Physical properties of bright class I methanol masers

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Outlook

- Class I and Class II CH_3OH masers
- Observational properties of CH_3OH masers
- Pumping schemes of Class I and Class II masers
- Bright Class I CH_3OH masers

Methanol masers

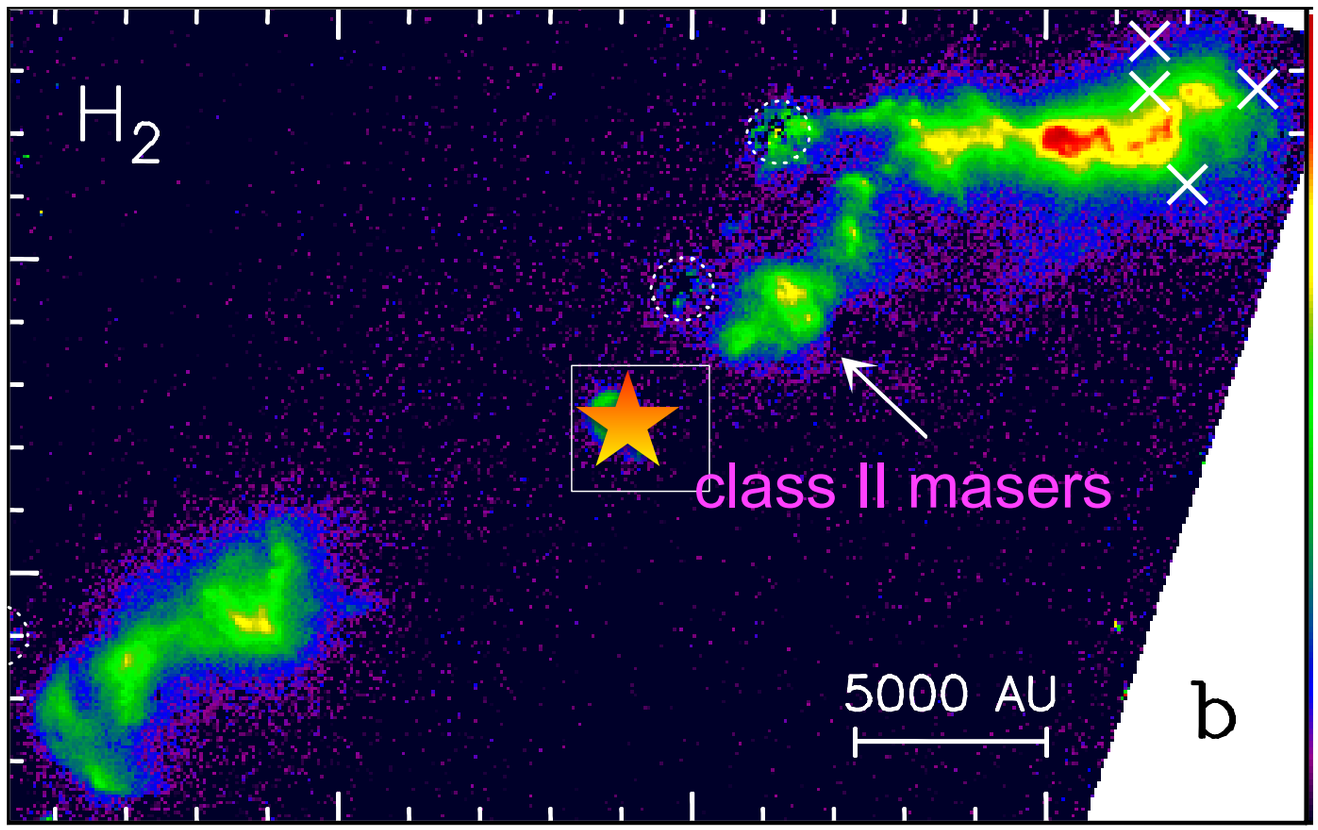
Class II methanol (CH_3OH) masers

- Located in the nearest vicinity of YSOs
- IR radiation excitation from a massive YSO
- Regions of high mass star formation only

Class I methanol (CH_3OH) masers

- Scattered around YSOs (up to a parsec)
- Collisional excitation (e.g. by shocks)
- Regions of star formation (high & low mass)

IRAS 20126+4104



class I masers

Cesaroni+2013, Moscadelli+2010, Kurtz+2004

Class II maser properties

Class II methanol (CH_3OH) masers

- brightest lines (12.2 GHz and 6.7 GHz) discovered in the late ‘80s (Wilson+1985, Menten+1991)
- associated with intermediate/massive YSOs

Talks from Moscadelli, Stecklum, Chibueze, Hunter

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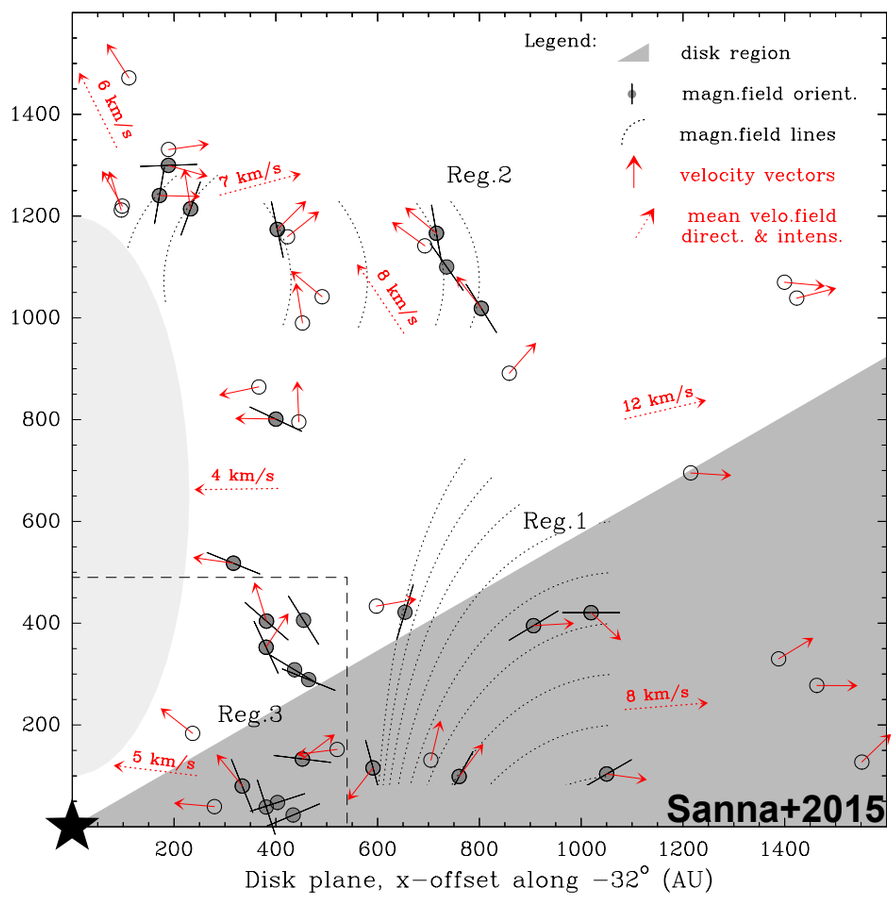
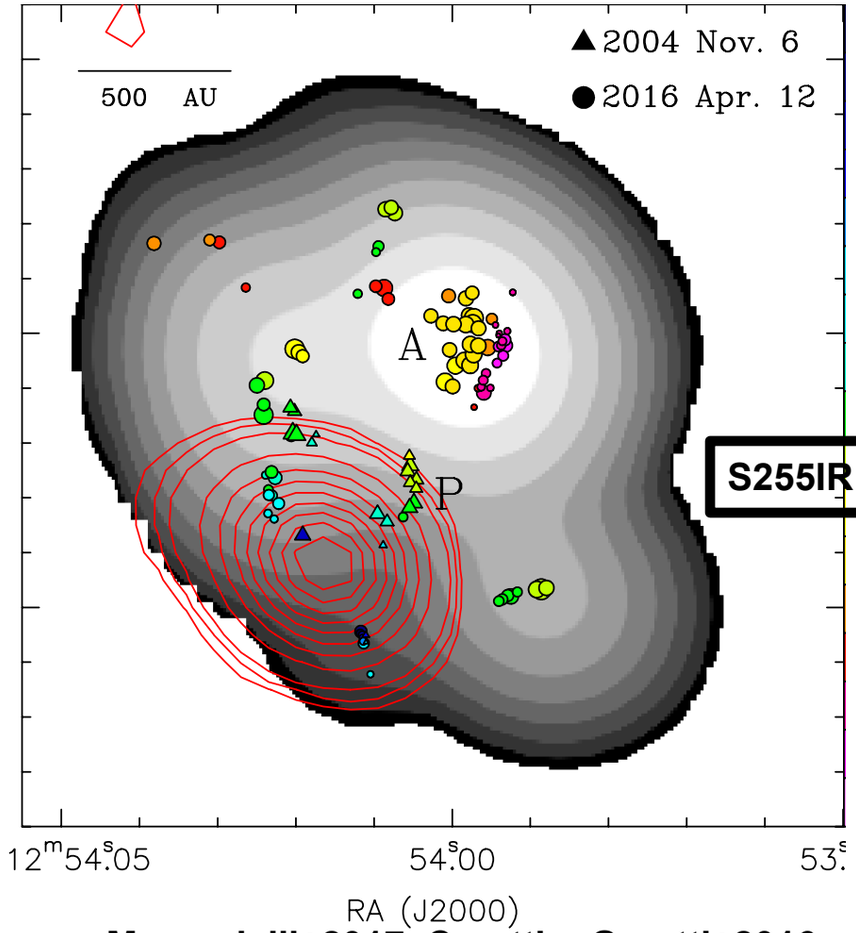
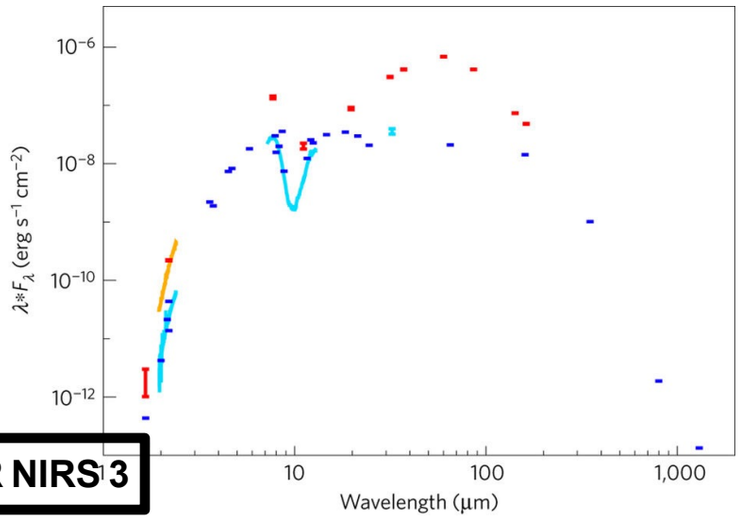


Sanna+2015



Moscadelli+2017, Caratti o Garatti+2016



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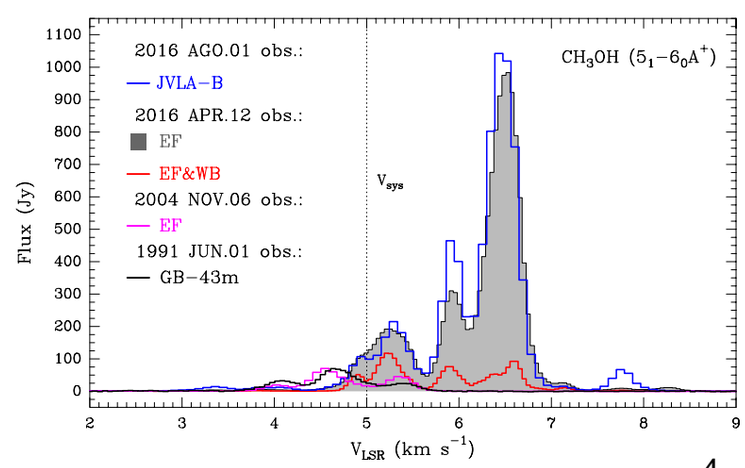
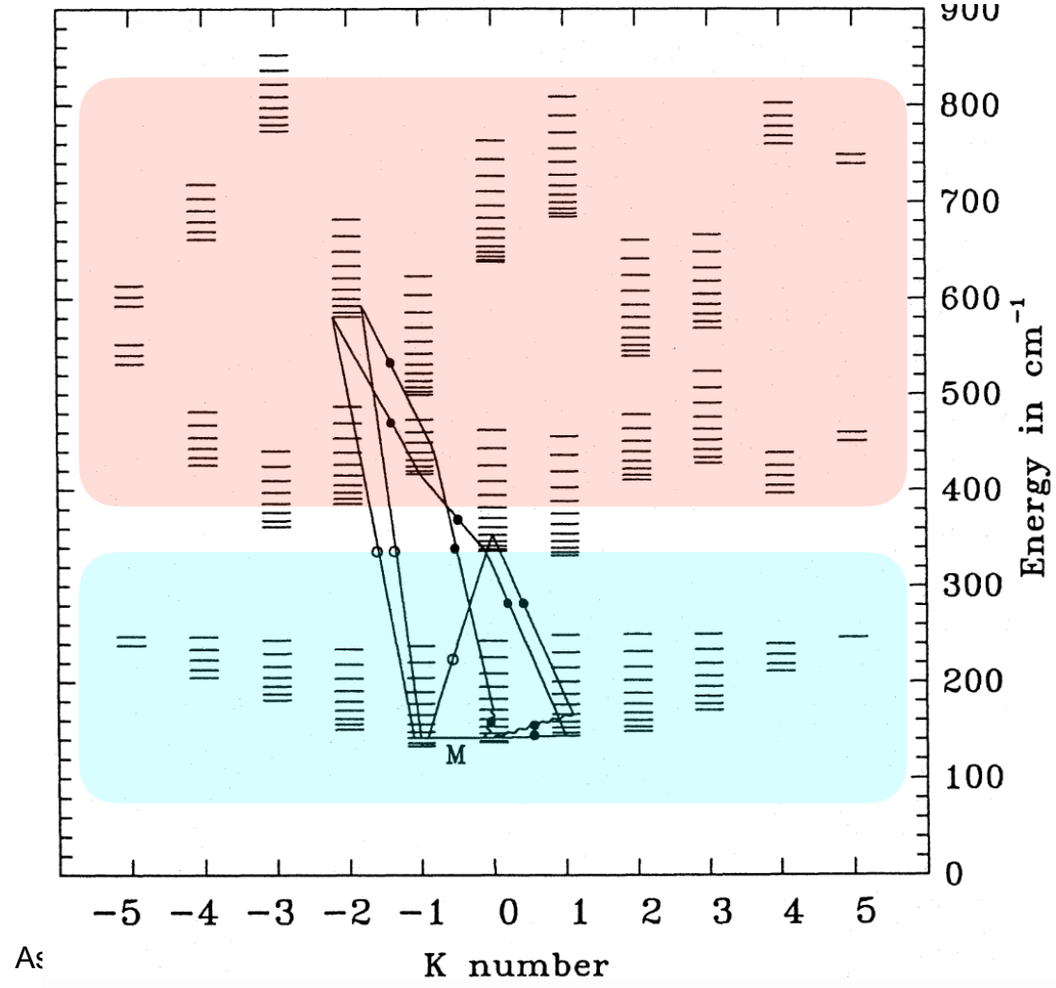


Class II maser properties: Pumping mechanisms

Class II methanol (CH_3OH) masers

- brightest lines (12.2 GHz and 6.7 GHz) discovered in the late ‘80s (Wilson+1985, Menten+1991)
- associated with intermediate/massive YSOs ⇒ radiative pumping to vibrationally excited levels (Wilson+1985, Sobolev&Deguchi1994, Sobolev+1997, Cragg+2005)



IR radiation from warm dust promotes molecules to $v_t \geq 1$ states, from which they decay back to the ground state in one or more steps



20/30 μm

large reservoir of $v_t = 0$ molecules

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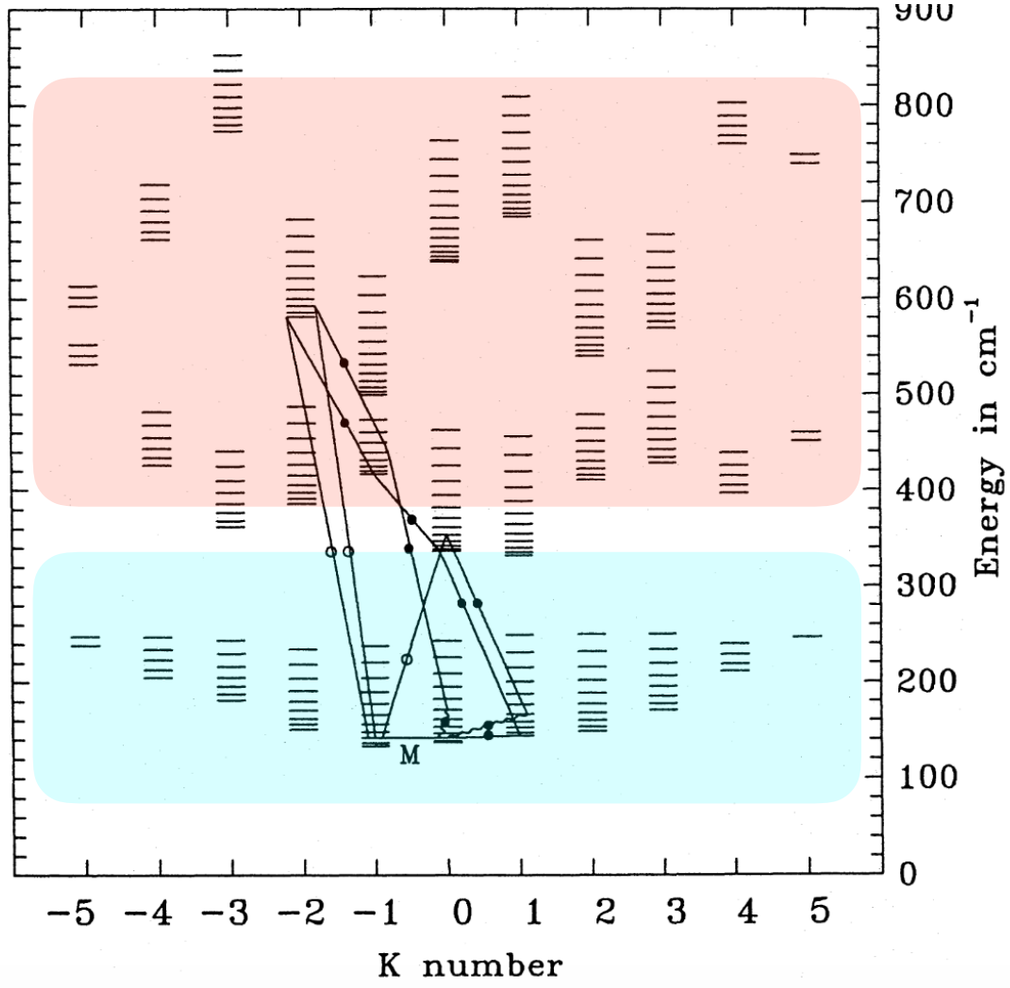


Cragg+2005 include v_t up to 4:

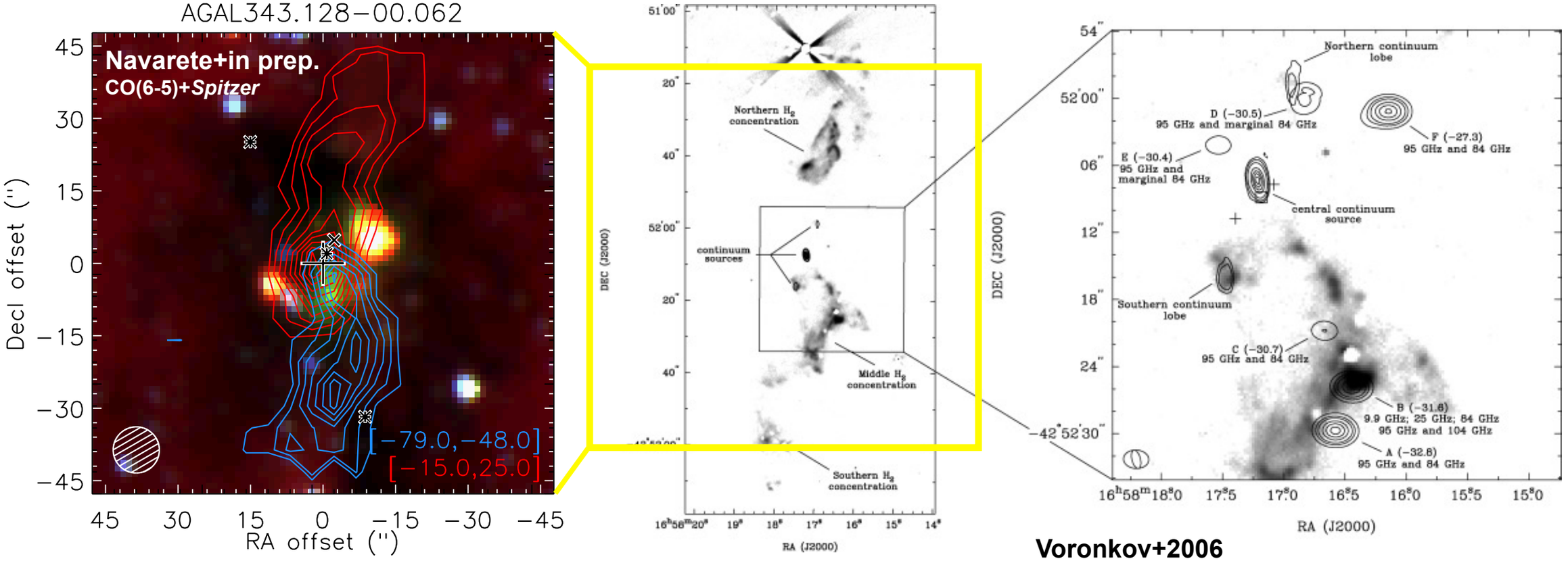
- Class II masers at T>100 K iare clearly due to v_t =2 *levels*
- Adequate models for Class II masers at 300 K are obtained when including levels up to v_t =3

However, collisional rates with a larger set of levels and with H_2 as collisional partner are now available (Rabli & Flower 2010ab, 2011) and detailed modelling should be re-run

Class I maser properties

Class I methanol (CH_3OH) masers

- First detection in the $J_{k=2}-J_{k=1}$E at 25 GHz in the '70s, followed by the brighter 7_0-6_1-*A* + and $4_{-1}-3_0$-E lines at 44 and 36 GHz (Barrett+1971, Morimoto+1985)
- generally associated with astrophysical shocks (molecular outflow, SNRs, cloud-cloud collision) ⇒ collisional pumping



Voronkov+2006

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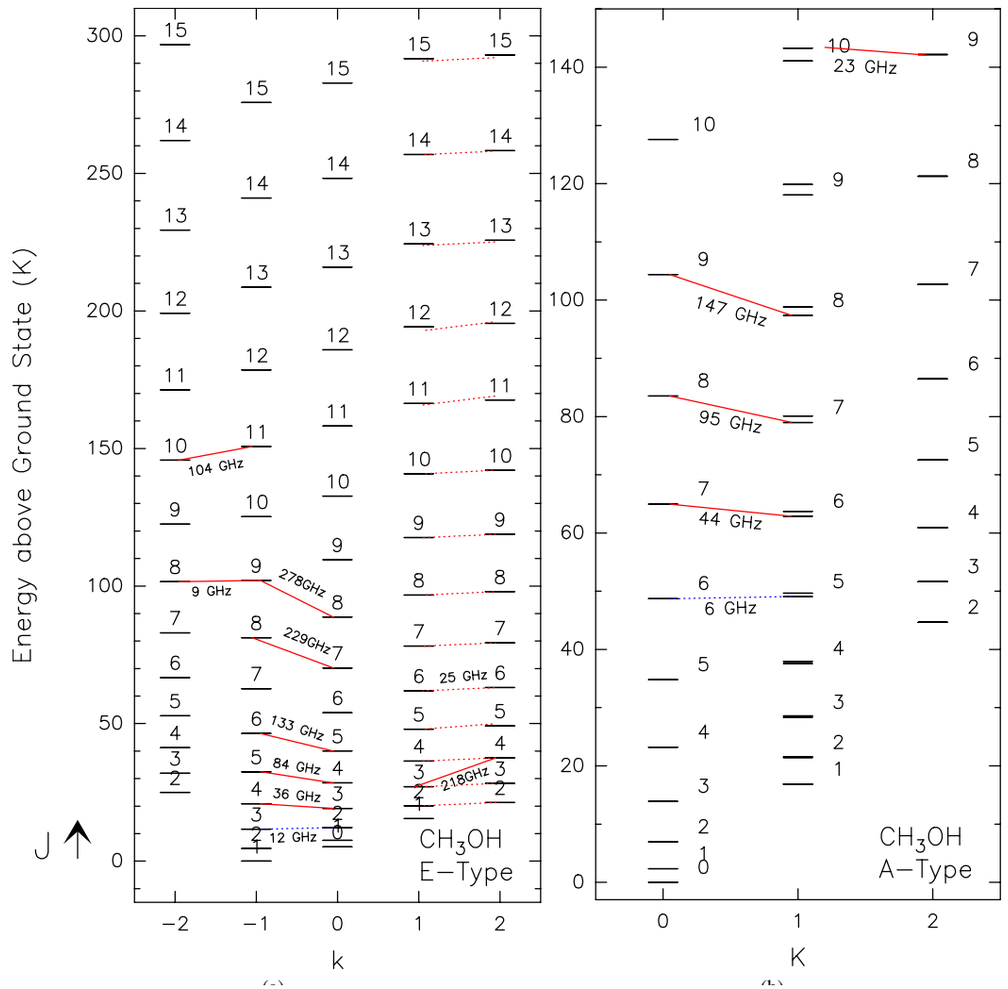

Maser action in these lines comes from basic properties of the molecule:

- **$(J+1)_{-1}-J_0$-E/$(J+1)_0-J_1$-A type series:** Collisional rates show a propensity for $\Delta k = 0$ collisions and a dependence upon ΔJ as $1/\Delta J$: molecules collisionally excited into high J_K states rapidly decay and overpulate the E k=-1 ladder (A K=0) relatively to neighbour levels

- **J_2-J_1-E series:** *ad hoc additional preference* for the $\Delta k = 3$ collisions over $\Delta k = 2$ (Johnston+1992), or *totally unselective collisions* (Cragg+1992)

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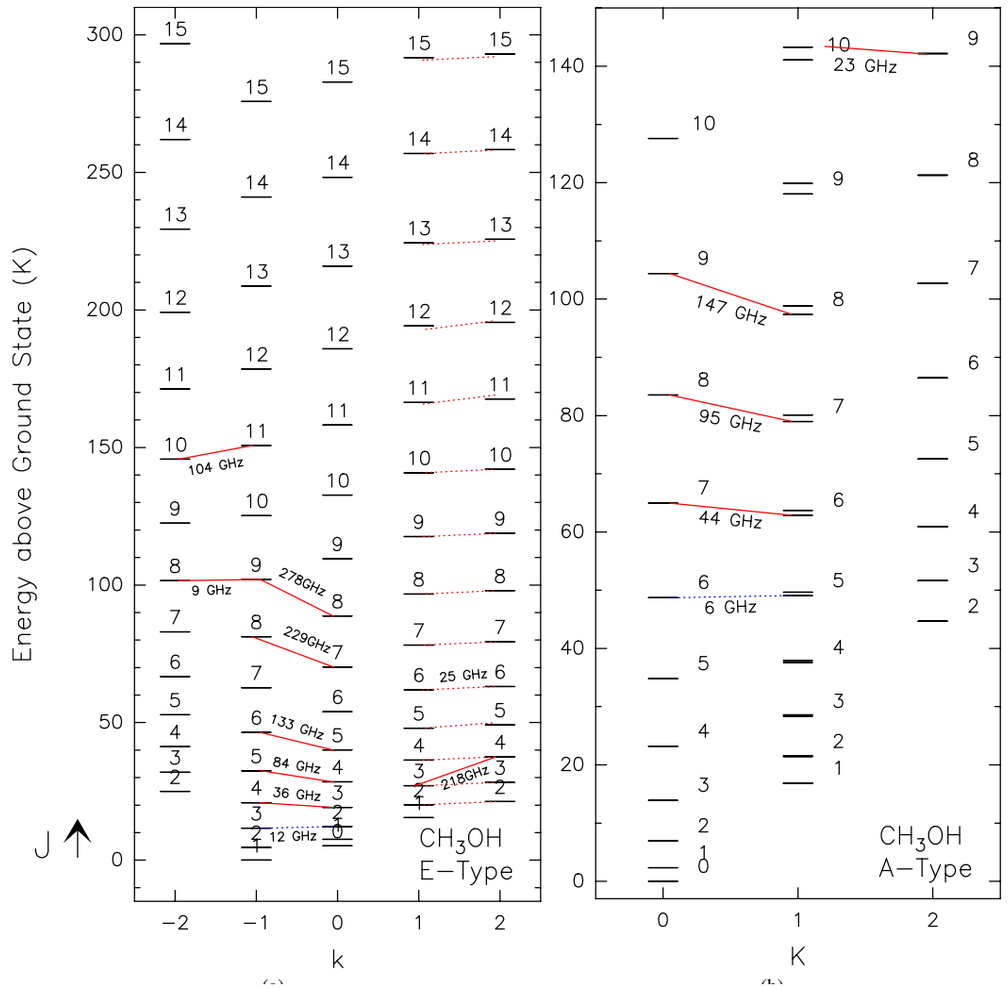


collisional rates with a larger set of levels and with H_2 as collisional partner are now available (Rabli & Flower 2010ab, 2011)

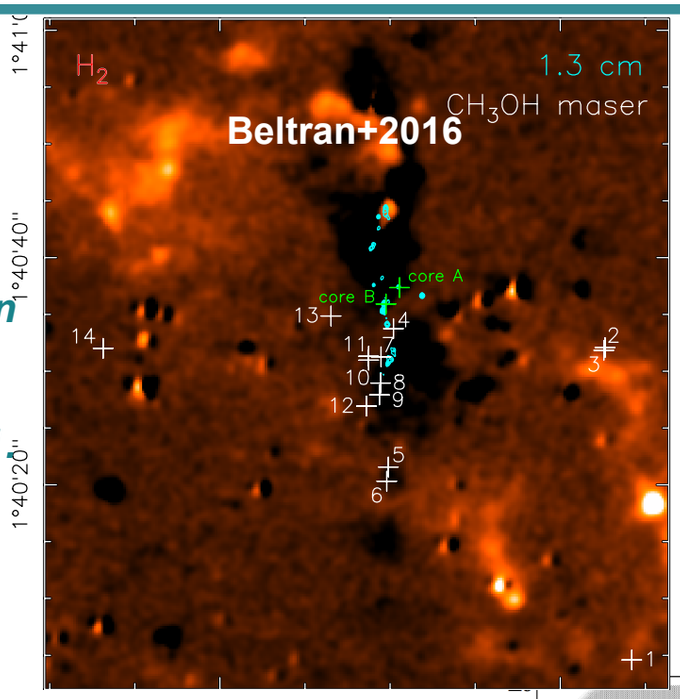
Class I masers: Observational properties

- Class I masers have typical luminosities of ~ 10^{-6} $L_\odot$ ⇒ completely unimportant energetically compared to Class II masers (L>10^{-6} $L_\odot$ and up to 10^{-3} $L_\odot$, Pestalozzi+2007)
- BUT signposts of interaction regions of shocks with dense ambient material

Talks from Voronkov, Kalenskii,Rodrígez-Garza

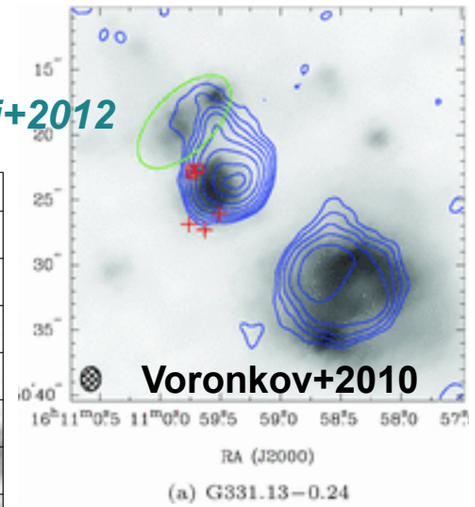
outflows

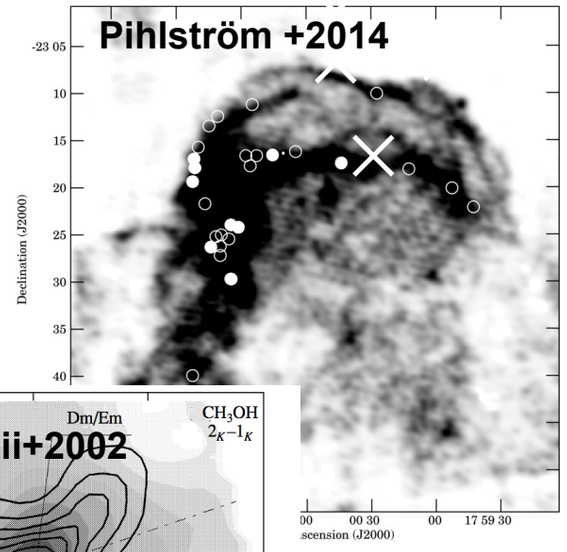
HM: Plambeck & Menten 1990, Cyganowski+2009 Voronkov+2006, 2014…
LM: Kalenskii et al. 2010a,b



expanding HII region

Voronkov+2010,2014, Cyganowski+2012



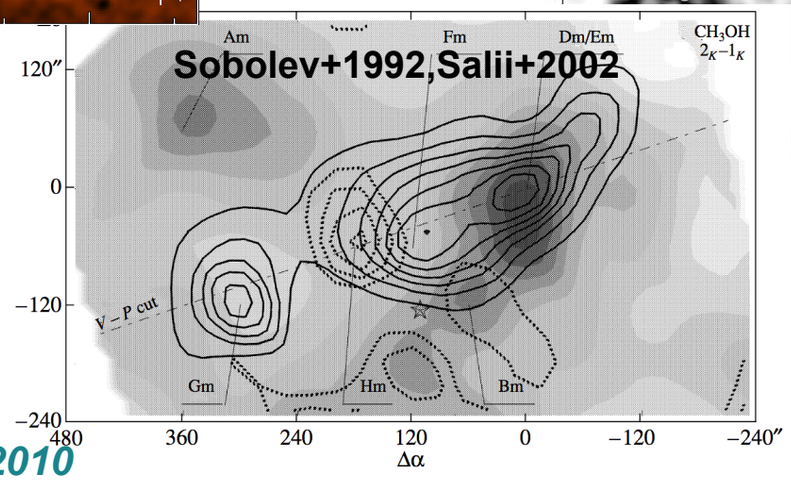


SNRs

Yusef-Zadeh+2008,Sjouwerman+2010; Pihlström+2011,2014…

cloud-cloud collision

Sobolev+1992, Sjouwerman+2010



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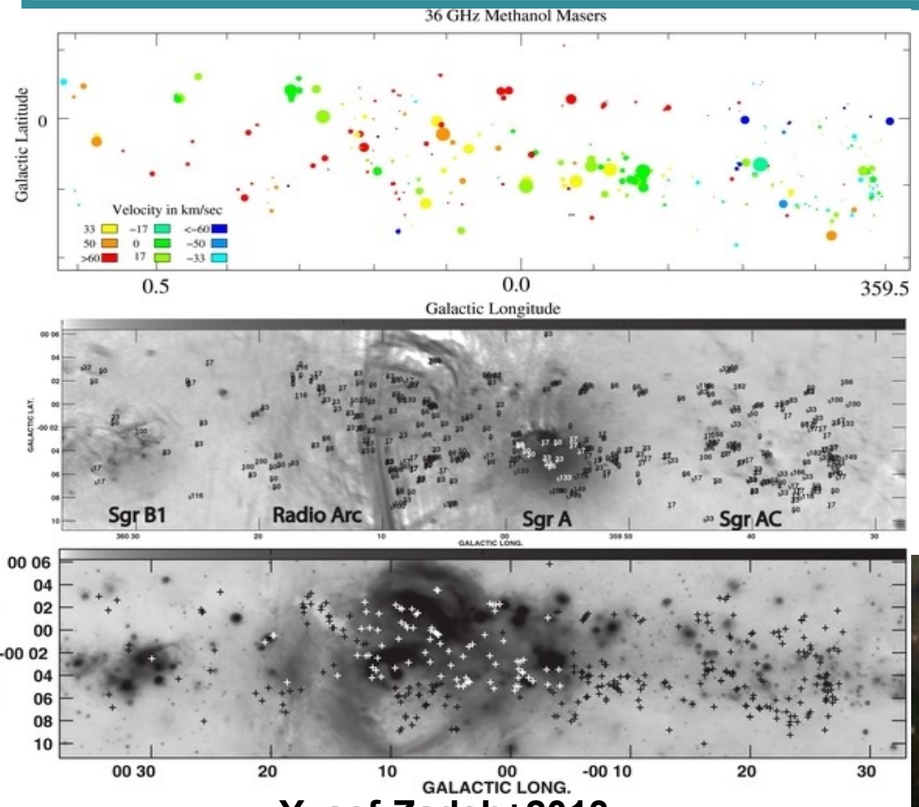
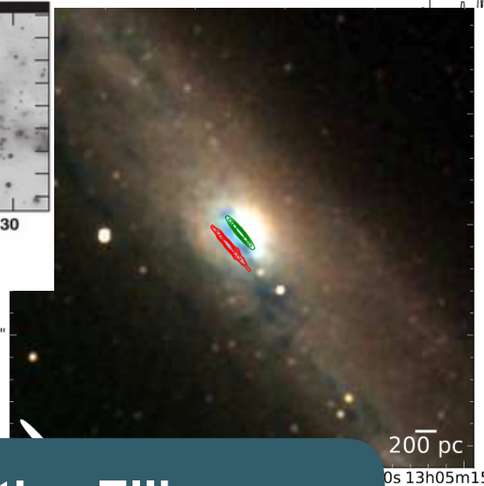
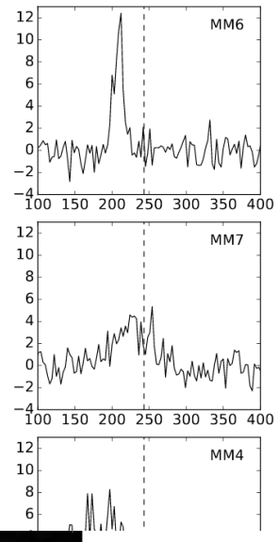
- BUT important signposts of interaction regions of shocks with dense ambient material
- and recently also toward the Galactic center and in extragalactic sources

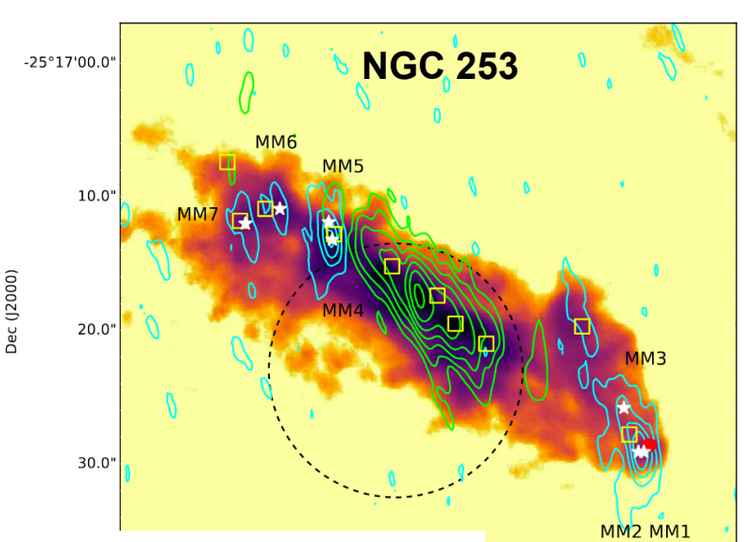


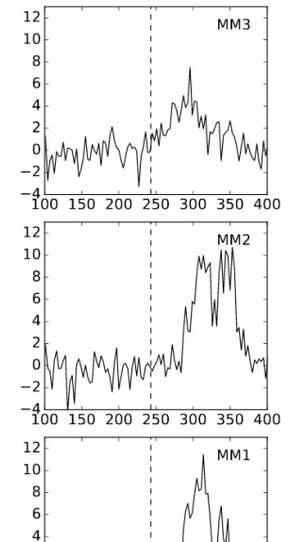
Yusef-Zadeh+2013

but see also Cotton&Yusef-Zadeh 2016

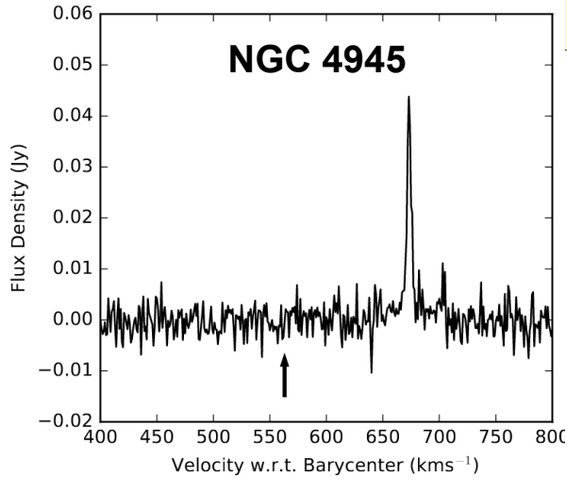








Ellingsen+2017



McCarthy+2017

Talks from Henkel, Chen, McCarthy, Ellingsen

Bright Class I methanol masers…
what are they good for?

- efficient outflow tracers, unaffected by extinction and strong at mm wavelengths

  ⇒**potentially a powerful tool for protostellar activity in extremely embedded objects**

- detection of circular/linear polarisation in class I masers (Sarma&Momjian 2009, 2011, Kang+2016)

  ⇒***tool to measure magnetic fields in interstellar shocks***

Talks from Surcis, Kang

but see also
Ellingsen 2006
Yanagida+2014, G34.43+00.24 MM3
Cotton& Yusef-Zadeh 2016, The Brick

Physical characteristics of bright Class I methanol masers

Osservatorio Astronomico di Cagliari

Leurini, Menten, Walsmley 2016

Assumptions:

- we focus on bright class I masers: **$(J+1)_{-1}-J_0$-E/$(J+1)_0-J_1$-A and J_2-J_1-E type series**

⇒ **but we predict maser action in *all observed transitions***

- we concentrate on geometry independent maser properties
- we use an LVG approximation with a plane-parallel slab geometry
- the maser emission is described through the pump rate coefficient (q), the maser loss rate (Γ), and the inversion efficiency of the pumping scheme (η)

see also P0.3 Sobolev

following formalism of H_2O masers (Elitzur+1989,Hollenbach+2013)

$$q = \frac{1}{2} \times \frac{P_u + P_l}{n^2 \times (\mathrm{CH_3OH})}$$

$$\Gamma = \frac{g_u \Gamma_u + g_l \Gamma_l}{g_u + g_l}$$

$$\eta = \frac{P_u \Gamma_l - P_l \Gamma_u}{P_u \Gamma_l + P_l \Gamma_u}.$$

P_m, Γ_m: pump, loss rates

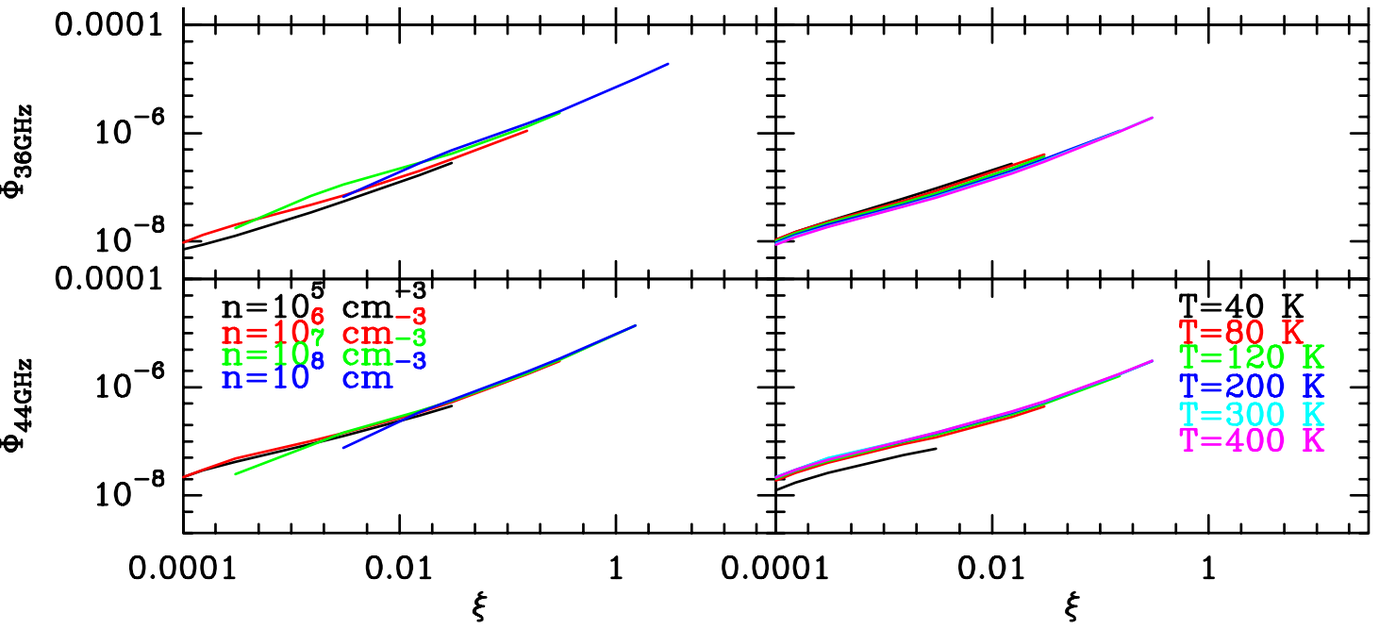
⇒ they allow to determine observable quantities (e.g., critical mean intensity J_s for saturation, the photon production rate Φ_m linked to the observed flux)

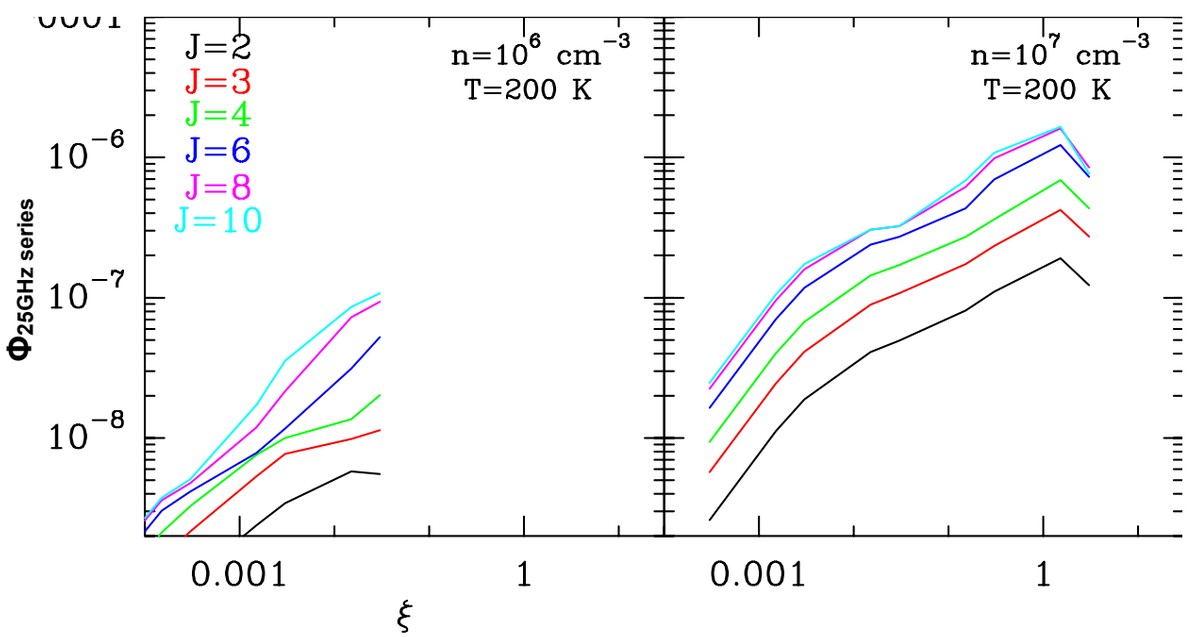
Physical characteristics of bright Class I methanol masers

Leurini, Menten, Walsmley 2016

$$\xi = \frac{n(\mathrm{H_2}) \times \frac{N(\mathrm{CH_3OH})}{\mathrm{d}v}}{3.3 \times 10^{24}}.$$

$$\Phi_{\mathrm{m}} = \frac{g_u g_l}{g_u + g_l} \times 2n^2 X(\mathrm{CH_3OH}) \eta \mathrm{q}$$



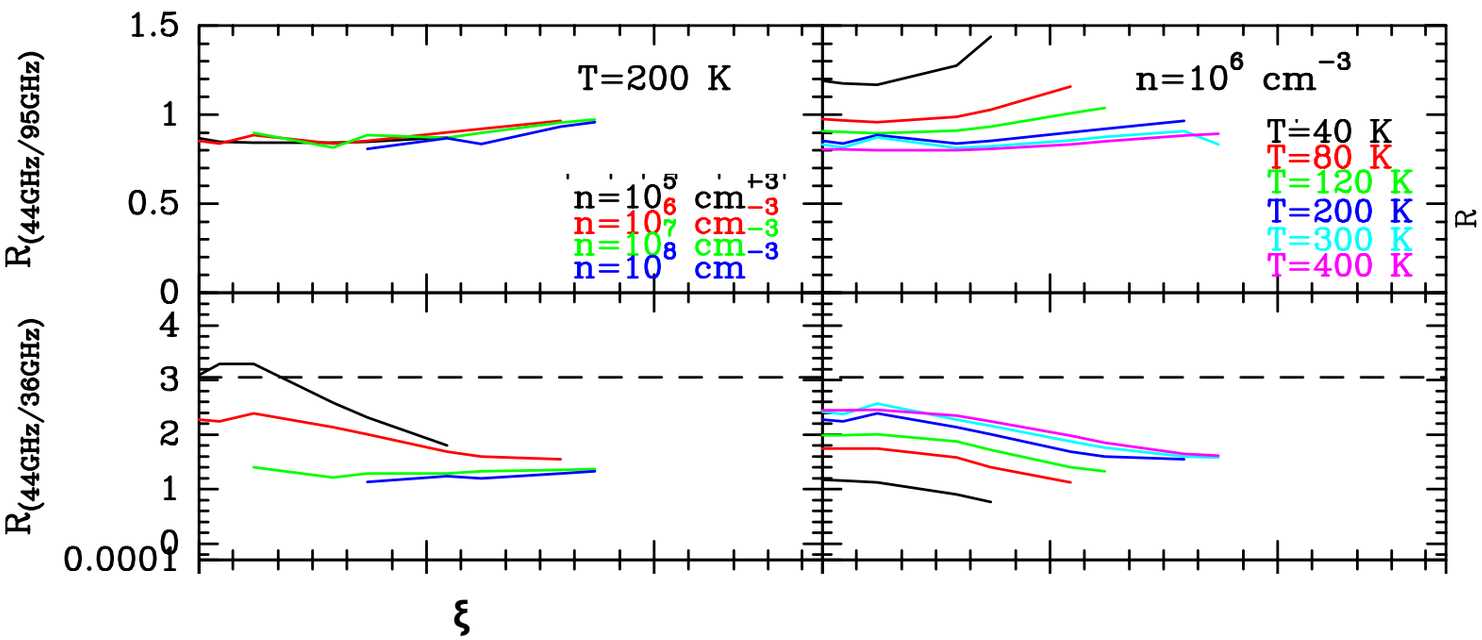


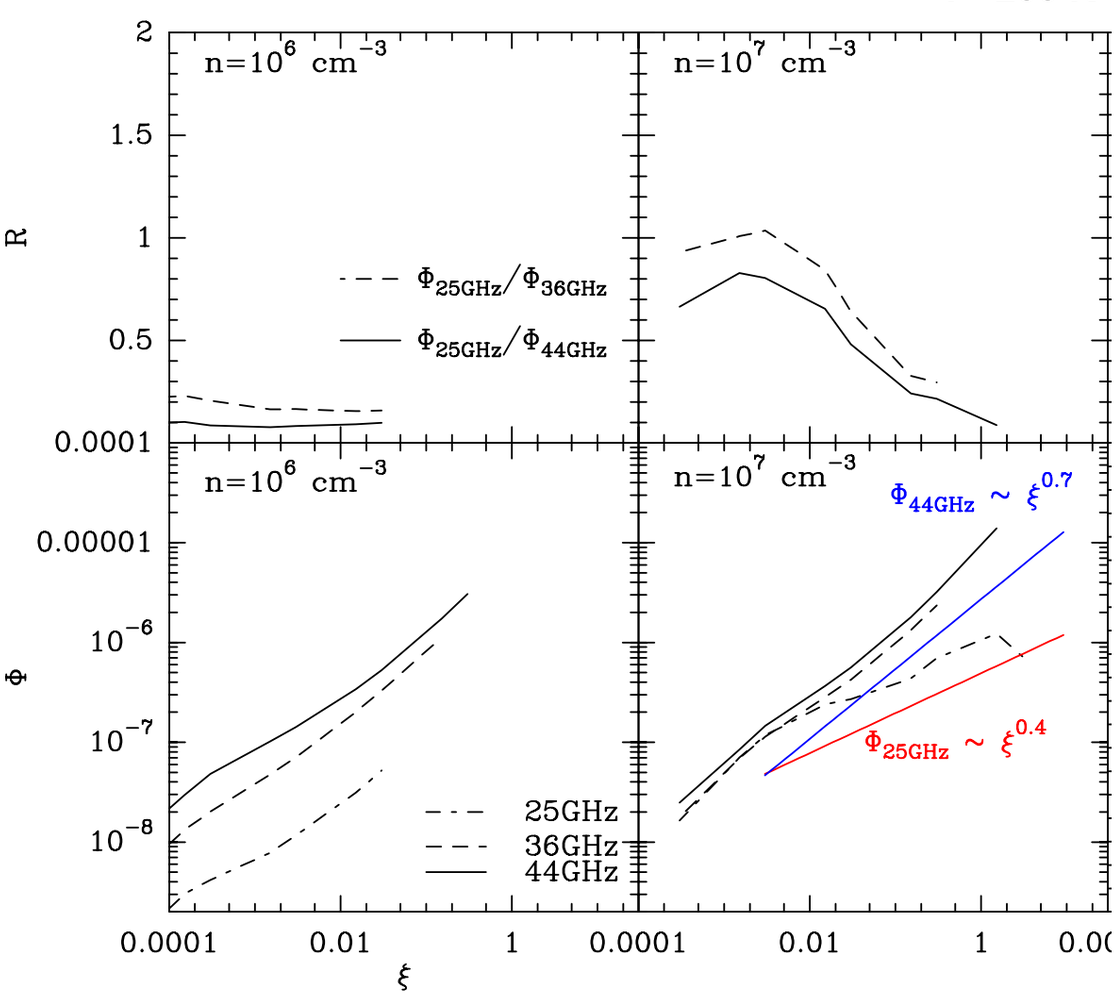
- Φ increases with ξ until thermalisation ⇒ bright Class I masers trace high CH_3OH emission measure at high densities ($n(H_2) \sim 10^7 - 10^8$ cm^{-3}), high temperatures (>100 K), and high column densities
- independently on T_k and n (in the range $10^5 - 10^7$ cm^{-3}), all bright Class I masers quench at a constant specific column density of ~10^{17} cm^{-2} km^{-1} s

Physical characteristics of bright Class I methanol masers

Leurini, Menten, Walsmley 2016

- 3 *families*: **$(J+1)_{-1}-J_0$-E, $(J+1)_0-J_1$-A and J_2-J_1-E series.** *Different slope of Φ_m vs ξ* depending on density
- The 25 GHz line are only inverted at n>10^6 cm^{-3} in contrast to other lines (>10^4 cm^{-3})





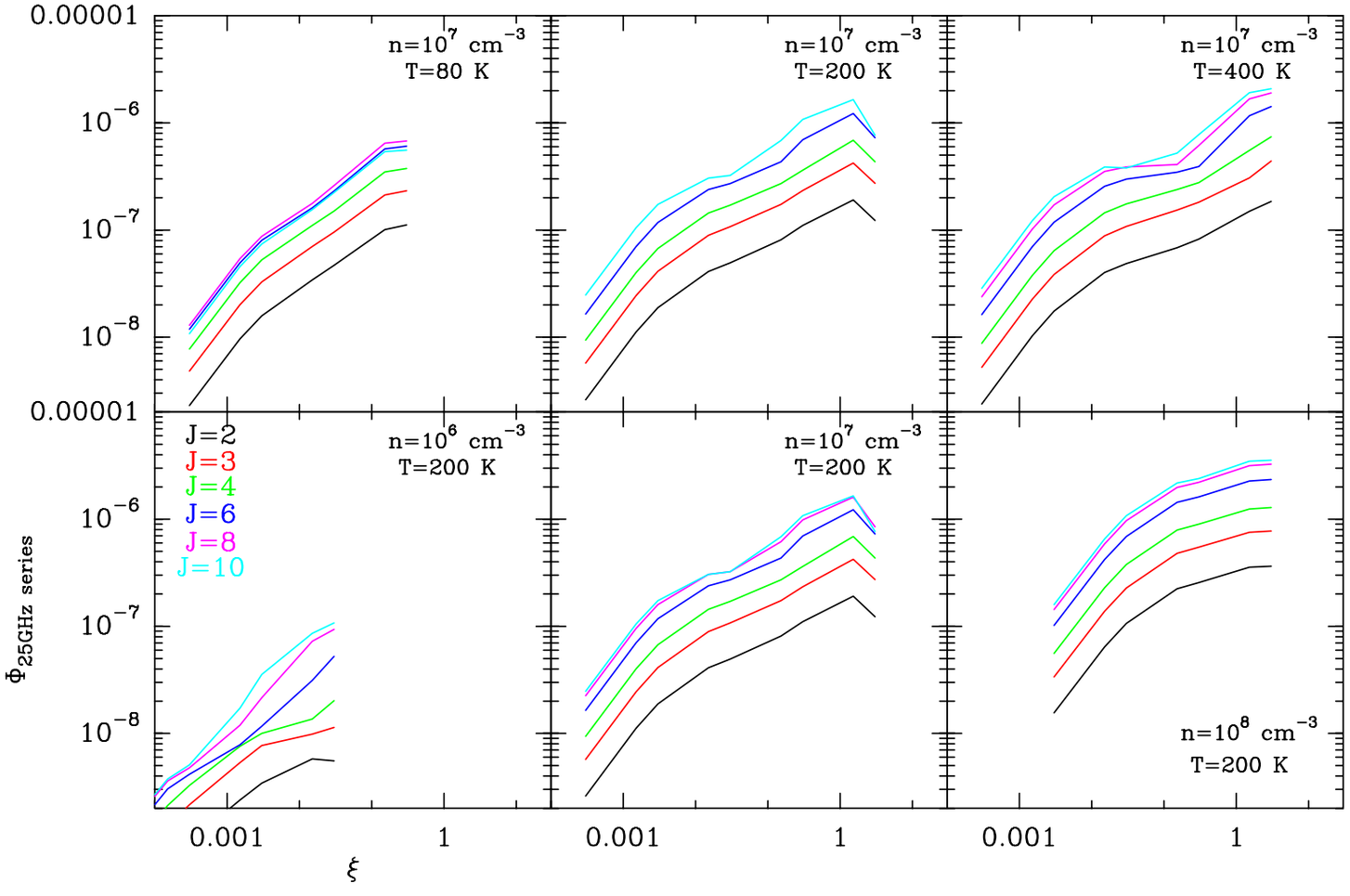
Physical characteristics of bright Class I methanol masers

Osservatorio Astronomico di Cagliari

Leurini, Menten, Walsmley 2016

Comparison with observations:

- the 44 GHz line is almost always stronger than the 36 GHz maser, except at low temperatures and high densities
- the luminosity of the 25 GHz series is lower than that of the other Class I masers
- the ratio between fluxes of different 25 GHz lines is constant ($6_2 \rightarrow 6_1/3_2 \rightarrow 3_1 \sim 3$, see Menten+1986)



Peak at J=9, while Menten+1986 observe it at J=6

⇒ ***the J_2–J_1-E lines poorly known,***

only about ~10-15 sources

(Menten+1986; Voronkov+2006; Britton & Voronkov 2012)

Summary

cIMMs talks/posters at this symposium:

Leurini, Surcis, Kalenskii, Chen, McCarthy, Ellingsen, Voronkov, Rodrígez-Garza, Kang

P.03 Sobolev, P.09 Cyganowski, P.48 Cunningham, P.49 Bayandina

- Class I CH_3OH masers are collisional pumped⇒They trace interstellar shocks
- Class I CH_3OH masers are potentially powerful shock tracers in deeply embedded sources

  - *They trace high ξ (high densities ($n(H_2) \sim 10^7-10^8\ cm^{-3}$), high temperatures (>100 K), and high column densities with ξ close to the limits set by collisional quenching)*

  - *They can be separated into the 3 families in terms of Φ_m vs ξ*

  - *The 25 GHz lines behave in a different way from other bright masers likely because they are inverted through $\Delta k \neq 0$ collisions. They are only inverted at high densities above $10^6\ cm^{-3}$*

  - *Under the assumption that Class I masers are saturated, our calculations reproduce reasonably well most of the observed properties of Class I CH_3OH masers in massive star forming regions.*