Cosmic Rulers: Masers as Tools for Probing Galactic Structure from au to kpc

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ICRAR International Centre for Radio Astronomy Research
Universität zu Köln
Universidad de Guanajuato
Sokendai
Keele University

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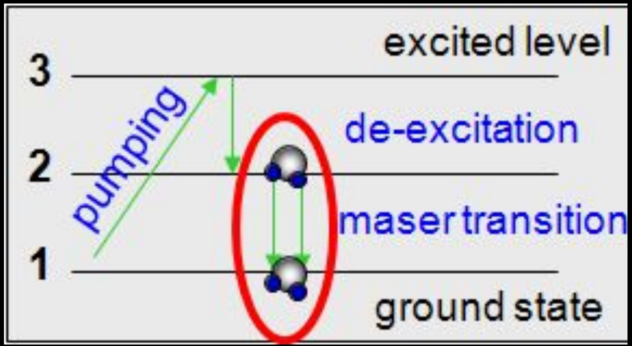
“A-masing” masers



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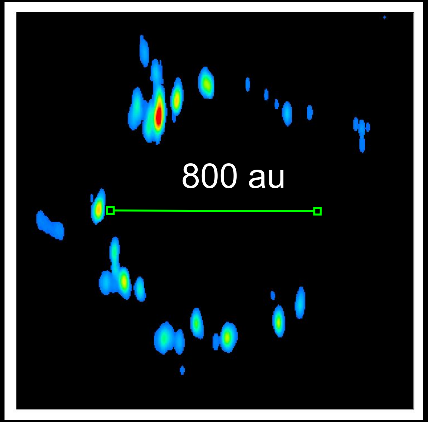
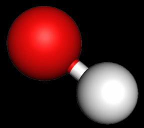
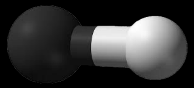


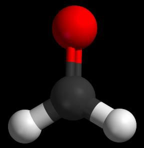
Bartkiewicz et al. 2005, 2020

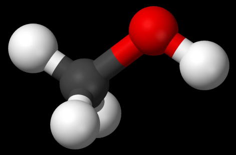
- ➢ Arise in specific n,T
- ➢ Spatially compact
- ➢ Bright
- ➢ Narrow spectral profile
- ➢ Ideal for astrometry, kinematics and polarimetry

Maser emission in SKA-MID bands

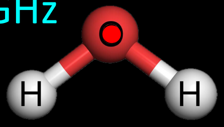
hydroxyl (OH) 

methylidyne (CH) 

formaldehyde (H_2CO) 

methanol (CH_3OH) – class I, II 

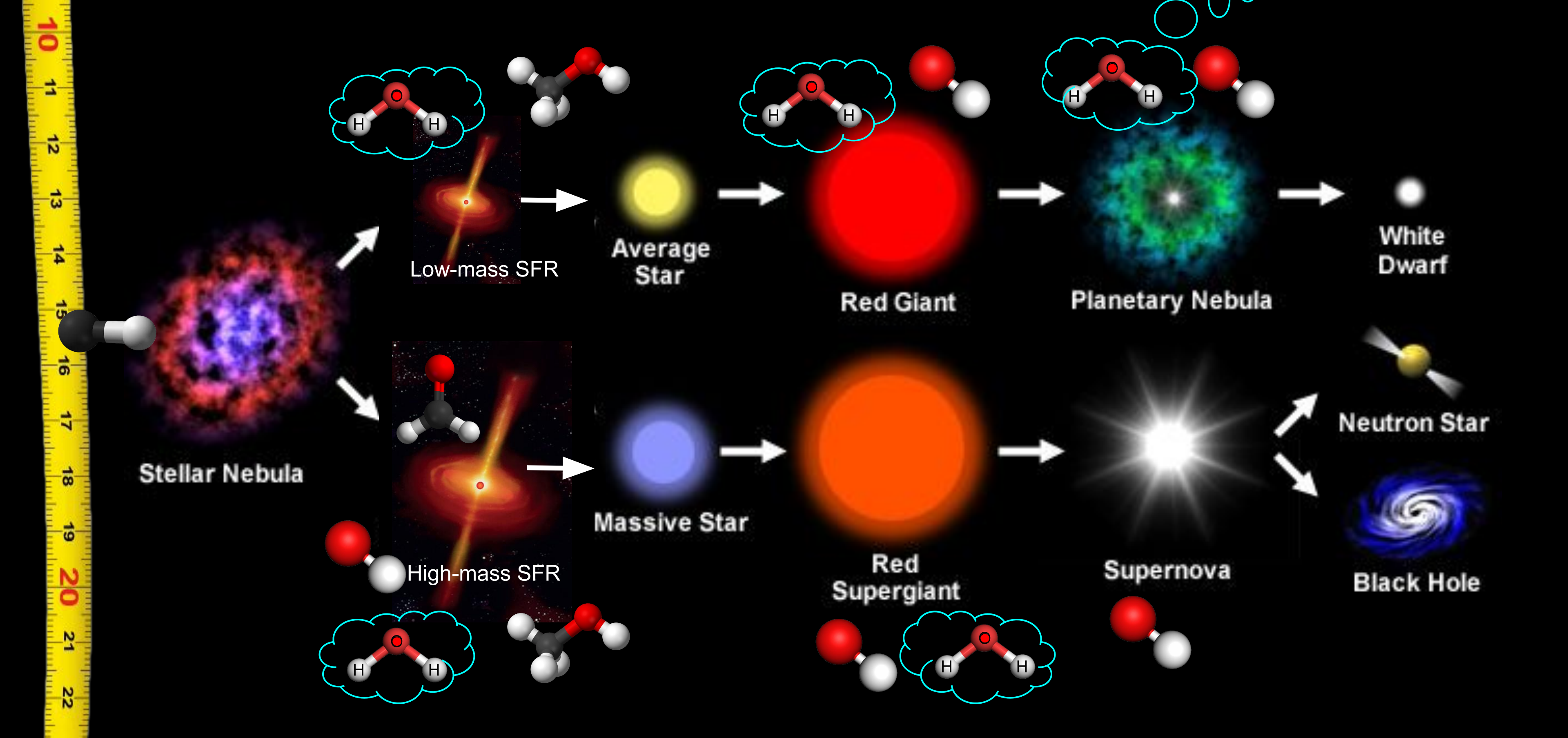
water (H_2O) if SKA-MID extended to 22.235 GHz



Molecule	Transition	Frequency (GHz)	Band
CH_3OH cI?	1_1-1_1 $A^{\pm}(v_t=0)$	0.834267	1
g-OH	$^2\Pi_{3/2}$ J=3/2, F=1-2	1.61223	2
g-OH	$^2\Pi_{3/2}$, J = 3/2, F=1-1	1.66540	2
g-OH	$^2\Pi_{3/2}$, J = 3/2, F=2-2	1.66736	2
g-OH	$^2\Pi_{3/2}$, J = 3/2, F=2-1	1.72053	2
CH_3OH c?	2_1-2_1 $A^{\pm}(v_t=0)$	2.502778	3
CH	$^2\Pi_{1/2}$ J=1/2, F=0-1	3.264	4
CH	$^2\Pi_{1/2}$ J=1/2, F=1-1	3.335	4
CH	$^2\Pi_{1/2}$ J=1/2, F=1-0	3.349	4
ex-OH	$^2\Pi_{1/2}$, J = 3/2, F=1-1	4.65024	5a
ex-OH	$^2\Pi_{1/2}$, J = 1/0, F=2-2	4.76556	5a
H_2CO	$1_{1,0}$-$1_{1,1}$	4.82966	5a
CH_3OH cI?	3_1-3_1 $A^{\pm}(v_t=0)$	5.005321	5a
ex-OH	$^2\Pi_{3/2}$, J = 5/2, F=2-2	6.03075	5a
ex-OH	$^2\Pi_{3/2}$, J = 5/2, F=3-3	6.03509	5a
CH_3OH cII	17_{-2} - 18_{-3} $E(v_t=1)$	6.18113	5a
CH_3OH cII	5_1 - 6_0 $A^{+}(v_t=0)$	6.66852	5a
CH_3OH cII	12_4-13_3 $A^{-}(v_t=0)$	7.68223	5a
CH_3OH cII	12_4-13_3 $A^{+}(v_t=0)$	7.83086	5a
CH_3OH cI	9_{-1} - 8_2 $E2(v_t=0)$	9.936202	5b
CH_3OH cII	2_1 - 3_0 $E(v_t=0)$	12.1786	5b
H_2CO	$2_{1,1}$-$2_{1,2}$	14.48848	5b

Masers related to SKA-MID trace …

if SKA-MID extended
to 22.235 GHz



Blind *sensitive* 6.7 GHz methanol maser surveys

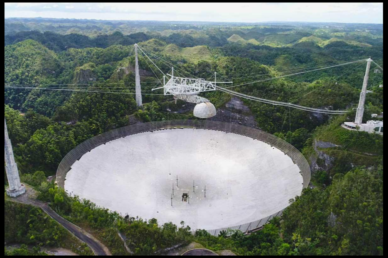
Understand 6.7 GHz methanol - only MYSO?

Complete catalog incl. **weak** methanol masers, for Galactic star formation studies

Combine with surveys of other maser species/transitions

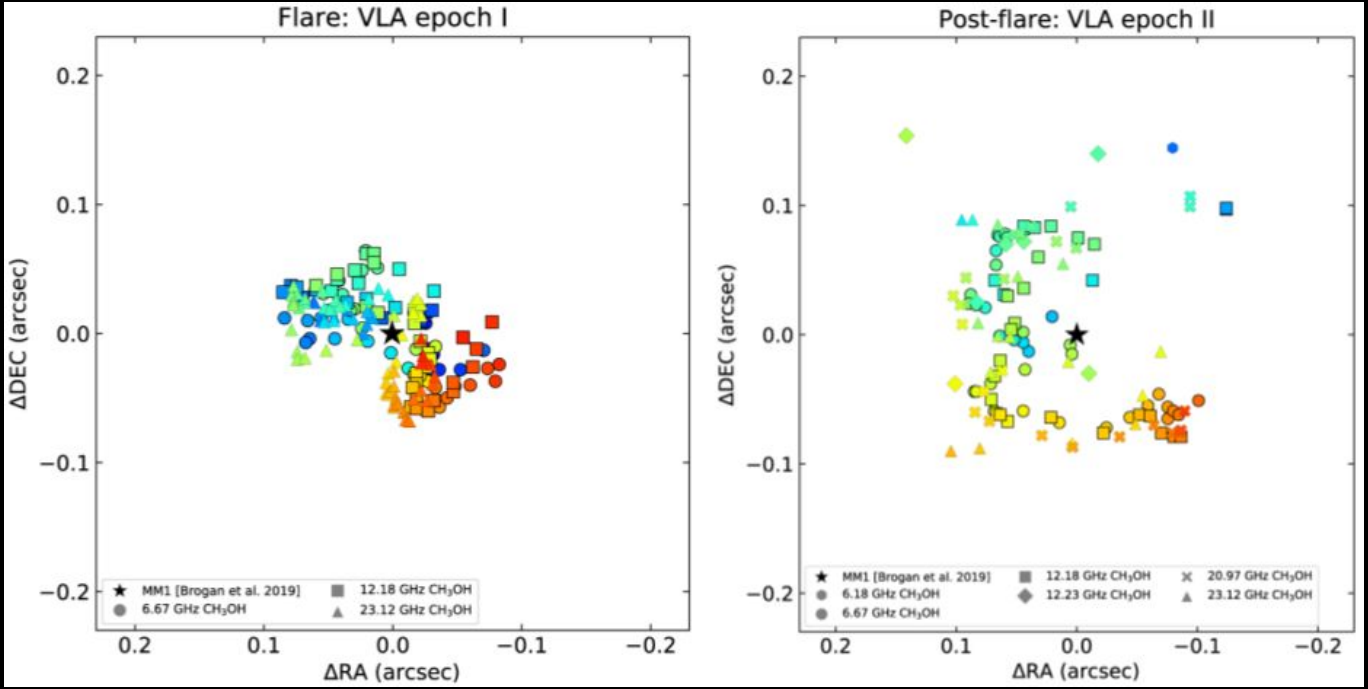
Catch accretion flares!

Survey	Sensivity (1σ) (Jy)	Galactic Longitude	# detections/new	References
26-m Mt Pleasant	0.9	325º – 335º	50/26	Ellingsen et al. (1996)
ATCA		330.8º – 339.8º	57/21	Caswell (1996)
25-m Onsala	0.6	35º – 220º	11/4	Pestalozzi et al. (2005)
32-m Torun	0.6	20º – 40º	100/26	Szymczak et al. (2002)
Arecibo	0.27	35.2º – 53.7º	86/48	Pandian et al. (2007)
64-m Parkes	0.17	345º – 0º – 6º	183/48	Caswell et al. (2010)
64-m Parkes	0.17	6º – 20º	119/42	Green et al. (2010)
64-m Parkes	0.17	330º – 345º	198/80	Caswell et al. (2011)
64-m Parkes	0.17	186º – 330º	207/89	Green et al. (2012)
64-m Parkes	0.17	20º – 60º	265/64	Breen et al. (2015)
VLA (D-conf.)	0.018^a	−2º – 60º	554/84	Nguyen et al. (2022)
SKA-Mid 10 min	0.0051^a			



Methanol flares from accretion bursts

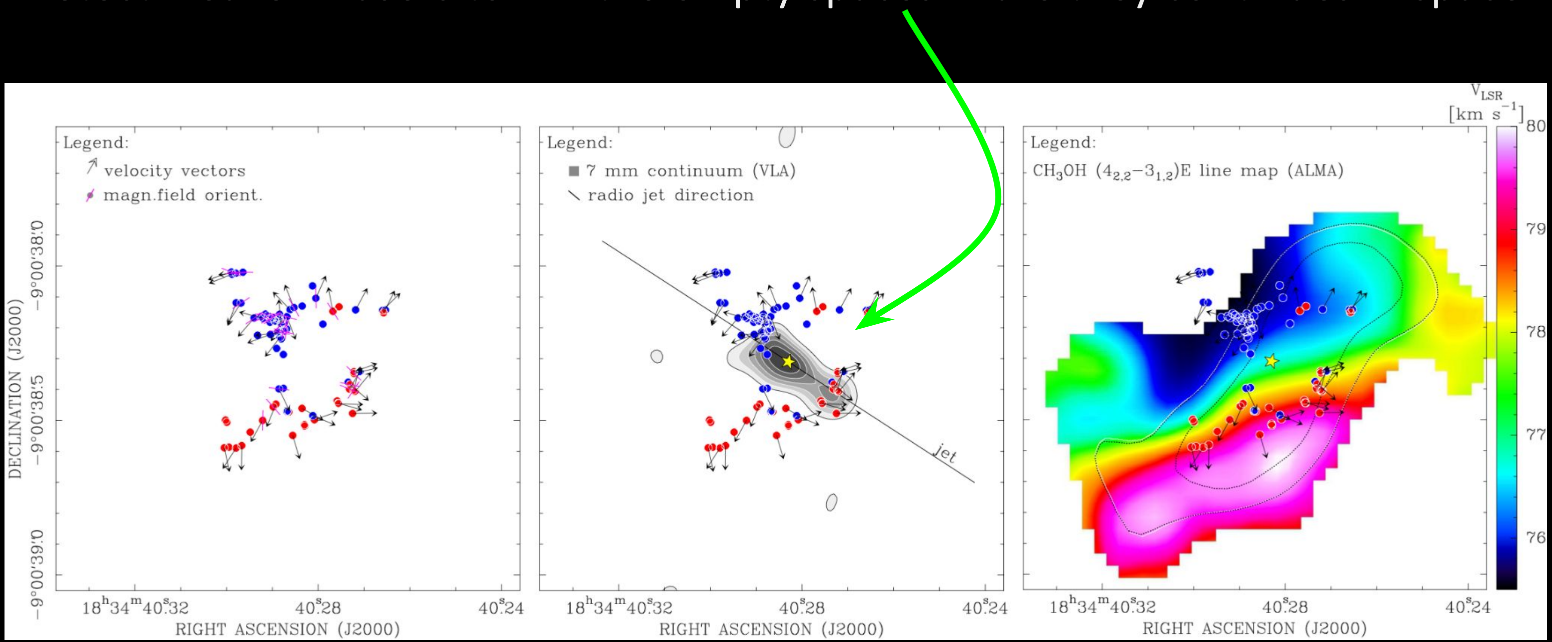
and also other maser species flare, but less bright



Adapted figure from Bayandina et al. 2022

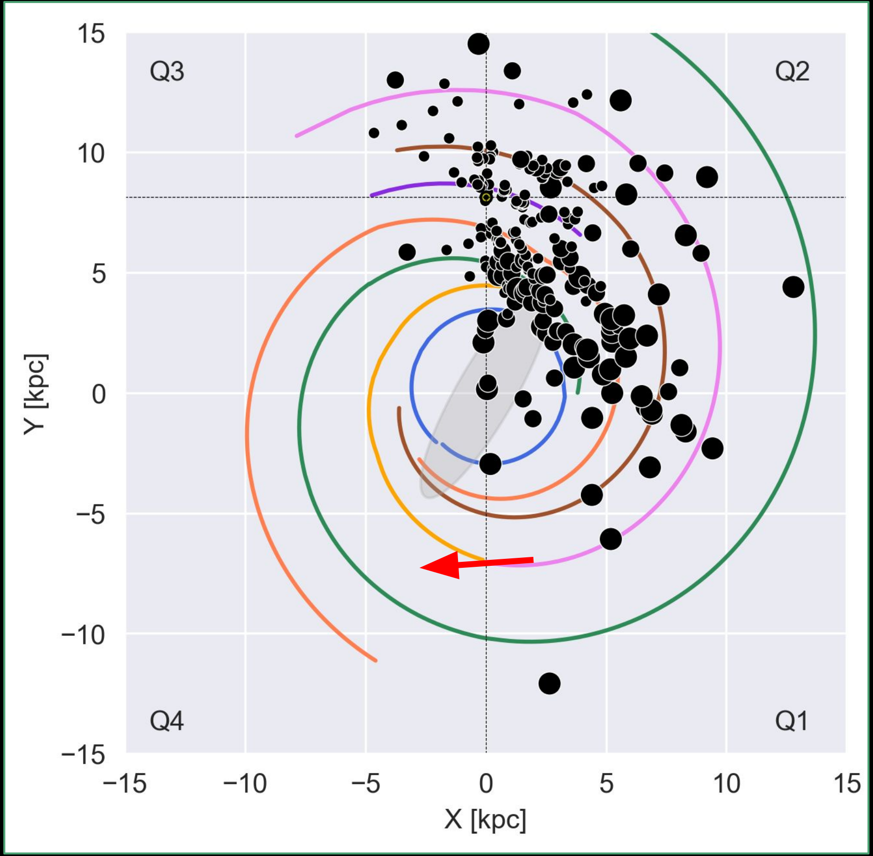
Massive YSO environment and kinematics

Combine with SKA-Mid continuum emission (jet or ionization by Hii region)
Detect weaker masers to “fill the empty spaces” - are they continues in space?



Adapted figure from Sanna et al. 2015 & 2019

3D kinematic distances @ far side of the Galaxy



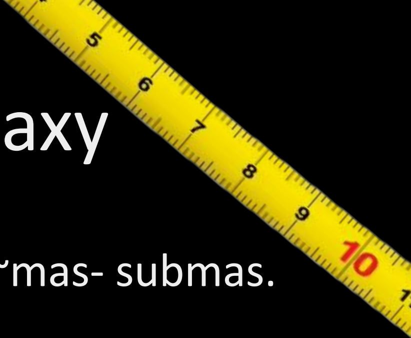
SKA-Mid position accuracy ~mas- submas.

Large (~400 km/s) apparent motions of MYSOs in the far side of the Galaxy due to Gal. rot result in proper motions of several mas/year.

-> 3D kinematic distances (Reid 2022),

which have smaller error bars at large distances than trigonometric parallaxes.

← Figure after Immer & Rygl 2022, data: Reid+ 2019, Hirota+ 2020, Xu+2022, Hyland+2023



Masers in evolved stars

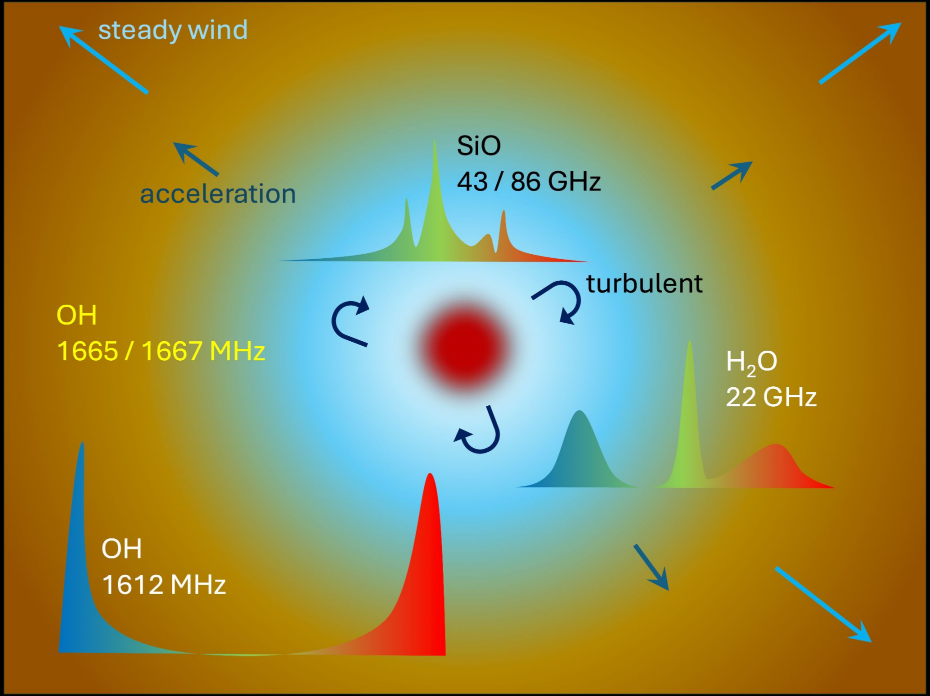


Figure: J. van Loon

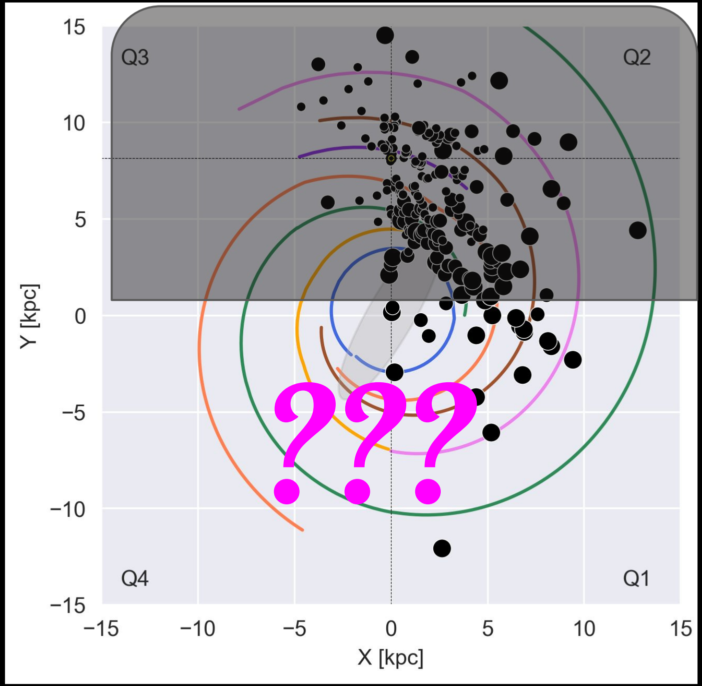
Masers can be used to study:

- Kinematics and dynamics of gas in the envelope;
- Mass-loss phenomena;
- Magnetic fields.

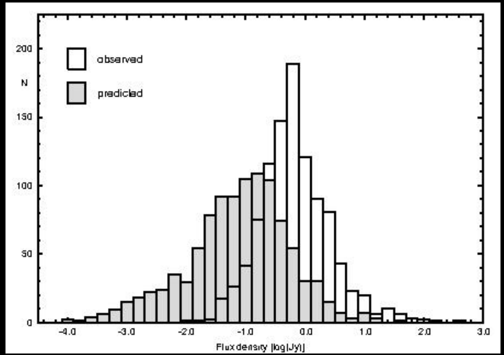
New light on the 'Zona Galactica Incognita'

The stellar population in the far side of our Galaxy is not well studied.

Only with the SKA sensitivity these evolved stars will be detectable through OH maser emission.



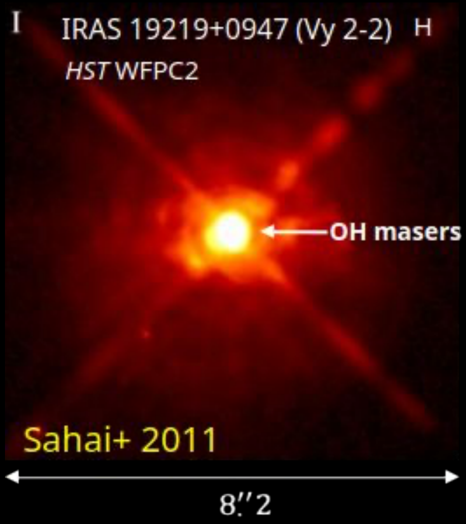
Galactic distribution of OH-bearing evolved stars



← Figure after Immer & Rygl 2022, data: Reid+ 2019, Hirota+ 2020, Xu+2022, Hyland+2023

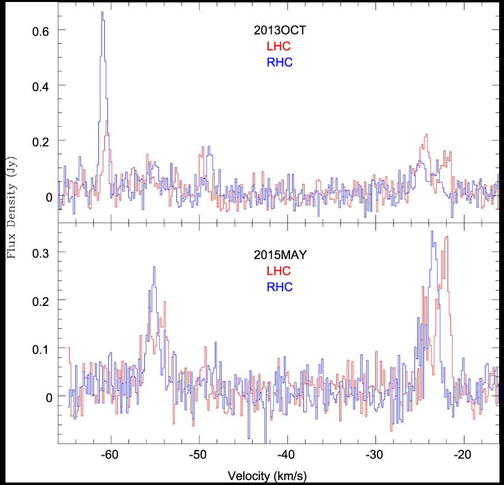
OH-masers in Planetary Nebulae

OH masers track the first 10^3 yr of PNe, thus important for understanding their onset.



Few known with masers (6), SKA sensitivity would boost their number.

Zeeman splitting observed -> Bfield information.



Qiao et al. 2016

Stellar evolution in low-Z environments

Sensitive OH maser observations may open the door to mass-loss studies of evolved stars in extreme low metallicity environments (0.2-0.5 Zsun) as the LMC, SMC, and NGC 6822.

No. 2, 1986 OH / IR STAR IN LMC L83

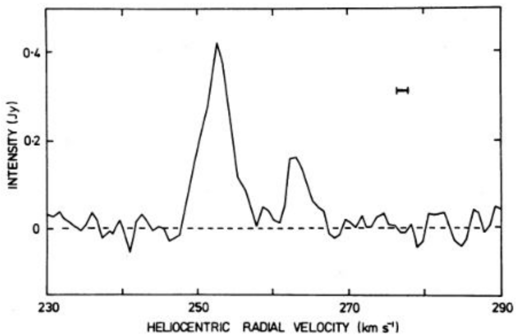


FIG. 2.—The 1612 MHz maser emission associated with IRAS 04553−6825. The spectrum has been smoothed to a velocity resolution of 1.5 km s^{-1}, represented by the horizontal bar.

Goldman 2017,2018

SKA-Mid sensitivity: a boost for stellar maser science

High sensitivity & spectral resolution, multiple zoom bands to cover multiple lines in one band, tens mas angular resolution, large FOV

Deeper unbiased surveys, build more complete maser catalogs, detect weak and extended masers: will improve our understanding of maser excitation mechanisms and kinematics+ phys conditions in SFRs.

3D kinematic distances in the (far side of the) Galaxy

Detect new further evolved stars through OH masers, far side of the Galaxy and even in nearby galaxies in extreme metal poor environments.

Uncover the initial PNe phase through OH masers

Some numbers for sensitivity and spectral resolution

High sensitivity & spectral resolution, multiple zoom bands to cover multiple lines in one band, tens mas angular resolution, large FOV

B2: 3σ sensitivity ~ 10 mJy (evolved star at far side of the Galaxy)

B2: 5σ sensitivity ~ 10 mJy (PNe, detect OH with 40% circular polarization)

B2: 1σ sensitivity << 4 mJy (searching for OH masers in SMC/LMC)

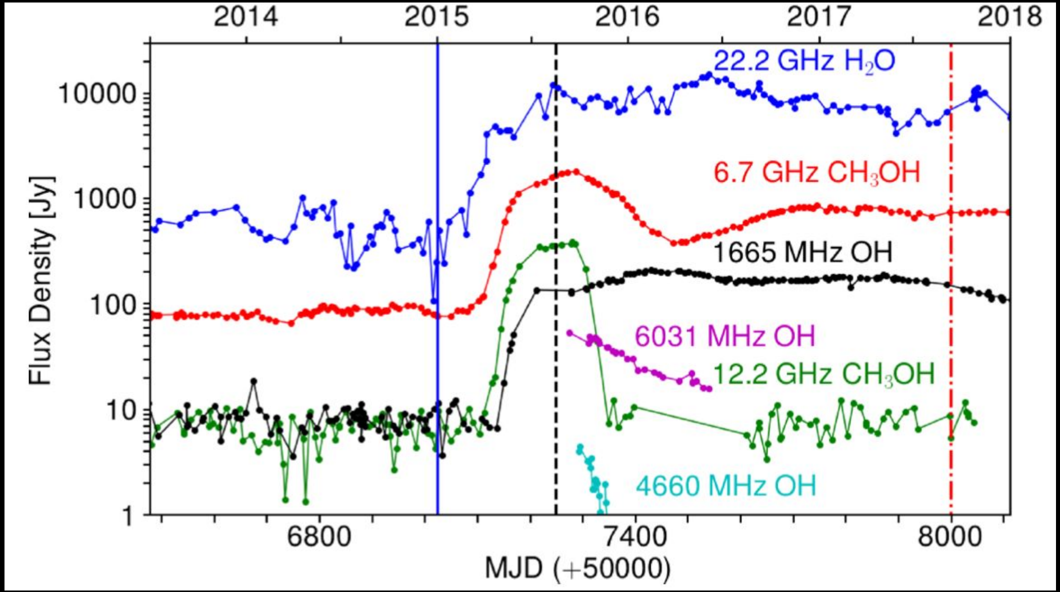
B5a: 1σ sensitivity < 10 mJy (improve blind methanol surveys by factor >2)

B5a: 3σ sensitivity < 1mJy (weak methanol emission in the YSO environment)

Bandwidth for sensitivity ~ 0.1 km/s

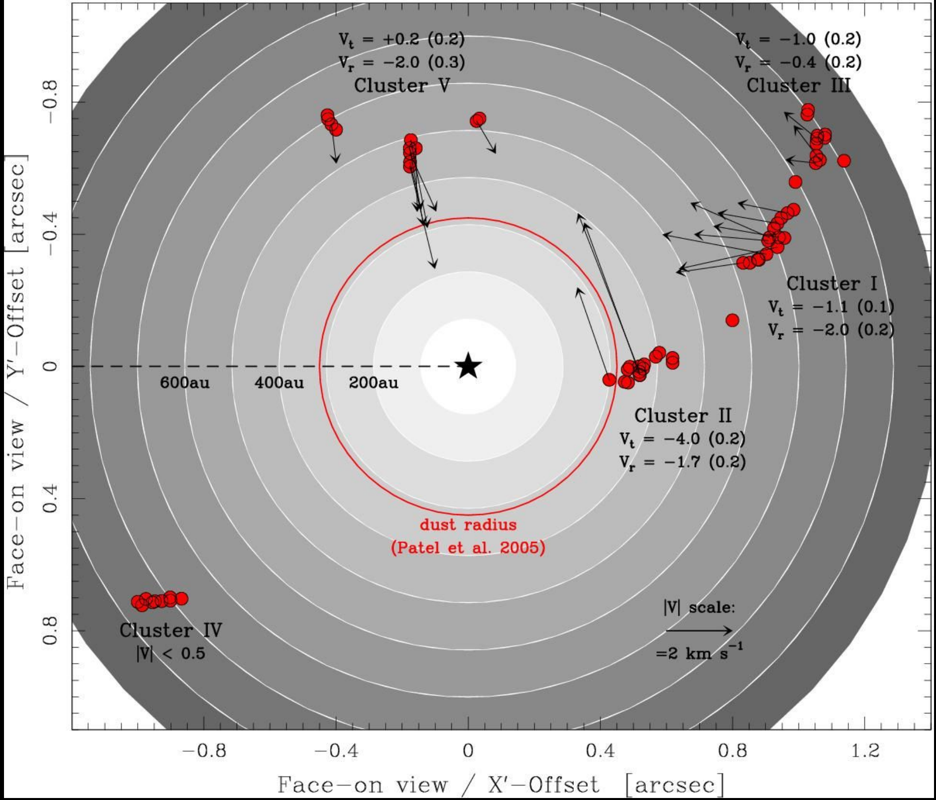
Spectral resolution ~ down to 10 m/s

Accretion burst in SFR NGC 6334I



MacLeod et al. 2018

Massive YSO kinematics



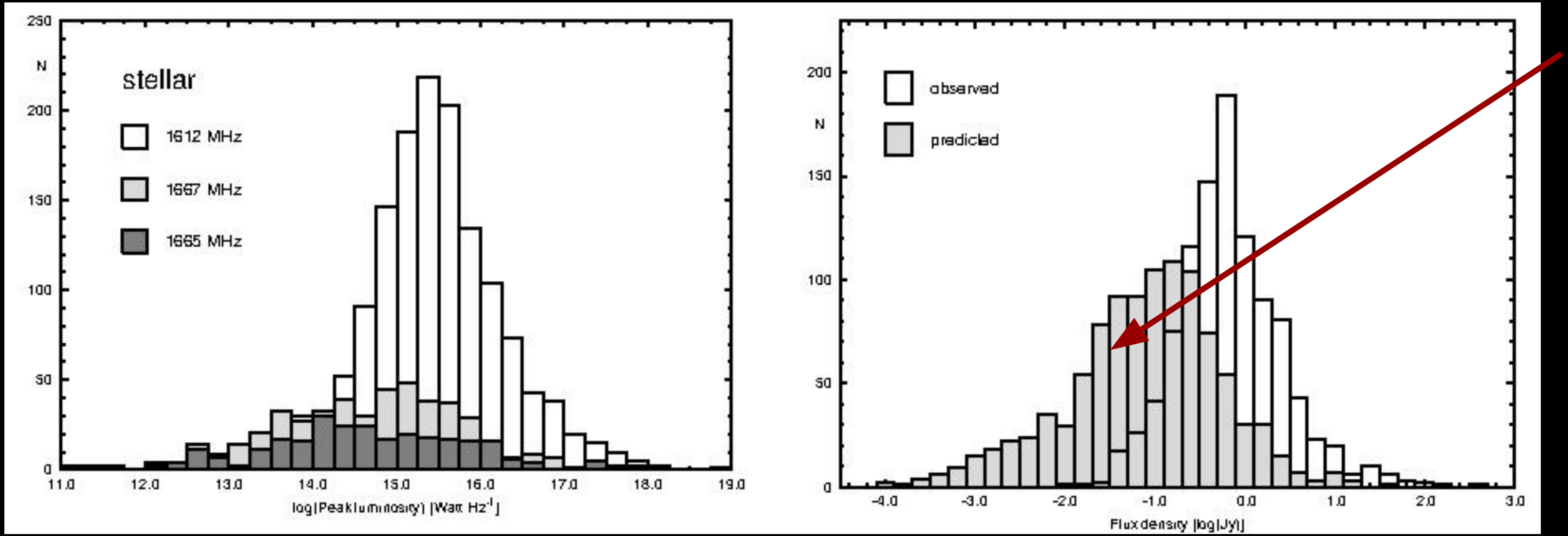
We can trace motions of the gas at the level of a few km/s!
E.g.
Sanna et al. (2017):

- ❑ planar infall of CH_3OH,
- ❑ gas around **HMSFR**

Cepheus A HW2,

- ❑ contraction of the gas,
- ❑ central mass of 5–6 M_{Sun}

New light on the 'Zona Galactica Incognita'



Based on known~3000 OH 1612 MHz masers, calculations show a steep increase of the number of stars with decreasing OH maser luminosity with a maximum at 2x10^{15} W/Hz. The decrease in number at lower luminosities is very likely due to incompleteness by the sensitivity limits of the past surveys (Etoka et al. 2015). SKA-MID will be sensitive enough to shed new light on the ZGI - *the zoom mode for spectral line observations is requested.*

water (H_2O)