BLACK HOLES IN THE UNIVERSE

&

THE QUEST FOR MICROQUASARS

Félix Mirabel

CEA/Saclay-France

THE IDEA OF "BLACK HOLE"

Michell: in 1783, in the context of the classical concept of gravitation and corpuscular theory of light, proposed the existence of **"bodies from which light could not arrive at us".**

Could be detected in stellar binary systems

Laplace:

- **"Corps obscurs"** en aussi grand nombre que les etoiles


EXPOSITION
DU SYSTEME
DU MONDE,
PAR PIERRE-SIMON LAPLACE,
de l'Institut National de France, et du Bureau des Longitudes.
TOME SECOND.
A PARIS,

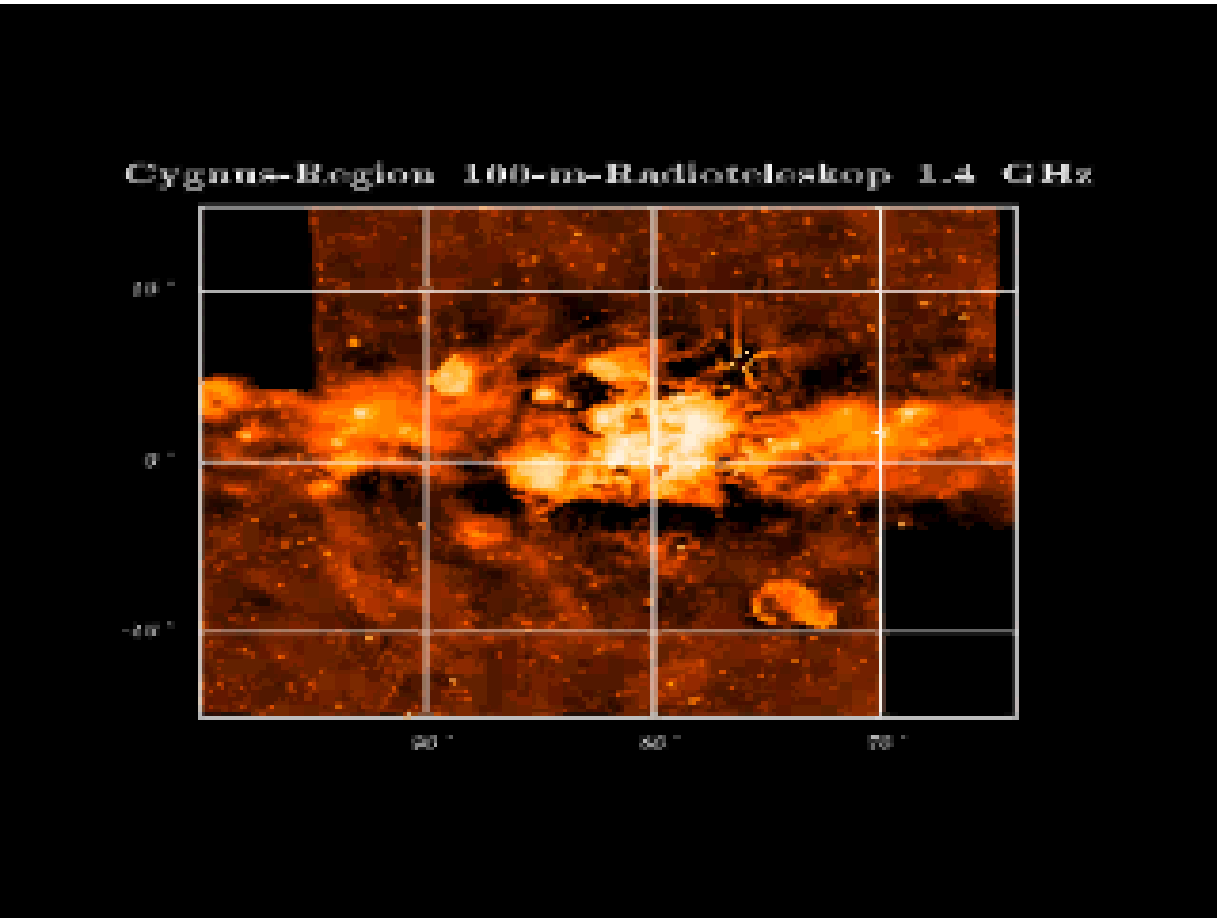
- **"**Il est possible que **les plus grands corps de l'univers, soient par cela meme, invisibles**."

⇒ **Supermassive Black Holes**

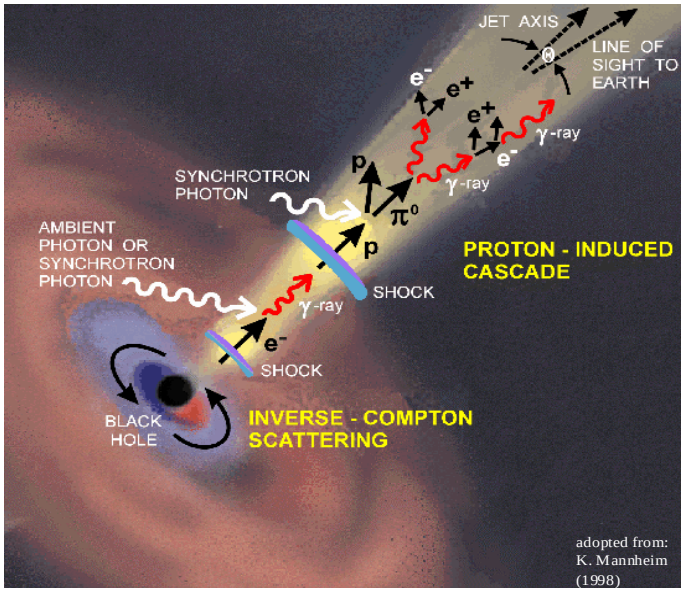
The idea of "black hole" was forgotten for ~ 140 yr

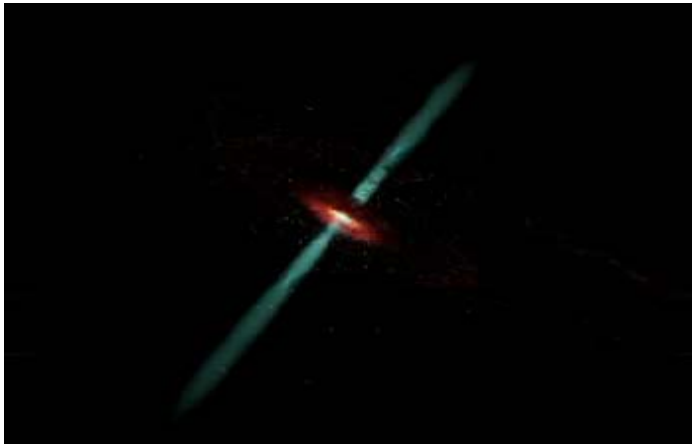
QUASARS & RADIO-GALAXIES

SINCE THE 1970´s THE TIME VARIABILITY IN QUASARS & RELATIVISTIC JETS IN RADIO GALAXIES **SUGGESTED** THE EXISTENCE OF SUPERMASSIVE BHs



VLBI: Krichbaum et al. (1999)

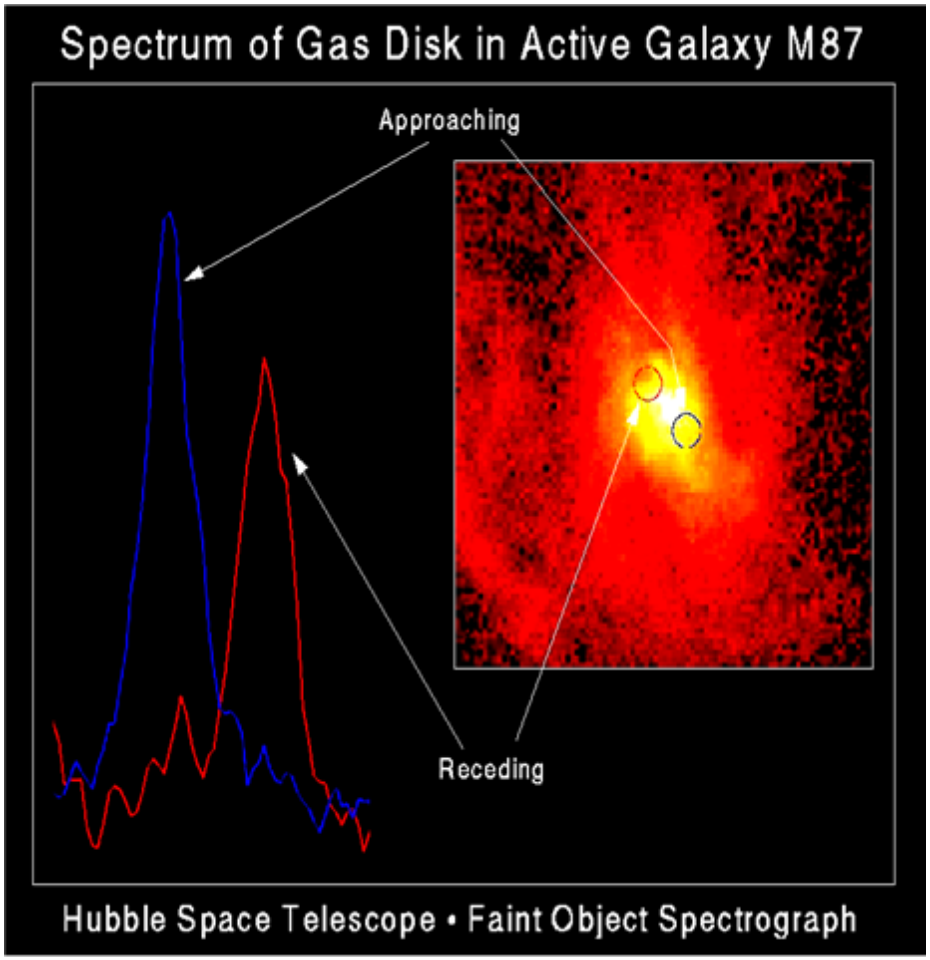




DYNAMIC EVIDENCES (MASS) OF SUPER-MASSIVE BLACK HOLES

Kinematics of the H_α line with HST

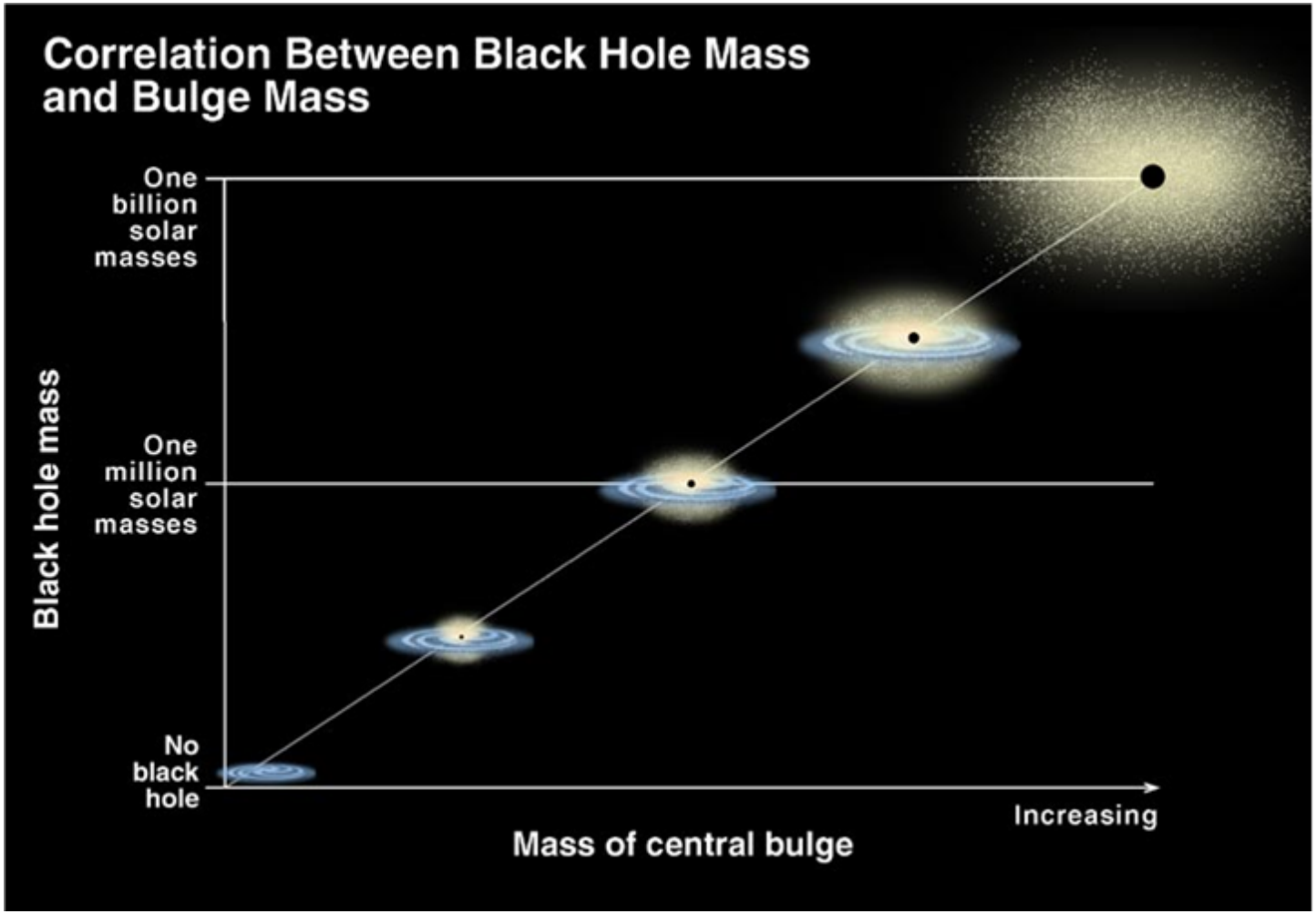
$\Rightarrow M_{BH} \sim 10^8 M_\odot$ in M 87



H_2O masers with VLBA

$\Rightarrow M_{BH} \sim 10^7 M_\odot$ in NGC 4258

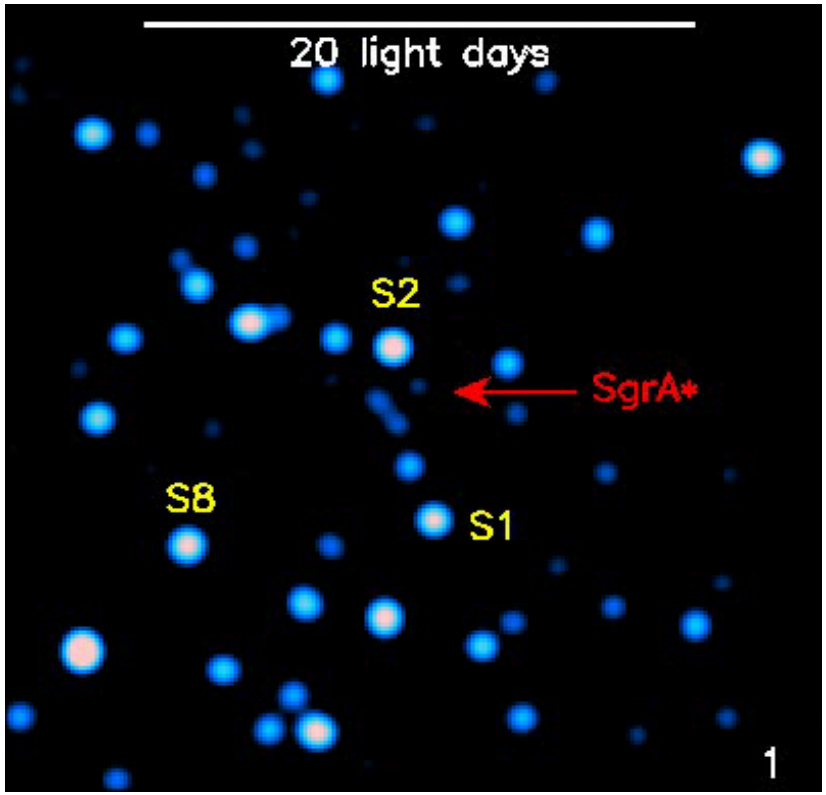
MASSIVE GALAXIES HOST SUPERMASSIVE BLACK HOLES

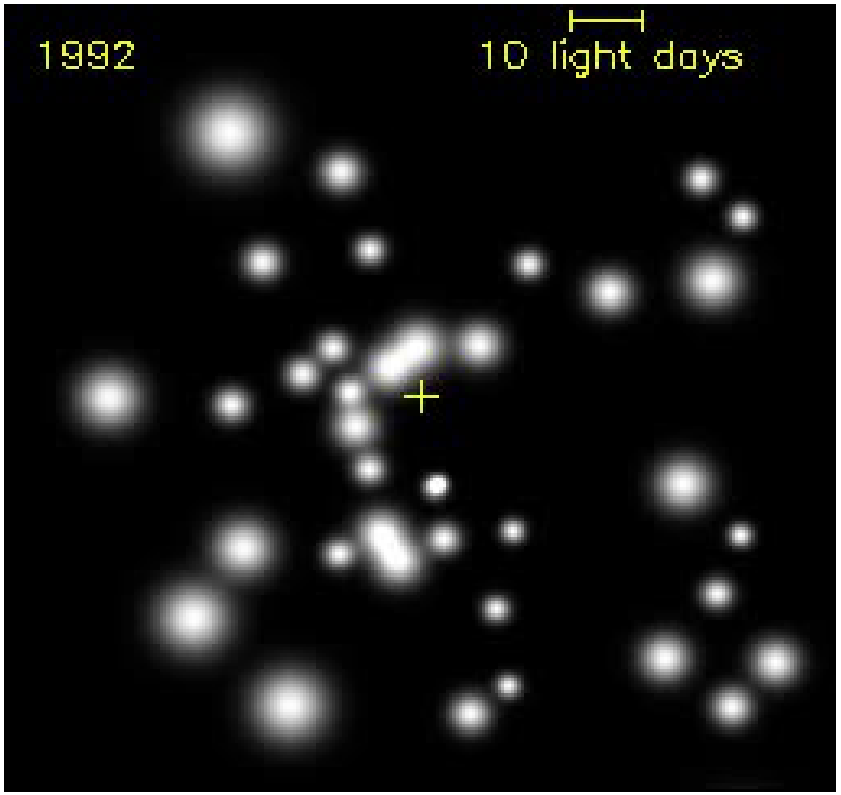


- **HOW ARE SUPERMASSIVE BLACK HOLES FORMED ?**

SUPERMASSIVE BLACK HOLE AT THE GALACTIC CENTRE

- The black hole of ~4 millon solar masses at the Galactic Center
- Infrared monitoring with adaptive optics (Genzel et al., 2008)



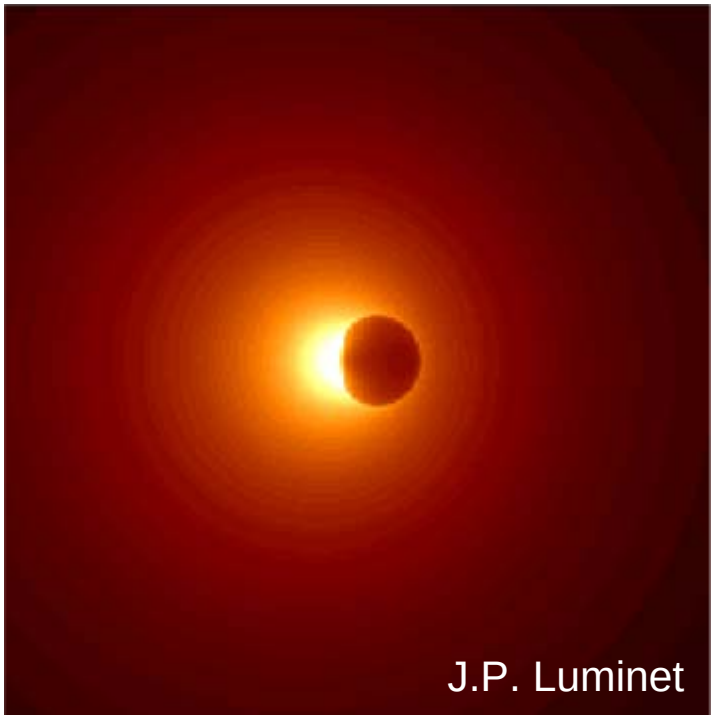


- How could a cluster of massive stars < 10^7 yr old exist in such environment ?
- Still without direct evidence of the event horizon

CAN WE OBTAIN A DIRECT IMAGE OF THE BLACK HOLE AT THE GALACTIC CENTER ?

"HORIZON": DEFINING CONCEPT OF BLACK HOLE

- Dark circle caused by radiation from sources behind that are being swallowed by the event horizon.
- Bright ring due to rays deflected by BH
- Shadow is off-centre due to flung of photons in the direction of BHs' rotation

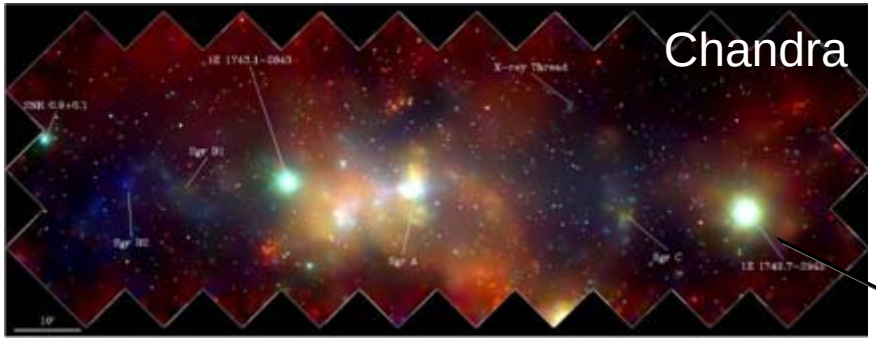


- **4 x 10^6 $M_\odot$ confined in a region enclosed by the orbit of the Earth**
- **D = 30 μarcsec to be imaged with VLBI at sub-millimeter or X-rays**

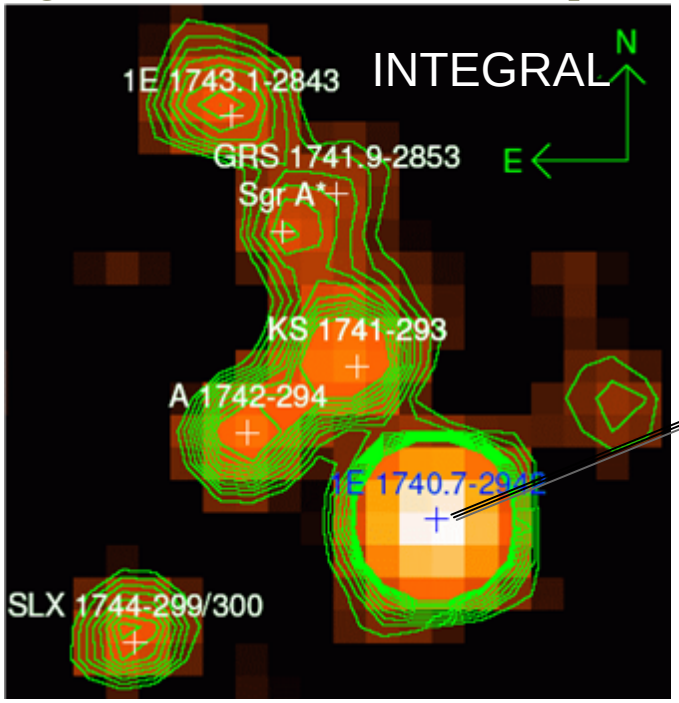
Is this BH the **annihilation source of e+e- at 511 keV?**

A "MICROQUASAR" AT THE GALACTIC CENTRE REGION

Wang et al. ApJ 2002

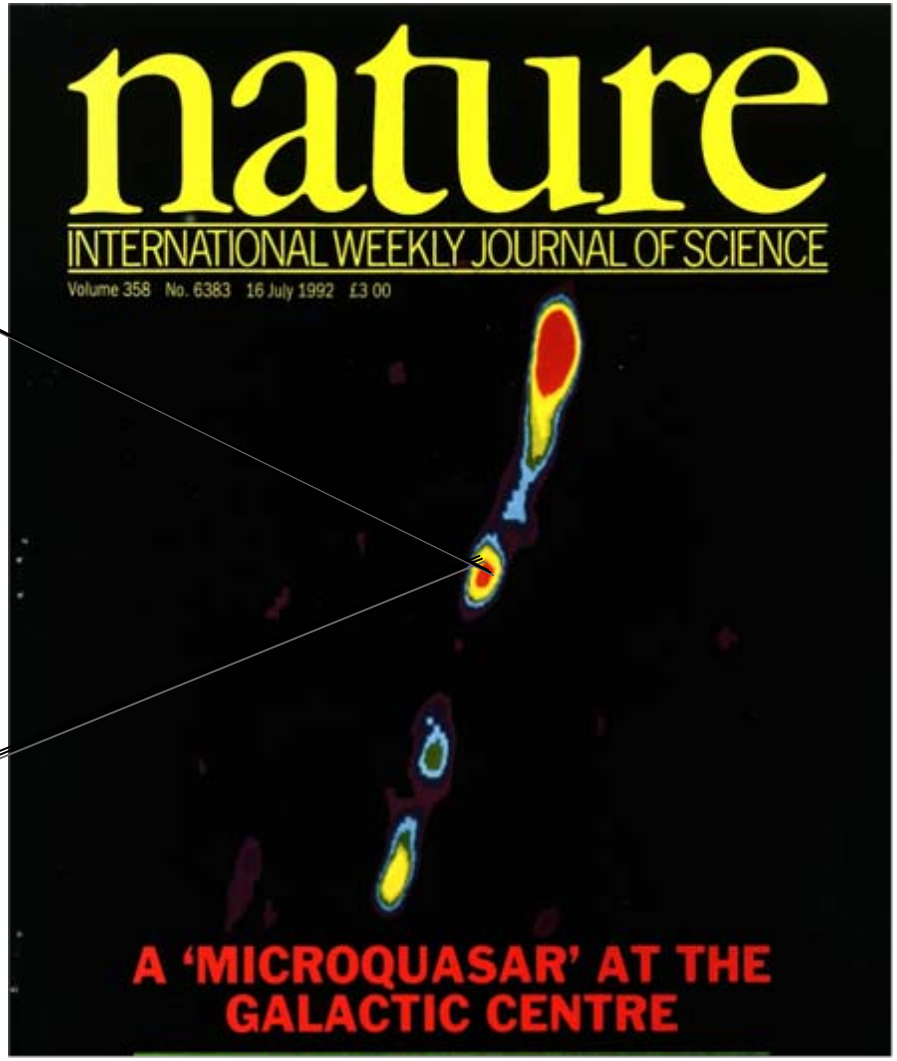


Belanger, Goldwurm, Goldoni, ApJ 2003



IR counterpart not identified

Mirabel, Rodríguez, Paul, Cordier, Lebrun (1992)

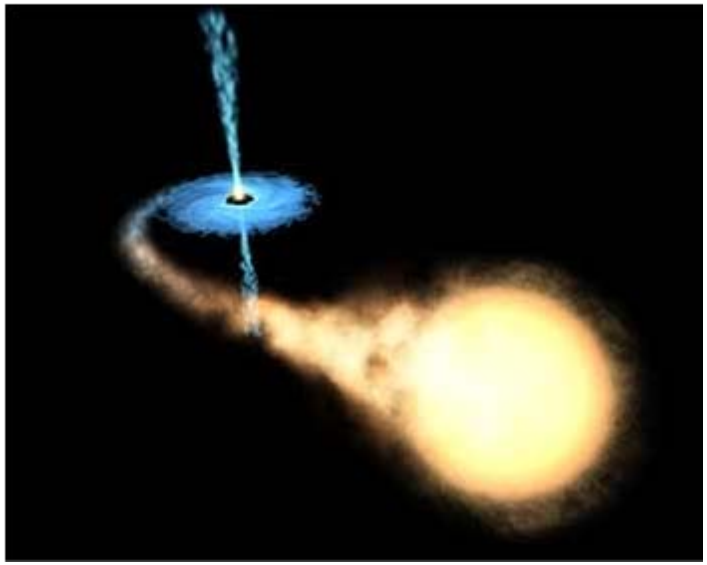


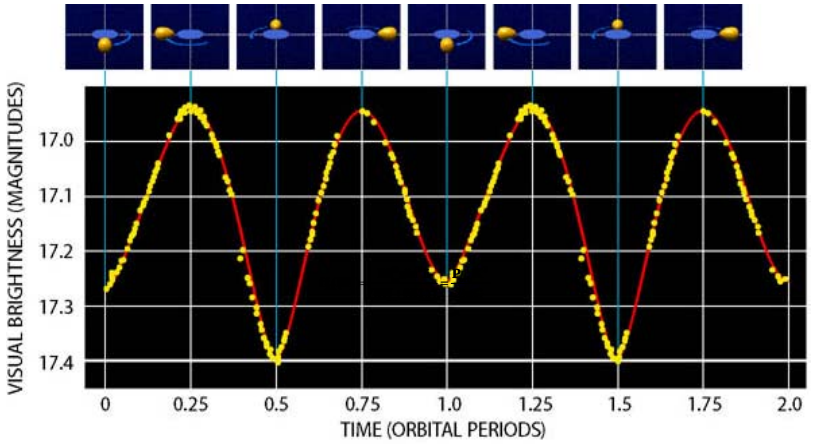
Seven international workshops.
Next as IAU Symp in BsAs (2010)

STELLAR-MASS BLACK HOLES

DISCOVERED AS X-RAY SOURCES

(Giacconi,1962…Nobel Prize in 2002)





Fonction de masse: $f_X(M) = \frac{M_n^3 \sin^3 i}{(M_n + M_X)^2} = \frac{P_{orb} K}{2\pi G}$

Minimum de masse de l'objet compact

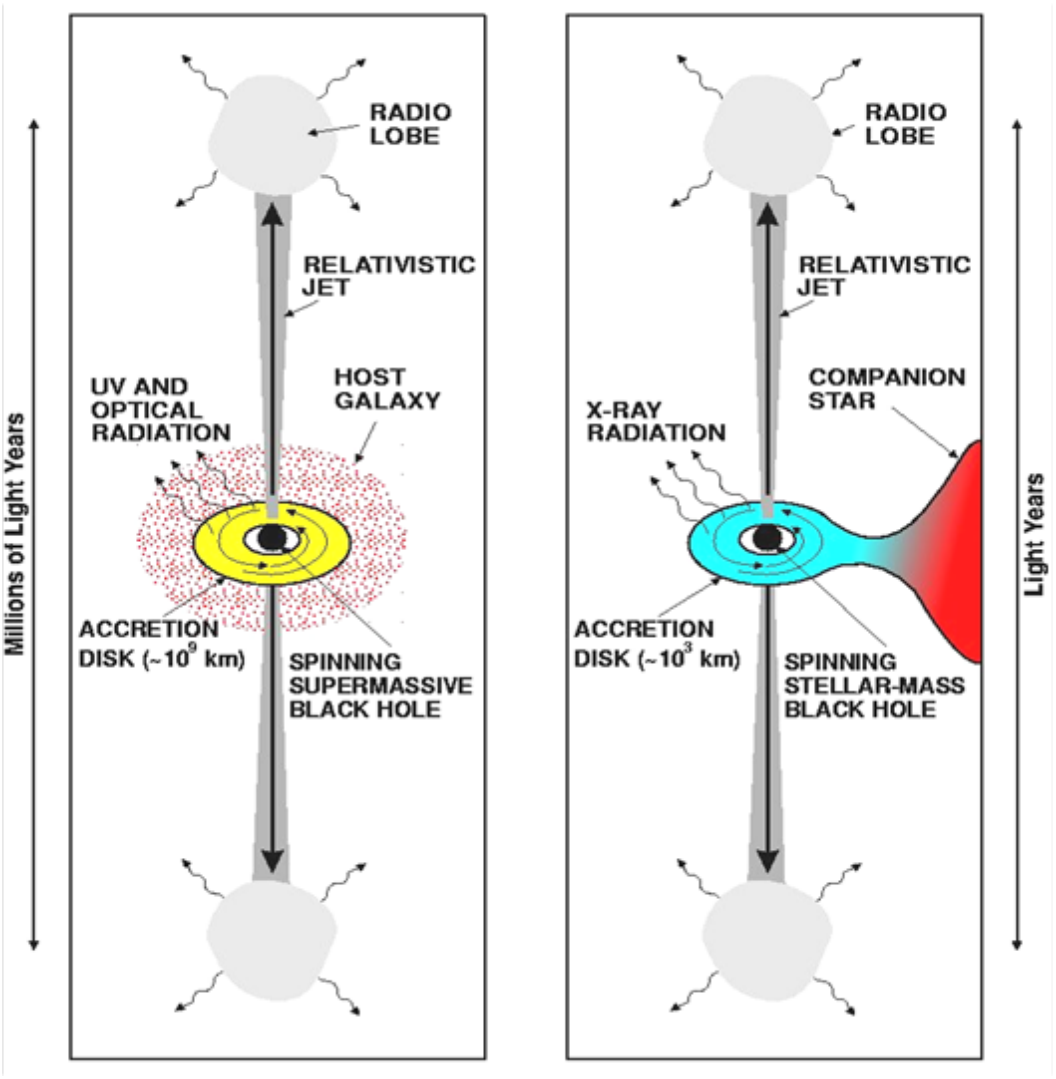
IN BINARY STELLAR SYSTEMS:

as predicted by Michell (1783)

$M > 3\ M_\odot \Rightarrow$ BLACK HOLE

- ~30 BHs known in binaries and other 20 additional candidates
- Estimated population in the Galaxy ~ 3×10^8 $\Rightarrow$
- Assuming ~10 $M_\odot$ this form of dark mass is ~ 4% of total baryonic mass of the Galaxy
- Outweighs the supermassive black hole at Galactic Centre by a factor of 10^3

QUASAR-MICROQUASAR ANALOGY



Mirabel & Rodríguez: Nature 1998

The scales of length and time are proportional to M_{BH}

$$R_{sh} = 2GM_{BH}/c^2 \; ; \; \Delta T \; \alpha \; M_{BH}$$

Unique system of equations:

The maximum color temperature of the accretion disk is:

$$T_{col} \, \alpha \, (M/\, 10M_{\odot})^{-1/4}$$

(Shakura & Sunyaev, 1976)

Waited era of space astronomy

For a given accretion rate:

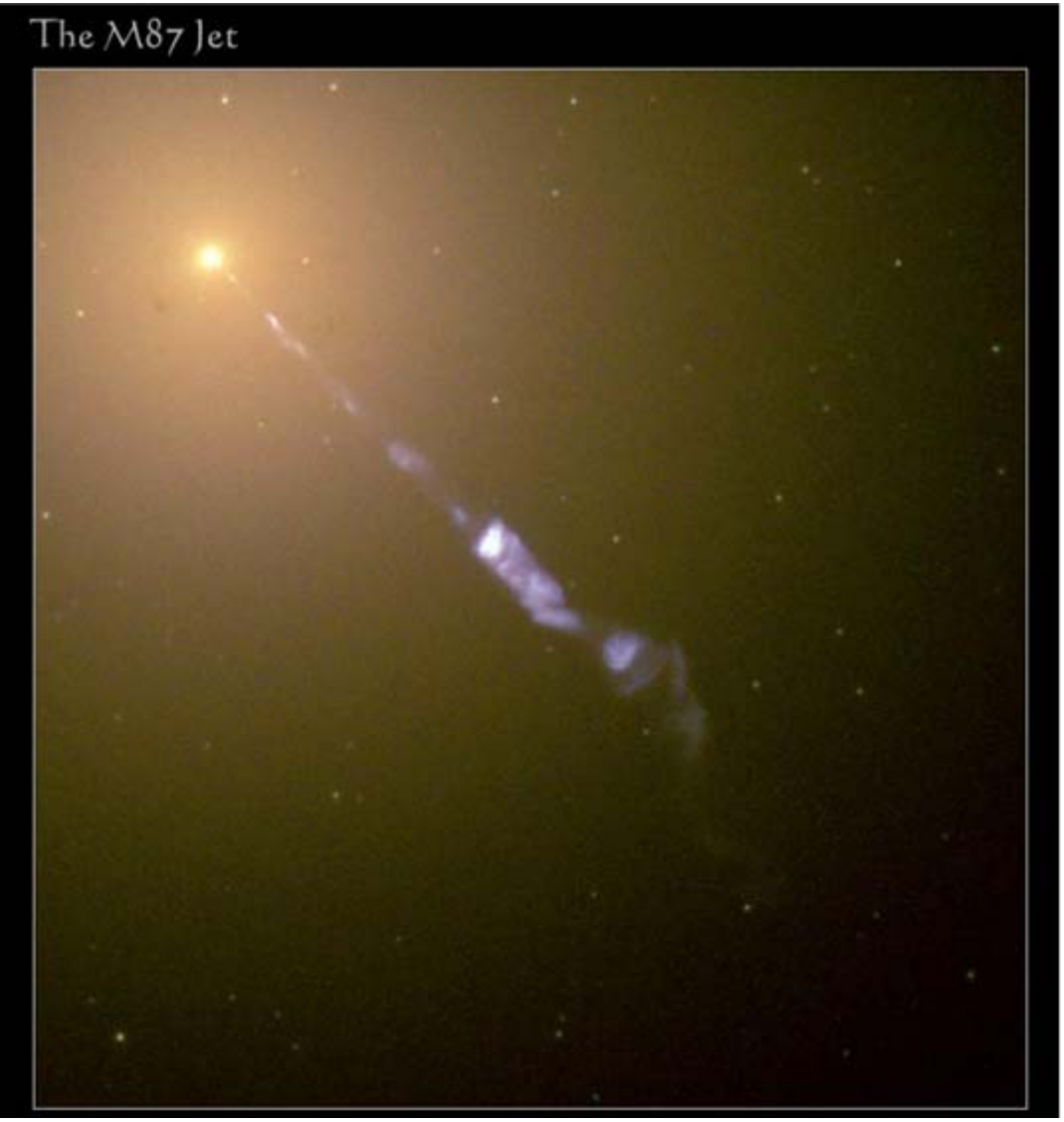
$$L_{Bol} \, \alpha \, M_{BH} \; ; \; l_{jet} \, \alpha \, M_{BH} \; ;$$

$$\varphi \, \alpha \; M_{BH}^{-1} \; ; \; B \, \alpha \, M_{BH}^{-1/2}$$

(Sams, Eckart, Sunyaev, 96; Rees 04)

APPARENT SUPERLUMINAL MOTIONS IN μQSOs AS IN QSOs ?

SUPERLUMINAL MOTIONS IN QSOs & AGN



- OBSERVED IN ~ 30 QSOs & AGN
- IN RADIO & OPTICAL WAVES
- PROPER MOTION SEEN IN YEARS
- V_{app} UP TO 20c
- WHAT IS THE NATURE ?

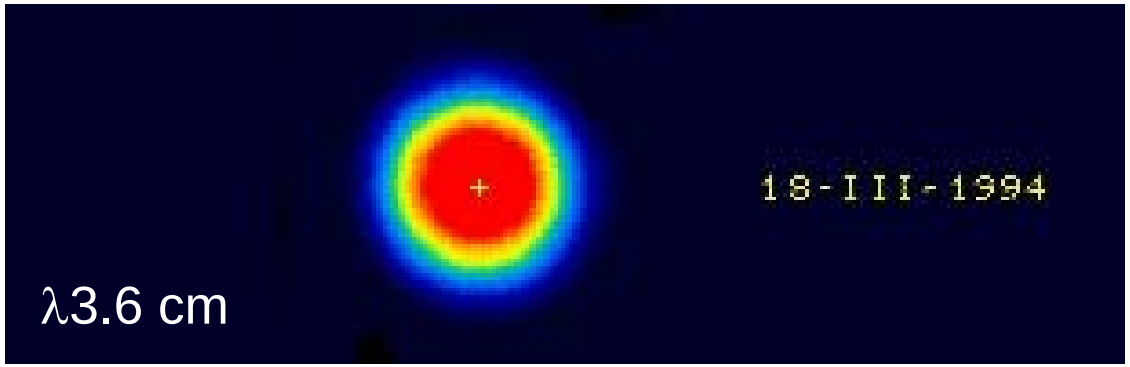
"PLASMONS" OR SHOCKS ?

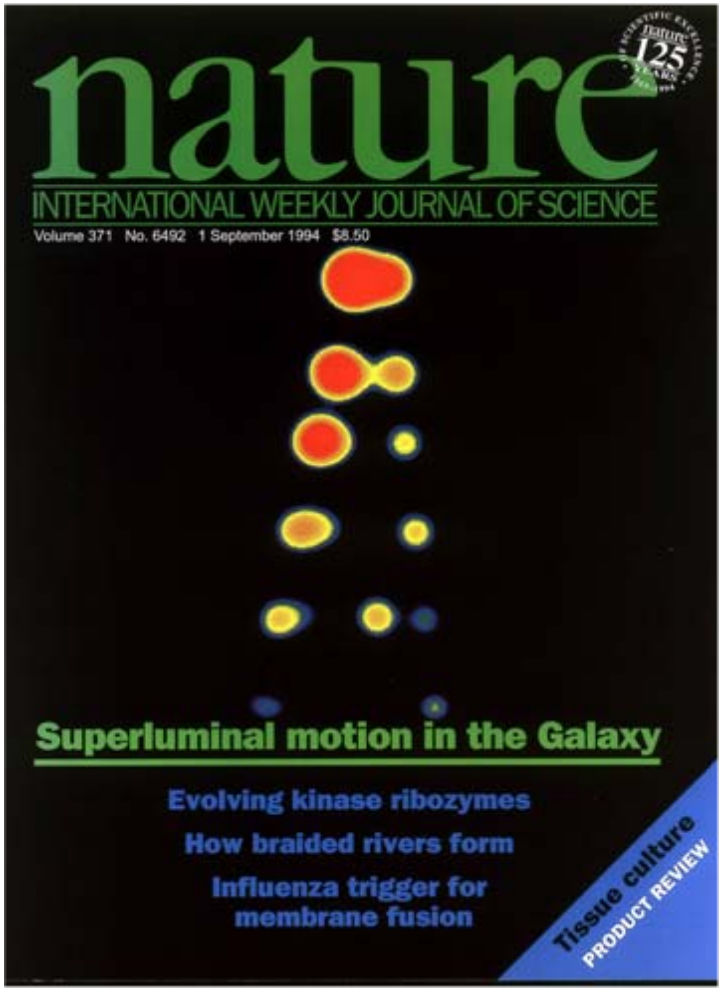
SUPERLUMINAL EJECTION IN A μQSO

- GRS 1915+105 (discovered with GRANAT)
- 1 $M_\odot$ red giant orbiting a 14 $M_\odot$ BH (Greiner et al.)

Mirabel & Rodriguez, 1994

1 arcsec

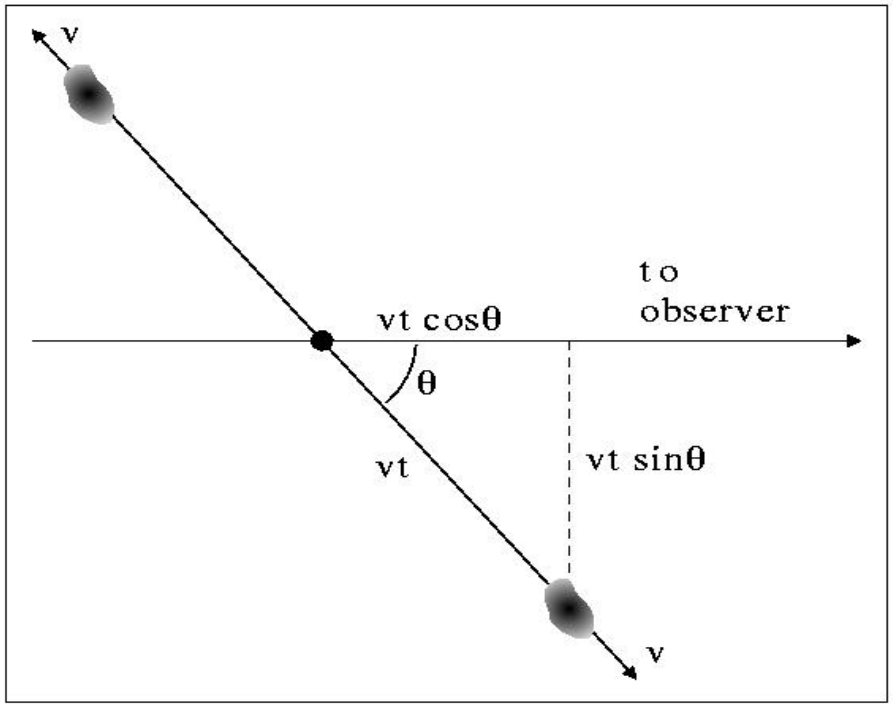




V_{app} > C Jets have apparent superluminal motions

RELATIVISTIC ABERRATION IN ANTISYMMETRIC TWIN JETS

Mirabel & Rodríguez, Nature 1994



$$\frac{S_a}{S_r} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{k-\alpha},$$

$$\mu_a = \frac{\beta\sin\theta}{(1-\beta\cos\theta)}\frac{c}{D},$$

$$\mu_r = \frac{\beta\sin\theta}{(1+\beta\cos\theta)}\frac{c}{D},$$

$$\beta\cos\theta = \frac{\mu_a-\mu_r}{\mu_a+\mu_r},$$

$$D = \frac{c\tan\theta}{2}\frac{(\mu_a-\mu_r)}{\mu_a\mu_r}.$$

Same bulk Lorentz factors as in QSOs: 2-10

$$D \leq \frac{c}{\sqrt{\mu_a\mu_r}}.$$

Relativistic upper limit: D < 14 kpc

RELATIVISTIC METHOD FOR DISTANCES IN ASTRONOMY

Mirabel & Rodríguez, Nature 1994

$$\left[\frac{\mu_{a,r}}{radians\ sec^{-1}}\right] = \frac{v\ sin\theta}{(1 \mp (v/c)\ cos\theta)\ D}$$

FROM PROPER MOTIONS

IF THE JETS ARE DOMINATED BY ELECTRON-PROTON PLASMA:

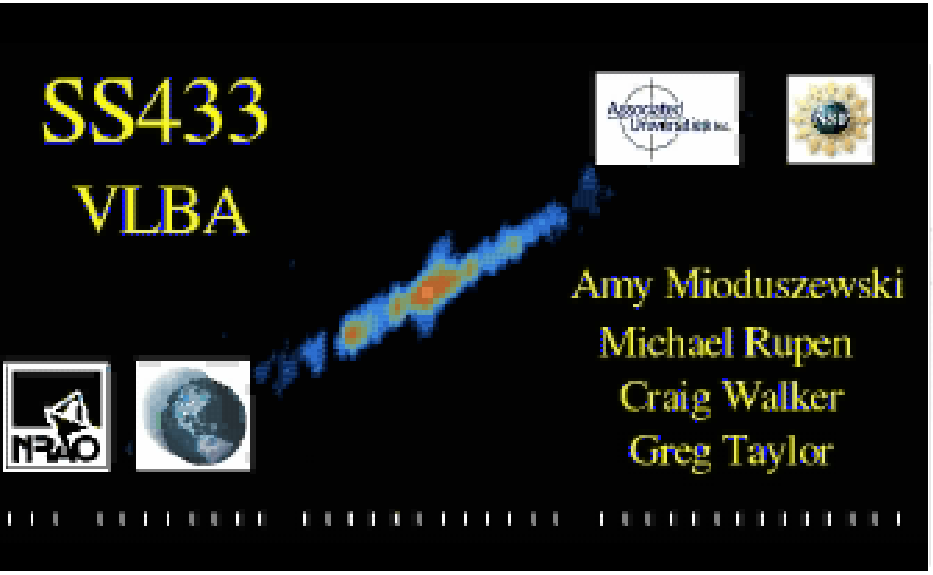
$$\frac{\lambda_{a,r}}{\lambda_{rest}} = \frac{(1 \mp (v/c)\ cos\theta)}{[1-(v/c)^2]^{1/2}}$$

FROM DOPPLER FACTOR OF ION LINES

- **IF JETS ARE ANTISYMMETRIC, V, Θ, & D CAN BE FOUND**
- **BUT SPECTRAL LINES (H, He, Fe) HAVE BEEN SO FAR DETECTED ONLY IN SS 433**

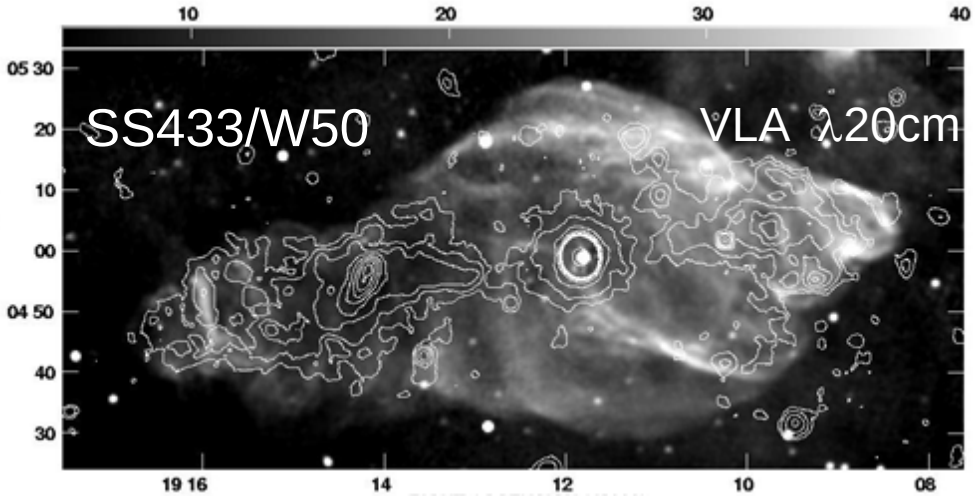
WHY ?

POWERFUL DARK JETS FROM BLACK HOLES



1arcsec

Radio (Dubner et al); X-rays: (Brinkmann et al)



$1^o = 60$ pc

- ATOMIC NUCLEI MOVING AT 0.26c ⇒
- MECHANICAL LUMINOSITY > 10^{39} erg/sec
- NON RADIATIVE JETS = “DARK” JETS
- >50% OF THE ENERGY IS NOT RADIATED

MOVING X-RAY JETS IN A μQSO

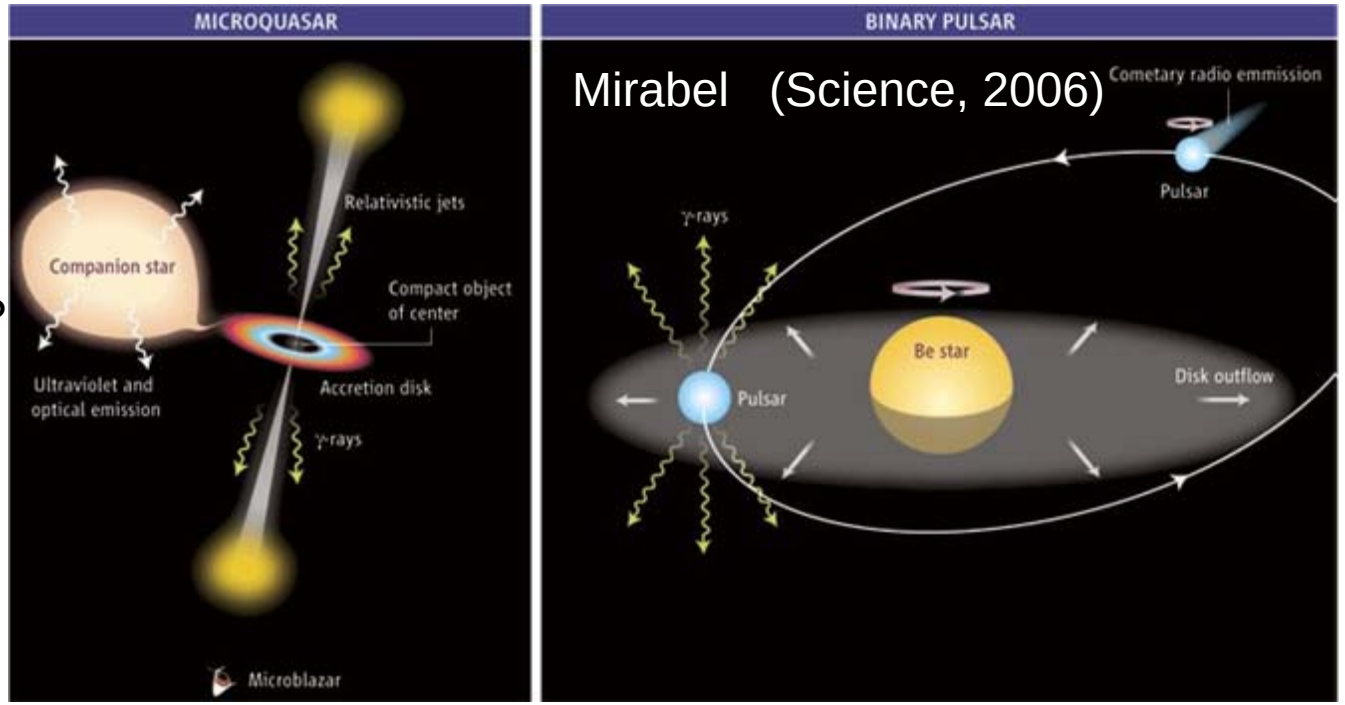
μQSOs XTE J1550-564 & H1743–322 Corbel et al. Science (2002, 2005)

X-rays are produced by synchrotron ⇒ electrons accelerated to TeV energies

TeV PHOTONS FROM COMPACT BINARIES

- **TeV electrons in μQSOs** XTE J1550-564 & H1743-322 (Corbel et al. Science 02, 05)
- **VHE (>100 GeV)** from LS 5039, PSR B1259-63, LSI +61 303 & **Cyg X-1**

Cyg X-1 ?



PSR B1259-63

LSI +61 303

&

LS 5039 ?

Pulsar wind: In LSI +61 303 it spins as a function of orbital phase (Dhawan et al. 2006)

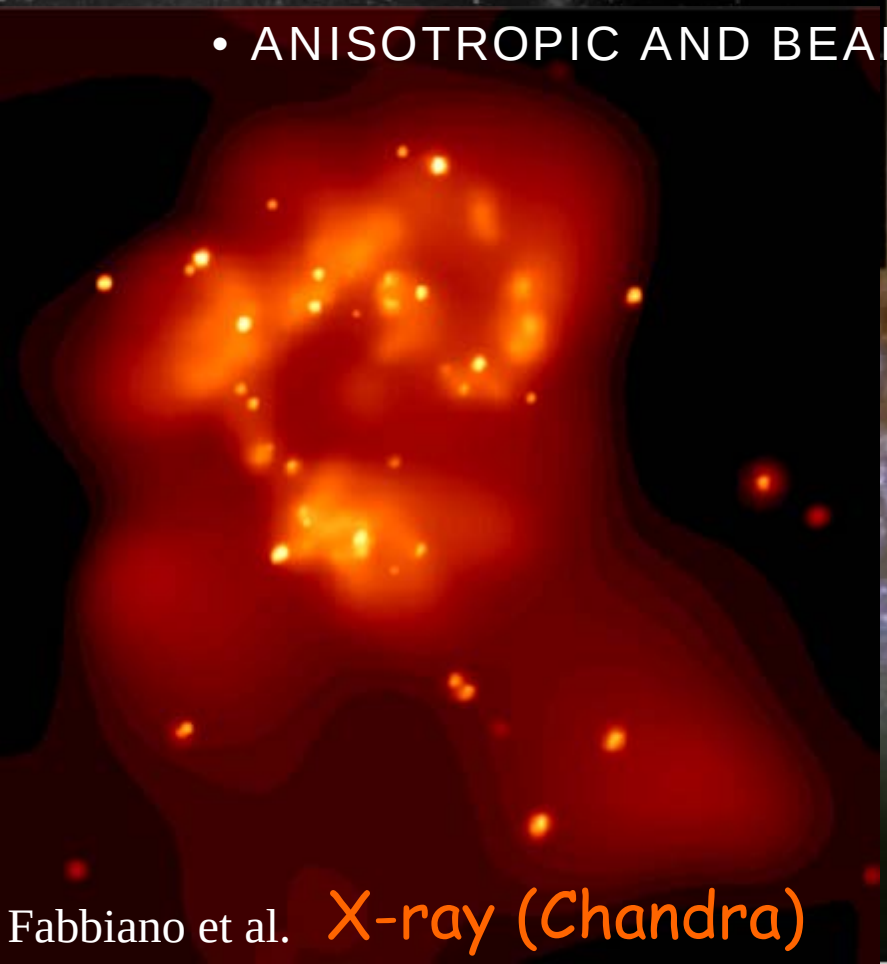
μQSO jets in no μblazar source Cyg X-1: Romero (2005); Albert…Paredes in Science

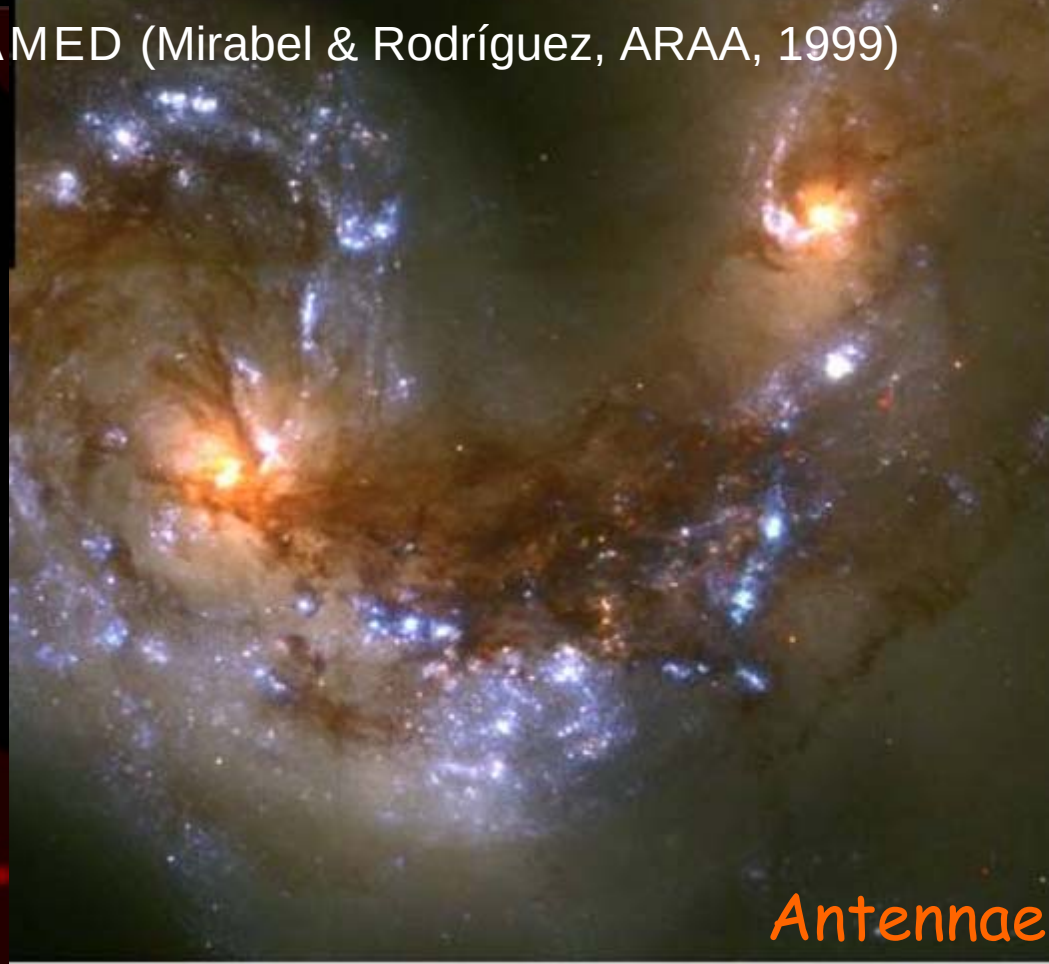
TeV intraday variability from M87 supports jet models (Aharonian... Science, 2006)

ULTRALUMINOUS X-RAY SOURCES

Are most of them microquasars in external galaxies ?

- BLACK HOLES OF INTERMEDIATE MASS (10^2- 10^4 $M_\odot$) ?
- ISOTROPIC BUT $M_{BH} > 30\ M_\odot$ (Pakull et al. 2002)
- ANISOTROPIC BUT NOT BEAMED (King et al. 2001)
- ANISOTROPIC AND BEAMED (Mirabel & Rodríguez, ARAA, 1999)





MICROBLAZARS

(Mirabel & Luis Rodríguez, ARAA 1999)

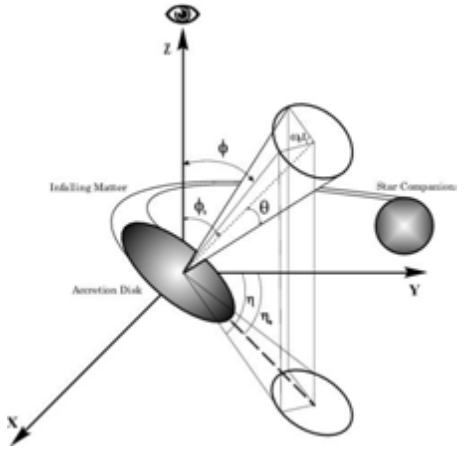
Due to relativistic beaming: $\Delta t \propto 1/2\gamma^2$; $I \propto 8\gamma^3$

e.g. **If** $\gamma = 5$, $\Theta < 10^o \Rightarrow \Delta t < 1/50$ **and** $\Delta I > 10^3$

SHOULD APPEAR AS SOURCES WITH FAST AND INTENSE VARIATIONS OF FLUX $\Rightarrow$ DIFFICULT TO FOLLOW AND TO FIND

Possible μblazars in BH HMXBs

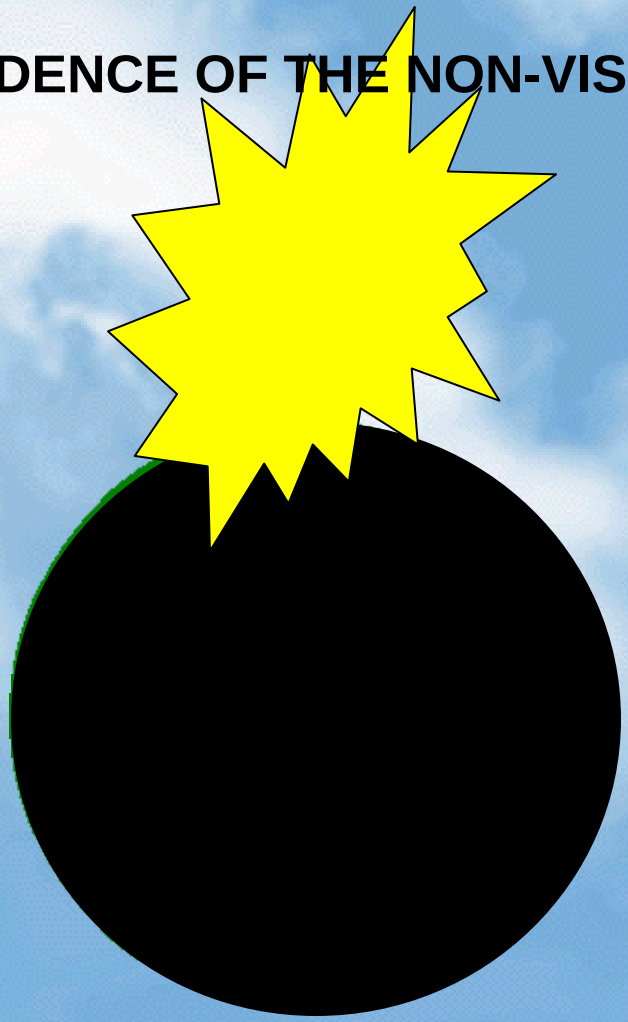
(Romero, Kauffman, Mirabel, 2002)



HORIZON IS THE BASIC CONCEPT THAT DEFINES BLACK HOLES

IT IS DIFFICULT TO OBTAIN DIRECT EVIDENCE OF THEIR EXISTENCE

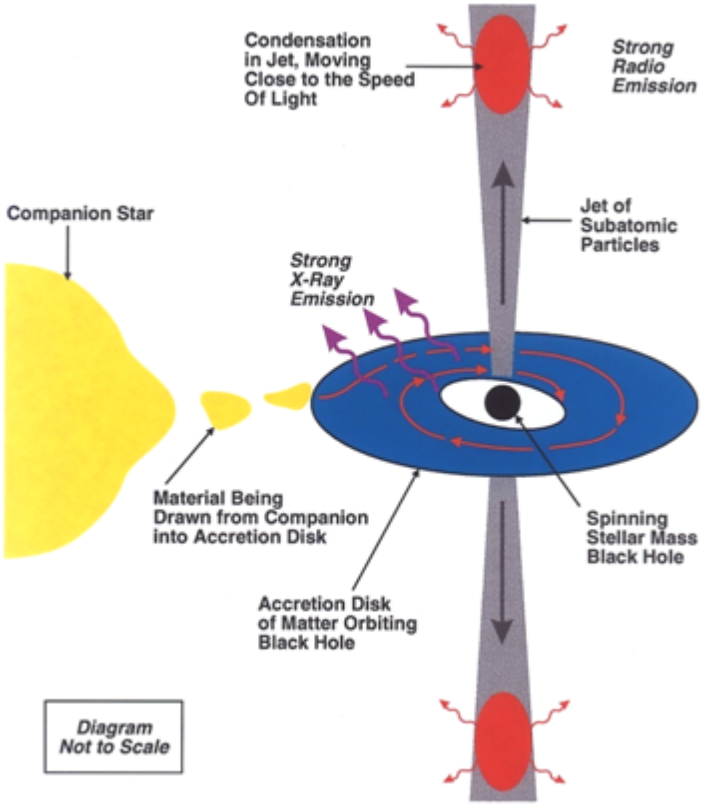
“FAITH IS THE EVIDENCE OF THE NON-VISIBLE” (St. Paul)



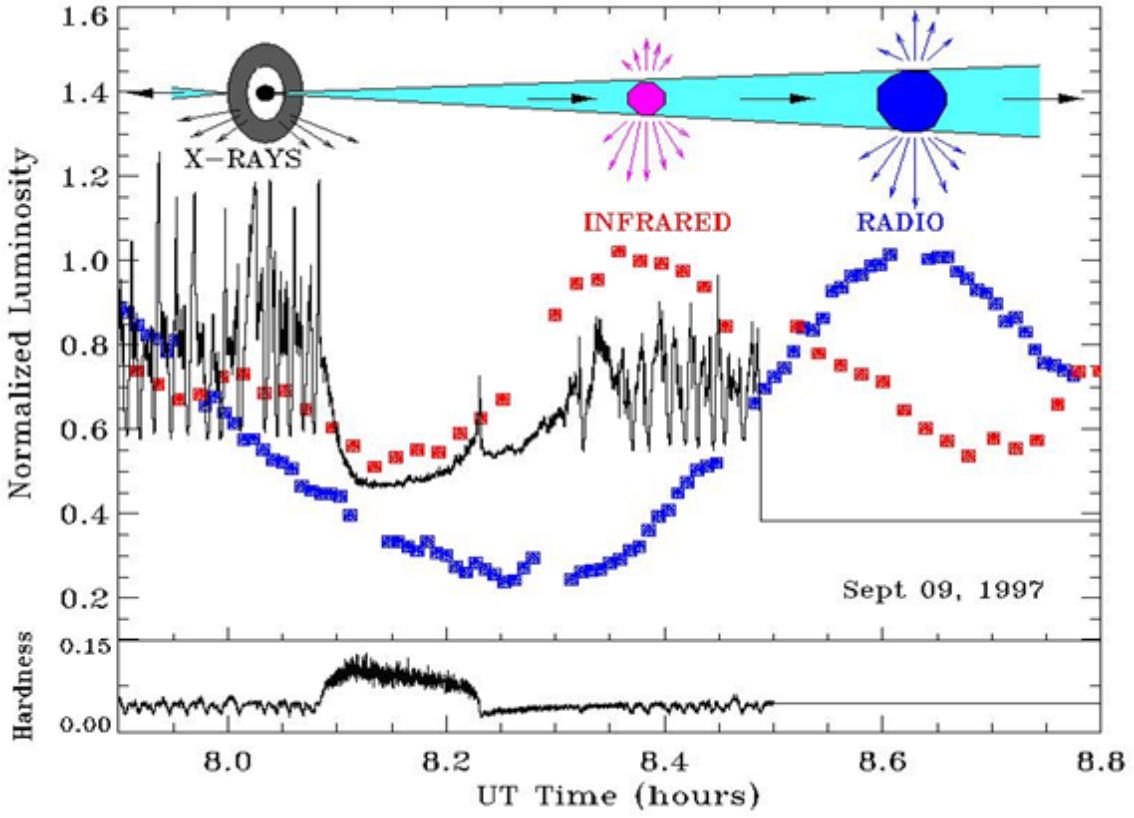
ACCRETION–JET CONNECTION

$\Delta T \propto M_{BH}$

1 hr = 30 yr in SgrA*



GRS 1915+ 105 (Mirabel, Chaty et al. 1998)



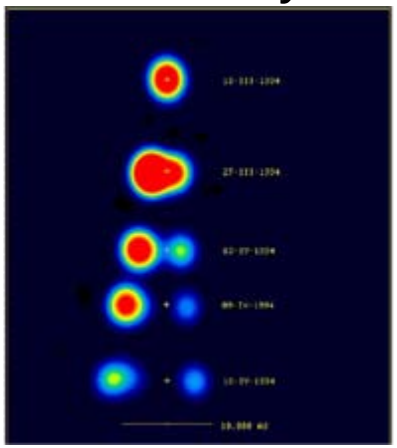
- **ABSCENCE OF EVIDENCE FOR A MATERIAL SURFACE IN A M_{BH} =14 $M_{\odot}$**
- **THE ONSET OF THE JET IS AT THE TIME OF A X-RAY "SPIKE"**
- **SUDDEN REFILL OF THE DISK & SHOCK THROUGH COMPACT JET**

UNIVERSAL DISK-JET COUPLING IN BLACK HOLES

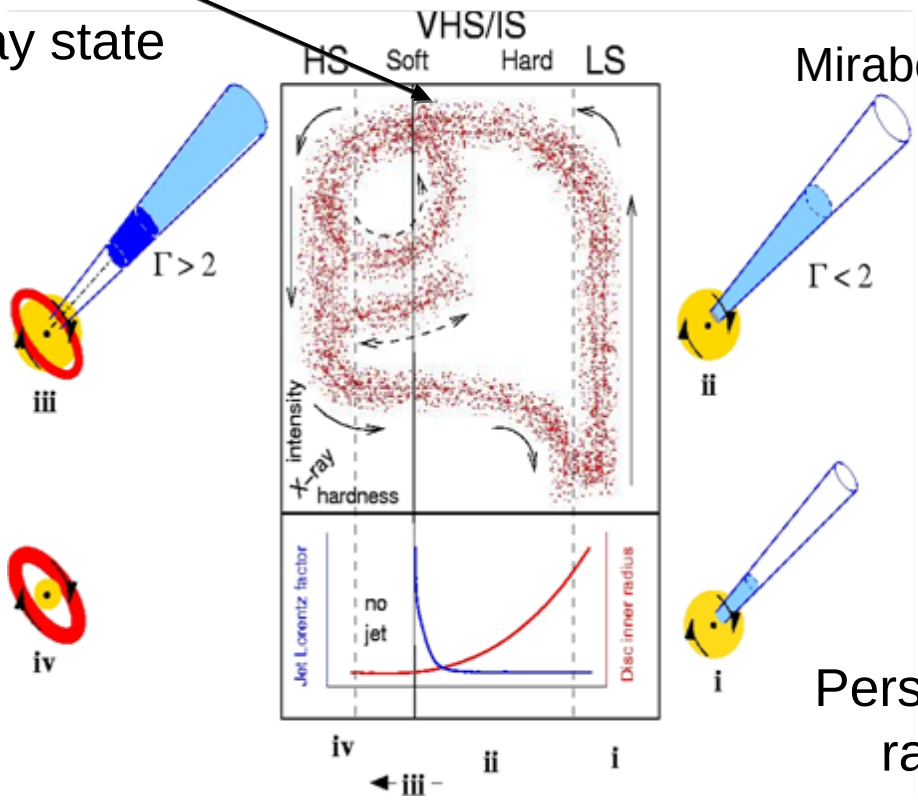
Outburst with rapid transition from hard to soft X-ray state

Fender et al. (2006)

Soft X-rays

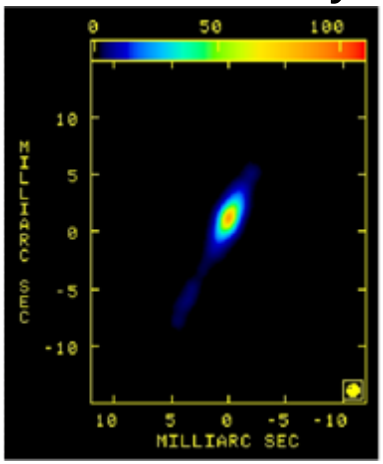


Transient, optically thin radio jets: $\Gamma > 2$



Mirabel, Chaty et al. (2005)

Low-hard X-rays



Persistent, flat spectrum radio source: $\Gamma < 2$

- The transient radio jets are produced by internal shocks
- Disk-jet coupling also observed in QSOs (Marscher et al Nature 2004)
- How are BH binary states related to AGN types ? (Köerding et al.)

GAMMA-RAY BURSTS: FORMATION OF STELLAR BLACK HOLES

THE MOST POWERFUL EXPLOSIONS AFTER THE BIG BANG

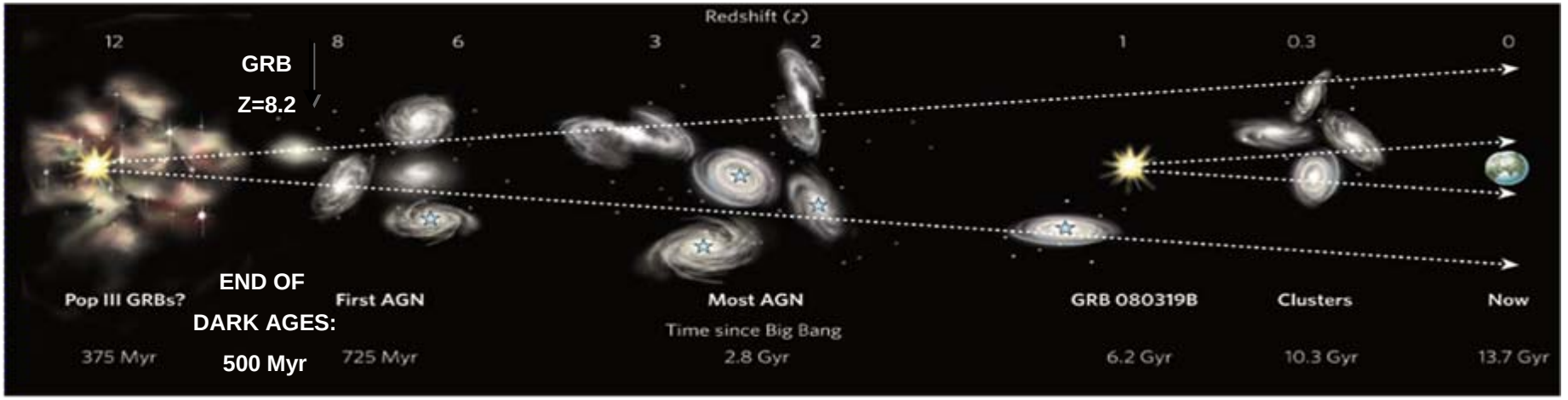
Collapse of stars & super-relativistic jets

Hiper-novae explosions of type SN $I_{b/c}$

BUT

- Two nearby LGRBs with no bright SNe
- A faint core collapse $SN_{b/c}$ (Nat.4/6/09)

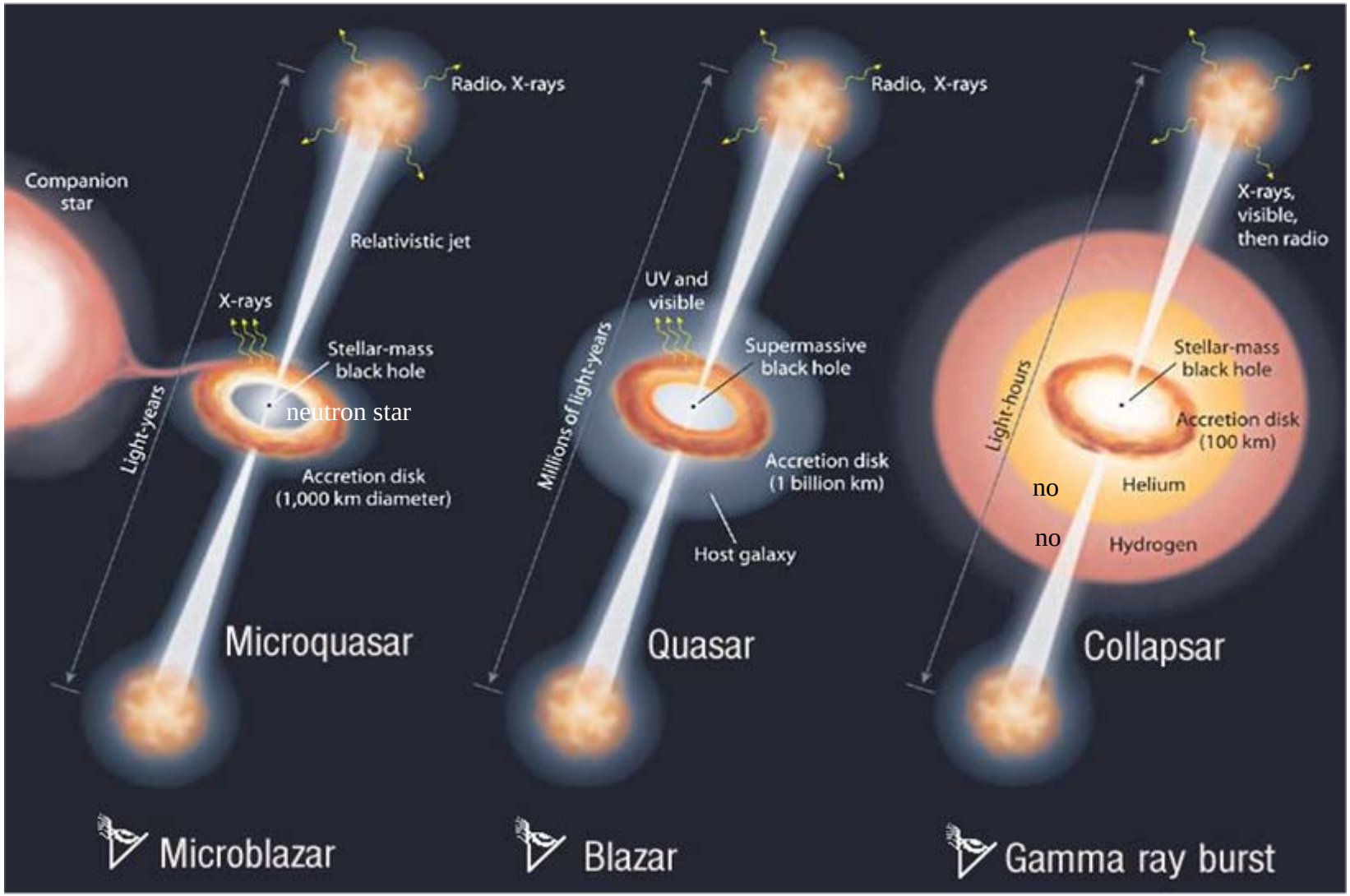
.μQSs ⇒ BHs may form by implosion



Timeline of the Universe since the formation of the first stars

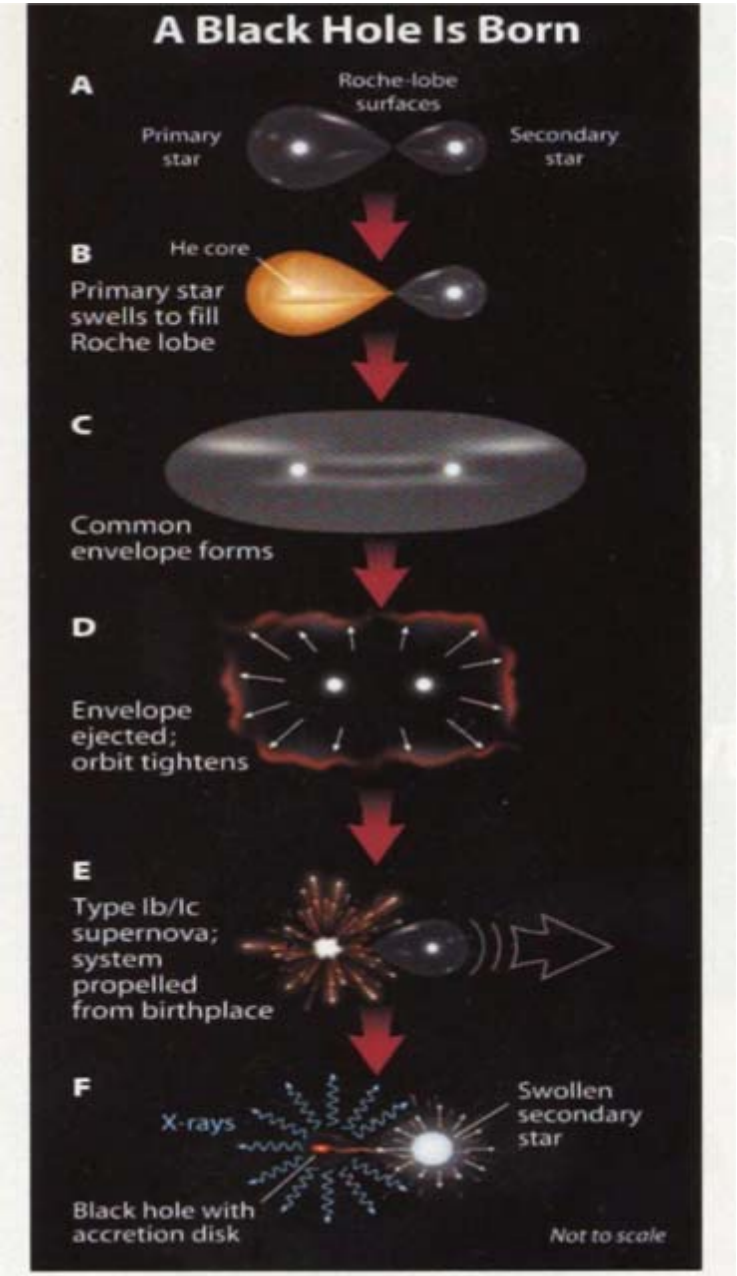
QSO - μQSO - GRB ANALOGY

HAVE THE SAME 3 BASIC INGREEDIENTS (Mirabel & RodrÍguez, S&T 2002)



AN UNIVERSAL MAGNETO-HYDRODINAMIC MECHANISM FOR JETS ?

HOW ARE STELLAR BLACK HOLES FORM ?



CORE COLLAPSE MODELS:

DELEYED VERSUS DIRECT COLLAPSE AS A FUNCTION OF THE MASS OF THE CORE:

Massive black holes ($M>10\ M_{\odot}$) should form without luminous SNe & energetic kicks

(Fryer & Kalogera ; Woosley & Heger; Nomoto et al.)

BUT NO OBSERVATIONS TO TESTS:

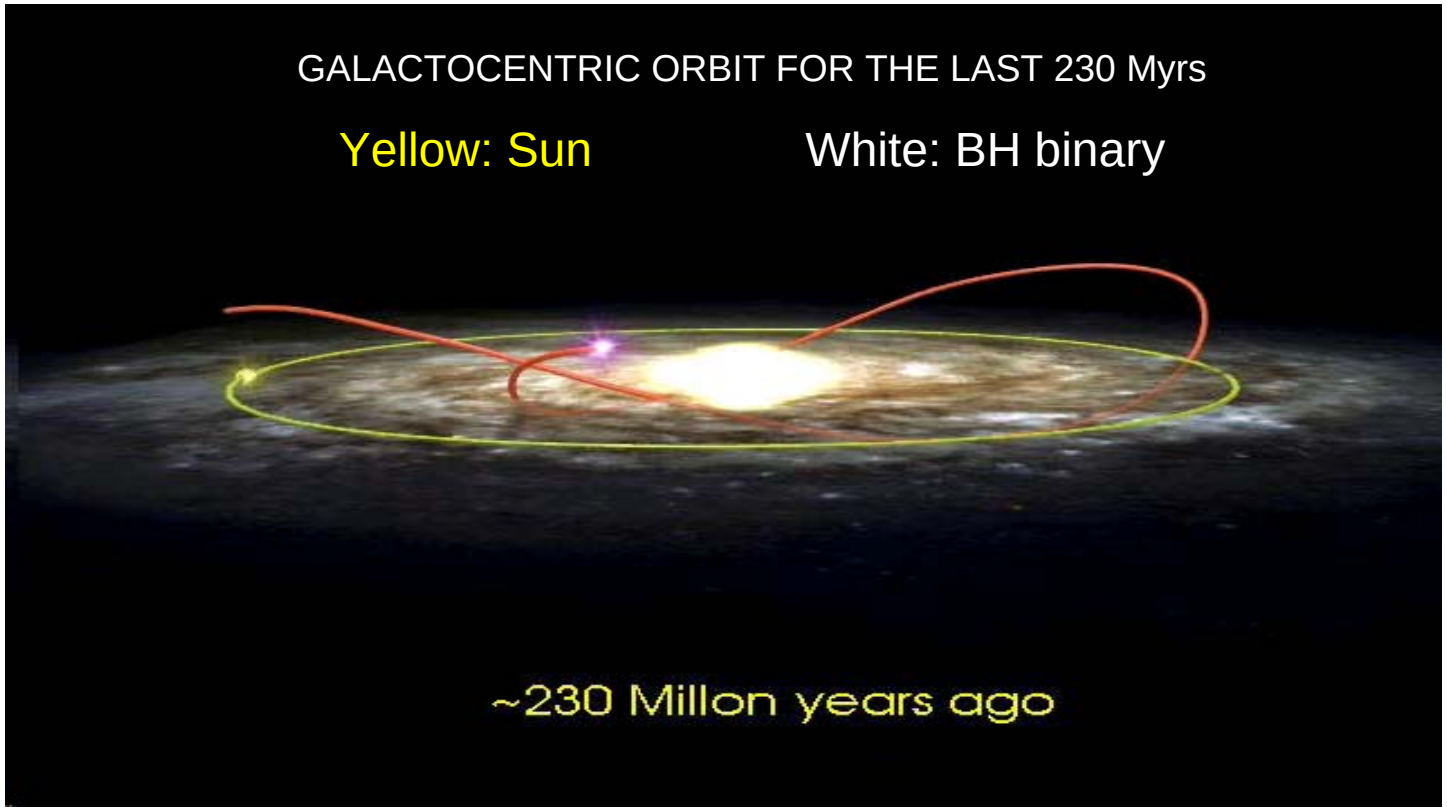
USE THE KINEMATICS OF μQSOs TO TEST THE CORE COLLAPSE MODELS

Mirabel & Irapuan Rodrigues (2001-2009)

A RUNAWAY BLACK HOLE IN THE GALACTIC HALO

XTE J1118+480 M_{BH}~7 $M_\odot$ M_*=0.1–0.5 $M_\odot$; l=158º b=+62º ; D=1.9 kpc

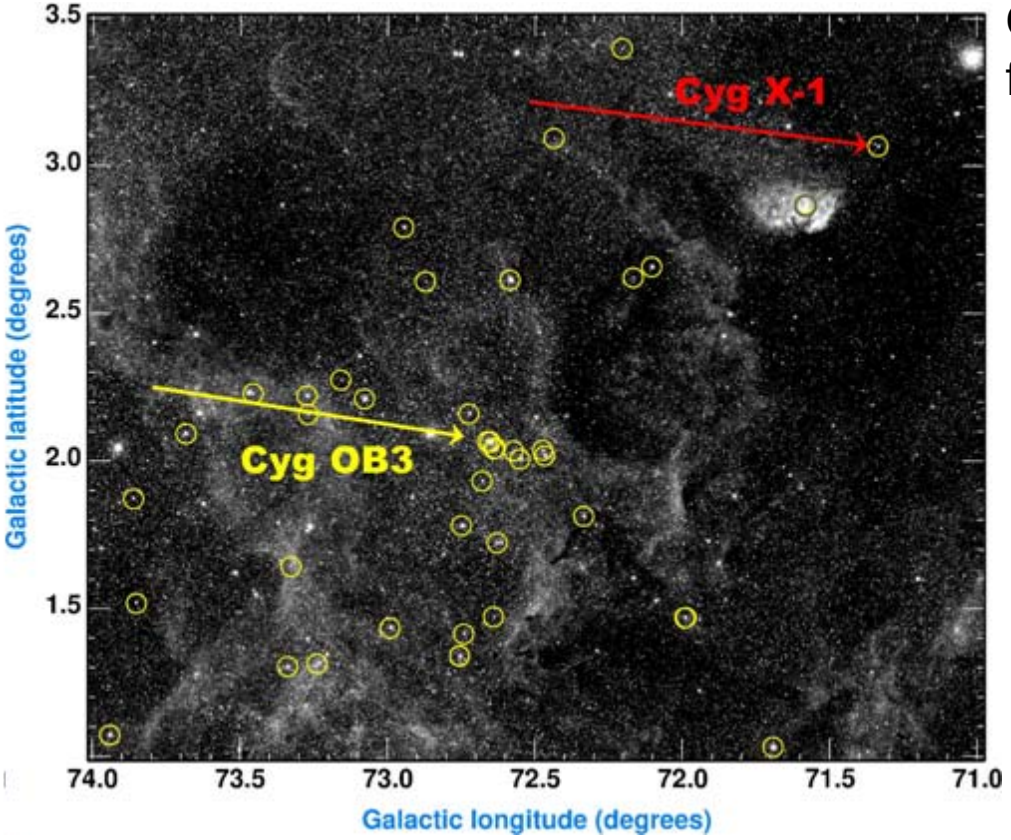
Mirabel, Rodrigues, et al. (Nature, 2001)



WAS THIS LOW-MASS BLACK HOLE FORM IN A GLOBULAR CLUSTER OR WAS IT SHOT OUT FROM THE GALACTIC THIN DISK BY AN ENERGETIC NATAL SN EXPLOSION ?

THE ~10 $M_\odot$ BLACK HOLE IN Cyg X-1 WAS BORN IN THE DARK

Mirabel & Irapuan Rodrigues (Science, 2003)



V < 9+/-2 km/s ⇒ < 1 $M_\odot$ ejected in SN

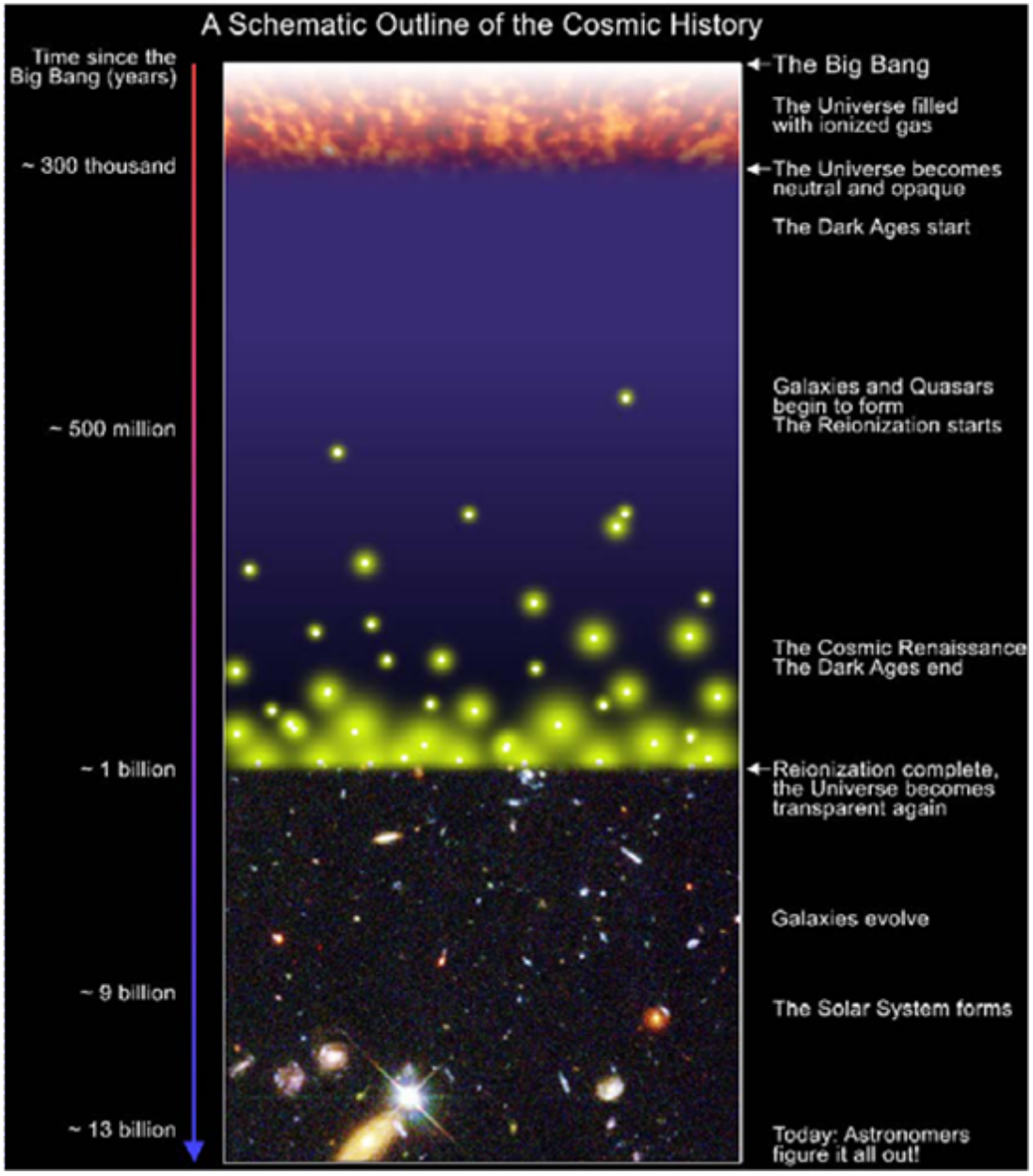
Otherwise it would have been shot out from the parent stellar association

- In addition, the 14 $M_\odot$ in GRS 1915+105 & the15 $M_\odot$ in V404 Cyg black holes move on the plane. Their peculiar motions can be explained by Galactic diffusion.
- Two LGRBs at z ~ 0.1 with no bright SNe: M(56Ni) < 10-3 $M_\odot$
- Discovery of low-energy core-collapse SNe without envelope (Nature, 2009)

DO BLACK HOLES OF > 10 $M_\odot$ FORM BY DIRECT COLLAPSE ?

Mirabel (2009, in preparation)

BLACK HOLES AND COSMIC EVOLUTION

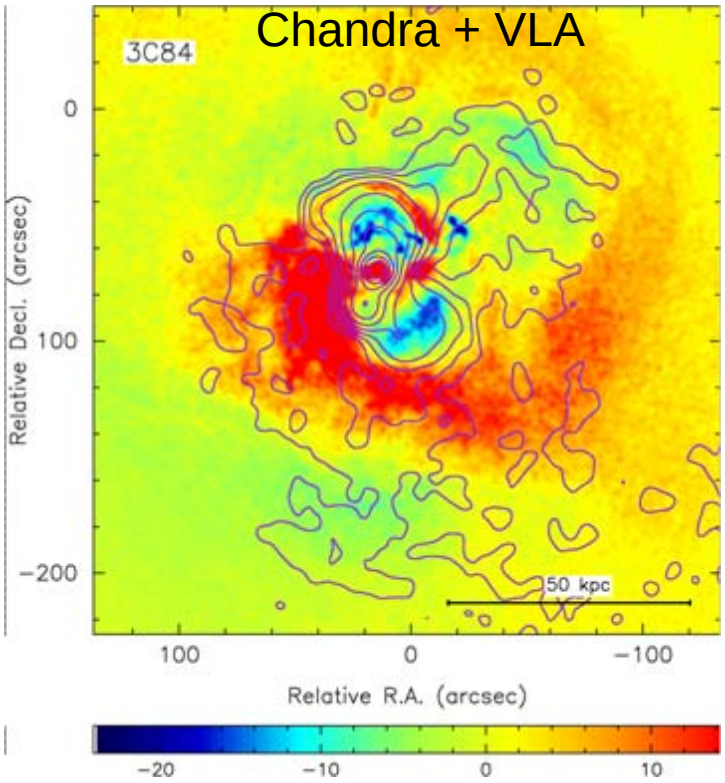


1) **At z = 6-14: black holes & massive stars make the universe transparent**

2) **At Z ~ 2: AGN stall cooling flows & regulate the growth of massive galaxies**

Fabian et al. 2004

Chandra + VLA

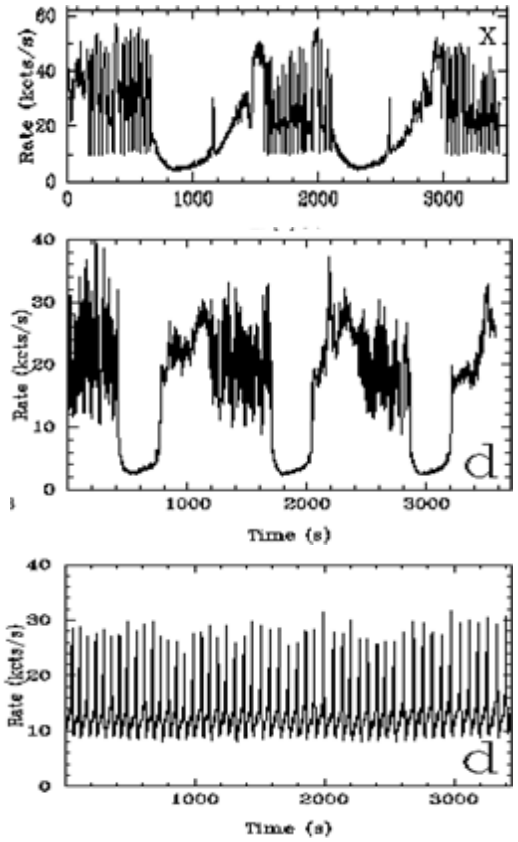


MEASURING THE SPIN OF BLACK HOLES FROM:

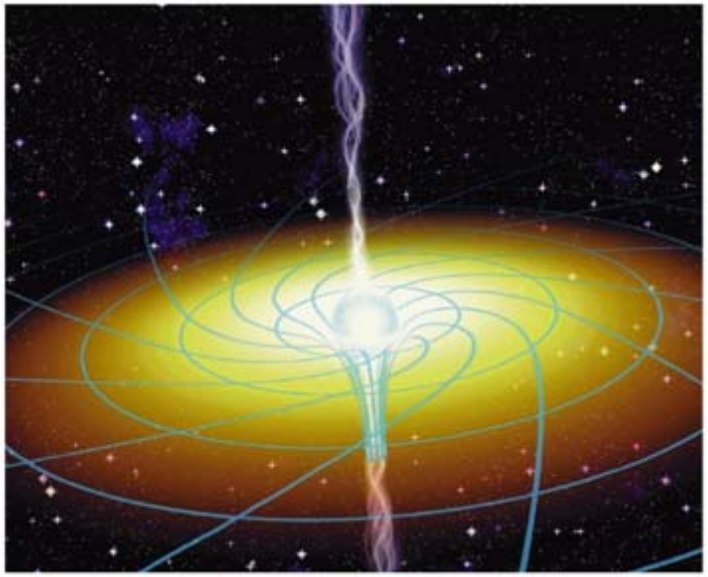
- Quasi-periodic oscillations (QPOs) of maximum fix frequency
- Accretion disk parameters
- Shape of the Fe Kα lines

QPOs AND GENERAL RELATIVITY

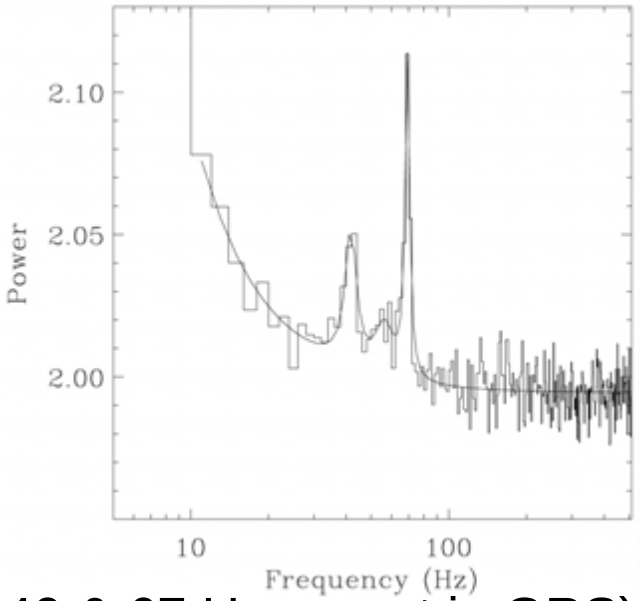
XTE & INDIAN SAT.



Jerome Rodriguez et al.



GRS 1915+105 (Strohmayer)

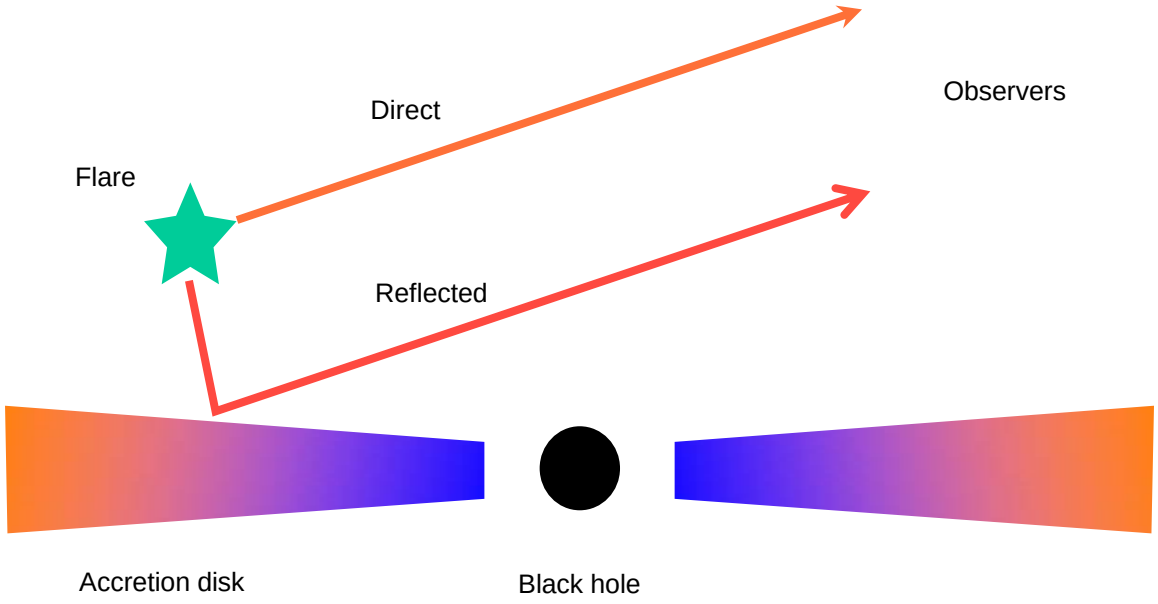


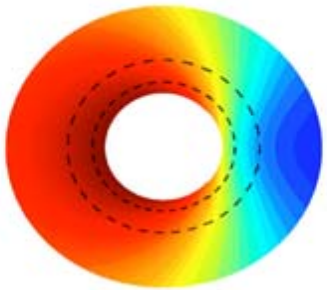
- High frequency QPOs (e.g. 40 & 67 Hz repeat in GRS)
- This 3:2 ratio now found in 4 BHXBs (Remillard et al.) ⇒ must depend on fundamental properties of black hole

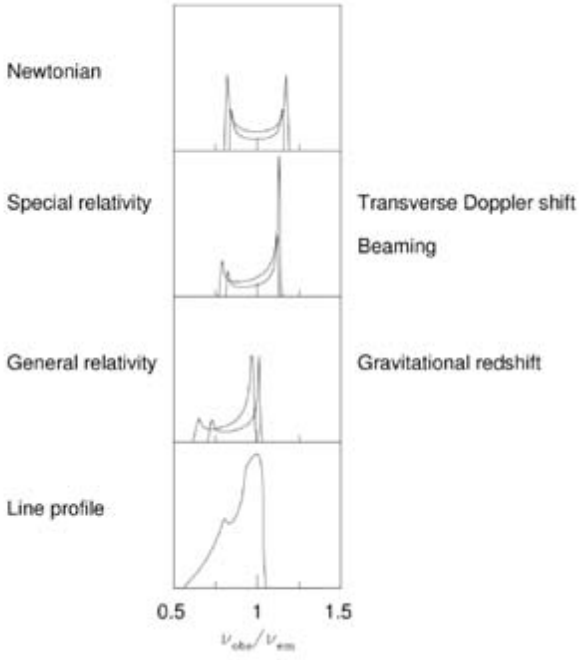
$\nu_{max} = f(M_{BH}, Spin) \Rightarrow$ DETERMINE THE SPIN OF BLACK HOLES

IN 4 BLACK HOLES THE SPINS DERIVED FROM QPOs & FROM DISK TEMPERATURES ARE CONSISTENT

Fe Kα LINES IN KERR BLACK HOLES





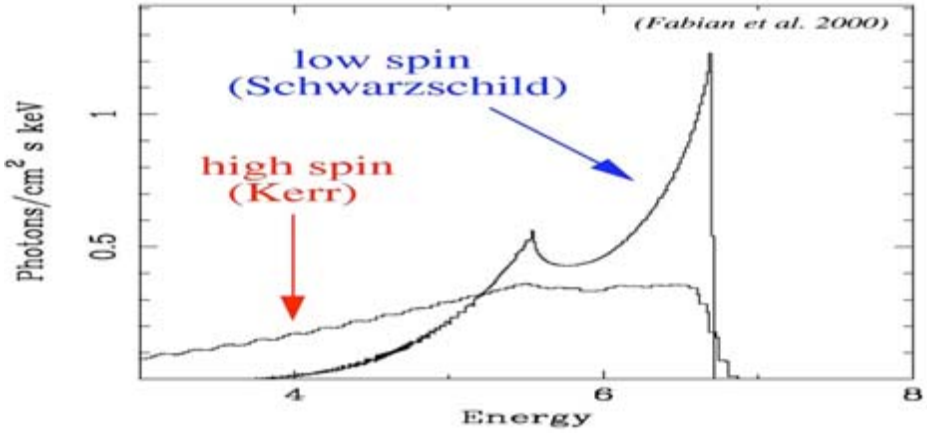


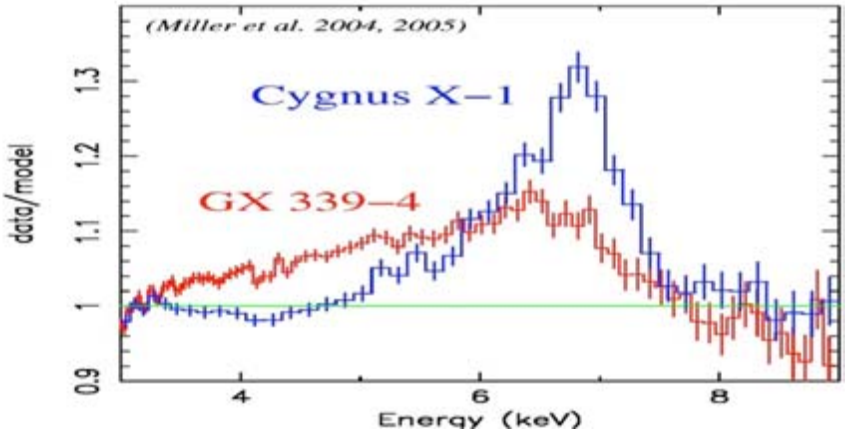
- Fluorescence lines are produced through reflection of X-rays on a cool accretion disk
  - The profile of the line is subject to gravitational redshifts, Doppler shifts, light bending effects & beaming

Fabian et al. (2000)

Broad lines in μQSOs ⇒ large spins

Miller (2009)

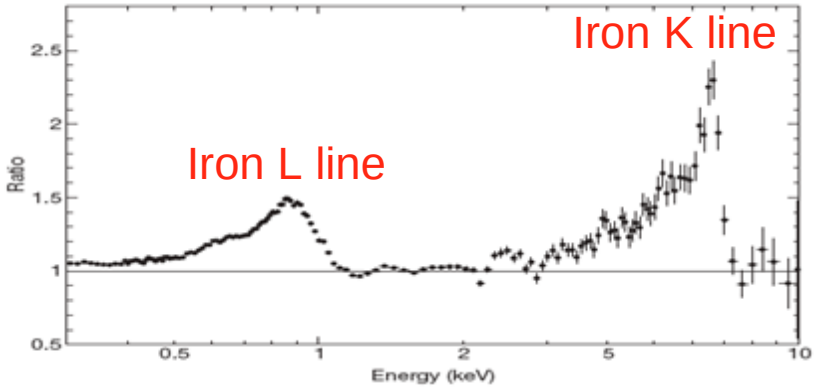




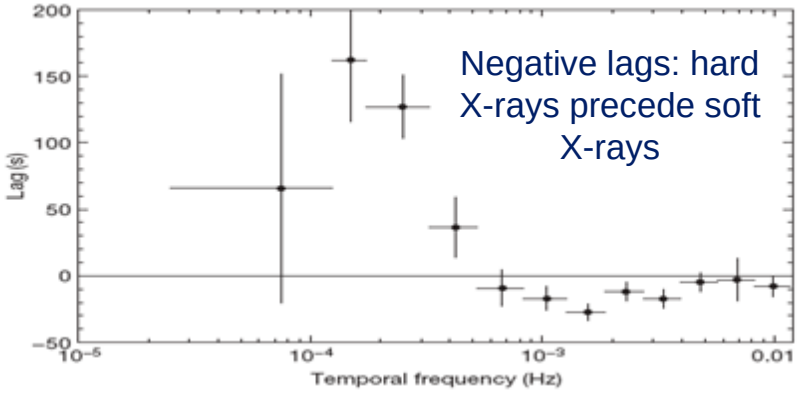
Broad line in the AGN 1H0707-495

Confirm the reflection model (Fabian et al. Nature, 2009)

Residual X-ray spectrum



Lag spectrum between the 0.3–1-keV and 1–4-keV bands



SUMMARY

Microquasars provide insight into:

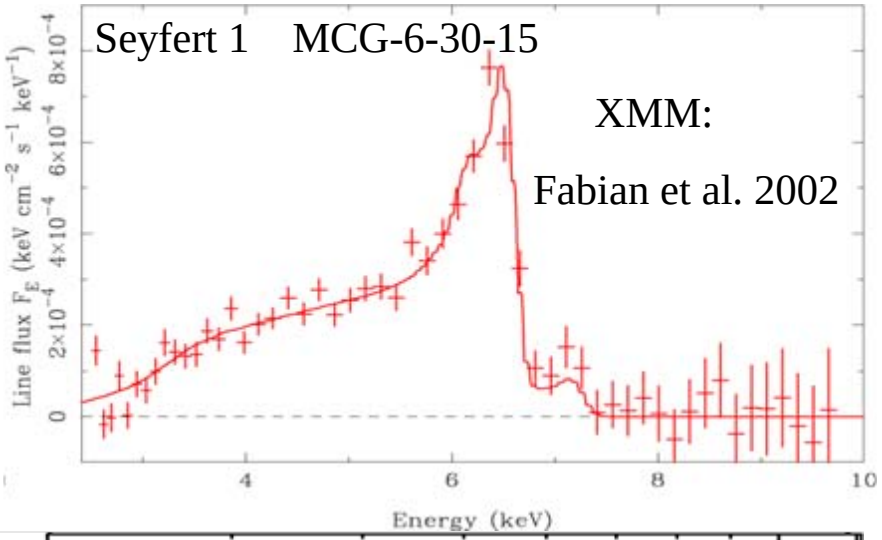
- **THE PHYSICS OF RELATIVISTIC JETS FROM BH's**
- **THE CONNECTION BETWEEN ACCRETION & EJECTION**
- **THE FORMATION OF STELLAR-MASS BLACK HOLES**

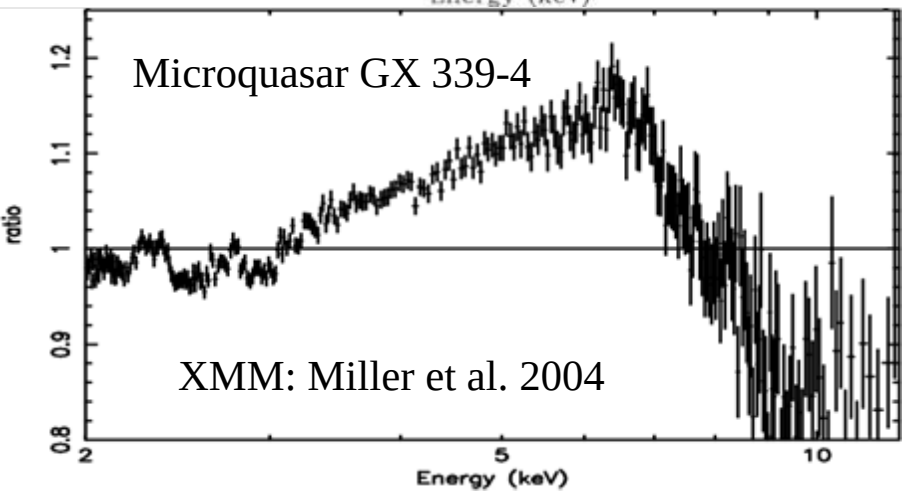
Microquasars could provide insight into:

- **A LARGE FRACTION OF ULXs IN NEARBY GALAXIES**
- **SOME OF THE DARK LGRBs AT LOW REDSHIFTS**
- **TeV EMISSION FROM COMPACT BINARIES & AGN**

THERE ARE HISTORICAL AND EPISTEMOLOGICAL ANALOGIES BEWEEN BLACK HOLE ASTROPHYSICS AND STELLAR ASTROPHYSICS

Fe Kα LINES IN KERR BLACK HOLES





General Relativity in the limit of the strongest gravitational fields

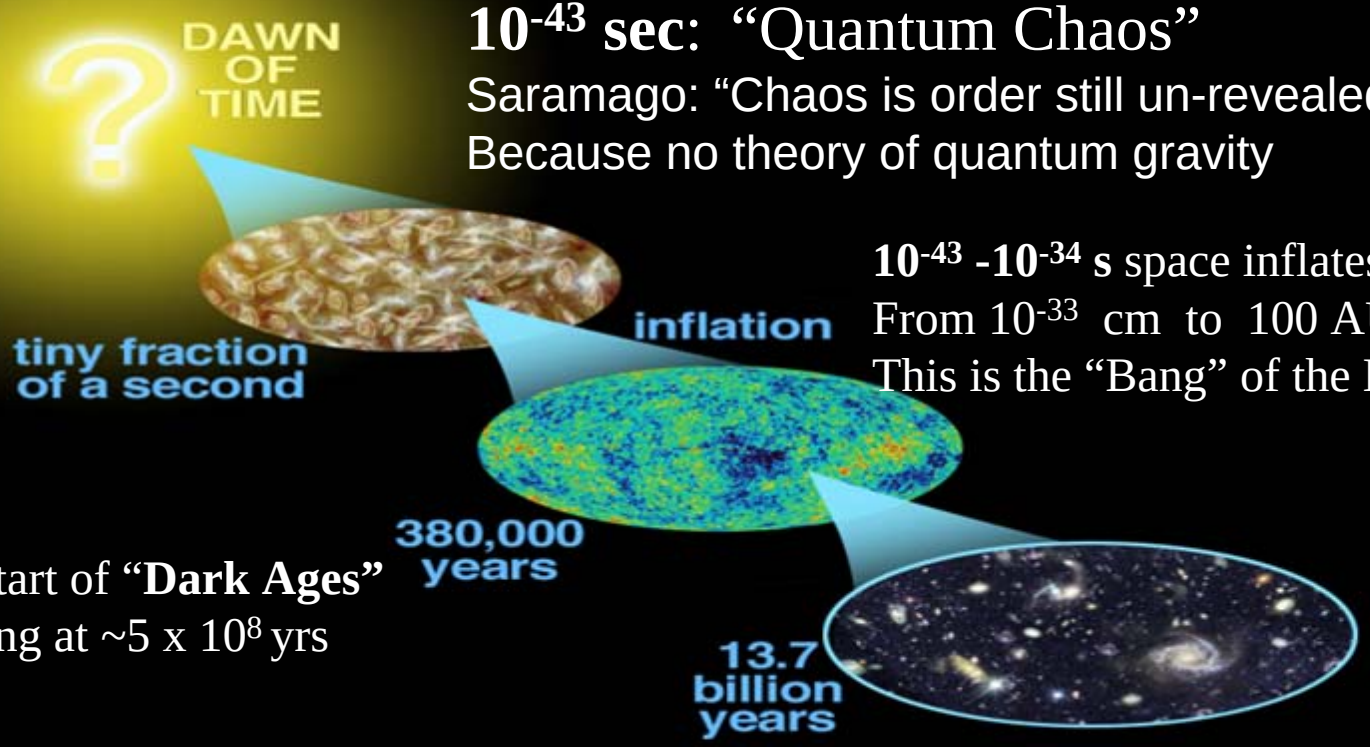
(Fabian & Tanaka)

- Seen in ~6 μQSOs and several AGN
- Asymmetry due to gravitational redshift & transverse-Doppler shift
- Broad component from inner disk

μQSOs ARE THE BEST LABORATORIES TO STUDY IN SHORT TIME SCALES THE Fe Kα LINES AS A FUNCTION OF X-RAY STATE

BLACK HOLES AND THE EVOLUTION OF THE UNIVERSE

Analogous singularities: Black Holes & "Big Bang"



10^{-43} sec: "Quantum Chaos"
Saramago: "Chaos is order still un-revealed"
Because no theory of quantum gravity

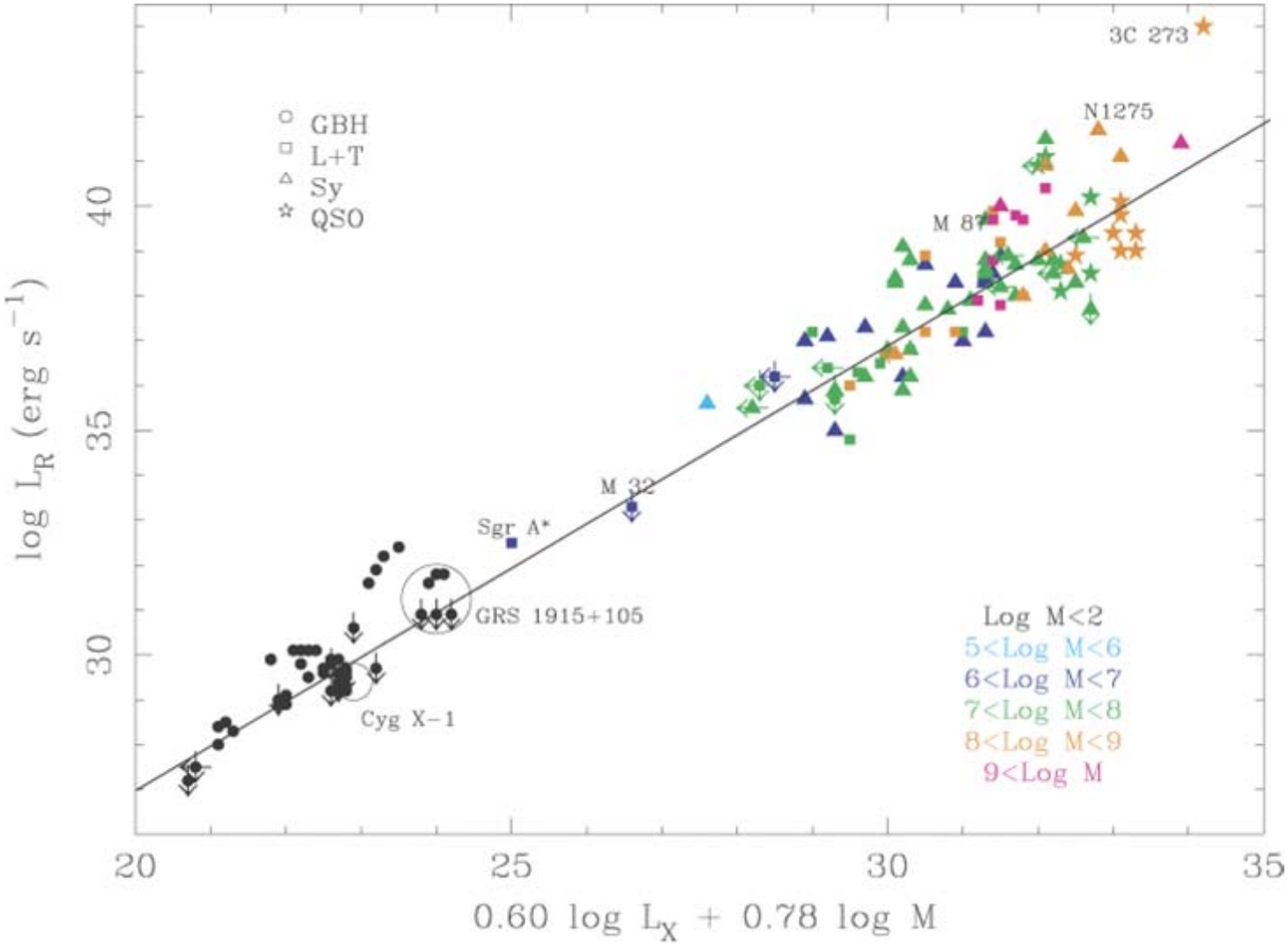
10^{-43} -10^{-34} s space inflates by 10^{50}
From 10^{-33} cm to 100 AU (>> c)
This is the "Bang" of the Big Bang

Atoms form. Start of "**Dark Ages**"
at 10^{7} yrs ending at ~5 x 10^{8} yrs

- **Stellar Black Holes & Massive Stars ended the "Dark Ages"**
- **Super-Massive Black Holes limited the growth of galaxies**

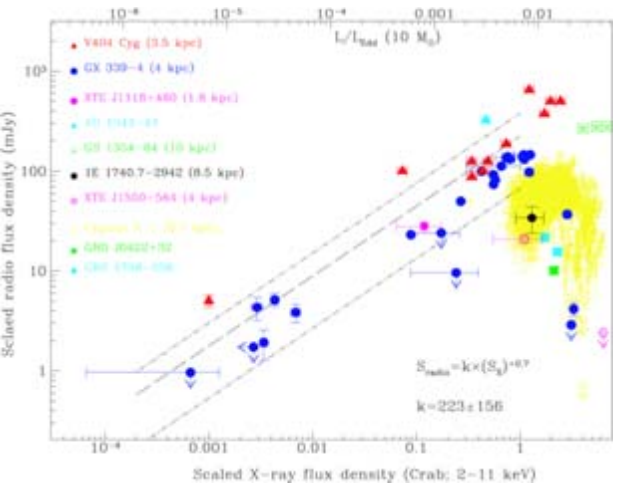
IS THERE A BLACK HOLE FUNDAMENTAL PLANE ?

Merloni et al. Falke, Koerding et al.

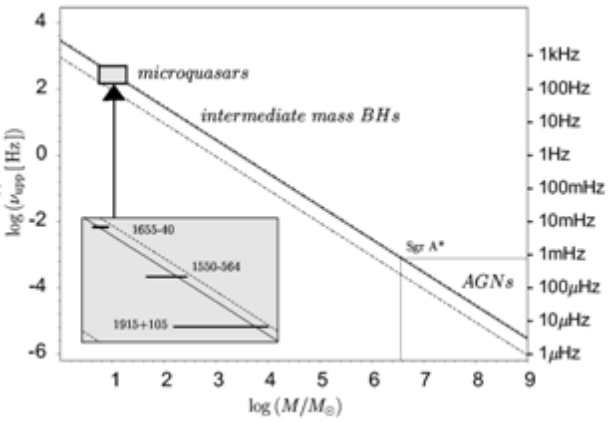


IF THE EMPIRICAL CORRELATIONS

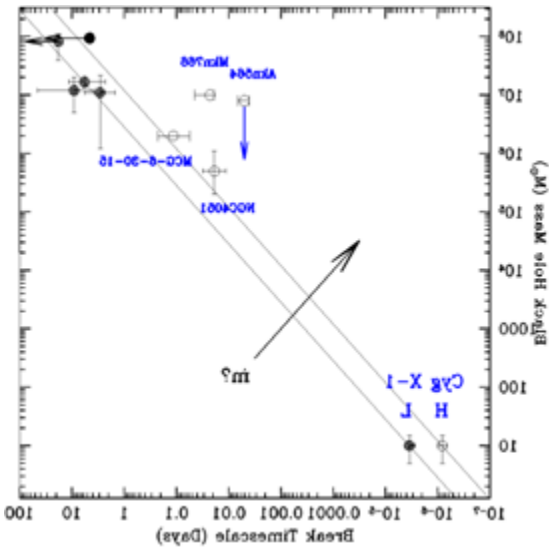
X-ray/radio/mass
Gallo et al. 2004



QPOs/mass
Abramovics, 2005



Noise-spectrum/mass
Uttley et al. 2004



BECOME MORE ROBUST, INDEPENDENTLY OF THE MODELS, THE MASS AND SPIN OF BLACK HOLES WILL BE DETERMINED

HISTORICAL & EPISTEMOLOGICAL ANALOGIES BETWEEN STELLAR & BH ASTROPHYSICS

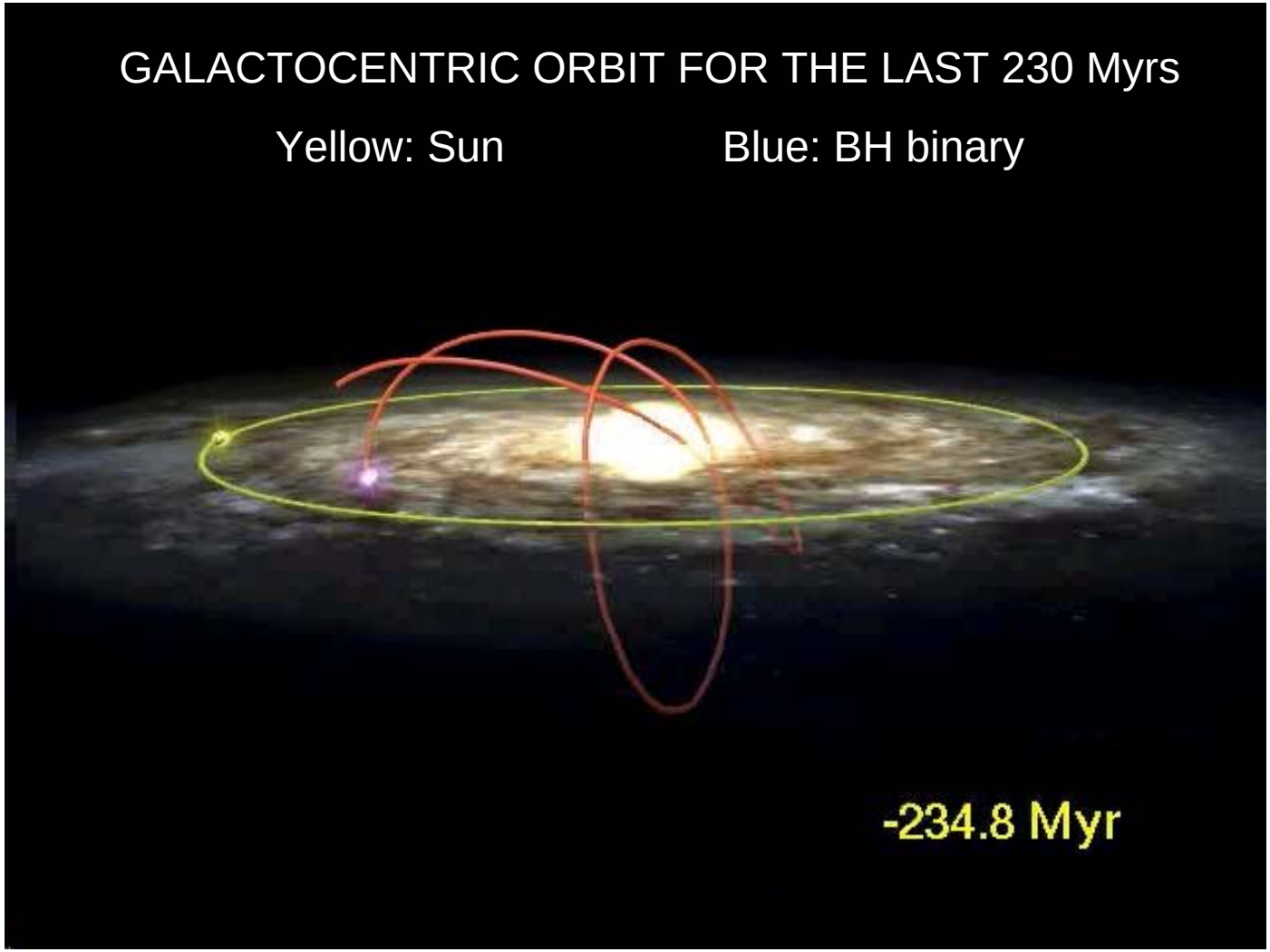
- BH ASTROPHYSICS IS TODAY IN SIMILAR SITUATION AS STELLAR ASTROPHYSICS IN THE FIRST DECADES OF THE XX CENTURY WHEN THE HR DIAGRAM WAS ESTABLISHED.

- IN BOTH AREAS OF ASTROPHYSICS, EMPIRICAL CORRELATIONS PRECEEDED THE DEEP PHYSICAL UNDERSTANDING OF THE OBJECTS (STARS AND BHs).

  FROM OBSERVABLES CAN BE DERIVED THE MASS AND SPIN OF STARS AND BLACK HOLES.

THE GALACTIC TRIP OF SCORPIUS X-1

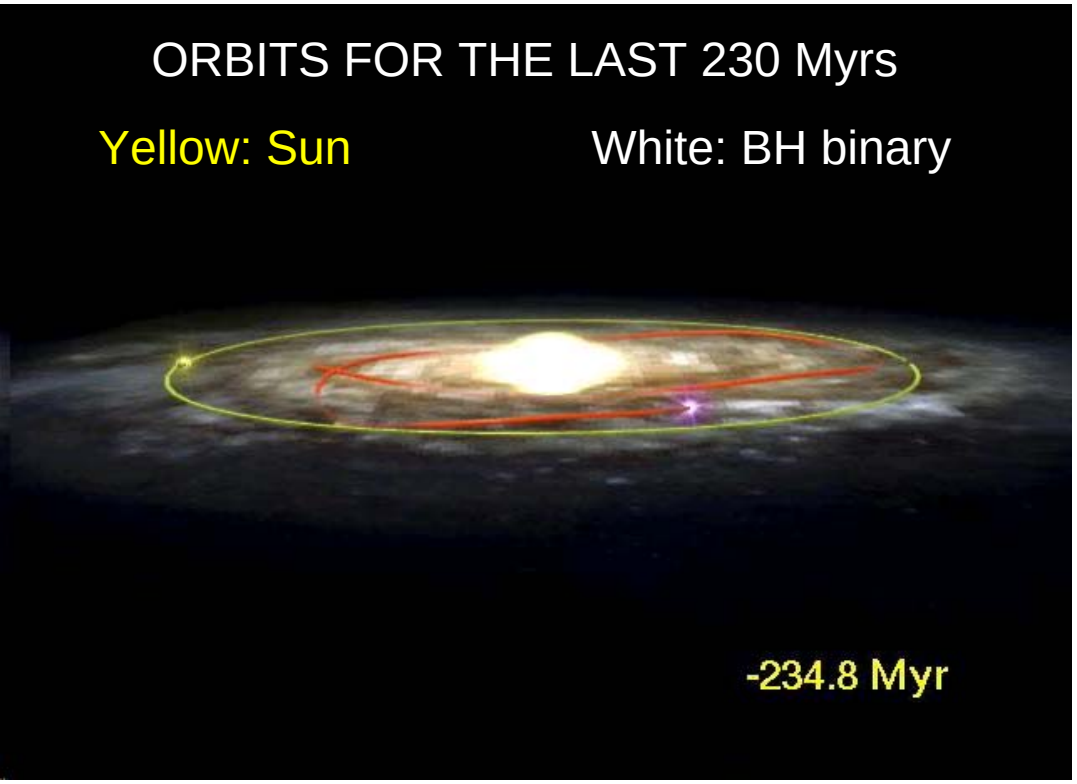
Mirabel & Rodrigues (A&A 398, L25, 2003)



GLOBULAR CLUSTERS ARE FACTORIES OF XRBs

A RUNAWAY BLACK HOLE

GRO J1655-40: M_{BH} ~ 4-6 $M_{\odot}$



FOSSIL OF A GRB FORMED IN AN HYPER-NOVA ?

(Israelian et al. Nature 2001)

Mirabel, Irapuan Rodrigues et al.

(A&A 395, 595, 2002)

Proper motion with HST +

radial velocity from ground

RUNAWAY VELOCITY ~120 km/s

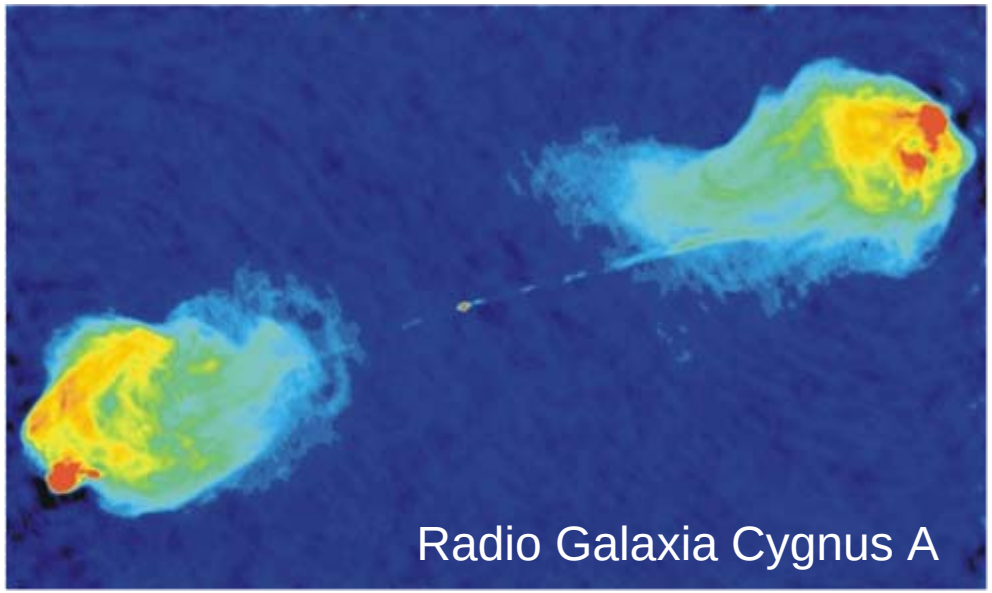
MOMENTUM = 550 $M_{\odot}$ km/s

as in runaway neutron stars

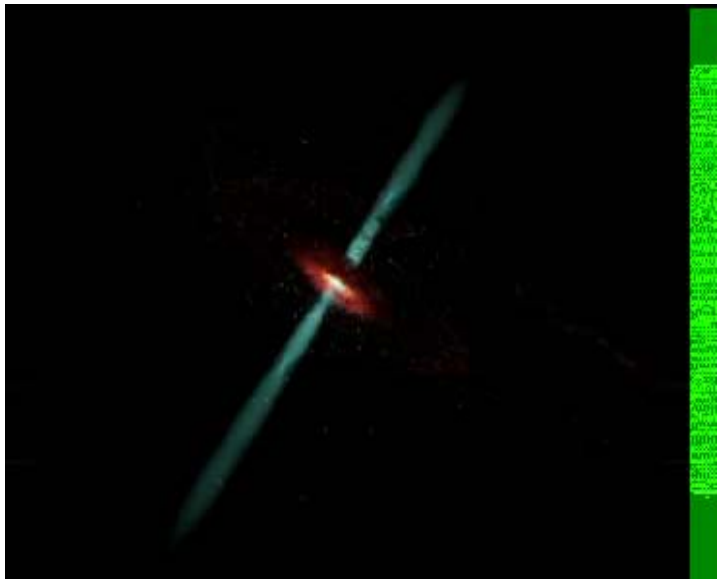
LOW-MASS BLACK HOLES FORM WITH ENERGETIC SUPERNOVAE ?

QUASARS & RADIO-GALAXIES

IN 1970´s THE TIME VARIABILITY IN QUASARS & RELATIVISTIC JETS IN RADIO GALAXIES **SUGGESTED** THE EXISTENCE OF SUPERMASSIVE BLACK HOLES



~500.000 años luz

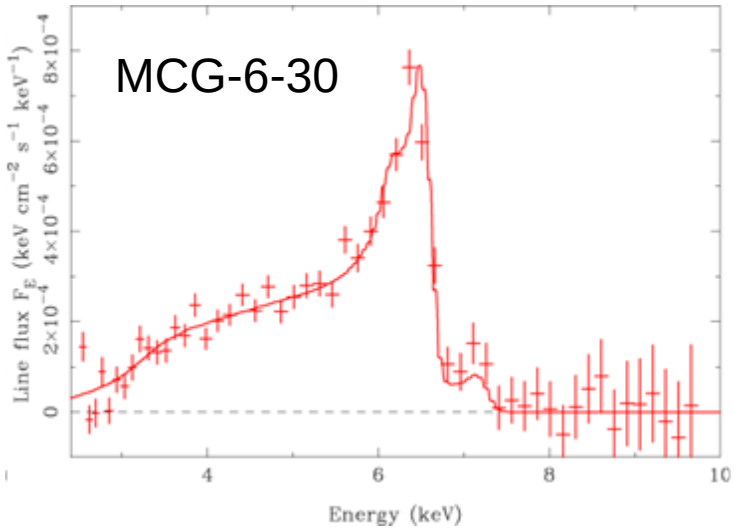


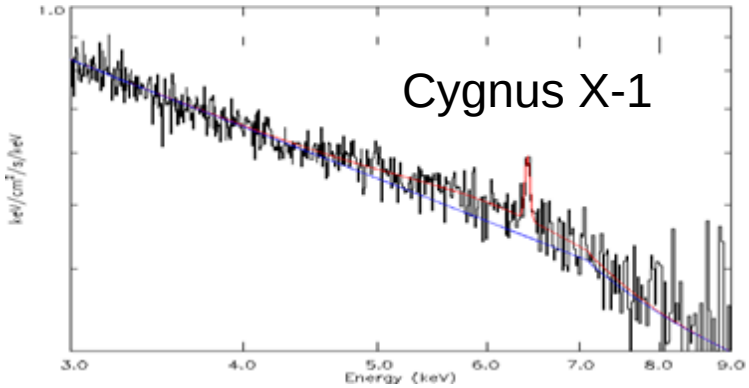
Magnetohydrodinamics

RELATIVISTIC JETS ARE POWERED AND COLLIMATED BY:

- Angular momentum of the compact object
- Angular momentum of the accretion disk
- Entrained magnetic fields

Fe Kα LINES FROM ACCRETING BHs





CHANDRA, XMM & Beppo-SAX

- Asymmetry: gravitational redshift, Doppler & transverse-Doppler shift
- Narrow component from outer disk ?
- Broad component from inner disk

ALSO FOUND IN ~6 MICROQASARS

SPINNING BLACK HOLES ?

μQSOs MAY BE GOOD LABORATORIES TO STUDY IN SHORT TIME SCALES THE Fe Kα LINES AS A FUNCTION OF X-RAY STATE (e.g. GRS 1915+105)