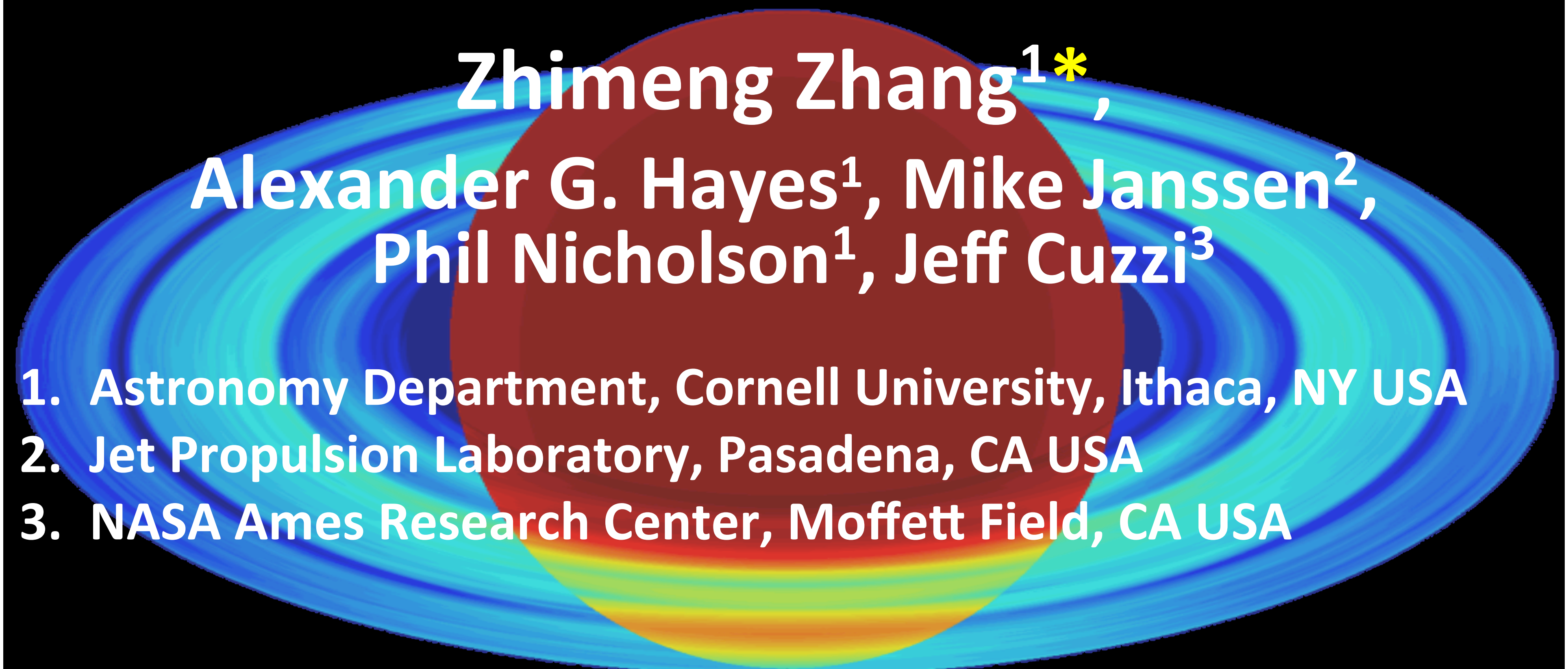
Zhimeng Zhang

Cornell University

Cleaning Up Saturn's Rings: Microwave Emission from Non-Icy Ring Material



Zhimeng Zhang[1*],

Alexander G. Hayes[1], Mike Janssen[2], Phil Nicholson[1], Jeff Cuzzi[3]

1. Astronomy Department, Cornell University, Ithaca, NY USA
2. Jet Propulsion Laboratory, Pasadena, CA USA
3. NASA Ames Research Center, Moffett Field, CA USA

Planetary Rings Workshop, Boulder, CO USA

Wednesday, August 13th, 2014

The Origin of Saturn's Rings

- YOUNG (Post-Voyager, Pre-Cassini)
  - Collisional Disruption of Satellite (Roche 1847, Harris 1984)
    -- Disrupt existing satellite within Roche limit via bombardment
  - Tidal Disruption of Comet or Centaur (Dones 1991)
    -- Disrupt Chiron-sized object crossing within Saturn's Roche zone
- OLD (Pre-Voyager, Post-Cassini)
  - Primordial Remnant (Stewart 2007, Esposito 2010)
    -- Continual recycling of primordial material
  - Collisional Disruption of Satellite (Harris 1984, Charnoz 2009)
    -- Disrupt existing satellite during late heavy bombardment
  - Tidal Disruption of Differentiated Satellite (Canup 2010)
    -- Strip mantle from Titan-sized satellite as it falls into Saturn

- The Nature and abundance of non-icy material can constrain the origin & evolution of Saturn's ring system

Microwaves Observations of Saturn's Rings with Cassini: Why Should We Care?

- At microwave frequencies (λ = 2.2cm), pure icy ring particles are transparent while contaminants behave as blackbodies

  -- Water-ice absorbs in the UV, VIS, and IR

- Cassini (i.e., in-system) microwave observations are ideal for investigating cm-scale ring particles

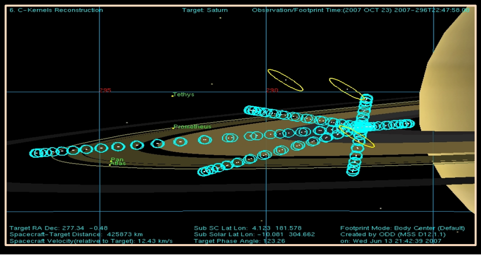
  -- Observe scattered emission from Saturn at a wide range of geometries

  -- Sensitive to size distribution of sub-meter particles

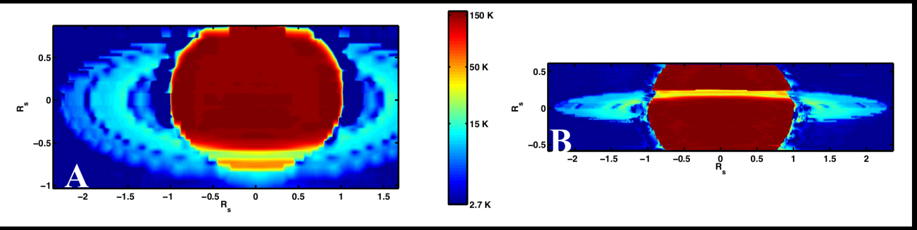
  -- High resolution as compared to ground-based data

Outline

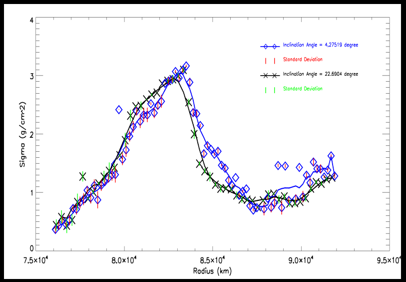
- Description of Observations



- Overview of Calibration/Processing Procedure

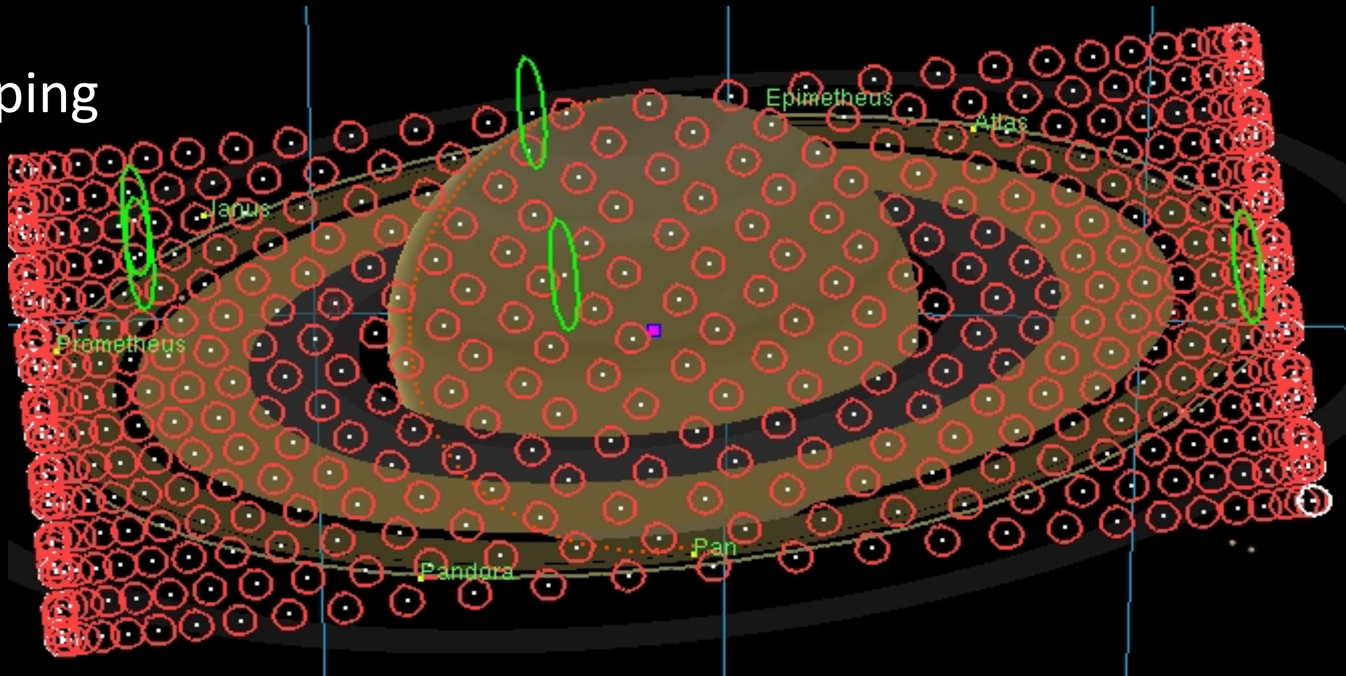


- Abundance of Non-Icy Material from Microwave Thermal Emission

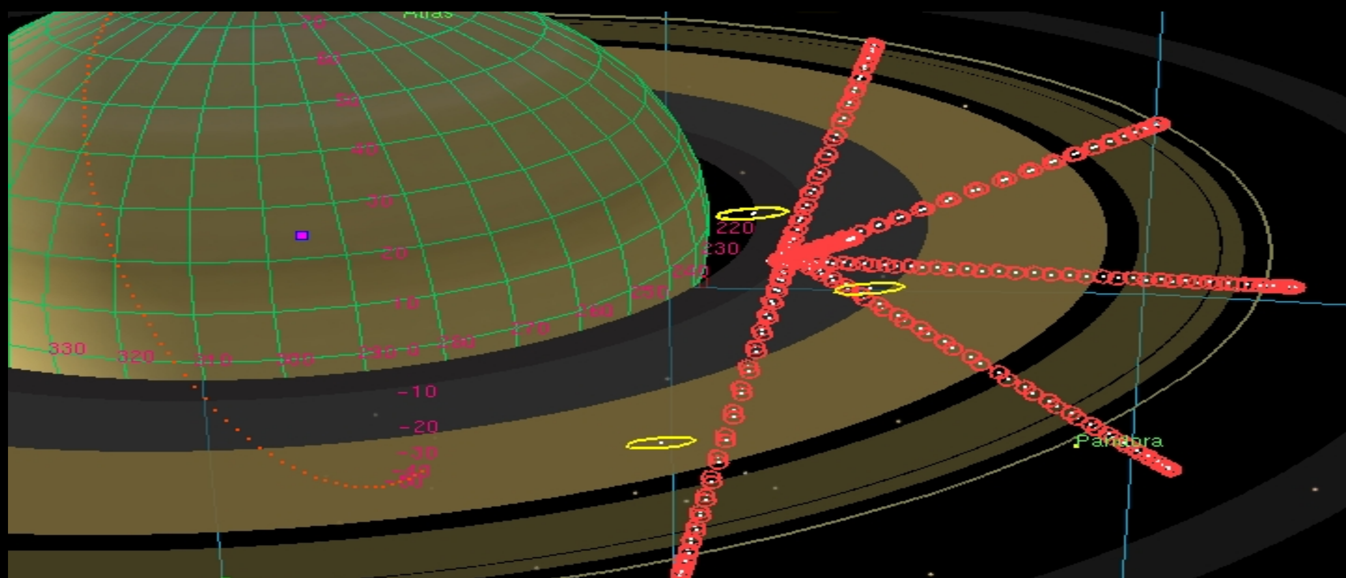


Two Flavors of Ring Observations

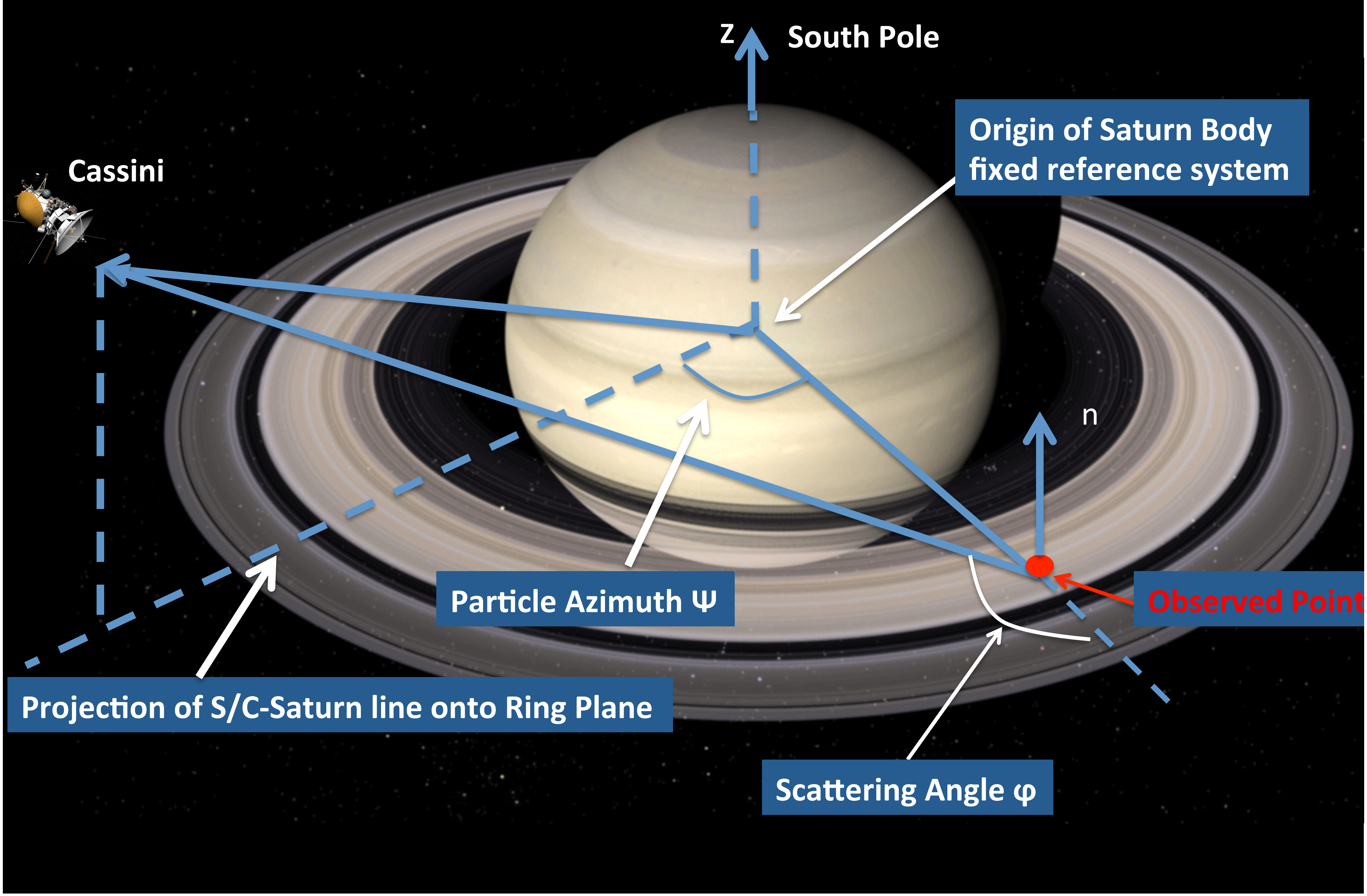
Low Resolution Mapping



High Resolution Spoke Scans



Coordinate Systems



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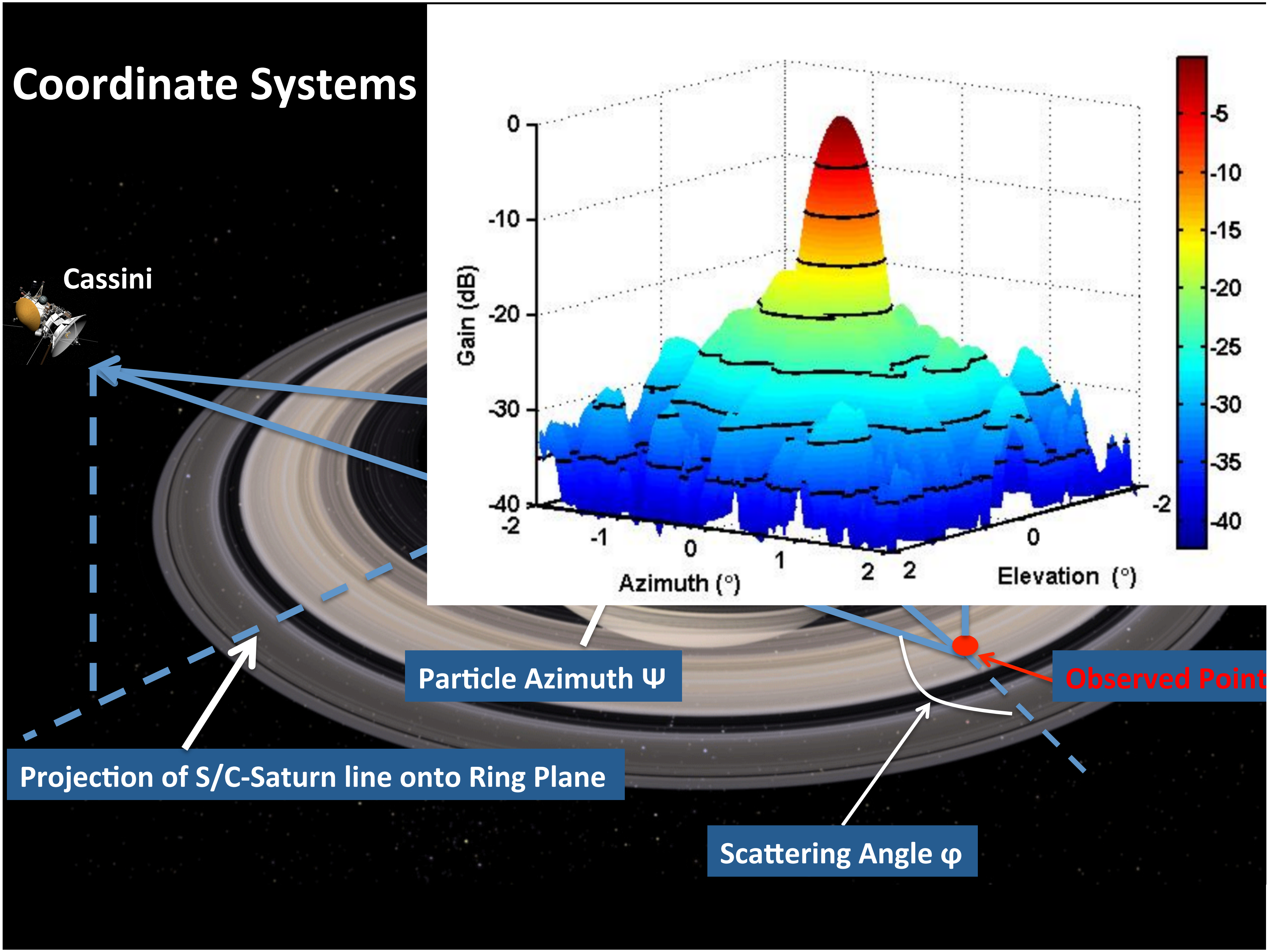
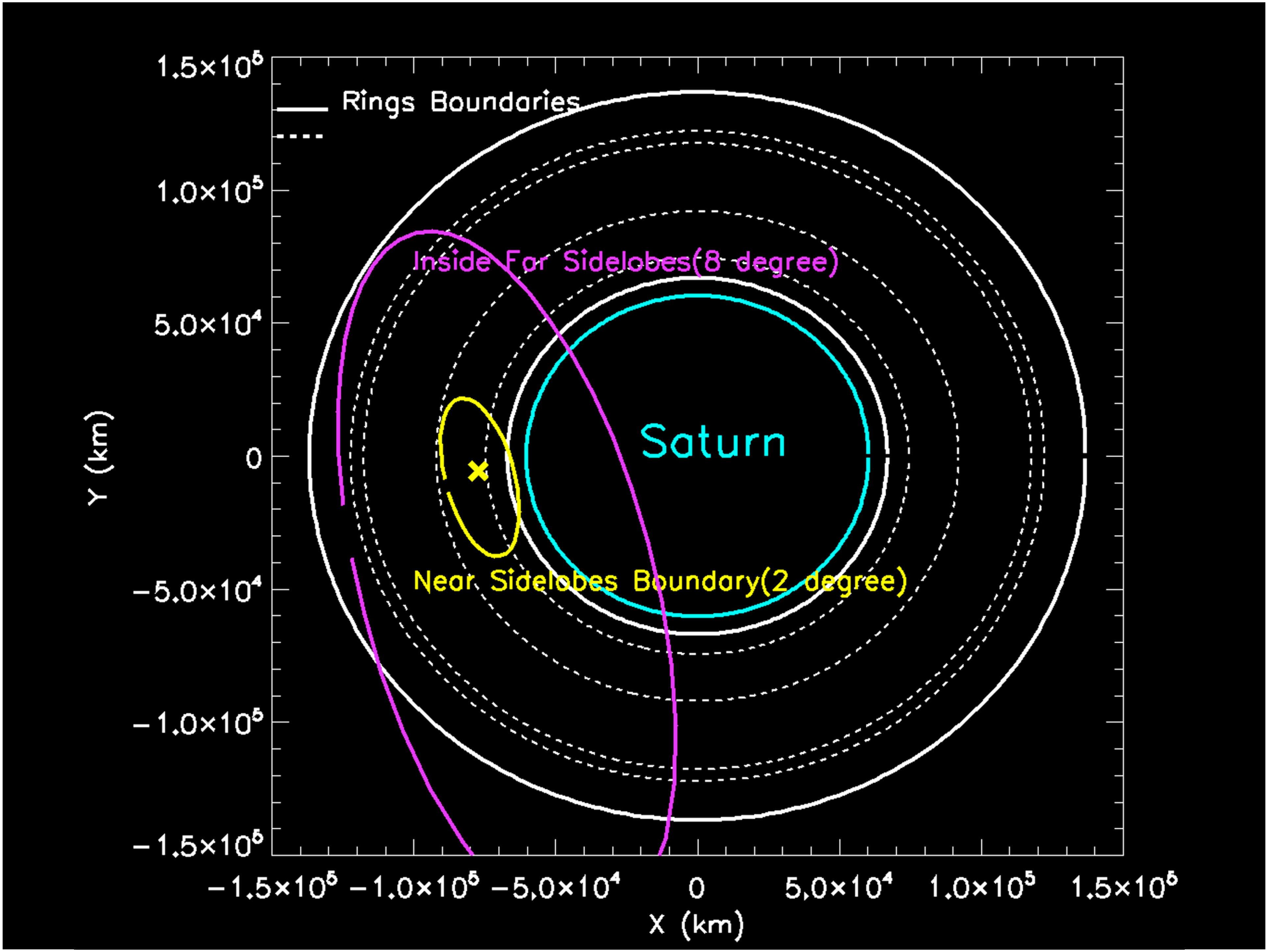
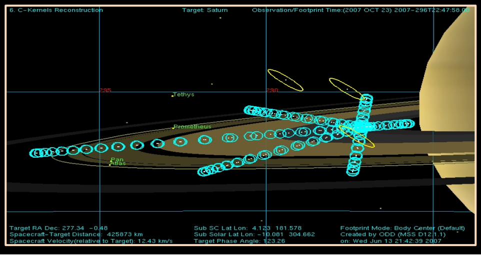




Rings Boundaries
Inside Far Sidelobes(8 degree)
Saturn
Near Sidelobes Boundary(2 degree)
Y (km)
X (km)
1.5×10^5
1.0×10^5
5.0×10^4
0
−5.0×10^4
−1.0×10^5
−1.5×10^5

Outline

- Description of Observations



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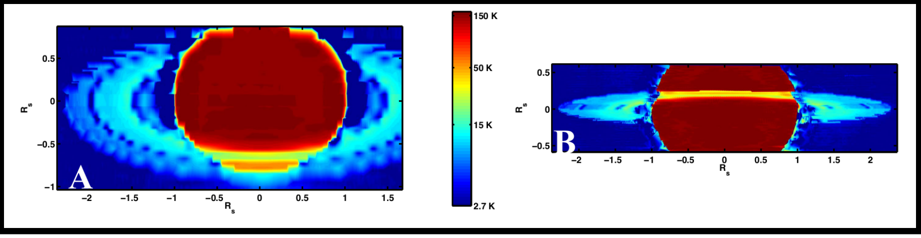
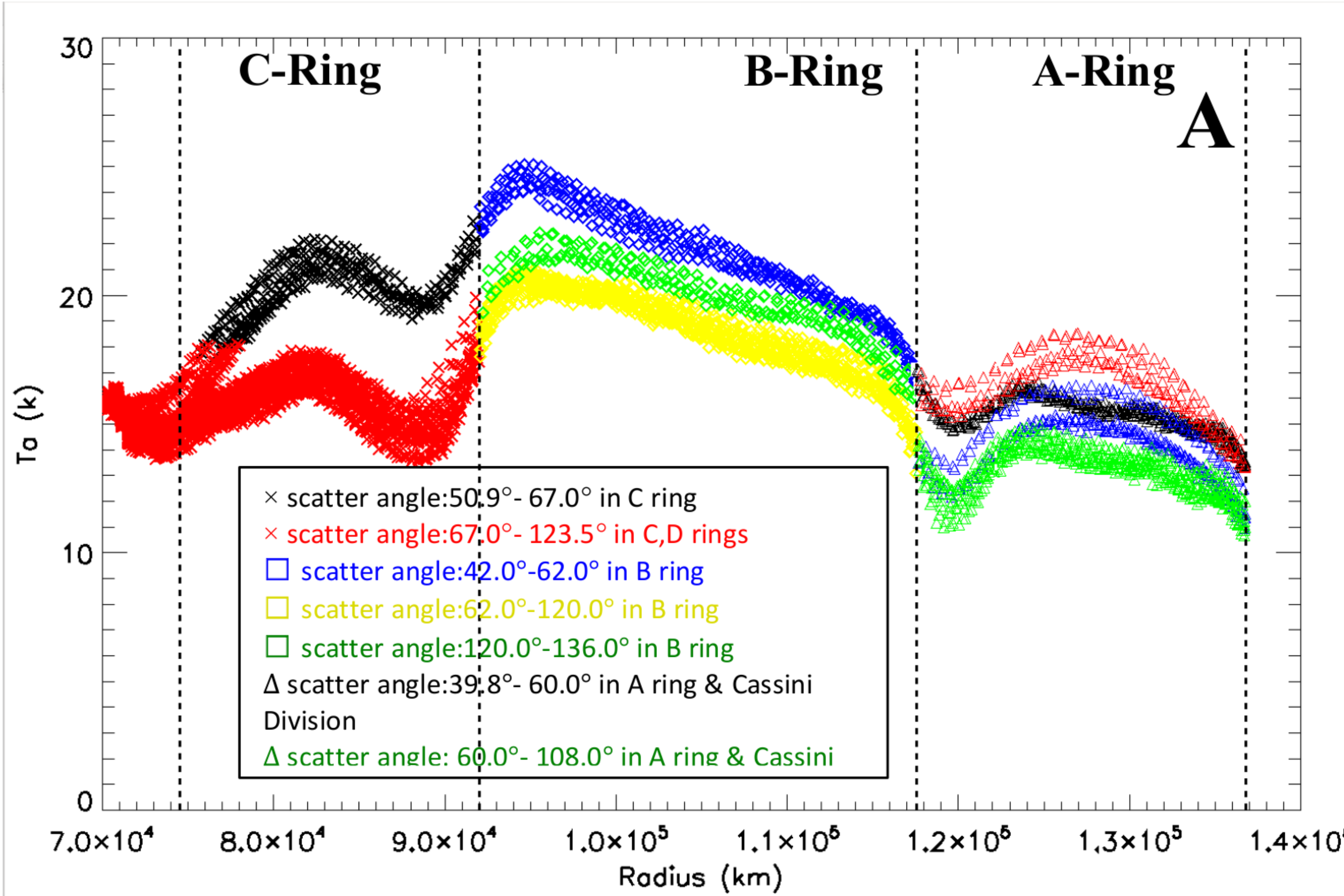
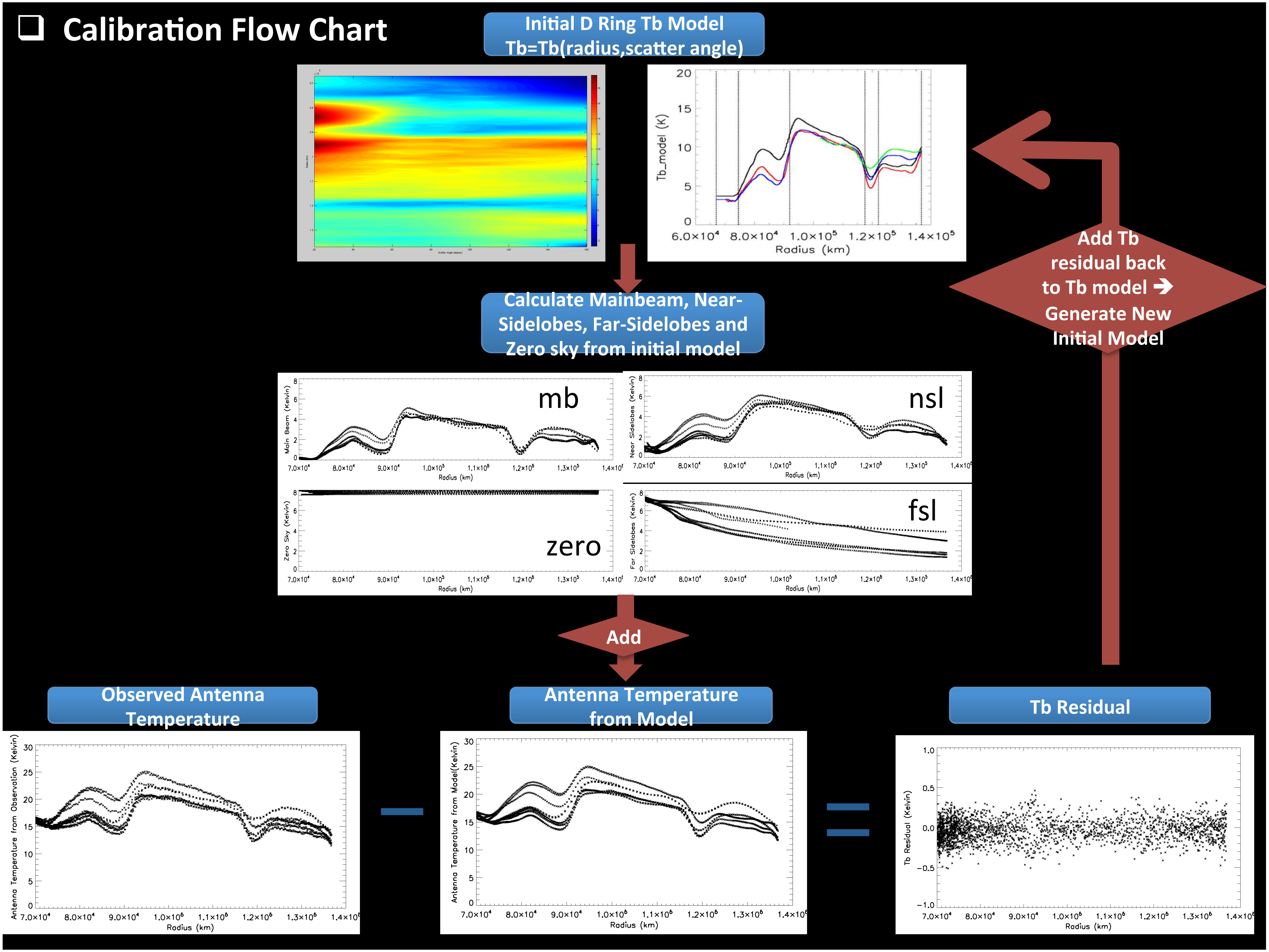
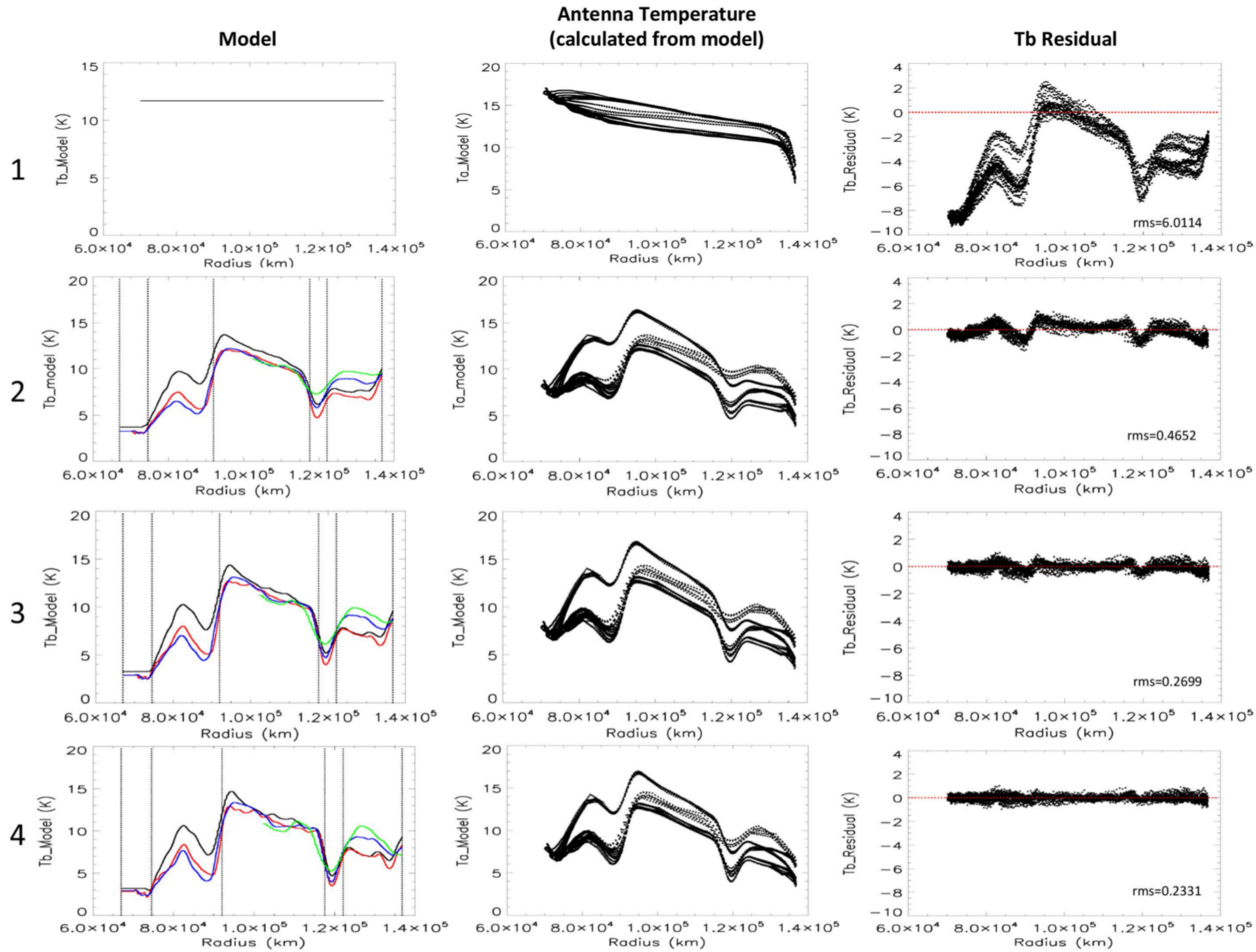


❑ Antenna Temperature

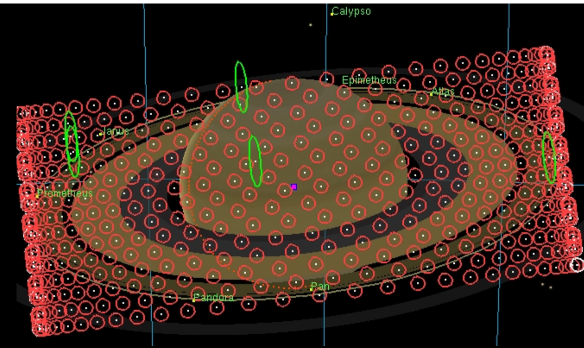



Calibration Flow Chart
Initial D Ring Tb Model
Tb=Tb(radius,scatter angle)
Tb_model (K)
Radius (km)
Calculate Mainbeam, Near-Sidelobes, Far-Sidelobes and Zero sky from initial model
mb
nsl
zero
fsl
Main Beam (Kelvin)
Near Sidelobes (Kelvin)
Zero Sky (Kelvin)
Far Sidelobes (Kelvin)
Add
Add Tb residual back to Tb model ➔ Generate New Initial Model
Observed Antenna Temperature
Antenna Temperature from Observation (Kelvin)
Antenna Temperature from Model
Antenna Temperature from Model(Kelvin)
Tb Residual
Tb Residual (Kelvin)
Radius (km)

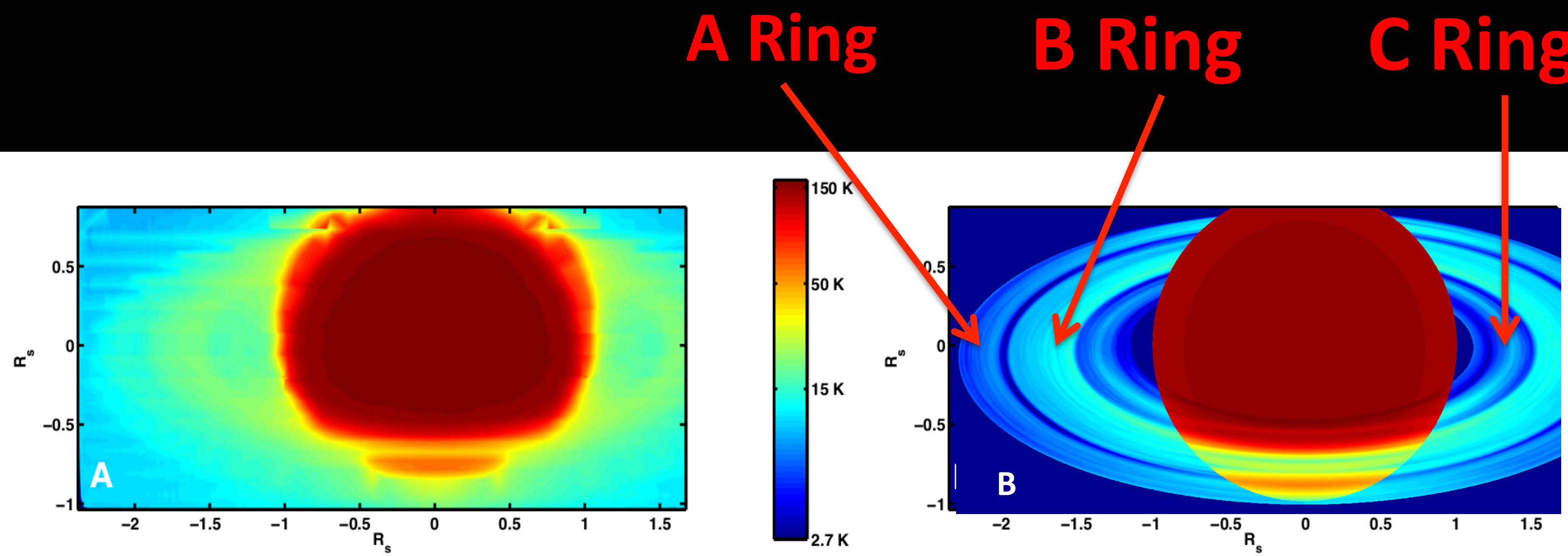


Model
Antenna Temperature
(calculated from model)
Tb Residual
1
2
3
4
Tb_Model (K)
Tb_model (K)
Ta_Model (K)
Ta_model (K)
Tb_Residual (K)
Radius (km)
6.0×10⁴
8.0×10⁴
1.0×10⁵
1.2×10⁵
1.4×10⁵
rms=6.0114
rms=0.4652
rms=0.2699
rms=0.2331

Preliminary Calibration Results

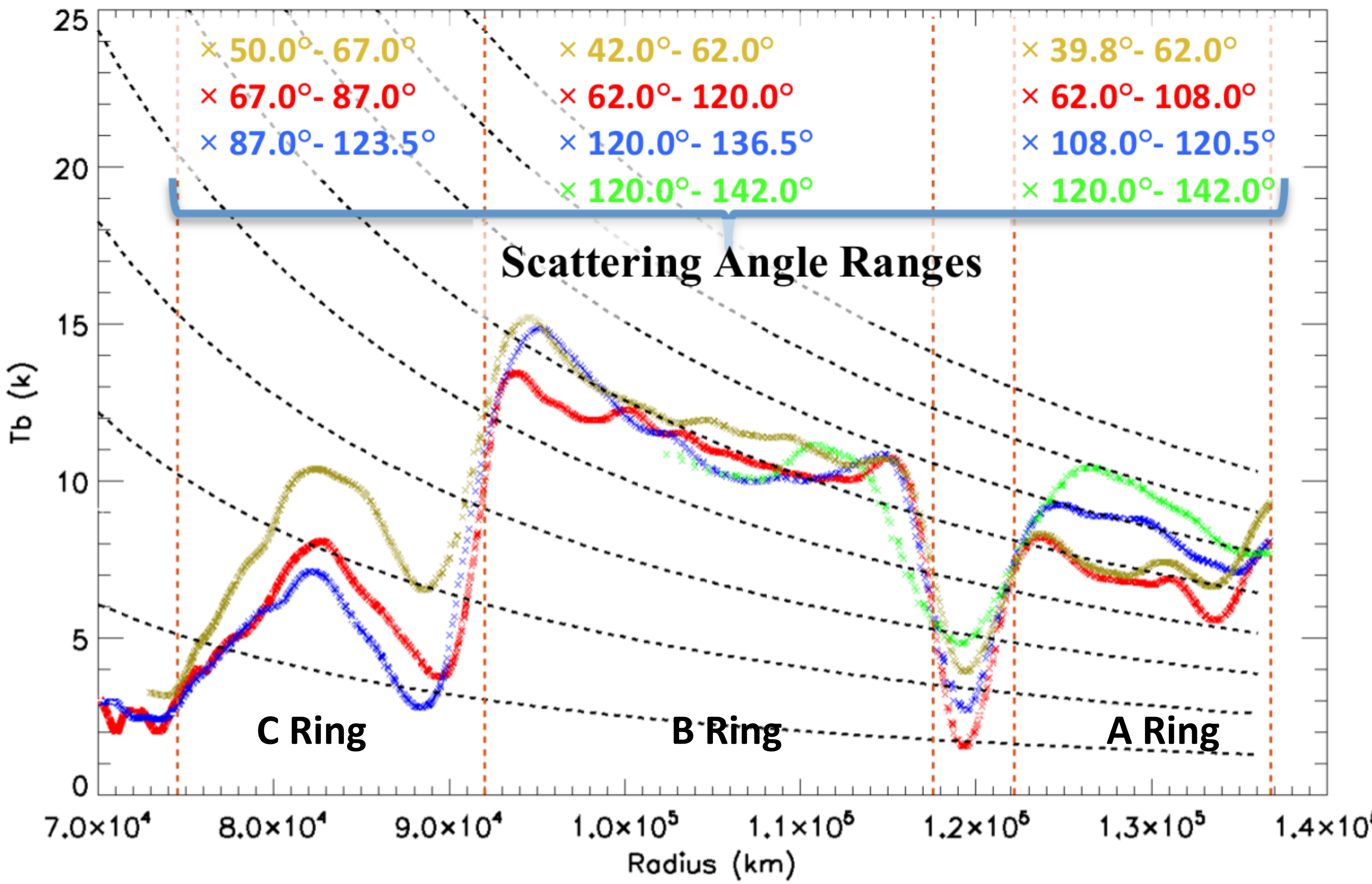


- Low Resolution (12-Sep-2006; Inclination Angle =22°)



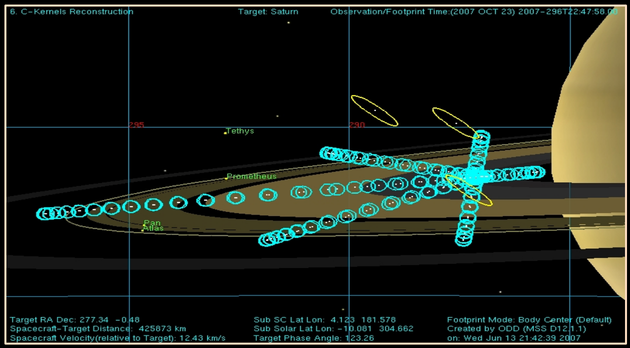
BEFORE **AFTER**

- High Resolution (11-Sep-2006; Inclination Angle =20°)

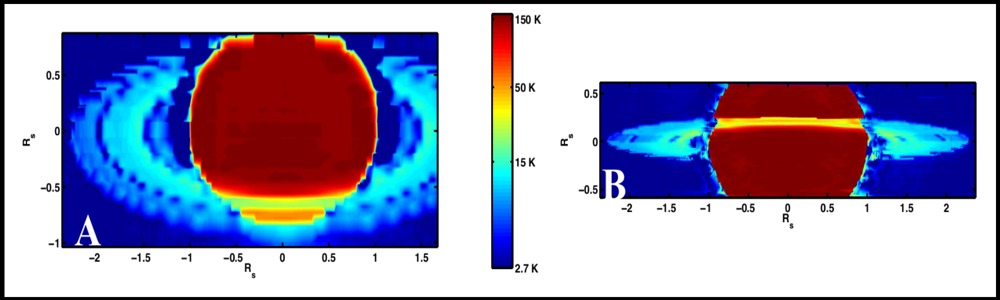


Outline

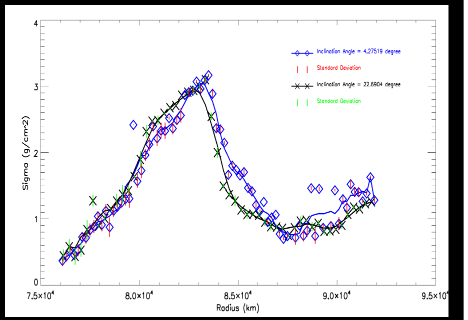
- Description of Observations



- Overview of Calibration/Processing Procedure



- Abundance of Non-Icy Material from Microwave Thermal Emission



$$T_b = T_{scatter} + T_{thermal}$$

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Light source:

Saturn's Thermal Emission

- -Saturn has brightness temperature ~150k. After being scattered by the ring particles, part of the light from Saturn Emission is collected by Cassini.

$$T_b = T_{scatter} + T_{thermal}$$

Light source:

Saturn's Thermal Emission

- -Saturn has brightness temperature ~150k. After being scattered by the ring particles, part of the light from Saturn Emission is collected by Cassini.

Light source:

Thermal emission from contaminated ring particles

-- Thermal photons originate inside the ring disk. After being scattered by the ring particles, some of them will get out of the ring disk.

$T_{scatter}$ -- Scattered Saturn's Emission Light

-- Calculated by Monte Carlo Code Simrings (Dunn et al 2002)

Part 1. Trace the path of each photon after being emitted from Saturn

- *Record the path of the photon*
- *Record how many times the photon is scattered by ring particles*

Part 2. Calculate each time interaction between a photon and a ring particle

- *Record the probability for the photon not to be absorbed after the interaction with the ring particle.*
- *Record the change to the photon's path after being scattered, if not absorbed.*

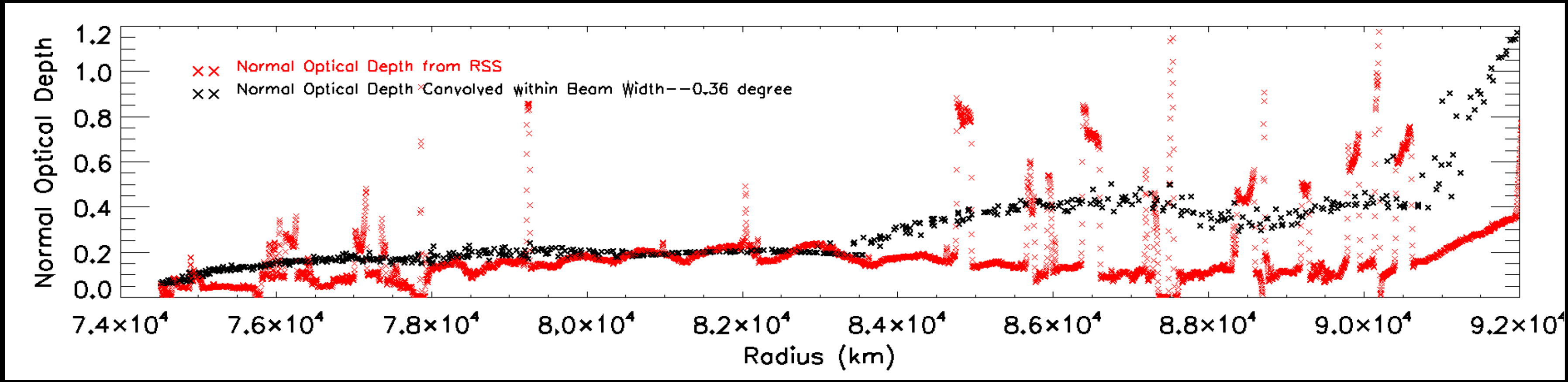
Part 1. Trace the path of each photon after being emitted from Saturn

Key factor: Normal optical depth

- -- Decides the average number of scatters a photon would experience before escaping the ring disk

- -- We use normal optical depth from RSS (Resolution ~ 5 km); then convolve it with Cassini main beam gain pattern (Angular diameter ~ 0.36°, Resolution ~ 2000 km)

$$1 - e^{-\bar{\tau}/\mu(\vartheta=0)} = \frac{\int_{\varphi=0}^{2\pi}\int_{\vartheta=0}^{0.18^o} (1 - e^{-\tau(\vartheta,\varphi)/\mu(\vartheta,\varphi)}) \cdot g(\vartheta,\varphi) \sin\vartheta \, d\vartheta \, d\varphi}{\int_{\varphi=0}^{2\pi}\int_{\vartheta=0}^{0.18^o} g(\vartheta,\varphi) \sin\vartheta \, d\vartheta \, d\varphi}$$



Part 2. Calculate each time interaction between a photon and a ring particle

Key factors:

1. Particle Size Distribution:
   (French & Nilcolson 2000)

$$n(a) = n_0 a^{-q}$$

$$C-Ring: a_{min} = 0.4cm, a_{max} = 450cm, q = 3.15$$
$$A/B-Ring: a_{min} = 30cm, a_{max} = 630cm, q = 2.75$$

2. Effective Dielectric Constant:
   (Effective Medium Theory, Cuzzi et al. 2014)

$$\varepsilon_{\text{eff}} = \varepsilon_{\text{m}} \left(1 + \frac{3 \sum_i f_i \frac{\varepsilon_i - \varepsilon_{\text{m}}}{\varepsilon_i + 2\varepsilon_{\text{m}}}}{1 - \sum_i f_i \frac{\varepsilon_i - \varepsilon_{\text{m}}}{\varepsilon_i + 2\varepsilon_{\text{m}}}} \right)$$

Composition:

Medium – $Ice: \; n = 1.78 - i \cdot 1.88\text{e-}05, \quad \varepsilon = 3.17 - i \cdot 6.68\text{e-}05$

Inclusion – $Tholin: \; n = 1.48 - i \cdot 3.37\text{e-}03, \quad \varepsilon = 2.20 - i \cdot 1.0\text{e-}02 \;, 0.35\% mass-fraction$

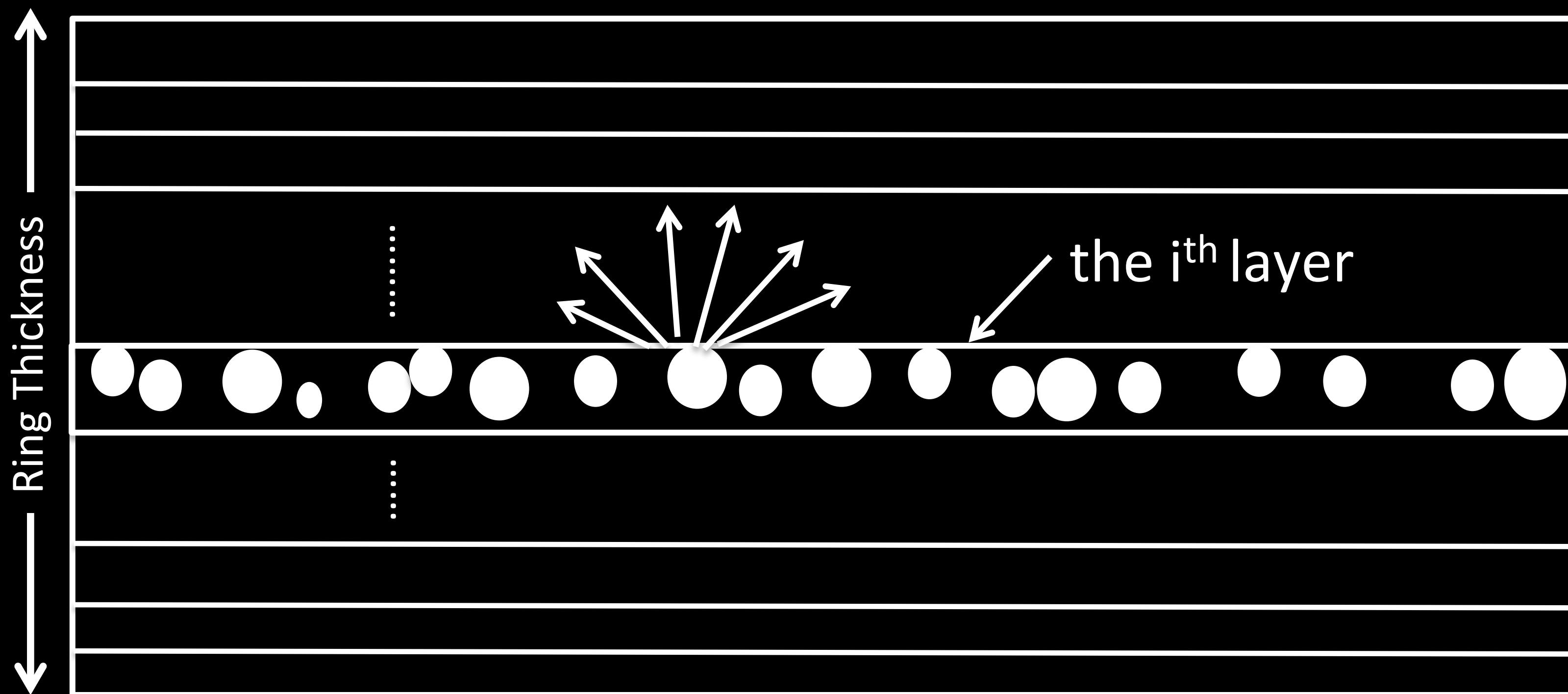
$Acidic-Rock: \; n = 2.32 - i \cdot 2.9\text{e-}02, \quad \varepsilon = 5.38 - i \cdot 1.34\text{e-}01$

3. Phase Function:
   a. Mie Phase Function (Spherical Particle)
   b. Correction for Non-sphericity of the particles:
      -- *combine Isotropic Scattering & Mie Scattering*

$$p(u', \phi', u_{cassini}, \phi_{cassini}) = p(\alpha) = (1 - f_{iso}) p_{Mie}(\alpha) + f_{iso} p_{iso}(\alpha)$$

$T_{thermal}$ -- Intrinsic Thermal Emission

- Separate Rings thickness into some optically thin layers



- For each optically thin layer

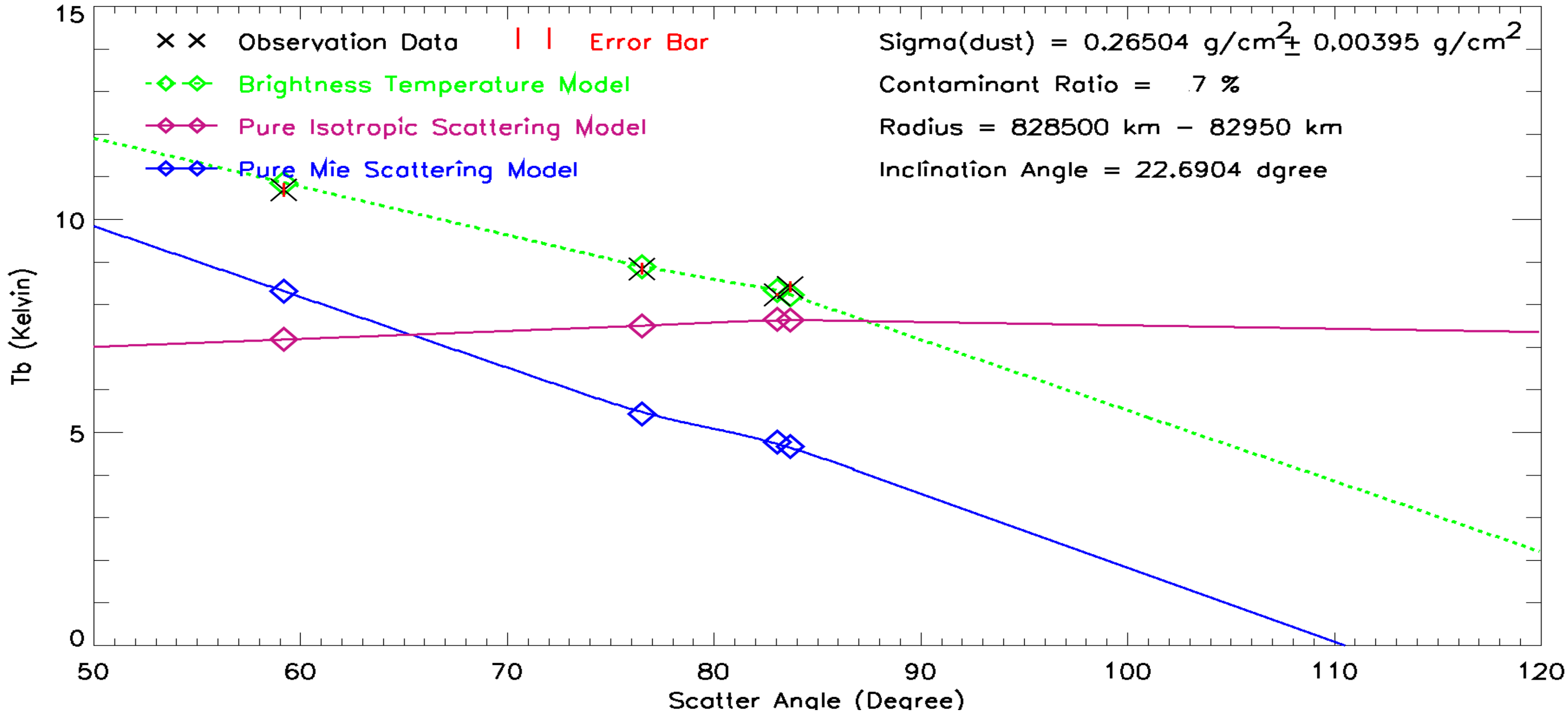
$$T^{i}_{thermal} \sim \tau^{i}_{abs} \cdot T^{i}_{physical}$$

$$\tau_{abs}/\tau \approx 1 - \omega_{single\_scatter} \sim \varepsilon_i^{eff}$$

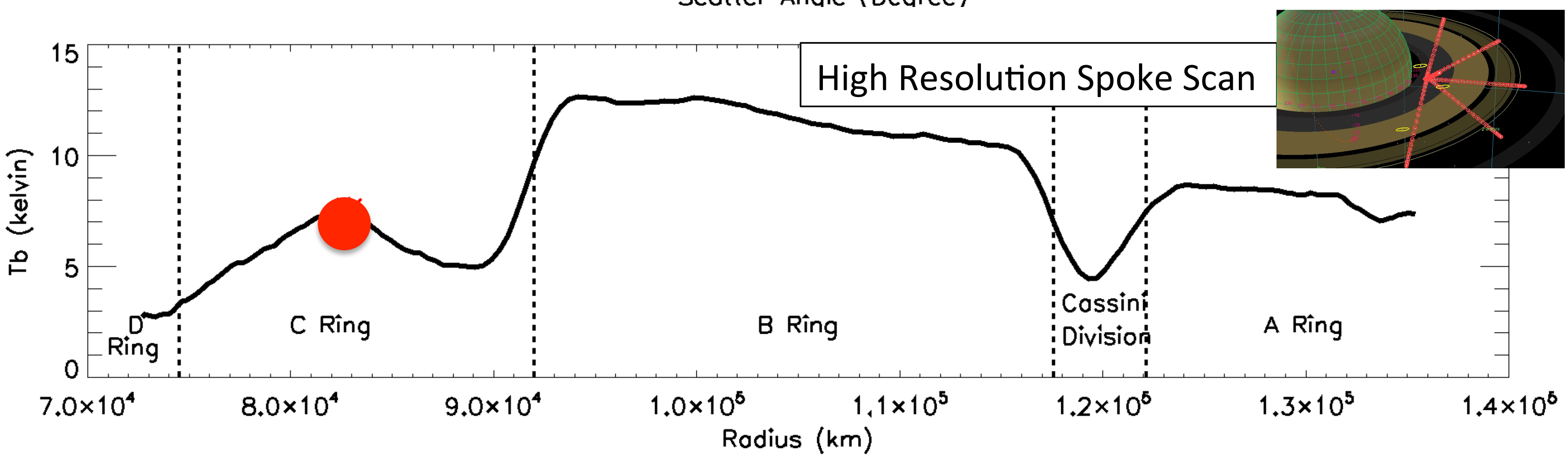
$$\varepsilon_i^{eff} \approx f_v^{ice} \cdot \varepsilon_i^{ice} + f_v^{non-ice} \varepsilon_i^{non-ice}, \qquad \varepsilon_i^{ice} = 6.68\text{e-}05 << \varepsilon_i^{non-ice} = 1.34\text{e-}01$$

- Insert thermal photons $n^{i}_{thermal} \propto T^{i}_{thermal}$, isotropically from the i^th layer, and let them scatter

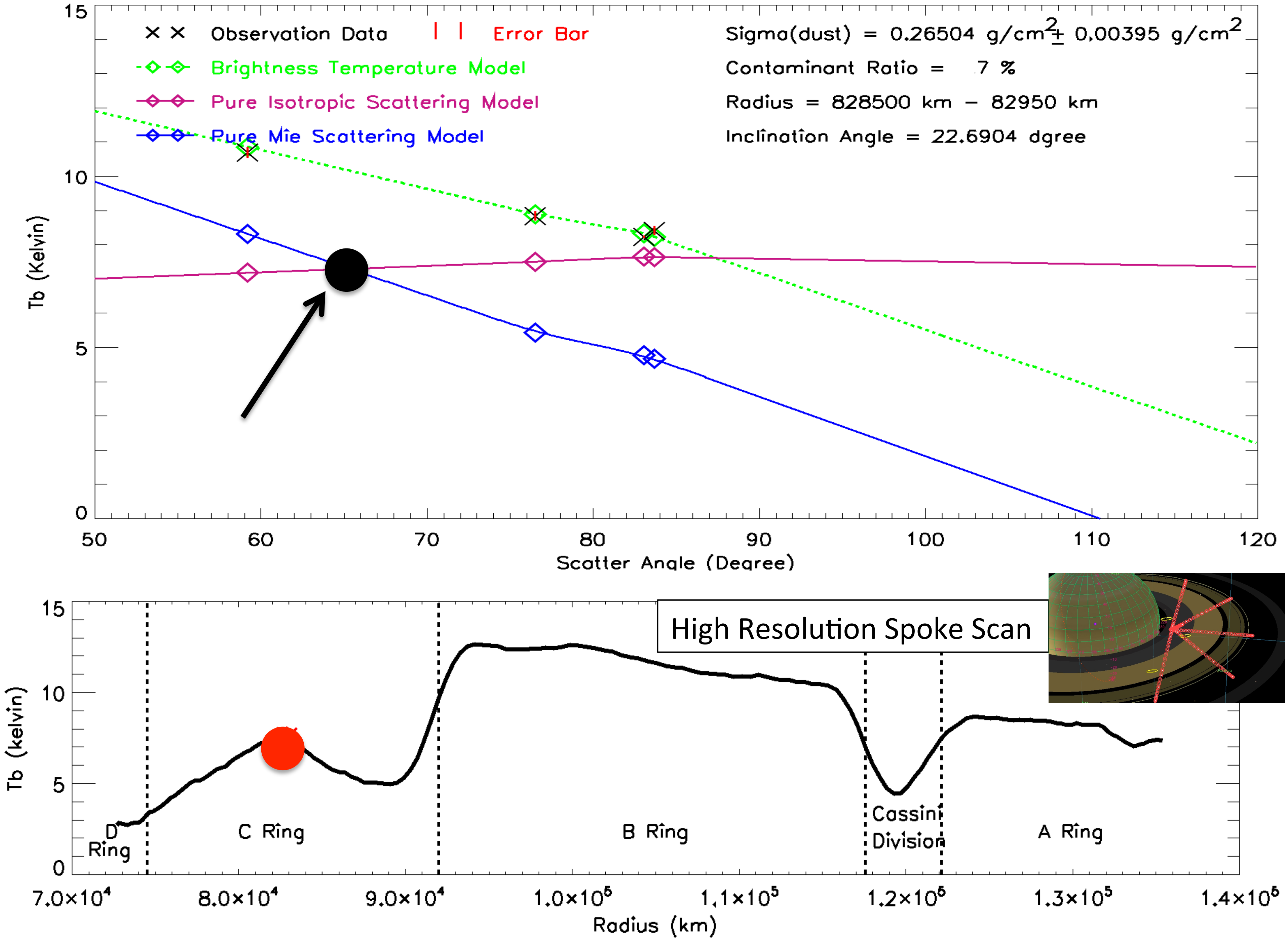
C Ring



× × Observation Data
| | Error Bar
Brightness Temperature Model
Pure Isotropic Scattering Model
Pure Mie Scattering Model
Sigma(dust) = 0.26504 g/cm^2 ± 0.00395 g/cm^2
Contaminant Ratio = 7 %
Radius = 828500 km − 82950 km
Inclination Angle = 22.6904 dgree
Tb (Kelvin)
Scatter Angle (Degree)
15
10
5
0
50
60
70
80
90
100
110
120



High Resolution Spoke Scan
D Ring
C Ring
B Ring
Cassini Division
A Ring
Tb (kelvin)
Radius (km)
15
10
5
0
7.0×10^4
8.0×10^4
9.0×10^4
1.0×10^5
1.1×10^5
1.2×10^5
1.3×10^5
1.4×10^5



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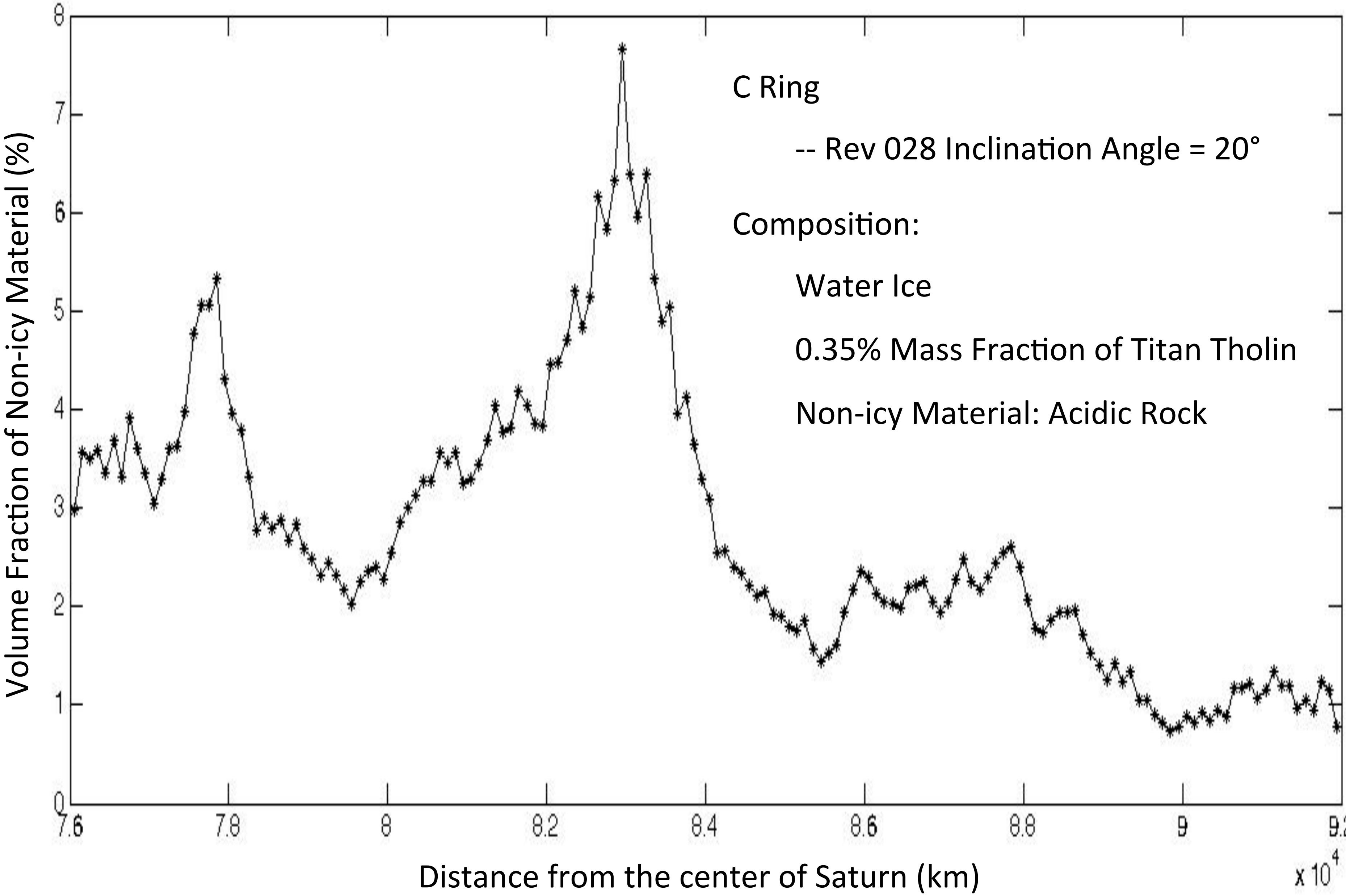
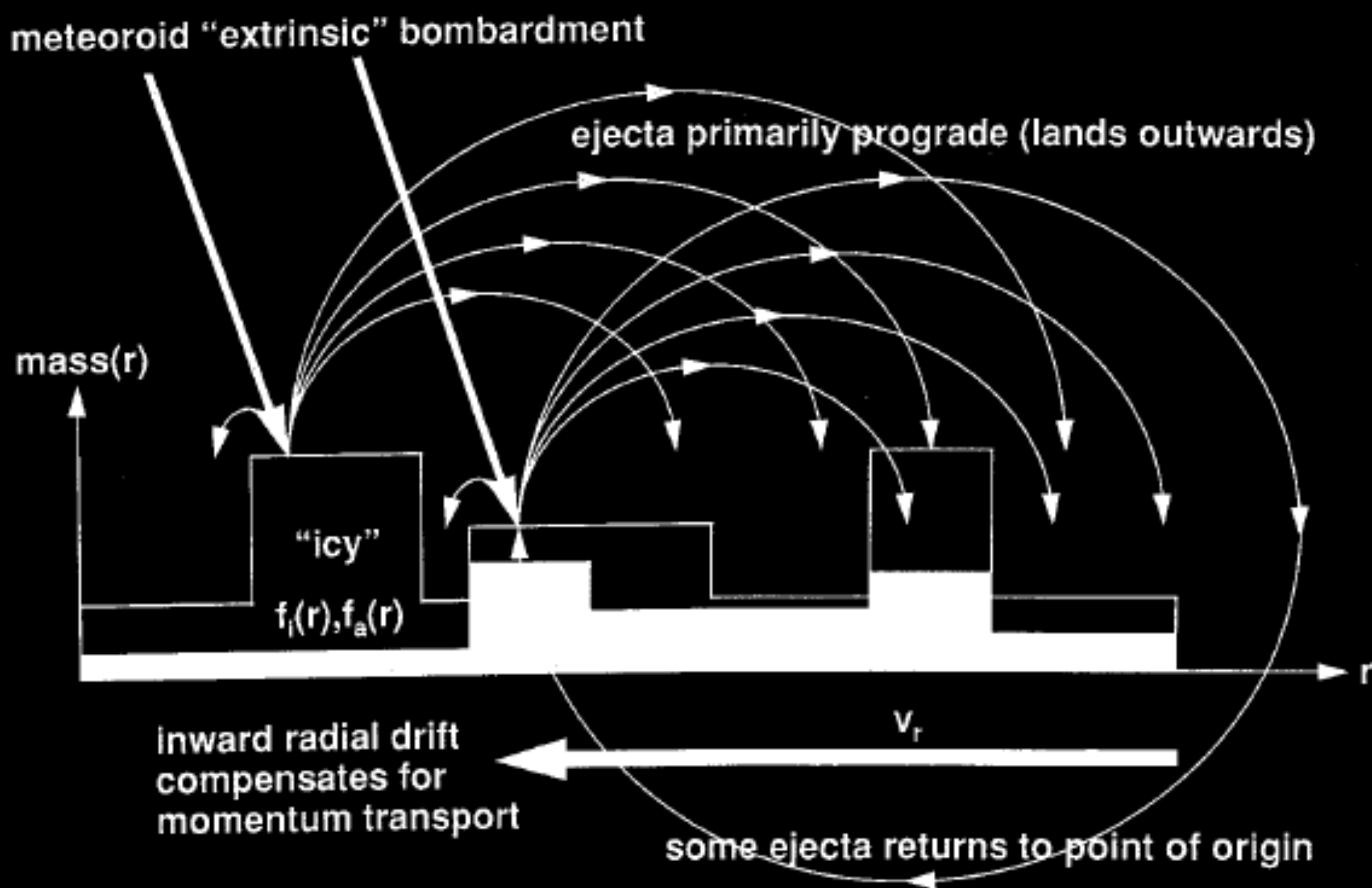
60
70
80
90
100
110
120
0
5
10
15
High Resolution Spoke Scan
Tb (kelvin)
Radius (km)
D Ring
C Ring
B Ring
Cassini Division
A Ring
7.0×10^4
8.0×10^4
9.0×10^4
1.0×10^5
1.1×10^5
1.2×10^5
1.3×10^5
1.4×10^5


C Ring
-- Rev 028 Inclination Angle = 20°
Composition:
Water Ice
0.35% Mass Fraction of Titan Tholin
Non-icy Material: Acidic Rock
Volume Fraction of Non-icy Material (%)
Distance from the center of Saturn (km)
0
1
2
3
4
5
6
7
8
7.6
7.8
8
8.2
8.4
8.6
8.8
9
9.2
x 10^4

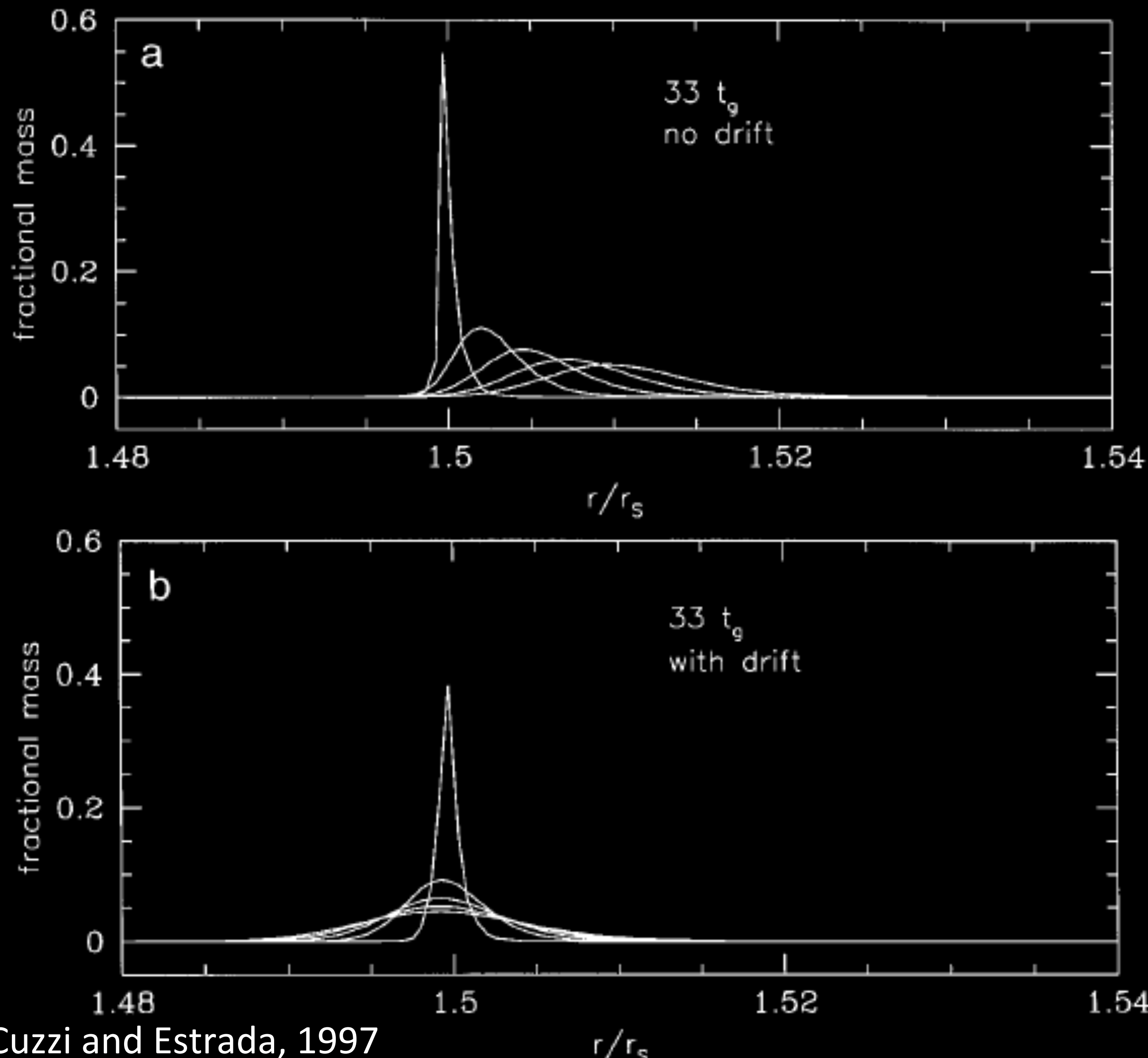
Compositional Evolution of Saturn's Rings Due to Meteoroid Bombardment

Jeffrey N. Cuzzi and Paul R. Estrada

Received April 10, 1997; revised October 6, 1997

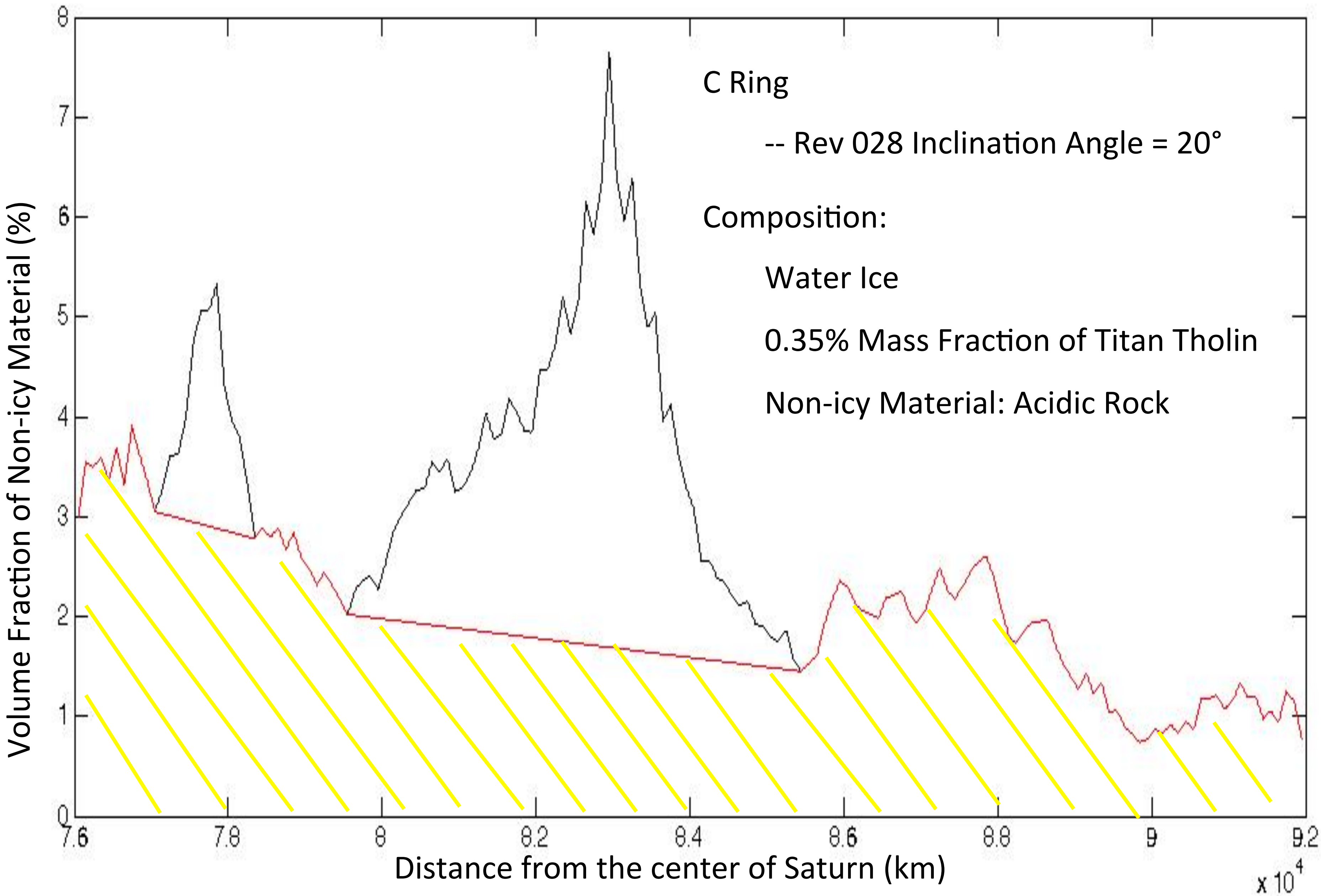


COMPOSITIONAL EVOLUTION OF SATURN'S RINGS



Cuzzi and Estrada, 1997

FIG. 7. Examples of the spread of "pollutant" from an initially narrow annulus into surrounding regions with radial drift off (a) and on (b). The profiles of fractional mass of non-icy absorber are uniformly spaced in time from 0 to $33t_g$.



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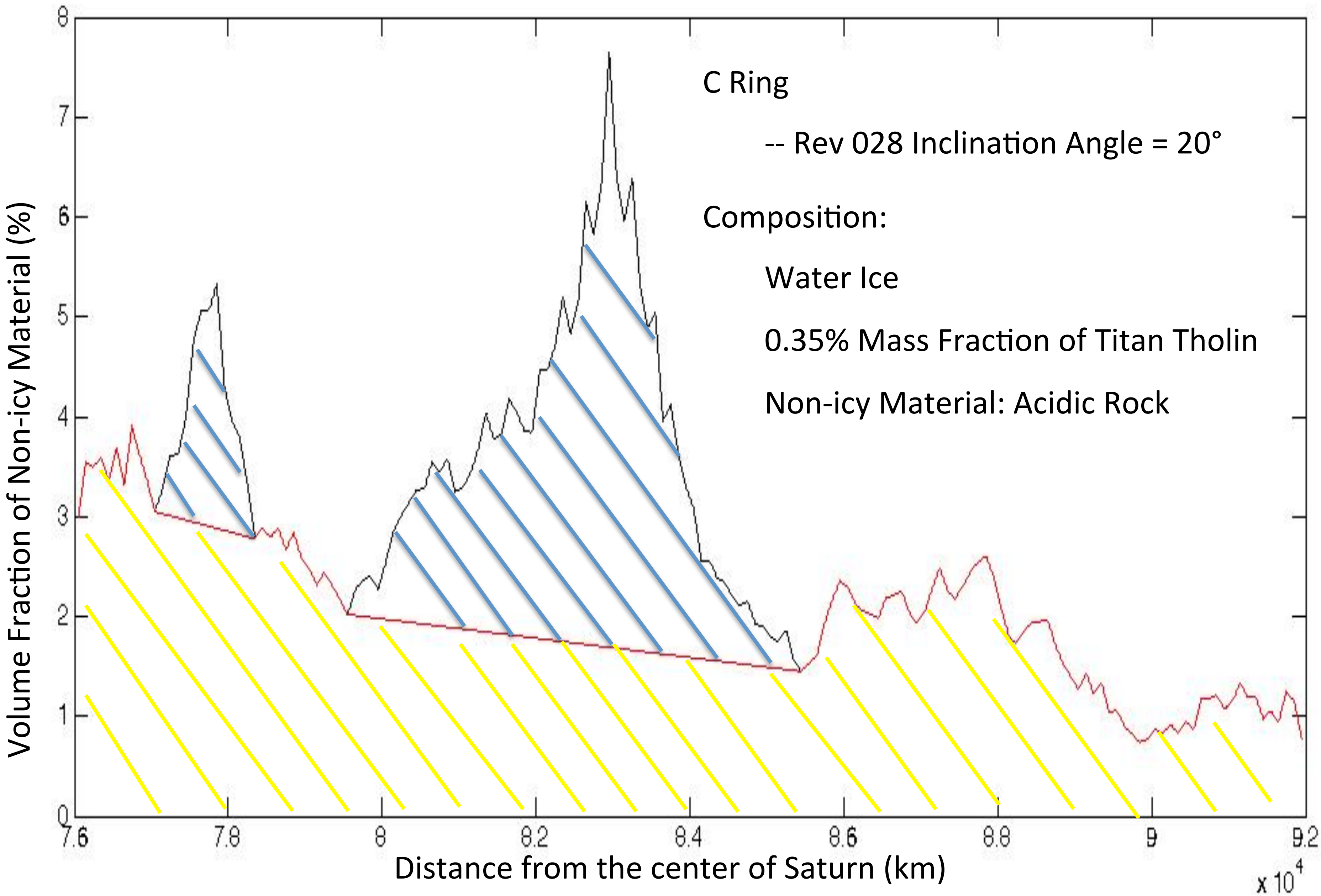
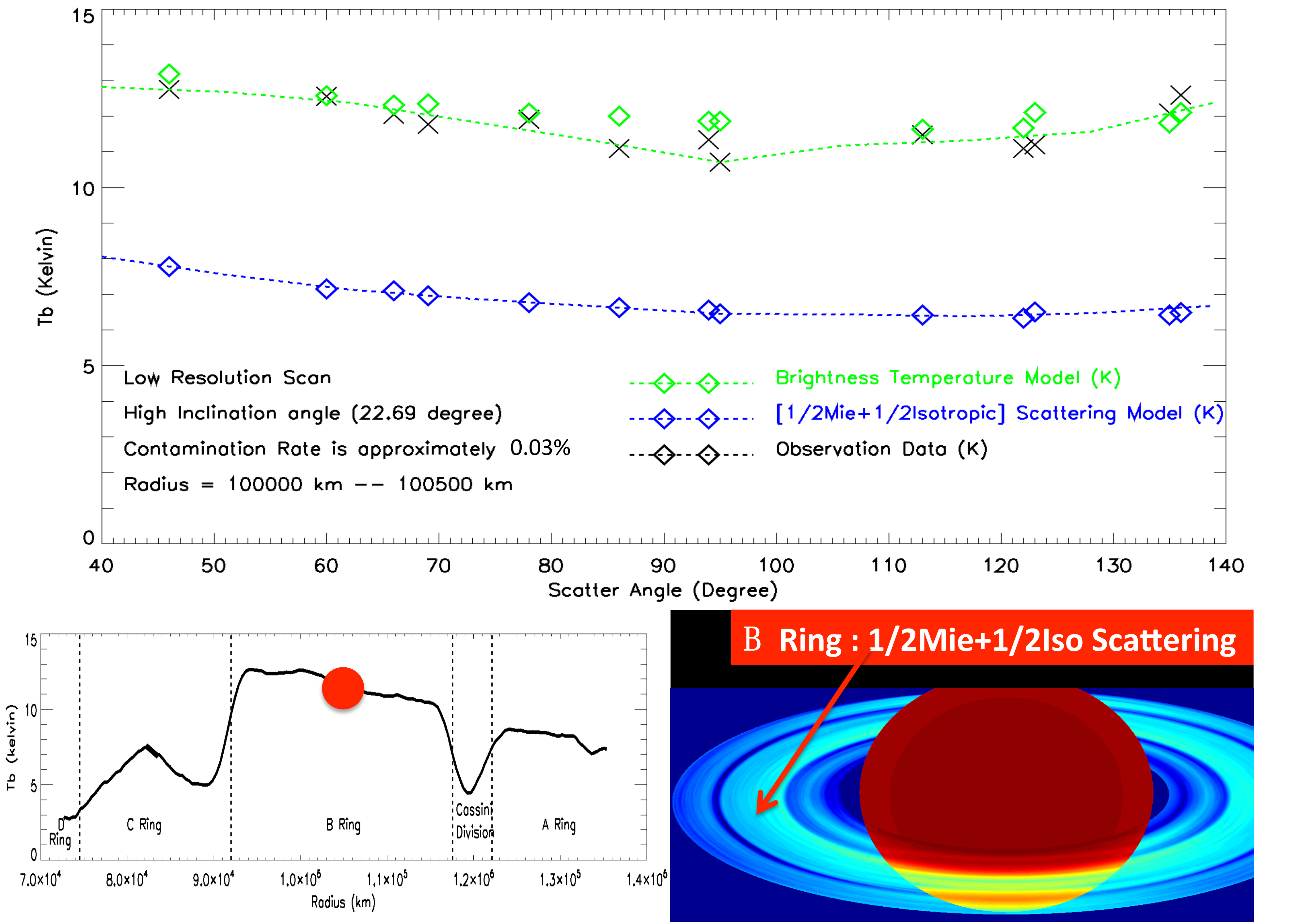
Composition:
Water Ice
0.35% Mass Fraction of Titan Tholin
Non-icy Material: Acidic Rock
Volume Fraction of Non-icy Material (%)
Distance from the center of Saturn (km)
x 10^4
0
1
2
3
4
5
6
7
8
7.6
7.8
8
8.2
8.4
8.6
8.8
9
9.2

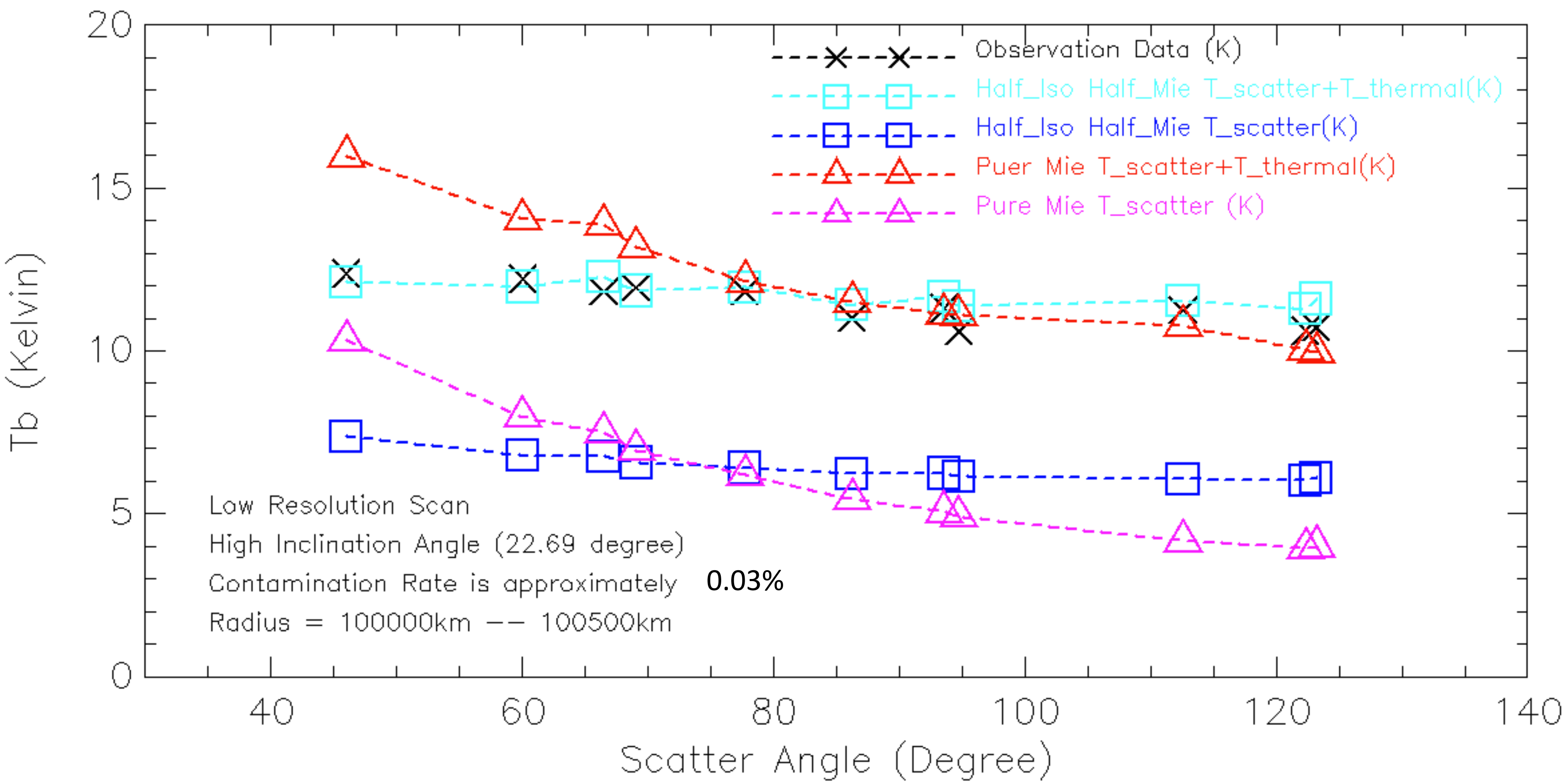


C Ring
-- Rev 028 Inclination Angle = 20°
Composition:
Water Ice
0.35% Mass Fraction of Titan Tholin
Non-icy Material: Acidic Rock
Volume Fraction of Non-icy Material (%)
Distance from the center of Saturn (km)
x 10^4
0
1
2
3
4
5
6
7
8
7.6
7.8
8
8.2
8.4
8.6
8.8
9
9.2

B Rings



Low Resolution Scan
High Inclination angle (22.69 degree)
Contamination Rate is approximately 0.03%
Radius = 100000 km -- 100500 km
Brightness Temperature Model (K)
[1/2Mie+1/2Isotropic] Scattering Model (K)
Observation Data (K)
Tb (Kelvin)
Scatter Angle (Degree)
Tb (kelvin)
Radius (km)
D Ring
C Ring
B Ring
Cassini Division
A Ring
B Ring : 1/2Mie+1/2Iso Scattering


Observation Data (K)
Half_Iso Half_Mie T_scatter+T_thermal(K)
Half_Iso Half_Mie T_scatter(K)
Puer Mie T_scatter+T_thermal(K)
Pure Mie T_scatter (K)
Low Resolution Scan
High Inclination Angle (22.69 degree)
Contamination Rate is approximately 0.03%
Radius = 100000km -- 100500km
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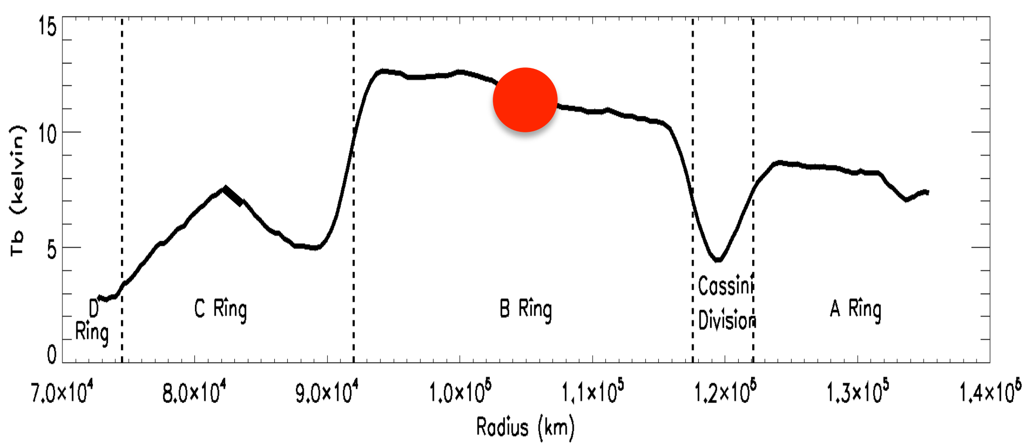
140


Tb (kelvin)
D Ring
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Cassini Division
A Ring
Radius (km)
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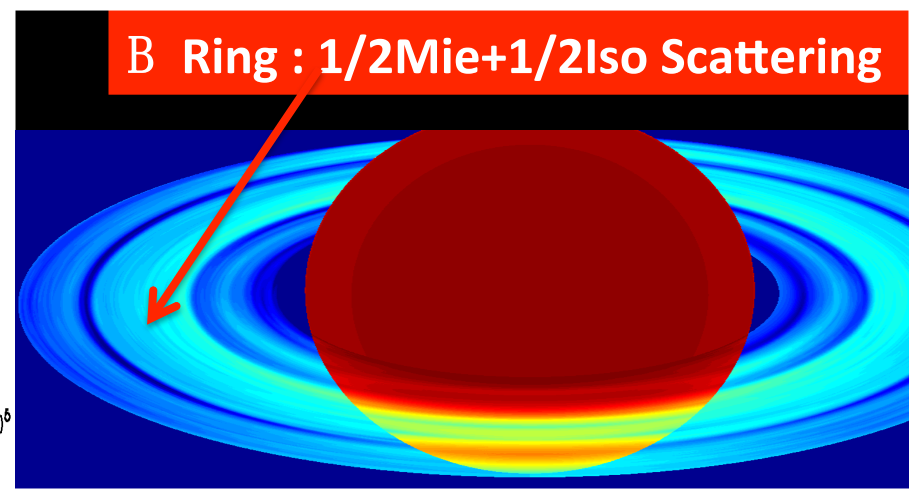
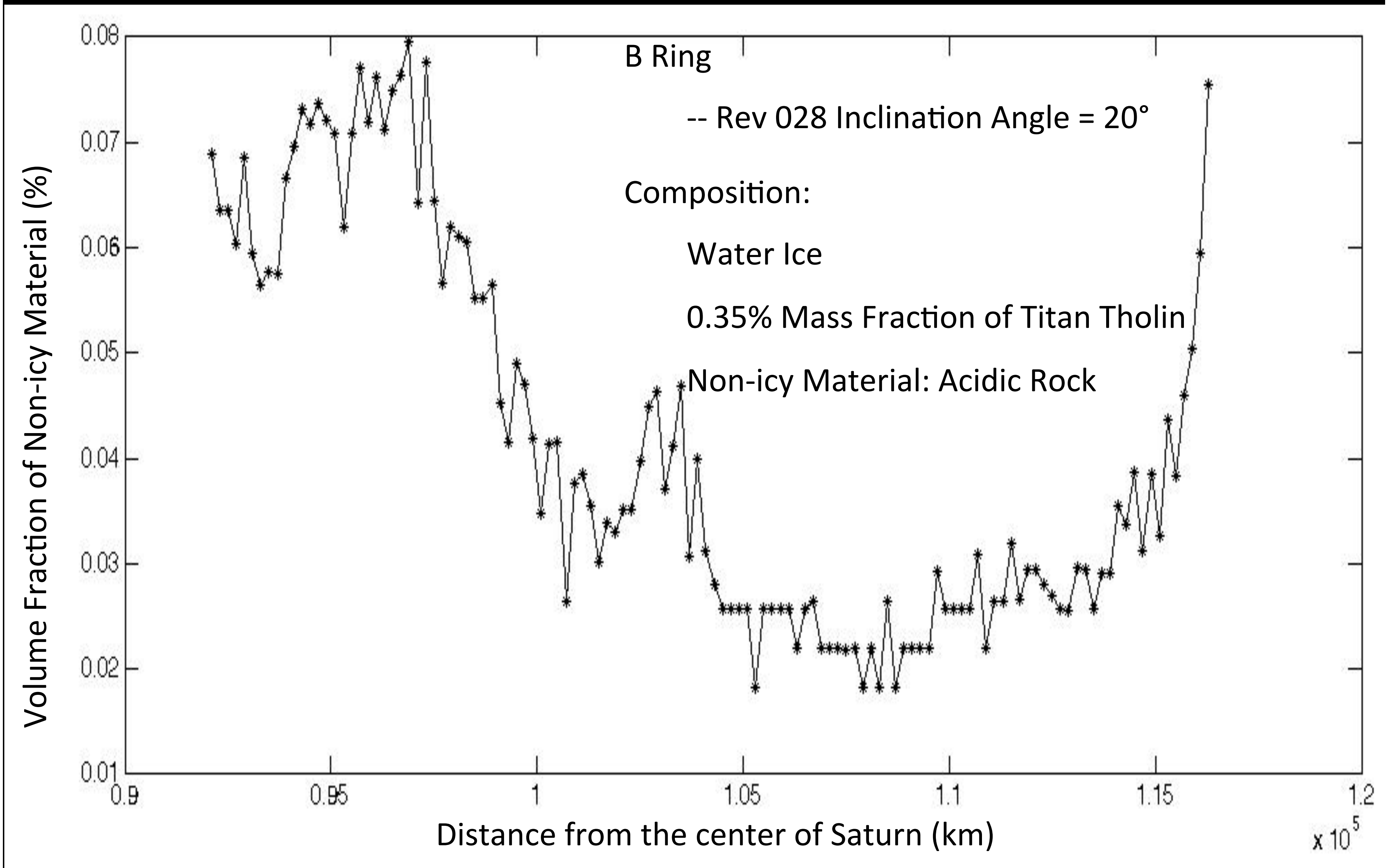
1.1x10^5
1.2x10^5
1.3x10^5
1.4x10^5

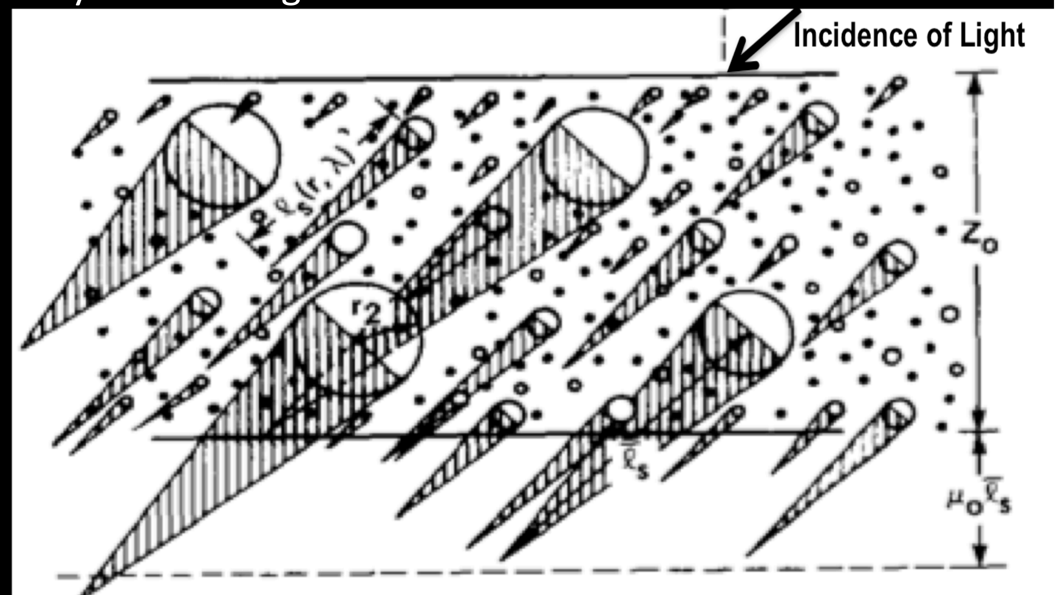

B Ring : 1/2Mie+1/2Iso Scattering


B Ring
-- Rev 028 Inclination Angle = 20°
Composition:
Water Ice
0.35% Mass Fraction of Titan Tholin
Non-icy Material: Acidic Rock
Volume Fraction of Non-icy Material (%)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.9
0.95
1
1.05
1.1
1.15
1.2
x 10^5
Distance from the center of Saturn (km)

Problem & Limitation of Current Model

- Problem:
  Non-ice fraction in the B Ring is much smaller than the upper limits derived in other references.

- Limitation of Current Model:
  Unable to deal with shadowing effect in optically thick B Ring



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  Non-ice fraction in the B Ring is much smaller than the upper limits derived in other references.

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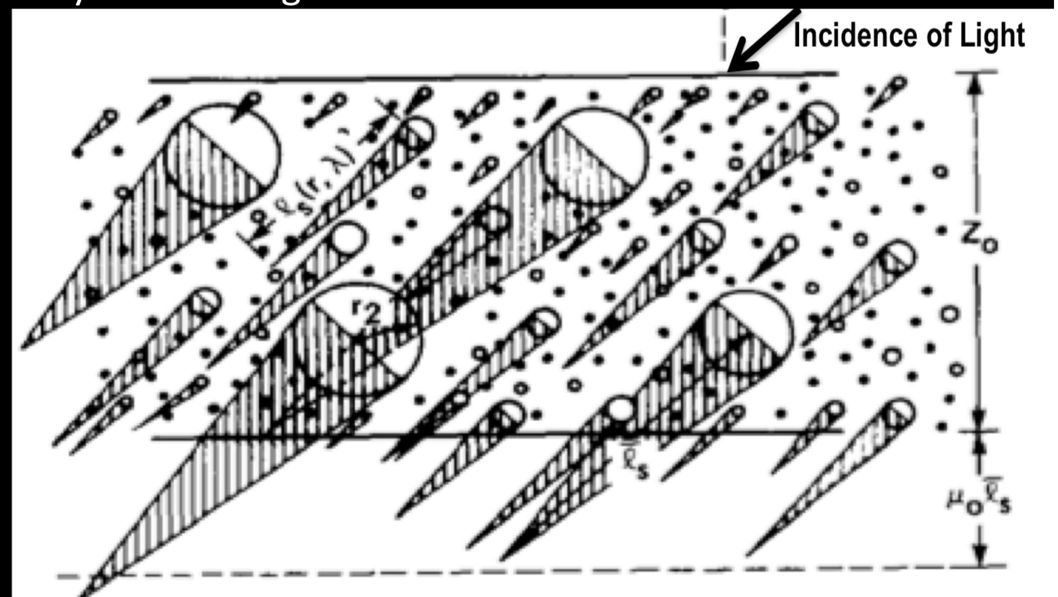
  Unable to deal with shadowing effect in optically thick B Ring

- Interaction between Large Particle & Photon
  - Diffraction



  - Geometric-optics Scattering
    – Scattering not caused by diffraction

  - Absorption

Problem & Limitation of Current Model

- Problem:
  Non-ice fraction in the B Ring is much smaller than the upper limits derived in other references.

- Limitation of Current Model:
  Unable to deal with shadowing effect in optically thick B Ring

- Interaction between Large Particle & Photon
  - Diffraction
    - Near Field → Far Field boundary:

      $$l_s \sim a^2 / \lambda$$

    - Distance between particles:

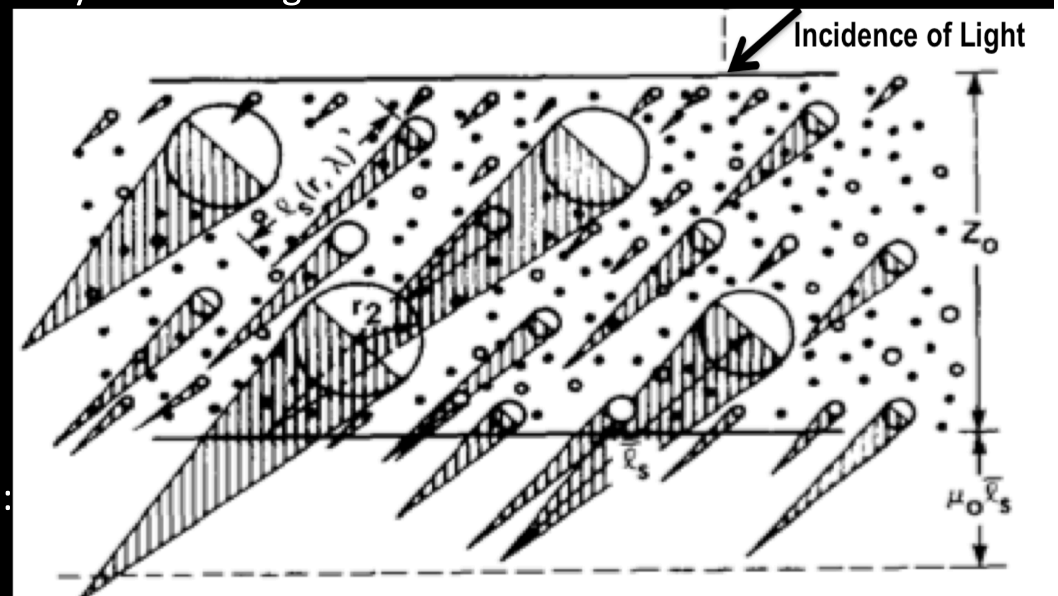
      $$l^* \sim r / D$$

    - Far field approximation fails when:

      $$l_s > l^*$$

  - Geometric-optics Scattering
    – Scattering not caused by diffraction

  - Absorption



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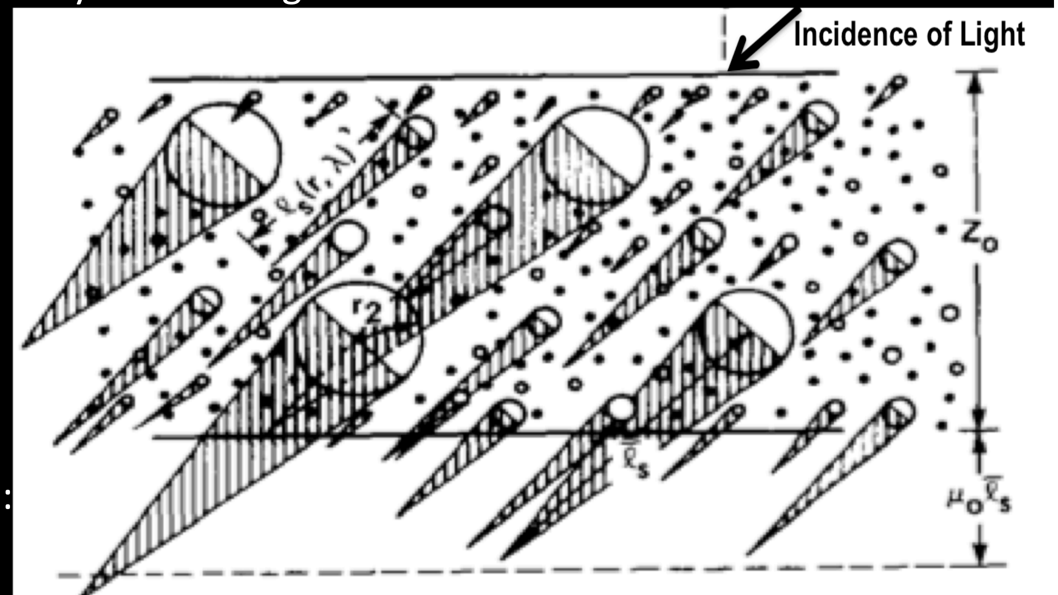
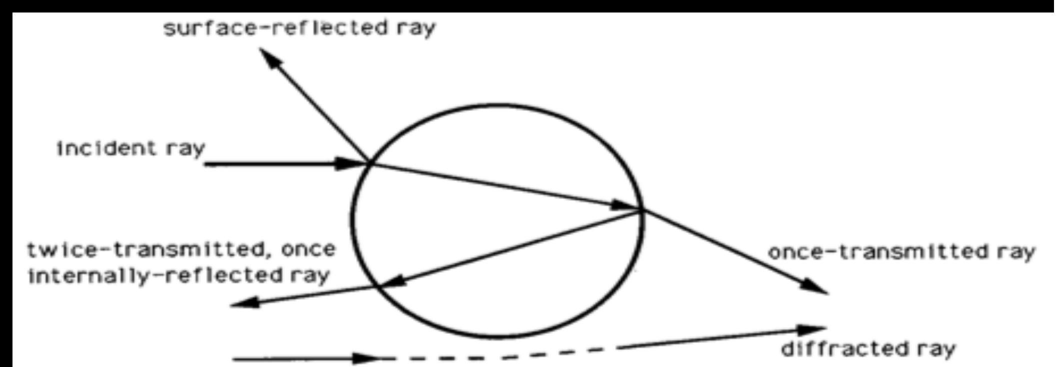
  - Geometric-optics Scattering
    – Scattering not caused by diffraction
    - Surface reflection
    - Refracted Rays

    (Pollack & Cuzzi 1980)
  - Absorption





Problem & Limitation of Current Model

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    - Near Field → Far Field boundary:

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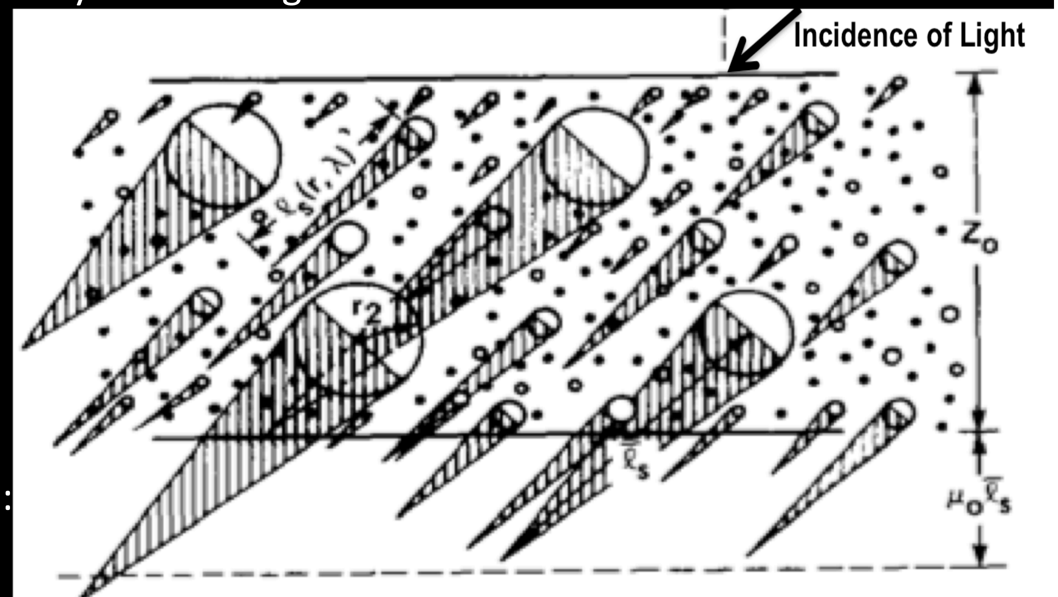
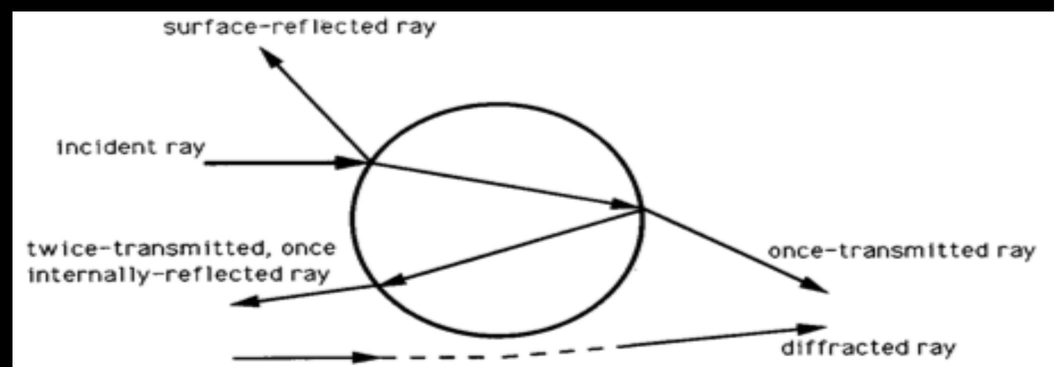


  - Geometric-optics Scattering
    – Scattering not caused by diffraction
    - Surface reflection
    - Refracted Rays

    (Pollack & Cuzzi 1980)



  - Absorption
- Possible Solutions
  - Discrete Dipole Approximation Model (DDA Model)
  - Separate scattering phase function in the near field into Diffraction and Geometric-scatter

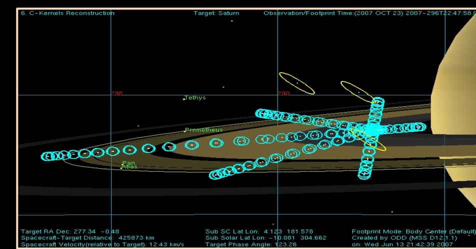
Summary of Observations

Thank you !

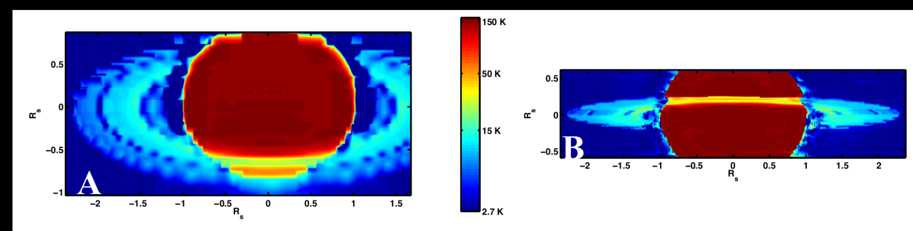
[redacted]

Outline

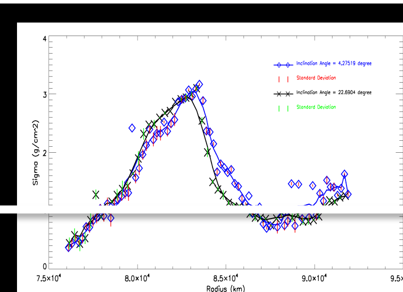
- Description of Observations



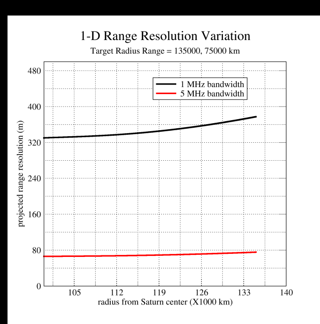
- Overview of Calibration/Processing Procedure

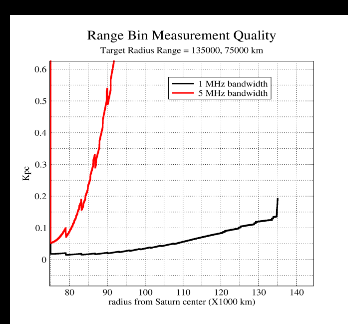


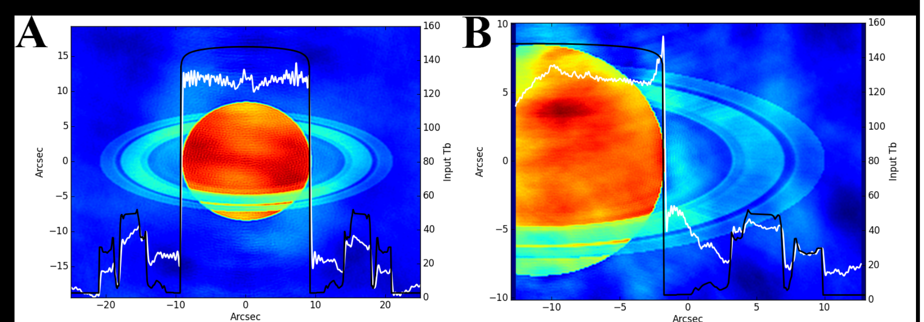
- Abundance of Non-Icy Material from Microwave Thermal Emission



- Next Steps / Follow-up Investigations



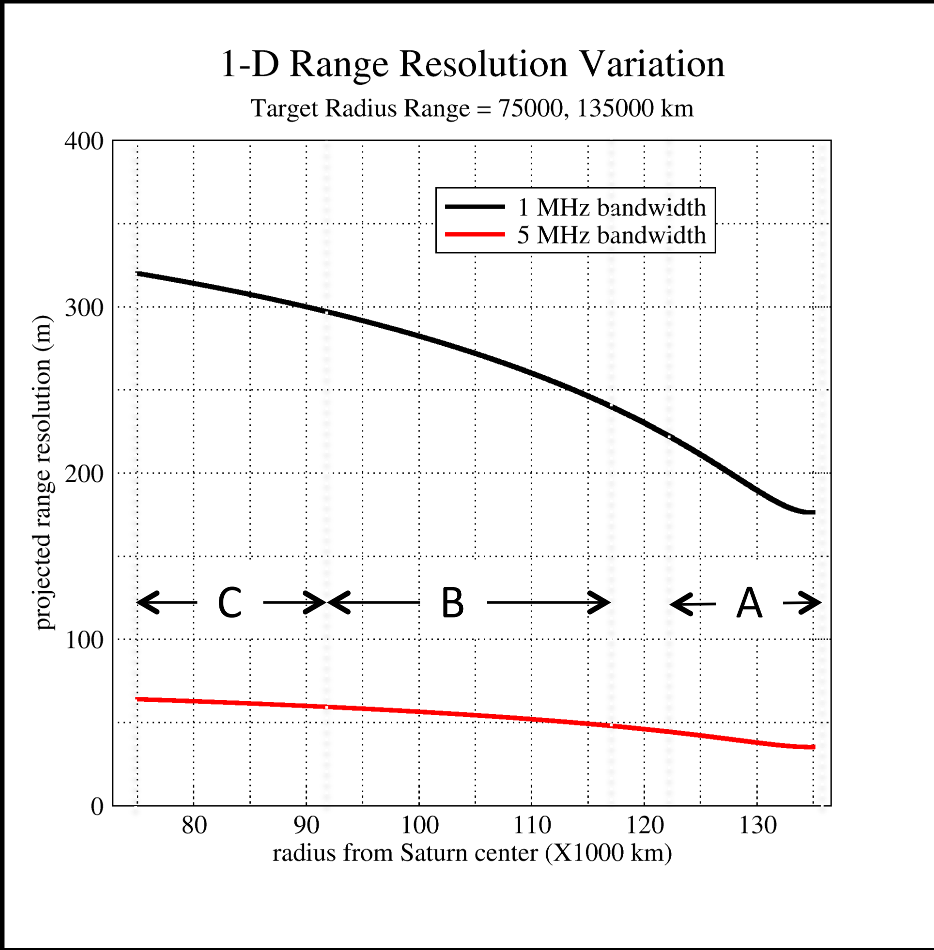




Next Steps

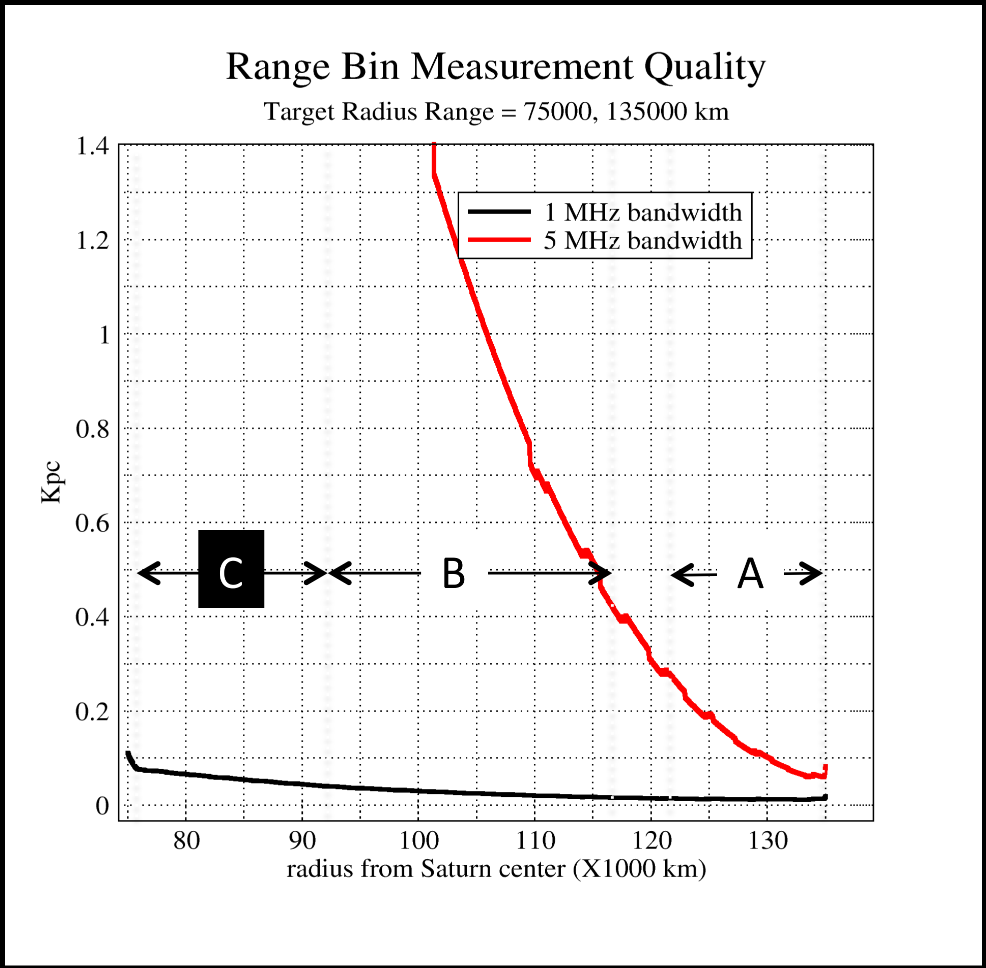
Next Steps

1-D Performance - F-ring Orbit
1. resolution



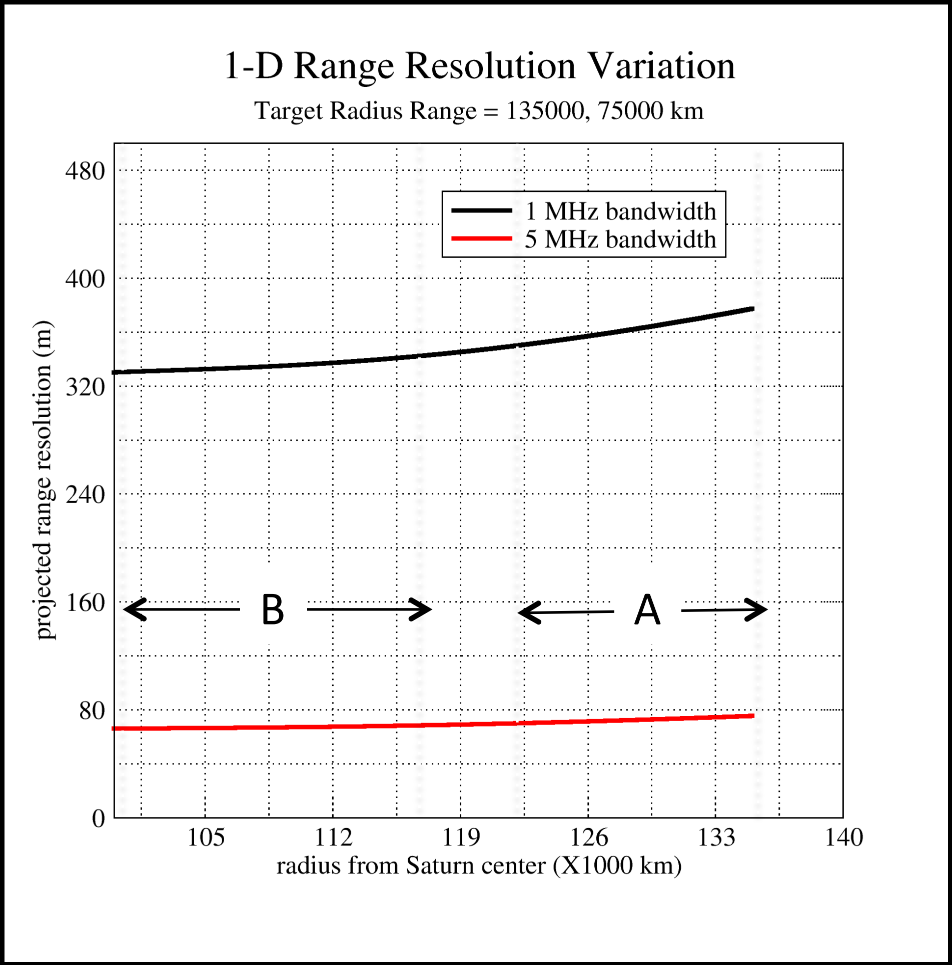
- Pointing design sweeps all the rings, sequences range settings to keep rings in window
- Extremes of BW chosen
- Resolution comes at the price of SNR (see next slide)

1-D Performance - F-ring Orbit
2. SNR



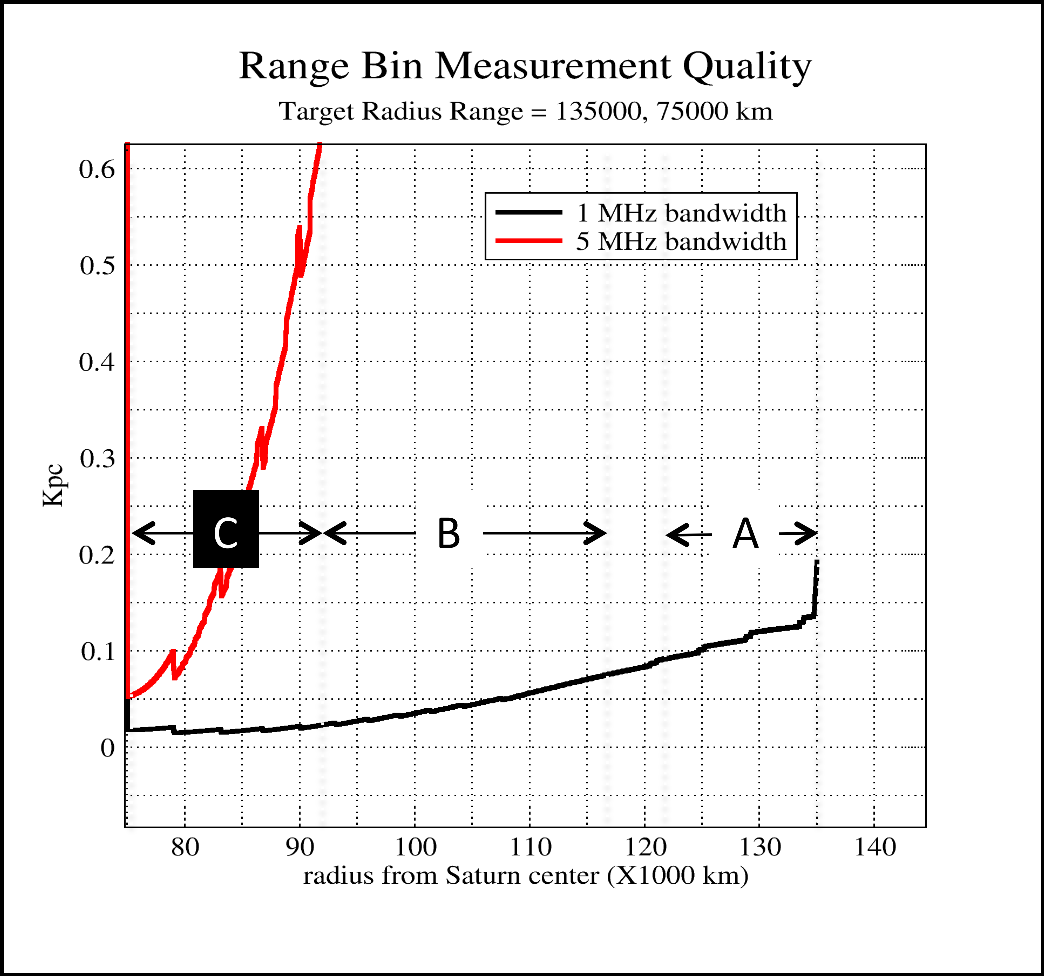
- Kpc is the normalized standard deviation of sigma0 (expected value/ standard deviation) in each range bin
- Performance is insensitive to timing error within ~ 30 s

1-D Performance – Proximal Orbit
1. resolution



- Pointing design sweeps all the rings, sequences range settings to keep rings in window
- Extremes of BW chosen
- Resolution comes at the price of SNR (see next slide)

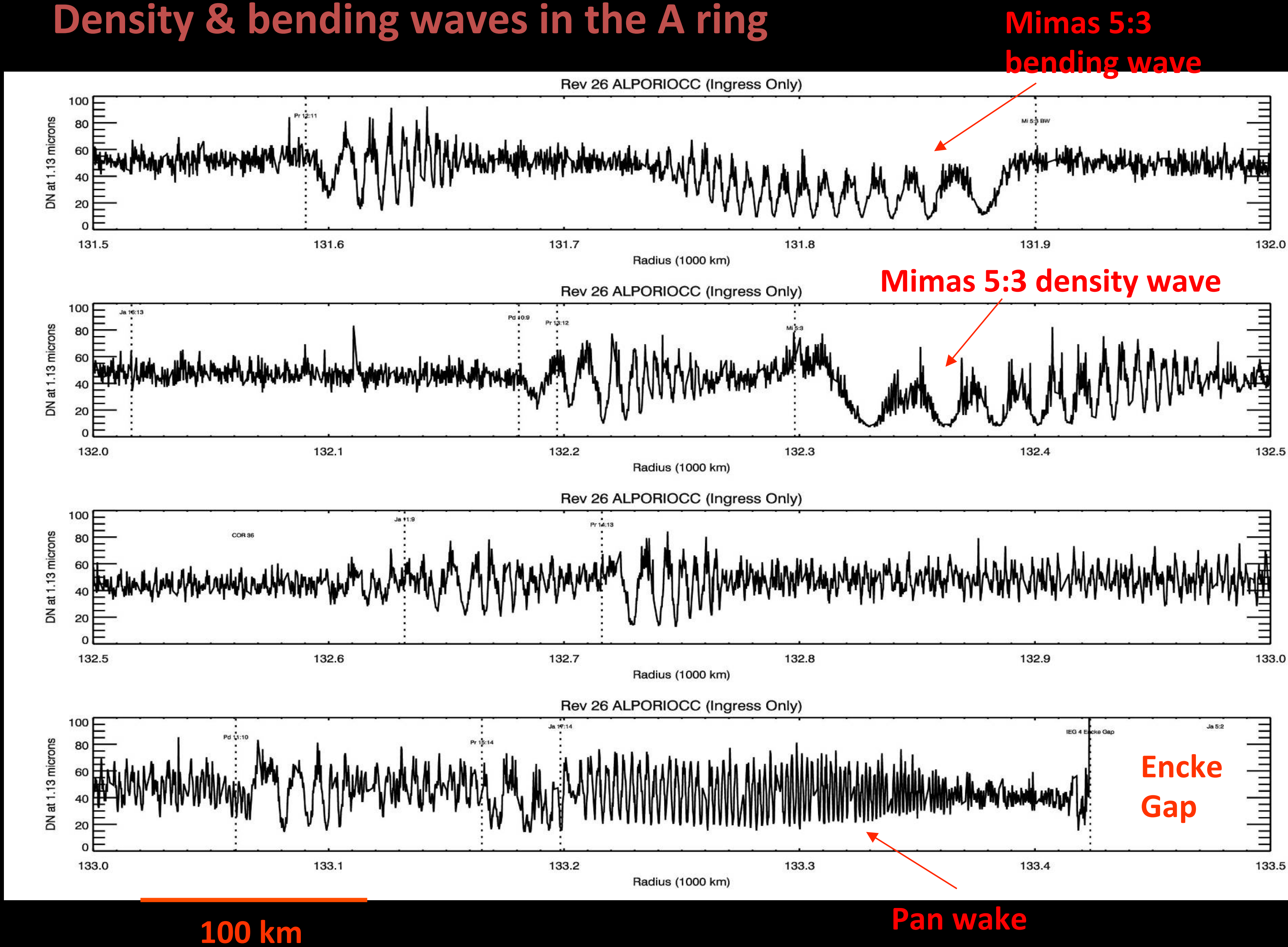
1-D Performance – Proximal Orbit
2. SNR



Kpc is the normalized standard deviation of sigma0 (standard deviation/expected value) in each range bin

Performance is more sensitive to timing error, however

Density & bending waves in the A ring



Observing Requests and Priorities

- **Obtain 1-D active observations through rings in at least one half of one F-ring orbit (and one half of one proximal orbit?)**
  - **Measure radial structure through all rings to resolution < 500m**
- **Obtain passive observations through rings in at least one half of one F-ring orbit (and one half of one proximal orbit?)**
  - **Measure bistatic scattering law through all rings to resolution ~ 1000 km**
- Obtain 1-D active observations through rings in one full F-ring orbit and/or one full proximal orbit
  - Measure wave propagation, azimuthal structure (?)
- Obtain 2-D data in SAR mode on at least one point in the outer C-ring during one F-ring orbit
  - Legacy data set that may constrain future ring models
- Ride-along radiometry in active-mode orbits
  - Comes for free
- Obtain spokes (i.e., radial) scans at less contested times
  - Fill out lower-resolution scattering map

"In the coming years, unencumbered by new data from space missions, we can hope to digest the new information, pull together the data from Earth and space, answer some of the current burning questions, and prepare the outlines of the next space missions."

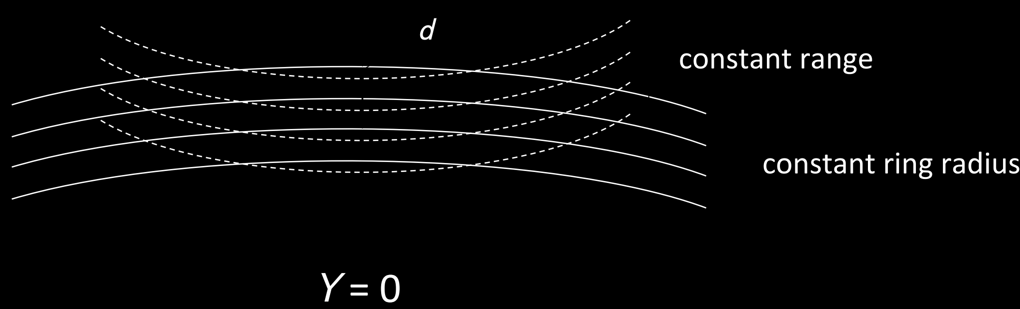
Larry Esposito

L. W. Esposito et al., "Saturn's Rings: Structure, Dynamics, and Particle Properties", in "Saturn" (ed. T. Gehrels and M. S. Mathews), University of Arizona Press, 1984, pg. 545

1-D Range Slicing

S/C

q half-power beamwidth (greatly exaggerated)



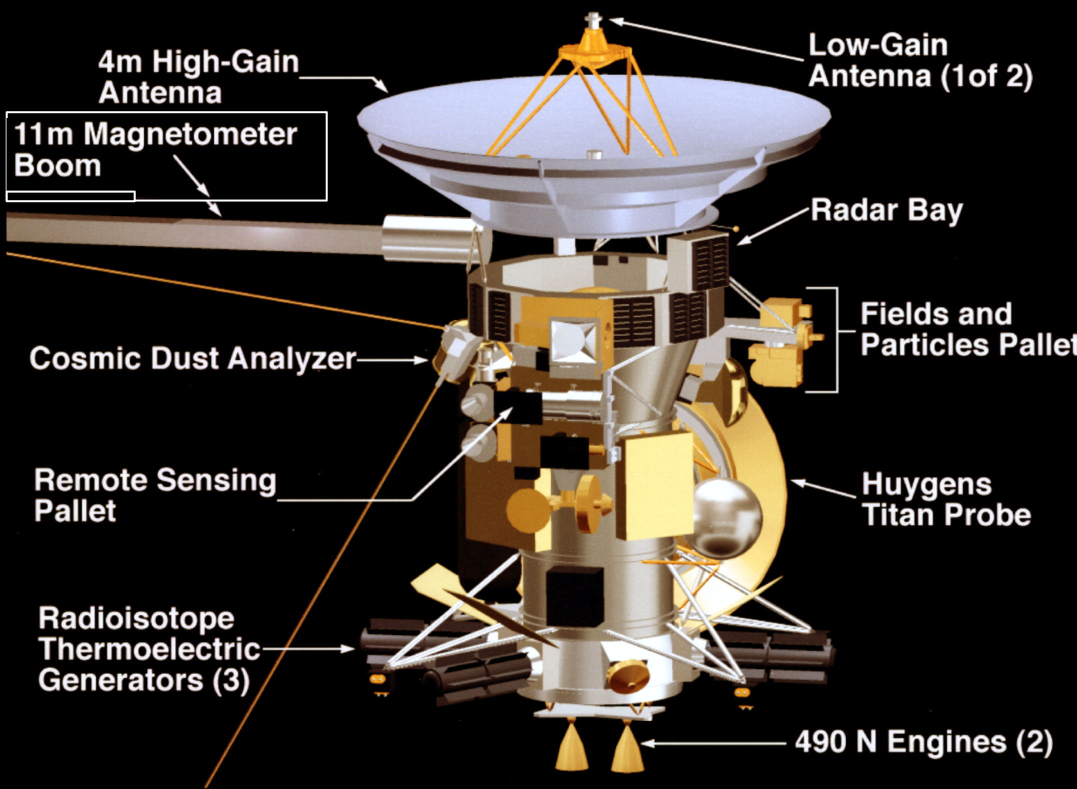
Observing point centered at zero azimuth angle relative to spacecraft

Geometric Smearing

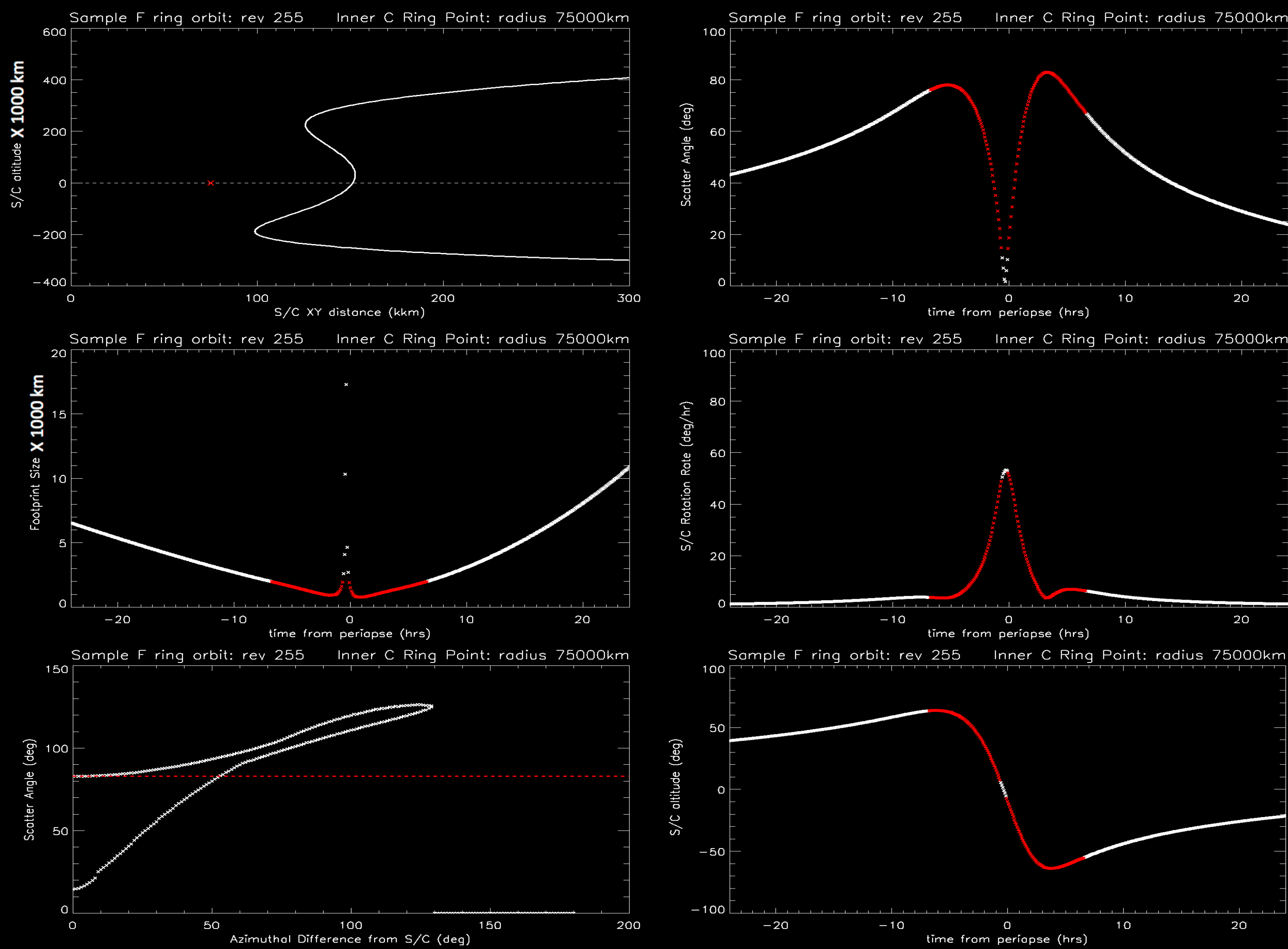
d	Inner C Ring [m]	Outer A Ring [m]
F-Ring Orbit		
Proximal orbit		

Cassini Spacecraft and RADAR

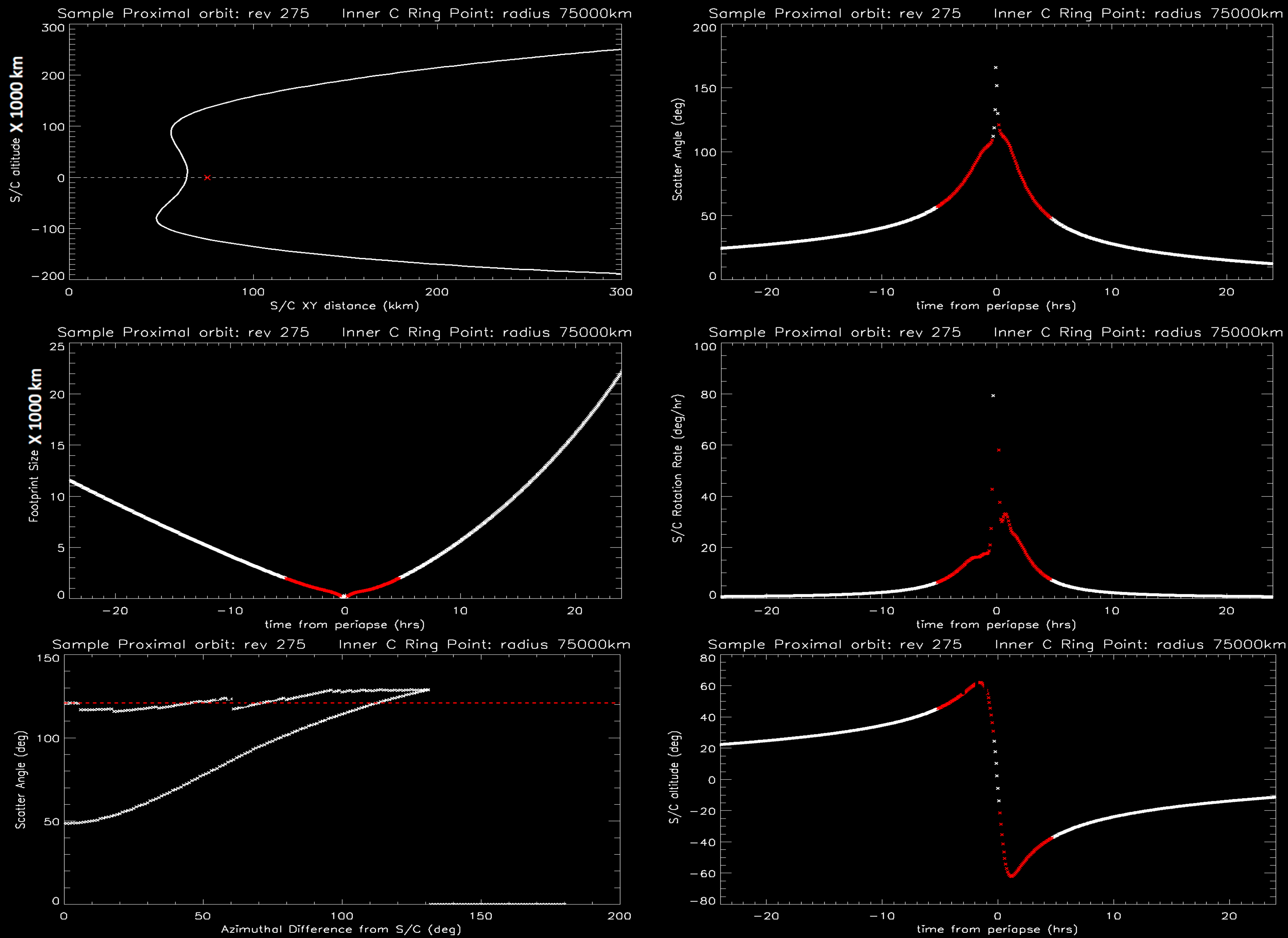
- Radar (active)
  - SAR (5-beam)
  - HiSAR (single beam)
  - Altimetry
  - Scatterometry
  - a
- Radiometry (passive)
  - Operates alone and in all active modes
  - 0.35° beamwidth
  - 1 linear polarization



F-Ring Orbit, inner C-Ring Point



Proximal Orbit, inner C-Ring Point



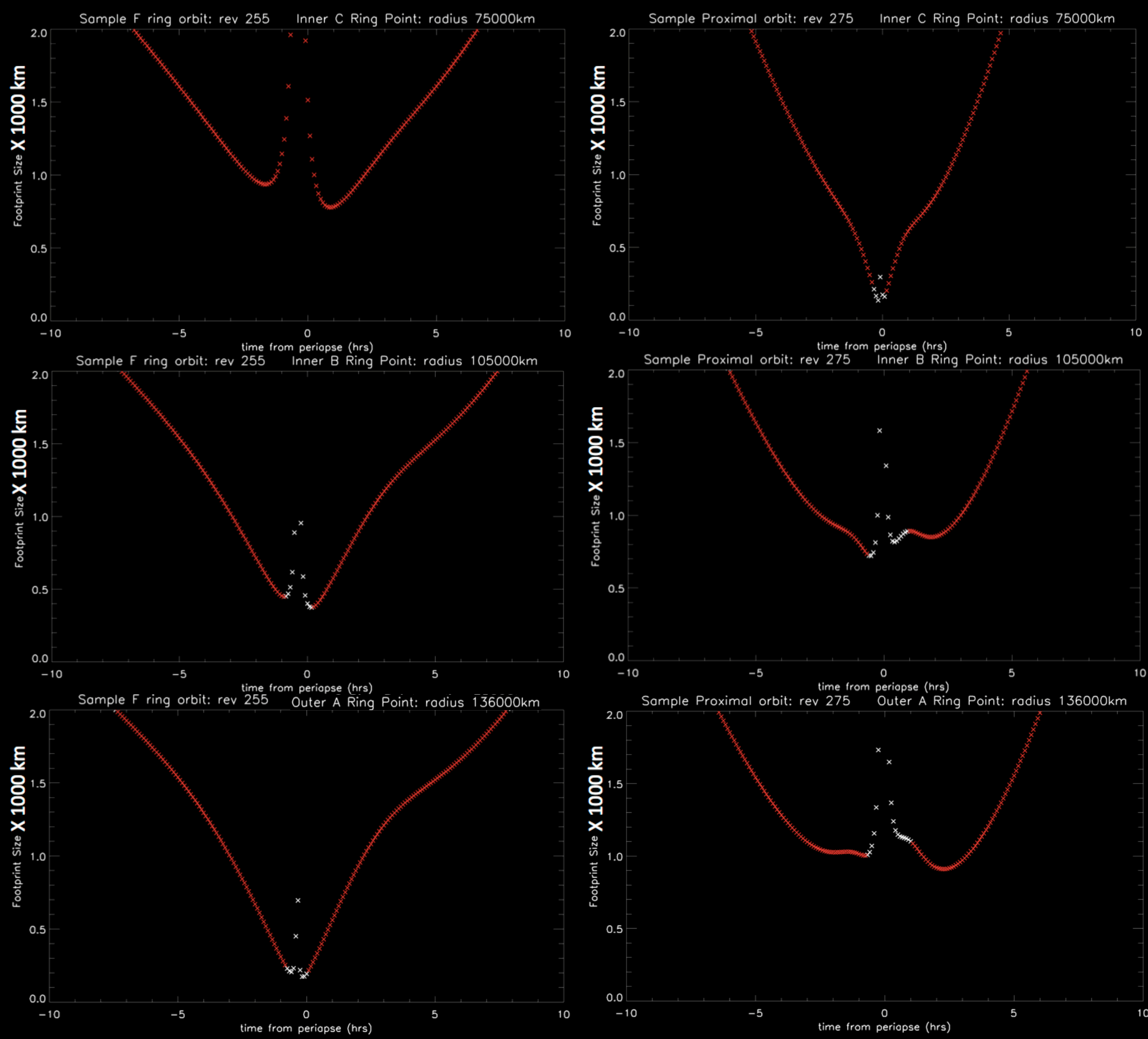
Projected Footprint, All Cases

F-Ring Orbit: rev 255 | Proximal Orbit: rev 275

Inner C Ring

Inner B Ring

Outer A Ring



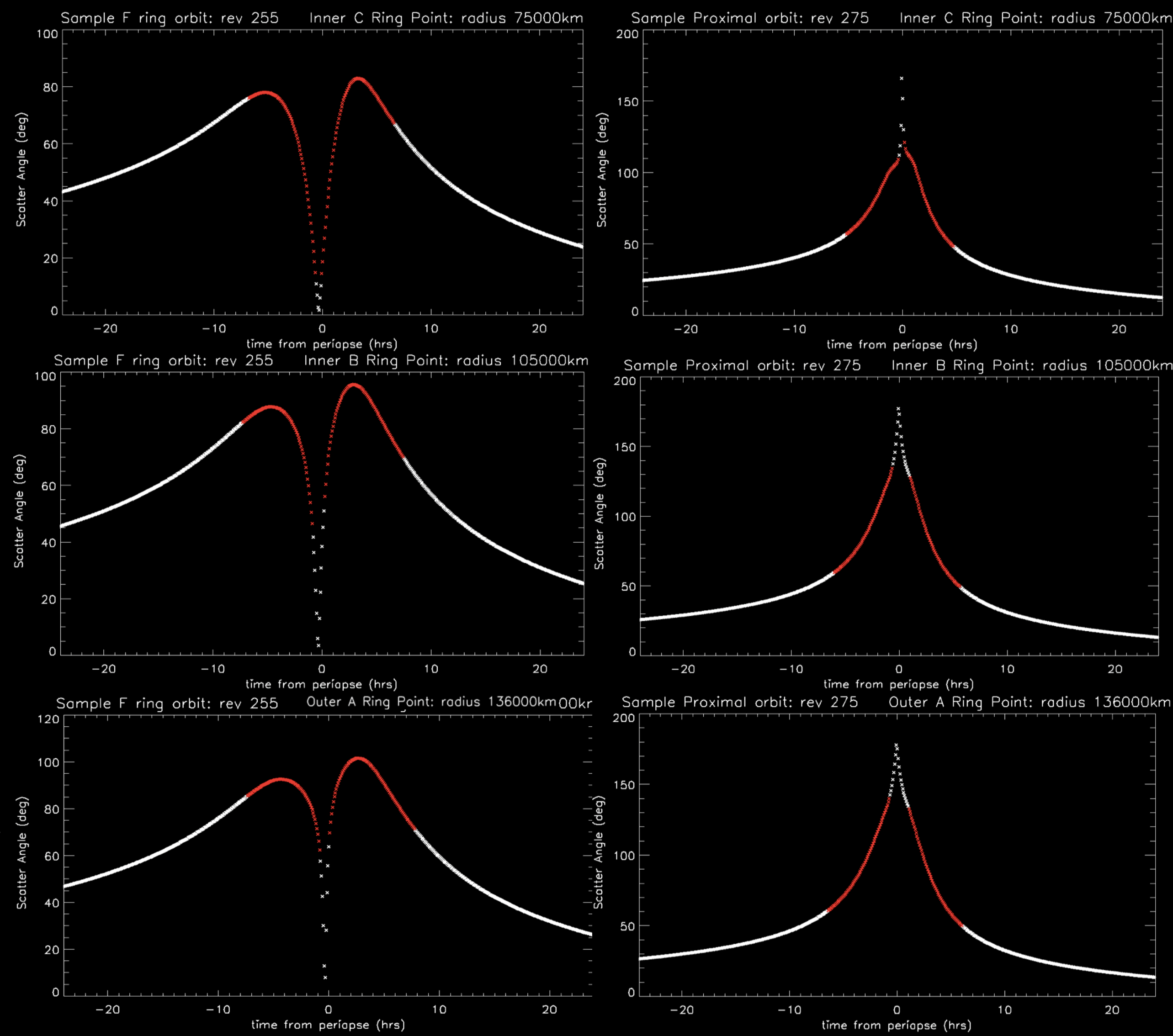
Scatter Angle Range, All Cases

F-Ring Orbit: rev 255 | Proximal Orbit: rev 275

Inner C Ring

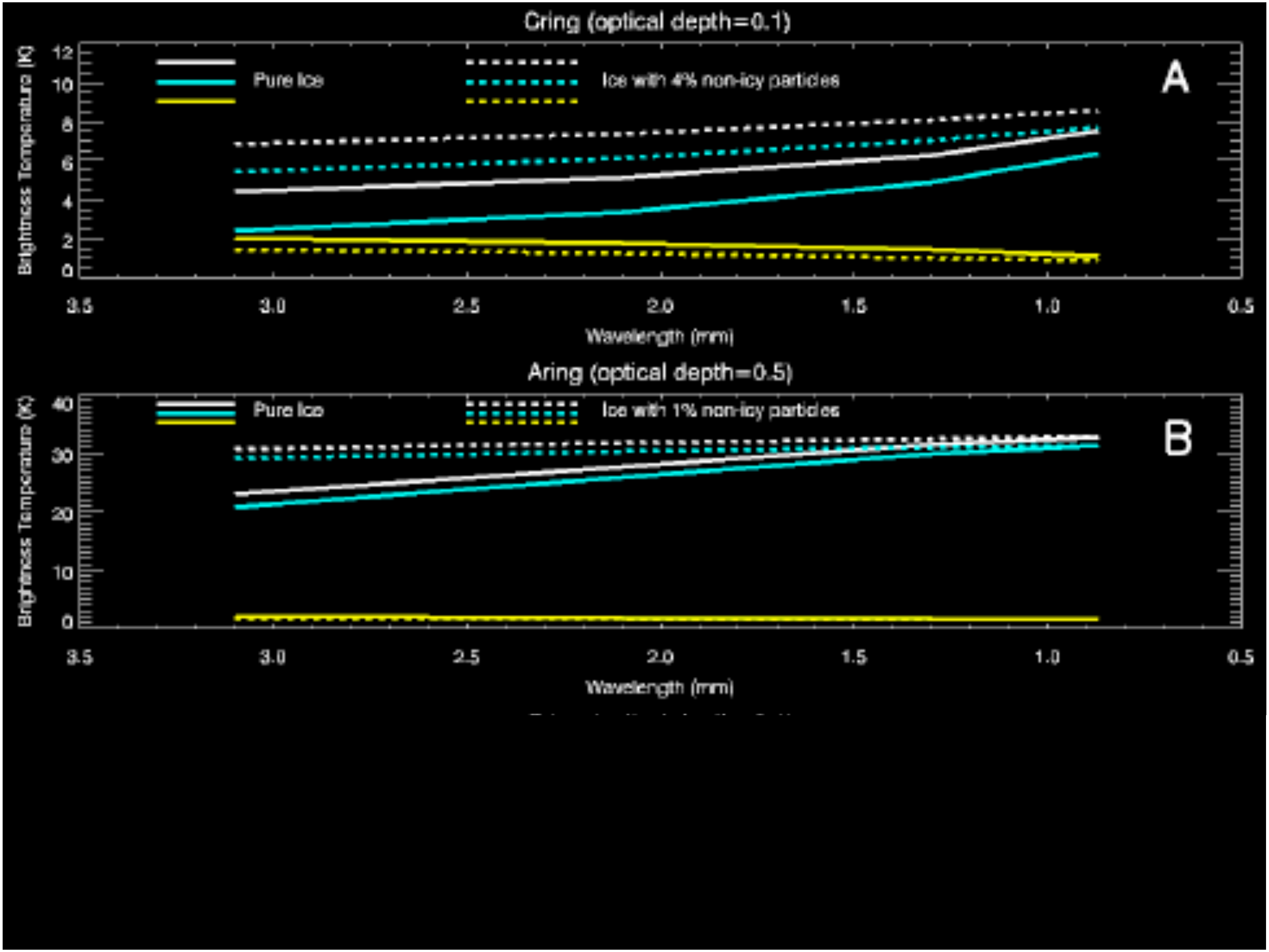
Inner B Ring

Outer A Ring

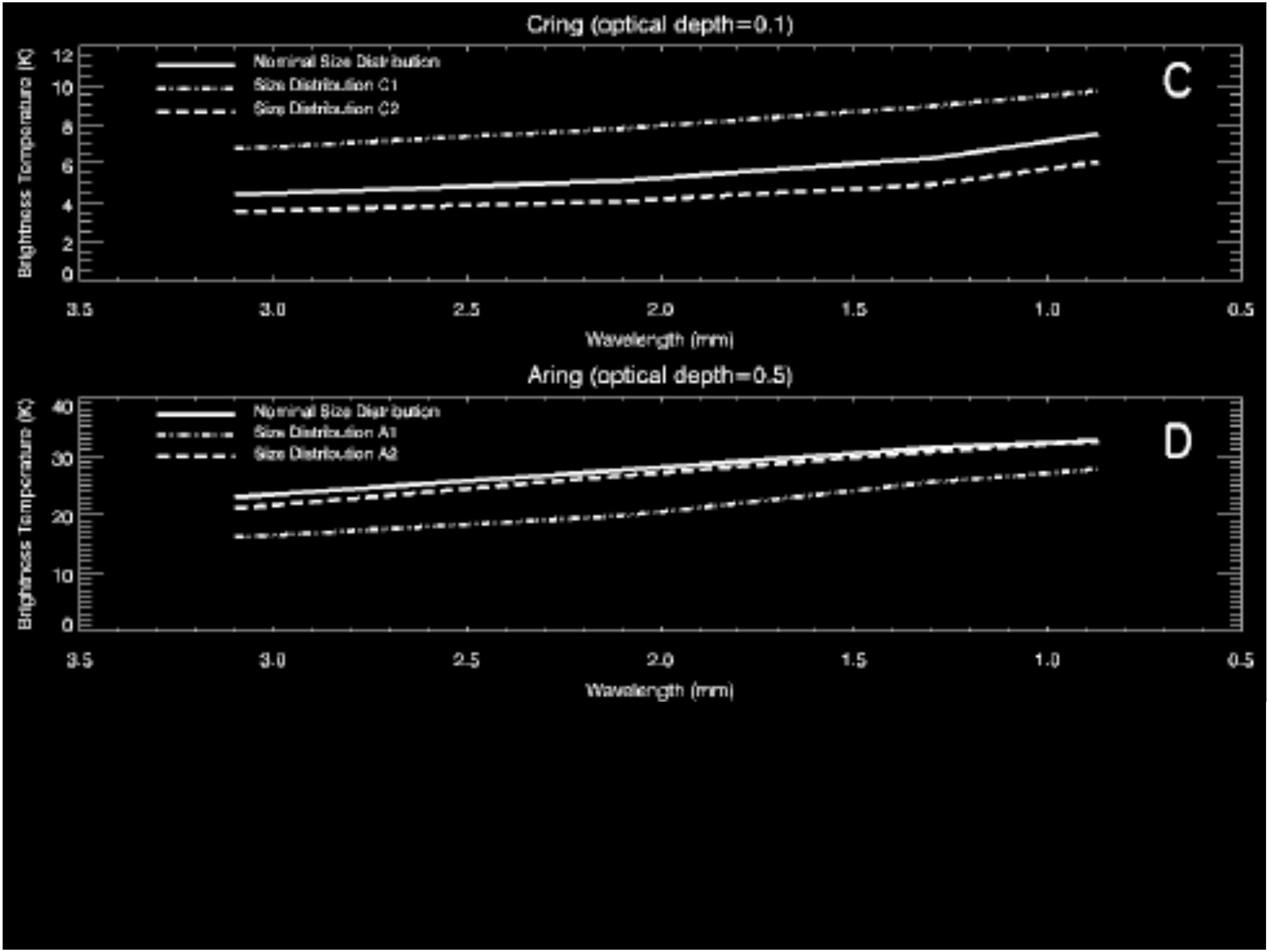


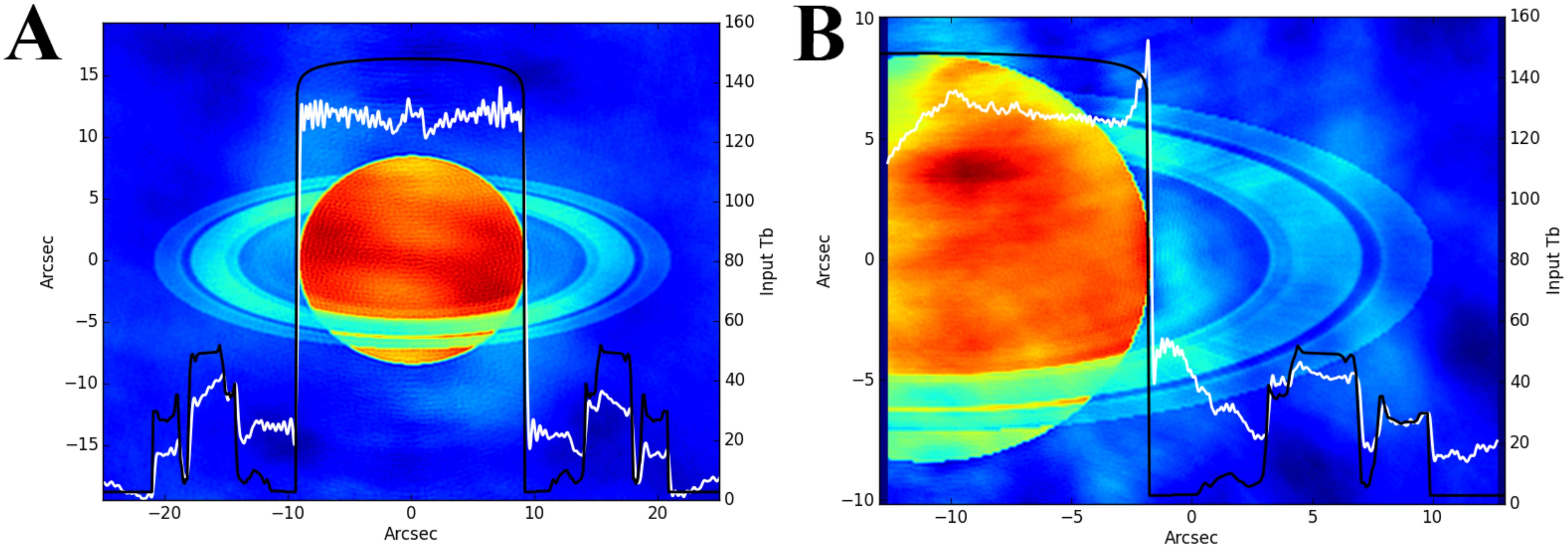
Active Observations - Summary

- SNR limits useful active observations to < ~100,000 km
  - SAR imaging < ~30,000 km
  - Real aperture scatterometry < ~100,000 km
  - F-Ring and Proximal orbits make active observations possible
- Two modes of operation envisioned
  - SAR imaging (2-D processing)
    - Spotlighting of discrete points needed to gain SNR
    - ~1 km resolution in ~100 km footprint estimated
  - 1-D range slicing
    - 50-m radial resolution with real-aperture data expected
    - 500 km range width possible at this resolution
  - Only one of these two modes may be used at a time
    - However, one point may be observed in both modes in one orbit if mode is switched at ring-plane crossing
    - Note: Radiometry is obtained in all modes
- Examples shown in following for inner C and outer A Rings
  - Caveat: Calculations are based on range-Doppler spread for solid-body surfaces and assume new software is written to incorporate shear



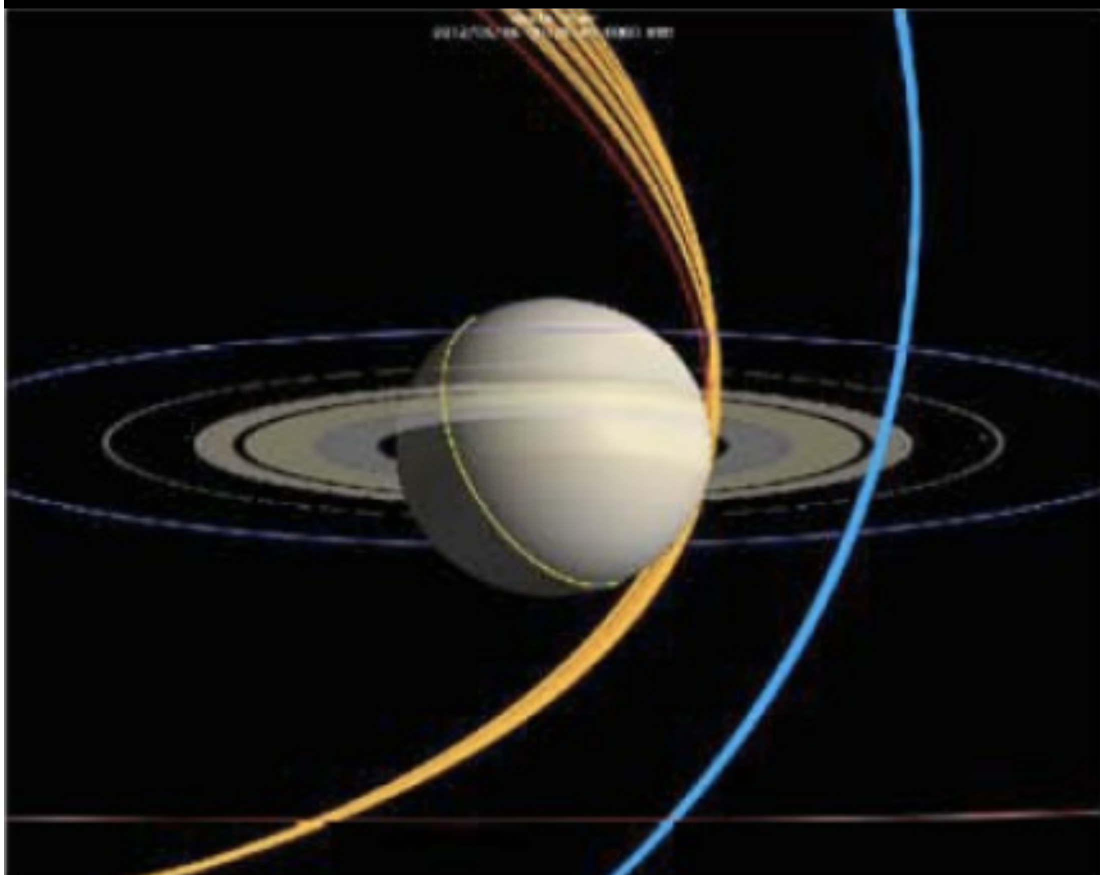
Cring (optical depth=0.1)
Pure Ice
Ice with 4% non-icy particles
A
Brightness Temperature (K)
Wavelength (mm)
Aring (optical depth=0.5)
Pure Ice
Ice with 1% non-icy particles
B
Brightness Temperature (K)
Wavelength (mm)

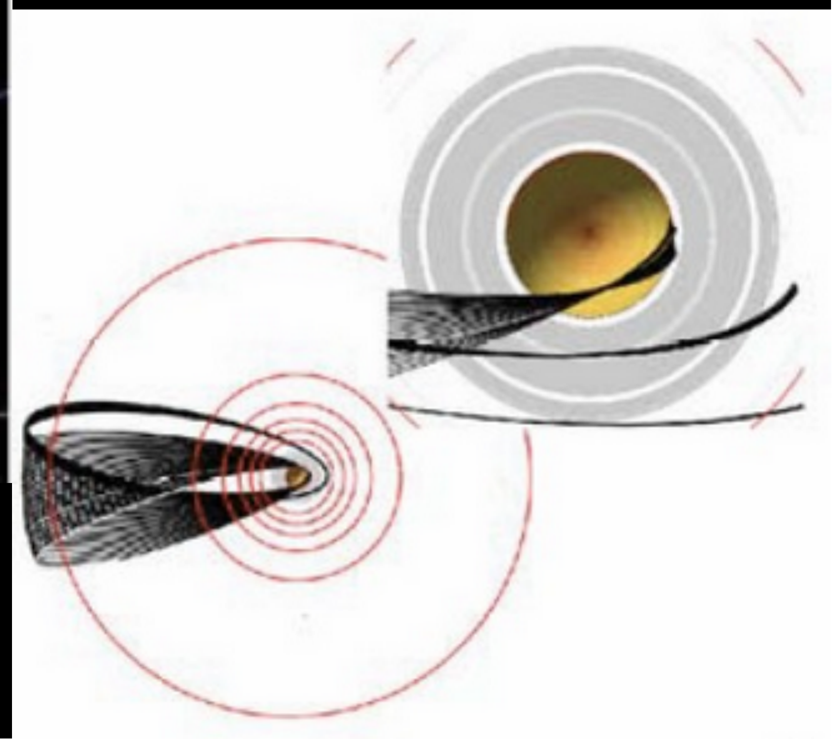

Cring (optical depth=0.1)
Nominal Size Distribution
Size Distribution C1
Size Distribution C2
C
Brightness Temperature (K)
Wavelength (mm)
Aring (optical depth=0.5)
Nominal Size Distribution
Size Distribution A1
Size Distribution A2
D
Brightness Temperature (K)
Wavelength (mm)


A
B
Arcsec
Arcsec
Input Tb
Arcsec
Arcsec
Input Tb
−20
−10
0
10
20
15
10
5
0
−5
−10
−15
160
140
120
100
80
60
40
20
0

[redacted]

Proximal / F-Ring Orbit Requests to be Studied At the End of Cassini Mission





Observational Scenarios in F-Ring and Proximal Orbits

- Passive Mode
  - ❖ Scientific Objectives
    - *Constrain particle size, small-scale spatial distribution, dielectric properties*
    - *Constrain bulk composition*
  - ❖ Observational Scenarios
    - *Spotlight observations at a few radial positions to measure scattering curve*
    - *Obtain high resolution spoke scans as targets of opportunity*

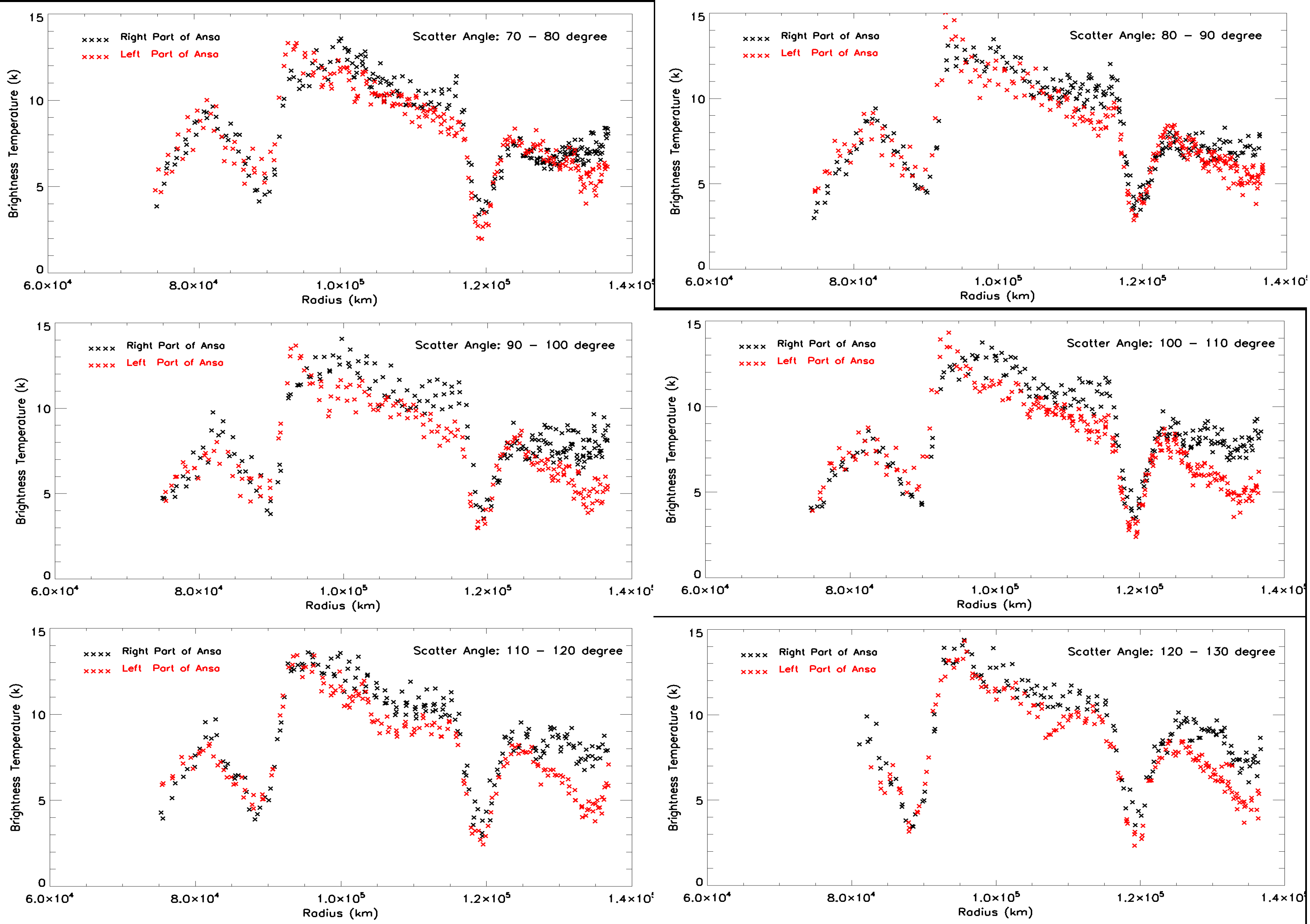
- Active Mode
  - ❖ Scientific Objectives
    - *Constrain particle size, vertical distribution, and dielectric properties*
    - *Address large-scale distribution & dynamics*
  - ❖ Observational Scenarios
    - *Obtain high resolution on density structures by SAR imaging or range slicing*

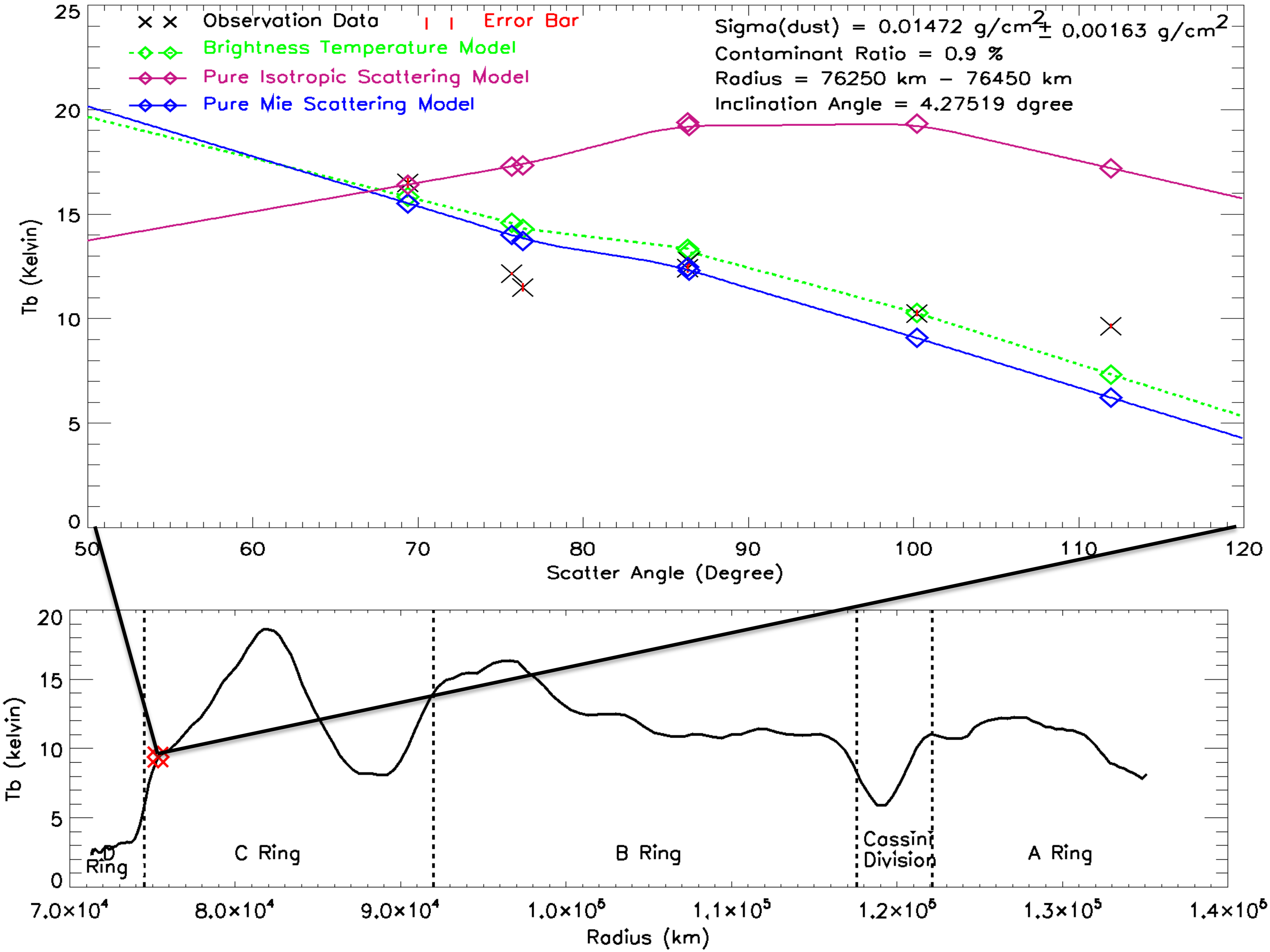
Thank you !

[redacted]

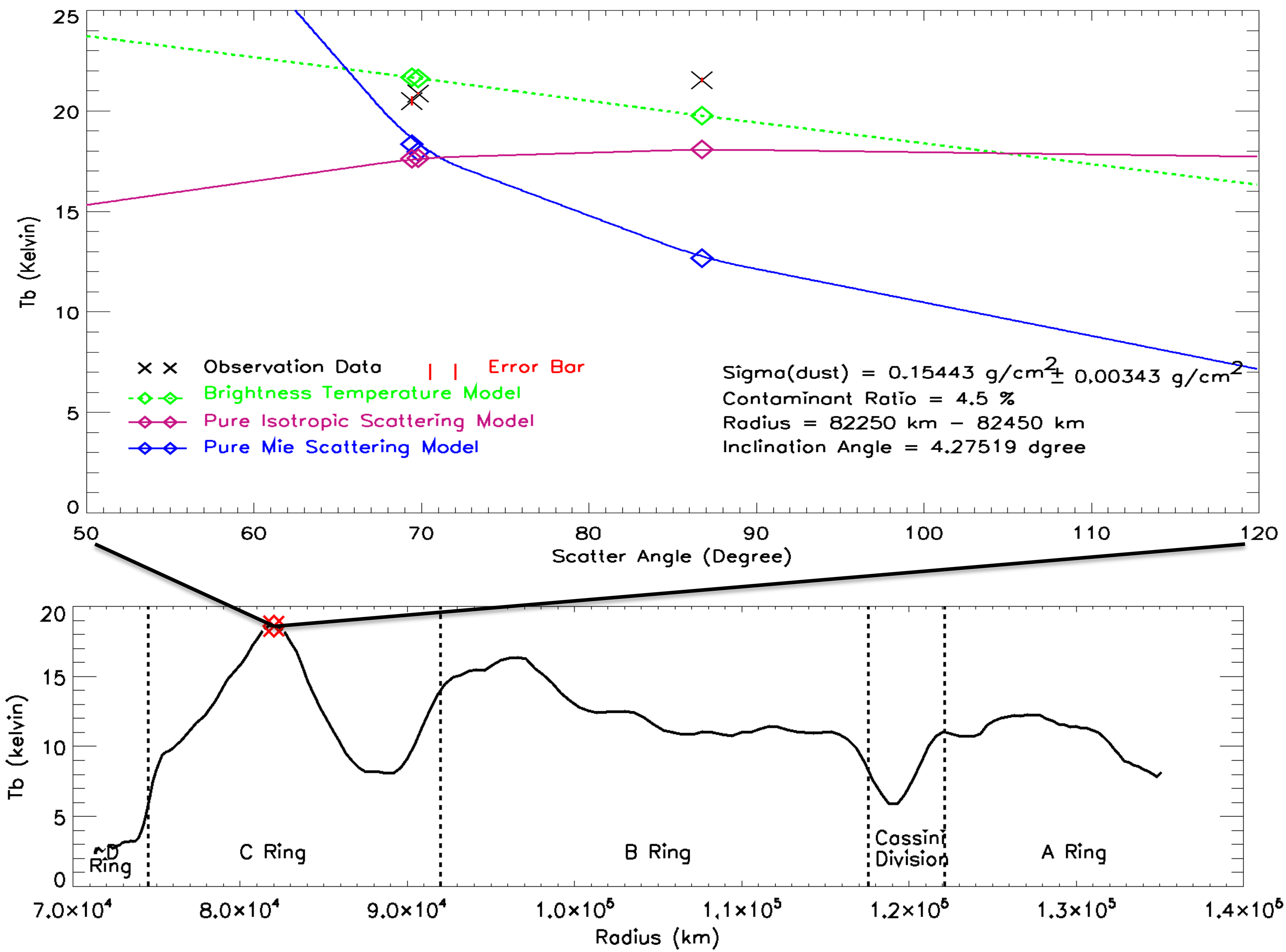
Back Up

Portions of Dataset Remain Untapped: Asymmetry in the Ansae

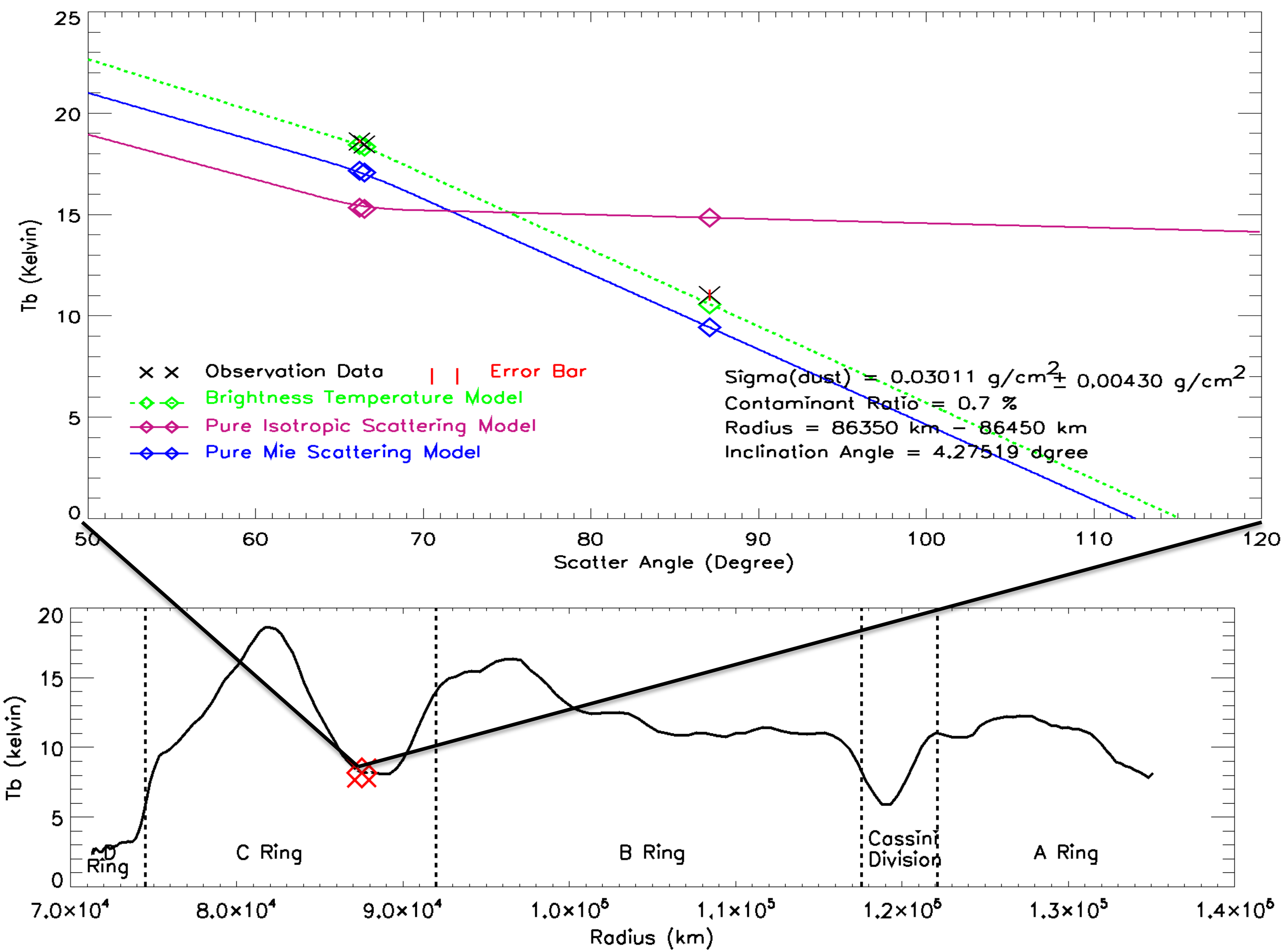




Observation Data
Error Bar
Brightness Temperature Model
Pure Isotropic Scattering Model
Pure Mie Scattering Model
Sigma(dust) = 0.01472 g/cm2 ± 0.00163 g/cm2
Contaminant Ratio = 0.9 %
Radius = 76250 km – 76450 km
Inclination Angle = 4.27519 dgree
Tb (Kelvin)
Scatter Angle (Degree)
Tb (kelvin)
D Ring
C Ring
B Ring
Cassini Division
A Ring
Radius (km)

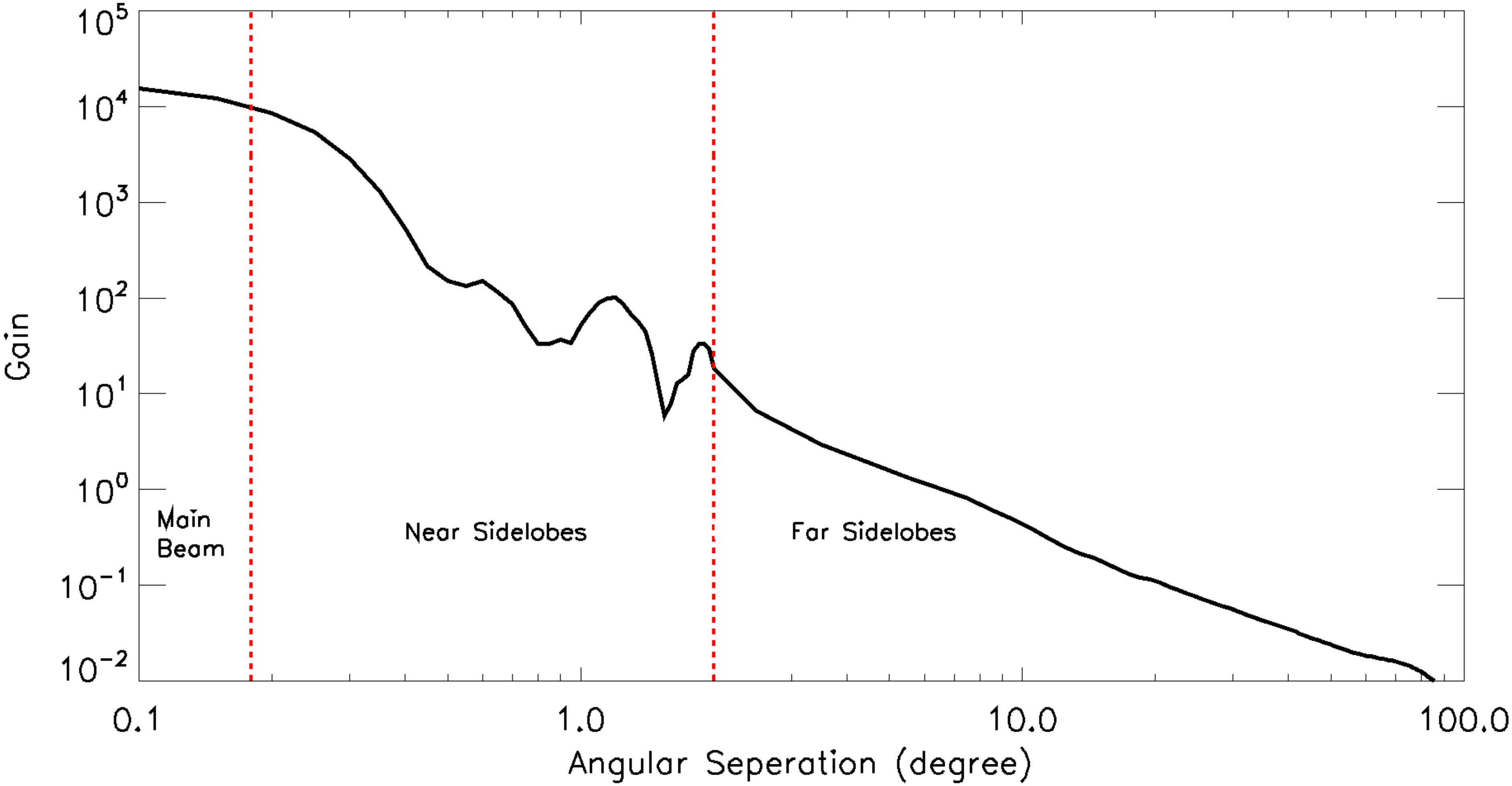


Tb (Kelvin)
Scatter Angle (Degree)
Observation Data
Error Bar
Brightness Temperature Model
Pure Isotropic Scattering Model
Pure Mie Scattering Model
Sigma(dust) = 0.15443 g/cm2 ± 0.00343 g/cm2
Contaminant Ratio = 4.5 %
Radius = 82250 km − 82450 km
Inclination Angle = 4.27519 dgree
Tb (kelvin)
Radius (km)
D Ring
C Ring
B Ring
Cassini Division
A Ring

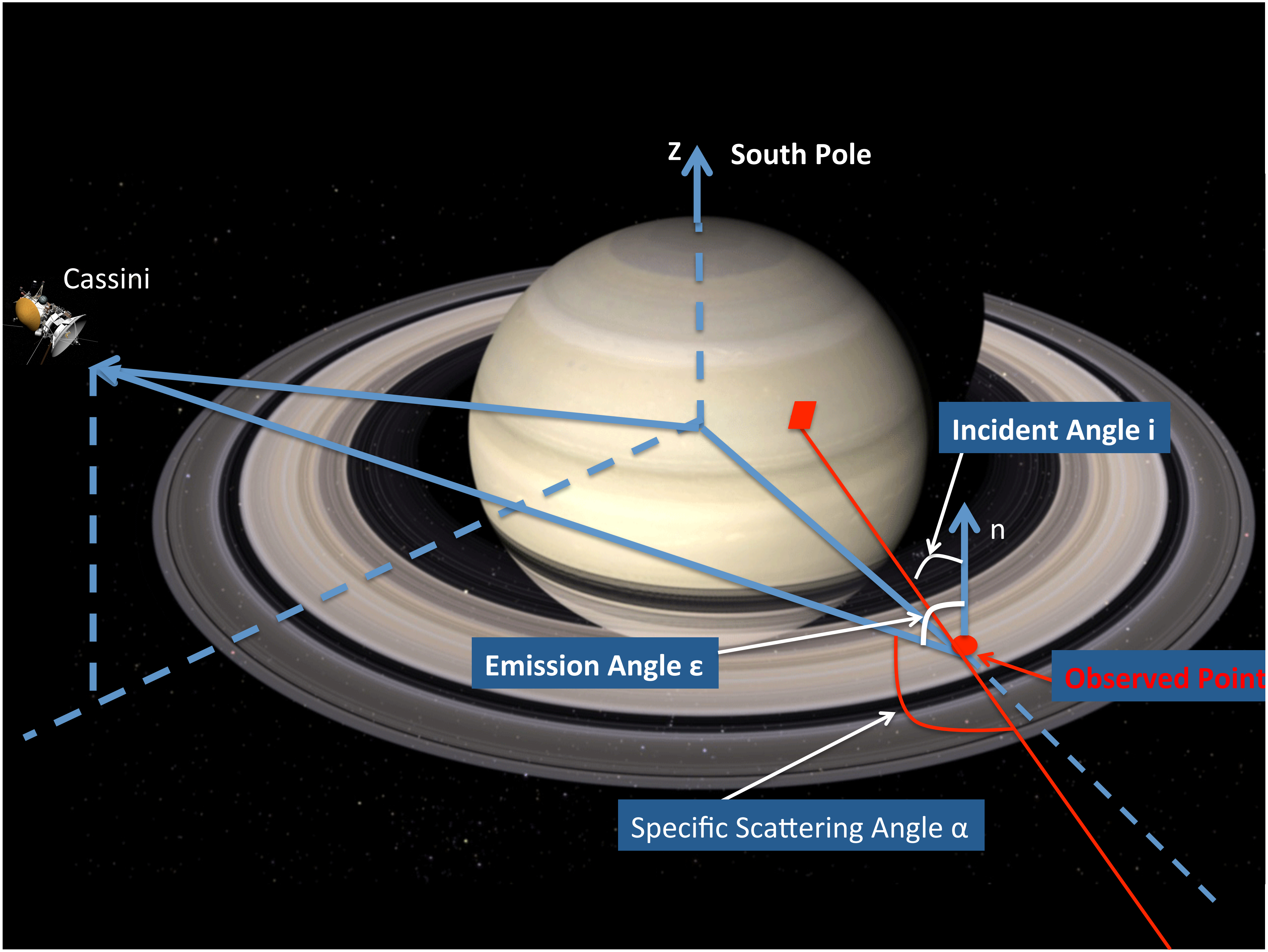


Tb (Kelvin)
Scatter Angle (Degree)
Observation Data
Error Bar
Brightness Temperature Model
Pure Isotropic Scattering Model
Pure Mie Scattering Model
Sigma(dust) = 0.03011 g/cm2 ± 0.00430 g/cm2
Contaminant Ratio = 0.7 %
Radius = 86350 km - 86450 km
Inclination Angle = 4.27519 dgree
Tb (kelvin)
Radius (km)
D Ring
C Ring
B Ring
Cassini Division
A Ring

[redacted]



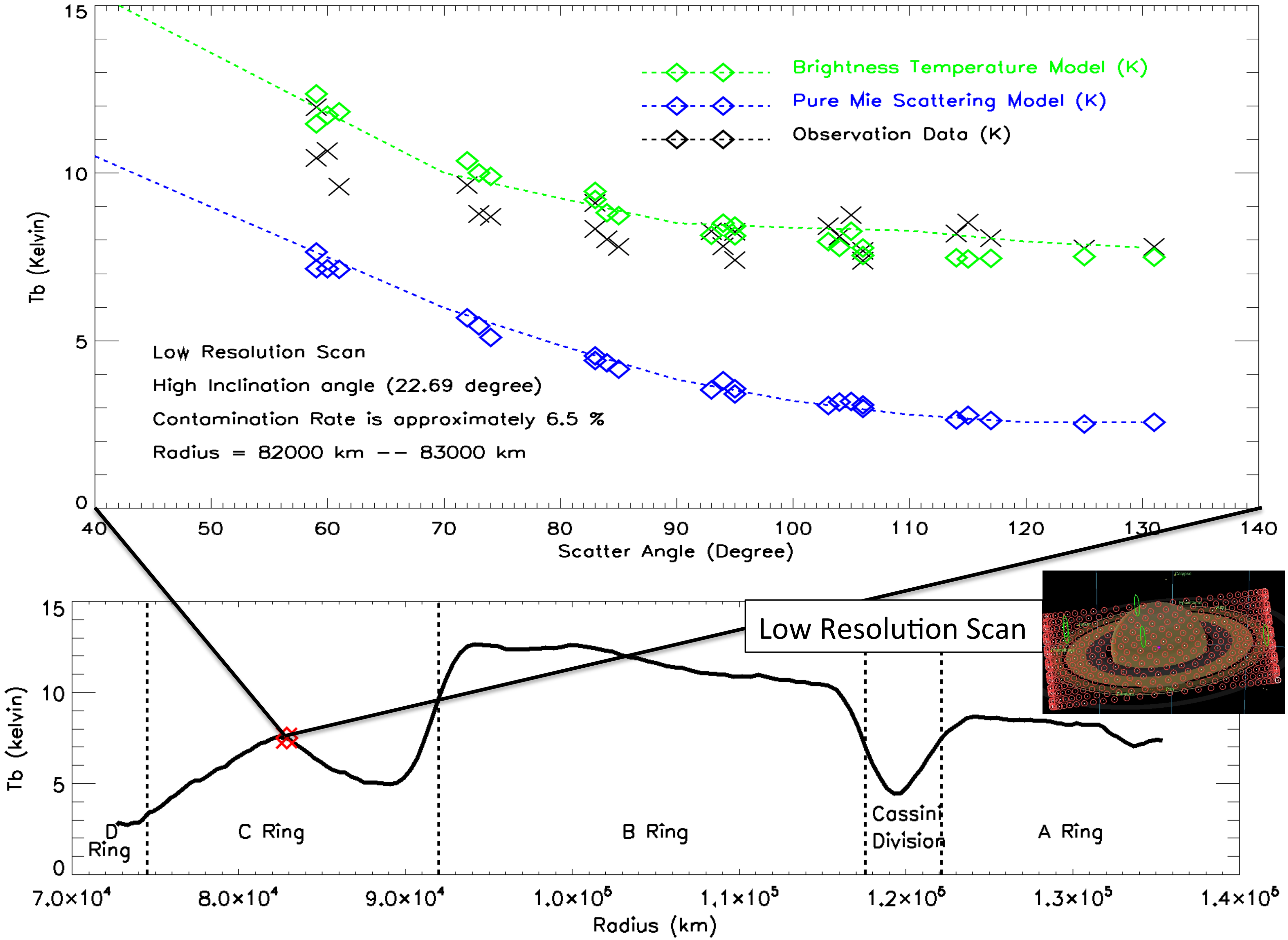
[redacted]



z
South Pole
Cassini
Incident Angle i
n
Emission Angle ε
Observed Point
Specific Scattering Angle α

- **Physical Modeling** – *Monte Carlo Codes from Professor David Dunn*

- Individual Particle (size a) *V.S.* Single Photon (wavelength λ)
  - Mie theory
    – determine single particle properties, scattering and extinction cross section
  - A linear combination of isotropic and Mie scattering
    -- get the phase function corrected for non-spherical nature of ring particles
- Radiative Transfer in Ring Plane
  - Scattered Light
    -- track photons in their interaction with a path of ring until reaching their final destination
  - Internal Thermal Emission
    -- distribute photons uniformly in the ring plane and track their scattering


Brightness Temperature Model (K)
Pure Mie Scattering Model (K)
Observation Data (K)
Low Resolution Scan
High Inclination angle (22.69 degree)
Contamination Rate is approximately 6.5 %
Radius = 82000 km -- 83000 km
Tb (Kelvin)
Scatter Angle (Degree)
15
10
5
0
40
50
60
70
80
90
100
110
120
130
140
Low Resolution Scan
Tb (kelvin)
Radius (km)
D Ring
C Ring
B Ring
Cassini Division
A Ring
7.0×10^4
8.0×10^4
9.0×10^4
1.0×10^5
1.1×10^5
1.2×10^5
1.3×10^5
1.4×10^5

Proximal / F-Ring Orbit Requests to be Studied

- Saturn Radiometry
  - Mike J. has started working on these
- Active measurements of Saturn
  - Measure backscatter from cloud droplets (Richard W.)
- High resolution ring spoke scans (radiometry)
  - Similar to prime mission observations
- Roll spacecraft while targeting various locations in A,B,C-rings with radiometry and scatterometry
  - Highly resolved scattering function + thermal emission
- Active SAR (with passive rad.) of the A and D Rings
  - Richard W. has done preliminary studies
    - Can obtain ~2 km resolution in A ring and ~500 m resolution in D Ring (observe +/- 30 minutes from ring plane crossing)

Scientific Objectives and Observational Scenarios - Active

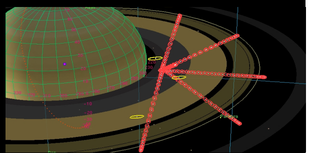
- Scientific Objectives:
  – Constrain particle size distribution, vertical distribution, and dielectric properties
  – Address large-scale distribution & dynamics
- Observational Scenarios
  – Spotlight observations at a few radial points to measure the scattering curve
    - Inner C Ring and Outer A Ring best
    - Points observed within orbit plane
  – Use range slicing or SAR to image in one or two dimensions respectively
  – On same ring point, SAR for half-orbit for imaging, range slicing for half-orbit for highest resolution in one dimension
  – Only one point per orbit may be fully examined

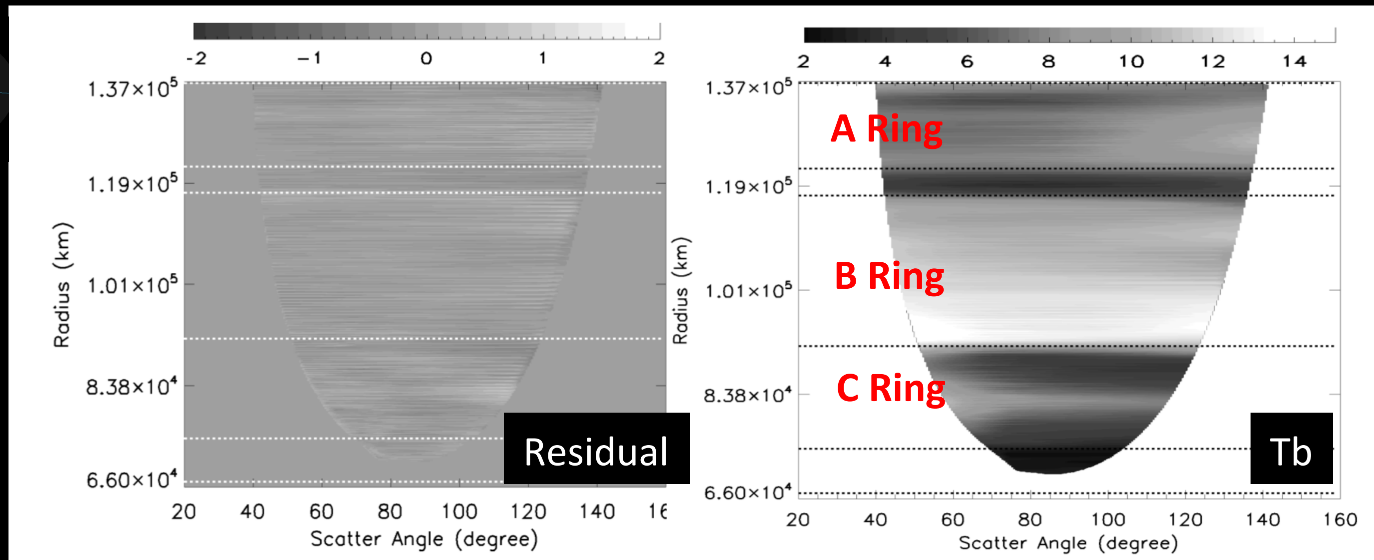
Scientific Objectives and Observational Scenarios - Passive

- Scientific Objectives:
  - Constrain particle size and small-scale spatial distribution, and dielectric properties
  - Constrain bulk composition
- Observational Scenarios
  - Spotlight observations at a few radial positions to measure the scattering curve
    - All ring radii can be usefully examined
    - Spots observed within and outside of orbit plane desired to obtain range in scatter angle
    - Multiple points may be observed in a single orbit
    - Polarization of chosen points requires separate orbits
  - Obtain high resolution spoke scans as targets of opportunity
    - fill out inclination/scattering angle/radius map
    - To be carried out away from closest approach

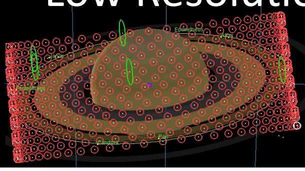
Preliminary Calibration Results

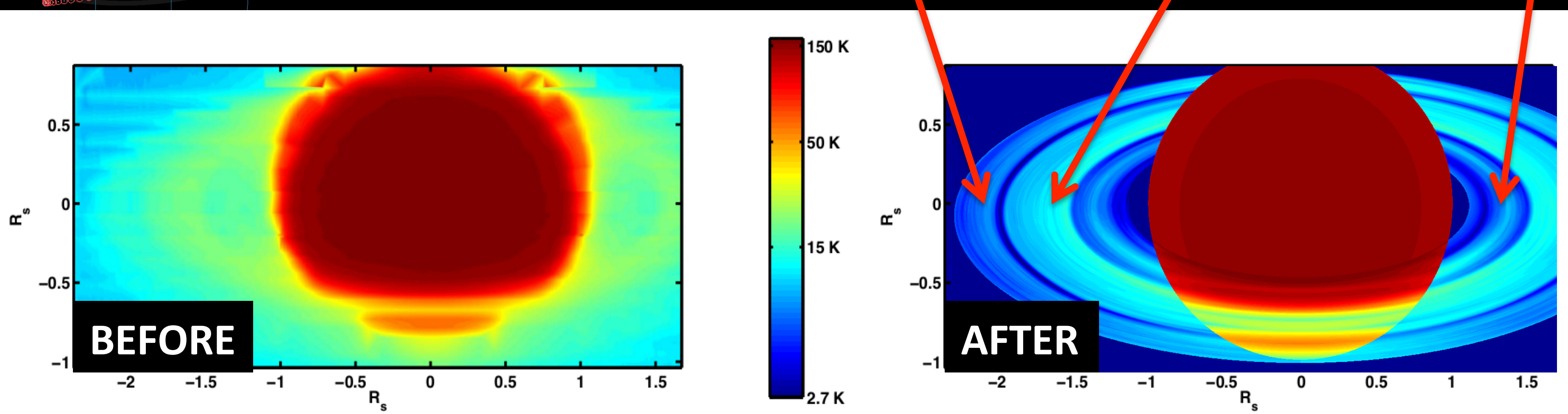
- High Resolution (11-Sep-2006; Inclination Angle = 20°)

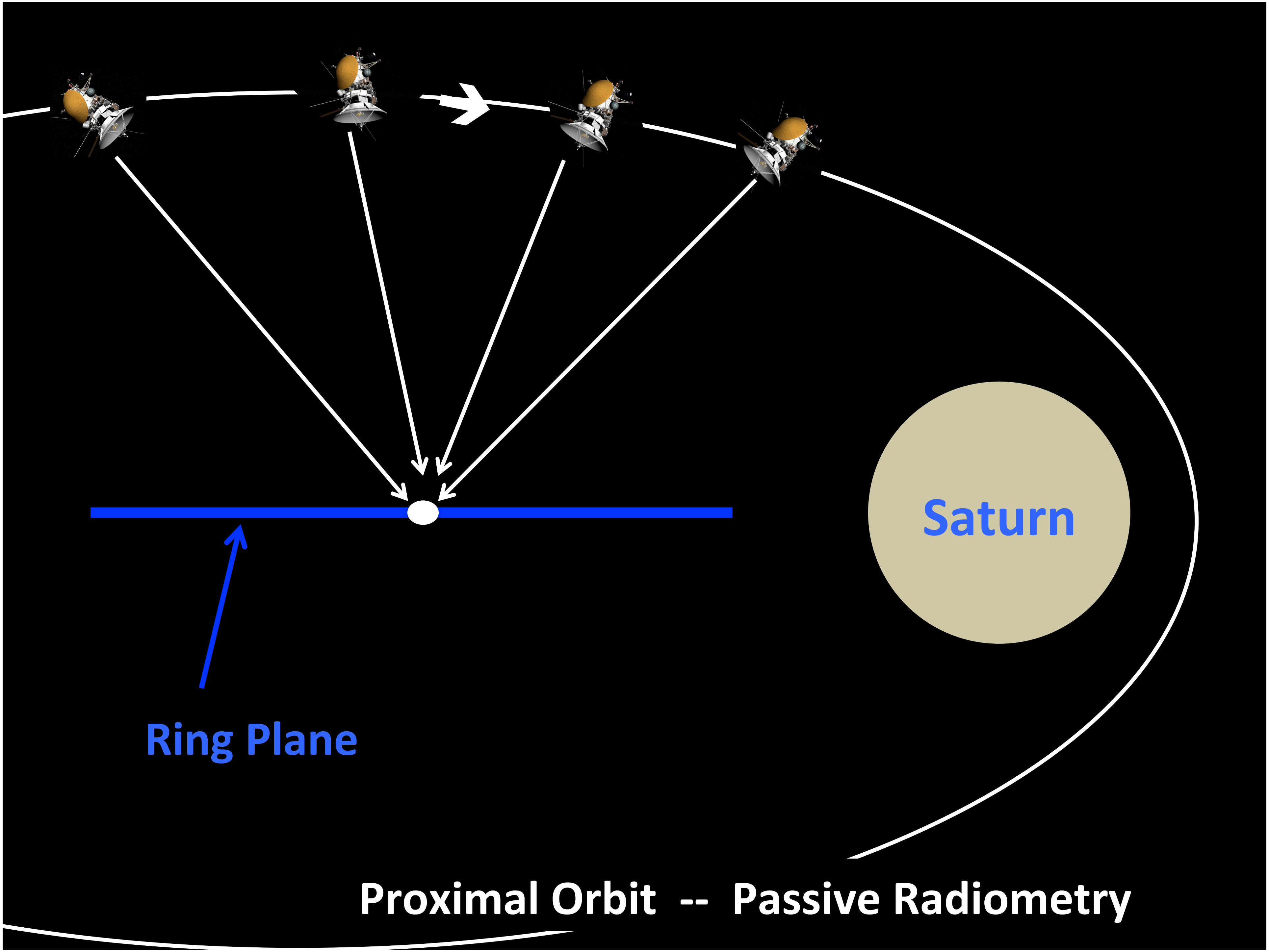


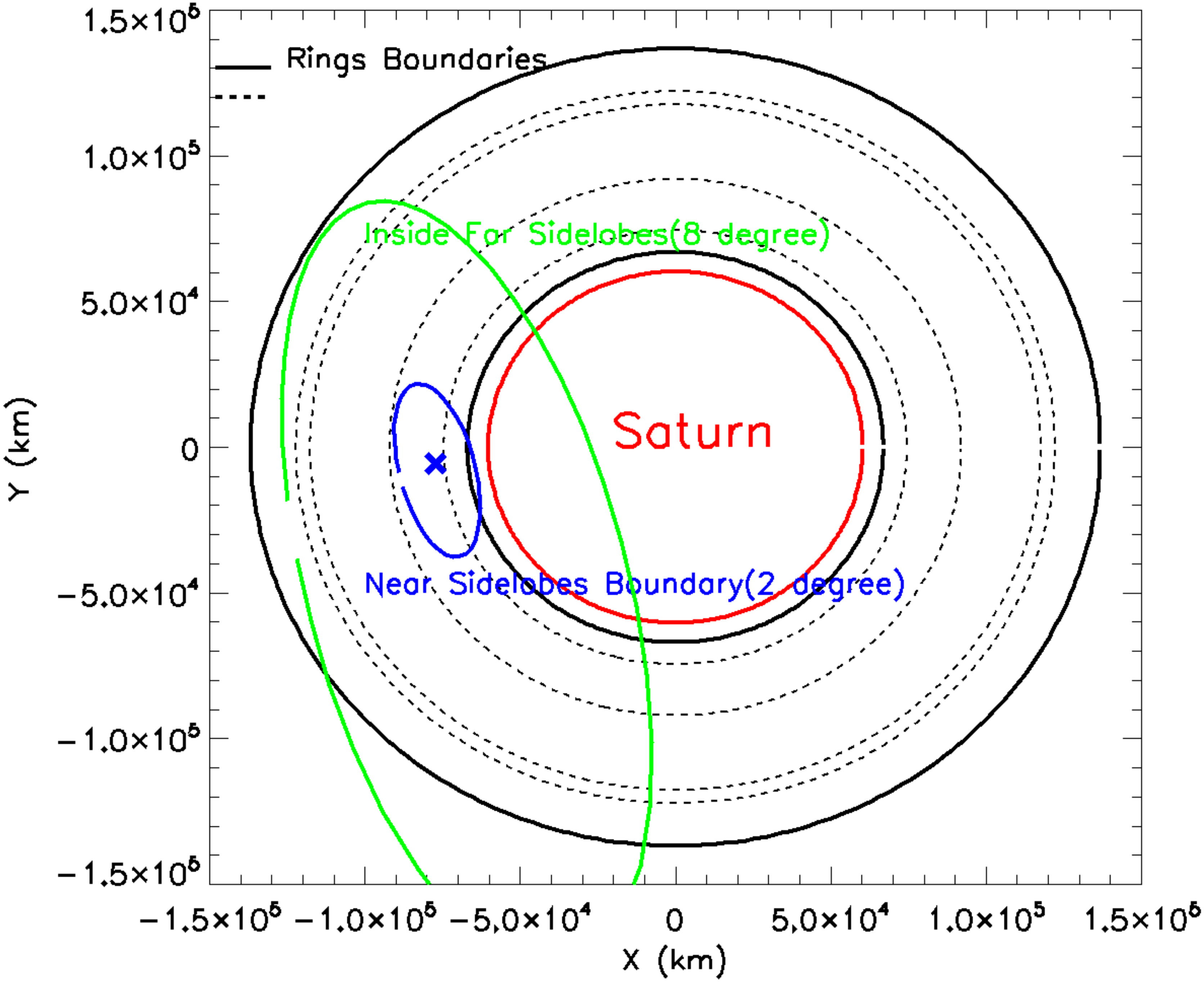


- Low Resolution (12-Sep-2006; Inclination Angle =22°)



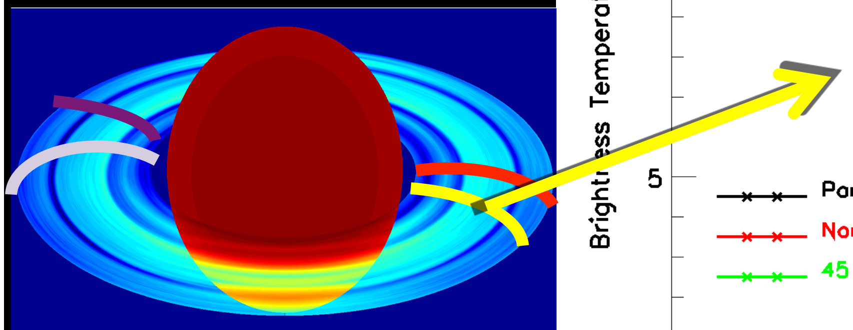


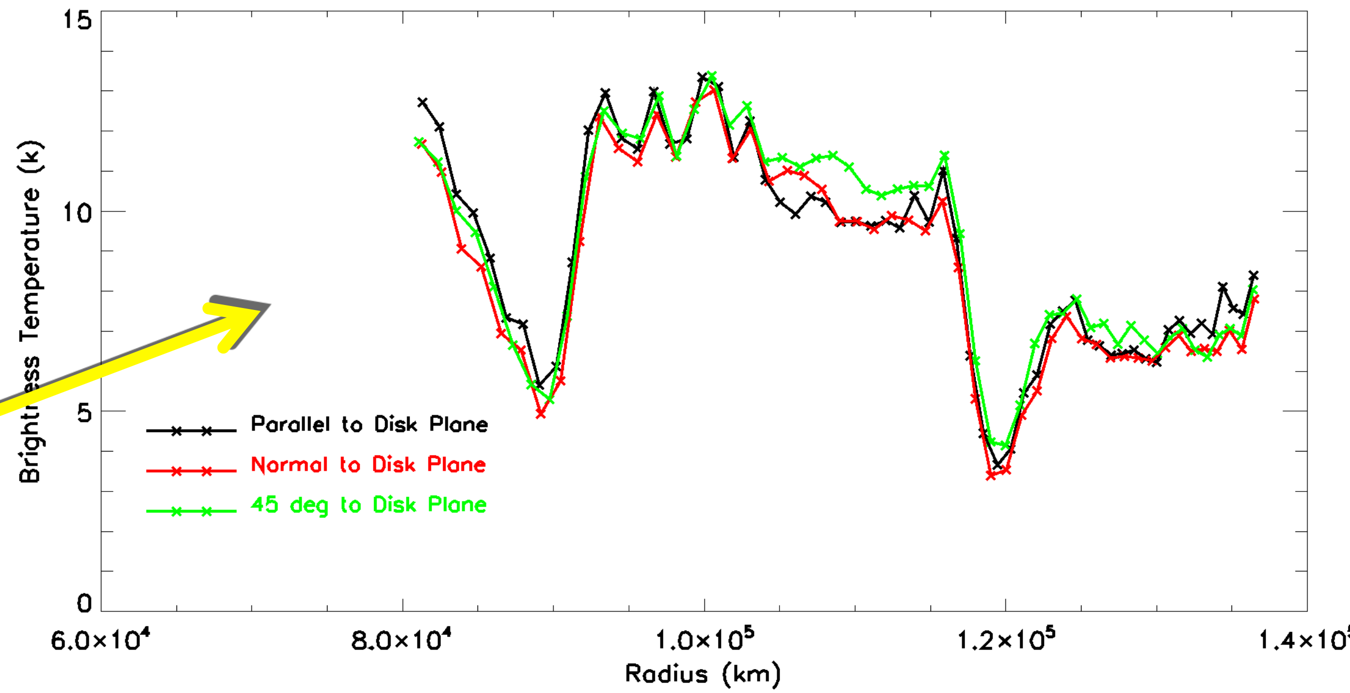

Saturn
Ring Plane
Proximal Orbit -- Passive Radiometry



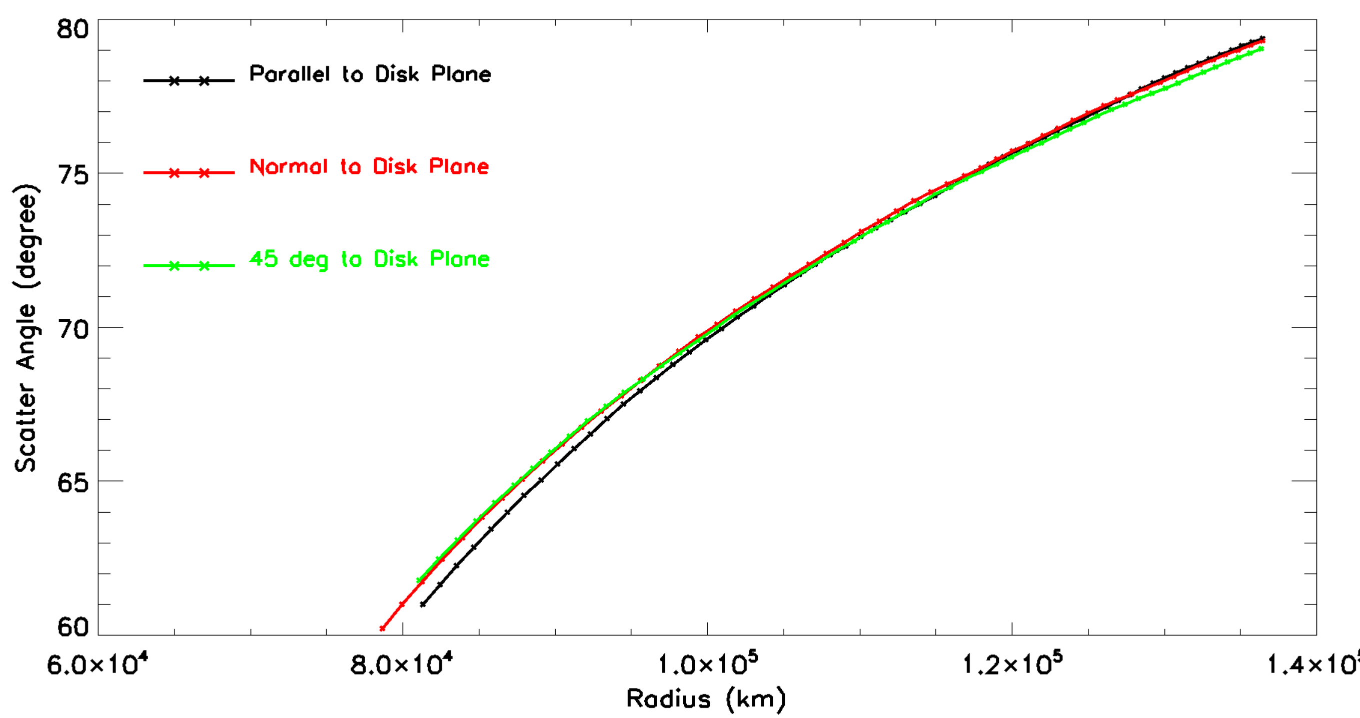
Rings Boundaries
Inside Far Sidelobes(8 degree)
Saturn
Near Sidelobes Boundary(2 degree)
1.5×10⁵
1.0×10⁵
5.0×10⁴
0
−5.0×10⁴
−1.0×10⁵
−1.5×10⁵
Y (km)
−1.5×10⁵
−1.0×10⁵
−5.0×10⁴
0
5.0×10⁴
1.0×10⁵
1.5×10⁵
X (km)

Polarization Effects

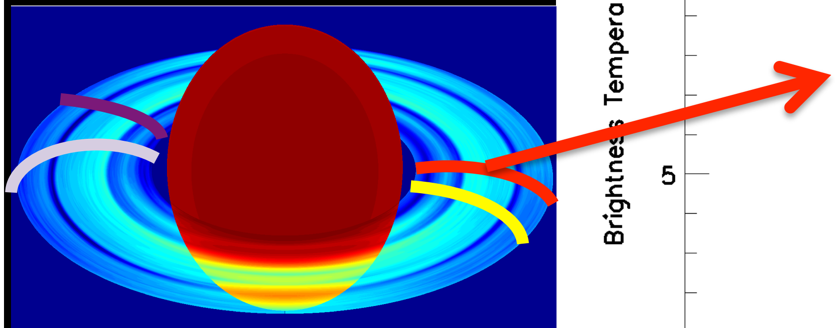


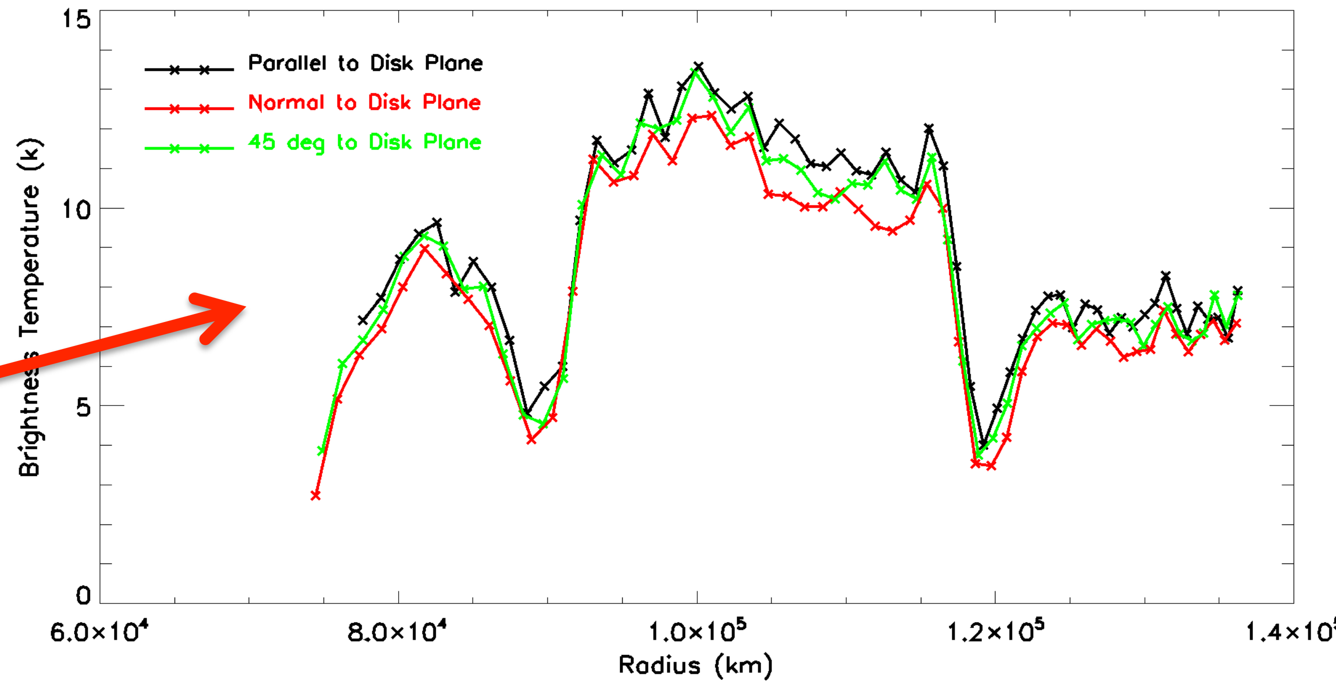


Position 1
Right Hand Side Ansae

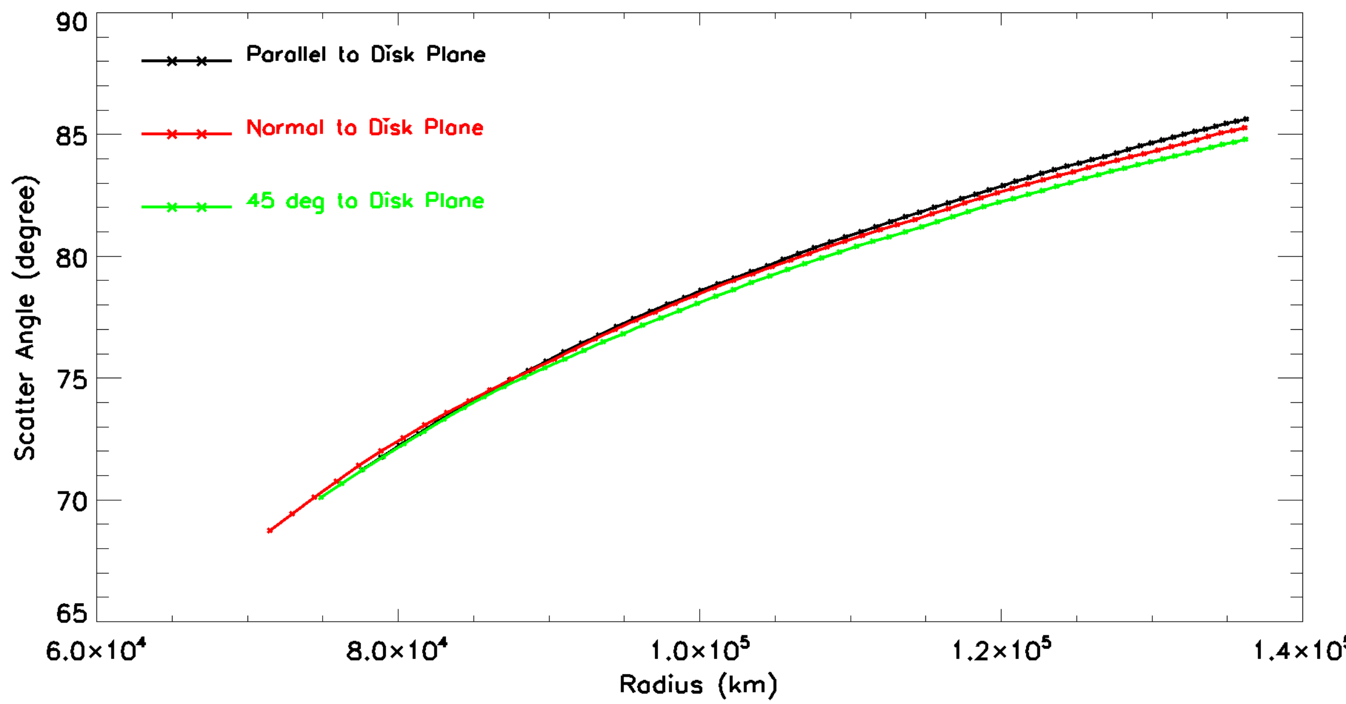


Polarization Effects

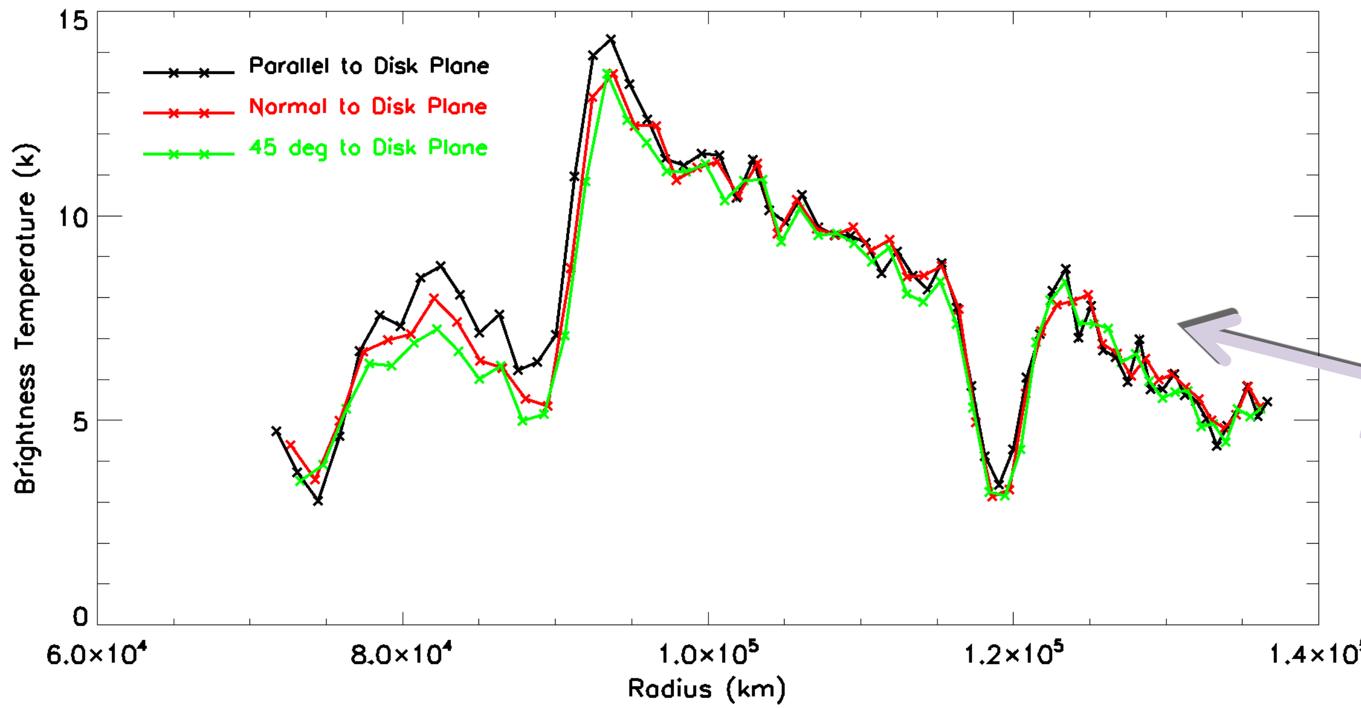


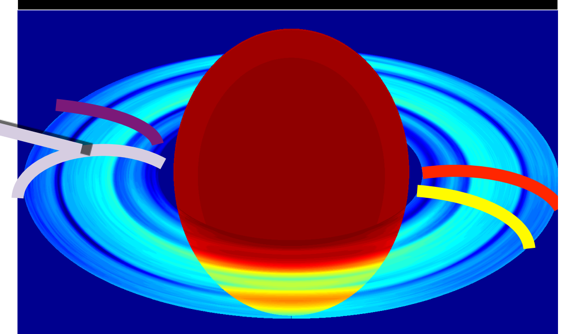


Position 2
Right Hand Side Ansae

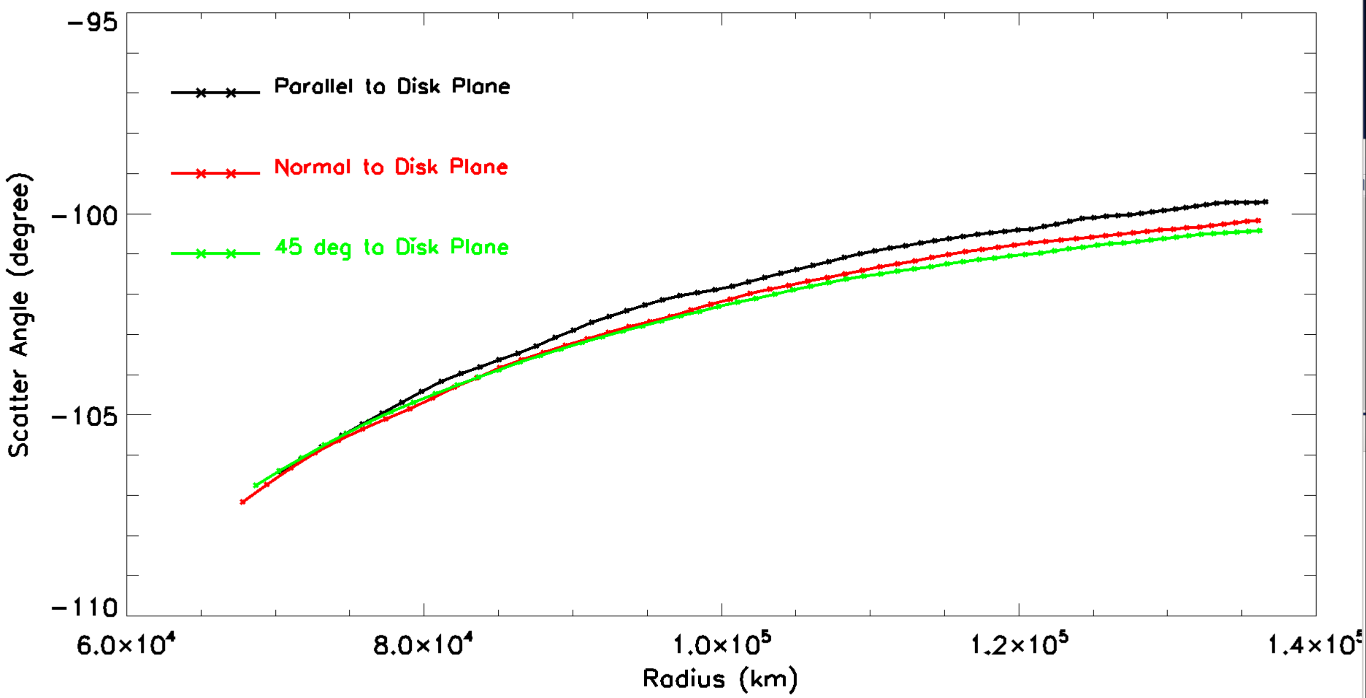


Polarization Effects

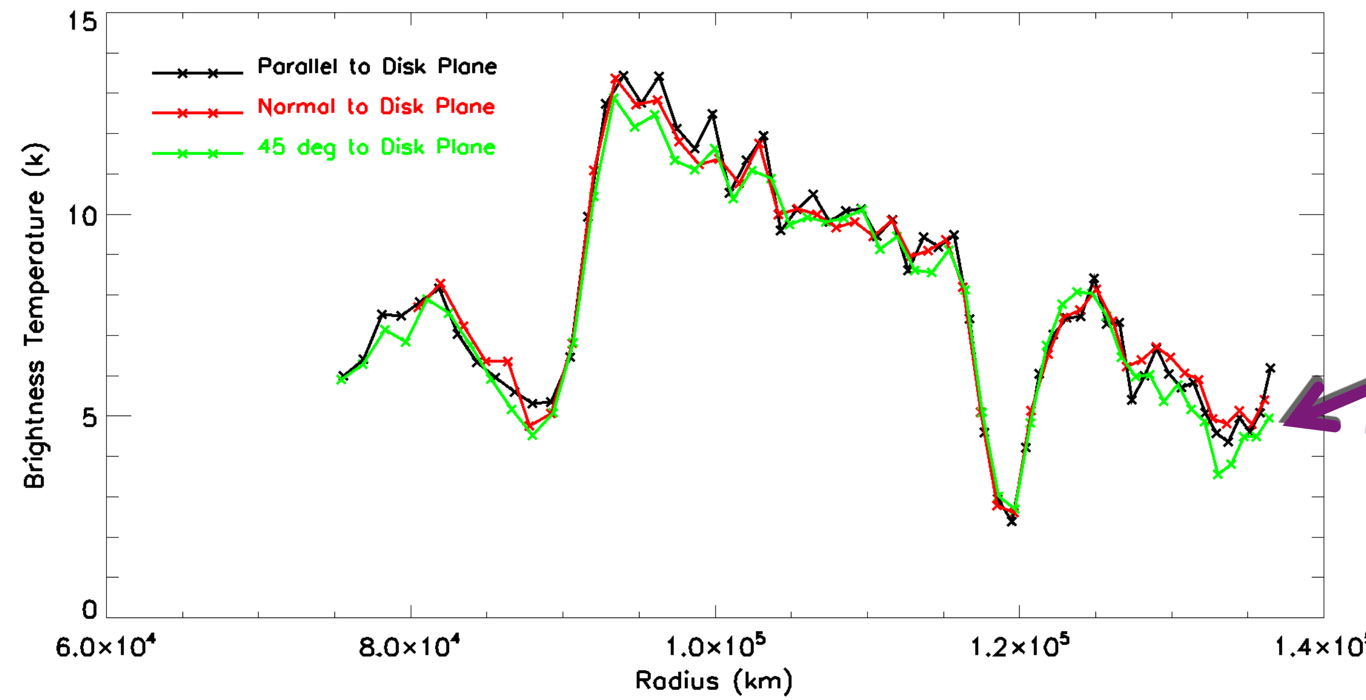


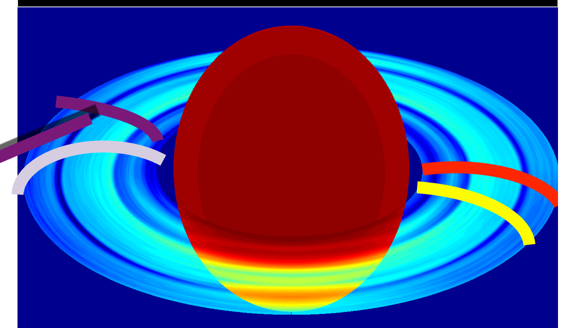


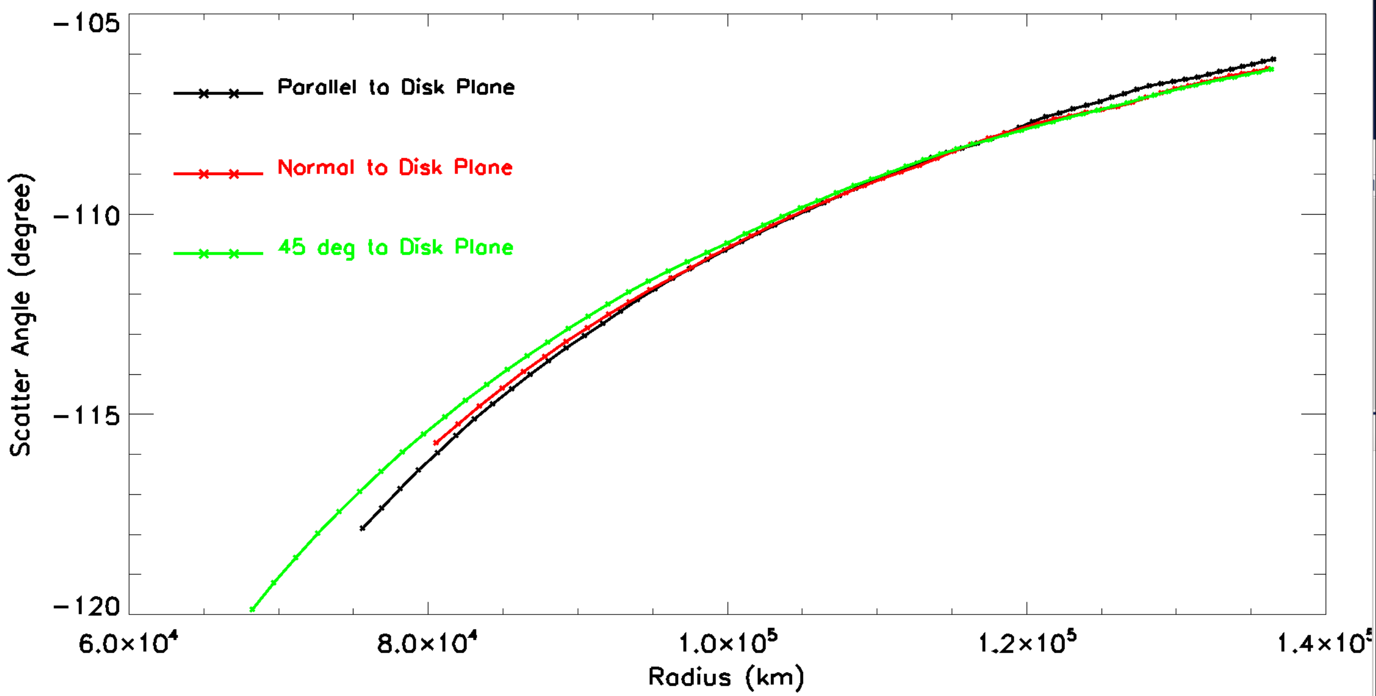
Position 3
Left Hand Side Ansae



Polarization Effects

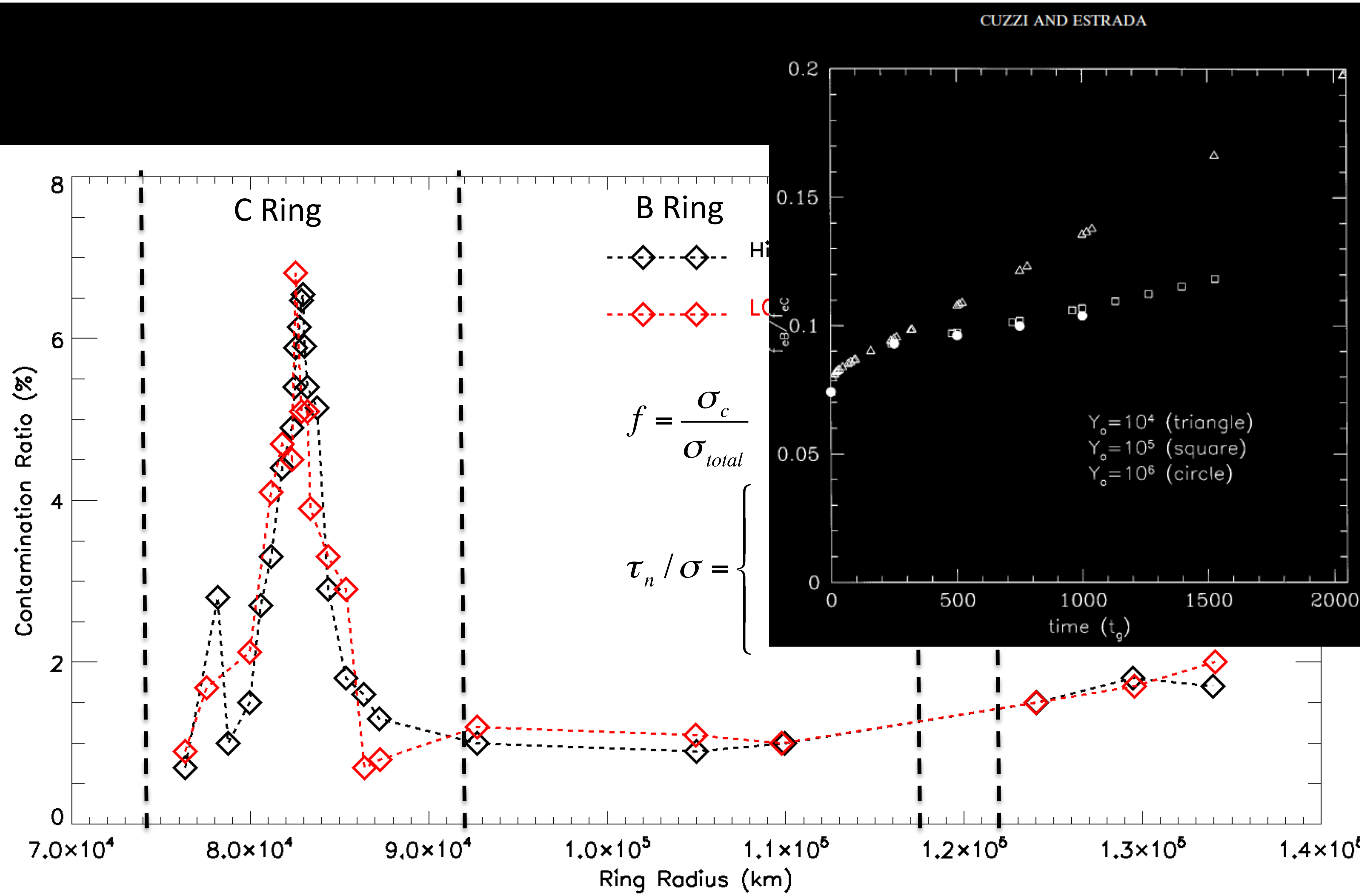




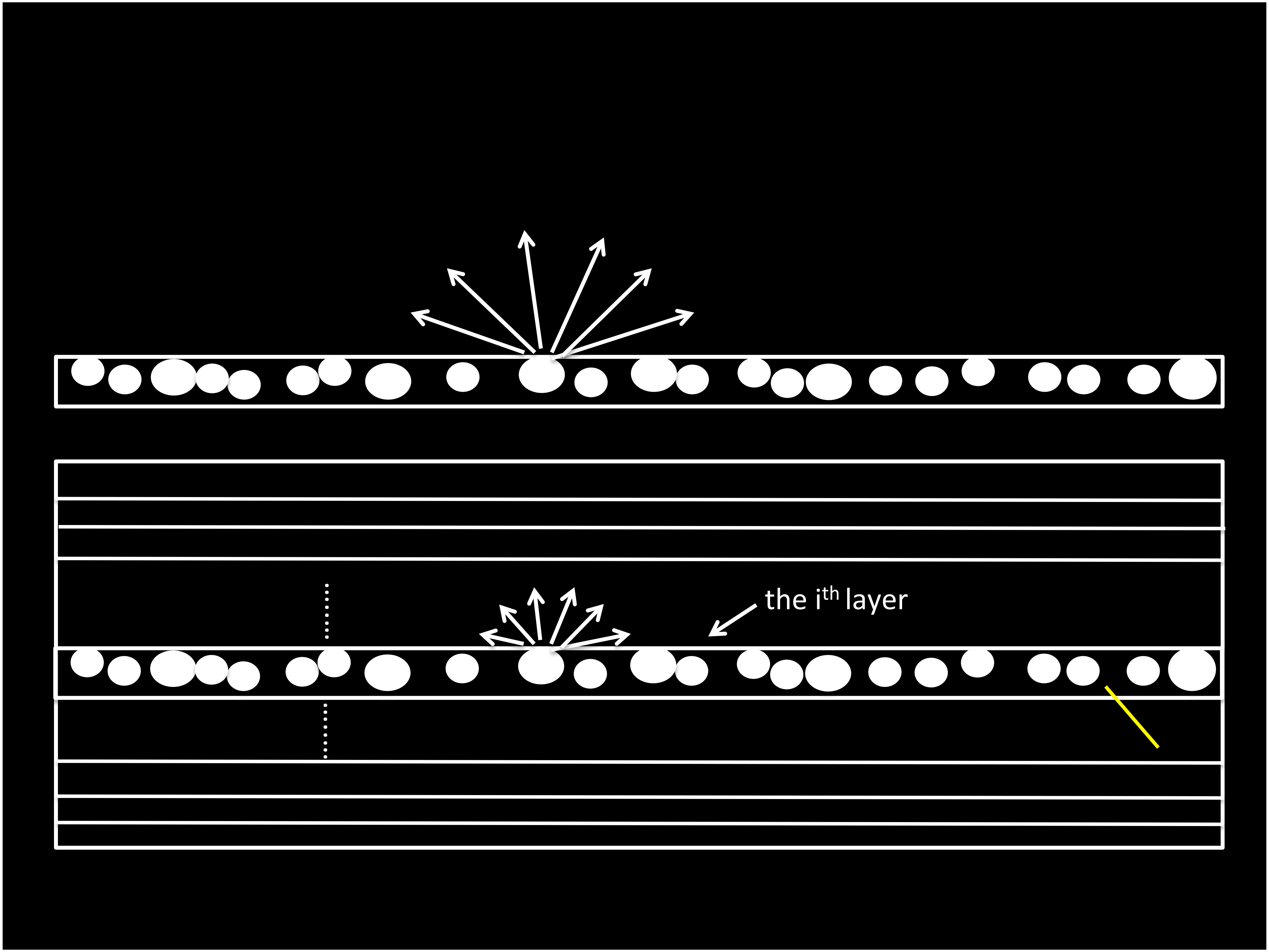


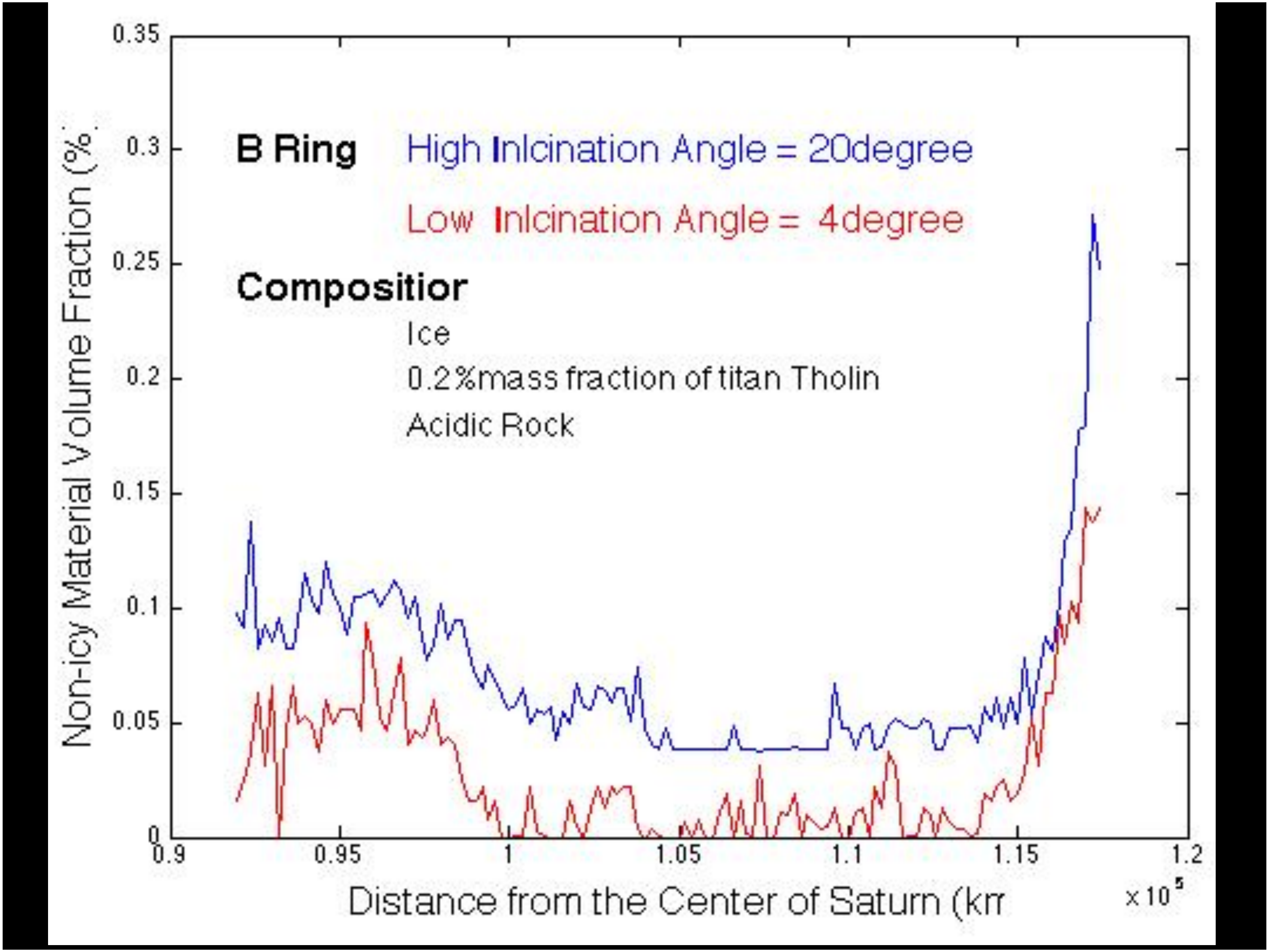
Position 4
Left Hand Side Ansae

[redacted]

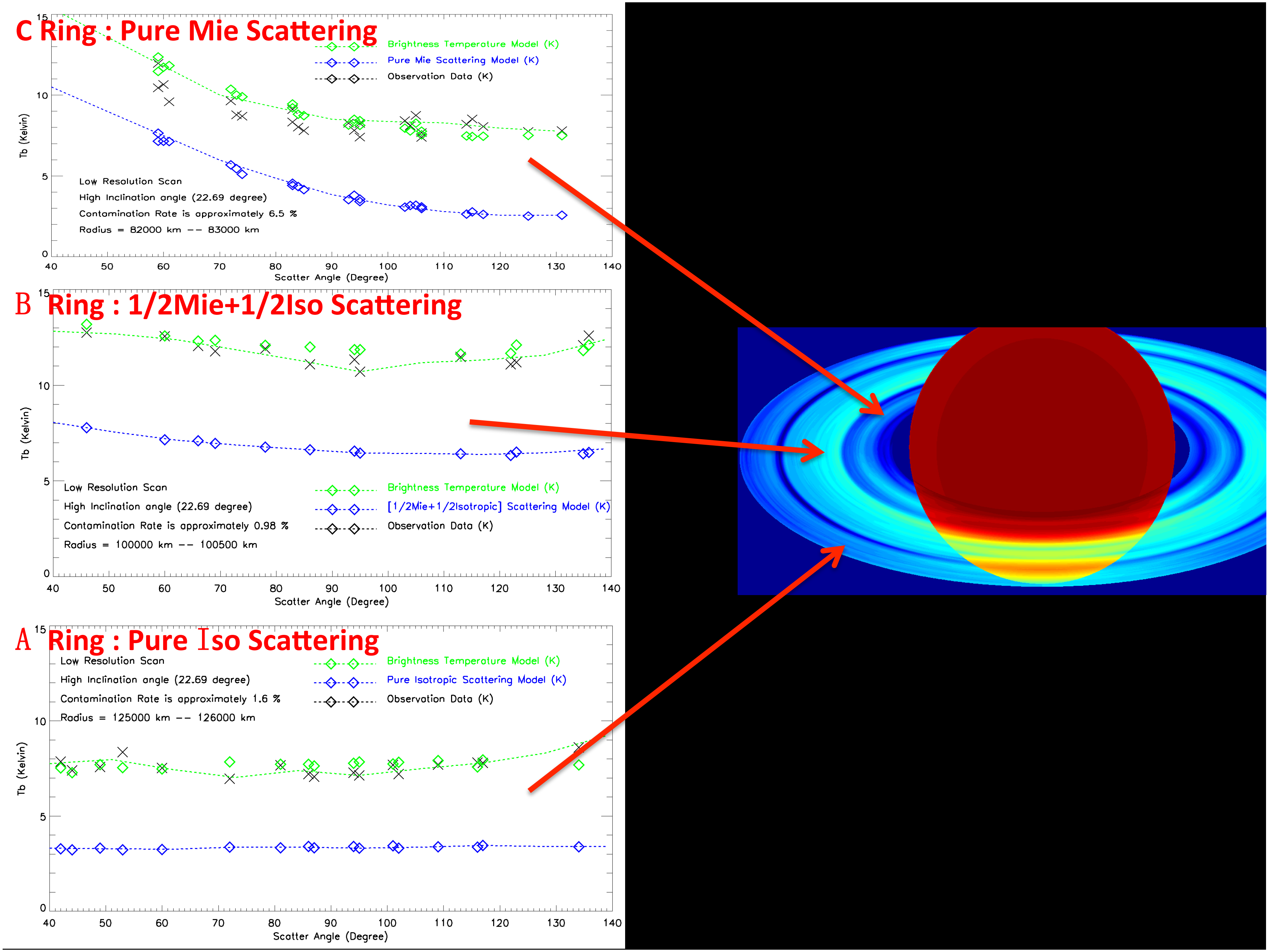


[redacted]


the i^th layer



B Ring
High Inlcination Angle = 20degree
Low Inlcination Angle = 4degree
Compositior
Ice
0.2%mass fraction of titan Tholin
Acidic Rock
Non-icy Material Volume Fraction (%)
Distance from the Center of Saturn (km
x 10^5
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.9
0.95
1
1.05
1.1
1.15
1.2



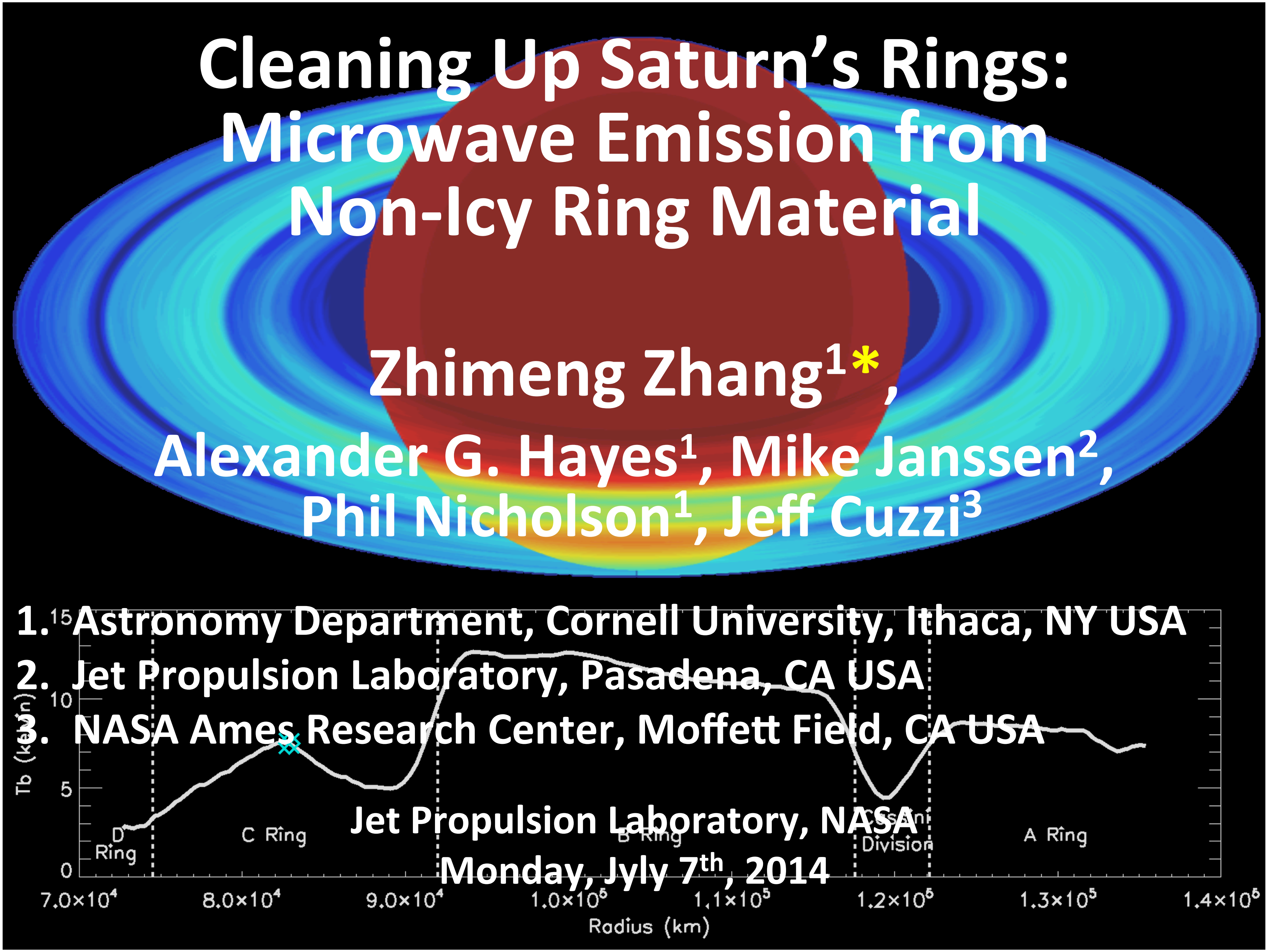
C Ring : Pure Mie Scattering
Brightness Temperature Model (K)
Pure Mie Scattering Model (K)
Observation Data (K)
Low Resolution Scan
High Inclination angle (22.69 degree)
Contamination Rate is approximately 6.5 %
Radius = 82000 km -- 83000 km
Tb (Kelvin)
Scatter Angle (Degree)
B Ring : 1/2Mie+1/2Iso Scattering
Low Resolution Scan
High Inclination angle (22.69 degree)
Contamination Rate is approximately 0.98 %
Radius = 100000 km -- 100500 km
Brightness Temperature Model (K)
[1/2Mie+1/2Isotropic] Scattering Model (K)
Observation Data (K)
Tb (Kelvin)
Scatter Angle (Degree)
A Ring : Pure Iso Scattering
Low Resolution Scan
High Inclination angle (22.69 degree)
Contamination Rate is approximately 1.6 %
Radius = 125000 km -- 126000 km
Brightness Temperature Model (K)
Pure Isotropic Scattering Model (K)
Observation Data (K)
Tb (Kelvin)
Scatter Angle (Degree)

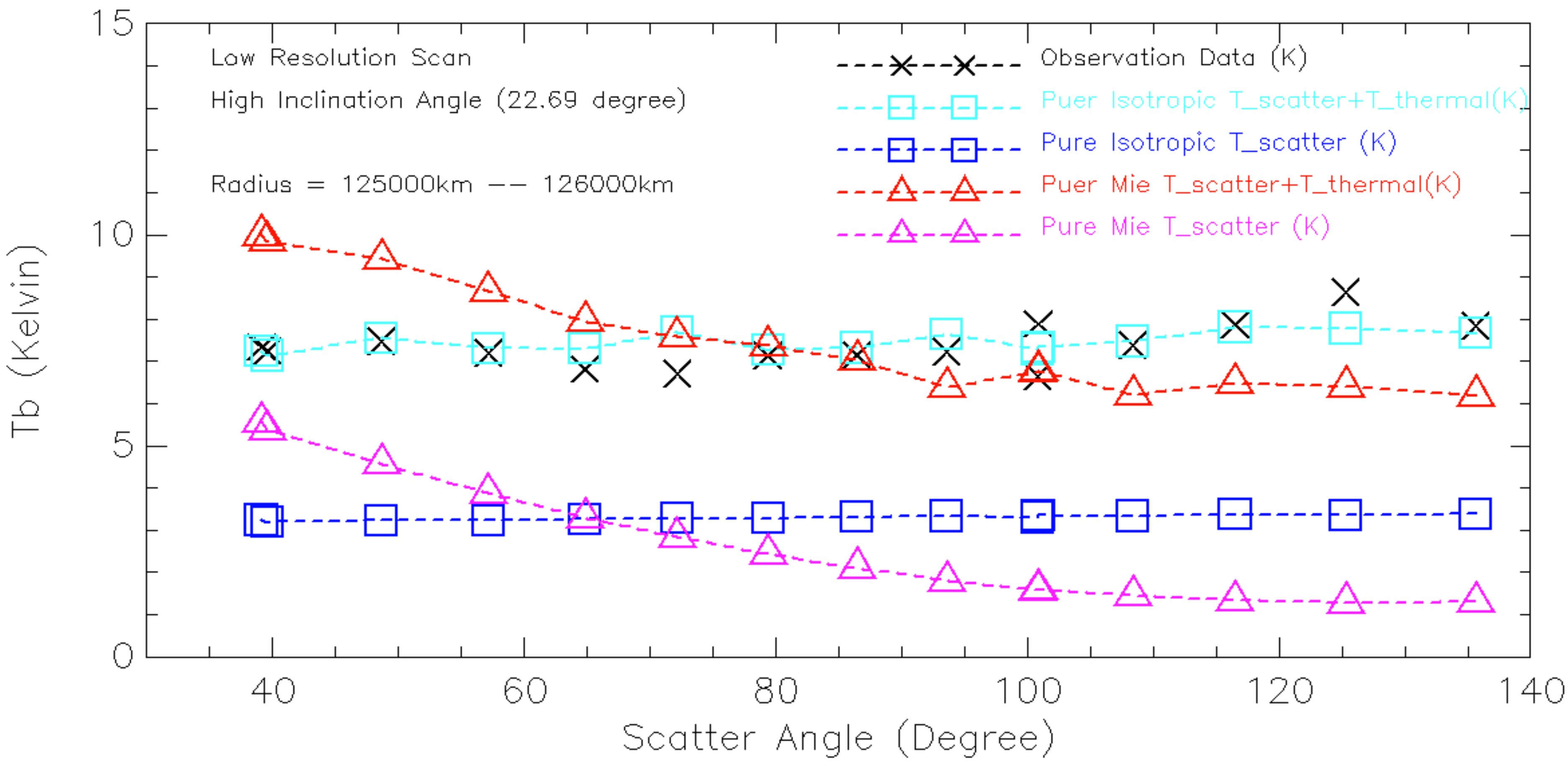
Cleaning Up Saturn's Rings: Microwave Emission from Non-Icy Ring Material

Zhimeng Zhang[1]*,
Alexander G. Hayes[1], Mike Janssen[2], Phil Nicholson[1], Jeff Cuzzi[3]

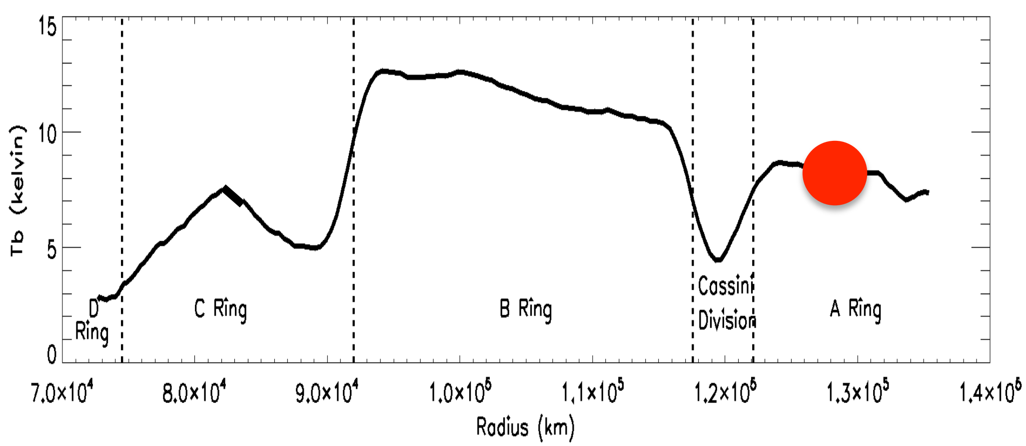
1. Astronomy Department, Cornell University, Ithaca, NY USA
2. Jet Propulsion Laboratory, Pasadena, CA USA
3. NASA Ames Research Center, Moffett Field, CA USA

Jet Propulsion Laboratory, NASA
Monday, Jyly 7th, 2014

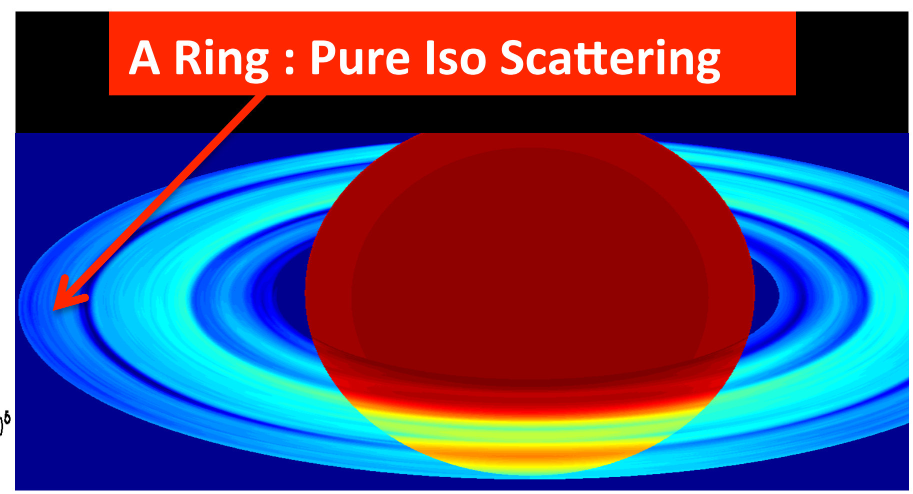




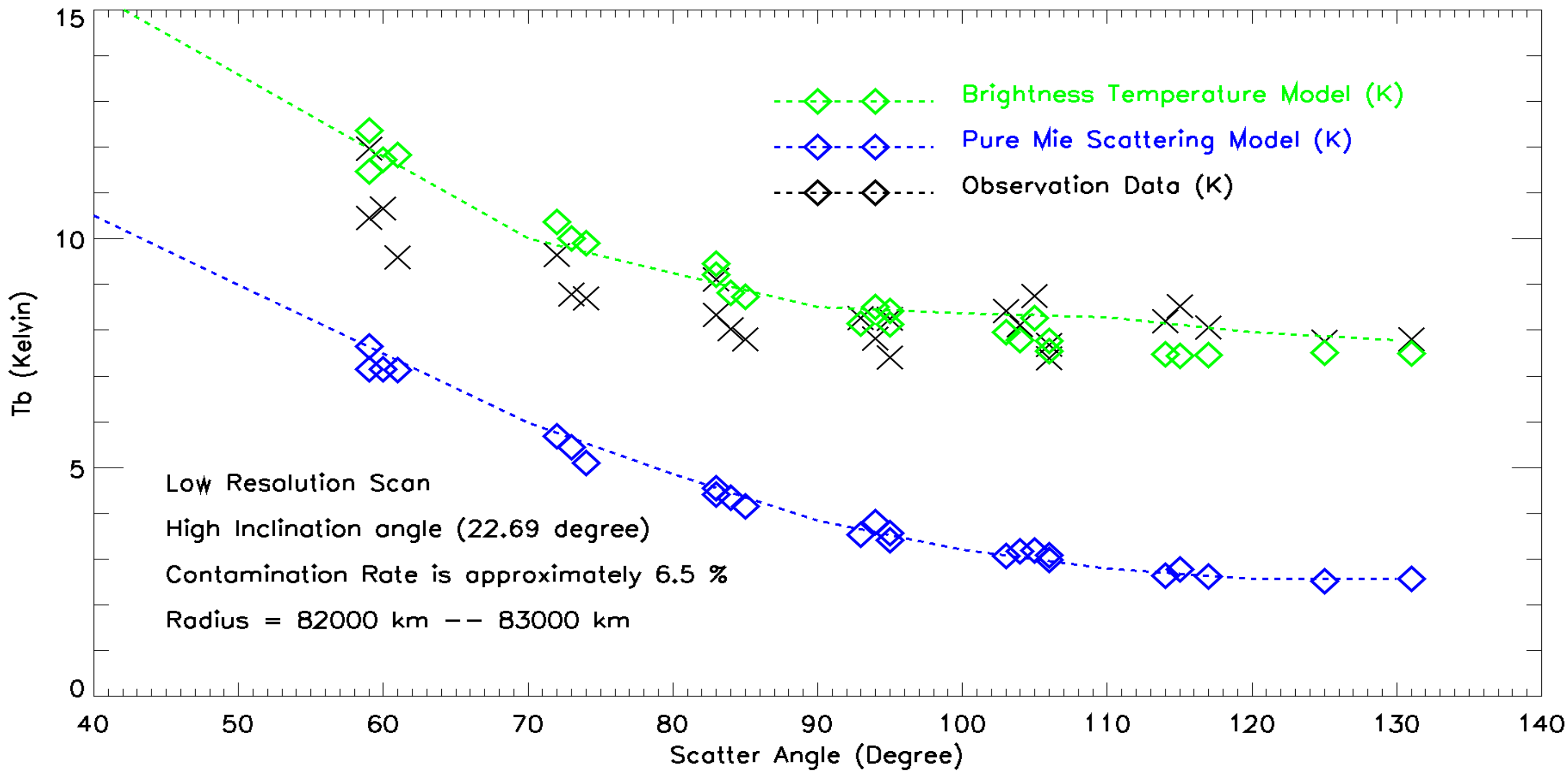
Low Resolution Scan
High Inclination Angle (22.69 degree)
Radius = 125000km -- 126000km
Observation Data (K)
Puer Isotropic T_scatter+T_thermal(K)
Pure Isotropic T_scatter (K)
Puer Mie T_scatter+T_thermal(K)
Pure Mie T_scatter (K)
Tb (Kelvin)
Scatter Angle (Degree)
15
10
5
0
40
60
80
100
120
140

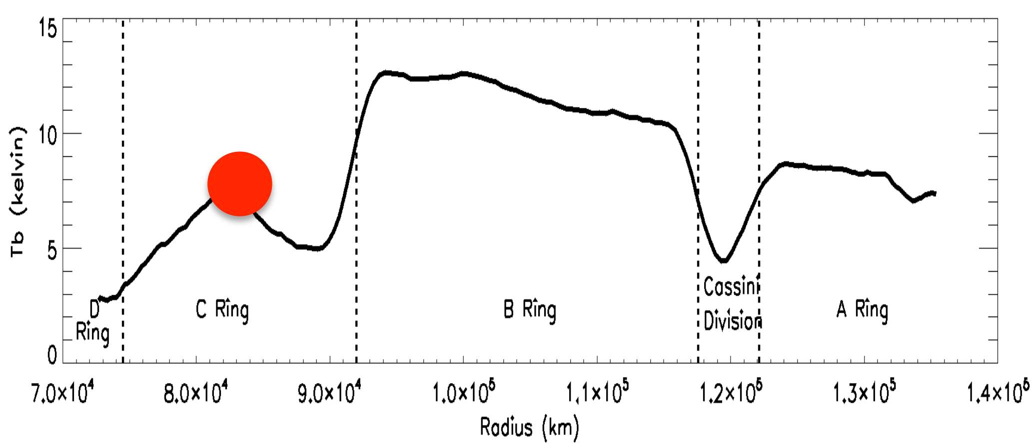


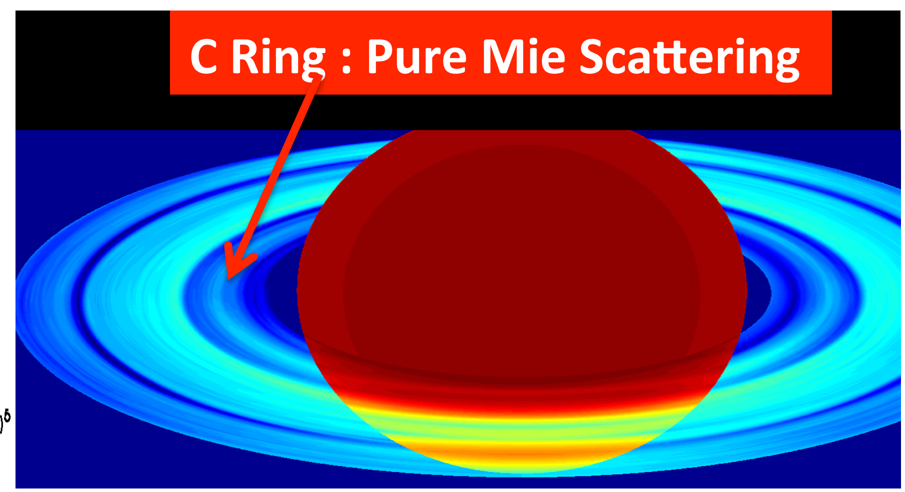
Tb (kelvin)
Radius (km)
D Ring
C Ring
B Ring
Cassini Division
A Ring
15
10
5
0
7.0×10^4
8.0×10^4
9.0×10^4
1.0×10^5
1.1×10^5
1.2×10^5
1.3×10^5
1.4×10^5

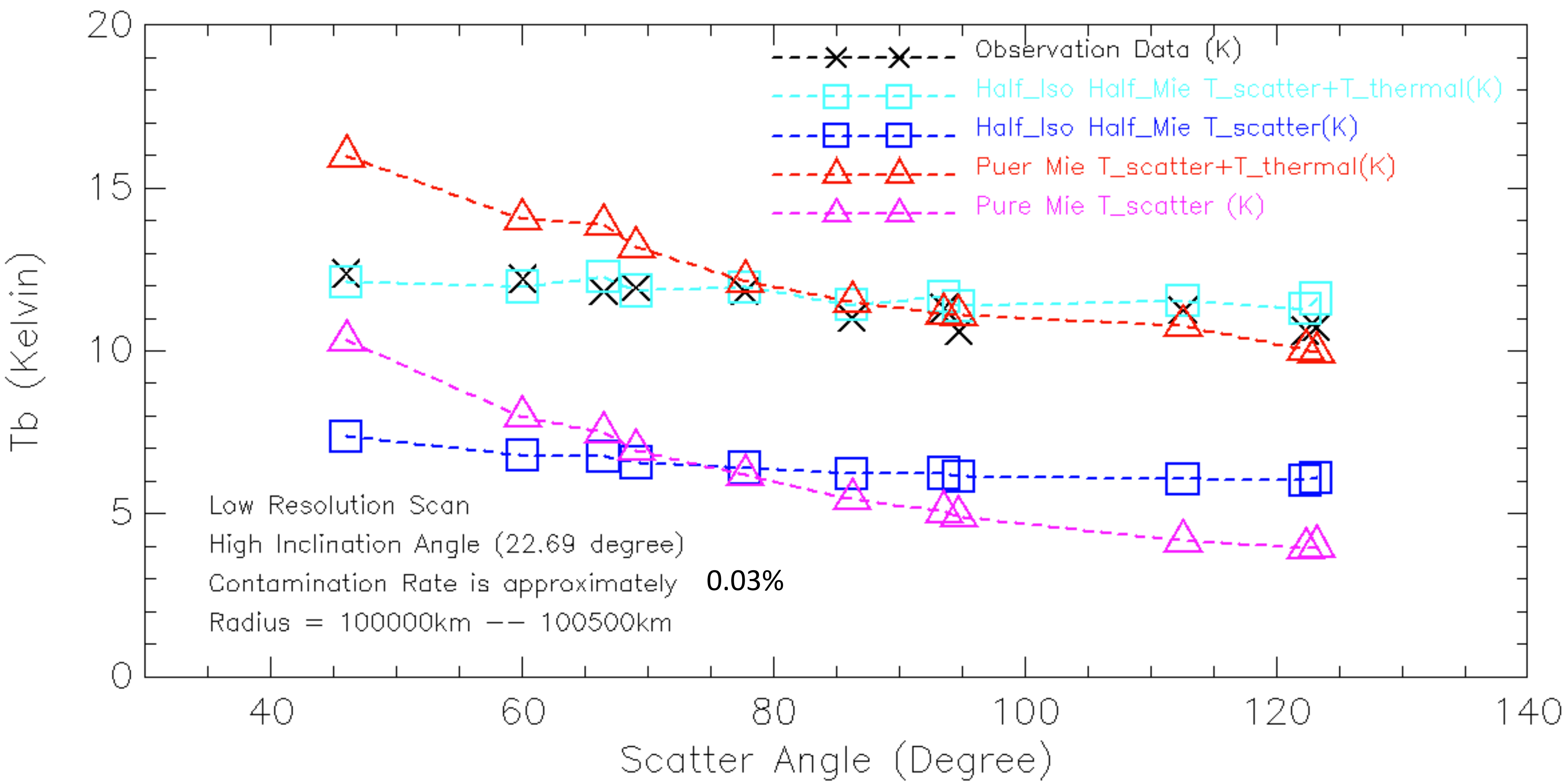


A Ring : Pure Iso Scattering

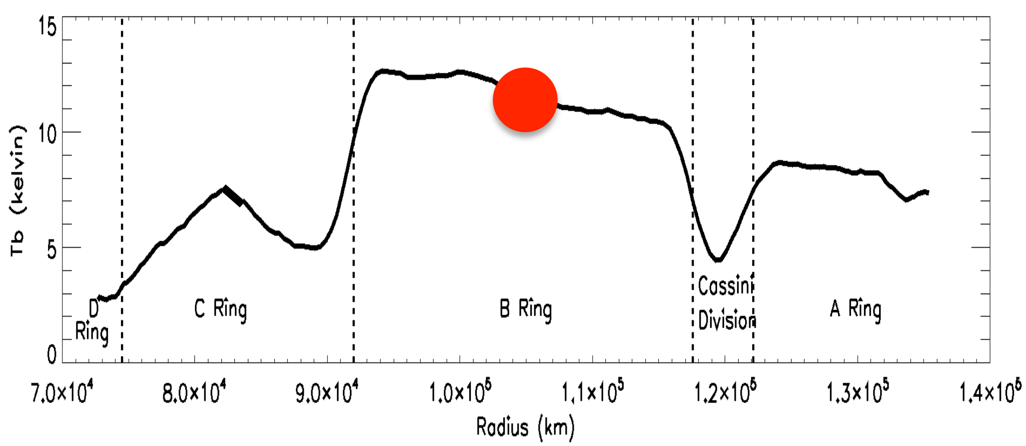

Brightness Temperature Model (K)
Pure Mie Scattering Model (K)
Observation Data (K)
Low Resolution Scan
High Inclination angle (22.69 degree)
Contamination Rate is approximately 6.5 %
Radius = 82000 km -- 83000 km
Tb (Kelvin)
Scatter Angle (Degree)
0
5
10
15
40
50
60
70
80
90
100
110
120
130
140


Tb (kelvin)
Radius (km)
D Ring
C Ring
B Ring
Cassini Division
A Ring
0
5
10
15
7.0×10^4
8.0×10^4
9.0×10^4
1.0×10^5
1.1×10^5
1.2×10^5
1.3×10^5
1.4×10^5

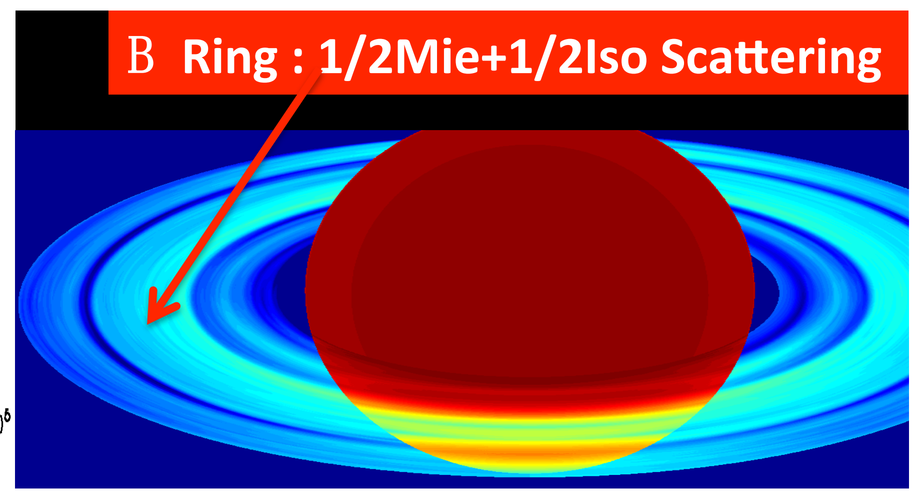

C Ring : Pure Mie Scattering



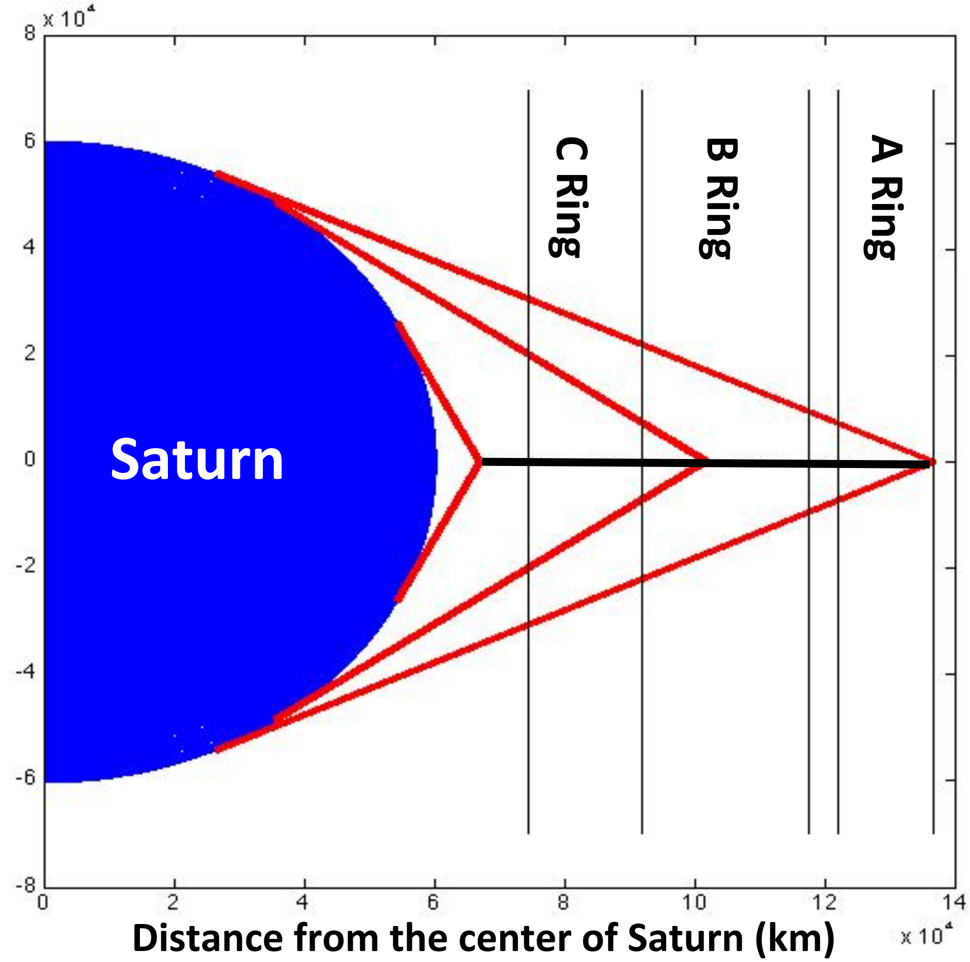
Observation Data (K)
Half_Iso Half_Mie T_scatter+T_thermal(K)
Half_Iso Half_Mie T_scatter(K)
Puer Mie T_scatter+T_thermal(K)
Pure Mie T_scatter (K)
Low Resolution Scan
High Inclination Angle (22.69 degree)
Contamination Rate is approximately 0.03%
Radius = 100000km -- 100500km
Tb (Kelvin)
Scatter Angle (Degree)
0
5
10
15
20
40
60
80
100
120
140



Tb (kelvin)
D Ring
C Ring
B Ring
Cassini Division
A Ring
Radius (km)

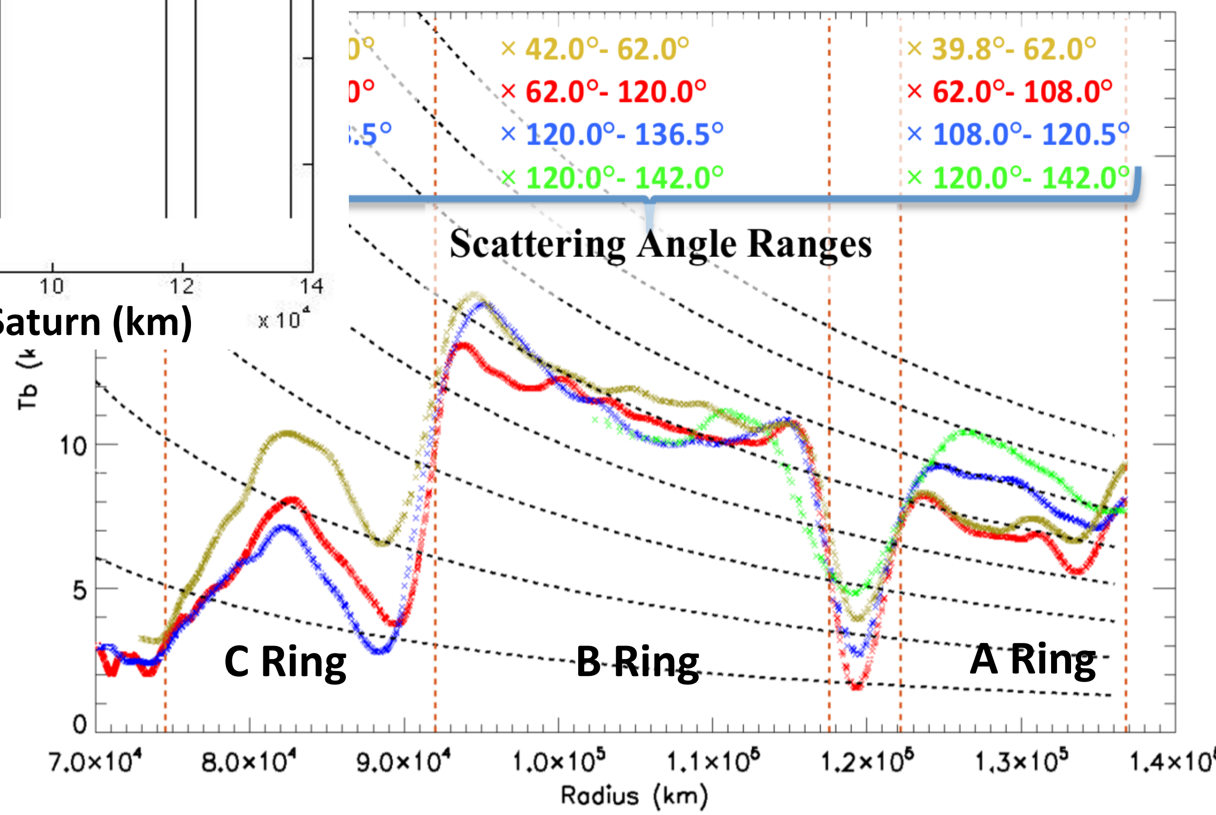


B Ring : 1/2Mie+1/2Iso Scattering

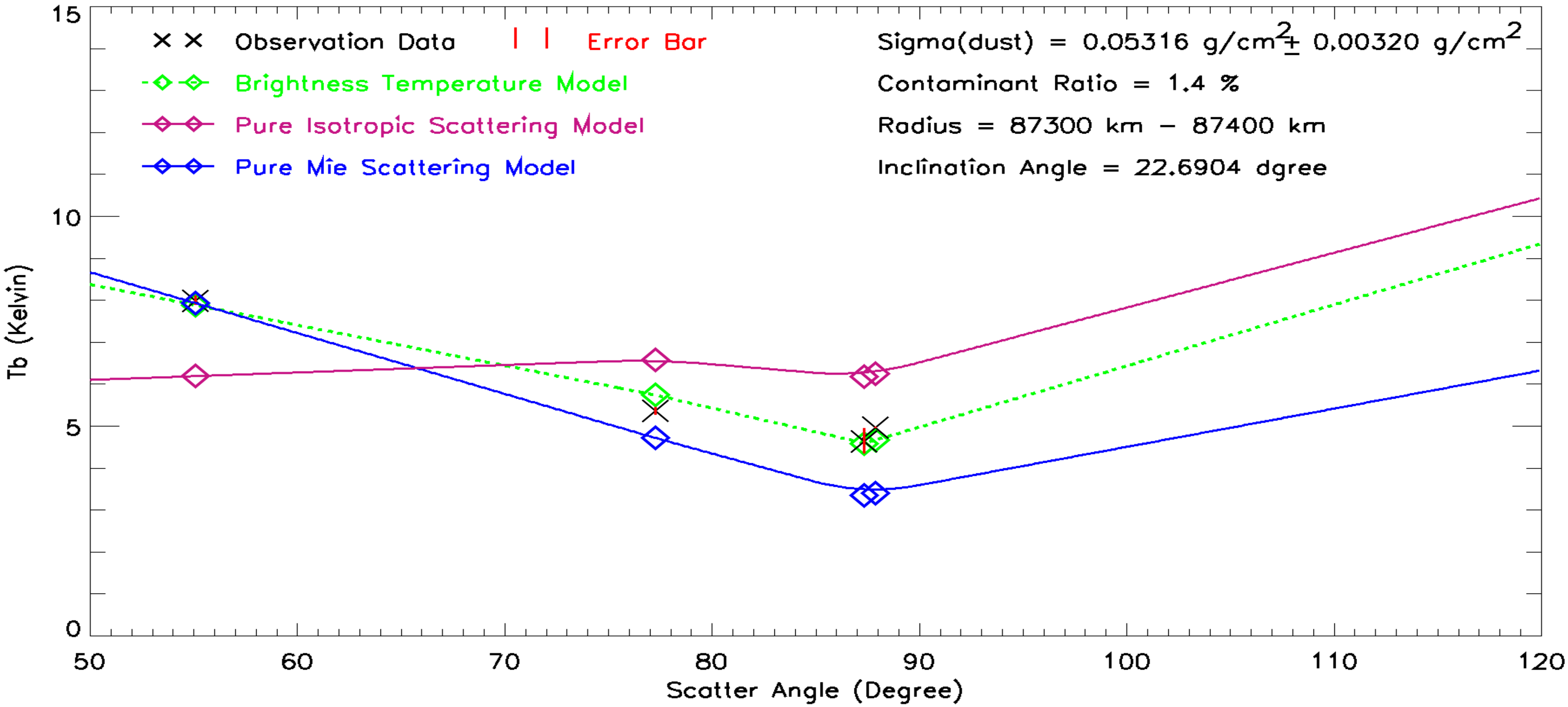


$$\pi F_\nu = \int_{4\pi} I_\nu(\cos\theta)\cos\theta\, d\omega$$

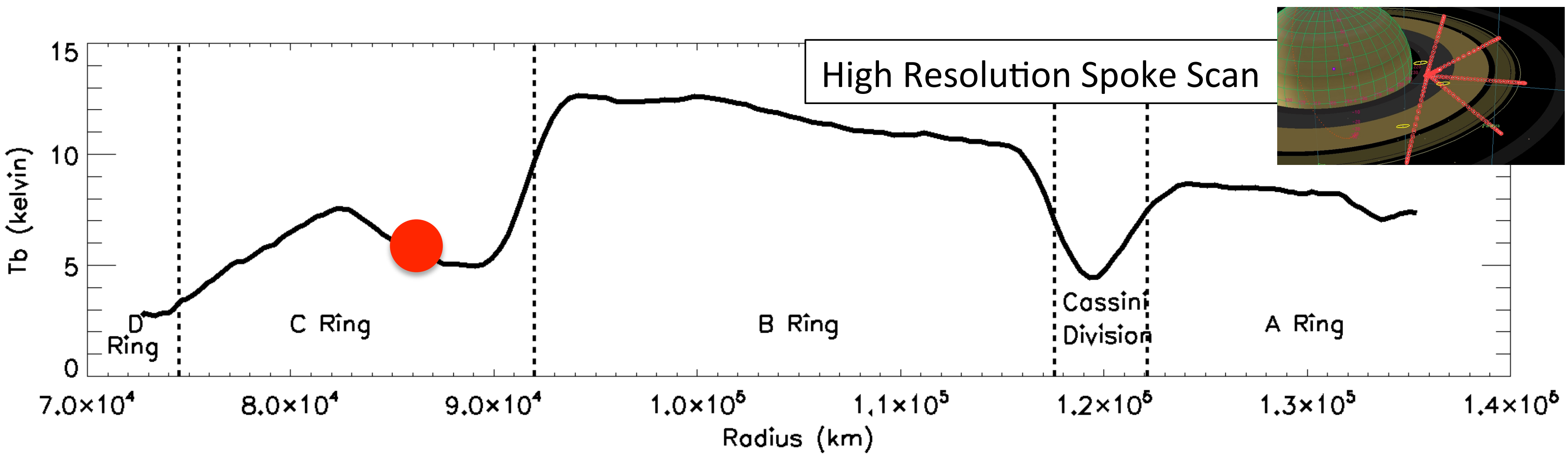
[redacted]



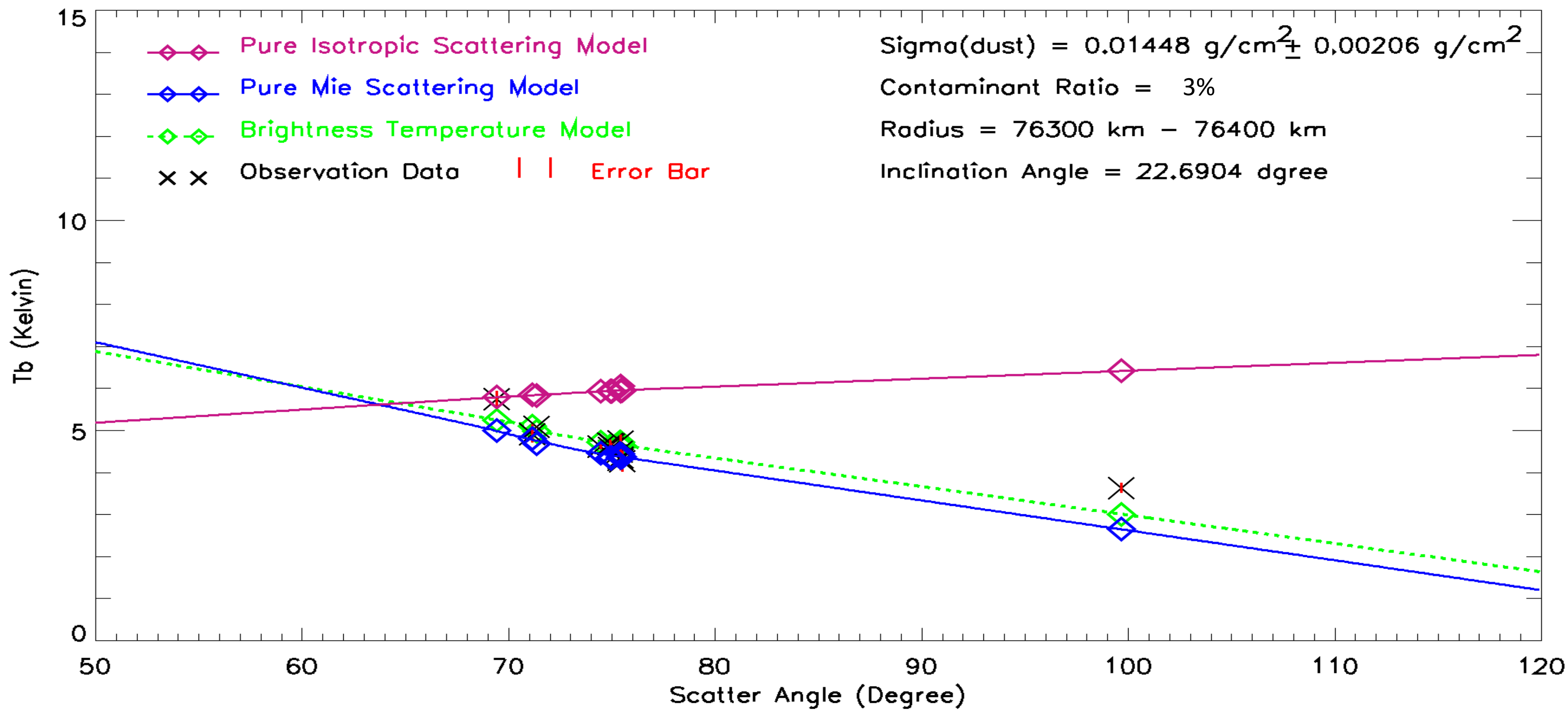
[redacted]

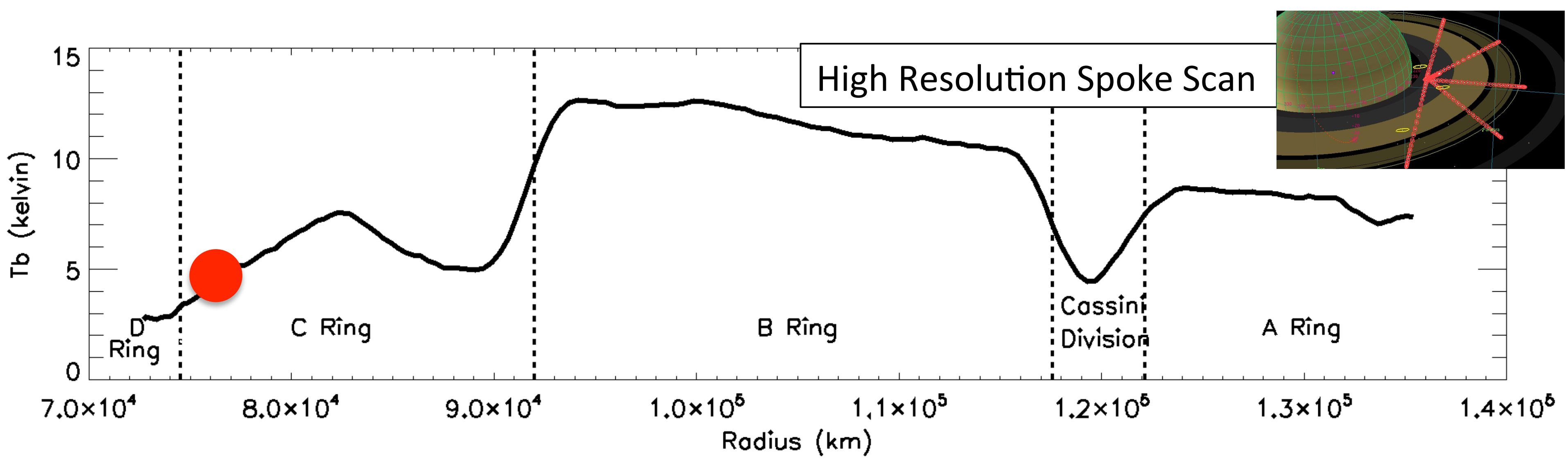


Observation Data
Error Bar
Brightness Temperature Model
Pure Isotropic Scattering Model
Pure Mie Scattering Model
Sigma(dust) = 0.05316 g/cm^2 ± 0.00320 g/cm^2
Contaminant Ratio = 1.4 %
Radius = 87300 km – 87400 km
Inclination Angle = 22.6904 dgree
Tb (Kelvin)
Scatter Angle (Degree)
0
5
10
15
50
60
70
80
90
100
110
120



High Resolution Spoke Scan
Tb (kelvin)
Radius (km)
D Ring
C Ring
B Ring
Cassini Division
A Ring
0
5
10
15
7.0×10^4
8.0×10^4
9.0×10^4
1.0×10^5
1.1×10^5
1.2×10^5
1.3×10^5
1.4×10^5


Pure Isotropic Scattering Model
Pure Mie Scattering Model
Brightness Temperature Model
Observation Data
Error Bar
Sigma(dust) = 0.01448 g/cm^2 ± 0.00206 g/cm^2
Contaminant Ratio = 3%
Radius = 76300 km – 76400 km
Inclination Angle = 22.6904 dgree
Tb (Kelvin)
Scatter Angle (Degree)
0
5
10
15
50
60
70
80
90
100
110
120


High Resolution Spoke Scan
Tb (kelvin)
Radius (km)
D Ring
C Ring
B Ring
Cassini Division
A Ring
0
5
10
15
7.0×10^4
8.0×10^4
9.0×10^4
1.0×10^5
1.1×10^5
1.2×10^5
1.3×10^5
1.4×10^5