BLACK HOLES IN THE UNIVERSE: THE QUEST FOR MICROQUASARS

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on leave from CEA-France

THE IDEA OF BLACK HOLE

First proposed by John Michell in 1783

(Philosophical Transactions of the Royal Society)

IN THE CONTEXT OF CORPUSCULAR THEORY OF LIGHT:

"…suppose the particles of light to be attracted

in the same manner as all other bodies…"

THERE SHOULD EXIST BLACK HOLES:

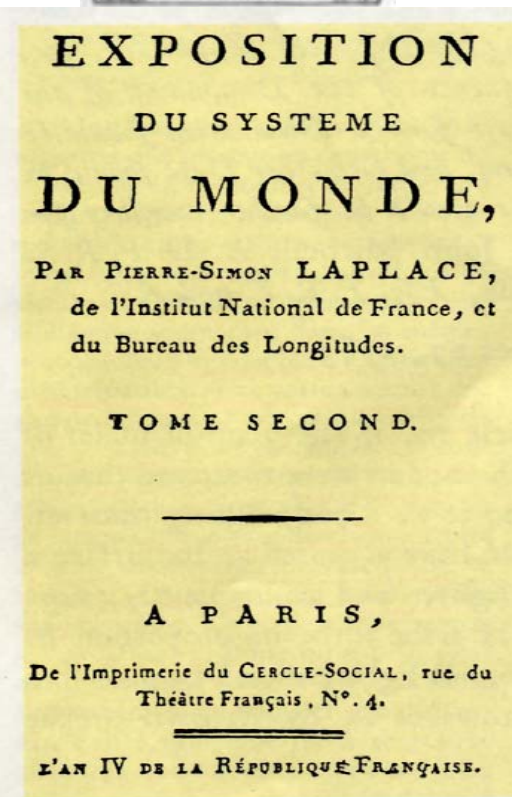
"…there should exist in nature bodies from which light could not arrive at us…"

CAN BE DETECTED BY THE MOTION OF COMPANION STARS:

"…we might still perhaps from the motions of these revolving bodies infer the

existence of the central objects with some degree of probability…"

SUPERMASSIVE BLACK HOLES


EXPOSITION

DU SYSTEME

DU MONDE,

PAR PIERRE-SIMON LAPLACE,
de l'Institut National de France, et
du Bureau des Longitudes.

TOME SECOND.

A PARIS,

De l'Imprimerie du CERCLE-SOCIAL, rue du
Théâtre Français, N°. 4.

L'AN IV DE LA RÉPUBLIQUE FRANÇAISE.

(in the context of Newtonian physics)

BLACK HOLES MAY EXIST:

"…tous ces **corps devenus invisibles**…"

IN VERY LARGE NUMBERS:

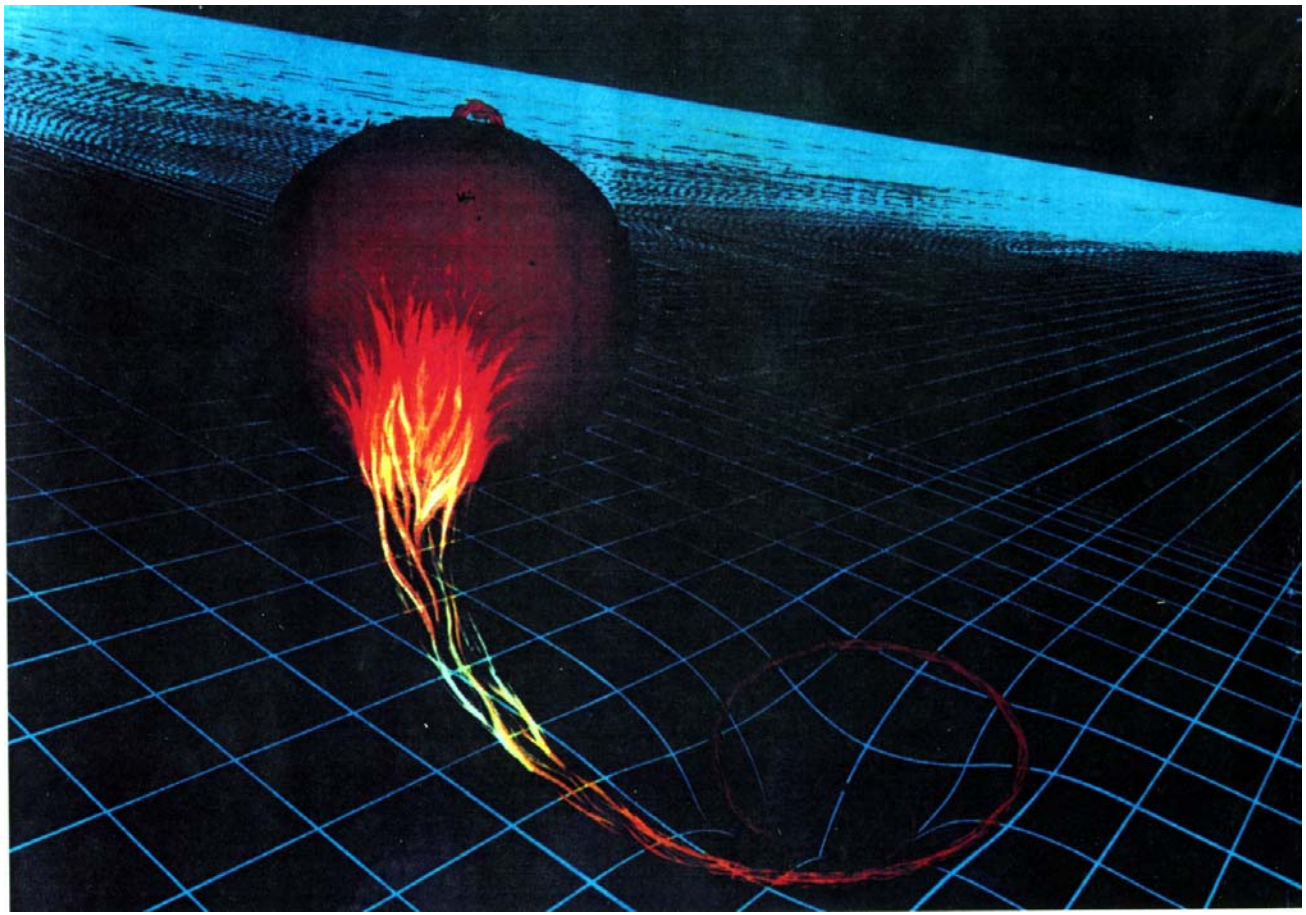
"…Il existe donc dans les espaces celestes, des corps obscurs aussi considerables, et peut etre en aussi grand nombre, que les etoiles."

THE LARGEST OBJECTS IN THE UNIVERSE:

"…ne lesserait en vertu de son attraction, parvenir aucun de ses rayons jusq'a nous; il est donc possible que les plus grands corps lumineux de l'univers, soient par cela meme, invisibles."

Idea remained silent due to the ondulatory theory of light

RELATIVISTIC GRAVITY



LIGHT IS DEFLECTED AND λ MODIFIED IRRESPECTIVE OF THE CORPUSCULAR OR WAVE NATURE OF LIGHT

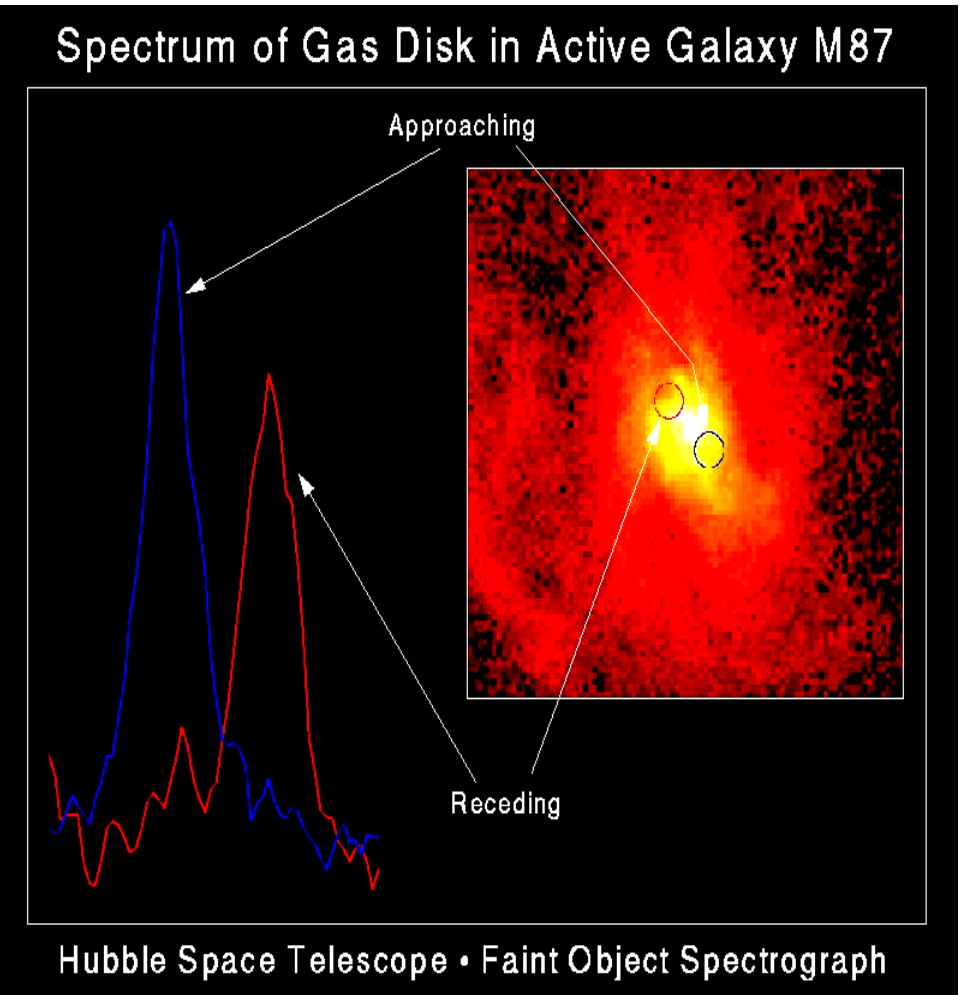
SUPERMASSIVE BLACK HOLES IN THE UNIVERSE

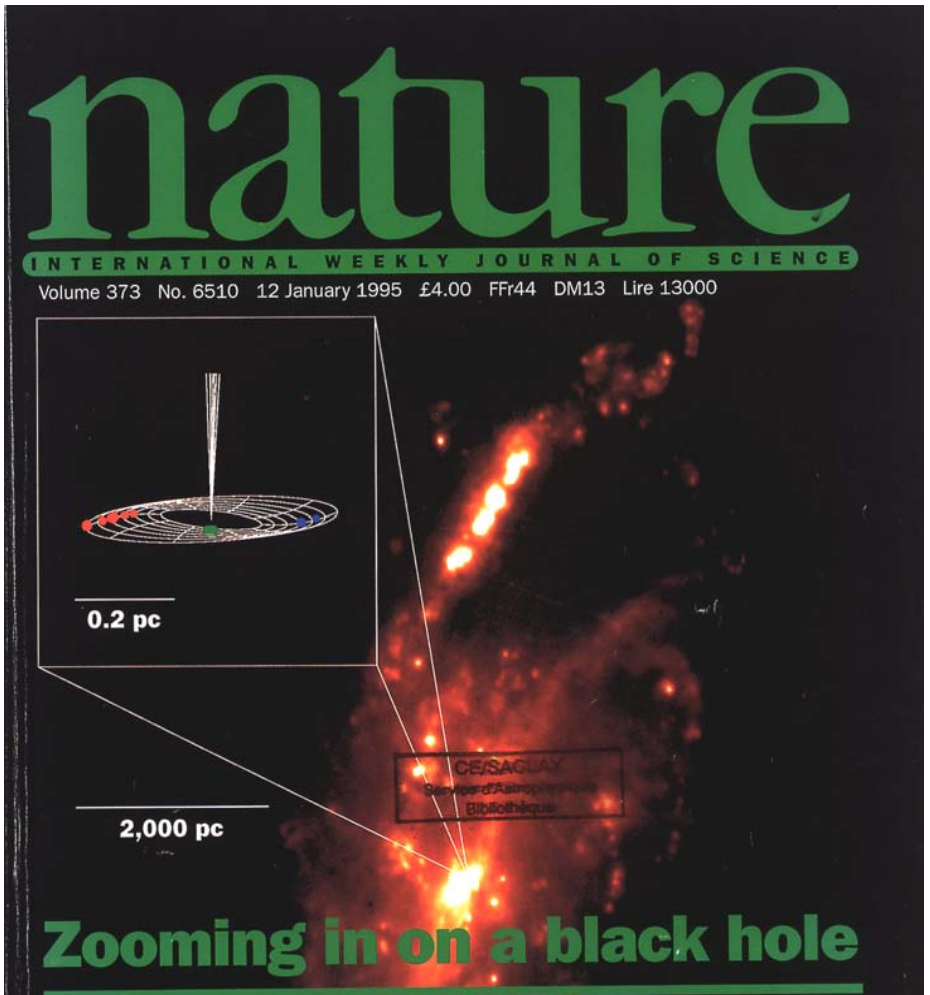
Kinematics of the H_α line with HST

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

H_2O masers with VLBA

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

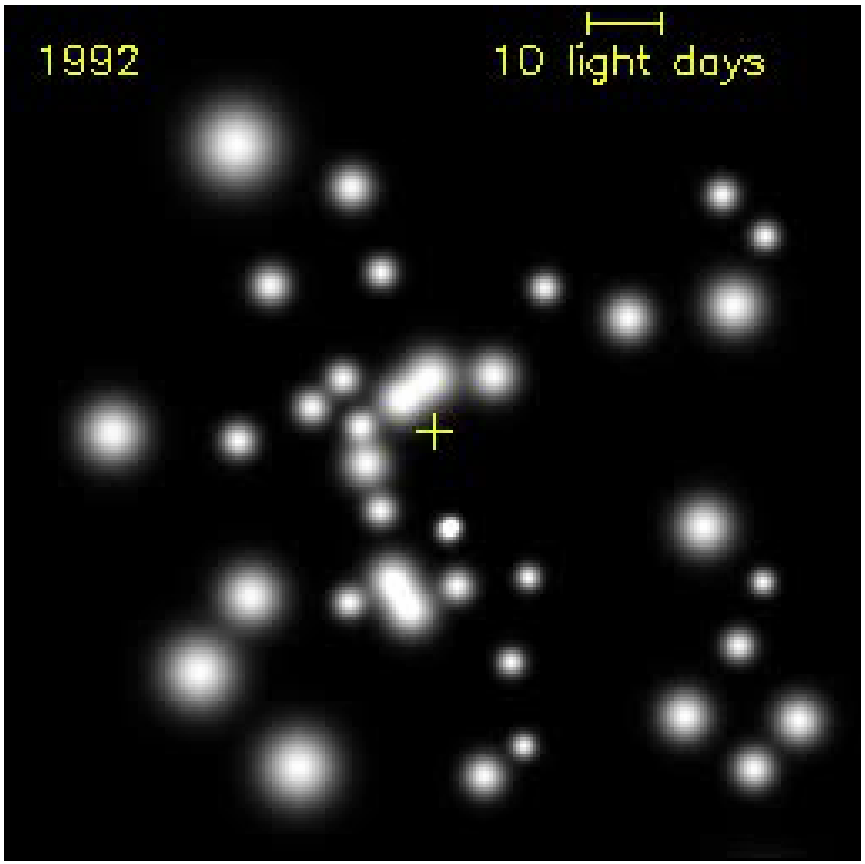


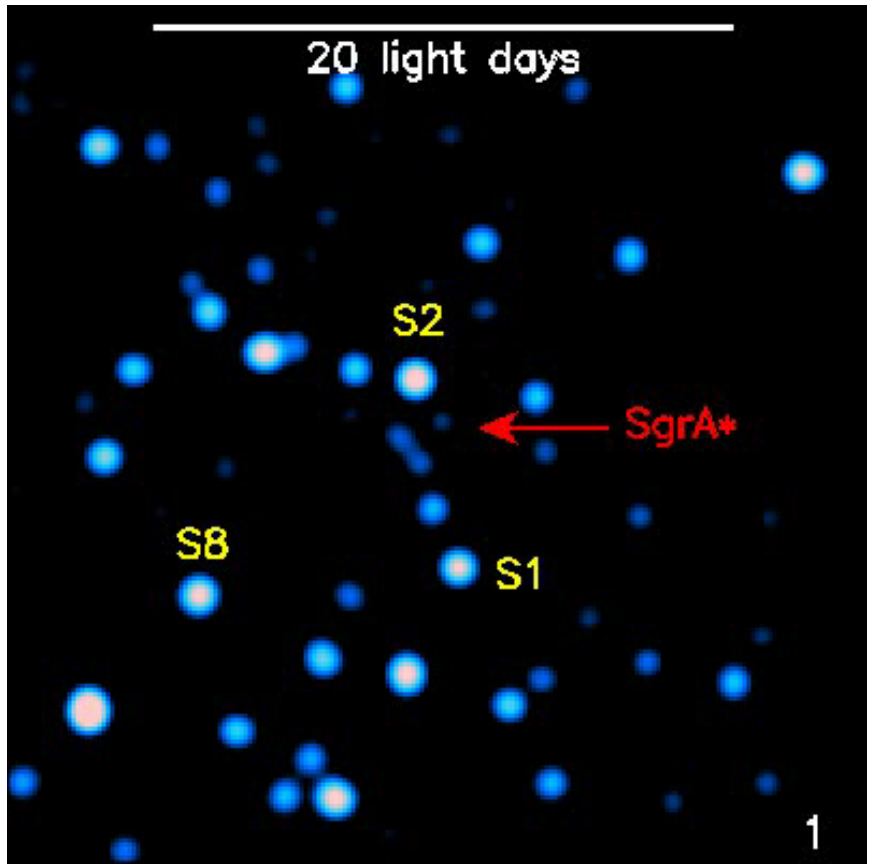


BLACK HOLE IN THE GALACTIC CENTER

- Adaptive optics: ground based astronomy competitive with space
- Black Hole mass = 3 x 10^6 solar masses

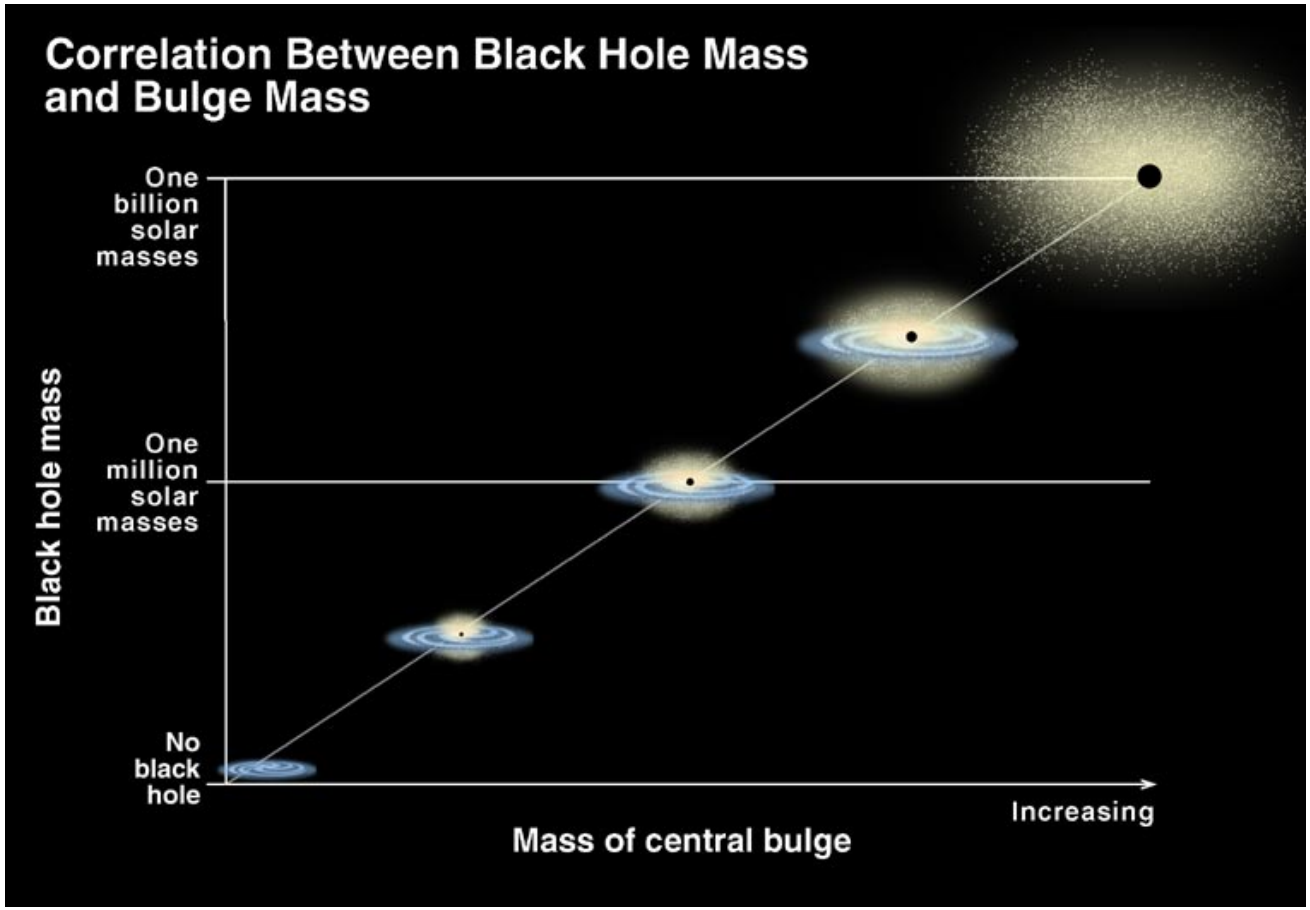
Genzel, Rouan, et al. (IR with VLT-ESO)





How could a cluster of massive stars < 10^7 yr old exist in such environment ?

MASSIVE GALAXIES HOST SUPERMASSIVE BLACK HOLES

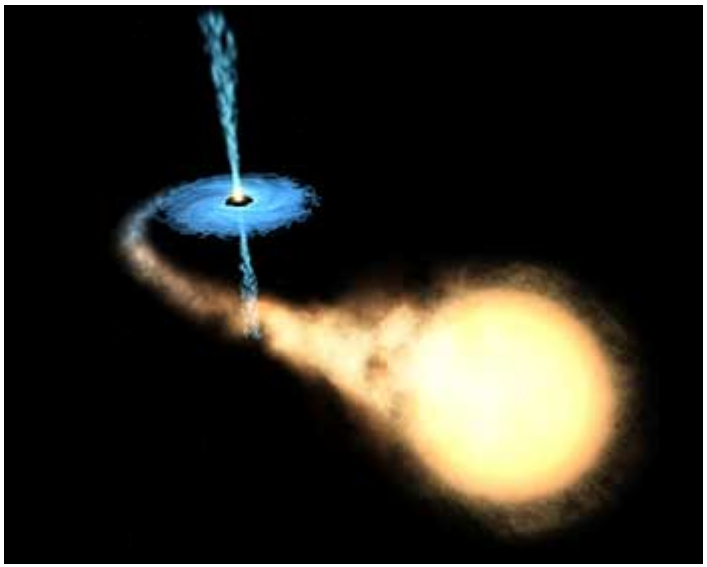


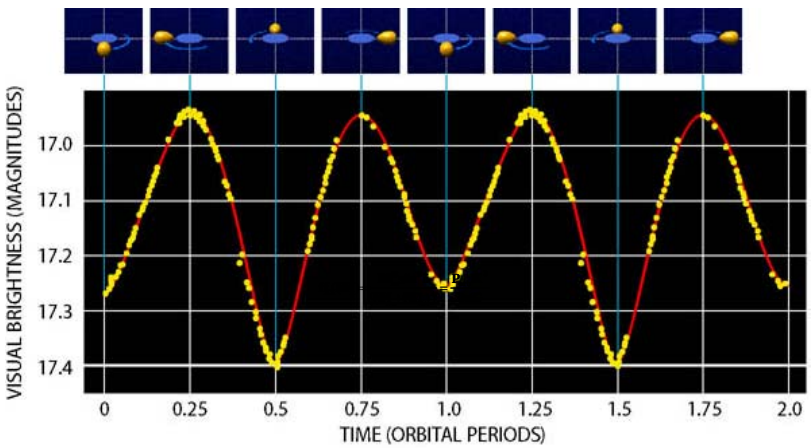
- **HOW ARE SUPERMASSIVE BLACK HOLES FORMED ?**
- **ARE THERE RUNAWAY SUPERMASSIVE BLACK HOLES ?**
- **ARE THERE BHs OF INTERMEDIATE MASS (10^2- 10^4 $M_\odot$) ?**

STELLAR-MASS BLACK HOLES

DISCOVERED AS X-RAY SOURCES

(Giacconi 1962…2002 Nobel Prize)





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:

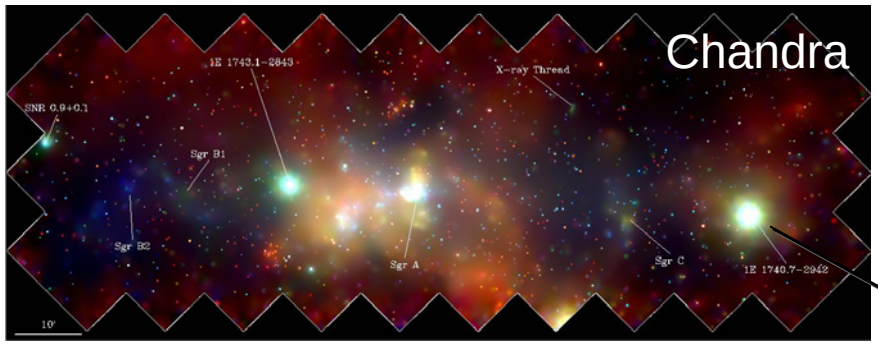
as predicted by Michell (1783)

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

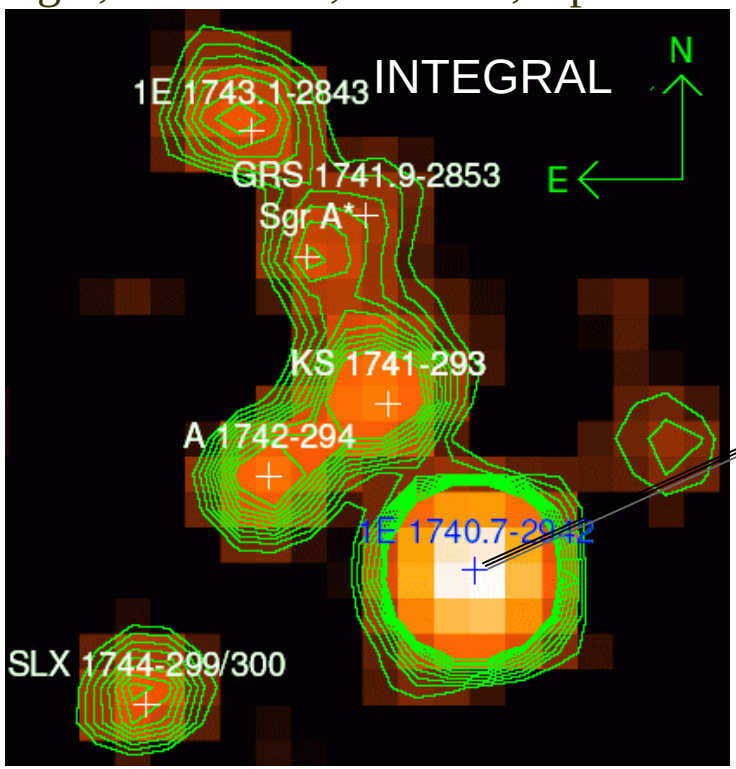
- 20 BHs known in binaries and other 20 additional candidates
- Estimated population in the Galaxy ~ 3×10^8 $\Rightarrow$
- Assuming ~10 $M_\odot$ this form of dark mass is ~ 4% of total baryonic mass of the Galaxy
- Outweighs the supermassive black hole at Galactic Centre by a factor of 10^3

MULTI-λ APPROACH TO HIGH ENERGY SOURCES IN THE GALACTIC CENTRE REGION

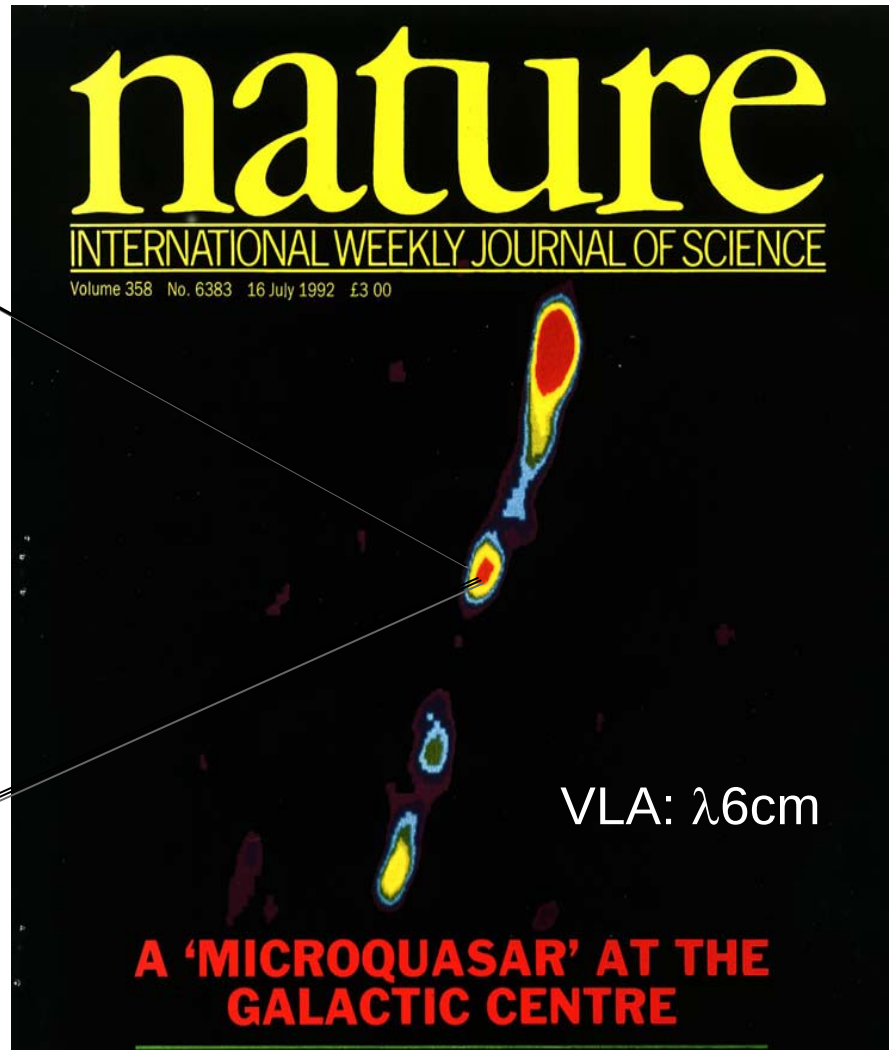
Wang et al. ApJ 2002



Belanger, Goldwurm, Goldoni, ApJ 2003

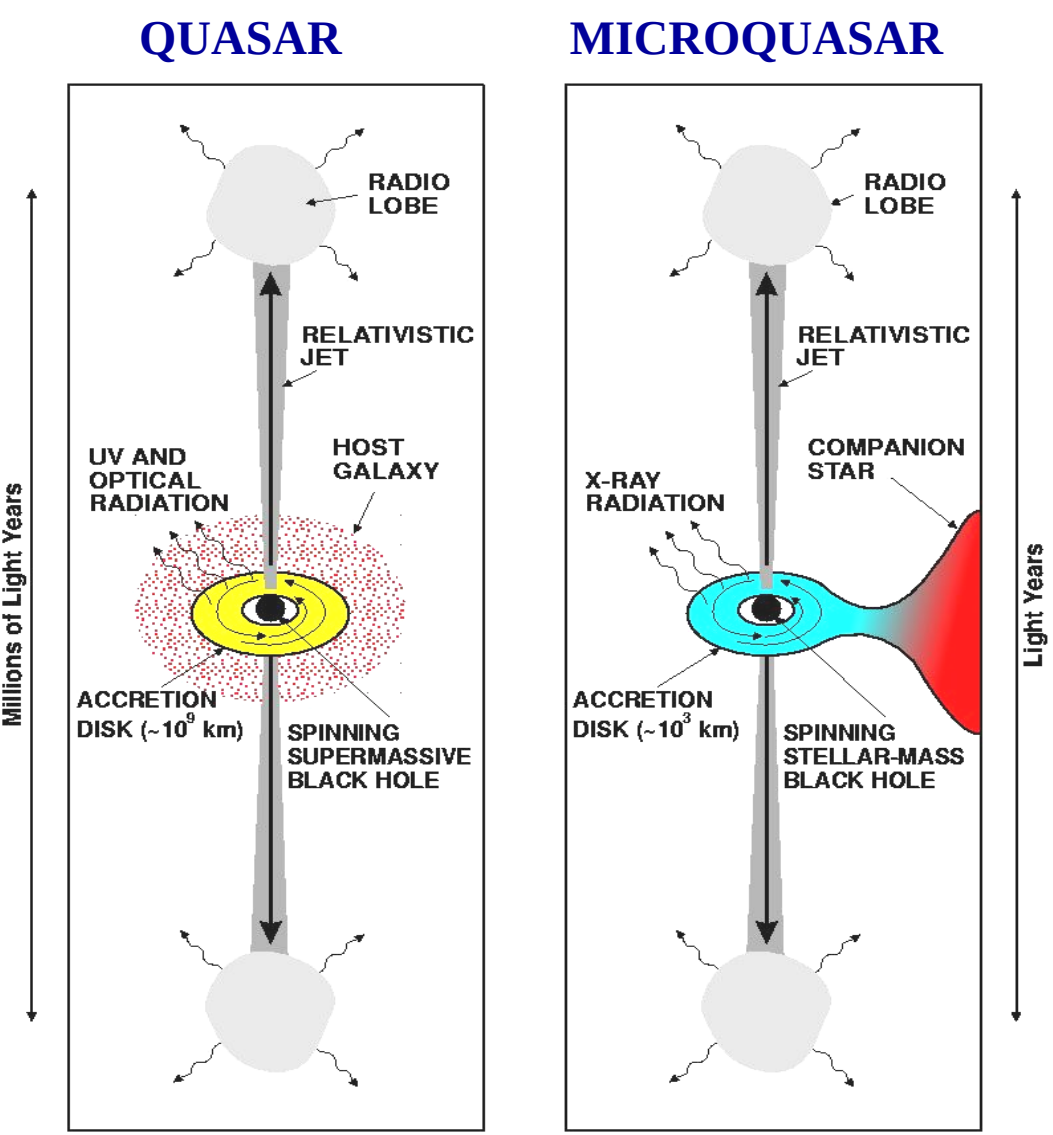


Mirabel & L.F. Rodriguez, et al, 1992



Six international workshops since 1992

QUASAR-MICROQUASAR ANALOGY



Mirabel & Rodriguez (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 concepts:

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:

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

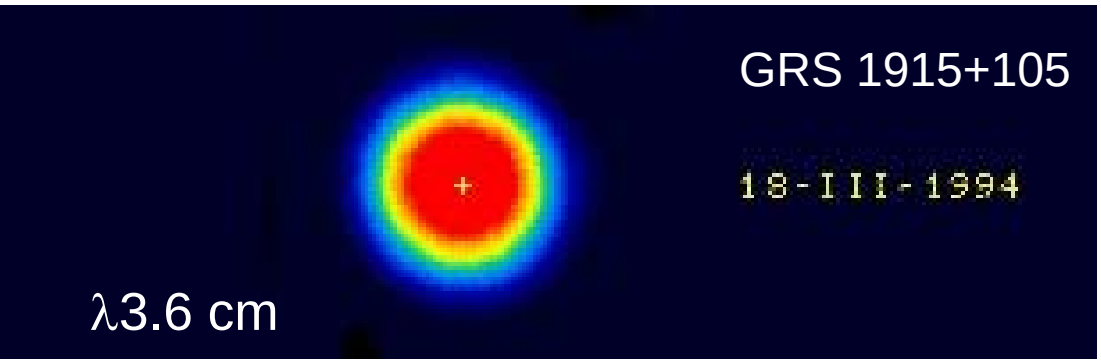
$$\varphi \, \alpha \; M_{BH}^{-1} \; ; \; B \, \alpha \, M_{BH}^{-1/2}$$

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

APPARENT SUPERLUMINAL MOTIONS IN μQSOs AS IN QSOs ?

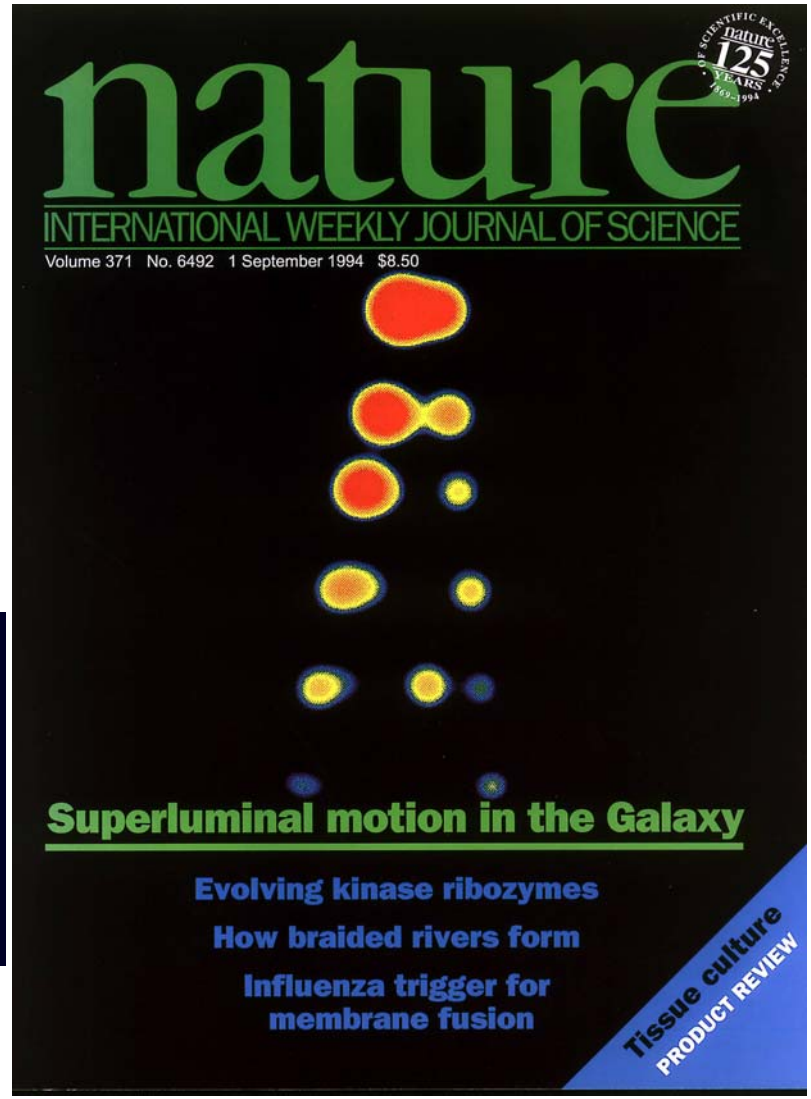
SUPERLUMINAL EJECTION IN A μQSO

1 arcsec

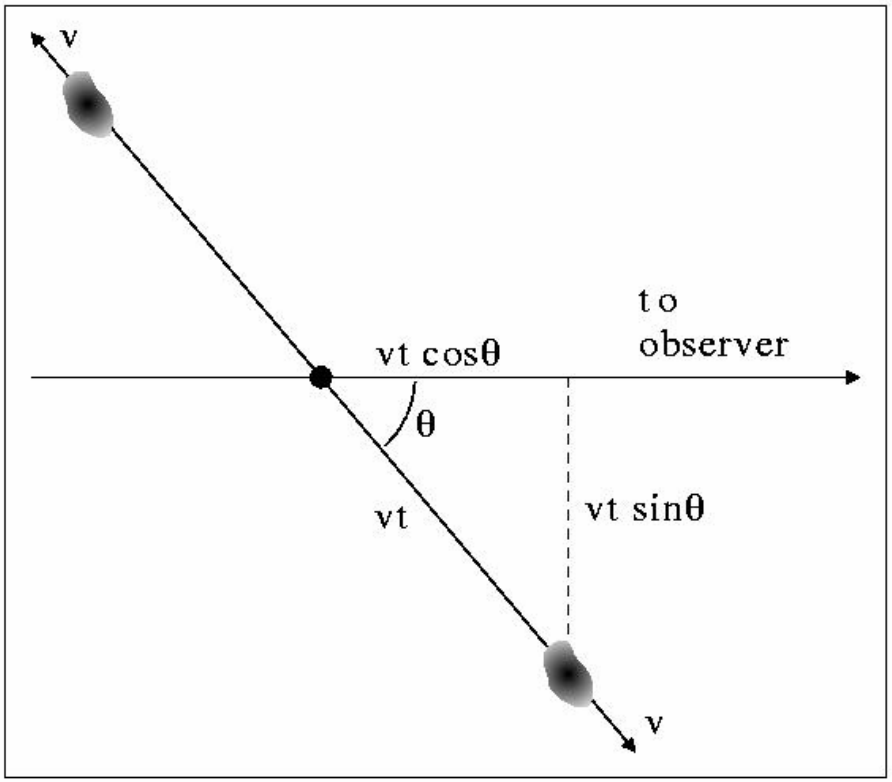


$V_{app} > C$ for a DISTANCE > 8 Kpc

Mirabel & Rodriguez, 1994



RELATIVISTIC ABERRATION IN ANTISYMMETRIC TWIN JETS



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

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

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

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

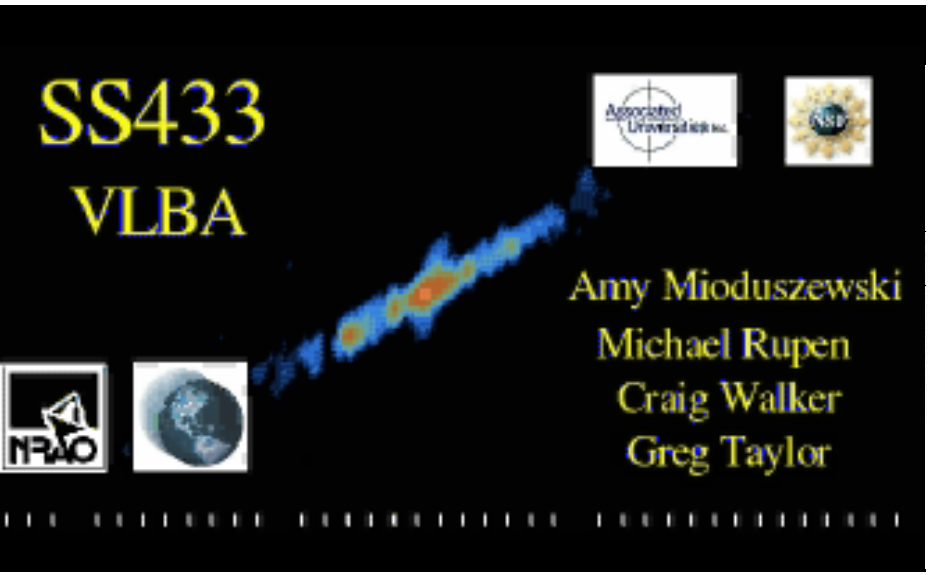
$$D = \frac{c\tan\theta}{2}\frac{(\mu_a-\mu_r)}{\mu_a\mu_r}.$$

Same bulk Lorentz factors as in QSOs: 2-10

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

Relativistic upper limit: D < 14 kpc

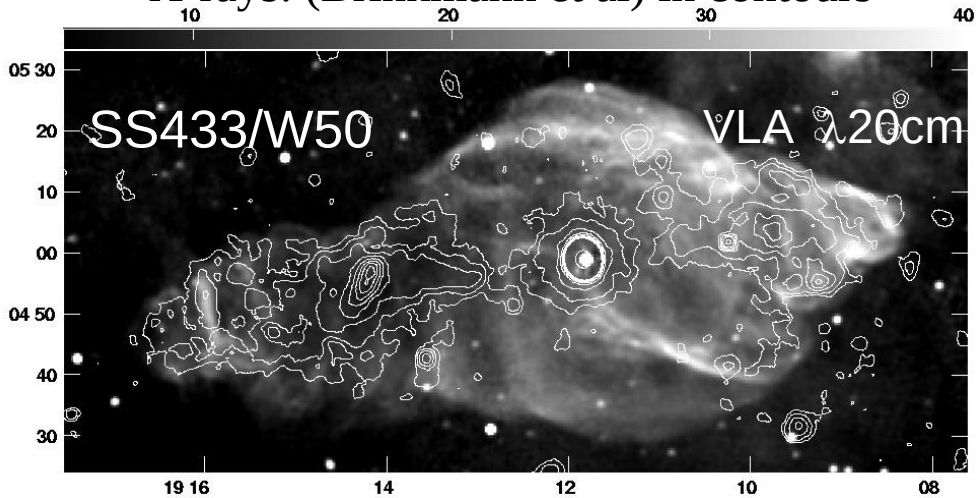
POWERFULL JETS FROM STELLAR BLACK HOLES



1arcsec

Radio: (Dubner et al) in gray

X-rays: (Brinkmann et al) in contours

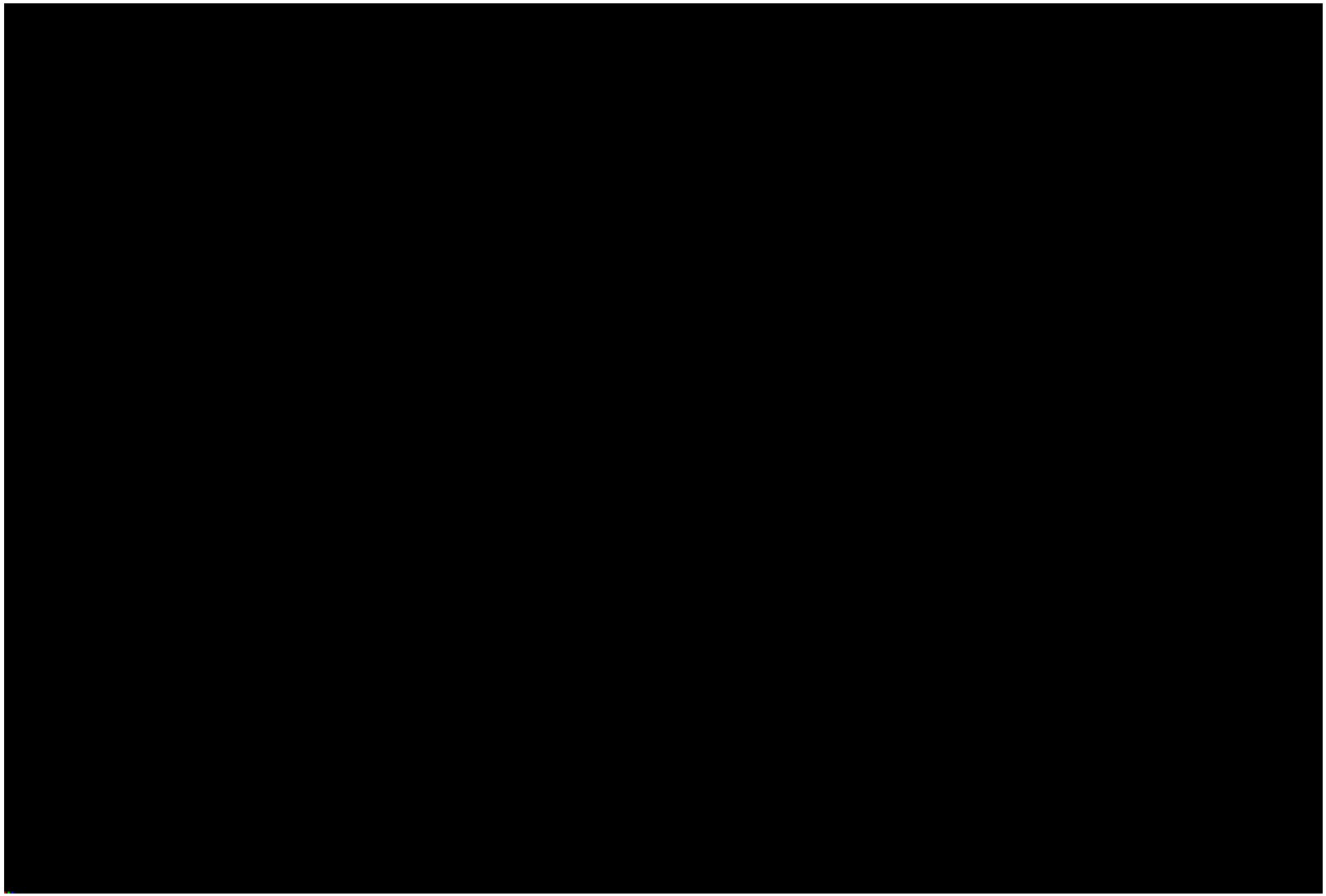


1^o = 60 pc

- MECHANICAL LUMINOSITY > 10^{39} erg/sec
- RELATIVISTIC HADRONS WITH V = 0.26c (BARIONIC LOADED)
- IN μQSOs > 50% OF THE ENERGY IS NOT RADIATED
- RADIATIVELY INEFFICIENT JETS ⇒ “DARK” JETS

MOVING X-RAY JETS IN A μQSO

μQSOs XTE J1550-564 & H1743–322 Corbel et al. (2002, 05)



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

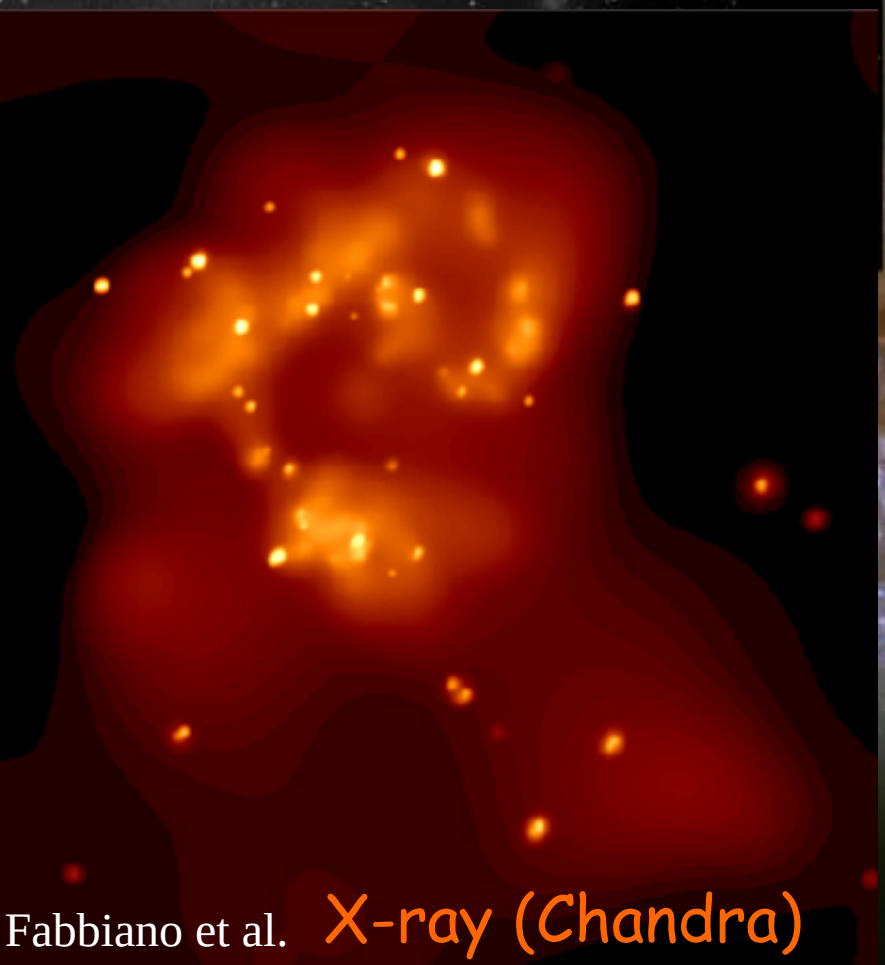
ULTRALUMINOUS X-RAY SOURCES

Most are microquasars in external galaxies

ISOTROPIC BUT $M_{BH} > 30\ M_{\odot}$ (Pakull et al. 2002)

ANISOTROPIC BUT NOT BEAMED (King et al 2001)

ANISOTROPIC AND BEAMED (Mirabel & Rodriguez, 1999)



Fabbiano et al. X-ray (Chandra)

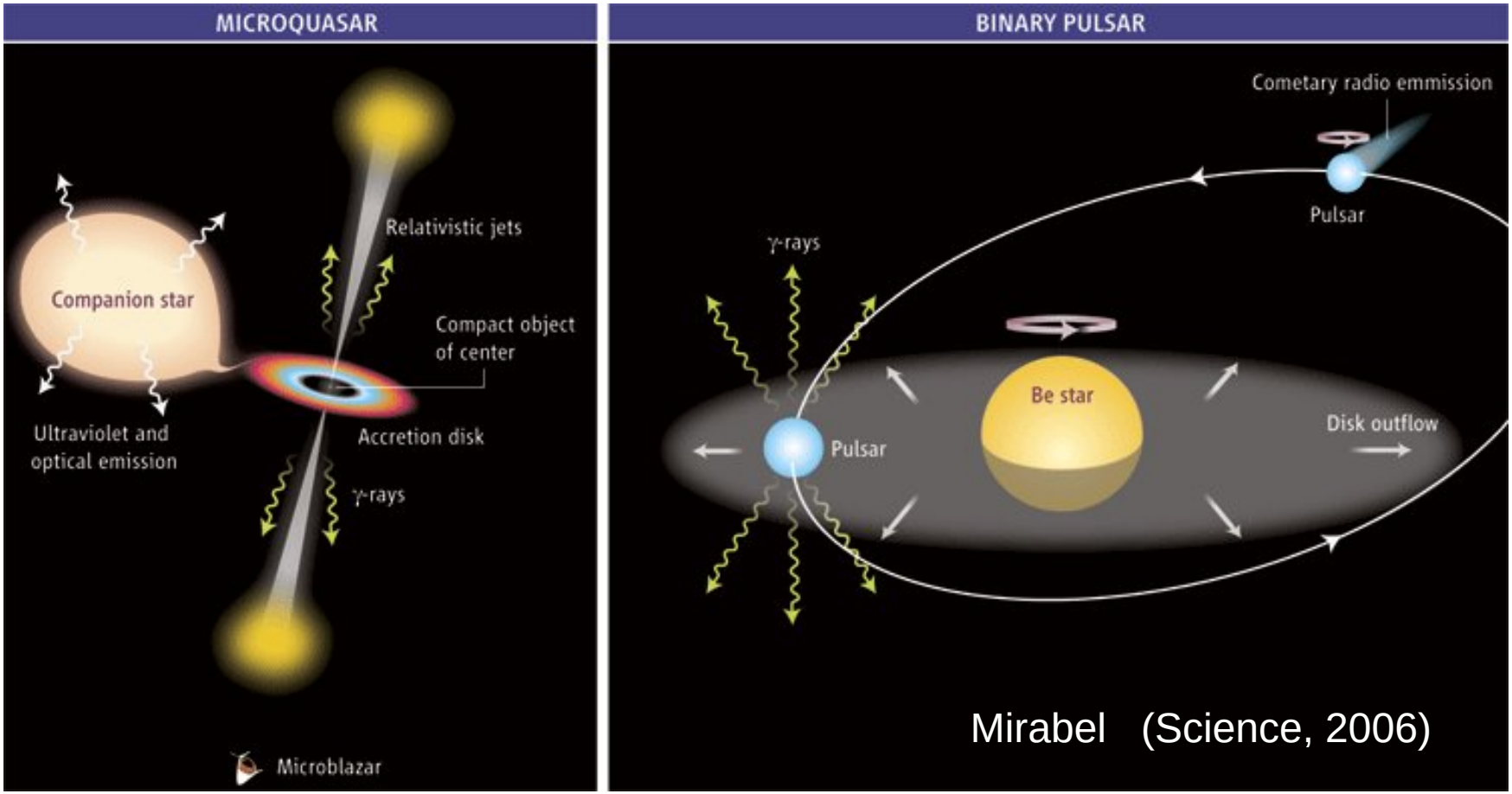
Antennae

TeV GAMMA-RAY BINARIES

Aharonian et al.; Albert et al. (in Science 2006)

LS 5039 ?

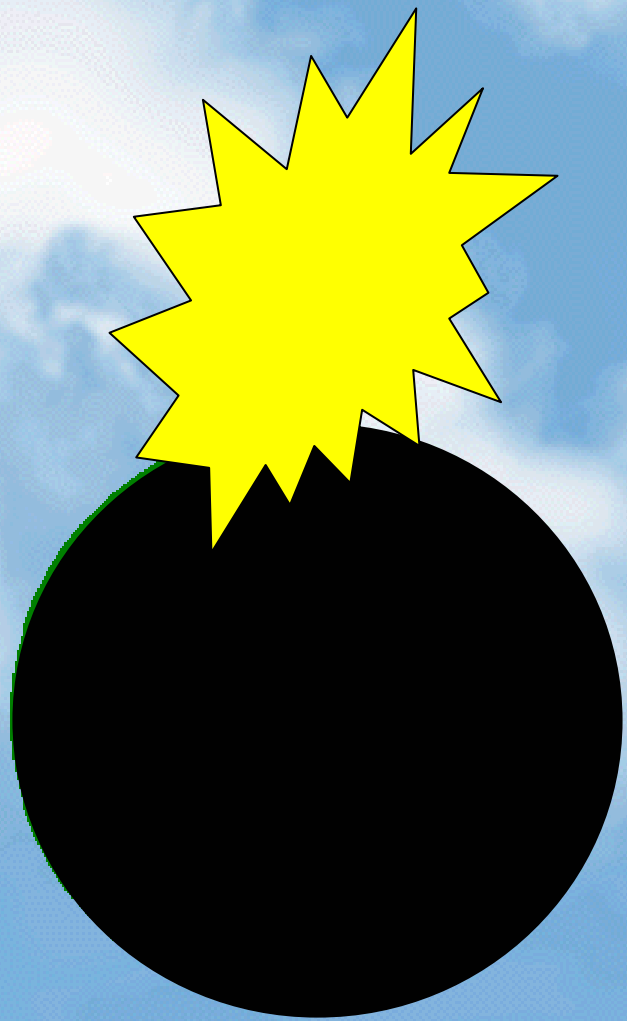
PSR B1259-63 & LSI +61 303 ?



Microquasar: Possibly LS 5039 if double-sided jets do not spin (Paredes et al.)

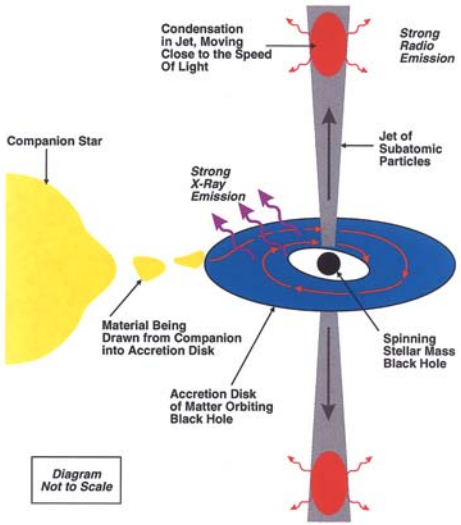
Pulsar wind: LSI +61 303 because wind spins as a function of orbital phase (Dhawan)

HORIZON IS THE BASIC CONCEPT THAT DEFINES BLACK HOLES AND IT IS DIFFICULT TO OBTAIN DIRECT EVIDENCE OF THEIR EXISTENCE

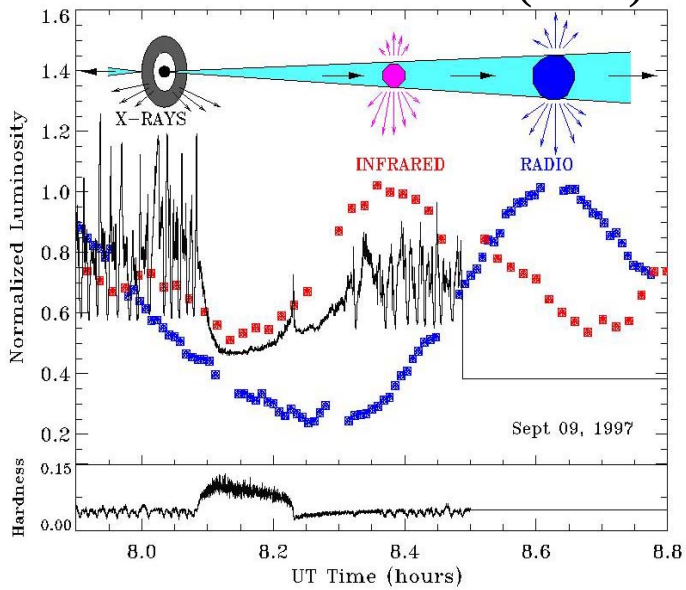


ACCRETION–JET CONNECTION

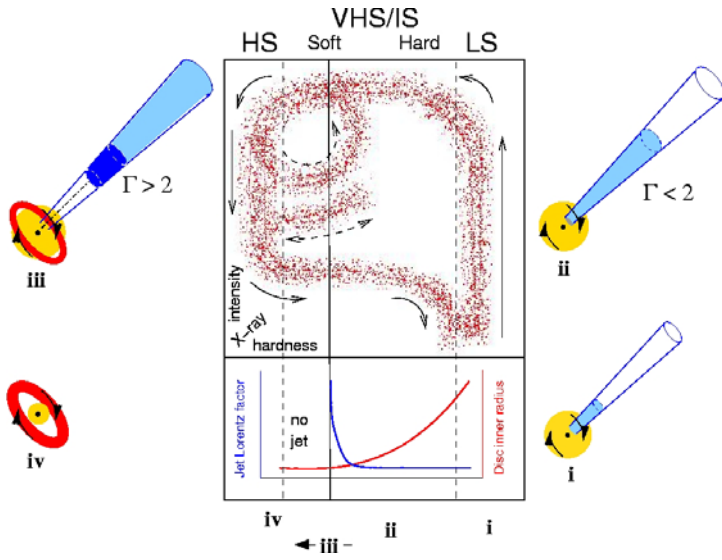
$\Delta T \alpha M_{BH}$ 1 hr in GRS 1915+105 ~ 30 yr in SgrA*



Mirabel et al. (1998)



Fender et al. (2002)



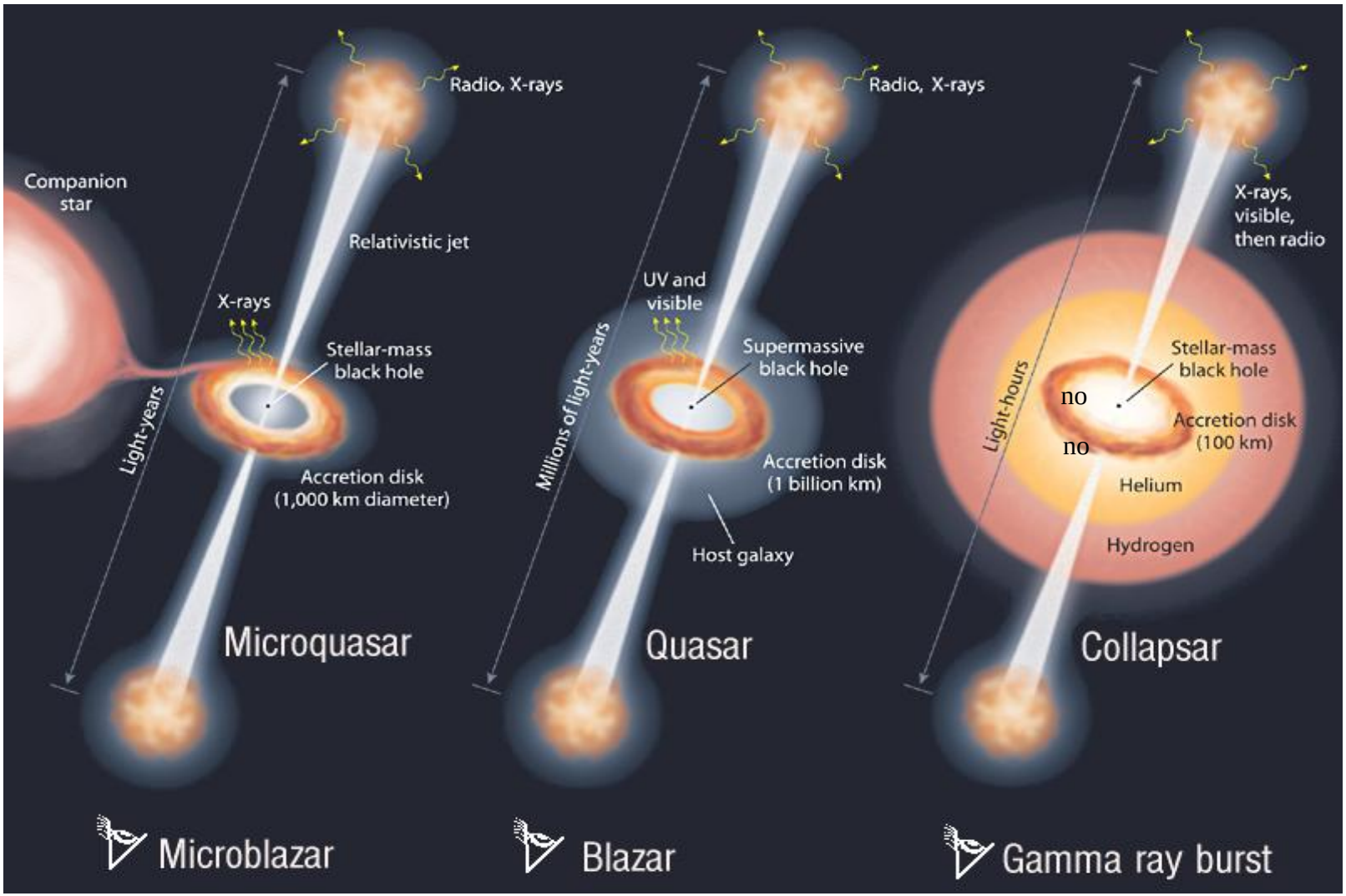
- **JETS ARE COUPLED TO TRANSITIONS BETWEEN LOW HARD AND HIGH SOFT X-RAY STATES. AFTER THE X-RAY ENERGY DISSAPEARS. THE X-RAY "SPIKE" MARKS THE ONSET OF A SHOCK THROUGH THE COMPACT, STEADY JET. X-RAYS ARE INVERSE COMPTON, IR & RADIO SYNCHROTRON. ANALOGOUS TO WHAT IS BEEN OBSERVED IN Sgr A*** (Genzel et al.; Yusef-Zadeh)

- **ANALOGOUS ACCRETION-JET CONNECTIONS FOUND IN 3C120, 3C279 & 3C390**

QSO - μQSO - GRB ANALOGY

FOR DISK-JET COUPLING FOR ALL ACCRETING BLACK HOLES

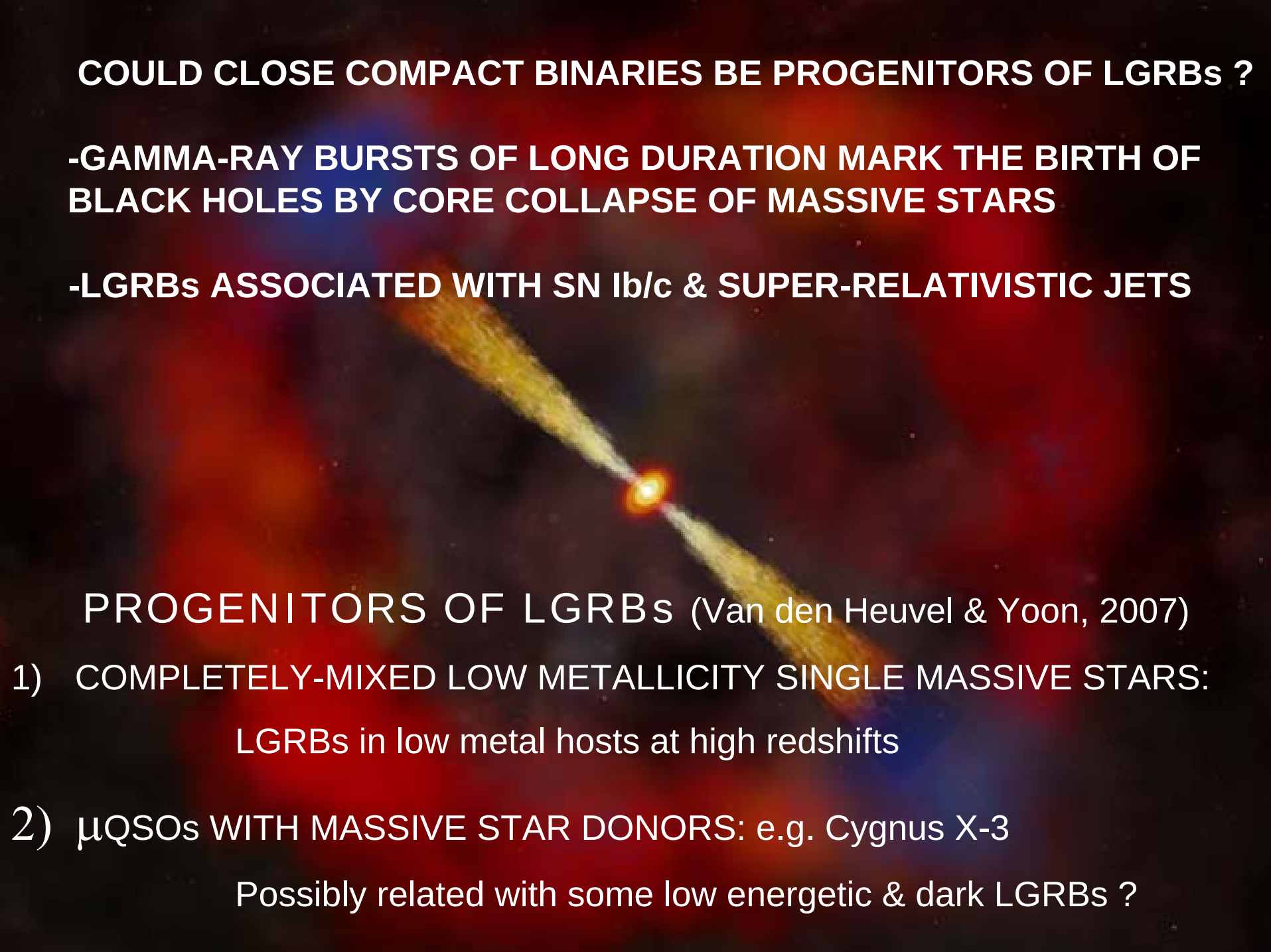
HAVE THE SAME 3 BASIC INGREEDIENTS (Mirabel & Rodriguez, S&T 2002)



COULD CLOSE COMPACT BINARIES BE PROGENITORS OF LGRBs ?

-GAMMA-RAY BURSTS OF LONG DURATION MARK THE BIRTH OF BLACK HOLES BY CORE COLLAPSE OF MASSIVE STARS

-LGRBs ASSOCIATED WITH SN Ib/c & SUPER-RELATIVISTIC JETS



PROGENITORS OF LGRBs (Van den Heuvel & Yoon, 2007)

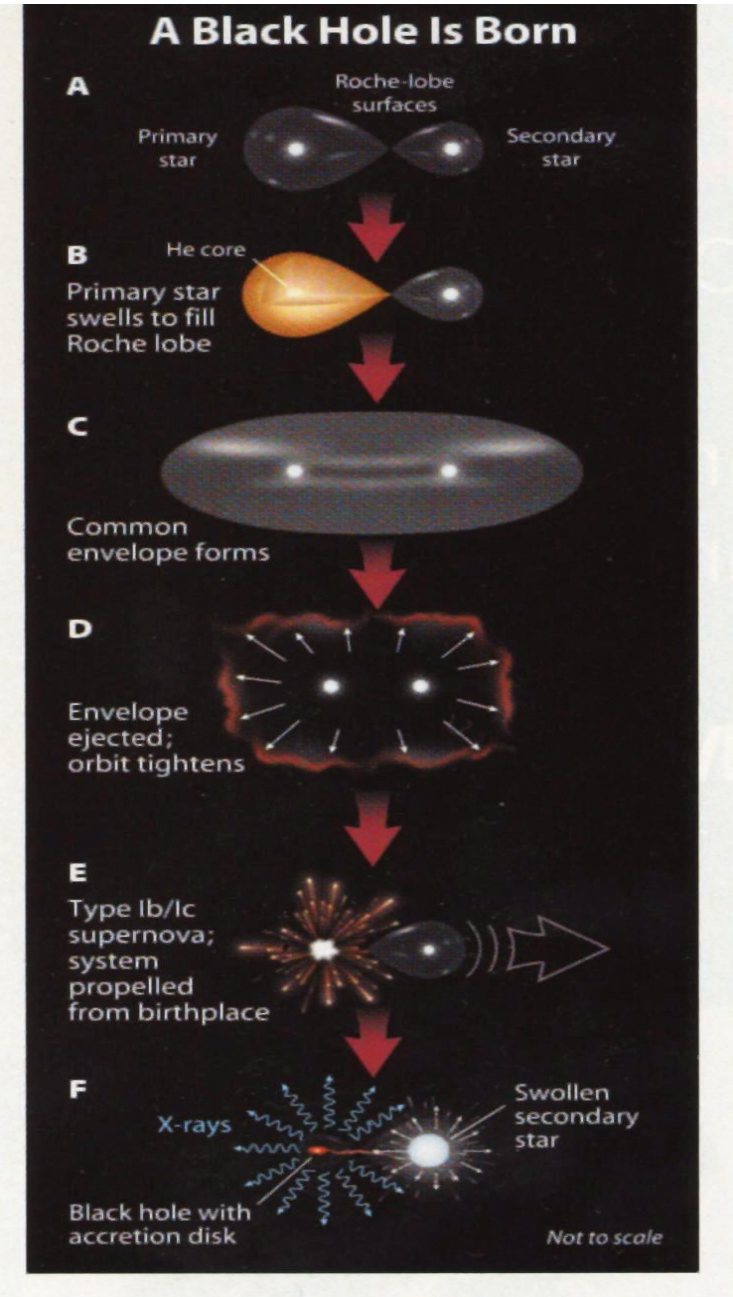
1) COMPLETELY-MIXED LOW METALLICITY SINGLE MASSIVE STARS:

LGRBs in low metal hosts at high redshifts

2) μQSOs WITH MASSIVE STAR DONORS: e.g. Cygnus X-3

Possibly related with some low energetic & dark LGRBs ?

HOW ARE BLACK HOLE BINARIES FORM ?



THERE ARE THEORETICAL MODELS

e.g. Fryer & Kalogera ; Woosley & Heger (2002)

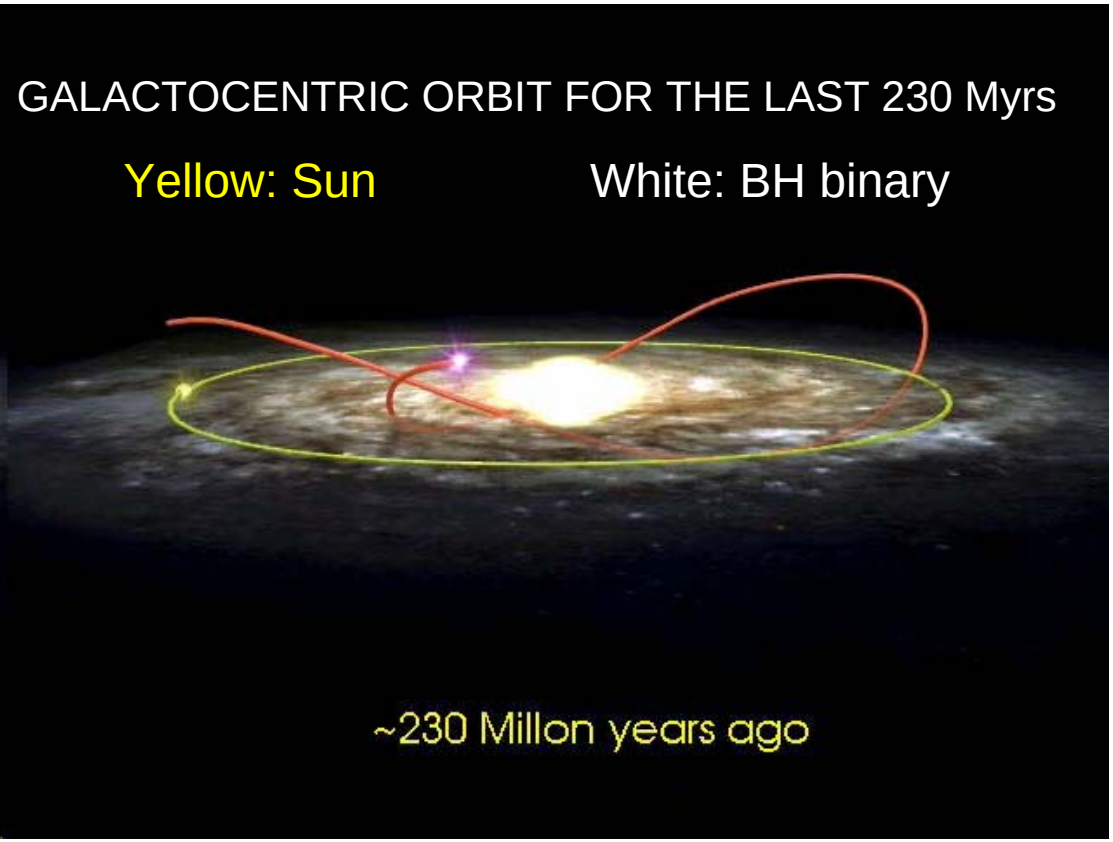
BUT FEW OBSERVATIONS !

THE KINEMATICS OF μQSOs PROVIDES CLUES TO ANSWER QUESTONS ON THE ORIGIN OF STELLAR BLACK HOLES

(Mirabel & Irapuan Rodrigues)

A 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



Born in a globular cluster ?

(Mirabel & Rodrigues, Nature 2001)

stripped remains of a formerly massive star with CNO cycle (Haswell et al. 2002)

or

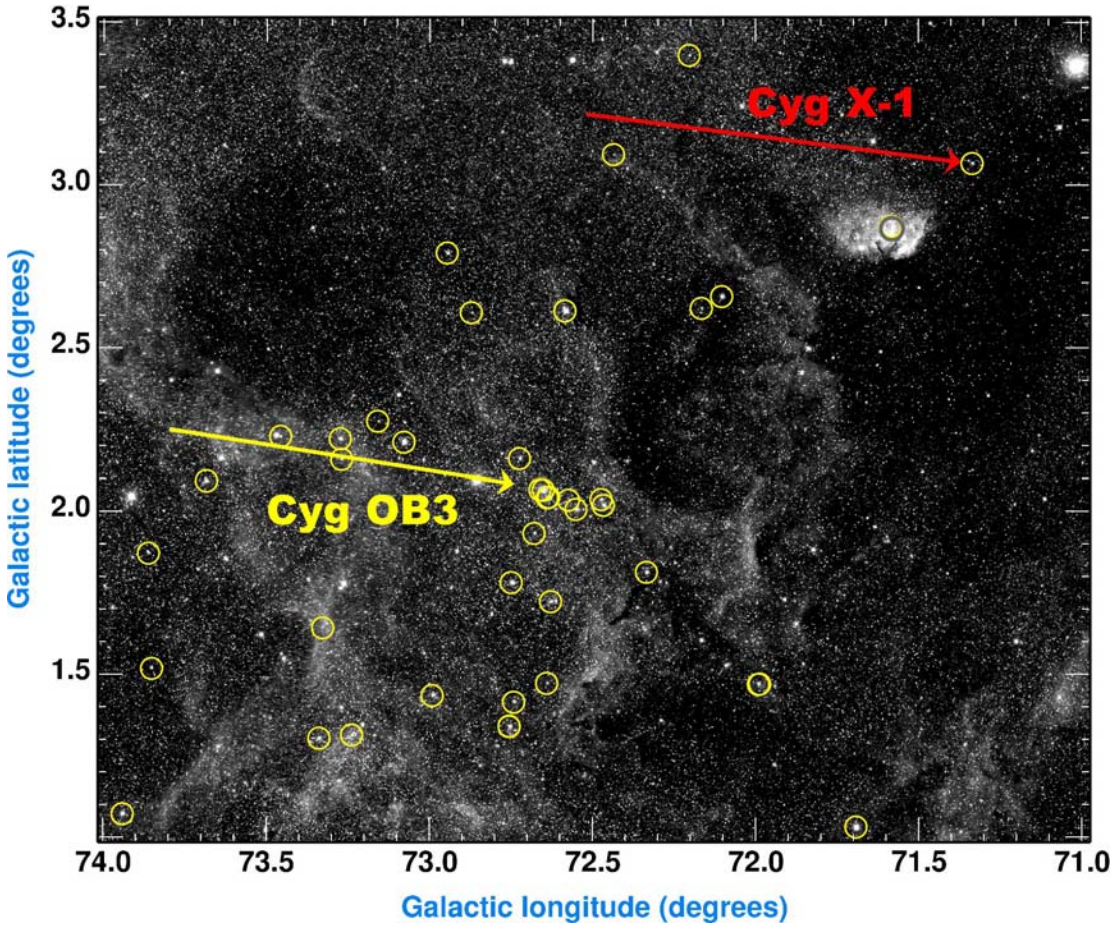
was it shot out from the plane by an hyper-nova ?

(Gonzalez et al. 2006)

WAS THIS BH FORMED IN THE HALO, THICK DISK, OR IN THE GALACTIC THIN DISK IN A VIOLENT NATAL 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 $\Rightarrow$

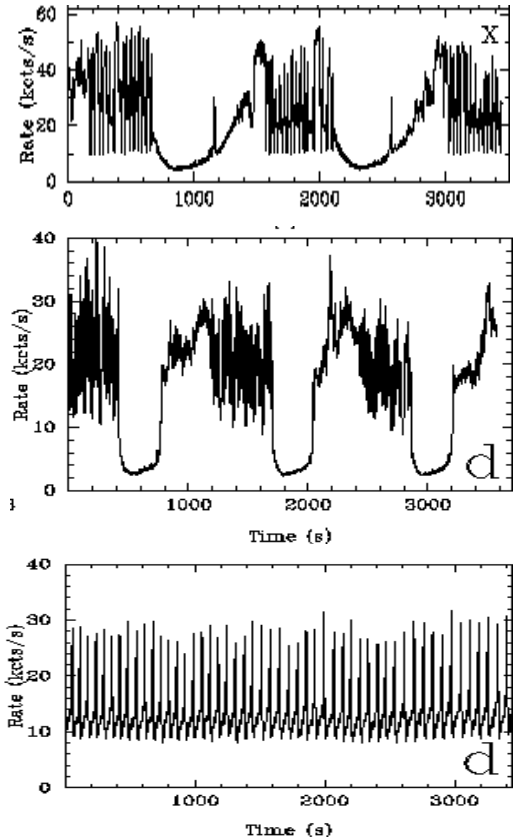
< 1 $M_\odot$ ejected in SN

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

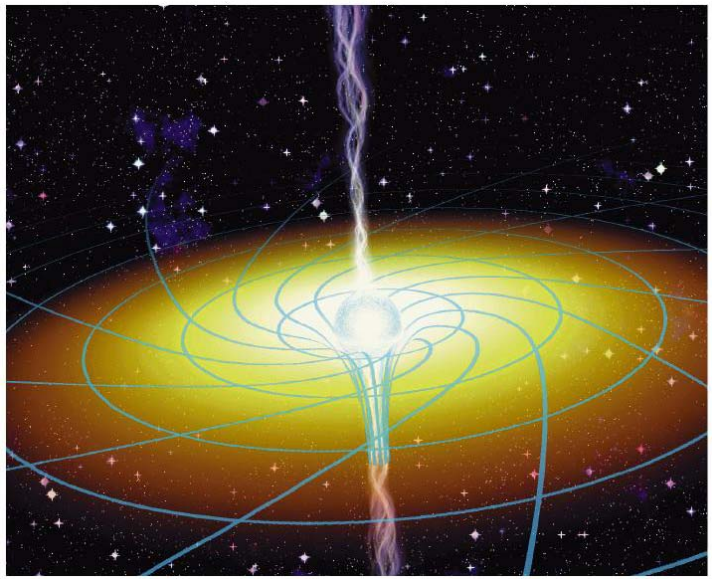
Relation with the two LGRBs at z < 0.2 with no energetic SNe ?

QPOs AND GENERAL RELATIVITY

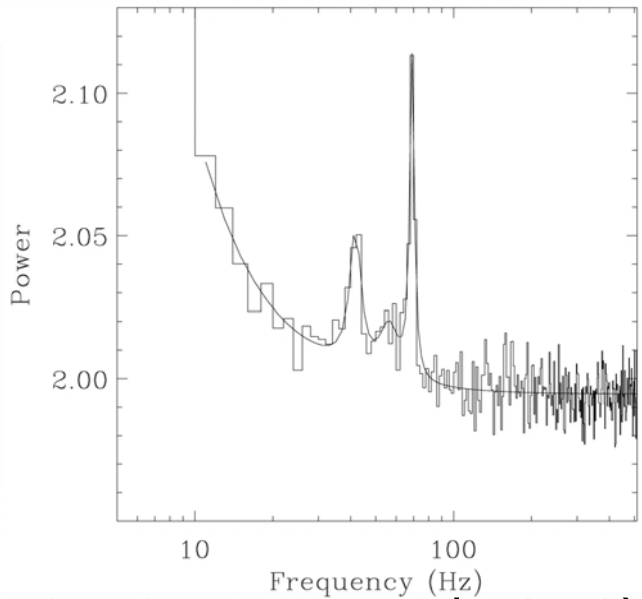
XTE & INDIAN SAT.



Jerome Rodriguez et al.



GRS 1915+105 (Strohmayer)

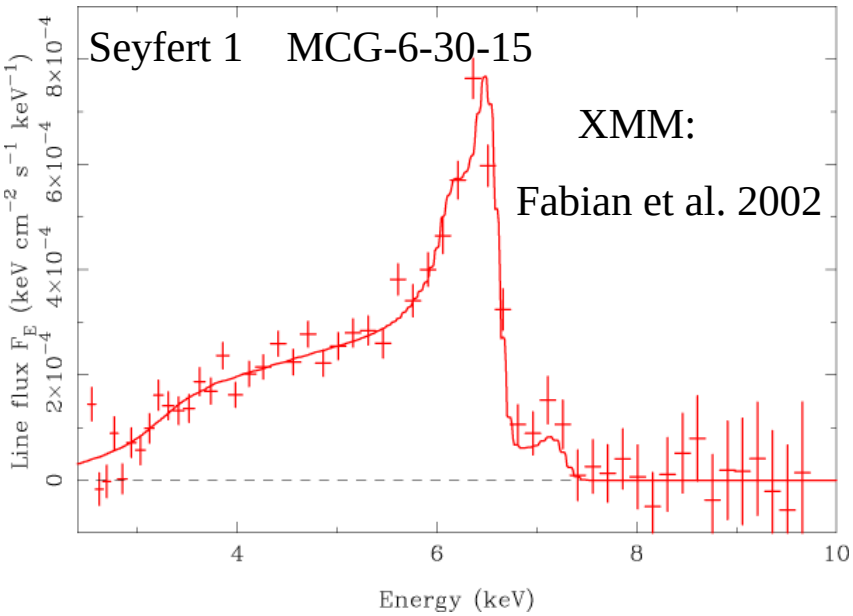


- High frequency QPOs (e.g. 40 & 67 Hz repeat in GRS)
- This 3:2 ratio now found in 4 BHXBs (Remillard et al.) ⇒ must depend on fundamental properties of black hole

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

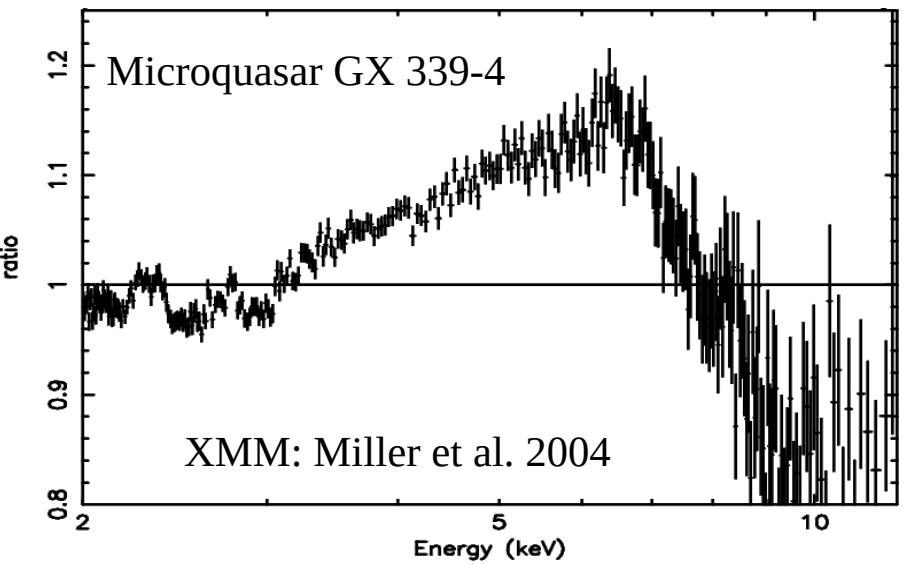
FOR 4 BLACK HOLES THE SPINS DERIVED FROM QPOs & FROM DISK TEMPERATURES ARE CONSISTENT

Fe Kα LINES IN KEER BLACK HOLES



General Relativity in the limit of the strongest gravitational fields

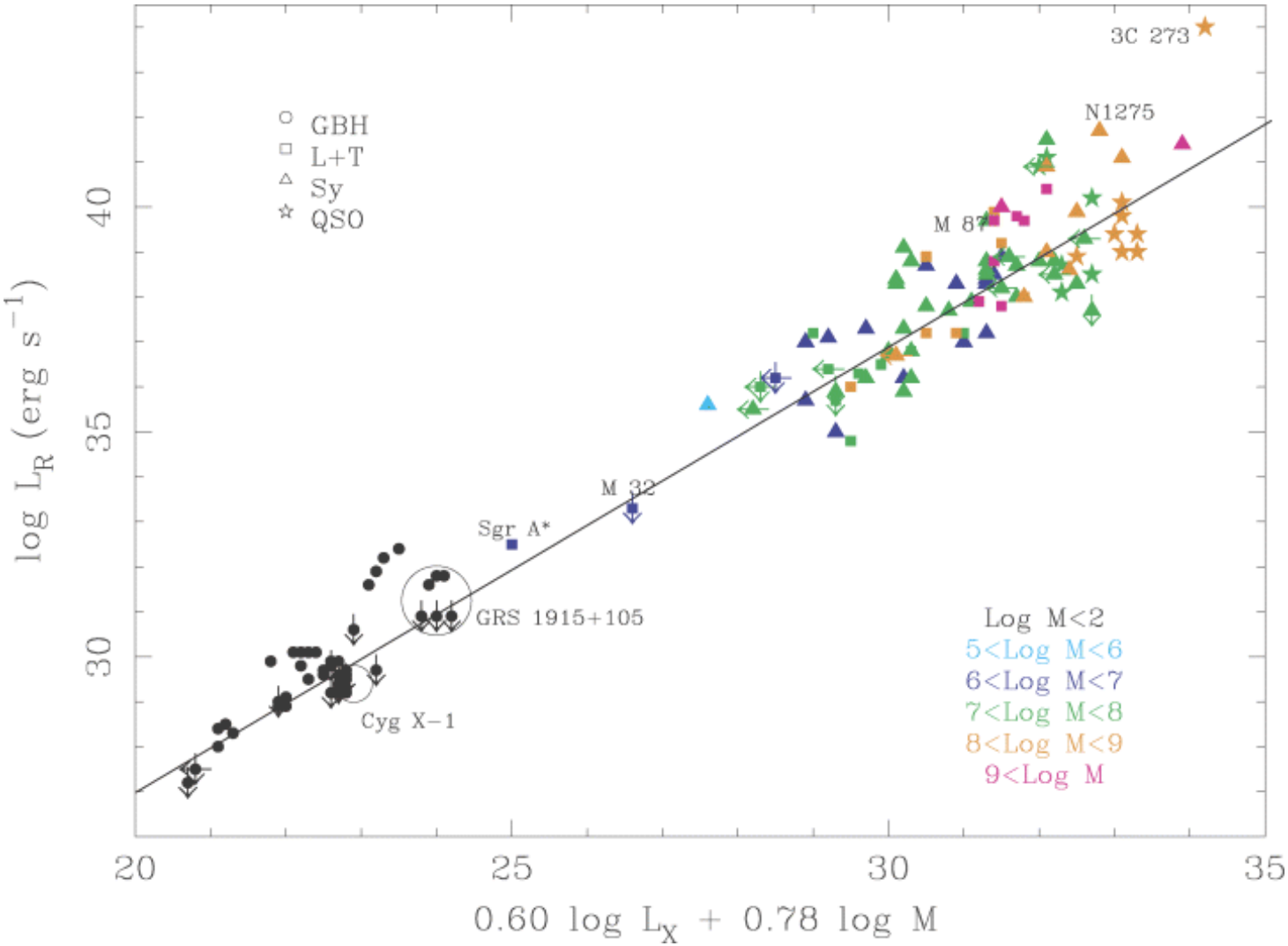
(Fabian & Tanaka)



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

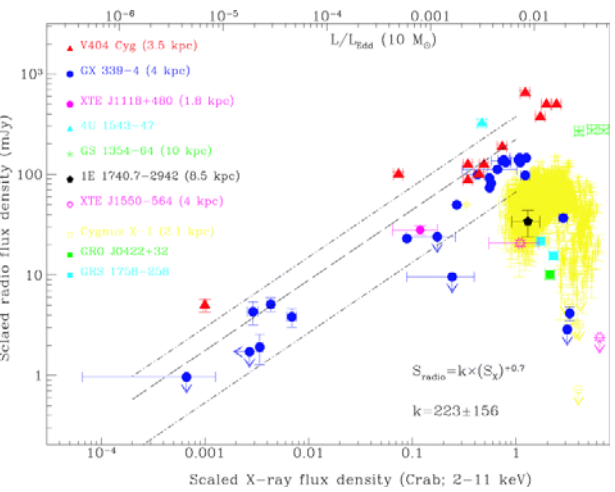
THE BLACK HOLE FUNDAMENTAL PLANE

Merloni et al. Falke, Koerding et al.

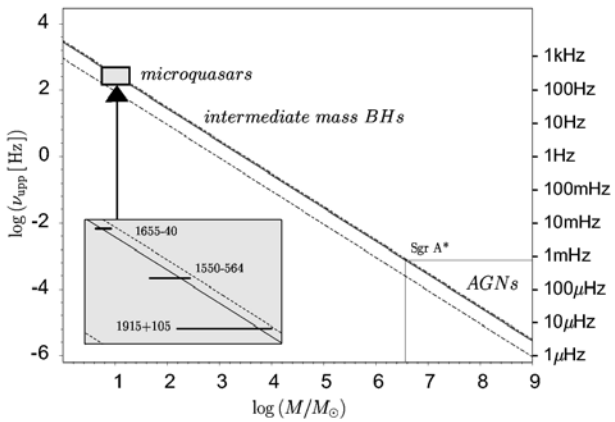


IF THE EMPIRICAL CORRELATIONS

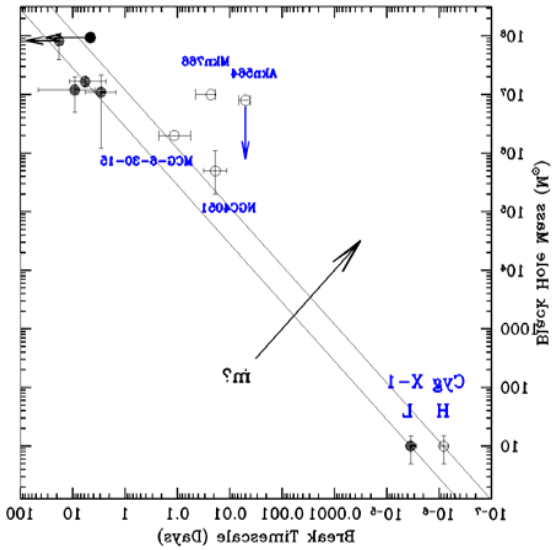
X-ray/radio/mass
Gallo et al. 2004



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.

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**

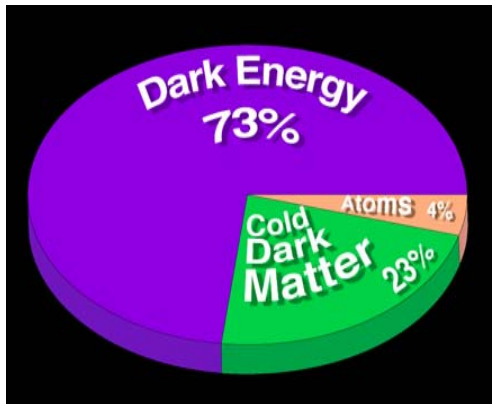
Microquasars could provide insight into:

- **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

CURRENT QUESTIONS

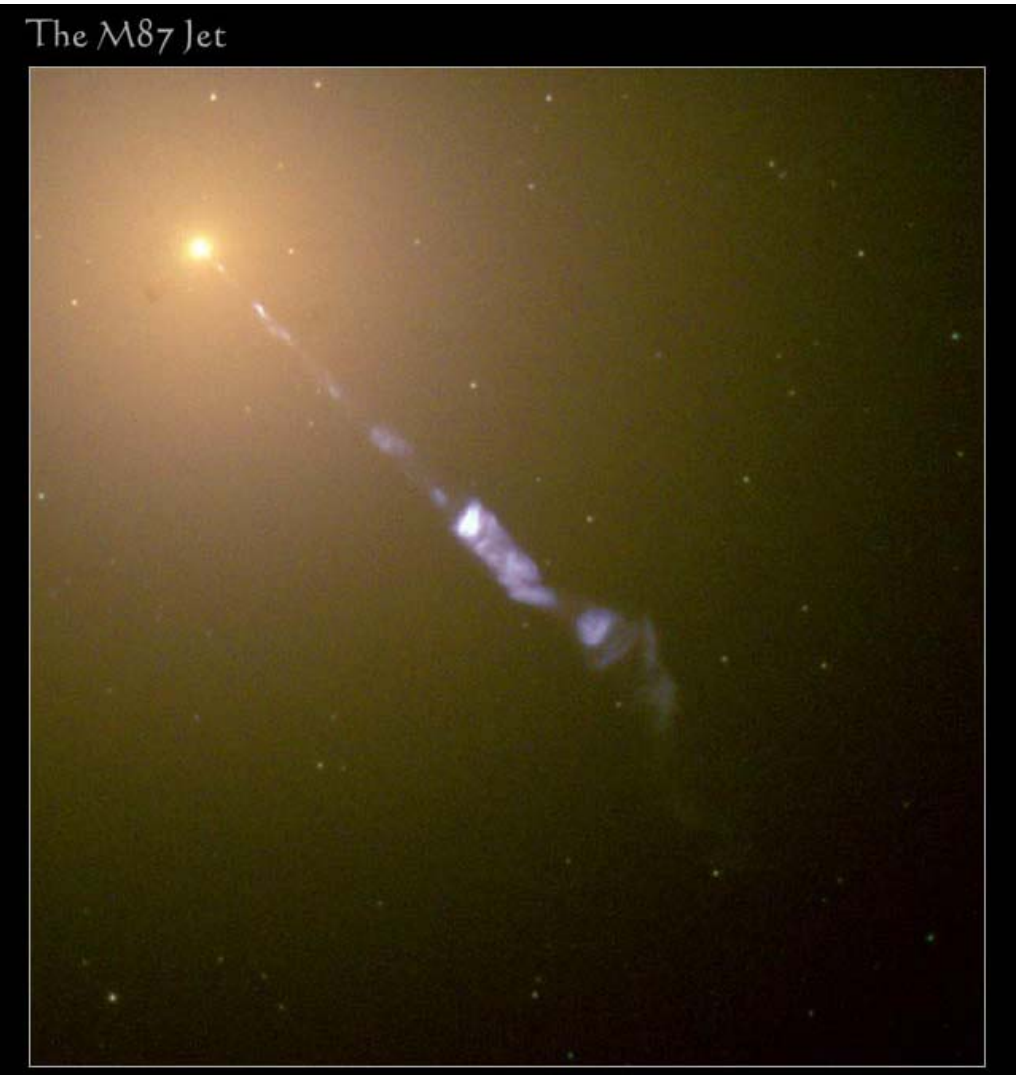
- Was the Big Bang the explosion of a BH ?
- Is the universe inside a BH ? $\Omega \sim 1$, $M \sim 10^{23}\ M_s$, R ~ 30 x 10^9 light yrs
- How are BHs, dark matter and dark energy related ?



- How to explain the improbable combination of parameters ("secret harmony") that made possible the existence of life ?
  Creationism ("intelligent design") versus evolutionary theory of the cosmos, where in each Big Bang universe the physical constants change in aleatory way to make a persistent universe, as a result of evolution and natural selection.

BLACK HOLES COULD BE FUNDAMENTAL ACTORS IN THE HISTORY OF THE UNIVERSE

SUPERLUMINAL MOTIONS IN QSOs & AGN

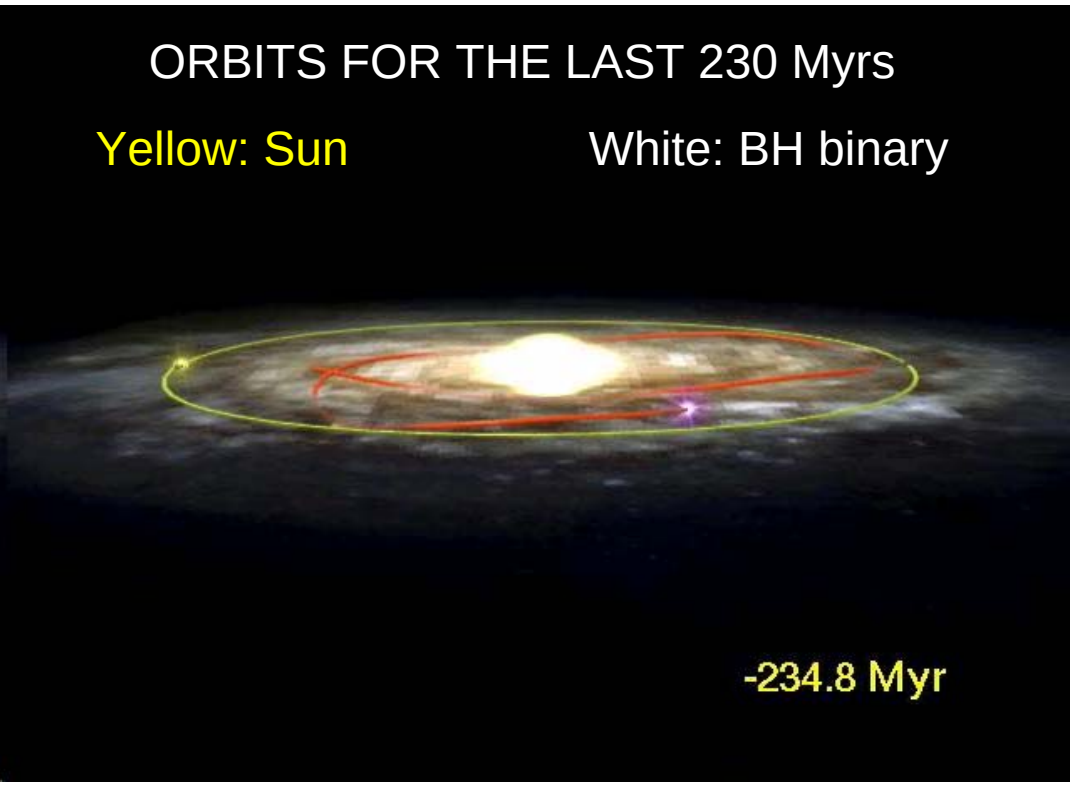


- OBSERVED IN > 30 QSOs & AGN
- IN RADIO & OPTICAL WAVES
- PROPER MOTION SEEN IN YEARS
- V_{app} UP TO 30c in blazars
- One sided because of Doppler boosting
- WHAT IS THE NATURE ?

"PLASMONS" OR SHOCKS ?

A RUNAWAY BLACK HOLE

GRO J1655-40 $M_{BH} \sim 4\ M_{\odot}$



A FOSSIL OF A GRBs 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

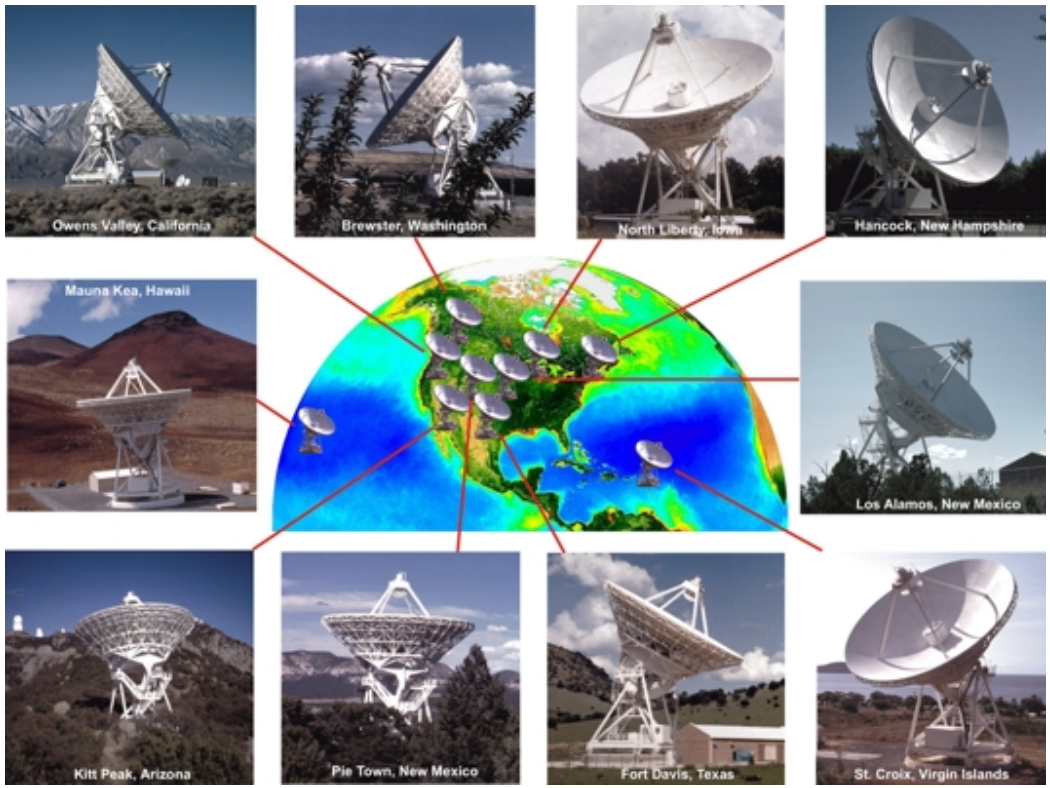
MOMENTUM = 550 $M_{\odot}$ km/s

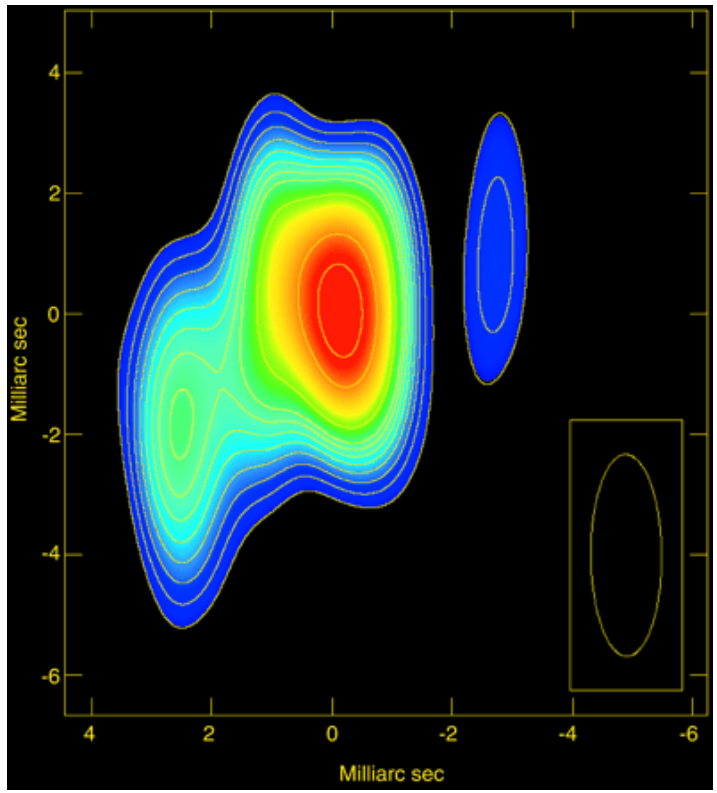
as in runaway neutron stars

LOW-MASS BLACK HOLE FORMED IN A LUMINOUS SUPERNOVA

Gamma-ray Binaries in the Milky Way

Discovery a **persistent microquasar**, which also displays **Very High-Energy Gamma-Ray emission** of TeVs (Paredes et al. 2000, **Science**, 288, 2340)





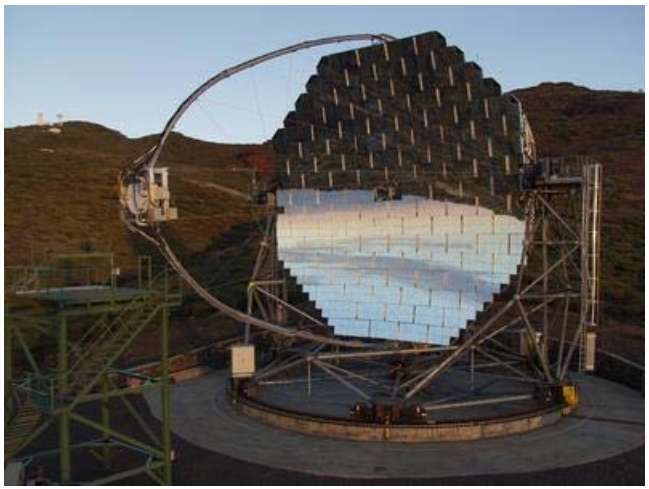
Very Long Baseline Array (VLBA)

It is a runaway HMXB (Ribo et al.)

Group on Galactic Compact Sources at High Energies.
Universitat de Barcelona & Institut de Ciències del Cosmos.

Very-High-Energy Gamma-Ray Astrophyisics (MAGIC International Collaboration)

Discovery of the **first HMXB** showing **variable very-high-energy gamma-ray emission** at TeV energies (Albert et al. 2006, **Science**, 312, 1771).



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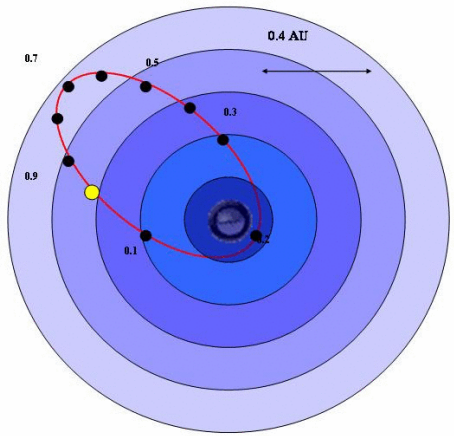
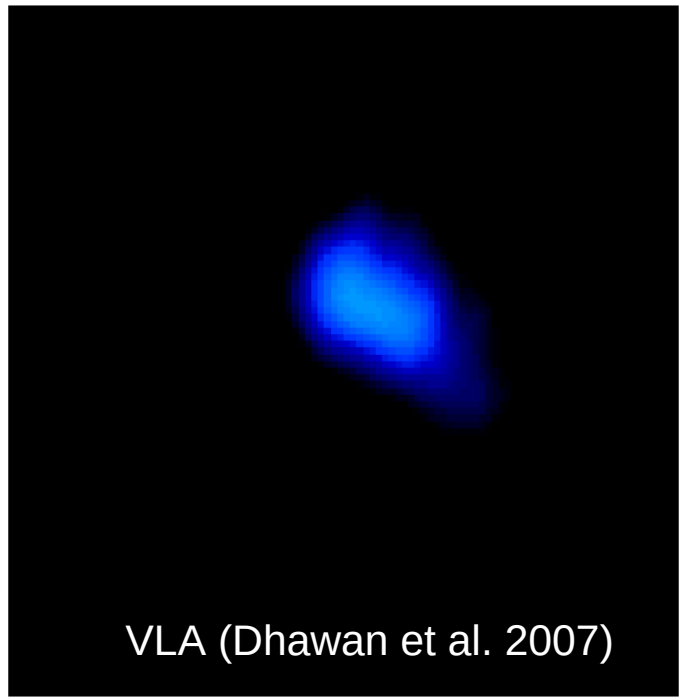




MAGIC telescope

Group on Galactic Compact Sources at High Energies.
Universitat de Barcelona & Institut de Ciències del Cosmos.

GAMMA-RAY BURSTS OF LONG DURATION (LGRBs) MARK THE BIRTH OF BLACK HOLES BY CORE COLLAPSE OF MASSIVE STARS

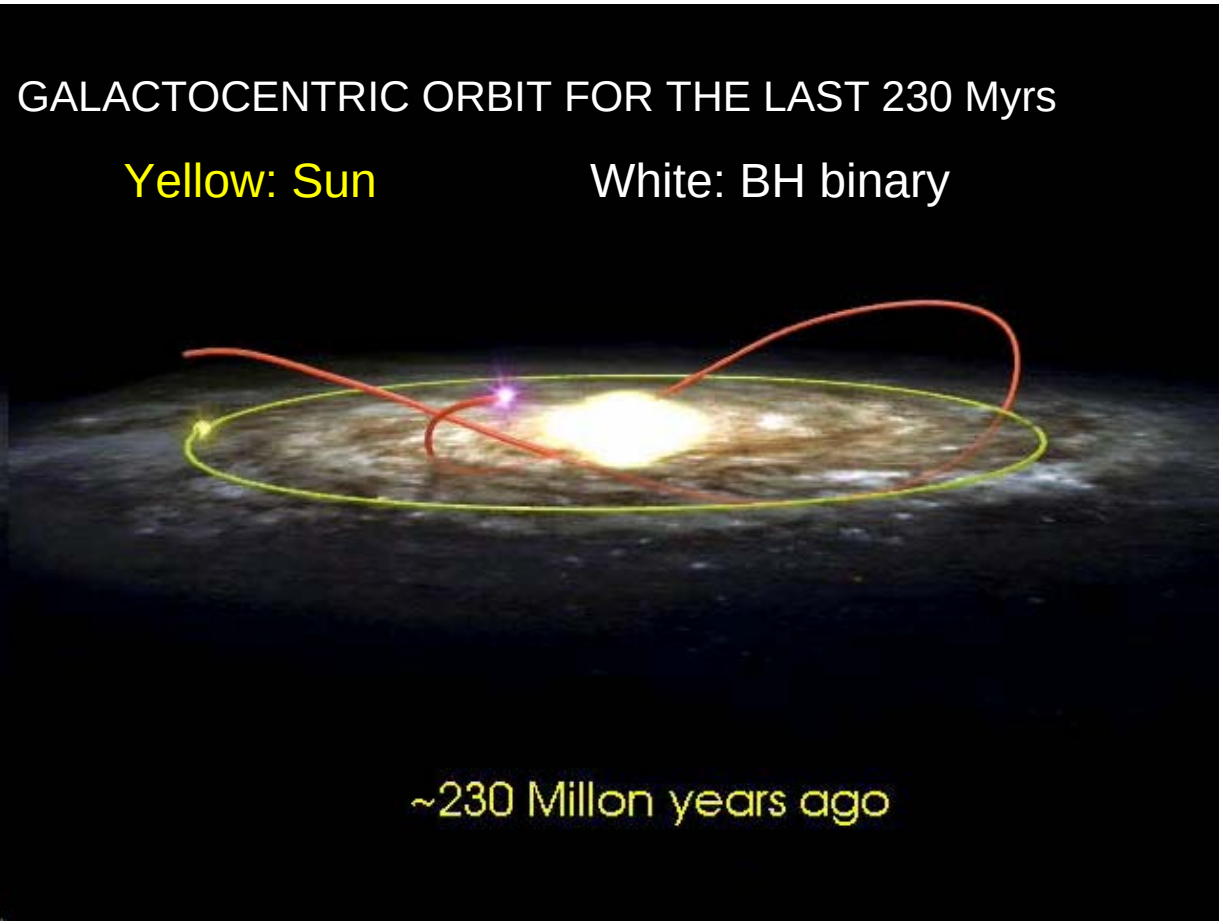
COMPACT HMXBs COULD BE PROGENITORS OF SOME LGRBs

Those of relative low energy and sometimes dark LGRBs in spiral galaxies

(e.g. Cygnus X-3 (Marti et. al, 2001; Van den Heuvel & Yoon, 2007)

THE GALACTIC PATH OF BLACK HOLES

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



Mirabel & I. Rodrigues, (Nature, 2001)

•One of the several millons black holes that should be wondering in the Galactic Halo ?

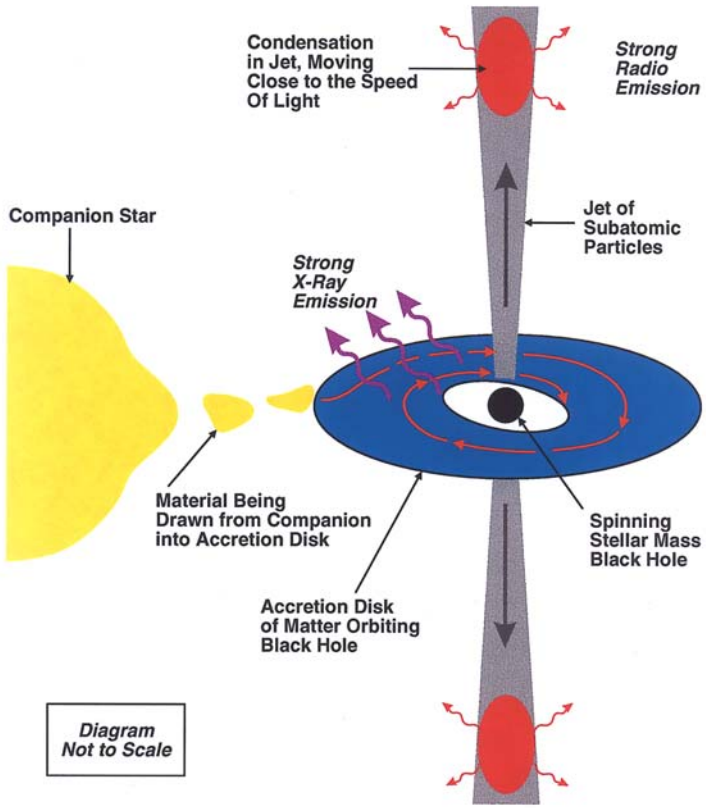
•From the kinematics of 7 μQSOs it is suggested:

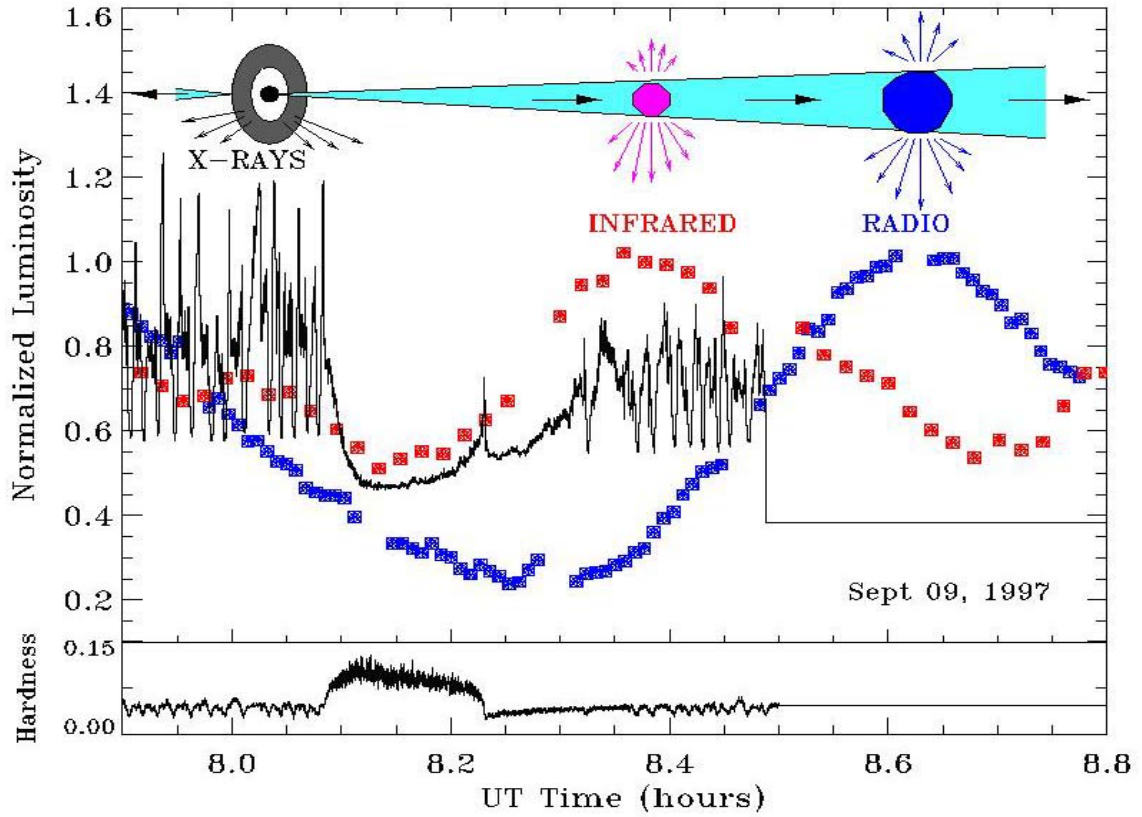
LOW MASS BLACK HOLES FORM IN VIOLENT NATAL EXPLOSIONS WHEREAS MASSIVE BLACK HOLES FORM WITHOUT ENERGETIC SUPERNOVA EXPLOSIONS

ACCRETION–JET CONNECTION

$\Delta T \propto M_{BH}$ **1 hr = 30 yr in SgrA***

Mirabel, Chaty, et al. (1998)





- JET ONSET COUPLED WITH A SUDDEN CHANGE OF THE X-RAY STATE
- THIS ACCRETION-JET COUPLING HAS ALSO BEEN OBSERVED IN QSOs
- SAME INTERNAL SHOCK MODELS FOR AGN, μQSOs & GRBs