

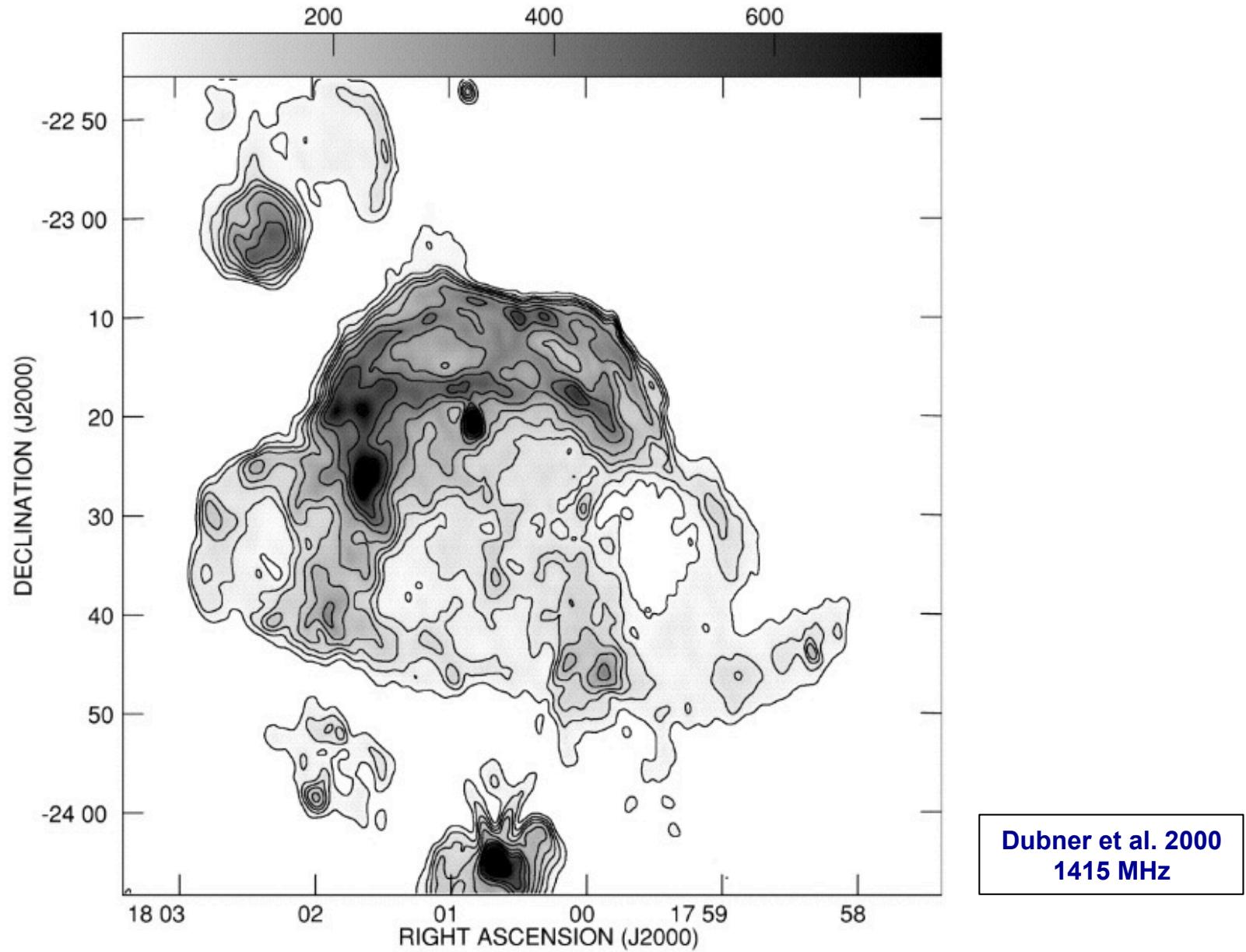
# Irradiated shocks in the G5.89-0.39 massive star forming region

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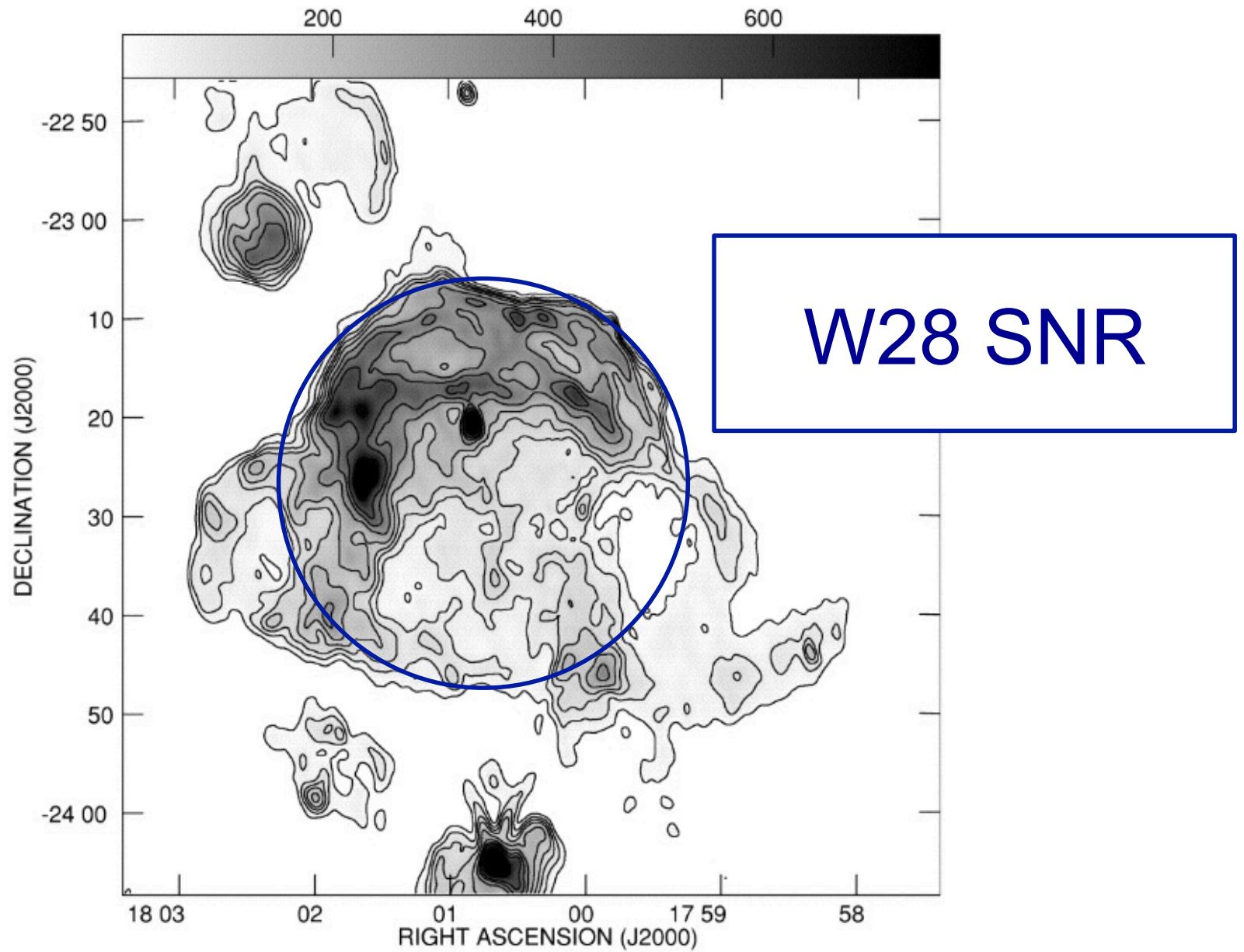
...and the PRISMAS Team

# The W28 region

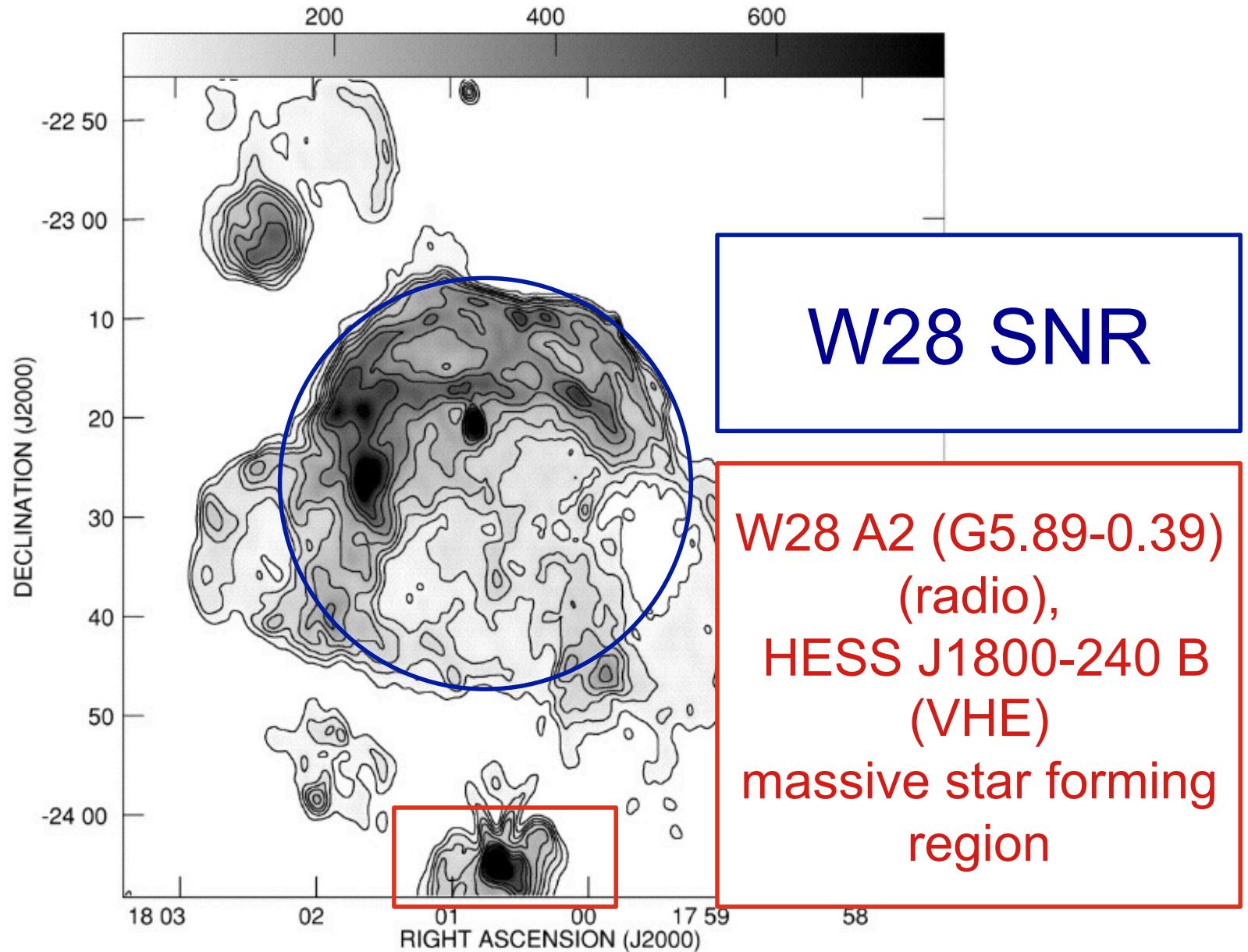


# The W28 region

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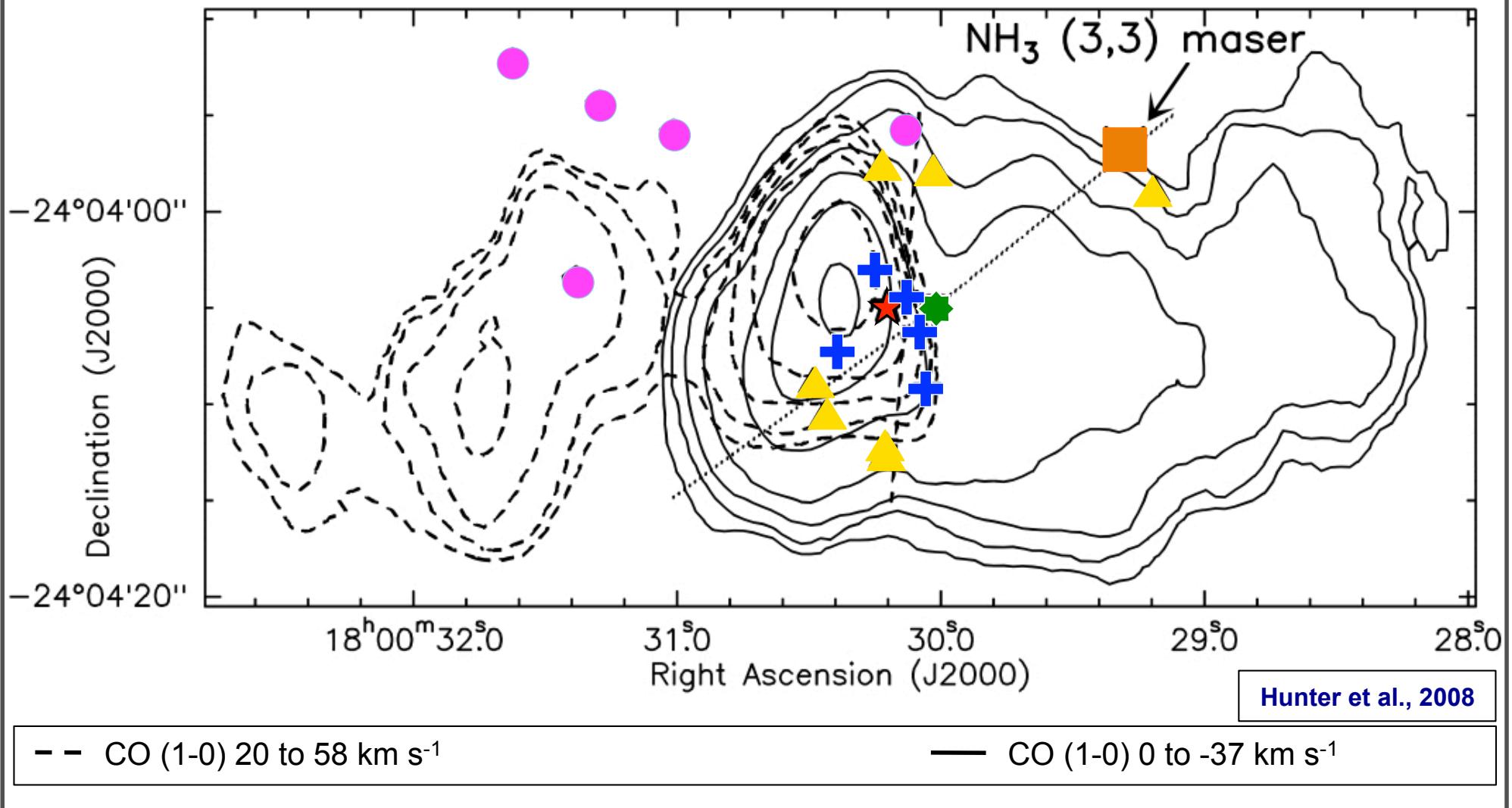


# The W28 region



# What is the W28 A2 outflow ?

Also known as “G5.89-0.39”, or the “Harvey & Forveille 1988” outflow



# Outline

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- MOTIVATIONS
- THE STRUCTURE OF THE W28 A2 REGION
- CO OBSERVATIONS
- IRRADIATED SHOCKS
- ENERGETICS
- COSMIC RAYS
- CONCLUSIONS & PERSPECTIVES

# MOTIVATIONS

# Motivations: star formation

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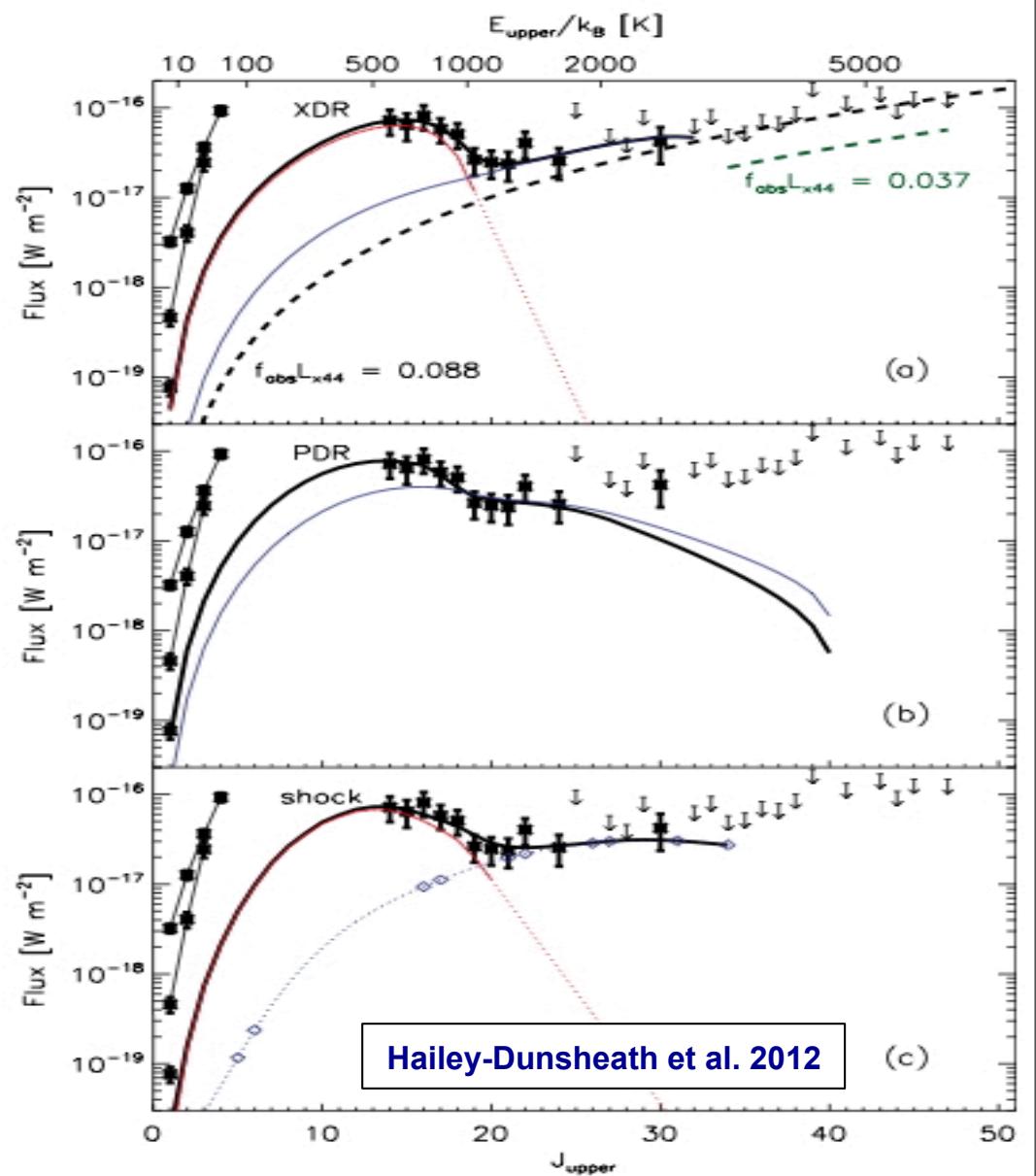
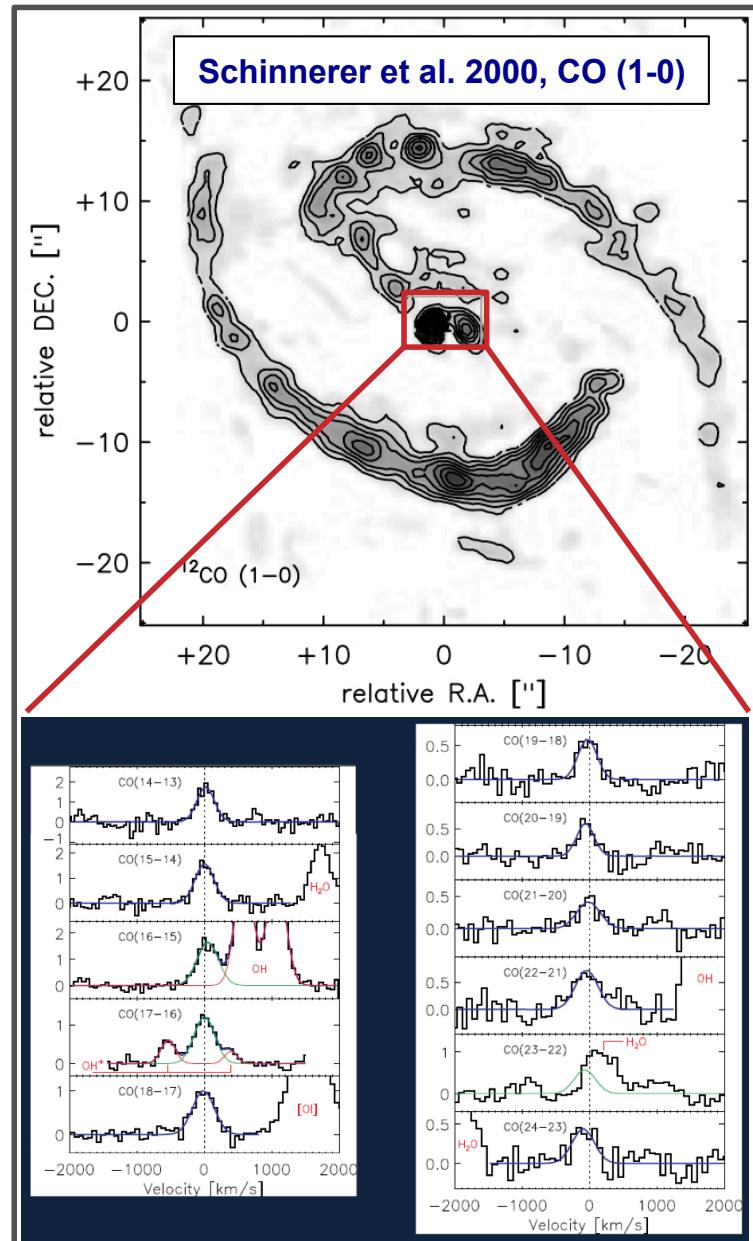
- How do massive stars form despite the radiation pressure ?
  - turbulent core model/monolithic collapse, scale-up of low-mass
  - highly dynamical competitive accretion involving cluster formation
- Studying the outflow activity allows us to progress on these questions:
  - Are the massive protostar outflows similar to the low-mass ones ?
  - Can we quantify the role of the protostar's radiation field ?

# Motivations: ISM properties

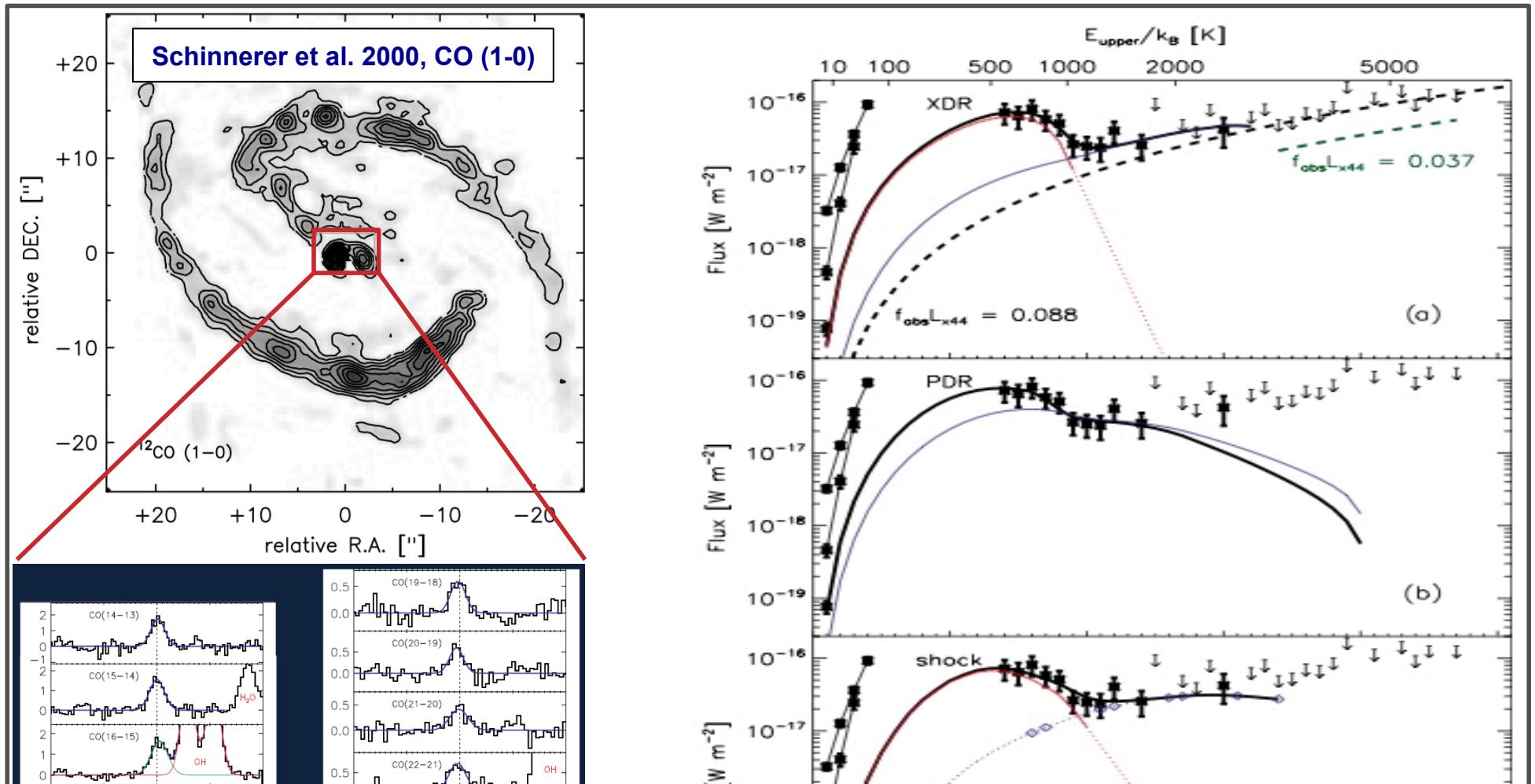
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- Study of shocks in extreme environments
  - what are the physical processes at work ?
  - what is the feedback they exert on the ambient ISM in terms of chemistry / what is their contribution to the cycle of matter in galaxies ?

# Motivations: energetics

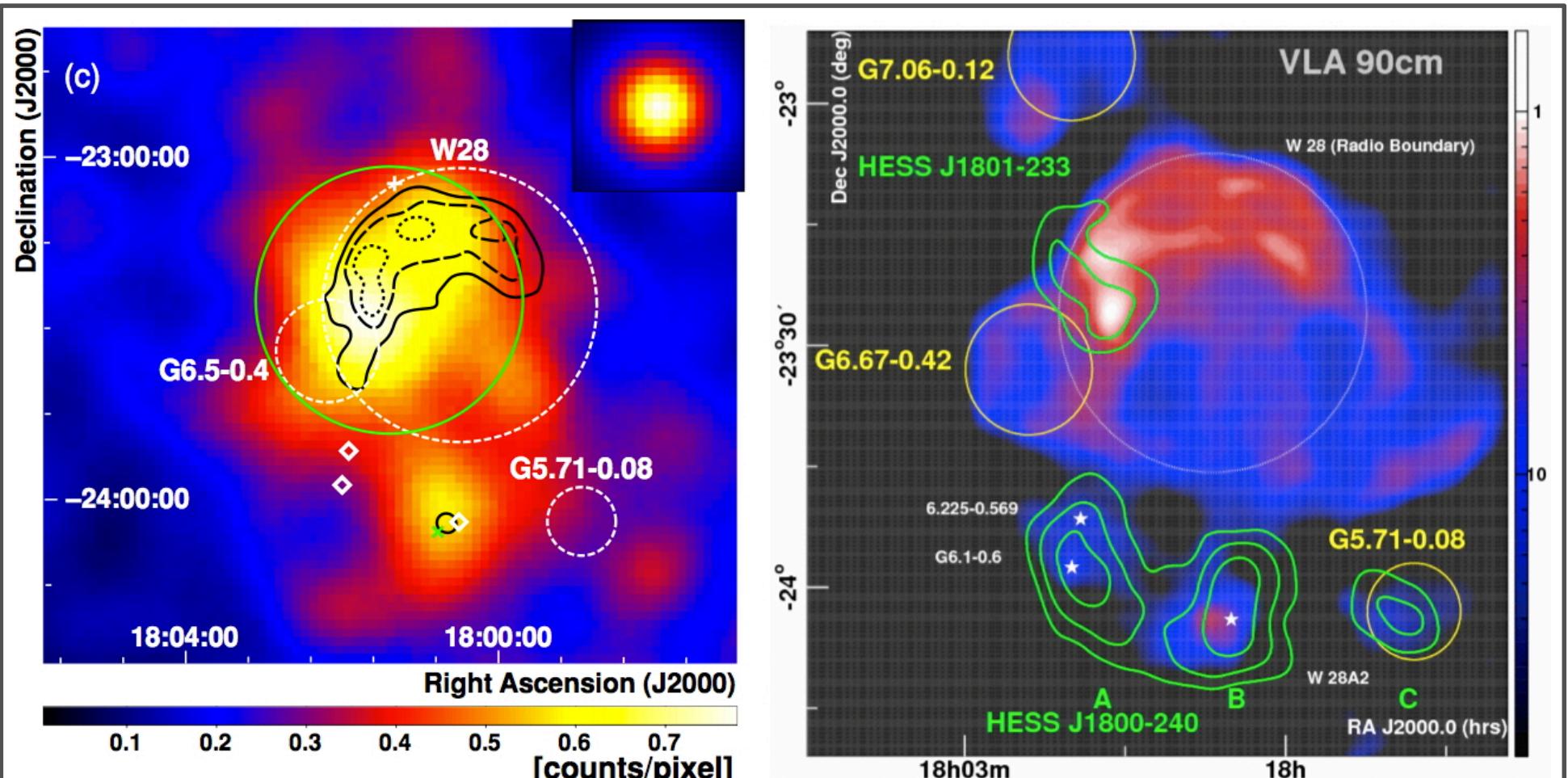


# Motivations: energetics



NGC 253 Hailey-Dunsheath et al. 2008, Rosenberg et al. 2014a ; M 82 Panuzzo et al. 2010, Kamenetzky et al. 2012 ; NGC 891 Nikola et al. 2011 ; NGC 1068 Hailey-Dunsheath et al. 2012 ; NGC 6240 & Mrk 231 Meijerink et al. 2013 ; Mrk 299 Rosenberg et al. 2014b...  
+ a review (inc. Galactic objects) in Kamenetzky et al. 2014

# Motivations: cosmic rays

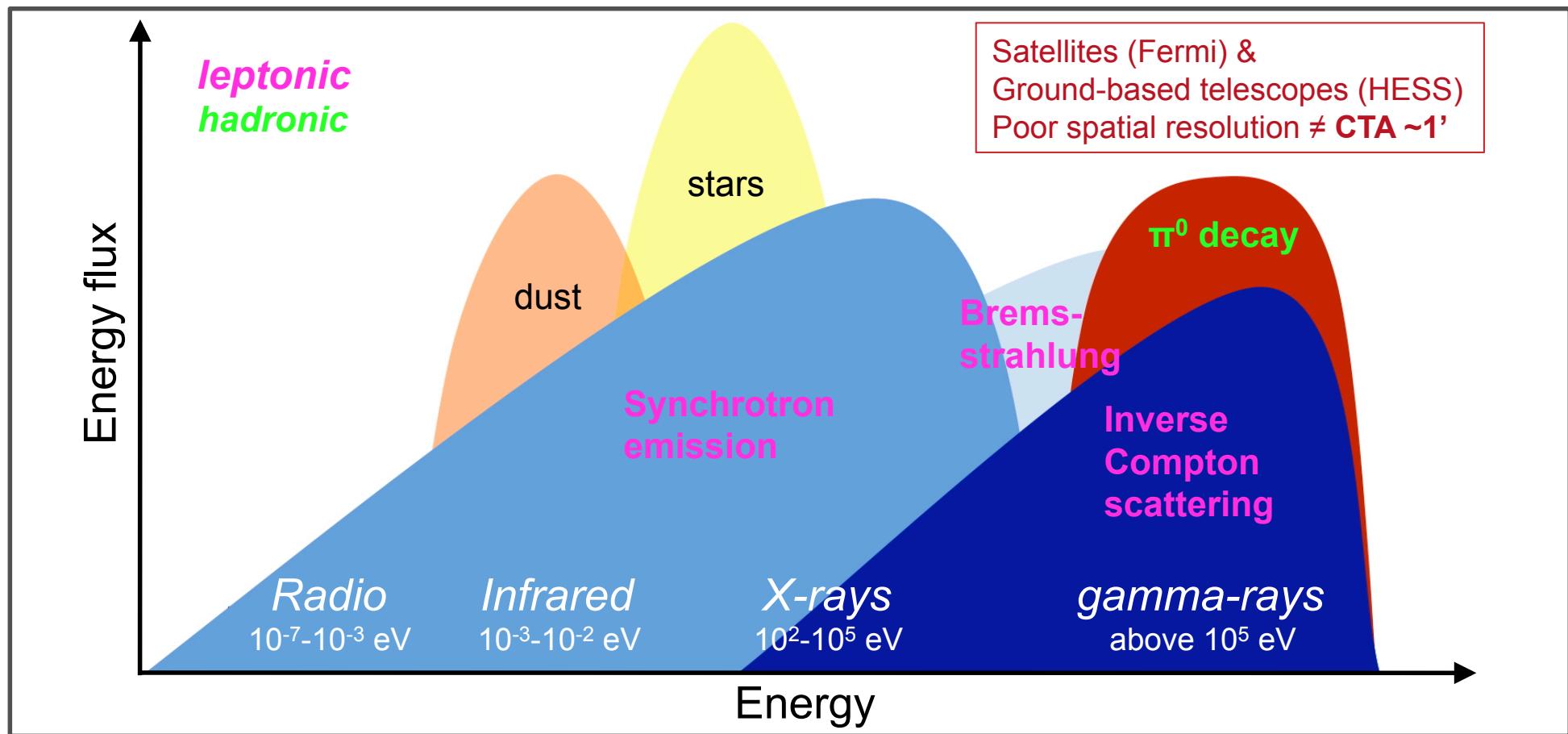


- The Fermi-lat count map  
2-10 GeV with  $0.2^\circ$  resolution  
Abdo et al. 2010

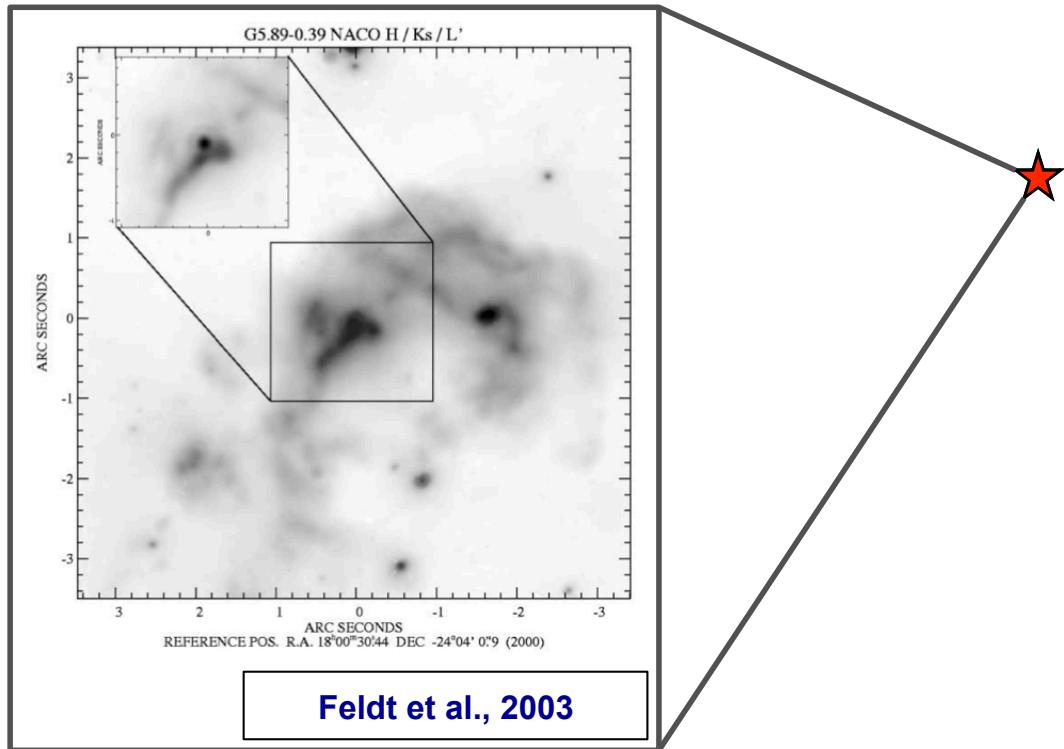
- The HESS count map  
Above 320 GeV with 5-6' resolution  
Aharonian et al. 2008

# Motivations: cosmic rays

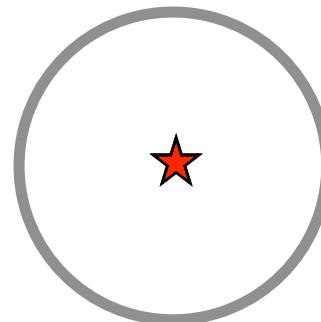
- Origin of the  $\gamma$ -rays emission: partly due to **cosmic rays**
  - collisions with the ambient gas: **hadrons**  $\rightarrow \pi^0 \rightarrow$  detectable  $\gamma$ -rays
  - Inverse Compton effect **relativistic  $e^-$**  - low- $E$  photons
  - Bremsstrahlung of **relativistic  $e^-$**  on electrons of interstellar nuclei
  - Possible neighbouring Pulsar Wind Nebula



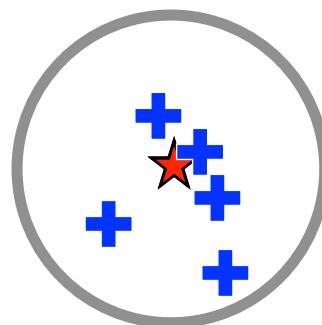
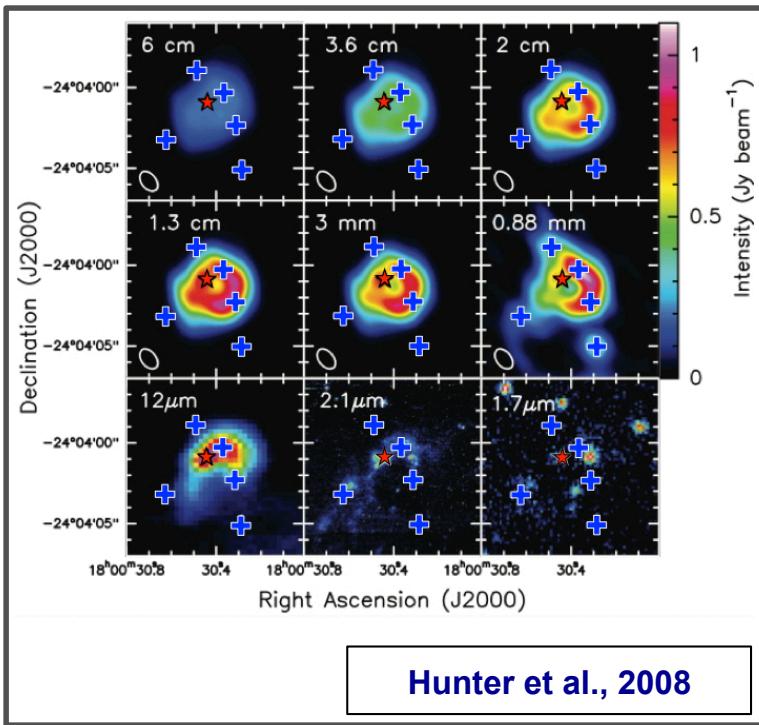
# THE STRUCTURE OF THE W28A2 REGION



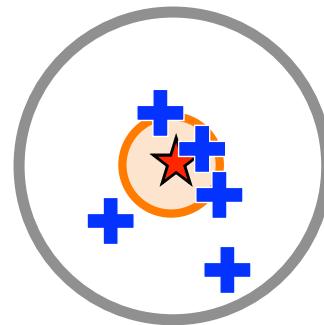
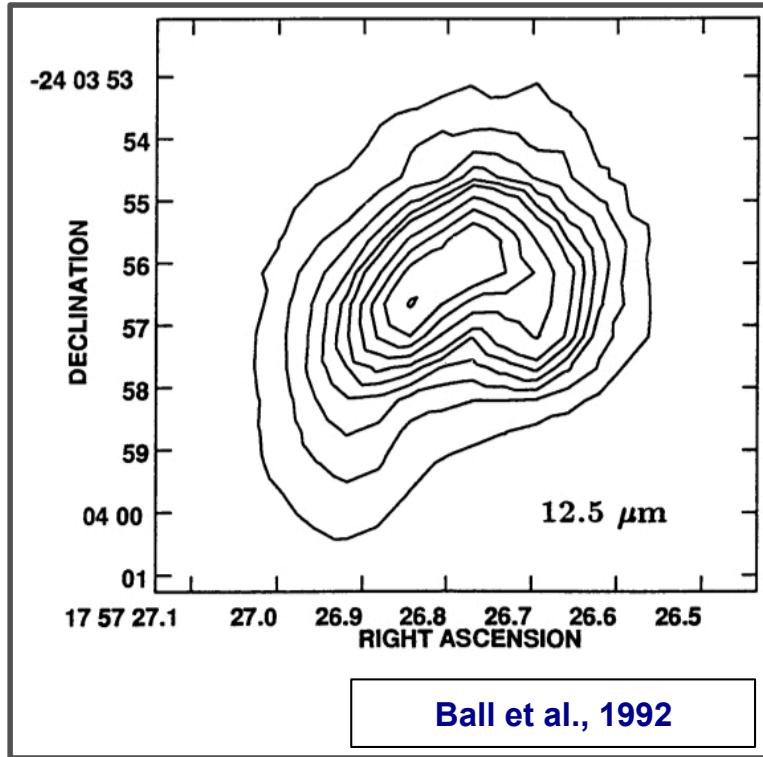
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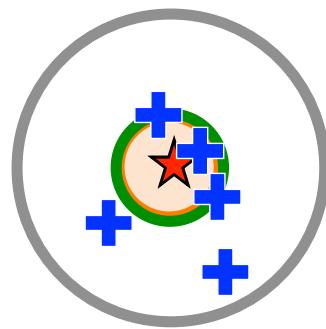
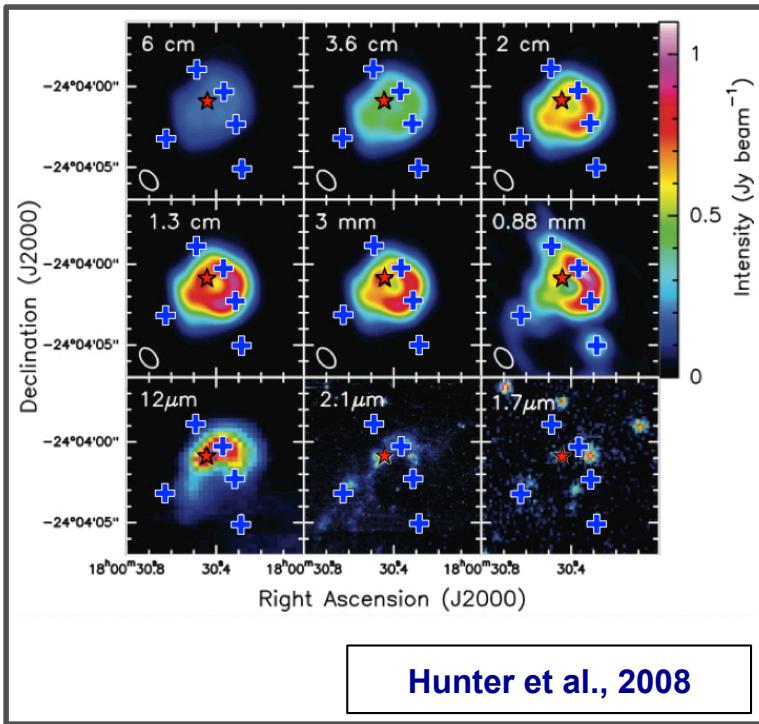
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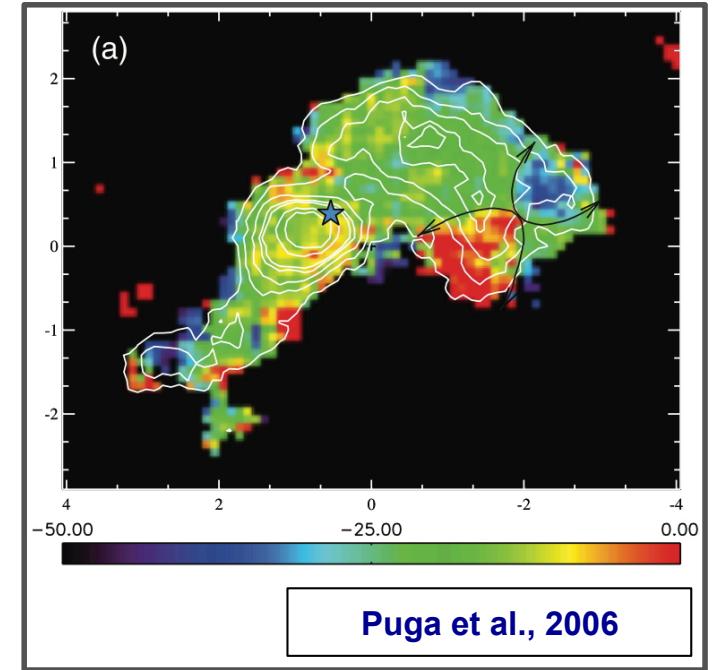
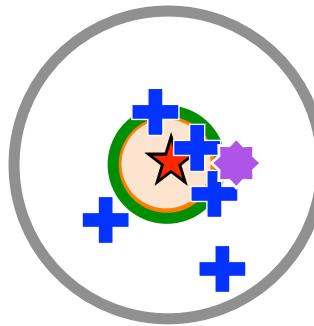
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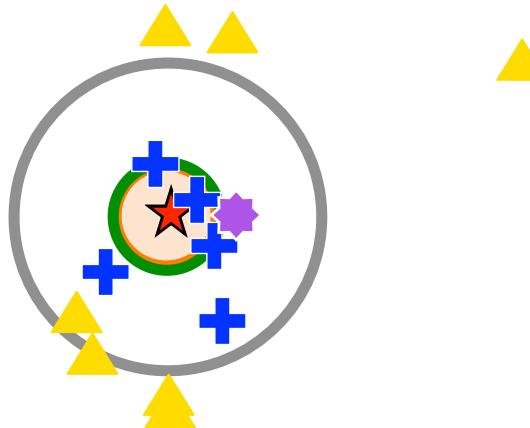
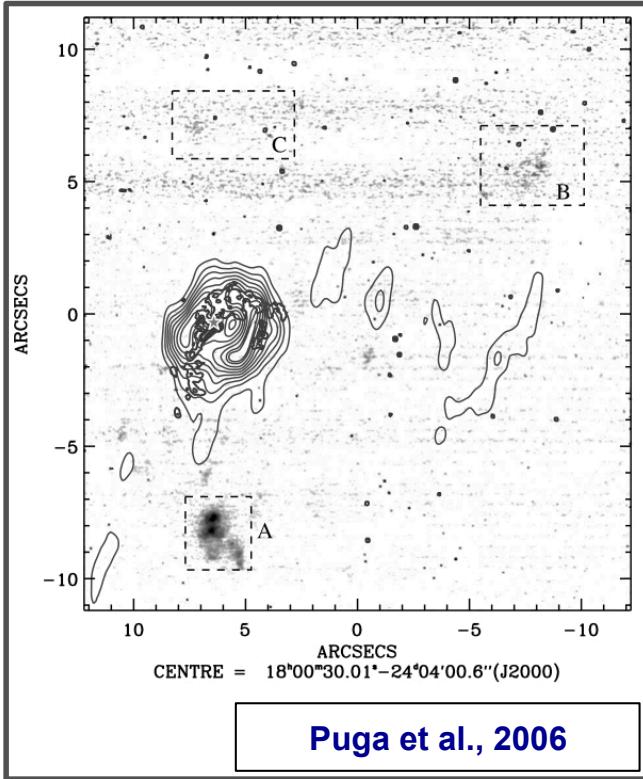
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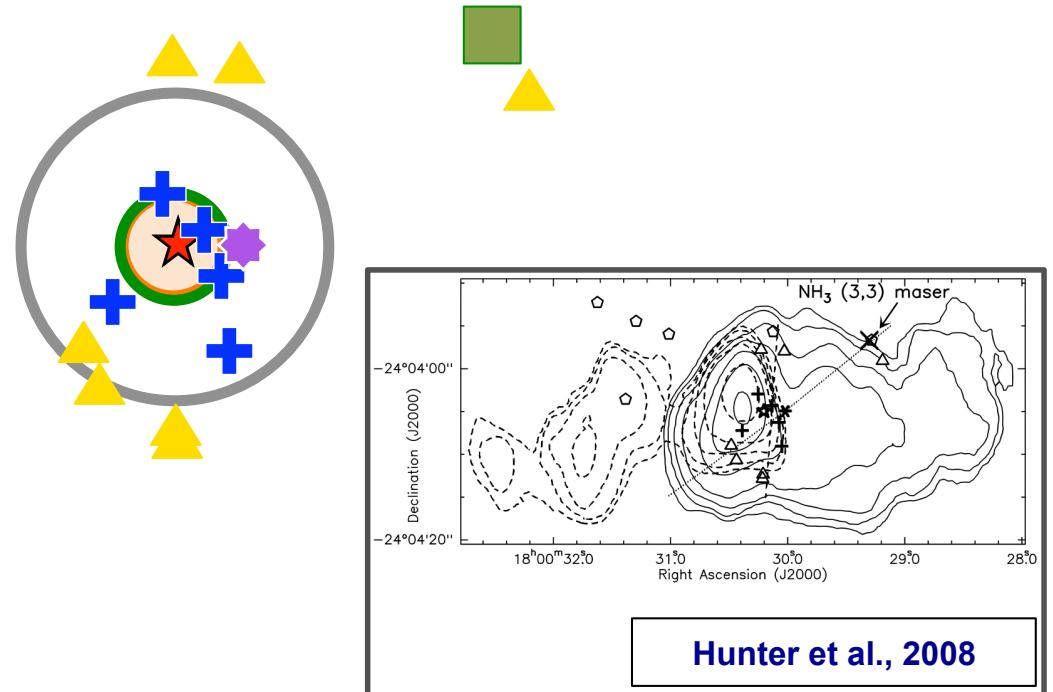
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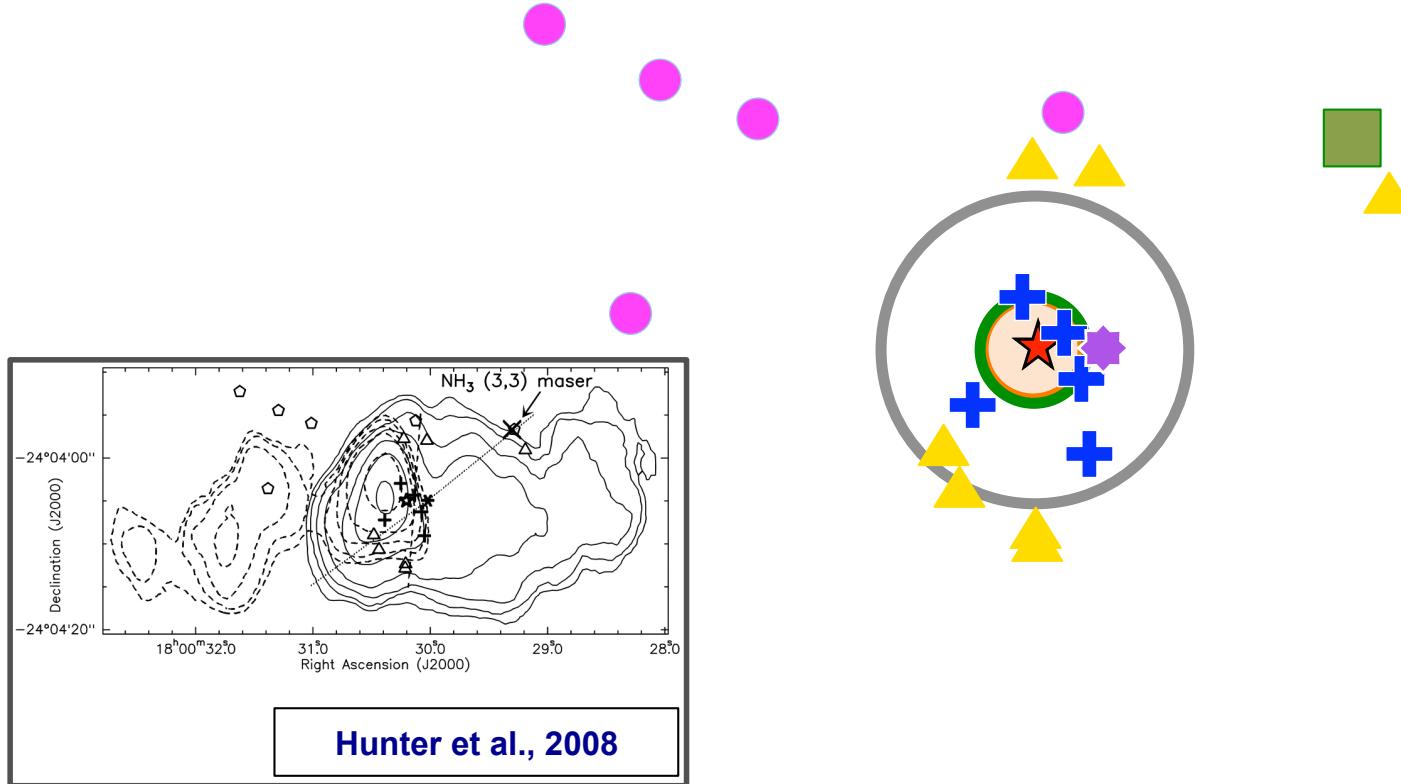
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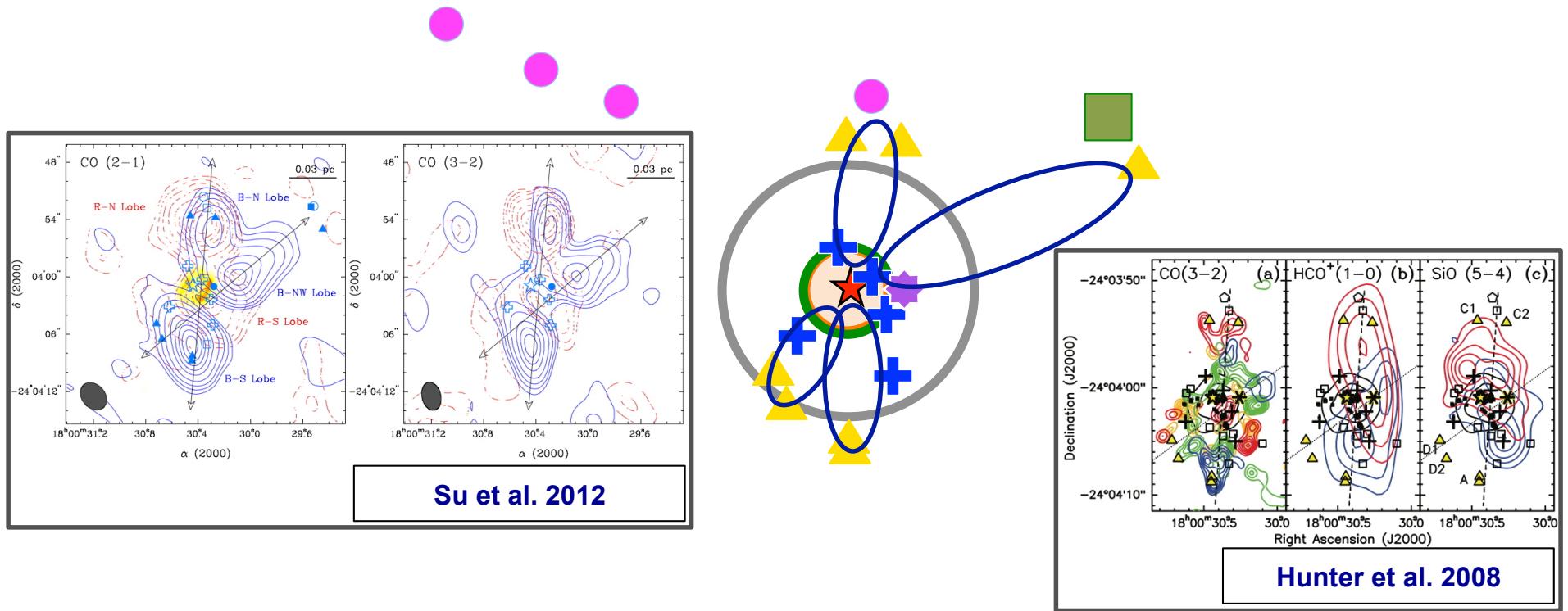
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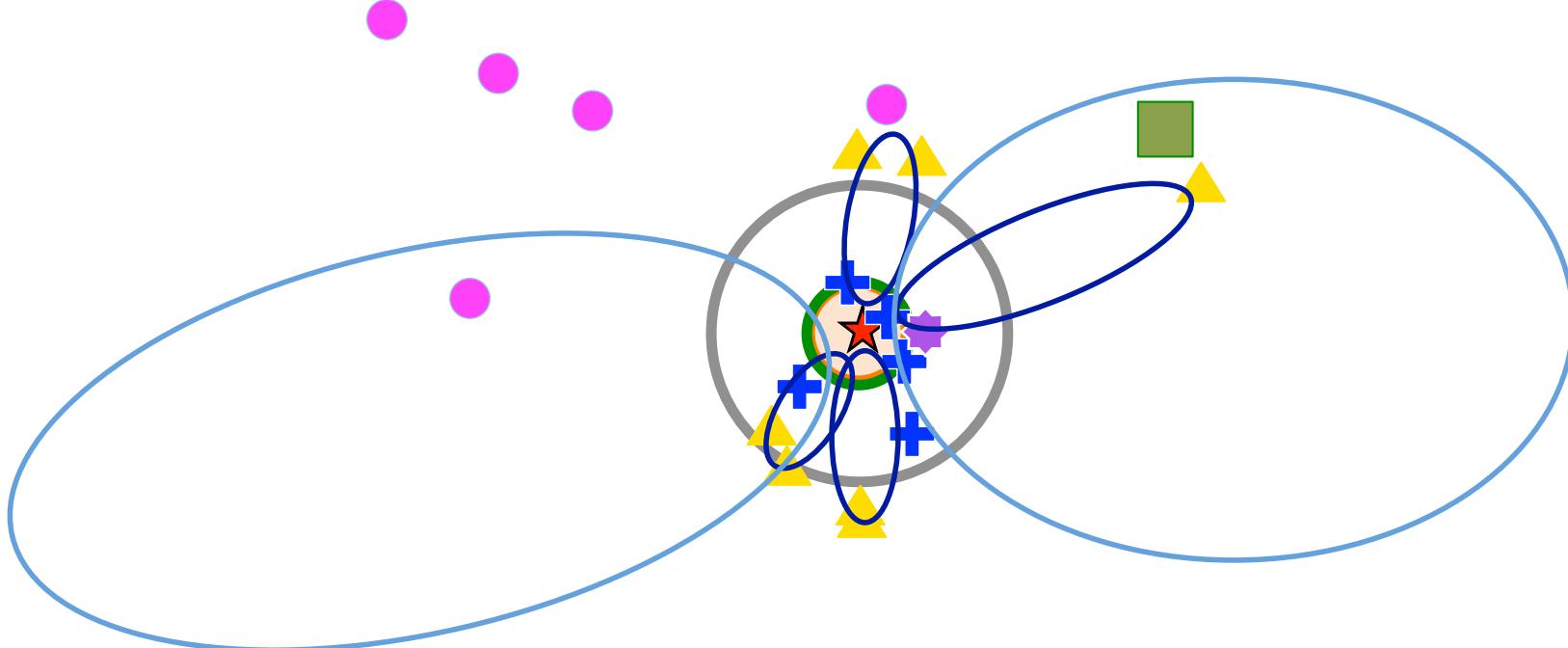
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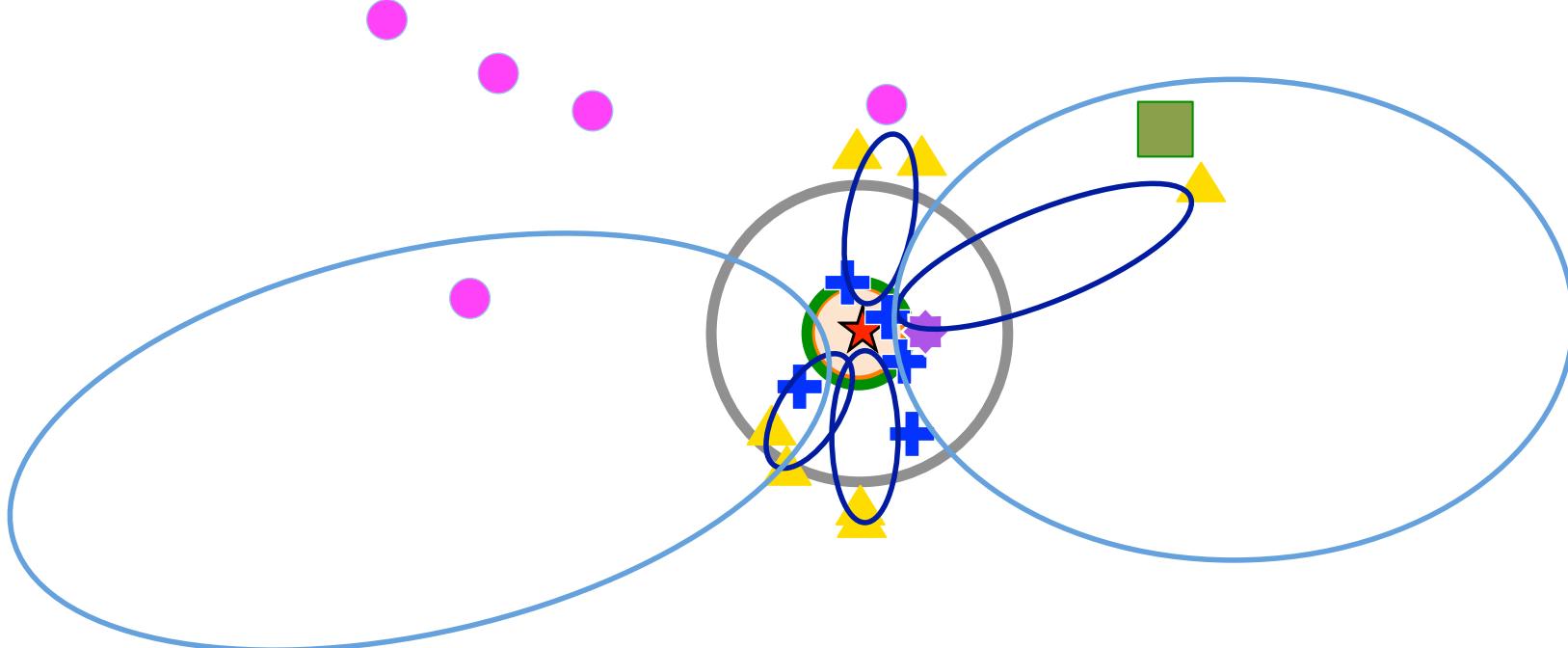
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- Two small outflows, seen in SiO (Sollins et al. 2004, Klaassen et al. 2006), CO (Klaassen et al. 2006 Hunter et al. 2008, Su et al. 2012), and other tracers (HCO<sup>+</sup>, Klaassen et al. 2006 and Hunter et al. 2008)

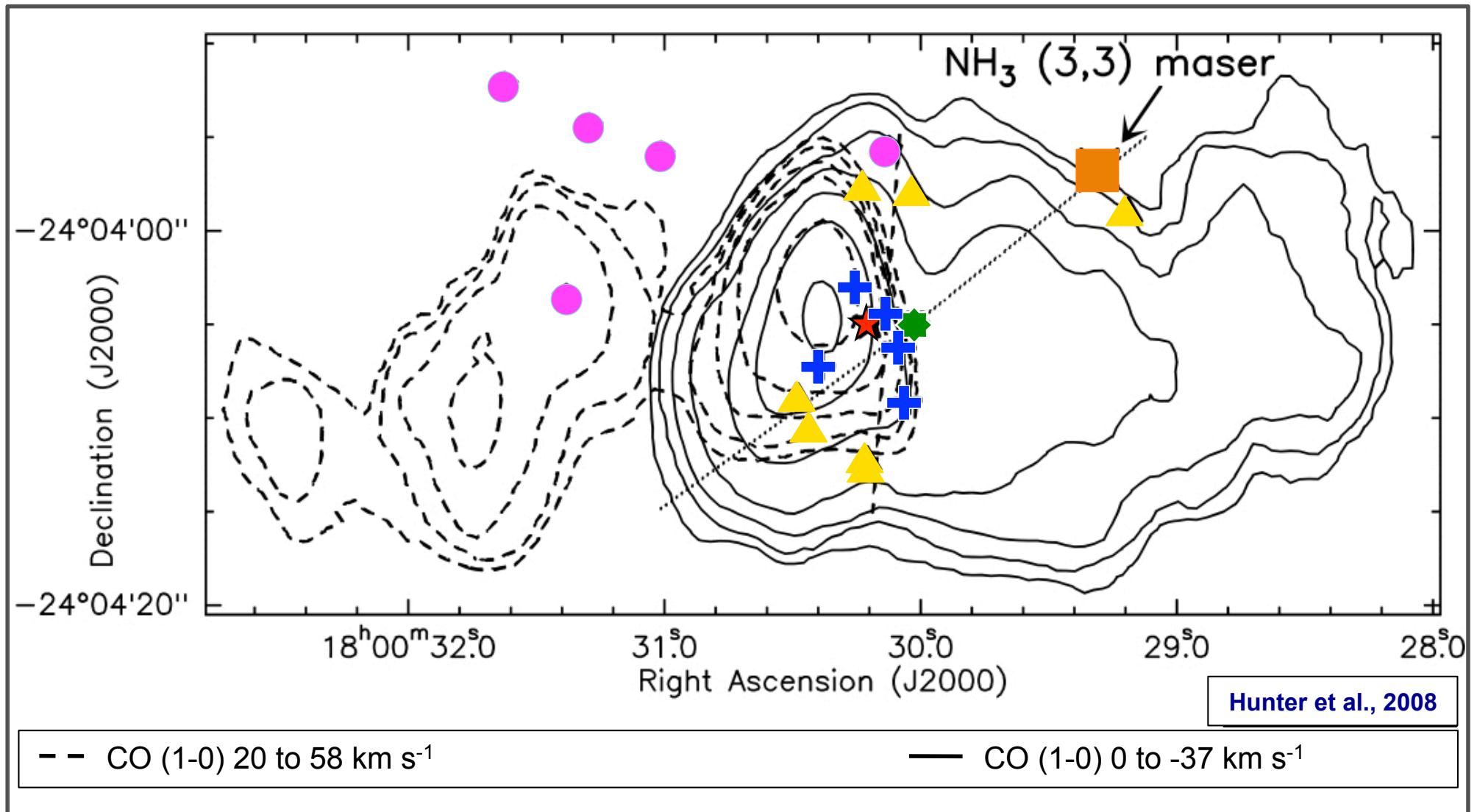


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- A massive bipolar outflow seen in CO (Harvey & Forveille 1988)
- Also not shown:  $H_2O$  masers (Hofner & Churchwell 1996), and OH masers (Stark et al. 2007)

# The wide scale

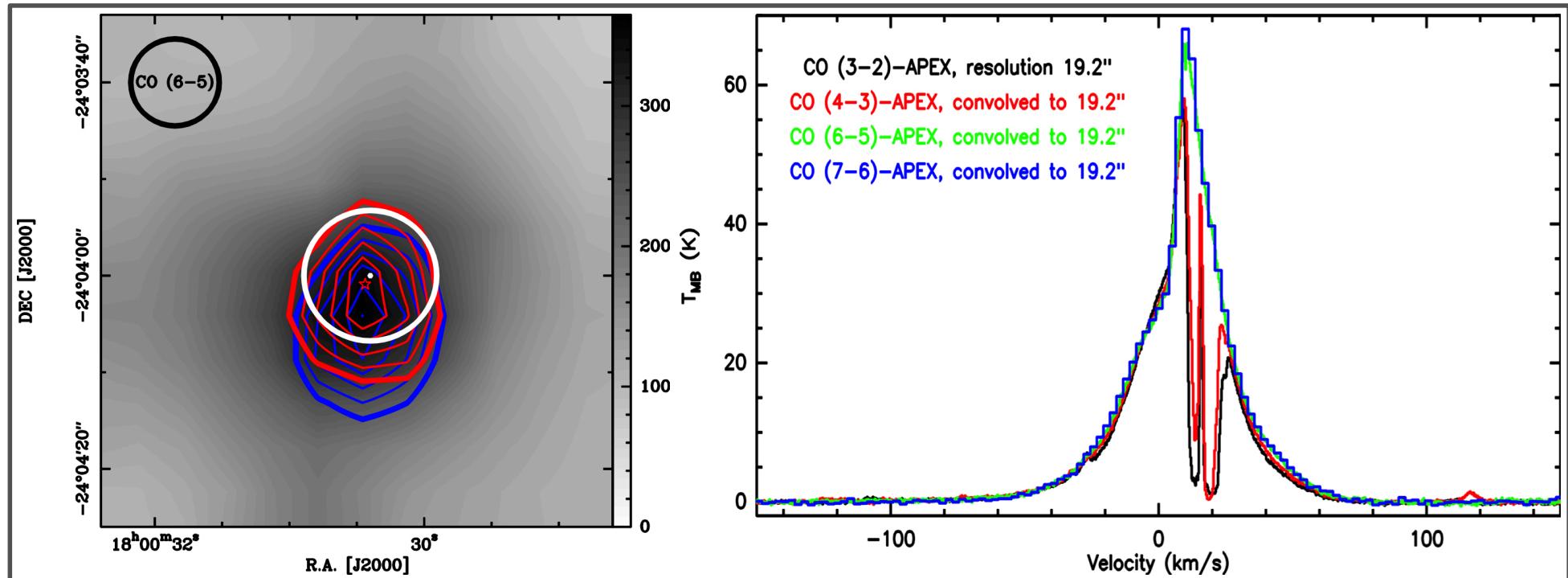


# Other existing constraints

- **Distance:**
  - Old estimates: 1.9-4 kpc ([Velazquez et al. 2002](#), [Fish et al. 2003](#)) ; [Hunter et al. 2008](#) used 2.6 kpc
  - more recently: [1.28 kpc](#), by [Motogi et al. 2011](#)
- **The central star:**
  - Direct observations by [Feldt et al. 2003](#) : O5
  - Classification by [Motogi et al. 2011](#) : O8
- **Magnetic field:**
  - OH masers : 1.49 mG ([Caswell 2001](#)), [-2.4;1.2] mG ([Fish & Reid 2006](#)), [-2;2] mG ([Stark et al. 2007](#))
  - Dust continuum polarization studies : 2-3 mG ([Tang et al. 2009](#))
- **Spectral index:** of the HII region: 0.15-0.20 between 1.95 - 73.5 cm i.e. 408 MHz to 15.75 GHz ([Goudis et al. 1976](#) )

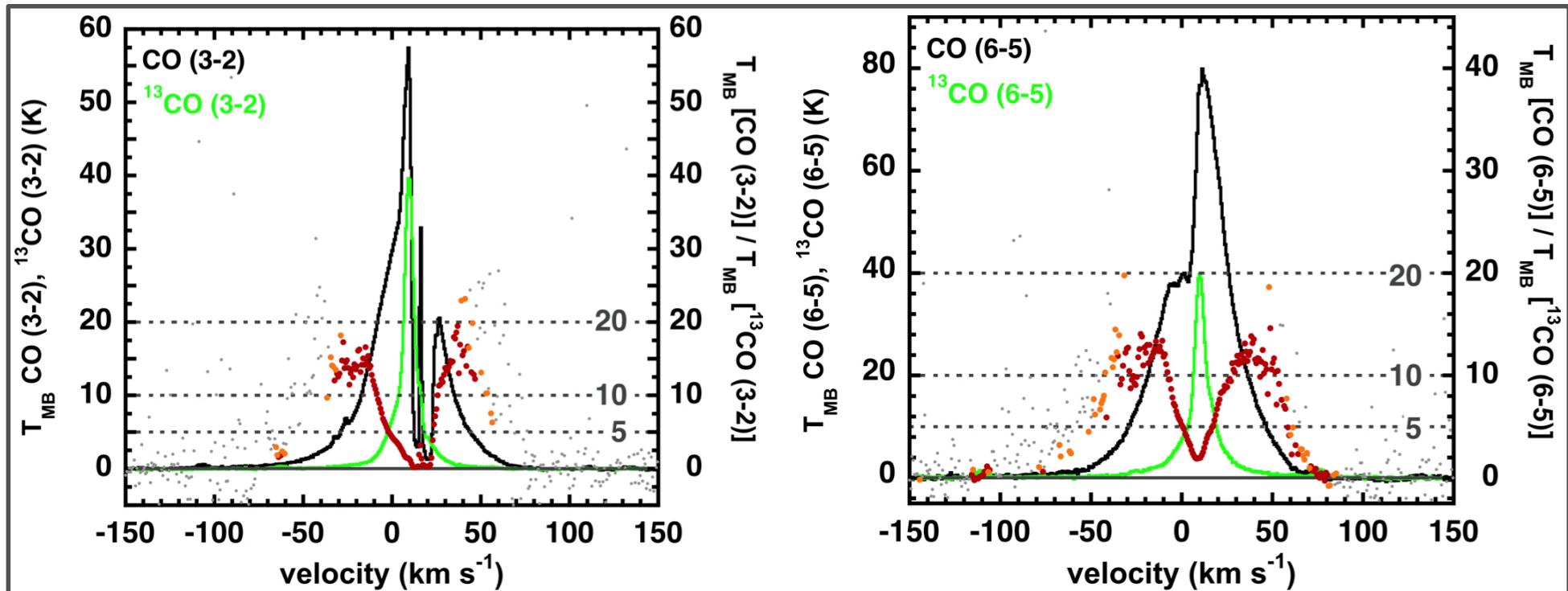
# CO observations

# CO observations



- APEX CO (6-5) line map:
  - ambient integrated intensity -4 to 16.5 km/s
  - blue-shifted integrated intensity -100 to 4 km/s
  - red-shifted integrated intensity 16.5 to 100 km/s
- The white beam is the beam of our analysis  $\sim 12.5''$   
=> We consider a filling factor of 1 for CO

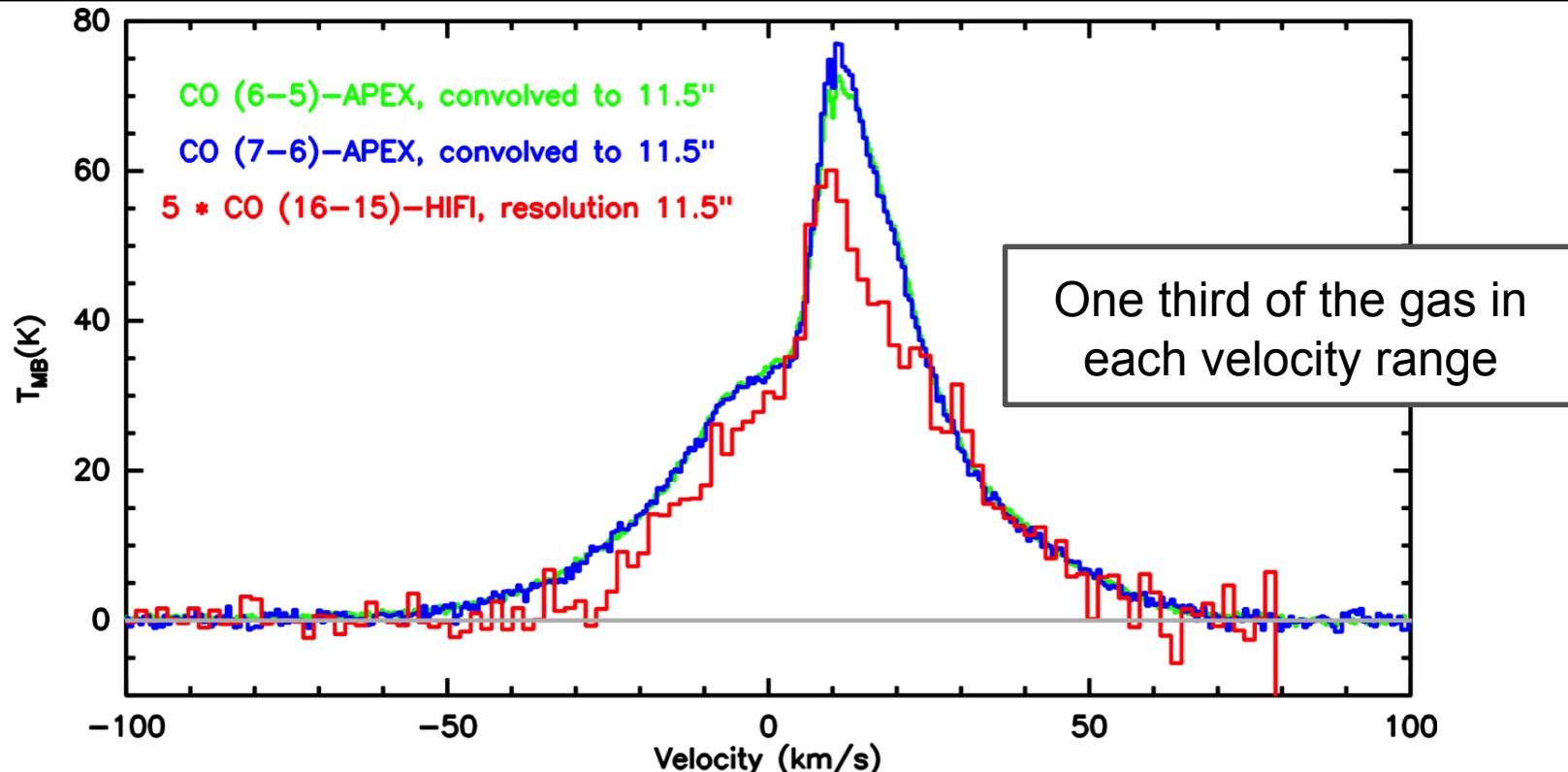
# CO observations



- Red dots:  $3\sigma$  detection for  $^{13}\text{CO}$
  - Orange dots:  $2\sigma$  detection for  $^{13}\text{CO}$
  - Grey dots: less than  $2\sigma$  detection for  $^{13}\text{CO}$
- Line ratio  $\sim 5$  to  $15 \Rightarrow$  optical thickness  $\sim 3$  to  $12.5$   
 $\Rightarrow$  CO lines accessible from the ground are optically thick, even in the wings

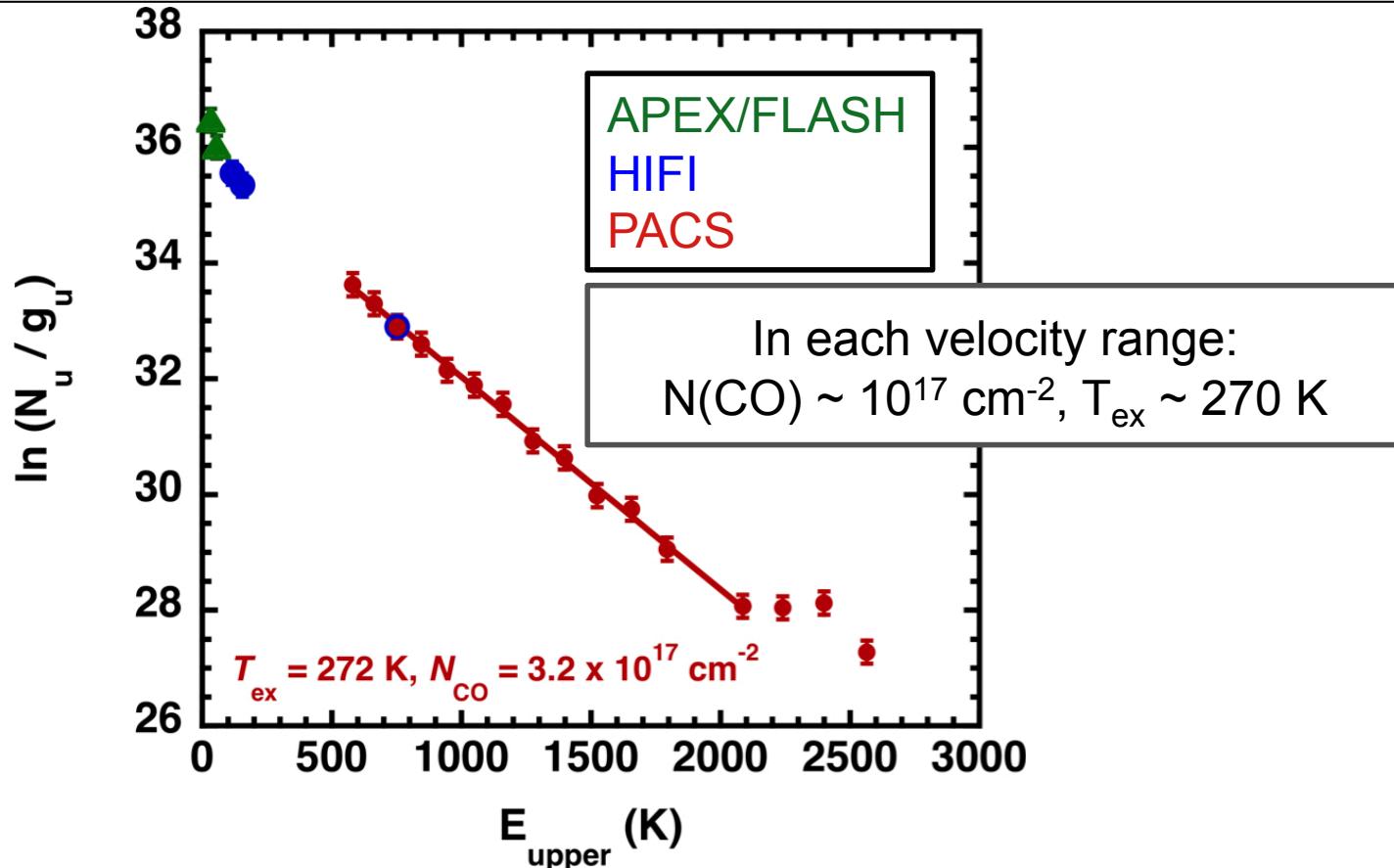
# CO observations

- Two lines are of particular importance:
    - CO (16-15) by HIFI & PACS, single pointing => calibration & gas distribution over the whole velocity range
    - CO (15-14) PACS  $^{12,13}\text{CO}$  observations => ratio  $\sim 47$  optically thin !
- => Rotational diagram over a 12.5" area



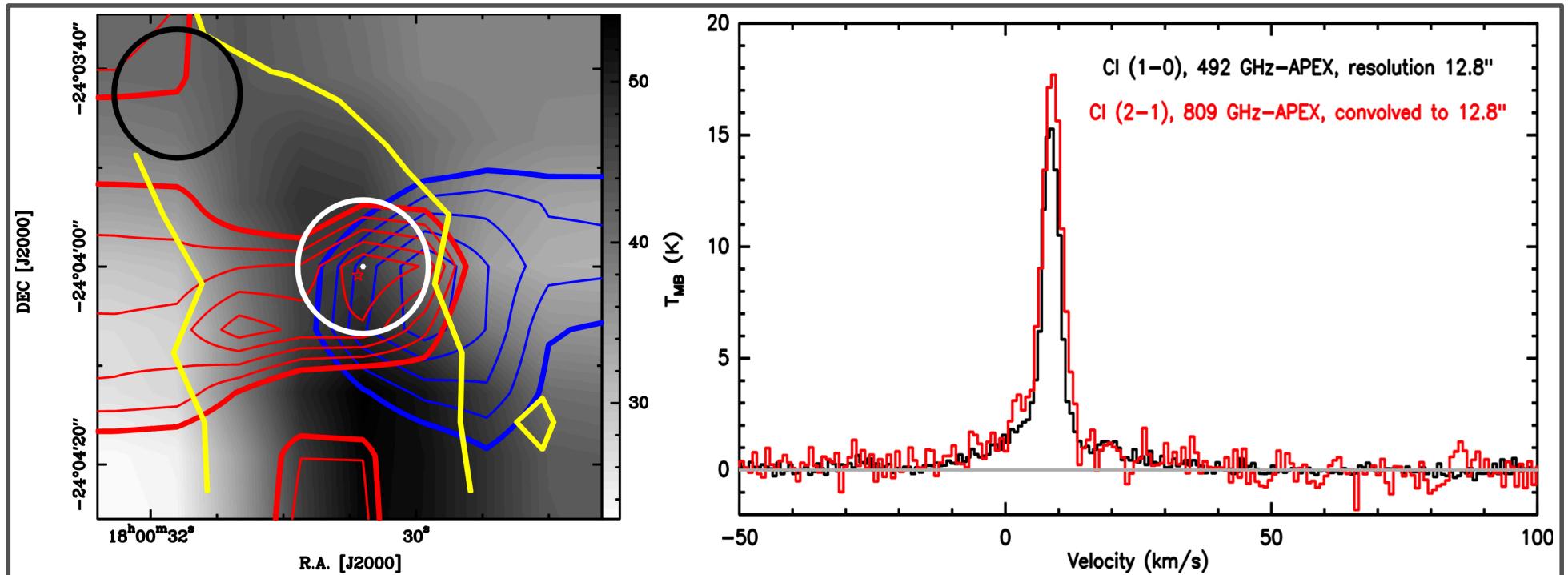
# CO observations

- Summary:
  - APEX => filling factor = 1 for beam of 12.5", low- $J$  are optically thick
  - *Herschel* => higher- $J$  lines optically thin, HIFI-PACS cross-calibration
  - Both show a similar gas distribution in the line wings



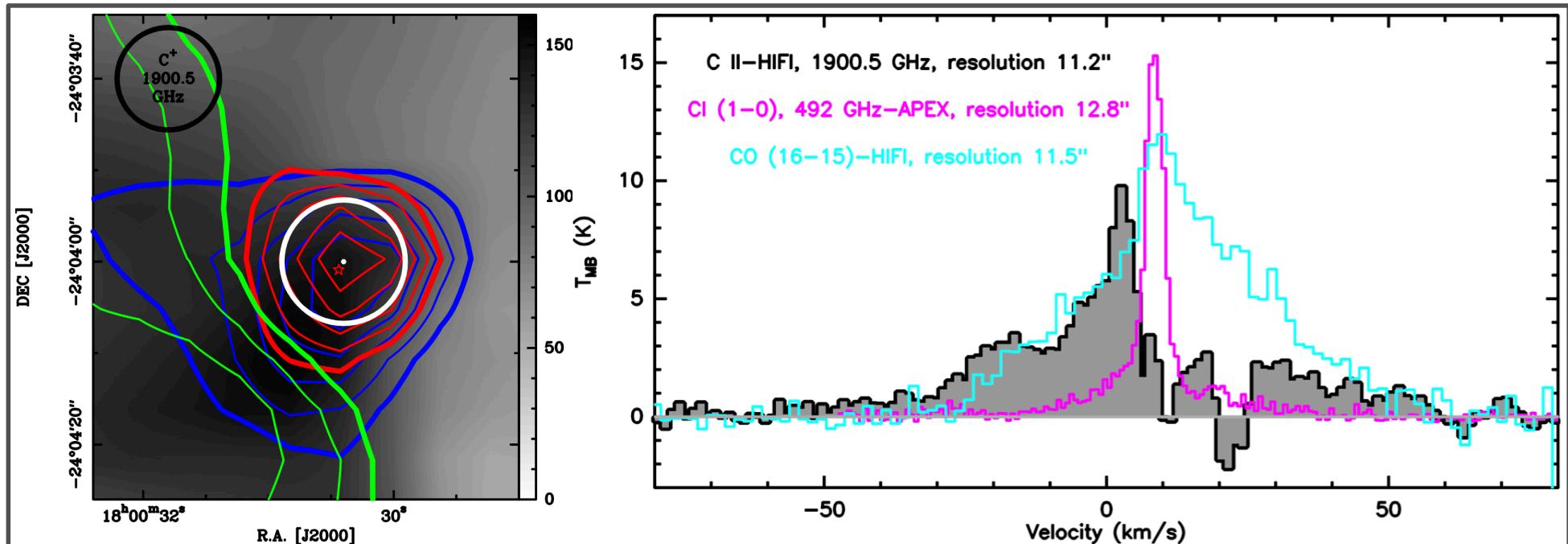
# Irradiated shocks

# Irradiated shocks: CI observations



- APEX CI ( ${}^3\text{P}_1$ - ${}^3\text{P}_0$ ) line map:
  - ambient integrated intensity 4 to 16.5 km/s (**70% of maximum**)
  - blue-shifted integrated intensity -20 to 4 km/s
  - red-shifted integrated intensity 25 to 40 km/s
- LVG analysis of CI ( ${}^3\text{P}_1$ - ${}^3\text{P}_0$ ) and ( ${}^3\text{P}_2$ - ${}^3\text{P}_1$ )
- In each velocity range:  $\text{N(Cl)} \sim (1.5\text{-}3) \times 10^{17} \text{ cm}^{-2}$ ,  $T_{\text{ex}} \sim 60\text{-}270 \text{ K}$

# Irradiated shocks: C<sup>+</sup> observations



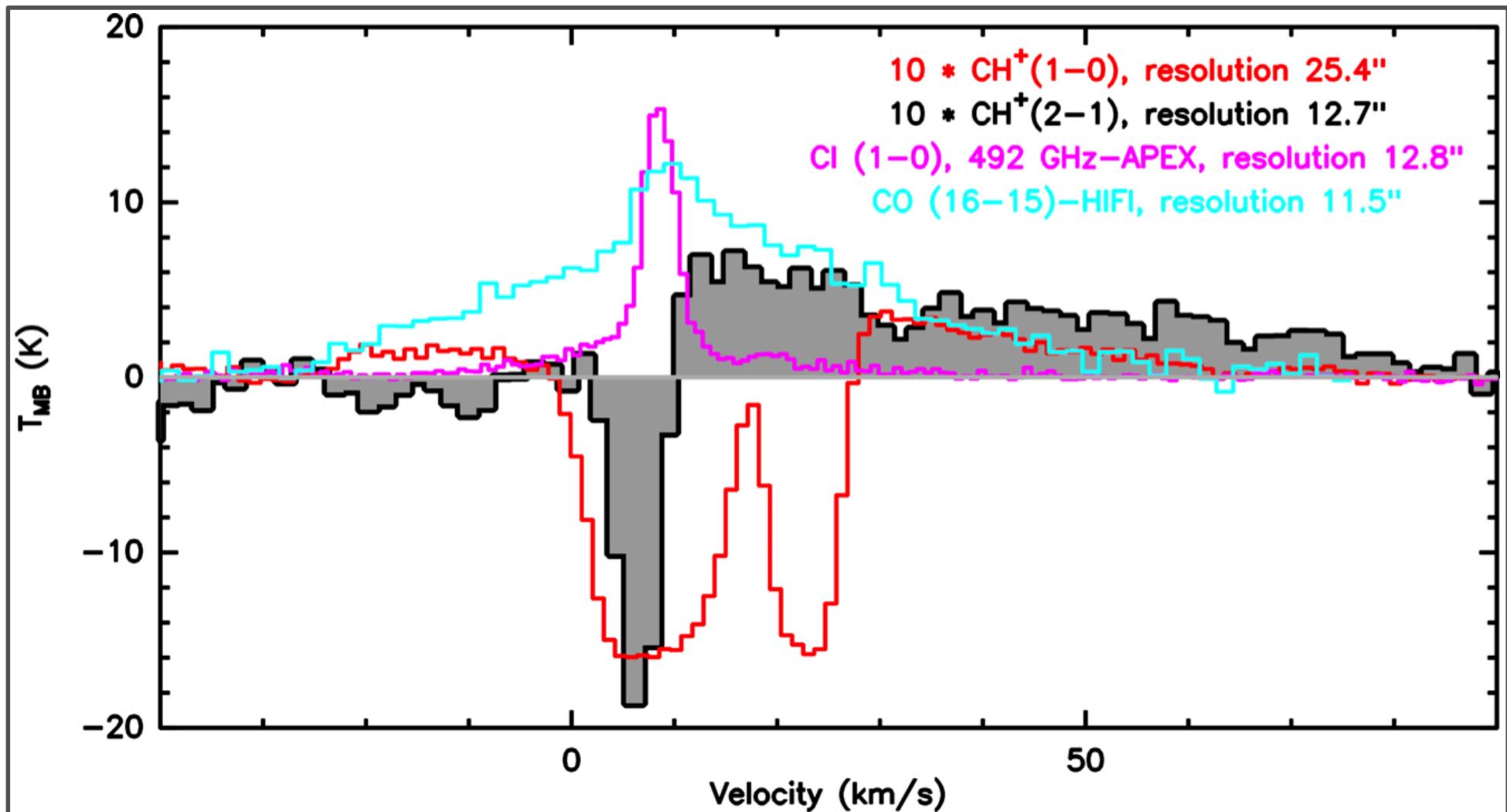
- *Herschel C<sup>+</sup> ( $^2P_{3/2}$ - $^2P_{1/2}$ ) line map:*
  - total integrated intensity -80 to 80 km/s
  - blue-shifted integrated intensity -80 to 4 km/s
  - red-shifted integrated intensity 25 to 80 km/s
  - ambient emission 4 to 16.5 km/s
- LTE + optically thin + FF = 1,  $T_{\text{ex}}$  of 50-250 K  
blue-shifted:  $N(\text{C}^+) \sim (0.5-1.2) \times 10^{18} \text{ cm}^{-2}$ ; red-shifted:  $N(\text{C}^+) > (1.5-3.5) \times 10^{17} \text{ cm}^{-2}$

# Irradiated shocks: conclusions

species	$N$ (blue-shifted) ( $\text{cm}^{-2}$ )	$N$ (red-shifted) ( $\text{cm}^{-2}$ )
CO	$1 \times 10^{17}$	$1 \times 10^{17}$
C	$(1.5\text{-}3) \times 10^{17}$	$(1.5\text{-}3) \times 10^{17}$
$\text{C}^+$	$(5\text{-}12) \times 10^{17}$	$> (1.5\text{-}3.5) \times 10^{17}$
$\Sigma[\text{CO+C+}\text{C}^+]$	$(7.5\text{-}16) \times 10^{17}$	$> (4\text{-}7.5) \times 10^{17}$
H equivalent	$(1.1\text{-}2.2) \times 10^{22}$	$> (0.6\text{-}1.1) \times 10^{22}$

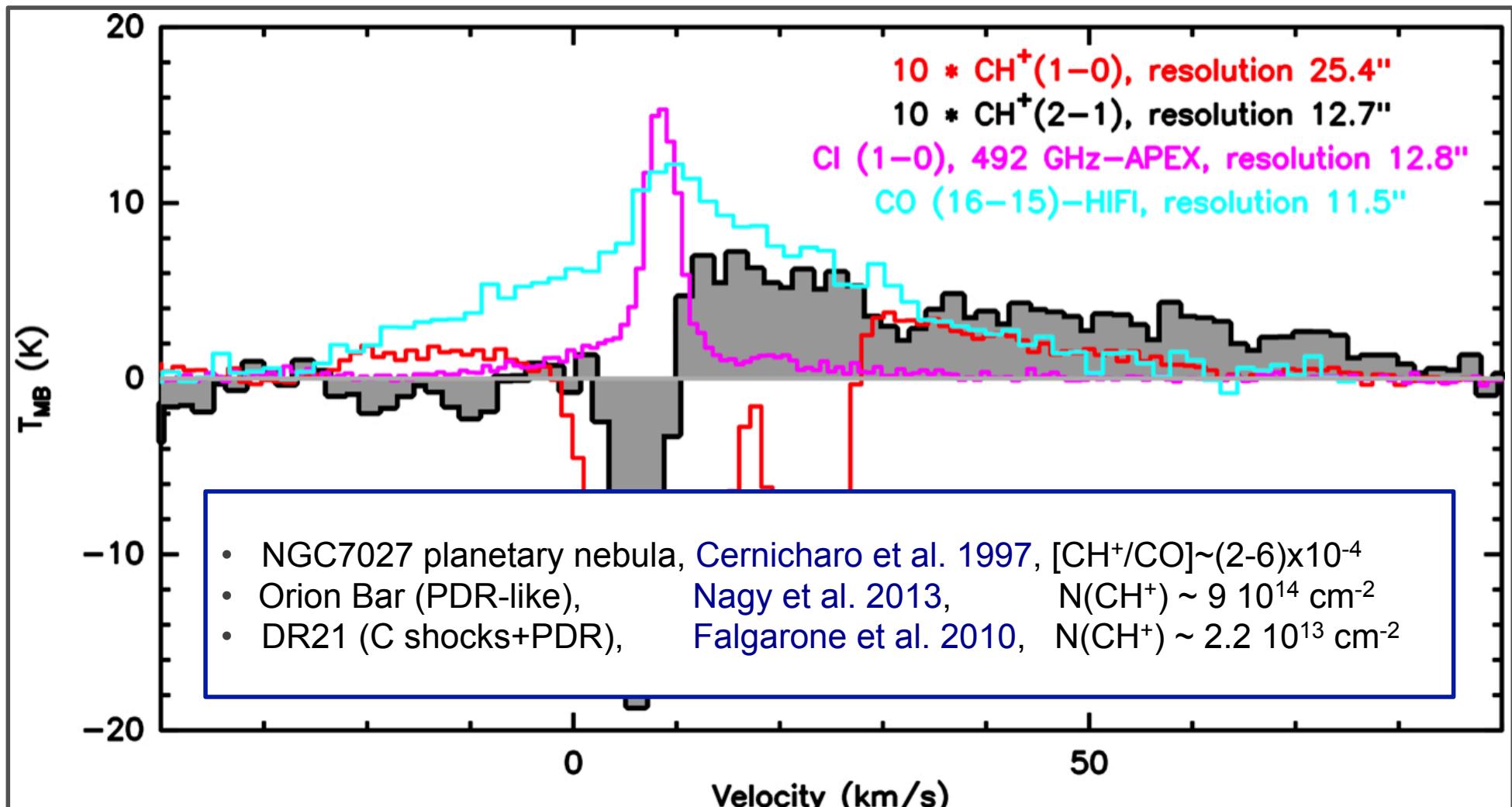
- The presence of Cl and  $\text{C}^+$  can not be neglected with respect to CO
- The outflow shocks are **irradiated** by the UV field of the massive protostar

# Irradiated shocks: CH<sup>+</sup> observations



- LTE + optically thin + FF = 1,  $T_{ex}$  of 50-250 K  
red-shifted:  $N(\text{CH}^+) \sim (4.4-12.7) \times 10^{12} \text{ cm}^{-2}$ ;  $[\text{CH}^+/\text{CO}] \sim (4.4-12.7) \times 10^{-5}$

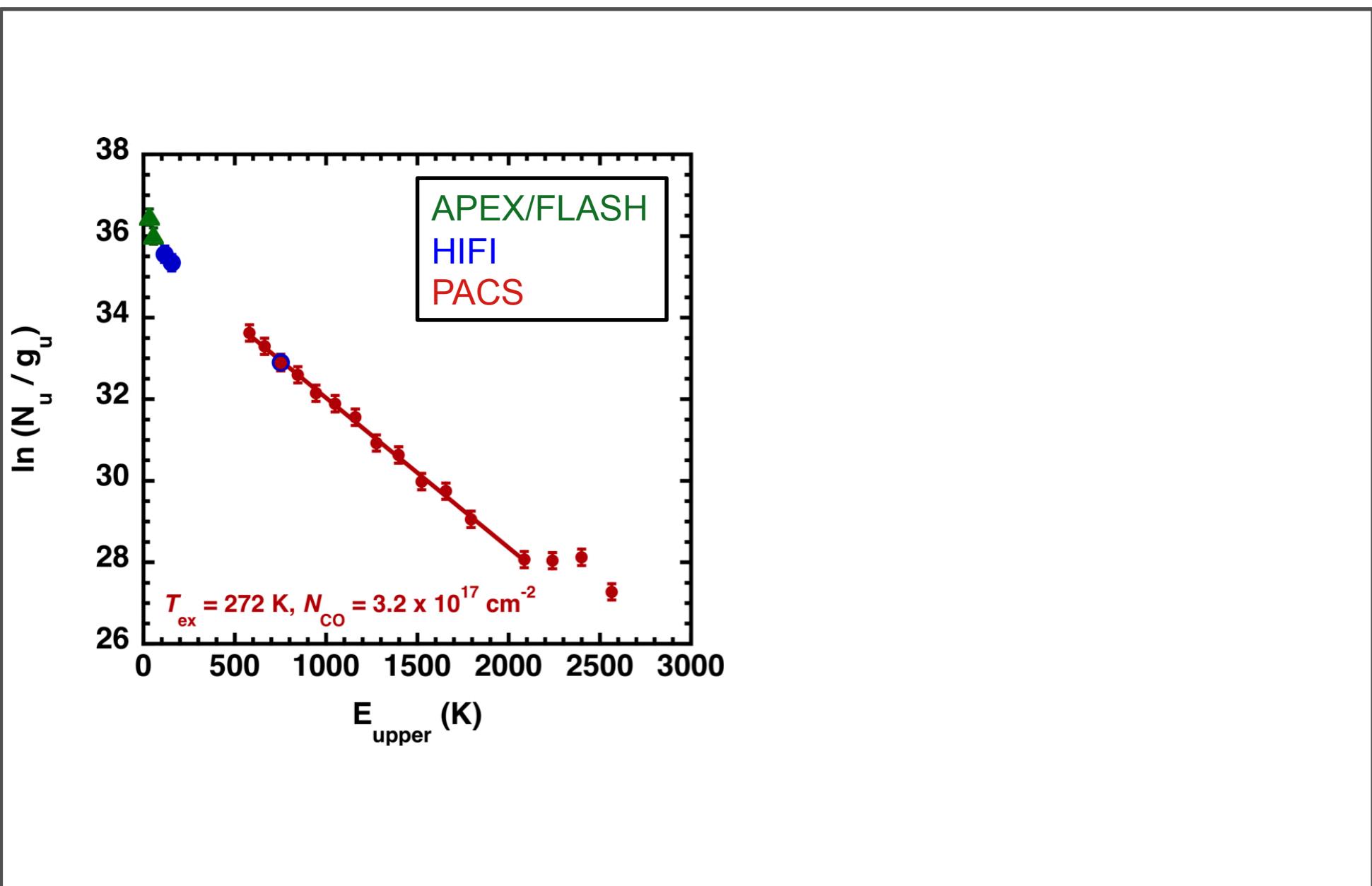
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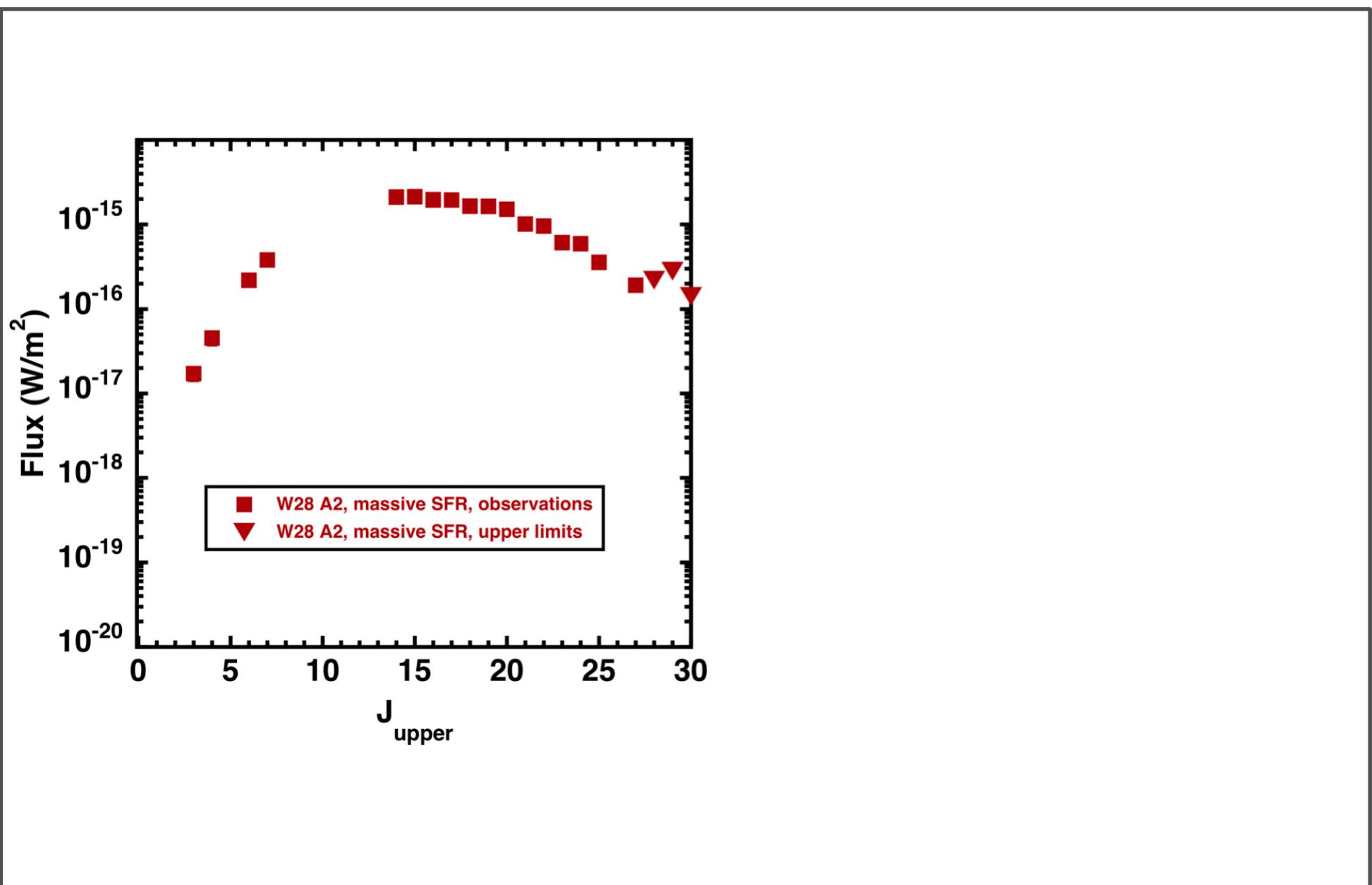
- LTE + optically thin + FF = 1, T<sub>ex</sub> of 50-250 K  
red-shifted: N(CH<sup>+</sup>) ~ (0.4-1.3) x 10<sup>13</sup> cm<sup>-2</sup> ; [CH<sup>+</sup>/CO] ~ (0.4-1.3) x 10<sup>-4</sup>

# **ENERGETICS**

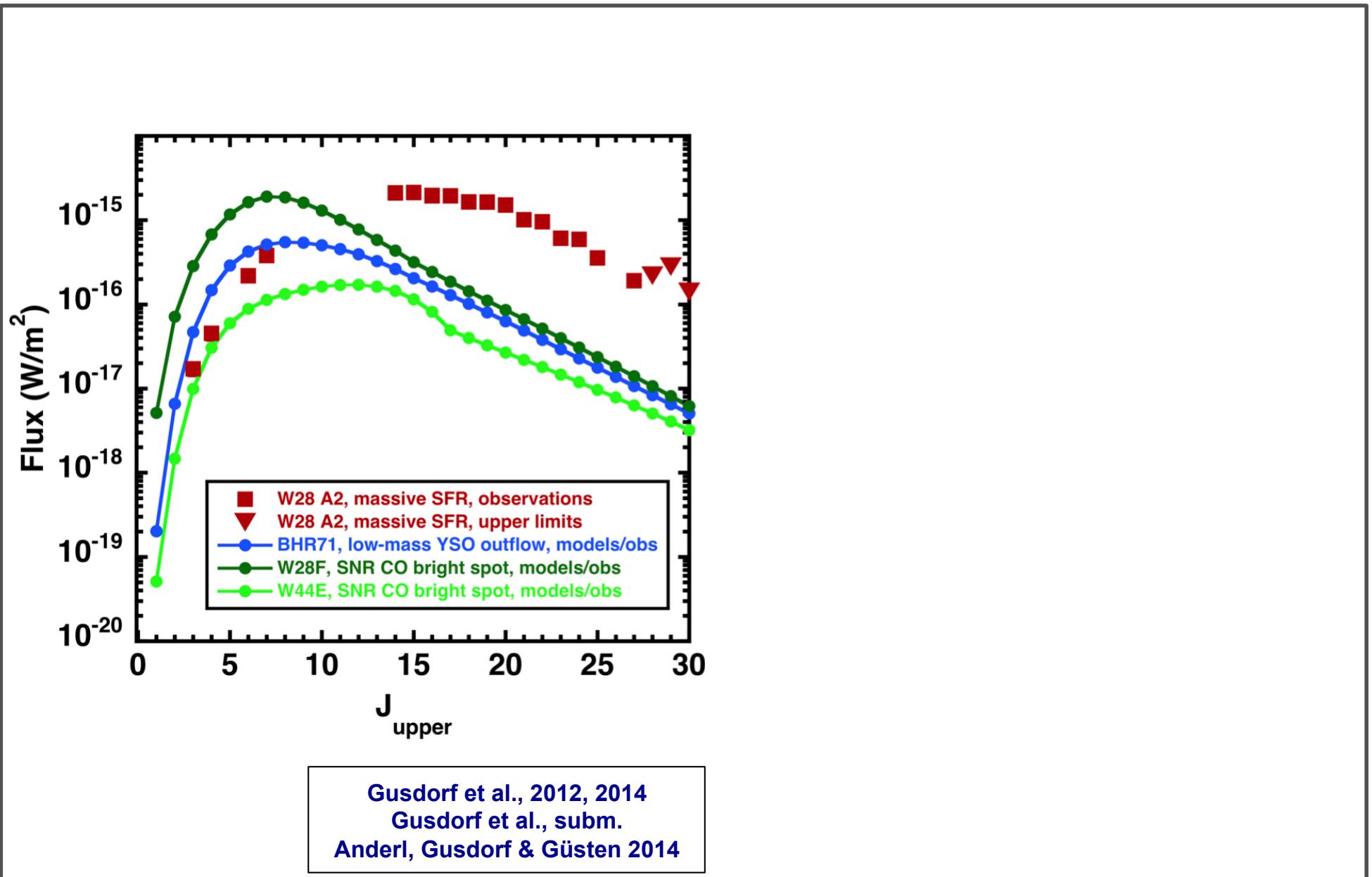
# Energetics: CO ladder or SLED



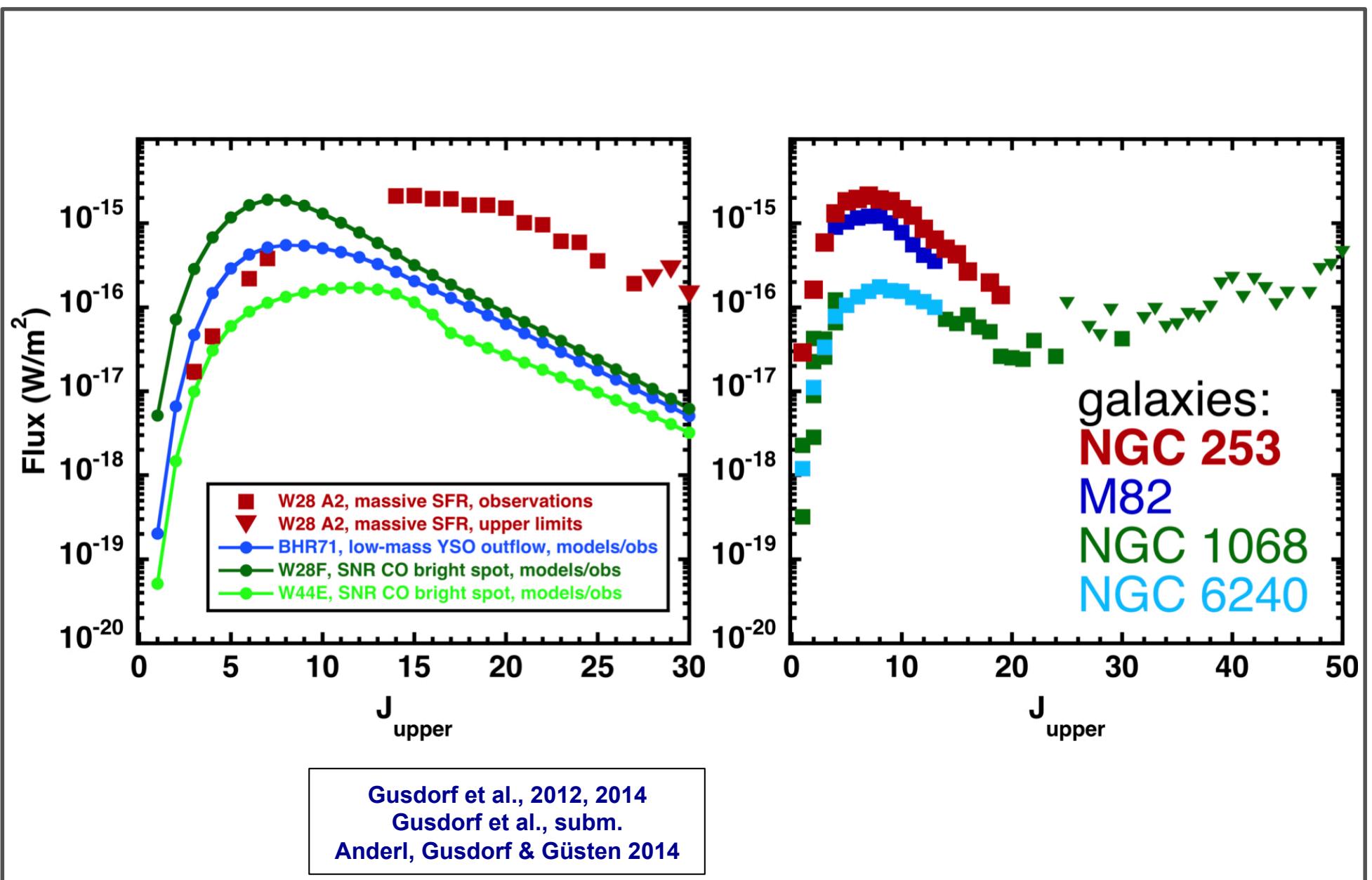
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# Energetics: CO ladder or SLED



# Energetics: CO ladder or SLED



# Energetics: outflow parameters

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$$t_d = R/\delta v_{\max}$$

$$M = N \times \pi R^2$$

$$\dot{M} = M/t_d$$

$$P = M \times \delta v_{\max}$$

$$F_m = M \times \delta v_{\max}/t_d$$

$$E_k = M \times \delta v_{\max}^2/2$$

$$L_{\text{mech}} = E_k/t_d$$

# Energetics: outflow parameters

$t_d = R/\delta v_{\max}$	component	blue	red	total
$M = N \times \pi R^2$	$N (10^{22} \text{ cm}^{-2})$	1.1–2.2	>(0.6–1.1)	>(1.7–3.3)
$\dot{M} = M/t_d$	$M (M_\odot)$	0.4–0.8	>(0.2–0.4)	>(0.6–1.2)
$P = M \times \delta v_{\max}$	$\delta v_{\max} (\text{km s}^{-1})$	50	50	50
$F_m = M \times \delta v_{\max}/t_d$	$t_d (\text{yr})$	760	760	760
$E_k = M \times \delta v_{\max}^2/2$	$\dot{M} (10^{-4} M_\odot \text{ yr}^{-1})$	5.4–10.8	>(3.0–5.4)	>(8.4–16.2)
$L_{\text{mech}} = E_k/t_d$	$P (10 M_\odot \text{ km s}^{-1})$	2.1–4.1	>(1.1–2.1)	>(3.2–6.2)
	$F_m (10^{-2} M_\odot \text{ km s}^{-1} \text{ yr}^{-1})$	2.7–5.4	>(1.5–2.7)	>(4.2–8.1)
	$E_k (10^{45} \text{ erg})$	10.3–20.7	>(5.6–10.3)	>(15.8–31)
	$L_{\text{mech}} (10 L_\odot)$	11.2–22.4	>(6.1–11.2)	>(17.3–33.6)

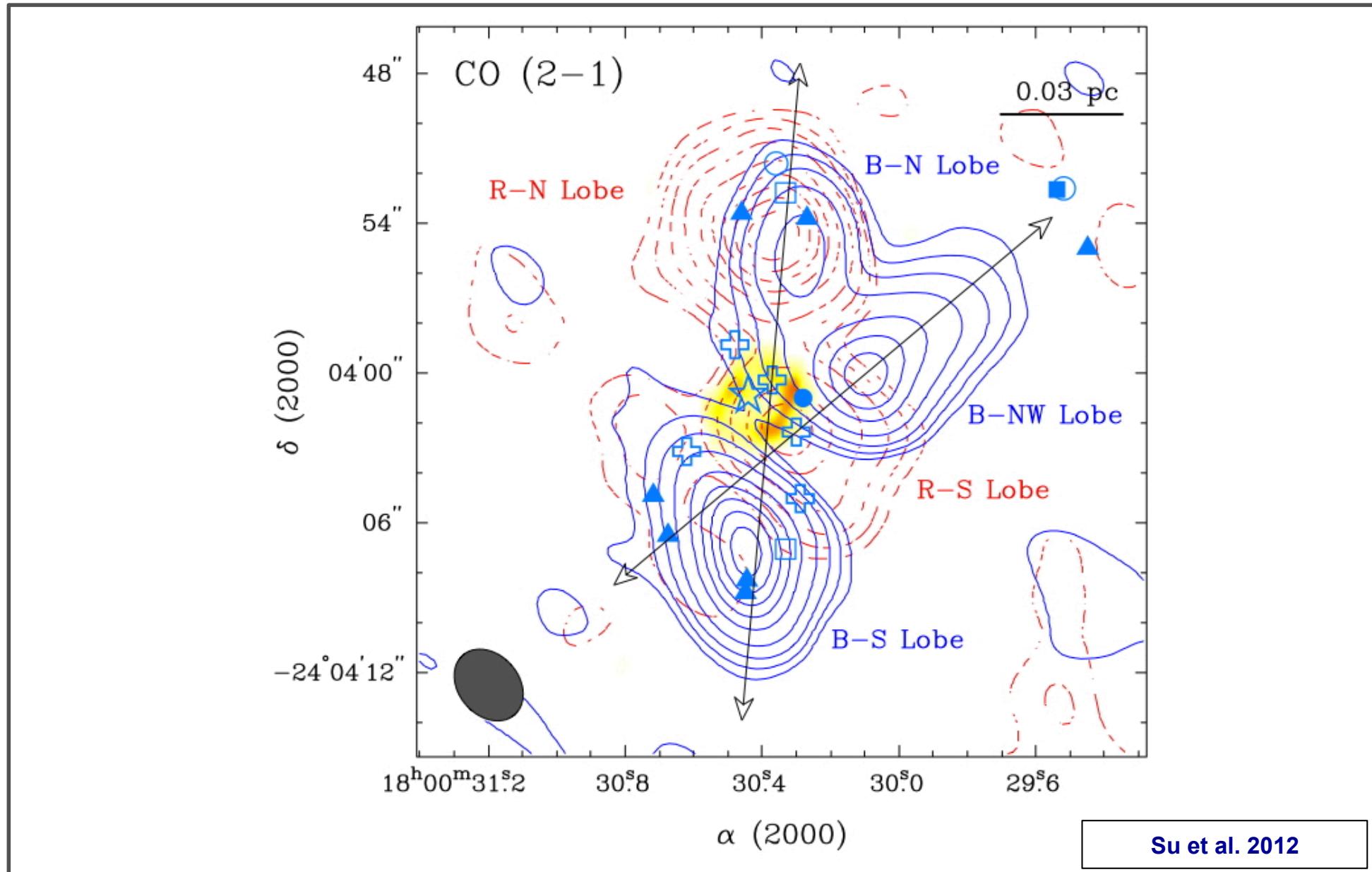
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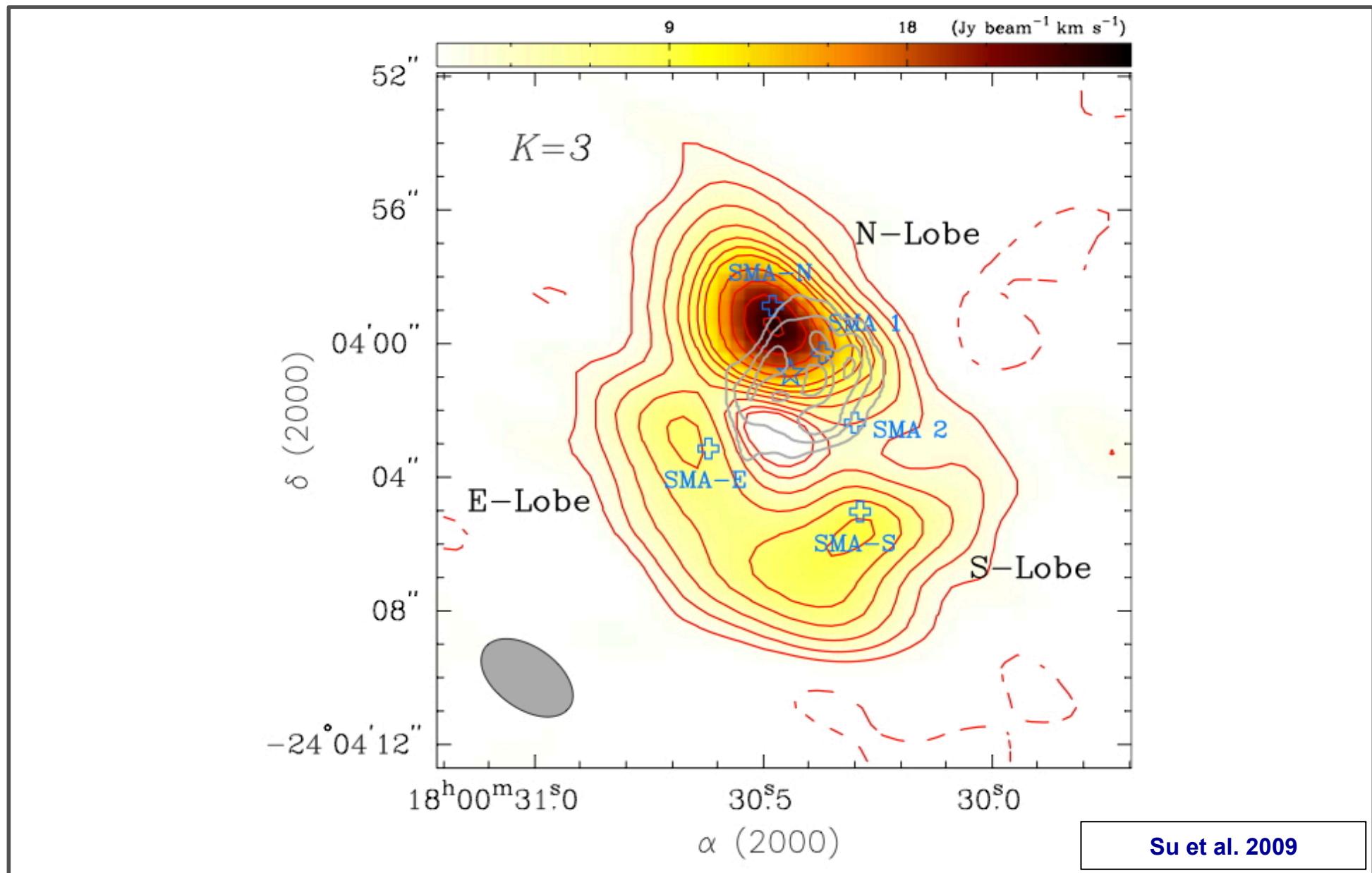
- 21 high-mass SFR, [Beuther et al. 2002](#): very energetic (high  $\dot{M}$ ,  $E_k$ ,  $F_m$ ,  $L_{\text{mech}}$ ) for its size
  - Confirmed by comparison with [Zhang et al. 2005](#): 69 luminous IRAS point sources
  - More in the range of values of [Lopez-Sepulcre et al. 2009](#): 11 very luminous objects likely to harbour one or more O-type stars
- Less luminous sources

# COSMIC RAYS

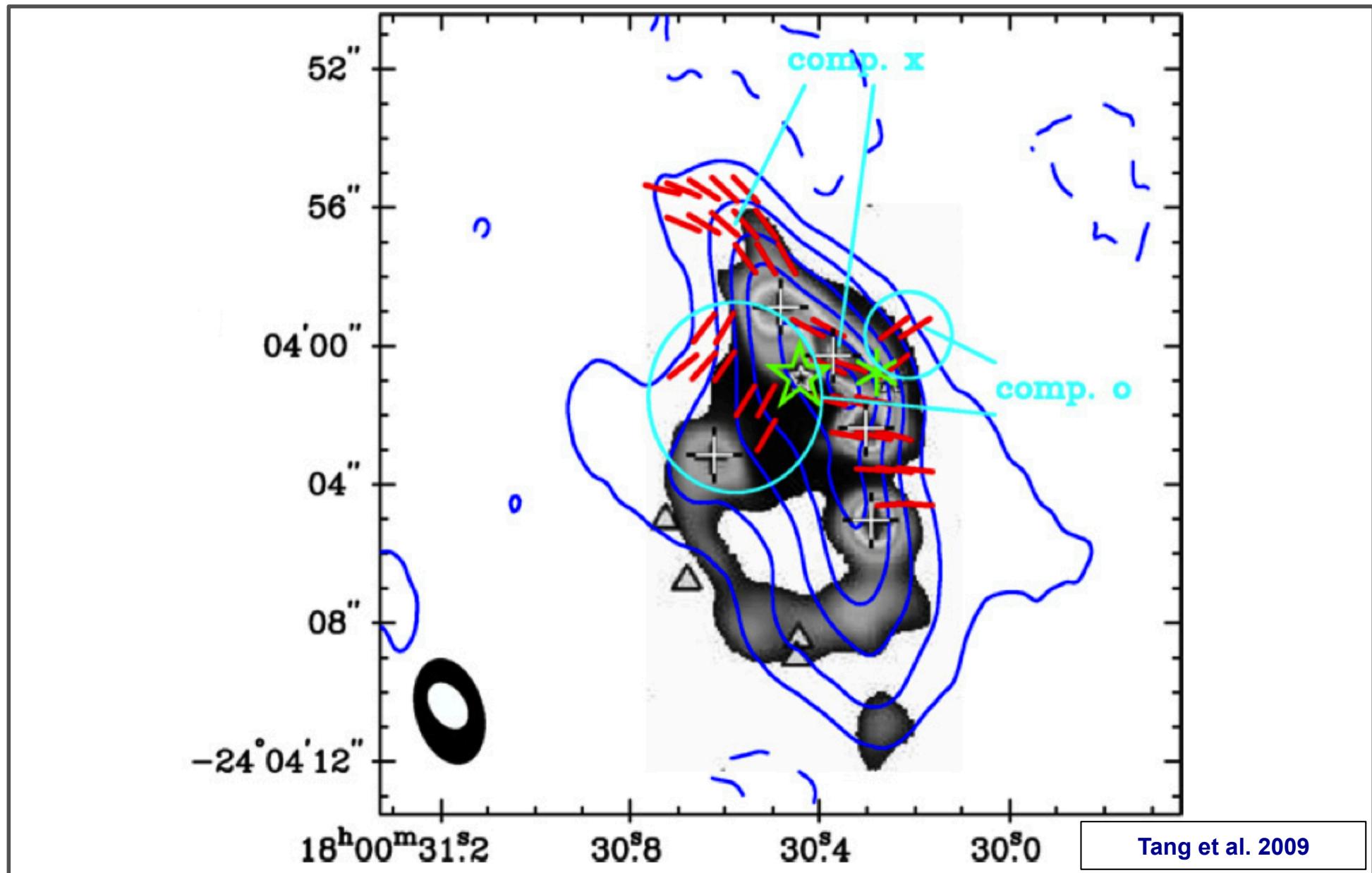
# Cosmic rays: Mechanical energy...



# Cosmic rays:...an HII region...



# Cosmic rays: and strong magnetic fields



# Cosmic rays: *in situ* acceleration ?

- Global approach: estimate the maximum energy attainable by CRs
- **Scenario (1): in the irradiated bipolar outflows**
  - $v \sim 50 \text{ km/s}$ ,  $t \sim 750 \text{ yr}$ ,  $n_H \sim 10^5 \text{ cm}^{-3}$ ,  $B \sim 2 \text{ mG}$ ,  $T \sim 10^2 \text{ K}$ ,  $R \sim 16000 \text{ AU}$
  - $x_e \sim 10^{-4}$  => ion-neutral collisions prevent particles to become relativistic
  - one would need much faster shocks to accelerate CRs
- **Scenario (2): in the HII region**
  - $v \sim 50 \text{ km/s}$ ,  $t \sim 600 \text{ yr}$ ,  $n_H \sim 5 \cdot 10^5 \text{ cm}^{-3}$ ,  $B \sim 2 \text{ mG}$ ,  $T \sim 10^4 \text{ K}$ ,  $R \sim 3300 \text{ AU}$
  - $E_{\max}(e^-) \sim 5 \text{ GeV}$ , but probably weak emission
  - $E_{\max}(\text{hadrons}) \sim Zx(5-135) \text{ GeV}$
- **Scenario (3): in the stellar wind**
  - much more speculative, fast shocks  $\sim 2000-3000 \text{ km/s}$ ,
  - depends on (highly uncertain) star's age

# CONCLUSIONS & PERSPECTIVES

# Conclusions

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- **Physical and chemical conditions:**
  - CO is not the only/principal carrier of carbon
  - need to take CO, CI, and C<sup>+</sup> into account for any modelling attempt
  - detection of wing-emission in C<sup>+</sup> and CH<sup>+</sup> => irradiated shocks
- **Star formation:**
  - Shocks are denser than those associated to low-mass SF
  - Shocks are irradiated by the UV radiation field of the protostar
- **Energetics:**
  - CO ladders reveal high-J lines excitation
  - Strong outflows are powered, meaning strong accretion
- **Chemical feedback:** C<sup>+</sup>, CH<sup>+</sup>, (unshown) strong SiO emission up to 12-11
- **Cosmic rays:** acceleration is possible in the termination shock/HII region

Thanks for your attention  
and for giving me the opportunity to  
present this work !