The Atacama Large Millimeter Array

Science drivers and operations

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European Project Scientist (interi
Chair ESAC

Outline

- ALMA science drivers
- ALMA overview
- ALMA operations in Chile
- ALMA operations in Europe
- Early science observing

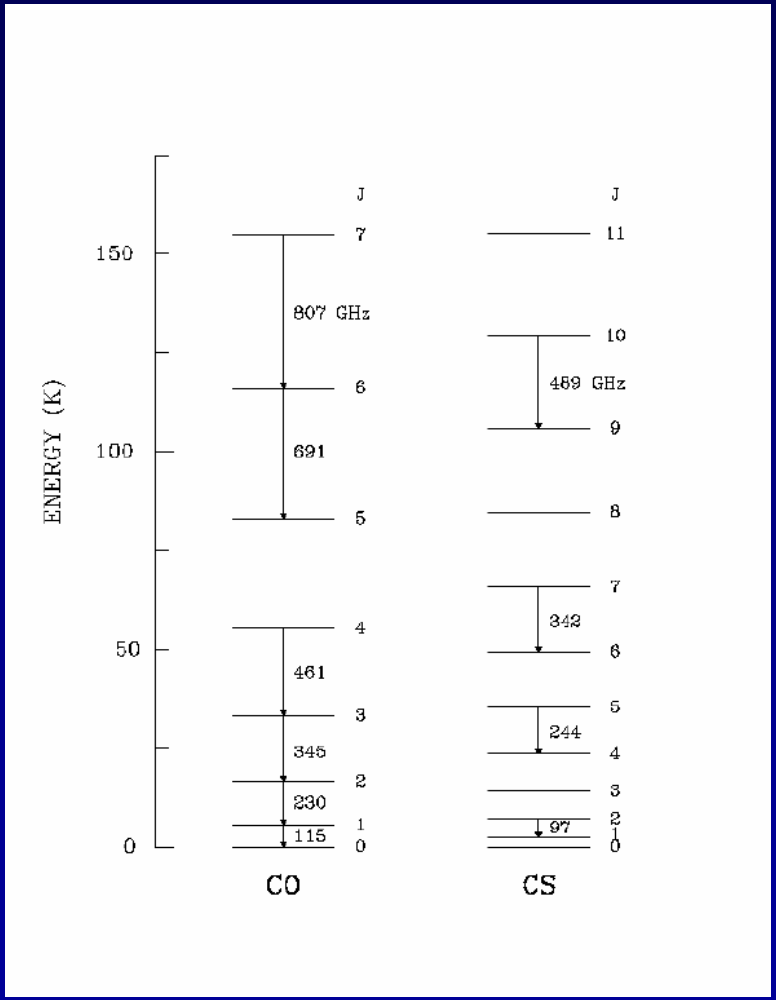
What is ALMA?

- Europe-North America bilateral project
- 64 x 12m antenna's; 7238 m^2 total area
- Frequency range 30-900 GHz (7 – 0.35 mm)
- Configurations from 150m to 14km, with spatial resolution down to 0.01"
- High (5000m) dry site in northern Chile

Radiation at mm wavelengths

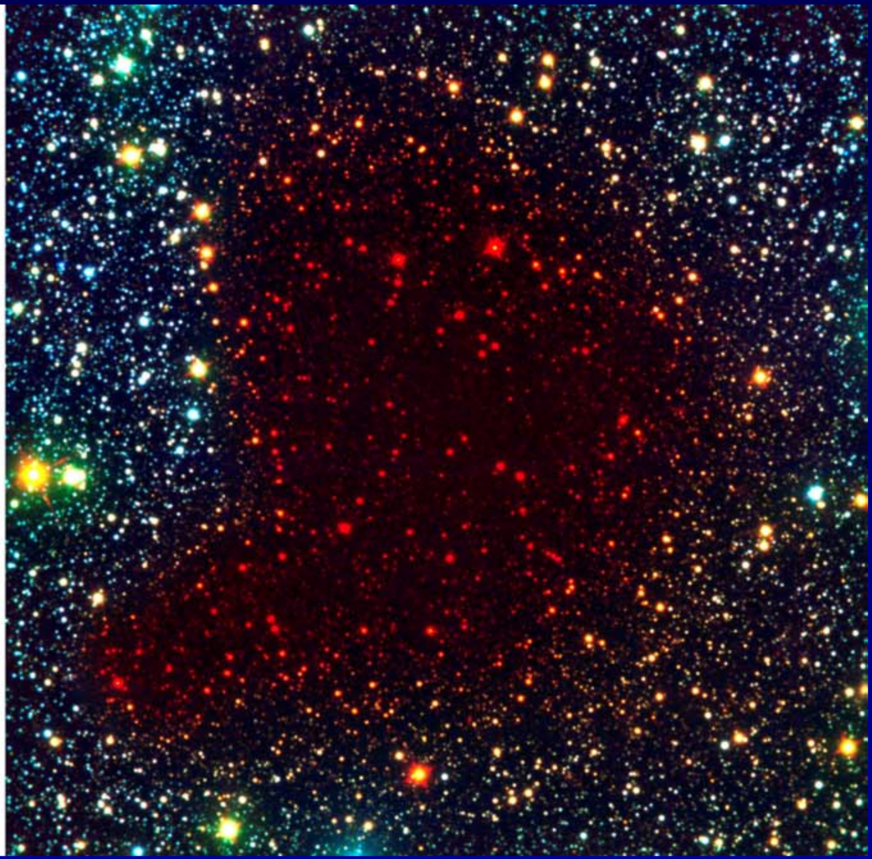
- **Continuum: cold dust at 10-100 K; steep spectrum with ν^3**
- **Lines: pure rotational transitions of molecules**

ALMA probes cold molecular clouds of gas and dust



B68 dark cloud

Optical | **Infrared**



Such obscured star-forming regions can be probed directly at mm wavelengths

Alves et al. 2001

ALMA science drivers

- **Main scientific themes:**
  - **Formation and origin of high-z galaxies**
  - **Birth of stars and planetary systems**
- **ALMA can probe obscured regions (A_V >100 mag), in contrast with optical telescopes**
- **Combination of high angular resolution (0.01''-1'') with high sensitivity will allow applications in every branch of astronomy**

Pioneering Millimeter Arrays

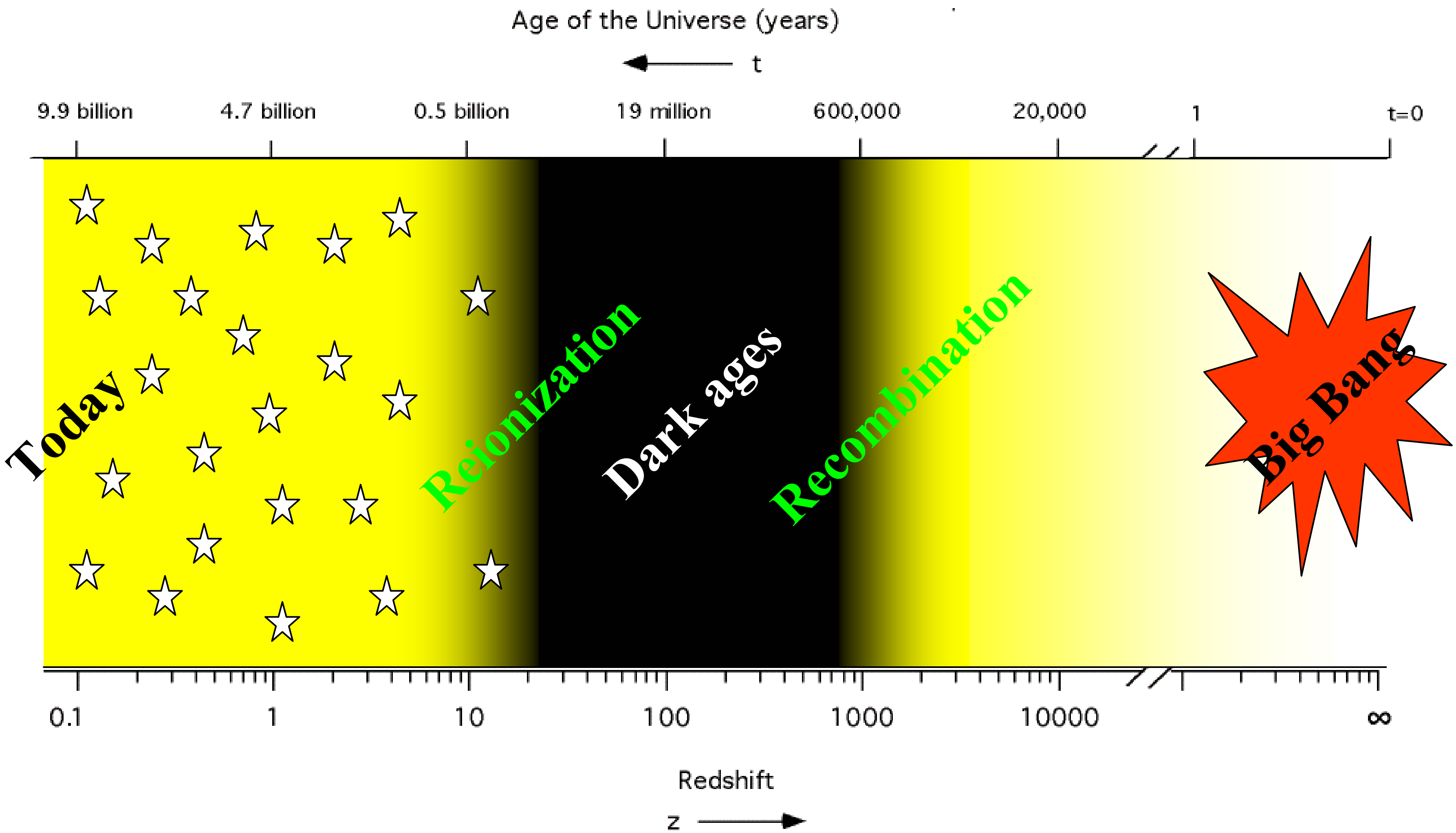
CARMA = OVRO + BIMA

IRAM
Plateau de Bure

These arrays are small and at (relatively) low elevations

Complemented by large single dish telescopes

Questions about the Early Universe



- When did the first stars form => reionization?

- When did elliptical galaxies form?

P. Shaver

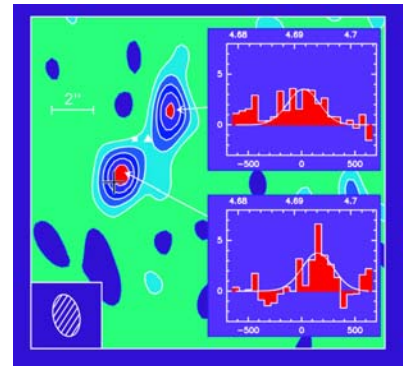
ALMA and the deep Universe

- Evidence for large population of dusty galaxies:
  - Far-IR background
  - Submm continuum sources
  - High-z CO

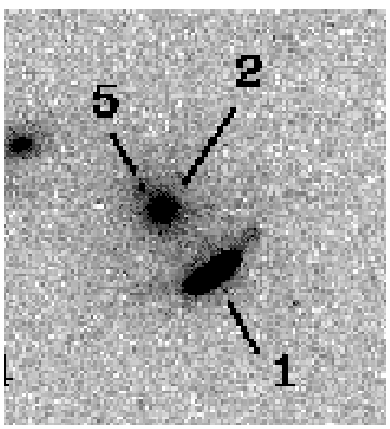
Recent developments in mm/submm astronomy

From z ~ 0 to z ~ 5

in just 5 years

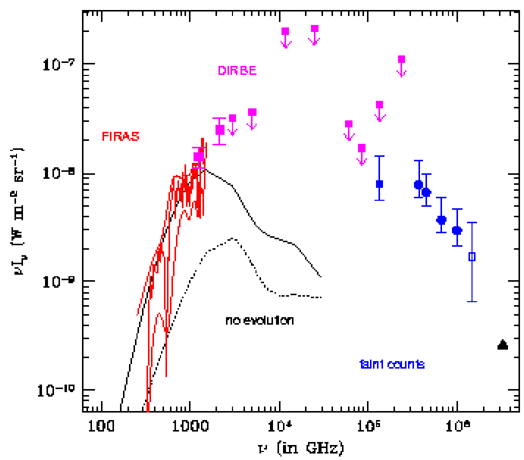


CO at $z = 2$



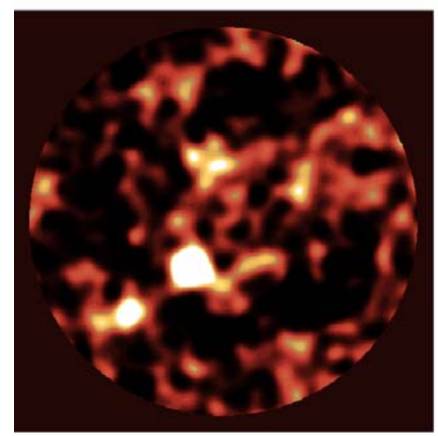
(Eisenhardt et al. 1996)

FIR background



(Guiderdoni et al. 1999)

SCUBA sources



(Hughes et al. 1998)

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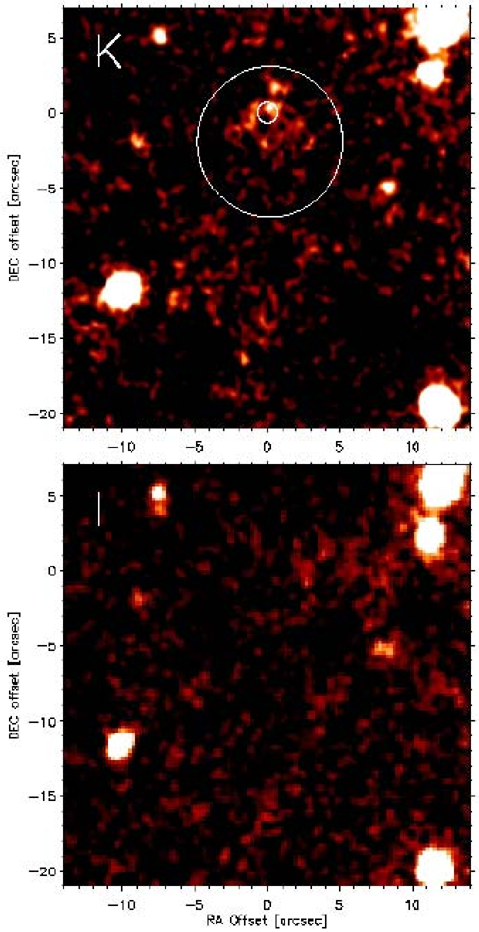
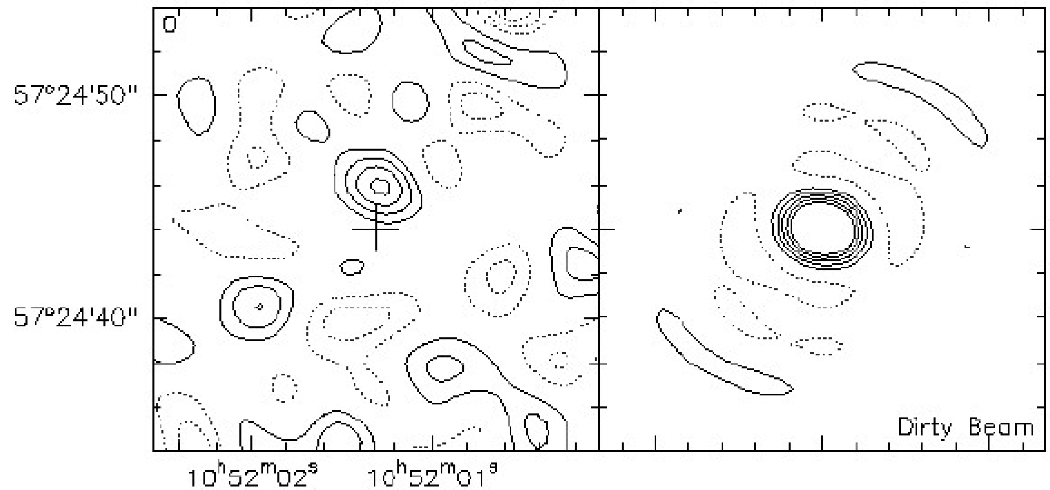
Example: Lockman850.1

Massive elliptical at z~3 in formation?



K

I

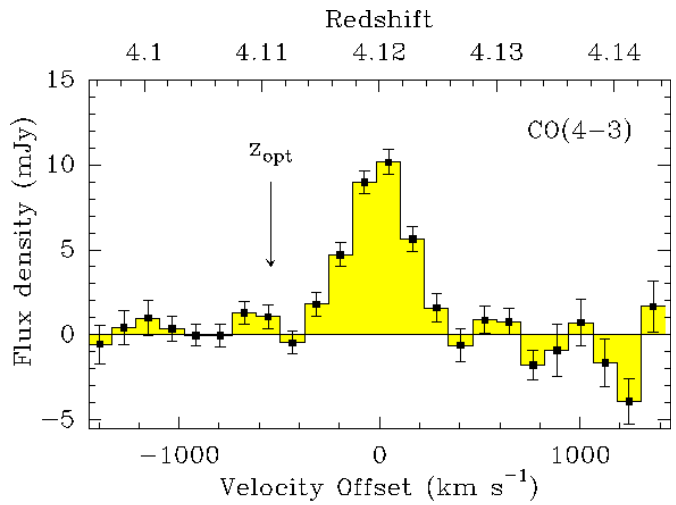


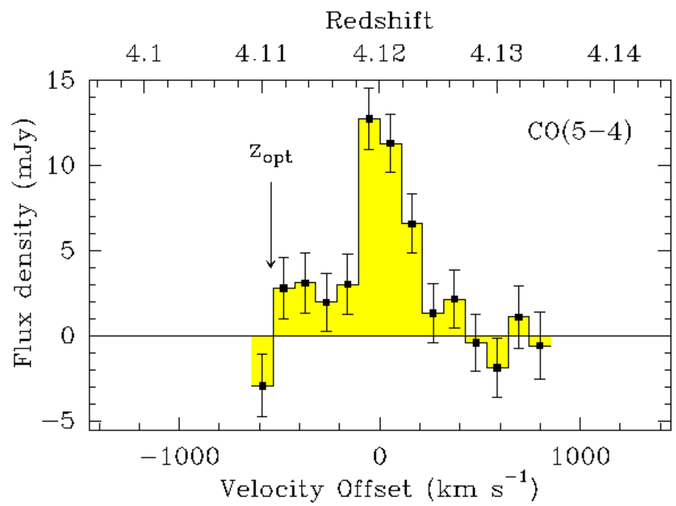
Plateau de Bure 1.3 mm

Identifications are extremely faint or impossible at optical/IR; redshift determination?

Lutz et al. 2001

CO in the quasar PSS 2322+1944





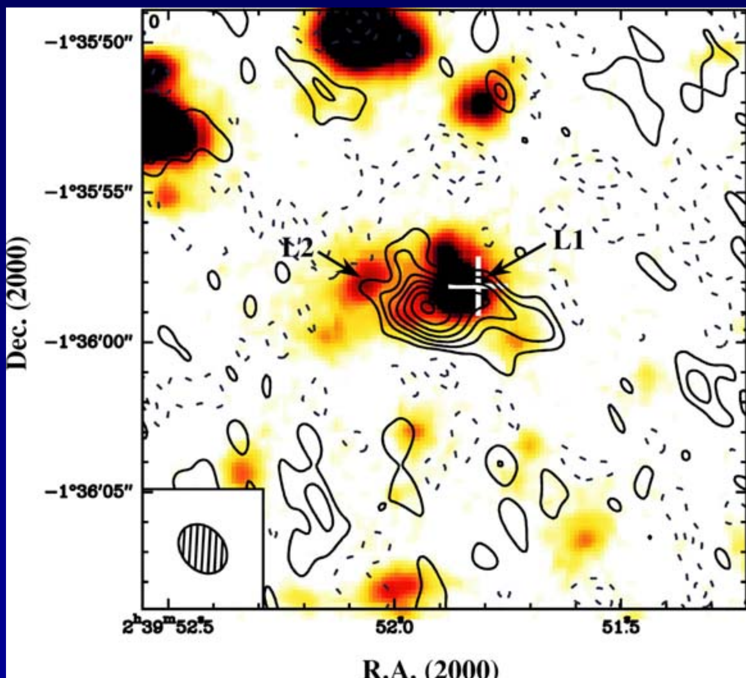
z=4.12

Determination of redshift from CO at mm wavelengths

Cox et al. 2002

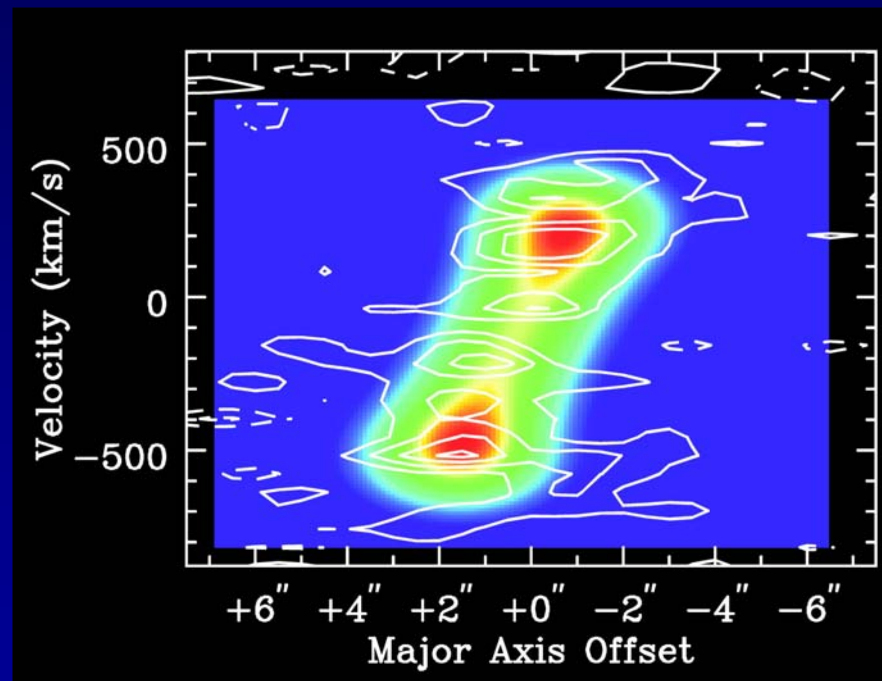
Starting to study them…

CO 3-2 at z=2.80



SMM J020399-0136

CO rotation curve



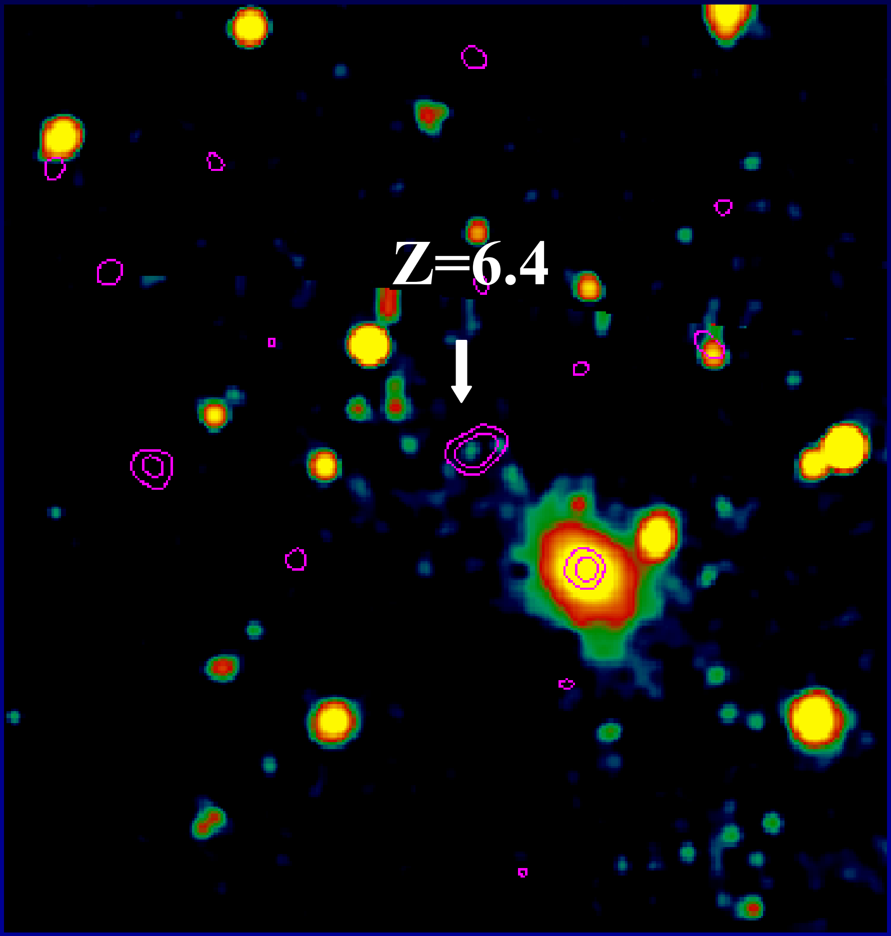
Genzel et al. 2003

$M > 4 \times 10^{11}\ M_{sun}$ within 8 kpc => challenge for standard hierarchical galaxy merger scenarios

Dust and CO at z=6.4!

Sloan survey optical image

Contours: dust



IRAM 30m MAMBO

Bertoldi et al. 2003

=> Heavy elements formed shortly after Big Bang

Understanding galactic physics locally

Antennae galaxies

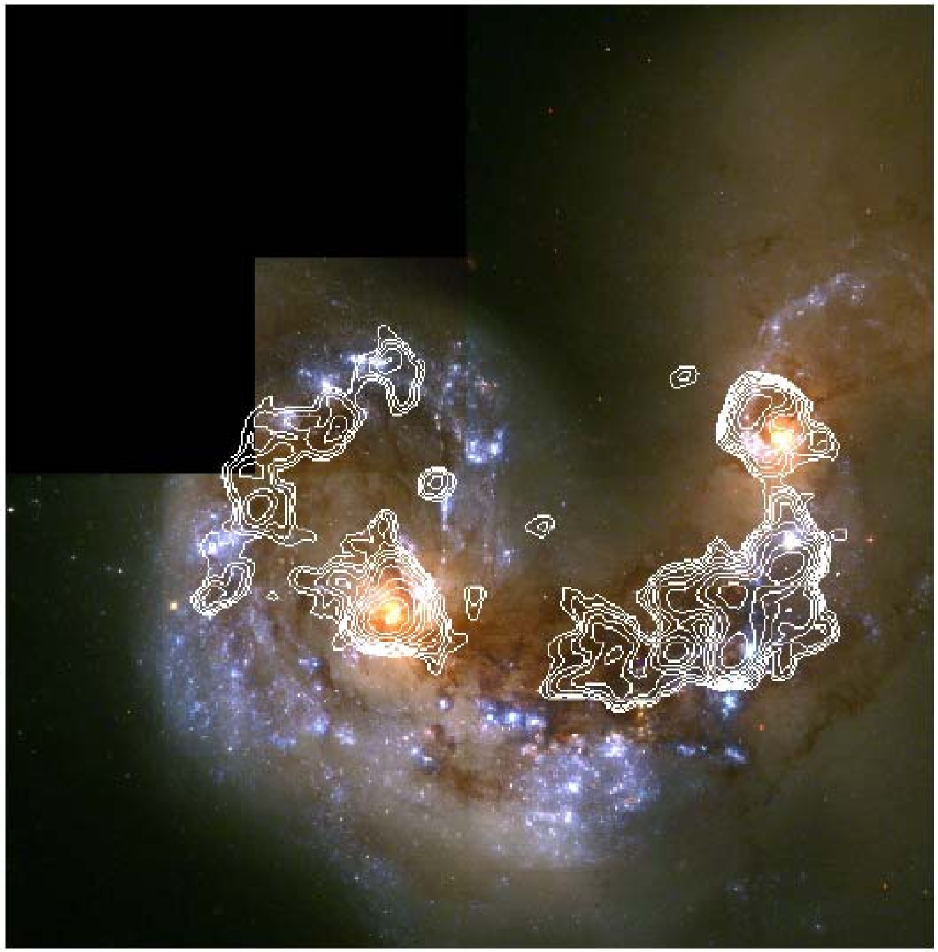


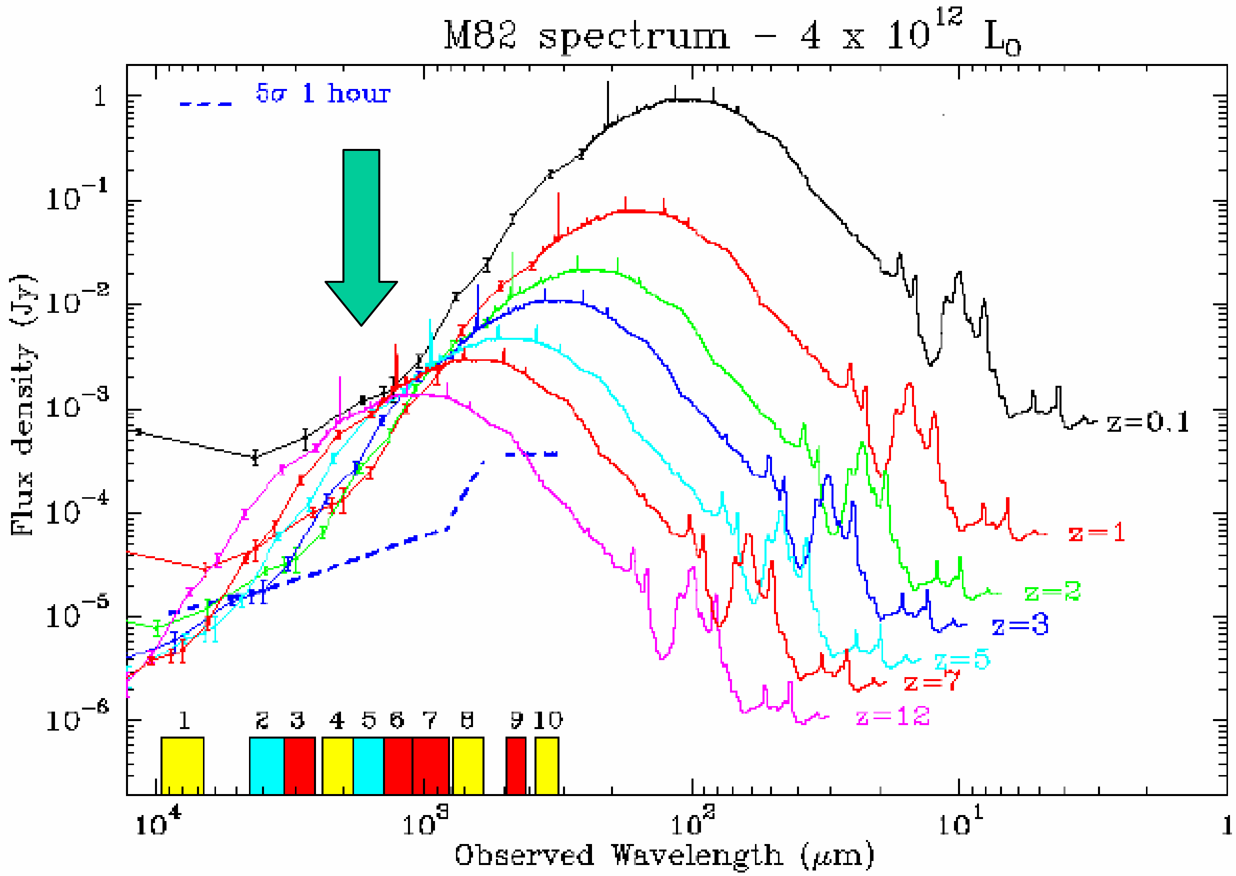
Image: HST
Contours: CO

Wilson et al. 1999

Strongest CO emission comes from optically invisible region!

ALMA can detect throughout the Universe:

- Starburst galaxy in minutes
- Milky-Way galaxy in hours

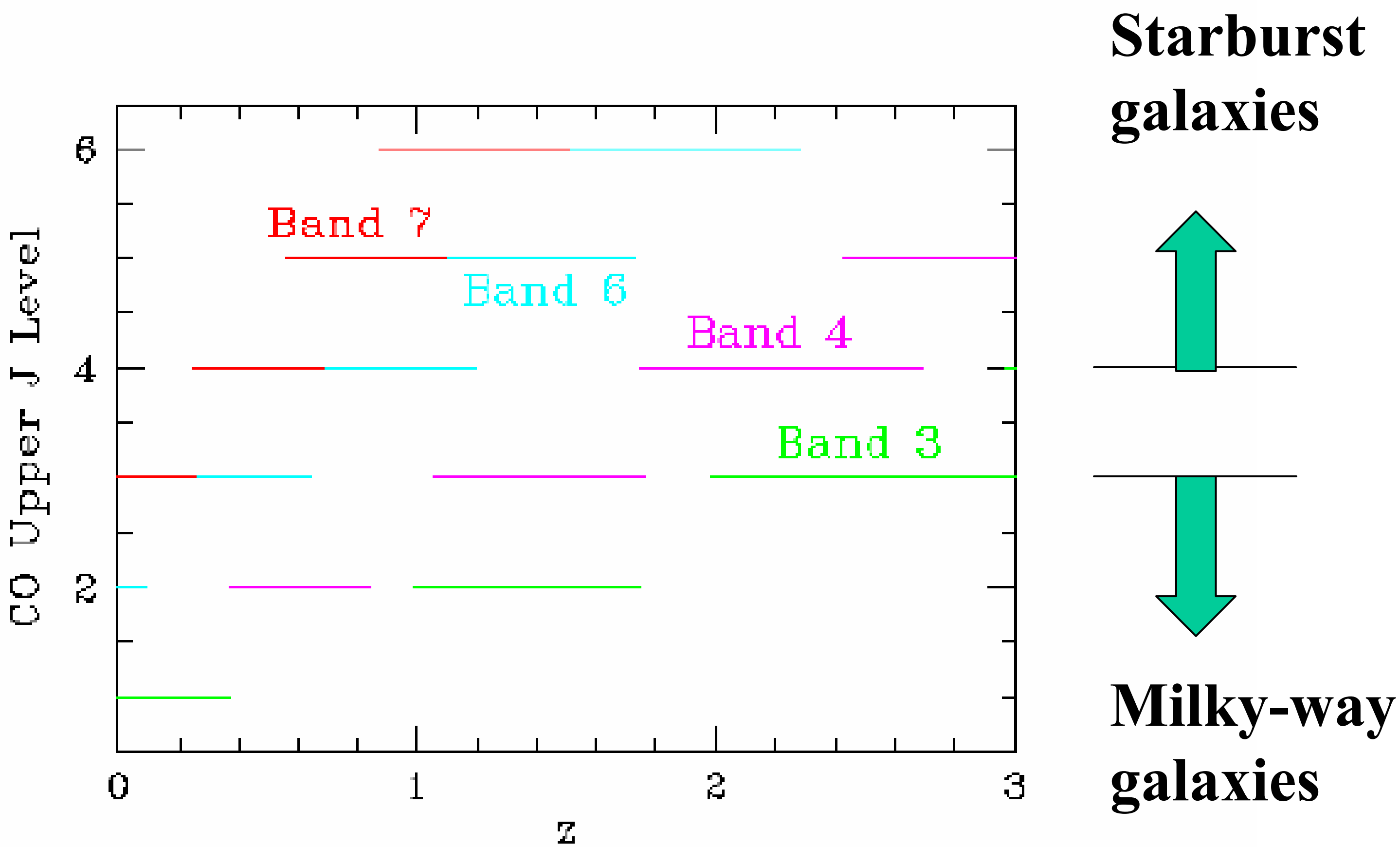


Cox,
priv. comm

ALMA as a redshift machine

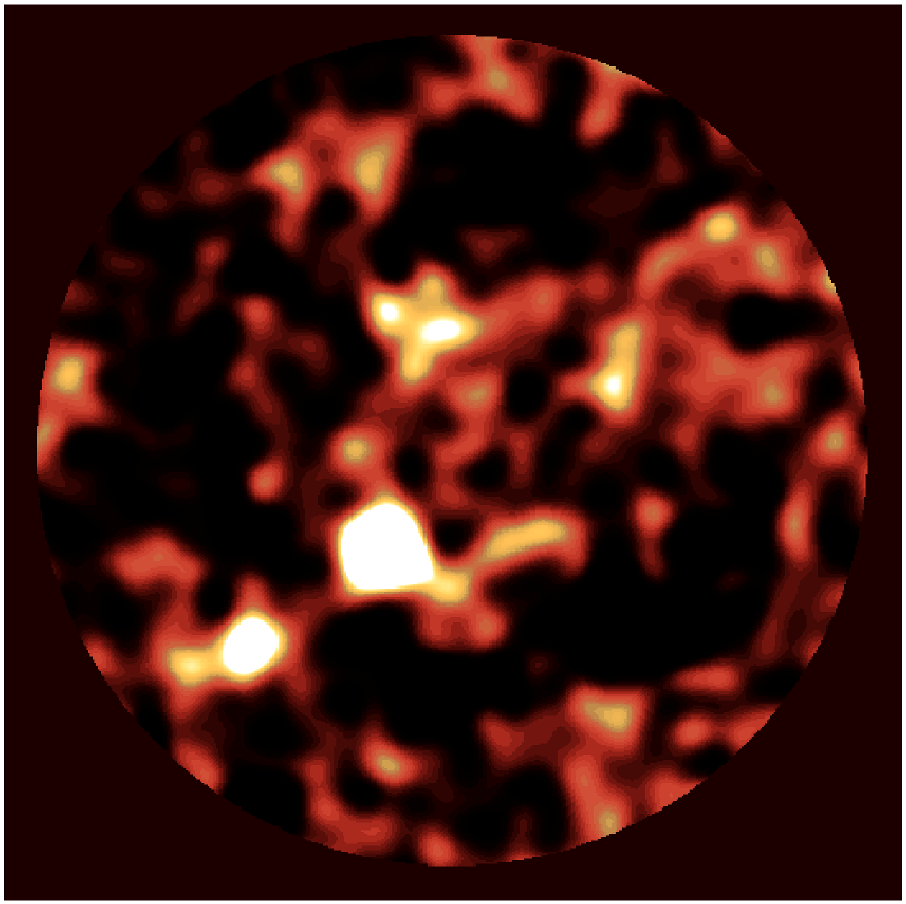
- Distance between CO lines: 115 GHz/(1+z) $\Delta\nu$=8-16 GHz => a few settings are sufficient to detect at least 1 CO line
- Driver for:
  - Large collecting area
  - Wide frequency coverage

Redshifted CO with frequency bands



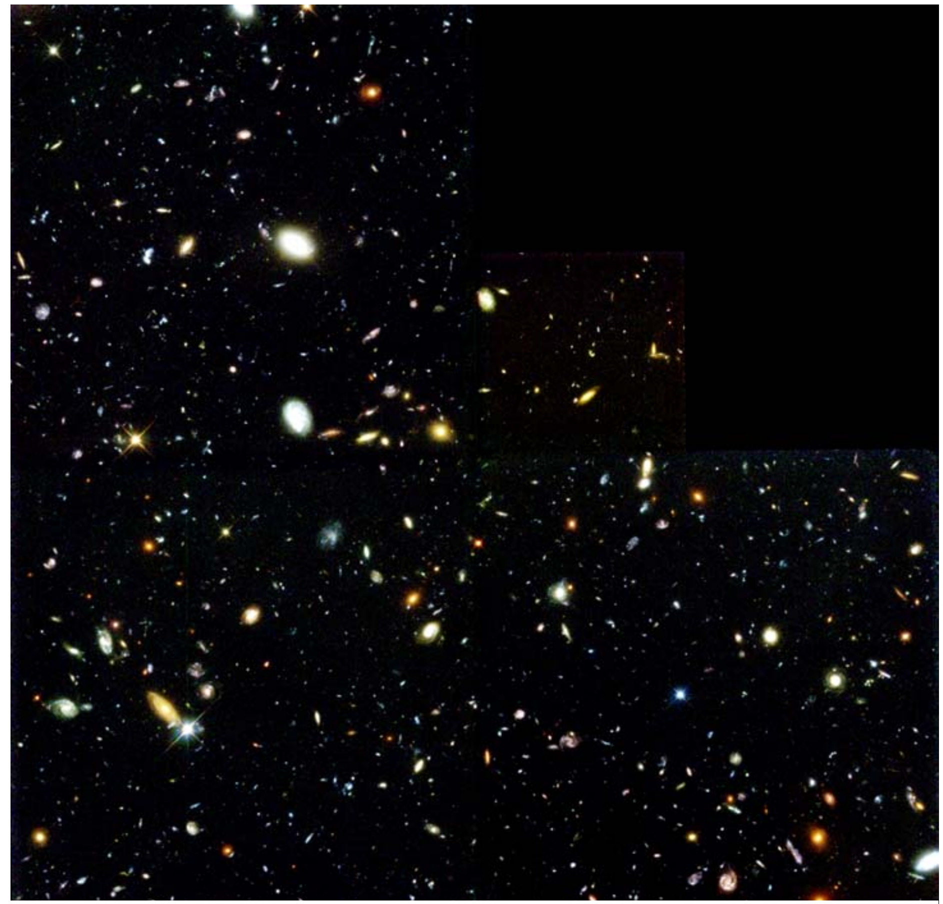
High Angular Resolution for Identifications

SCUBA resolution



Hughes et al. (1998)

ALMA resolution



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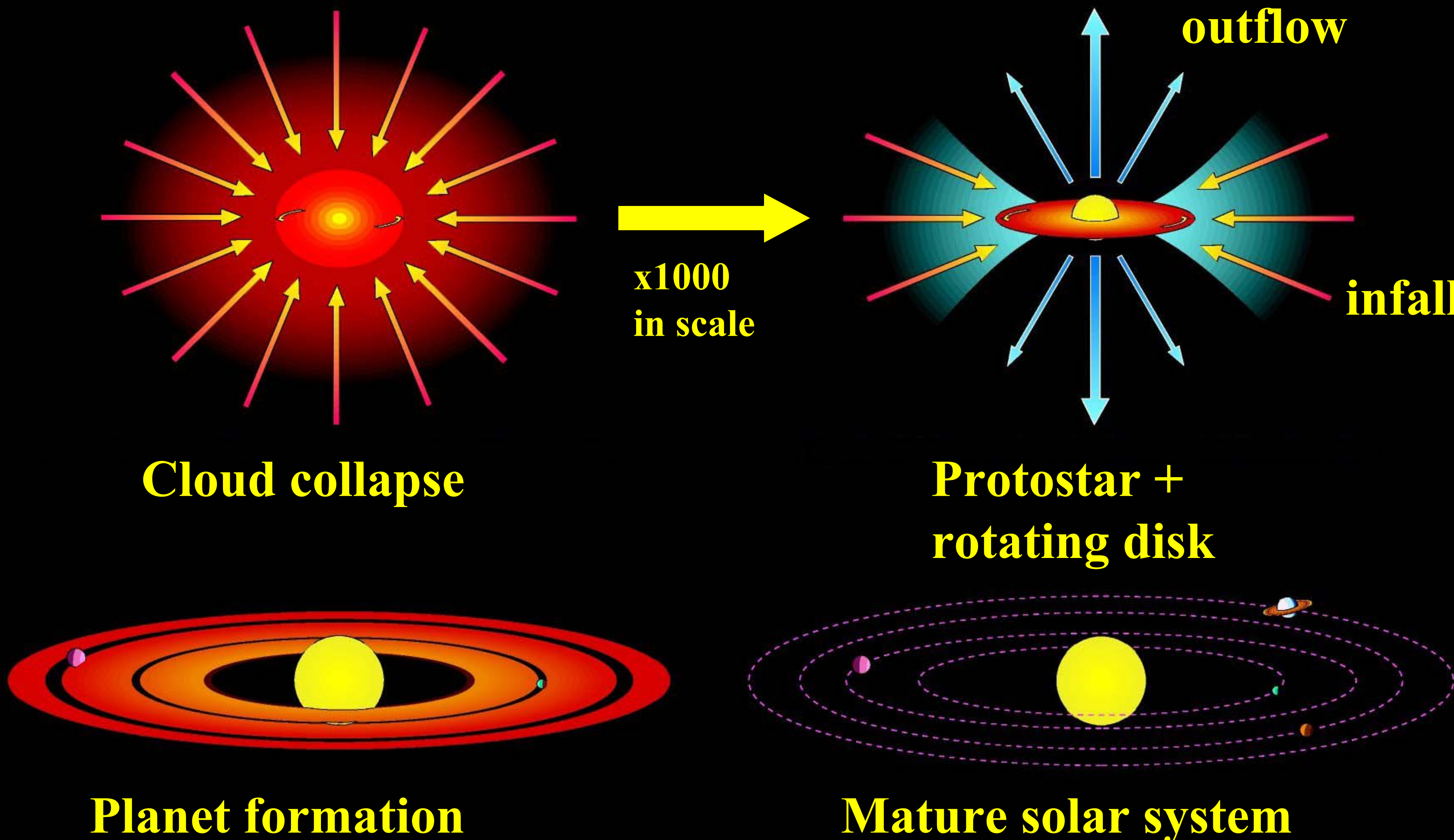
ALMA and the Formation of Stars and Planets

How are single stars created?



Scenario largely from indirect tracers

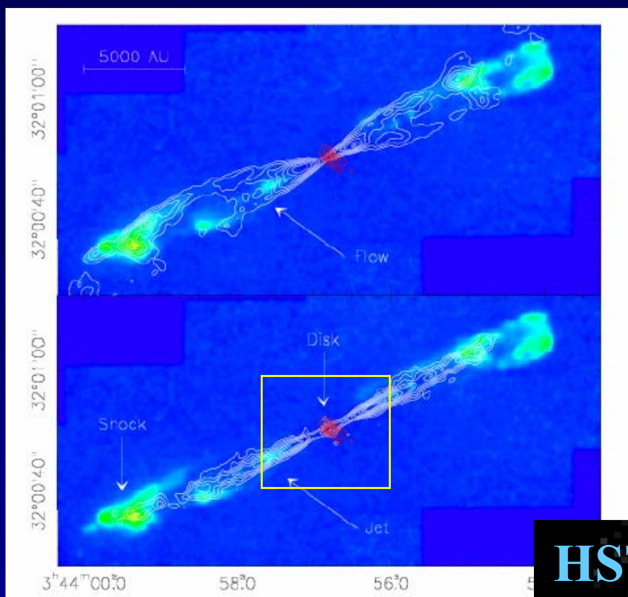
Fig. by McCaughrean

ALMA & outflows from young stars:

Progress requires high resolution imaging

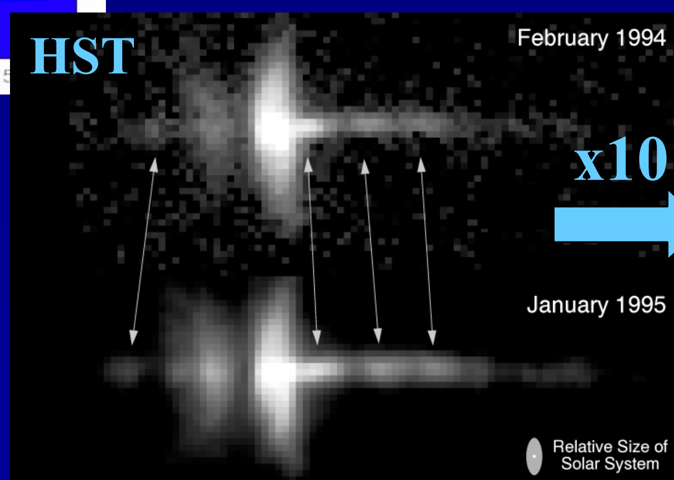
Current mm arrays can only image large scale structures.

ALMA can study the outflows on solar system size scales.

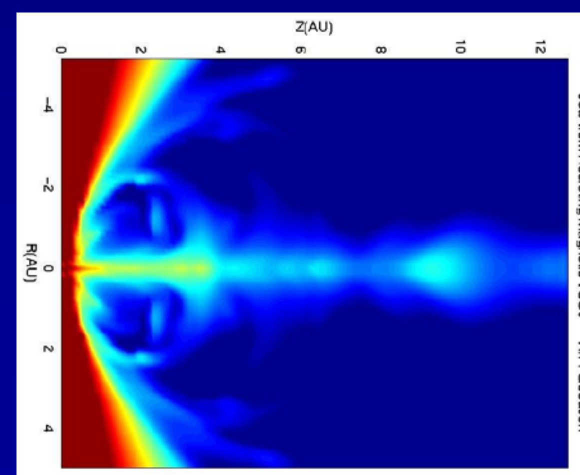


HH211 IRAM

x10



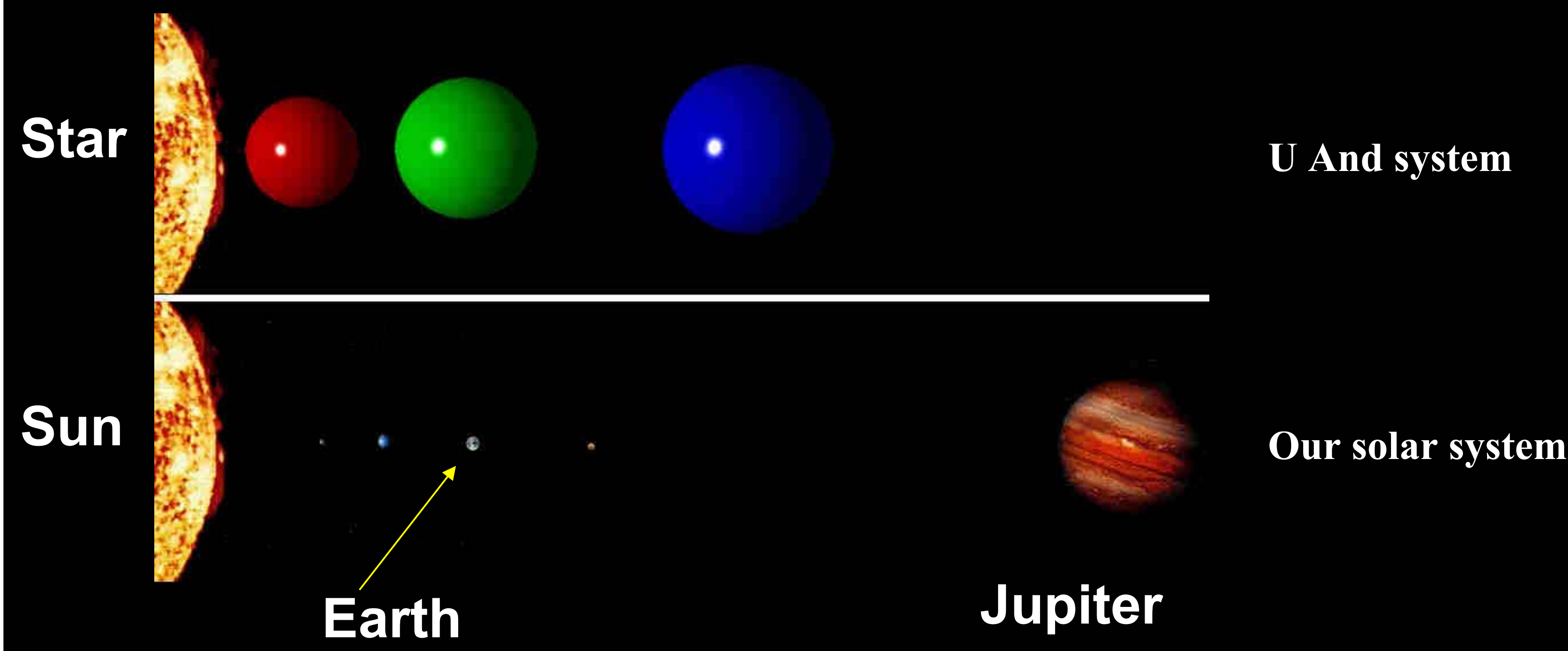
x10



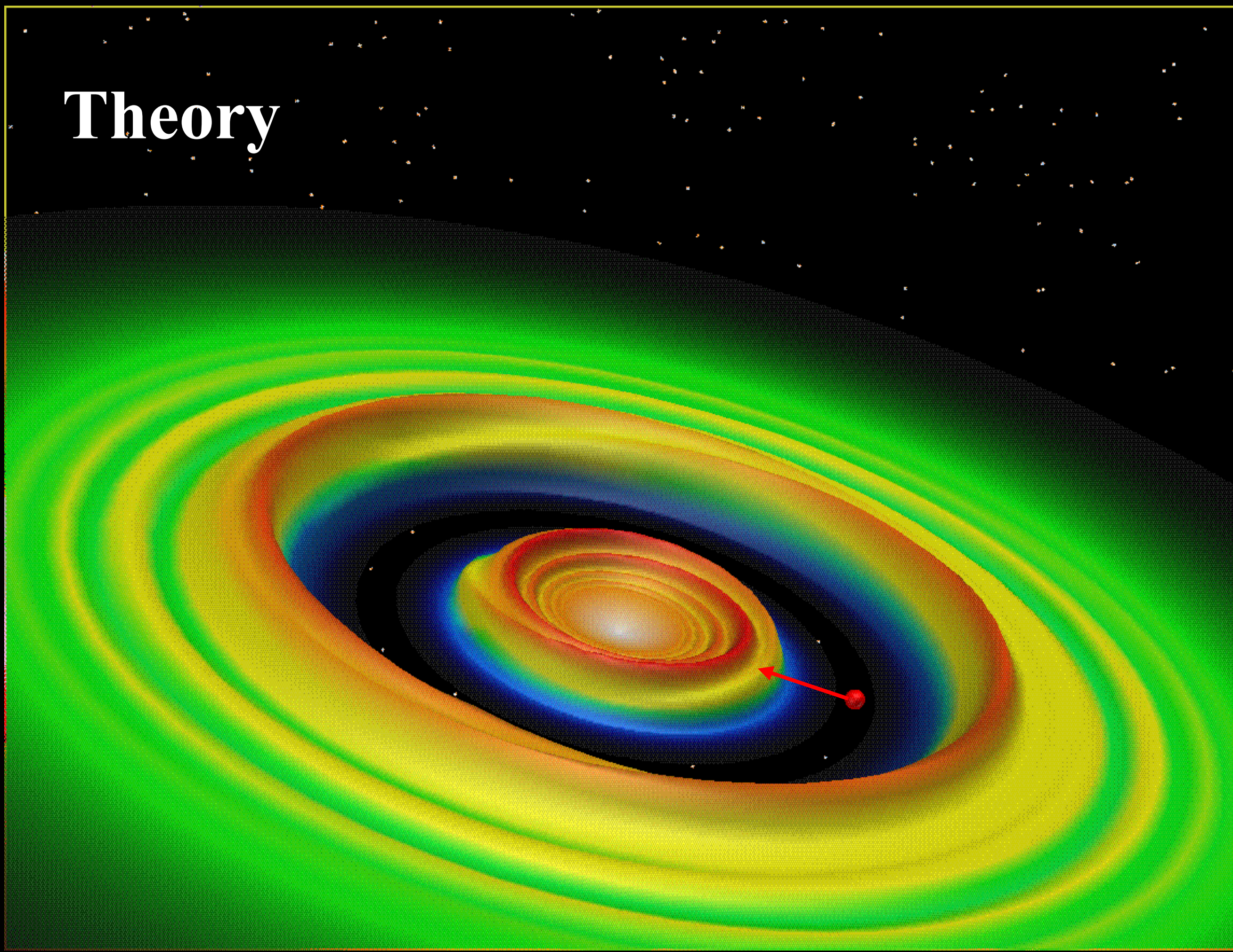
Source: G. Blake

Some exoplanetary systems have Jupiter(s) at the distance of Mercury/Venus!

How does this happen?



Star-Disk-Planet Systems

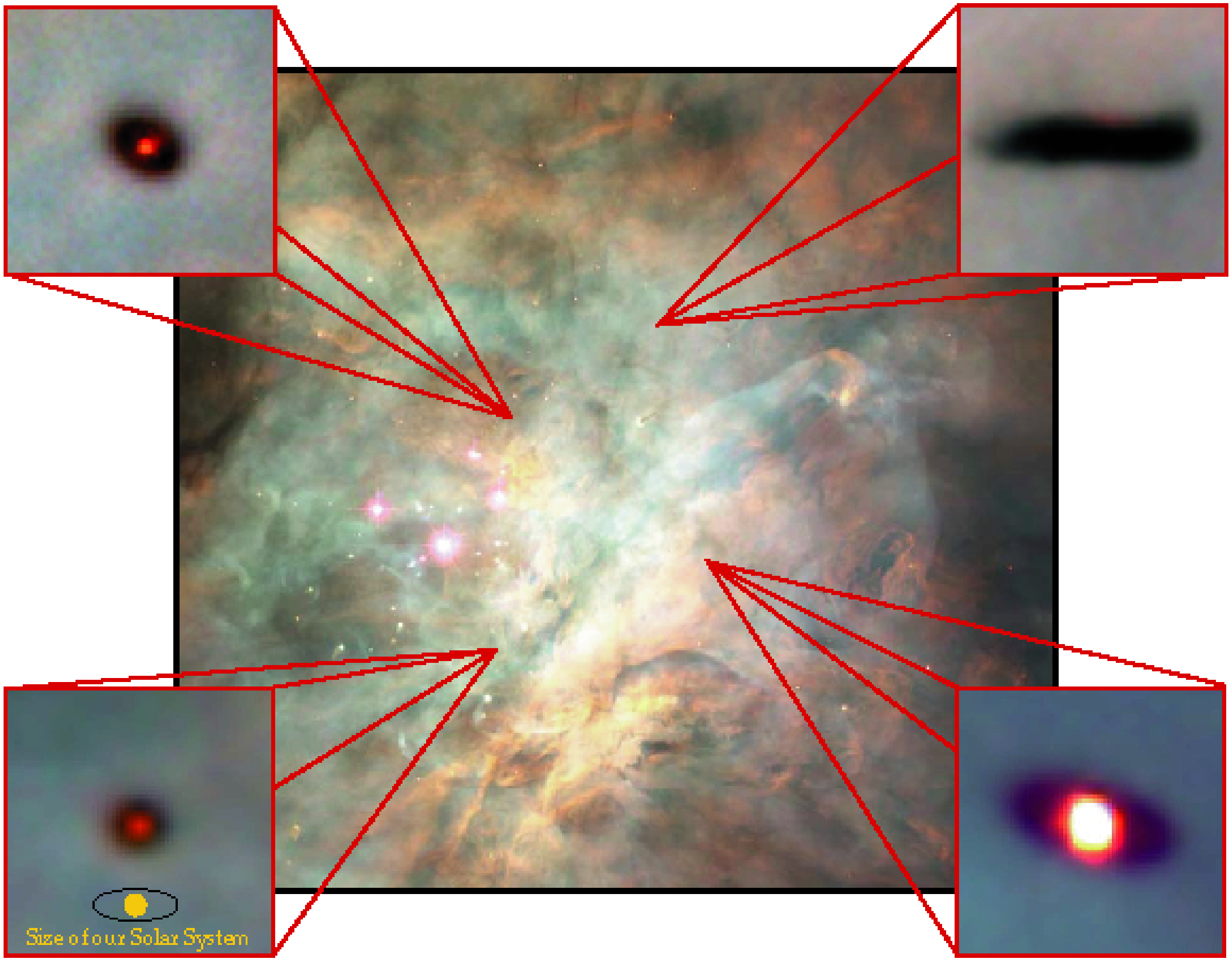


The answer lies in the past, during the time when the star and its planets are being assembled.

Simulation G. Bryden

Need ALMA observations!

Protoplanetary disks



Size disks
~10^{10} km =
2xSun-Pluto

Young disk in Taurus

ALMA and protoplanetary disks

Massive gas-rich disks

$M(gas + dust)=0.01\ M_{sun}$
t=few Myr
gas + dust interstellar

Planet building phase

Tenuous debris disks

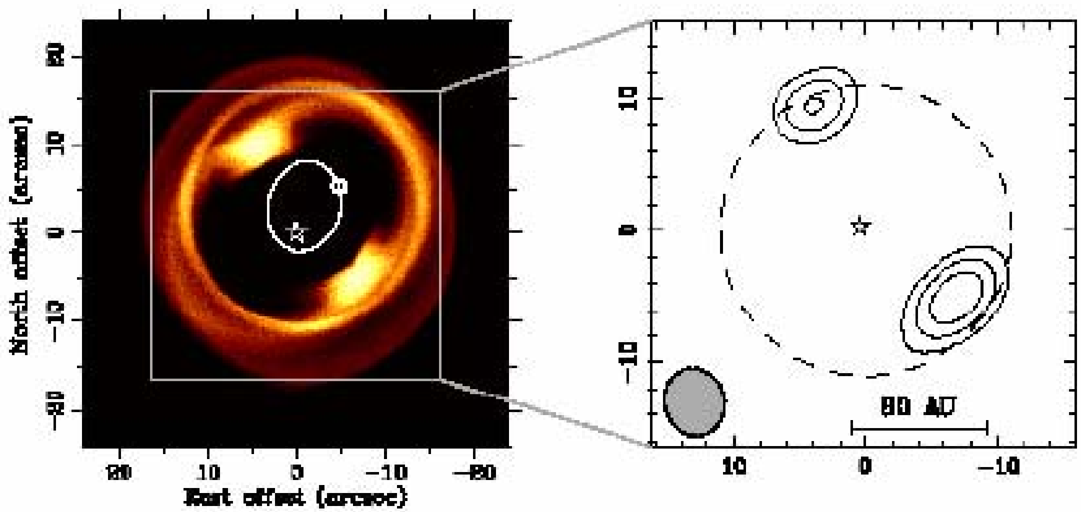
$M(dust)<1\ M_{earth}$
t>10 Myr
dust produced in situ

- **Time scale for gas and dust dissipation?**
- **Physical structure disks (T, n, v, ….)**
- **Evidence for planet formation?**
- **Chemical evolution gas + dust**

Example: Vega debris disk

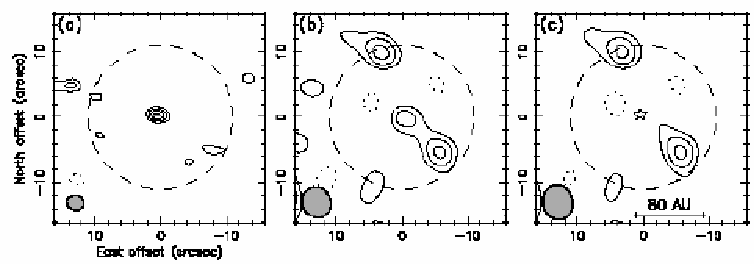
Dust trapped in resonances due to unseen planet with few M_{Jup}?

Simulation **PdB 1mm data**



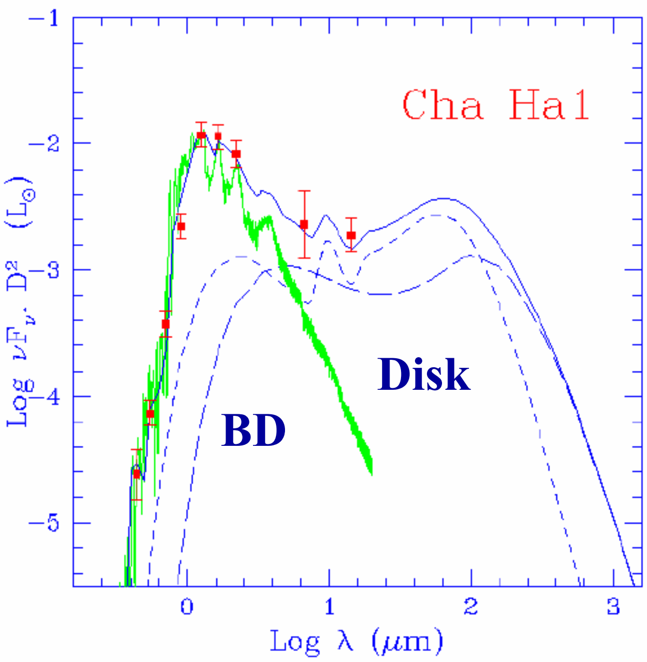
Wilner et al. 2002

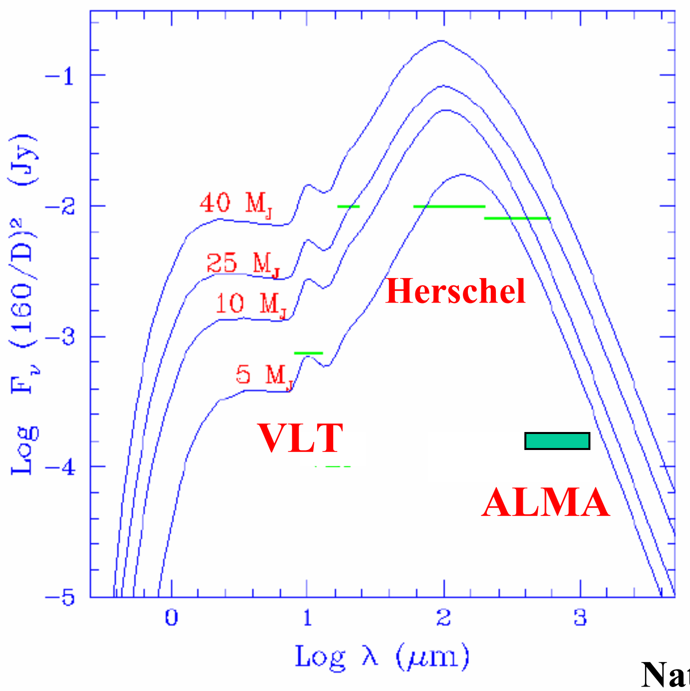
star



Disks around brown dwarfs

Example of synergy between facilities





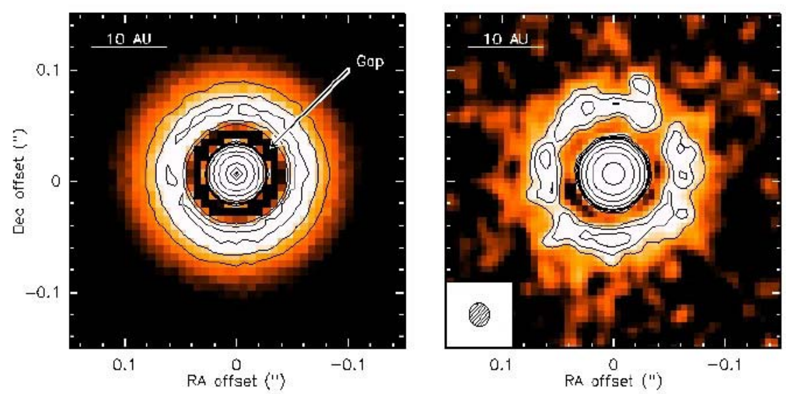
10σ
1hr

Natta & Testi 2001

-Brown dwarf with VLT
-Peak disk luminosity with Herschel (unresolved)
-Mass + image disk with ALMA

ALMA and protoplanetary disks

- ALMA can provide:
  - Statistics on hundreds of pre-main sequence stars down to 0.01 M_{Earth} of cold dust at 100 pc
  - High precision images and kinematics of inner disk down to 1 AU
- Driver for:
  - Large collecting area
  - Highest angular resolution
  - High-resolution spectroscopy (<0.1 km/s)

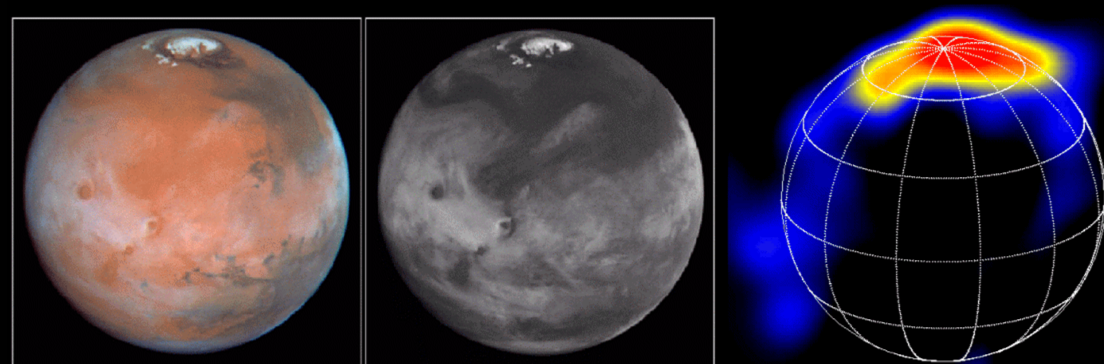


Wolf et al. 2002

ALMA and the Solar System

ALMA will also revolutionize our understanding of objects as diverse as comets…

Mars Opposition - March 1997 **HDO**



HST WFPC2-
Color composite[1]
Surface features

HST WFPC2-
Blue filter (410 nm)[1]
Cloud structure

OVRO - Integrated HDO
Emission (1.3 mm)[2]
Water vapor distribution

… and planetary atmospheres.

[1] P. James (U. Toledo), T. Clancy (SSI), S. Lee (U. Colorado), and NASA

[2] M. Gurwell (CfA), D. Muhleman (Caltech)

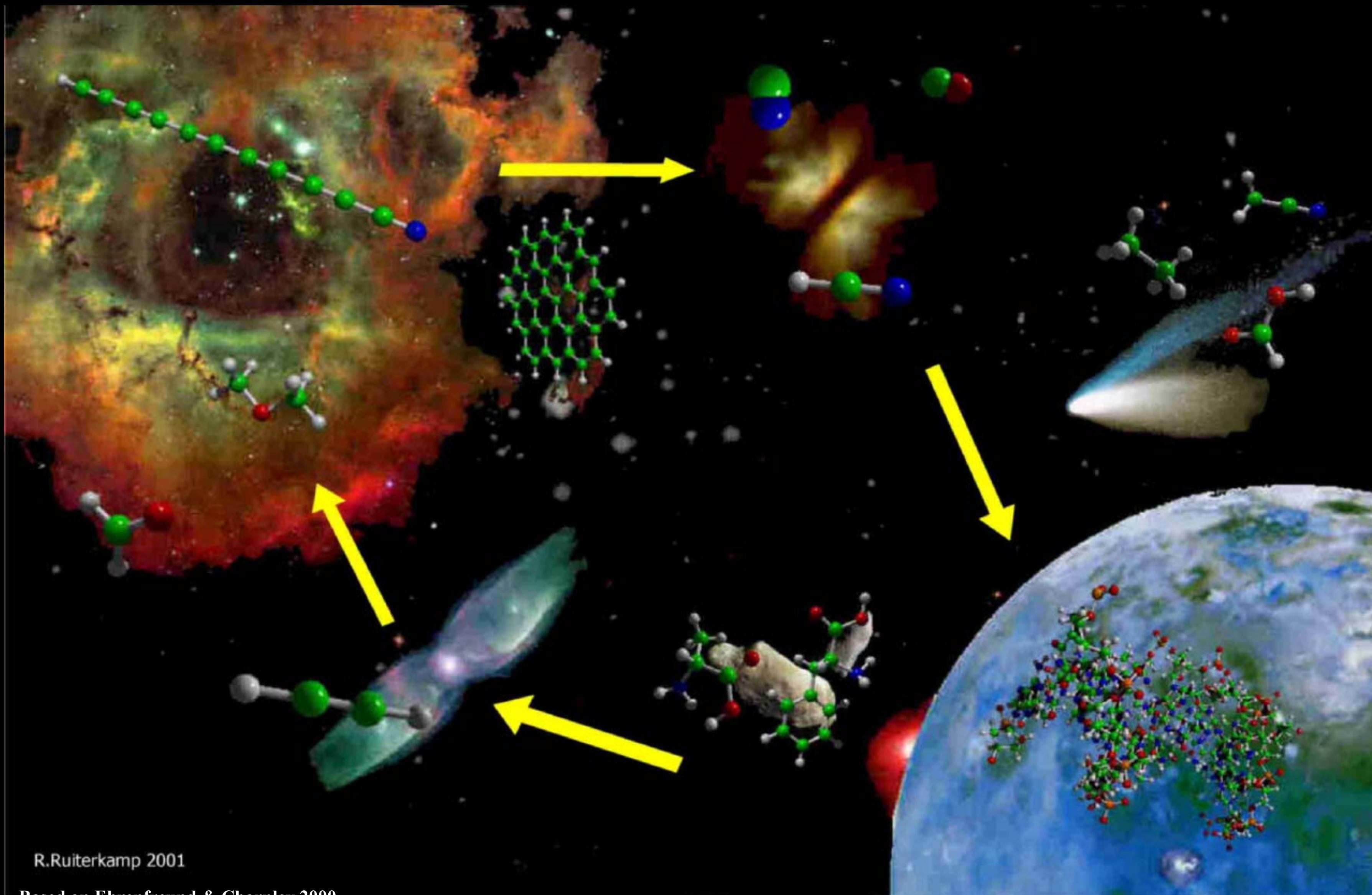
Source: G. Blake

Minor planets in solar system

Size Quaoar measured at mm wavelengths

Bertoldi et al. 2002

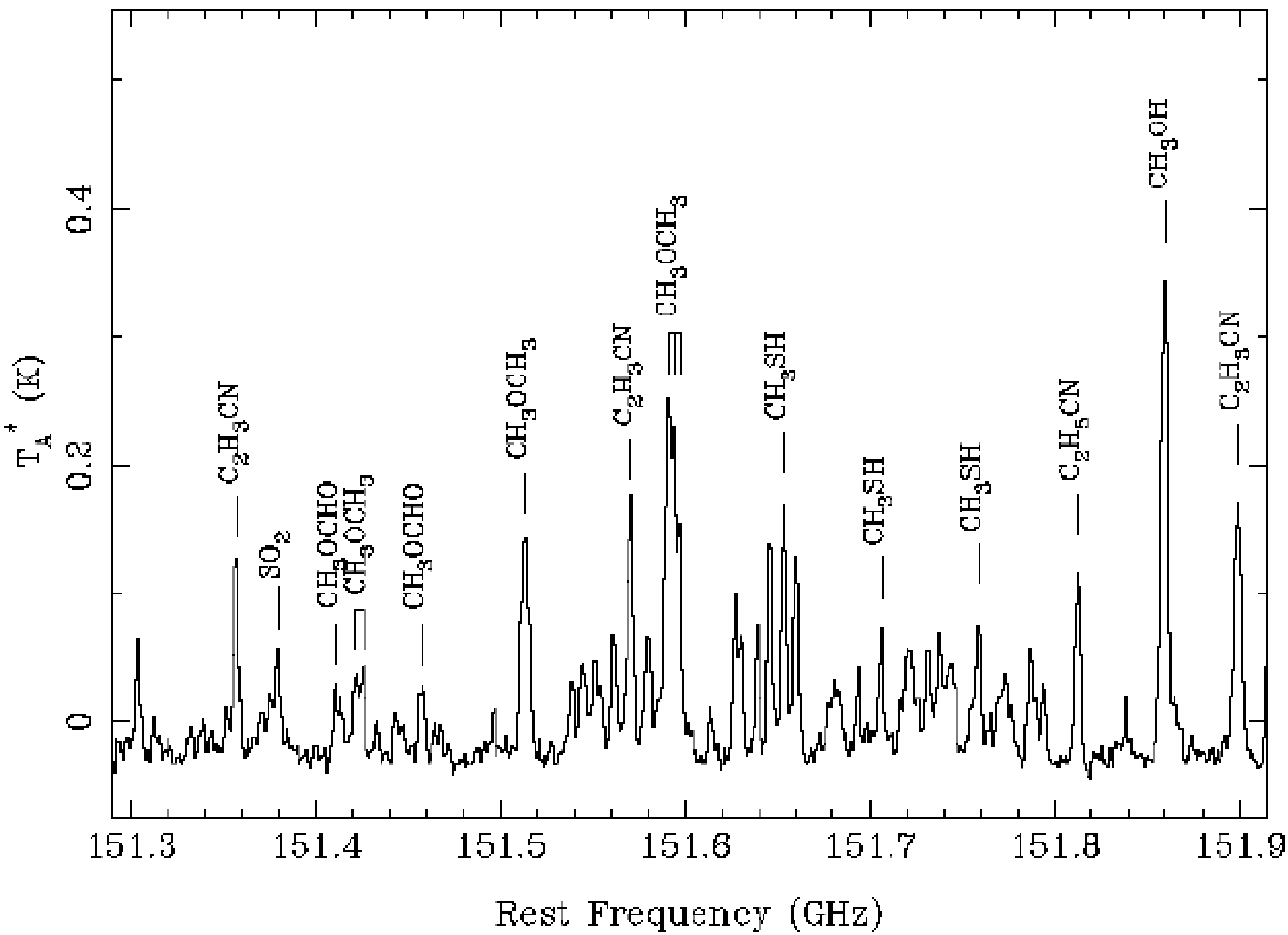
ALMA and Astrochemistry



Based on Ehrenfreund & Charnley 2000

What are building blocks for live elsewhere in the Universe?

Hot core associated with massive YSO

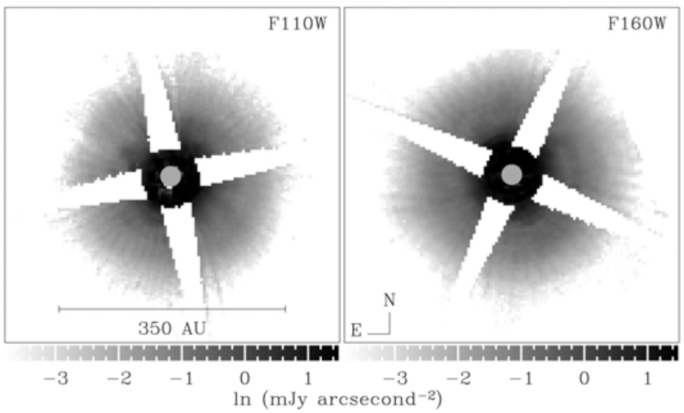


Chemical factory in the sky!

Detection of DCO^+ in a circumstellar disk

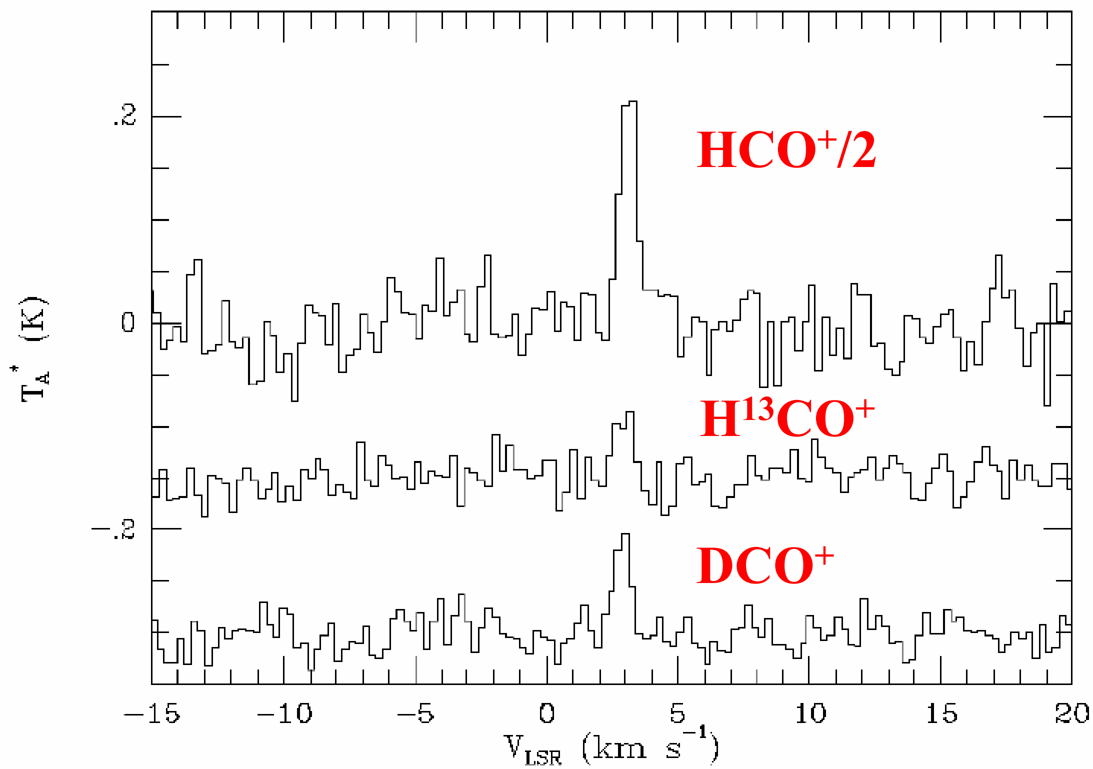
TW Hya face-on disk

1.1 μm 1.6 μm



Weinberger et al. 2002

Scattered light



$DCO^+/HCO^+=0.035$ => gas in disks is cold with heavy depletions

Van Dishoeck et al. 2003

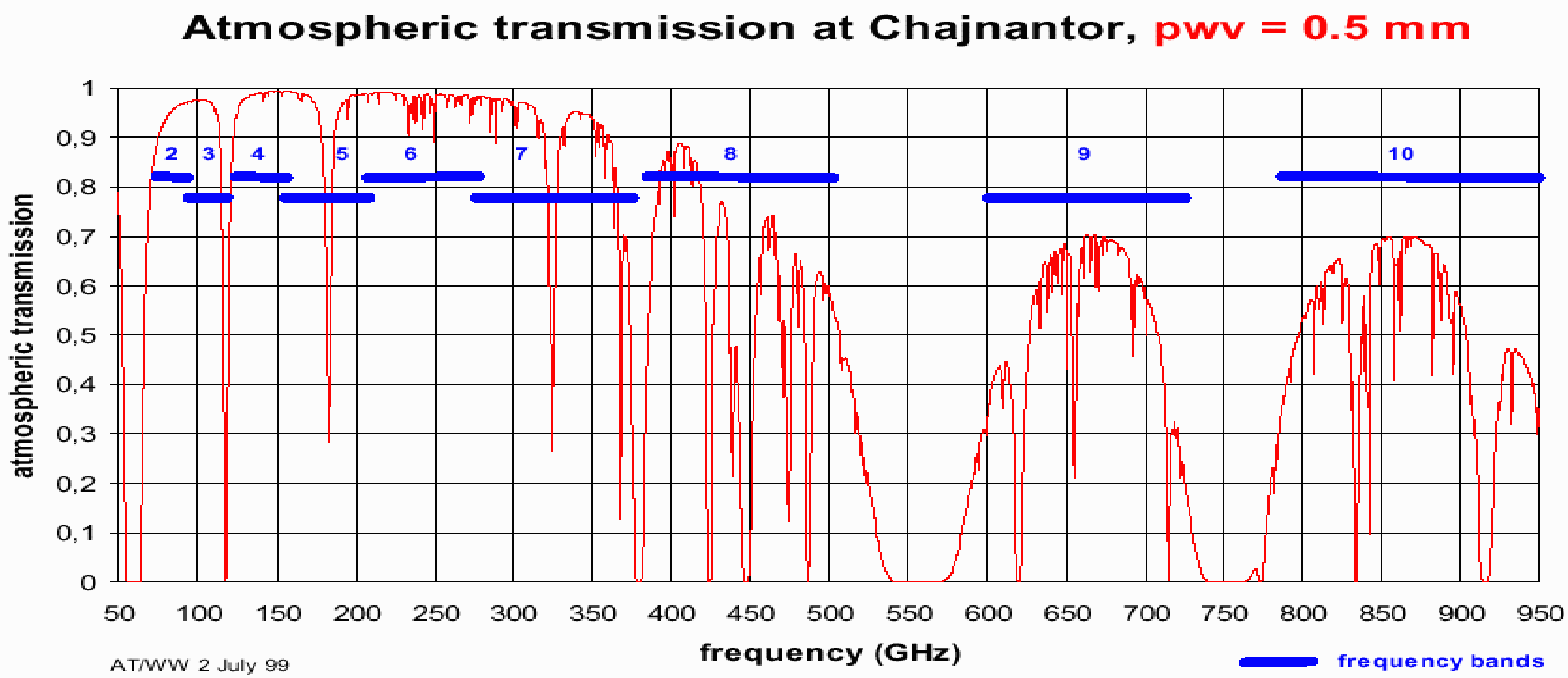
ALMA Level 1 science requirements

- The ability to detect CO or C^+ in a normal galaxy like the Milky Way at z=3 in less than 24 hr
- The ability to image the gas kinematics in protostars and protoplanetary disks at a distance of 150 pc
- The ability to provide precise images at an angular resolution of 0.1”

ALMA overview

- Europe-North America agreement signed February 2003: 552 M Dollar total (Y2000)
- 64 x 12 m antenna's; 7238 m^2 total area
- 30 – 900 GHz (7 mm – 0.35 mm)
  4 out of 10 receiver bands initially; 8 GHz BW
  - Band 3: 84-119 GHz
  - Band 6: 211-275 GHz
  - Band 7: 275-370 GHz
  - Band 9: 602-720 GHz
- Correlator (2016 baselines; 16 GHz per antenna)
- 183 GHz Water Vapor Radiometers for phase cal

Atmospheric transmission on good day



Bands 3, 6, 7 and 9 installed initially

ALMA overview (cont'd)

- **High spatial resolution: (0.25''/B_{km})λ_{mm}**
  - **0.08" at 1mm with 3 km baselines**
  - **0.01" at 0.35 mm with 14 km baselines**
- **This corresponds to 1.5 AU in nearest star-forming regions, 85 AU at Galactic Center, 1 pc at Virgo**

⇒***ALMA will be 10,000 times faster for continuum, 500 times faster for line data, and will see 50 times sharper than existing facilities!***

ALMA will be unique

ASAC/ESAC

- ASAC: 5 from each side
  - P. Cox, J. Richer, P. Schilke, L. Testi, E. van Dishoeck
  - C. Carilli, L. Mundy, P. Myers, J. Turner, C. Wilson
  - Project scientists are ex-officio members
  - 1 Chilean member, 3 Japanese observers
- New ESAC has members from each ESO country (J. Yun from Portugal)
- ASAC/ESAC reports and minutes on Web

Science Operations:
Astronomers Perspective

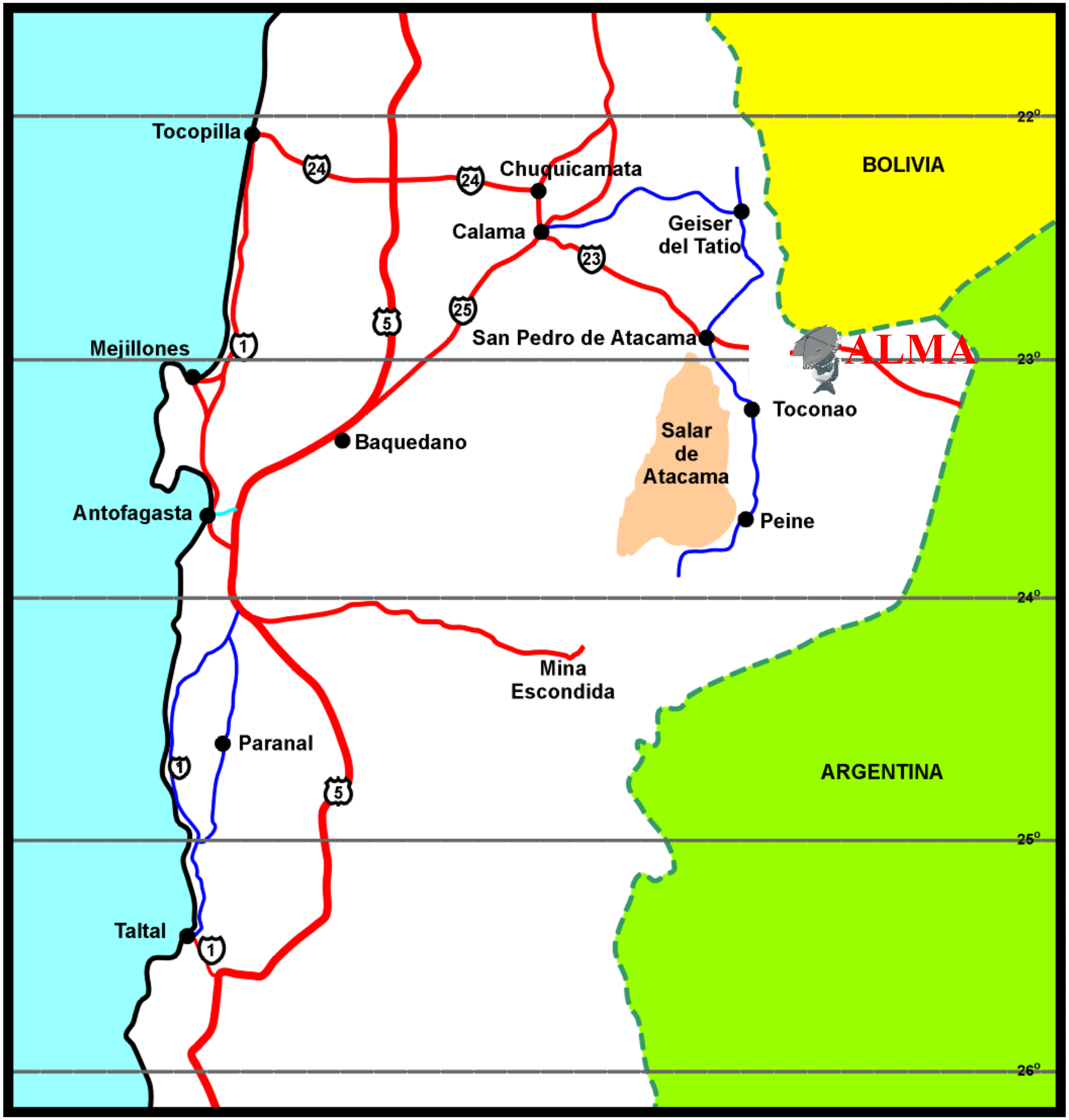
- Non-experts should be able to use ALMA
- Dynamic scheduler to match observing conditions
- Reliable and consistent calibration:
  - 1% at mm, few % at submm goal
- Data public in timely fashion

ALMA Operations

• Array Operations Site	Chajnantor
• Operations Support Facility	San Pedro
• Central Office	Santiago
• Regional Support Centers	NA/EU
• Development / Upgrades	NA/EU

Subject to changes by ALMA Board!

ALMA Location



The New York Times

Sunday, March 3, 1996

Travel

Section 5

TRULY HIGH AND DRY

In southwestern Bolivia, the sun paints thousands of miles of salt and even the inn is made of it.

BY LOGAN WARD 13

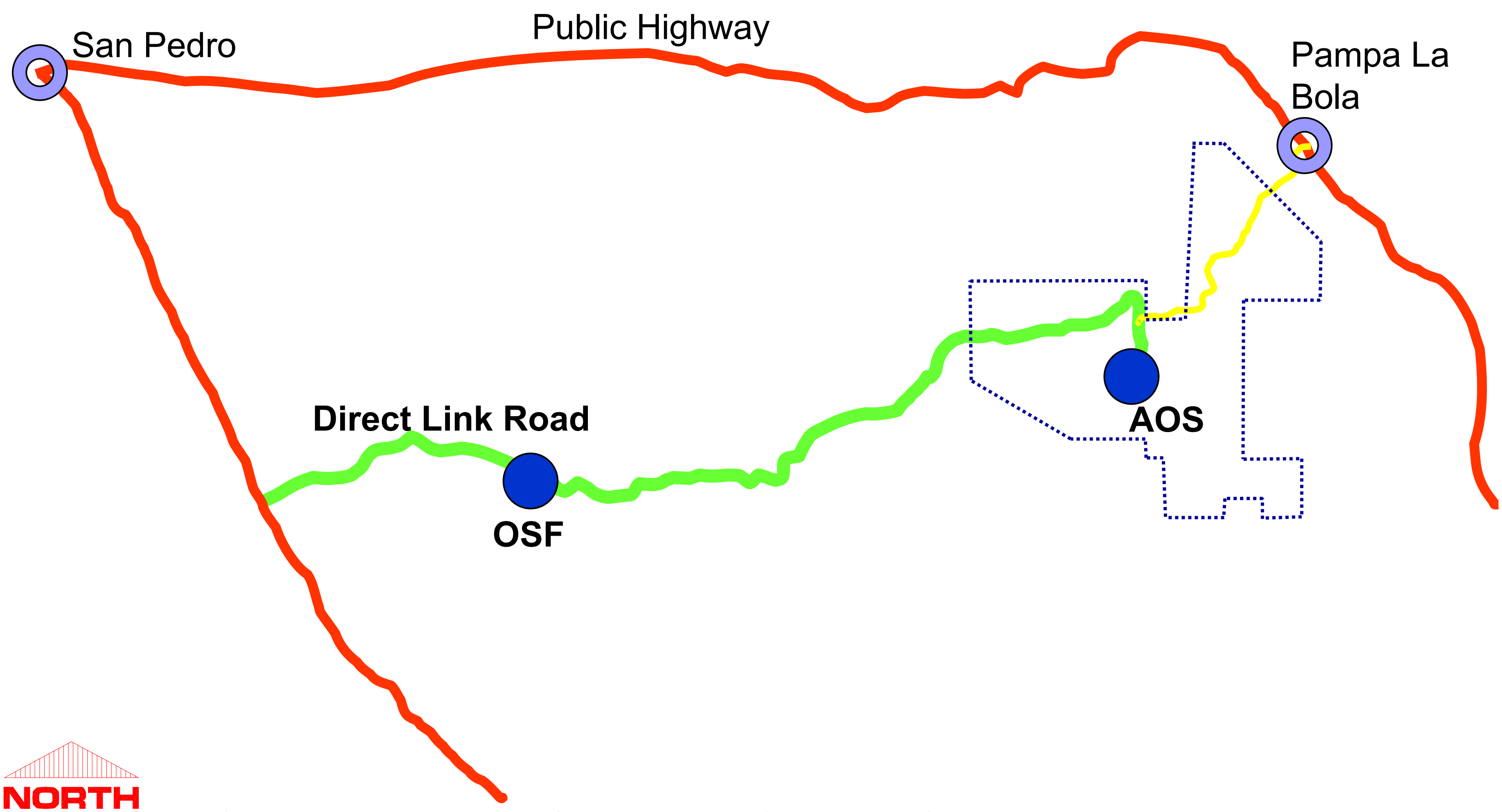
The archeological center of Chile is perhaps the driest place on earth.

BY JOHN R. ALDEN 12

ABOVE Church in San Pedro de Atacama, Chile.
TOP Andean volcanoes near San Pedro.
LEFT Enjoying a natural hot spring in Bolivia.

Church
San Pedro

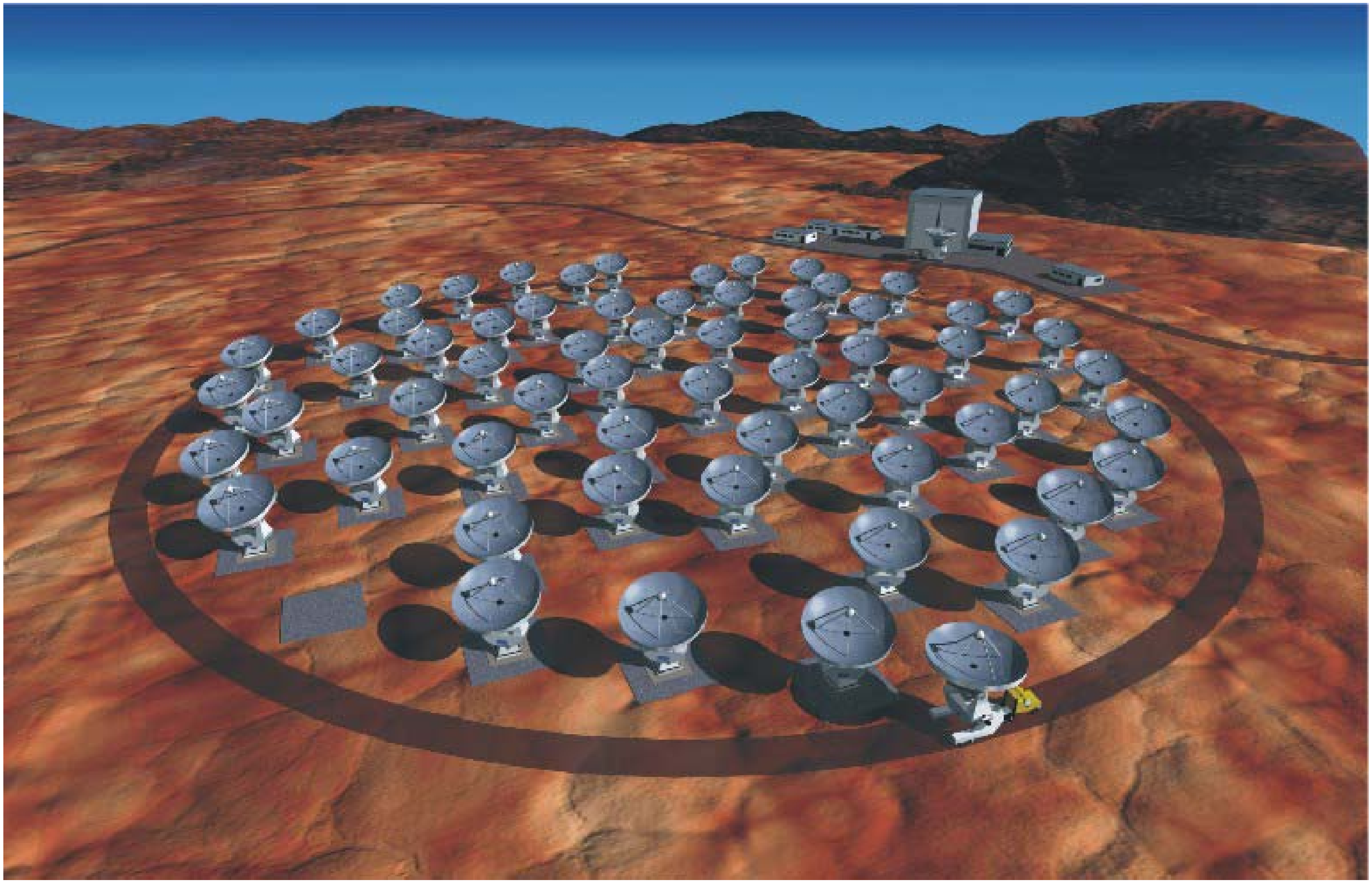
Main square San Pedro


San Pedro
Public Highway
Pampa La Bola
Direct Link Road
OSF
AOS

NORTH

Chajnantor

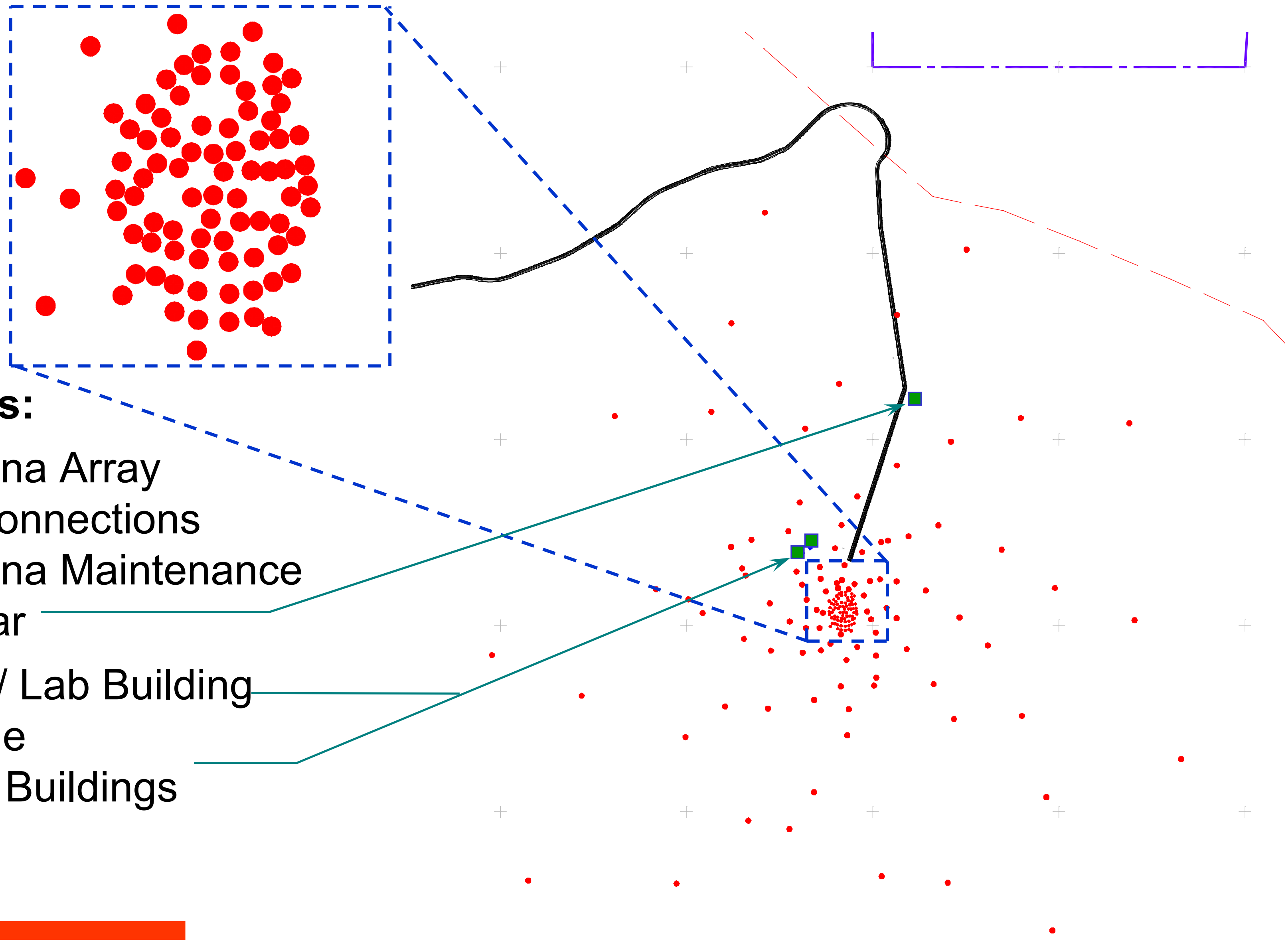
ASAC at center of ALMA array



Main Functions AOS

- Antenna re-configuration (continuous)
- Instrument module exchange
- Security of site

Array Operations Site



Facilities:

- Antenna Array
- Interconnections
- Antenna Maintenance Hangar
- Tech / Lab Building
- Refuge
- Utility Buildings

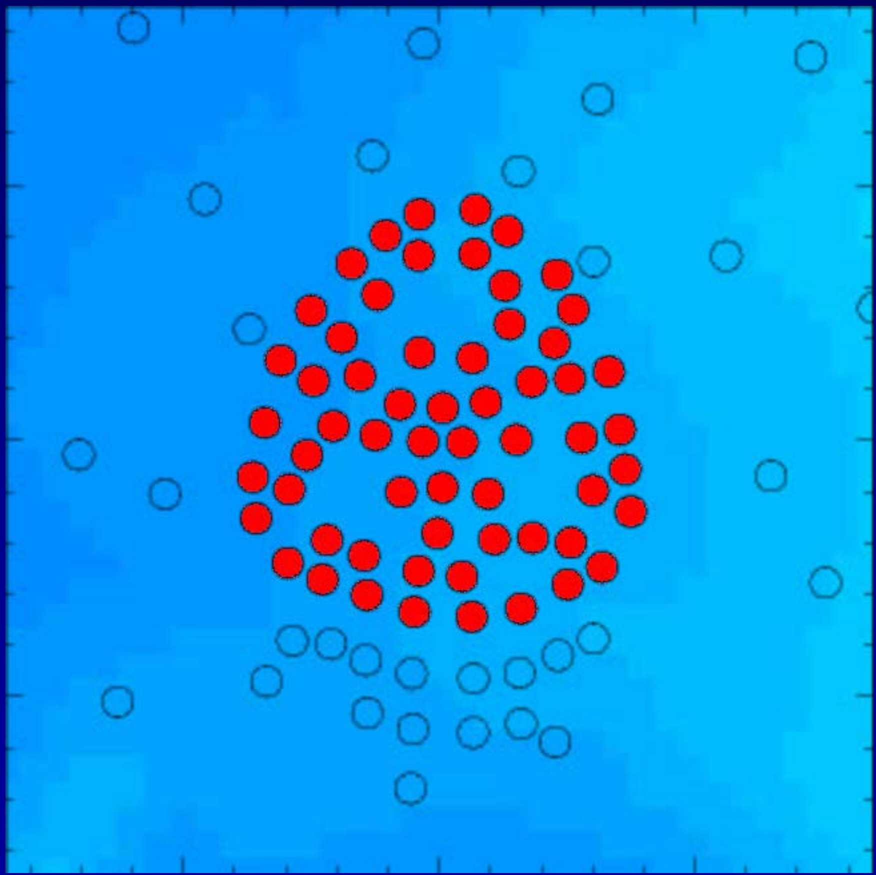
NORTH

0 km 1

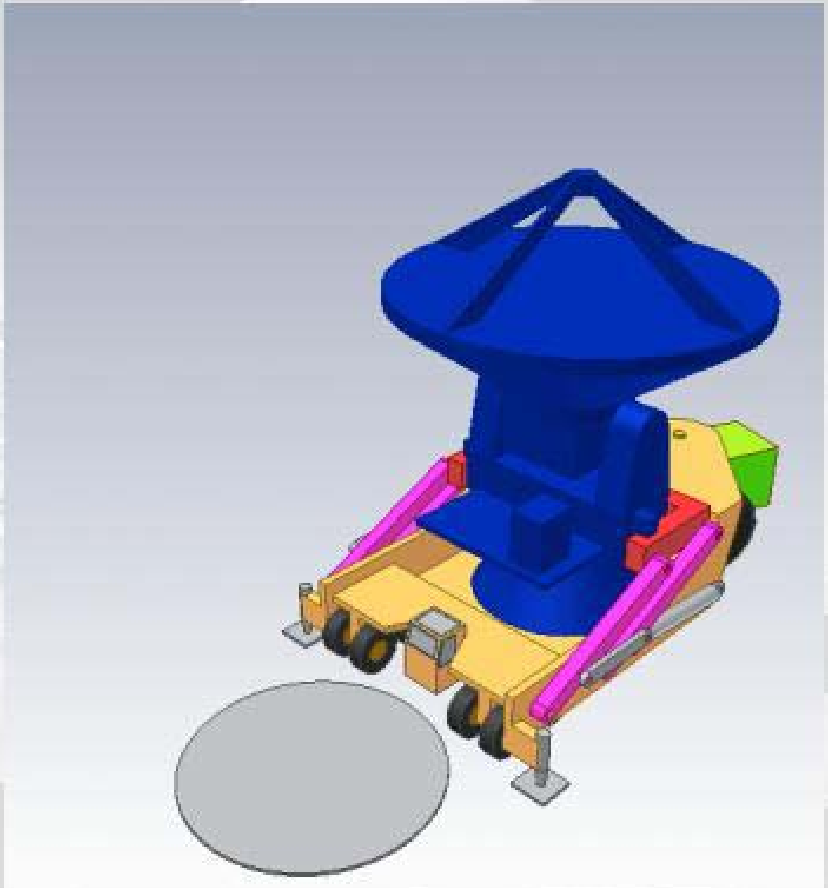
The ALMA `Camera' concept:

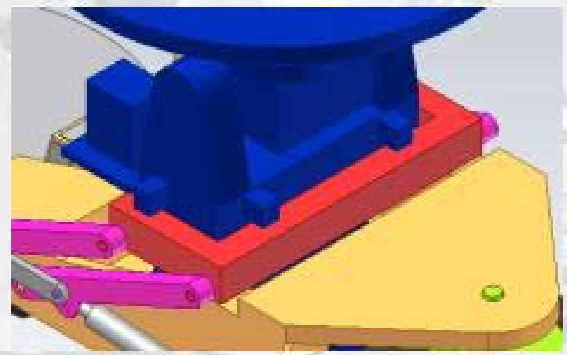
Configurations evolve smoothly from compact (150m) to extended (14km)

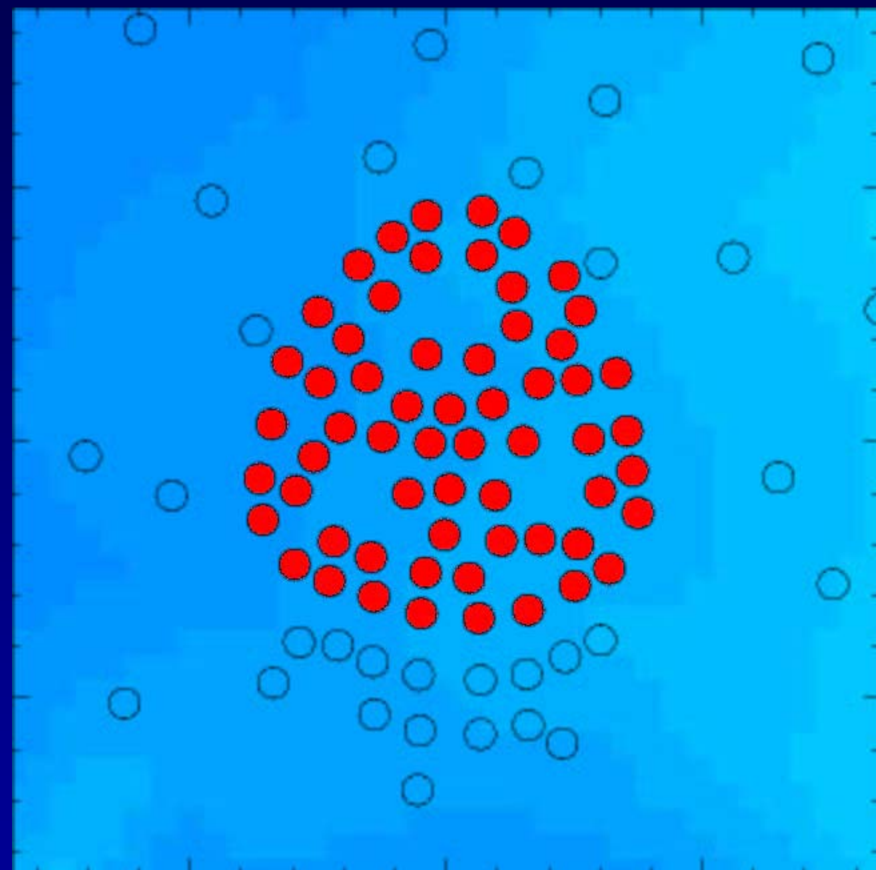
Compact array: as densely packed as possible, with minimal shadowing and still allowing all antennas to be accessed by the transporter.

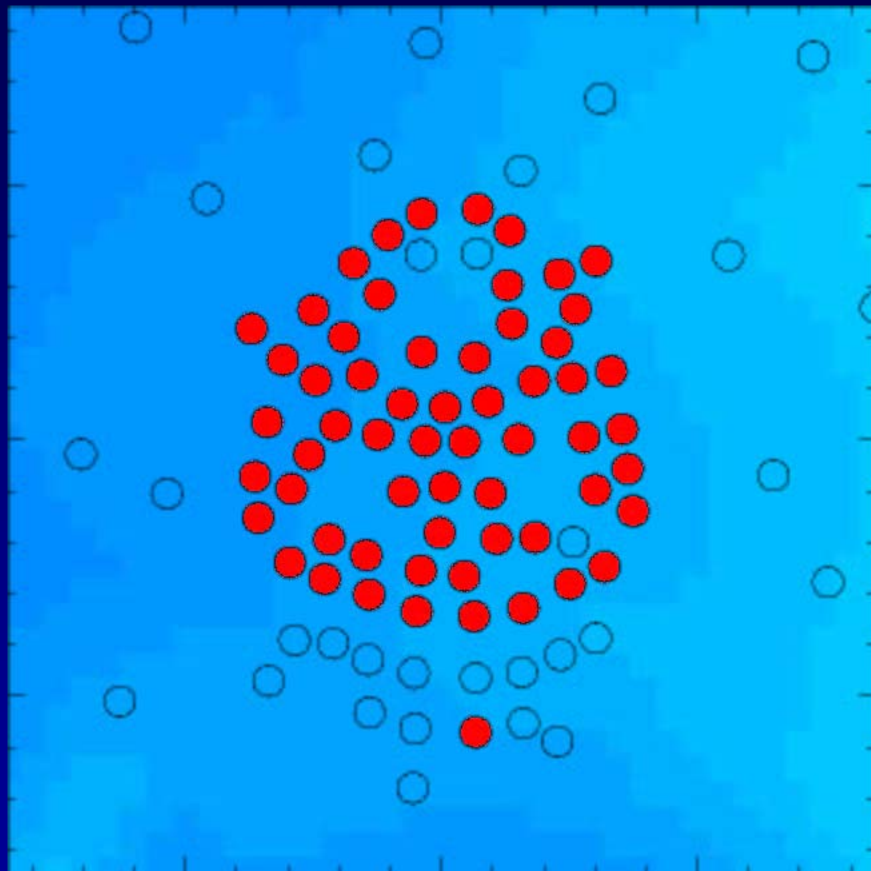


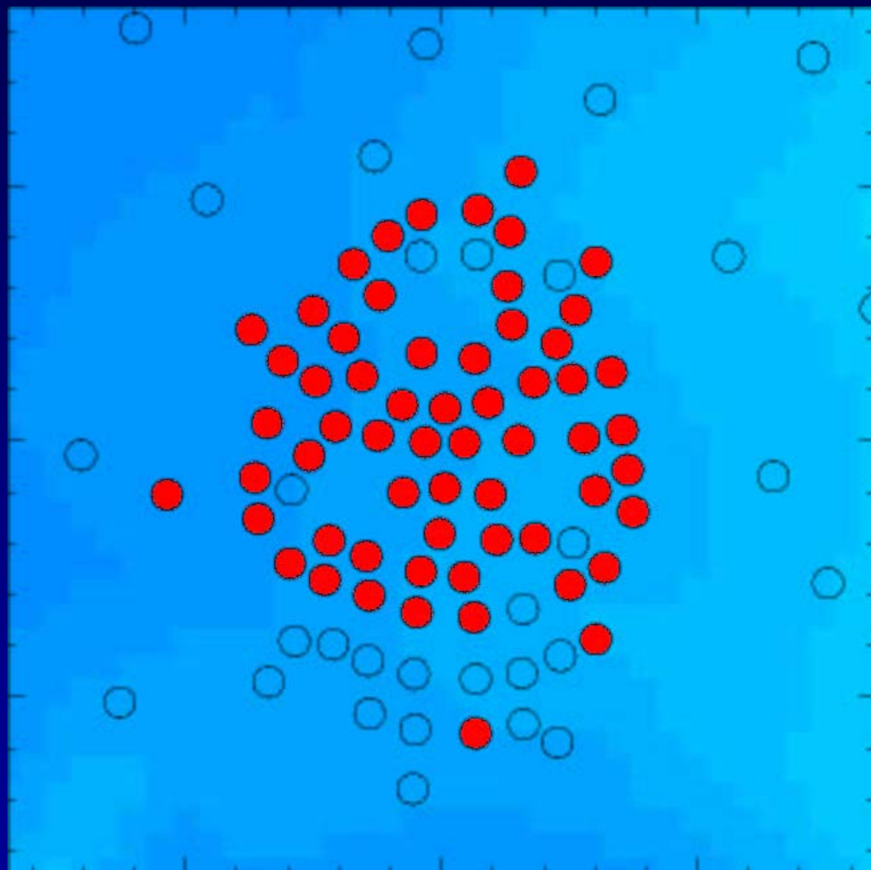
Current Transporter Concepts

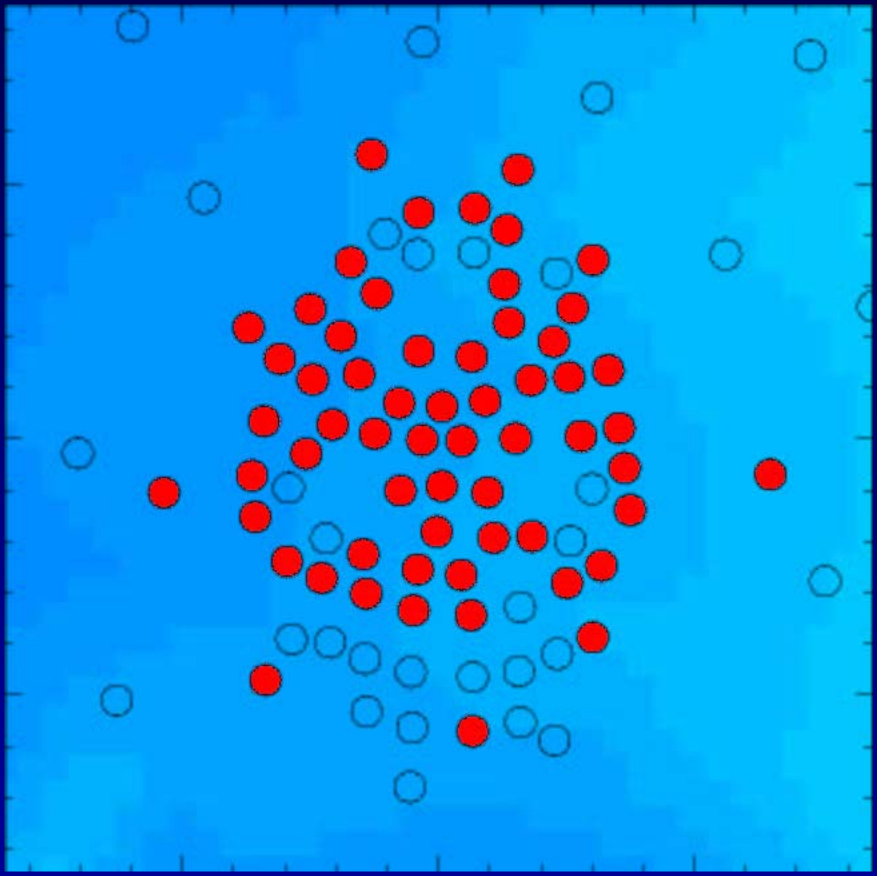


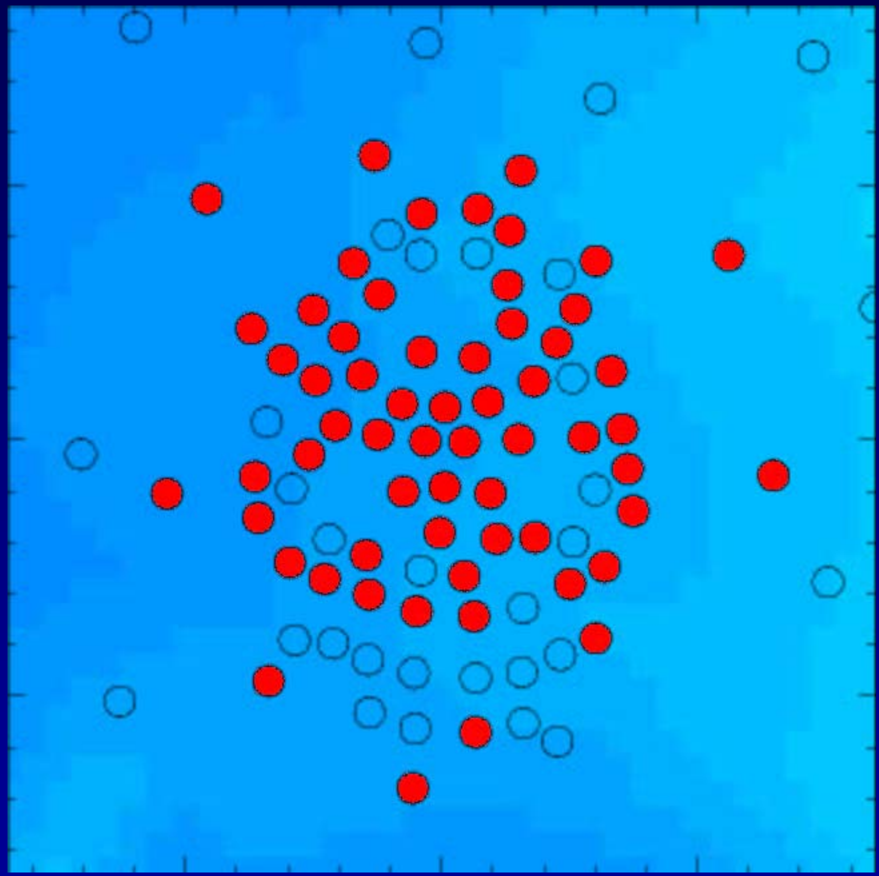


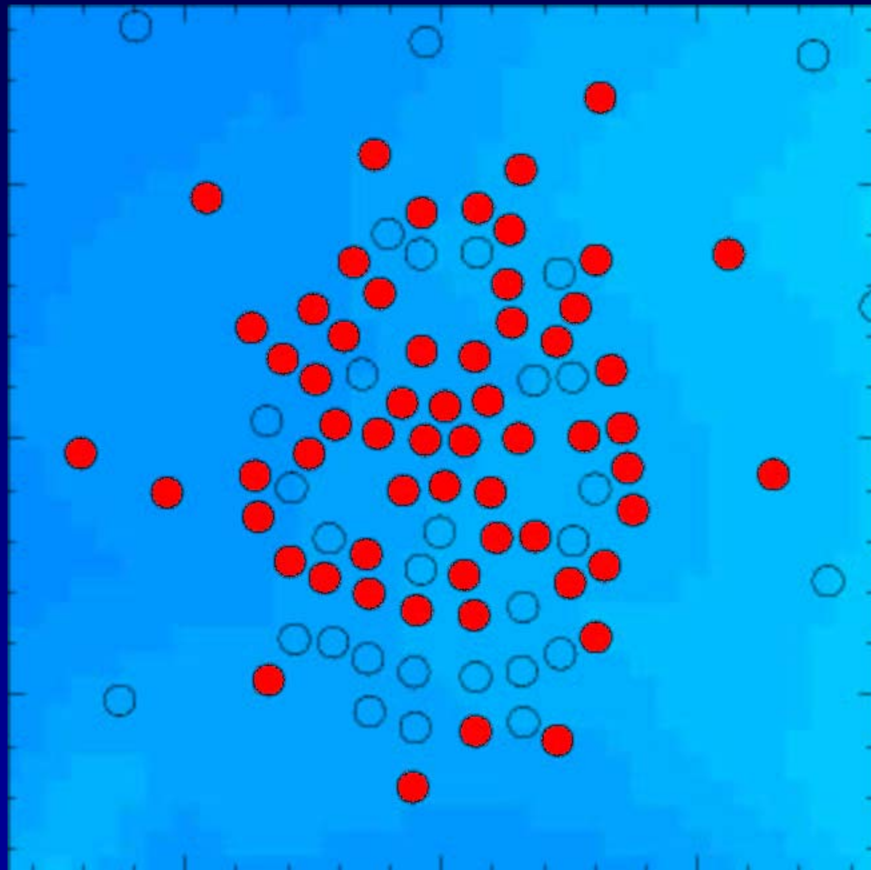


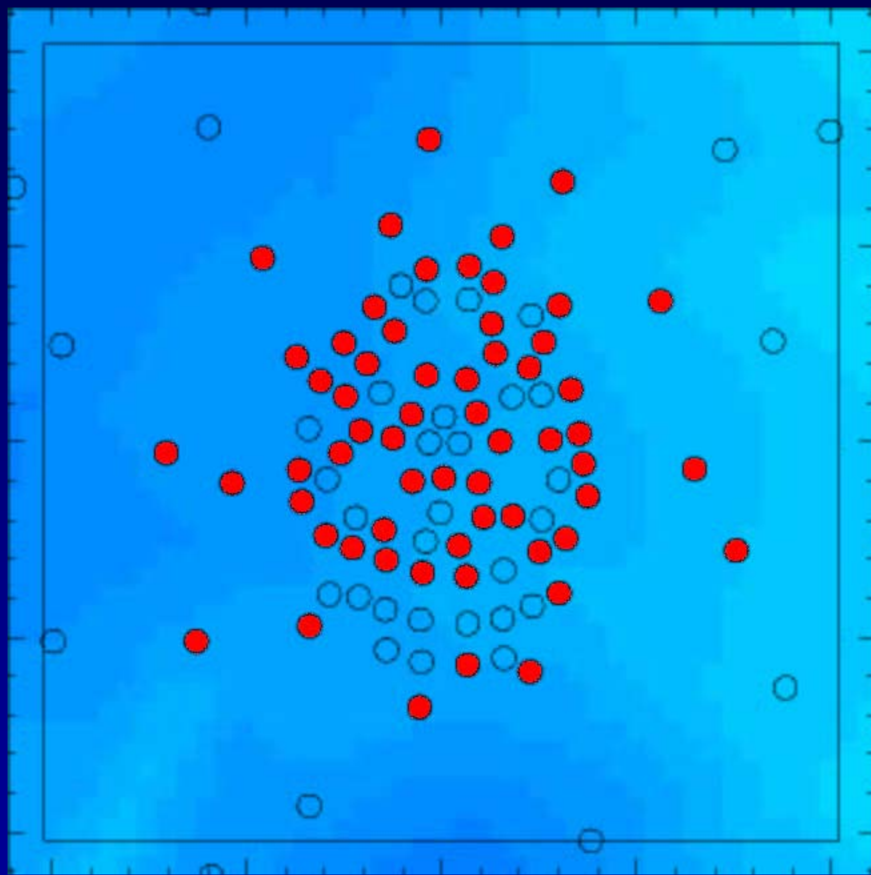


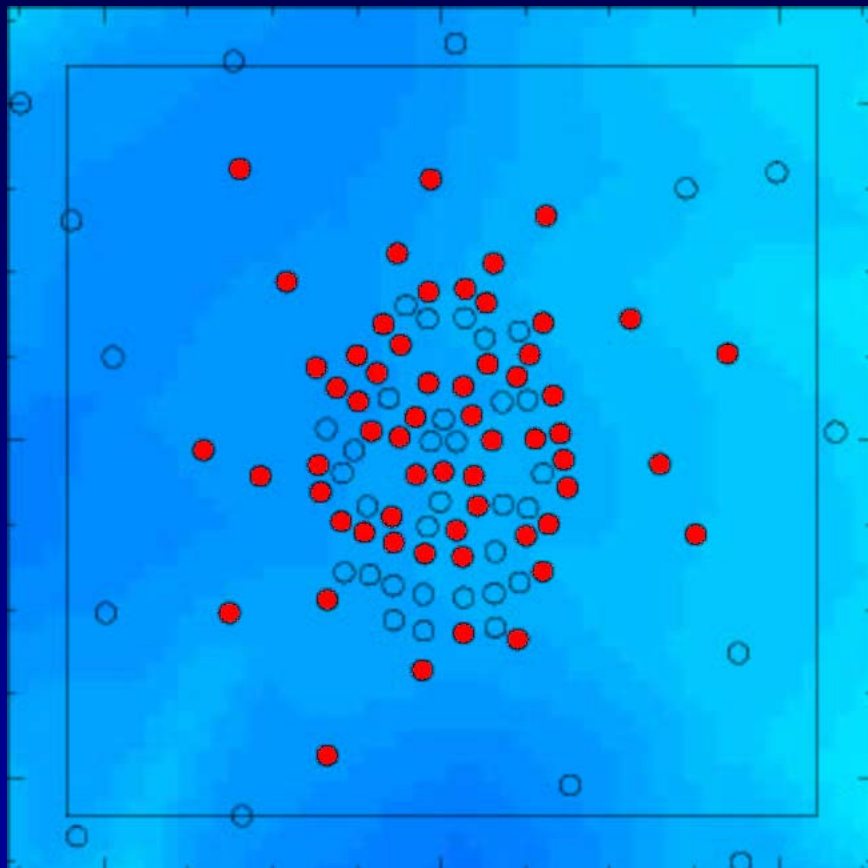


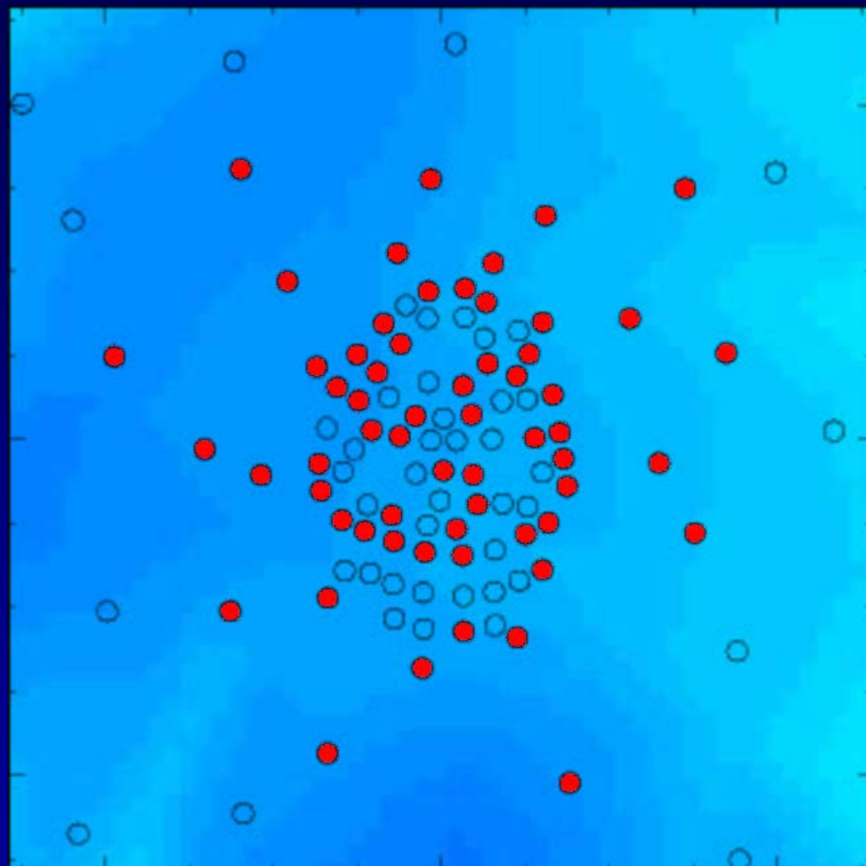


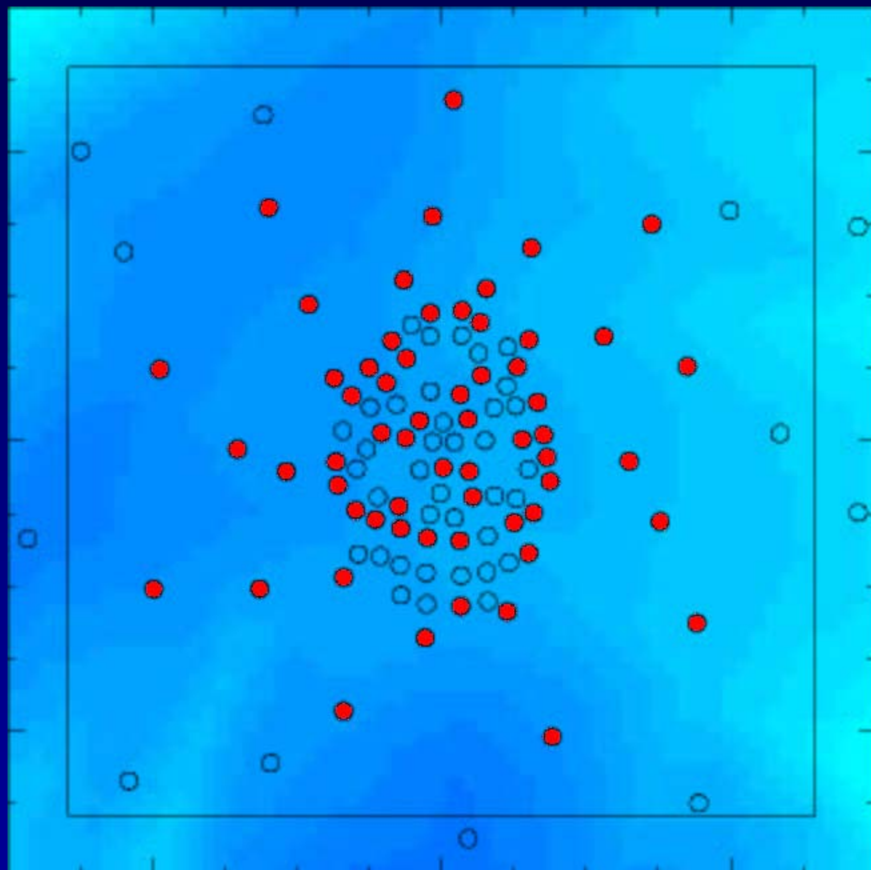


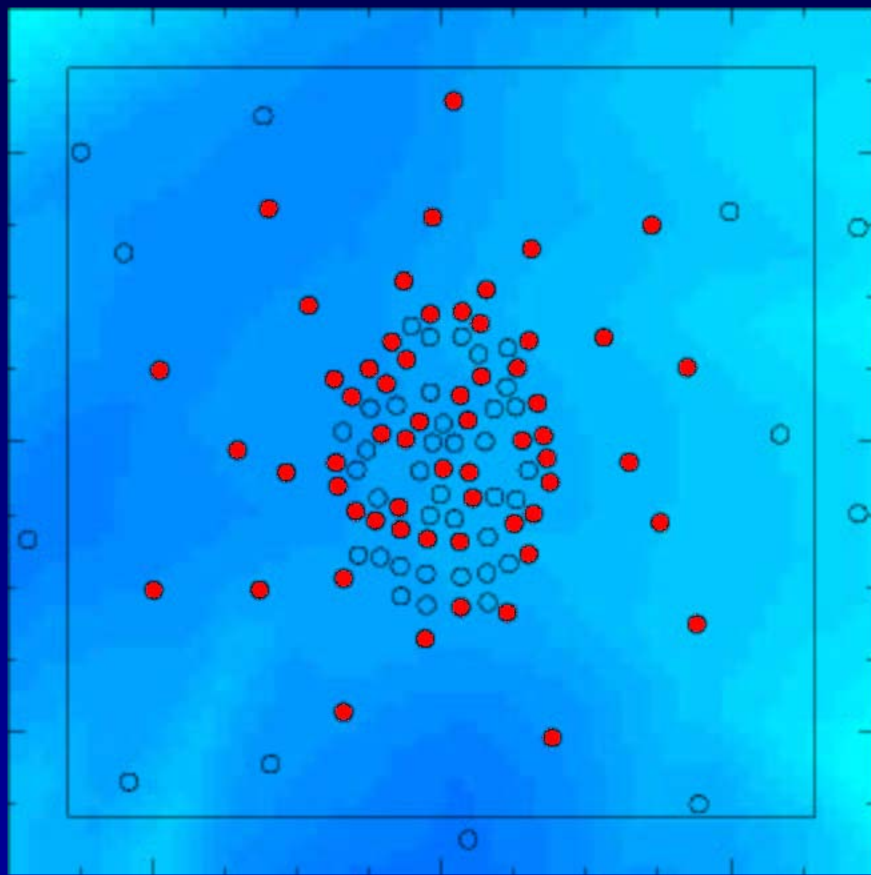


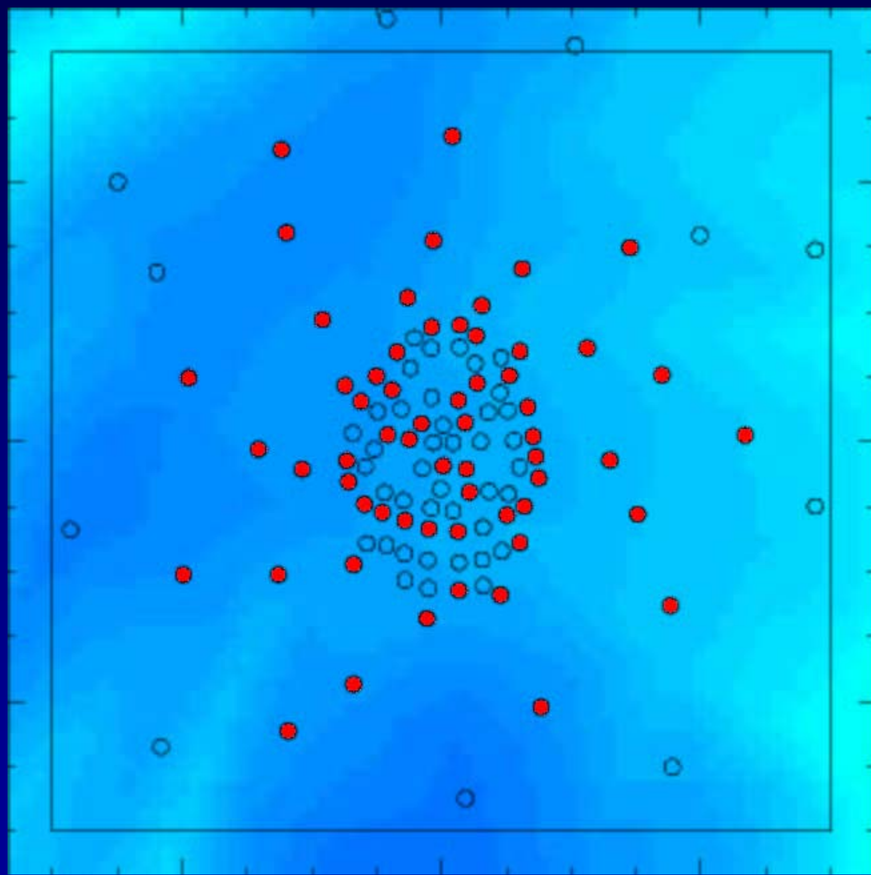


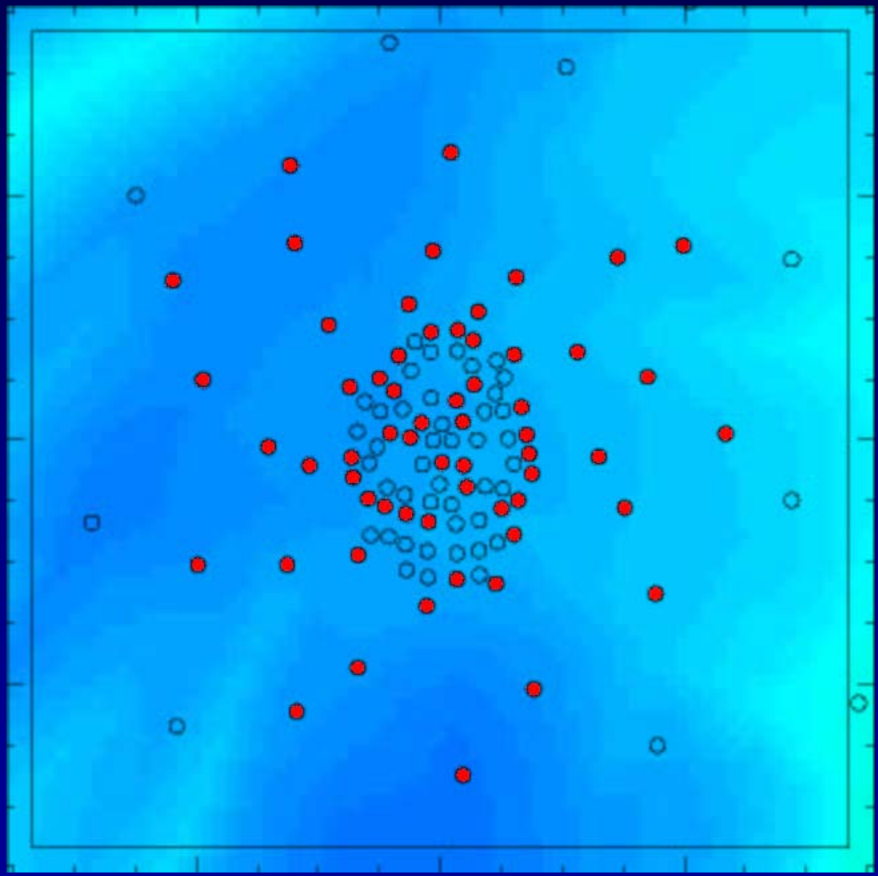


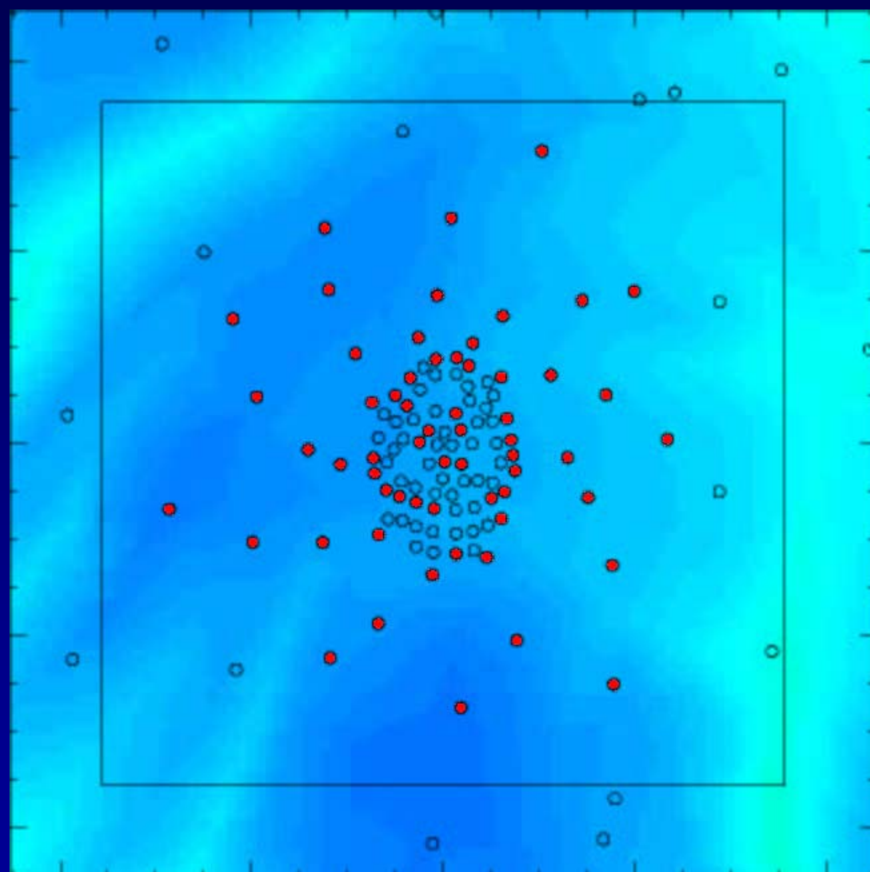


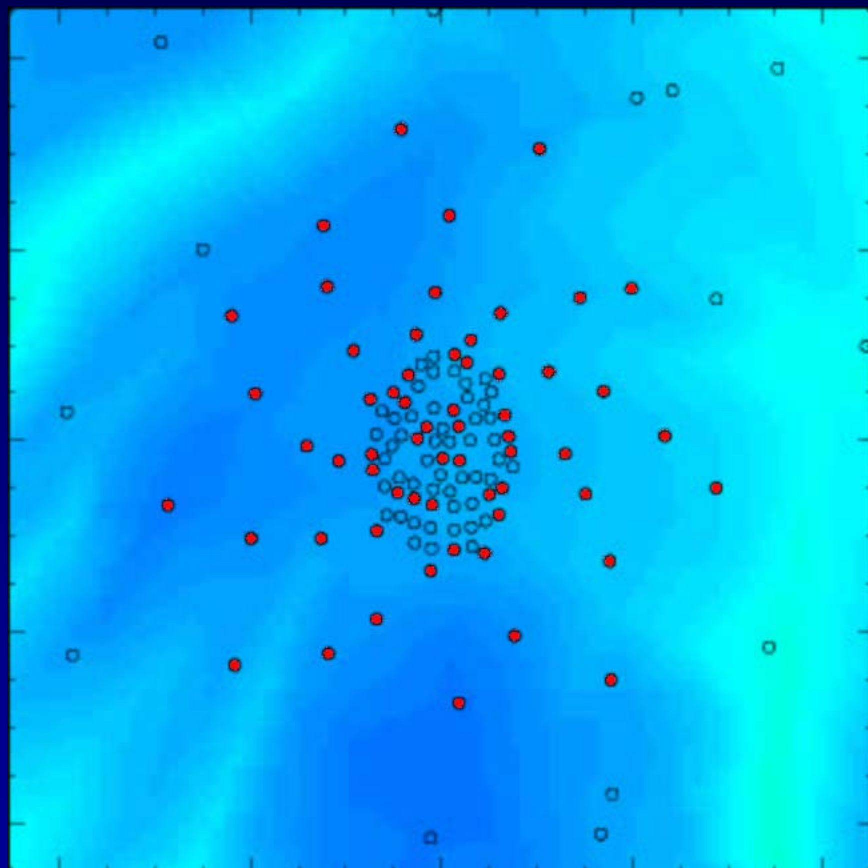


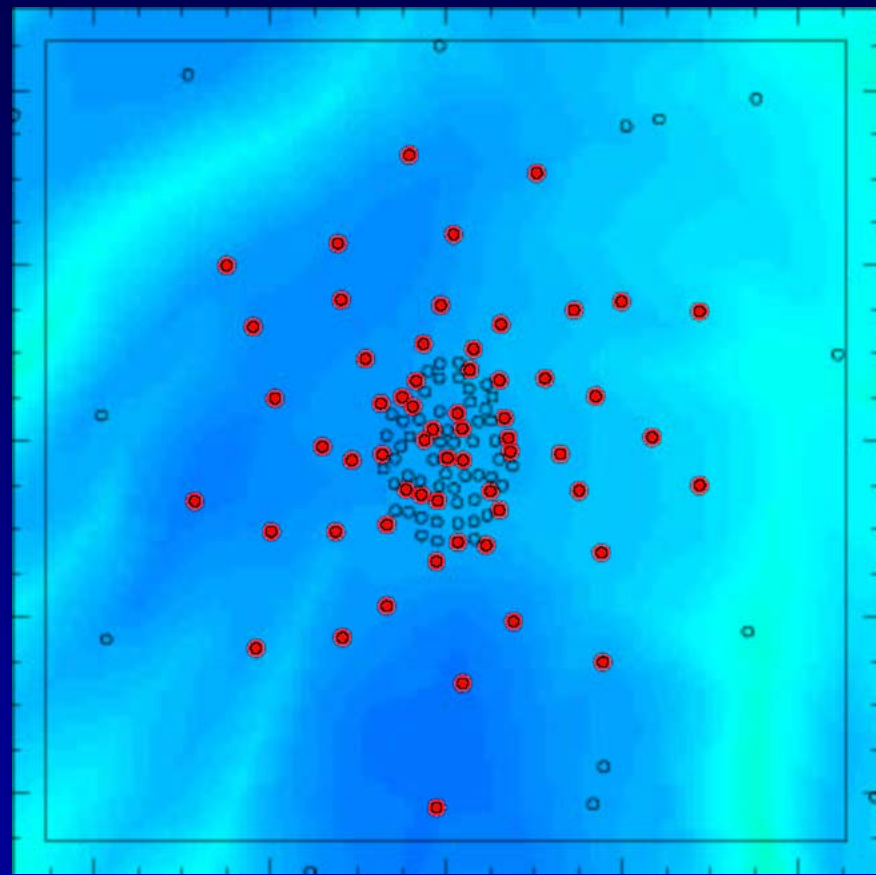


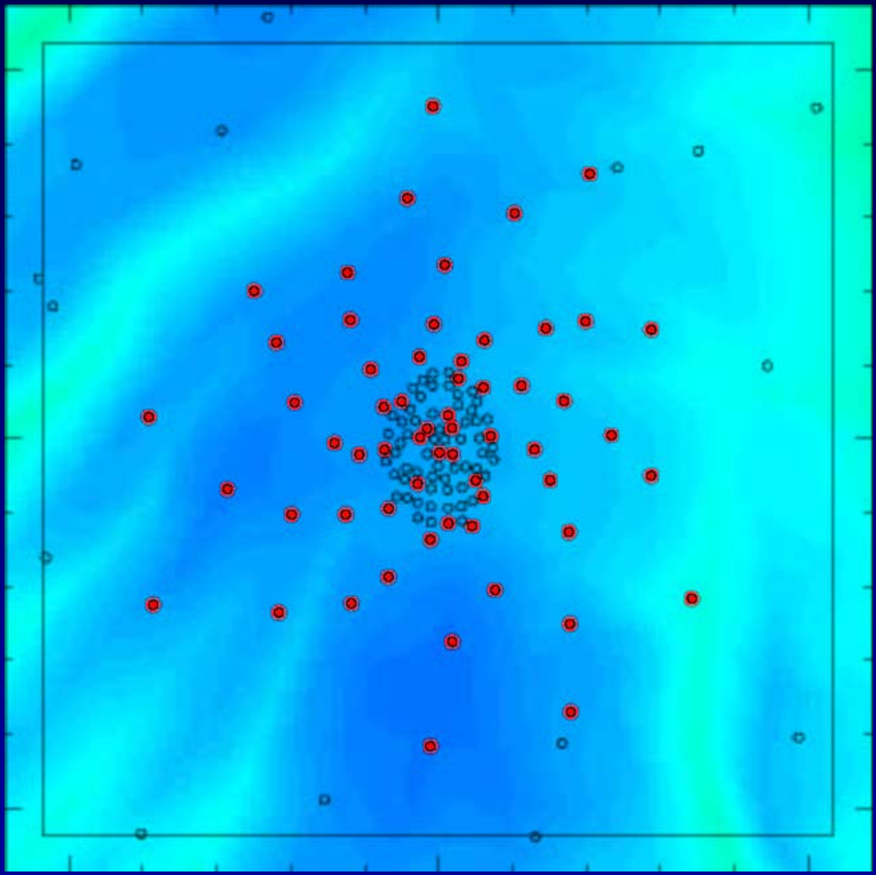


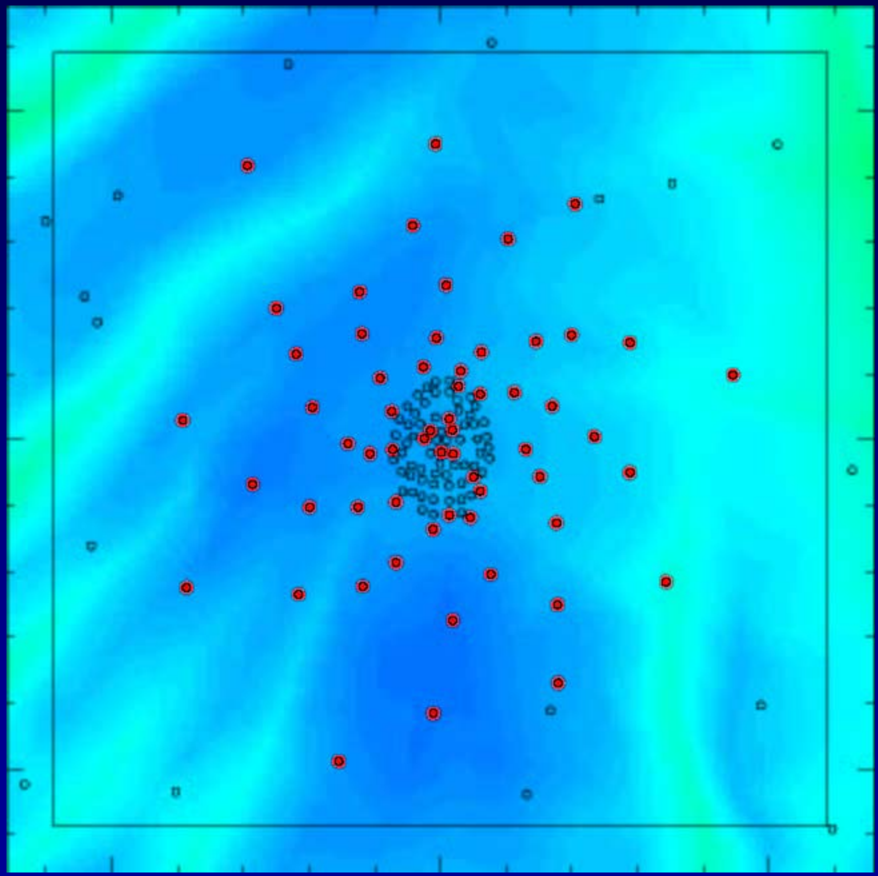


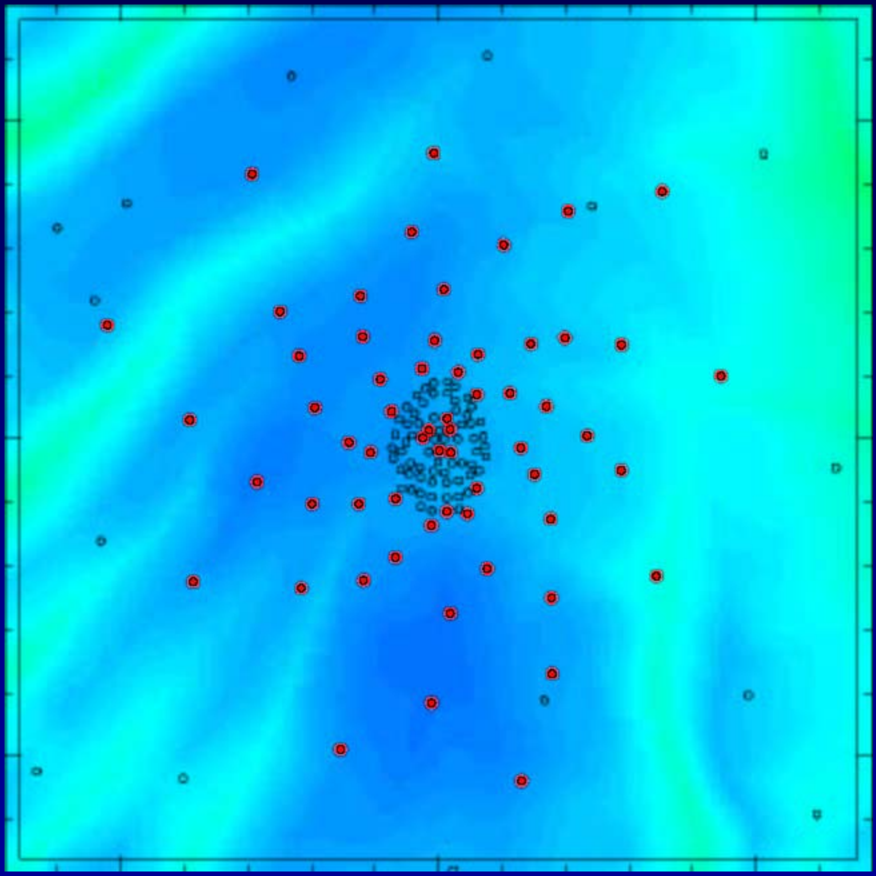


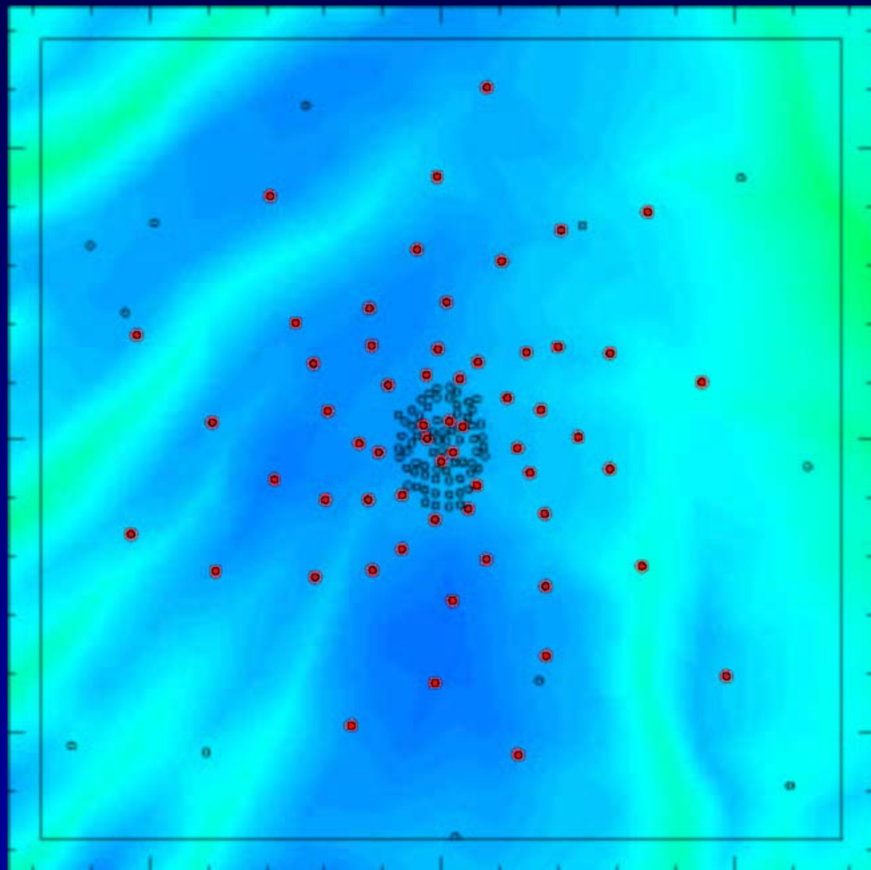


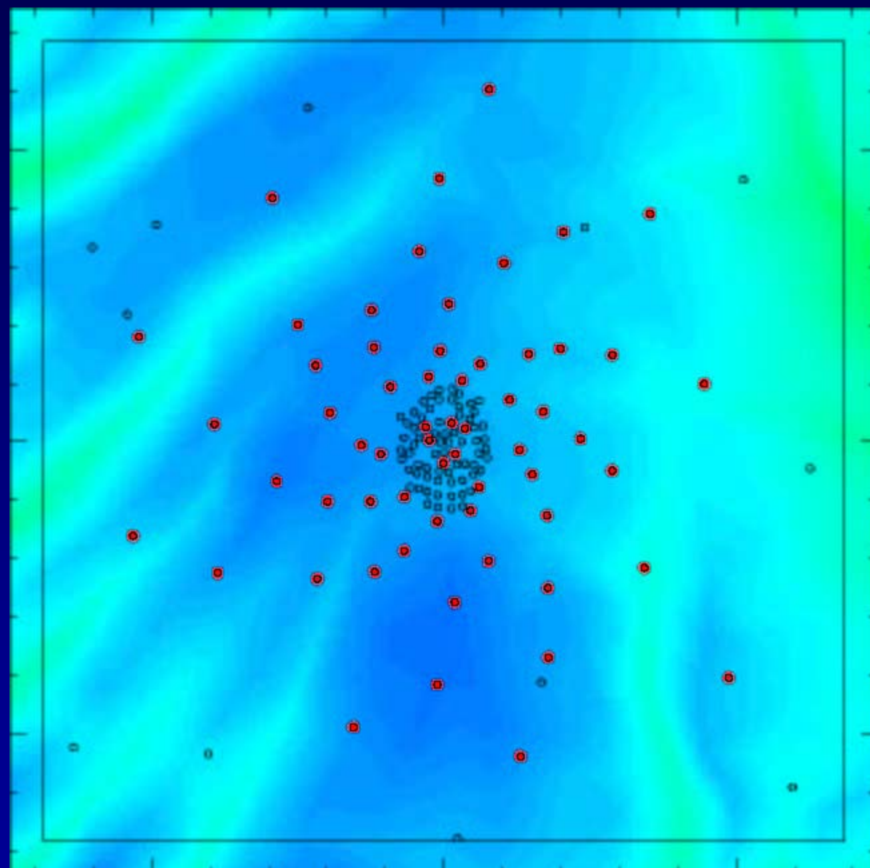


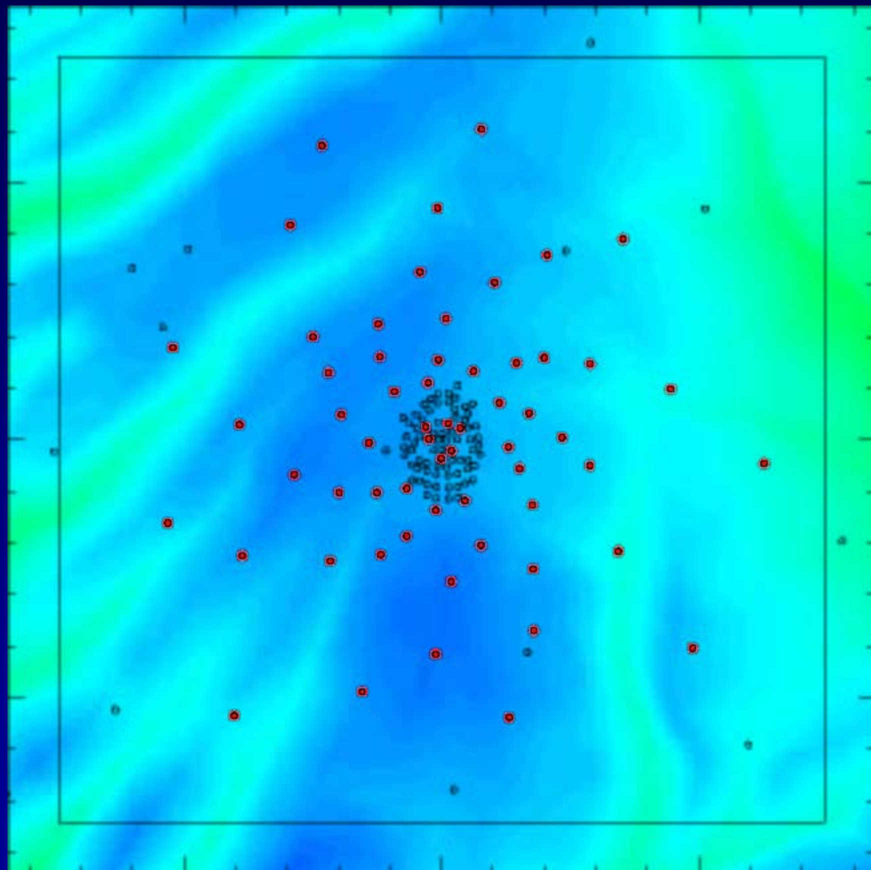


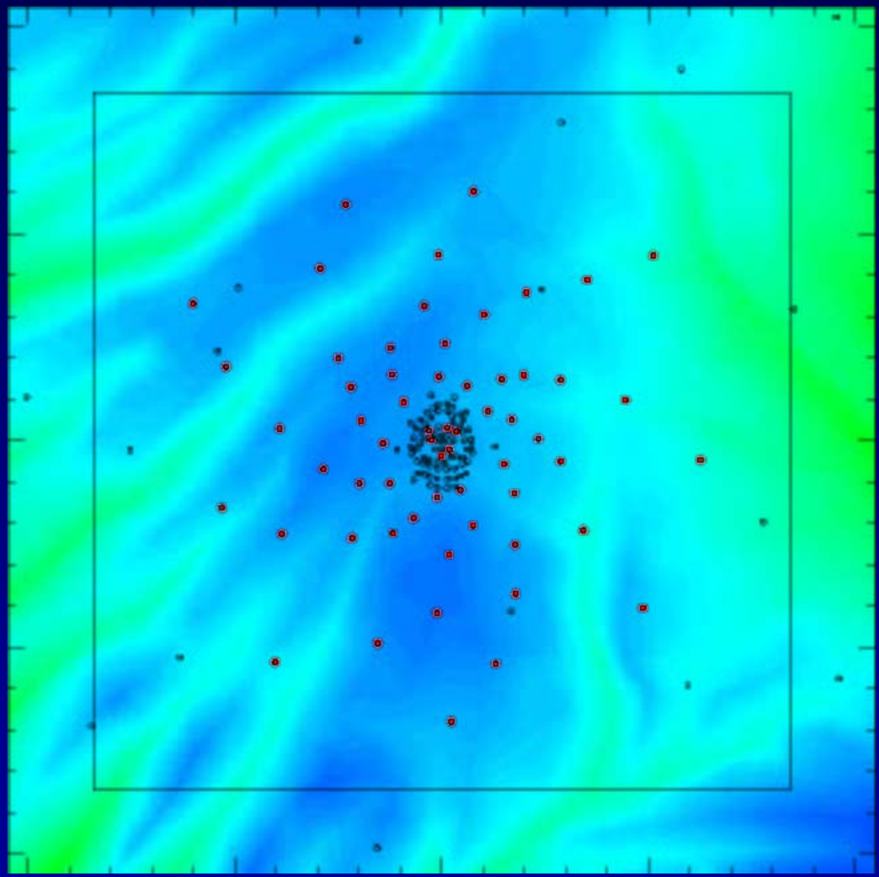


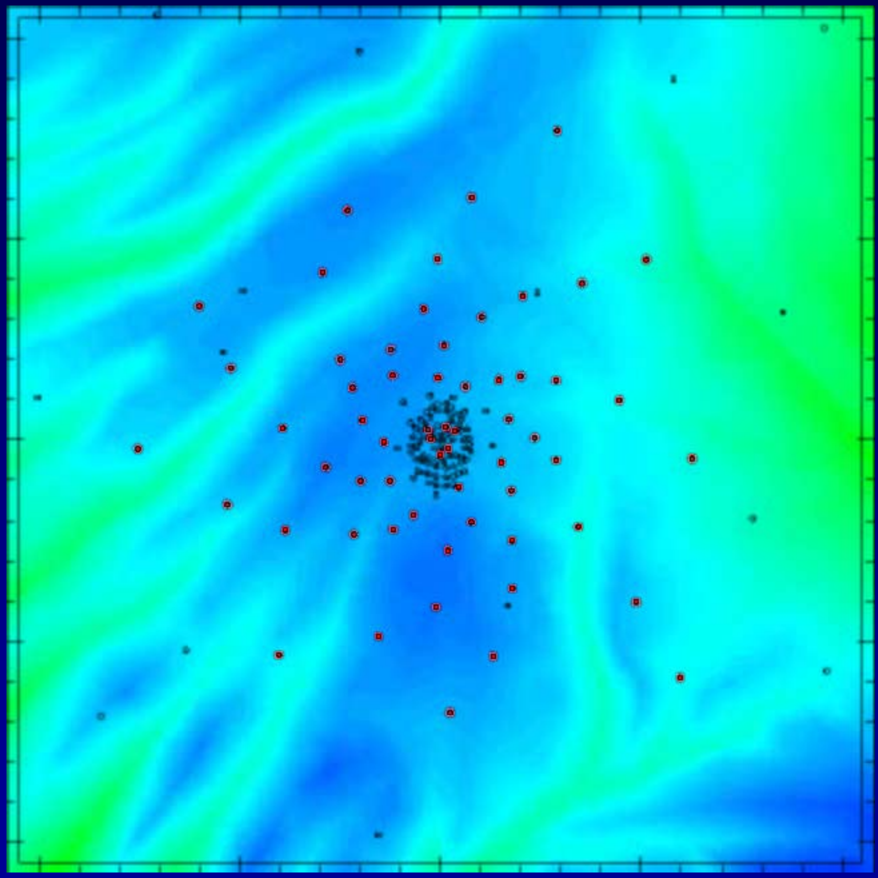


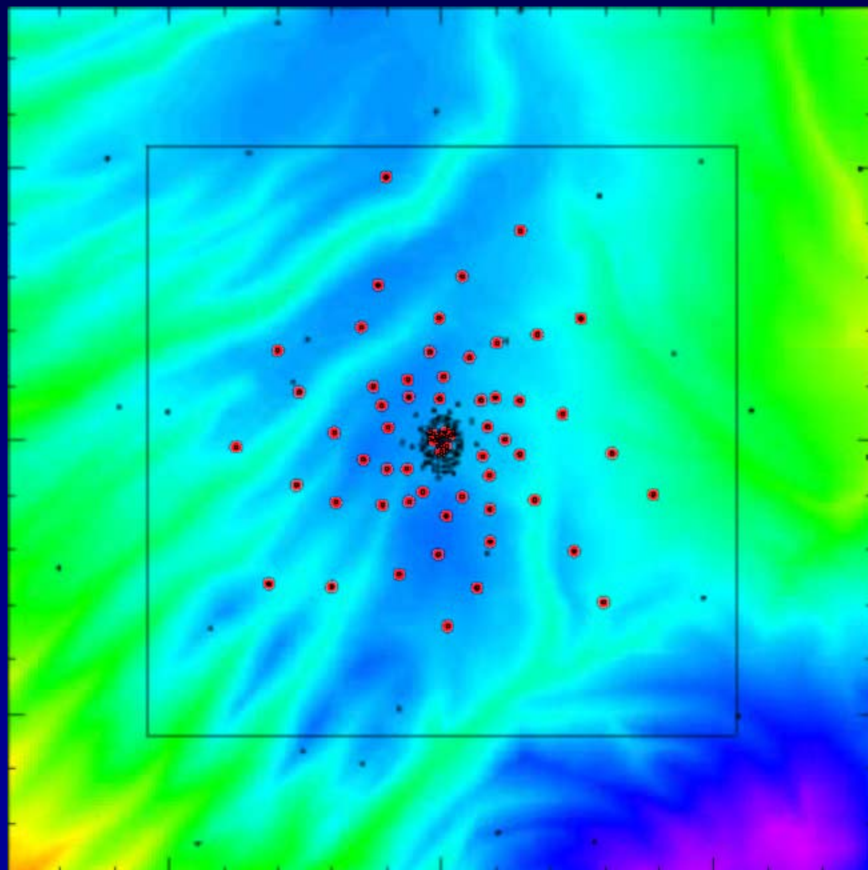


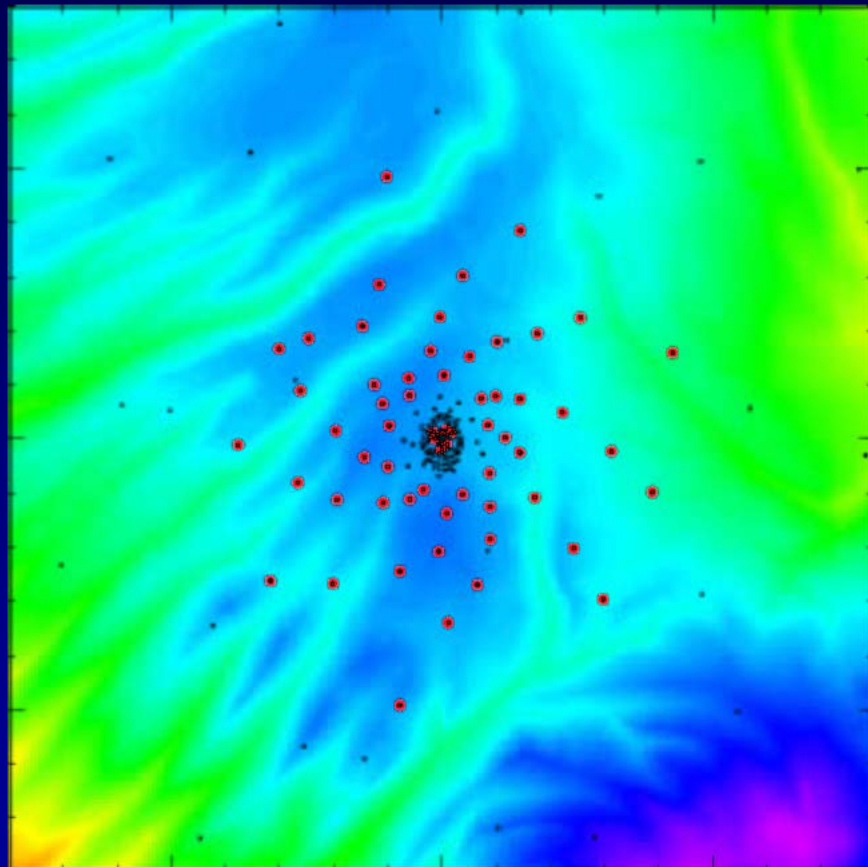


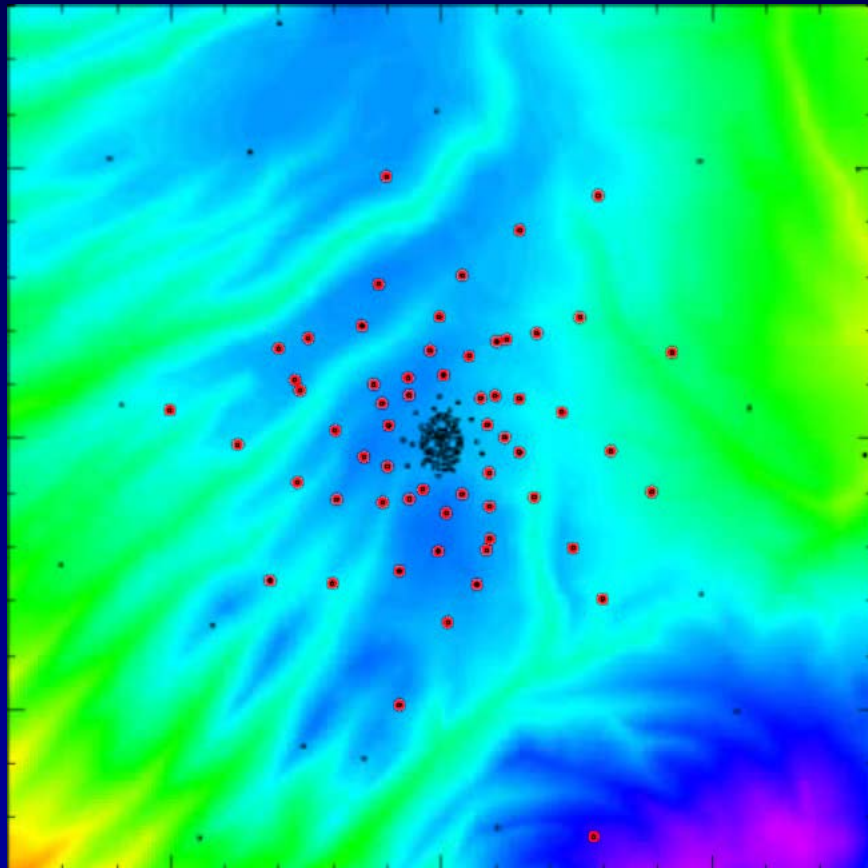


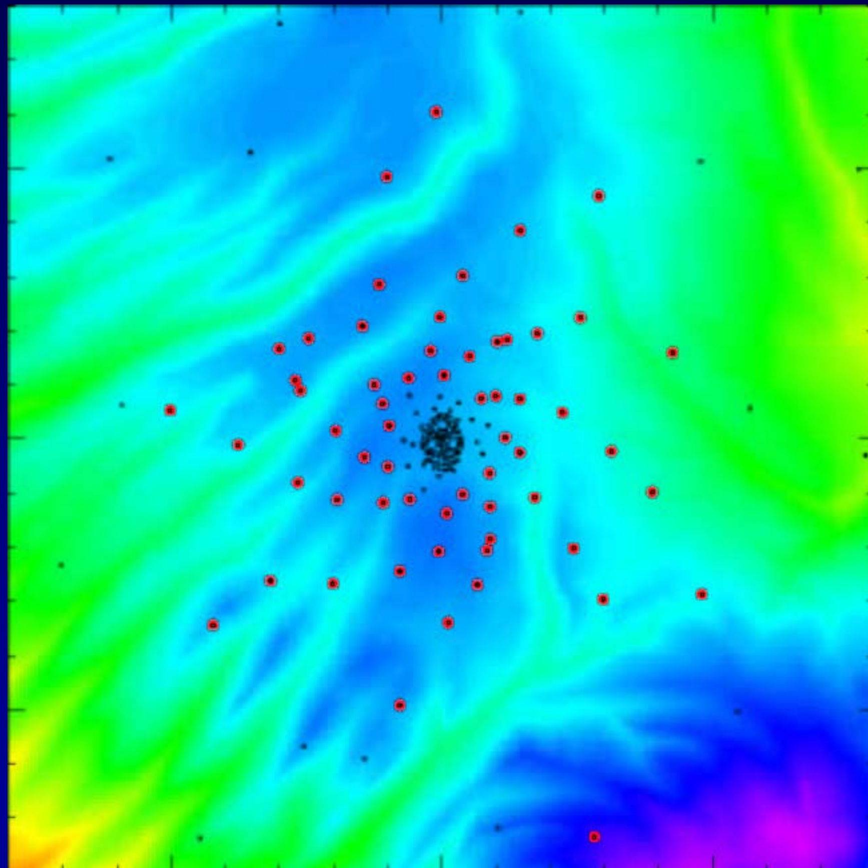


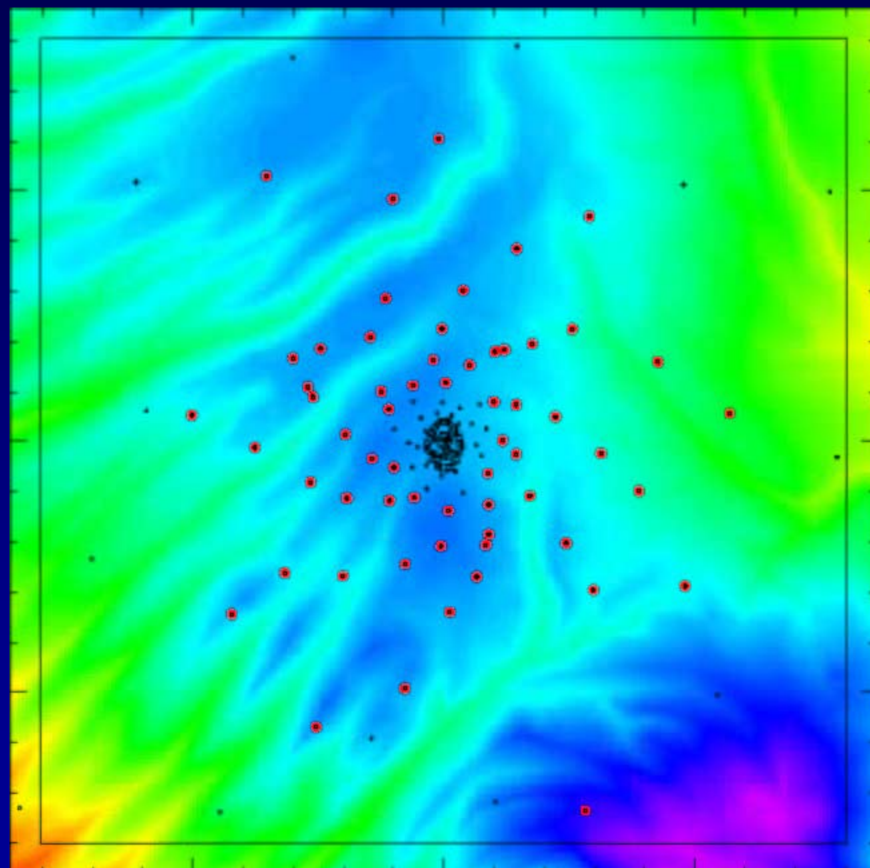


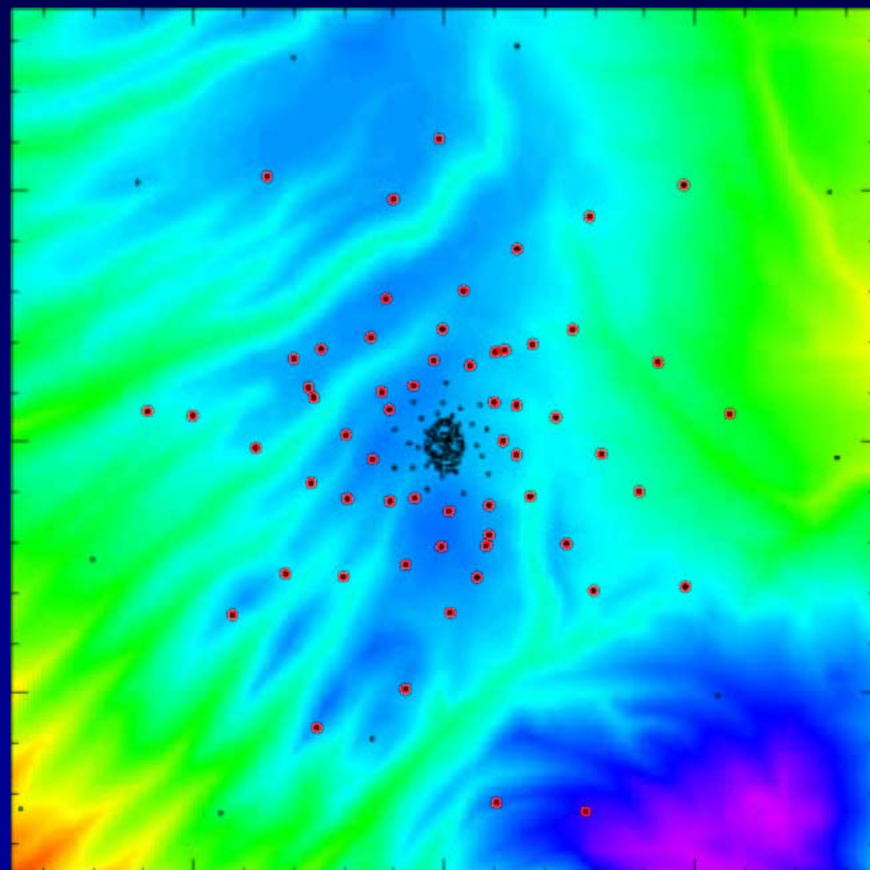


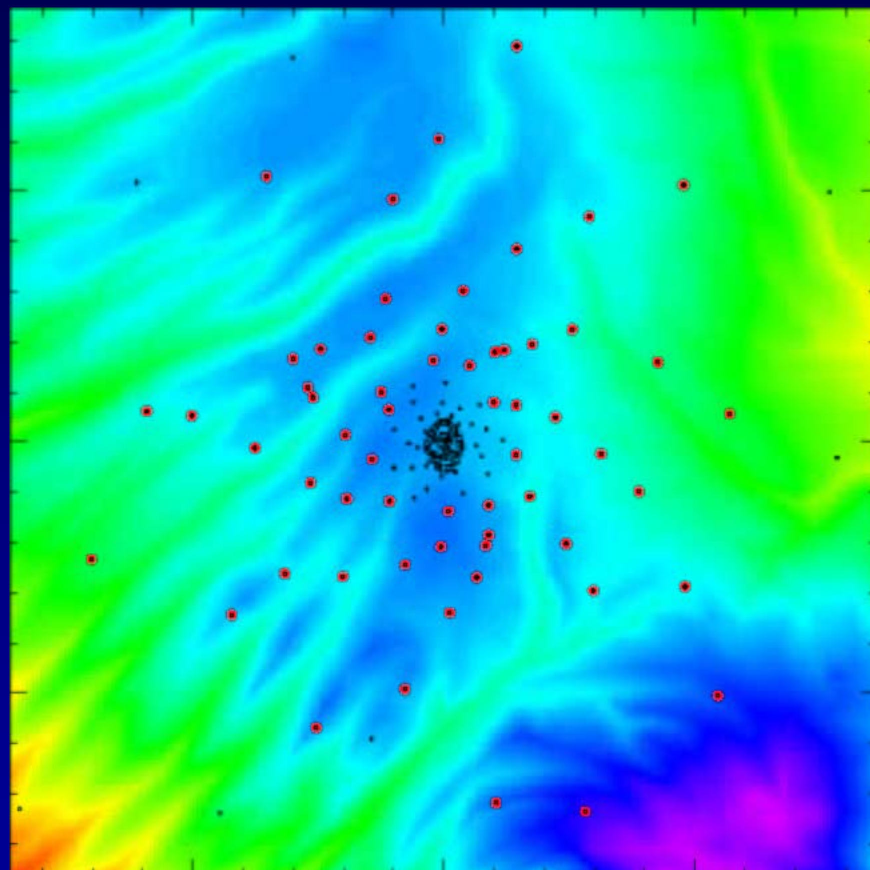


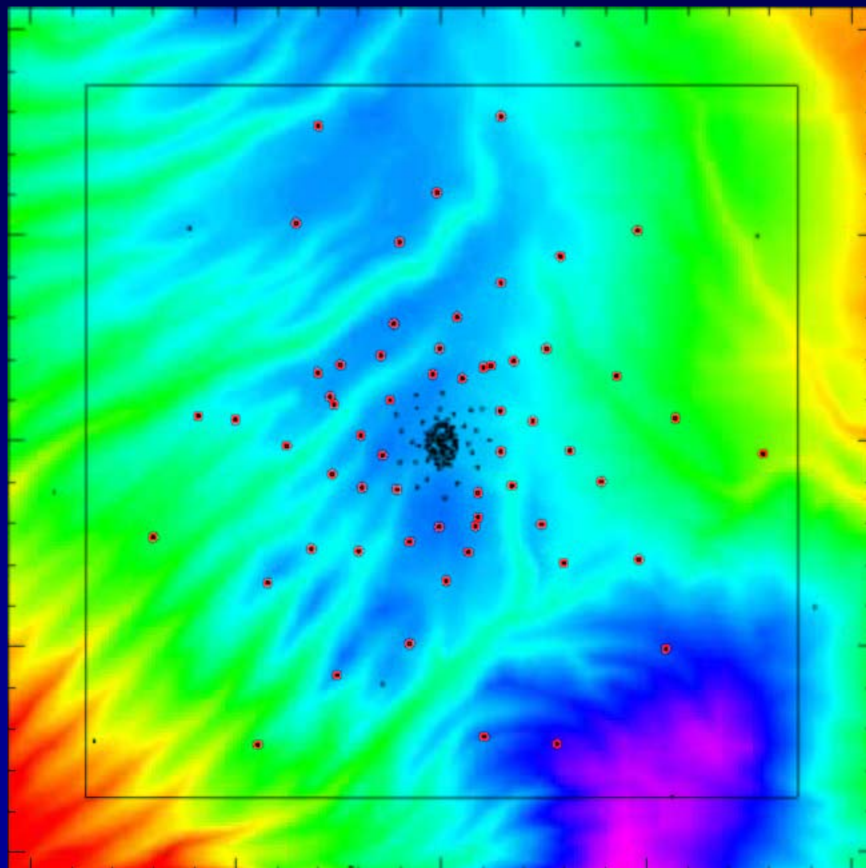


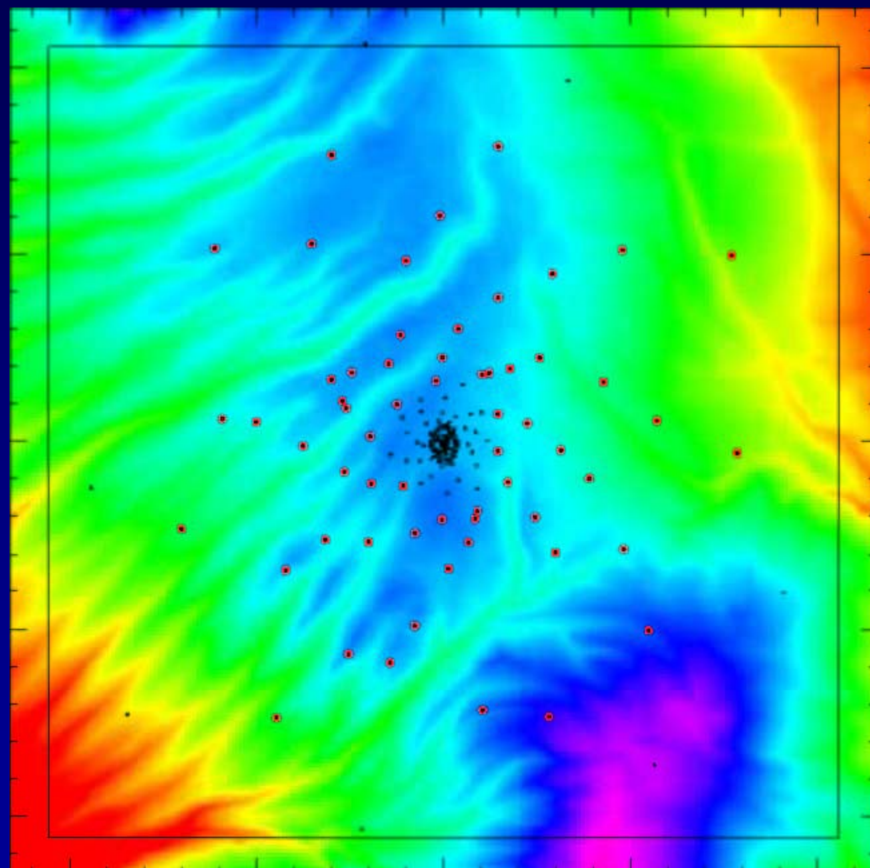


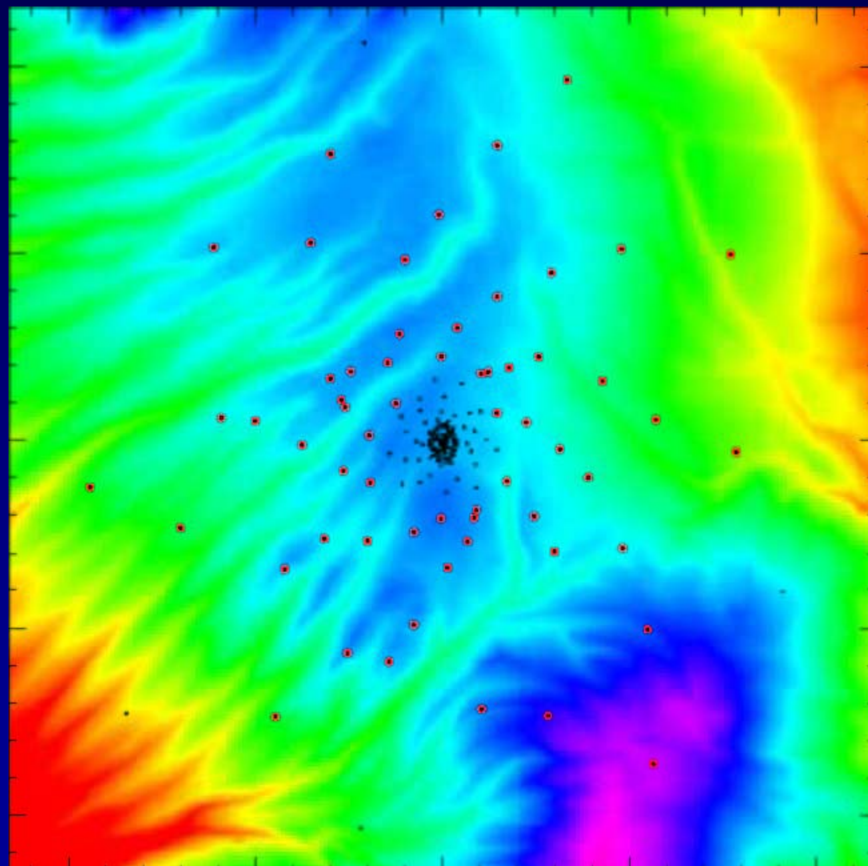


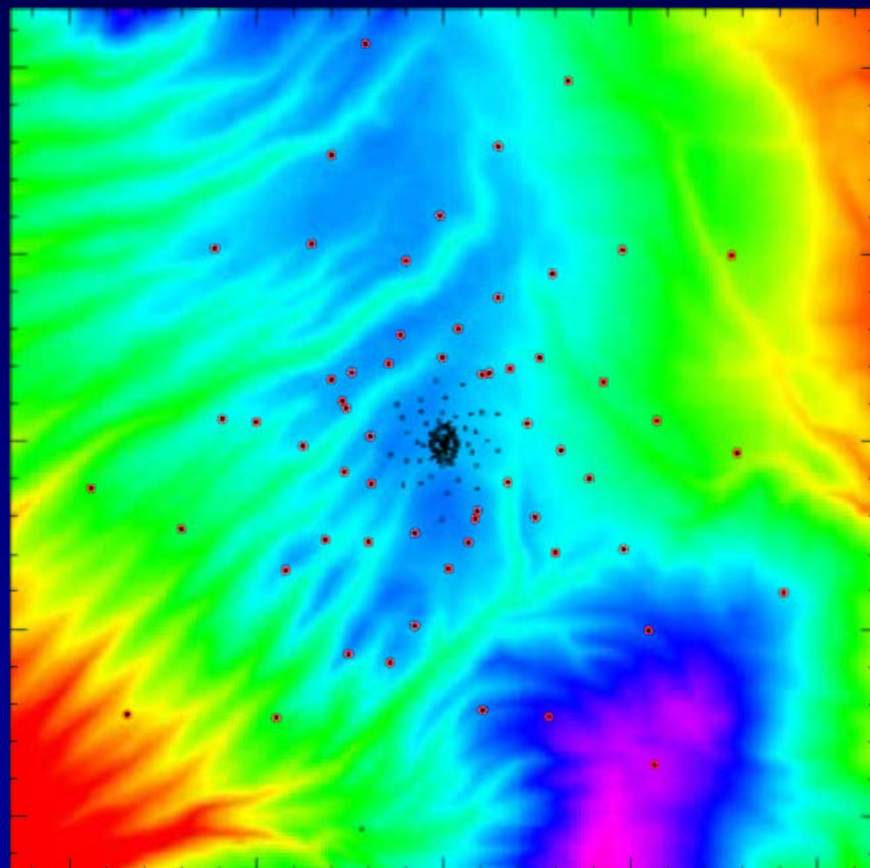


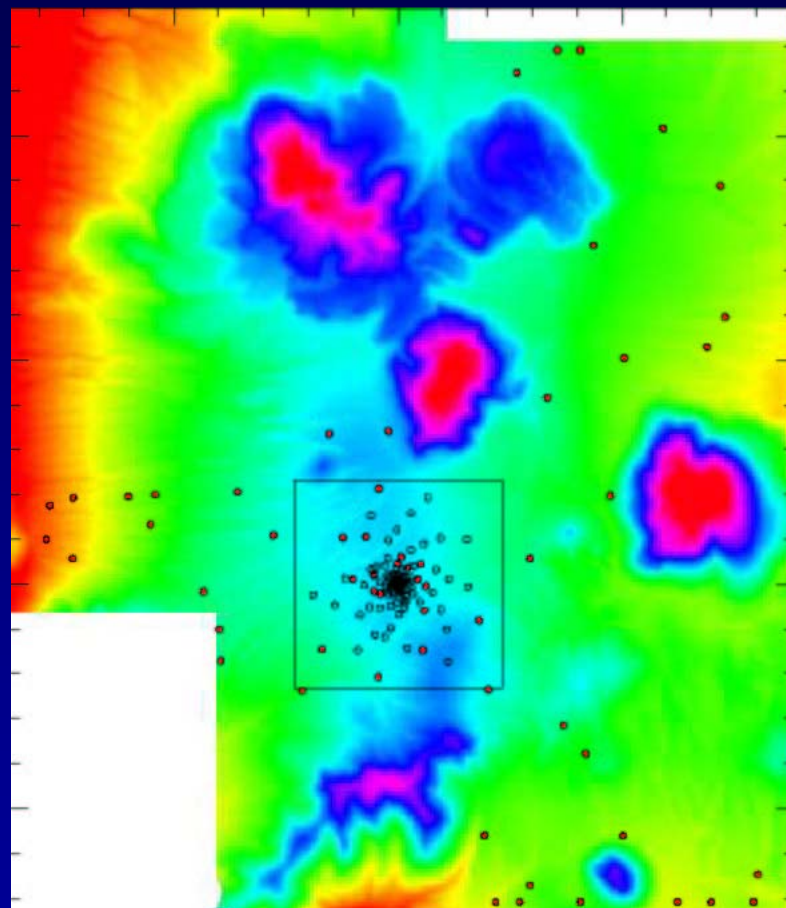




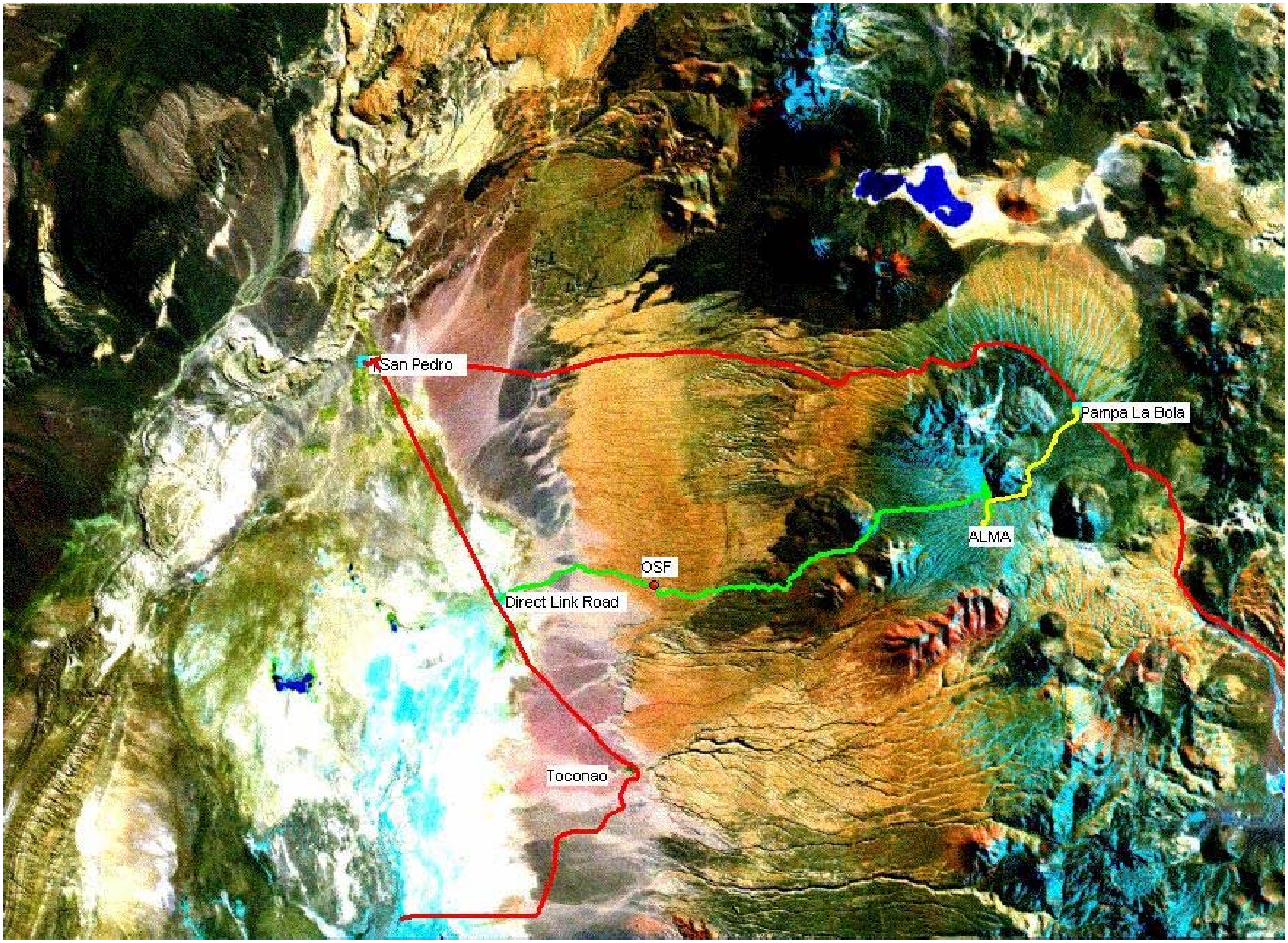








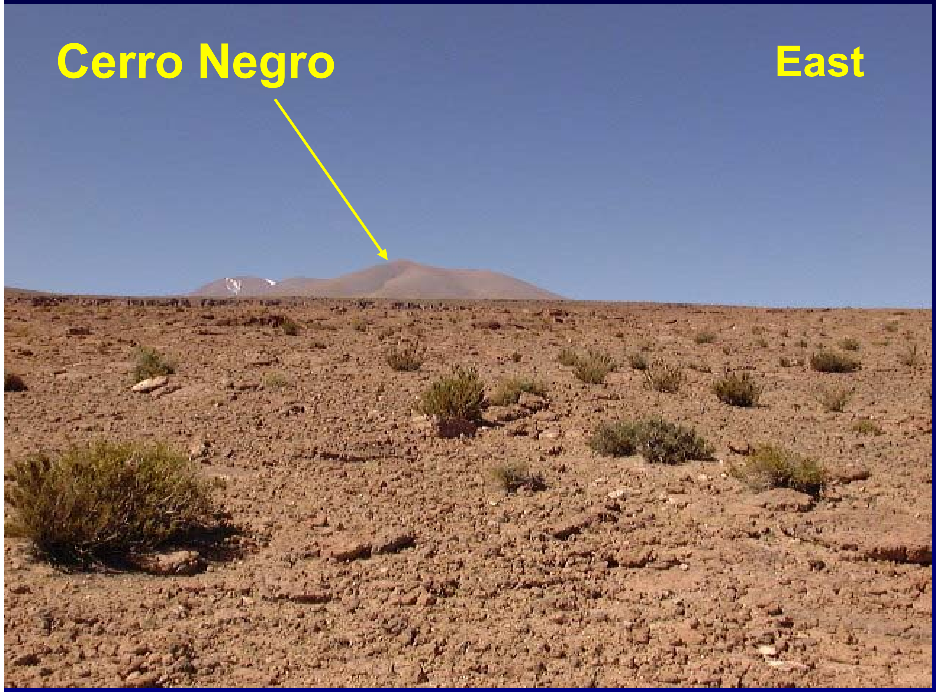
Location OSF

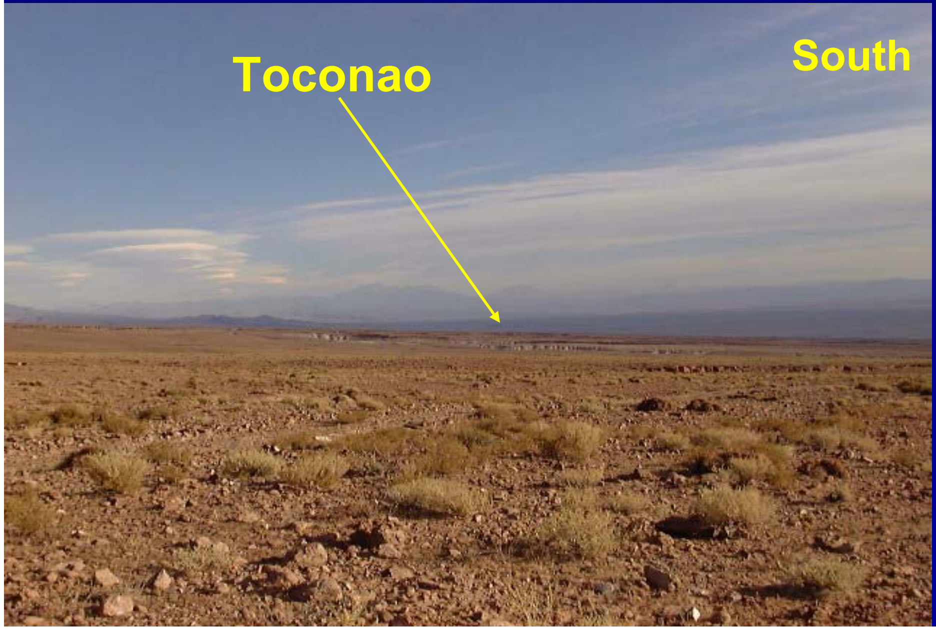


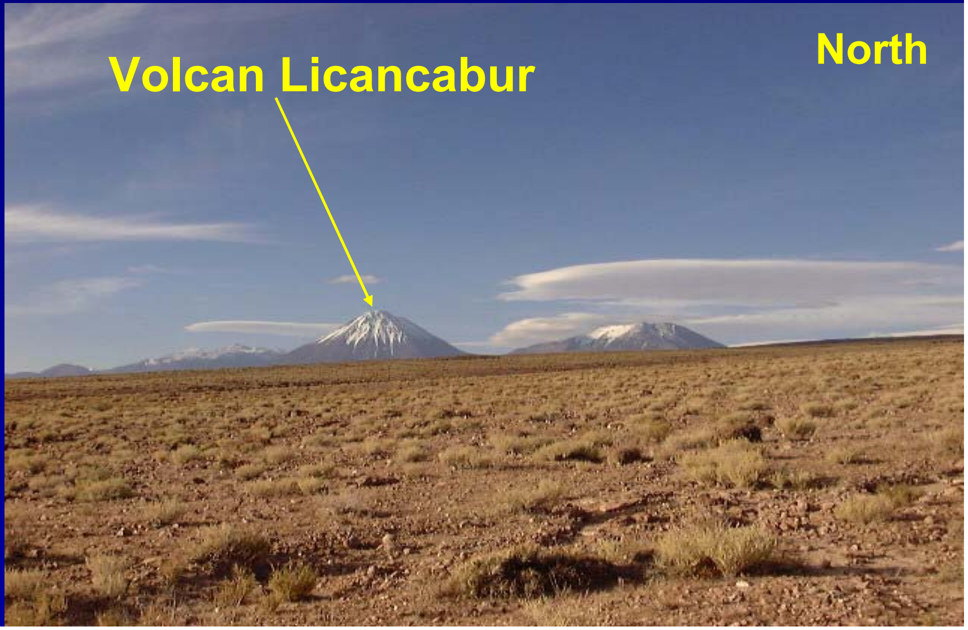
NORTH

Access Road to O.S.F.

Views from O.S.F. Area at 2800 m







Main functions OSF: *near San Pedro*

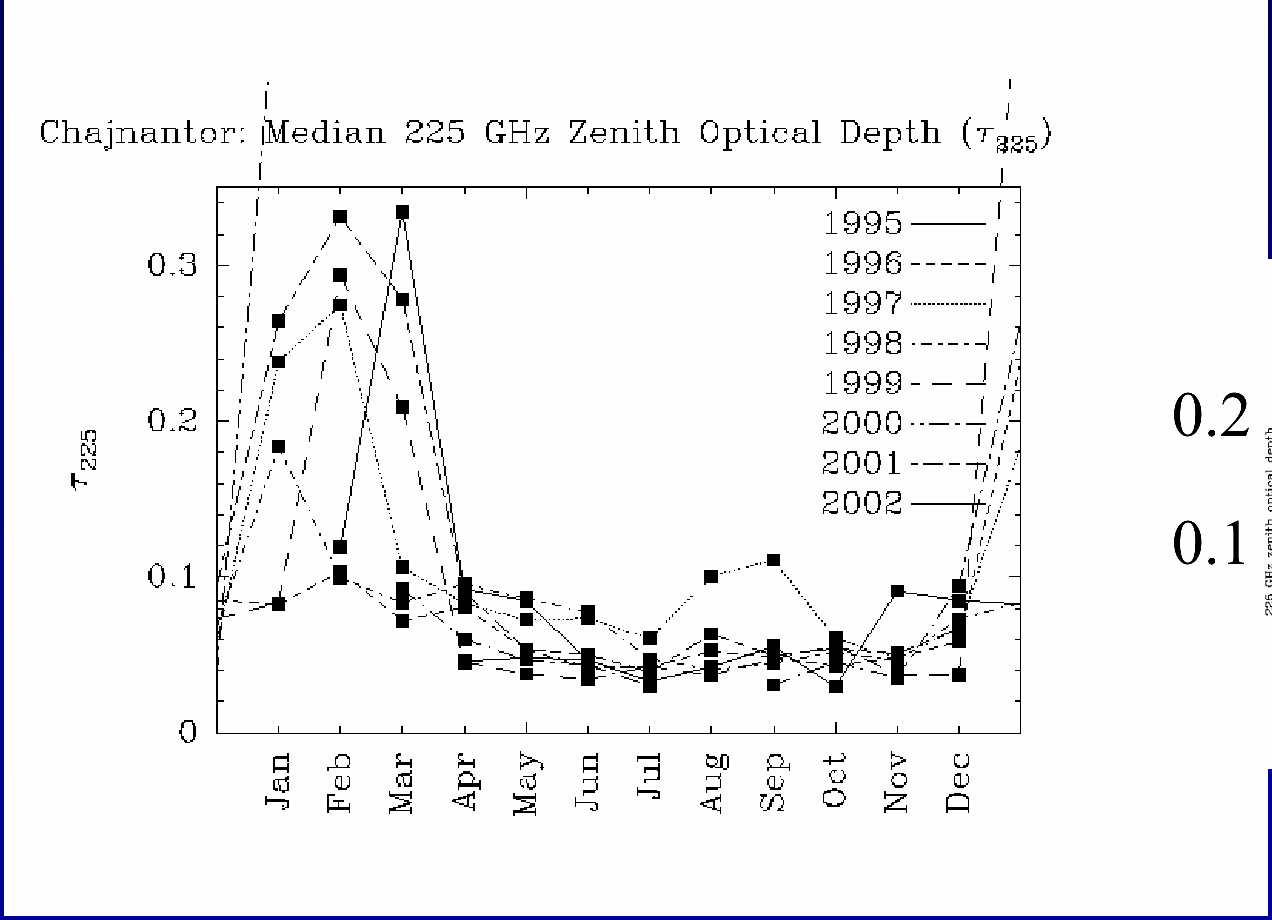
- Array scheduling and operations
- Quick-look data reduction
- Maintenance and repair antennas
- Maintenance and repair instrumentation
- Administration, safety

Dynamic Scheduler

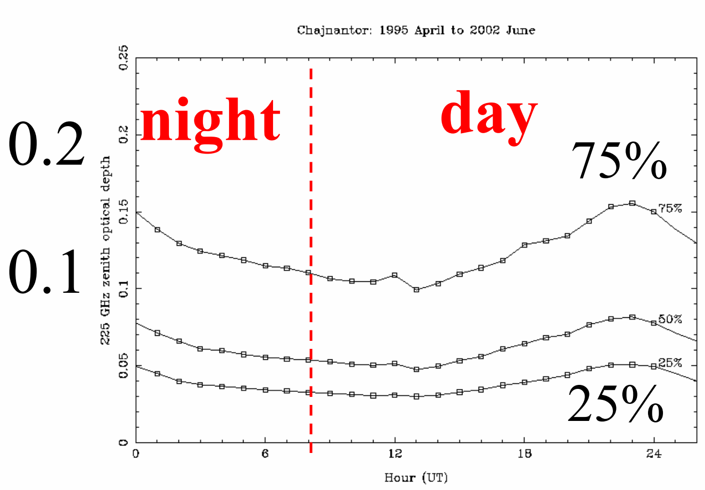
- Dynamic scheduler selects programs according to:
  - Science rating
  - Weather conditions: transparency, phase rms , …. (`stringency')
  - Execution status
  - Array configuration
  - Partner parity

Transparency Variations

Annual variation

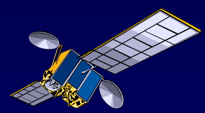


Diurnal variation

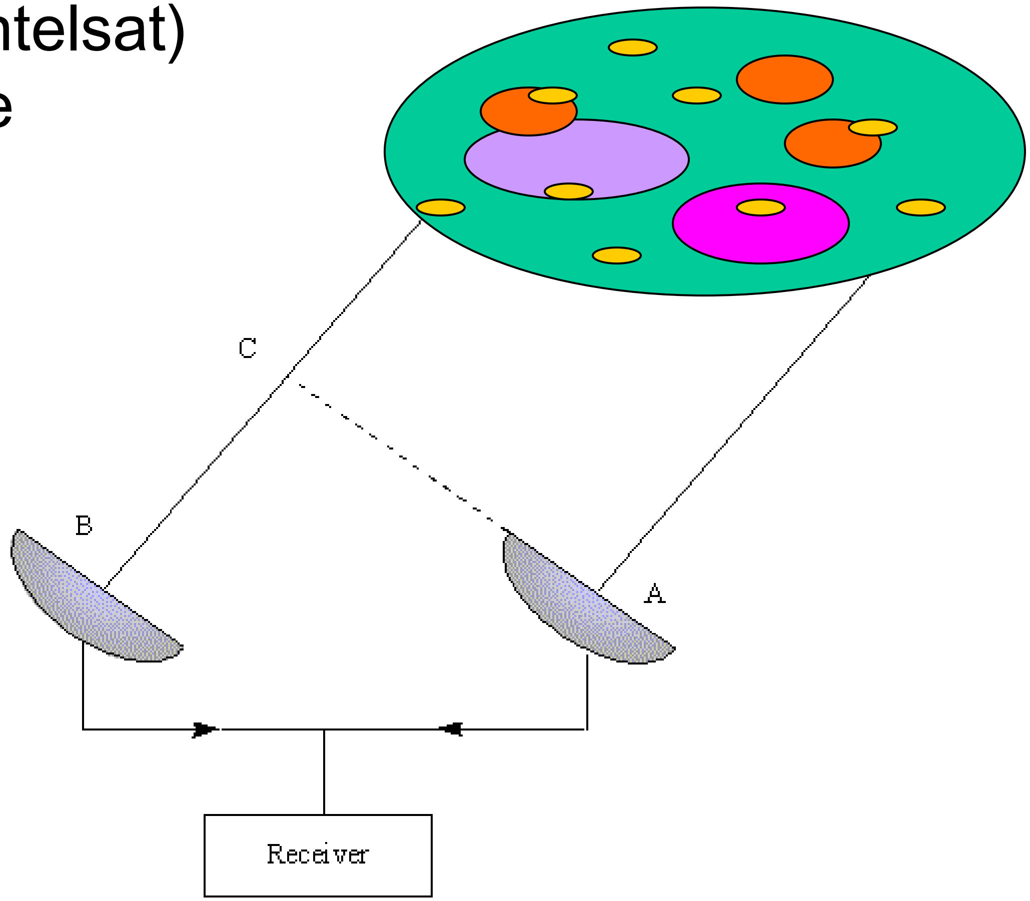


τ=0.05 corresponds to ~1 mm precipitable water vapor

Site Test Interferometer



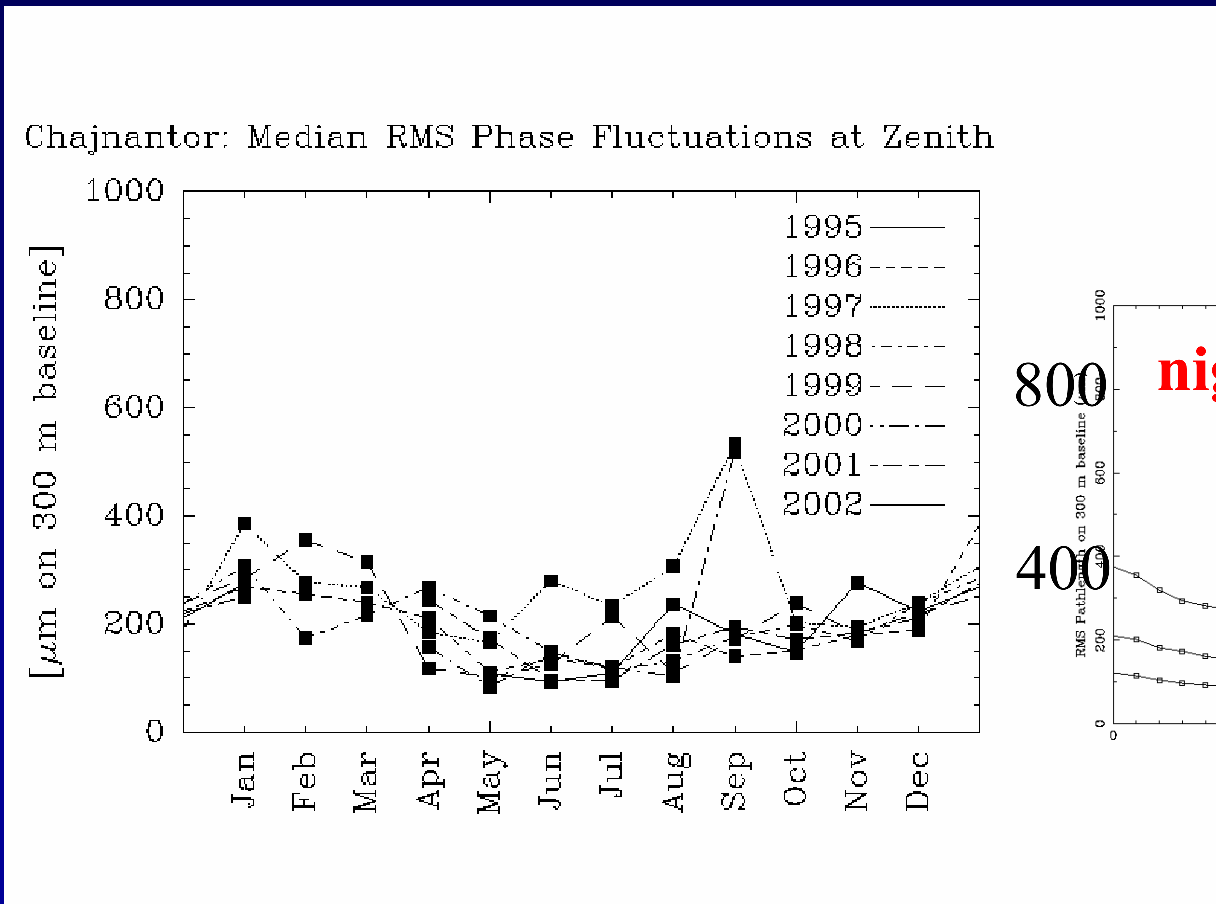
11.198 GHz (Intelsat)
300 m baseline
36° el.



Phase Stability Variations

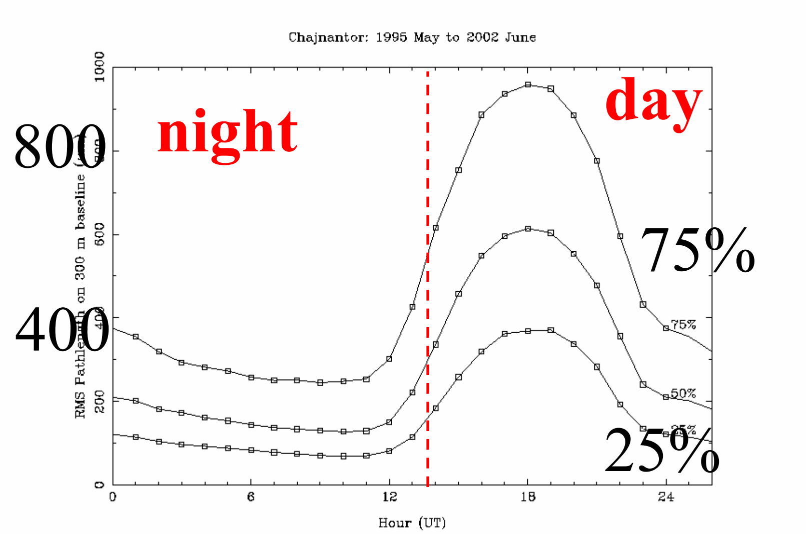
Annual variation

11.2 GHz



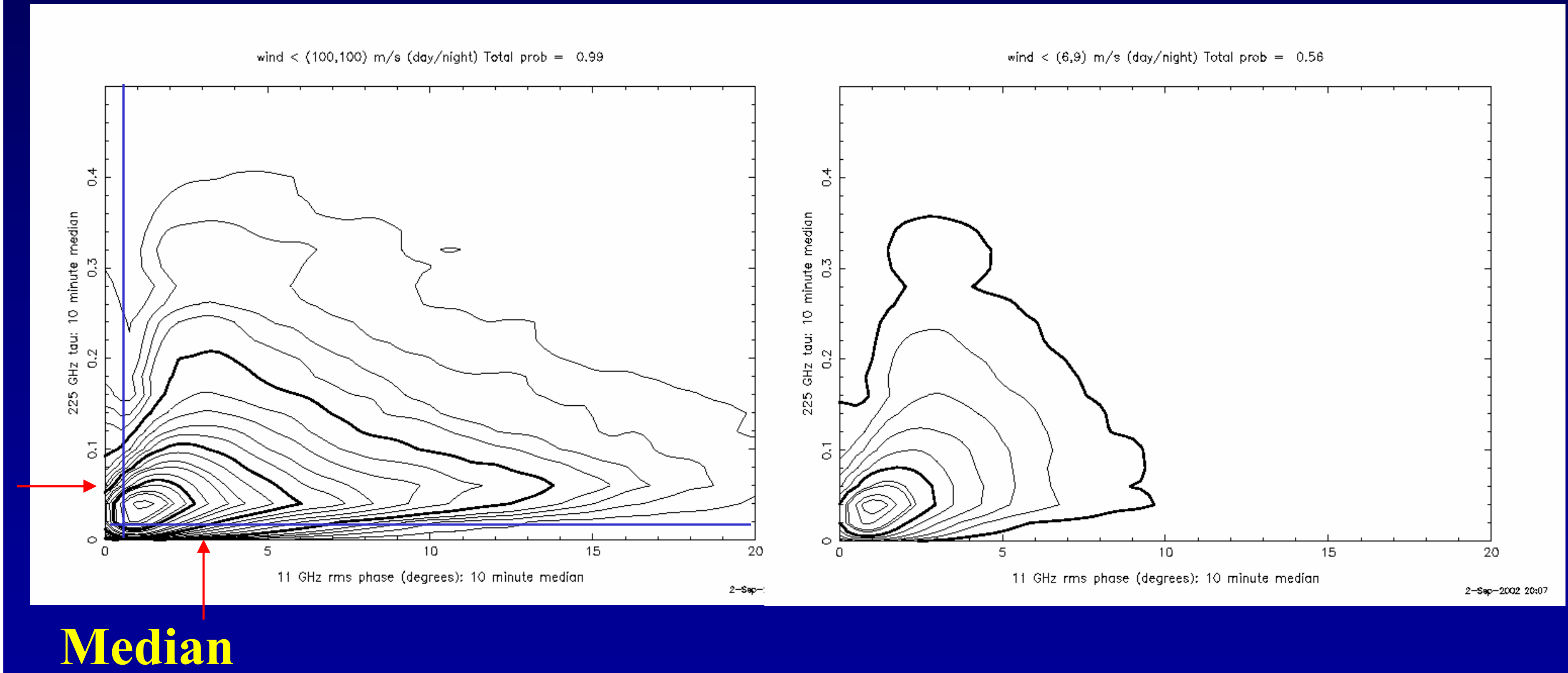
Diurnal variation

36° el.



φ<100 μm needed to image to 0.2" at 345 GHz without phase correction

Transparency and Phase Stability



Note tail in statistics of periods with good transparency but large phase rms ¬> phase correction essential!

Main functions Central Office: *Santiago*

- Pipeline data reduction
- Quality assessment
- Production of archive
- Business functions
- Science offices

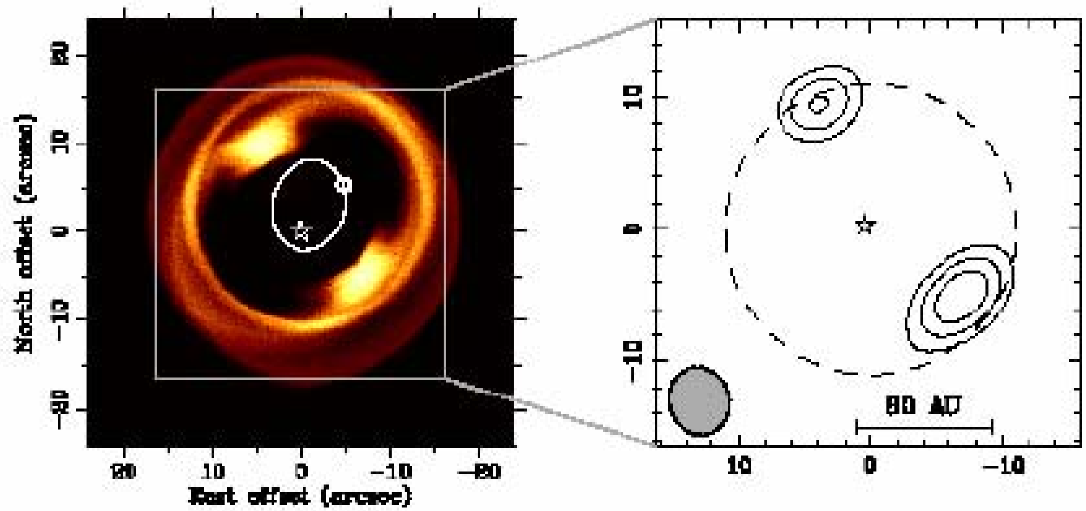
Science operations in practice

- Phase I + II proposals through RSCs
  - Powerful time estimator and end-to-end data simulator ¬> scheduling blocks to OSF
- Scheduler selects programs; assures homogeneous + consistent calibration; possibility of eavesdropping and `breakpoints'
- Pipeline data reduction, quality control, production of archive, VO compatible
  - *Complete data management system*
- Advanced data reduction at RSCs

Example: Vega debris disk

Dust trapped in resonances due to unseen planet?

Simulation **PdB 1mm data**



Wilner et al. 2002

Use simulator to `observe' model in same way as actual data

Regional Support Centers: *Core Functions*

- Proposal handling
- User support for proposals and data reduction beyond the standard pipeline products
- Host of copy of archive

Core functions are controlled by ALMA Observatory

Regional Support Centers: *Additional Functions*

- Advanced software and techniques (e.g. large OTF maps)
- Training, summer schools, outreach
- Research funding, ……

Additional functions may differ between RSCs

Models for European RSC

True Center in single location

Central Node with distributed network

Favored by Community

Virtual Center distributed throughout Europe

Central Node with network

- Strong Central Node for user support
- Development within distributed network, to ensure optimal use of expertise in European institutes

Community comments welcome!

Development / Upgrades

- New / upgrade instrumentation over lifetime of array, e.g.:
  - Additional receiver bands
  - Second generation correlator
  - Improved software
- To be done mostly at institutes in partner countries, under contract from ESO
- Development funding included in operations budget (~5 MEu/ year Europe)

Early Science observing:
>Q3 2007

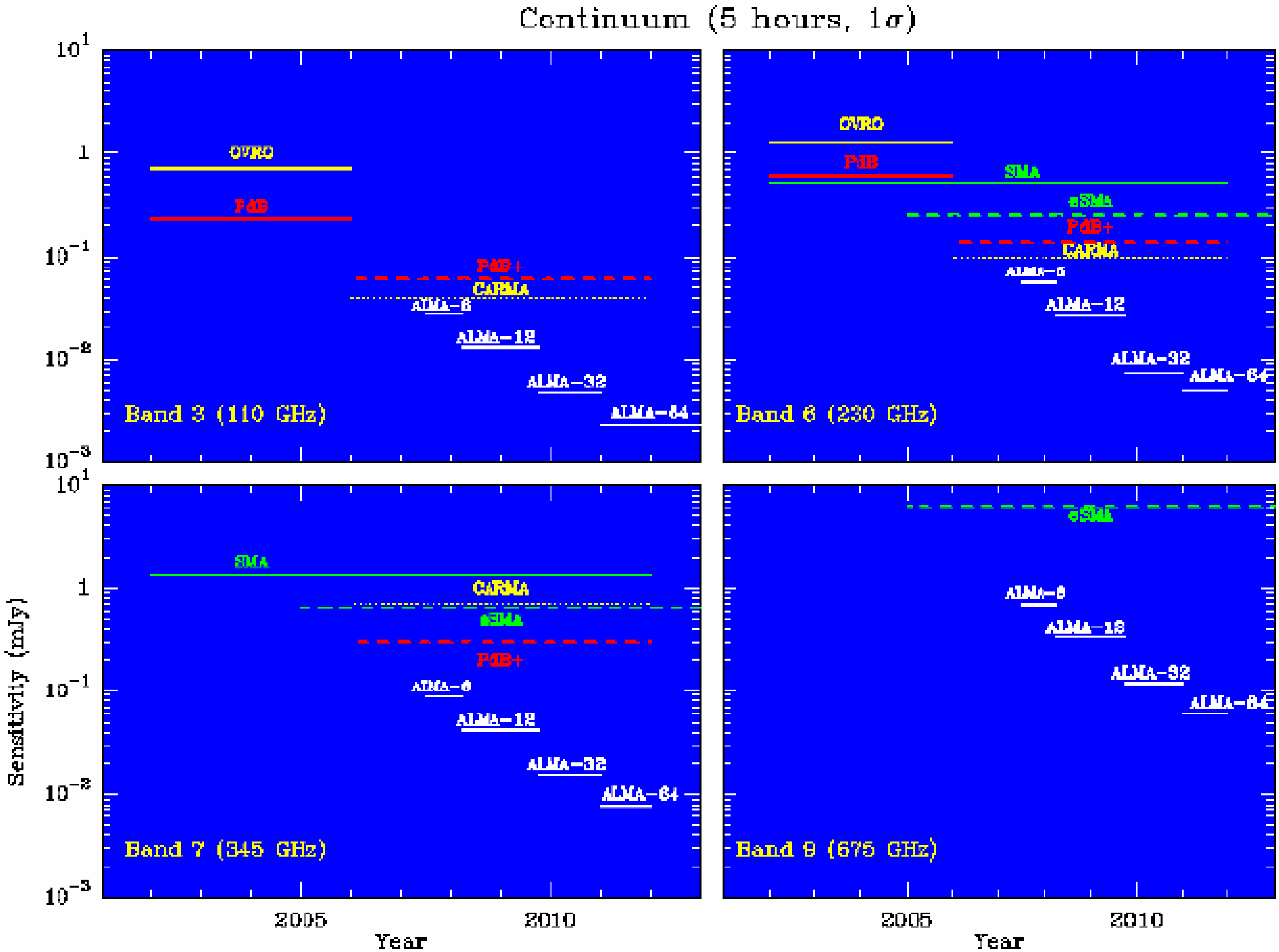
- **Follows Commisioning and Science Verification**
- **Open to community through call for proposals**
- **Should demonstrate unique ALMA capabilities to all astronomers**
- **Provides feedback to ALMA operations**

Operations with full array will start in 2012

Unique ALMA capabilities for Early Science

- Sensitivity: gain over existing facilities once >6 antenna's
- Long baselines ¬> high angular resolution
- High frequencies
- Southern sky

Early science sensitivities

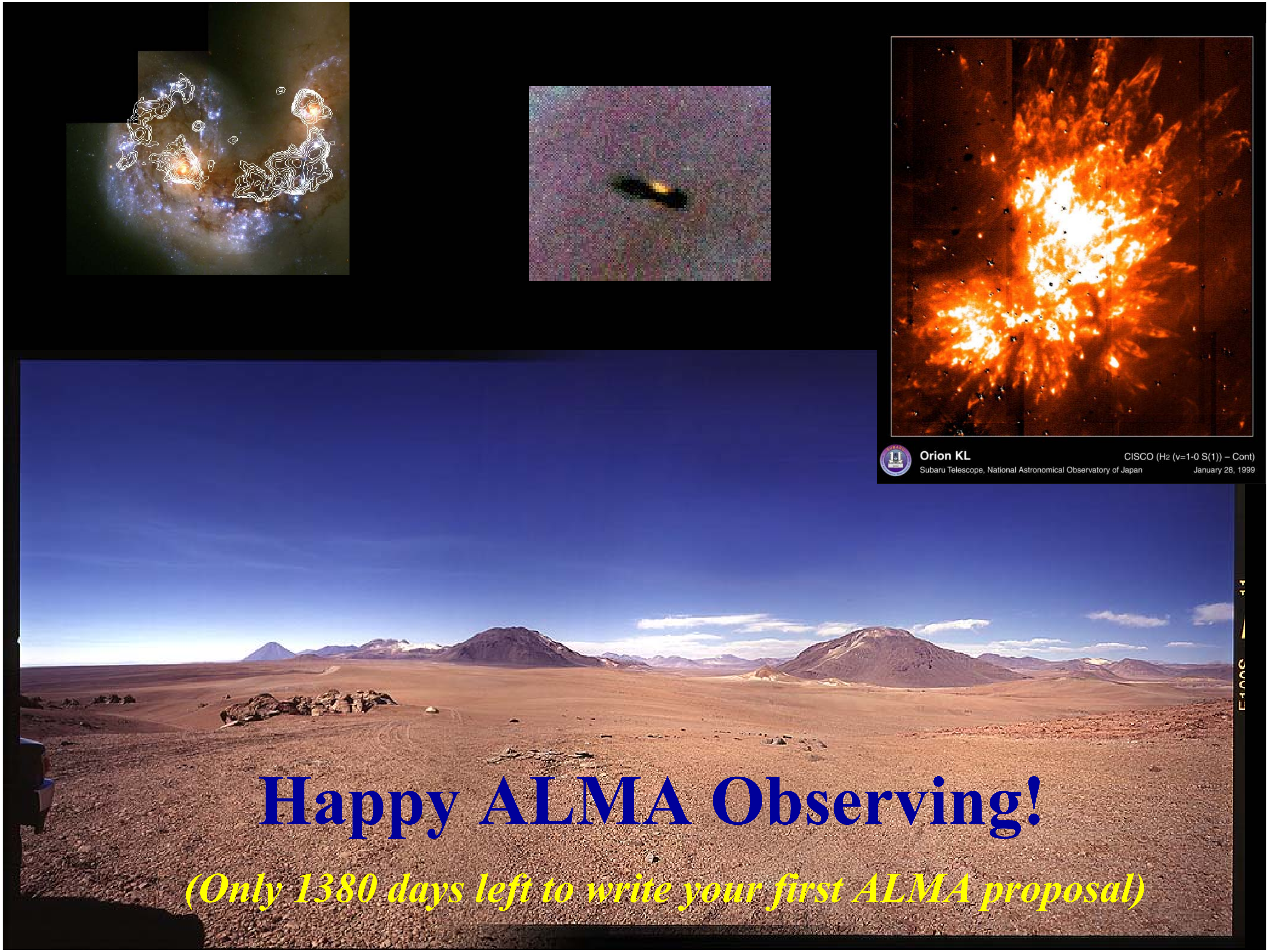


Atacama Pathfinder EXperiment

MPIfR, Sweden, ESO

Copy of one prototype antenna installed on Chajnantor June 2003

Observations starting next year


Orion KL
CISCO (H2 (v=1-0 S(1)) – Cont)
Subaru Telescope, National Astronomical Observatory of Japan
January 28, 1999
Happy ALMA Observing!
(Only 1380 days left to write your first ALMA proposal)