DESHIMA 2.0 at ASTE

ultra-wideband spectroscopy of distant galaxies

Matus Rybak for the DESHIMA collaboration (A. Endo, A. Moerman, K. Karatsu, A. Taniguchi, K. Kohno, Y. Tamura, T. Takekoshi, Y. Nishimura, etc.)



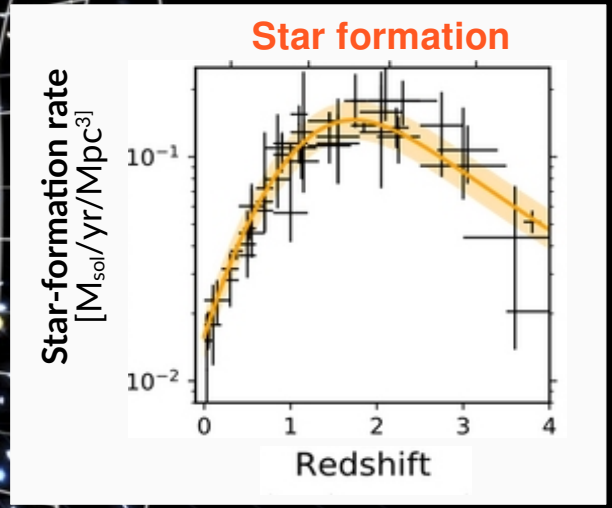
Dusty star-forming galaxies (DSFGs)

t = 3 billion years

50% stars have formed

Big Bang





Walter+2020

Age of the Universe: 13. 7 billion years

Dusty star-forming galaxies (DSFGs)

Extreme star formation
SFR = 100-1000 M_{sol}/yr
(e.g., Casey+2014)

Contain up to 50% of all stars – *representative!*
(Swinbank+2014)

Difficult to reproduce in simulations
(McAlpine+2019, Lovell+2021, Dave+2021)

Turbulent, excess of high-mass stars?



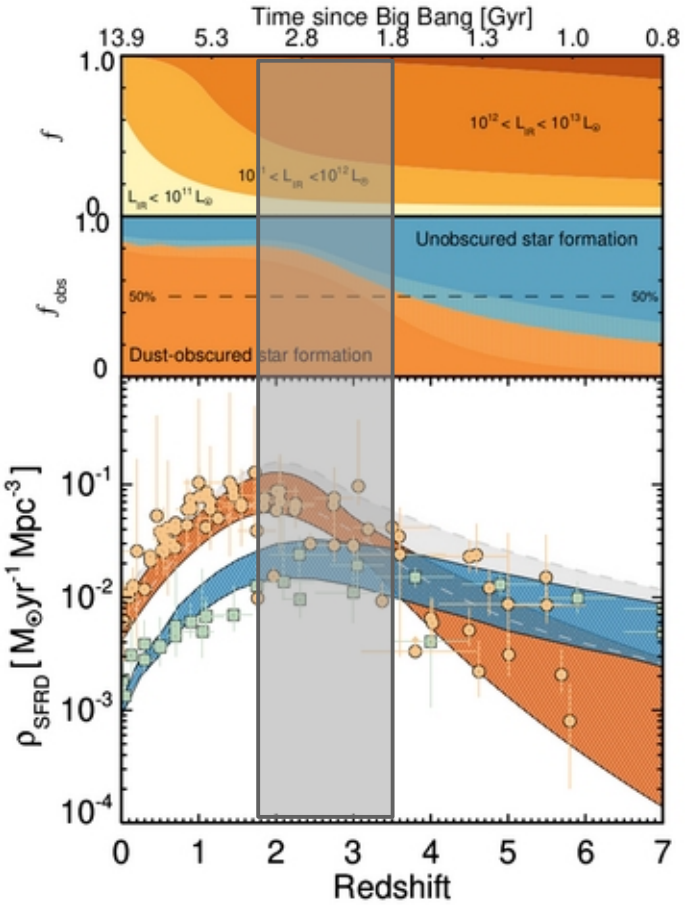
Dust-obscured, but **sub-mm** bright



Hubble - purple
ALMA - orange
(not detected by Hubble)

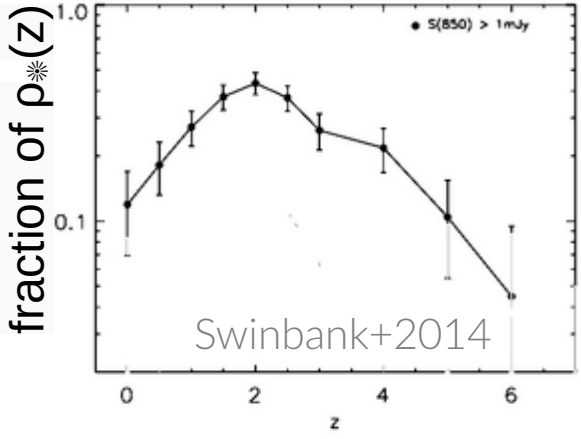
Image credit: NASA / ESO / NRAO

Why DSFGs matter



Zavala+2021

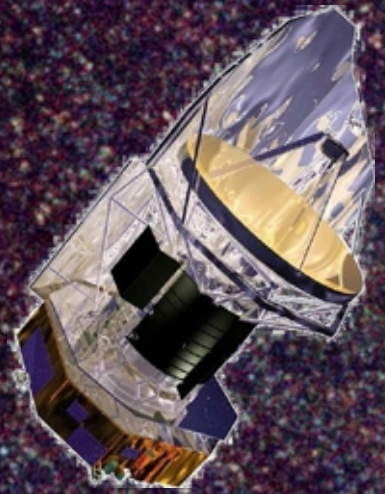
- Obscured star-formation dominant at least out to z~4
- For z>2, this is chiefly due to DSFGs with $L_{FIR}>10^{12}$ L_{sol}



- DSFGs contain up to 50% of stellar mass at z~2 → *representative environments*!

Finding DSFGs: wide-field continuum surveys

(e.g., Herschel, SPT, SCUBA-2, LABOCA)



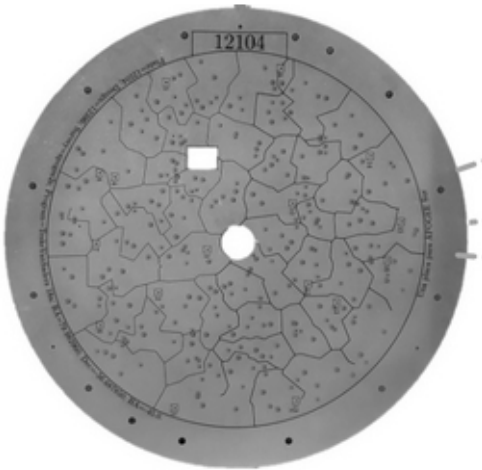
Gravitational lensing!

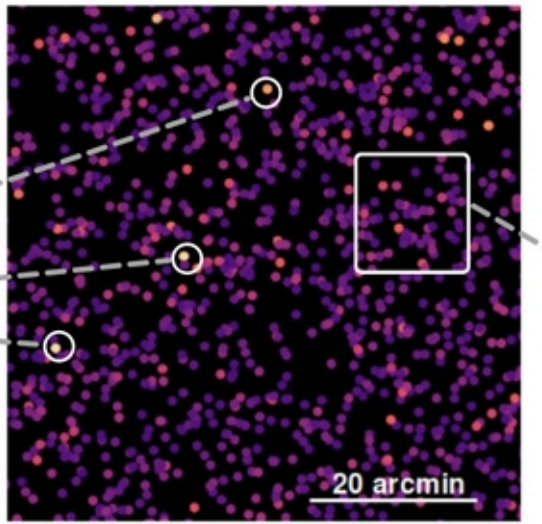


SPIRE 250/350/500 um

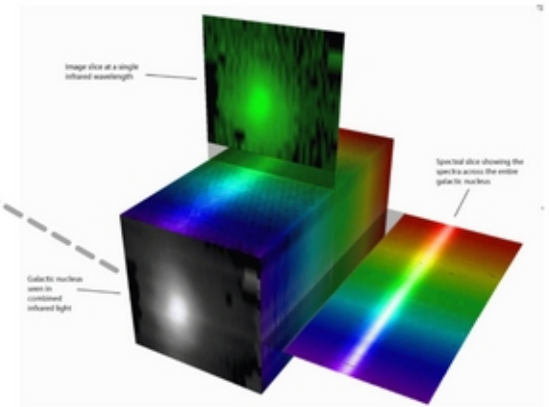
Optical vs sub-mm spectroscopy: the technology gap

Multi-object spectroscopy
(targeted)





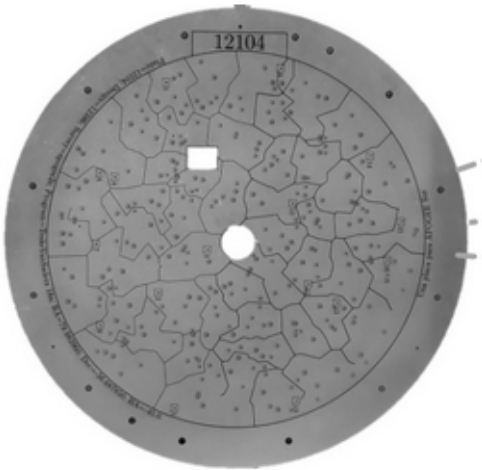
Integral Field Units
(“blind”)

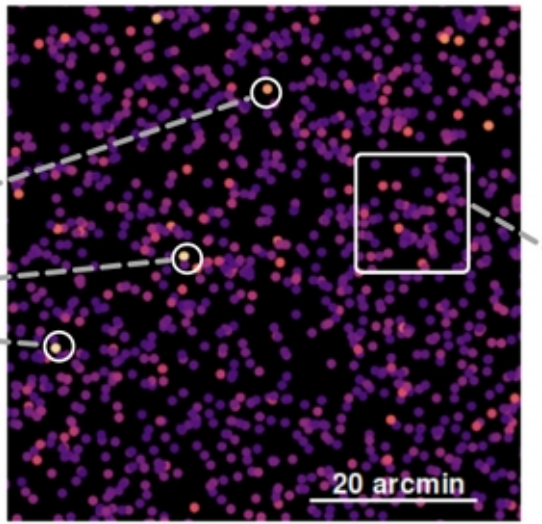


Regime	Fractional bandwidth	Multi-object	“IFU” FoV
Optical / NIR	1 - 3 octaves (best)	100’s-1000’s	>1 arcmin^2, >10,000 px
sub-mm	**2%- 10%; 30% (best)**	**1**	Multi-pixel: 64 Interferometers: 0.1 arcmin^2

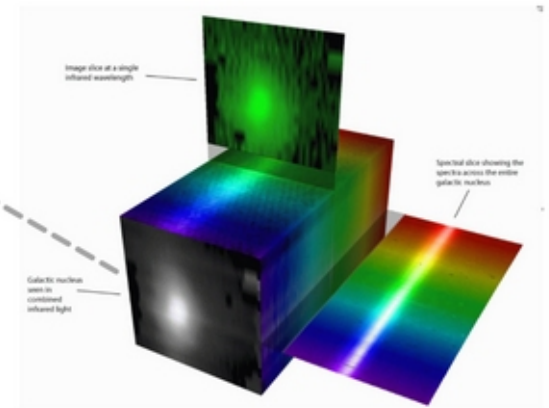
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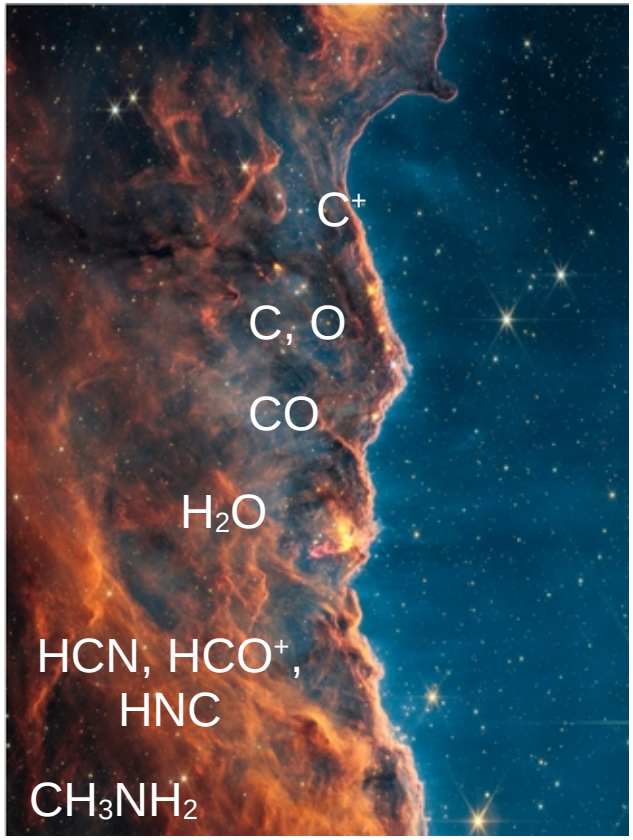


Integral Field Units
(“blind”)



Regime	Fractional bandwidth	Multi-object	“IFU” FoV
Optical / NIR	1 - 3 octaves (best)	100’s-1000’s	>1 arcmin^2, >10,000 px
sub-mm	DESHIMA: 1 octave	1	TIFUUN: 100+ px

Spectroscopy give us a view of gas masses & thermodynamics

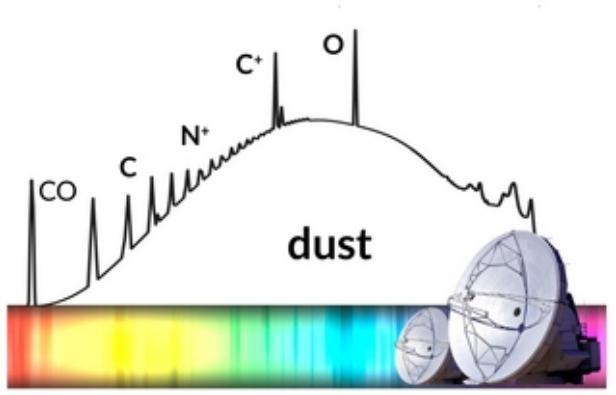


- CO / C+ / C emission lines trace the total molecular gas mass:
Important for measuring

- DSFGs have often 50-80% of their baryons in gas rather than stars

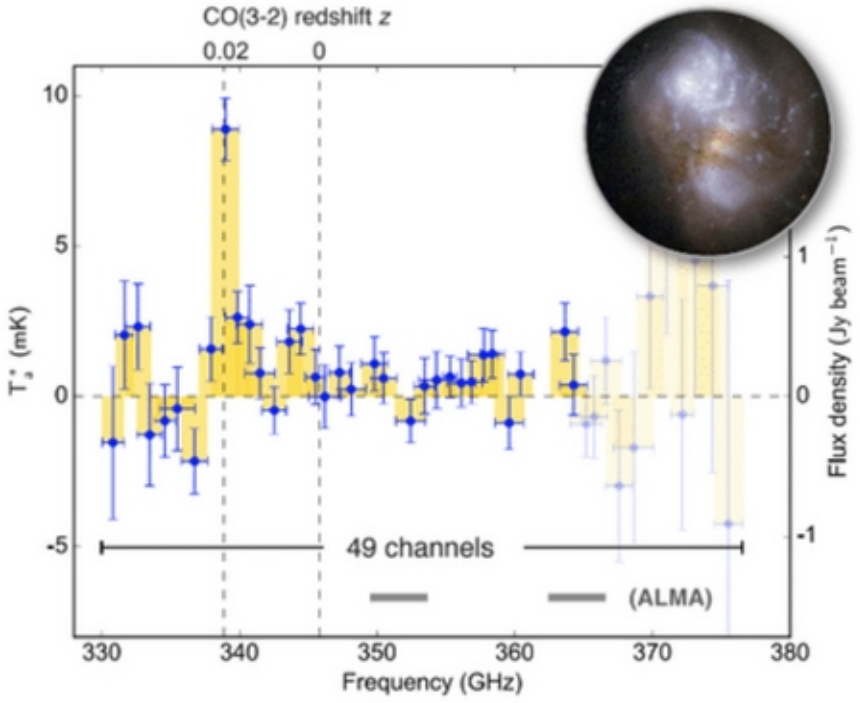
Gas thermodynamics
(Density, temperature, turbulence, shocks ...)

Observed spectra

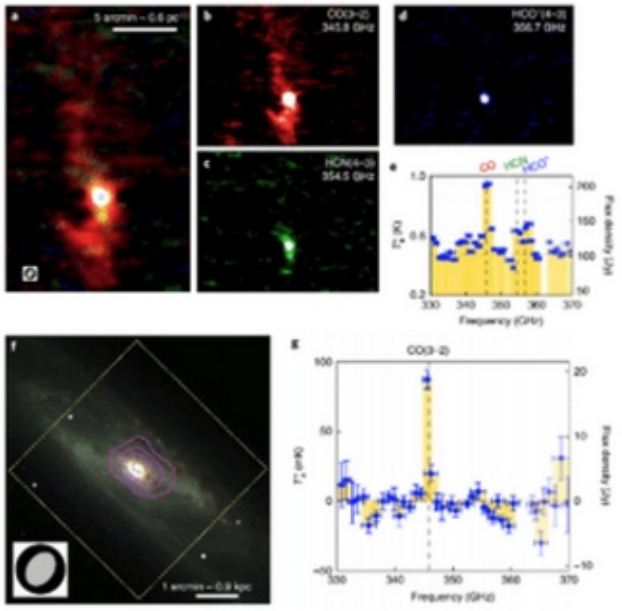


2017: first light of DESHIMA 1.0

Redshifted CO from LIRG (VV 114)

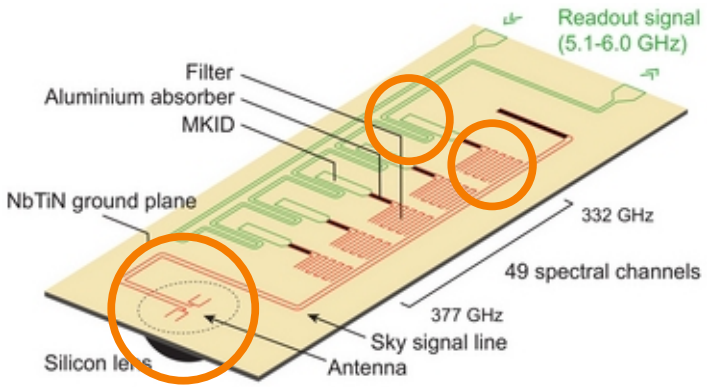


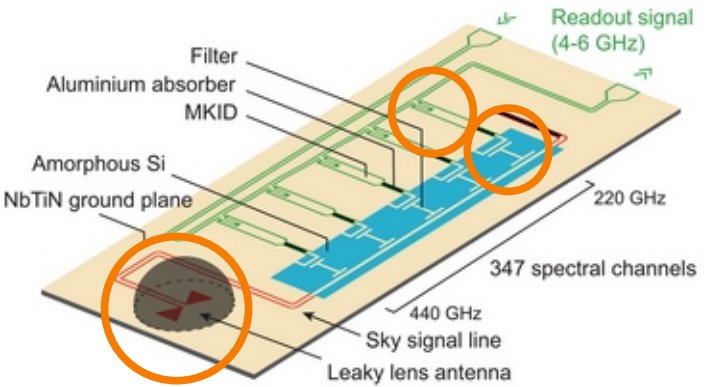
Spectral Maps of Orion & NGC 253



Endo+2019, Nature Astronomy 3, 989–996

DESHIMA 1.0 DESHIMA 2.0



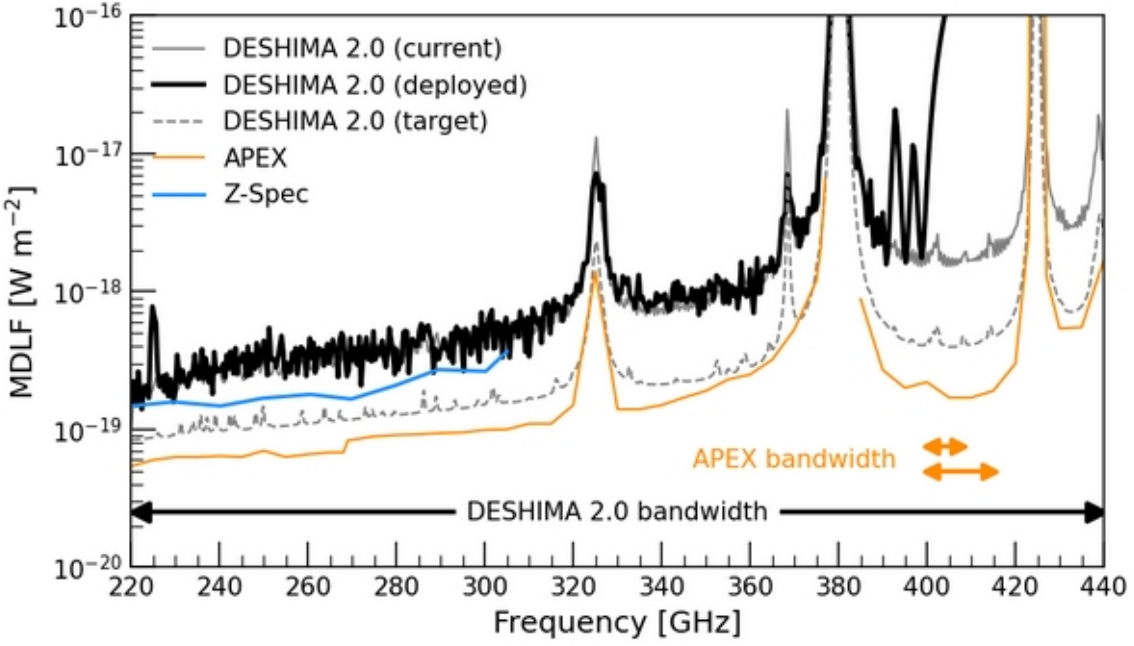


Frequency range:	332 - 377 GHz	**220 - 440 GHz**
Channels:	49	**347**
Freq. Resolution:	~800 km/s	**~600 km/s**
Optical efficiency:	2%	**~8 %**

Endo+2019, **Taniguchi+2022**, Rybak+2022

Predicted performance

(Taniguchi+2020, Rybak+2020)



Minimum line flux detectable at 5σ in 8 hours

DESHIMA 2.0 vs APEX
- 3x worse sensitivity
- 15x wider bandwidth
- overall spectral survey advantage:

DESHIMA is 1.5x faster than APEX!

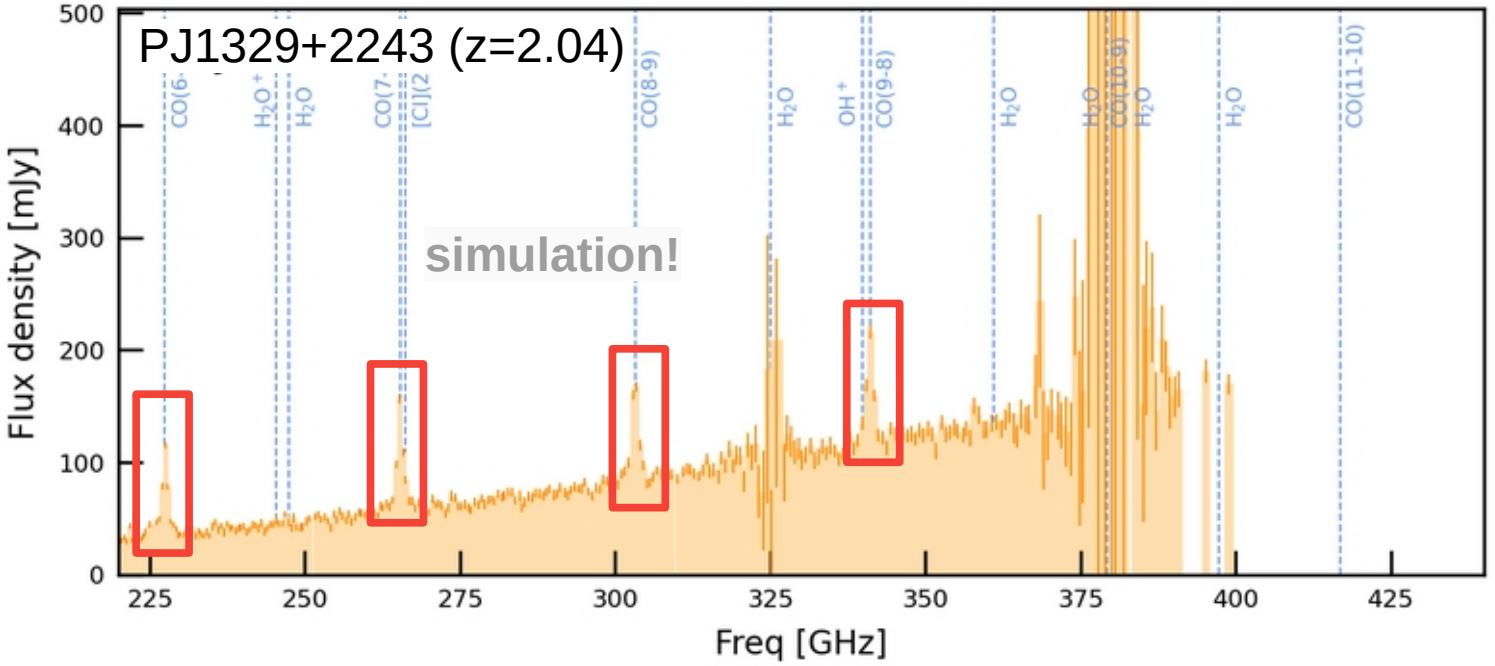
Future upgrade?
DESHIMA 2.1? vs APEX
- **2x** worse sensitivity
- **18x** wider bandwidth (out to 440 GHz)

DESHIMA ~4.5x faster than APEX!

Predicted performace: mock spectra

PJ1329: the brightest CO lines in a z>1 galaxy (Harrington+2021)

Spectra, 2 nights on-source, pwv = 0.5 mm



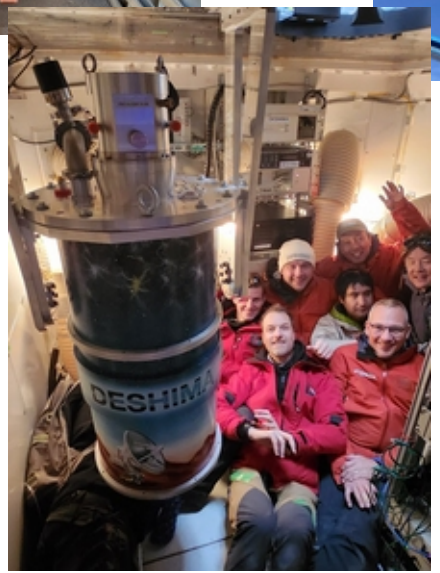
DESHIMA 2.0 on ASTE

Oct 2023 – Dec 2024, 6 months of science, 30 remote observers





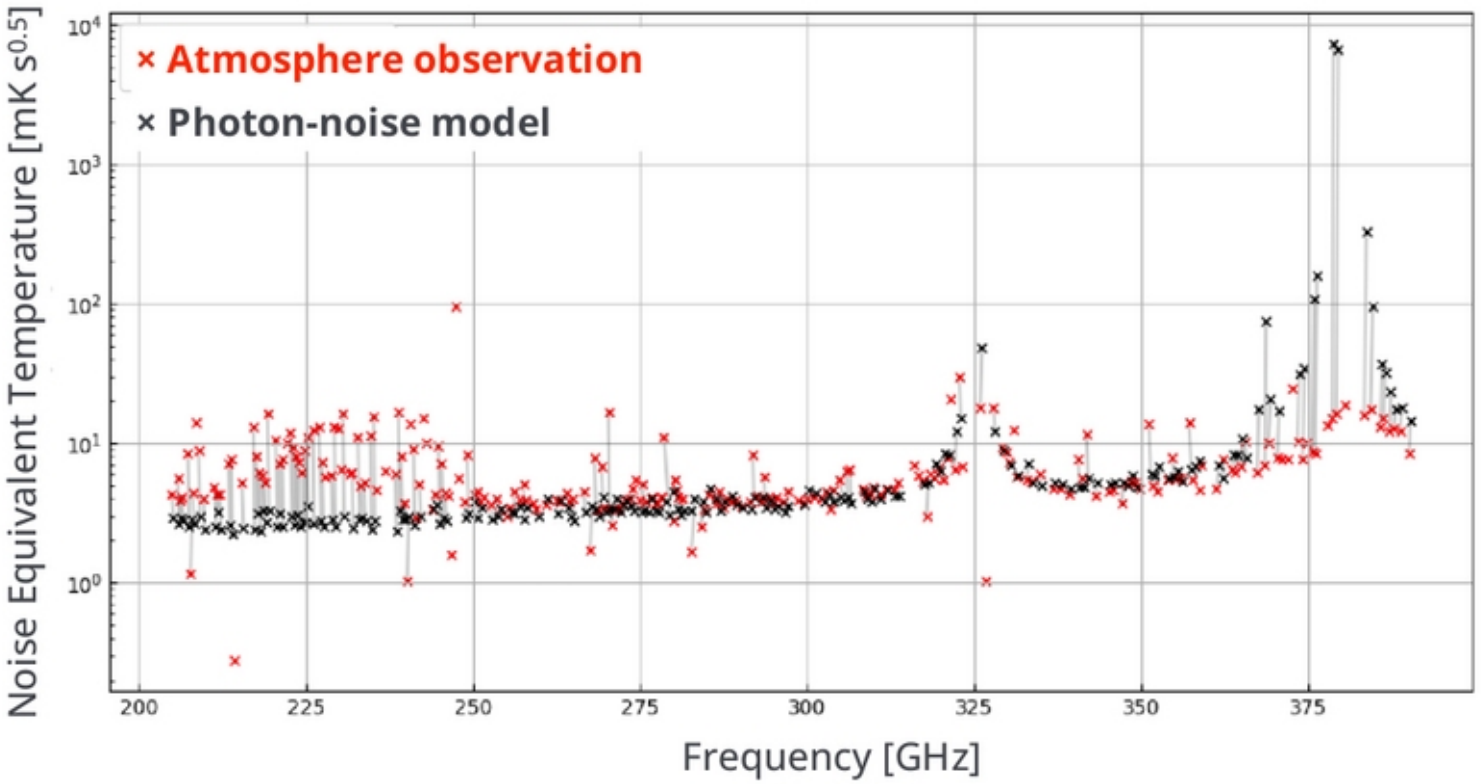








On-sky performance matches the expectations

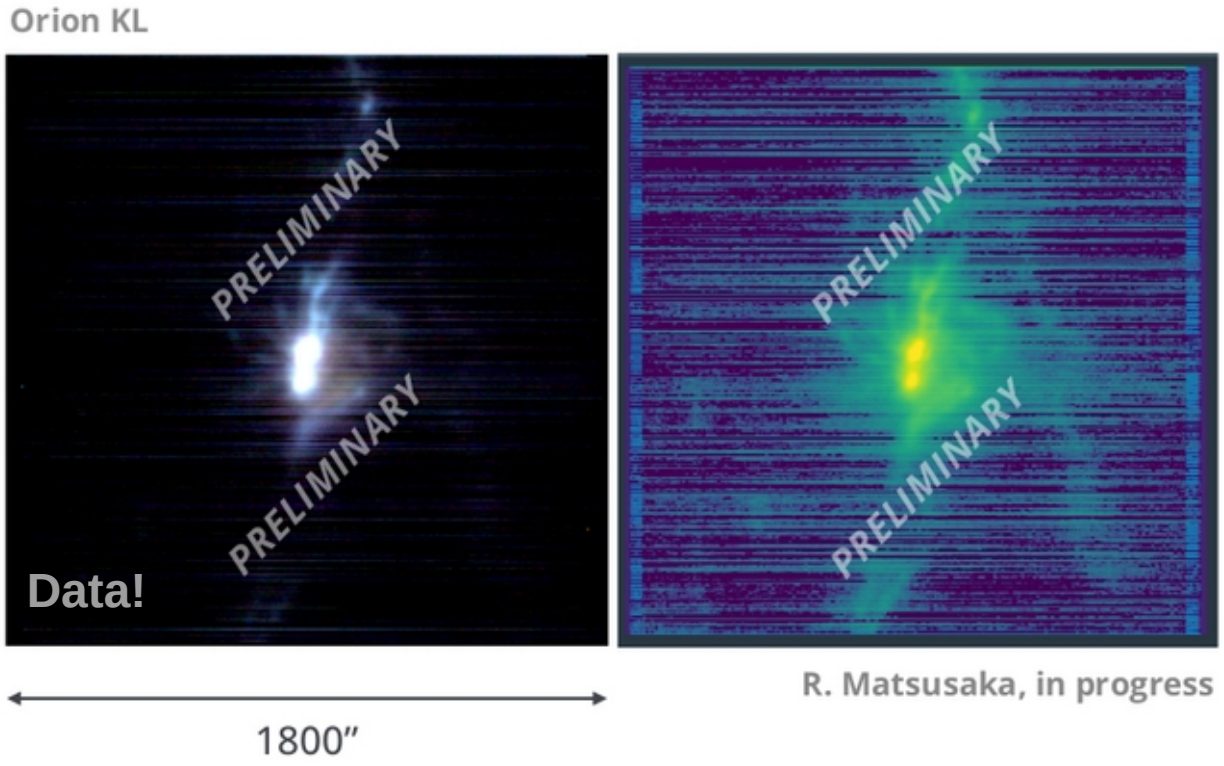


M. Peters, Bachelor's thesis, 2024

DESHIMA 2.0: overview of targets

Target type	Sources	Time observed
ULIRGs	NGC1068, ESO173-G030, IRAS17208-0014	100 hr
High-z: [CII] demonstration	SPT0346-52, SPT2103-60	128 hr
High-z: multiple lines	PJ0116, PJ0209, PJ1053, PJ1329	127 hr
High-z: blind redshift surveys	ACT (6 sources) AS2LXS (3 sources) ALMARED (1 source) LOFAR (2 sources)	110 hr 55 hr 18 hr 25 hr
Total		**~570 hr**

Nearby star-forming regions



- Wide-field imaging of nearby star-forming regions
- Quick maps of **continuum + many lines** (CO, ^{13}CO, C^{18}O, HCN, HCO+, HNC, CN)

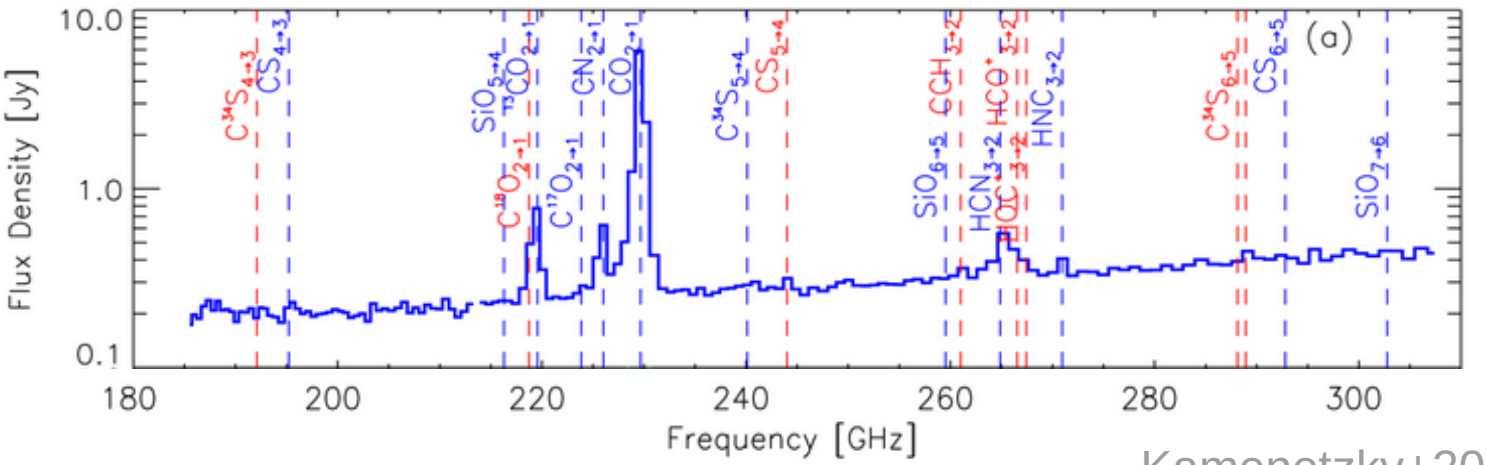
- Lines narrow (~10 km/s) but bright
- Complementing high-res ALMA observations

Ultraluminous Infrared Galaxies (ULIRGs)

- Nearby highly star-forming galaxies

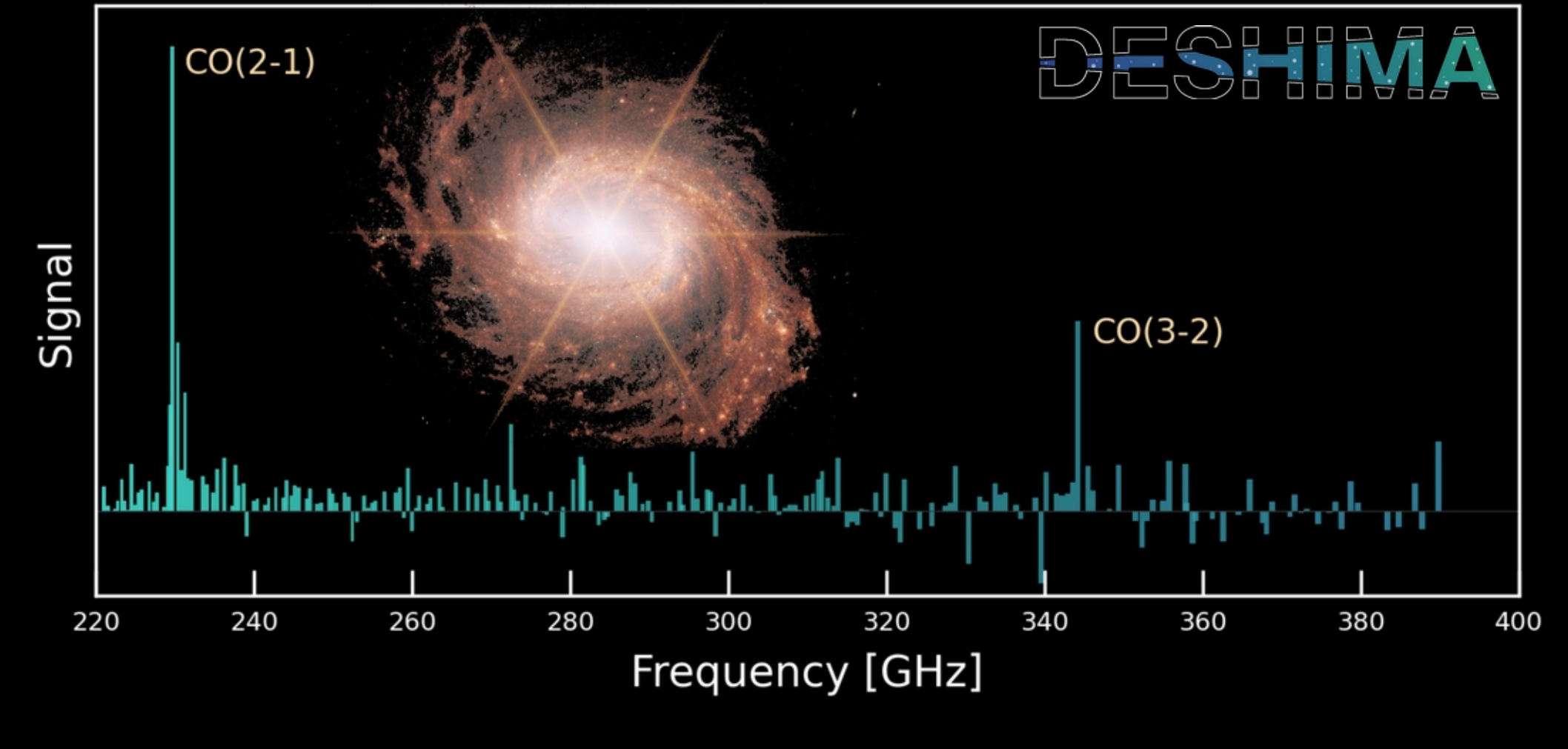
- CO(2-1) and CO(3-2) lines (detectable in a few minutes)
- Multiple transitions of HCN, HCO+, HNC, CN … (deeper integrations)

- Great for checking the system performance



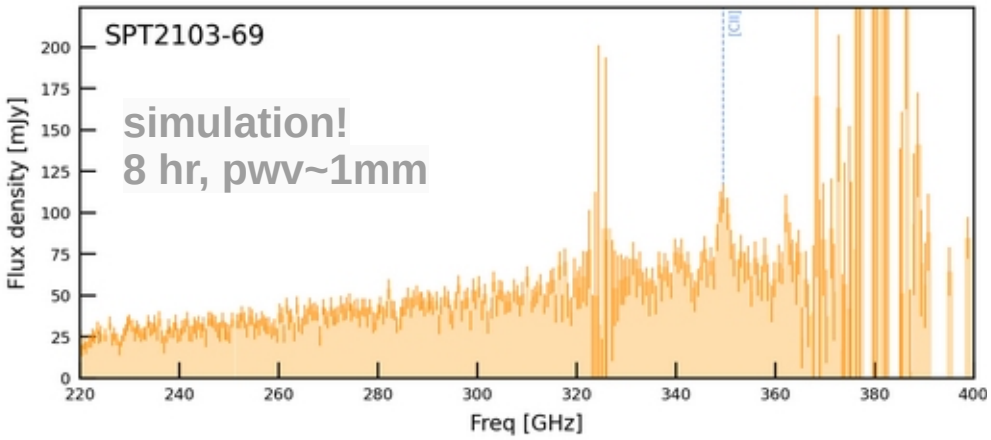
Kamenetzky+2011, Z-Spec

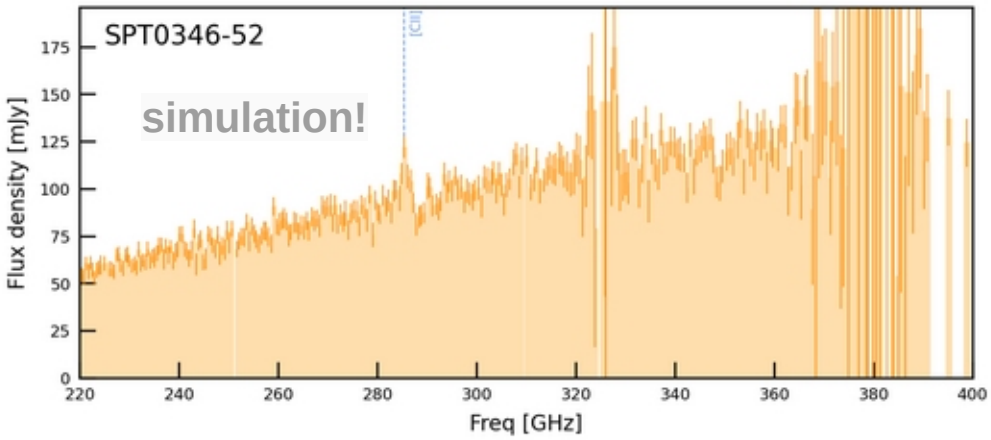
First light spectrum: NGC 1068



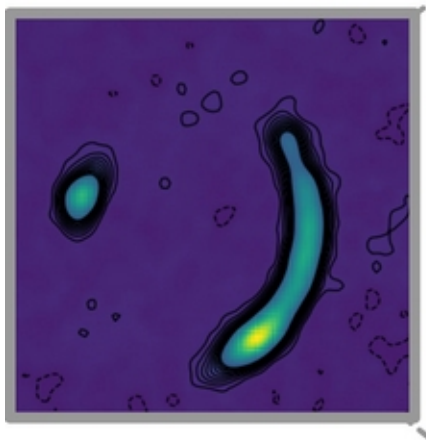
Bright high-z lensed galaxies

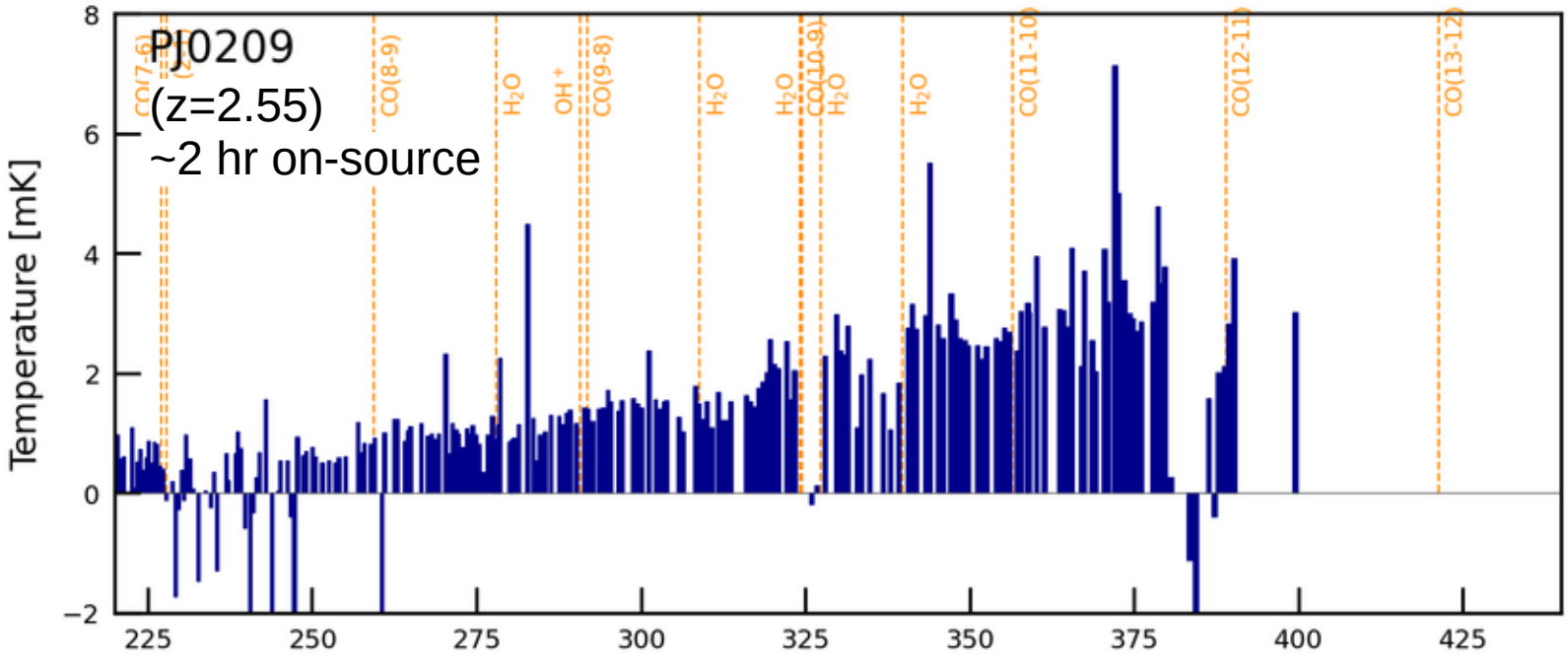
- **Demonstrate that DESHIMA 2.0 can detect high-z galaxies**
- Four super-bright (lensed) sources from the Planck sample
  - Bright detected CO lines: can we reproduce & get new detections?
- Two bright lensed sources from SPT with detectable [CII] lines





First (cautious) stacking

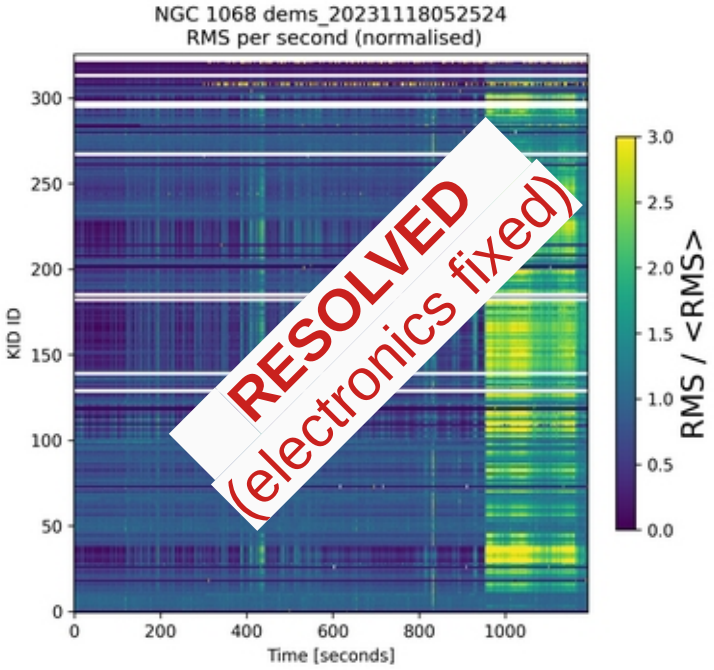




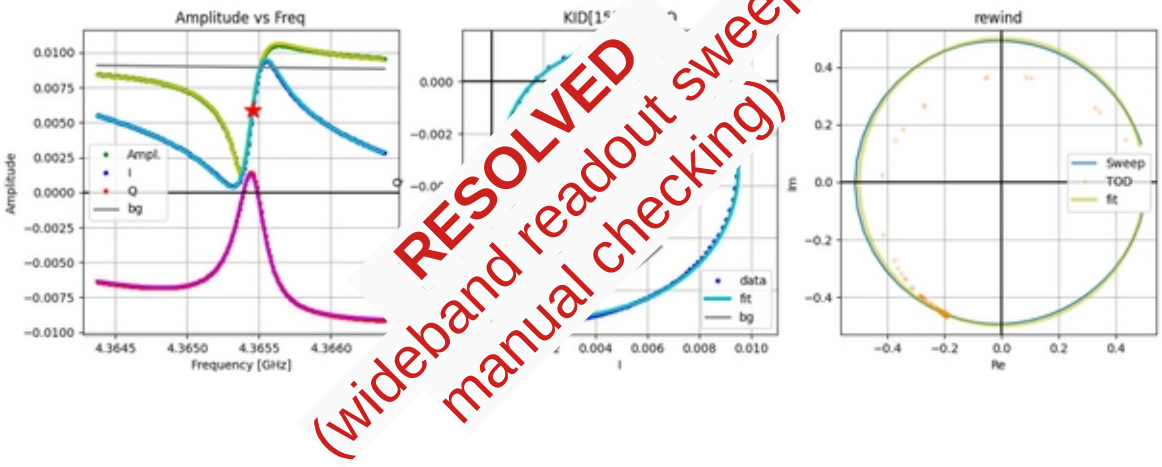
no lines detected so far (as expected)

Data-processing challenges (2023)

Electronic noise

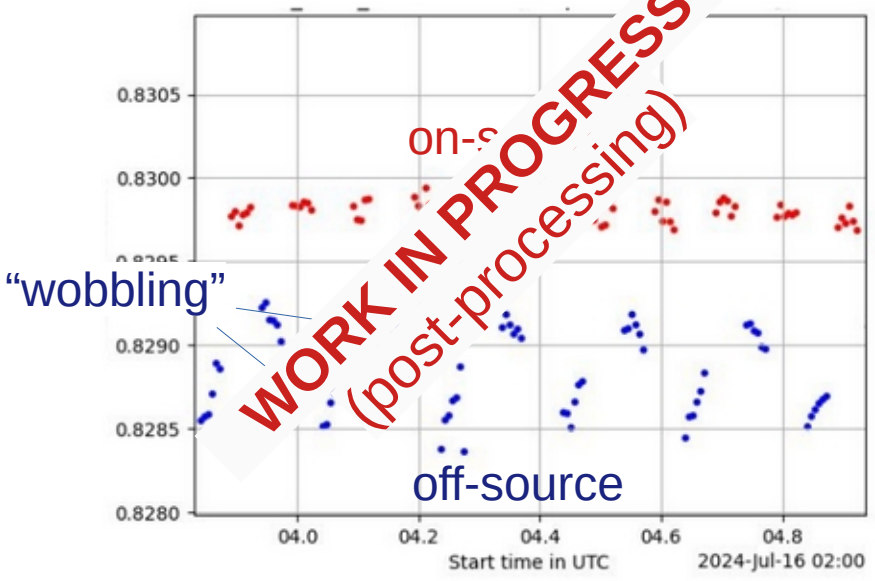


Readout frequencies “reshuffled”

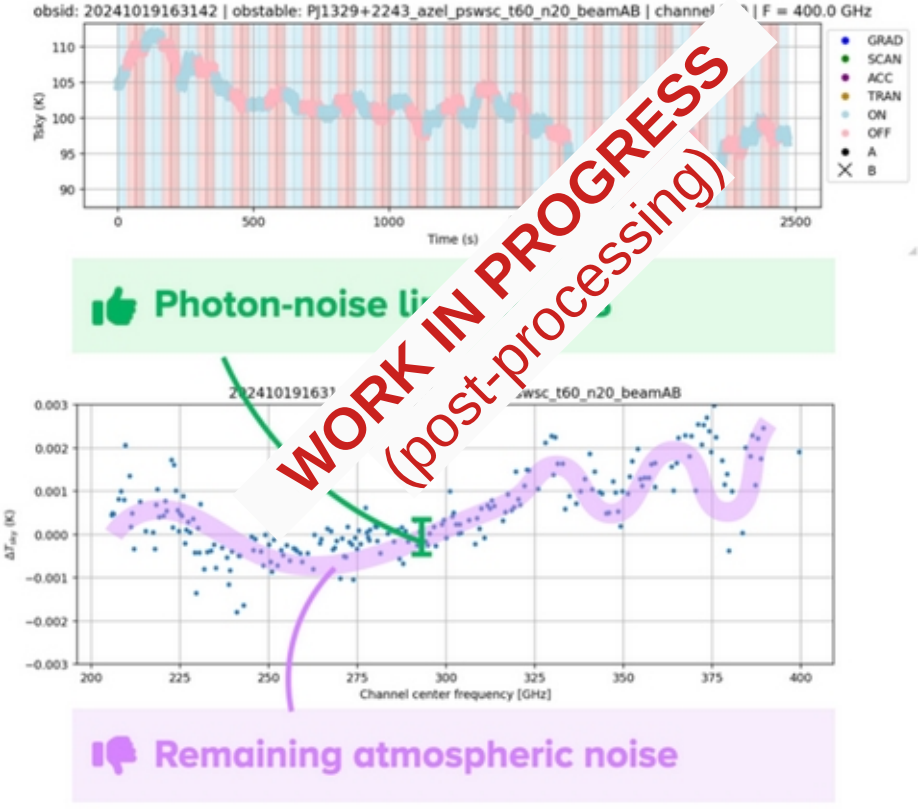


Data-processing challenges (2024)

Chopper wobbling causes fluctuations in the off-source T_{sky}



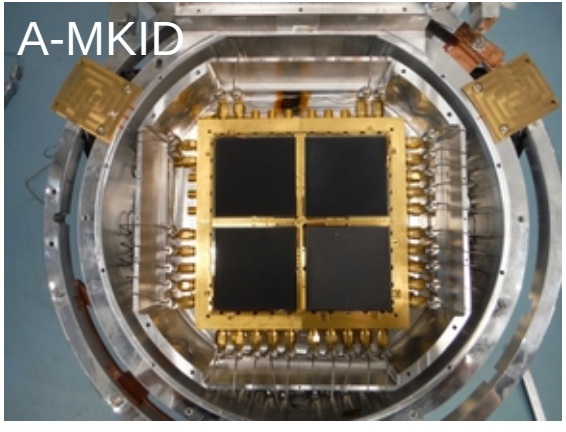
Leftover atmospheric noise

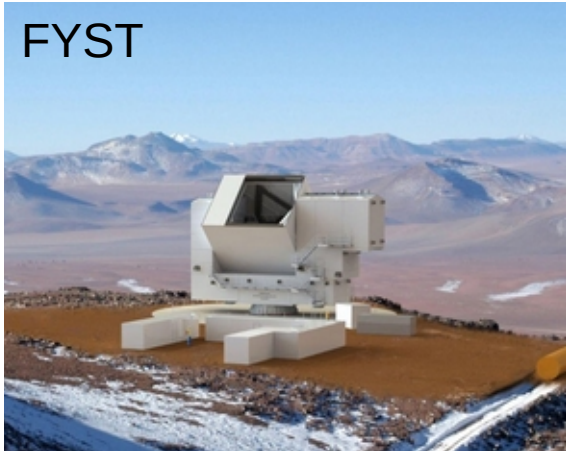


Future: complementing wide-field mm-wave surveys?

Several next-generation mm-wave continuum surveys underway
- SPT-3G
- ACT
- A-MKID @ APEX
- TolTEC @ LMT
- near-future: CCAT-p/FYST

- will require significant (additional) manpower and funding



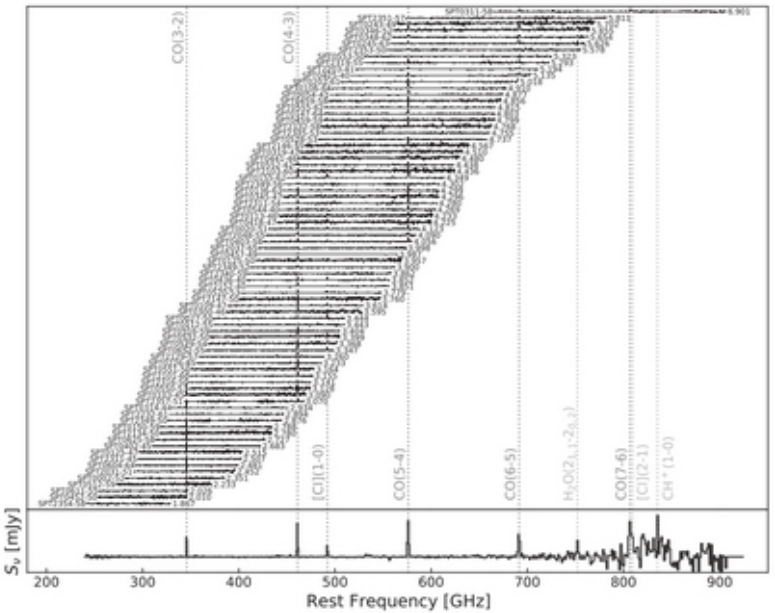


Can DESHIMA@ASTE compete with ALMA?

SPT galaxies: a case study

- **SPT galaxies:** 83 spec-z confirmed sources (Vieira+2013, Reuter+2020)
- ALMA: 96 – 103 GHz scans, 25 – 45 mins/source, **CO lines**
- **ALMA Cycles 1 – 7**: seven years!

- DESHIMA: keep current performance, extend to 440 GHz, assume **1000 hr** in total (12 hours per source) → doable in 1 year
- **[CII] line**
- 70/83 galaxies detected at S/N>3: **~80% yield!** (assuming deLooze+2014 [CII]-FIR)



Reuter+2020

DESHIMA@ ASTE might be an alternative to ALMA spectral surveys for the Japanese community

Conclusions

- DESHIMA 2.0 has completed 5+ months of scientific observations on ASTE

- Data processing to be polished, key issues solved
- Clear line detections in nearby galaxies, high-z will take a few months to process

- Significant interest from international collaborations (e.g., ACT, SCUBA-2 survey teams)

- Complementary to continuum surveys (A-MKID, SPT-3G, FYST)
- Future DESHIMA@ASTE would be a useful tool for the Japanese community

First light spectrum: NGC 1068

