The Renaissance of High Resolution Astronomical Spectroscopy

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RINEM
Cagliari, Sardegna
4 September 2018

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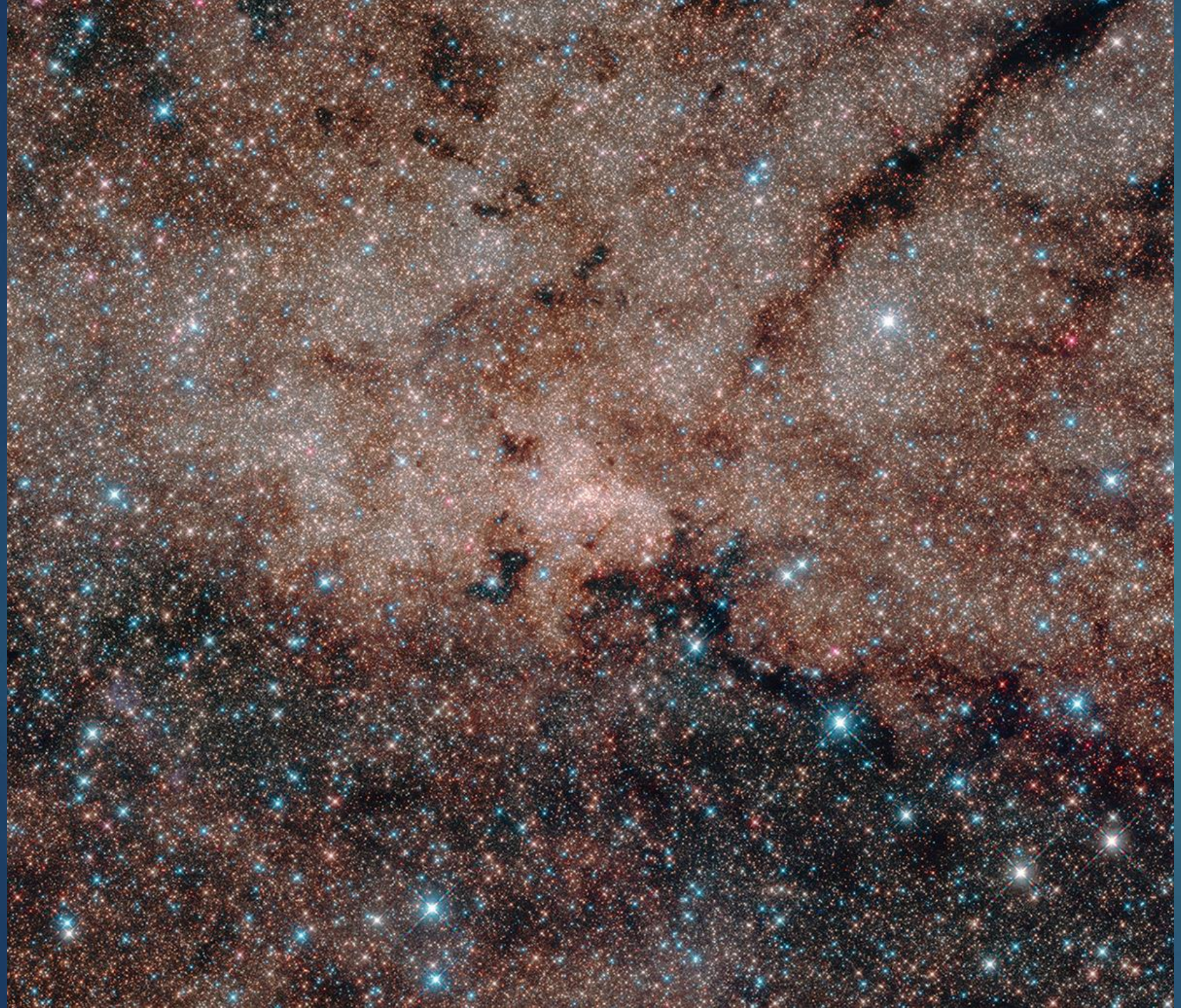
Outline of This Talk

- Why Submillimeter Spectroscopy
- Importance of High Spectral Resolution
- Carrying out Submillimeter Observations
- Some Astronomical Results
- Current and Future Technology
- Current and Future Facilities



Dust in the interstellar medium (ISM)

Absorbs light from stars at visible & near-IR wavelengths

Dust grains have size ~0.1 μm

Critical for structure of ISM: H_2 molecules formed on grain surfaces

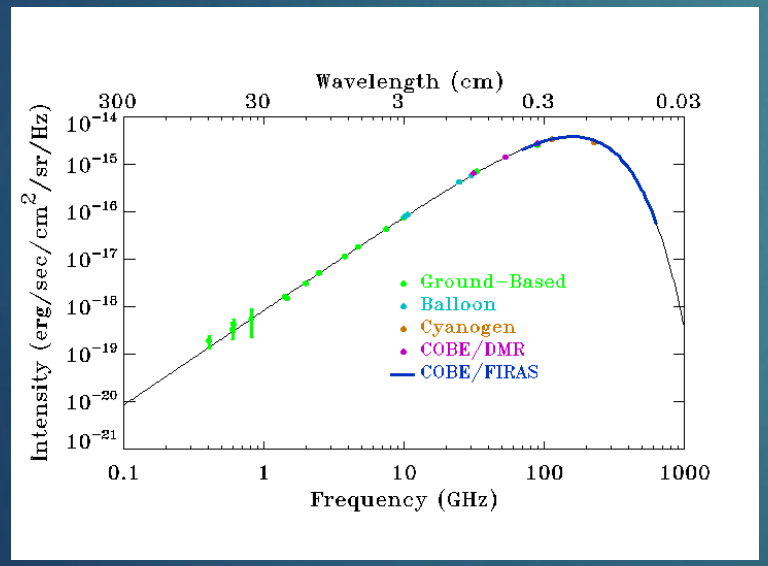
Dust blocks UV and allows rich array of molecules to exist in interstellar clouds

Sombrero Galaxy

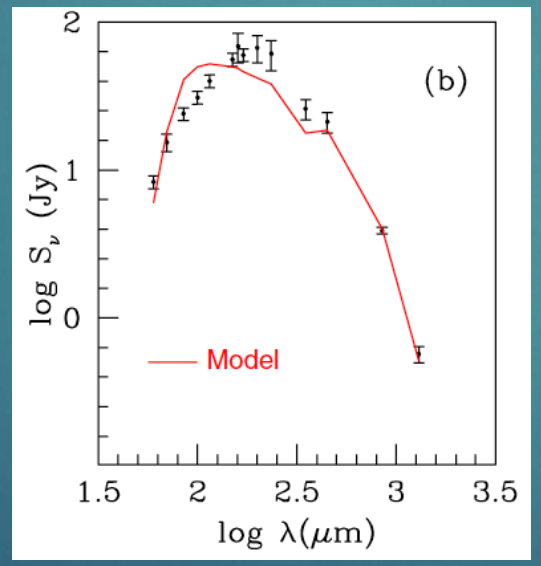
Interstellar Dust

- Absorbs and scatters short-wavelength (visible) radiation
- Absorbs at longer wavelengths, but must emit as well
- Observations of dust thermal emission over wide wavelength range can determine the dust temperature
- Dust emission &temperature are fundamental for understanding energetics

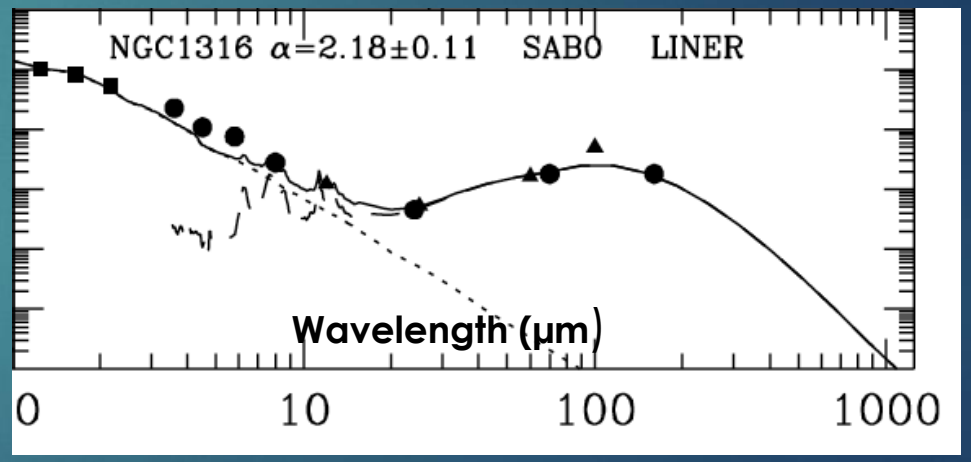
Dust observations tell us **nothing** about KINEMATICS – measuring the MOTIONS (via Doppler shifts of lines) tells us what is going on **– spectroscopy required!**



2,73 K CMB radiation



Emission from dust in dark cloud (Shirley+ 2011)



Emission from Galaxy – multiple dust temperatures (Dale+ 2005)

Why Submillimeter Spectroscopy?

Submm spectral lines provide vital insight into the chemistry and physics of the interstellar medium (ISM) and how clouds of dust and gas in the ISM evolve to form new stars.

These processes control the evolution of galaxies and formation of planetary systems.

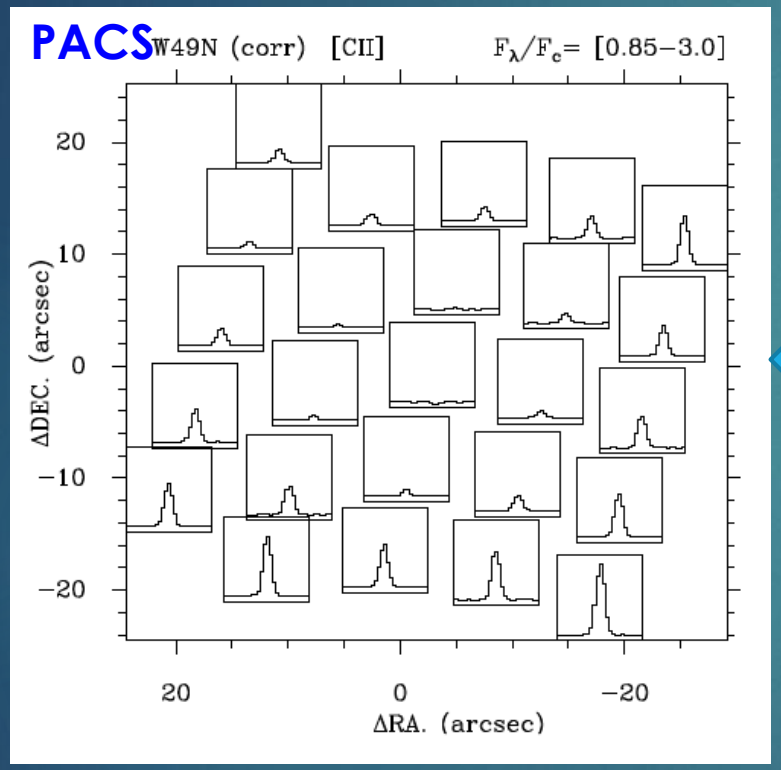
Unique probes

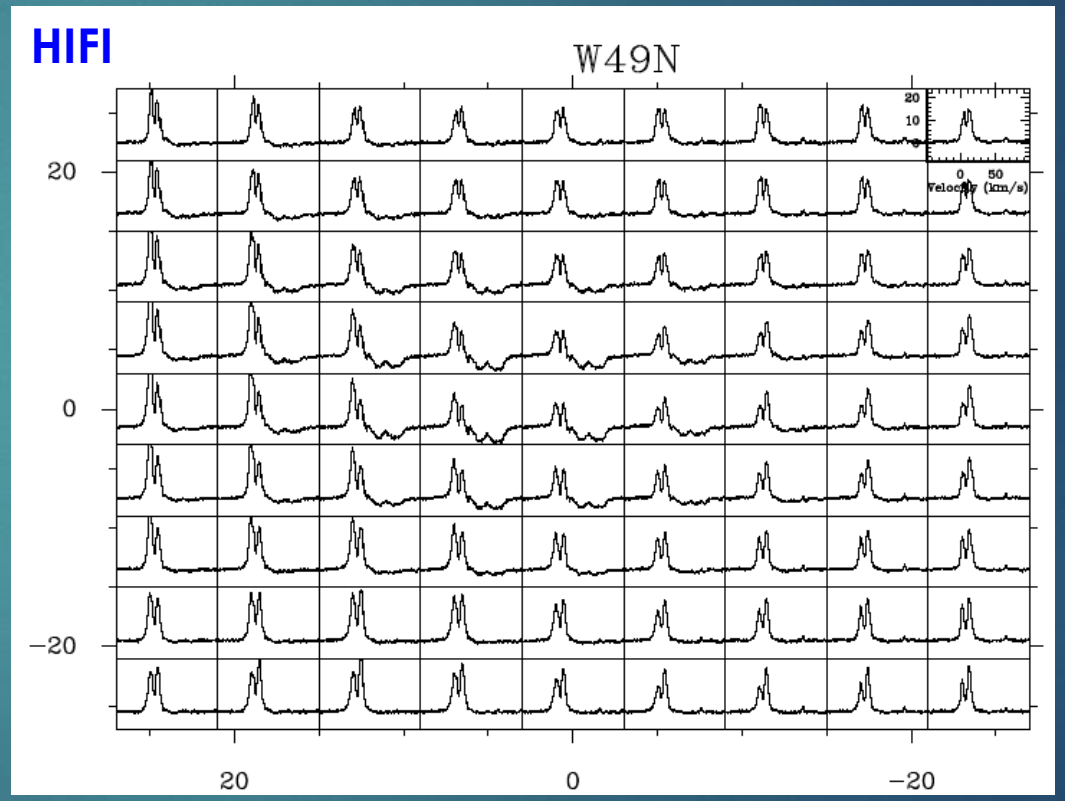
1. fine structure lines: **atomic carbon [CI] at 492 and 810 GHz**
   ionized carbon [CII] at 1900 GHz
   ionized nitrogen [NII] at 1461 and 2460 GHz
   atomic oxygen [OI] at 2060 and 4745 GHz
2. Higher rotational lines of key tracers including CO allowing study of interstellar shocks, outflows from young stars, and protostellar disks
3. Key biogenic molecule – **WATER (H_2O)** and others (HF, ArH, O_2,…)

High spectral resolution allows measuring motions within these clouds, cores, and disks, and thus to understand what they are doing

High Spectral Resolution Essential for Correct Interpretation of Observations of the Complex Interstellar Medium

A heterodyne" system is required





Gerin et al. 2015

Line/Continuum ratio drops dramatically as continuum gets stronger giving a completely erroneous result IF YOU ARE NOT SPECTRALLY RESOLVING THE LINE !

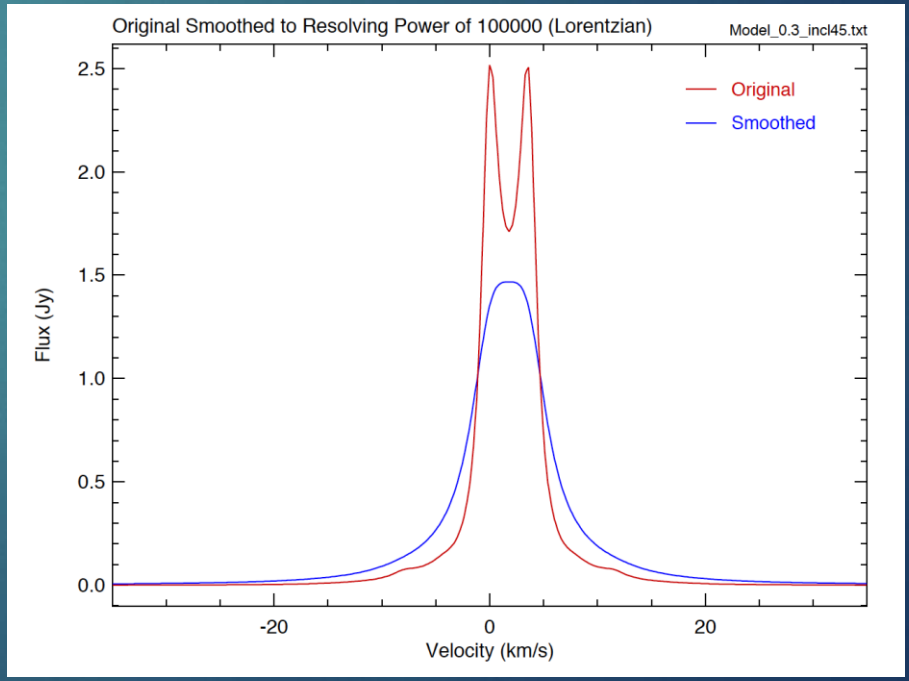
Protoplanetary Disks Require High Spectral Resolution to Extract Meaningful Results

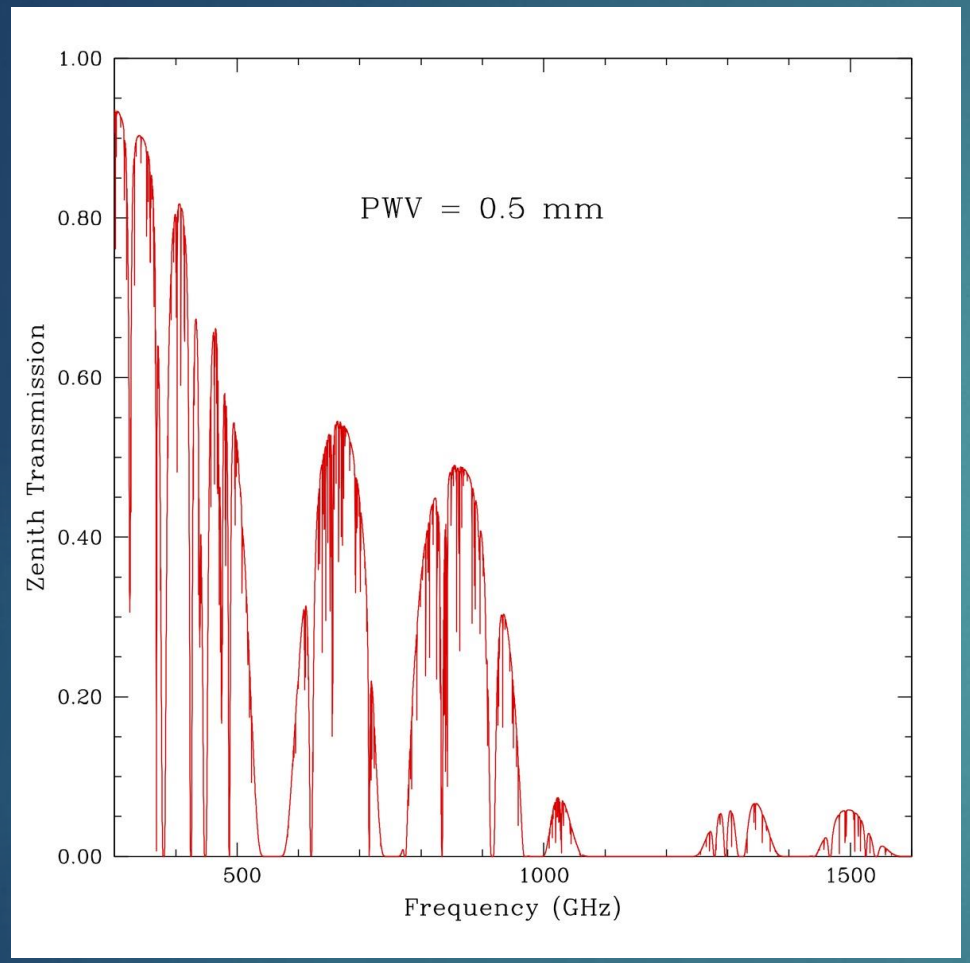
CO in disk around HL Tau
ALMA collaboration 2015

557 GHz 1_{10}—1_{01} water line fromKeplerian disk with 45^0 angle

Line shape determines rotation velocity at "snow line" and distribution of gaseous water

Spectral resolution of 10^5 (3 km/s) with Fabry-Perot interferometer looses all interesting information except detection of water





The Atmosphere is a Major Challenge for Submillimeter Astronomy

Water vapor (primarily) makes atmospheric transmission ~ 0 from sea level

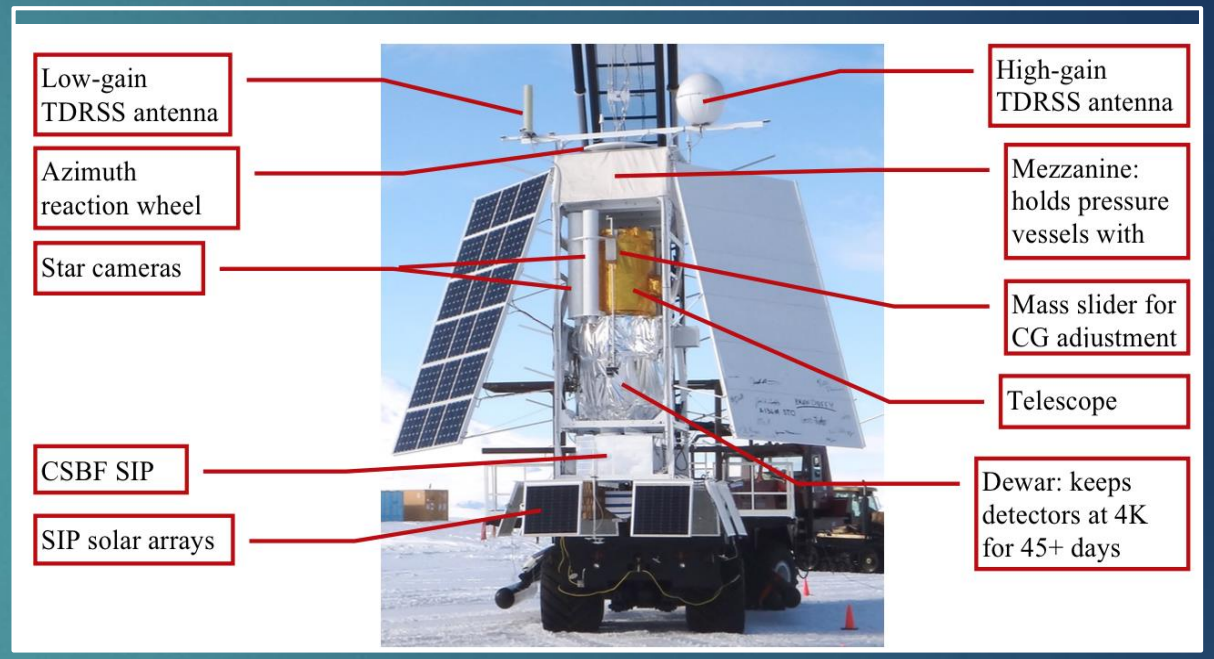
From very high, dry sites there are "windows" that offer partial transmission

At aircraft altitude (14 km) the situation is much better, but there are still blocked spectral regions

A balloon (40 km) is good except for frequencies near telluric lines

Complete access is possible only from space

To Obtain the Submillimeter High Resolution Astronomical Spectral Line Data You Want – (1) Get Above the Water in the Earth's Atmosphere

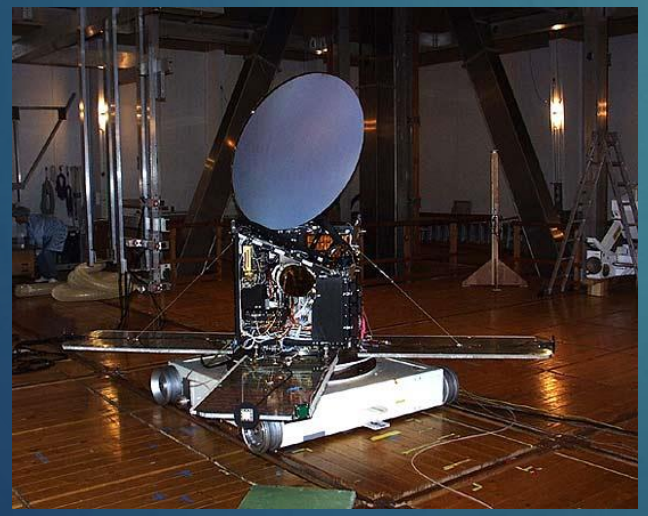


Stratospheric Observatory for Infrared Astronomy (SOFIA)
NASA/DLR
2.5m telescope at ambient temperature @14 km altitude
Multiple instruments

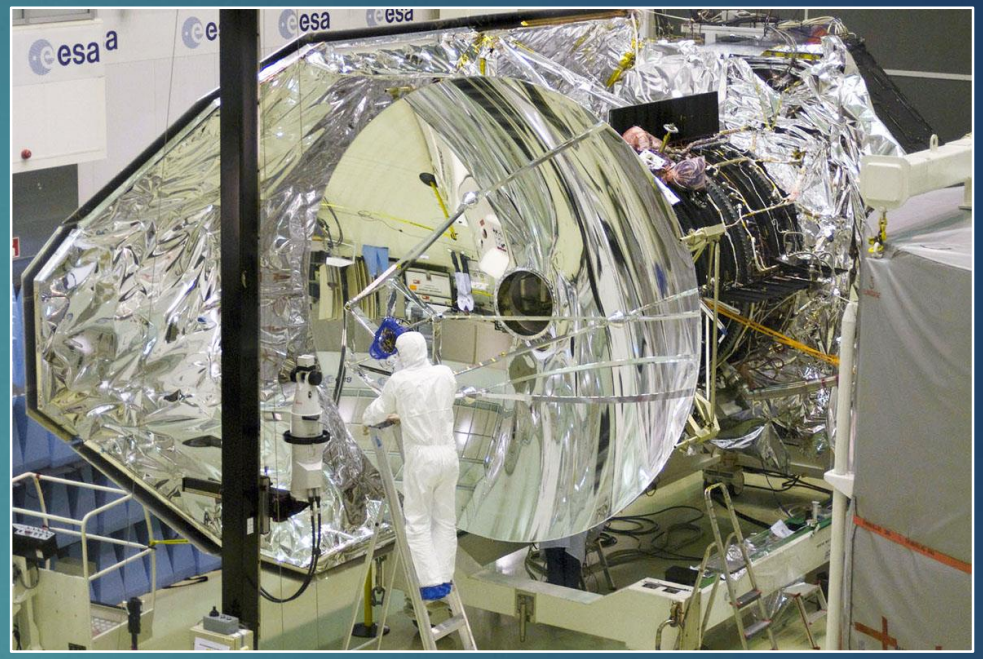
STO2 Balloon – 22 day flight Dec. 2016
40 km altitude
HEB mixers cooled with LHe
Good performance at 1900 GHz

To Obtain the Submillimeter High Resolution Astronomical Spectral Line Data You Want – (2) Get Into Space!

SWAS (1998)
54x68cm offset
Cassegrain
490/550 GHz
CI,O_2,^{13}CO,H_2O
Schottky diode 2nd
harmonic mixers at 150 K



Odin (2001)
1.1m offset
Gregorian
486-581 GHz
tunable
Numerous lines
Schottky mixers
cooled to 140 K



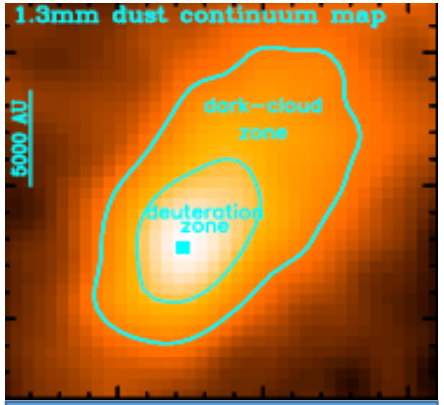
Herschel (2009)
3.5m symmetric Cassegrain
antenna cooled to 80K
480-1900 GHz
SIS and HEB mixers operating at 4K

P.F. Goldsmith 2012, Ch. 16 in Imbriale, Gao, and Boccia, eds., **Space Antenna Handbook**, J. Wiley & Sons

Four Interrelated Phases of the Water Trail

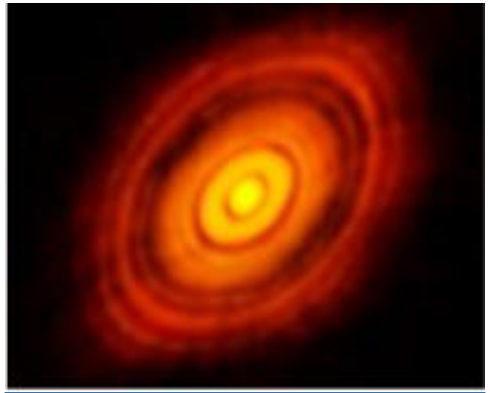
WATER IN INTERSTELLAR CLOUDS

Water formation in gas and on grains
Gas & grain processing
Water traces shocks & outflow chemistry
Water probes feedback from star formation



WATER IN CLOUD CORES

Water processing in cold environment
Deuteration
Water traces kinematics of collapsing star forming cores



WATER IN PROTOSTELLAR DISKS

Water processing by visible, UV, X-rays
Thermal environment determines the snowline that defines the gas phase water distribution

WATER IN THE SOLAR SYSTEM

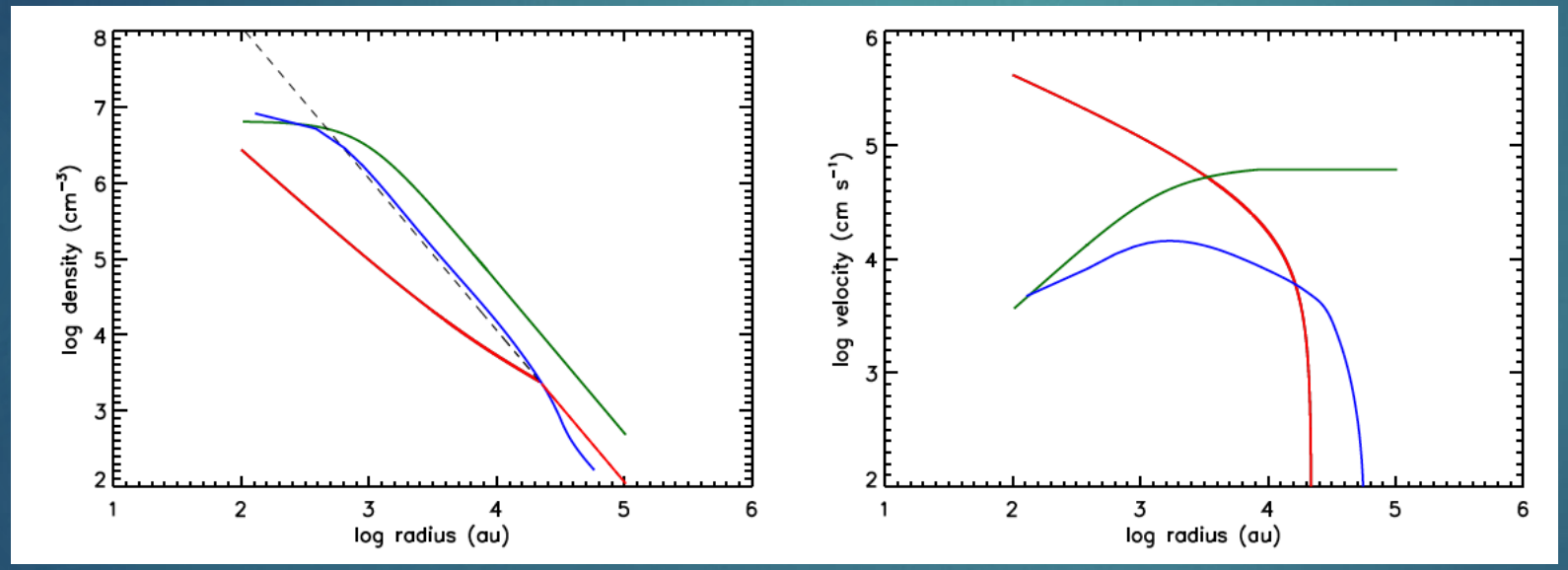
Segregation of water with planetesimals
Water distribution determined
Water transported to the Earth in the early history of Solar System

Water as Tracer of Dense Core Kinematics

Cold (8-12 K), compact (0.1 pc) dense(10^3-10^7 cm^{-3})
Precursors to new stars; should be collapsing
What is the velocity field in collapsing cores?

All models have **~same** n(r) but vastly **different** v(r)

Keto, Caselli, Rawlings 2015



Singular Isothermal Sphere

Larson-Penston

Unstable B-E Sphere

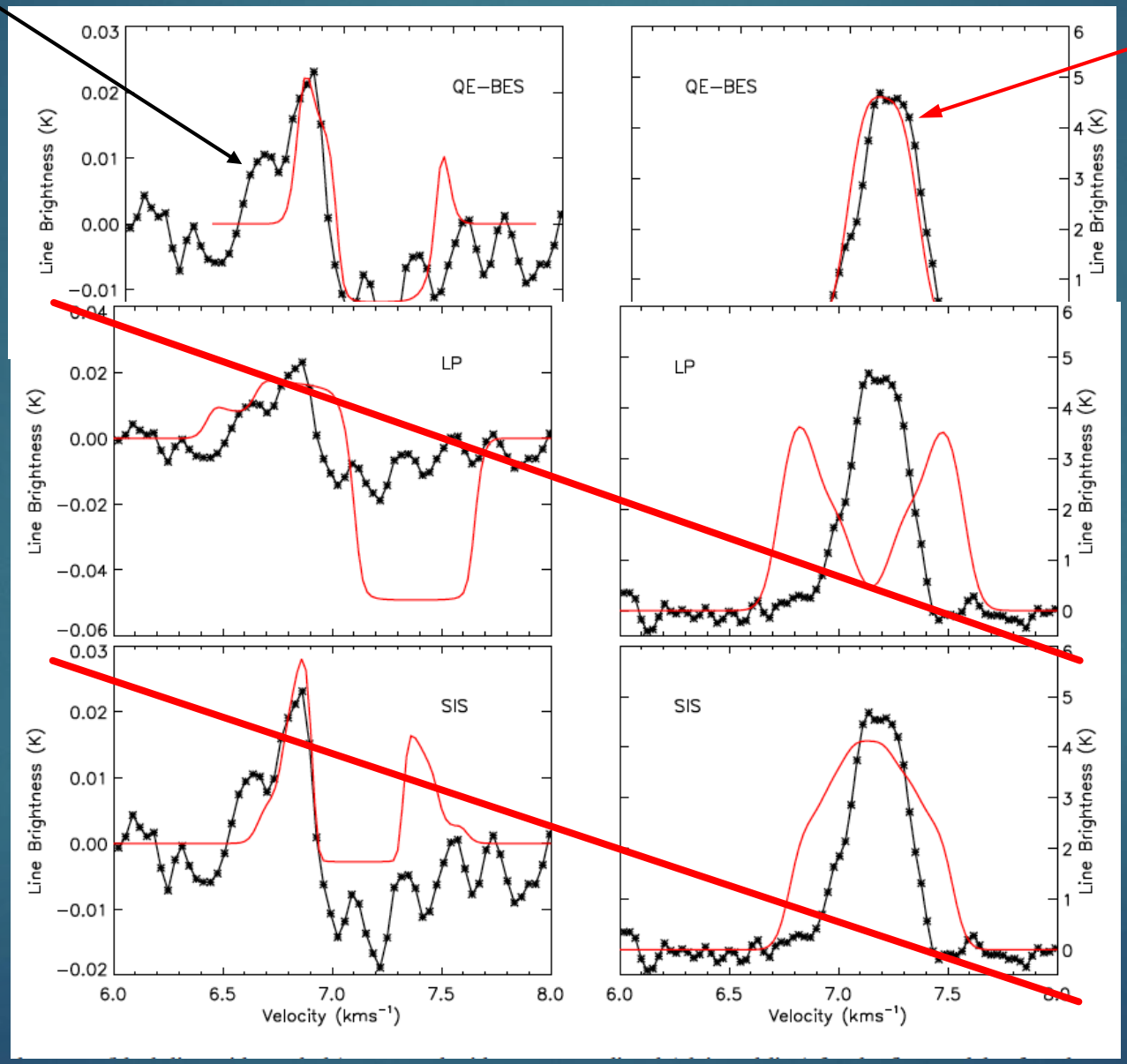
Water: demanding excitation => tracers innermost, densest regions
$C^{18}O$: easy to excite--traces overall core and its motions

L1544 H_2O 557 GHz data from Herschel HIFI
Note velocity resolution

H_2O

$C^{18}O$

Theoretical Models



Only the Quasi-Equilibrium Bonnor-Ebert Sphere model reproduces observations of L1544

Water and the Habitability of Planets Forming in Protostellar Disks

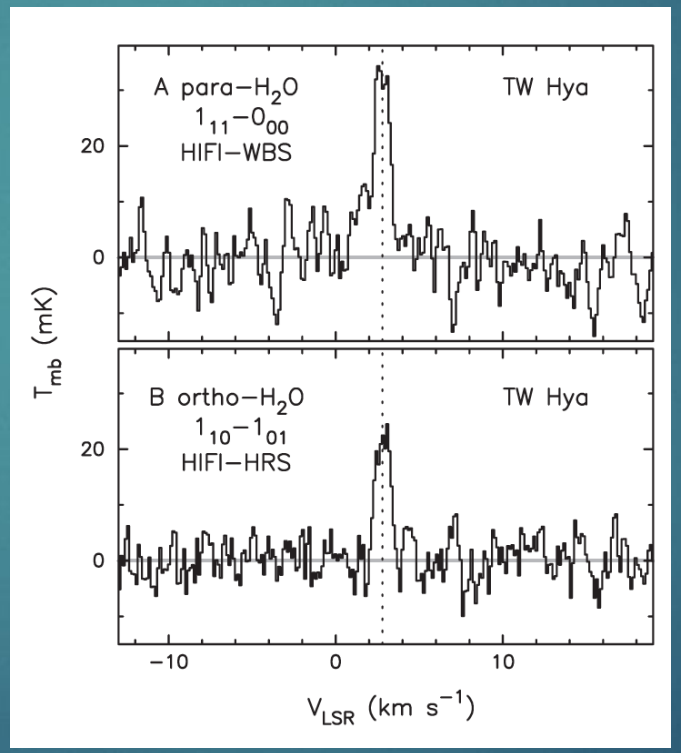
ALMA Image of CO in HL Tau disk
Angular resolution = 0.3" (5 AU @ 140 pc)

< 1" resolution necessary to resolve the gaps possibly indicative of planet formation

Observations of WATER are critical to determine the likelihood of habitable planets

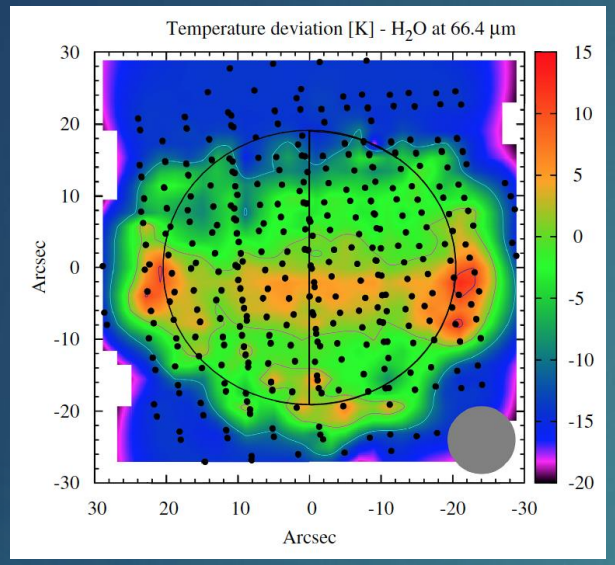
This cannot be done even from balloon due to small velocity shifts of nearby young stars & disks. Detected with Herschel but not spatially resolved

Subm Heterodyne Interferometer required to make desired observations ($\delta v < 0.5$ km/s; $\delta\theta = 0.3''$ @ 1 THz)

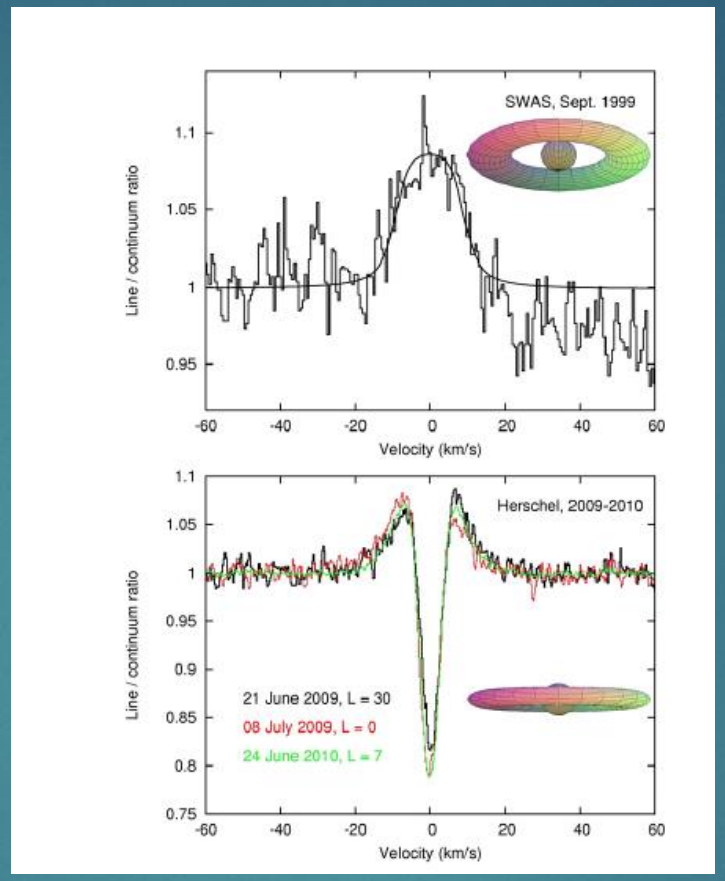


ALMA Image of CO in HL Tau disk
Angular resolution = 0.3" (5 AU @ 140 pc)
ALMA partnership 2015

Water Throughout the Solar System

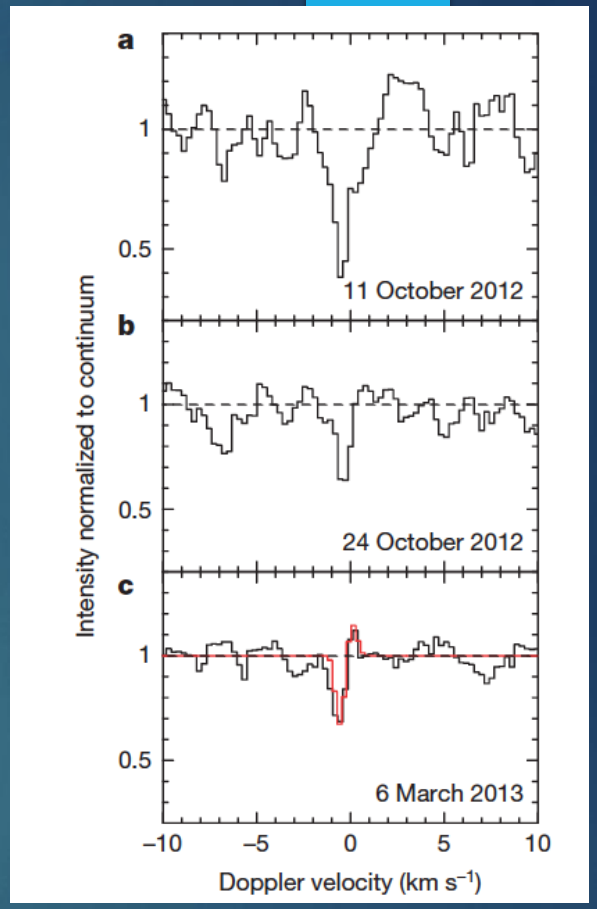


In Jupiter's atmosphere
Cavalié et al. (2010)
Herschel/PACS



In **Saturn's moon Enceladus**
Hartogh et al. (2011)
557 GHz 1_{10}-1_{01}

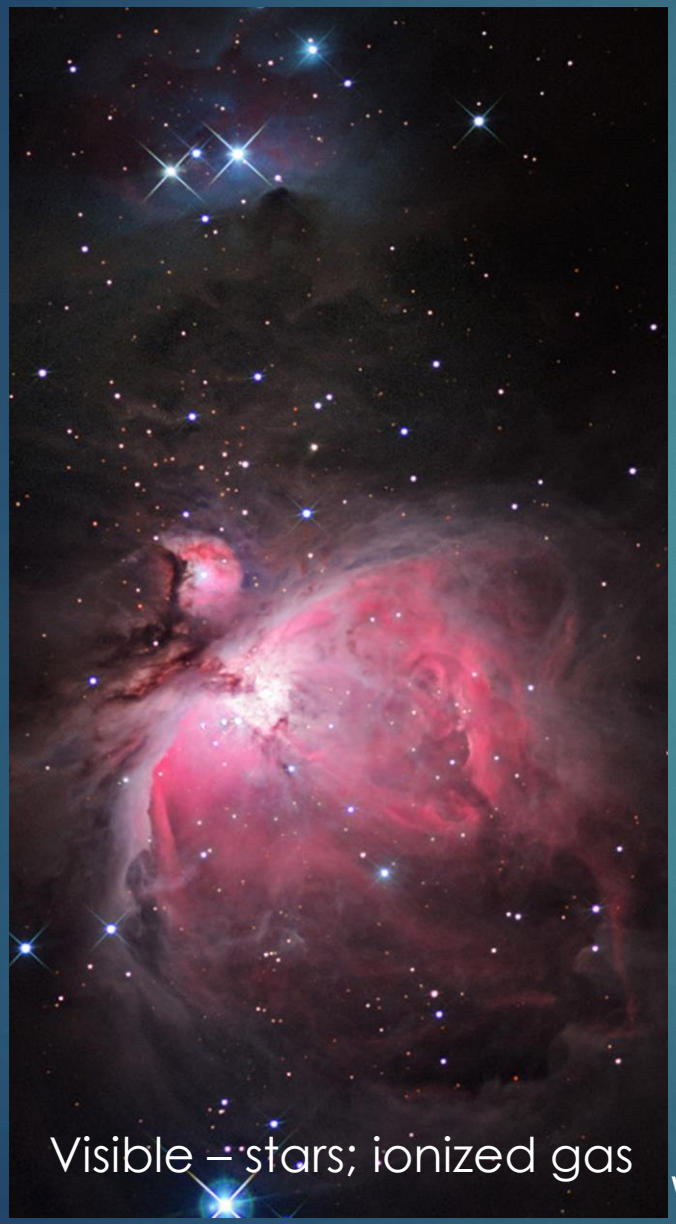
SWAS and *Herschel*/HIFI

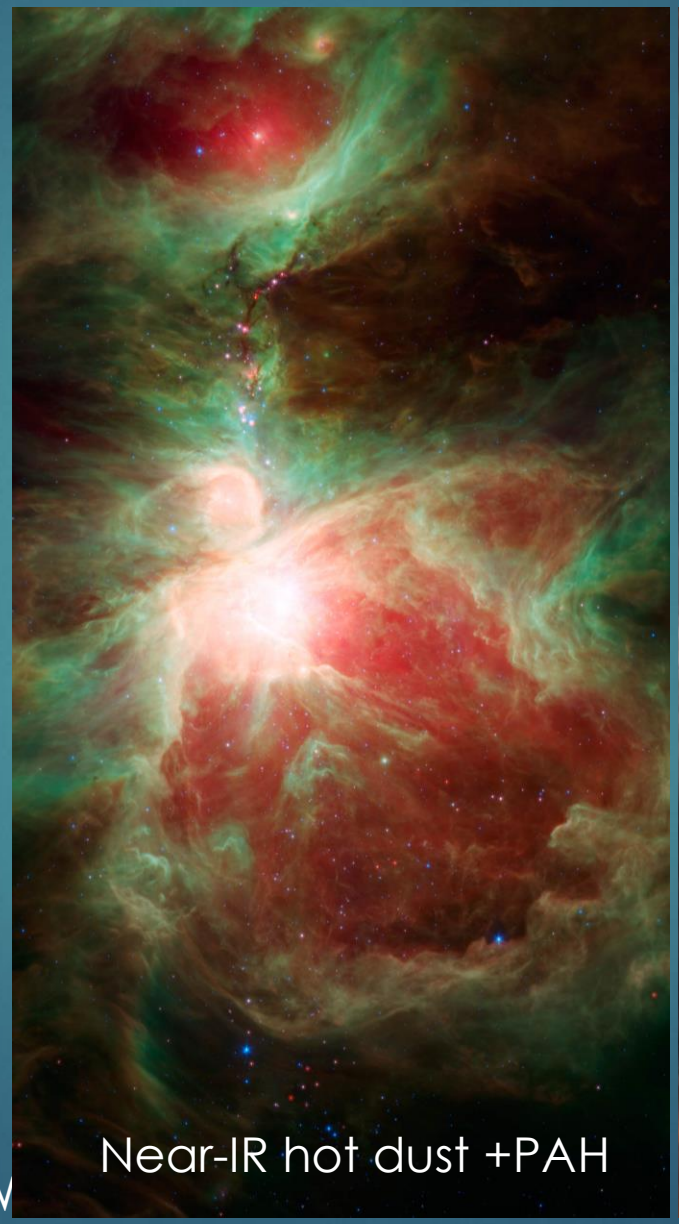


In **dwarf planet Ceres**
Küppers et al. (2014)
Herschel/HIFI 557 Ghz

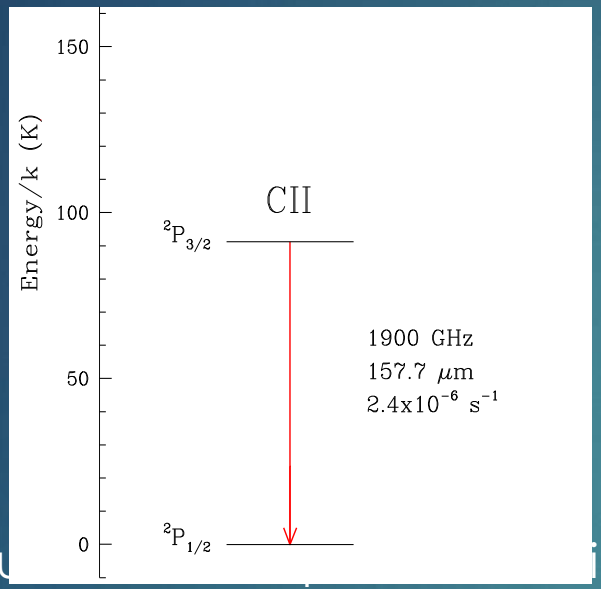
ORION – A Case Study of the Nearest Region of Massive Star Formation

Thanks to
X. Tielens
C. Pabst
S, Suri





[CII] 158 μm Fine Structure Line

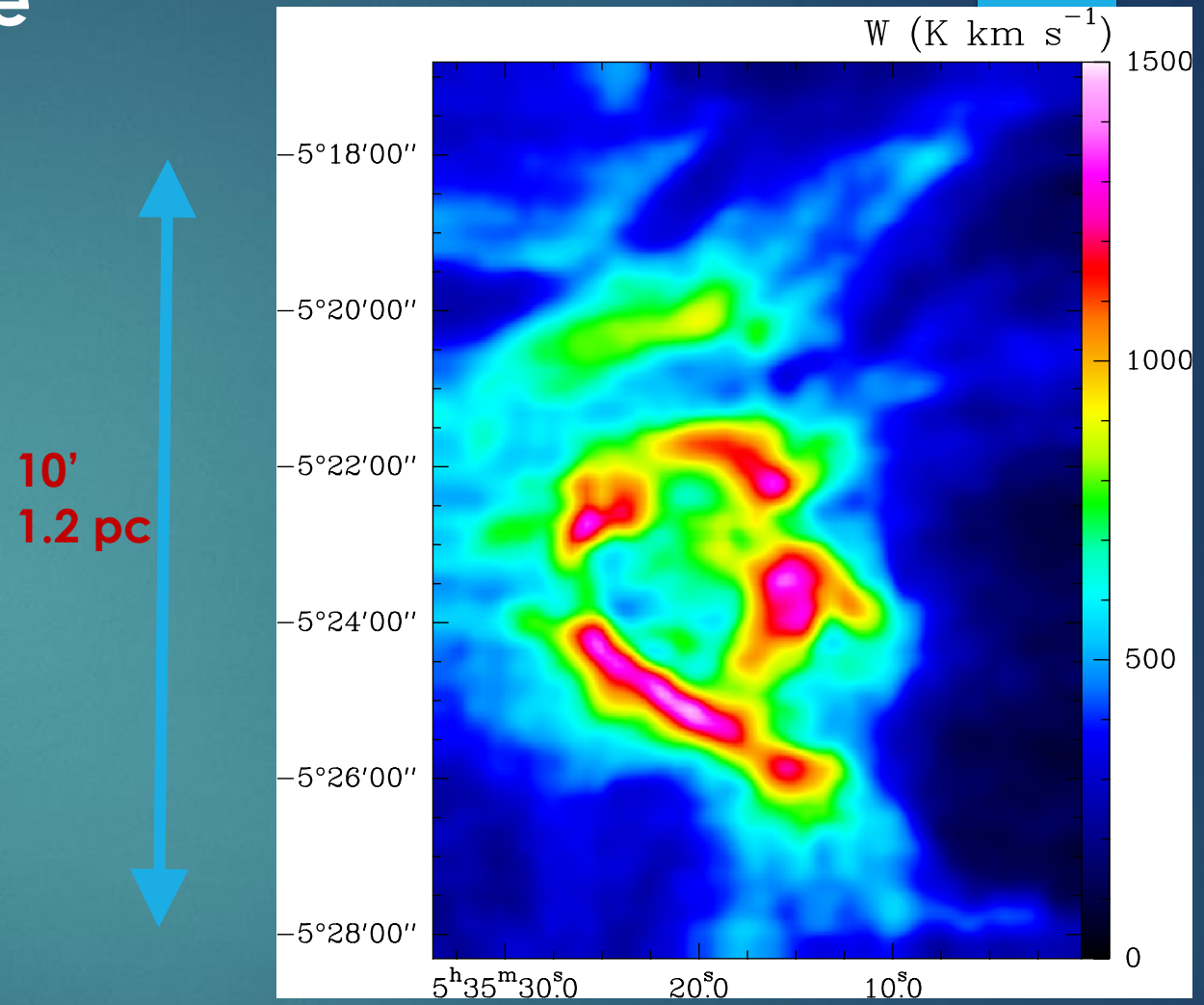


Most lu in Milky Way and other galaxies

Primary coolant of diffuse ISM – regulates temperature of atomic clouds

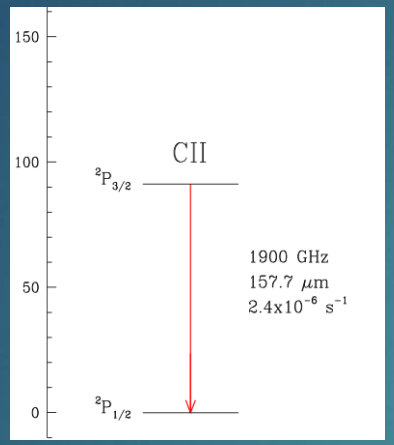
[CII] also from regions where hydrogen is ionized and from boundaries of dense clouds

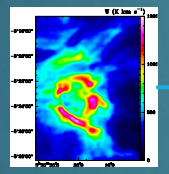
Excellent probe of star formation



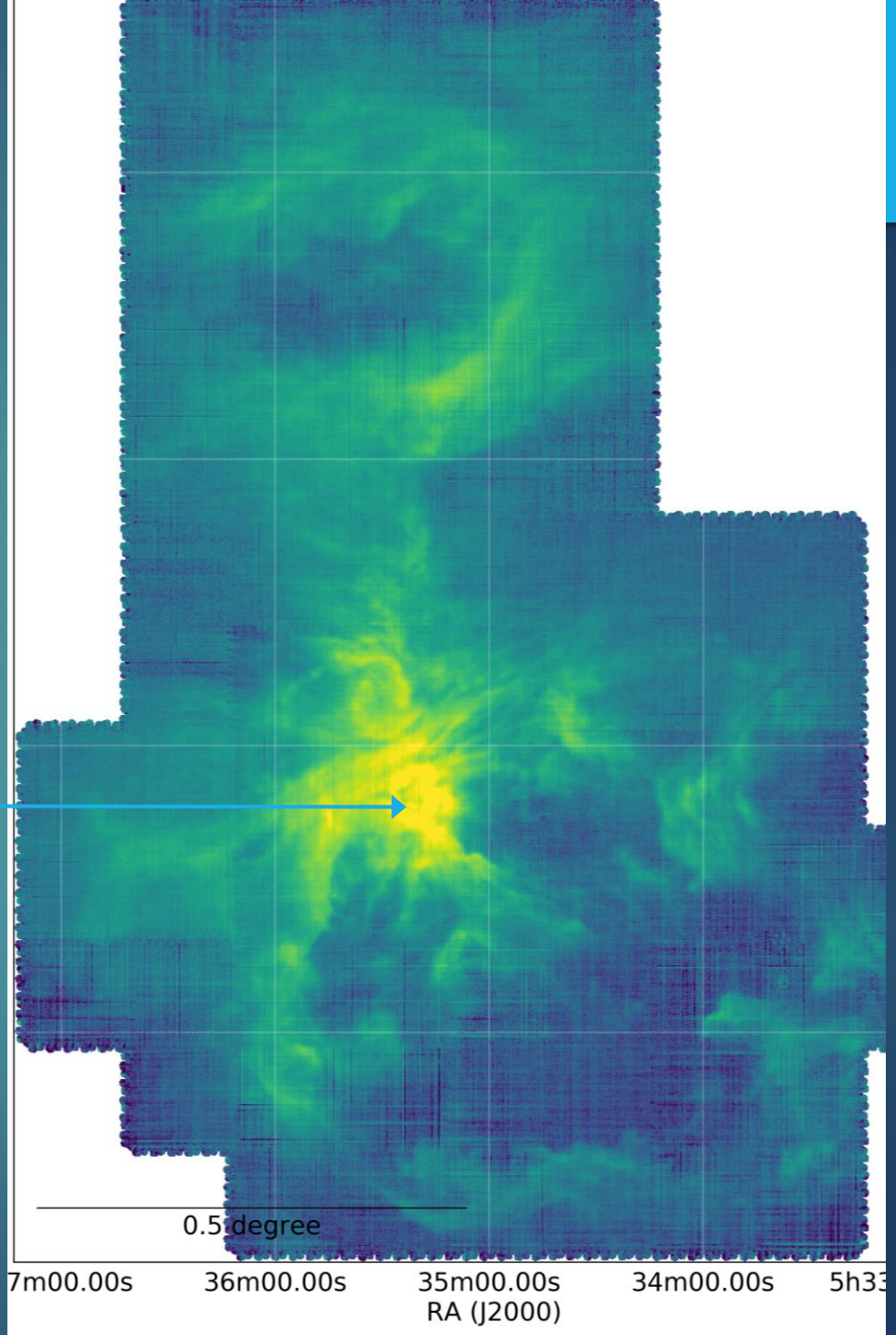
[CII] Integrated Emission in Orion from Herschel/HIFI
Goicoechea et al. (2015)

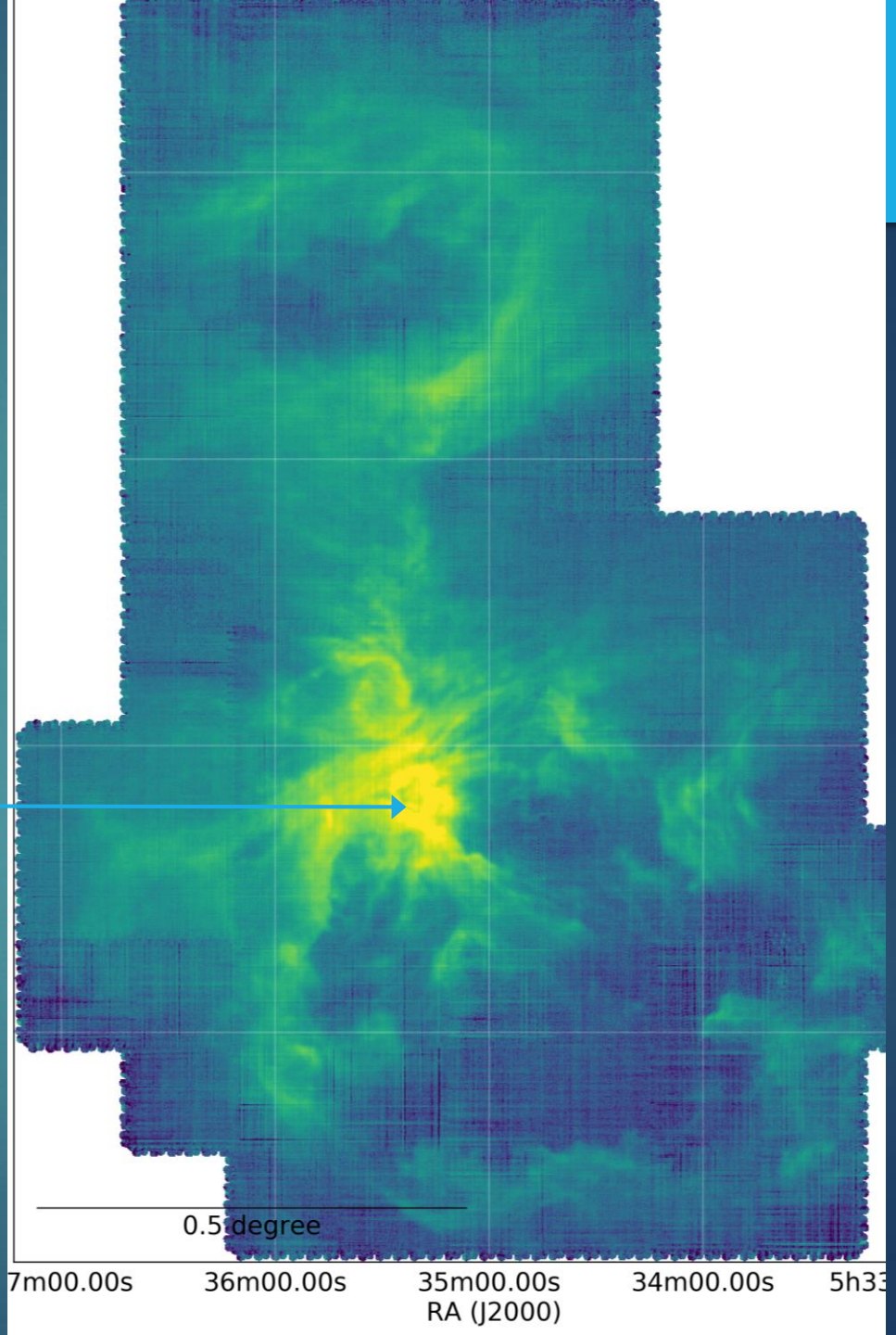
[CII] 158 μm Fine Structure Line

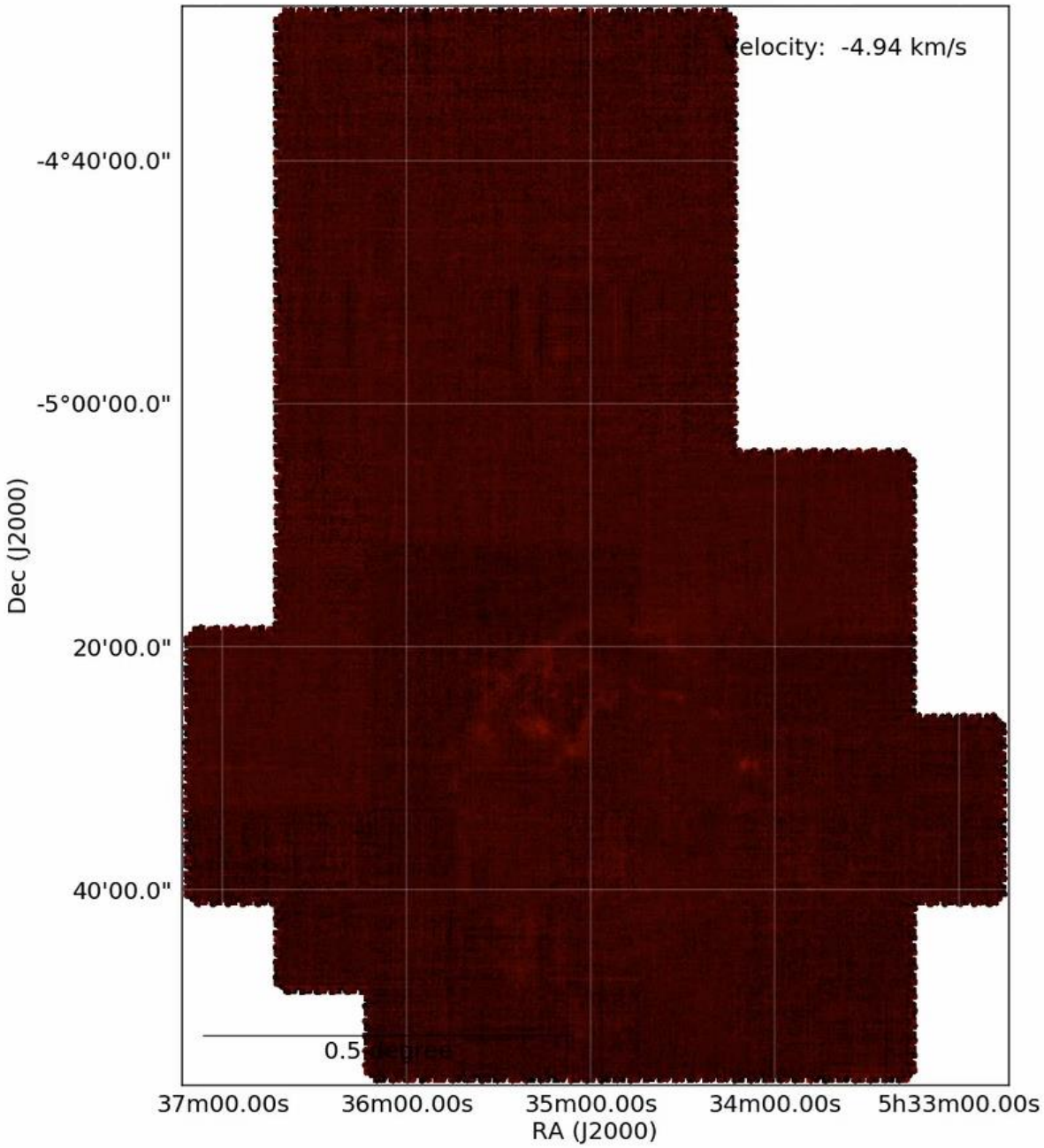




9 hours with Herschel/HIFI
1 element receiver
Undersampled map




0.5 degree
7m00.00s
36m00.00s
35m00.00s
34m00.00s
5h33
RA (J2000)



40 hours with SOFIA upGREAT
7-element receiver
Fully-sampled image
2.5 million spectra

X. Tielens, C. Pabst, S. Suri

The Intertwined Requirements of Sensitivity, Angular Resolution and Spectral Resolution

- High Sensitivity – fainter lines; more distant objects, faster mapping speed; effectively larger field of view
- High Spectral Resolution – necessary to study more quiescent regions in ISM; resolve kinematics; determine structure of solar system objects
- High Angular Resolution – resolve structures; smaller structures often have narrower line widths

The interstellar medium is extended and to understand it we need 3D images with high spatial dynamic range (SDR), where SDR = Image size/Angular Resolution

Angular resolution sets the scale of smallest resolvable objects

Image size requirement set by scale of physical processes

Higher angular resolution demands higher spectral resolution =>

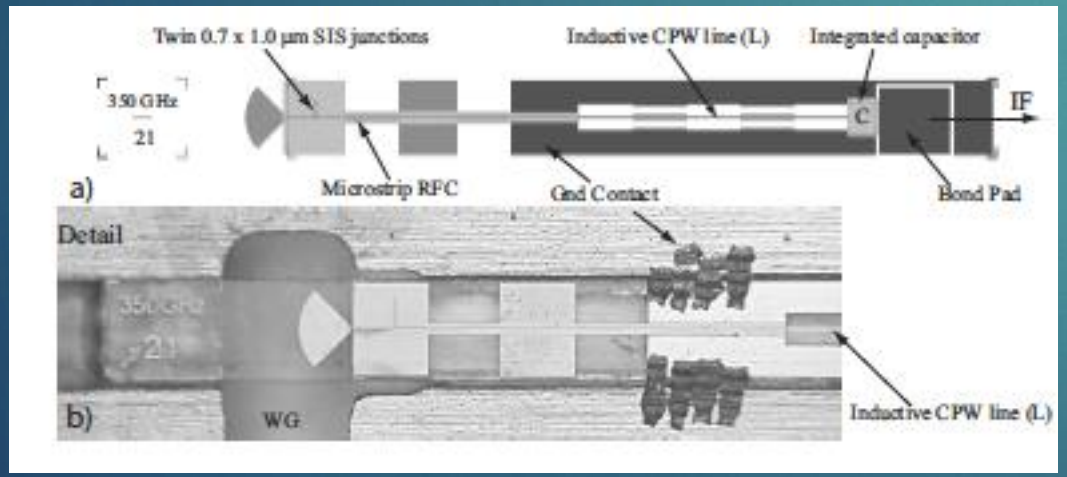
Time required becomes unreasonable unless you have higher sensitivity

THE ONLY SOLUTION IS TO EMPLOY FOCAL PLANE ARRAYS TO INCREASE MAPPING SPEED

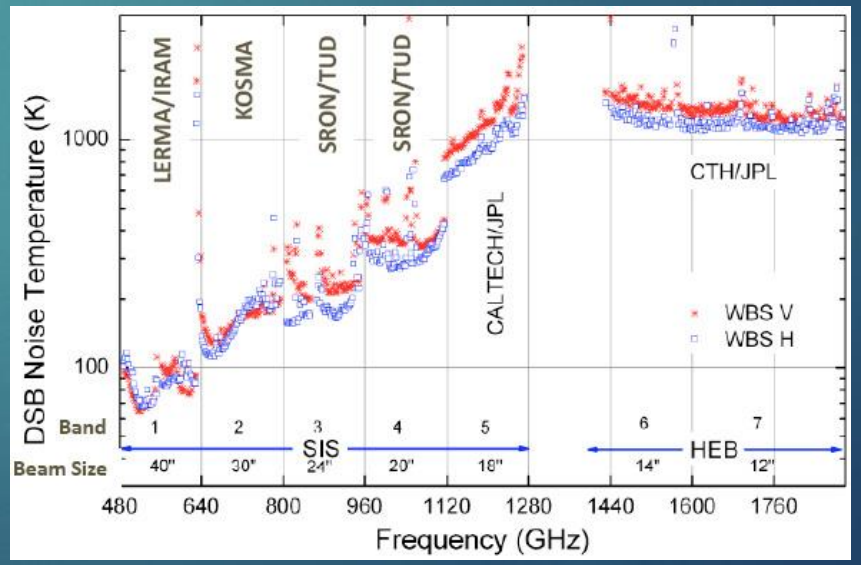
Technology Enabling Submm Spectroscopic Imaging

Enormous progress is last decades in ALL critical areas

1. High Sensitivity Mixers: SIS (excellent to ~ 1000 GHz), HEB (good but could be better)
2. Local Oscillators – few μW per mixing element, tunable, spectrally pure
3. Broadband IF amplifiers
4. Digital spectrometers –multi-GHz bandwidth



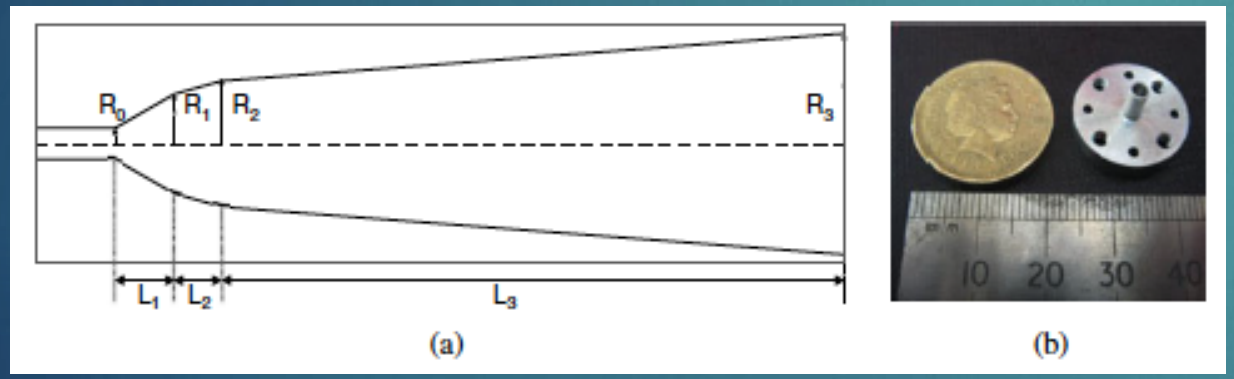
Balanced 350 GHz SIS mixer (Kooi et al. 2011)

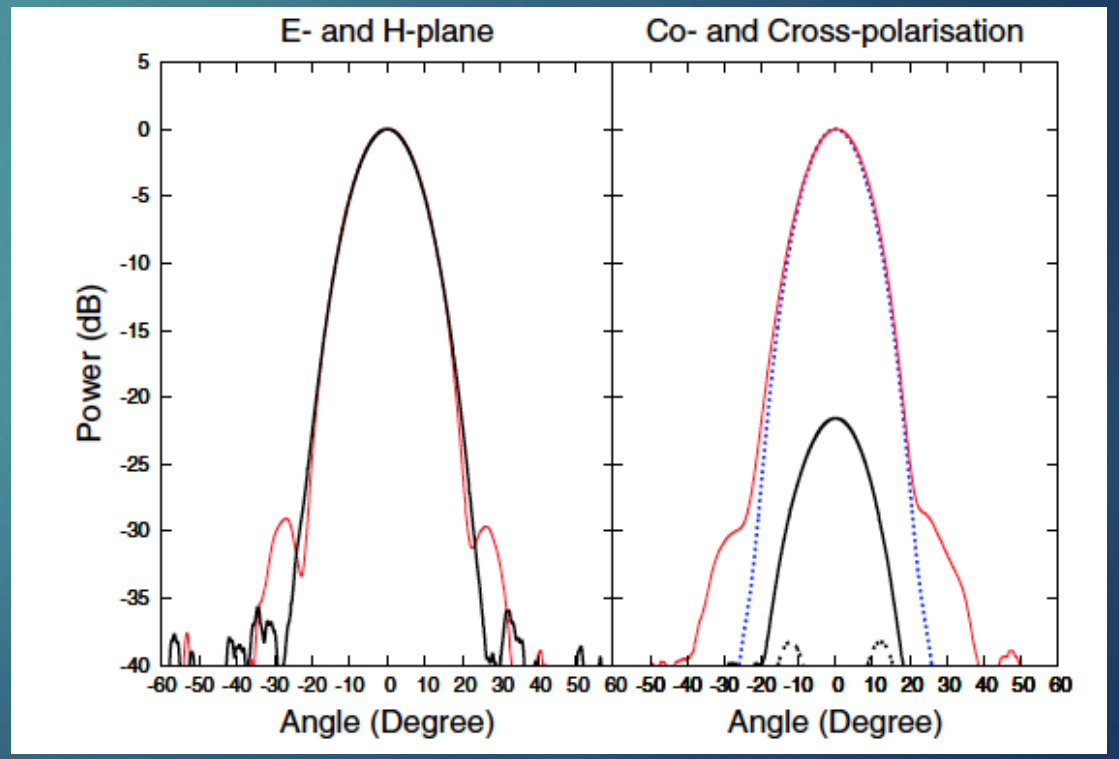


Current challenge: Large-format Heterodyne Focal Plane Arrays (HFPAs)

Feed Elements – multisection smooth-walled feedhorns are now well-understood, offering excellent performance over substantial bandwidths (~30%). They are excellent for submillimeter wavelengths, offering performance comparable to scalar feedhorns with ease of construction comparable to e.g. diagonal feedhorns

For fundamental reasons, high-quality feeds in an array produce beams on the sky separated by a MINIMUM angle $\Delta\theta$ = 2. FWHM beam width

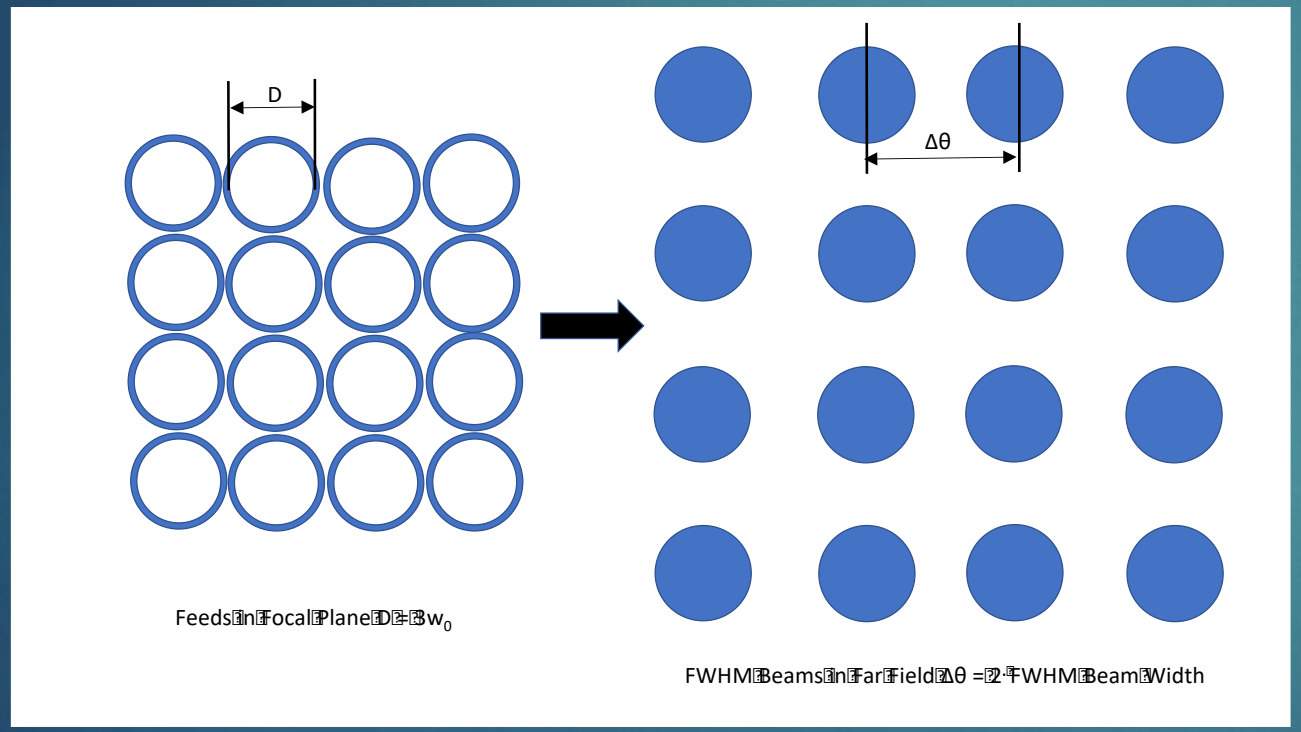




700 GHz feedhorn
Tan et al. (2012) J. Infrared Milli. Terahz. Waves

Coherent Systems Undersample the Sky

Close-packed array of high-quality feed horns leads to beams on sky separated by ~ 2 beamdwidths



Strategies to deal with this

Extended sources:

Scan telescope (OTF map)
Reconstruct image at desired angular resolution

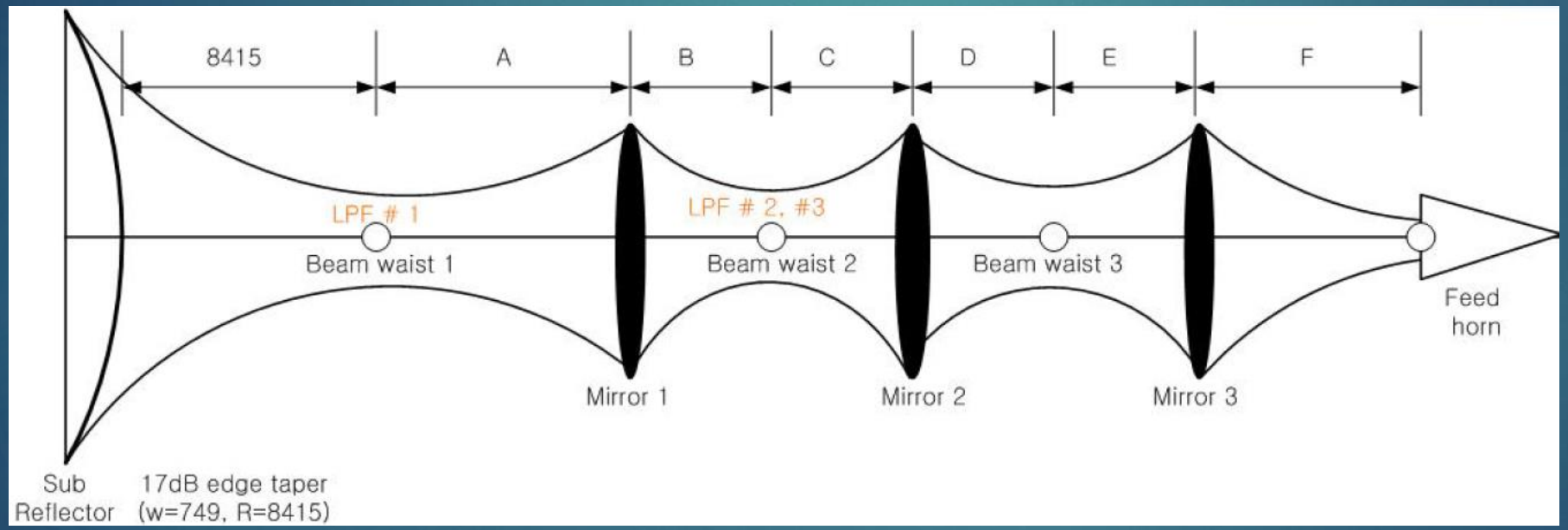
Small sources:

More of a problem
Can compensate in one dimension using polarization duplexing

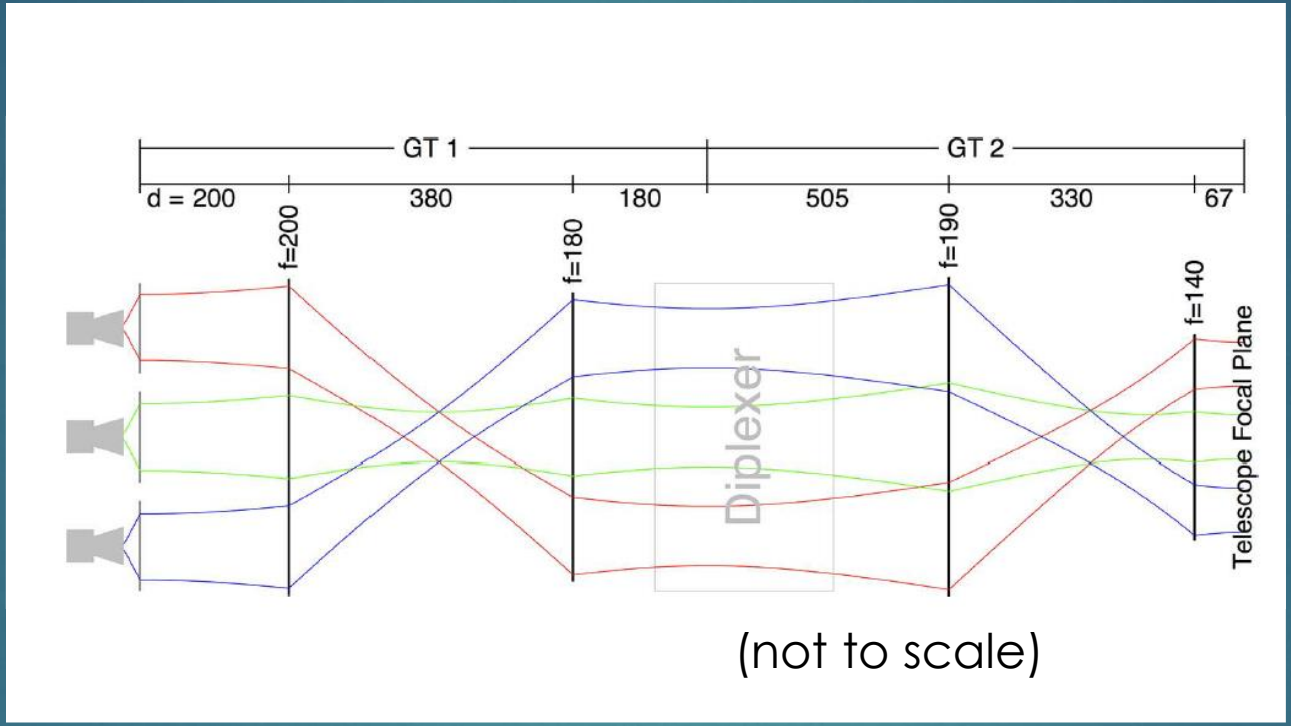
Field-sampling arrays being developed at microwave frequencies

Gaussian Beam Propagation Allows Efficient Design of Reimaging Systems

Good for determining sizes of optical elements
Cannot overcome undersampling of focal plane by high-quality feeds

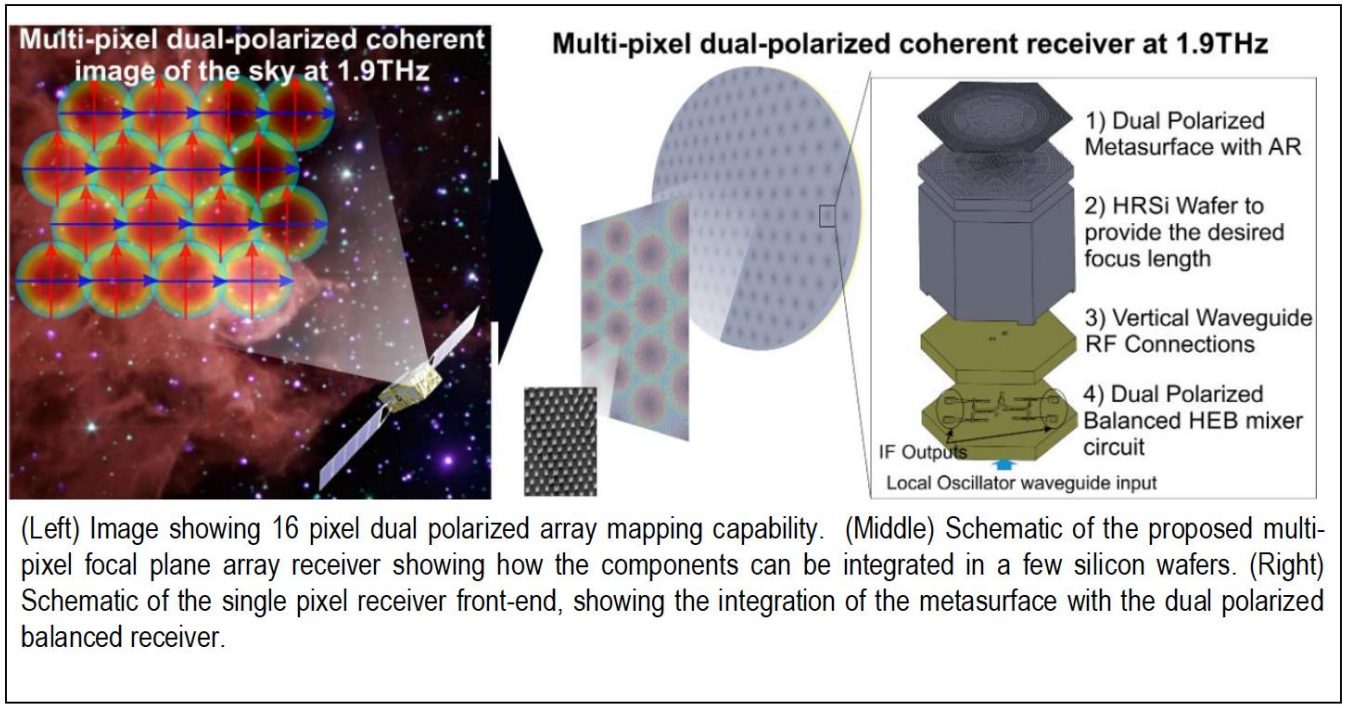


Reimaging of Array Elements (Lateral Offsets) is More Complicated

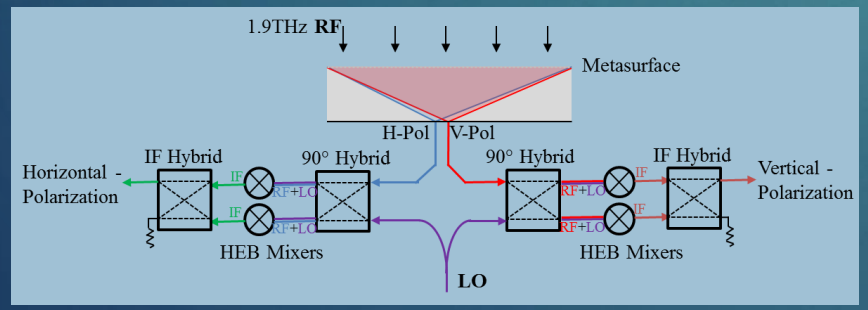


Small angles are unproblematic but this really requires verification with physical optics program

Towards Kilopixel Heterodyne Arrays:
Metasurfaces and Si Multilayer stacks



(Left) Image showing 16 pixel dual polarized array mapping capability. (Middle) Schematic of the proposed multi-pixel focal plane array receiver showing how the components can be integrated in a few silicon wafers. (Right) Schematic of the single pixel receiver front-end, showing the integration of the metasurface with the dual polarized balanced receiver.

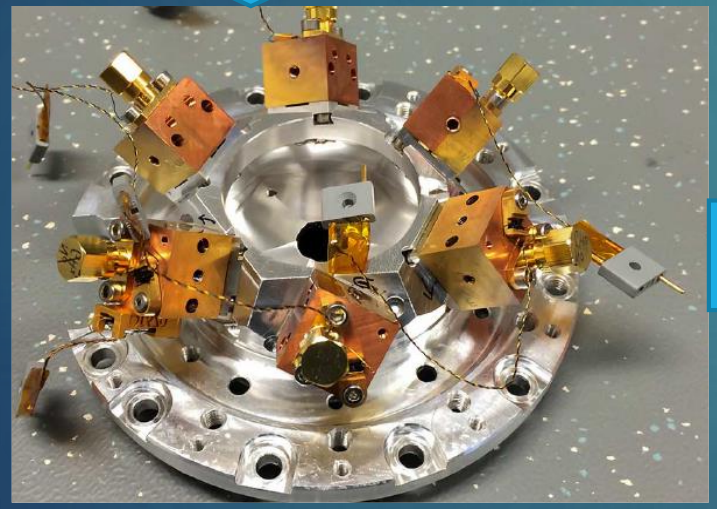


From Alonso et al. 2017 APRA (selected)

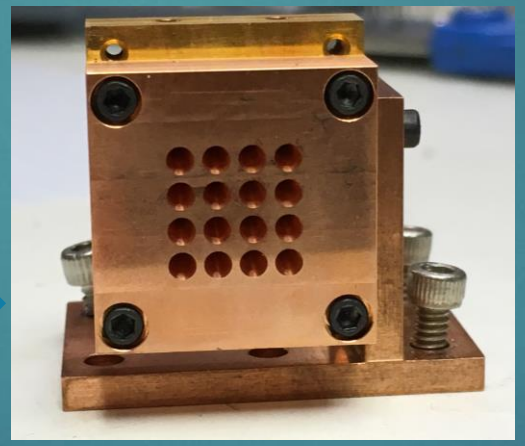
- Metasurface lens couples radiation from antenna to dual polarized balanced HEB mixer
- Receiver fabricated on "stack" of silicon wafers
- Readily scalable as metasurface design can compensate for aberrations of main reflector thus enhancing field of view
- Can more nearly fully sample focal plane than array of individual feed horns

Heterodyne Focal Plane Arrays: Individual Devices ➡ More Highly Integrated Arrays

Individual
1900 GHz HEB
mixers
Herschel/HIFI

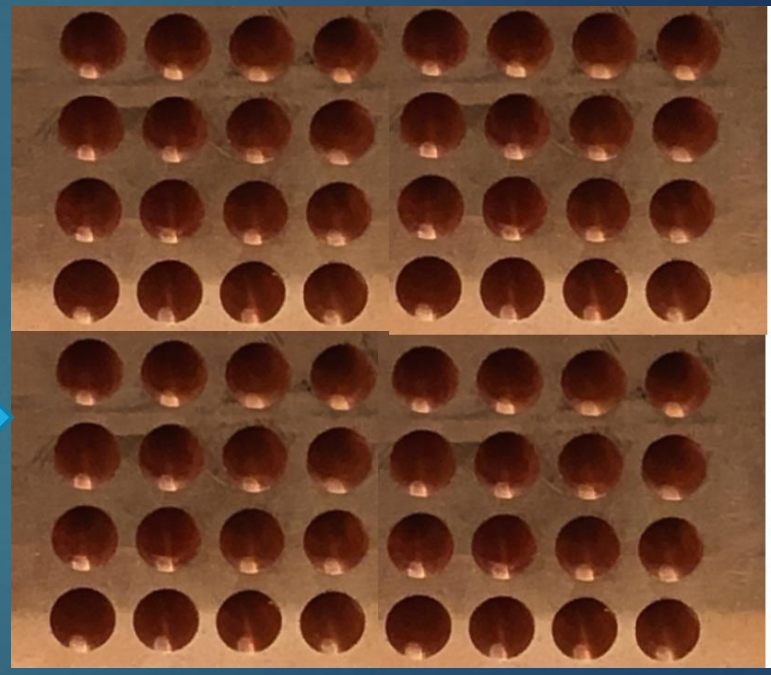


6 (of 14) individual mixers of **SOFIA/upGREAT** 2016



Integrated 16-pixel mixer module demonstrated at JPL

J. Kawamura



64 pixel module - one of two for SHASTA SOFIA instrument (2018)

Local Oscillators for Submillimeter Heterodyne Arrays

CURRENT OPTIONS

1. Quantum Cascade Lasers (QCL) – almost any frequency; ample power, but limited tunability, high DC power dissipation, require cooling, and non-trivial to frequency or phaselock.

2. Frequency-multiplied sources – limited to x2 and x3, so cascaded stages required to reach above 1000 GHz. >10% tunability. Power adequate for modest number of mixers.

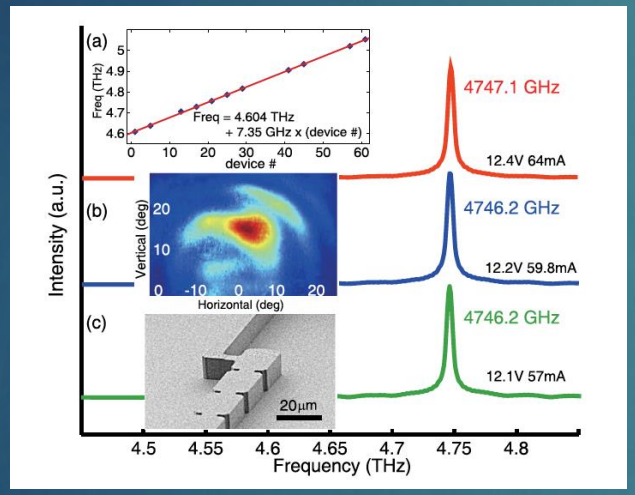
While complex, an "ideal" array system has independently adjustable power for each mixer. Readily achieved with multiplier cascades with individual final chains.

See Ligan, Liu, and Wang (2017) for recent review.

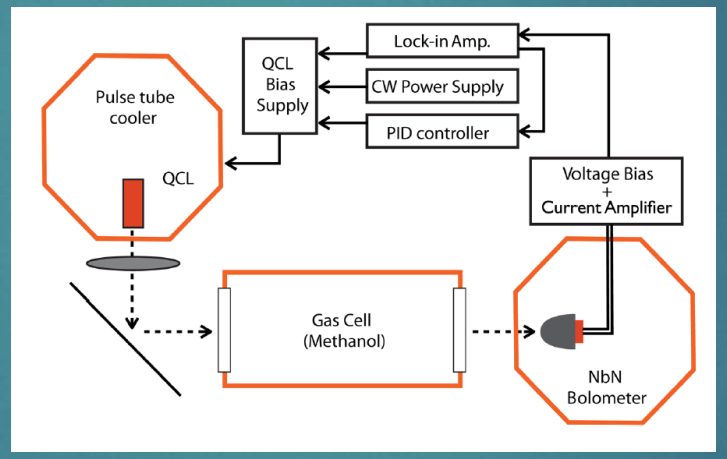
Quantum Cascade Laser (QCL) – multiple strongly-coupled quantum wells allow electron transitions between resulting subbands. With resonator structure, a relatively clean output results, having some current and temperature tunability.

Multiple lasers designed to operate at different (adjacent) frequencies can be used to increase frequency coverage

Submm QCLs must be cooled to 10 -12 K (sometimes higher); dissipate significant DC power but provide 200 – 500 mW while providing 200 – 1000 μW submillimeter power



Kloosterman et al. (2013)
QCL dissipates 700 mW @ 10 K

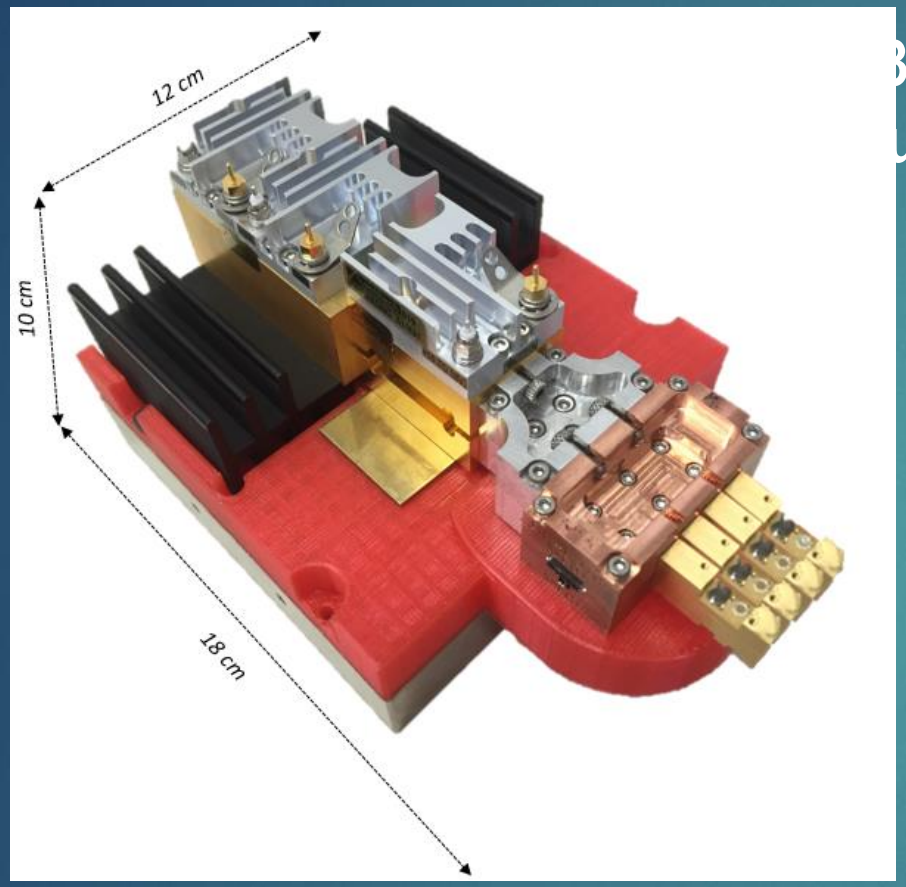


Frequency locking: Ren et al. (2012)
Phase Locking: Rabanus et al. (2009)

QCL used as LO for HFA channel of 7-element upGREAT receiver on SOFIA

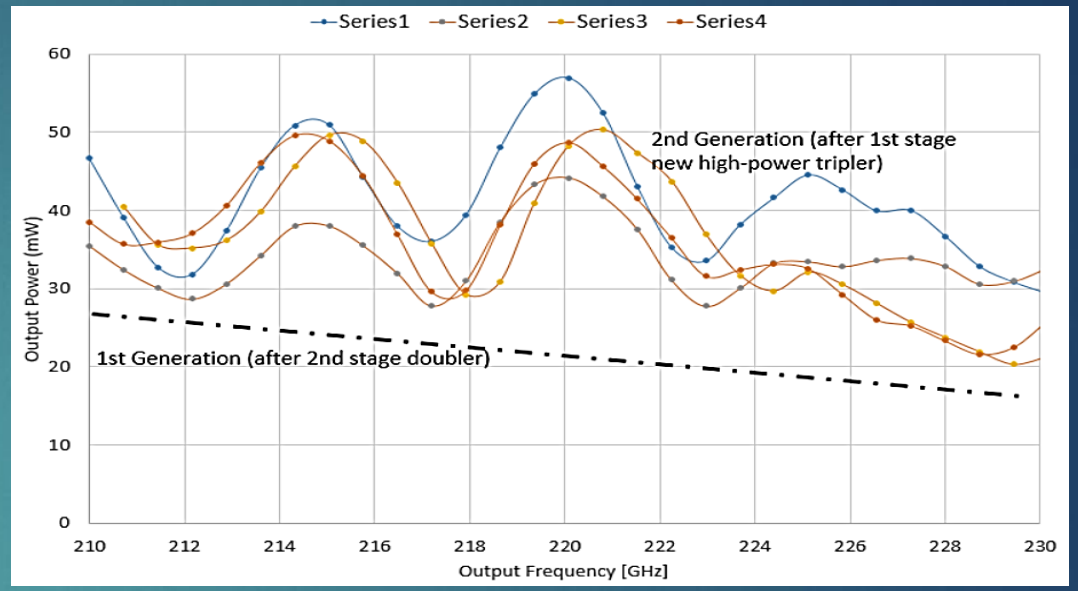
Risacher et al. (2011); Richter et al. (2015)

2nd-Generation 1.9 THz 4-Pixel LO system



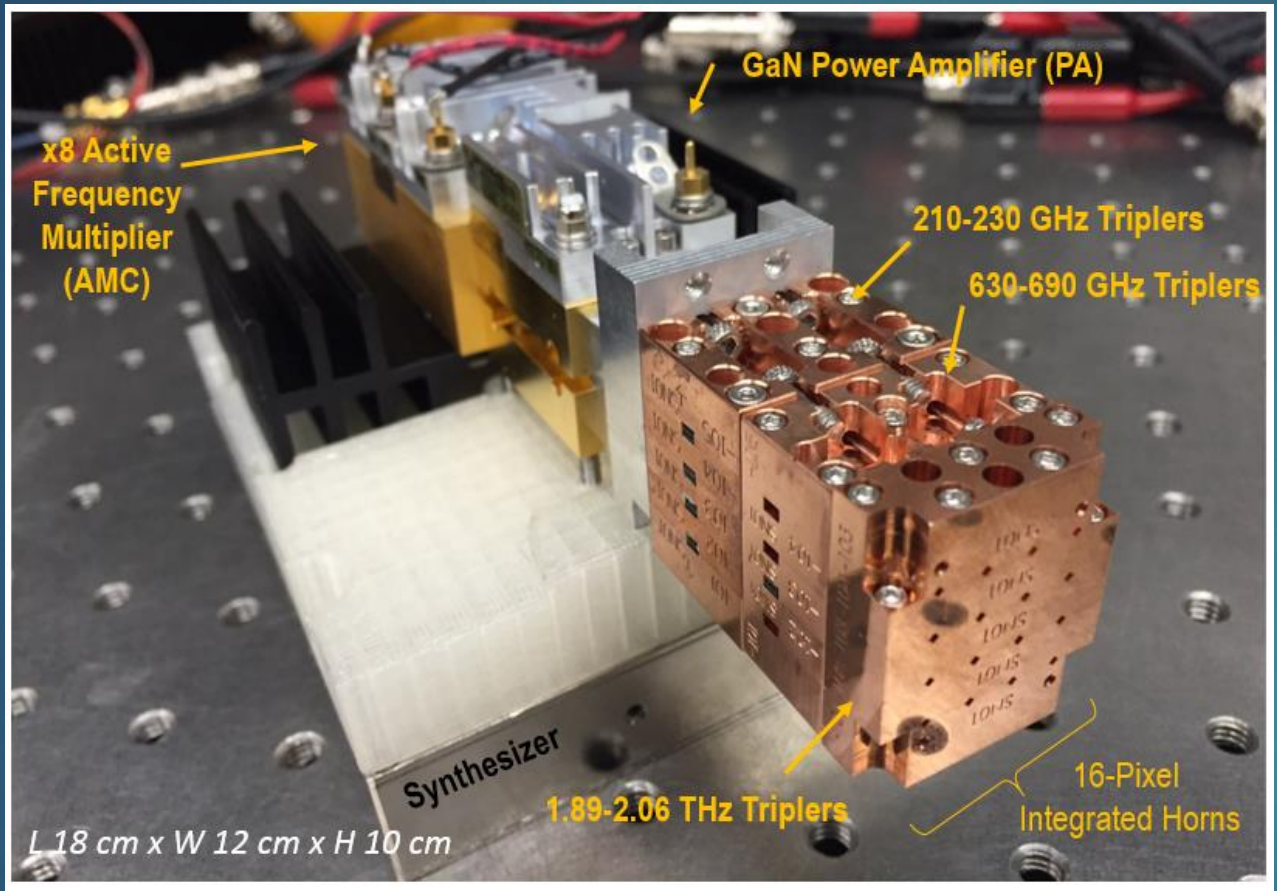
2nd Generation 1.9 THz 4-Pixel Frequency Multiplied Chain

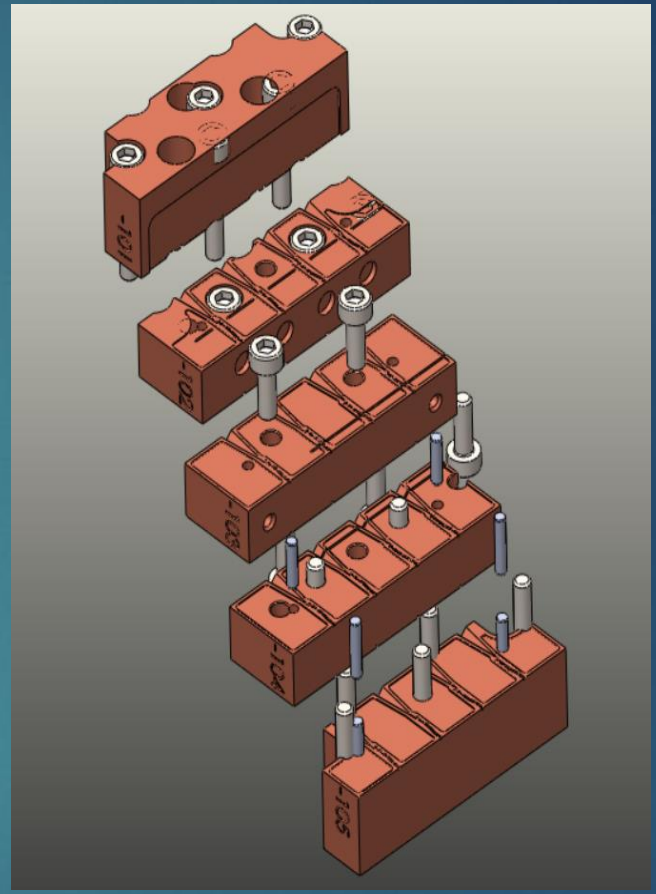
Power Consumption= 5.5 Watts/pixel



Main improvements relative to 1st generation are (i) compactness and (ii) increase in power delivered at the output of the X3 1st stage (Gen 2) compared to the output of the X3X2 stage in Gen 1.

16-pixel 1.9 THz lo system: STACKING





The LO module can be mounted with either two or four 1x4 pixel layers vertically stacked to form 8-pixels or 16-pixel configurations..

X3X3X3 Architecture

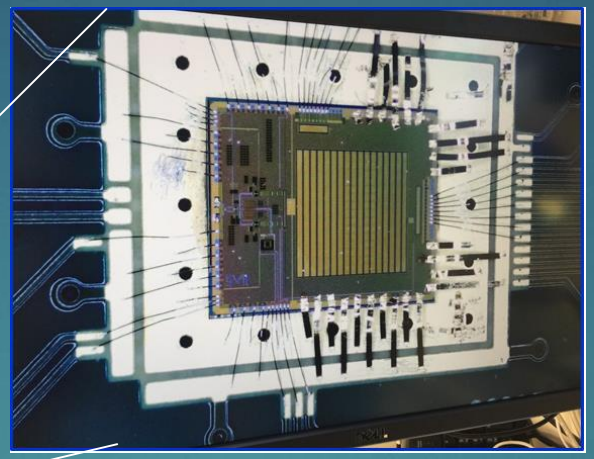
Power Consumption= 2.3 Watts/pixel or
1.25 Watts/pixel using W-band CMOS synthesizers

Reduced Power Consumption and Improved Performance for Arrays

Digital CMOS ASIC Spectrometers

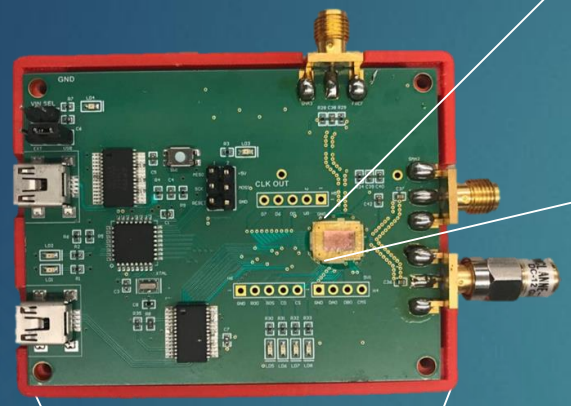
- Current FPGA spectrometers require 10-20 W/pixel for ~3 GHz bandwidth 4 kchan spectrometer required for high-efficiency submillimeter spectroscopy
- A 100 pixel FPGA spectrometer is MARGINAL for SOFIA and prohibitive for space mission
- **Custom ASIC System on Chip (SoC) can reduce this power by an order of magnitude** NOW, with further improvements expected in the future
- JPL has been pushing ASIC development through effort led by Adrian Tang
- This avenue must be pursued to enable centopixel and ultimately kilopixel spectroscopic arrays in space

CMOS ASIC Spectrometers



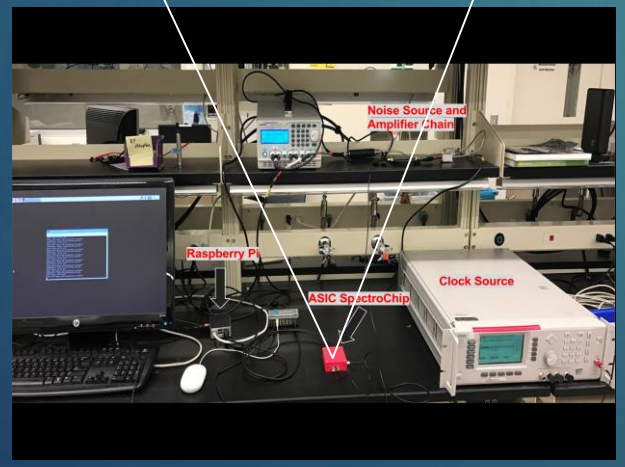
RF Input

USB Output



SVII Chip
4096 chan.
3 GHz BW

Includes A/D converter, spectrometer, memory, USB output

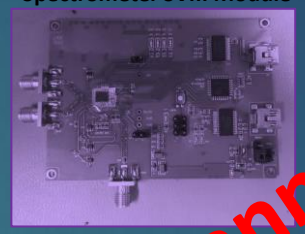


Test setup at ASU
SURP 2017

UCLA High-Speed Electronics Laboratory

Spectrometer S-VIII

Spectrometer SVIII Module



System-on-Chip

Planned Chip

Absolute Maximum Electrical Ratings

Parameter	Minimum	Typical	Maximum	Unit
RF Input Power	-3	0	+3	dBm
Clock Input Power	-3	0	+3	dBm
V18	1.7	1.8	2.0	V
VDD	0.95	1.00	1.10	V
Idle Mode Current	-	450	700	mA
Running Mode Current (1.0V)	-	1150	1400	mA
Running Mode Current (1.8V)	-	1	2.5	mA

Electrical Parameters

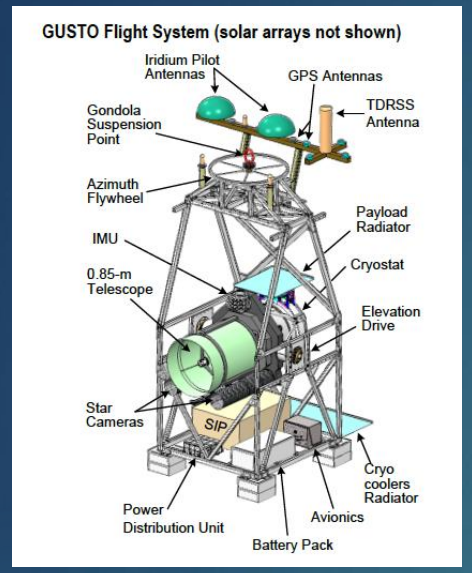
Parameter	Minimum	Typical	Maximum	Unit
Clock Frequency	1	-	12000	MHz
Aliasable Bandwidth	-	-	15000	MHz
Interleaving Factor	-	2	-	X
Physical Number of Bits	-	3	-	bit
Signal to Quantization Noise Ratio	14.2	16.8	19	dB
Number of FFT Channels	-	4096	-	#
Windowing Type	-	Hanning	-	-
Input Format	-	Differential	-	
Output Format	-	USB 2.0	-	-
MultiPixel Synchronization	-	TTL Trigger	-	-

Specifications subject to change without notice

12/5/2017 Revision 3.00-A

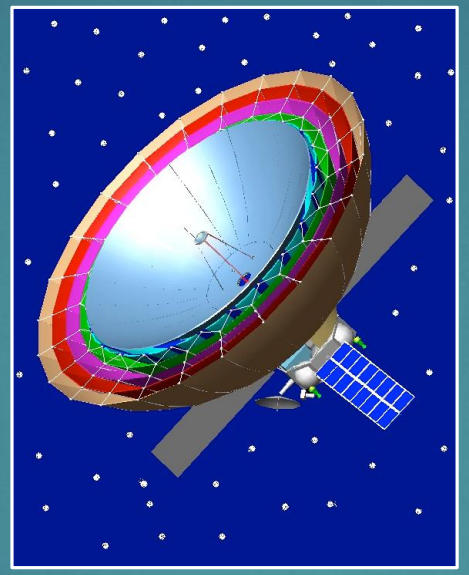
SVIII Chip –
6 GHz BW is one possibility

Near-Term and Future Facilities for Submillimeter Spectroscopy

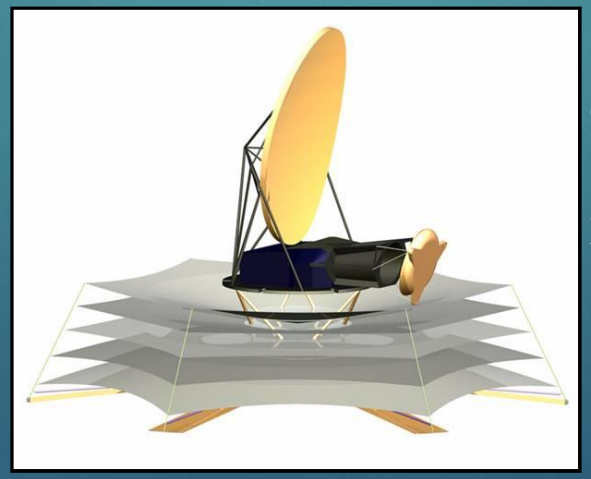


GUSTO
Ultra Long Duration Balloon (100d)
24 HEB mixers at 1460, 1900, and 4745 GHz
Launch Dec. 2021

ASTHROS
reuse BLAST 1.8 m telescope
J. Pineda (JPL) PI – 2021
Both [NII] F.S. lines

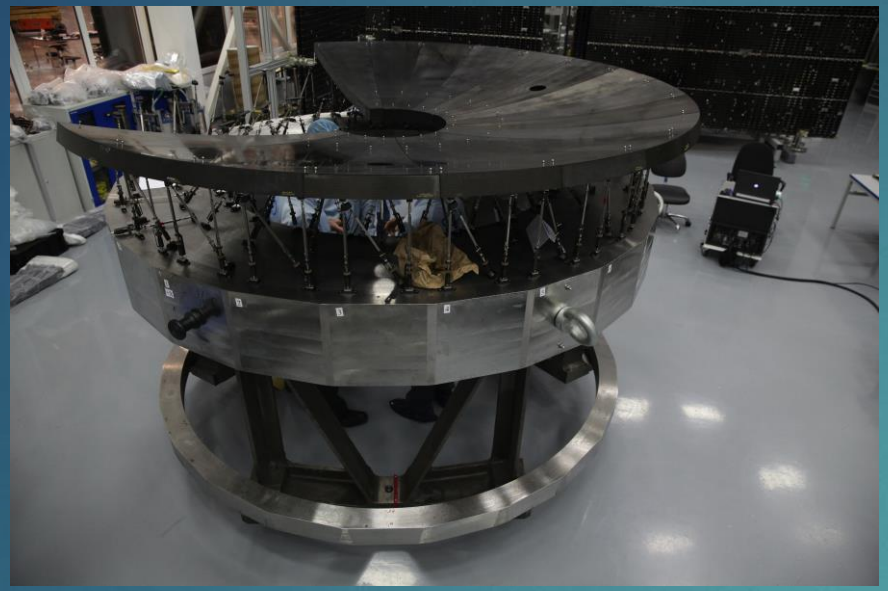


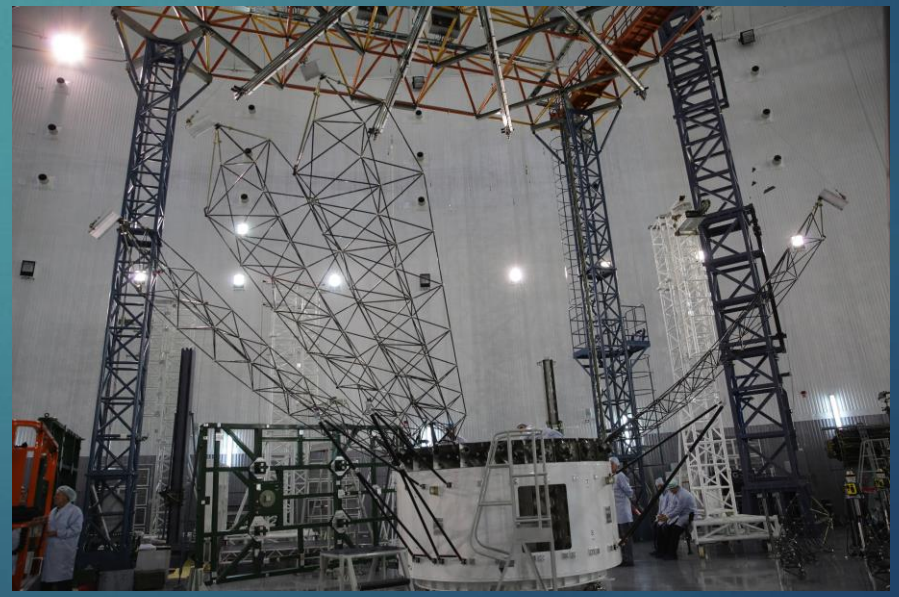
Millimetron (Russia)
10m Deployable Antenna cooled to 6 K
Earth-Space VLBI
Heterodyne spectroscopic instrument TBD

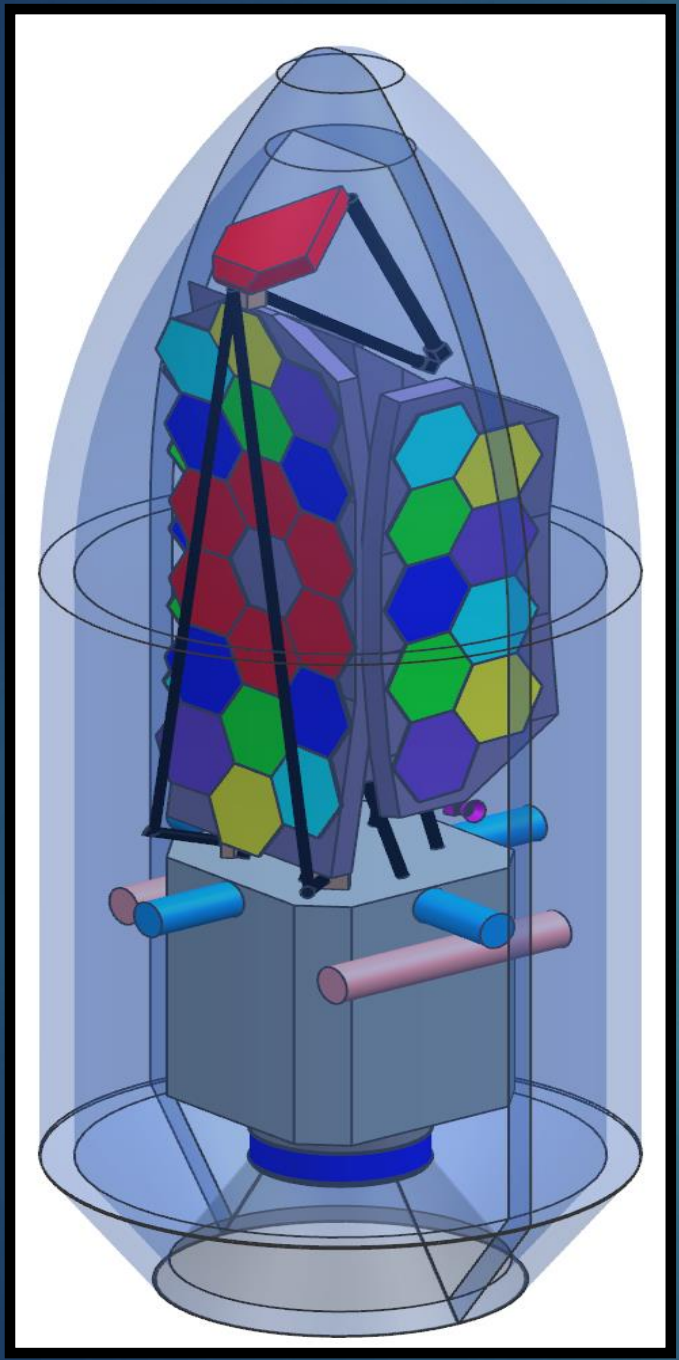


Origins Space Telescope (OST)
6 – 10 m dia. Telescope cooled to < 6 K
2020 U.S. Decadal Study Flagship Mission
Possible heterodyne instrument "HERO"

Millimetron Development







Thanks to Otto Polanco for graphics

The Future: ISM Probe Mission Concept

IMAGE the extended interstellar medium of the Milky Way and nearby galaxies in H_2O, CO, and key fine structure lines to probe the life cycle of the ISM

6-7m dia. Cassegrain fits in shroud of Falcon 9 Heavy

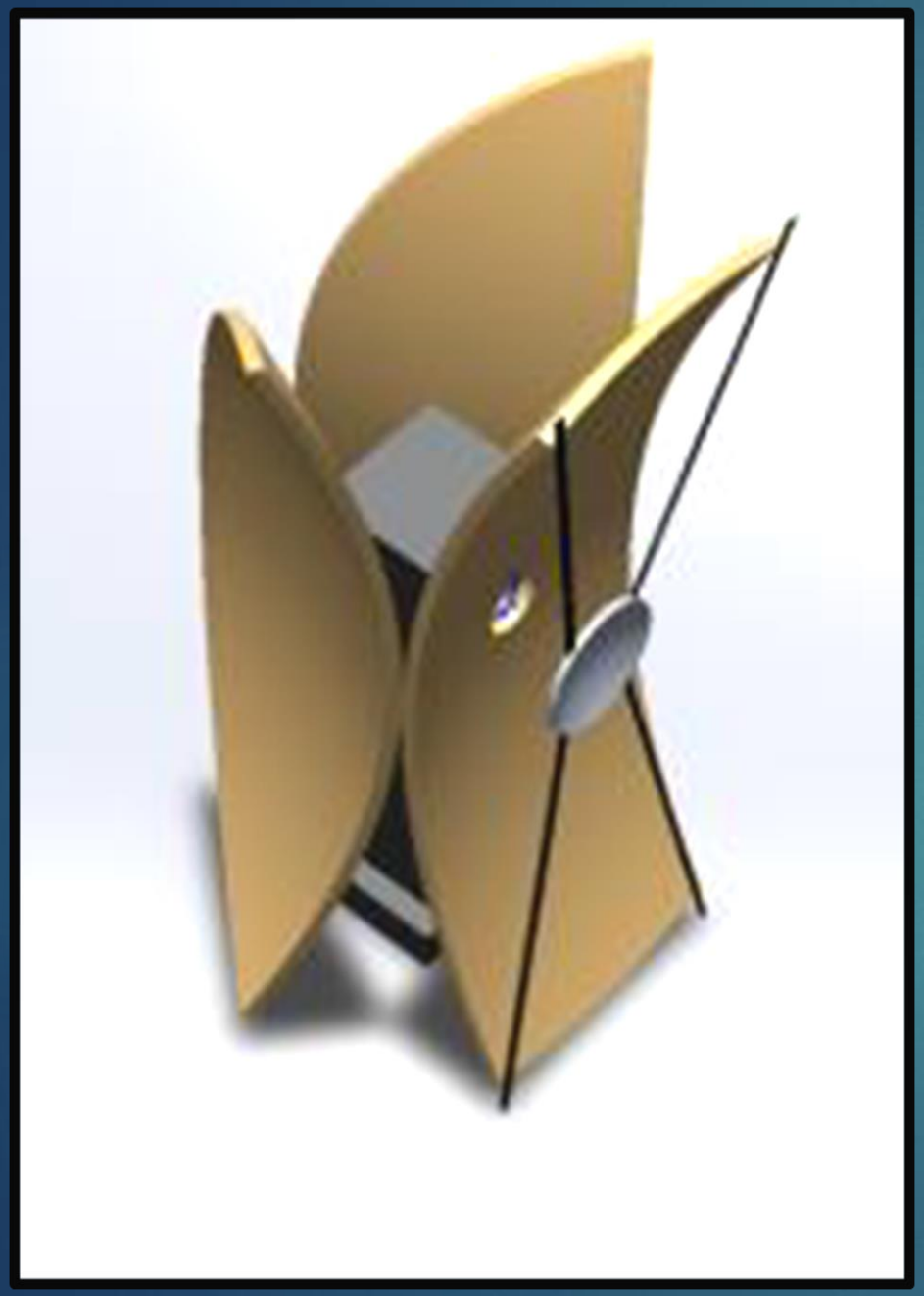
This version employs 36 ~1m hexagonal panels

NOT NECESSARY TO COOL THE TELESCOPE

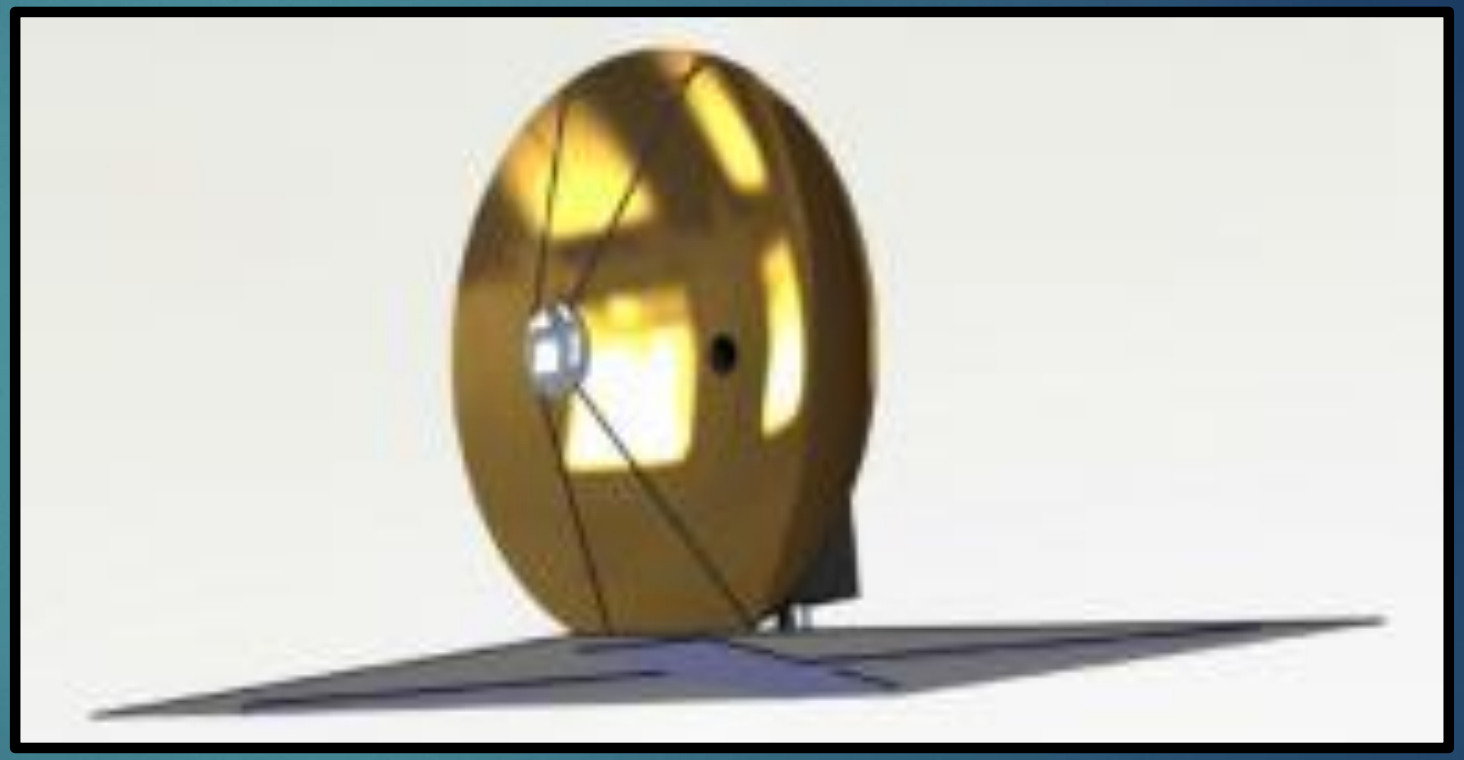
Limiting minimum wavelength to 250 μm means that accuracy requirement is 100x less demanding than JWST

Possible materials include SiC (as Herschel) but could also be made of carbon fiber core + aluminum skins

Pre-Decisional Information -- For Planning and Discussion Purposes Only



Deployable Quasi-Monolithic Telescope Structure



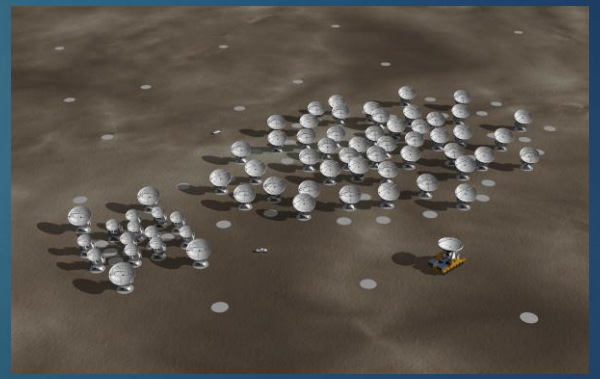
10m x 12m single-layer sunshade with solar panels on lower side

Submillimeter Heterodyne Interferometer Concept

- Need many telescope to give good uv-plane coverage and high-quality images
- Individual telescopes of modest (~5m) aperture to give substantial field of view that overlaps with resolution of single telescopes
- A "swarm" of telescopes in space for source observations plus additional satellites to carry out correlations and calibration

250 - 5m telescopes in 250m diameter region give ~10% filling factor

Angular resolution = 0.1" at λ = 112 μm – resolve distribution of gas (HD) in protostellar disks and distribution of water in forming solar systems. Configuration can be enlarged when needed/possible



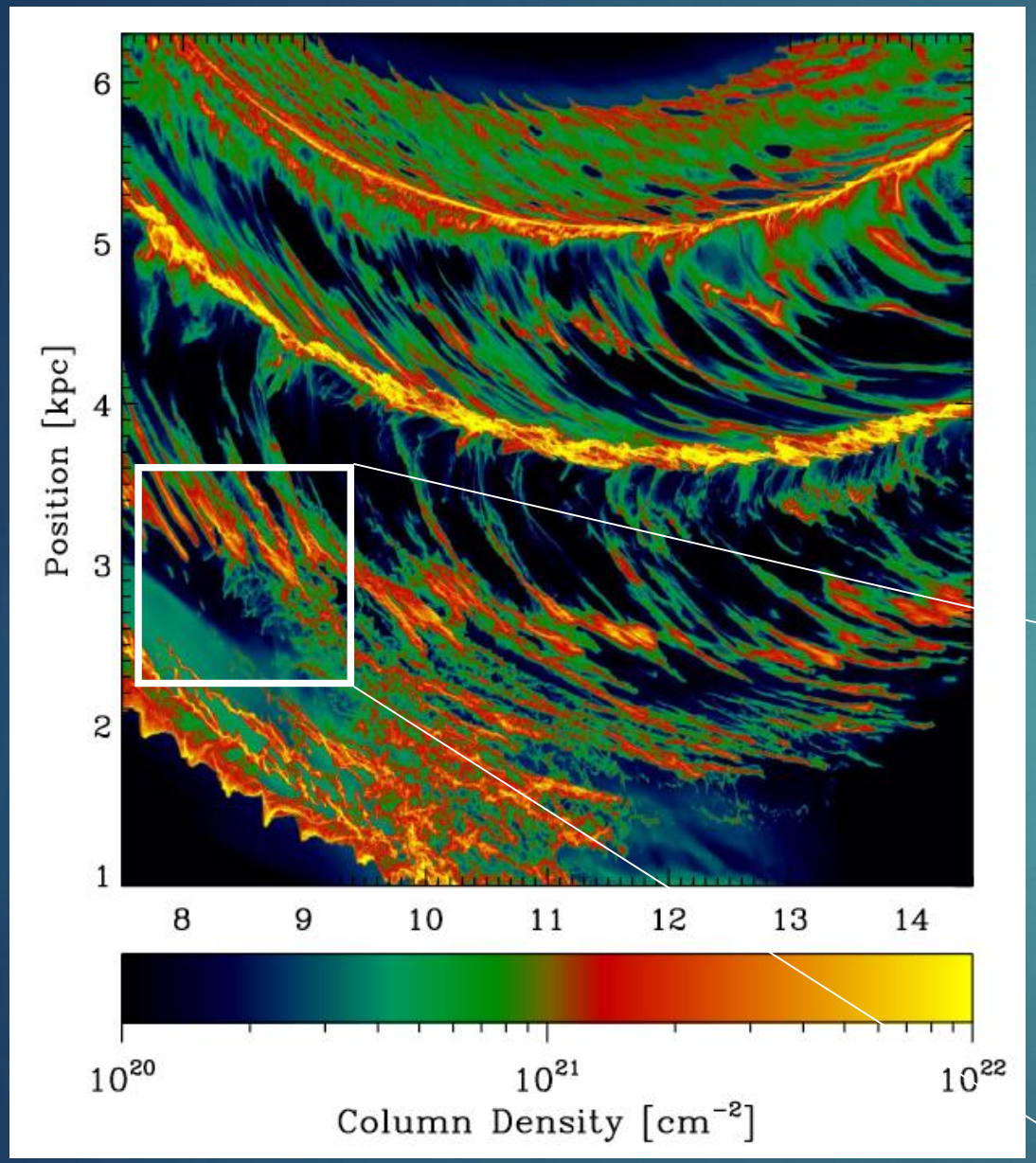
ALMA IN SPACE

Total effective area ~ 550x Herschel

- Station-keeping requirements are modest and baselines can be measured by calibration observations

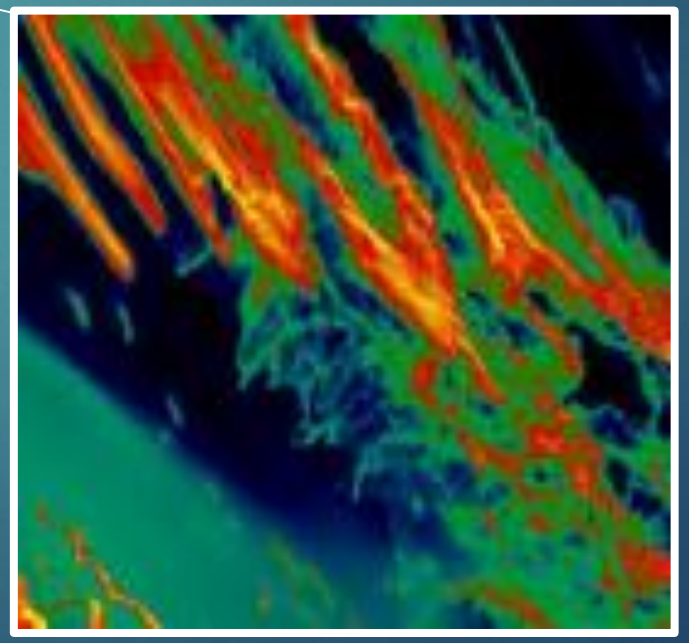
Pre-Decisional Information -- For Planning and Discussion Purposes Only

Submillimeter Heterodyne Inteferometer: Imaging Spiral Arm Spurs



Simulation of Milky Way disk Smith: + 2014

Enhanced C+ due to efficient photoionization along short axis having low extinction.
Major contributor to CO-dark molecular gas
Mass reservoir for star formation
"Input" to spiral arm shocks



Spur width = 10 pc @ M51 (D = 7.1 Mpc)
θ = 0.3"

Narrow line widths ~ few km/s (total)

The Renaissance of High Resolution Astronomical Spectroscopy- Summary

- Submillimeter spectroscopy allows observation of key tracers of **star formation**, the **water trail**, and properties of **solar system objects**
- High spectral resolution allows measurement of motions within star-forming cores, protoplanetary disks, and solar system objects
- A variety of platforms above the Earth's atmospheric water vapor – airborne, balloon, and in space now enable observations at **all** submillimeter wavelengths
- Technological progress in heterodyne systems now allows wide range of wavelengths to be observed with **high sensitivity** and **spectral resolution**
- Local oscillator, SiGe amplifier, and ASIC technology are opening up the possibility of **truly large—format heterodyne focal plane arrays**
- Today's observing platforms are impressive but **higher sensitivity and angular resolution are still wanted!**