ALMA

Robert Laing
European Instrument Scientist

Herschel Open Time Key Programme Workshop
Noordwijk, February 21, 2007

Overview

- **What is ALMA?**
- **Main performance numbers**
  - Sensitivity
  - Resolution
  - Spatial scales
  - Spectral-line modes
- **Synergy between ALMA and Herschel**
  - Science
  - Wavelengths, resolutions, surveys and follow-up
  - Examples
  - Calibration

What is ALMA?

Atacama Large Millimetre/Submillimetre Array

- Aperture synthesis array optimised for millimetre and sub-millimetre wavelengths.
- High, dry site, Chajnantor Plateau, Chile
- North America (NRAO) + Europe (ESO) + Japan (NAOJ) + Chile
- EU/NA: 50 dishes with 12m diameter. Baselines from ~15m to 14km.
- ALMA Compact Array (ACA) provided by Japan
  - 12 7m dishes in compact configurations
  - 4 12m dishes primarily for total-power

What is ALMA (2)?

- Low-noise, wide-band receivers.
- Digital correlator giving wide range of spectral resolutions.
- Software (dynamic scheduling, imaging, pipelines)
- Will eventually provide sensitive, precision imaging between 30 and 950 GHz in 10 bands
  - 350 GHz continuum sensitivity: about 1 mJy in one second
  - Angular resolution will reach ~0.05 arcsec at 100 GHz
- Resolution / arcsec ≈ 0.2 (λ/mm) / (D/km)
- Primary beam / arcsec ≈ 17 (λ/mm)

Highest-level science goals

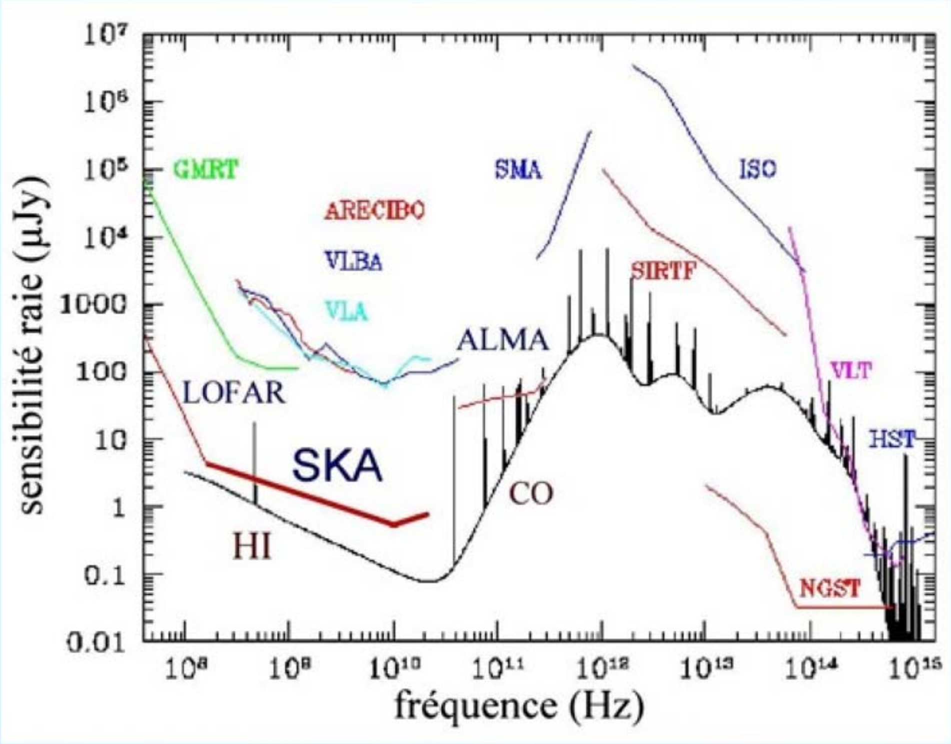
- Image spectral line emission from CO or C+ in a galaxy with similar mass to the Milky Way at a redshift of z = 3, in less than 24 hours of observation.
- Image the gas kinematics in a solar-mass protostellar/ protoplanetary disk at a distance of 150 pc. Study the physical, chemical, and magnetic field structure of the disk and detect the tidal gaps created by planets undergoing formation.
- Provide precise images at a resolution of 0.1 arcsec.

Spectrum of a normal galaxy

Z=2 in this example

$L(CO)_{1\text{-}0} \sim 5\times10^{8}$ $K\,km\,s^{-1}pc^{2}$ $\sim L(CO)_{2\text{-}1}$

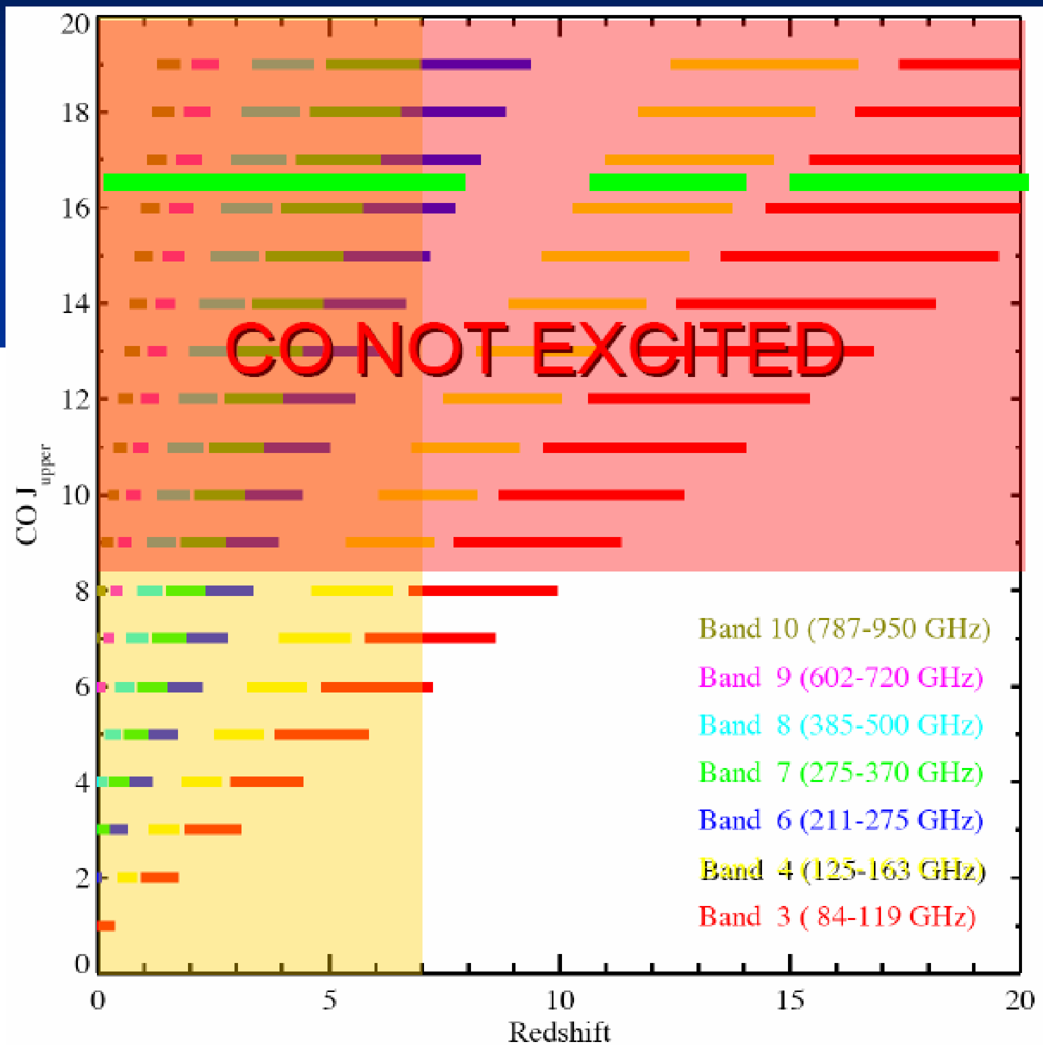
$S_{CO_{2\text{-}1}} \sim 0.1\,mJy$



Detection of spectral lines of a 'standard' spiral galaxy at $z = 2$

5σ in 1hour

ALMA as a redshift machine

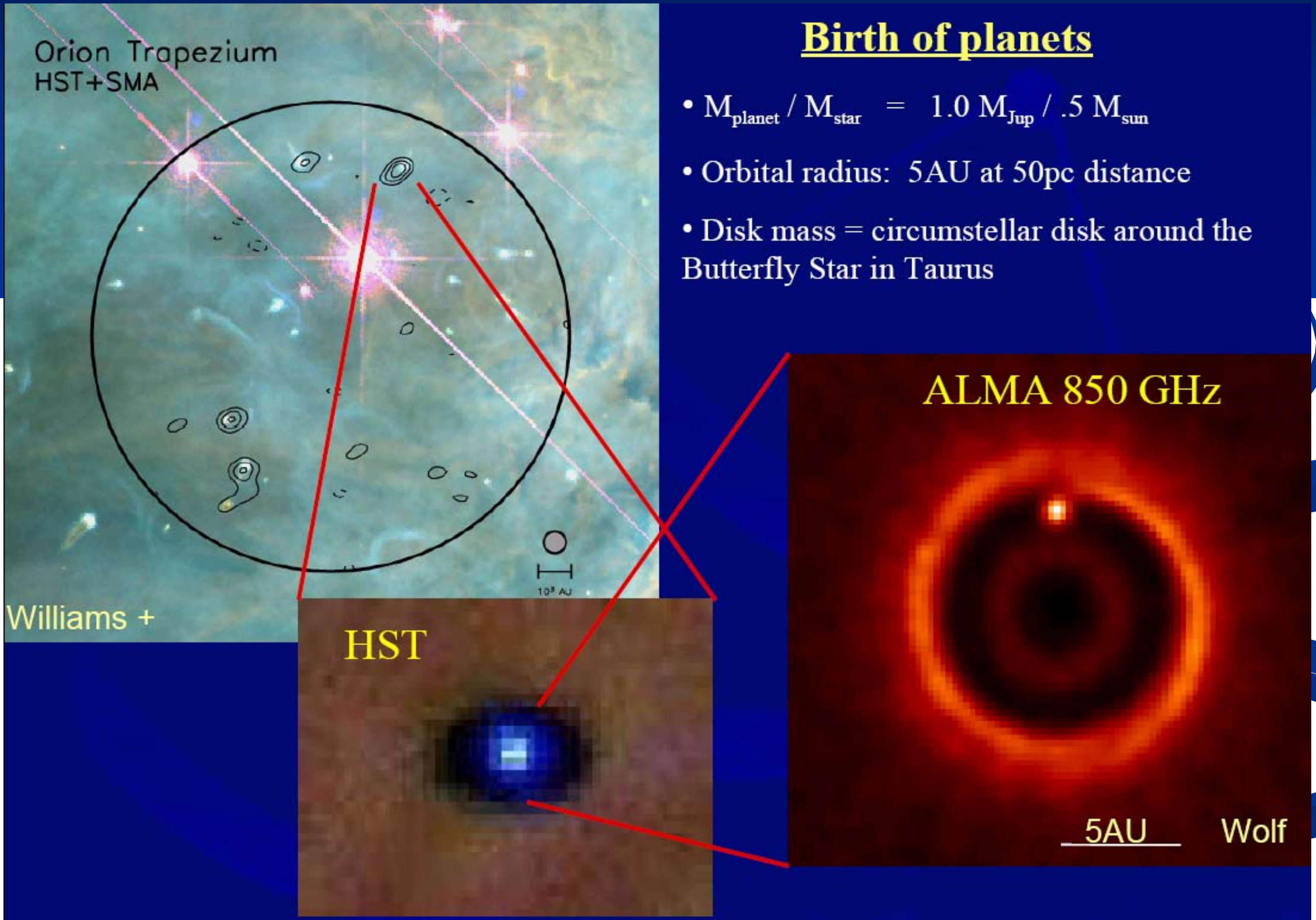


CII – line of choice for EoR studies
Case for Band 5

CO transitions for z < 7

ter, M eeting
2006

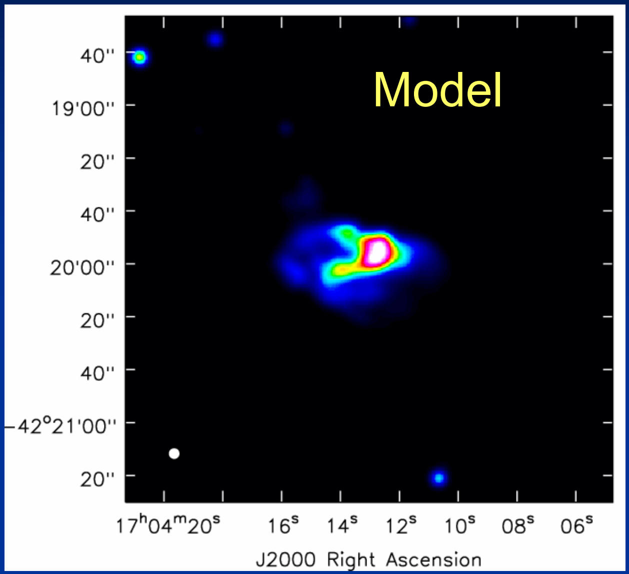
Protoplanetary disks

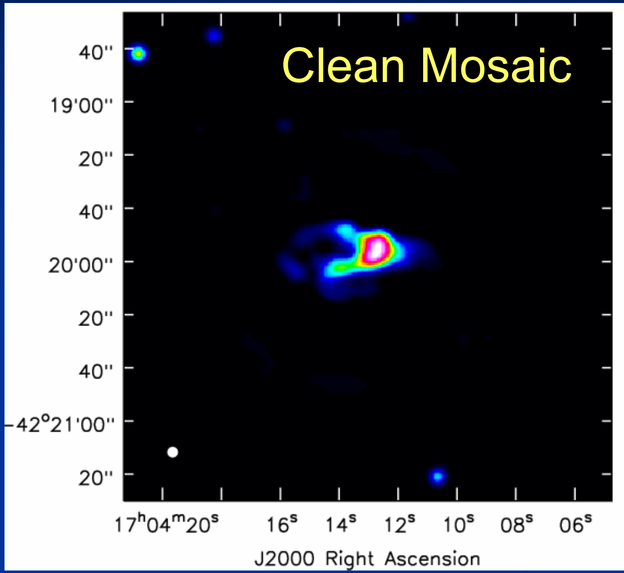


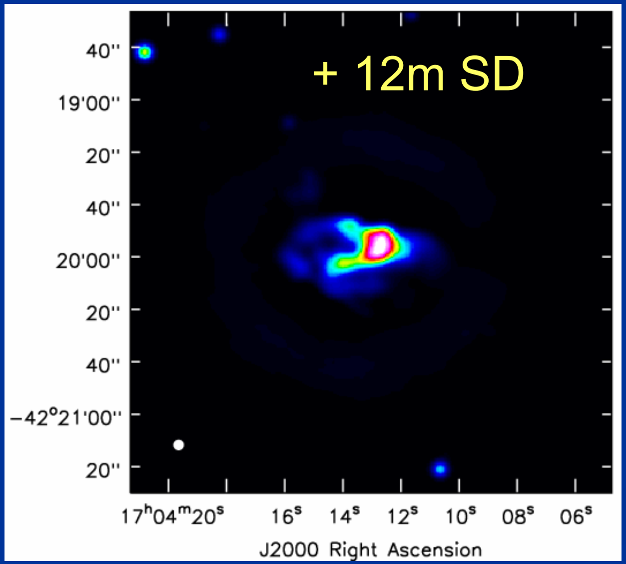
Birth of planets

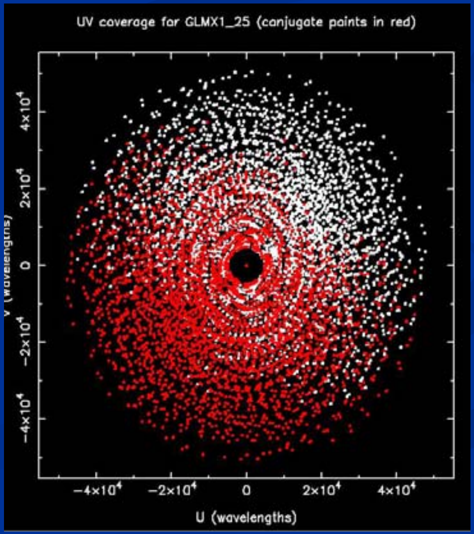
- $M_{planet} / M_{star} = 1.0 M_{Jup} / .5 M_{sun}$
- Orbital radius: 5AU at 50pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus

Imaging: 50 antennas + SD









uv coverage
(3 mins)

Mosaics and wide-field imaging

- Basic problem of extremely small fields, limited by primary beam and short spacing coverage
- Combination of a mosaic of pointings with the main array and single-dish data can be used to sample a larger range of spatial scales.
- Pointing errors severely limit the image fidelity unless scales around 10m uv distance are properly sampled.
- ACA 7m antennas fill in short-spacing coverage
- Four 12m antennas used to supply total power data (beam- switching using nutator + on-the-fly mapping)

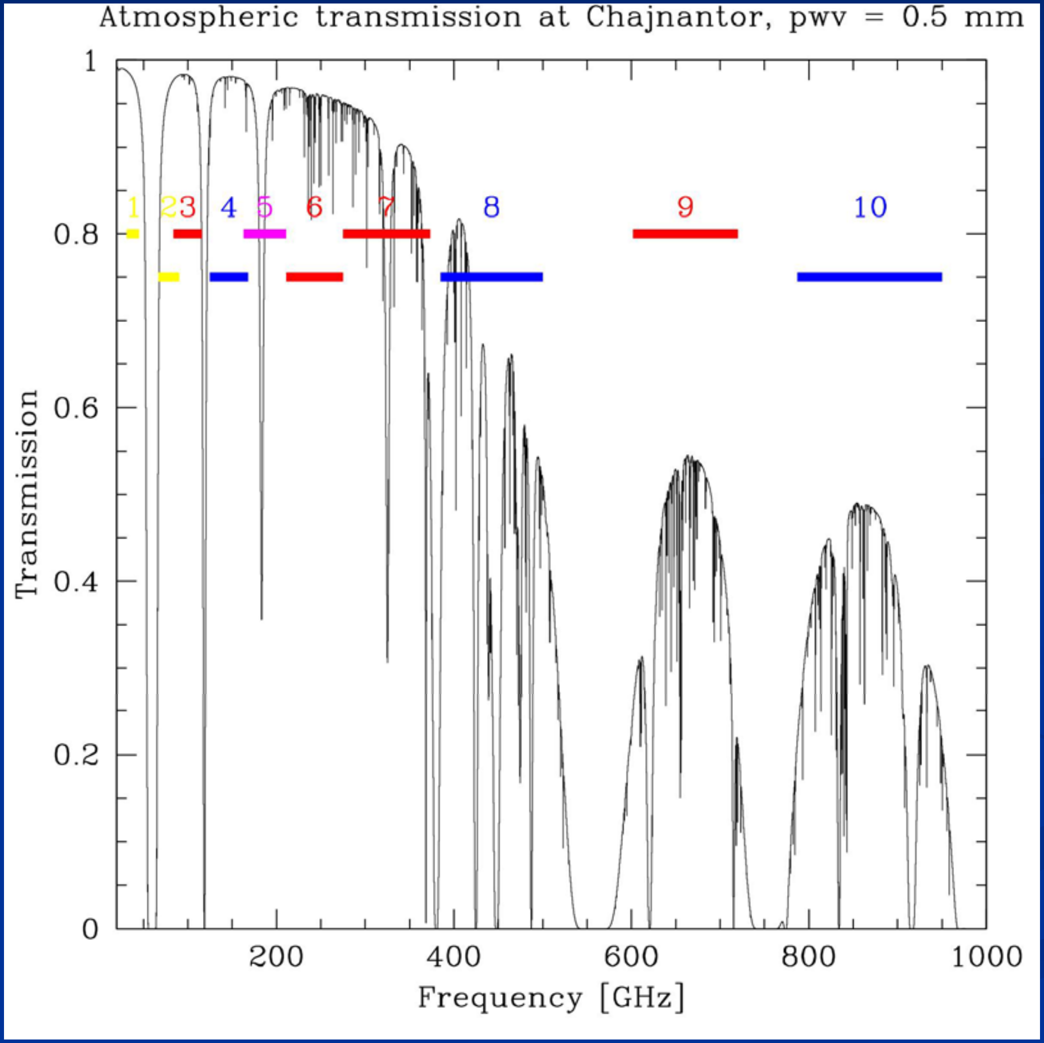
Key performance numbers

- Baseline range 15m – 14.5 km + ACA + single dish
- Resolution/ arcsec ≈ 0.2(λ/mm)/(max baseline/km)

  0.04 arcsec at 100 GHz, 14.5 km baseline

  0.005 arcsec at 900 GHz, 14.5 km baseline
- Wide bandwidth (8 GHz/polarization), low noise temperatures, good site and antennas, … → excellent continuum sensitivity
- Full polarization

Transparent site allows full spectral coverage



Sensitivity in 1 minute

ν	ΔS	ΔT_B
GHz	mJy	K
35	0.019	0.0003
110	0.033	0.0004
345	0.14	0.0018
409	0.31	0.0040
675	3.8	0.049
	0.46	0.0059
850	5.9	0.080
	1.1	0.014

RMS for 2 polarizations, each with 8GHz bandwidth; elevation of 50º. Brightness temperatures are for a maximum baseline of 200m; 50 antennas

Median PWV = 1.5mm

Best 5% PWV = 0.35mm

ALMA Memo 276

Some receivers will exceed specification

Sensitivity calculator available at

http://www.eso.org/projects/alma/science/bin/sensitivity.html

Sampling of large spatial scales

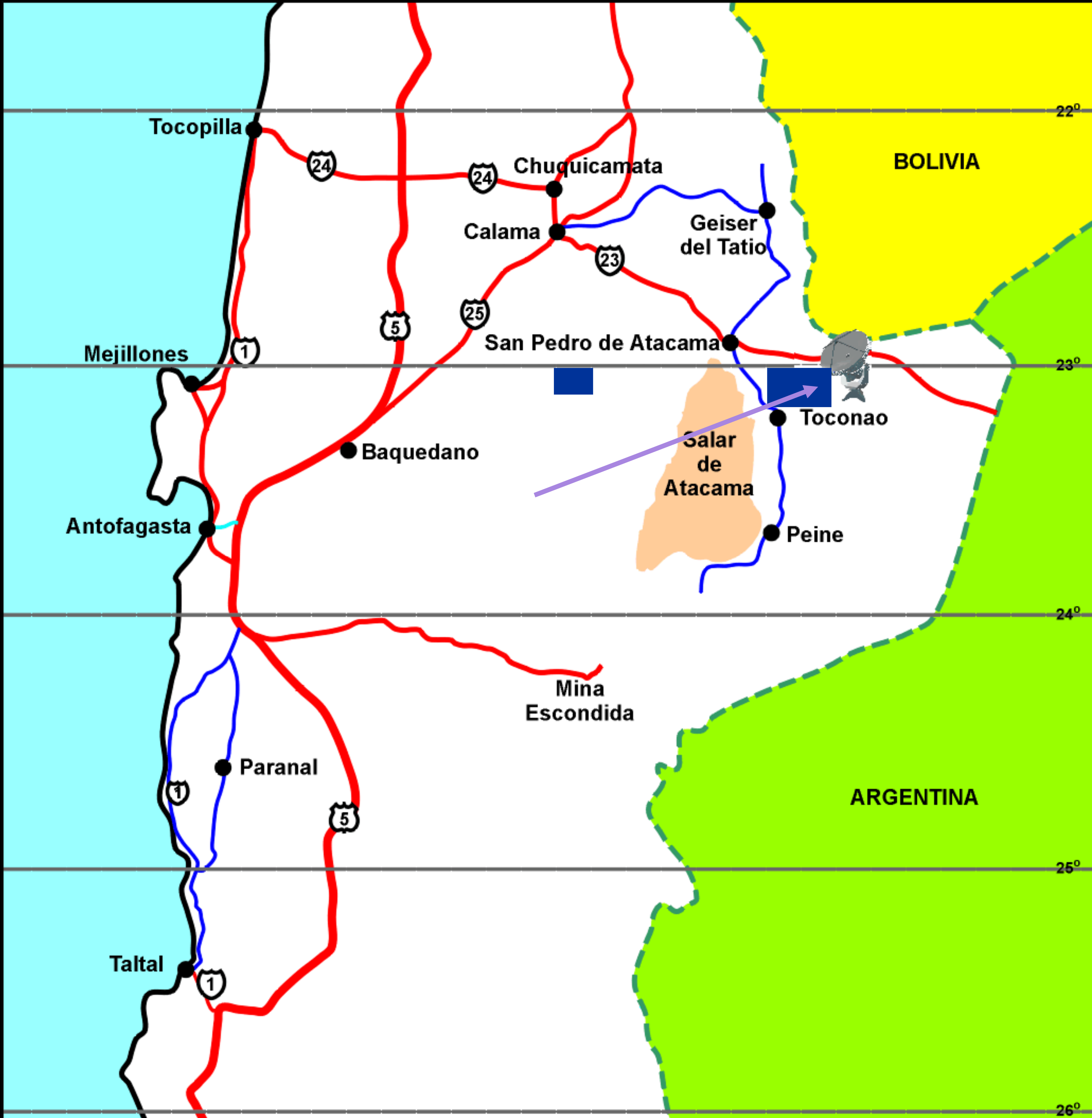
1 Mpc corresponds to ~125 arcsec at z = 1

ν GHz	Primary beam λ/D arcsec 12m	7m	Minimum λ/D arcsec Compact	ACA	Resolution arcsec Compact
35	170	291	116	199	10
110	56	99	37	64	3.1
230	27	46	18	31	1.5
345	18	31	12	21	1.0

Also combine with 12m (single-dish) observations

Location

Chajntantor Plateau at 5000m in northern Chile



Robert Laing
European Instrument Scientist

The Chajnantor plateau

Work in progress

AOS Technical Building

A small problem

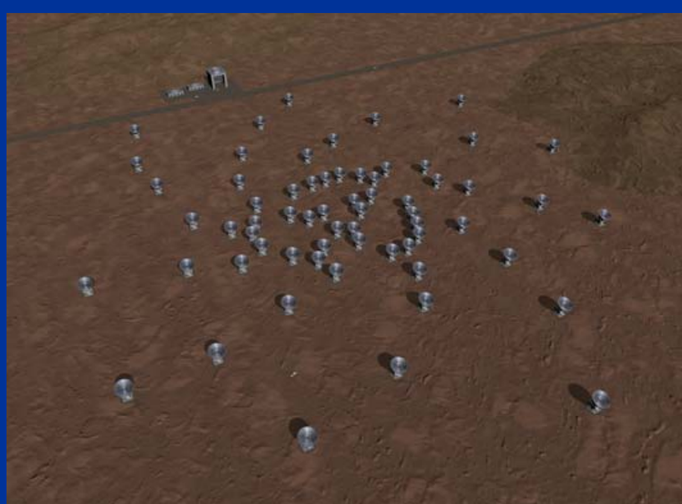
Key antenna specifications

- 12m diameter
- 25 μm rms surface accuracy (goal 20 μm); measure using tower and interferometric holography
- 2 arcsec rms absolute pointing; 0.6 arcsec rms offset
- Tracking speed for on-the-fly mapping 1 deg/s
- Fast switching required between target and calibrator (1.5^{o} in 1.5s)
- Three prototypes (Vertex/RSI, EIE/Alcatel, Mitsubishi) tested at VLA site; all meet specification as far as can be tested at lower altitude.

The three prototype antennas at the ATF

12 Meter Diameter, Carbon Fiber Support Structures

Continuous reconfiguration from compact to extended configuration



ALMA Bands

Band	Frequency	Status
1	31.3 – 45 GHz	
2	67 - 90 GHz	
3	84 - 116 GHz NRAO	
4	125 – 163 GHz	
5	163 – 211 GHz	
6	211 – 275 GHz HIA	
7	275 – 373 GHz IRAM	
8	385 – 500 GHz	
9	602 – 702 GHz SRON	
10	787 – 950 GHz	

Under construction (NA/Europe)

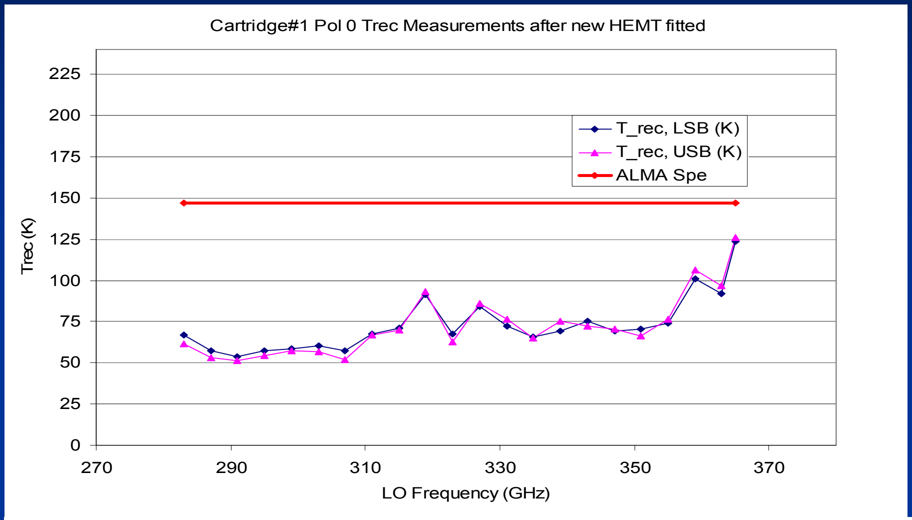
Under construction (Japan)

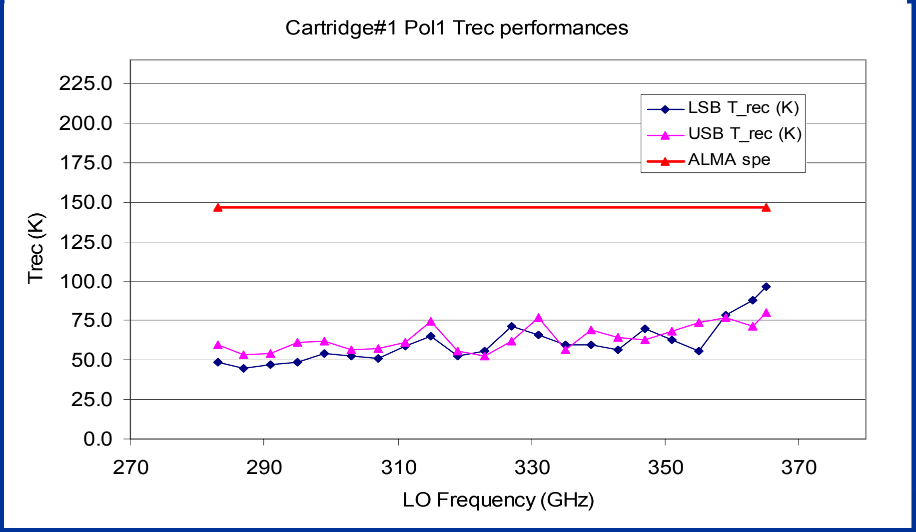
Development study (Japan)

EU FP6 (6 antennas)

Not yet funded

Band 7 noise performance





Spectral modes

- Channel bandwidth 31.25 MHz – 2 GHz (4 channels)
- Maximum 4096 x (4/N) x (2/P) spectral points/channel, where N = 1, 2 or 4 is the number of channels and P=2 for full polarization; 1 for parallel hands only.
- Maximum spectral resolution 3.8 kHz.
- Tunable FIR filter bank to subdivide bandwidth into 32 (possibly overlapping) sub-channels
- Flexible combinations of centre frequency and resolution

Project Status

- "Rebaselining" complete – cost and schedule – major reviews Oct 2005 – Jan 2006. Descope to 50 antennas.
- Prototype systems integration (ATF). First fringes between prototype antennas March 2007
- First production antenna delivered 2007Q3
- First interferometry at AOS 2009
- Commissioning and science verification 2009-10
- "Early Science" (open call) 2010
- Full operations 2012

Early Science

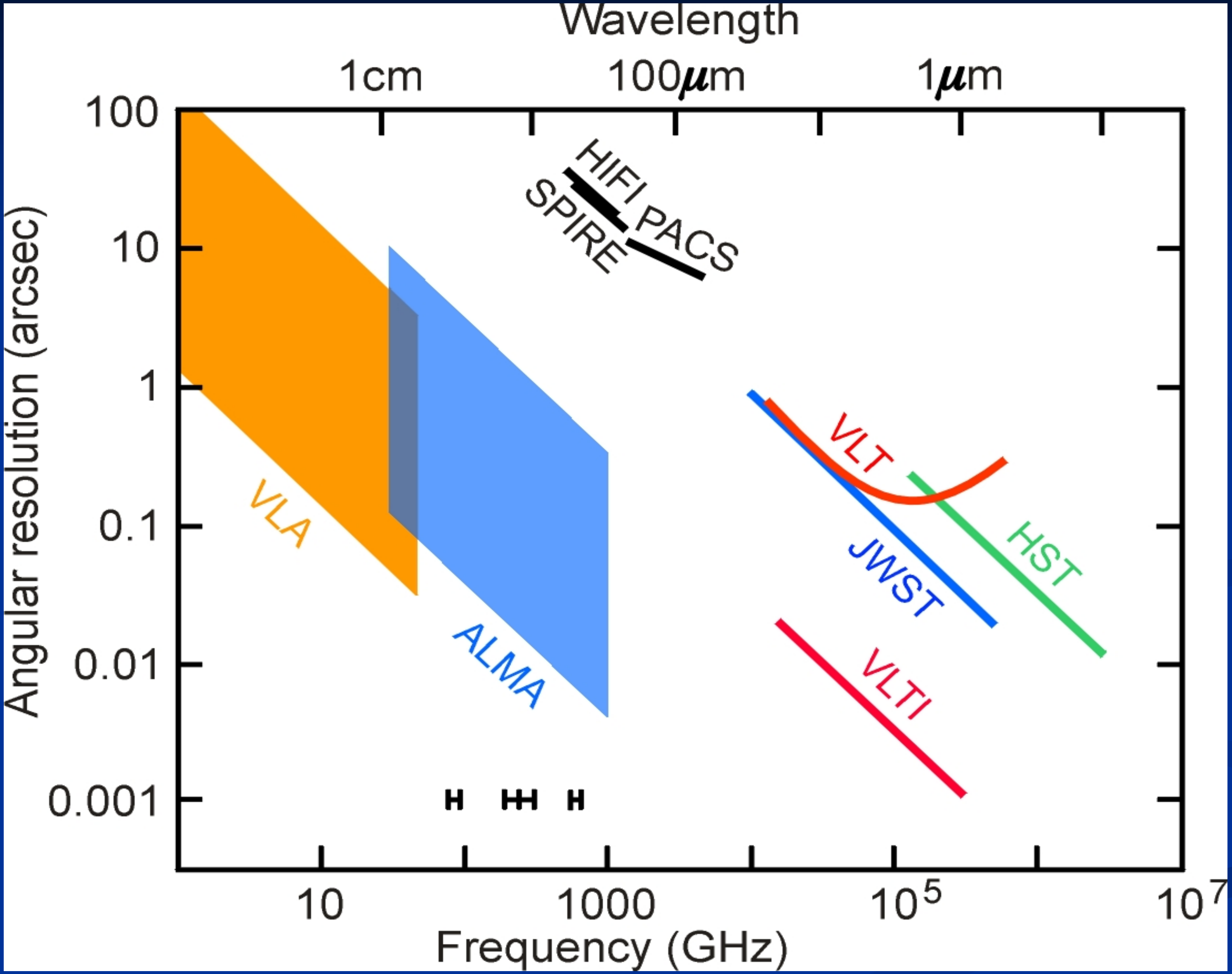
- At least 16 antennas fully commissioned (more in process of integration)
- Receiver bands 3, 4, 6, 7, 8, 9
- Interferometry in single field or pointed mosaic mode
- Significant range of spectral modes, including Tunable filter bank
- Circular and linear polarization (not mosaic)
- Single-dish mosaic (position and beam-switch) and OTF.
- 2 subarrays operational
- Formal proposal call

Science Verification

- Happens before Early Science
- Main goals
  - Test ALMA modes end-to-end (includes projects from user community)
  - Feedback to commissioning team
  - Early access to ALMA data for the community
- Modes fully commissioned
- Open call for proposals, fast, not using formal machinery; review for scientific value (+external) and feasibility
- Data public immediately
- Projects executed by commissioning team/Operations
- ALMA Public Images – pretty pictures

The Herschel-ALMA Synergies

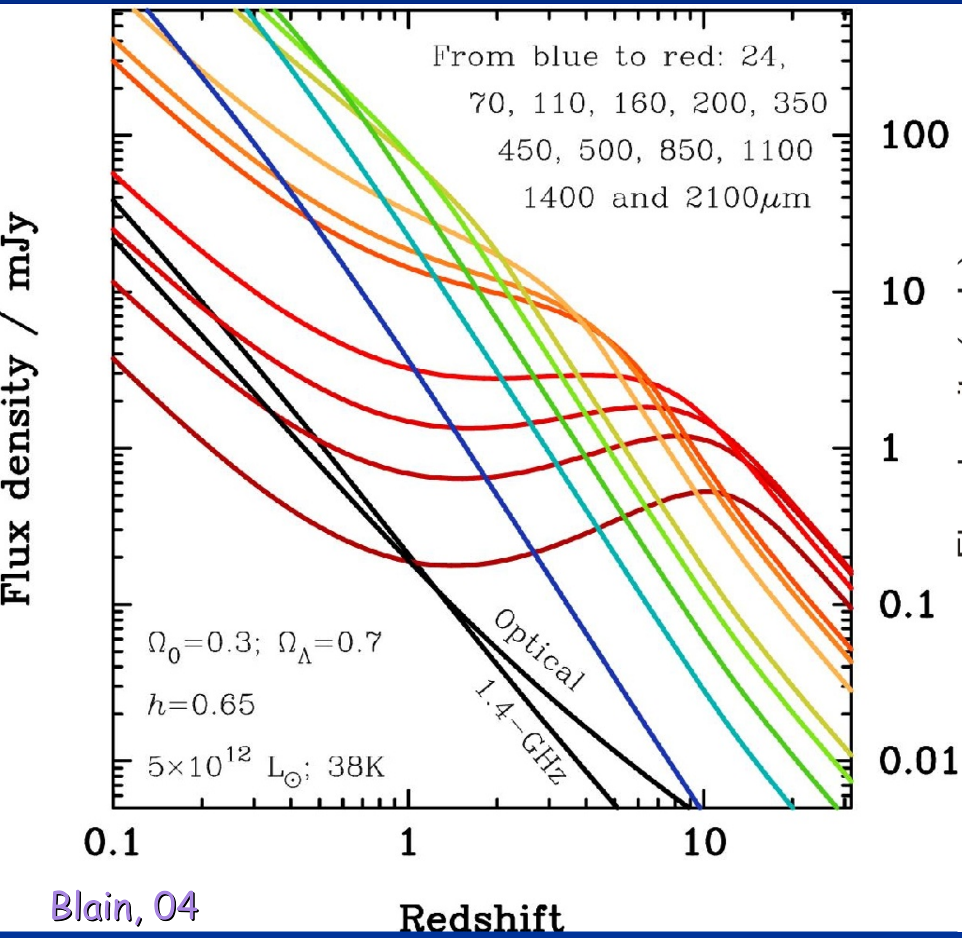
- ESA-ESO Working Group 2
  - Chair Tom Wilson/co-chair David Elbaz
  - Report August 2006
- Science areas
- ESO and ESA
  - Expected science return
  - Competition and complementarity
  - Open areas
  - Case for coordination


Wavelength
1cm
100μm
1μm
100
10
1
0.1
0.01
0.001
Angular resolution (arcsec)
HIFI
SPIRE
PACS
VLA
ALMA
VLT
JWST
HST
VLTI
10
1000
10^5
10^7
Frequency (GHz)

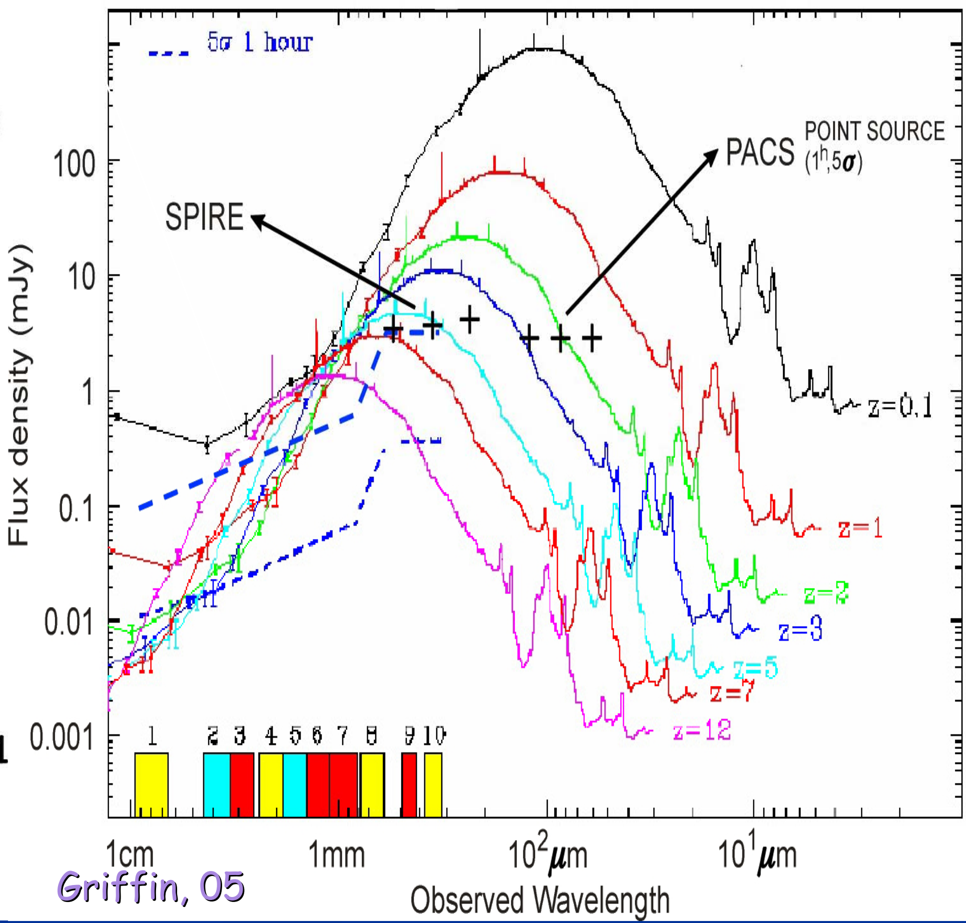
Complementarity

- **Wavelength coverage**
  - ALMA 320 µm – 1 cm; atmospheric transmission bands
  - Herschel 60 – 625 µm; not limited by atmosphere
- **Resolution and field of view**
  - ALMA has high spatial resolution; limited instantaneous field
  - Herschel has limited spatial resolution; bolometer arrays can cover a wide area fairly quickly
- Spectral coverage and resolution
  - ALMA flexible, subject to trade-off between bandwidth and resolution set by correlator capacity
  - PACS, SPIRE (FTS), HIFI also give a wide range of resolutions.

Starburst Galaxies

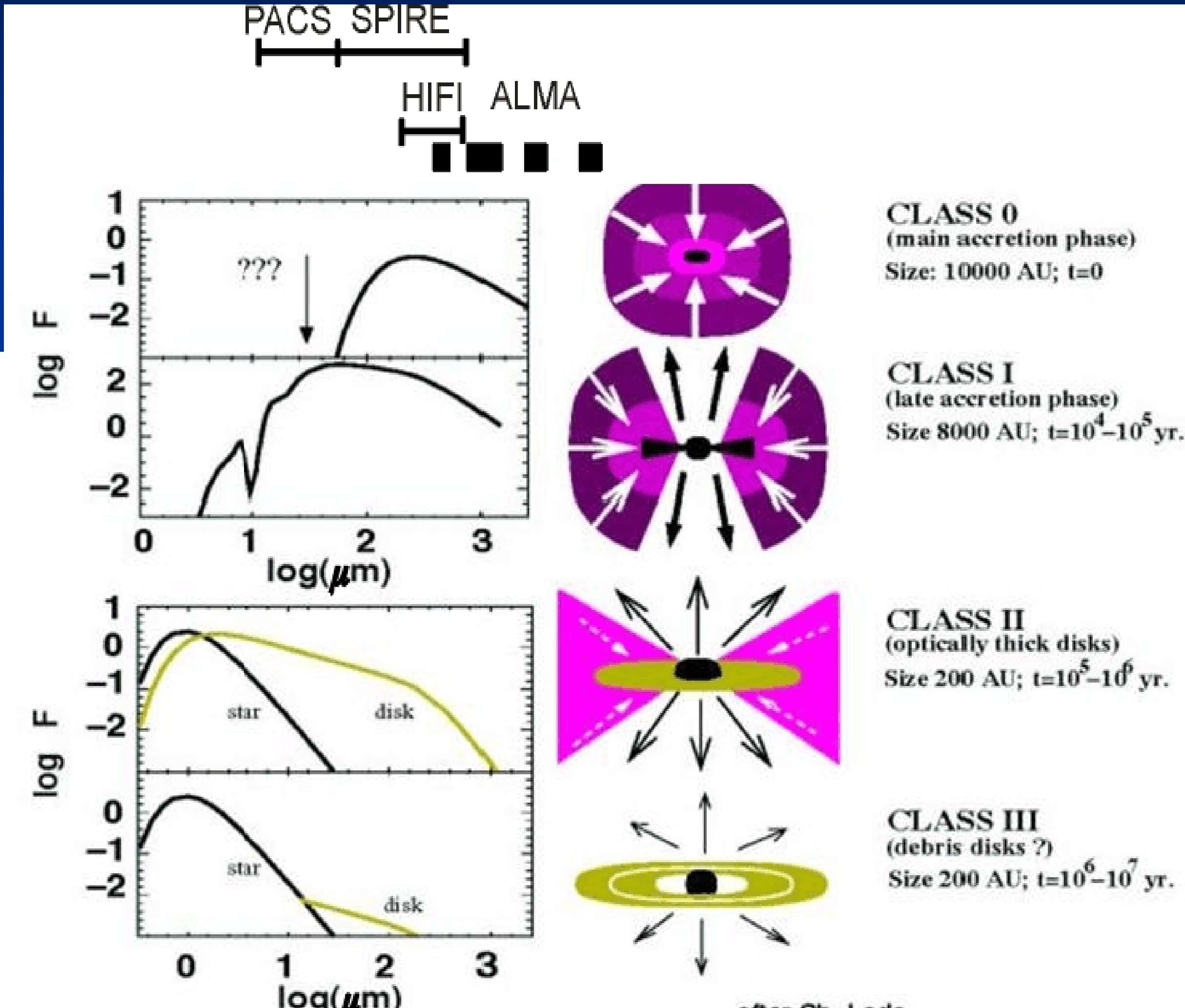


Blain, 04



Griffin, 05

Star Formation



after Ch. Lada,
figs: M. Hogerheijde

Surveys

- **Herschel**
  - Fairly large fields
  - Low spatial resolution → vulnerable to confusion
  - Efficient finding surveys
  - All-sky
- **ALMA**
  - Limited sky coverage
  - High spatial resolution → not vulnerable to confusion
  - Instantaneous field limited by primary beam, but fast mosaics are possible
  - Deep, narrow-field surveys (continuum/line)
  - Follow-up of wide-field surveys.

Example surveys with ALMA

- Broadband continuum survey; 4 x 4 $arcmin^2$ at 290 GHz); 130 pointings; 30 min each; rms 20μJy, 100 – 300 sources
- Continuum, 4 x 4 $arcmin^2$ at 90 GHz, 16 pointings; 4 hr each; rms 1.5 μJy
- Line, 50 kms^{-1} spectral resolution, 4 centre frequencies, 4 mJy km s^{-1} for 300 km s^{-1} line, 1 CO line for z > 2, 2 for z > 6
- Then repeat at 200 GHz (6 days)

Observing Water

- **Herschel**
  - Water is an important and abundant molecule in star-forming regions – a unique probe of physics and chemistry.
  - Unique application of Herschel (especially HIFI)
- **ALMA**
  - Water is a problem – absorption and tropospheric phase fluctuations. Water-vapour radiometry at 183 GHz
  - Site is good enough that observations in Band 5 (163 -211 GHz) should be possible in best 20% of conditions
  - Six single-polarization Band 5 receivers delivered end 2009/2010
  - High spatial resolution follow-up of Herschel detections

Calibration

- **ALMA requirements**
  - There are few stable, small primary amplitude calibrators at high frequencies
  - Need to identify primary and secondary calibrators for ALMA – bright, well modelled on relevant spatial scales
  - Outer planets, asteroids, moons of giant planets
- **Herschel**
  - Preparatory work in modelling directly relevant to ALMA
  - Flux density measurements

Complementarity, not Competition