Dust and low temperature plasma of Saturn

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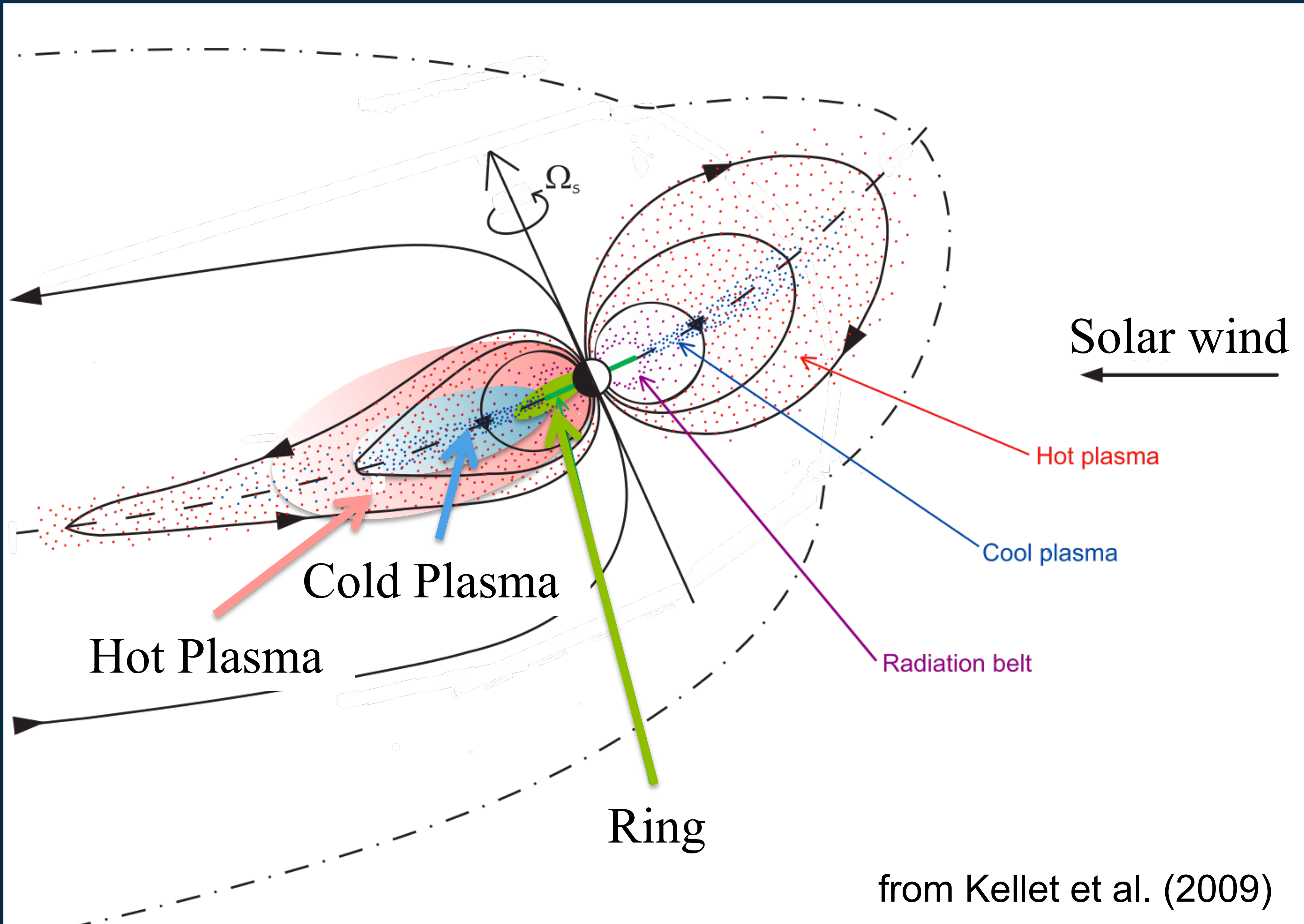
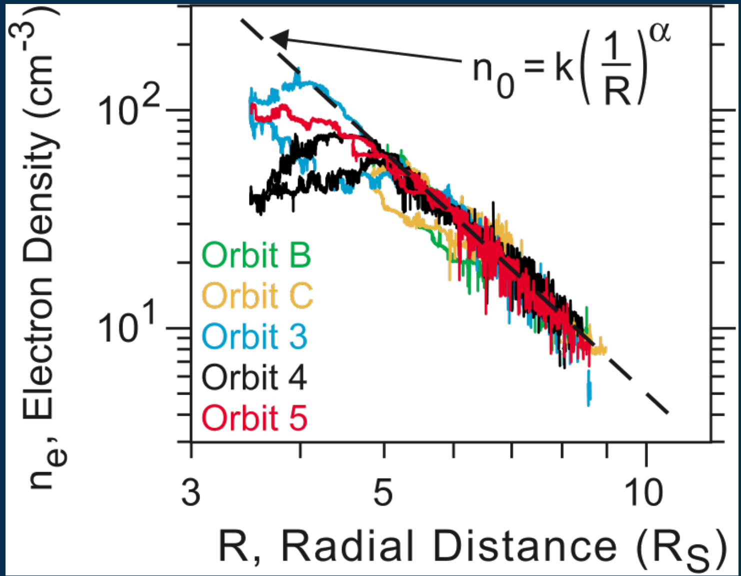
Outline

- Plasma source of Saturn's magnetosphere
- Moon Enceladus and its plume observations
- Cold and dusty plasma observation by RPWS/LP
- Dusty plasma effect in the magnetosphere (suggestion)

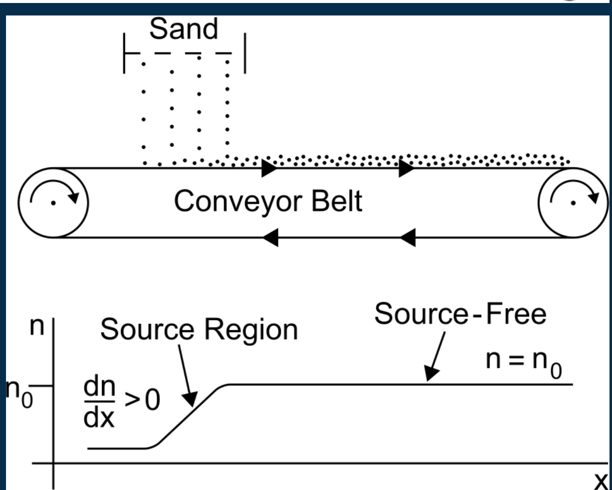
Plasma in Saturn's magnetosphere



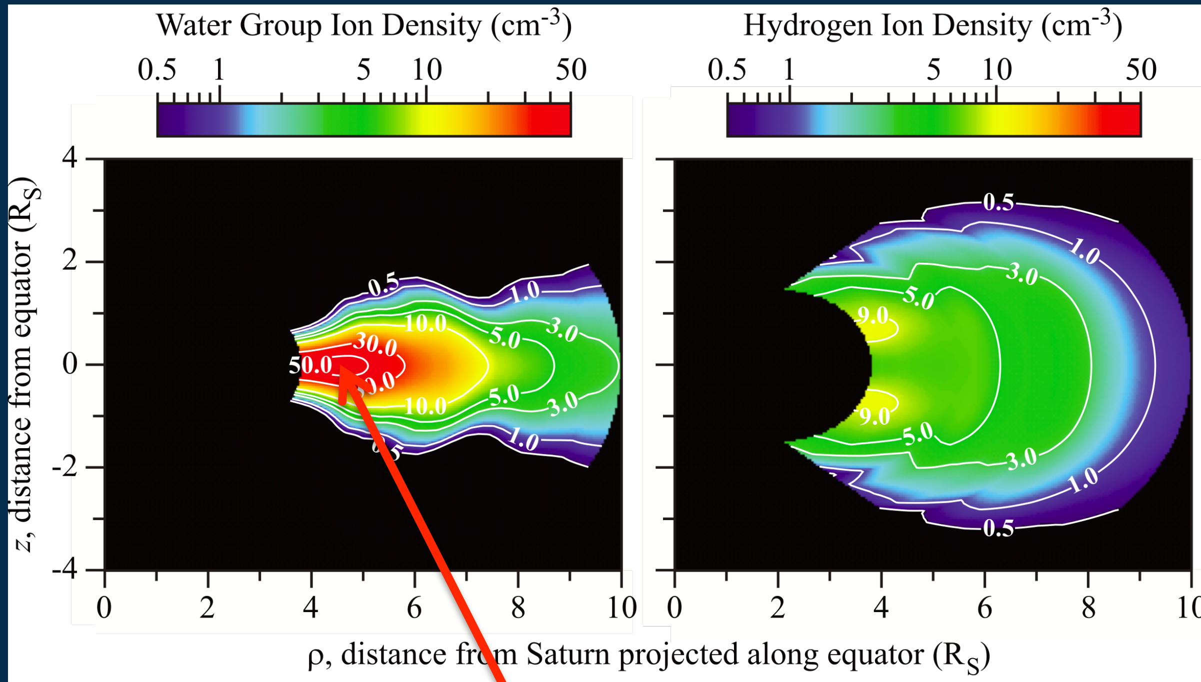
Plasma in Saturn's magnetosphere



Plasma are accumulated until $5R_S$ and centrifugally transported outward.



← Persoon et al. (2005)   Persoon et al. (2009) ↓



Water rich plasma disk center

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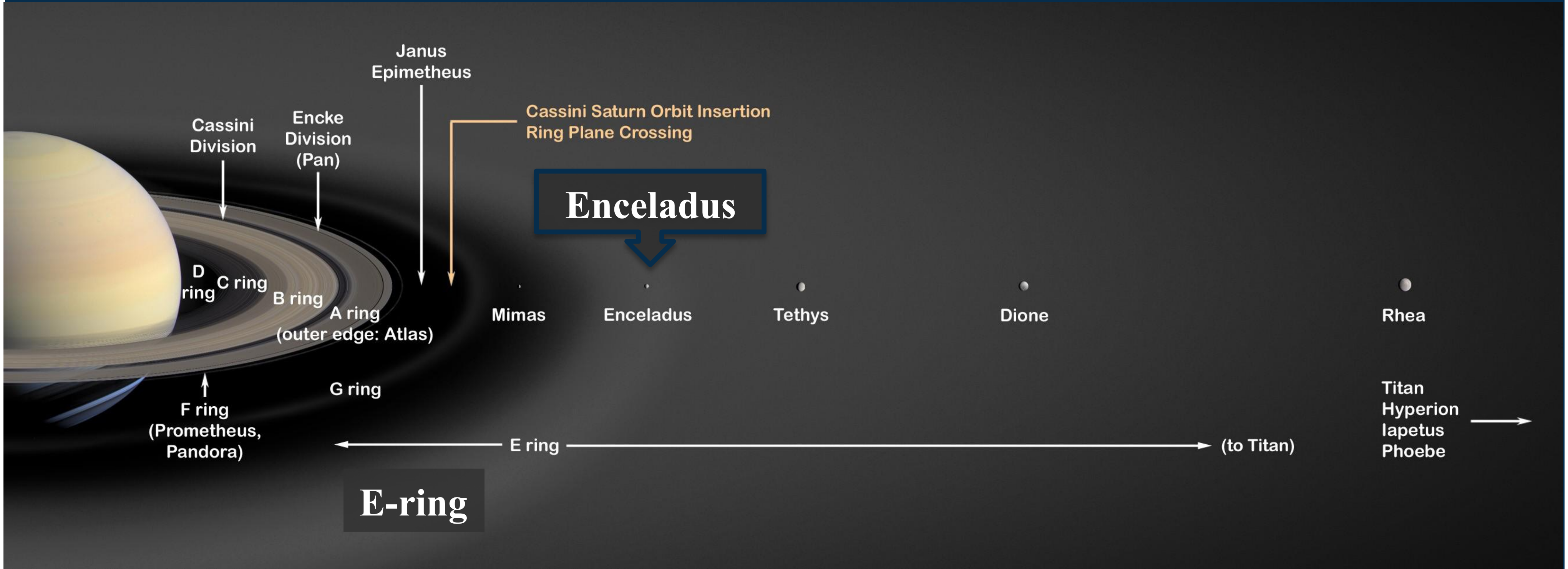

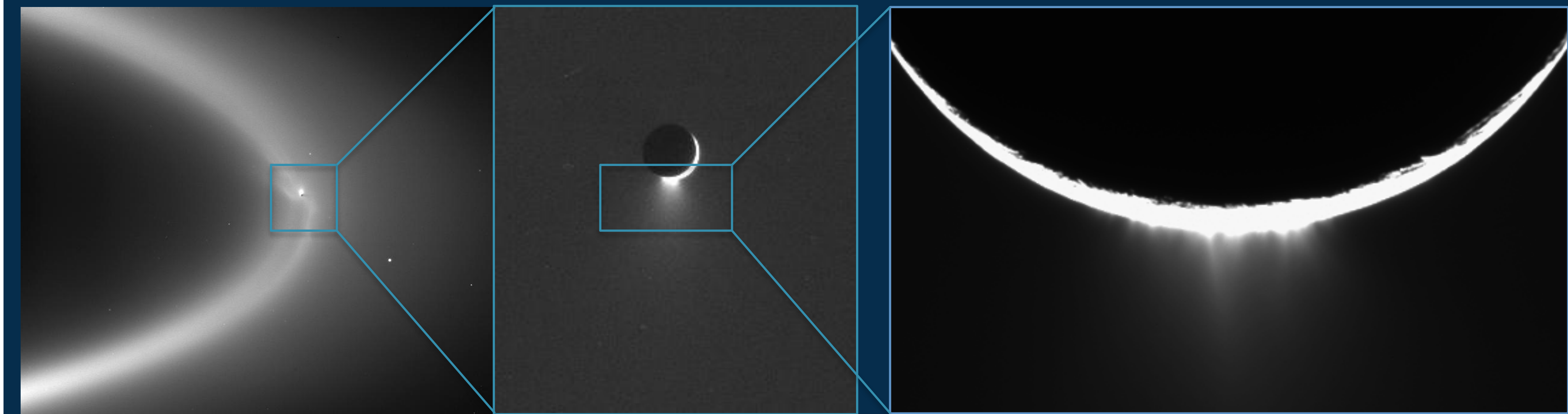

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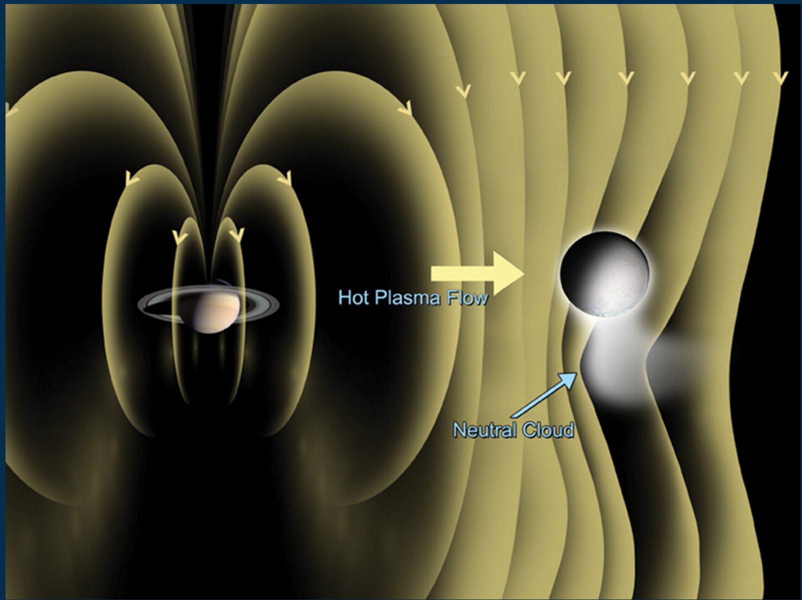
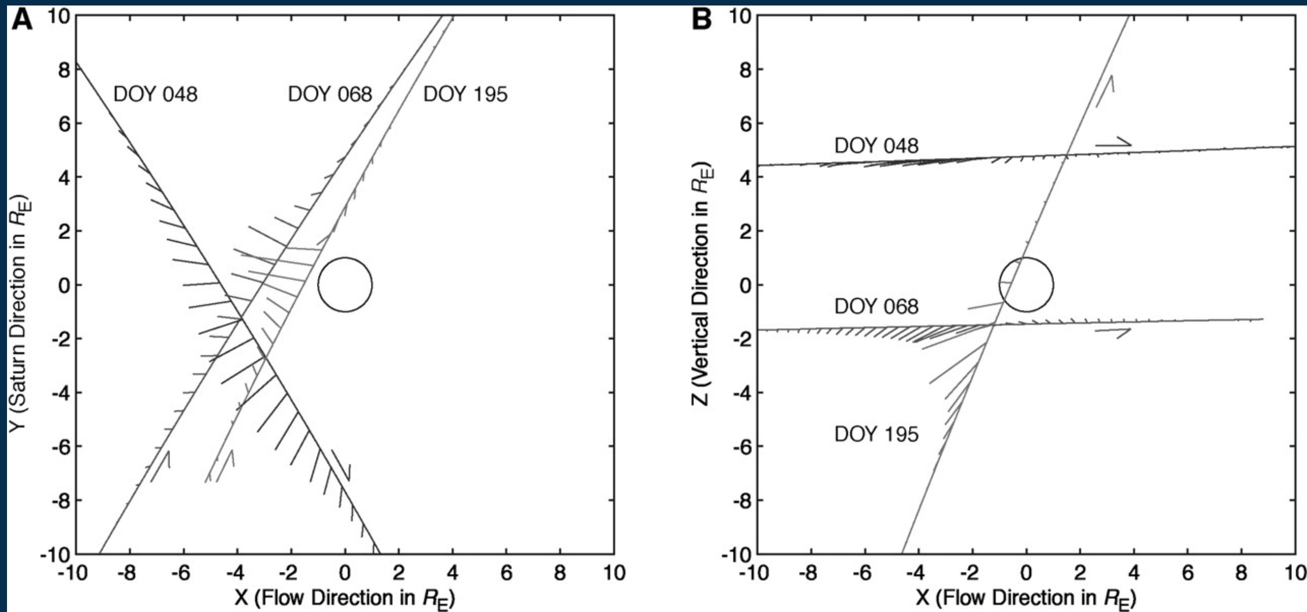
Enceladus plume detected by MAG

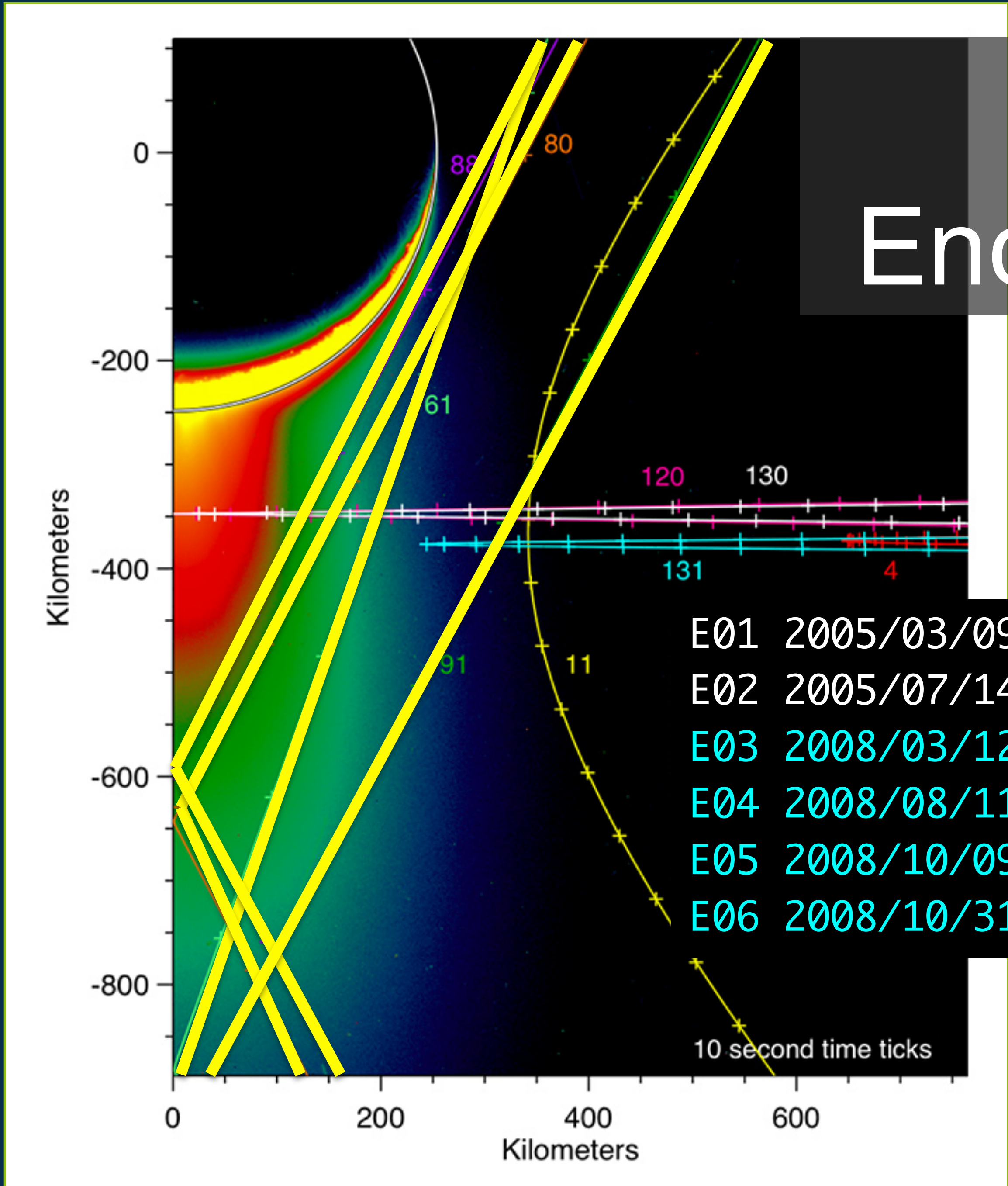


- Bx shows the expected Alfvén wing of the southern plume.
- By are rather difficult to interpret.

Dougherty et al. (2006)



Cassini Enceladus flybys



E01	2005/03/09	500	E07	2009/11/02	99
E02	2005/07/14	172	E08	2009/11/21	1603
E03	2008/03/12	52	E09	2010/04/28	99
E04	2008/08/11	50	E10	2010/05/18	198
E05	2008/10/09	25			
E06	2008/10/31	197			

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Enceladus plume/E ring observations

- Plume detection by B perturbation:

  Dougherty et al. (2006)
- Neutral observations:

  Waite et al. (2006), Water vapor in the plume
- Dust observations:

  Kempf et al. (2010), CDA sub-μm sized dust

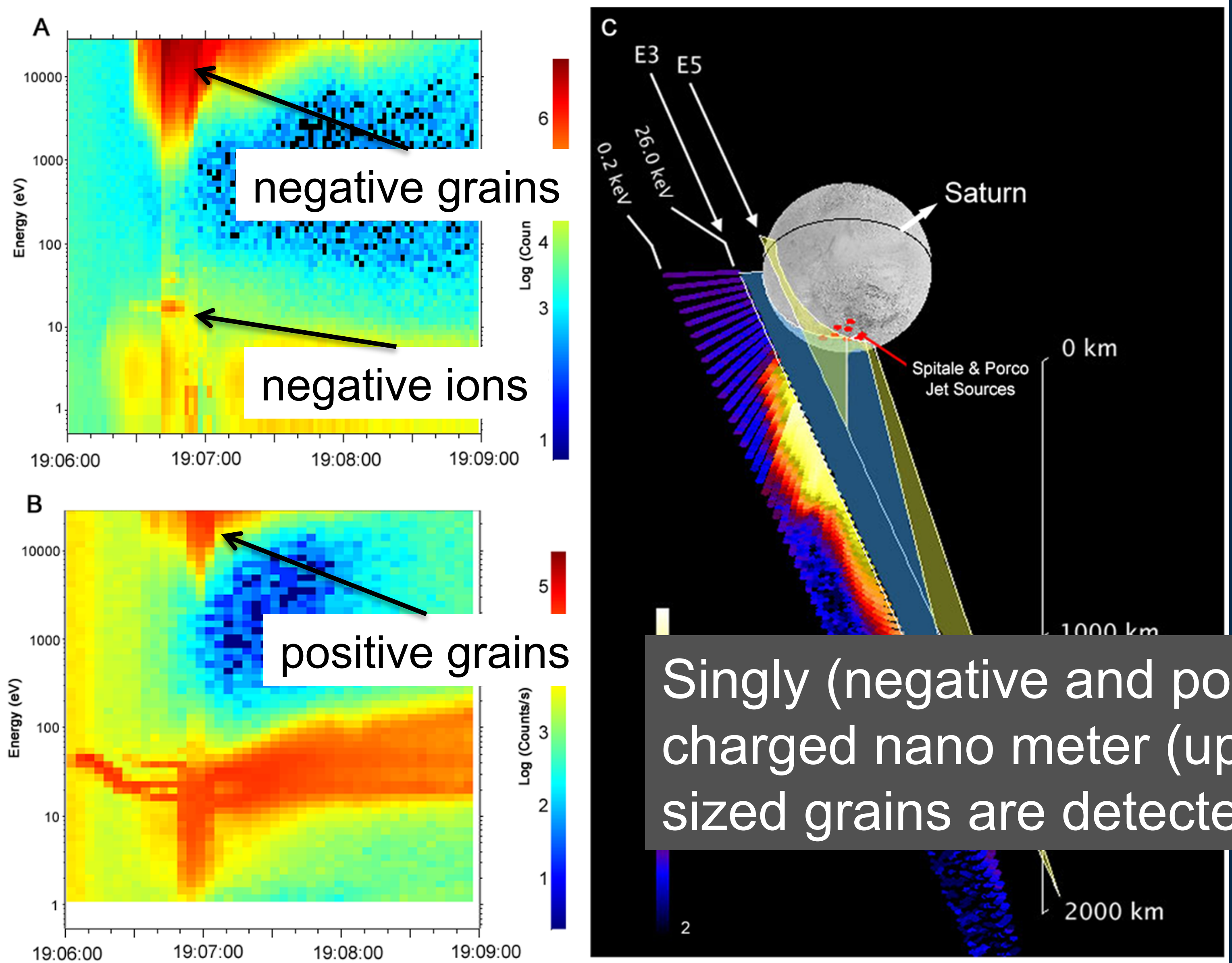
  Kurth et al. (2006), RPWS sub-μm sized dust

  Jones et al. (2009), Coates et al. (2010), ≤ nano meter sized dust
- Dust and Plasma observations:

  Tokar et al. (2009), high energy ions slowing down

  Farrell et al. (2010), CAPS & RPWS comparison and suggesting dust pick up

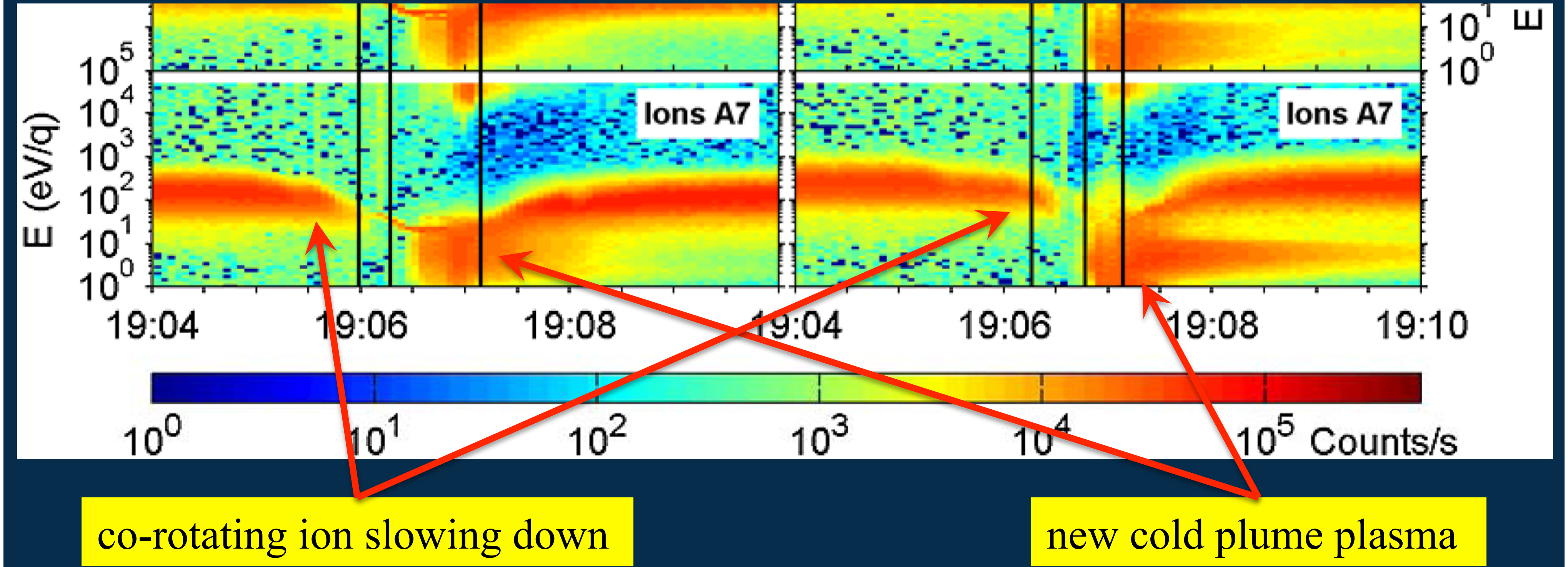
nano meter sized dust grains



Singly (negative and positive) charged nano meter (up to 2 nm) sized grains are detected.

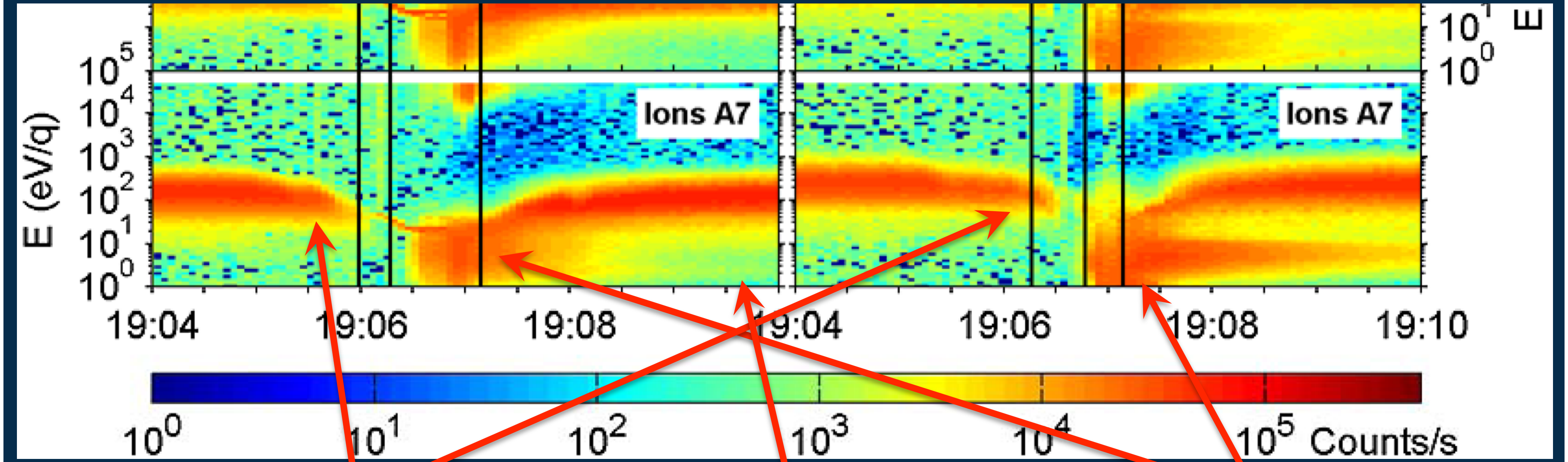
Jones et al. (2009)

Slowing down of co-rotating ion



Tokar et al. (2009)

Slowing down of co-rotating ion



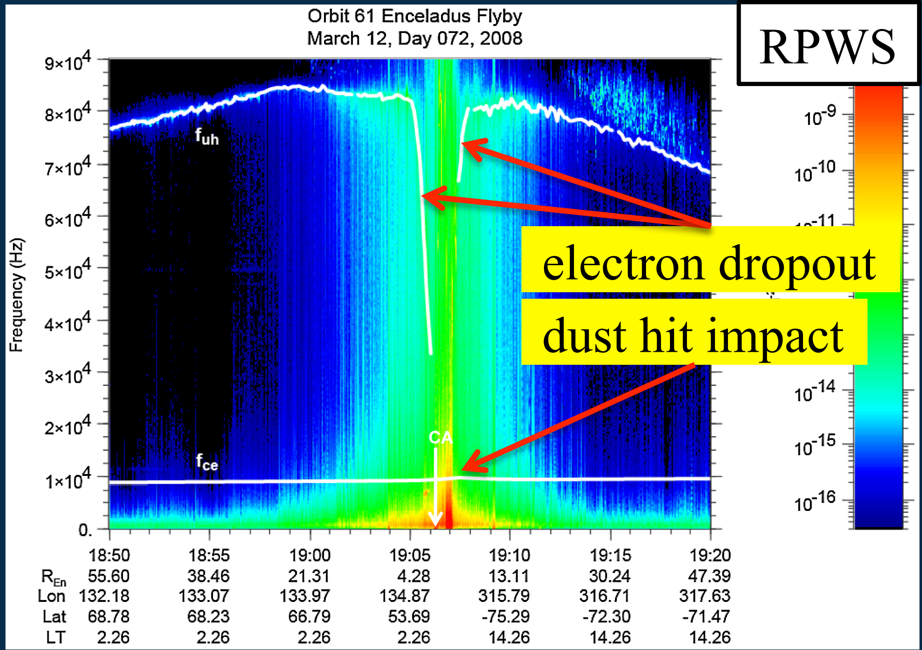
co-rotating ion slowing down

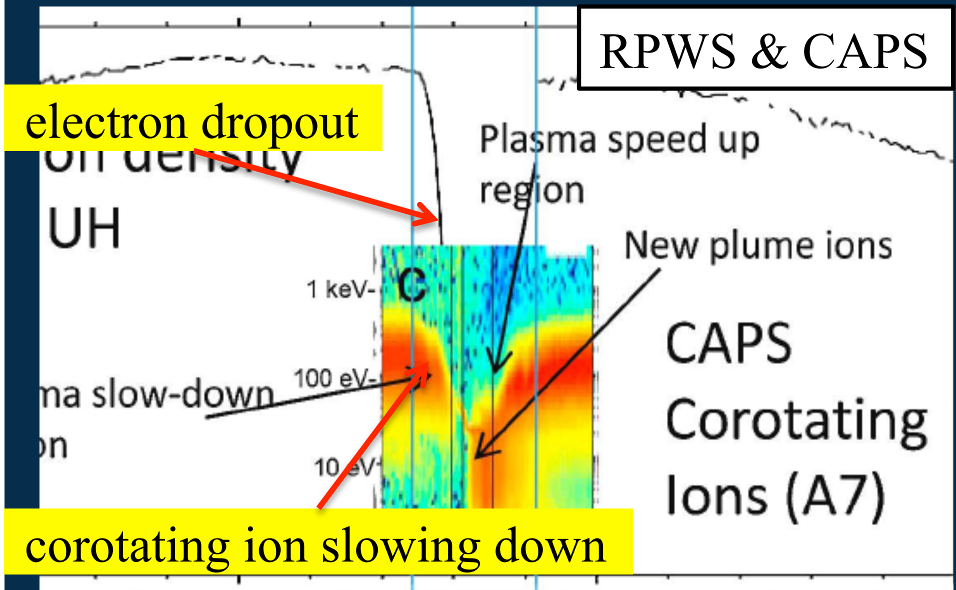
new cold plume plasma

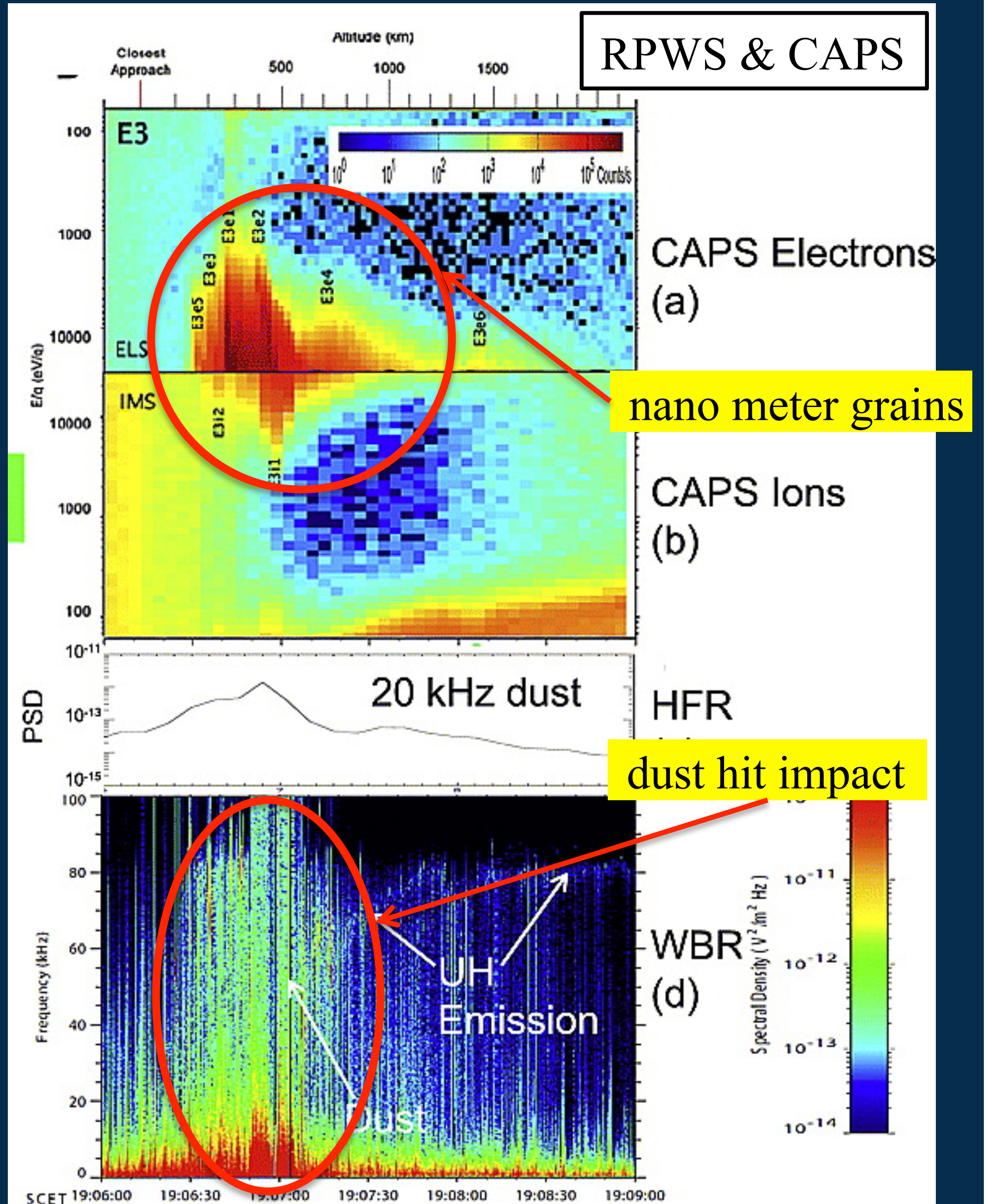
very cold ion also here?

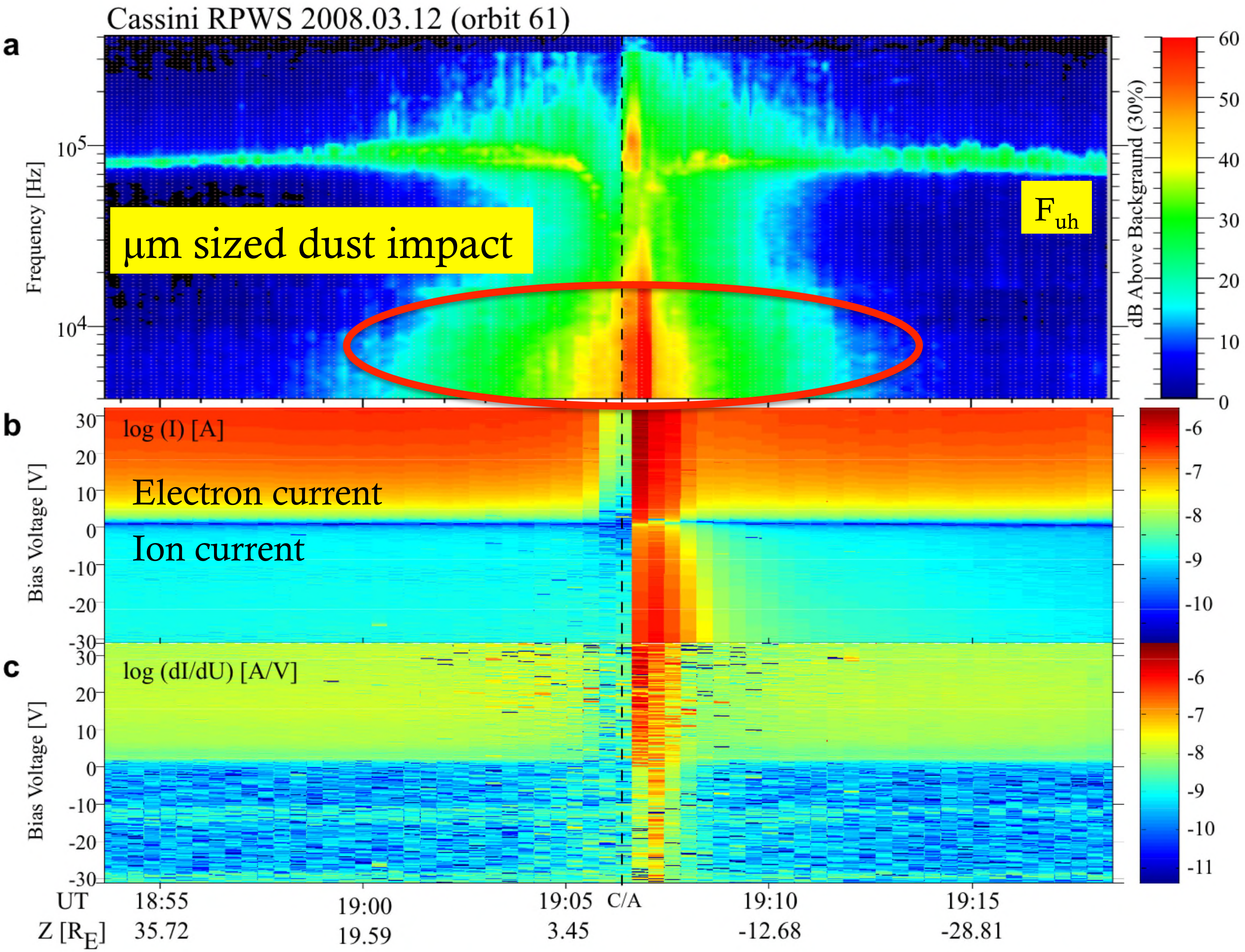
Tokar et al. (2009)

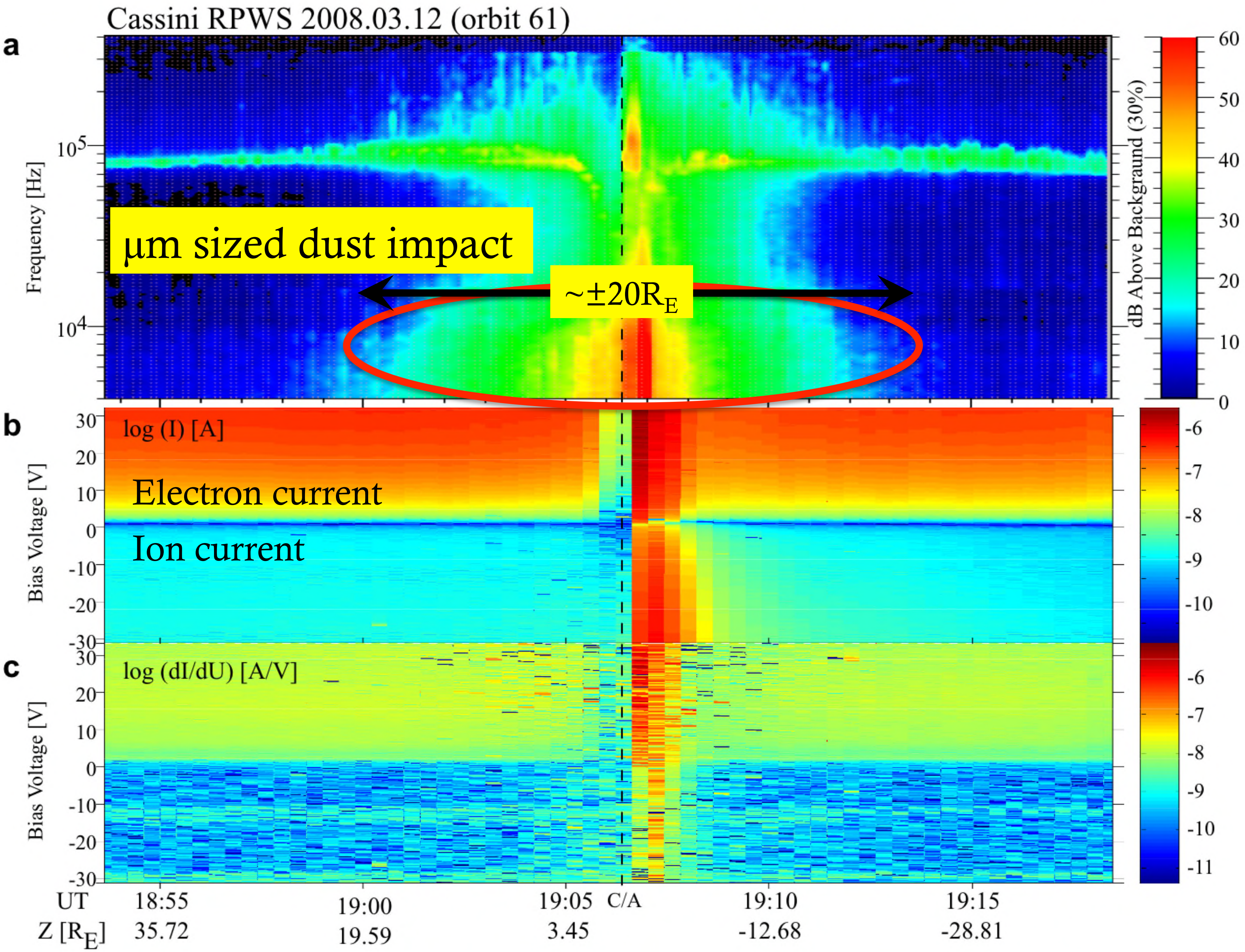
Farrell et al. (2009, 2010)

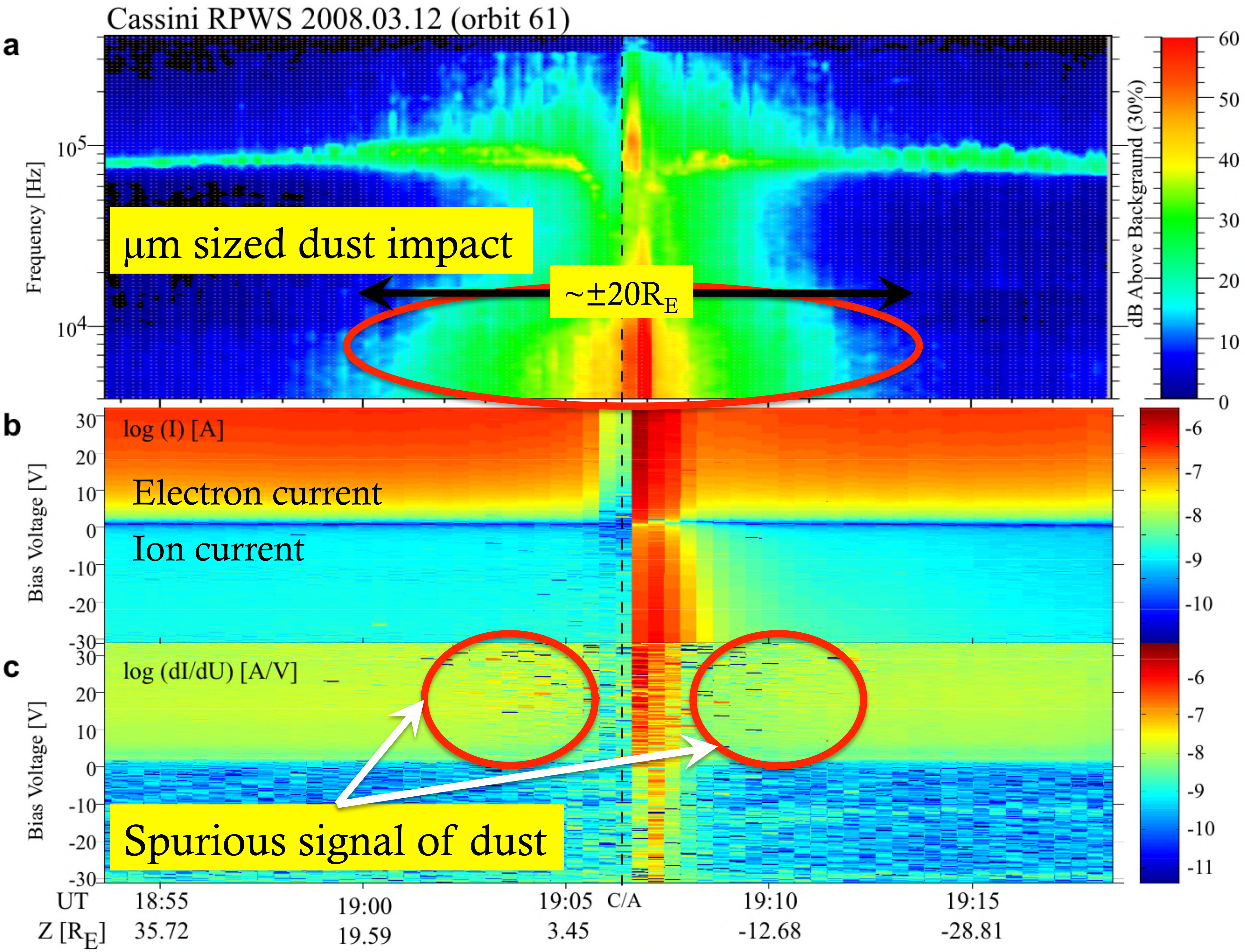




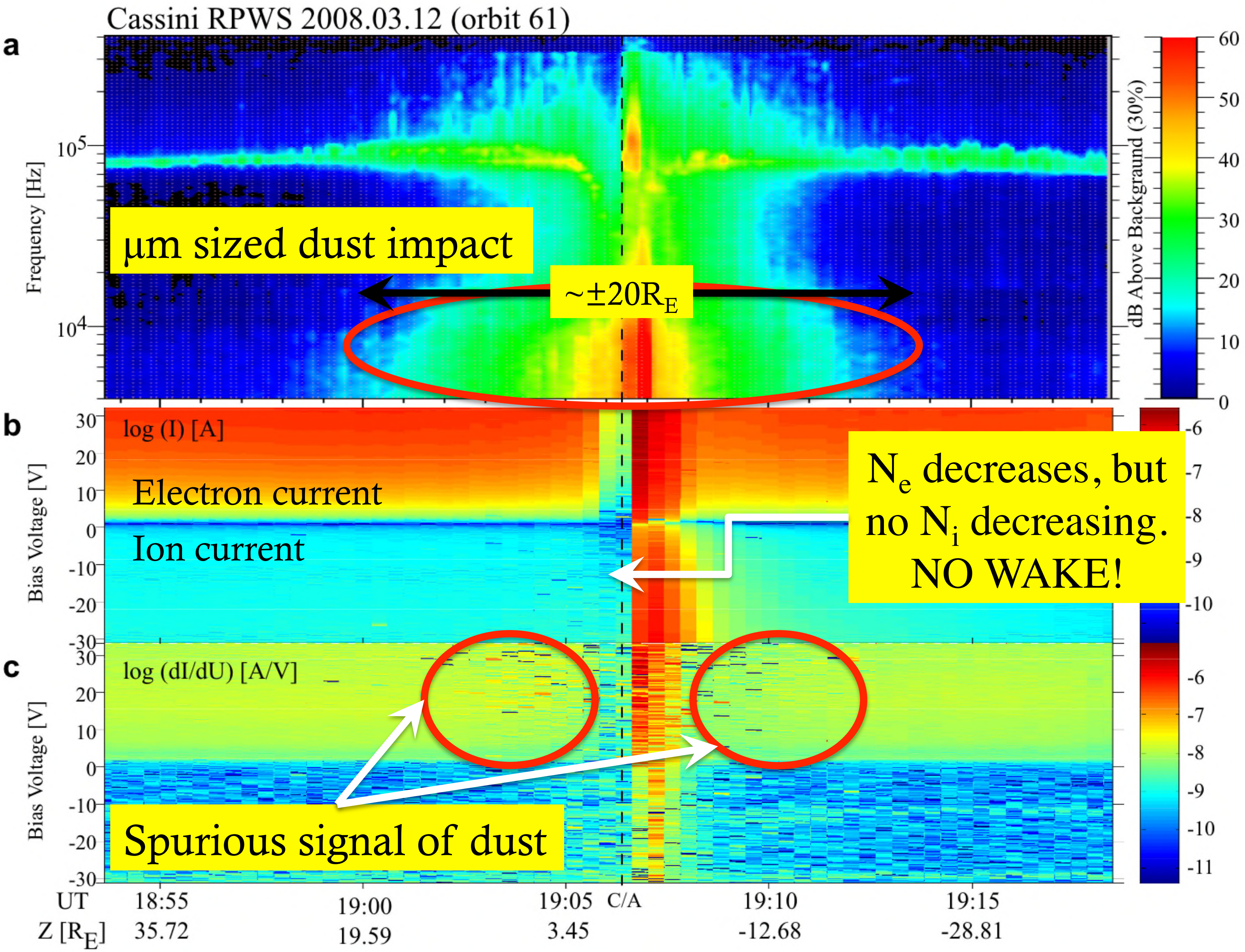



Cassini RPWS 2008.03.12 (orbit 61)
a
b
c
Frequency [Hz]
10^5
10^4
μm sized dust impact
F_{uh}
dB Above Background (30%)
60
50
40
30
20
10
0
log (I) [A]
Electron current
Ion current
Bias Voltage [V]
30
20
10
0
-10
-20
-30
-6
-7
-8
-9
-10
log (dI/dU) [A/V]
-11
UT
18:55
19:00
19:05
C/A
19:10
19:15
Z [R_E]
35.72
19.59
3.45
-12.68
-28.81

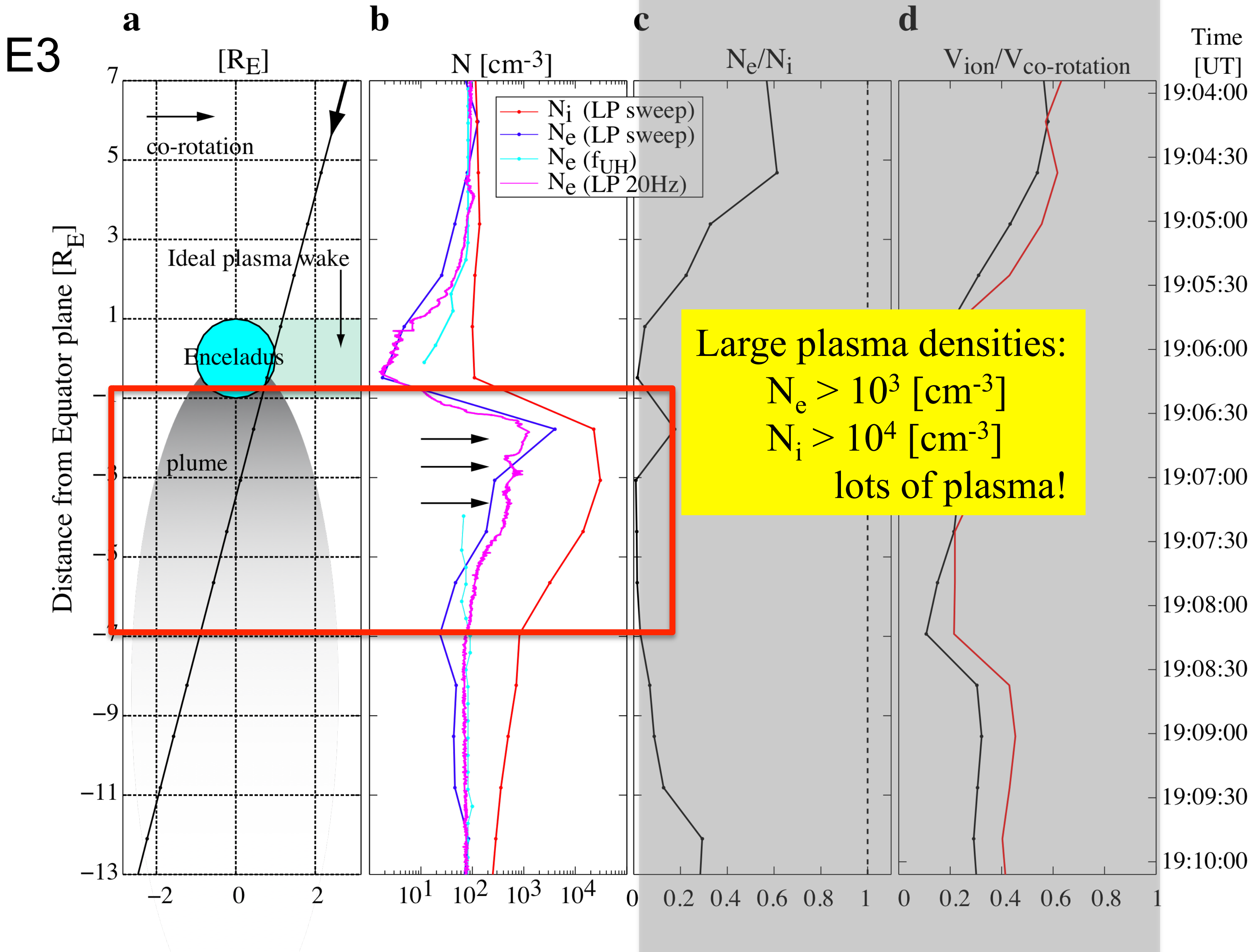

Cassini RPWS 2008.03.12 (orbit 61)
a
b
c
Frequency [Hz]
10^5
10^4
μm sized dust impact
~±20R_E
dB Above Background (30%)
60
50
40
30
20
10
0
log (I) [A]
Electron current
Ion current
Bias Voltage [V]
log (dI/dU) [A/V]
UT
Z [R_E]
18:55
35.72
19:00
19.59
19:05
3.45
C/A
19:10
-12.68
19:15
-28.81

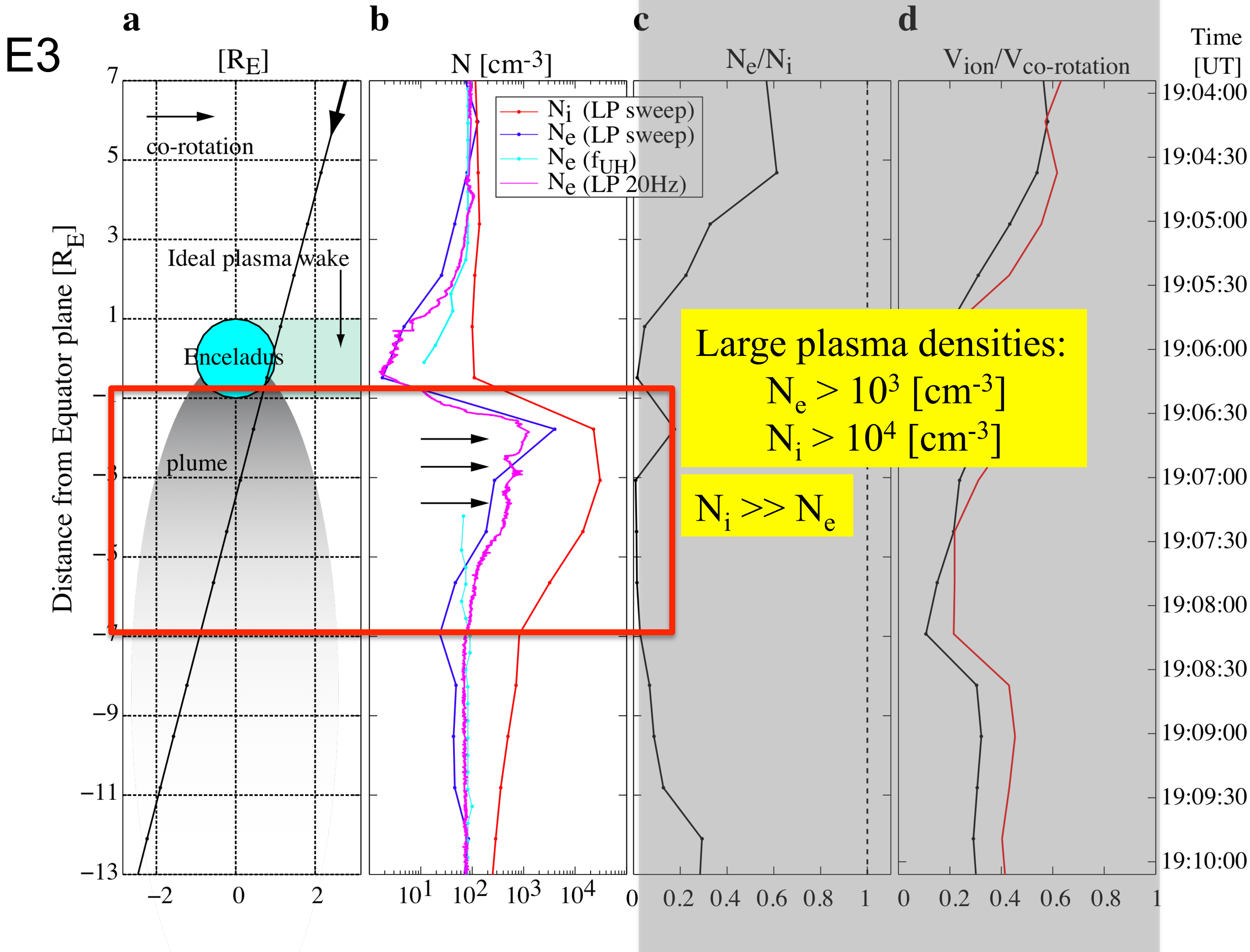


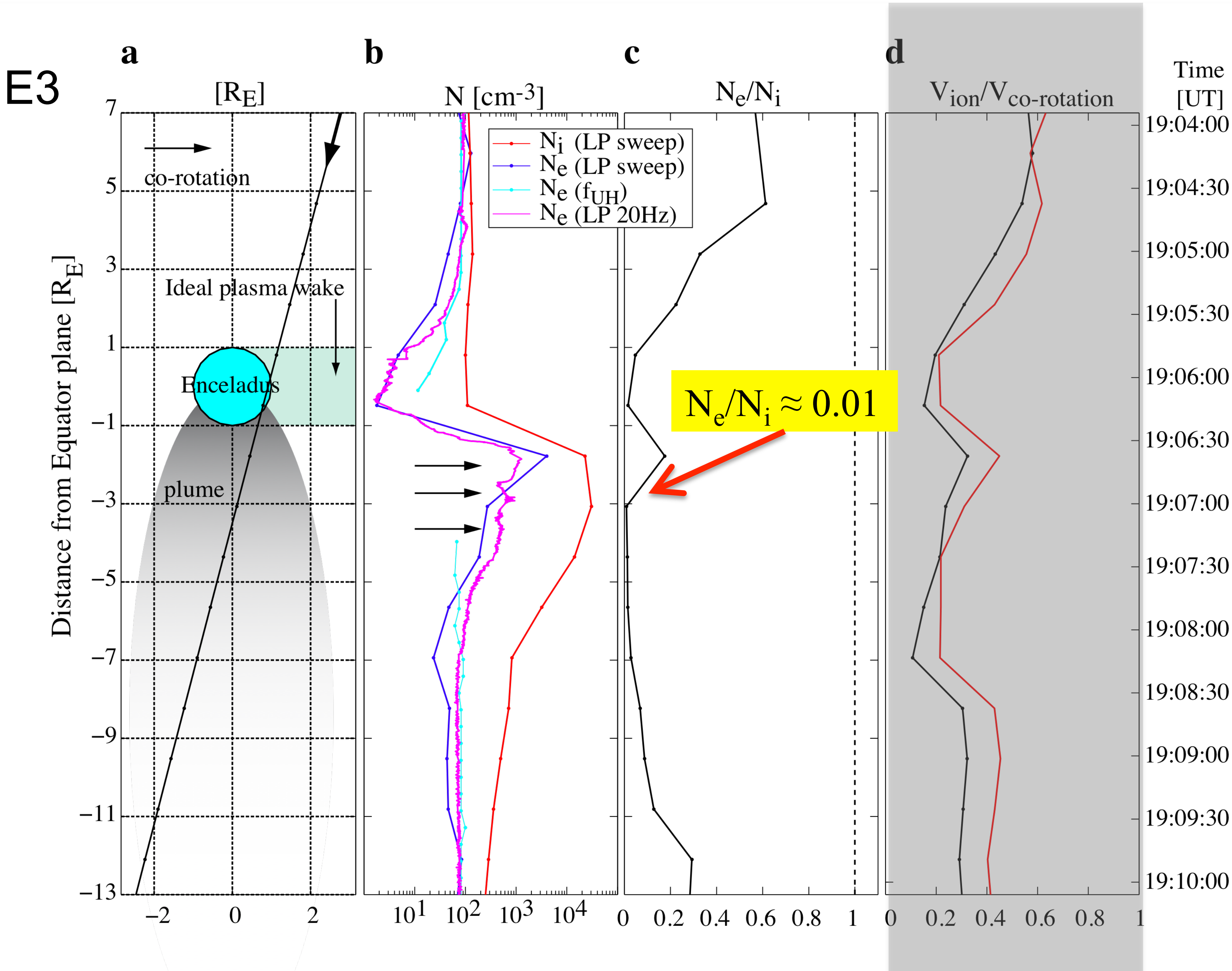
Cassini RPWS 2008.03.12 (orbit 61)
a
b
c
Frequency [Hz]
dB Above Background (30%)
μm sized dust impact
~±20R$_E$
log (I) [A]
Electron current
Ion current
log (dI/dU) [A/V]
Bias Voltage [V]
Spurious signal of dust
UT
Z [R$_E$]
18:55
35.72
19:00
19.59
19:05
3.45
C/A
19:10
-12.68
19:15
-28.81



Cassini RPWS 2008.03.12 (orbit 61)
a
b
c
Frequency [Hz]
dB Above Background (30%)
μm sized dust impact
~±20R$_E$
log (I) [A]
Electron current
Ion current
N$_e$ decreases, but
no N$_i$ decreasing.
NO WAKE!
log (dI/dU) [A/V]
Spurious signal of dust
Bias Voltage [V]
UT 18:55 19:00 19:05 C/A 19:10 19:15
Z [R$_E$] 35.72 19.59 3.45 -12.68 -28.81


E3
a
b
c
d
[R_E]
N [cm^-3]
N_e/N_i
V_ion/V_co-rotation
Time [UT]
co-rotation
Ideal plasma wake
Enceladus
plume
Distance from Equator plane [R_E]
N_i (LP sweep)
N_e (LP sweep)
N_e (f_UH)
N_e (LP 20Hz)
19:04:00
19:04:30
19:05:00
19:05:30
19:06:00
19:06:30
19:07:00
19:07:30
19:08:00
19:08:30
19:09:00
19:09:30
19:10:00
Large plasma densities:
N_e > 10^3 [cm^-3]
N_i > 10^4 [cm^-3]
lots of plasma!


E3
a
b
c
d
[R_E]
N [cm-3]
Ne/Ni
Vion/Vco-rotation
Time [UT]
Distance from Equator plane [R_E]
co-rotation
Ideal plasma wake
Enceladus
plume
Ni (LP sweep)
Ne (LP sweep)
Ne (fUH)
Ne (LP 20Hz)
Large plasma densities:
Ne > 10^3 [cm-3]
Ni > 10^4 [cm-3]
Ni >> Ne
19:04:00
19:04:30
19:05:00
19:05:30
19:06:00
19:06:30
19:07:00
19:07:30
19:08:00
19:08:30
19:09:00
19:09:30
19:10:00



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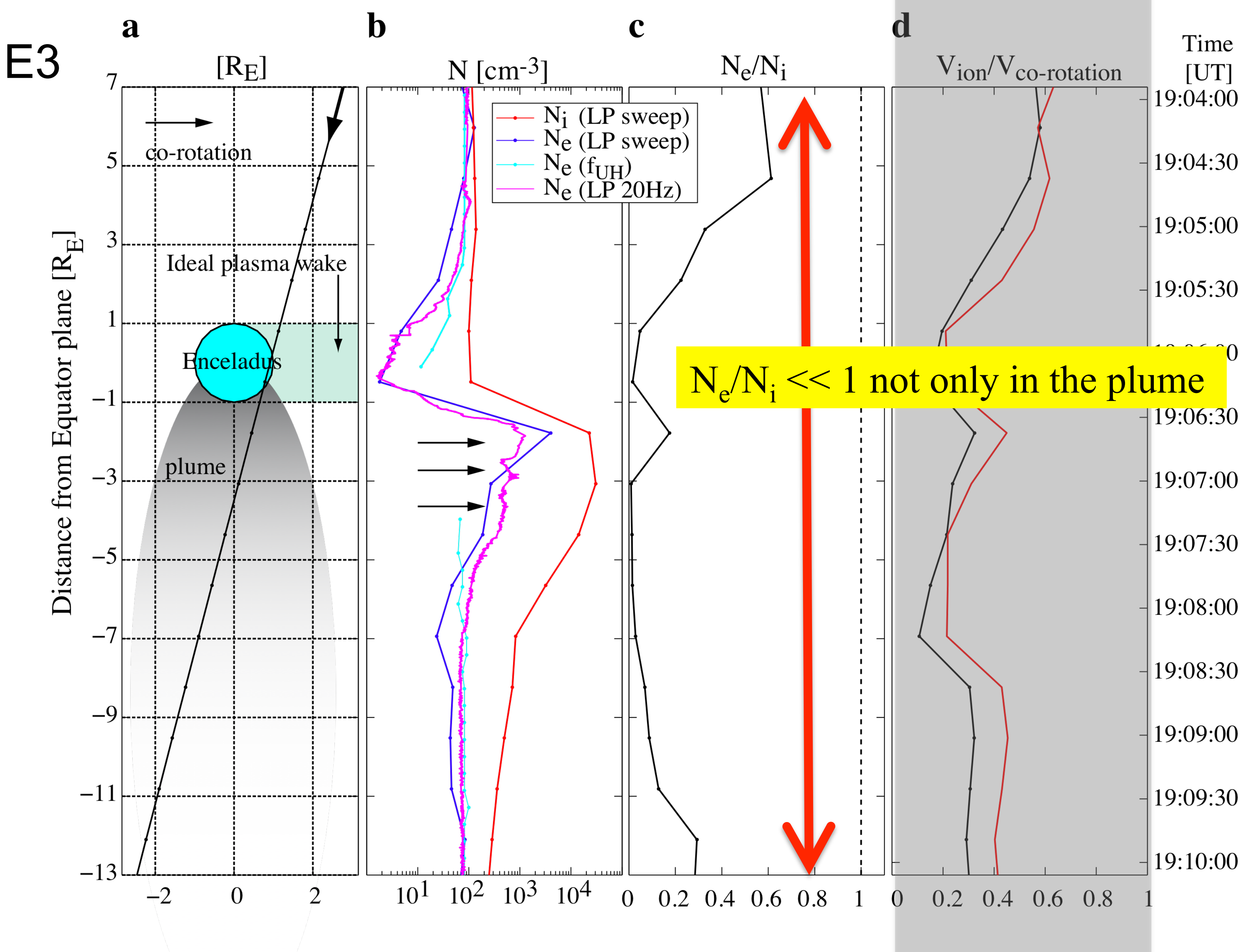

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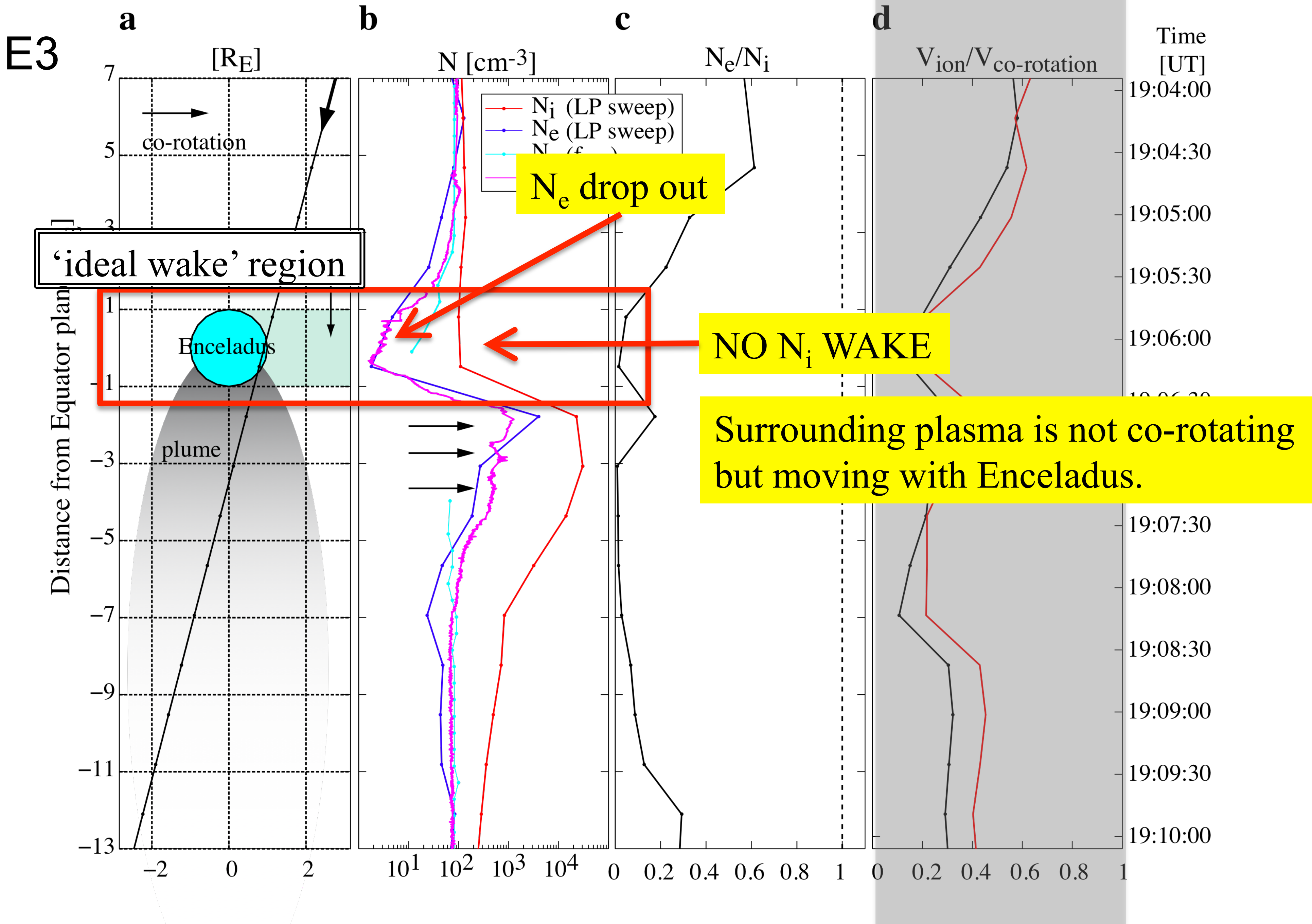
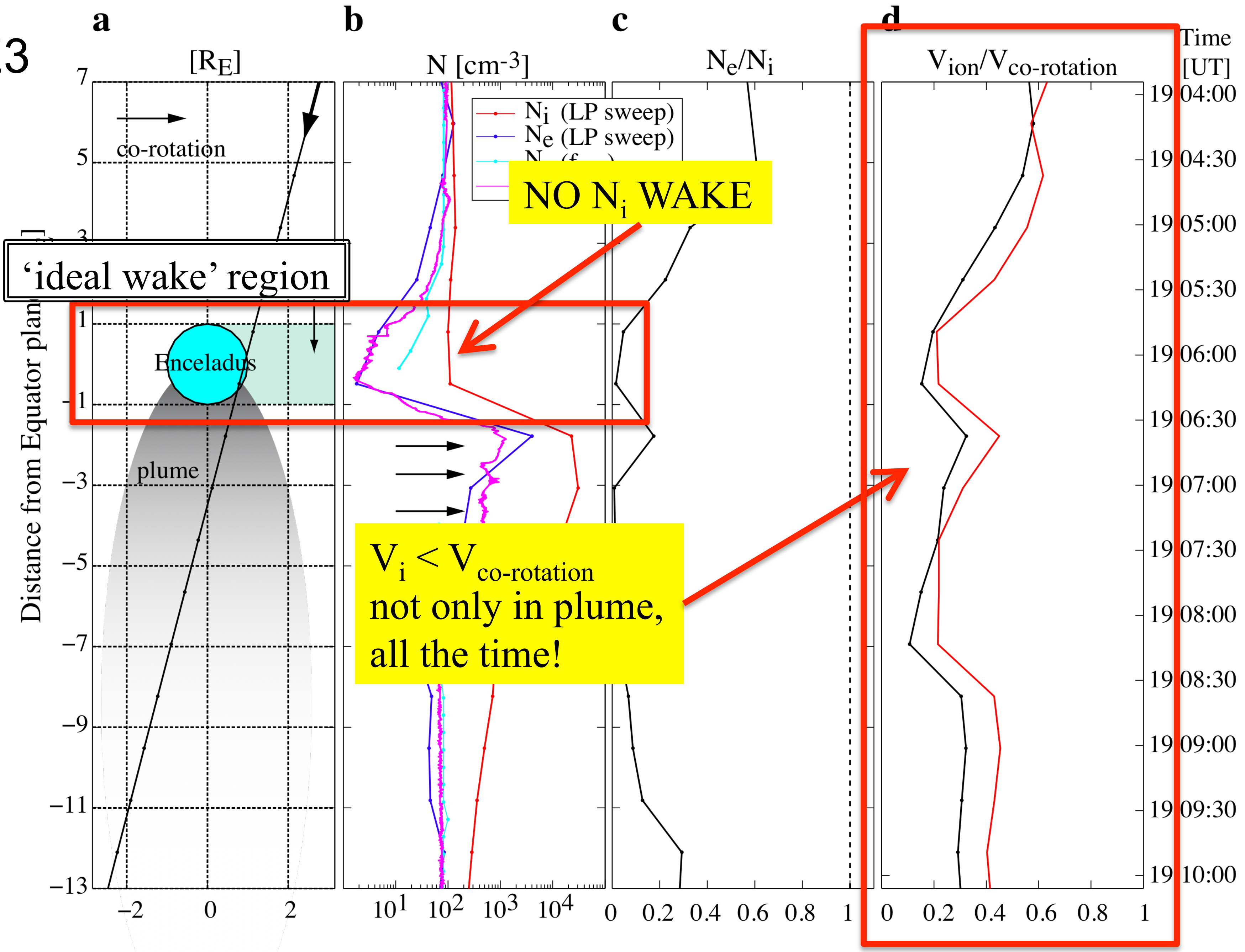
Saturn's Dust and low tempetarure plasma


E3
a
b
c
d
[R$_E$]
N [cm^{-3}]
N_e/N_i
$V_{ion}/V_{co\text{-}rotation}$
Time [UT]
co-rotation
'ideal wake' region
Enceladus
plume
Distance from Equator plan
N_i (LP sweep)
N_e (LP sweep)
N_e drop out
NO N_i WAKE
Surrounding plasma is not co-rotating but moving with Enceladus.
19:04:00
19:04:30
19:05:00
19:05:30
19:06:00
19:07:30
19:08:00
19:08:30
19:09:00
19:09:30
19:10:00

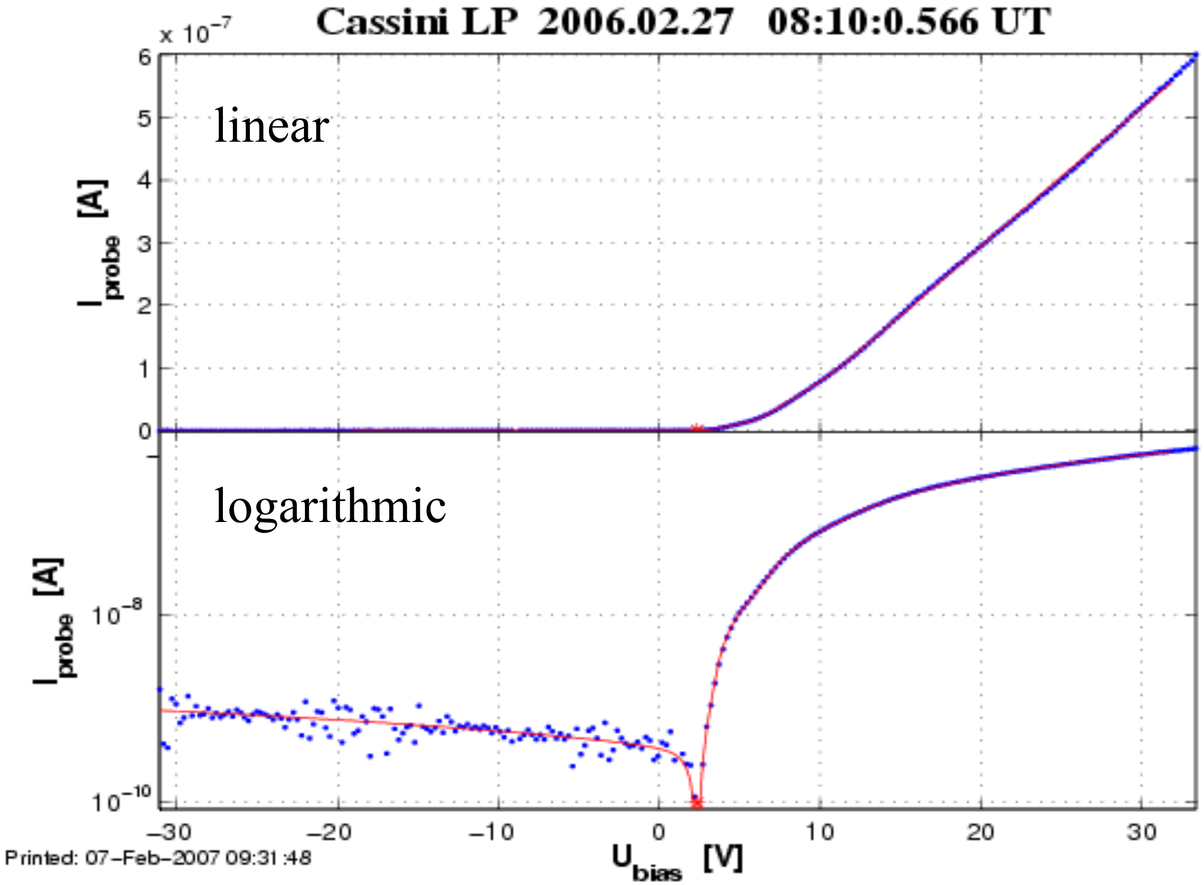
E3


a
b
c
d
[R_E]
N [cm-3]
Ne/Ni
Vion/Vco-rotation
Time [UT]
co-rotation
Enceladus
plume
Distance from Equator plan
Ni (LP sweep)
Ne (LP sweep)
'ideal wake' region
NO Ni WAKE
Vi < Vco-rotation
not only in plume,
all the time!
19 04:00
19 04:30
19 05:00
19 05:30
19 06:00
19 06:30
19 07:00
19 07:30
19 08:00
19 08:30
19 09:00
19 09:30
19 10:00

Langmuir probe theory

LP measured currents: $I = I_i + I_e + I_{ph,\ Ly\text{-}\alpha} + I_{e*,\ i*} + I_{dust}$

From OML theory (with Maxwellian distribution function, Fahlesson approximation):



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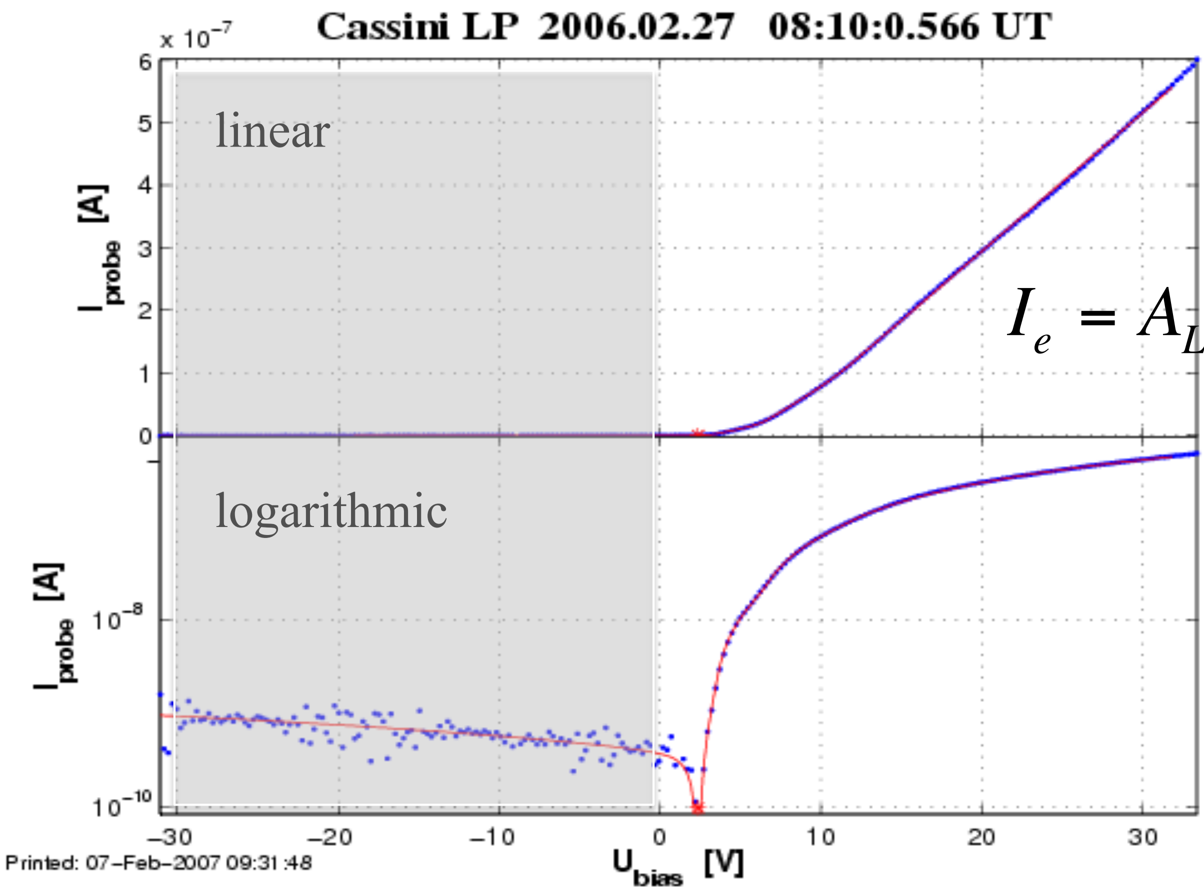


U > 0 (electron side)

$$I_e = A_{LP} n_e q_e \left(1 - \frac{e(U_{bias} + U_{float})}{k_B T_e}\right)$$

Langmuir probe theory

LP measured currents: $I = I_i + \cancel{I_e} + I_{ph,\,Ly\text{-}\alpha} + \cancel{I_{e*,\,i*}} + I_{dust}$

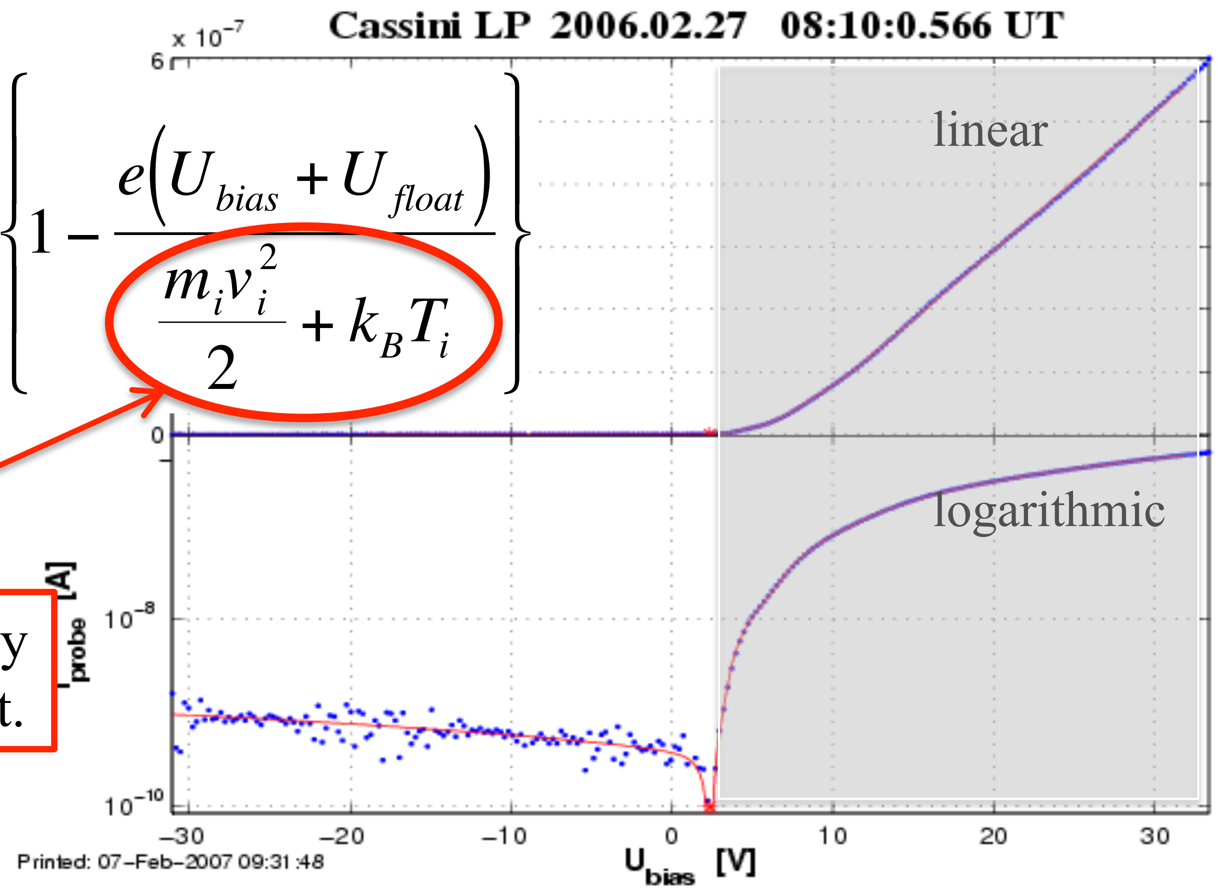
From OML theory (with Maxwellian distribution function, Fahlesson approximation):

U < 0 (ion side)

$$I_i = A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2\pi m}} \left\{ 1 - \frac{e\left(U_{bias} + U_{float}\right)}{\frac{m_i v_i^2}{2} + k_B T_i} \right\}$$

* v_i is relative to S/C speed

Current of any large energy particles becomes constant.



Langmuir probe theory

LP measured currents: $I = I_i + \cancel{I_e} + I_{ph,\,Ly\text{-}\alpha} + \cancel{I_{e^*,\,i^*}} + I_{dust}$

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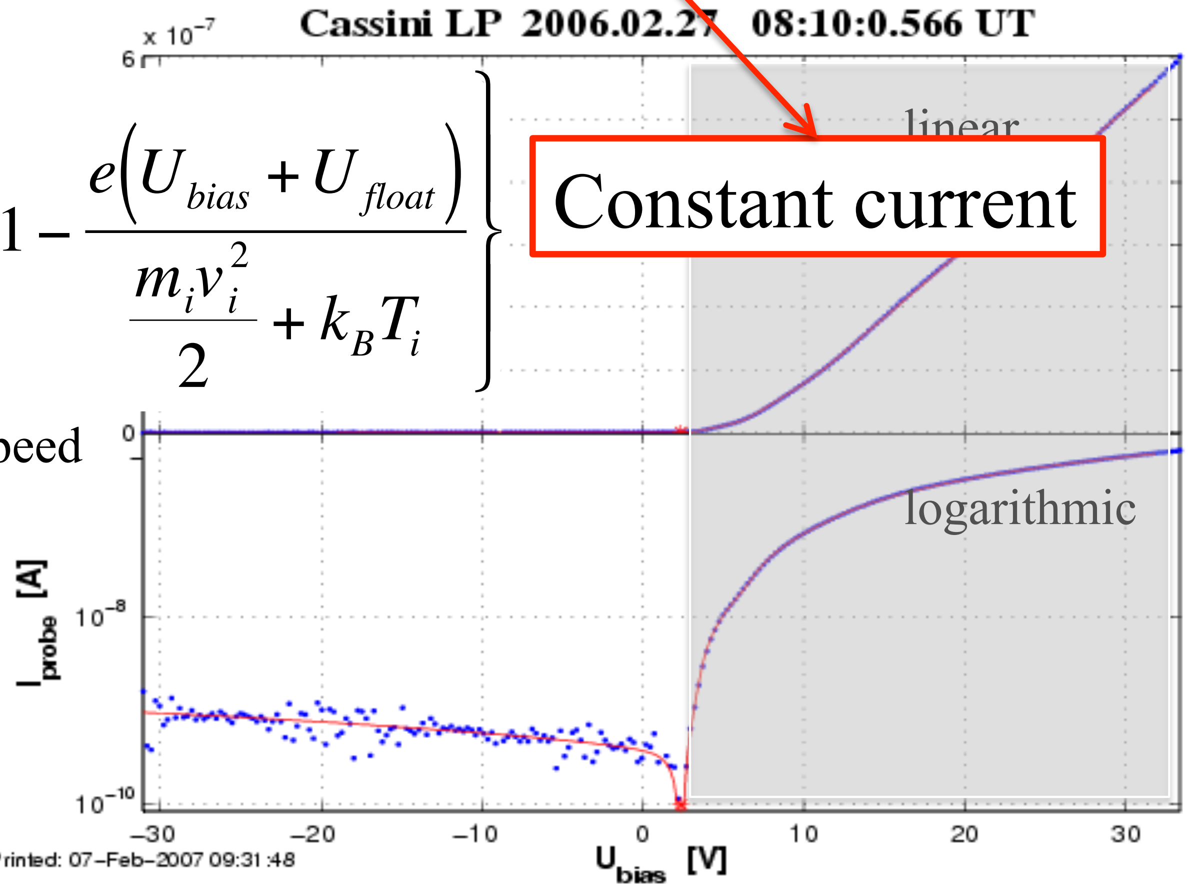
* v_i is relative to S/C speed



Langmuir probe theory

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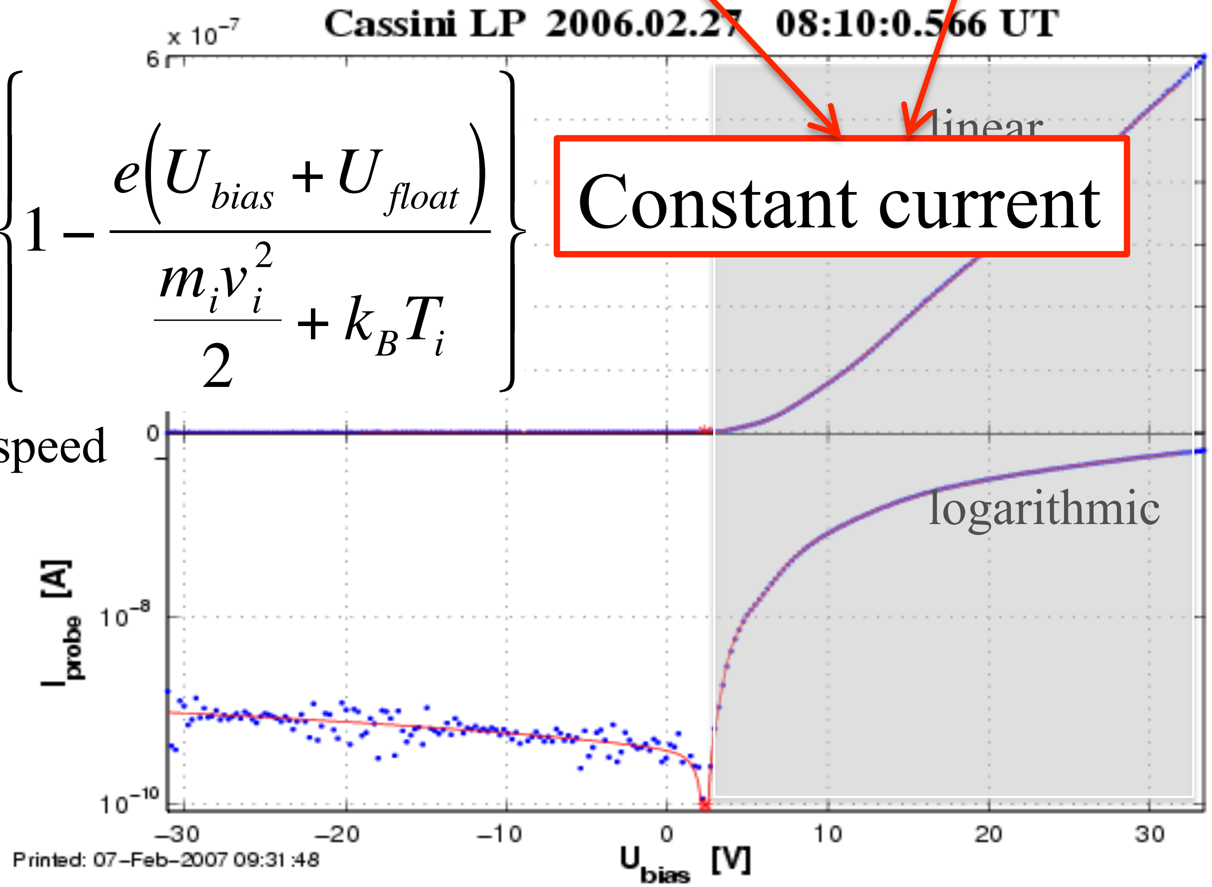
* v_i is relative to S/C speed

Constant current



Langmuir probe theory

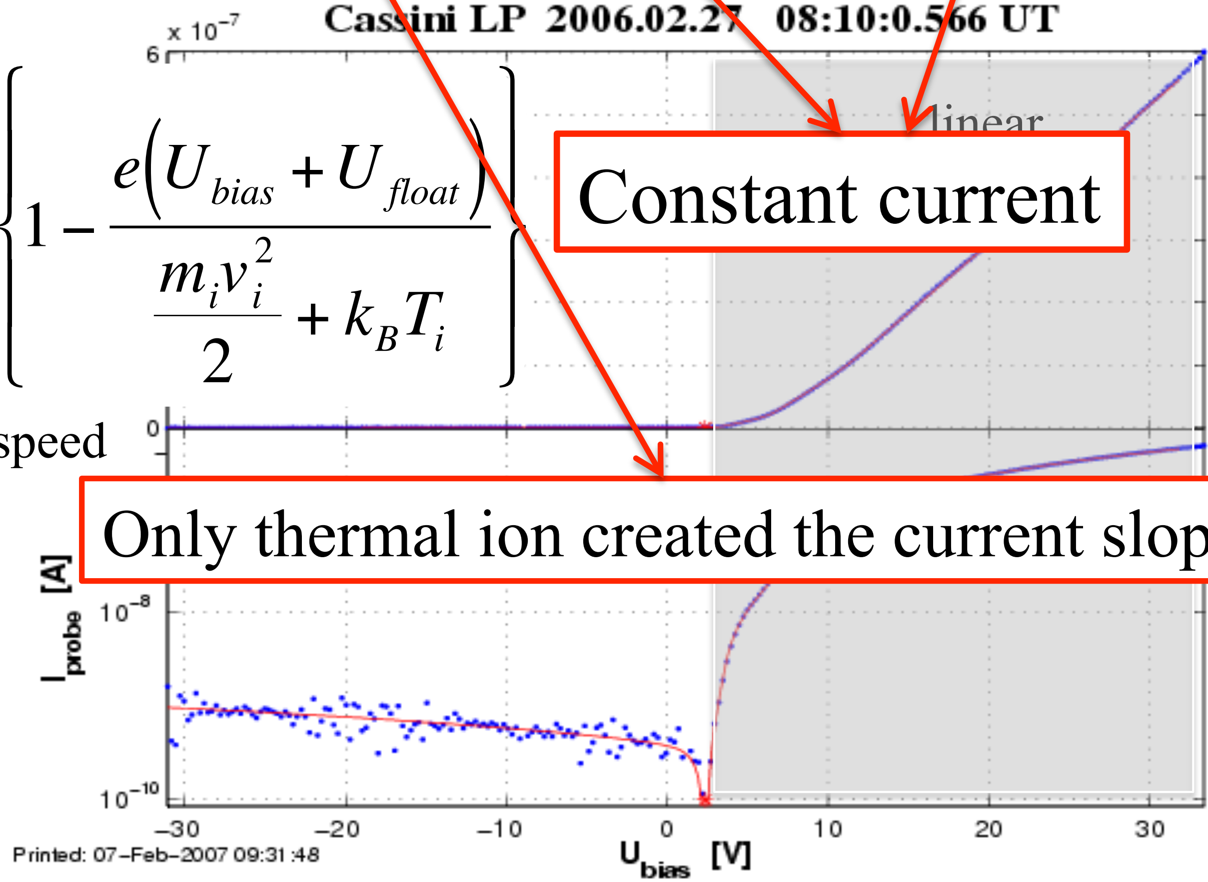
LP measured currents: $I = I_i + I_e + I_{ph,\, Ly\text{-}\alpha} + I_{e*,\, i*} + I_{dust}$

From OML theory (with Maxwellian distribution function, Fahlesson approximation):

U < 0 (ion side)

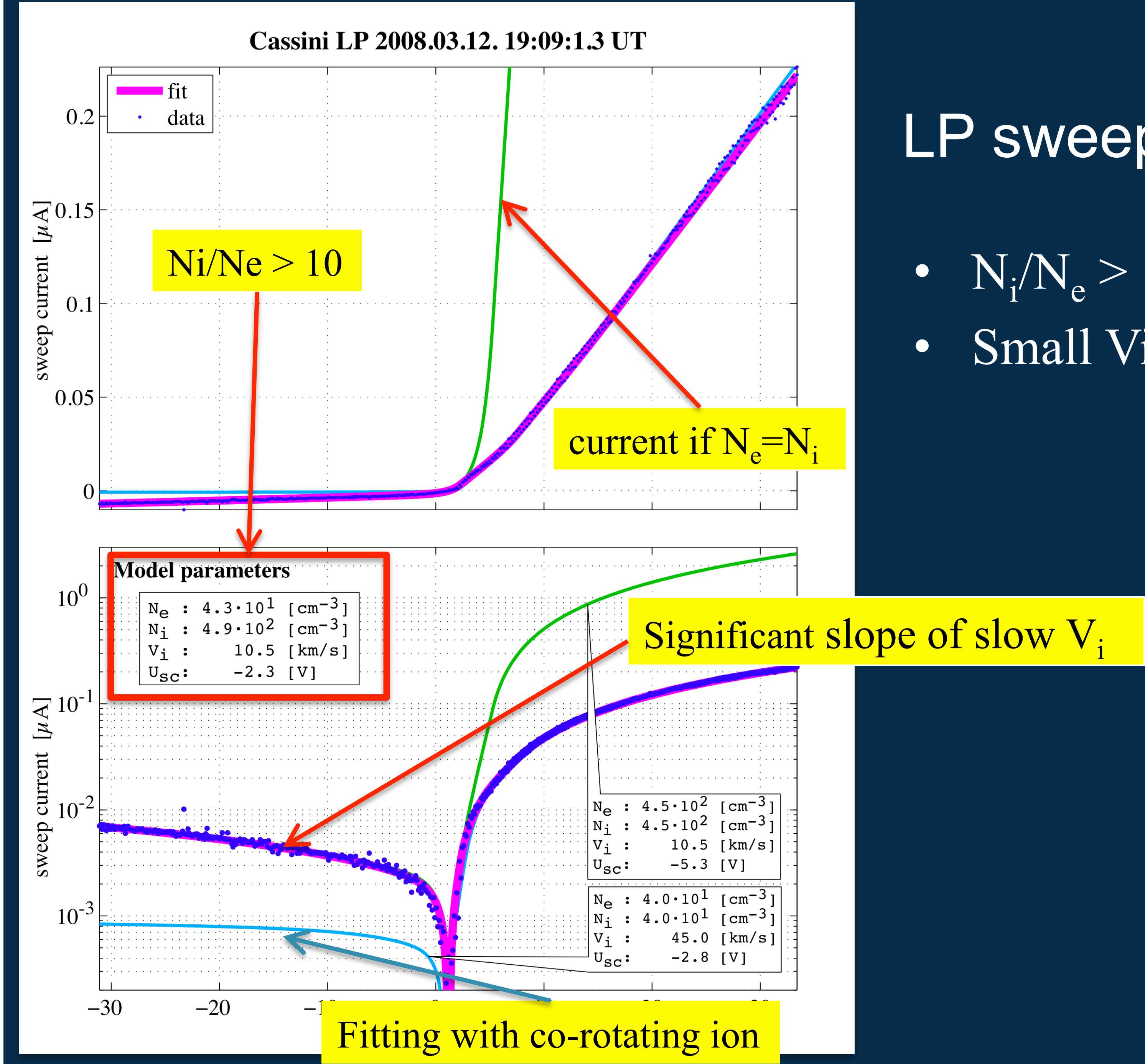
$$I_i = A_{LP} n_i q_i \sqrt{\frac{v_i^2}{16} + \frac{k_B T_i}{2\pi m}} \left\{ 1 - \frac{e\left(U_{bias} + U_{float}\right)}{\frac{m_i v_i^2}{2} + k_B T_i} \right\}$$

* v_i is relative to S/C speed



Constant current

Only thermal ion created the current slope



LP sweep in the plume

- $N_i/N_e > 10$
- Small Vi

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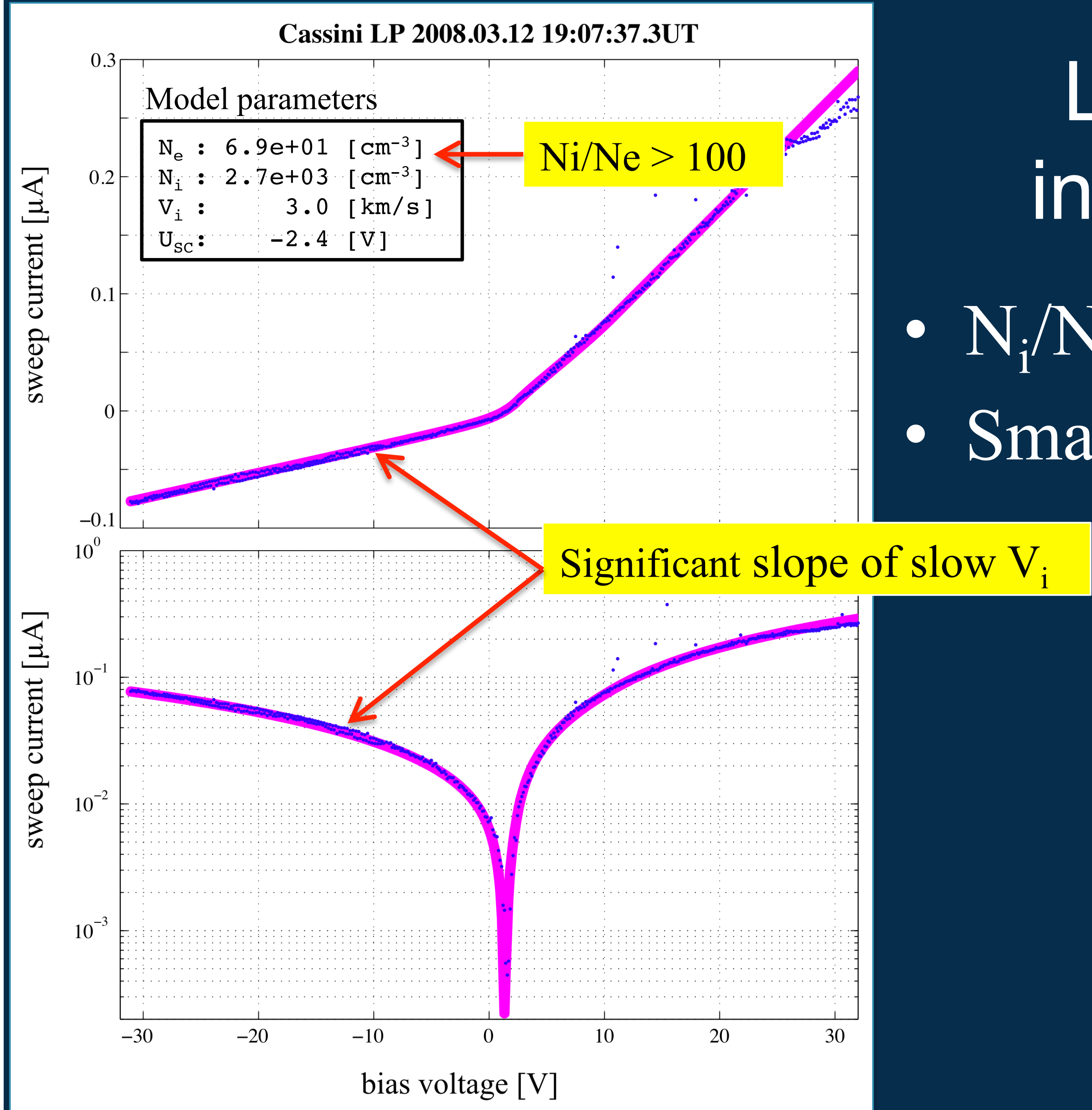

LP sweep in the plume

- $N_i/N_e > 100$
- Small Vi

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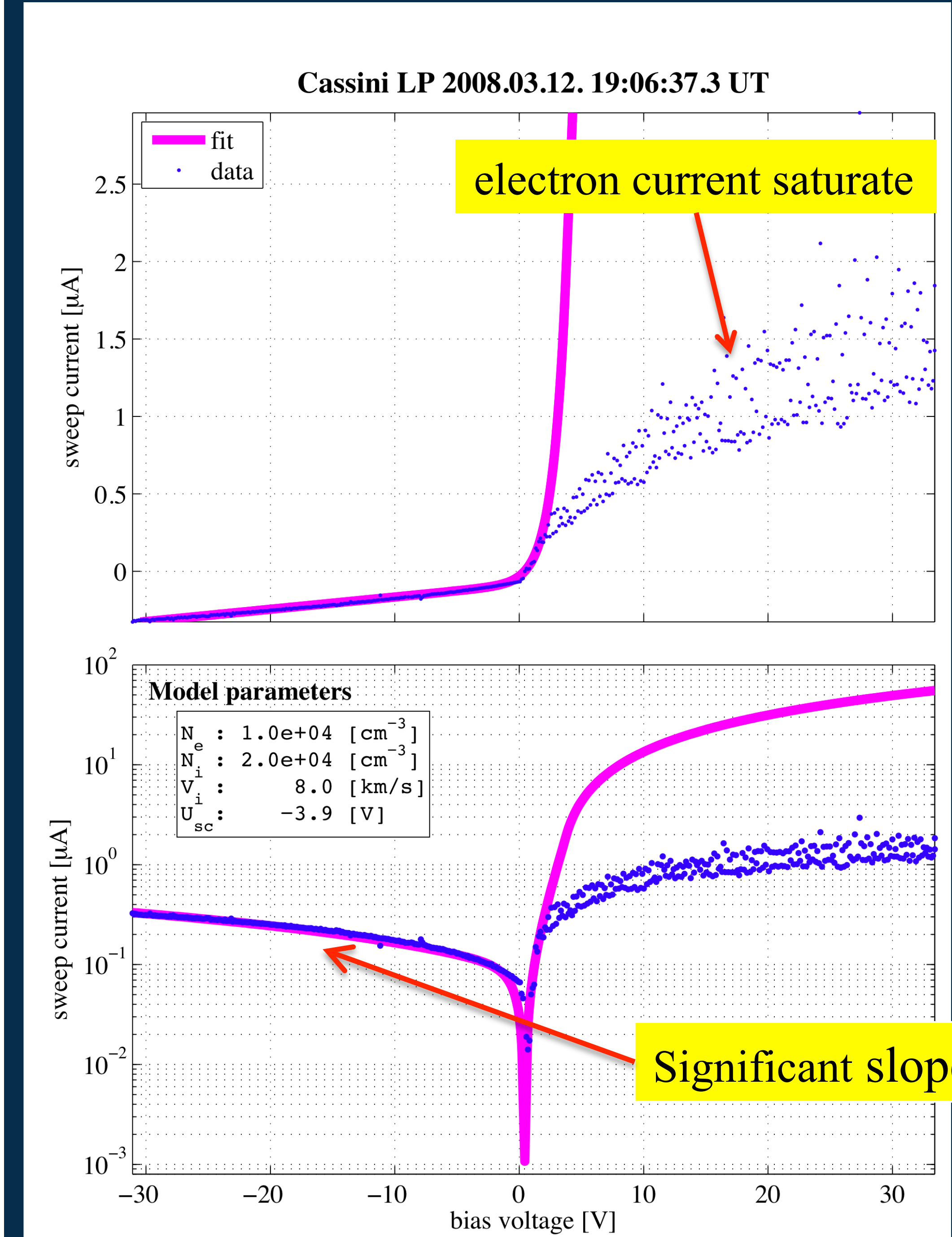
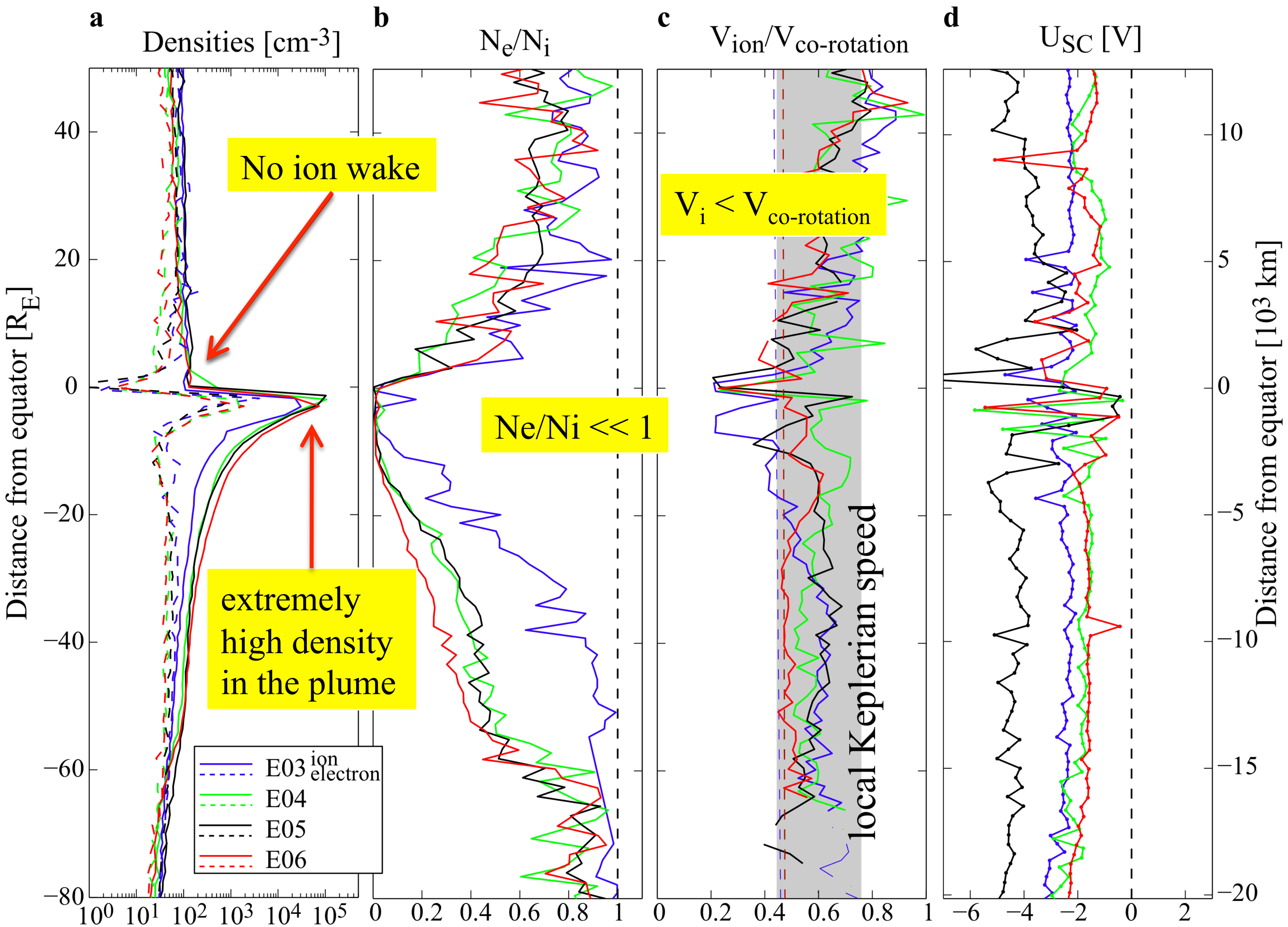
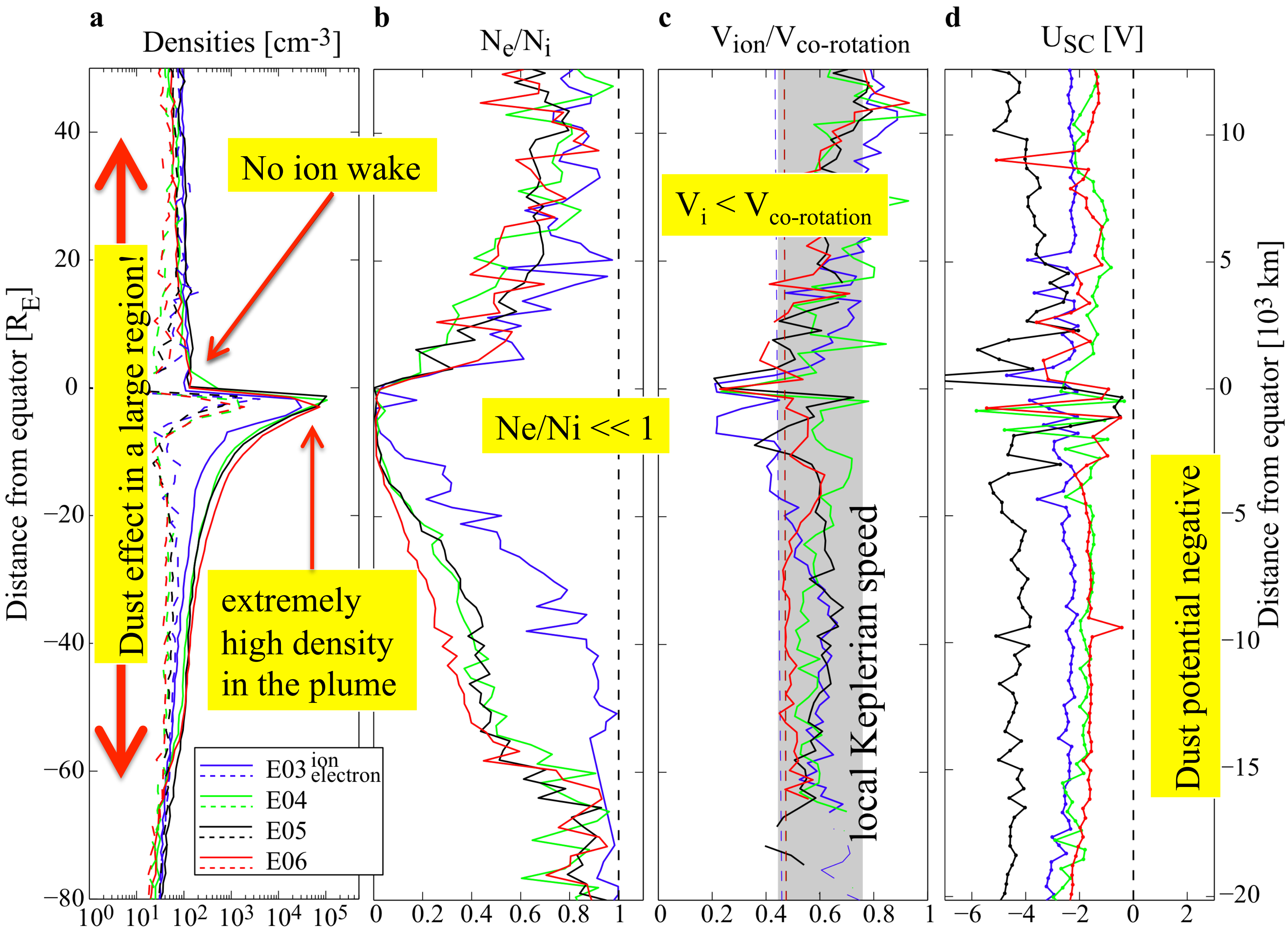
LP sweep in the plume centre



- Electron current saturates due to very low Te.
- I_e saturation also indicates the dust-plasma potential is very small.
- Again, the ion current slope is due to the small V_i.



a
Densities [cm-3]
b
Ne/Ni
c
Vion/Vco-rotation
d
USC [V]
No ion wake
extremely high density in the plume
Ne/Ni << 1
Vi < Vco-rotation
local Keplerian speed
Distance from equator [RE]
Distance from equator [10^3 km]
E03 ion electron
E04
E05
E06



a
Densities [cm-3]
b
Ne/Ni
c
Vion/Vco-rotation
d
USC [V]
Distance from equator [RE]
Distance from equator [10^3 km]
No ion wake
Dust effect in a large region!
extremely high density in the plume
Vi < Vco-rotation
Ne/Ni << 1
local Keplerian speed
Dust potential negative
E03 ion electron
E04
E05
E06

RPWS/LP observation shows:

- ✓ Large Ne and Ni in the Enceladus plume.
  → Enceladus creates dense plasma.
- ✓ $N_e/N_i << 0.5$ (≤ 0.01 in the plume). → Electron attaches to dust.
- ✓ No N_i wake effect. → Surrounding plasma is not co-rotating.
- ✓ $V_i \sim V_{Kepler} < V_{co\text{-}rotation}$.

Electrons are attached to nm- μm sized dust grains,
and the charged dusts drag ions to slower speed.

$a_d << d_g << \lambda_D$,
Charged dust participate in collective dynamics

	Enceladus plume	outside plume (E ring)
N_e	300 cm^{-3}	80 cm^{-3}
N_i	30,000 cm^{-3}	100 cm^{-3}
T_e	2 eV	2 eV
U_{SC} ($\approx U_d$)	-3 V	-2 V
Nd	95 cm^{-3}	0.25 cm^{-3}
d	0.13 cm	0.98 cm
λ_d	6.04 cm	78 cm

using dust distribution of Yaroshenko (2009) (→ Nd)

Havnes number

$$P = \frac{T_p}{N_p} a N_d = \frac{T_p}{N_p} \int a W(a) da$$

Using Havnes number, the balance condition for the electric current into the dust grains can be expressed as [*Barkan et al., 1994*]:

$$I_d = I_i + I_e$$

$$\sqrt{\frac{m_i}{m_e}} \left(1 + \frac{4\pi\varepsilon}{e} P \frac{eU}{kT}\right) \exp\left(\frac{eU}{kT}\right) + \frac{eU}{kT} - 1 = 0$$

relationship between P and $\frac{eU}{kT}$

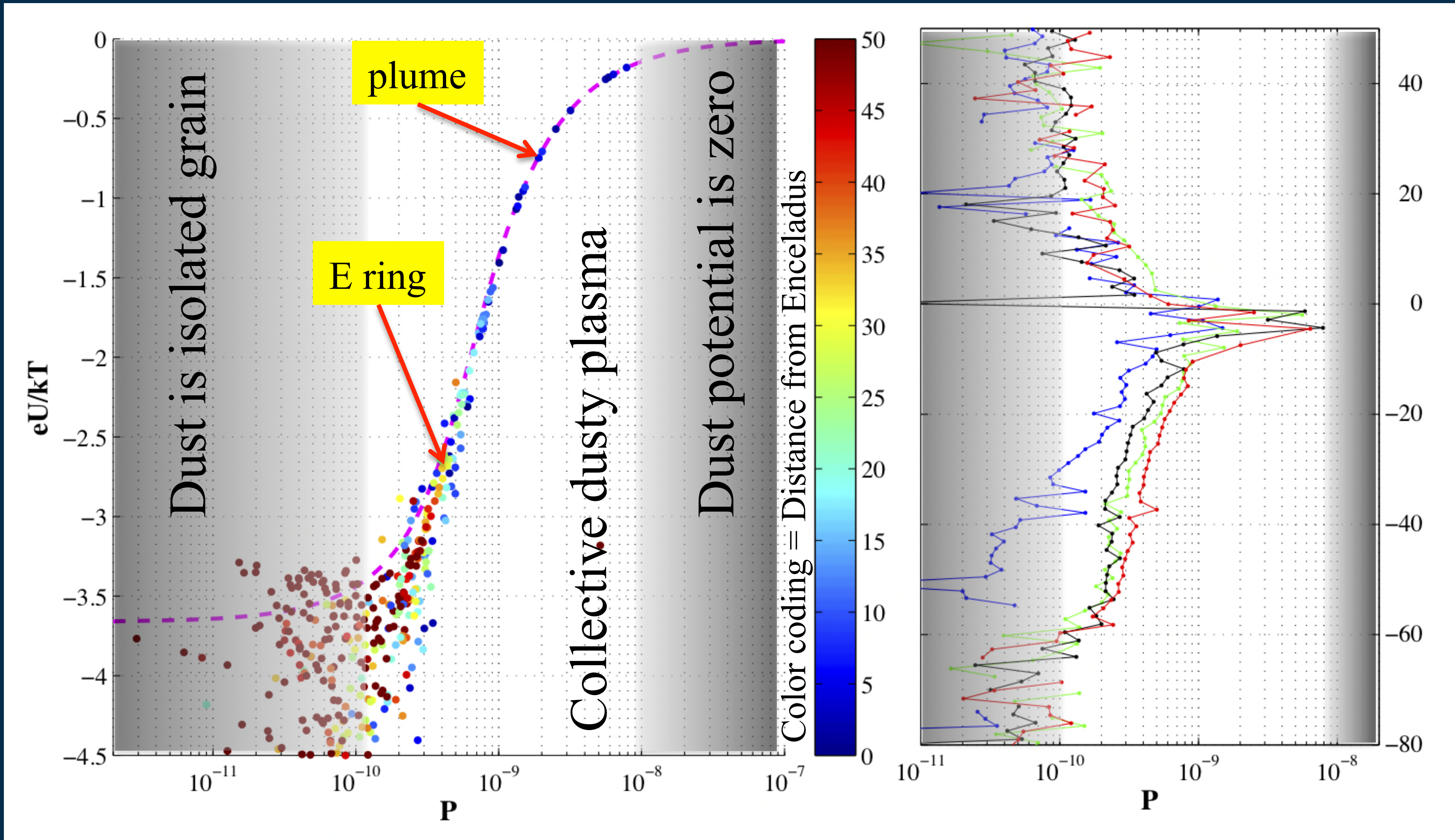
Using the relationship of the total charge density of dust

$$\rho_d = 4\pi\varepsilon \int a W(a) da = q(n_i - n_e)$$

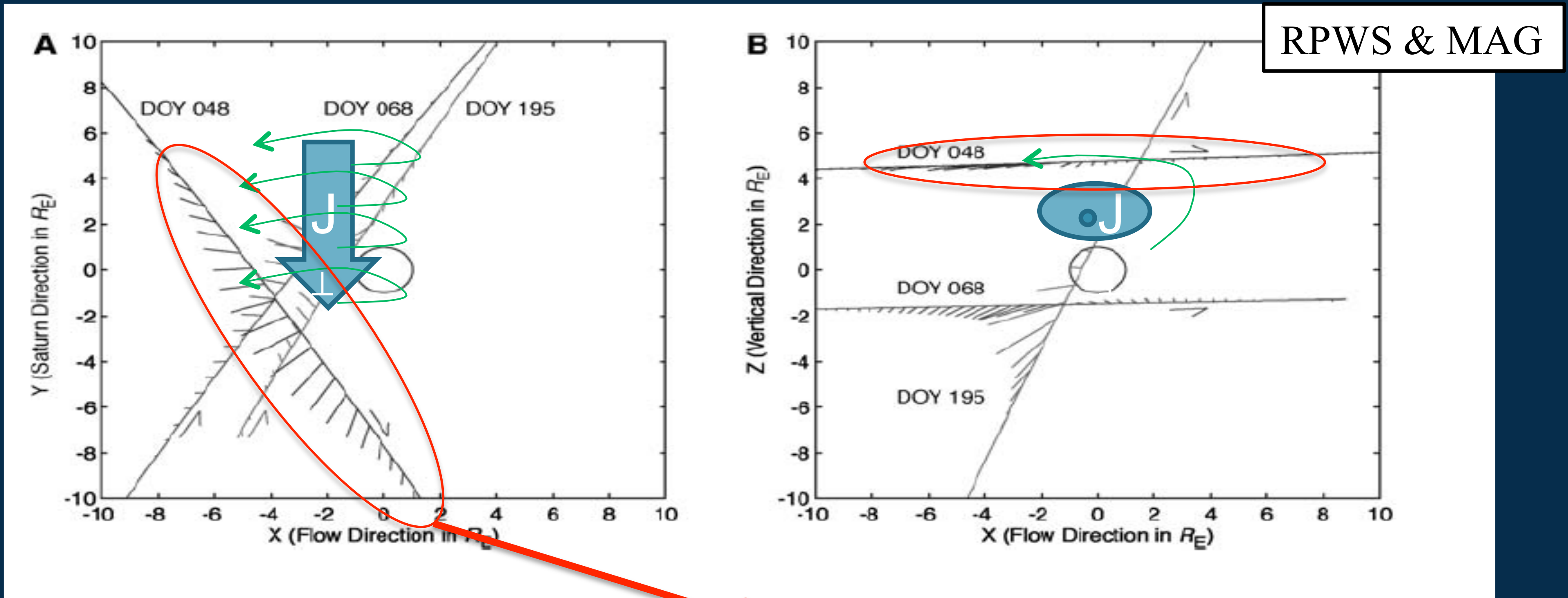
$$P = \frac{T_p}{N_p} a N_d = \frac{T_p}{N_p} \frac{q(N_i - N_e)}{4\pi\varepsilon U}$$

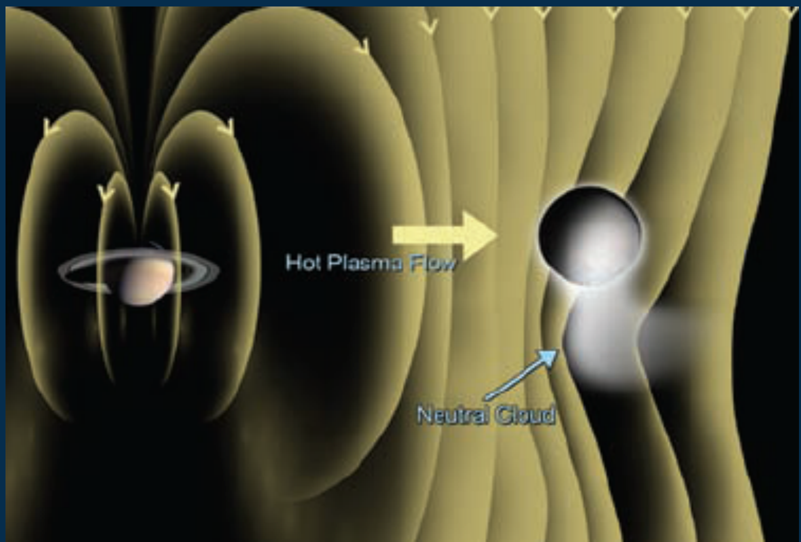
Calculation does not depend on dust distribution.

Havnes Parameter for our measurements



MOP 2011 Boston, Morooka et al.
Saturn's Dust and low tempetarure plasma





- DOY 048: Pass over north hemisphere, 4 Re away
- See strong –Bx perturbation in northern hemisphere
- Difficult to place this pass in context with more localized S source

also suggesting the dust pick up process near Enceladus

from Farrell et al MAPS 2011 talk

Enceladus plume/E ring studies

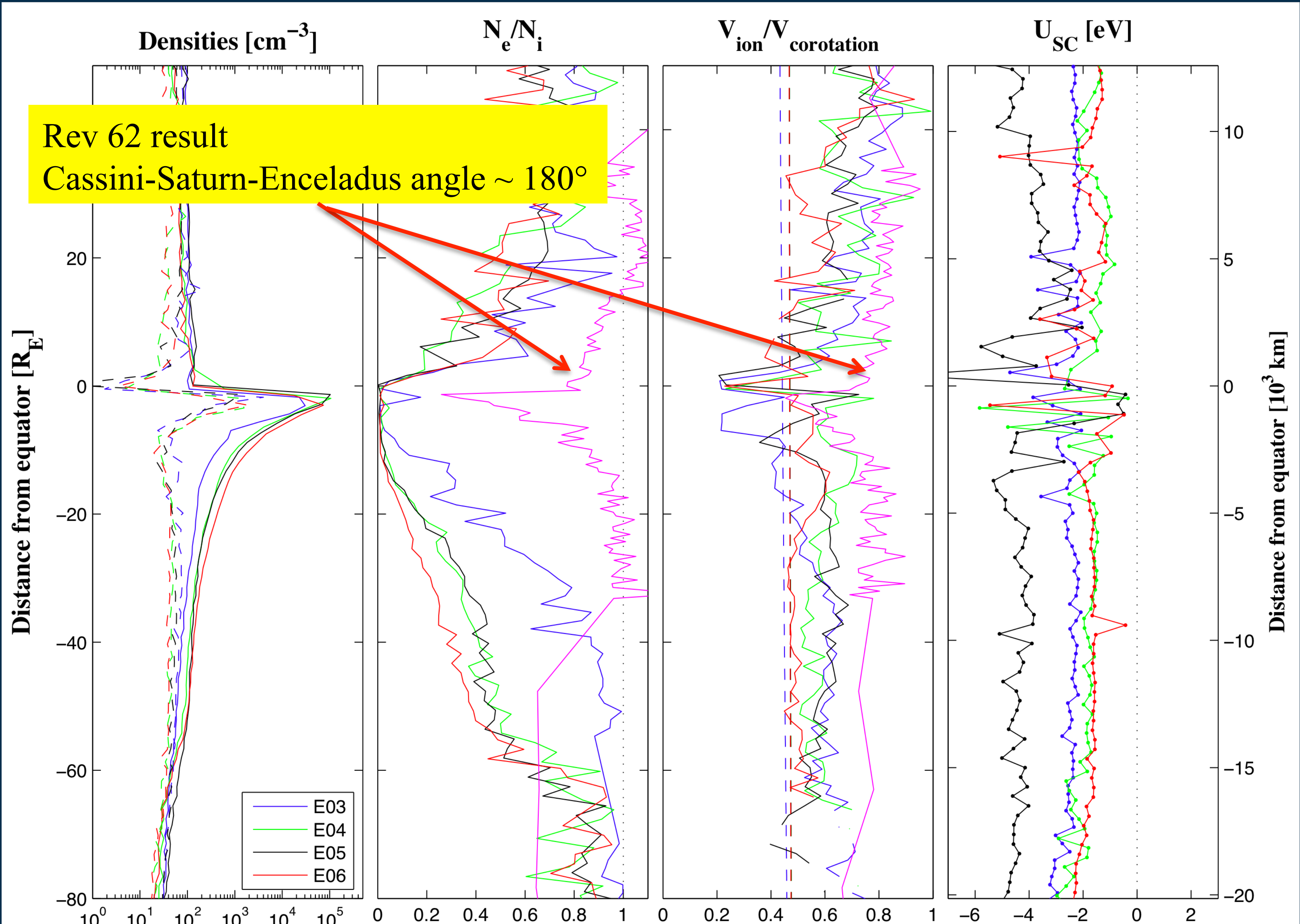
- Plume detection by B perturbation:
  Dougherty et al. (2006)
- Neutral observations:
  Waite et al. (2006), Water vapor in the plume
- Dust observations:
  Kempf et al. (2010), CDA submicron sized dust
  Kurth et al. (2006), RPWS submicron sized dust
  Jones et al. (2009), Coates et al. (2010), ≤ nano meter sized dust
- Dust and Plasma observations:
  Tokar et al. (2009), high energy ions slowing down
  Farrell et al. (2010), CAPS & RPWS comparison and suggesting dust pick up
- Hybrid simulation study

  Simon et al. (2011), Kreigel et al. (2011),

  Enceladus-magnetosphere interaction considering dusty plume can explain mysterious By component.
- Nano meter sized dust density estimation by CAPS

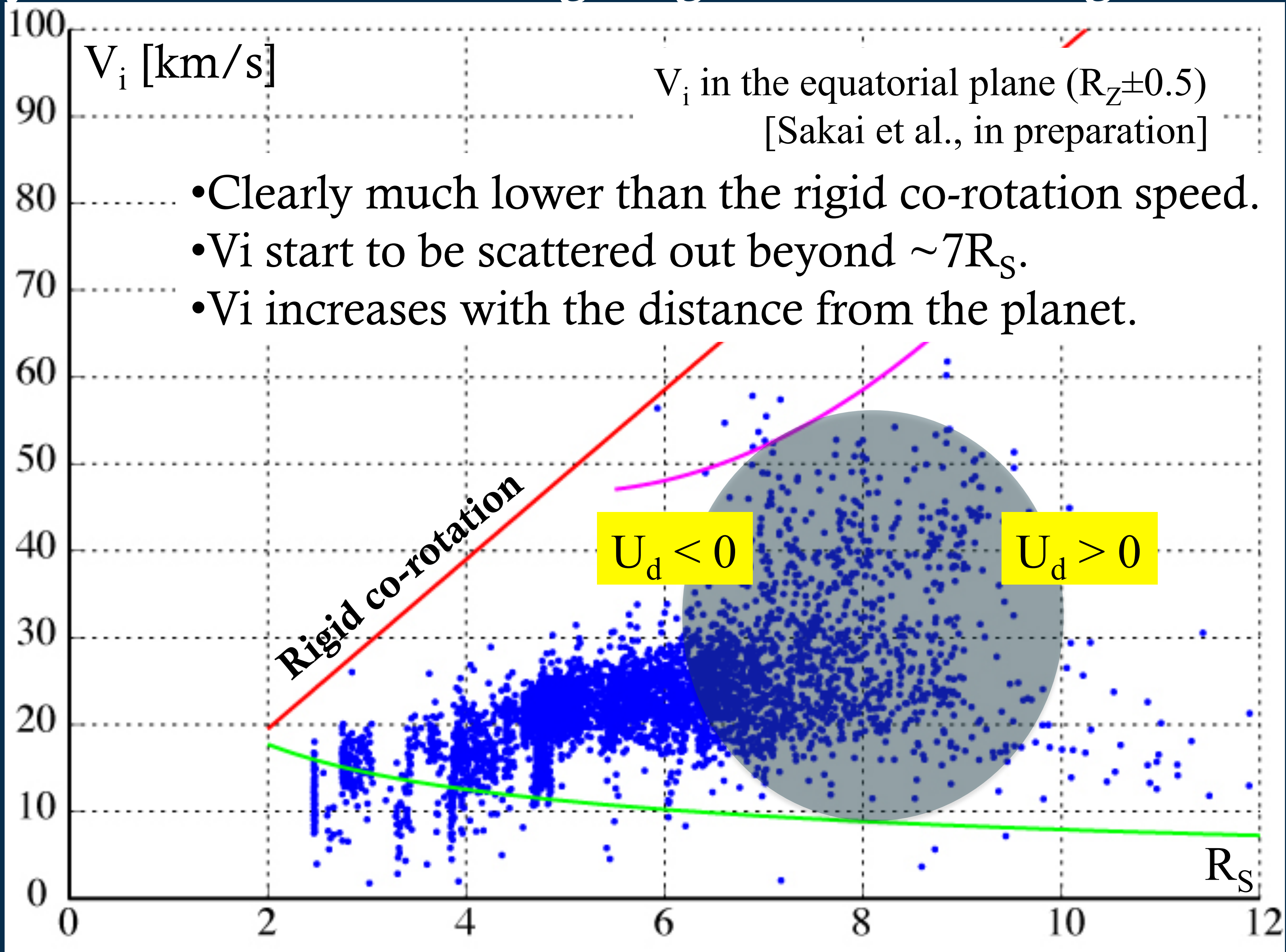
  Hill et al. (talk yesterday),

  Negative grains density ≈ 10^3 [cm^{-3}]

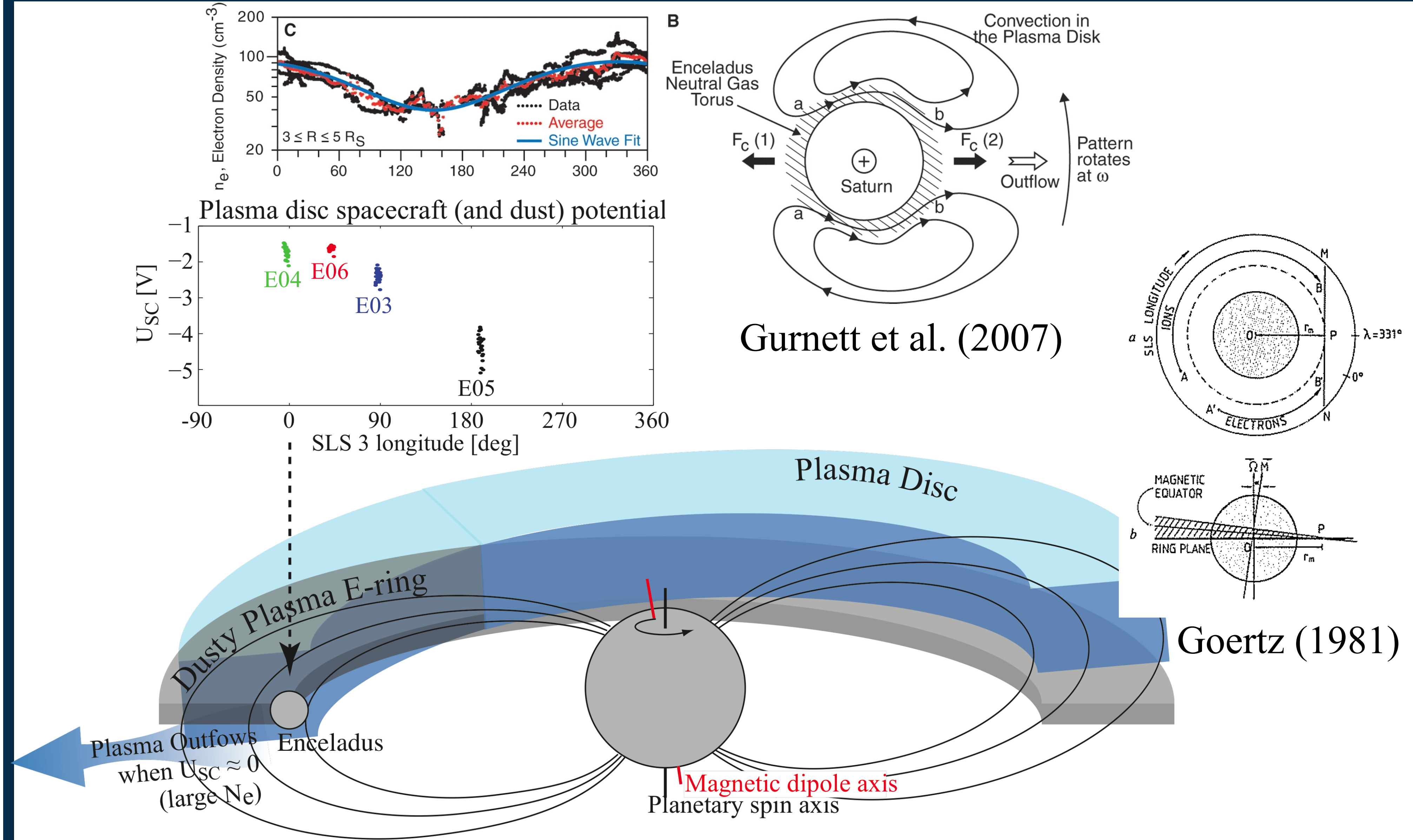


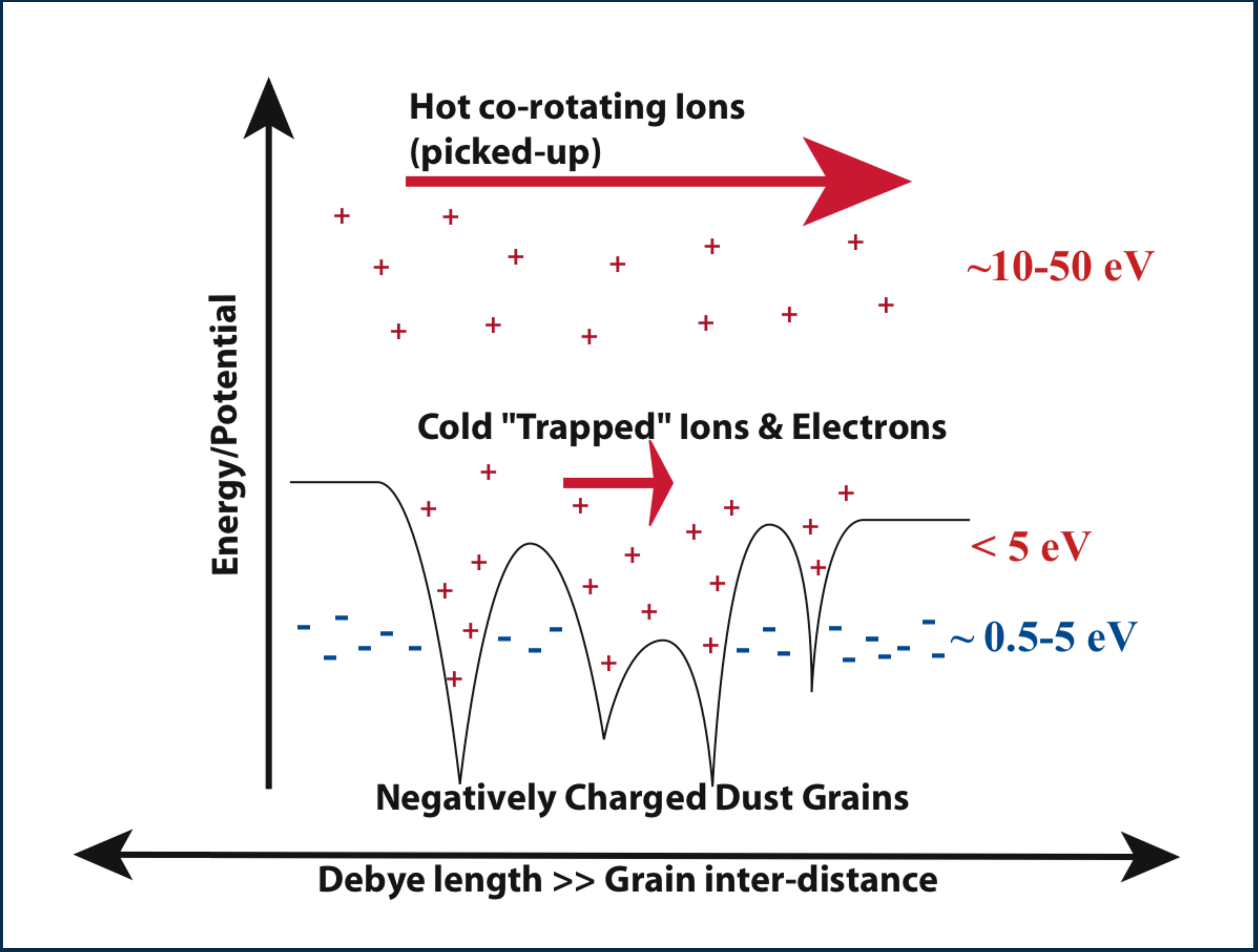
MOP 2011 Boston, Morooka et al.
Saturn's Dust and low tempetarure plasma

Dusty Plasma effect in a large region of the E-ring.



Effect of the dusty plasma in the magnetosphere (suggestion)



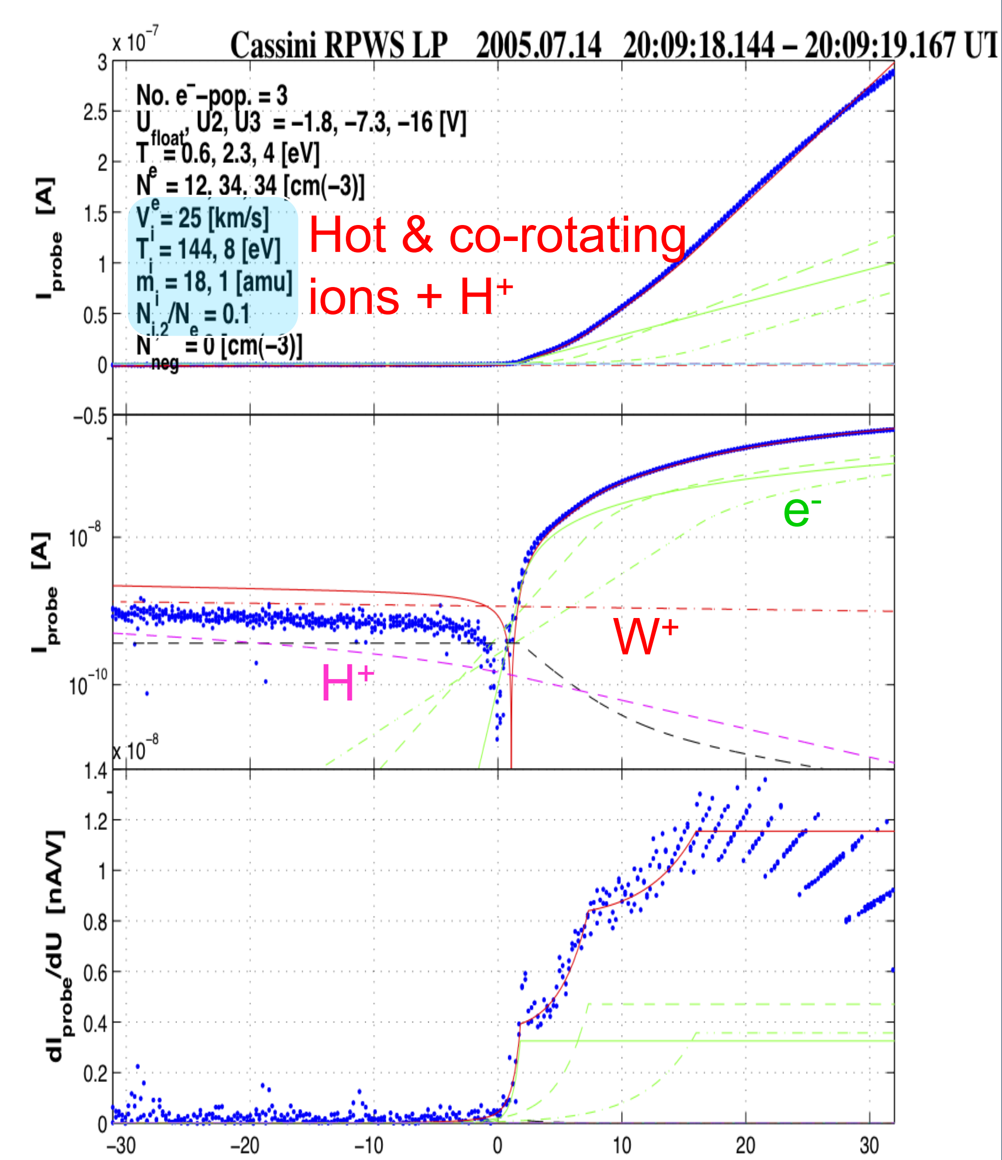


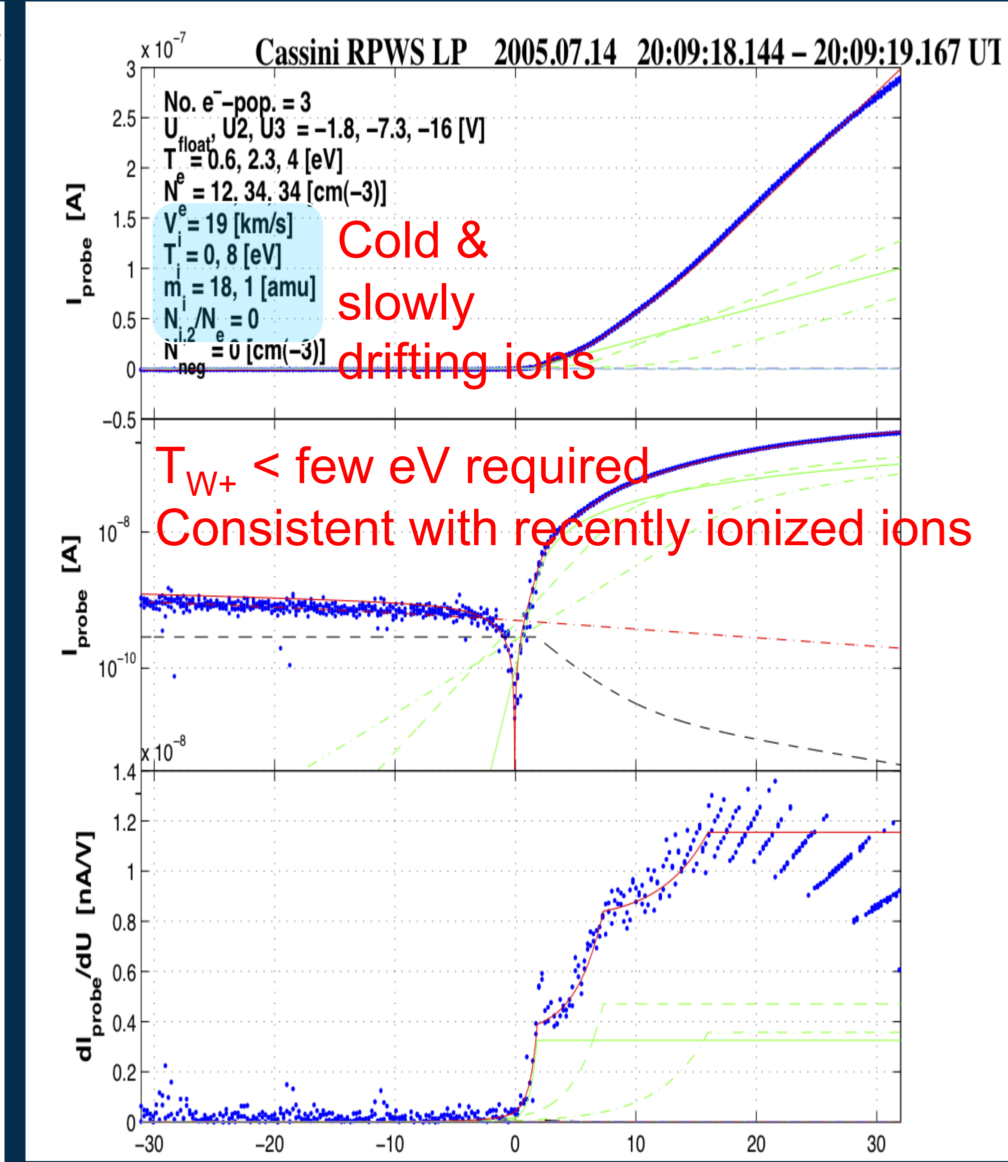
Wahlund et al., (2009)

$r_d << d << \lambda_{D,}$ Charged dust participate in screening & collective dynamics of ensemble

Enceladus far plume

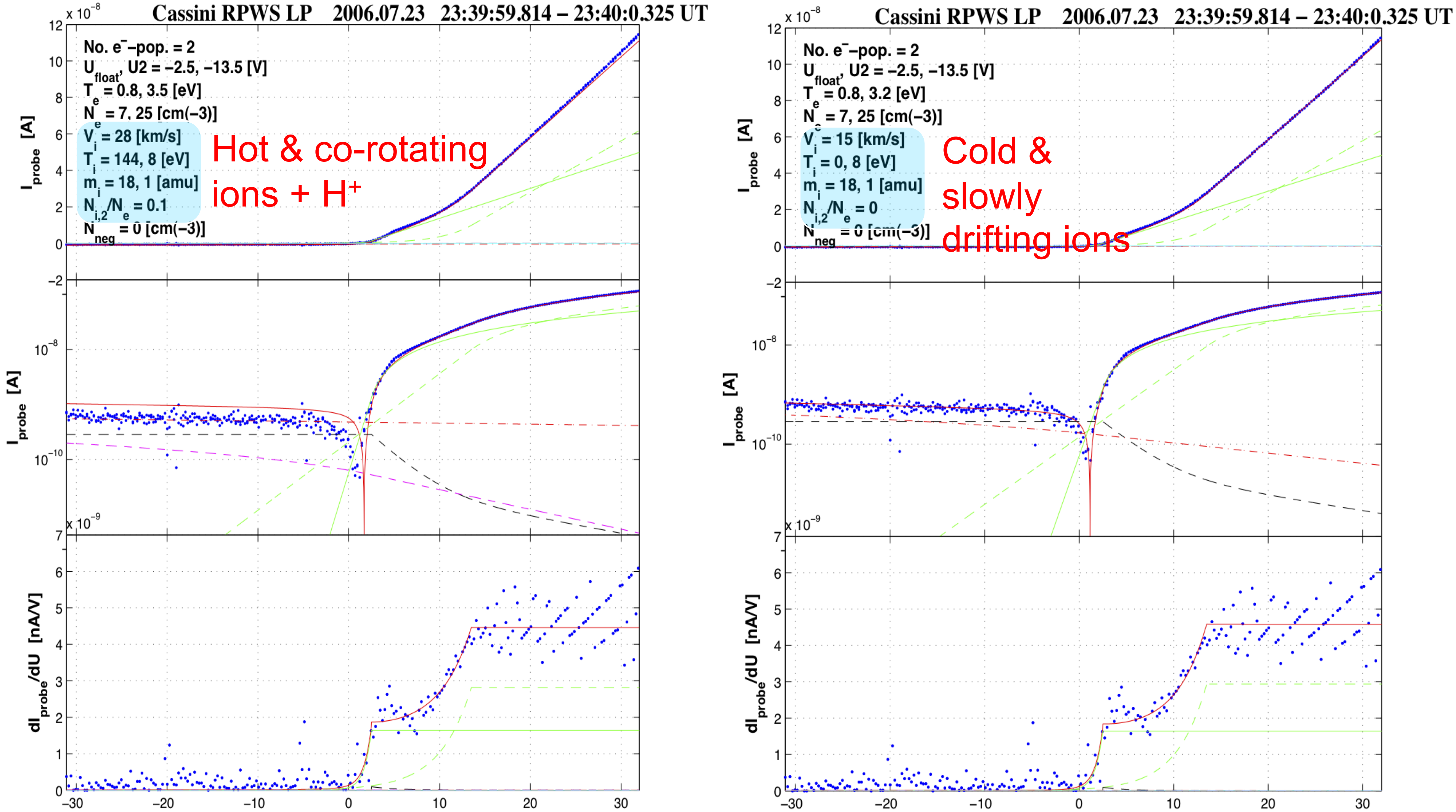
Contribution from secondary electrons will make ions colder & slower !
[see also *Jacobsen et al., 2009*]





U_{bias} [V]

E-ring plasma

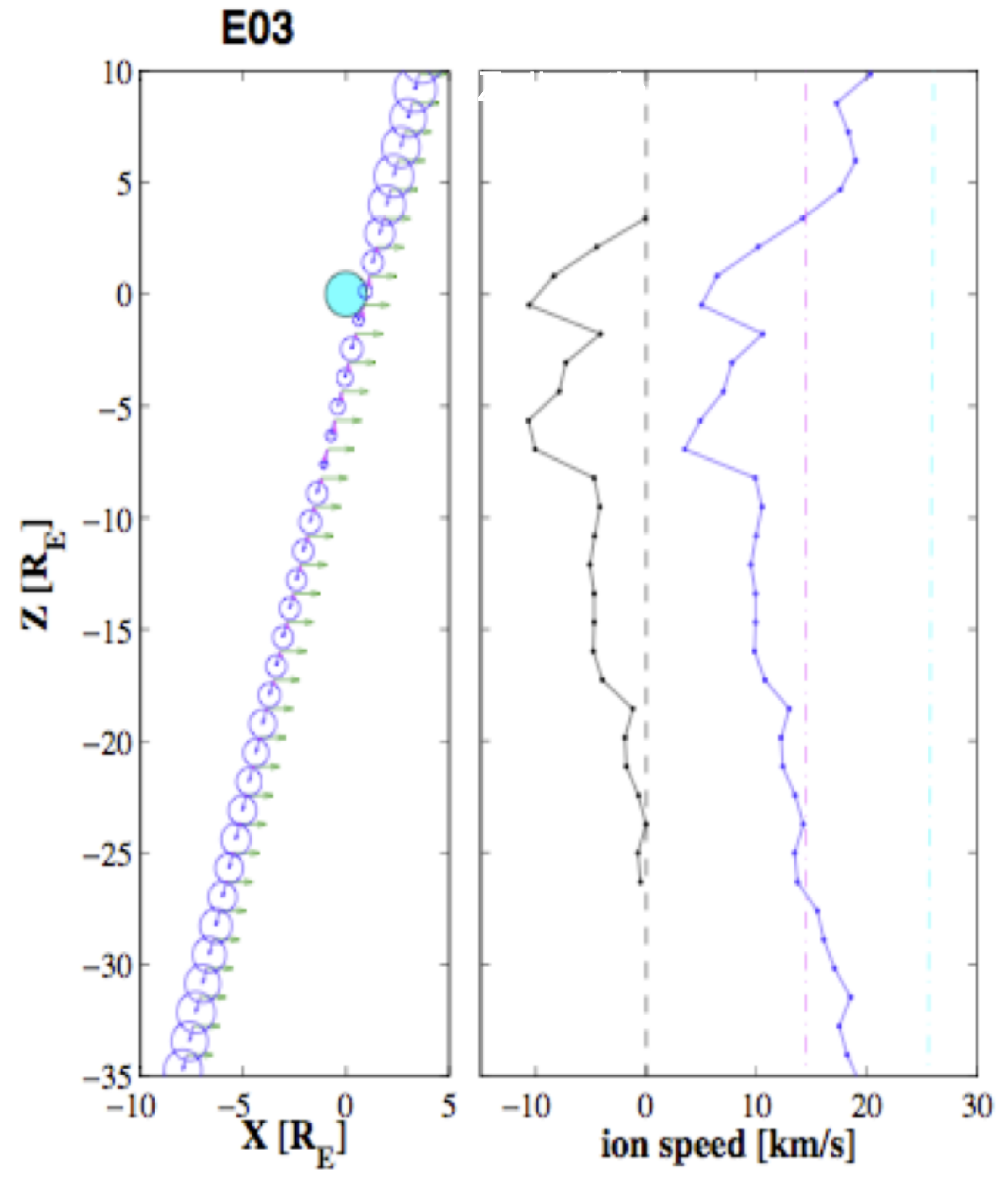


U_{bias} [V]

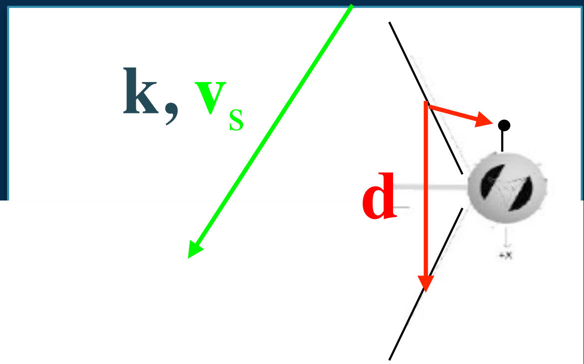
Ion transport along plume

Minimum

- RPWS/LP derived ion speeds
  - The **spacecraft velocity vectors** for each LP sweep sample position in the XZ plane
  - Each circle represents the required end position of the ion velocity
  - The rigid co-rotation velocity vectors
- $V_{z,min}$ >5-10 km/s
  - Plasma is actively accelerated near Enceladus.



Plasma Speed from Interferometry



Phase: $$\varphi = \mathbf{k}\cdot\mathbf{d} + n\pi$$

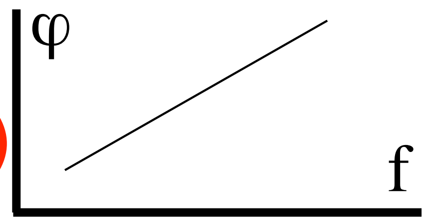
Phase Dispersion: $$\frac{\partial\varphi}{\partial\omega} = \frac{\partial}{\partial\omega}\left[\mathbf{k}\cdot\mathbf{d} + n\pi\right] \quad\Rightarrow\quad \frac{\partial\omega}{\partial\mathbf{k}} = \left(\hat{k}\cdot\hat{d}\right) d\left[\frac{\partial\varphi}{\partial\omega}\right]^{-1}$$

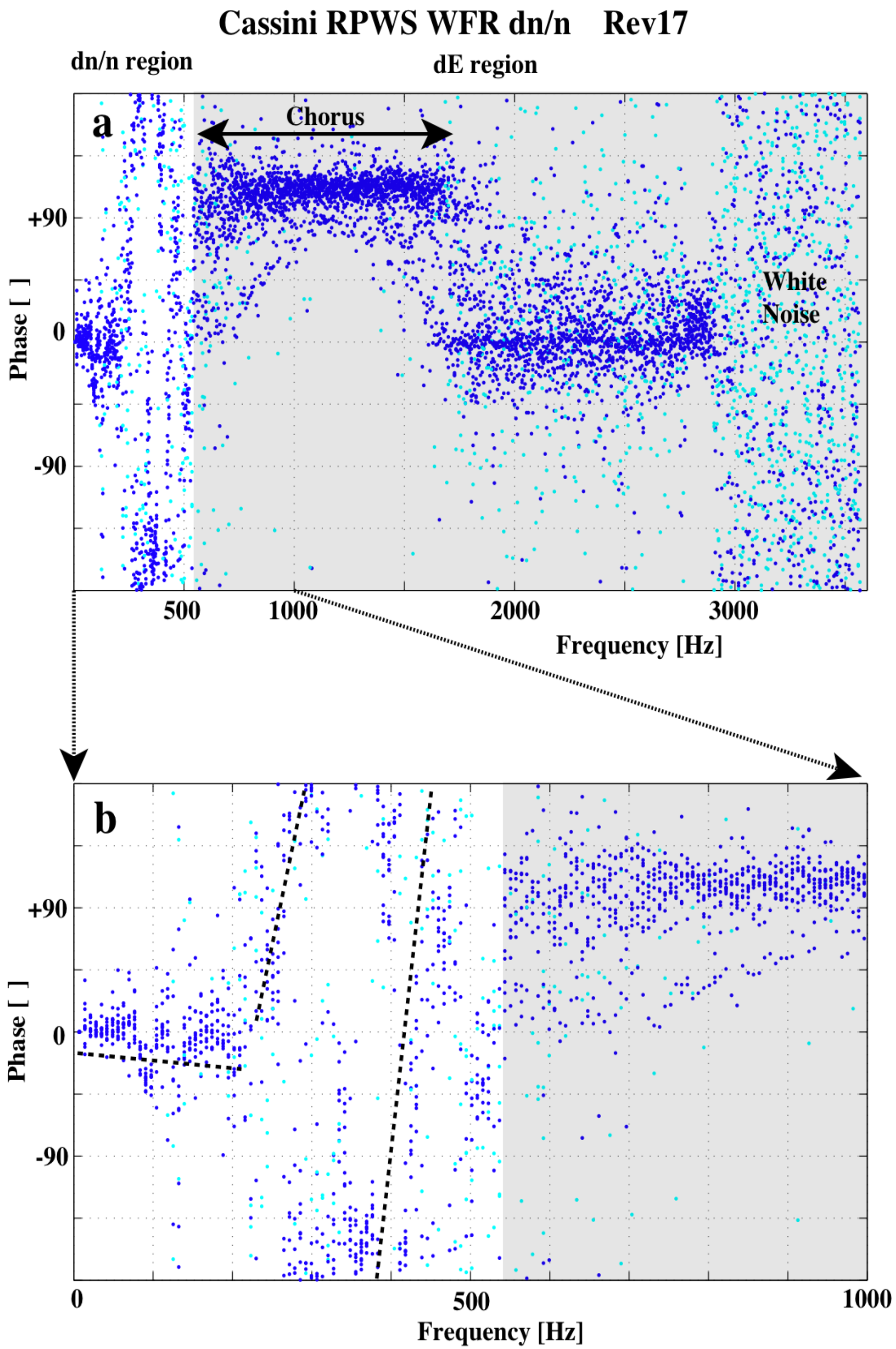
Doppler: $$\omega = \omega_0 + \mathbf{k}\cdot\mathbf{v}_s \qquad \text{where} \quad \mathbf{v}_s = \left(\mathbf{v}_{sc} - \mathbf{v}_{plasma}\right)$$

$$\text{giving} \quad \frac{\partial\omega}{\partial\mathbf{k}} = \frac{\partial\omega_0}{\partial\mathbf{k}} + \left(\hat{k}\cdot\hat{v}_s\right) \mathrm{v}_s$$

Equating: $$\underbrace{\frac{\partial\omega_0}{\partial\mathbf{k}}}_{<<} + \underbrace{\left(\hat{k}\cdot\hat{v}_s\right)}_{=1}\mathrm{v}_s = \left(\hat{k}\cdot\hat{d}\right) \mathrm{d} \left[\frac{\partial\varphi}{\partial\omega}\right]^{-1}$$

Plasma inhom.: $$\mathrm{v}_s = \cos\theta_{sd}\; d\,\Delta f\left(\frac{2\pi}{\Delta\varphi[\mathrm{rad}]}\right)$$





Interferometer results

[Wahlund et al., PSS, 2009]

512 fft, 32 averages, 13 such

Two δn/n-signature slopes!

42-55 km/s (θ_{sd}= 0 assumed)

Co-rot: 46-48 km/s, Scales ~100 m

12-14 km/s (θ_{sd}= 0 assumed)

Keplerian: 11.5 km/s, Scales ~λ_D