Far-infrared Frontiers

Structure formation and evolution on all scales

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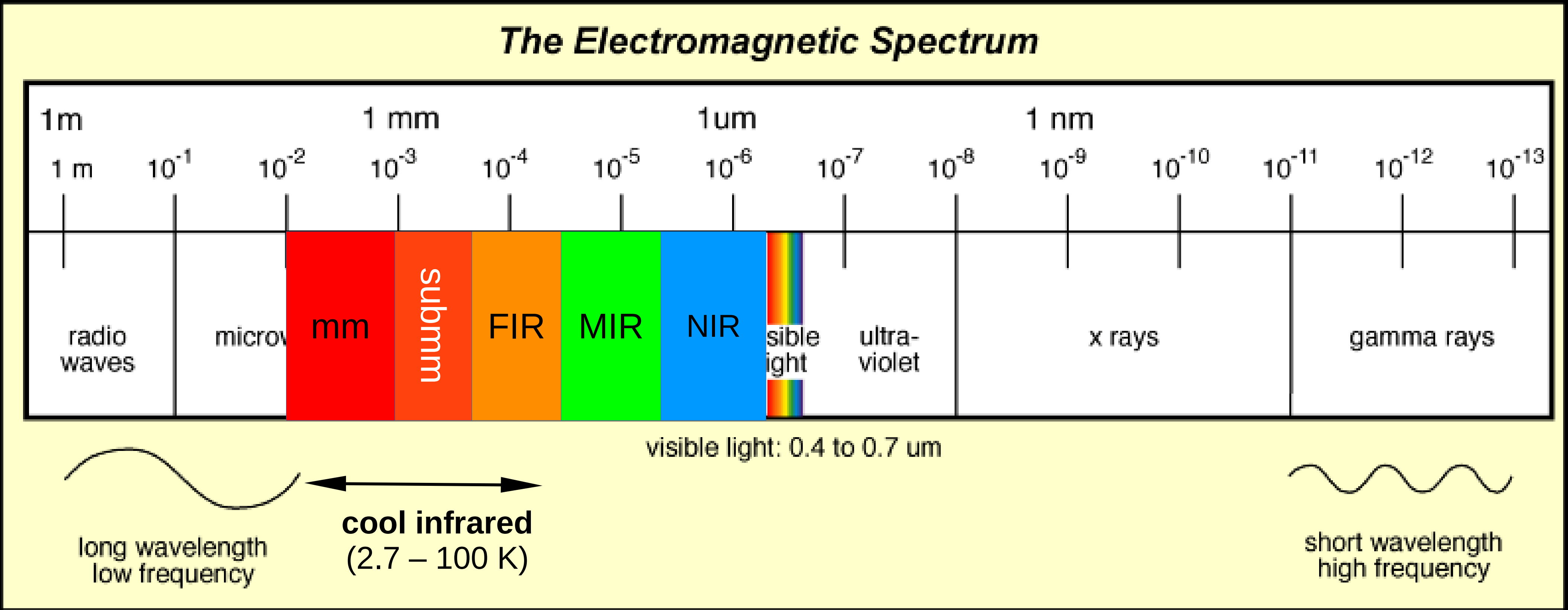
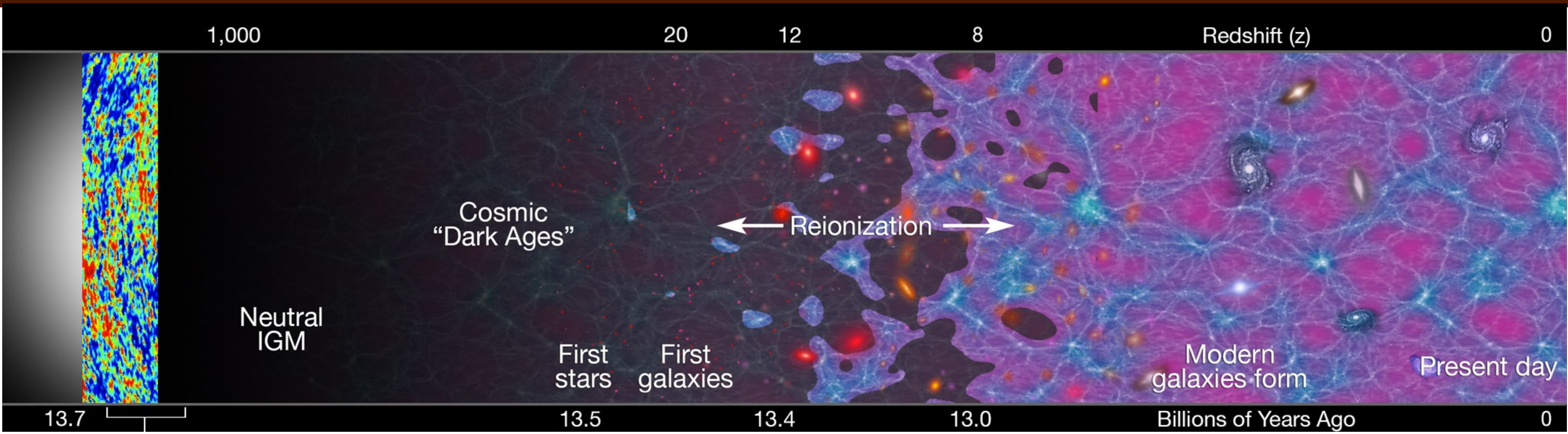
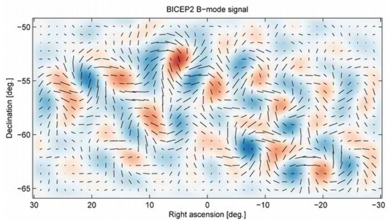
The far side of infrared



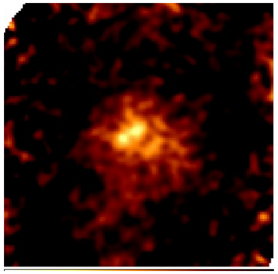
Structure formation, evolution & FIR



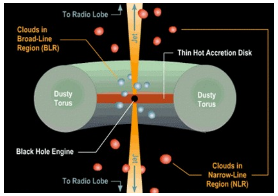
Star forming
galaxies
(10um – 3 mm)



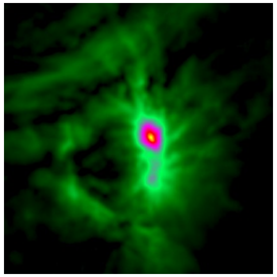
CMB
(1-3 mm)



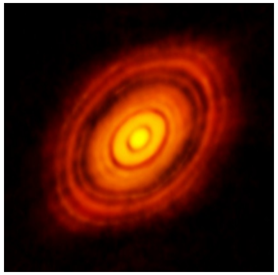
clusters
(1-3 mm)



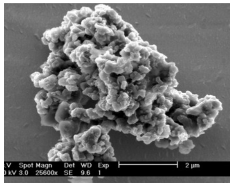
AGN
(Type II)



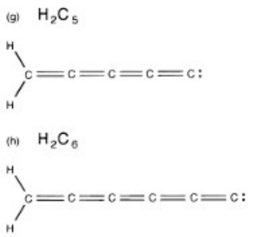
Star-forming
Regions



Protoplanetary
disks



dust

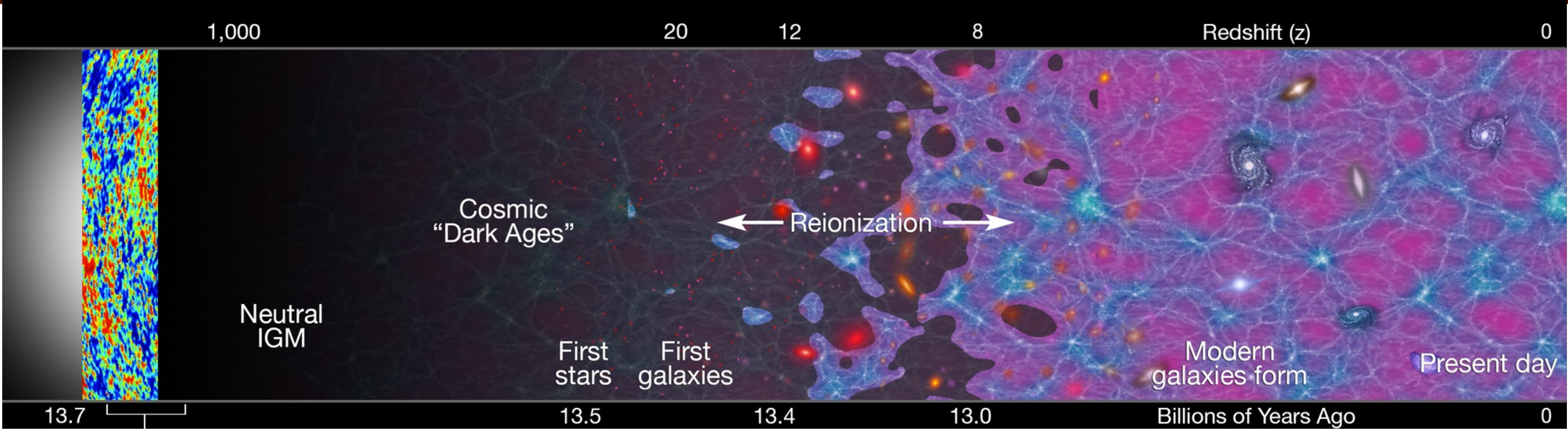


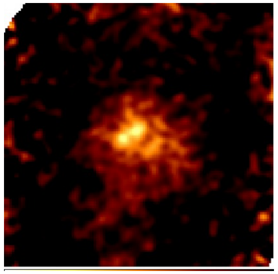
C—O

H_2

molecules

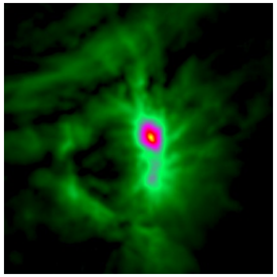
Structure formation & FIR



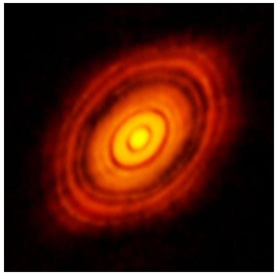


clusters
(1-3 mm)

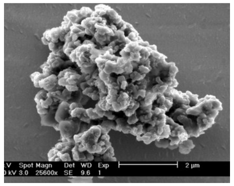
Star forming galaxies
(10um – 3 mm)



Star-forming Regions



Protoplanetary disks



dust

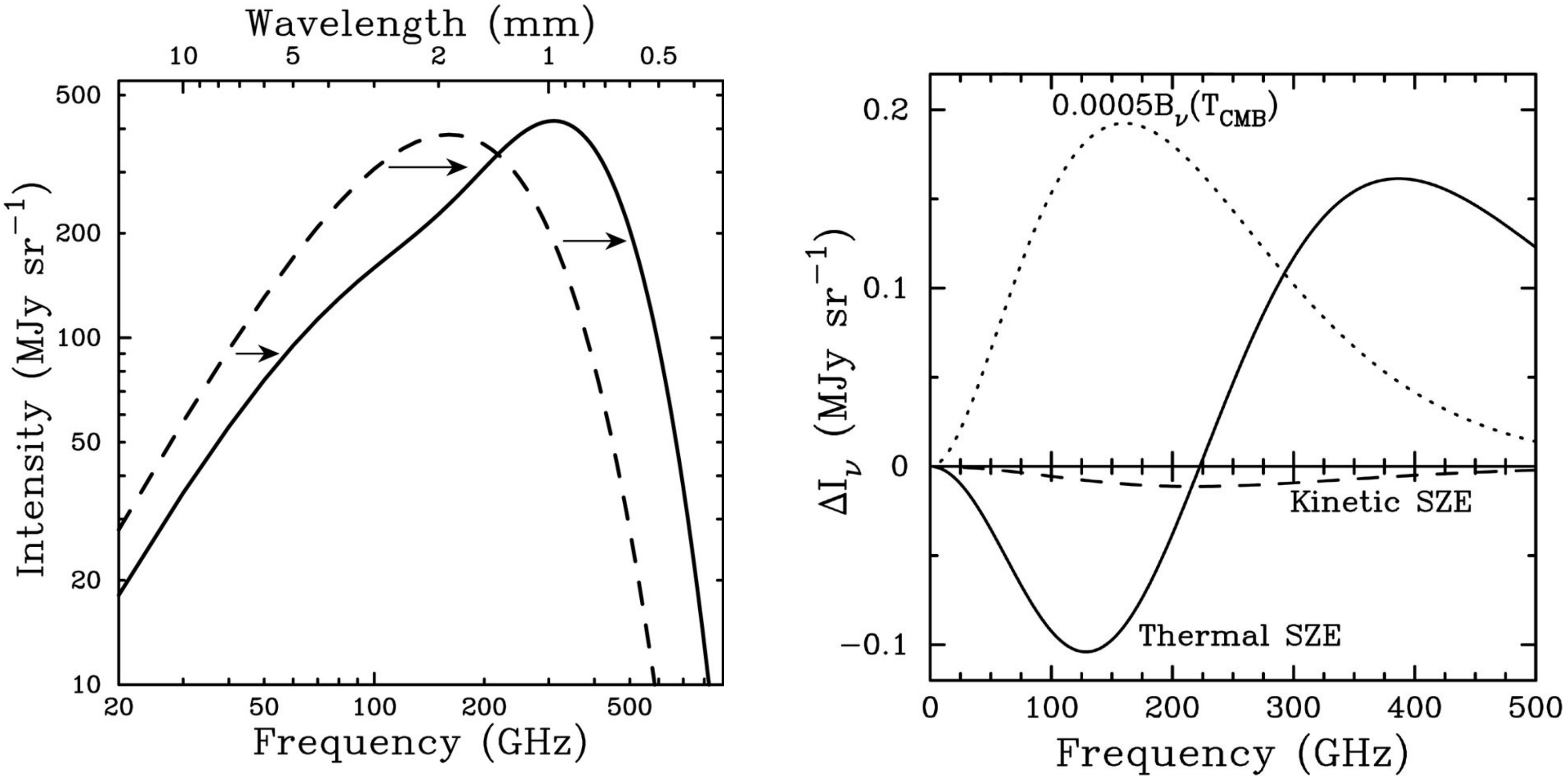
Outline

1. Sunyayev-Zel’dovich clusters
2. Starburst galaxies
3. SOFIA / HAWC+ (polarization)
4. SOFIA / HIRMES (planetary disks)

Part I.

Sunyayev–Zel’dovich Clusters

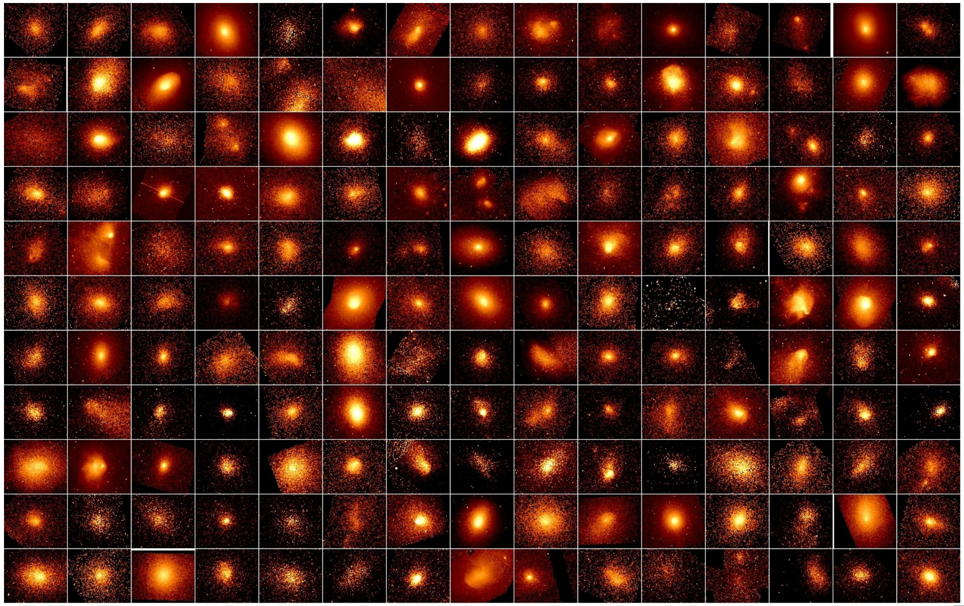
Sunyayev-Zel'dovich effect



S-Z clusters

Planck

Chandra-Planck clusters

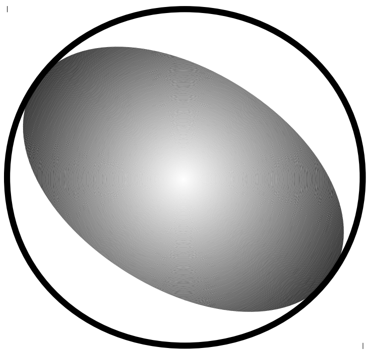


SPT

ACT

SZA

S-Z: what's next

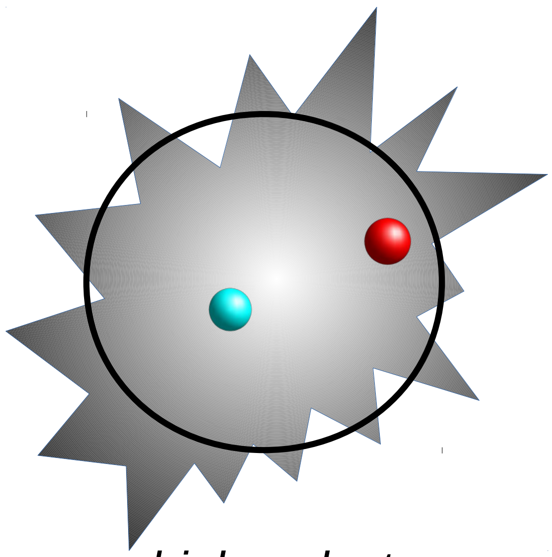


We assume…

Virialized (fully formed)

Relaxed (no substructure)

No bright mm-wave sources embedded



Nevertheless...

Mergers and interactions

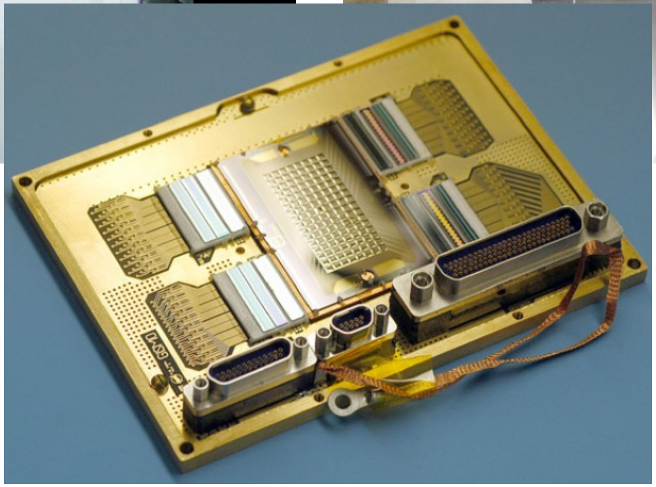
Disturbed

Brightest Cluster Galaxies

Lensed high-z galaxies

GISMO at the IRAM 30-m

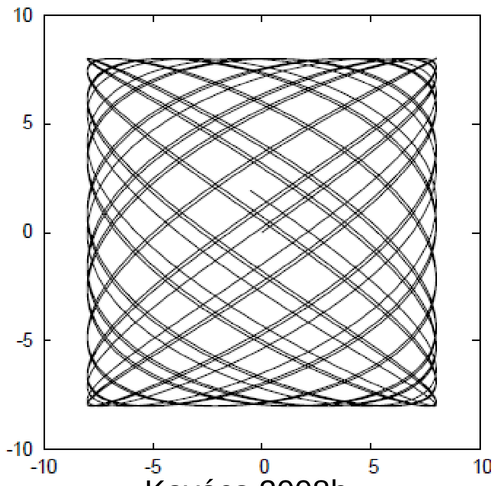
GISMO



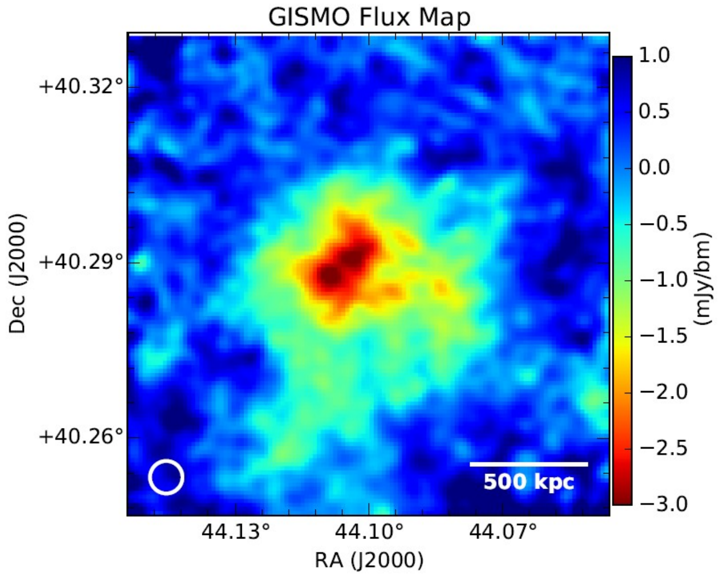
Staguhn et al. 2008

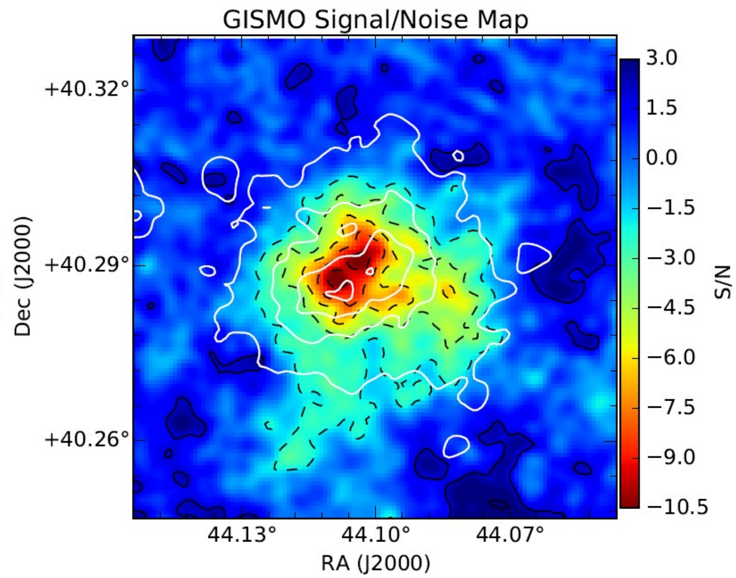
Resolved S-Z: PLCK G147.3-16.6

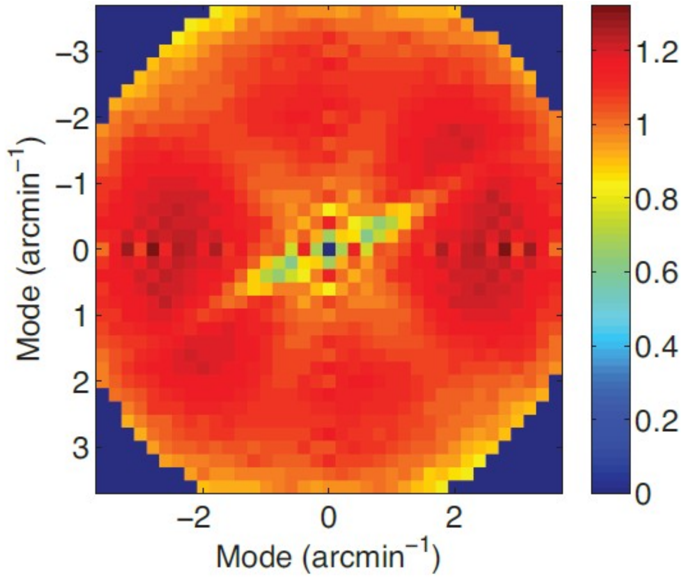
Mroczkowski, Kovács, et al. (2015)

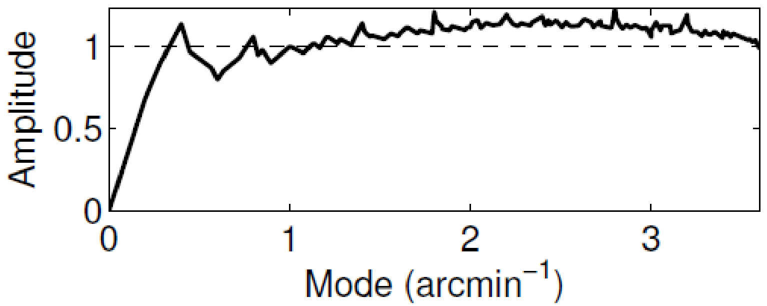


Kovács 2008b

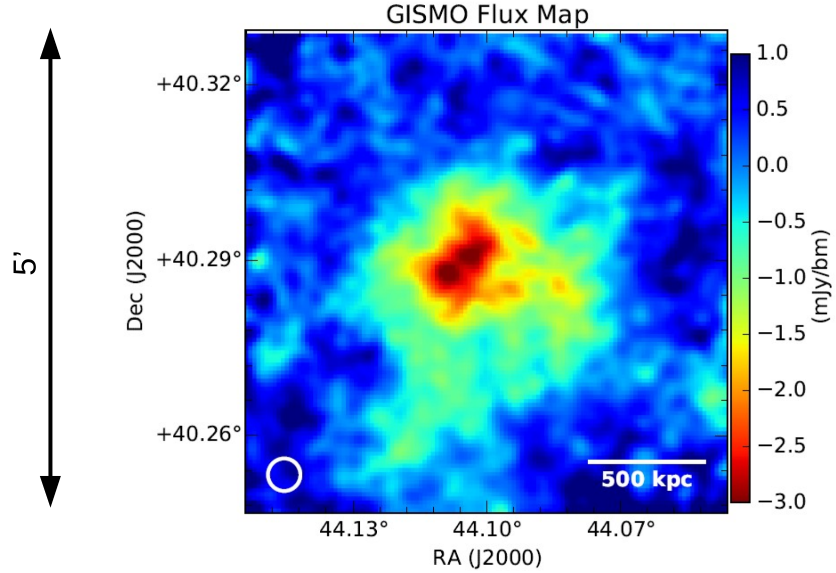


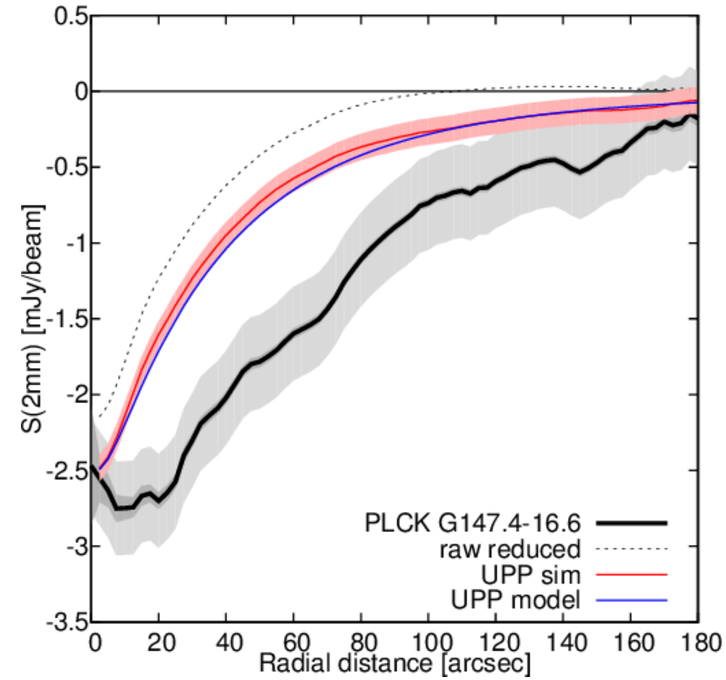


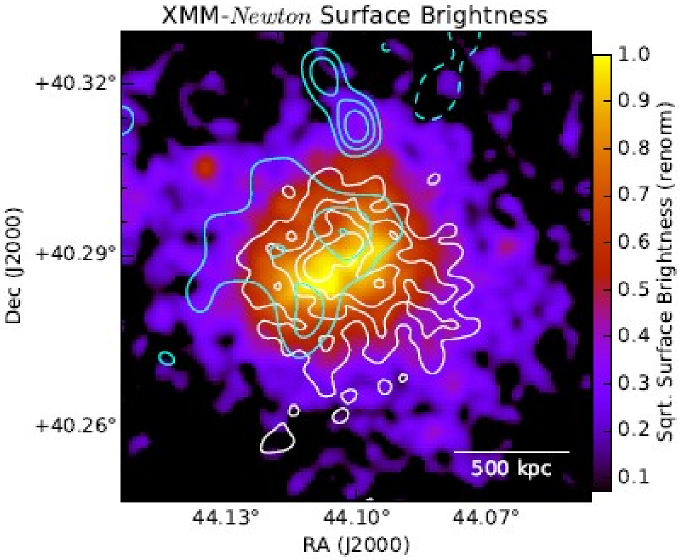


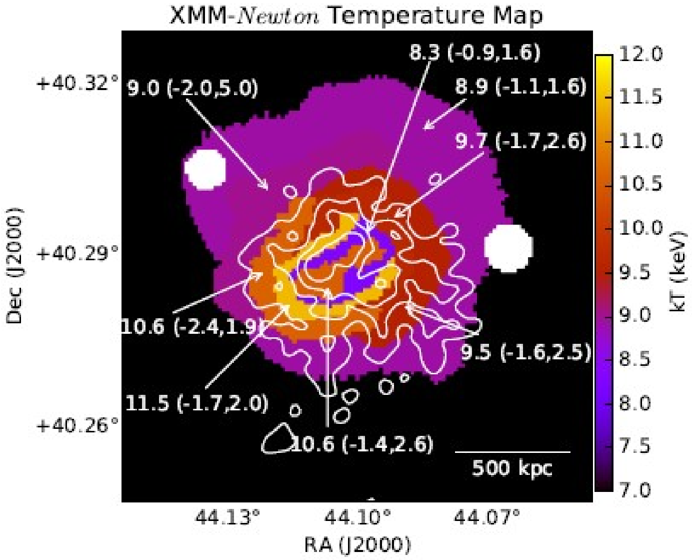


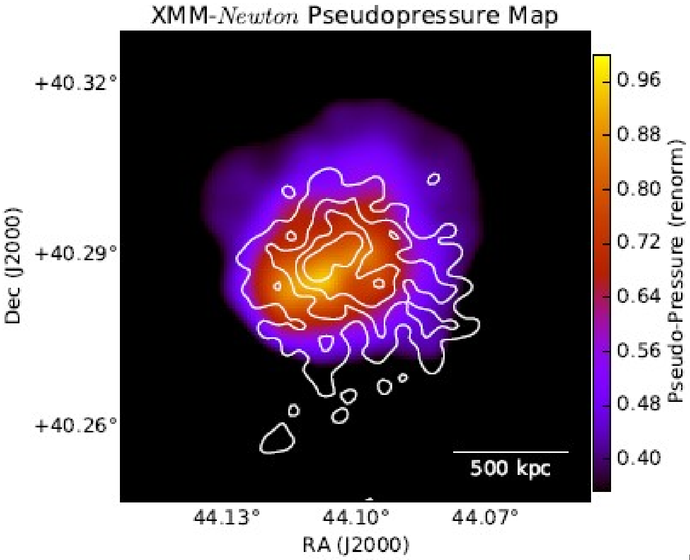
Resolved S-Z: PLCK G147.3-16.6



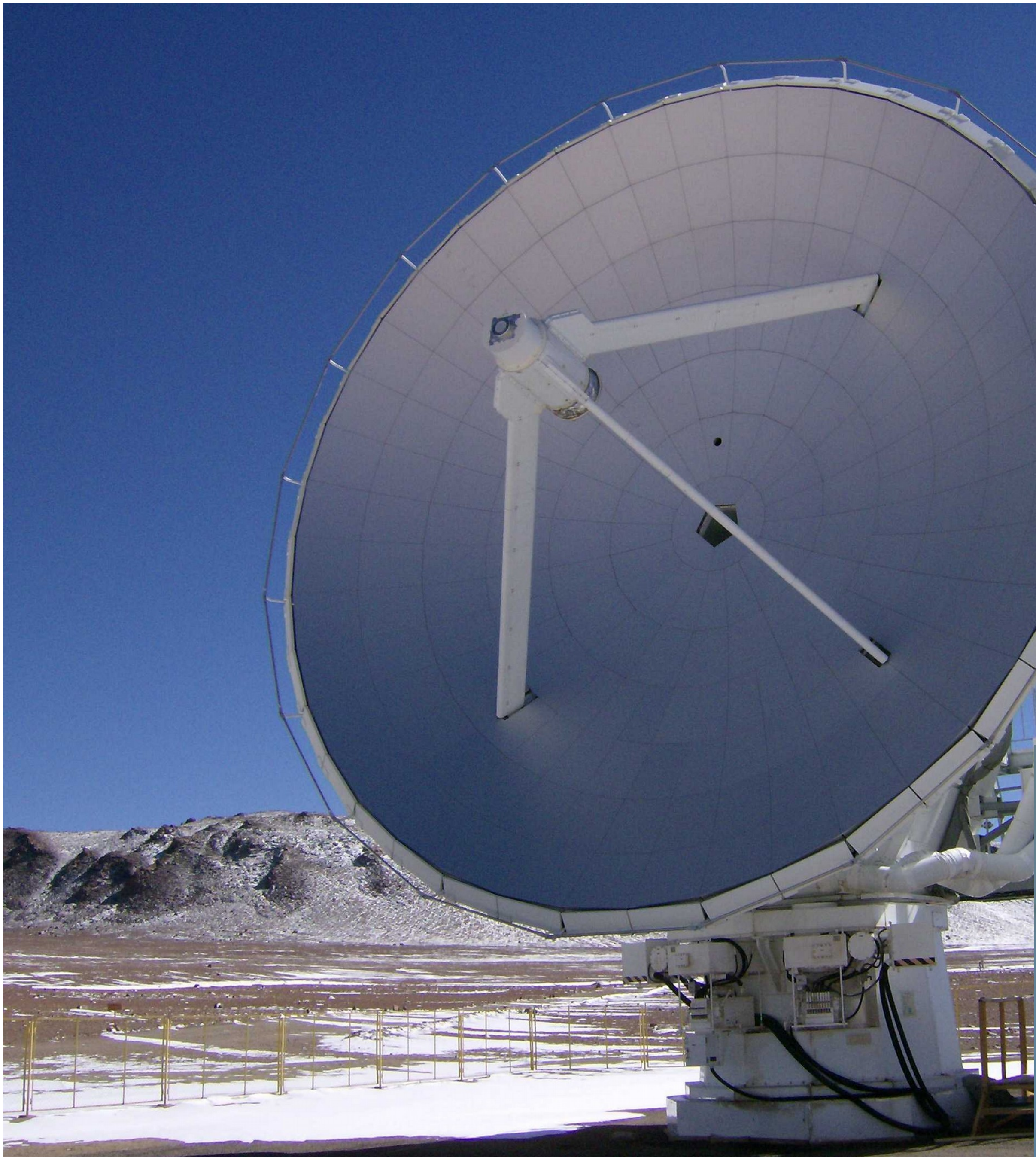




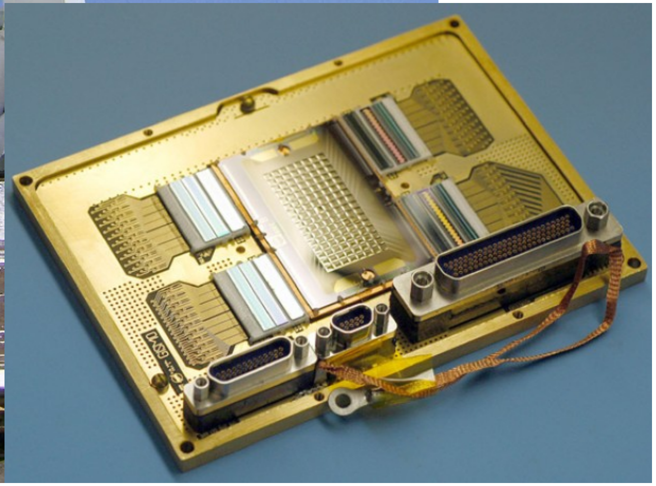




to be continued on the LMT(?)...



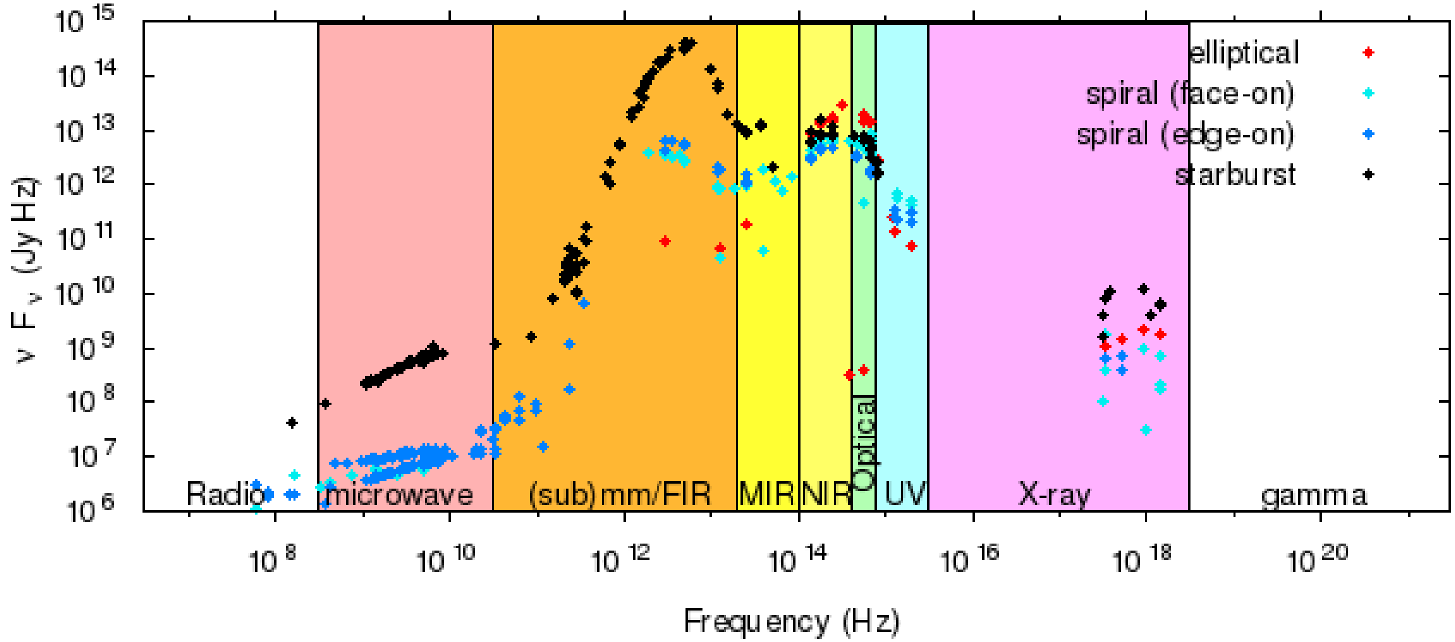
an improved GISMO!



Part II.

Star-forming galaxies

Galaxy SEDs

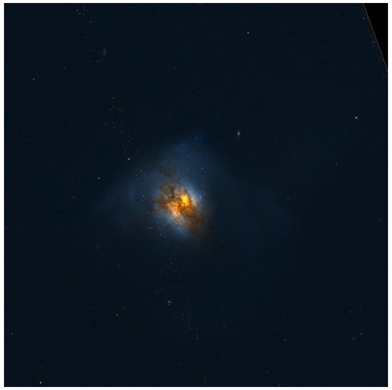


NGC 4365

E6 elliptical

M 66
NGC 3627

NGC 253

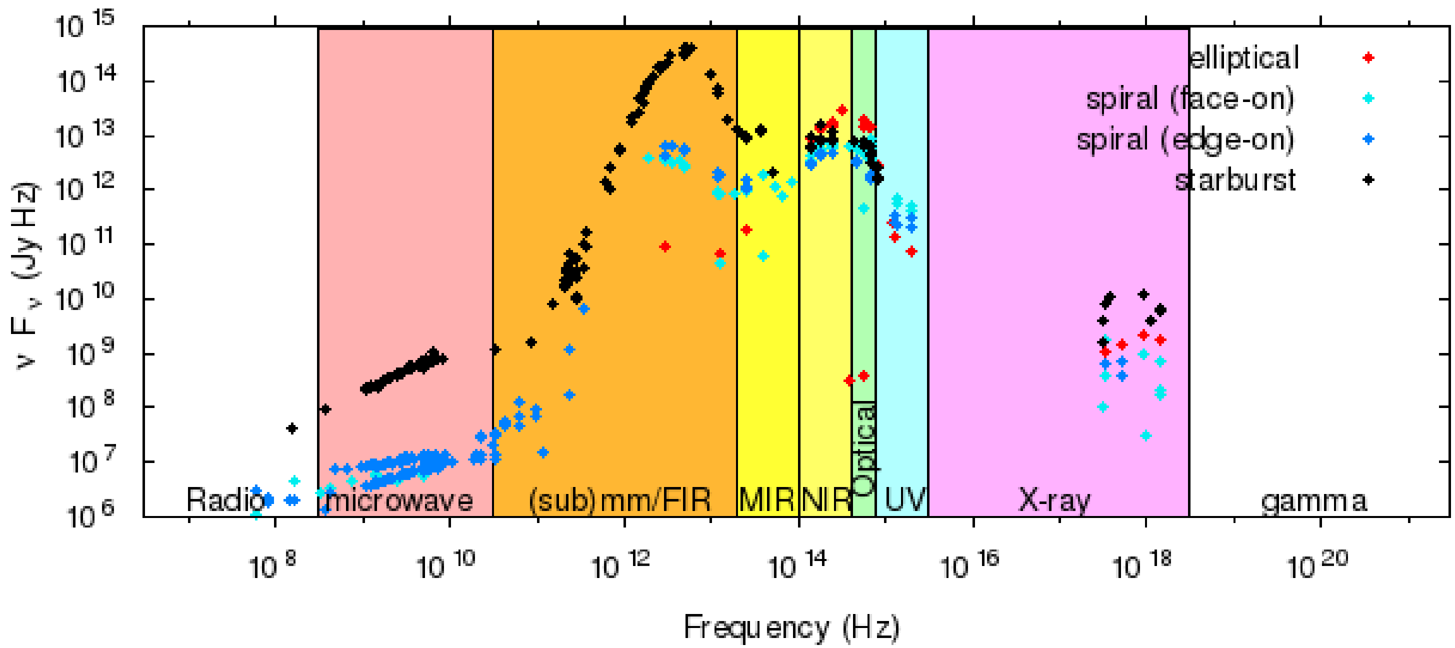


Arp 220

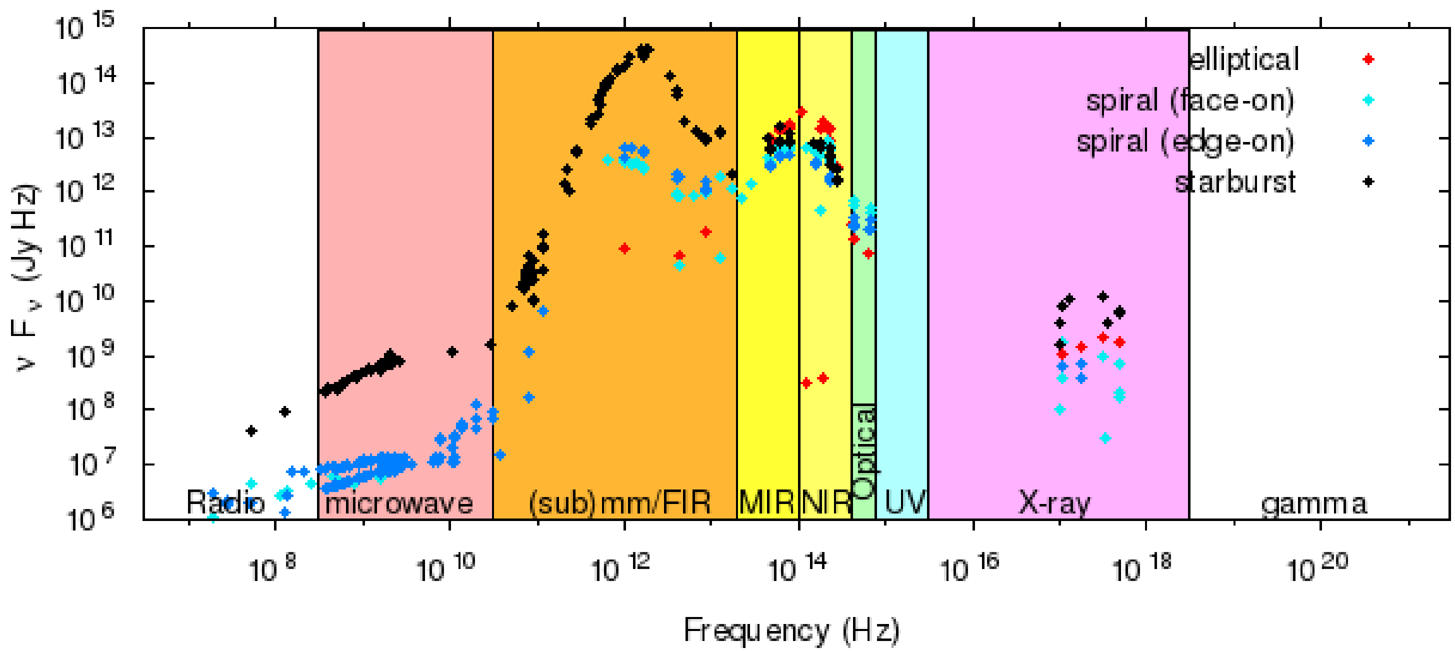
starburst

High-z galaxies

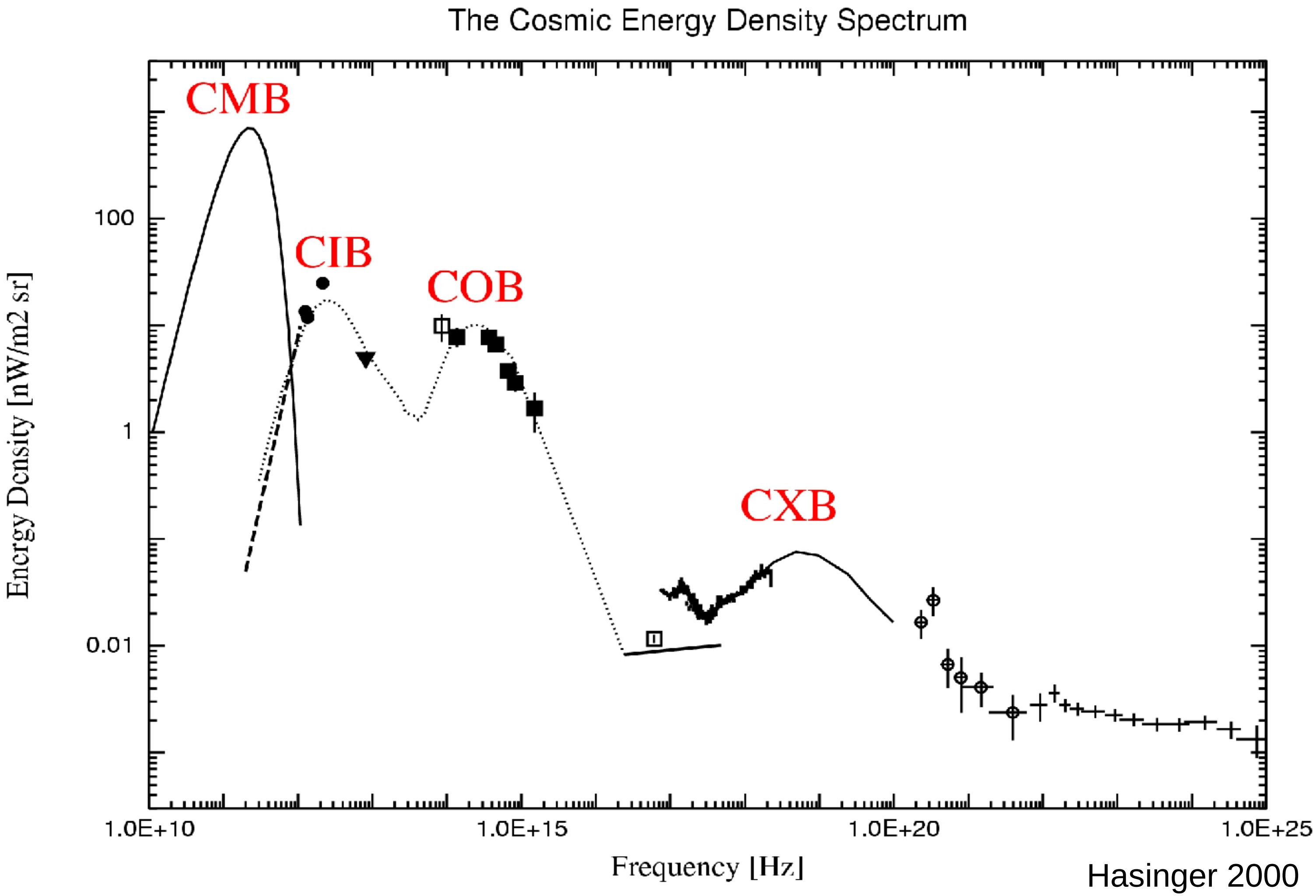
z = 0



z = 2

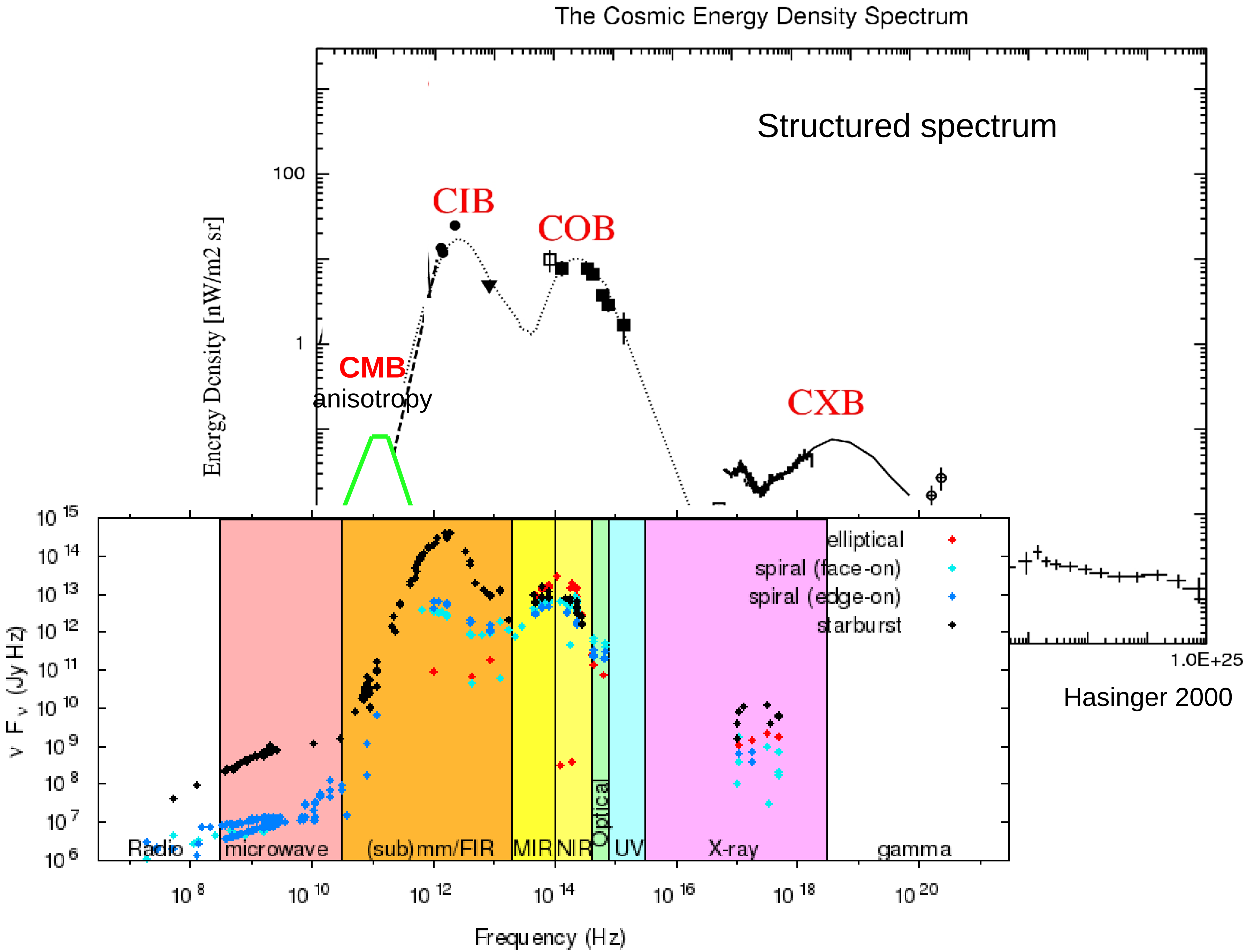


Cosmic backgrounds

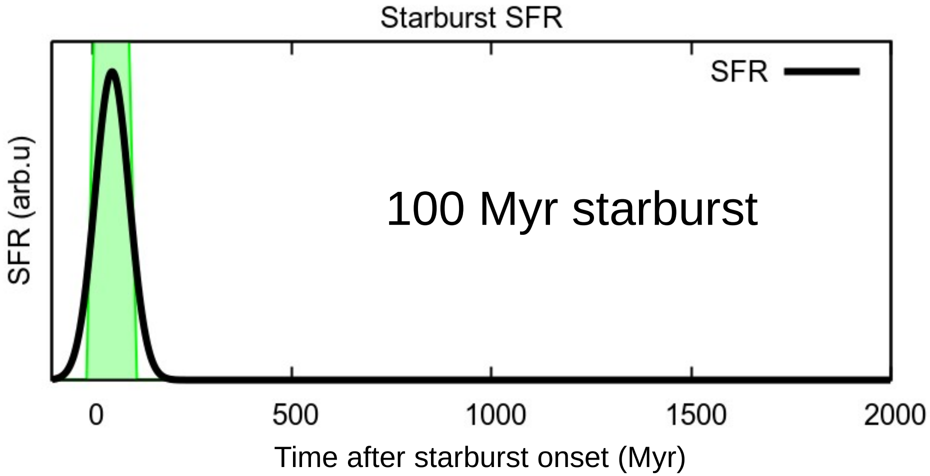


Hasinger 2000

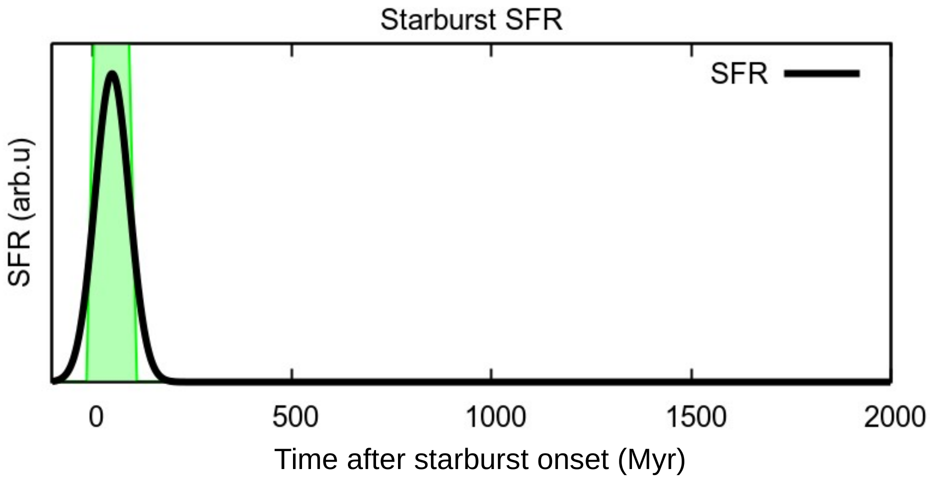
Cosmic backgrounds



Visibility evolution of a starburst



Visibility evolution of a starburst



Initial Mass Function (IMF)

$$\frac{dn}{dM} \propto M^{-2.35}$$ (*Salpeter*)

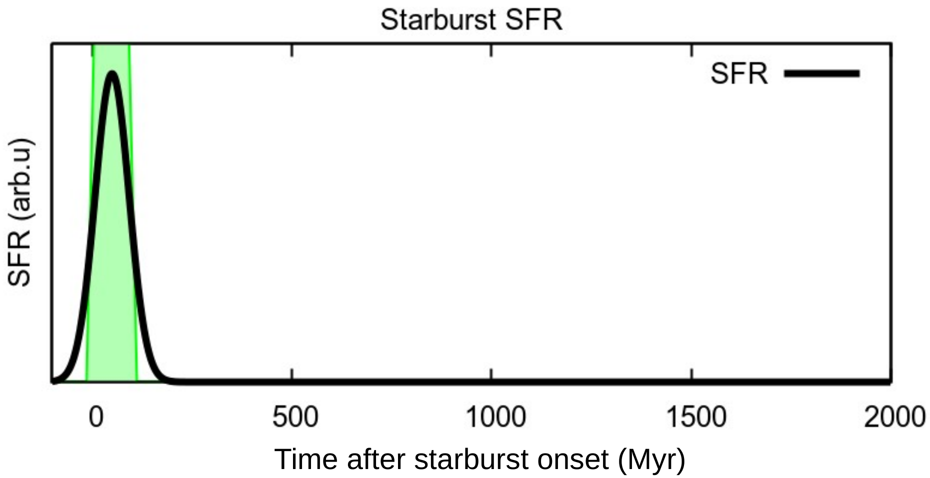
Luminosity function

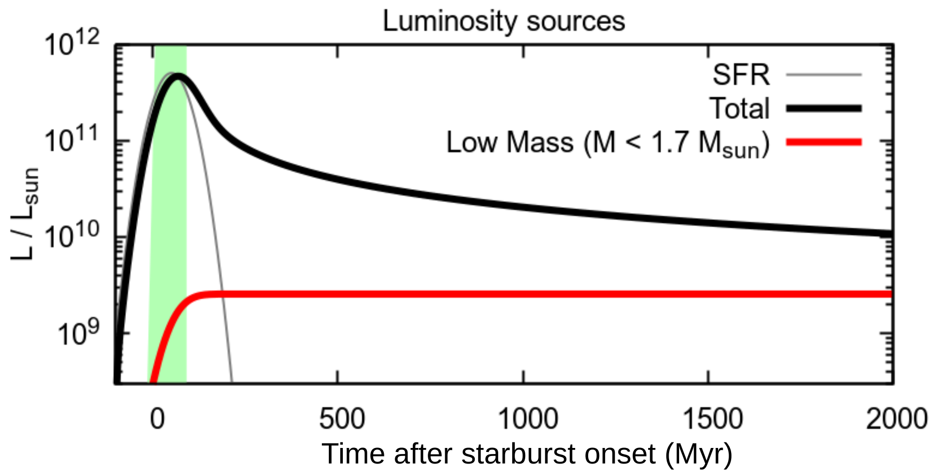
$$L \propto M^{4}$$ (*medium mass*)

Stellar lifetime

$$T = 10^{10} M^{-3} \, yr$$

Visibility evolution of a starburst





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$$L \propto M^4$$ (*medium mass*)

Stellar lifetime

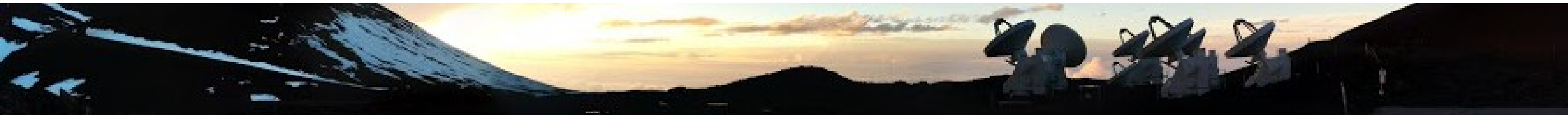
$$T = 10^{10} M^{-3} yr$$

Luminosity evolution

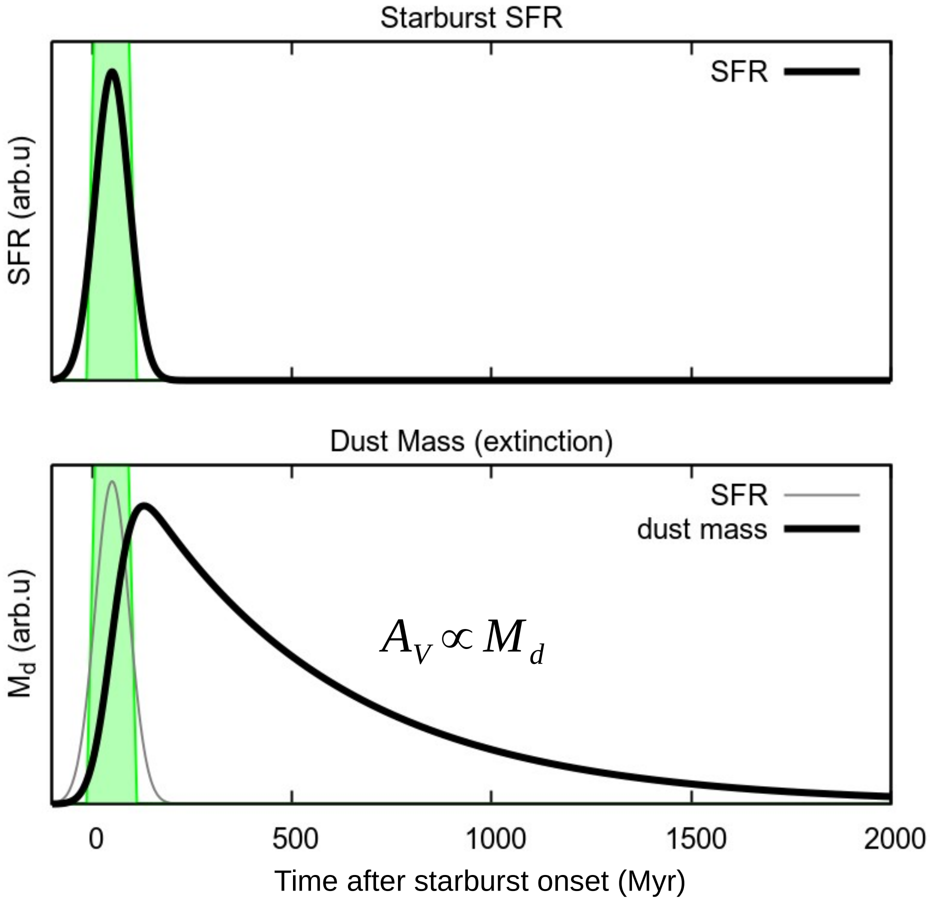
$$\frac{dL(t,t_0)}{dt_0} \propto SFR(t_0) \cdot \left[\frac{t-t_0}{10^{10}\,yr}\right]^{-0.88}$$

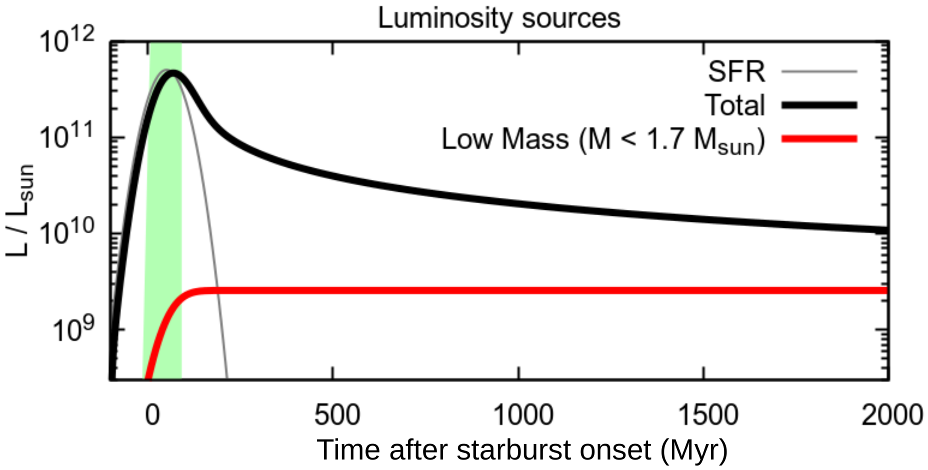
Low-mass luminosity

$$L_{LM} \propto \int SFR(t)\,dt$$



Visibility evolution of a starburst

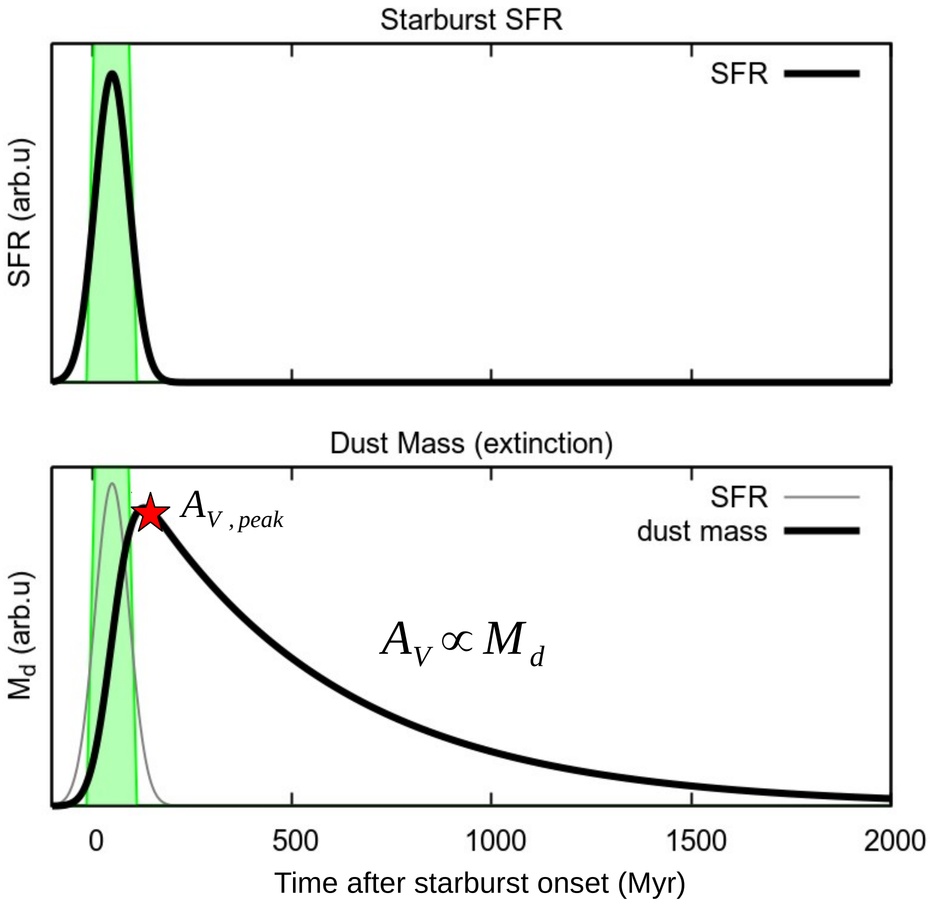


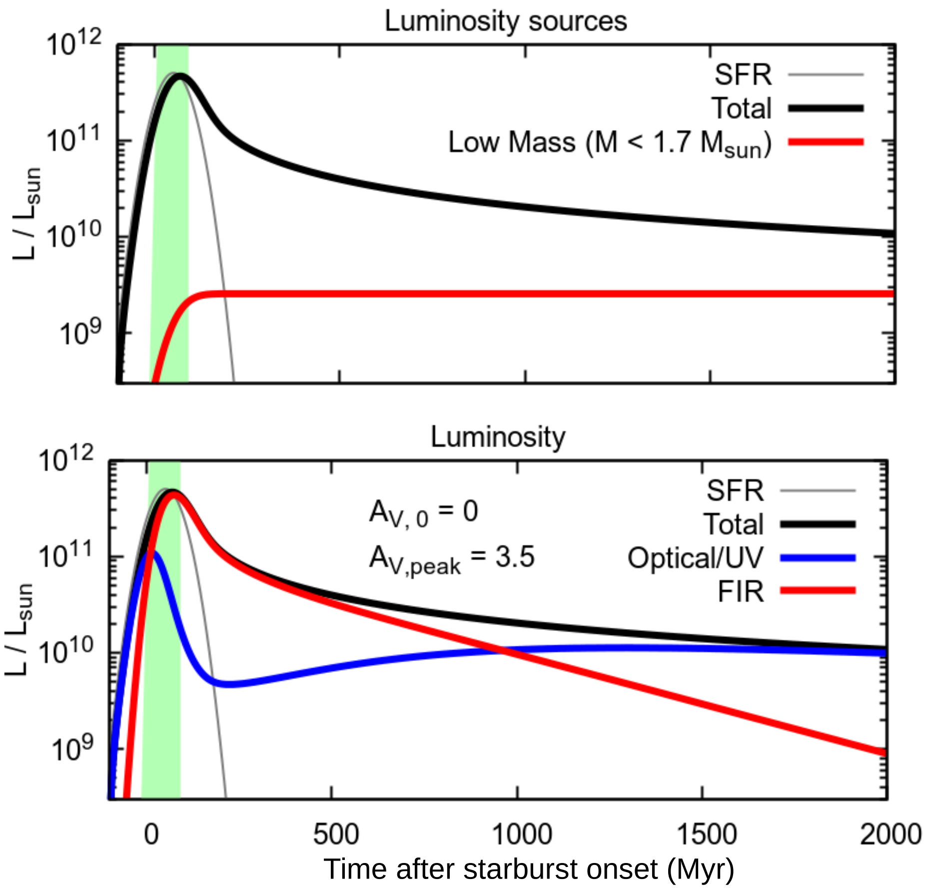


Dust mass (extinction) evolution

$$\frac{dM_d}{dt} \propto SFR(t) - \frac{M_d(t)}{500\,Myr}$$

Visibility evolution of a starburst

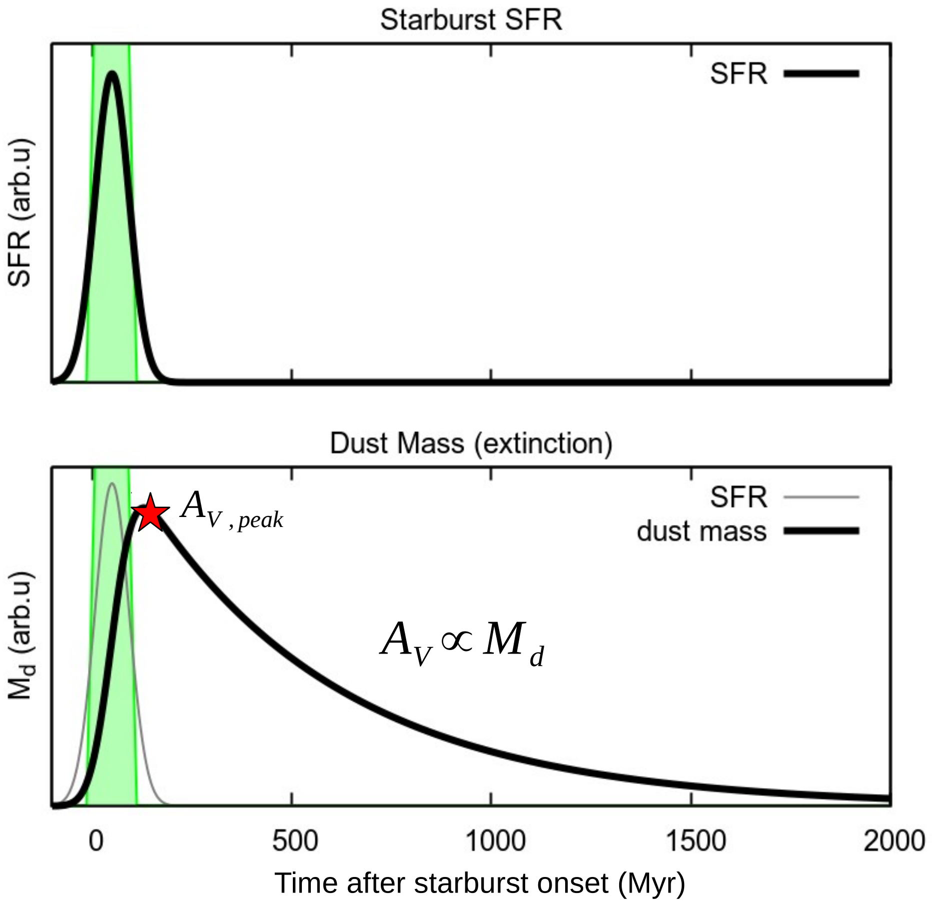


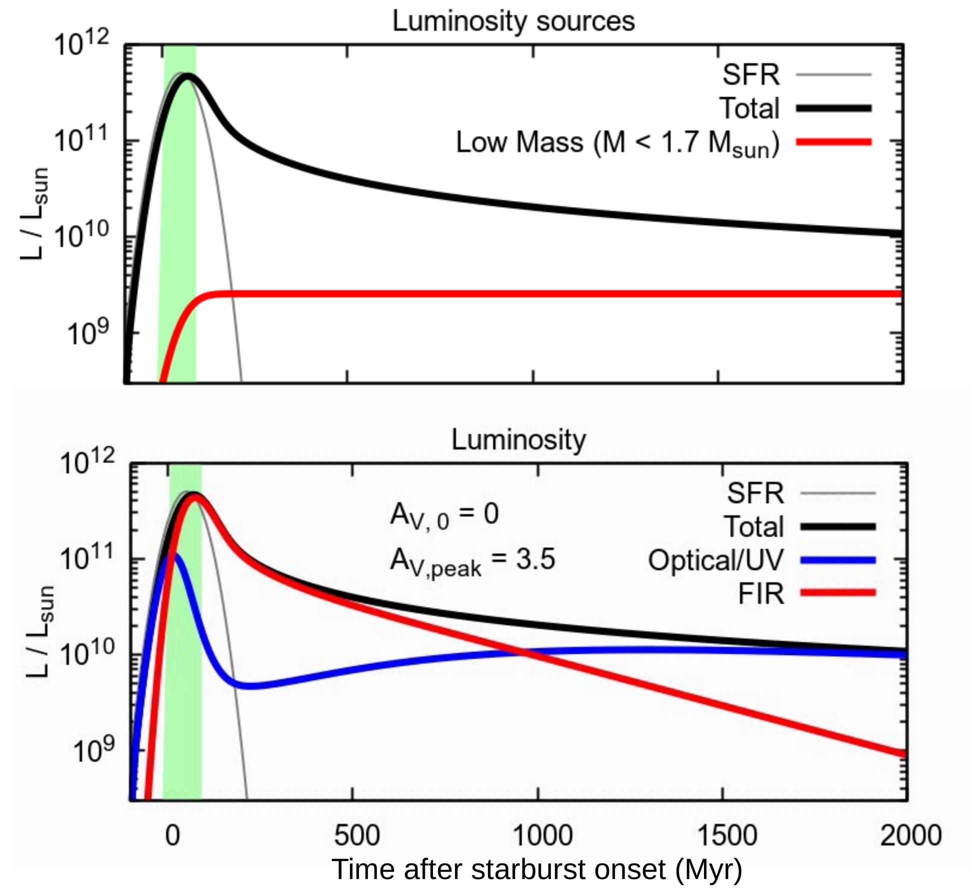


$$L_{opt} = L \exp(-0.92\, A_V)$$

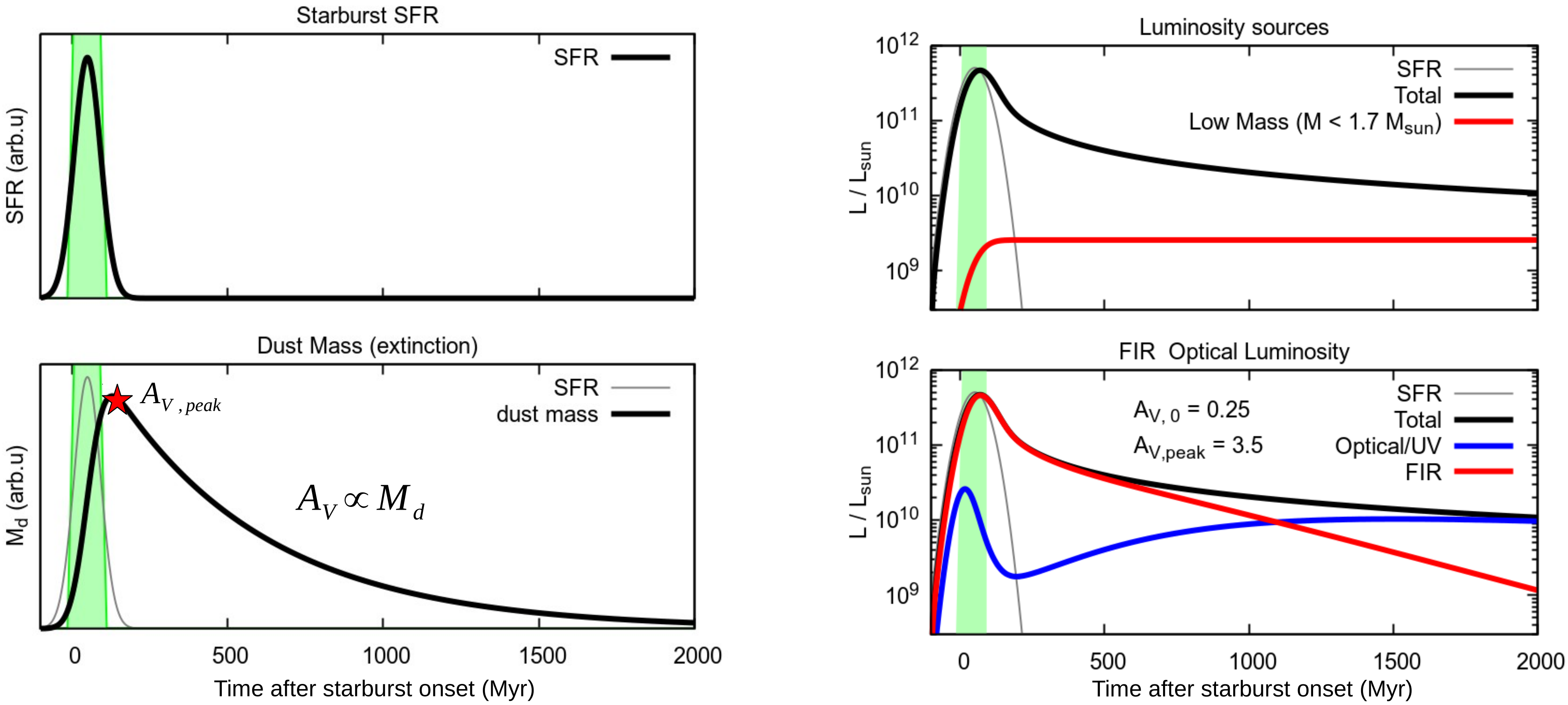
$$L_{FIR} = L - L_{opt}$$

Visibility evolution of a starburst

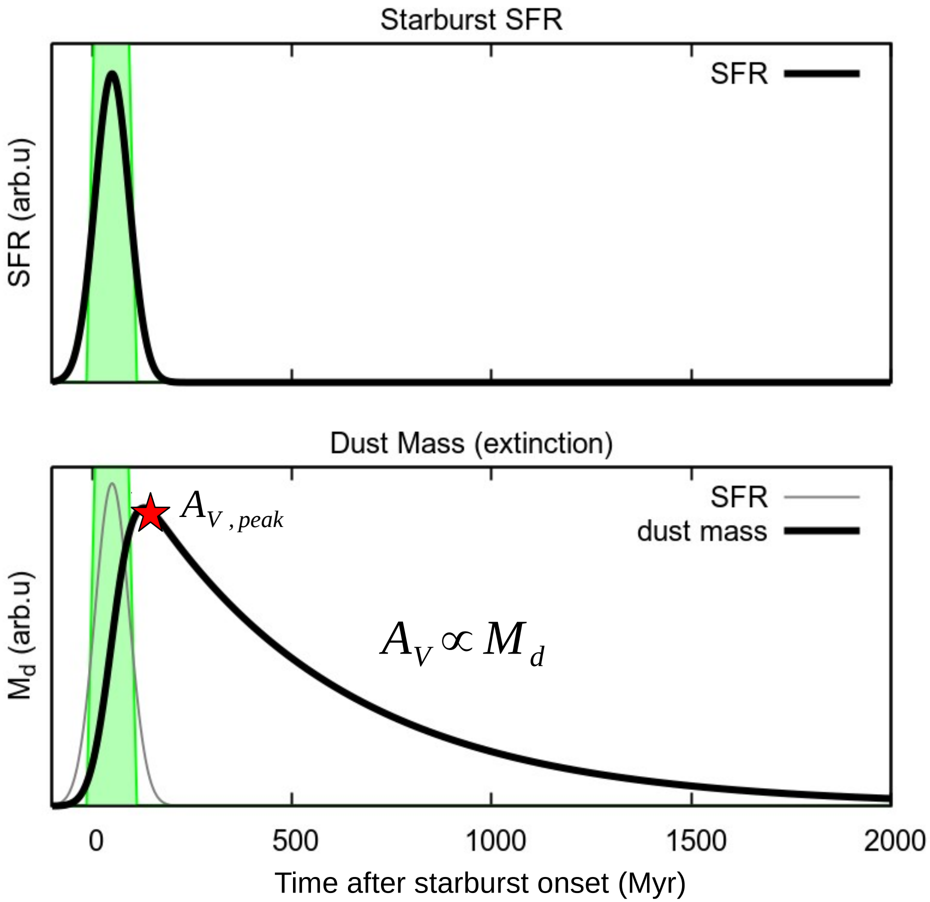


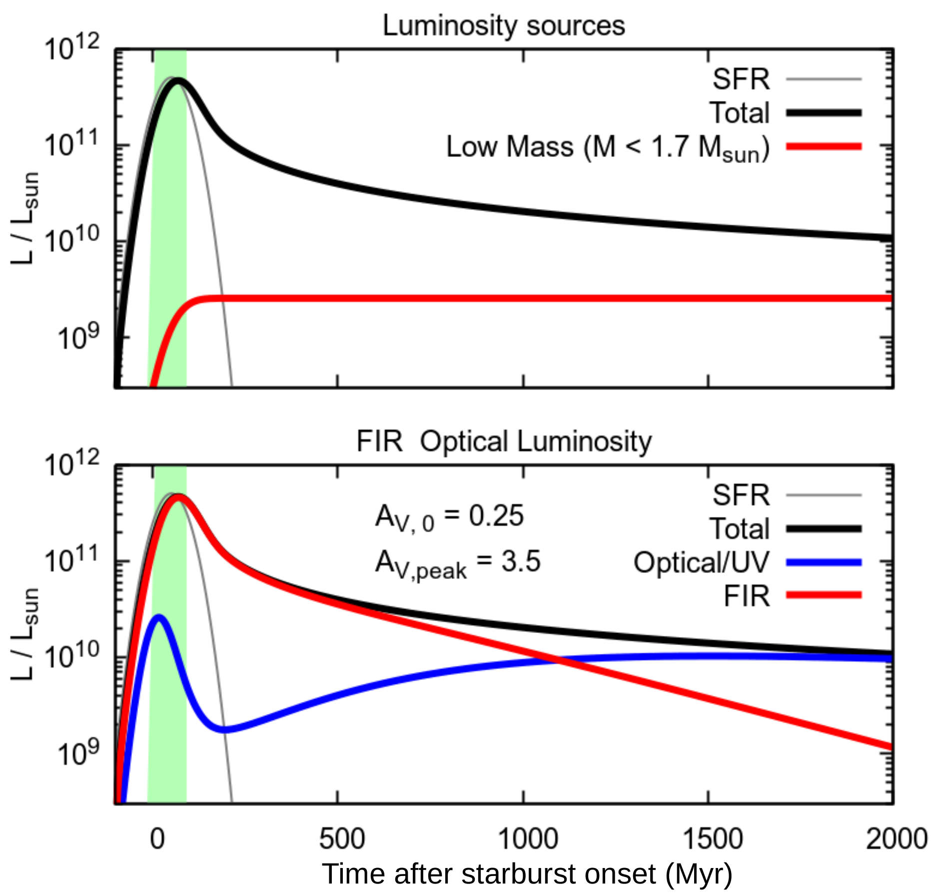


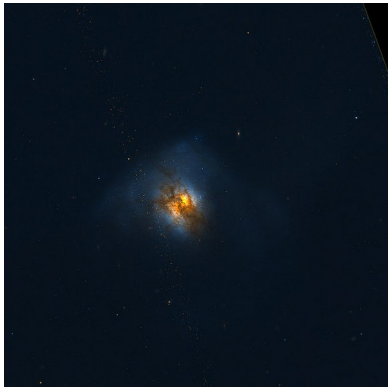
Visibility evolution of a starburst



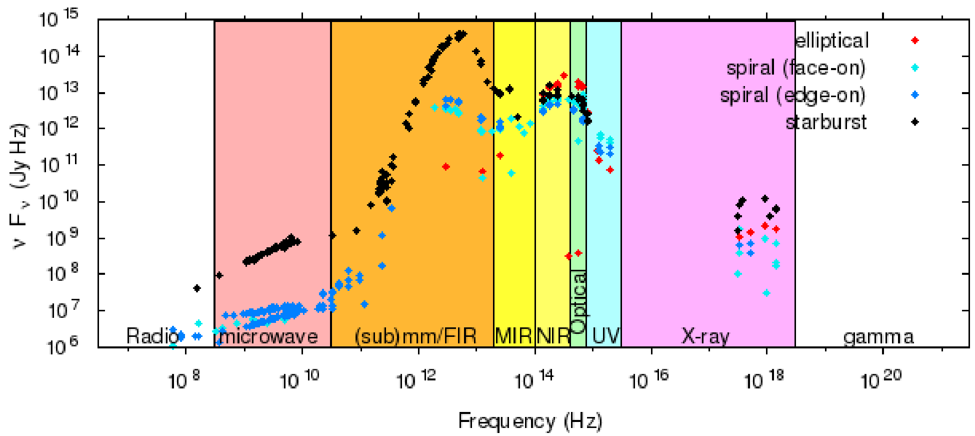
Visibility evolution of a starburst



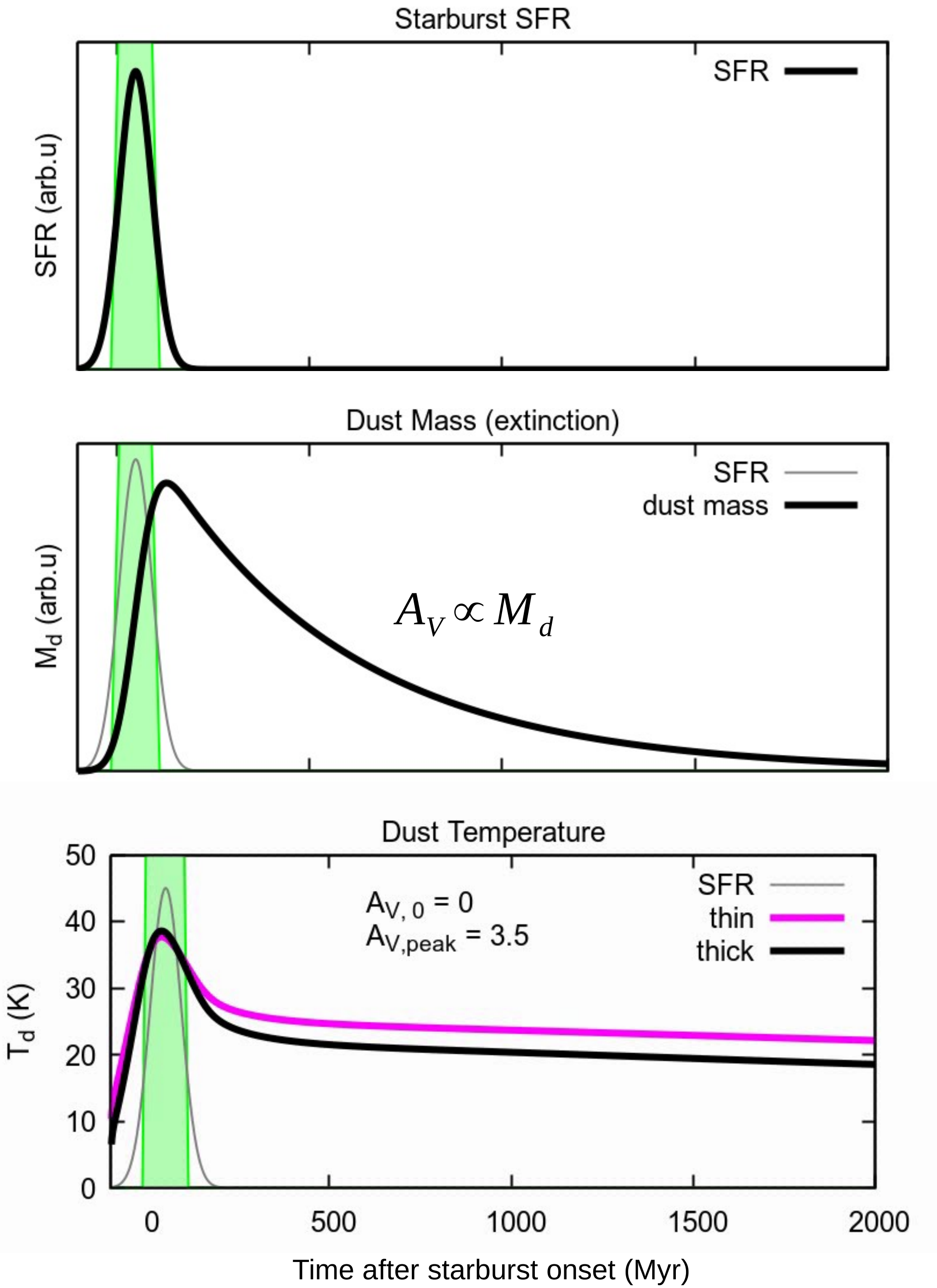


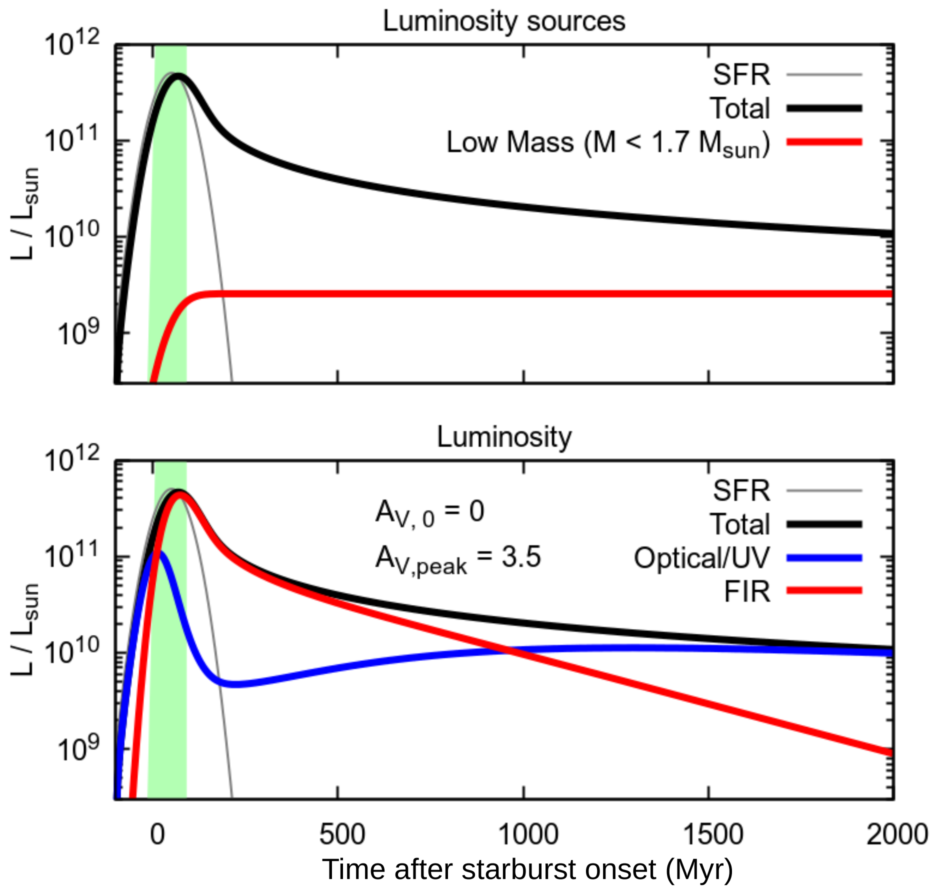


Arp 220



Visibility evolution of a starburst

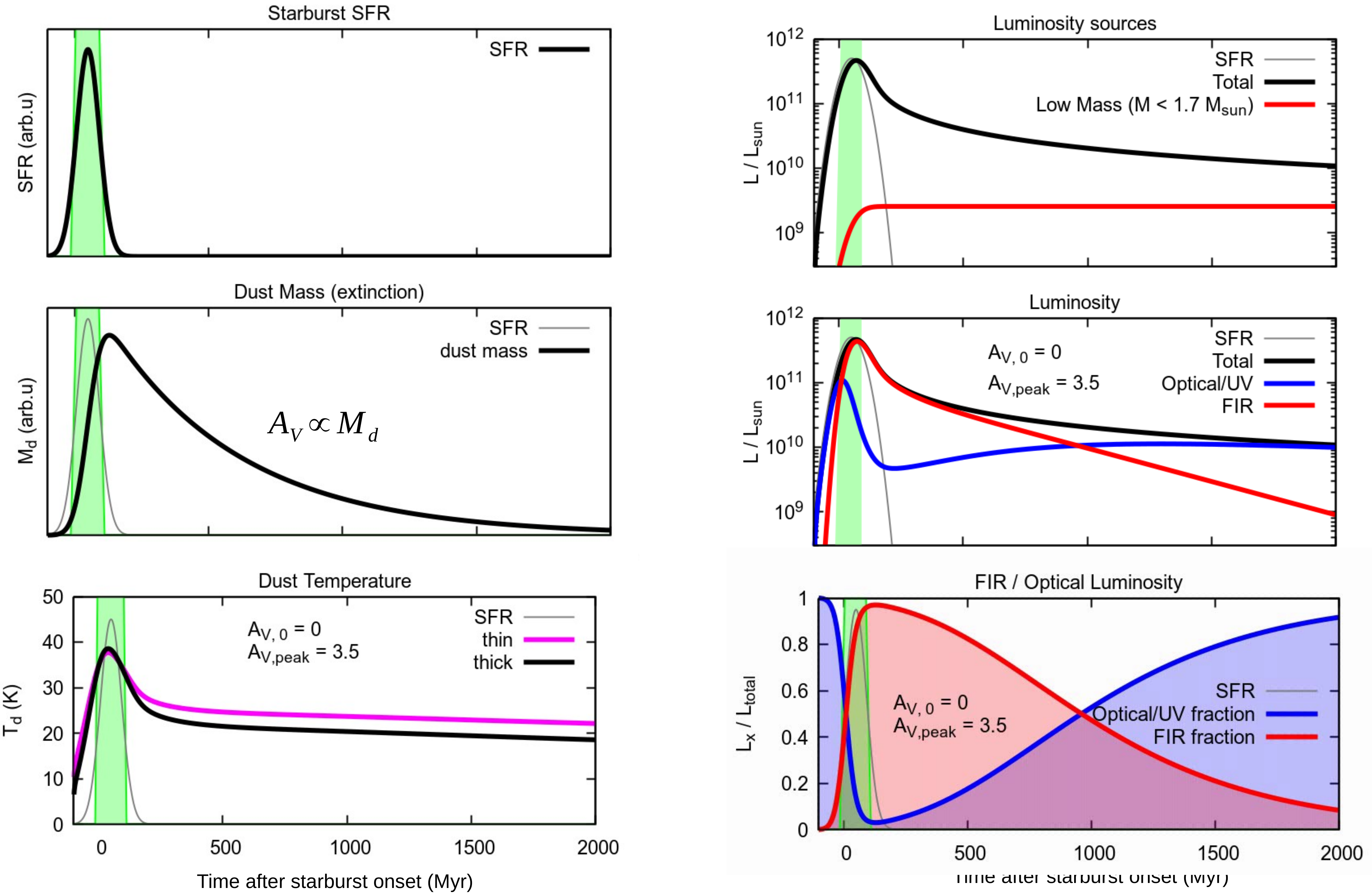




$$L \propto T^{(4+\beta_{eff})}$$

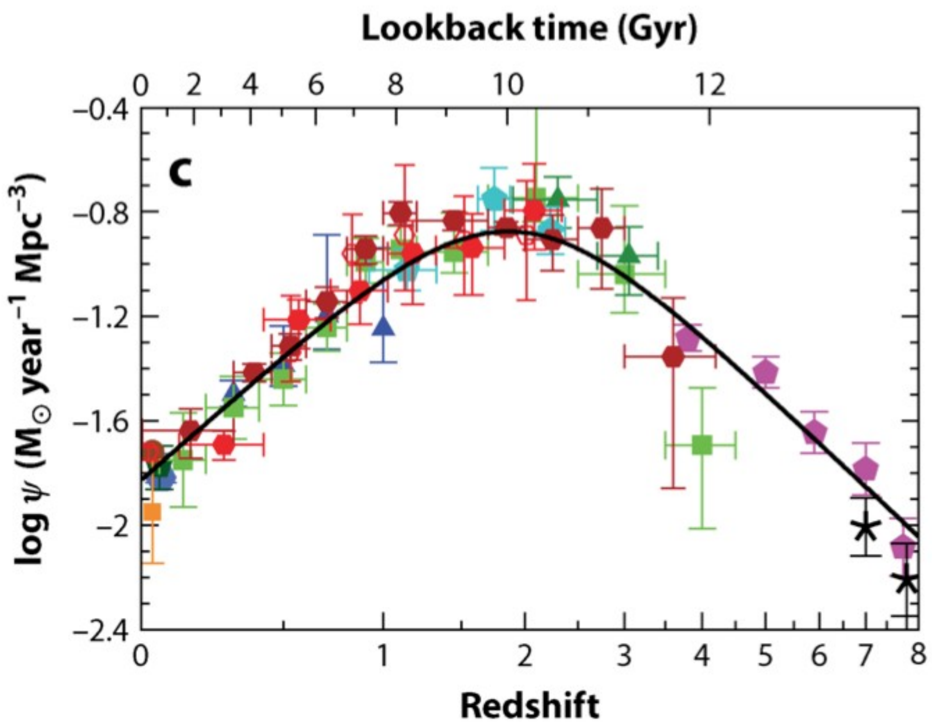
$\beta_{eff} \sim 0 - 2$

Visibility evolution of a starburst



Starburst conclusions

1. Starburst galaxies stay optically faint / FIR-bright for ~1 Gyr.

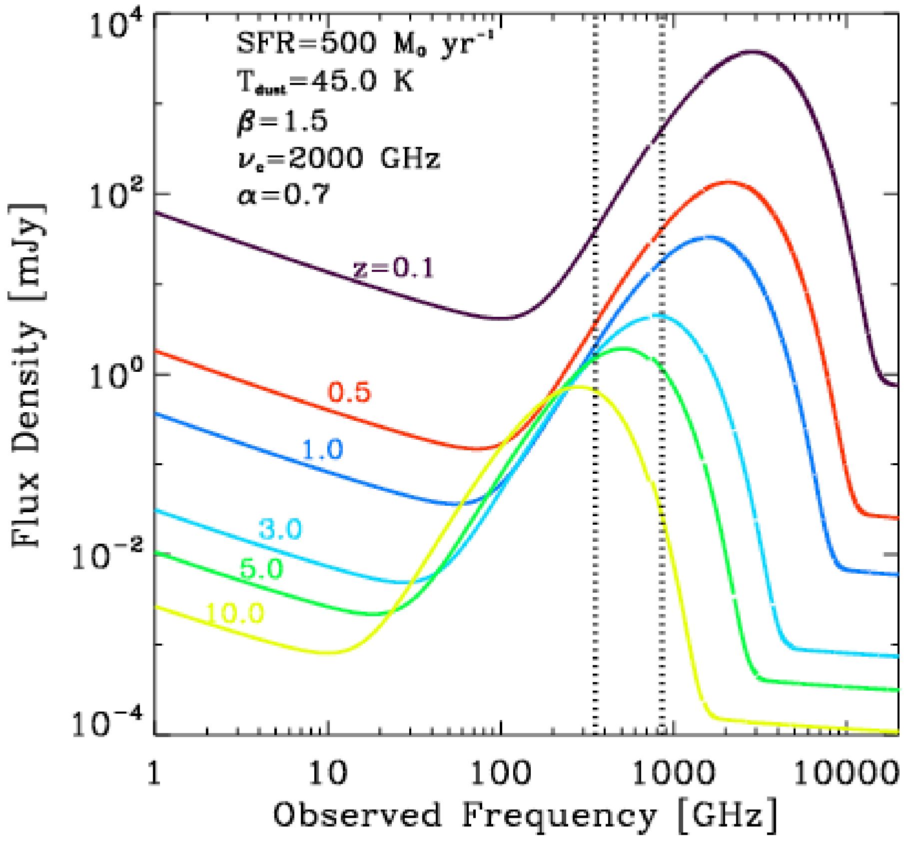


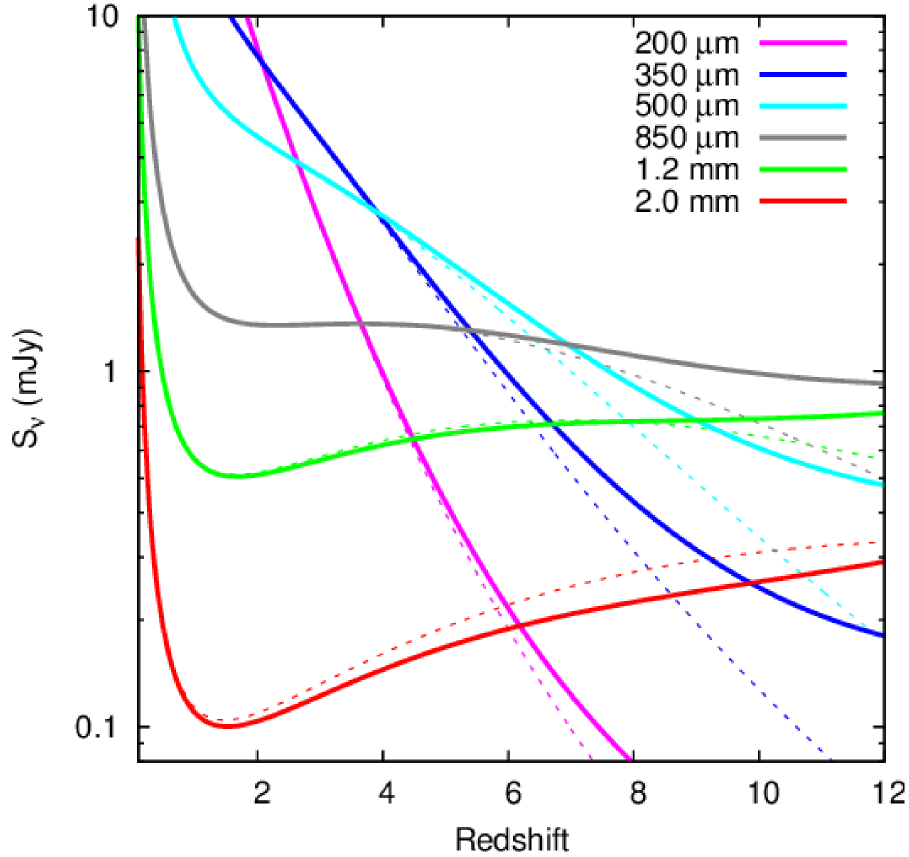
2. Galaxies at higher redshift are more likely to be optically faint.

3. FIR background is dominated by galaxies at the SFR peak (z ~ 2-3).

4. Optical background is dominated by evolved, lower-z galaxies.

Flat *z*-selection for star-forming galaxies





GISMO Deep field

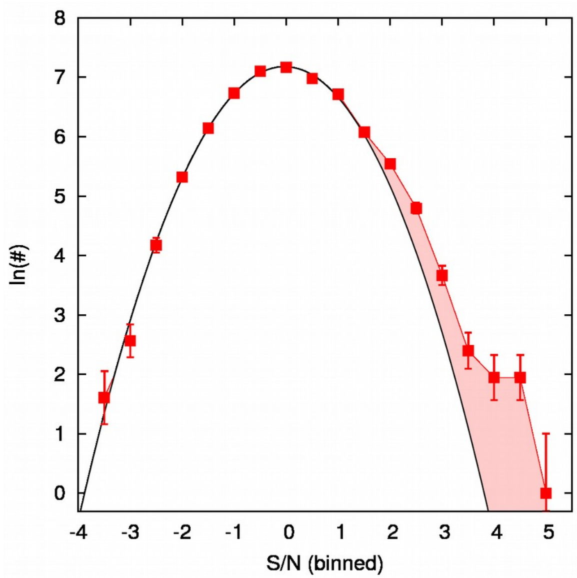
~35 hours

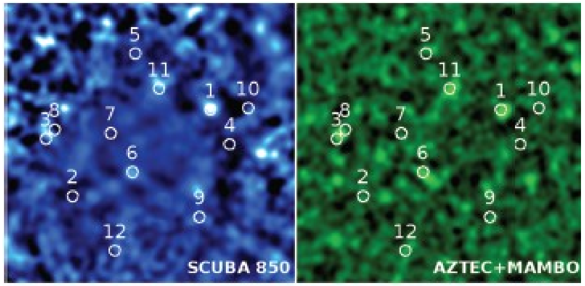
4’ diameter

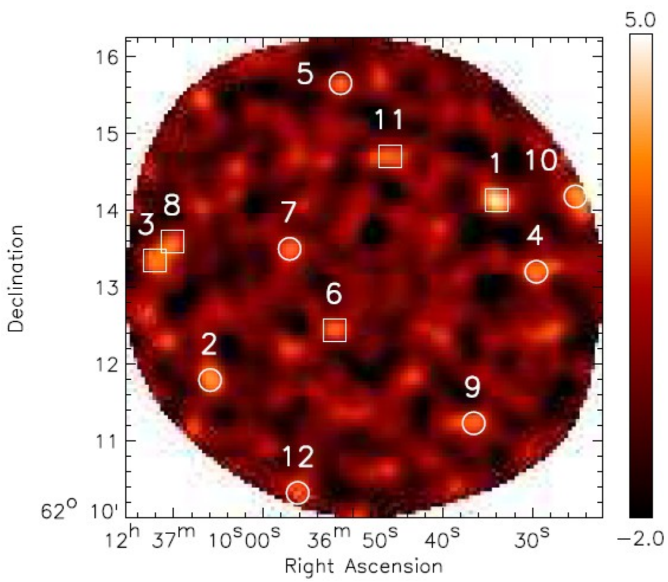
~120 uJy depth

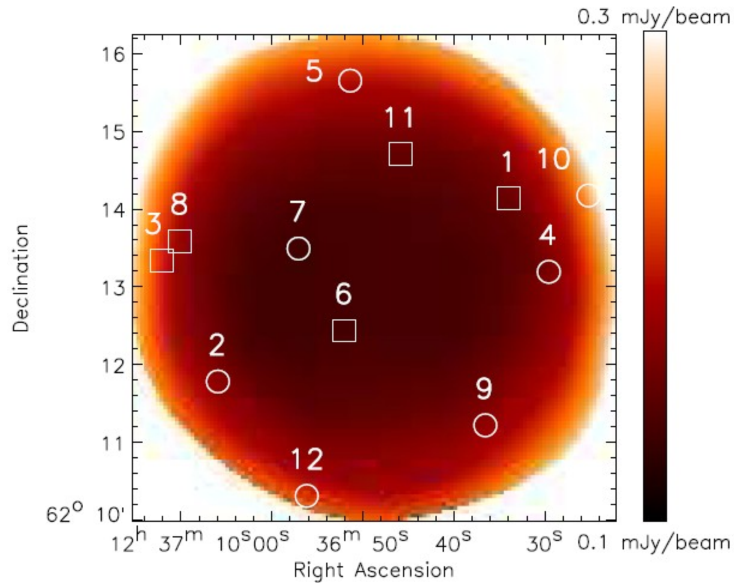
partly confusion limited

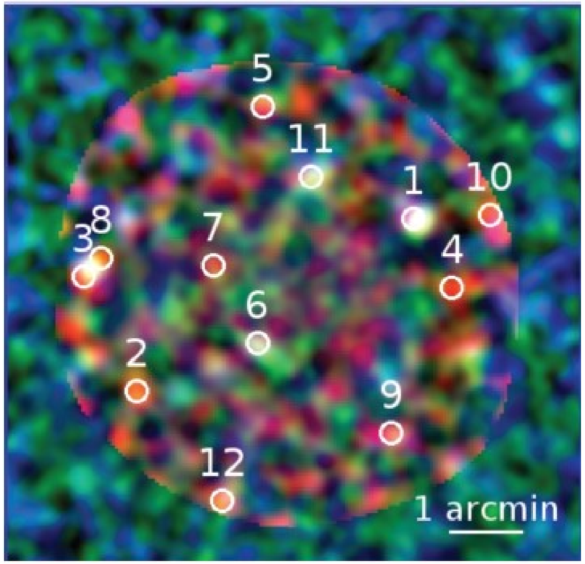
Staguhn, Kovács, et al. 2014





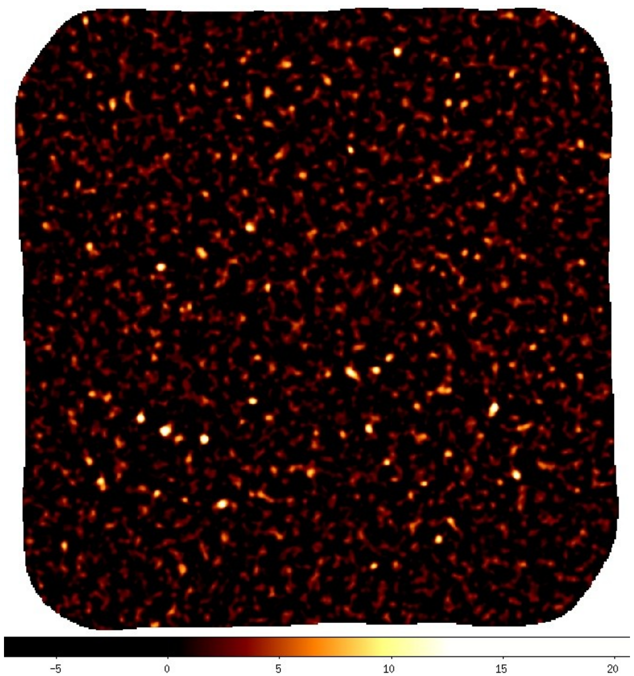




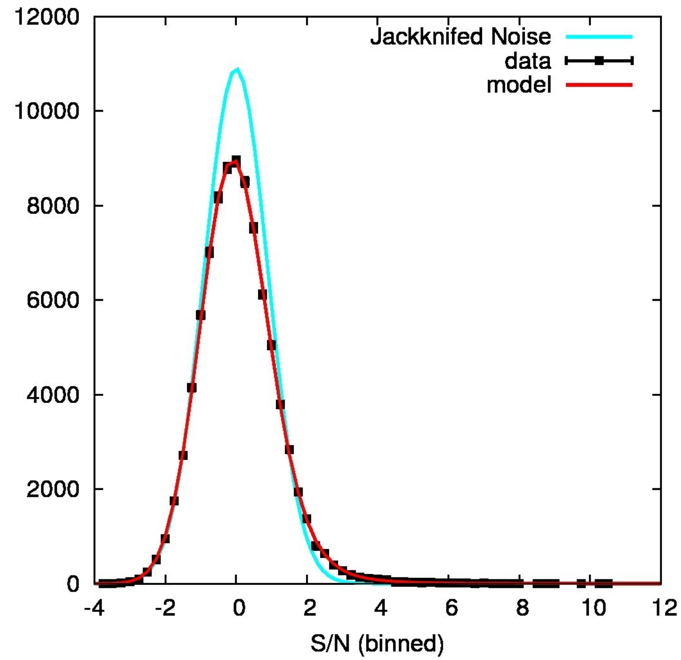


LABOCA deep field (LESS)

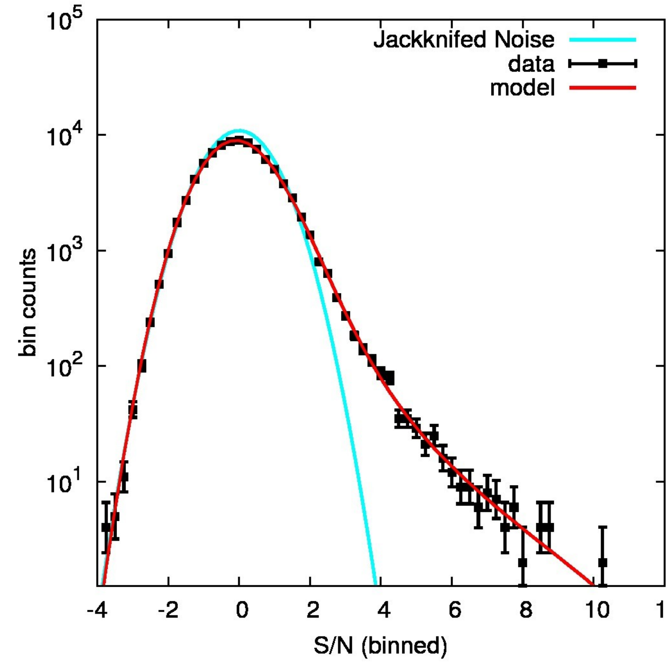
Observed distribution is a product of the source distribution and the underlying noise...

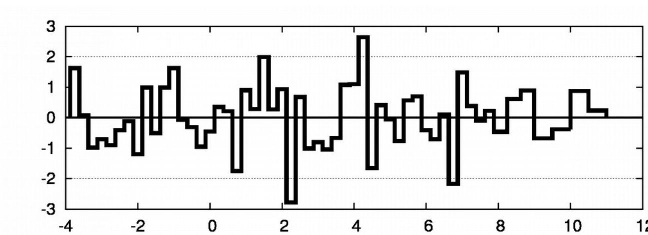


Many faint sources
Widen distribution
(confusion)



Bright sources
produce tail





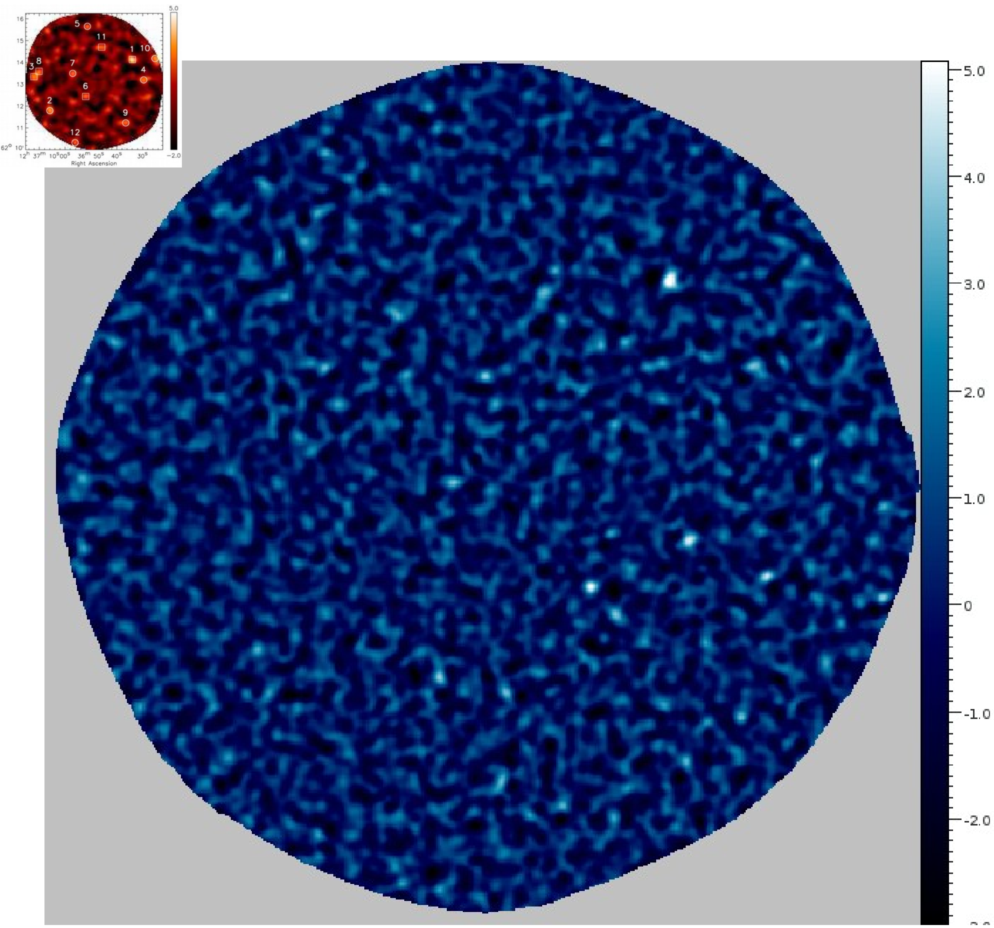
Can fit a number of parameters, depending on S/N:

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

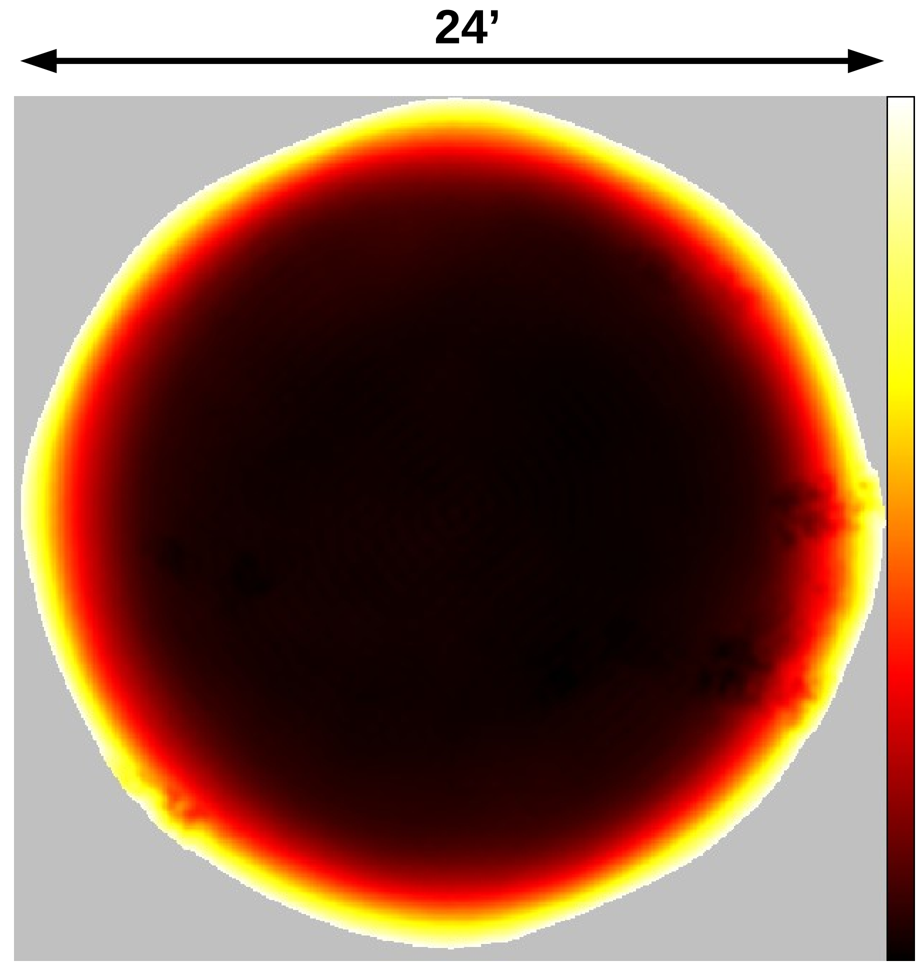
GISMO: COSMOS field

84 hours

Attila Kovács (*data reduction, P(D) analysis*)
Johannes Staguhn

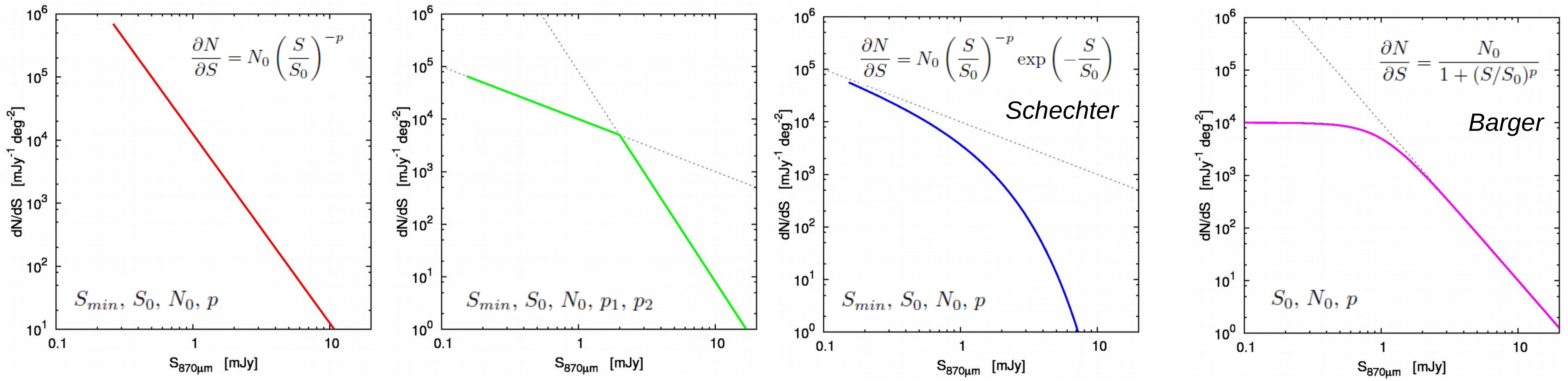


Signal-to-noise

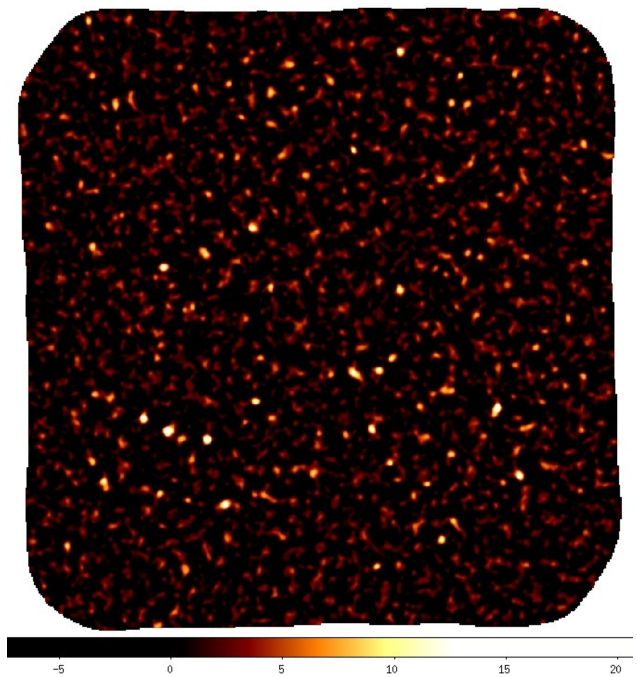


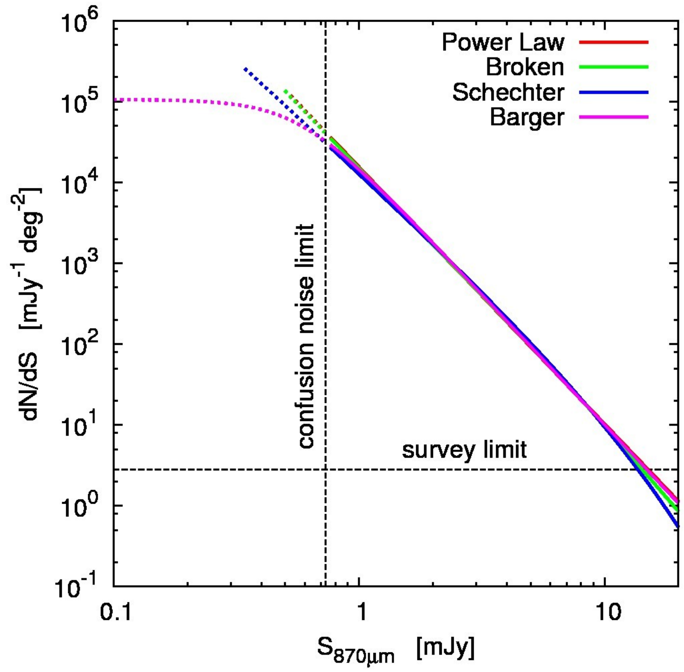
coverage map
200 – 400 uJy

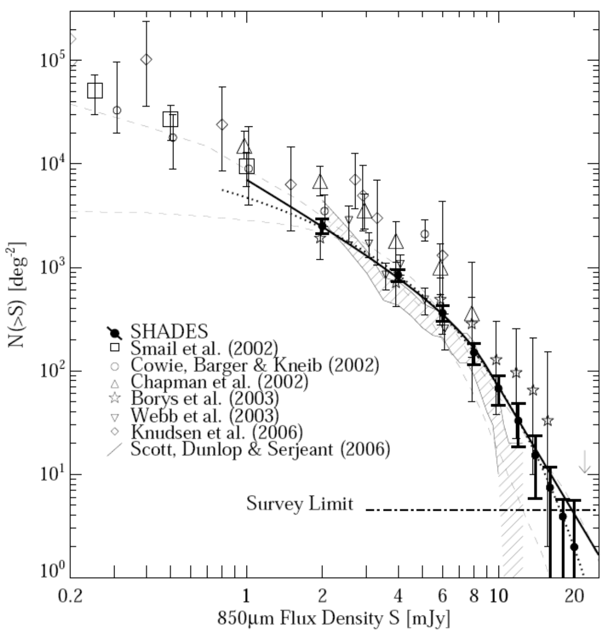
LESS P(D) results...



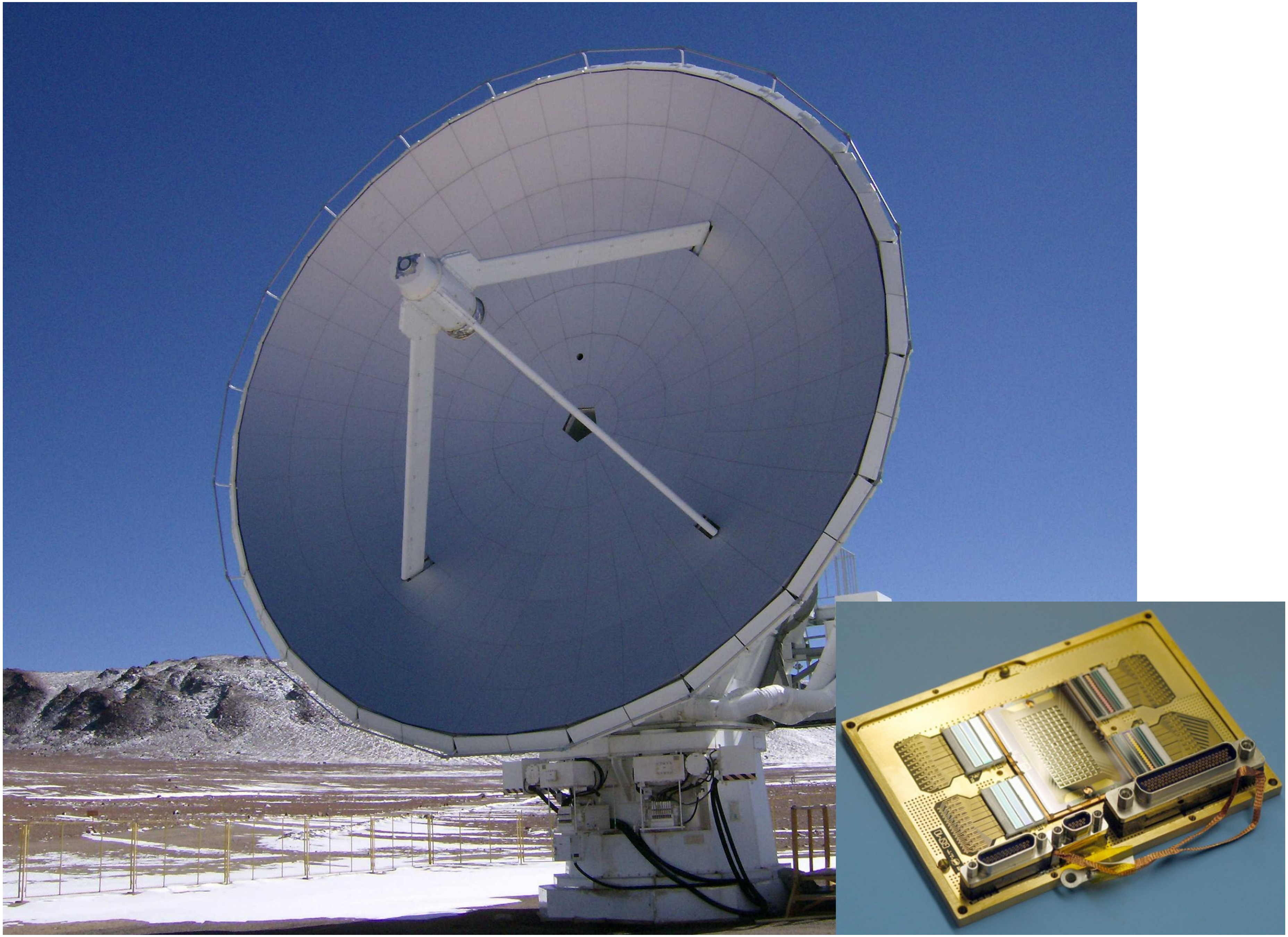
Weiss, Kovács, et al. 2010



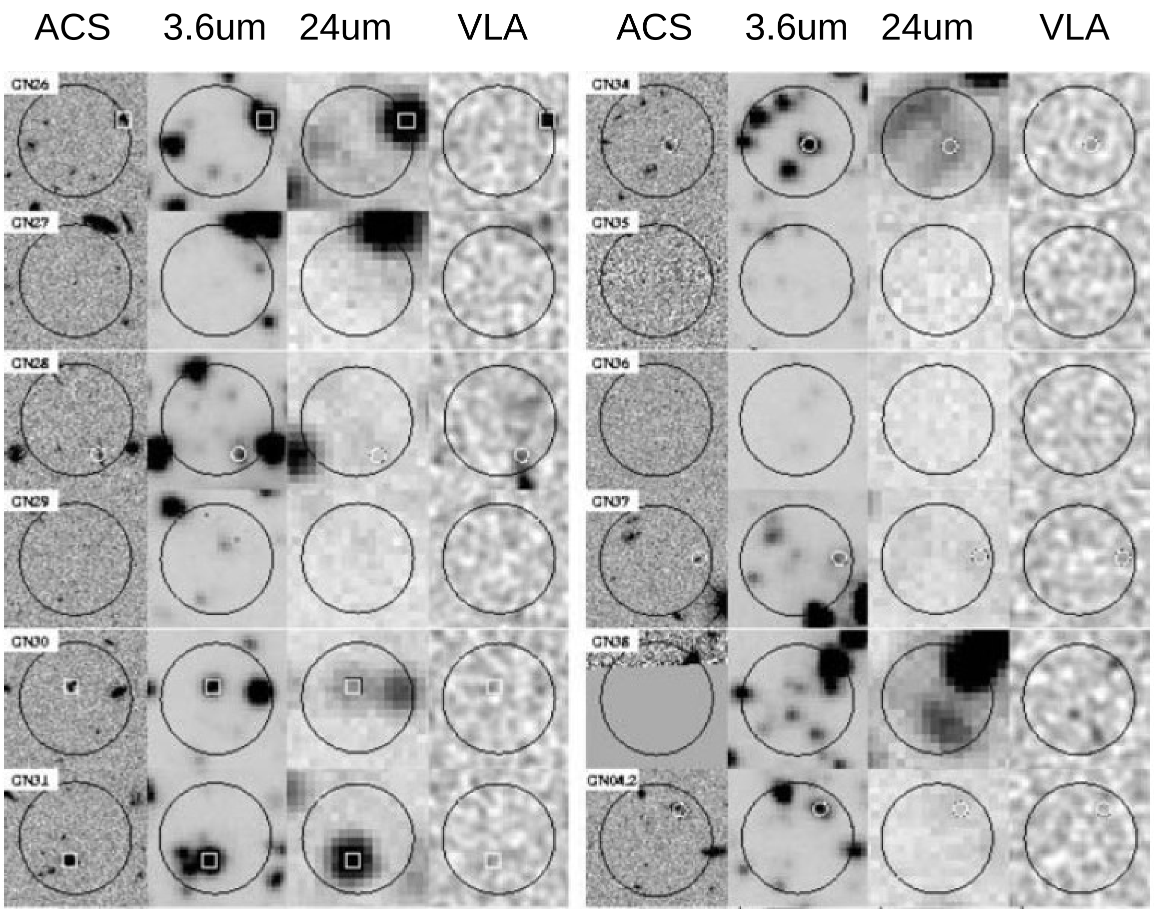




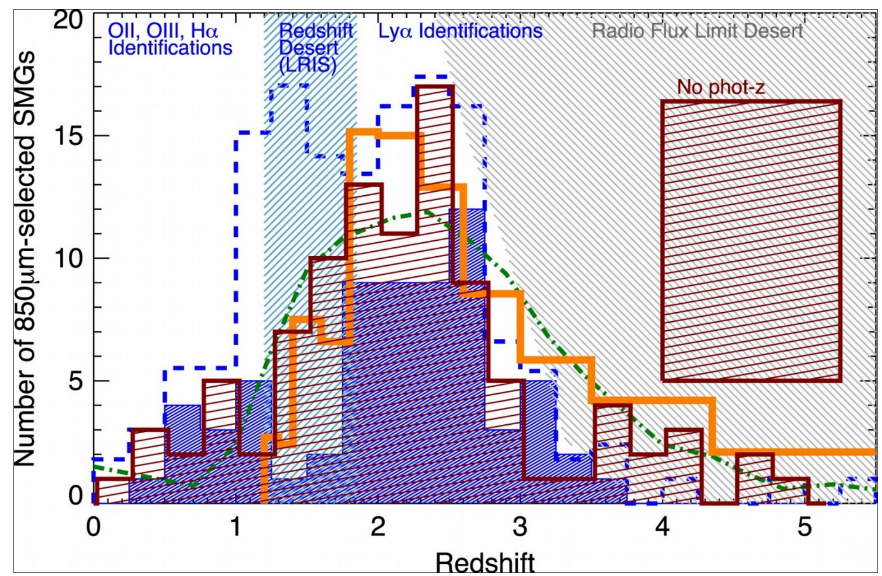
GISMO on the LMT



Redshift identification: the challenge



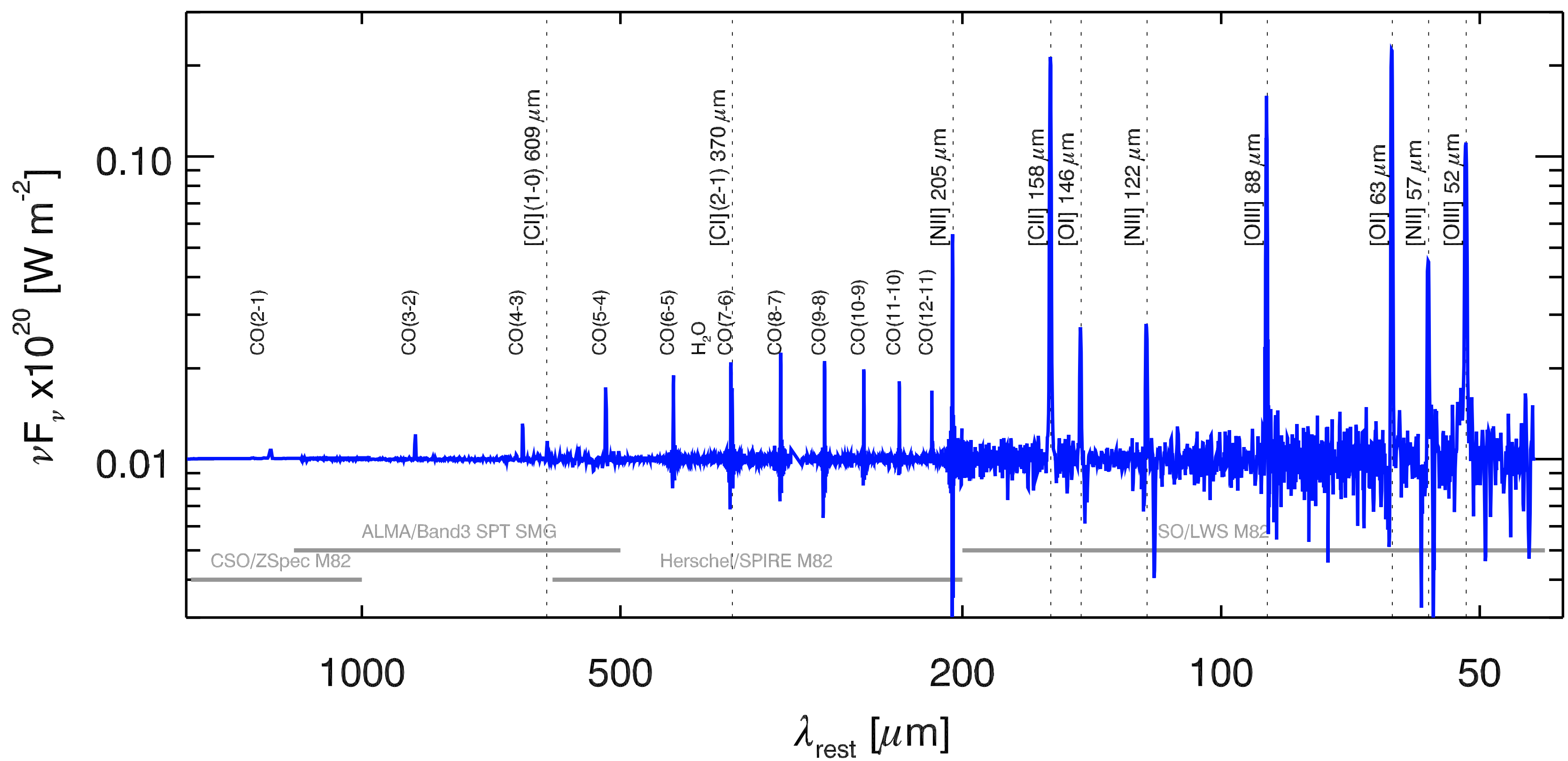
Pope et al. 2006



Casey et al. 2014

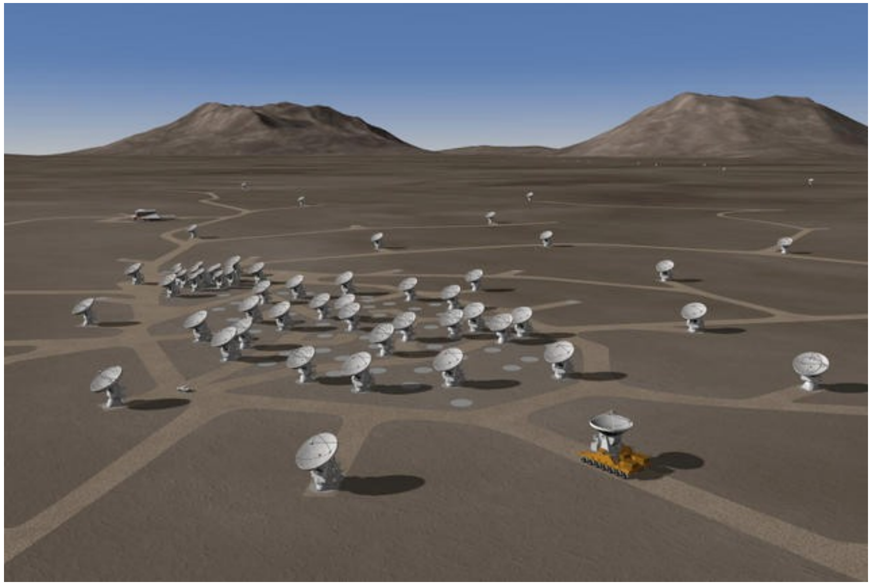
Redshift identification in the cool infrared

Continuum subtracted spectrum of M82 – J. Viera



Redshifts identification in the cool infrared

ALMA
+
EVLA



SMA

large aperture multibeam R~700 spectro-scopy

Comparative advantage

Time the produce the same quality

	cloth	wine
England	**100 hours**	**120 hours**
Portugal	**90 hours**	**80 hours**

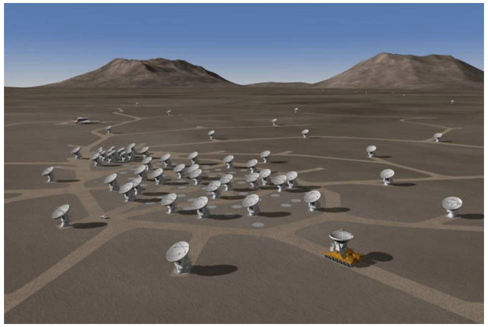
David Ricardo
(*1772 – 1823*)

Highest overall productivity:

Portugal **100% WINE**

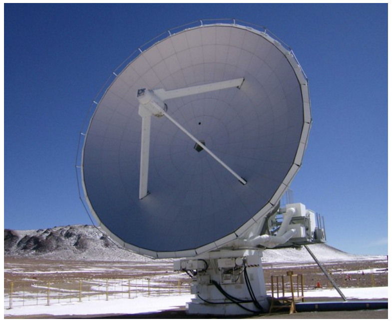
England **100% CLOTH**

Comparative advantage



Time the produce the same science

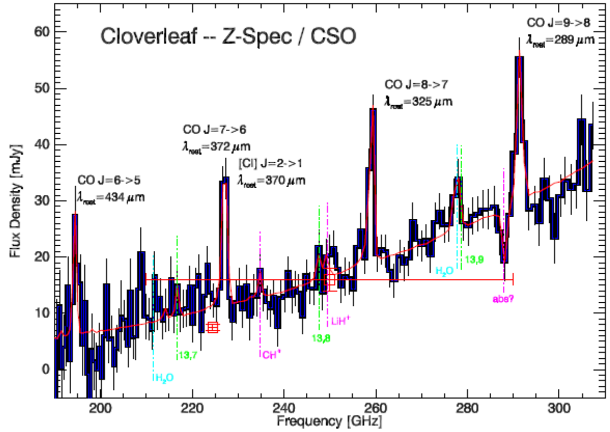
	sensitivity	resolution	map speed
ALMA	1 hour	0.034”–0.80”	1
LMT	4+ hours	10”–30”	10,000+
SMA	32 hours	1”–10”	0.25 – 1.5

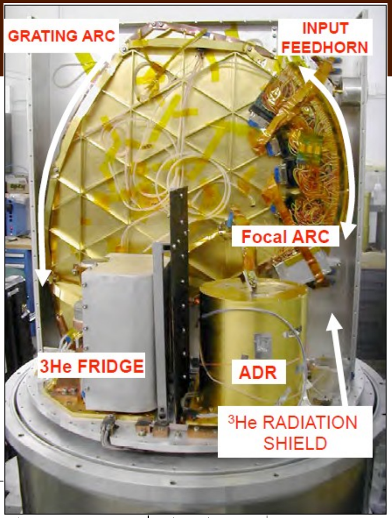


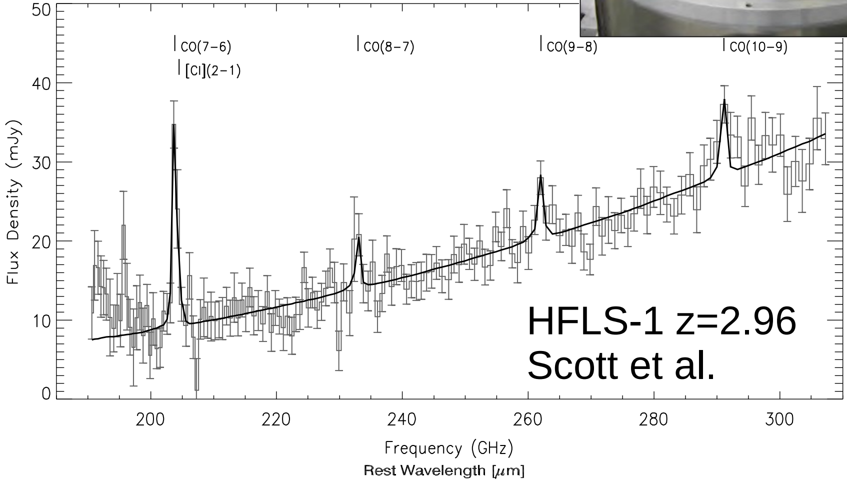
ALMA may be master of (almost) all, but to get the most science, it should be focused on where it’s strongest at...

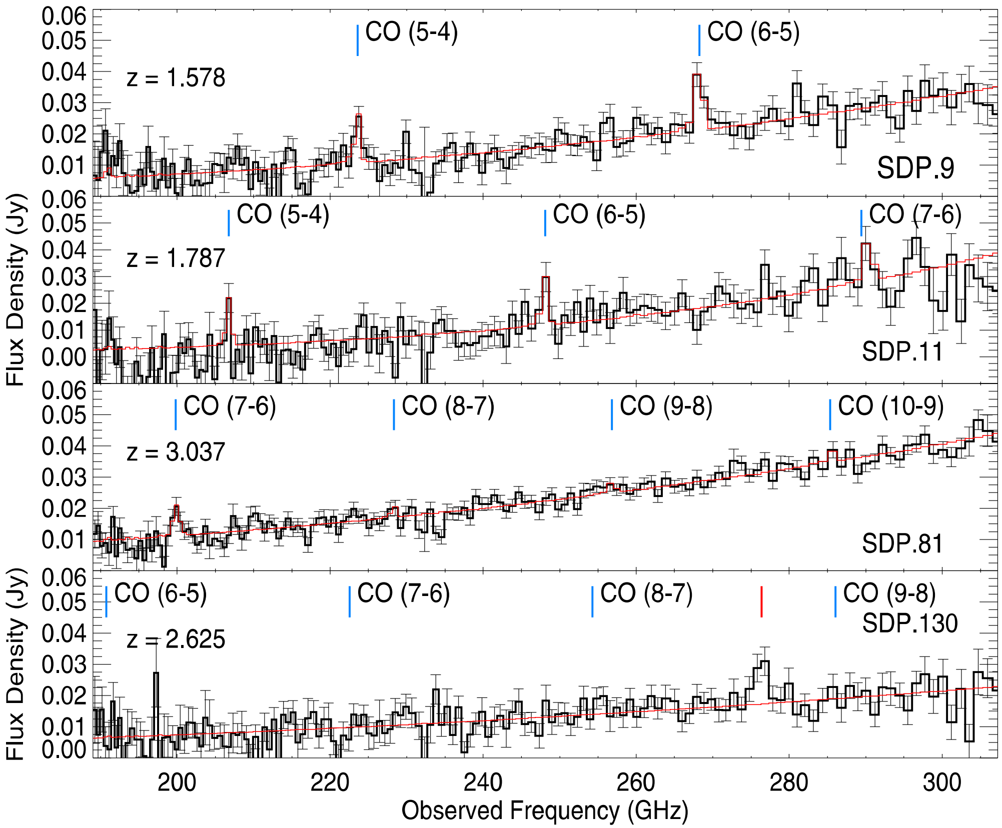
ALMA	**RESOLUTION**
LMT	**LARGE-SCALE SURVEYS**
Everything else	**DETECTION / SPECTROSCOPY**

Z-Spec on the CSO and APEX

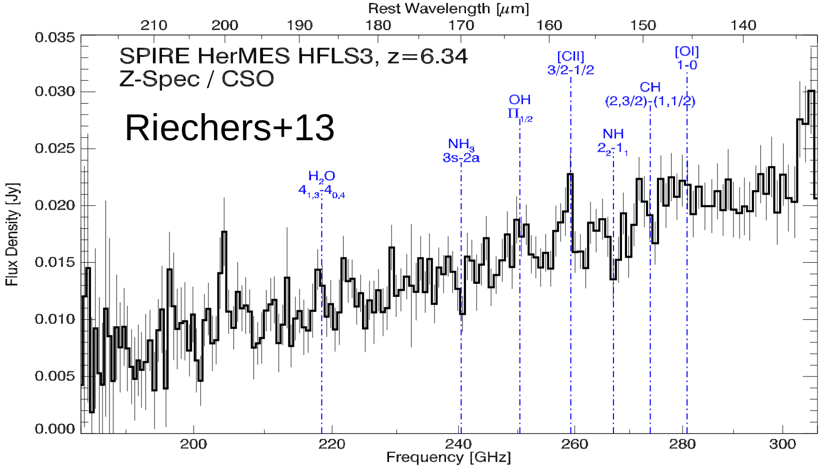




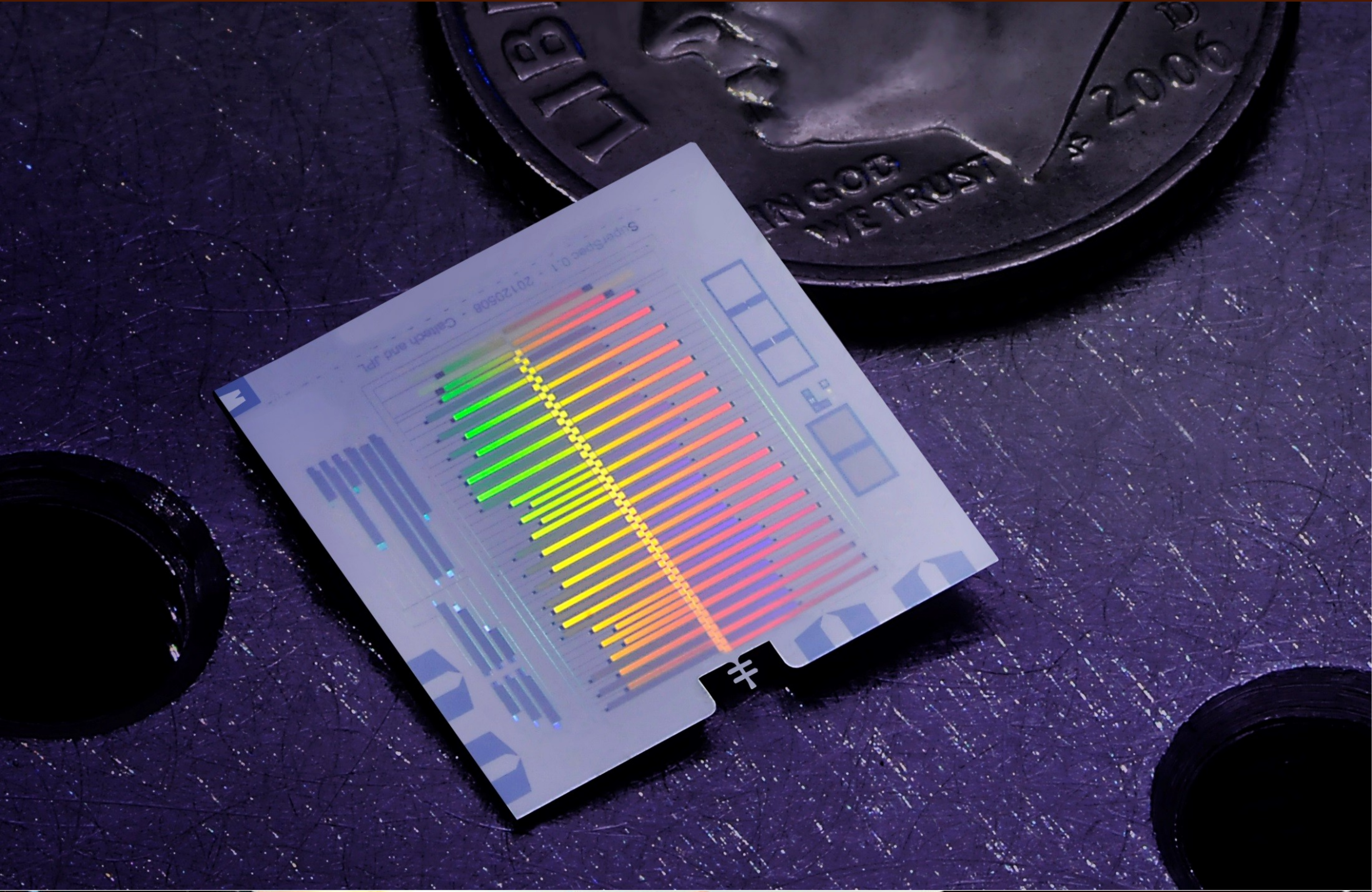




H-Atlas (Lupu et al.)



SuperSpec: an on-chip 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)

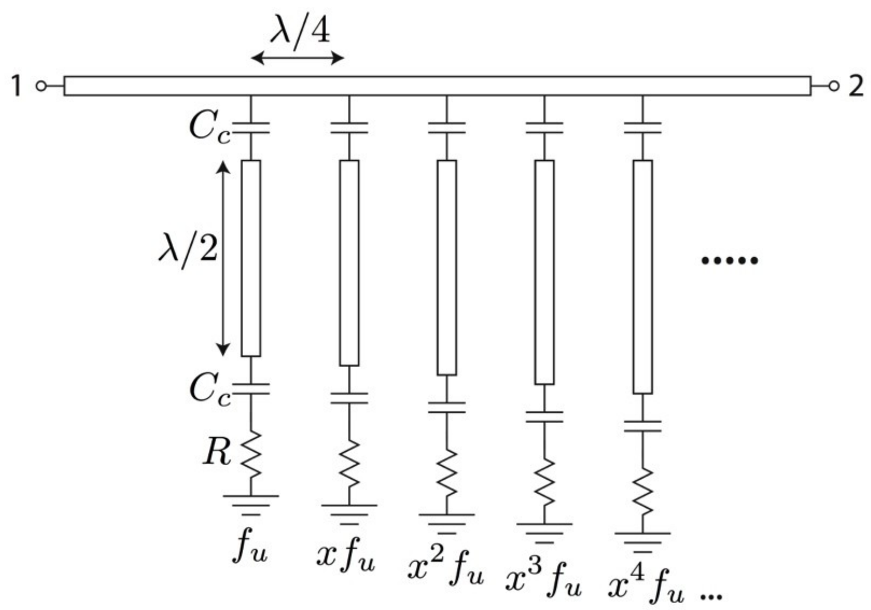
Dalhousie University

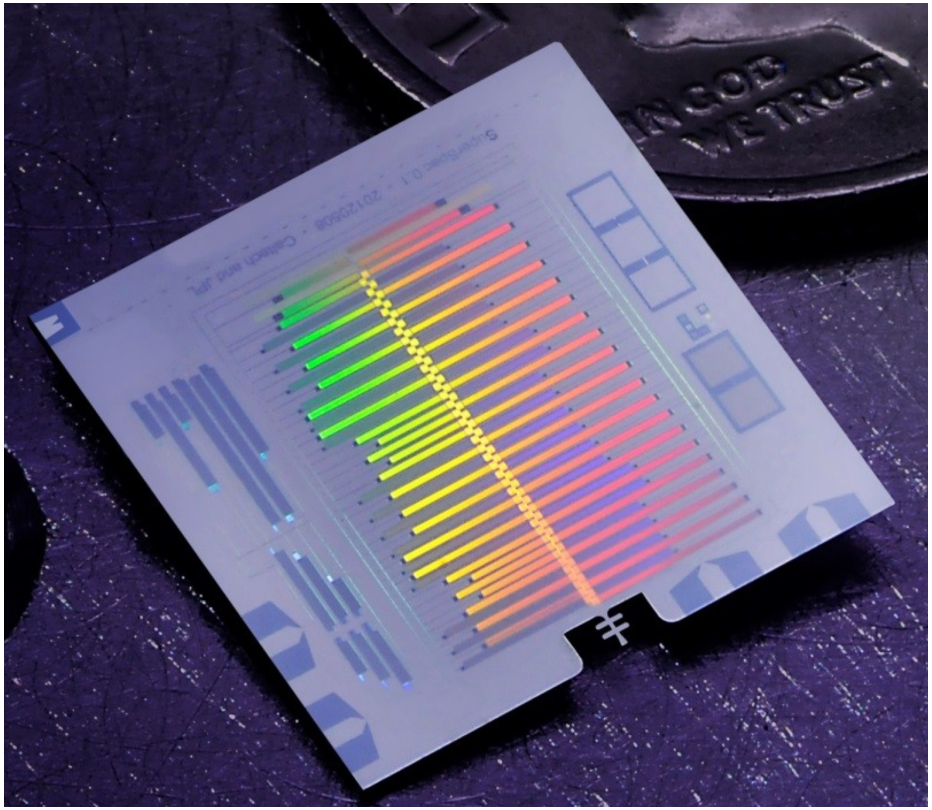
S. Chapman
C. Ross

SuperSpec: overview

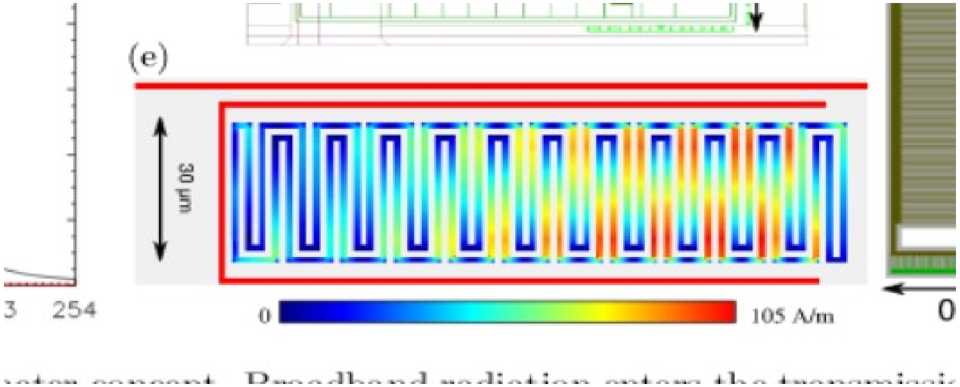
- SuperSpec is an on-chip spectrometer we are developing for moderate resolution, large bandwidth, (sub)millimeter astronomy
- A single chip integrates
  - antenna
  - moderate resolution (R ~ 100 – 500) filterbank with large BW (δν/ν ~ 0.6)
  - associated detectors (KIDs) and readout circuitry.
- Each chip is ~few cm^2 in size

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



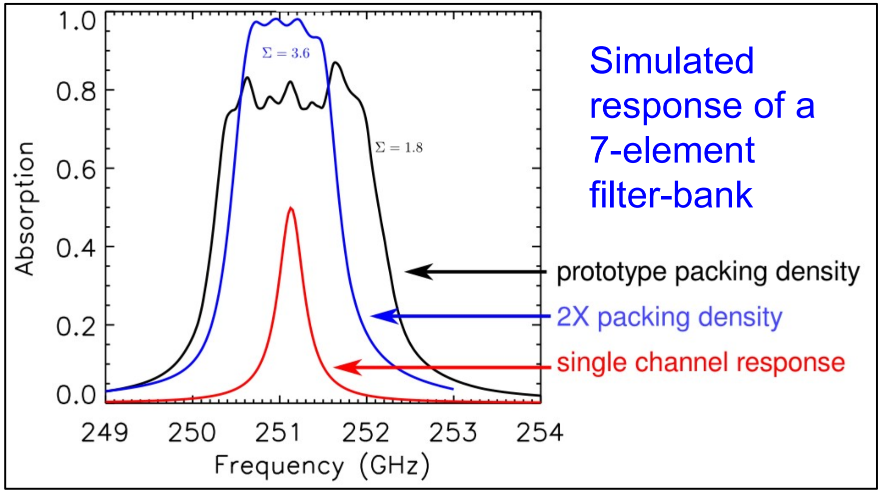


SuperSpec: coupling structures

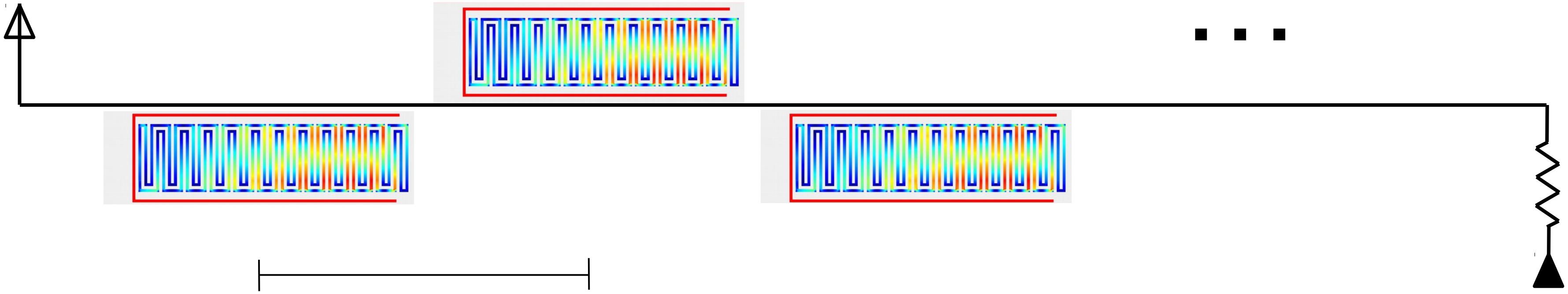


$$\frac{1}{R} = \frac{1}{Q_c} + \frac{1}{Q_i}$$

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

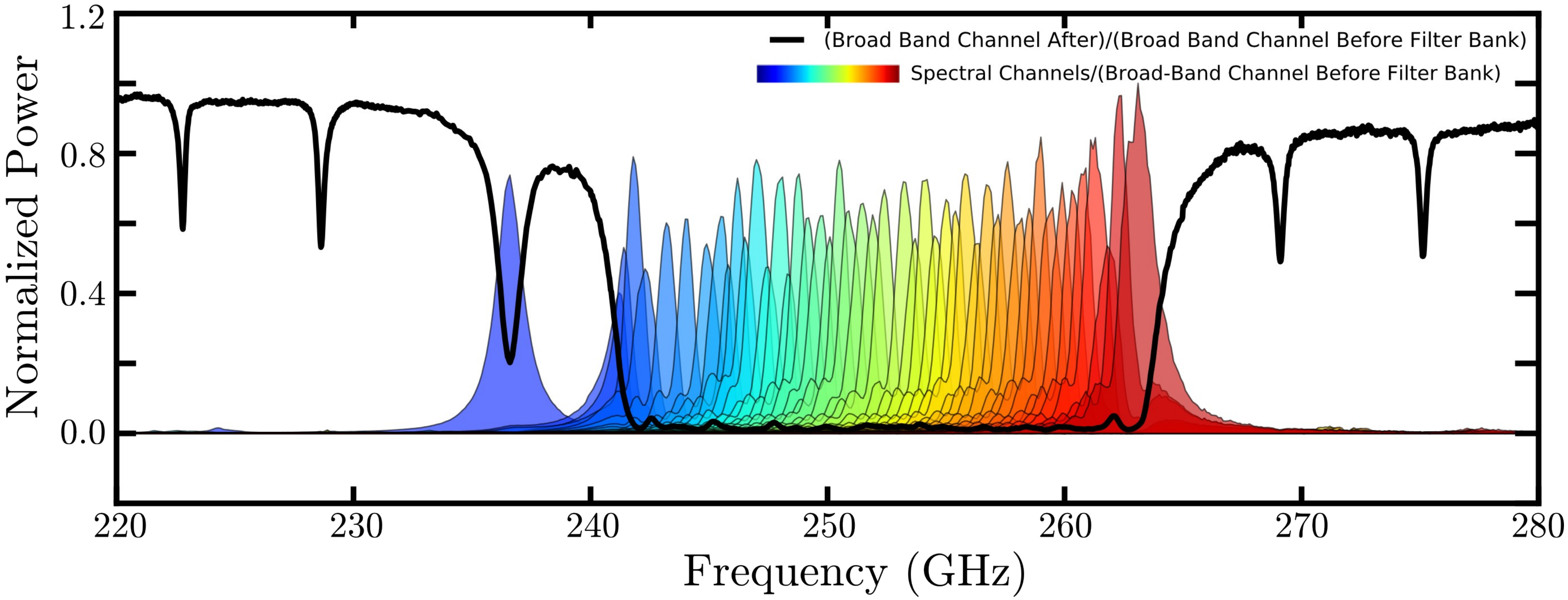


Monotonically decreasing in frequency



λ/4 or 3λ/4 spacing

SuperSpec: 50-channel prototype



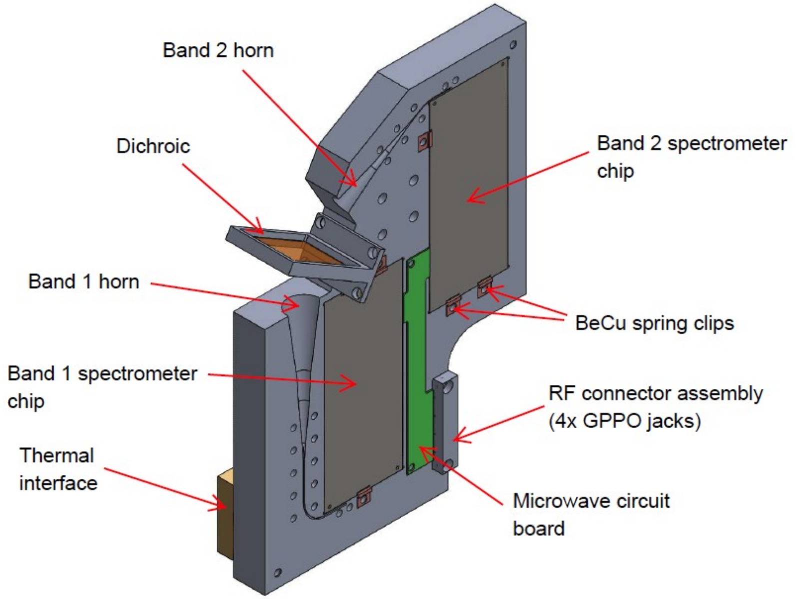
100% yield (on 2 dies)

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

SuperSpec: destination LMT

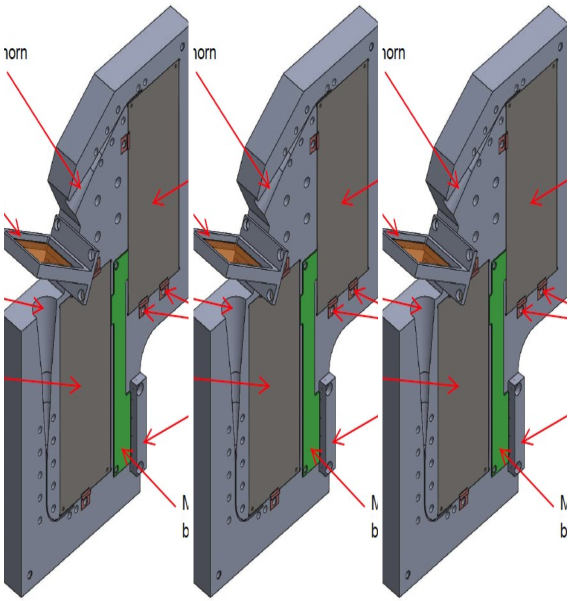


dual-band
(2-octave)

spectrometer
unit

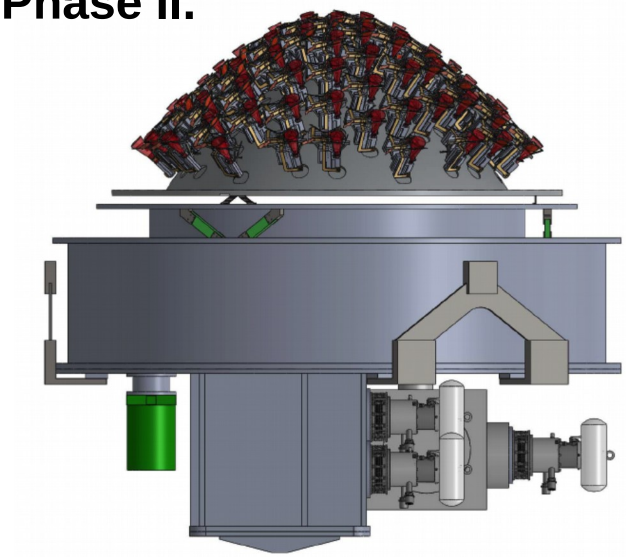
LMT

Phase I.



a small number of spectrometer chips

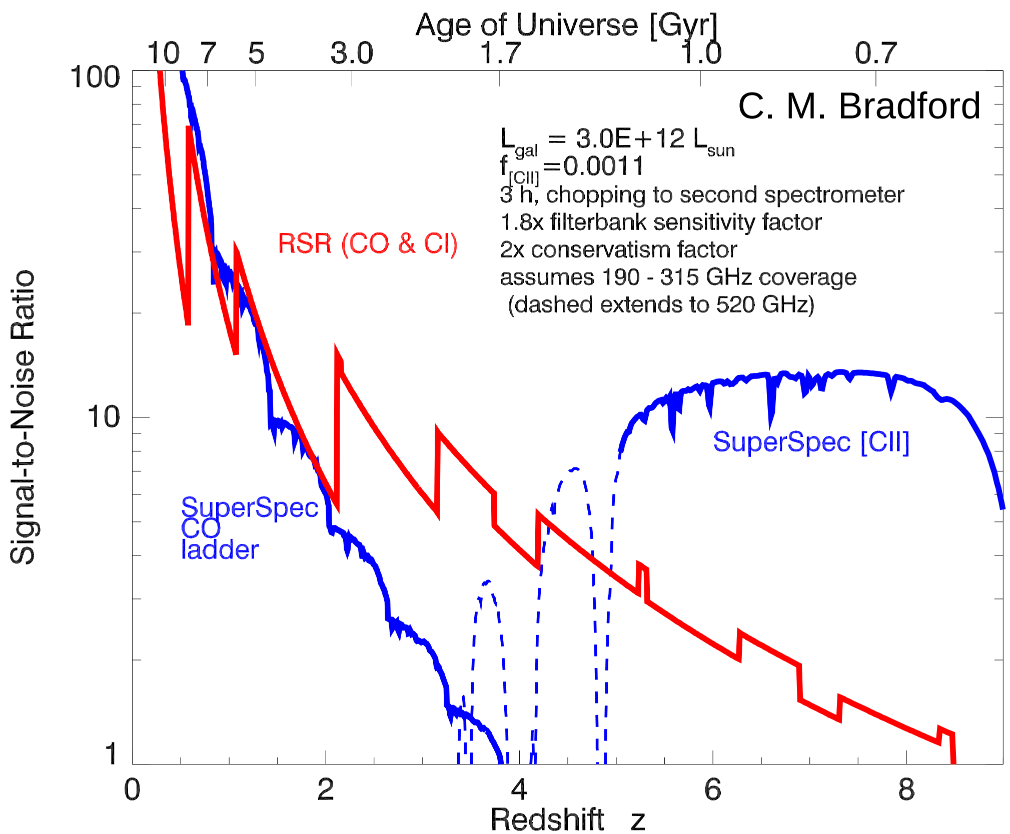
Phase II.



MOS

C. M. Bradford

SuperSpec: science case...



Complete CO SED ladder sampling (e.g. J = 4, 5, 6 … for z ~2–3)

4 arcmin field, 30 beams Bethermin model...

4 am/30obj	ULIRG all	ULIRG z>5	3e11 all	3e11 z>5
Int time [h]	6.75		62	
Effective num	21	0.35	30 (87 in field)	2.1 (if can ID)
Rate [/ hour]	3.1	0.06	0.48	0.03
Rate [/ week]	260	4.3	41	2.8
Rate [/ year]	13,000	220	2000	142

Optical KIDs

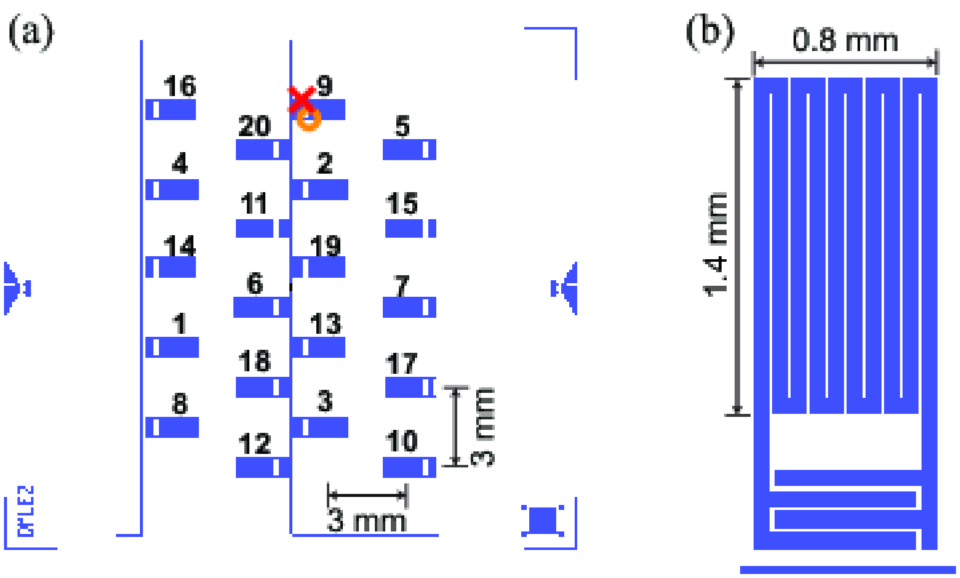
Why KIDs are good for optical/IR:

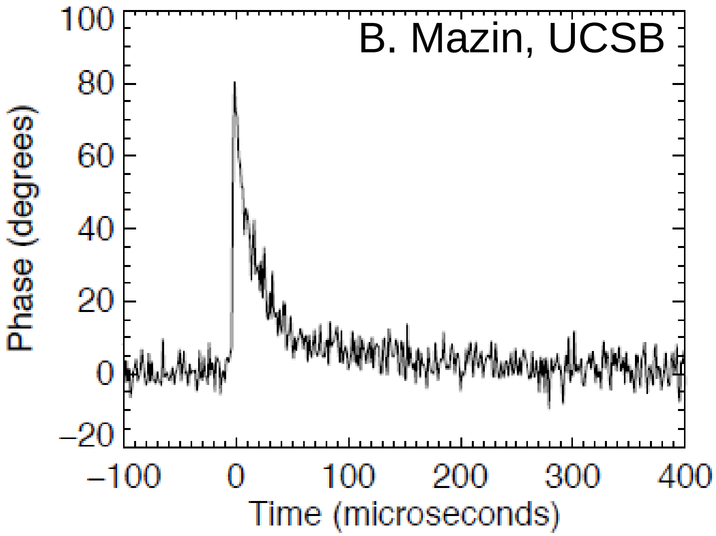
Time resolved imaging (~10 us resolution)

scan-mode imaging

HIRMES-style spectroscopy

LBT





photon-counting

Part III.

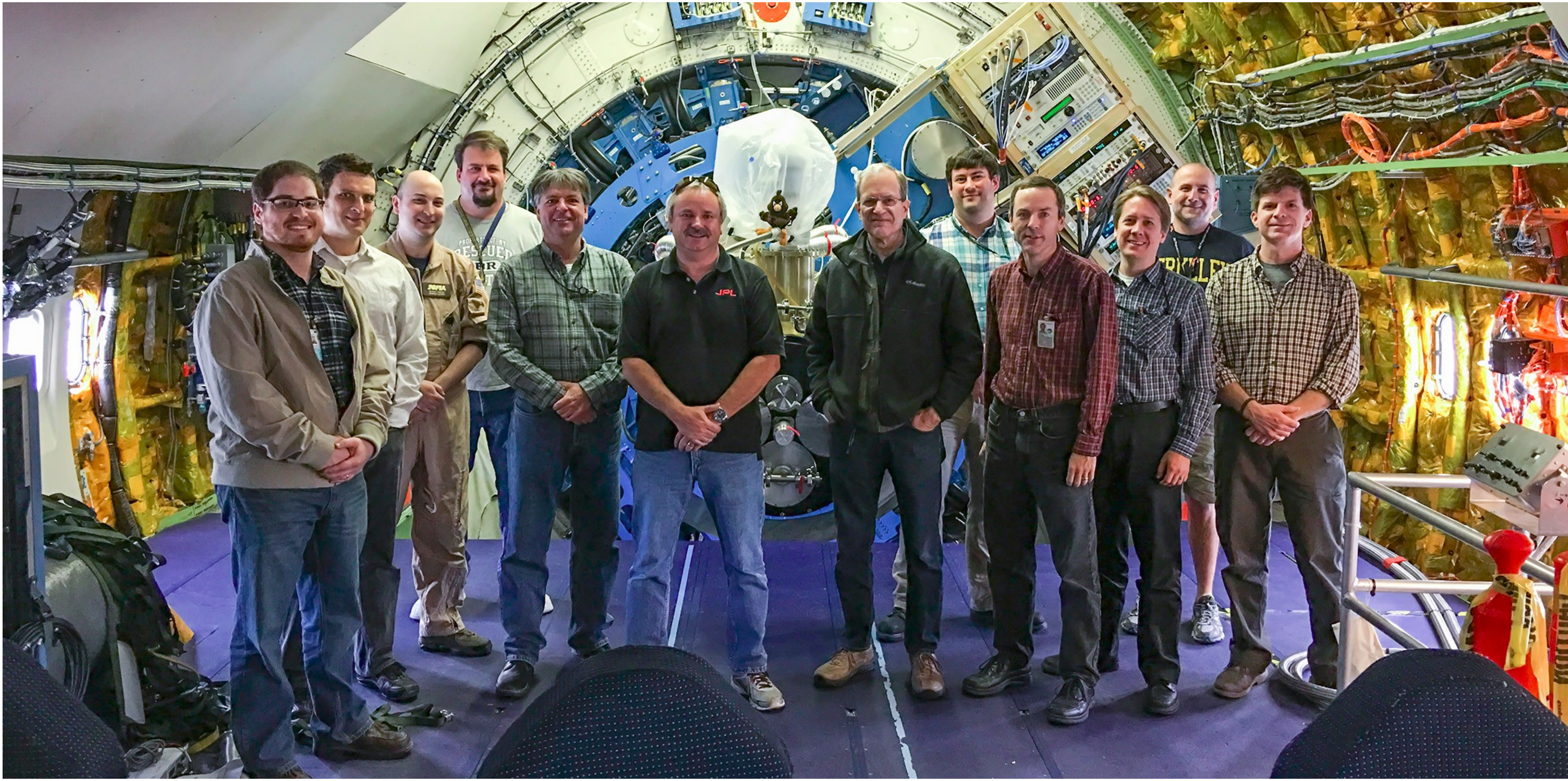
SOFIA / HAWC+


SOFIA
STRATOSPHERIC OBSERVATORY
FOR INFRARED ASTRONOMY

SOFIA / HAWC+

- **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)

SOFIA / HAWC+



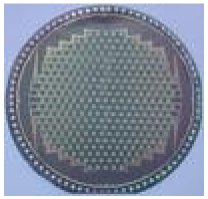
SOFIA / HAWC+: imaging pipeline

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

SHARC-2

350um

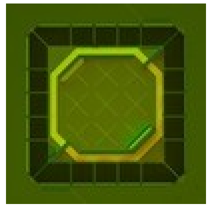
CSO
(2003)



LABOCA

870um

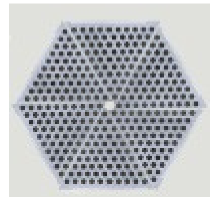
APEX
(2007)



SABOCA

350um

APEX
(2008)



ASZCA

2mm

APEX
(2006)

p-ArTeMiS

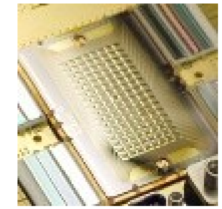
200um
350um
450um

APEX
(2011)

PolKa

870um
polarimetry

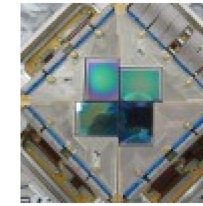
APEX
(2010)



GISMO

2mm

IRAM
(2008+)



SCUBA-2

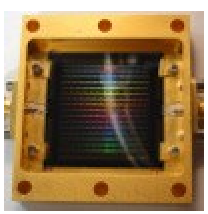
450um
850um

JCMT
(2010+)

sharcsolve (SHARC-2)

BoA (LABOCA, SABOCA, ASZCA, p-ArTeMiS)

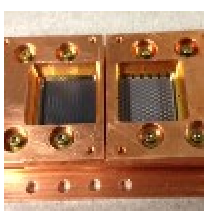
SMURF (SCUBA-2)



MAKO

350um

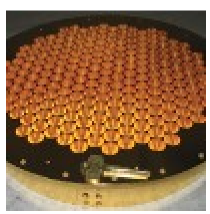
CSO
(2014)



MAKO-2

350um
850um

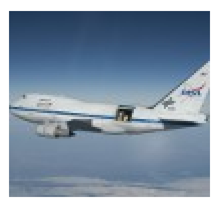
CSO
(2014)



MUSTANG-2

3mm

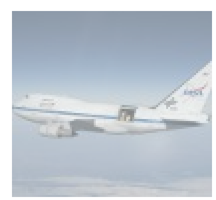
GBT
(2015)



HAWC+

53 – 217 um

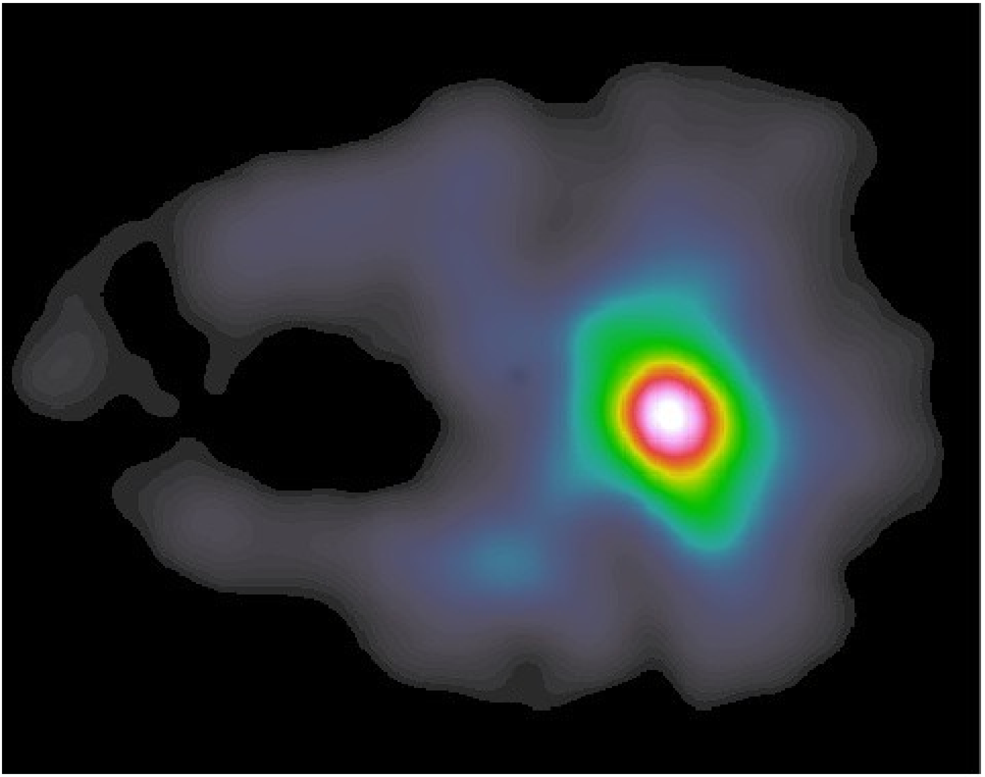
SOFIA
(2015)



HIRMES

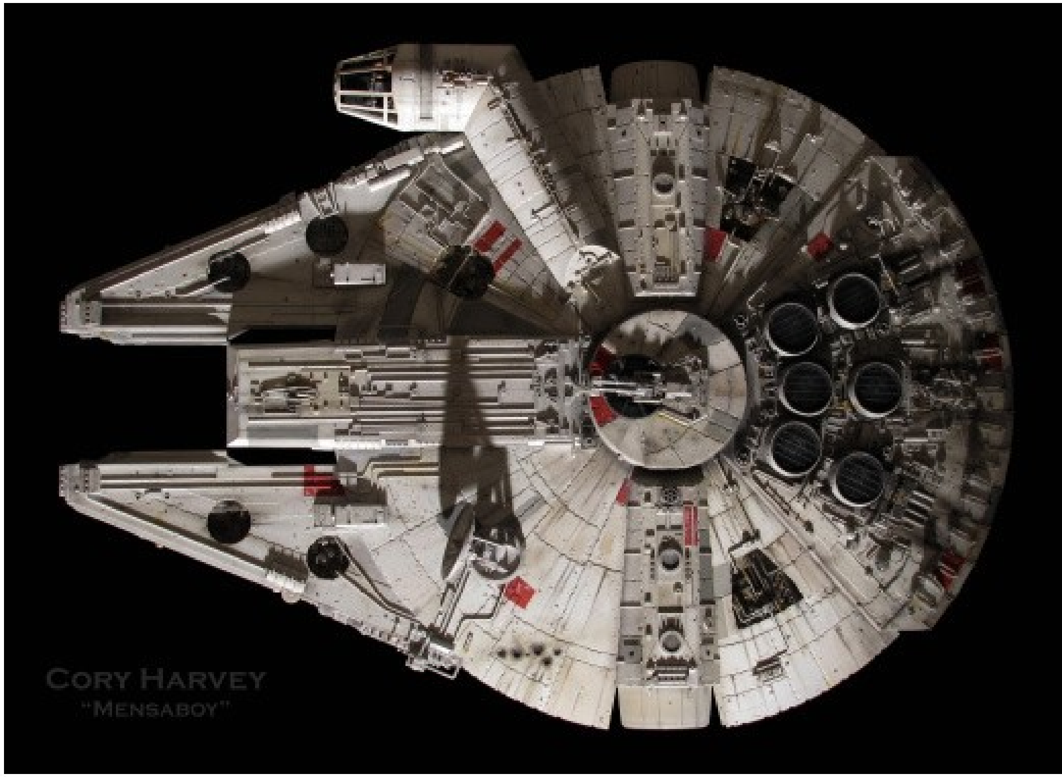
25 – 122 um

SOFIA
(2019)



DR-21

observed by SOFIA/HAWC+
at 53 microns on 2016-05-04

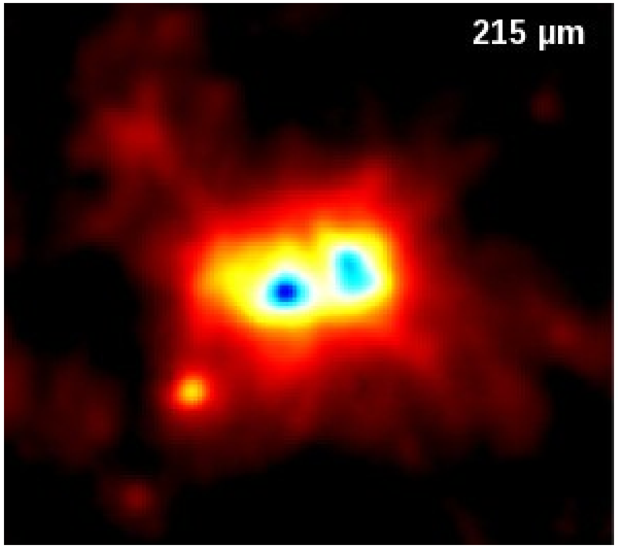


The Millenium Falcon

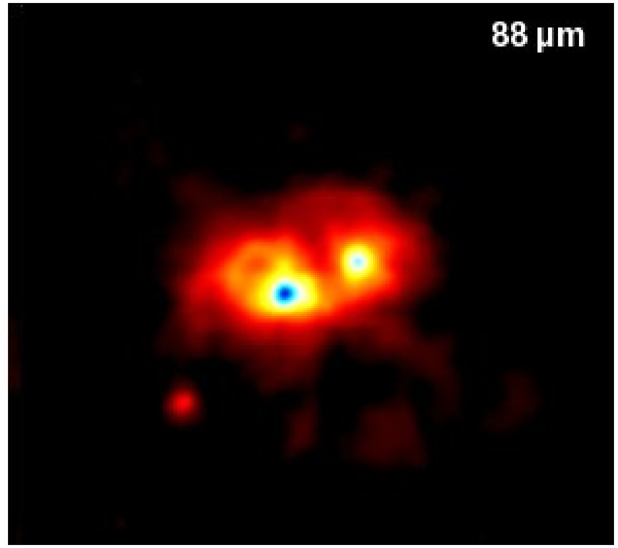
A long time ago, in a galaxy far, far away...

HAWC+: W3

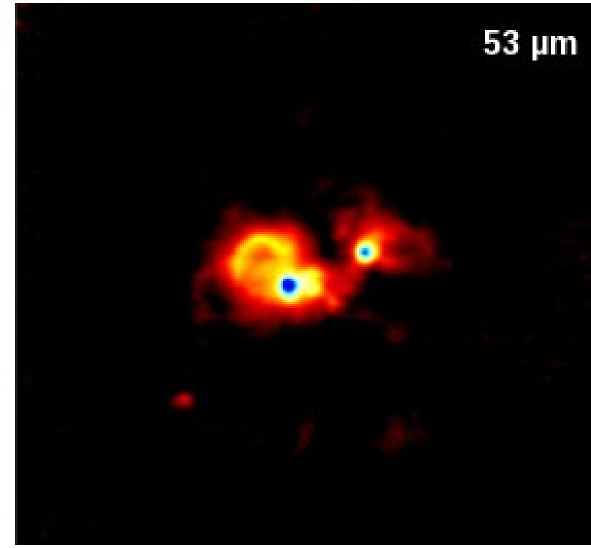
Commissioning flights, 3–5 October 2016



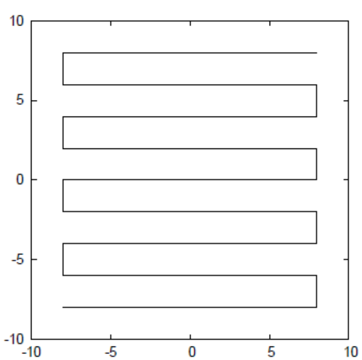
2.2 min. (elapsed time)

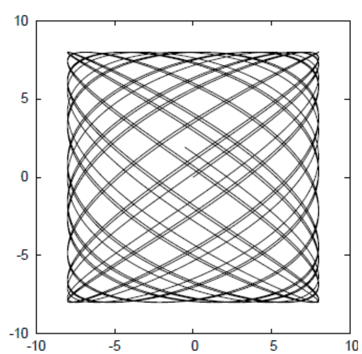


4.1 min. (elapsed time)

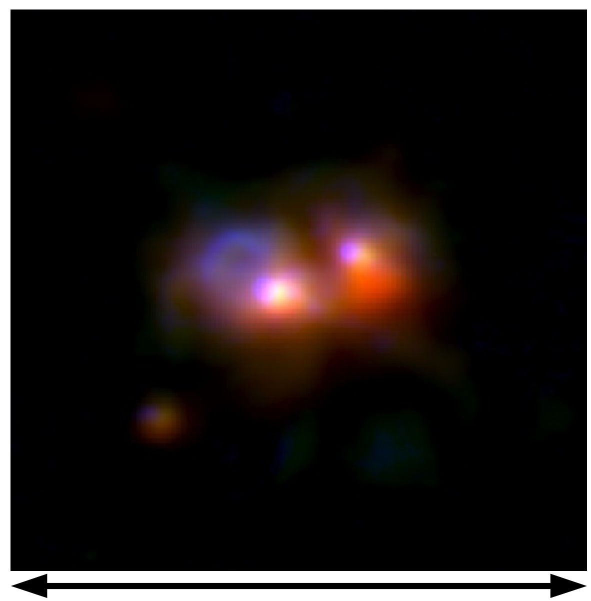


3.0 min. (elapsed time)

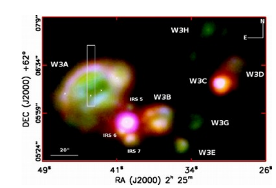




Kovács, 2008b

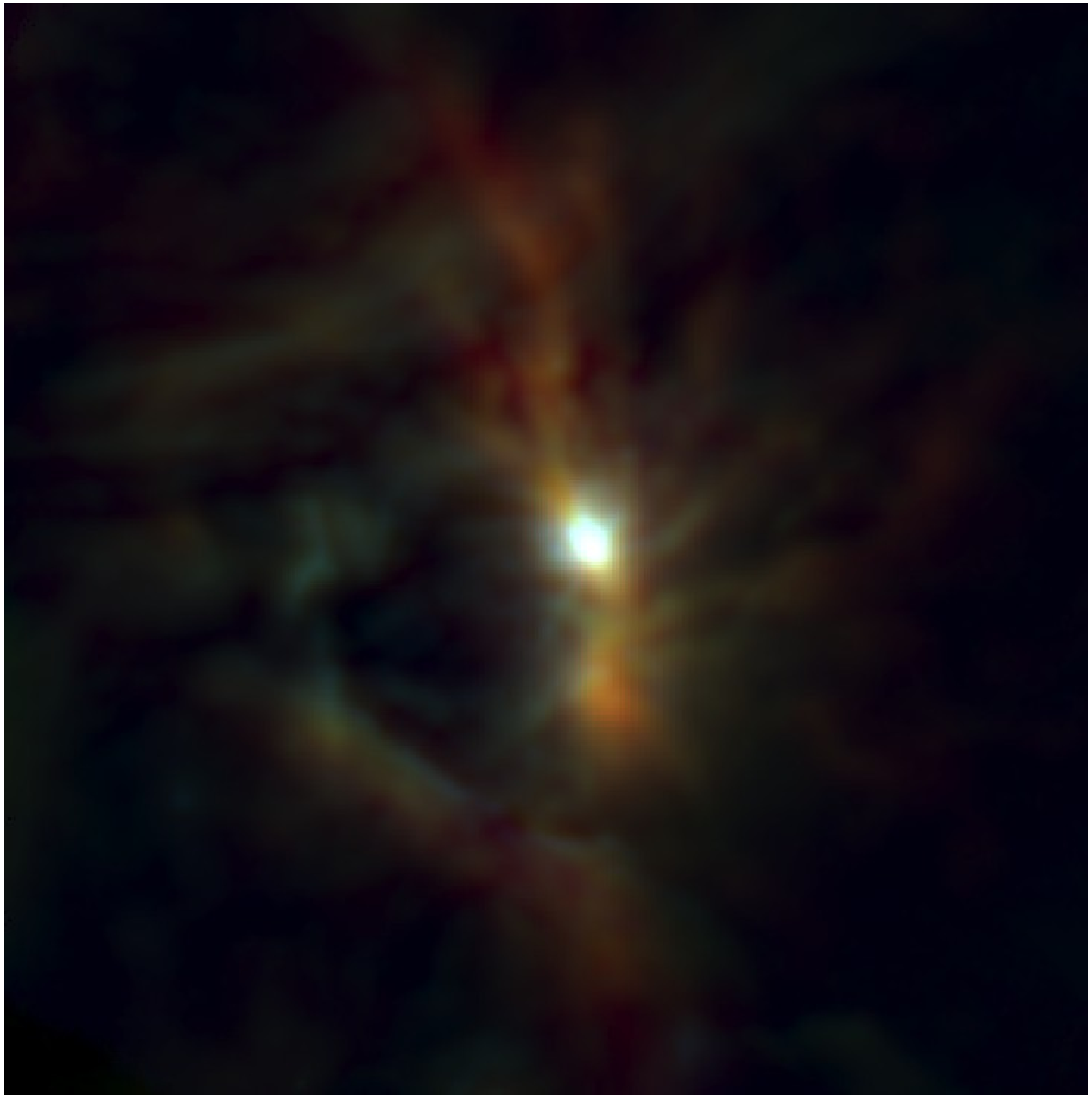


9’

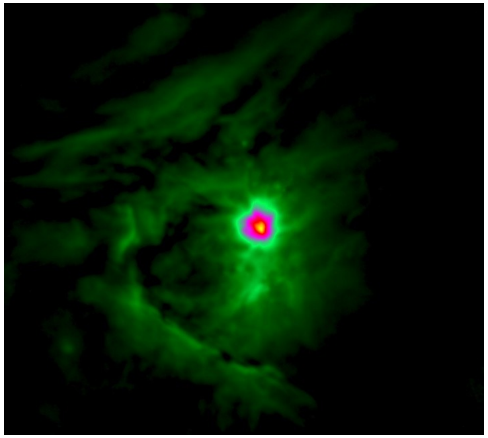


HAWC+: OMC-1

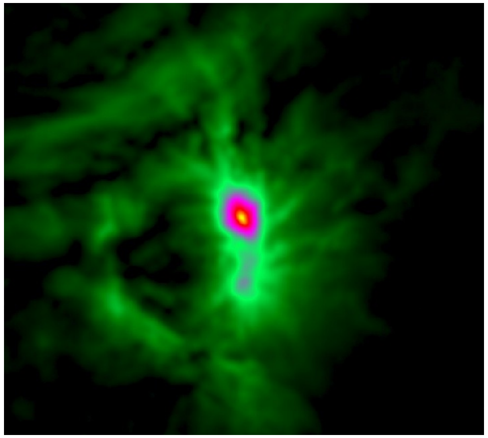
images by CRUSH



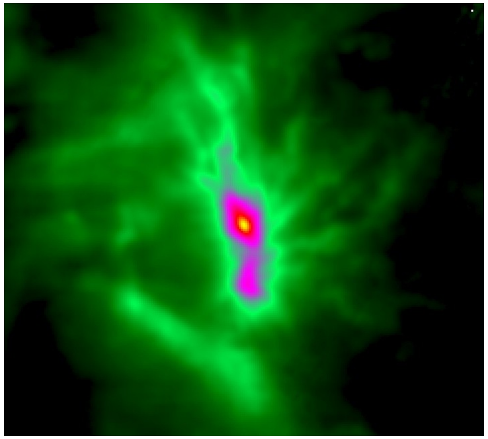
R: 155μm G: 89μm B: 53μm



53μm

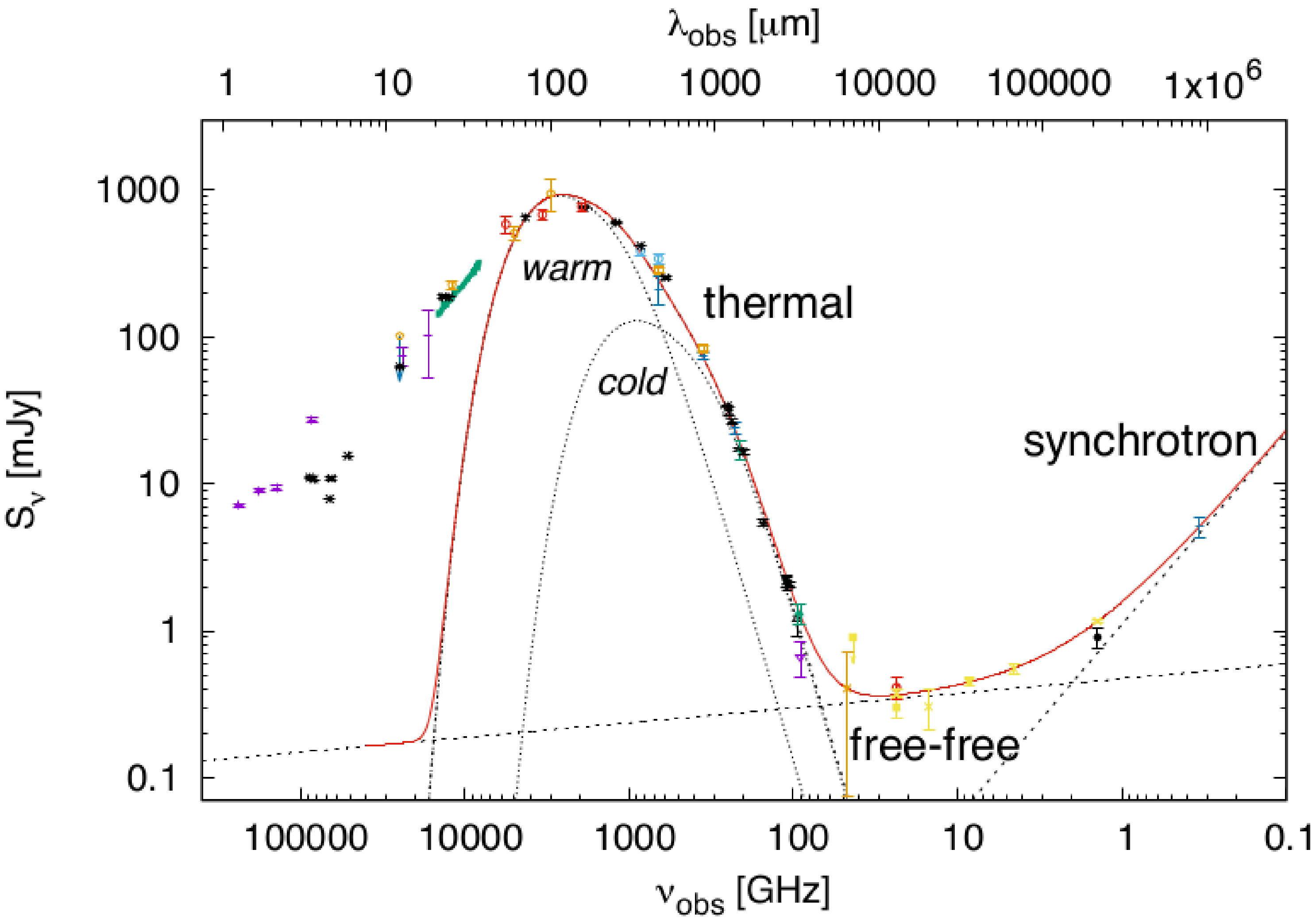


89μm



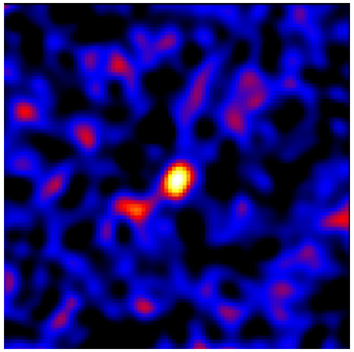
155μm

SOFIA / HAWC+: APM 08279+5255

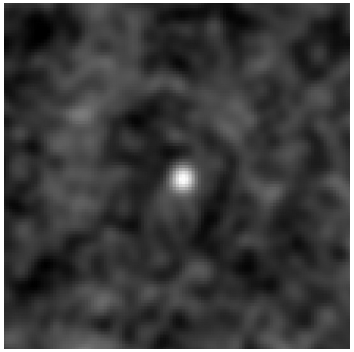


D. Riechers

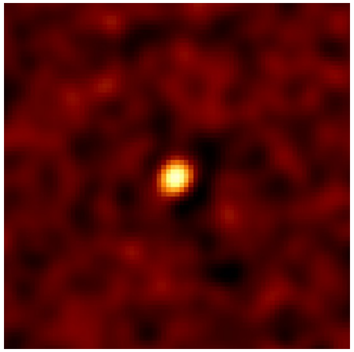
z = 3.91



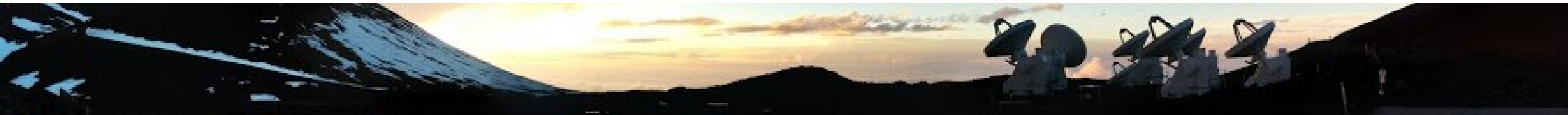
53μm



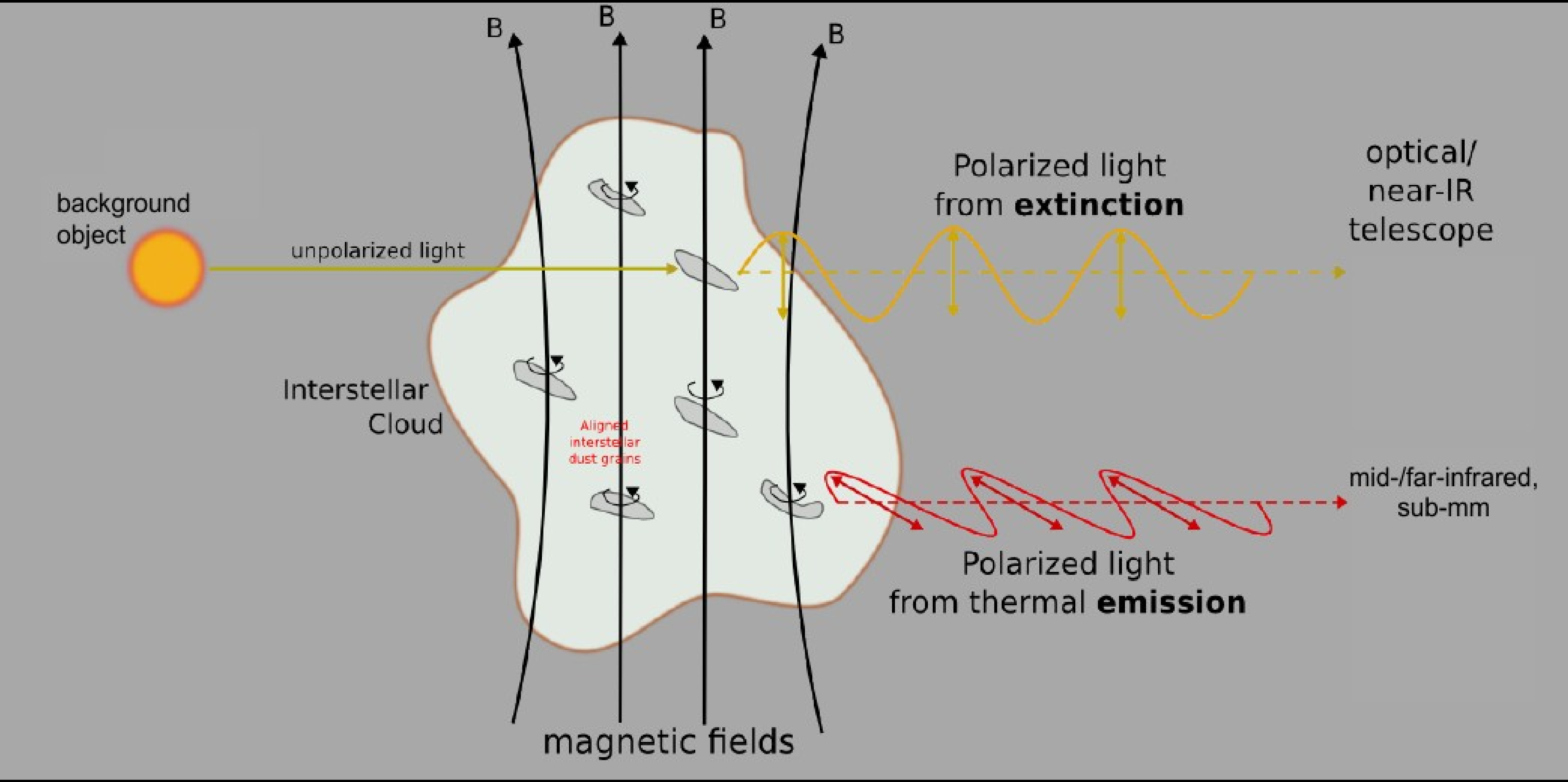
89μm



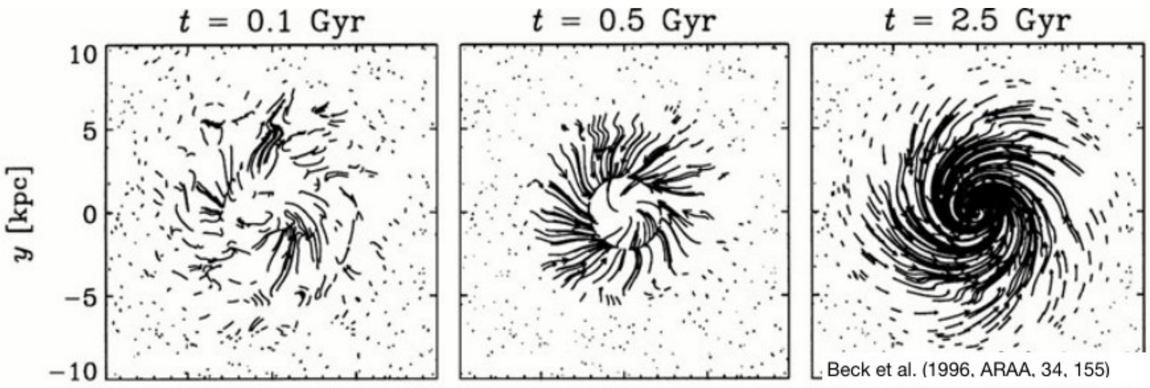
155μm



Polarimetry



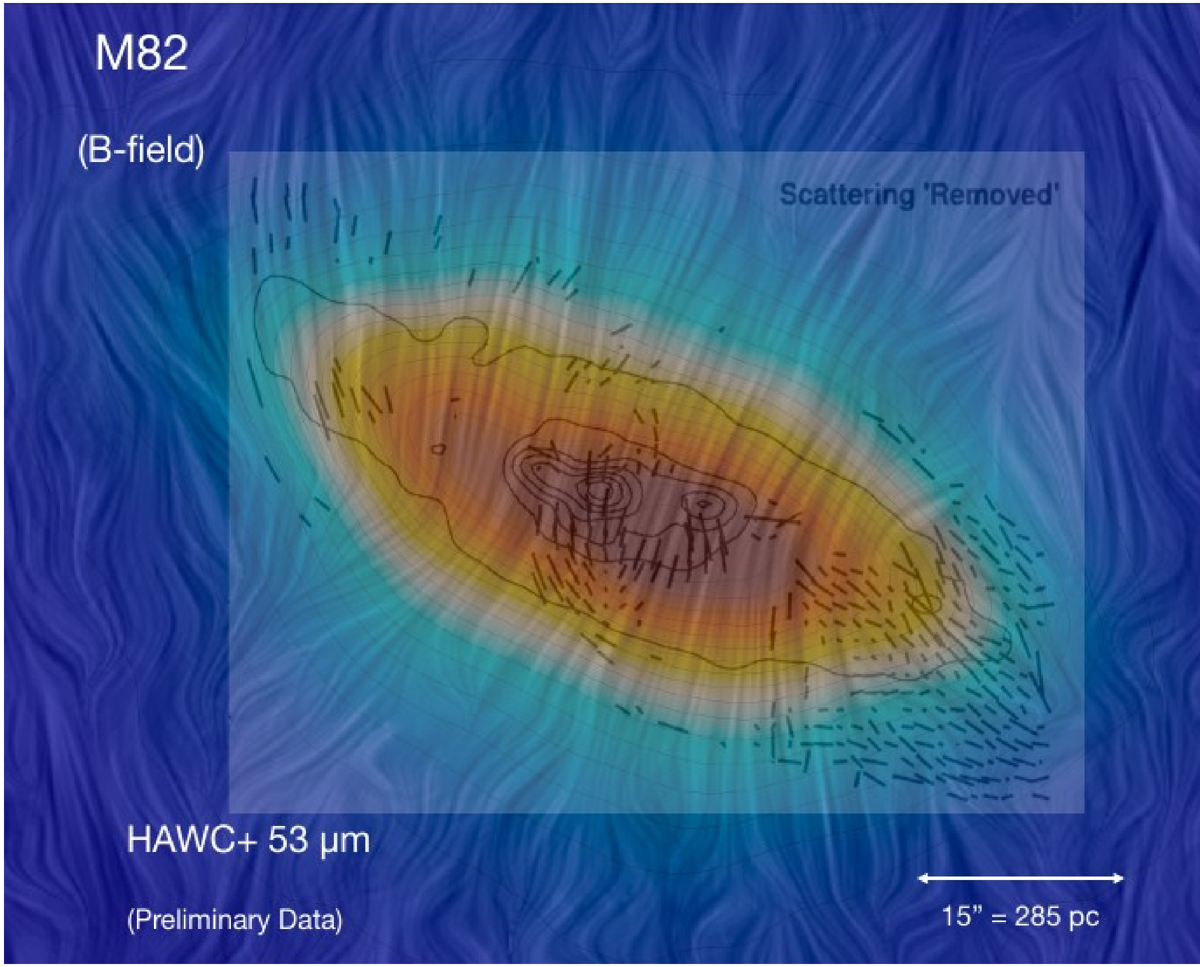
SOFIA / HAWC+: B-fields in galaxies



E. Rodriguez, 2018 AAS

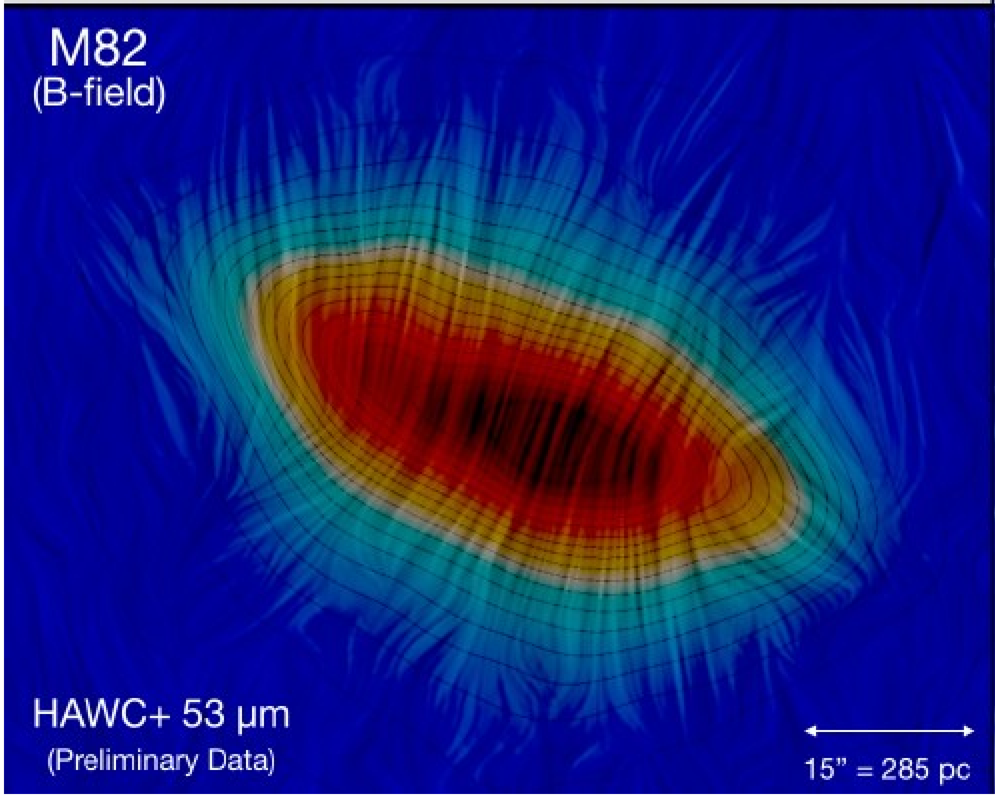
Absorption vs Emission

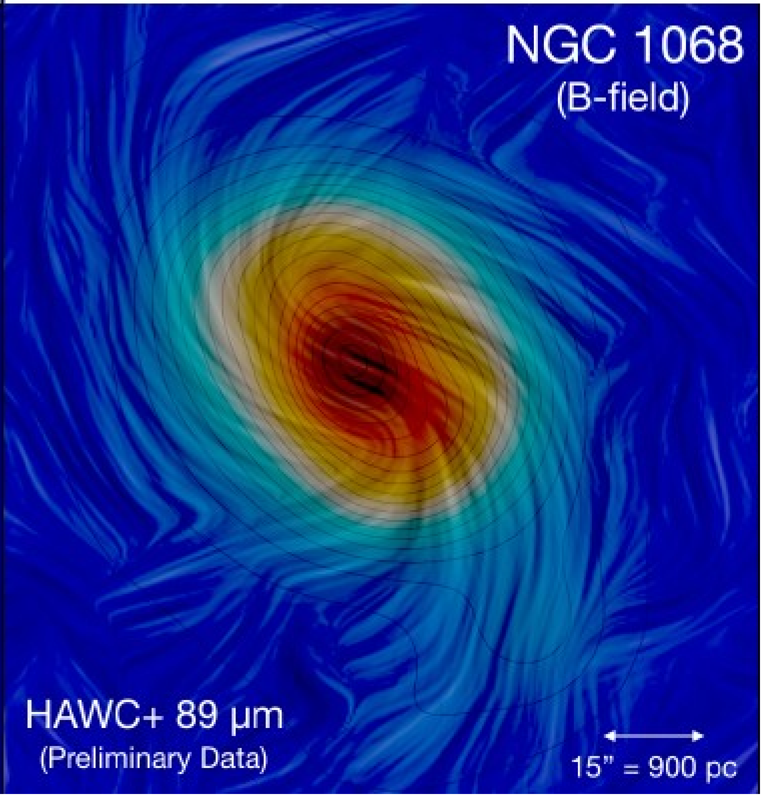
2.2μm overlaid vectors
Jones 2000, ApJ, 120, 2920



SOFIA / HAWC+: B-fields in galaxies

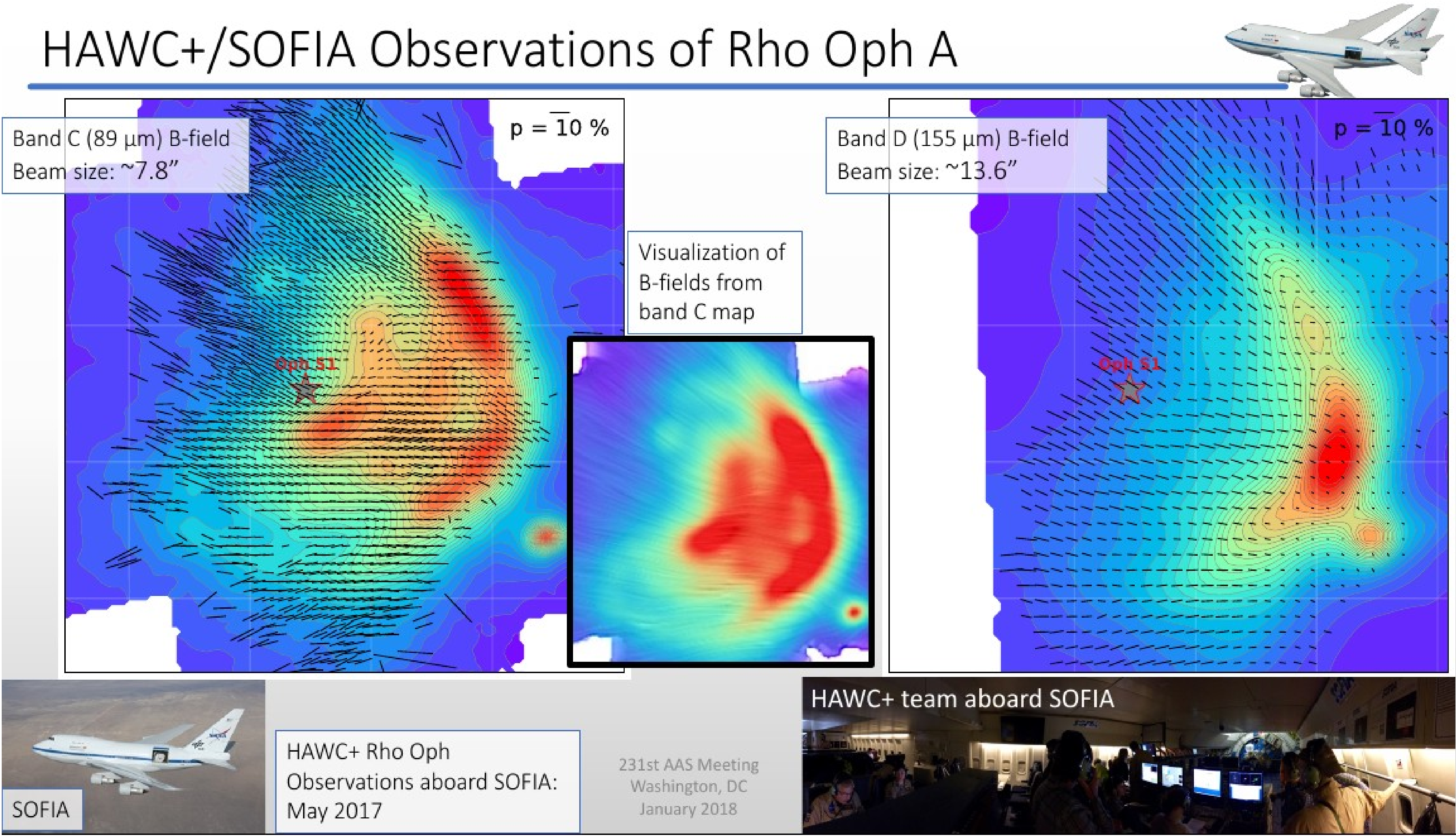
STARBURST GALAXY	MASSIVE SPIRAL GALAXY
What are we learning here?	
Galactic dusty outflows are polarized due to magnetically aligned dust grains	Magnetic arms due to polarized emission from aligned dust grains
Polar magnetic fields	Spiral magnetic fields





E. Rodriguez, 2018 AAS

SOFIA / HAWC+: Rho Ophiuchi

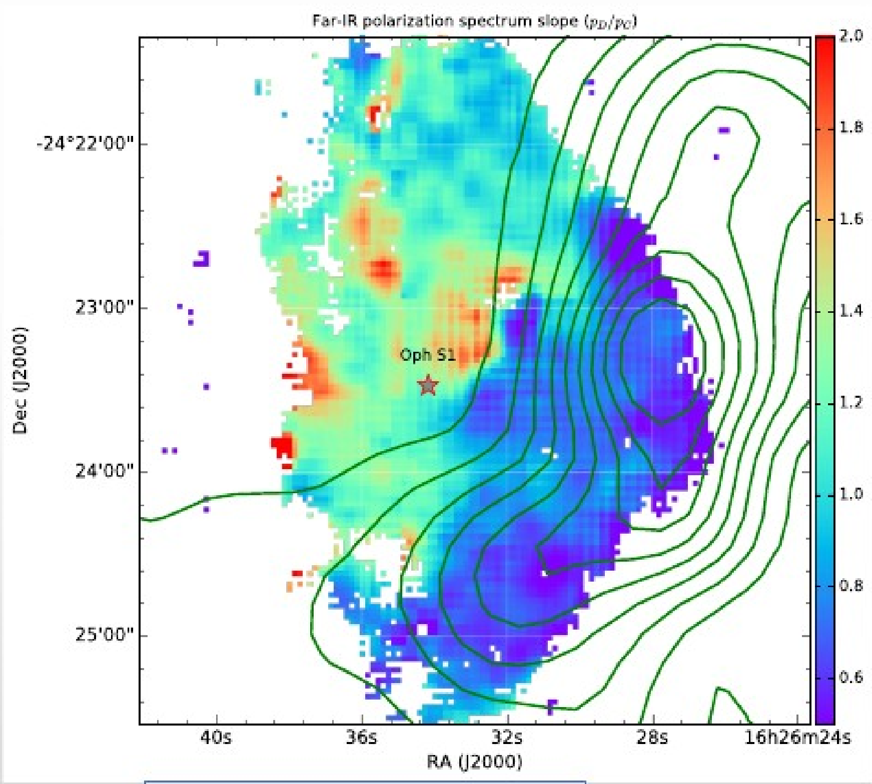


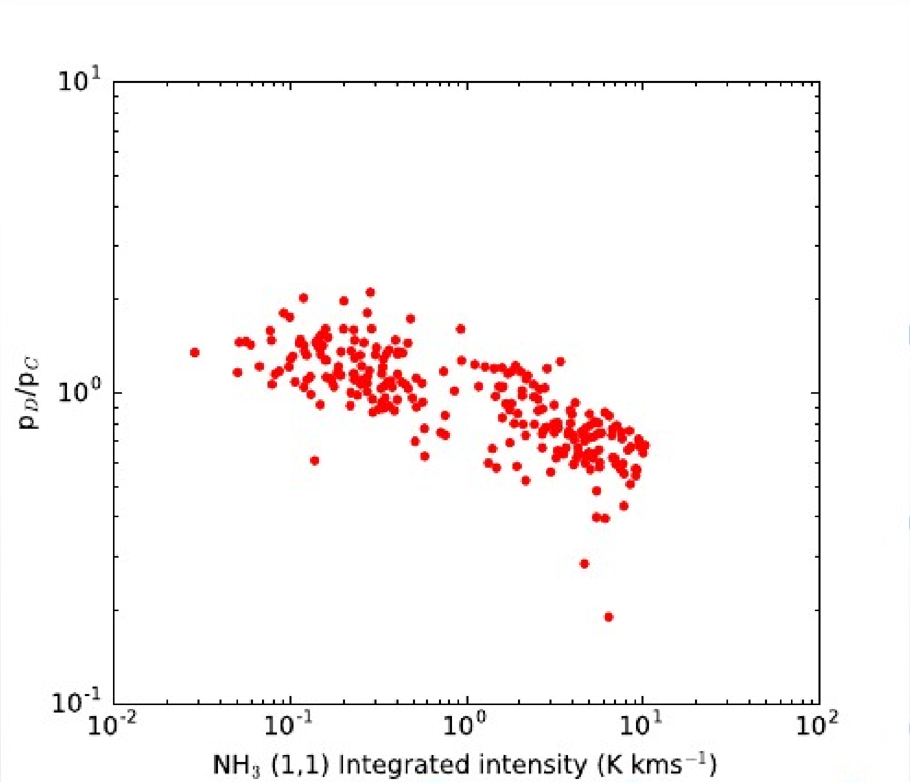
F. Santos, AAS 2018

SOFIA HAWC+: a slightly unexpected result...

Far-infrared polarization spectrum of Rho Oph A

- Good correlation of (p_D / p_C) with NH_3 emission: **the slope of the polarization spectra is negative at higher densities.**





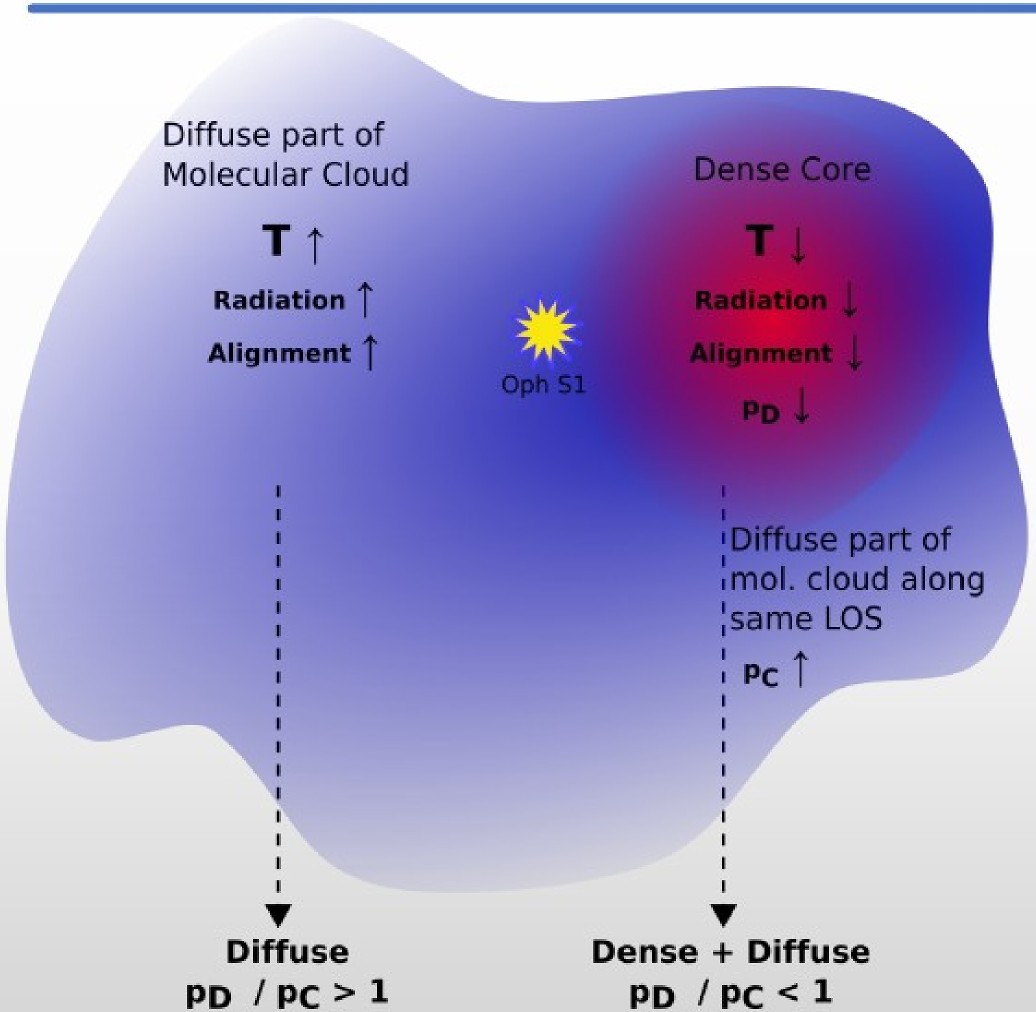
Contours: NH_3 (1,1) from Friesen et al. (2017)

231st AAS Meeting - Washington, DC – January 2018

F. Santos, AAS 2018

SOFIA / HAWC+: Rho Ophiuchi

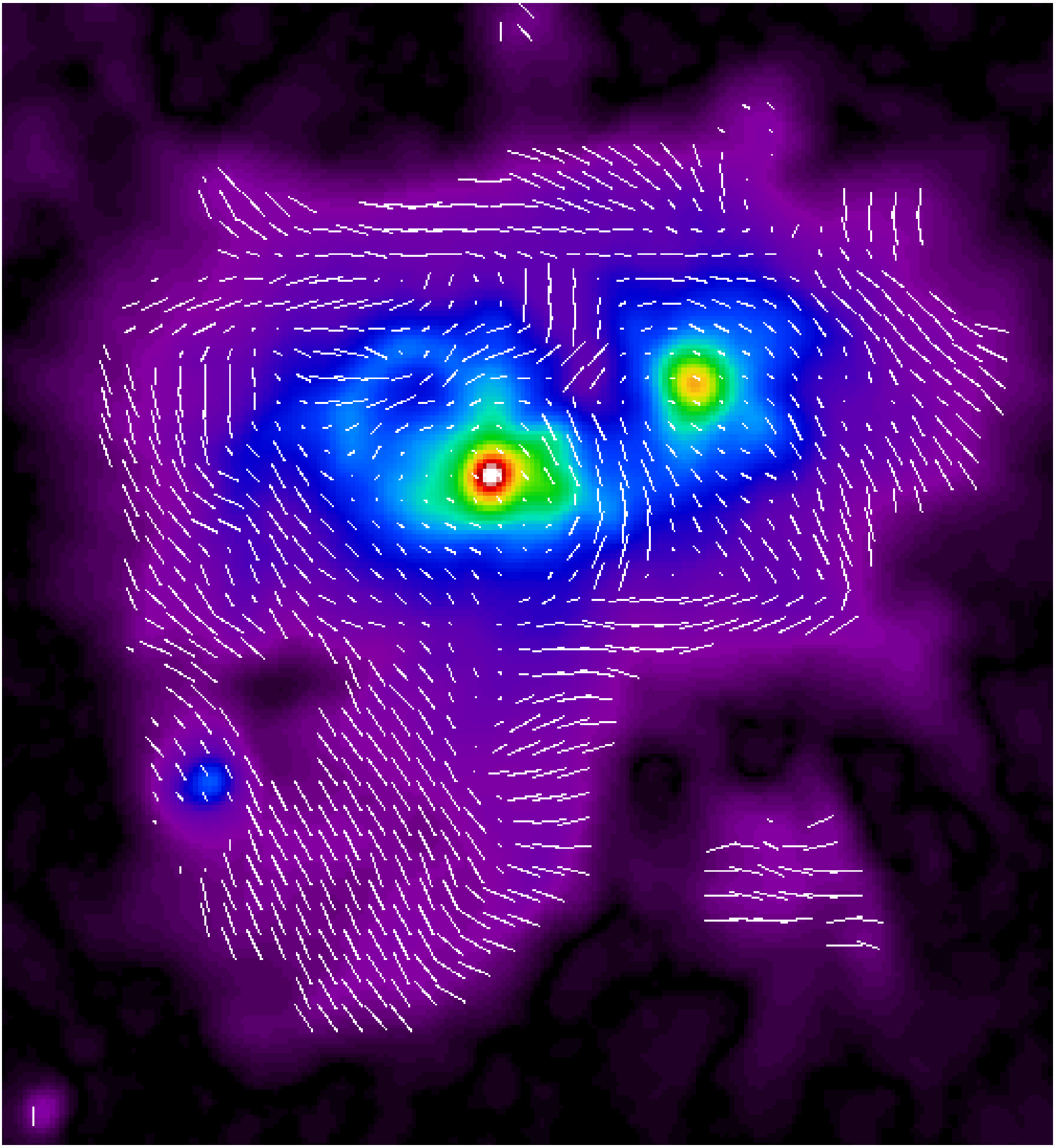
Discussion of schematic model



- Diffuse lines-of-sight:
  - Positive pol. spectrum slope as expected from grain models (e.g., Bethell et al 2007): Higher temperature and radiation incidence, efficient grain alignment
- Dense + Diffuse cloud lines-of-sight:
  - Inner portions – poorly aligned cold grains (emission best represented by band D): low p_D
  - Outer layers – better aligned warmer grains (emission best represented by band C): high p_C;
  - Integrating along the LOS: smaller p_D/p_C ratio

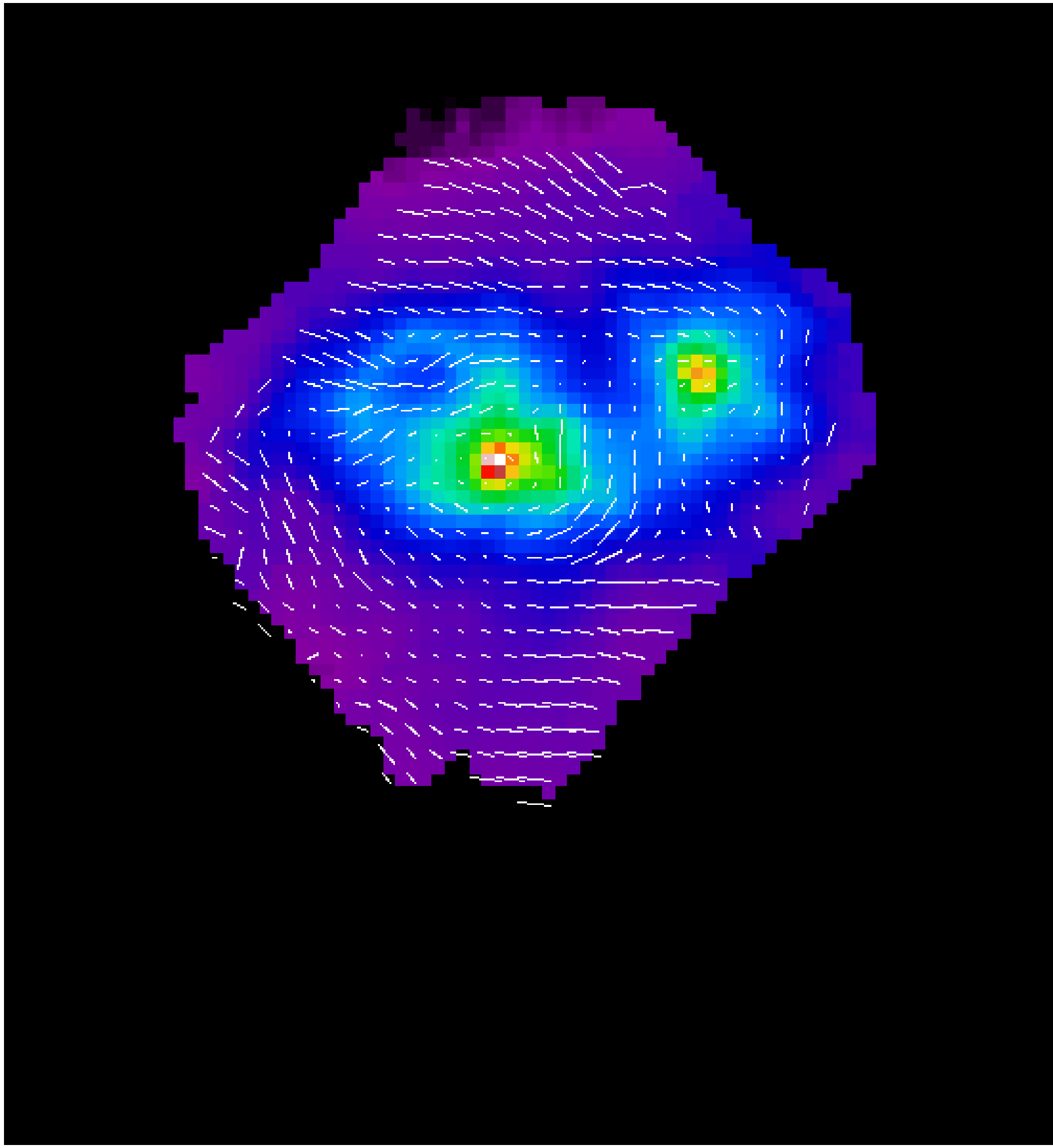
F. Santos, AAS 2018

SOFIA / HAWC+: Scan-mode polarimetry?



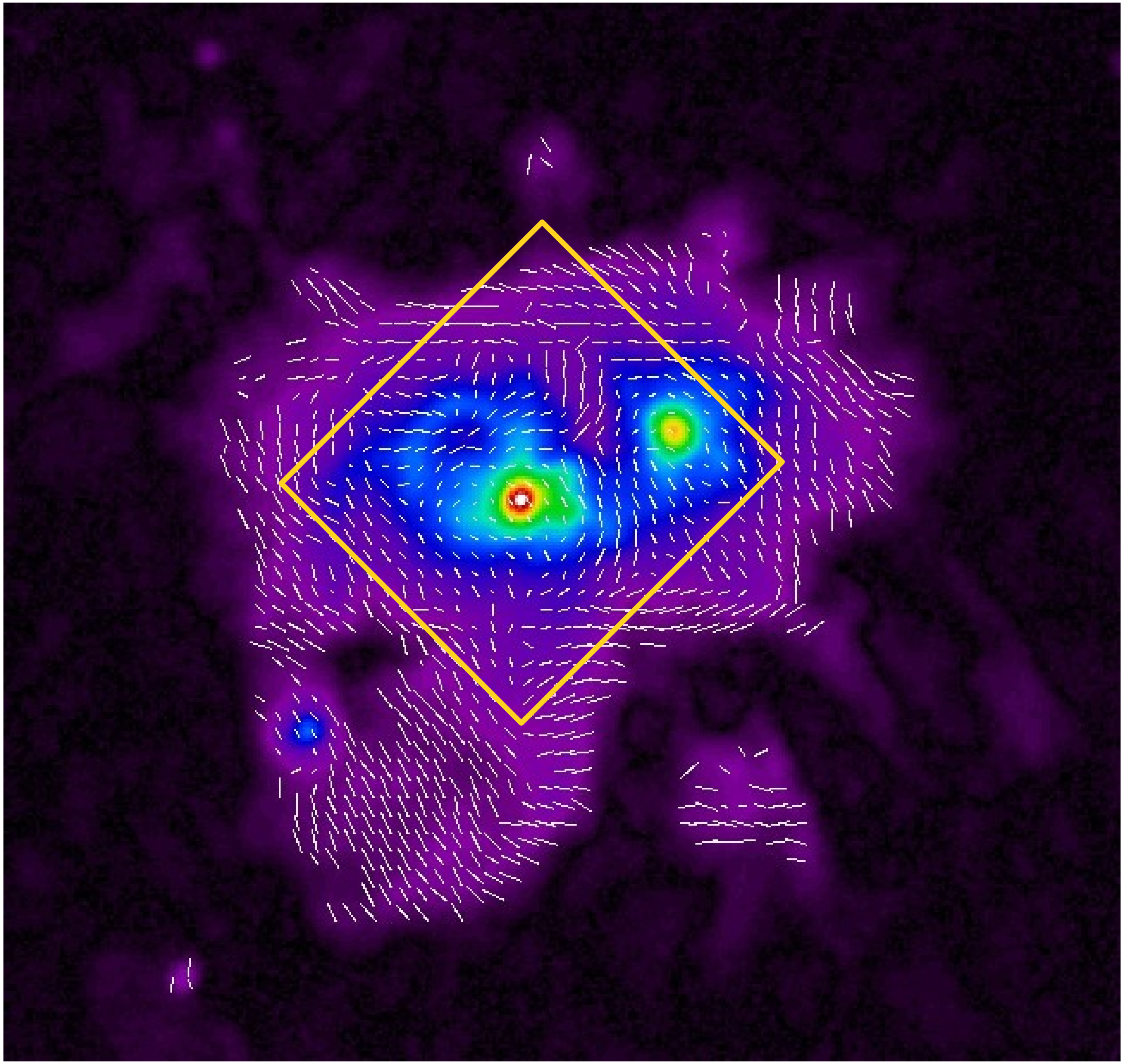
scan-mode (~10 minutes)

reduced by CRUSH



chop-nod-dither (~30 minutes)

SOFIA / HAWC+: Scan-mode polarimetry

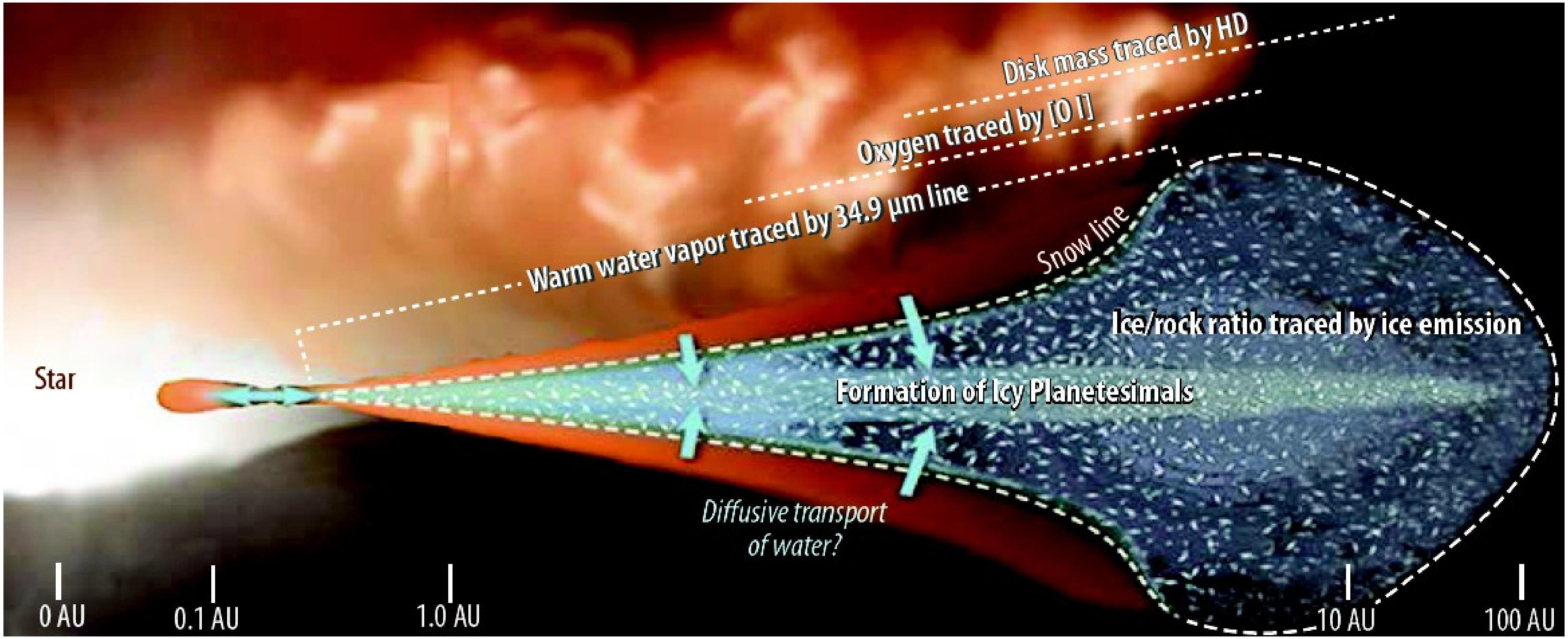


Full 10-minute scan-mode field of W3 at 155μm with CRUSH

SOFIA / HIRMES

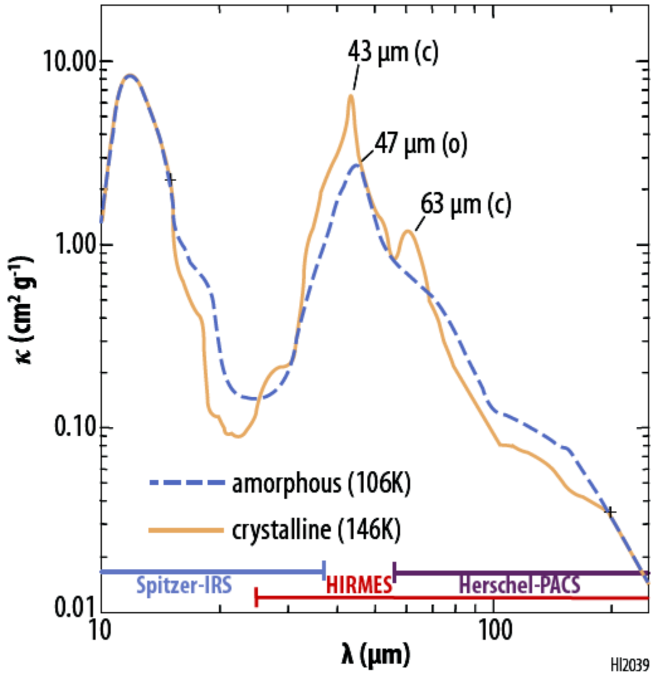
High-Resolution Mid-infrarEd Spectrometer

- 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

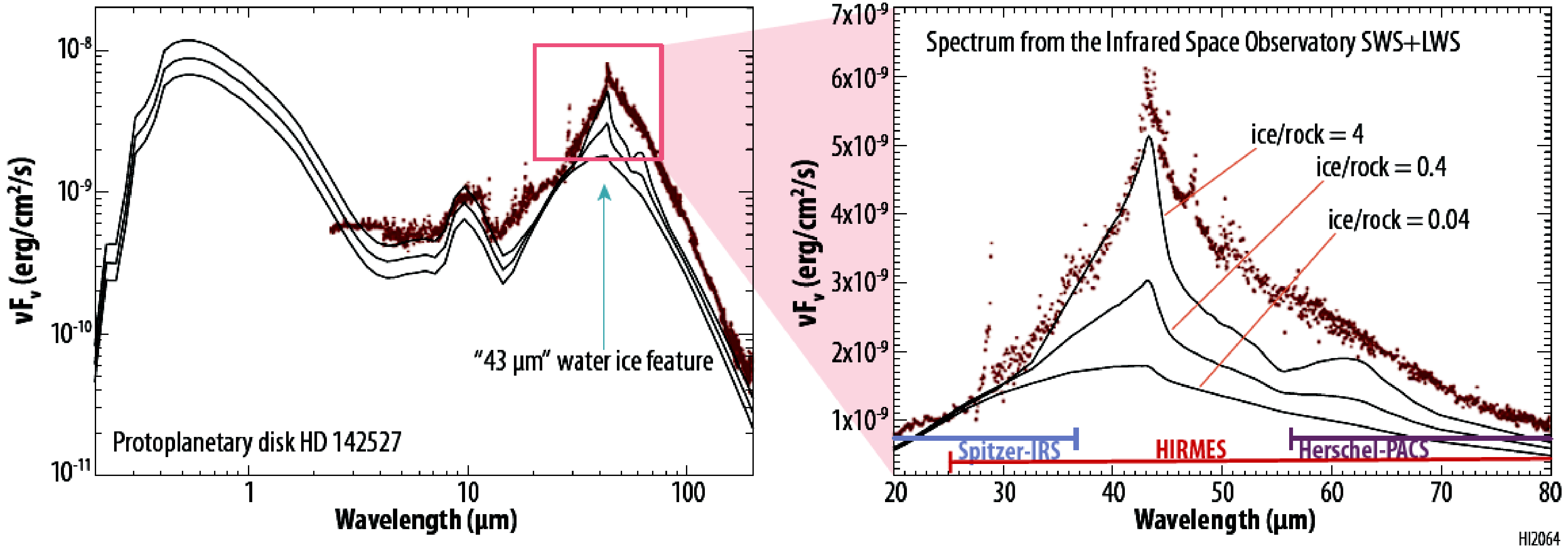


HIRMES: ices

Ice composition

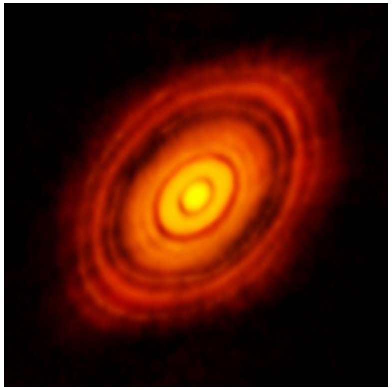


ice / rock ratios

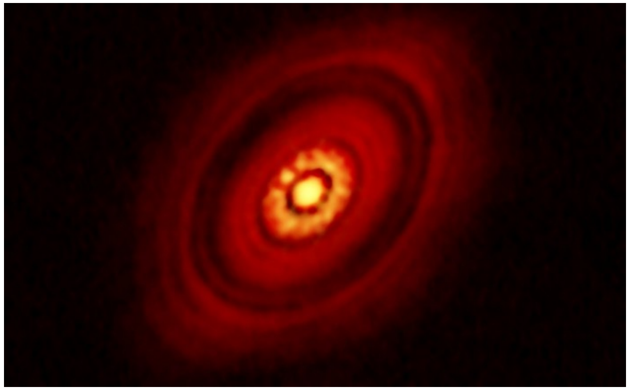


HIRMES: molecular and atomic lines

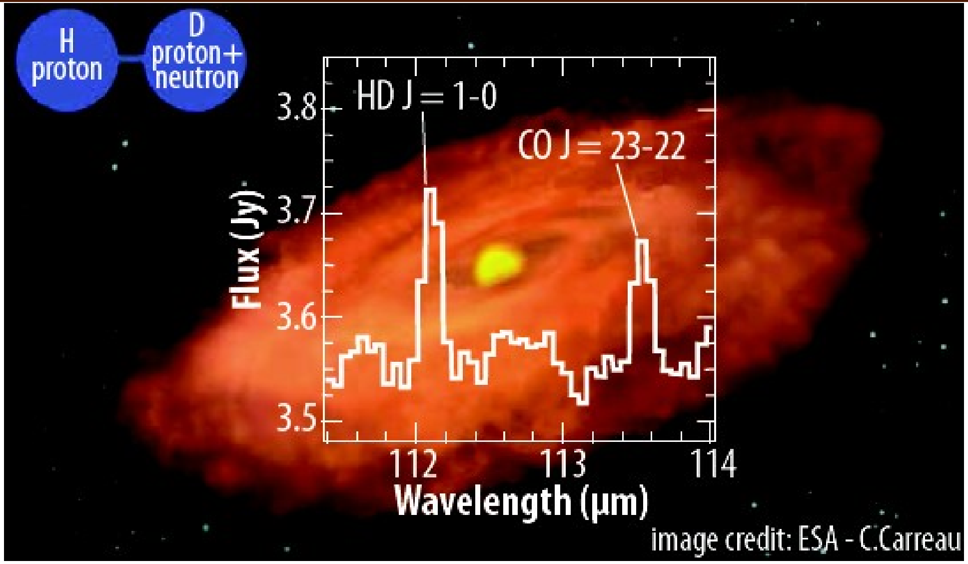
HL Tau

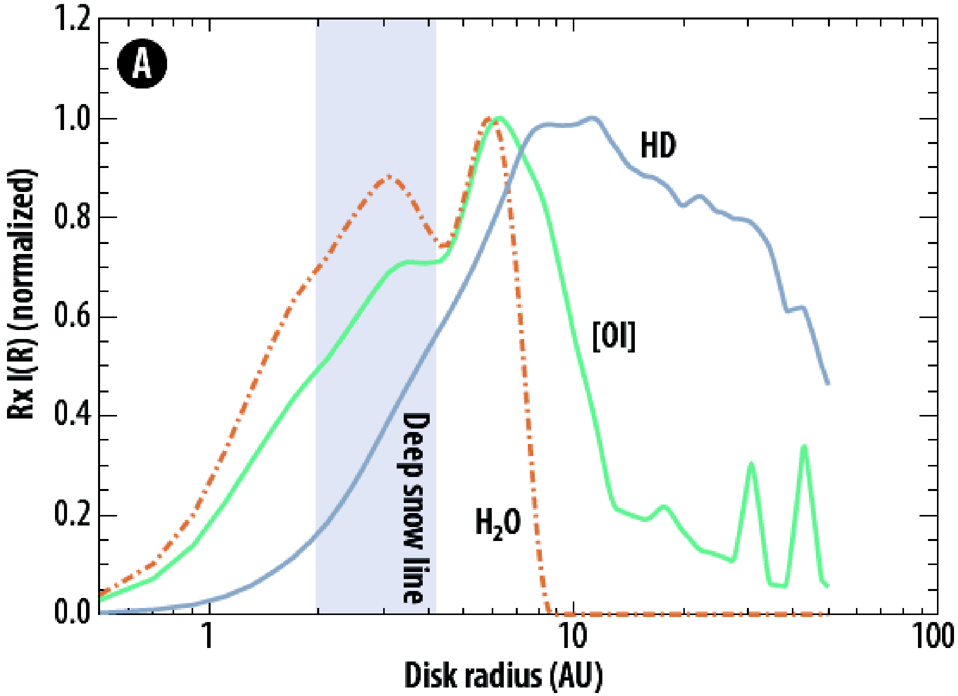


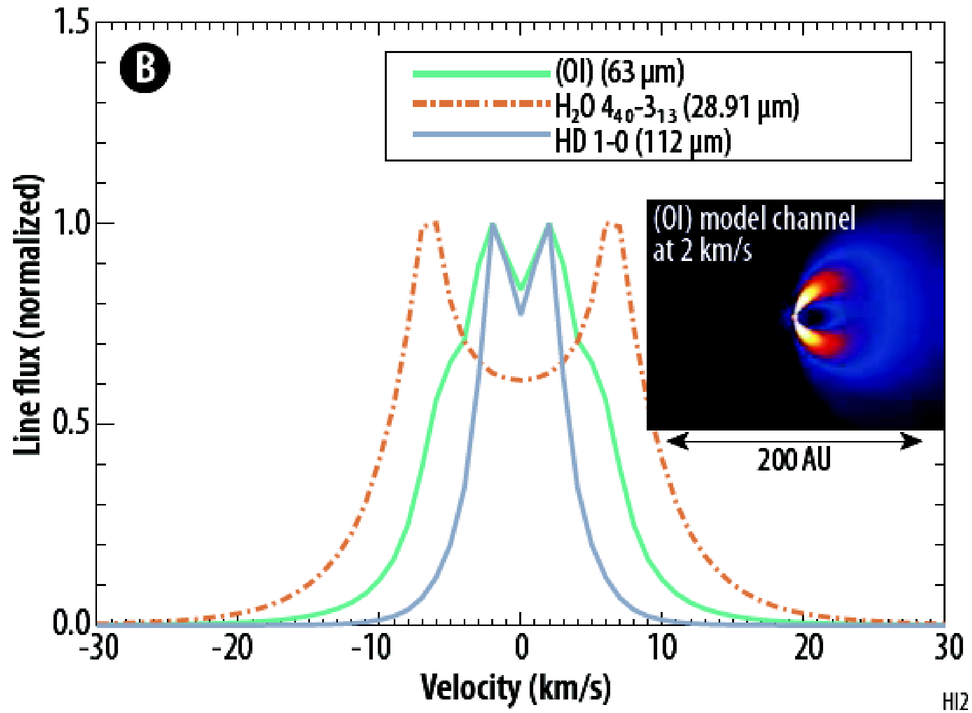
ALMA



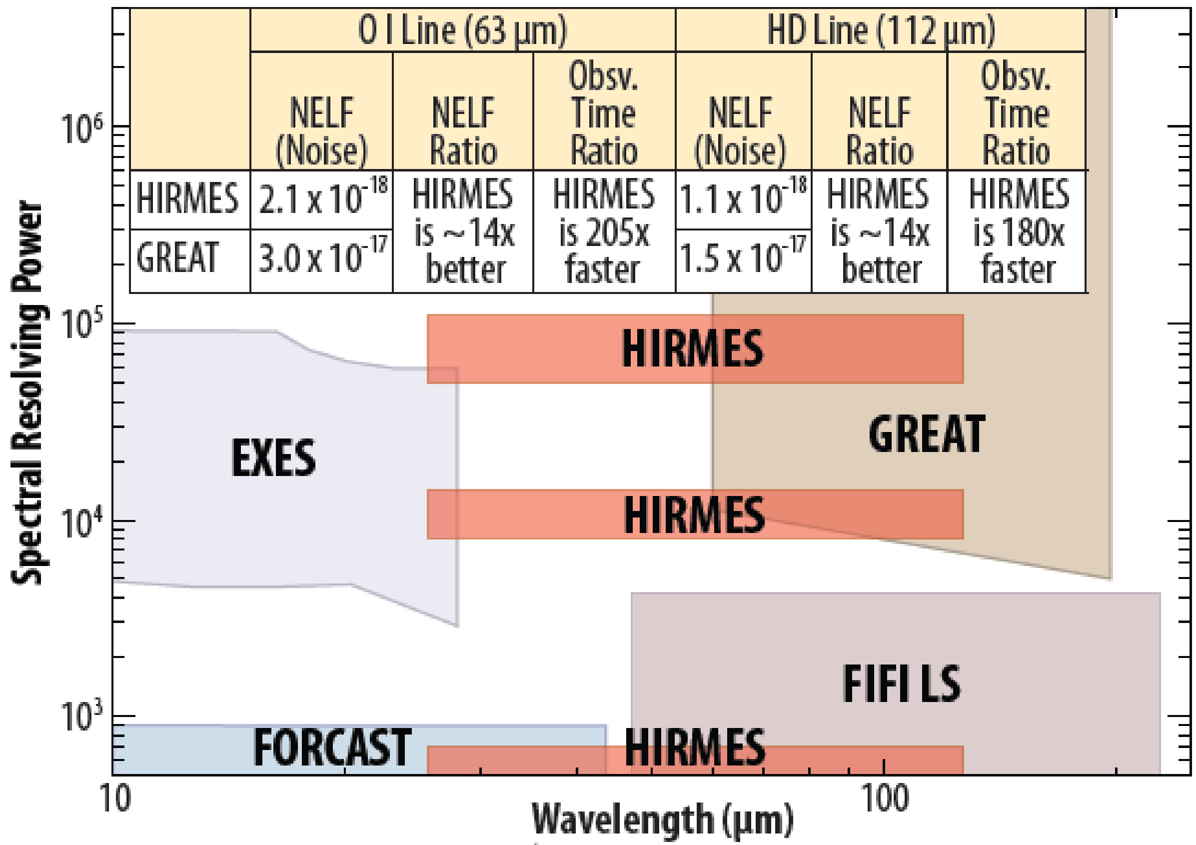
VLA







HIRMES: capabilities

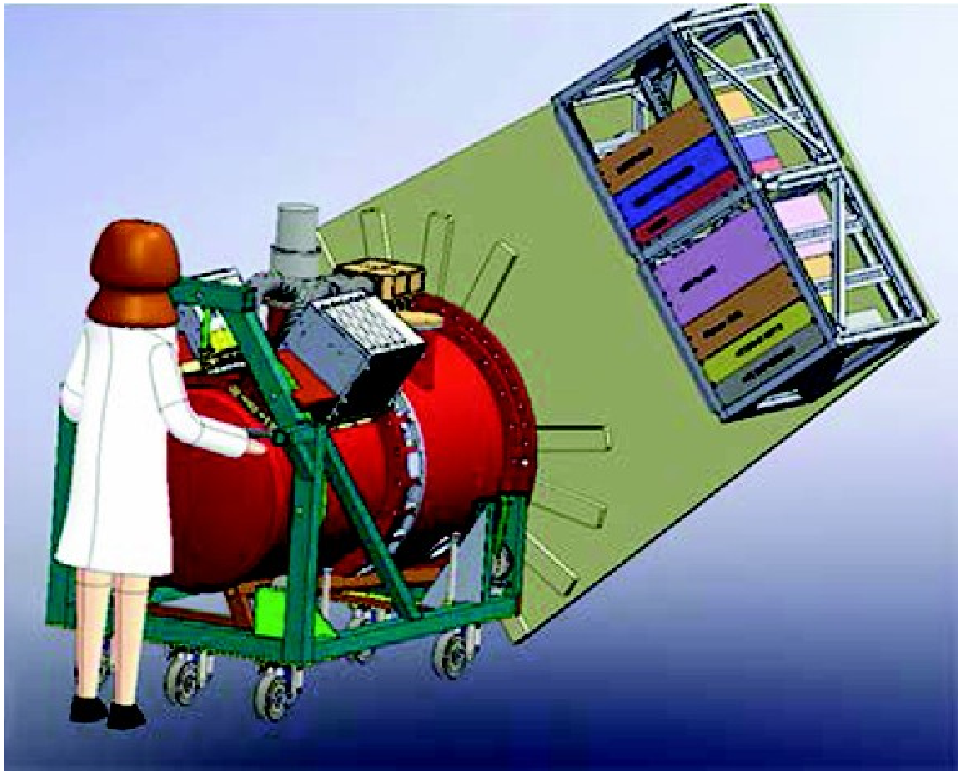


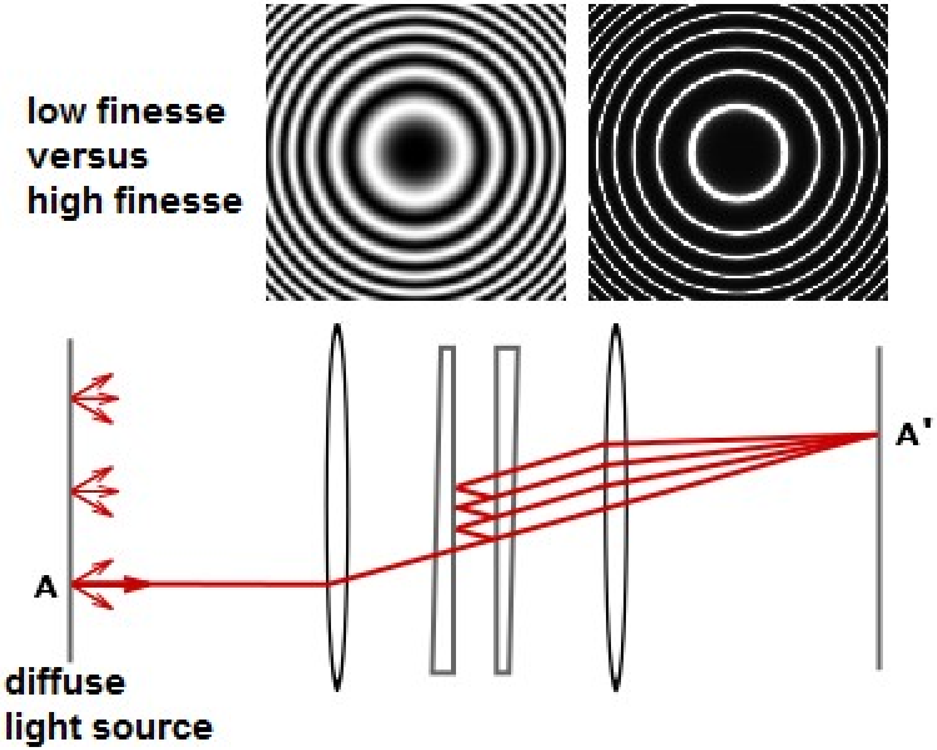
	O I Line (63 μm)			HD Line (112 μm)		
	NELF (Noise)	NELF Ratio	Obsv. Time Ratio	NELF (Noise)	NELF Ratio	Obsv. Time Ratio
HIRMES	2.1×10^{-18}	HIRMES is ~14x better	HIRMES is 205x faster	1.1×10^{-18}	HIRMES is ~14x better	HIRMES is 180x faster
GREAT	3.0×10^{-17}			1.5×10^{-17}		

NELF = Noise Equivalent Line Flux (W/√Hz)

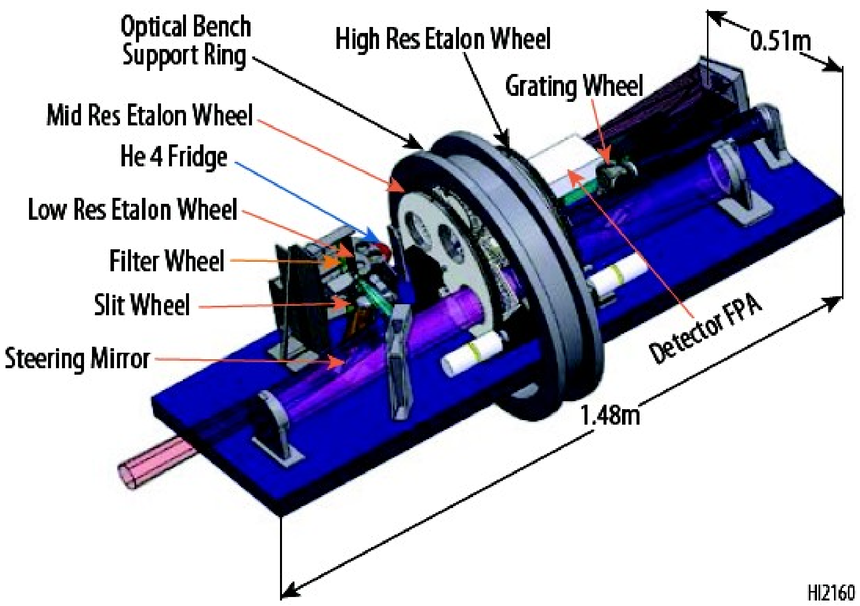
Parameters	High-Res	Mid-Res	Low-Res	Spectral Imaging
Sensitivity (5σ, 1 hour)	$\leq 1 \times 10^{-17}$ W/m^2	~1×10^{-16} W/m^2		
Resolving Power, $R = \lambda/\delta\lambda$	50,000 – 100,000	12,000	600	2,000
Angular Resolution	Diffraction limited			
Slit Size (arcsec)/FOV	Length: 139.5″; Width: 8.7″,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

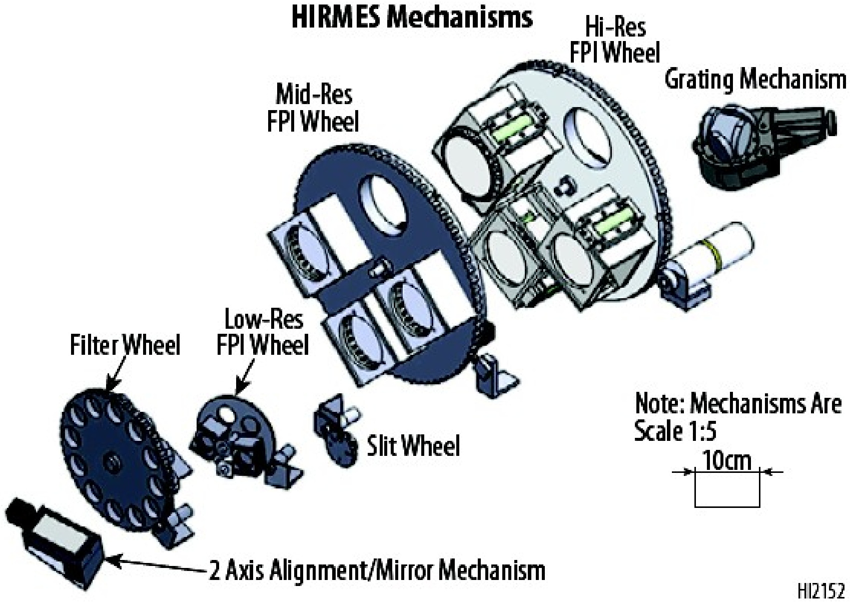
HIRMES: overview

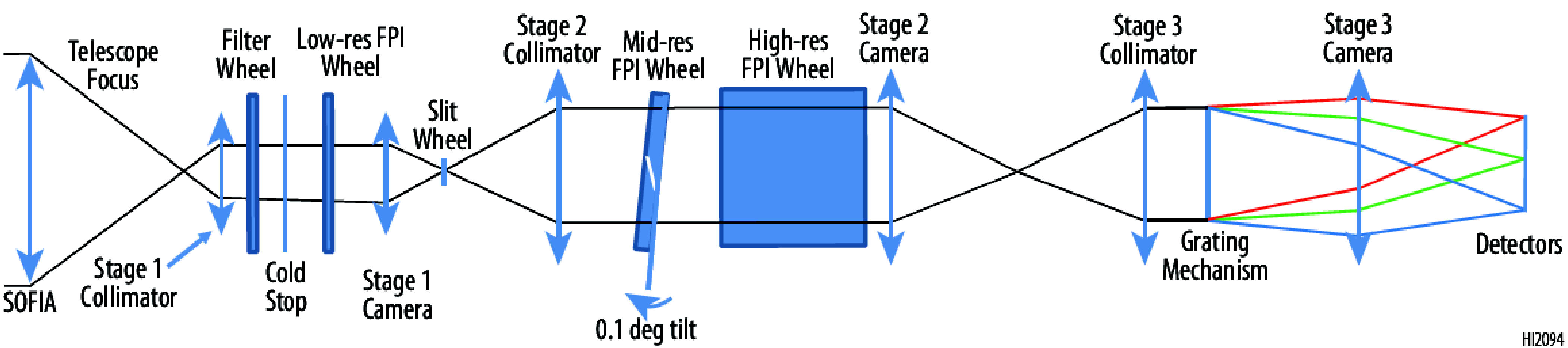




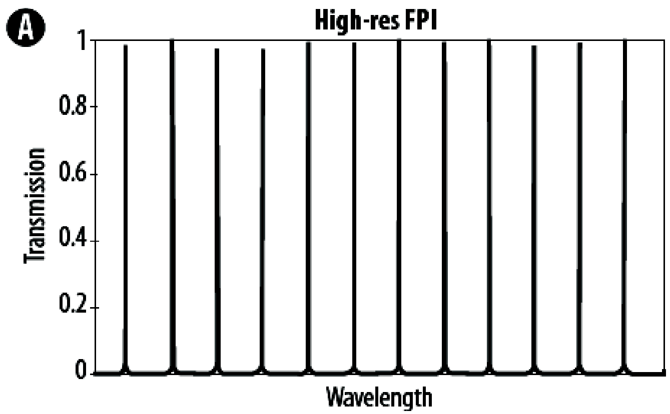
HIRMES: optics





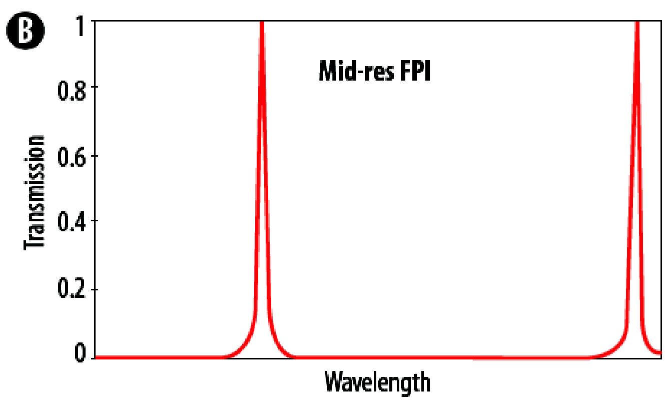


HIRMES: how it works...

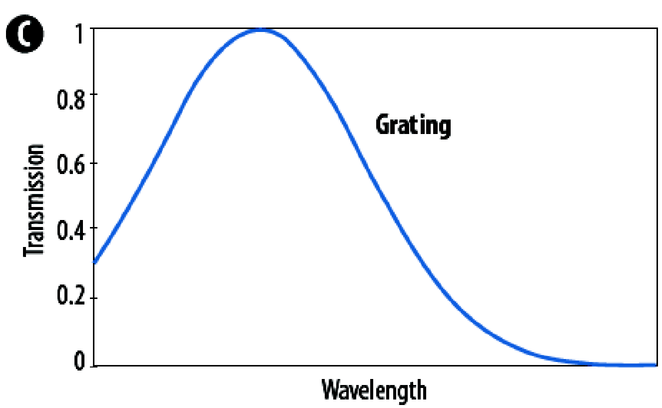


Finesse ~40–60
Order ~2400

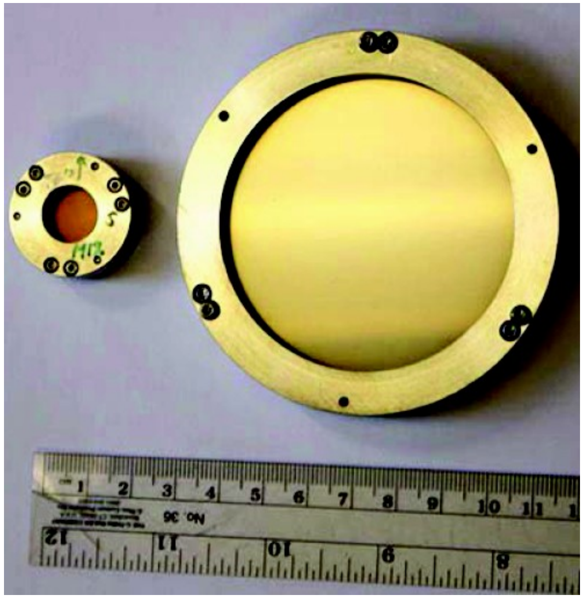
R ~ 100,000

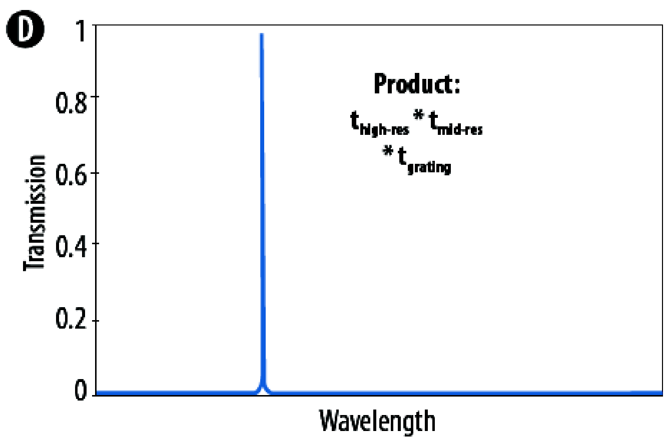


R ~ 2,000



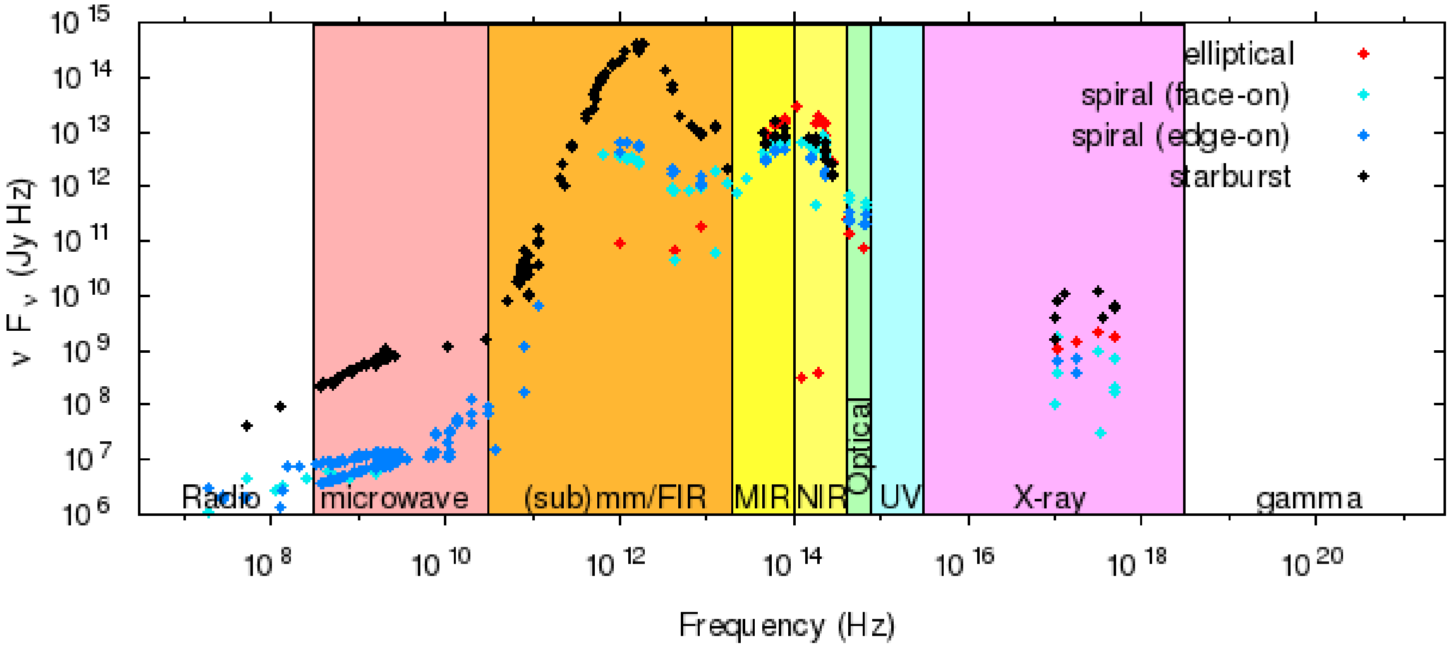
R ~ 600

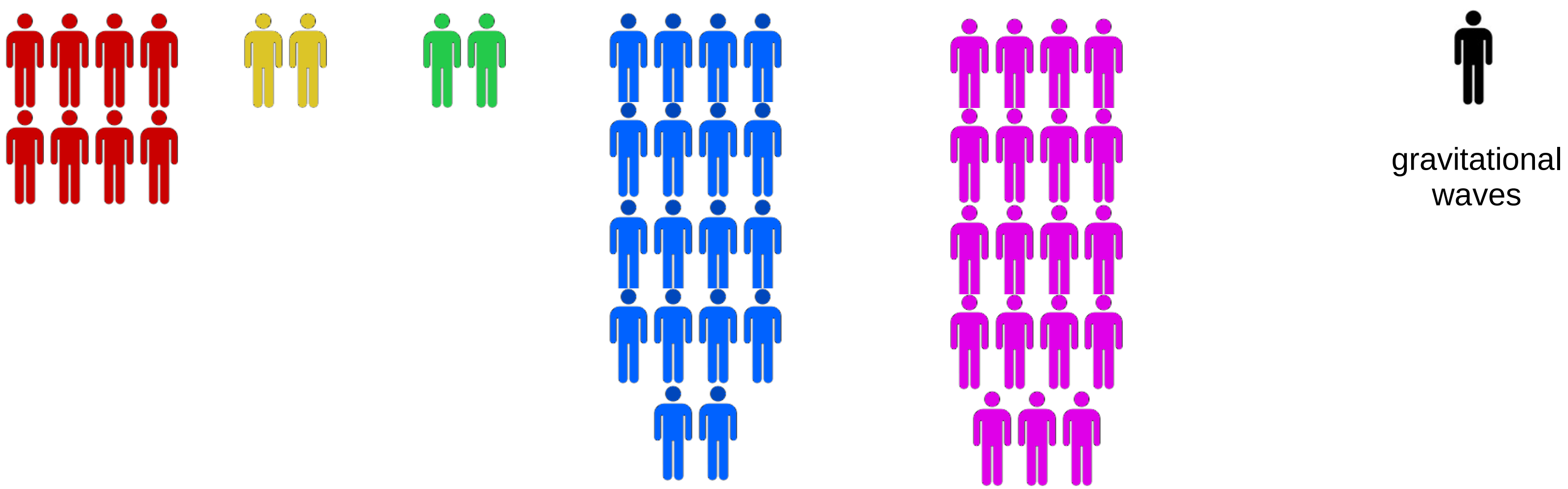




Summer 2019

Astrophysics Landscape





Based on ADS keyword searches in titles…

Conclusions

The cool infrared is ideal to study structure formation on all scales.

New instrumentation will bring exciting new opportunities.

Students: the future is in your hands!

The End

"Would you say Attila is doing an excellent job, a good job, or a poor job?"