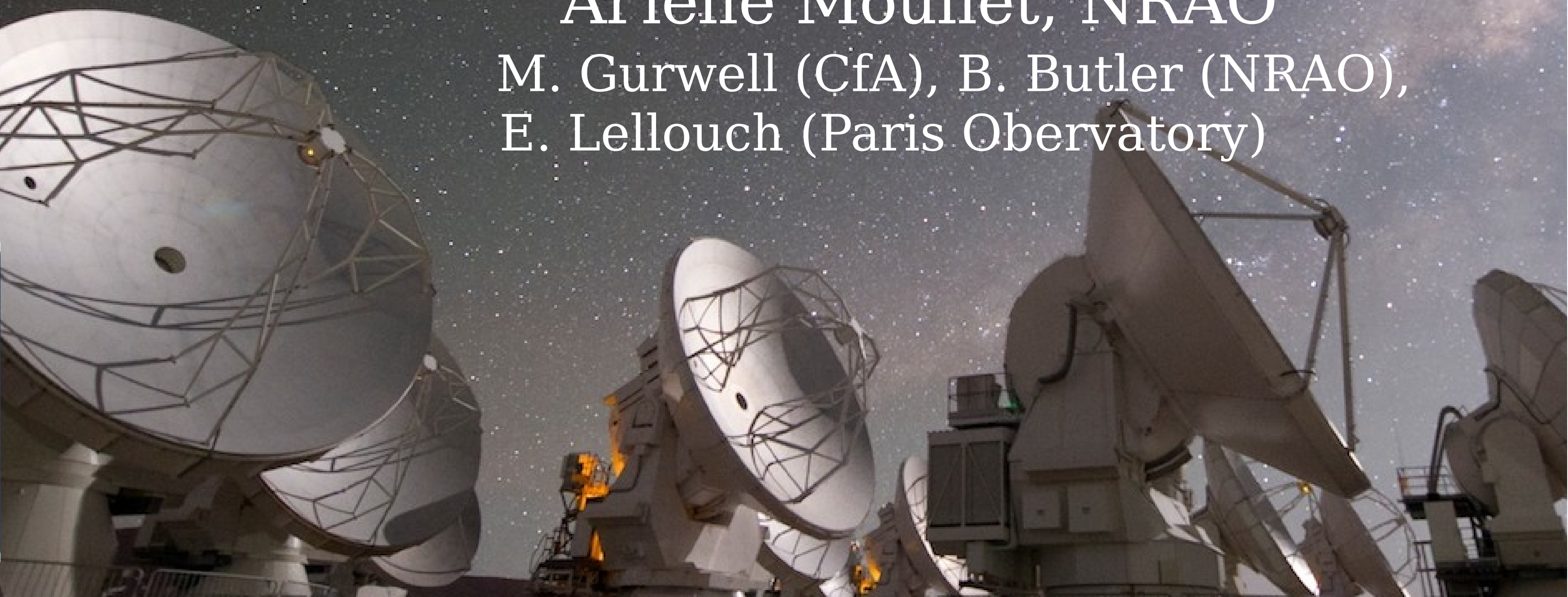
Exploring the Physical and Chemical Diversity of the Solar System: The Submillimeter Approach

Arielle Moullet, NRAO
M. Gurwell (CfA), B. Butler (NRAO),
E. Lellouch (Paris Obervatory)



NRAO

Studying a closeby evolved system: what's the point?

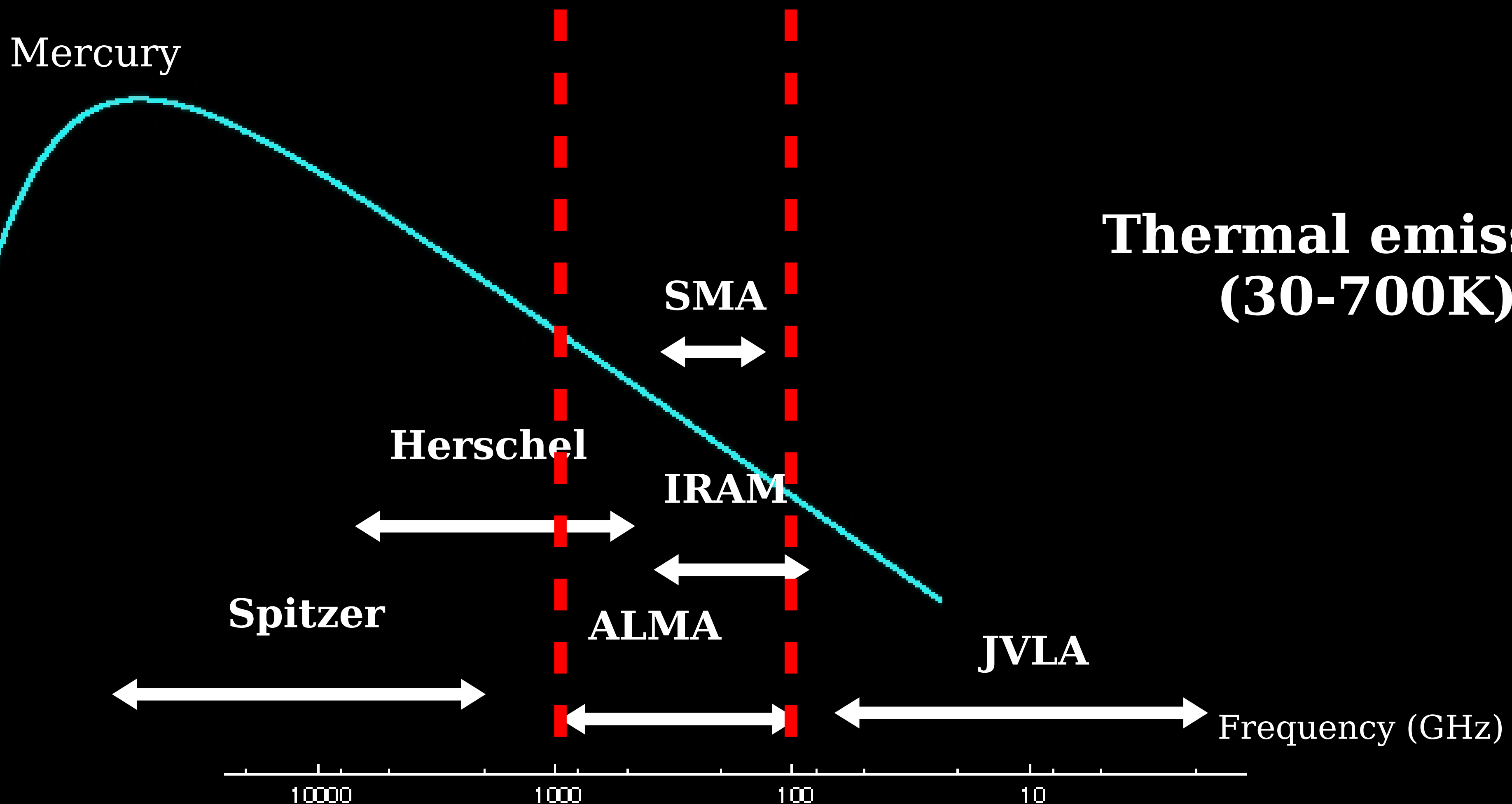
Information relevant to exoplanetary systems and disks:

• clues to **<u>system formation</u>**:
isotopic ratios, bulk densities, dynamical families, ...

- characterization of **<u>chemical and physical processes</u>**:
seasonal cycles, gas escape, surface alteration, volcanism, ...

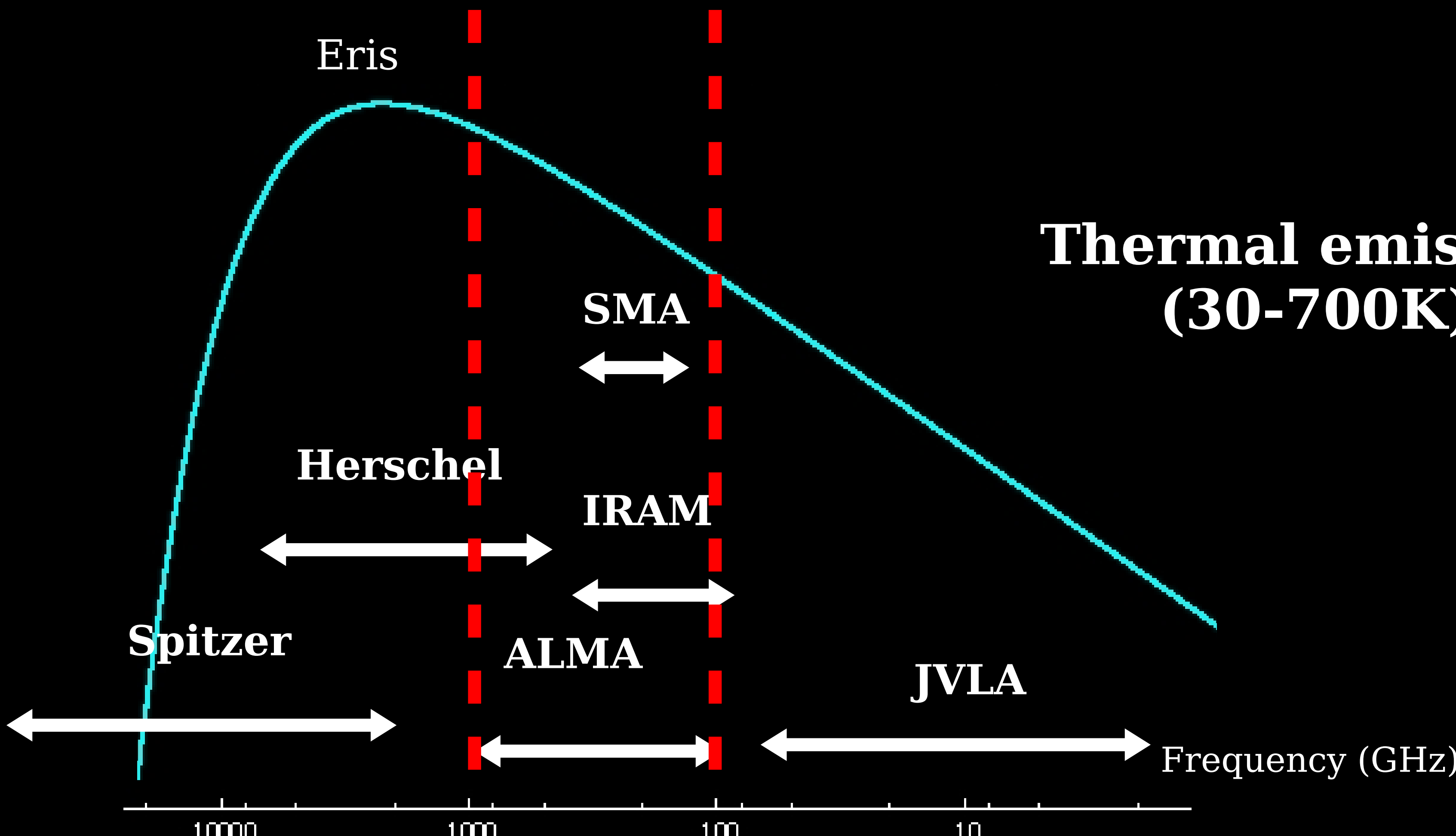
- retracing the **<u>history of individual bodies</u>** :
climate, water content, organic chemistry

What is (sub)mm radiation in the solar system?



Thermal emission (30-700K)

What is (sub)mm radiation in the solar system?

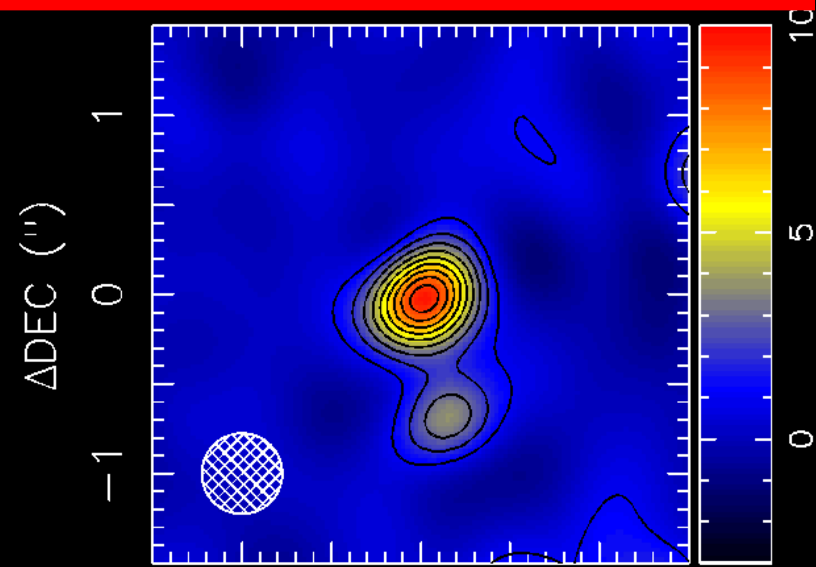


Thermal emission (30-700K)

What is (sub)mm radiation in the solar system?

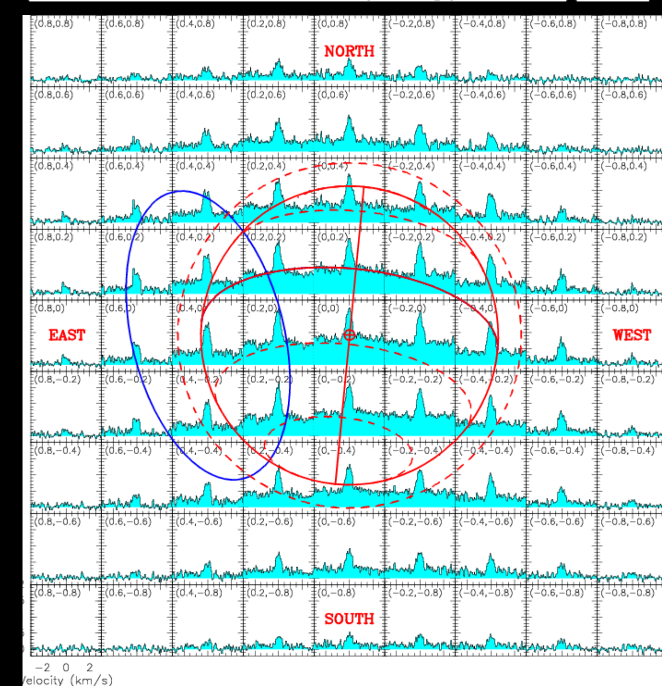
- Surface continum emission
(airless bodies/ transparent atmosphere

Pluto/Charon system, SMA,
Gurwell et al., 2005



- Atmospheric pseudo-continuum
collisional emission (pressures ~1 bar)

HC_3N line on Titan, IRAM-
Moreno et al., 2005



- Atmospheric rotational lines
(pressures 1bar -> 1microbar)

Performed observation projects

Brightness temperature measurements

Mapping CO, Detection SO_2, H_2O, HDO, SO
Mesospheric dynamics

Mapping CO
Detection H_2O_2, H_2O,HDO
Winds

PH_3, H_2O, NH_3, CO, CS detections
HCN mapping

Io : mapping SO_2, SO
Detection NaCl, KCl
Winds

Detection PH_3, CO,H_2O

Titan : Detection HCN, CO, HC_3N, CH_3CN, H_2O
Winds

Detection H_2O

Detection CO, HCN, H_2O

Detection of Pluto and 7 other Kuiper Belt Objects, CO detection

Outline

I) Atmospheric **composition**

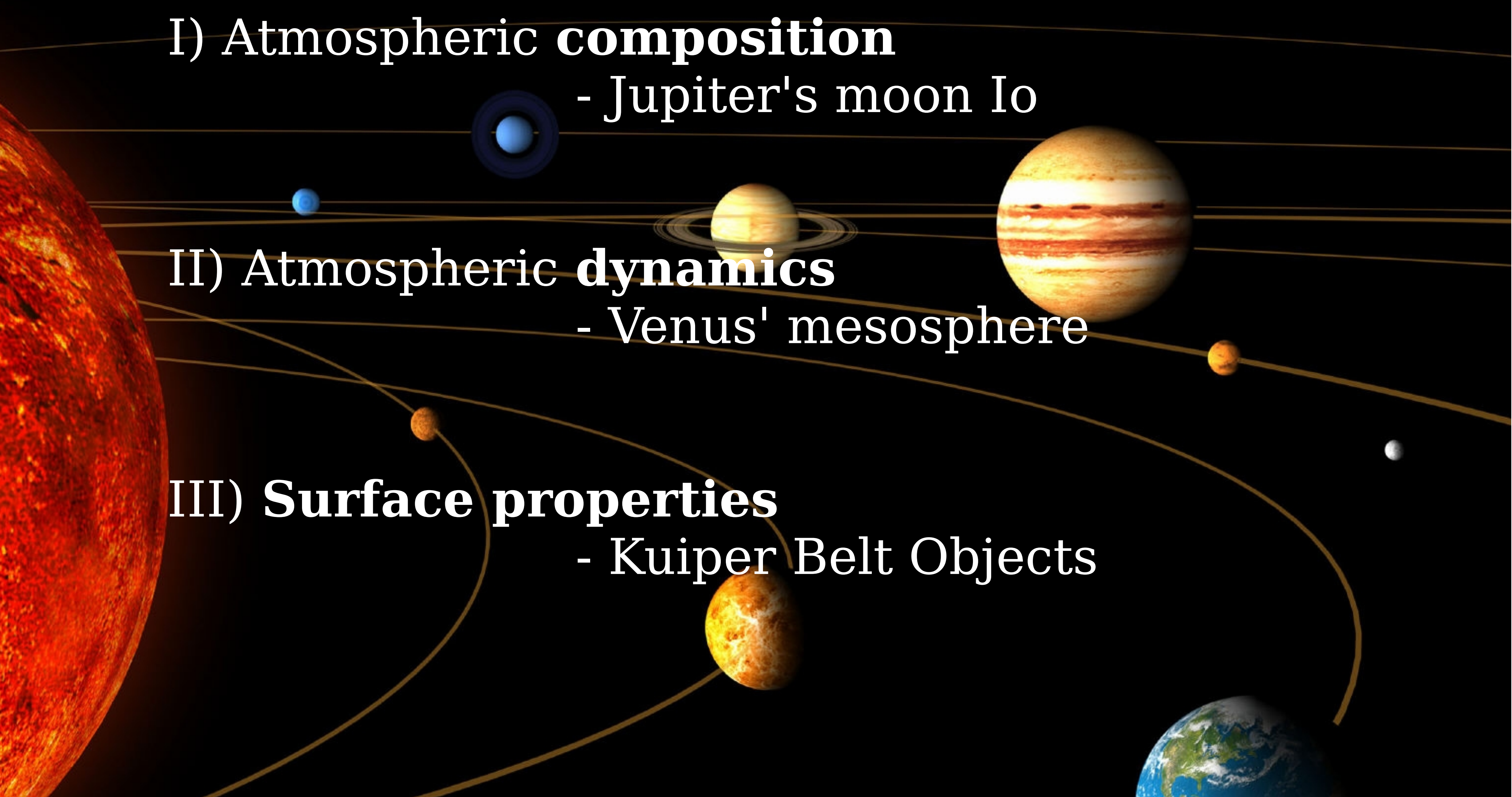
- Jupiter's moon Io

II) Atmospheric **dynamics**

- Venus' mesosphere

III) **Surface properties**

- Kuiper Belt Objects

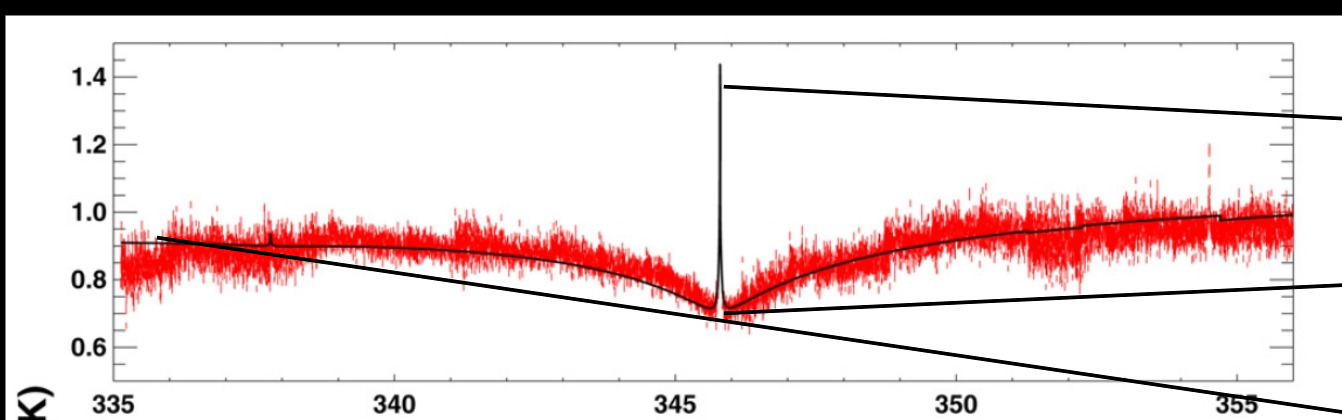


I) Atmospheric composition

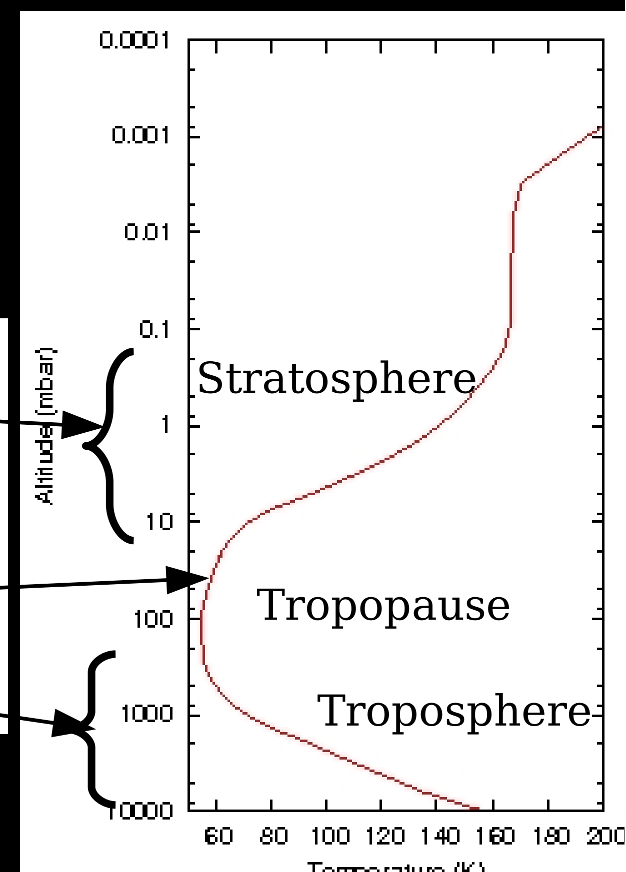
Detection of rotational lines of atmospheric compounds:
CO, HCN, HDO, H_2O, SO_2, SO, ...

- Line profile analysis: **column density- vertical mixing profile**

LTE emission
Collisional and Doppler broadened profiles
Differential sounding



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

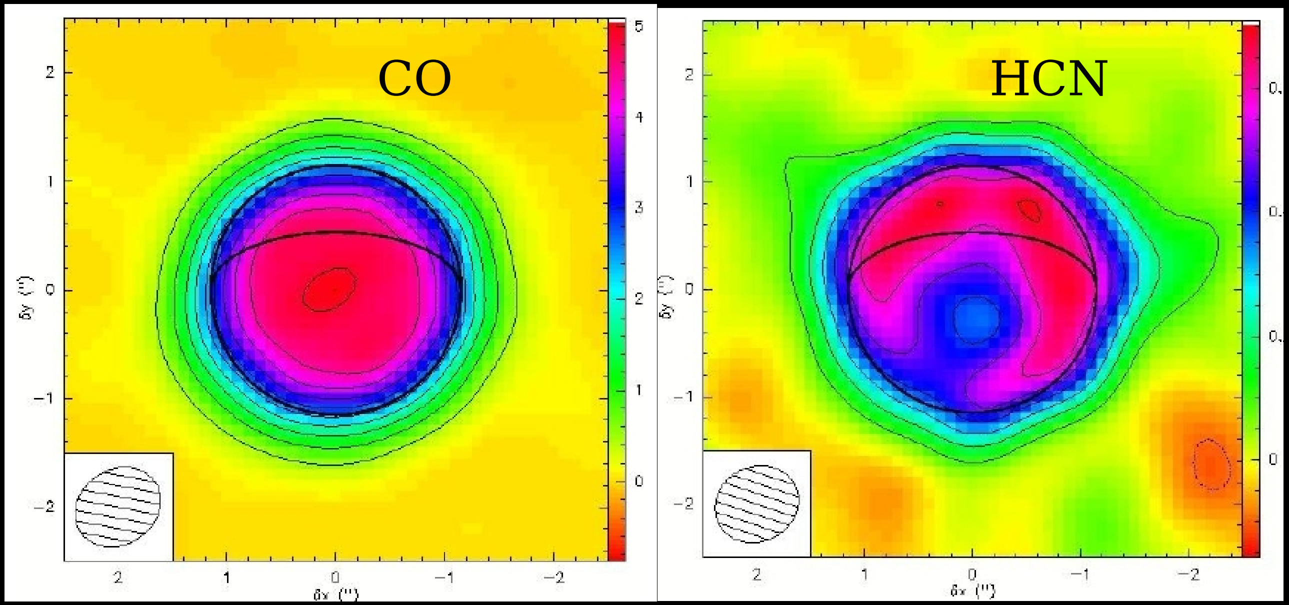


I) Atmospheric composition

- Line emission mapping : **horizontal distribution**

Single dish instruments: Venus, Jupiter
Interferometers: ice giants, Mars, large moons and asteroids, Pluto (ALMA)

CO(3-2) and H(4-3) integrated line emission on Neptune, SMA, Moullet et al., 2011



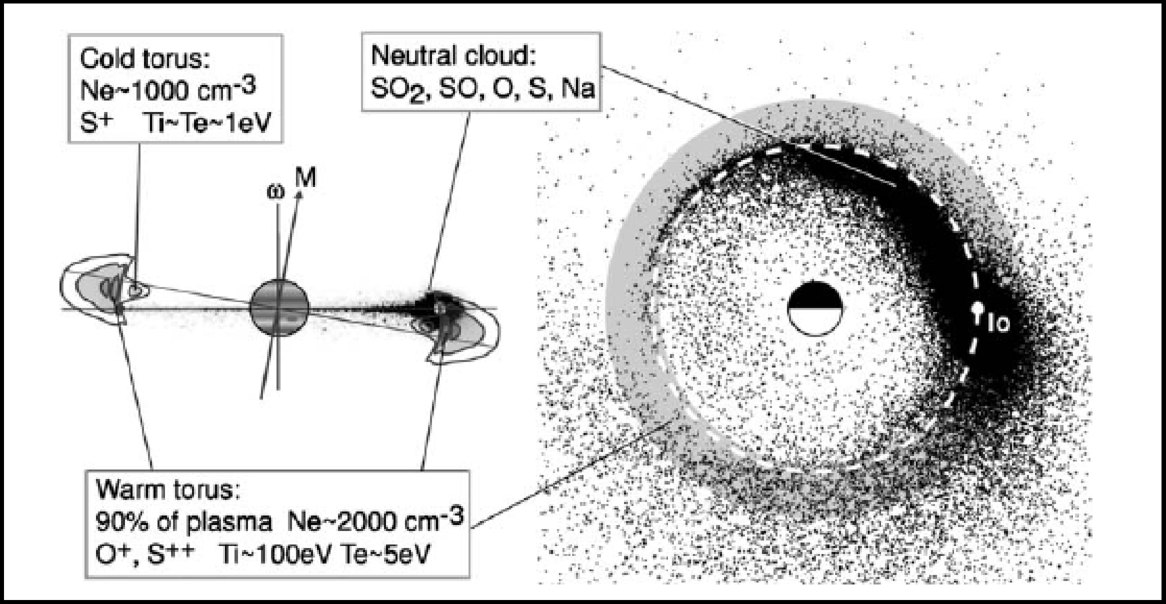
Io, Jupiter's volcanic moon

- Strongest **volcanic activity** in solar system

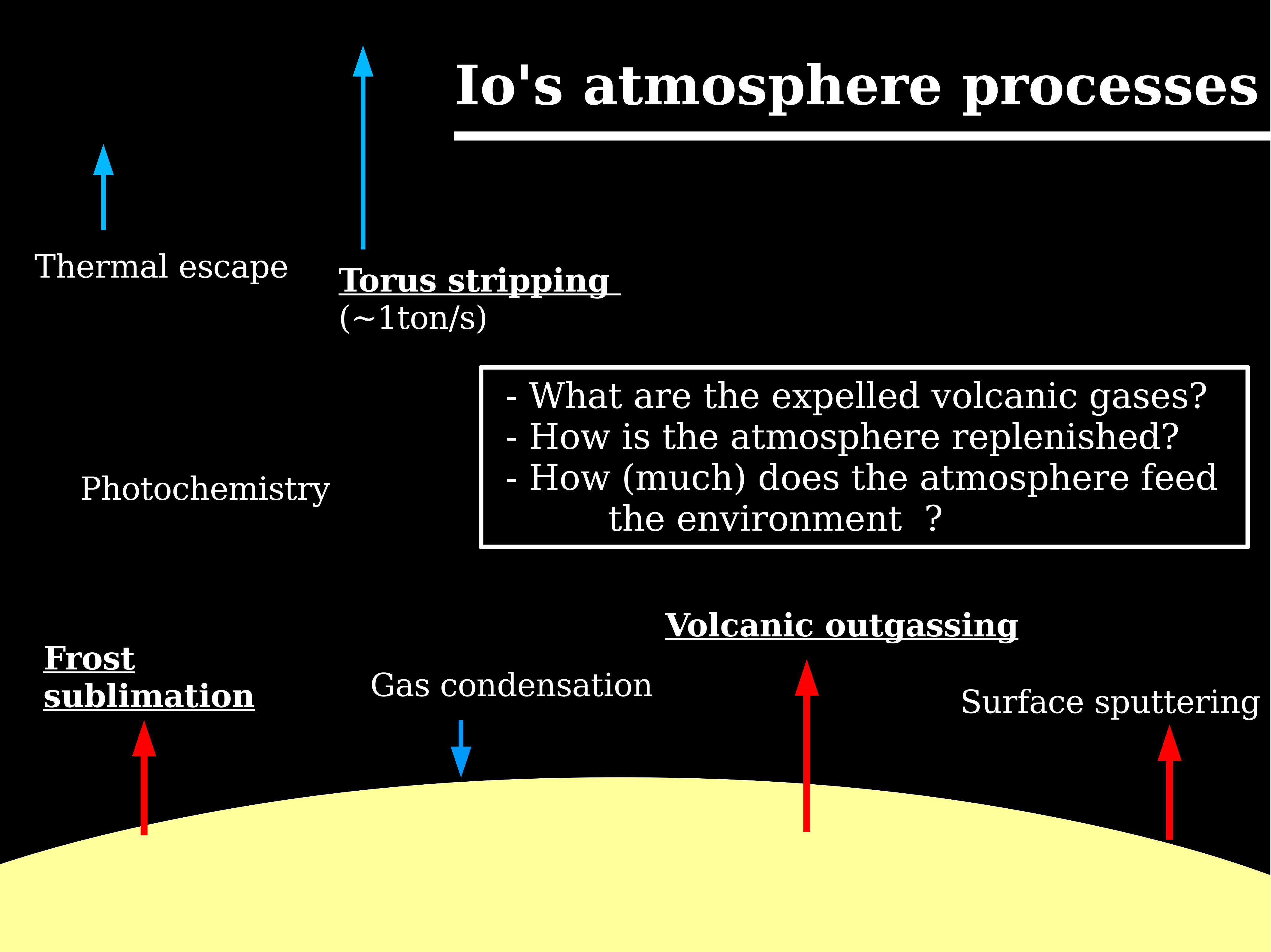
- **SO_2 frost-**covered surface

- Environment: neutral clouds and **plasma torus**

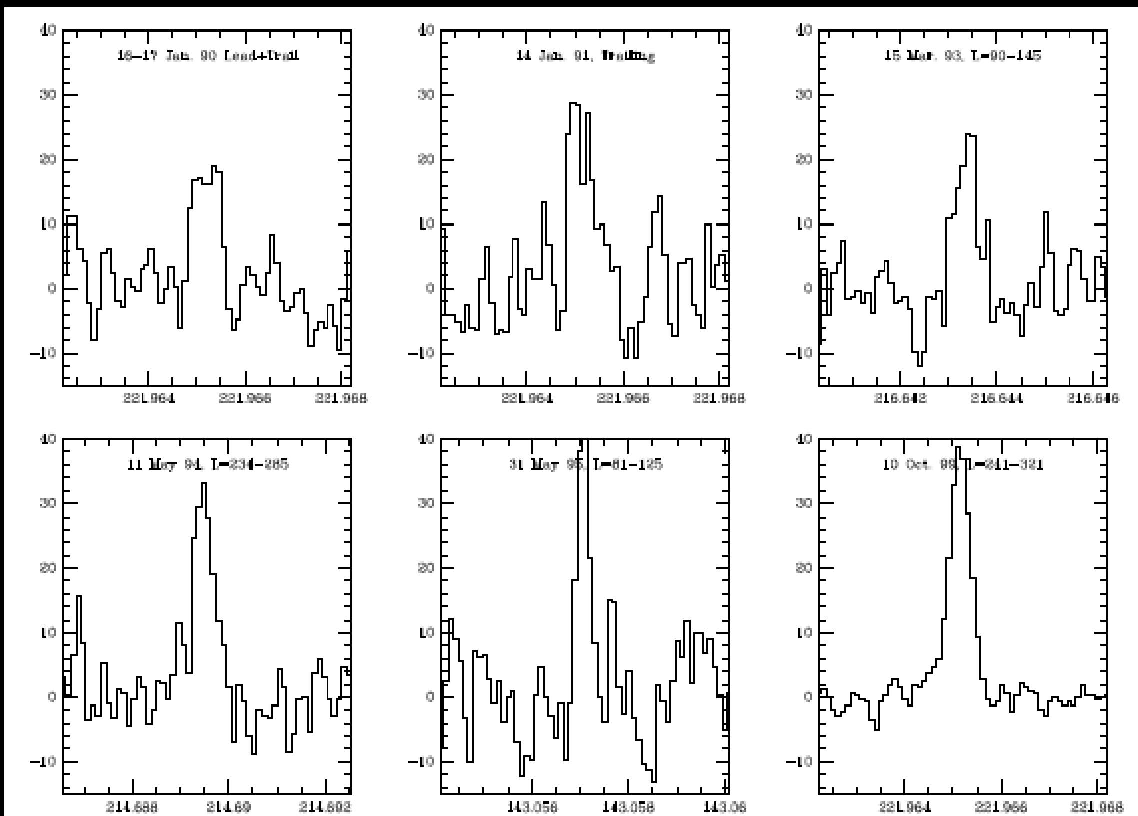
- **SO_2 atmosphere**. tenuous (1-10nbar)



Schneider and Bagenal, 2007


Io's atmosphere processes
Thermal escape
Torus stripping
(~1ton/s)
- What are the expelled volcanic gases?
- How is the atmosphere replenished?
- How (much) does the atmosphere feed the environment ?
Photochemistry
Volcanic outgassing
Frost sublimation
Gas condensation
Surface sputtering

SO_2 lines analysis



SO_2 lines, IRAM-30m,
Lellouch et al., 1990

Atmospheric structure interpretations from disk-integrated observations :

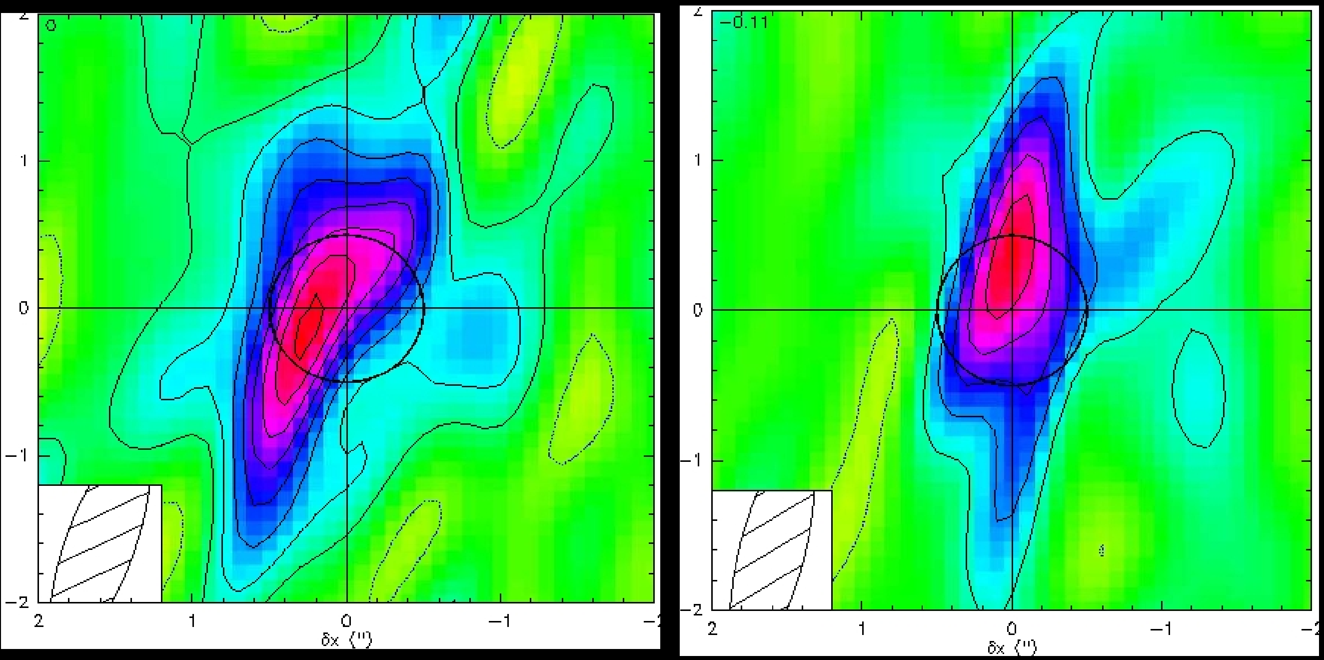
- very **localized** (<20%)
hot (~500 K)
quite dense (~6e^{17}cm^{-2})

- **spread-out**,
cold (~140 K),
lower density (~1e^{16} cm^{-2})

SO_2 mapping

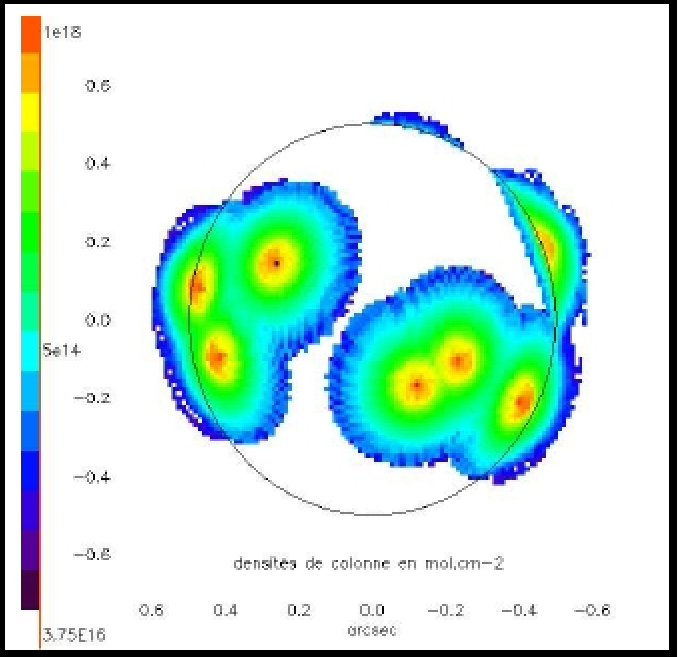
Jupiter direction

Leading hemisphere   Trailing hemisphere



SO_2 integrated emission,
IRAM-PdBI,
Moullet et al., 2008

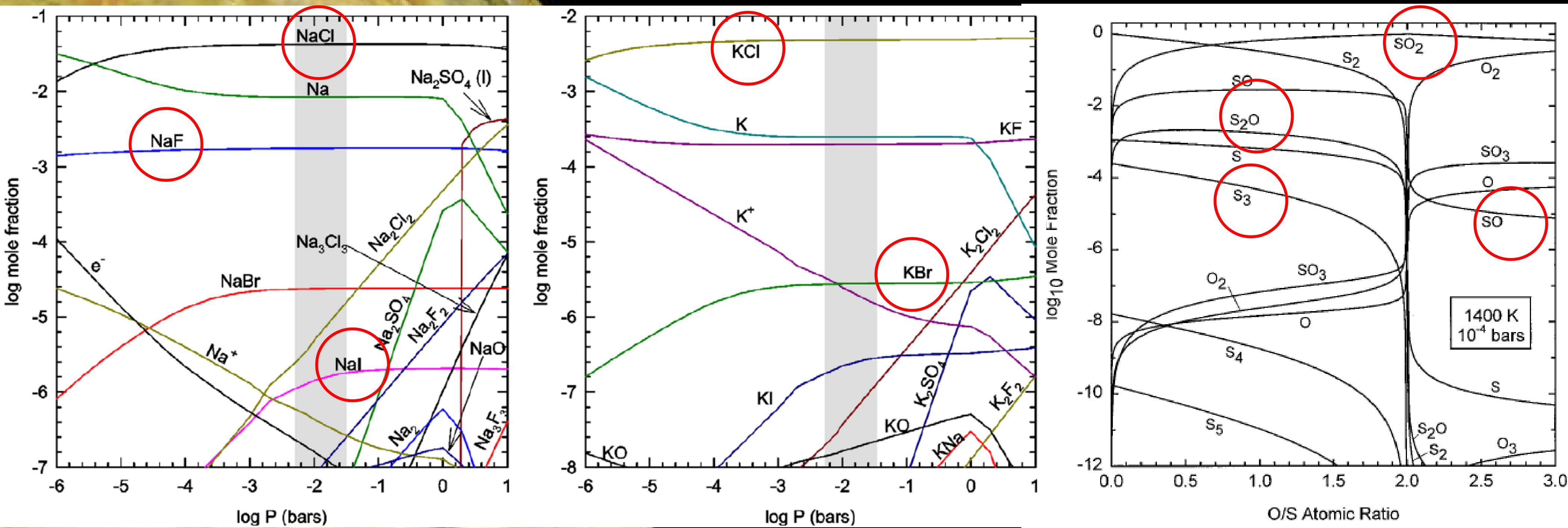
Simulation of a volcanically-sustained atmosphere based on Galileo plume localisation



- SO_2 spatially extended, local-hour restricted: Coherent with **sublimation-sustainment**

- Comparison to plume emission models: **volcanic contribution is minor**

Volcanic gases exploration



Schaefer et al., 2004

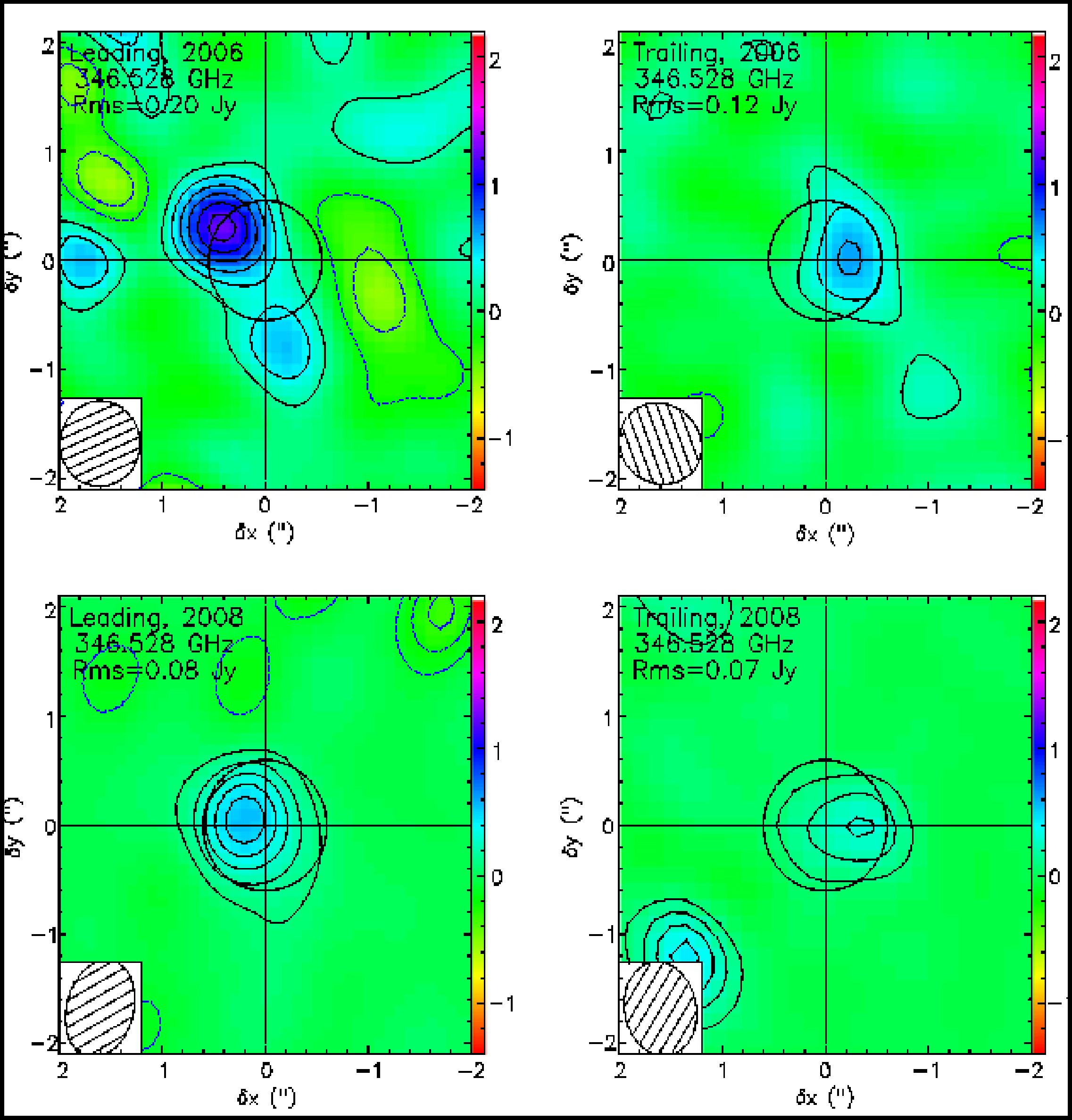
Zolotov et al., 1998

Plume composition depends on vent temperature, conduit pressure, atomic ratios : **defines volcanic regimes**

Sulfur monoxide

Jupiter direction

Leading hemisphere Trailing hemisphere



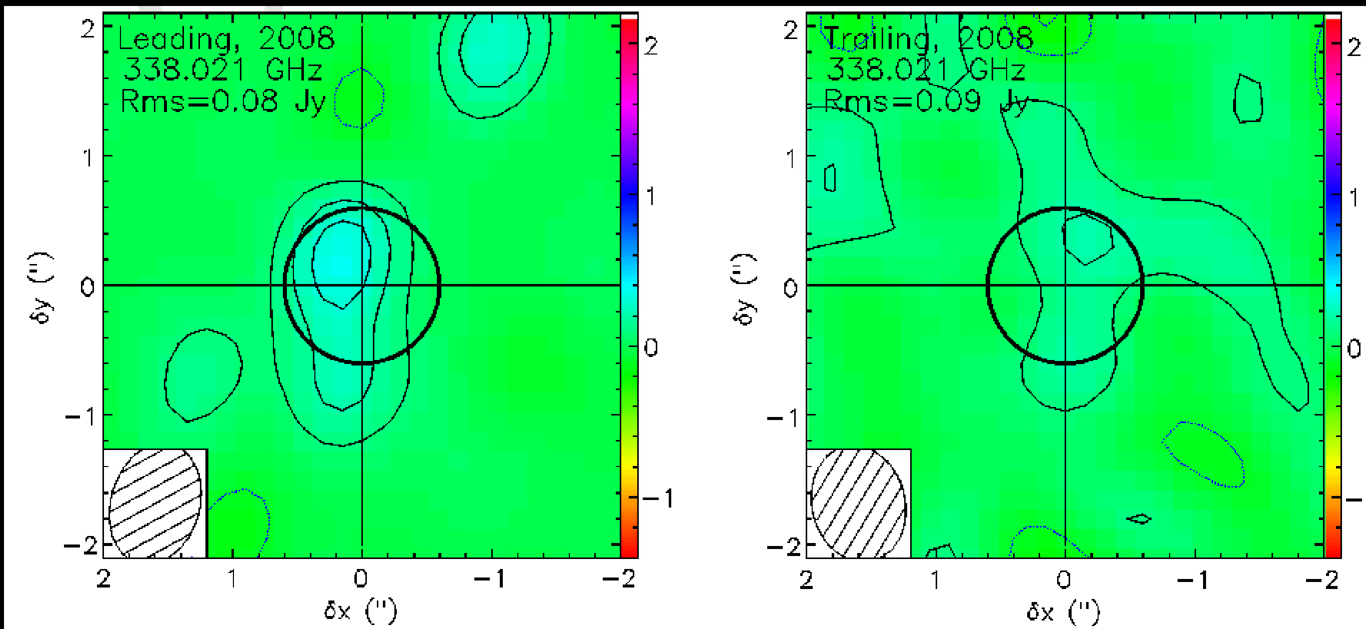
SO emission, SMA, Moullet et al., 2010

- more **spatially concentrated** than SO_2
- volcanic emission can contribute to <30% of SO content
- coherent with **SO_2-photolysis** being the main SO source

Sodium chloride

Leading hemisphere

Trailing hemisphere



NaCl emission, SMA, Moullet et al., 2010

- (Low quality) Mapping suggests localized emission
- **Volcanism can be the sole NaCl source** if $NaCl/SO_2$ 0.6-2.5 %
- Short atmospheric lifetime: **plume activity tracer on day-side**

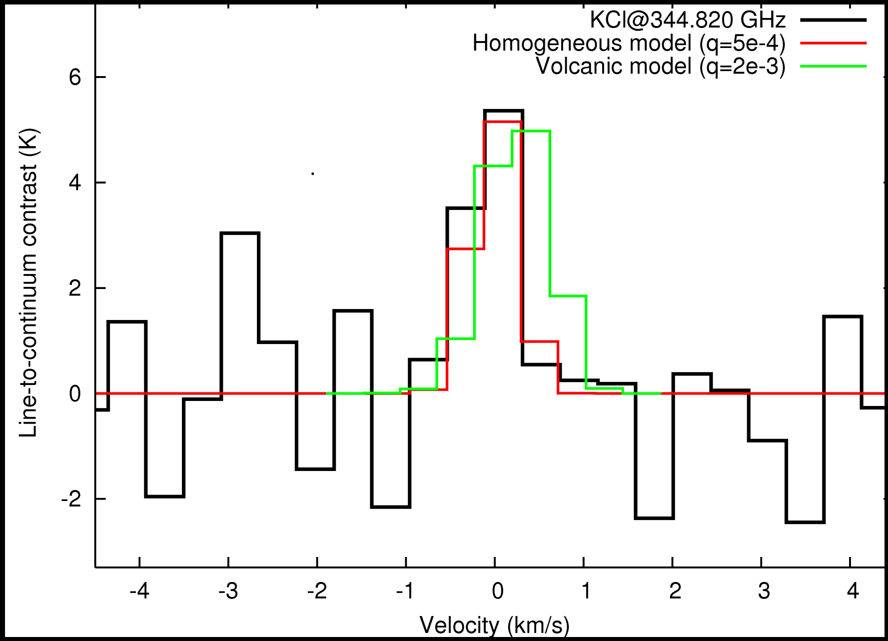
Potassium chloride

Expected source of K in neutral clouds, Jupiter's rings

- **Tentative detection:**
KCl/SO2 = 5(+/-2) x 10^{-4}

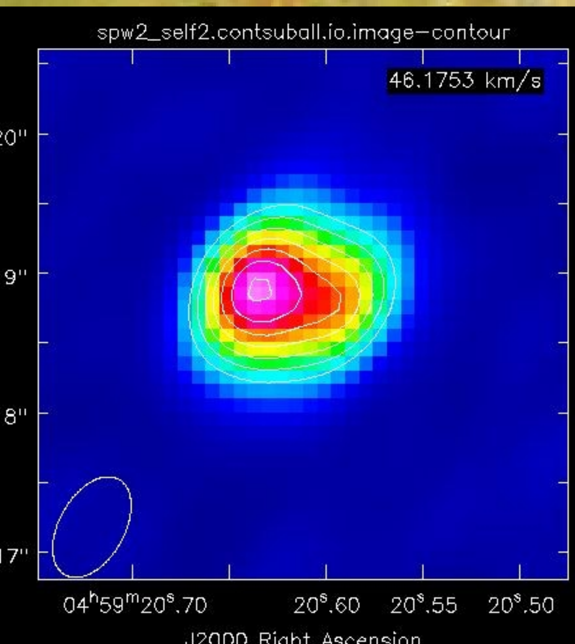
- **Consistent with purely volcanic sustainement**

Very low Na/K ratio (~2.7):
Ultra-potassic lavas?
Vaporization fractionation?



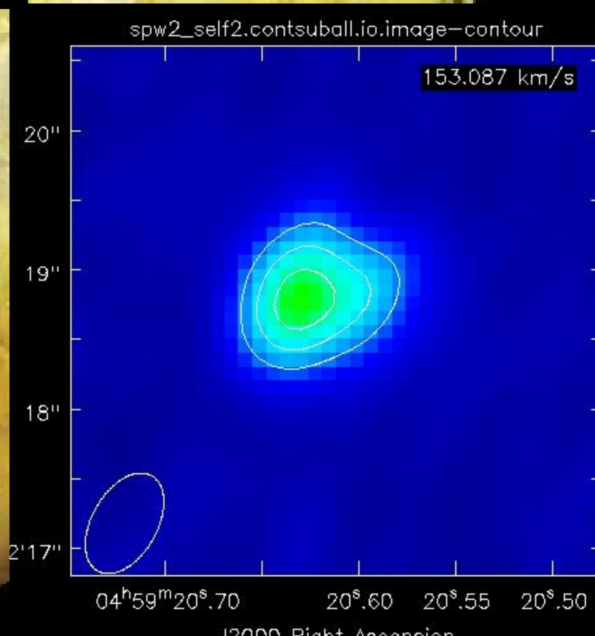
Tentative detection of KCl line, APEX, Moullet et al., 2013

Next composition exploration: ALMA



ALMA Cycle 0 :
SO_2

ALMA Cycle 0 :
SO



Observing time awarded in Cycle 0 and Cycle 1

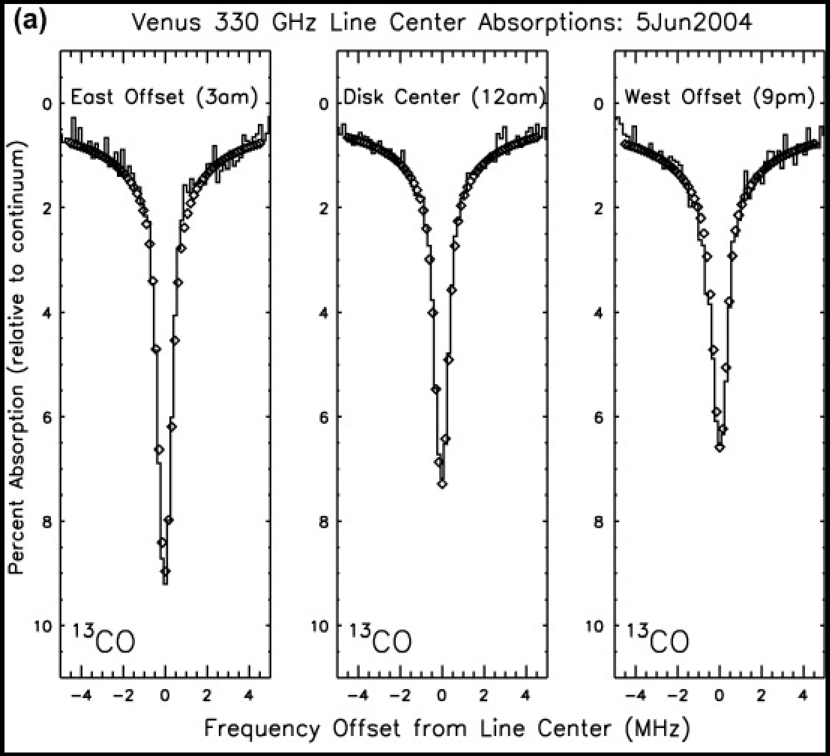
Goals : firm detection of KCl, detections of SiO, S_2O, ^{34}S.. :
→ **constrain volcanism**

Spatial resolution ~0.3'':
→ **characterize sublimation**

II) Atmospheric dynamics

Doppler-shift mapping in line cores directly indicate
projected wind velocity

High altitudes **rarely probed by other techniques**

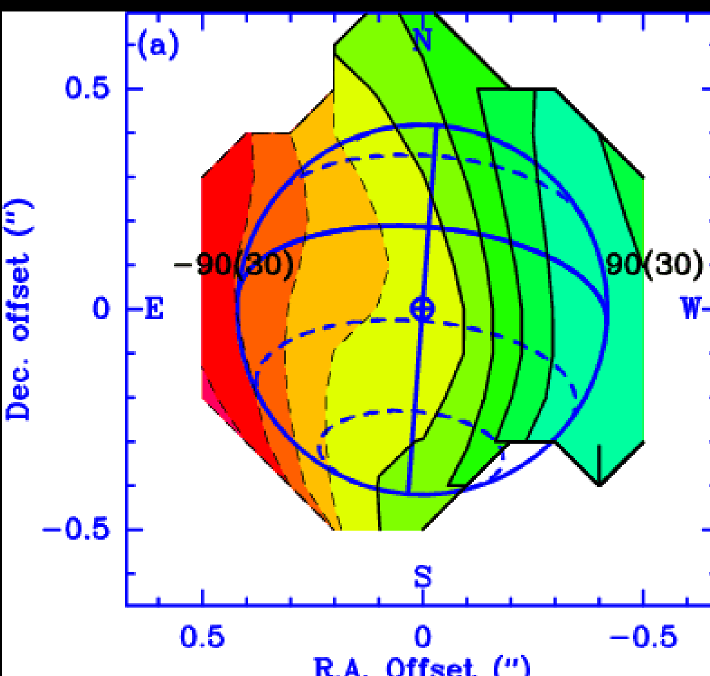


^{13}CO line cores in Venus,
JCMT, Clancy et al., 2012

Coupling of temperature and wind-field to
constrain GCMs (global circulation models)

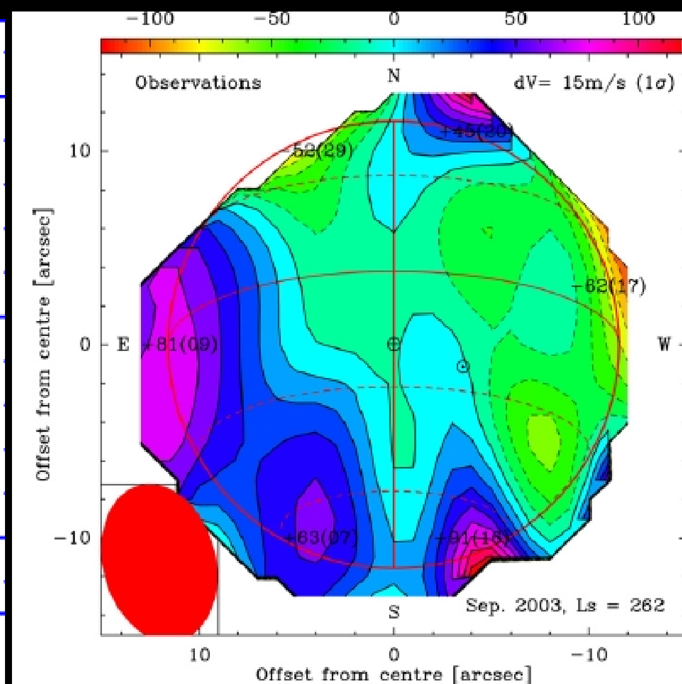
II) Atmospheric dynamics

Titan
(450km altitude)



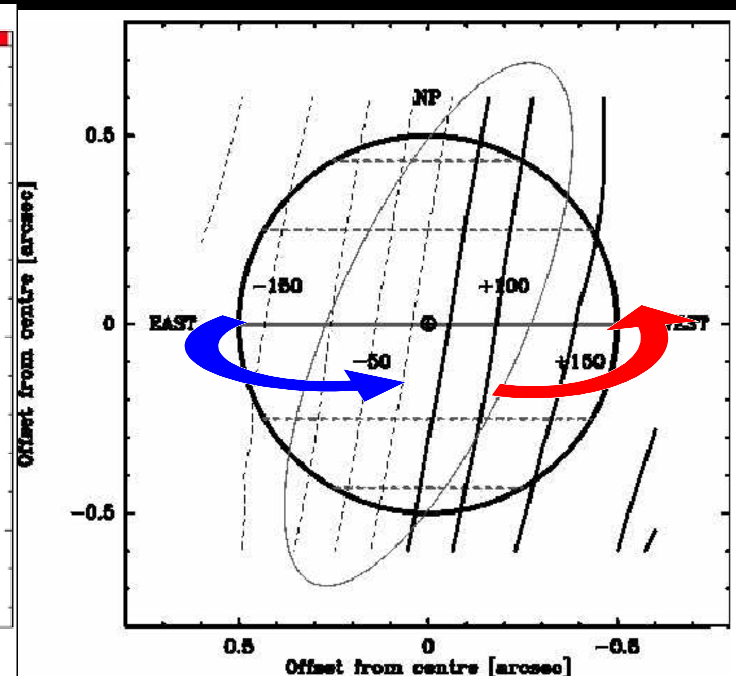
CH_3CN Doppler-shifts, IRAM-PdBI, Moreno et al., 2005

Mars
(50km altitude)



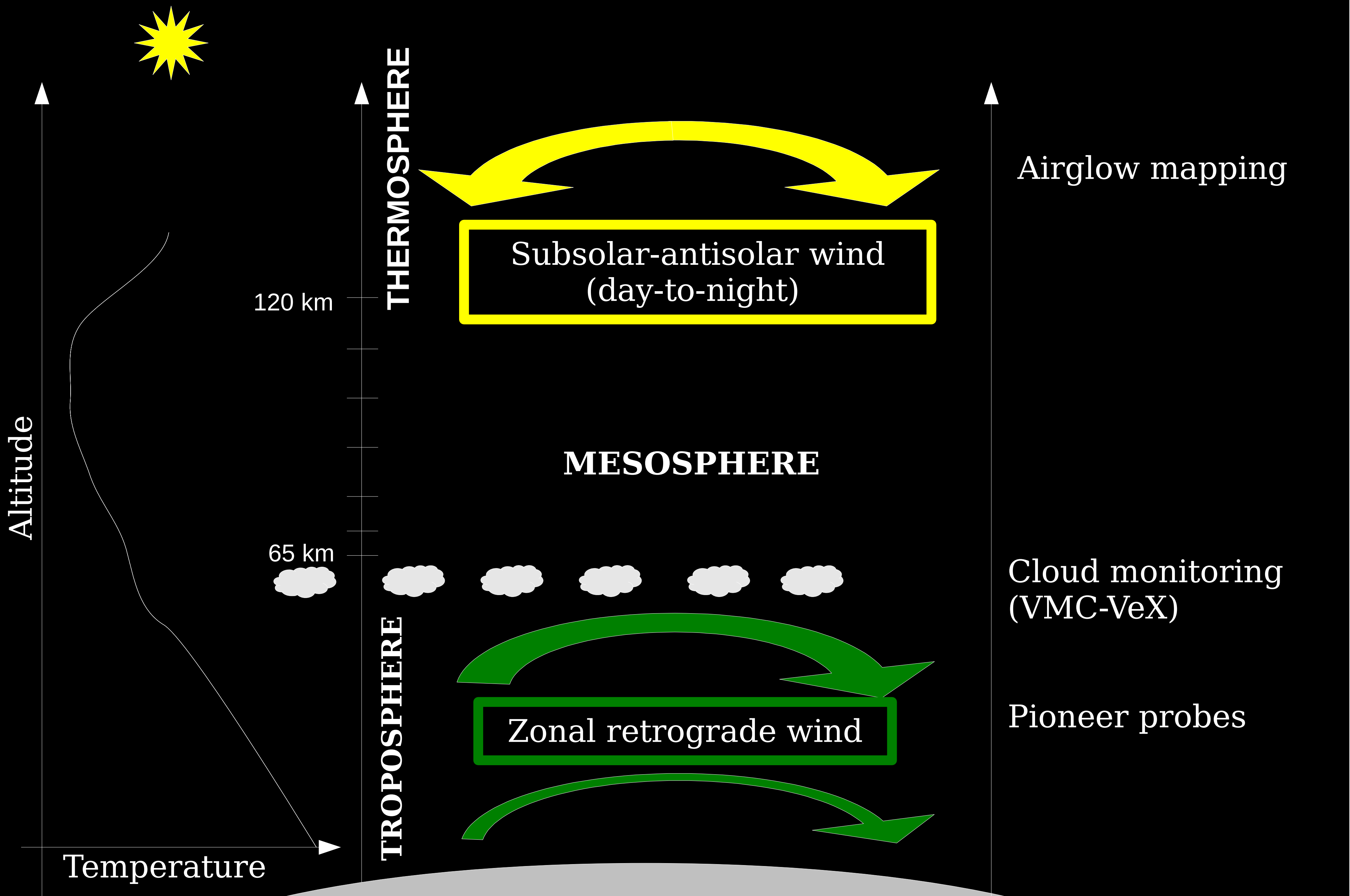
CO Doppler-shifts, IRAM-PdBI, Moreno et al., 2009

Io
(ground level)

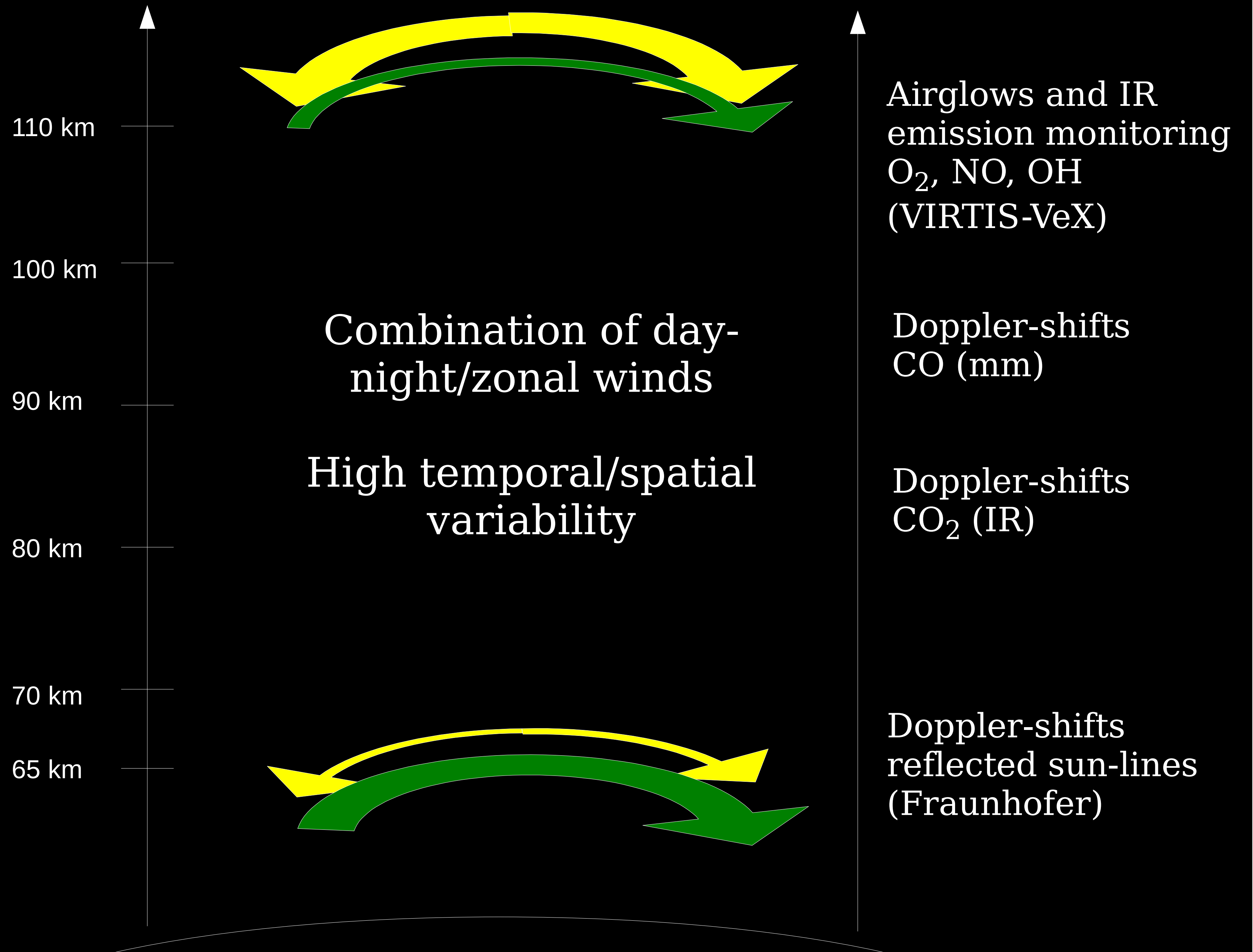


SO_2 Doppler-shifts, IRAM-PdBI, Moullet et al., 2008

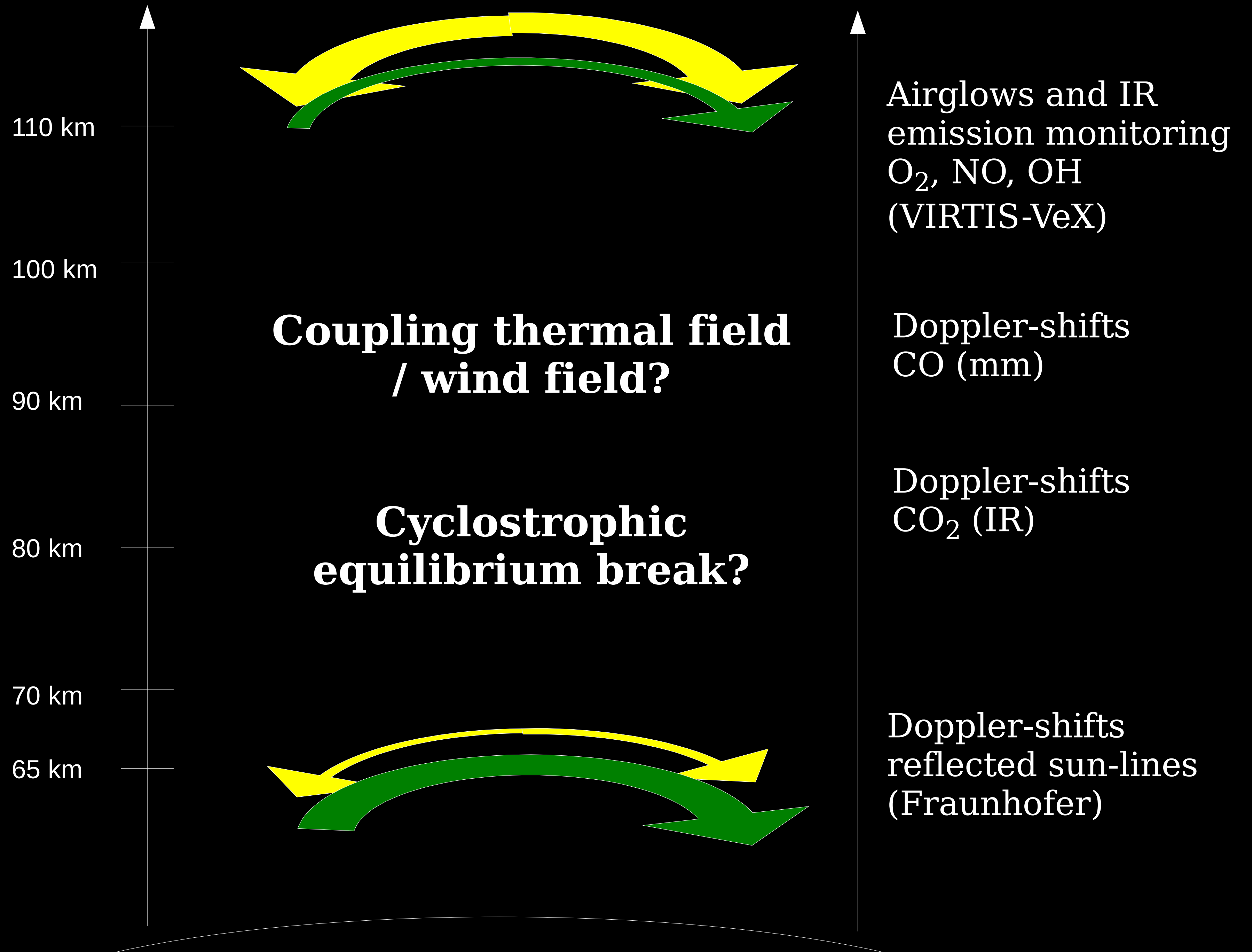
Venus' atmosphere dynamic structure



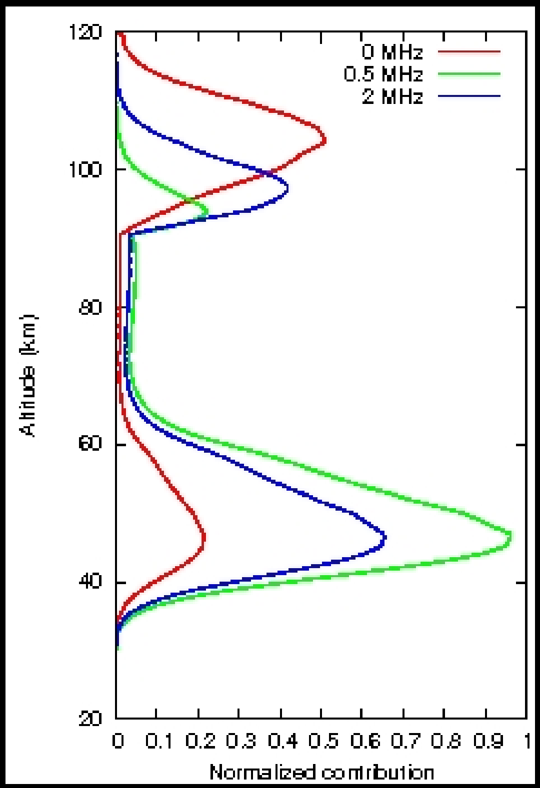
Venus' atmosphere dynamic structure



Venus' atmosphere dynamic structure

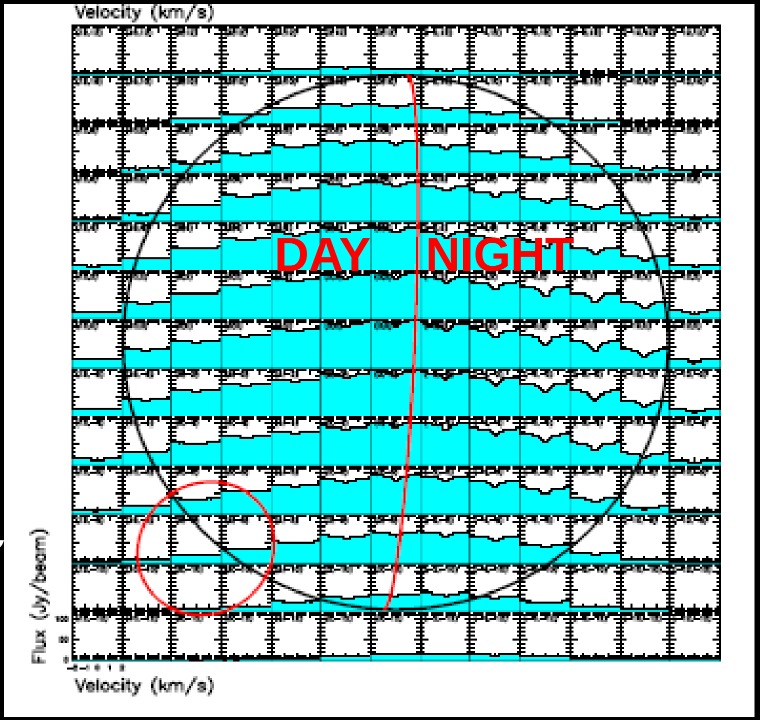


CO horizontal distribution



CO(1-0) altitude line contributions, Moullet et al., 2012

CO(1-0) mapping, morning hemisphere, IRAM-PdBI, Moullet et al., 2012



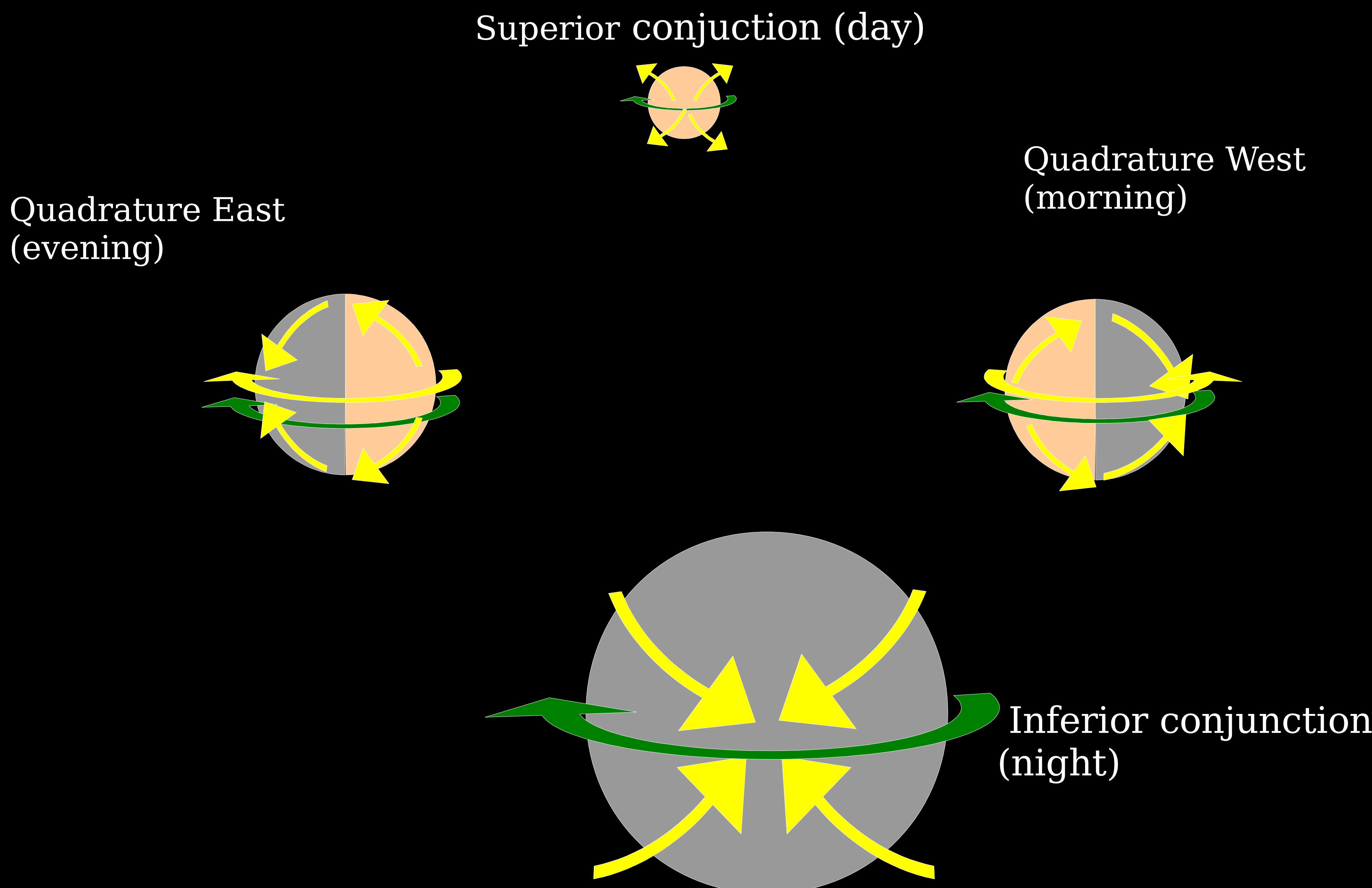
CO line cores sound:

90-105 km CO(1-0)
95-110 km CO(2-1)

CO lines are deeper on the night-side:

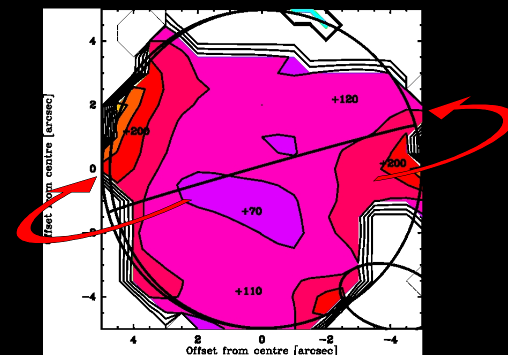
Displacement of CO from day to night-side

Venus' phases and wind geometry

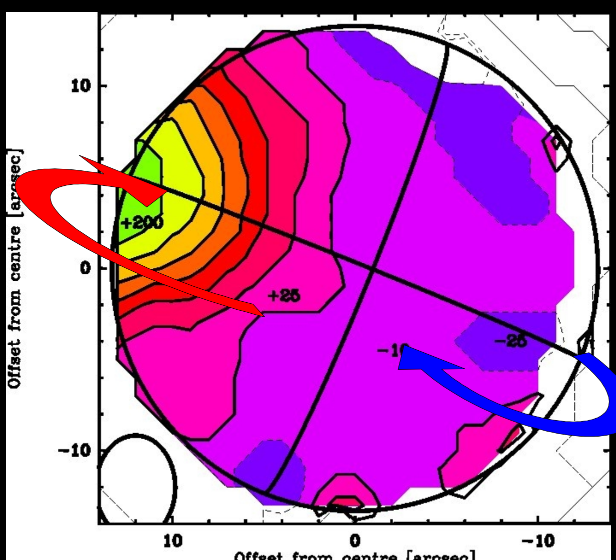


Interferometric Doppler-shift mapping

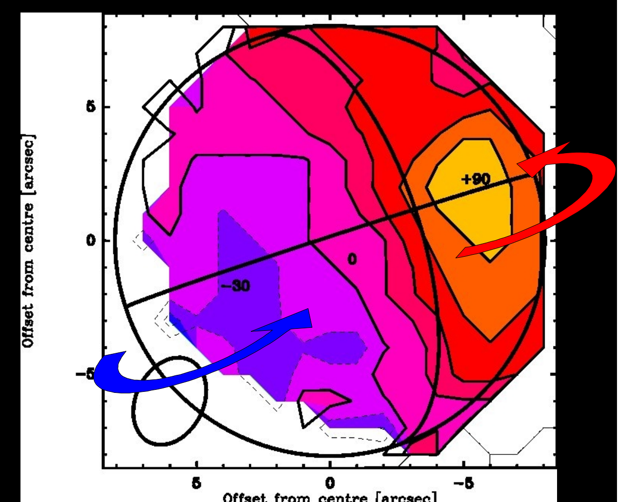
Superior conjunction



Quadrature East



Quadrature West



CO(1-0) and CO(2-1) mapping,
SMA and CARMA.
Errors 30-40 m/s

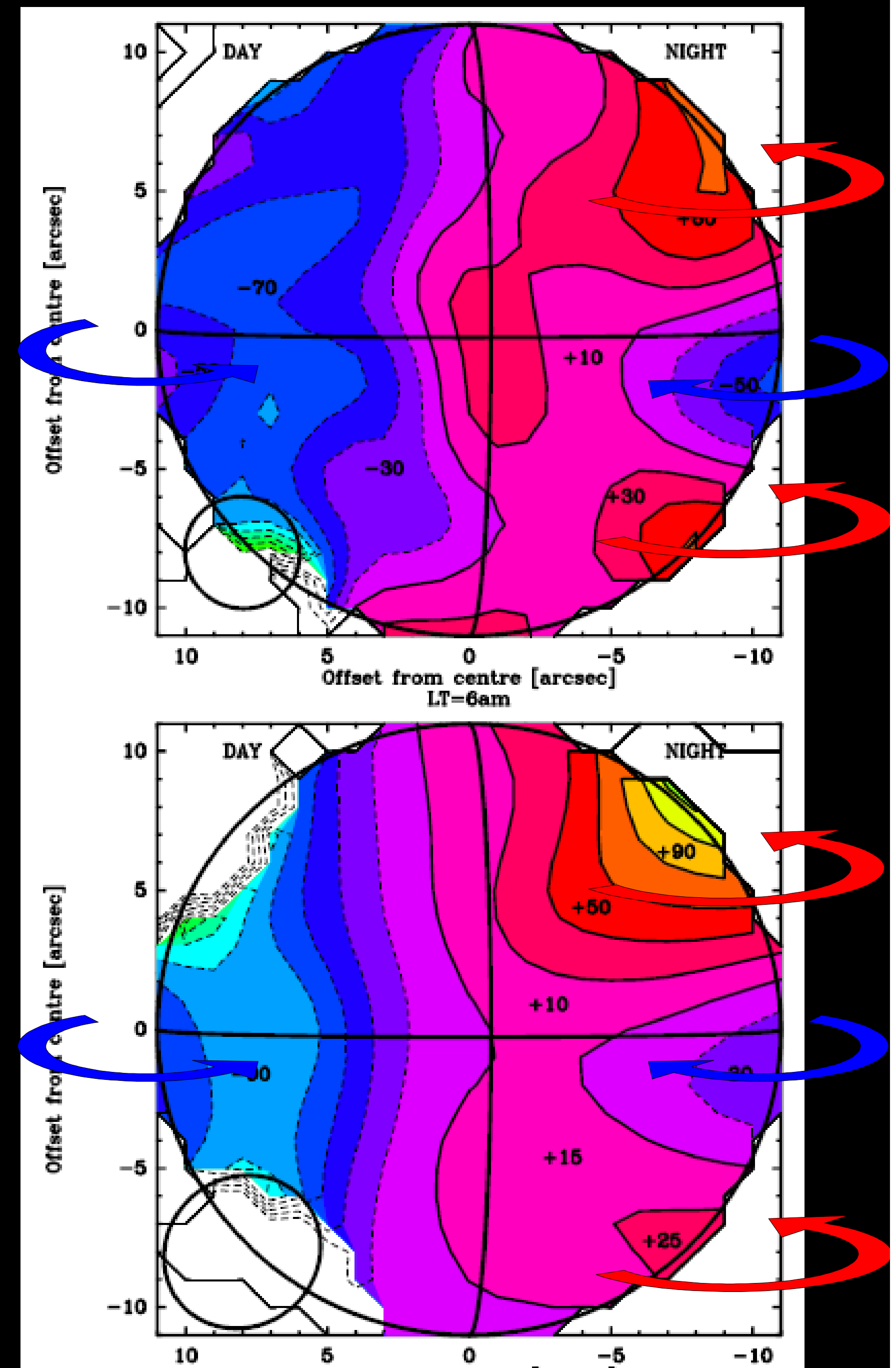
- **Day to night wind dominating**
- Significant velocity **variations with local-hour**

Interferometric Doppler-shift mapping

Observations IRAM-PdBI 2007/2009,
morning hemisphere,
precision 10-20m/s

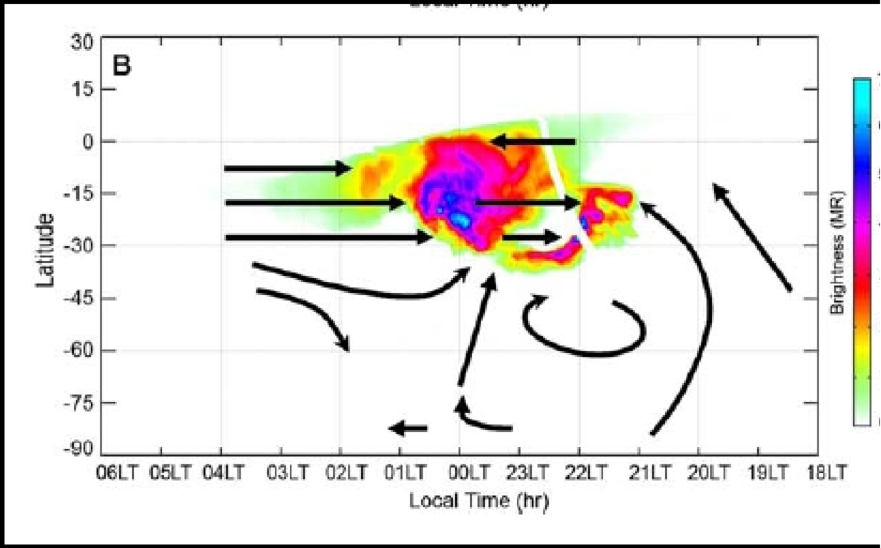
- Temporally stable wind-field
- Global **day-to-night flow 200 m/s**
- **Equatorial retrograde zonal jet** ~100m/s
- Latitudinal / local hour wind variations

CO(1-0) Doppler-shifts,
morning hemisphere,
IRAM-PdBI,
Moullet et al., 2012



Further investigations

Wind structure **more complex than a combination of day-to-night / zonal flow**



Oxygen airglow monitoring, VEx-VIRTIS, Hueso et al., 2008

To estimate altitude wind-shear:
→ simultaneous use of **multiple lines**

To detect wind variations at high latitudes:
→ **high spatial resolution** (~0.5-1'')

To detect quick temporal variations (~1 hour):
→ **snapshot** wind measurements

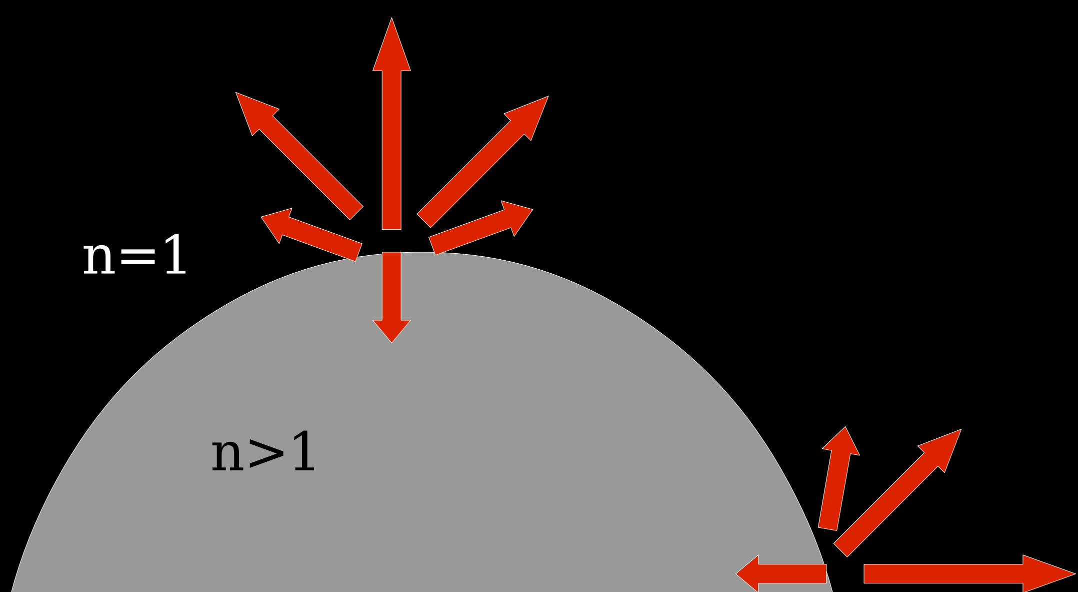
} **ALMA**

III) Surfaces properties

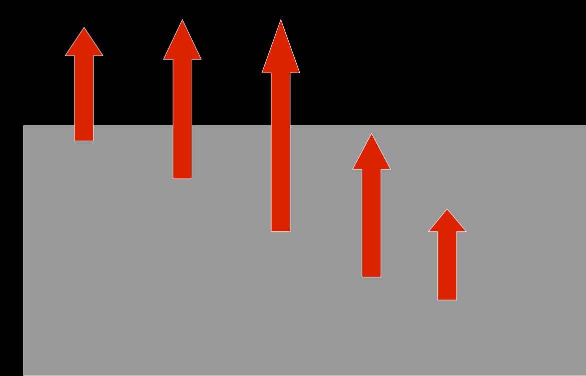
Thermal emission radiative effects:

Snell-Fresnel laws at surface/air interface:
  -> **refraction index, surface roughness**

Surfaces not transparent at thermal wavelengths:
-> **absorption coefficient**

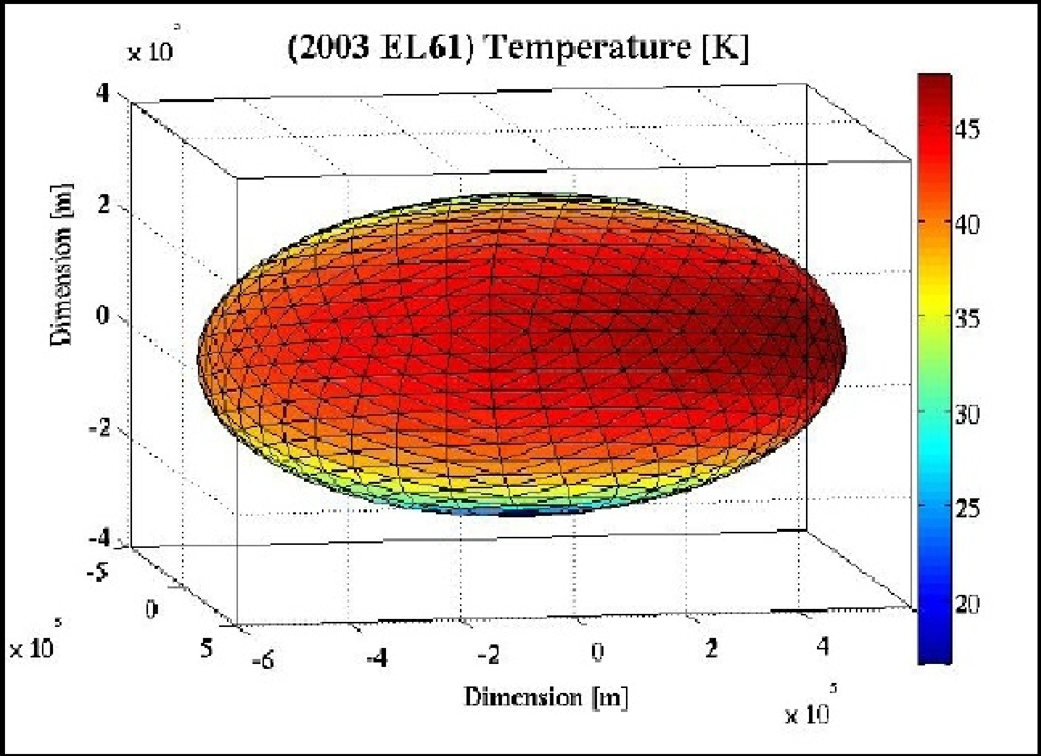


The total emission combines contributions from different depths, down to ~ 10 λ



III) Surfaces properties

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



Temperature distribution model for Haumea, Mueller et al., 2008

Temperature field depends on

geometric properties:
shape, rotation rate

orbital properties:
hel. Distance, pole direction

surface properties:
albedo, thermal inertia

Radiometric method

Morrison et al., 1977

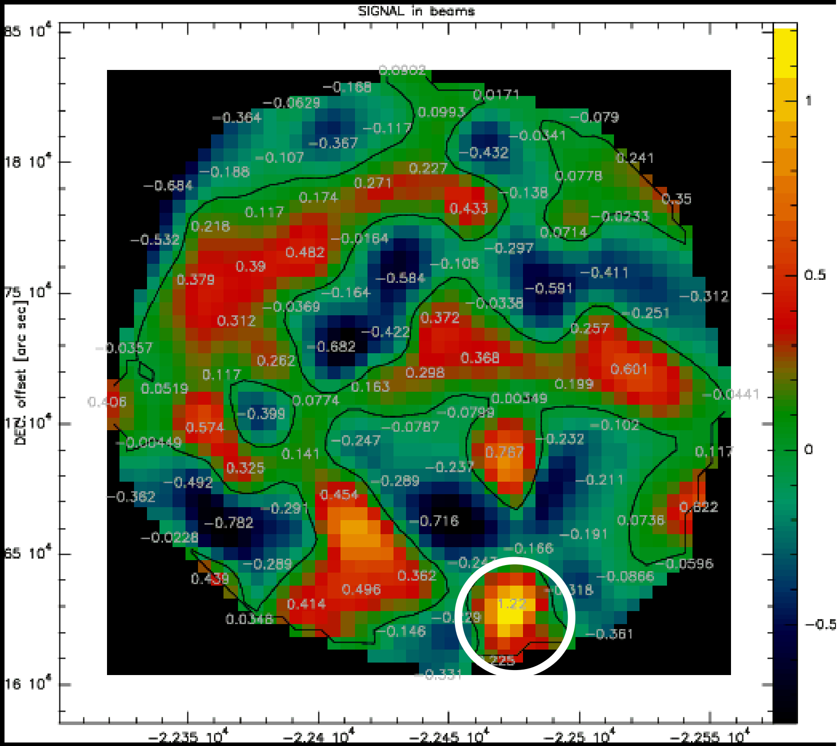
Optical magnitude $\propto$ albedo . D^2

Thermal emission $\propto B(\nu, T((1\text{-}a)^{0.25}))$. D^2

Independant estimate of **albedo and equivalent size**

If mass known (binaries): **density** estimate

Detection of Centaur 1999 TZ1, IRAM-30m, Moullet et al. 2008



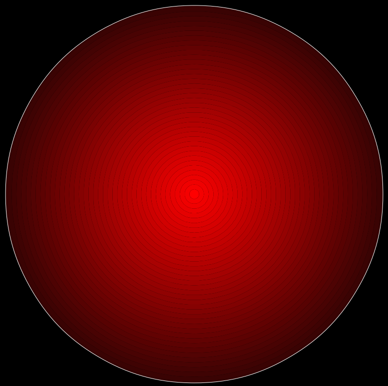
Radiometric method

Thermals models defined through beaming parameter η

Low inertia → High inertia

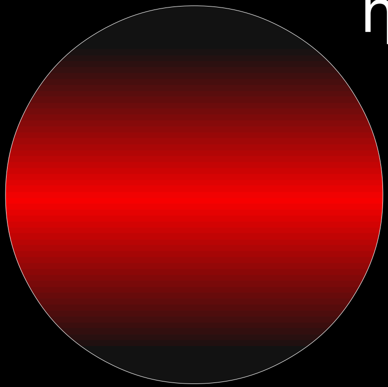
Varying η

η=1



Slow Rotator model

η=2

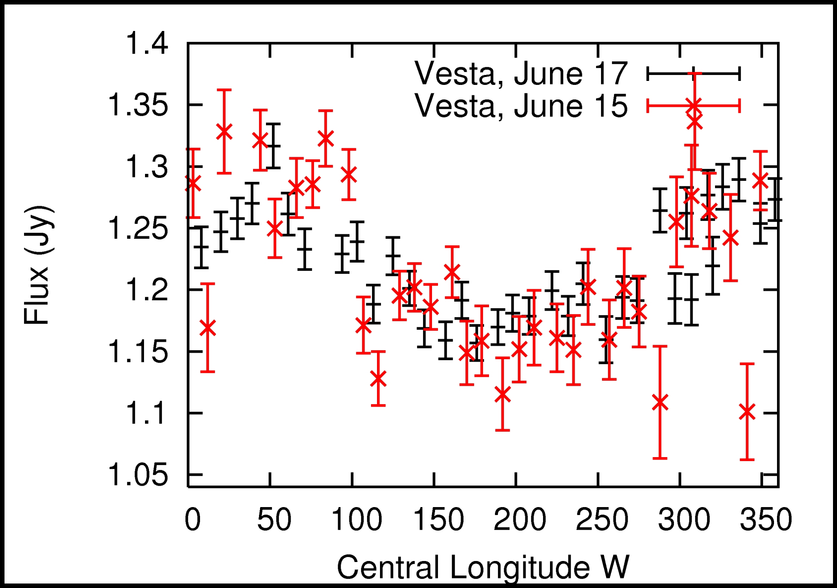


Quick Rotator model

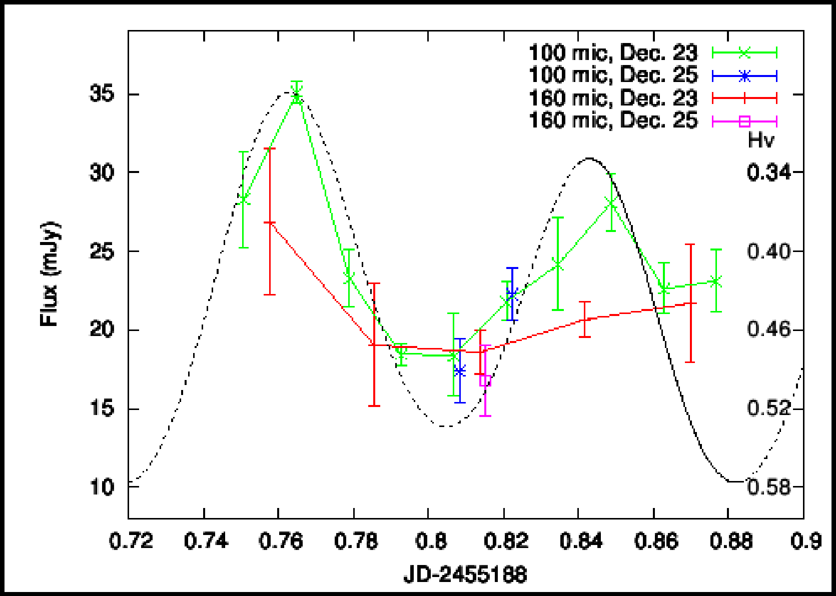
η constrained by multi-wavelengths thermal photometry

Thermal lightcurves

Time-resolved radiometric method can distinguish **albedo distribution/ shape** (apparent size variation)



Vesta's thermal lightcurve, SMA

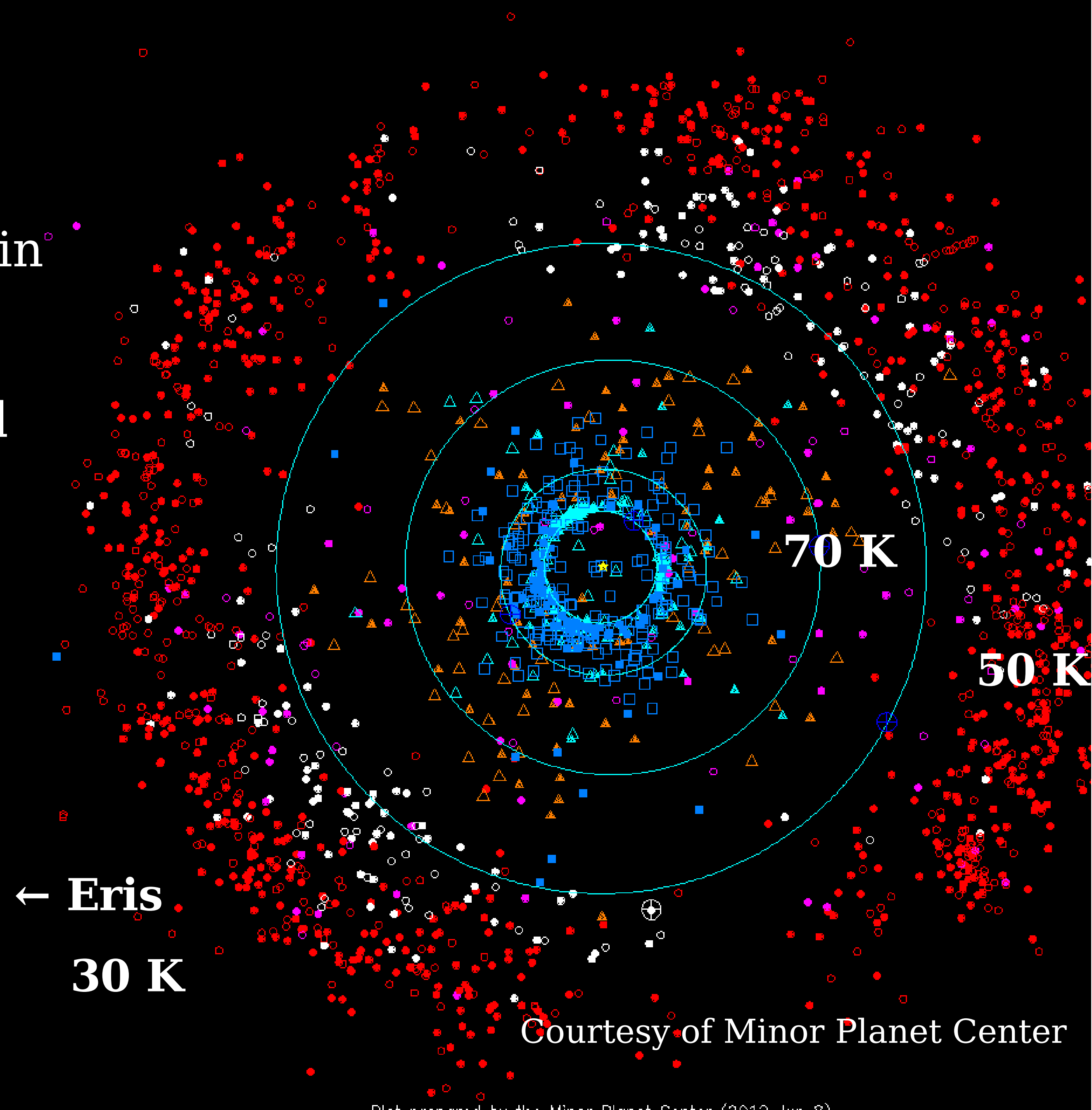


Haumea's optical and thermal lightcurves with Herschel, Lellouch et al., 2010

The case for Kuiper Belt Objects

- Analog of planetesimals in **debris disk**
- **Most pristine material** in the Solar System

1000+ KBOs
200 Scattered objects

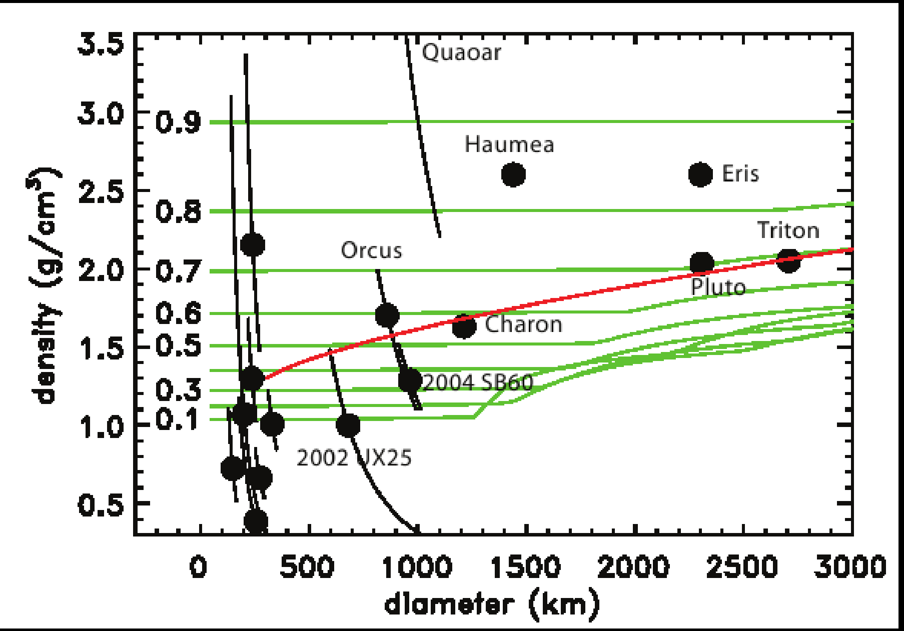


Courtesy of Minor Planet Center

Role of thermal observations

- Measurement of size distribution:
  collisional grinding/accretion in a planetesimal belt

- Density (ice to rock ratio):
  physical properties in the
  primitive Solar nebula



Densities and diameters, Brown et al., 2012

- Albedo distribution, albedo/size correlations:
  physical and collisional processes on cold/distant surfaces

Role of thermal observations

~4 sizes with ISO

~45 sizes with Spitzer-MIPS (Centaurs)

~8 sizes with IRAM-30m MAMBO bolometer

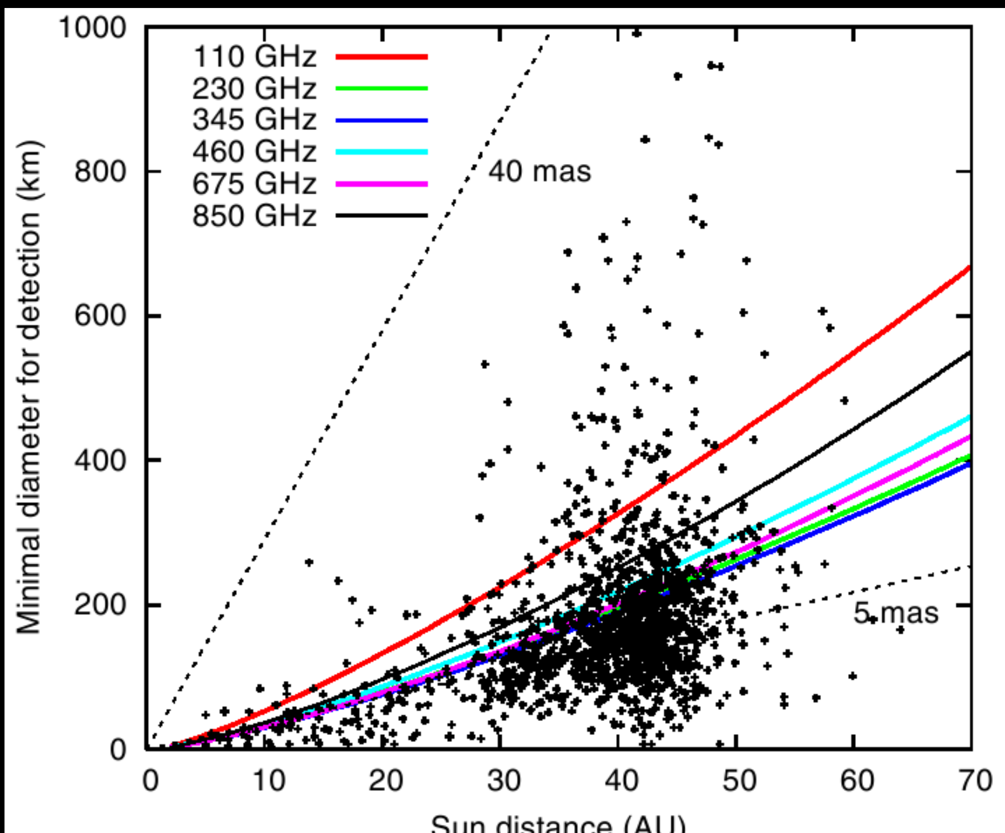
The trans-neptunian object UB_{313} is larger than Pluto

F. Bertoldi[1,2], W. Altenhoff[2], A. Weiss[2], K.M. Menten[2] & C. Thum[3]

- Herschel : 140 (40) detections PACS, 17 detections SPIRE

Sensitivity very limiting !

ALMA : KBO detection



Diameter detection threshold as a function of Sun distance, Moullet et al., 2011

ALMA B6/B7 (full science):
More efficient than Herschel

Diameter threshold for 5σ detection (~2 h integration)

- at 30 AU : **110 km**
- at 50 AU : **210 km**

→ **size/albedo** on 600+ objects

Filling **size distribution,** albedo/size database for correlations

ALMA : size and shapes

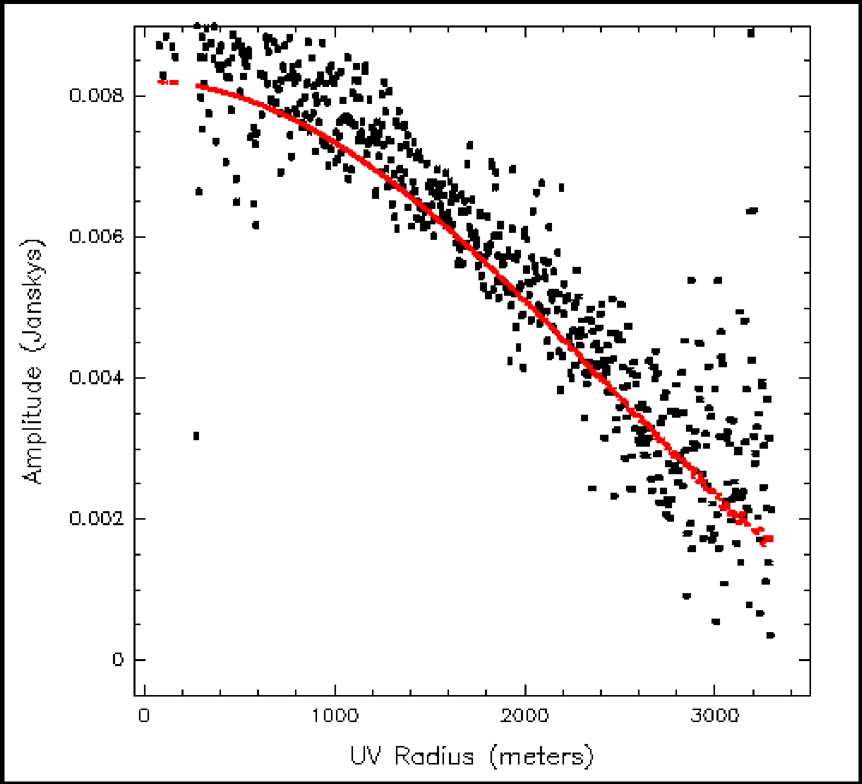
Direct analysis of visibilities (~ imaging) combined with lightcurve analysis

Possible on ~ 30 bodies larger than 0.015''

→ non model-dependant **sizes**

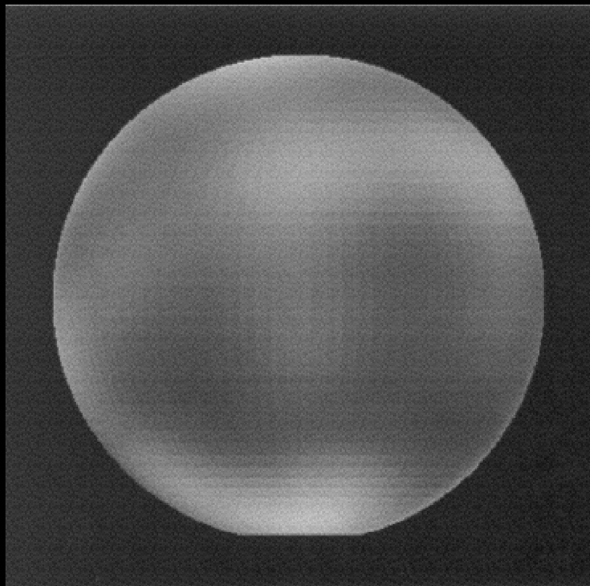
→ **ellipticities** or 3-D shape (even on pole on geometry)

Constraints on **internal strength, density**



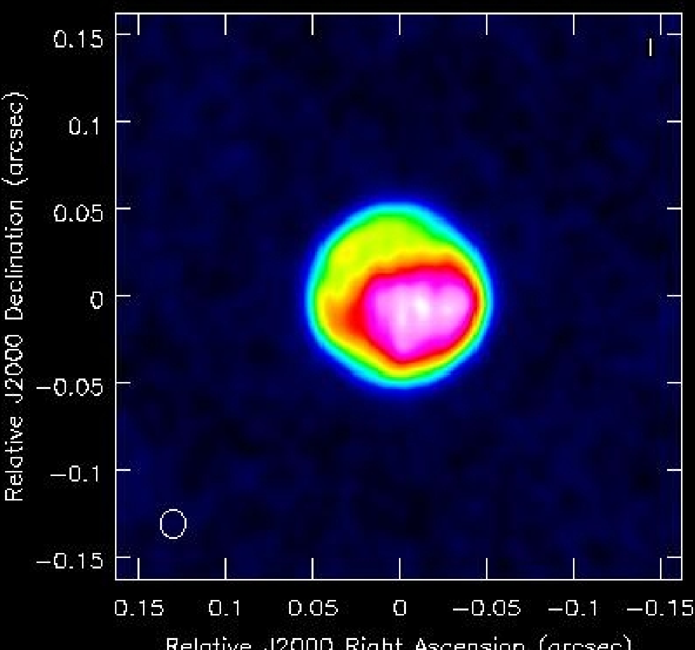
Simulated Charon visibilities @345 GHz, Moullet et al., 2011

ALMA : surface mapping



HST FOC Image of Pluto's sub-Charon hemisphere (North is up)

Young et al., 1998



First KBOs thermal mapping possible, **resolution ~15mas**

Detection of 10% temperature variations on 6 large bodies

→ horizontal **variations of albedo/ thermal inertia/ temperature**

Constraints on **resurfacing processes**

Pluto, Band 7, very extended configuration simulation

ALMA : multiple system imaging

Large fraction of multiple systems: ~10%. Many ~equally-sized

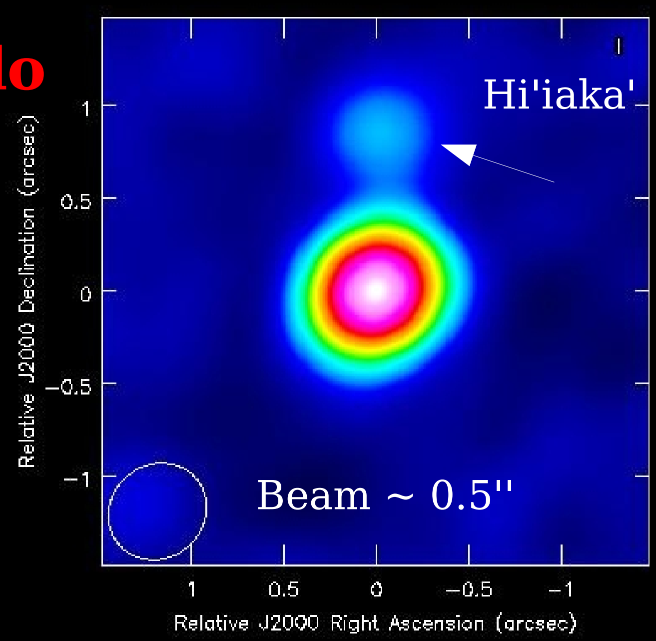
Separations 2'' → contact binaries.
ALMA resolution (B7) -> 0.01'' (Hubble: 0.04'')

→ **individual size/albedo**

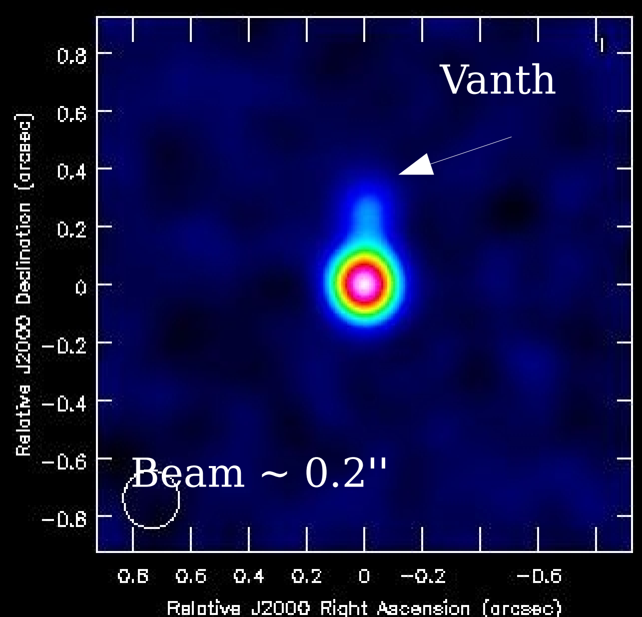
→ **system density**

Constraints on
system formation
(capture, disruption)

Simulation Haumea system, Band 7



Simulation Orcus system, Band 7



What does (sub)mm radiation in the Solar System tell us ?

- Atmospheric composition
- Atmospheric structure
- Wind and temperature fields
- Surface thermal and reflective properties
- Small bodies' equivalent sizes

Unique and essential measurements to constrain

- climates

- surface and atmospheric processes

- collisional /chemical evolution

(Sub)mm Solar System science in the ALMA era: a new range of possibilities

- **<u>Sensitivity increase</u>** (80-900 GHz): factor 10-40.

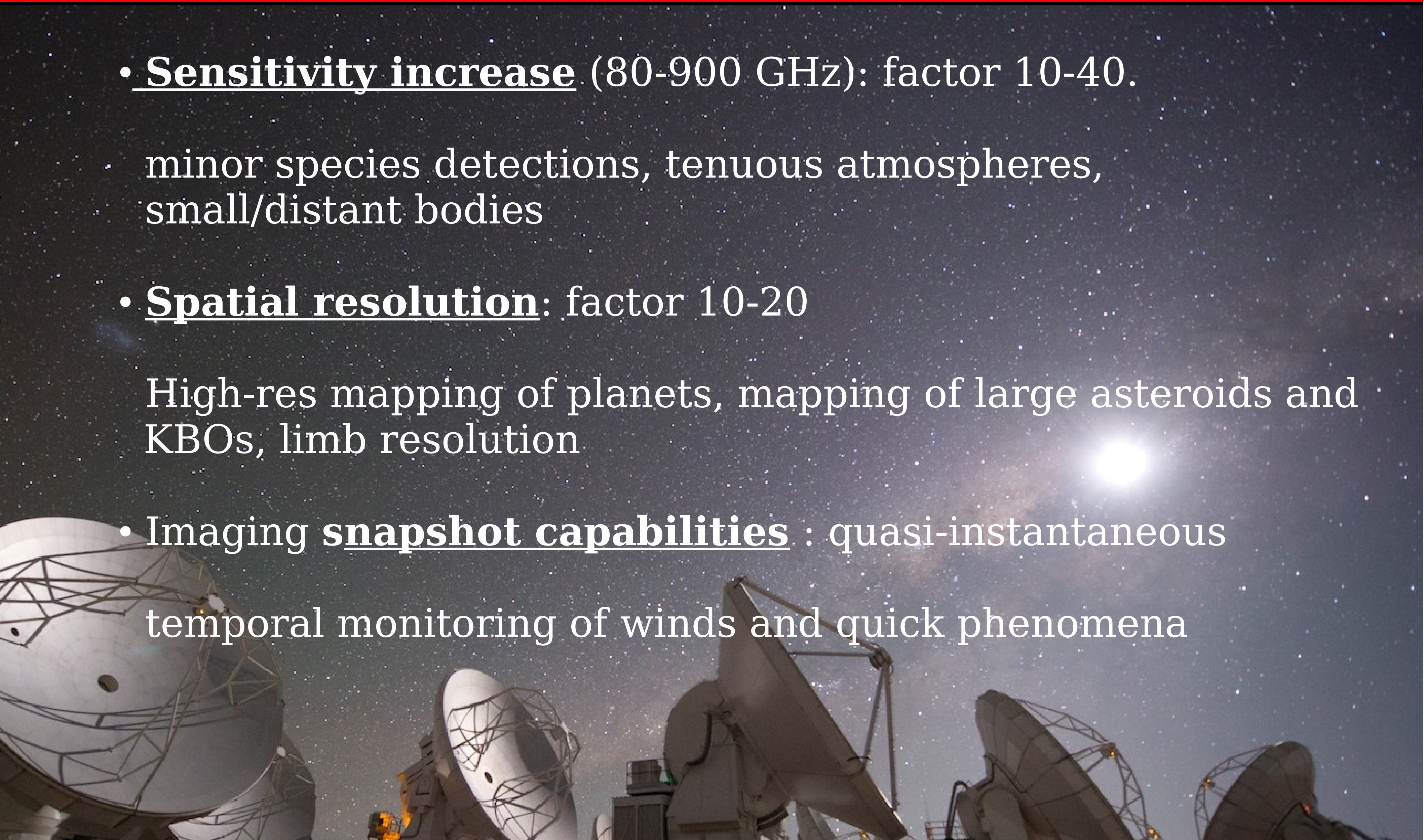
  minor species detections, tenuous atmospheres, small/distant bodies

- **<u>Spatial resolution</u>**: factor 10-20

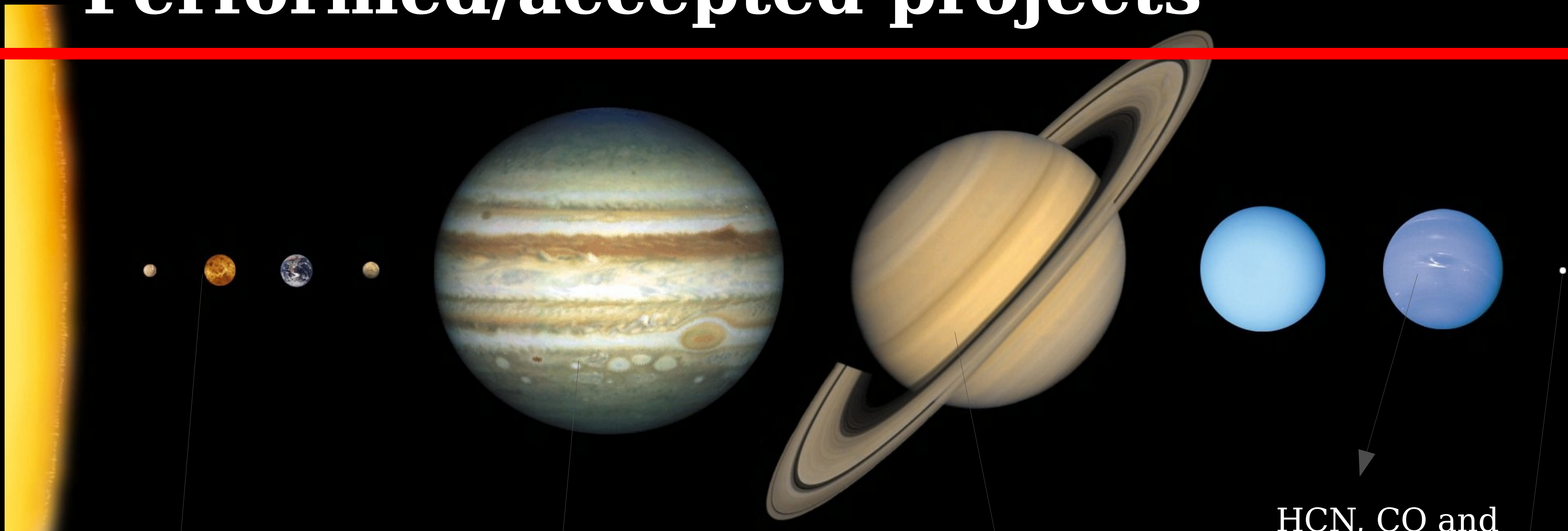
  High-res mapping of planets, mapping of large asteroids and KBOs, limb resolution

- Imaging **s<u>napshot capabilities</u>** : quasi-instantaneous

  temporal monitoring of winds and quick phenomena



Performed/accepted projects



Sulfur and
HDO mapping,
Chlorine
species,
winds

Io: chemistry,
winds

Storm CO and
temp. mapping

Titan: nitrile
detection and
mapping, winds

HCN, CO and
isotopologues

Medium-sized KBOs
detection

Comet PanStarrs