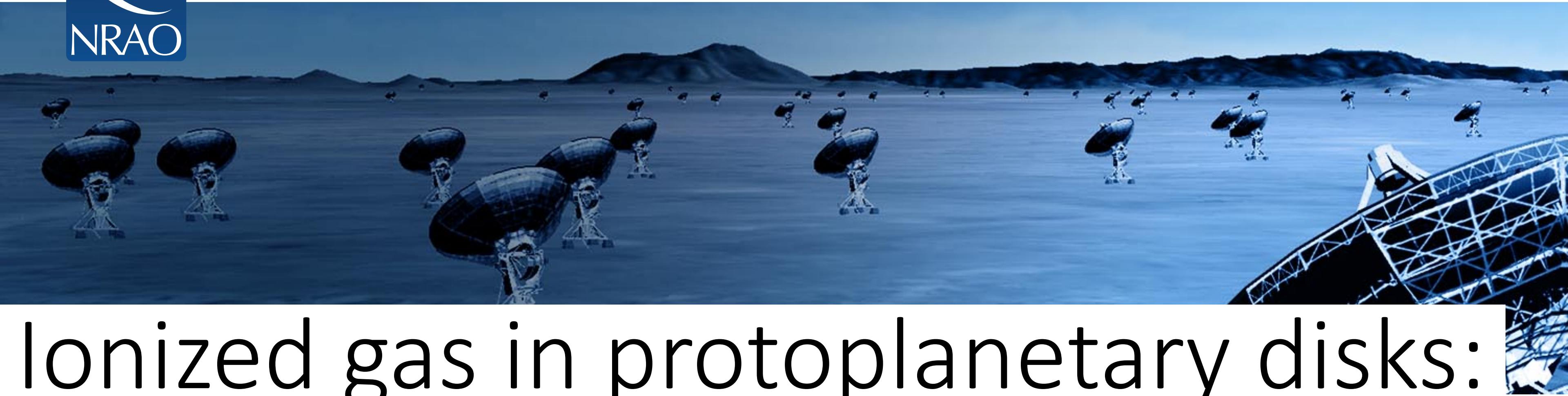
NATIONAL RADIO ASTRONOMY OBSERVATORY



Ionized gas in protoplanetary disks:

Radio jets or photoevaporative winds?

Enrique Macias

(Boston University)

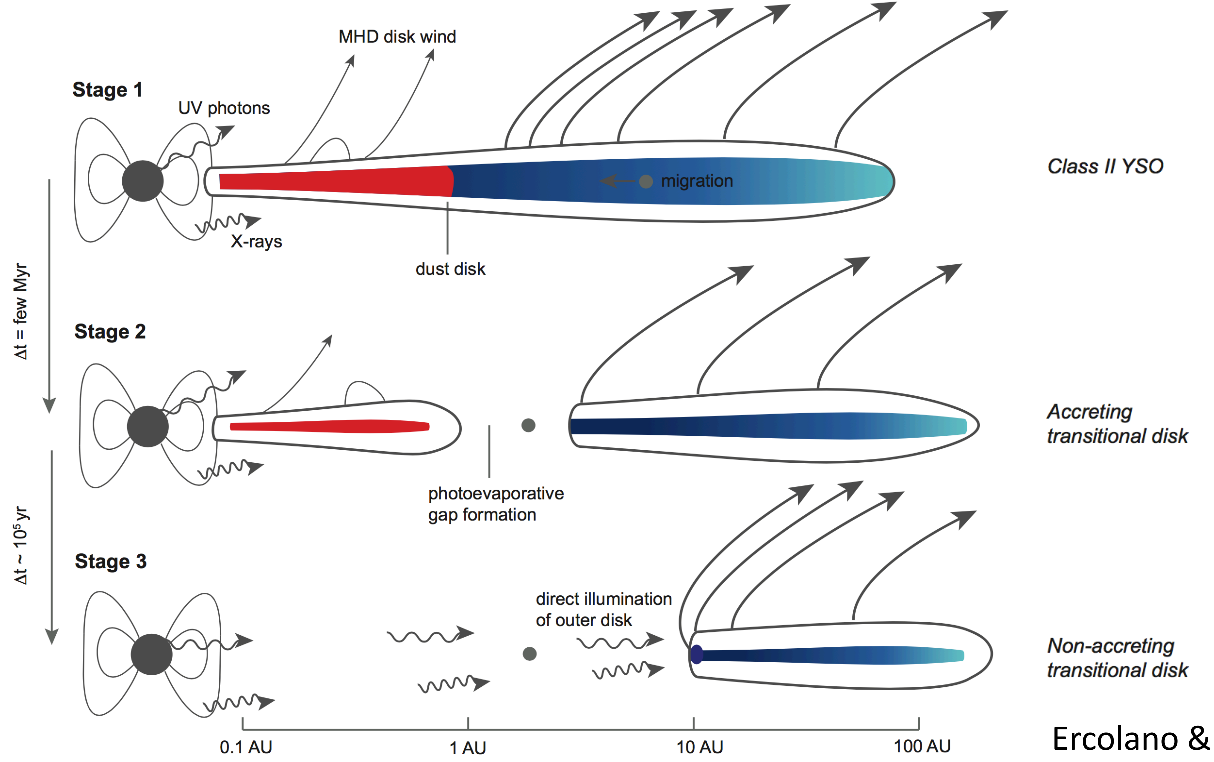
ngVLA

The Next Generation Very Large Array

Outline

- Introduction:
  - Photoevaporative winds
  - Radio jets
- VLA Observations: what can we do now?
- ngVLA: a game changer

Ionized gas: tracer of disk photoevaporation



Ercolano & Pascucci (2017)

Disk photoevaporation

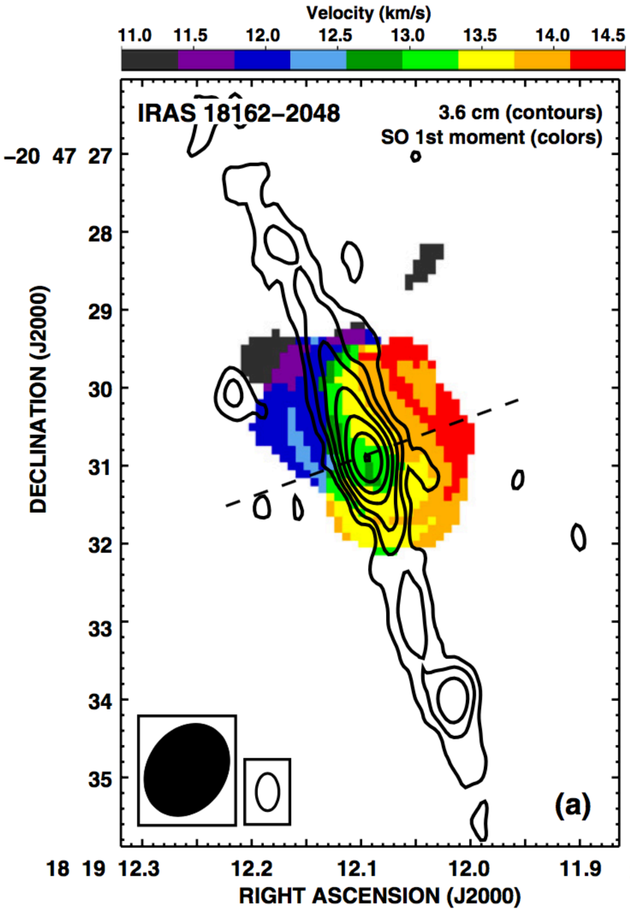
High energy radiation

- FUV ✓
- EUV ?
- X-rays ✓

- Forbidden lines (OI, NeII, ...)
- Free-free emission from photoionized gas.

Radio jets

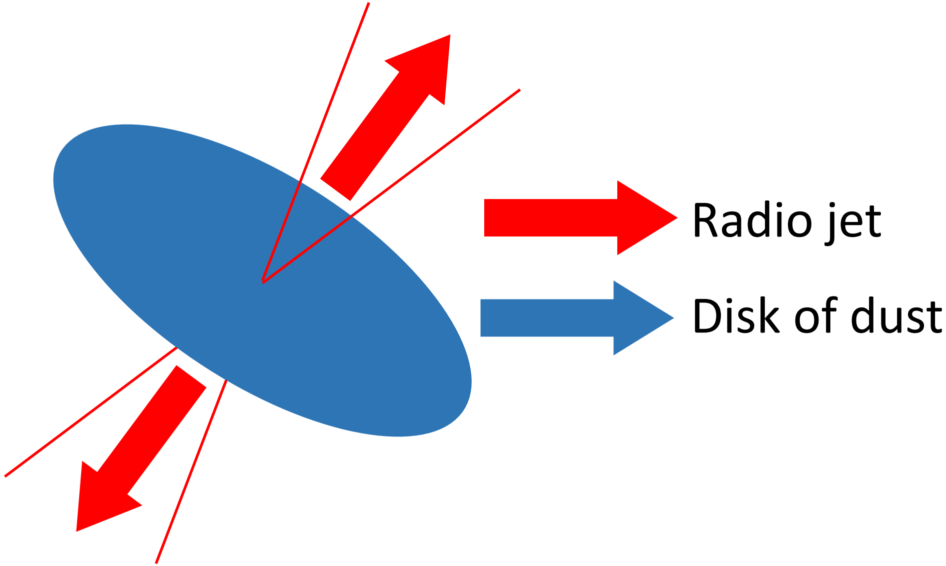
- Collimated ejection of material perpendicular to the disk.
- Ionized by shocks.



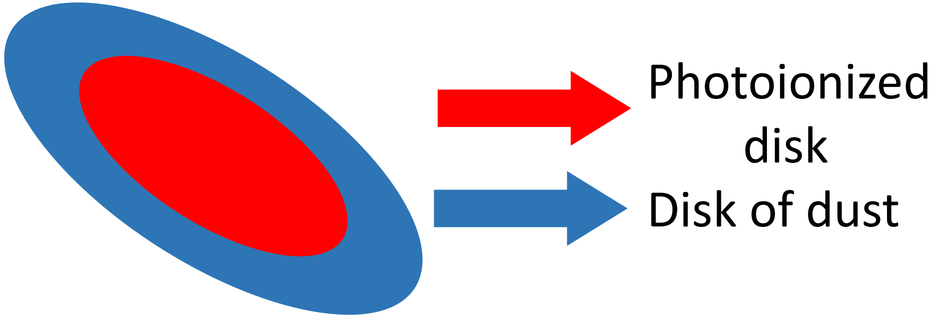
Carrasco-González et al. (2012)

Origin of the ionized gas

- Ionized jet:



- Photoionized disk:



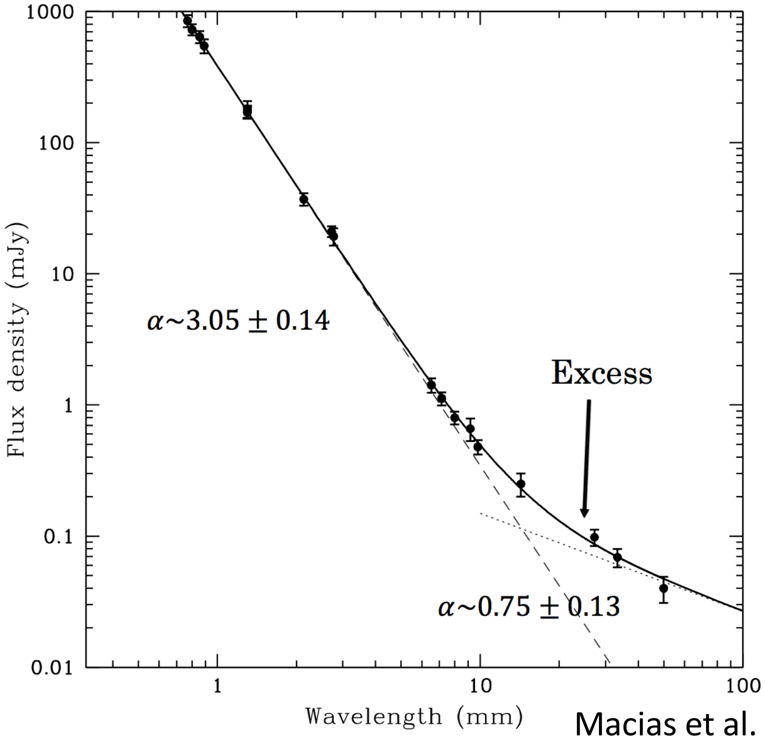
Radio emission of protoplanetary disks

- Dust thermal emission:

$$2 \leq \alpha \leq 3.5$$

- Free-free emission:

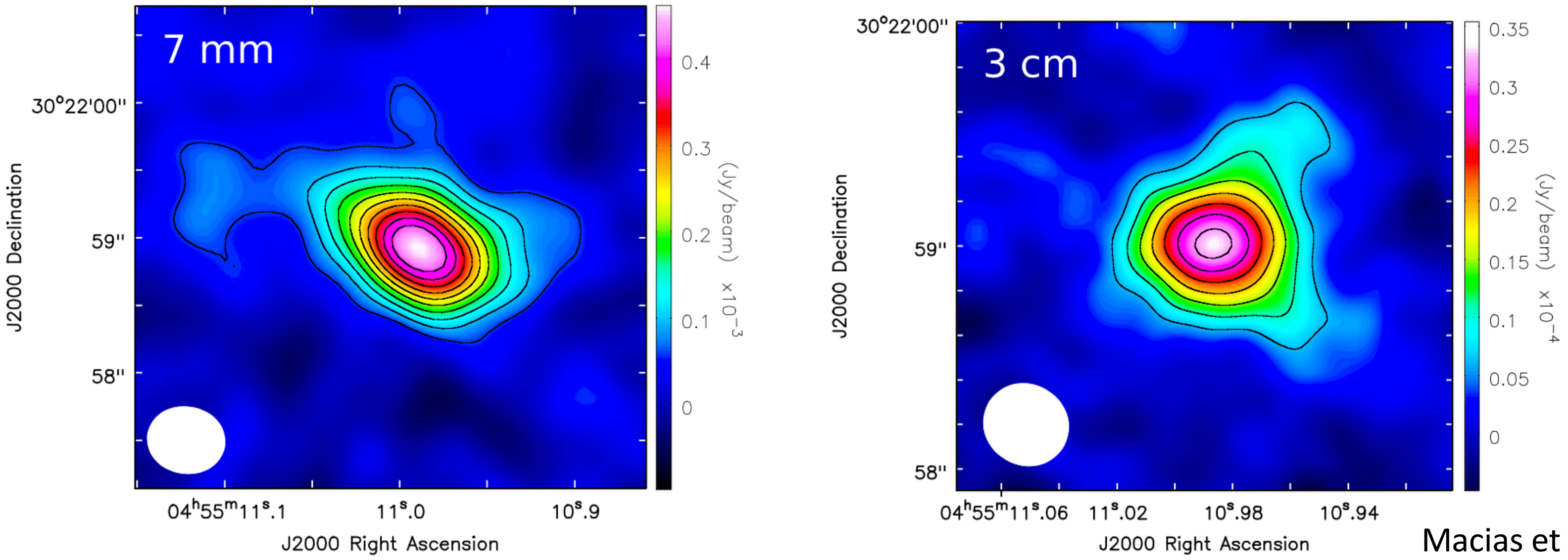
$$-0.1 \leq \alpha \leq 1$$



Macias et al. (2016)

GM Aur: VLA observations

- Multi-configuration VLA observations
- 7 mm and 3 cm



Macias et al. (2016)

GM Aur: Free-free emission

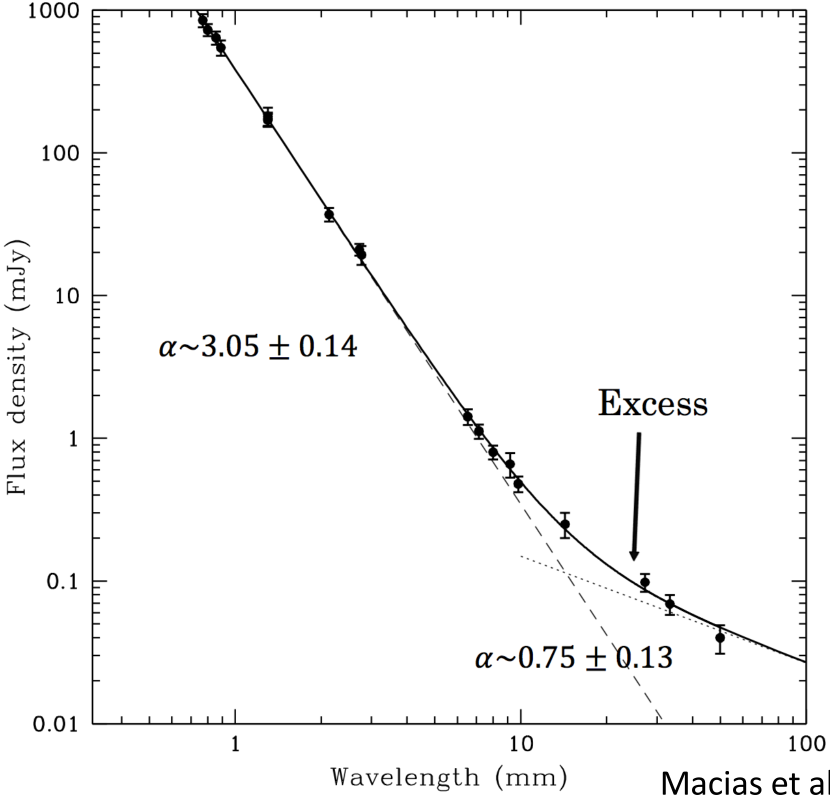
Two power laws:

- Dust thermal emission:
  $\alpha \sim 3.05 \pm 0.14$

- Free free emission:
  $\alpha \sim 0.75 \pm 0.13$

⬇

Ionized gas



Macias et al. (2016)

GM Aur: Free-free emission

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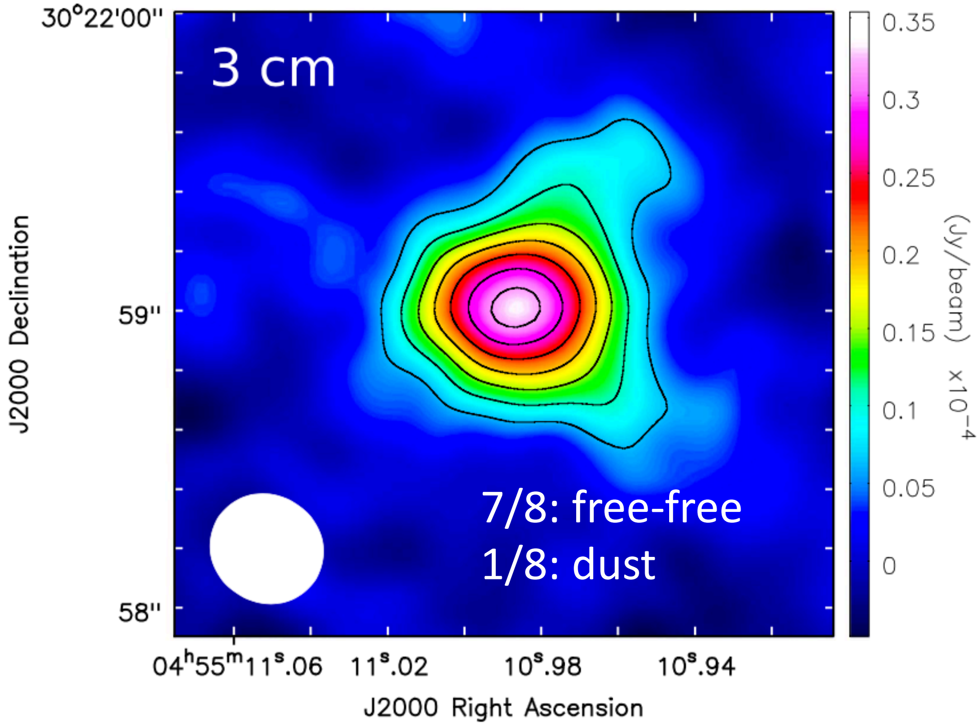
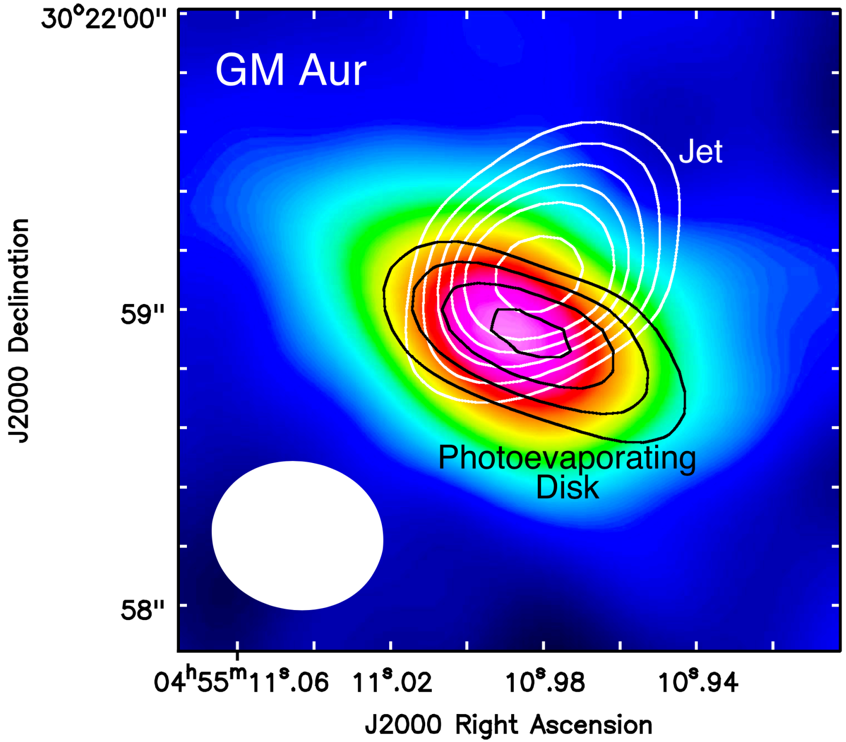
Ionized gas



Macias et al. (2016)

GM Aur: Two components of free-free emission

- Subtracted estimated dust emission.
- Two perpendicular components:
  - Ionized jet: $F_\nu \sim 45$ μJy
  - Photoionized disk: $F_\nu \sim 30$ μJy



Macias et al. (2016)

Photoionized disk

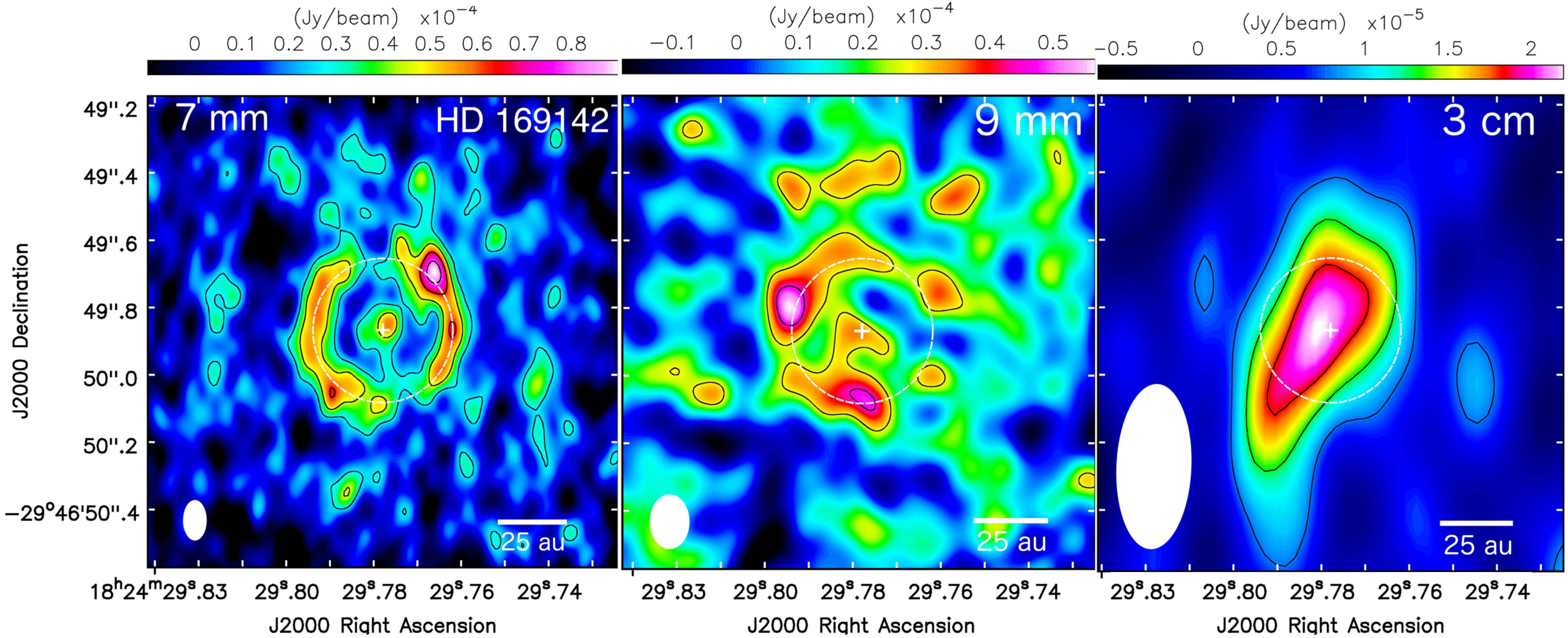
$$F_{\rm cm} \begin{cases} \propto \Phi_{\rm EUV} \\ \propto L_{\rm X} \end{cases}$$

Pascucci et al. (2012)

Measured L_X ~ 1.6×10^{30} erg s^{-1} ➡ 1/5 of free-free emission

Remaining emission ➡ $\phi_{\rm EUV}$ ~ 6×10^{40} s^{-1}

HD 169142: VLA observations



Macias et al. (2017)

HD 169142: VLA observations

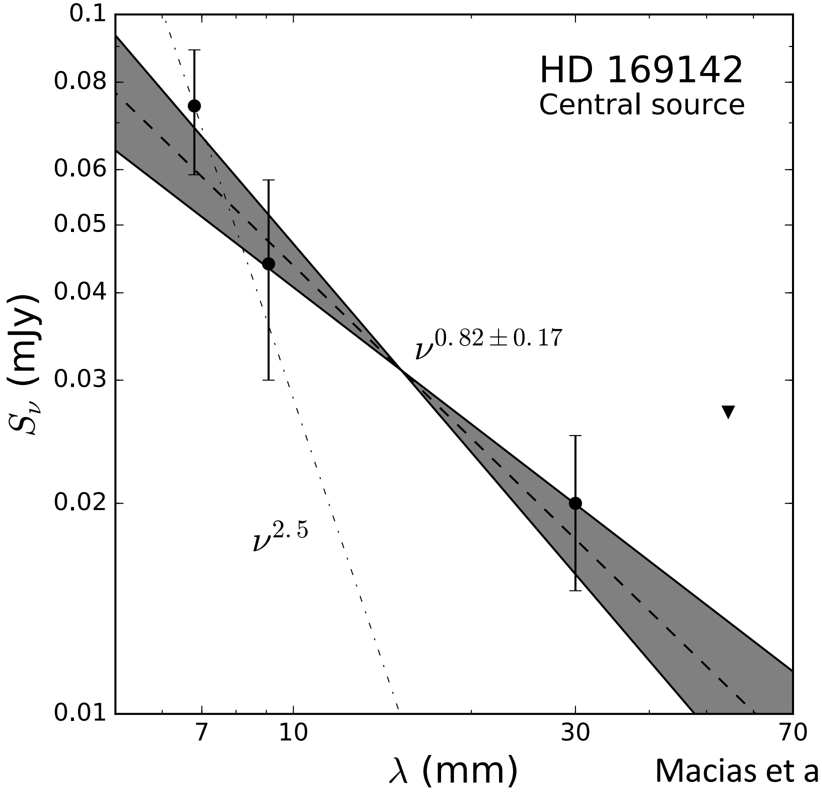
Spectral index:

$\alpha \sim 0.82 \pm 0.17$

⬇

Ionized gas

- Ionized jet
- Photoionized gas



Macias et al. (2017)

HD 169142: VLA observations

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Ionized gas

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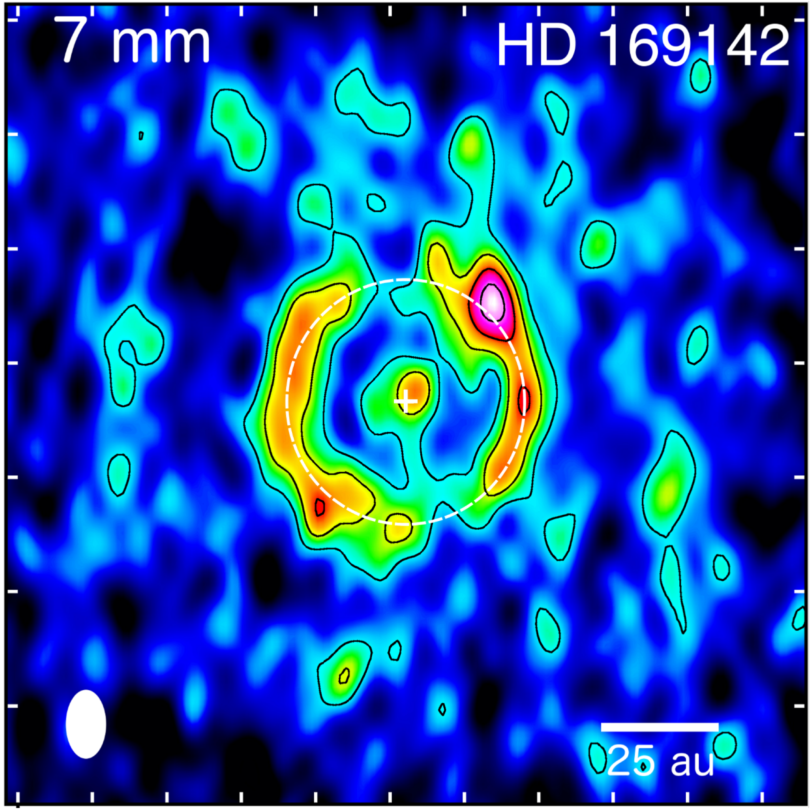


Future work: Larger sample

VLA project:
- 14 protoplanetary disks
- 3 cm
- C, B, and A configurations

Goals:
- Estimate EUV photon luminosities
- Photoionization: correlations with L_X, Sp. type, age, TD vs FD, etc.
- Ionized jets: photoionized gas? Correlations with accretion rate, TD vs FD, etc.

ngVLA

- 10 times more angular resolution:
  - More accurate separation of jet and wind.
  - Substructure of photoionized gas.

- 10 times more sensitivity:
  - Larger sample.
  - More advanced stages of disk photoevaporation.

ngVLA

Radio recombination lines (Hα) of photoionized gas:

- Line fluxes (d = 51 pc)
  - ~200 μJy at 3 mm (~H40α)
  - ~100 μJy at 1 cm (~H60α)

(Pascucci et al. 2012)

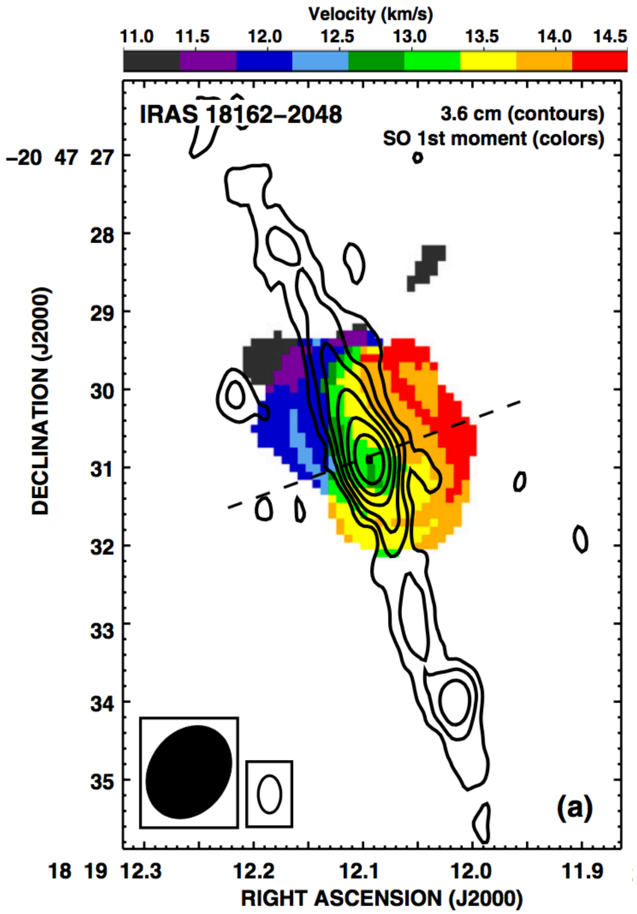
- ngVLA:
  - One line: SNR ~ 5 with ~8h, 10 km s^{-1}
  - Stacking of lines:
    - ~14 lines at 1 cm: SNR>5 in 1h (20 GHz bandwidth)
    - ~5 lines at 3 mm: SNR~5 in 2h (30 GHz bandwidth)

Summary

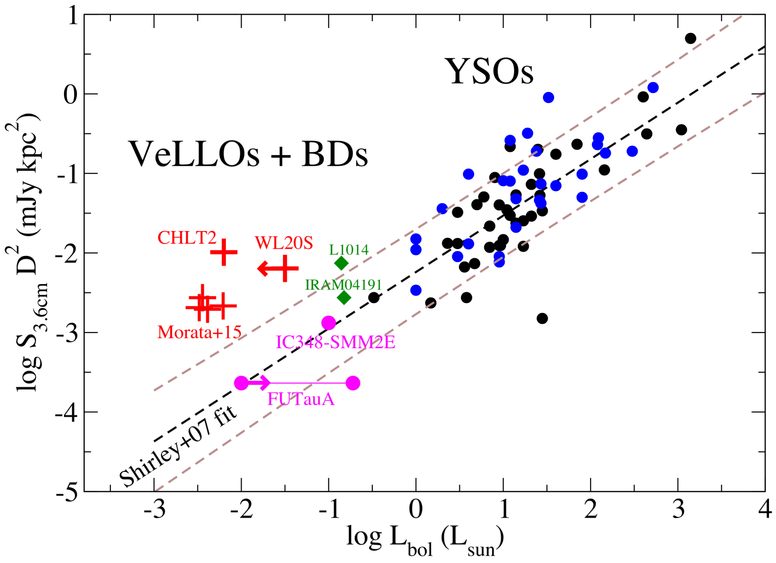
- Free-free emission in protoplanetary disks: ionized jets or photoionized gas.
- High angular resolution and sensitivity needed to separate both mechanisms.
- First resolved images of a (centrally) photoevaporating disk around a low mass star.
- ngVLA will be key to improve this study and extend it to a large sample of disks.
- ngVLA could allow the detection of radio recombination lines in protoplanetary disks.

Thanks!

Radio jets



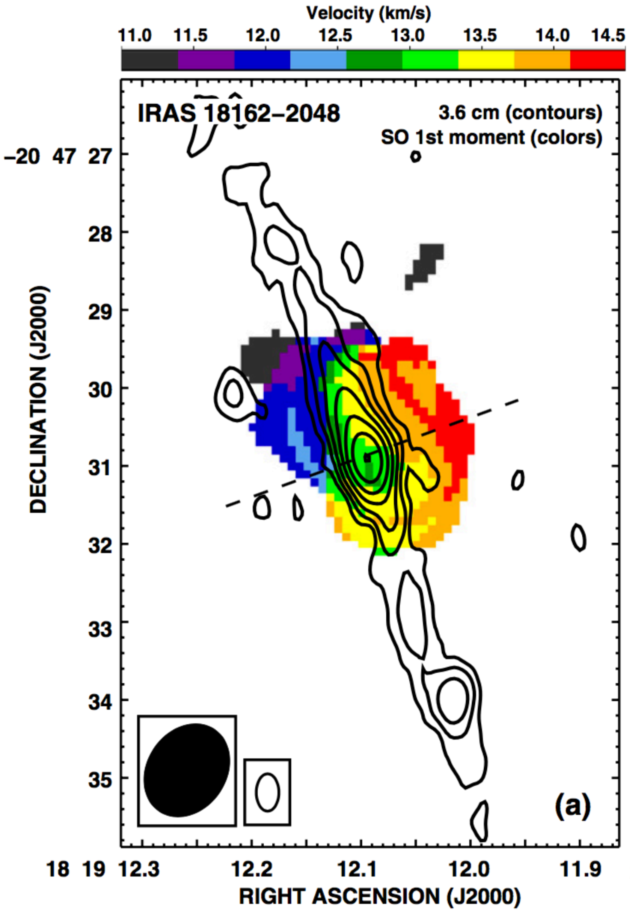
Carrasco-González et al. (2012)



Rodríguez et al. (2017)

Radio jets

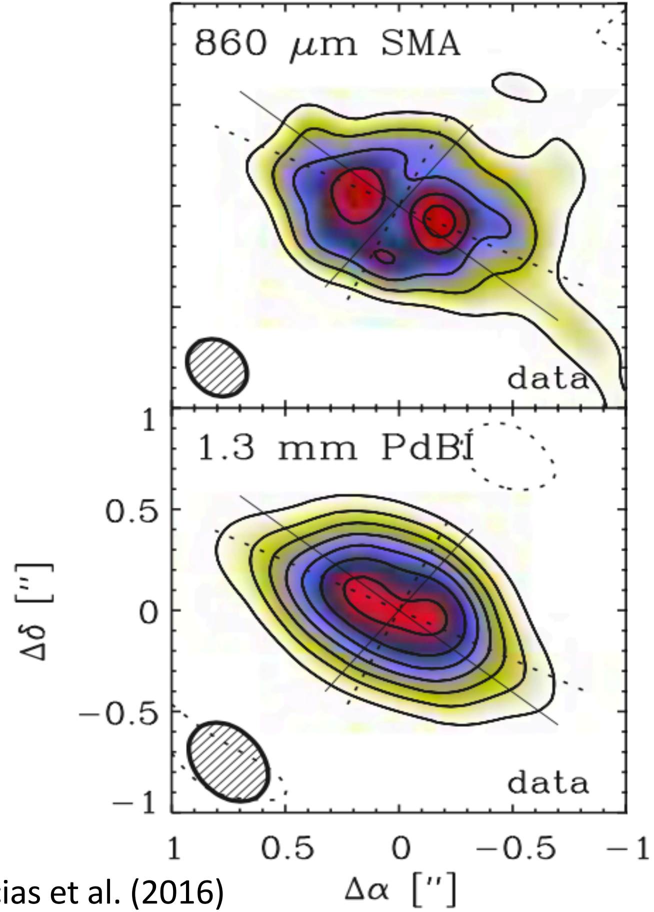
- Collimated ejection of material, perpendicular to the disk.
- Ionized by shocks.
- $\frac{\dot{M}_{\mathrm{out}}}{\dot{M}_{\mathrm{acc}}} \propto 0.1$



Carrasco-González et al. (2012)

GM Aur: a solar analogue

- Solar analogue
- ~1-2 Myr
- Transitional disk: cavity with radius of ~24 au



Macias et al. (2016)

Ionized jet

- Empirical correlations between free-free emission and outflow rates (Anglada et al. 2015):

$$F_{\mathrm{cm}} \propto \dot{M}_{\mathrm{out}} v$$

$$\Downarrow$$

$$\frac{\dot{M}_{\mathrm{out}} \sim (3-5) \times 10^{-9}\ \mathrm{M_\odot\ yr^{-1}}}{\dot{M}_{\mathrm{acc}} \sim (0.4-1) \times 10^{-8}\ \mathrm{M_\odot\ yr^{-1}}}$$

$$\Downarrow$$

$\frac{\dot{M}_{\mathrm{out}}}{\dot{M}_{\mathrm{acc}}}$ consistent with younger protostars (Cabrit 2007)