

# The Atacama Large Millimeter/submillimeter Array





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 Argelander-Institut für Astronomie

- **What is ALMA?**
- Construction status
- ALMA in Cycle 1
- ALMA operations: from a proposal to images
- Need help? The ALMA support structure
- Science Verification and Early Science results

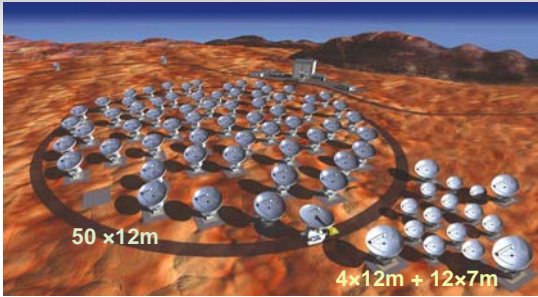


## What is ALMA?

- ALMA = Atacama Large Millimeter/submillimeter Array
- ALMA is an interferometer for millimeter and submillimeter astronomy
- The main scientific objectives are the origins of galaxies and the origins of stars and planets
- ALMA will be 10-100 times more sensitive and have 10-100 times better angular resolution than existing instruments
- ALMA is built and operated by Europe (ESO), North-America (NRAO) and East-Asia (NAOJ)




## ALMA main array + Atacama Compact Array




50 × 12m

4 × 12m + 12 × 7m

## Location



- Chajnantor plain (5000 m, AOS), Atacama desert, Northern Chile
- Latitude = -23 degrees



## Location



**Array Operations Site (AOS) at 5000m**  
**Operations Support Facility (OSF) at 2900m**

air pressure

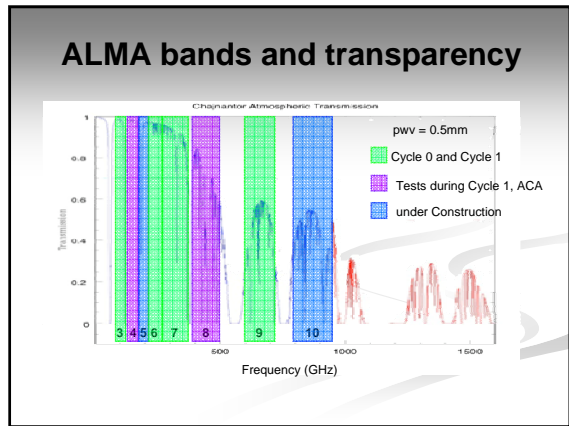
- at sea level: 1013 mbar
- at 2900m: 750 mbar
- at 5000m: 550 mbar



### ALMA's configurations

compact configuration  
(max. 150m):  
0.5 ... 5 arcsec

most extended  
configuration (max. 15km):  
0.005 ... 0.05 arcsec



### ALMA in Full Science Mode

Band	Full Science Capabilities					Most Compact		Most Extended	
	Frequency (GHz)	Wave length (mm)	Primary Beam (FOV, ")	Approx. Max. Scale (")	Configuration Sensitivity (mJy / beam)	Angular Resolution (")	$\Delta T_{\text{RMS}}$ (K)	Angular Resolution (")	$\Delta T_{\text{RMS}}$ (K)
1 <sup>†</sup>	31.3-45	6.7-9.5	143-135	93	4	13-9	4	0.14-0.1	4
2 <sup>†</sup>	67-90	3.3-4.5	91-68	53	†	6-4.5	†	0.07-0.05	†
3	84-116	2.6-3.6	72-52	37	0.07	4.9-3.6	0.04	0.05-0.038	430
4	125-163	1.8-2.4	49-37	32	0.06	3.3-2.5	0.048	0.035-0.027	330
5	163-211	1.4-1.8	37-29	23	-	-	-	-	-
6	211-275	1.1-1.4	29-22	18	0.09	2.6-1.5	0.03	0.021-0.016	490
7	275-373	0.8-1.1	22-16	12	0.15	1.5-1.1	0.08	0.016-0.012	814
8	385-500	0.6-0.8	16-12	9	0.40	1.07-0.82	0.28	0.011-0.009	1900
9	602-720	0.4-0.5	10-8.5	6	1.4	0.65-0.57	0.9	0.007-0.006	3900
10	787-950	0.3-0.4	7.7-6.4	5	1.2	0.52-0.43	1.6	0.006-0.005	-

<sup>†</sup>To be developed in the future. <sup>\*</sup>Available on a limited number of antennas.

### ALMA in comparison

Improvements:

- Sensitivity: 10-100x
- Spatial Resolution: 10-100x
- Bandwidth: ~2x

Circles Show Collecting Area (sensitivity)

## ALMA parameters

- 50 12-m antennas (main array)
- 12 7-m antennas + 4 12-m single dishes (ACA)
- Baselines up to 14.7 km (0.005" at 650 GHz) in "zoom lens" configurations
- Full coverage of all atmospheric bands up to 1 THz
- State-of-the-art low-noise, wide-band receivers (8 GHz bandwidth)
- Flexible correlator with high spectral resolution at wide bandwidth
- Full polarization capabilities
- A resource for ALL astronomers!

## ALMA Science

### ALMA Science Drivers:

- detect line emission from CO or CII in a Milky Way type galaxy at  $z = 3$ , in 24 hours
- image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distance of 150 pc
- provide precise images at an angular resolution of 0.1 arcsec

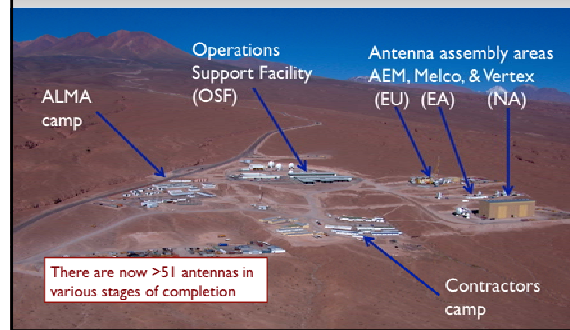
### other fields of research:

- star Formation, protoplanets in nearby disks
- astrochemistry
- interstellar medium (Galaxy, Local Group)
- high-redshift deep fields

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## Antenna construction



## Antenna construction



## Assembly, Integration and Verification (AIV)





## Current status

- 42 antennas at 5000m site
  - Seven European antennas, ten 7m antennas
  - Antenna acceptance rate is now >2 per month
- Good progress on Front Ends
  - All antennas have **four bands**: 3, 6, 7 and 9
  - Band 5 first "light" at AOS, bands 4 and 8 first fringes
- Correlators (ACA and main) working
- Permanent Power System approaching operations

## Construction outlook

- No show-stoppers
  - All main subsystems basically work
  - Latency of software being improved
  - Need to cope better with bad weather
- Schedule
  - Cycle 1 starts 1 January 2013
  - ALMA inauguration March 2013
  - All antennas delivered mid-2013

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## ALMA in Cycle 1

Still Early Science!

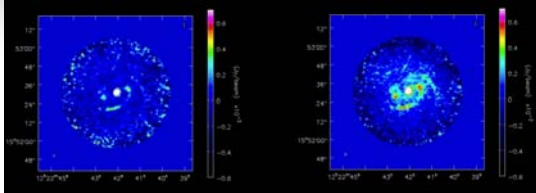
- >1100 proposals (deadline: 12 July 2012)
- review panel meetings took place October 1-5, 2012
- **Observing period:**
  - 10 months (1 January – 31 October 2013)
  - 800 hours available for science observing
- **32 main-array** antennas (12m) and **9 ACA** antennas (7m) and **2** 12m single-dish antennas
- No discrete configurations, but expanding and contracting
  - **Maximum baseline lengths: 150m ... 1000m**
  - PIs applied for a required resolution, largest angular scale and sensitivity (not for a configuration or time!)

## ALMA in Cycle 1

Band	Cycle 1 Capabilities				Most Compact		Most Extended			
	Freq. (GHz)	Wave-length (mm)	Primary Beam (FOV, °)	Continuum Sensitivity (mJy/beam)	Angular Resolution (")	Approx. Max. Scale (") (see P11)	$\Delta T_{\text{sys}}$ (K)	Angular Resolution (")	Approx. Max. Scale (") (see P11)	$\Delta T_{\text{sys}}$ (K)
3	84-116	2.6-3.6	73-52	0.11	4.4-3.2	29-21	0.09	0.7-0.5	19-7	3.4
6	211-275	1.1-1.4	29-22	0.14	1.7-1.3	12-9	0.11	0.27-0.21	4.1-3.1	4.5
7	275-373	0.8-1.1	22-16	0.24	1.4-1.0	8.9-6.6	0.18	0.21-0.15	3.1-2.3	7.5
9	602-720	0.4-0.5	10-8.5	2.2	0.6-0.5	4.1-3.4	1.8	0.09-0.08	1.4-1.2	80

**sensitivities:** integration time of 60 seconds, continuum bandwidth of 7.5 GHz, spectral resolution of 0.976 MHz  
**velocity resolution at 300 GHz:** 0.031 ... 31.2 km/s (dual polarization), 0.015 ... 15.6 km/s (single polarization)

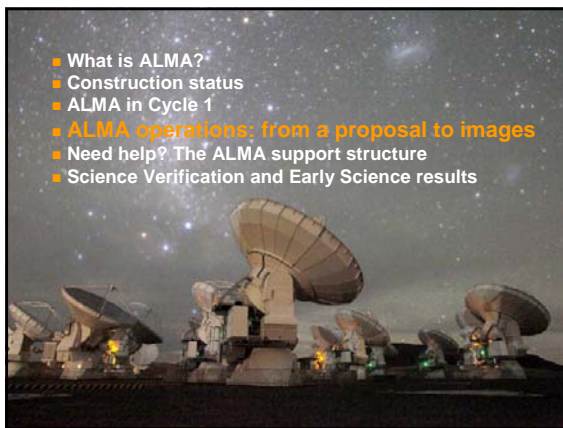
## ALMA in Cycle 1: including the ACA



- CO(1-0) in M100 at  $z=0.05$  observed for 8 hours
- *left*: only main array (most extended), *right*: including the ACA

## ALMA in Cycle 1: including the ACA

frequency	angular resolution	angular resolution	max. angular scale	max. angular scale with ACA
	extended	compact	compact	
Band 3 - 100 GHz	0.57"	3.7"	25"	44"
Band 6 - 230 GHz	0.25"	1.6"	11"	19"
Band 7 - 345 GHz	0.16"	1.1"	7.1"	13"
Band 9 - 675 GHz	0.08"	0.55"	3.6"	6.5"

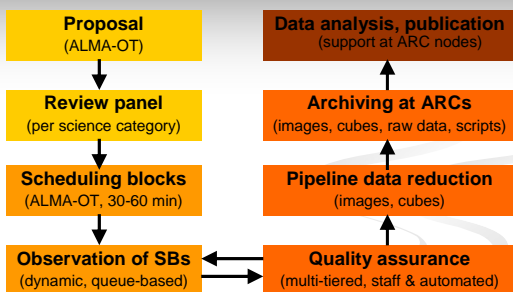


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## ALMA science operations

- Observations **only in service observing mode** with flexible (dynamic) scheduling
- Observations **24h/day** interrupted by maintenance periods
- All observations executed in the form of **scheduling blocks (SBs)**
- The Joint ALMA Observatory (JAO) is responsible for the **data product quality**
- Default output: **reliable images**, calibrated and imaged using the data reduction pipeline
- All science and calibration raw data are captured and **archived**

## Life of an ALMA project



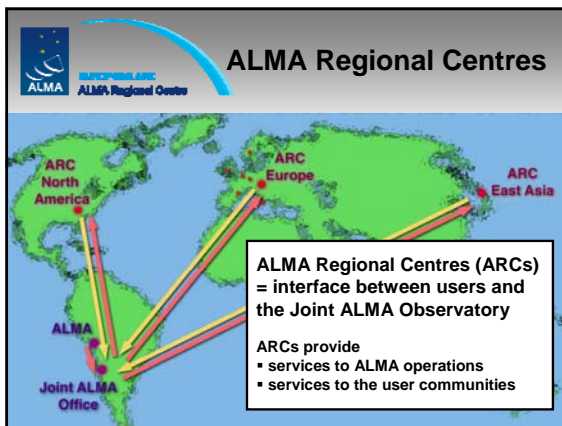
## Quality Assurance

- Goal: "deliver to the PI a reliable final data product that has reached the desired control parameters outlined in the science goals, that is calibrated to the desired accuracy and free of calibration or imaging artifacts"
- For Cycle 0 and 1: **QA on best effort basis**
- QA approach: Breakdown of QA into broad steps that mimic the data flow
  - Data Taking: QA0 (SB-level) & QA1 (Observatory Tasks)
  - Data Reduction: QA2 (Data Reduction/Science Pipeline)
  - Post-Data Reduction: QA3 (Feedback from users)

## What is being delivered

- Cycle 0: self-consistent tar files, delivered through ftp
- Cycle 1: delivery of data through Science Portal
- 1 year proprietary time starts after data are available to PI
- **scripts**: a priori calibration, calibration and imaging
- **raw**: data after a priori calibration
- **calibration**: all calibration tables and associated diagnostic plots.
- **calibrated**: fully calibrated (and flux equalized) data (no self-cal)
- **product**: FITS images and cubes
- **log**: all logs
- **qa**: checklists, diagnostic plots and printouts

- What is ALMA?
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- Current capabilities (Cycle 1)
- ALMA operations: from a proposal to images
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## The European ARC structure



In the EU executive, the ARC consists of a network of regional nodes with a central node at ESO, Garching



## The European ARC structure



- Tasks of the central ARC node:**
- helpdesk
  - basic (pipeline) data analysis and quality assessment
  - archive
  - user training
  - press and public relations

- Tasks of the regional nodes:**
- face-to-face user support
  - EU-wide support in special expertise areas
  - contact to local scientific community
  - community development
  - local public outreach

## The German ARC node

- Universities of Bonn and Cologne
- special expertise: polarimetry, advanced data analysis and modeling



## The German ARC node

### Technical Projects:

- Adaptable Radiative Transfer Innovations for Submillimeter Telescopes (ARTIST) - Astronet
- Coherent set of Astrophysical Tools for Spectroscopy (CATS) - Astronet
- Polarization calibration - BMBF-VF
- Zero spacings for continuum data - BMBF-VF
- Cologne Database for Molecular Spectroscopy - DLR, BMBF-VF

### Science:

- evolution of AGB stars, circumstellar chemistry
- astrochemistry, molecular clouds and star formation
- magnetic fields in star formation processes
- starburst galaxies and AGN
- galaxy evolution and structure formation in the early universe

## The German ARC node

### What we can offer:

- dedicated ARC room with workstations  
access to all required software (OT, CASA) and the data archive
- server with sufficient computing power  
effective data reduction and analysis
- dedicated contact scientist  
personal support to guarantee a productive stay in Bonn
- personal desk with internet connection for your laptop
- parent-child room
- free tea and coffee
- a vibrant research environment (Argelander-Institut für Astronomie, MPIfR, University of Cologne)



## How to get help

### What's the latest ALMA-related news?

- ESO Science Portal, homepage of the German ARC node
- DARC newsletter, EU-wide mailing list

### I have a specific question ...?

- ask your contact scientist (approved projects)
- use the helpdesk (or send an email to your ARC node)

## How to get help

### How can I learn more about interferometry?

- ALMA documents (Science Portal)
- lecture course *Practical Radio Interferometry*
- ALMA community days, meetings, conferences

### Who can help me with my ALMA proposal?

- ALMA Community Days, ALMA documents
- arrange a visit to your ARC node (via the helpdesk)

**Winter Semester 2012/13**  
**Practical Radio Interferometry**  
Lectures and Tutorials (AIPS, CASA)

A practical overview of interferometry fundamentals, aimed at students and post-graduate researchers. The course will cover the basics of interferometry, including the theory and practice of data reduction and imaging. Remote access may be possible.

**Wednesdays, 17 Oct – 6 Feb**  
13:30 – 15:00 lecture  
15:15 – 16:45 tutorial  
AlfA room 0.008

Lecturers: Alves, Bertoldi, Brunthaler, Hornegger, Kramer, Maercker, Mühle, Schilke, Wucknitz

[www.astro.uni-bonn.de/ARC/pri2012](http://www.astro.uni-bonn.de/ARC/pri2012)

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## How to get help

### **My proposal was approved! What's next?**

- email with logistical details (assigned node)
- your contact scientist supports you throughout the project

### **How can I learn how to reduce ALMA data?**

#### **Help, my data set is huge!!!**

- CASA data reduction guides (Science Portal > ALMA Data > Science Verification)
- CASA tutorial (in *Practical Radio Interferometry*)
- arrange a visit to your ARC node (via the helpdesk)

## The helpdesk

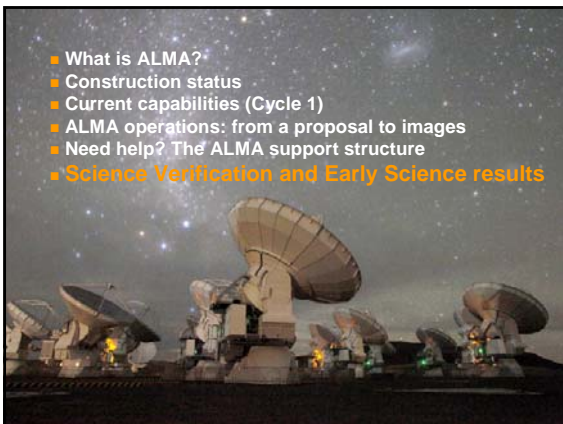
## The helpdesk

## The helpdesk

### Advantages of the helpdesk:

- (growing) knowledgebase
- always the right person (via triage)
- holiday etc. replacement (fast feedback, log)

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## Science Verification (SV)

- The process by which ALMA demonstrates that it is capable of producing data of the required quality
- So far focused on reproducing results already obtained with other telescopes
- The reduced and calibrated datasets are available to the community for download
  - raw data
  - data reduction scripts and CASA guides
  - data products: images, cubes



## SV data available

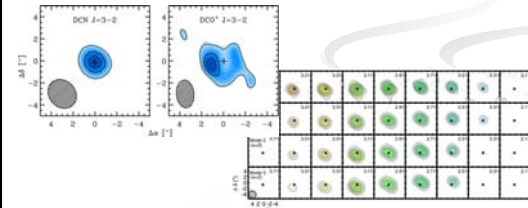
- **TW Hya**: band 3,6,7, high spectral resolution *band 7 CASA guide*
- **NGC3256**: band 3, low spectral resolution *band 3 CASA guide*
- **Antennae galaxies**: band 6,7, high spectral resolution *band 7 CASA guide*
- **M100**: band 3, low spectral resolution *band 7 CASA guide*
- **SgrA\***: band 6, recombination lines
- **BR1202-0725**: band 7, low spectral resolution
- **IRAS16293**: band 6,9, high spectral resolution *band 9 CASA guide*
- **Centaurus A**: band 6, high spectral resolution
- **Orion KL**: band 6, high resolution spectral survey

paper(s) published    paper(s) in preparation

## ALMA SV: Deuterium fractionation

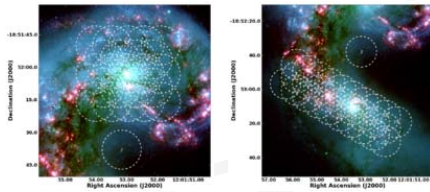
Deuterium fractionation in TW Hya (band 6):

- Evidence for multiple pathways to Deuterium enhancements in protoplanetary disks
- **Öberg et al. 2012, ApJ 749, 162**



## ALMA SV: Antennae galaxies

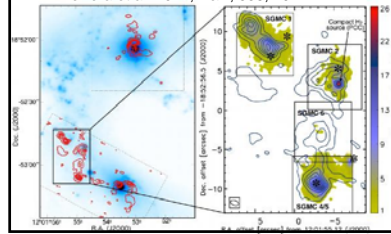
- nearby (22 Mpc) pair of merging galaxies
- ALMA band 7: CO(3-2)
- first ALMA mosaics: one south, one north



## ALMA SV: Antennae galaxies

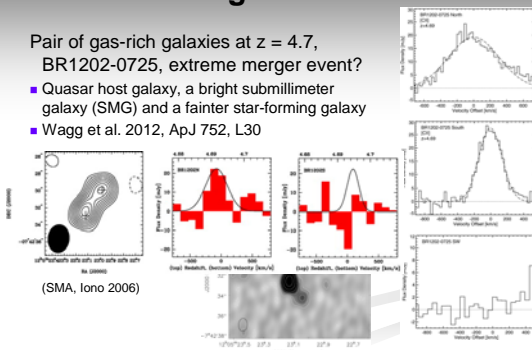
ALMA CO and VLT/SINFONI H2 observations of the Antennae overlap region

- H2 and CO(3-2) as tracers of energy dissipation and gas mass
- **Herrera et al. 2012, A&A, 538, L9**



## ALMA SV: galaxies at z = 4.7









- Pair of gas-rich galaxies at z = 4.7, BR1202-0725, extreme merger event?
- Quasar host galaxy, a bright submillimeter galaxy (SMG) and a fainter star-forming galaxy
  - **Wagg et al. 2012, ApJ 752, L30**










## Science Verification continues

- Goal: demonstrate the full range of Cycle 1 capabilities
  - large mosaics
  - mixed correlator modes
  - ACA and zero spacing
- Also, commissioning and science verification of
  - longer baselines
  - polarization
  - solar observing
  - on-the-fly mosaics

### New SV Targets

Mars	3,6,7 (CH <sub>4</sub> , CO)	12m+ACA+SD	mixed, 1spw/BB	multi-field calibration to exclude telluric lines	
comet C/2009 P1 Garradd	3 (CO, HCN)	12m	mixed, 1spw/BB	external ephemeris files, transients	
VV114	9 (CO)	12m+ACA	low spectral res		
SHADES	7 (contin)	12m	low spectral res	astrometry and multi-field interferometry	
Fornax Cluster	3 (CO)	12m+ACA	low spectral res	multi-field and multi-velocity interferometry	
NGC1512/10	3 (CO)	12m+ACA+SD	mixed, 1spw/BB	large mosaic	
Lambda Orionis	3 (contin)	12m+ACA+SD	low spectral res	large mosaic, continuum SD	
CB54	7 (CO(3-2), HCO+(4-3), ....)	12m	mixed, multiple spw/BB	large mosaic	

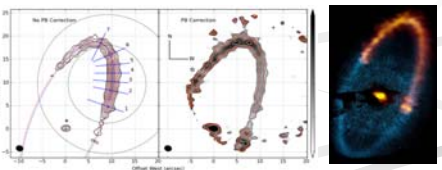
### New SV Targets (continued)

HR 3126/IC 2220	3 (CO, CN)	12m+ACA+SD	mixed, 1spw/BB	large mosaic	
Chameleon	6 (CO, SiO)	12m	mixed, 1spw/BB	multi-field interferometry, long baselines	
M83	7 (CO)	12m+ACA	mixed, 1spw/BB	On The Fly mosaic	
RXCJ1347-1145	3 (contin)	12m+ACA	low spectral res		
M16	6 (CO)	12m+ACA+SD	mixed, 1 spw/BB	large mosaic	
G34.26+0.15	9 (H21a, CH3CN, 34SO2, SO2, CH3CN, 13CO)	12m+ACA+SD	mixed, multiple spw/BB		
321, 325, 658 GHz water masers	7,9 (H2O)	12m	mixed, 1spw/BB	spectral averaging, high angular res, survey mode (non-multi-field)	

### Early Science Results: debris disk

ALMA Observations of the Debris Disk around Fomalhaut

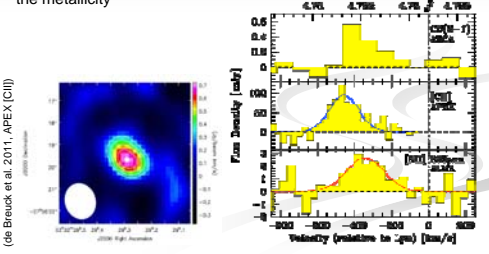
- Boley et al. 2012, ApJ, 750, L21
- Sharp ring of mm-size grains, indirect evidence for shepherding planets



### ES Results: metallicity of high-z galaxy

[NII] in the high-z galaxy LESS J03322

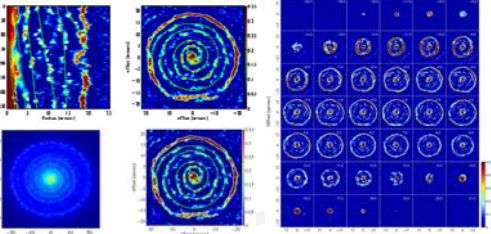
- Nagao et al. 2012, A&A 542, L34
- [NII] at z~4.76, first [CII]/[NII] allows estimate of the metallicity



### ES Results: detached shell

ALMA Observations of the Carbon AGB star R Scl

- Maercker et al. 2012, Nature, in press, 11 October 2012



### Summary

- ALMA is a revolutionary new facility for mm and submm astronomy**
  - 10-100x more sensitivity, 10-100x better angular resolution
- construction and commissioning well on track**
  - official inauguration planned for March 2013
- Science Verification data available for download**
  - several papers already published or in preparation
- Early Science observations ongoing**
  - first results on conferences and in refereed journals
- extensive support structure**

ALMA is for *all* astronomers!

A photograph of the ALMA radio telescope array at night, showing several large white dish antennas illuminated against a dark sky filled with stars.

***Interested in ALMA?***

**Let's stay in touch!**  
German ARC node, newsletter etc.  
<http://www.astro.uni-bonn.de/ARC/>  
ALMA Science Portal at ESO:  
<http://almascience.eso.org/>