ORIGEN DEL PROYECTO LLAMA

Félix Mirabel (IAFE-CONICET)

"LARGE LATIN-AMERICAN MILLIMETER ARRAY"

- **ALMA:** Fusión de MMA(USA), LMA (Japón) y LSA (Europa)

- MMA y LMA a → Chile en Chajnantor, Atacama

- **LSA:** Área colectora de 10.000 m^2 provista por 50 antenas de 16m para observaciones hasta 350 GHz con una resolución de 0.1" ⇒ instalación en alturas entre 3400m y 4000m.

BUSQUEDA DE SITIO EN ARGENTINA PARA LSA

- 1985-1987: Con el auspicio de un subsidio de la National Science Foundation de USA se propone instalar en el IAR el autocorrelador del Observatorio de Arecibo para observaciones en líneas centimétricas del radical OH en el Cometa Halley. Estas observaciones dieron lugar a varias publicaciones y presentaciones en congresos. El correlador permaneció en el IAR.

View from Macon in the province of Salta (Foto by Gaspare Locurto)

ULIRs en 1985 con D.B. Sanders. En 1986 se comienza a explorar el Noroeste de Argentina (Salta, Jujuy, Catamarca...) para estudiar las condiciones atmosféricas para el posible desarrollo en nuestro país de la astronomía milimétrica, sub-milimétrica y en el infrarrojo intermedio (λ>5 micrones)

- Con el apoyo de la gobernación y la colaboración del Dr. Viramonte y geólogos de la provincia de Salta se comienza la búsqueda de posibles sitios para la instalación de LSA en la Puna (Salta y Catamarca). Se identifican sitios potenciales a lo largo de la vía del tren de las nubes en Macon, Pocitos, etc. Se envía un informe sobre los sitios en la Puna a IRAM y ESO.
- Mas tarde MMA, LMA y LSA se fusionan en el proyecto ALMA a ser instalado en Chajnantor

EARLY HISTORY OF PROJECT LLAMA

- 2007: A manuscript with the idea of LLAMA is presented to the president of CONICET & minister of MinCyT of Argentina & the Director of ALMA
- 2007: The idea of LLAMA is dicussed with Brazilian and Argentinian colleagues
- 2008: LLAMA becomes the first priority project for astrophysics in the road map of MinCyT
- 2008: The project is presented at the IAU general Assembly in Rio.

- 2010: Take the lead of LLAMA

Argentina: IAR (Arnal & Morras)
Brazil: Univ. Sao Paulo (Lepine, Abraham, Gouveia Dal Pino)
México: UNAM (Rodríguez, Lizano) provided instruments for site tests directed by Ricardo Morras. But Mexico could not participate in LLAMA because of their involvement in he 60m MM telescope.

A WINDOW OF OPPORTUNITY FOR SOUTH AMERICAN ASTRONOMY

The possibility of installing two radio telescopes for millimeter and sub-millimeter wavelengths, in the Argentinean side of the Atacama desert at distances of 180-210 km from Chajnantor (the site of ALMA), and altitudes greater than 4700 meters, has been discussed among astronomers of Argentina and Brazil.

The support to this idea has been ratified in September 2008 by the Argentinean Astronomical Assembly. In Brazil it is being studied as one of the possible key science goals of the recently approved Astrophysics National Science Institute by the Brazilian National Council of Research - CNPq. Top authorities of Science and Technology in Argentina informed that in the context of regional integration, funds may be available for original projects on basic sciences, with technology transfer components.

The initial US$ 20 million investment of LLAMA would allow Argentine and Brazilian scientists to develop millimeter and sub-millimeter single dish radio astronomy, as well as integration in global experiments with Very Long Baseline Interferometer networks. Of particular interest may be VLBI with already existing radio telescopes in Chajnantor (APEX and ASTE), and in the long run with elements of the ALMA array. Site testing in Argentina has been carried out for three years in Macón (4600m, 180km SE of ALMA) with equipment provided by UNAM (México), and further site testing started at other site 180 km SE of Chajnantor (see attached map). A proposal for initial funding to carry on the in depth study of this project will be submitted by December 2009.

We invite you for an open meeting on this project that will take place on Tuesday August 11 at 17:30 in room 2.11.

I.F. MIRABEL, M. ARNAL, R. MORRAS, G. ROMERO, J. LEPINE, Z. ABRAHAM, EL. M. DE GOUVEIRA DAL PINO

LOCATION OF CHAJNANTOR, MACÓN AND CHORRILLOS. THE YELLOW LINE SHOWS THE BORDER BETWEEN ARGENTINA AND CHILE, THE BLACK LINE THE RAILWAY TRACK SALTA-ANTOFAGASTA.

Millimeter VLBI Science

- **Studies of regions a few times larger than the horizon of super-massive black holes (e.g. Sgr A*, Cen A, etc.).**
- **How relativistic jets are released, accelerated & collimated.**
- **Afterglow spectra of LGRBs**
- **Hiper-starbursts at high redshifts (universe <1 Gyr old)**

- Extra-solar planets and proto-planetary disks
- Megamasers, Masers & stellar envelopes
- Molecular absorption in front of quasars at very high z
- Non-thermal processes in stellar magneto-spheres
- Solar phenomena at unprecedented angular resolution
- Solar system studies: Comets, etc…
- Searches for molecules in circumstellar environments

Science in stand alone mode

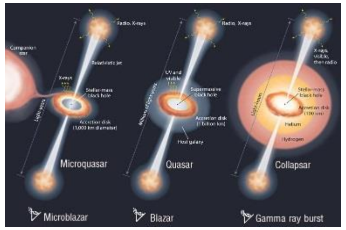
- Several surveys. In 2009 the oversubscription in the ESO time of APEX as large as for VLT

CONCLUSION: The advantages of LLAMA

- **Take the lead in the follow up of a global project** that the central countries could not start to fund before ~2018. The anticipation by the countries of the region would place them in an advantageous position to participate in all ALMA science that requires higher angular resolution.
- **A ~US$ 20 million investment would allow partial integration in a global project that entails an investment of ~US$ 1.4 billion.**
- **It is an original, scientific-technological project** . It will not repeat goals already achieved (e.g. optical and near IR telescopes installed in Chile decades ago)
- **it will serve as testing ground to correct regional scientific-technological integrations, step by step, and in progressive way,** since in the long run, this project may require the installation of antennae in several countries of the region.
- **LLAMA is an ideal context to train human resources** in material engineering and microwave technologies, which has applications in telecommunications, surveys of natural resources, microelectronics and business management, at national and regional level.

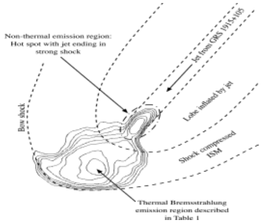
CURRENT RESEARCH ON THE IMPACT OF μQSOs IN BH ASTROPHYSICS

- **PHYSICS: Accretion-jet connection in black holes**



Mirabel, Rodriguez et al. (1992-2004)

- **STAR FORMATION: Induced by BH jets** Rodriguez, Mirabel+ (2009-2016)



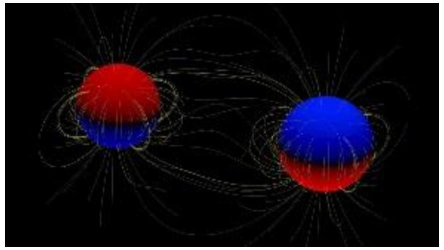
- **COSMOLOGY: Early heating of the universe by BH-HMXBs (μQSOs)**

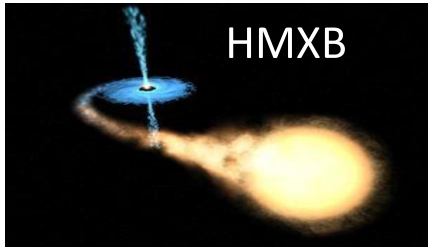
Mirabel, Loeb, Diskra et al. (2011-2013) continue by Douna & Pellizza (2014-2016)

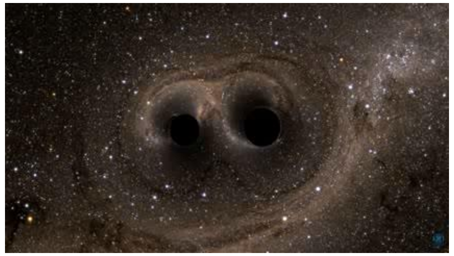
$M_{min} \sim 10^9 (\rho/100\rho_c)^{-1/2} (\mu/0.6)^{-3/2} [T(K)/10^4]^{3/2} [(1+z)/10]^{-3/2} M_\odot \Rightarrow$ impact on #s of dwarf galaxies & λCDM model

- **SOURCES OF GRAVITATIONAL WAVES: Formation of BBHs**

Based on work by Mirabel, Rodrigues, Dhawan, Rodriguez+ (2016)

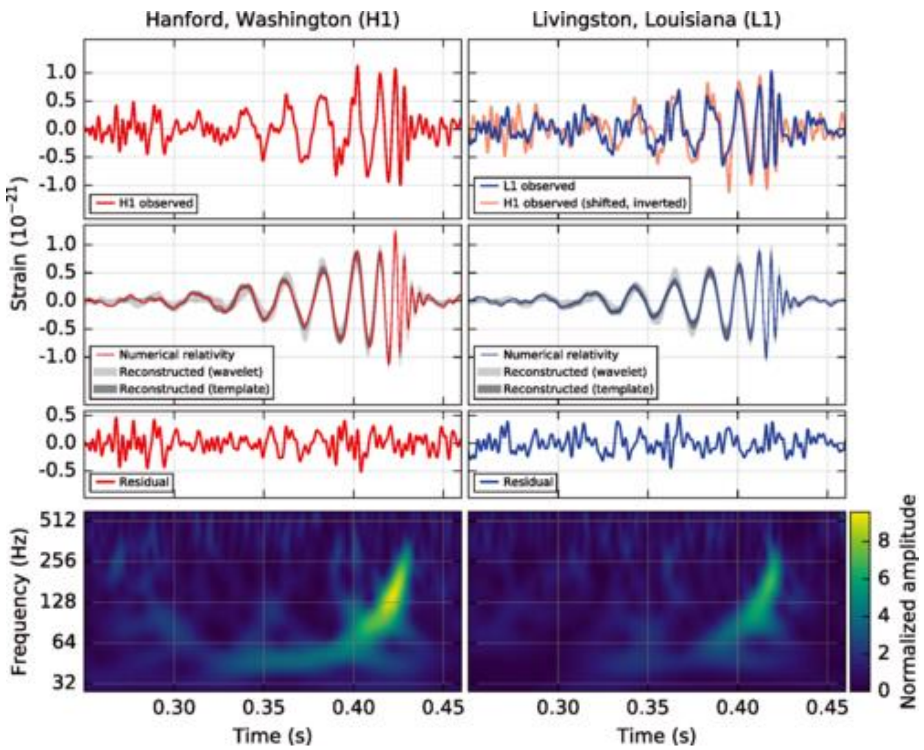


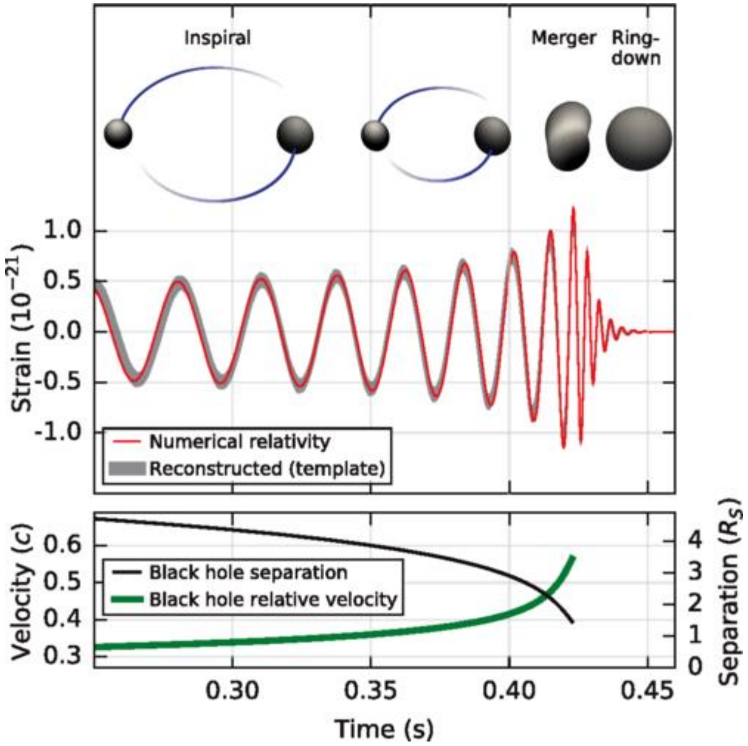




OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE

Abbott et al. (LIGO & Virgo collaborations (Physical Review Letters, 11 Feb 2016)





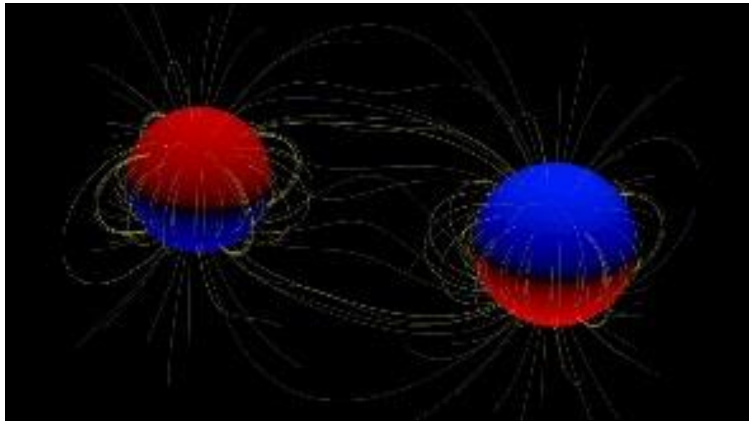
$$\mathcal{M}=\frac{(m_1 \times m_2)^{3/5}}{(m_1+m_2)^{1/5}}=\frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} \times f^{-11/3}\dot{f}\right]^{3/5},$$

- Luminosity distance of 410 +/- 170 Mpc (z~0.09)
- Merger of a 36 $M_\odot$ & 29 $M_\odot$ BHs with a final BH of 62 $M_\odot$ and 3 $M_\odot$ radiated in GWs
- Peak gravitational wave energy of 3.6 x 10^56 erg/s with no electromagnetic or neutrino counterpart

FROM MASSIVE STELLAR BINARIES TO BBHs

MASSIVE STELLAR BINARY

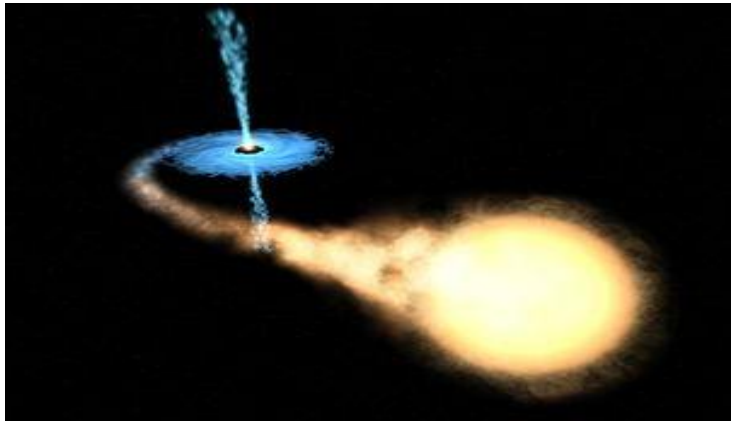
>80% found in multiple systems



BLACK HOLE HIGH MASS X-RAY BINARY

BH-HMXB

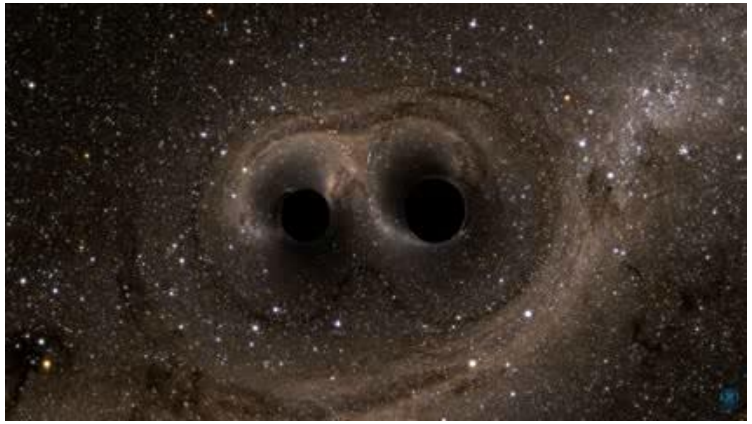
Only 3 known in the Milky Way



BINARY BLACK HOLE

BBH

GW150914



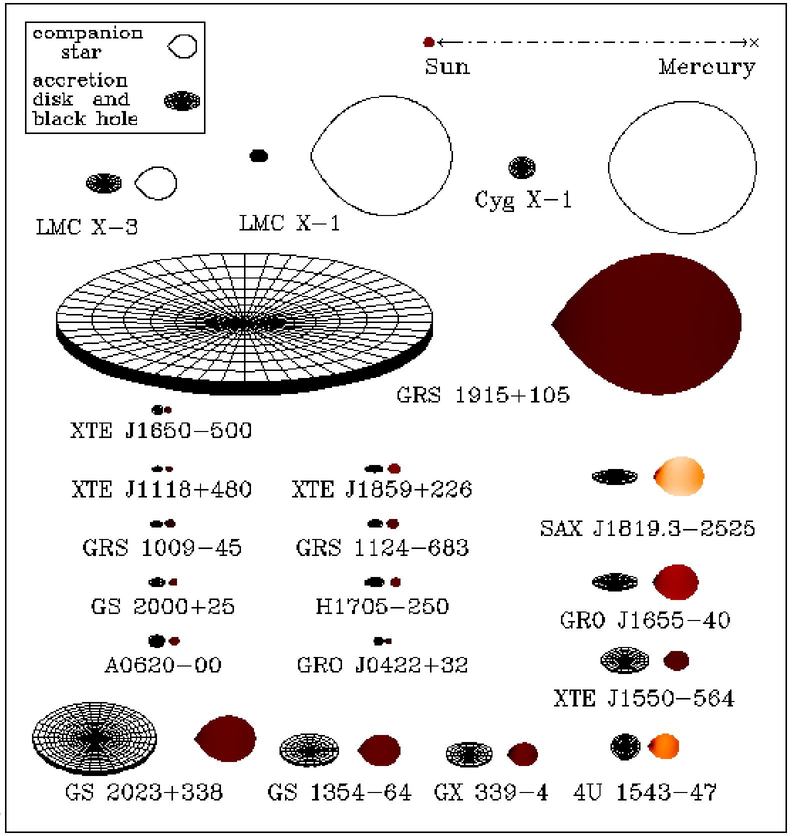
- In “Stellar black holes at the dawn of the universe” Mirabel et al. A&A 2011 was predicted a prolific formation of BH-HMXBs which motivated a News & Views in Nature (Haiman, 2011)
- What fraction of massive stellar binaries end as BH-HMXBs, and what fraction end as BBHs?

BLACK HOLE X-RAY BINARIES (from Orosz)

Among the estimated 3x10^8 BHs in the Galaxy only 20 have been confirmed

XTE 118+480
Mbh=7.6 $M_\odot$
K7 V–M1 V
Kick=183 km/s

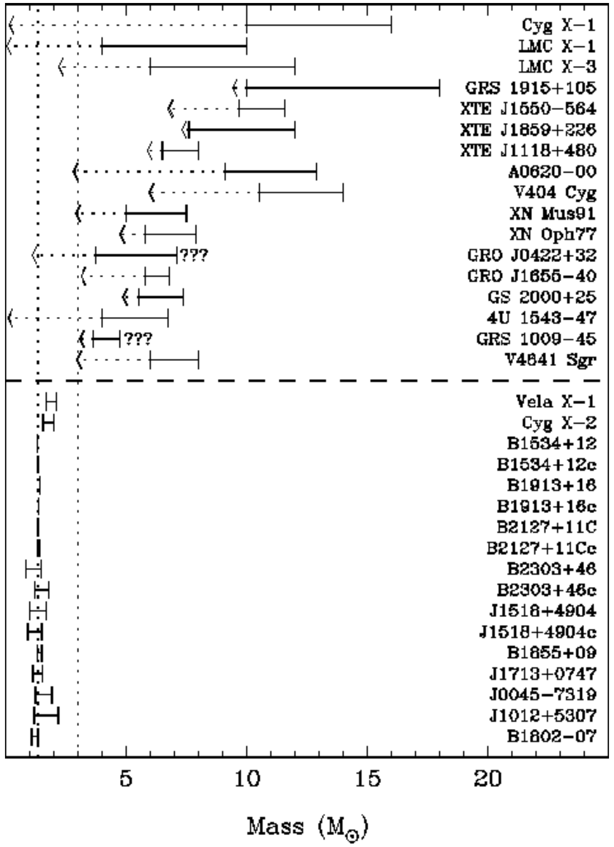
GS 2023+338
Mbh=7.5 $M_\odot$
K0 IV donor
Kick=39.6 km/s



Cyg X-1
Mbh=14.8 $M_\odot$
09.7lab donor
Kick<9 km/s

GRS 1915+105
Mbh=12.4 $M_\odot$
K-M III donor
Kick<22 ± 24 km s−1,

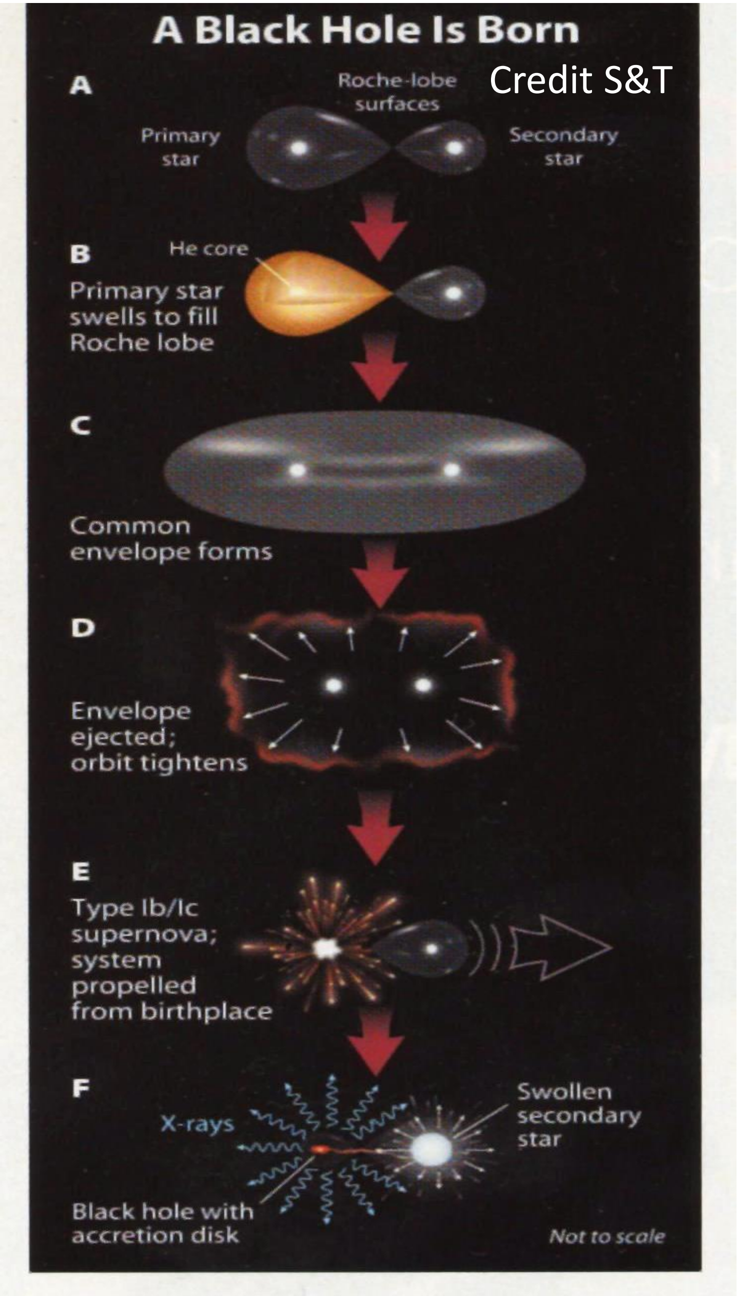
GRO J1655-40
Mbh=5.3 $M_\odot$
F6 III donor
Kick=112 km/s



Schematic diagram of the 20 dynamically confirmed black hole binaries. Seventeen have low mass companions (i.e. stars with masses less than about 3 solar masses), and the three on the top have high mass companions. The color scale for the 17 objects with low mass companions represents the temperature of the star(Cyg X-1, LMC X-1, and LMC X-3 all have companions which are considerably hotter

A compilation of the mass ranges for the 17 black holes pictured above. The arrows for the black holes point to the mass function, which is a firm lower limit for the mass of the black hole. In most cases the mass function is quite well known. In a few cases like GRS 1915+105, XTE J1550-564, and XTE J1859+226, the error on the mass function is still relatively large.

DO StBHs RECEIVE NATAL SN KICKS?



FORM WITH OR WITHOUT ENERGETIC NATAL SNe?

CORE COLLAPSE MODELS:

Massive stellar black holes (M>10 $M_\odot$) may form with no energetic kicks

(Fryer & Kalogera; Woosley & Heger; Nomoto+...)

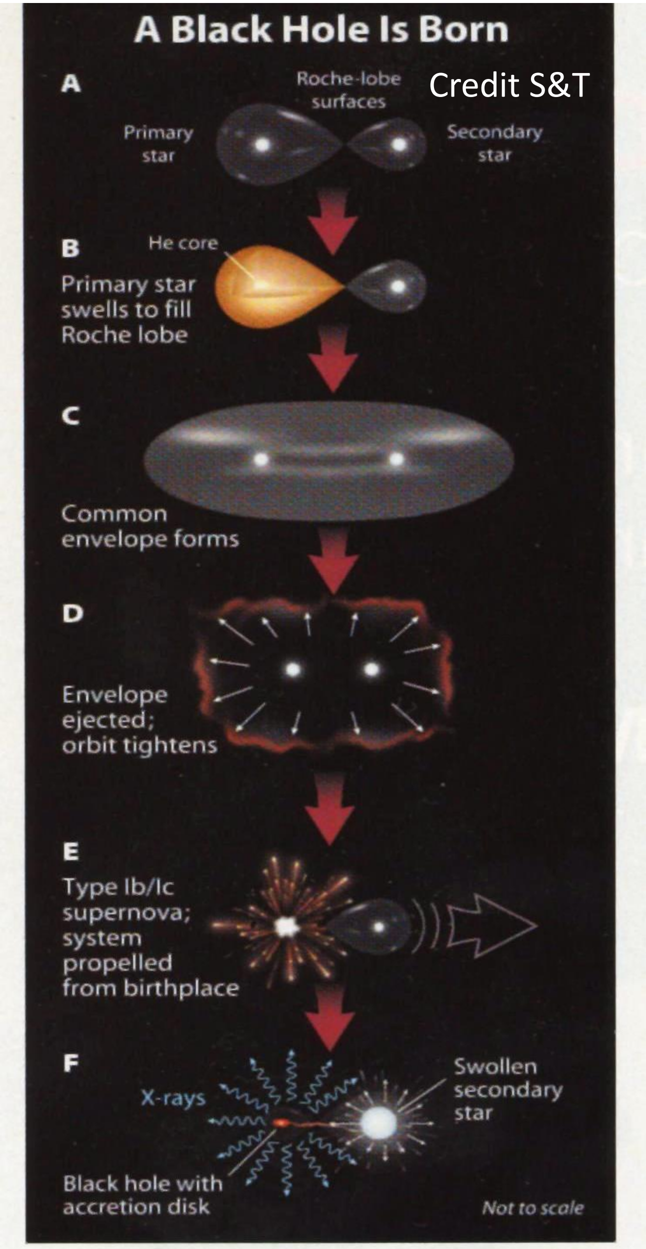
- **IS THERE ANY EVIDENCE OF StBH FORMATION BY DIRECT COLLAPSE?**
- **IS THERE A RELATION BETWEEN KICK VELOCITIES AND BH MASS?**

CORE COLLAPSE MODELS TESTED USING THE KINEMATICS OF BH μQSOs: {(5/20 BHs)/3x10^8}

Mirabel et al. (2001-2009)

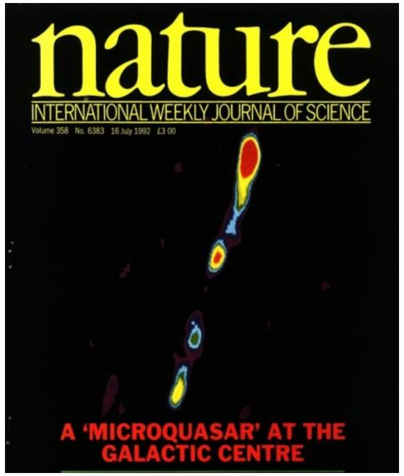
APPROACH BASED ON KINEMATICS (Mirabel & Rodrigues 2001-2009)

With VLBI get sub-miliarc sec precision. Proper motions with VLBI of compact jets and/or optical images with HST



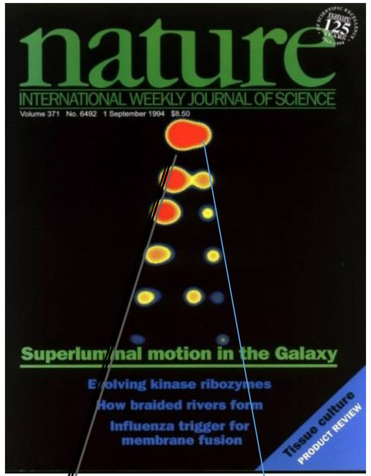
STEADY JETS

Mirabel + 1992



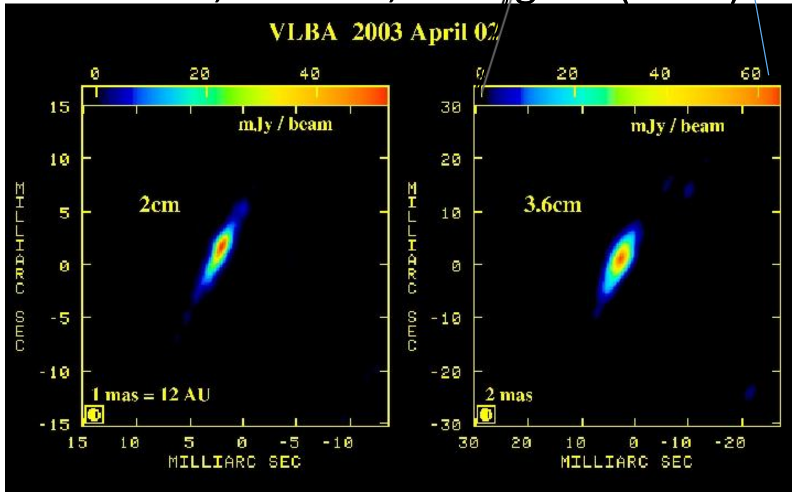
TRANSIENTJETS

Mirabel-Rodríguez 1994



COMPACT JETS

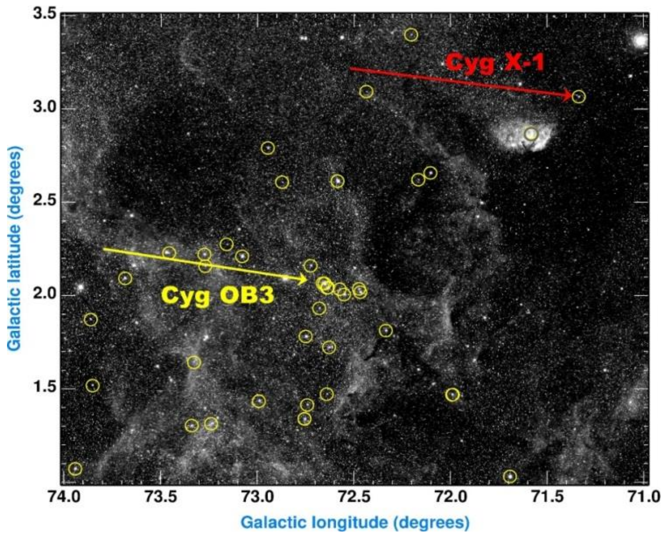
Dhawan, Mirabel, Rodríguez (2007)



In low hard state compact jets have Sizes ~ 100 AU & Same PA as large scale jets.

RESULTS FROM FIVE BH-XRBs

Mirabel & Rodrigues (Science, 2003)



Cygnus X-1: $V_p < 9 \pm 2$ km/s $\Rightarrow < 1\ M_\odot$ ejected in a SN

GRS 1915+105: $V_p = 22 \pm 24$ km/s $\Rightarrow$ Galactic diffusion

- **BHs WITH >10 $M_\odot$ FORM BY IMPLOSION**

Mirabel et al.(Nature 2001)

XTE J1118+480; GRO J1655-40 & V404 Cyg

- **BHs OF < 10 $M_\odot$ ARE RUNAWAY BLACK HOLES**

CONSISTENT WITH:

1) **PREDICTIONS FROM THEORETICAL MODELS**
2) **CHEMICAL ELEMENTS IN THE DONOR STARS** (Israelian+ Nature 1999; Gonzalez+ 2006
3) **PROGENITORS OF CORE COLLAPSE SNe with masses <18 $M_\odot$** (Smartt 2015)

ASTROPHYSICAL IMPLICATIONS

Abbott et al. 2016, ApJ 818 L22 A2016

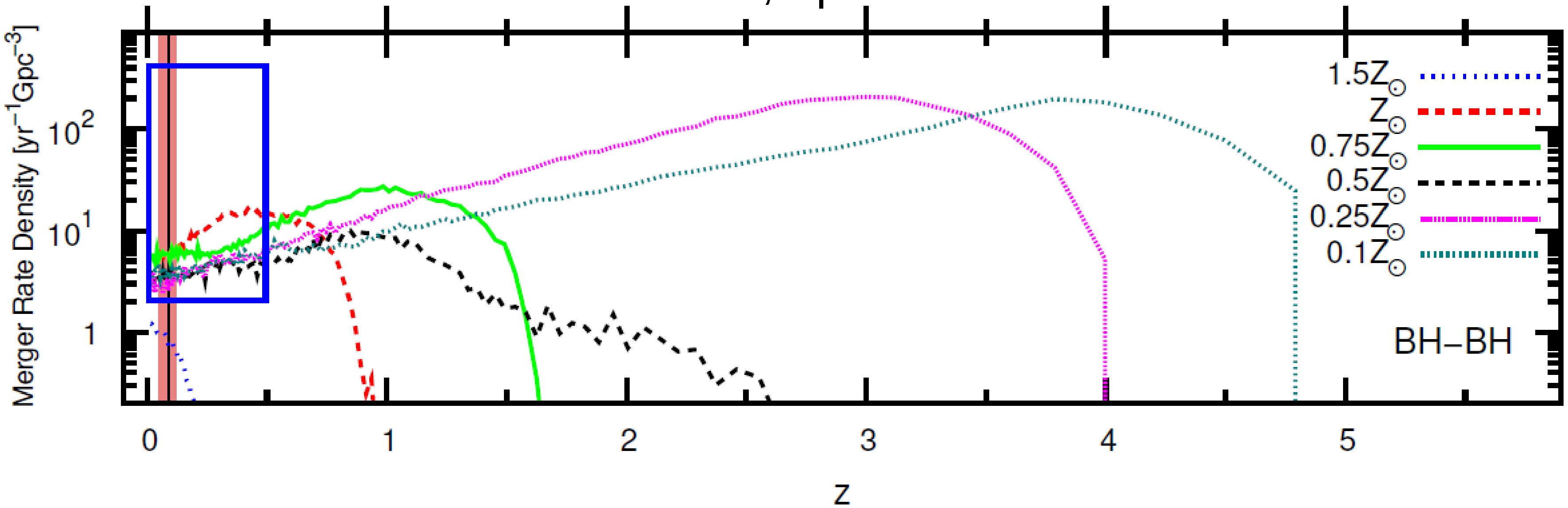


Figure 2. Predictions of BBH merger rate in the comoving frame (Gpc^{-3} yr^{-1}) from isolated binary evolution as a function of redshift for different metallicity values (adopted from Figure 4 in Dominik et al. 2013). At a given redshift, the total merger rate is the sum over metallicity. The redshift range of GW150914 is indicated by the vertical band; the range of the BBH rate estimates and the redshift out to which a system like GW150914 could have been detected in this observing period are indicated by an open blue rectangular box.

- What would be the merger rate of BBHs produced at z>6 with Z<0.1 $Z_\odot$?
- Up to what small masses can BHs be components of BBHs?
- Can BBHs be form at $Z_\odot$?
- How large may be the population of binary black holes that would contribute significantly to a stochastic gravitational-wave background by the incoherent superposition of all the merging binaries in the universe?
- Would the propagation of light be significantly affected by such GWs? i.e. the cosmic microwave background?

LOS COMIENZOS DE LA GESTION DE LLAMA

- Ricardo Morras dirige los estudios de las condiciones atmosféricas en Macón, Chorrillos, etc con instrumentación facilitada por la UNAM gracias a la gestión de L.F. Rodríguez y S. Lizano.
- 2006-2009: Presentaciones de la idea de LLAMA a: Charreaux (Presidente del CONICET) y Barañao (Ministro del MinCyT) en Argentina, Jacques Lepine, Thijs de Graauw (Director de ALMA), y en la Asamblea General de la Unión Astronómica Internacional en Brasil.

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Diario de la UAI en 2008

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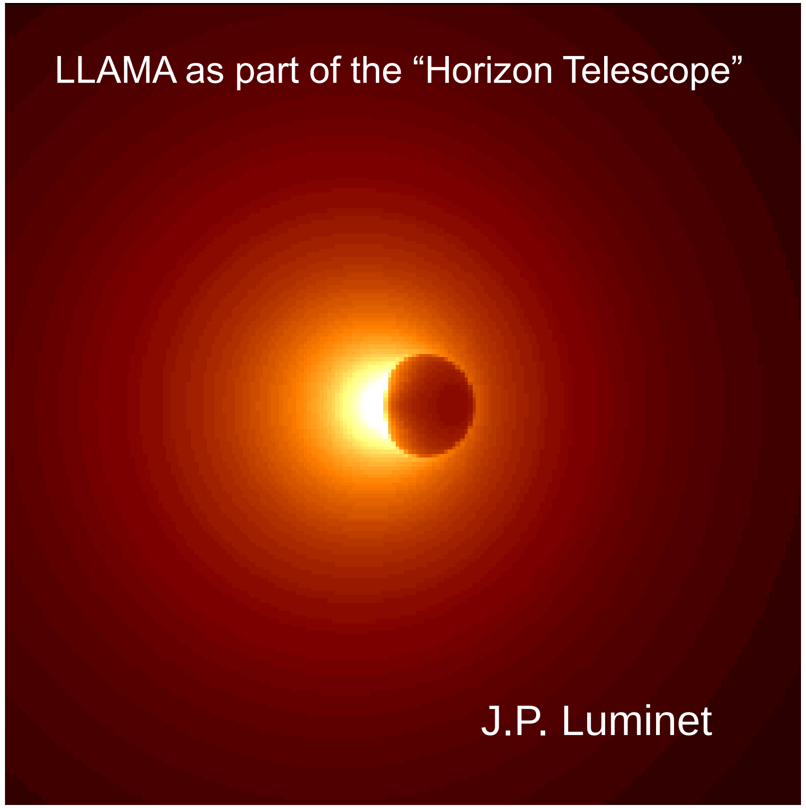
- En reuniones con el Dr. Ceccatto se acuerda que el IAR es el instituto por parte de Argentina que debe gestionar la construcción de LLAMA en colaboración con Brasil.

GR IMAGE OF THE SMBH IN Sgr A*

- **Dark circle caused by radiation from behind BH being swallowed by the event horizon (R = 10 μas = 0.1 UA)**
- **Bright ring = rays deflected by BH**
- **Shadow is off-centre due to flung of photons in the direction of BHs' spin**

- **VLBI @ 1.3mm with a resolution of 40μas showed that the bulk of the emission is not centered on the BH** (Doeleman et al. in Nature Sept. 2008)

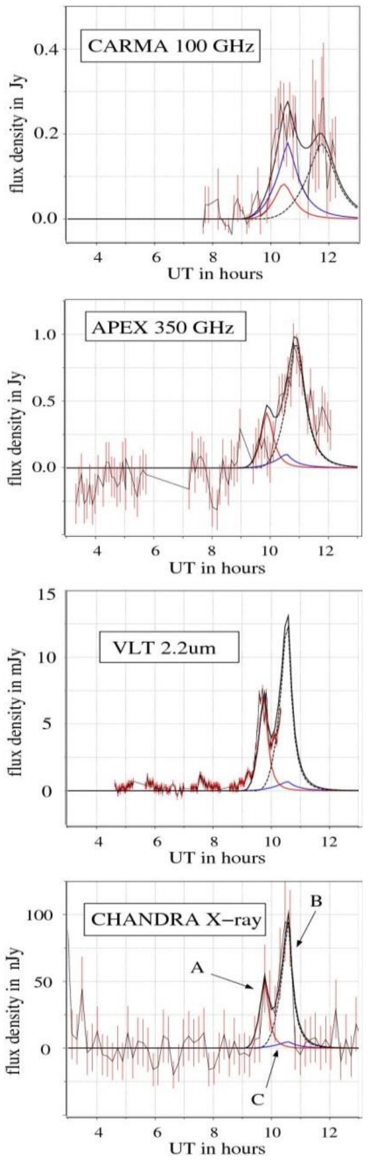


- **4 x 10^6 $M_\odot$ confined in a region enclosed by less the orbit of the Earth**
- **R < 10 μarcsec could be imaged with VLBI at sub-millimeter or X-rays**

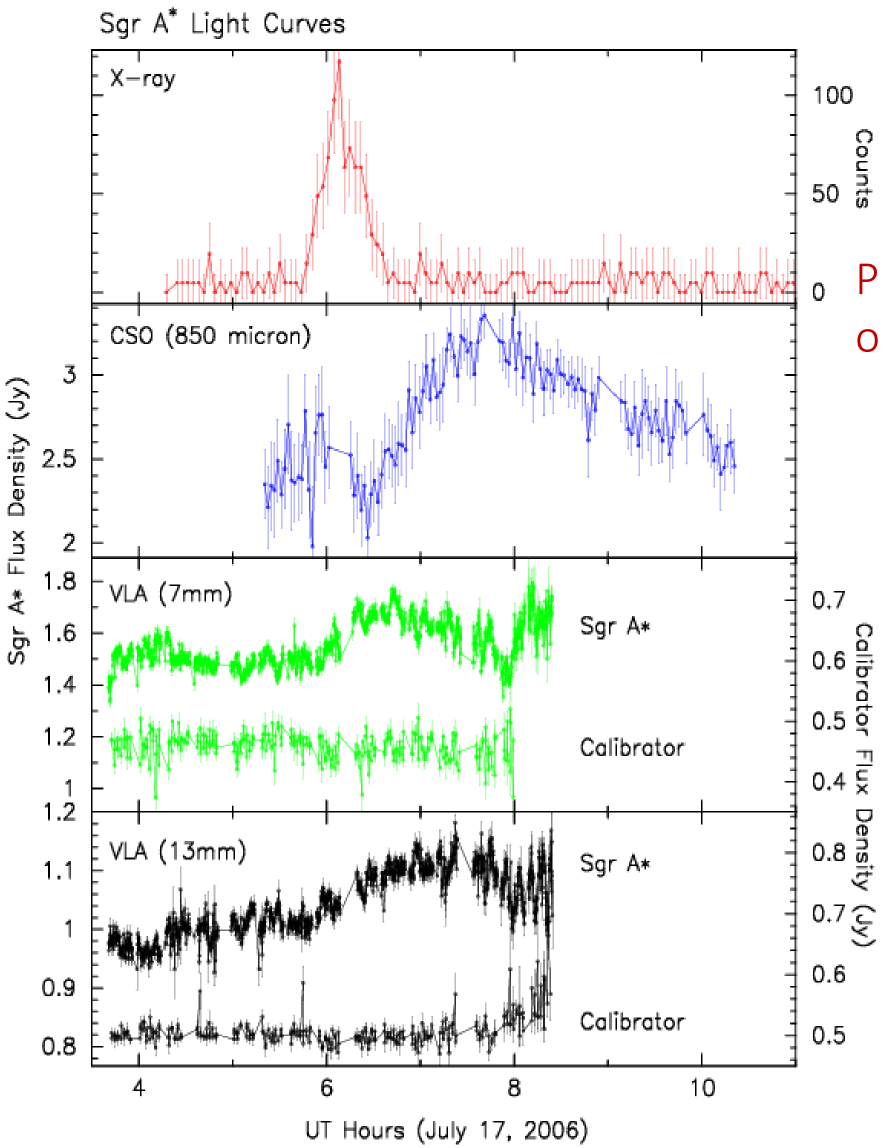
INTERCONTINENTAL VLBI WITH ALMA…THE FIRST GR IMAGE?

Millimeter flares in Sgr A*

How relativistic jets are released, accelerated & collimated?



Eckart et al. (2012)

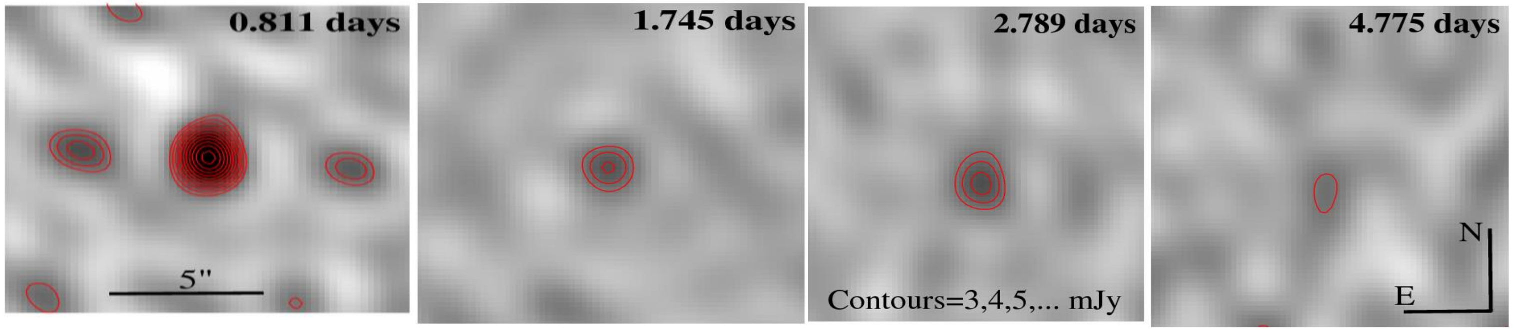


Yusef-Zadeh et al (2011)

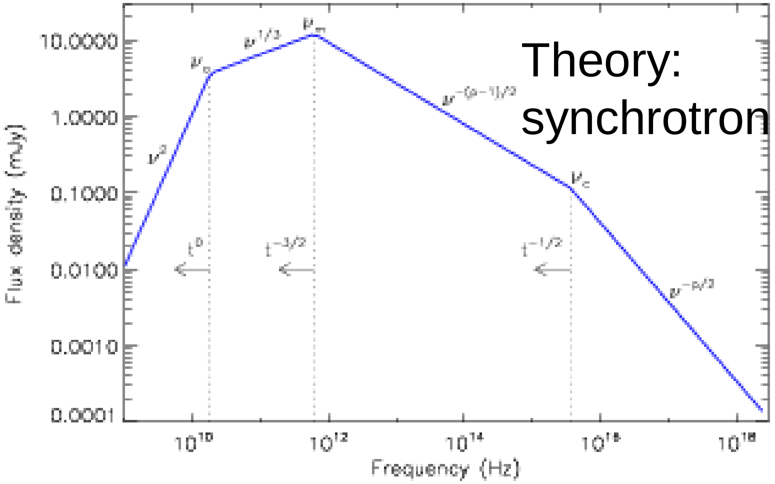
Plasma ejections from Sgr A* observed in mm waves

Multi-wavelength observations of flares suggest an adiabatically expanding blob model to explain the observed time lags between the infrared/X-ray and millimeter flares.

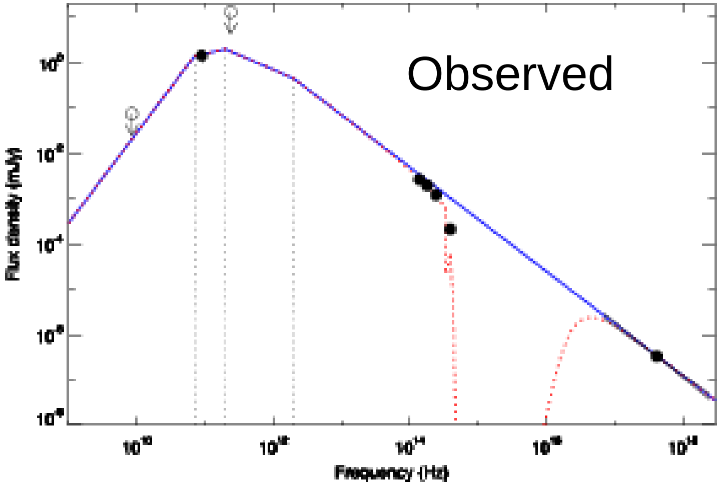
GAMMA-RAY AFTERGLOWS IN THE MM/SUB-MM RANGE



Observations of GRB100418A obtained with SMA during the first 5 days after the GRB (adapted from de Ugarte Postigo et al. 2012)



The synchrotron afterglow spectrum expected from a simple fireball model (Sari et al.)



SED of GRB 050904 at redshift z = 6.29 using the detection from PdBI 5.896 days after the burst (Castro-Tirado et al. 2012).