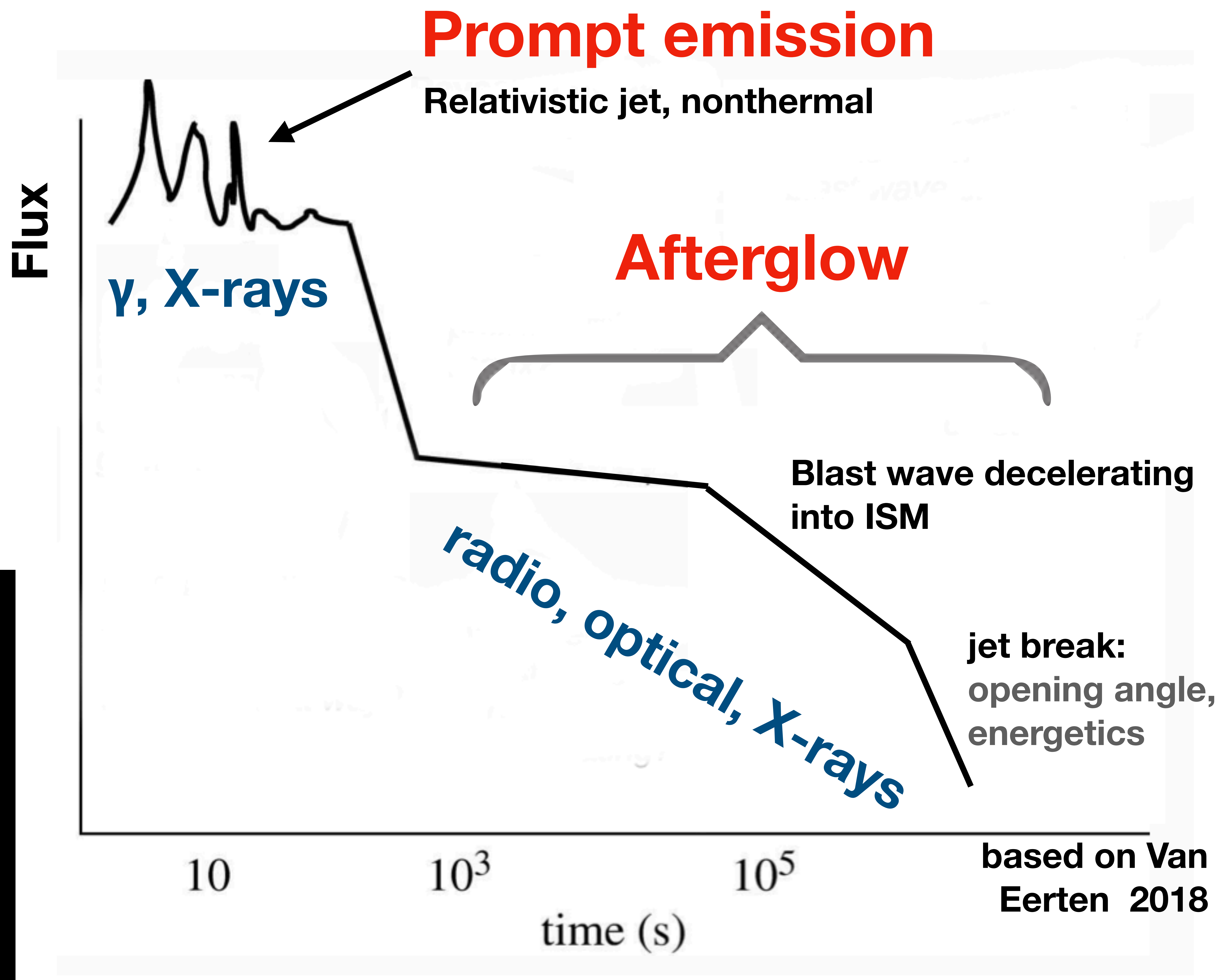
∴ duration > few seconds

GRB followed by isotropic explosion: *superluminous supernovae (type Ic SNe)*

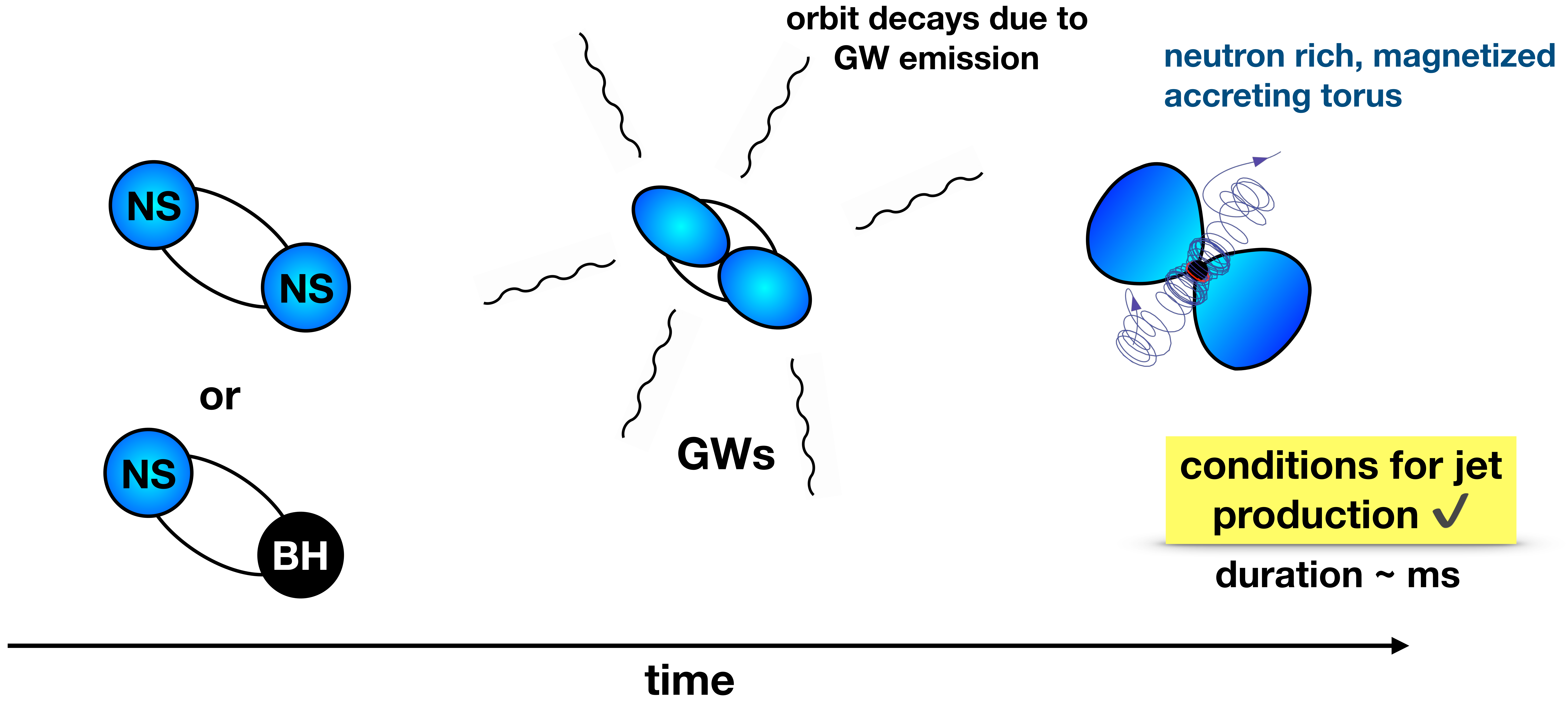
MacFadyen 2001; Woosley & Bloom 2006

Long GRBs light curve





Mergers of binary neutron stars: Short GRBs



Paczynski 1986; Eichler et al. 1989; Narayan et al. 1992

Short GRB multimessenger time series: GWs + light

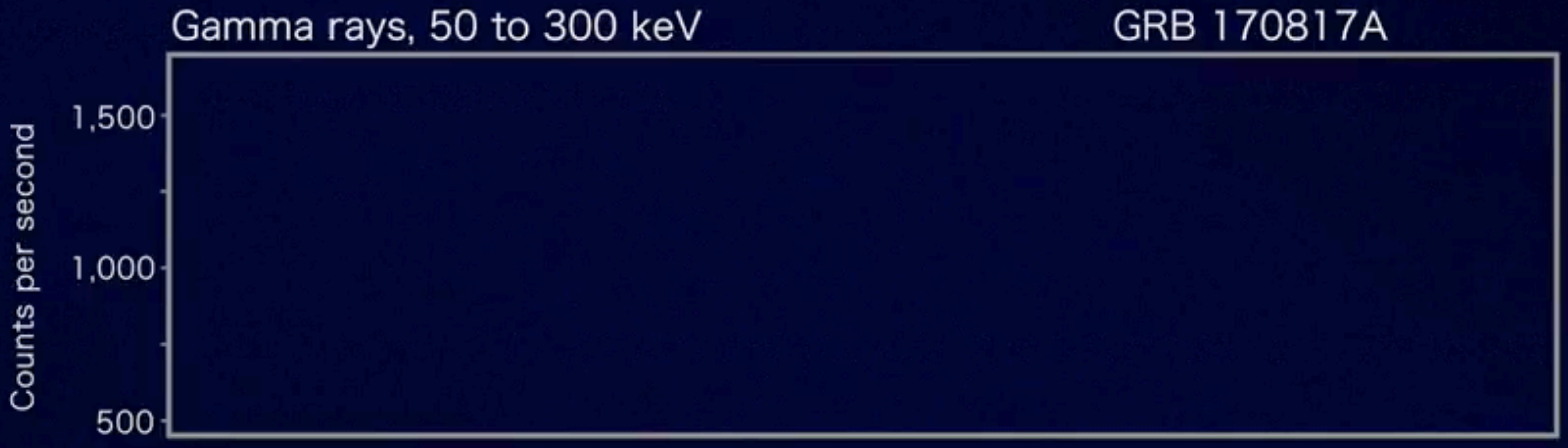
Fernandez & Metzger 2016

produces many Earth-mass amounts of precious metals (r-process, lanthanides)

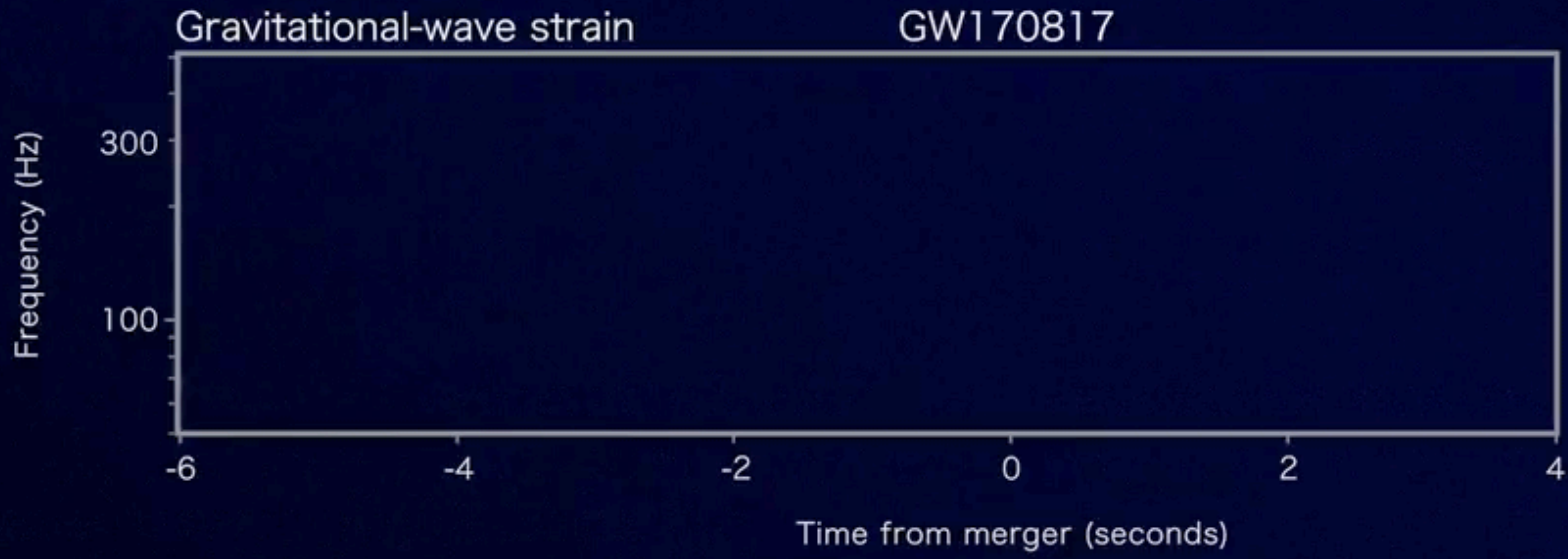
Lattimer & Schramm 1974

Birth of multimessenger astronomy: GWs and EM radiation from GW170817

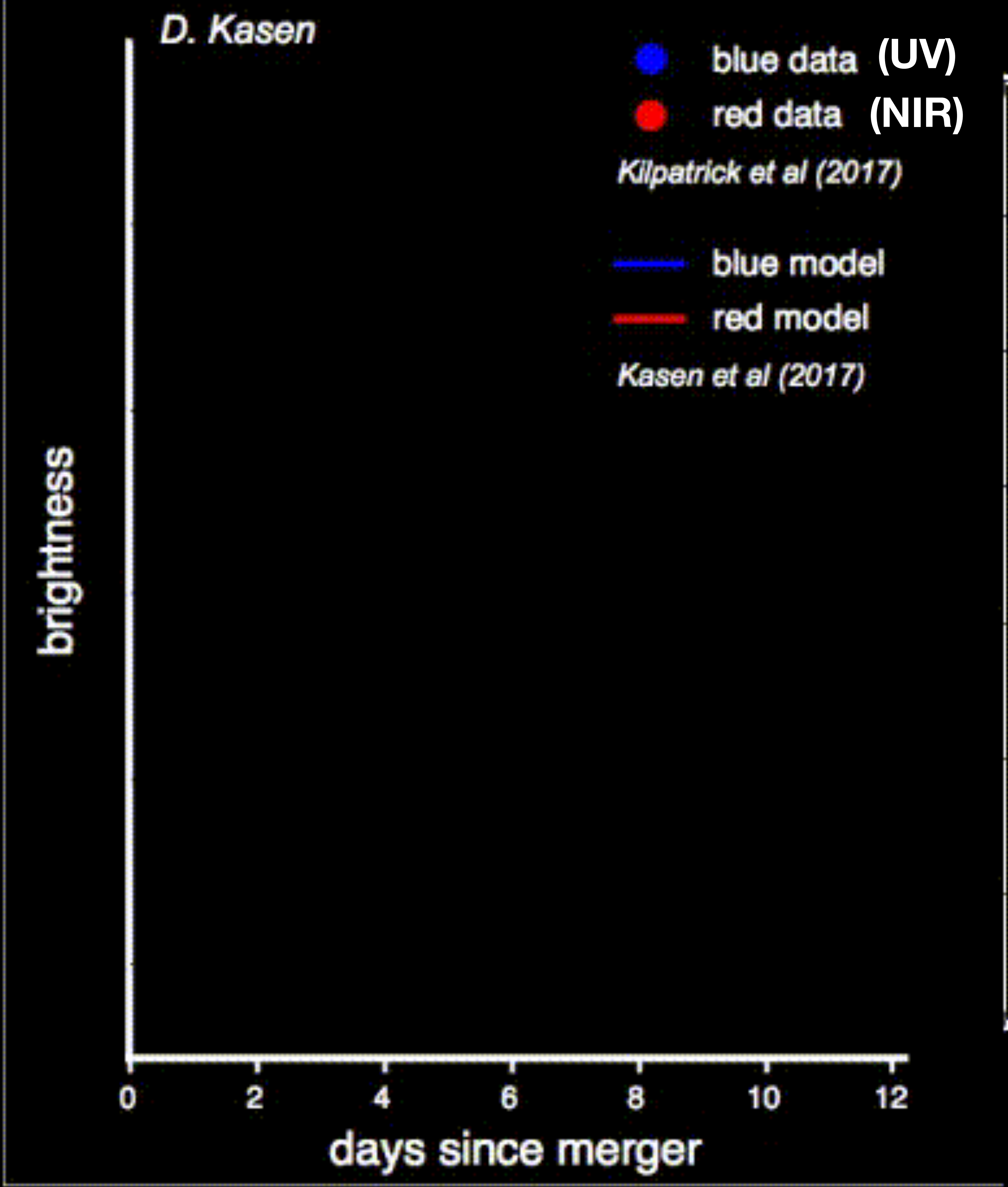
Fermi

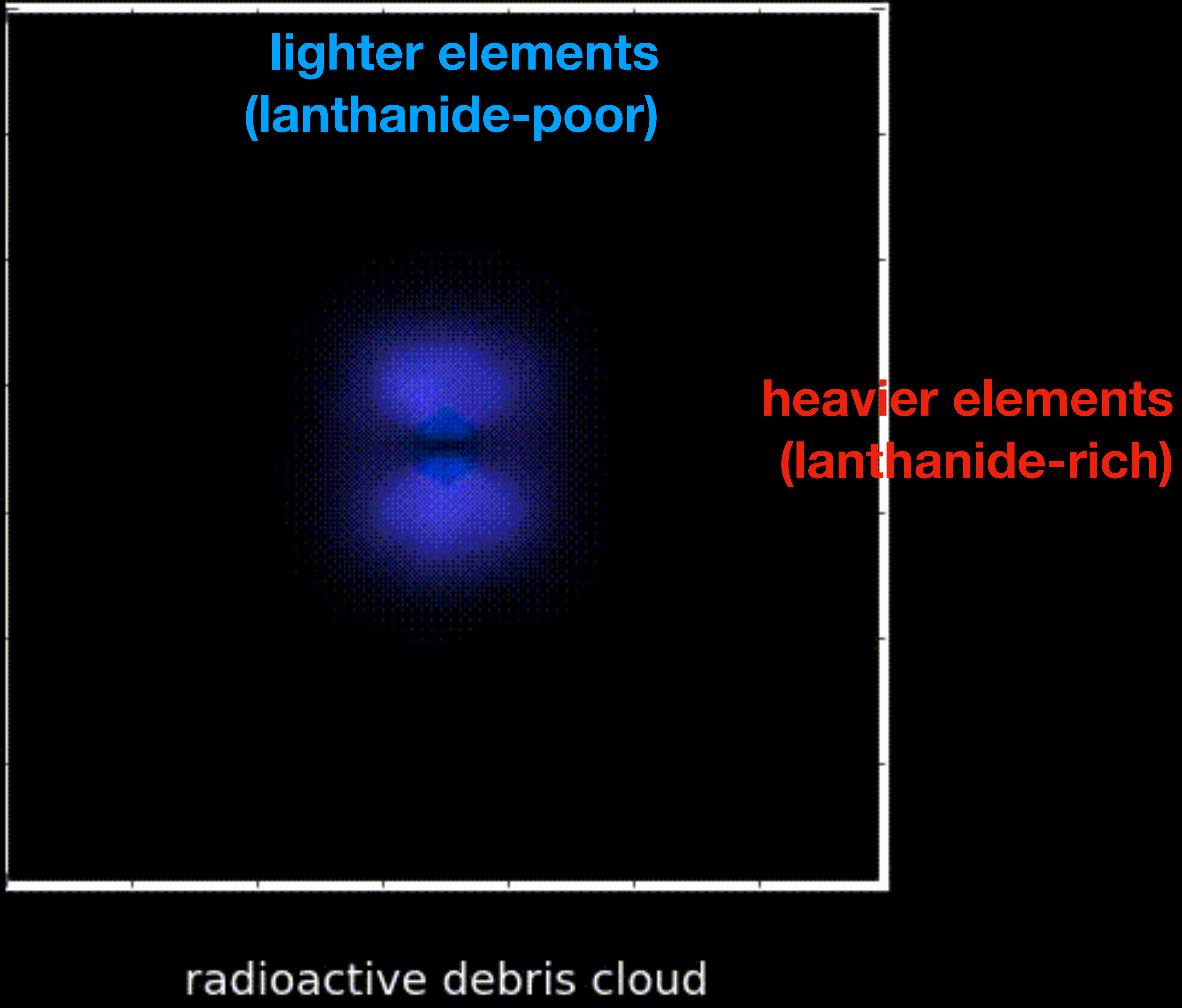


LIGO



Kilonova opportunities for GMT

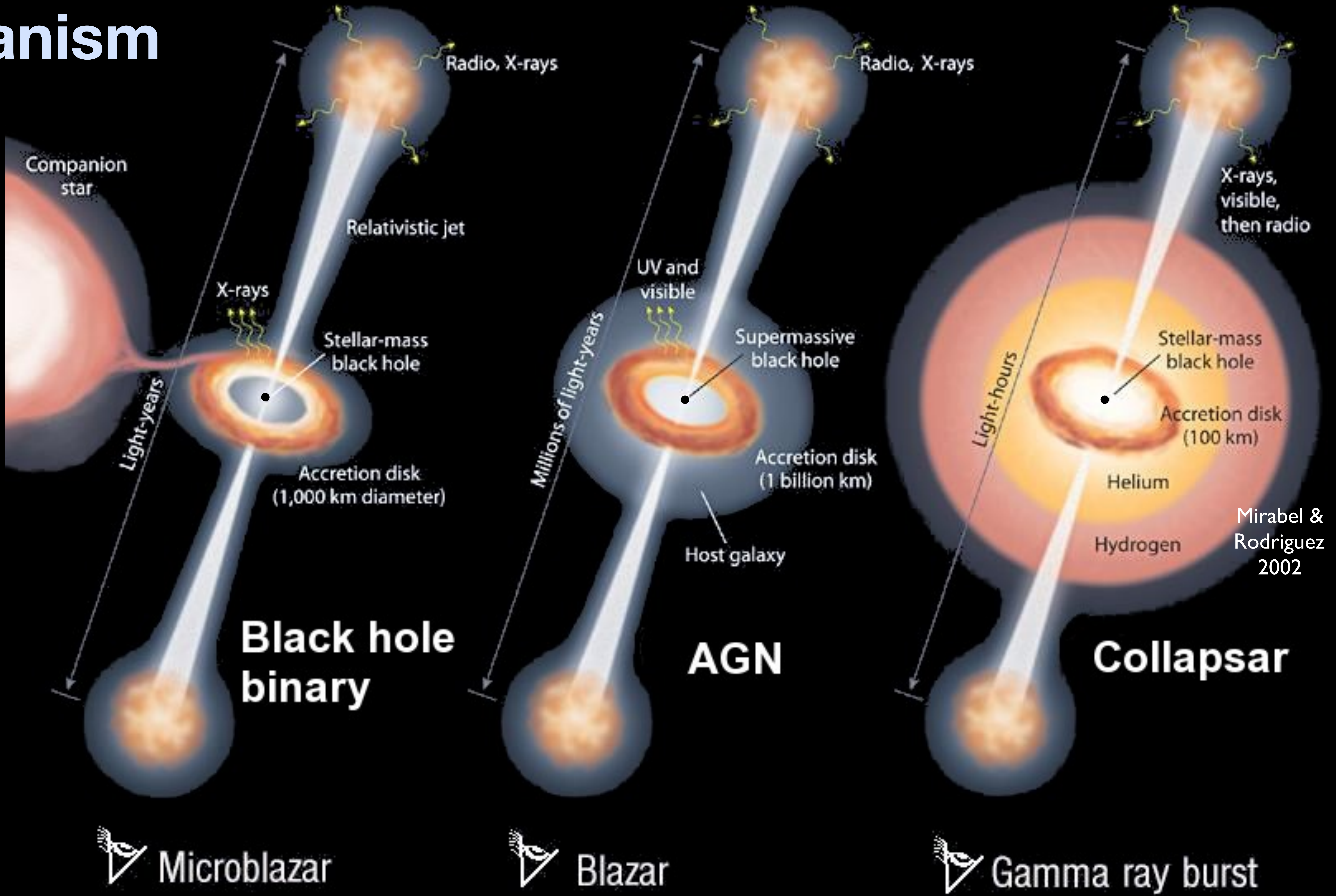




cf. also Cowperthwaite+2017

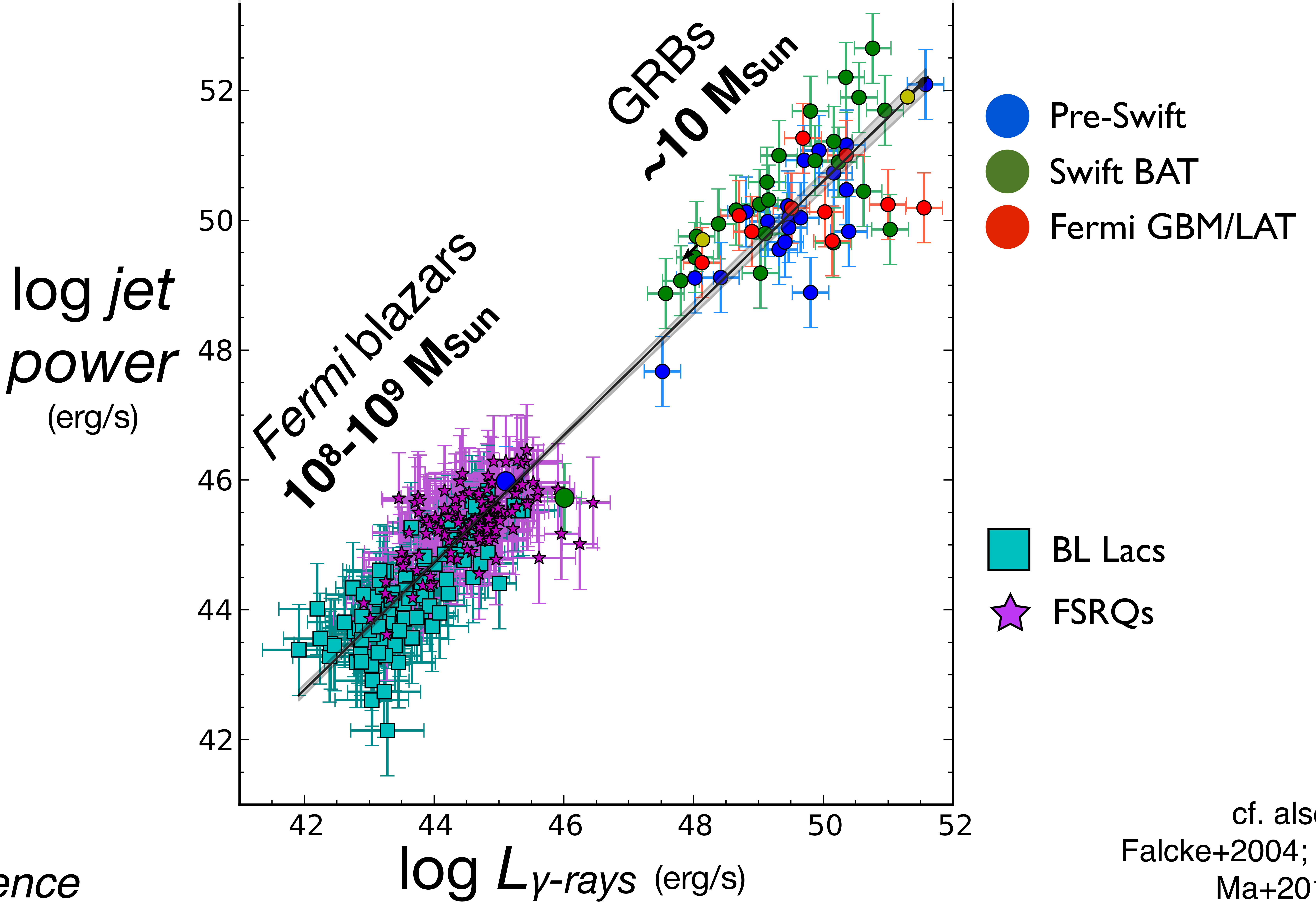
Black hole unification

Black hole accretion seems to be a universal, scale-free mechanism



Mirabel

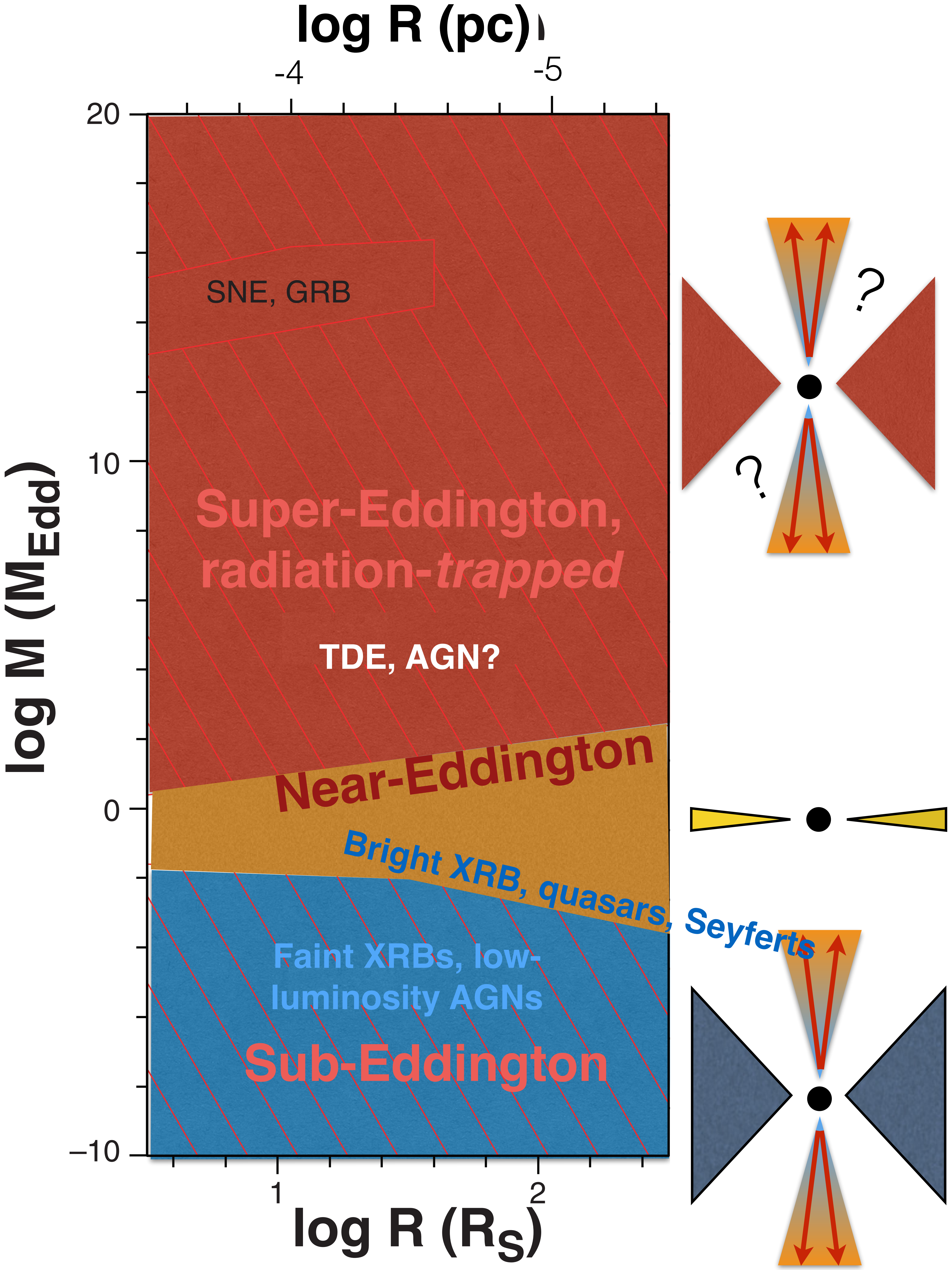
Black hole jets are scale-free: knowledge-transfer from stellar to supermassive ones



Nemmen+2012, *Science*

cf. also Merloni+2003; Falcke+2004; McHardy+2006; Ma+2014; Lamb+2017;

Regimes of BH accretion



slide from BASS ESO 2018 talk

Adapted from Narayan & Quataert 2005

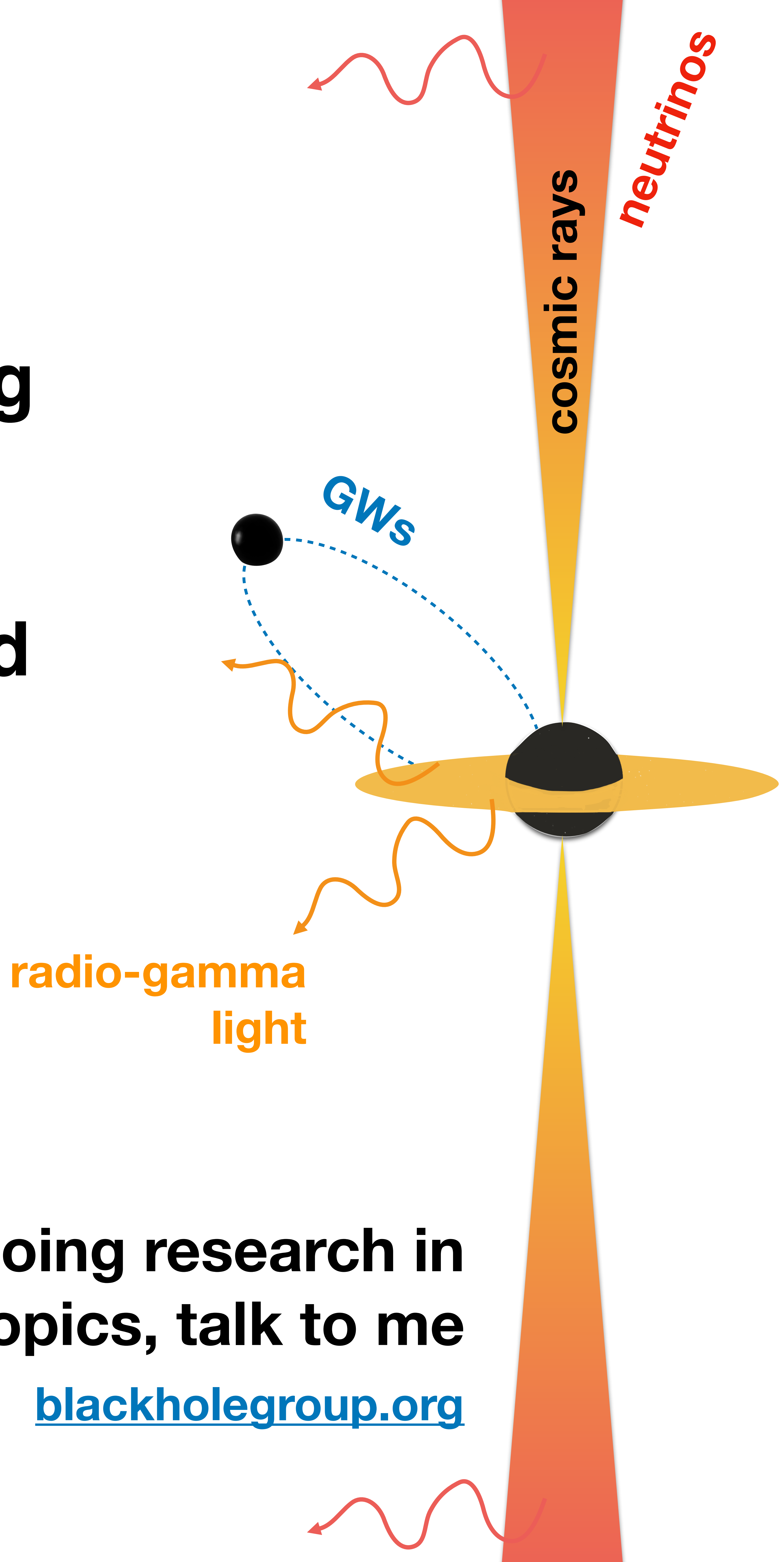
Next week:
multimessenger astronomy
gamma-ray bursts

Summary: Black holes in astrophysics

- Black holes: collapsed objects from which nothing can escape (once inside)
- Astrophysical labs of general relativity, fluid dynamics and electrodynamics that can't be found on Earth

- ☆ Brightest systems in the universe
- ☆ Produce powerful outflows
- ☆ Important for galaxy formation/evolution

- ☆ Cosmic particle accelerators
- ☆ Sources of gravitational waves
- ☆ Soon: first image of an event horizon



If interested in doing research in these topics, talk to me

blackholegroup.org

Director’s cut

AGN Unified Model

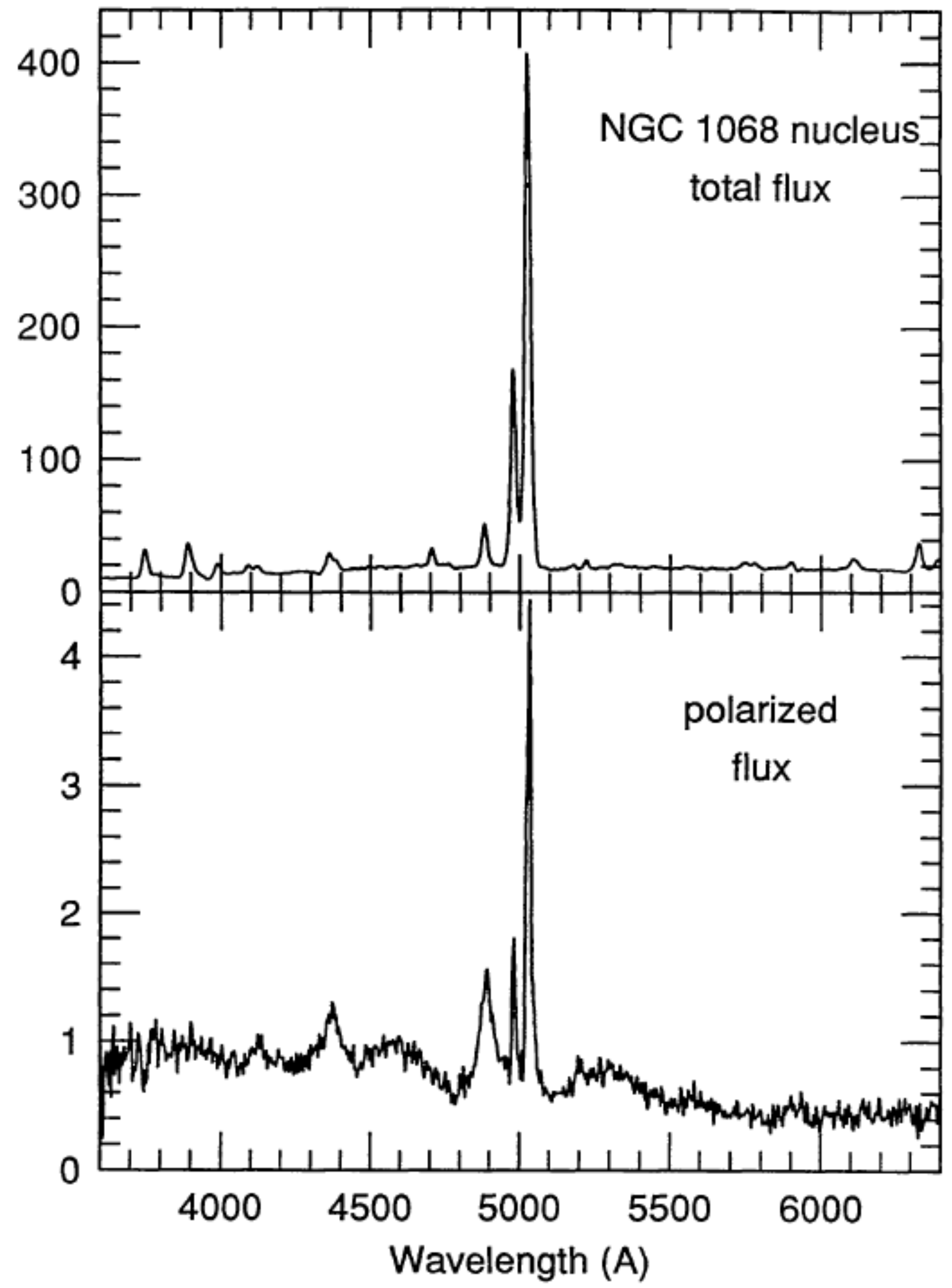
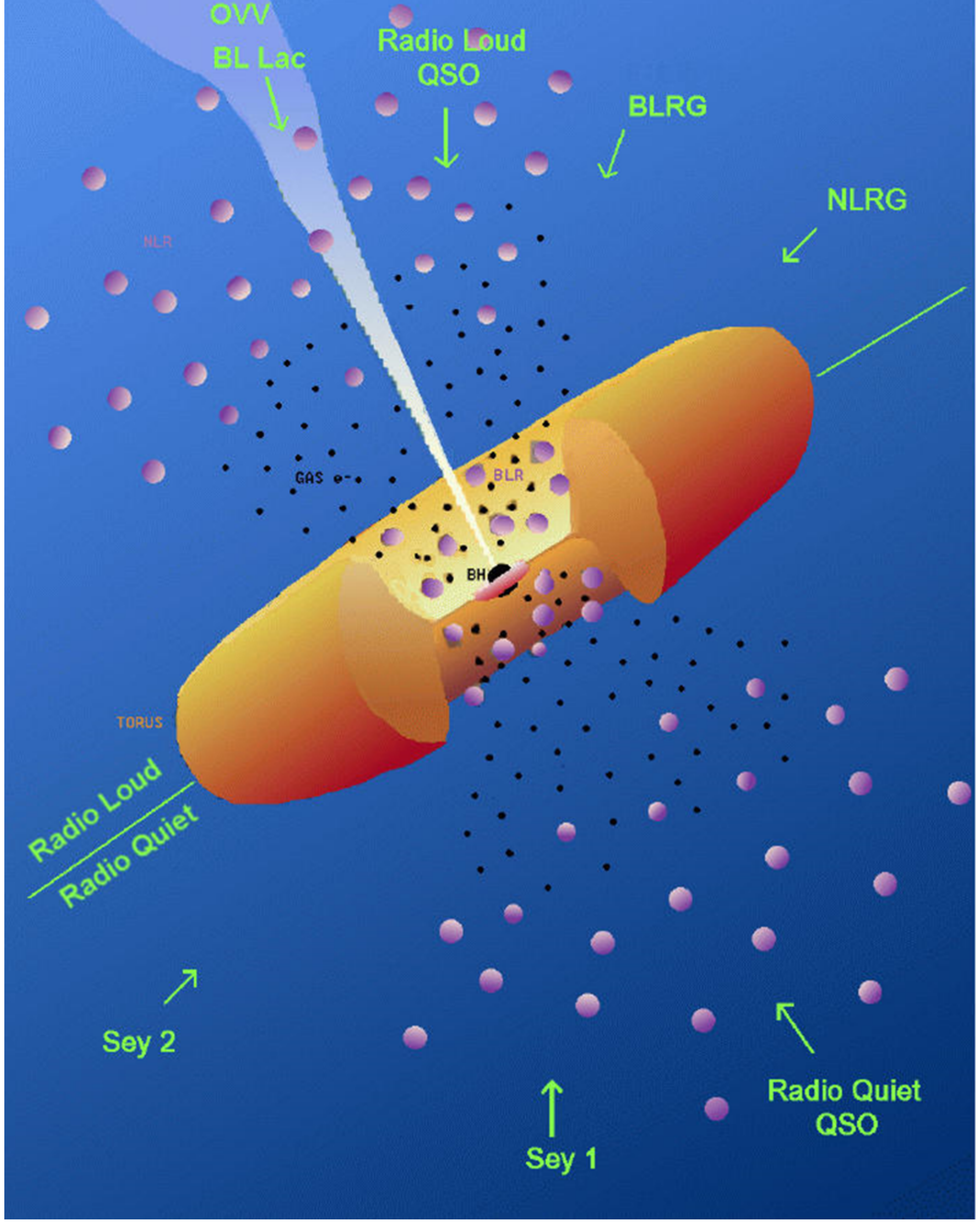
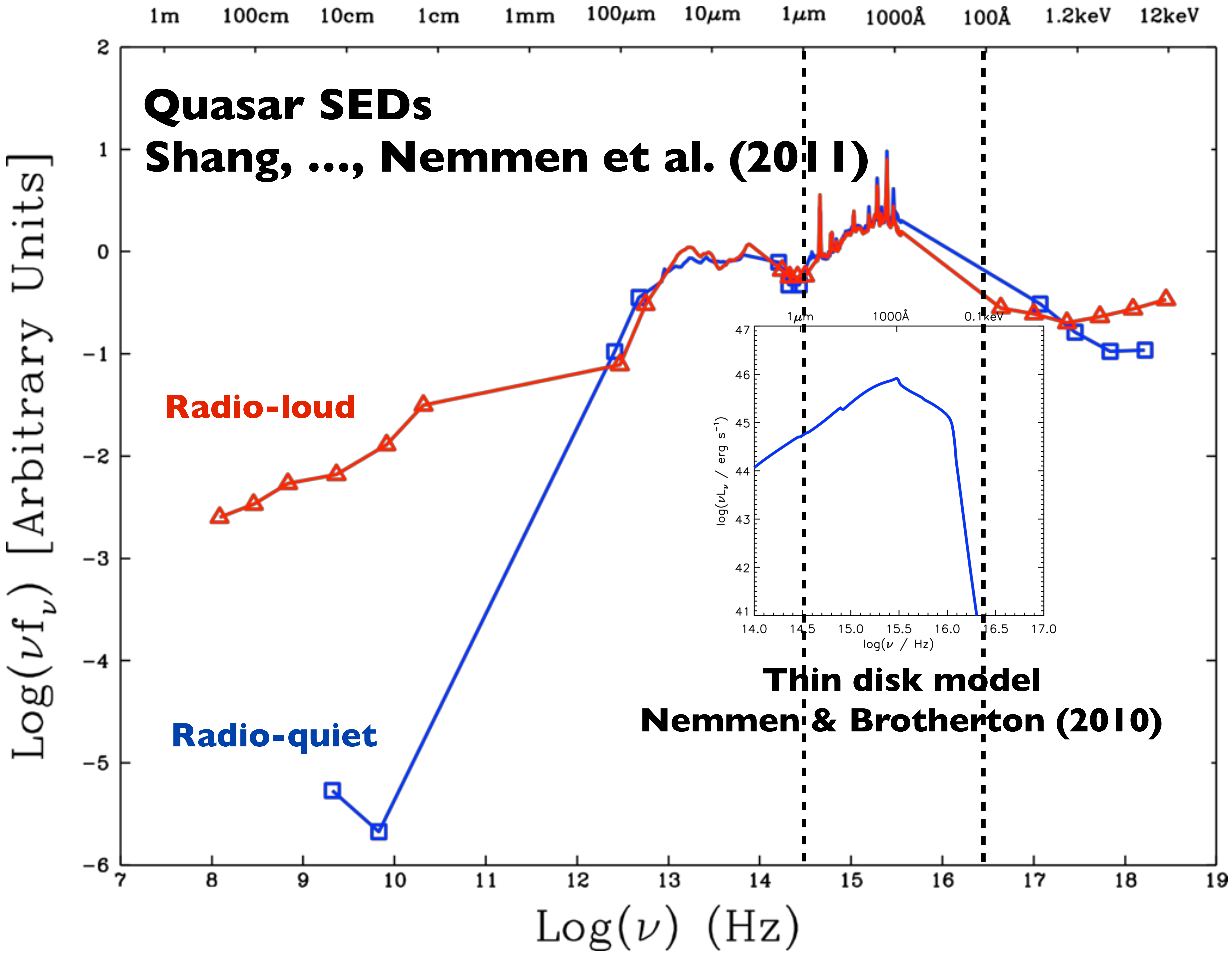


Figure 2 Spectropolarimetry of NGC 1068 by Miller et al 1991. The flux spectrum (*top*) indicates a Type 2 classification, while the polarized flux (*bottom*) is indistinguishable from the flux spectra of Type 1 Seyferts.

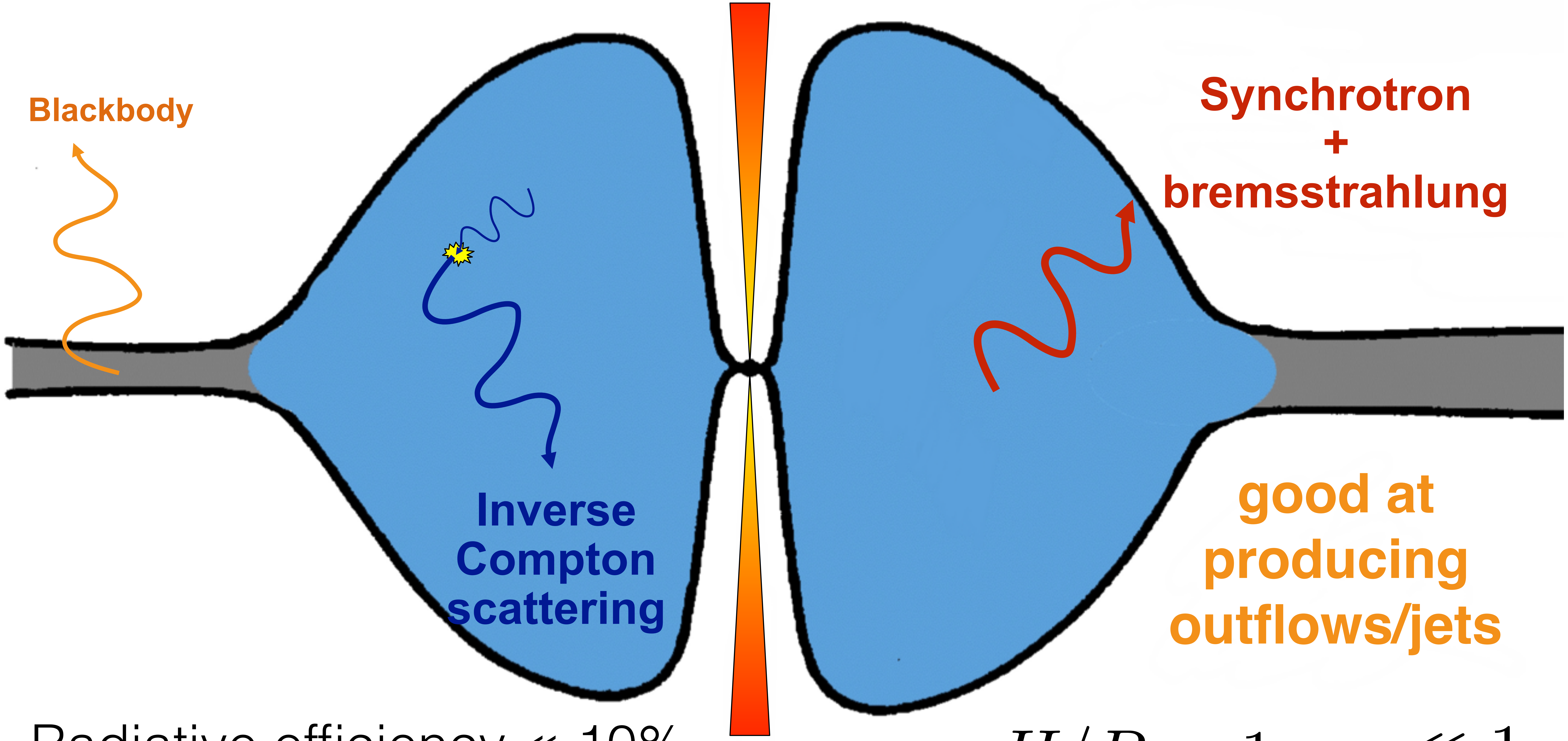


SEDs of thin accretion disks in AGNs peak in the ultraviolet: BIG BLUE BUMP



ADAFs

explain low-luminosity AGNs (i.e. most galactic nuclei at $z \sim 0$) and stellar-mass black holes in low/hard state



good at producing outflows/jets

Radiative efficiency « 10%

$$\dot{M} \lesssim 0.01 \dot{M}_{\mathrm{Edd}}$$

$$L/L_{\mathrm{Edd}} \lesssim 0.01$$

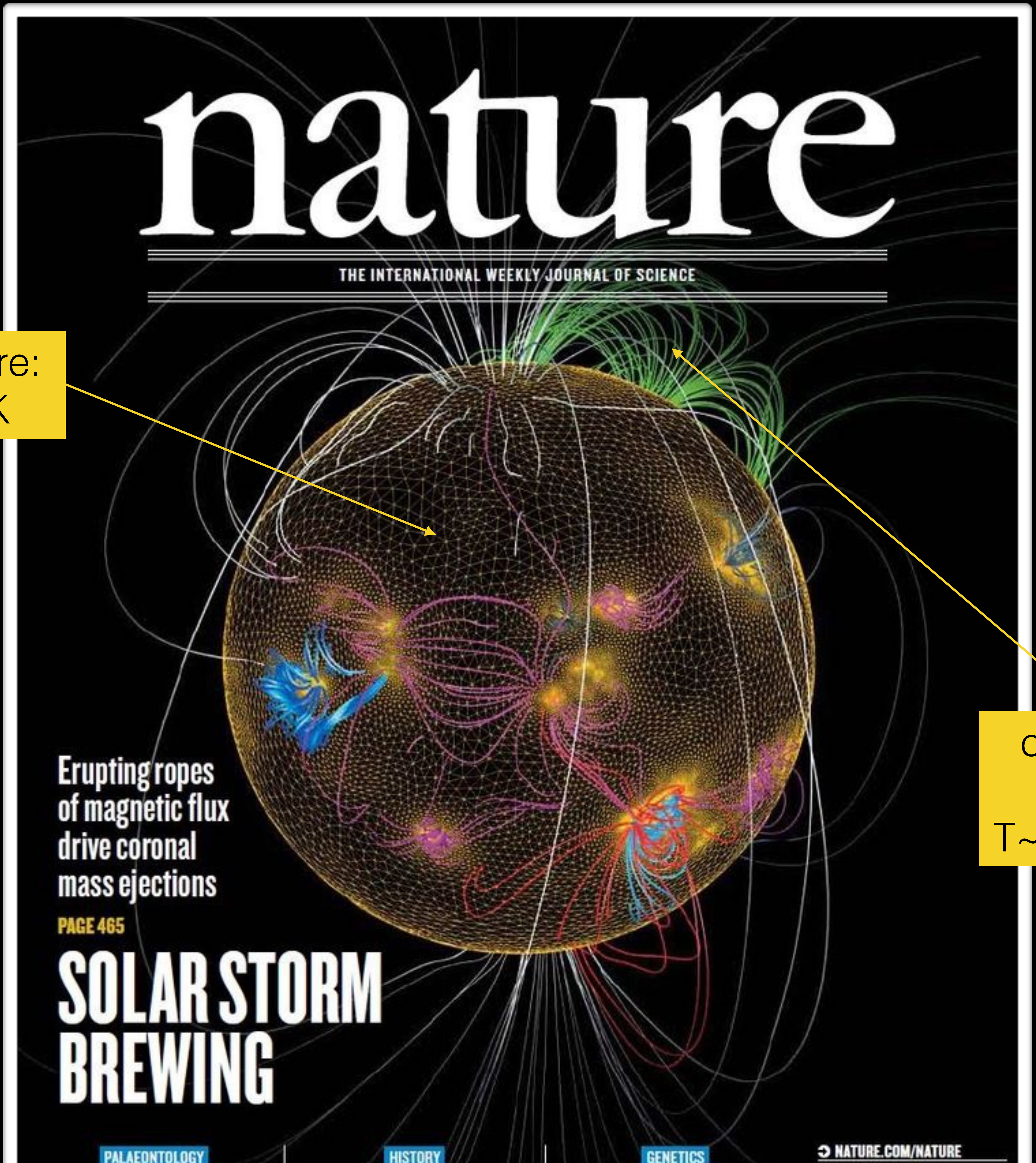
$$H/R \sim 1 \quad \tau \ll 1$$

$T_i \sim 10^{12} \, (R_S/R)$ K

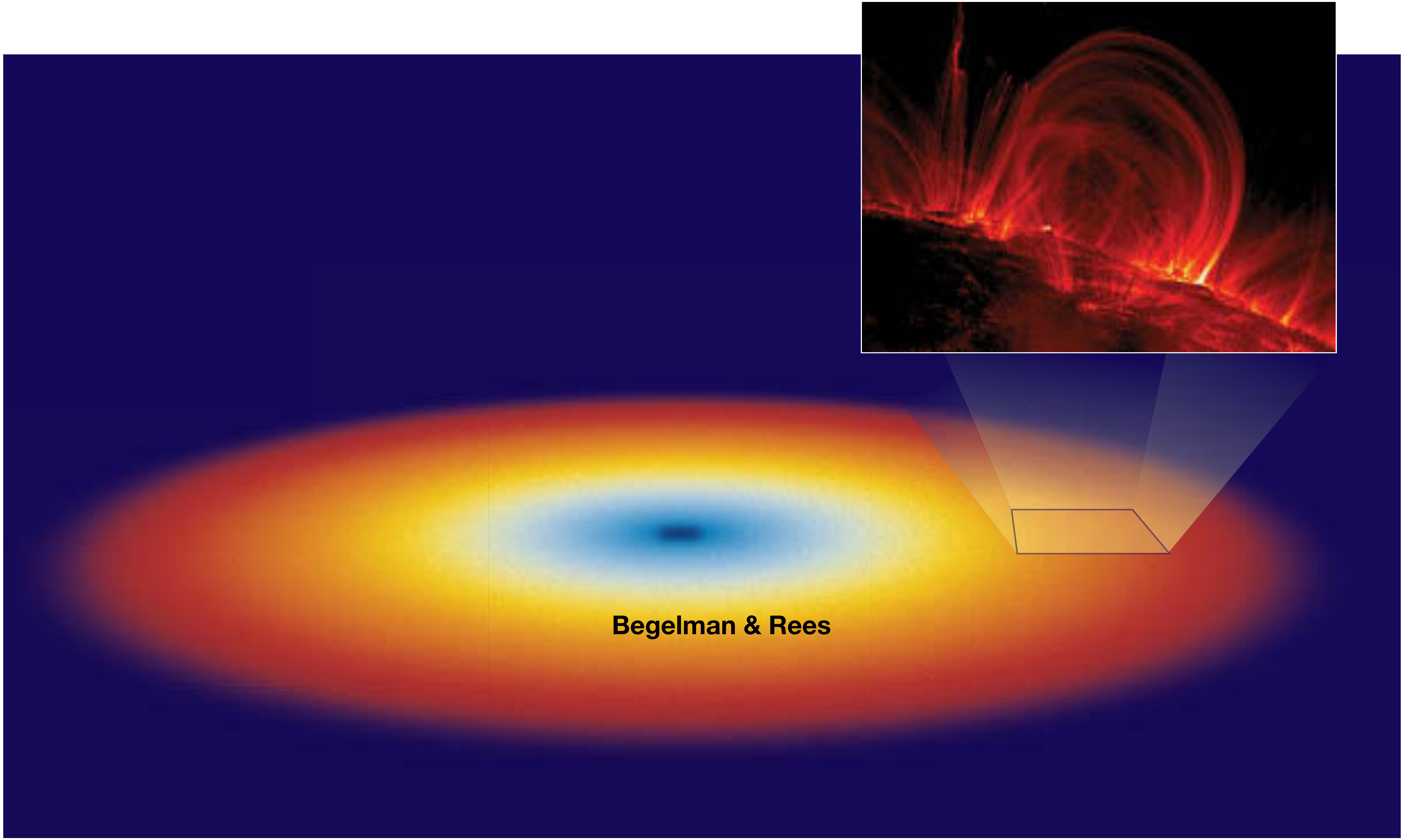
$T_e \sim 10^9$ - 10^{11} K

radiate in all frequencies

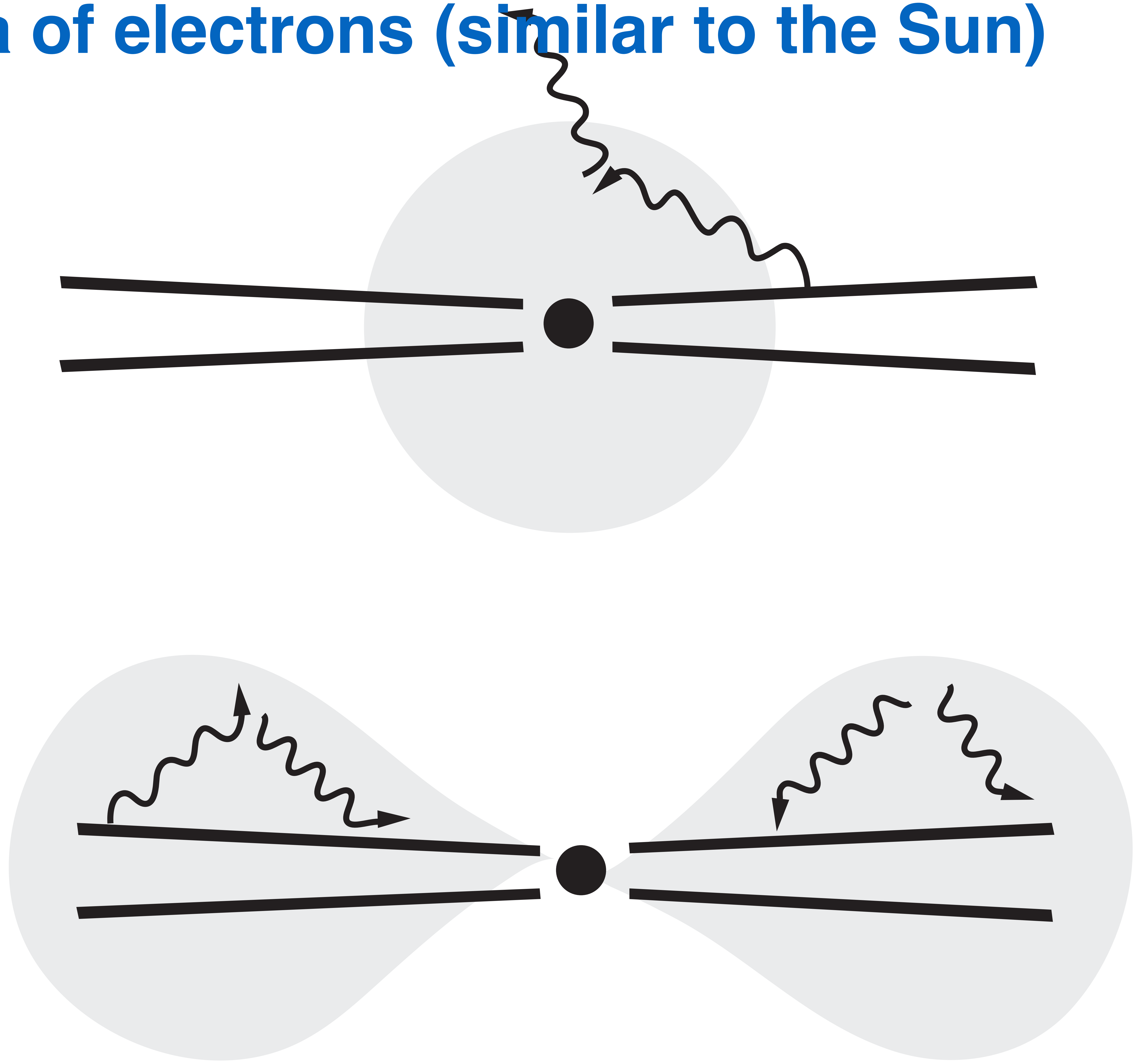
photosphere:
$T \sim 5000$ K



corona and flares:
$T \sim (2\text{-}4) \times 10^6$ K

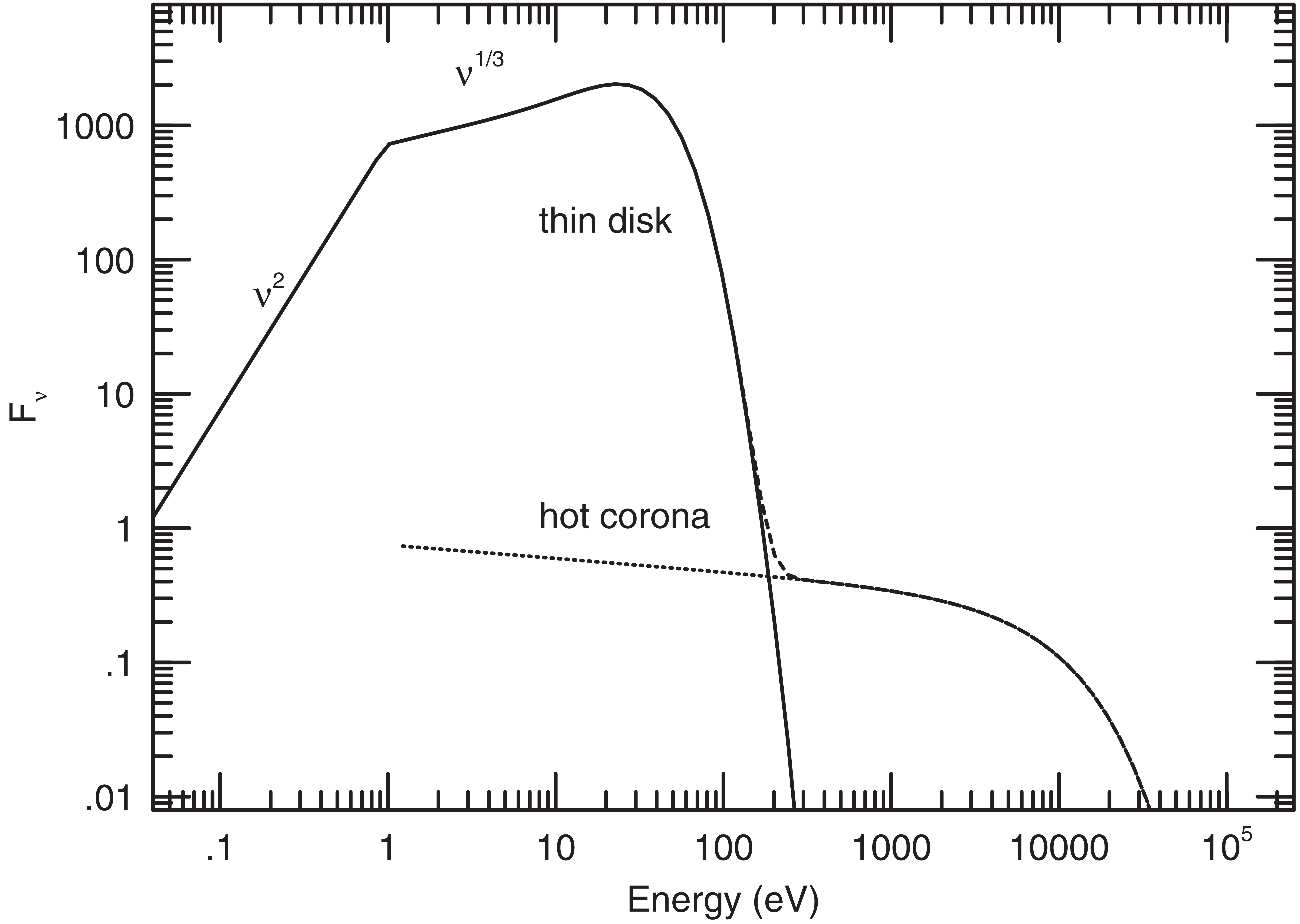

Begelman & Rees

Possible source of X-rays in luminous AGNs: Hot corona of electrons (similar to the Sun)



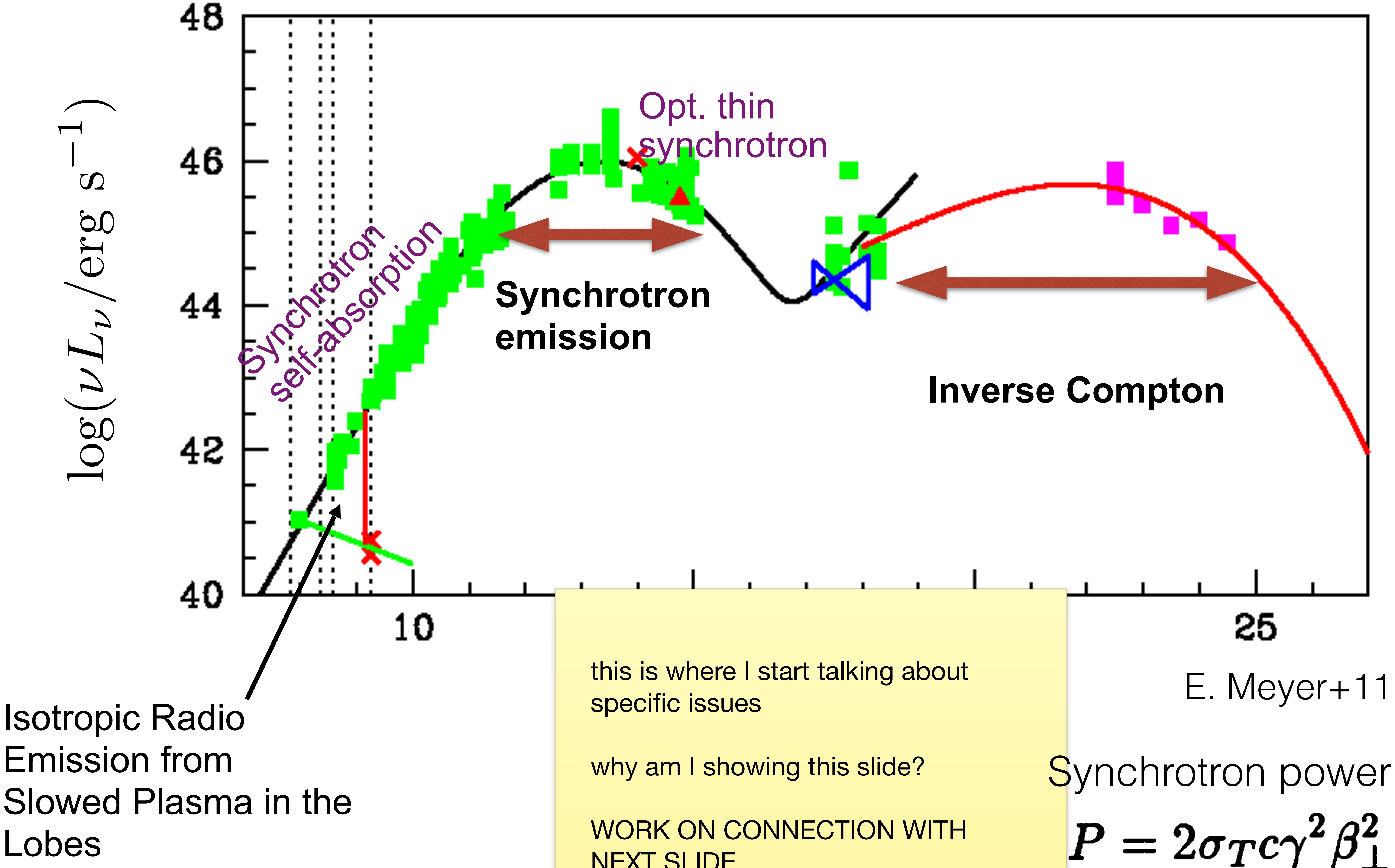
Netzer

Schematic spectrum of thin disk ($T < 10^5$ K) + hot corona ($T = 10^8$ K)



Netzer

Blazars: looking down the barrel of the gun, observe the full, c
beamed power of the relativistic jet



E. Meyer+11

this is where I start talking about specific issues

why am I showing this slide?

WORK ON CONNECTION WITH NEXT SLIDE

Synchrotron power:

$$P = 2\sigma_T c \gamma^2 \beta_\perp^2 \left(\frac{B^2}{8\pi}\right)$$