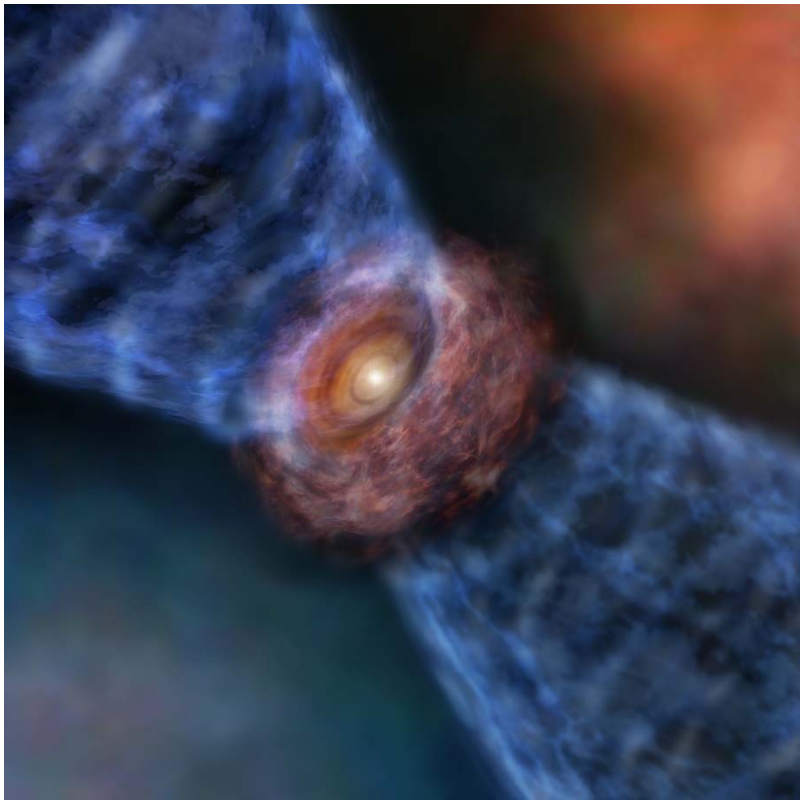
Understanding high-mass star formation through KaVA observations of water and methanol masers

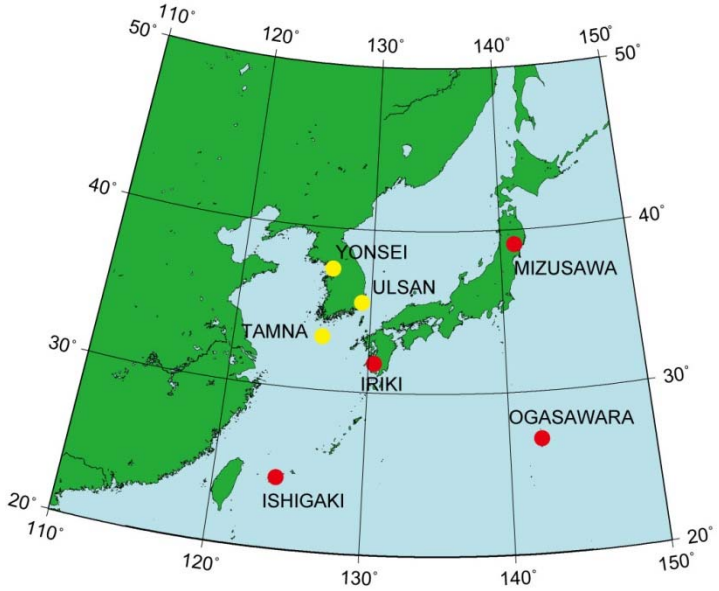


Tomoya Hirota (NAOJ), Kee-Tae Kim (KASI),

on behalf of KaVA SFRs sub-WG

KaVA large program (LP)

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

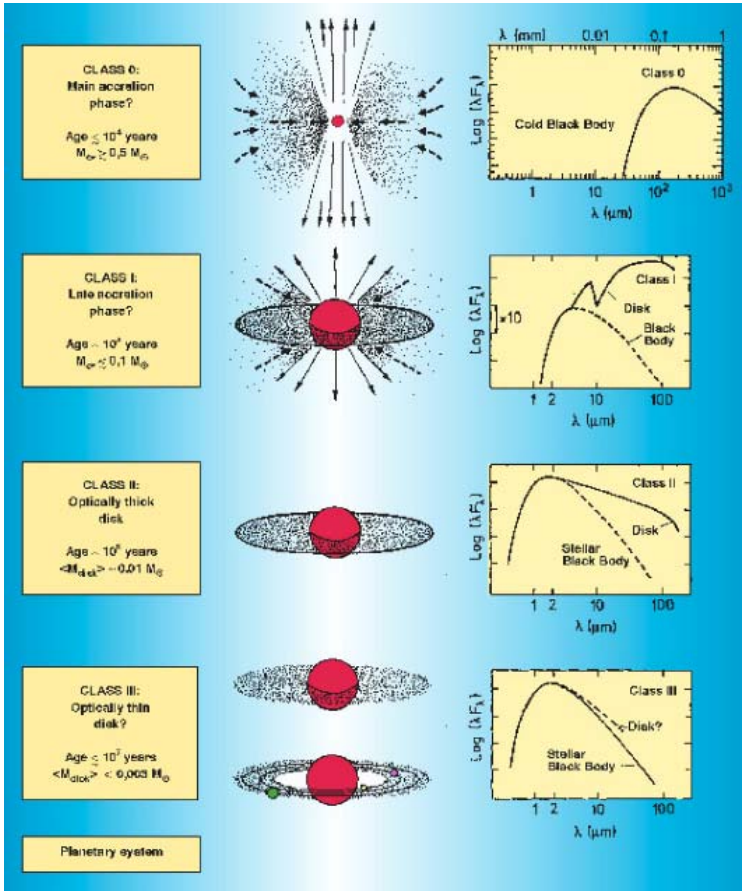


KaVA SFRs LP

- **Understanding high-mass star formation through KaVA observations of water and methanol masers**
- VLBI monitoring/survey 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

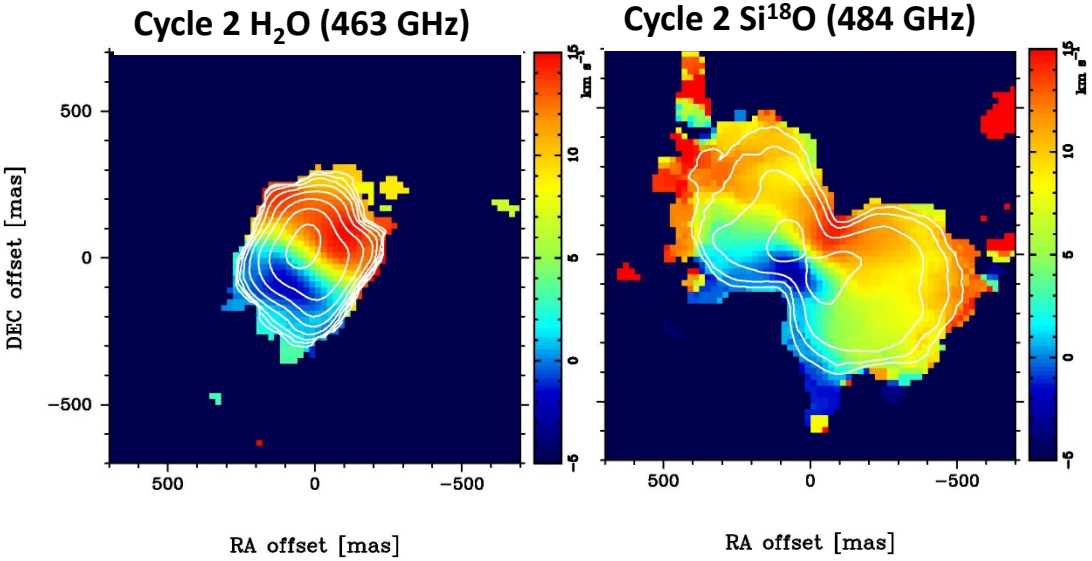
Why HM-YSOs?

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

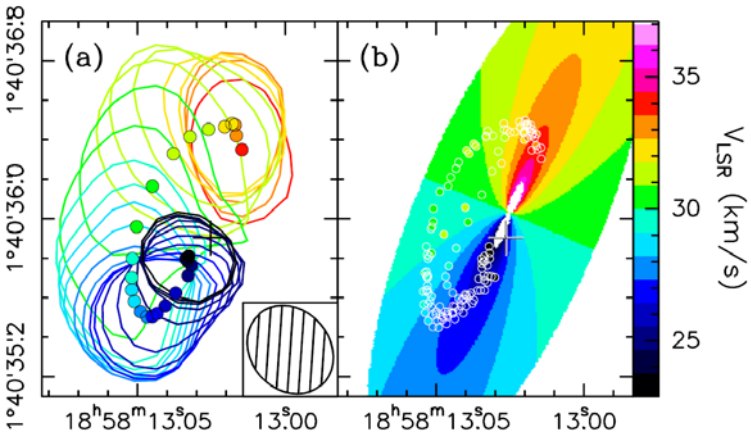


Mass accretion/ejection in HM-YSOs

- 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



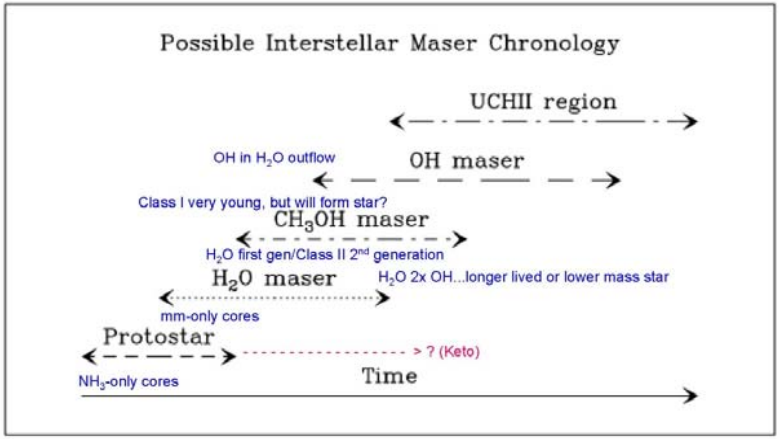
Orion Source I (Hirota et al. 2017)

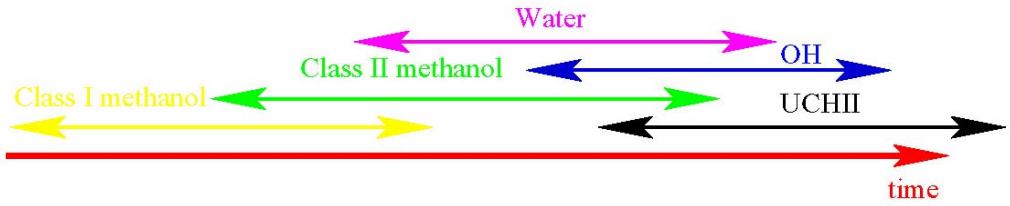


G35.20-0.74N (Sanchez-Monge et al. 2013)

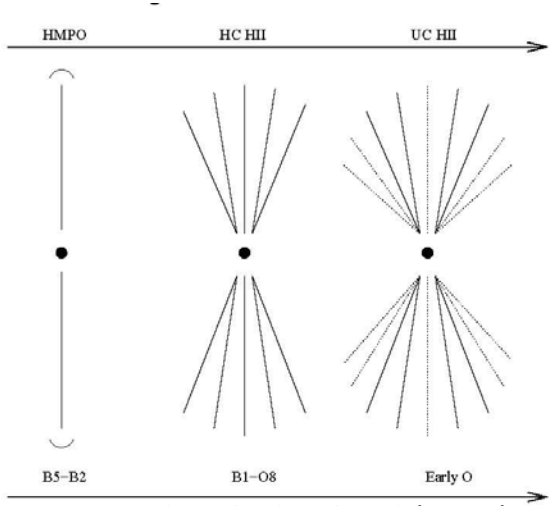
Debate on evolutionary phase

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

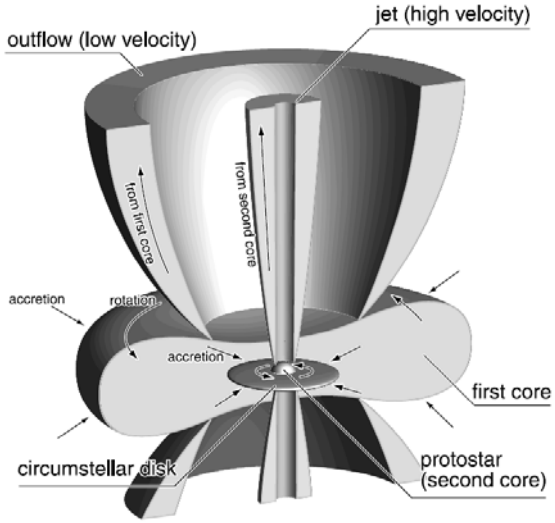




Reid (2007) vs Ellingsen (2007)
Updated with slight modification but still controversial



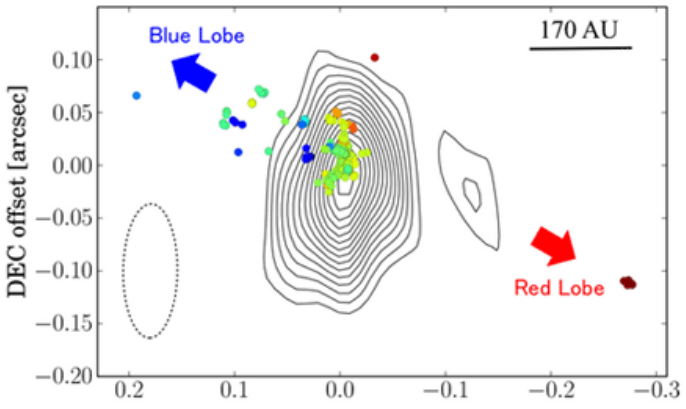
Beuther & Shepherd (2005)



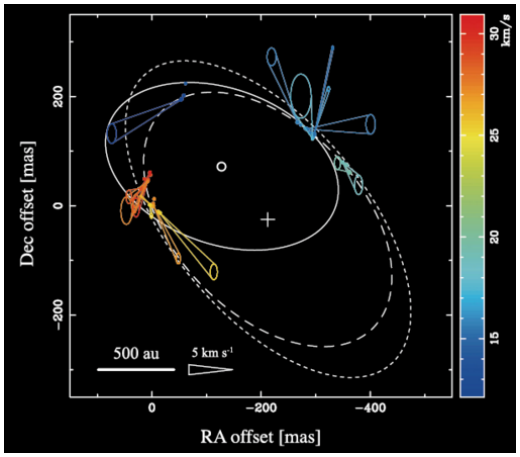
Machida et al. (2008, but for low-mass YSO)

Our tracers

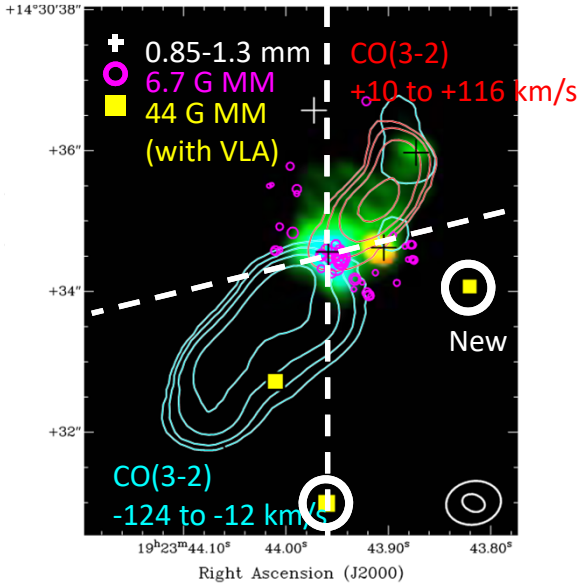
- Centimeter/millimeter maser lines
  - 22 GHz H_2O; high-velocity jet/outflow
  - 6.7 GHz CH_3OH; low-velocity outflow/disk
  - 44 GHz CH_3OH; low-velocity outflow



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 maser (Matsumoto et al. 2014)
  - Advantage to obtain both extended structures and compact components

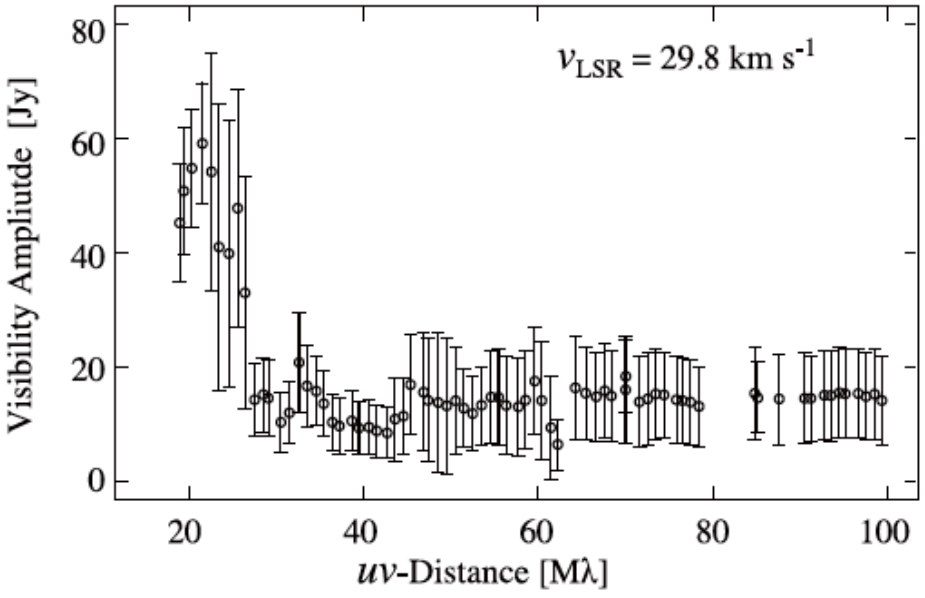
THE ASTROPHYSICAL JOURNAL LETTERS, 789:L1 (6pp), 2014 July 1 doi:10.1088/2041-8205/789/1/L1

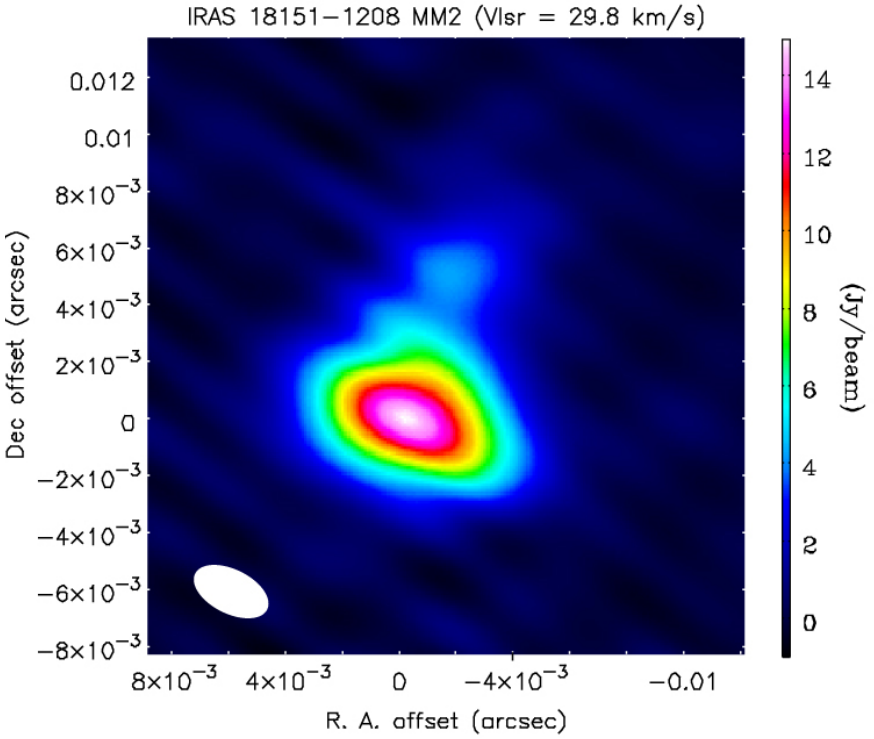
THE FIRST VERY LONG BASELINE INTERFEROMETRY IMAGE OF A 44 GHz METHANOL MASER WITH THE KVN AND VERA ARRAY (KaVA)

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

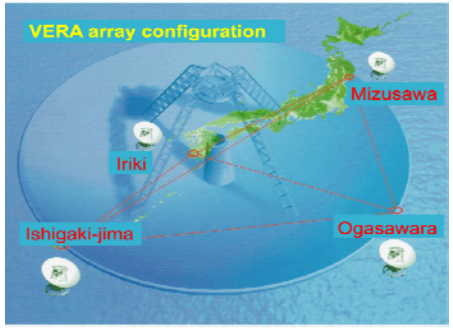
- First VLBI image of 44 GHz methanol maser (Matsumoto et al. 2014)
  - Advantage to obtain both extended structures and compact components



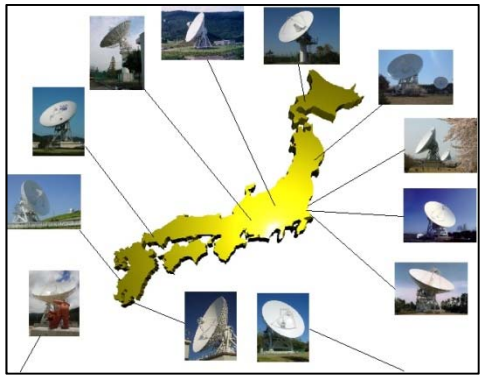


Planned Observations

- 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

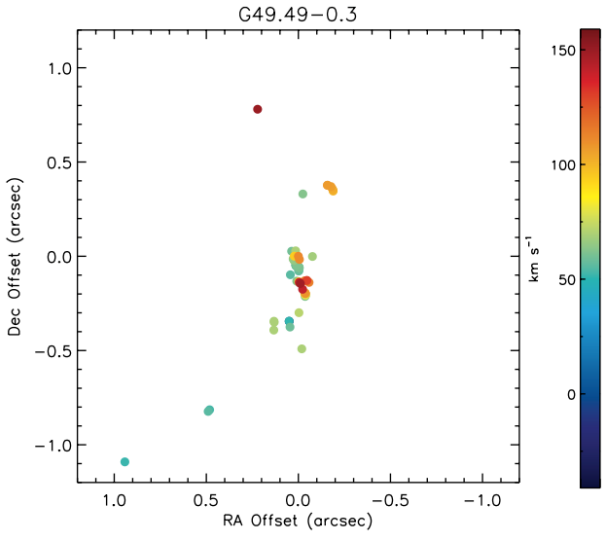

6.7GHz methanol masers

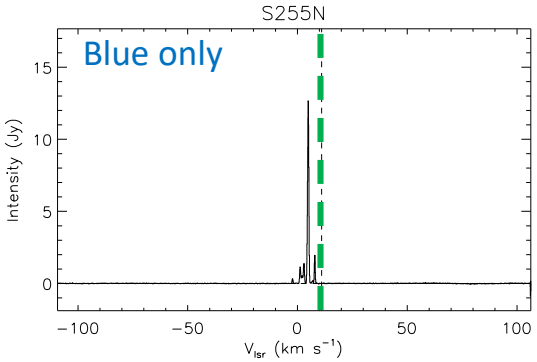
Thermal continuum/lines

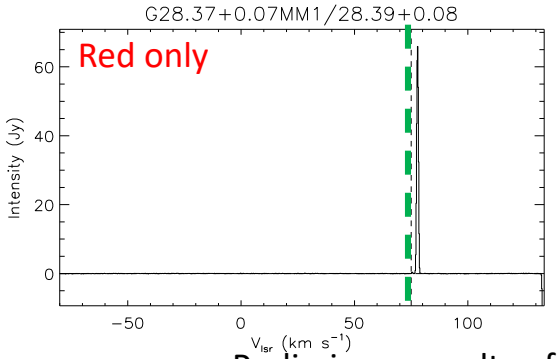

Large-scale structure

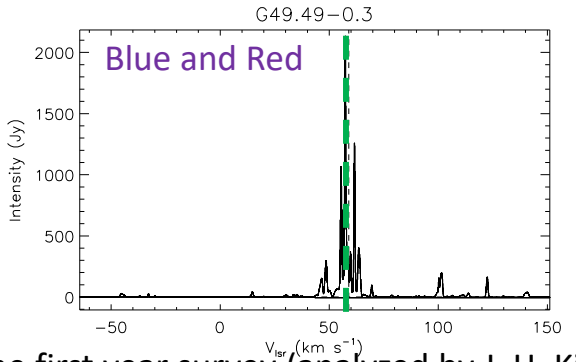
H_2O maser at 22 GHz

- Status for the first year (2016-2017)
  - Snap-shot imaging survey
  - 25 high-mass YSOs
  - Selected mainly from KVN single-dish survey (K.T. Kim et al.) but with no VLBI data





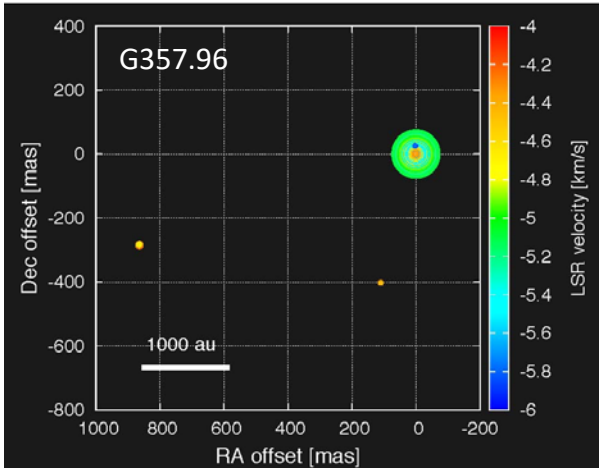


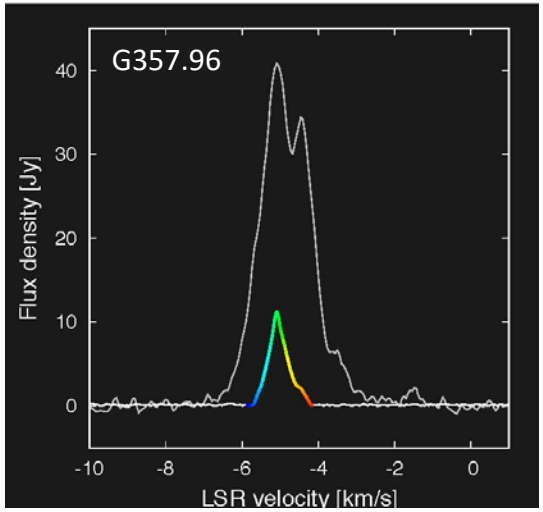


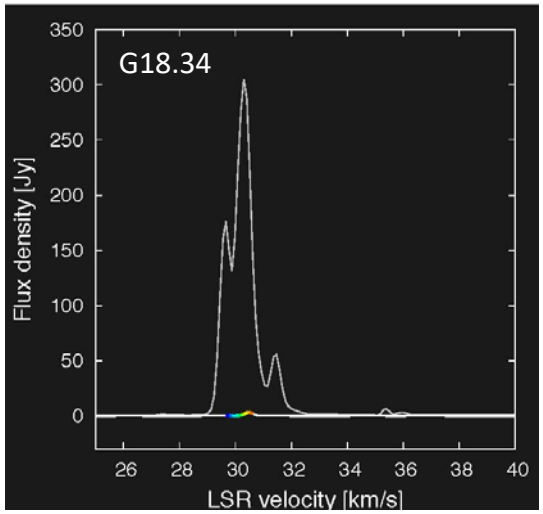
Preliminary results of the first year survey (analyzed by J. H. Kim)

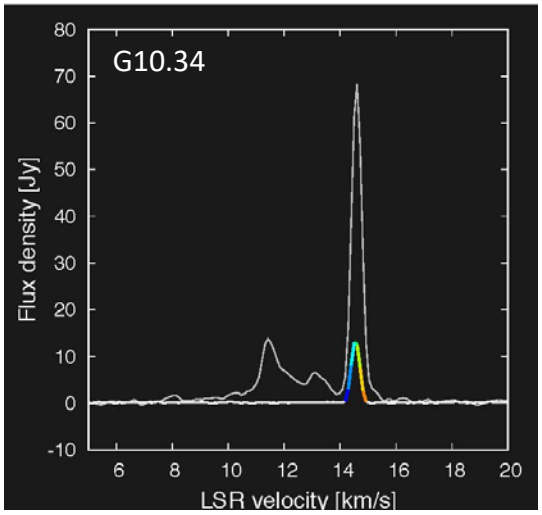
CH_3OH maser at 44 GHz

- Status for the first year (2016-2017)
  - First VLBI imaging survey
  - 18 high-mass YSOs
  - Selected from KVN single-dish survey (K.T. Kim et al.)









Preliminary results of the first year survey (analyzed by Sugiyama)

Future and summary

- Timeline of KaVA SFRs LP
  - Early 2017 (1st yr); initial survey/snap-shot imaging
  - 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 new members at anytime!
- SFRs LP will welcome collaboration/new ideas with other instruments/theory!