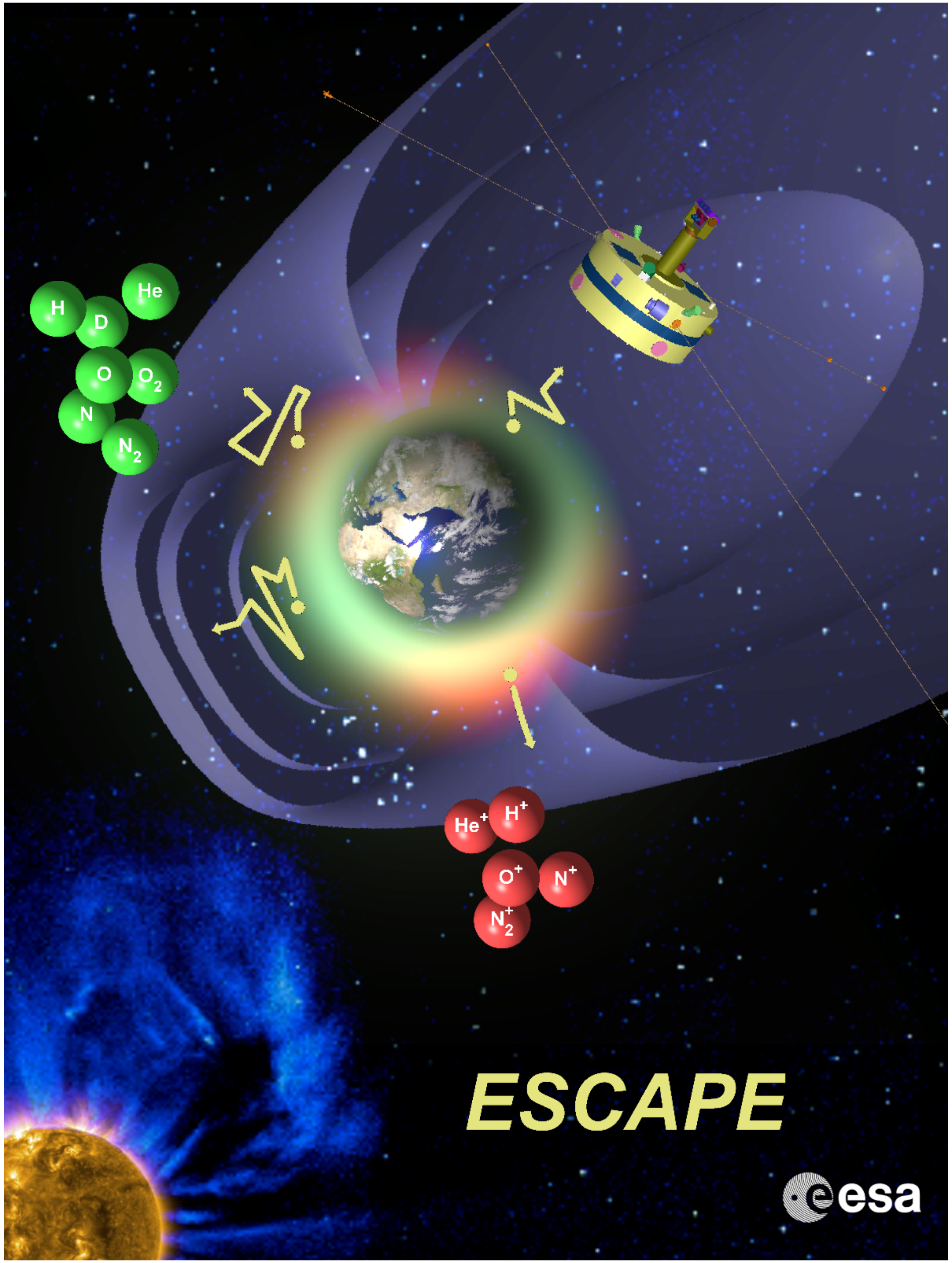


European SpaceCraft for the study of Atmospheric Particle Escape

I. Dandouras, M. Yamauchi, and ESCAPE proposal team

A mission proposal to **ESA's M5 call** to understand the atmospheric escape from the Earth, a magnetized planet.

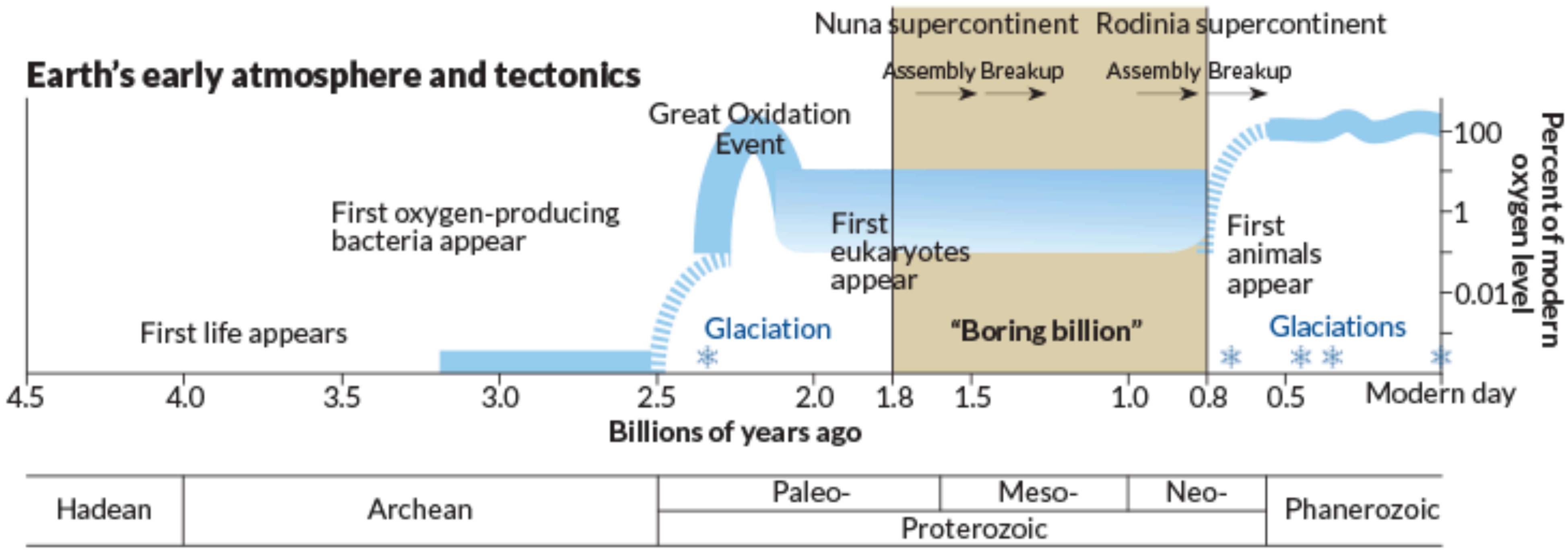
Why atmospheric escape?

Compositions of the Earth, Mars, and Venus are so different
(e.g., D/H ratio indicates water at Mars/Venus was 0.1% of the Earth 4.5 Byr ago, and Thermal (inc. photochemical) mechanism cannot explain water)
⇒ **Estimate contributions from different escape mechanisms** with different mass-filtering efficiency

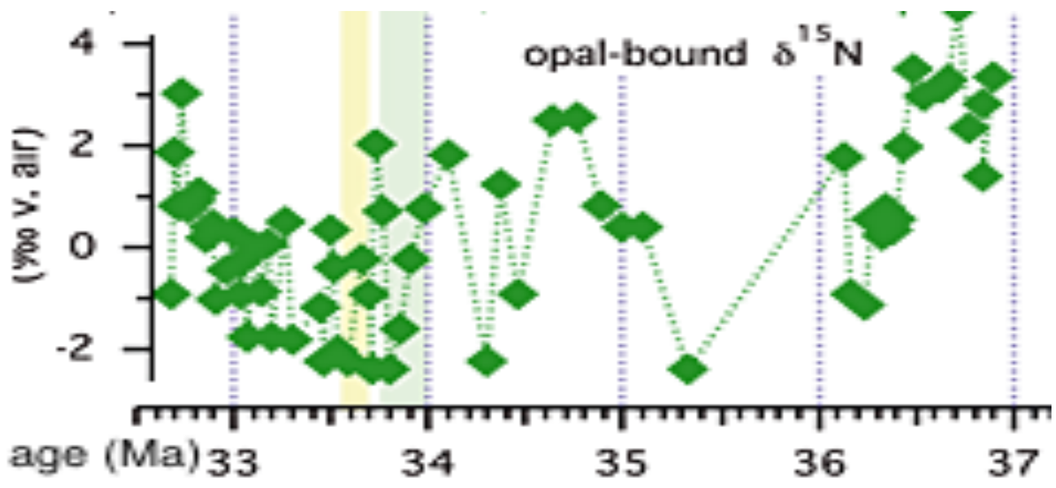
How much is the Earth special in terms of habitability?
(Evolution of the atmospheric composition and ocean pH must have allowed life to survive and evolve. If the escape was too much or too little, such condition might not be satisfied. Inversely, B-field, biologic & subsurface activities played roles?)
⇒ **Estimate possible roles of escape in habitability**

Life might have extincted and revived many times???
(Atmospheric conditions during the life emergence is one of the key)
⇒ **Estimate atmospheric evolution right after life emerged**

⇒ **Need independent studies from subsurface route**
(Subsurface inventory is large, but could recycle without loss)



O2 model *(Lyons et al., 2014)*



Ocean ^{15}N *(Robinson et al., 2015)*

Past N/O ratio fluctuated a lot

How much ion escape explains N/O ratio & pH changes?

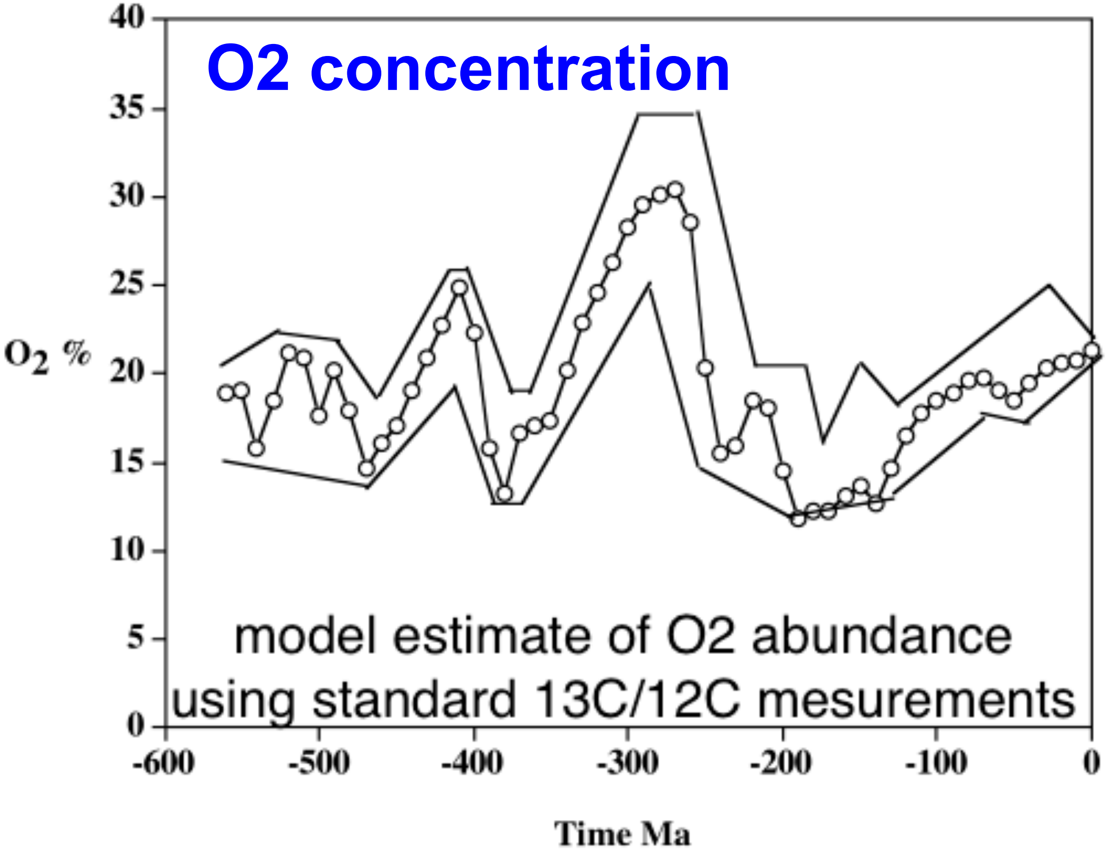
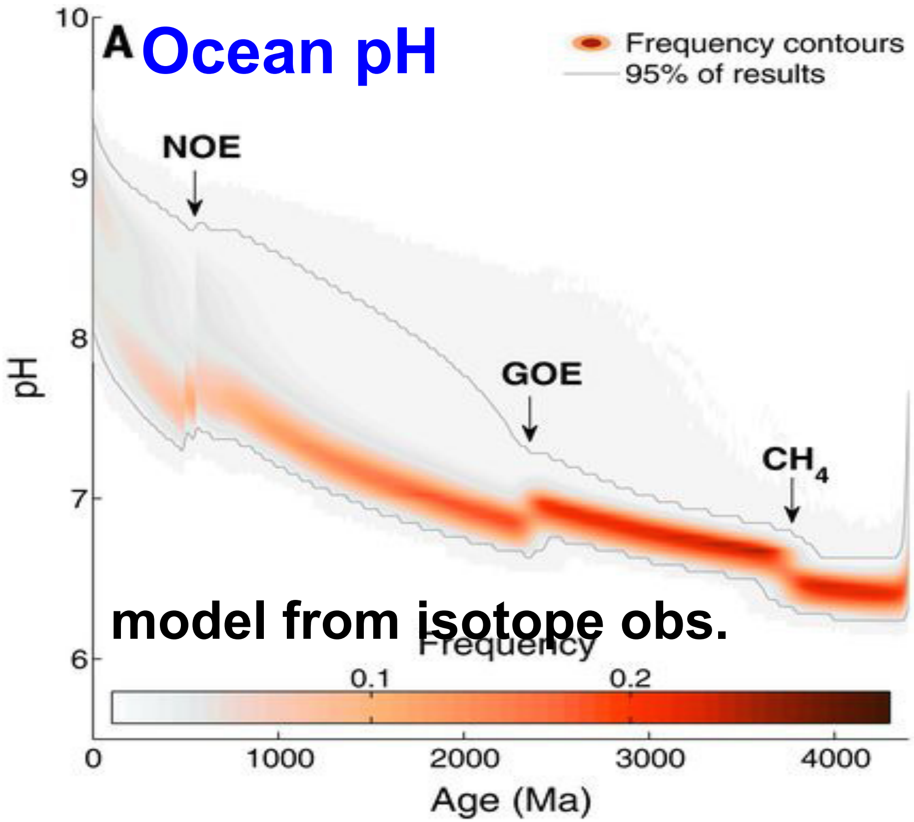
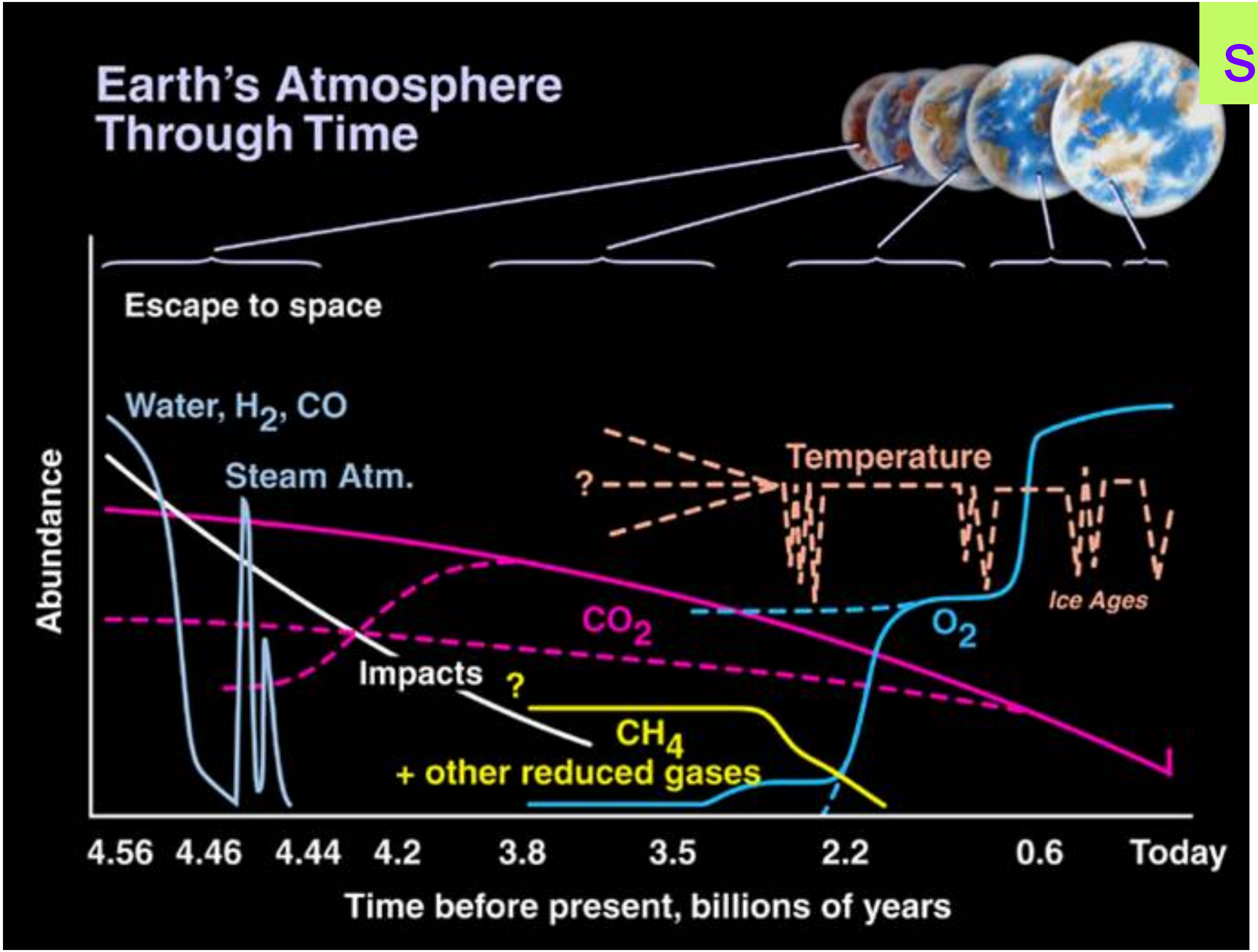


Fig. 20. Plot of O_2 vs time for the standard GEOCARBSULF model with



(Berner, 2006)

(Halevy, 2017)


Earth's Atmosphere
Through Time
Escape to space
Water, H_2, CO
Steam Atm.
Temperature
?
Ice Ages
CO_2
O_2
Impacts
?
CH_4
+ other reduced gases
Abundance
4.56
4.46
4.44
4.2
3.8
3.5
2.2
0.6
Today
Time before present, billions of years

skip

Mission objective

To obtain the composition and flux of the atmospheric escape from the Earth and understand its effect on the atmospheric evolution.

- **The first-time exploration of the exosphere** to correctly model the thermal (inc. photochemical/hydrodynamic) escape.
- **Determination of the dominant non-thermal escape mechanisms** to evaluate relative importance of thermal and non-thermal escape.

To investigate fundamental parameters in space.

- **The first-time measurements of actual efficiencies** of the isotope fractionation and ionisation/neutralisation in the space environment, to estimate the past escape from a planet using the present atmospheric composition.

ESCAPE Scientific Objectives

How and at what rate is Earth slowly losing its atmosphere to space?

1. Build a quantitative and comprehensive picture for 500-2000 km altitudes

- Determine **exospheric** altitude density profiles and temperature profile **as a function of different drivers** such as **solar EUV, solar wind and geomagnetic conditions**.
- Establish **isotope ratios** for both **neutrals and ions** and compare them with those found at the Earth's surface and in other solar system objects.
- Determine **exospheric altitude profiles of ion/neutral ratios** and estimate ionisation / neutralisation efficiencies.
- Measure **temporal and spatial variations** of the density of **major exospheric species**.
- Correlate such **variability** with upper atmosphere parameters, and with different incident energies when **particle precipitation** is present.

2. Determine the dominant escape mechanisms, and their dependence on the drivers

- Estimate **thermal escape flux** for neutral and ion species **for different conditions**.
- Estimate the **prevailing escape mechanisms** and the relative importance of thermal or non-thermal escape **for different driver conditions**.
- Estimate the **response** of the ionisation / neutralisation efficiencies, isotope fractionation and the N/O ratio **to different drivers**.
- Estimate the **degree of recirculation of plasma** after it has left the ionosphere.

Escape Mechanisms of Heavy Ions/Neutrals

Type	Mechanism	Explanation
thermal	**Jeans escape (H, He)**	Thermal tail exceeds the escape velocity
non-thermal	**Charge exchange**	Heavy (trapped) ions collide with atoms
thermal	**Momentum exchange**	Light neutrals collide with heavy molecules
thermal	**Hydrodynamic blow off (H, He)**	Same as solar wind formation mechanism
chemical	**(Photochemical heating)**	Release of e.g. recombination energy of the excited state that accelerates the atom
combined	**(Ion pickup)**	Ions that are newly exposed to solar wind are removed by the solar wind ExB
non-thermal	**(Atmospheric sputtering)**	The energetic ions/atoms interact with the upper atmospheric molecules/atoms/ions
non-thermal	**Large-scale momentum transfer & instabilities**	Solar wind dynamic pressure and EM forces push the planetary plasma anti-sunward
non-thermal	**Ion energisation by EM waves and $E_{//}$**	EM disturbances / static E-fields energise ions, by e.g. the ion cyclotron resonance
non-thermal,	**Plasmaspheric wind & plumes**	Plasma instabilities near the plasmapause
non-thermal	**Boundary shadowing**	Drifting ions overshoot the magnetopause

neutrals

ions

Escape Mechanisms (continued)

	Type	Mechanism	Where?	Δv for same T
	thermal	**Jeans escape**	exobase (M>E≥V)	exp()
neutrals	non-thermal	**Charge exchange**	above mirror altitude (E)	m^0
	thermal	**Momentum exchange**	above exobase (M>V)	m^0
	thermal	**Hydrodynamic blow off**	near exobase (ancient, all)	$m^{-0.5}$ to m^0
	chemical	**Photochemical heating**	exosphere (M>V~E)	$m^{-0.5}$
	combined	**Ion pickup**	outer exosphere (M, V)	m^0
	non-thermal	**Atmospheric sputtering**	around and above exobase (M, V>E)	m^0
	non-thermal	**Large-scale momentum transfer & instabilities**	magnetospheric boundary (E>M~V)	m^0
ions	non-thermal	**Ion energisation by EM waves and $E_{//}$**	upper ionosphere & magnetosphere (E>M>V)	?
	non-thermal,	**Plasmaspheric wind, plasmaspheric plumes**	plasmasphere (E>M~V)	m^0
	non-thermal	**Boundary shadowing**	ring current (E)	m^0

What will be measured?

Basic altitude profiles in the exosphere & upper ionosphere (500–2000 km).

- **Temperature** and **densities** of major **neutrals and ions** (H, He, O, N, O_2, N_2, NO, and CO_2).
- **Isotope ratios** ($^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{15}N/^{14}N$, D/H).
- Their **variability** in space and time (+ correlation with drivers)

Differential fluxes (energy-angle distributions) of the hot ions (N+, N2+, O+, H+, and He+) in the lower magnetosphere and upper ionosphere > 800 km.

$\Rightarrow$ Correlation with external drivers: solar EUV flux, solar wind, and ionospheric/geomagnetic conditions.

What will be measured?

What to measure	Target range	Particle SI*	Other SI*
Density of major neutrals and cold ions, simultaneously	neutrals 1–10^6/cc ions 0.1–10^3/cc	INMS, WCIMS	UVIS, SLP ASPOC
Density of minor isotopes (neutrals and ions)	neutrals 10^{-2}–10^3/cc ions 10^{-4}–10^1/cc	INMS	SLP, ASPOC
Neutral temperature	500–1500 K	WCIMS	density +model
The energy distribution of major outflow ions	$10^{5\text{-}9}$ keV cm^{-2} s^{-1} str^{-1} keV^{-1}	MIMS, NOIA	MAG, SLP
The flux of major returning energetic ions	$10^{6\text{-}9}$ keV cm^{-2} s^{-1} str^{-1} keV^{-1}	EMS	MAG
The energy distribution of electron and photoelectron	$10^{7\text{-}11}$ keV cm^{-2} s^{-1} str^{-1} keV^{-1}	ESMIE	MAG
Ionospheric auroral condition	$10^{2\text{-}6}$ R		AMC
DC/AC field energy flux into to the ionosphere	1–10^2 W/km^2		MAG, WAVES
Electromagnetic wave associated with ions	0.1–10^3 Hz		MAG, WAVES
ENA flux for charge-exchanged keV ions	$10^{2\text{-}5}$ cm^{-2} s^{-1} str^{-1}	ENAI	

Why Earth?

skip

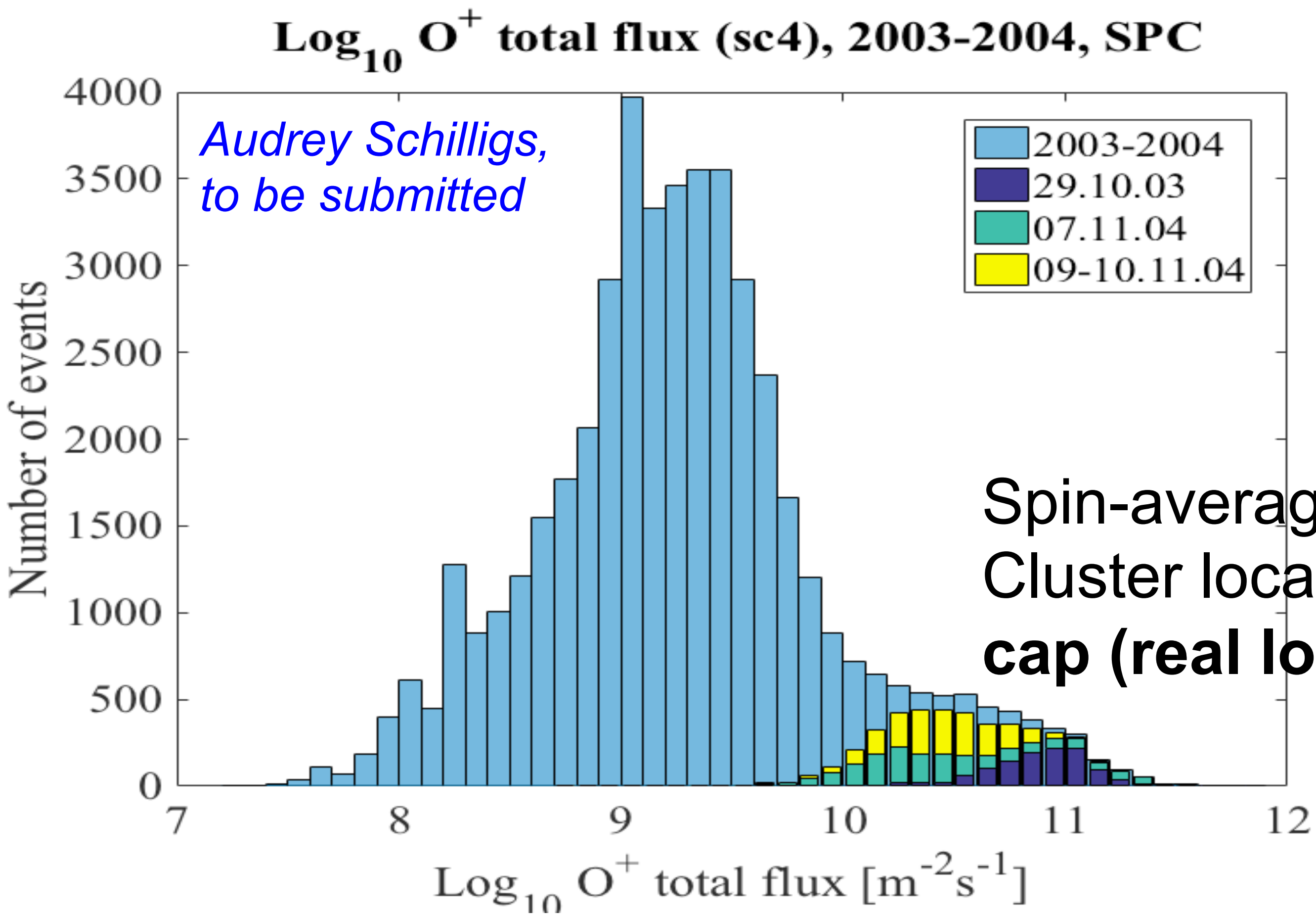
Related to the past and future of the **habitable environment of the Earth**.

- **Rich database** (e.g., solar wind since 1960's) to allow probability assessment when **scaling back to the past.**

Can obtain the **best knowledge among all planets** thanks to many other measurements at and from the ground.

- Basically **common exospheric** structure with Mars and Venus.
- Sufficient **spacecraft resource** in the instrumentation and data transmission.
- Advantage of **ground-based** observations, e.g., EISCAT_3D.
- **Subsurface route** is best known.
- Some key area is less understood than Mars/Venus.

Why Earth? Amount matters skip



Spin-averaged values at Cluster location **in the polar cap (real loss!)**

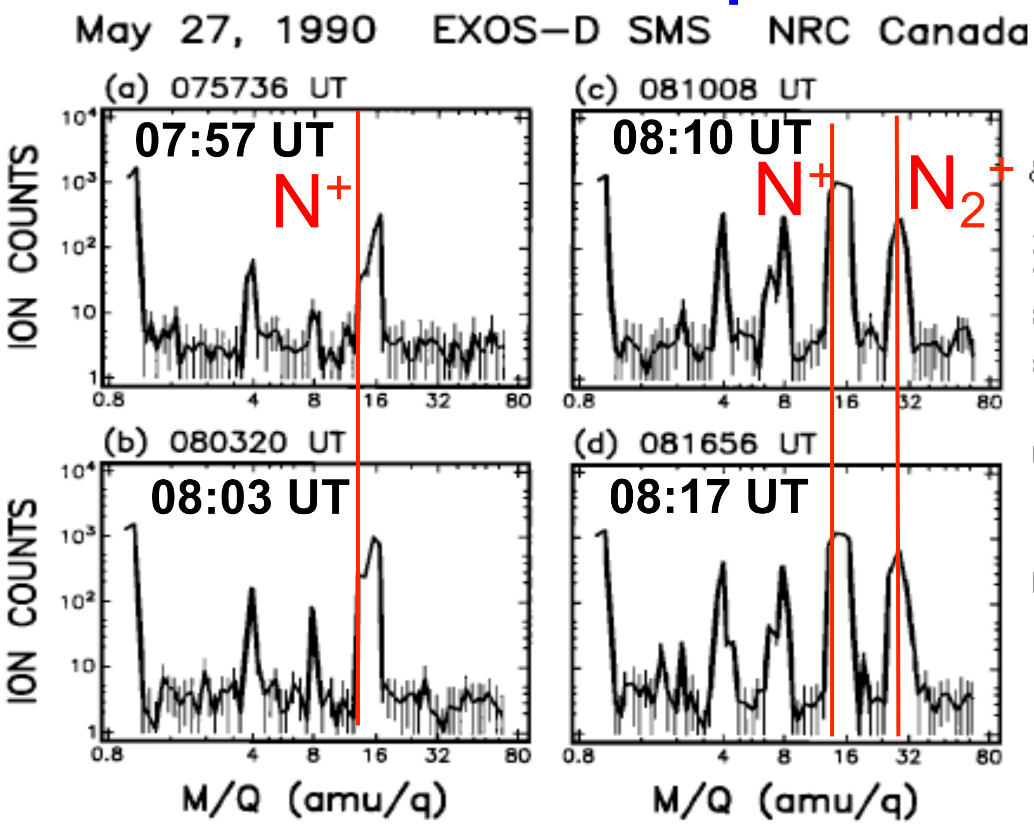
- Average O^+ loss rate is about 10^{25} ions/s.
- Increase by > 10 during storms.
- Increase by 10^2 during big event. ⇒ **10^{27} ions/s during big events**

high N/O ratio in ancient time?

skip

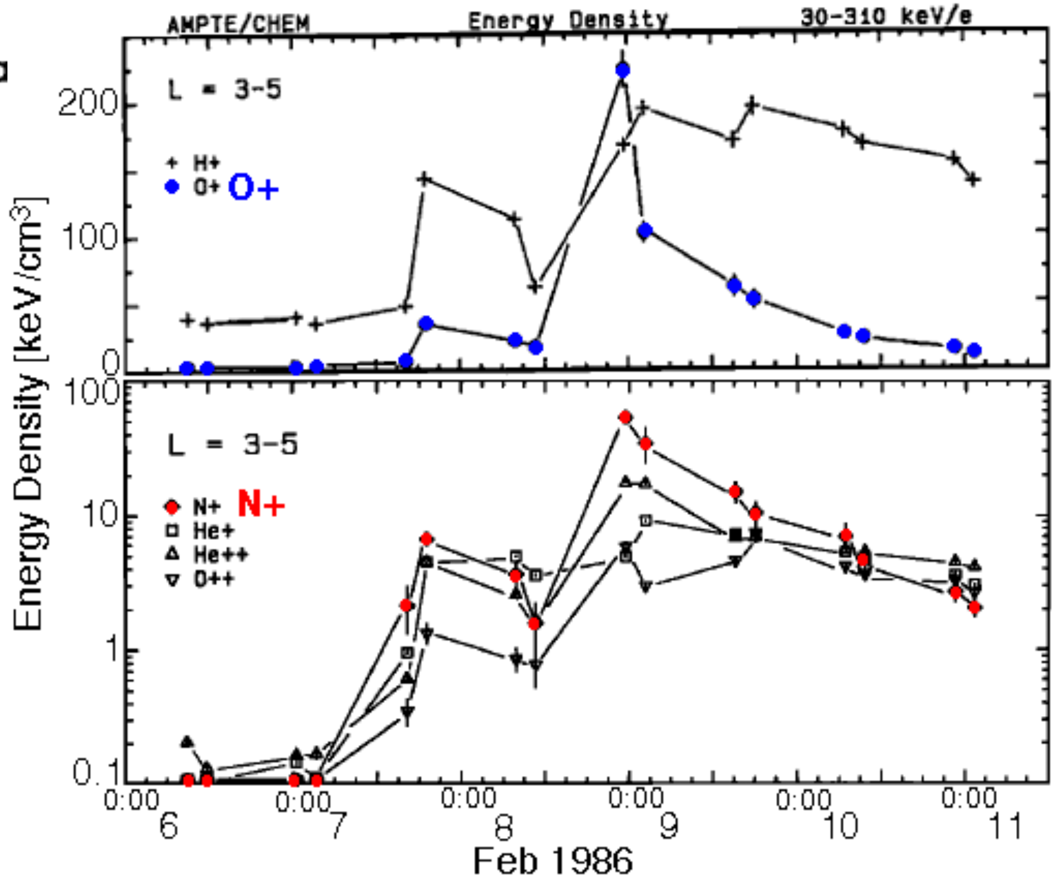
N/O ratio increases with activity

N^+/O^+ increase up to ~ 1



(Yau et al., 1993)

AMPTE result



(Hamilton et al., 1988)

Small number of big events may account majority of N^+ escape

Why Earth? Amount matters skip

Biosphere responds to a few % change in the atmospheric O/N ratio (or water pH). ⇒ a 10% loss of nitrogen inventory in the biosphere (~ $5 \cdot 10^{18}$ kg ~ $2 \cdot 10^{44}$) matters. ⇒ **$2 \cdot 10^{43}$ loss of nitrogen influences the evolution of life**.

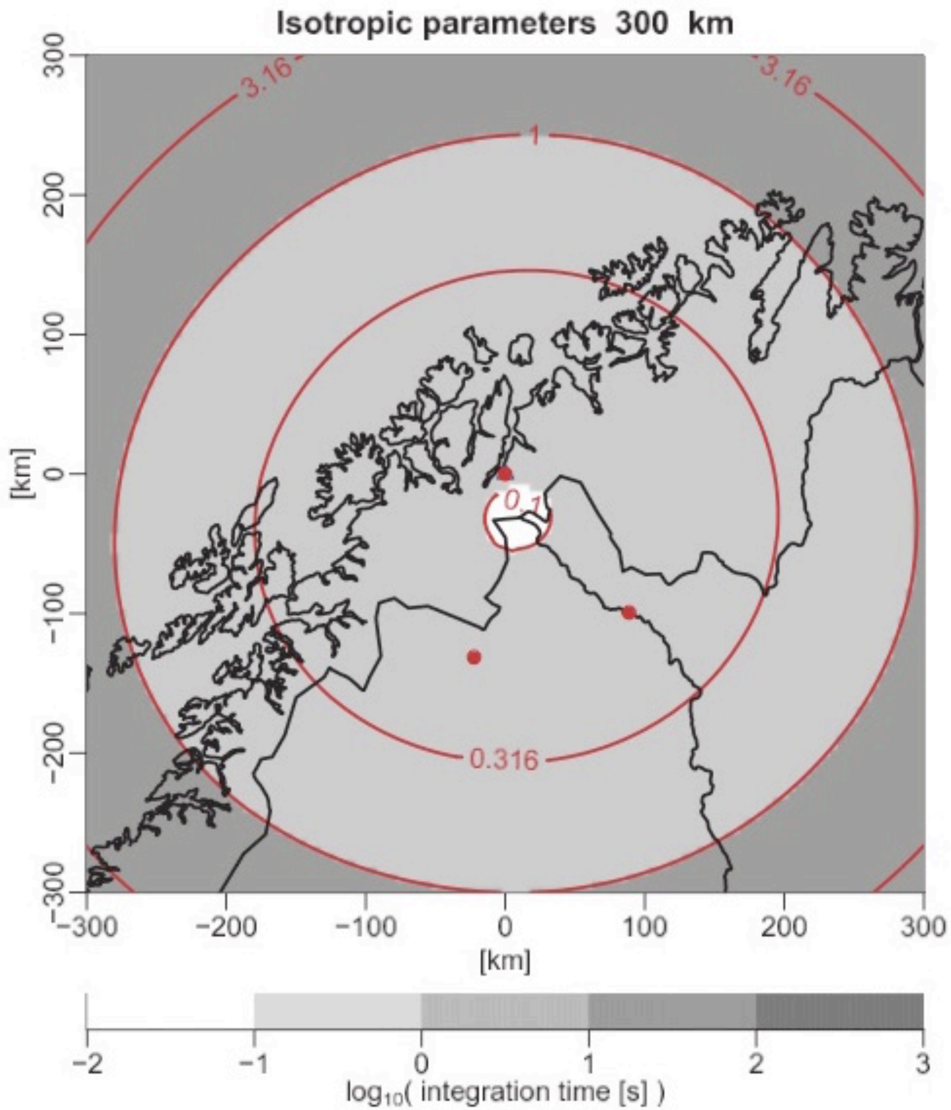
- **10^{27} s^{-1} x 600 million years** ($2 \cdot 10^{16}$ sec) = $2 \cdot 10^{43}$.
- **N/O ratio may reach to 1** during big events.
- **Big events are good proxy for ancient time** (according to Sun-In-Time project) with **fast solar wind** and fast rotation (**strong solar dynamo**) for young G-type (Sun-time) stars.

Non-thermal escape (of N^+) alone could have influenced the biosphere

(in addition, subsurface circulation influences too).

Advantage of the Earth

Covering area of EISCAT_3D



High sensitivity in more than 500 km diameter (grey area) ≈ 15° longitudinal range.

⇓

5 % of polar orbits traverses this region in average.

+

More conjugacy if we consider geomagnetic tracing.

+

Remote sensing can target this area from distance.

Why Exosphere?

Mandatory for thermal (inc. photochemical) escape modeling
(For thermal and some non-thermal escape)

Dynamic and structured
(Mars observation indicates unknown controlling factors other than EUV, e.g., atmospheric coupling)

Poor observational knowledge for the Earth
(No knowledge of > 800 km for nitrogen, > 1500 km for oxygen, and all altitude for isotope ratio)

Generate seeding cold ions through ionisation
(They contribute feeding ions of non-thermal escape)

Determine charge-exchange escape of trapped ions
(Including magnetopause shadow, majority of return flow from the tail will finally escape, and important input in estimating ENA flux)

Exosphere = thermal/photochemical

Mandatory for thermal (inc. photochemical) escape modeling

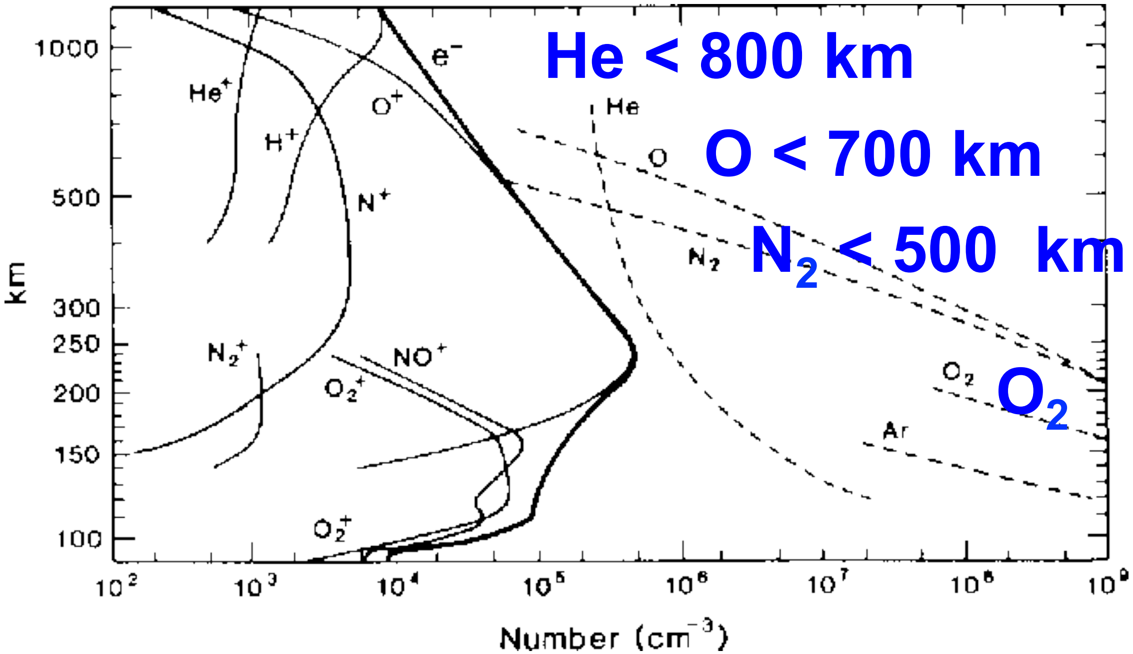
height	surface	500 km			2000 km		
	velocity	O (eV)	N (eV)	H_2 (eV)	O (eV)	N (eV)	H_2 (eV)
Earth	11 km/s	9.7	8.	1.2	8.0	7.0	1.0
Venus	10 km/s	8.2	7.2	1.0	6.7	5.8	0.8
Mar	5.0 km/s	1.8	1.6	0.23	1.3	1.1	0.16
Moon	2.4 km/s	0.5	0.4	0.06	0.31	0.27	0.04

before		after	extra energy
O_2^+ + e-	-->	2O	3–7 eV
N_2^+ + e-	-->	2N	3–6 eV
N + O_2	-->	NO + O	2–4 eV

Why Exosphere? poor knowledge

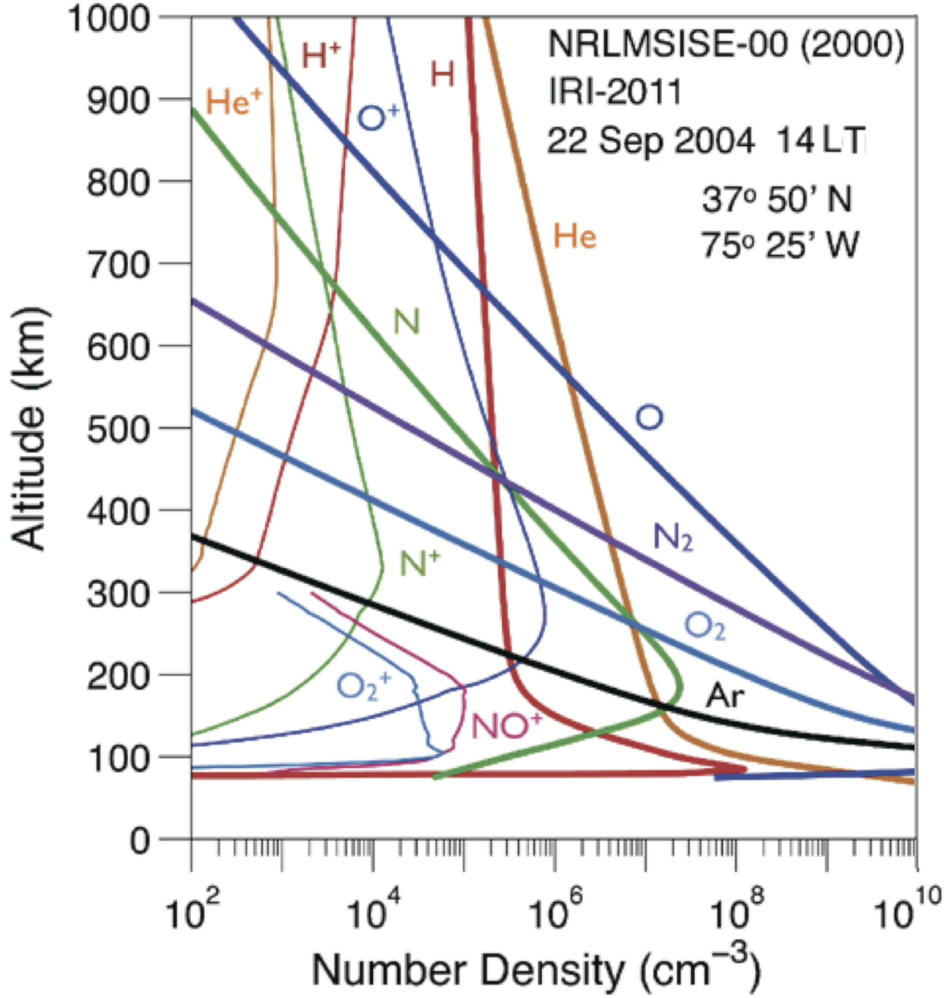
No systematic in-situ observations > 800 km

(except H)



In-situ measurements are really old, and we need to update.

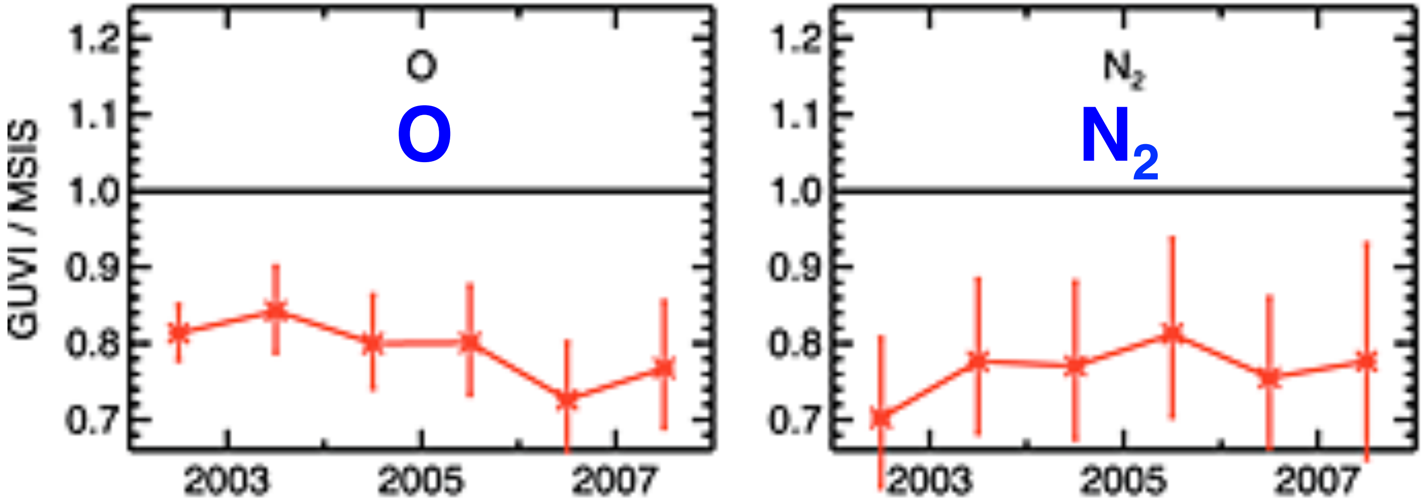
(Johnson, 1969)



MSIS-2000 model (smooth > 200 km)

(Pfaff, 2012)

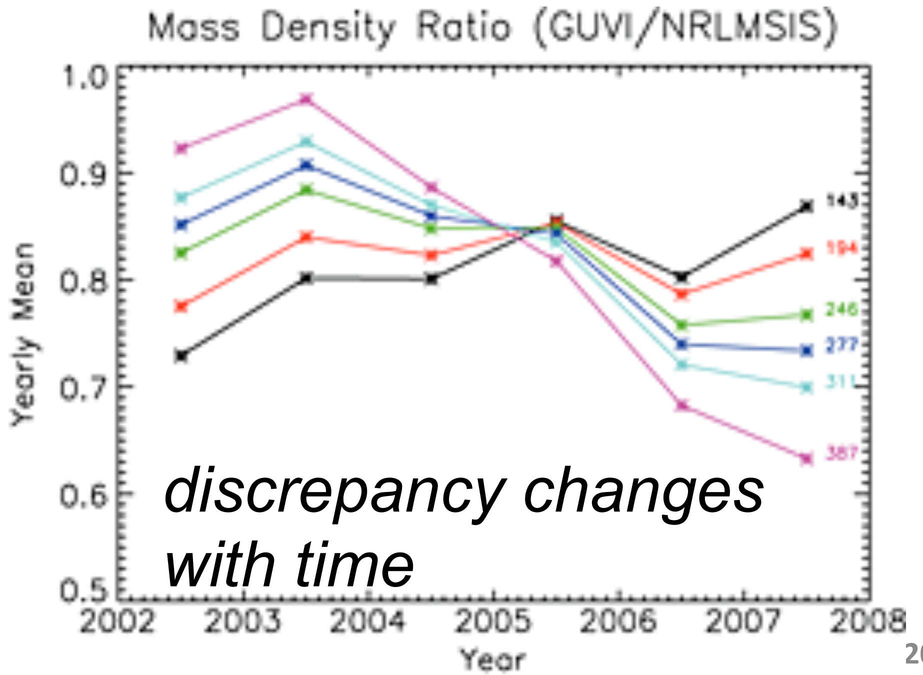
Why Exosphere? poor knowledge



(TIMED) GUVI

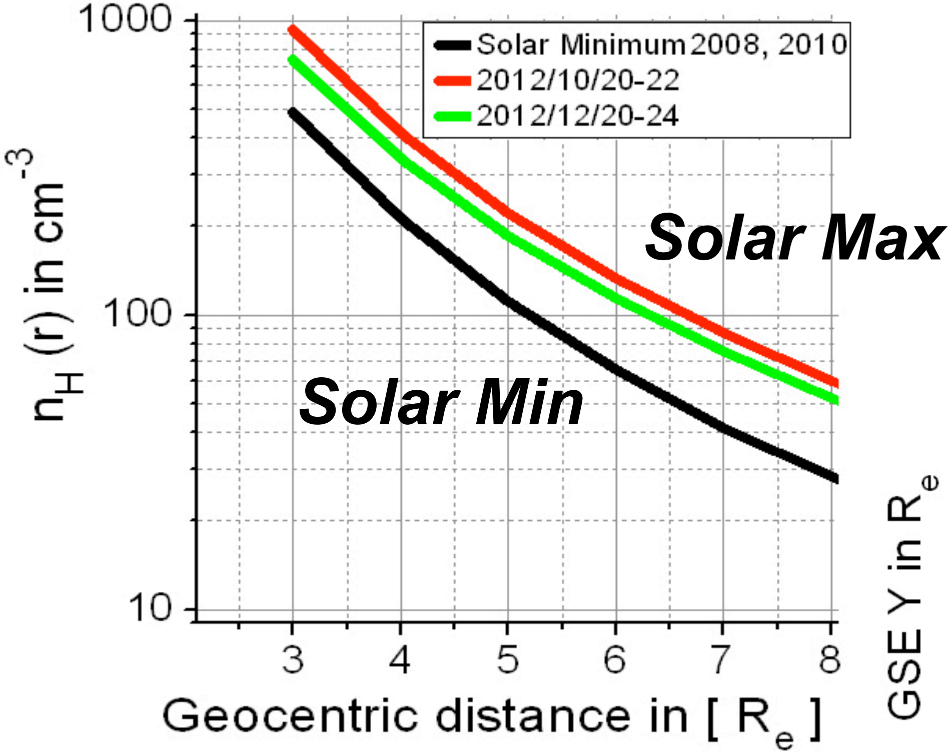
GUIV obs. vs. MSIS model

Even the lower altitude (thermosphere) is not well known



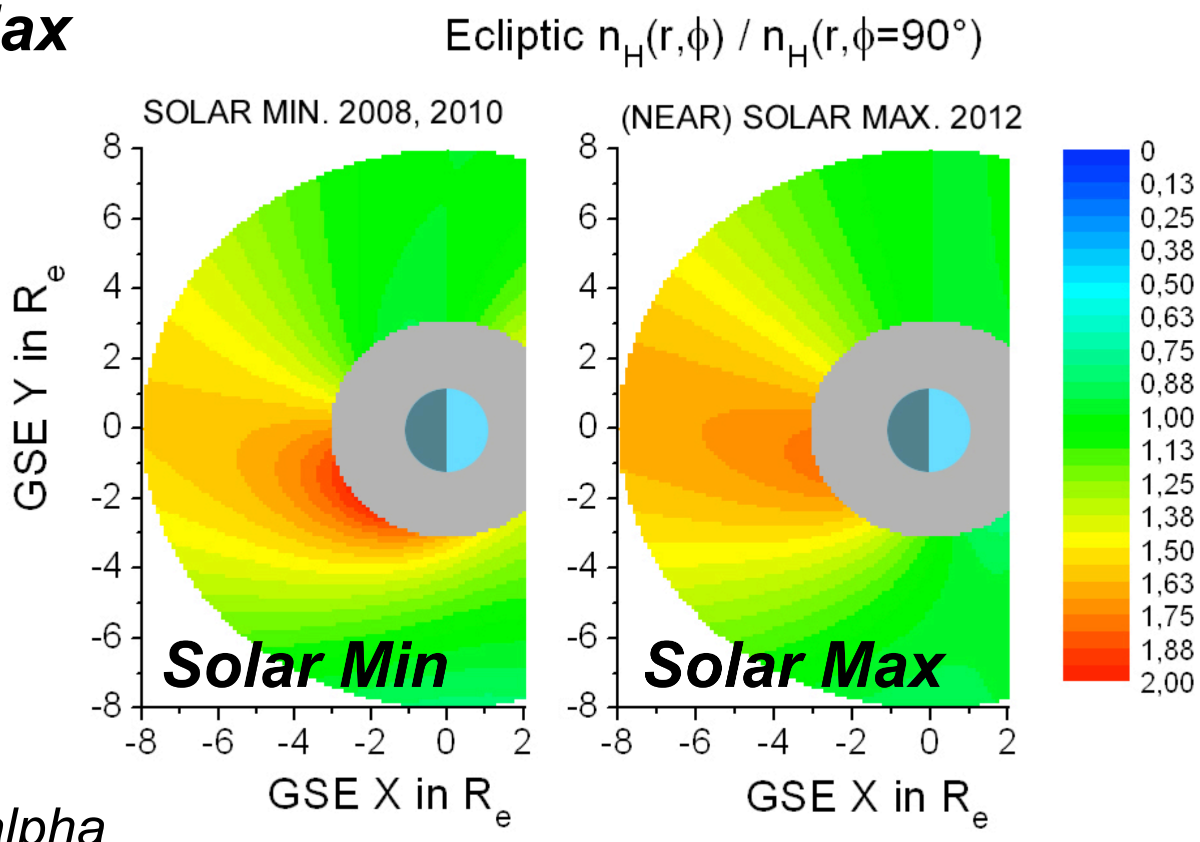
Left: GUVI / NRLMSIS ratio at 194 km altitude for geomagnetically quiet condition.
*Right: GUVI / NRLMSIS ratio of mass at different altitudes from 143 km to 387 km (**Meier et al., 2015**).*

Exosphere: structured & dynamic



Altitude profiles of H

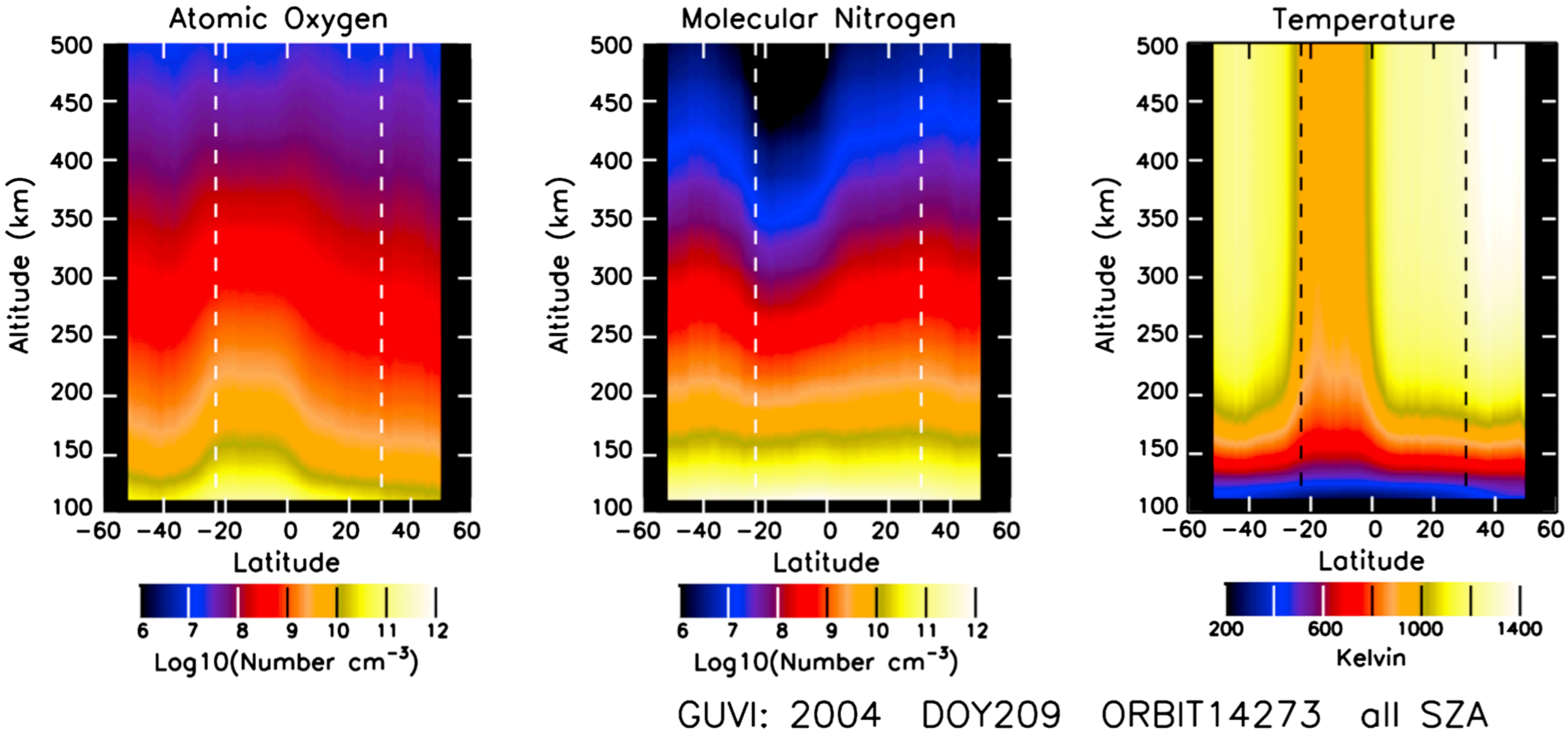
(TWINS) Lyman-alpha



Nightside distribution of H

*Model-fitted H density from Lyman-alpha line-of-sight stereo observations by the two TWINS spacecraft (**Zoennchen et al., 2015**)*

Exosphere: structured & dynamic



*Model-fitted GUVI observation for 27 July 2004. (**Meier et al., 2015**) during magnetic storm (F10.7=128, Ap = 186). Temperature increased summer auroral region*

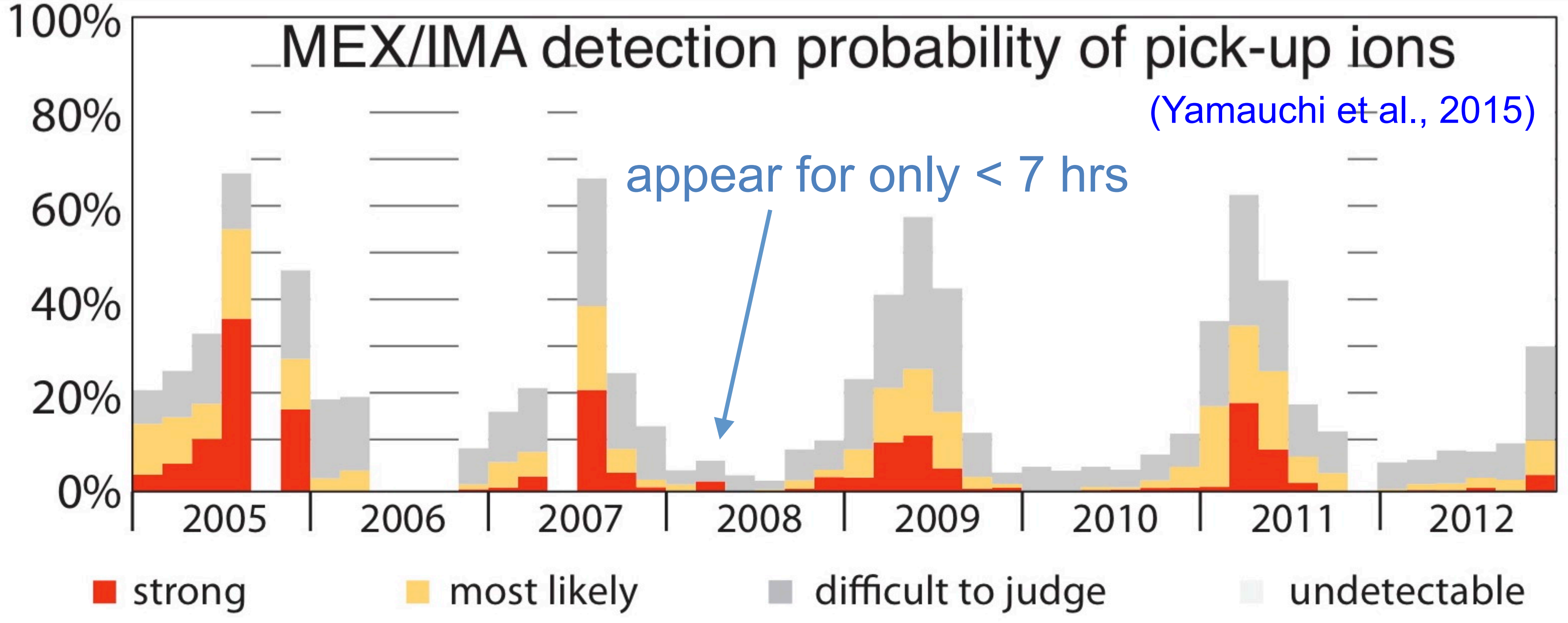
No dedicated Exospheric missions

Mission	UV instrument	Particle instrument
IMAGE	Lyman-alpha	ENA
TWINS	Lyman-alpha	ENA
GOES	Lyman-alpha	hot ions
TIMED	multi-wavelength (thermosphere)	
Hisaki	multi-wavelength (planetary)	
Polar		hot ions
Cluster		hot ions
Akebono		cold ions with N/O separation, hot ions
e-POP		cold ions with N/O separation

Why exosphere?

skip

(Mars Express) newly-formed cold ions



- >10 ion flux change by 20% change in Sun-Mars distance
- >3 ion flux change within 7 hours

Why isotope ratio?

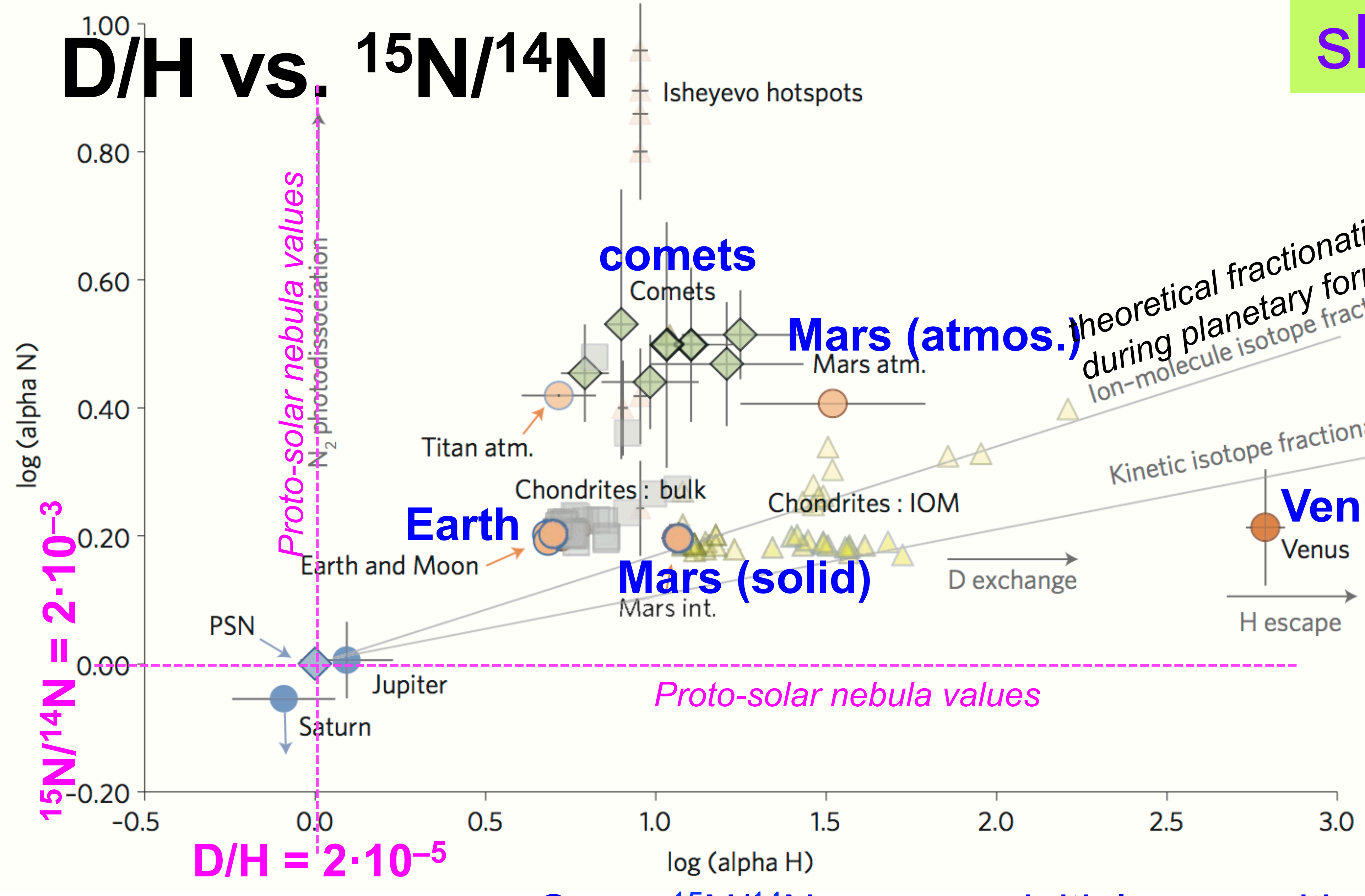
Used as indicator of (thermal) escape from planet, but only qualitatively
(isotope ratios are different between different escape processes)

Gives important information on hydrostatic thickness
(the dependence is also exponential to the mass x thickness)
⇒ **We expect both temporal and horizontal variation**
(MAVEN detect it)

Poor knowledge for the Earth's upper atmosphere
(no systematic observation in the magnetosphere/ionosphere for seeding population, and the mass-filtering depends on ionization altitude)

D/H vs. $^{15}N/^{14}N$

skip



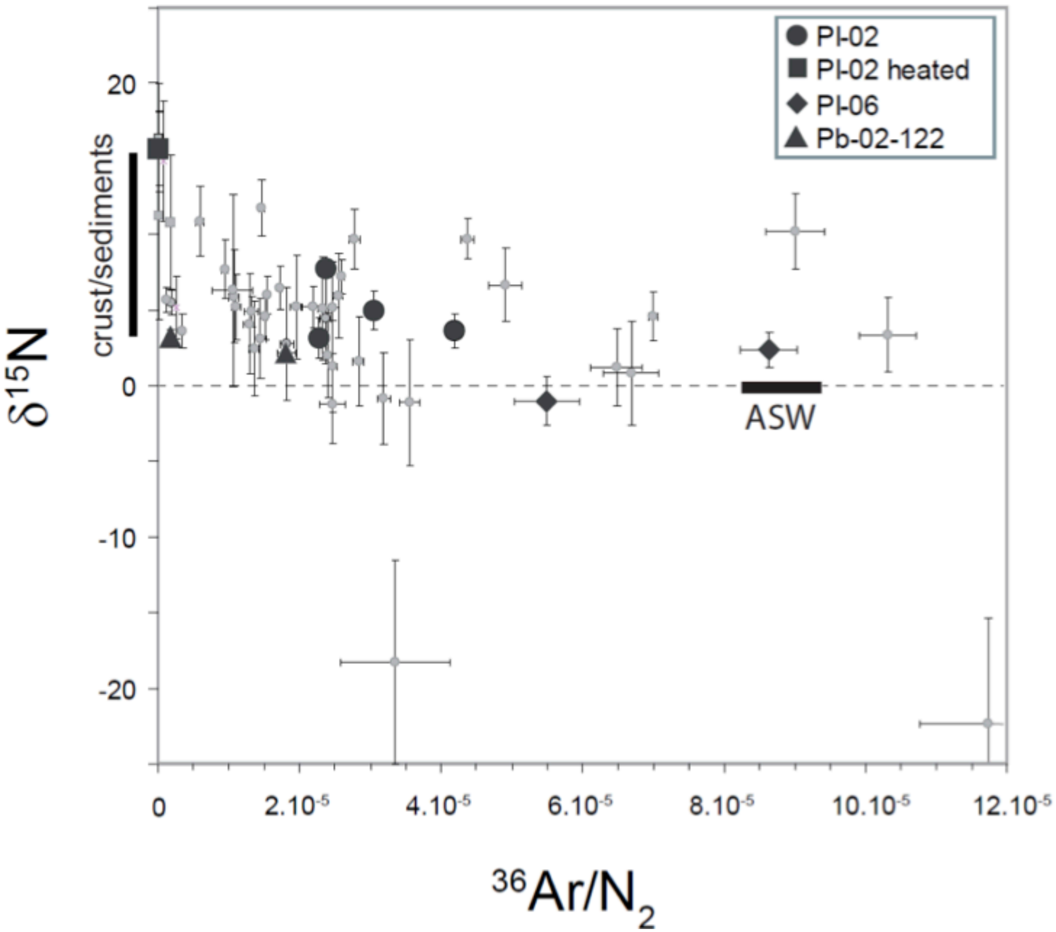
Same $^{15}N/^{14}N$ ⇒ same initial composition

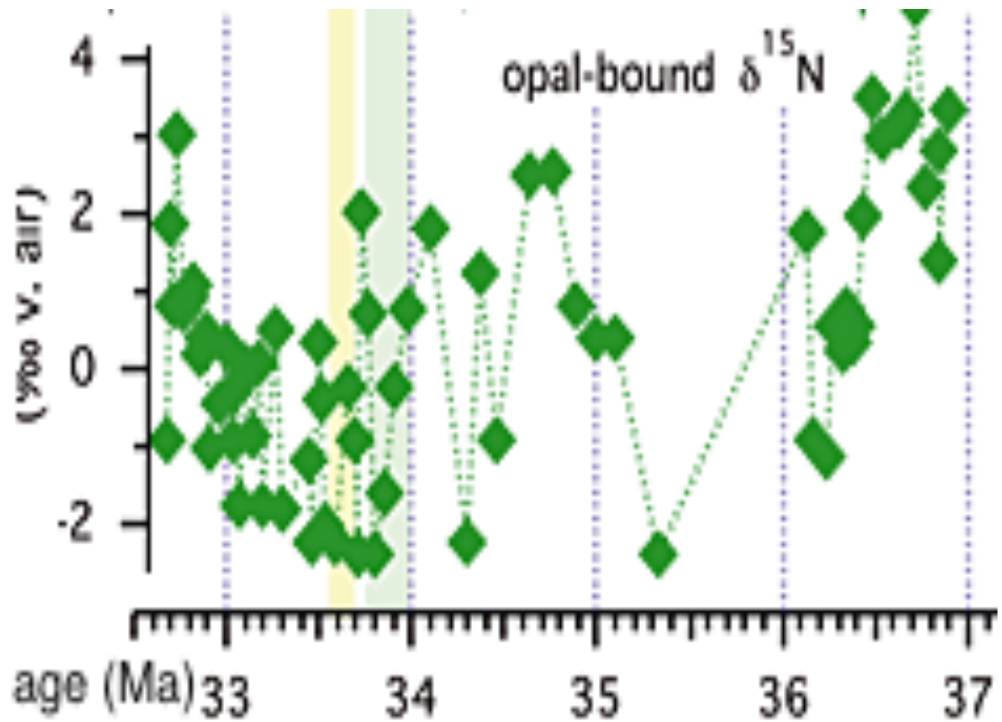
(***Füri and Marty, 2015***).

Alpha H and alpha N are deviations of D/H and $^{15}N/^{14}N$ from protosolar nebula values.

constant $^{15}N/^{14}N$ ratio

changing $^{15}N/^{14}N$ ratio



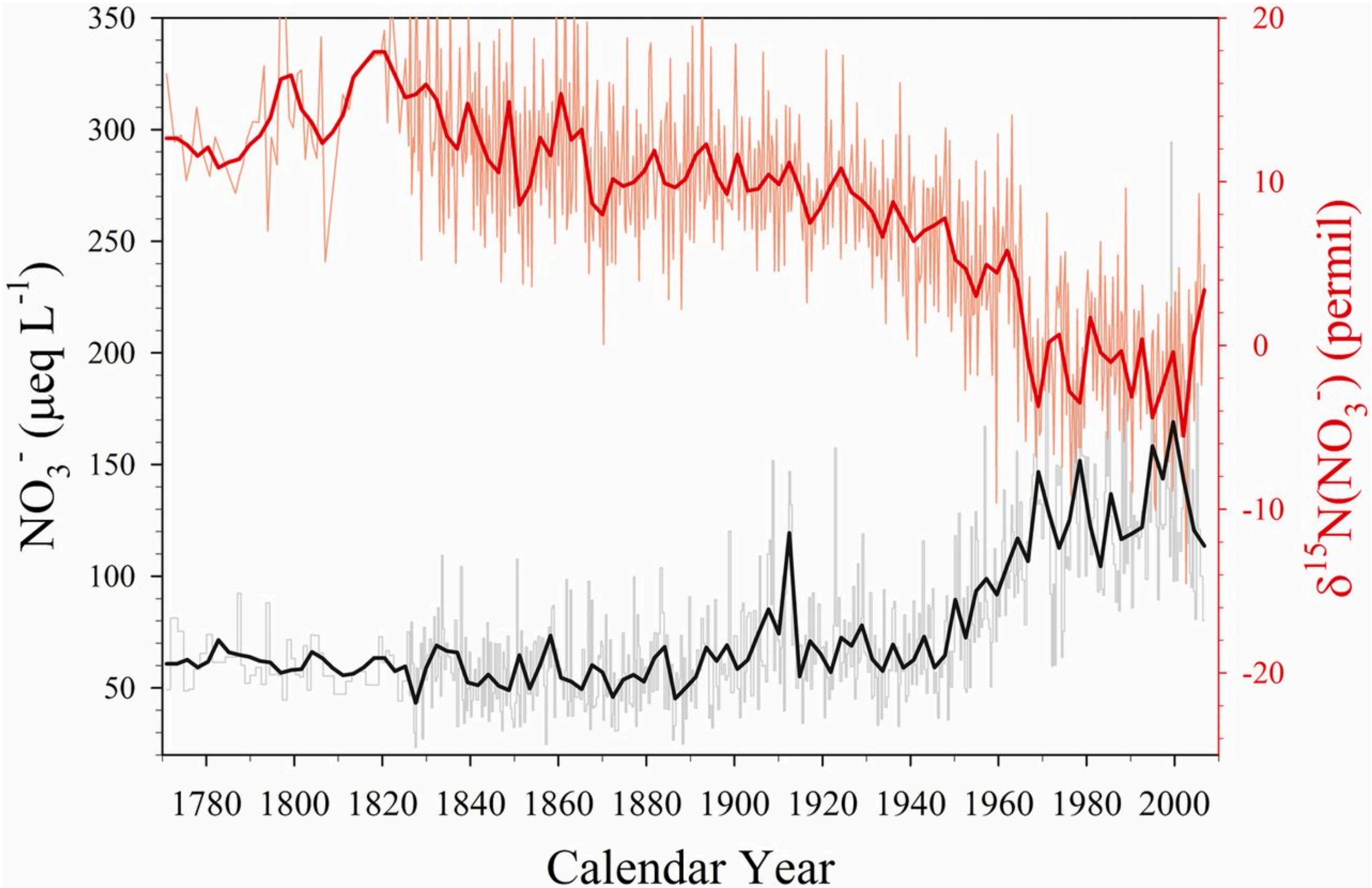


(Marty et al., 2013)

(Robinson et al., 2015)

$^{15}N/^{14}N$ ratio ~ acid level

Ice core observations of NO_3 past 200 years



(Geng et al., 2014)

Why isotope ratio?

skip

Hydrostatic pressure scale heights h is inversely proportional to the mass of atoms/molecules.

$\Rightarrow$ H, D, ^{16}O and ^{18}O, $h_H = 2*h_D = 16*h_{16} = 18*h_{18}$
(where h_H~300 km for the Earth's ionosphere)

$\Rightarrow$ when T is constant,
$n_D/n_H \sim \exp(-z/h_H)$ & $n_{18}/n_{16} \sim \exp(-2*z/h_H)$

$\Rightarrow$ **Scale height of isotope ratio ~ scale height of H**.

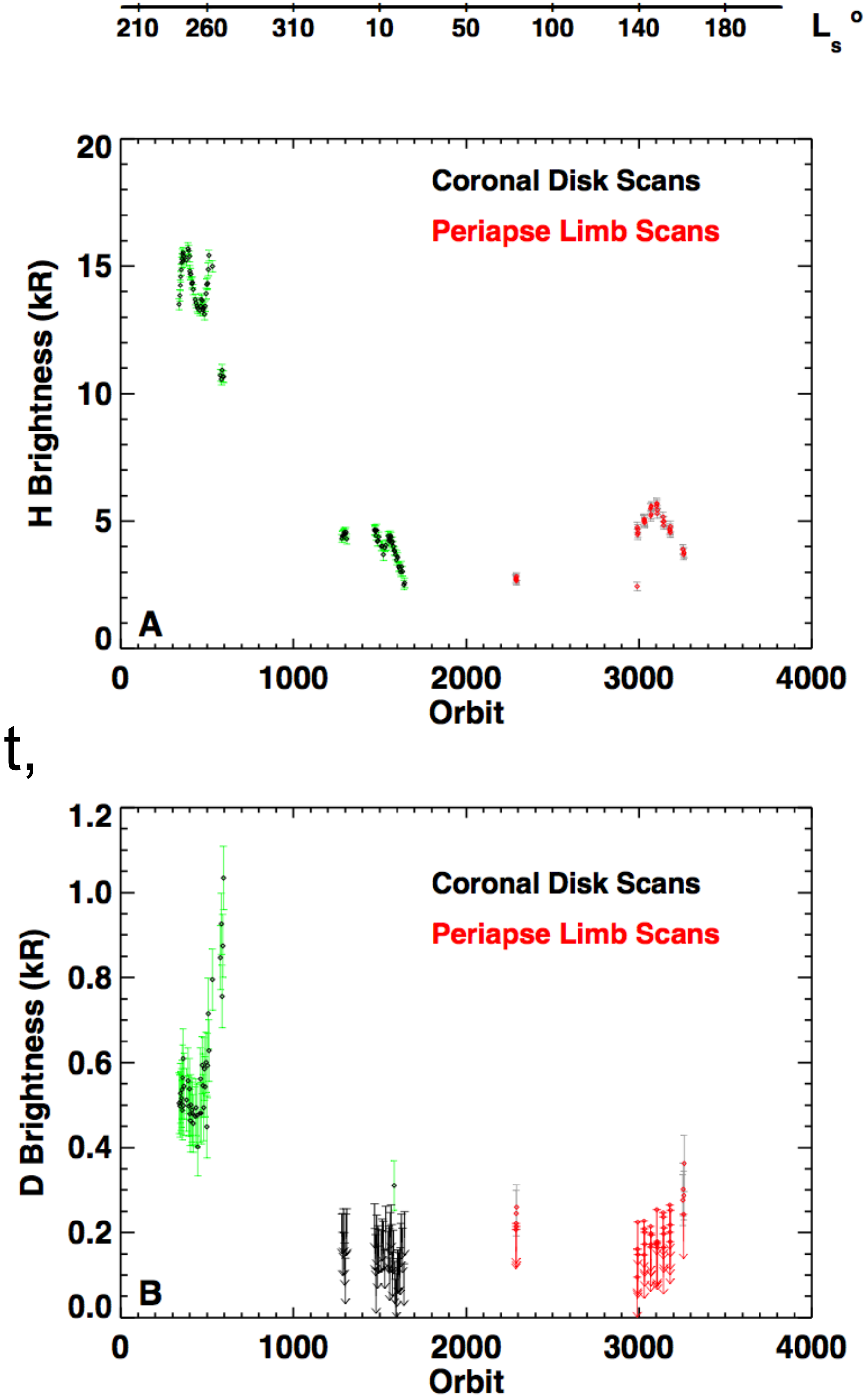
The thickness of the hydrostatic layer (or degree of vertical convection) is one of the leading factor that **determines the isotope ratio (cf. Table 1).**

$\Rightarrow$ **Isotope ratio can be dynamic and structured.**

Isotope ratio is dynamic

(MAVEN) UVI

The variations of H and D are different, indicating changes in the D/H ratio in time.



MAVEN observation of H and D in the Martian exosphere (Courtesy by John Clark; Clark et al., 2016, submitted to JGR).

Non-thermal escape?

Evaluate the composition change by escape

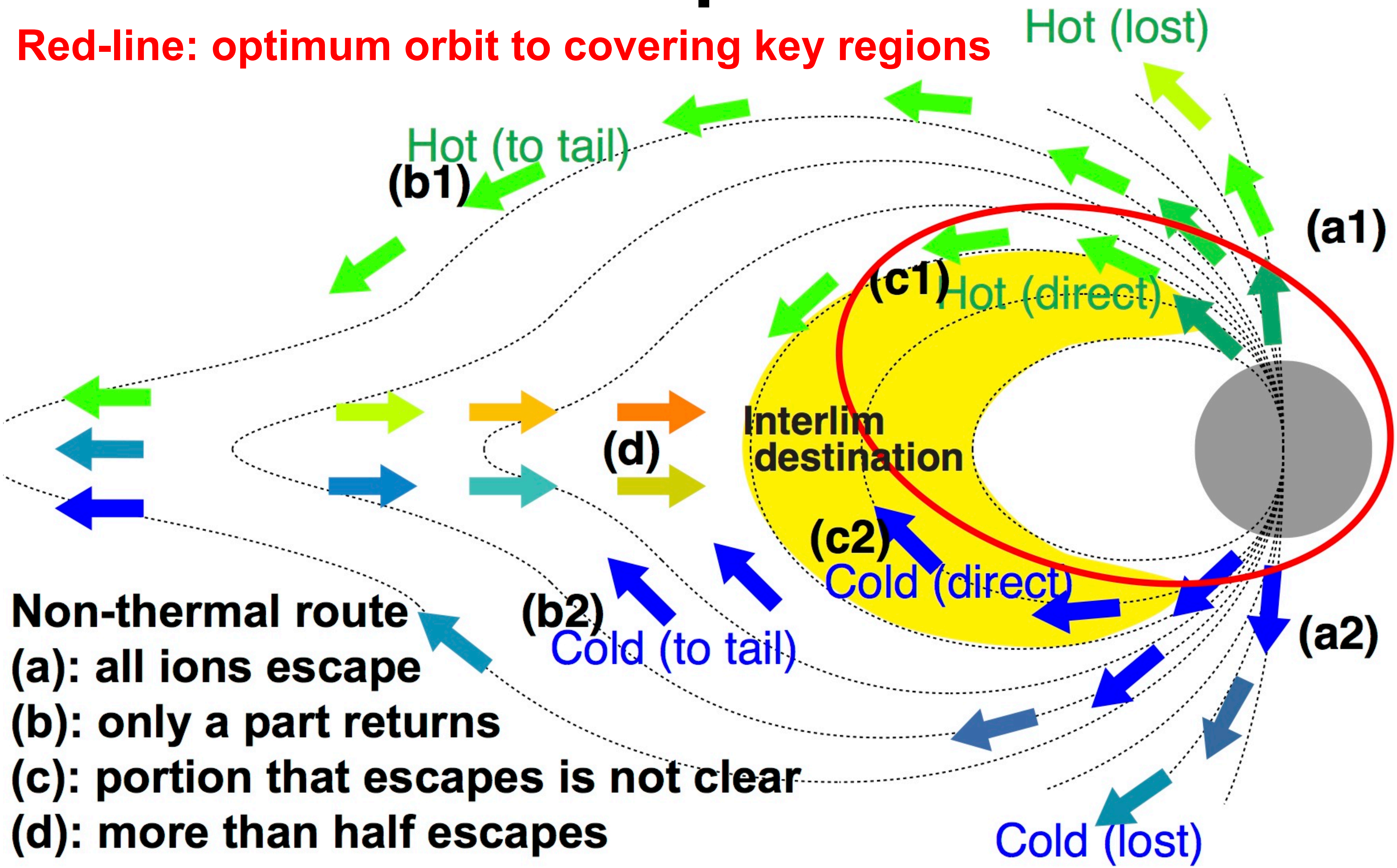
⇒ **Relative contribution of thermal & non-thermal escapes**
(They have different mass-filtering effect)

At moment, we do not know if they are related (they might even anti-correlate to each other, but who knows?)
⇒ **Need simultaneous observation**

No systematic observation at the Earth
(all observations have been done instrument-level but not mission level)

Where is the optimum orbit?

Red-line: optimum orbit to covering key regions



Fate of ions in each route

(a) Polar outflow to **solar wind:** **all ions escape (O^+~10^{25} s^{-1})**
cf. Prognoz-7, but not enough statistics → Cluster answered.
(Hawkeye without composition)

(b) Polar outflow to **magnetotail:** **some escapes (O^+~10^{24-25} s^{-1})**
cf. Geotail, but too many assumptions → Cluster corrected.

(c) Auroral/subauroral outflow to **inner magnetosphere & plasmasphere**: portion that escapes is **not clear for O^+**
cf. Geosynchronous, DE-1, etc., but not enough coverage
→ Cluster found it could be **H^+≥10^{27} s^{-1}** in average.

(d) Return from magnetotail: **>50% escapes (O^+~10^{24-25} s^{-1})**
cf. simulations + many past missions → Cluster confirmed.

Summary of amount

(a) polar outflow

Satellite	R (Re)	Energy Range keV	Outflow Rate (10^{25} s^{-1})		References
			H^+	O^+	
Cluster (CIS)	> 8	0.028-40		escape ~ 2	Nilsson et al. 2012 Slapak et al. 2017
Cluster (EFW)	> 10	supersonic	tail ~ 10		Engwall et al. 2009
Polar (Apogee)	8.5	0.015–33	1	1.5	Lennartsson et al. 2004
DE–1	4	0.010–17	1	0.7	Yau et al. 1986 Collin et al. 1988
Polar (Perigee)	2-2.3	0.015–33	0.3	0.3	Peterson et al. 2001
Akebono	2.3	< 0.07	2	0.2	Cully et al. 2003a
FAST	1.4	0.003–12	-	0.2	Andersson et al. 2005

(b) magnetotail (x10^{25} s^{-1}): earthward O^+~0.6 / tailward ~0.5 / net return ~0.1

(c) inner magnetosphere / Cluster

Instrument	phenomenon	method	escape rate (10^{25} s^{-1})	References
WHISPER	Plume	ω_{ce}	peak H^+ > 100	Darrouzet et al. 2009
CIS (cold)	Wind	direct	H^+ ~ 50	Dandouras et al. 2013
CIS (hot)	Heating	direct	H^+ < 0.01	Yamauchi et al. 2012

(d) returned flow: about half are lost < 0.1·10^{25} s^{-1}

key region to measure

skip

Exosphere

Ionosphere

(Ionospheric condition should influence non-thermal escape, and need to monitor even lower part simultaneously.)

Plasmasphere

(Plasmasphere could be partly filled by the exosphere directly)

Magnetosphere

(energy coming from the magnetosphere must be major external force as well as solar UV, and some outflow returns.)

Solar wind

(Essential external condition Continuously observed)

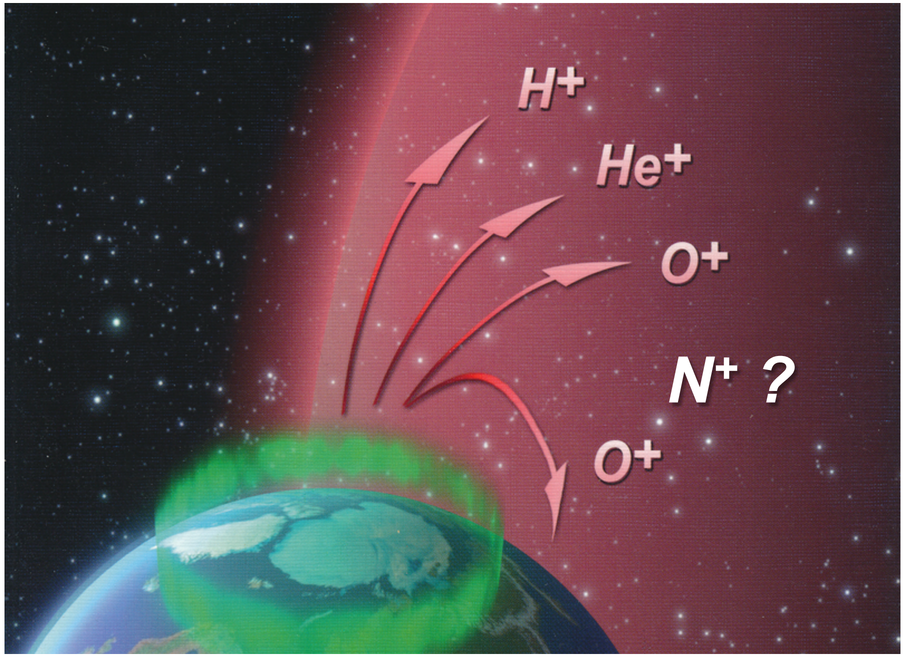
Particular interest on N^+ and N_2^+ skip

Good mass filtering test for non-thermal escape
(M/dM > 700 works only for cold ions, and need other method to extract mass-filtering by the non-thermal mechanism)

Behavior is different from Oxygen with similar mass
($N_2 \rightarrow N_2^+ \rightarrow N^+$ whereas $O_2 \rightarrow O \rightarrow O^+$, and completely different solar/geomagnetic dependence)

dissociation energy for molecules:
- N_2: 945 kJ/mole (9.79 eV)
- O_2: 497 kJ/mole (5.15 eV)
- H_2: 436 kJ/mole (4.52 eV)

Ionisation energy for atmos:
- N: 1402 kJ/mole (14.53 eV)
- O: 1314 kJ/mole (13.62 eV)
- H: 1312 kJ/mole (13.60 eV)



Summary of Scientific Objective

#1: What is the quantitative state of the atmosphere at altitudes of 500-2000 km?

- Exospheric temperature and density altitude profiles as a function of different drivers (solar EUV, solar wind and geomagnetic conditions).
- Establish isotope ratios for both neutrals and ions and compare them with those found at the Earth's surface and in other solar system objects.
- Exospheric altitude profile of ion/neutral ratios and estimate ionisation/neutralisation efficiencies
- Temporal and spatial variations of the density of major exospheric species
- Correlation of such variability with upper atmosphere parameters, and with different incident energies when particle precipitation is present

skip

Summary of Scientific Objective

#2: What are the dominant escape mechanisms, and their dependence on drivers?

- Estimate thermal escape flux for neutral and ion species for different conditions.
- Estimate the prevailing escape mechanisms and the relative importance of thermal or non-thermal escape for different driver conditions.
- Estimate the response of the ionisation and neutralisation efficiencies, isotope fractionation and the N/O ratio to different drivers.
- Estimate the degree of recirculation of plasma after it has left the ionosphere.

skip

Summary of Scientific Objective

#3: How are fundamental physics/chemistry processes affected by the space environment?

- How are isotopes fractionated in the space environment?
- What are the ionisation/neutralising efficiencies in the space environment?

skip

Observation strategy

#1: Density and temperature distribution of Exosphere

- **Combine in-situ and line-of-sight integrated observation (particle instrument + UV imaging spectrometer)**
- Measure ions and neutrals simultaneously

#2: Both thermal and non-thermal

- **Elliptic orbit with high-inclination**
- Return flow is also measured

#3: External/internal drivers' condition as much as possible

- Monitor ionospheric & magnetospheric conditions
- Take advantage of EISCAT_3D

Spin-off

skip

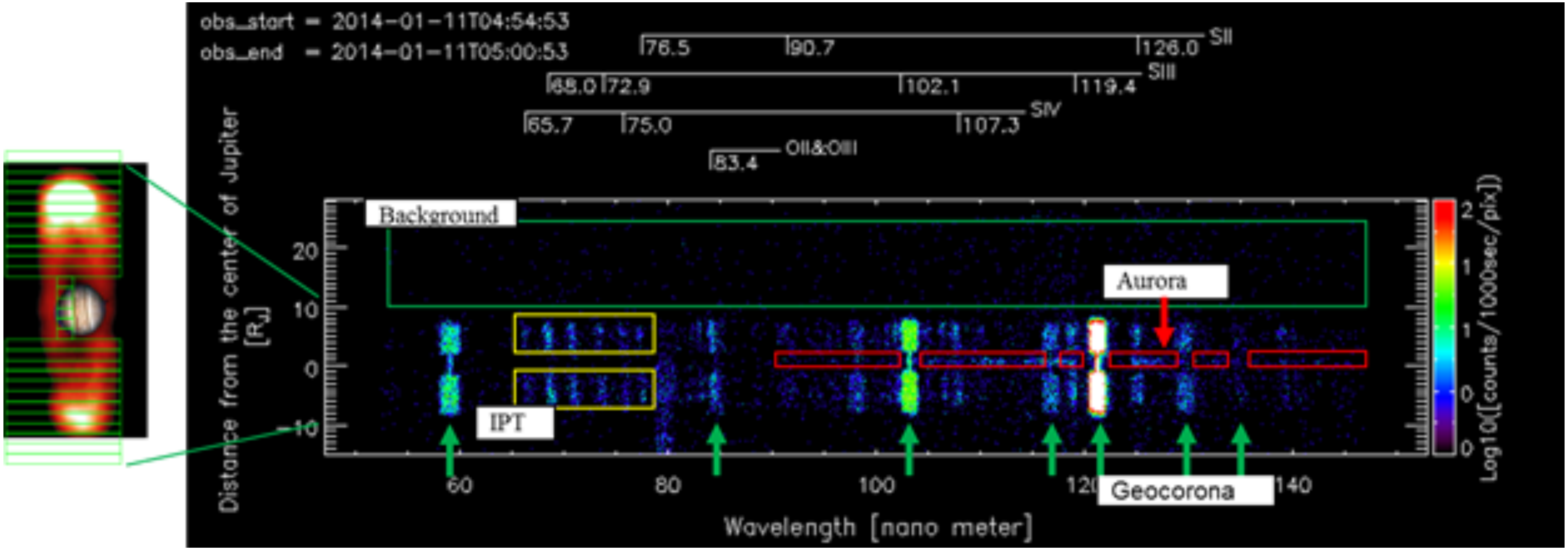
Correction of exospheric contamination/abroption in optical (astrophysical) observation
(cf. Hisaki background from 1000 km altitude is very high)

Ionospheric physics
(together with e.g., EISCAT_3D)

Exospheric effect on Ionosphere-Plasmasphere coupling
(through ionisation as well as neutralisation)

Magnetosphere-ionosphere coupling
(covering both region + N^+/O^+ difference as tracer of different start time)

Exospheric contamination (Hisaki)



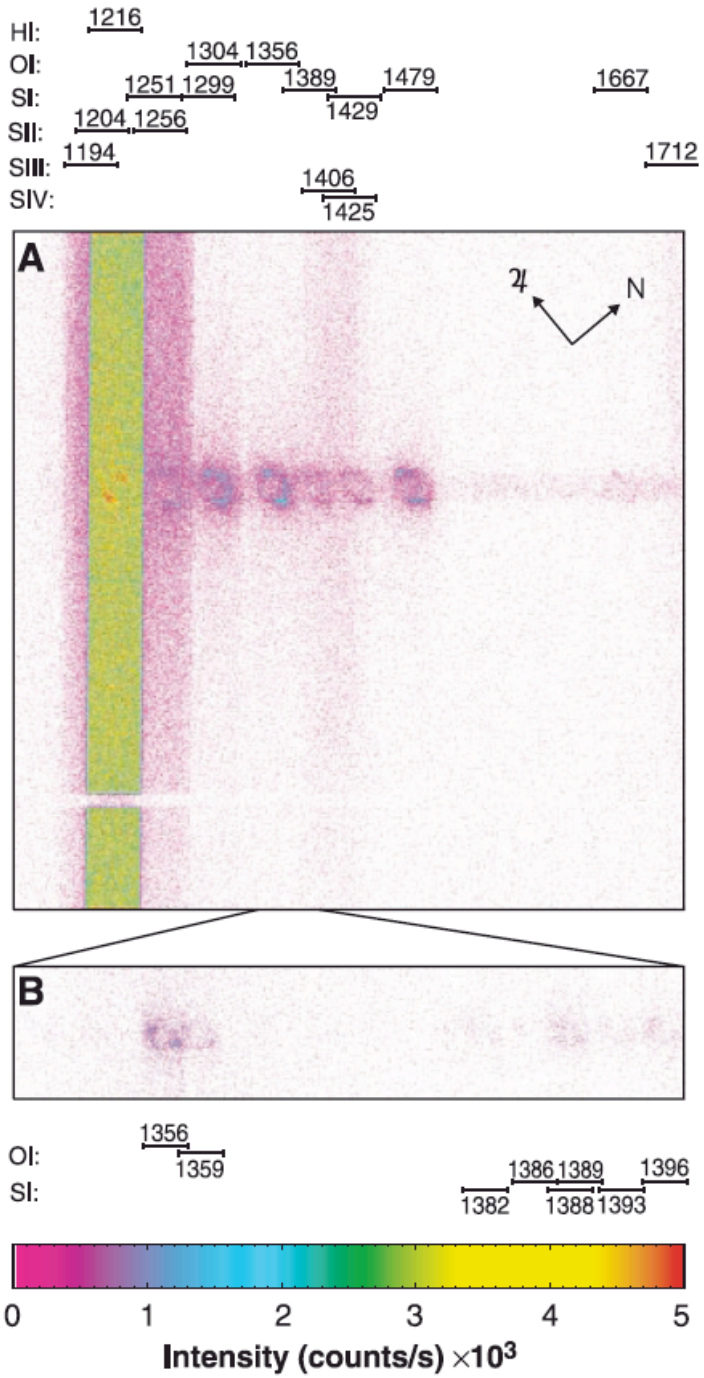
*An example (a 6 min cycle) of EUV (50-150 nm) observation of Jupiter by Hisaki (**Yoshikawa et al., GRL, in press**).*

Green = emission from exosphere

Yellow = emission from Io plasma torus

Red = Jovian aurora

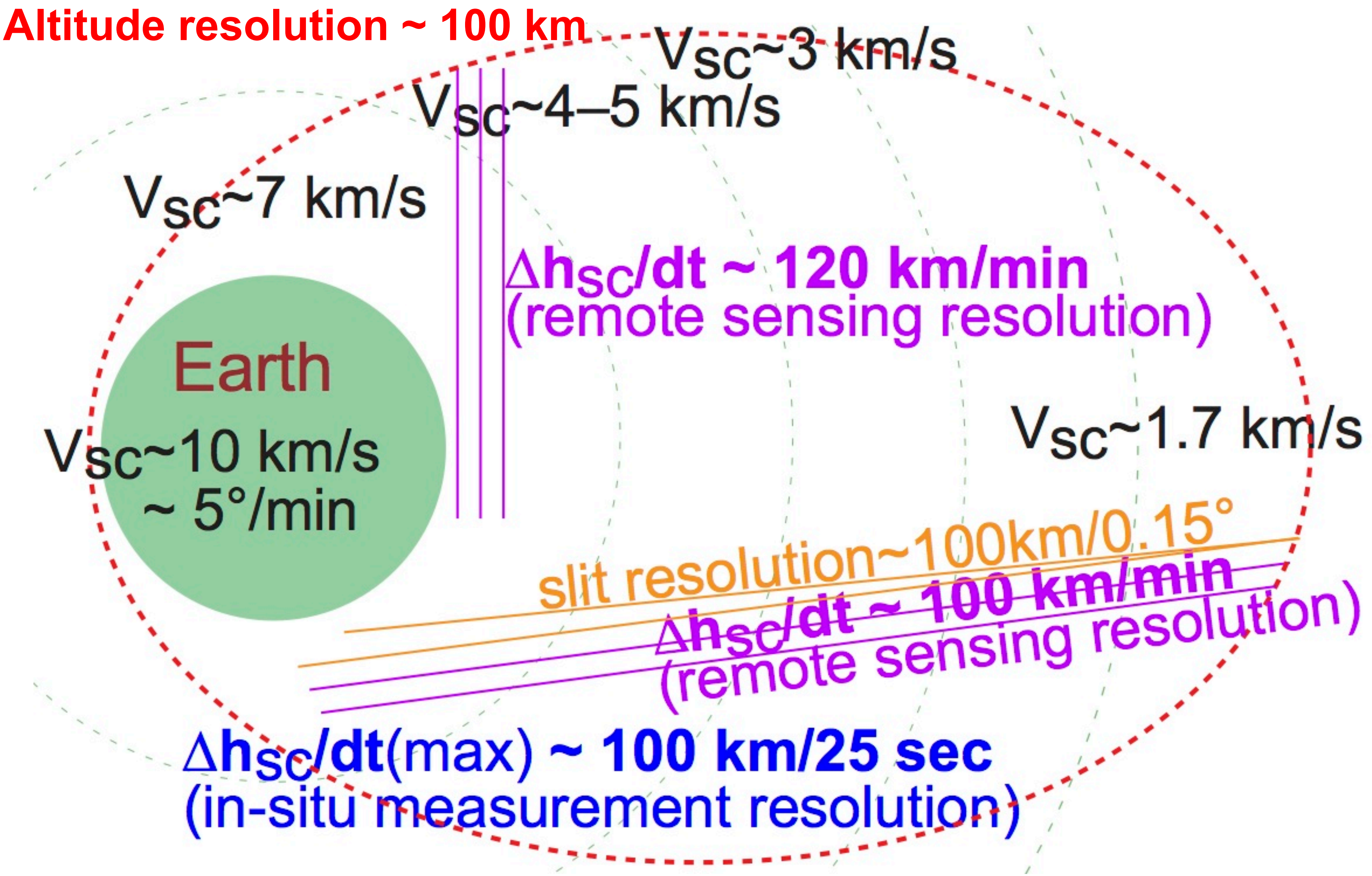
skip



exospheric contamination/ absorption

Example of geocoronal noise in an observation taken with the Space Telescope Imaging Spectrograph onboard the Hubble Space Telescope **(Roesler et al. 1999, Science**). The vertical bars are in parts due to contamination by geocoronal emission, in particular the green bar shows Lyman-alpha emission from the geocorona. The disks in this figure represent images of the scientific target of these observations, i.e. the emission from Jupiter's moon Io at various FUV wavelengths.

Targeting 100 km alt. resolution



Payload

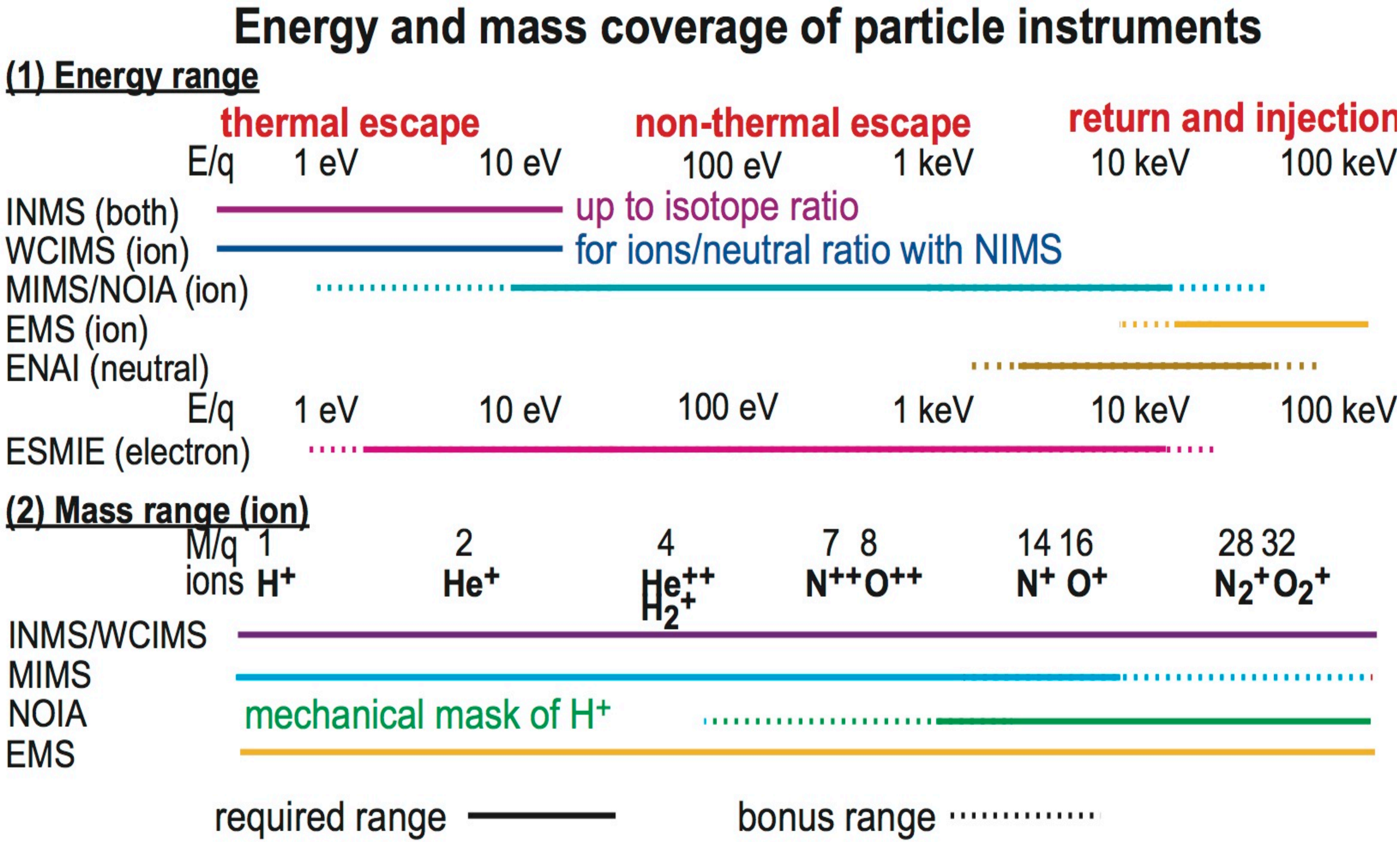
in-situ particle	TRL
INMS: Cold ion & neutral mass spectrometer ($M/\Delta M > 1000$): U. Bern	7 - 8
WCIMS: Cold ions & neutral f_{dist}: NASA-GSFC	7
MIMS: Light hot ions (M < 20, < 40 keV/q): IRAP, Toulouse	5
NOIA: Heavy hot ions (M > 10, < 30 keV/q): IRF, Kiruna	$\geq$ 6
EMS: Energetic ions (20–200 keV): U. New Hampshire, USA	$\geq$ 6
ESMIE: Electrons (~5 eV – 20 keV): UCL/MSSL, London, UK	$\geq$ 6

in-situ field	TRL
SLP: Sweeping Langmuir probe: e-density, spacecraft potential: BIRA-IASB, Brussels	4 - 5
MAG: Magnetic field: IWF, Graz	8
Waves (5 Hz –20 kHz): ASCR, Prague Search Coil: LPC2E, Orléans	$\geq$ 5

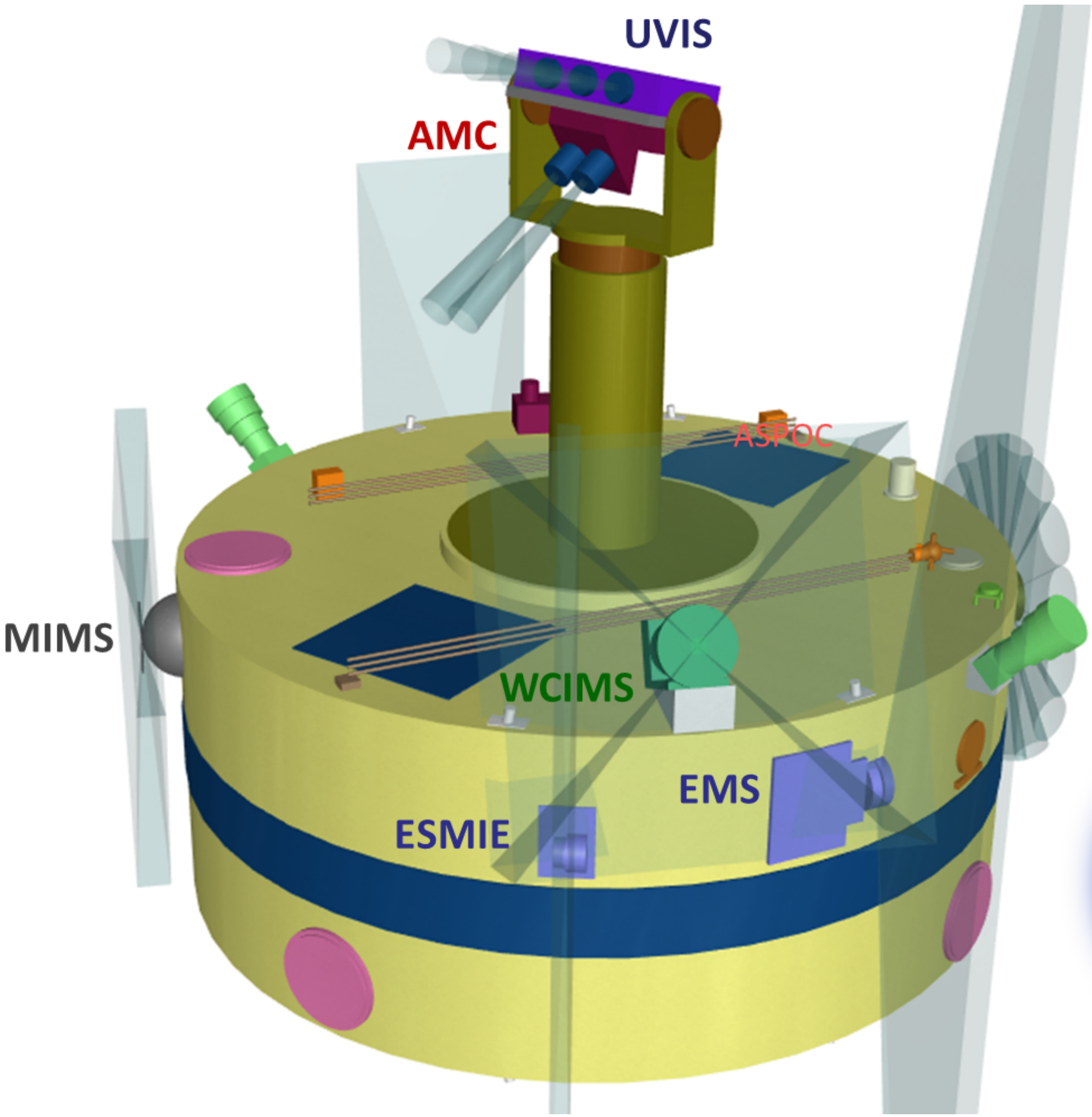
Line-of-sight integrated values	TRL
UVIS: UV imaging spectrometer (85 – 140 nm, 83, 58, 30 nm for H, N, O, O^+, He, He^+): U. Tokyo	6 - 7
AMC: Aurora monitoring camera (670 nm and 630 nm): Tohoku U.	7 - 8
ENAI: ENA imager (2–200 keV): INAF/IAPS, Rome	> 5

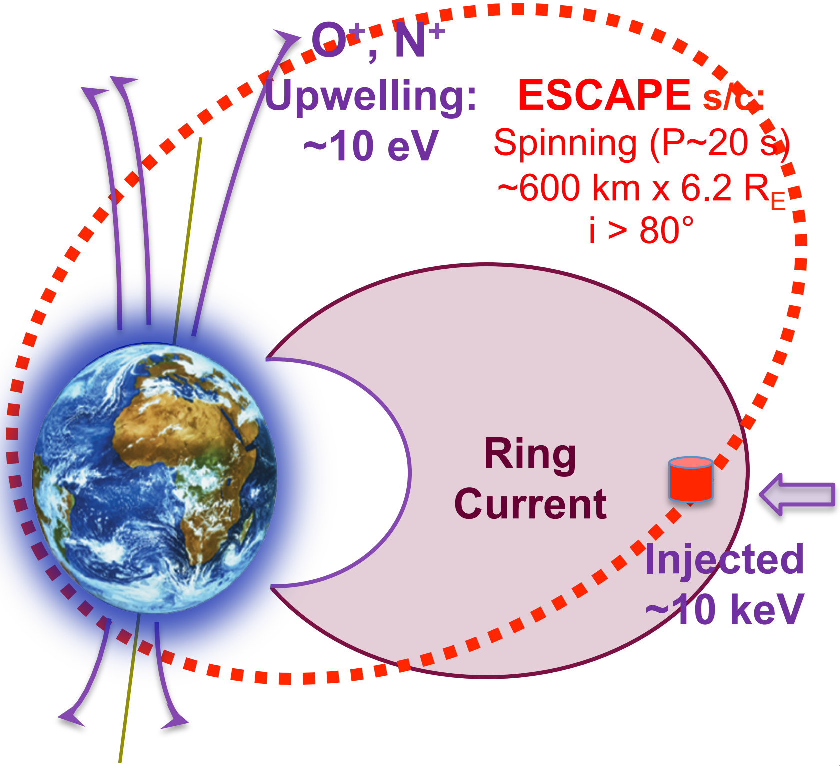
Mass coverage

skip



Spacecraft (spin+despun) and orbit





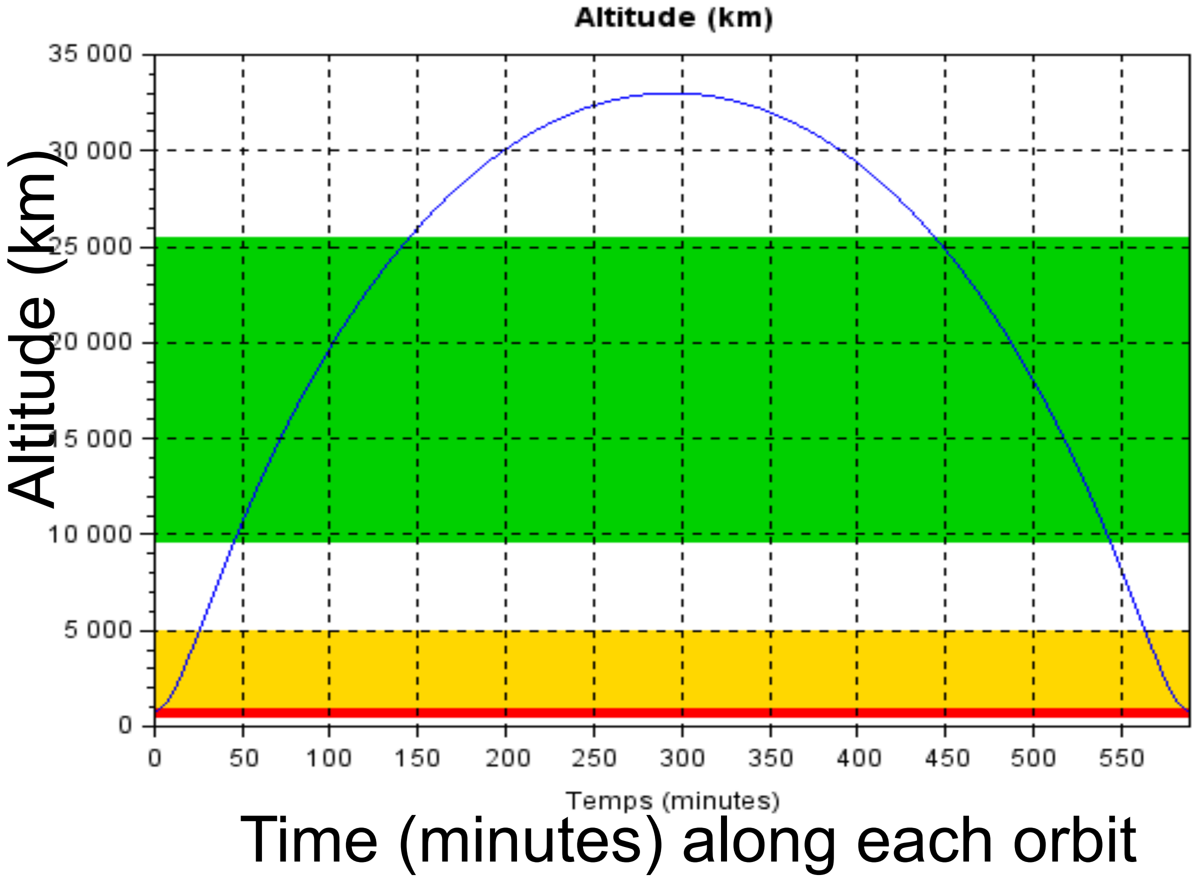
skip

Orbit evolution

- Initial perigee altitude : **800 km**
- Apogee altitude : **33 000 km** (6.2 R_E geocentric distance)
- Orbital plane inclination : **90°**
- Initial latitude of the line of apsides: **85°N**
- Argument of perigee: 255°
- **9 h 45** orbital period (2697 orbits in 3 years)
- No need for orbit maintenance manoeuvres
  (unless we want to gradually change the orbit characteristics)
- **-0.21°/ day rotation** of the line of apsides in this plane (230° in 3 years)
- Slow oscillation of the perigee altitude, **between 800 and 480 km**
- Need for deorbiting at the end of mission

Region of interest

skip



Ring current region (2.5 - 5 R_E, lat < 45°): 34 % per orbit, i.e. > 8 hours per day

Upwelling region (1000-5000 km, lat > 70°): 1.47 % of traversals, i.e. ~21 minutes per day

Exosphere (500-1000 km): 1.56 % per orbit, i.e. ~22 minutes per day

White and green zones (> 5000 km altitude) are perfectly suited for remote sensing observations of the lower exosphere and limb.

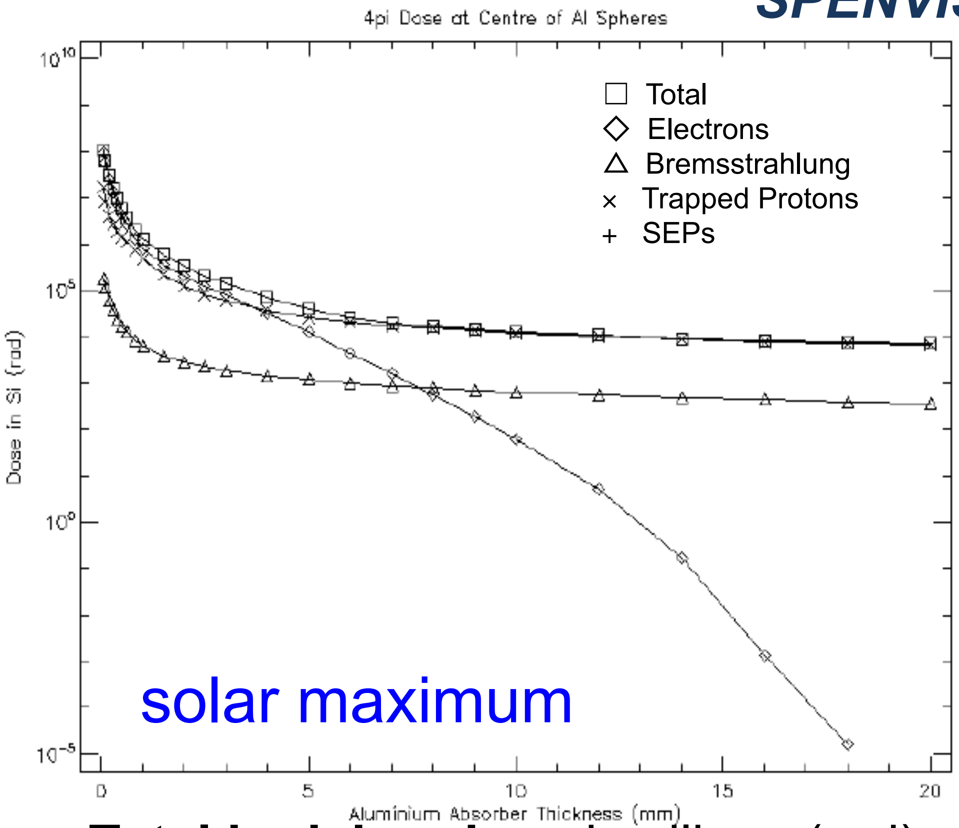
skip

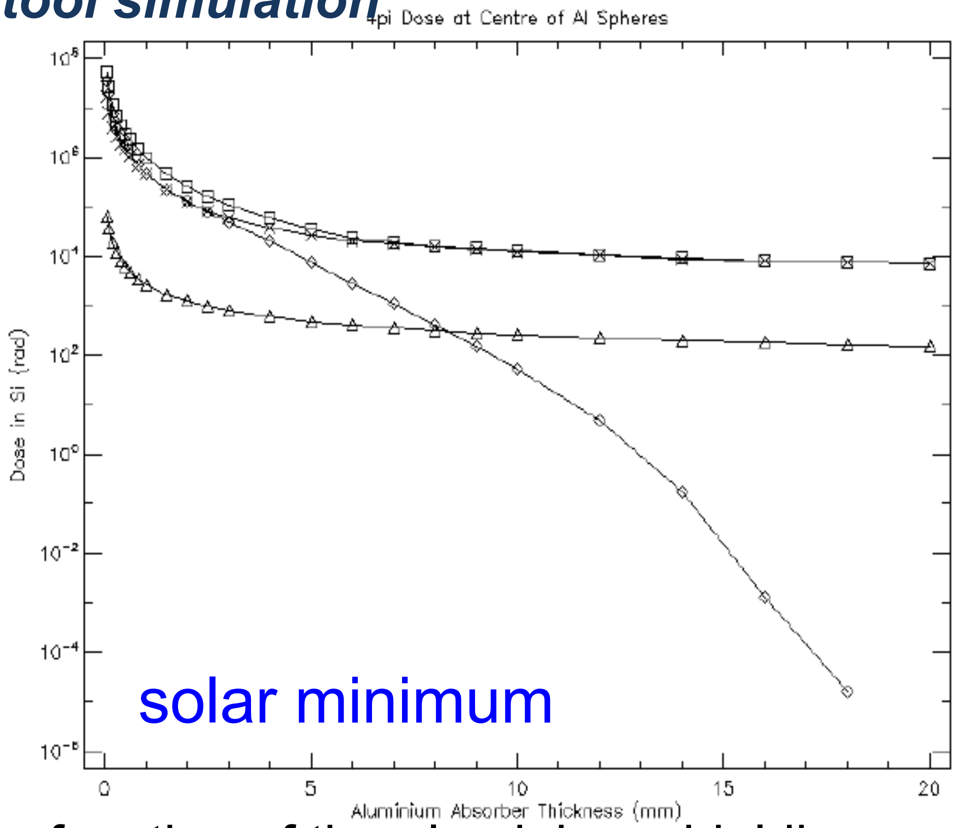
Radiation dose

Total ionising doses after 3 years

~ 35–40 krad behind 5 mm of aluminium shielding

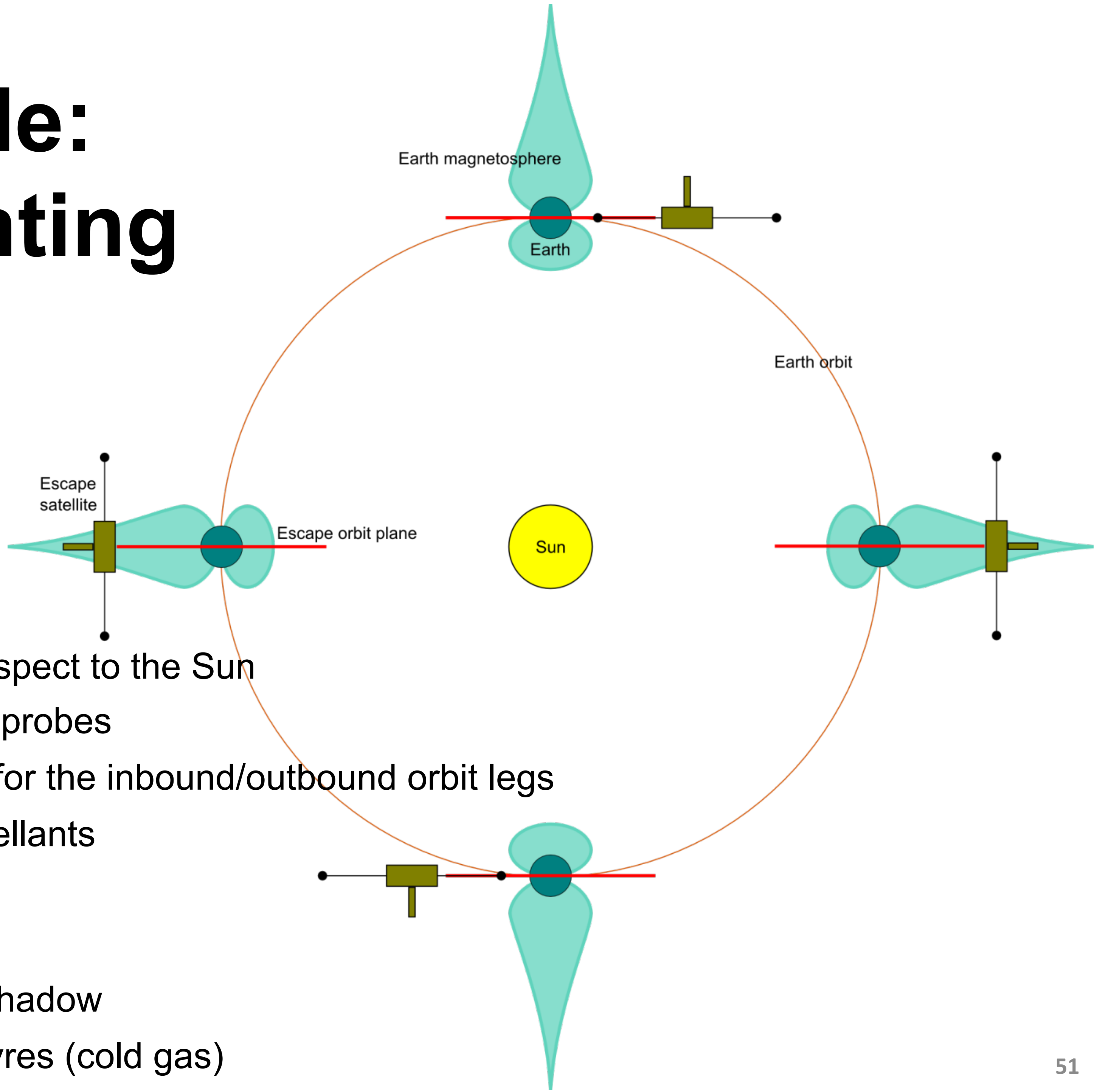
SPENVIS tool simulation





Total ionising dose in silicon (rad) as a function of the aluminium shielding thickness (mm)

Attitude: sun-pointing



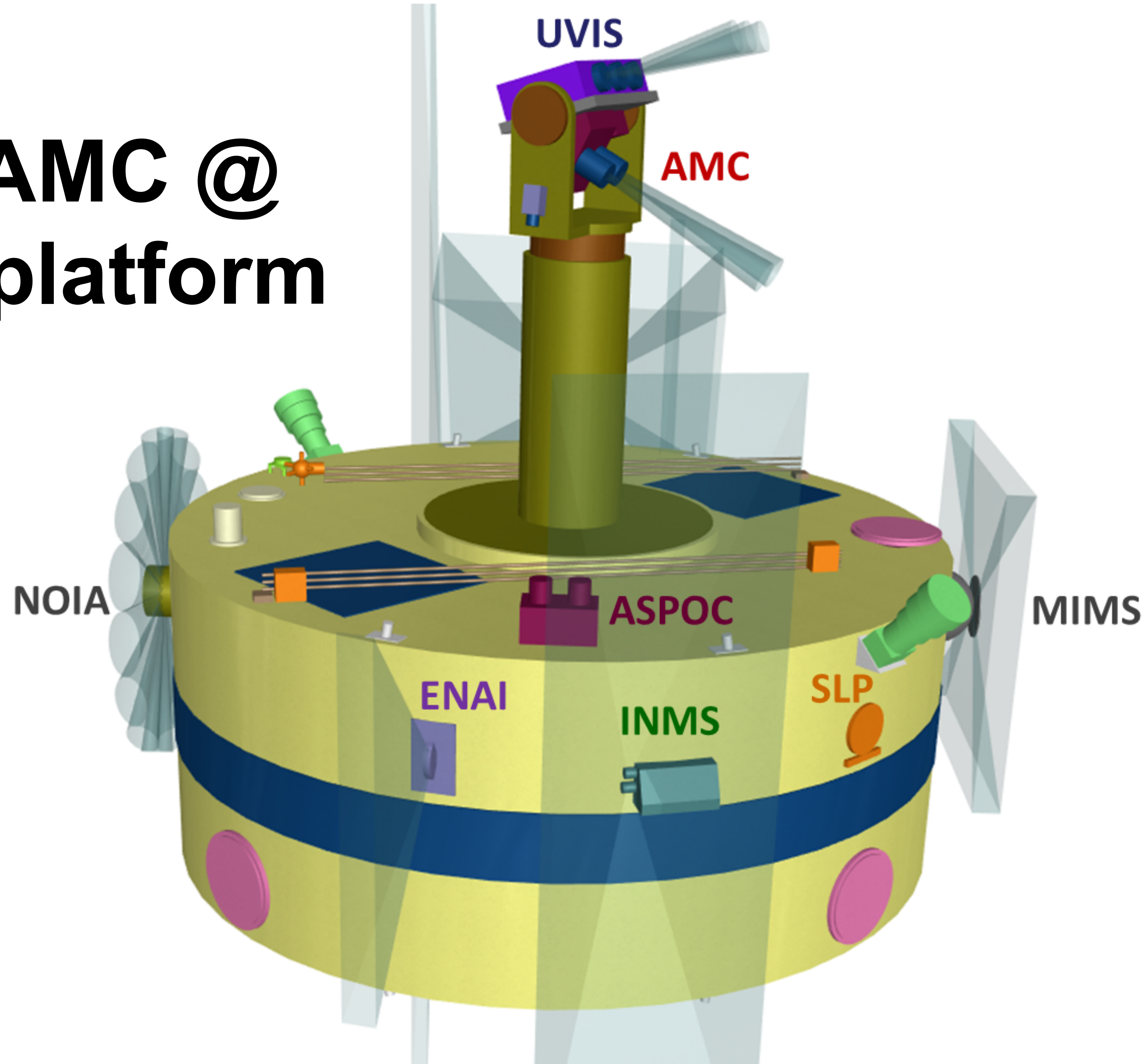
Requirements:

- 3 rotations / minute
- Constant attitude with respect to the Sun
- No shadows on the SLP probes
- Allow auroral zone view for the inbound/outbound orbit legs
- No nitrogen or CH_4 propellants

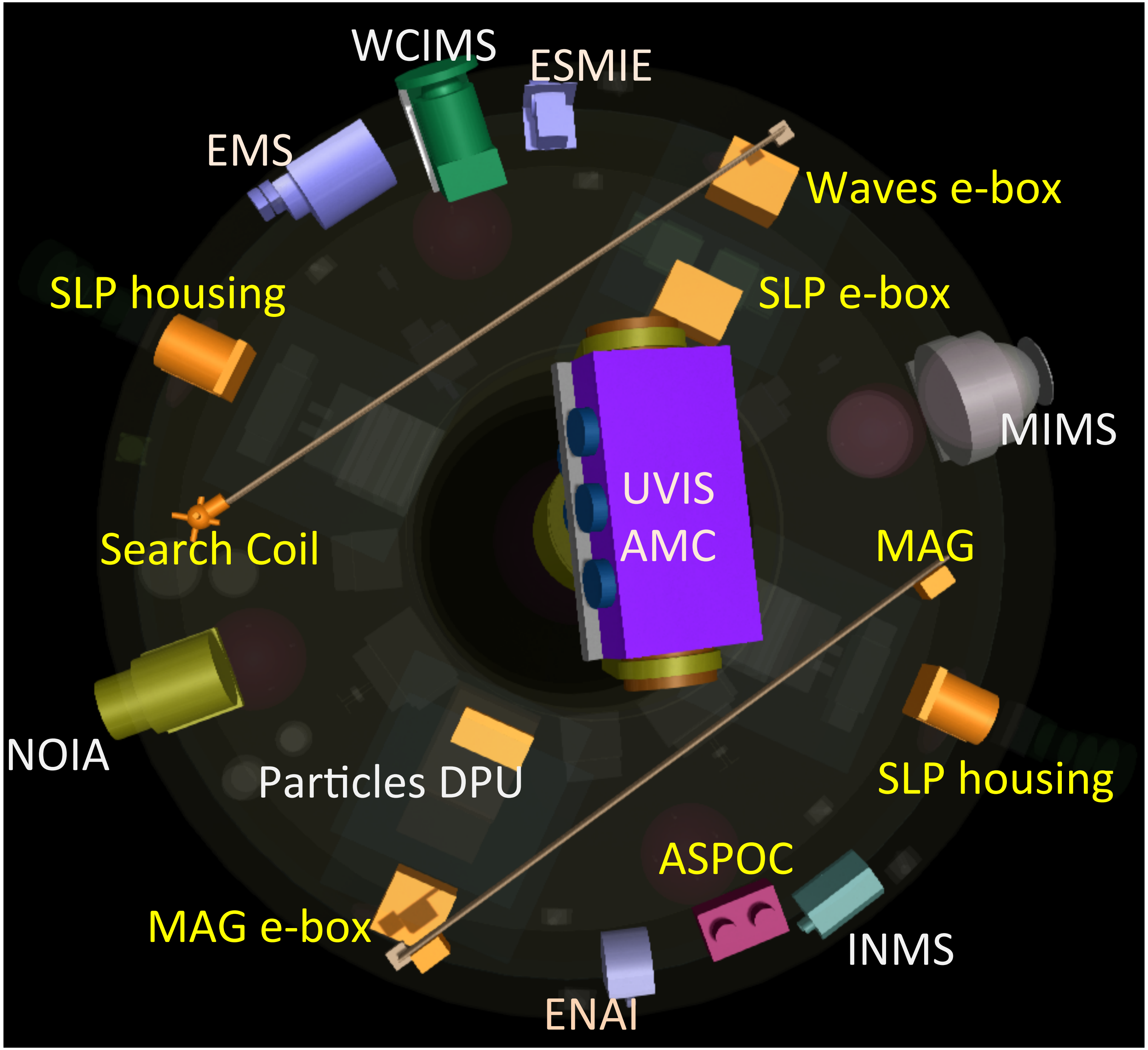
Resulting Design:

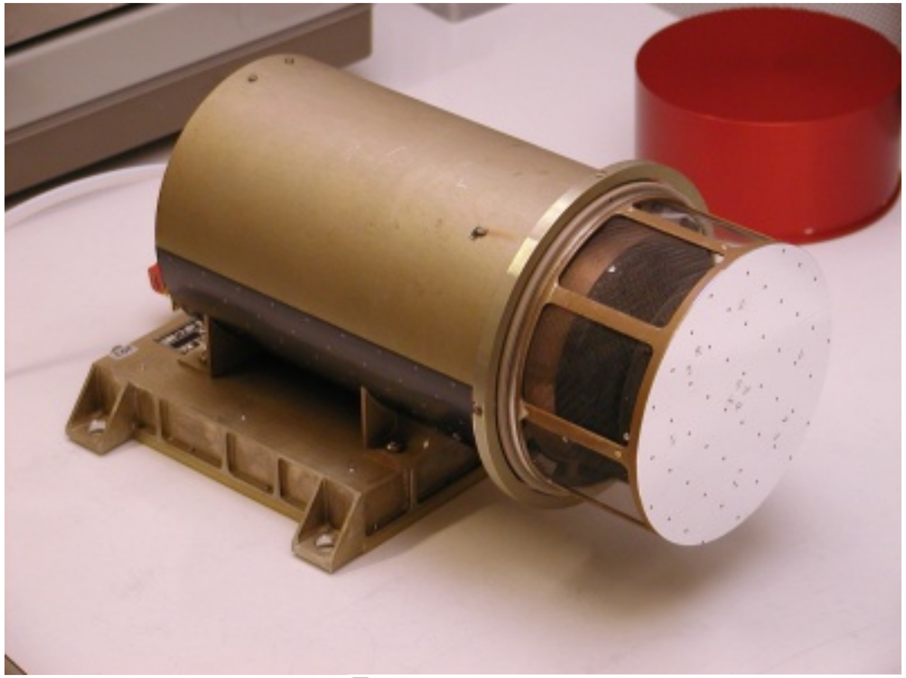
- Sun-pointing spin axis
- Despun platform in the shadow
- 1°/ day attitude manoeuvres (cold gas)

UVIS + AMC @ despun platform



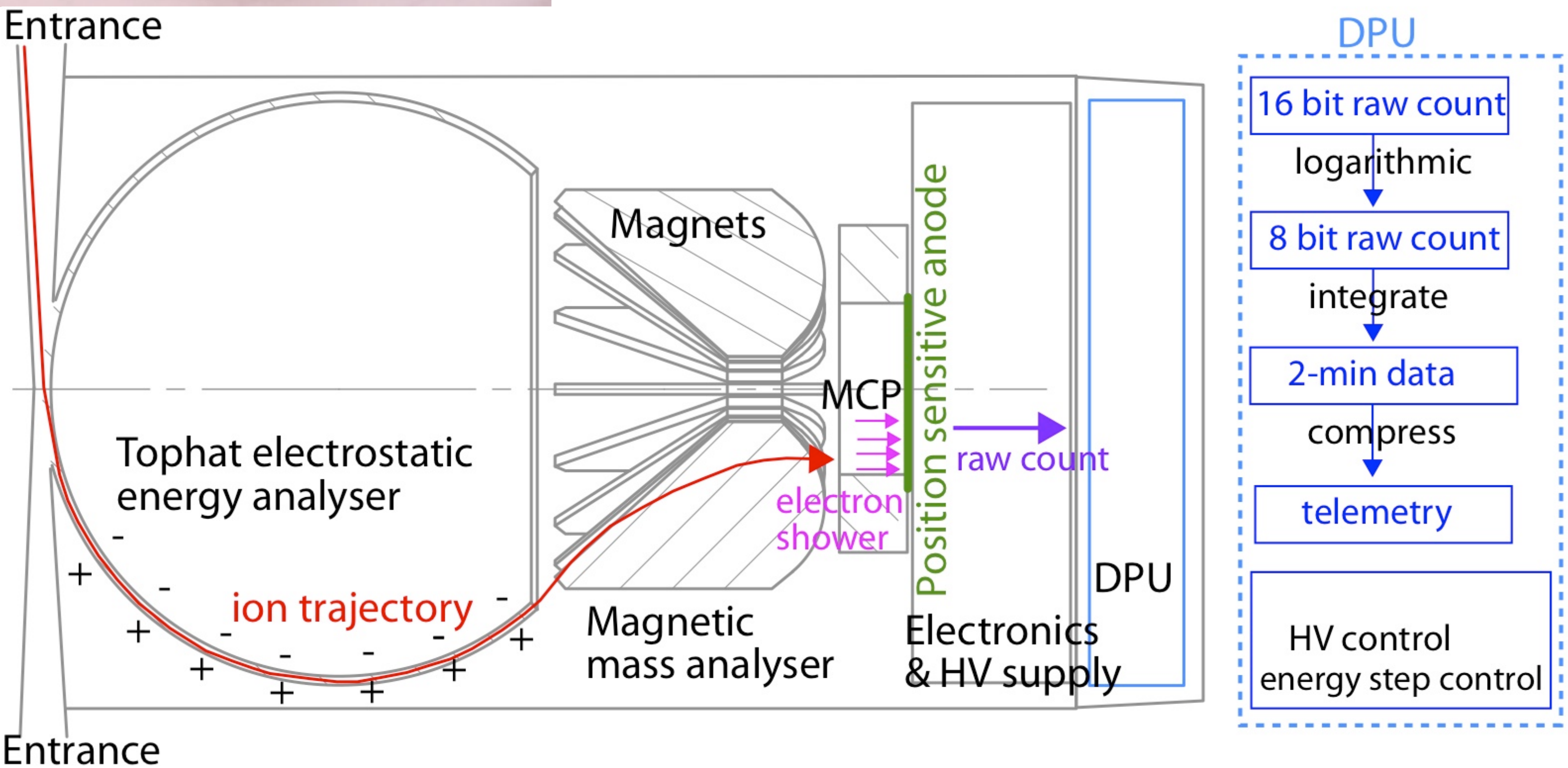
Accomo-dation



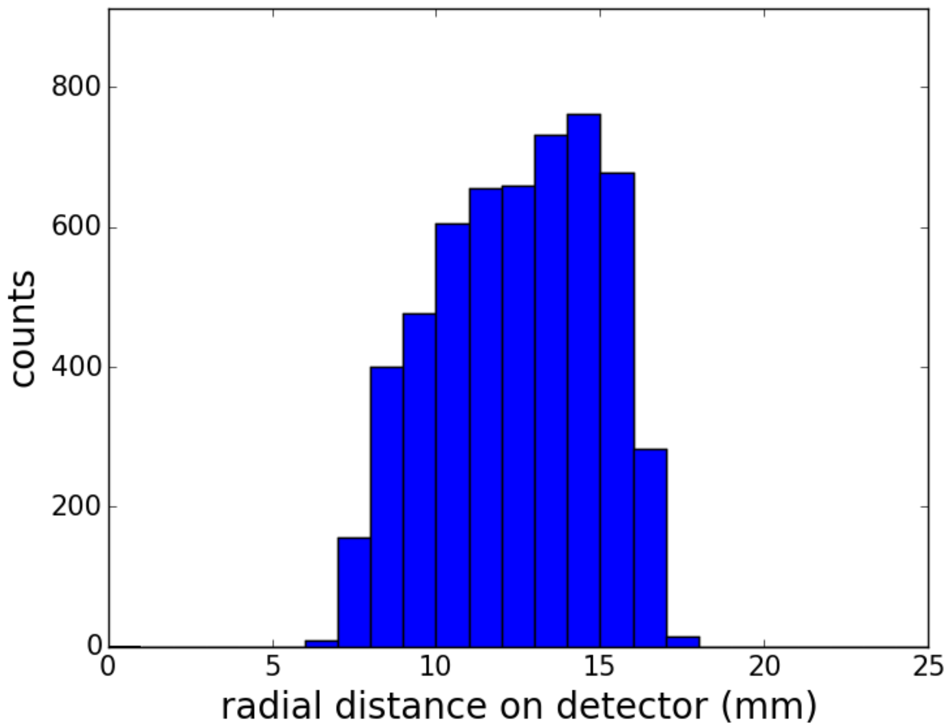


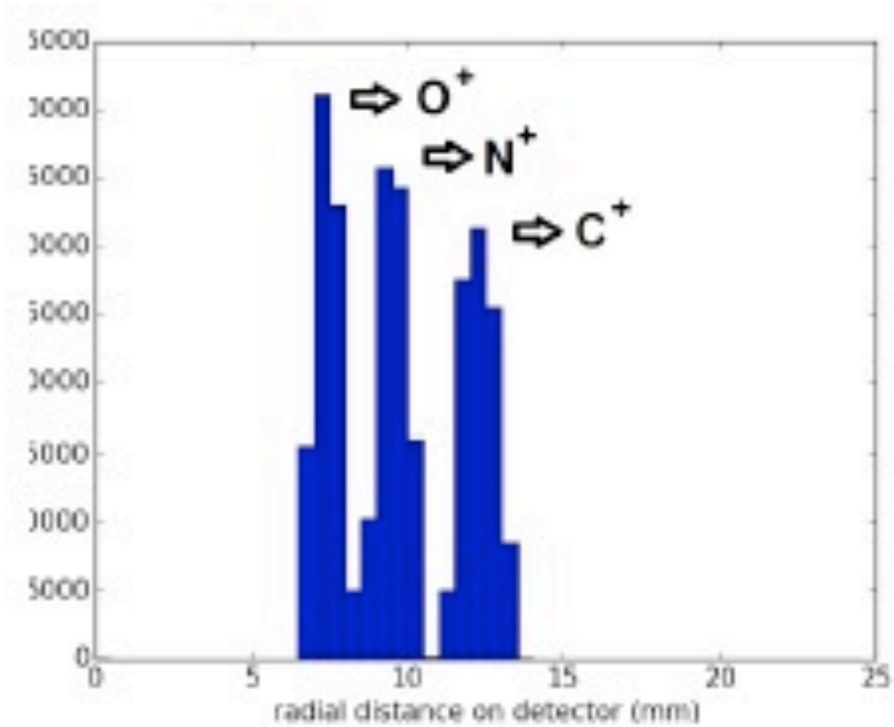
IMA/ICA → NOIA

Will be 4 cm longer and 6 cm wider than this, but entrance is narrower



estimated resolution



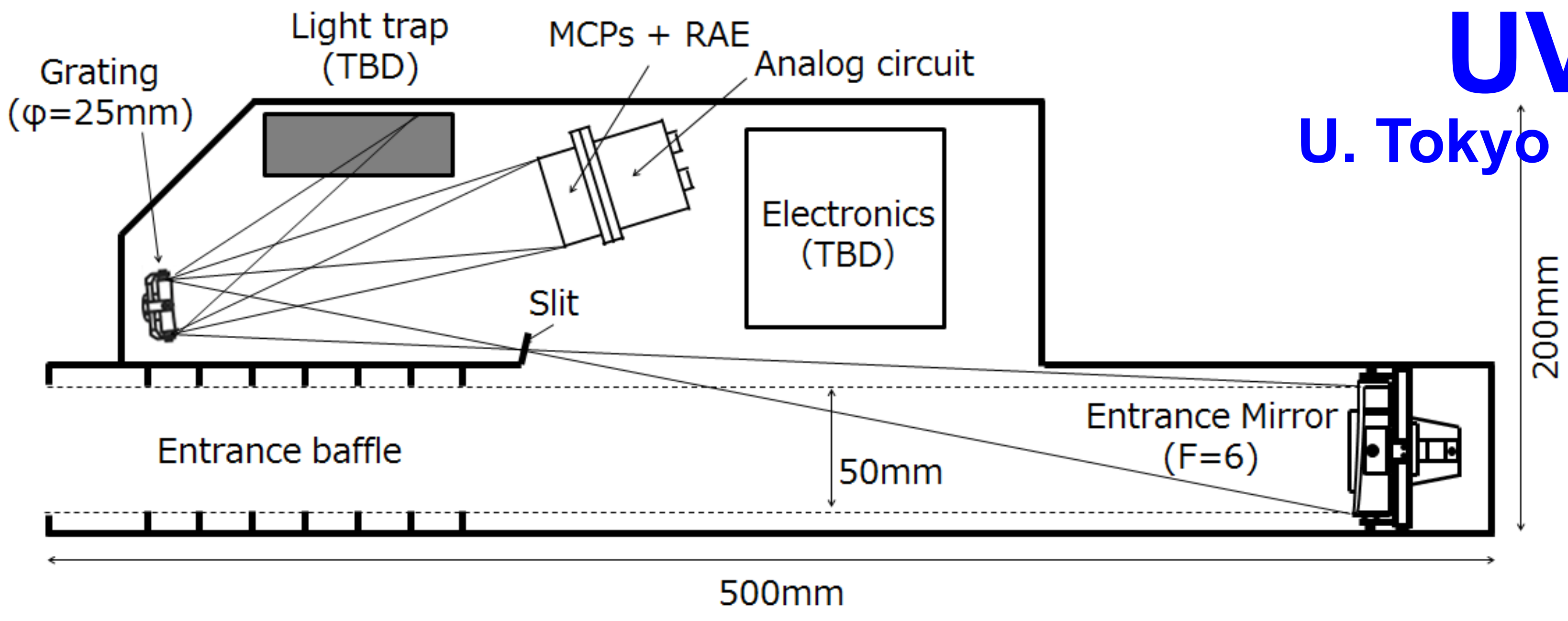


By Georgios Nicolaou

END

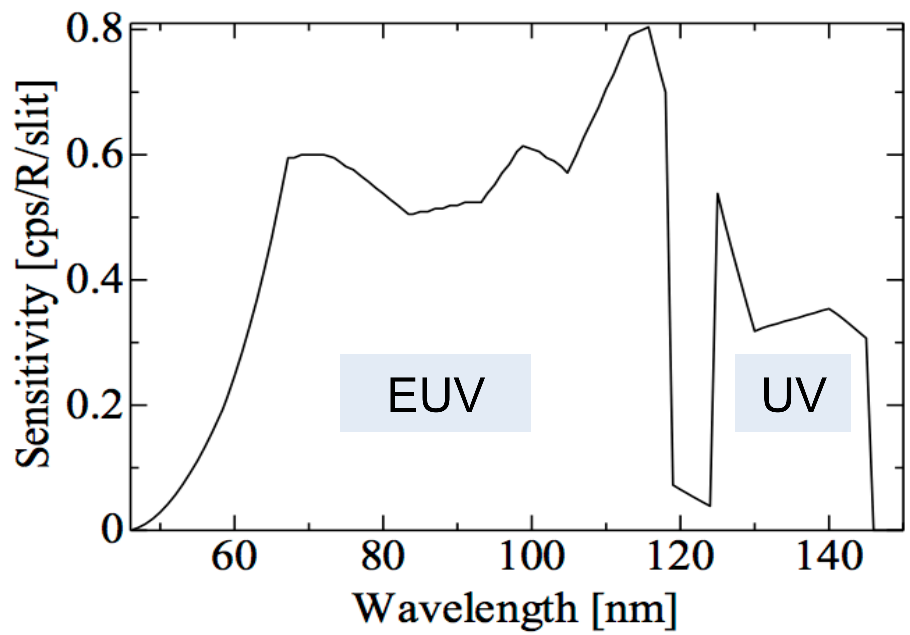
UVIS

U. Tokyo (Yoshikawa)



Size: 100 x 200 x 500 mm

- 20 slits of 0.1° x 1°
- 85–140 nm for H, N, O; and at 83 nm (O^+), 58 nm (He), 30 nm (He^+).
- Size: 10 cm x 20 cm x 50 cm with Ø = 5 cm mirror
- Mass: 7 kg (after 7 mm Al)

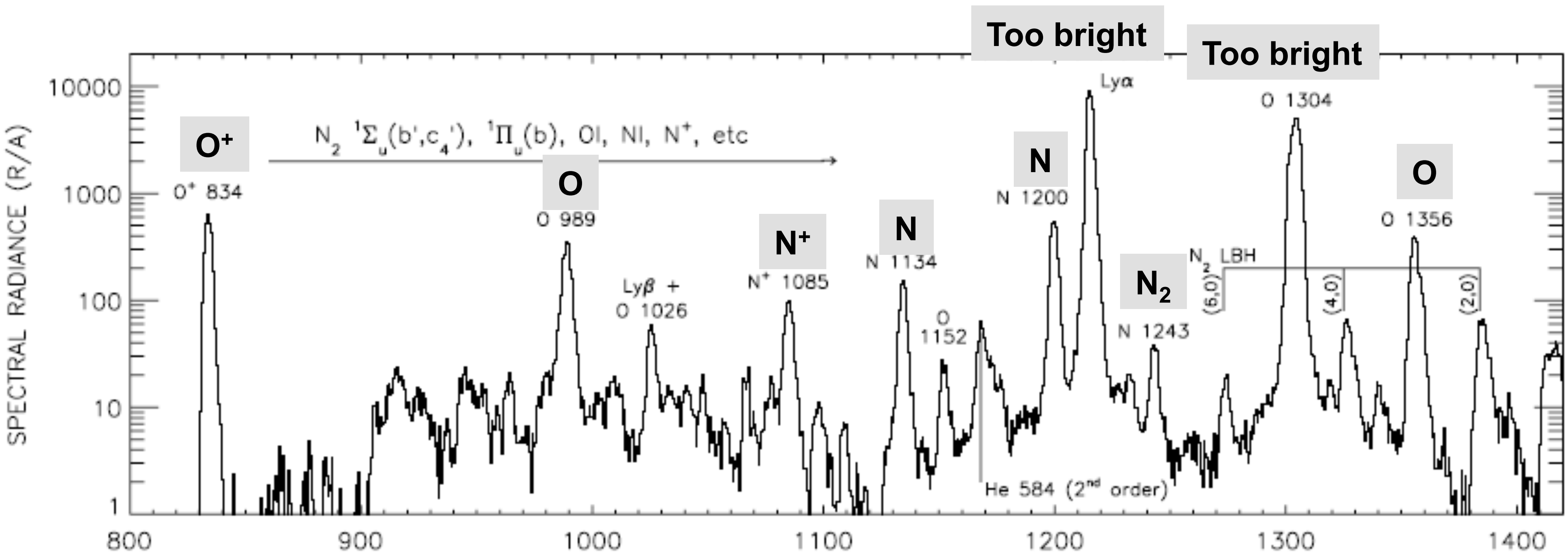


Science of UVIS

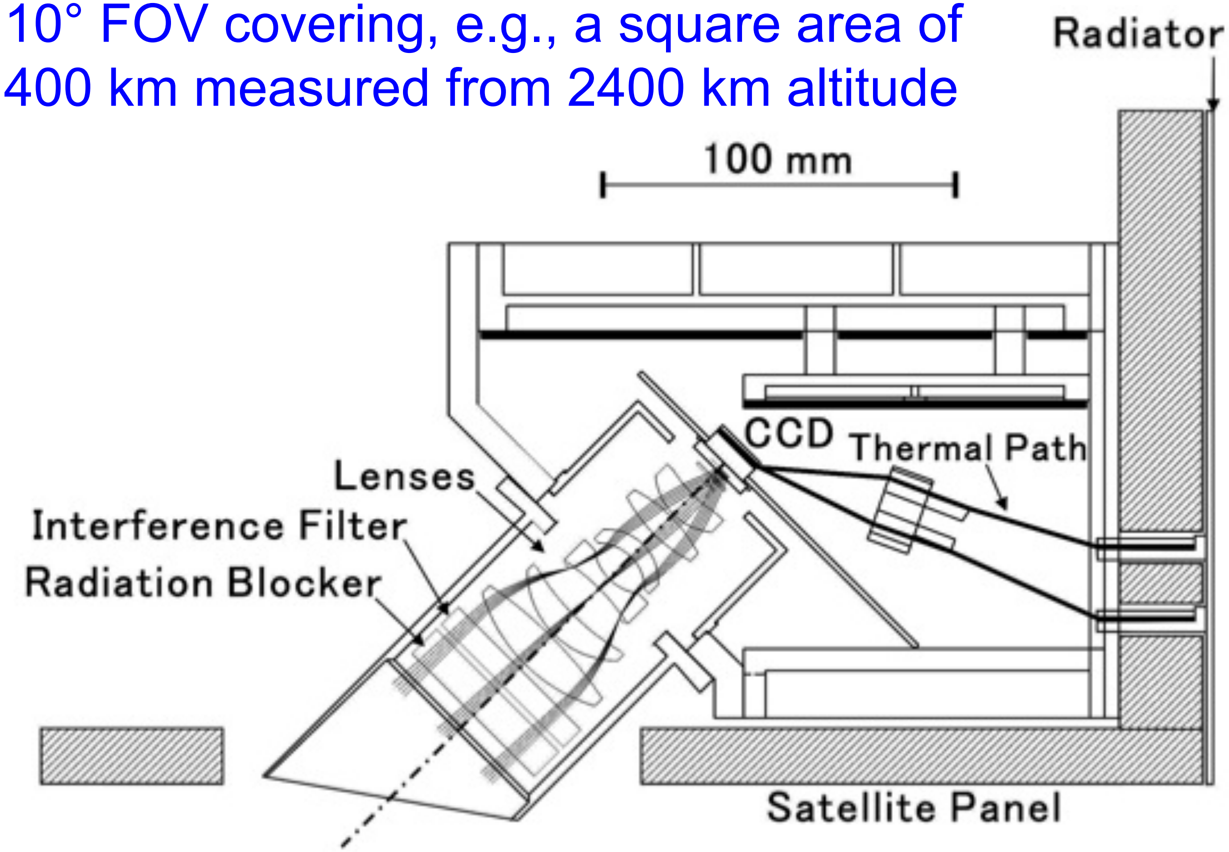
skip

Density altitude profiles (+ variability) of neutrals and ions in the exosphere (O, N, N_2, H, He).

Will measure in coordination with other instruments

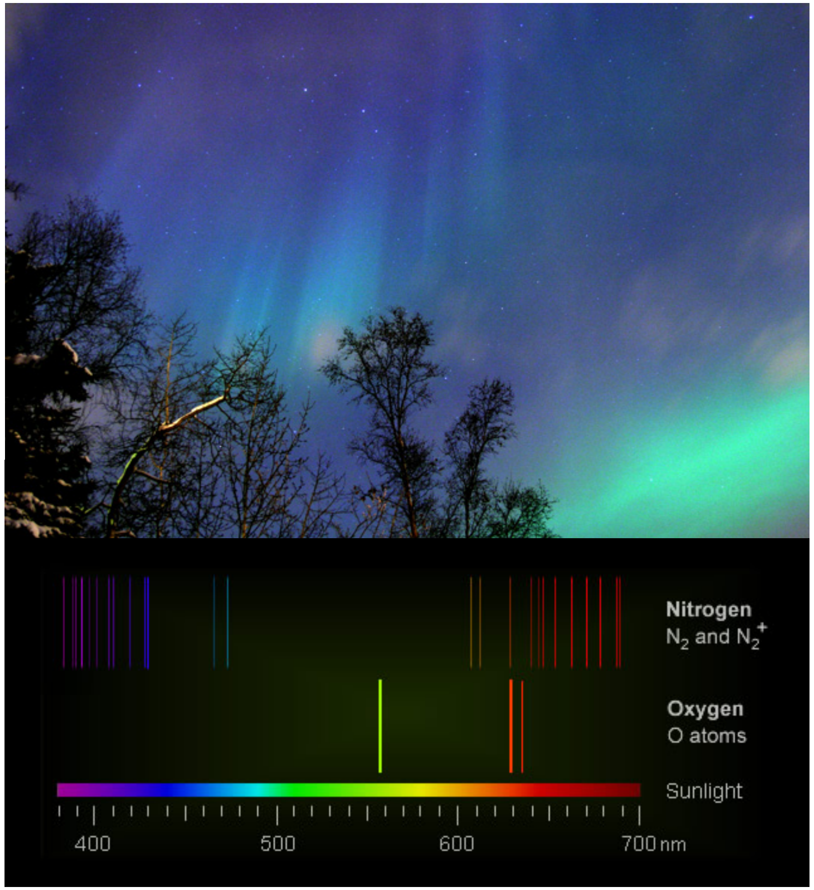


10° FOV covering, e.g., a square area of 400 km measured from 2400 km altitude



AMC

Tohoku U. (Sakanoi)



Visible

O : 630 nm (high altitude)
N_2 : 670 nm (very low altittude)
O : 558 nm (relatively low altitude, optional)

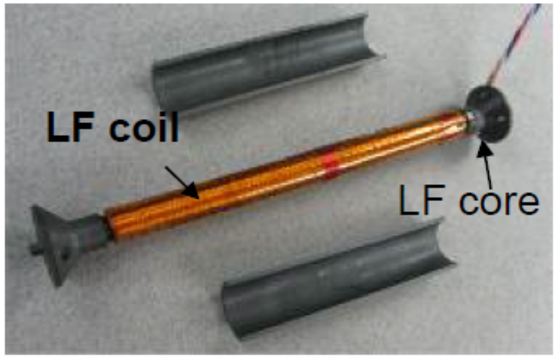
AI: space-proof CCD instead of commercial comp.

Search Coil (wave)

Col: Kanazawa U. (Yagitani)

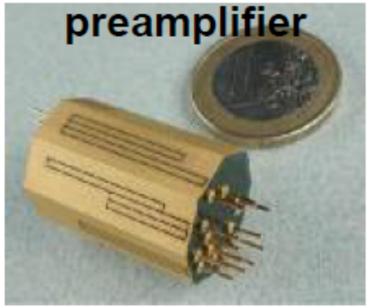
- **Sensor (ELF-VLF)**
  - 3 mono band ELF-VLF antennas

  [5 Hz – 20 kHz]



- **Preamplifier**

  3 channels (3 ELF-VLF).
  Miniaturized preamplifier integrated inside the sensor's foot.



- **Sensor's foot**

  - orthogonal assembly of the 3 antennas
  - mechanical interface

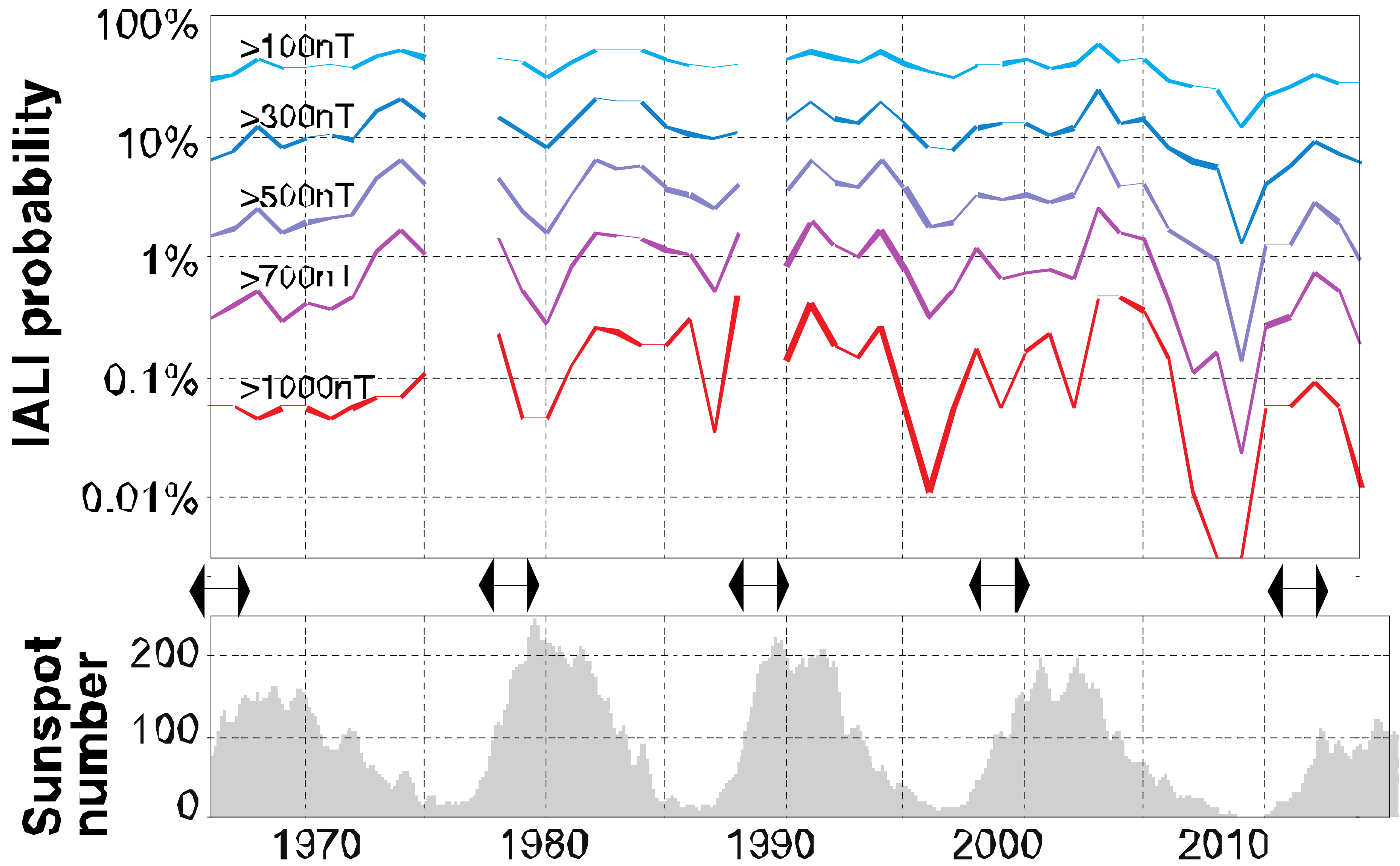
S/C specification

skip

orbital period	~10 hr
attitude control	Spin (22-26 sec)
attitude reference	Sun-pointing
control method	cold gas
time resolution	≤ 1 min
angular resolution	//, ⊥, and anti-//
telemetry	~ 200 kbps
life time	3 year

Are 3 years sufficient?

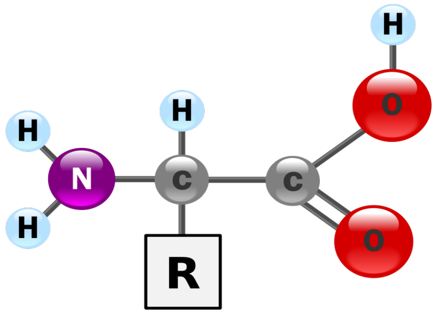
skip



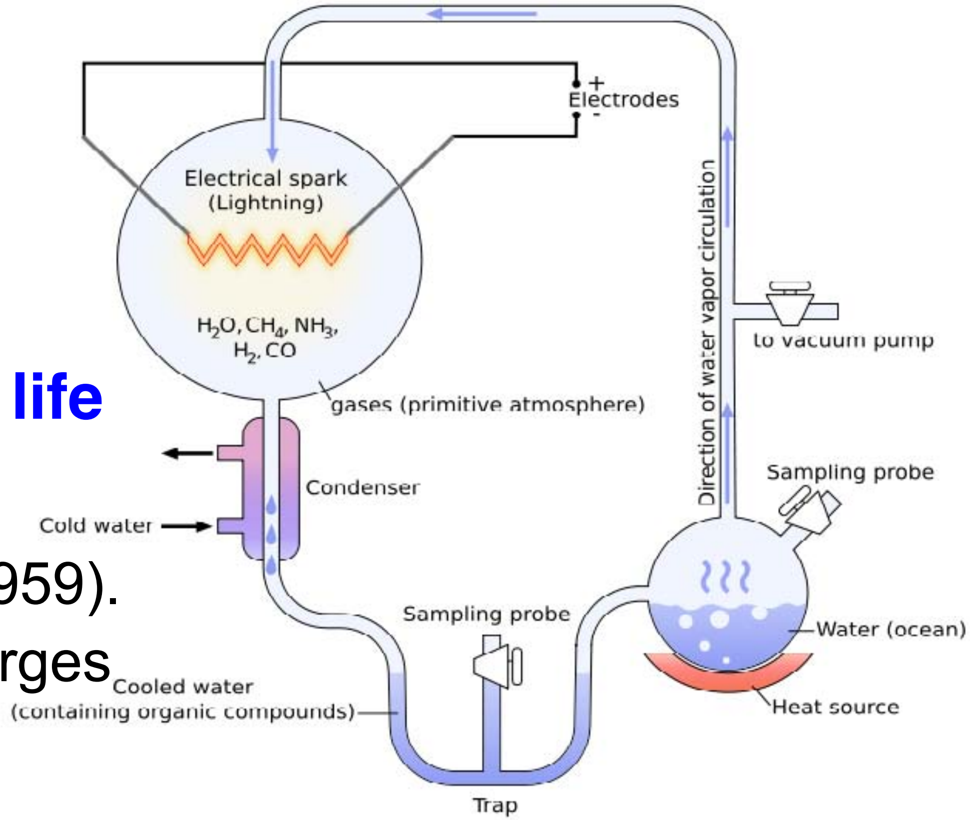
We expect the inclining phase during 2030-2033

Why nitrogen? 2. Important

skip



Nitrogen is an essential element for life



Miller's experiment (Miller and Urey, 1959).

Pre-biotic type atmosphere + discharges

$\Rightarrow$ formation of **amino-acids !**

The result depends on the **oxidation state of N**

reduced form (NH_3)

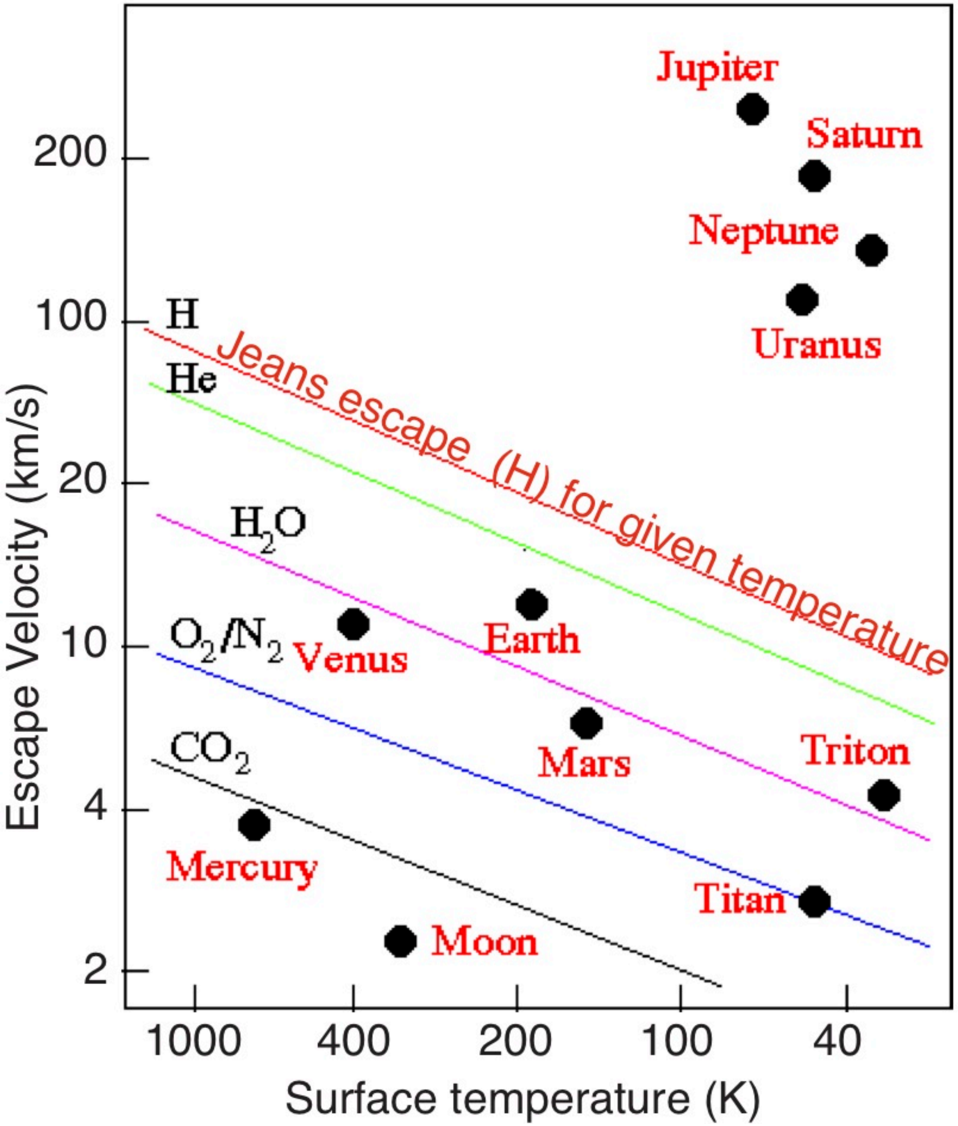
neutral form (N_2)

oxidized form (NO_x)

Nitrogen is missing on Mars

skip

Jeans escape does not explain it.



Planetary formation does not easily explain it.

Condensation temperature of

$T_C(N_2) \sim T_C(CO) << T_C(CO_2) \sim T_C(NH_3)$

indicates that condensation of N and C most likely occurred in the form of N_2–CO pair (~ 30°K) or NH_3–CO_2 pair (50 ~ 90°K). Therefore, N_2 content should be Mars > Earth > Venus.

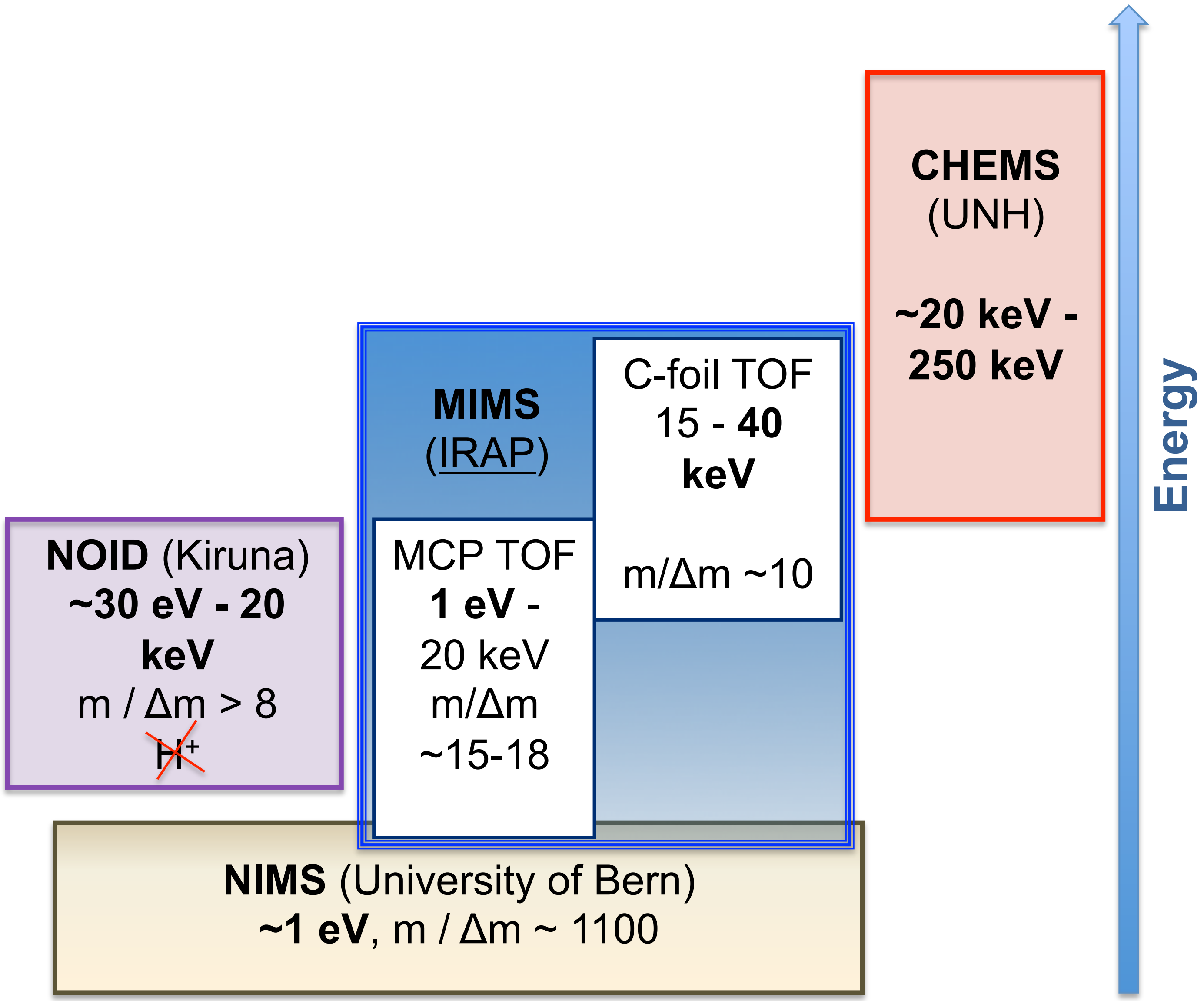
N_2-delivery model does not easily explain it.

It should deliver on Mars too

Omit

Mass and energy range

skip



Roles of support instruments skip

Magnetometer (shortest boom will do the work)
Pitch angle information and large-scale current system

Langmuir Probe (shortest boom will do the work)
Spacecraft potential for accurate ion energy measurements.

Electron detector
Identifying the region in terms of plasma region
Photoelectron information gives connectivity to the ionosphere

Aurora monitoring camera (baseline/optional ?)
Monitoring the ionospheric (ion source) condition

Wave package
Modes of waves associated with energization of ions

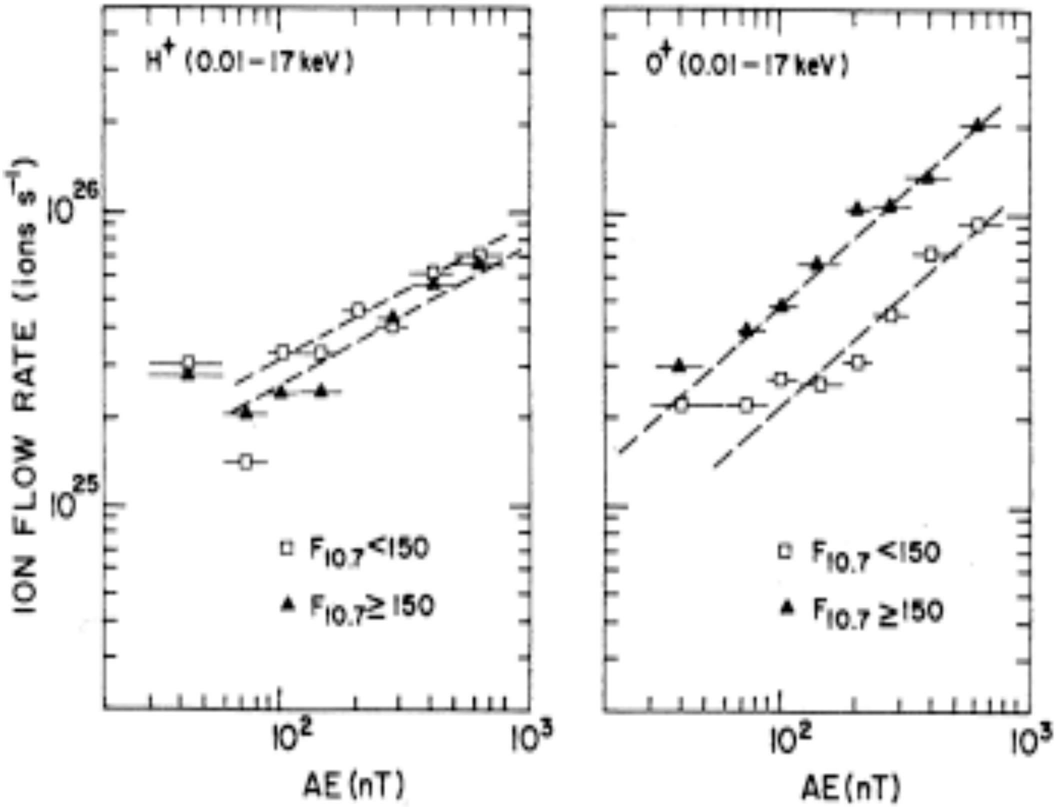
Energetic Neutral Atoms
In-situ monitoring of substorm activity

Why nitrogen? 3. Amount

Altitude (km)	H^+	O^+ (inc N^+)
50000 km (Polar)	$1 \cdot 10^{25}$	$1.5 \cdot 10^{25}$
20000 km (DE-1)	$1 \cdot 10^{25}$	$7 \cdot 10^{24}$
8000 km (Polar)	$3 \cdot 10^{24}$	$3 \cdot 10^{24}$
9000 km (Akebono)	$2 \cdot 10^{25}$	$2 \cdot 10^{24}$
3000 km (FAST)	-	$2 \cdot 10^{24}$

(Peterson et al., 2006)

> 10 keV (Peterson et al., 2002)



Polar/TIMAS
(Peterson, 2002)

Omit

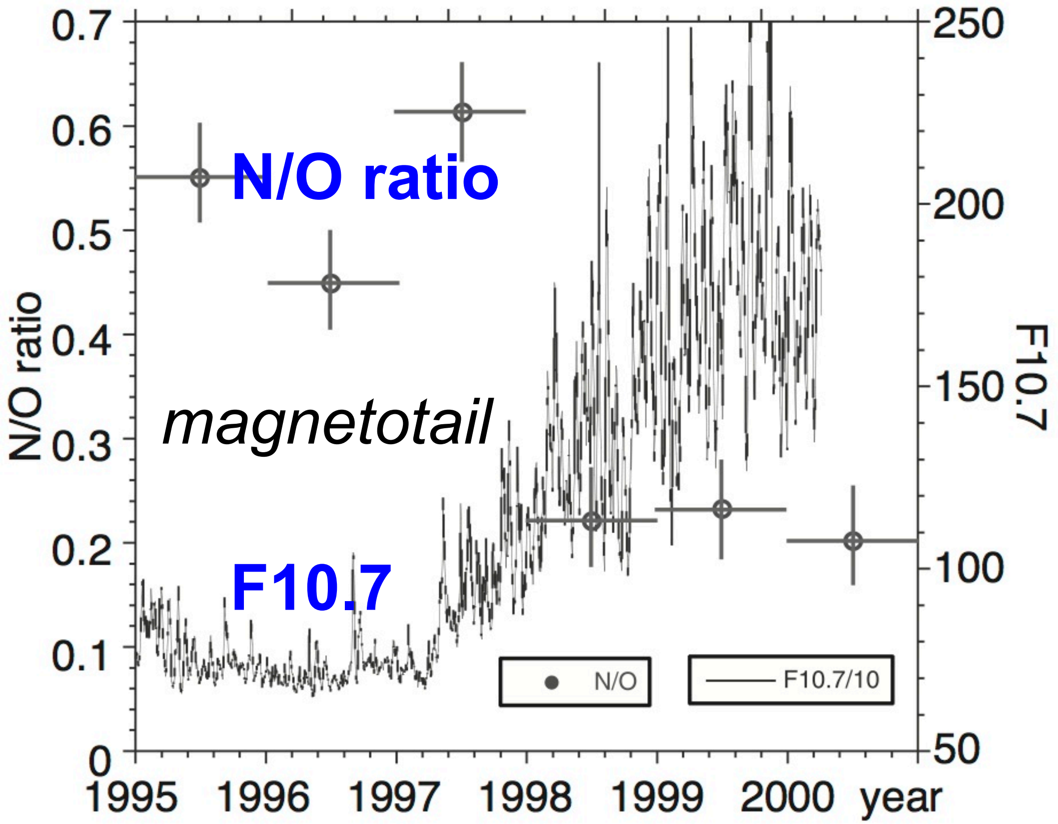
Why N^+ and N_2^+? some puzzle

skip

O/H ratio also increases with activity

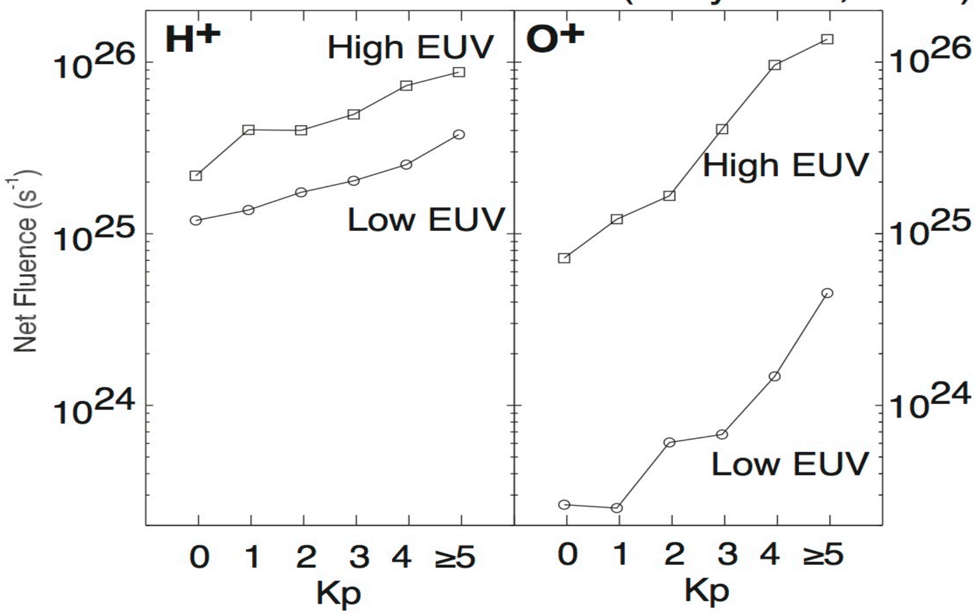
O^+/H^+ increase to >> 1

WIND/PHA observations at 8-38 RE (10-210 keV)



(Mall et al., 2002)

Akebono cold ion statistics (Cully et al., 2003)



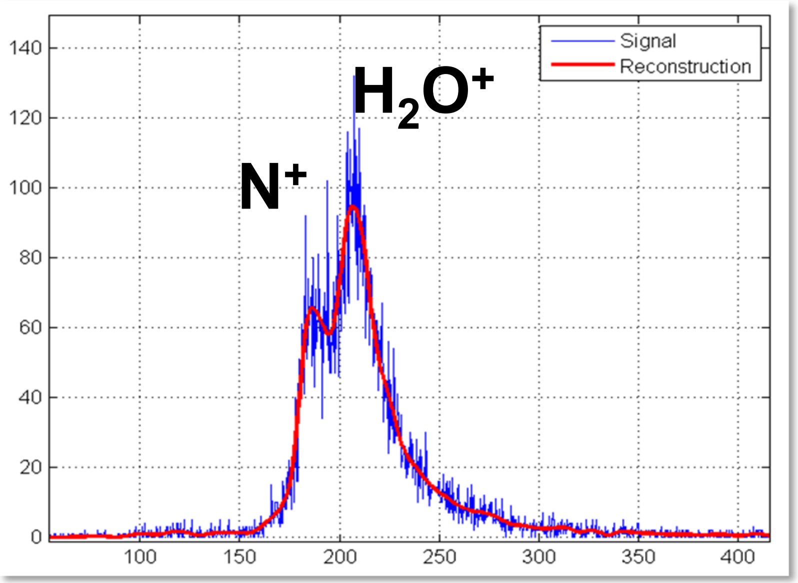
energy < 20 eV, high EUV: $F_{10.7}$ > 150

The same trend for 0.02-30 keV
(Polar/TIMAS, Peterson et al., 2002)

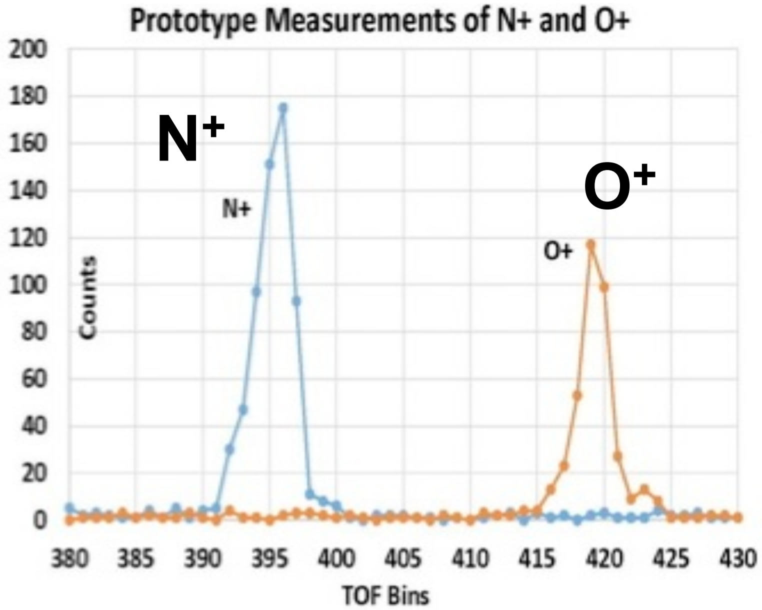
N/O ratio in anti-phase with activity

Why nitrogen? possible to det skip

Hot ion (lab calibration)

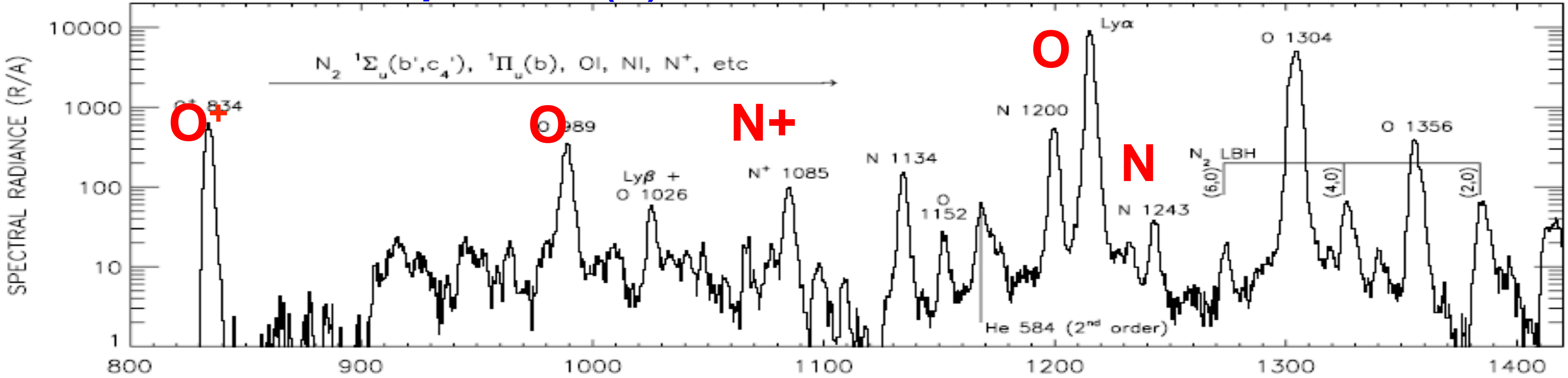


Cold ion (lab calibration)



69

UV Spectrum (Å)



Our knowledge on Earth's N^+ behavior is poor

(a) Dependence on geomagnetic activities is **larger for N^+ than O^+** for both <25 eV (Yau et al., 1993) and > 30 keV (Hamilton et al., 1988).

(b) **N^+/O^+** ratio varies from <0.1 (quiet time) to ≈ 1 (large storm). What we call **O^+** is normally a mixture of **N^+** and **O^+**. This also applies to **O^{++}**.

(c) [CNO group]$^+$ at <10 keV range is **abundant in the magnetosphere**.

(d) Ionization altitude of **N** (eventually **N_2**) is likely higher than for **O** in the ionosphere (when **O^+** is starting to be heated, majority of **N** is still neutral).

(e) **N/O ratio at Mars** (and C/O ratio at Moon) **are extremely low** compared to the other planets.

(f) Molecular N_2 was detected Martian soil and comet, but the ratio was very low.

(g) Isotope ratio (e.g., **$^{15}N/^{14}N$**) is different between different planets/comets.

One thing clear is that O+ behavior and N+ behavior are completely different!

Omit

baseline payload

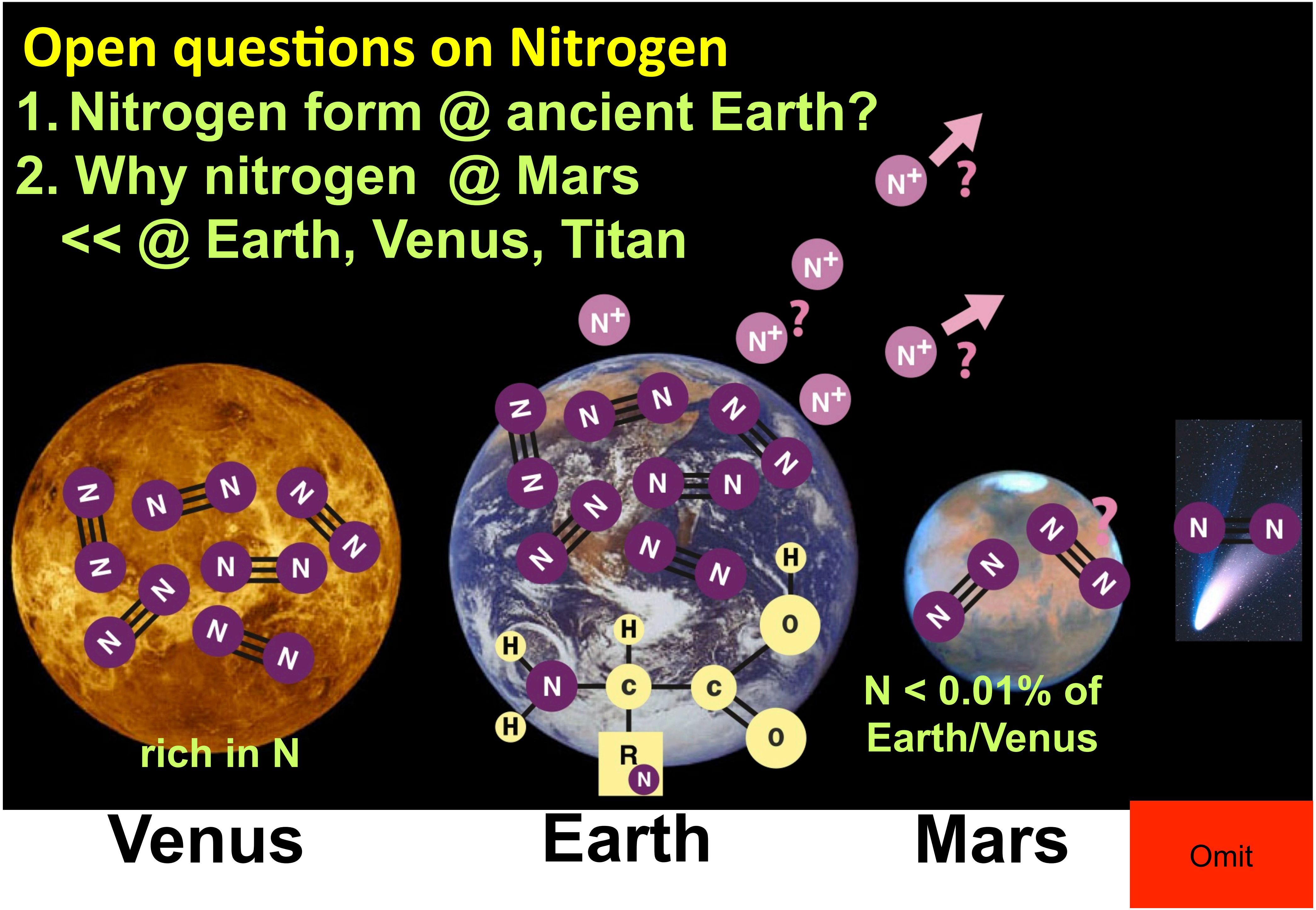
Measurement	SI (PI institute)	Required ability to measure
light hot ions:	MIMS (IRAP)	H+, He++, He+, O++, N+, O+ (10 eV - 20 keV),
heavy hot ions:	NOID (IRF)	N+, O+, N2+ (10 eV - 20 keV/q),
cold ions:	NIMS (UBern)	H+, He++, He+, N++, O++, N+, O+, N2+, O2+ (< 10 eV),
energetic ions:	CHEMS (UNH)	H+, He++, He+, O++, N+, O+ (20-200 keV/q),
SC potential:	SLP-IS (BIRA-IASB)	1 V accuracy, every spin
UV/visible emission:	NUVO (LATMOS)	91 nm (N+), 108 nm (N+), 391 nm (N2+), 428 nm (N2+)
magnetic field:	MAG (IWF)	-5000 - +5000 nT,
electrons:	PEACE (MSSL)	10 eV - 10 keV,

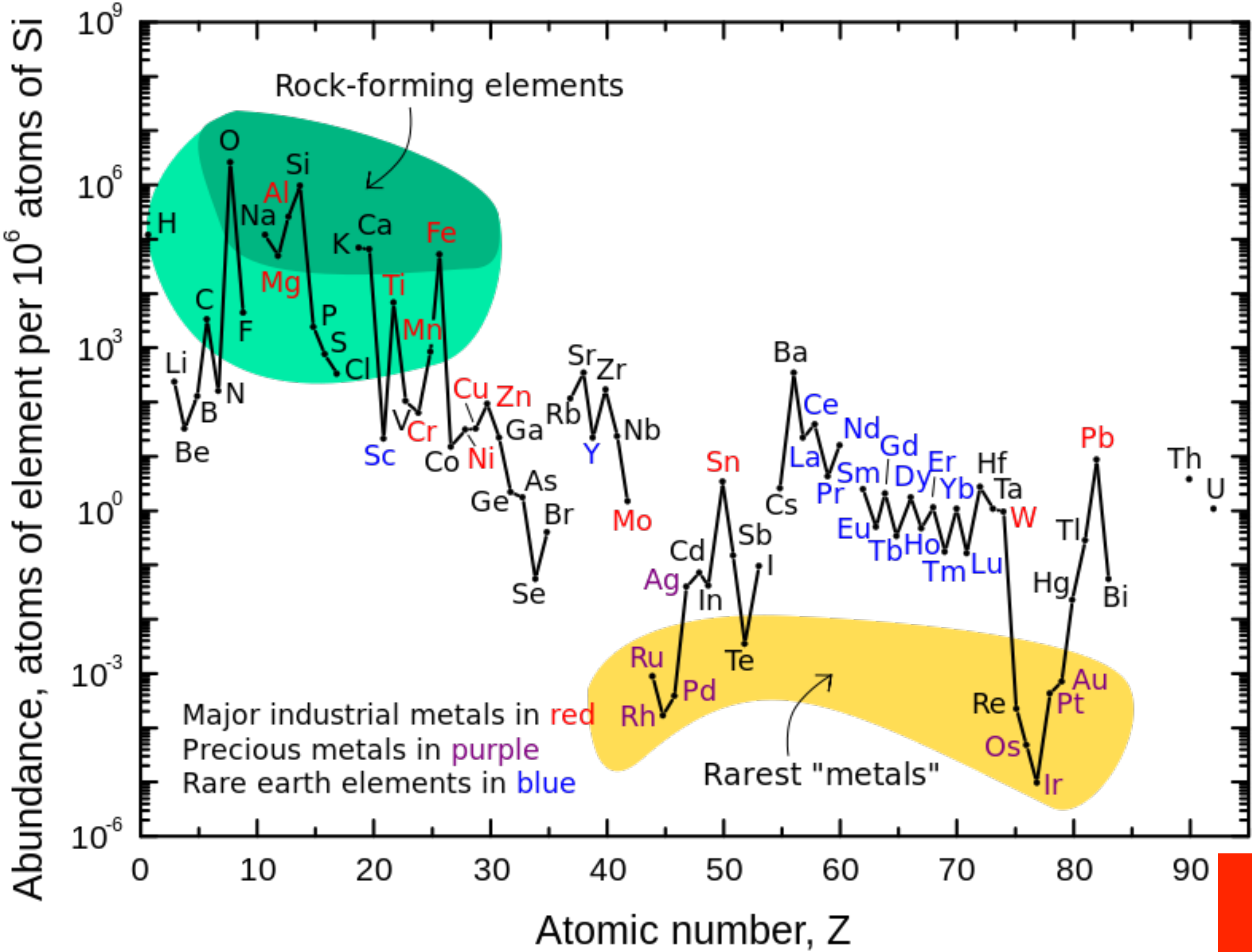
Omit

optional payload

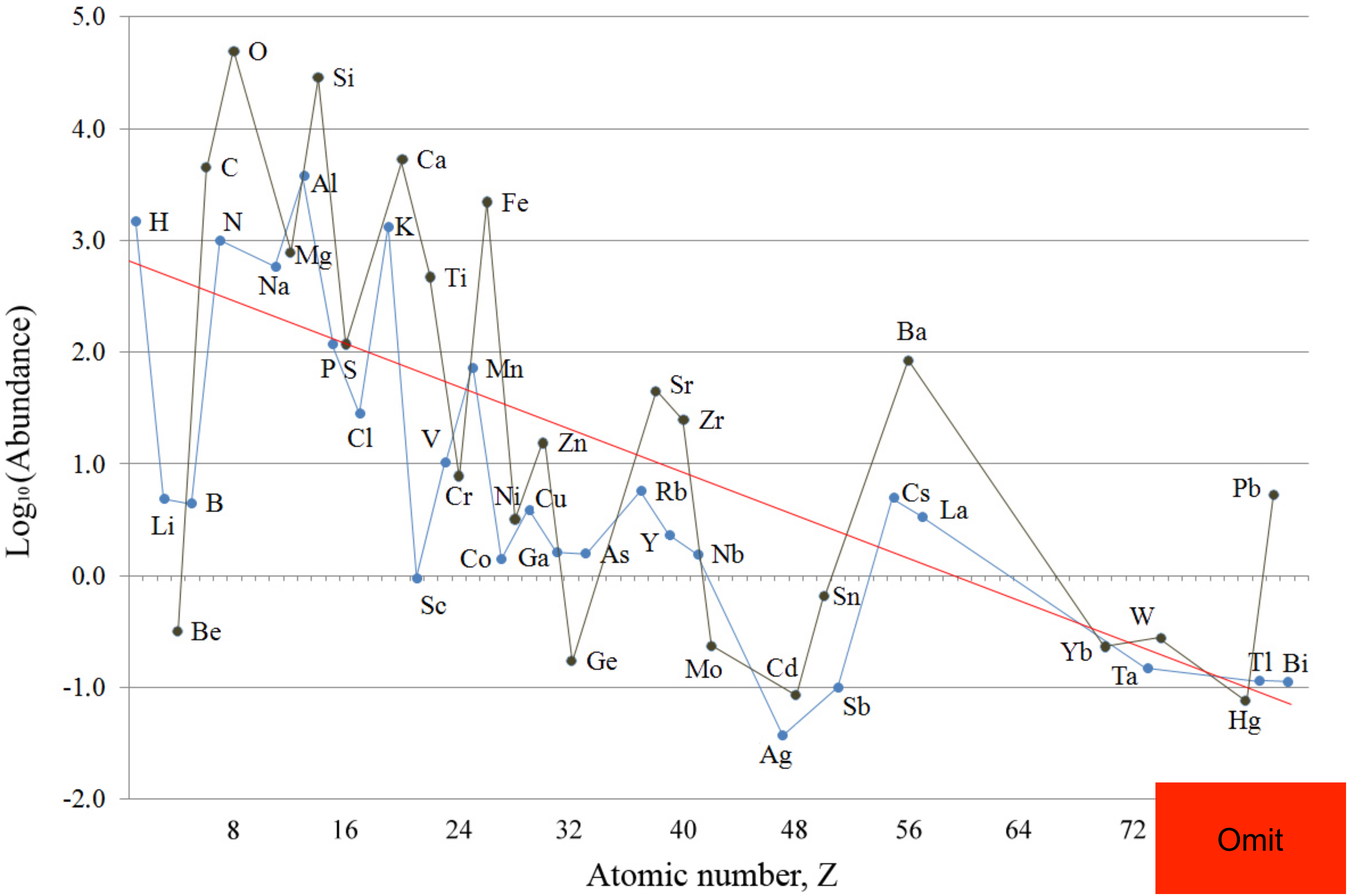
Measurement	SI (PI institute)	Required ability to measure
IR emission:		
airglow/aurora emission	CAAC (TohokuU)	two of auroral emission
cold ions and neutrals:	CINMS (NASA/ GSFC)	H+, He++, He+, N++, O++, N+, O+, N2+, O2+, N, O
wave analyser	WAVES (ASCR/IAP)	10 Hz – 1 KHz,
waves detector		together with WAVES
ENA		

Omit


Open questions on Nitrogen
1. Nitrogen form @ ancient Earth?
2. Why nitrogen @ Mars
<< @ Earth, Venus, Titan
rich in N
N < 0.01% of Earth/Venus
Venus
Earth
Mars
Omit

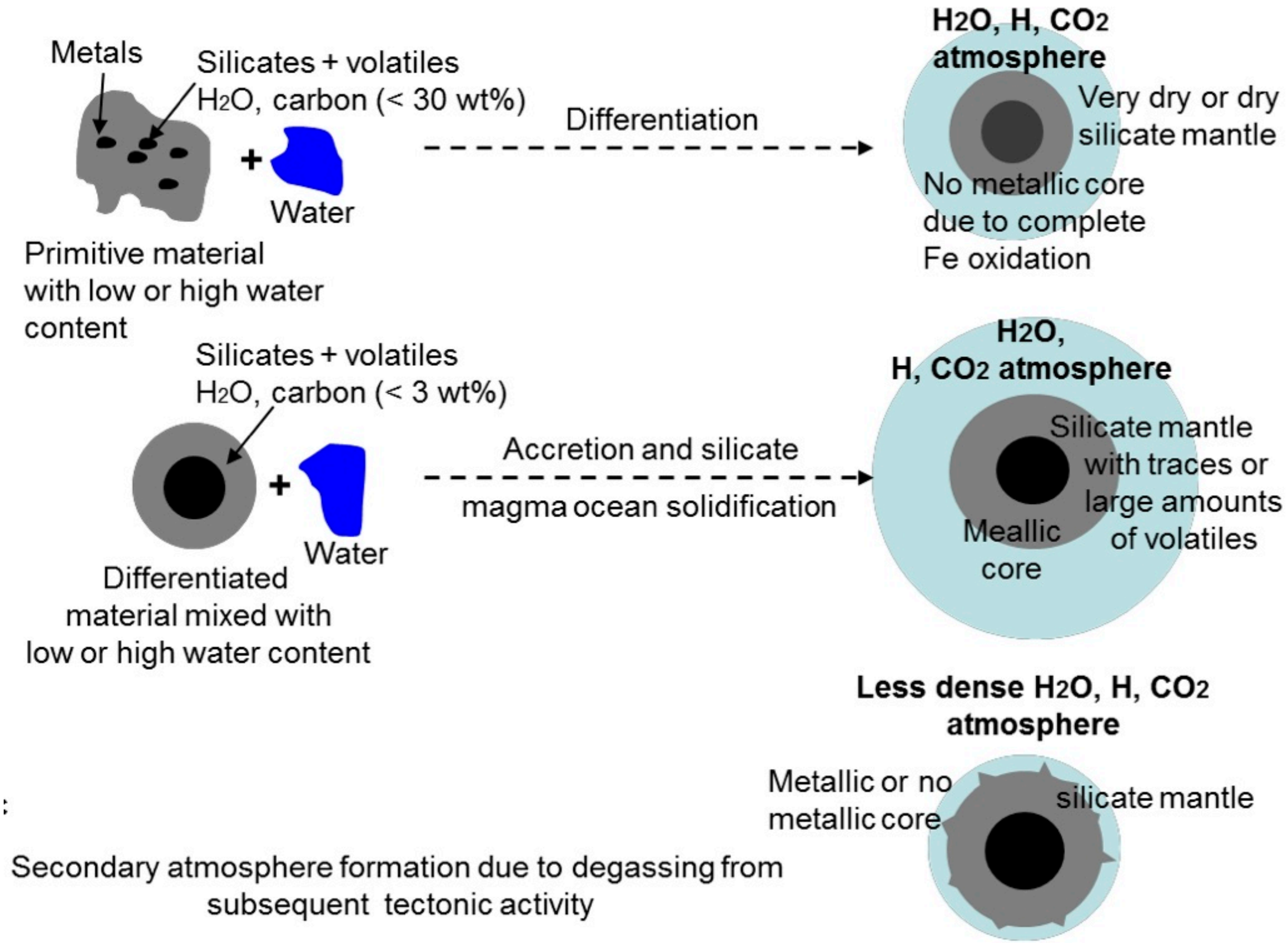

Rock-forming elements
Rarest "metals"
Major industrial metals in red
Precious metals in purple
Rare earth elements in blue
Abundance, atoms of element per 10^6 atoms of Si
Atomic number, Z
10^9
10^6
10^3
10^0
10^-3
10^-6
0
10
20
30
40
50
60
70
80
90
H
Li
Be
B
C
N
O
F
Na
Mg
Al
Si
P
S
Cl
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

Omit



5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
Log10(Abundance)
8
16
24
32
40
48
56
64
72
Atomic number, Z
H
Li
Be
B
C
N
O
Na
Mg
Al
Si
P
S
Cl
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Rb
Sr
Y
Zr
Nb
Mo
Ag
Cd
Sn
Sb
Cs
Ba
La
Yb
Ta
W
Hg
Tl
Pb
Bi
Omit

Atmosphere formation models



Omit