EVN Symposium – Granada, 8 September 2018

CHALMERS
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Revealing magnetic fields towards massive protostars: a multi-scale approach using masers and dust

+ one extra

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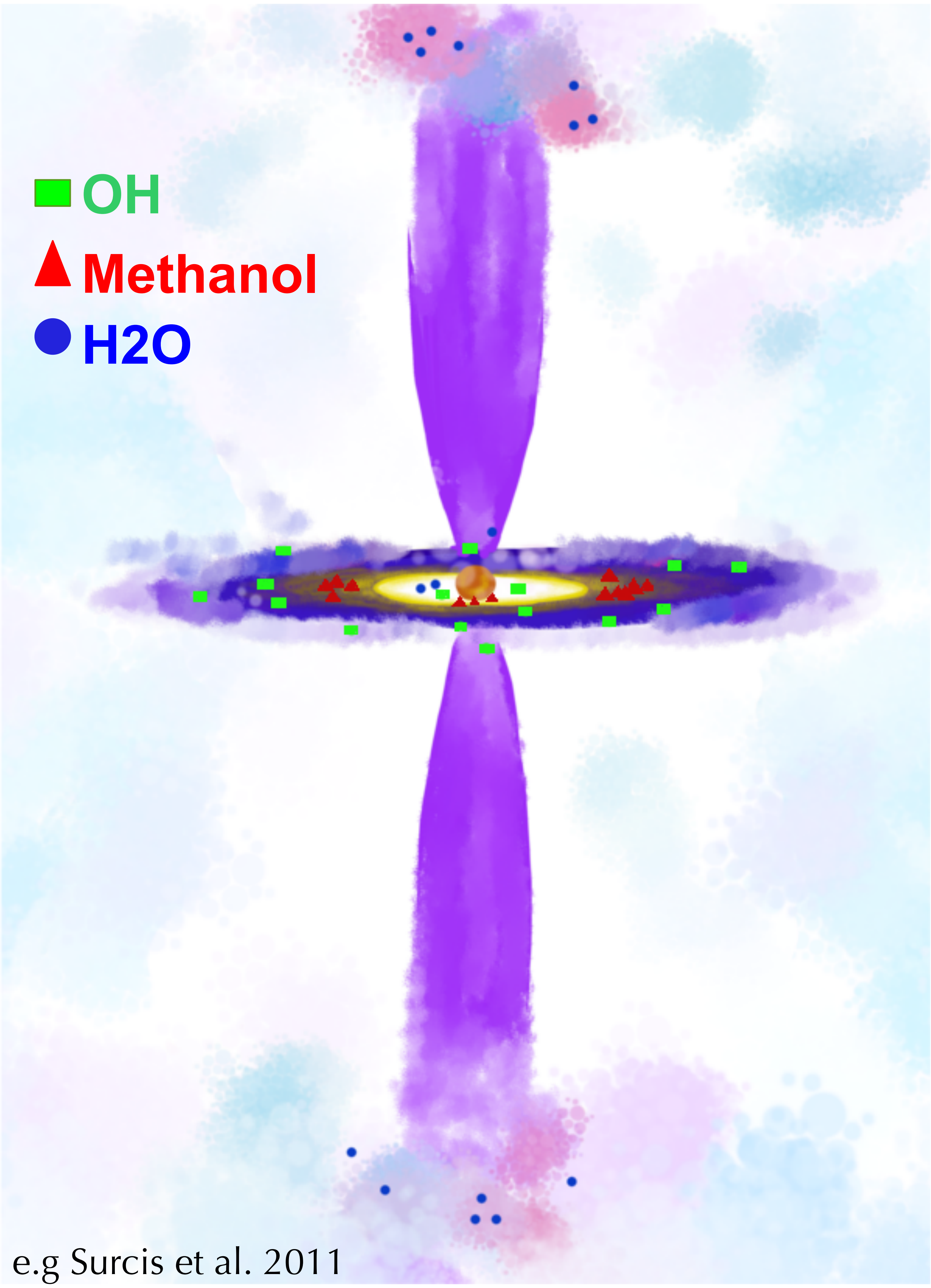
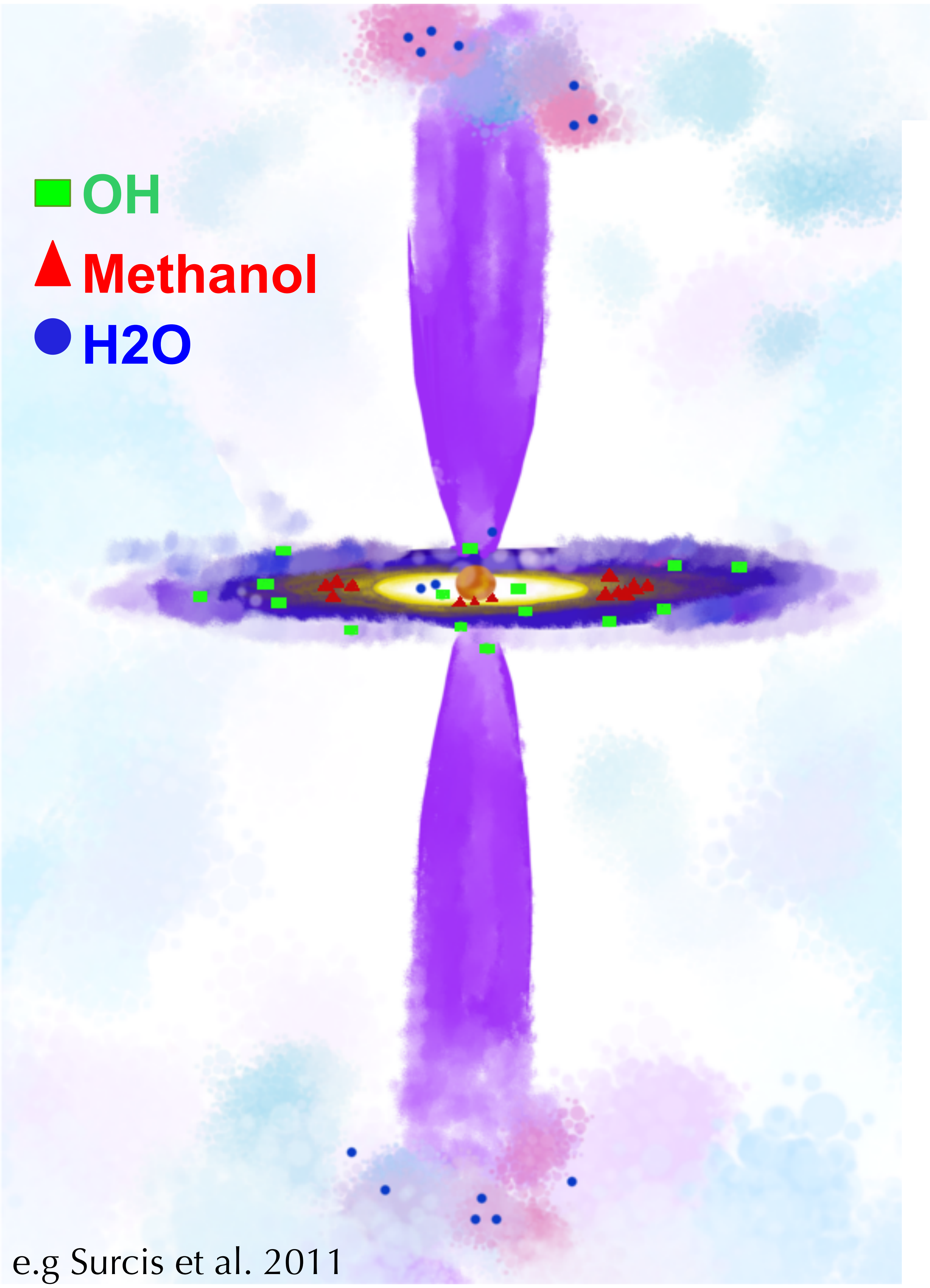
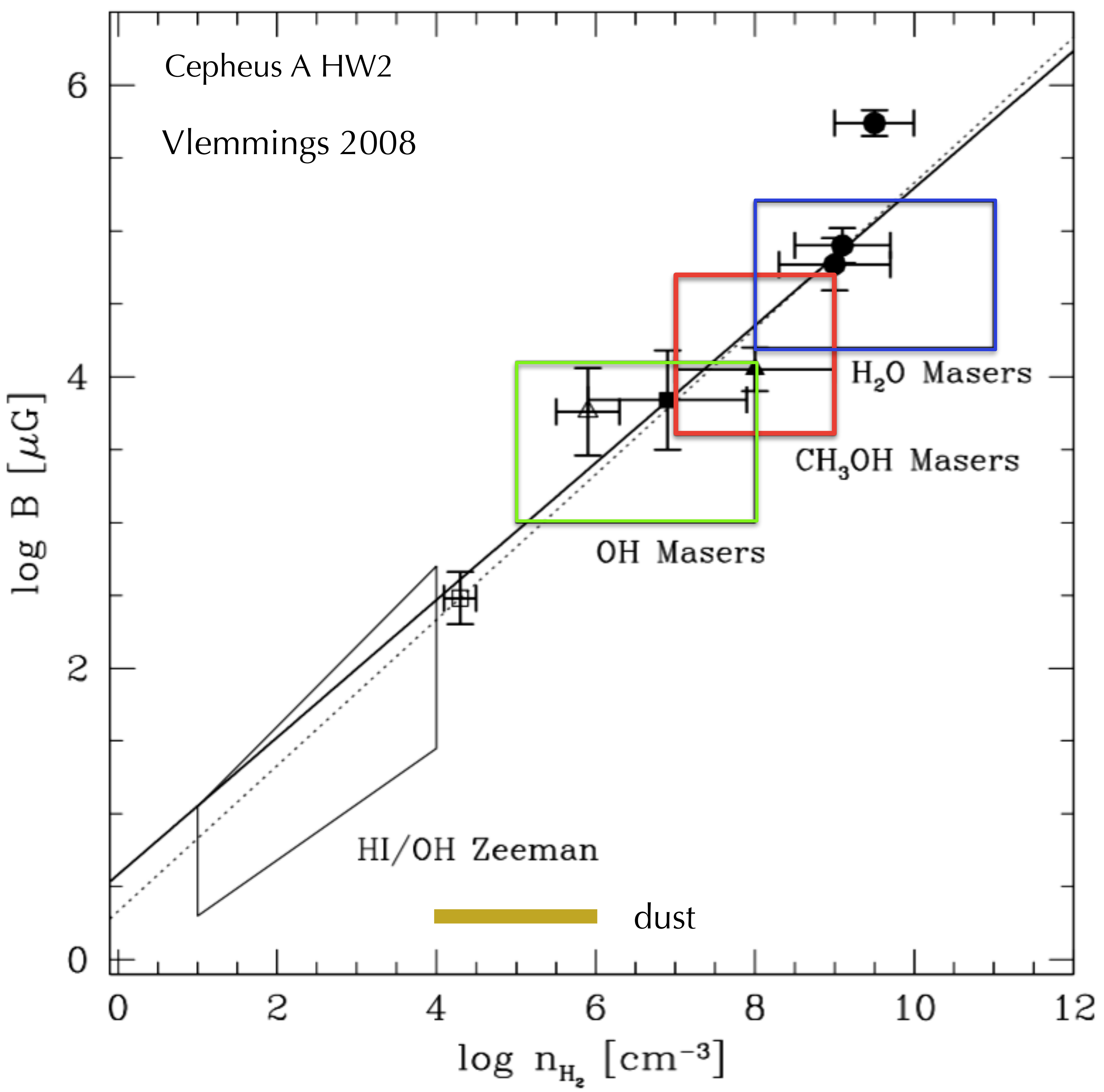
Masers and dust



small scales ~ 100-1000 AU

Masers and dust





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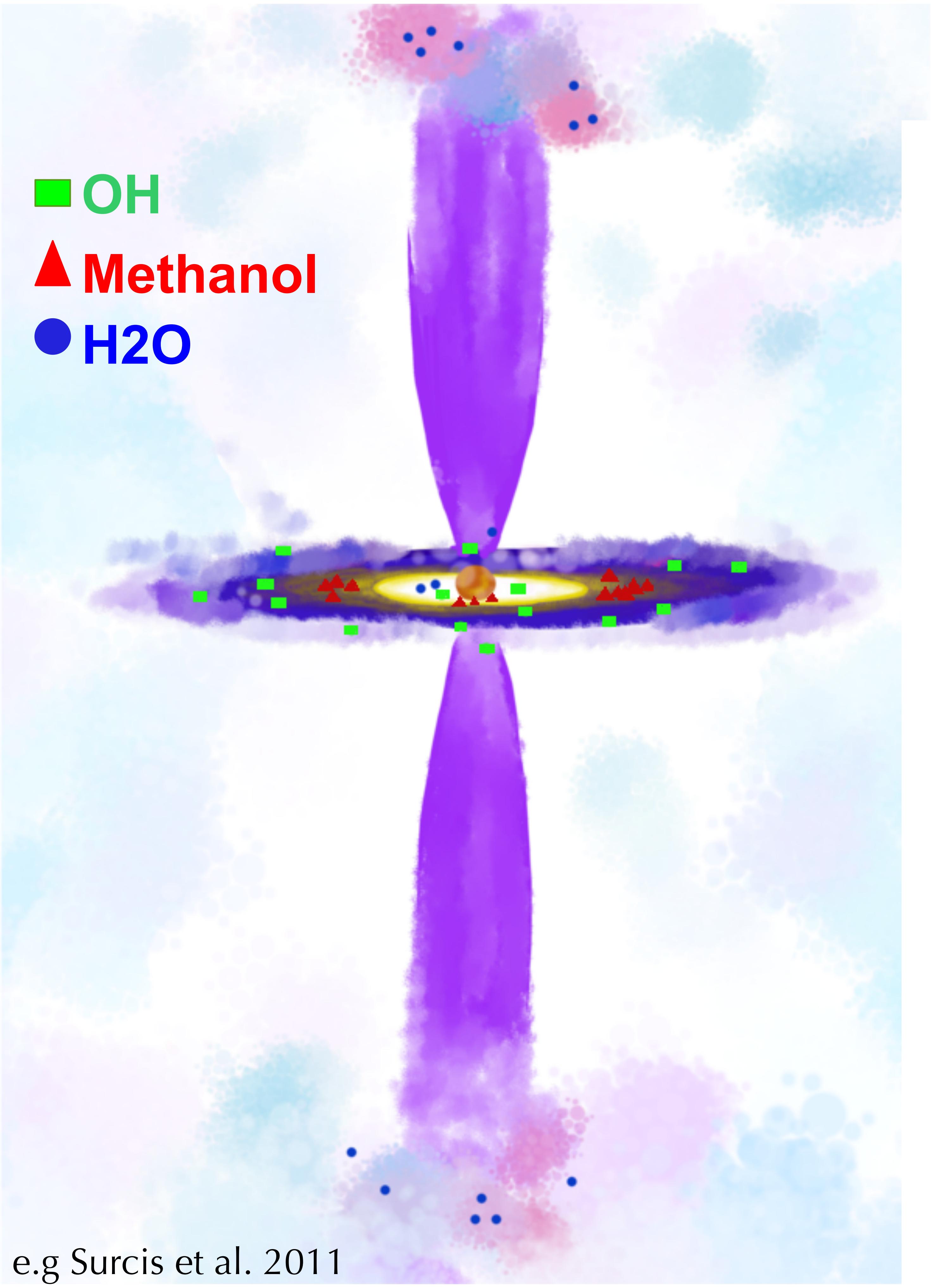
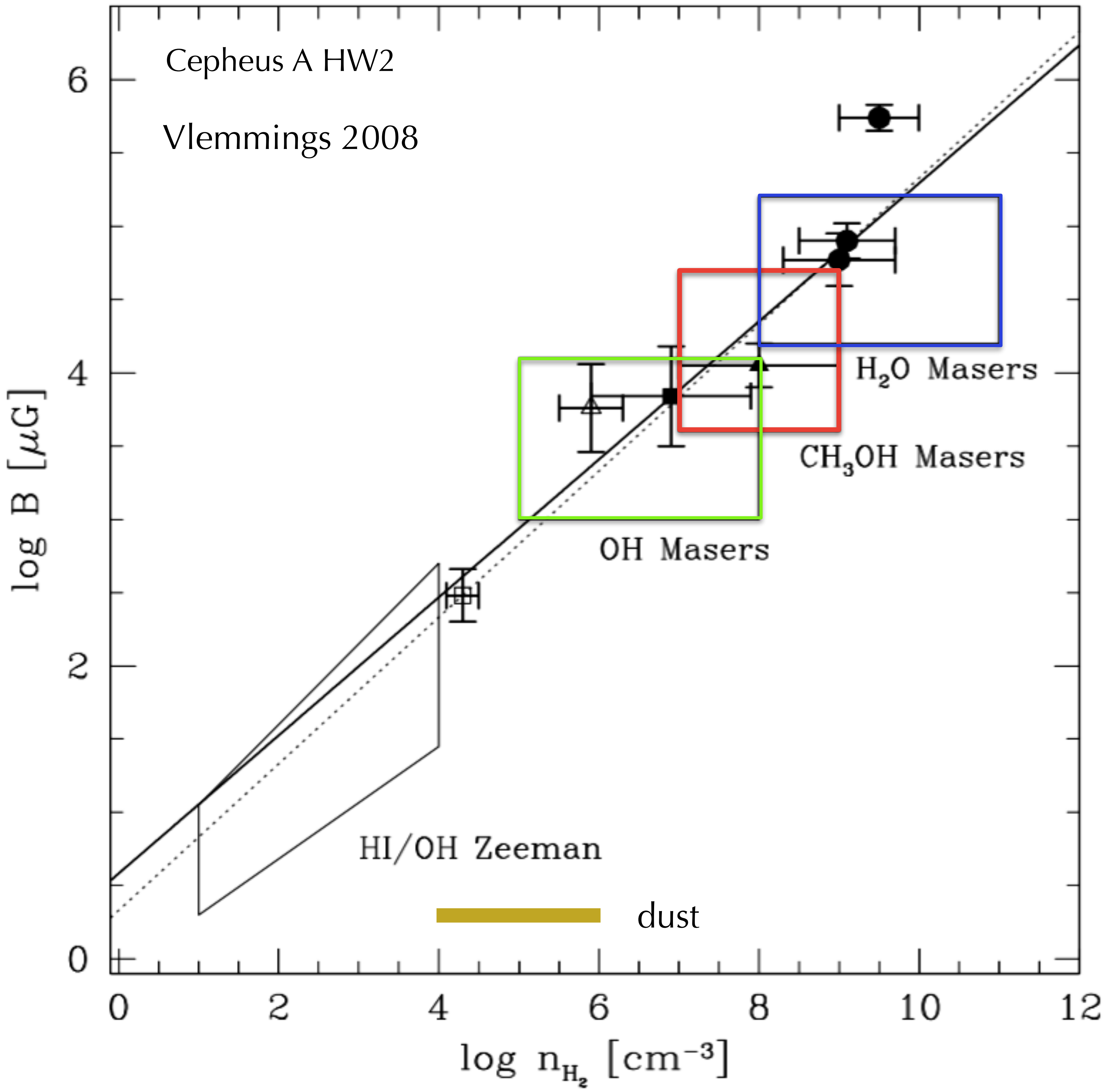
Masers and dust

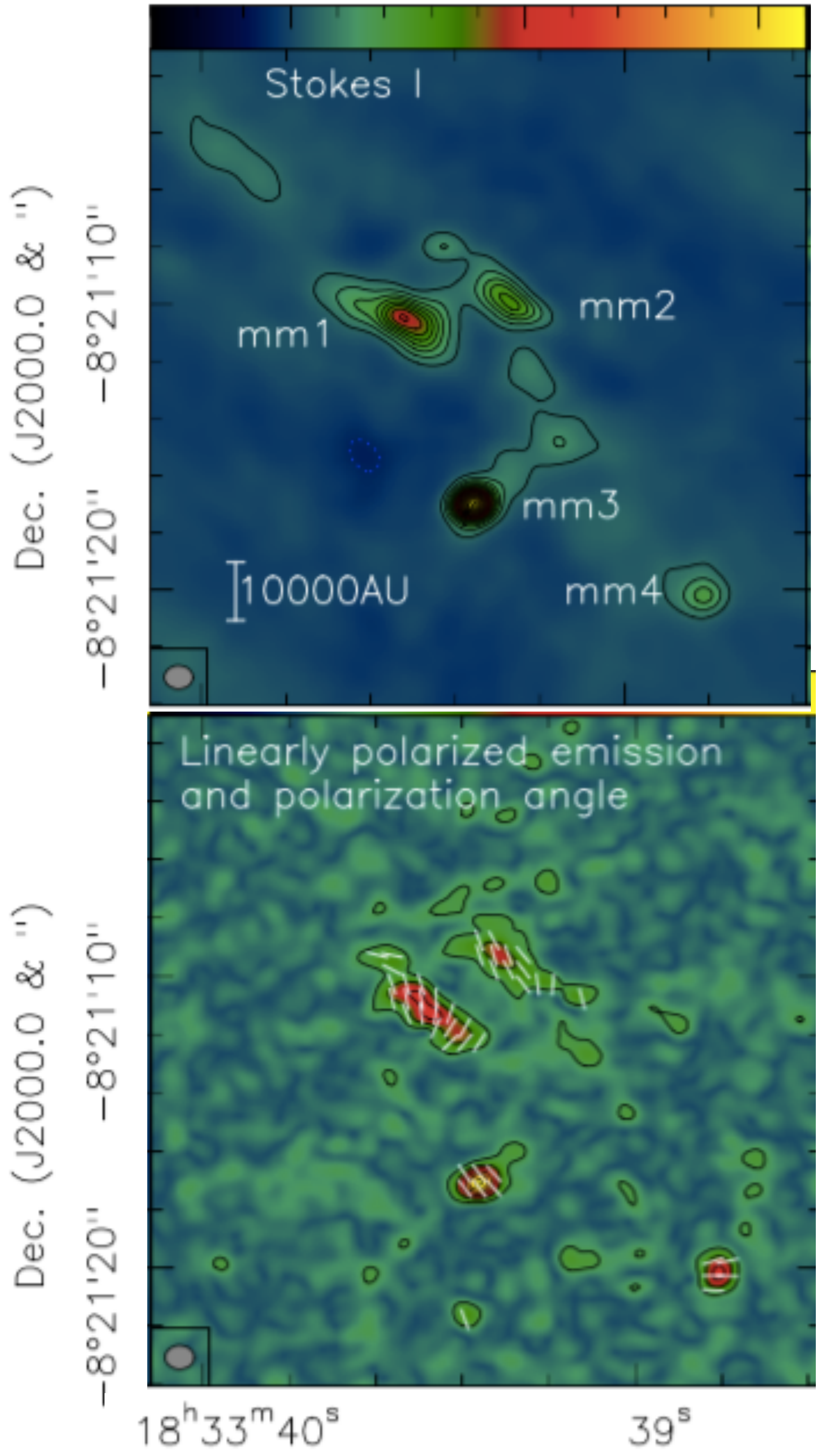


small scales ~ 100-1000 AU

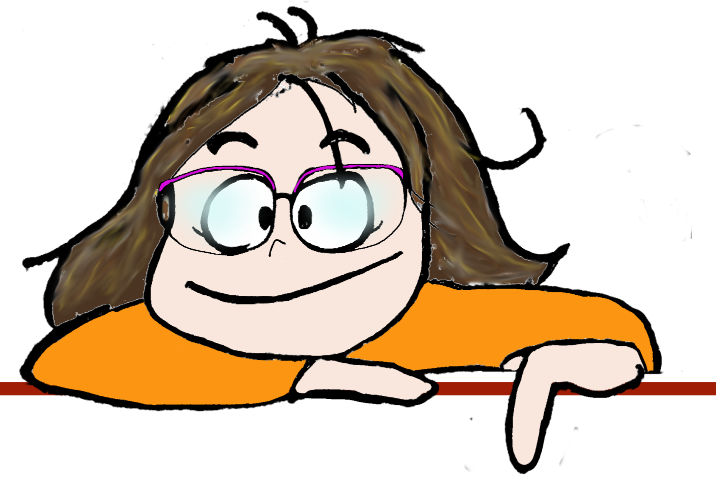


Beuther et al. 2018

IRDC18310-4 ALMA band 7



large scales ~ 1000 AU - parsec



Is the maser field morphology related to the large scale field?

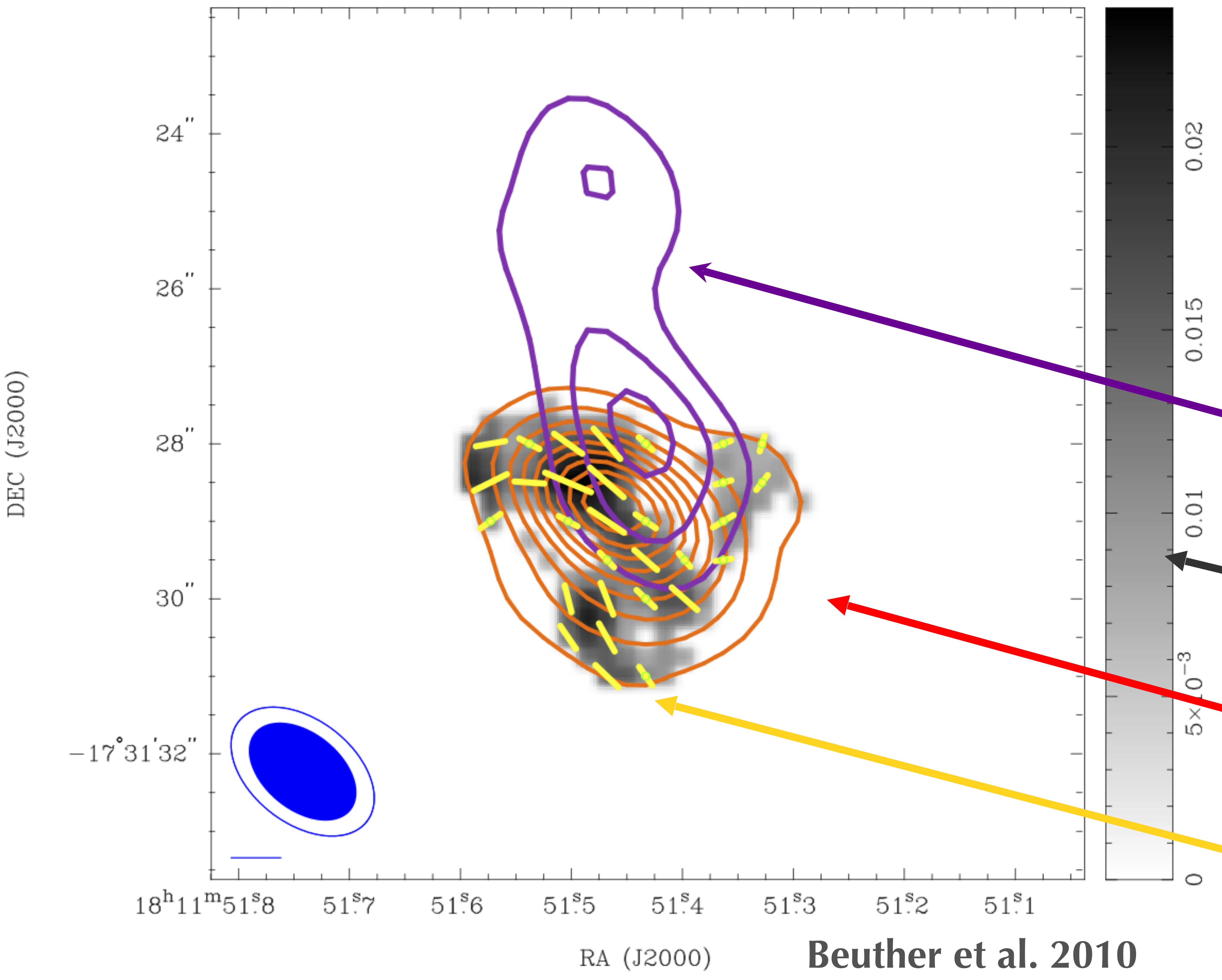
The case of IRAS 18089-1732

L ~ 1.3x10⁴ L⊙

Hot core

d ~ 2.34 kpc

M ~ 1000 M⊙



Beuther et al. 2010

SiO(8-7) outflow

Linearly polarised 880 μm continuum image

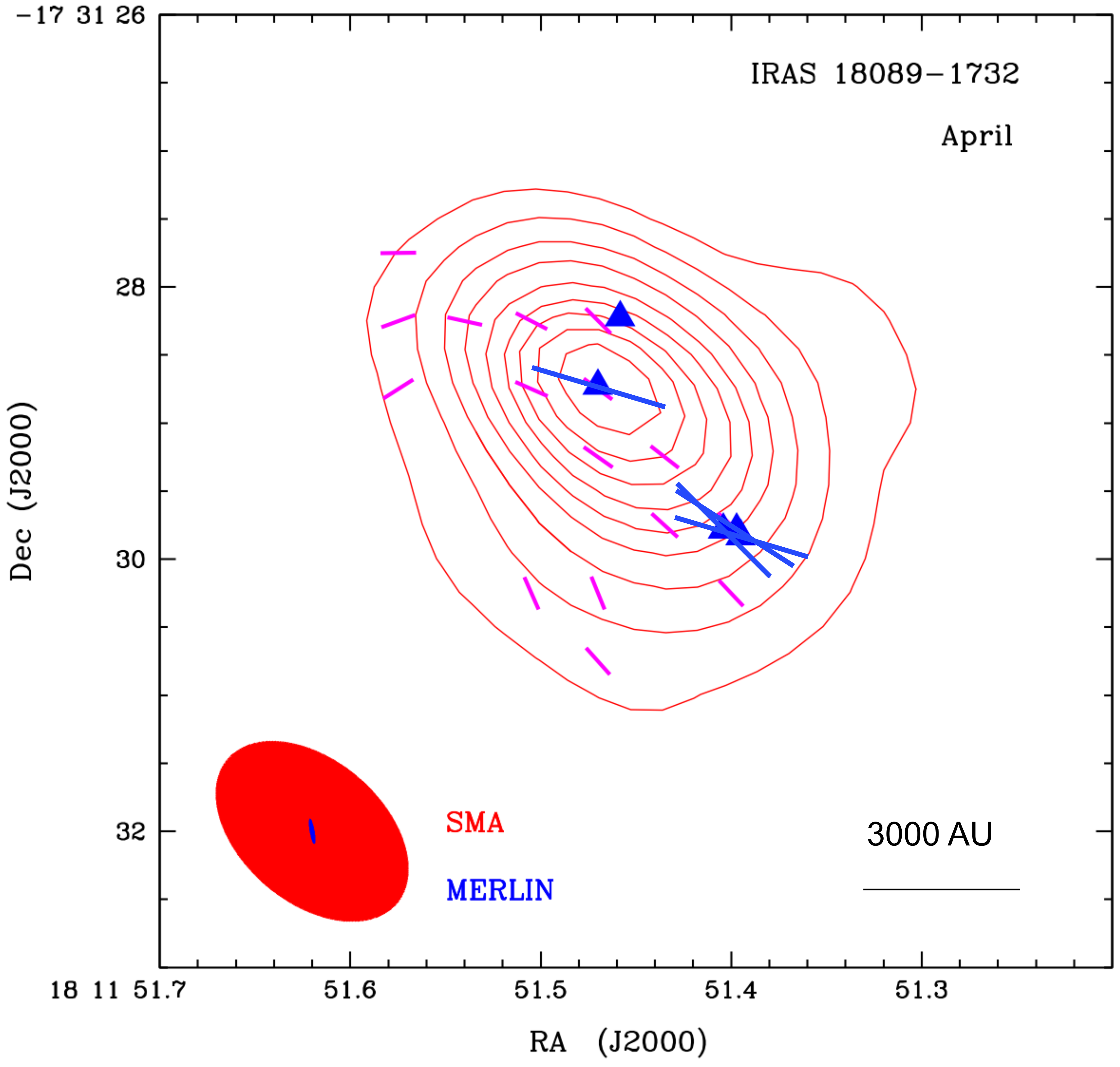
continuum

segments mark magnetic field direction

Our results

Small-scale magnetic field probed by masers is consistent with the large-scale magnetic field traced by dust

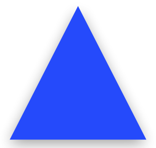
Methanol masers
6.7 GHz



Dall'Olio et al. 2017

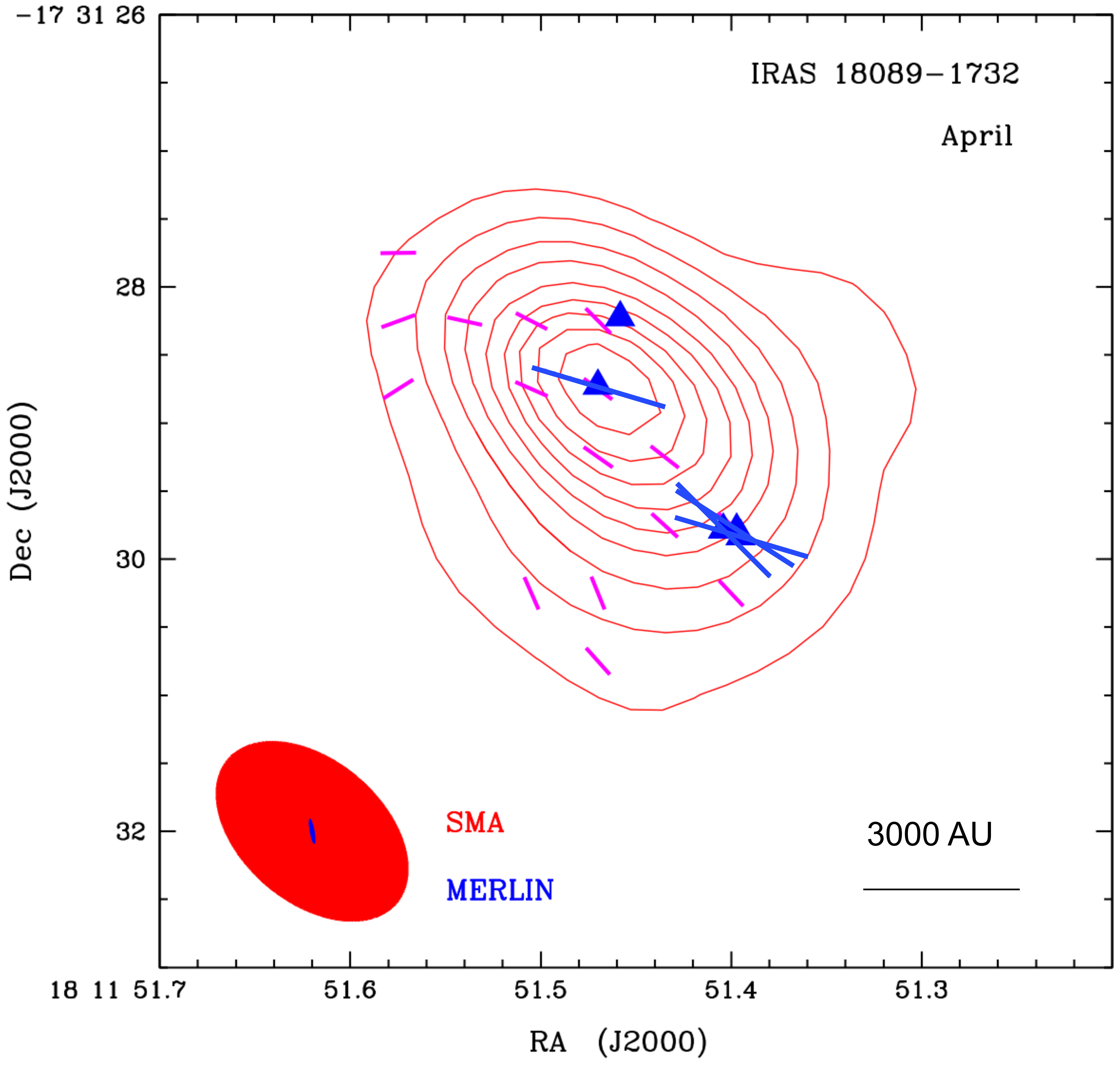
Our results

Small-scale magnetic field probed by masers is consistent with the large-scale magnetic field traced by dust



Methanol masers
6.7 GHz

The magnetic field structure stays constant over many orders of magnitude in scales !



Dall'Olio et al. 2017

Our results

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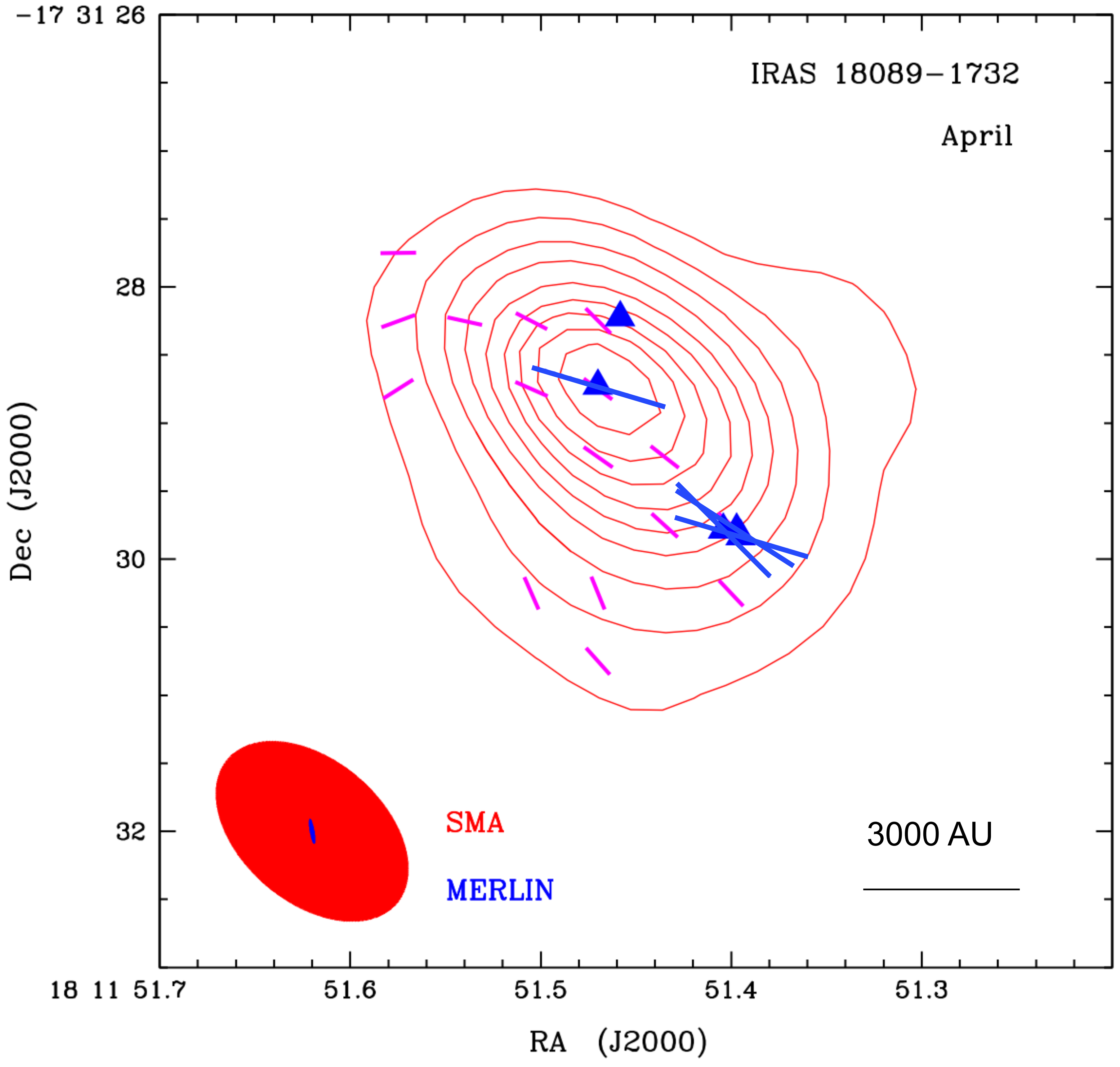
Methanol masers
6.7 GHz



The magnetic field structure stays constant over many orders of magnitude in scales !

B_{LOS} ~ 5.5 mG masers
B_{POS} ~ 11 mG dust

Dall'Olio et al. 2017

The case of G9.62+0.20

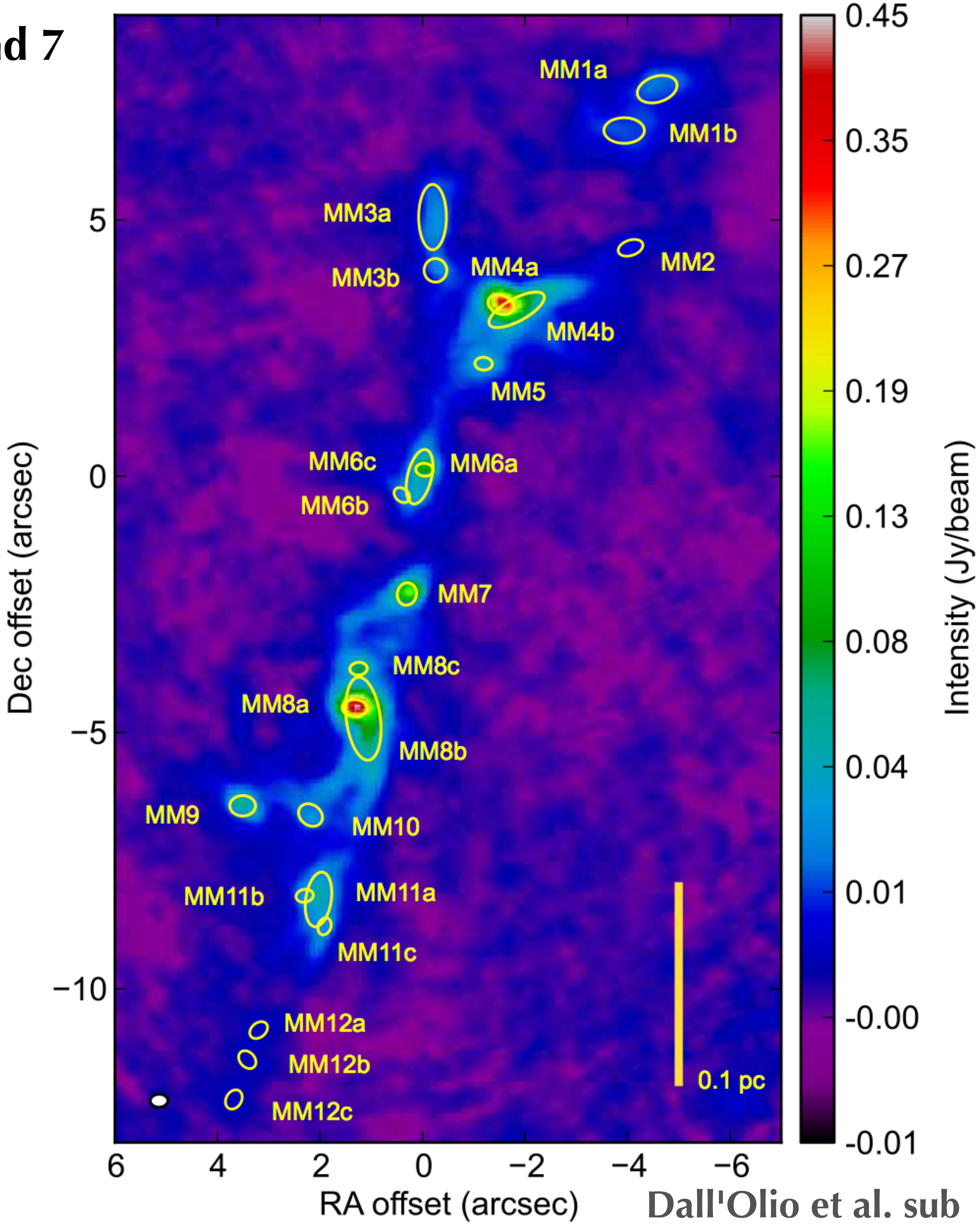
Several cores
at different evolutionary stages

ALMA band 6

- MM3
  starless core
- MM8 youngest HC
  CO and SiO outflow
- MM4 oldest HC
  no outflow

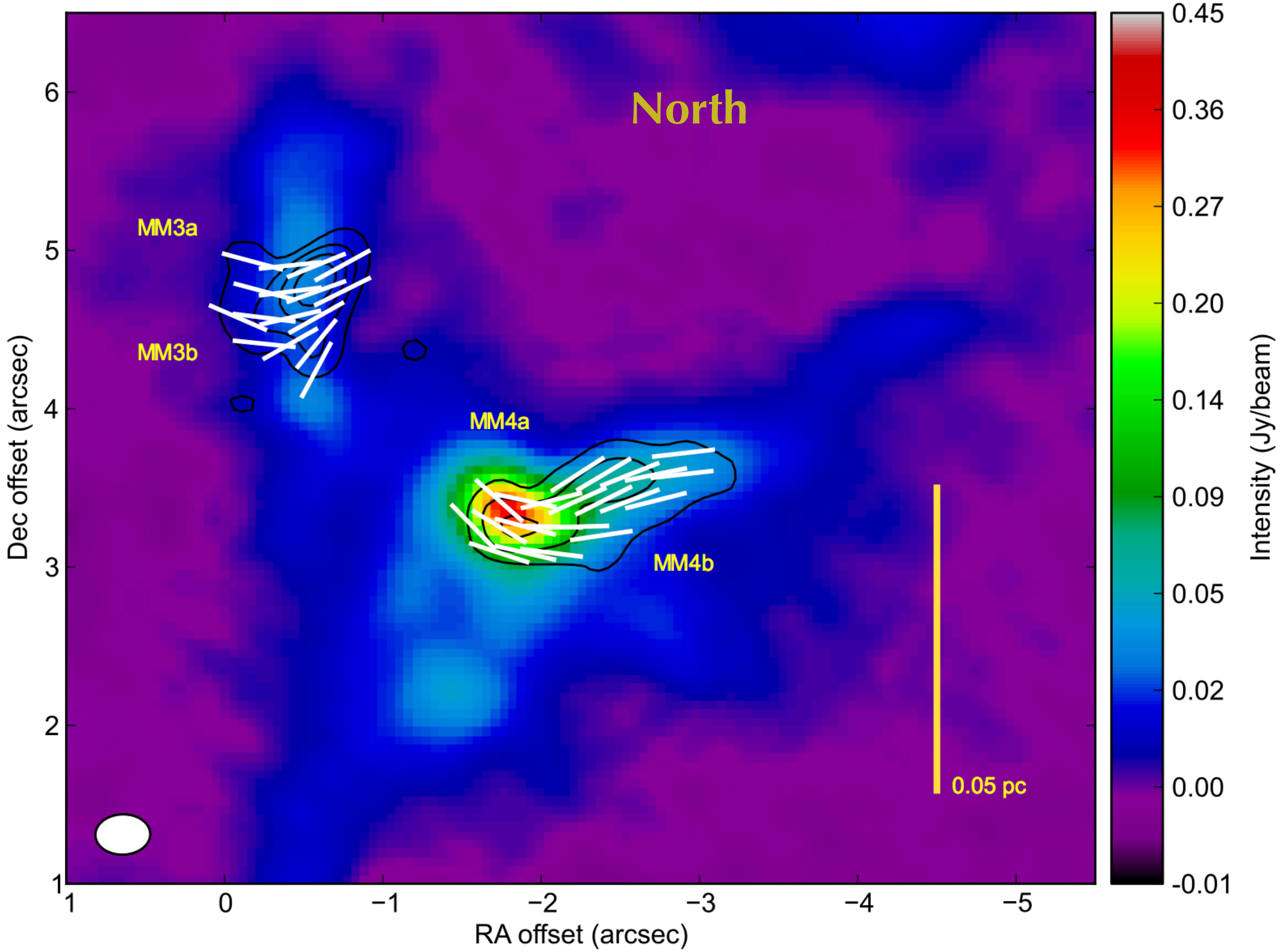
Liu et al. 2017

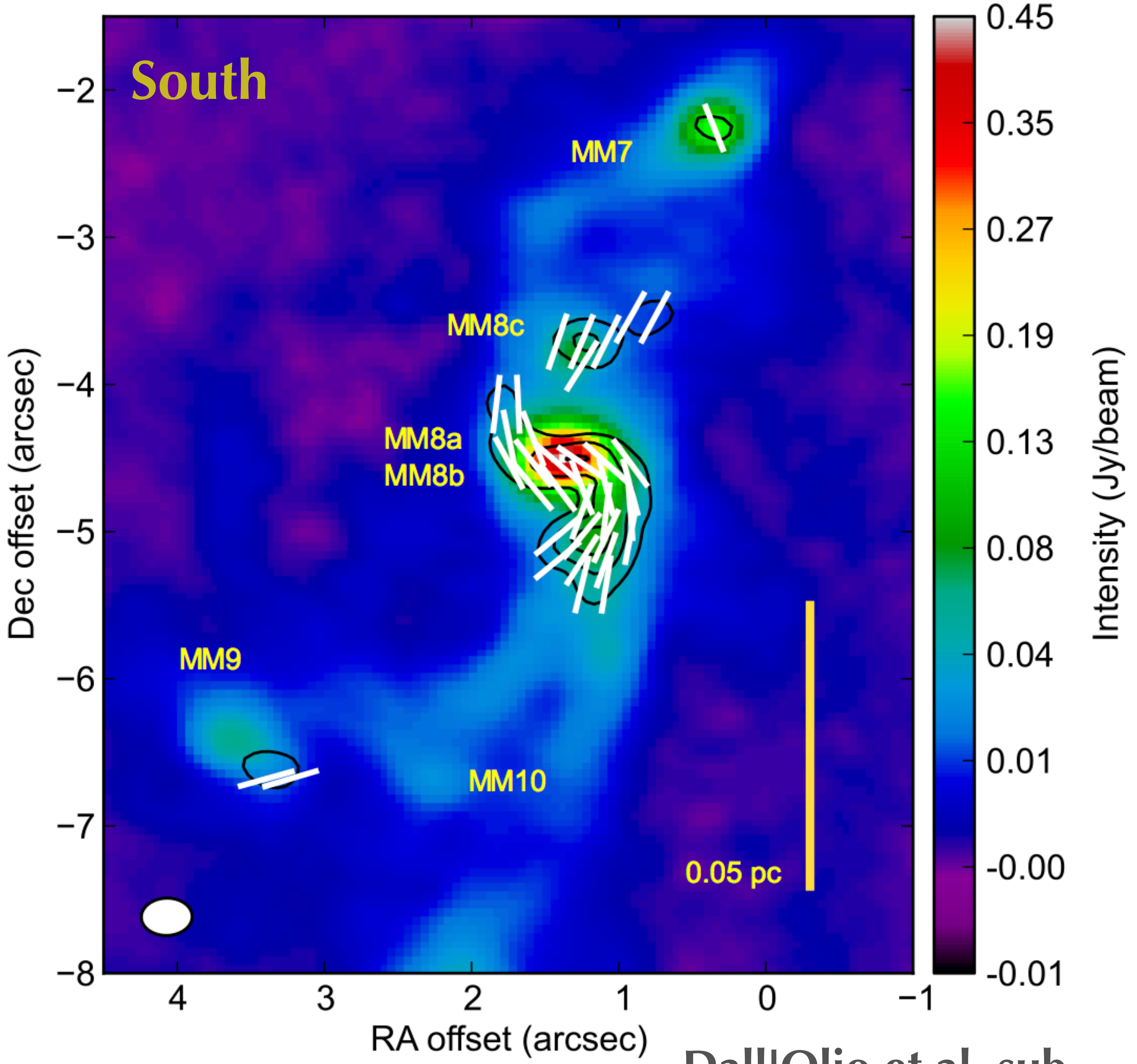
ALMA Band 7



Dall'Olio et al. sub

Our results



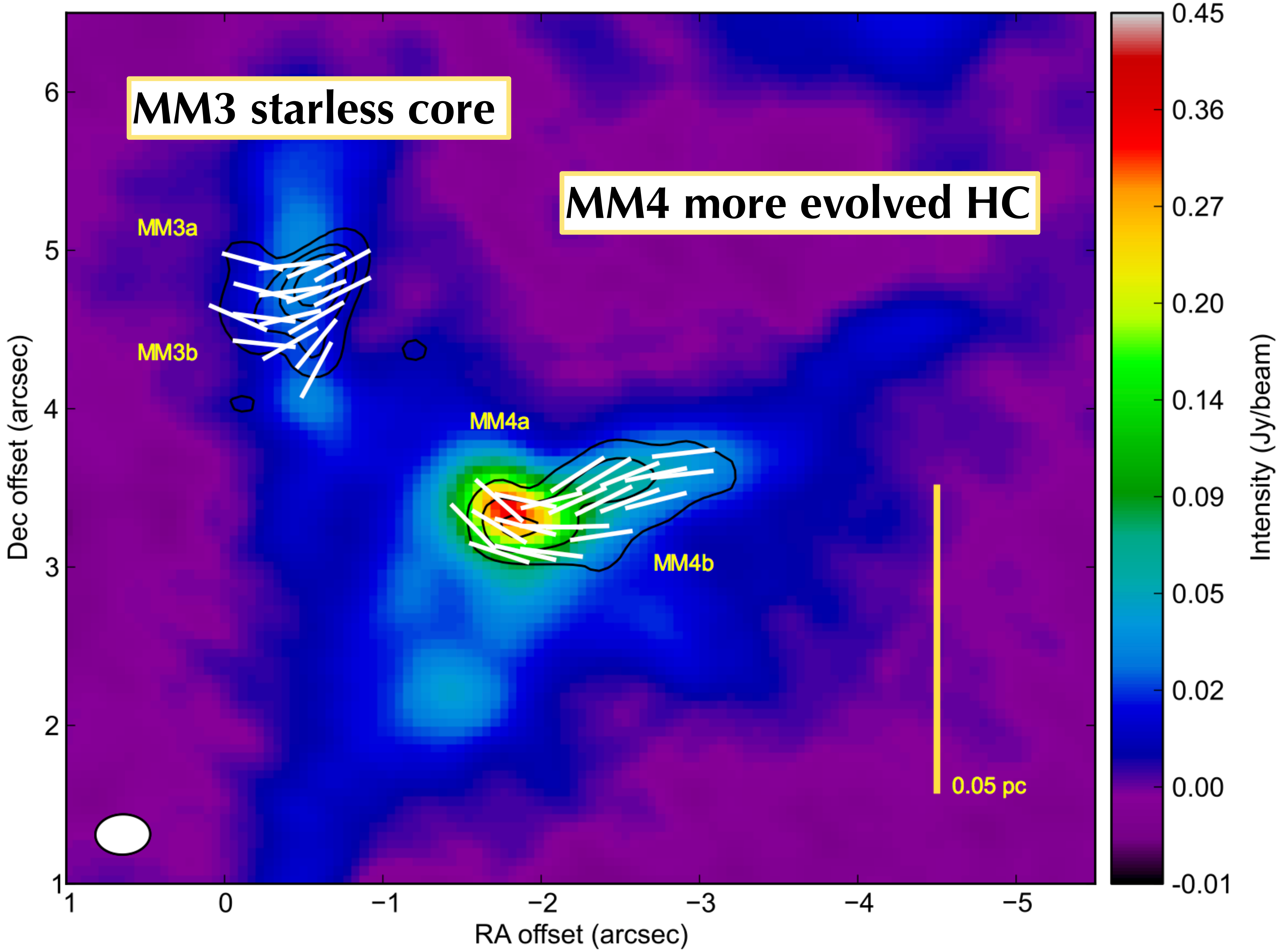


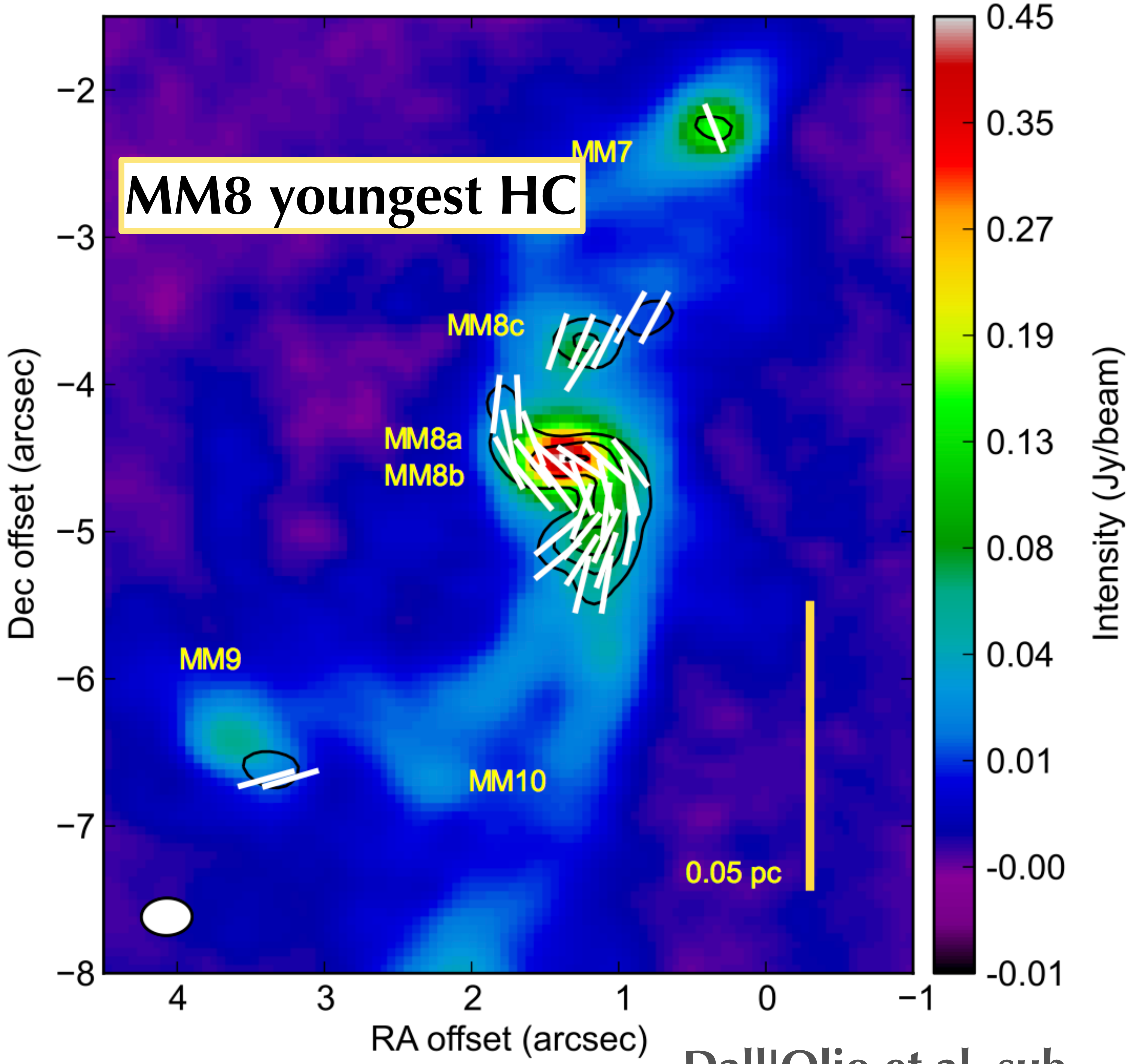
Dall'Olio et al. sub

Contours POLI : 0.6, 1.1, 1.7, 2.2 mJy/beam

Our results

Evolutionary sequence of the magnetic field morphology and strength





Dall'Olio et al. sub

Our results

Evolutionary sequence of the magnetic field morphology and strength

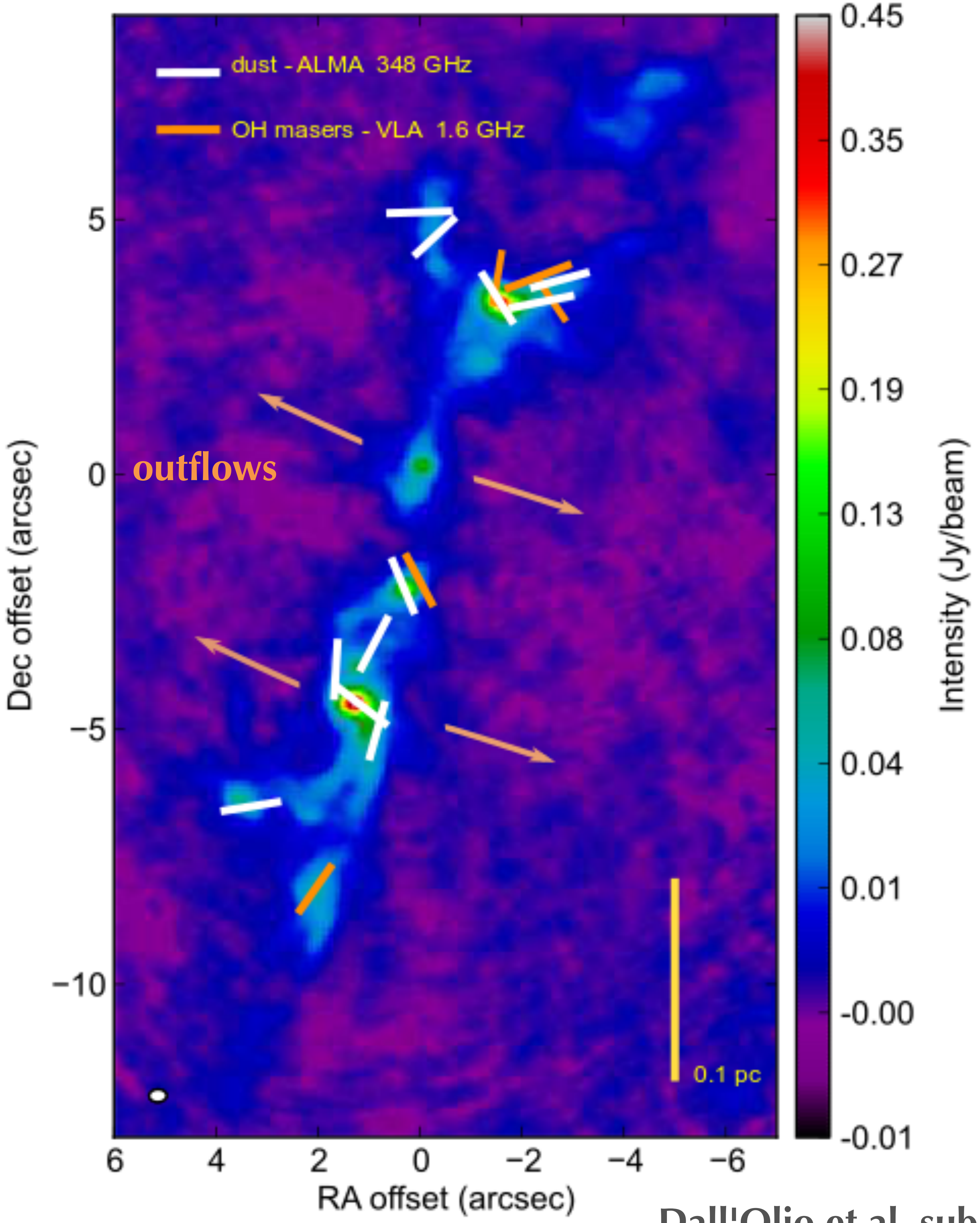
Dall'Olio et al. sub

Our results

Comparing dust and masers

- **Magnetic field morphology: 1.6 GHz OH masers (Fish et al. 2005)**

on average
B probed by masers and B probed by dust are aligned



Dall'Olio et al. sub

Our results

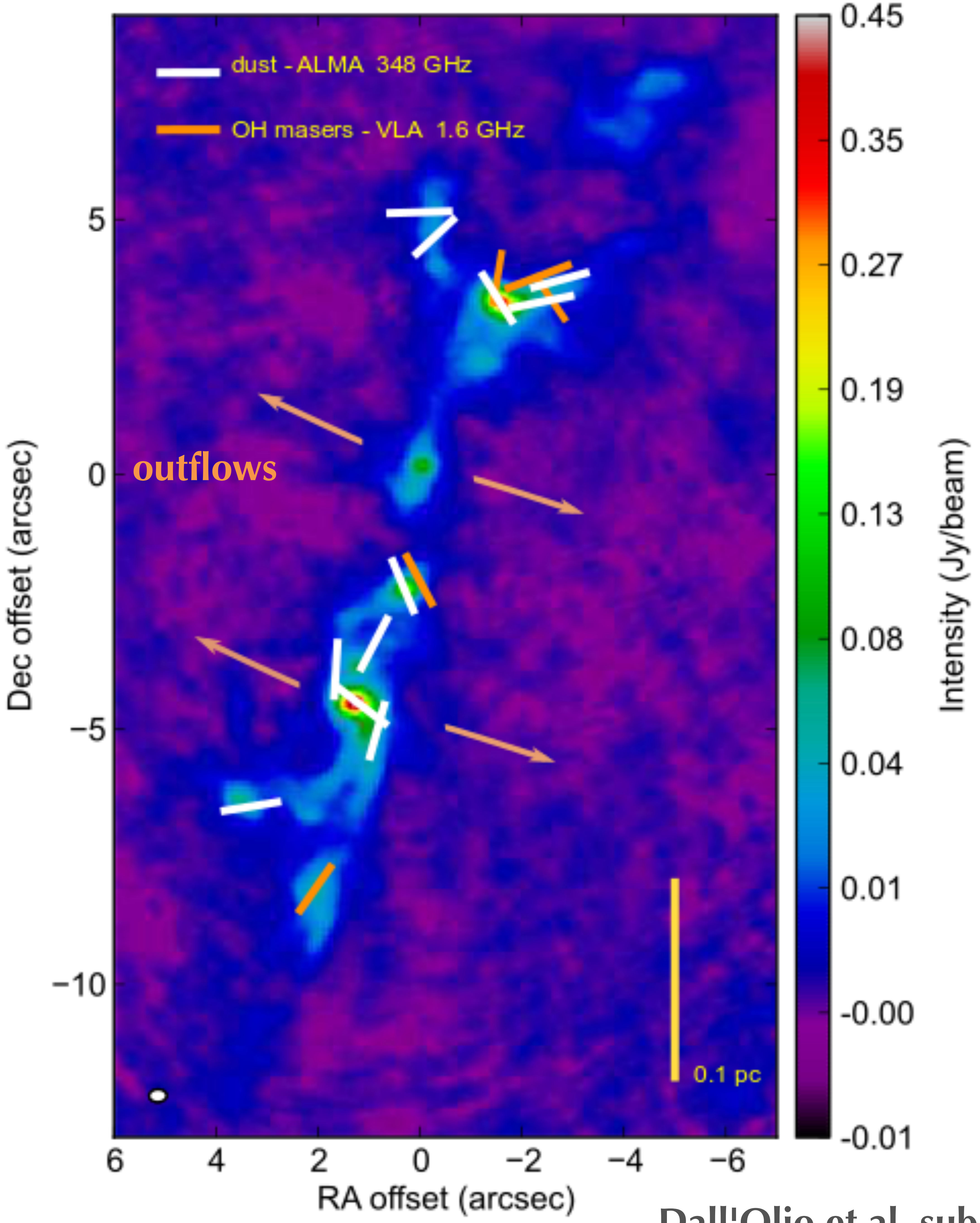
Comparing dust and masers

- **Magnetic field morphology:**
  1.6 GHz OH masers
  (Fish et al. 2005)

on average
B probed by masers and B probed by dust are aligned

- **Magnetic field strength:**
  6.7 GHz methanol masers ~10 mG
  (Vlemmings et al. 2008)

on average
B probed by masers and B probed by dust are consistent



Dall'Olio et al. sub

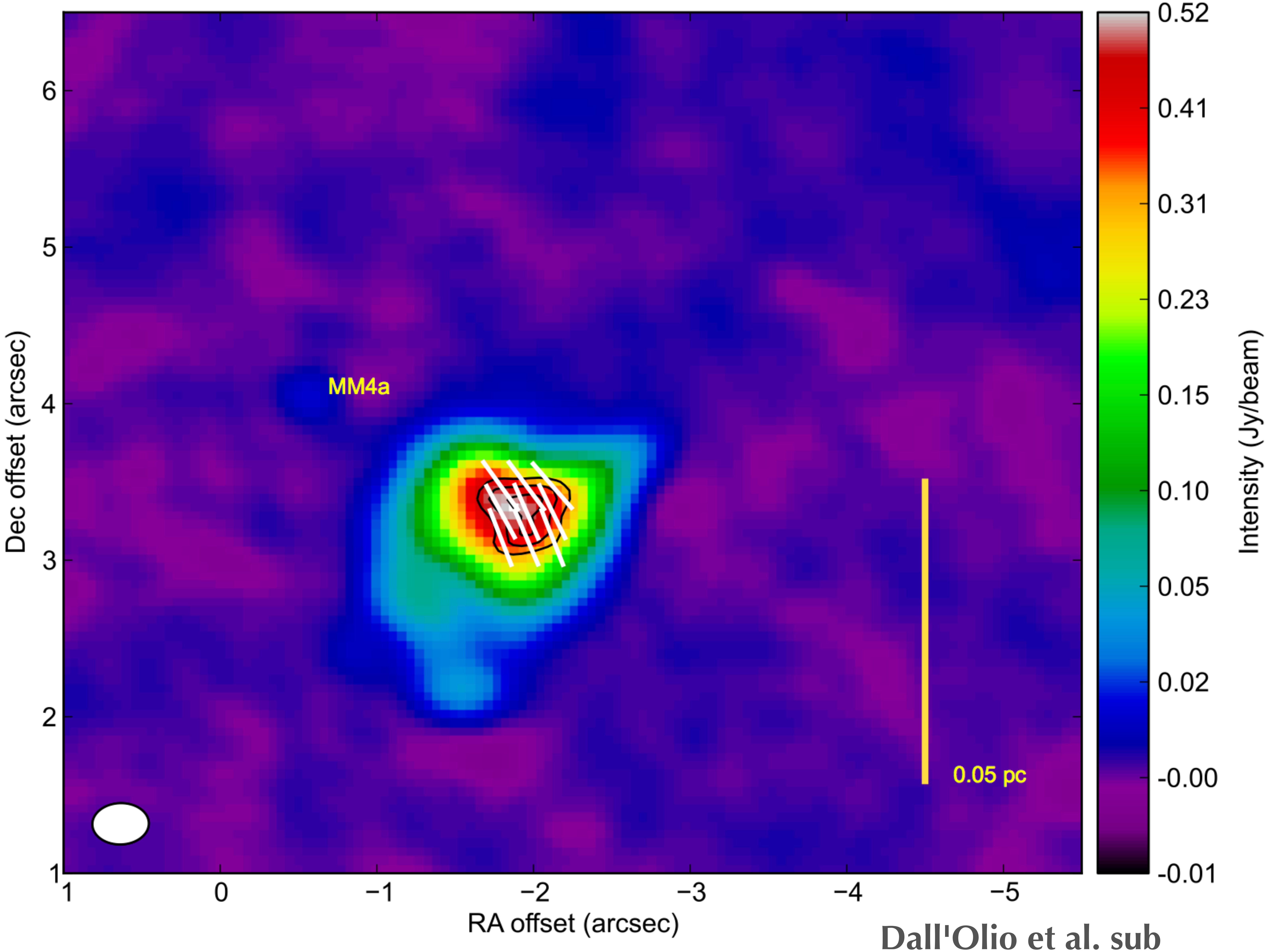
…and what about the extra?

Our results

Thermal line polarization

Probably CH_3OH or SO_2

Contours POLI : 1.4, 1.9, 2.3 mJy/beam



Dall'Olio et al. sub

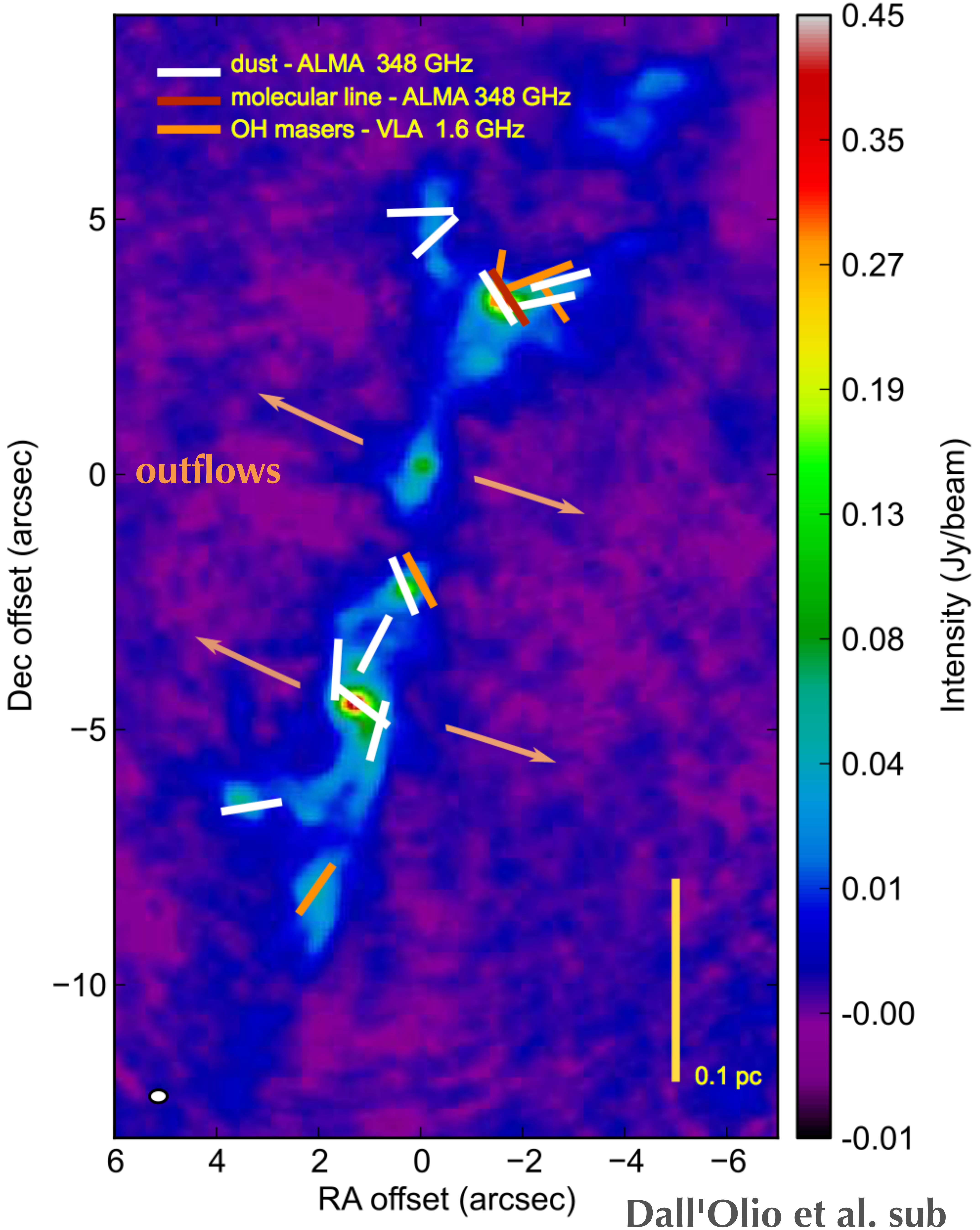
Our results

Comparing dust, masers and thermal line polarization

Magnetic field morphology:

- 1.6 GHz OH masers (Fish et al. 2005)
- 348 GHz dust
- 348 GHz methanol or sulfur dioxide line

on average
B probed by masers, by dust and thermal molecular lines seems to be aligned



Dall'Olio et al. sub

Future work

Accepted!

- ALMA proposal on massive protostar IRAS 18089

  Study 3D morphology of B by looking for thermal line polarization
  and Goldreich-Kylafis effect

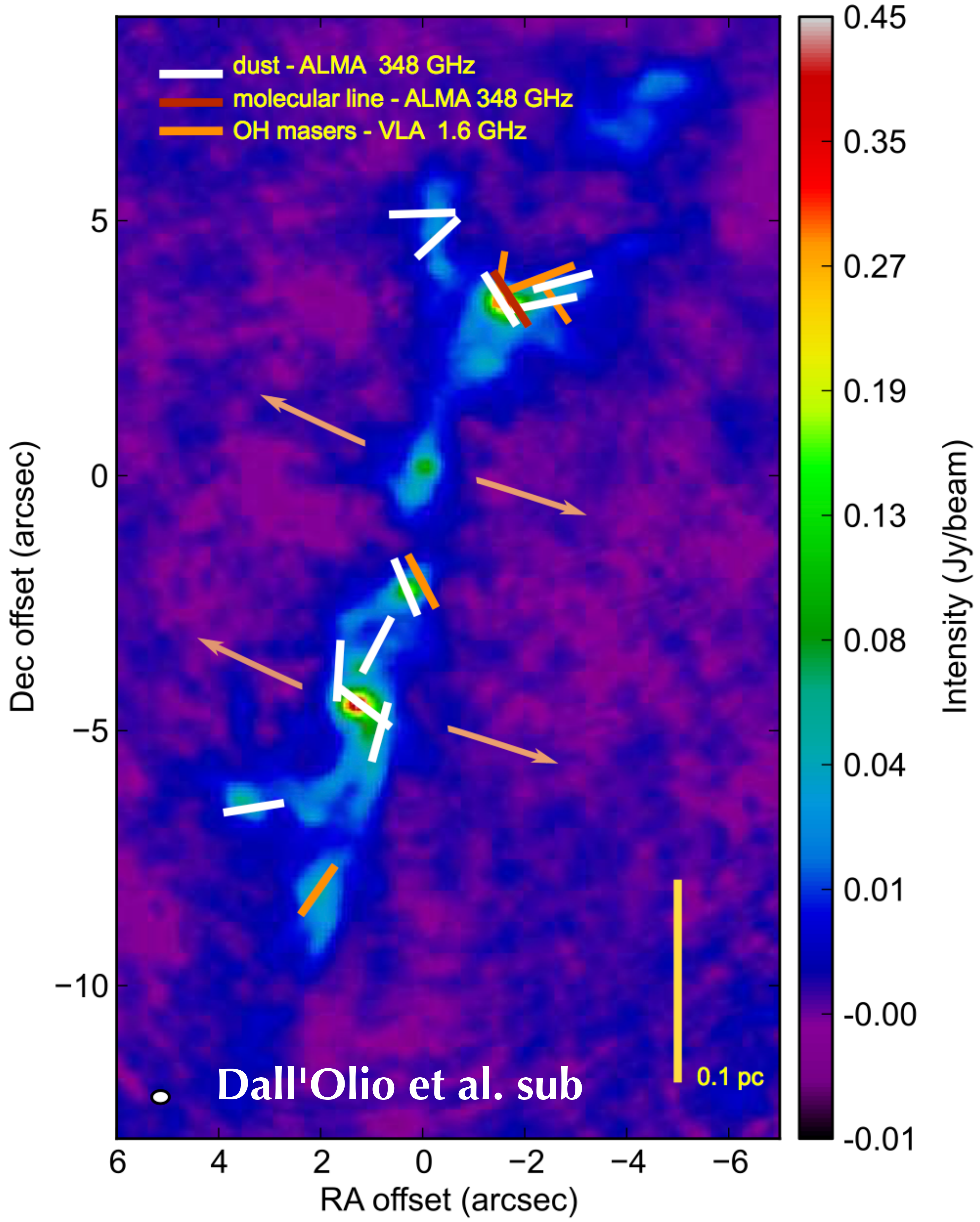
- e-MERLIN Legacy Project "Feedback process in MSF"

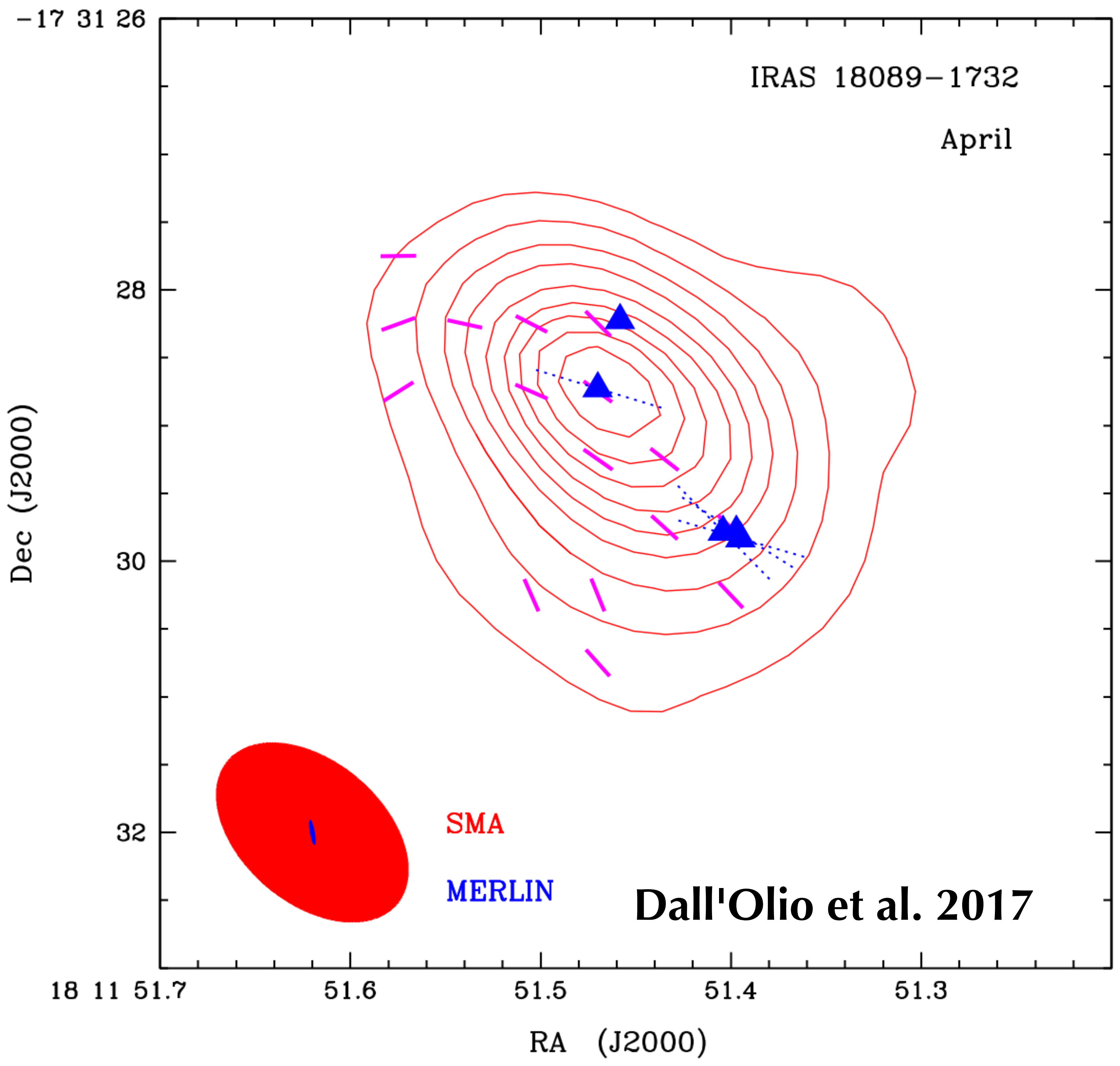
  Study a large sample of massive protostars at different evolutionary stages

  masers   (6.7 GHz methanol)

Conclusion

Small-scale magnetic field probed by masers is consistent with the large-scale magnetic field traced by dust.





Combine masers, dust and thermal line polarization observations is fundamental to understand magnetic field morphology.

Synergies between several instruments are fundamental!

Backup slides

How to probe the magnetic field methods

1) Masers	Linear and circular polarisation Zeeman effect	B_{LOS} B
2) Dust	Linearly polarised continuum emission Davis-Chandrasekar-Fermi Method (DCF) Structure Function (SF)	B_{POS}
3) Molecular lines	Linear polarisation Goldreich-Kylafis effect	

Crutcher 2012 A&A Annual Rev.

Background magnetic fields

The ISM is magnetised

Cores (white)

VS

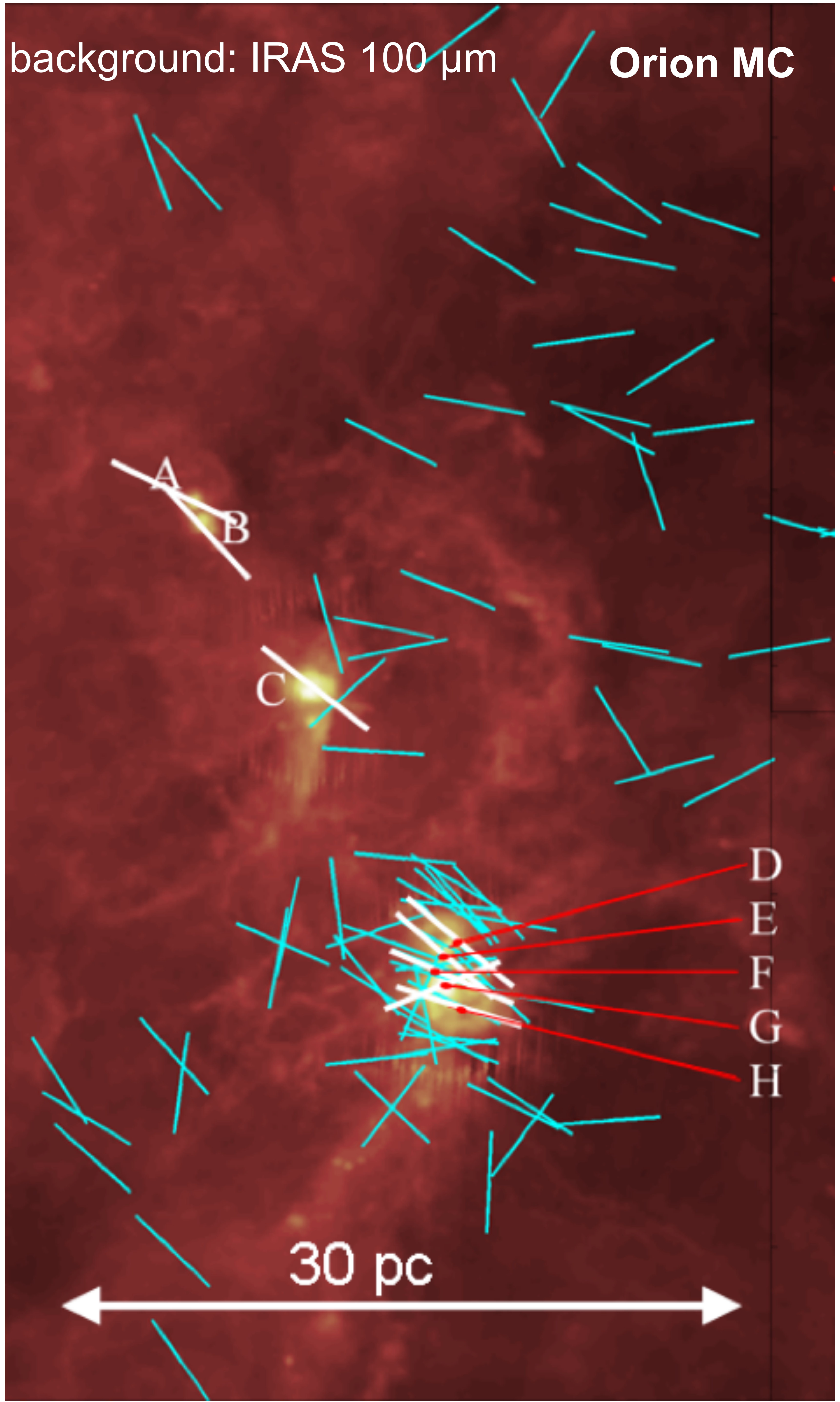
diffuse gas (cyan)

Correlation!

between the B field direction
in the cores and
in the surrounding more diffuse gas

Li et al., 2009

Caltech Submillimeter Observatory (pol. Dust)

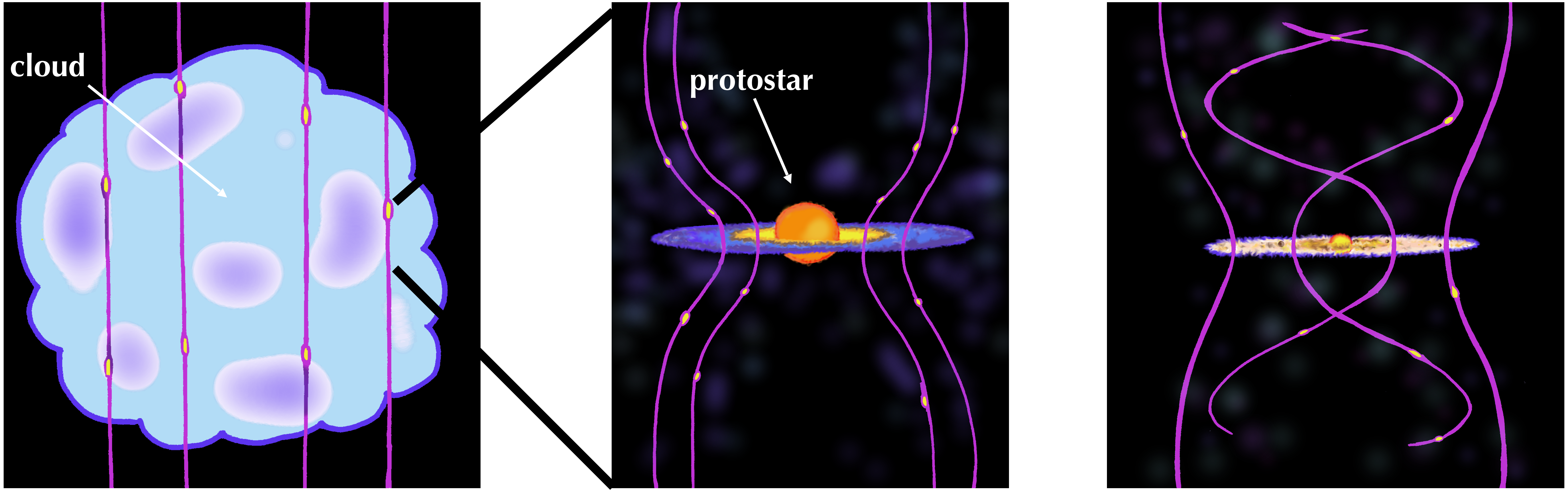


Background

magnetic fields

few parsec

0.01—0.05 pc



B lines across the ISM

B lines drift
during the collapse

B lines distortion due to
the rotation of the disc

Krumholz et al. 2013, Tan et al. 2014, Li et al. 2014, Machida et al. 2014, Seifried et al. 2015, Zhao et al. 2016

How to probe the magnetic field — methods

3) Circular polarisation

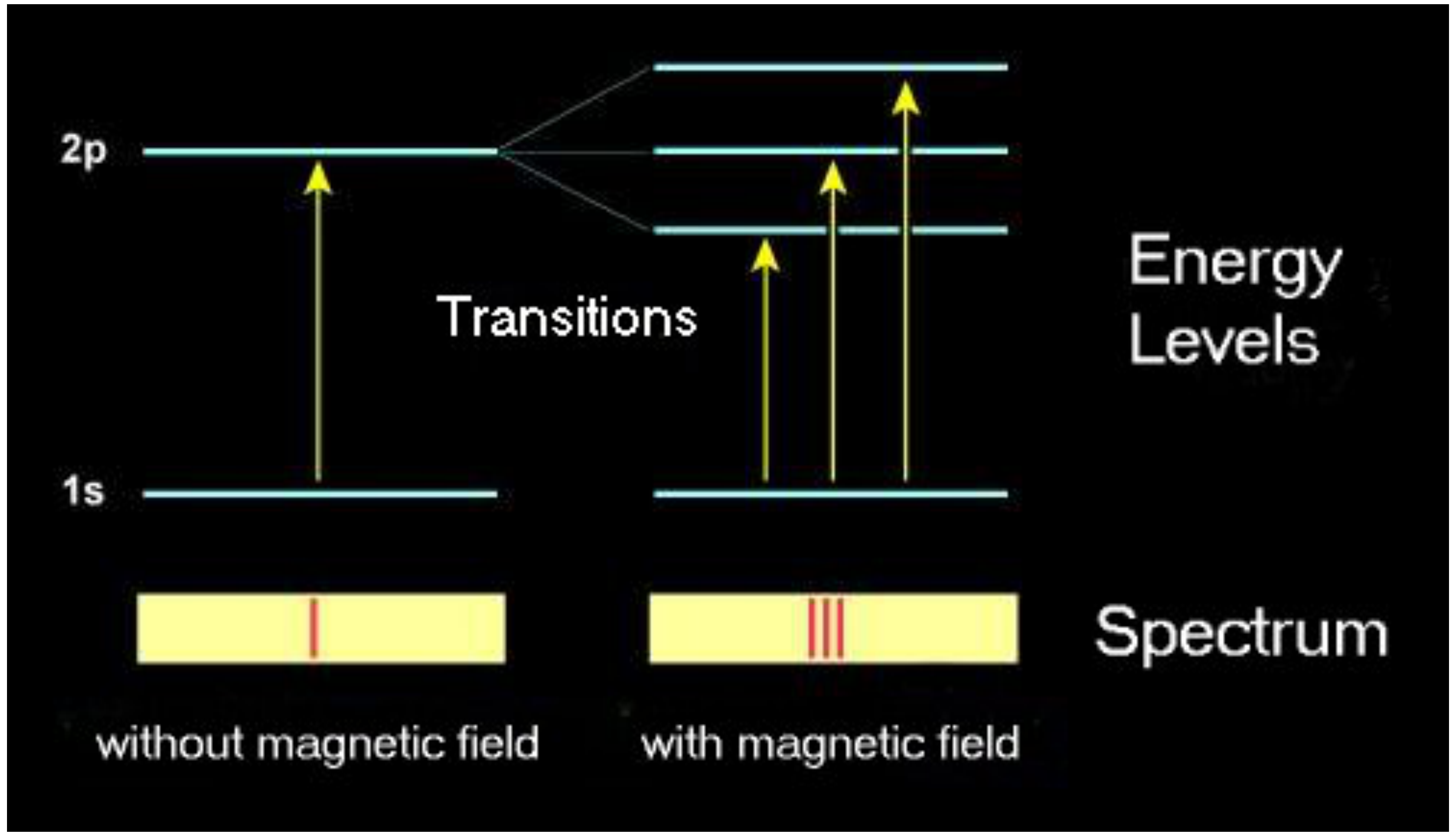
Zeeman splitting

$\Delta\nu_z = z \ |\mathbf{B}|$

z = Zeeman Coefficient

Depends on the transition and on the molecule

frequency shifts between right and left circularly polarised components



Difficult !!!

$\Delta\nu_z \ll \delta\nu$

How to probe the magnetic field
methods

3) Circular polarisation

The observed V spectrum is a sin-shaped function, corresponding to the derivative of I
(Troland & Heiles, 1982)

$$V = aI + b\, dI/d\nu$$

a
$b = z\, B \cos\theta$

θ = angle between the magnetic field and the line of sight

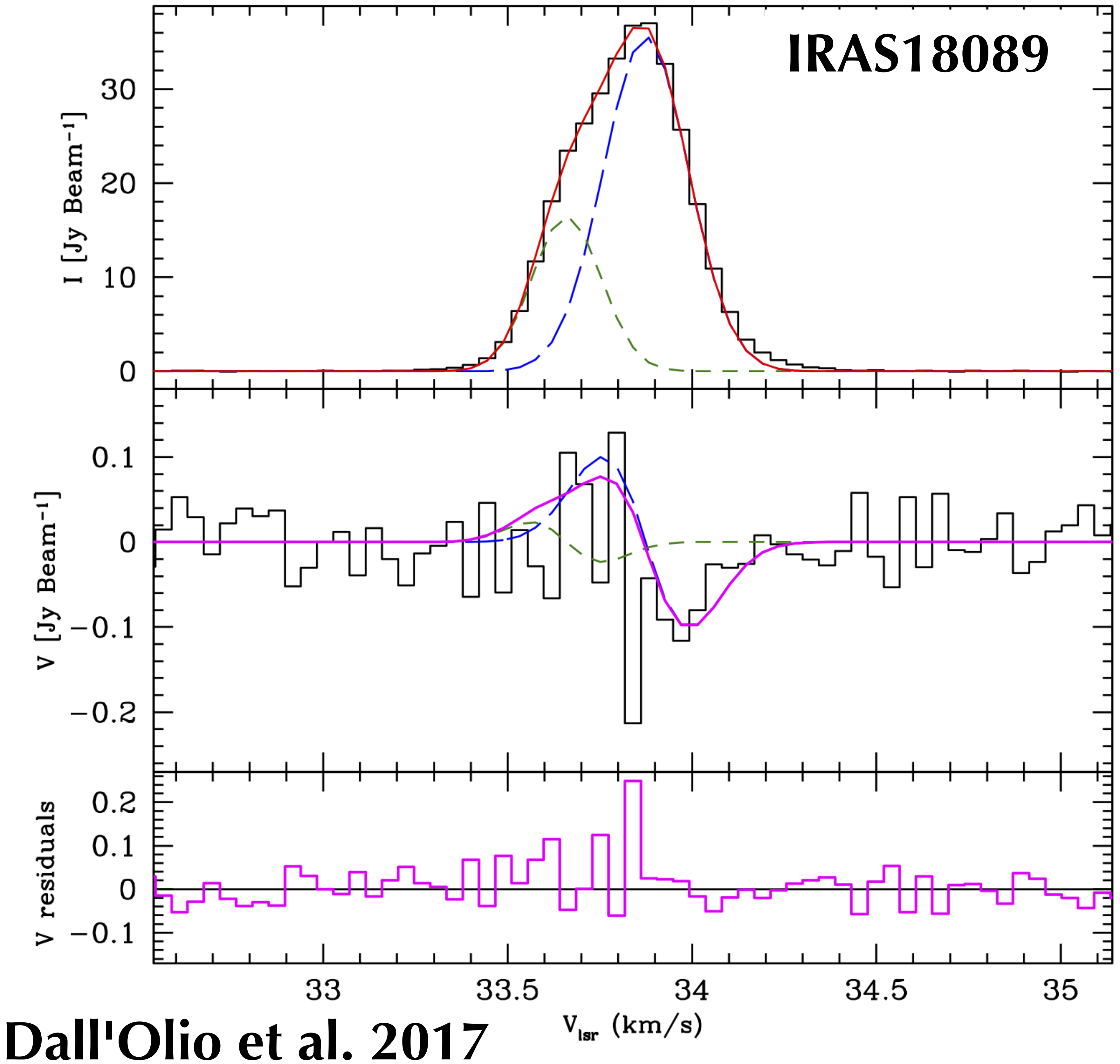
$B_{LOS} = B \cos\theta$

z = Zeeman splitting coefficient

Masers

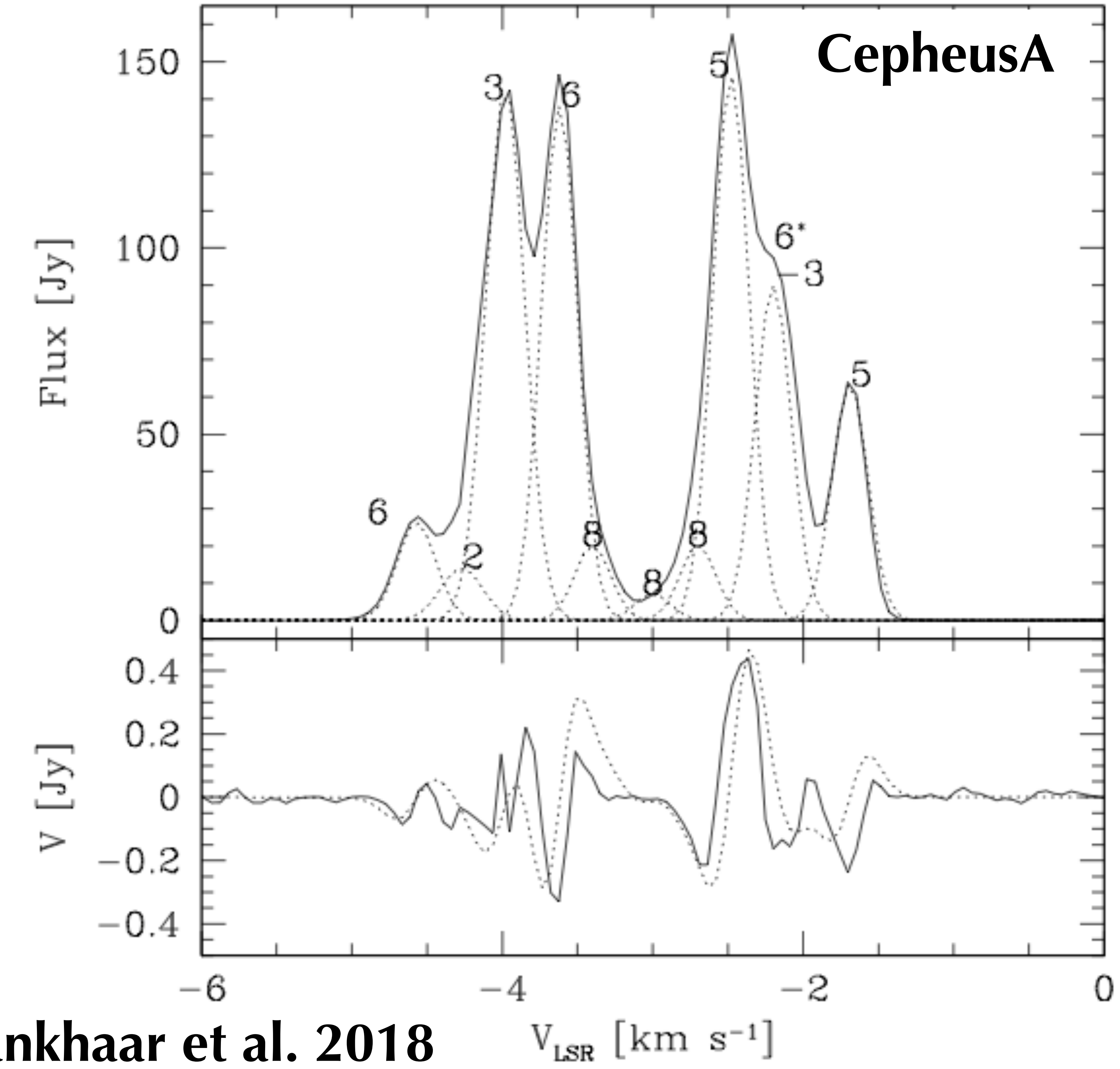
6.7 GHz
Methanol

2 hyperfine components



Dall'Olio et al. 2017

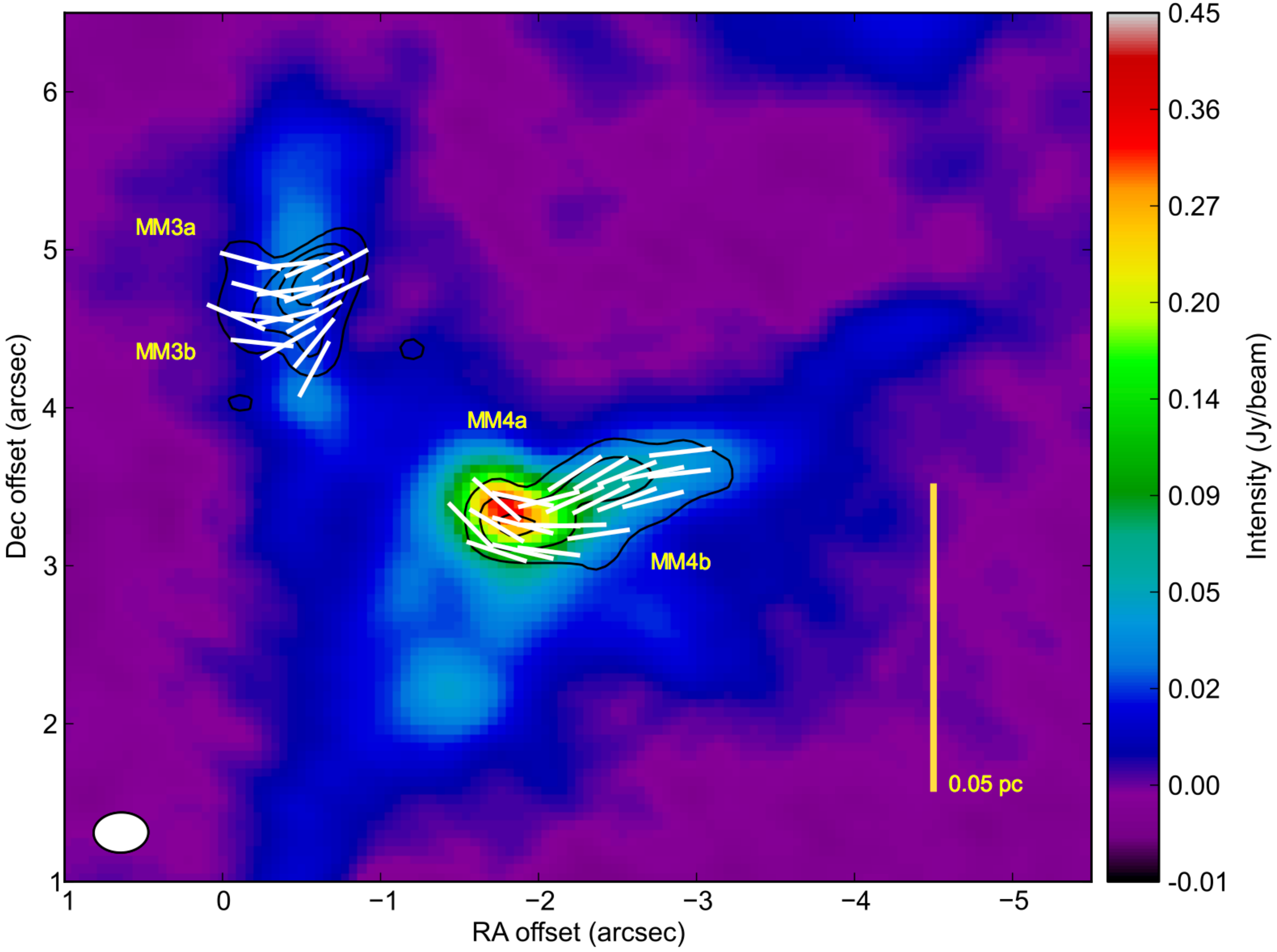
several components



Lankhaar et al. 2018

Dust

G9.62
ALMA band 7

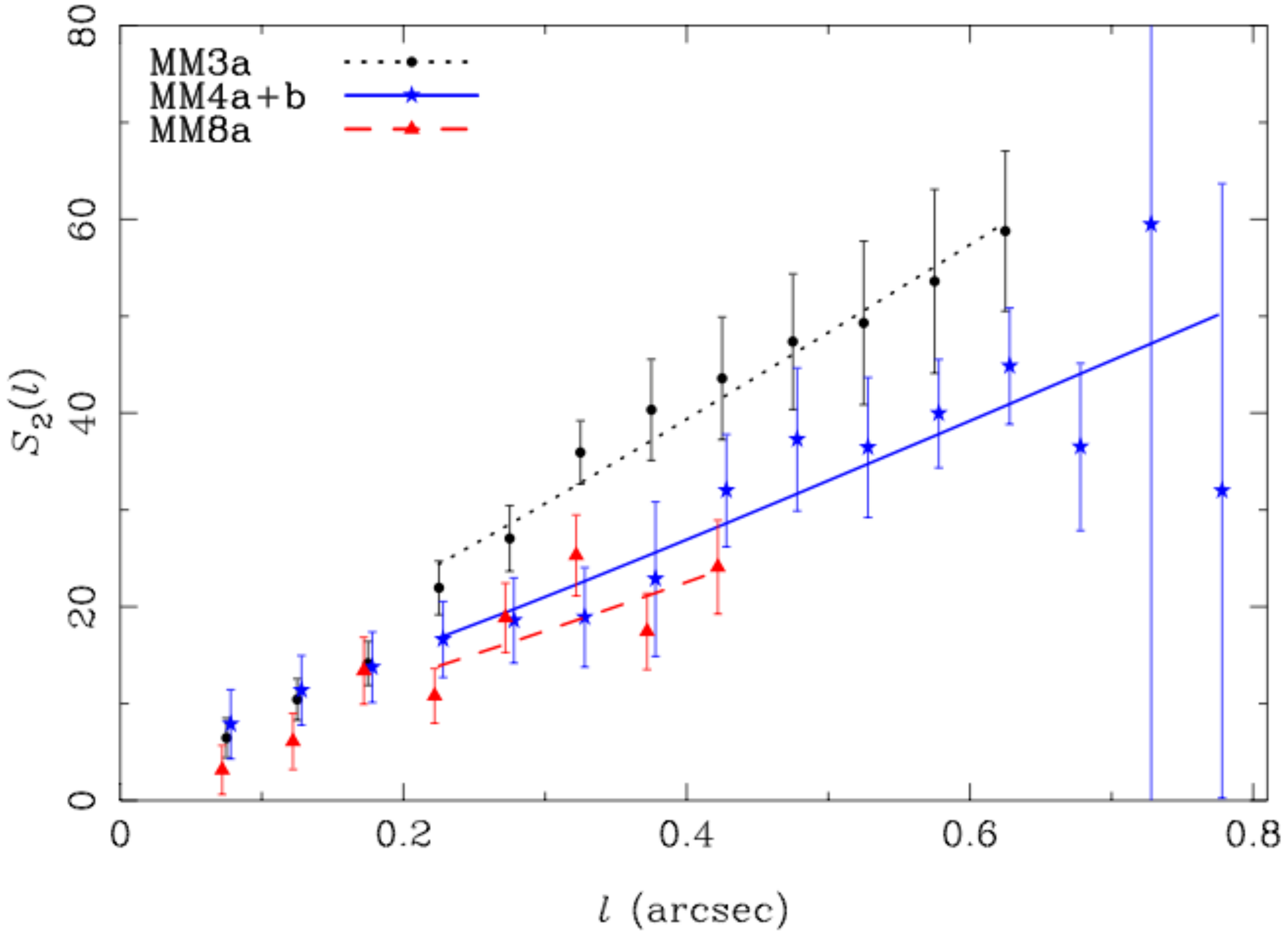


Davis Chandrasekhar Fermi method

$$B_{\perp}^{\mathrm{DCF}} = \xi \sqrt{4\pi\rho} \frac{\sigma_{\nu}}{\sigma_{\psi}}$$

Structure Function method

$$B_{\perp}^{\mathrm{SF}} = \sqrt{8\pi\rho} \frac{\sigma_{\nu}}{b}$$



Our results

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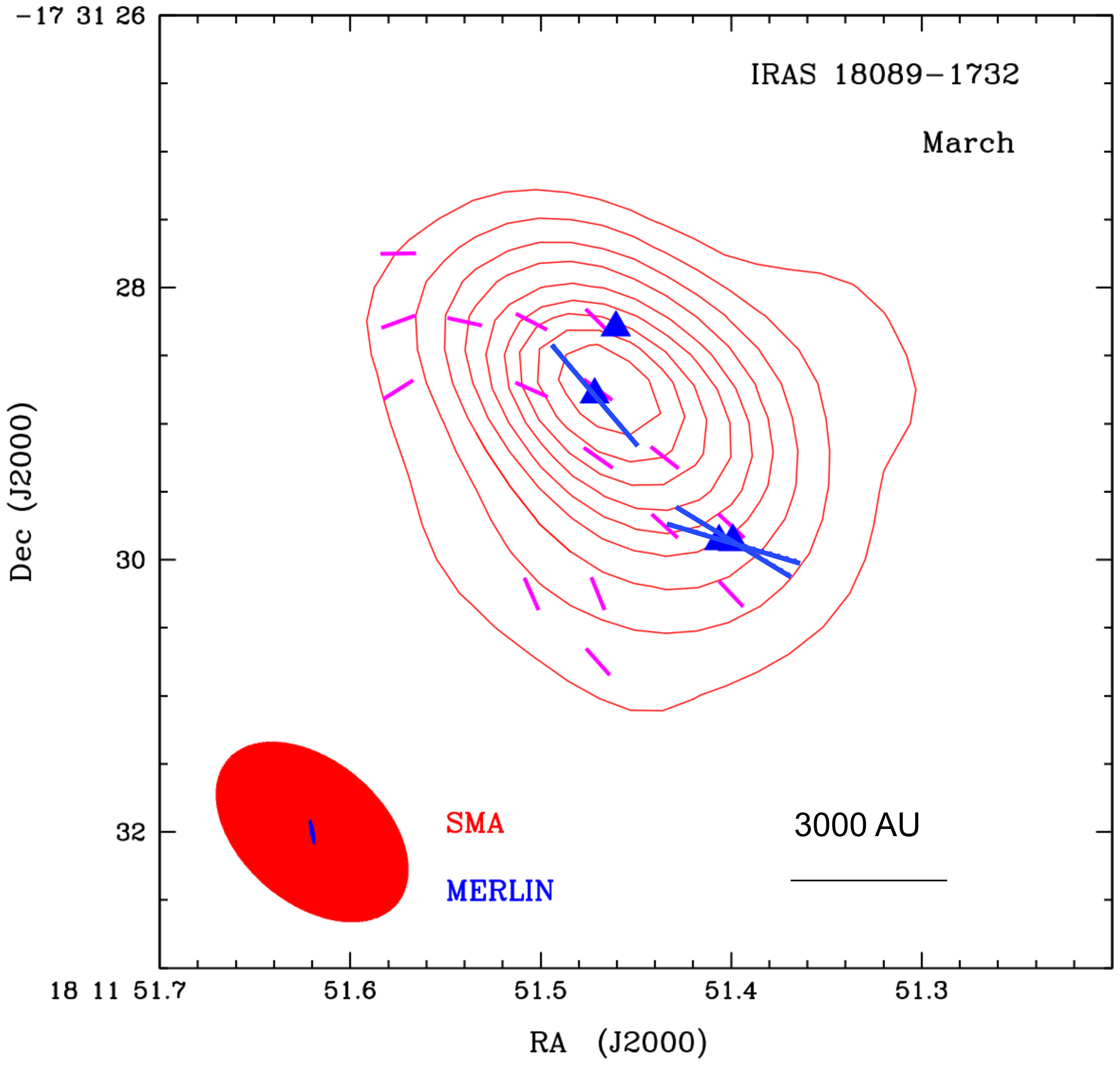
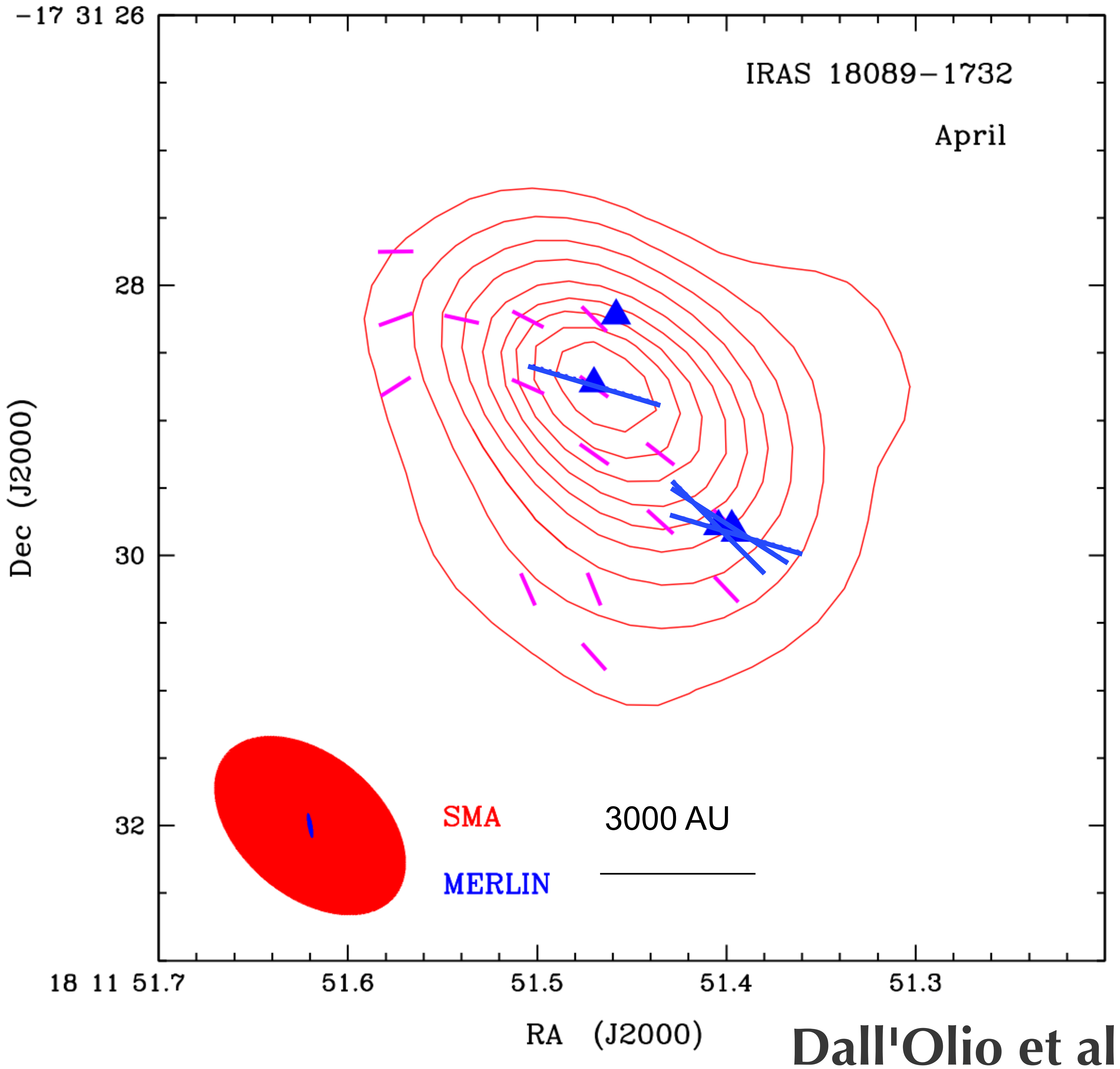


Methanol masers 6.7 GHz

Two epochs



Dall'Olio et al. 2017

B_{LOS} ~ 5.5 mG masers
B_{POS} ~ 11 mG dust

How to probe the magnetic field methods

1) Polarised continuum emission by dust

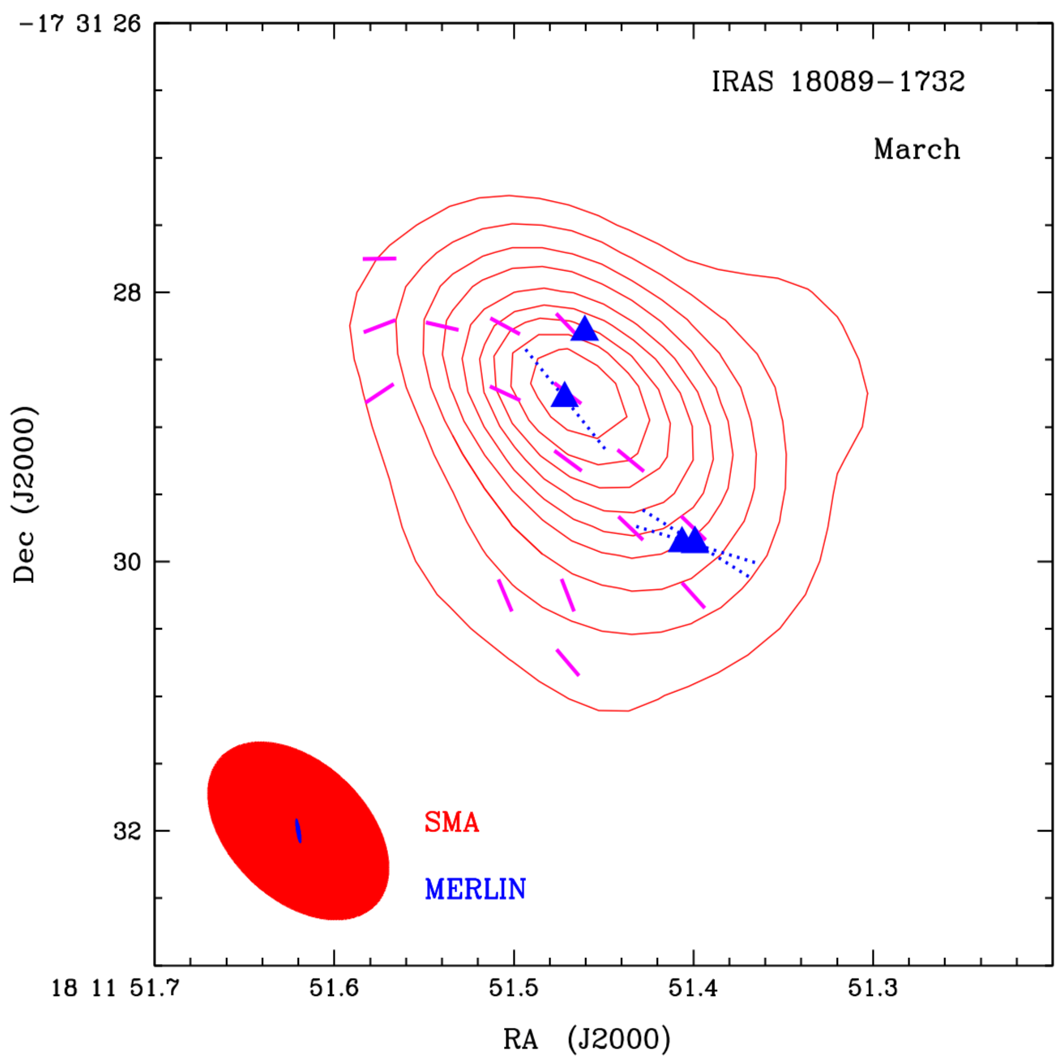
2) Linear polarisation of molecular rotational emission lines

} B_{POS}

Goldreich-Kylafis effect

3) Circular polarisation } B B_{LOS} masers

Dall'Olio et al. 2017



Combine masers, thermal lines and dust polarised observations!

The case of G9.62+0.20

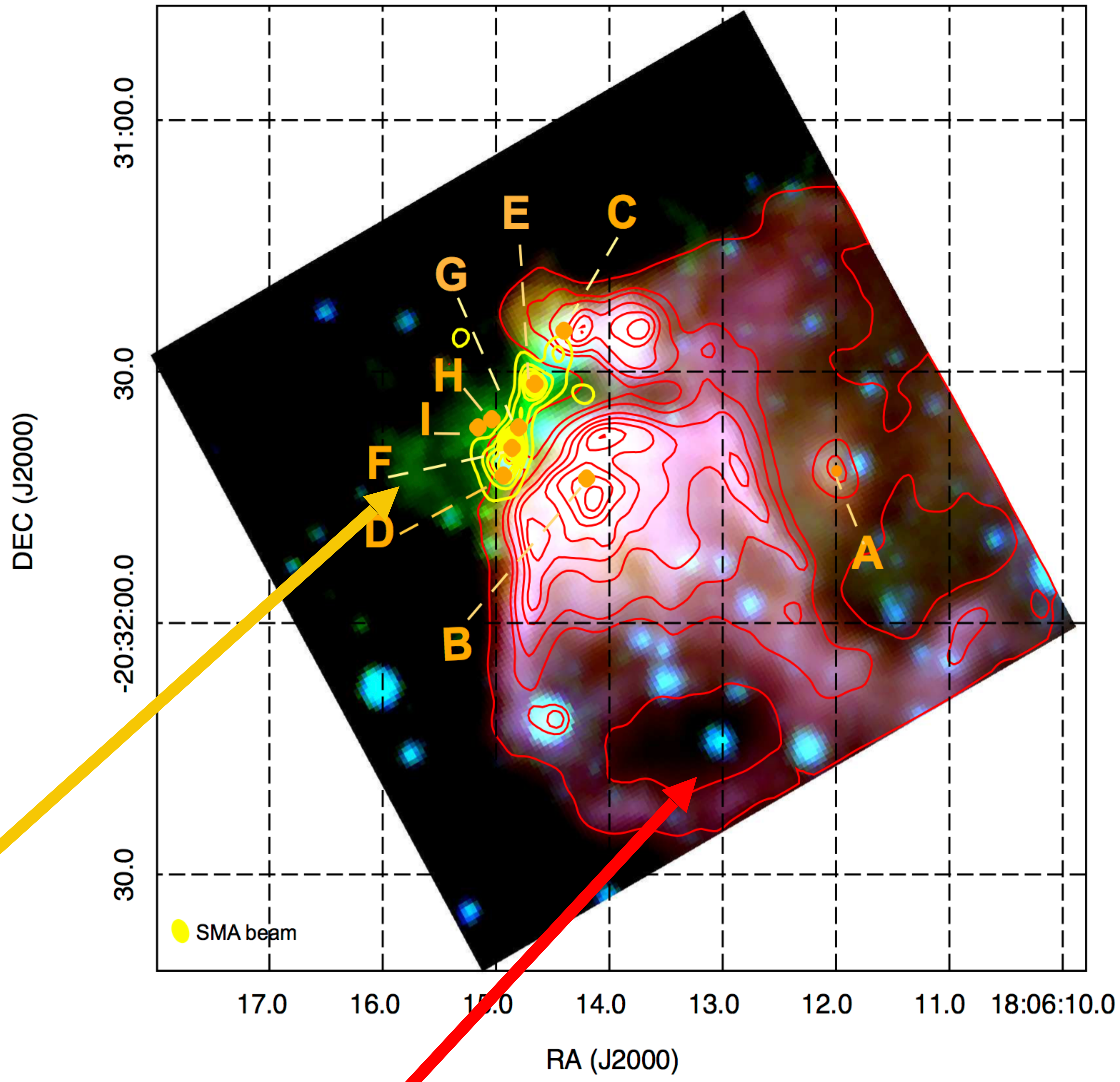
SF region containing
several UCHII

Sequential MSF

D ~ 5.2 kpc

Spitzer/IRAC (3 color)

8 μm red
4.5 μm green
3.6 μm blue



860 μm continuum
emission SMA

PAH emission
PDR of evolved HII regions
(radio sources A B C)

Cesaroni 1994, Testi et al. 1998, Persi et al. 2003,
Vlemmings 2008, 2011 Liu et al. 2011, 2014, 2017

The case of G9.62+0.20

SF region containing
several UCHII

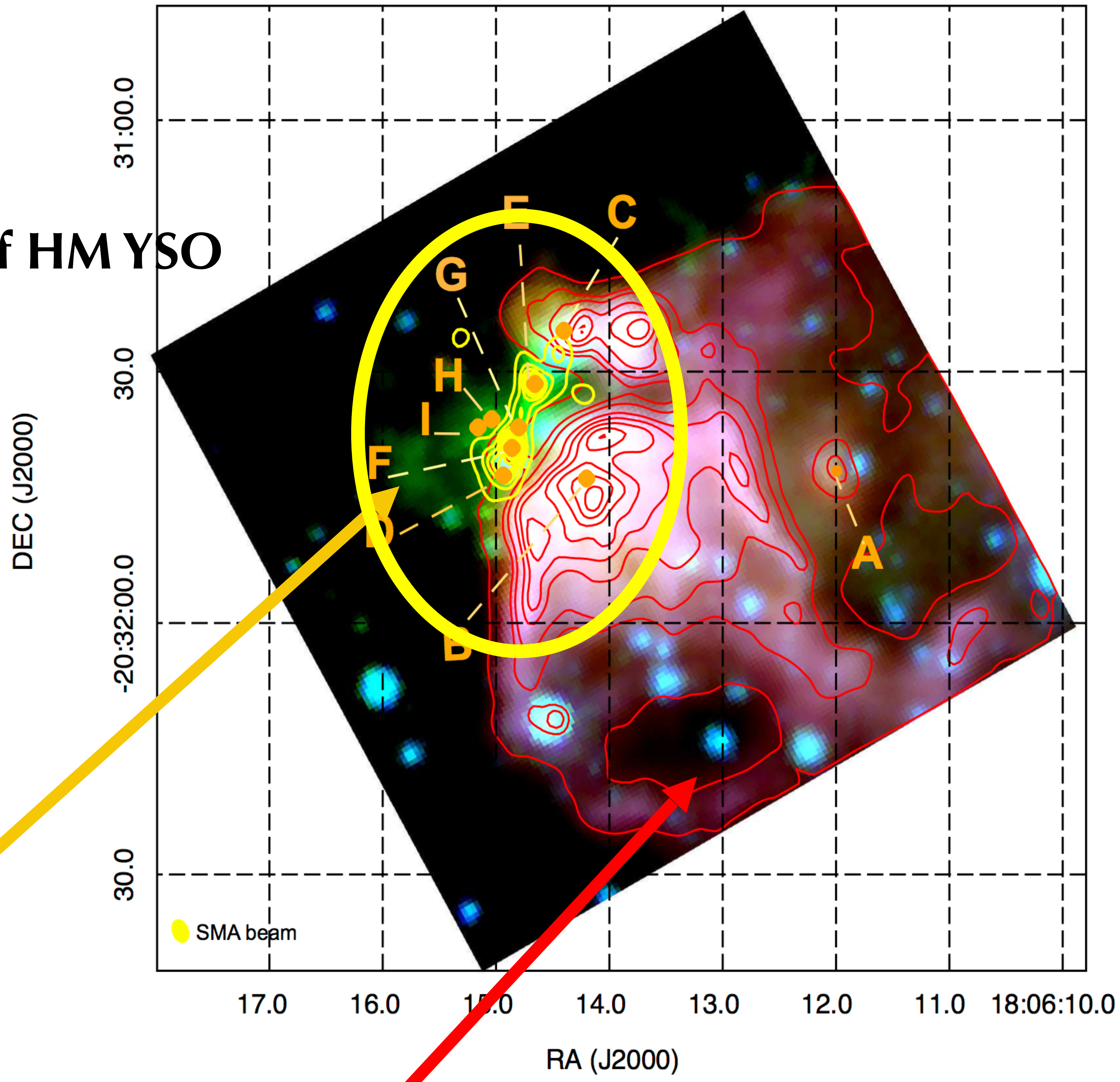
Sequential MSF

D ~ 5.2 kpc

Spitzer/IRAC (3 color)

8 μm red
4.5 μm green
3.6 μm blue

New generation of HM YSO



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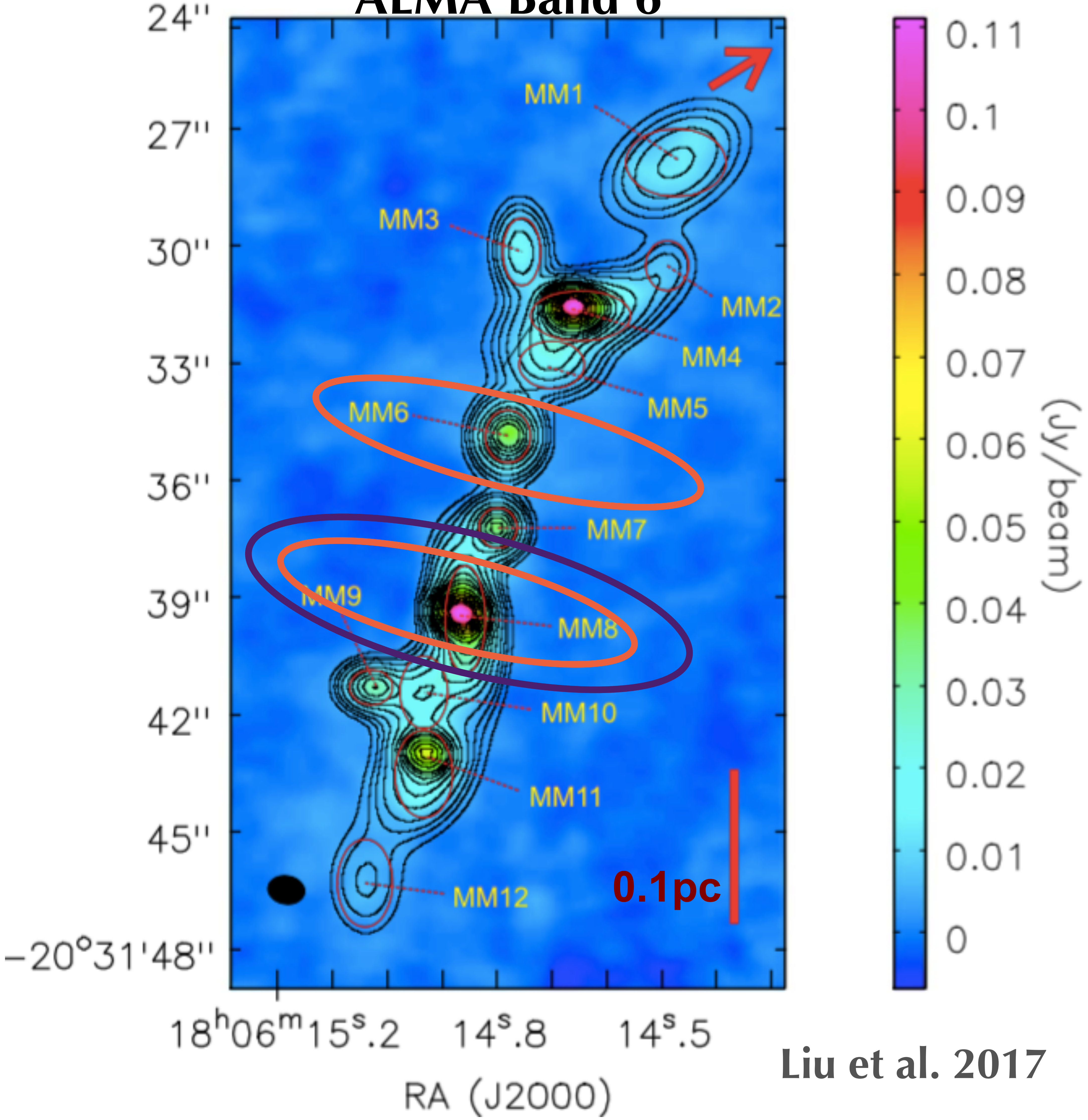
The case of G9.62+0.20

ALMA Band 6



Liu et al. 2017

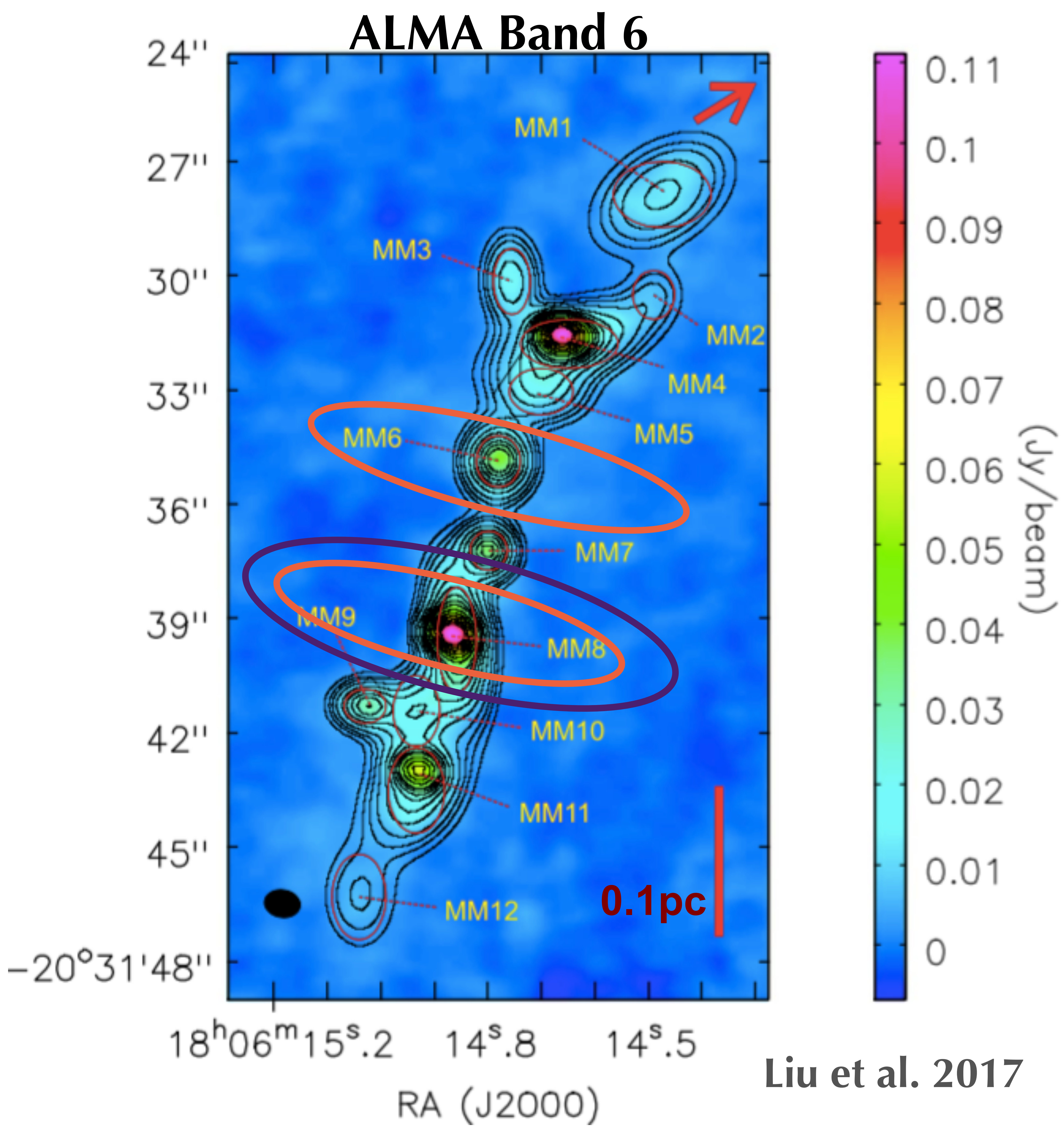
Several cores
at different evolutionary stages

MM3 (younger)
starless core

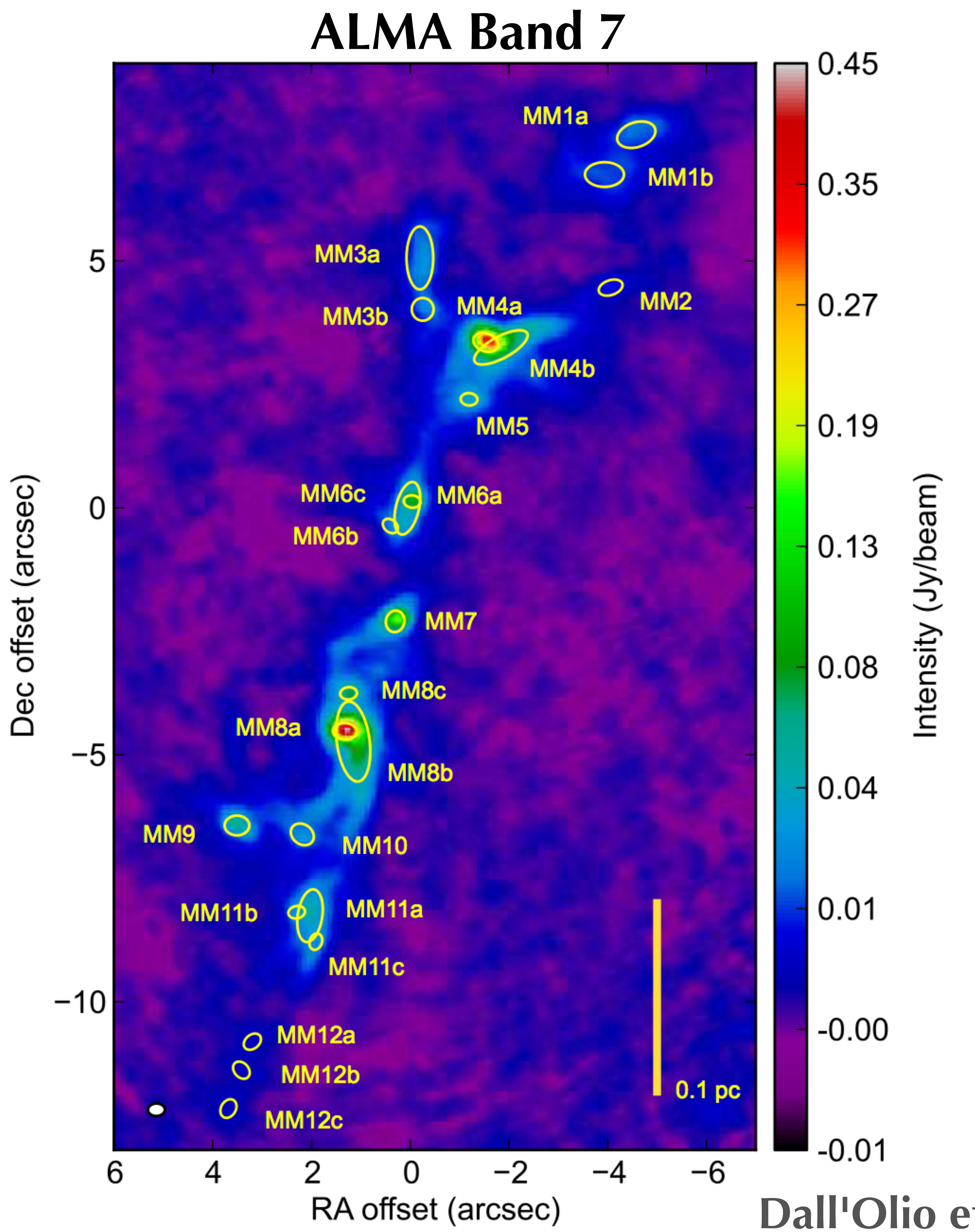
MM8
CO and SiO outflow

MM4 (oldest)
no outflow

The case of G9.62+0.20



Liu et al. 2017



Dall'Olio et al. sub

Our results

Dall'Olio et al. sub

Contours POLI : 0.6, 1.1, 1.7, 2.2 mJy/beam