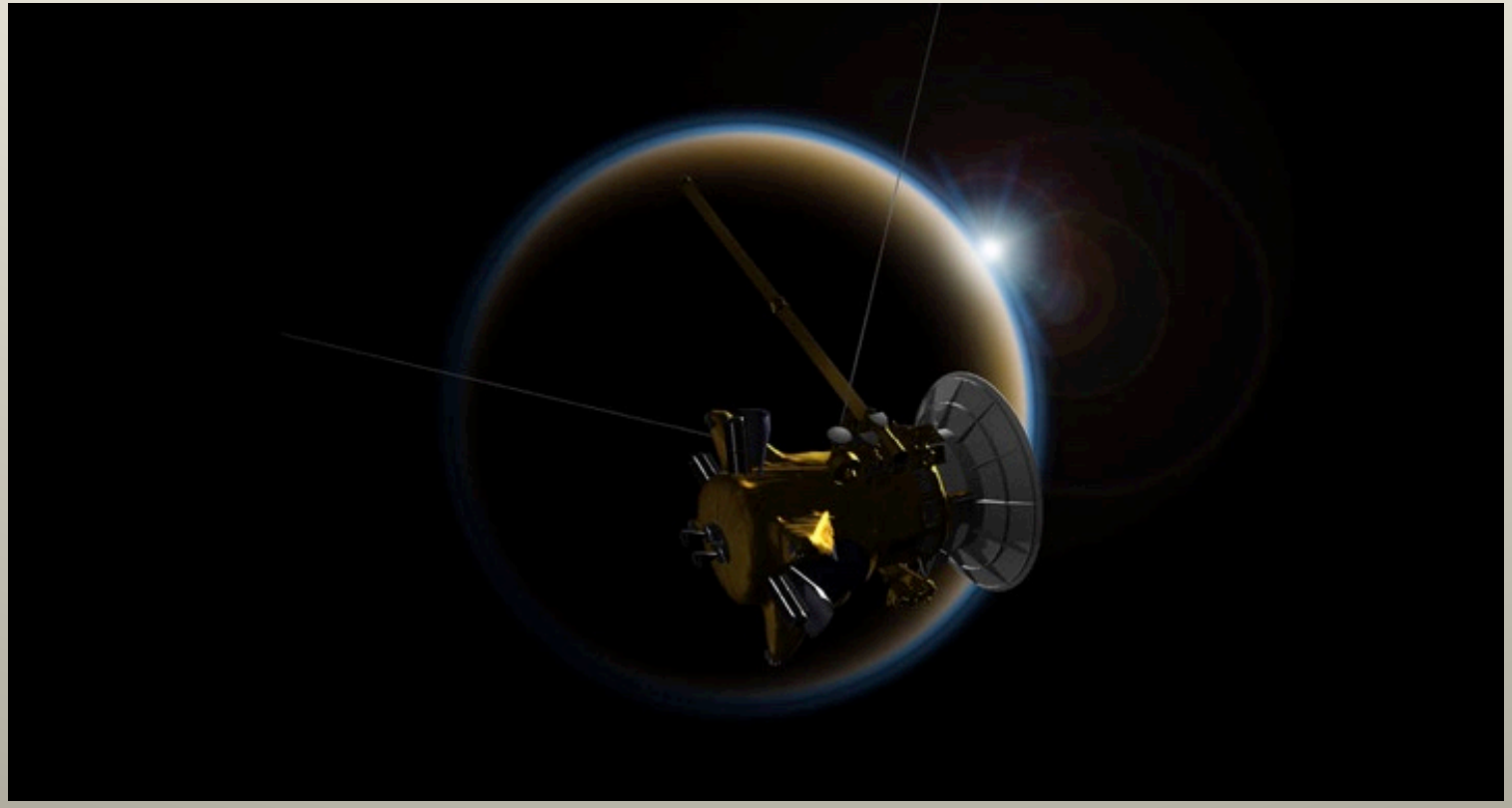
Modeling of CH_4 Escape in Titan's Atmosphere



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Thermal and Non-thermal Escapes

- Thermal
  - Jeans escape (evaporation)
  - Hydrodynamic blow-off (bulk fluid flow)

- Non-thermal
  - Dissociative recombination: $A_2^+ + e \rightarrow A^* + A^* + \Delta E$
  - Photodissociation: $A_2 + \nu \rightarrow A^* + A^* + \Delta E$
  - Charge exchange: $A^+ + B^* \rightarrow A + B^+$
  - Atmospheric sputtering: $A^+ + B \rightarrow A^+ + B^*$

Fluid Equations & Escape

e.g., solve 1D radial equations: Jeans parameter: $\lambda = U/kT$

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho v) = 0$$

$$\frac{\partial}{\partial r}\left(\frac{1}{2}v^2\right) + \frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{GM}{r^2} = 0$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left\{\rho v\left(\frac{1}{2}v^2 + \tilde{c}_p T + \mathrm{U}\right) - \kappa\frac{\partial T}{\partial r}\right\}\right] = \mathrm{q}$$

Given n_o, T_o at lower boundary r_o & q (*heating + radiative cooling*)

still need upper boundary conditions

collisional → collisionless

Typically Assume

a sonic point (blow-off): $2\,m\,c_s^2 \cong U(r_s)$

If conduction is inefficient

Integrated energy eq. → $\phi_{es} \sim Q_{net} / U(r_{UV})$

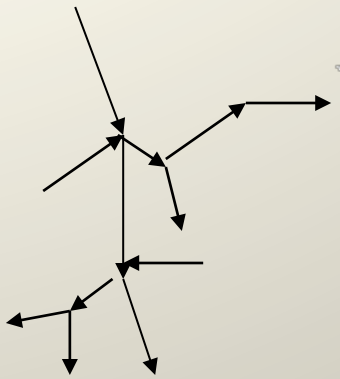
or

Jeans escape (modified Jeans)

Molecular Kinetic Simulations

Direct Simulation Monte Carlo (DSMC)

(e.g. Bird 1994)



Equivalent to solving Boltzmann equation for a gas

- Simulate atmosphere using representive molecules with weights
- Track molecules in gravity field subject to collisions & heating
- MC choice of collision outcomes: cross sections
- Gas properties constructed from density & speed distributions

Kn = Mean free path for collision/ length scale

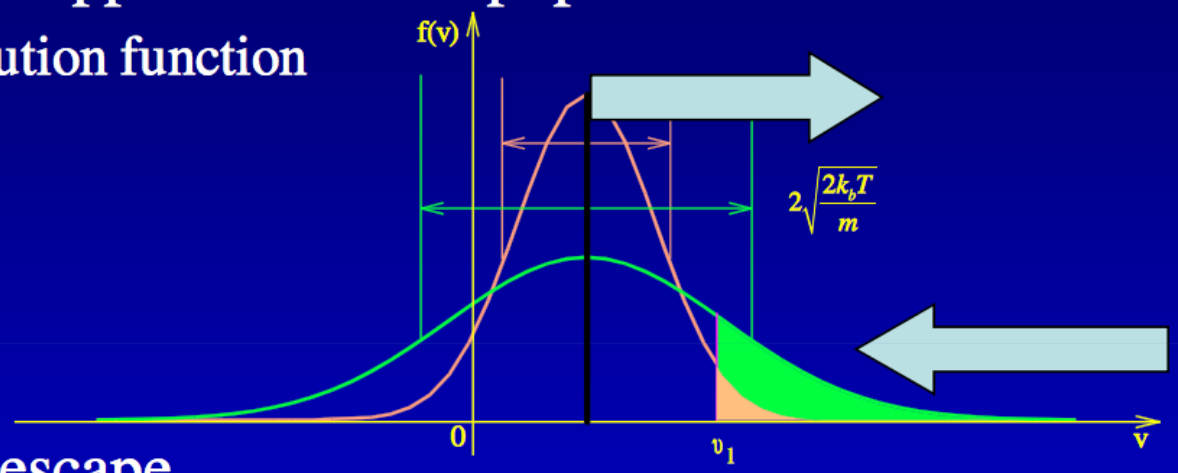
Kn < ~ 0.1 Fluid equations

Exobase: Kn ~ 1 → high prob. of molecular escape

Hydrodynamic vs Molecular

Basically kinetic approach for the population

- Particle distribution function



Hydrodynamic escape

- Concerns the escape of the pdf core

Jeans escape

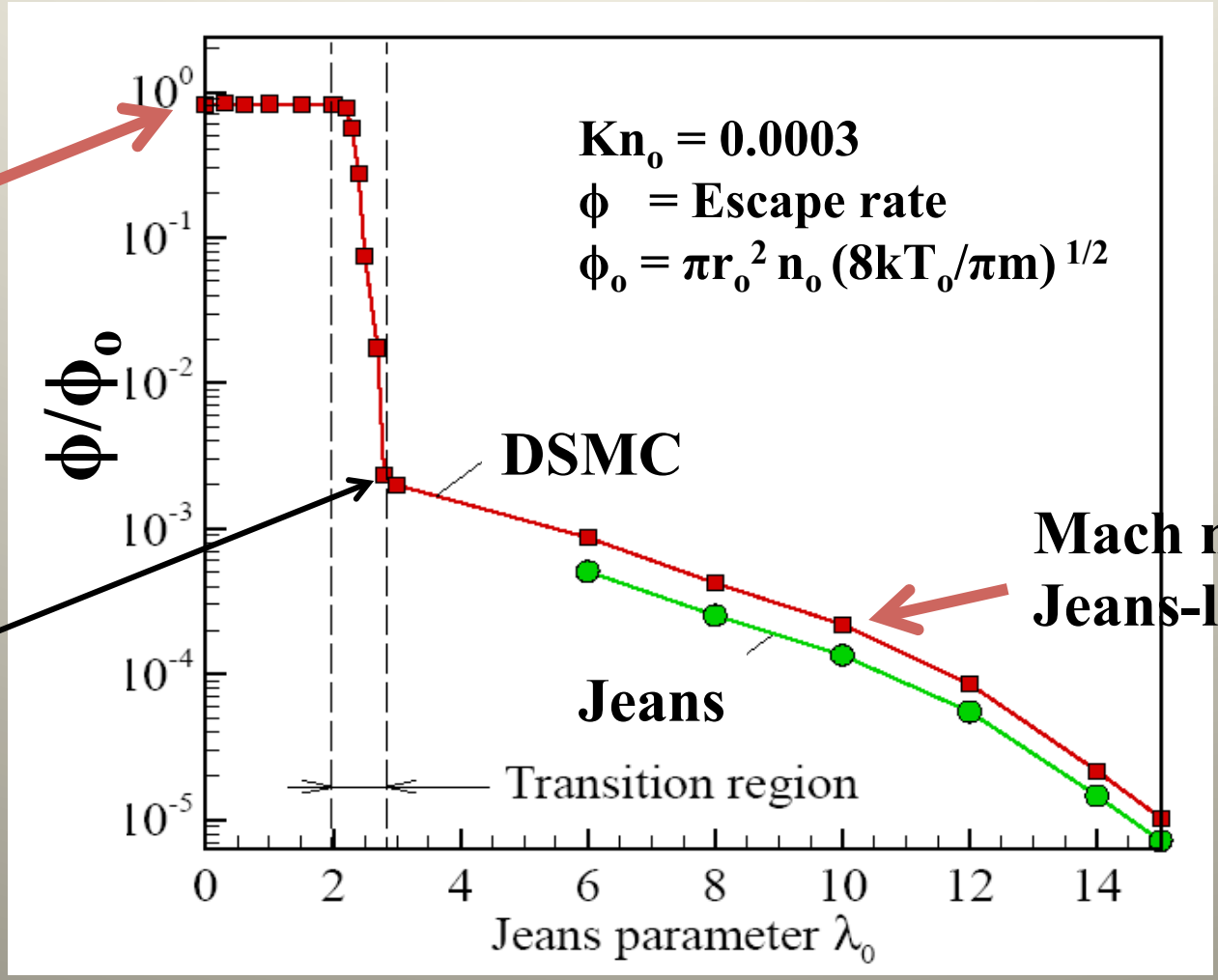
- Concerns the escape of the pdf tail

Use Molecular Kinetic Model to:

Check the energy limited escape rate
Check validity of using Jeans bc
Find a criterion for when the atmosphere goes sonic
Test the sonic solutions

Scaled Escape Rate: Q = 0 for r > r_o

Volkov et al. 2011; Gruzinov 2011



Blow-off

$\lambda_o \sim C_p$

Mach number << 1
Jeans-like escape

Hydrodynamic → Jeans Escape occurs over *narrow* range of λ

Modeling upper atmosphere with UV/EUV heating

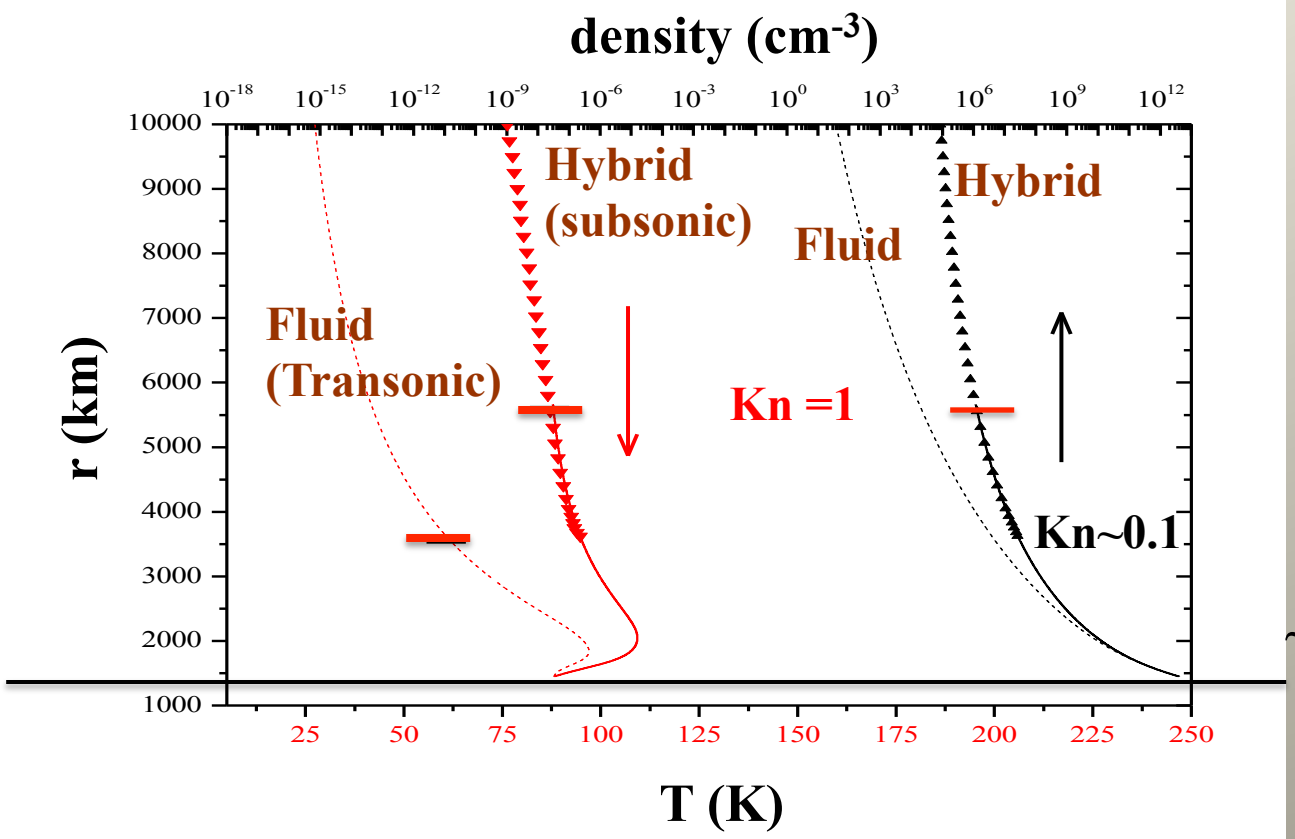
Used fluid model Kn < ~0.1 attached to a kinetic model for Kn > ~0.1

Fluid/DSMC Example for Pluto

(Tucker et al. 2012)

Solar Min: UV/ EUV heating of CH_4 and N_2

λ_o=23



~occultation boundary

Fluid → Transonic
Hybrid→ Subsonic

λ_{exo} ~ 5 ; r_{exo}/r_p ~ 4.5

Escape rate
~ 0.9*Energy limited
Fluid ~ 100 x Jeans
Hybrid ~ 1.9 x Jeans

Energy limited escape is reasonable

(with a major caveat: heating efficiency)

But flow *not* necessarily transonic

Blow-off (Transonic)
Hydrodynamic escape

↓

T & n decrease rapidly
Concentrations ~ const.

Evaporative (Subsonic)
Jeans-like escape

↓

T & n decrease more slowly
Diffusive separation

Affects: Escape of trace species
Interaction with external fields
UV/EUV absorption radius

Transonic Threshold?

$\phi \sim Q_{net} / U(r_a) \sim n_s c_s 4 \pi r_s^2$

$c_s^2 \sim U(r_s)/2m$

$Kn(r_s) < Kn_m \sim < 0.1$

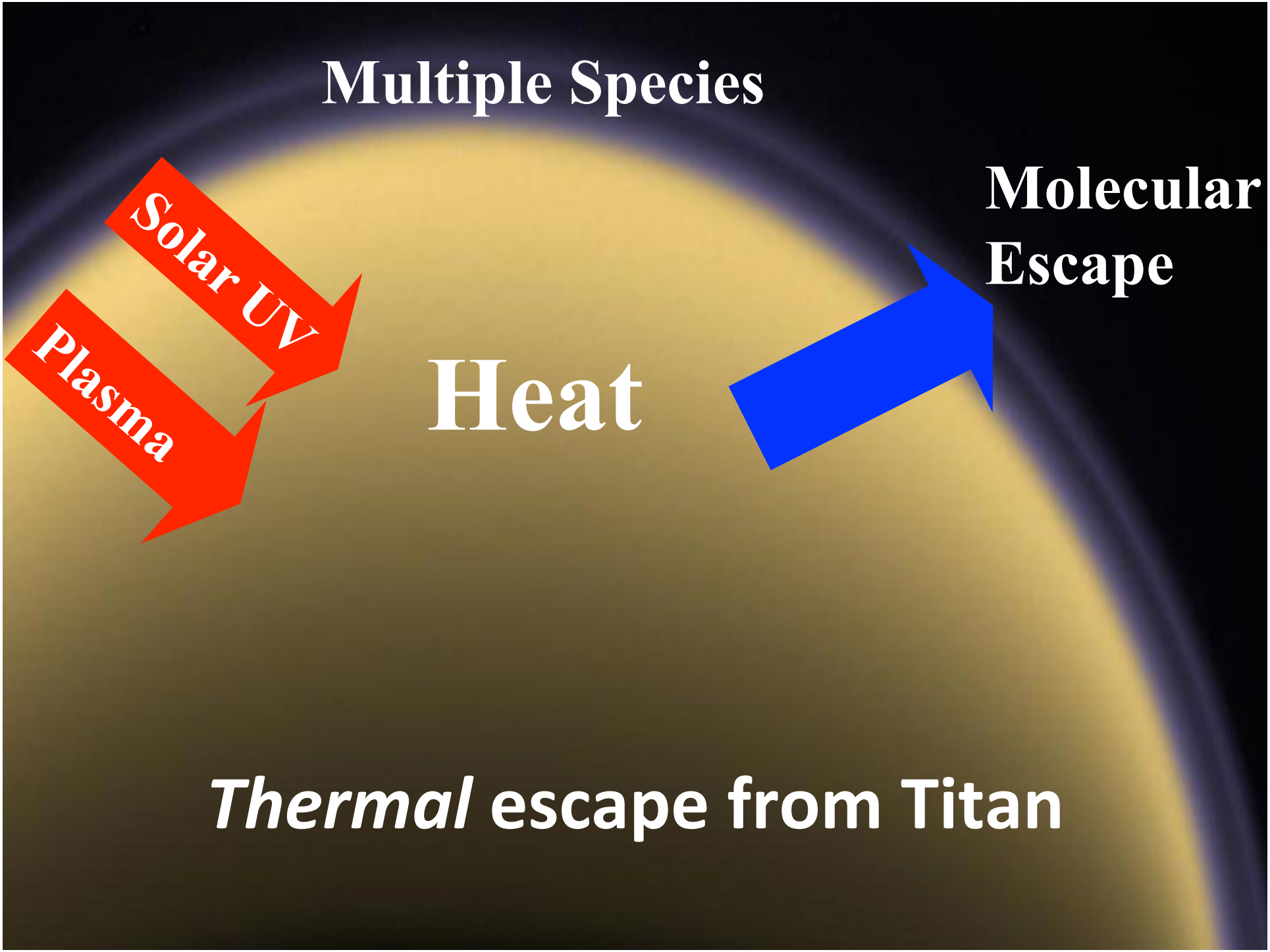
$Q_{net} > 4 \pi (2U(r_s)/m)^{1/2} U(r_a) \gamma /(\sigma_c Kn_m)$

r_a is the mean absorption depth

r_s is the sonic point ($> r_a$)

$Q_{net} = \varepsilon 4\pi r_a^2 F_{UV/EUV}$ – radiative cooling

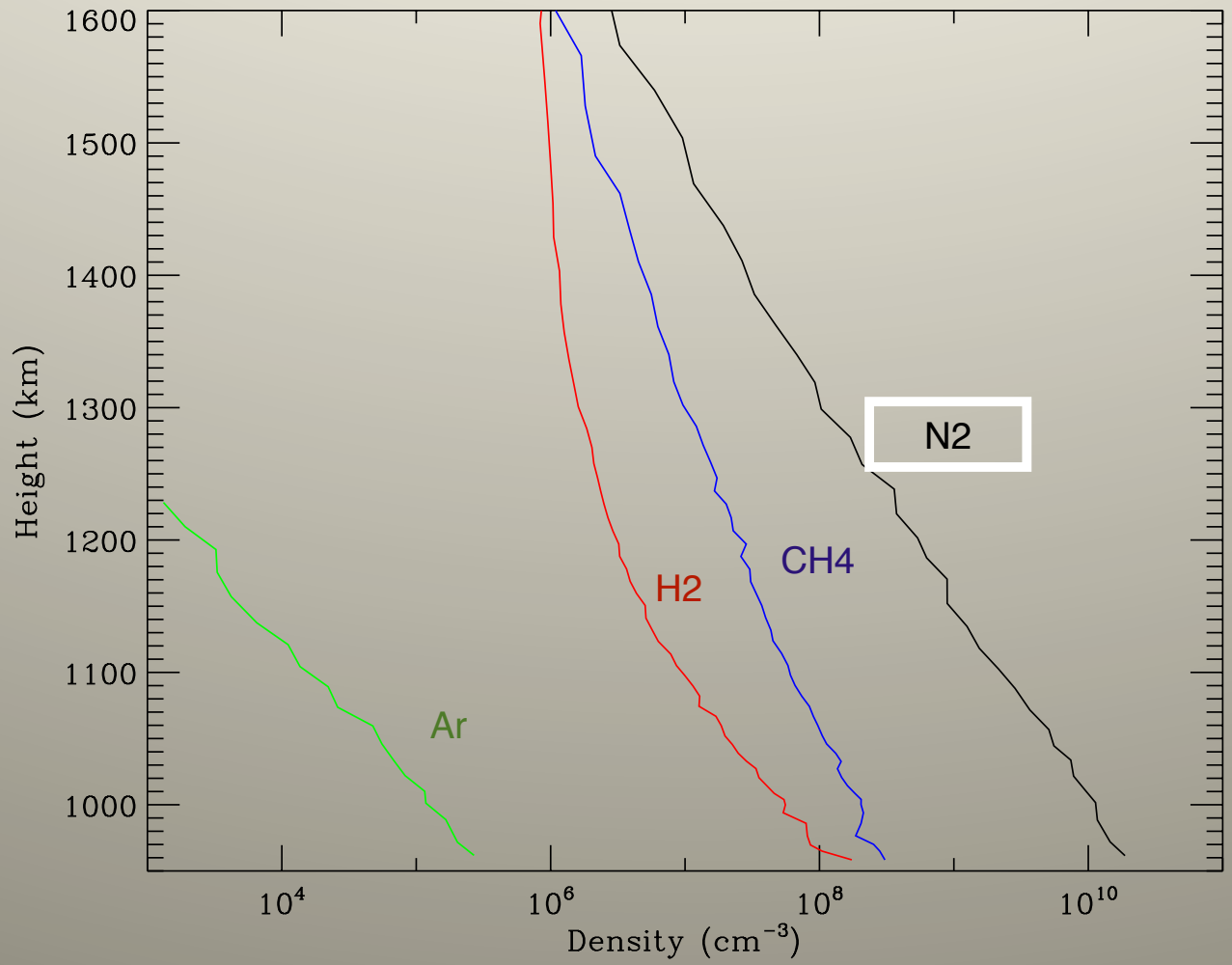
ε = 'heating' efficiency



Thermal escape from Titan

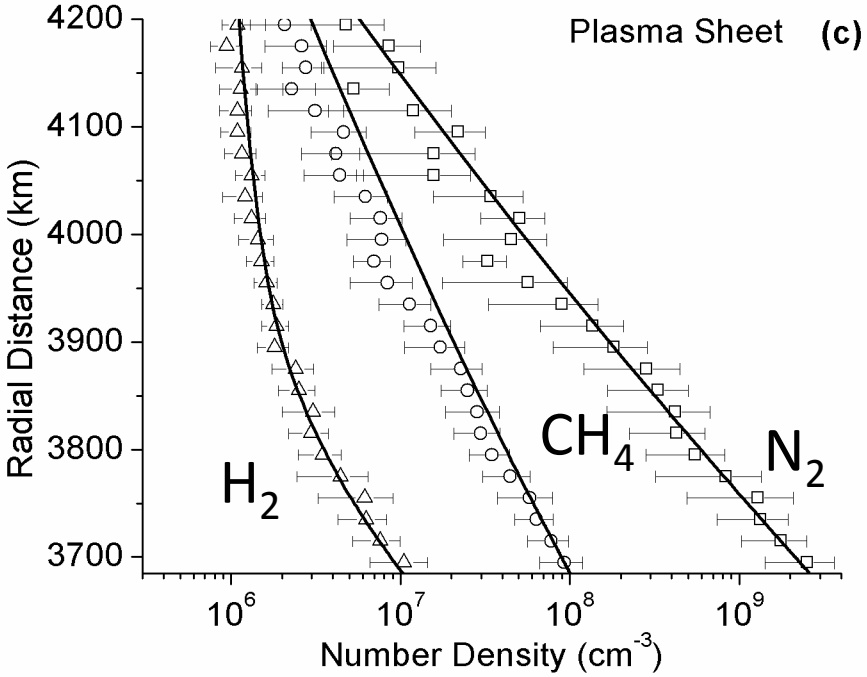
Cassini INMS Data

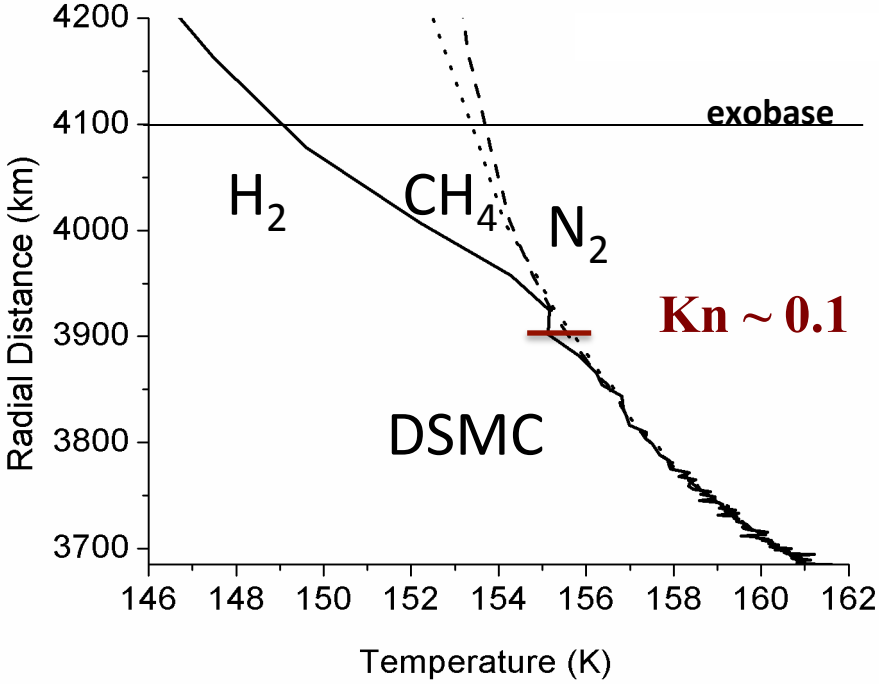
(Global Average over 90+ Flybys, *Cui et al. 2011*)



DSMC: Titan N_2, CH_4 and H_2

heat mostly deposited below lower boundary





Averaged Cassini densities during high plasma heating encounters

- **N_2 & CH_4 densities reproduced without a significant escape rate**
- **H_2 escape *cools* N_2 & CH_4**
- **H_2 is not in thermal equilibrium with other species below the exobase.**

Comments and Future Work

- DSMC is able to reproduce N_2 and CH_4 densities without requiring a significant upward flux
- Thermal escape of H_2, CH_4 and N_2 is 'Jeans' like (molecules escape with energy ~ KT)
- Consider effects of non-thermal processes on velocity distributions, heating and escape in exophere

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