Based on Research Plan Proposed to JSPS

New 2mm (Band-4) Receiver (“B4R”) for LMT

Bunyo Hatsukade

(Institute of Astronomy, The University of Tokyo)

Ryohei Kawabe (PI, NAOJ)

David Hughes (INAOE)
Pete Schloerb (UMass), & LMT team
Kotaro Kohno
(Science Adviser, U. Tokyo)
Tai Oshima, Takashi Noguchi
(System Adviser, NAOJ)
Akio Taniguchi
(FMLO System, U. Nagoya)

Yoichi Tamura (FMLO system Leader, U. Nagoya)
Kunihiko Tanaka (XFFTS & M/C System leader, Keio U.)
Takeshi Sakai (Receiver Leader, U. Electro-Communication)

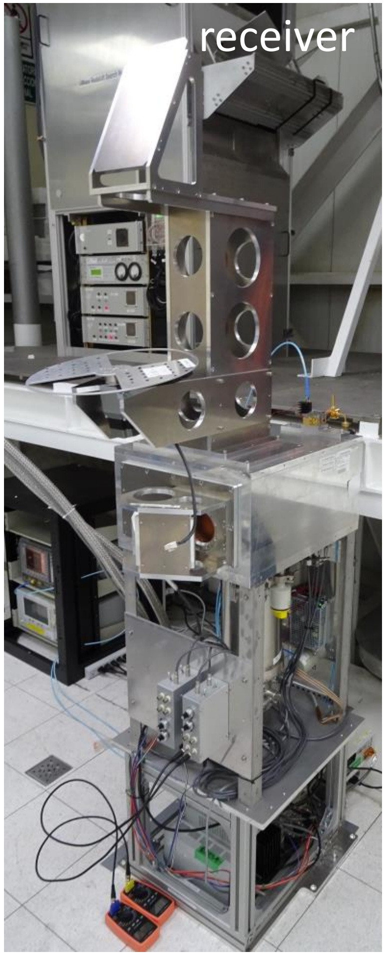
Outline

- Introduction of “B4R”
  - 2 mm-band receiver + spectrometer system for LMT
- Science cases
  - Galactic, High-z
- Status of commissioning
  - Commissioning is ongoing
- Future plan
  - Science operation
  - Common use
  - Upgrade

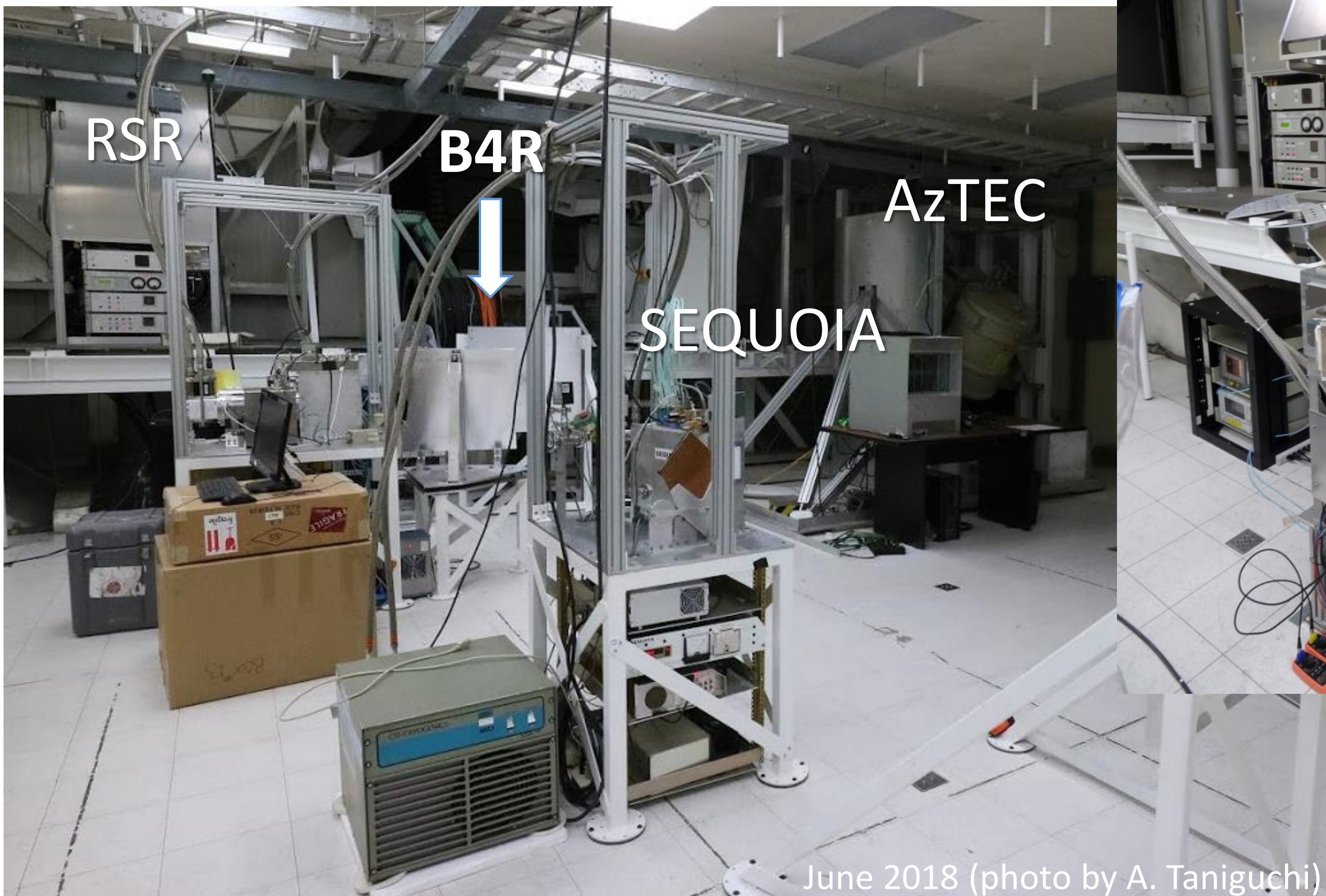
New 2-mm (Band-4) Receiver: **B4R**

2-mm (Band-4) Receiver: **B4R**

- Single beam dual-polarization receiver + spectrometer system for LMT
- Receiver:
  - based on the ALMA Band-4 receiver developed by NAOJ (Asayama+14)
  - RF frequency range: 125 - 163 GHz
  - state-of-the-art SIS mixers: T_{RX}(SSB) ~ 50 K
- Spectrometer:
  - consists of 4 XFTTS boards (8 in full B4R)
  - each board covers 2.5 GHz
  - spectral resolution: 88.5 kHz or 0.19 km/s



Frontend Room

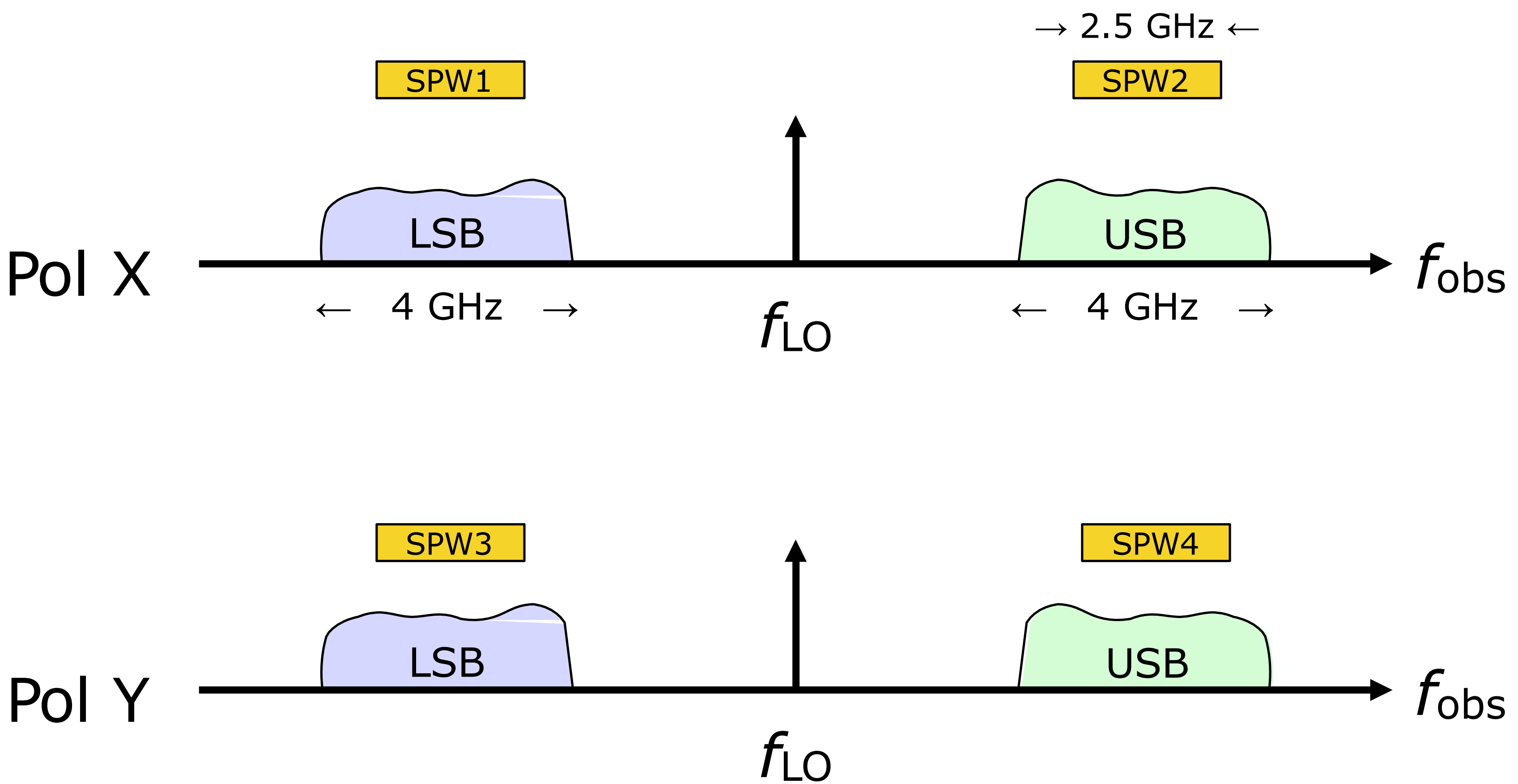


June 2018 (photo by A. Taniguchi)

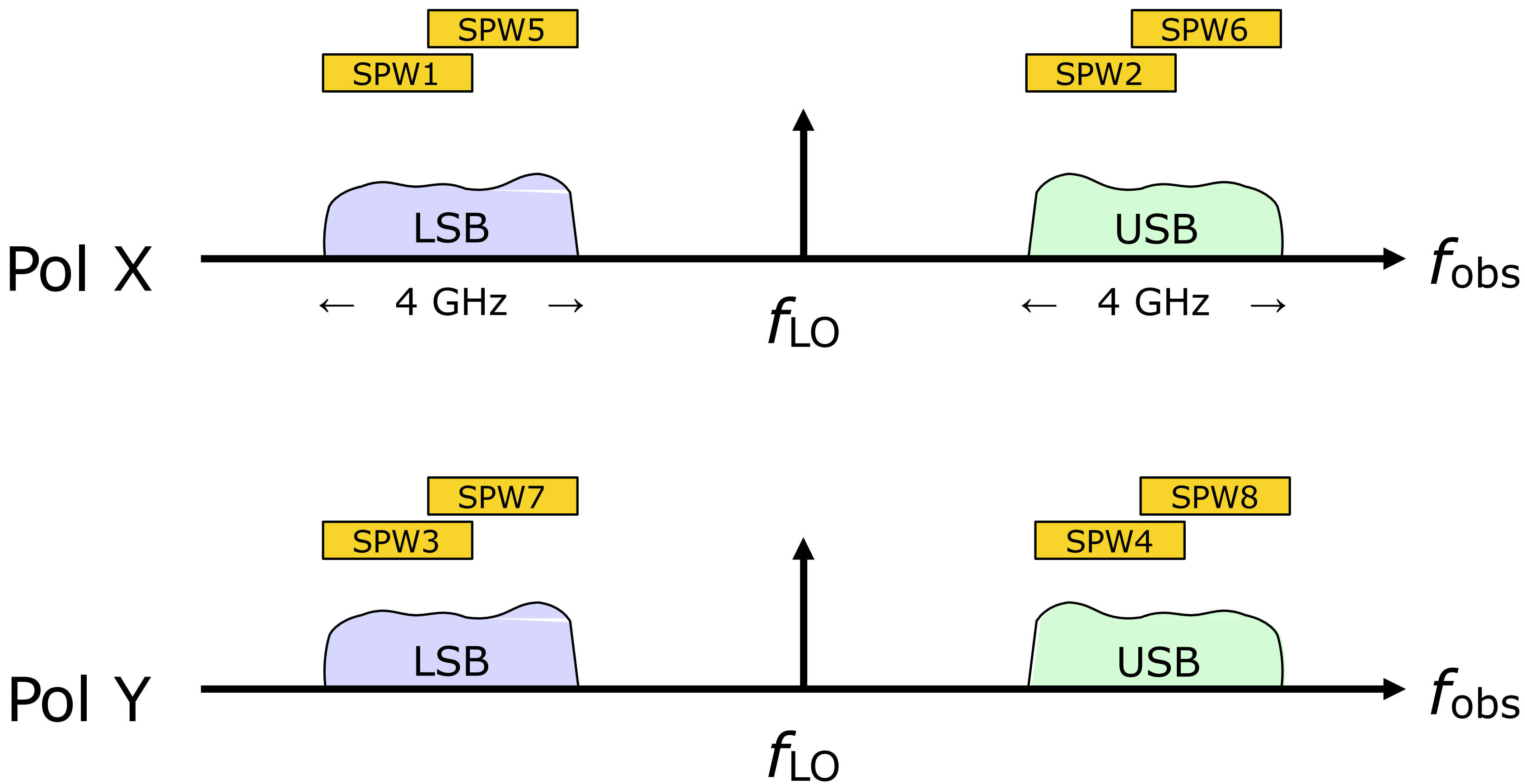
Specifications of B4R/LMT

Receiver specification	Value	Note
RF frequency	125 – 163 GHz	
Wavelength	2.34 – 1.84 mm	
IF frequency	4 – 8 GHz	
Trx	50 K	Asayama+2014, PASJ
# of polarization	2	
# of spectral windows	4	8 for “full” B4R
bandwidth/spw	2.5 GHz	
# of frequency channels	32768	
Spectral resolution	88.5 kHz	0.19 km/s at 140 GHz
Spatial resolution	12” – 8”	
Tsys	~70 – 140 K	PWV 1 – 6 mm

Spectrometer Configuration



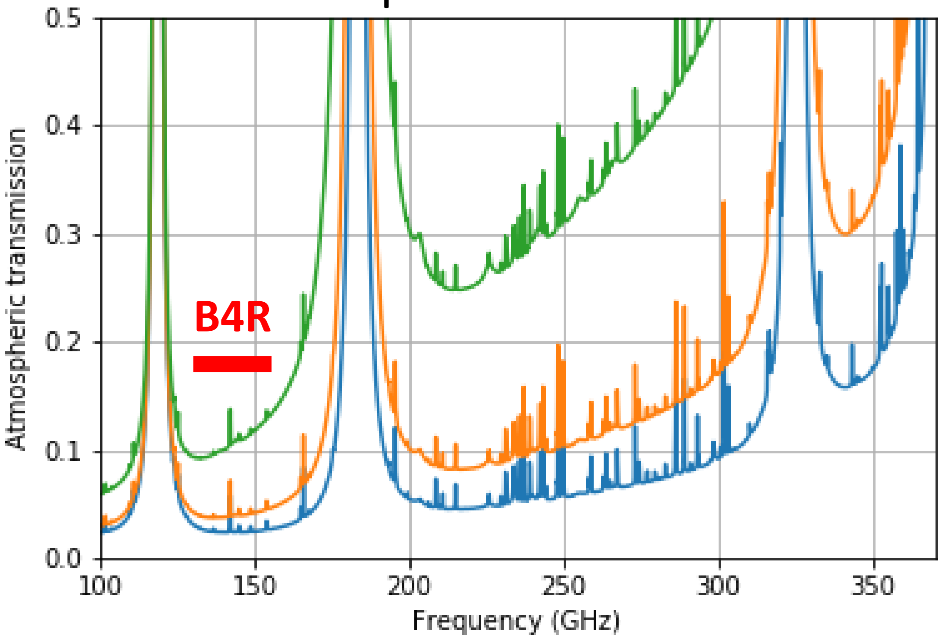
Spectrometer Configuration (full B4R)



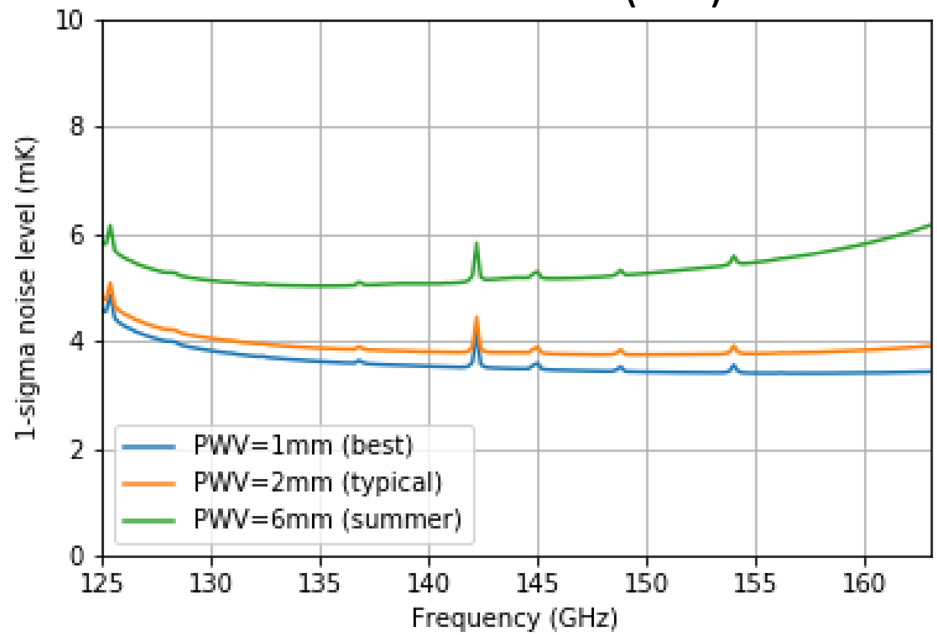
Expected Sensitivity

- typical weather (Tsys ~ 100 K)
- ΔV = 1.5 km/s (8 ch binning, Δν = 0.7 MHz)
- on-source 10 min ➔ 1σ ~ 5 mK

Atmospheric transmission



1σ noise level (mK)



Science Case

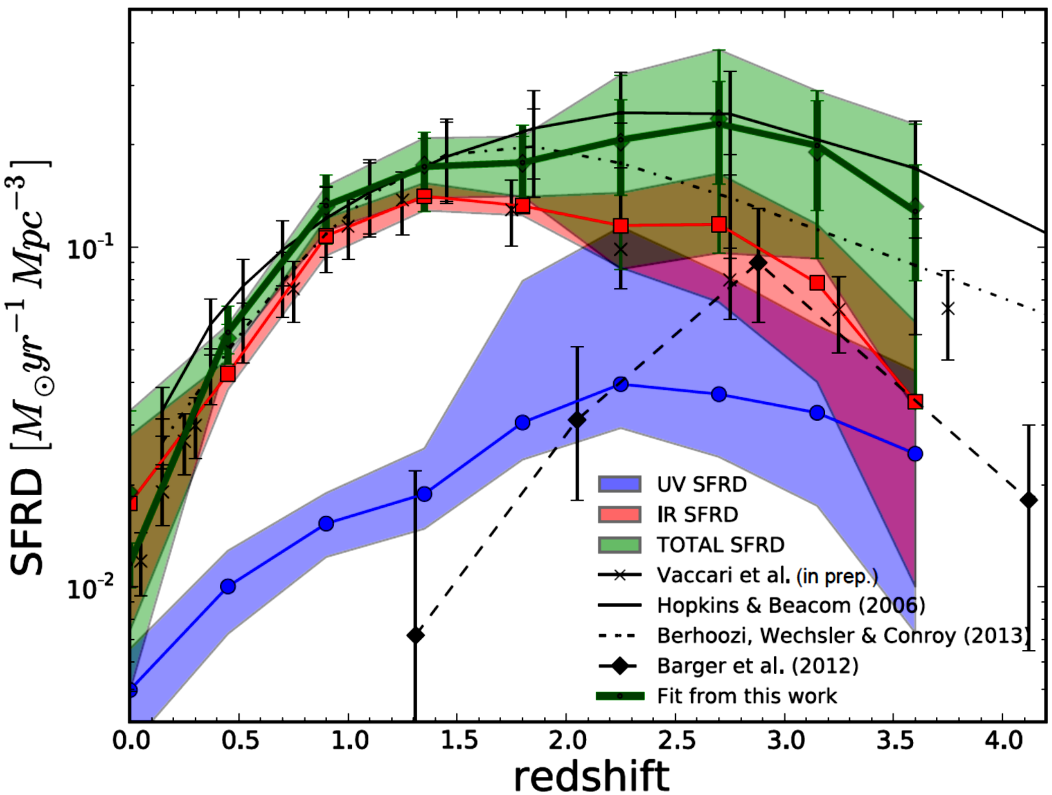
Science Case

- Wide range of studies from Galactic to High-z

- Blind redshift search for SMGs
  - Detecting multiple CO lines together with RSR/LST
- Searching for z ≥ 5 SMGs
  - Contribution of dusty starbursts to the cosmic SF density
- CO SLED for z ≥ 4-5 SMG diagnostics
  - Search for SMGs hosting proto-QSOs
- Deuterium fractionation ratio in massive clouds
  - Formation mechanism of high-mass stars
- Statistical Study of Cloud-Cloud Collision (CCC) sites
  - Are CCC promoting or suppressing SF?

Obscured Star Formation

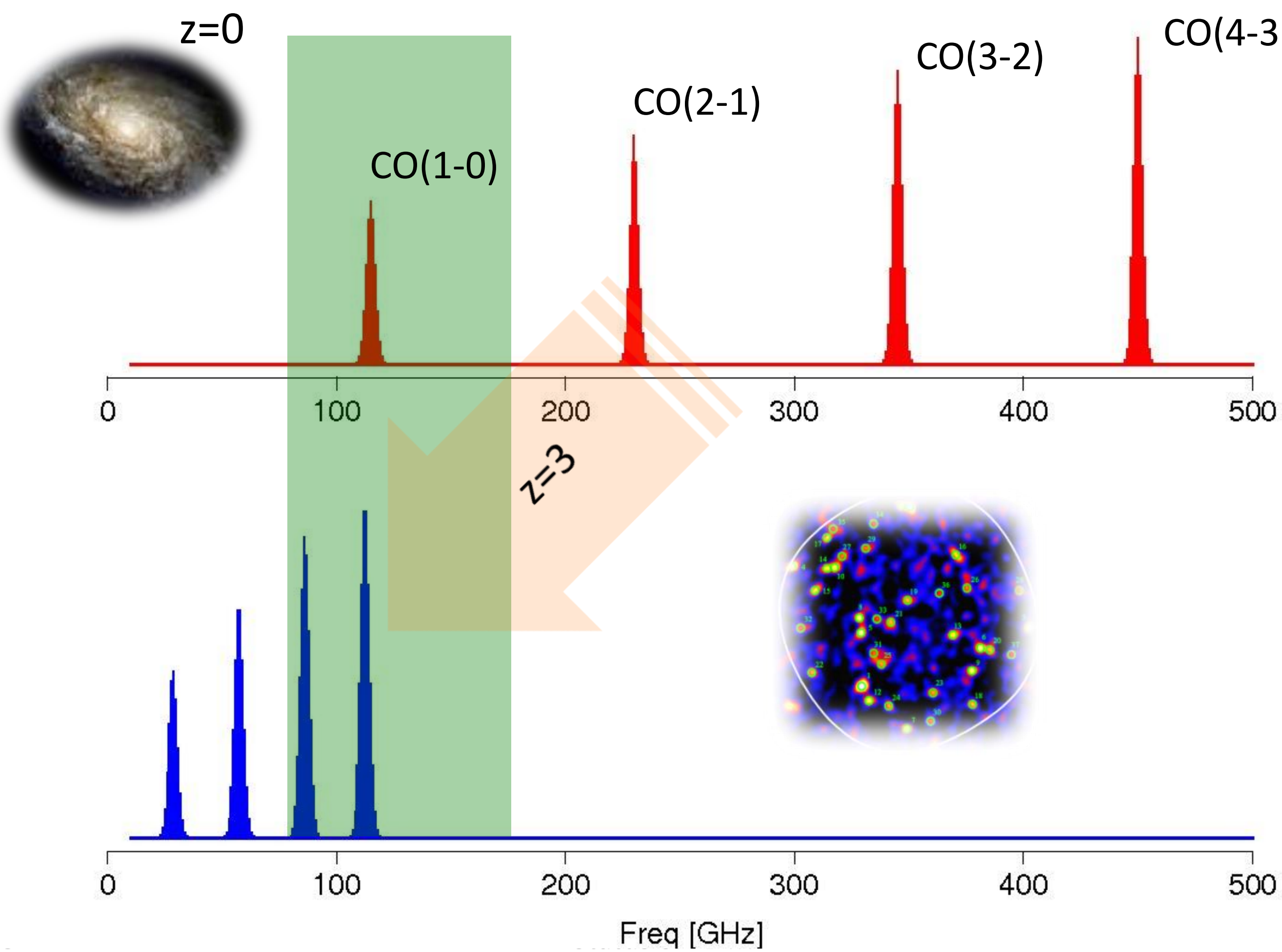
- Star formation at high-z is dominated by dusty galaxies
- It is difficult to determine redshifts through optical spectroscopy due to the faintness at optical



Burgarella+13

Redshift Search of SMGs

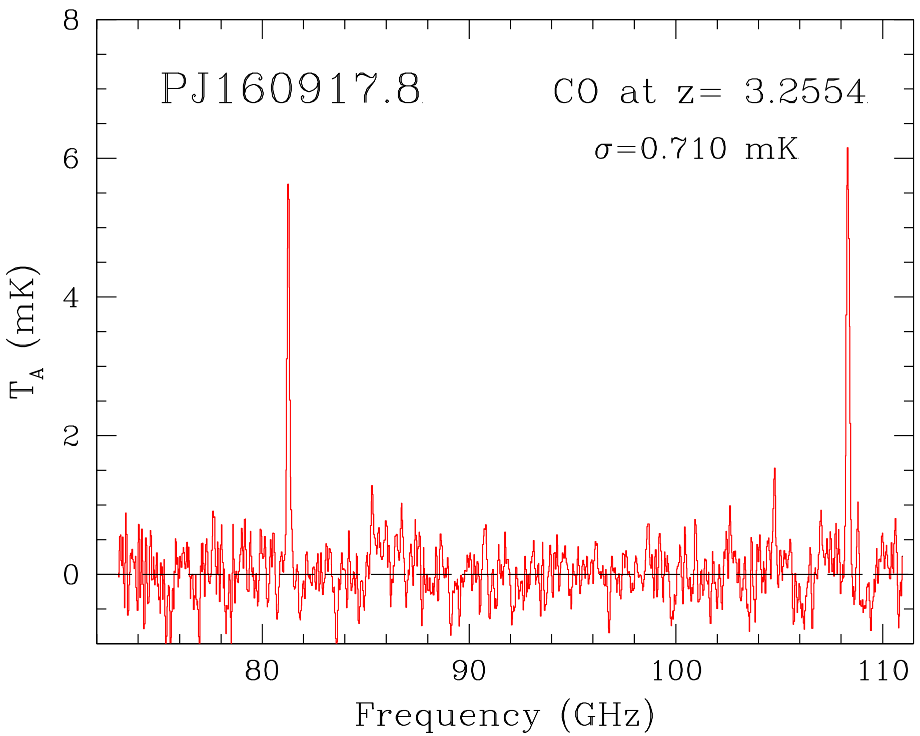
- Obtain secure redshifts of dusty starbursts by blindly detecting two consecutive CO J transitions

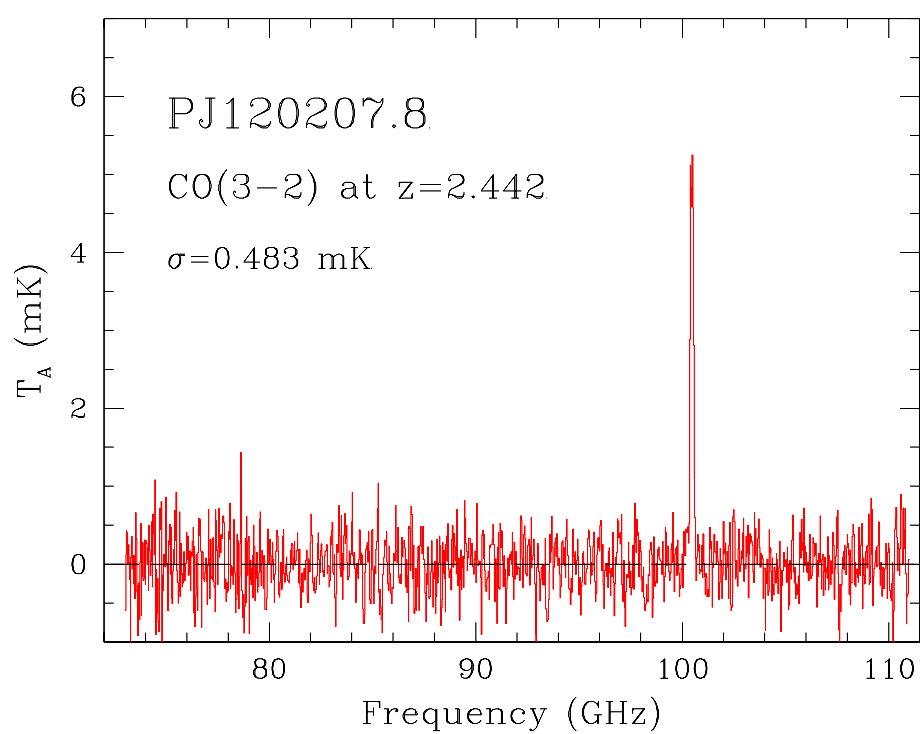


Example of RSR Observations

- Single CO line detection ➔ redshift is not determined

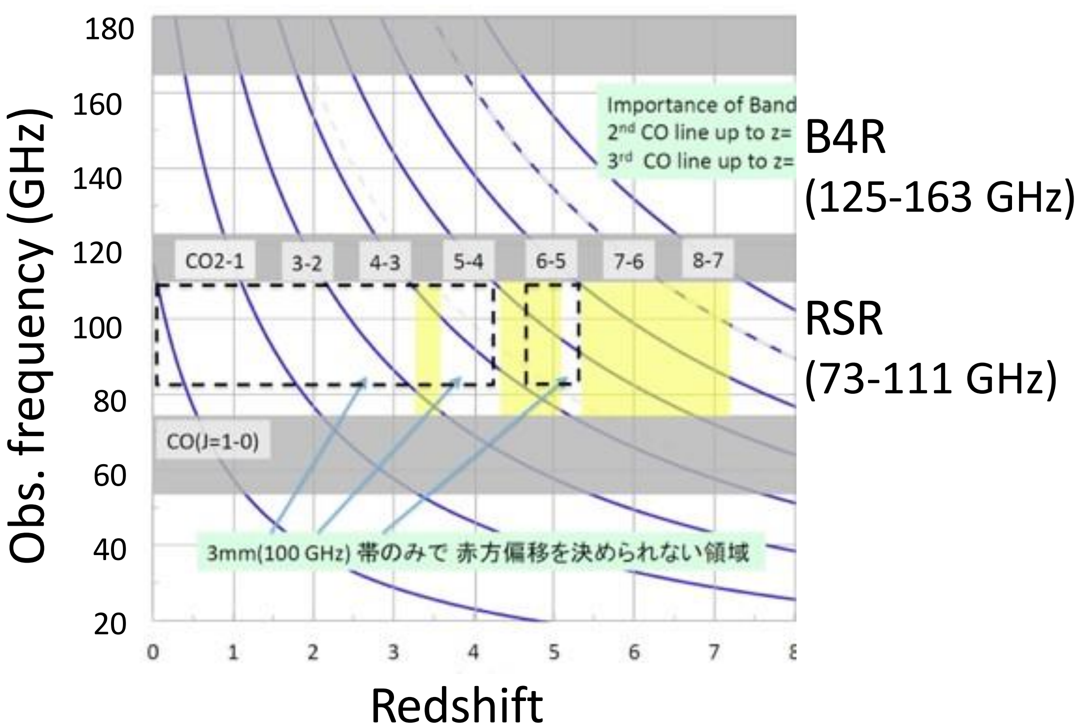
(Harrington et al. 2016)



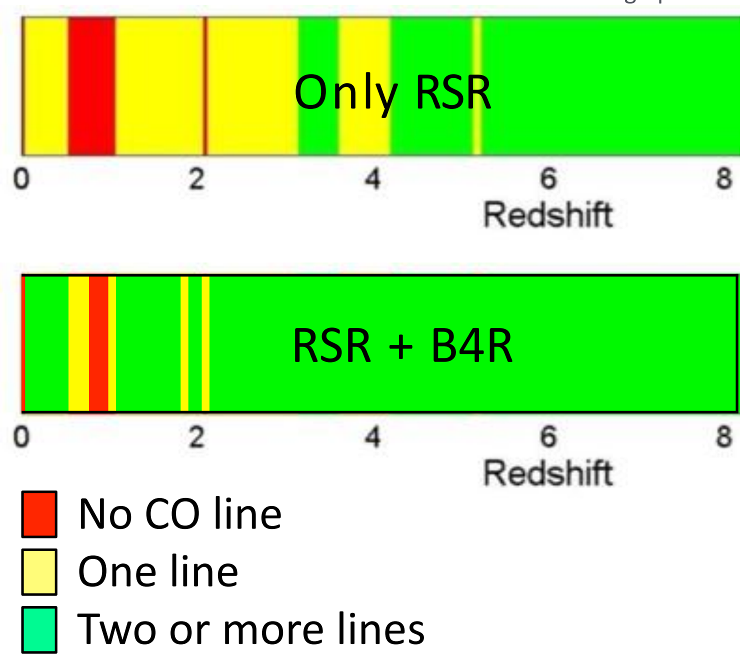


Blind Redshift Search

- B4R fills the “single-line gaps” at important redshifts, where the cosmic SF was peaked

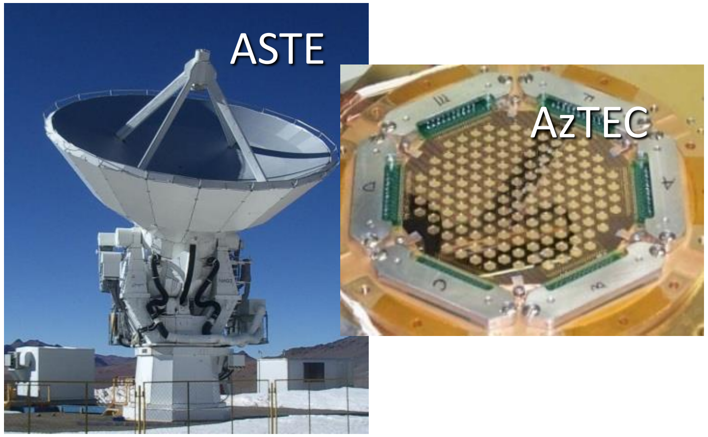


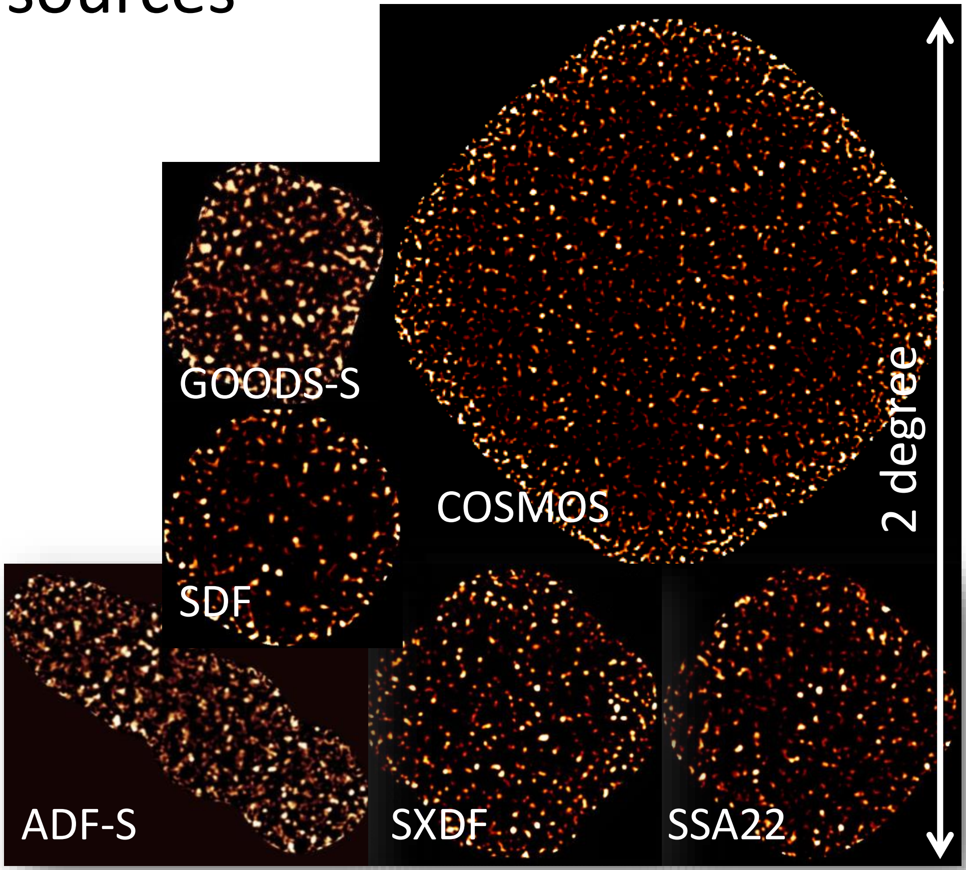
Drawn from David’s viewgraph



Targets for Redshift Search

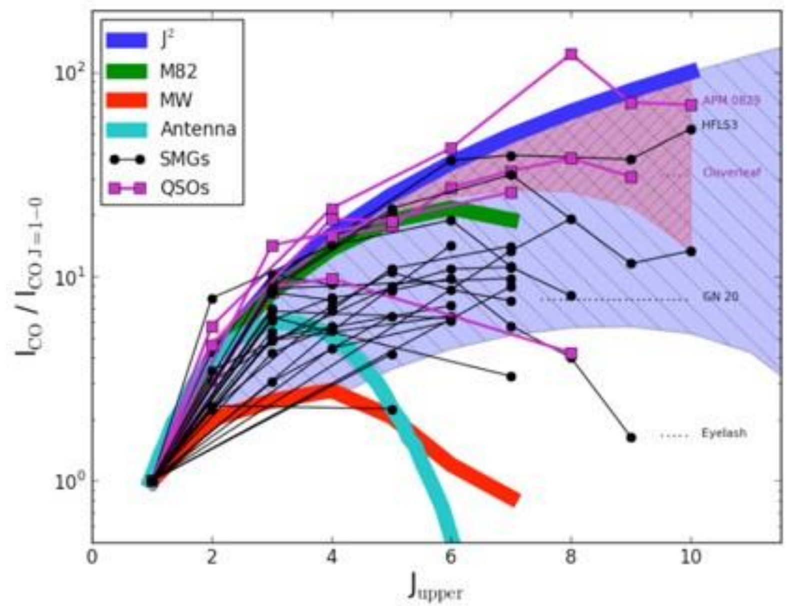
- We have uncovered >1000 SMGs under collaboration among INAOE – UMASS – ASTE
- Herschel-selected lensed sources

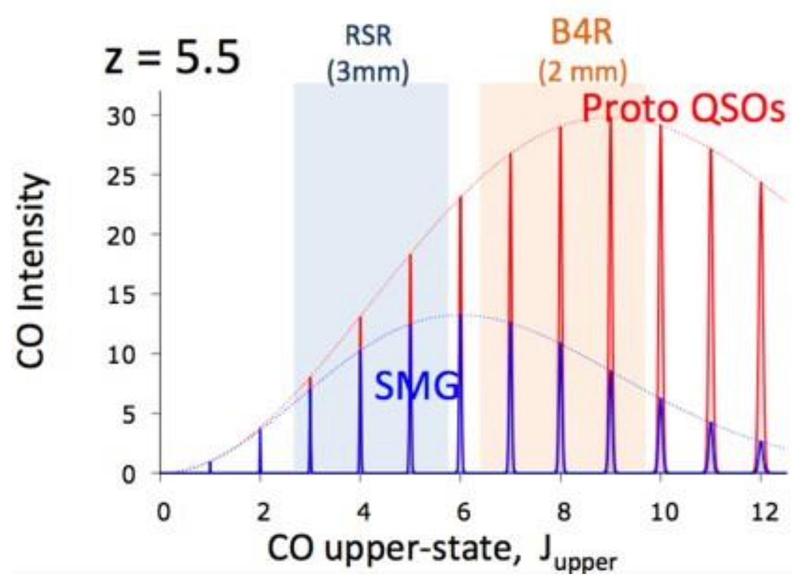




Signature of AGNs

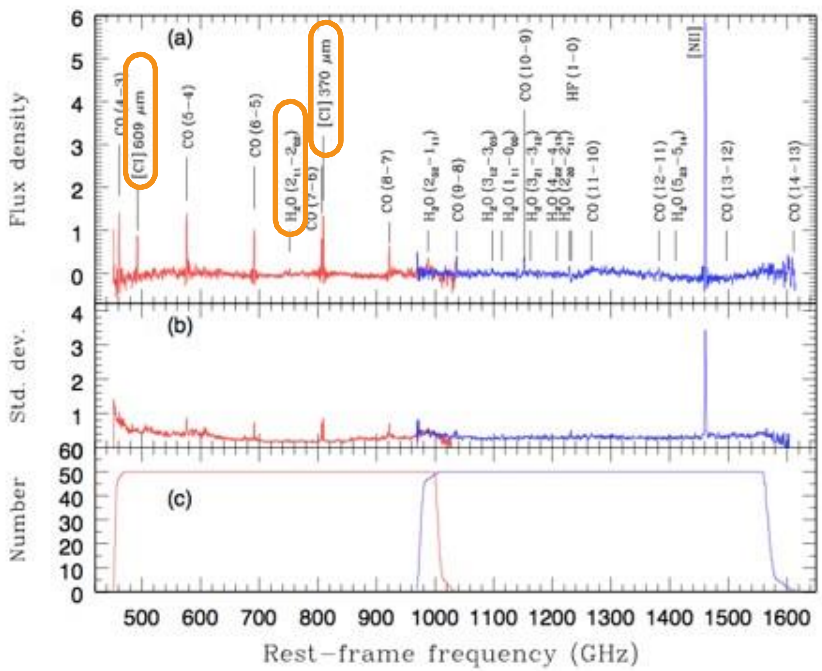
- B4R covers high-J transitions of CO, which should be bright if buried powerful AGNs (proto-QSOs) exist
  - XDR models (rather than PDR models) reasonably account for the high-J (J >~ 7) excitation in the AGN hosts (Meijerink+05)



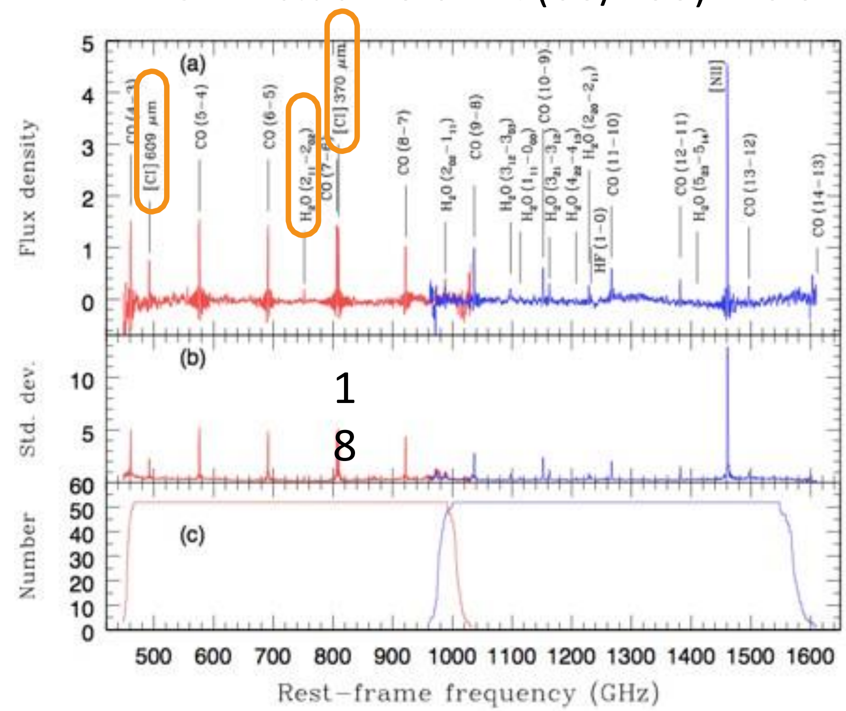


- [CI] $^3P_1$–$^3P_0$ (492 GHz), $^3P_2$–$^3P_1$ (809 GHz) → G_0, n_H
- H_2O 2_{11}–2_{02}, … → AGN signature?

"Pure-SB" stack: 0.3 < C(60/100) < 0.6



"AGN" stack: 0.6 < C(60/100) < 0.9



Lu et al. (2017), ApJS

Deuterium Fractionation in Massive Clumps

- Molecules are highly deuterated in molecular clouds

$$H_3^+ + HD \rightleftarrows H_2D^+ + H_2 + 230\ K$$

$$CH_3^+ + HD \rightleftarrows CH_2D^+ + H_2 + 370\ K$$

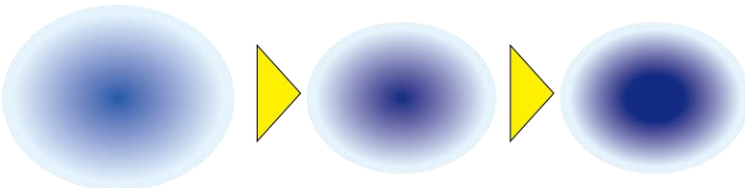
$$C_2H_2^+ + HD \rightleftarrows C_2HD^+ + H_2 + 550\ K$$

- CO depletion (< ~20 K).

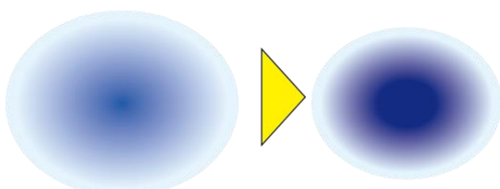
$$H_2D^+ + CO \not\rightarrow HCO^+ + HD$$

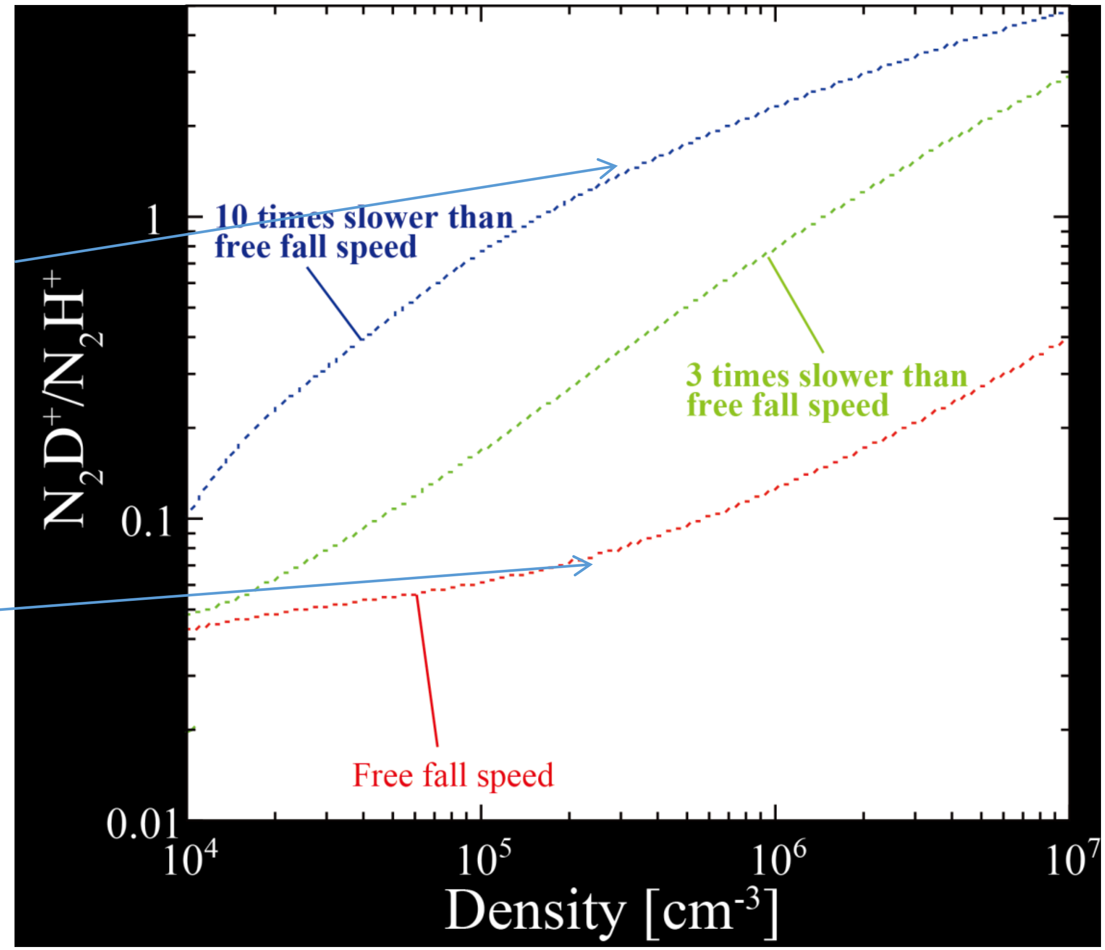
Deuterium Fractionation

Slowly collapsing core



Fast collapsing core

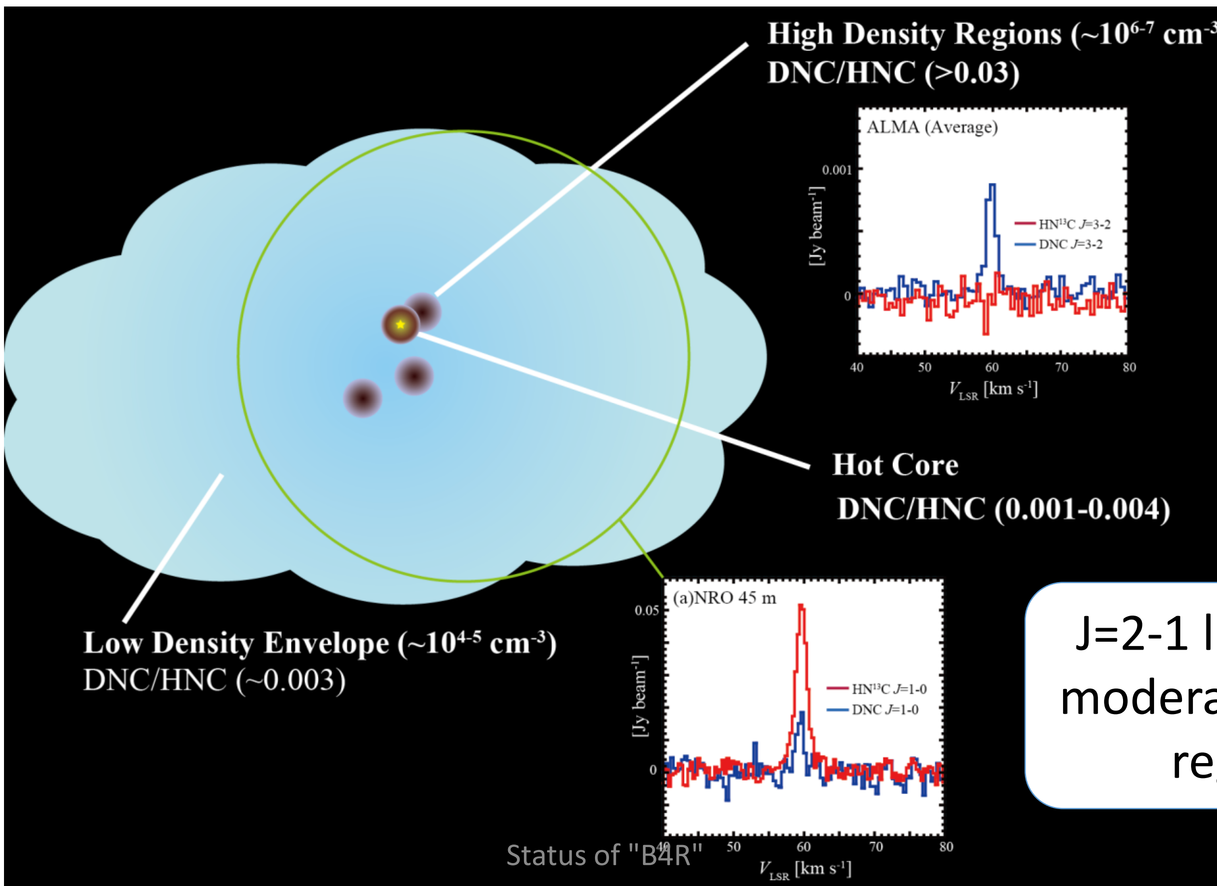




Deuterium fractionation ratios depend on the formation timescale of a dense core
➔ Formation mechanism of high-mass stars can be distinguished

Multi-transition Line Observations

- Deuterated molecules
  - *J*=1-0 (Band 2: 70 GHz)
  - *J*=2-1 (Band 4: 140 GHz)
  - *J*=3-2 (Band 6: 210 GHz)
- Normal molecules
  - *J*=1-0 (Band 3: 90 GHz)
  - *J*=2-1 (Band 5: 180 GHz)
  - *J*=3-2 (Band 6: 270 GHz)



J=2-1 lines trace moderate density regions

Cloud-Cloud Collisions (CCC) in the GC (K. Tanaka)

- Controversy about cloud-cloud collision (CCC)
  - Efficient mechanism to form massive stars and clusters (*Habe&Ohta+91*) ?
  - Suppressing SF by enhancing turbulence in MCs (*Dobbs+11*) ?
  - No systematic observational study on CCCs

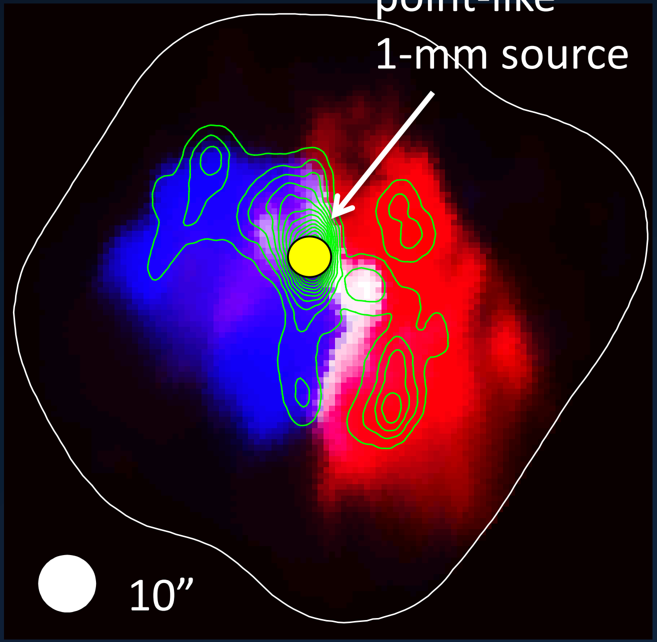
- Central Region of MW: suitable region for study of CCCs
  - An archetypical CCC-triggered starburst region Sgr B2
  - Many CCC-candidate regions not forming stars (Brick, SE-extention of Sgr B2; *higuchi+14, Tsuboi+15*)

  - Compact enough (~200 pc radius) for complete survey with single-dish telescope
    → statistical study
  - Close enough for high-resolution mapping (~0.01 pc) with ALMA
    → details of how CCC promotes/suppresses SF

How can CCC region be identified?

- Case study of the CCC candidate CO–0.3 (*KT+15*)

  Cy-2 Band-6 observations with ALMA 7-m array



HCN 3–2 : Fundamental dense gas structure

Two clouds with different kinematics that are tightly spatially anti-correlated

Methanol Lines : Shocked gas/Heated dust

Thin layers near the boundary between the two clouds

Blue : HCN 3–2 @ 0 km s^{-1}
Read : HCN 3–2 @ 50 km s^{-1}

Contour : CH3OH 5_2–4_1 E

Two colliding clouds & CCC-shock layer

- Combination of fundamental dense gas tracers (HCN, HCO^+, <u>CS</u>) and shock tracers (<u>SiO</u>, <u>methanol</u>, <u>formaldehyde</u>) is useful for identification of CCCs
- Band-7 Observation (Cy-3) for further details of the region
  - N-PDF study, search for SF cores, filament formation in the turbulent gas, etc…

What to do with LMT/B4R

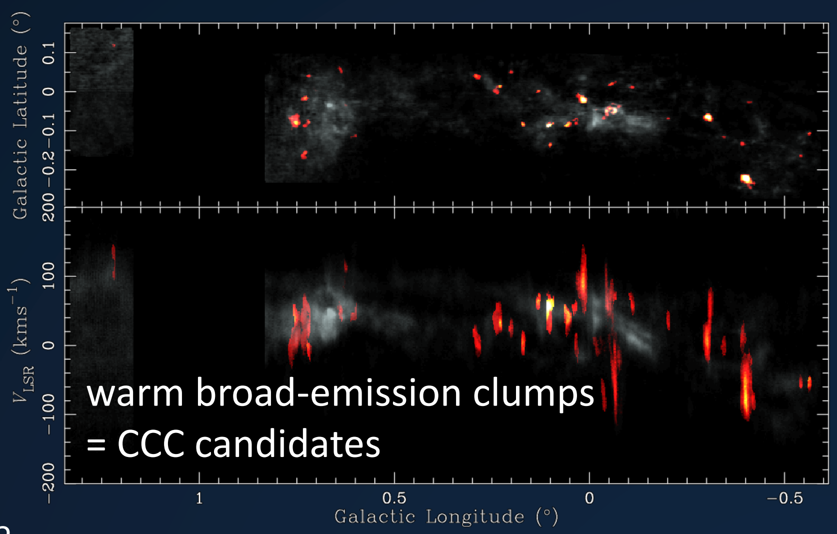
- Identification of CCCs in GC
  - ALMA : unsuitable for survey-type observation
  - NRO45-m, ASTE 10-m : insufficient spatial resolution (~22")
  - LMT /w B4R : ~10" resolution (just enough) + excellent mapping capability

fundamental structure of colliding gas

- Target Lines (2 IF settings)
  - CS 3–2 : 146.969 GHz
  - SiO 3–2 : 130.269 GHz
  - p-H_2CO : 145.602 GHz
  - (a few a-CH_3OH lines near CS 3–2 ~ 0.1 K)

~ 1 K

CCC-shock layer



- Time Estimate
  - T_{sys} = 60 K, ΔT_{rms} = 0.05 K, 5"x5"x2 kms^{-1} grid
  - 10 arcmin^2 OTF mapping per source (without FMLO)
  - 15 min/source x 2IFs x ~10 CCC candidates = a few – 10 hrs?

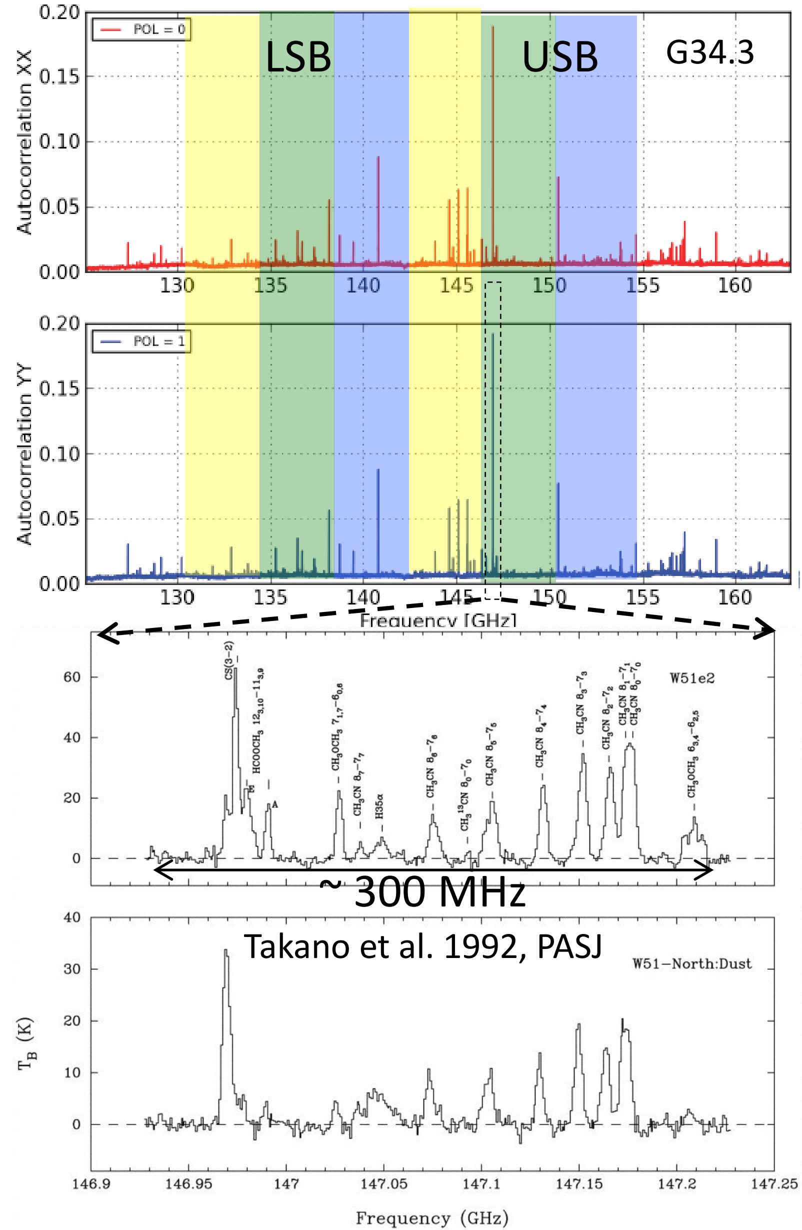
Ohter Science Cases

- Line Survey
  - 3 freq. settings cover 24 GHz (full B4R)

- Chemistry, Galactic Science

Deuterated molecule	DCO+, DCN(J=2-1)
Shock chemistry	CH3OH(3-2), CS(3-2), CH3CN, H2CO
Hot core chemistry	CH3OCH3, HCOOCH3
Dense gas tracer	C34S(3-2), H2CO
Ultra-compact HII region	Recombination Lines
Cloud-cloud collision	CS(3-2), SiO(3-2), p-H2CO, a-CH3OH lines

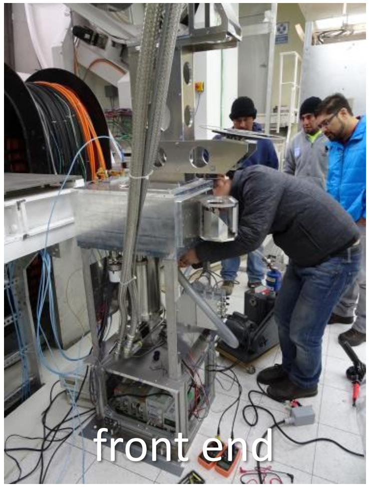
- 2mm VLBI?
  - SiO(3-2) or Continuum

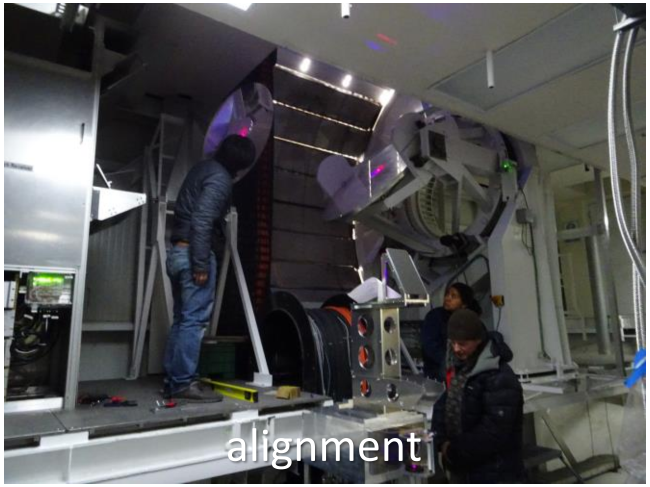


Commissioning & Schedule

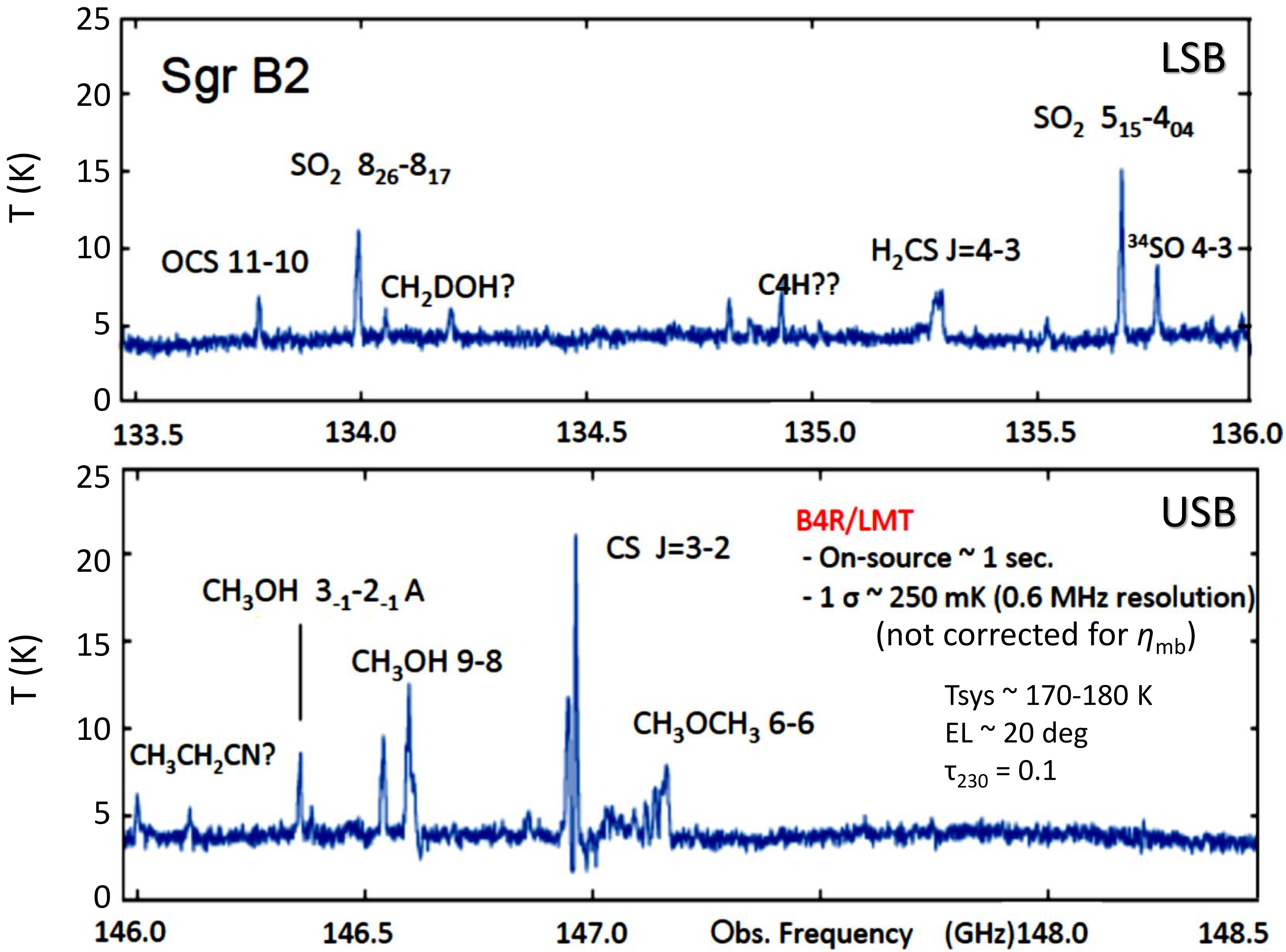
Commissioning: Mar. 2018

- Mar. 6 – 16, 2018
- Installation & Engineering Tests



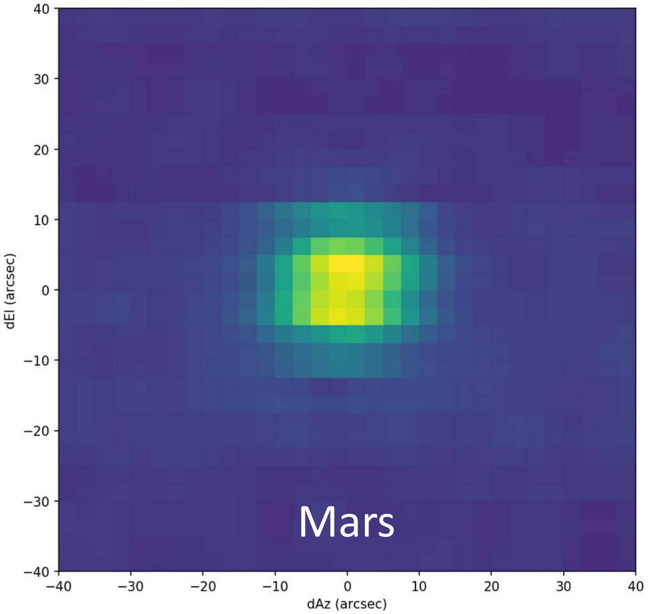


- Succeeded in first light!
  - Jupiter
  - Sgr B2


Sgr B2
LSB
T (K)
25
20
15
10
5
0
SO2 8_26-8_17
SO2 5_15-4_04
OCS 11-10
CH2DOH?
C4H??
H2CS J=4-3
34SO 4-3
133.5
134.0
134.5
135.0
135.5
136.0
USB
B4R/LMT
- On-source ~ 1 sec.
- 1 σ ~ 250 mK (0.6 MHz resolution)
(not corrected for ηmb)
Tsys ~ 170-180 K
EL ~ 20 deg
τ230 = 0.1
CS J=3-2
CH3OH 3-1-2-1 A
CH3OH 9-8
CH3OCH3 6-6
CH3CH2CN?
146.0
146.5
147.0
Obs. Frequency (GHz)
148.0
148.5

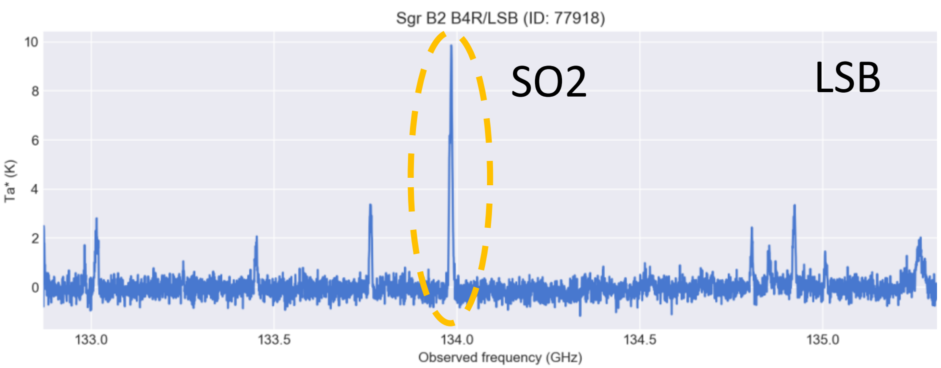
Commissioning: Jun. 2018

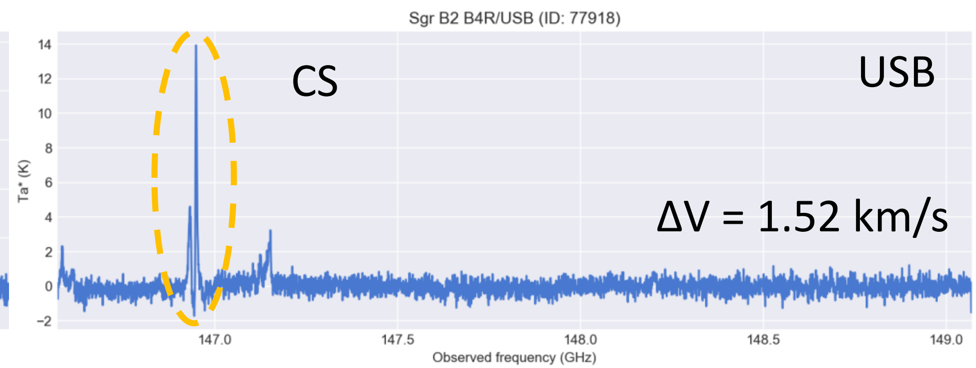
- Jun. 7-20, 2018
- Installation of M5 and alignment
- Replacement of motor & driver for chopper
- Measurements of Tsys, frequency characteristics, sideband ratio
- Focusing & Pointing
- Measurement of beam pattern
- Test observations
- Installation of FMLO system
- First light with FMLO

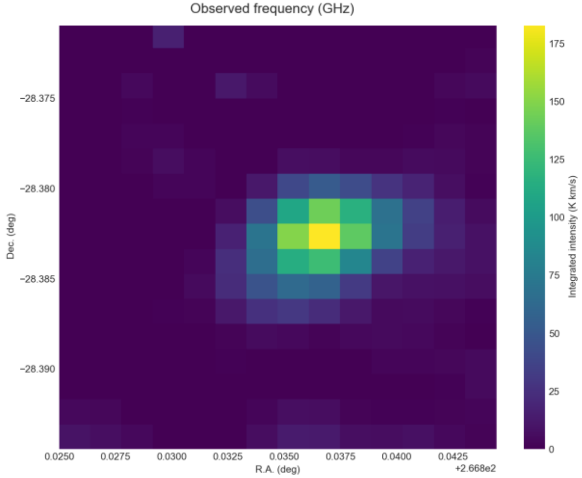


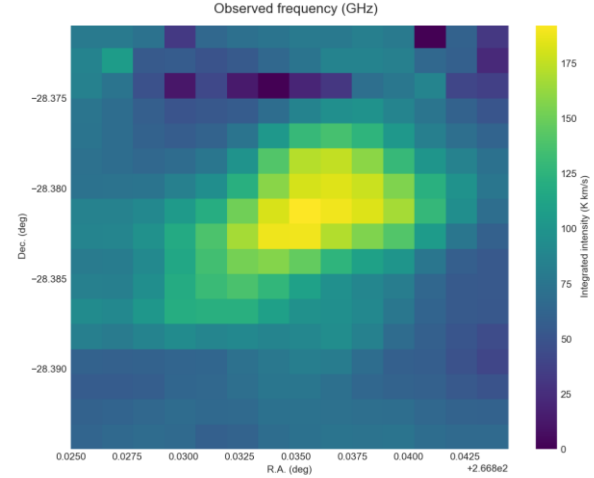
Commissioning: Jun. 2018

- Sgr B2
  - OTF 60” x 60” map
  - Tsys ~ 300 K, EL ~ 20 deg, tau = 0.46
  - Total on-source time = 59 sec (➔ ~1 sec / 5” pix)









Commissioning Plan

- Schedule
  - 25 Sep. – 15 Oct. 2018(?)

- Receiver upgrade (mainly day-time)
  - installation of new motor driver for chopper, rain cover, web camera etc.
  - improvement of grounding, total power stability, optimization of the receiver
  - measurements of Tsys, stability
  - knowledge transfer of B4R system & operation

- On-sky test
  - test of observation modes (PSW, FMLO)
  - measurements of beam pattern, efficiency
  - demo science observations (Orion-KL, Sgr B2, lensed SMGs)

Future Plan

- Science operation & common use in 2019
  - on a shared-risk basis
  - depending on the progress of the commissioning, the commissioning of other instruments, and LMT activities

- Future upgrade
  - 4 XFFTS boards ➔ 6 ➔ 8 (full B4R)
  - improvements of flexibility of frequency setups
  - implementation of FMLO
    - a new off-point-less observing method by modulating 1st LO, developed by Y. Tamura, A. Taniguchi et al.

Summary

- B4R
  - Single beam dual-pol. 2-mm band receiver + spectrometer system
  - 125 - 163 GHz
  - 4 x 2.5 GHz spws (8 in full B4R)
  - spectral resolution of 88.5 kHz or 0.19 km/s
- Commissioning is ongoing (Mar. 2018~)
- Science operation & common use in 2019
  - depending on the progress of commissioning