Tiny-scale Molecular Structure Investigated by W-band VLBI Absorption Observations

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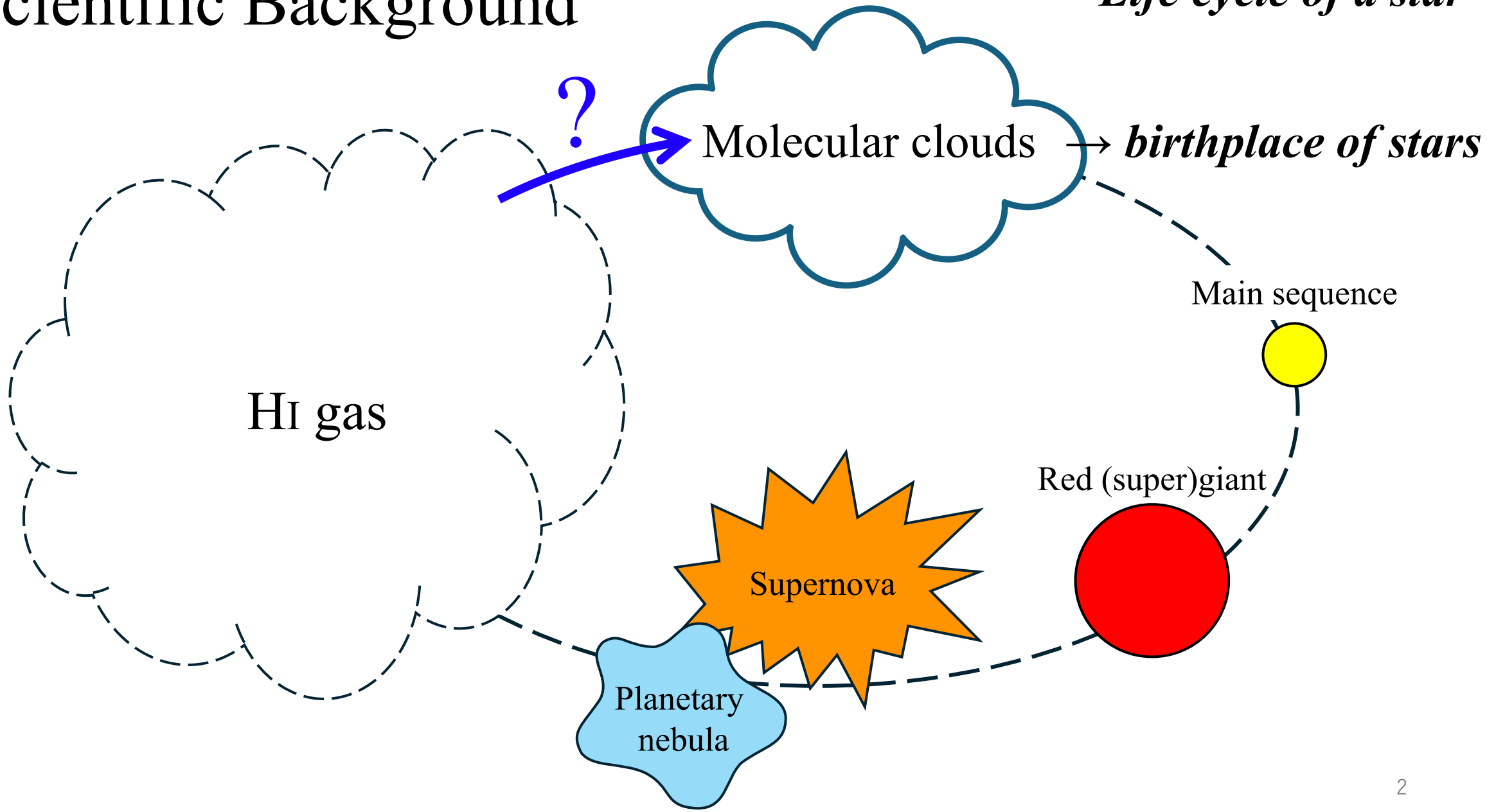
Hiroshi Imai (Kagoshima U.), Youngjoo Yun (KASI)

国立大学法人 鹿児島大学 KAGOSHIMA UNIVERSITY

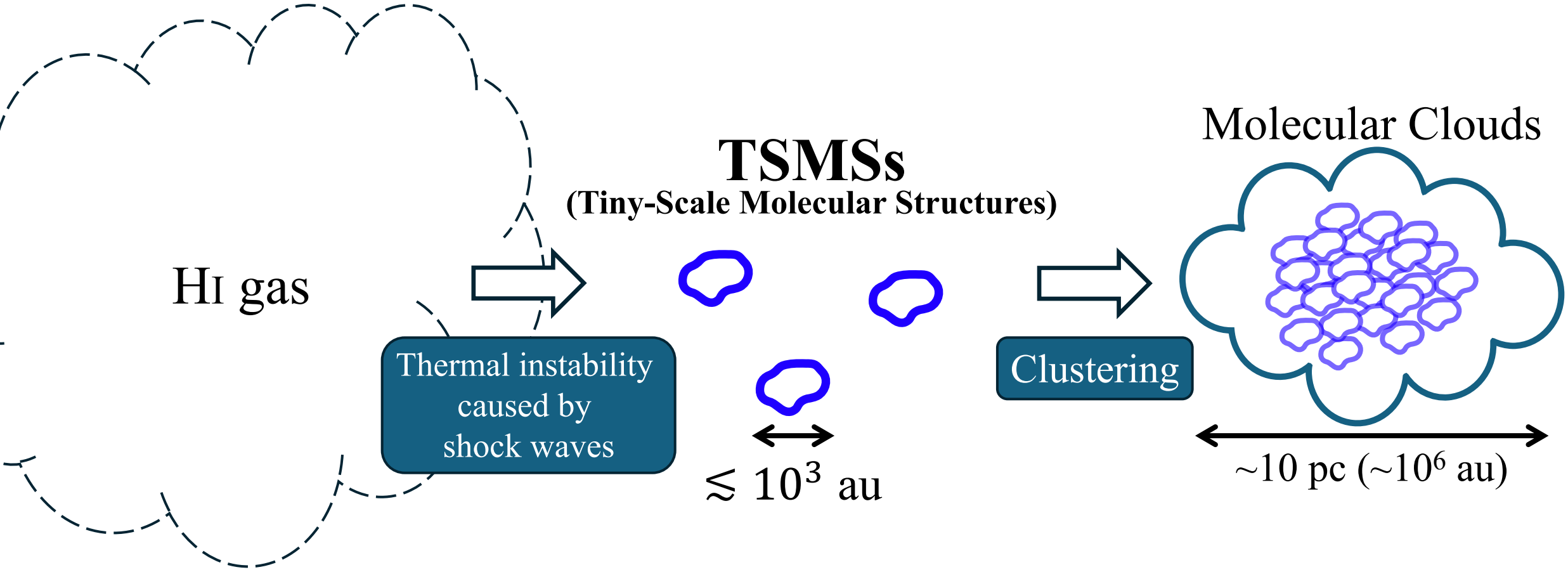
国立天文台 NAOJ



Scientific Background

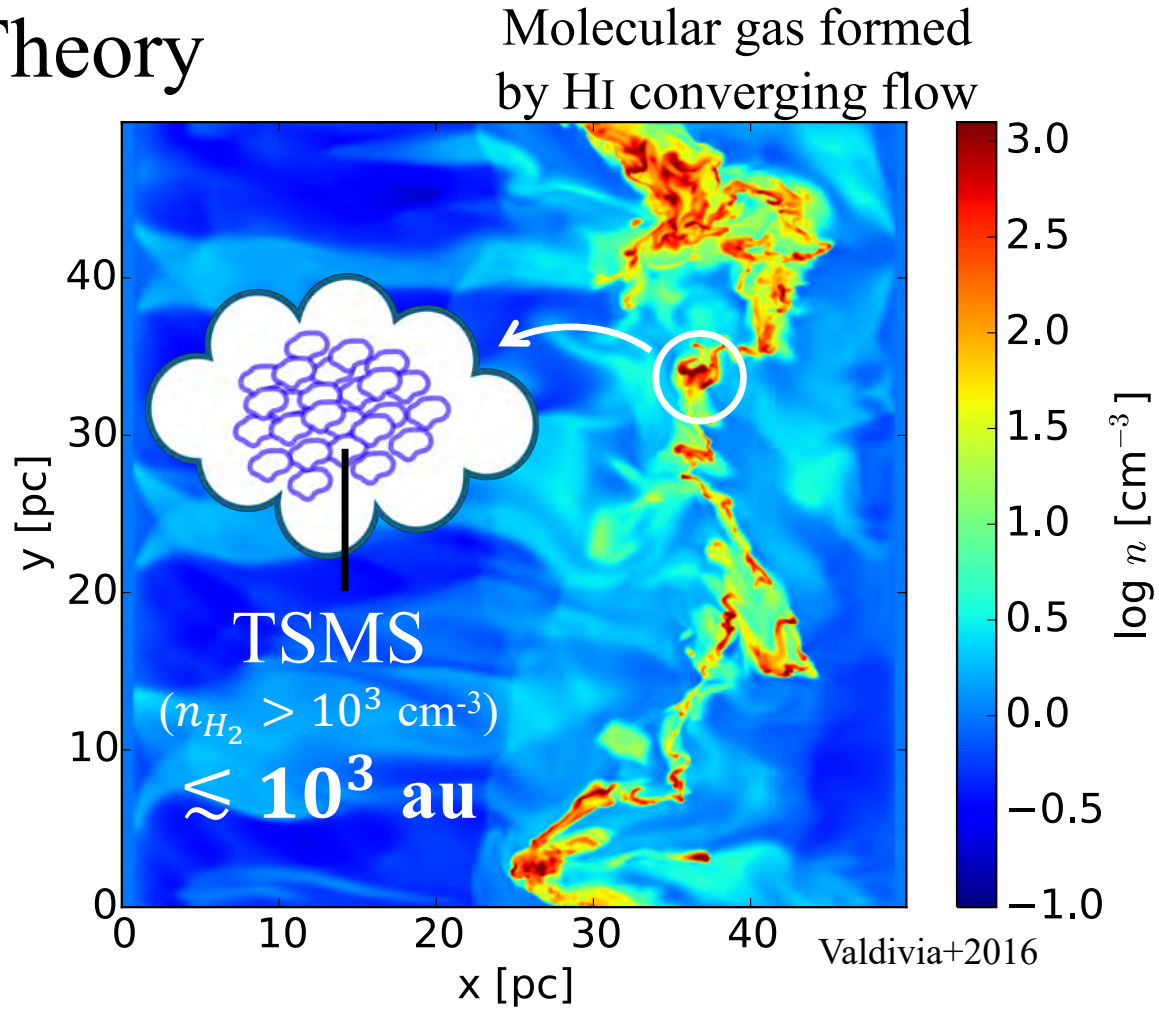


Molecular Cloud Formation —TSMS Cluster Model



Previous Studies on TSMSs (tiny-scale molecular structures)

Theory



Observations

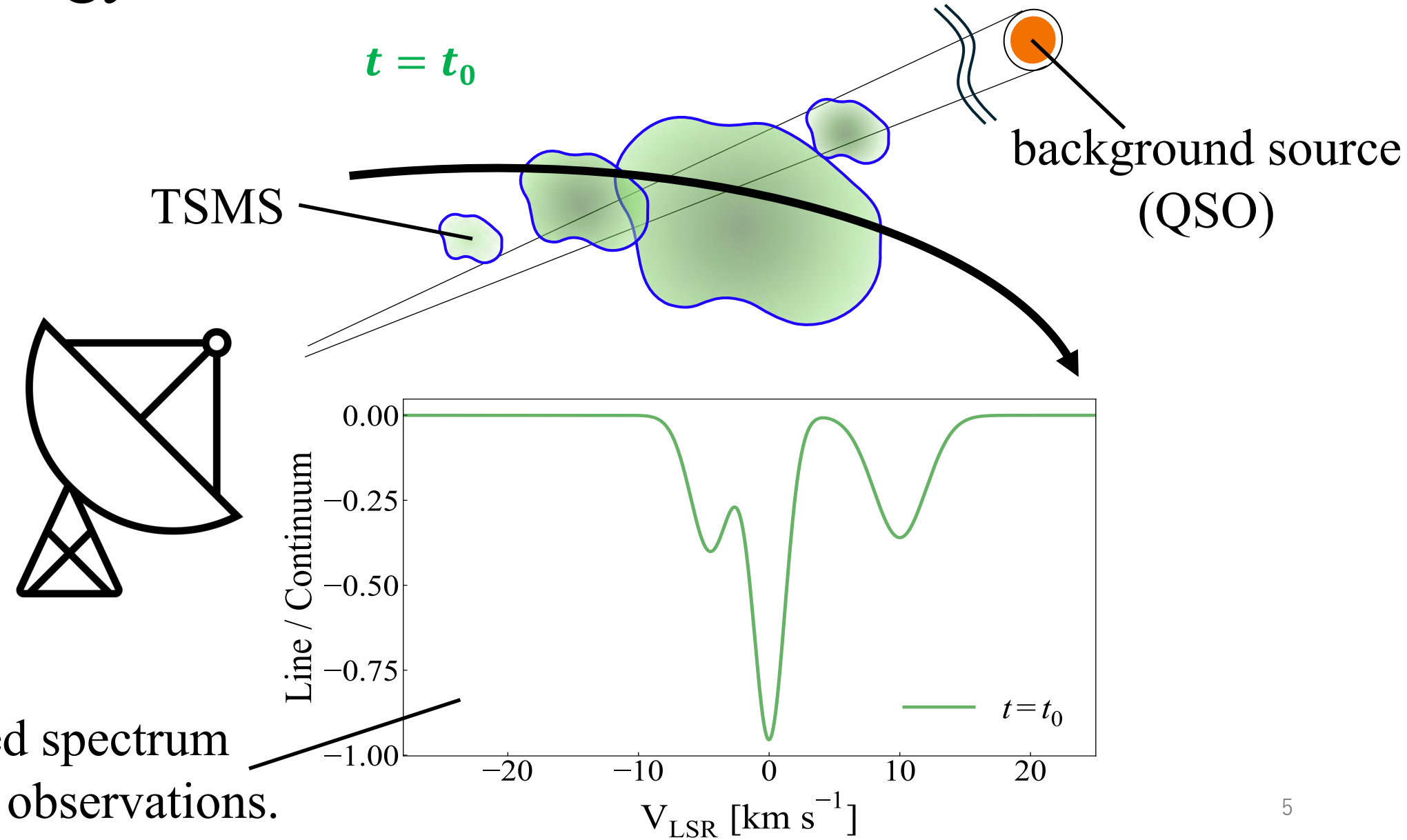
Detections are extremely limited due to insufficient angular resolution of connected arrays.

e.g., Structures resolvable with ALMA (W-band = Band 3)

$> 10^3$ au at 1 kpc from us

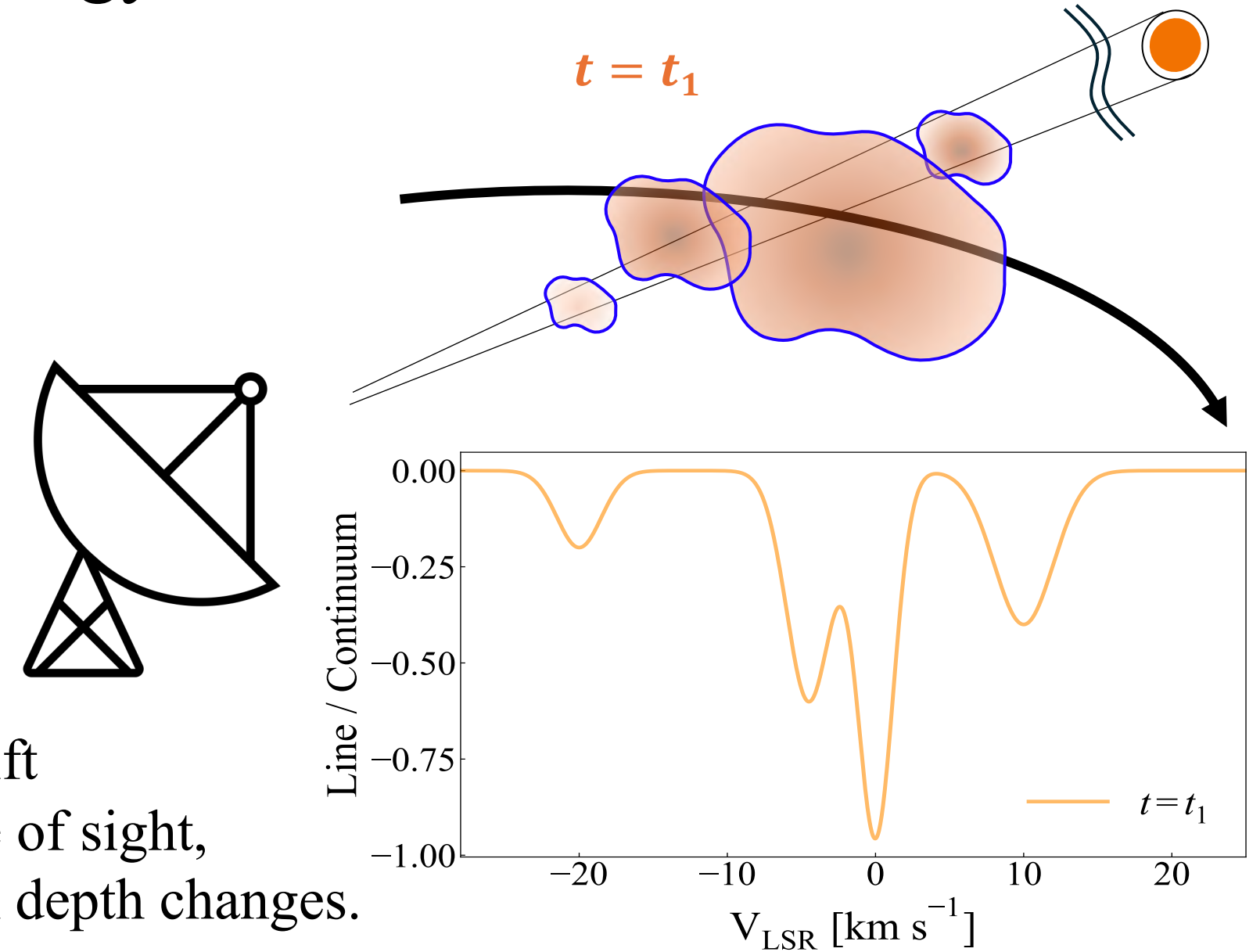
The existence of even smaller structures is also predicted.

Methodology for the Indirect Detection of TSMSs



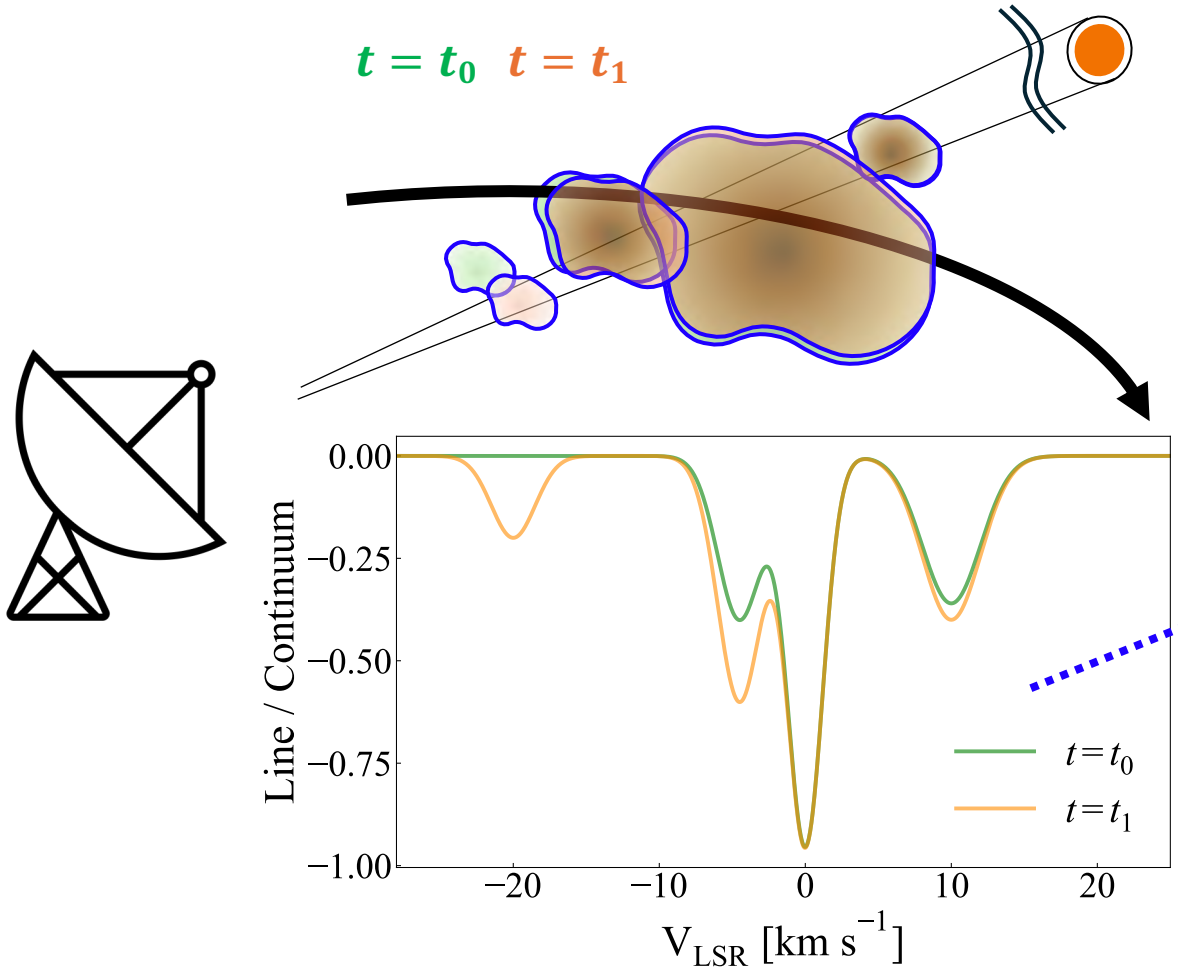
The normalized spectrum obtained from observations.

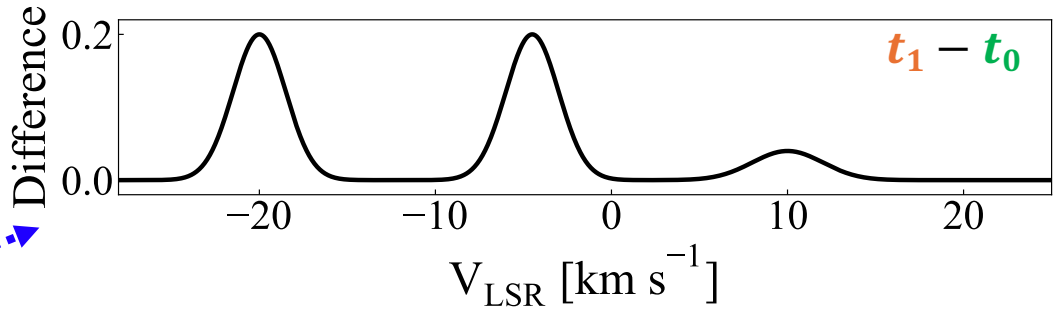
Methodology for the Indirect Detection of TSMSs



As TSMSs drift
across the line of sight,
the absorption depth changes.

Methodology for the Indirect Detection of TSMSs





Absorption depth variation corresponding to TSMS size and motion.

Time variation in absorption depth → Indirect evidence of TSMS existence

Observation Setup

KVN (Korean VLBI Network): $\theta_{\rm res} \sim 1.5$ mas, $T_{\rm sys} \sim 200$ K

The only W-band (~89 GHz) VLBI system with multi-epoch capability within a year.

- Observed molecular lines:

  HCN ($J = 1 \rightarrow 0, \sim 88.6$GHz);

  HCO^+ ($J = 1 \rightarrow 0, \sim 89.2$GHz) e.g., Ando+2016

  — known to produce deep absorption

- Observed Background Sources:

  NRAO 150; 3C 111; BL Lac; 3C 454.3

- Observation epochs:

  Nov. 2023; Jan. 2024; Dec. 2024

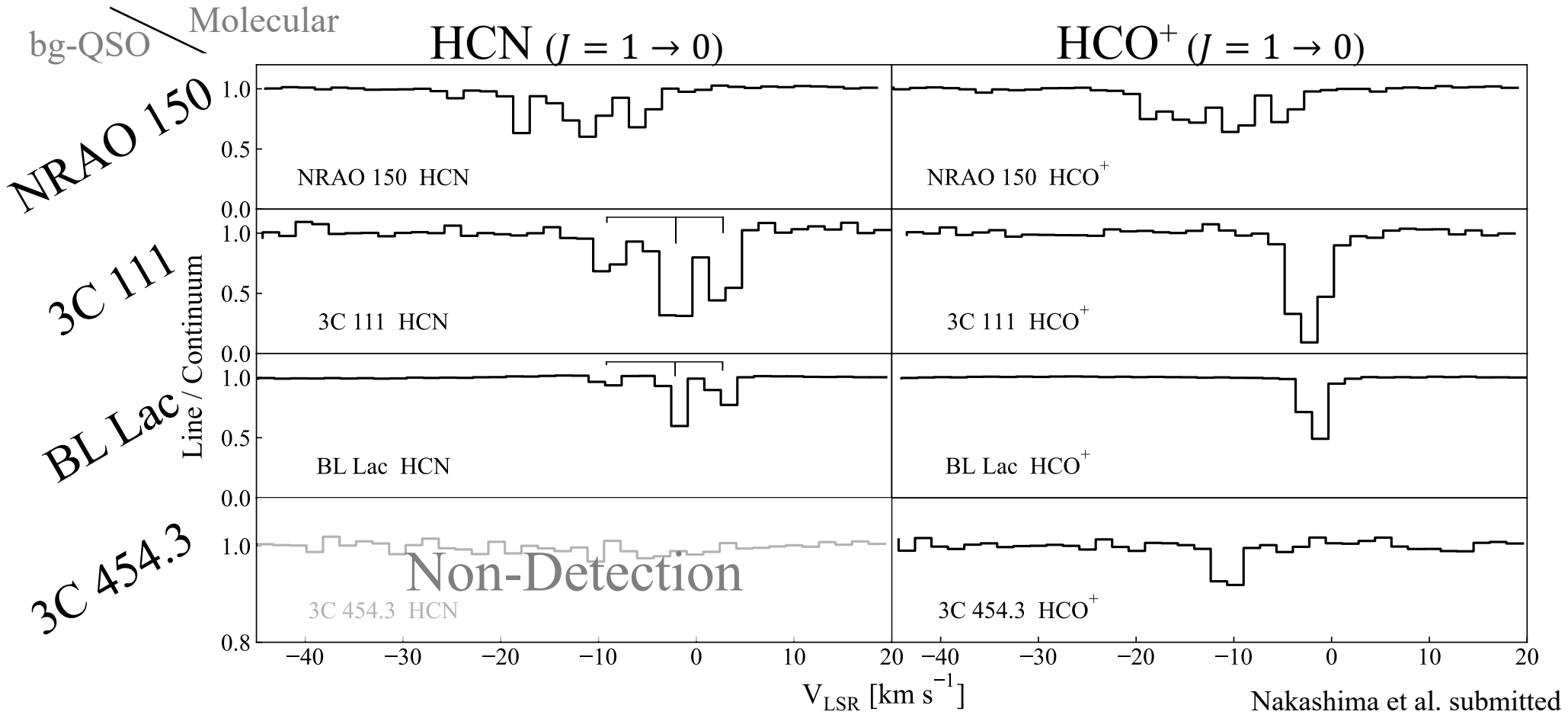


Main Observation Goals

1. Evaluate the detectability of molecular absorption with VLBI. ←Nov. 2023
2. Investigate possible time variability in absorption depth. ←Jan. 2024 + Dec. 2024

Spectra Observed in Nov. 2023

✓ Successful detection of molecular absorption lines **with VLBI!**



Comparison with the Previous Studies

Same gas properties?

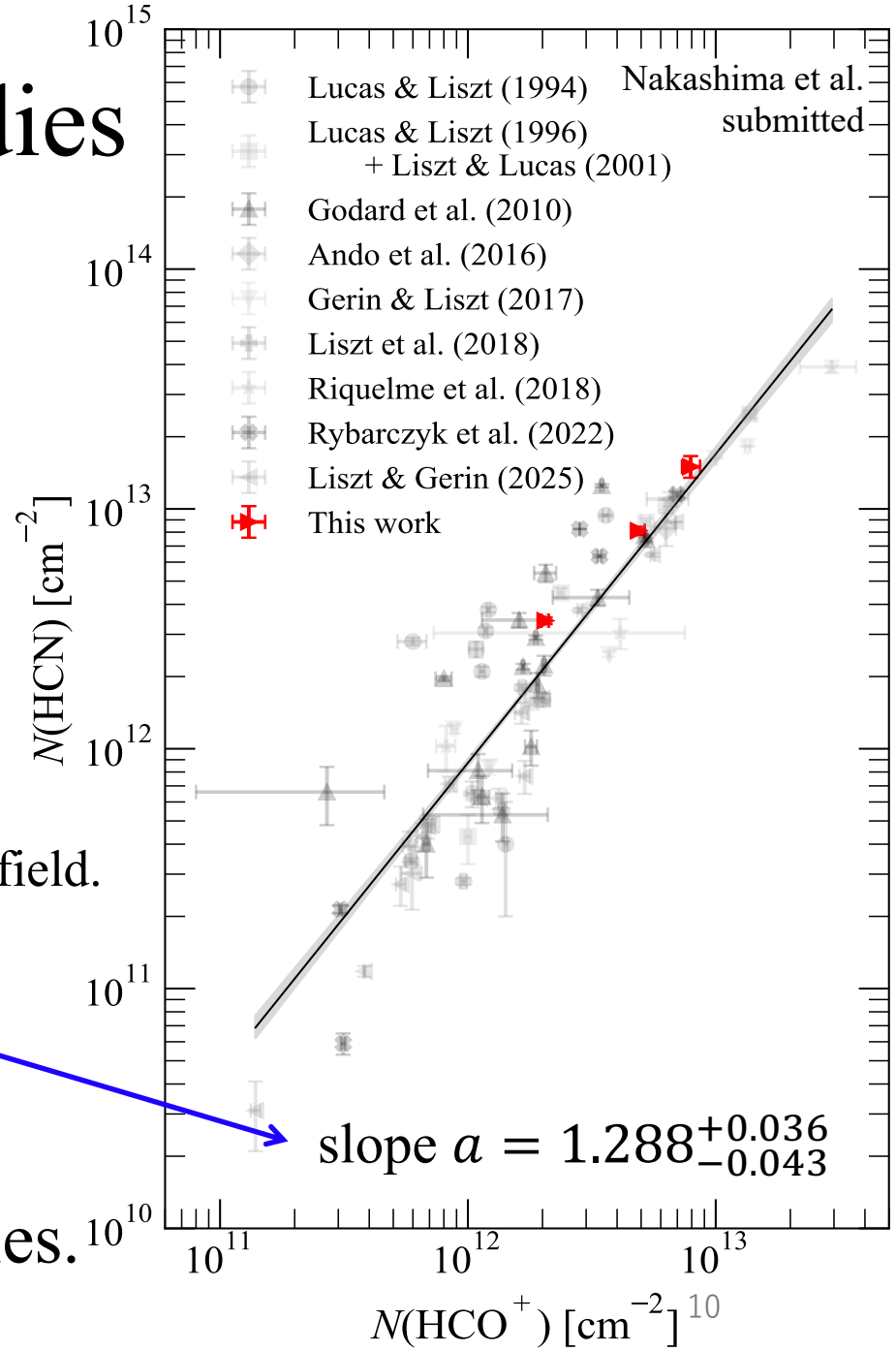
Source	Column density	
	$N_{\rm total}^{\rm HCN}$ [10^{12} cm^{-2}]	$N_{\rm total}^{\rm HCO^+}$ [10^{12} cm^{-2}]
NRAO 150	8.11 ± 0.32	$4.88^{+0.29}_{-0.28}$
3C 111	$14.99^{+1.62}_{-1.50}$	$7.92^{+0.73}_{-0.61}$
BL Lac	3.42 ± 0.11	2.05 ± 0.07
3C 454.3	< 0.15	0.30 ± 0.04

+ known values of Galactic diffuse gas (43 lines of sight)

$N(\mathrm{HCN})/N(\mathrm{HCO^+})$ is used as an indicator of interstellar UV radiation field.

Consistent with the previously reported slope ($a = 1.25 \pm 0.06$) within the uncertainties.

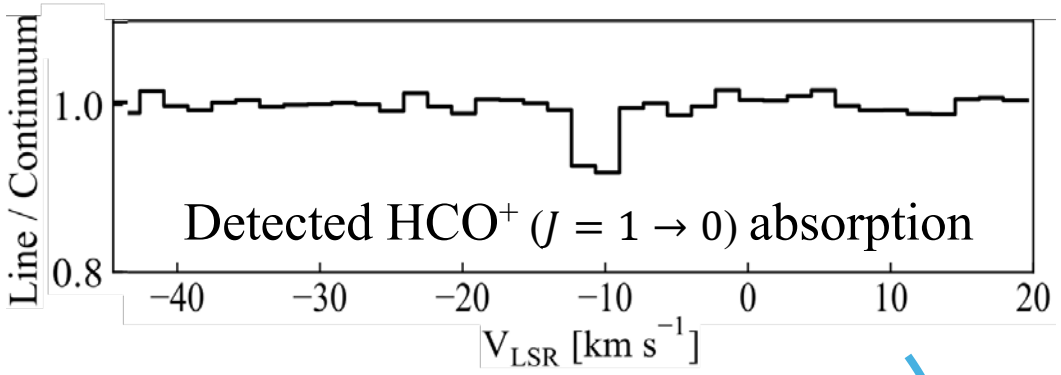
Liszt & Gerin 2025

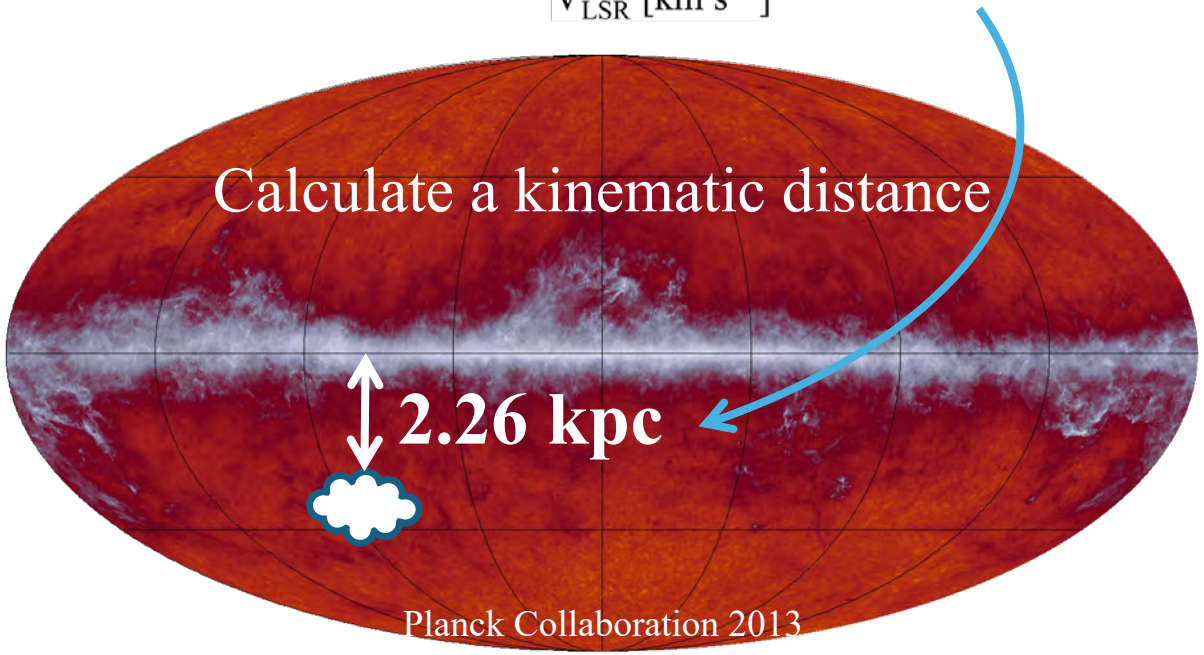


✓ Chemical properties consistent with previous studies.

Investigation for the interstellar environment for the sources

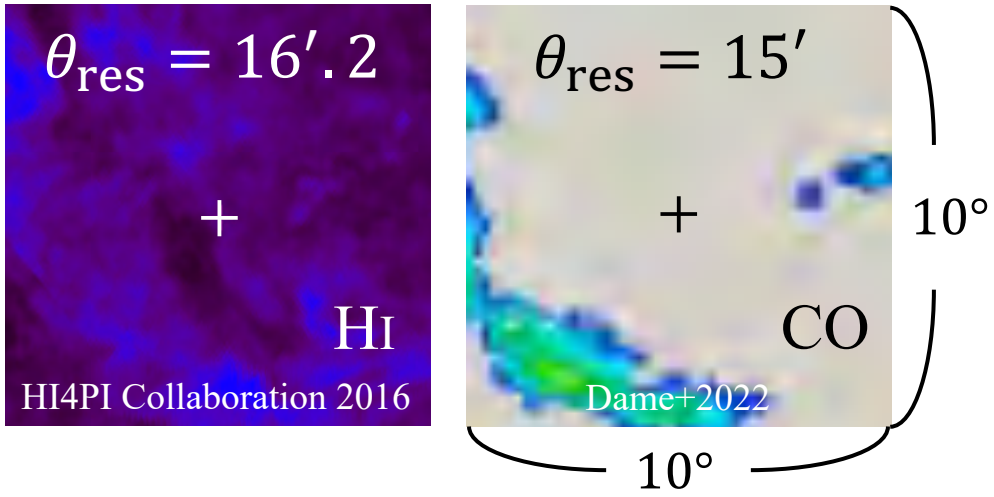
Molecular gas structure toward 3C 454.3





Edge-on map of the Galactic plane

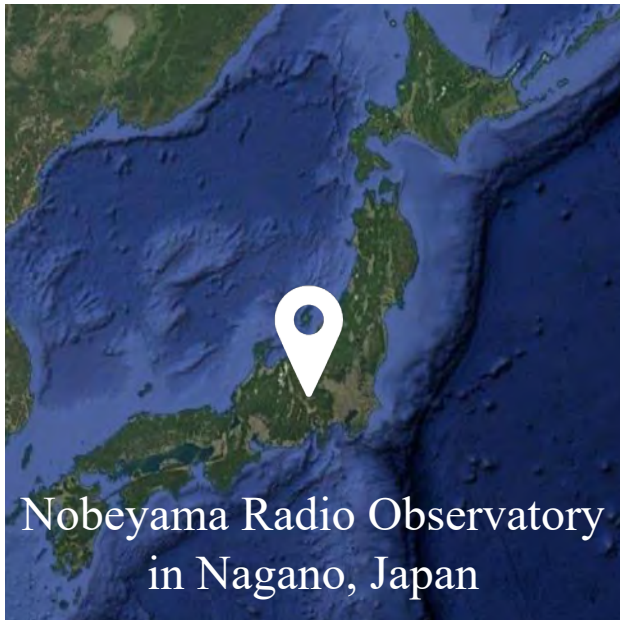
Previous surveys in this region.



The angular resolution was insufficient to identify the gas.

New CO Single-Dish Observations

Nobeyama 45-m telescope





Nobeyama 45-m

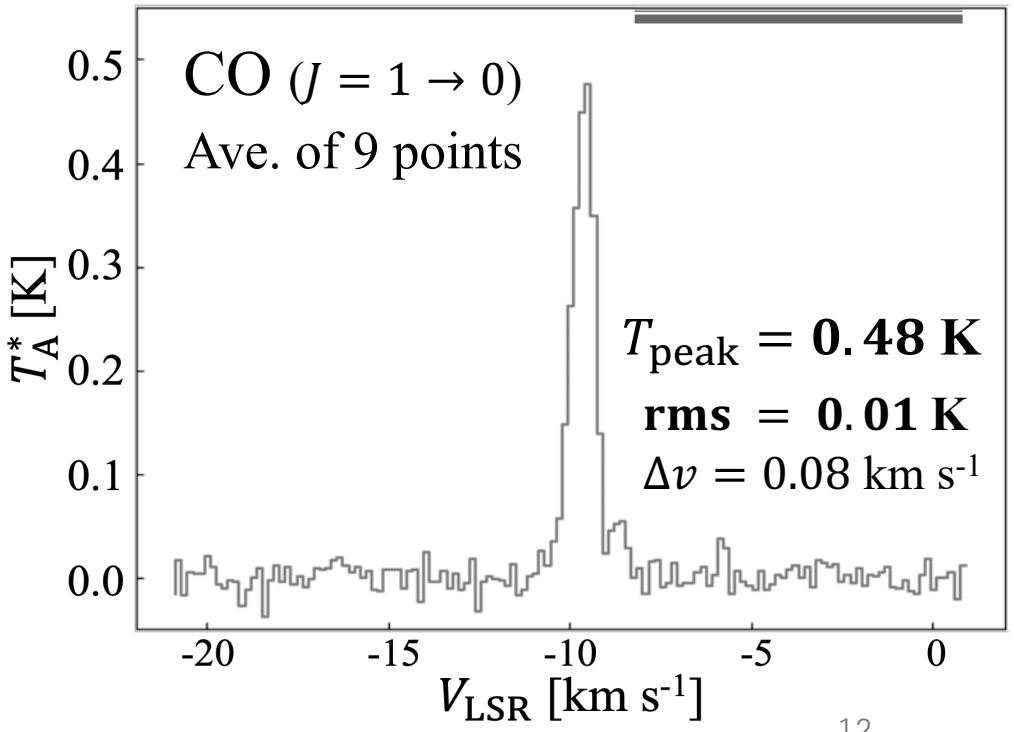
- One of the world's largest high-sensitivity millimeter-wave telescopes (mirror precision 0.1mm), in scientific operation since 1982.
- Equipped with several receivers, capable of observing 20–120 GHz.
- Beam waveguide optics facilitate receiver development.

9-point observation centered on bg-QSO

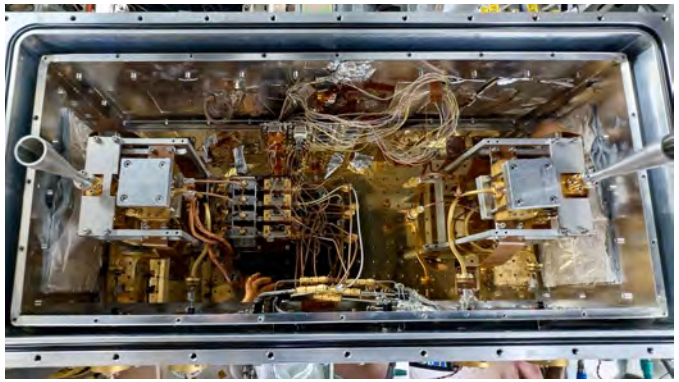
Obs. Date: Dec. 25 & 27, 2024

Total obs. time: 6hr

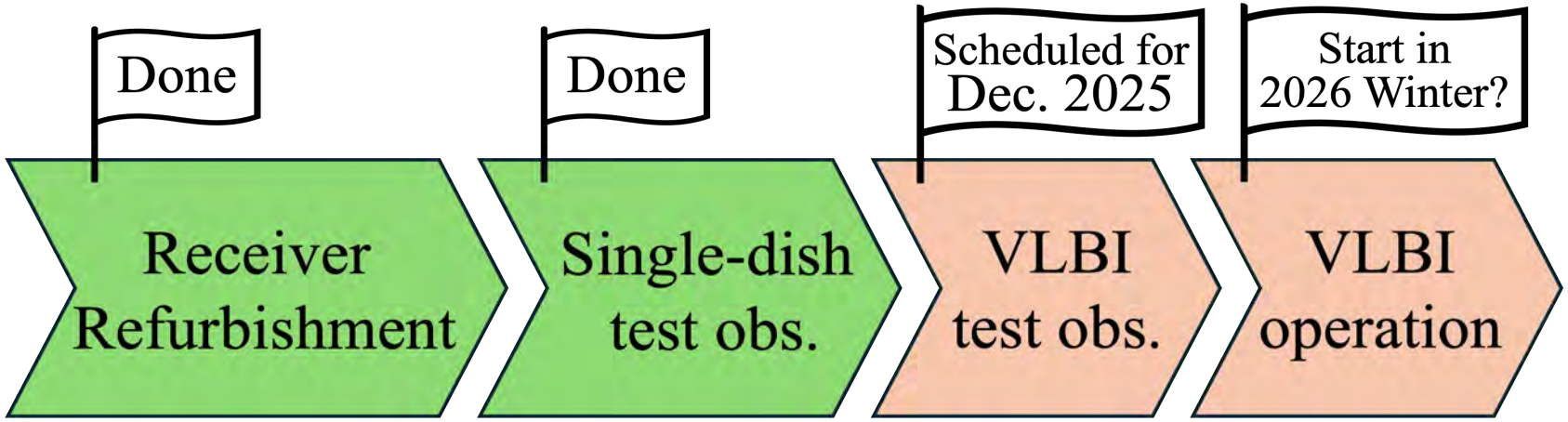
$\boldsymbol{\theta_{res} = 15''}$ (x60 better than before)



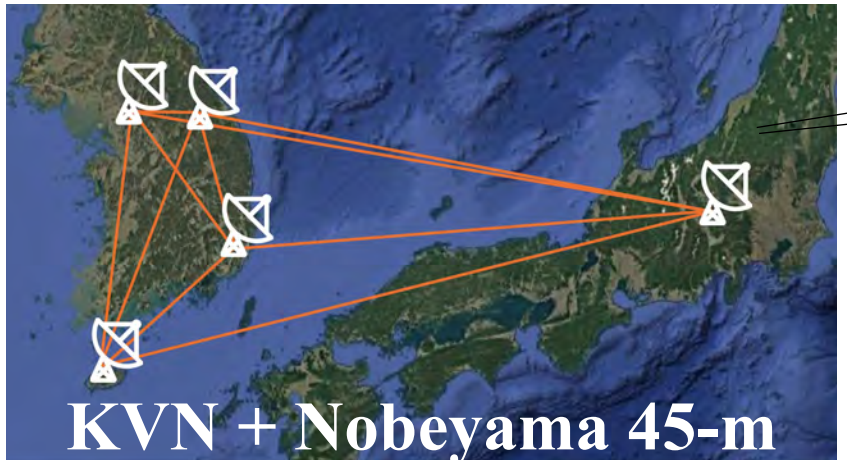
Future Work **W-band VLBI system development at the Nobeyama 45-m**



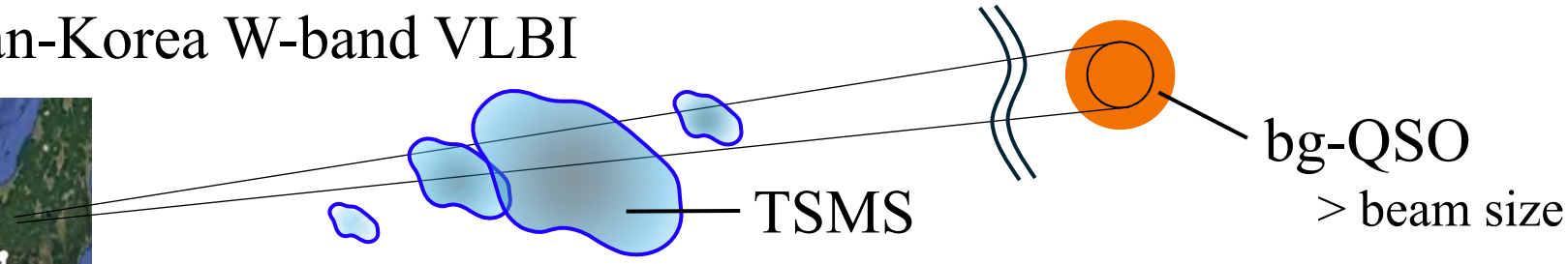
W-band receiver



TSMS Exploration with Japan-Korea W-band VLBI



x3 better $\theta_{\rm res}$ than KVN alone



$\boldsymbol{\theta_{\rm res} \sim 0.5\ \rm mas}$ → resolve bg-QSO ($\theta \sim 1$ mas)

→ The τ-map from molecular absorption directly probes the structure of TSMS.

Summary

- **Investigation of a tiny-scale molecular structure called TSMS ($\lesssim 10^3$ au),**
  of which existence is predicted theoretically but observationally constrained insufficiently,
  by using VLBI absorption line observations with 1.5 mas high angular resolution.

- Successful detection of HCN and HCO^+ absorption lines
  in multiple directions **with VLBI!**

- VLBI-detected gas shows chemical properties consistent with previous studies.
  (The same trend appears even with angular resolution differing by three orders of magnitude.)

- A ~ 2 pc molecular cloud was found ~ 2.26 kpc away from the Galactic mid-plane.