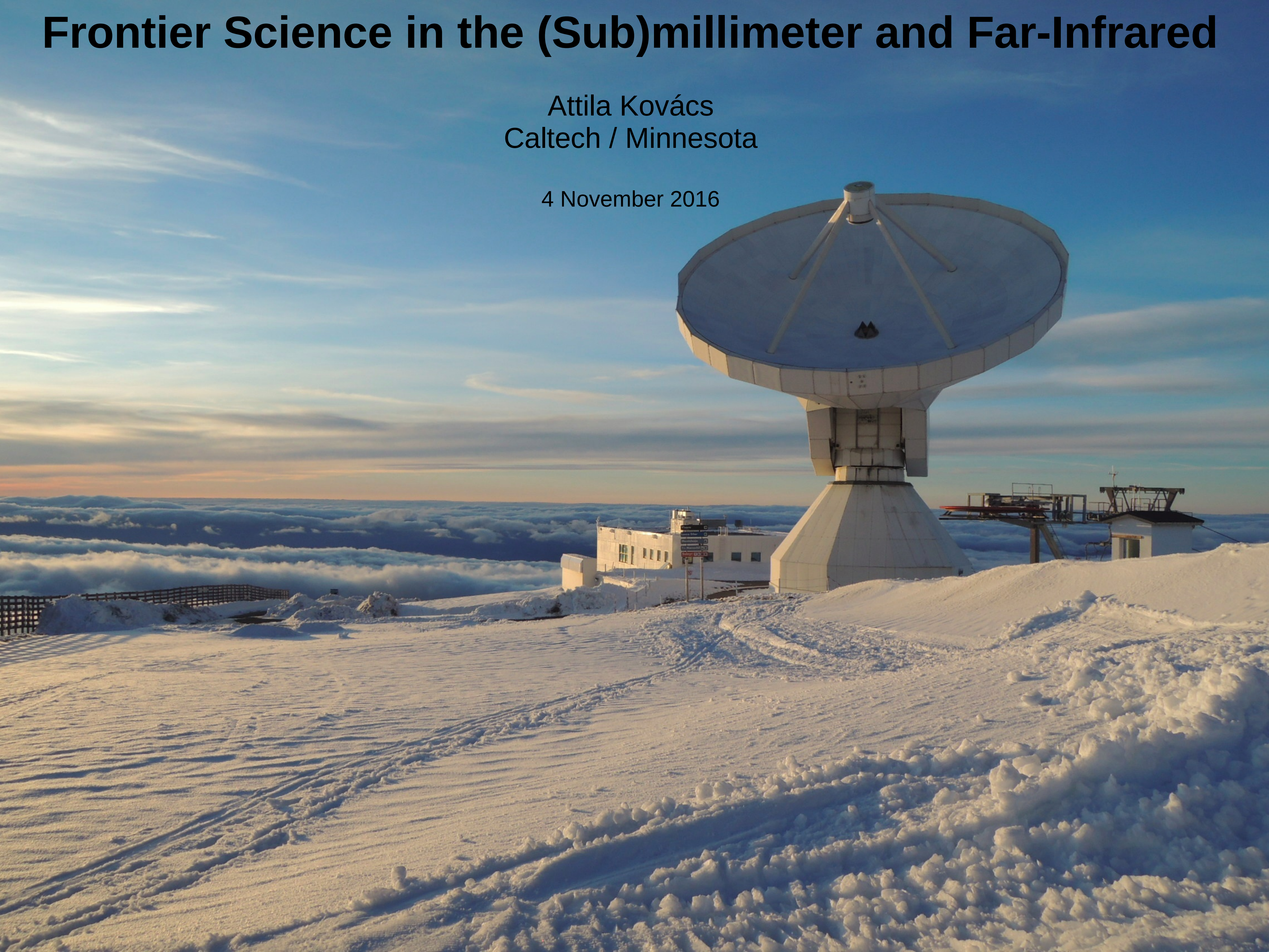
Frontier Science in the (Sub)millimeter and Far-Infrared

Attila Kovács
Caltech / Minnesota

4 November 2016



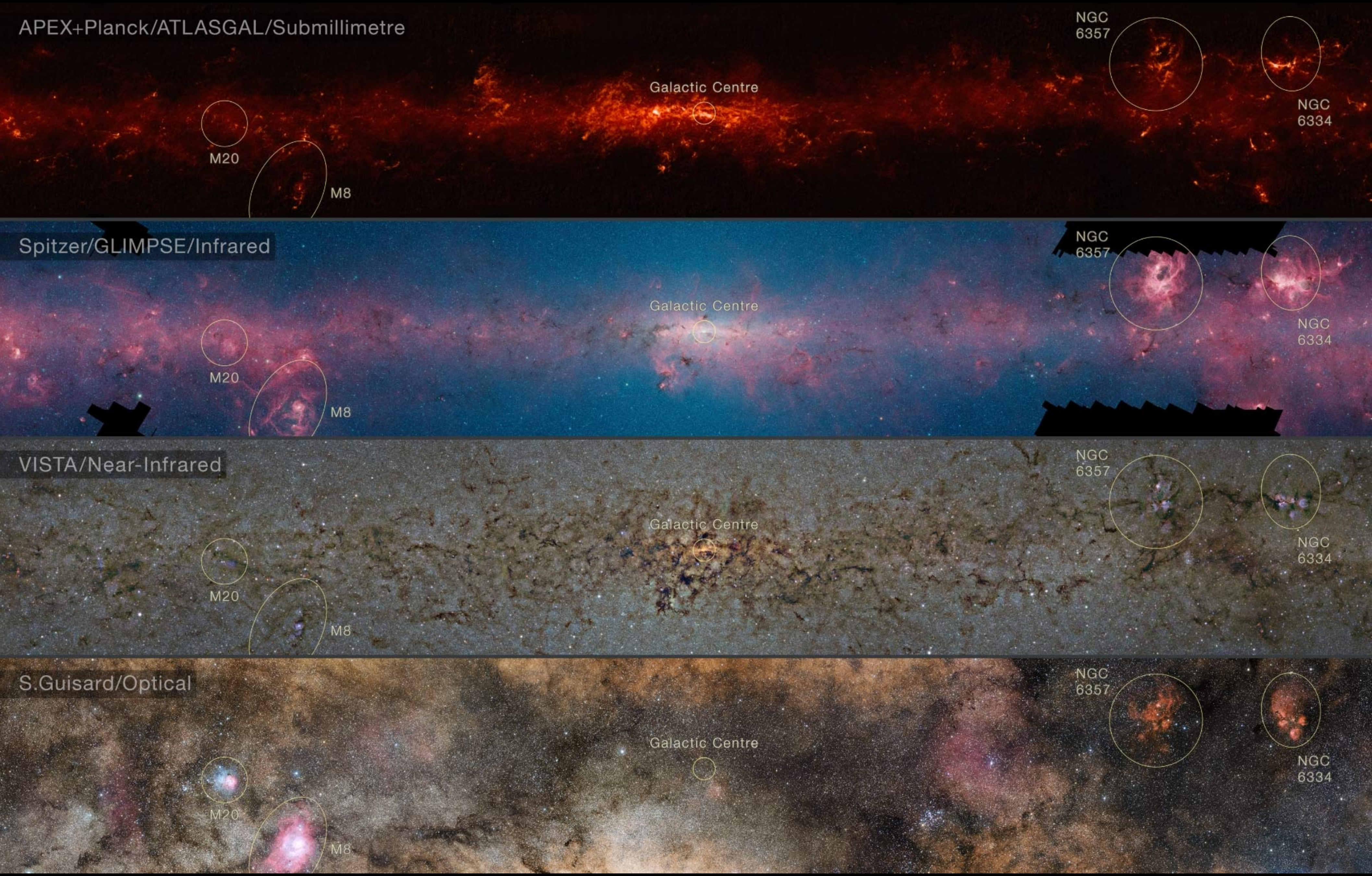
FIR / (sub)mm specialties

Ongoing star formation

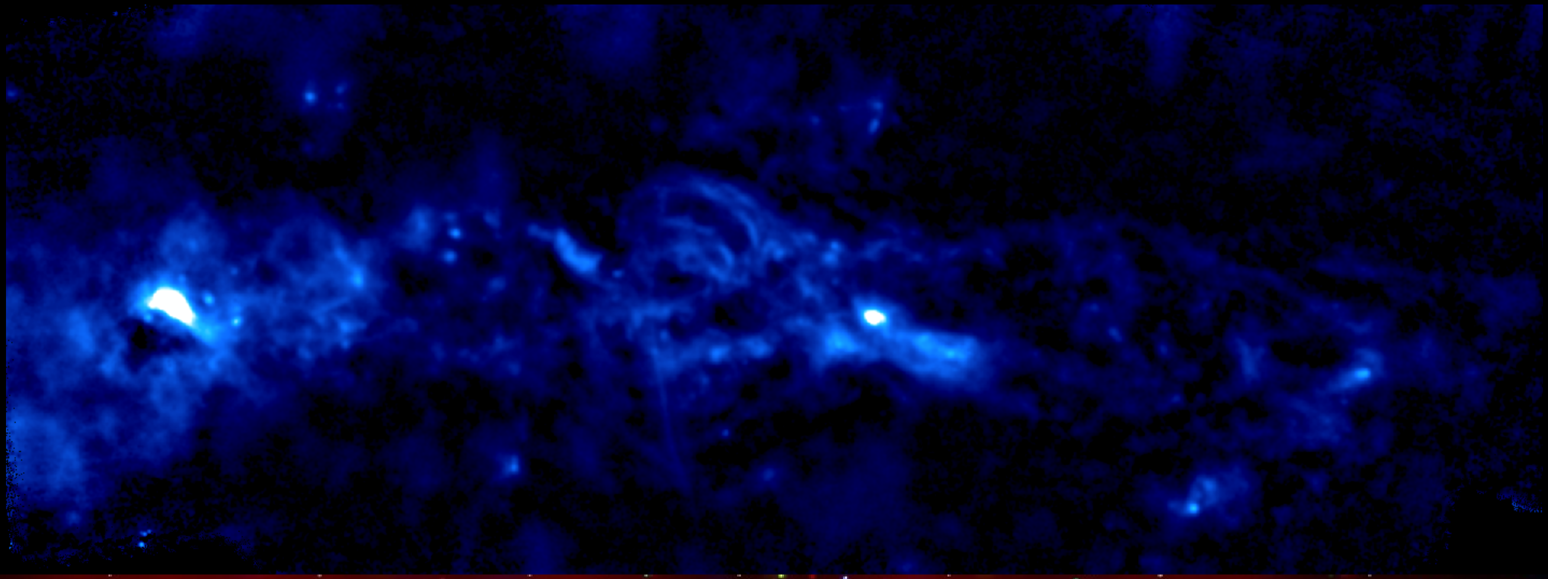
Structure formation / evolution

Flat selection

FIR / (sub)mm vs other bands



FIR / (sub)mm vs X-ray



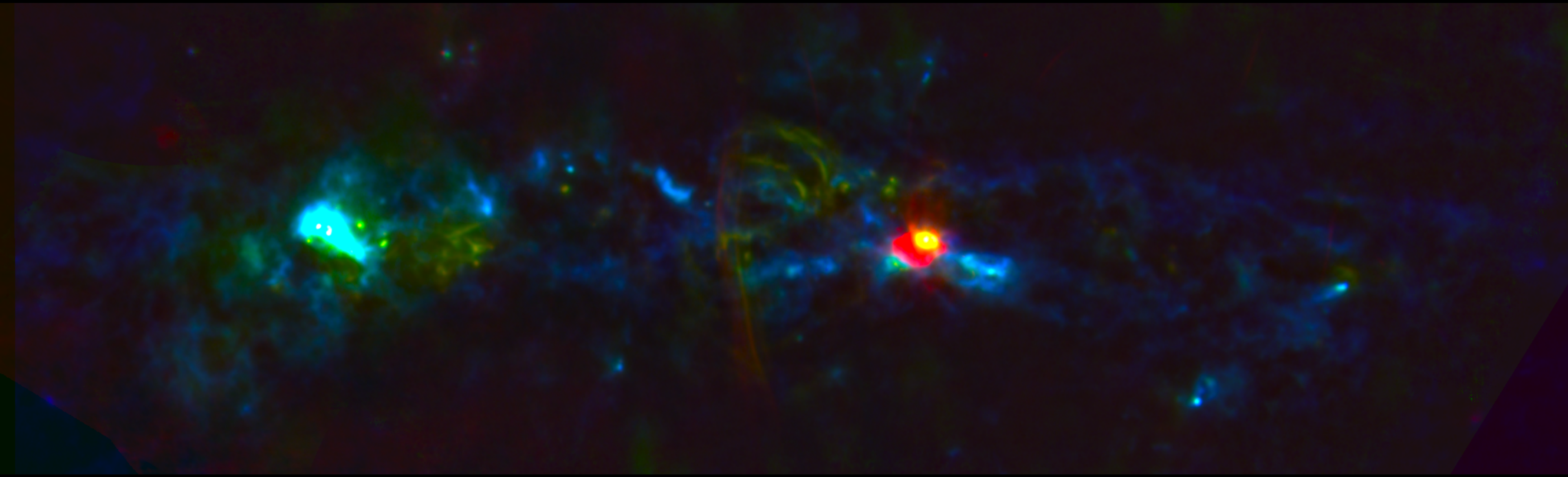
IRAM / GISMO 2 mm
reduced by CRUSH

Galactic Center in radio / (sub)mm

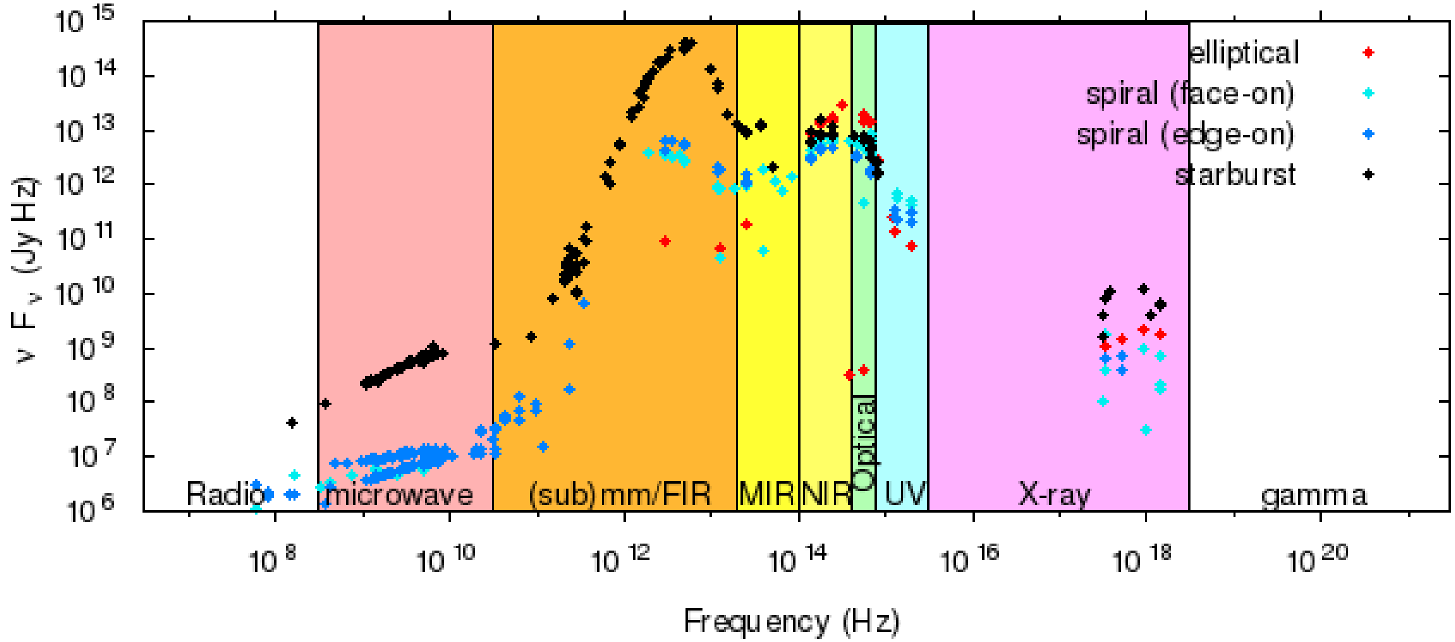
VLA 1.4 GHz

IRAM / GISMO 2 mm

APEX / LABOCA 870 um



Galaxies

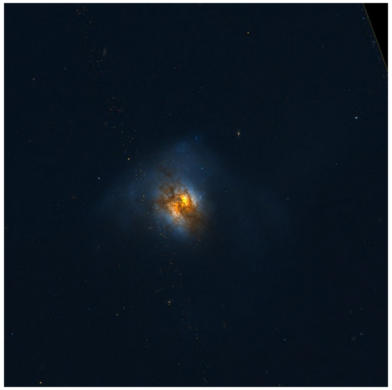


NGC 4365

E6 elliptical

M 66
NGC 3627

NGC 253

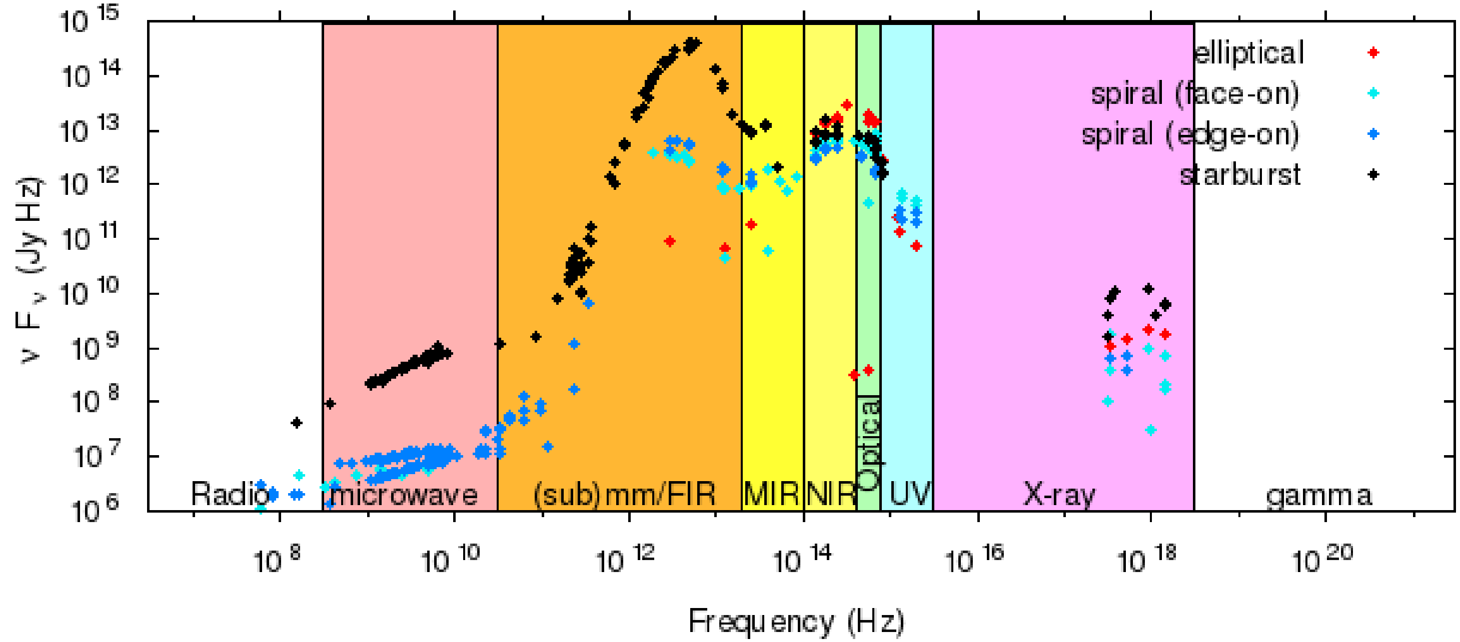


Arp 220

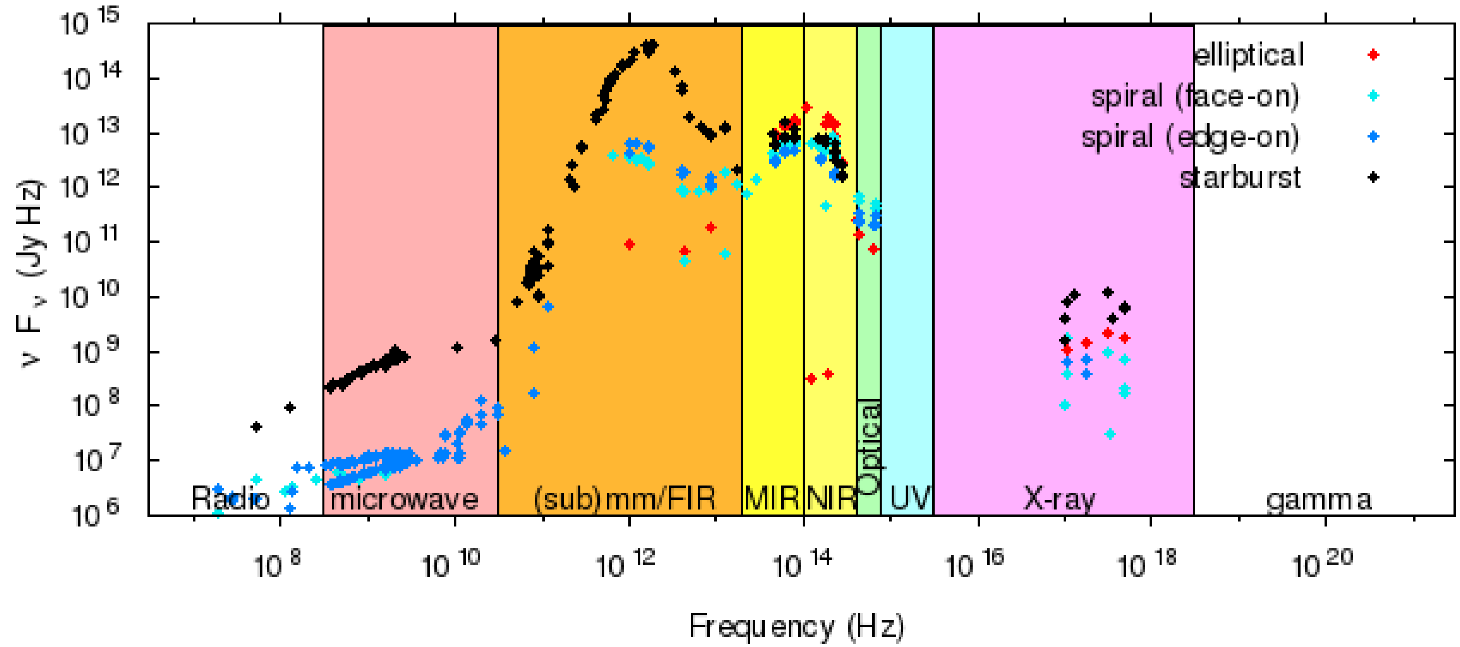
starburst

Galaxies

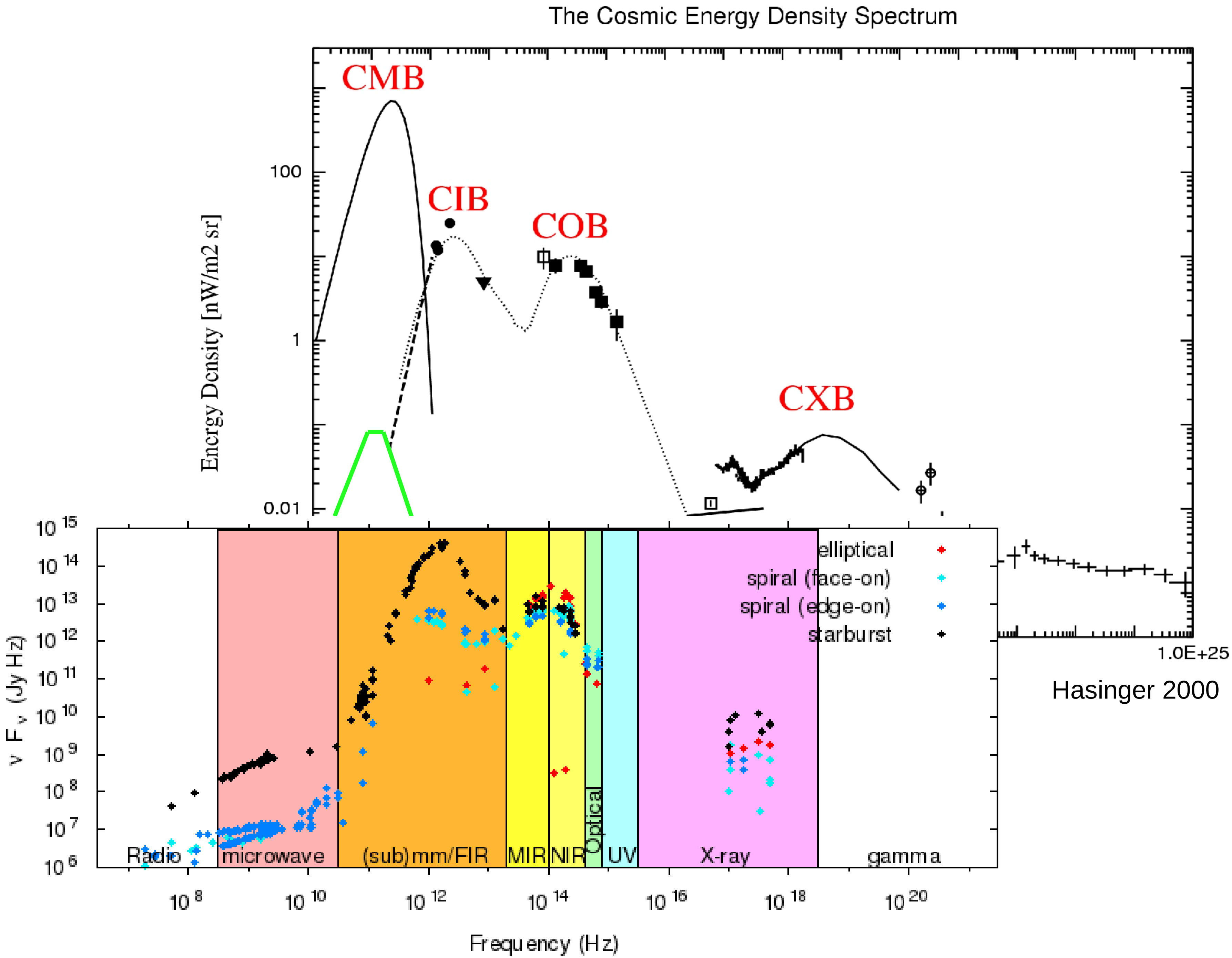
***z* = 0**



***z* = 2**

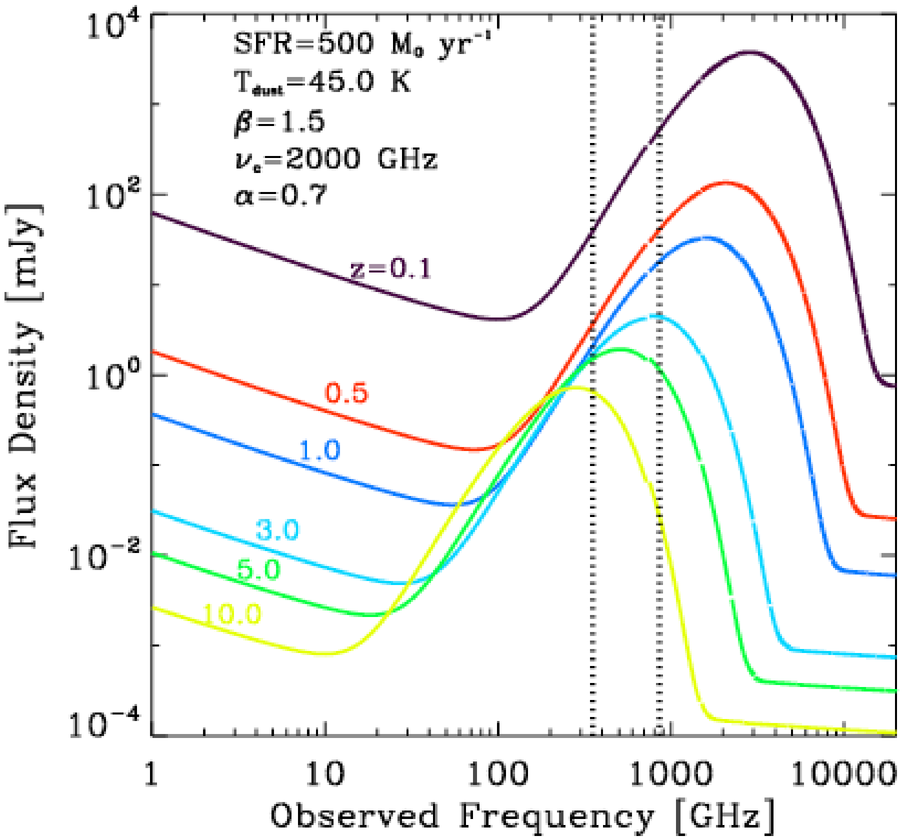


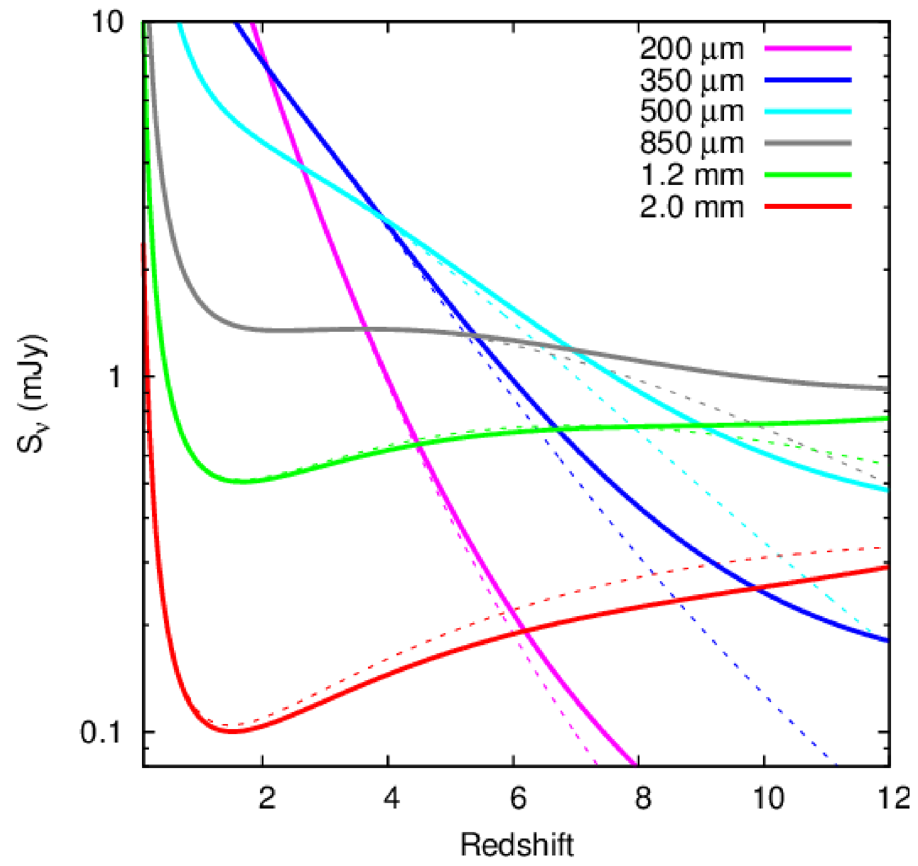
Cosmic backgrounds



Hasinger 2000

Flat selection I: high-z galaxies





Plan

recent → future

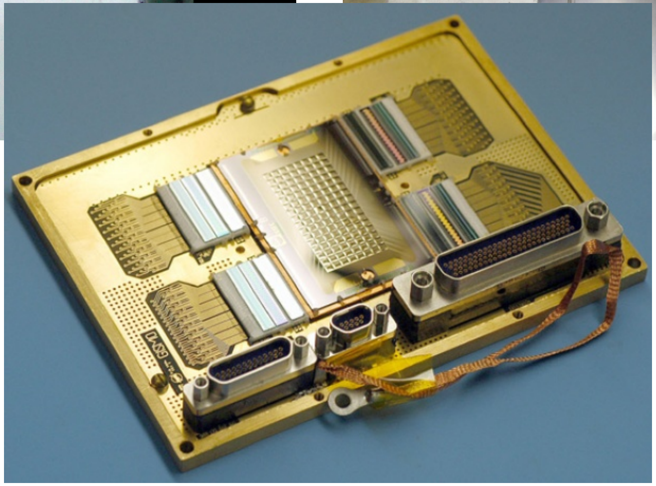
mm-wave → far-infrared

astrophysics → instrumentation

extragalactic → Galactic

GISMO @ IRAM 30m

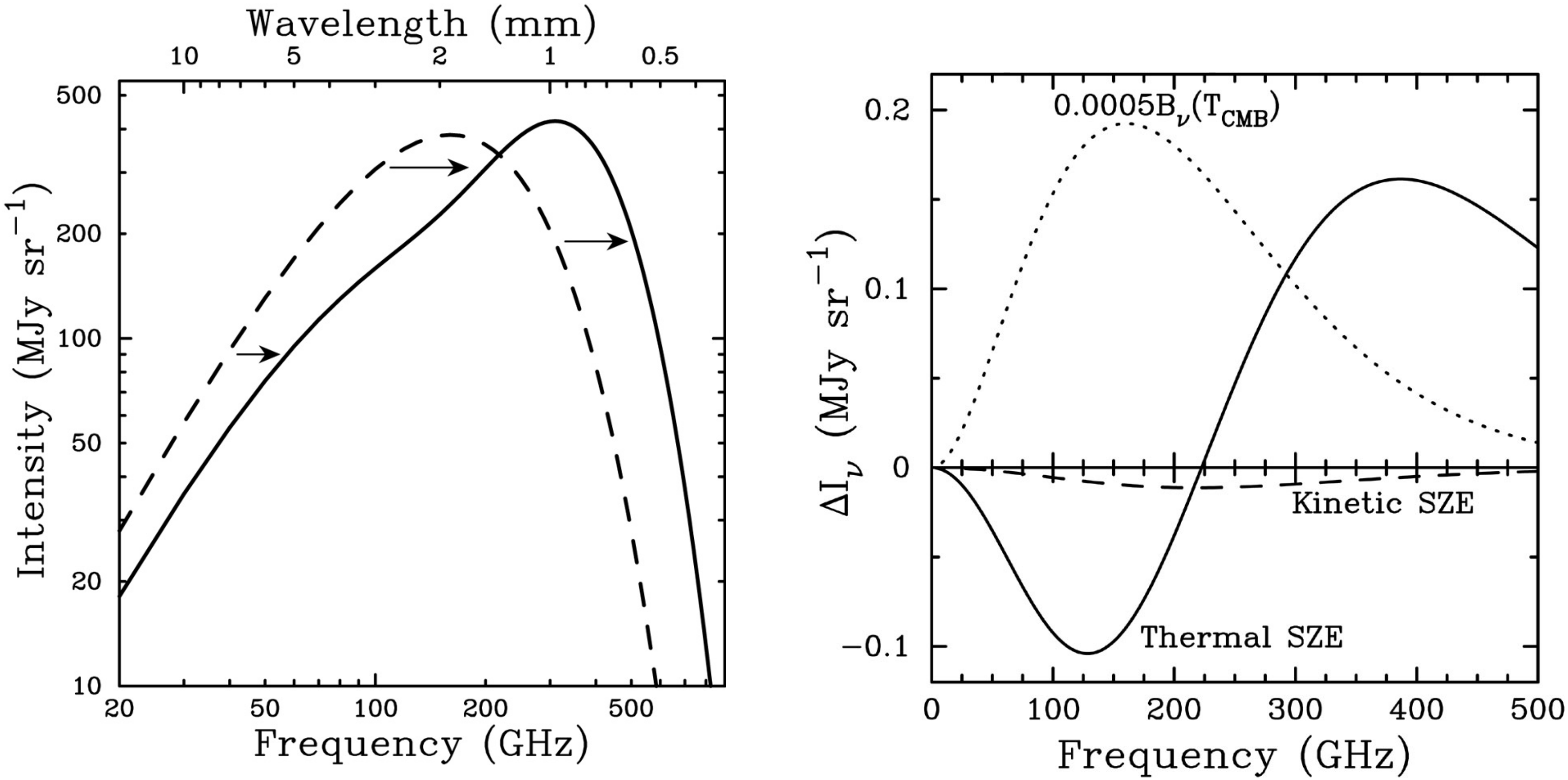
GISMO



Staguhn et al. 2008

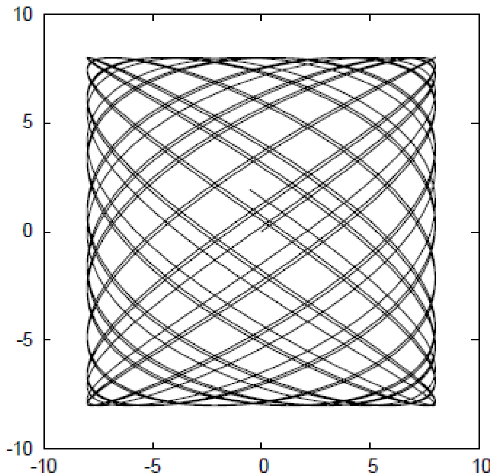
IRAM 30m

Flat selection II: Sunyaev-Zel'dovich effect

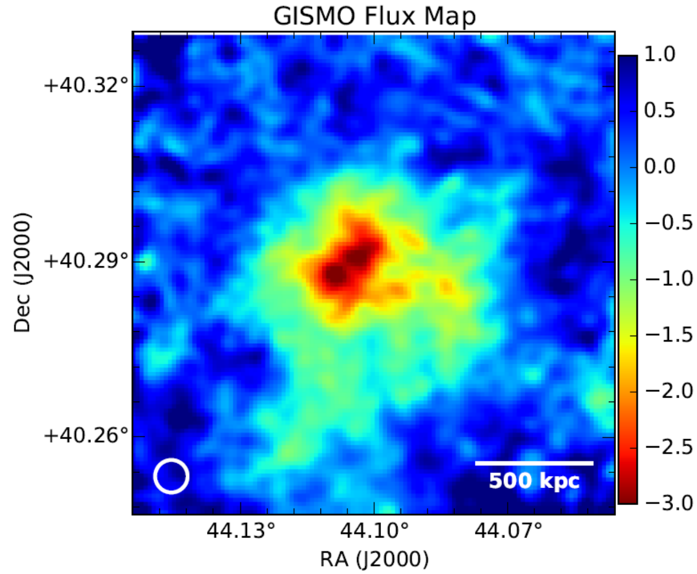


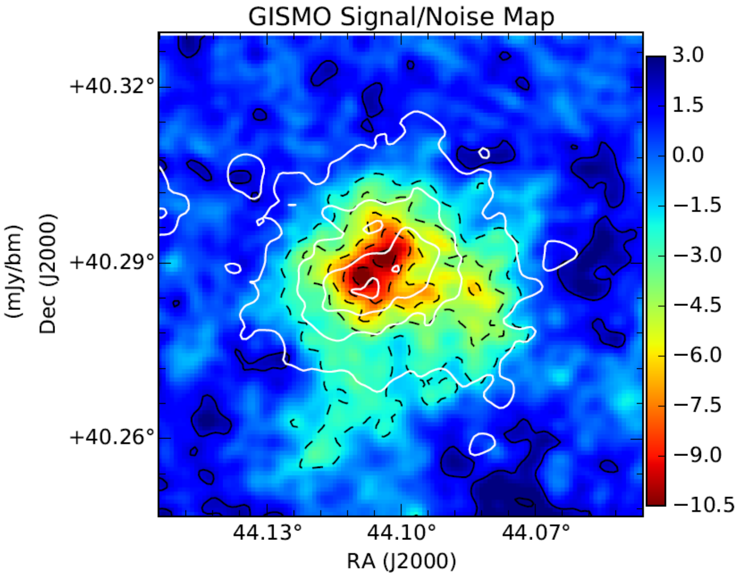
SZ Clusters with GISMO: PLCK G147.3-16.6

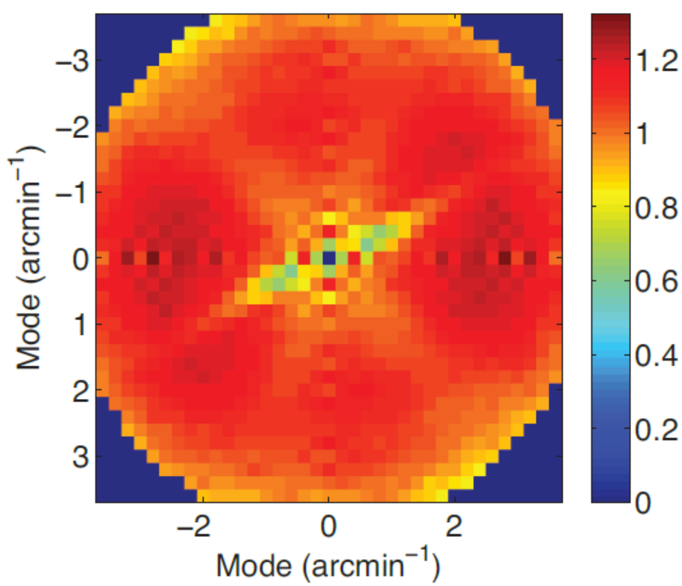
Mroczkowski, Kovács, et al. (2015)

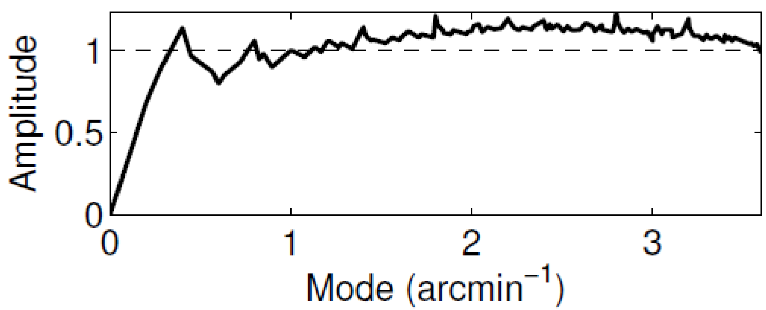


Kovács 2008b

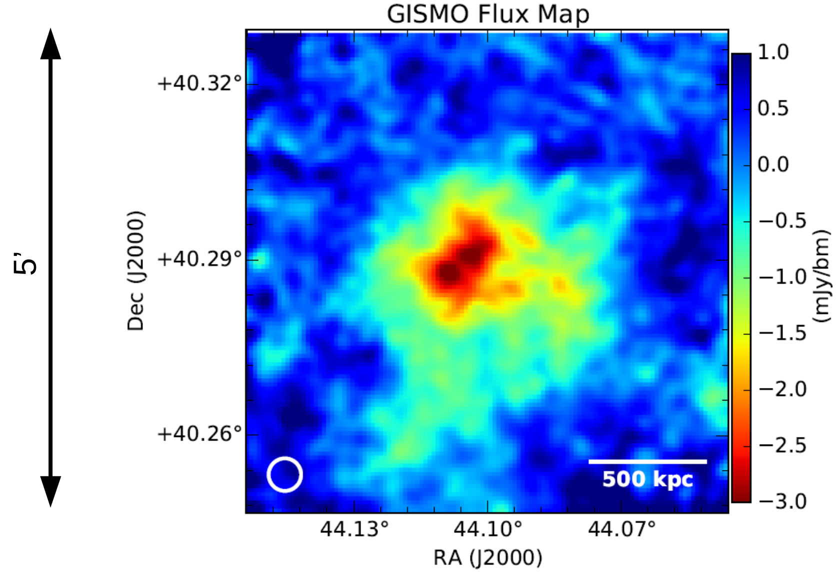


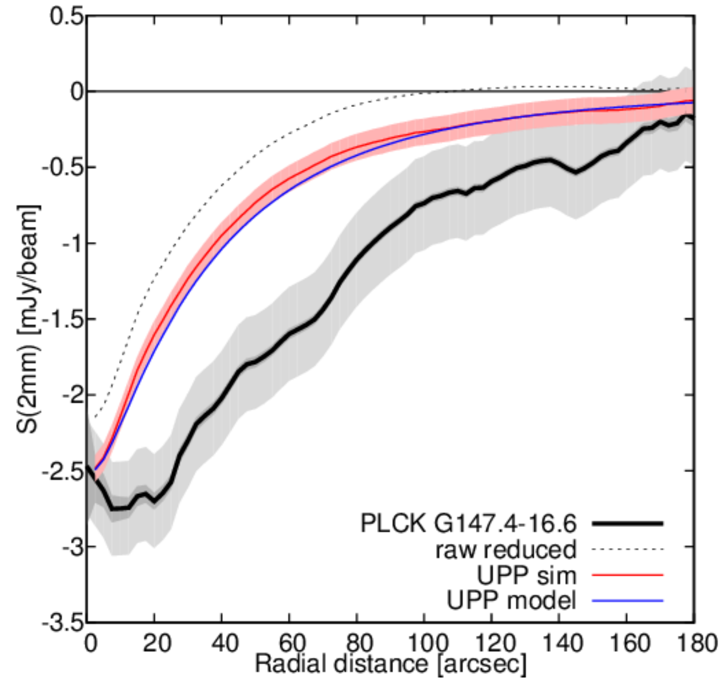


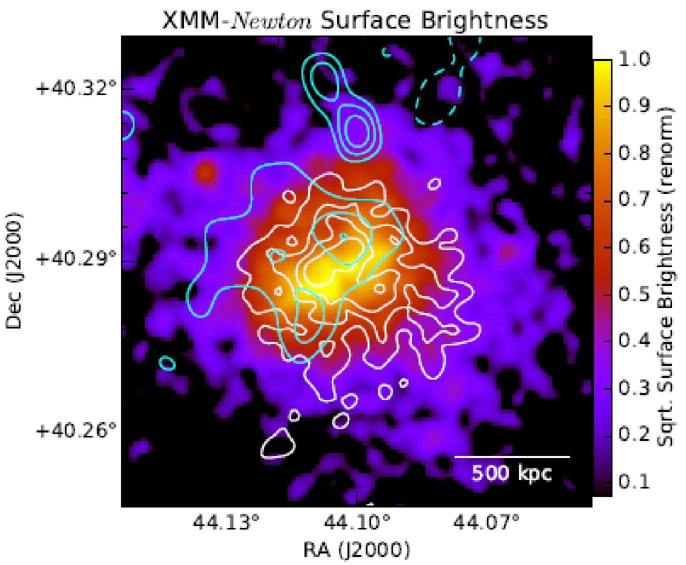


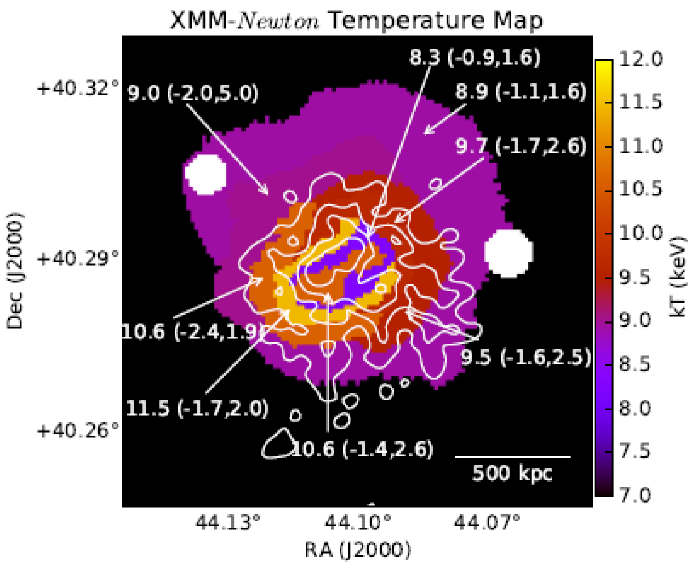


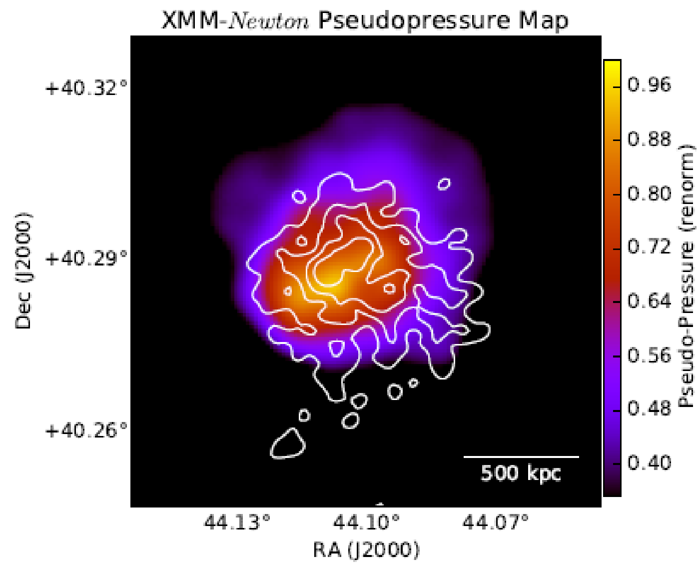
SZ Clusters with GISMO: PLCK G147.3-16.6

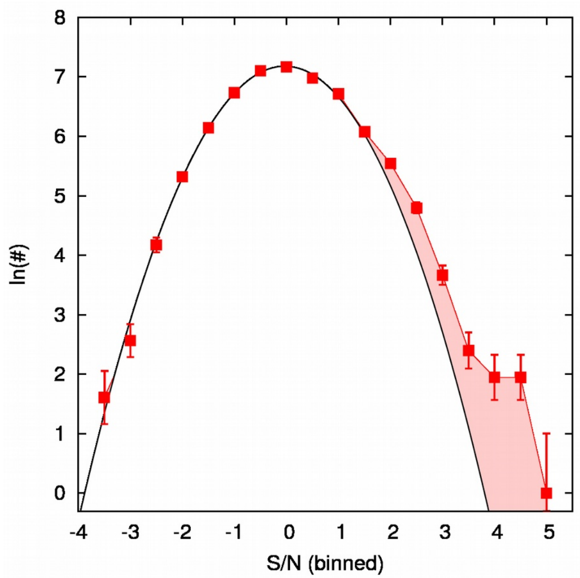












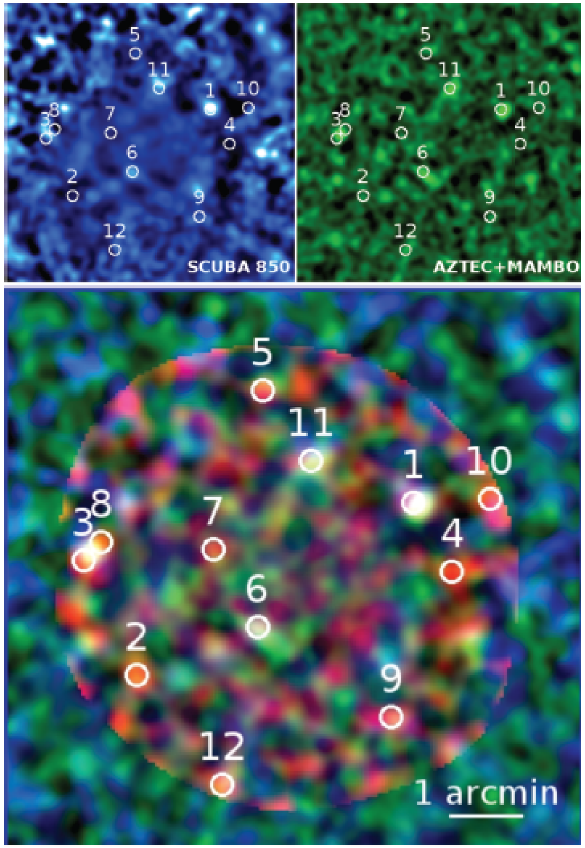
~35 hours

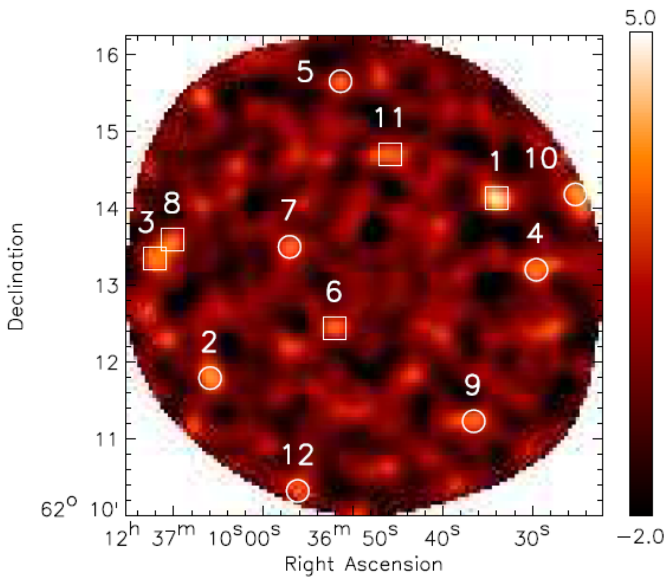
4’ diameter

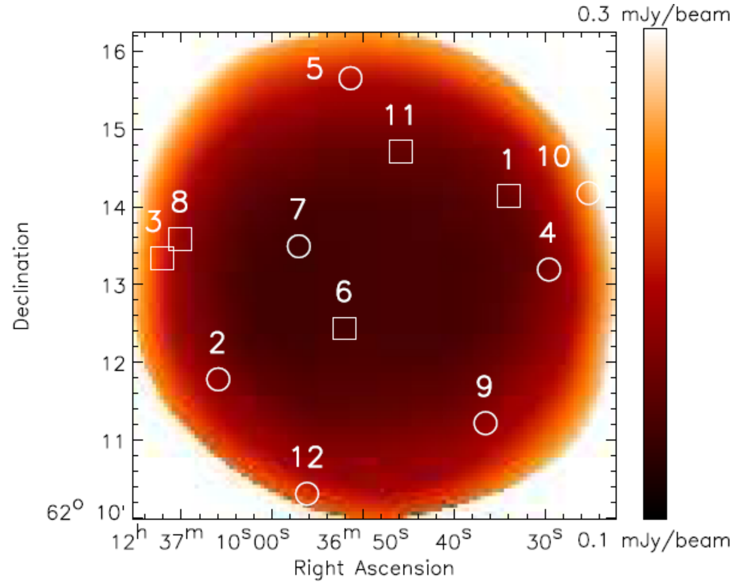
~120 uJy depth

approaching confusion

Staguhn, Kovács, et al. 2014

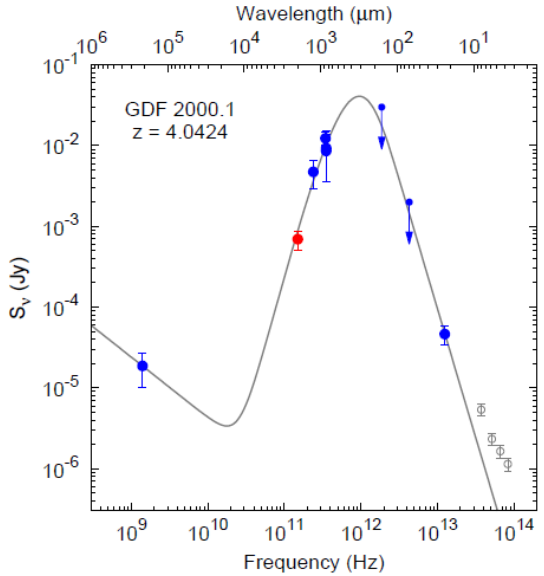






The GISMO Deep Field

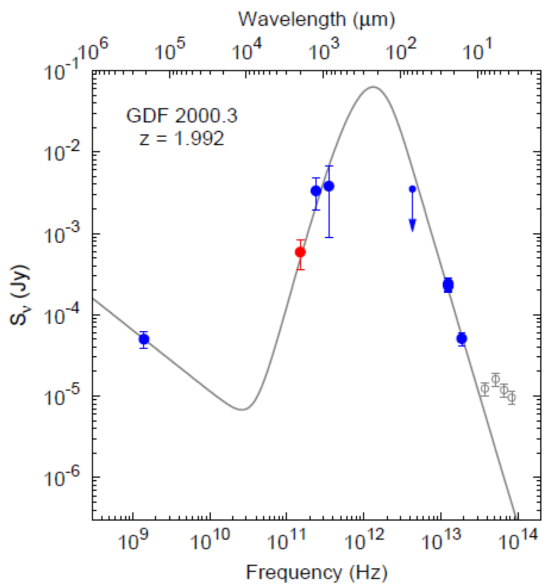
SEDs & FIR properties



GDF 2000.1
GN 850.10
AzGN 03

z = 4.042

T_d = 51.2 +/- 2.0 K
log M_d = 8.53 +/- 0.07
log L = 13.52 +/- 0.06

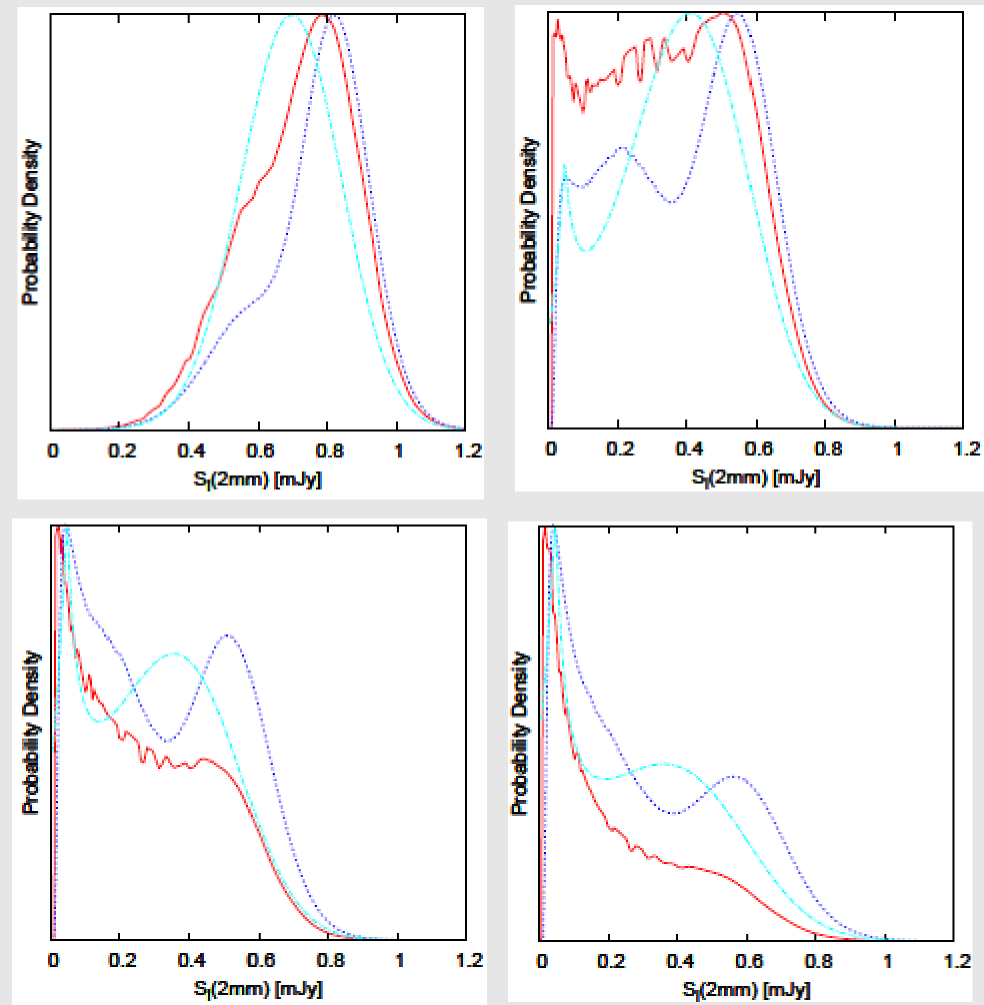


GDF 2000.3
GN 850.39
GN 1200.3
AzGN 07A

z = 1.992

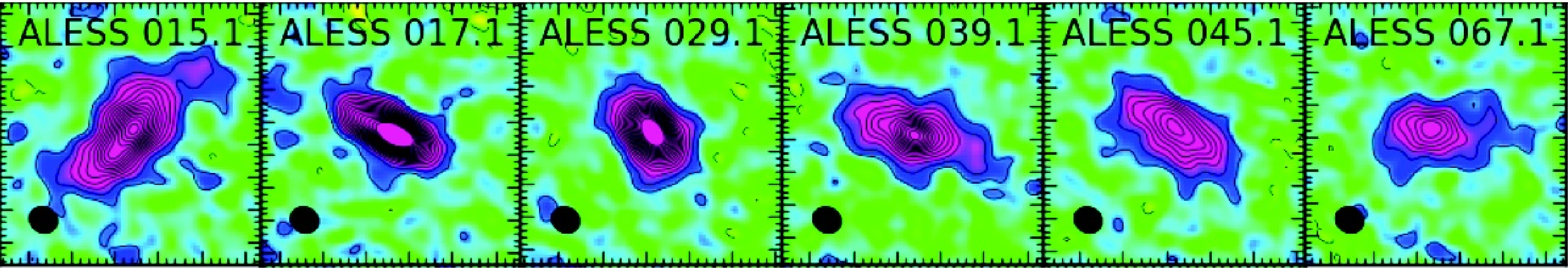
T_d = 40.8 +/- 0.7 K
log M_d = 8.59 +/- 0.14
log L = 13.10 +/- 0.03

Flux deboosting



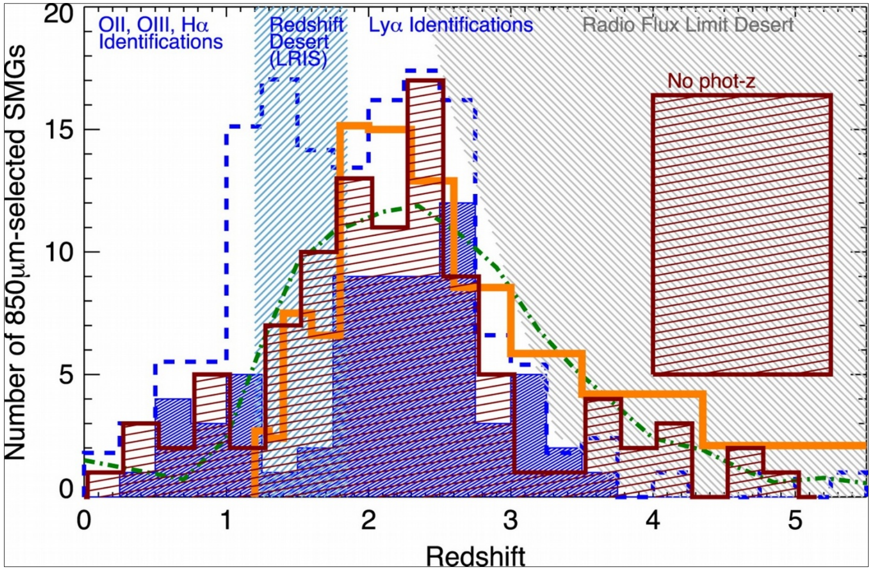
need to know number counts
to get it right...

About SMGs

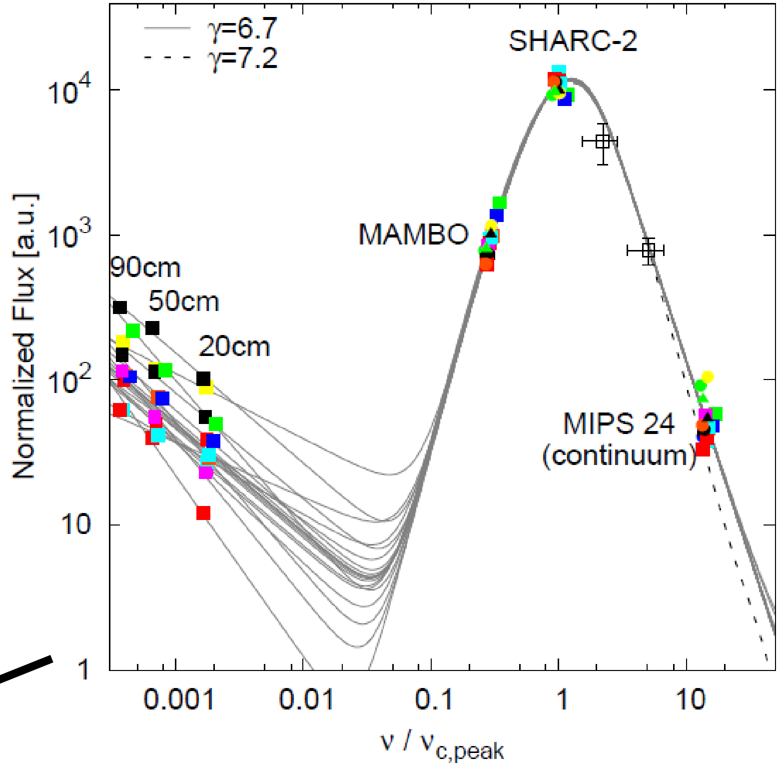


Hodge et al. 2016

smooth SF disks ~ 1.6 kpc diameter



Casey et al. 2014

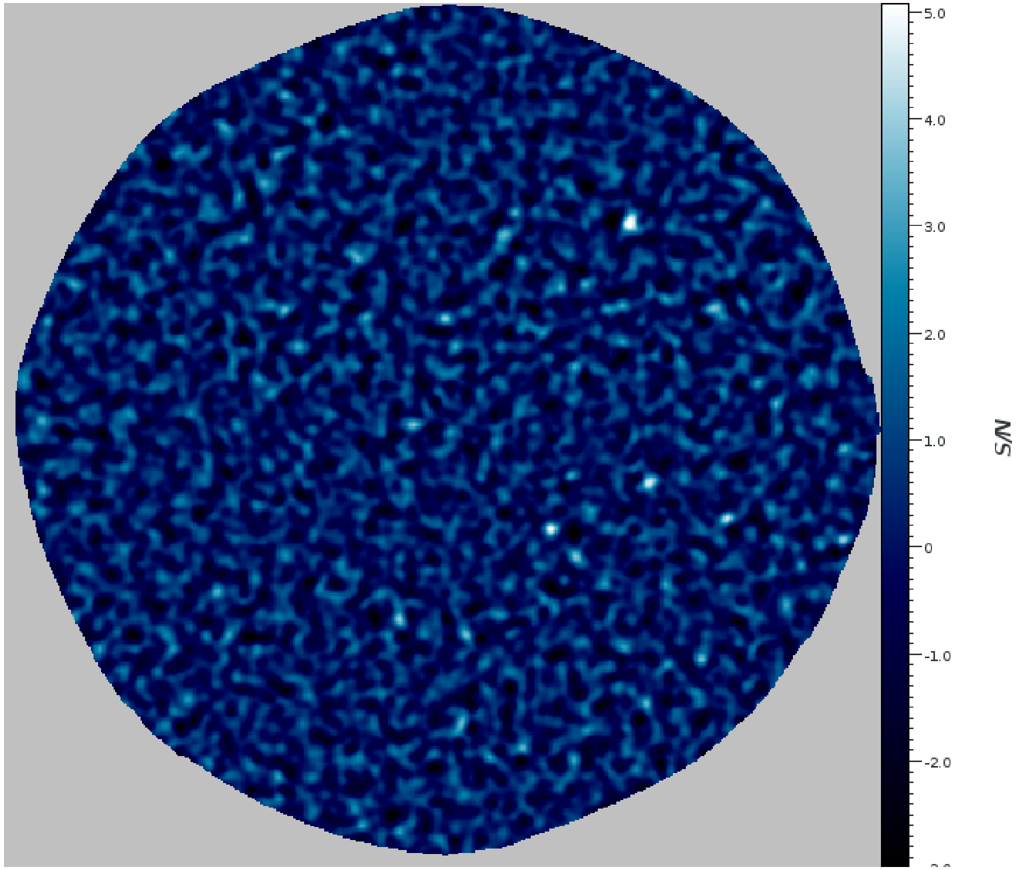


Kovács et al. 2010

D ~ 2 kpc

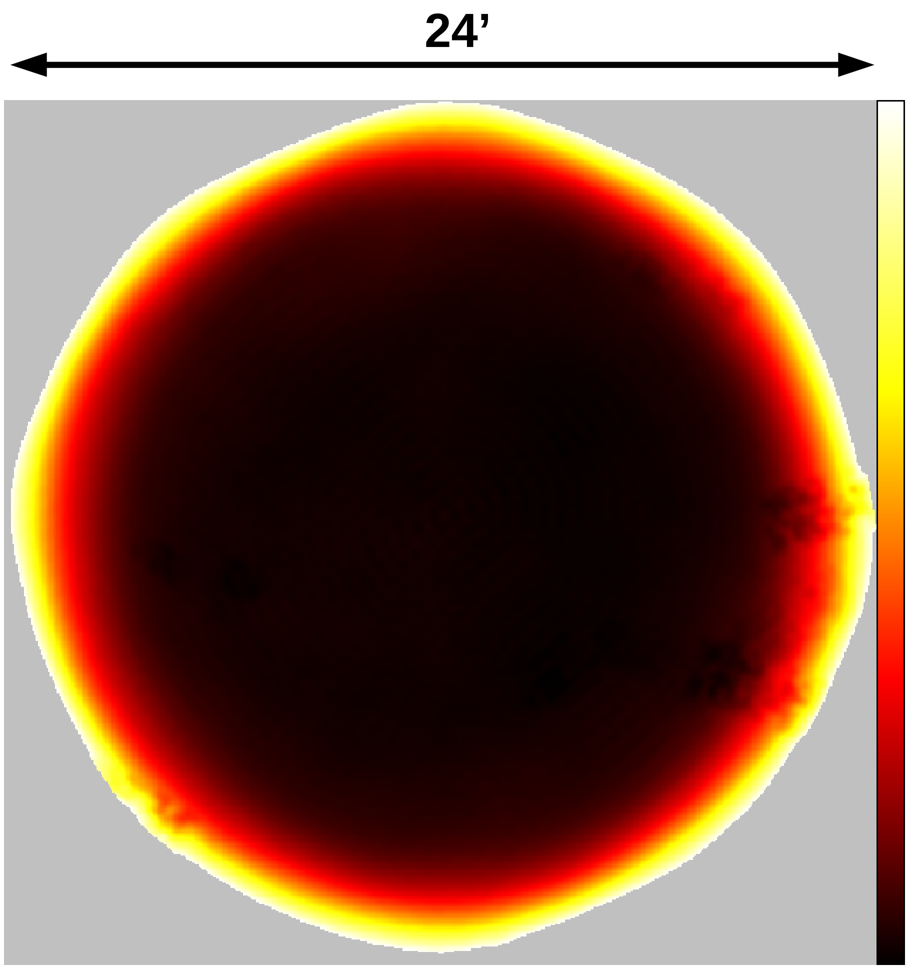
84 hours

Alexander Karim (*catalog and stacking*)
Attila Kovács (*data reduction, P(D) analysis*)
Johannes Staguhn



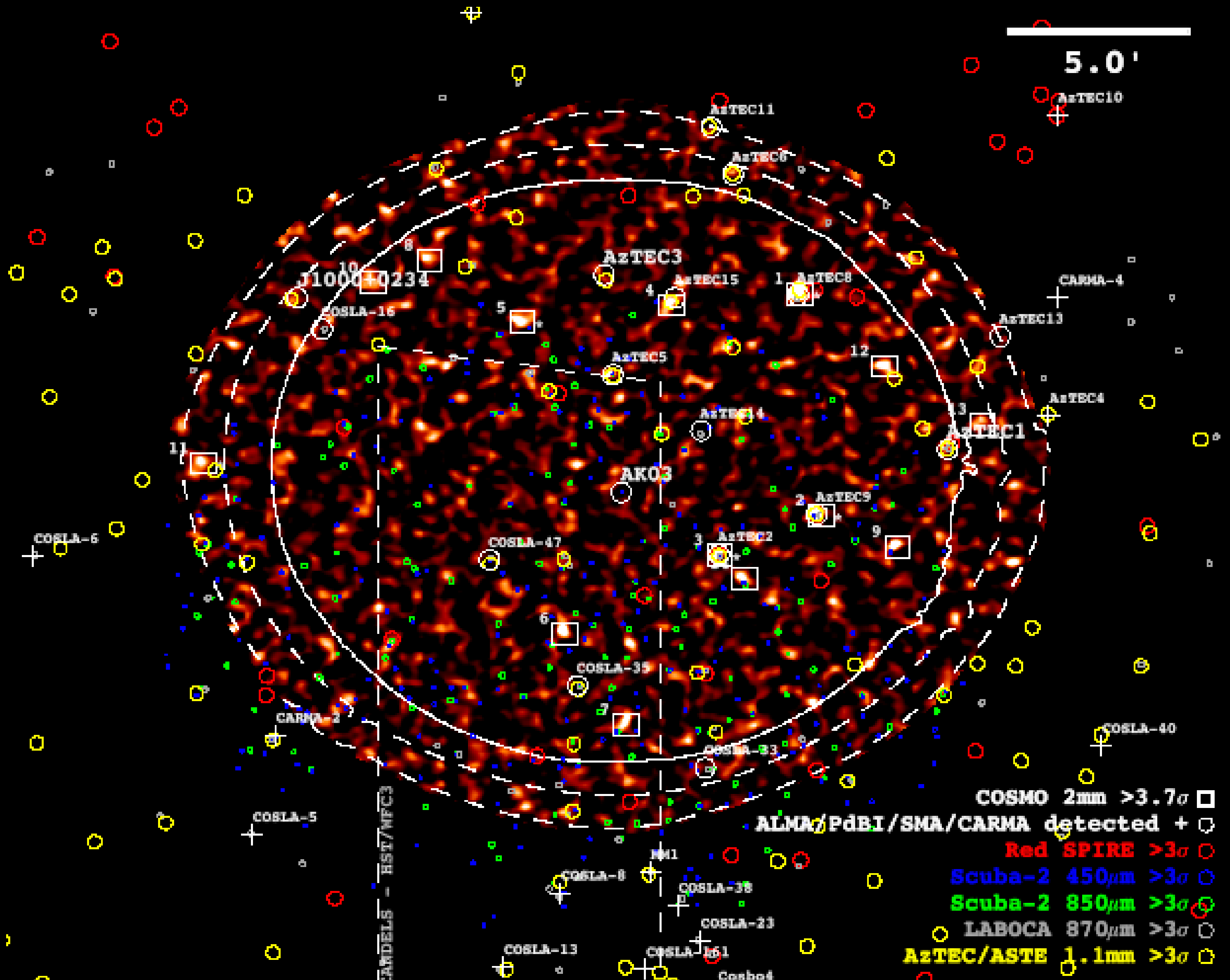
Signal-to-noise

24'



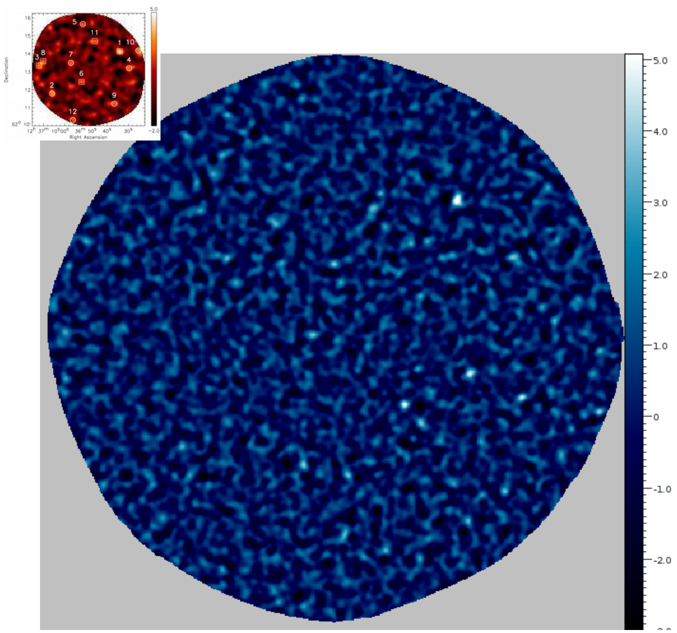
coverage map
200 – 400 uJy

GISMO: COSMOS field

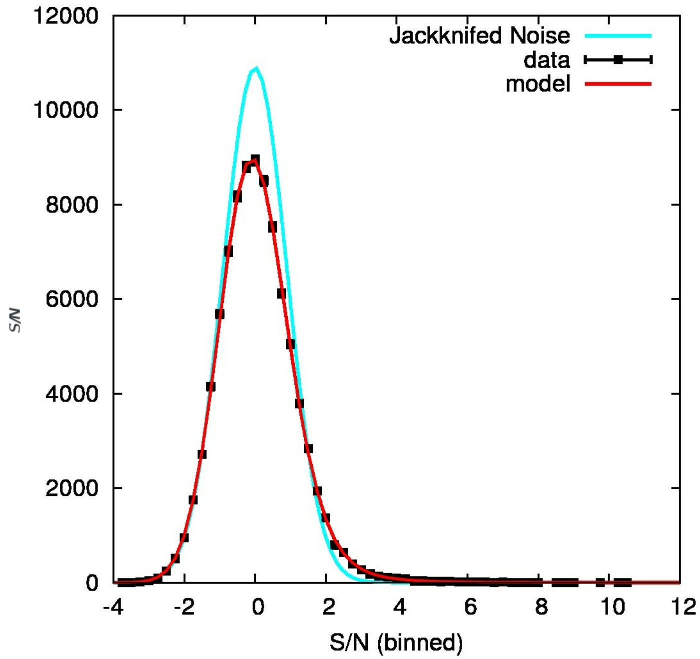


Deep fields: *P*(*D*) analysis

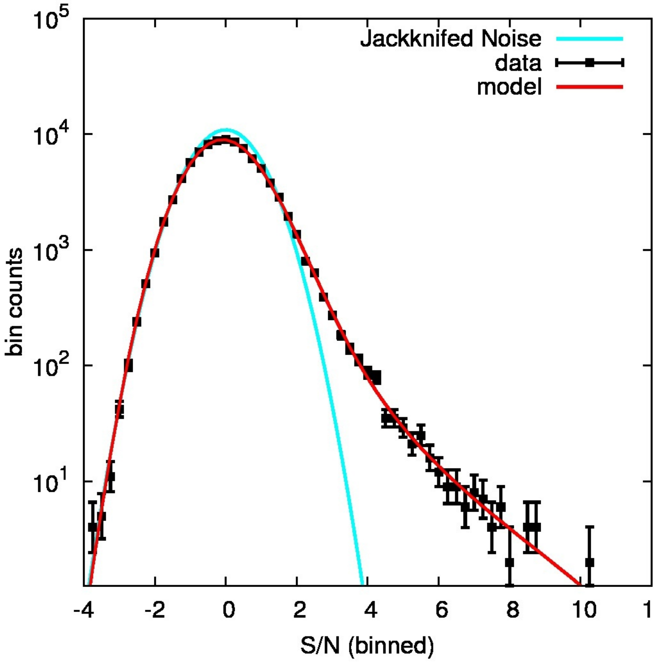
Observed distribution is a product of the source distribution and the underlying noise...

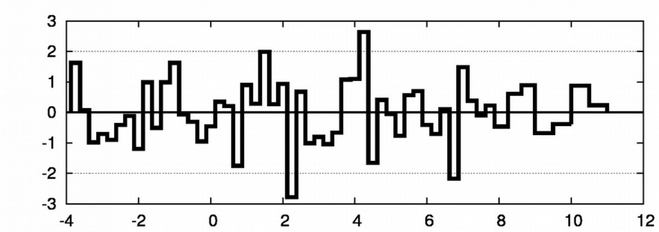


Many faint sources
Widen distribution
(confusion)



Bright sources
produce tail

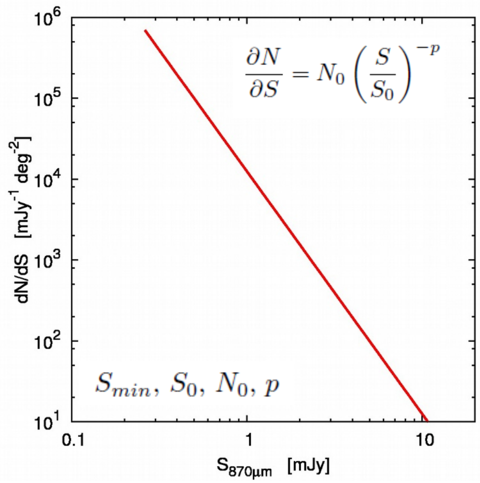


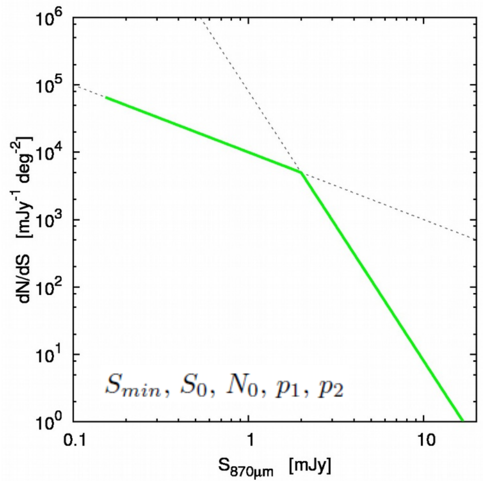


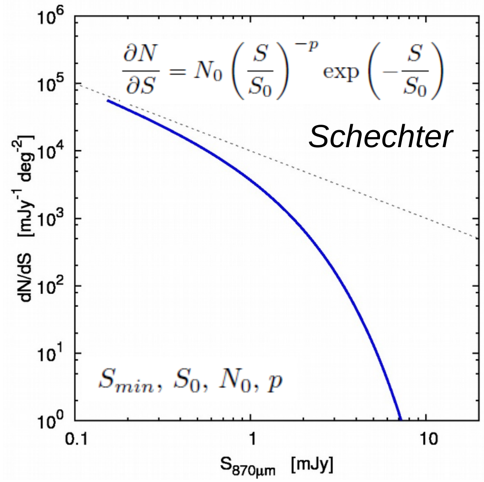
Can fit a number of parameters, depending on S/N:

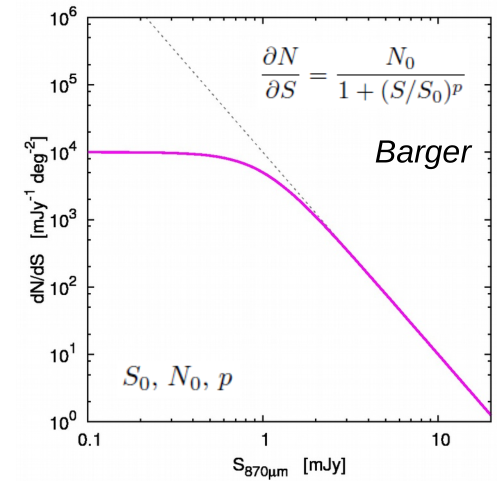
- size (brightness) distribution
- evolution
- clustering
- unresolved background

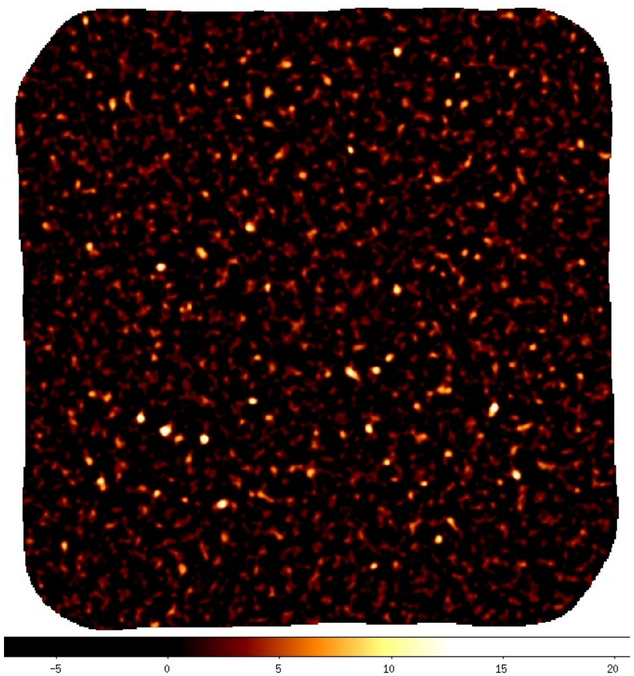
Deep fields: $P(D)$ examples

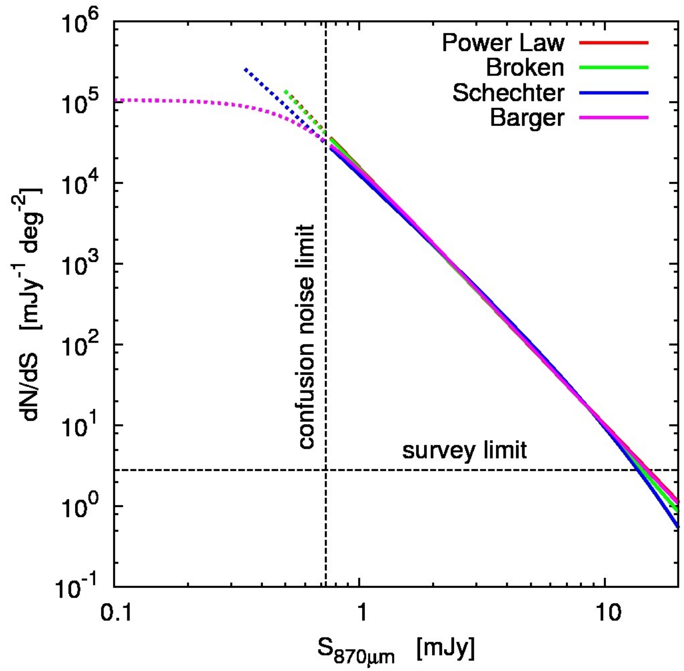


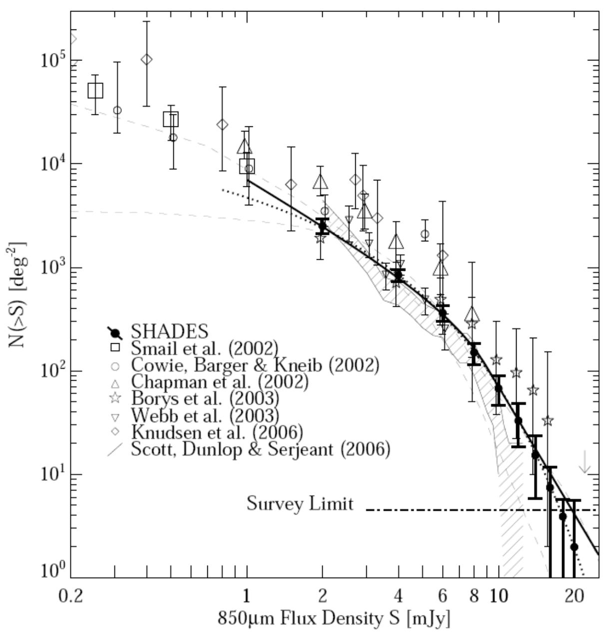




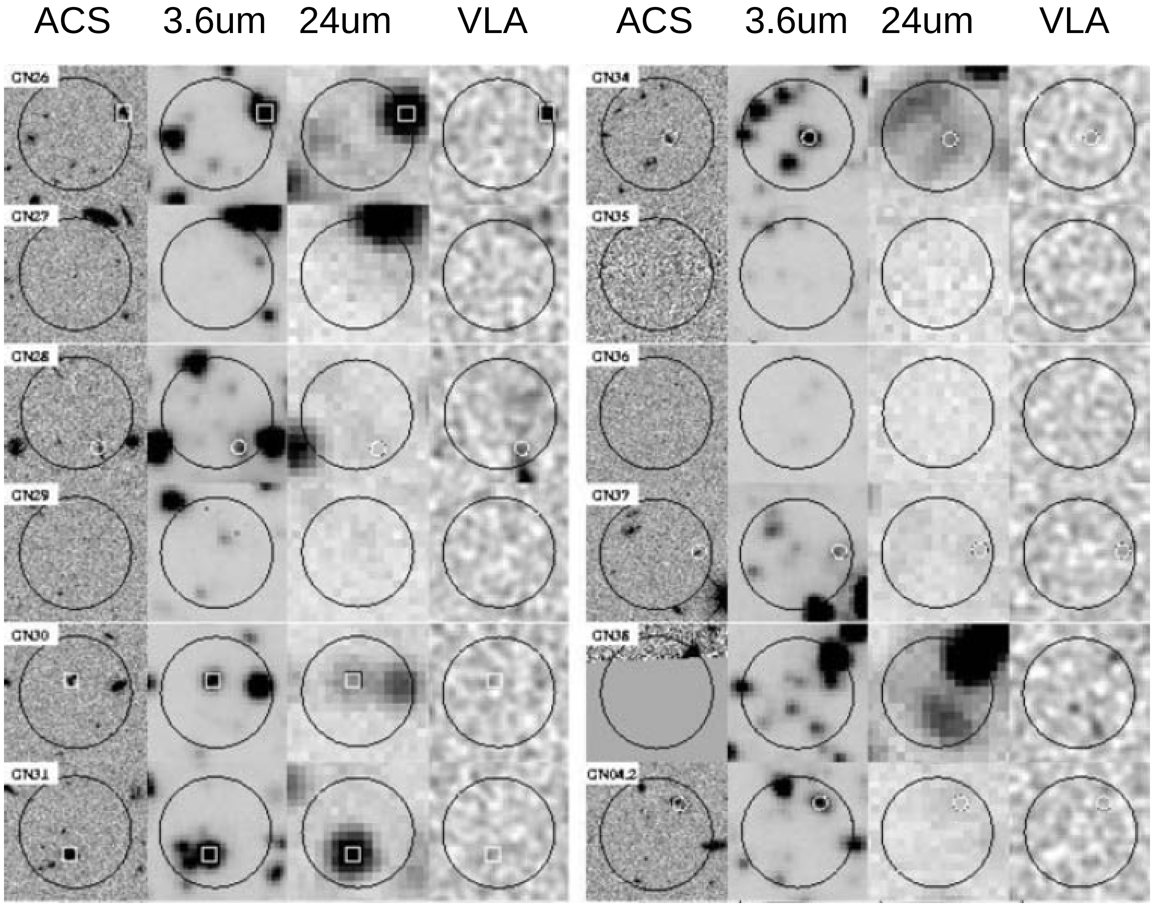




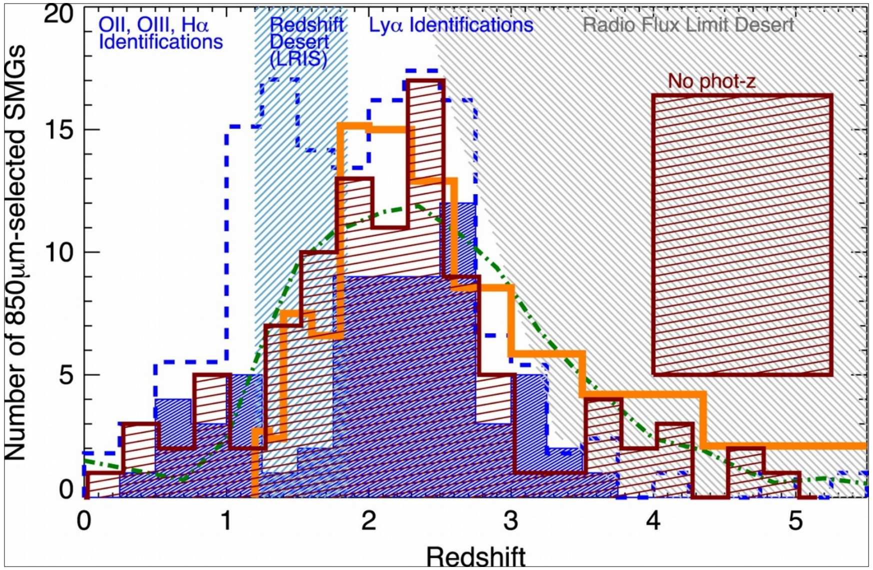




Deep fields: identification & redshifts



Pope et al. 2006

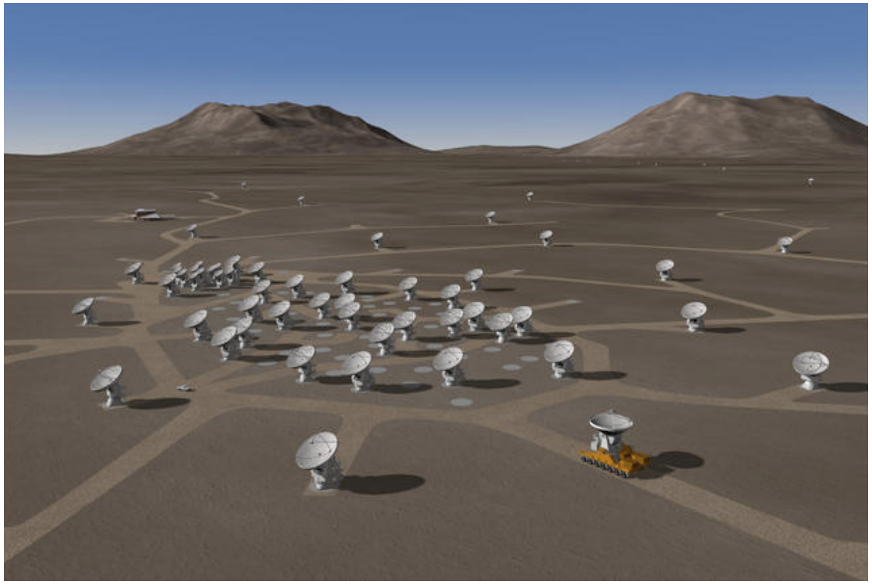


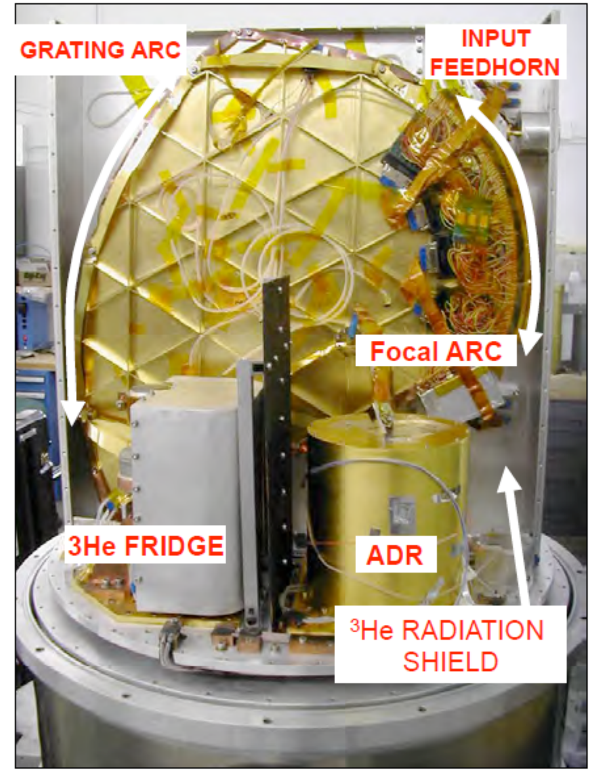
Casey et al. 2014

astrophysics → instrumentation

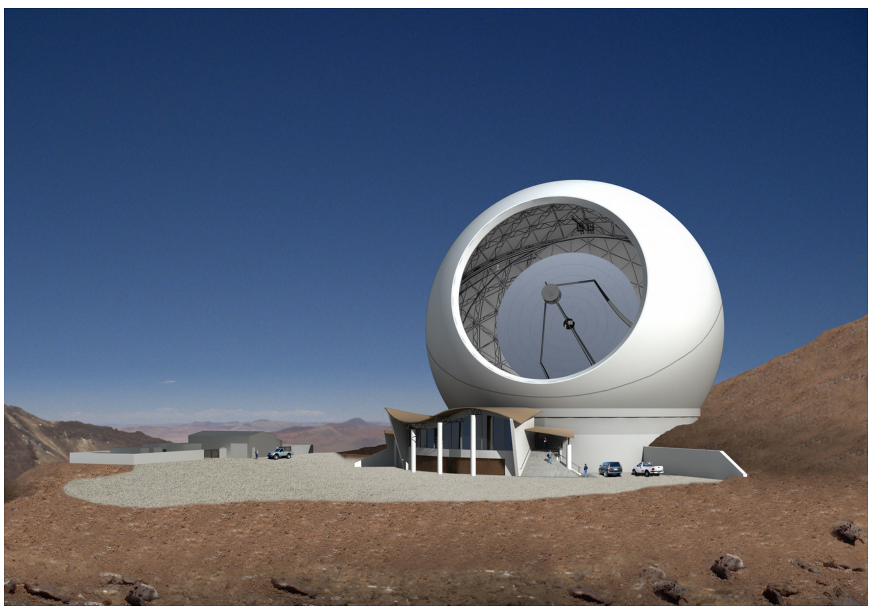
Deep fields: (sub)millimeter redshifts

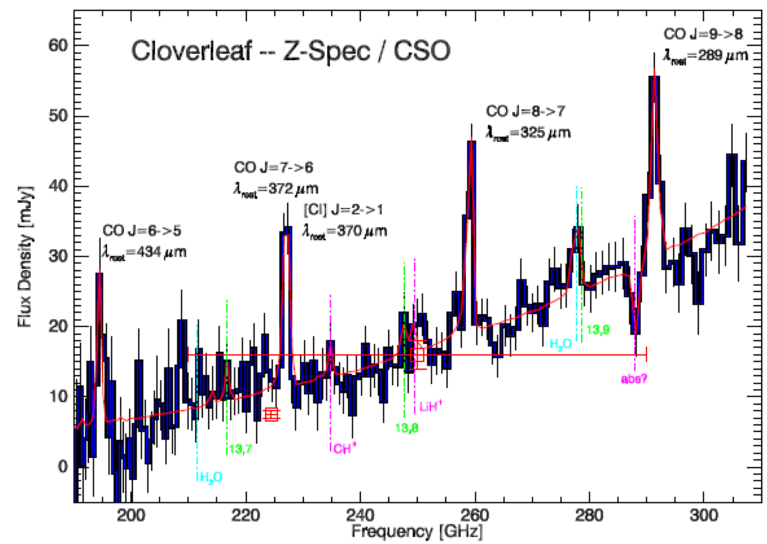
ALMA
+
EVLA



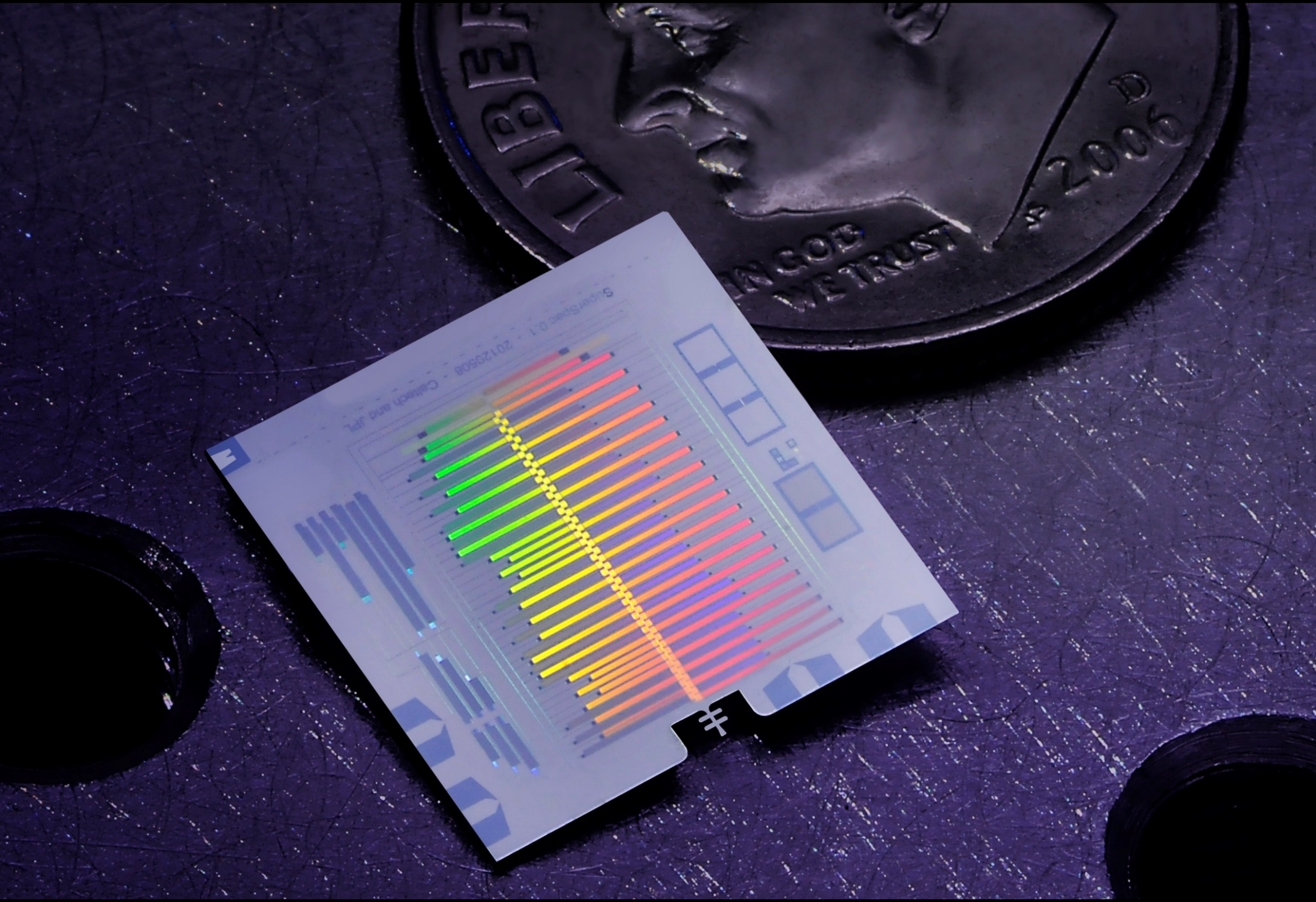


large aperture multibeam R~700 spectro-scopy





SuperSpec: a litographic spectrometer for the (sub)mm



SuperSpec: team

Caltech/JPL
C. M. Bradford
S. Hailey-Dunsheath
M. Hollister (-> Argonne)
A. Kovács
H. G. LeDuc
R. O'Brient
T. Reck
C. Shiu (-> Princeton)
J. Zmuidzinas

University of Chicago
E. Shirokoff
R. McGeehan
P. Barry (just arrived)

Cardiff University
S. Doyle
C. E. Tucker

Arizona State University
P. Mauskopf
G. Che

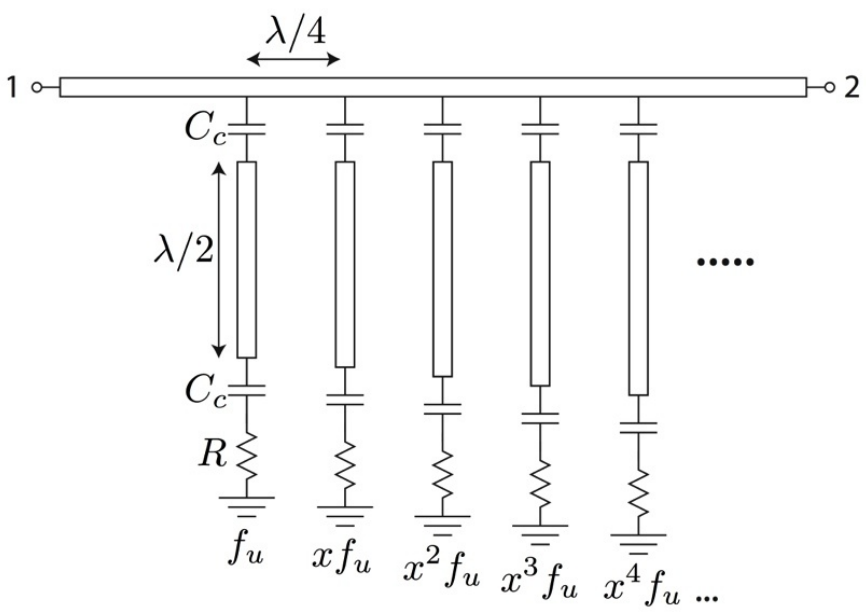
University of Colorado
J. Glenn
J. Wheeler (NSTRF grad fellow)

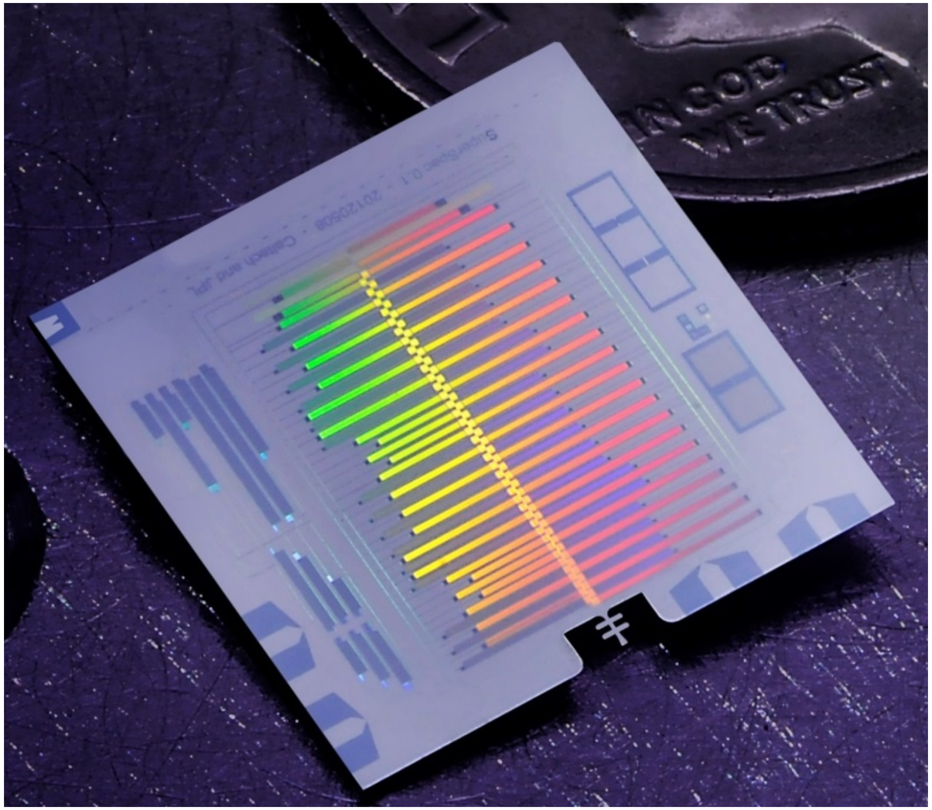
Dalhousie University
S. Chapman
C. Ross

SuperSpec: overview

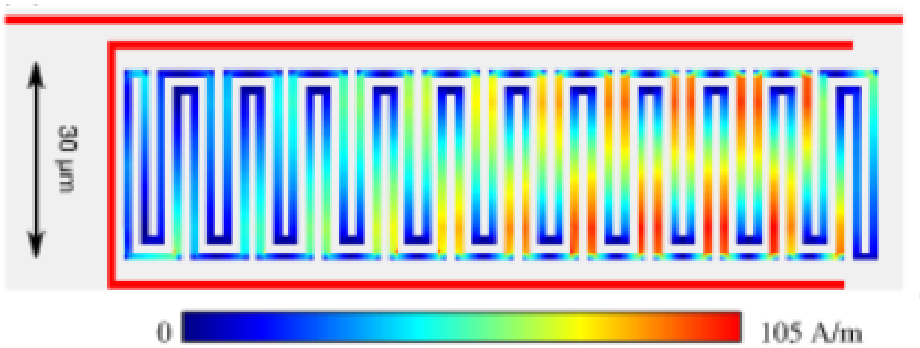
- SuperSpec is an on-chip spectrometer we are developing for moderate resolution, large bandwidth, (sub)millimeter astronomy
- A single chip integrates
  - antenna
  - moderate resolution (R ~ 100 – 500) filterbank with large BW (δν/ν ~ 0.6)
  - associated detectors (KIDs) and readout circuitry.
- Each chip is ~few cm² in size

- Prototype chips covering 200 – 300 GHz range. Also looking to higher frequencies.



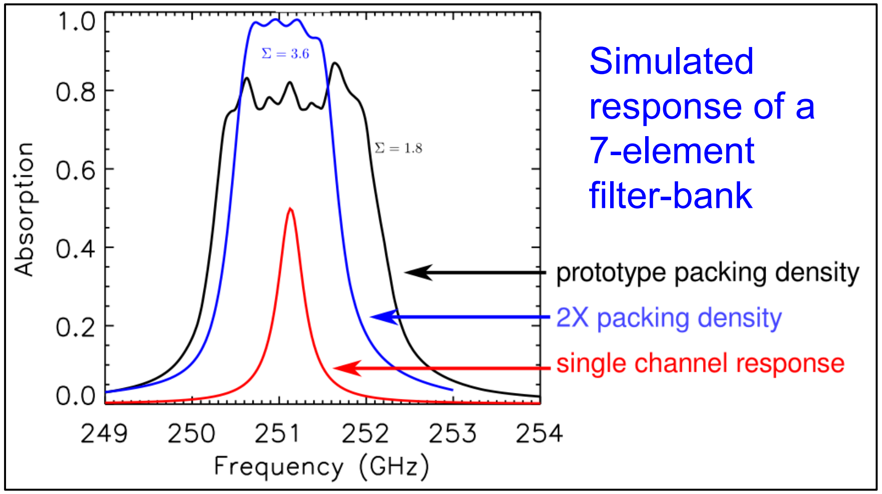


SuperSpec: coupling structure

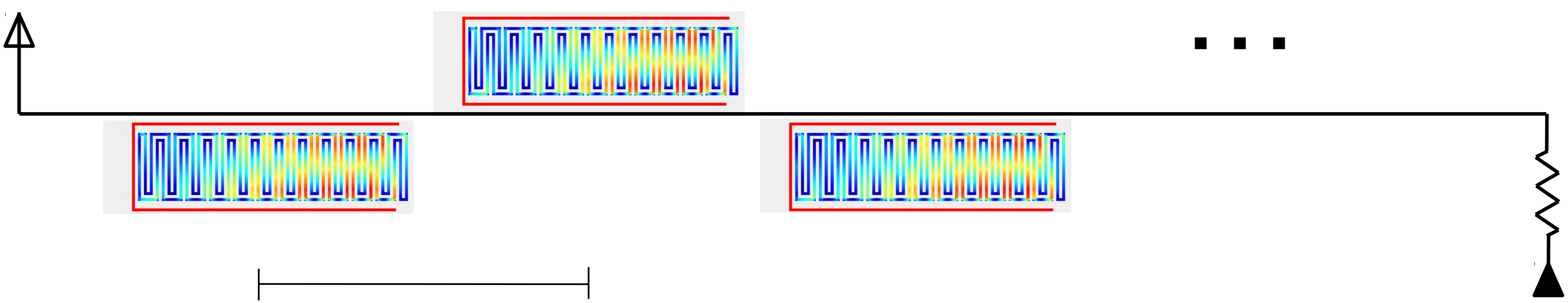


$$\frac{1}{R} = \frac{1}{Q_c} + \frac{1}{Q_i}$$

$$Q_c = Q_i \rightarrow \eta = 50\%$$

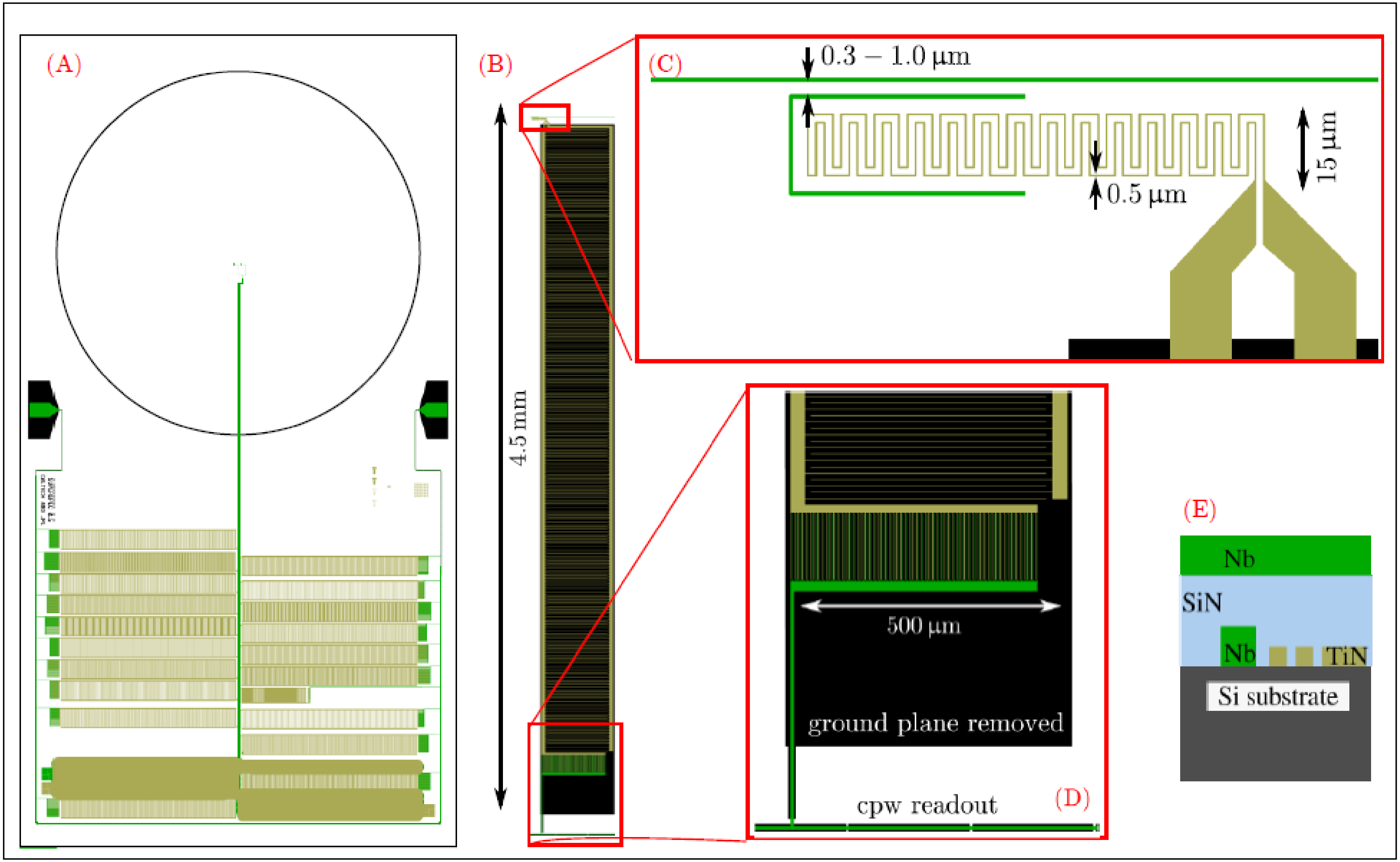


Monotonically decreasing in frequency



λ/4 or 3λ/4 spacing

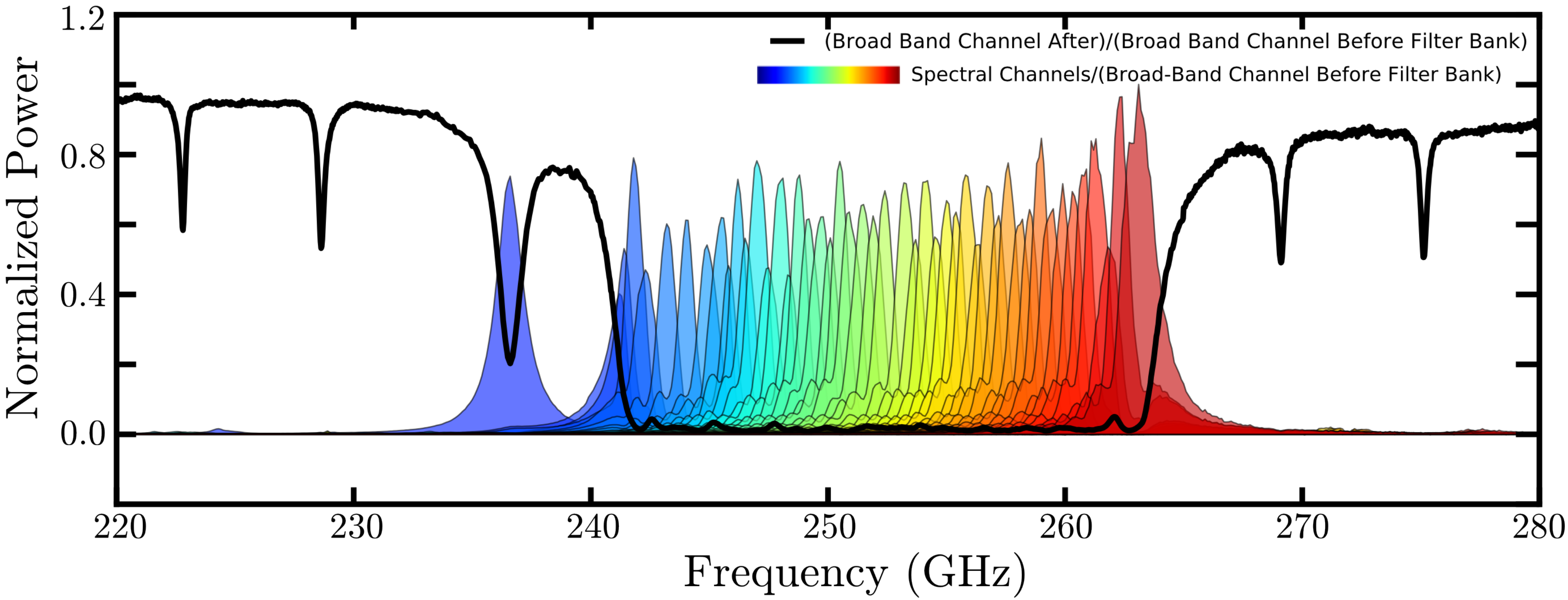
SuperSpec: example full-die layout



TiN: f_r = 100 – 200 MHz T = 220 mK

Qi ~ 10^5 T_c = 1.2 K

SuperSpec: 50-channel log-spaced filterbank



100% yield (on 2 dies)

T_c ~ 1.8 K (designed for 1.2 K)

NEP ~ 1.5 x 10^{-17} W $Hz^{-0.5}$

Q_{loss} ~ 1100

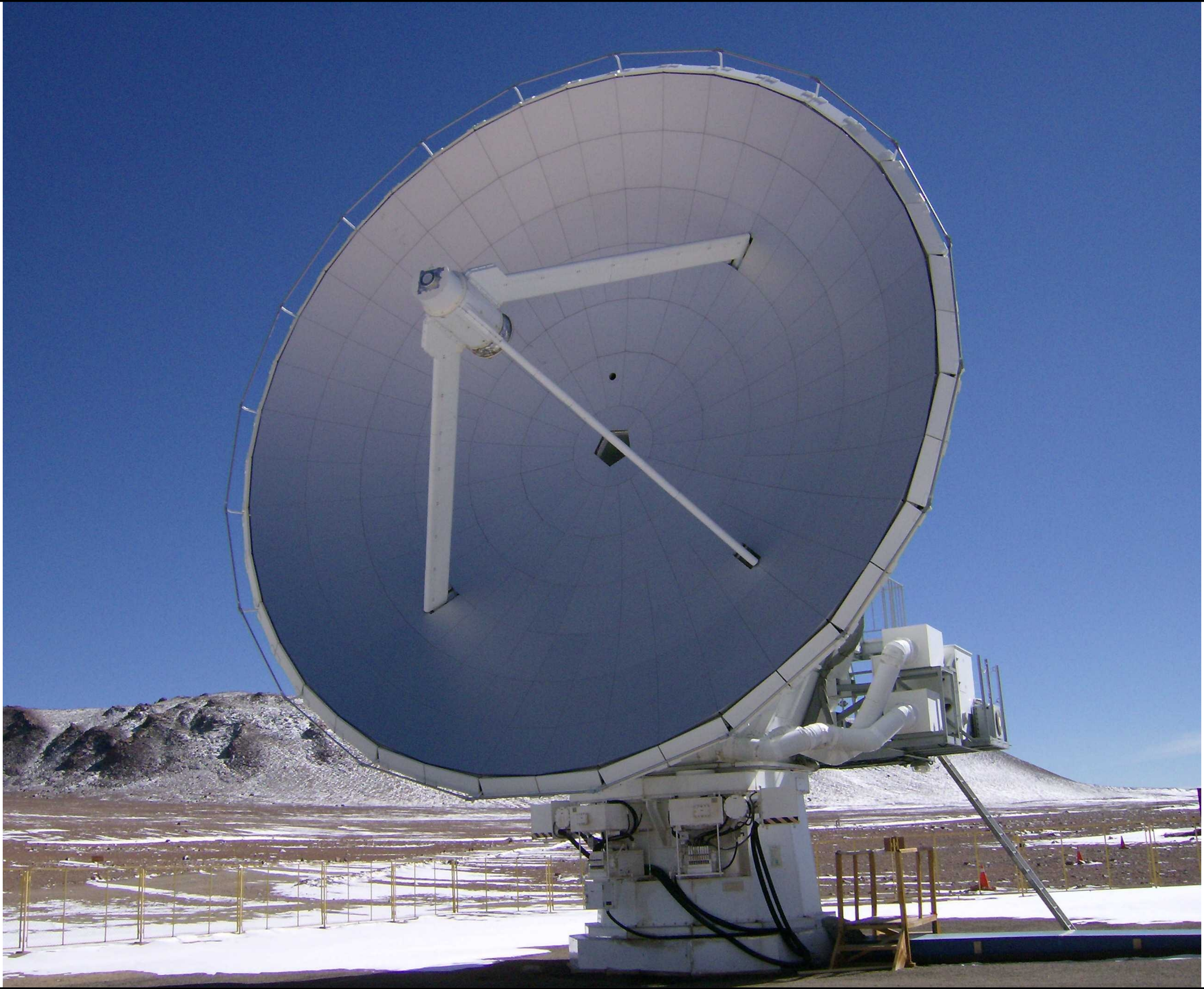
Q_i ~ 620 (designed for 800)

Q_c ~ 420 (designed for 462)

Q_r ~ 200 (designed for 293)

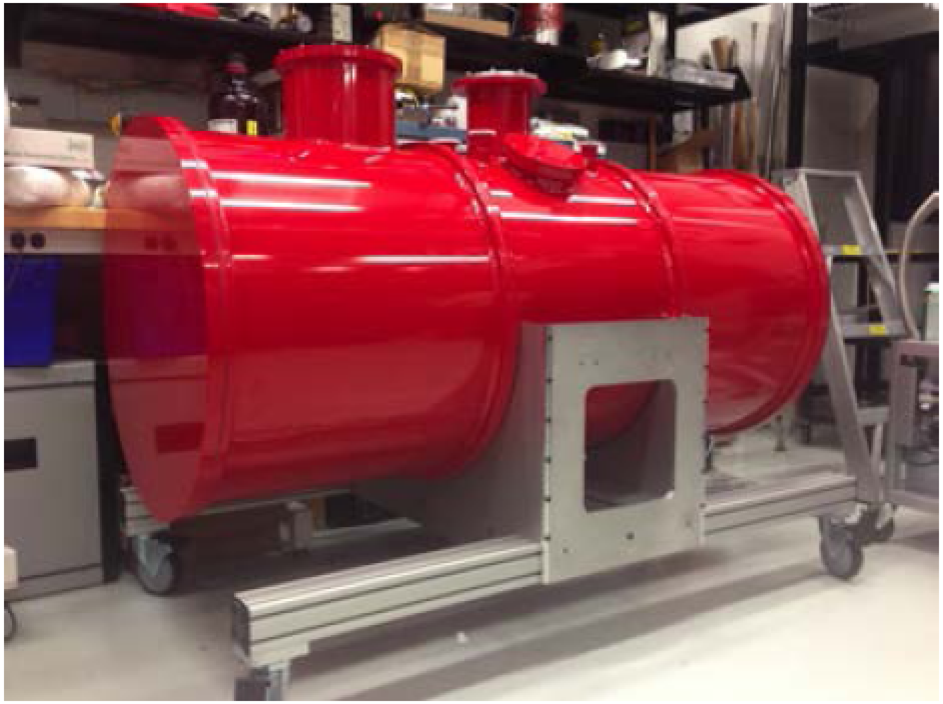
peak coupling ~ 0.24

Destination: LMT



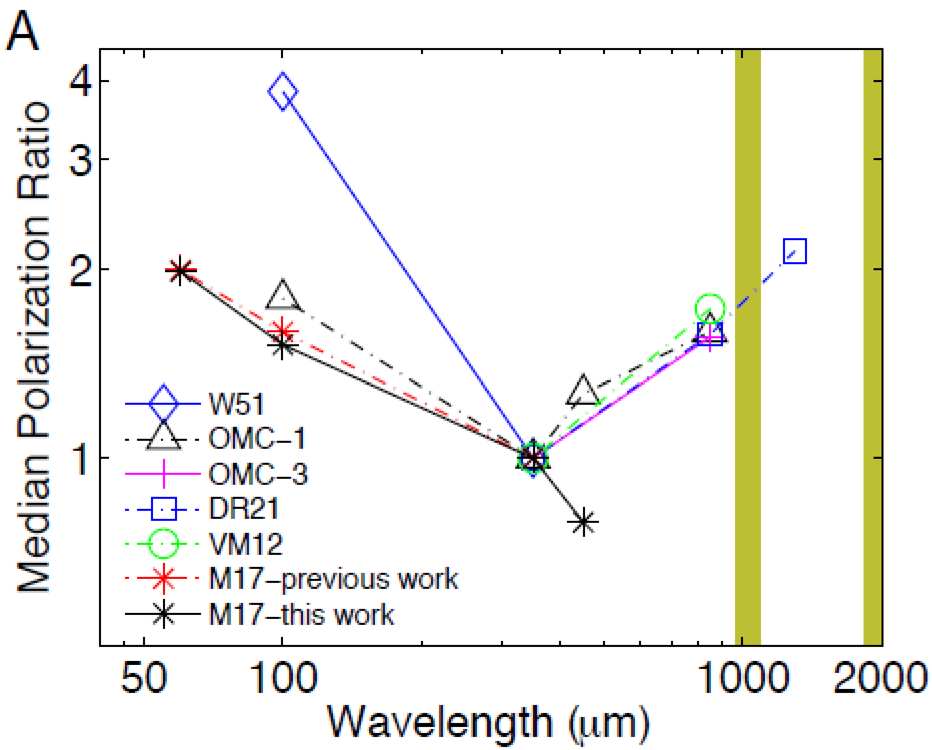
Improvements:

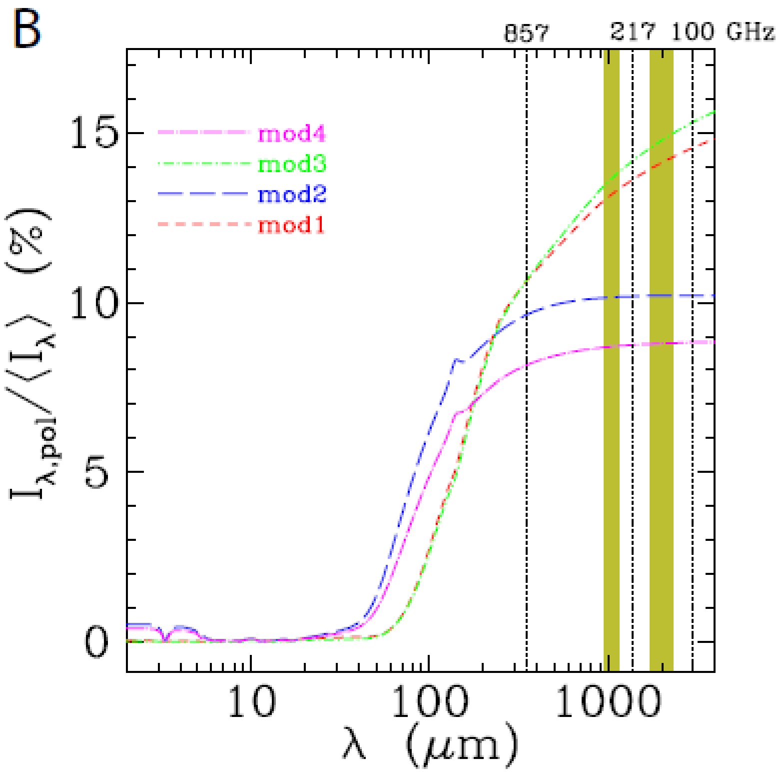
Colors:	2mm → 1mm & 2mm
Size:	8x16 → 32 x 40
Sensitivity:	8 mJy $s^{0.5}$ → <~ 3 mJy $s^{0.5}$
Mapping Speed:	70x @ 2 mm
Resolution:	17” → 10”

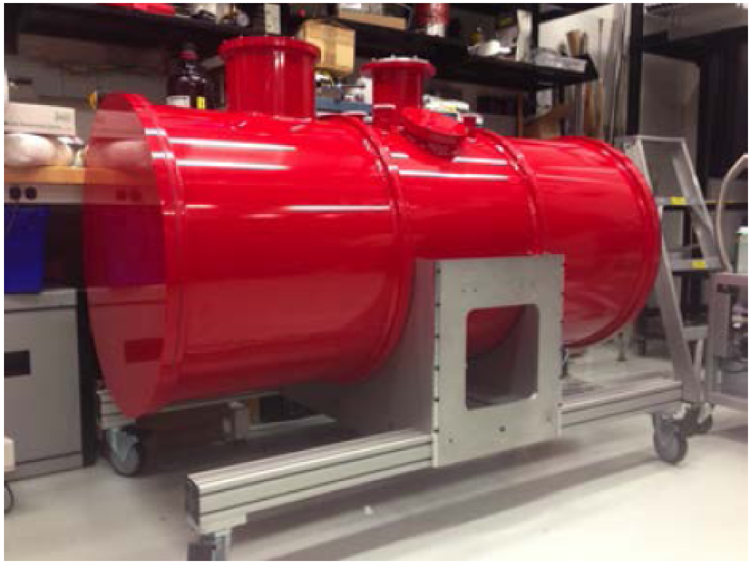


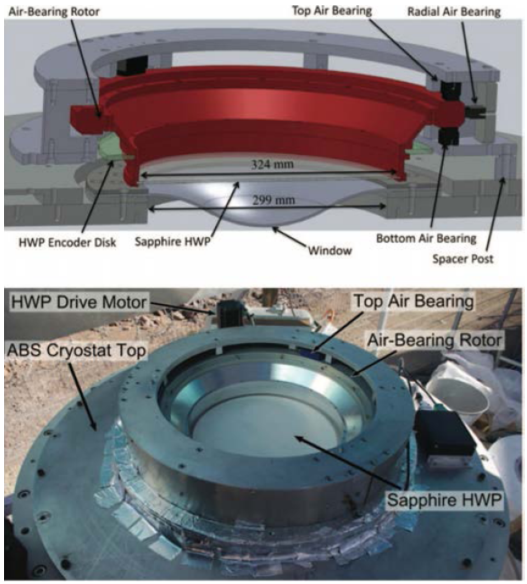
GISMO-2 (PI: Staguhn)

extragalactic → Galactic





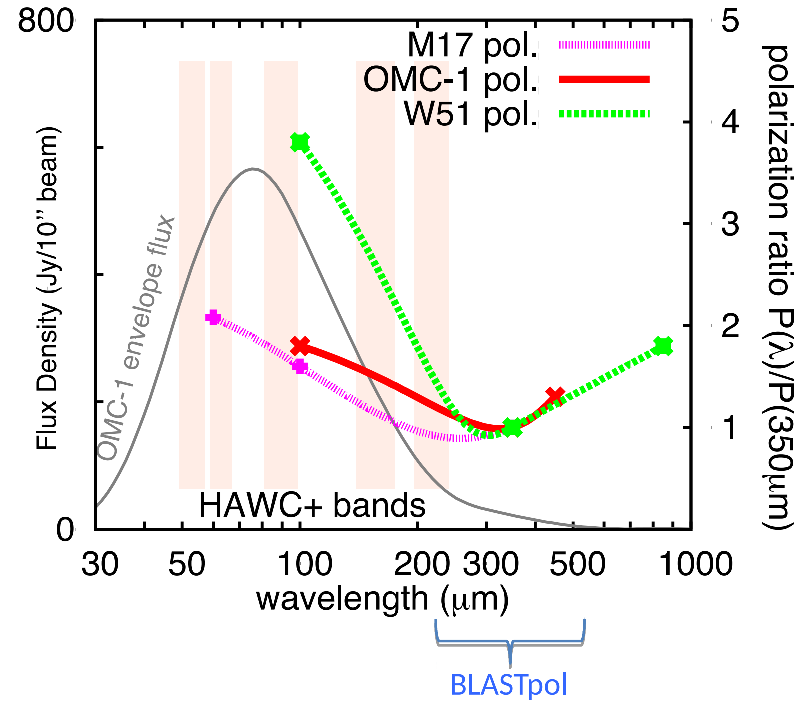


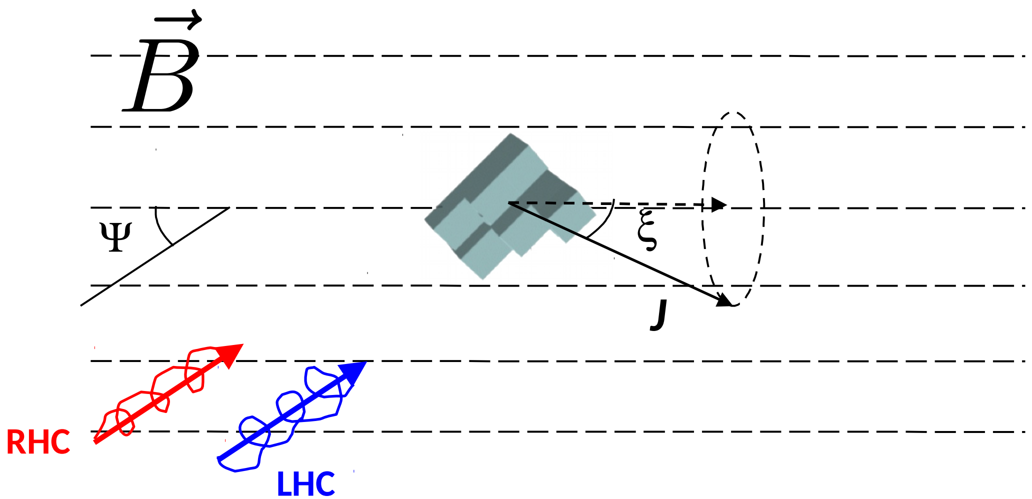


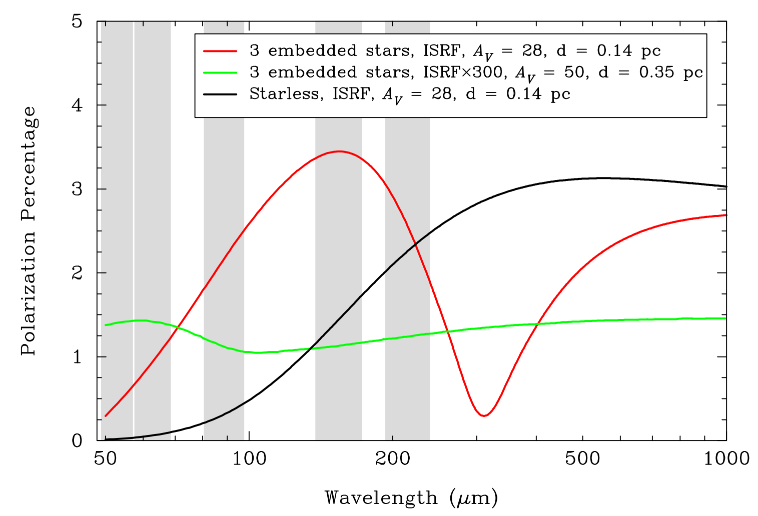
PI: Dave Chuss, Villanova

Dust grain alignment

- Dust grain alignment is an unsolved problem of astrophysics. Only recently has radiative alignment become favored theory over paramagnetic relaxation.
- No matter what, alignment is with respect to magnetic field: Larmor precession ($t \approx 10^6$ s) washes out alignment with respect to any other direction. (Martin 1971)
- Radiative alignment, requiring asymmetric grains and an asymmetric radiation field, is currently the leading theory (Dolginov & Mytrophanov 1976; Draine & Weingartner 1996/7; Lazarian & Hoang 2007).
  - Test #1: Does the degree of grain alignment depend on the strength of the radiation field?
  - Test #2: Is there spectral evidence for better alignment of large grains?







SOFIA

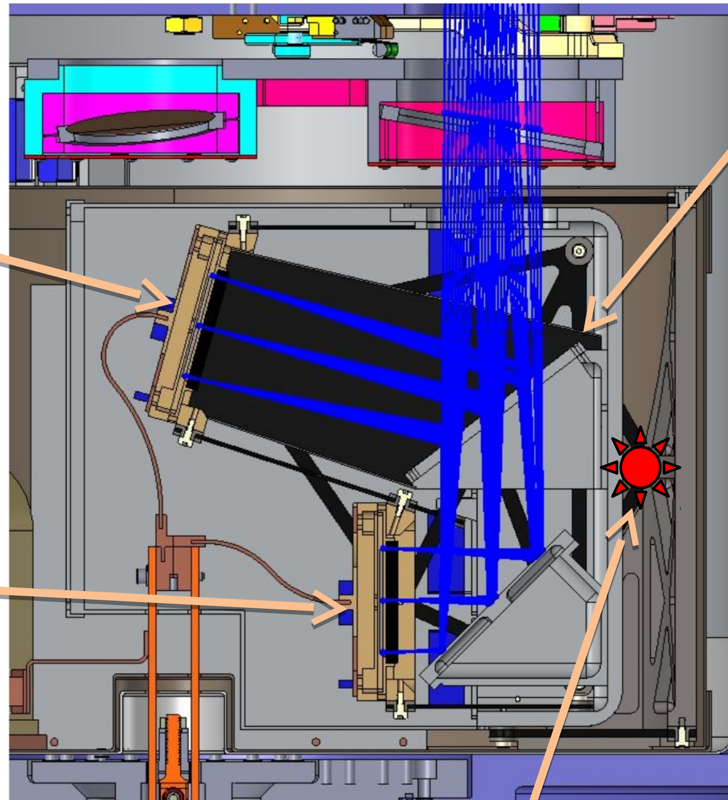
SOFIA / HAWC+ team

- JPL/Caltech: lead design, I&T, commissioning, analysis software, management:
  - D. Dowell, L. Hamlin, M. Hollister, A. Kovacs, M. Runyan, A. Toorian, G. Voellmer (w/ Neon)
- U. Chicago: engineering support, I&T, control & analysis software
  - M. Berthoud, A. Harper, J. Wirth
- GSFC/JHU/NIST/Stanford: detector arrays, engineering support:
  - S. Banks, D. Benford, E. Buchanan, D. Fixsen, G. Hilton, K. Irwin, C. Jhabvala, T. Miller, H. Moseley, E. Sharp, L. Sparr, J. Staguhn, E. Wollack
- SSAI: control software
  - S. Maher
- Northwestern U.: analysis software
  - G. Novak, F. Santos, (N. Chapman)
- U. British Columbia: readout electronics
  - M. Amiri, M. Halpern
- U. Illinois: cryogenic motor
  - L. Looney
- Villanova, NASA-Ames: I&T and commissioning support
  - D. Chuss, J. Dotson
- USRA/SOFIA: carts, commissioning, airworthiness & documentation support
  - R. Hamilton, M. Kandlagunta, E. Lopez Rodriguez, E. Sandberg, (J. Vaillancourt)

- plus thanks to SOFIA program for help leading to commissioning

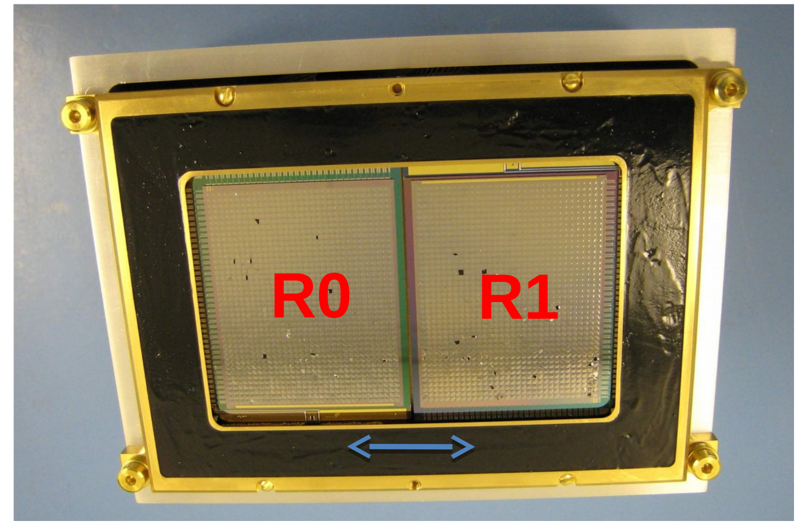
SOFIA / HAWC+

‘R’
detector array

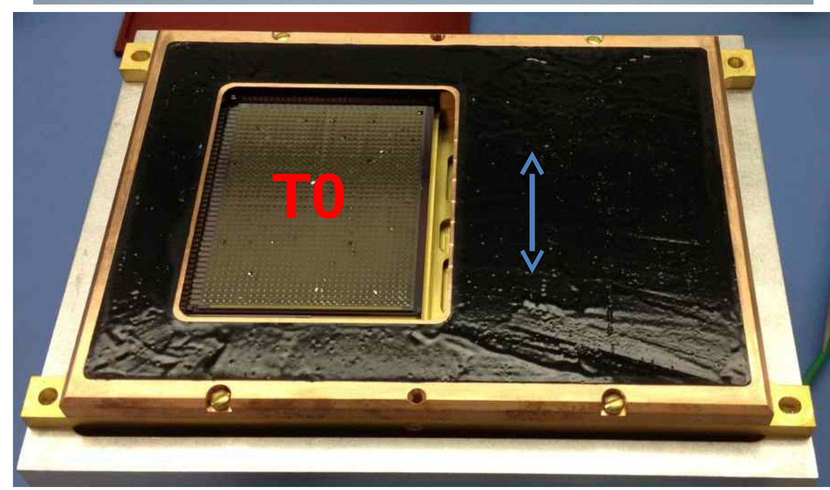


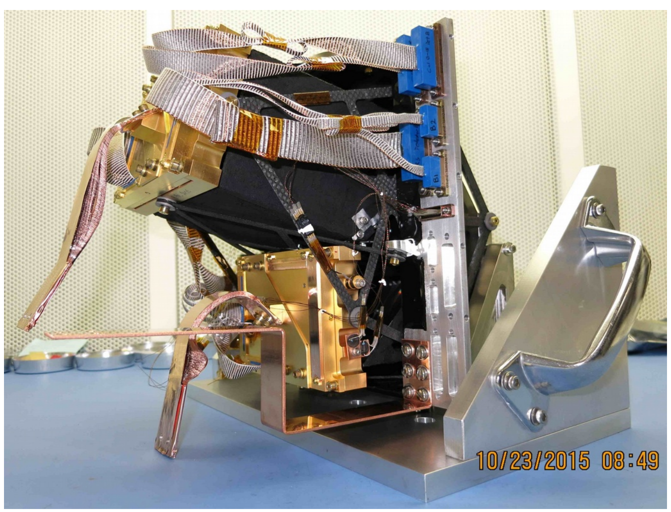
polarizing beamsplitter

HAWC+ detector arrays

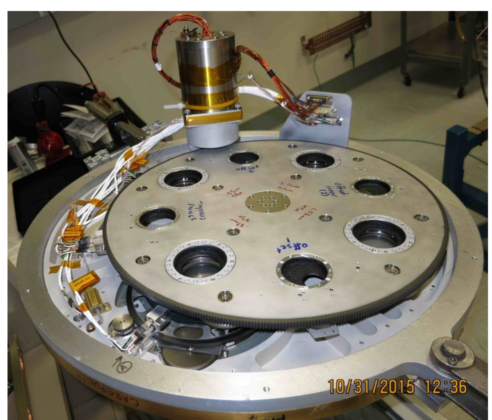


‘T’
detector array

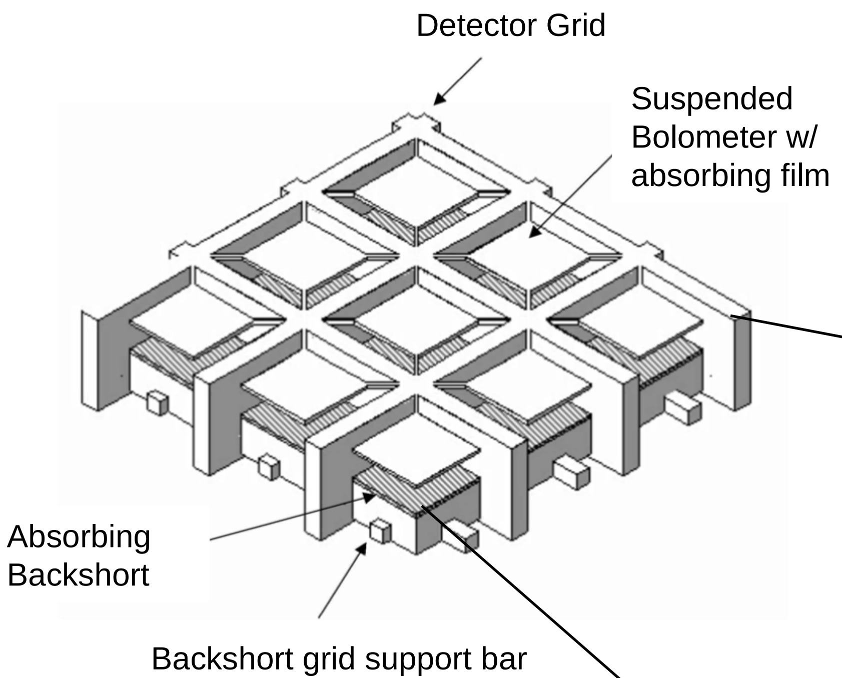


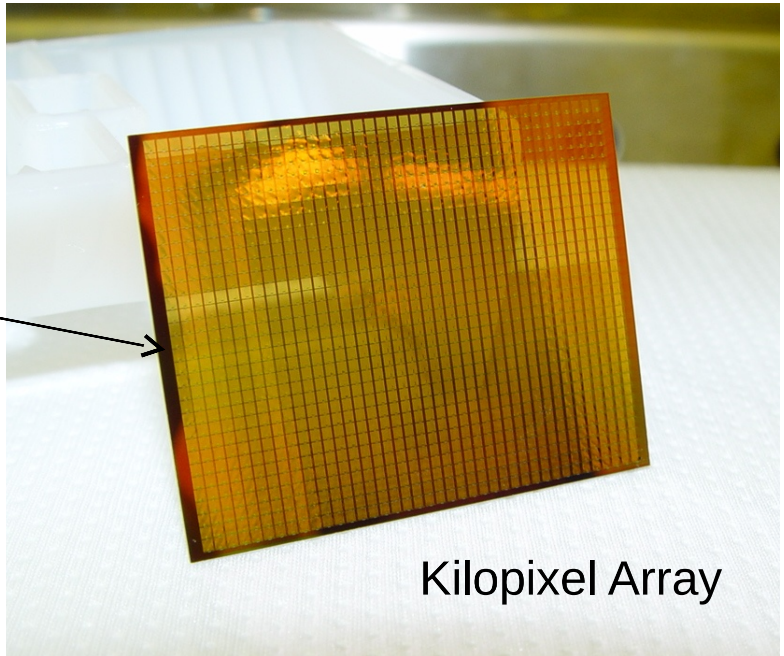


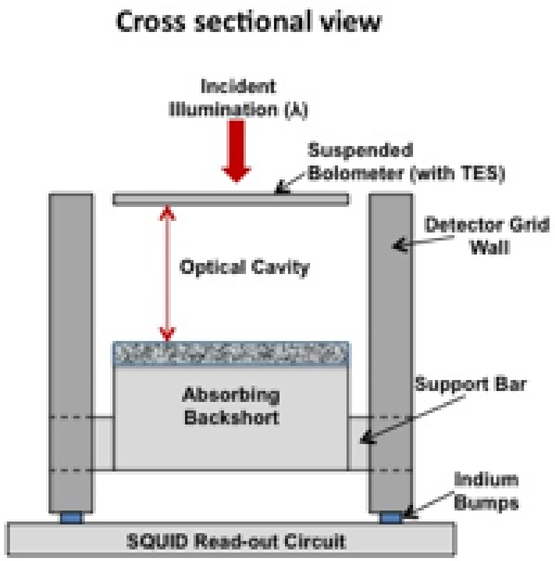
internal calibrator (IR-50)

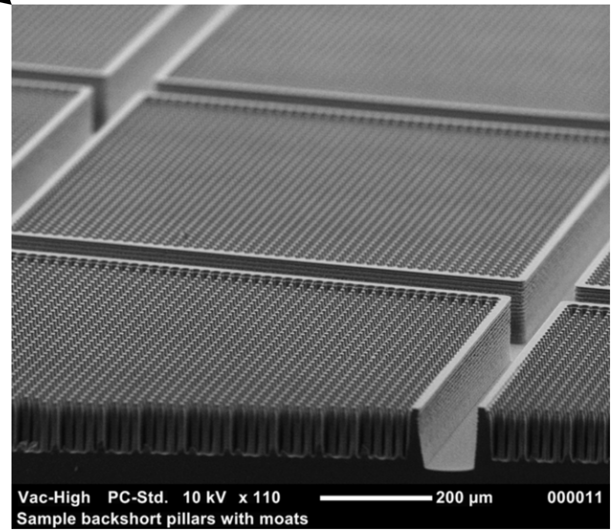


SOFIA / HAWC+ (and GISMO-2) detectors





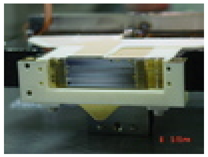




Absorbing Backshort

SOFIA / HAWC+ scan-mode pipeline

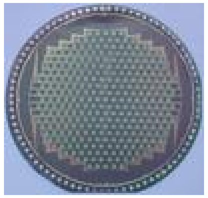
CRUSH
Comprehensive Reduction Utility for SHARC-2 (and more...)



SHARC-2

350um

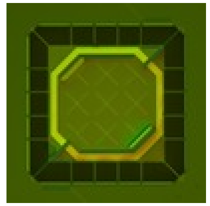
CSO
(2003)



LABOCA

870um

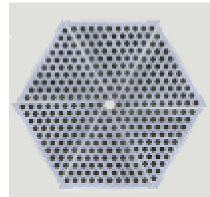
APEX
(2007)



SABOCA

350um

APEX
(2008)



ASZCA

2mm

APEX
(2006)

p-ArTeMiS

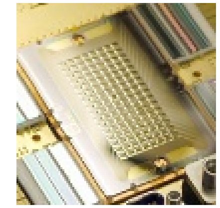
200um
350um
450um

APEX
(2011)

PolKa

870um
polarimetry

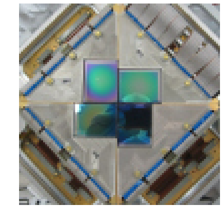
APEX
(2010)



GISMO

2mm

IRAM
(2008+)

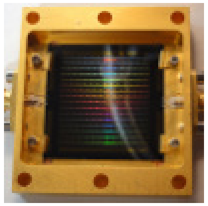


SCUBA-2

450um
850um

JCMT
(2010+)

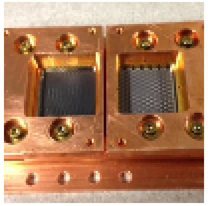
sharcsolve (SHARC-2) — **BoA** (LABOCA, SABOCA, ASZCA, p-ArTeMiS) — **SMURF** (SCUBA-2)



MAKO

350um

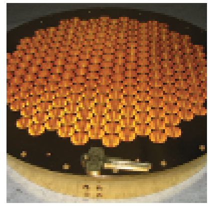
CSO
(2014)



MAKO-2

350um
850um

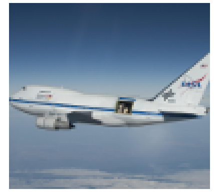
CSO
(2014)



MUSTANG-2

3mm

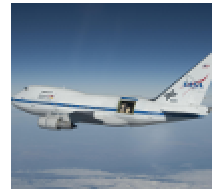
GBT
(2015)



HAWC+

53 – 217 um

SOFIA
(2015)



HIRMES

25 – 122 um

SOFIA
(2015)

SOFIA / HAWC+ scan-mode pipeline

About CRUSH

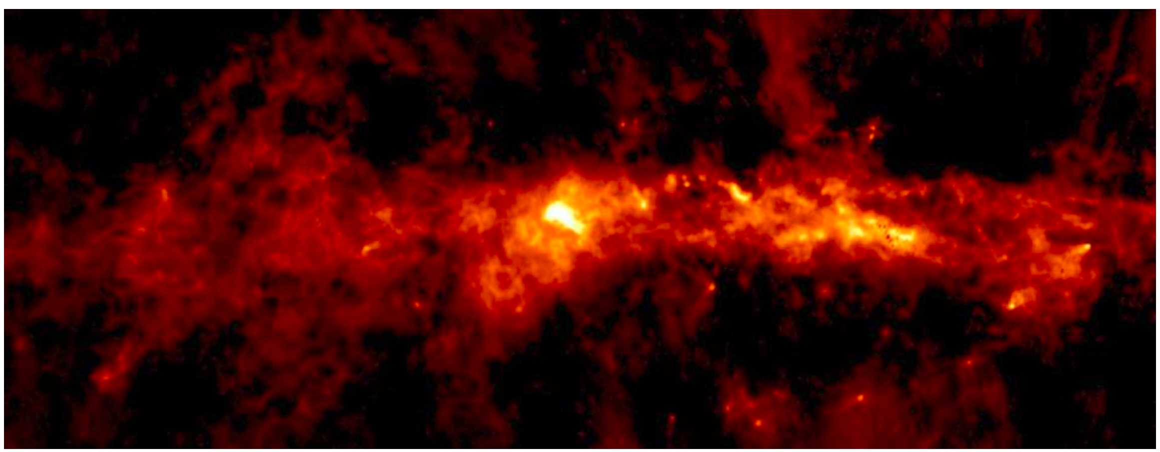
www.submm.caltech.edu/~sharc/crush

Iterated pipeline

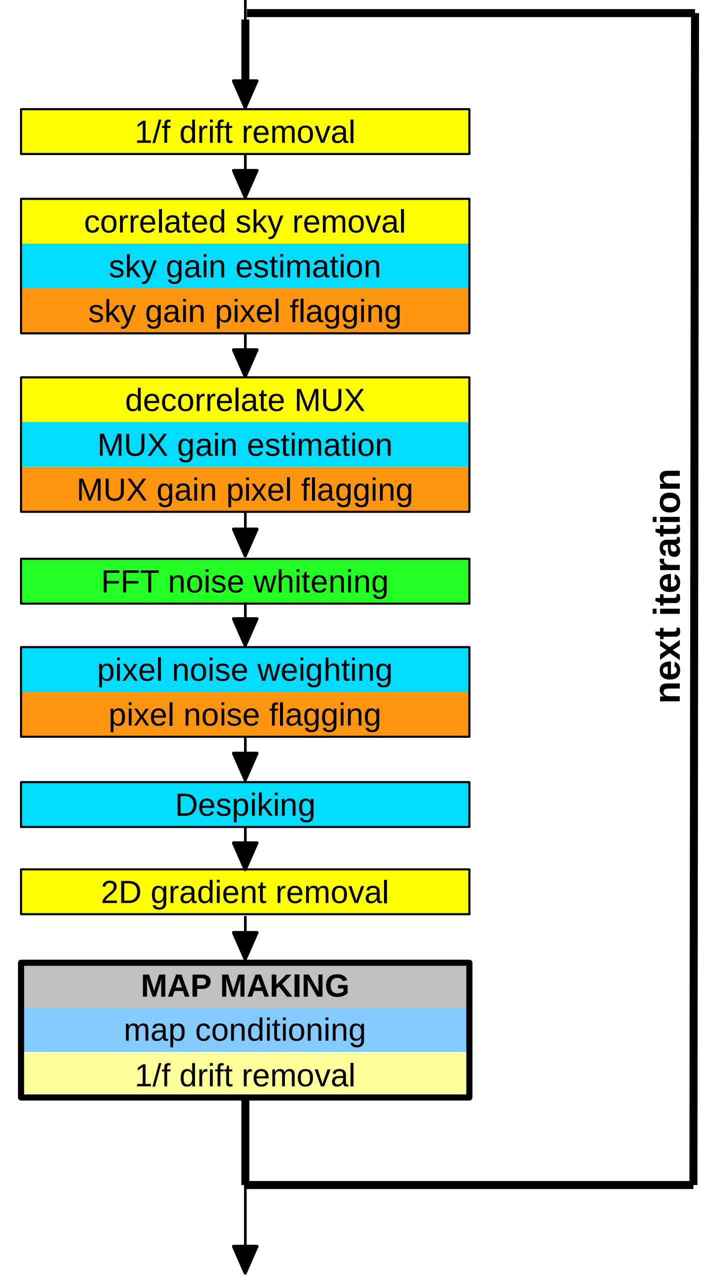
state-of-the art reduction for several cameras
(e.g. SHARC-2, SCUBA-2, LABOCA, GISMO)

parallellized, blazing-fast architecture

runs on all platforms (Java!)
(Mac OS, Linux, BSD, Windows, Solaris…)

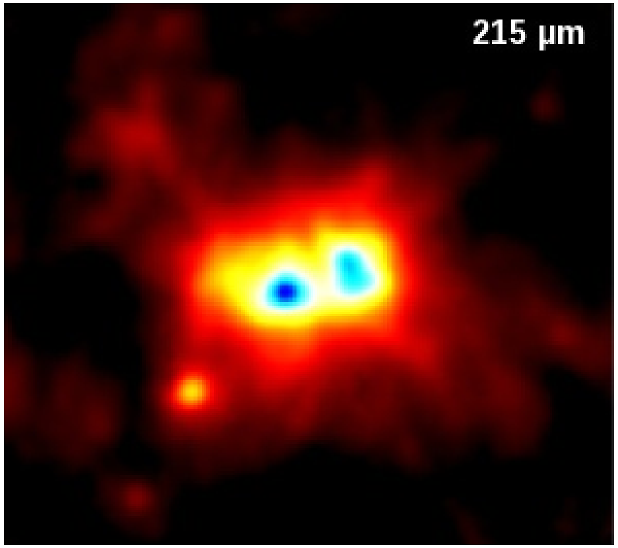


The Galactic Center at 870um by LABOCA – reduced with CRUSH

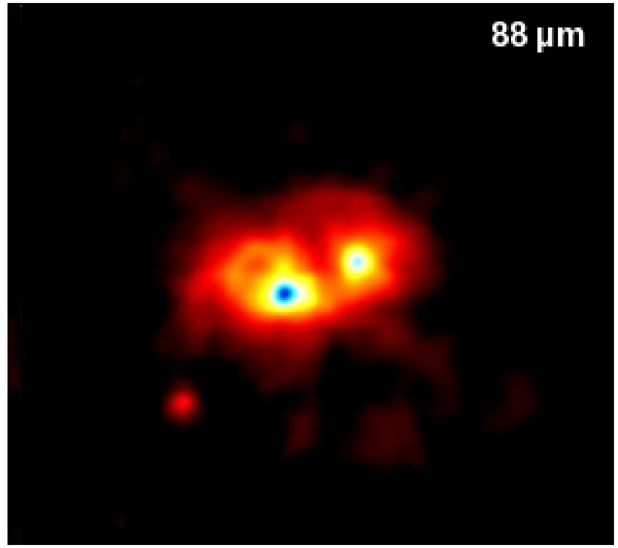


SOFIA / HAWC+ eyes on W3

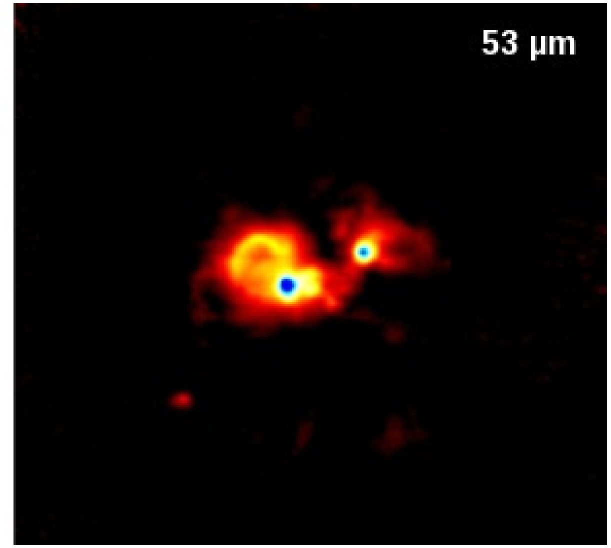
Commissioning flights, 3–5 October 2016



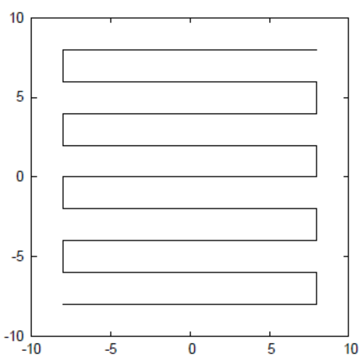
2.2 min. (elapsed time)

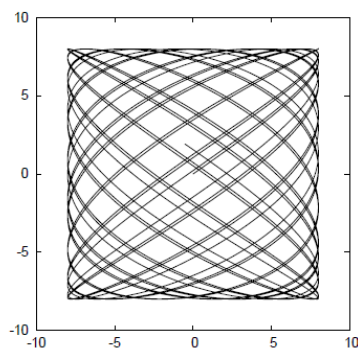


4.1 min. (elapsed time)

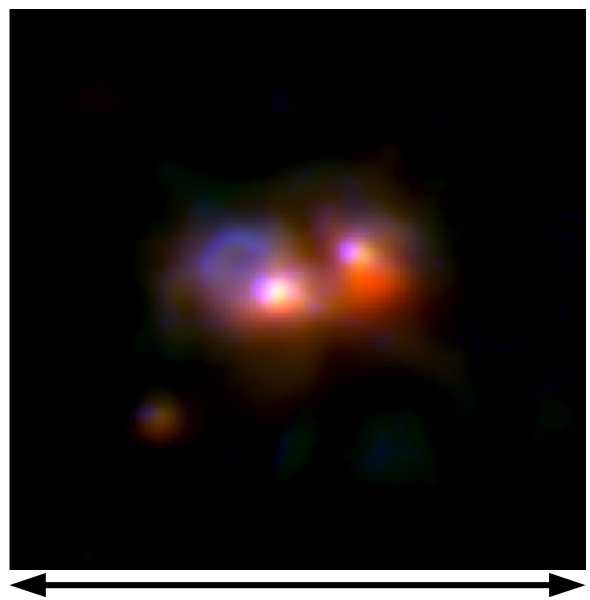


3.0 min. (elapsed time)

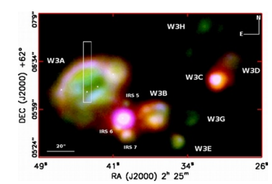




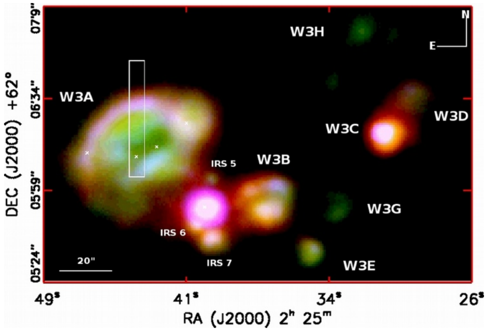
Kovács, 2008b



9’

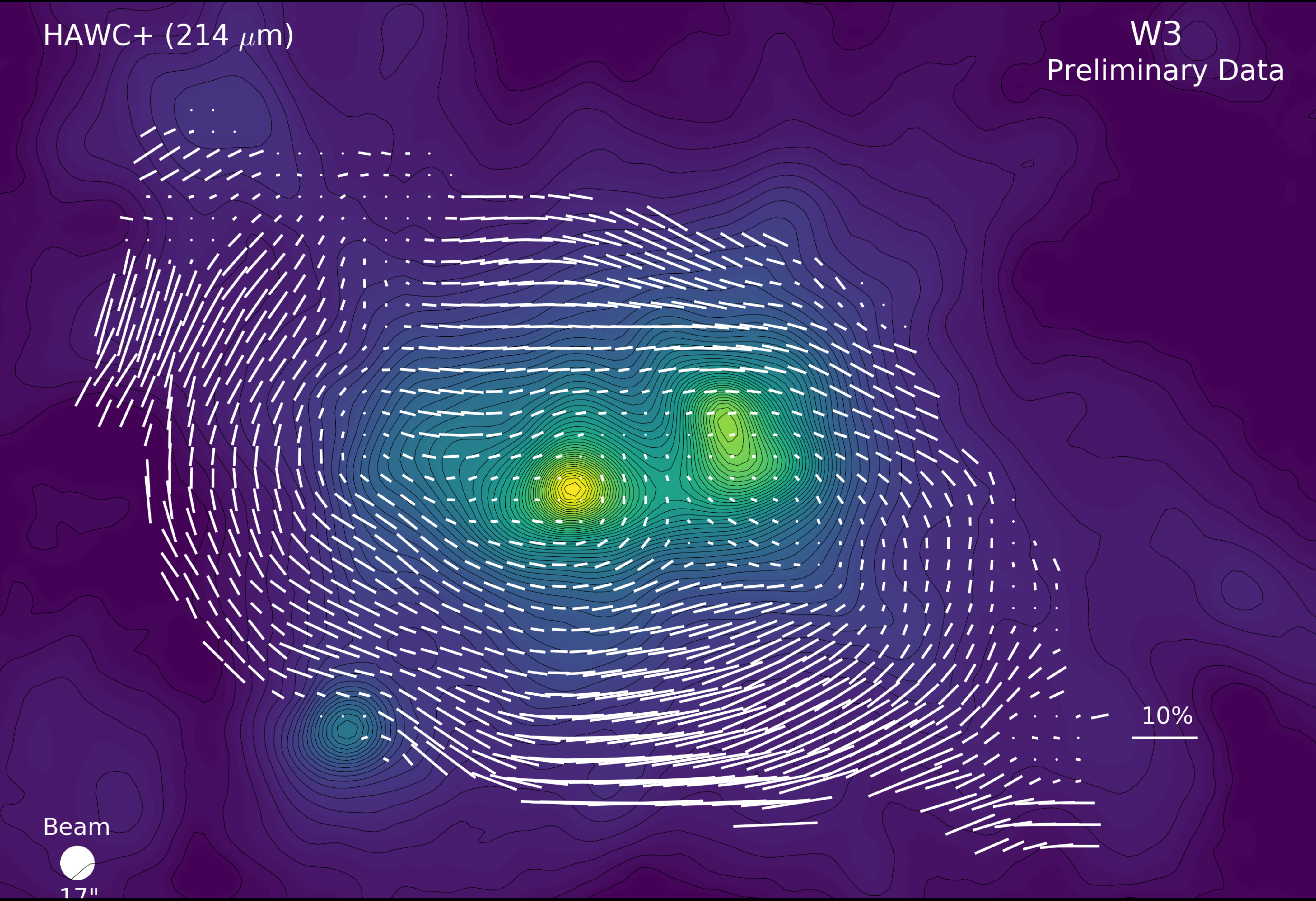


SOFIA / HAWC+ eyes on W3

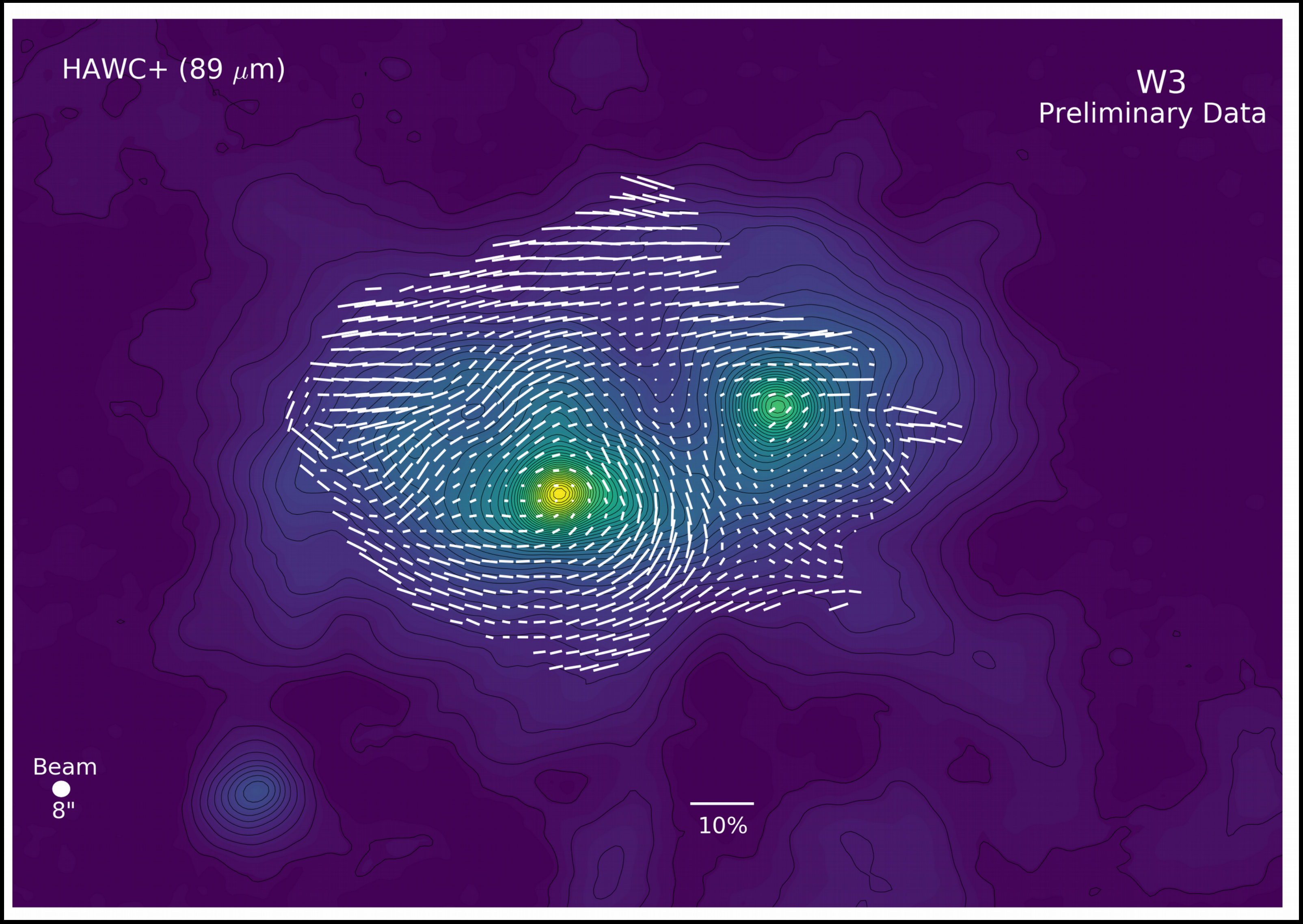


SOFIA/FORCAST
7.7/19.7/37.1 μm
(Salgado+ 2012)

SOFIA / HAWC+: first polarization results (214 um)

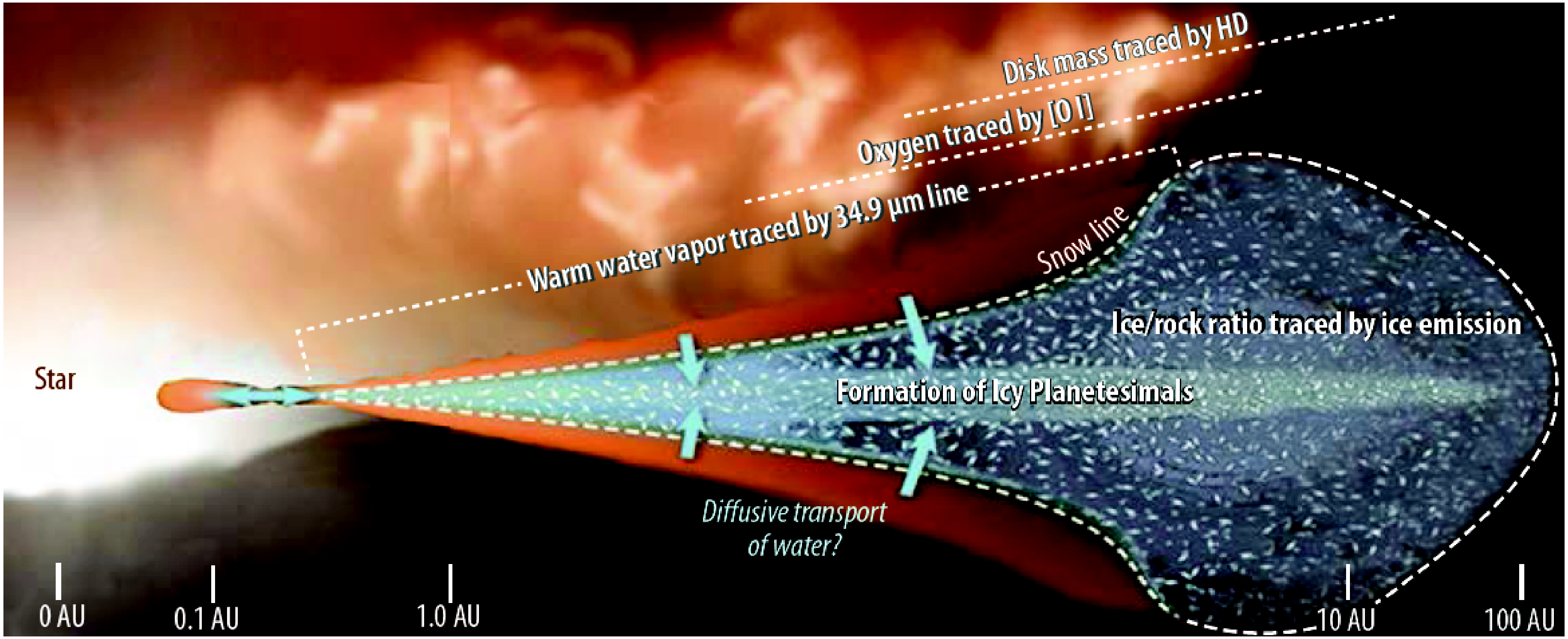


SOFIA / HAWC+: first polarization results (89 um)



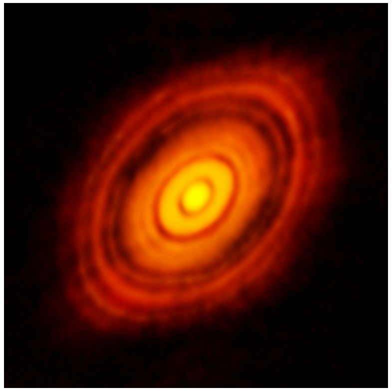
High-Resolution Mid-infrarEd Spectrometer

- Over ~ 10 million years, protoplanetary disks evolve into young planetary systems
- Bulk of mass is cold molecular gas and ice – both hard to observe
- Hinders testing & development of planet formation theories
- Mid-IR bandpass contains features from key disk constituents
- Molecular hydrogen and HD: Dominates the mass of disk
- Neutral oxygen: Strong line used to trace the kinematics of the disk
- Water vapor: How is it transported through the disk?
- Water ice: Critical for giant planet cores and perhaps Earthlike planets

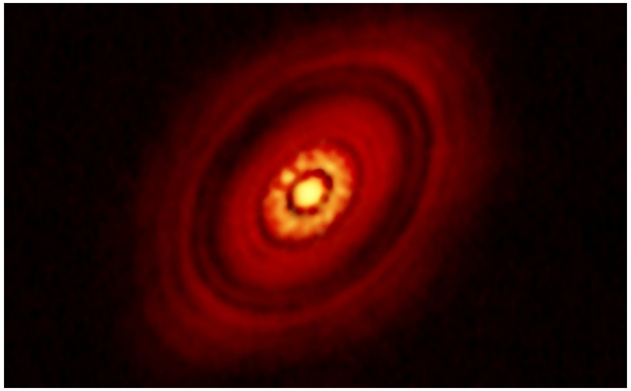


HIRMES: molecular and atomic lines

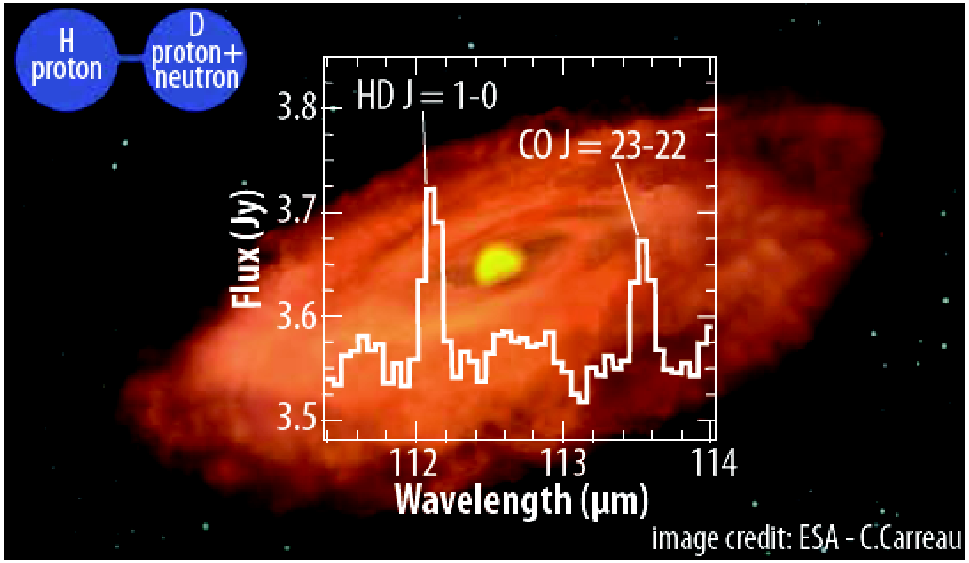
HL Tau

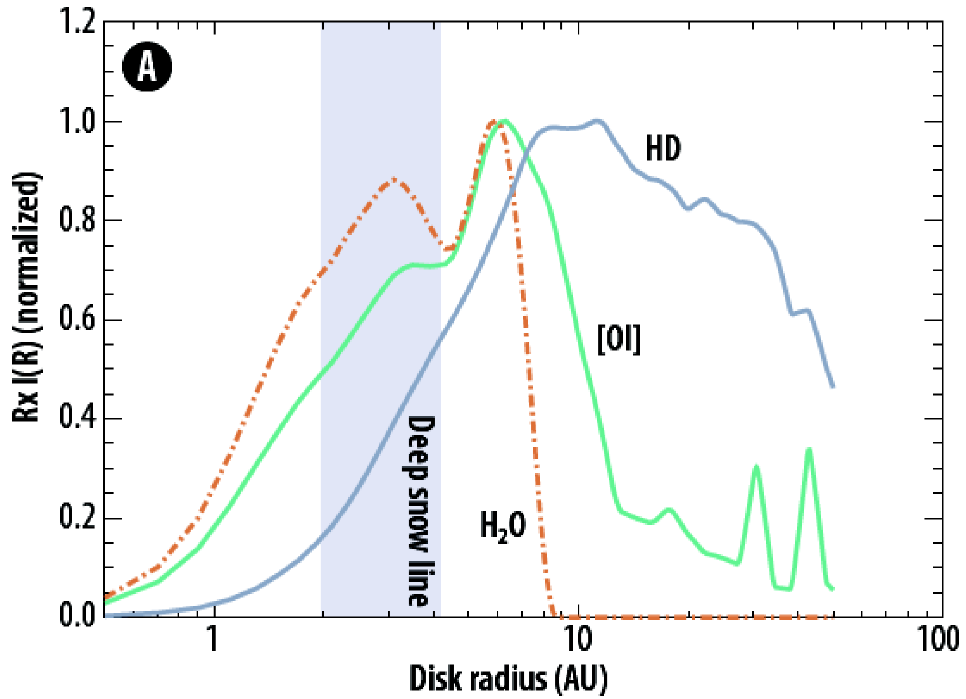


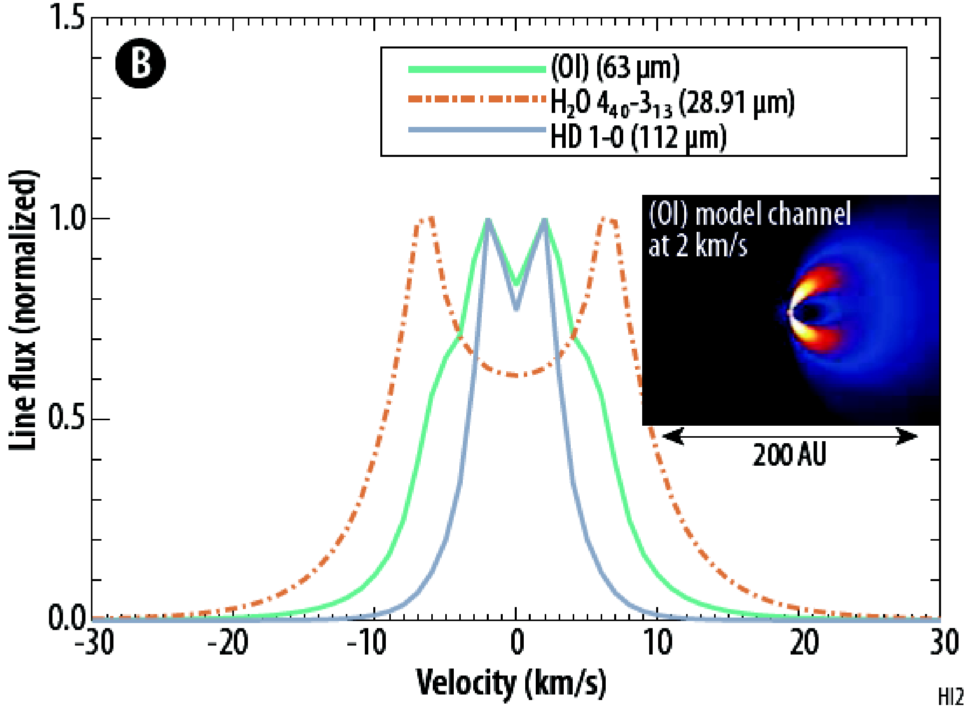
ALMA



VLA

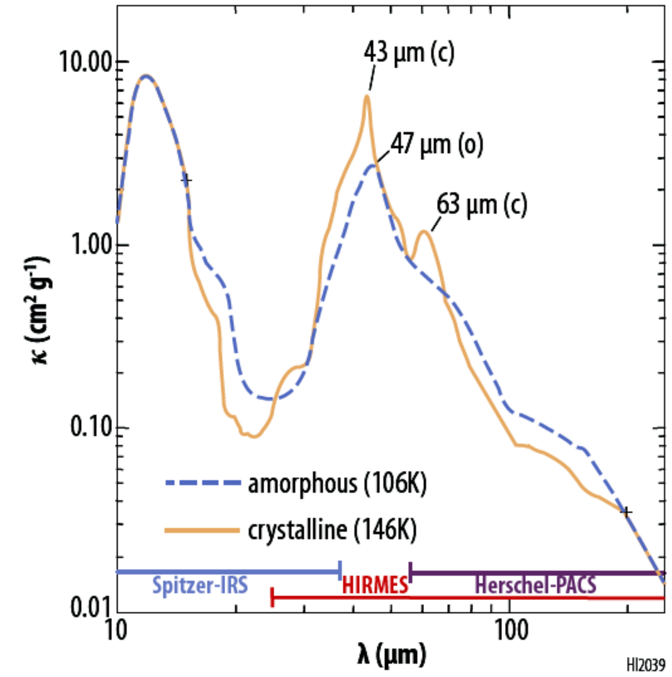




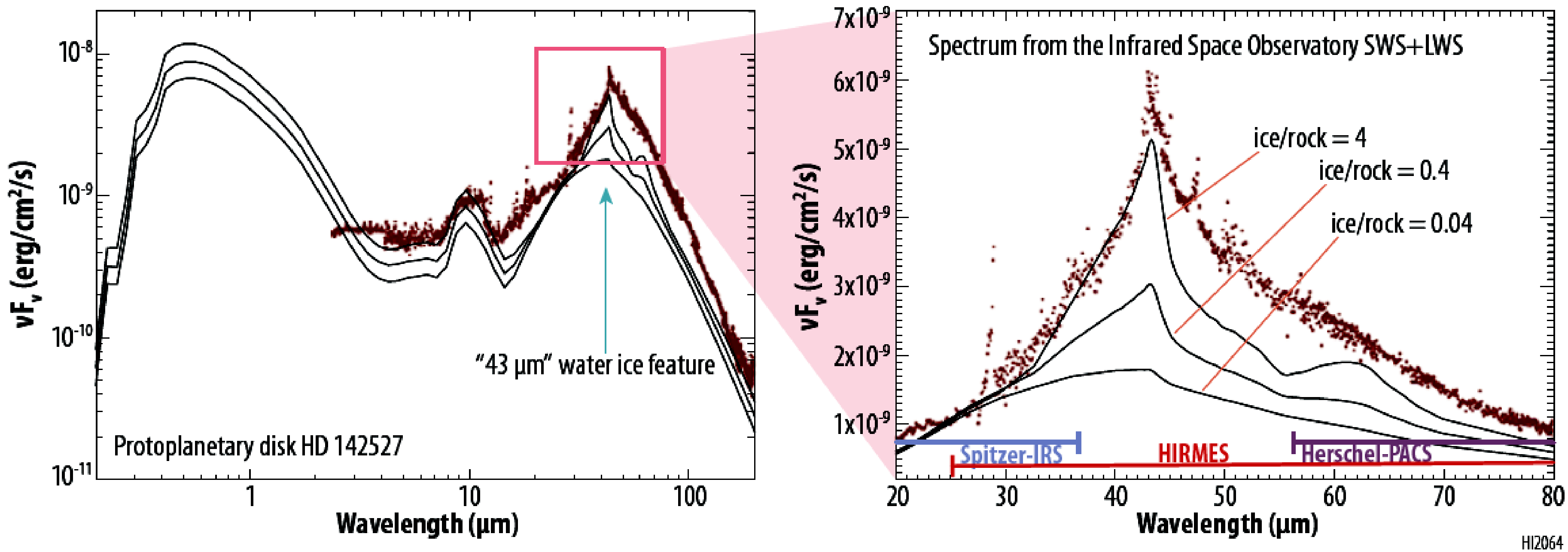


HIRMES: ice

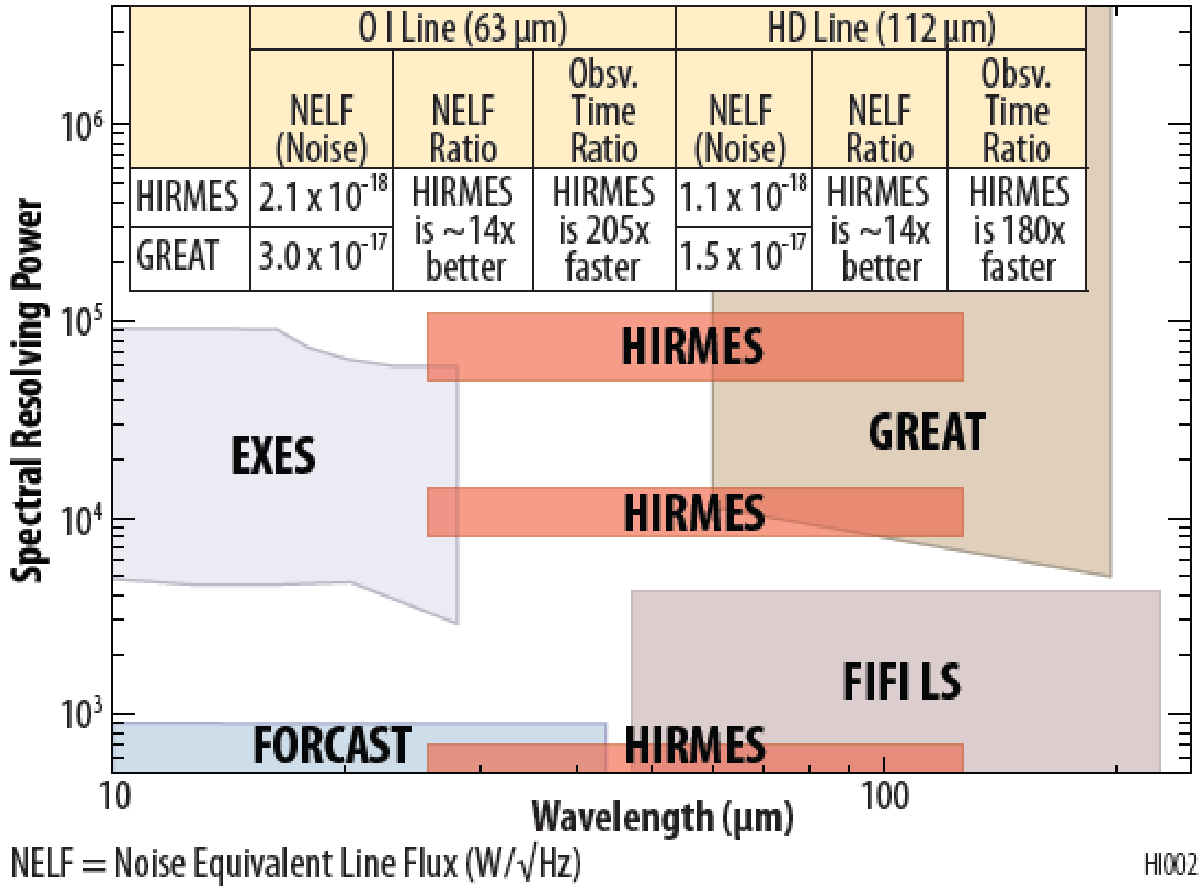
Ice composition



ice / rock ratios

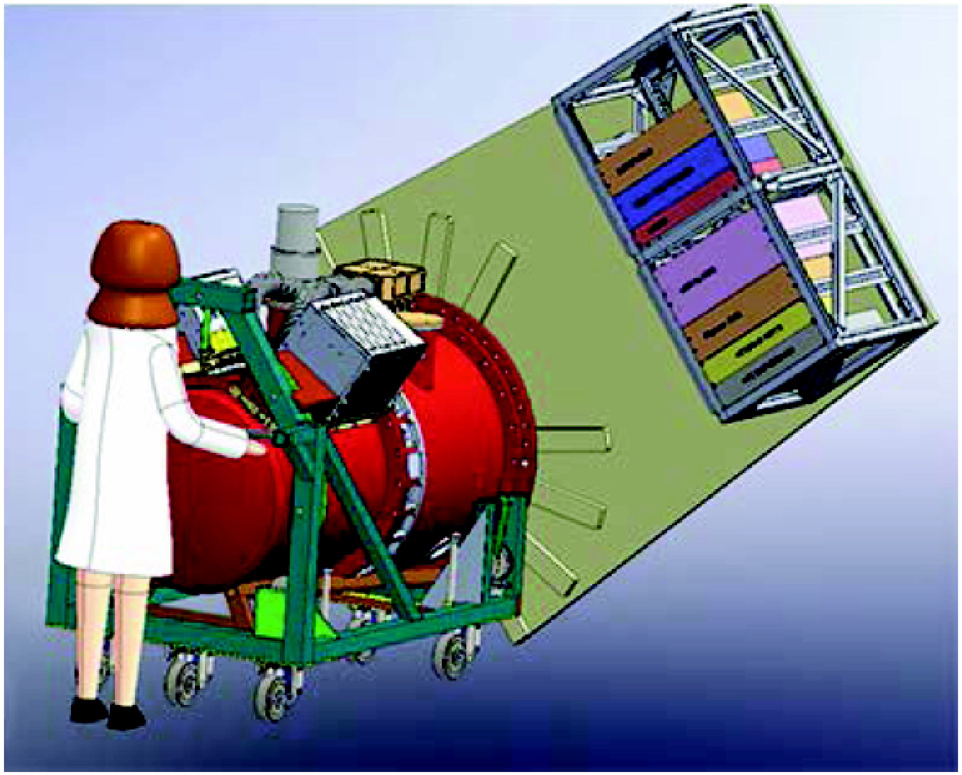


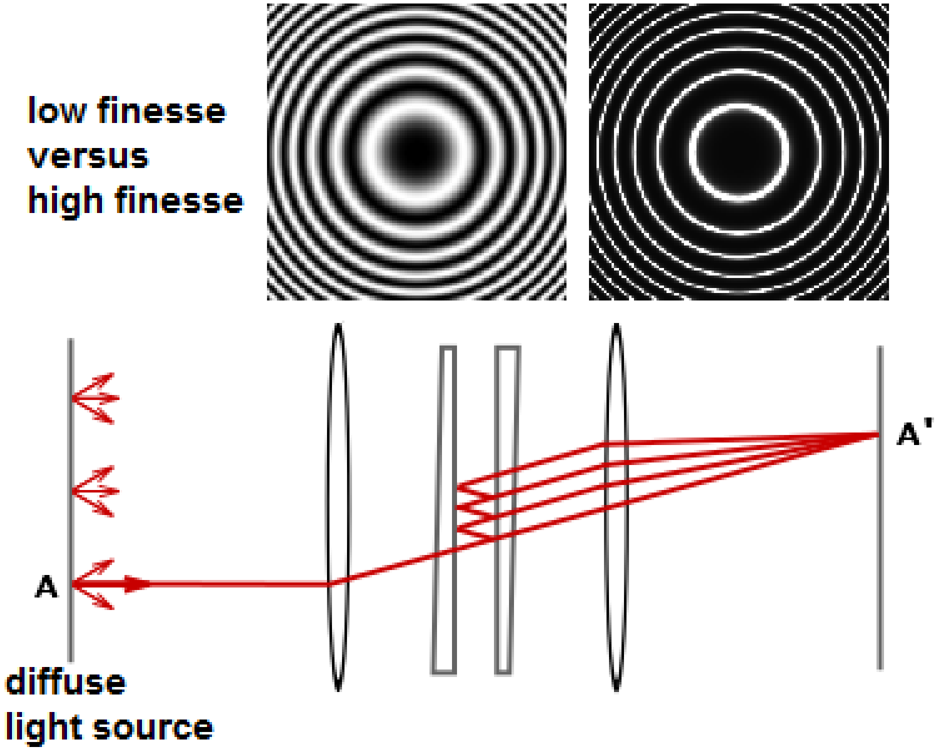
HIRMES: capabilities



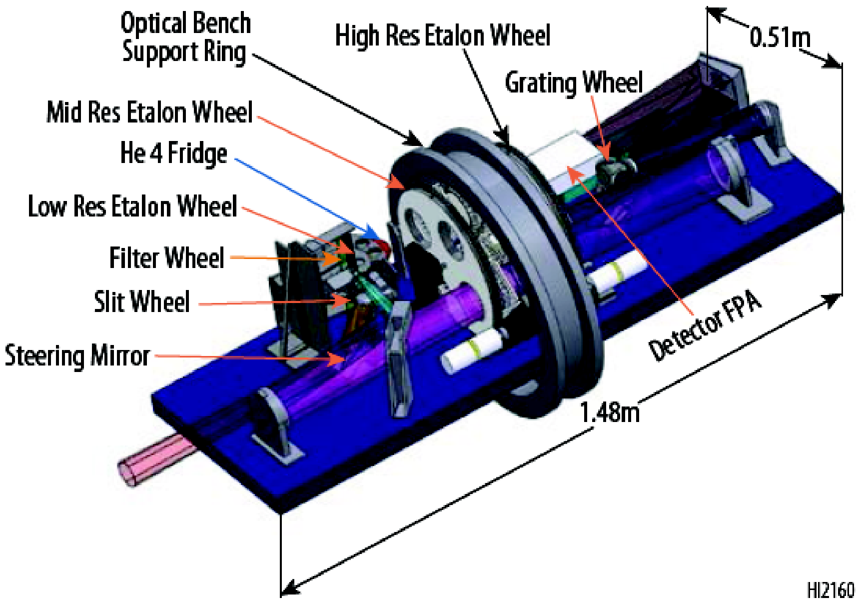
Parameters	High-Res	Mid-Res	Low-Res	Spectral Imaging
Sensitivity (5σ, 1 hour)	≤ 1 x 10^{-17} W/m²	~1 x 10^{-16} W/m²		
Resolving Power, R = λ/δλ	50,000 – 100,000	12,000	600	2,000
Angular Resolution	Diffraction limited			
Slit Size (arcsec)/FOV	Length: 139.5″; Width: 8.7″, 6.1″, 4.2″ and 3.0″			113.0″ x 106.8″ (FOV)
Spectral Range	25–122 µm			Selected lines*

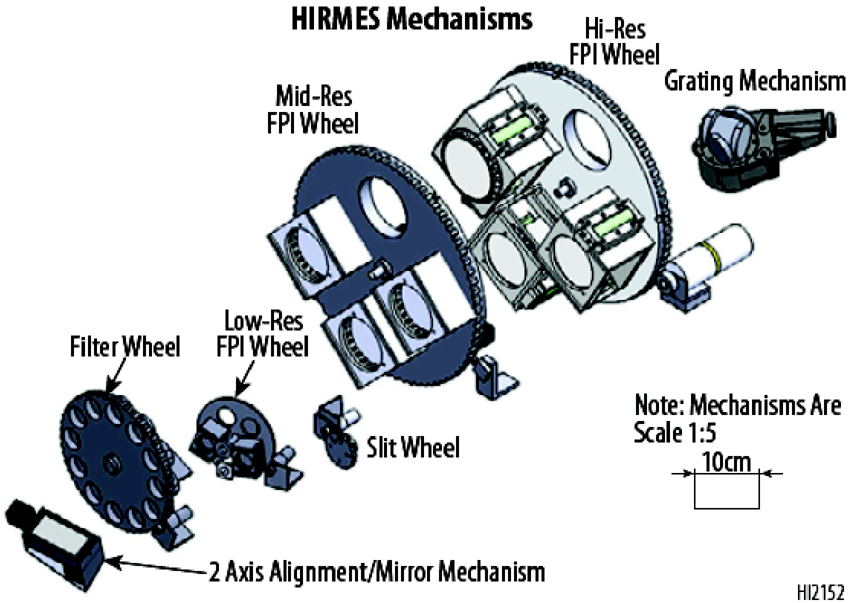
HIRMES: overview

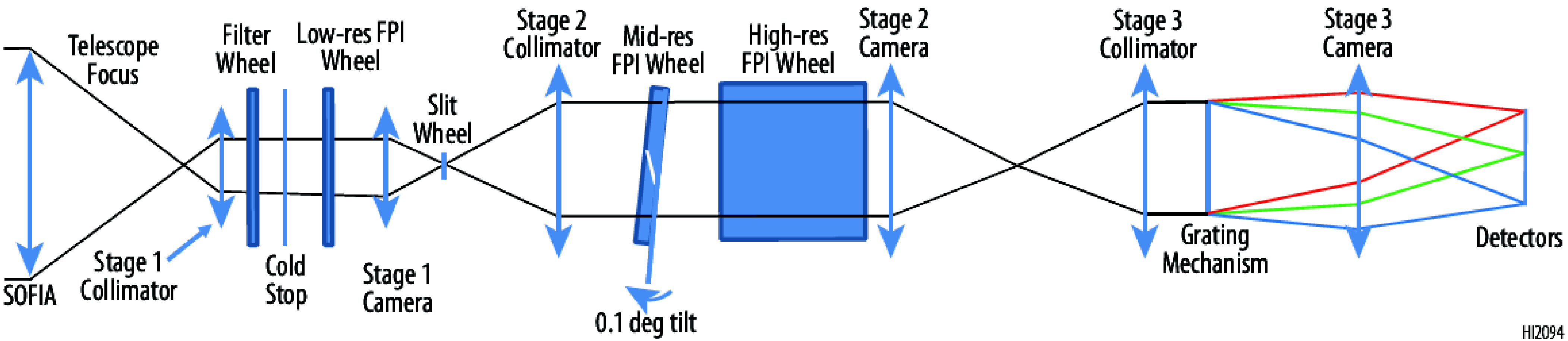




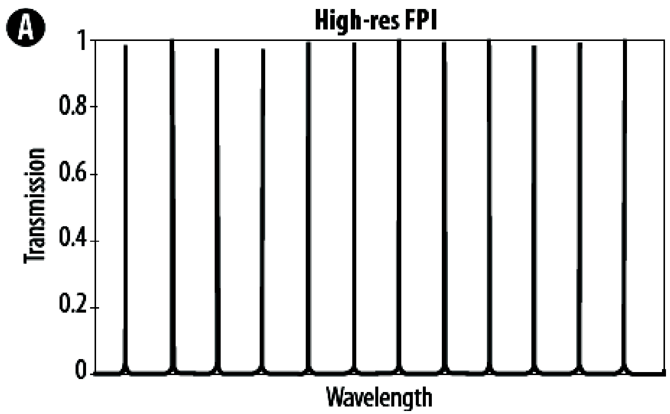
HIRMES: schematic





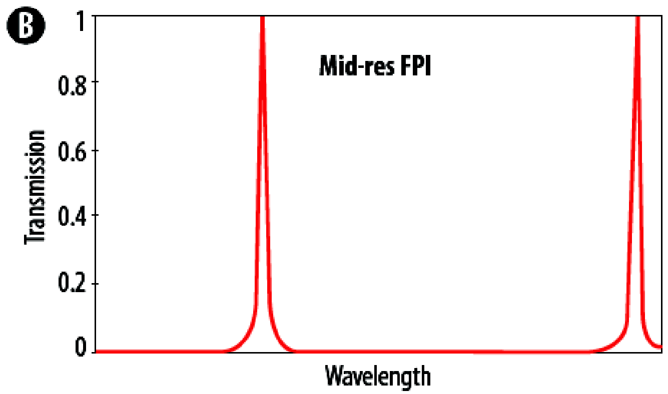


HIRMES: how it works...

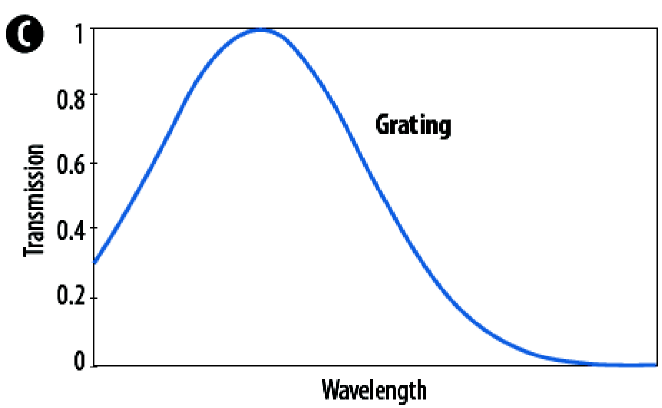


Finesse ~40–60
Order ~2400

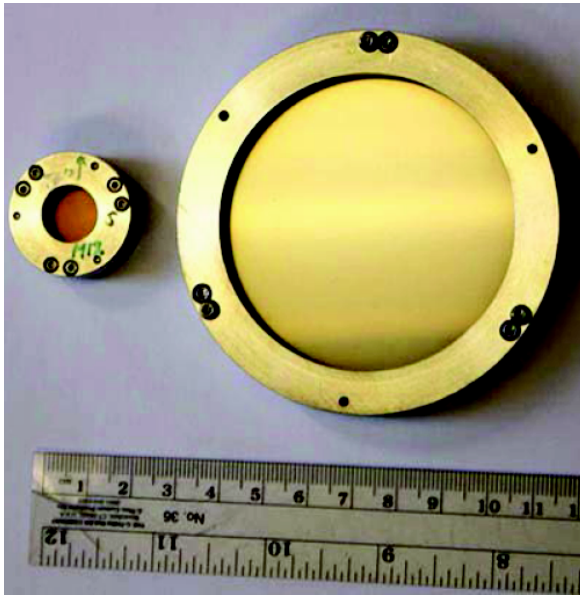
R ~ 100,000

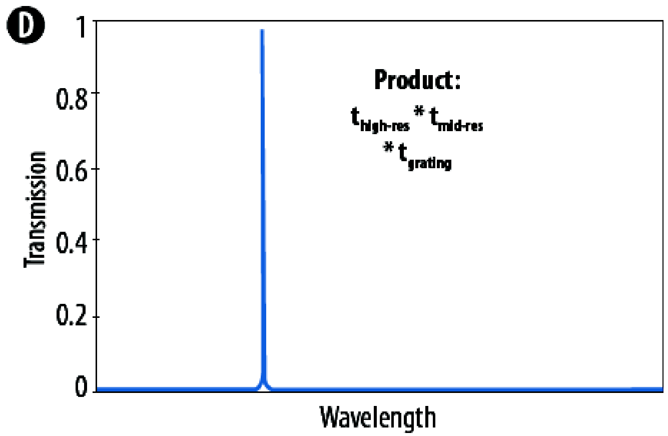


R ~ 2,000



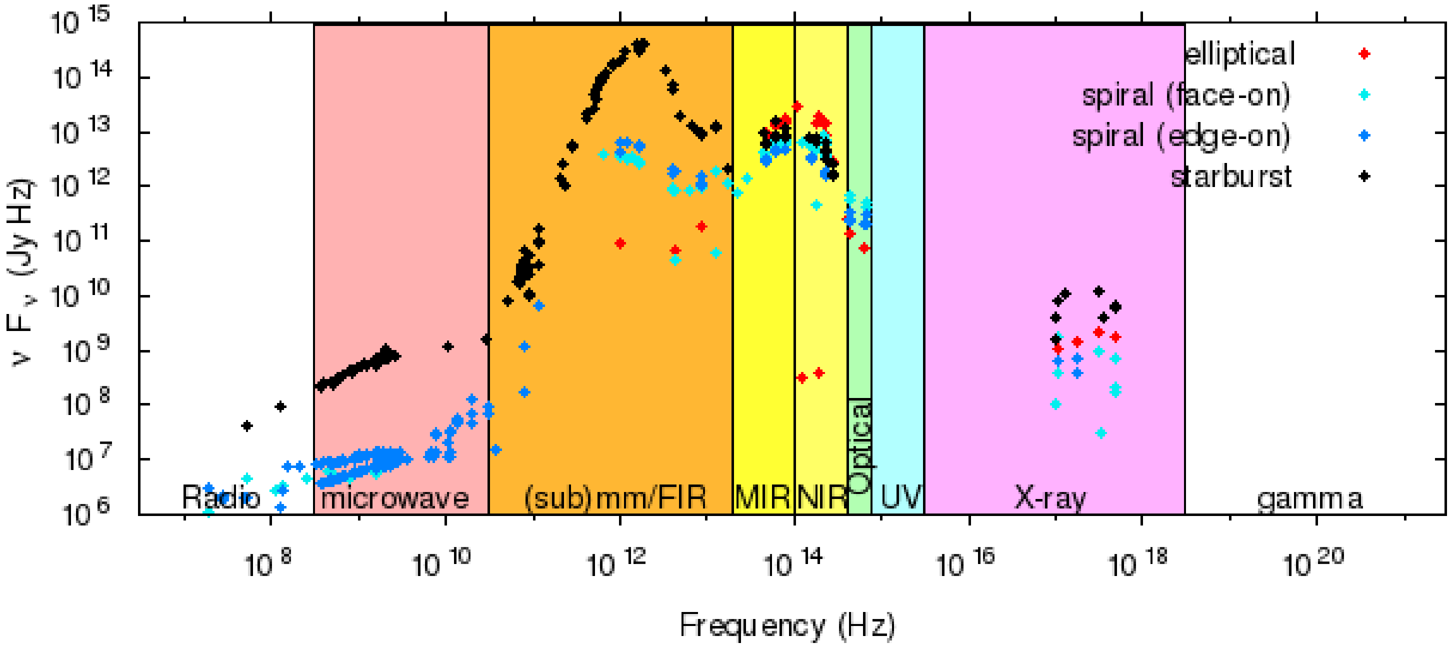
R ~ 600

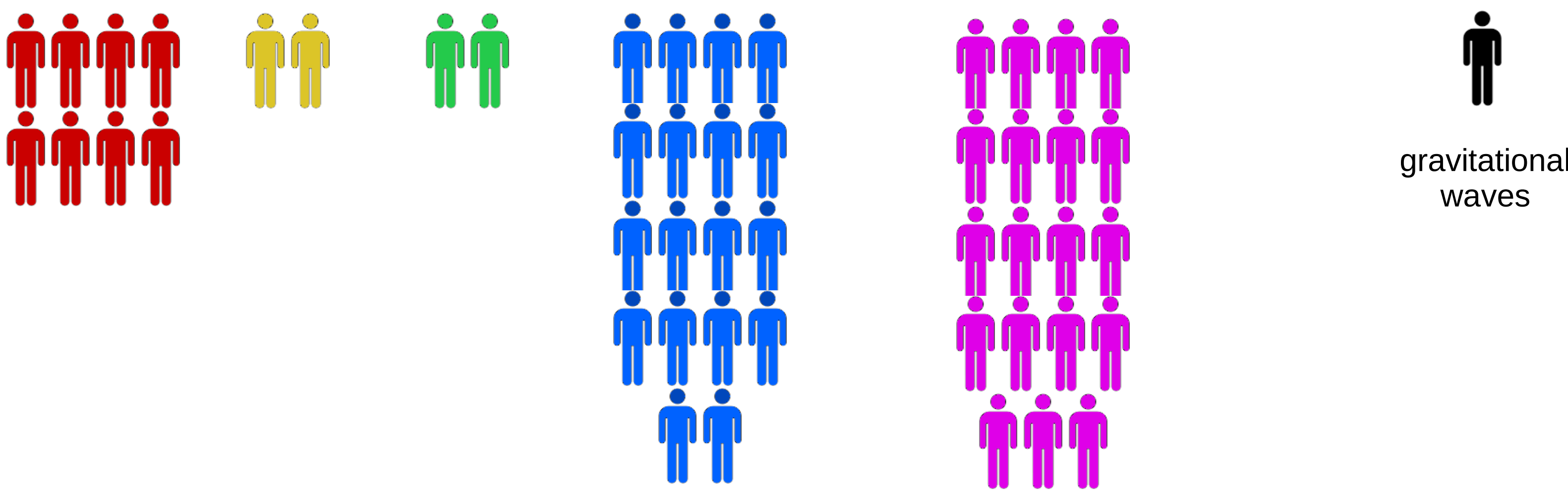




Summer 2019

Astrophysics landscape





Based on ADS keyword searches in titles…

FIR / (sub)mm specialties

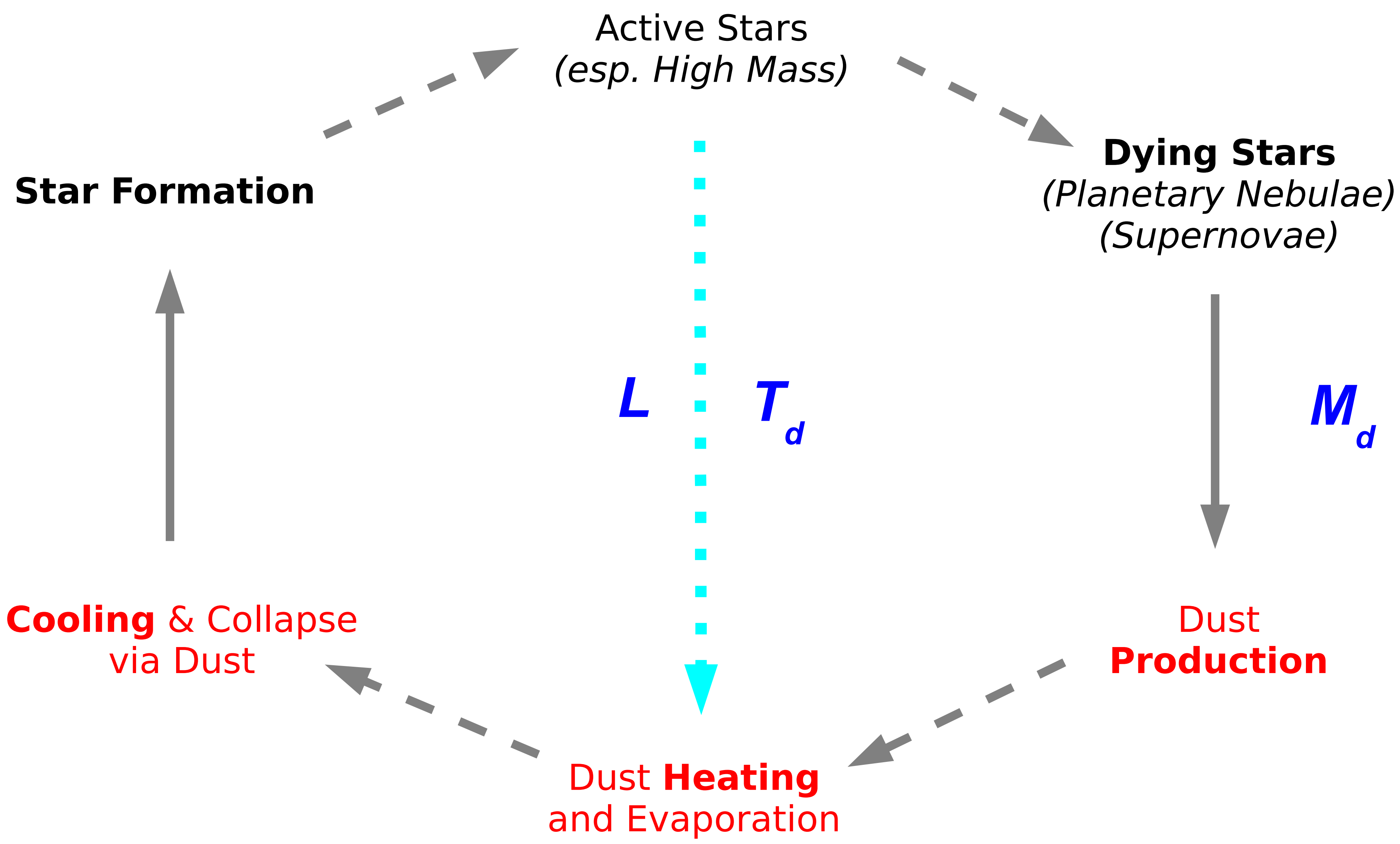
(Obscured) Star-formation

Structure formation / evolution

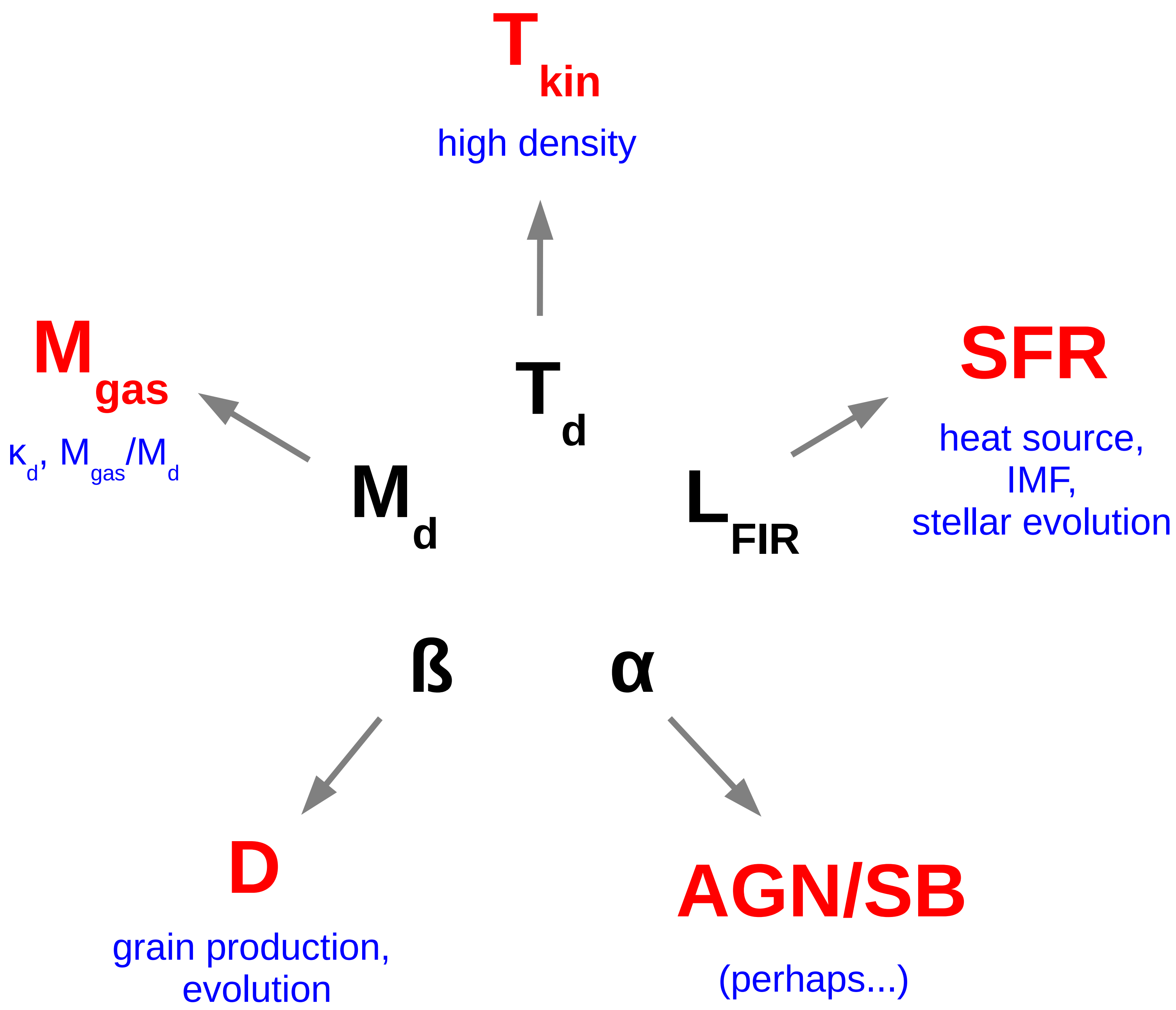
flat selection – from local Universe to high-z

THE END

Dust life cycle



What we can learn from dust



Cosmic timeline