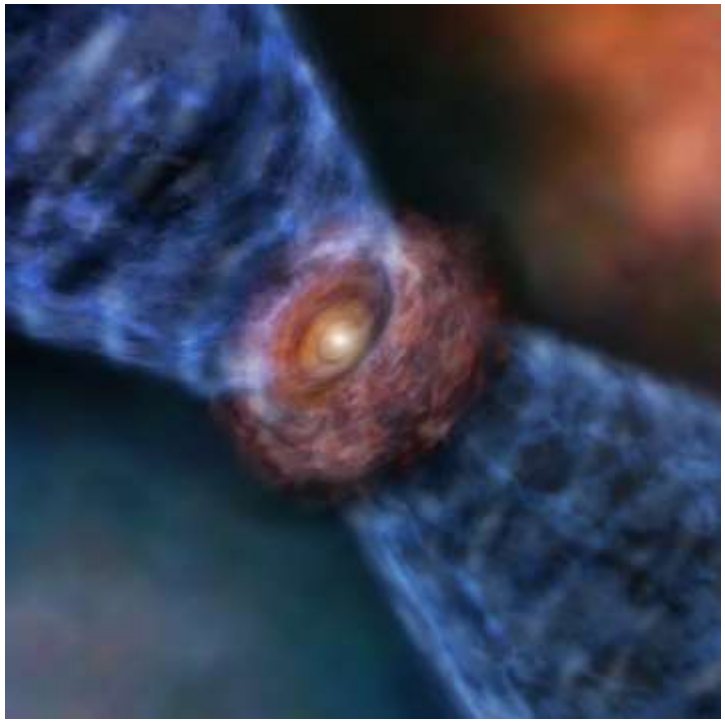
Understanding high-mass star formation through KaVA observations of water and methanol masers

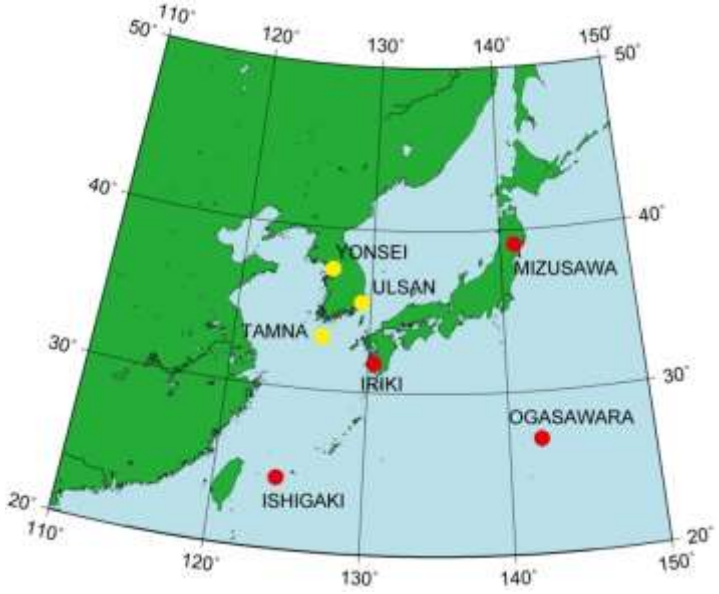


Kee-Tae Kim (KASI), Tomoya Hirota (NAOJ),
on behalf of KaVA SFRs sub-WG
(James Chibueze, Jungha Kim, K. Motogi, K. Sugiyama, K. Sunada)

KaVA large program (LP)

- KaVA: KVN and VERA Array
- Three LPs since 2015
  - SFR (K. T. Kim and Hirota)
  - Late-type stars (Cho and Imai)
  - AGN (Sohn and Kino)
- Allocation of ~200 hrs/yr
- Long-term program ~4 yr



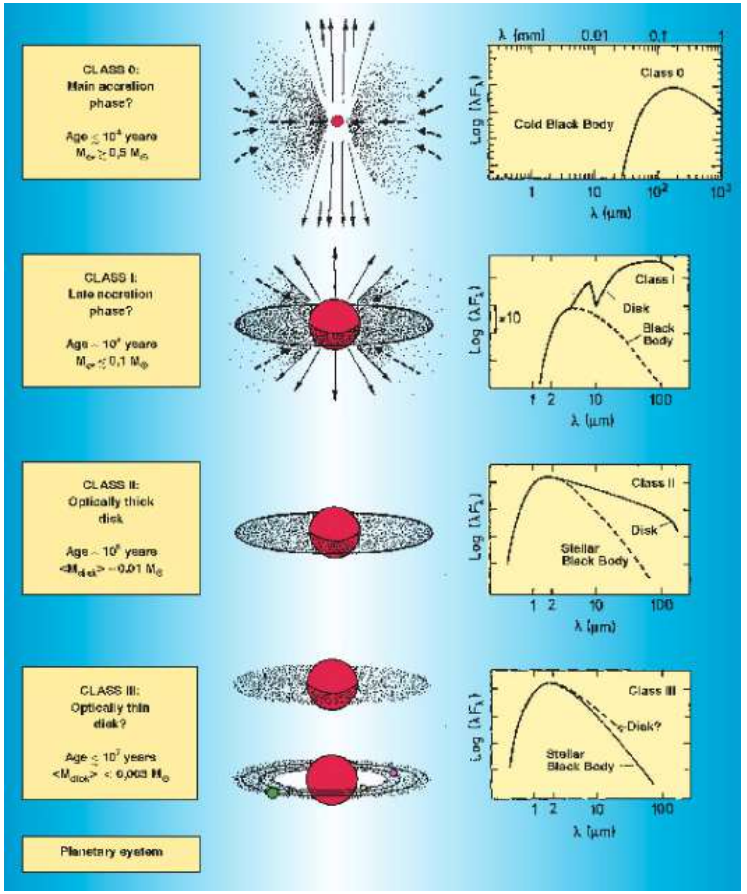


KaVA SFRs LP

- **Understanding high-mass star formation through KaVA observations of water and methanol masers**
- VLBI survey/monitoring to reveal 3D velocity and spatial structures of 22GHz H_2O/44GHz CH_3OH maser lines in 87 high-mass YSOs (HM-YSOs)
  - Physical/dynamical properties of disk/jet/outflow
  - Evolution of disk/jet/outflow and maser chronology

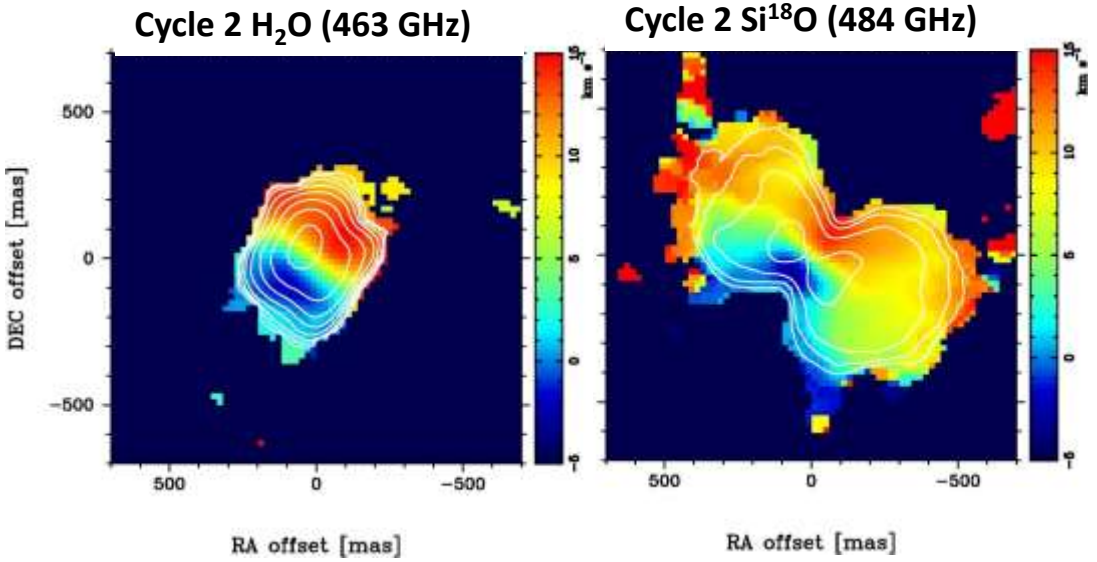
Why HM-YSOs?

- Major impact on astronomy
  - Strong influence on formation and evolution of stars, clusters, HI/MCs, and galaxies
- But not well understood in contrast to low-mass YSOs
  - Initial condition?
  - Accretion process?
  - Feedback process?
  - Initial mass function?

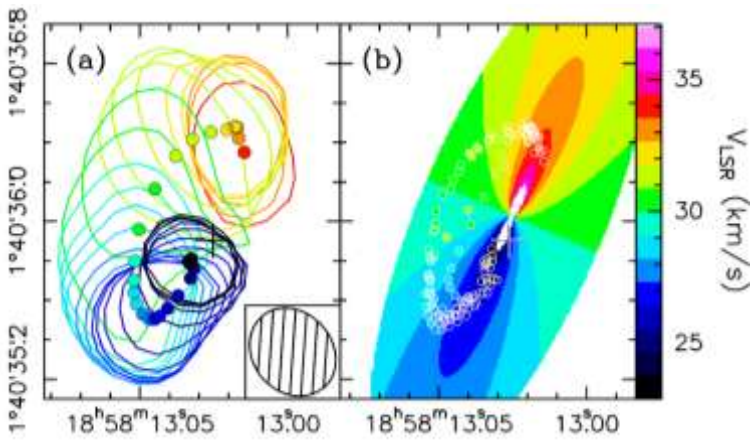


Mass accretion/ejection in HM-YSOs

- Evidence of disk/outflow system with 10-10^4 AU
  - But spatial resolution is insufficient even with ALMA
  - 3D velocity structure is unavailable (except full ALMA)
  - Need systematic VLBI survey



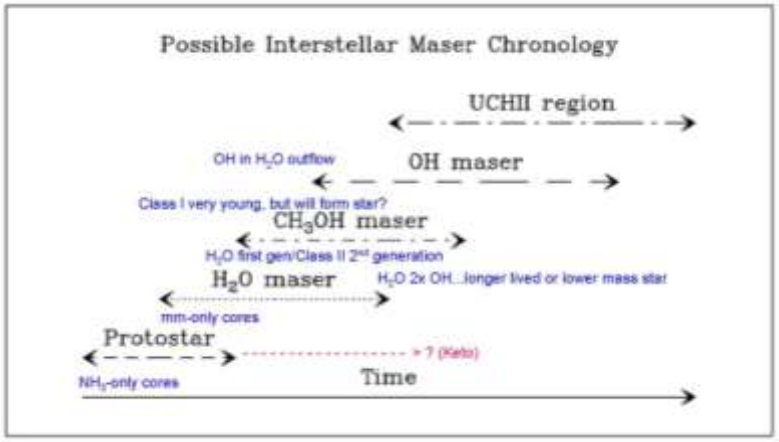
Orion Source I (Hirota+ 2017)

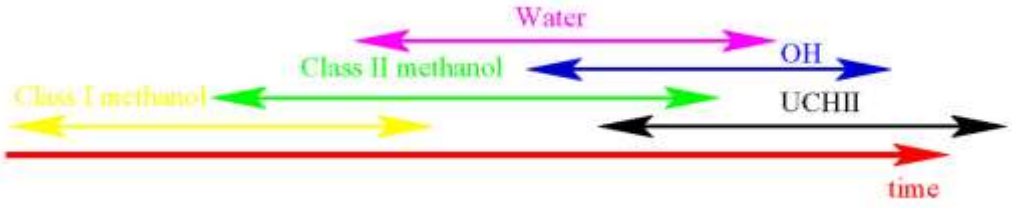


G35.20-0.74N (Sanchez-Monge+ 2013)

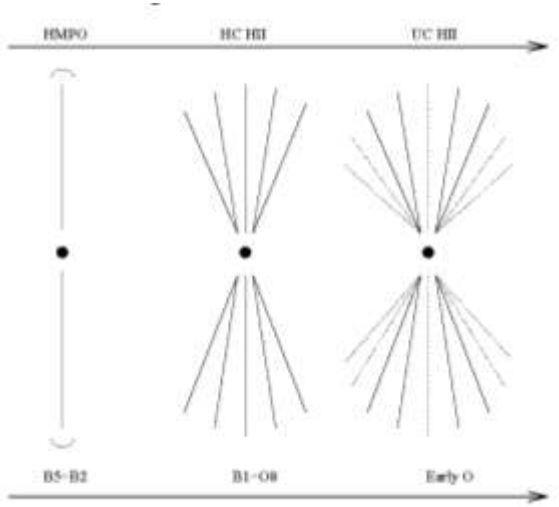
Debate on evolutionary phase

- Need statistical studies
  - Evolution of jet/outflow?
  - Evolutionary phase of masers?

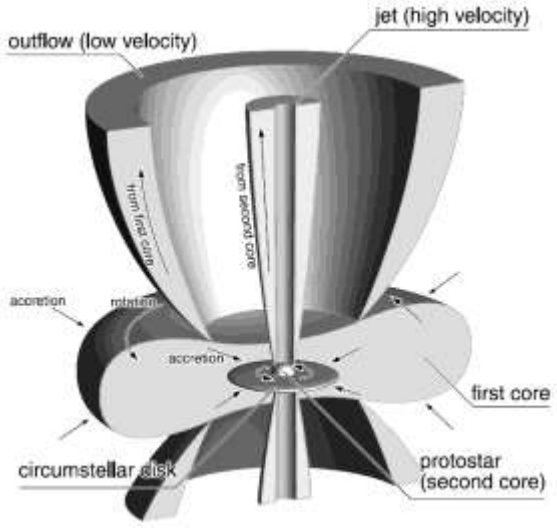




Reid (2007) vs Ellingsen (2007)
Updated with slight modification but still controversial



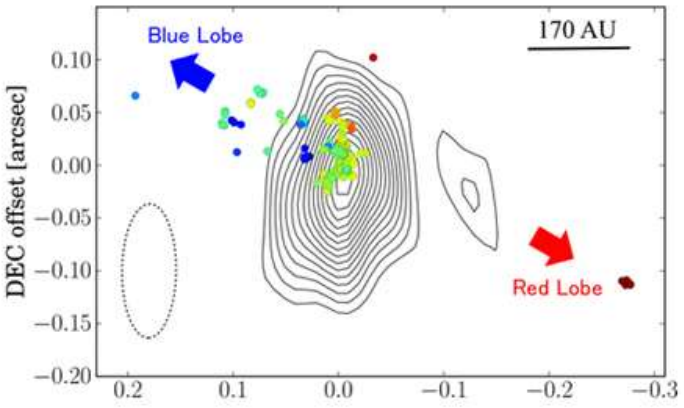
Beuther & Shepherd (2005)



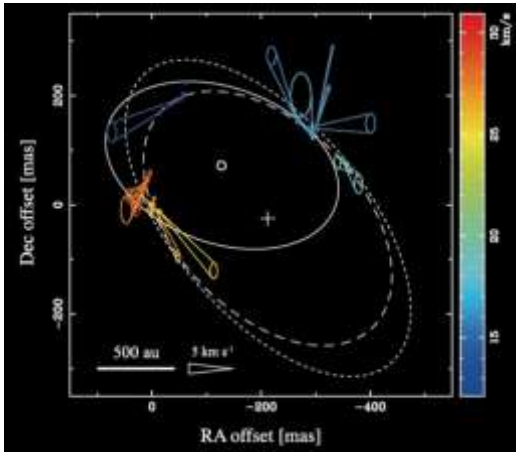
Machida et al. (2008, but lM-YSO)

Our tracers

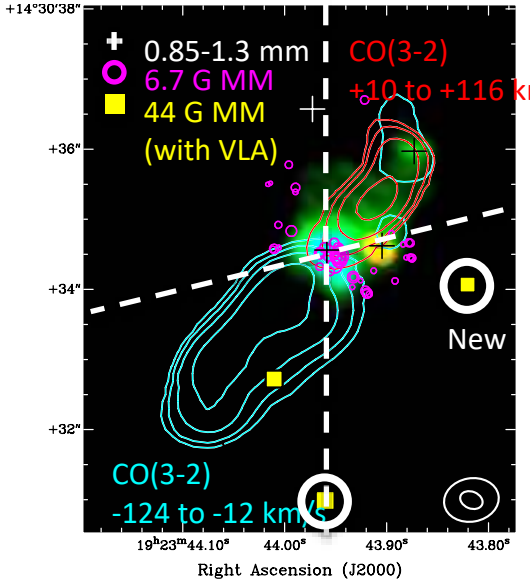
- Centimeter/millimeter maser lines
  - 22 GHz H_2O; high-velocity jet/outflow
  - 44 GHz CH_3OH; low-velocity outflow
  - 6.7 GHz CH_3OH; disk/low-velocity outflow (JVN/EAVN)



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



G6.79-0.25
(Sugiyama et al. 2015);
6.7 GHz CH3OH masers trace rotating disk



W51e2 (44GHz CH3OH maser by Sugiyama and SMA images by Shi et al. 2010)

Unique capability of KaVA

- First VLBI image of 44 GHz methanol masers in IRAS 18151-1208 MMS2 (Matsumoto et al. 2014)
  - Advantage to obtain both extended structures and compact components

The Astrophysical Journal Letters, 789:L1 (6pp), 2014 July 1 doi:10.1088/2041-8205/789/1/L1
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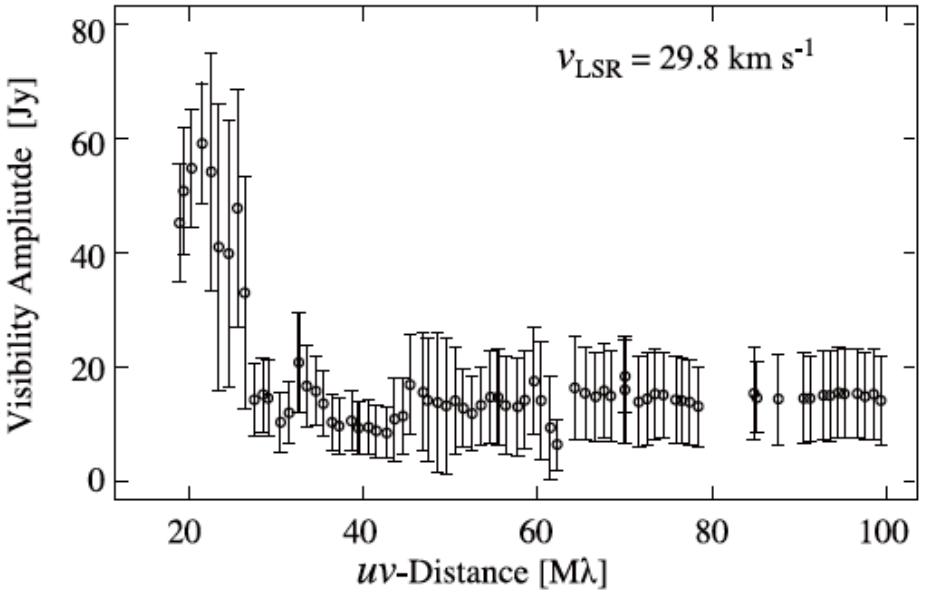
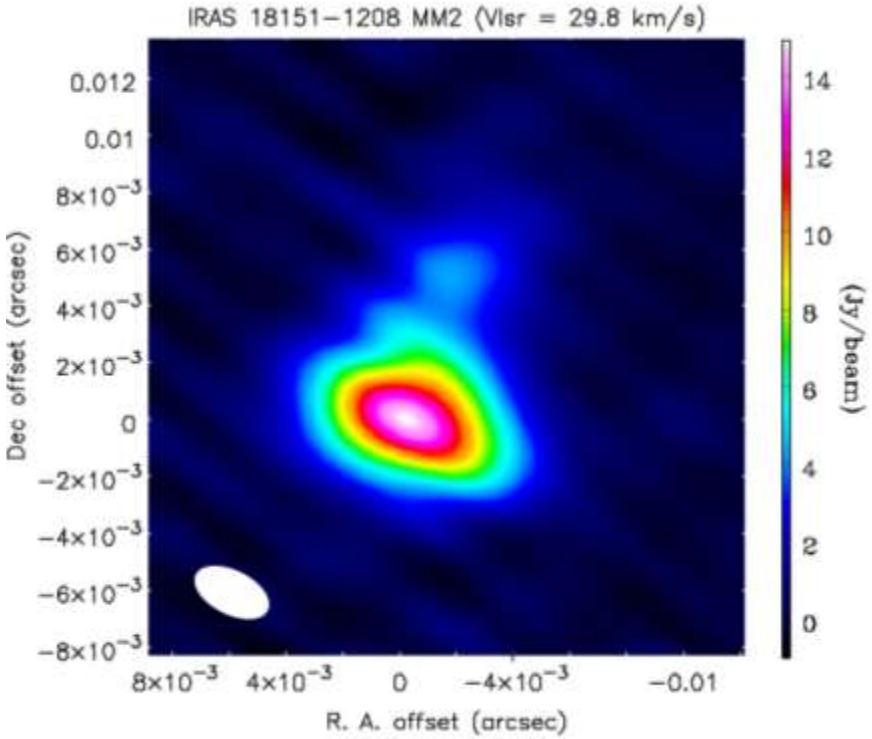
THE FIRST VERY LONG BASELINE INTERFEROMETRY IMAGE OF A 44 GHz METHANOL MASER WITH THE KVN AND VERA ARRAY (KaVA)

Naoko Matsumoto[1], Tomoya Hirota[1,2], Koichiro Sugiyama[3], Kee-Tae Kim[4], Mikyoung Kim[4], Do-Young Byun[4], Taehyun Jung[4], James O. Chibueze[5], Mareki Honma[1,2], Osamu Kameya[1], Jongsoo Kim[4], A-Ran Lyo[4], Kazuhito Motogi[3], Chungsik Oh[4], Nagisa Shino[2], Kazuyoshi Sunada[1], Jaehan Bae[4,6], Hyunsoo Chung[4], Moon-Hee Chung[4], Se-Hyung Cho[4], Myoung-Hee Han[4], Seog-Tae Han[4], Jung-Wook Hwang[4], Do-Heung Je[4], Takaaki Jike[1], Dong-Kyu Jung[4], Jin-seung Jung[4], Ji-hyun Kang[4], Jiman Kang[4], Yong-Woo Kang[4], Yukitoshi Kan-ya[1], Noriyuki Kawaguchi[1,2], Bong Gyu Kim[4], Jaeheon Kim[4], Hyo Ryoung Kim[4], Hyun-Goo Kim[4], Hideyuki Kobayashi[1], Yusuke Kono[1], Tomoharu Kurayama[1,7], Changhoon Lee[4], Jeong Ae Lee[4], Jeewon Lee[4,8], Jung-Won Lee[4], Sang Hyun Lee[4], Sang-Sung Lee[4], Young Chol Minh[4], Atsushi Miyazaki[4], Se-Jin Oh[4], Tomoaki Oyama[1], Sun-youp Park[4], Duk-Gyoo Roh[4], Tetsuo Sasao[1,4,9], Satoko Sawada-Satoh[1], Katsunori M. Shibata[1,2], Bong Won Sohn[4], Min-Gyu Song[4], Yoshiaki Tamura[1], Kiyoaki Wajima[10], Seog-Oh Wi[4], Jae-Hwan Yeom[4], and Young Joo Yun[4]

The first KaVA results

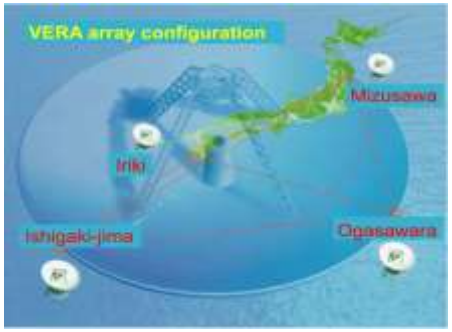
- First VLBI image of 44 GHz methanol maser in IRAS 18151-1208 MMS2 (Matsumoto et al. 2014)
  - 3 maser features in 100x100 mas^2
  - 5x2 mas^2, 10^{10} K





Planned Observations

- VLBI survey/monitoring of sources; 87
  - Bright 22 GHz H_2O/44 GHz CH_3OH masers
  - Association of multiple masers, high velocity jets, …
  - Statistics of HM-YSOs with uniform dataset
  - Possibly including multiple YSOs within FoV
- Follow-up projects



Annual parallax


6.7GHz methanol masers



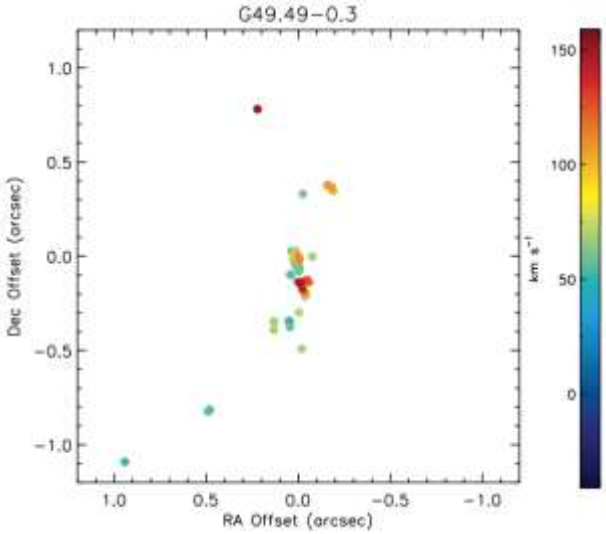
Thermal continuum/lines

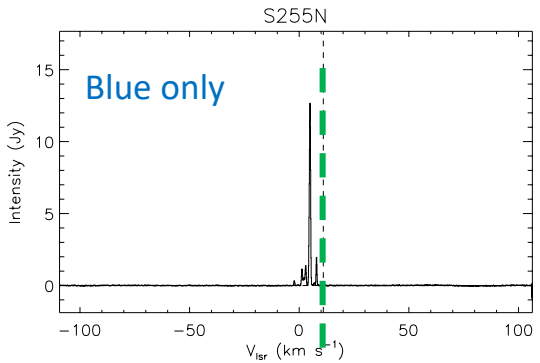


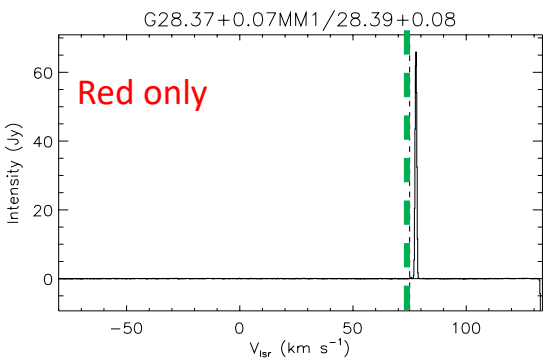
Large-scale structure

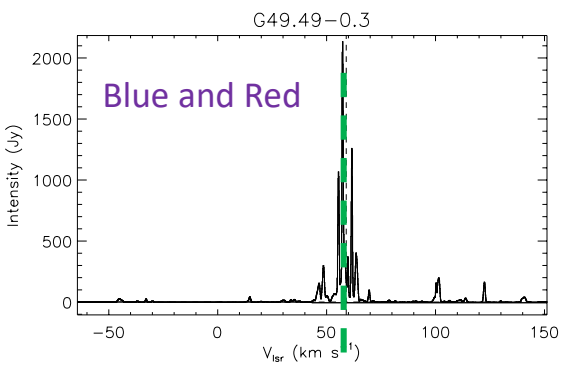
H_2O maser at 22 GHz

- Status for the first year (2016-2017)
  - Snap-shot imaging survey
  - 25 high-mass YSOs (P#34)
  - Selected mainly from KVN single-dish survey (e.g., Kang+15; Kim CH+17) but with no VLBI data





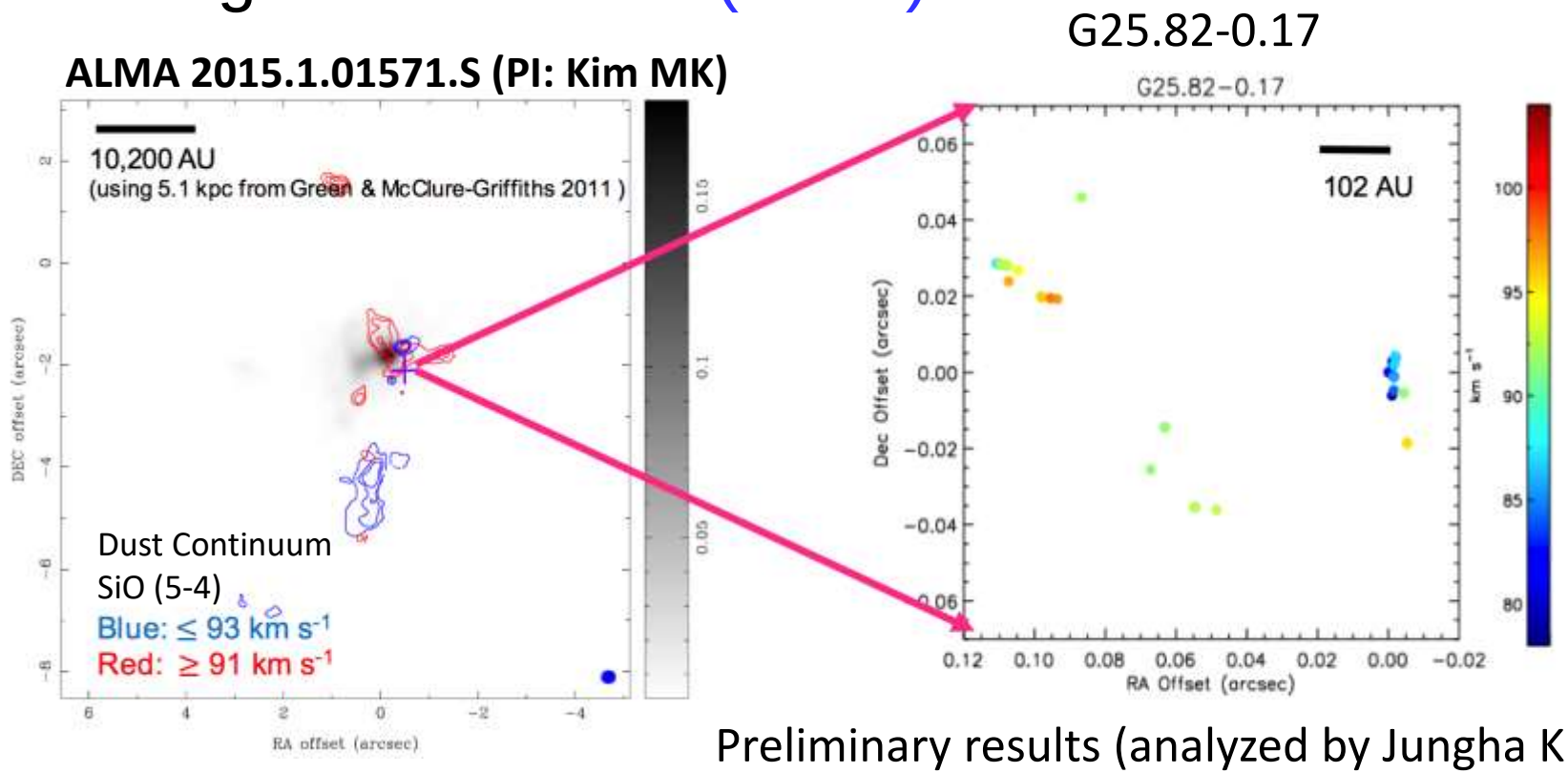




Preliminary results (analyzed by Jungha Kim)

H_2O maser at 22 GHz

- Status for the first year (2016-2017)
  - Snap-shot imaging survey
  - 25 high-mass YSOs (P#34)

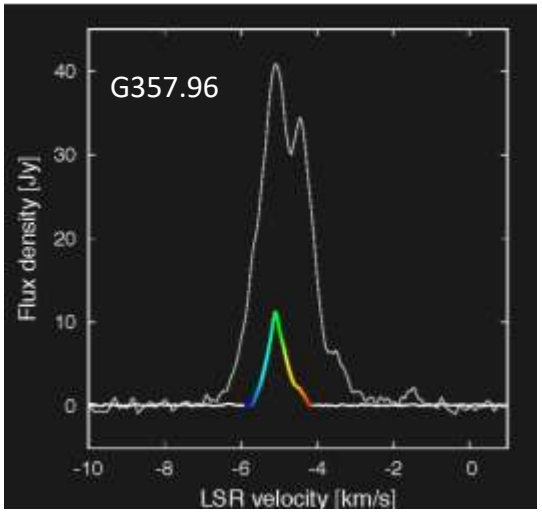


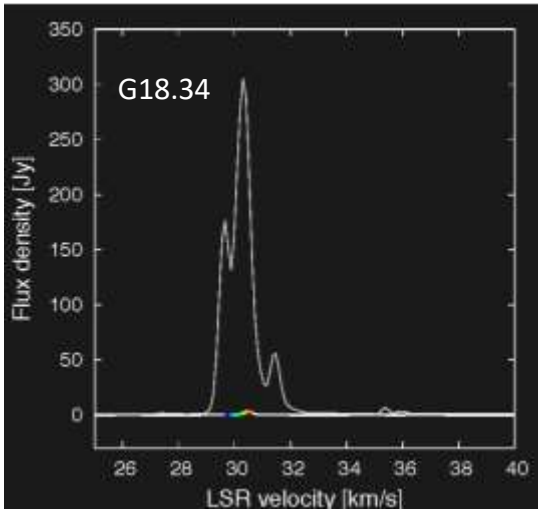
Preliminary results (analyzed by Jungha Kim)

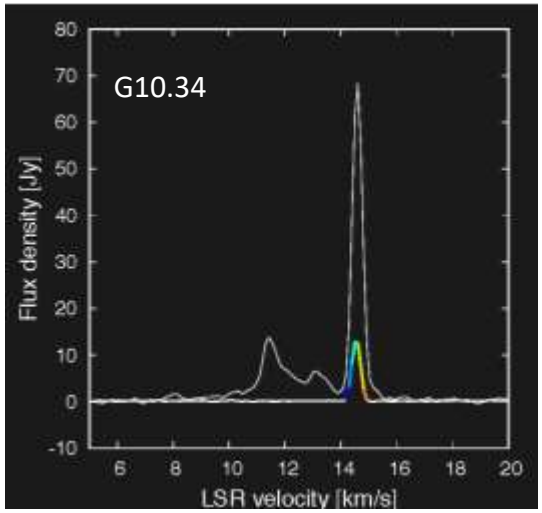
CH_3OH maser at 44 GHz

- Status for the first year (2016-2017)
  - First VLBI imaging survey
  - 19 high-mass YSOs
  - Selected from KVN SD & Fringe survey

    (Kim KT+12; Kang+15; Kim CH+17)



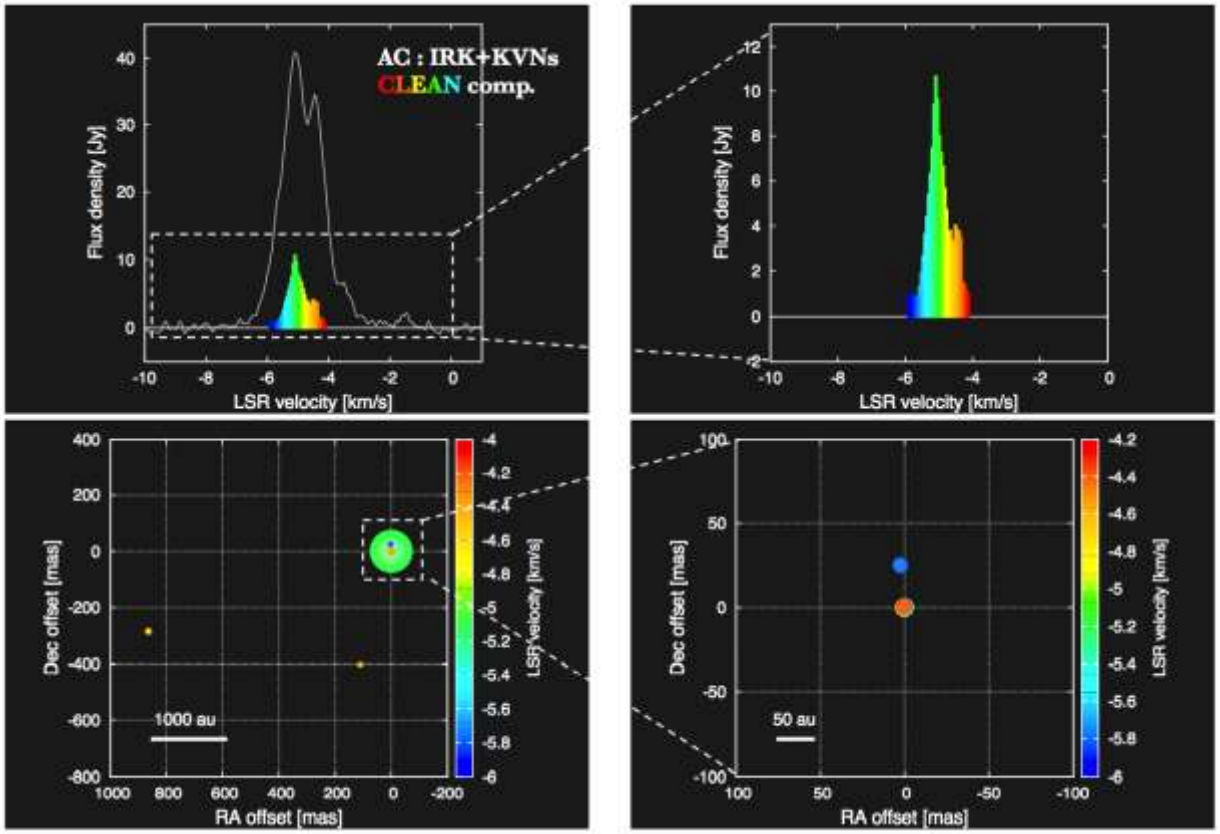




Preliminary results (analyzed by Sugiyama)

CH_3OH maser at 44 GHz

- Status for the first year (2016-2017)
  - First VLBI imaging survey **G357.967-0.163**



(analyzed by Sugiyama)

Future and summary

- Timeline of KaVA SFRs LP
  - Early 2017 (1st yr); initial survey/snap-shot imaging 25 water & 19 44GHz methanol maser sources
  - 2017 Nov.; interim review
  - Early 2018 (2nd yr); start of monitoring observations
- In parallel JVN (6.7 GHz), ALMA cycle 3, etc.
- SFRs LP will welcome collaboration/new ideas with other instruments/theory!