

# JET-INDUCED STAR FORMATION IN THE REIONIZATION EPOCH

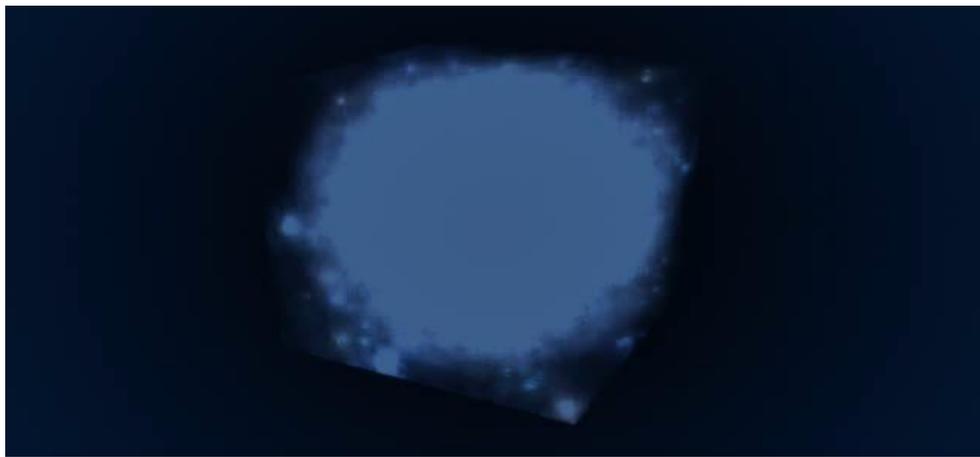
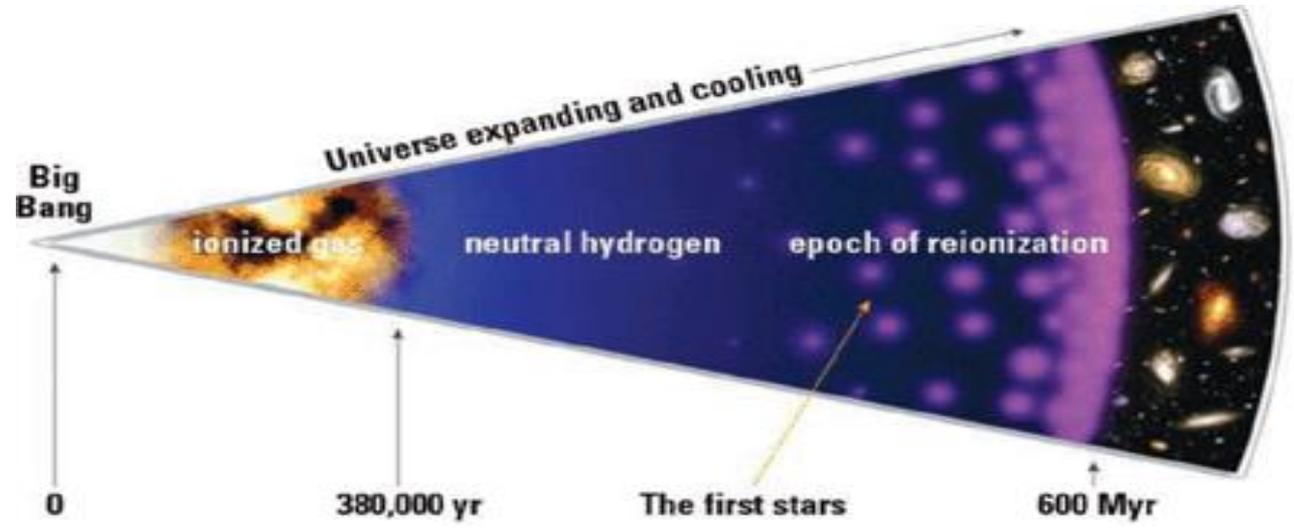
Félix Mirabel (IAFE-Argentina & CEA-France)

Rodriguez (UNAM), Chaty (U. Paris), Maury & Sauvage (CEA), Geballe (Gemini)



A subject at the crossroads of Star Formation,  
Black Hole High Energy Astrophysics & Cosmology

# RE-IONIZATION: A MAJOR FRONTIER IN COSMOLOGY



THE « SWISS CHEESE » MODEL  
for the re-ionization of the IGM

The IGM was fully ionized by the UV  
from the first stars (Pop III & II)  $\Rightarrow$   
HII regions expanding at  $< 100 \text{ Km/s}$

**WHAT WAS THE ROLE OF HIGH ENERGY SOURCES?**

# BLACK HOLES IN THE REIONIZATION EPOCH

## Based on theoretical & observational grounds

Mirabel in Invited Review (Proceedings of IAU Symp. 275, 2010)

Mirabel, Dijkstra, Laurent, Loeb, Pritchard (A&A 2011)  $\Rightarrow$  N&V in Nature (2011)

Douna, Pellizza, Mirabel, Pedrosa (A&A 2015).....

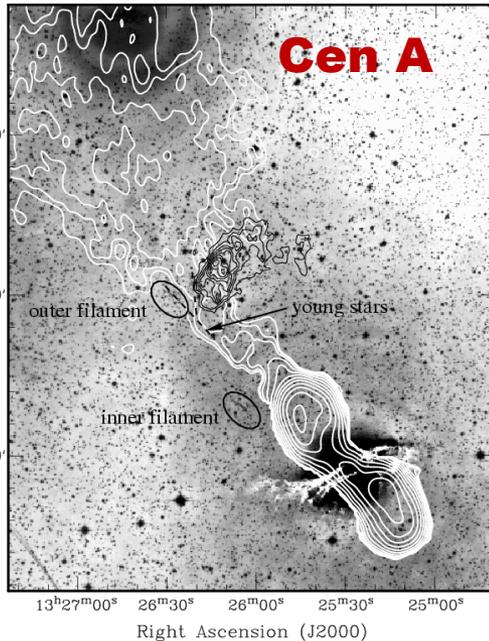
**At low  $Z$ s large fractions of Pop III&II end as BH-HMXBs, which are prolific sources of X-rays and relativistic outflows:**

- **X-rays heat** the gas to  $10^4$  K and partially ionize the bulk of the IGM over large distance scales. **Jets** at the interface with the ISM produce cosmic rays (Heinz & Sunyaev, 2002), which along with X-rays contribute to the reionization (Tueros, del Valle and Romero 2014)
- The rapid heating of the IGM by X-rays & Jets from stBHs **reduce the numbers of dwarf galaxies predicted by the  $\lambda$ CDM**
- The Jean's mass increases and there should be large numbers of **naked dark matter haloes with  $M < 10^9 M_{\odot}$  swirling around**
- The  $\lambda 21$  cm HI tomography with LOFAR, SKA ...of the reionization epoch will show a **smoother end of the dark ages** than that predicted by the current Swiss cheese models that only consider the UV radiation from massive stars

# JETS FROM ACCRETING BLACK HOLES

## DO BH JETS TRIGGER MASSIVE STAR FORMATION?

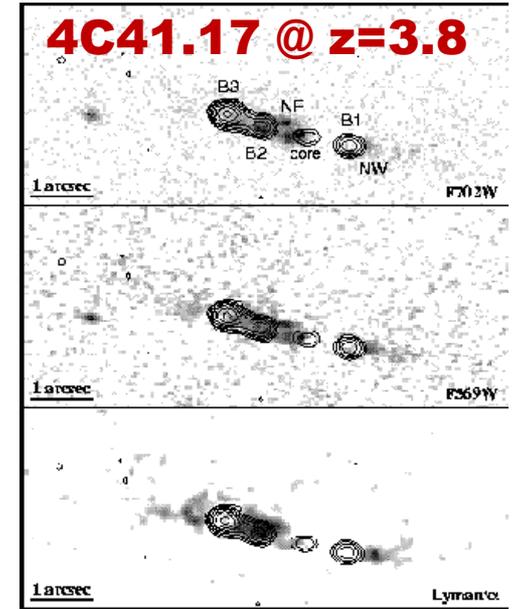
Blanco+1975...



van Breugel + 1985



Bicknell + 2000



## STATISTICAL STUDIES UP TO HIGH REDSHIFTS

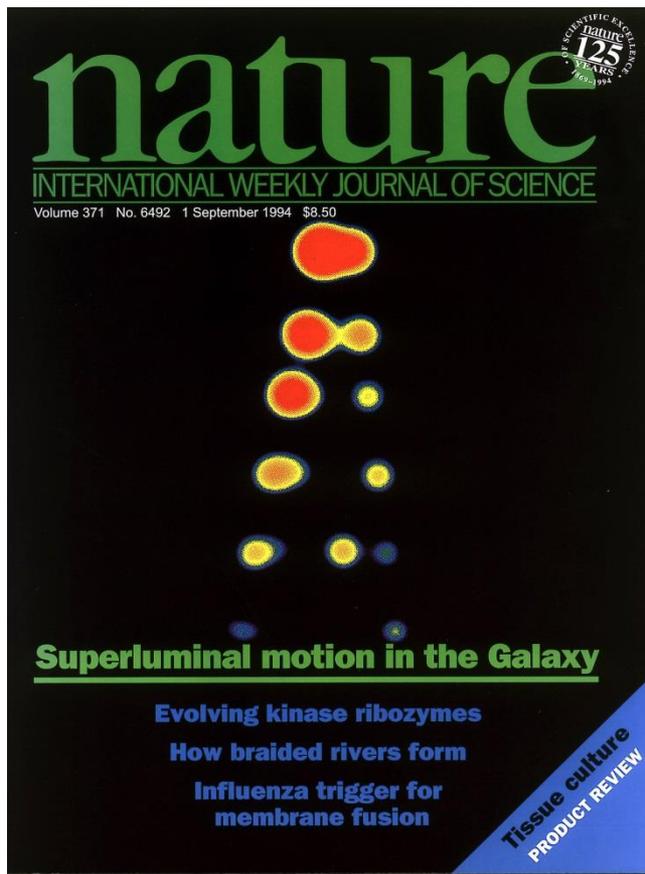
Chambers+ with Hubble (1987); McCarthy+ from the ground (1987)

- The physical size of jets decrease with  $z \Rightarrow$  enhancement of the IGM density
- In high  $z$  Radio Galaxies the  $H\alpha$  emission is aligned with the jet axis  $\Rightarrow H\alpha$  due to SF?

The physics of jet-cloud interaction that could lead to SF is not elucidated  $\Rightarrow$   
**Is there a nearby laboratory to study jet-induced star formation?**

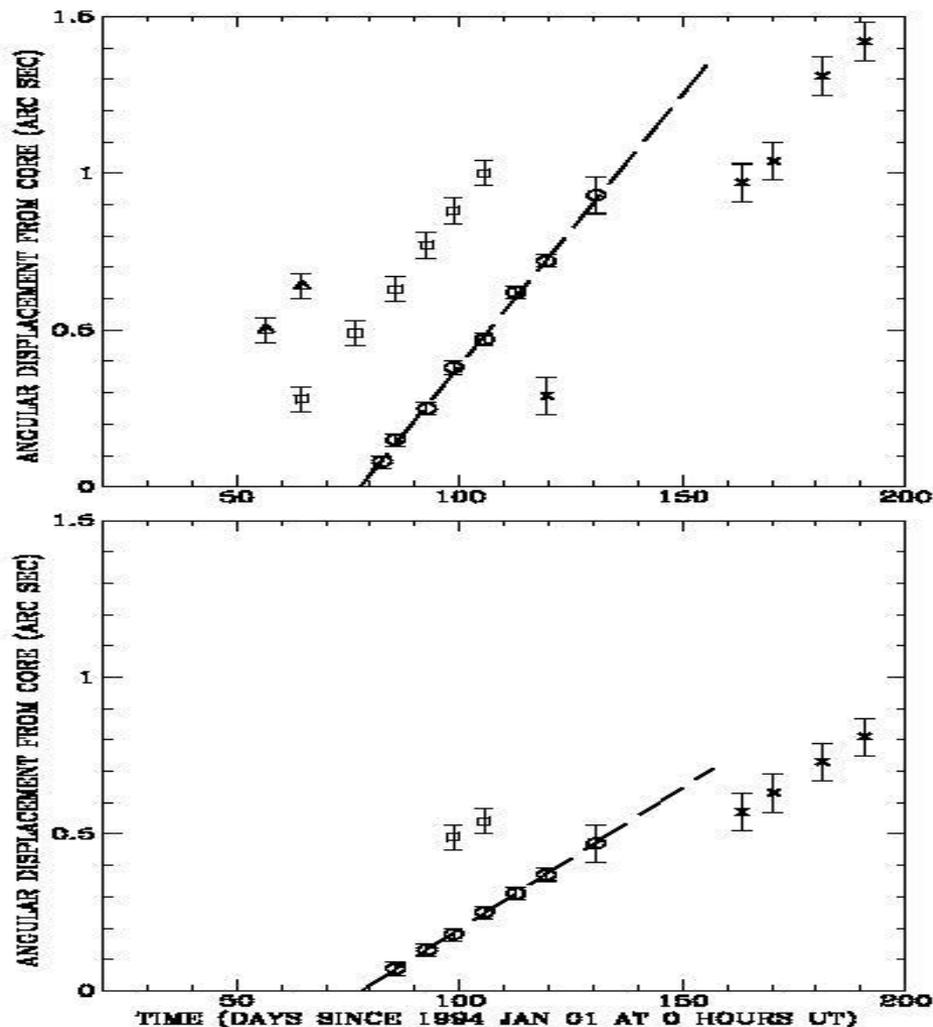
# GRS 1915+105: A SUPERLUMINAL $\mu$ QSO

Mirabel & Rodríguez, 1994



- A BH of  $12M_{\odot}$  accreting by Roche lobe overflow from a red giant of  $1 M_{\odot}$
- It must have been active for  $> 10^6$  yr

Rodríguez & Mirabel 1999)

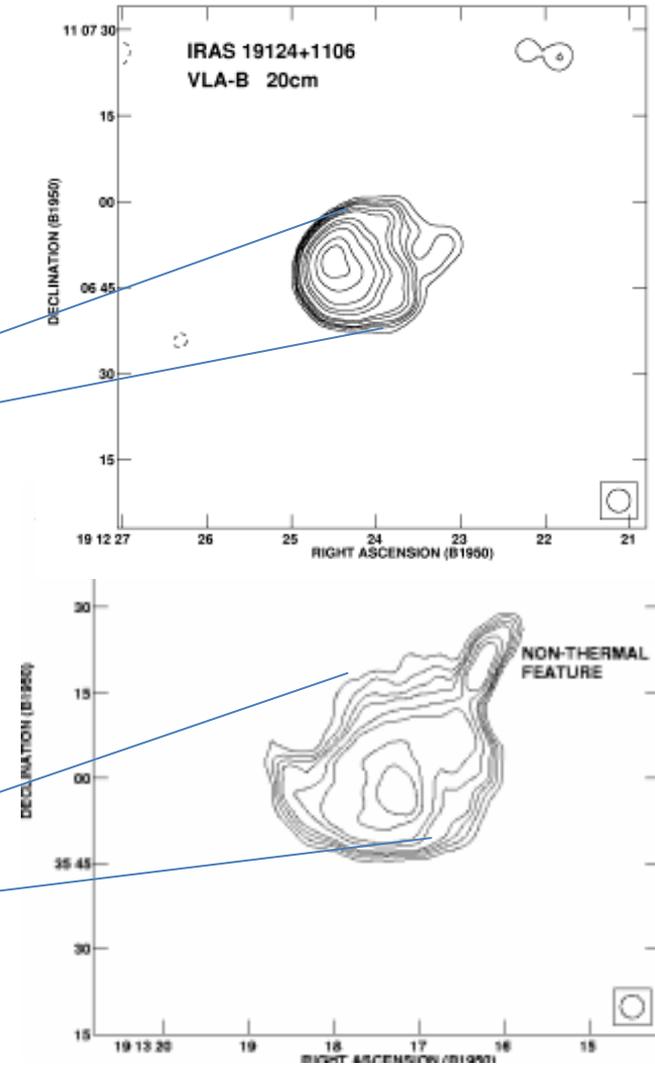
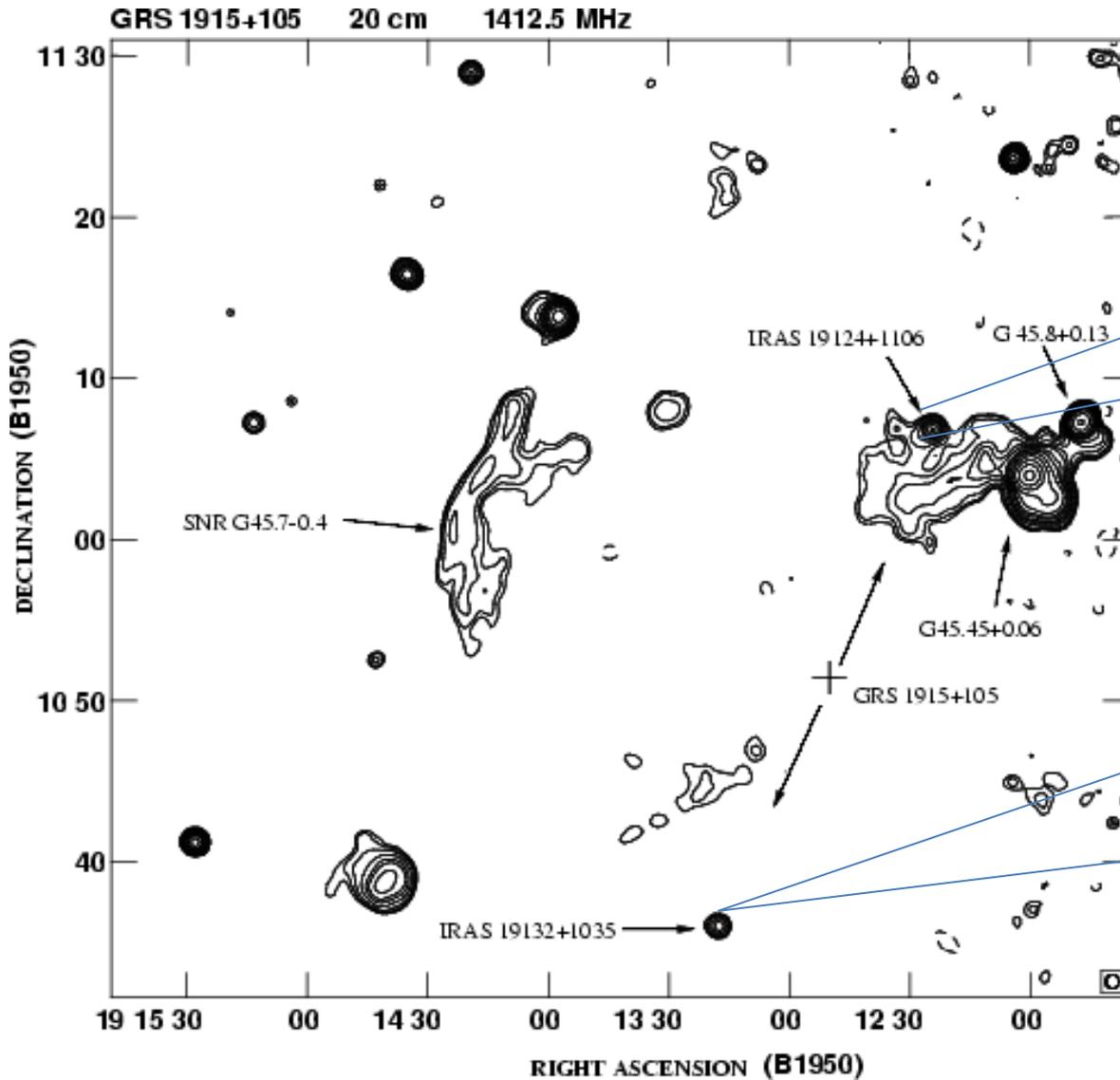


$$\text{Bulk } \Gamma = (1 - \beta^2)^{-1/2} \sim 5$$
$$E_{\text{kin}} = \text{few } 10^{46} \text{ erg}$$

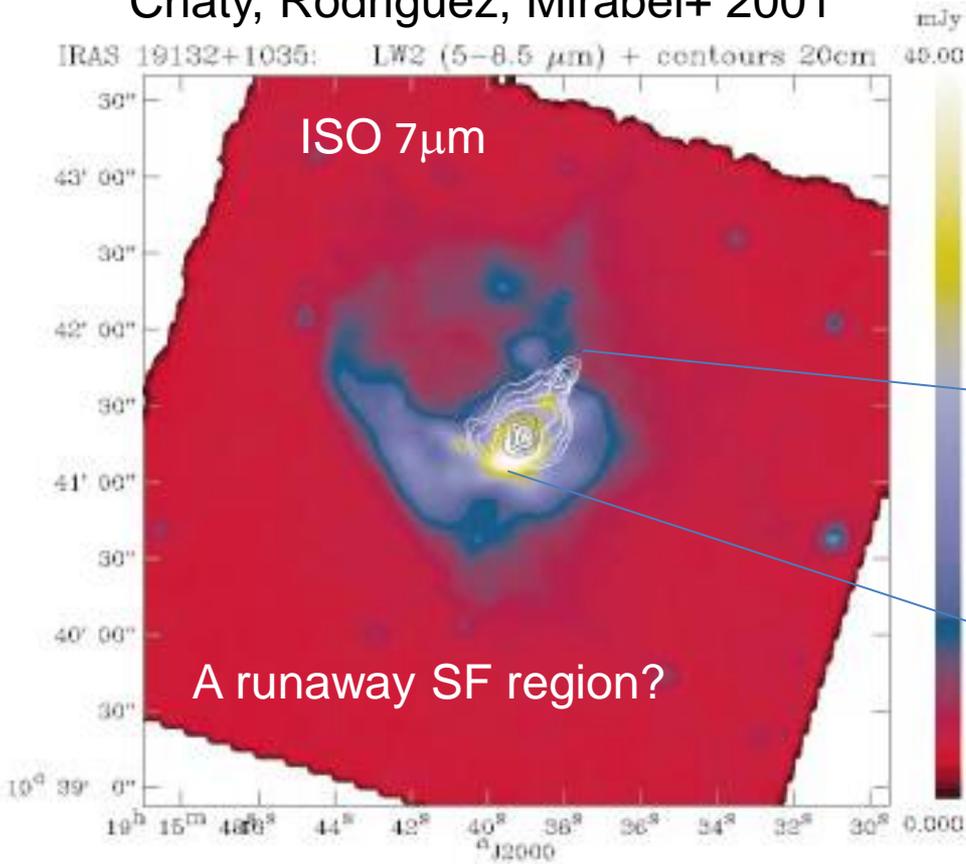
**Where has all the energy gone?**

# STAR FORMATION INDUCED BY $\mu$ QSO JETS?

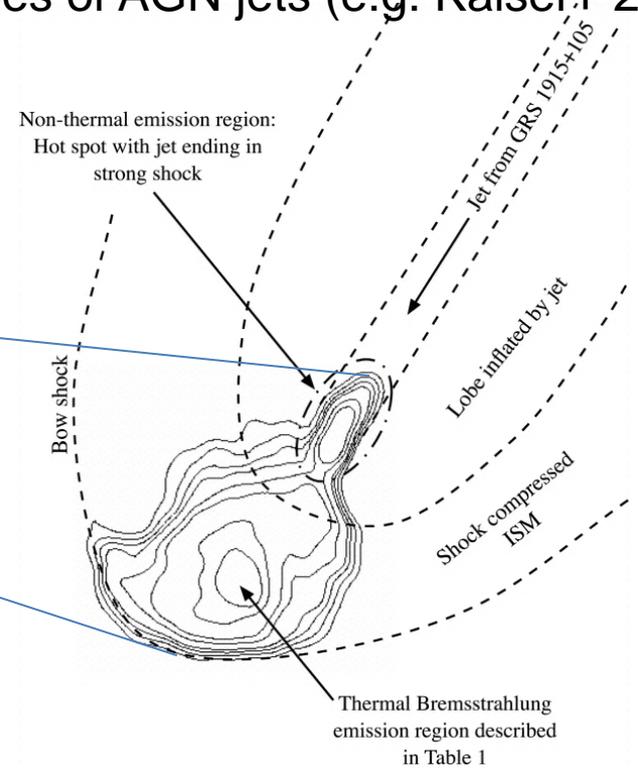
Rodríguez & Mirabel (1998)



Chaty, Rodriguez, Mirabel+ 2001



Consistent with models for the radio lobes of AGN jets (e.g. Kaiser+ 2004)



But in 2001 the distances of the SF region and jet source were uncertain...

**$\mu\text{QSO}$  and SF region are at same distance of 8.6 $\pm$ 1.4 kpc (Reid+2014)**

**$\Rightarrow \mu\text{QSO}$  jets very likely impact the SF regions at 50 pc**

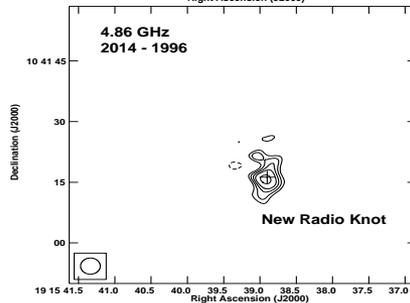
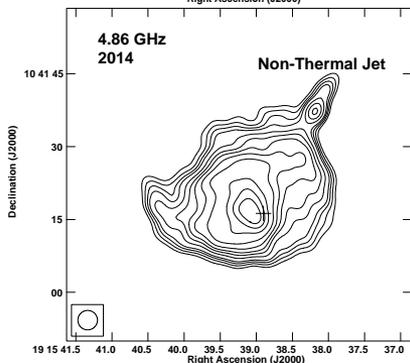
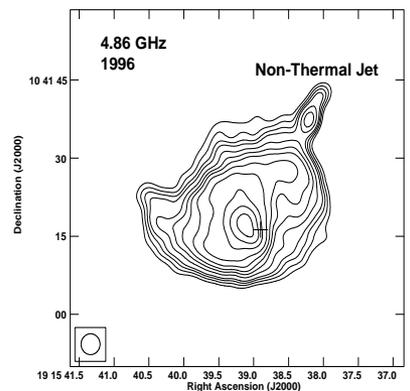
**Any unambiguous evidence for the impact of  $\mu\text{QSO}$  jets on the SF region?**

# On-going research on jet-induced SF

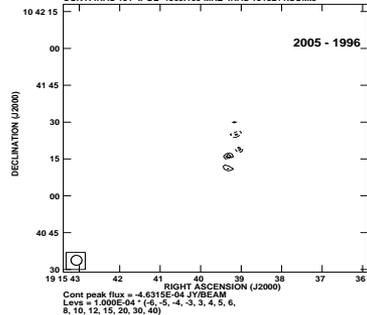
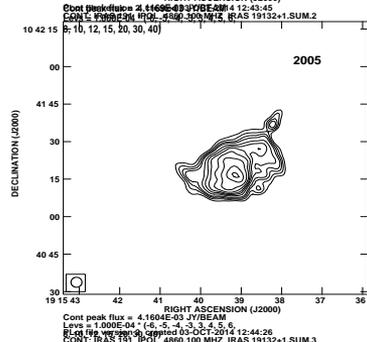
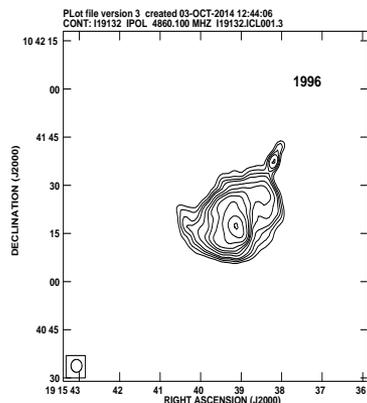
(Mirabel, Rodriguez, Chaty, et al. 2015)

Changes in brightness & position

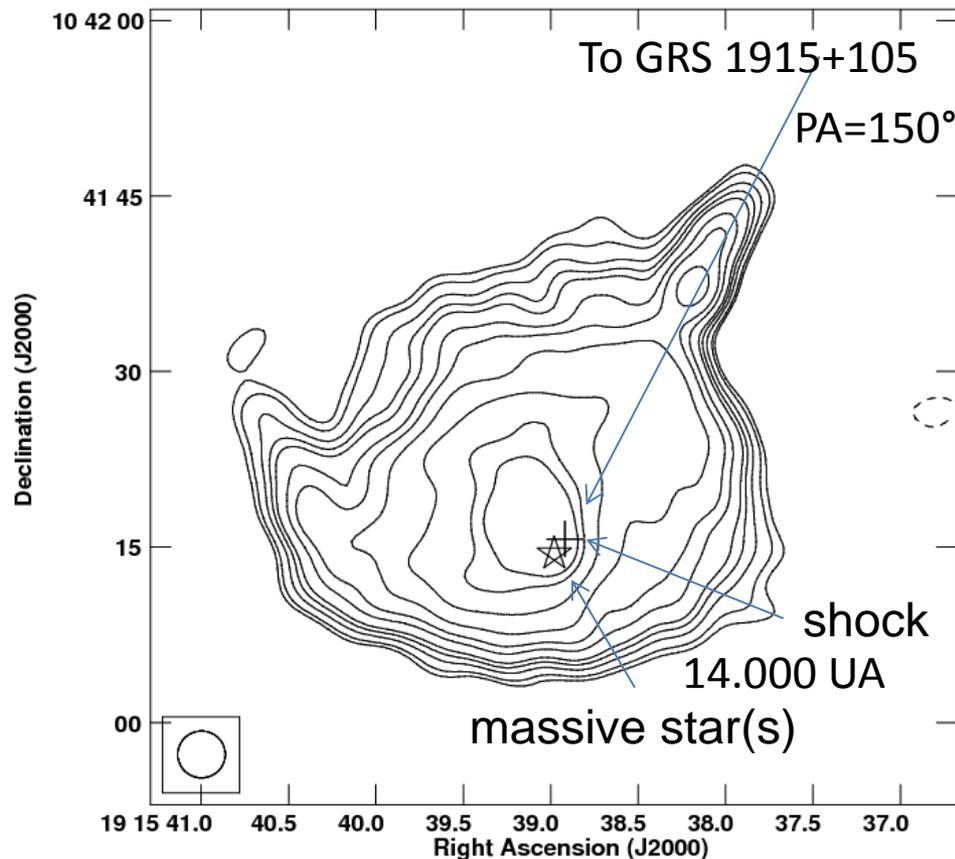
**New knot**



**V~40.000 km/s?**



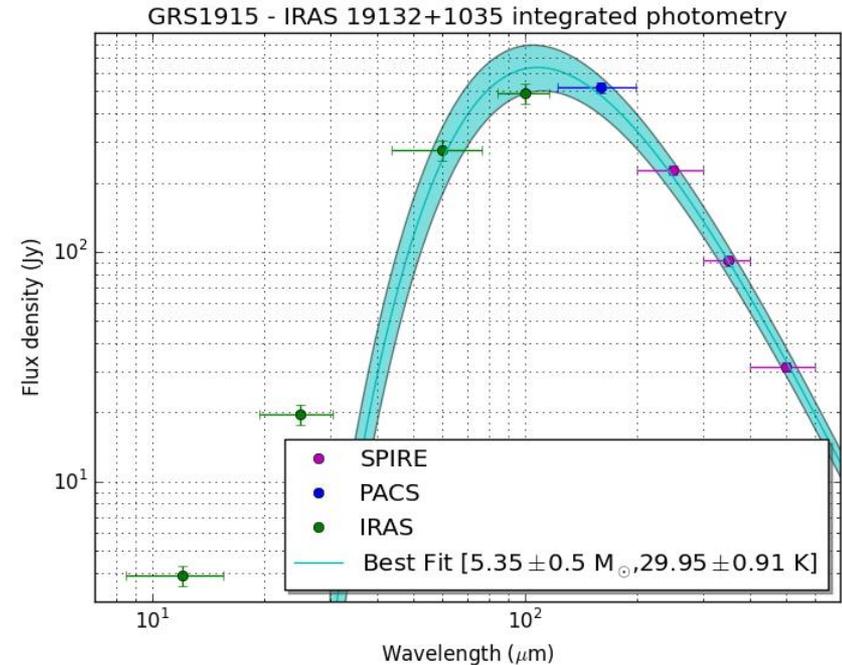
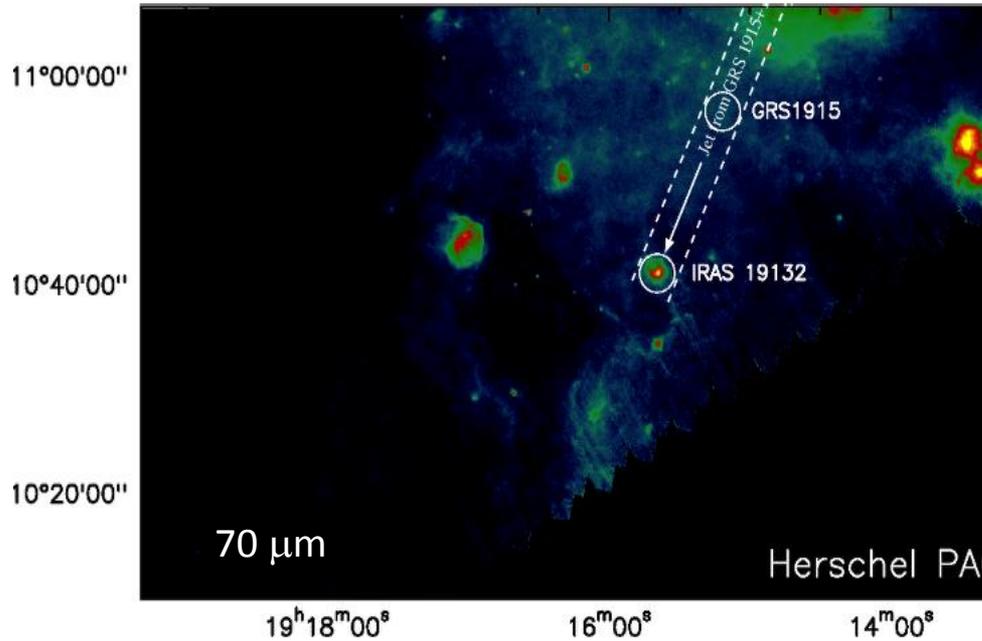
The direction that joins star, new knot & non-thermal feature has a PA=150°±5°, as the sub-arcsec jets in GRS 1915+105



Jets trigger SF & the progenitor molecular cloud?  
Follow-up with VLA, Gemini, ESO, IRAM, Herschel

# DUST & MOLECULAR GAS IN THE IRAS SOURCE

M., Chaty, Maury and Sauvage (in progress)



- Very compact star formation region of  $\sim 1$  pc size located along the jets
- $M_{\text{dust}} = 5 M_{\odot} \Rightarrow M_{\text{gas}} \sim 500 M_{\odot}$
- Herschel emission at  $>50 \mu\text{m}$  is fitted by a single black body with  $T \sim 30 K$
- 30m IRAM observations show extended turbulence in the molecular gas

**Could jets overpressure the ISM and induce the formation of the molecular clouds that ultimately collapse to form stars?**

# CONCLUSION:

## FEEDBACK FROM STELLAR BLACK HOLES IN THE REIONIZATION EPOCH

- **X-RAYS & JETS:** heat the IGM to  $10^4$  K and partially ionize it over large distance scales producing a smooth end of the dark ages, increasing the Jean's mass, and therefore limiting the overall mass of dwarf galaxies to  $M_{\text{tot}} > 10^9 M_{\odot}$
- **JETS:** Jet induced star formation in the present universe is not statistically significant, but during reionization, when the density of the IGM was several orders of magnitude larger than at present, following current theoretical models (e.g. Fragile+04; Gaibler+15), stellar black hole jets must have induced the formation of clusters of massive stars.