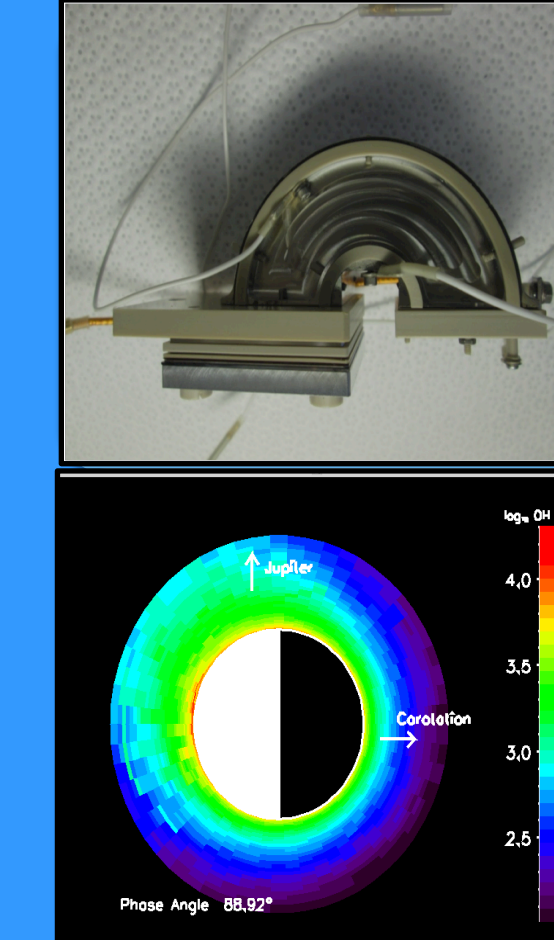


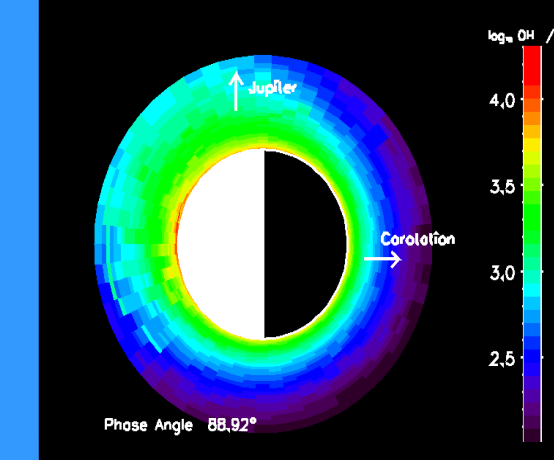
Towards a Carbon Nanotube Ionization Source for Planetary Atmosphere Exploration

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A Carbon Nanotube Electron Gun <CNTEG> is developed to ionize neutral atmospheres for future space spectrometry missions.

EGM simulations of Europa's Hydro-Exosphere show stark atmospheric structures dominated principally by Jupiter's gravitation.

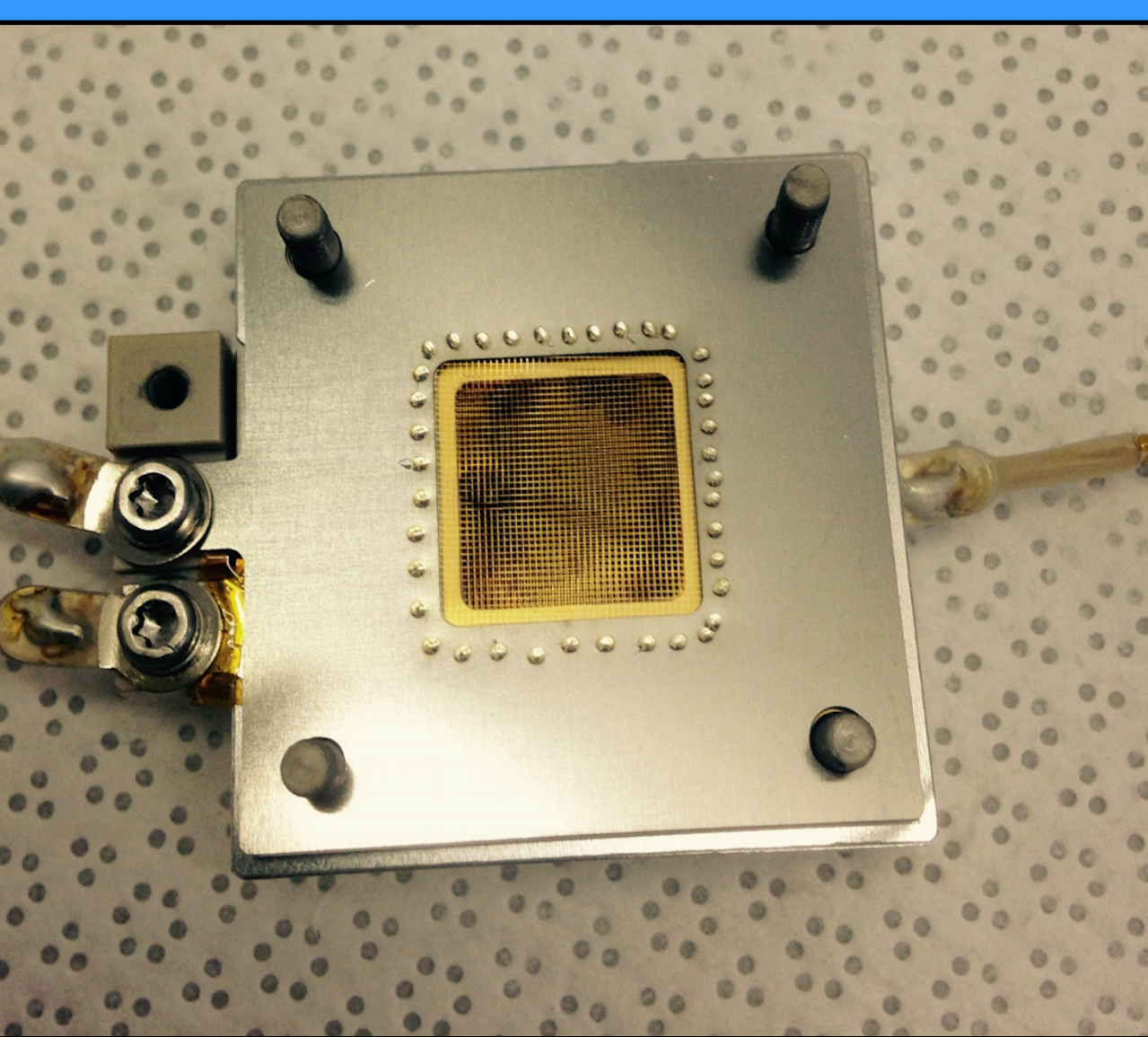


Technology Objective

A carbon nanotube electron gun (CNTEG) is constructed for the highly sensitive exploration of exospheres, i.e. extremely tenuous atmospheres ($n < 10^8 \text{ cm}^{-3}$). The CNTEG is based on the quantum principle of field emission¹ seeking to efficiently impact and therefore ionize diffuse neutrals known to be present around planetary bodies.

Fig. 1 CNTEG:

- Electric 'field effect emission' generates current due to solid-state quantum tunneling¹.
- Moderate E- field. ($E \sim 1 \text{ MV/m}$)
- Power-efficient. ($P < 0.1 \text{ Watts}$)
- Sufficiently powerful current ($I \sim 200 \mu\text{A} \pm 0.1 \mu\text{A}$)
- Very stable. $dI/dt < 0.1 \mu\text{A/s}$
- Light-weight and robust.



Carbon Nanotubes as Cold Cathodes

Fig. 2 15 mm² CNT chip in the lens of the G1 grid grounded at +OV.

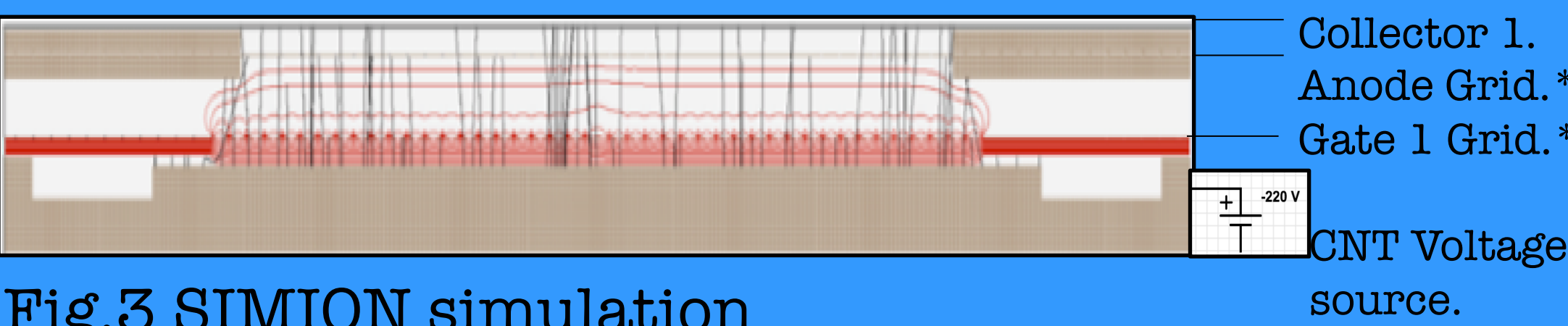
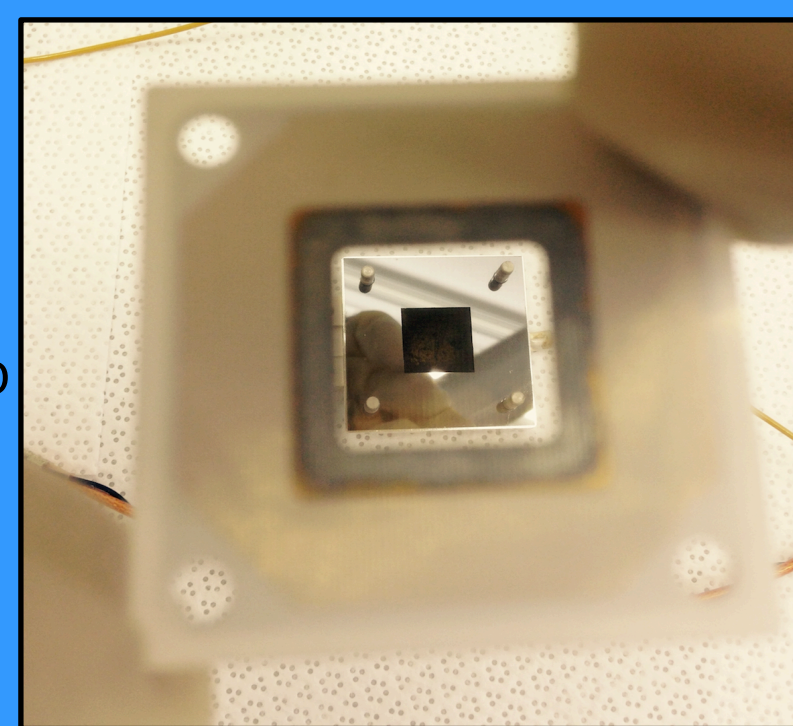


Fig. 3 SIMION simulation of CNTEG electrodes' equipotentials and e⁻ trajectories. *Grids are at 80% transparency.

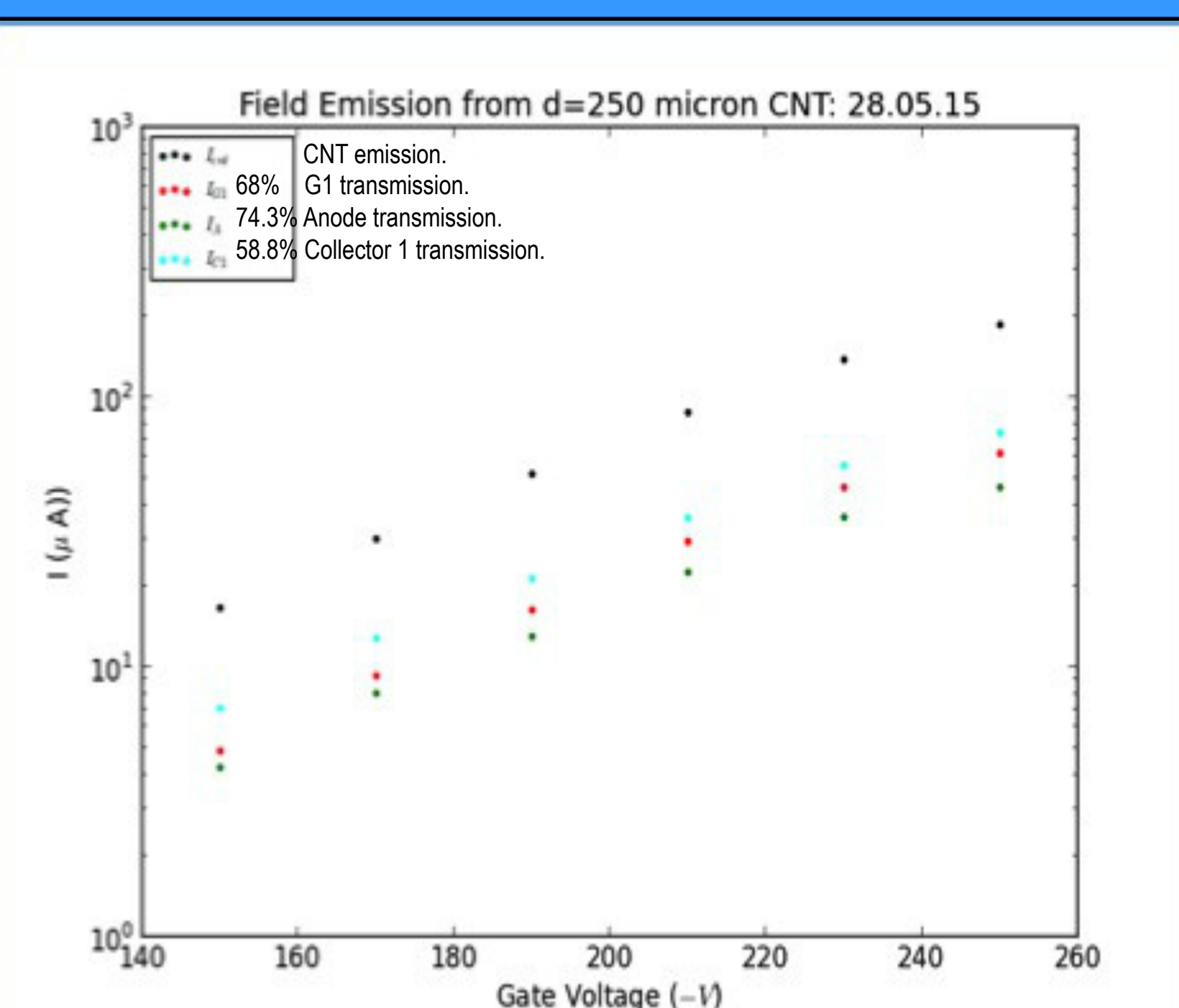
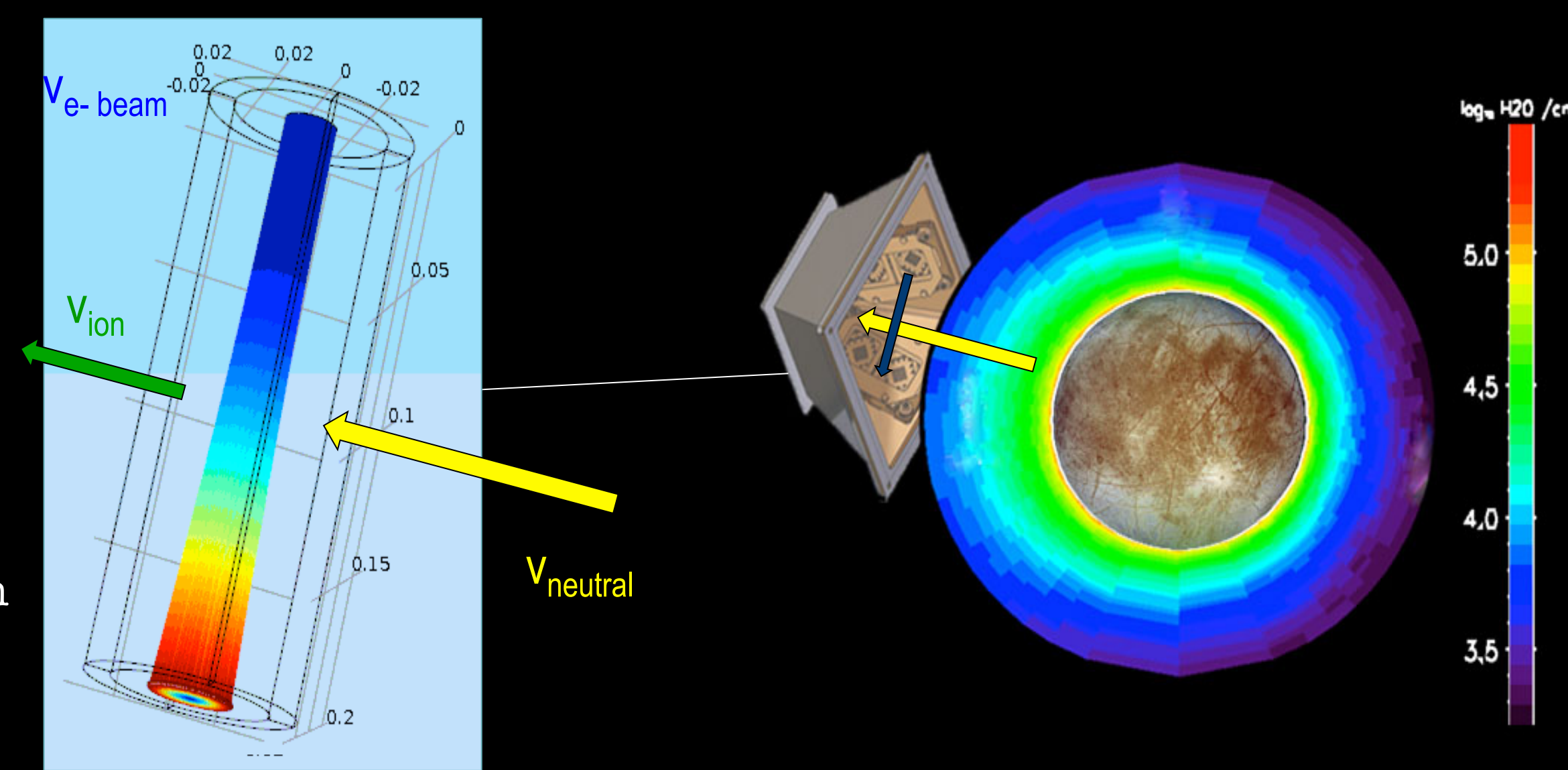


Fig. 4: CNTEG electron field emission measured at each electrode labeled above.

- CNTEGs are emitting consistently at ~ 60%.
- Anode emission is at 75%.
- Emission > 100μA is achieved with a cathode-gate distance of $d_{cg} = 250\mu\text{m}$

Exosphere Ionization

Fig. 5: Selected COMSOL simulation of ionization volume demonstrating ion production via e⁻ impact.



Goal: To simulate & design ideal ionization geometry yielding maximum ion yield while taking space charge effects into account.

- 1) Electric force balance: $d/dt(m_e v_e) = qE$
- 2) Poisson's equation (space-charge): $\nabla^2 \Phi = -\rho/\epsilon_0$
- 3) Electron-impact ion production rate: $dn/dt = n_A * n_B < \sigma v >_{AB}$

Europa's Hydro-Exosphere

H2O

Overall water exosphere is uniform in 1 ppt. HST detection² of excess H I Ly α, may be an anomaly.

Sub-Jovian water is more than 10x dense at high altitudes.

Slight H2O build-up at anti-jovian limb entering subsolar season.

O2

[Overlaid] HST observations⁵ of O I have been associated to electron impact dissociation of O2.

Sub-jovian O2 is > 1000 x more dense than the anti-jovian observations.

Jupiter is unique source of upper atmospheric O2. → Atomic O I more likely.

Fig. 6: Side view of water ($\phi = 308^\circ$) & molecular oxygen ($\phi = 90^\circ$) simulation and observation.

a_g

Atmospheric inhomogeneities due to Jovian gravitational field.

Upper exospheric oxygen behavior is identical to other water-products: H2, OH, H2O.

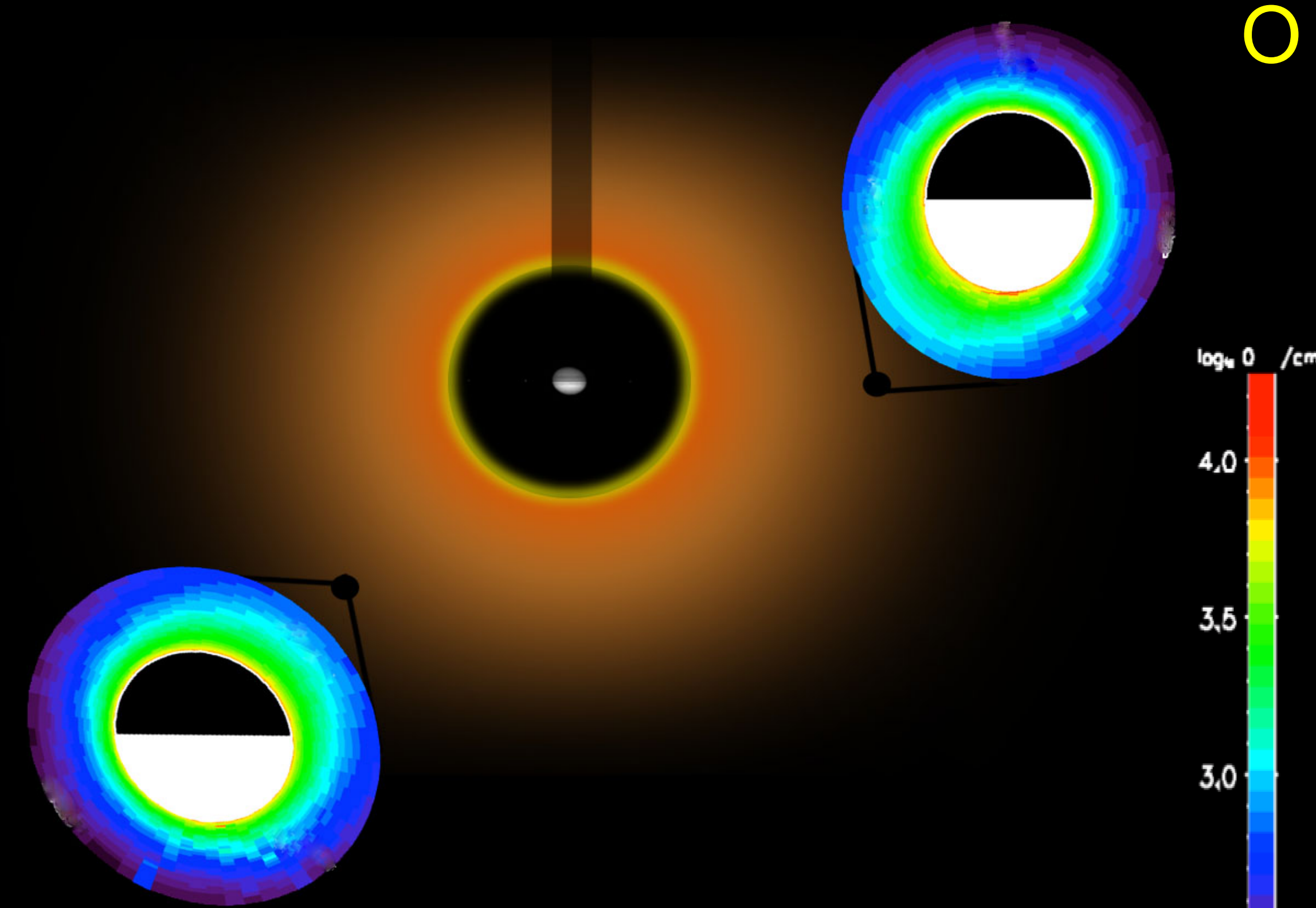
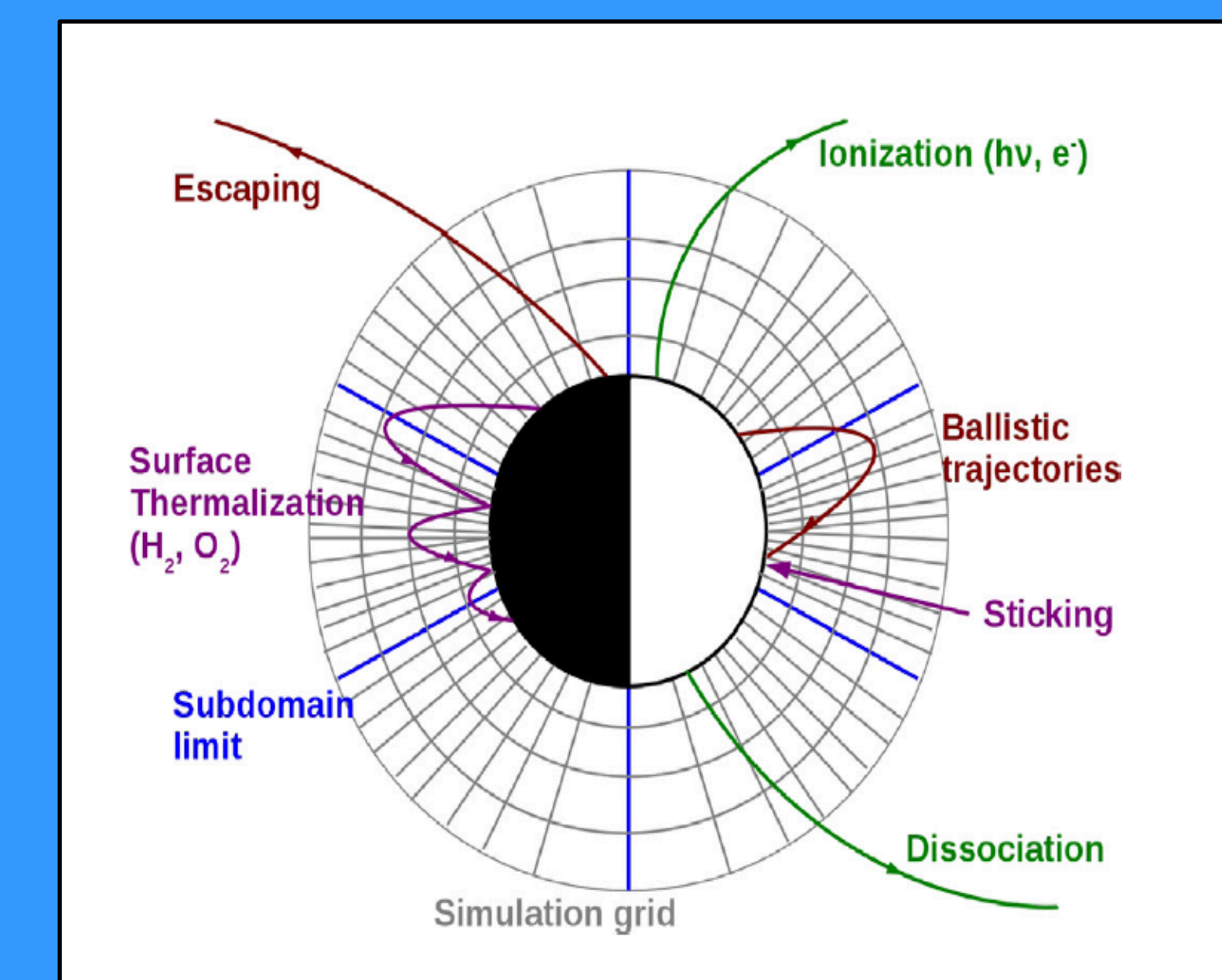


Fig. 7: Top view of simulated atomic oxygen exosphere.

Europa EGM

The Exospheric Global Model (EGM) is a 3D parallelized Monte Carlo code developed for the characterization of exospheres. Here, we model Europa. Test particles are ejected from Europa's surface up to $\sim 15 R_{Eu}$, following known energy distributions. The test particles are on ballistic trajectories and can escape, stick, and bounce on the surface. Furthermore the particles can be dissociated/ionized by physicochemical processes.

Fig. 8: EGM domain modeling physical processes in spherical coordinates.



Results

Extended Exosphere Clouds are simulated, due to:

- Jovian gravitational drag is evident.
- Similar to sodium clouds at Io⁶
- Escape rates could indicate an Enceladus-like hydrotorus.

Perspectives from Surface-Exosphere inhomogeneities:

- Sputtering may not be global⁹.
- O⁺, S⁺ ions may not dominate⁶.
- Water-product escape rates match previous studies⁷.
- O2 is thermalized to $T_{surface}$, speeds are not sufficient to populate upper exosphere.

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