From Pluto to Venus: the SMA at the forefront of thermal mapping in the Solar System

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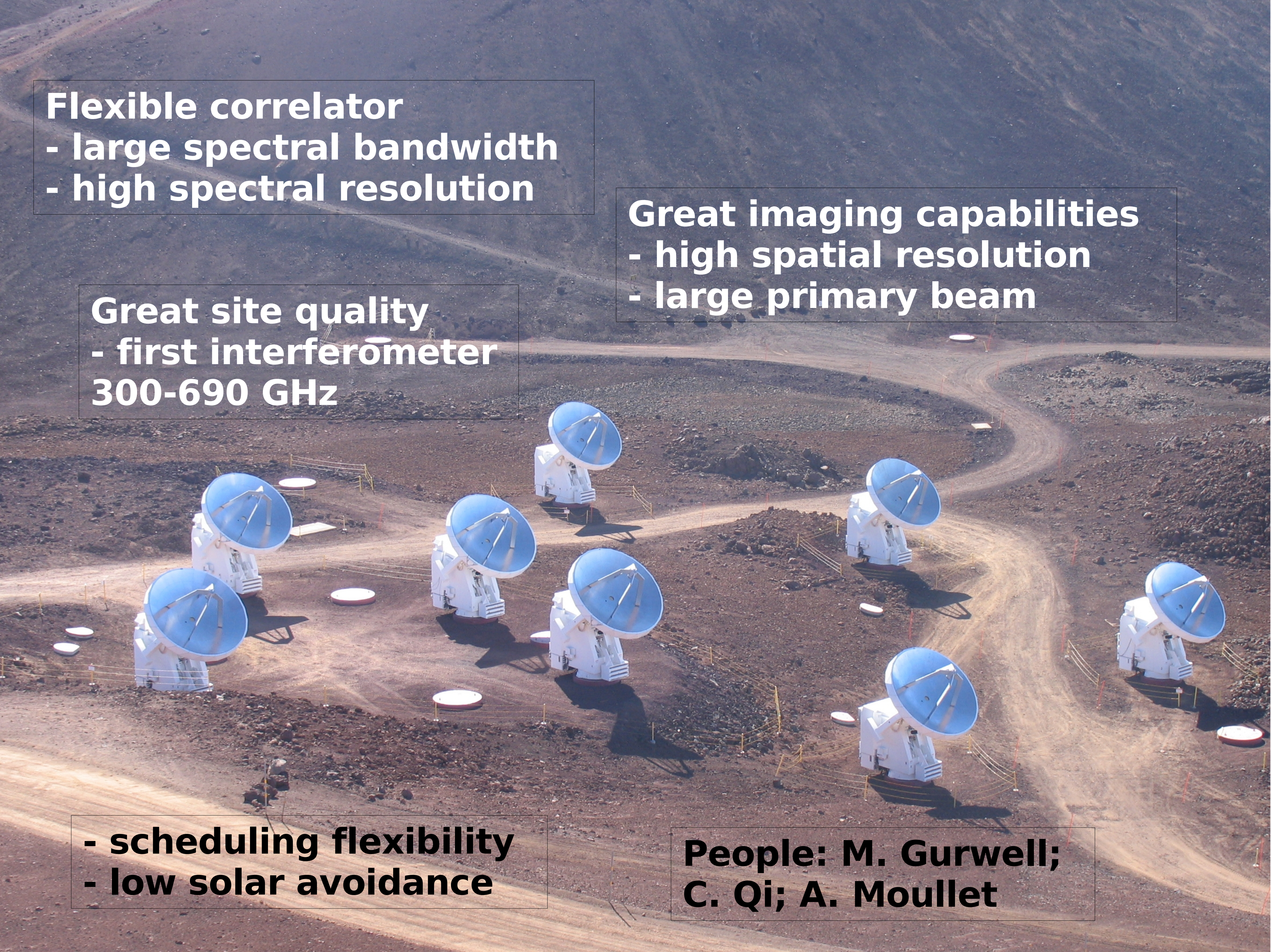
With contributions from Mark Gurwell and Charlie Qi, CfA

NRAO

SMITHSONIAN ASTROPHYSICAL OBSERVATORY SMA ACADEMIA SINICA IAA


Flexible correlator
- large spectral bandwidth
- high spectral resolution
Great imaging capabilities
- high spatial resolution
- large primary beam
Great site quality
- first interferometer
300-690 GHz
- scheduling flexibility
- low solar avoidance
People: M. Gurwell;
C. Qi; A. Moullet

Flexible correlator
- large spectral bandwidth
- high spectral resolution

Great imaging capabilities
- high spatial resolution
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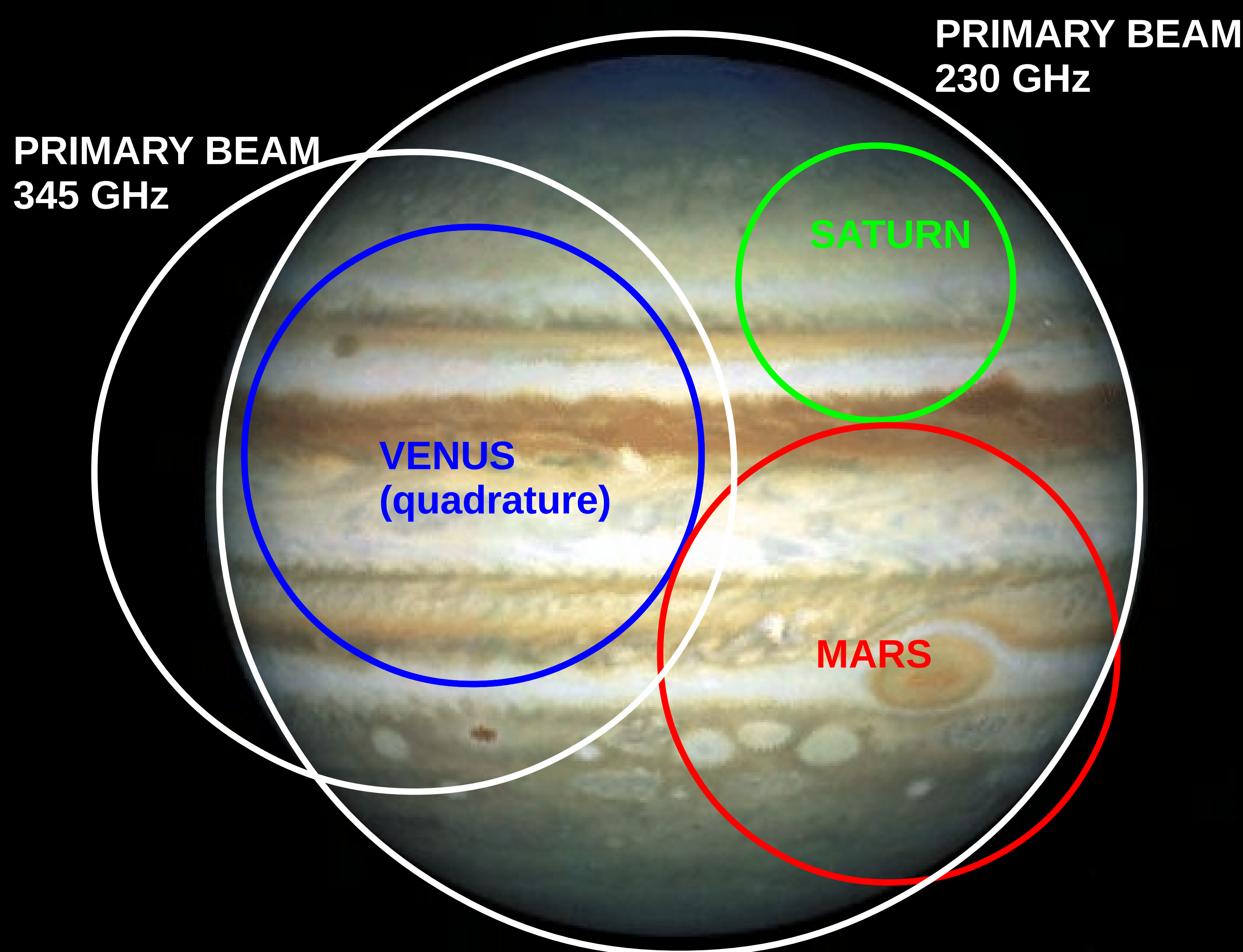
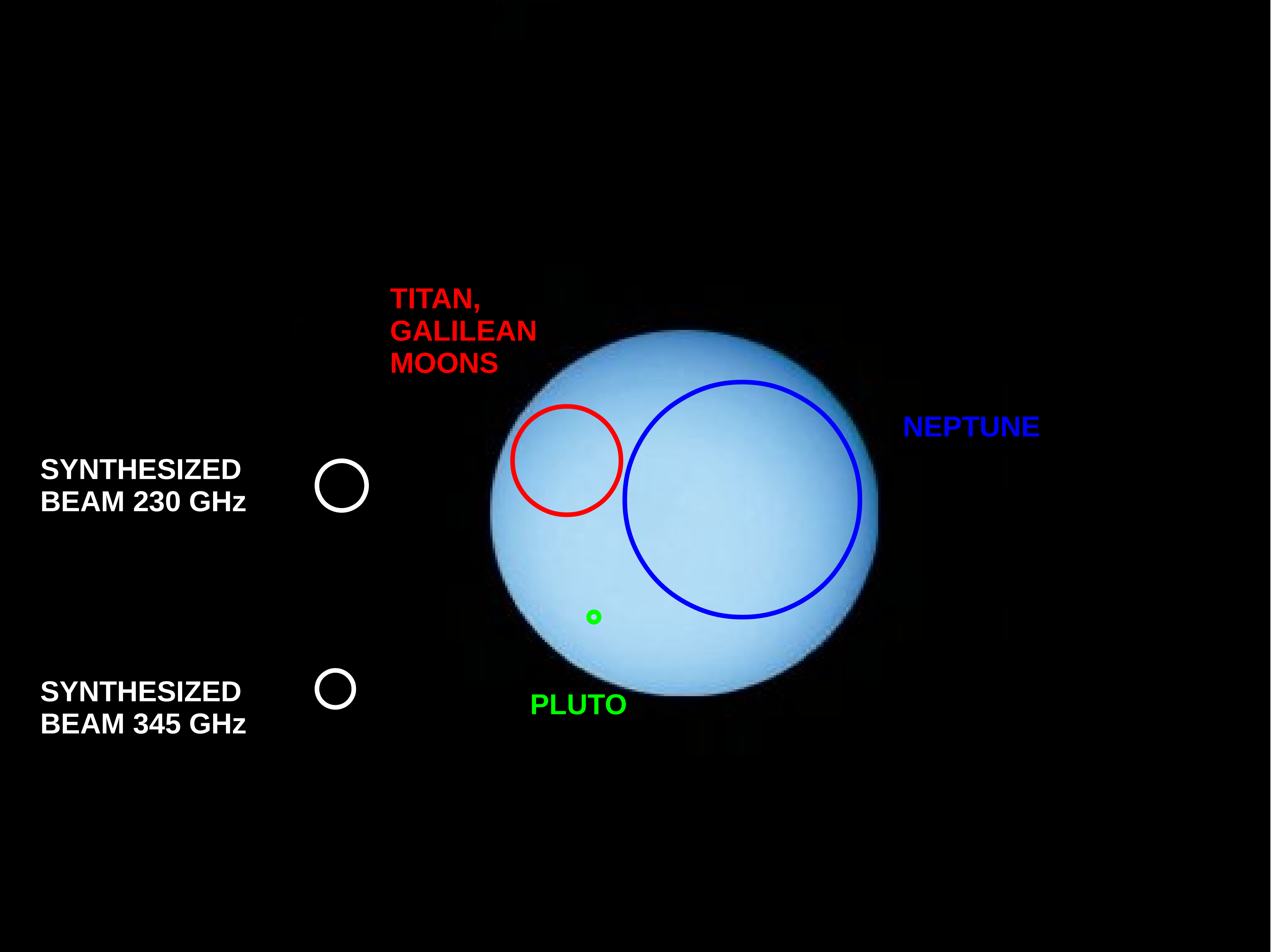
Great site quality
- first interferometer 300-690 GHz

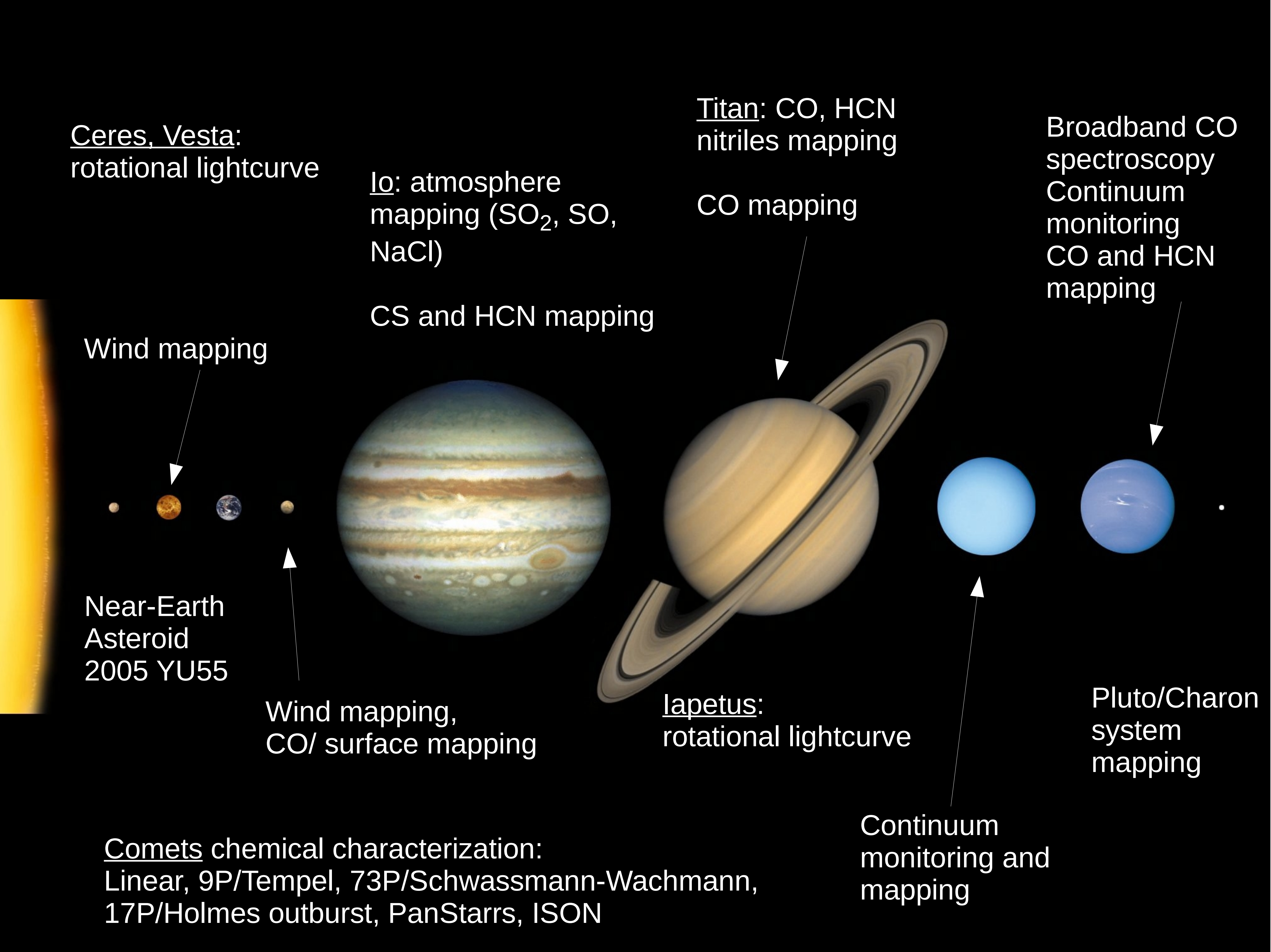
An all-around well-suited instrument for Solar System observations

- scheduling flexibility
- low solar avoidance

People: M. Gurwell; C. Qi; A. Moullet


PRIMARY BEAM
230 GHz
PRIMARY BEAM
345 GHz
SATURN
VENUS
(quadrature)
MARS


TITAN,
GALILEAN
MOONS
NEPTUNE
SYNTHESIZED
BEAM 230 GHz
SYNTHESIZED
BEAM 345 GHz
PLUTO


Ceres, Vesta: rotational lightcurve
Io: atmosphere mapping (SO_2, SO, NaCl)
CS and HCN mapping
Titan: CO, HCN nitriles mapping
CO mapping
Broadband CO spectroscopy
Continuum monitoring
CO and HCN mapping
Wind mapping
Near-Earth Asteroid 2005 YU55
Wind mapping,
CO/ surface mapping
Iapetus: rotational lightcurve
Pluto/Charon system mapping
Continuum monitoring and mapping
Comets chemical characterization:
Linear, 9P/Tempel, 73P/Schwassmann-Wachmann,
17P/Holmes outburst, PanStarrs, ISON

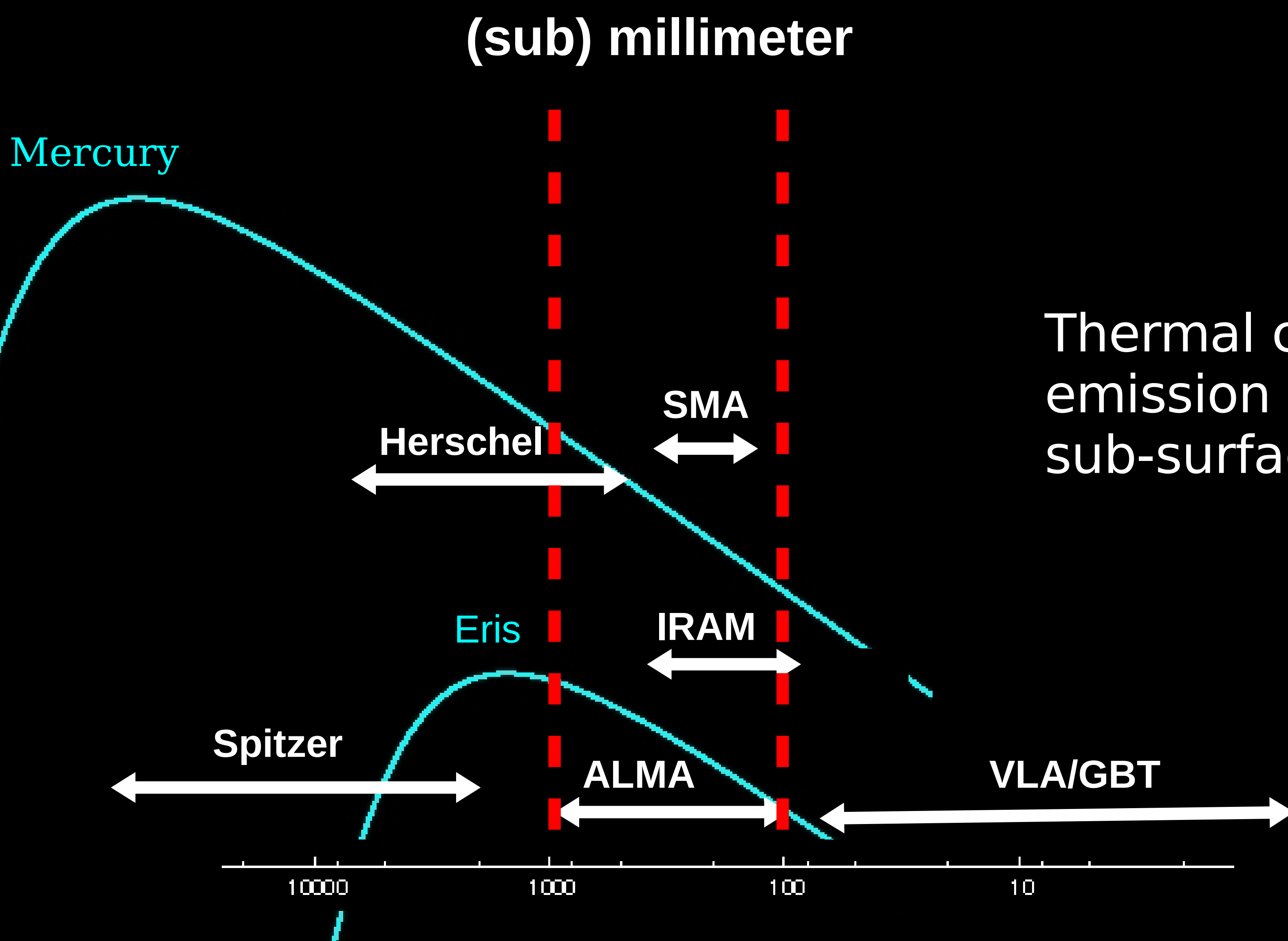
Solar System physical and chemical characterization constrains:

- **Conditions in the forming Solar System**:
  comets chemistry, Kuiper Belt Objects

- **Planetary processes**:
  seasonal cycles, volcanism, global wind system, impacts, organic chemistry

- **Evolution of individual bodies**:
  climate, surface alteration

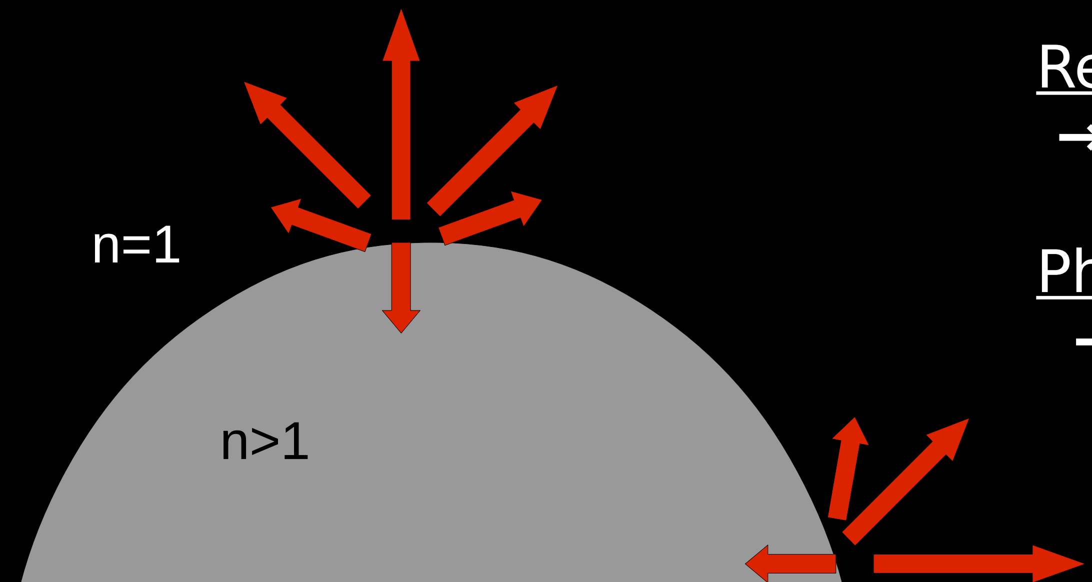
Mapping surface temperature fields



Thermal continuum emission from sub-surface (~10λ)

Surface brightness temperature distribution is directly linked to **insulation** and **surface properties** distribution

$$T_\phi = \left[\frac{(1-p_{bolo})F}{r_h^2 \varepsilon_{bolo}\sigma}\right]^{1/4} \Omega_{\Theta,i}(lat, long, z) = T_{SS}\Omega_{\Theta,i}(lat, long, z)$$



Radiative:
→ **refraction index, roughness**

Reflective:
→ **bolometric albedo**

Physical:
→ **thermal inertia, porosity, composition**

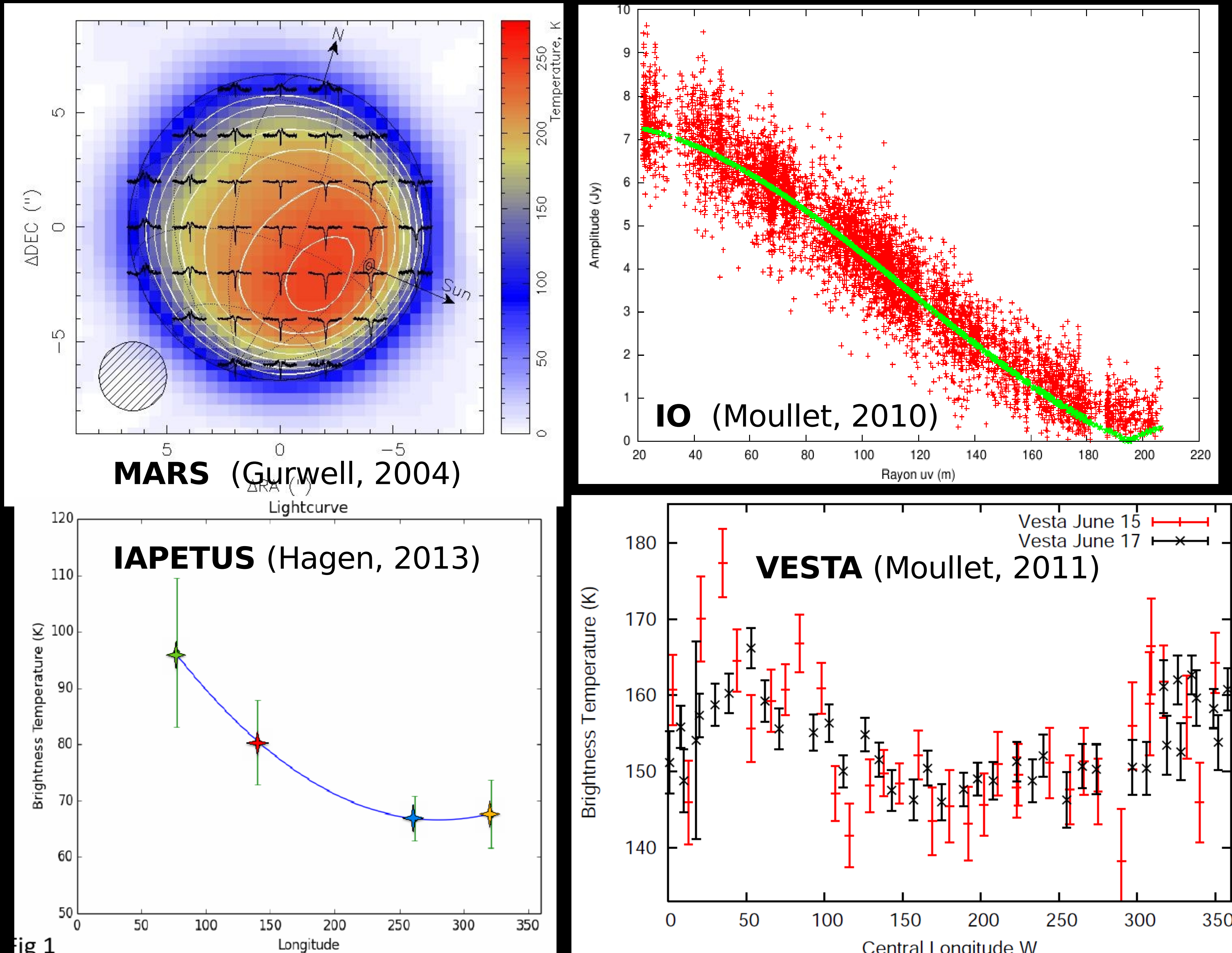
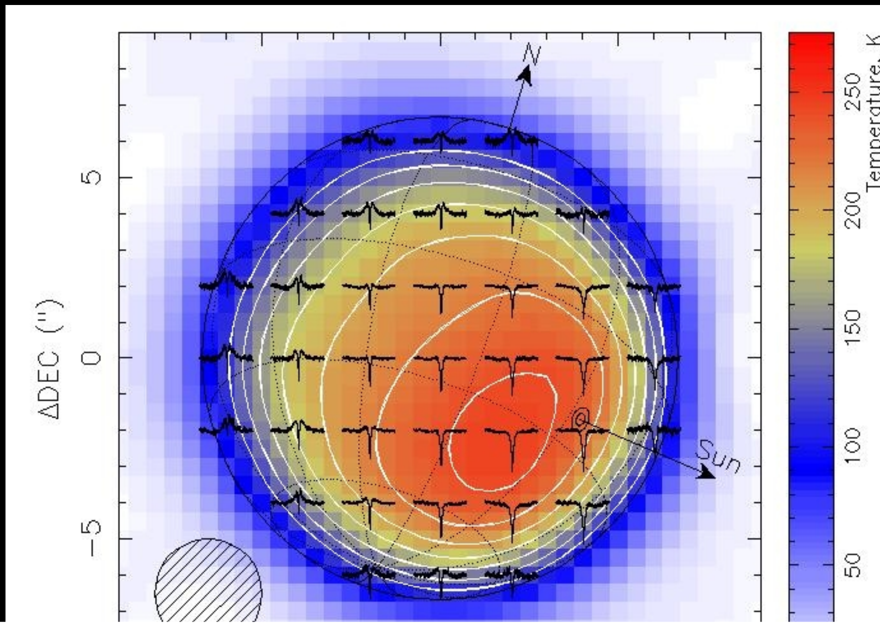
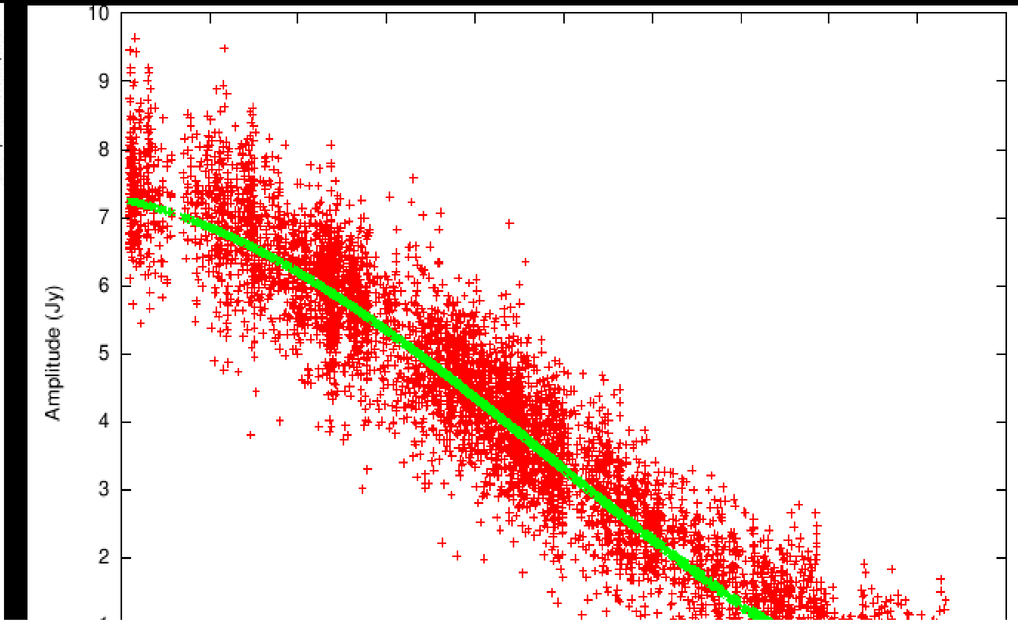
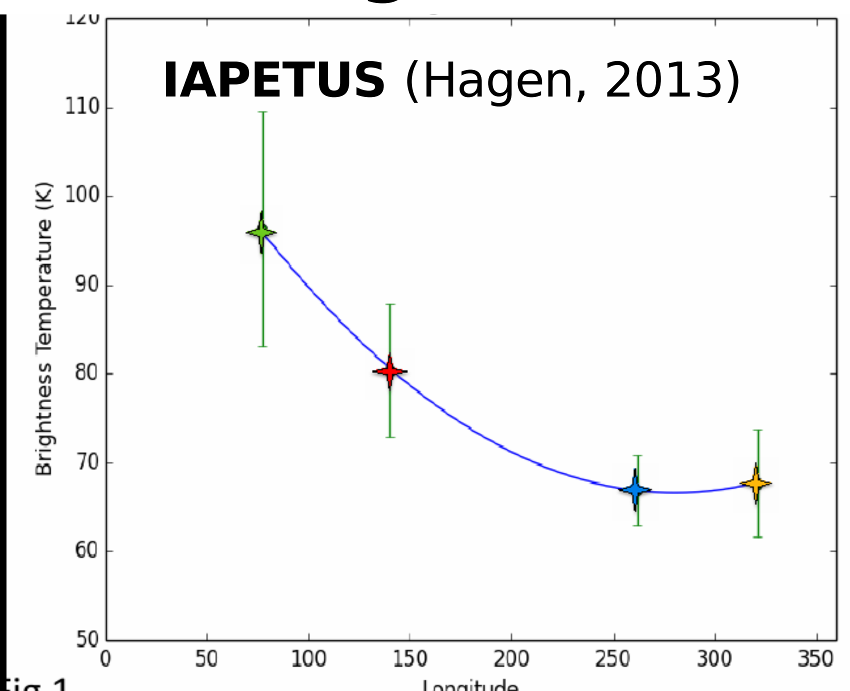

MARS (Gurwell, 2004)
ΔDEC (")
ΔRA (")
Temperature, K
N
Sun
IO (Moullet, 2010)
Amplitude (Jy)
Rayon uv (m)
Lightcurve
IAPETUS (Hagen, 2013)
Brightness Temperature (K)
Longitude
VESTA (Moullet, 2011)
Vesta June 15
Vesta June 17
Brightness Temperature (K)
Central Longitude W

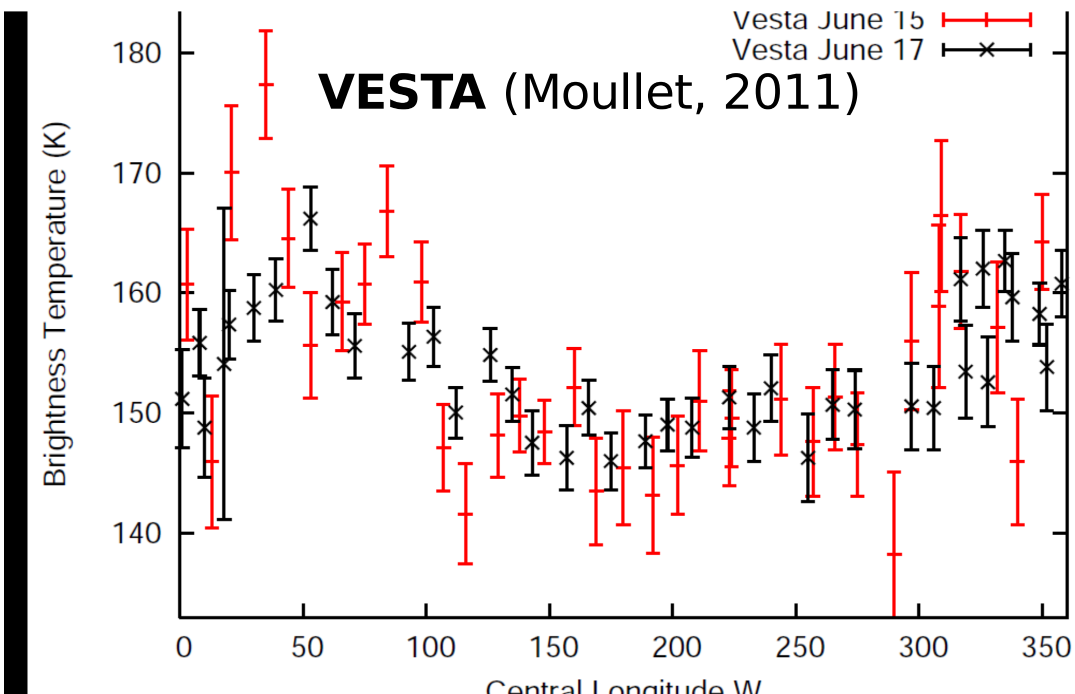
Fig 1



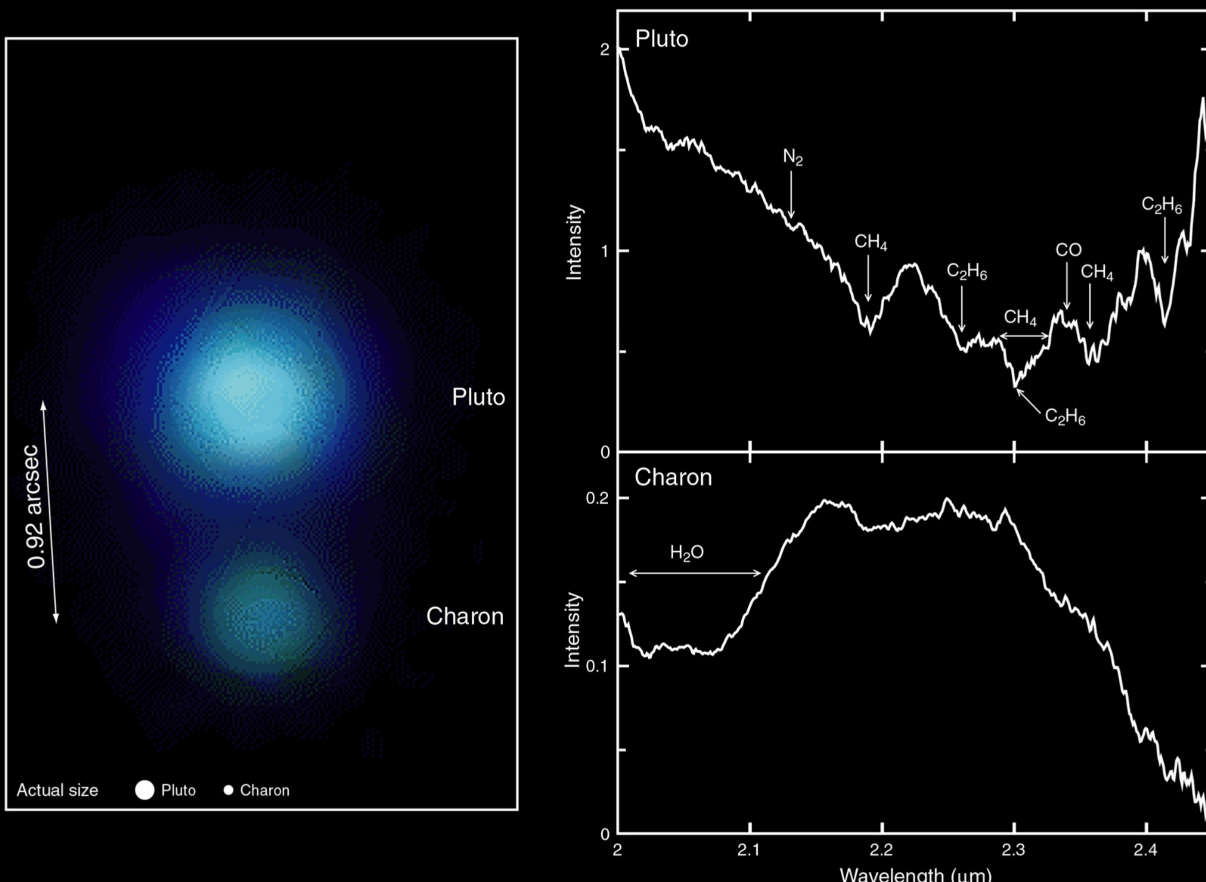


Continuum sensitivity → rotational lightcurve
→ **longitudinal temperature variations**





The Pluto / Charon system



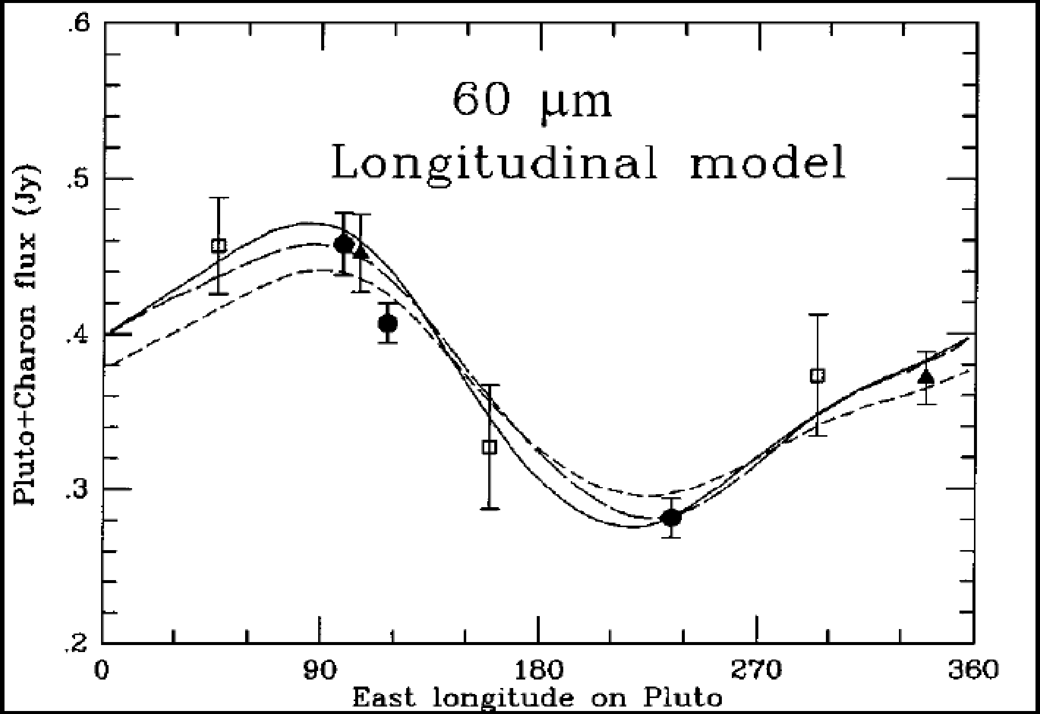
Pluto and the Satellite Charon
Subaru Telescope, National Astronomical Observatory of Japan

N_2, CO, and CH_4 ices: surface temperature controlled by N_2 sublimation

Water ice: surface temperature in equilibrium with insulation

Pluto-Charon separation ~ 0.9”:

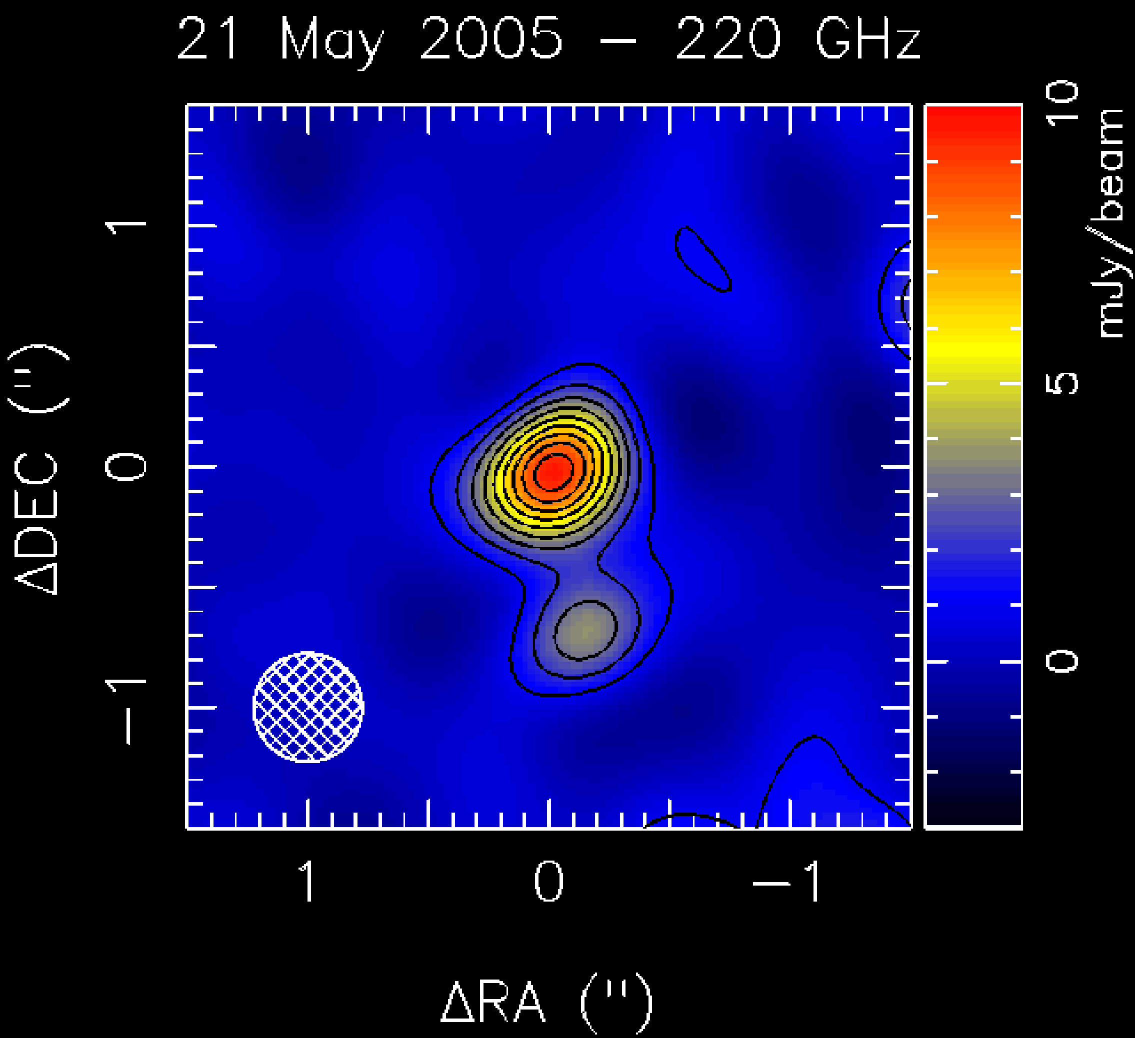
Single-dish thermal observations can only report **system-averaged** measurements



ISO 60 micron lightcurve, Lellouch et al., 2000

SMA 220 GHz (Gurwell, 2005):

first thermal resolved image of the system



Pluto: 9.8±0.6 mJy

T_B=37±2.3 K

Charon: 3.7±0.6 mJy

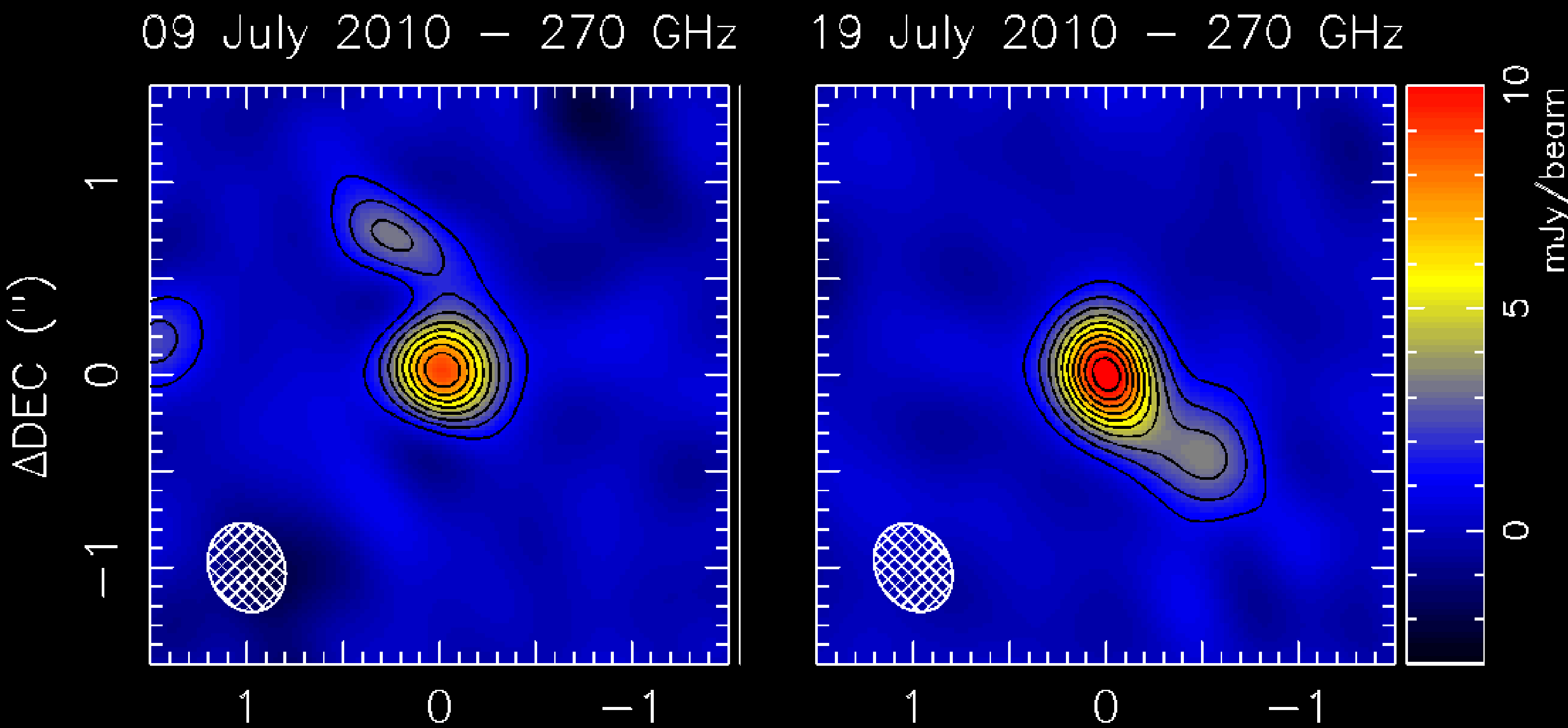
T_B=49±8 K

Mean surface temperature:
41 K / 54 K

Consistent with models

SMA 270 GHz (Gurwell, 2010):

Lower overall temperatures, may be linked to higher background emission



Pluto: 9.0±0.5 mJy = 26±2 K
Charon: 3.3±0.5 mJy = 34±5 K

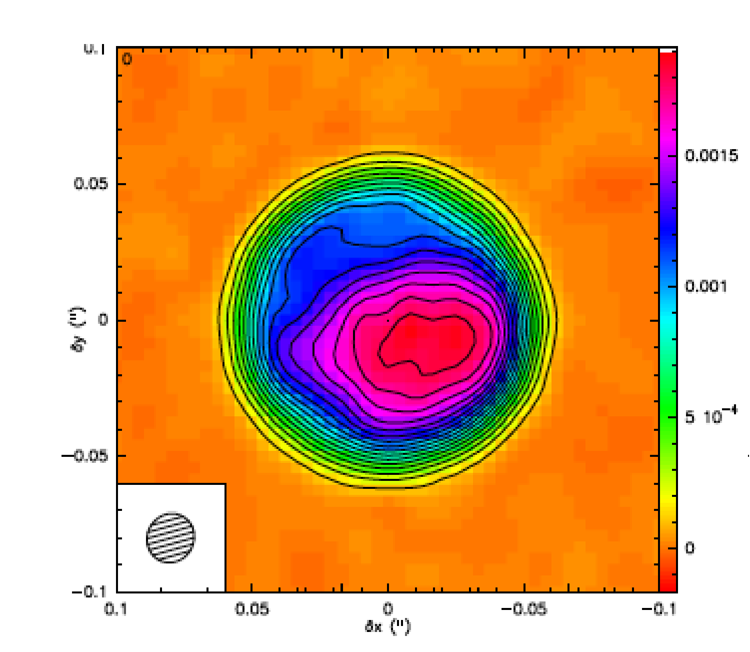
Pluto: 10.8±0.5 mJy = 31±2 K
Charon: 3.5±0.5 mJy = 35±5 K

SMA pioneered KBO thermal imaging to be pursued by ALMA:

• Imaging of **Pluto surface** (0.1”)

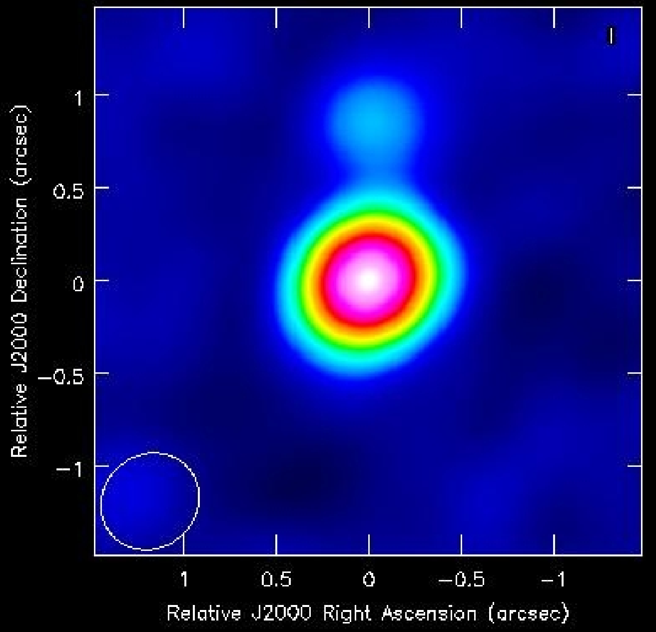
• Resolved imaging of **narrow binary systems** (>0.010” sep)

Cycle 2 accepted projects: Haumea/Orcus systems imaging



Simulation Pluto imaging, B7

Simulation Orcus imaging, B7



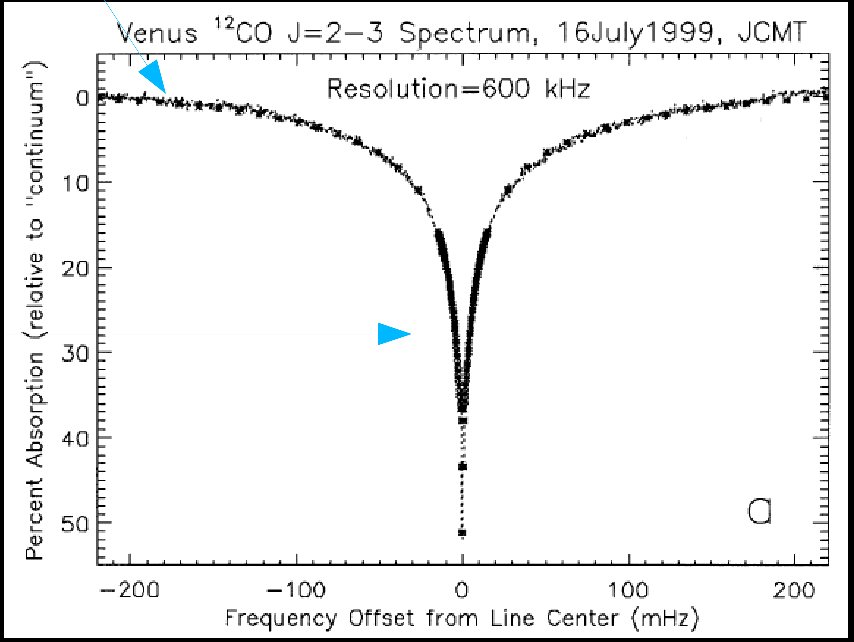
Mapping atmospheric properties

- **<u>Atmospheric pseudo-continuum</u>**

  - Produced by collision of major species (CO_2, H_2, N_2)
  - Sounds regions **~1 bar**

- **<u>Rotational lines</u>**

  - Sound regions **1bar → 1µbar**
  - Mostly minor species:
    CO, HCN, HDO, SO_2, SO, …



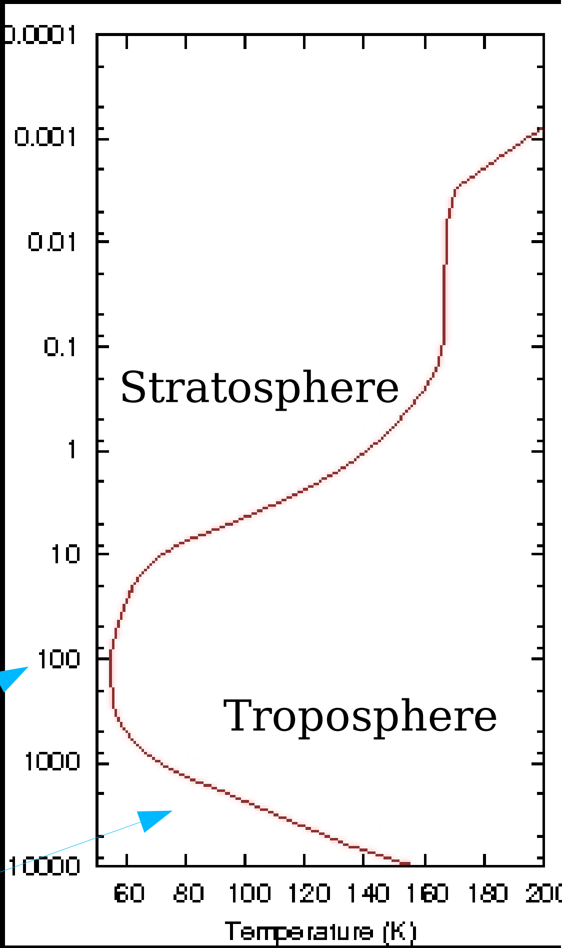
CO(3-2) line on Venus,
Clancy et al., 2003

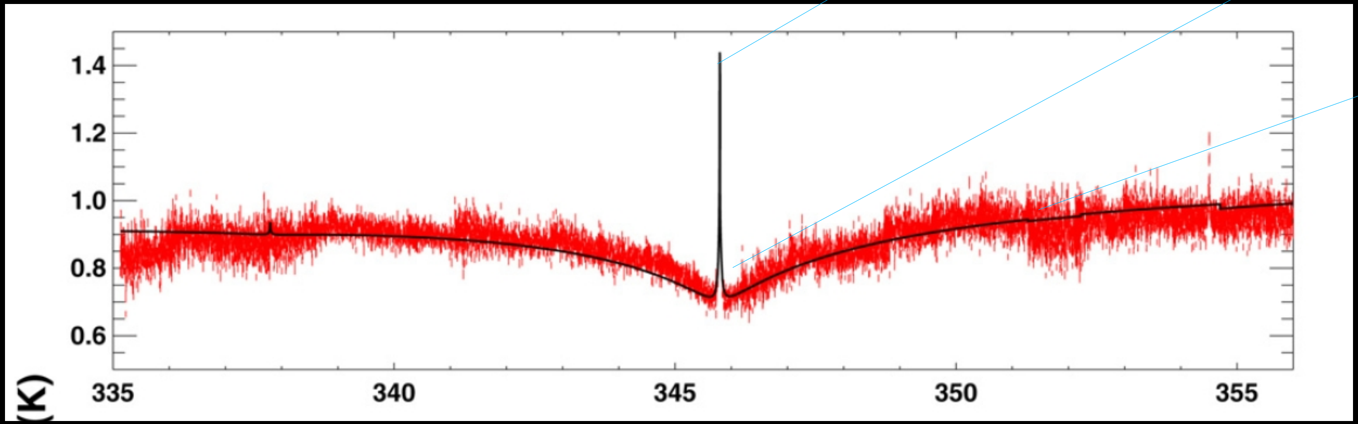
Spectral resolution to analyze pressure- and Doppler-broadened line profiles:

→ vertical **T/p/abundance** structure

Spatial resolution:

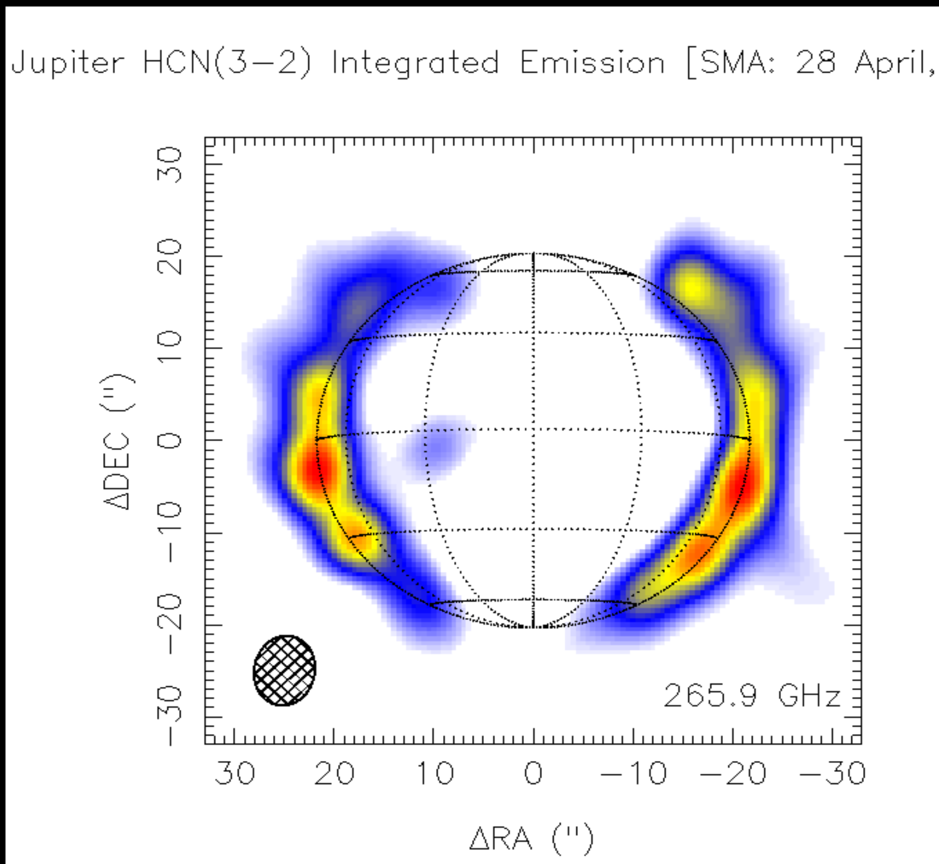
→ **horizontal molecular distribution**
→ Doppler-shift = **wind maps**

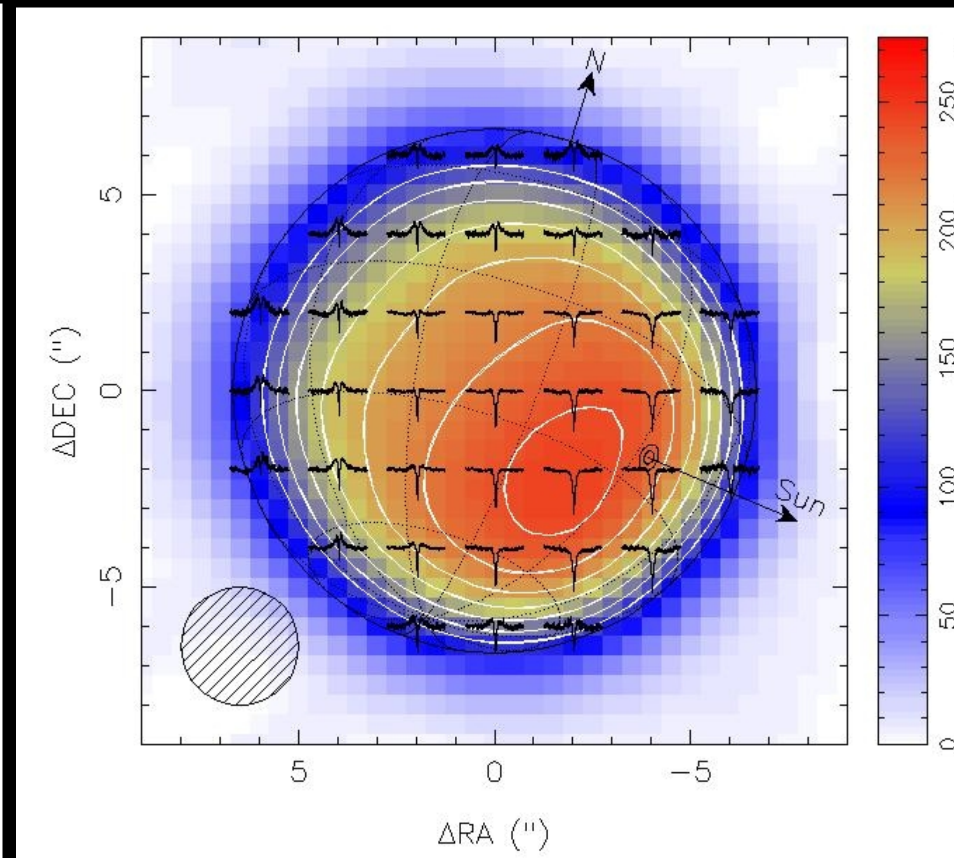




CO(3-2) line, JCMT, Hesman et al., 2007

Large-scale imaging

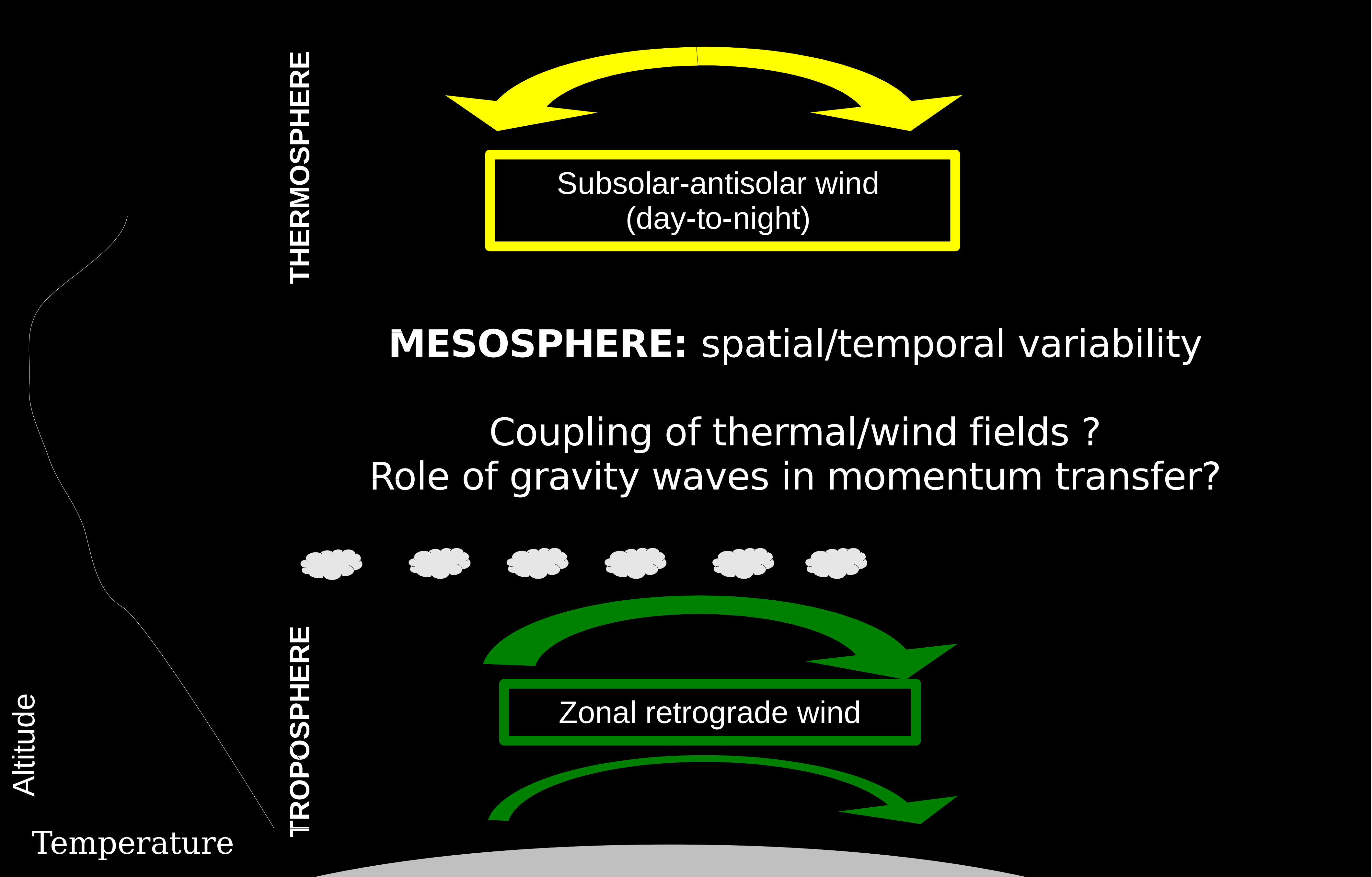


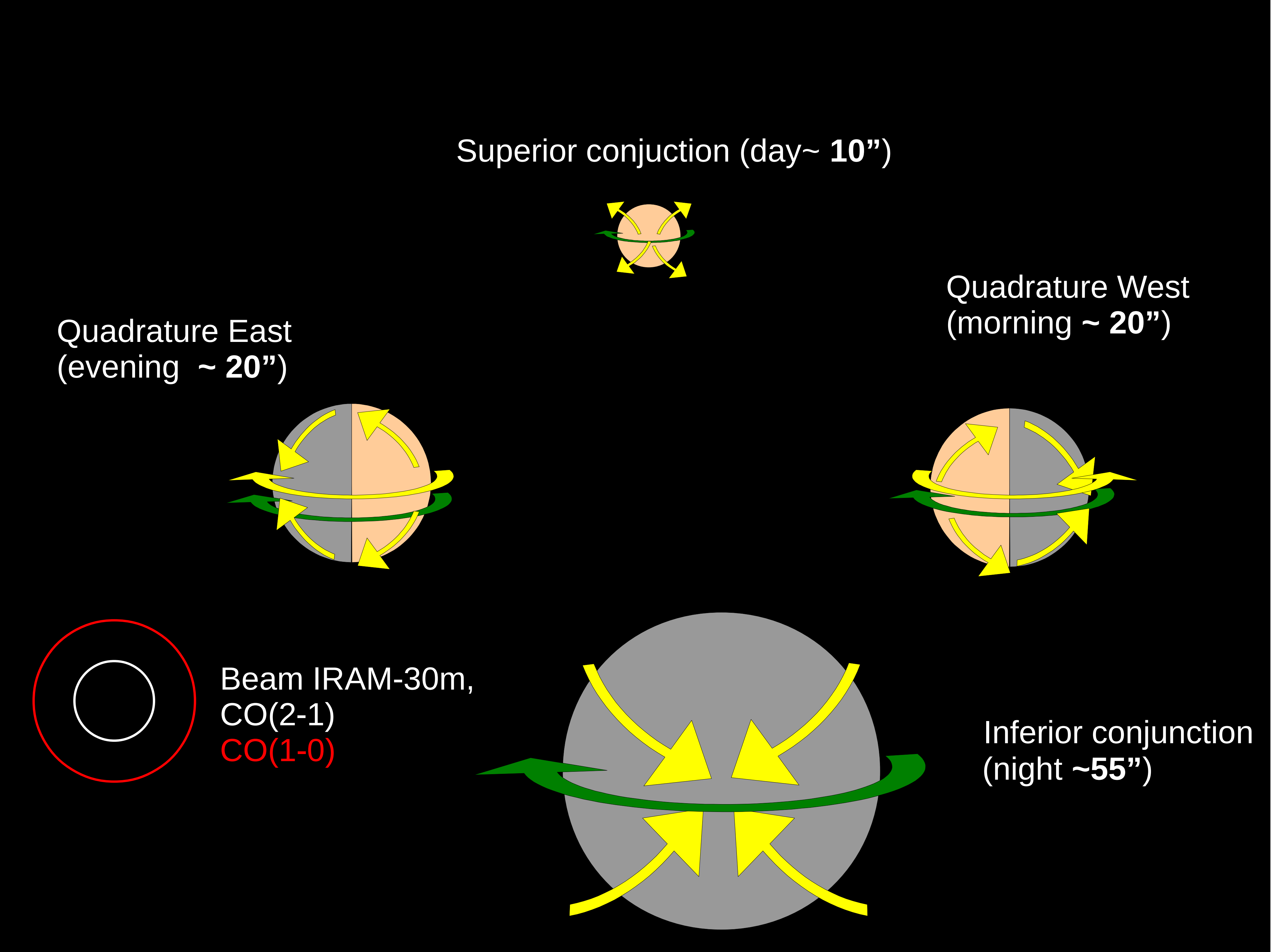


JUPITER - HCN (Moreno, 2007)

MARS - CO (Gurwell, 2004)

Venus' mesospheric winds

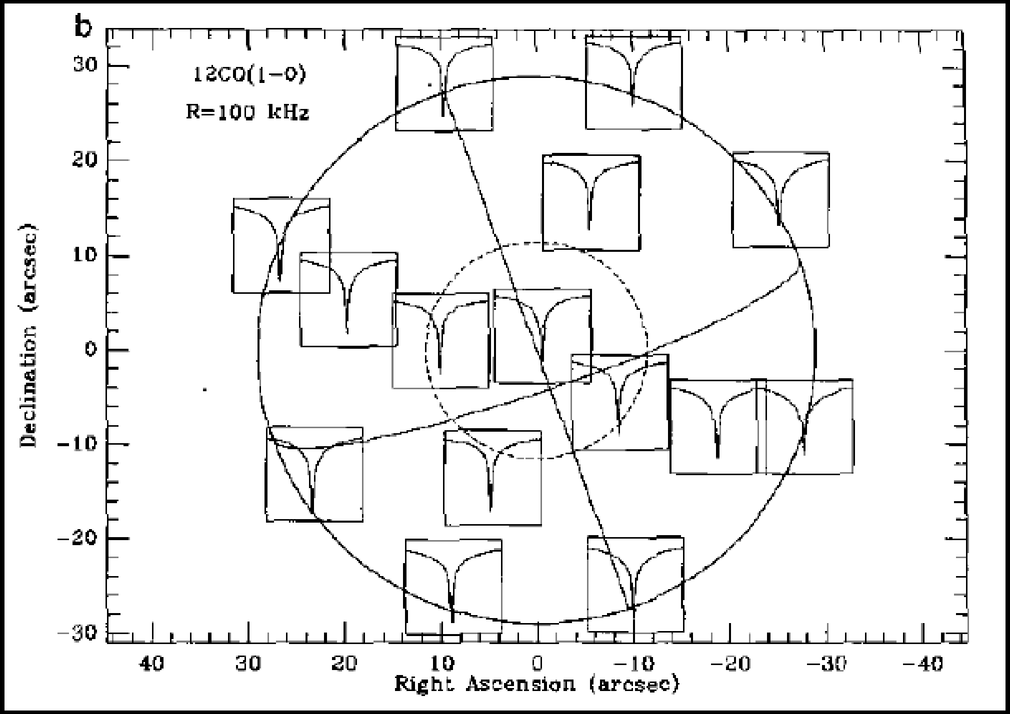




Superior conjuction (day~ **10”**)
Quadrature East
(evening ~ **20”**)
Quadrature West
(morning ~ **20”**)
Beam IRAM-30m,
CO(2-1)
CO(1-0)
Inferior conjunction
(night **~55”**)

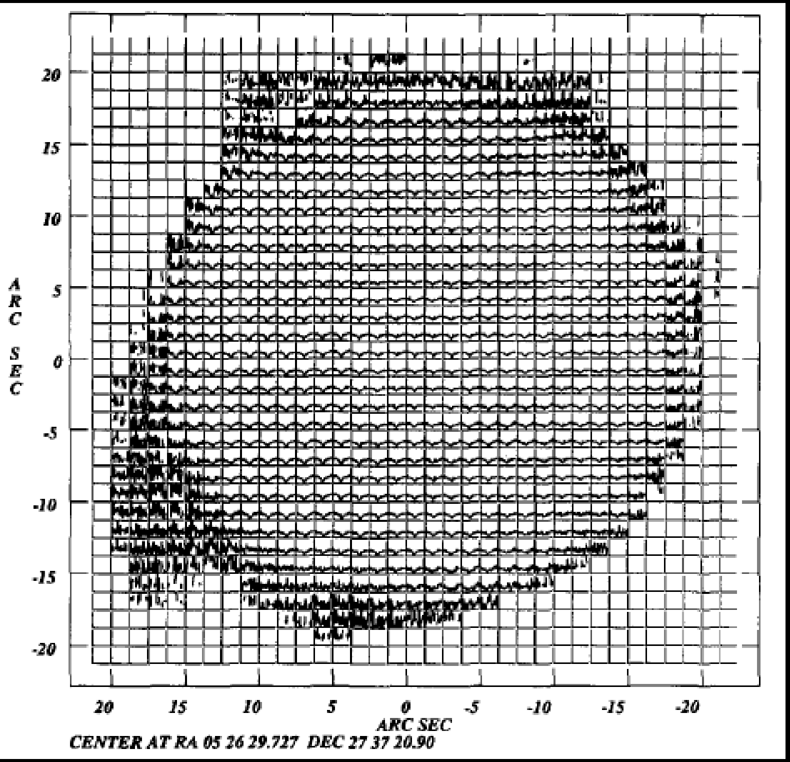
Doppler-shift mapping of CO rotational submm line cores, sounding the upper mesosphere (85-115 km)

Single-dish (IRAM)



Lellouch et al., 1994

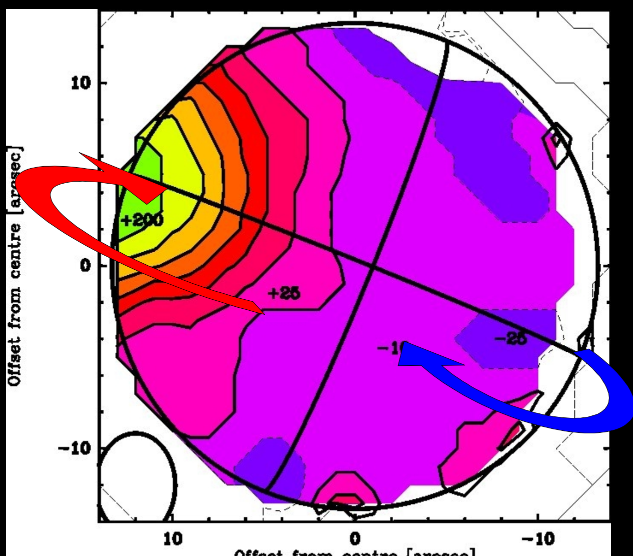
Interferometry (OVRO)

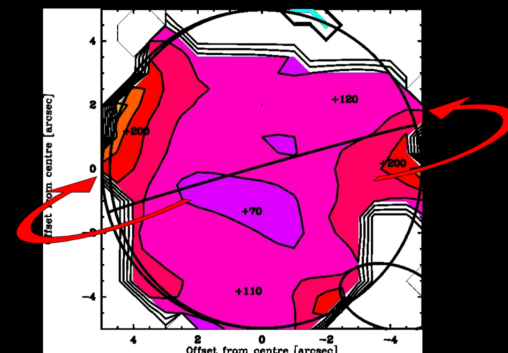


Shah et al., 1991

Combined analysis of SMA + CARMA CO(2-1) maps (2007-2009, PI Lellouch, Sagawa, Gurwell)

Quadrature East (SMA)

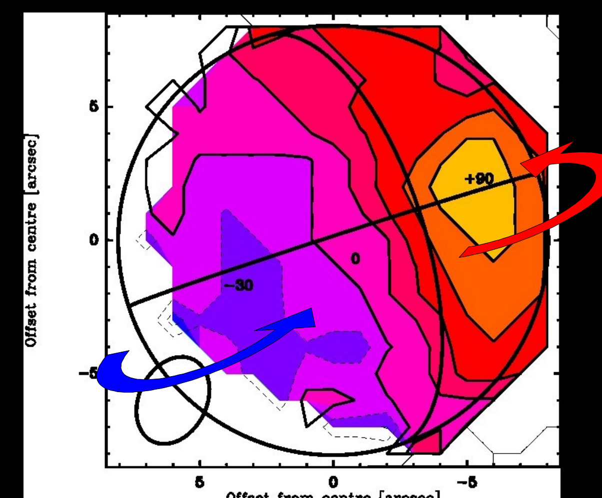




Superior conjunction
(day-side, CARMA)

Measurement errors
~30-40 m/s
(more for CARMA)

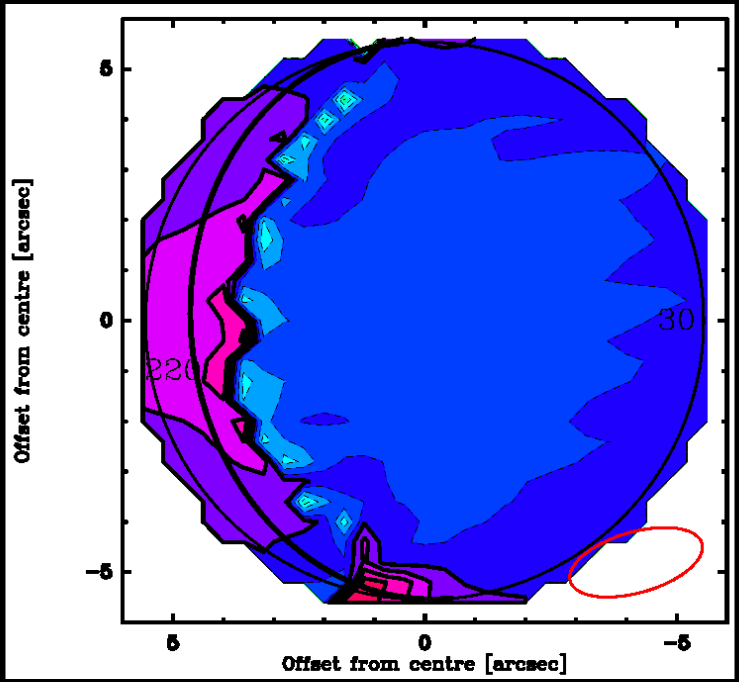
Quadrature West (SMA)



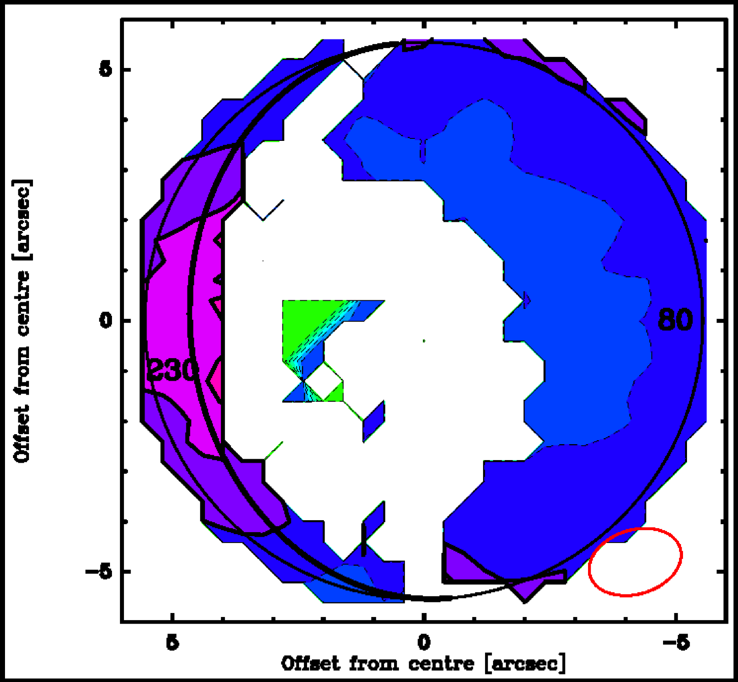
- **Subsolar-to-antisolar wind** dominating
- Significant velocity variations with local-hour
- Possible zonal retrograde jet at night near equator

Trends confirmed by high SNR **CO(3-2) ALMA day-side maps** (PI Encrenaz) (errors <10 m/s)

- **dominant SSAS wind (V_{ter}= 211/245 m/s)**
- zonal retrograde wind in an equatorial band (V_{equ}= 50/30 m/s)

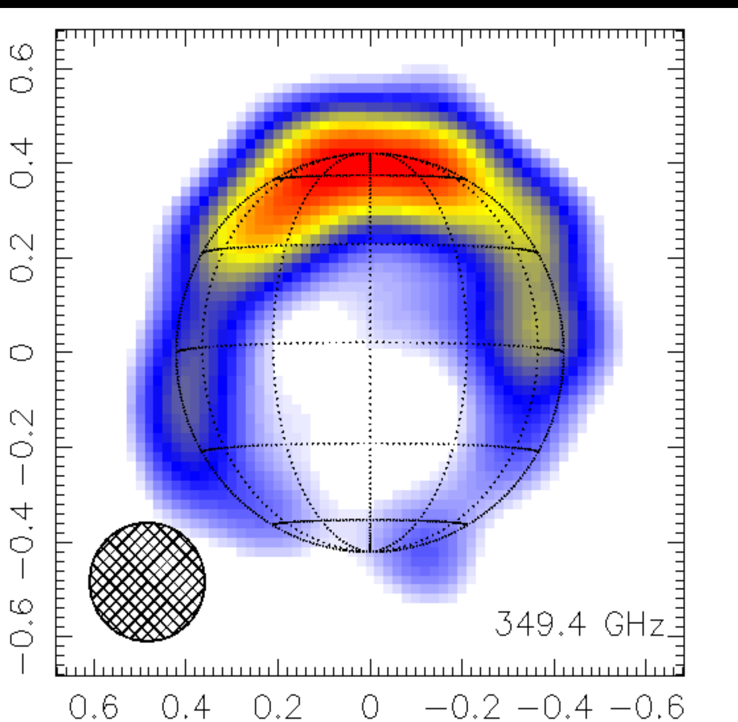


Doppler-shift map, Nov 14th,2011

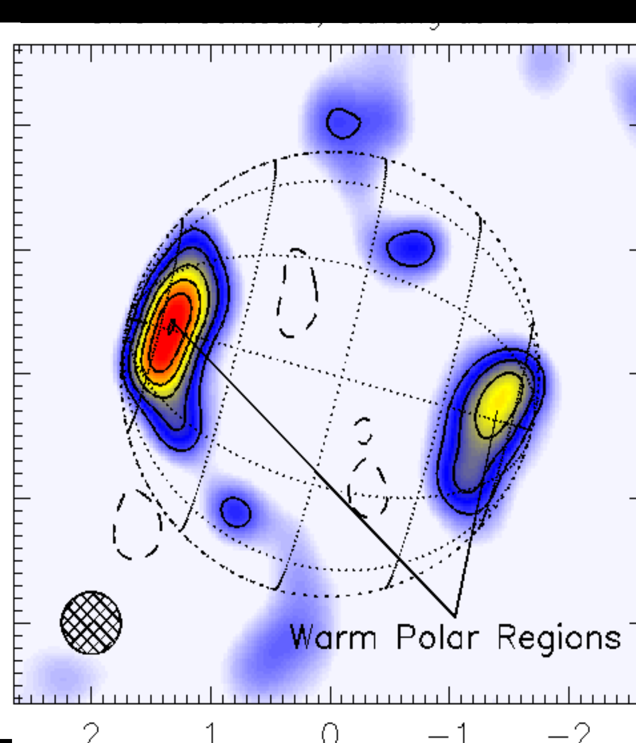


Doppler-shift map, Nov 15th, 2011

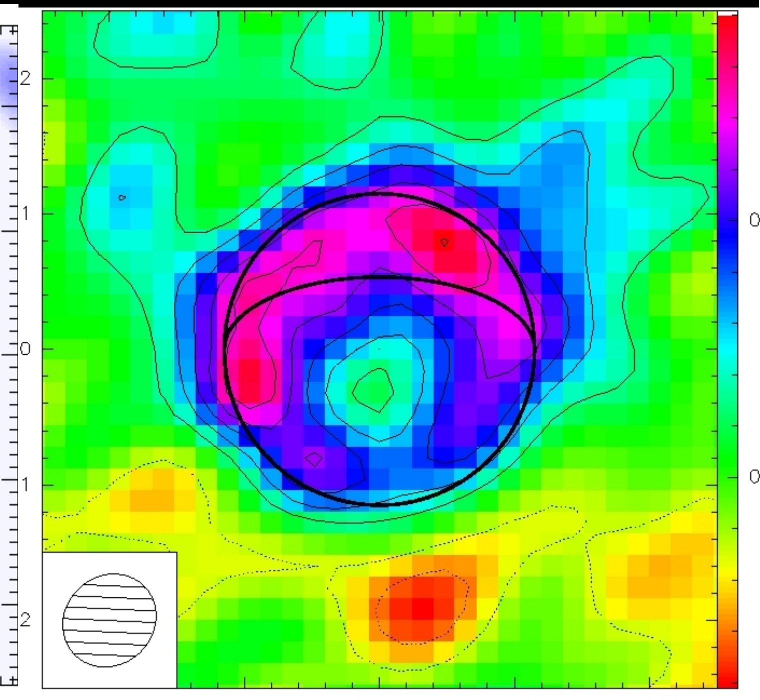
High-resolution imaging



TITAN - CH_3CN
(Gurwell, 2009)



URANUS - continuum
(Hofstadter, 2006)



NEPTUNE - HCN
(Moullet, 2010-2012)

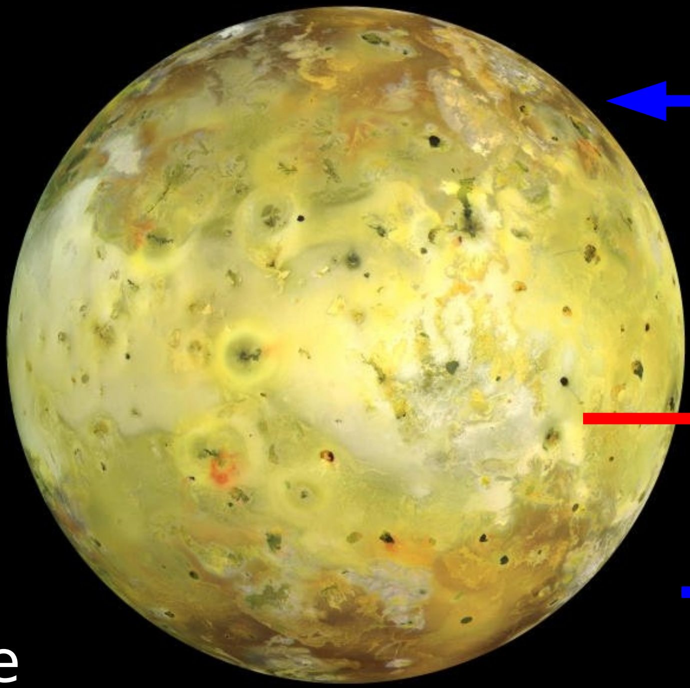
NASA/JPL/University of Arizona

Io's atmosphere

Composition:
SO_2 (SO)

Large **spatial variations** (~patchiness)

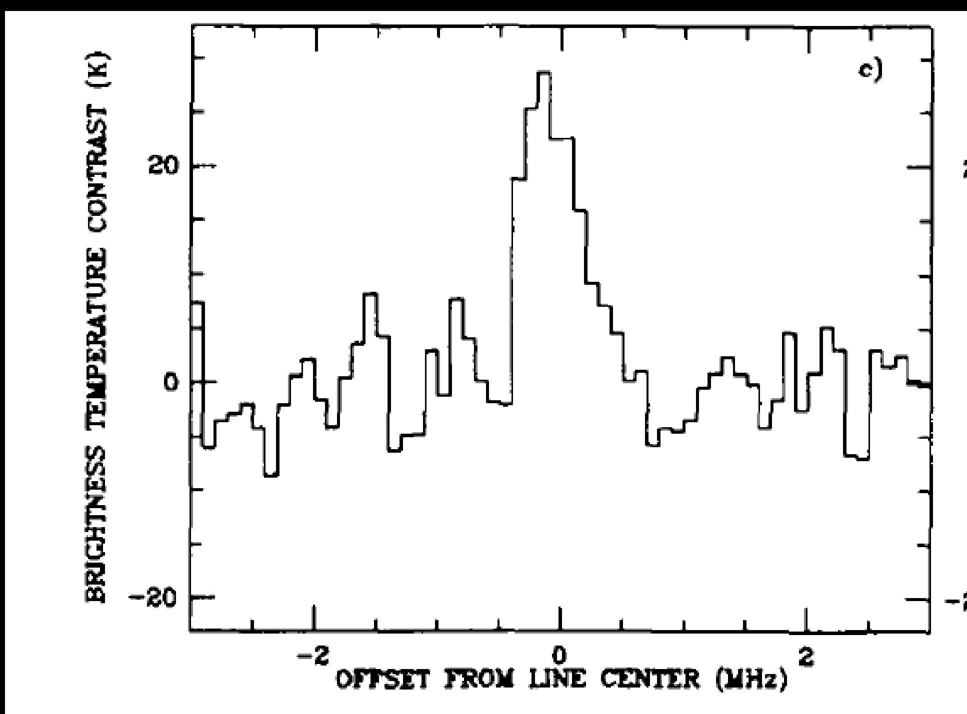
High temporal pressure variations (> factor 10)



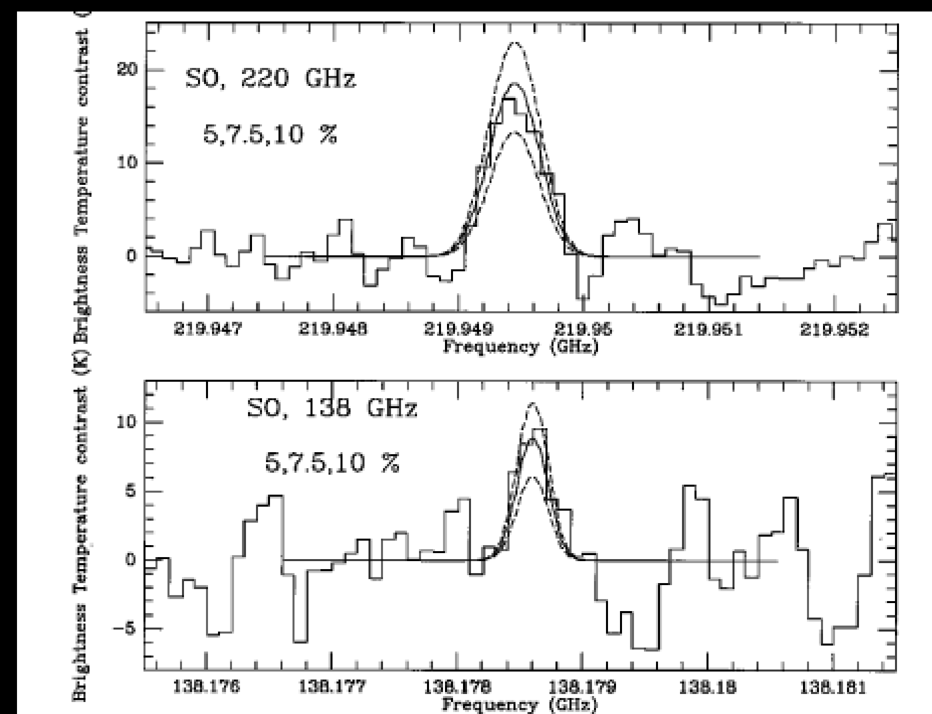
How is it **replenished**?
What controls its **spatial structure**?
What drives temporal variations?

Detection of rotational lines of main species (SO_2, SO, NaCl, Kcl,...) by disk-averaged single-dish data.

Evidence for SO_2 longitudinal variations, confirmed by HST.

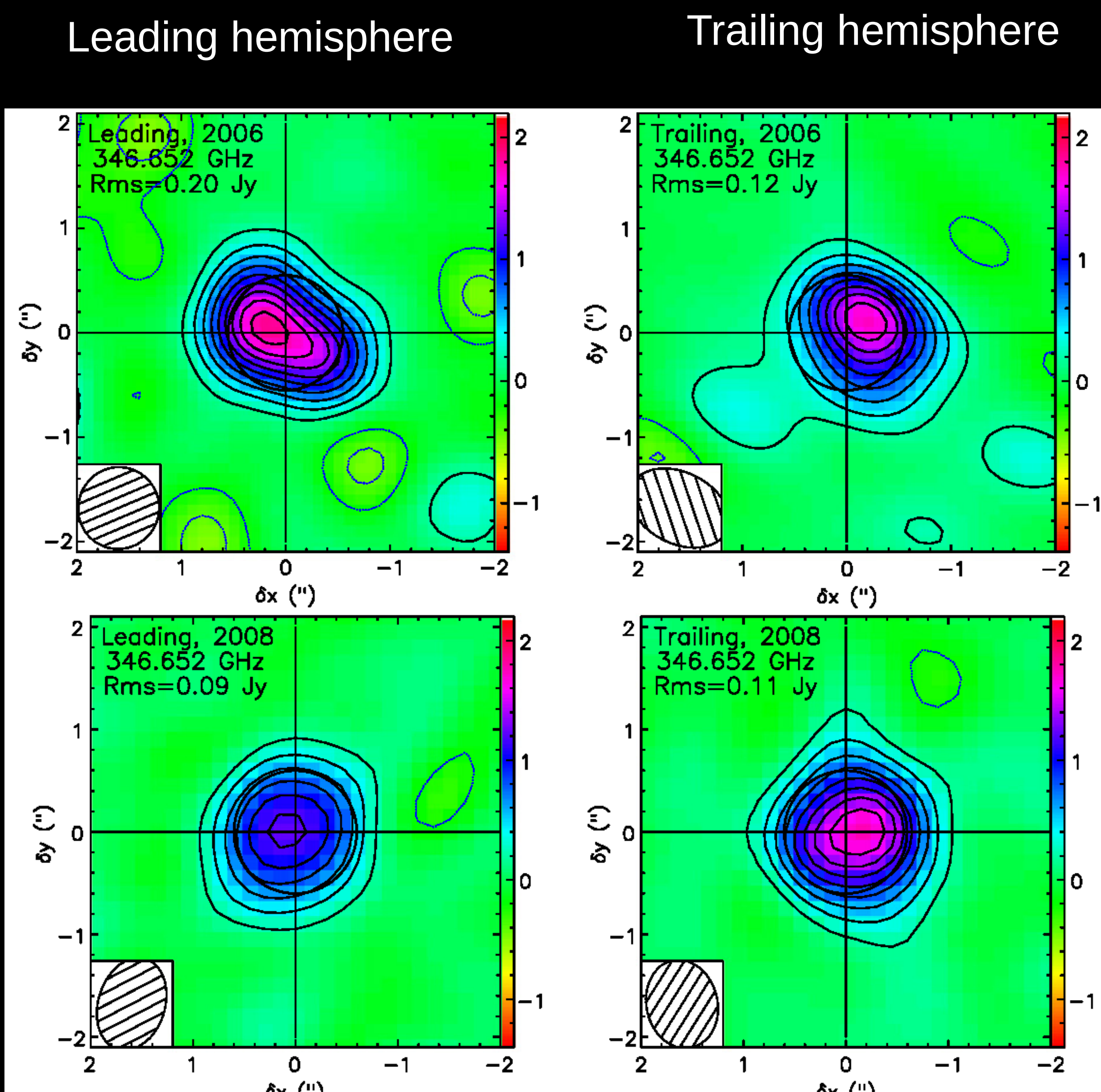


First SO_2 detection at IRAM-30m (Lellouch et al., 1992)



First SO detection at IRAM-30m (Lellouch et al., 1996)

SMA mapping of SO_2 (2006-2008, PI Moullet, Gurwell)



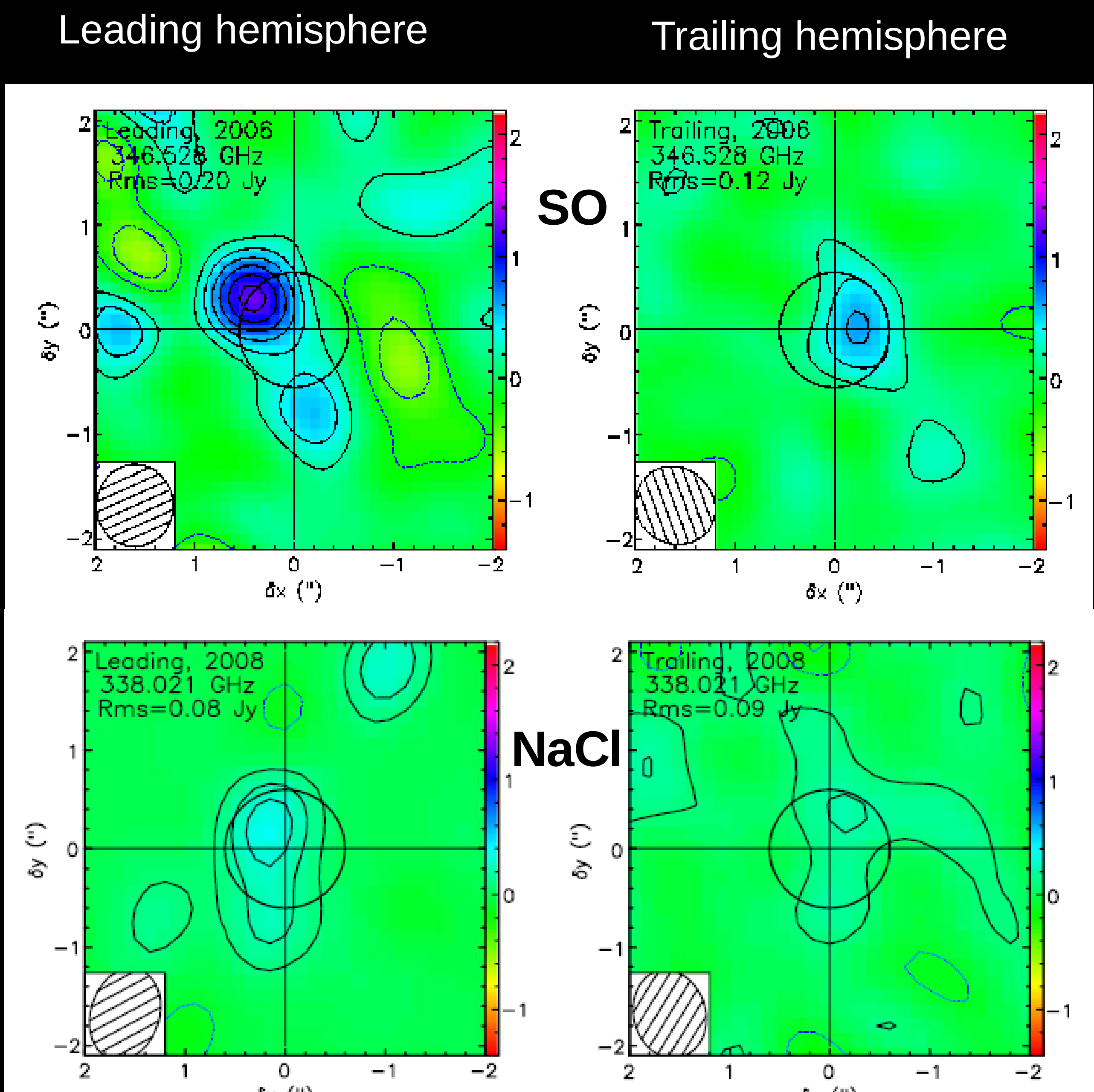
Moullet et al., 2010

Submm maps globally coherent with HST/ IRAM-PdBI

Spread-over distribution, Concentrated on anti-jovian hemisphere

Supporting **sublimation as main source for the bulk (SO_2) atmosphere**

first maps of minor species: SO and NaCl

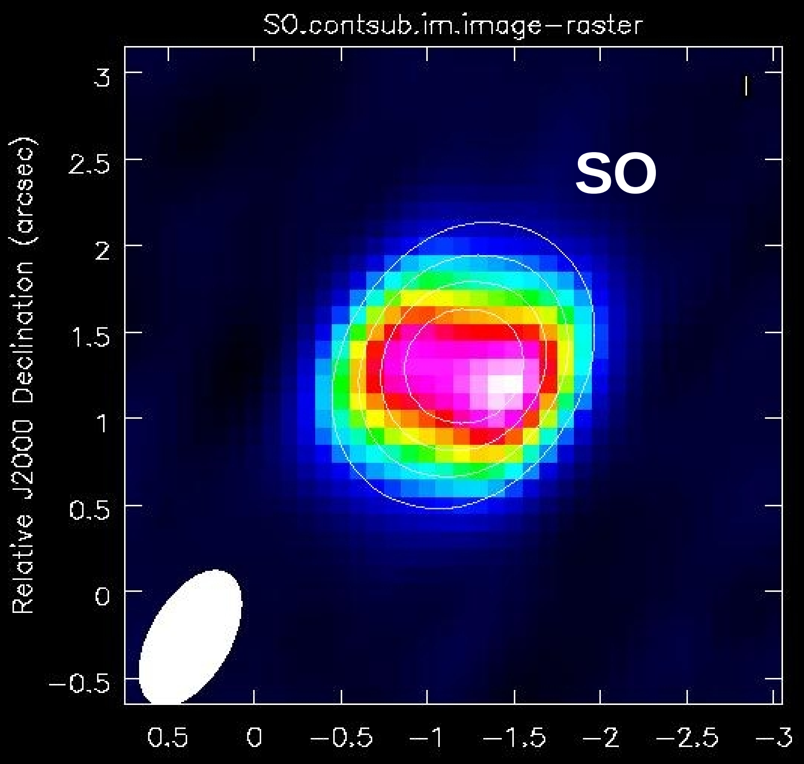


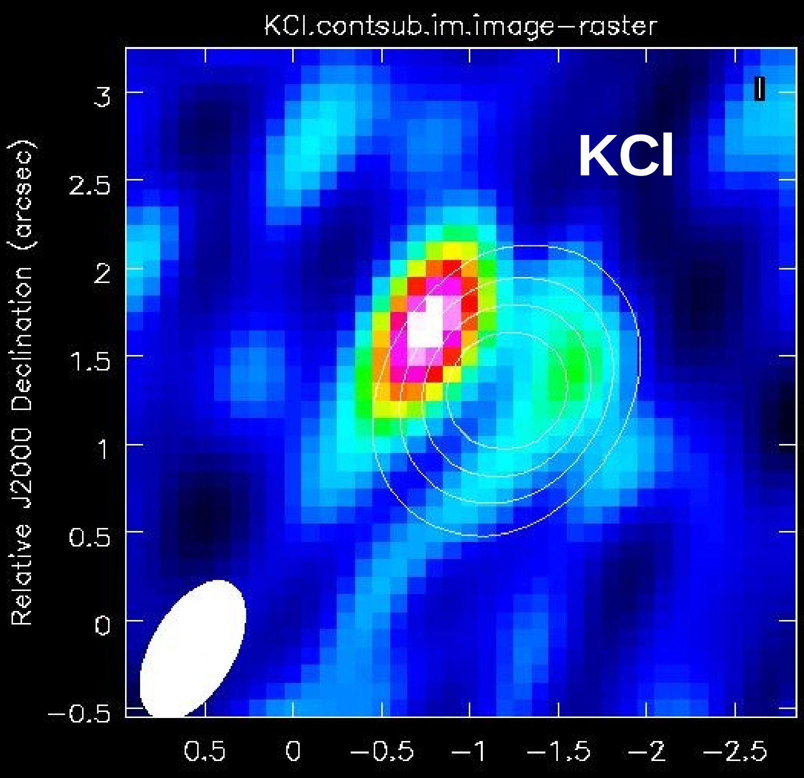
- **less extended** emission than SO_2: different sources
- SO: photochemistry and plume outgassing
- NaCl: plume outgassing

Expanding the study to other minor species with ALMA (PI A. Moullet) with enhanced resolution and SNR

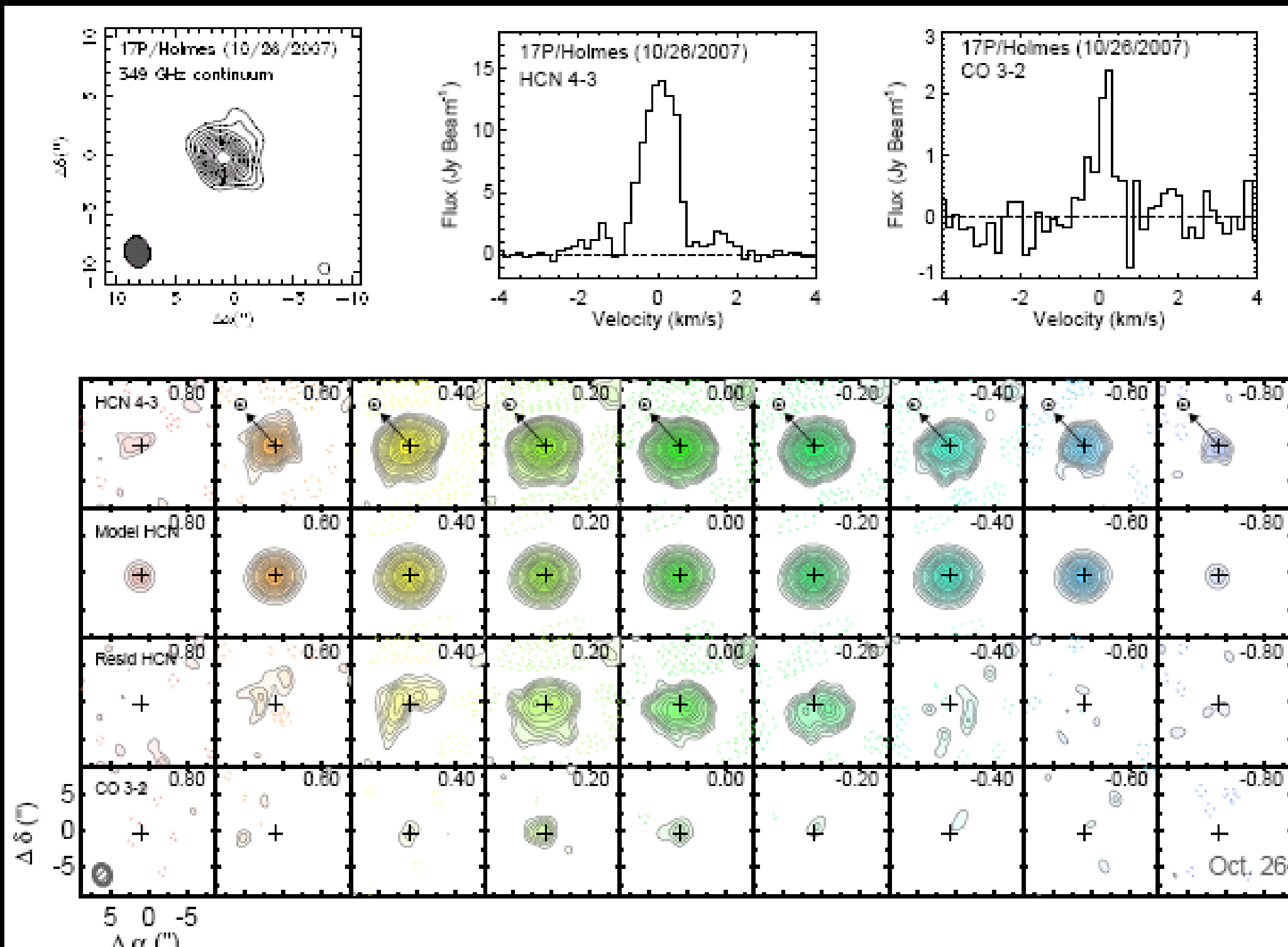
Volcanic species (KCl, SO) trace **location of active volcanoes**

Different maxima locations suggest various plume compositions





Comet 17P/Holmes outburst



Monitoring Oct. 2007 outburst (PI C. Qi)

Continuum, **CO, HCN, H_2CO and CS** lines mapping

Two outgassing structures with different composition:

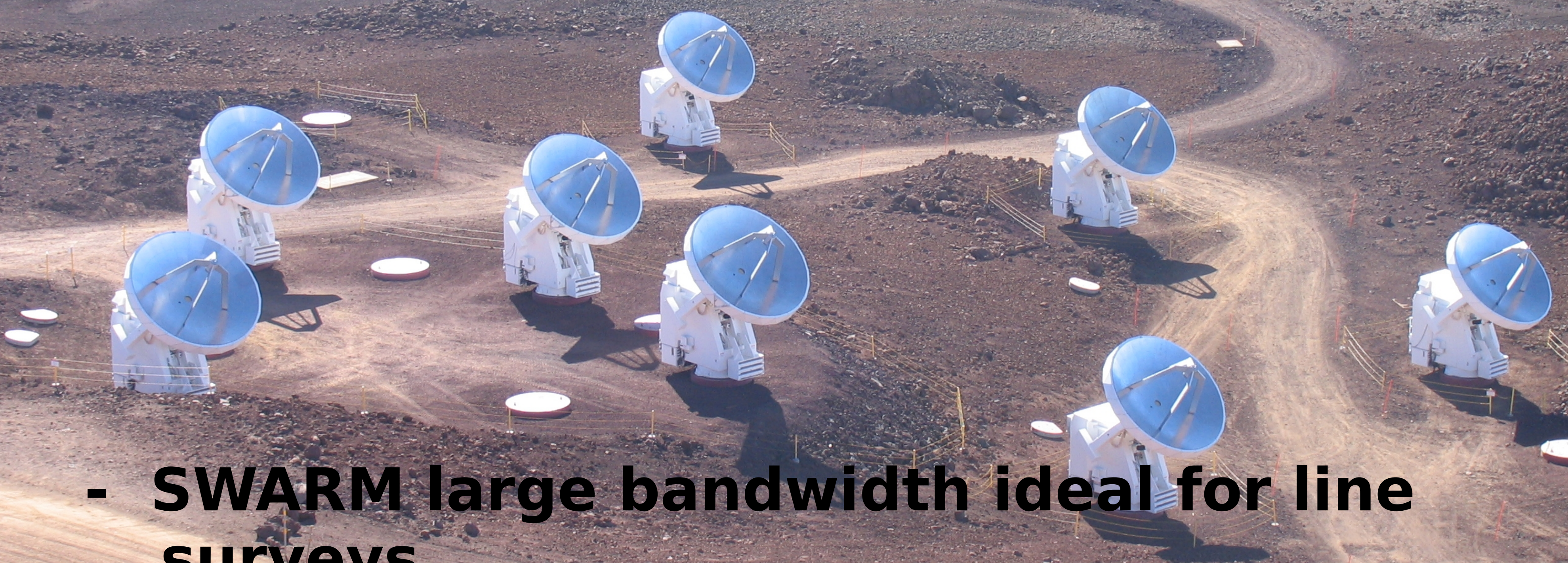
- **isotropic component**
- **jet (closer from nucleus)**

In its first decade, SMA has had a determinant role in demonstrating sub-mm interferometry for Solar System studies, paving the way to ALMA

Pioneered several mapping observations uniquely contributing to characterize planets, moons and asteroids

<u>SMA in the ALMA era</u>

- best Northern site
- imaging capacities for a variety of scales



- SWARM large bandwidth ideal for line surveys
- scheduling flexibility for monitoring and large-scale projects


!! Happy birthday SMA !!