Modeling the Interior of Haumea

Luke Probst
Astrobiology Coffee
Arizona State University
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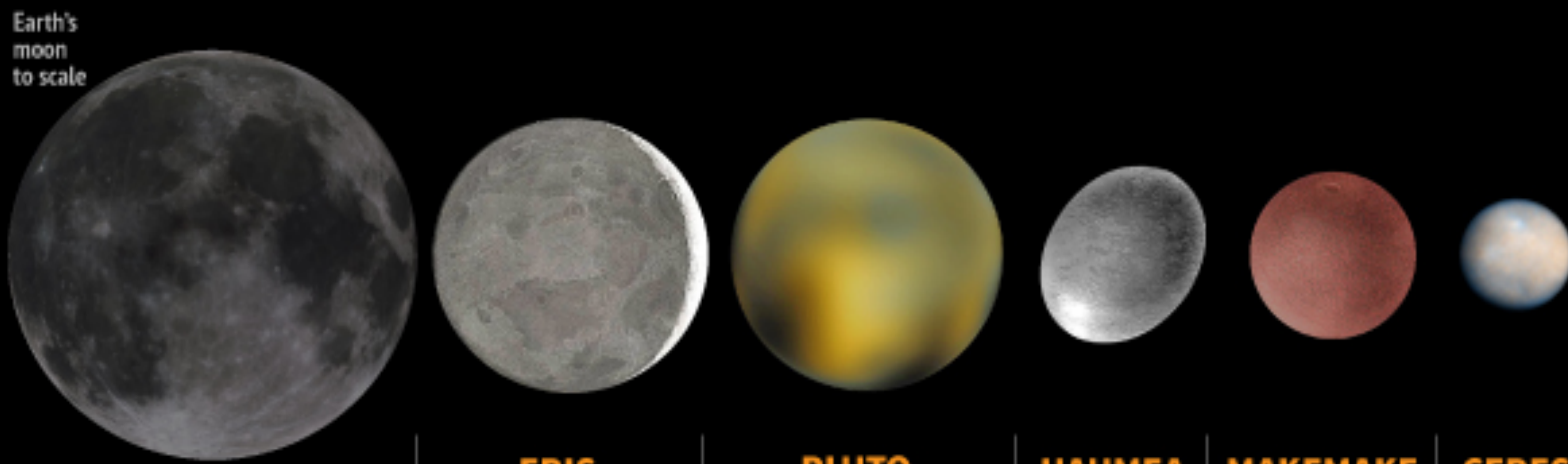
Outline

- Introducing Haumea
  - Location
  - Surface Properties
  - Bulk Properties: Mass, Size, Density
  - Formation Theories
- Jacobi Ellipsoids and Maclaurin Spheroids
- What the Code Measures
- Results for Haumea’s Most Likely Configuration
- Conclusions

Previous Image: http://news.nationalgeographic.com/news/2011/10/111026-pluto-twin-eris-dwarf-planets-occultation-space-science/

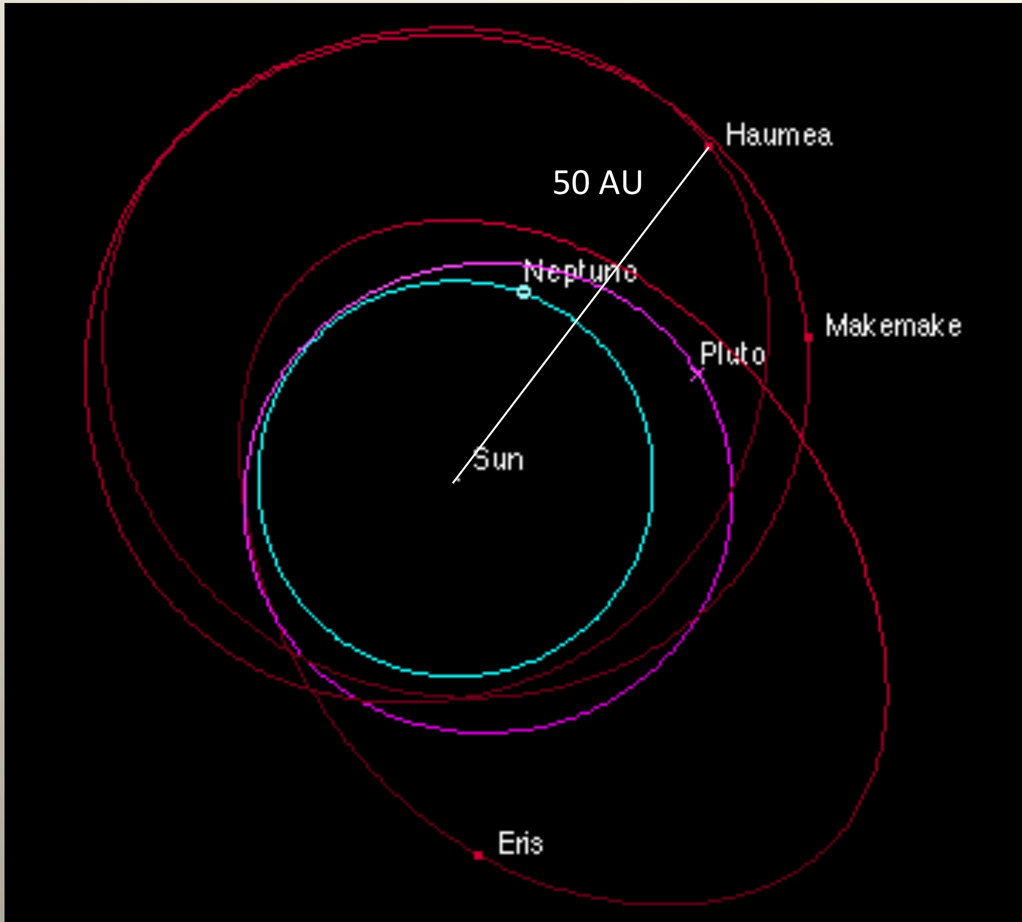
Dwarf Planets in the Solar System



	ERIS	PLUTO	HAUMEA	MAKEMAKE	CERES
Year of discovery	2003	1930	2003	2005	1801
Diameter (mean)	1,445 miles 2,326 km	1,430 miles 2,302 km	892.3 miles 1,436 km	882 miles 1,420 km	591.8 miles 952.4 km
Orbital period (Earth years)	561.4	247.9	281.9	305.34	4.6
Distance from sun (times Earth's distance)	68	39.5	43.1	45.3	2.8
Orbital inclination (degrees)	46.9	17.14	28.2	29	10.59
Rotation period	25.9 hours	6.39 Earth days	3.9 hours	22.5 hours	9.1 hours
Moons	1	5	2	0	0

SOURCE: NASA

Haumea's Orbit

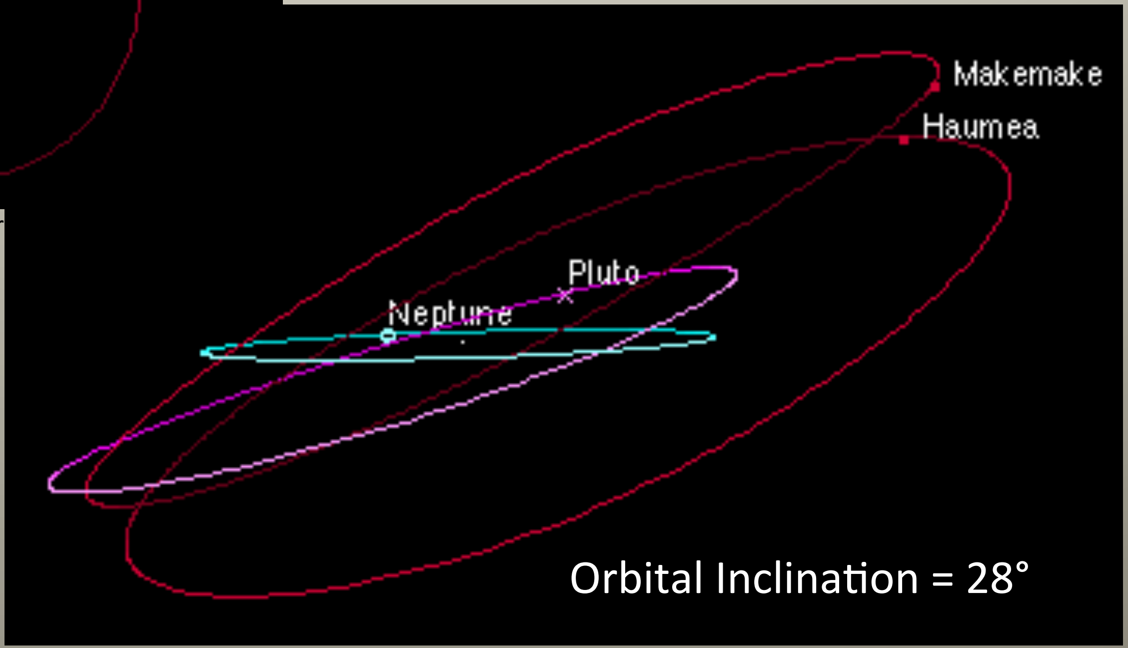


Nick Anthony Fiorenza/CarinaVoyager

Aphelion = 51.5 AU

Perihelion = 35 AU

Eccentricity = 0.19

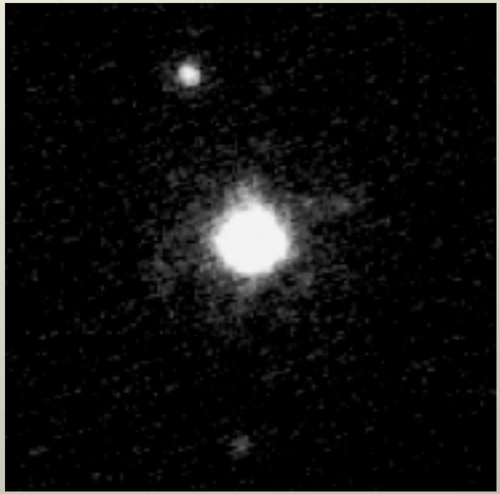


1 AU = 1.496×10^8 km

Haumea

- Discovered Dec. 28, 2004 by team led by Mike Brown at Palomar

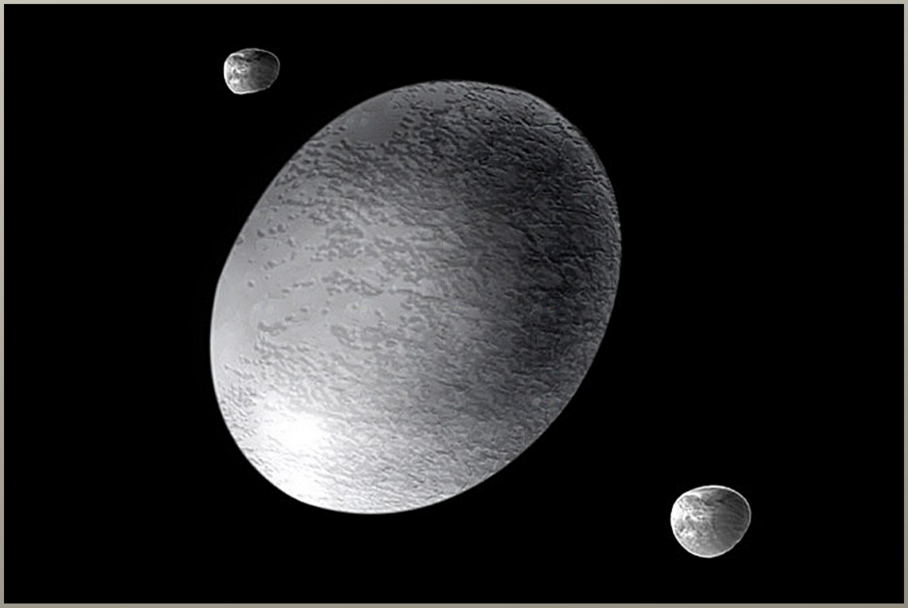
- Two satellites (Hi'iaka and Namaka) discovered one month later at Keck Observatory



Keck Telescope, CalTech, Mike Brown et al.

- Originally nicknamed Santa, its two moons were called Rudolph and Blitzen

- Inducted as a dwarf planet in 2008



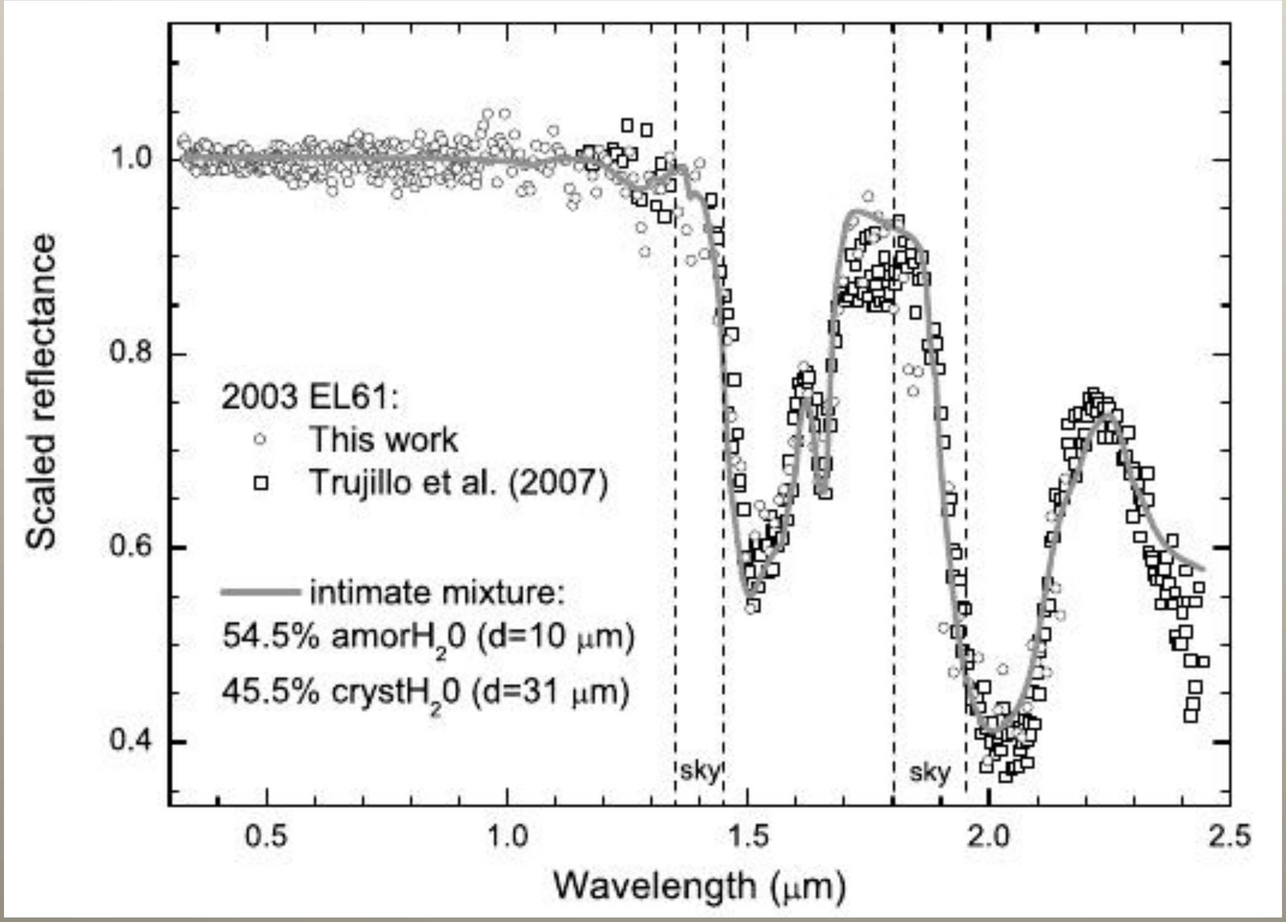
http://en.wikipedia.org/wiki/Haumea#/media/File:2003EL61art.jpg

Haumea in a Nutshell

- Mass = 4.006×10^{21} kg (measured from its moons' orbits; Ragozzine & Brown 2009)
- Surface spectrum shows almost pure H_2O ice
- Mean radius ≈ 715 km
- Bulk density ≈ 2600 kg m^{-3}
- Rotation period = 3.92 hours (fastest spinning large (>1000 km) object in the Solar System)
- Possesses an elongated shape due to its fast rotation

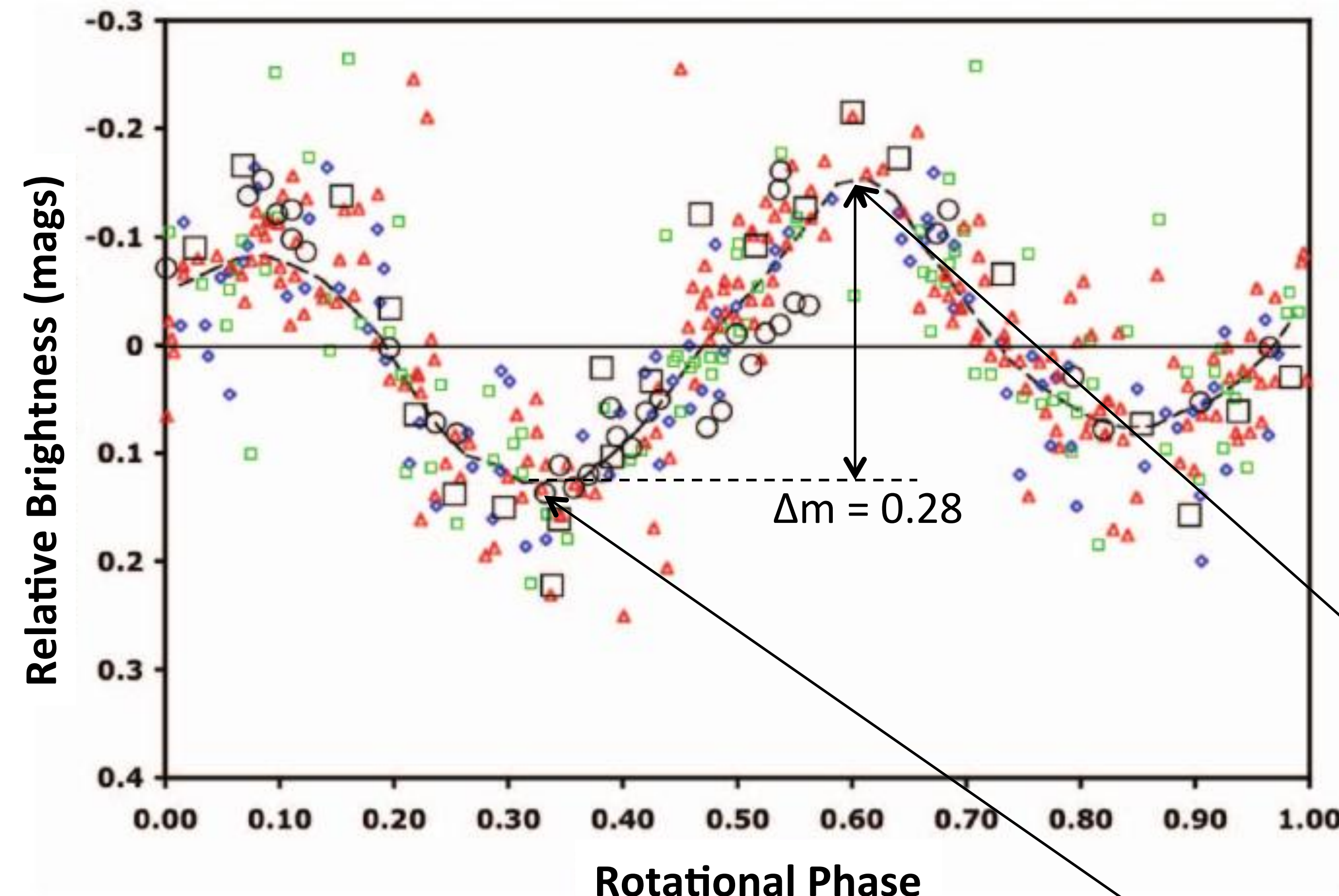
Surface

- Spectrum shows almost pure H_2O ice
- Crystalline ice signature at 1.65 µm



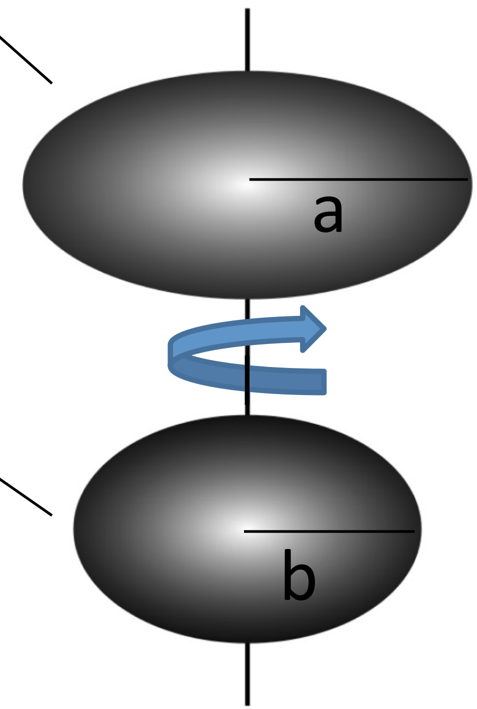
As for its size:

Pinilla-Alonso et al. 2009

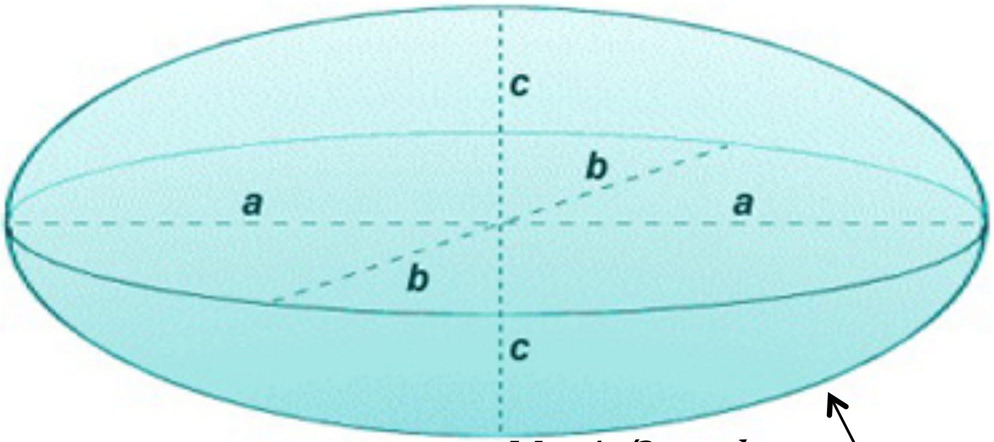


Rabinowitz et al. 2006

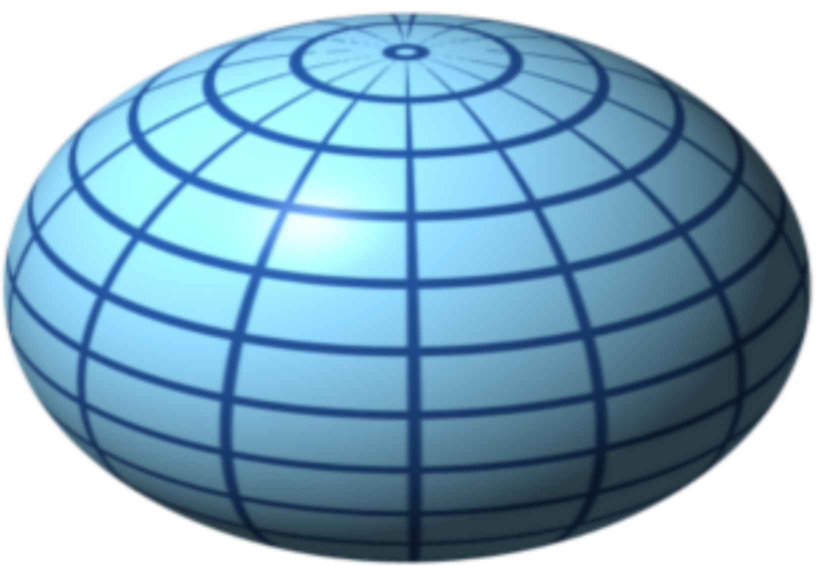
◇ = B-band, Cerro Tololo 1.3-m
□ = V-band, Cerro Tololo 1.3-m
△ = I-band, Cerro Tololo 1.3-m
□ = additional observations, Palomar 5.1-m
○ = additional observations, Tenagra 32"
- - - = median average



http://www.wikipedia.org/wiki/Haumea#Name



$M = 4/3\ \pi abc\rho$



Jacobi Ellipsoids:

$a > b > c$

$p = b/a$

$q = c/a$

$0.43 \leq q < p \leq 1$

Maclaurin Spheroids:

$a = b > c$

$p = 1$

q = flattening parameter

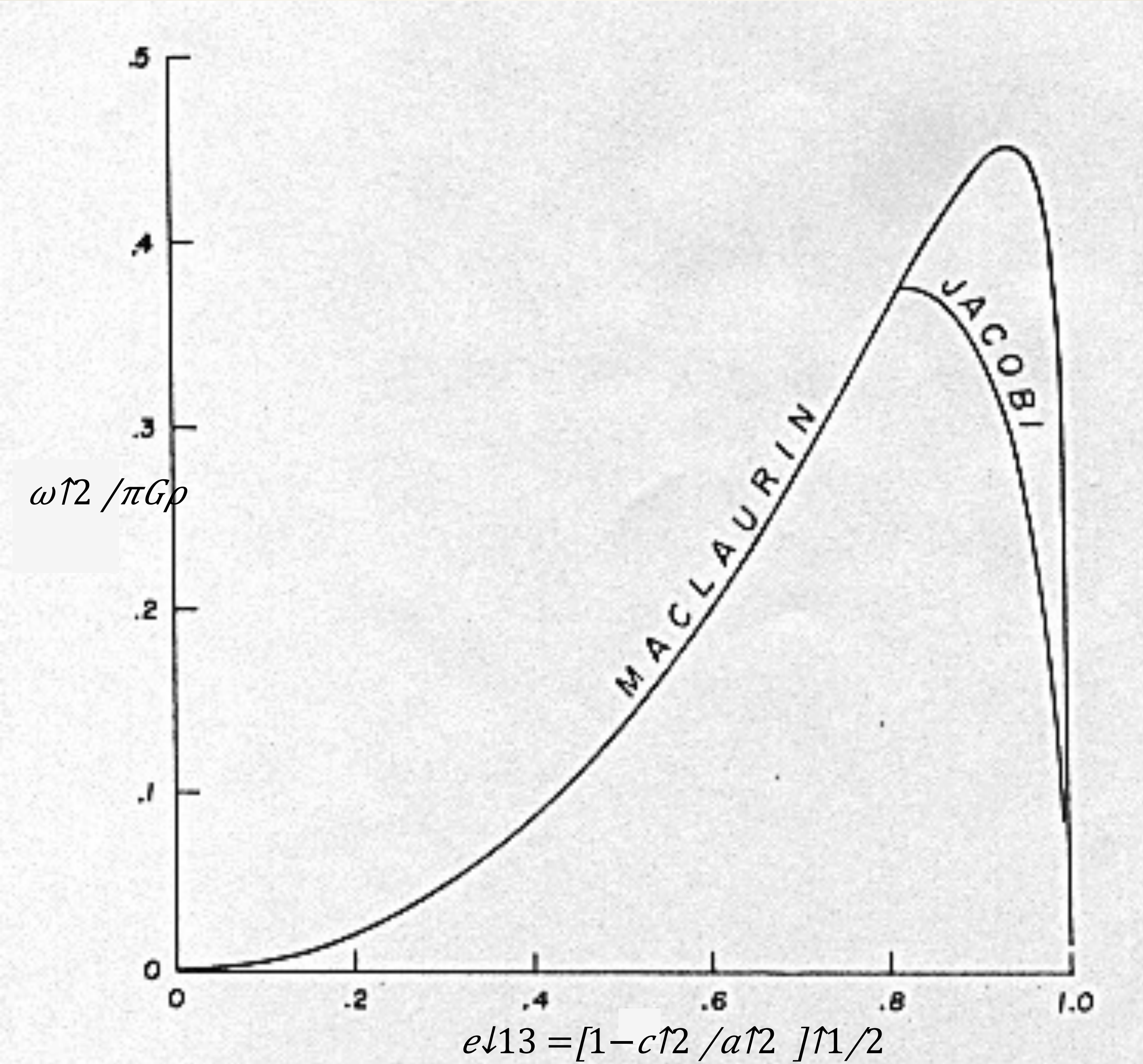
Ellipsoidal Figures of Equilibrium:

- For homogeneous Jacobi Ellipsoids:

$$\omega^2/\pi G\rho = 2abc\int_0^\infty u\,du/\Delta\,(a^2+u)(b^2+u)$$

where

$$\Delta = \sqrt{(a^2+u)(b^2+u)(c^2+u)}$$



Chandrasekhar 1987

Putting all equations together:

(1) $a/b \geq 10^{0.4\Delta m}$

(2) $M = \frac{4}{3} \pi abc\rho$

(3) $\omega^2 / \pi G\rho = 2abc \int_0^\infty u \, du / \Delta (a^2 + u)(b^2 + u)$

Leads to five different possible shapes for the outer surface:

(1-4: Rabinowitz et al. 2006;
5: Lellouch et al. 2010)

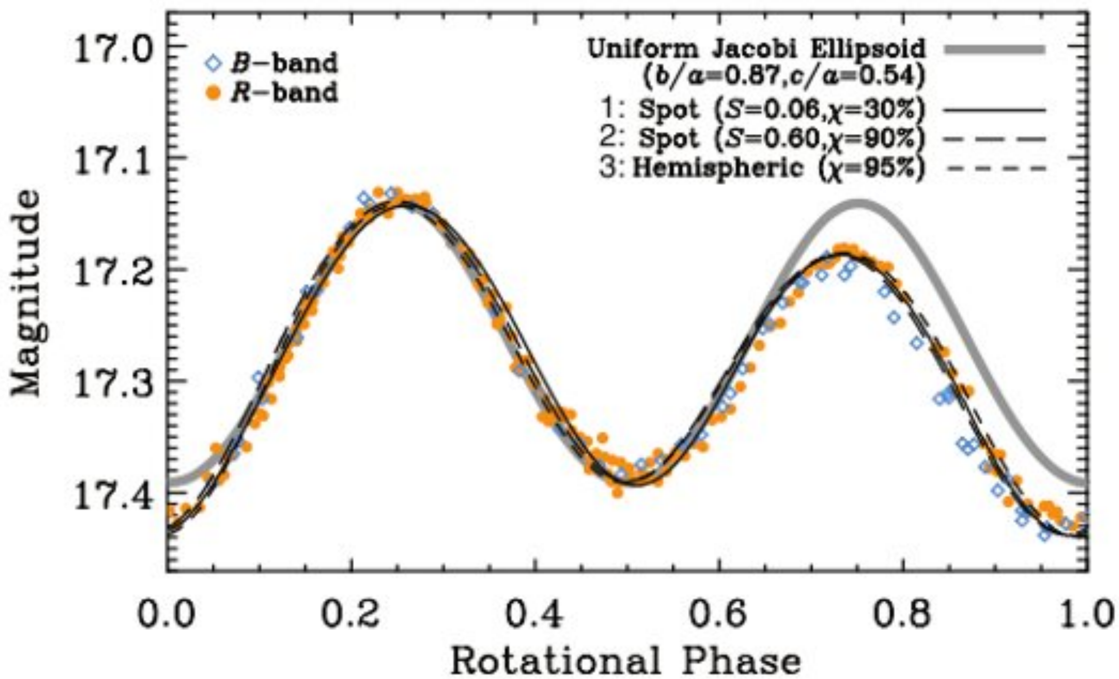
Jacobi Ellipsoids

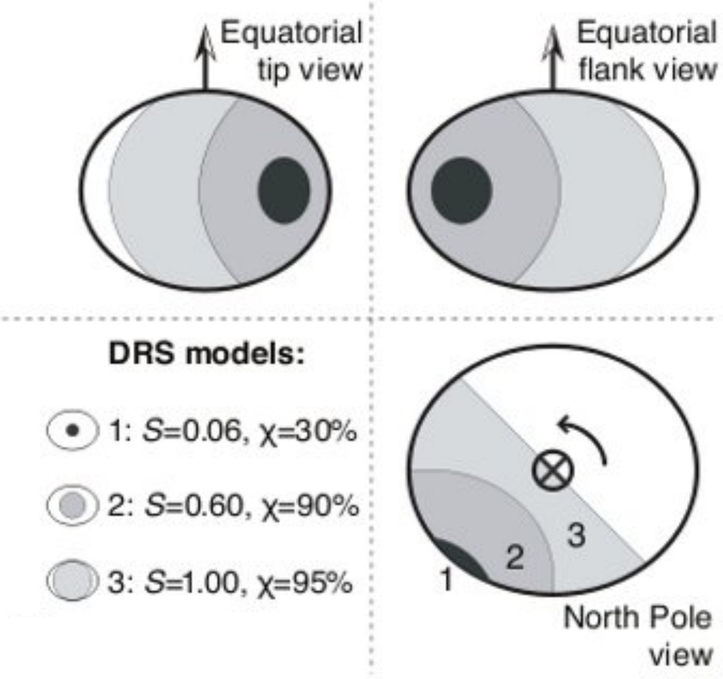
Maclaurin Spheroids

Most recent calculation

Shape	a (km)	b (km)	c (km)	Length (km)
1	980	759	498	1960
2	1250	540	430	2500
3	870	870	500	1740
4	750	750	524	1500
5	960	770	495	1920

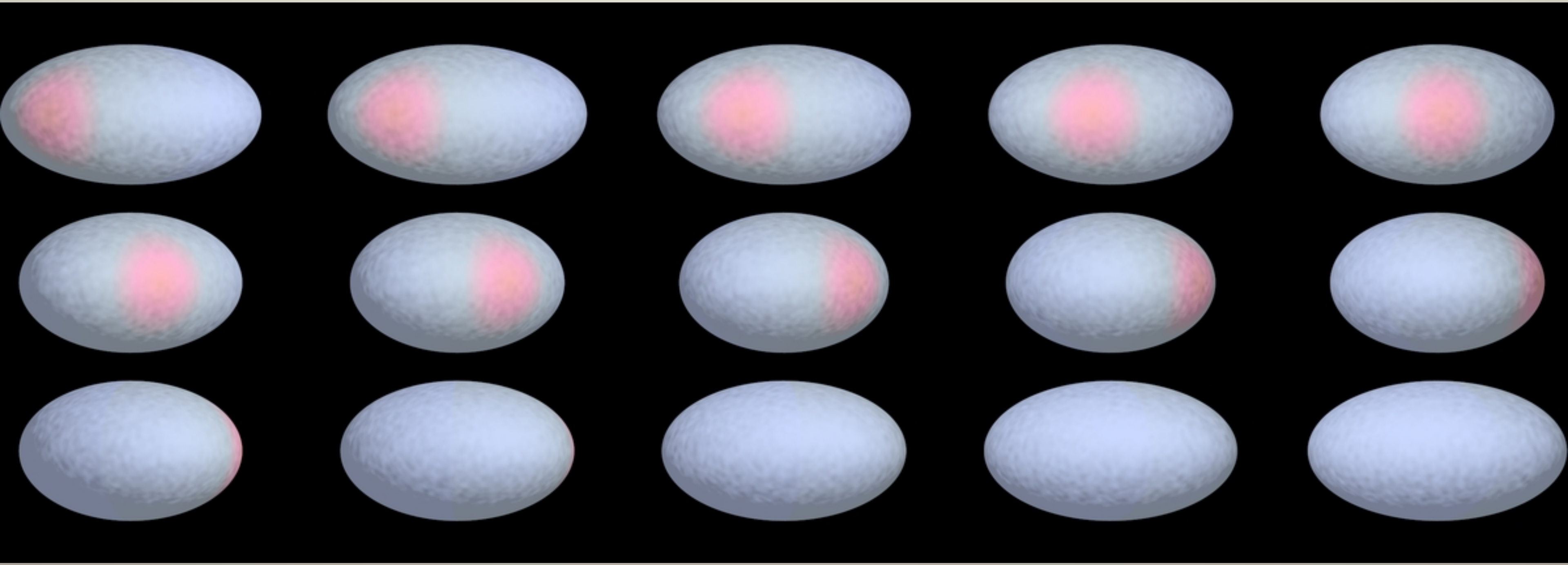
Is there a Dark Red Spot?





Lacerda 2009

Possible Location of Dark Red Spot



http://www.space.com/7289-strange-dwarf-planet-red-spot.html

Questions

- Why is Haumea so dense when we only see ice?

- Haumea has been treated thus far as a homogeneous ellipsoid, but we know it must be a two-phase, heterogeneous ellipsoid. How to reconcile this contradiction?

Satellites

Hi'iaka

$m = 1.79 \times 10^{19}$ kg

(~1/100 of Haumea)

$r = 160$ km

Namaka

$m = 1.79 \times 10^{18}$ kg

(1/10 of Hi'iaka)

$r = 80$ km

- Both satellites are covered in pure H_2O ice (Ragozzine & Brown 2009)
- Hi'iaka orbits in Haumea's equatorial plane (Rabinowitz et al. 2006)

Collisional Family

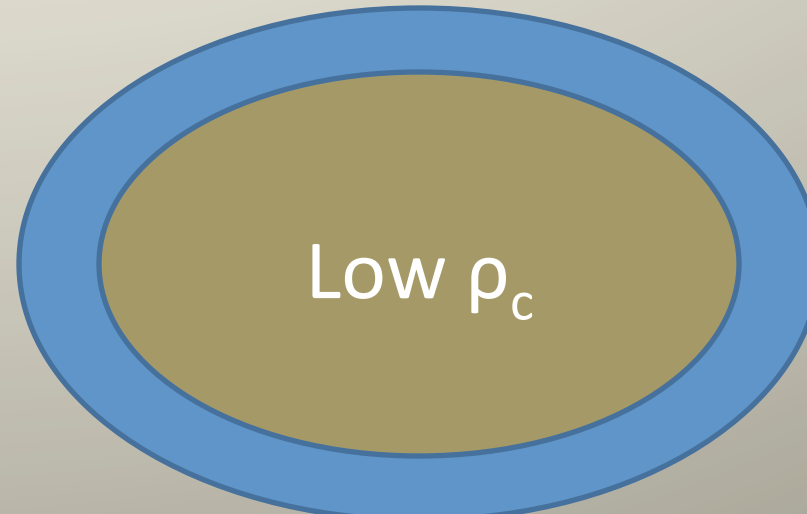
- Brown et al. (2007) discovered a family of KBOs with very similar orbits to Haumea
- Of 36 potential candidates:
  - 11 have similar H_2O ice surfaces to Haumea
  - Each has diameter between 70 – 365 km
- 7 dark candidates with higher Δv: pieces of Haumea's undifferentiated crust? ("Black Sheep", Cook et al. 2011)
- Only known collisional family in the Kuiper Belt

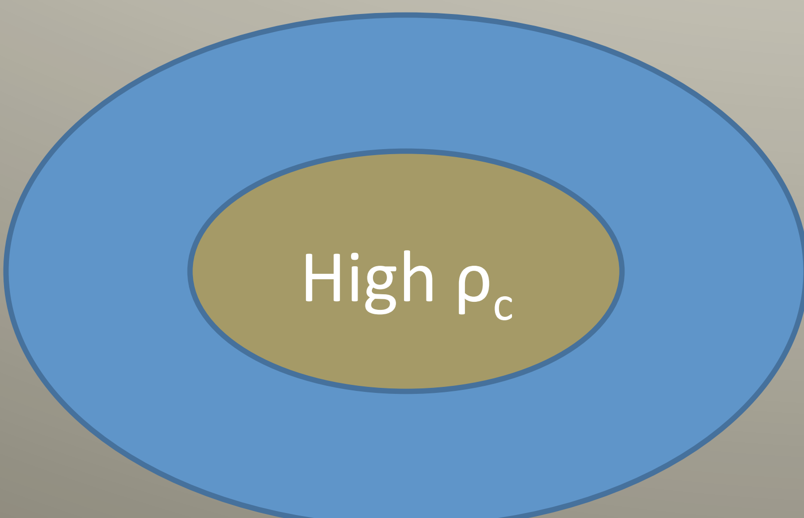
Formation Theories

- Catastrophic impact (Brown et al. 2007)
- Graze and merge scenario (Leinhardt et al. 2010)
- Double impact (Schlichting & Sari 2009)
- Desch & Neveu (2015): collision between two differentiated bodies each with radius 650 km and bulk density 2000 kg m^{-3}
  - Cores merged
  - Crusts and ice mantles were almost wholly ejected
  - Hydrothermal circulation and convection homogenized the core

Before Going Further: What Do We Expect of the Core?

- Axes are coincident with outer surface
- To preserve bulk density ($2600\ kg\ m^{-3}$): the lower the core density, the bigger it will be.



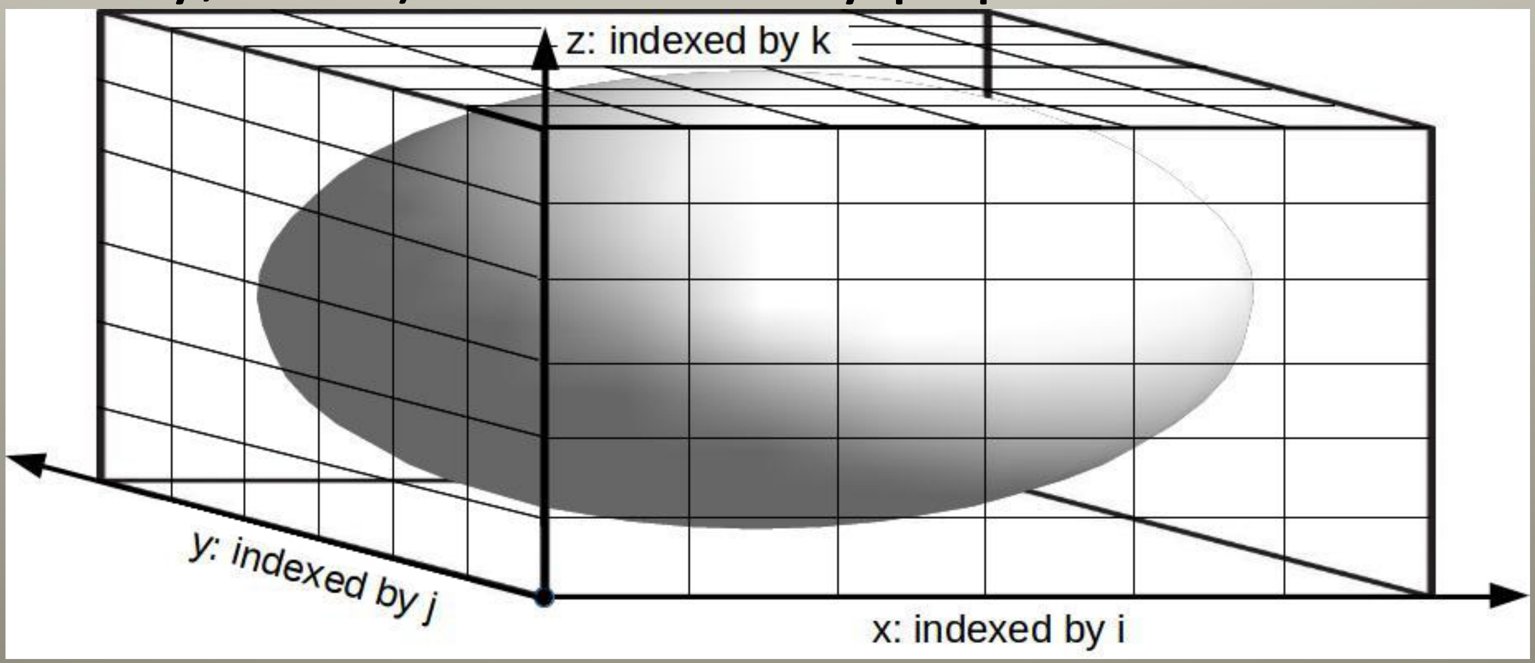


- The higher the core density, the smaller it will be.

- Shape? What are p_c and q_c?

Simulating a Two-Phase Haumea

- Set up a 3D rectangular space completely containing the ellipsoid, then discretized the space and assigned rock density to the core, ice density to the mantle, and zero density outside
- Grid cells straddling rock and ice (the core-mantle boundary, CMB) are randomly populated



Metric

- For a run, the following metric was calculated:

$$M = \oint_{S} n \cdot g \; dS \Big/ \oint_{S} dS$$

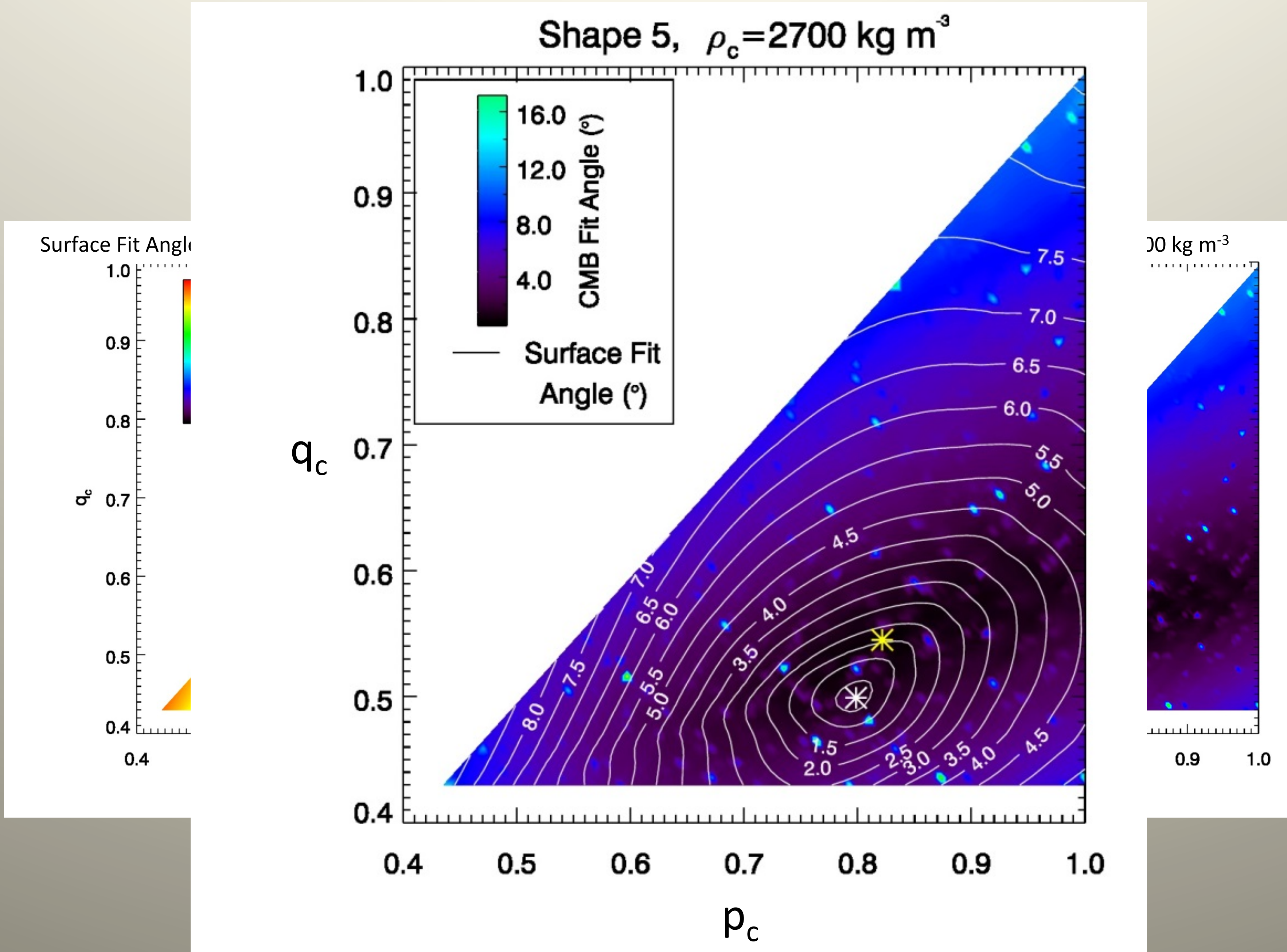
- n is the surface normal (downward)
- g is the total acceleration, including gravity and centrifugal effects
- Finally, $\cos^{-1}(M)$ gives the average "<u>fit angle</u>"
  - Should be 0° if in hydrostatic equilibrium
  - → Both the outer surface and the CMB are coincident with equipotential surfaces

Performing the Runs

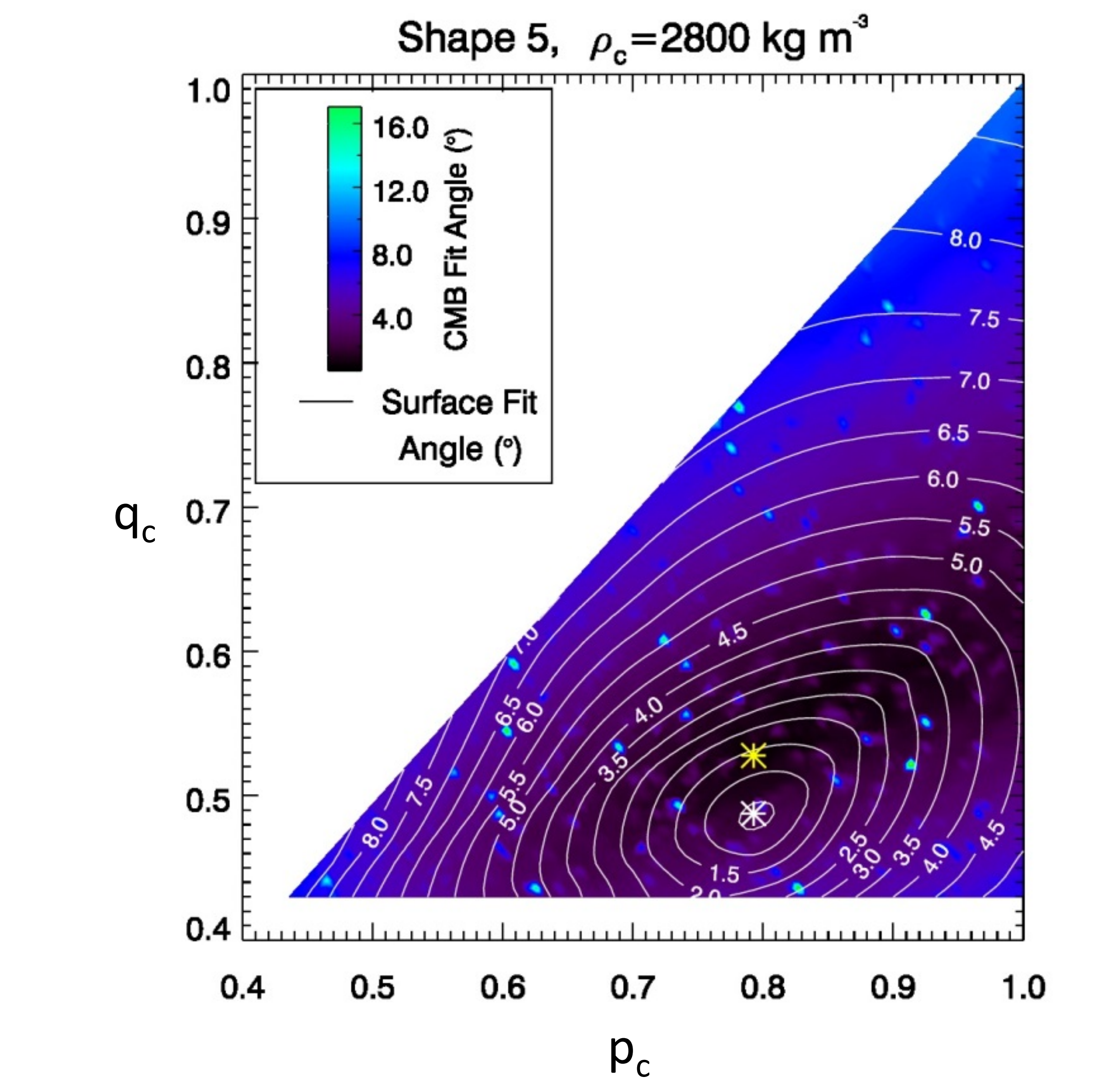
- Outer surface was fixed (Shapes 1 – 5)
- Ice density = 935 kg m^{-3}
- Core density ranged from 2700 – 3300 kg m^{-3}, in intervals of 100 kg m^{-3} (seven values)

  → 35 scenarios in all

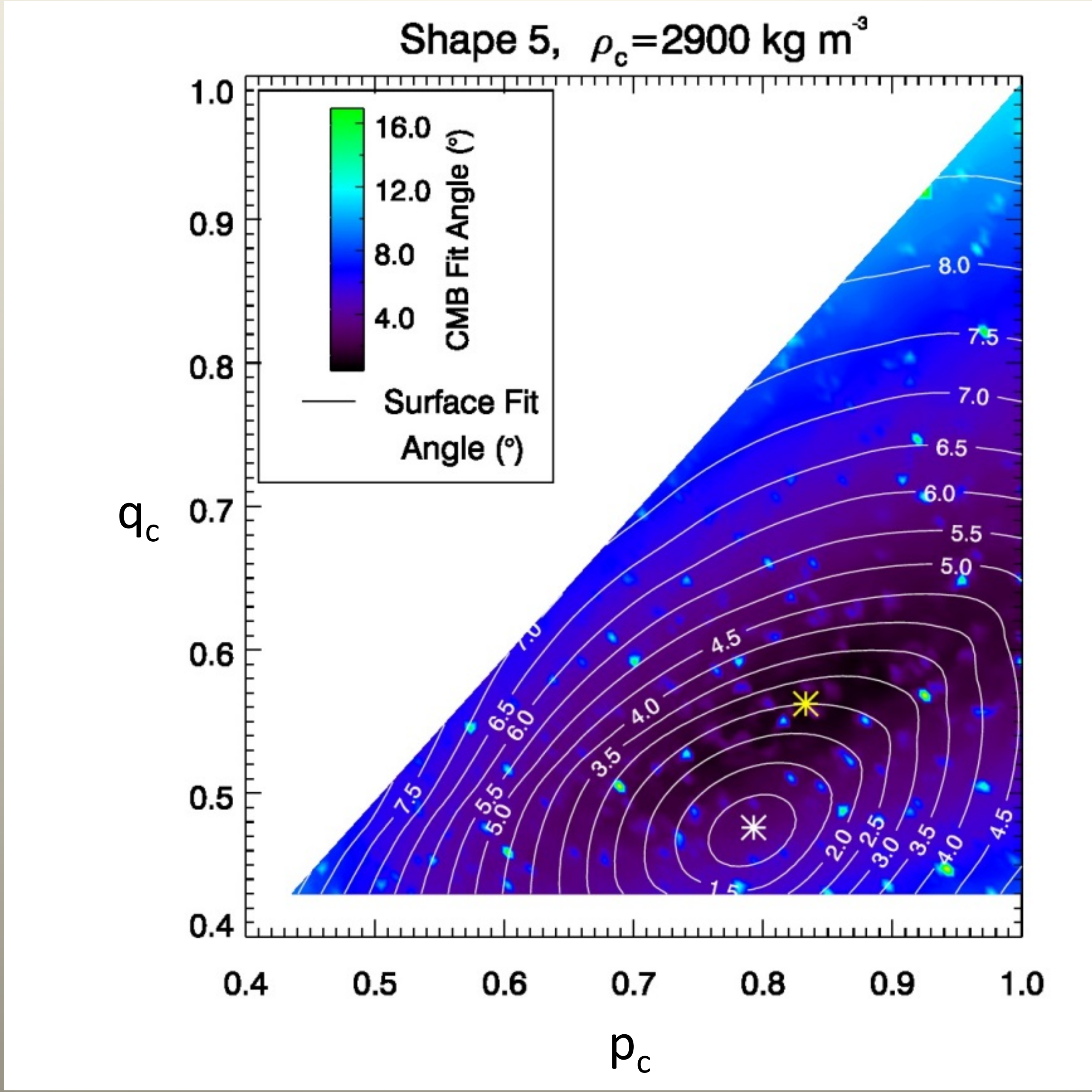
- Each scenario tested with all possible core shapes
- Highest resolution: 120 grid cells on each side
- At highest resolution, for homogeneous density case, the average fit angle was ~0.5°
  - This is the minimum achievable value.



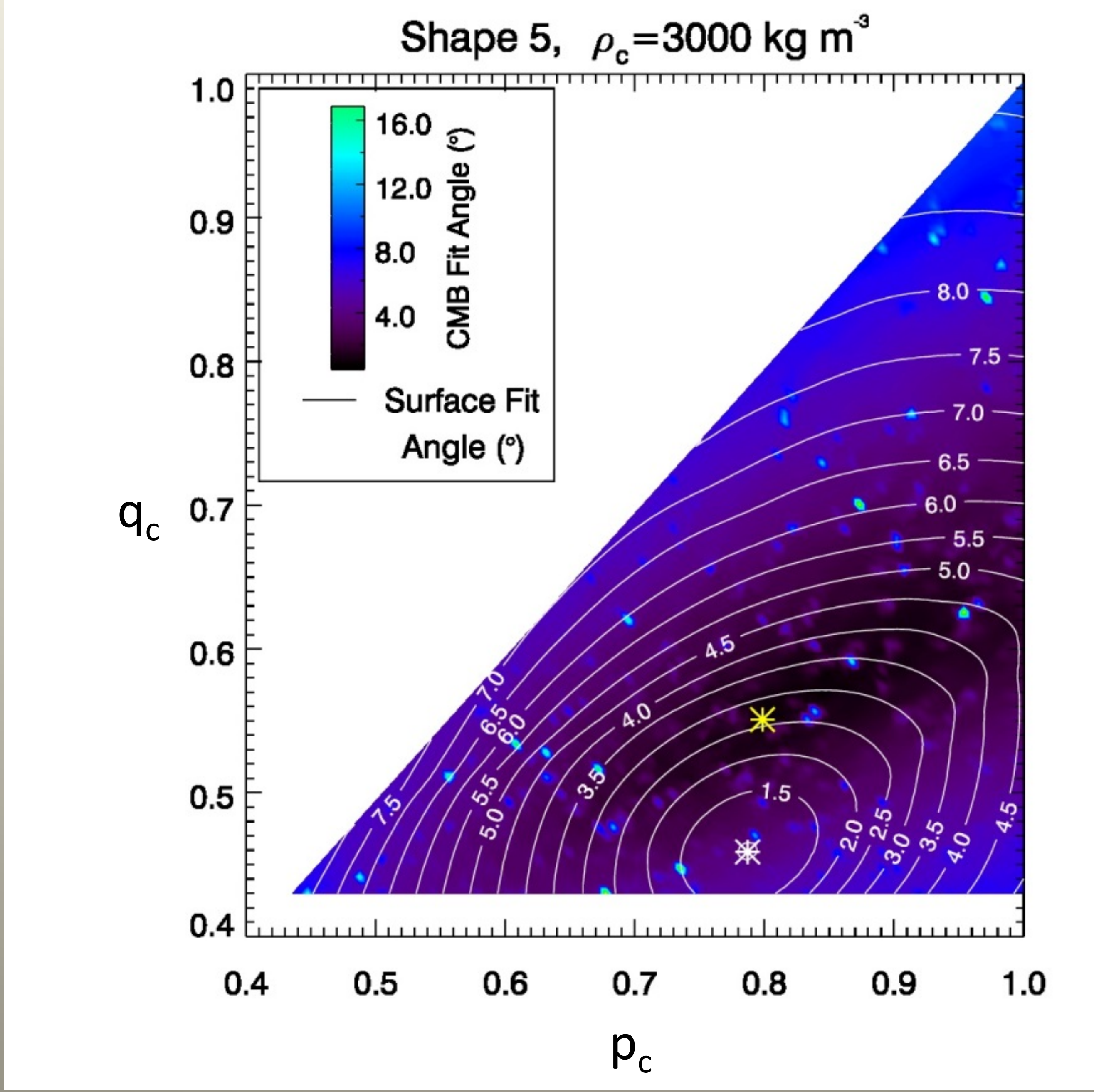
Surface Fit Angl
q_c
00 kg m^-3
Shape 5, ρ_c=2700 kg m^-3
CMB Fit Angle (°)
16.0
12.0
8.0
4.0
Surface Fit Angle (°)
q_c
p_c



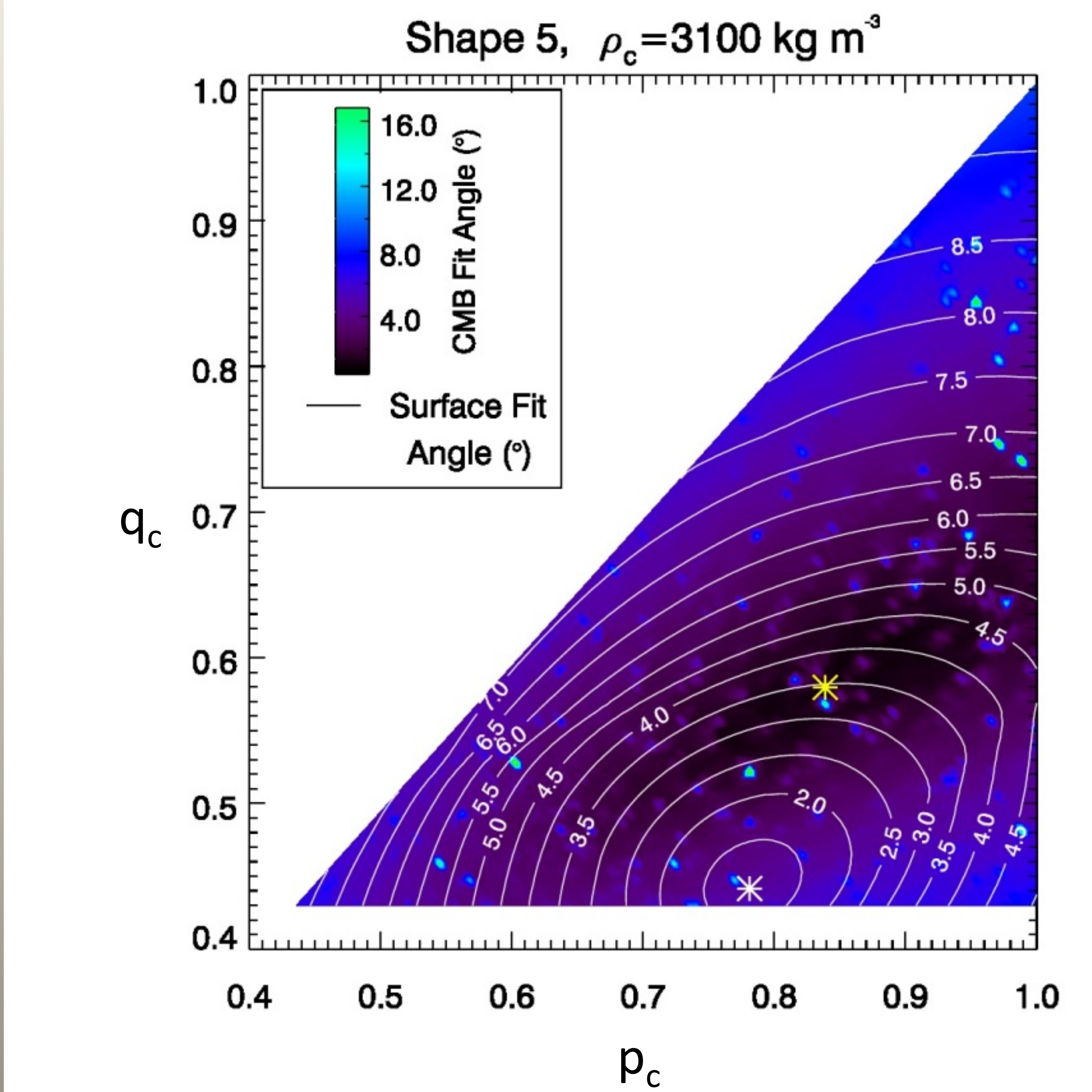
Shape 5, ρ_c=2800 kg m^{-3}
CMB Fit Angle (°)
16.0
12.0
8.0
4.0
Surface Fit Angle (°)
q_c
p_c
0.4
0.5
0.6
0.7
0.8
0.9
1.0
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5



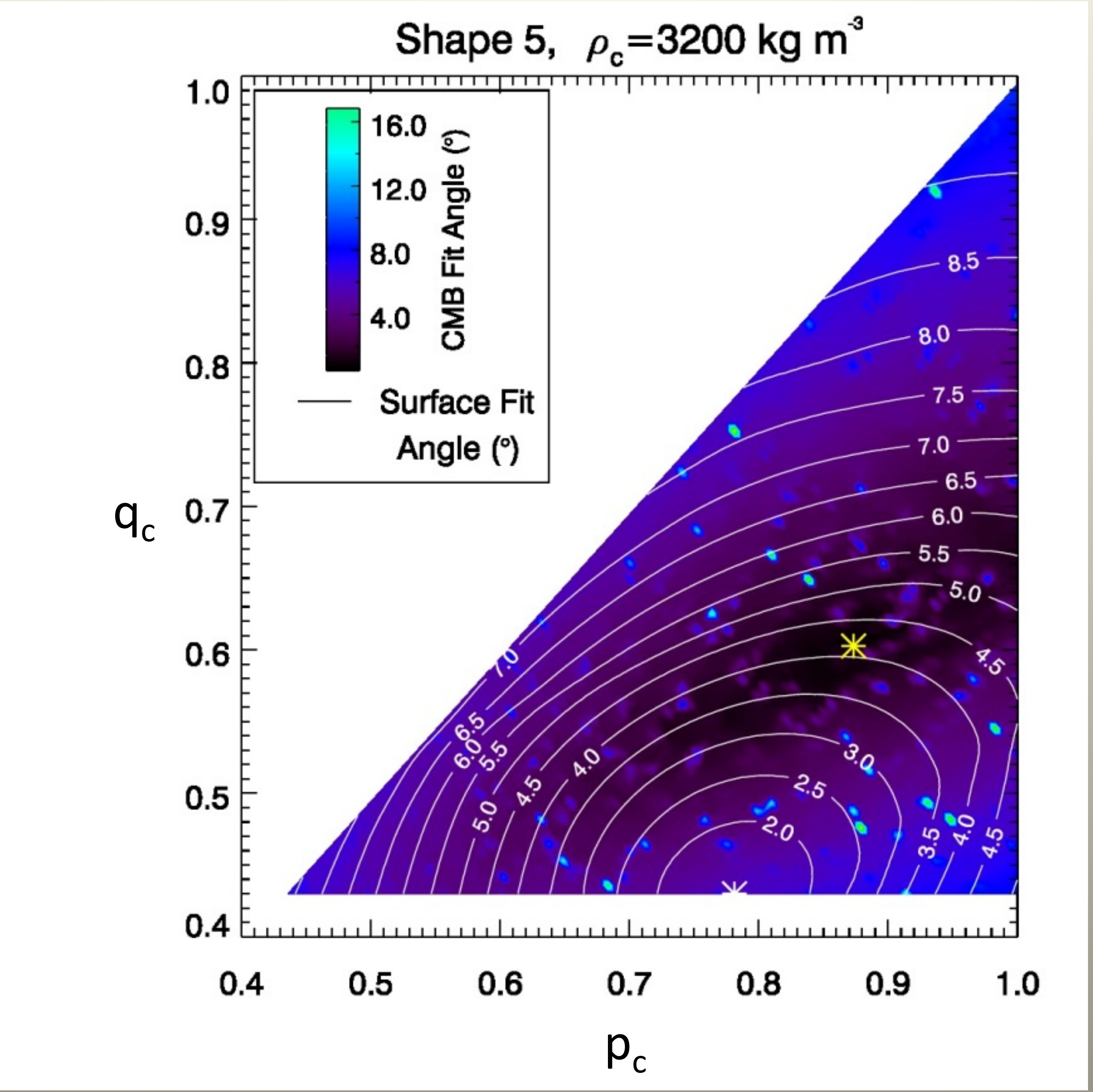
Shape 5, ρ_c=2900 kg m^{-3}
16.0
12.0
8.0
4.0
CMB Fit Angle (°)
Surface Fit Angle (°)
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
2.0
2.5
3.0
1.5
q_c
p_c
0.4
0.5
0.6
0.7
0.8
0.9
1.0



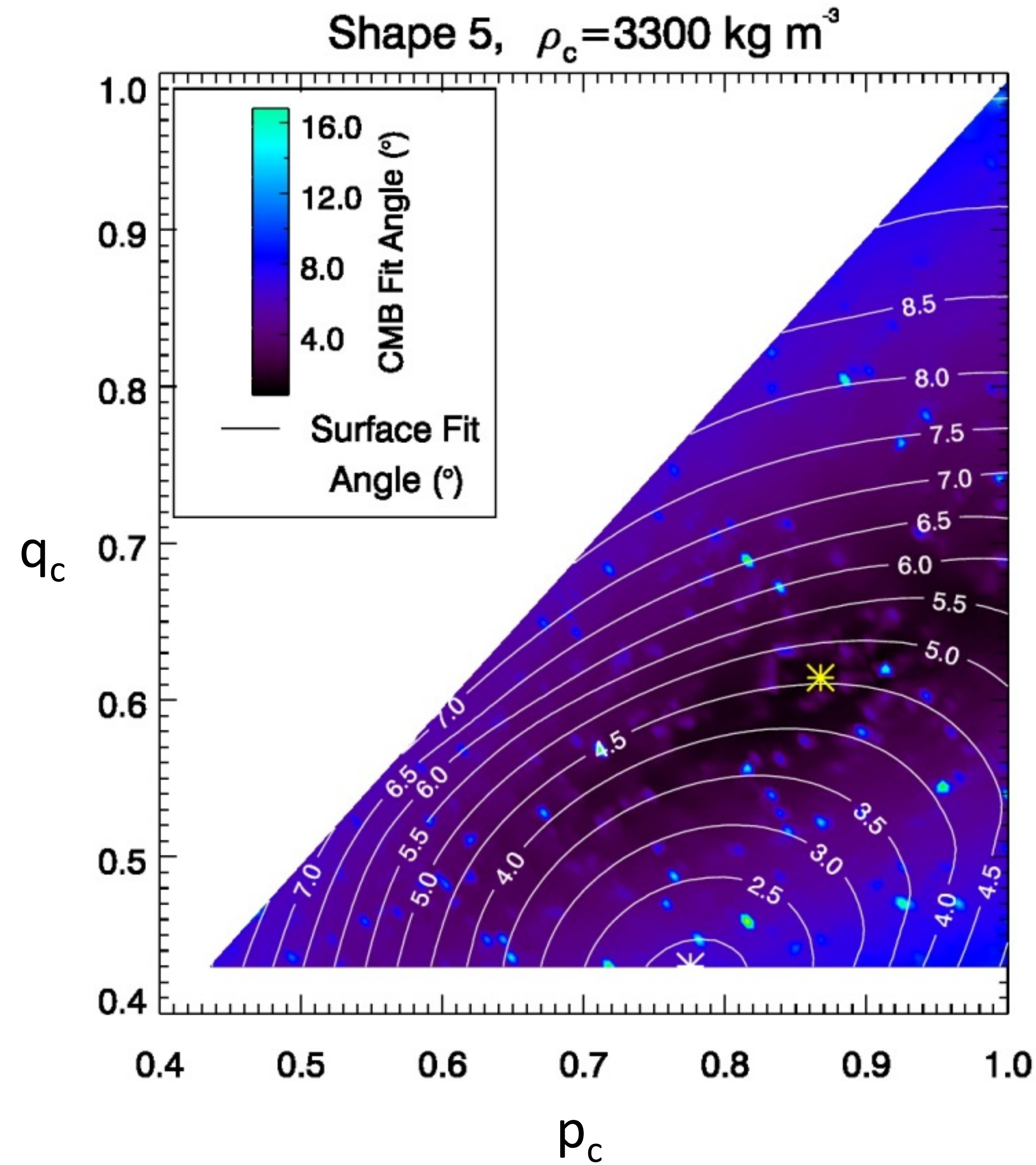
Shape 5, ρ_c=3000 kg m^{-3}
16.0
12.0
8.0
4.0
CMB Fit Angle (°)
Surface Fit
Angle (°)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.4
0.5
0.6
0.7
0.8
0.9
1.0
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
1.5
2.0
2.5
3.0
q_c
p_c



Shape 5, ρ_c=3100 kg m^{-3}
16.0
12.0
8.0
4.0
CMB Fit Angle (°)
Surface Fit Angle (°)
q_c
p_c
0.4
0.5
0.6
0.7
0.8
0.9
1.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0



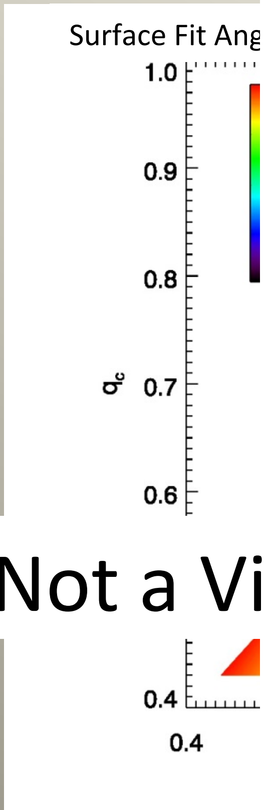
Shape 5, ρ_c=3200 kg m^{-3}
16.0
12.0
8.0
4.0
CMB Fit Angle (°)
Surface Fit
Angle (°)
q_c
p_c
0.4
0.5
0.6
0.7
0.8
0.9
1.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0



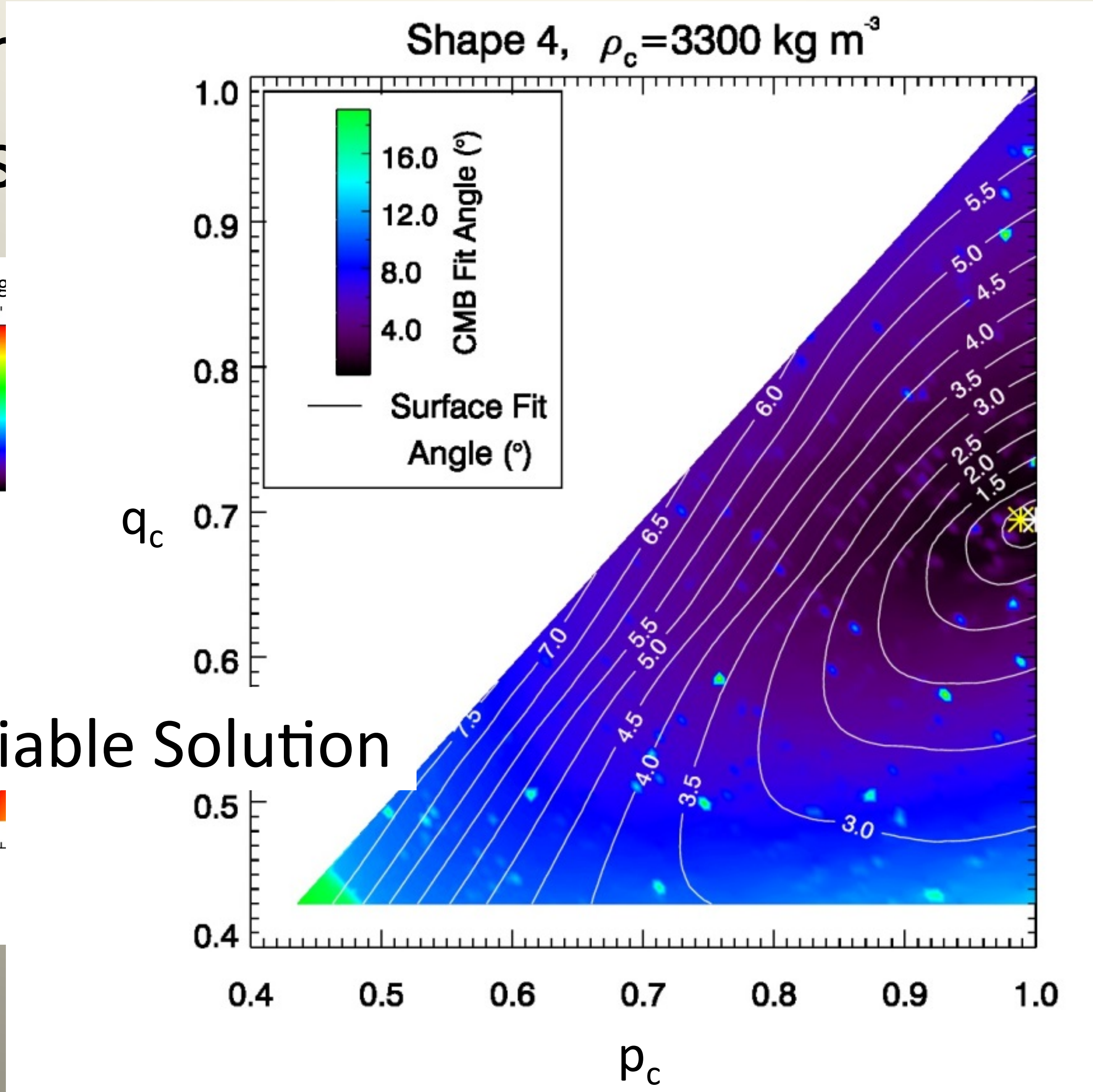
Shape 5, ρ_c=3300 kg m^{-3}
16.0
12.0
8.0
4.0
CMB Fit Angle (°)
Surface Fit
Angle (°)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
q_c
p_c
1.0
0.9
0.8
0.7
0.6
0.5
0.4

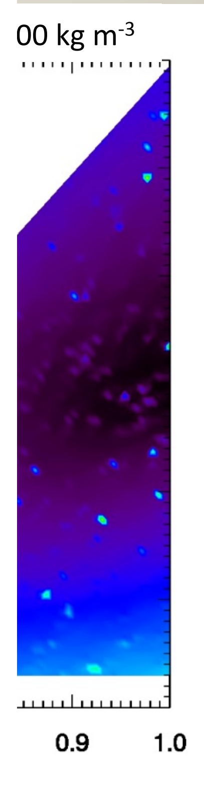
Sh m^{-3}:

Is n?

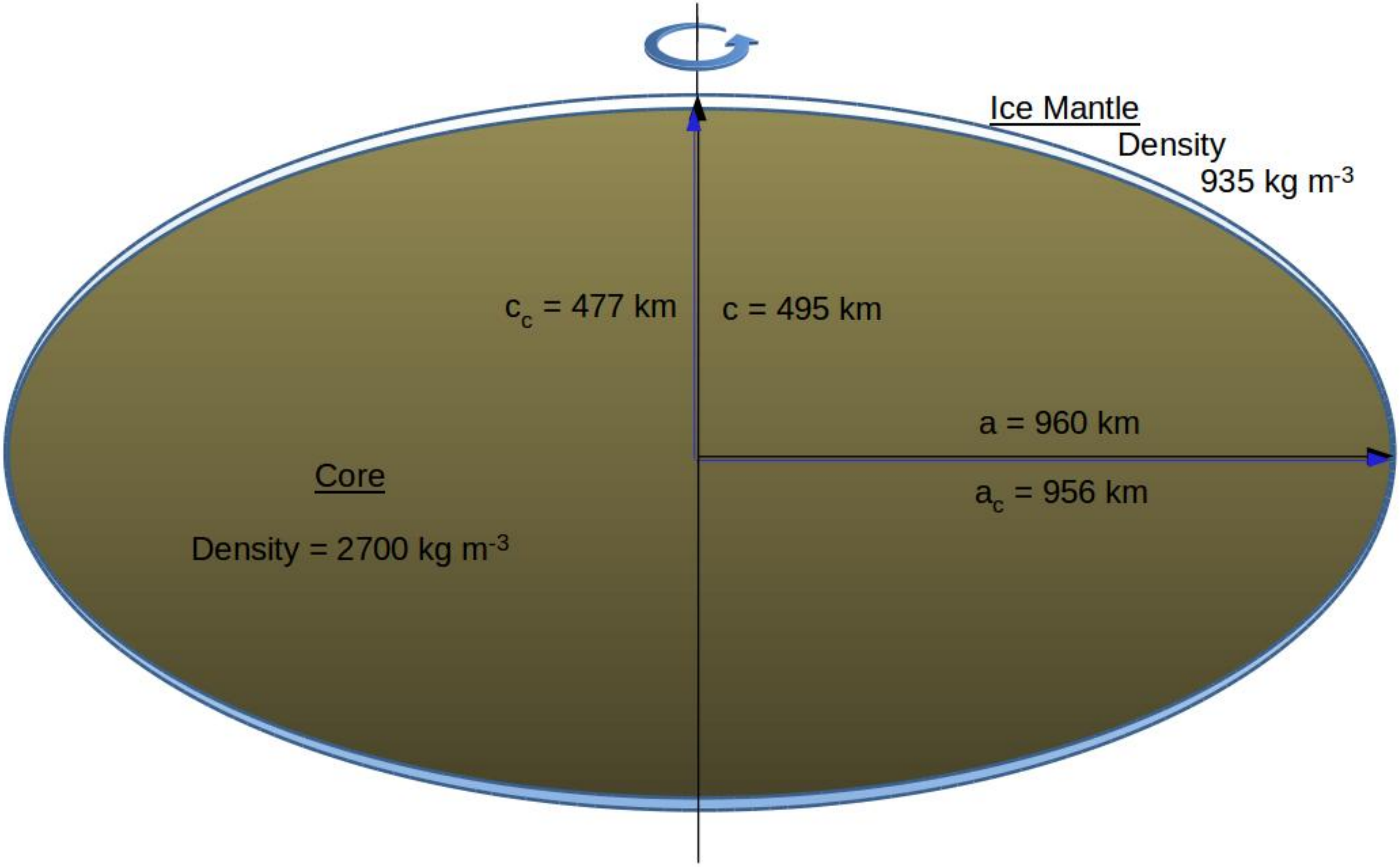


Not a Viable Solution

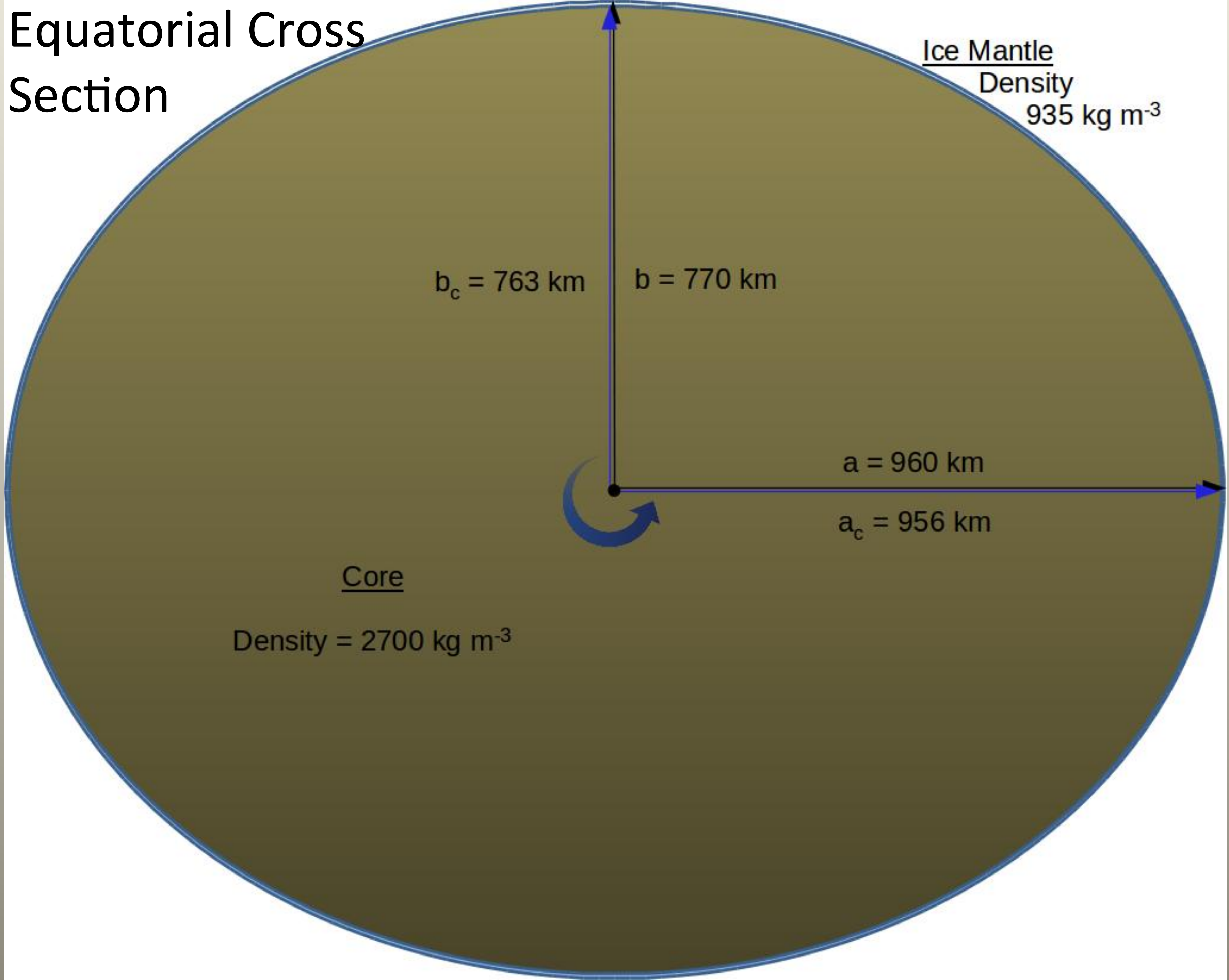




Haumea's Likely Interior: Vertical Cross Section



Equatorial Cross Section



Conclusions

- Haumea is a Jacobi ellipsoid (~Shape 5) with a core density in the range 2700 – 2800 kg m^{-3}
  - This closely matches Desch & Neveu's (2015) estimated core density of 2900 kg m^{-3}
- Silicate mass fraction is 96.5% – 98.2%
- Haumea is practically homogeneous
- Such low-density core material could be hydrated silicate, suggesting much mixture between water and rock in the past

Thank You!

Special Thanks to Steve Desch,
Anand Thirumalai, and Alex Spacek!