New Horizons at Pluto: Surface – Atmosphere Interactions

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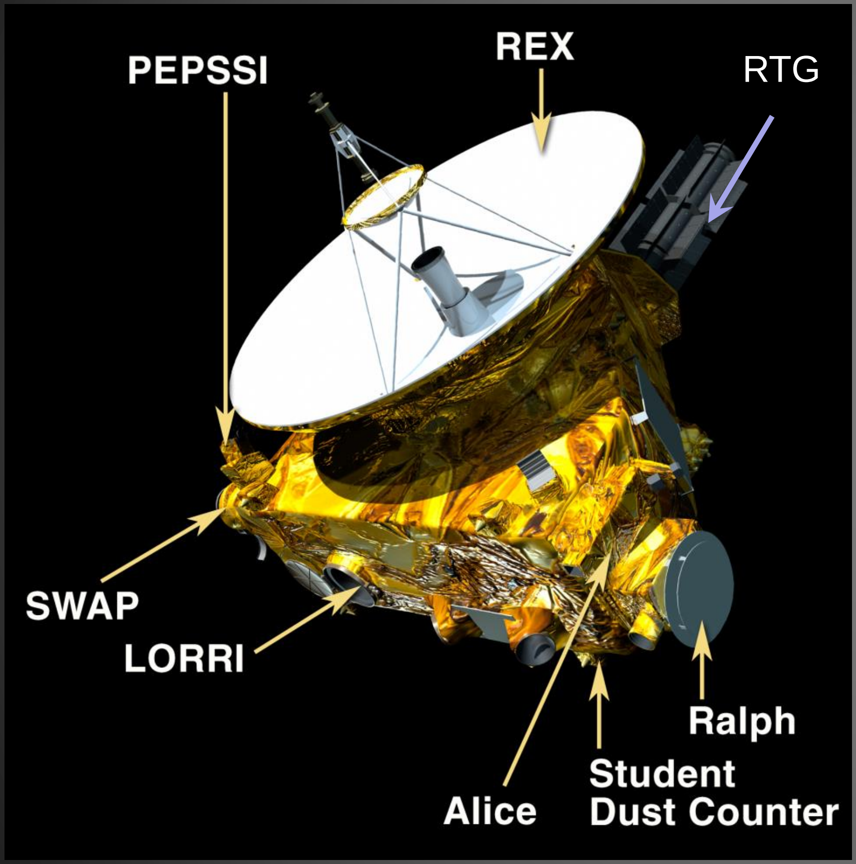
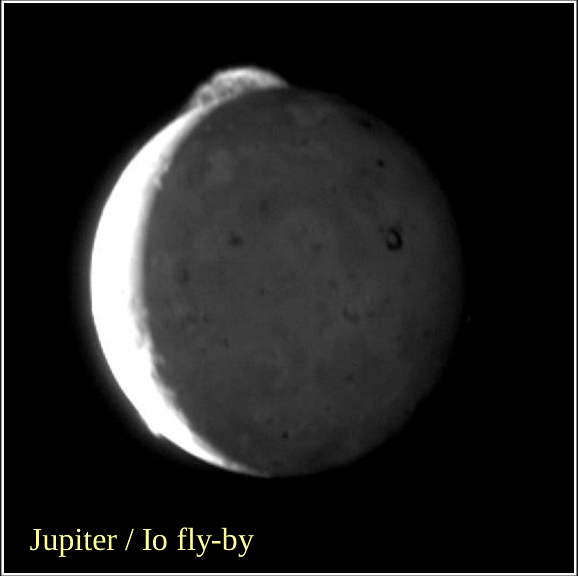
With many thanks to the New Horizons team
For a great mission
(and all the charts I stole…)

New Horizons: Science Instruments



Ralph:	Color Camera and IR Spectral Imager: Composition
Alice:	Ultraviolet Spectral Imager: Atmospheric studies
LORRI:	HiRes Panchromatic Camera: Geology, OpNav, Deep Searches for Moons and Rings
REX:	Radio Science Experiment: Atmospheric [T,P] profile and Surface Temperature
SWAP:	Solar Wind At Pluto
PEPSSI:	Energetic Particles: Atmospheric Escape
SDC:	Student Dust Counter
RTG:	Radioisotope Thermoelectric Generator

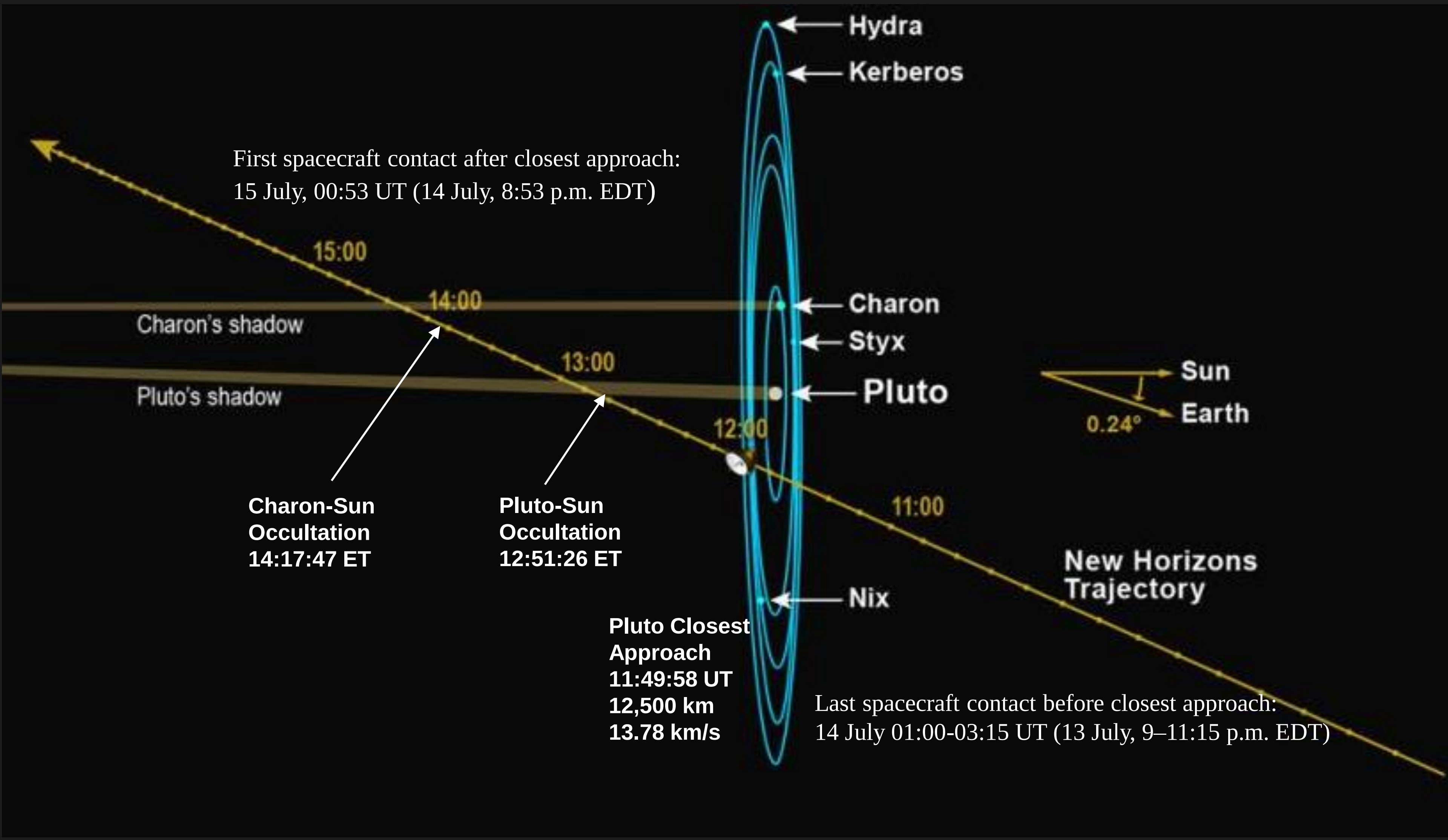


Jupiter / Io fly-by

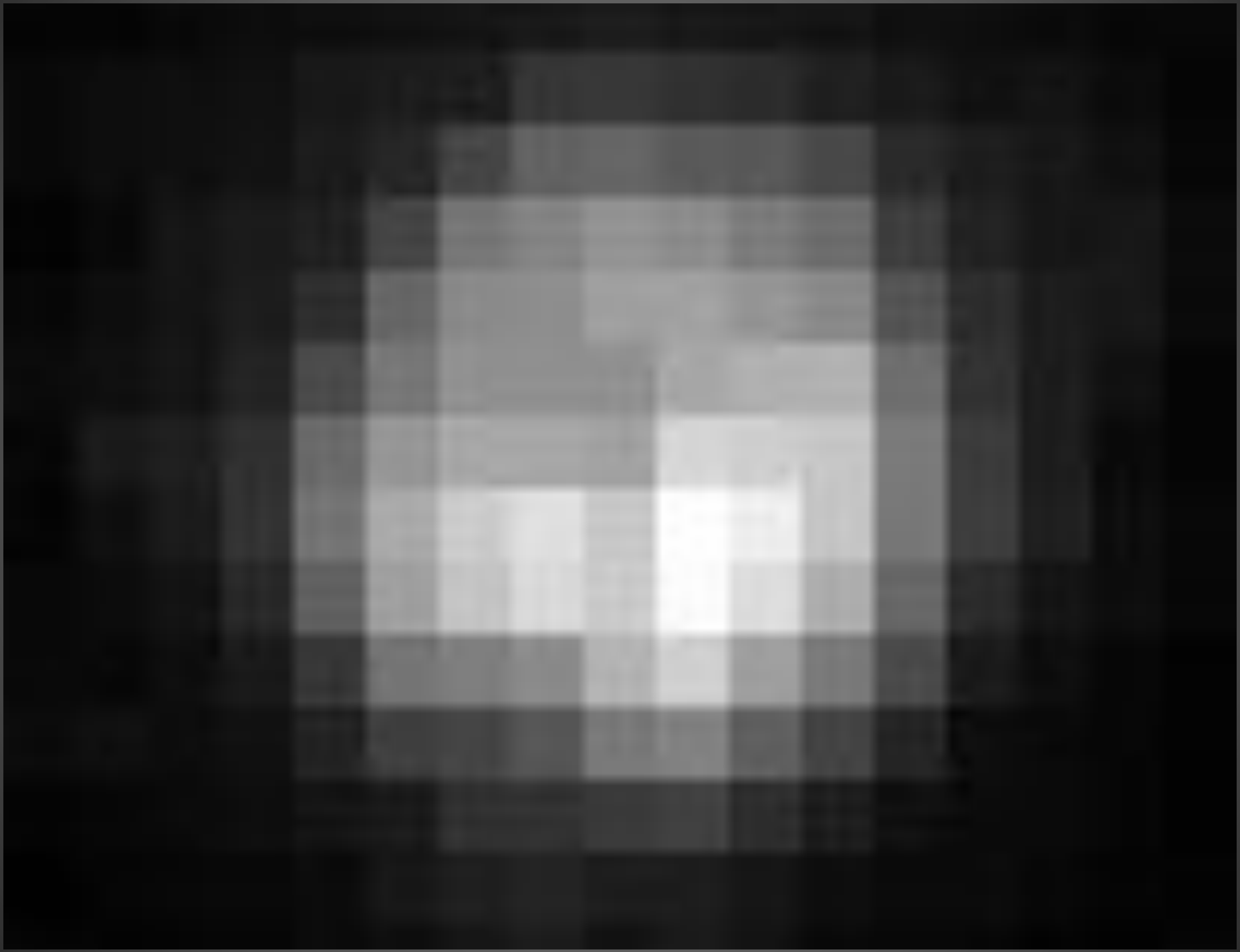
Launch: 19 January 2006

- Nearly perfect trajectory
- Fastest Earth departure ever (57,000 km/hr)
- Passed Moon's orbit in 9 hours
- Passed orbits of:
  - Mars on 7 Apr 2006 (< 3 months)
  - Jupiter on 28 Feb 2007 (~1 year)
  - Saturn on 8 Jun 2008 (~2.4 years)
  - Uranus on 18 Mar 2011 (~5.2 years)
  - Neptune on 24 Aug 2014 (~8.6 years)
- Pluto system encounter on 14 Jul 2015 (9.5 years)

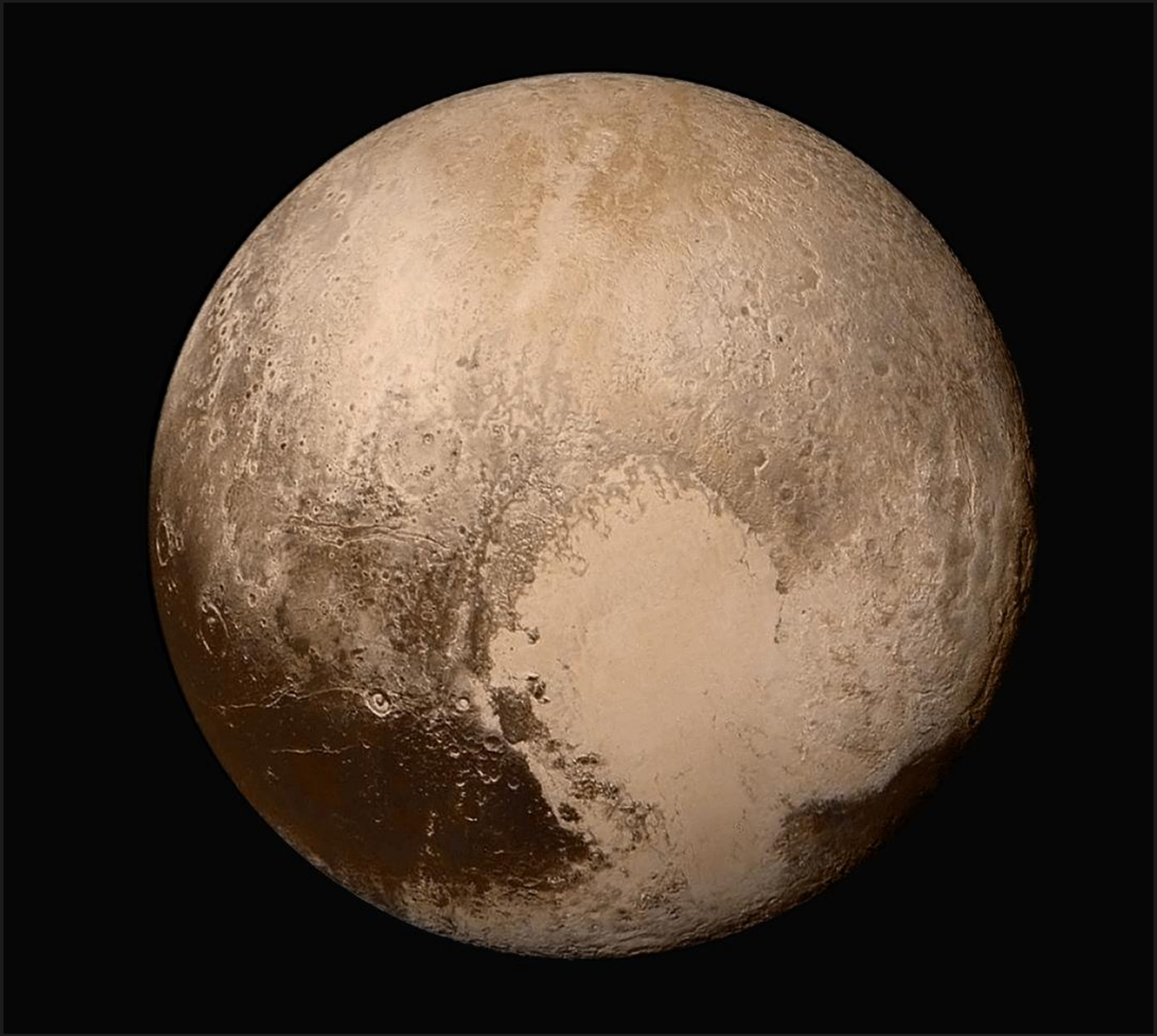
New Horizons Pluto Encounter



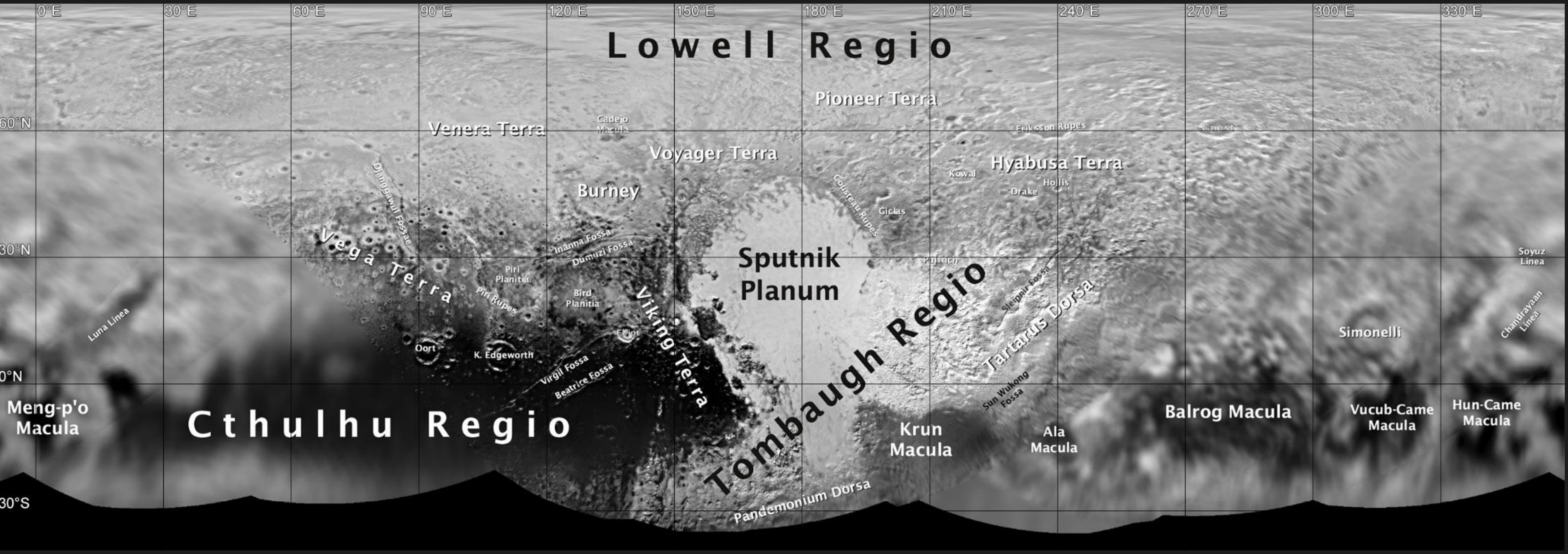
Pluto Before New Horizons



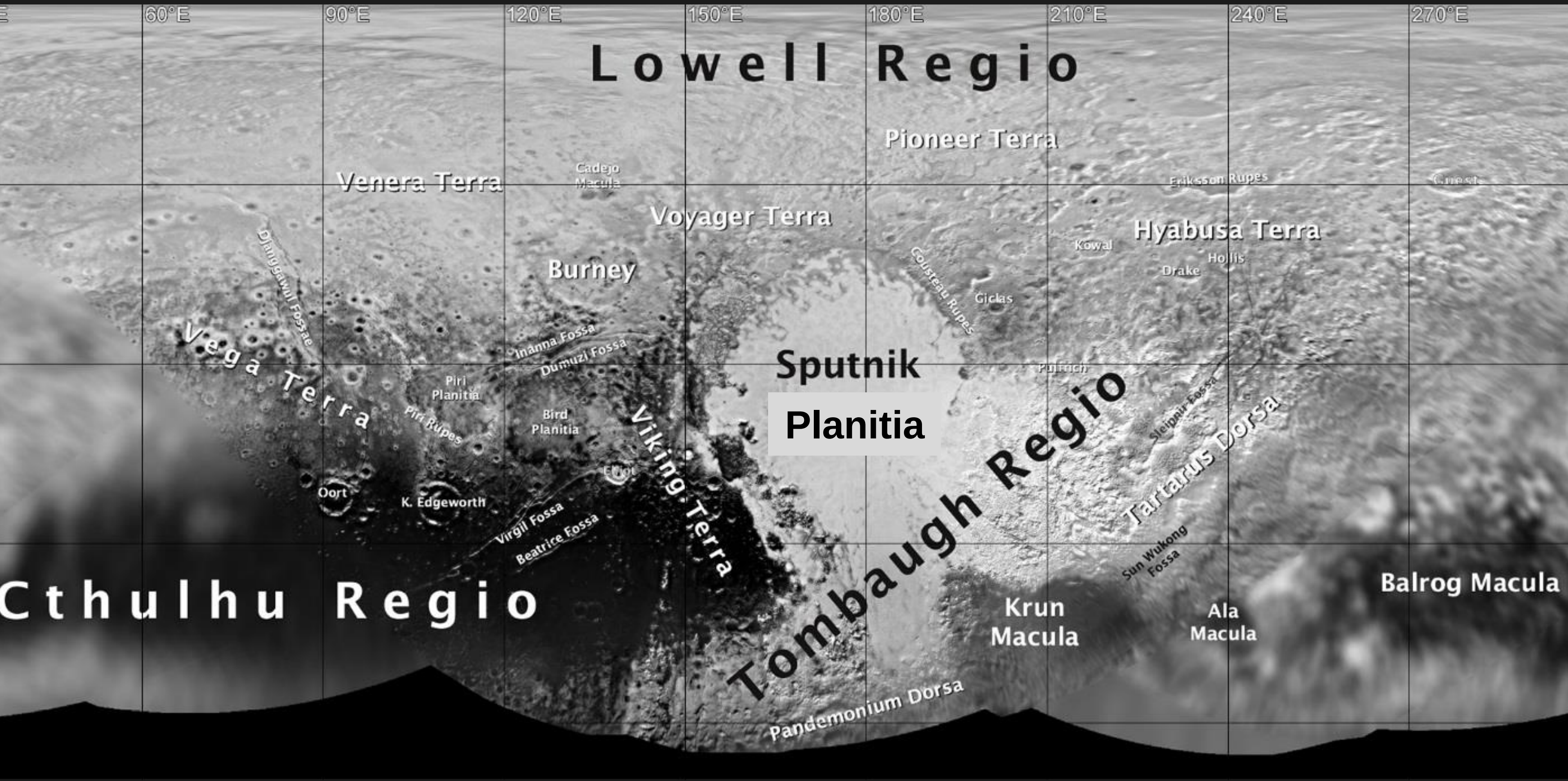
Pluto in Natural Color from New Horizons



Nomenclature – it's informal



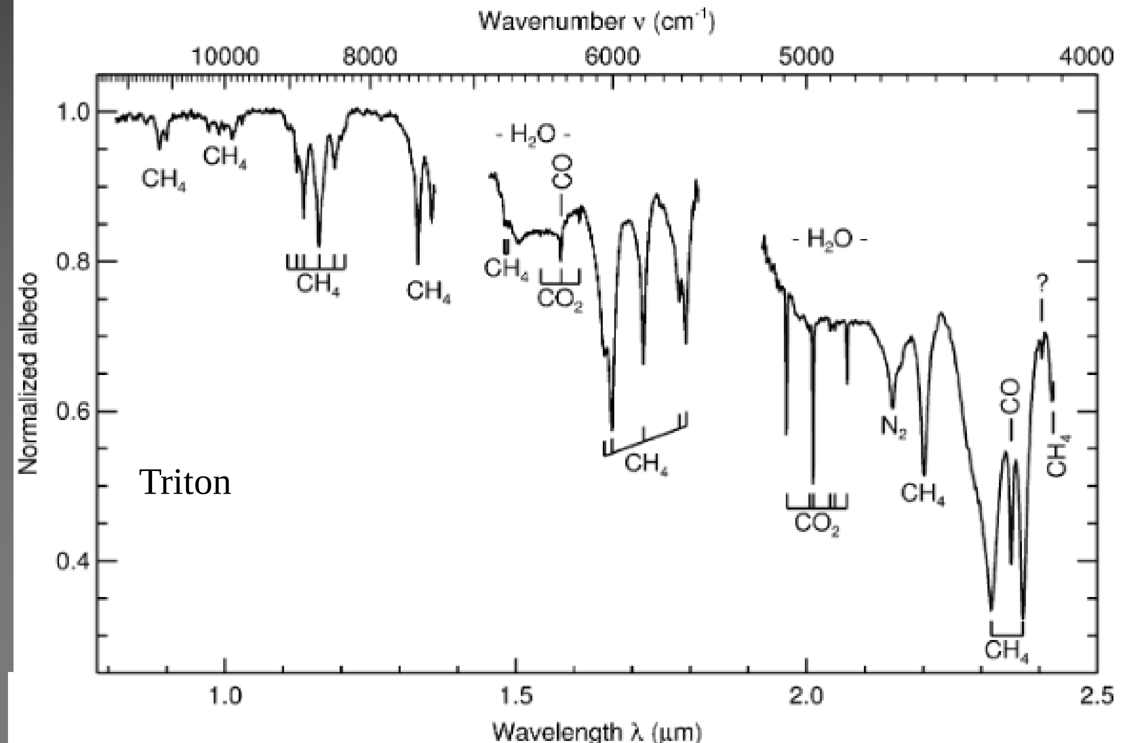
Nomenclature – it's informal

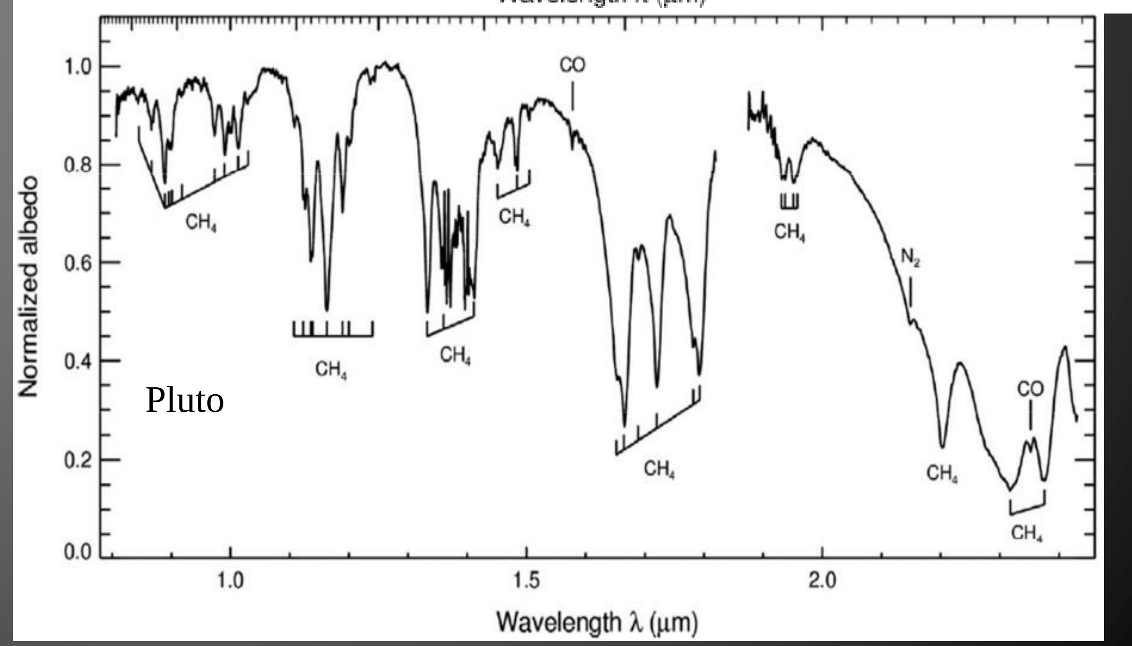


What are we seeing on Pluto's surface?

Volatile Ices on Pluto, Triton

- Ground-based spectra
  - Disk-integrated composition
- Volatile ices:
  - High vapor pressures
  - Low melting points
- Outer solar system volatile ices
  - N2
  - CO
  - CH4
  - Ar? O2?





LEISA Spectral Domains on Pluto

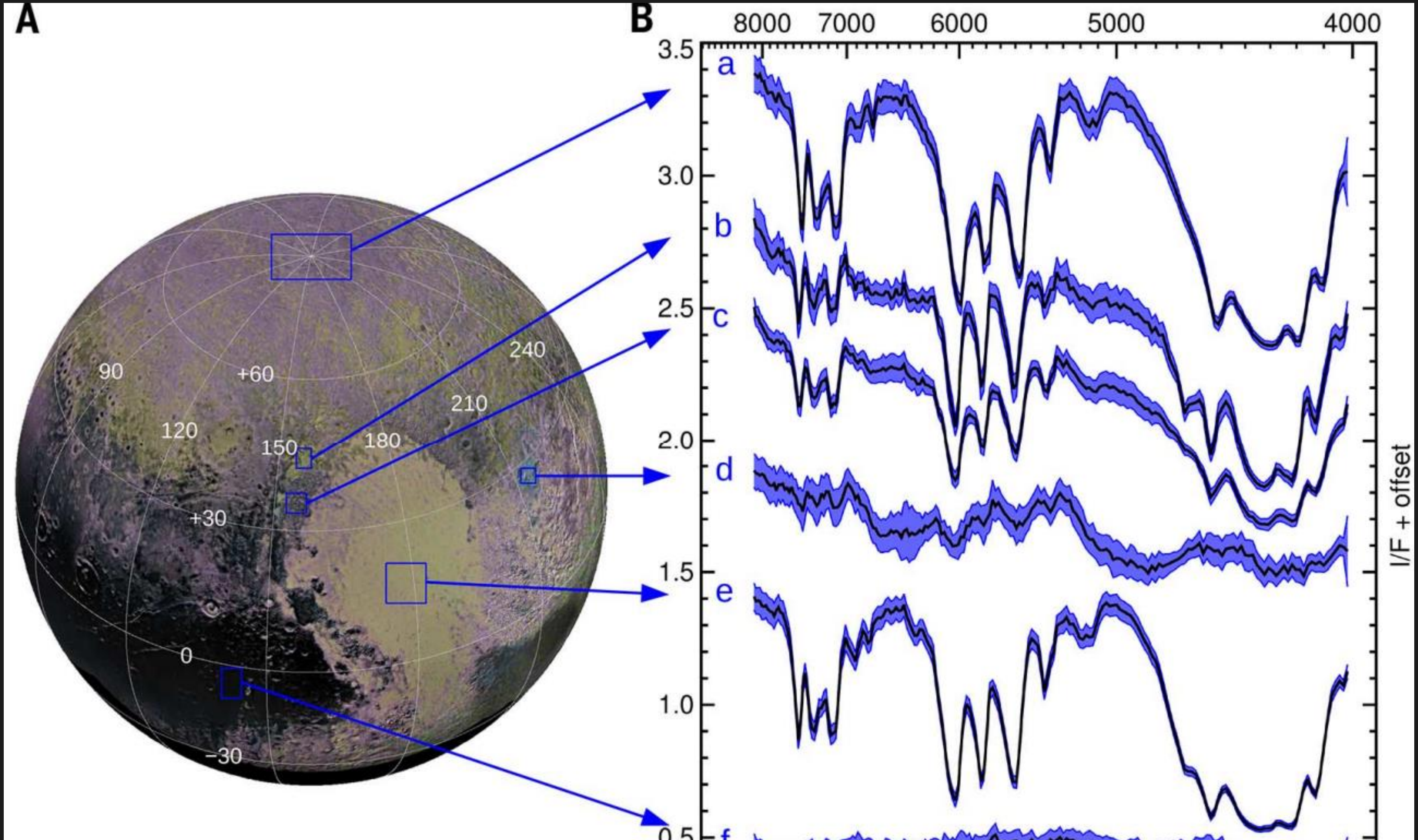
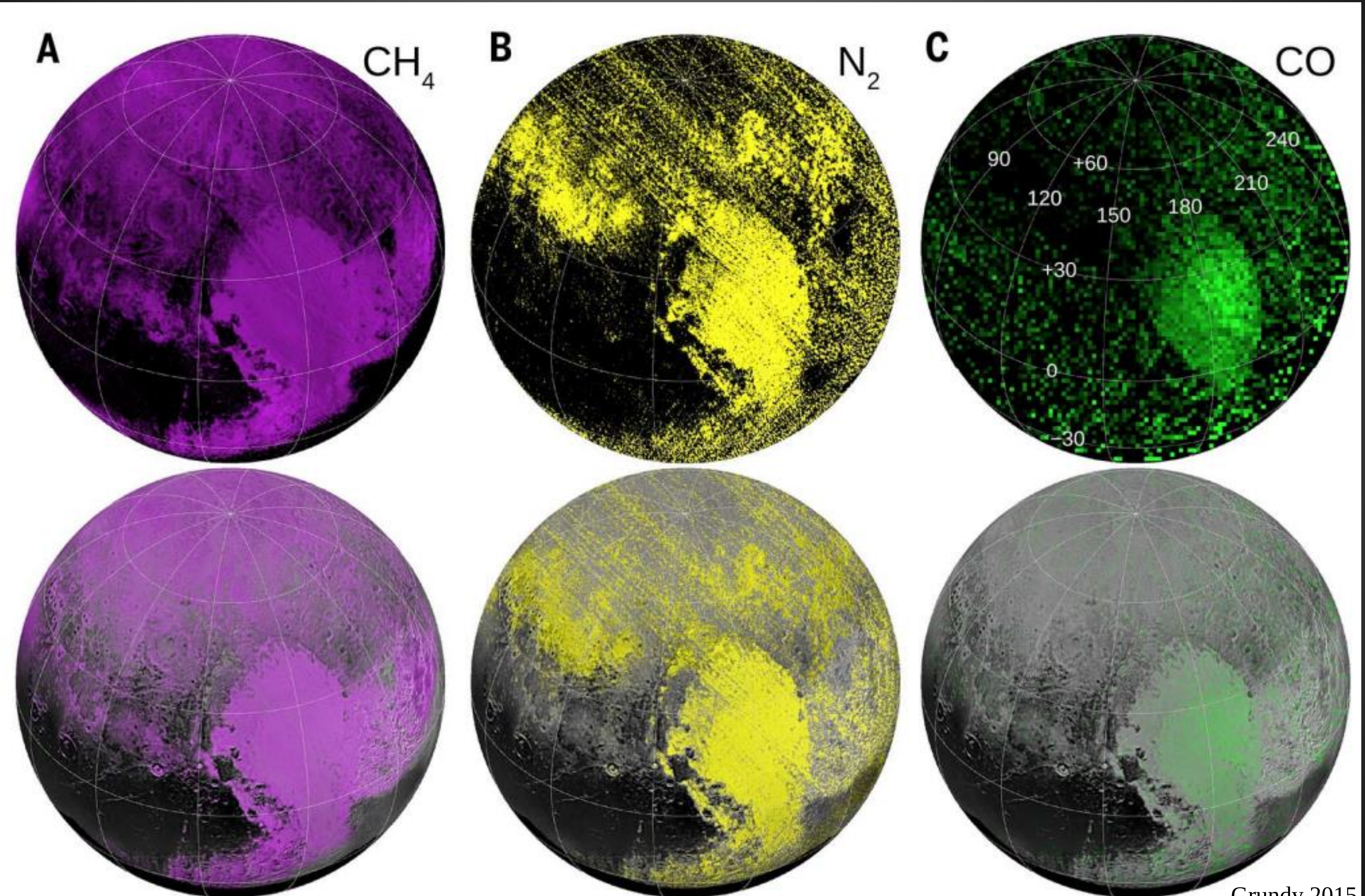


Fig. 3. LEISA spectra of Pluto. (**A**) Context map produced by averaging the red, green, and blue values from each of the colored maps across the bottom row in Fig. 1 and the right panel in Fig. 2.

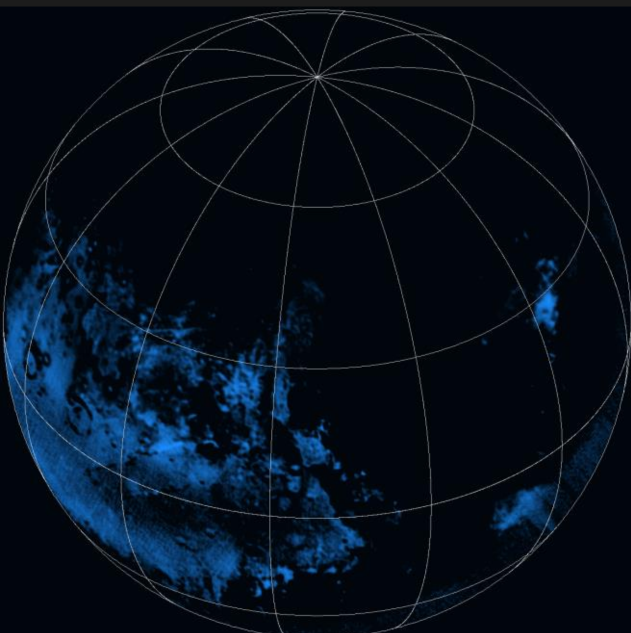
Grundy 2015

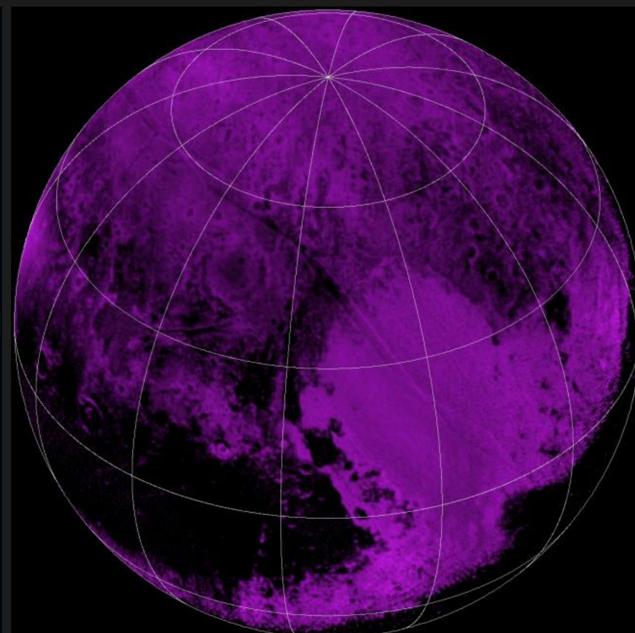
LEISA Spectral Maps of Pluto's Surface

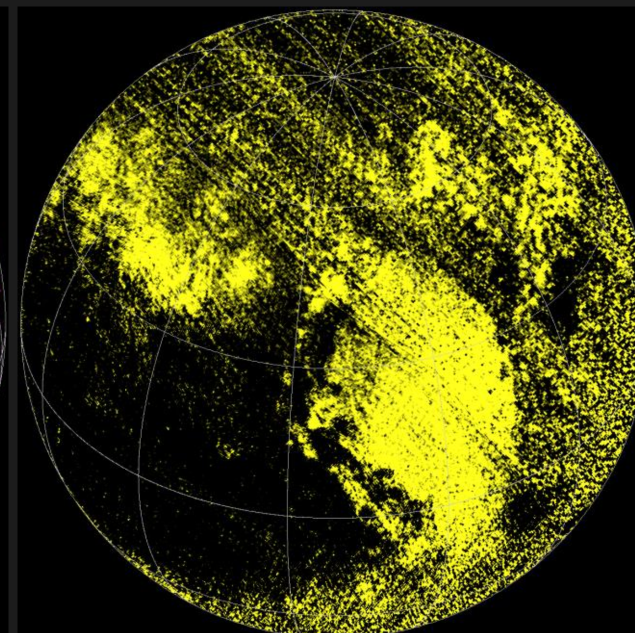


Grundy 2015

LEISA Spectral Maps of Pluto's Surface







H_2O CH_4 N_2

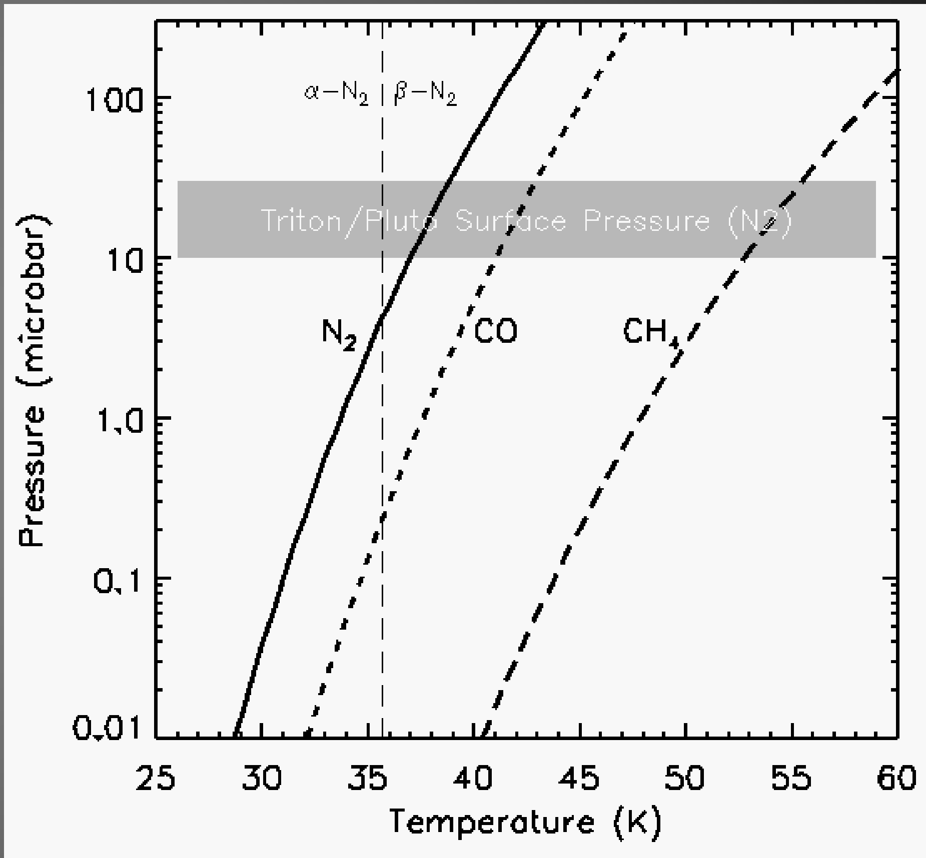
non-volatile

volatile

Grundy et al., *Science*, 2016

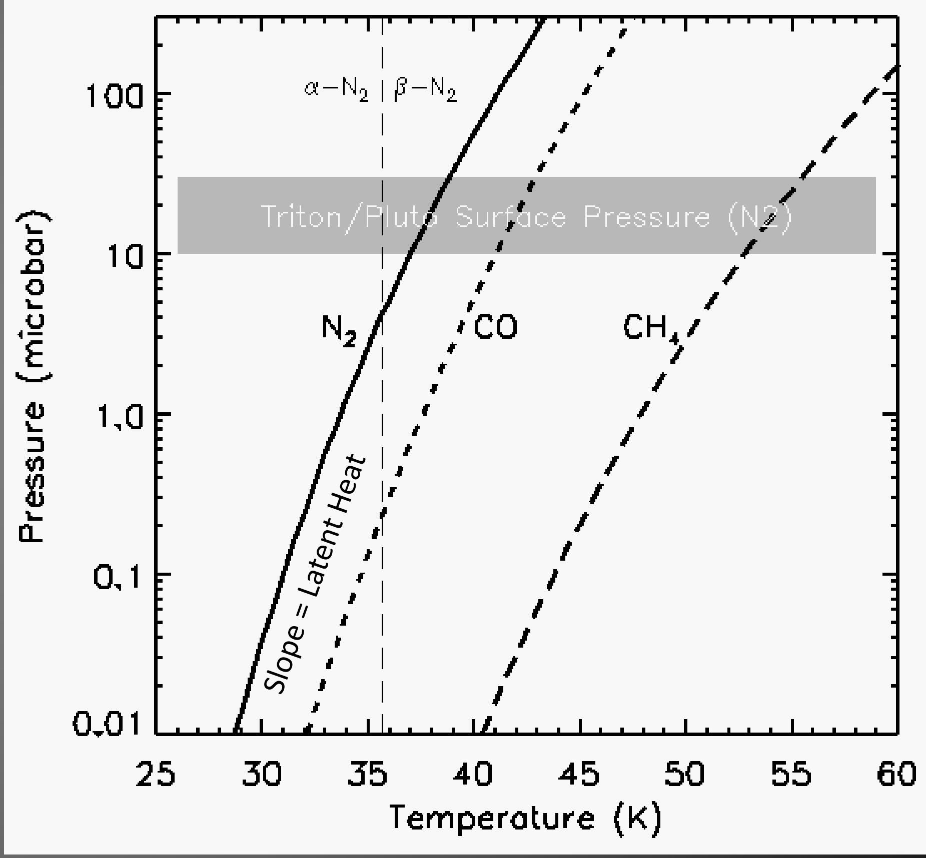
Vapor Pressures of Ices on Pluto, Triton

- N_2, CO and CH_4 ices have significant vapor pressures at relevant surface temperatures
- On low-gravity, low-temperature objects such as Pluto and Triton they are in the ice:gas phase equilibrium regime
- Seasonal transport of these ices is ocurring



Volatile Atmosphere of Pluto (and Triton)

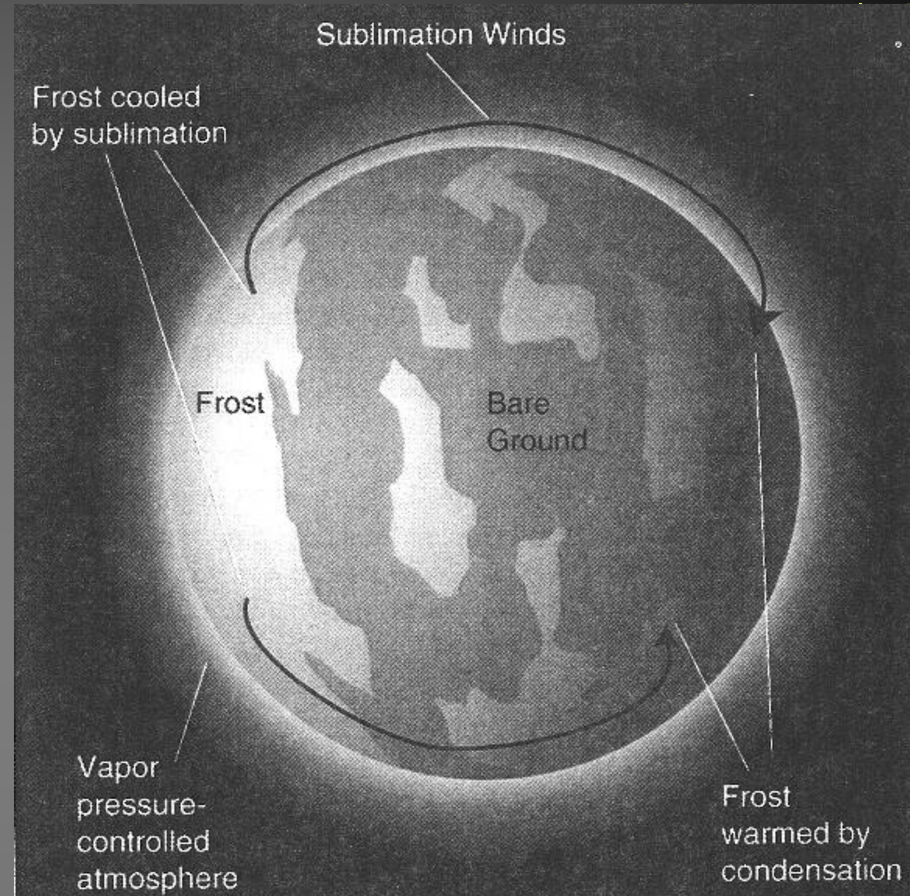
- Is 10 ubar a real atmosphere?
  - Fully collisional to many scale heights altitude
  - Pressure is ~uniform across the surface at a given radius / altitude
  - Yes – these are real atmospheres
- But – it is a different kind of real atmosphere
  - The *primary* constituent, N2, is a condensable species
  - Mars-like, not Earth-like
  - CH4 may behave like H2O in Earth's atmosphere

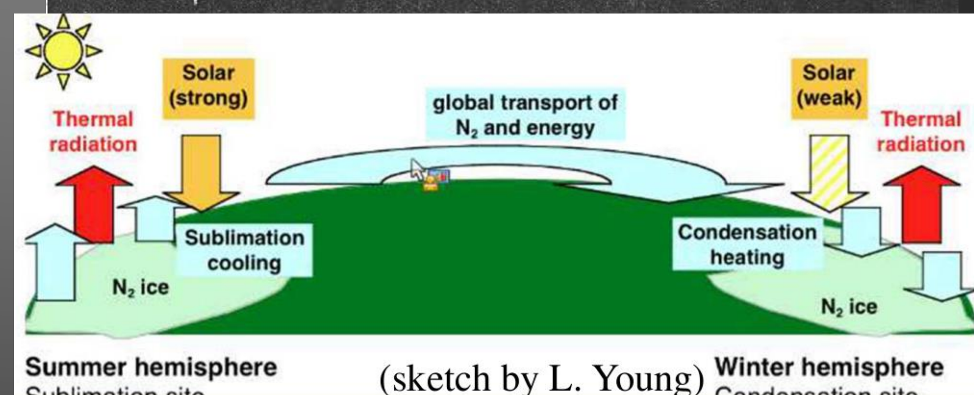


N_2 Ice Temperature is Constant over the Surface

Latent Heat Transport

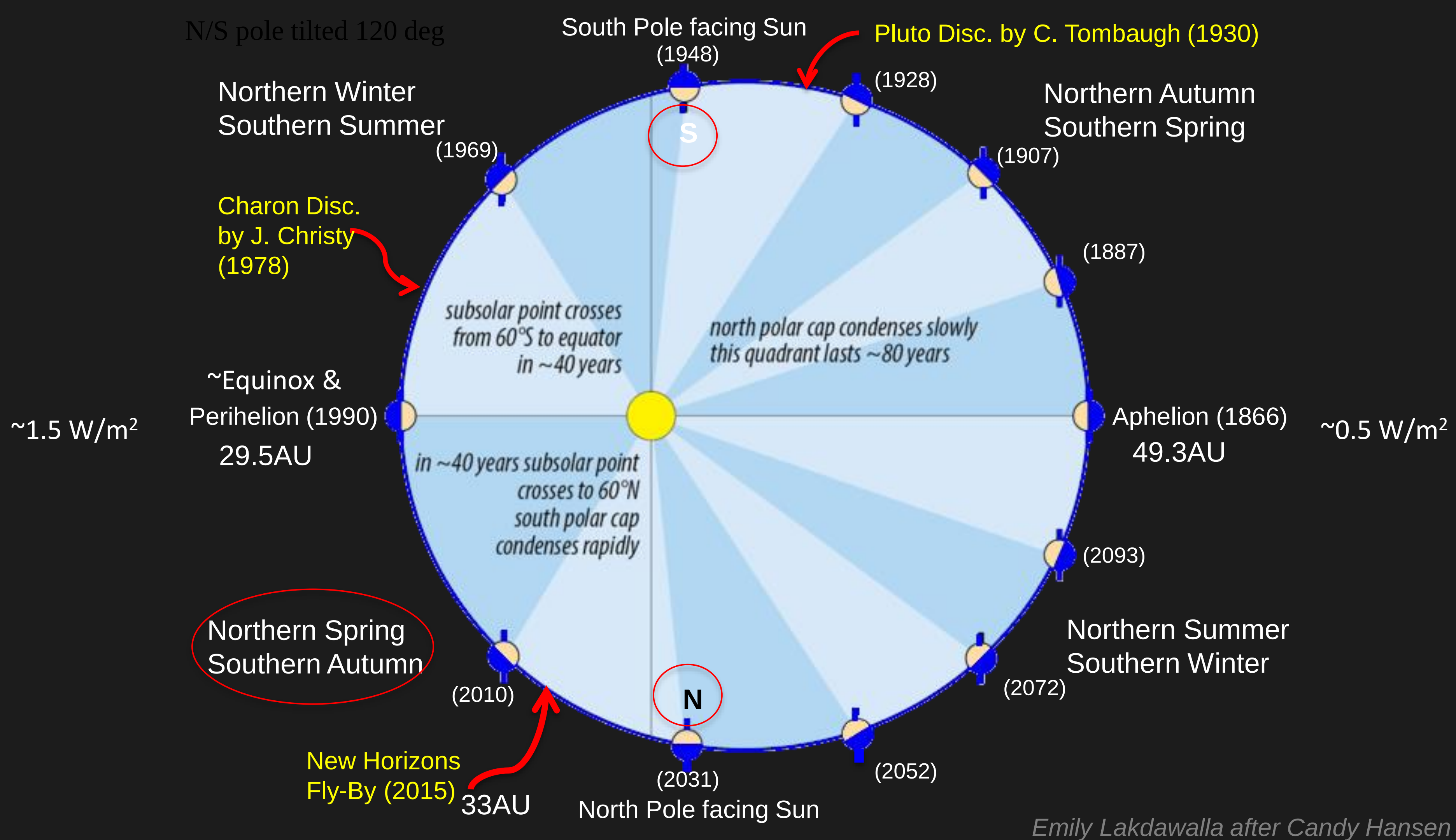
- N_2 dominates surface ices and the atmosphere
- Large latent heat of sublimation
  - small ΔT produces big ΔP
  - Sublimation (L dm/dt) balances σT^4
    - < 1.5 g/cm^2 /yr of ice
- Global sublimation winds require tiny pressure gradients
  - Eckmann layer, ≤ 1km deep
  - $V_{wind} \leq 5$ m/s (interhemispheric)
  - $C_{sound} = 125$ m/s
  - ***If*** $\Delta P/P = 0.1$, $\Delta T_{hemispheric} \approx 0.2$ K
    - $\Delta P/P \approx 0.02$ estimated (Ingersoll 1990 - for Triton)
  - ➔ N_2 ice globally isothermal
    - Pertains for $T_{frost} \geq 32$ K, $P \geq 0.5$ μb



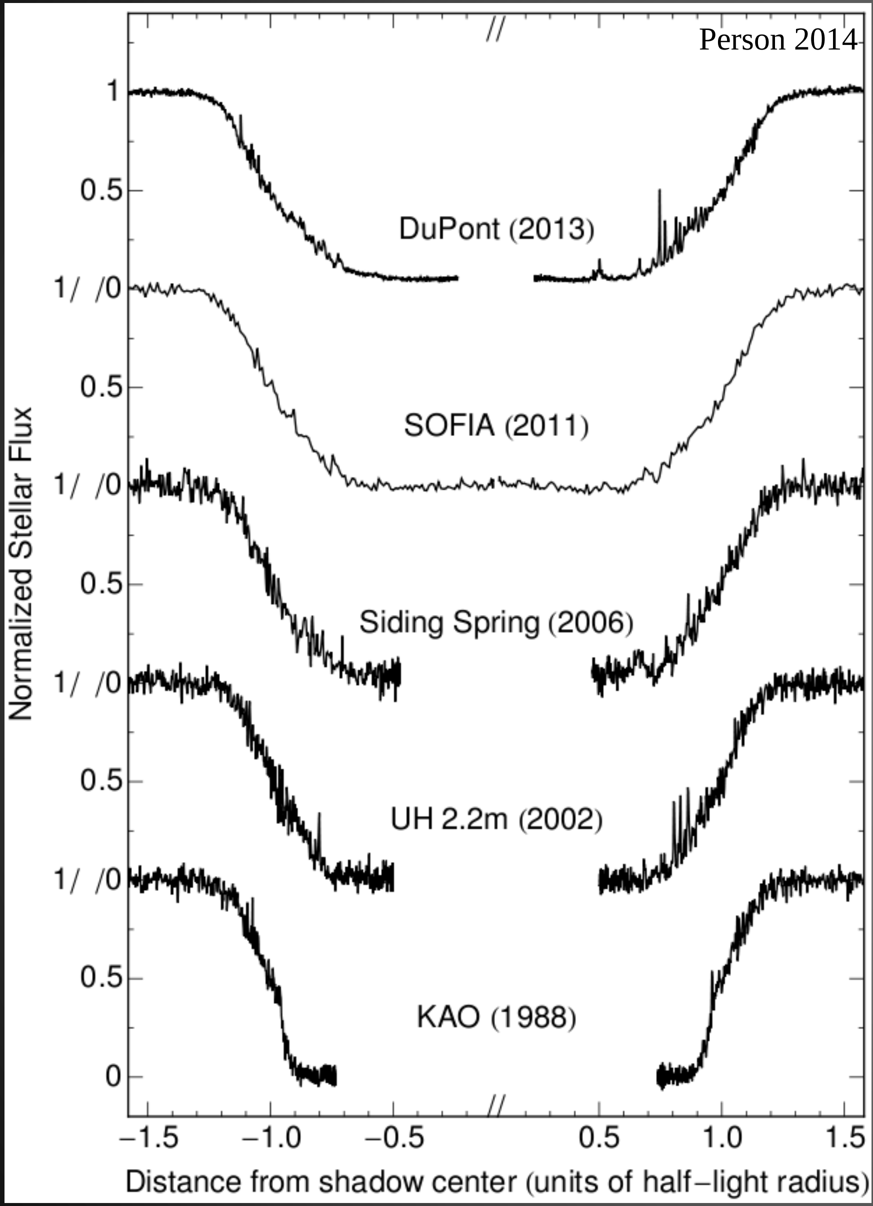


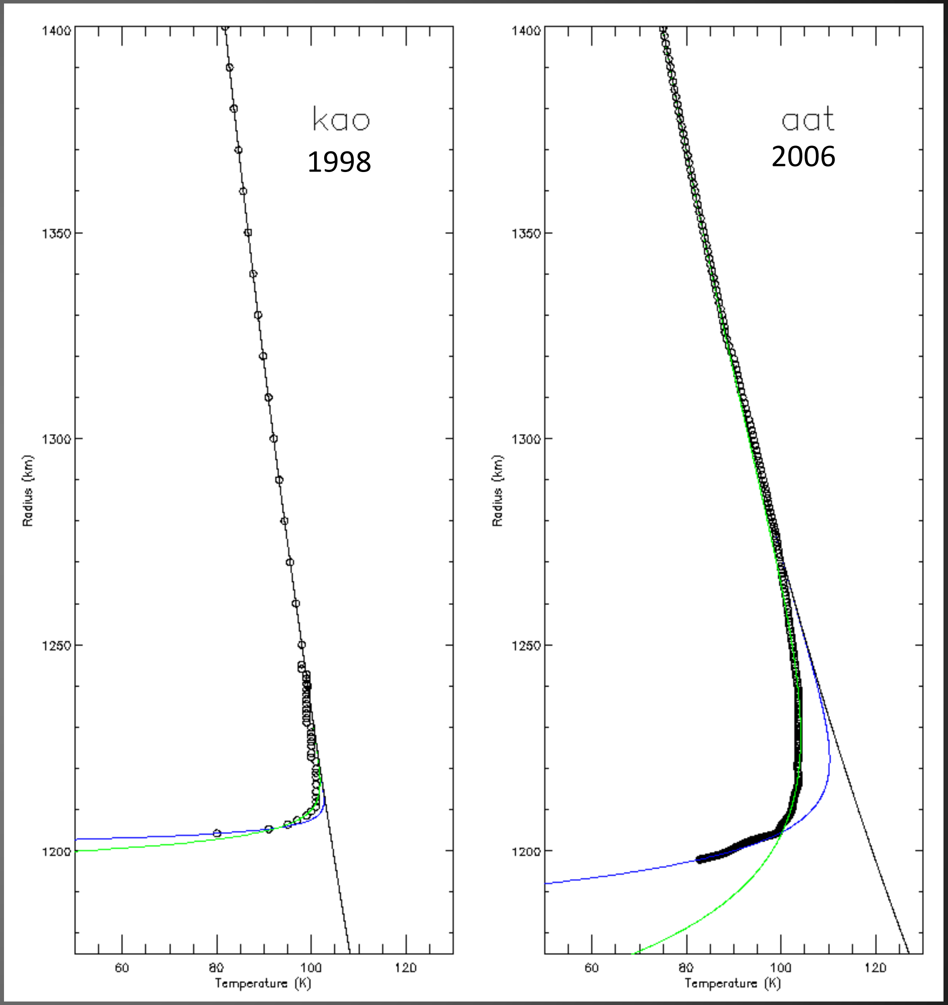
(sketch by L. Young)

Seasonal Forcing on Pluto



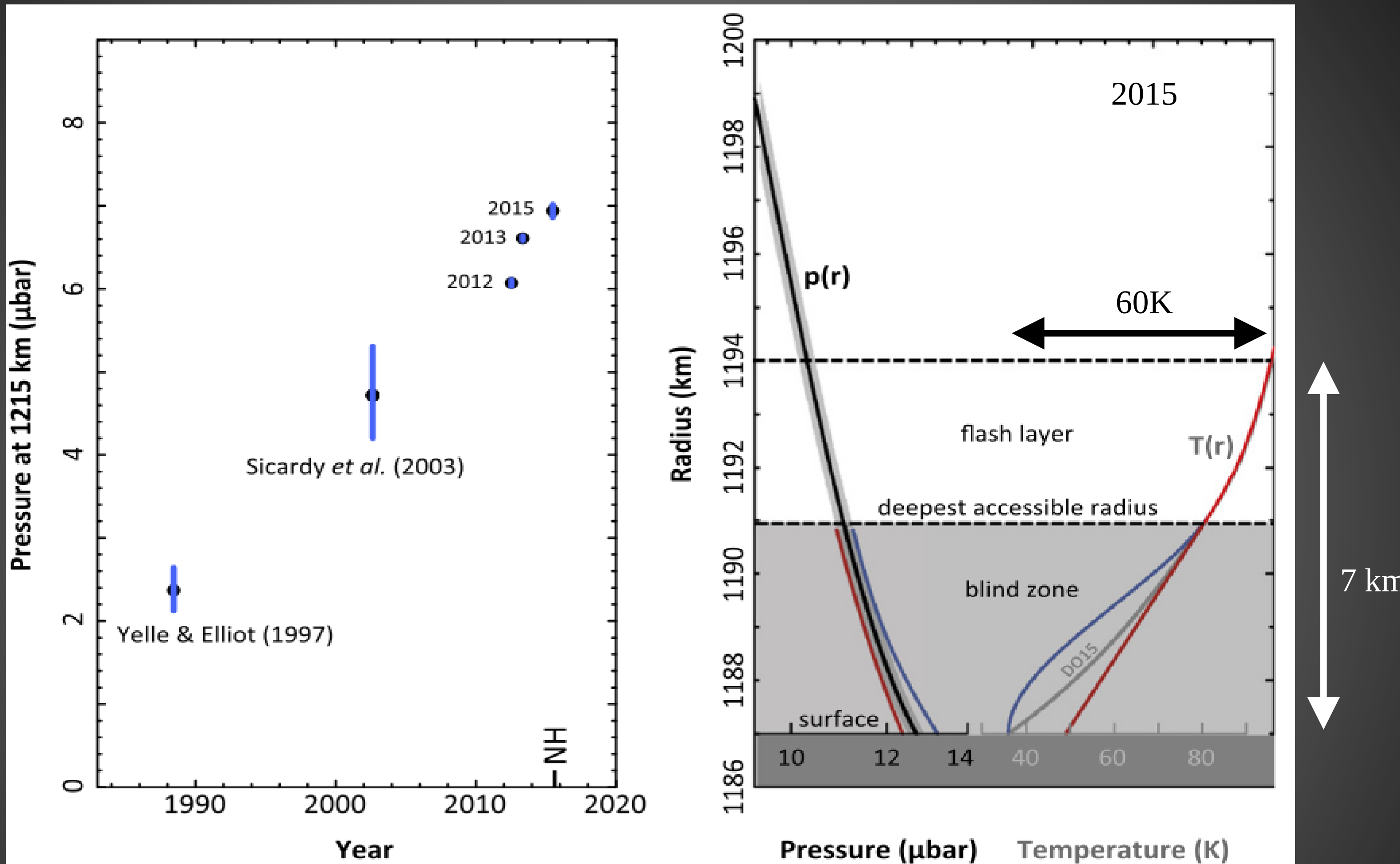
Pluto's Changing Atmosphere





Olkin 2015

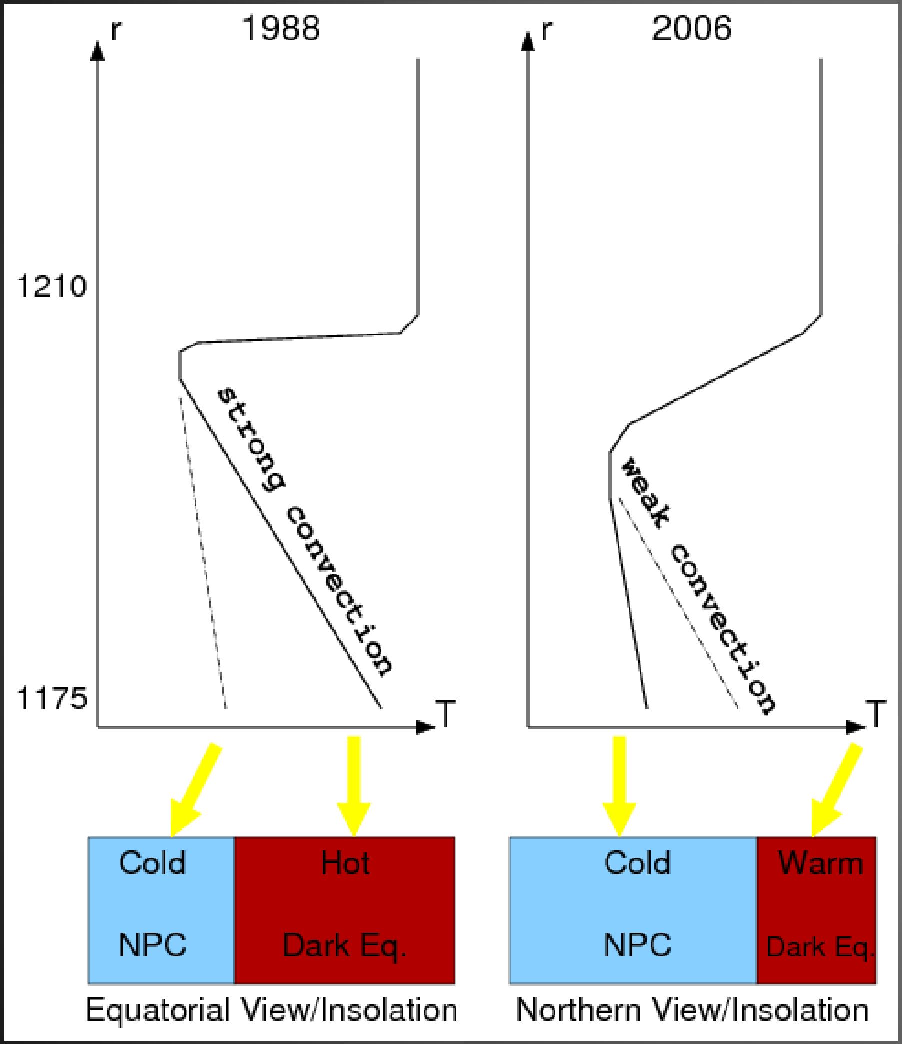
Pluto's Changing Atmosphere

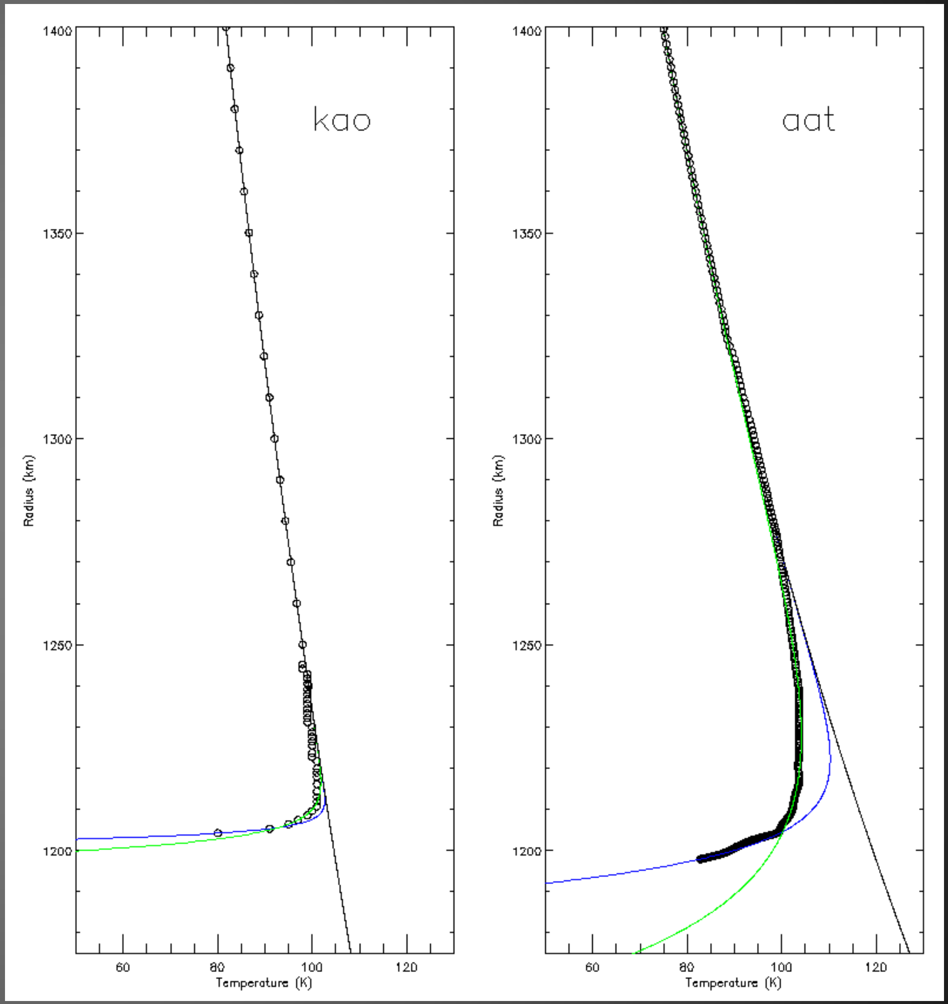


Sicardy 2015

Pluto's atmospheric pressure increased 3x between its discovery (1989) and the New Horizons encounter.

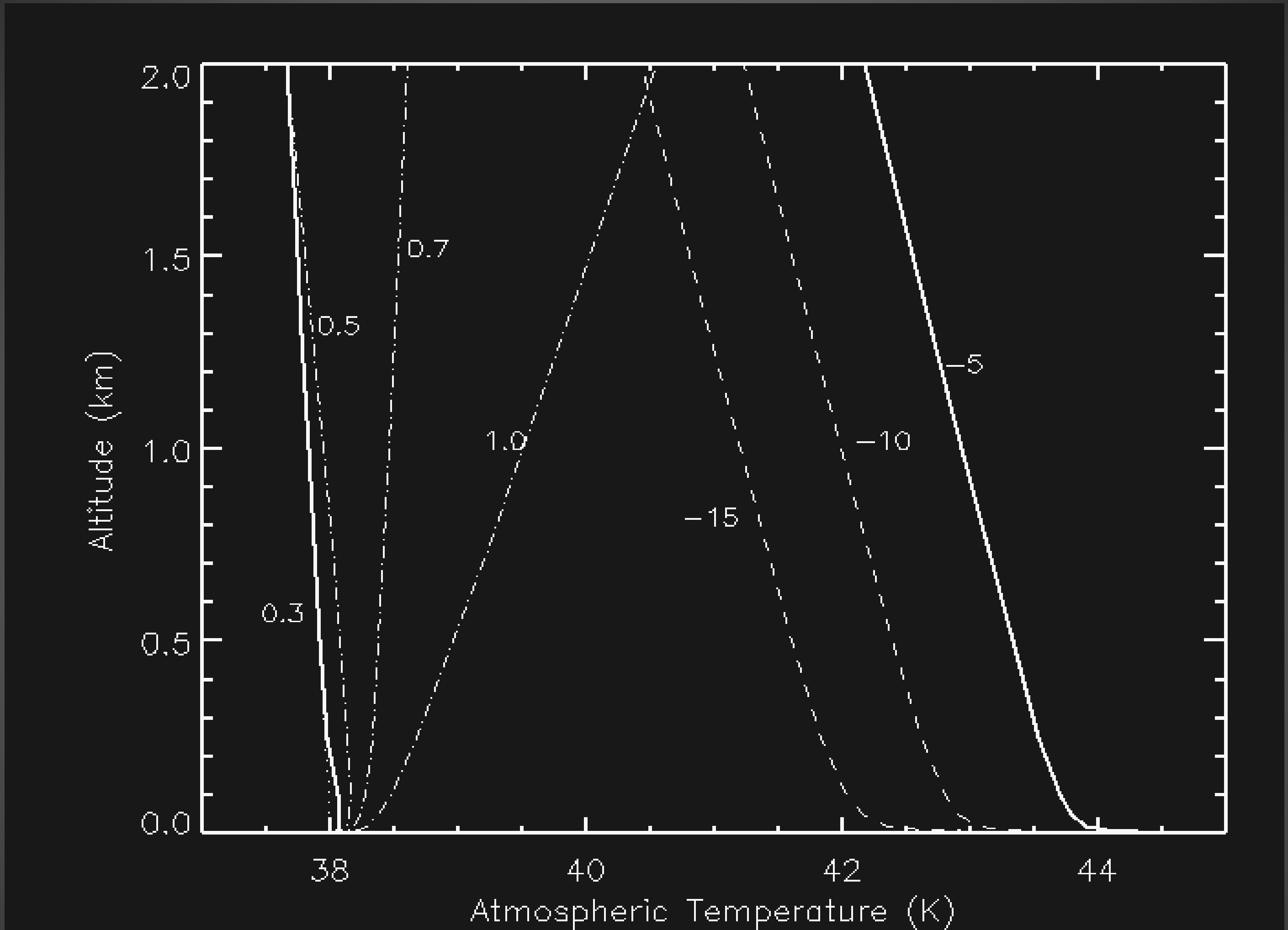
Changing Atmospheric Structure





Olkin 2015

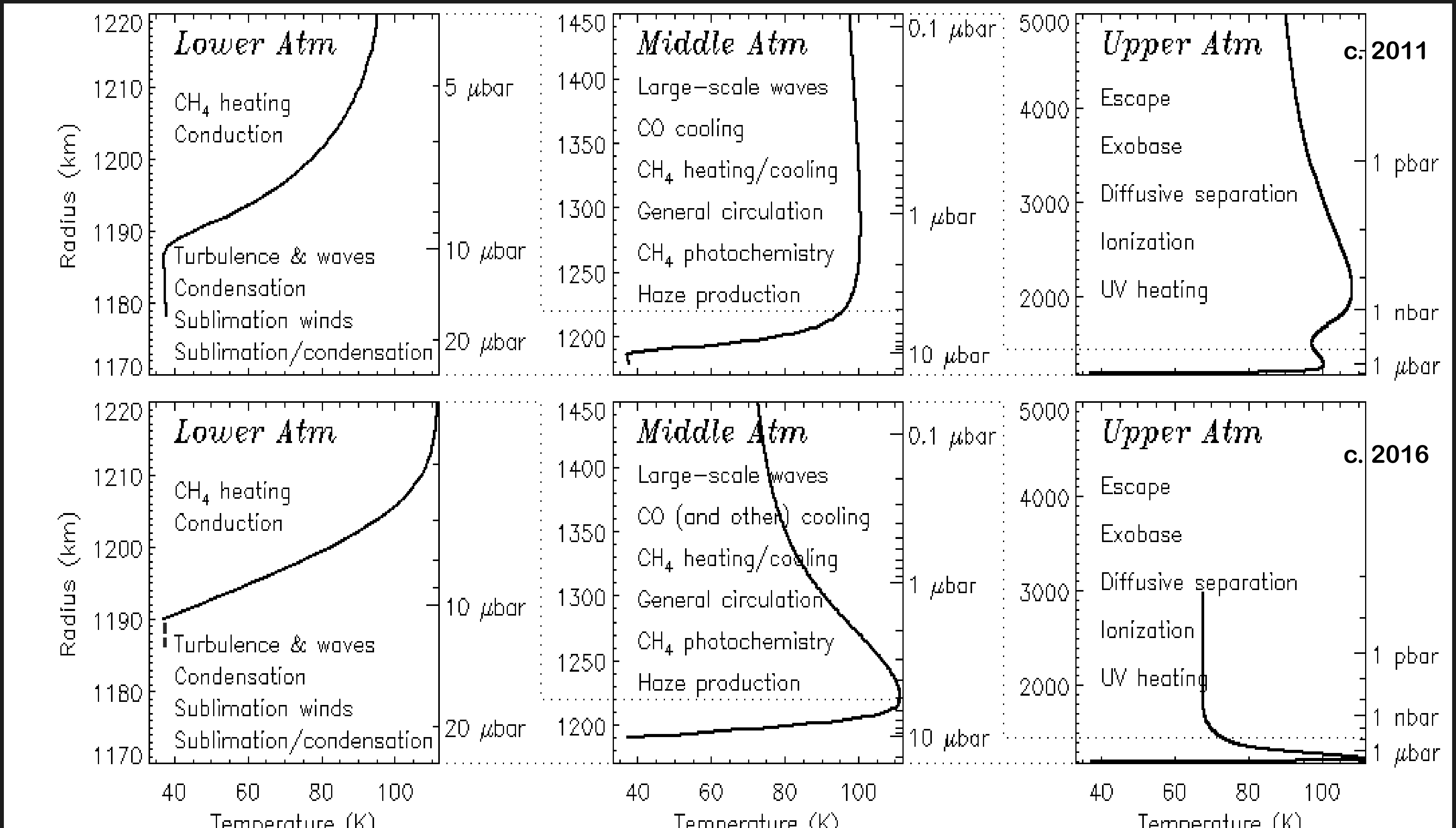
Atmospheric Heating & T Profiles



Stansberry et al. 1992

Lapse rate is adiabatic above warm areas, and is the saturated lapse rate over N2 ice.

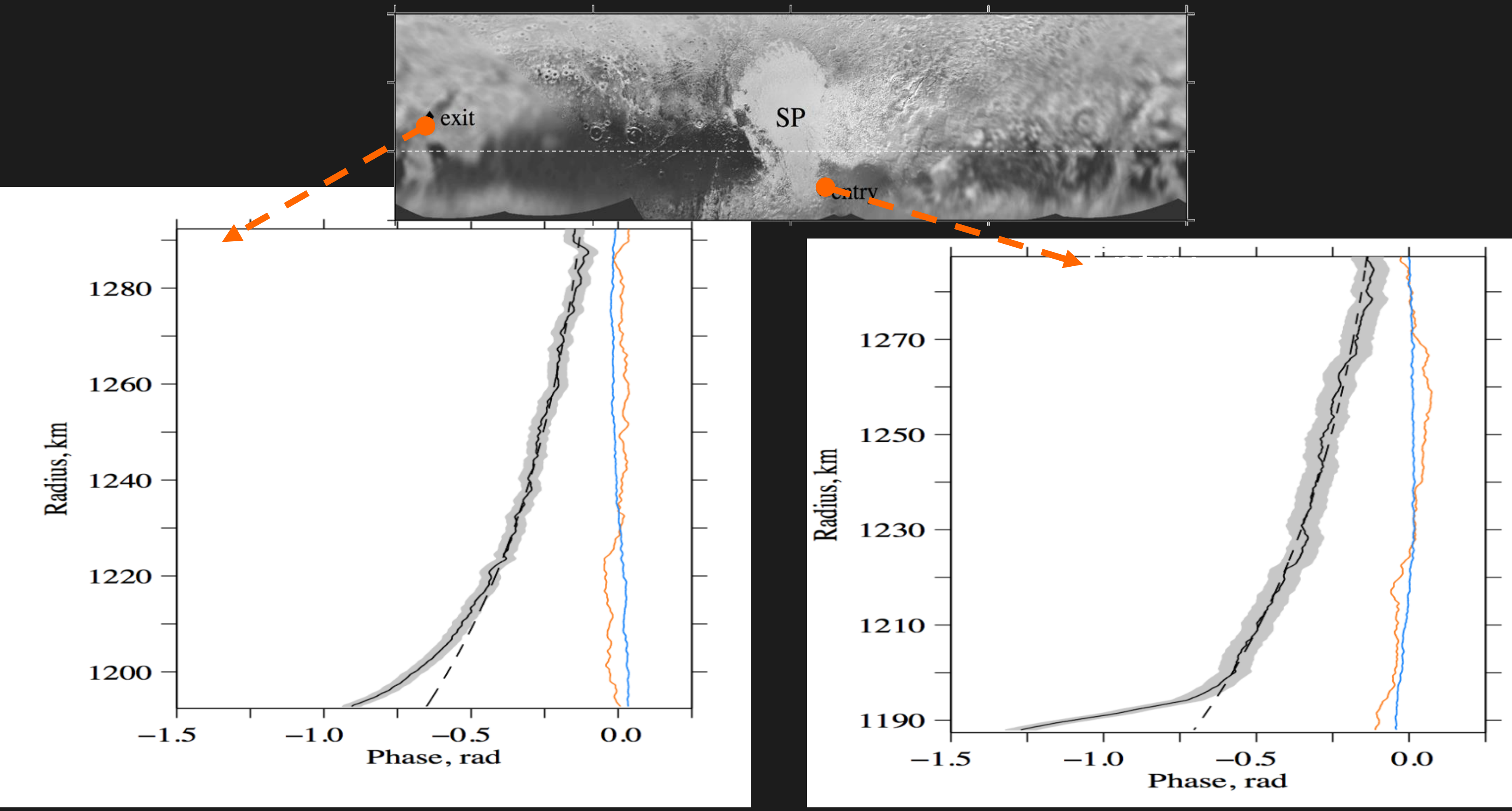
Pluto's Atmosphere: Expectation, Reality…



Stern+ 2015 (Science); Gladstone+ 2016 (Science)

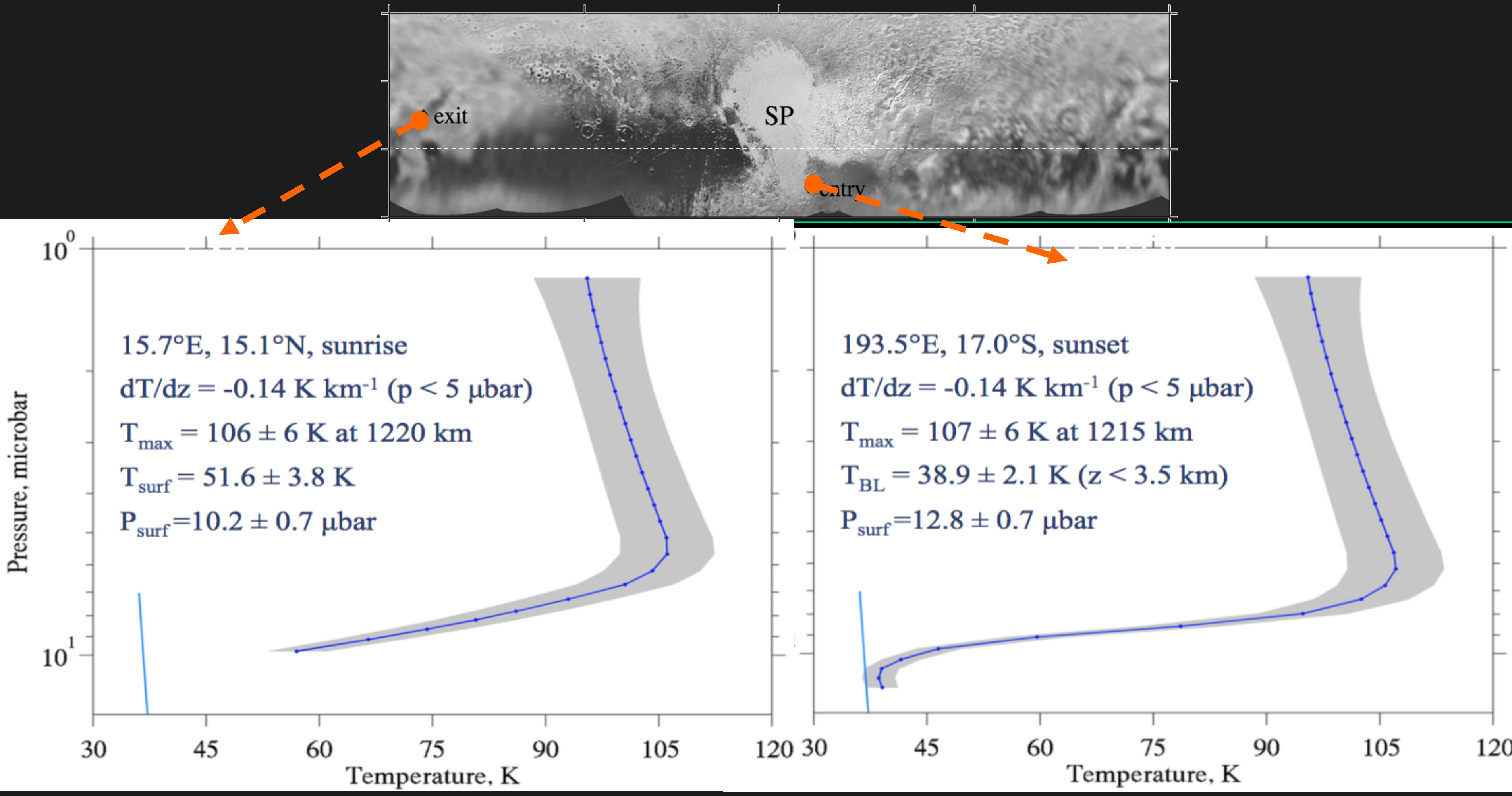
Is the cool upper-atmosphere seen by New Horizons consistent with the stellar occultations 1998 – 2015?

Lower Atmosphere from REX radio occultation



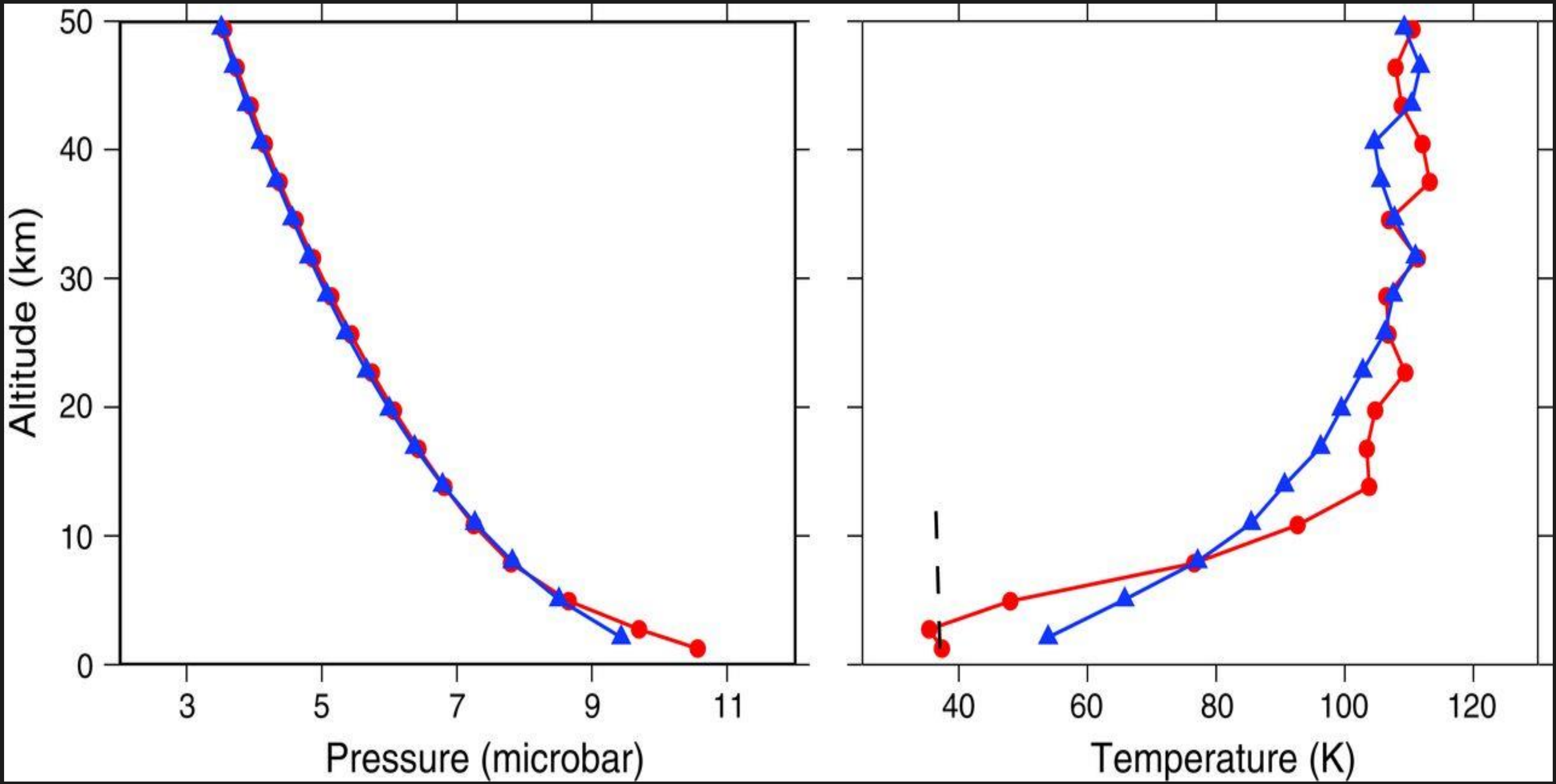
Gladstone+ 2016 (Science); Hinson+ (DPS48 224.03)

Lower Atmosphere from REX radio occultation



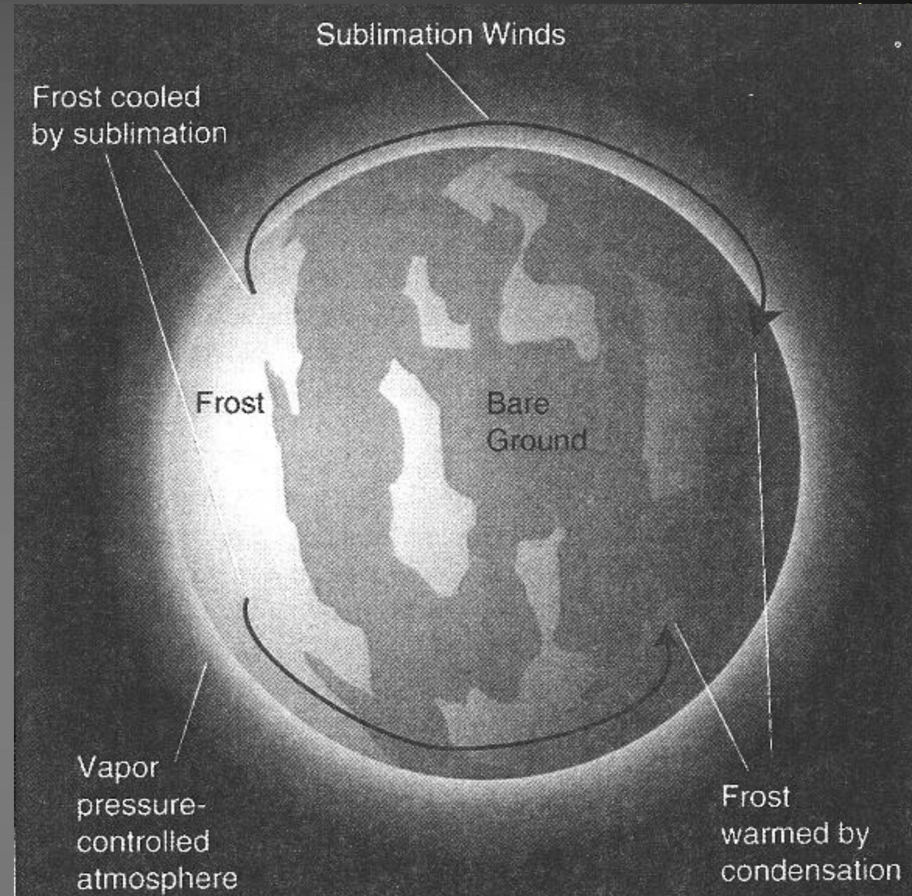
Gladstone+ 2016 (Science); Hinson+ (DPS48 224.03)

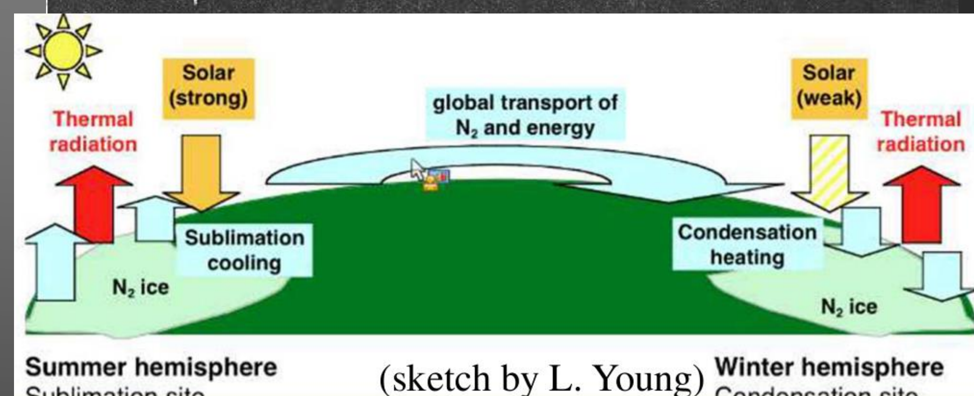
[P,T] Profile of Pluto's Lower Atmosphere



N_2 Ice Temperature is Constant over the Surface

Vapor Pressure ~Equilibrium atmospheres can do some weird stuff…



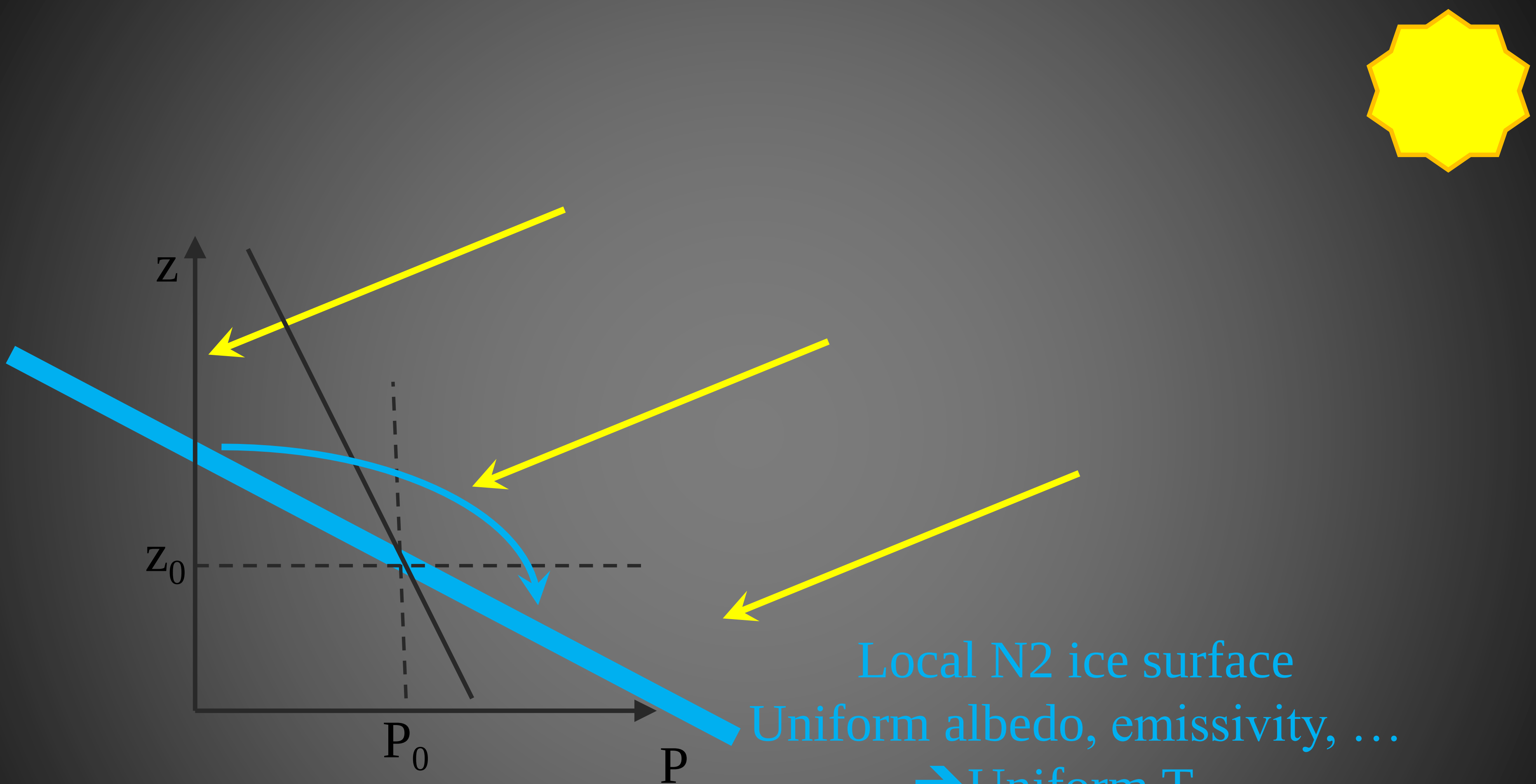


“Global” N_2 Ice Quantities

- N_2 Ice Temperature (T_{N2})
  - Set by globally-averaged equilibrium temperature of N_2 ice

    $S_0 (1-A_B) = \gamma\varepsilon\sigma T^4$
- Atmospheric Surface Pressure (P_0)
  - N_2 Vapor pressure at T_{N2}

Topography: Local Downhill Transport



Local N2 ice surface

Uniform albedo, emissivity, …

➔Uniform T_{EQ}

Mass flux is energy-limited (just as for other processes)

"Global" N_2 Ice Quantities

- N_2 Ice Temperature (T_{N2})
  - Set by globally-averaged equilibrium temperature of N_2 ice

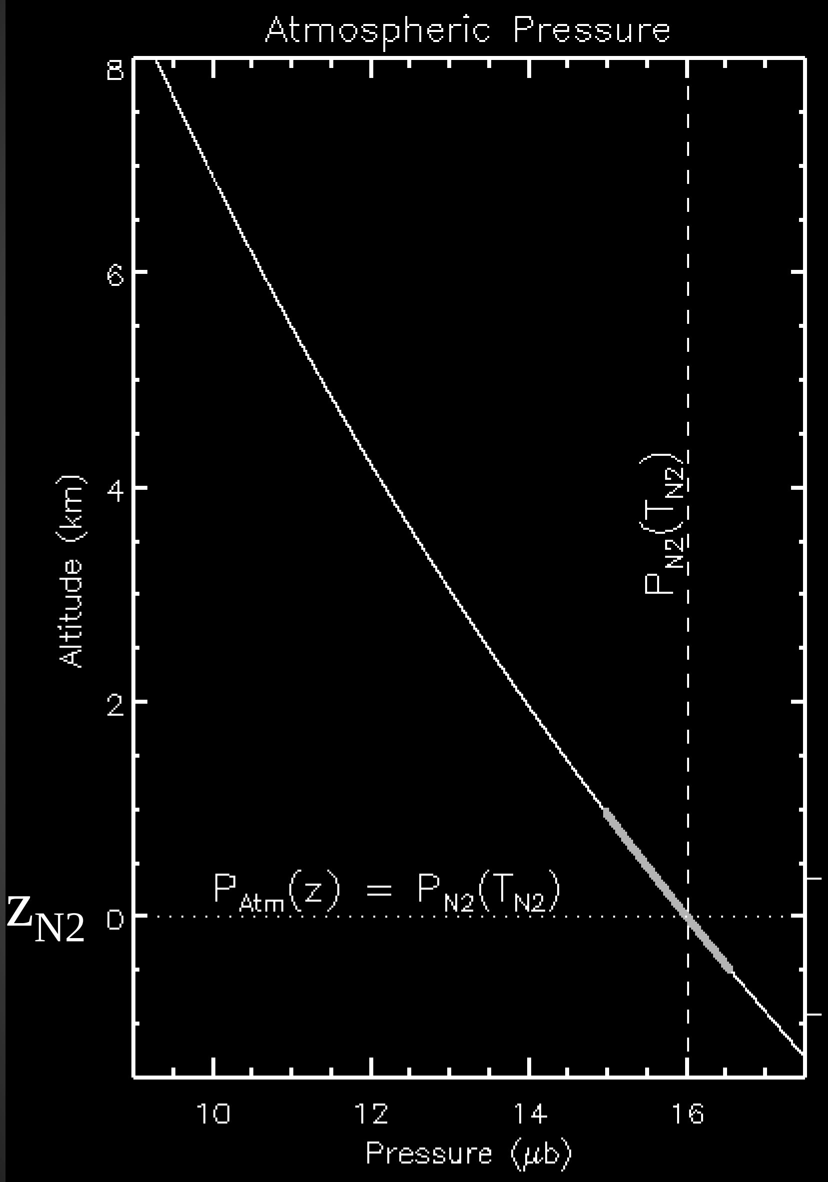
    $S_0 (1-A_B) = \gamma\varepsilon\sigma T^4$

- Atmospheric Surface Pressure (P_0)
  - N_2 Vapor pressure at T_{N2}

- N_2 Ice Elevation (z_{N2})
  - Height (radius) where $P_{Atm}(z) = P_{VP}(T_{N2})$

What happens to N2 ice at elevations other than z_{N2} ?

N2 Ice Elevation and Atmospheric Pressure

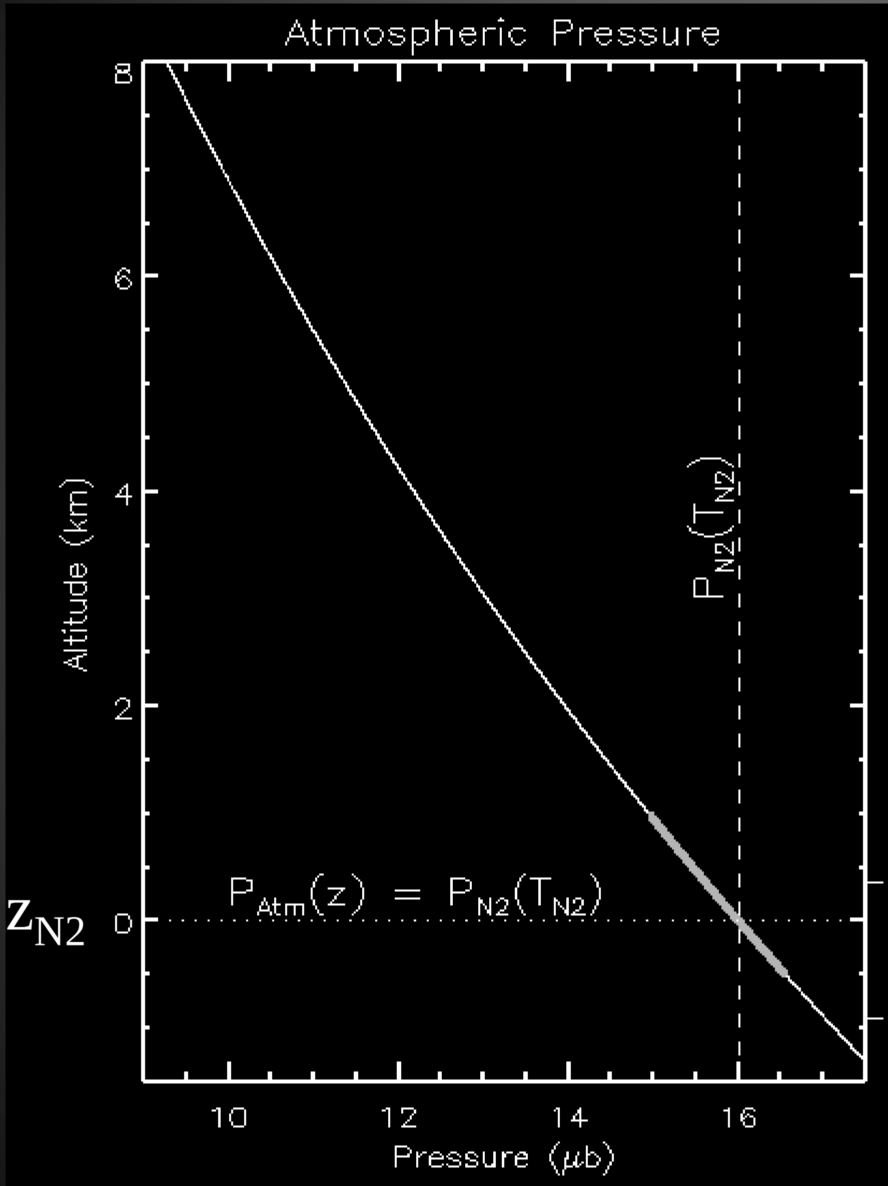


$\Delta P/\Delta z$ =1μb/km (H = 15km)

Hemispheric ΔP = 0.32μb

Energy-limited ΔP = 0.001μb

N2 Ice Elevation and Atmospheric Pressure



$\Delta P/\Delta z$ =1μb/km (H = 15km)

Hemispheric ΔP = 0.32μb

Energy-limited ΔP = 0.001μb

Energy-limited dm/dt = g/cm^2/yr

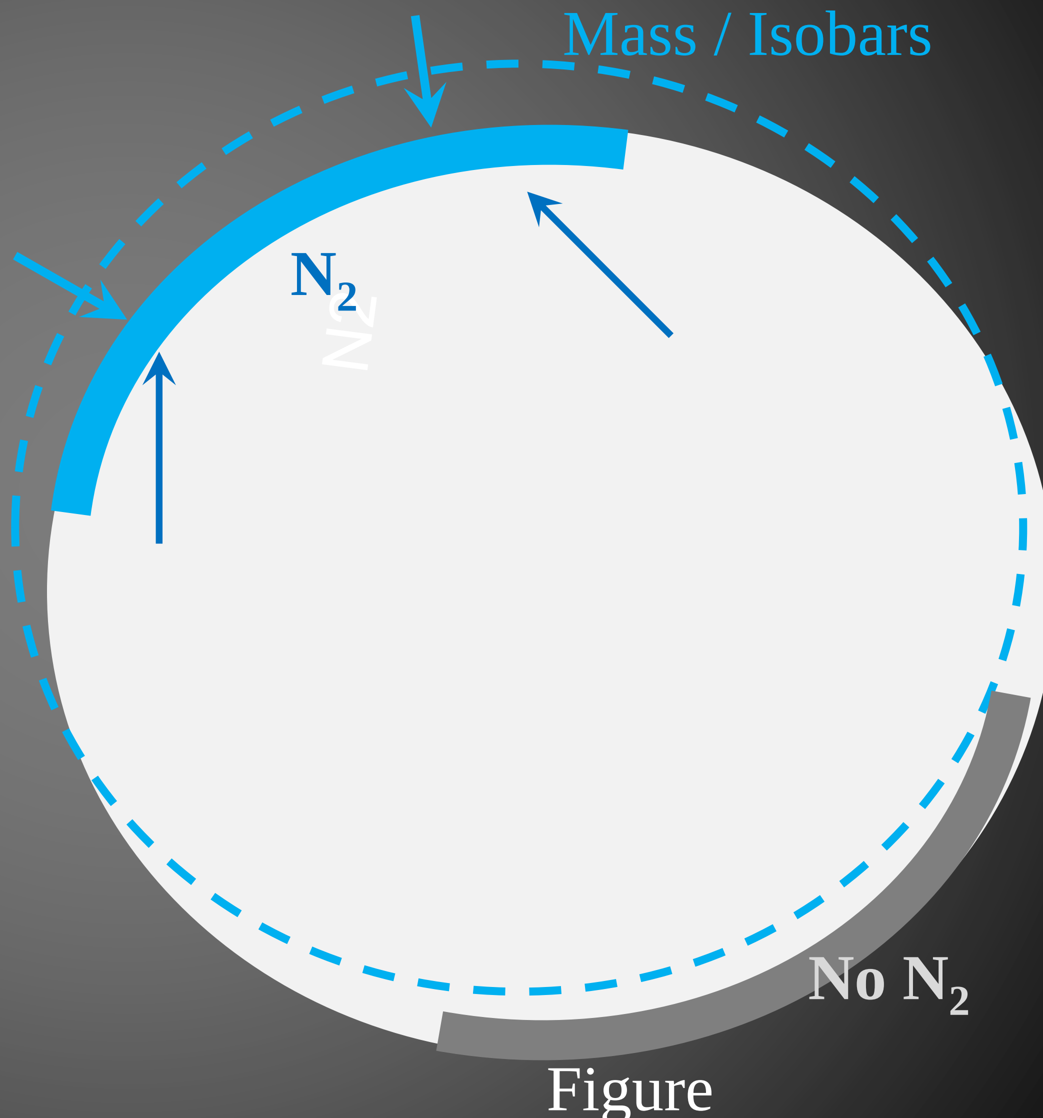
Trafton & Stansberry 2015 DPS:

- N_2 ice T(z) ~follows wet adiabat
  - Small departures drive mass fluxes
- Downhill transport occurs on the night/winter hemisphere
- Sublimation/deposition is much weaker than reported last year at DPS

Large Scale Topography

- Center of mass offset?
  - Global-scale biases in N2 distribution

- Highlands/lowlands dichotomy

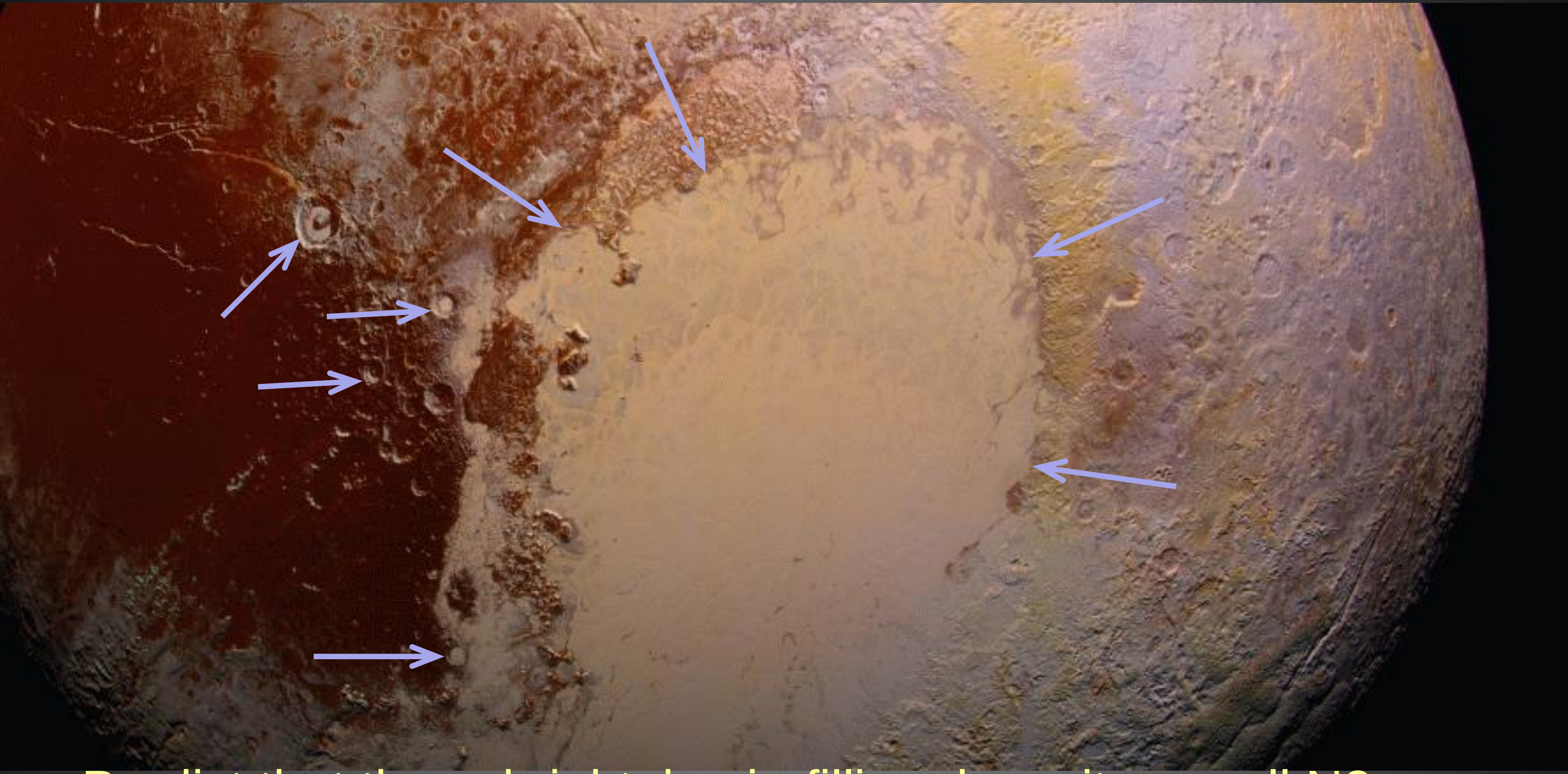


N_2-ice "Shorelines"

- Surface of volatile deposits will tend to a single height
  - Localized and global-scale downhill transport
    - Albedo, latitude, slope effects compete with topographic effects
  - Winter/night: conduction is only energy source
    - This will result in lower rates than stated above (need to quantify)
  - Timescales are of order 10^6 years for 1km of N_2 ice

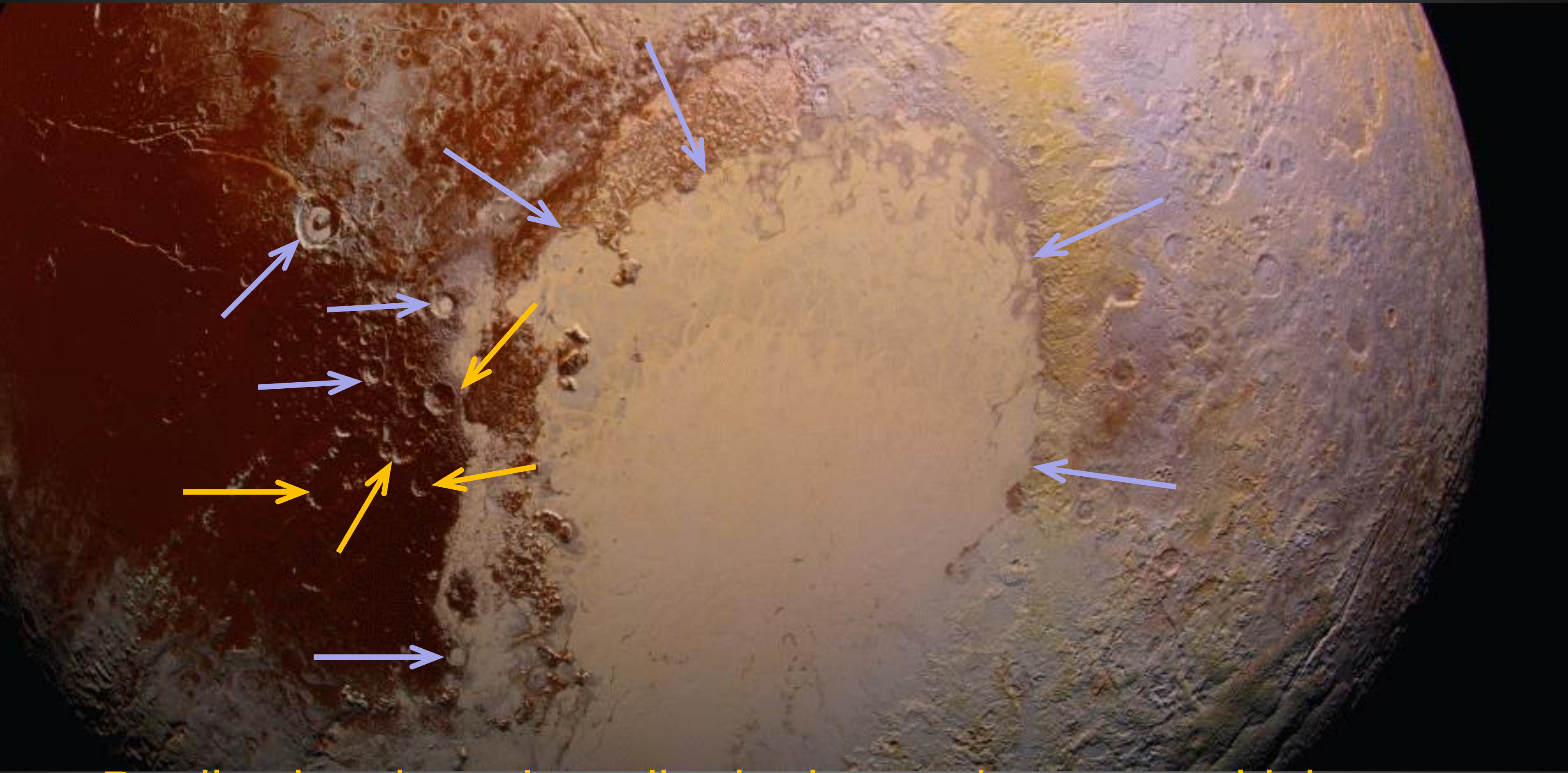
- N_2 ice will infill below a geopotential surface ("Ice Level")
  - Height defined by long-term global energy balance of the N_2
  - N_2 surface may serve as a global geological reference level
  - Seasonal, diurnal transport can produce short-lived N_2 deposits at higher elevations
  -

Sputnik Planum, Elliot Crater "Shorelines"



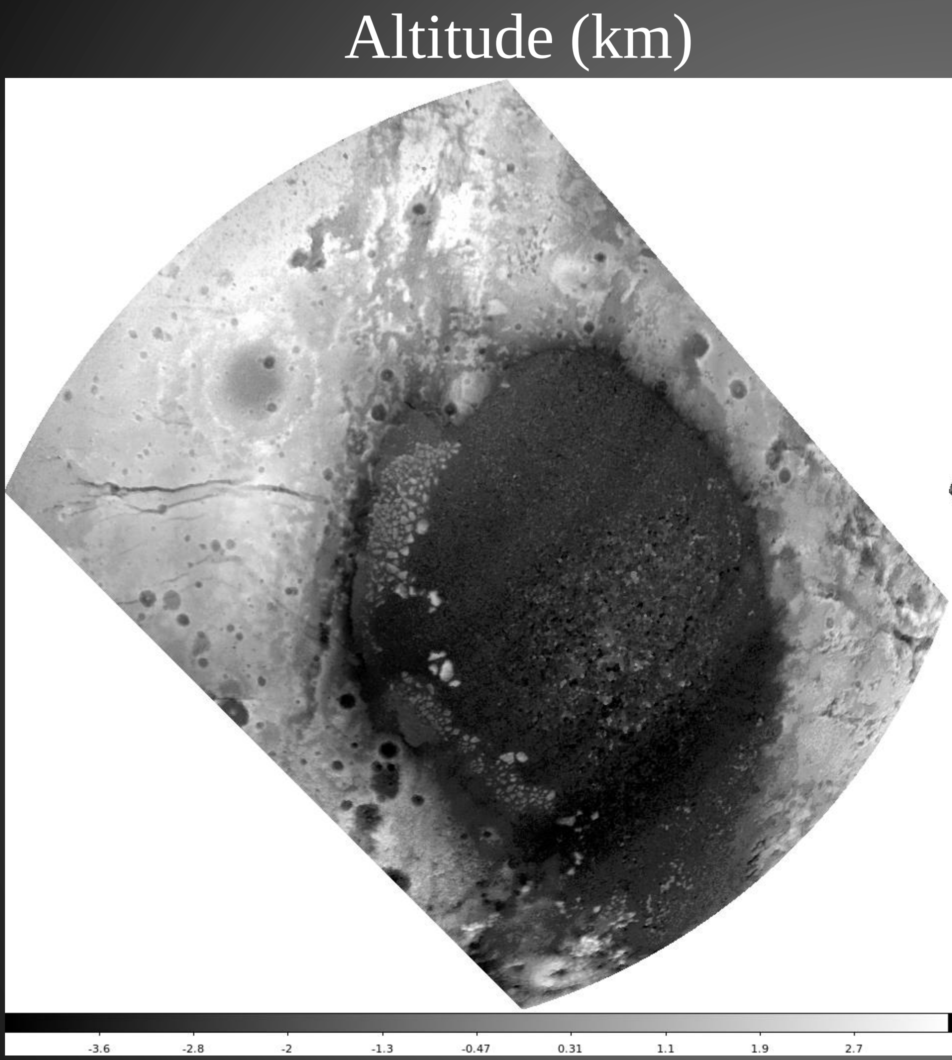
- Predict that these bright, basin-filling deposits are all N2 dominated, at nearly the same elevation
  - Existing N2 maps consistent, but S/N is rather low

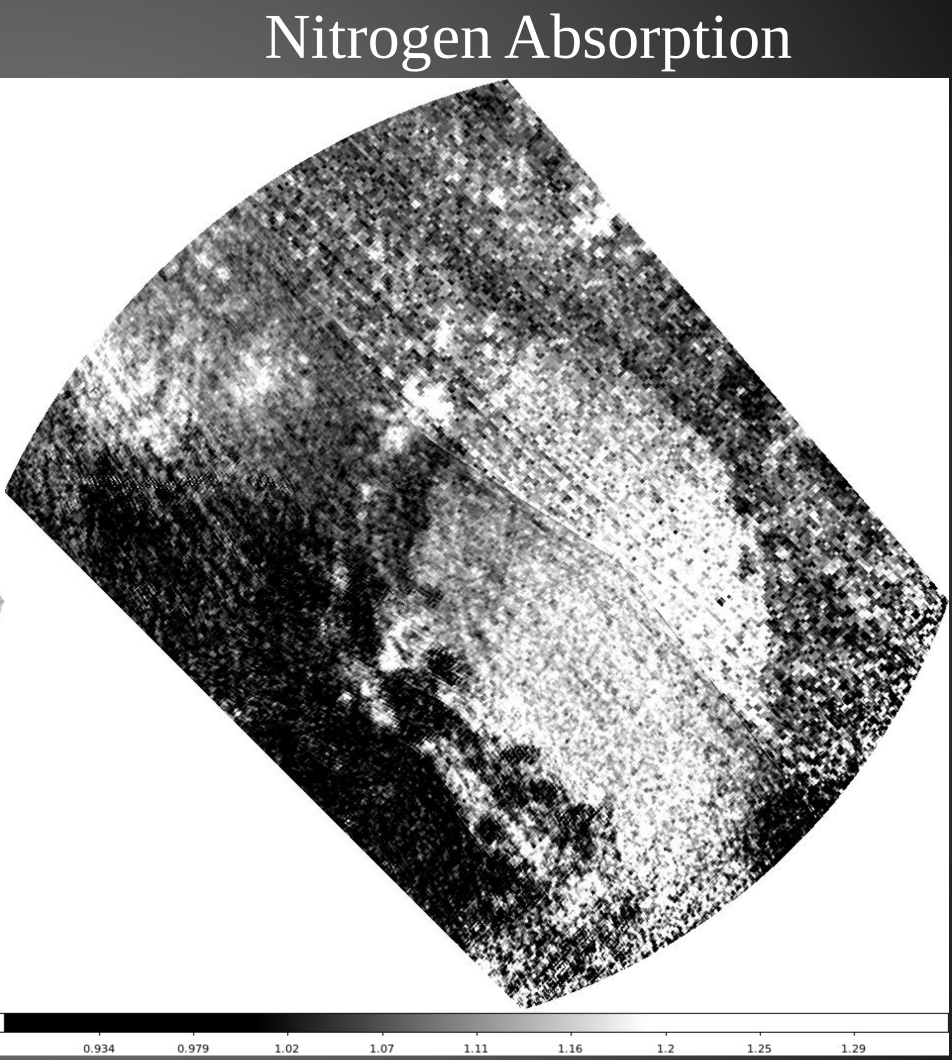
"Dead Seas"

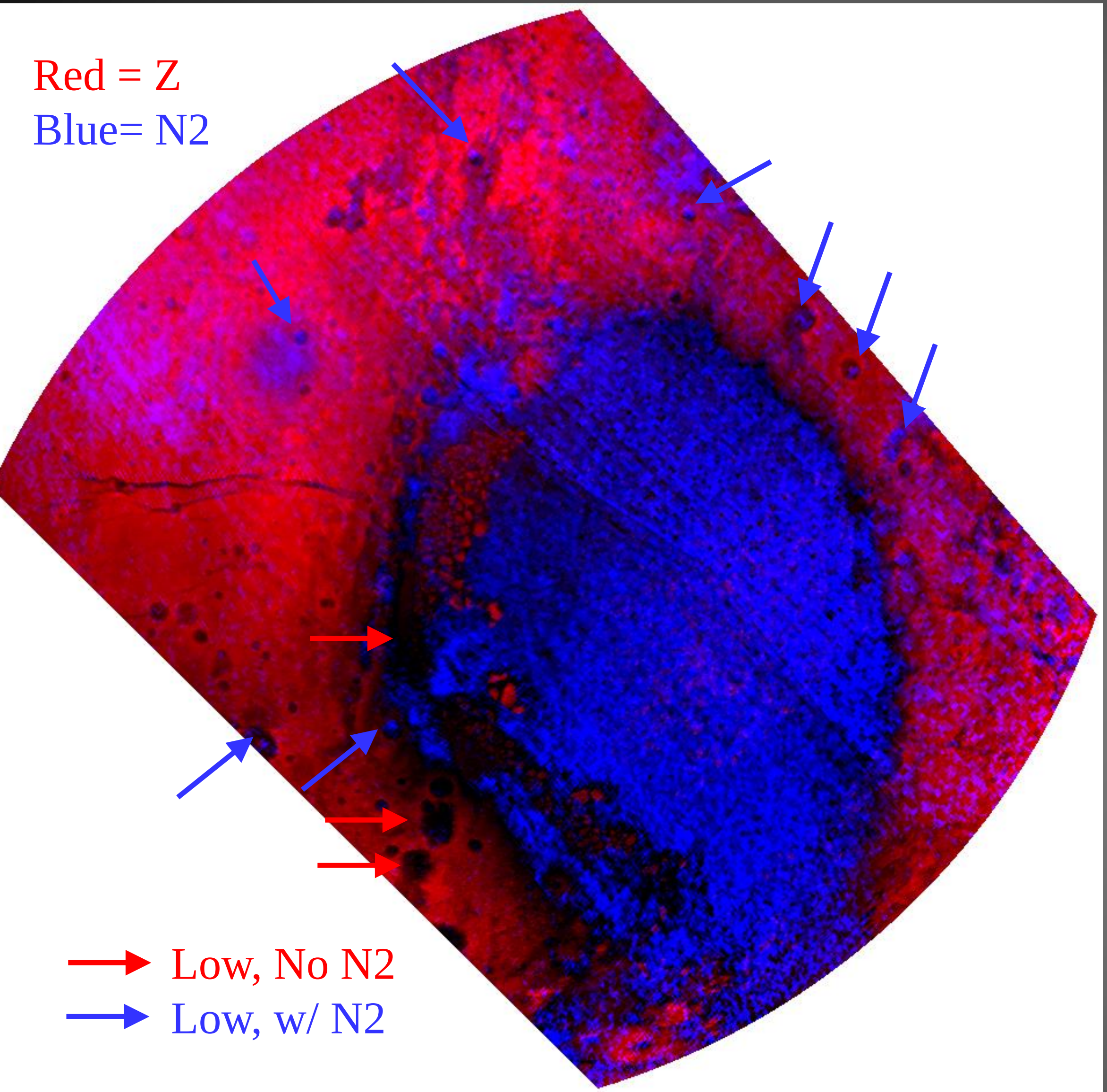


- Predict that these low-albedo depressions are at higher elevations than S.P., do not contain N_2

The Data Sets



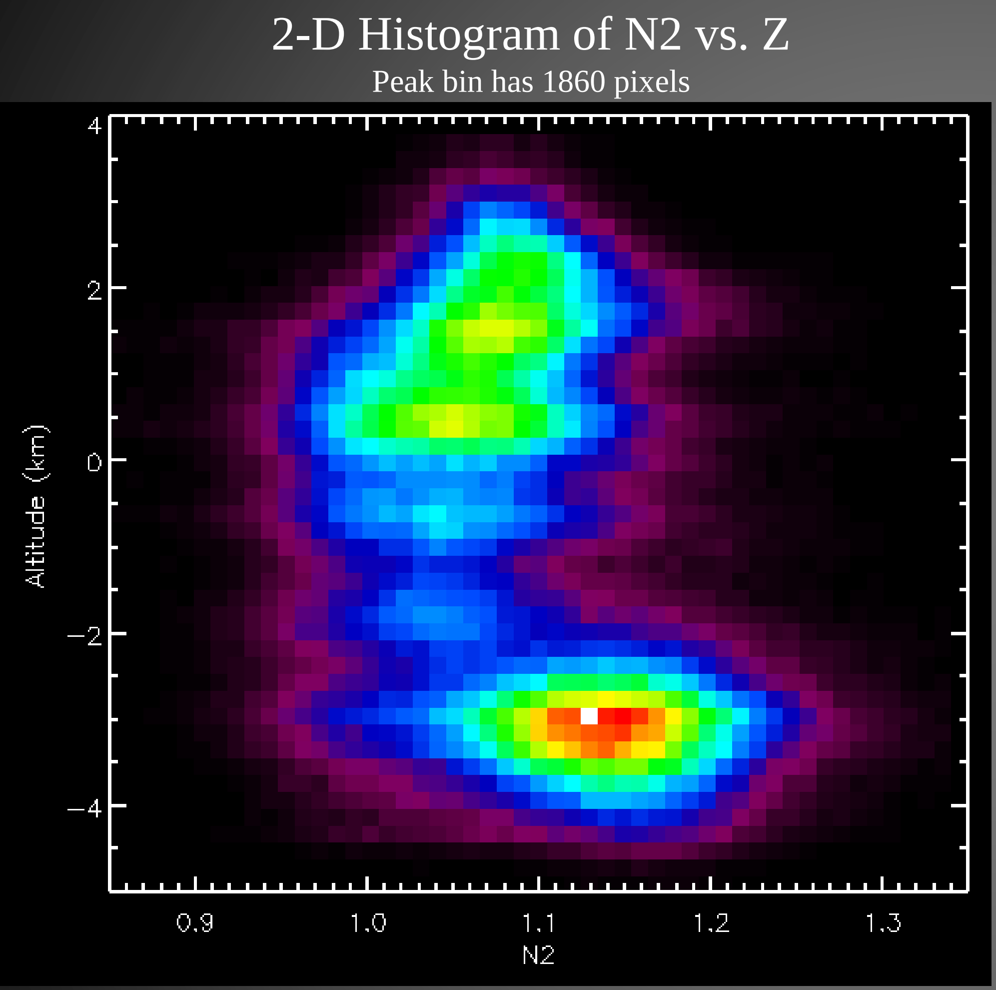




New Horizons data generally supports topographic transport model

- Sputnik Planitia is the prime example
- Other basins also show N2
- But – counter examples clearly exist
  - Series of craters SW of S.P.
  - Elliot crater has strong CO, but not much N2
- Data analysis is progressing
  - New DEM products and composition maps
  - Regional slopes are hard to constrain via DEM methods…

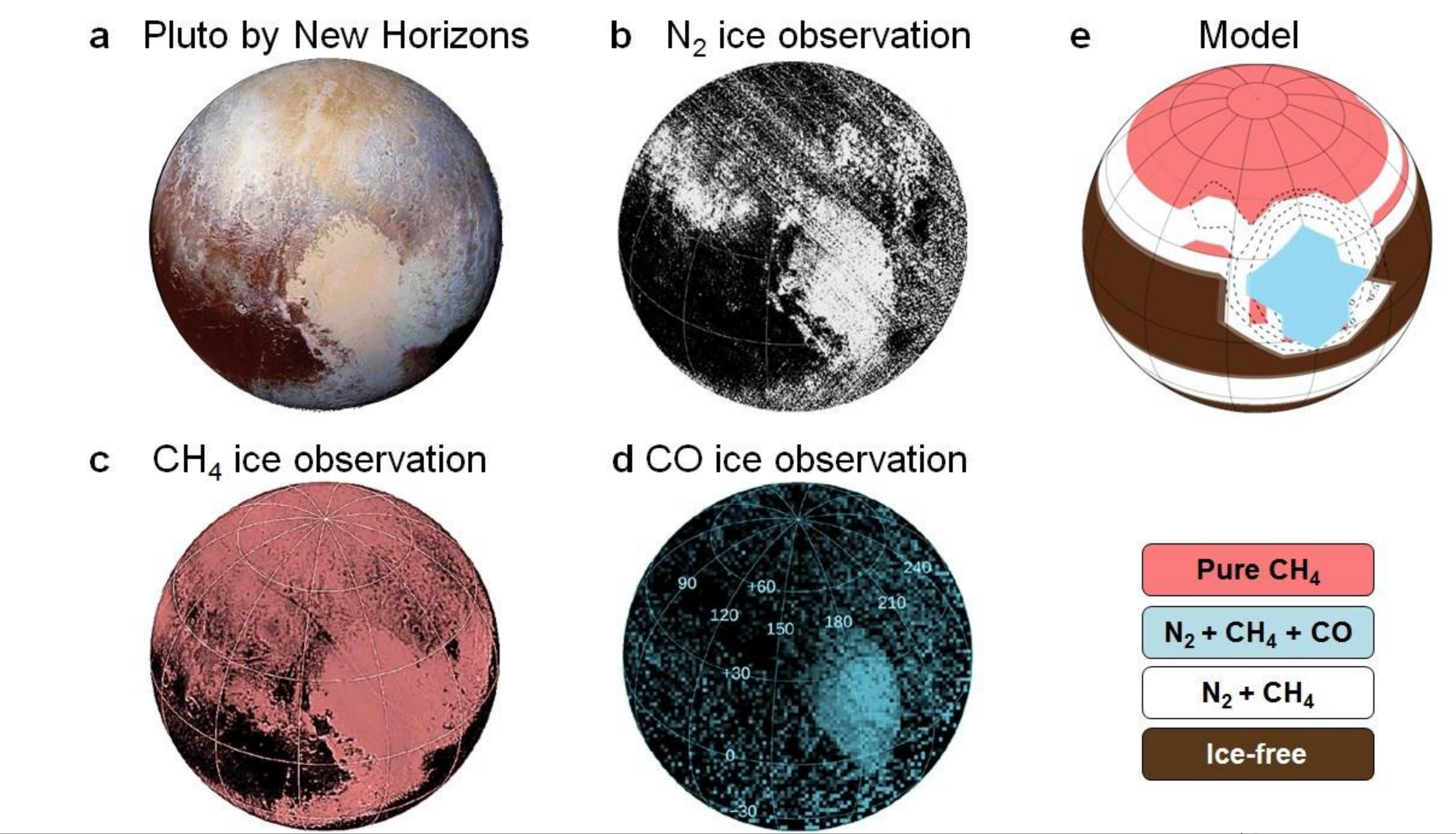
N_2 Distribution vs Z



- Divide data into ~2500 bins (~200 pix/bin if evenly distributed)
- S.P. clearly has concentration of the strongest N2 band, Elliot and a few other craters, too.

GCM Models for Pluto

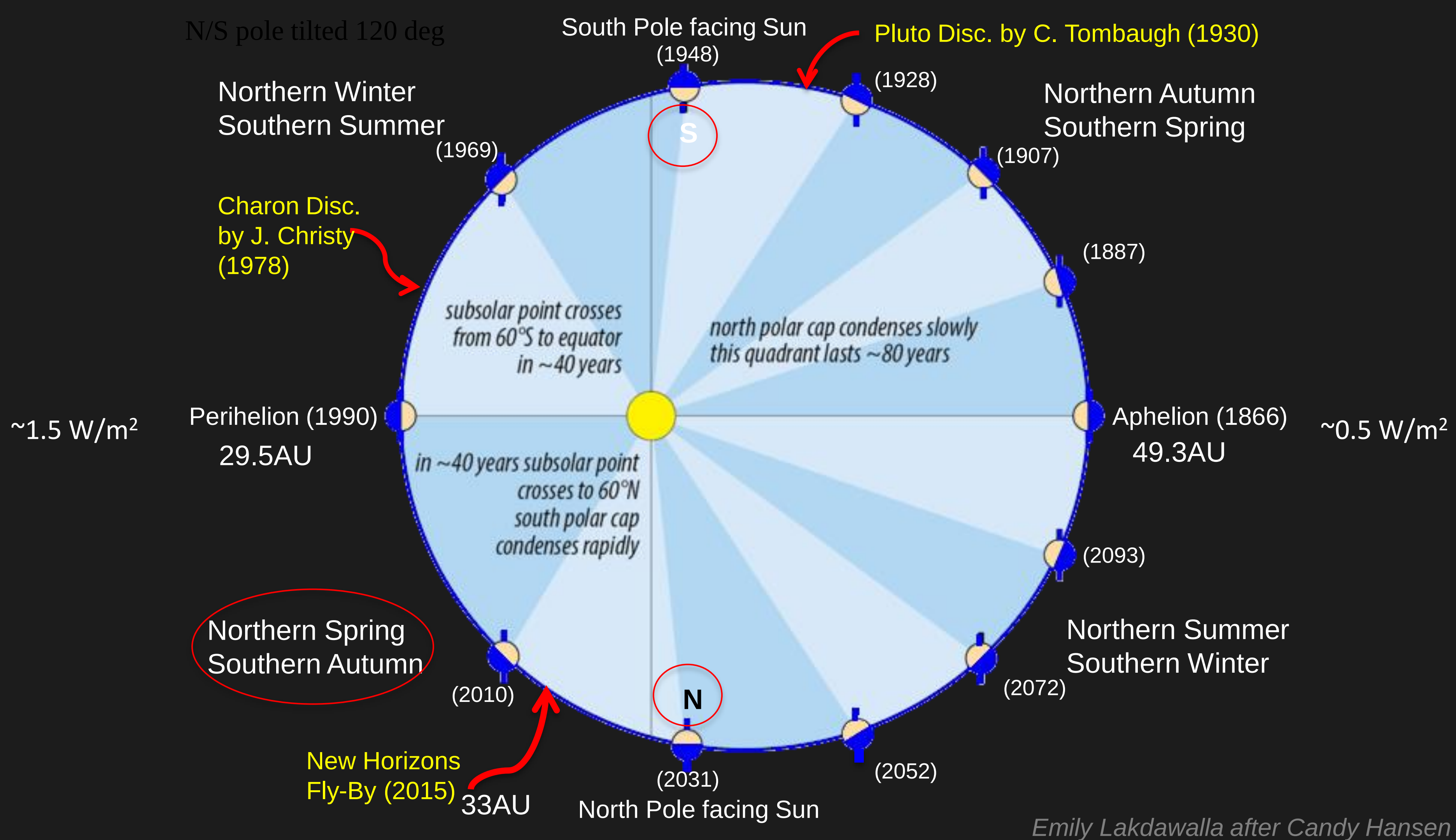
Bertrand & Forget 2016



Bertrand & Forget, Nature, 2016

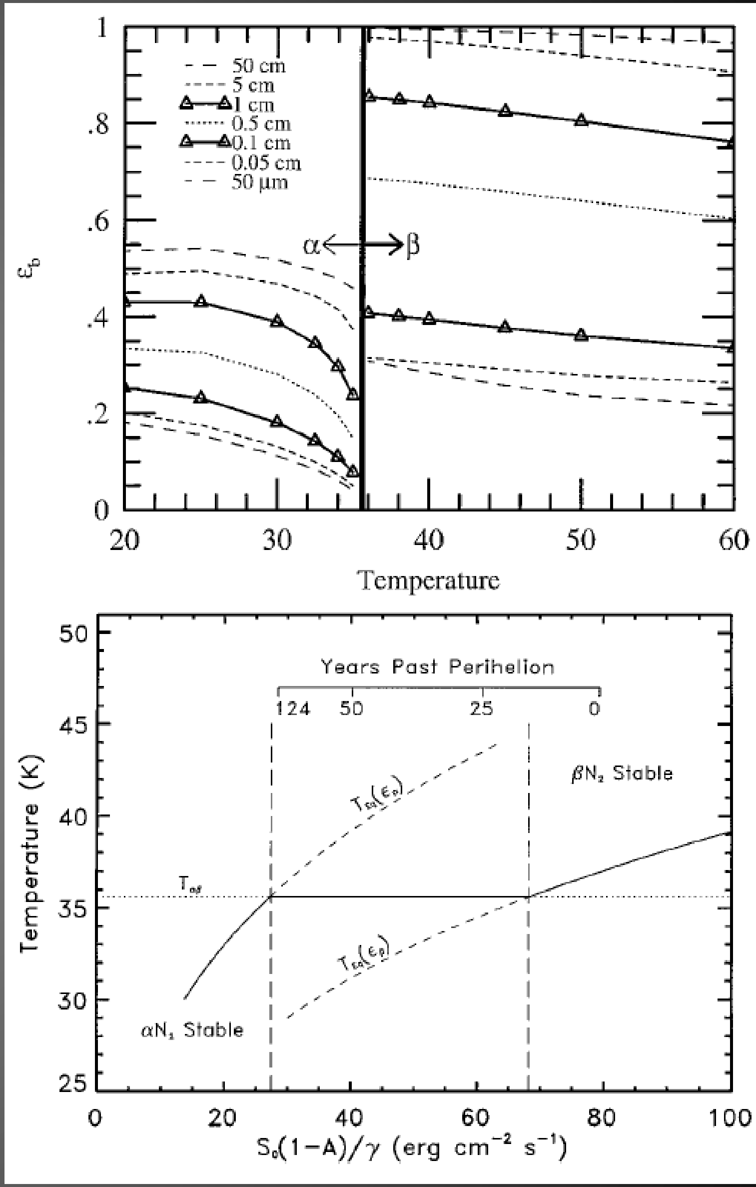
Good agreement with volatile ice distribution.
Wind speeds are moderate: atmosphere is ~isostatic, so N2 ice is still expected to be isothermal

Seasonal Forcing on Pluto



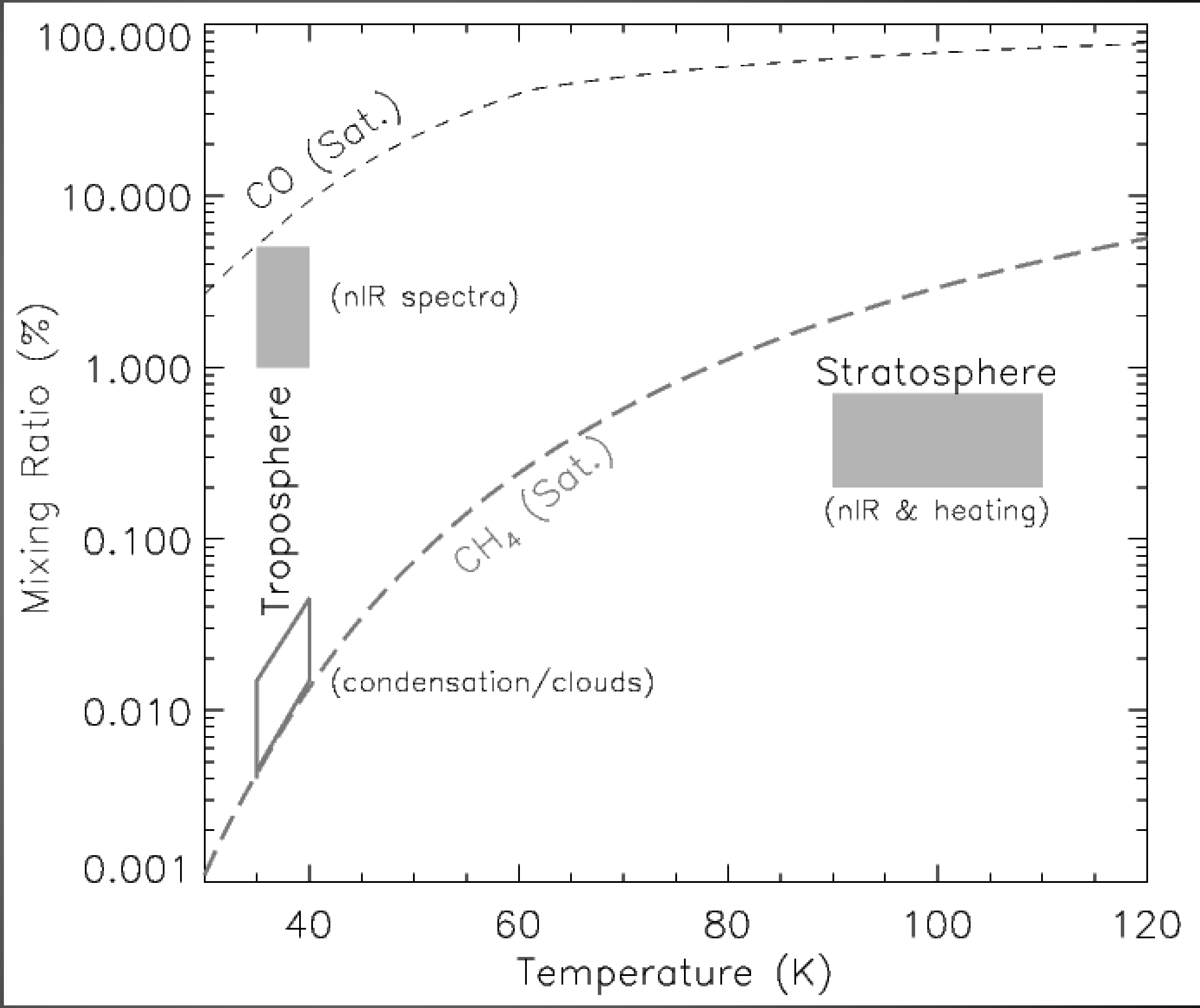
Emissivity and Fate

- Nitrogen α – β phase transition at 35.6K
  - α phase has a much lower emissivity
    - Higher equilibrium temperature for N2
  - P(35.6 K) = 4.2 μb
    - hydrostatic equilibrium, isothermal N2 ice
    - 3-phase equilibrium
- No atmospheric freeze-out?
  - All β-N2 must disappear 1st
- Difficult to test
  - α-N2 confined to winter/night side



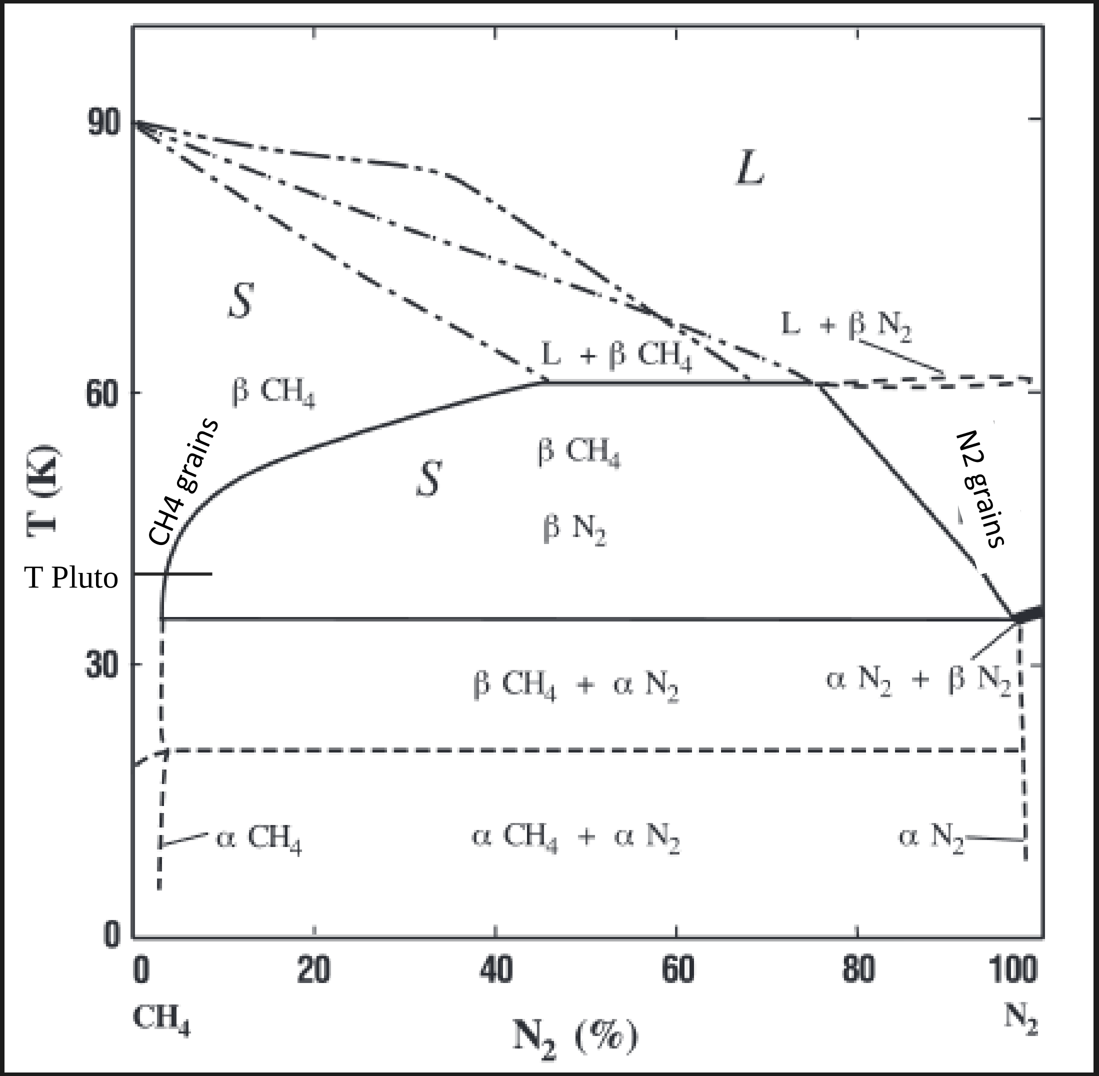
Methane: Overabundant in Atmosphere

- MAX mixing ratios
- $CH_4 : N_2$ solution depresses P_{vap} and X
- $CH_4 : N_2 \sim 1:100$
- CH_4 ice < 50 K
- CH_4 ice supplies atmosphere
  - photolysis

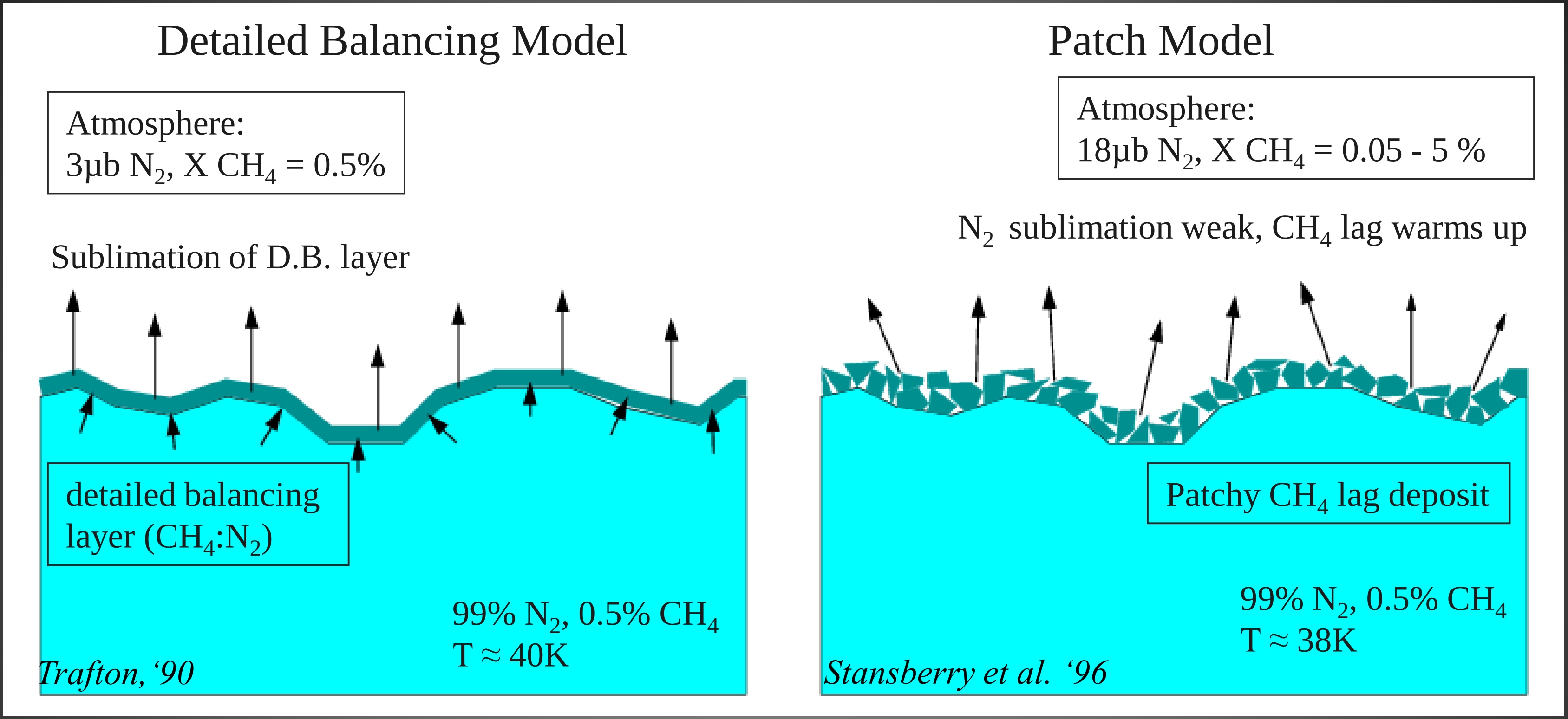


N2 : CH4 Phase Diagram

- N2 and CH4 are soluble as liquids and (slightly) as solids
- At Pluto's temperature their ices will be either CH4:N2 (few % N2) or N2:CH4 (few % CH4)



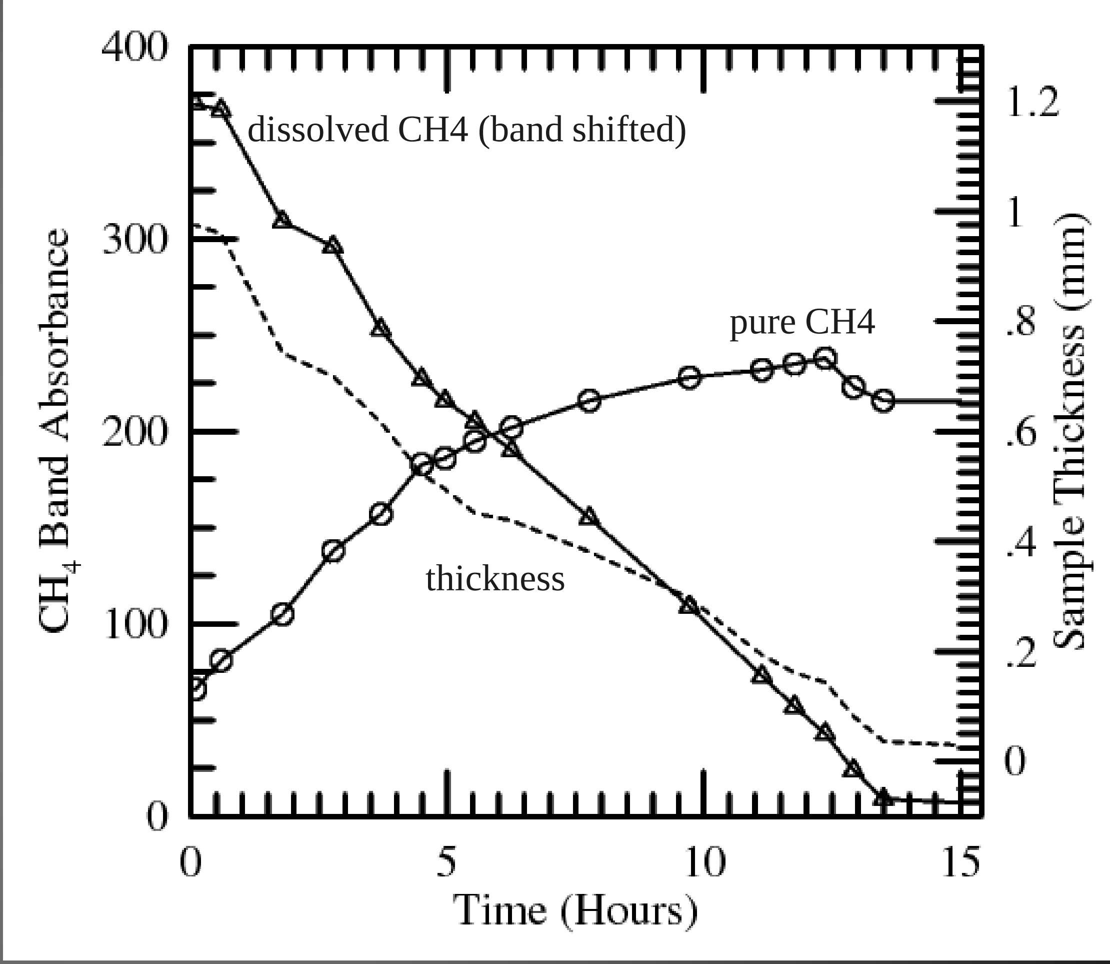
Methane: Overabundant in Atmosphere



- Upper atmosphere X CH_4 ≈ .5% (CH_4 thermostat; spectra)
  - ~ 10 – 10^3 enhancement over vapor pressure ratio (pure or Raoult)
  - Patch model: warm CH_4 patches, inefficient condensation
  - Detailed balancing: ~10 molecule CH_4 layer throttles N_2 sublimation

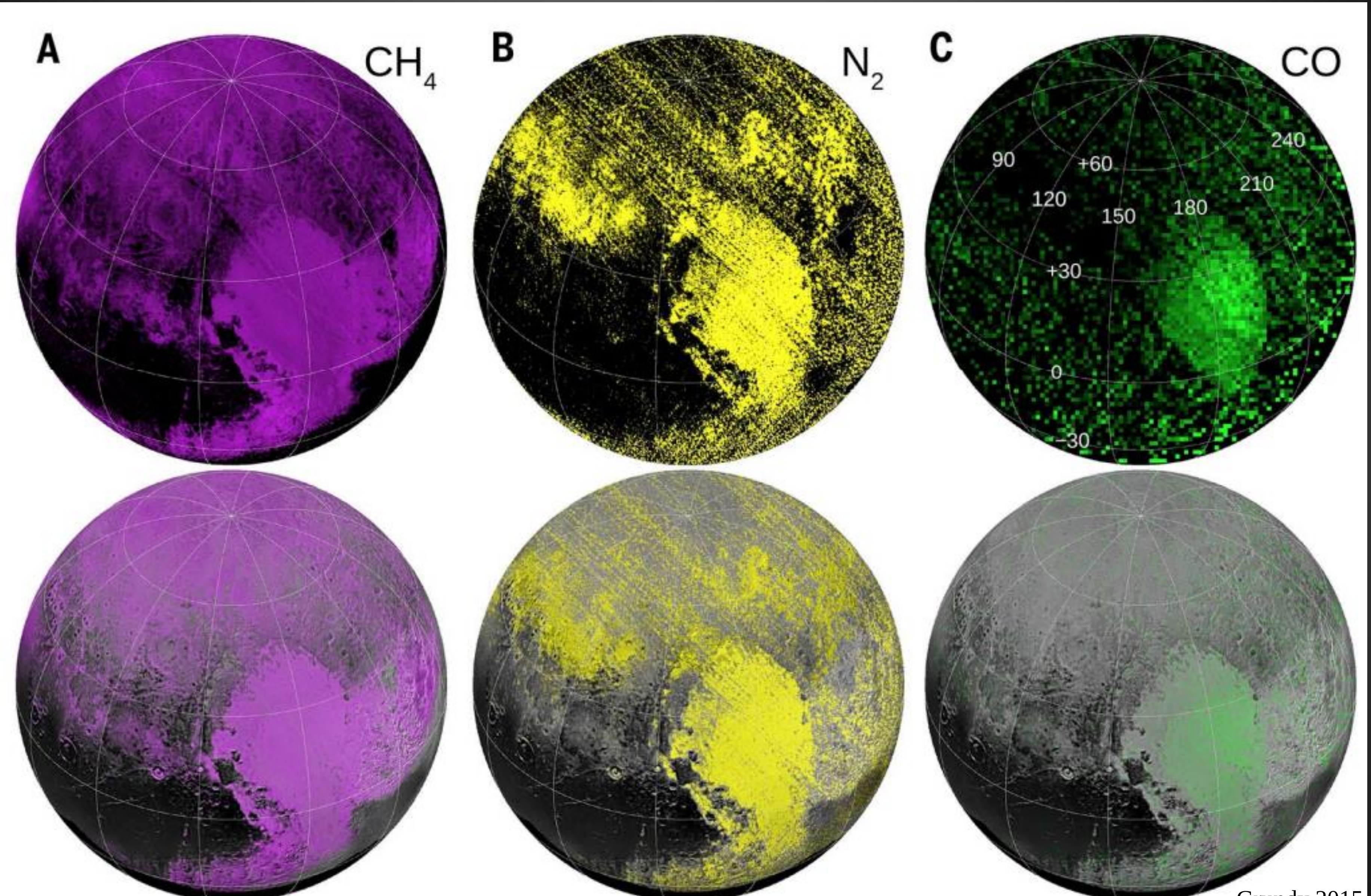
Sublimation of CH4:N2 Ice Sample (Lab)

- N2:CH4 mixture
  - Saturated composition (~5% CH4)
  - Shifted CH4 band dominates at the start
  - As the sample sublimes the shifted CH4 band weakens, and the un-shifted band of 'pure' CH4 grows



Stansberry et al. 1996

Abundance Maps for Volatile Ices on Pluto

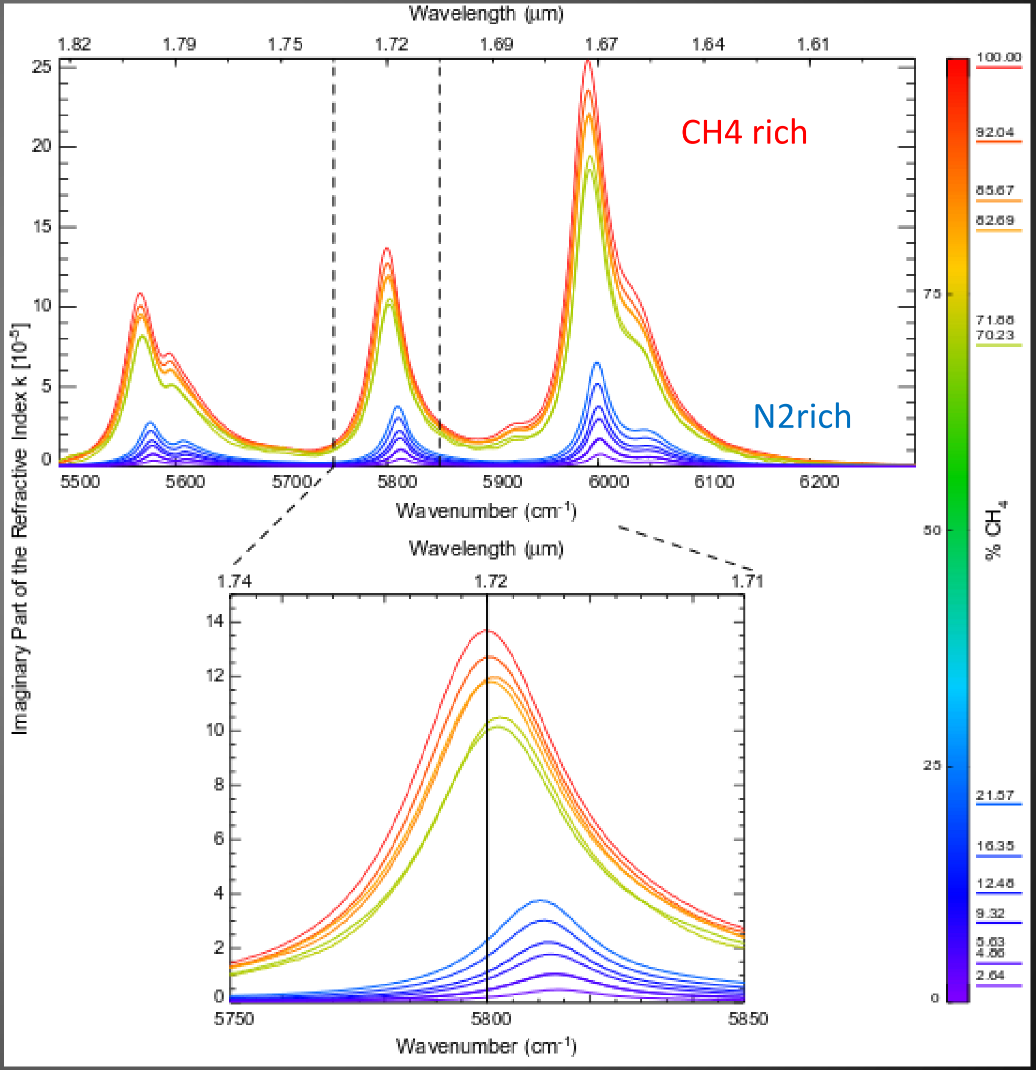


Grundy 2015

N2:CH4 Ice: Solid-state Dilution Effects

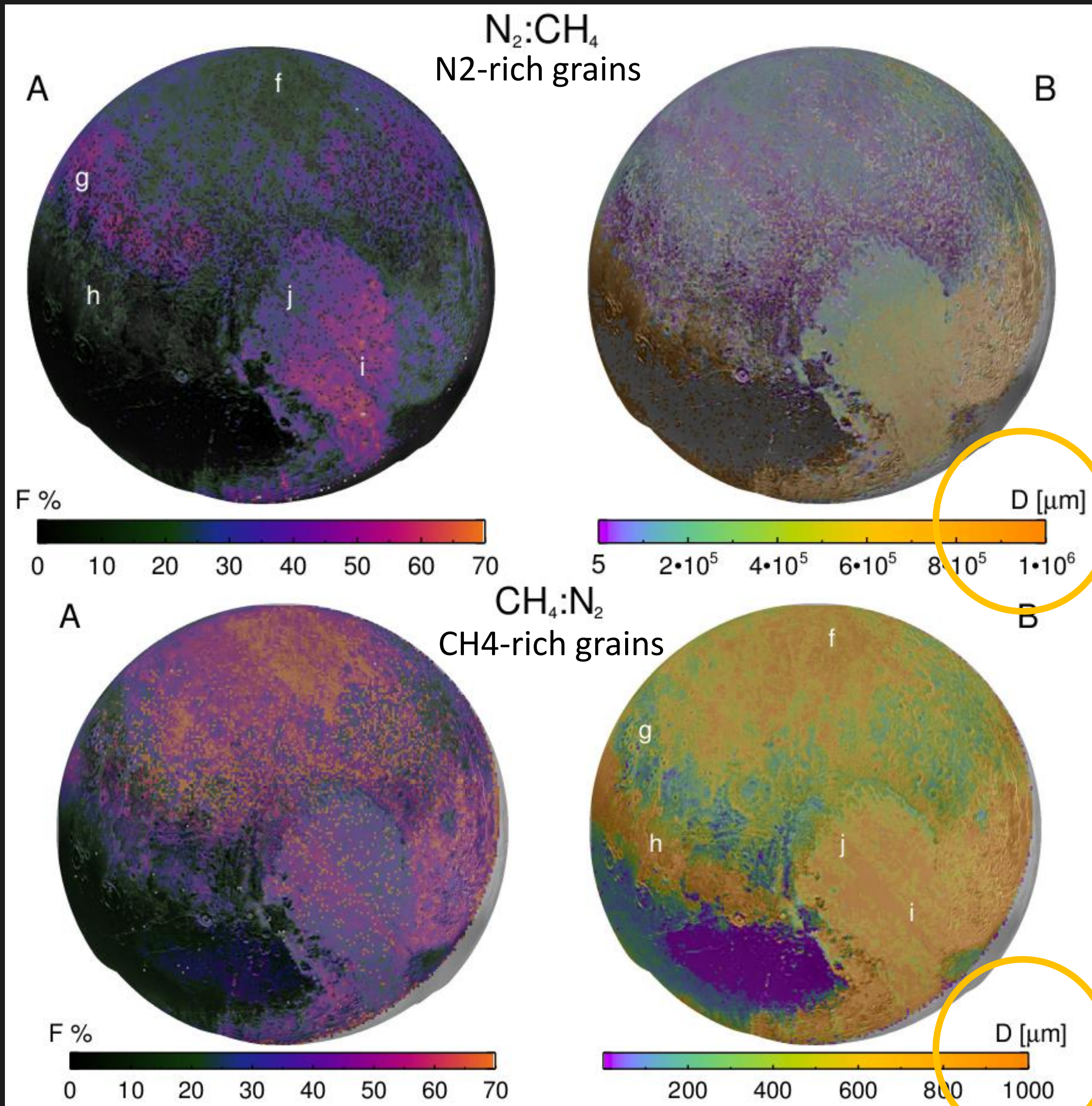
Protopapa et al. 2015

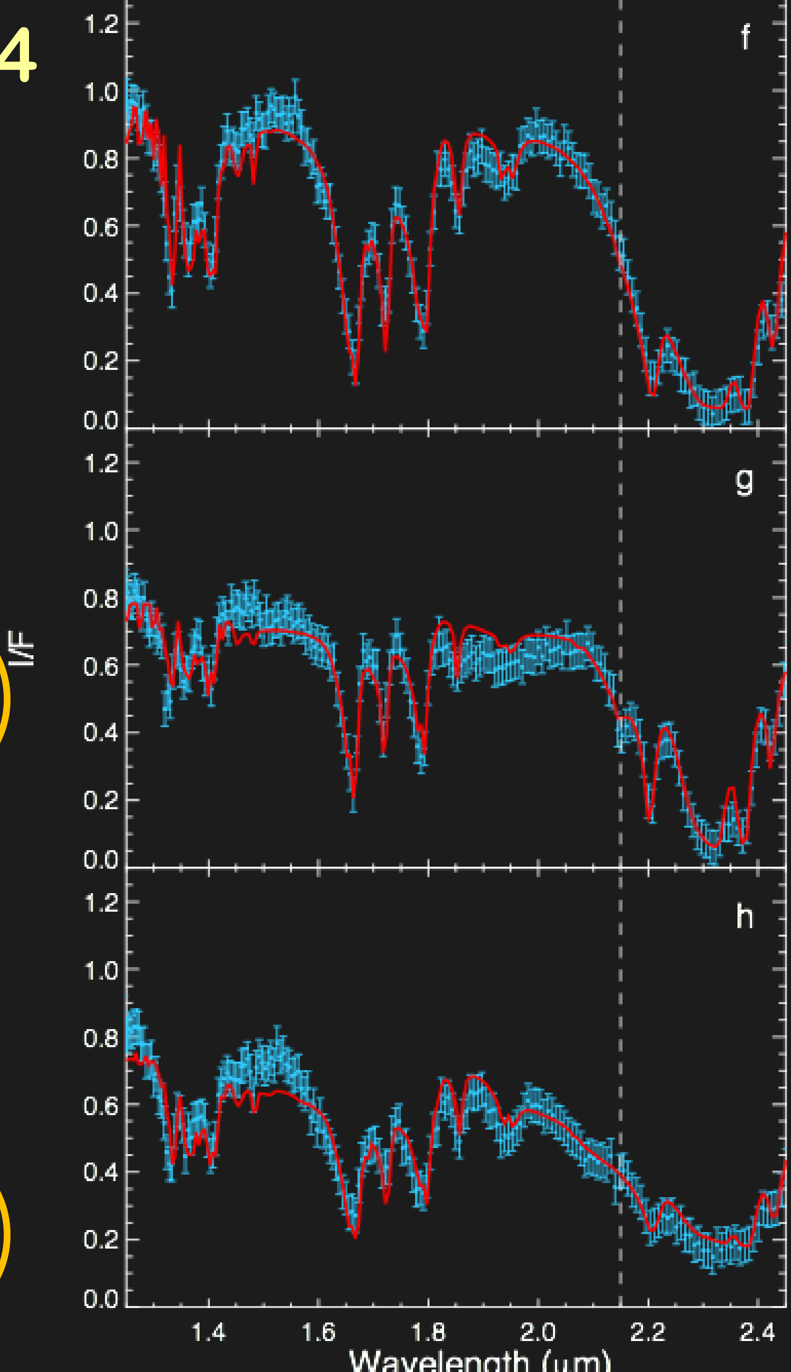
- CH4 rich solid solution
  - Band shape changes as N2 concentration grows
- N2 rich solid solution
  - Band shape changes
  - CH4 bands are shifted, and the shift is larger for lower CH4 concentrations

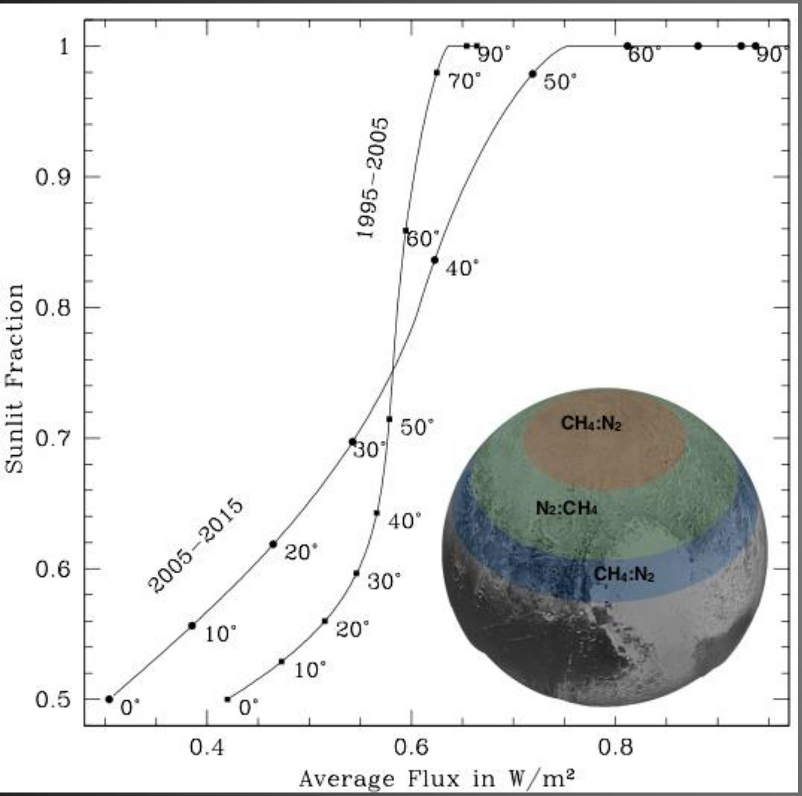


Solid State Solutions of N2:CH4

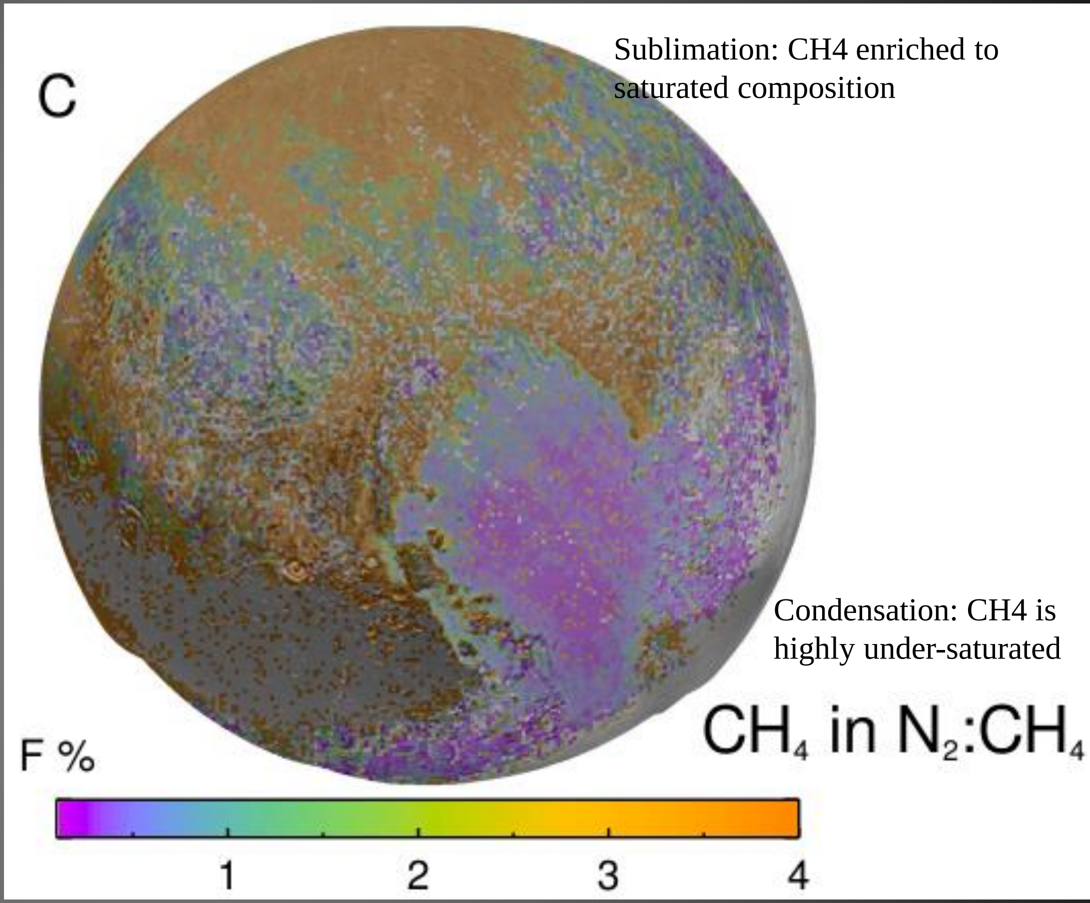
Protopapa et al. 2017





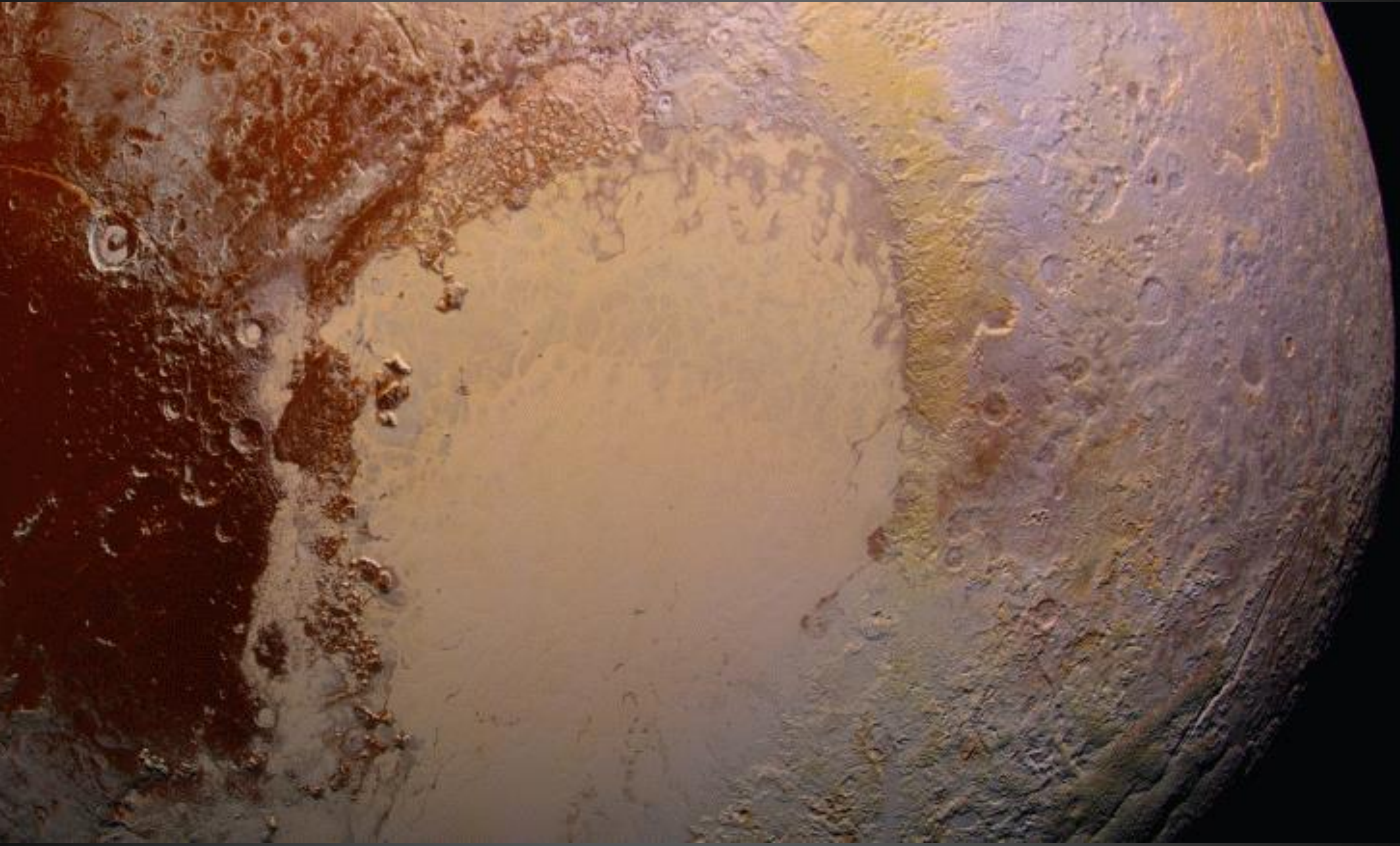


1995–2005
2005–2015
CH₄:N₂
N₂:CH₄
CH₄:N₂
Sunlit Fraction
Average Flux in W/m²



C
Sublimation: CH4 enriched to saturated composition
Condensation: CH4 is highly under-saturated
CH4 in N2:CH4
F %
1
2
3
4

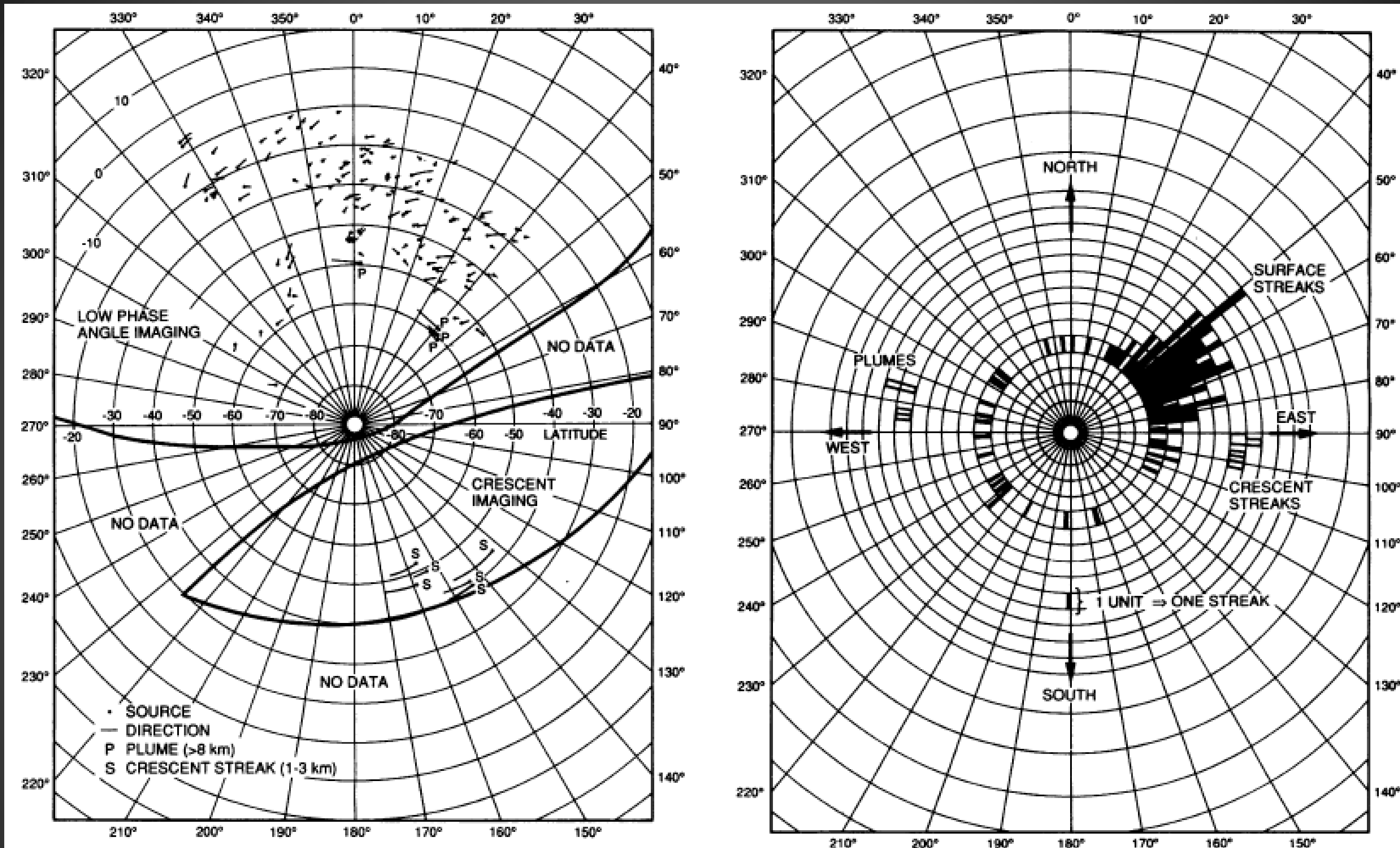
Vapor Pressure Atmospheres are Cool!



Vapor Pressure Atmospheres are Cool

IAC Winter School Lectures are ***OVER!***

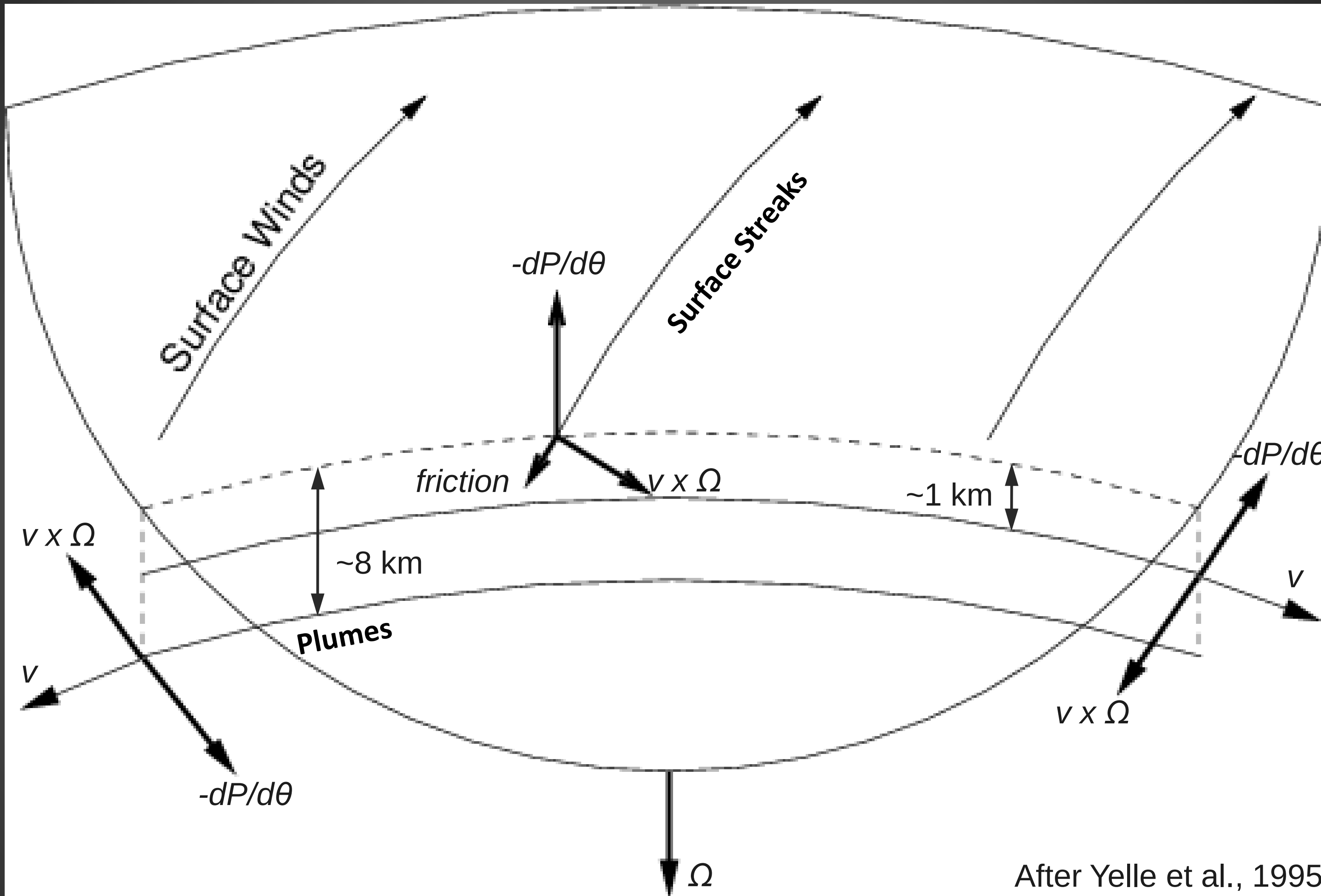
Triton's Sublimation Driven Winds



Surface winds trend NE, Streaks at 1km trend E (anticyclonic)
Plumes at 8km trend west (cyclonic)

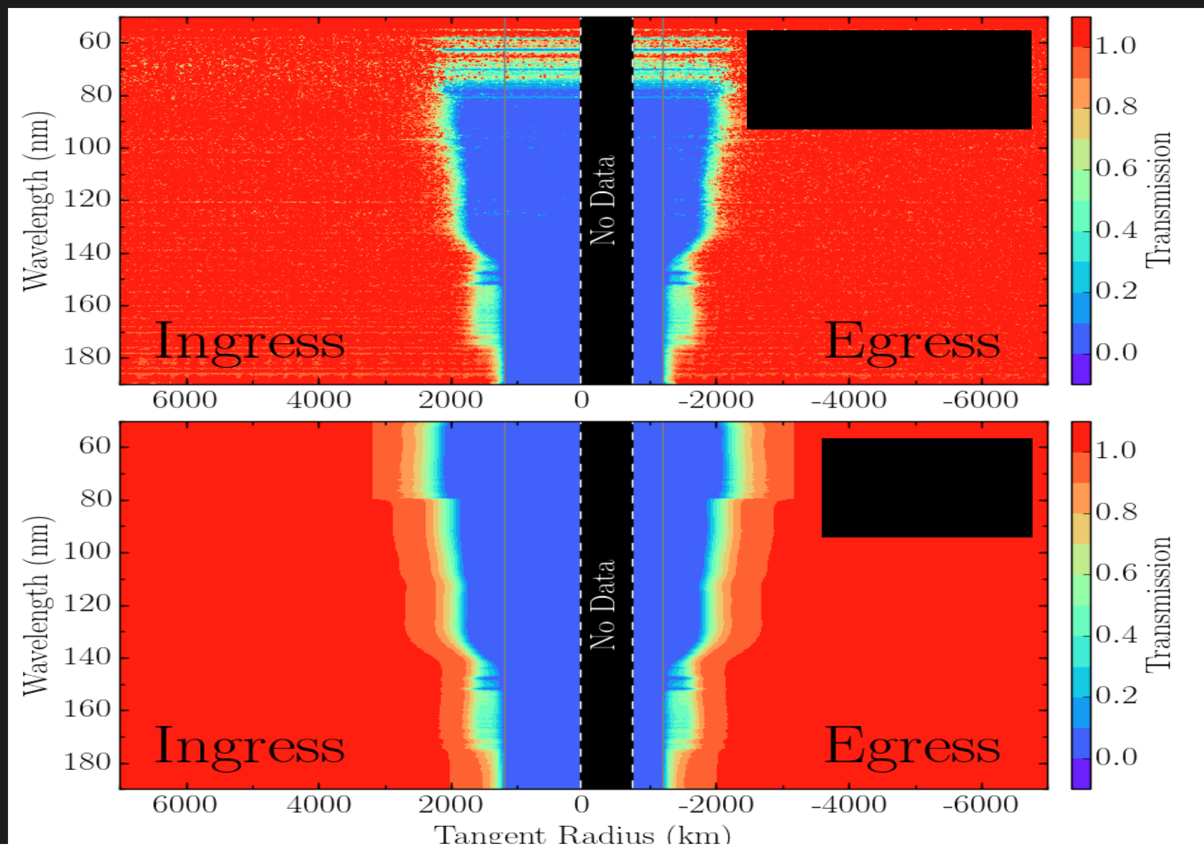
from Hansen et al. 1990

Triton's Lower Atmosphere Circulation



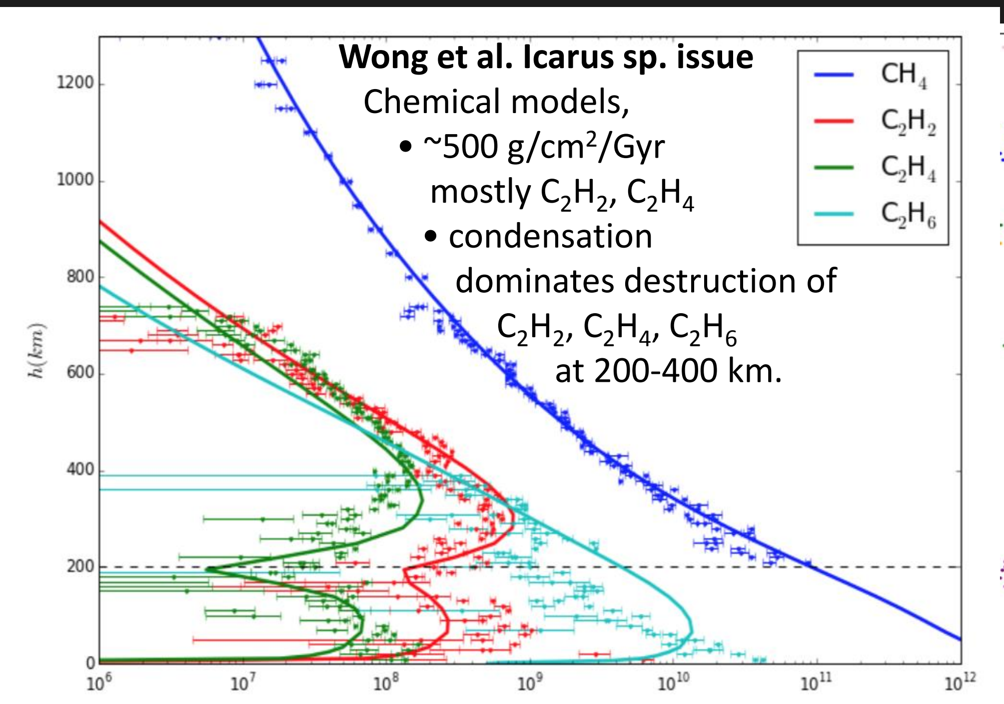
Surface & 1km winds driven by sublimation flow / polar high,
8km winds require hotter atmosphere over equator

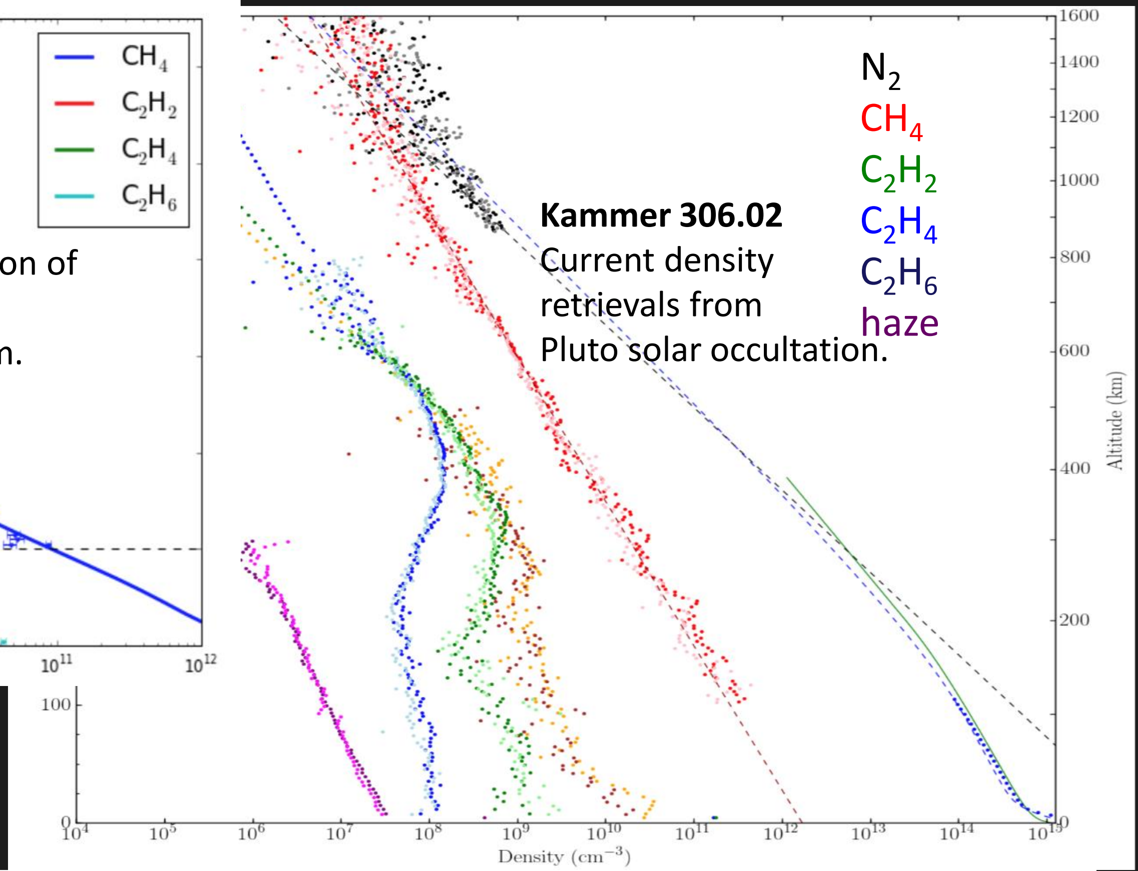
Composition of Pluto's Upper Atmosphere



Gladstone+ 2016 (Science); Kammer (DPS48 306.02); Young+ (in prep)

Composition and Chemistry





Gladstone+ 2016 (Science); Wong+ (Icarus special issue); Wong+, Kammer+ (DPS48 306.03, 306.02); Young+ (in prep)

Some Basic Parameters

Quantity	Triton	Pluto	units
g	75	65	cm/s^2
Rotation period	5.9	6.4	days
P (surface)	16	30	microbar
column mass	0.2	0.5	g/cm^2
T (nitrogen frost)	38	39	K
H (surface)	15	17	km
A (bolometric, N2 frost)	0.8		
ε (bolometric, N2 frost)	~0.6		
N2 sublimation rate	1.5		g/cm^2/yr
sublimation wind speed	5	2	m/s
Atm. recycle timescale	8	17	local days
A (hemispheric, bare grnd)	0.6	0.4	
T (bare ground)	50	55	K
Γ (diurnal)	~100?	15	J/m^2/s^0.5/K
Γ (seasonal)	300?	2000	MKS
Γ (water ice)	2000		MKS