KaVA Large Program for *High-Mass* Star-Formation

Tomoya Hirota (NAOJ) and Kee-Tae Kim (KASI)
On behalf of SFRs WG

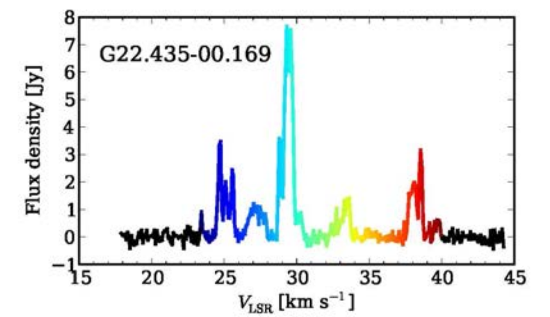
Organization

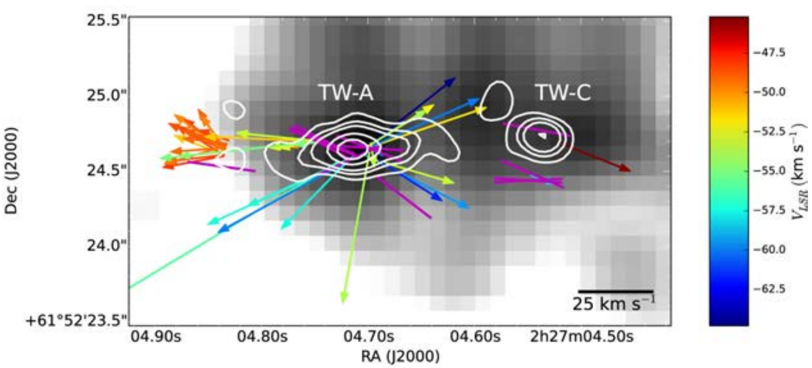
- Co-PI
  - T. Hirota (NAOJ) and K. T. Kim (KASI)
- Core members ~ 17, including 3 students
  - D. Y. Byun, J. O. Chibueze, K. Hachisuka, B. Hu, E. Hwang, J. Hwang, J. H. Kang, J. Kim, J. S. Kim, M. K. Kim, T. Liu, N. Matsumoto, K. Motogi, C. S. Oh, K. Sugiyama, K. Sunada, Y. W. Wu (~17, including 3 students)
- Other members ~ 40

- Regular skype meeting since 2011; **100th on Sep. 23**
- New members and collaborator are always welcome!

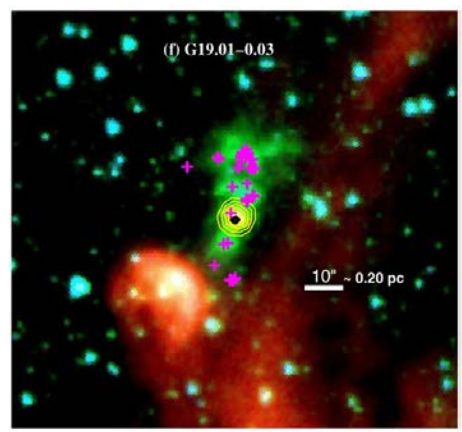
KaVA SFRs LP

- **Understanding high-mass star formation through KaVA observations of water and methanol masers**
  - Statistical VLBI monitoring/survey to reveal 3D velocity and spatial structures of 22GHz H_2O/44GHz CH_3OH masers associated with high-mass young stellar objects (HM-YSOs)

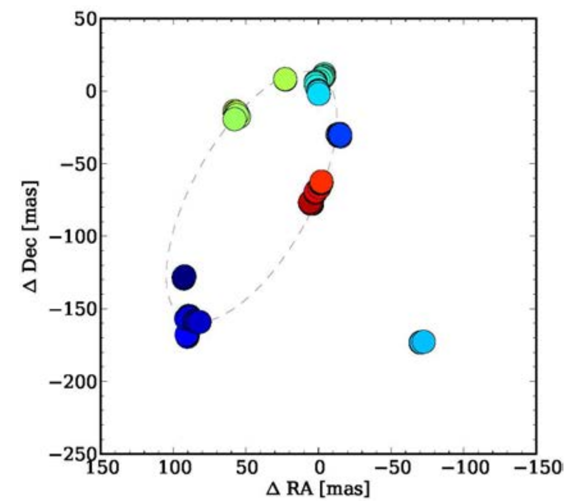




22 GHz H_2O masers; high-velocity outflow and jet (Goddi+2017)



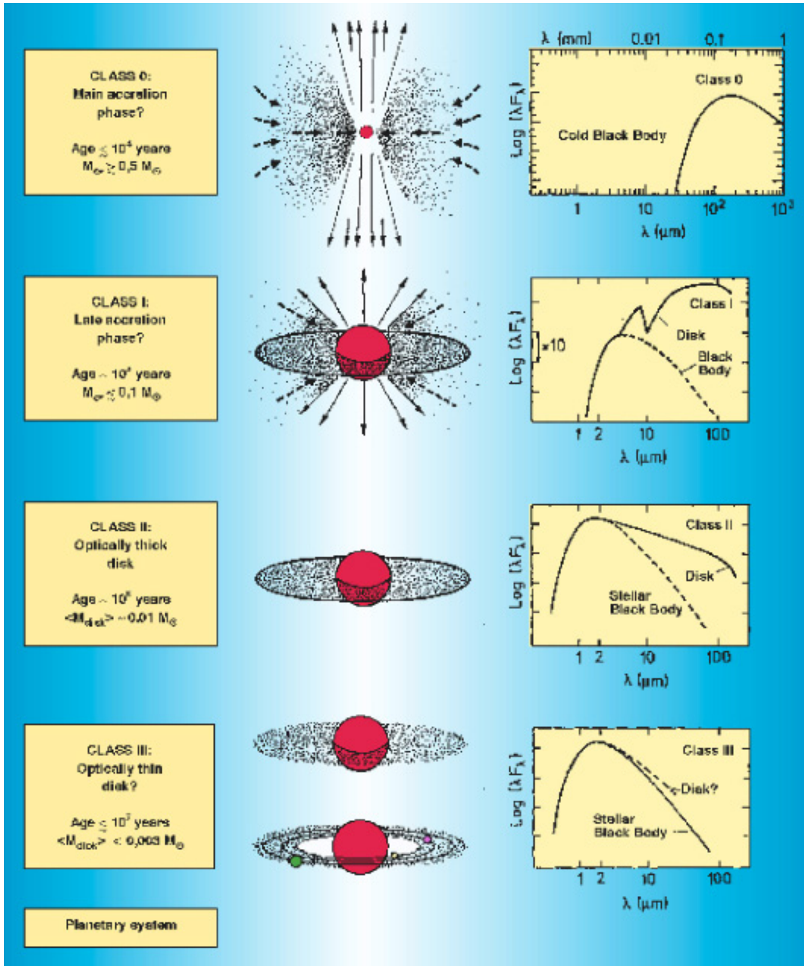
44 GHz Class I CH_3OH masers; low-velocity outflow (Cyganowski+2009)

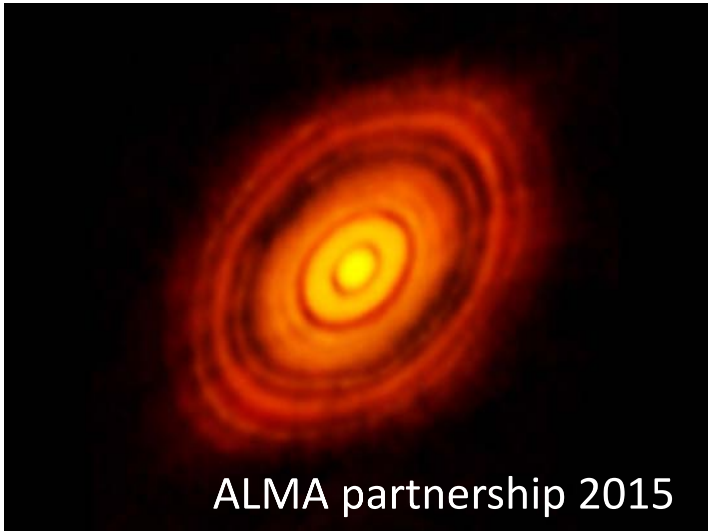


6.7 GHz Class II CH_3OH masers; disk, toroid or outflow (Bartkiewicz+2016)

Why star-formation studies?

- Direct link to planet formation
  - Origin of Solar system, Earth, and life
- In case of low-mass stars
  - Well established based on observational studies
  - Theoretically interpreted

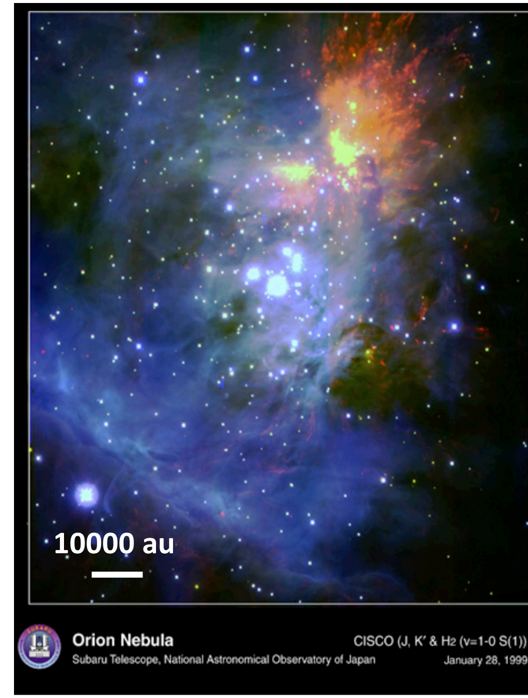




ALMA partnership 2015

What about high-mass stars?

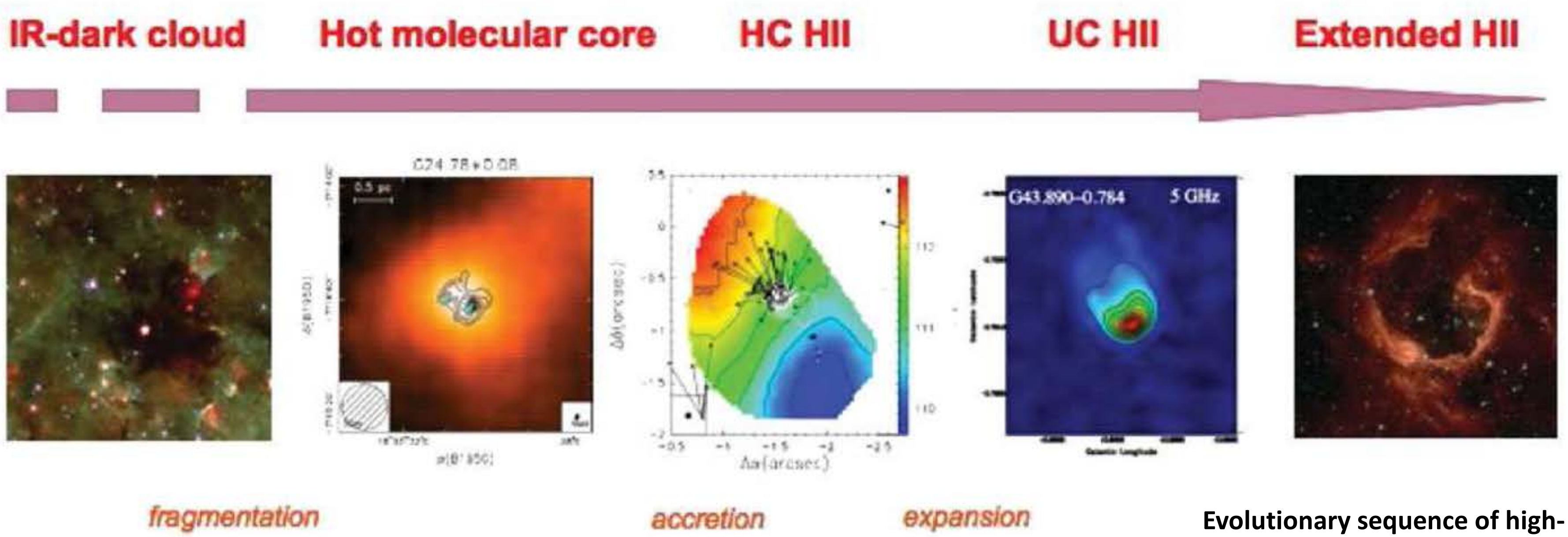
- How high mass (HM)?
  - Early B (B3 and earlier) and O stars
  - More massive than $8M_{Sun}$
  - More luminous than $10^3\ L_{Sun}$
- Significant impacts on astronomy, astrophysics, and astrochemistry
  - Influences on surroundings by strong UV, wind, explosion, ...



ALMA (ESO/NAOJ/NRAO).
Visible light image: the NASA/ESA Hubble Space Telescope

Why HM-YSOs still necessary?

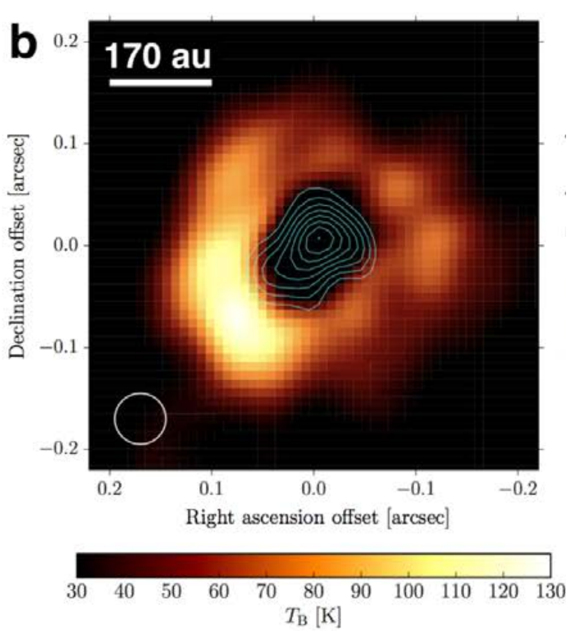
- Less understood in comparison with low-mass YSOs
  - Still challenging due to rarer population, short lifetime, further distances, and complicated structures in embedded clusters
  - There are unresolved issues such as initial condition, accretion process, feedback process, initial mass function, first star in the Universe, etc.



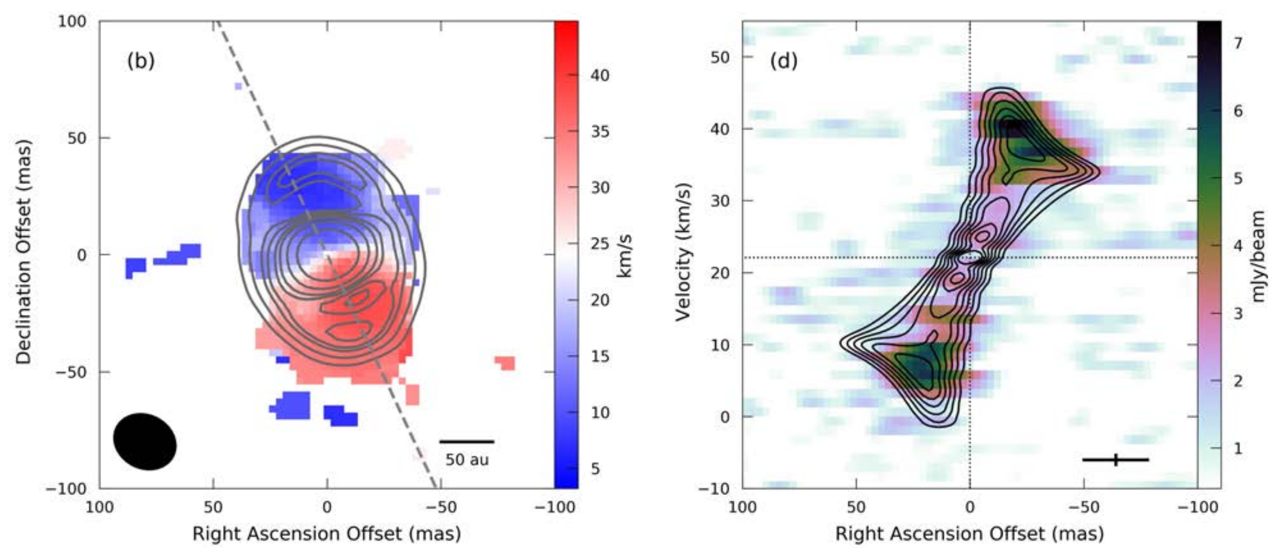
Evolutionary sequence of high-mass young star (Beltran 2011)

Recent progress in observations

- Evidence of disk/outflow system with 10-10^4 AU
  - At a few 10 mas resolution with the long baseline with ALMA
  - But 3D velocity structure is unavailable (except full ALMA)
  - Still insufficient number of targets at high resolution
  - VLBI will play unique roles to resolve dynamical structures



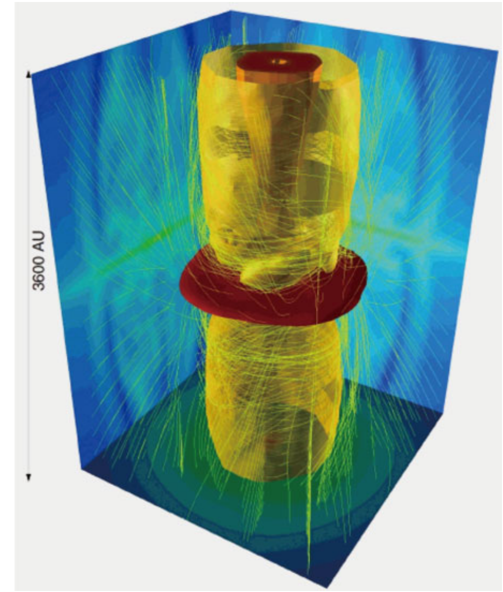
Face-on disk in G353.273+0.641 (Motogi et al. 2019)



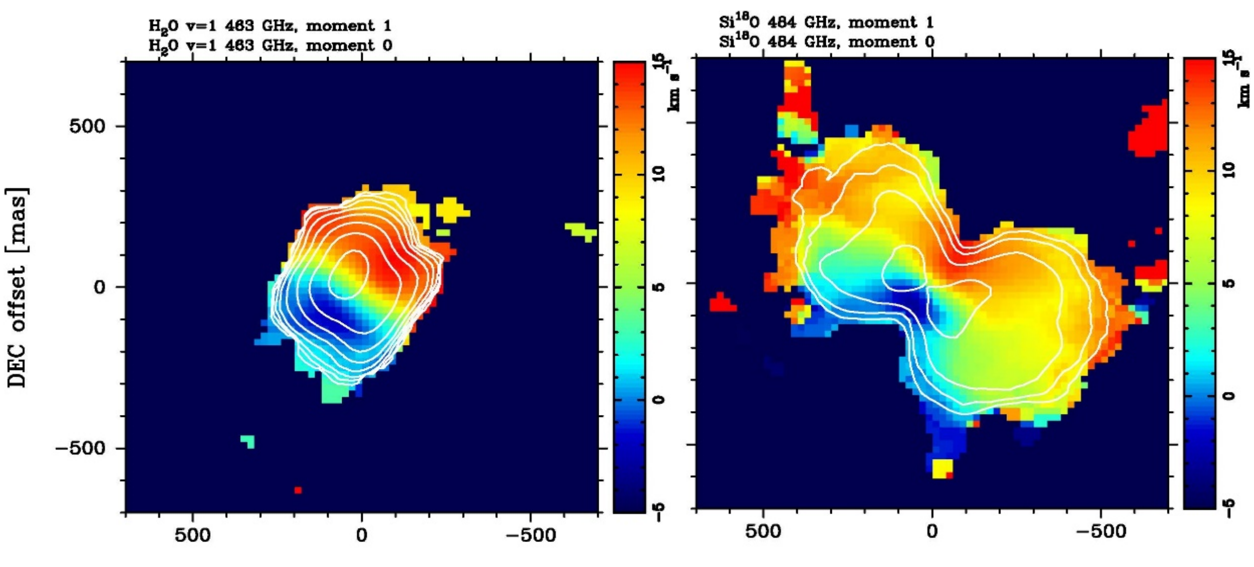
Keplerian disk in G17.64+0.14 traced by vibrationally excited H2O line (Maud et al. 2019)

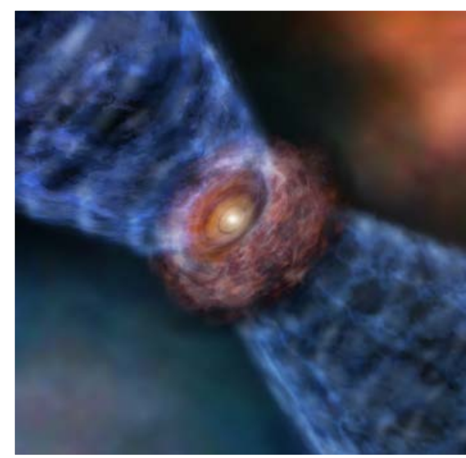
Science goals

- 3D dynamical structures of disks/outflows system traced by multiple masers
  - Achievable only by using VLBI through proper motion measurements



Matsuhita et al. (2017, 2018)

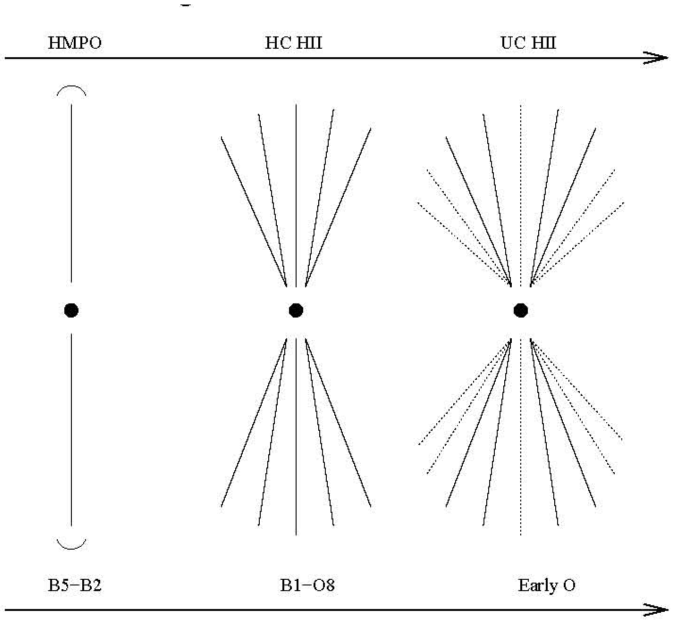




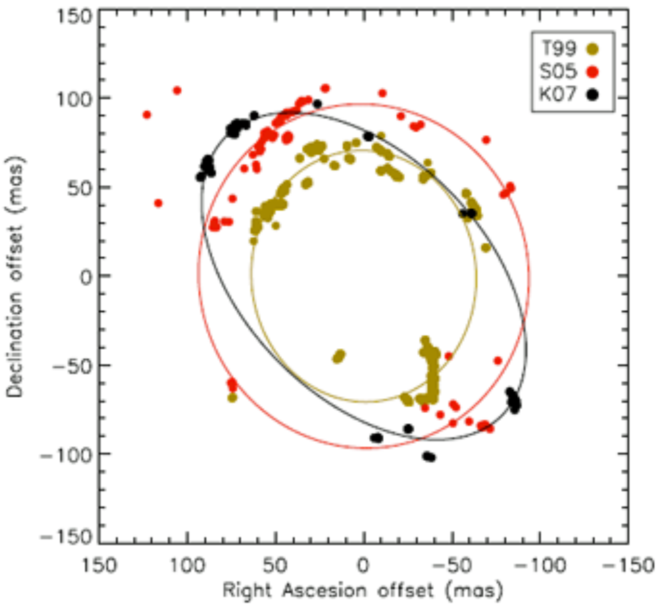
ALMA band 8 observations of SiO and H2O lines (Hirota+2017)

Science goals

- Evolutionary scenario of high-mass star-forming regions and their dynamical structures
  - Need statistical samples
  - Similar studies are in progress (Moscadelli et al. 2016, Sanna et al. 2018), but they are complementary with each other



Evolution of outflow (Beuther & Shepherd 2005)



Temporal variation of outflow in W75N (Kim. J. S. et al. 2013)

Science goals

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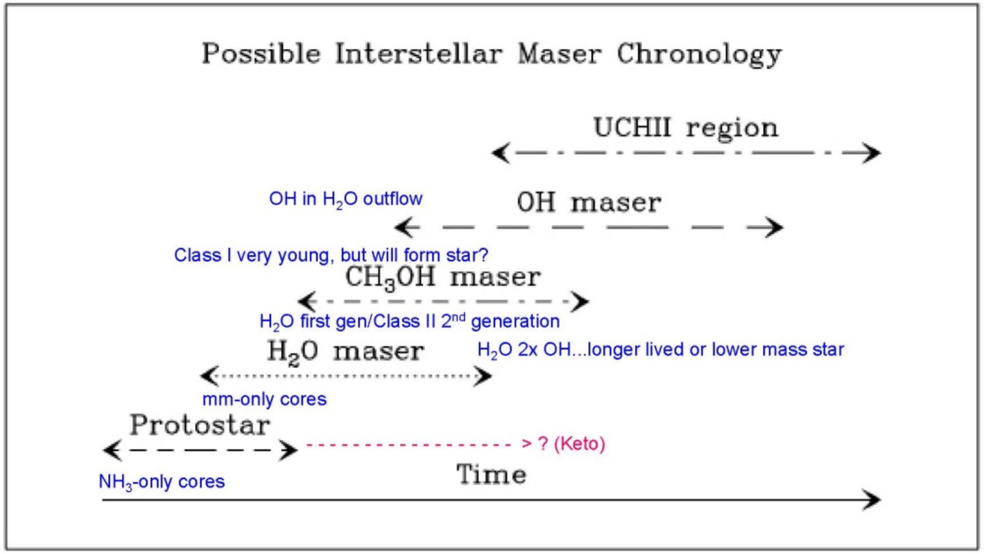
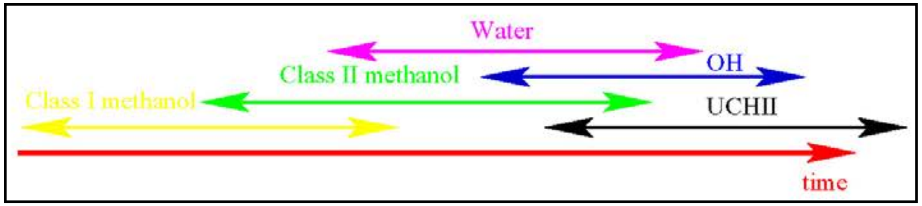
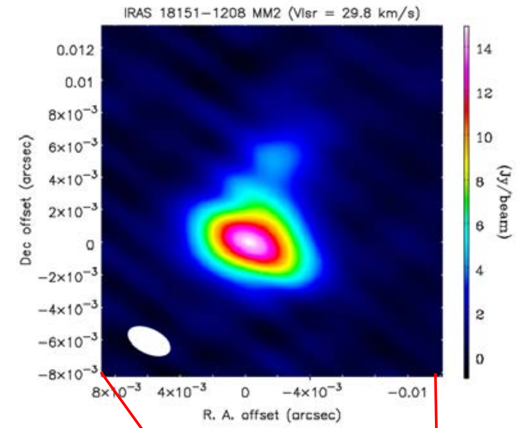


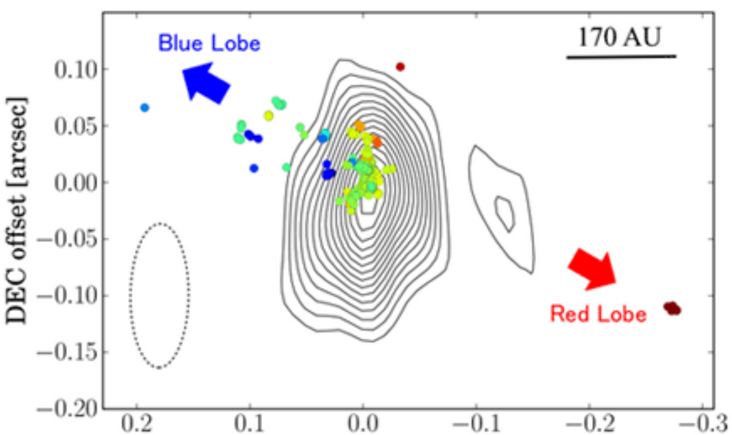


Maser chronology by Reid 2007 vs Ellingsen 2007

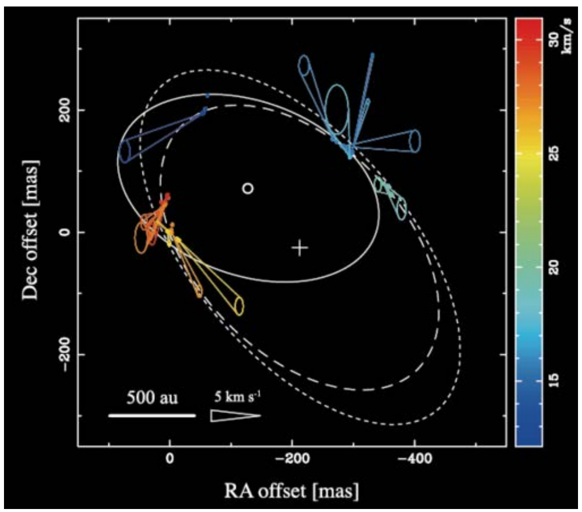
Our tracers

- Centimeter/millimeter maser lines
  - 22 GHz H_2O; high-velocity jet/outflow
  - 6.7 GHz CH_3OH; low-velocity outflow/disk
  - 44 GHz CH_3OH; low-velocity outflow
  - Complementary with each other;

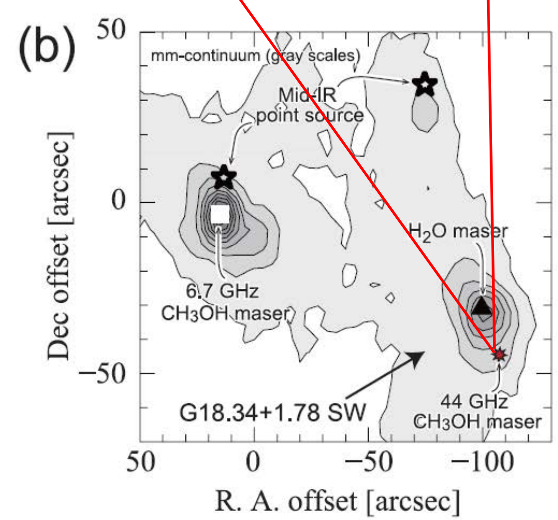




G353.273+0.641 (Motogi et al. 2016);
H2O masers tracing high velocity
(~100 km/s) jet



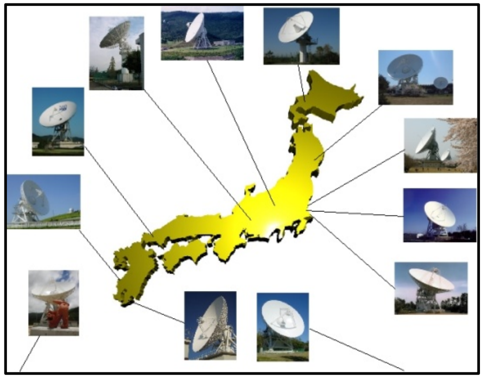
G6.79-0.25
(Sugiyama et al. 2015);
6.7 GHz Class II CH3OH masers
Associated with rotating disk



G18.34+1,78SW (Matsumoto+2014);
44 GHz Class I CH_3OH masers
distributed in low-velocity outflow

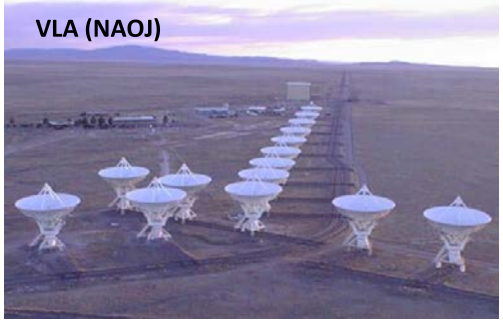
Follow-up observations

- All are complementary to KaVA results
  - VERA astrometry (Mikyoung Kim and Jugha Kim)
  - ALMA cycle 3 (PI: Mikyoung Kim, and others)
  - ALMA cycle 6 (PI: Jungha Kim)
  - VLA 2020A (PI: Kee-Tae Kim)
  - JVN (PI: Sugiyama)
  - JCMT and ASTE SD (PI: Tie Liu)

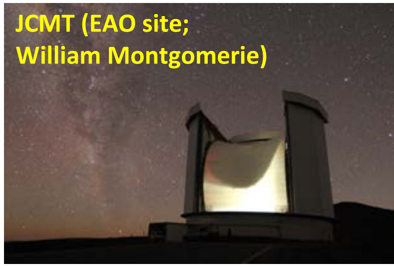


6.7GHz methanol masers (JVN)
Annual parallax (VERA)

Thermal continuum/lines



Radio continuum/methanol masers



Large-scale structure

Timeline

- First year (2016-2017)
  - Snap-shot survey of 25 H_2O masers at 22 GHz
  - Snap-shot survey of 19 CH_3OH masers at 44 GHz
  - Selected from SD/archive data, KVN SD/fringe-check
- Second year (2018-2019)
  - Monitoring of selected 16 H_2O masers at 22 GHz
  - Monitoring of selected 3 CH_3OH masers at 44 GHz
  - Selected from 1st year and VERA archive data
- Third year and beyond (2020-)
  - Further sources, intensive monitoring, other sciences (TBD)?

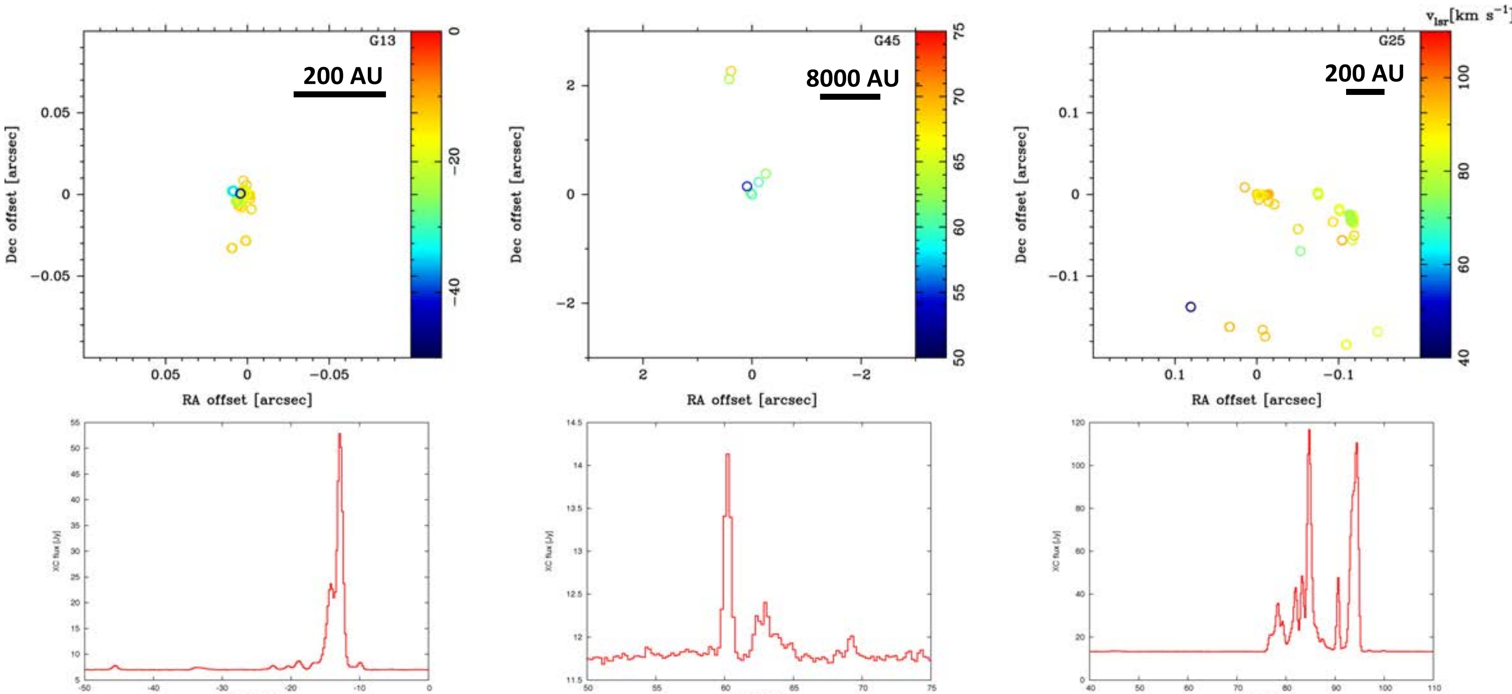
Second year; monitoring of selected sources

- Finished in last May
  - 16 H_2O masers
  - 3 CH_3OH masers
  - 4 epochs monitoring with 2 month interval
  - Additional observations in 2019B for 3 H_2O and 3 CH_3OH masers
- Publication plan
  - Some individual studies including the previous data
  - Summary (survey) papers

	H2O masers	Hirota
1	G13.87	Motogi
1	G10.62	Jungha
1	G45.07	
1	G25.82	Jungha, Giseon
2	G19.61	Eodam, Giseon
2	~~G34.24~~ G34.26	Byun
2	IRAS18018	
2	G30.82	Jungha
3	G354.61	
3	G351.24	Motogi
3	G0.54/RCW142	
3	IRAS18018	
4	IRAS18056	Jungha
4	IRAS20198	
4	G049.49	Eodam, Giseon
4	W51D	Eodam
	G12.88	
	IRAS18556	
	IRAS18094	
	G18.34SW	Burns
	CH3OH masers	Kee-Tae, Sugiyama
	G357.967	
	G18.34SW	Burns
	G049.49	

Survey results

- Imaging of H_2O maser sources (Hirota et al.)
  - Script for maser identification, proper motion fitting, plotting maser maps and proper motion vectors almost ready
  - To be compared with ALMA (waiting for allocation) and JVLA (proposal submitted) data



Some examples from preliminary results of the 22 GHz H_2O maser survey

Some examples of case studies

- KaVA+ALMA for G25.82-0.17 (Kim, J. et al. submitted)
  - Cycle 3 for CH_3OH samples (Mikyoung Kim)
  - Cycle 6 for H_2O samples (Jungha Kim)
  - Direct comparison of spatial/velocity structure by filling the gaps of sparse maser distributions

See talk by
Jungha Kim

Some examples of case studies

- KaVA imaging of G19.61-0.23 (Hwang, E. et al. in prep.)
  - Analyzed by currently developing “Parsel-Tongue” script
  - Imaging of extended maser features will become easier (e.g. 100 mas FoV in 1”x1” regions for 100 channels correspond to 10000 images!)

See talks by
Eodam Hwang

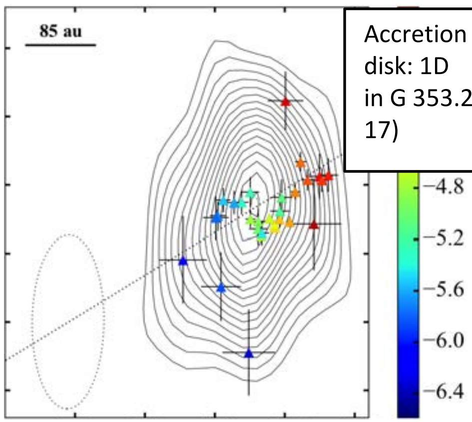
Possible future plan

- Collaboration with Maser Monitoring Organization (M2O)
  - Since 2017 September in IAUS 336 “Astrophysical masers”
  - ToO VLBI observations based on systematic SD monitoring
  - Follow-up observations (e.g. ALMA DDT approved yesterday)
  - Catching accretion burst events in high-mass YSOs

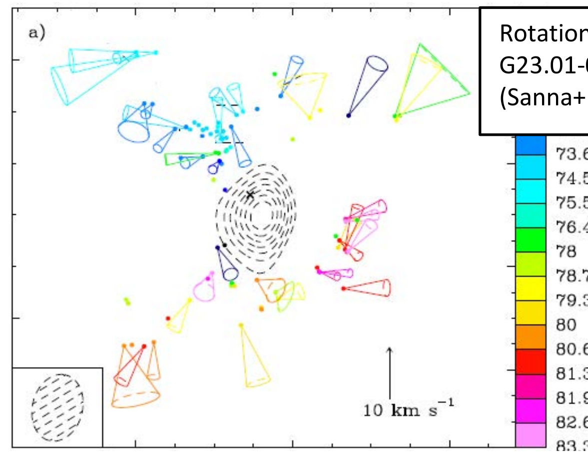
See talks by
Ross burns and Kitiyanee Asanok
and poster by
Koichiro Sugiyama

Possible future plan

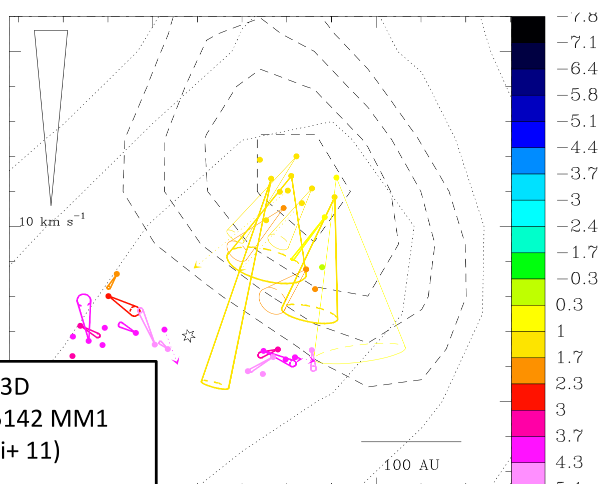
- EAVN LP for C-band methanol masers (Sugiyama et al.)
  - Complementary with H_2O and 44 GHz methanol masers



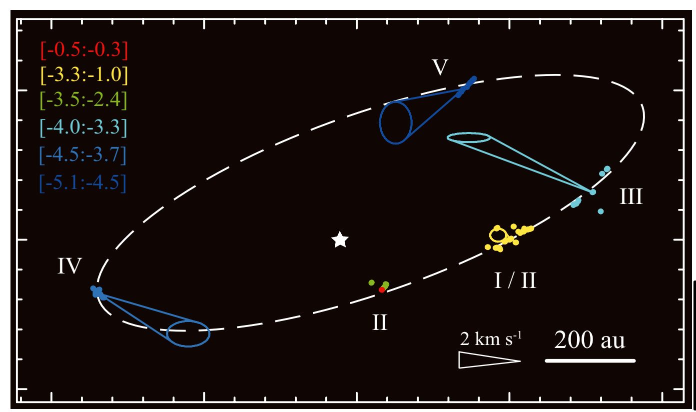
Accretion from 100 au scale disk: 1D
in G 353.273+0.641 (Motogi+ 17)



Rotation + Expansion
G23.01-0.41: 3D
(Sanna+ 10b)



Infall: 3D
AFGL5142 MM1
(Goddi+ 11)



Rotation + Infall
Cepheus A-HW2: 3D
(Sugiyama+ 14)

Methanol maser maps collected by Sugiyama

Tamna 21 m
KASI/KJJVC
Yonsei 21 m
Ulsan 21 m
Yamaguchi 32 m
© NAOJ
Mizusawa 20 m
Nanshan 26 m
KVN
Hitachi 32 m
©NAOJ
CVN
Tianma 65 m
VERA
JVN
TNRT40
Ishigakijima 20 m
C-band EAVN
(by Sugiyama)
20XX semester ??
The East-Asian VLBI Network
(Image Credit: Reto Stöckli, NASA Earth Observatory)
Iriki 20 m
Nobeyama 45 m
Ogasawara 20m

Summary and future

- KaVA LPs have started since 2016
  - Monitoring observations will be completed in 2019B
  - Data analysis are still on-going
  - Follow-up observations are carried out using VERA, ALMA, etc.
- Future EAVN LP will be discussed until 2020B
  - EAVN imaging of 6.7 GHz methanol masers will be complementary to the current KaVA LP
  - Time-domain maser studies under collaboration with M2O will be a key for understanding of accretion processes in HM-YSOs
  - Possible new sciences with polarimetry and astrometry

- New members/collaboration for EAVN LP are welcome