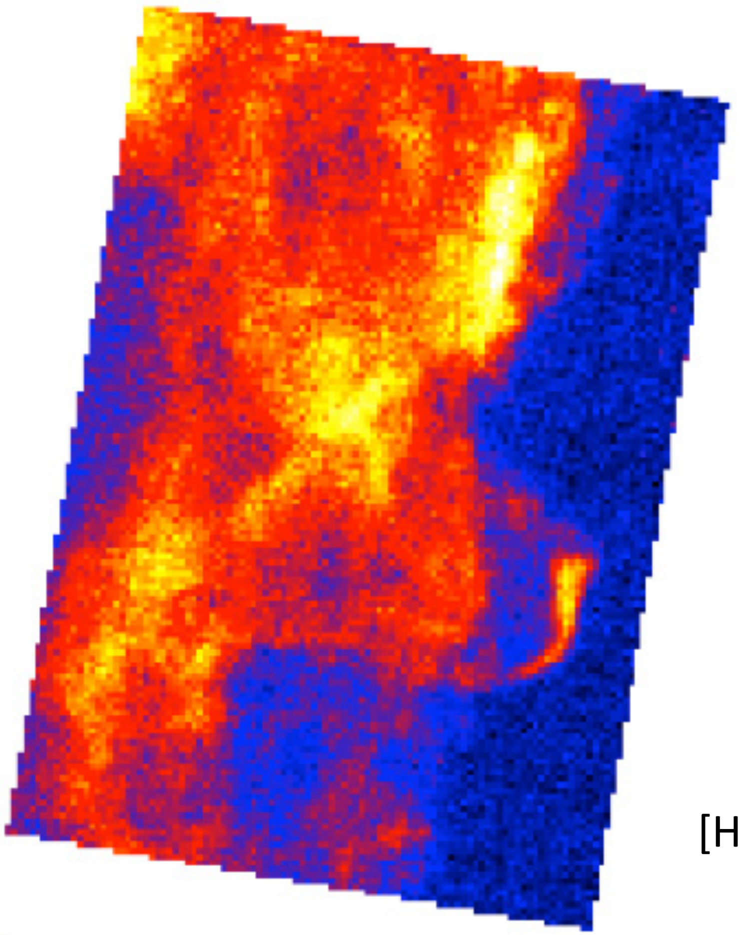
High Resolution Spectroscopy with GREAT and upGREAT



[Horsehead Nebula in CII using upGREAT]

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Support Scientist

[thanks to Ed Chambers,
GREAT instrument scientist]

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1. High Resolution Far-Infrared/ Sub-millimeter-wave Spectroscopy

High resolution spectroscopy powerful tool:

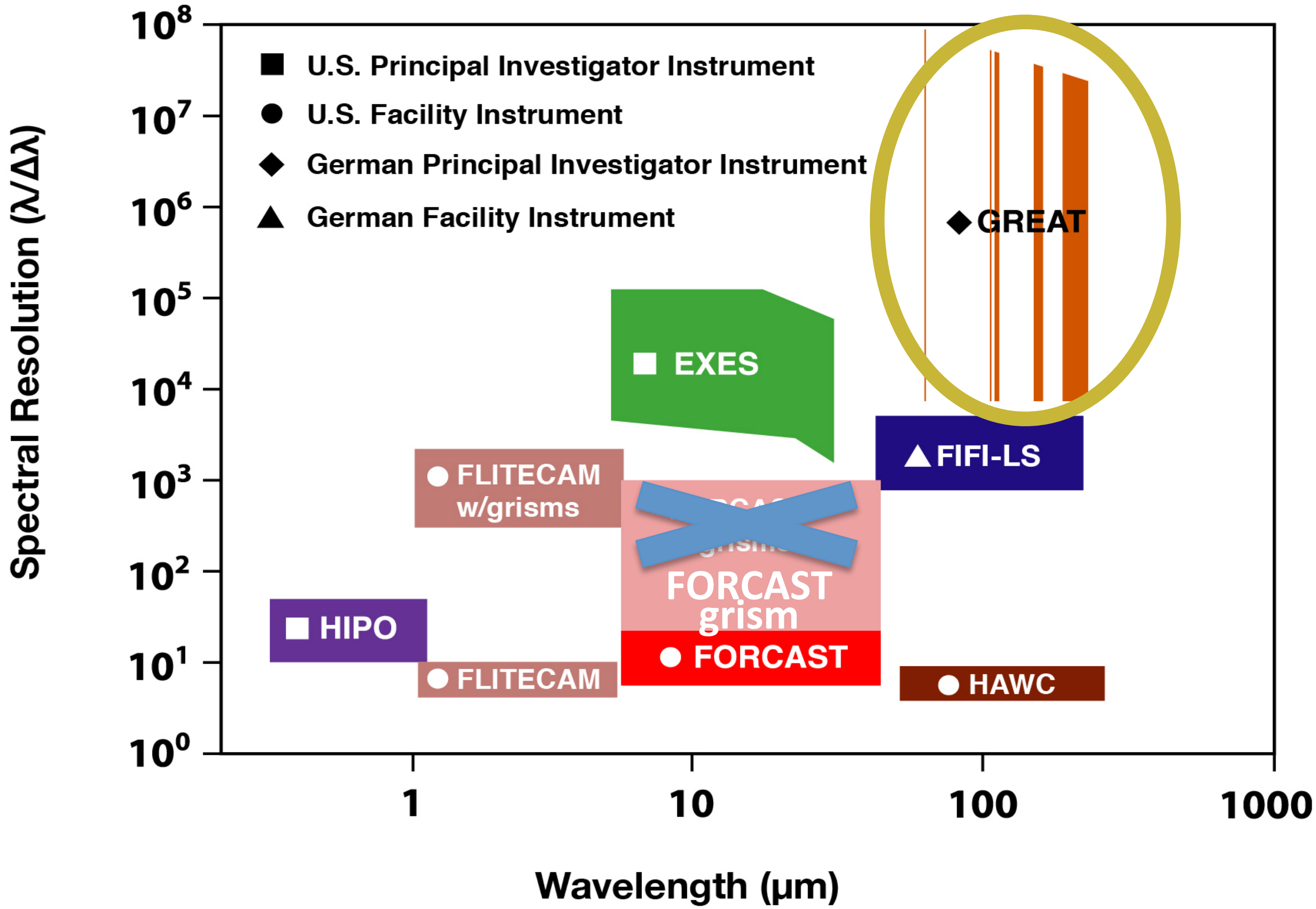
- Resolved line profiles yield kinematic origin of line emission/absorption at scales not always spatially resolvable, even with the largest telescopes, e.g.,
  - Infall
  - Outflow
  - Rotation

- Separation of spectroscopically crowded line regions
  - Emission line with foreground absorption
  - Closely spaced rotational transitions

- Higher contrast peak emission/absorption line increases detectability

- Separation telluric and astronomical line improves sky correction

1. High Resolution Far-Infrared/ Sub-millimeter-wave Spectroscopy



1. High Resolution Far-Infrared/ Sub-millimeter-wave Spectroscopy

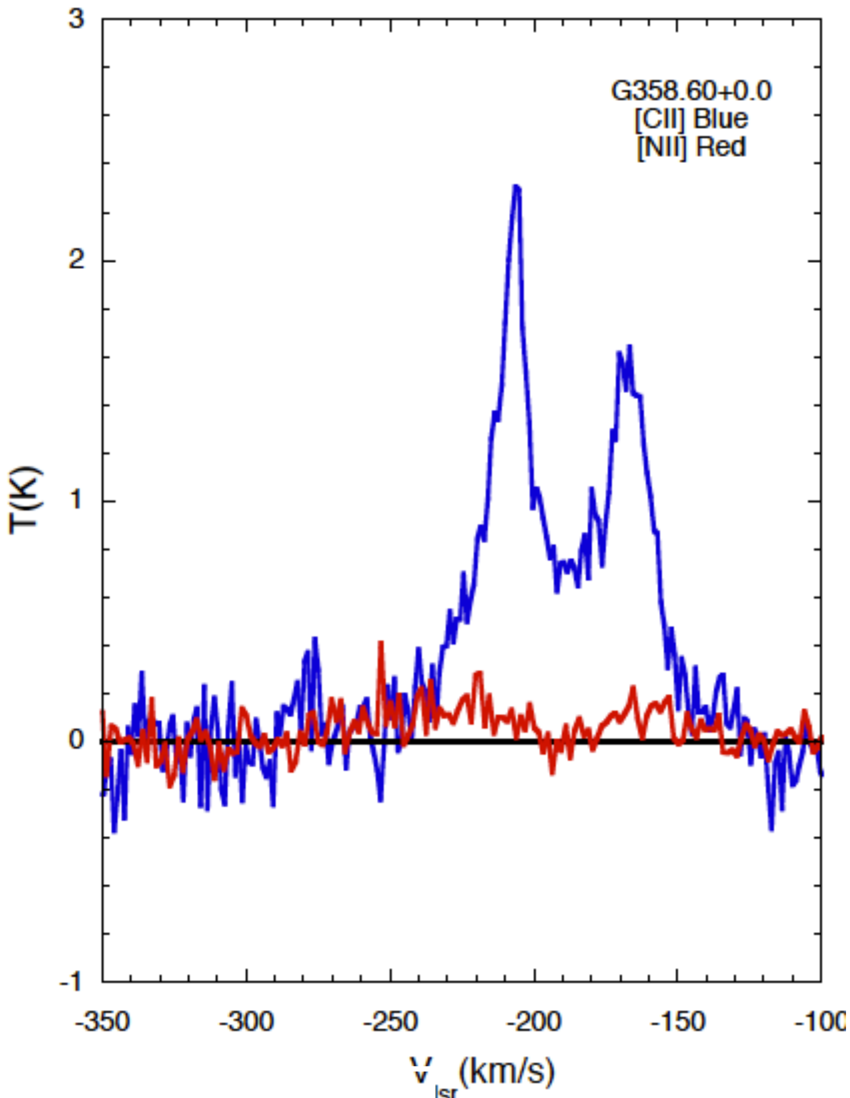
GREAT (**G**erman **RE**ceiver for **A**stronomy at **T**erahertz Frequencies):

- Heterodyne receiver
- R=10-50 million, i.e., <0.1 km/s
- 63 um (4.74 THz), 197-240 um (1.25-1.52 THz), 157-165 um (1.81-1.91 THz)
- spatial resolution: 6-24" (14.1" at C^+)
- single pixel on sky
- simultaneous observations of lines in different detector bands (e.g., C^+ and N^+)

upGREAT is like GREAT, but:

- 7 pixels on the sky, in 2 polarizations
- Only small frequency ranges around CII line at 1.91 THz (in near future +/-0.1 THz) or (being commissioned) OI line at 4.7 THz.
- CII array can be combined with single pixel 197-240 um (1.25-1.52 THz), OI array with single pixel 1.81 – 1.91 THz

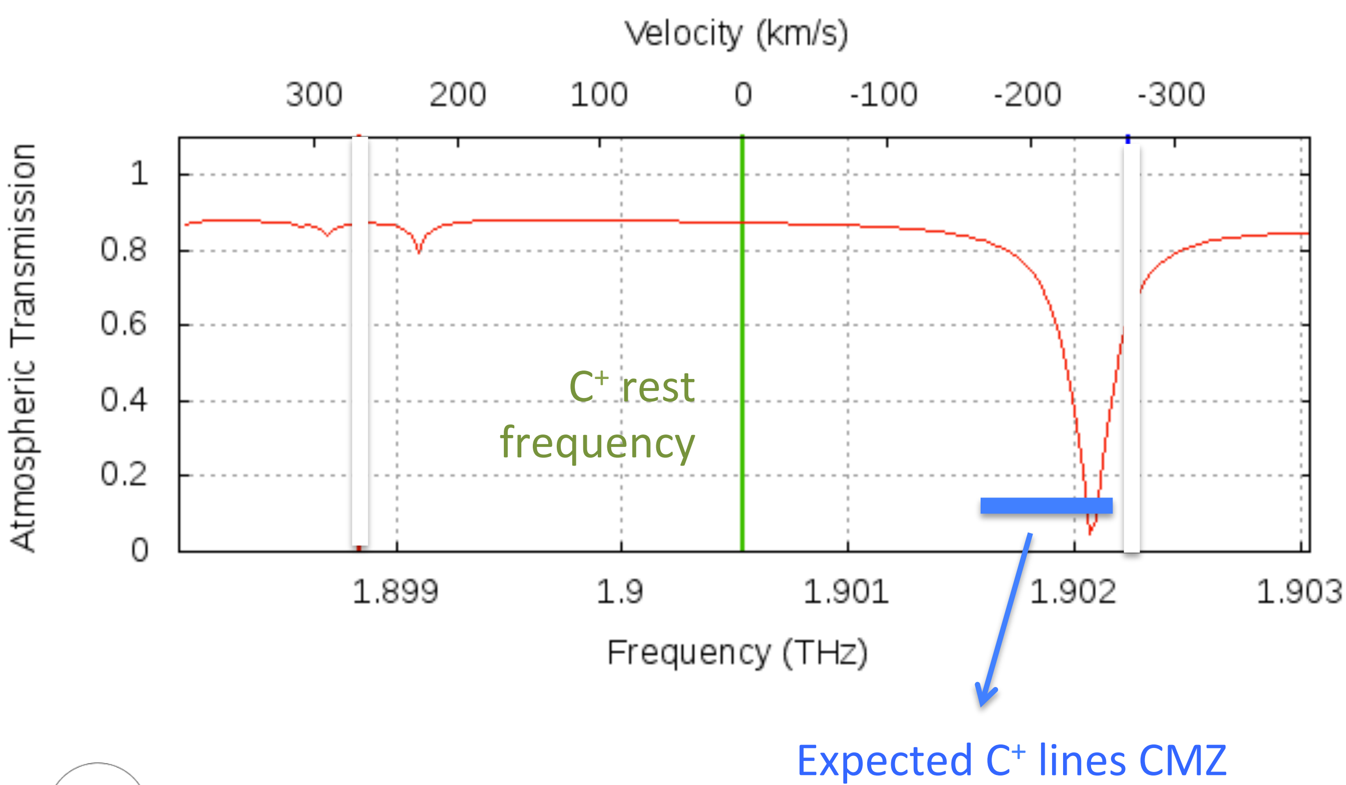
2. Preparing GREAT Single Point Observation



GREAT position switch ("total power") observation C^+ and N^+ toward the edges of the Central Molecular Zone around the Galactic Center (Langer et al. [2015A&A...576A...1L](2015A&A...576A...1L)

2. Preparing GREAT Single Point Observation: Atmosphere

Use GREAT time estimator tool to determine the atmospheric transmission:
https://great.sofia.usra.edu/cgi-bin/great/great.cgi



Atmosphere around C+ line good, but not for strongly blue shifted lines of CMZ targets:

V_{LSR}=-150- -250 km/s

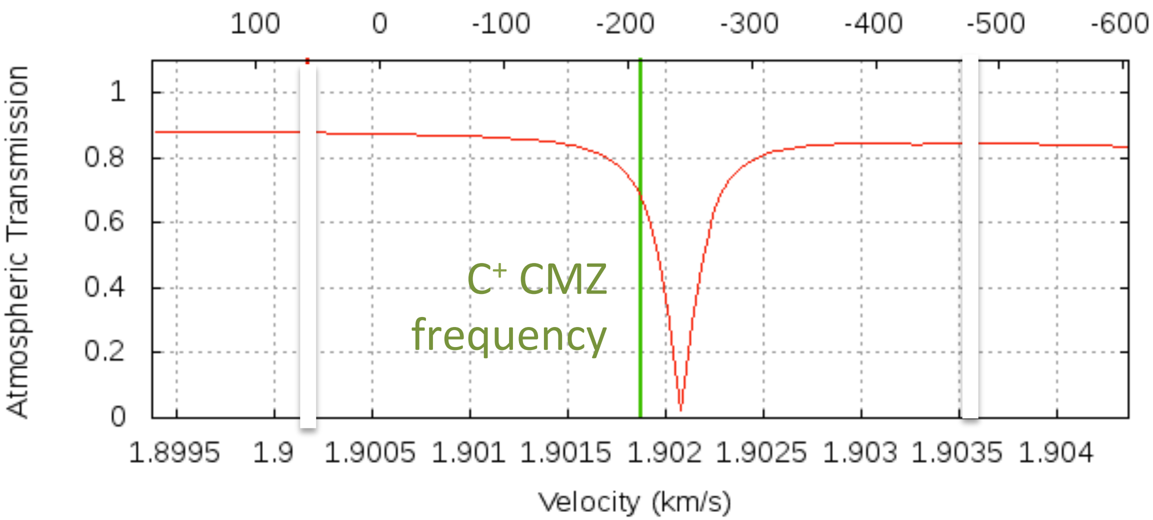
V_{HELIO}=-159- -259 km/s

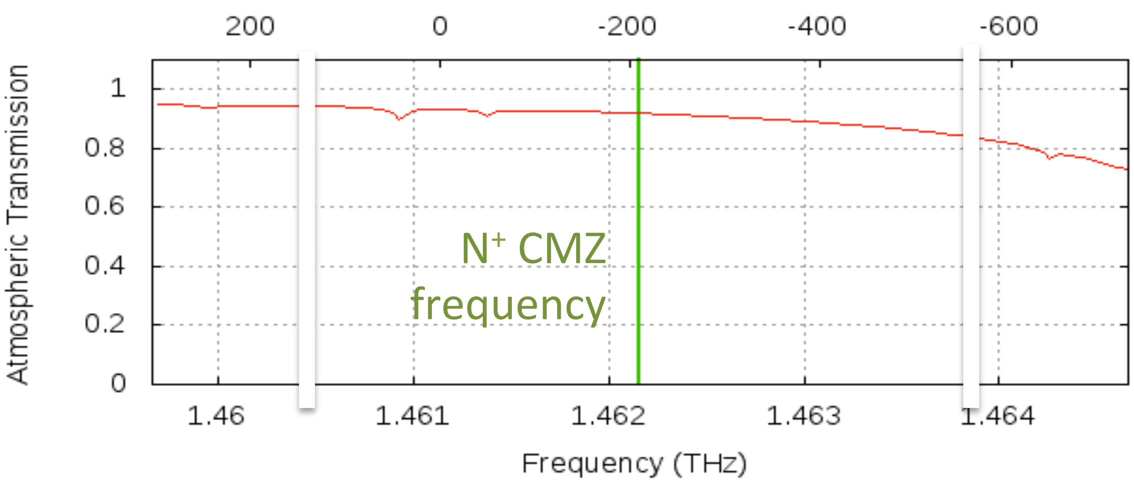
$V_{DOP}=V_{HELIO}$+/-17 km/s (extremes in october +17 and march -16 km/s). October a bit better.

Difficult project, but feasible (see section 2.1 in Langer et al.)

(for calculation details, see EXES slides)

2. Preparing GREAT Single Point Observation: Atmosphere





Use GREAT time estimator tool to determine the atmospheric transmission: https://great.sofia.usra.edu/cgi-bin/great/great.cgi

C^+ difficult at CMZ velocity shift

N^+ much easier

2. GREAT Instrument Status and Configurations Offered for Cycle 5

GREAT mixer bands:

- L1 1.25 – 1.52 THz (240-197 µm): not all frequencies available! Contact team or helpdesk.
  - E.g.: CO 12-11, OD, SH, H2D+, CO 13-12, [NII]
- L2 1.81 – 1.91 THz (166-157 µm): not all freq available! Contact team or helpdesk.
  - E.g., CO 16-15, [CII], NH3 3-2, OH 2Π1/2
- H 4.7448 THz (63.1837 µm): -25 to +90 km/s or -30 to -140 km/s
  - [OI]
- M channel: not offered in cycle 5
  - HD 1-0, 18OH 2Π3/2

Simultaneous observation L2+H or L2+HFA (e.g., C+ and OI) and LFA+L1 (e.g., C+ and N+) , depends on results of call. Also, check back in June CfP update!

Instantaneous usable band width ~1.8-2 GHz, but 0.9 GHz for H channel.

Contact SOFIA helpdesk (sofia_help@sofia.usra.edu) regarding non-standard tunings.

2. upGREAT Instrument Status and Configurations Offered for Cycle 5

upGREAT mixer bands offer 10 times faster On The Fly mapping than GREAT:

- Low Frequency Array (LFA): 1.9005 +/- 0.003 THz in 2 polarizations. Anticipation that at least one polarization will cover 1.81-1.91 THz (contact team or helpdesk!). Can observe together with L1.
- High Frequency Array (HFA; 4.7 THz): possibly commissioned after proposal deadline (shared risk). Can observe together with L2.

2. GREAT Frequency Tuning

GREAT is a Dual Sideband (DSB) receiver. The local oscillator signal is mixed with the sky signal. The difference $|\nu_{LO}-\nu_{SKY}|$ (IF, Intermediate Frequency) is detected:

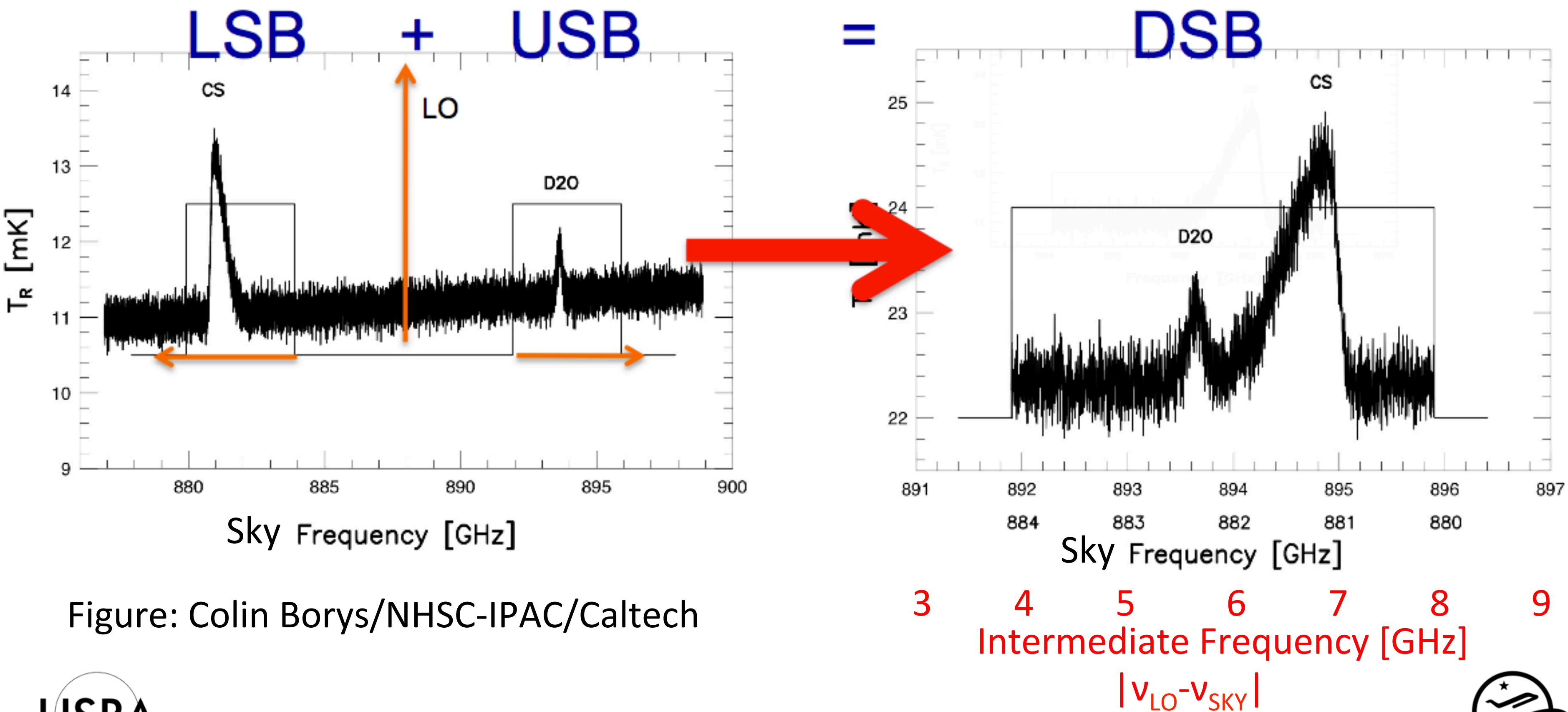
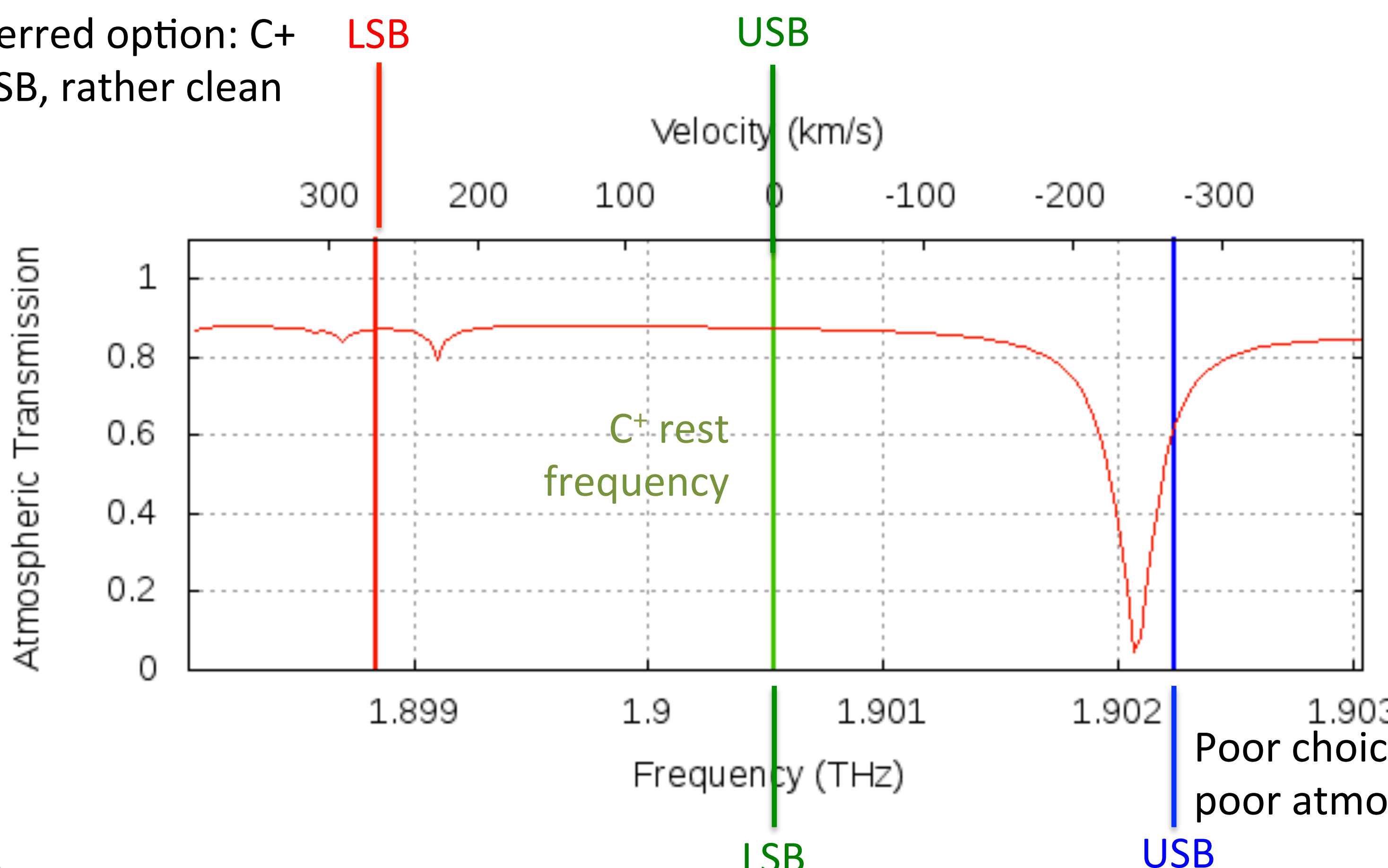


Figure: Colin Borys/NHSC-IPAC/Caltech

2. GREAT Frequency Tuning

At low Doppler shifts, the C+ line is best observed in the upper sideband (USB)

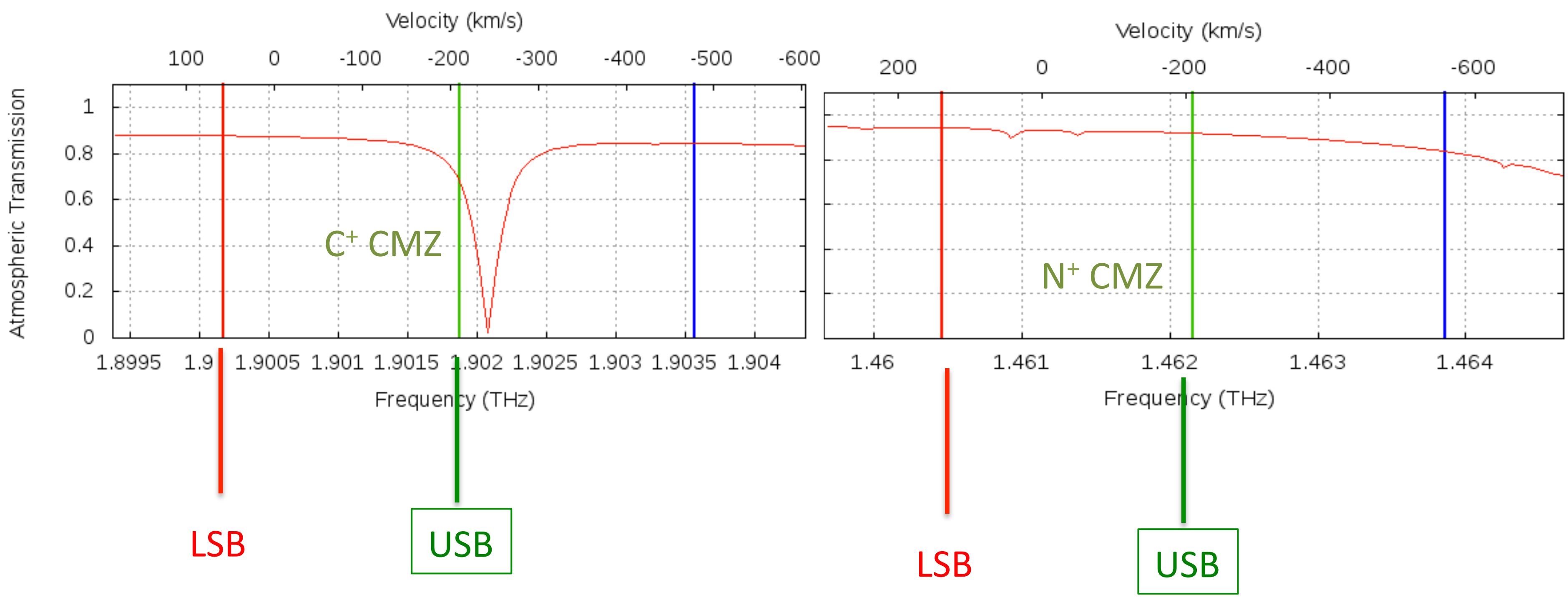
Preferred option: C+ in USB, rather clean LSB



Poor choice: C^+ in LSB, poor atmosphere USB

2. GREAT Frequency Tuning

At large, negative Doppler shifts, the sideband choice for C+ is less relevant, though USB slightly preferred, similar to N+ (better transmission in image sideband)



2. GREAT Observing Modes

- Single pointing:
  - dual beam switching (DBS) (chopping with the secondary <10 arcmin)
  - position switching (“Total Power”)

- On-the-fly mapping:
  - position switch (“Total Power”)
  - [single beam switch (SBS)]

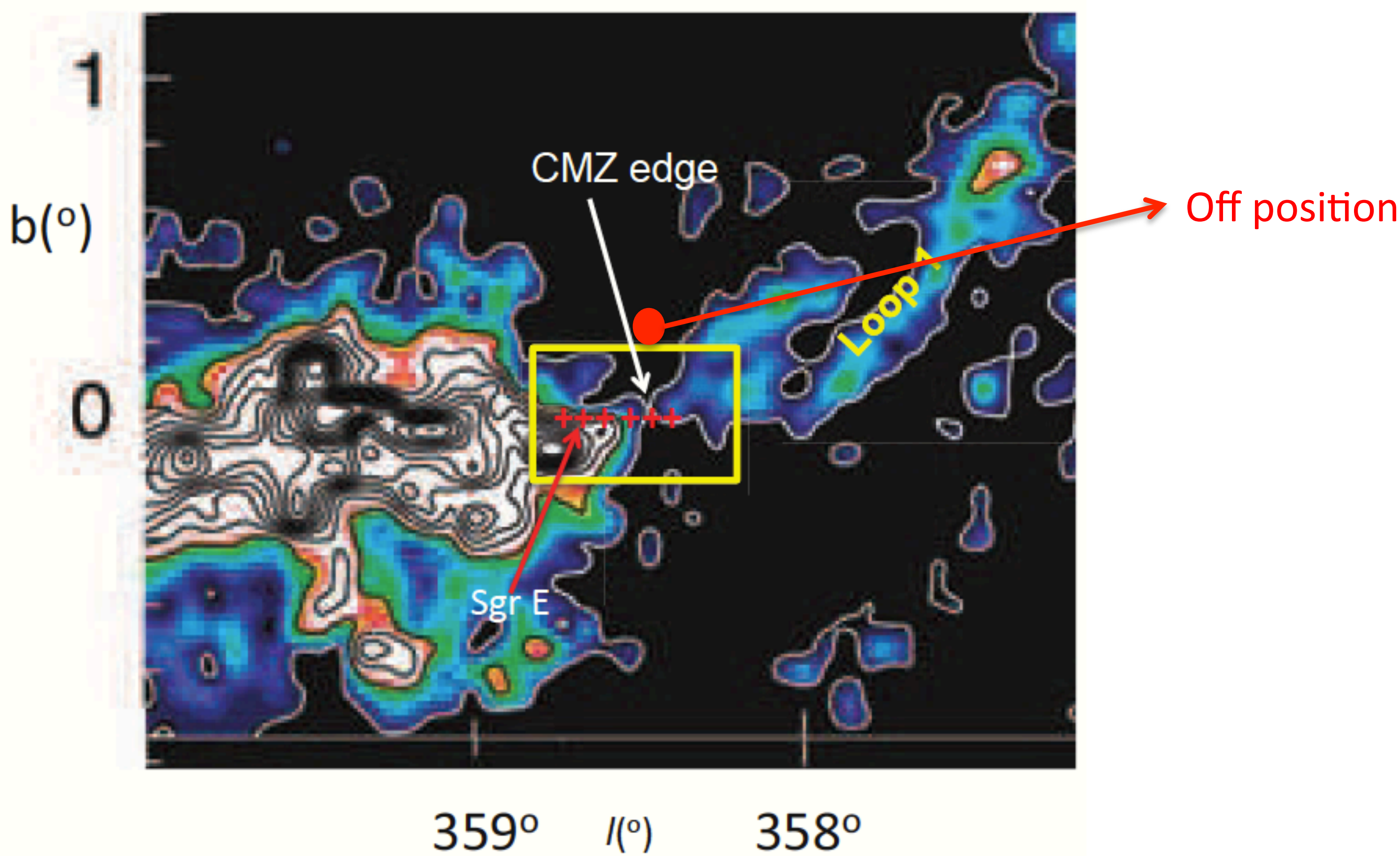
- Raster mapping:
  - dual beam switching (DBS)
  - position switching (“Total Power”)

CMZ: expected lines are weak (esp. N+), and the emission is expected to be very extended (more than 10 arcmin): Use single point, position switch mode.

Which position to switch to?

2. GREAT: Off Position

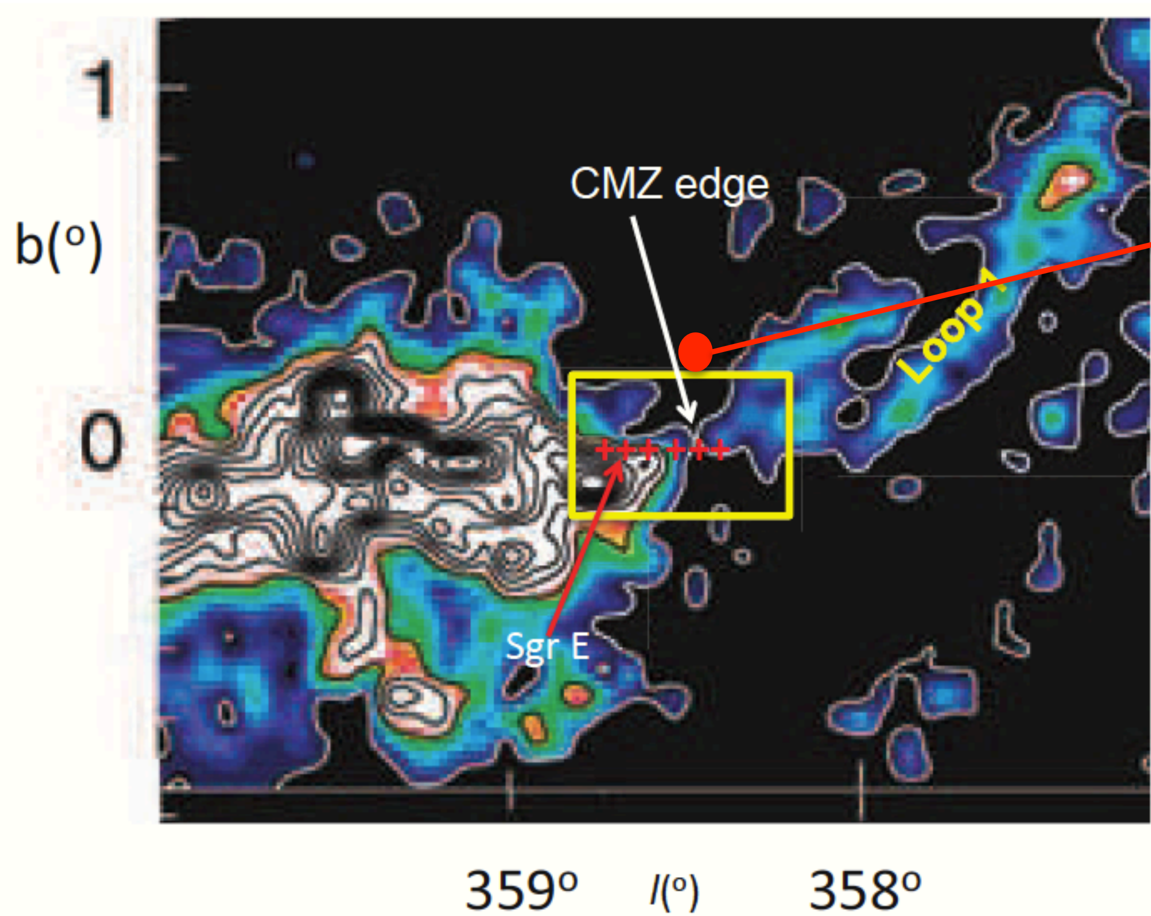
It is important to find a sky 'off' position that is clean (or as clean as possible). Requires literature search (and sometimes trial and error at the telescope):

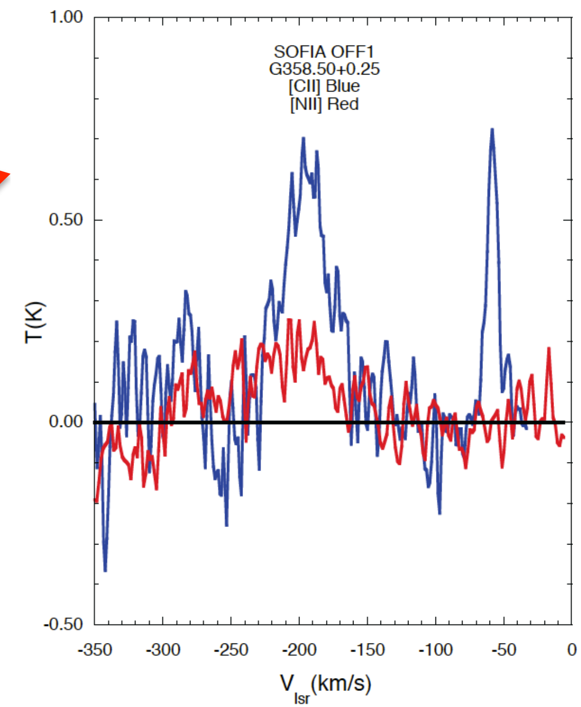


NANTEN CO(1-0) map (Fukui et al. 2006)

2. GREAT: Off Position

It is important to find a sky 'off' position that is clean (or as clean as possible):





Not so clean after all, but ok, and in fact correctable in data reduction.

2. GREAT Sensitivities, Exposure Time Calculations

GREAT observing time estimator is linked on SOFIA "SITE" page:

https://dcs.sofia.usra.edu/proposalDevelopment/SITE/index.jsp
https://great.sofia.usra.edu/cgi-bin/great/great.cgi

N^+ input:

- Rest frequency=1461.1319 GHz
- Velocity correction=-210 km/s
- Expected peak intensity T_R^*=0.1 K ($T_R^* = T_{MB} * \eta_{MB}$=0.15*0.67; Langer et al.)
- Desired S/N in line peak=3
- Resolution after smoothing: 2 km/s (native 88 KHz= 0.015 km/s)

→1350 seconds ON+OFF time. Add 100% overhead for nodding and chopping overhead, and add 2 minutes for tuning, and other setup overhead.

For C^+ line, observed simultaneously, 1350 sec ON+OFF: S/N=20 in 1 K line peak.

Note: smoothing parameter yields noise on all frequency scales (channel -channel, baseline fluctuations)

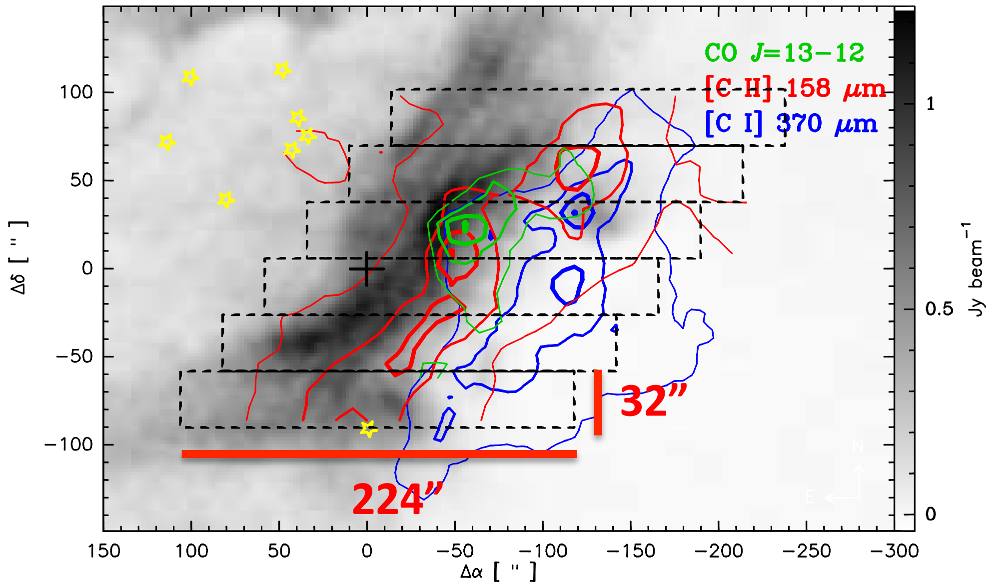
2. SOFIA/GREAT versus Herschel/HIFI

GREAT mixers significantly improved over those at HIFI, in system temperature and baseline quality (standing waves). Despite presence of atmosphere, GREAT (nearly) as sensitive as HIFI:

- C^+ line at 1900.5369 GHz, at rest velocity, 41,000 ft, smoothed over 2 km/s, 1000 seconds ON+OFF on T_R^* scale, fully extended emission:
  - GREAT: RMS=53 mK, T_{sys}=2840 K (T_{sys} incudes atmosphere!)
  - HIFI: RMS=45 mK, T_{sys}=2760 K
- Same after smoothing to 50 km/s (stability for broad lines):
  - GREAT: RMS=11 mK
  - HIFI: RMS=12 mK
- Also, HIFI had no mixers for N^+ and OI, and Herschel out of Helium
- However, HIFI more sensitive for point source emission (3.5 vs 2.5 meter mirror!).

3. Mapping with GREAT (single pixel)

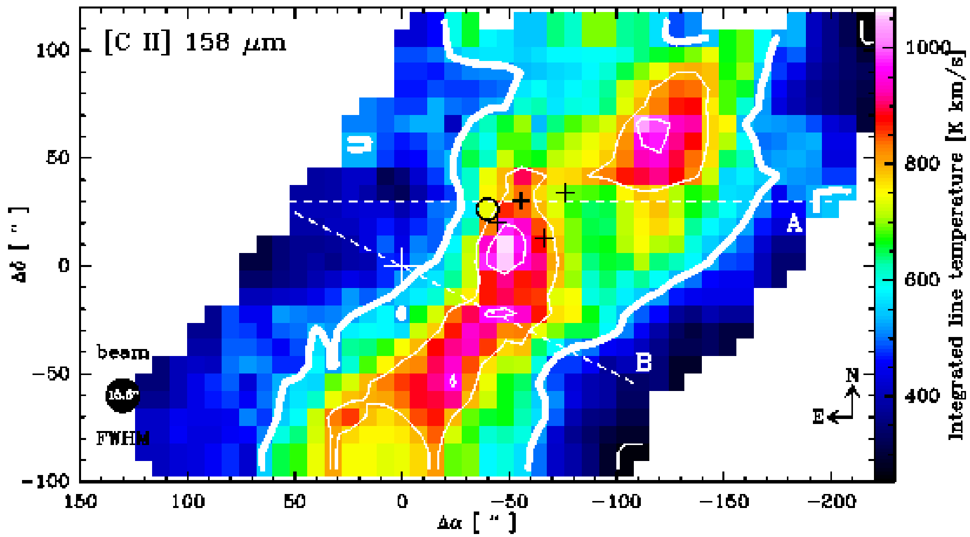
- Example: 3’x4’ on-the-fly map of M17-SW
- [C II] at 1900.5369 GHz (157.7 μm) [NOTE: best use upGREAT array for making this CII map]
- ^{12}CO J=13–12 at 1496.9229 GHz (200.3 μm) [NOTE: not possible in array mode]
- **Continuously taking data while moving over the source**
- **Beam size at** 1.9 THz is ~16”, so want 8” point separation for Nyquist sampling
- 6 strips, each
  - 224” long (=28 pointings)
  - 32” high (=4 pointings)



J.P. Perez-Beaupuits et al.
A&A 542, L13 (2012)

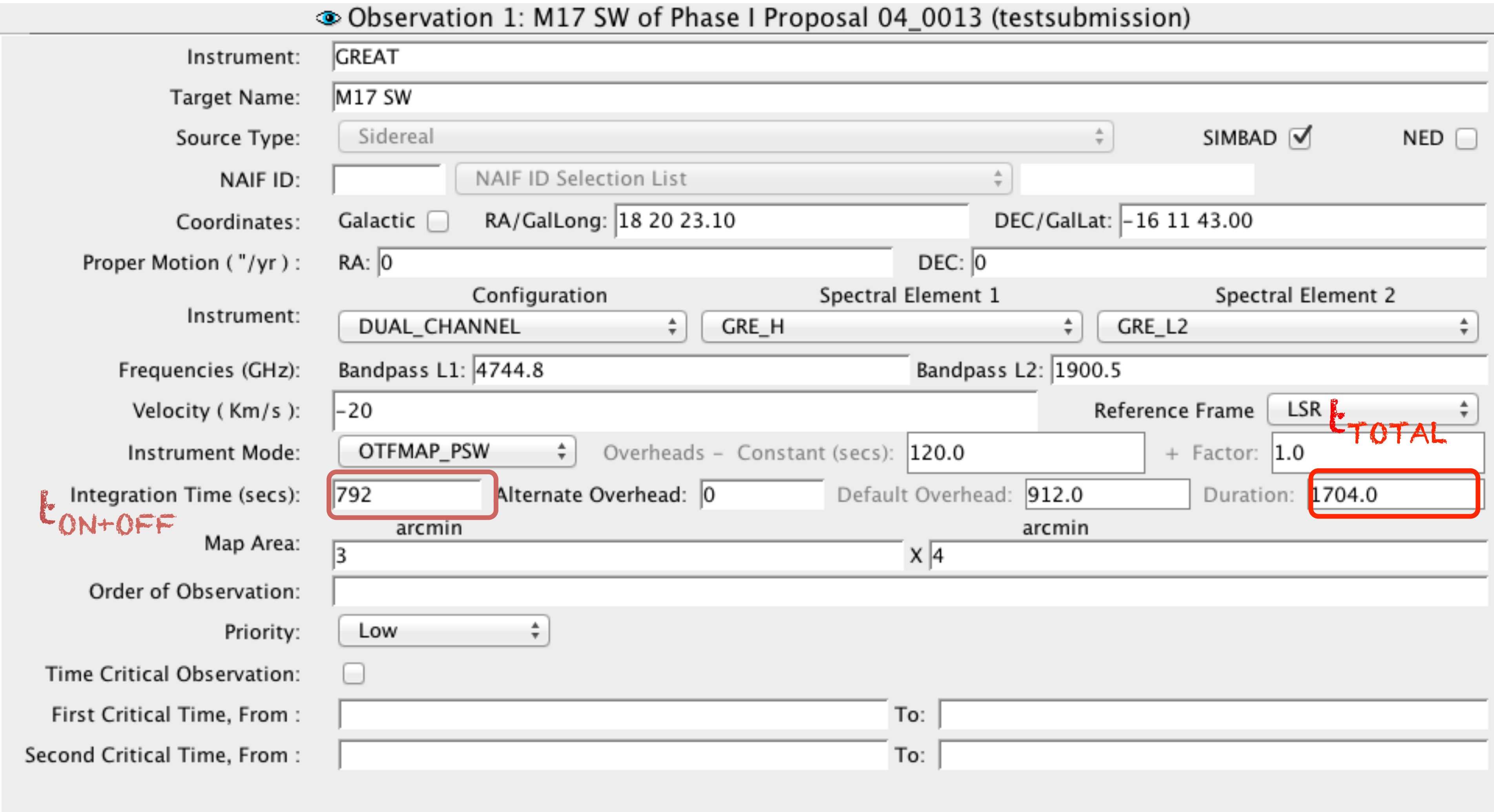
3. Mapping with GREAT (single pixel)

- Scan speed:
  - Time estimator: 1s x 1km/s -> ~3 K rms noise (enter 2 sec in online tool, as it assumes ON+OFF time). OK for this purpose, so 1 map sufficient.
- Time per line:
  - One line: 224/8=28 sec
  - Note: line should not exceed 30 sec
  - Reference position √28 ≈ 5 sec
  - Time per line: 28s+5s=33 sec
- Total time on sky:
  - Total lines: 4x6=24
  - Total integration time: 24x33 sec=792 sec
- Total time:
  - Overhead is 100% of sky time+ 2 minutes (SPT), i.e., 2*792+120=1704 sec (28 min)



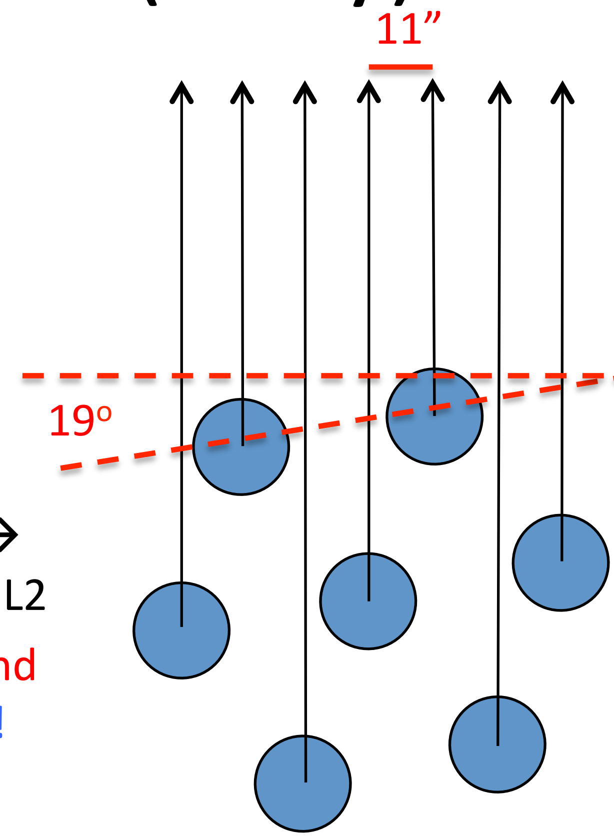
J.P. Pérez-Beaupuits et al.
A&A 542, L13 (2012)

3. Mapping with GREAT: SPT



4. Mapping with upGREAT (array)

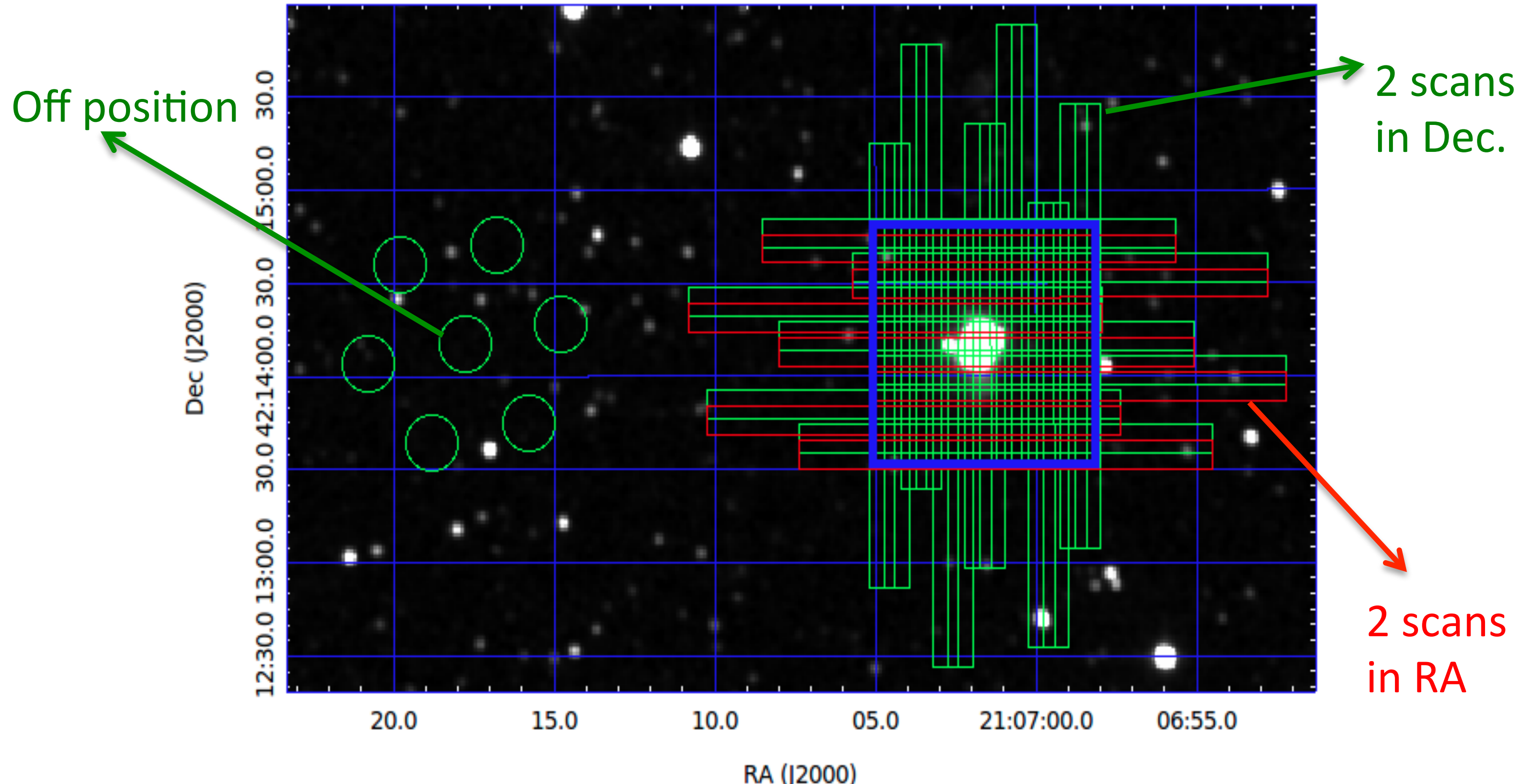
- Low frequency array (LFA; CII) and (shared risk) high frequency array (HFA; OI)
- Array of 14 pixels on 7 sky positions in 2 polarizations observed at the same time
- Current tuning range:
  - LFA CII: 1.9005 ± 0.003 THz (± 500 km/s)
  - HFA OI: 4.74477749 THz (-25 to +90 km/s or -30 to -140 km/s)
- Each pixel upGREAT LFA more sensitive than GREAT L2 → order of magnitude more efficient mapping than GREAT L2
- Cycle 5 combination: L2+H or L2+HFA (e.g., C+ and OI) and LFA+L1 (e.g., C+ and N+); Stay tuned for updates in June!
- Array tilted by 19 degrees for maximum efficiency
- Pixels 2 beams separated (~34")



Approx. beam pattern and scanning directions

4. Mapping with upGREAT (array)

Mapping in CII line. For worked out examples, see
https://www.sofia.usra.edu/sites/default/files/Guide_To_GREAT.pdf
https://www.sofia.usra.edu/sites/default/files/upGREAT_Mapping_AOT.pdf



This mapping pattern avoids striping (scans in RA and Dec) and is time efficient. However, it gives an incomplete map (cross over center) in the simultaneous single pixel L1 line.

4. Mapping with upGREAT (array)

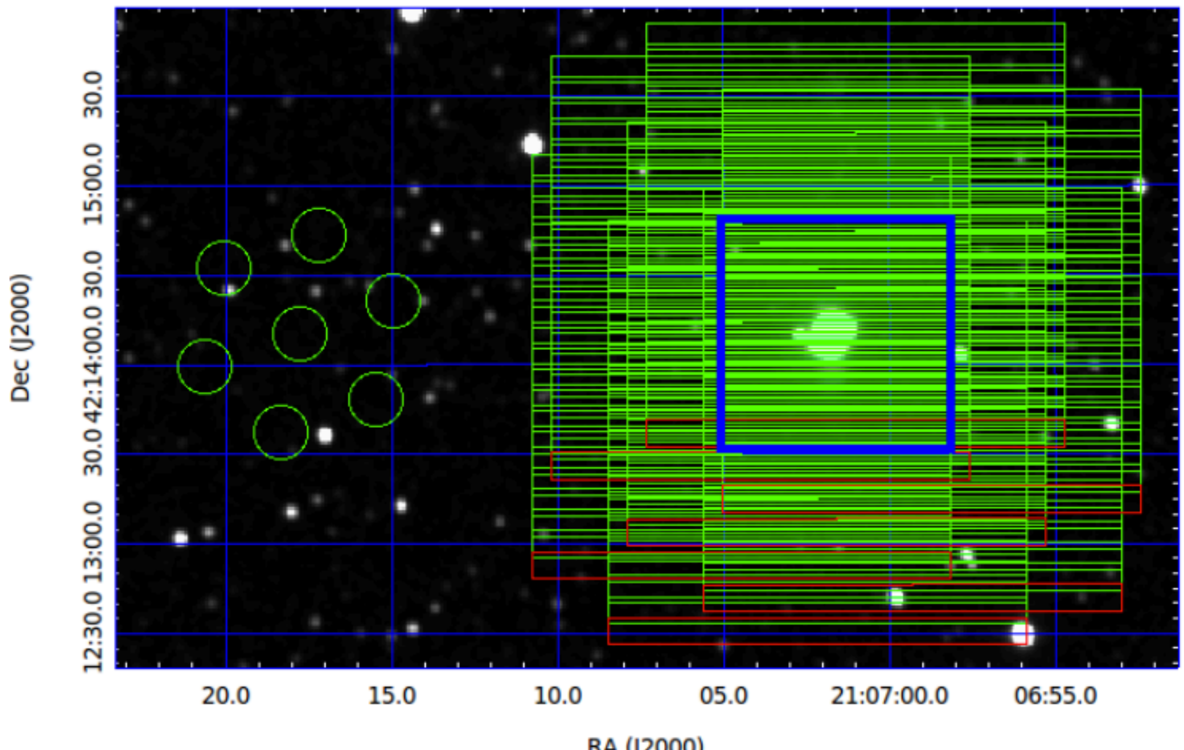
77x77” map of NGC 7027:

- Projected beam separation 11” at CII beam size of 14”: need 2 scans in each direction, separated by 5.5”, for fully sampled (actually slightly oversampled) map.
- For all pixels to see 77x77” box, start/end half array width before/after map center: total scan length 144”, which is 144/5.5=27 steps.
- Select integration time of 1 sec per spatial point (note, minimum is 0.3 sec): each scan takes 27 sec (should always be <30 sec)
- Off position: SQRT(27)~5 sec→ one scan takes 32 sec
- 2 scans in RA, 2 scans in Dec: 4*32=128 sec
- Overhead is 100%
- Total time: 2*128 sec, i.e., a bit more than 4 minutes.
- Time per spatial point: (2 sec in RA+2 sec in Dec)x2 polarizations=8 seconds
- Get RMS noise from time estimator (enter 16 seconds; time estimator ‘feature’: assumes ON+OFF time, but for OTF only ON time: N sec is N/2 sec on source)

4. Mapping with upGREAT (array)

77x77" map of NGC 7027:

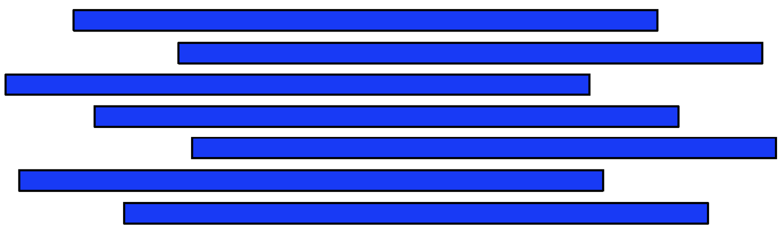
In previous case each LFA pixel will only see part of the map and the simultaneously used single pixel L1 will only cover a cross over the center. For mapping pattern to get fully sampled maps of L1 and each pixel LFA, see example 2 in https://www.sofia.usra.edu/sites/default/files/Guide_To_GREAT.pdf. 20 scans with 7 fully sampled maps in center (blue box) takes 4 times longer.



4. Mapping with upGREAT (array)

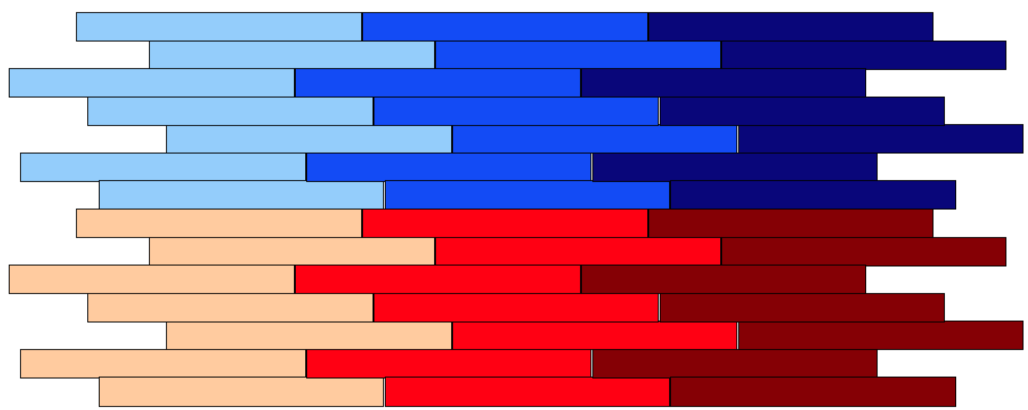
Mapping very large area: use blocks. See
https://www.sofia.usra.edu/sites/default/files/upGREAT_Mapping_AOT.pdf

Sparsely sampled block



Fully sampled block

Mosaic of blocks to map large region



5. For Further Reading

- Guide to Planning Observations with SOFIA/GREAT
  https://www.sofia.usra.edu/sites/default/files/Guide_To_GREAT.pdf
  https://www.sofia.usra.edu/sites/default/files/upGREAT_Mapping_AOT.pdf

- MPIfR sub-millimeter group (GREAT instrument team):
  http://www3.mpifr-bonn.mpg.de/div/submmtech/

6. GREAT as PSI Instrument

GREAT is Principal Investigator-class Science Instrument (PSI).

Call for proposals:

"Guest Investigators will receive calibrated data from the GREAT team."

"The GREAT PI may designate up to 3 coauthors."

Backup Slides

1. High Resolution Spectroscopy with SOFIA: Science Applications

Unique science applications with SOFIA:

- EXES:
    - ro-vibrational transitions molecules (**H_2O**, CH_4, CH_3, etc.)
    - rotational transitions H_2 (S(0), S(5)-S(8)). Note: S(1), S(2), and S(4) can be done from the ground (TEXES)
    - electronic transitions atoms (Fe, Ar)

- GREAT:
    - rotational transitions molecules (e.g., hydrides)
    - important fine structure (cooling) lines (OI, **CII, NII**)