MODELING
OF THE INTERPLANETARY DUST CLOUD

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My long time collaborators with Zodiac Matters:

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A Three-dimensional Model of the Interplanetary Dust Cloud

Seung Soo Hong , *Seoul National University*

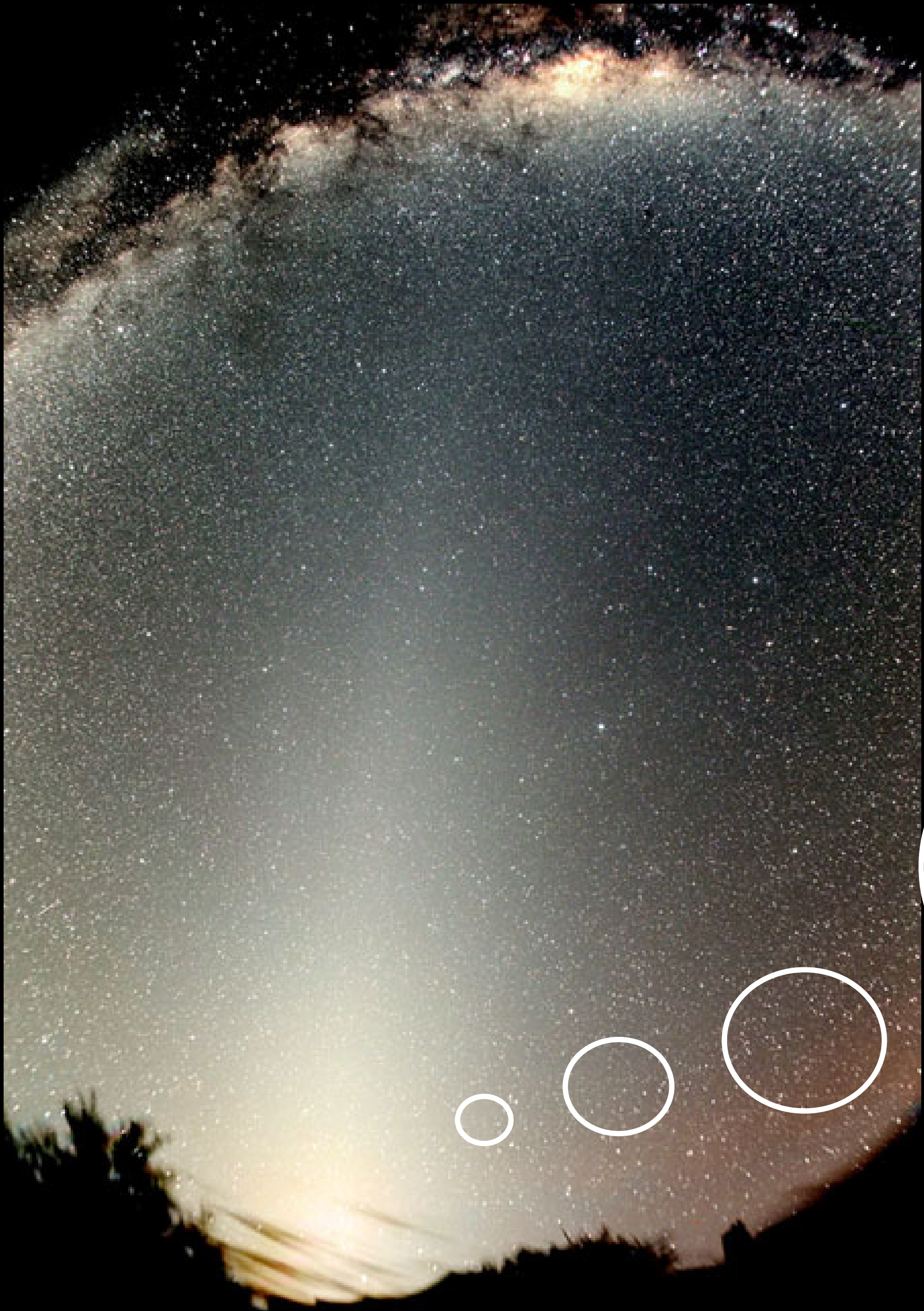
We are currently reducing the brightness of zodiacal emission (ZE) from the all sky IR survey observations of the Japanese IR satellite, AKARI, which commands fine spatial resolution and superb sensitivity. The resulting maps will determine the ZE brightness, at solar elongation 90 degrees, over the entire ranges of the ecliptic longitude and latitude. This lecture explains how one can make use of such fine resolution maps in probing three-dimensional structures of the interplanetary dust (IPD) cloud. An emphasis will be given to the limitations of the currently available 3-D models. For example, in building these empirical models of the IPD cloud, one often employs specific functional forms to describe the vertical density structure of the cloud, which leave unavoidable biases in the resulting 3-D models. Instead of relying on functional forms, we will directly invert the profile of ZE brightness, at solar elongation 90 degree, over ecliptic latitude from 0 through +/-90 degrees. This lecture will also explain how the pointing capability of the AKARI can be utilized in directly measuring the volumetric IR emissivities of the interplanetary dust particles near the Earth's orbit. We will analyze seasonal variations of the zodiacal emission brightness of the north and south ecliptic poles and locate the plane of maximum IPD density as accurately as possible.

金　我他

ON-AIR by Atta Kim (1958 ~) 現象の 重層性

International Center of Photography, June 2006, N.Y.

Dust in Space_090106

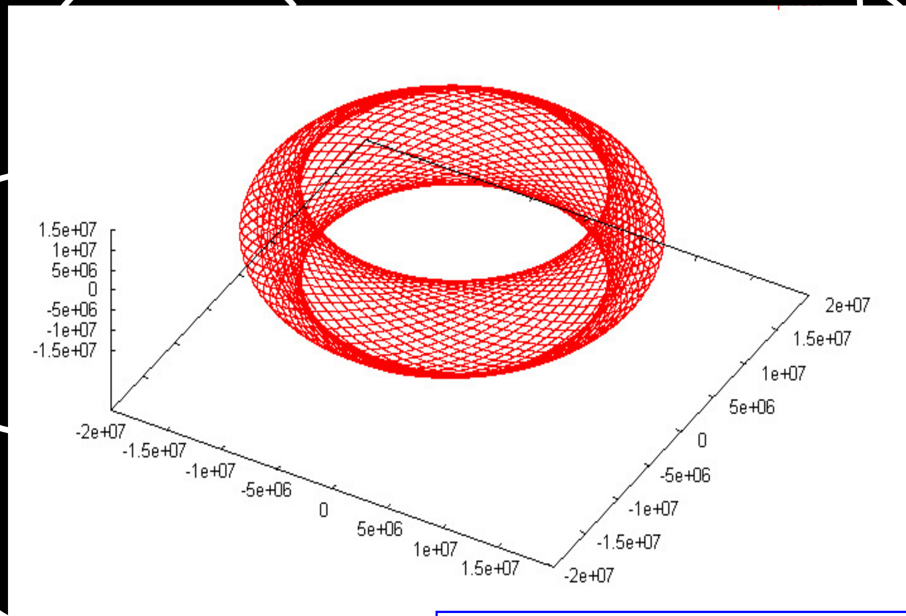


APOD : Aug 25, 2004

Taken in Namibia, May ‘04

by Stefan Seip

http://antwrp.gsfc.nasa.gov/apod/



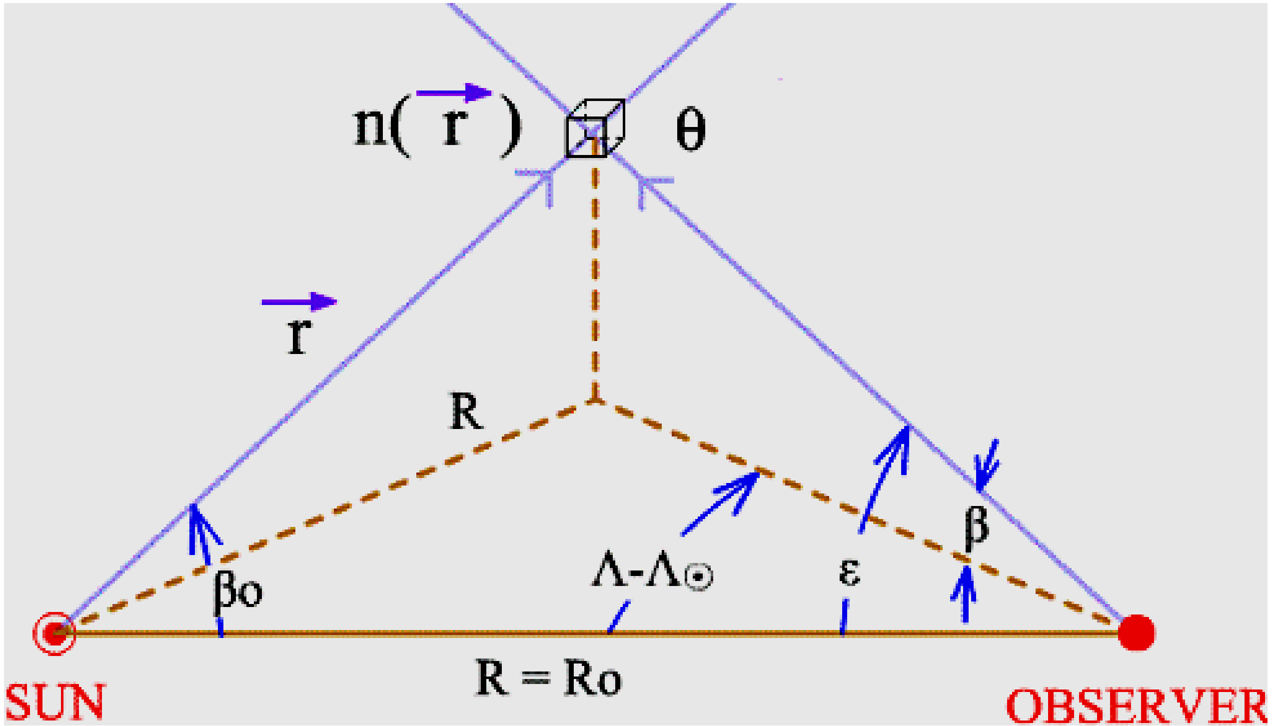
Original schematic

http://antwrp.gsfc.nasa.gov/apod/ap040825.html

How does the IPD cloud look like inside ?

1. how to construct a 3D model of the interplanetary dust cloud from the ZL and ZE brightness distributions over the sky
2. how to directly measure the volumetric emissivity of the interplanetary dust particles near the Earth's orbit
3. AKARI low resolution maps of the ZE brightness and preliminary analysis of the maps
4. limitations of a single-component approach to the 3D model construction

Chap 1. BASIC CONCEPTS AND GEOMETRY



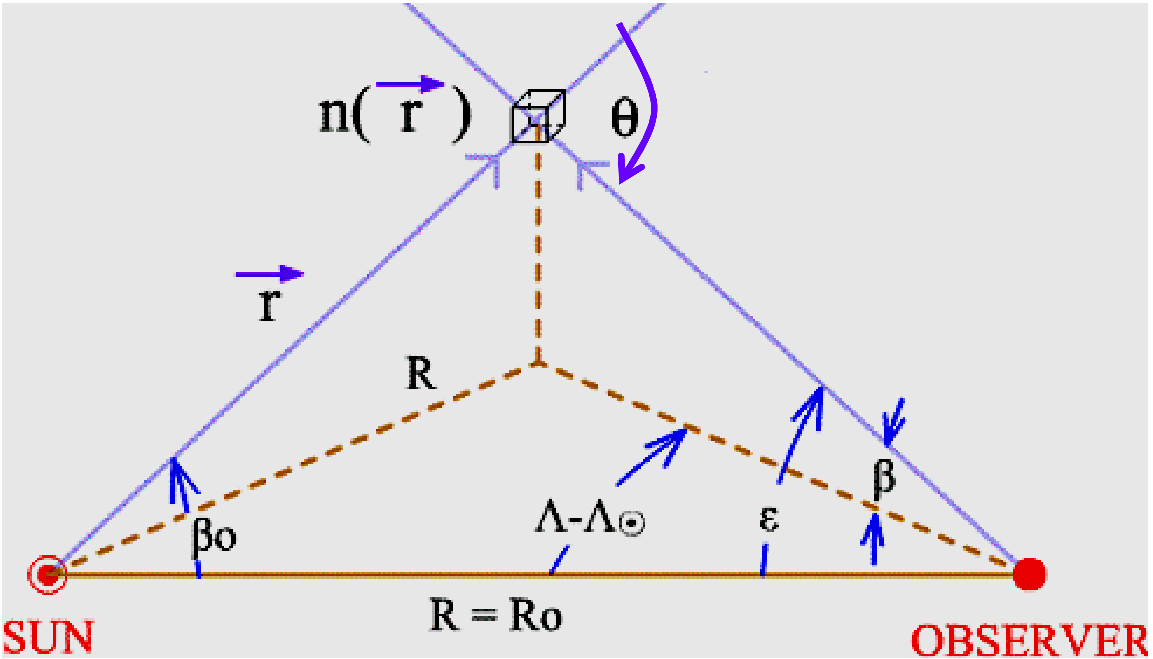
sunlight scattered by IPDs

⇒ Zodiacal VIS Light 黃道 散亂光 ZL(Λ, β)

sunlight absorbed by IPDs

⇒ Zodiacal IR Emission 黃道 放出光 ZE(Λ, β; λ)

1) ZODIACAL LIGHT BRIGHTNESS INTEGRAL



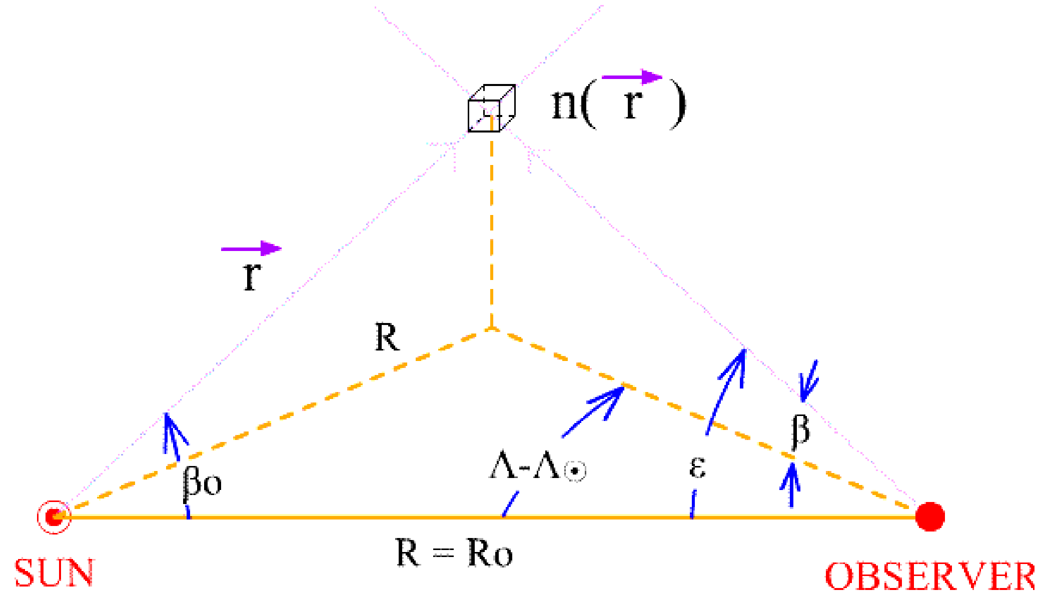
$$Z\,(\Lambda - \Lambda_{\odot}; \beta) = \int_0^{\infty} F(\vec{r}\,)\,n\,(\vec{r}\,)\,\overline{\sigma}\,(\vec{r}\,)\,\Phi(\Theta, \vec{r}\,)\,dl$$

2-D Distribution of ZL Brightness $\Leftarrow$ **OBSERVATION**

$\Rightarrow$ 3-D structure of the IPD cloud complex

IN-ECLIPTIC ZL BRIGHTNESS INTEGRAL

$$\beta = 0 \quad ; \quad \Lambda - \Lambda_{\odot} = \mathcal{E}$$



$$Z(\mathcal{E}) = \int_0^{\infty} F_o \left(\frac{R_o}{R}\right)^2 n_o \left(\frac{R_o}{R}\right)^{\nu} \overline{\sigma}\, \Phi(\Theta)\, dl$$

$$Z(\mathcal{E}) = \frac{F_o n_o R_o \overline{\sigma}}{\sin^{\nu+1} \mathcal{E}} \int_{\mathcal{E}}^{\pi} \Phi(\Theta) \sin^{\nu} \Theta \, d\Theta$$

It is possible to retrieve scattering phase function from the observed elongation dependence of the ZL brightness in the ecliptic.

2) IN-ECLIPTIC ZE BRIGHTNESS INTEGRAL

$$Z(\epsilon;\lambda) = \int_0^{\infty} n(r)\sigma_{\rm abs}(r;\lambda)B_\lambda[T(r)]dl$$

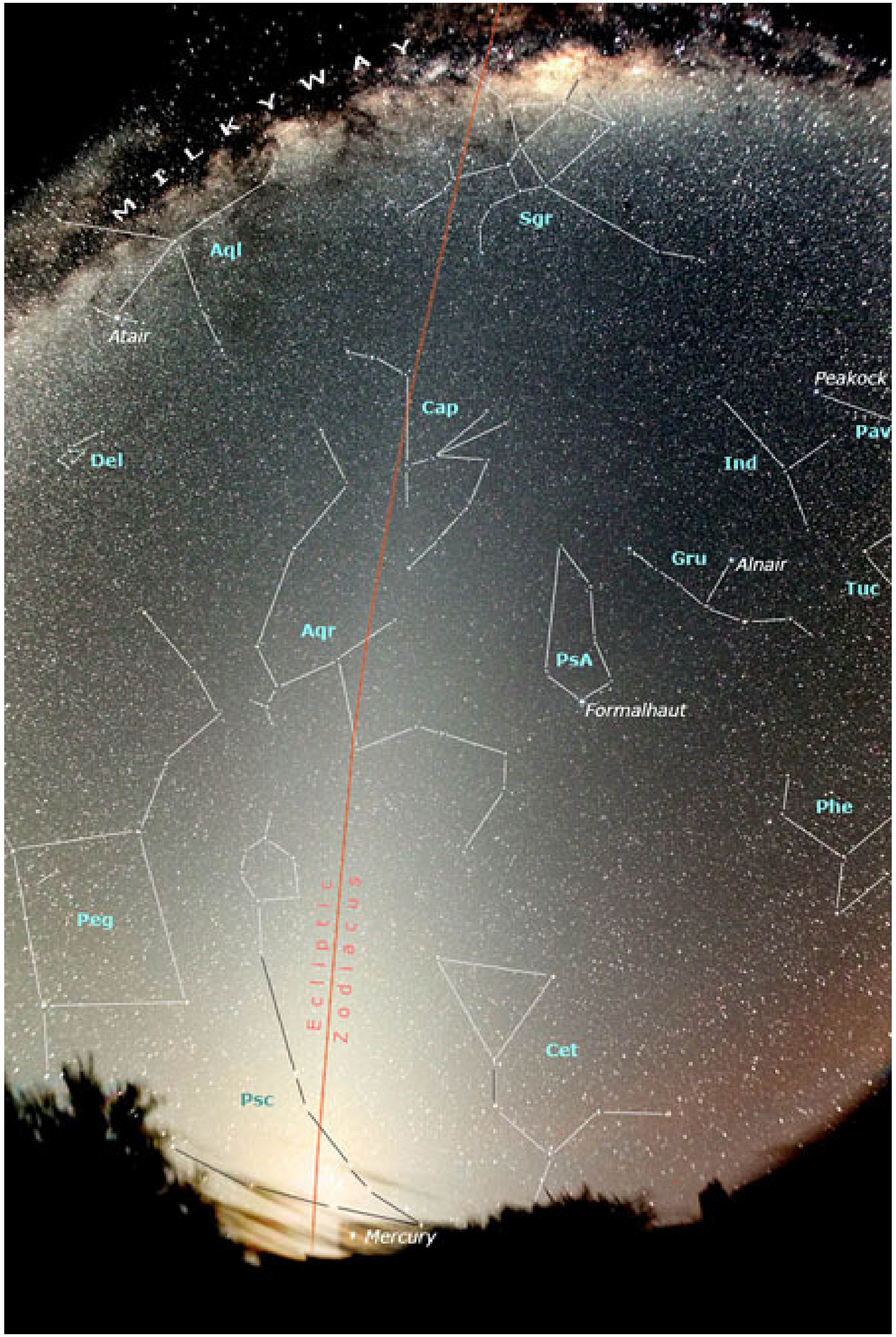
$$\zeta(r) = n(r)\sigma_{\rm abs}(r;\lambda) = \zeta_0\left(\frac{r_0}{r}\right)^{\gamma} \qquad T(r) = T_0\left(\frac{r_0}{r}\right)^{1/2}$$

$$Z(\epsilon;\lambda) = \frac{2hc^2}{\lambda^5}\,\frac{r_0\zeta_0}{\sin^{\gamma-1}\epsilon}\int_\epsilon^{\pi}\frac{\sin^{\gamma-2}\Theta}{\exp\left[\alpha(\sin\epsilon/\sin\Theta)^{1/2}\right]-1}\,d\Theta$$

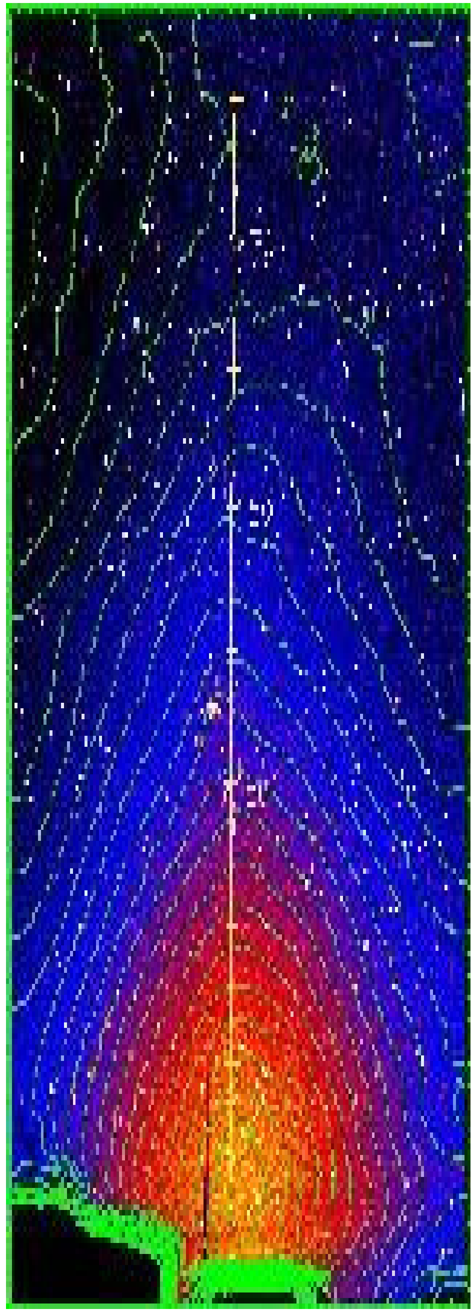
It is possible to retrieve power-exponent ν from observed elongation dependence of the ZE brightness in the ecliptic.

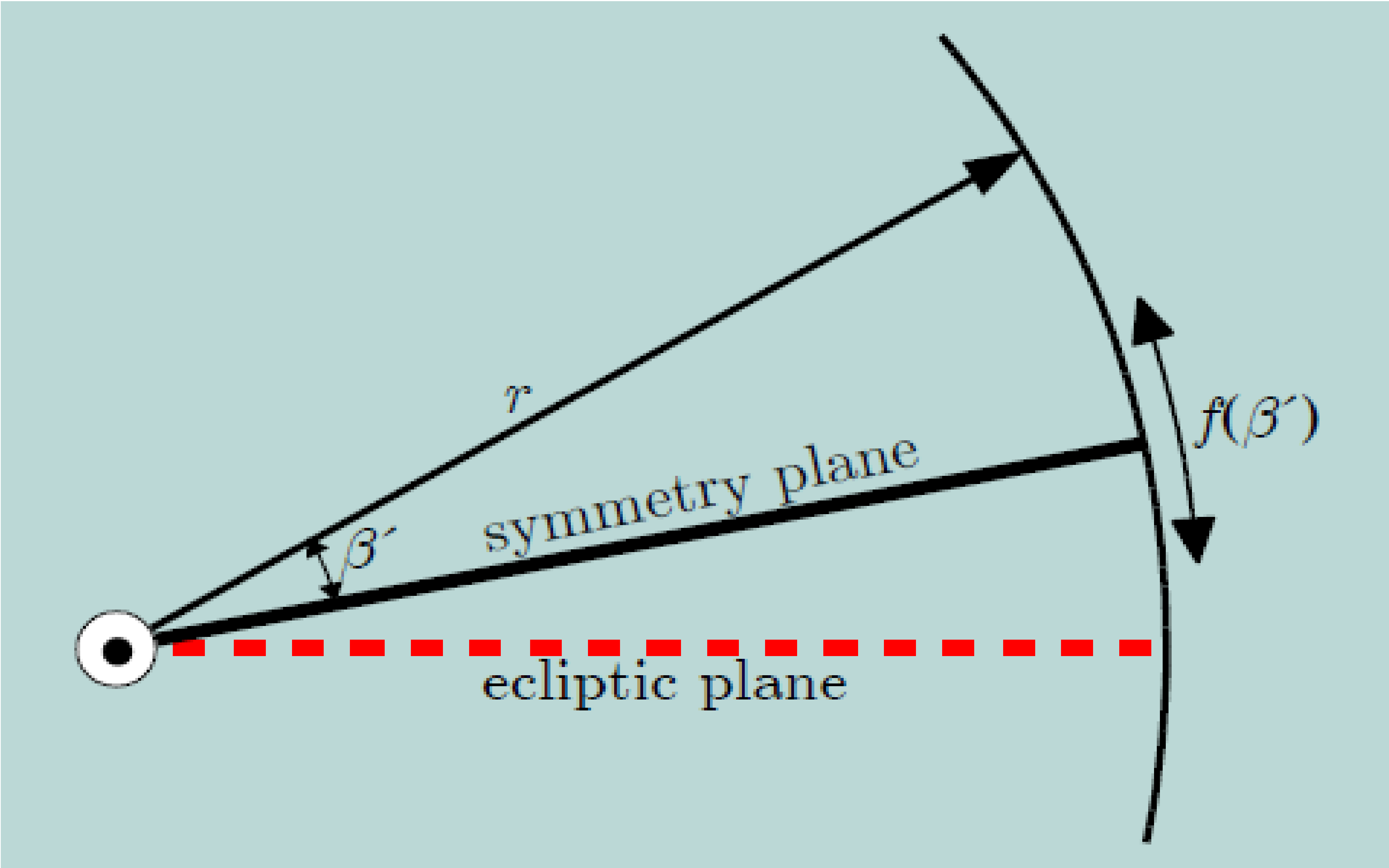
The grey exponent δ = ½ can be generalized to non-grey δ.

3) SYMMETRY PLANE



Provided by M. Ishiguro

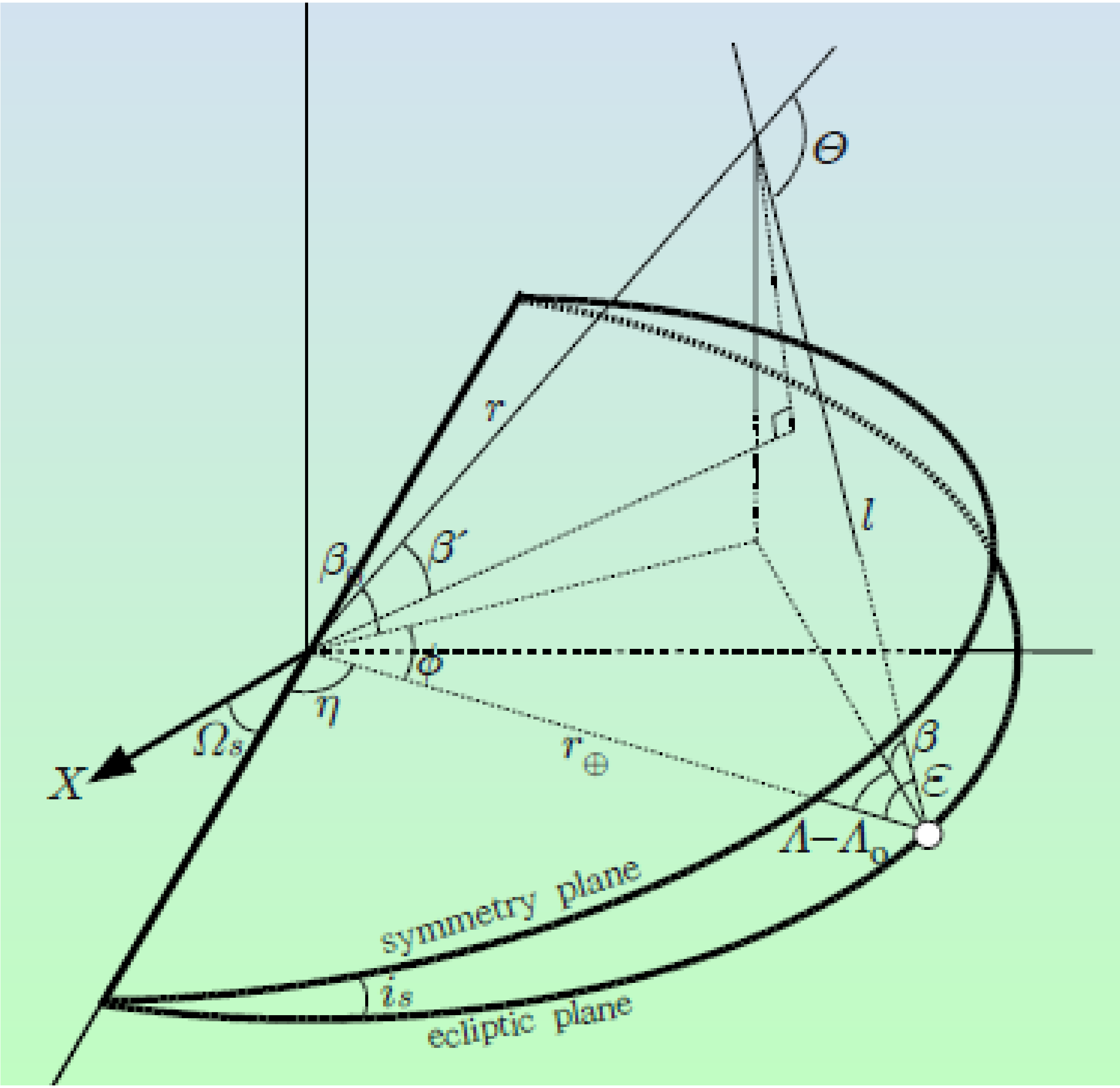




$$n(\mathbf{r}) = n_0 \left[\frac{r}{1\ \mathrm{AU}}\right]^{-\nu} f(\beta').$$

⇒ **3D shape of IPD cloud**

One needs to locate the plane of maximum IPD density in terms of inclination and longitude of the ascending node.



4) How does the IPD cloud look like ?

i) powe-law exponent ν_s for the volumetric scattering cross-section $n(r)\ \sigma_{sca}(r)$ *of IPDs*

ii) scattering phase function $\Phi(\Theta)$ *of IPDs*

Iii) power-law exponent ν_a for the volumetric absorption cross-section $n(r)\ \sigma_{abs}(r, \lambda)$ *of IPDs*

iv) power-law exponent δ for the dust temperature T(r)

v) location of the symmetry plane in terms of its inclination i_s *and the ascending node's longitude* Ω_s

vi) vertical structure function $f(\beta`)$

Crack n – sigma – nu – phi – delta – f Degeneracy

`` A 3 - D Model of the IPD Cloud ``

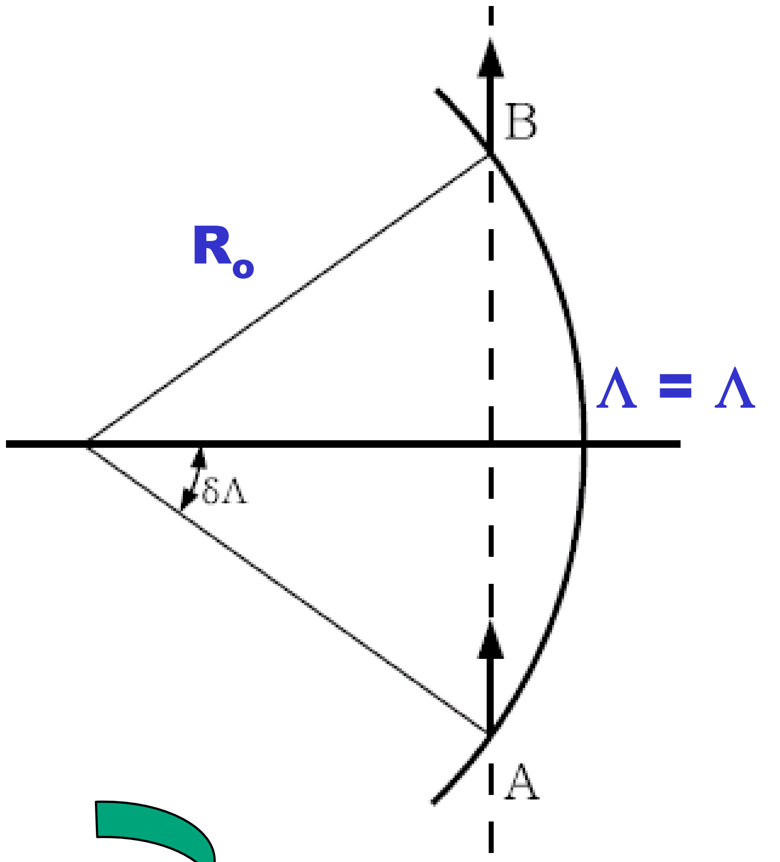
The IPD Cloud Structure & Optical Property of IPDs

Observations & Laboratory Experiments

Chap 2. DEGENERACY CRACKING

1) A GLIMPSE OF 'PROMISED LAND'

circular orbit



Dumont 1975

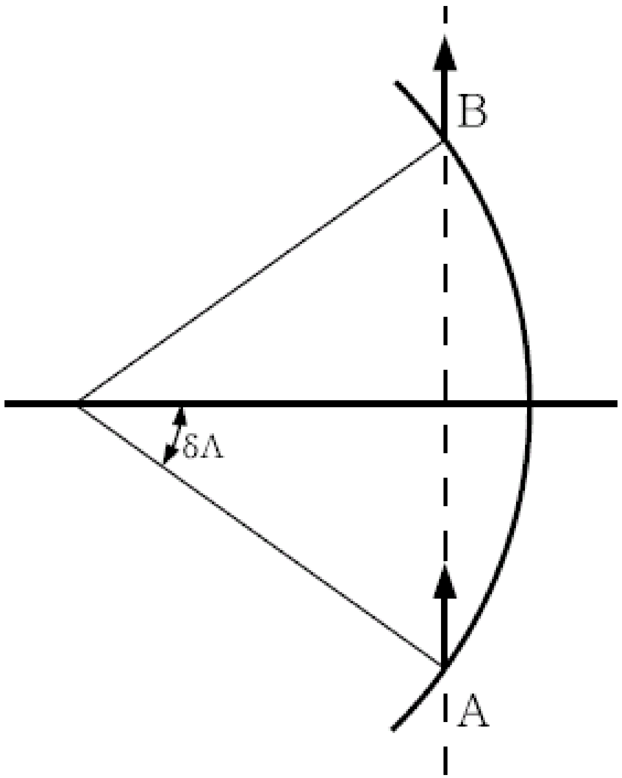
$$\Delta I_\lambda(\Lambda) \;=\; I_\lambda(A) - I_\lambda(B)\,; \quad \text{observationally}$$
$$\Delta I_\lambda(\Lambda) \;=\; 2R_\text{o}\,\delta\Lambda\,\mathcal{E}^\text{o}_\lambda(\Lambda) \quad ; \quad \text{physically}$$

$$\mathcal{E}^\text{o}_\lambda(\Lambda) \;=\; n(R_\text{o})\,\sigma_{abs,\lambda}(R_\text{o})\,B_\lambda(T_\text{o}) \;=\; \zeta_{\text{o},\lambda}\,B_\lambda(T_\text{o})$$

wavelength – dependence of the IR emissivity of local IPDs $\Rightarrow$ **material property**

2) NON-ZERO ECCENTRICITY OF THE EARTH ORBIT

elliptical orbit



$$\Delta I_\lambda(\Lambda) \simeq$$

$$2\,\delta\Lambda\, n_{\circ}\, R_{\circ}[1 - e_{\oplus}\cos(\Lambda - \Omega_{\oplus})]^{1-\nu} \quad \times$$

$$\sigma_{\rm abs}(\lambda)\, B_\lambda\left(T_{\circ}[1 - e_{\oplus}\cos(\Lambda - \Omega_{\oplus})]^{-\delta}\right)$$

Please note that $T/T_o = (r/r_o)^{-\delta}$.

modulation by the elliptical motion of Earth with eccentricity 0.0176

additional modulation due to the tilt of maximum density plane of IPD cloud with i and Ω_s

In summary, we may have the followings :

$$
\begin{aligned}
R(\Lambda) &= R_o\,(1 - e_\oplus \cos[\Lambda - \omega_\oplus]\,) \\
T(R) &\simeq T_o\,(1 + \delta e_\oplus \cos[\Lambda - \omega_\oplus]\,) \\
B_\lambda(T) &\simeq B_\lambda(T_o) + \frac{d}{dT_o} B_\lambda(T_o)\;\Delta T \\
&= B_\lambda(T_o)\left(1 + \frac{d\ln B_\lambda(T_o)}{d\ln T_o}\,\frac{\Delta T}{T_o}\right)
\end{aligned}
$$

$$
\begin{aligned}
B_\lambda(T) &\simeq B_\lambda(T_o)\;(\,1 + \alpha\,(T_o;\lambda)\,\delta\,e_\oplus \cos[\Lambda - \omega_\oplus]\,) \\
\zeta_\lambda(R) &\simeq \zeta_{o,\lambda}\,(\,1 + \nu e_\oplus \cos[\Lambda - \omega_\oplus]\,)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{E}_\lambda(\Lambda) &\simeq \mathcal{E}^o_\lambda\,[1 + (\alpha\delta + \nu)e_\oplus\,\cos(\Lambda - \omega_\oplus)]\cdot[1 + e_{\rm sym}\cos(2[\Lambda - \Omega_{\rm sys}])] \\
\mathcal{E}_\lambda(\Lambda) &\simeq \mathcal{E}^o_\lambda\,[1 + (\alpha\delta + \nu)e_\oplus\,\cos(\Lambda - \omega_\oplus) + e_{\rm sym}\cos(2[\Lambda - \Omega_{\rm sys}])]
\end{aligned}
$$

$$\Rightarrow \quad \mathcal{E}^o_\lambda,\;\; (\alpha\delta + \nu),\;\; e_{\rm sys},\;\; \Omega_{\rm sys}$$

3) DEGENERCY CRACKING STRATEGY

$$\mathcal{E}^{\mathrm{o}}_{\lambda}, \quad (\alpha\delta + \nu), \quad e_{\mathrm{sys}}, \quad \Omega_{\mathrm{sys}}$$

$$\alpha(T_{\mathrm{o}};\lambda) = \left[\frac{d\ln B_{\lambda}(T)}{d\ln T}\right]_{T_{\mathrm{o}}}$$

$$\left(\frac{\mathcal{E}^{\mathrm{o}}_{\lambda_m}}{\mathcal{E}^{\mathrm{o}}_{\lambda_n}}\right) = \left[\frac{\sigma_{\mathrm{abs}}(\lambda_m)}{\sigma_{\mathrm{abs}}(\lambda_n)}\right] \frac{B_{\lambda_m}(T_{\mathrm{o}})}{B_{\lambda_n}(T_{\mathrm{o}})}$$

$$\left(\frac{\mathcal{E}_{\lambda_m}(\Lambda)}{\mathcal{E}_{\lambda_n}(\Lambda)}\right) = \left[\frac{\sigma_{\mathrm{abs}}(\lambda_m)}{\sigma_{\mathrm{abs}}(\lambda_n)}\right] \frac{B_{\lambda_m}(T)}{B_{\lambda_n}(T)}$$

First take T_o as an analysis parameter ; derive δ from the emissvity color with the given value of T_o ; calculate α from T_o ; and then fix ν for the given wavelength ; and then use T_o-independency condition for δ and ν, which will fix all the unknowns !

seasonal modulation $(\alpha\delta + \nu)$ emissivity color $\delta(T_{\mathrm{o}})$

Planck function

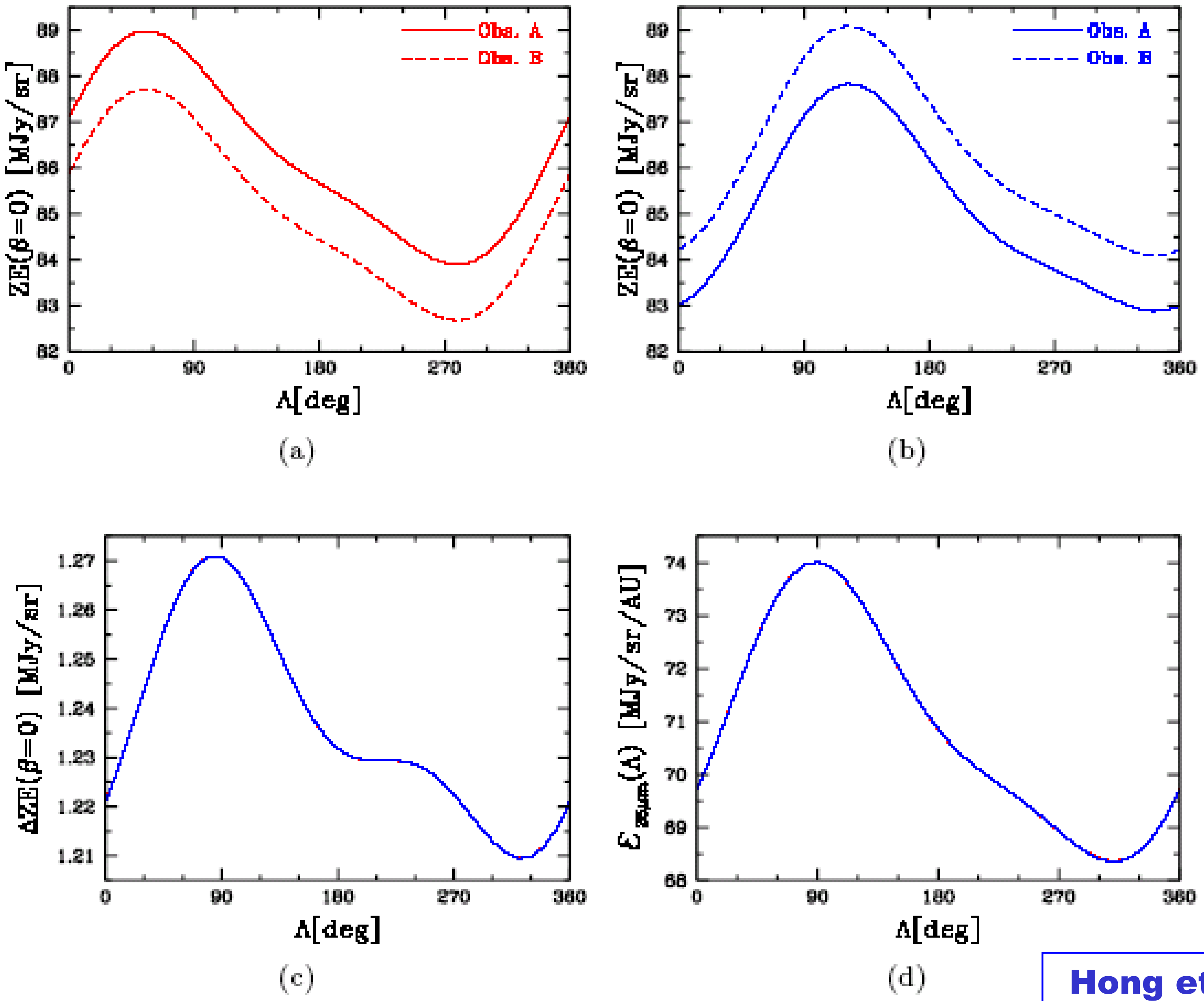
$$\alpha(T_{\mathrm{o}};\lambda) = \left[\frac{d\ln B_{\lambda}(T)}{d\ln T}\right]_{T_{\mathrm{o}}}$$

$$\Rightarrow \quad \nu(T_{\mathrm{o}};\lambda) = (\nu + \alpha\delta) - \alpha(T_{\mathrm{o}};\lambda)\delta(T_{\mathrm{o}})$$

Hong et al 2004, JKAS,37, 159

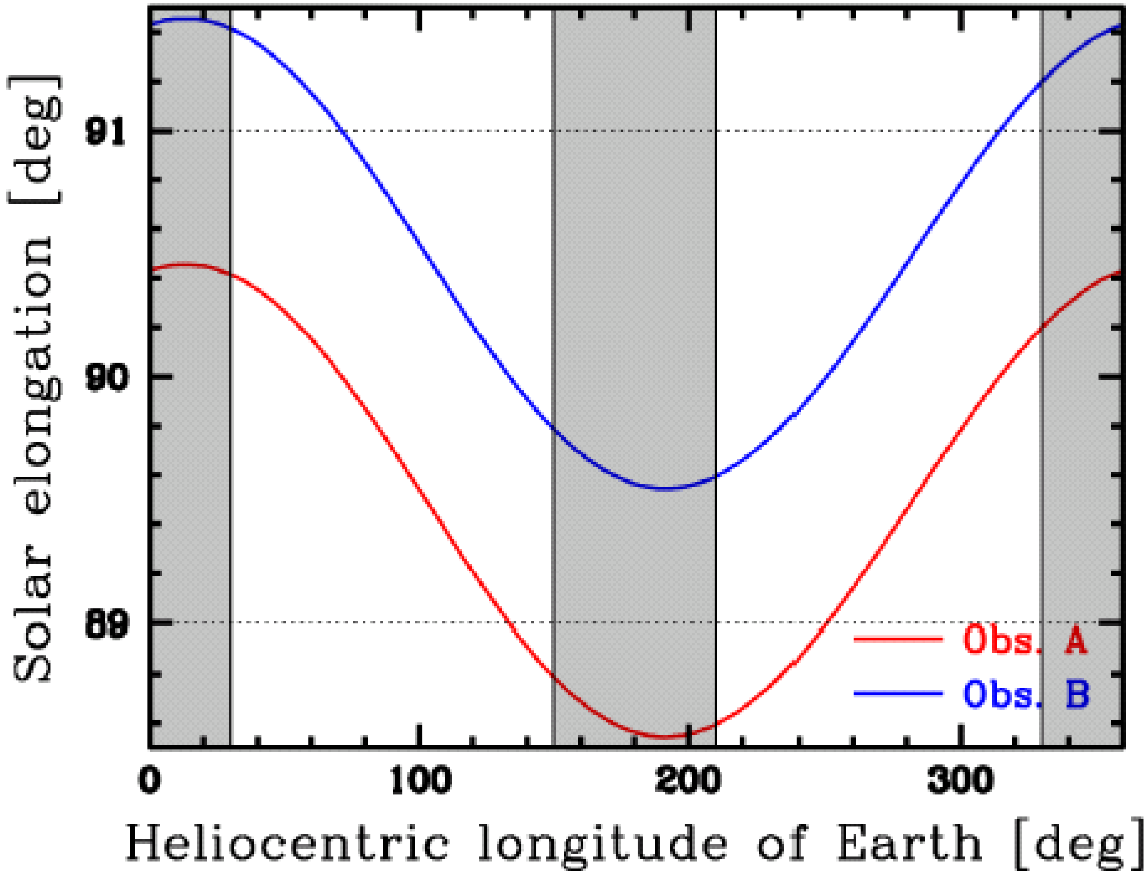
4) FEASIBILITY TEST :

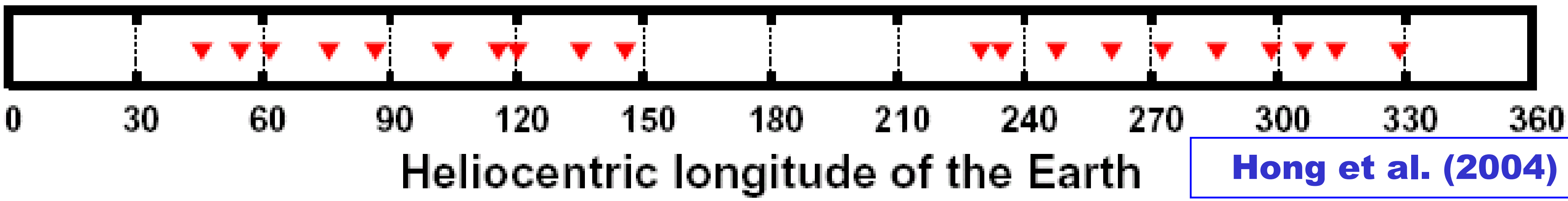
OBSERATIONAL DIFFERENTIATION



Hong et al. (2004)

FEASIBILITY TEST :
OBSERVING SESSIONS

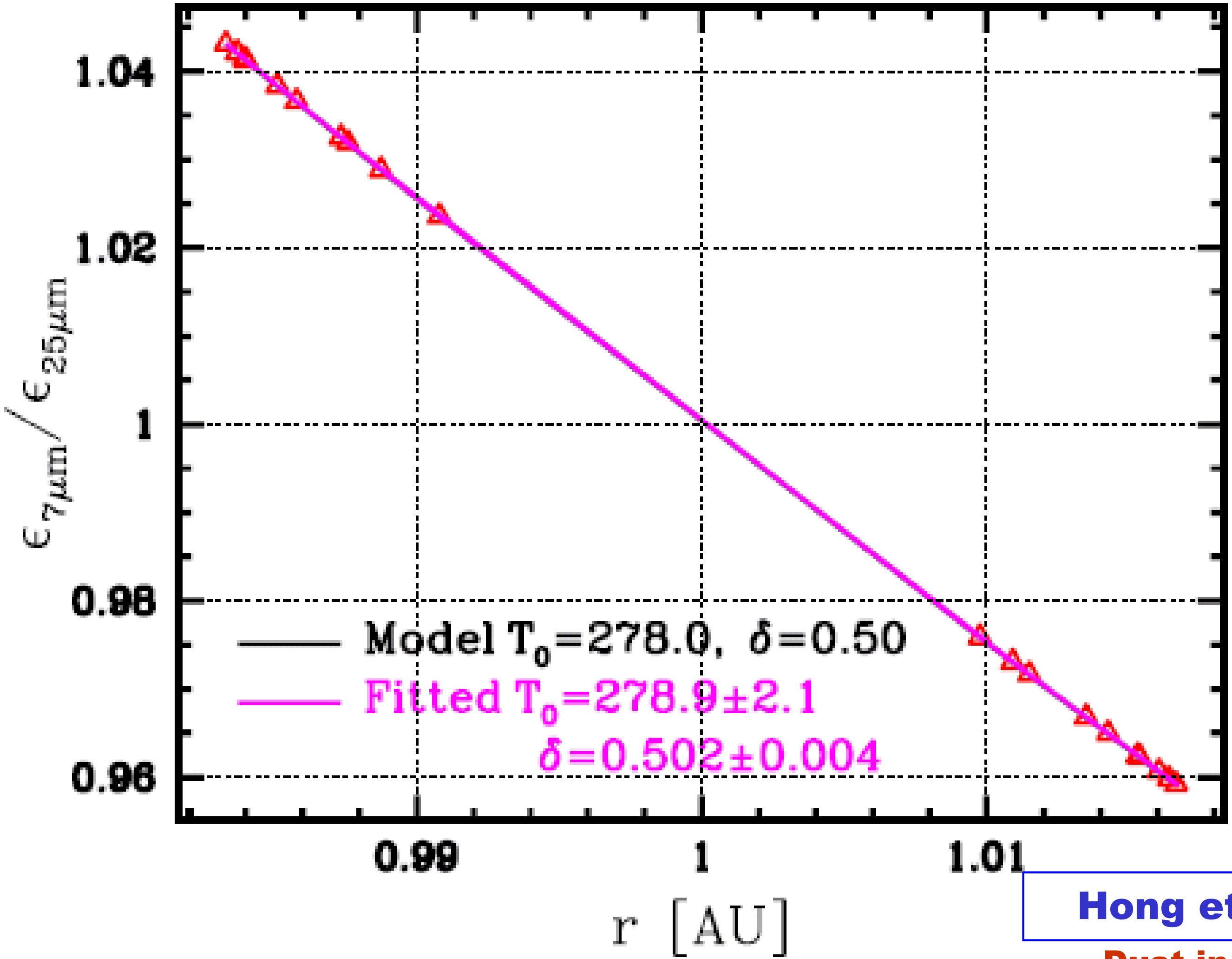




Hong et al. (2004)

FEASIBILITY TEST : Without Imposing Noise

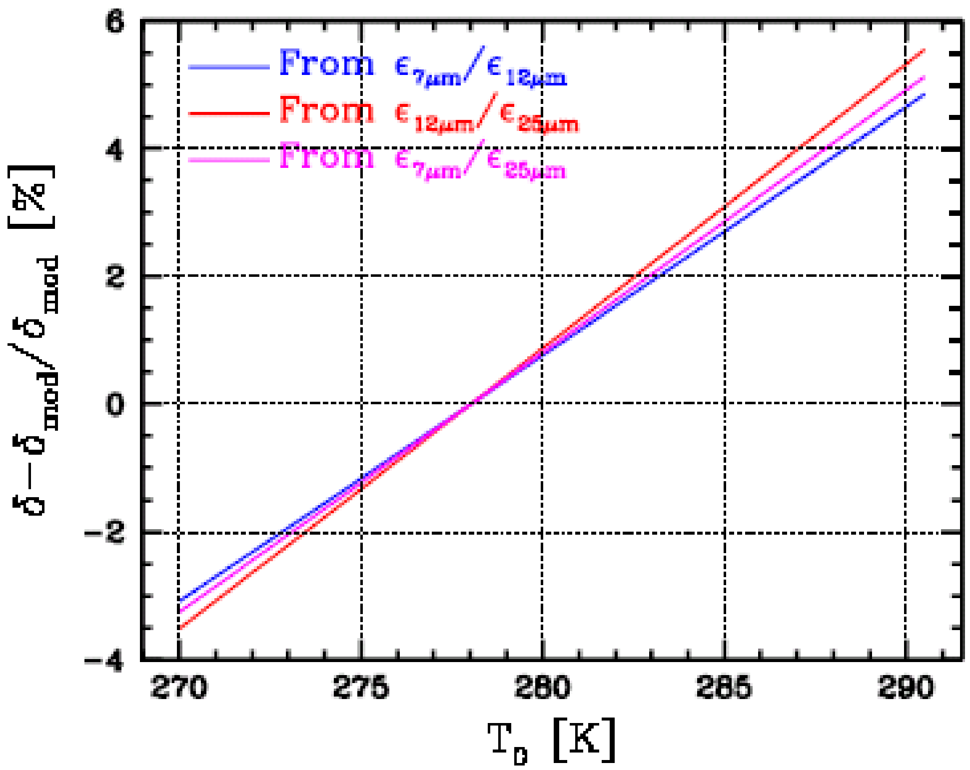
simultaneous measurement of To and delta

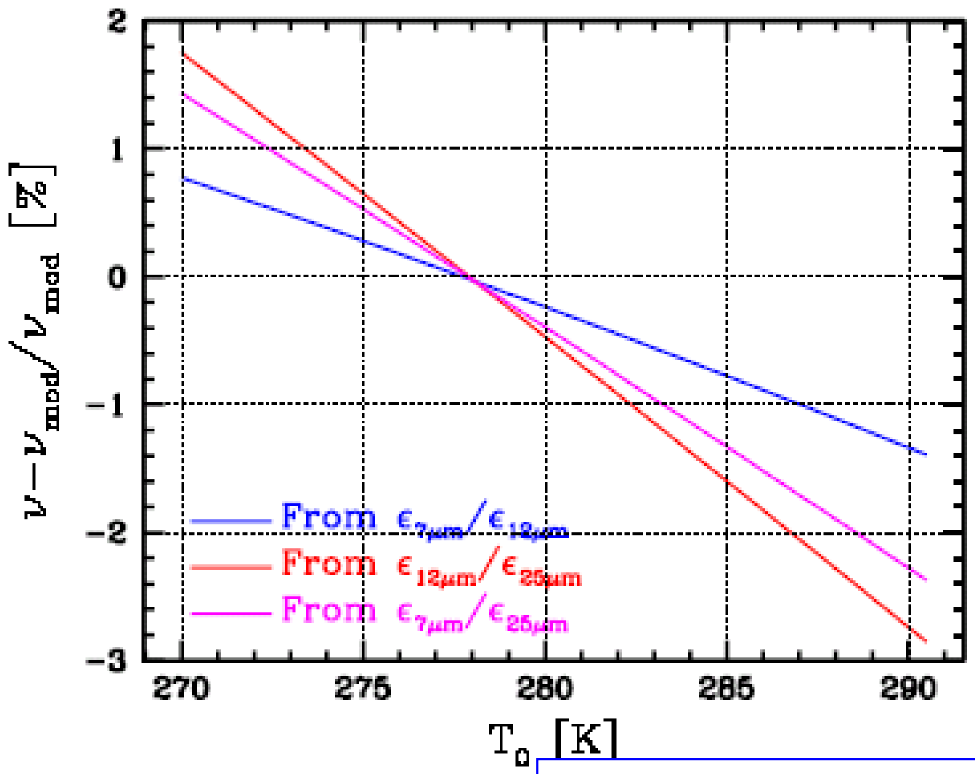


Hong et al. (2004)

FEASIBILITY TEST : Without Imposing Noise

T_o-parameter Approach





Hong et al. (2004)

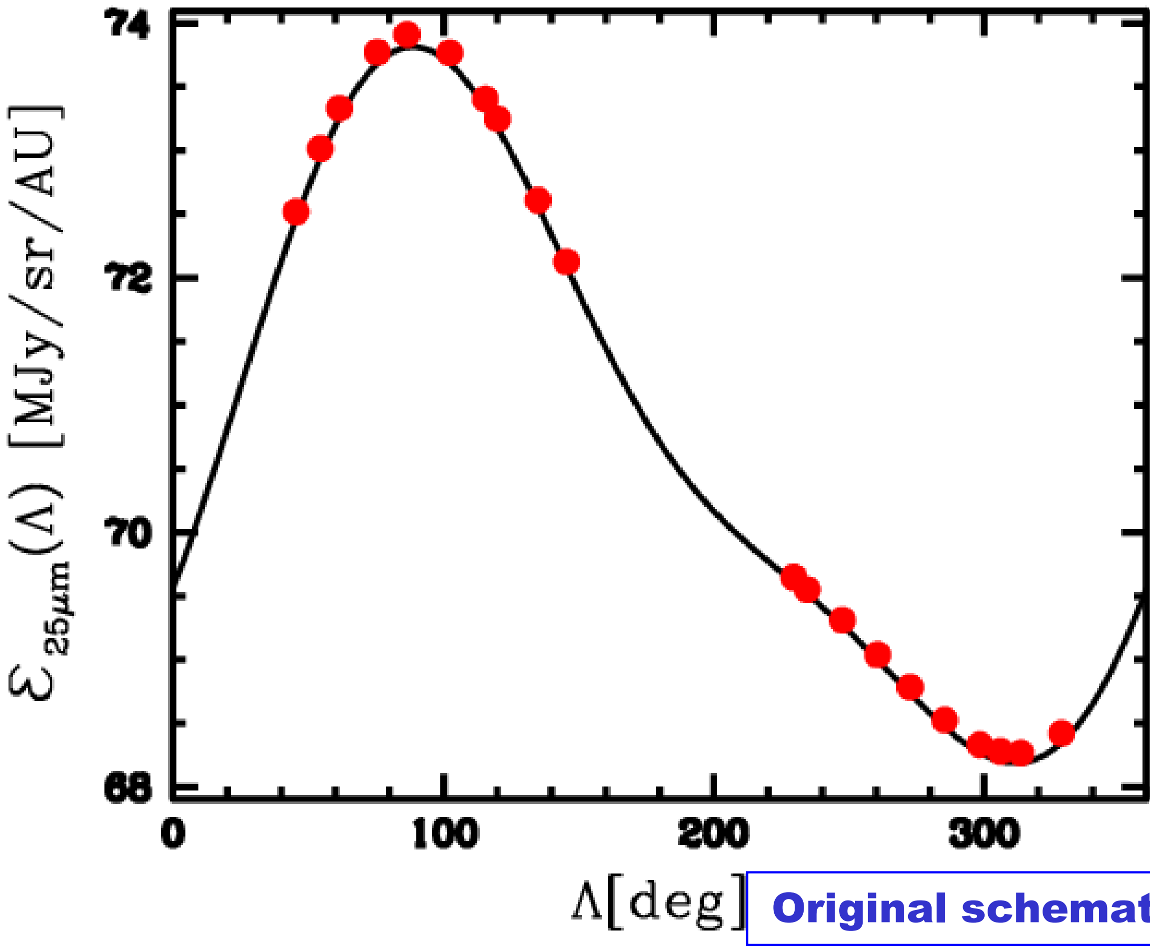
FEASIBILITY TEST : NOISE IMPOSED

Hong et al. (2004)

Table 1 : Zodiacal Emission Brightness and Co-Added Errors

Wavelength [μm]	ZE[1] [MJy/sr]	1σ Error [MJy/sr] 64 × 64 binning	1σ Error [MJy/sr] 128 × 128 binning	ASTRO-F Sensitivity[2] [MJy/sr]
7	26.6	4.75×10^{-4}	1.68×10^{-4}	0.152 (S7 band)
12	37.7	5.91×10^{-4}	2.09×10^{-4}	0.189 (S11 band)
25	84.1	1.41×10^{-3}	5.46×10^{-4}	0.494 (L24 band)

Errors corresponding to the 64x64 binnings are imposed on the ZE brightness itself, from which the differential brightness is formed, and hence we have the emissivity variation like the one shown on the right.

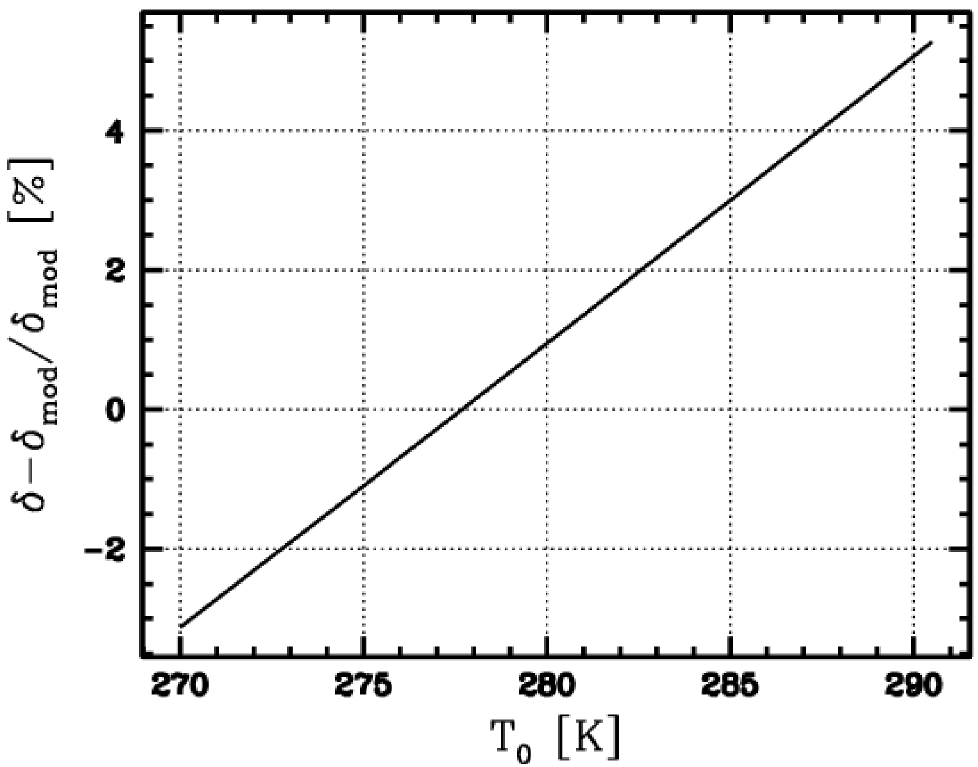


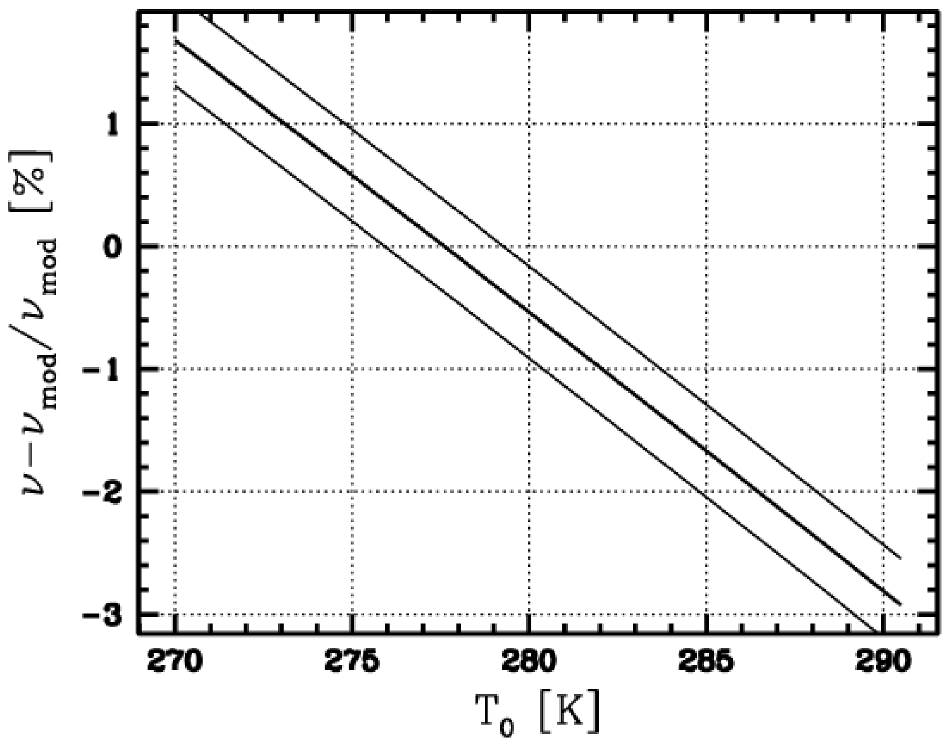
Original schematic

FEASIBILITY TEST : With Noise Imposed

64 x 64 binning, 12 μm/ 25 μm color

T_o-parameter Approach



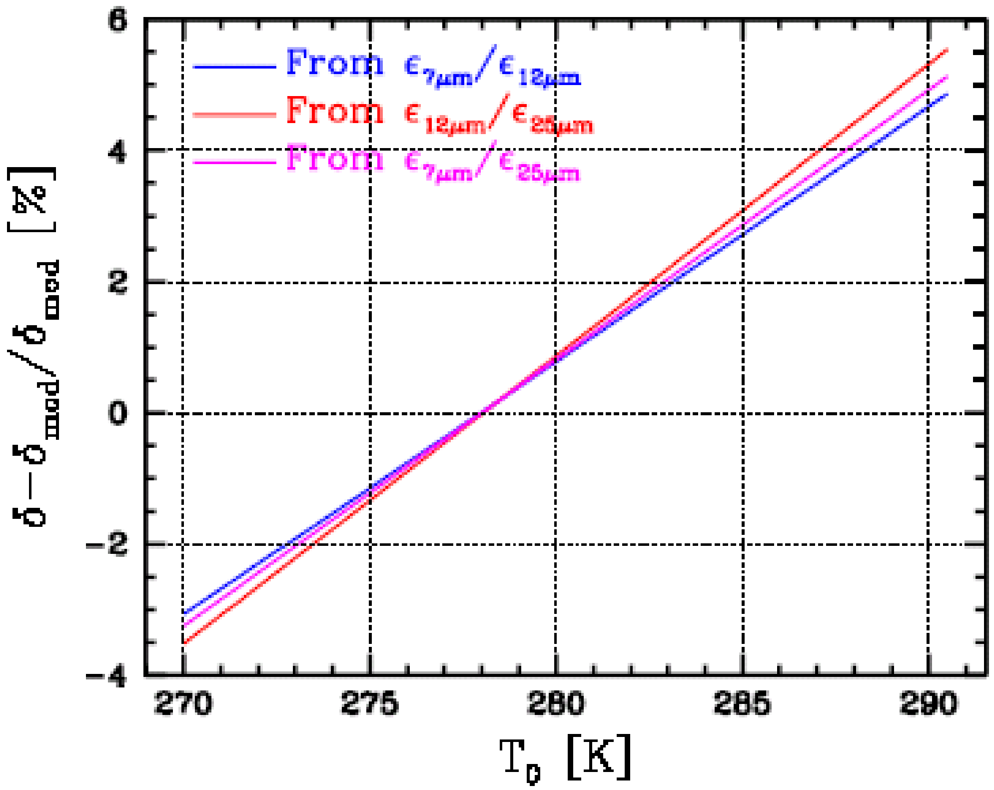


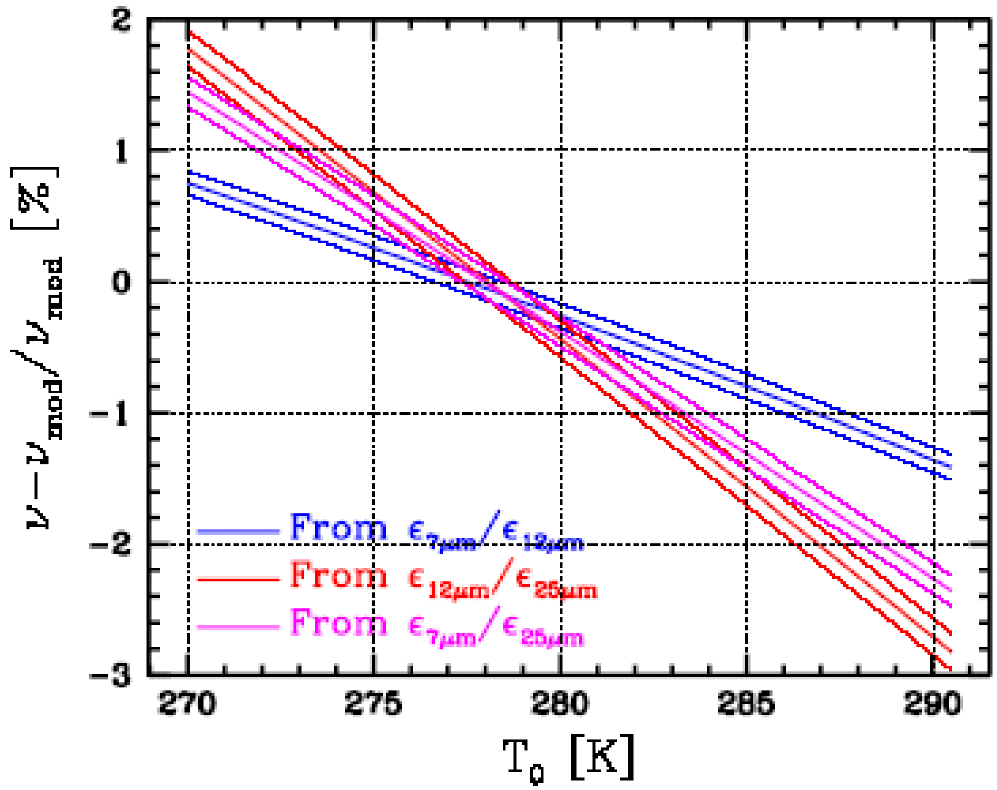
Original schematic

FEASIBILITY TEST ; With Noise Imposed

128 x 128 binning, 7 μm/ 12 μm/ 25 μm color

T_o-parameter Approach





Hong et al. (2004)

FEASIBILITY CONFIRMATION

Hong et al. (2004)

Table 2 : Determination of the Temperature and Density Exponents

	Without imposing noise		With imposing noise	
Wavelength	7 μm	25 μm	7 μm	25 μm
T_o [K]	278.9 ± 2.1		278.0 (fixed)	
δ	0.502 ± 0.004		0.504 ± 0.0002	
α	7.375 ± 0.056	2.364 ± 0.013	7.346	2.375
$\alpha\delta + \nu$	4.698 ± 0.003	2.184 ± 0.003	4.699 ± 0.001	2.185 ± 0.001
ν	0.991 ± 0.042	0.996 ± 0.012	0.996 ± 0.002	0.996 ± 0.001

inputs for model simulations : ν = 1.0, δ = 0.5, T_o = 278 K

- successfully recovered the input data
- wavelength selection for color base is important for success
- the color correction hasn't been made yet
- even 32 x 32 binning might make the analysis possible

5) REALITY OF THE PROMISED LAND

A year long monitoring is necessary to lift degeneracy.

Due to severe limitation in the AKARI's attitude maneuvering, we couldn't have enough number of pointing opportunities; but we have secured observations at both peri- and ap-helion positions.

Currently, efforts are underway to improve AKARI calibrations for diffuse source light; with the improved calibration, we expect to measure the local IPD emissivities for the first time.

Chap 3. VERTICAL INVERSION

1) PREVIOUS STUDIES

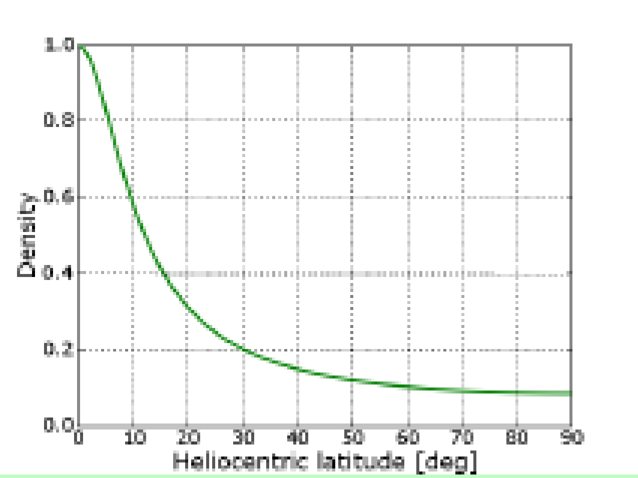
Distribution of dust particles

$$n(\mathbf{r}) = n_0 \left[\frac{r}{1\,\mathrm{AU}}\right]^{-\nu} f(\beta_{\mathrm{sym}})$$

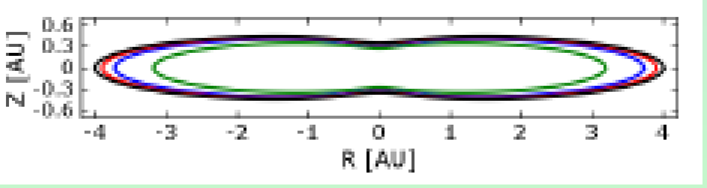
- Fitting to the observed vertical profiles of zodiacal light or zodiacal emission with models:
  - Ellipsoid model [Giese and Dziembowski 1969]

$$f(\beta') = \left[1 + (6.5 \sin \beta')^2\right]^{-0.65}$$

Plot of function



Shape of IPD cloud

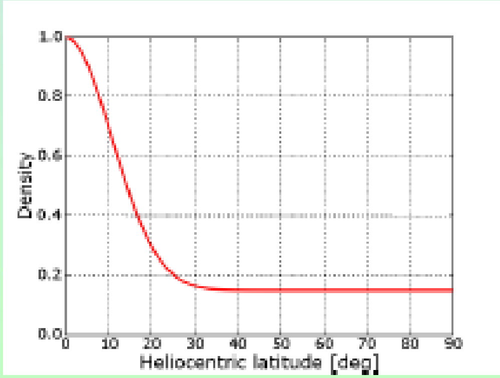


Original schematic

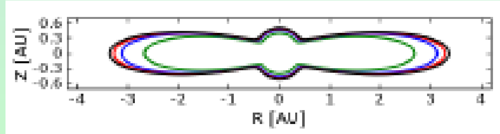
- Fitting to the observed vertical profiles of zodiacal light or zodiacal emission with models:
  - Cosine model [Rittich 1986]

$$f(\beta') = 0.15 + 0.85\cos^{28}\beta'$$

Plot of function



Shape of IPD cloud

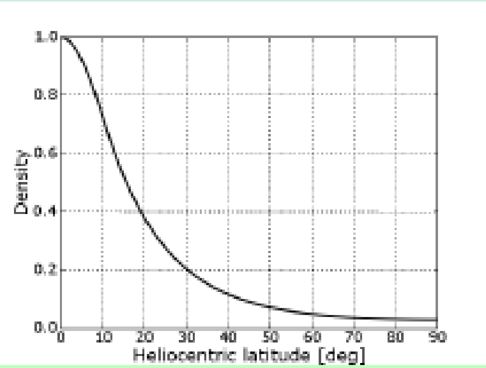


Original schematic

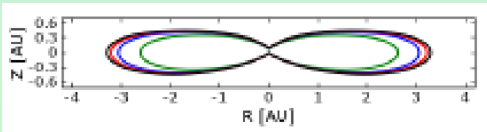
- Fitting to the observed vertical profiles of zodiacal light or zodiacal emission with models:
  - Kelsall *et al.*'s model [Kelsall et al. 1998]

$$f(\beta') = e^{-3.90g}\ ;\ g = \begin{cases} \sin^2\beta'/0.378 & \text{for } \sin\beta' < 0.189 \\ |\sin\beta'| - 0.0945 & \text{for } \sin\beta' \geq 0.189 \end{cases}$$

Plot of function



Shape of IPD cloud

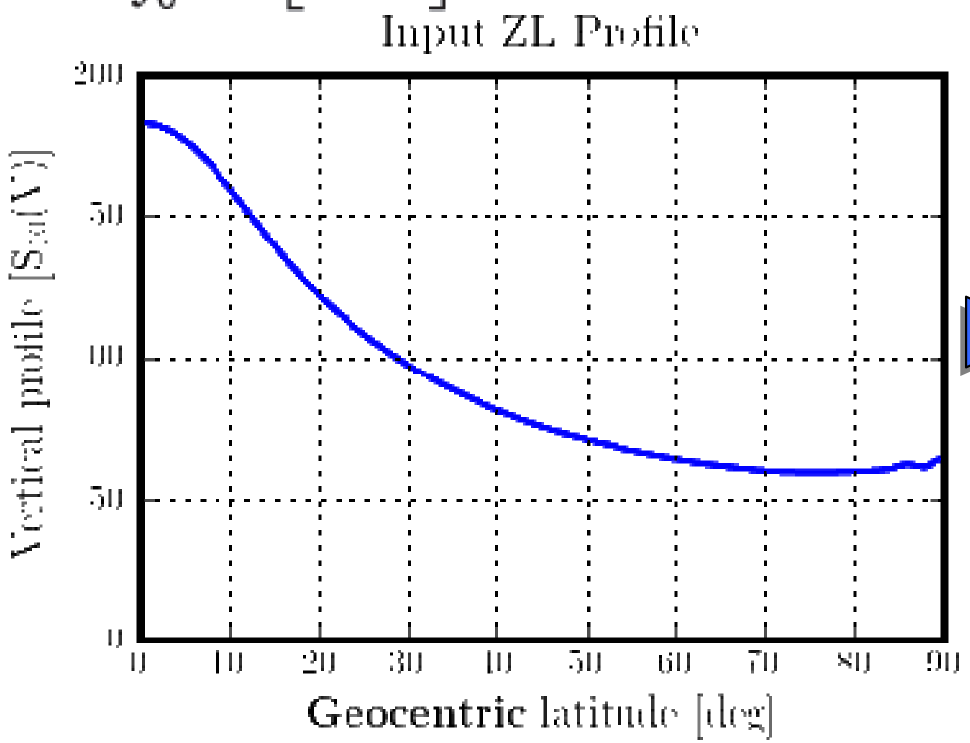


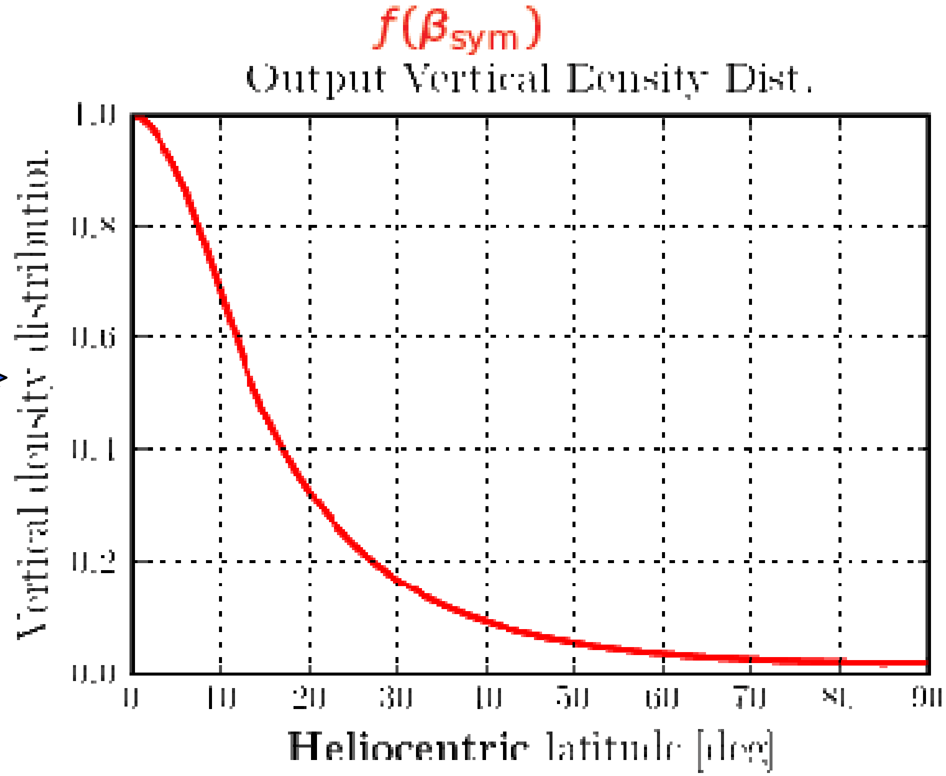
Original schematic

The resulting vertical profile is controlled by the imposed function itself.

▸ **Inversion** of brightness integrals

$$\mathrm{ZL}(\beta) = \int_0^\infty F_0 \left[\frac{1\,\mathrm{AU}}{r}\right]^2 n(r)\, f(\beta_{sym})\, \sigma_{sca} \Phi(\Theta)\, dl$$



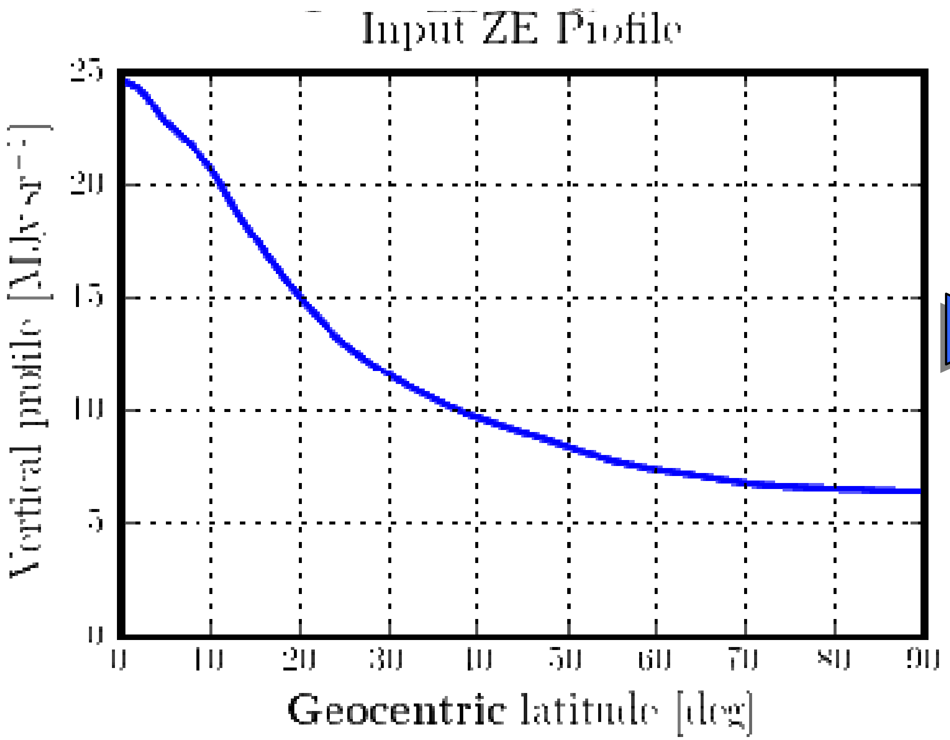


Original schematic

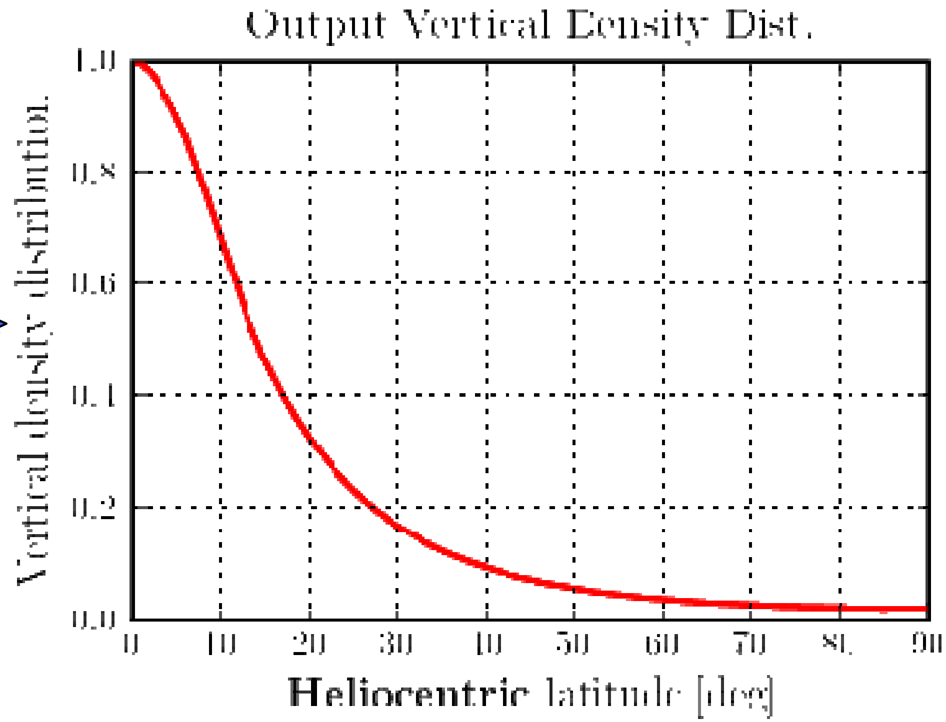
$\Lambda - \Lambda_\odot$: **is fixed at 90° .**

▸ **Inversion** of brightness integrals

$$\mathrm{ZE}(\beta) = \int_0^{\infty} n(r)\, f(\beta_{sym})\, \sigma_{abs} B_{\lambda}[T(r)]\, dl$$



$f(\beta_{sym})$



Original schematic

$\Lambda - \Lambda_{\odot}$ **is fixed at 90°.**

- **Brightness integrals with $\beta_\odot$ as integration variable**

$$\mathrm{ZL}(\beta) = \frac{F_0 n_0 \sigma_{\mathrm{sca},0} \cdot (1\,\mathrm{AU})}{\sin\beta} \int_0^{\sin\beta} \sin^{\nu_s - 1}\Theta\, \Phi(\Theta) f(\sin\beta_\odot)\, d\sin\beta_\odot$$

$$\mathrm{ZE}_\lambda(\beta) = \frac{n_0 \sigma_{\mathrm{abs},\lambda,0} \cdot (1\,\mathrm{AU})}{\sin\beta} \int_0^{\sin\beta} \sin^{\nu_a - 3}\Theta\, B_\lambda\left(T_0 \sin^\delta\Theta\right) f(\sin\beta_\odot)\, d\sin\beta_\odot$$

where $\cos\Theta = -\sin\beta_\odot / \sin\beta$.

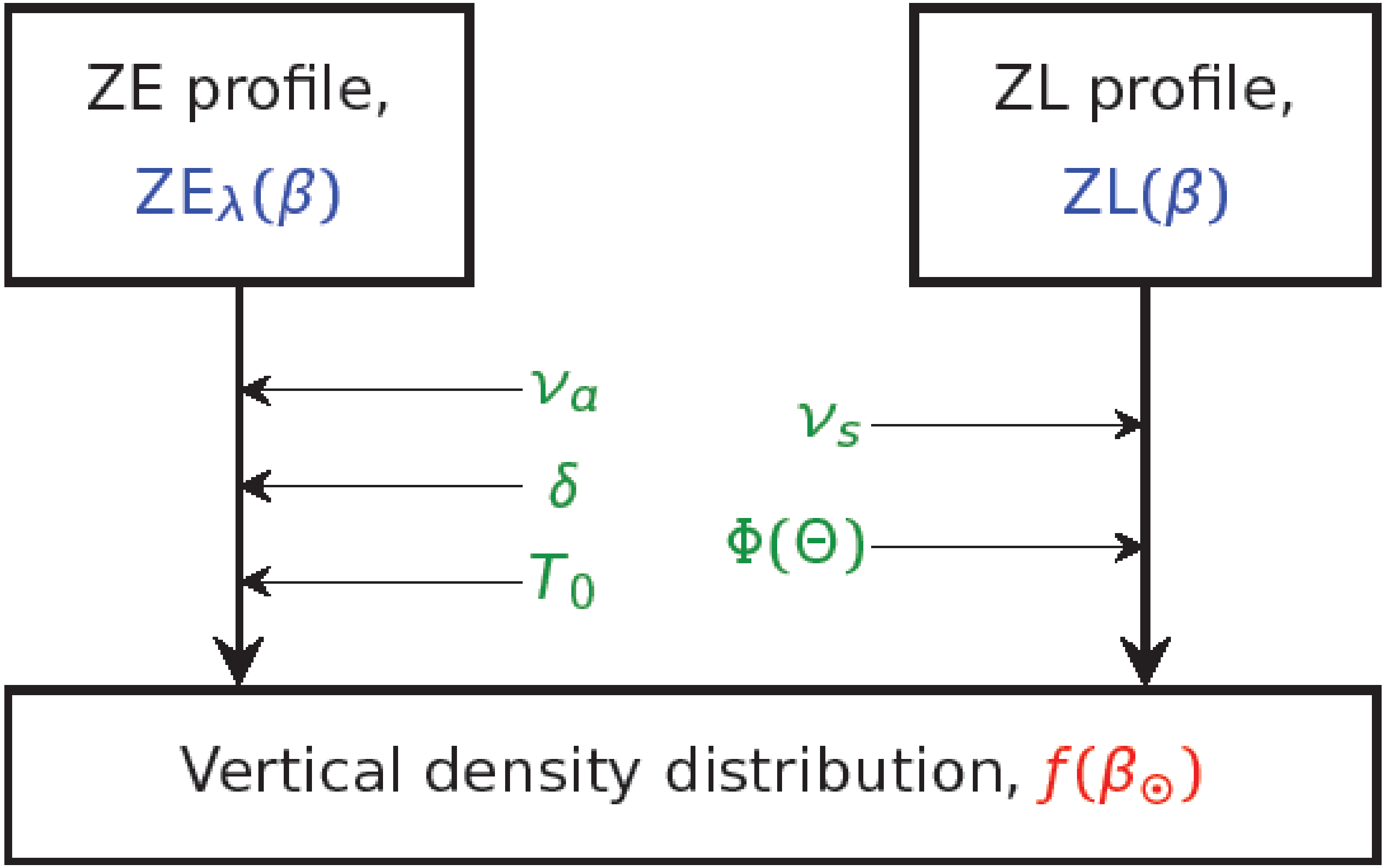
- **Volterra integral equations of the first kind**

$$g(t) = \int_0^t k(t, s) f(s)\, ds$$

where $t \equiv \sin\beta$ and $s \equiv \sin\beta_\odot$ with $t_{max} = 1$.

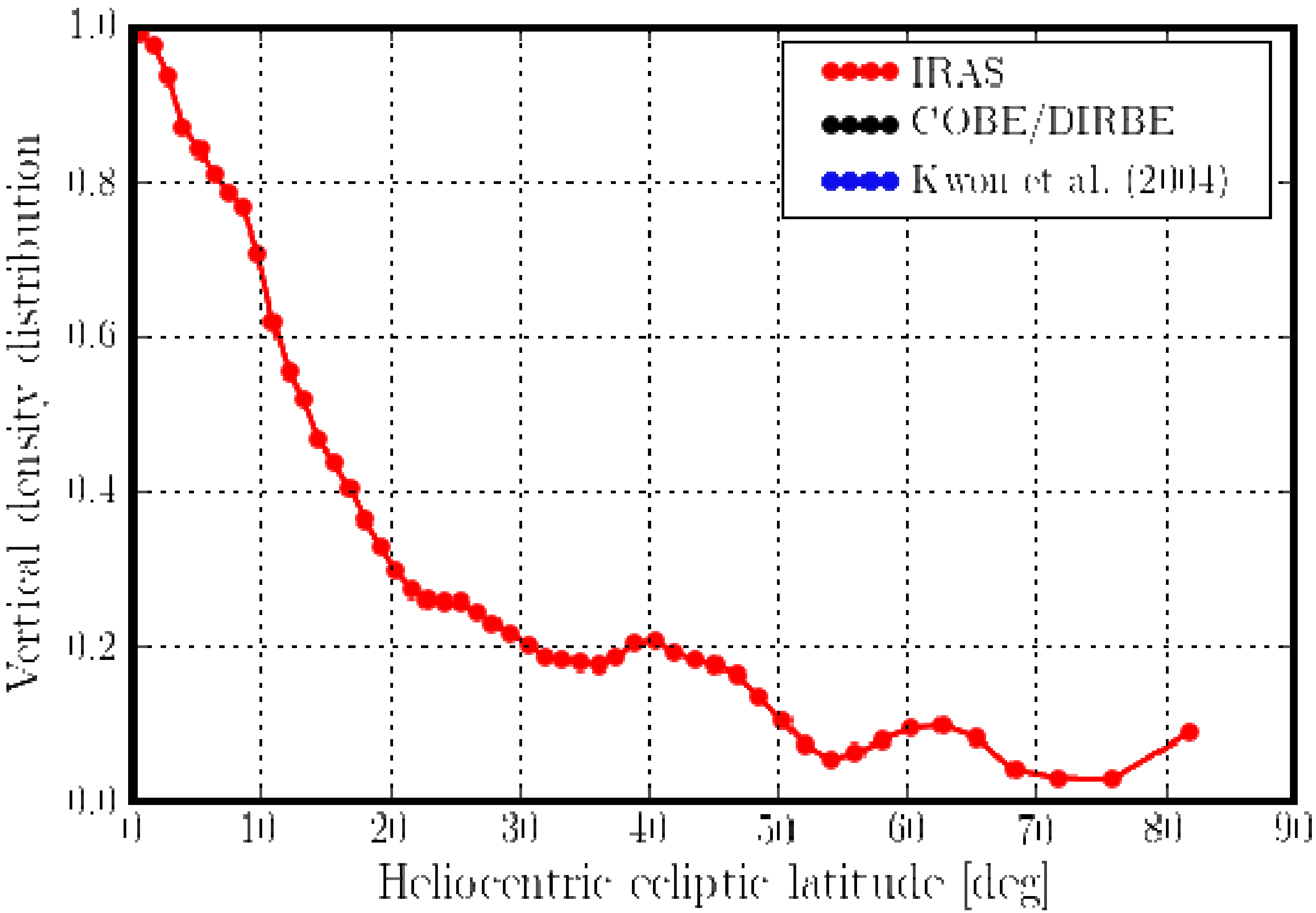
Replacing the integral by quadrature sum, one may construct a triangular system of simultaneous linear equations.

Summary



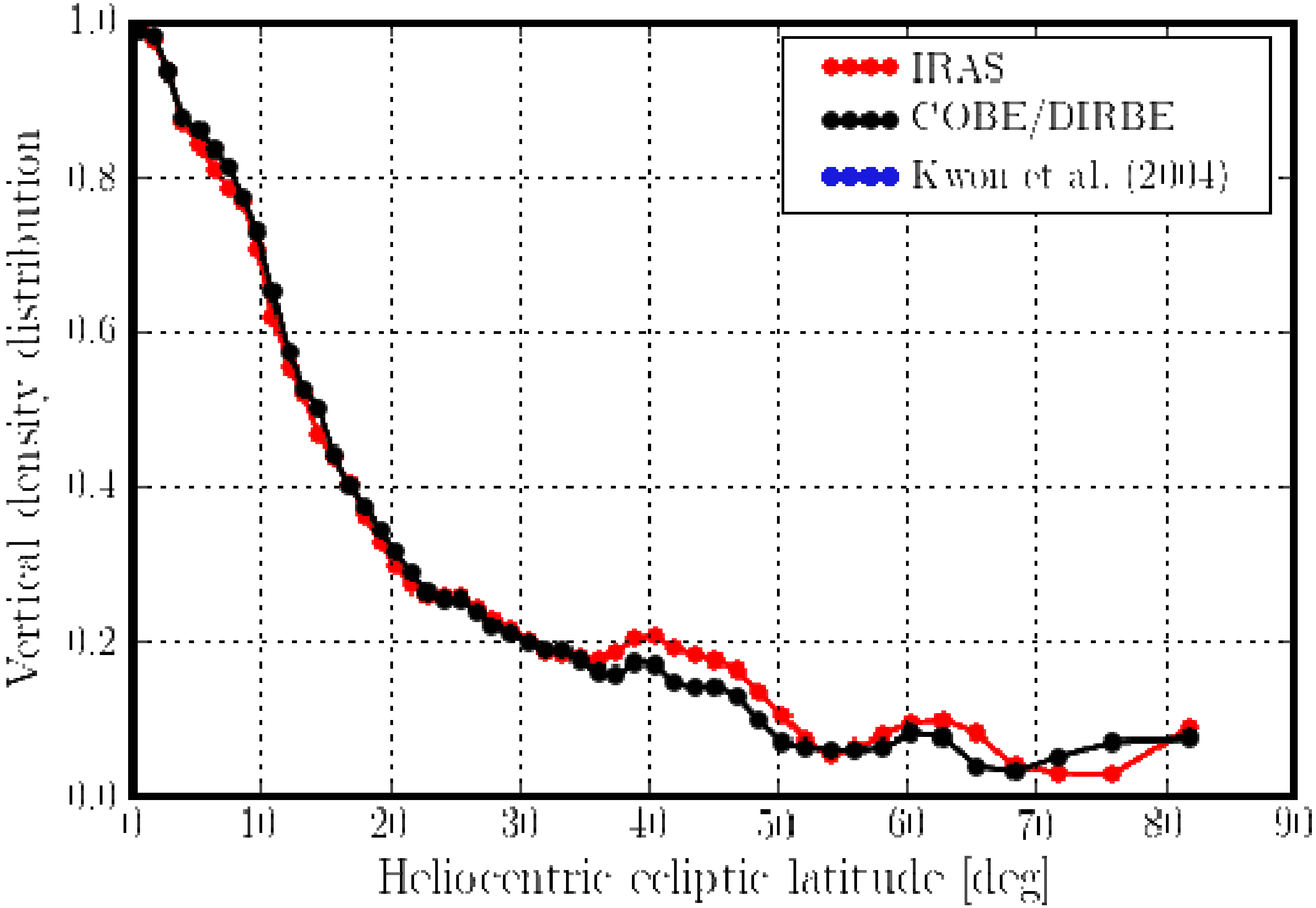
ZE profile,
$ZE_\lambda(\beta)$
ZL profile,
$ZL(\beta)$
ν_a
δ
T_0
ν_s
$\Phi(\Theta)$
Vertical density distribution, $f(\beta_\odot)$

3) RESULTS AND COMPARISON



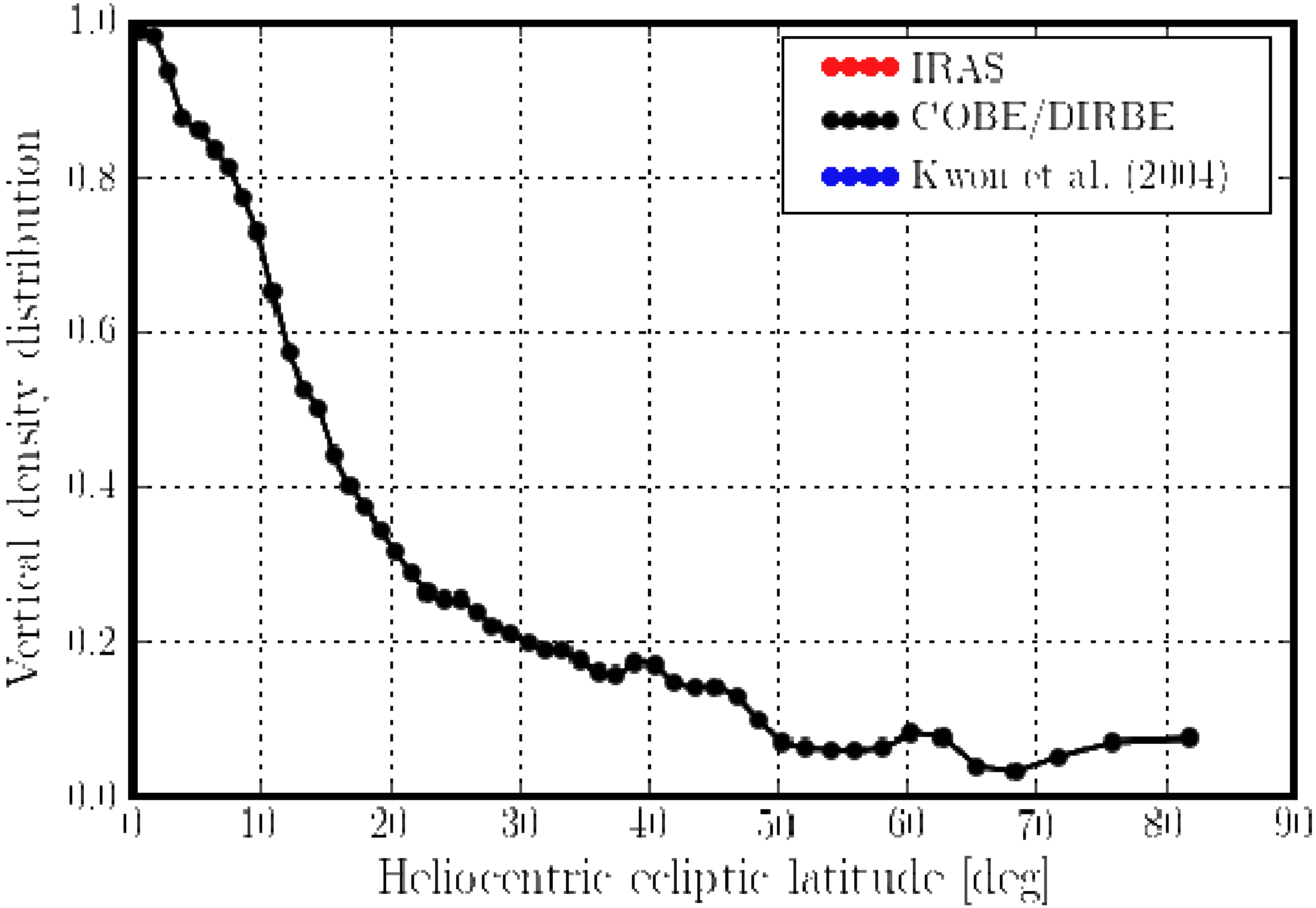
Pyo et al. (2009), submitted

3) RESULTS AND COMPARISON



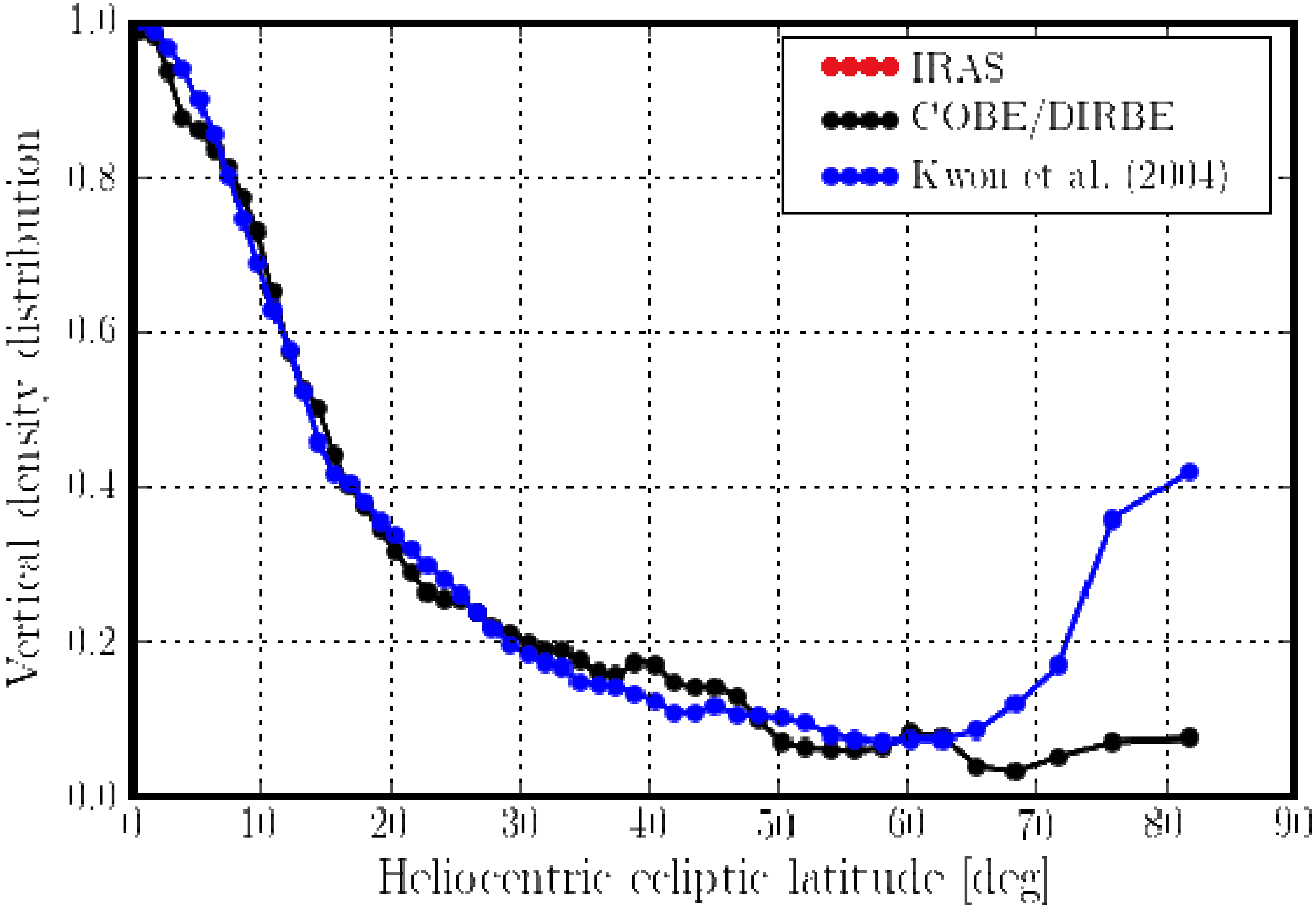
Pyo et al. (2009), submitted

3) RESULTS AND COMPARISON



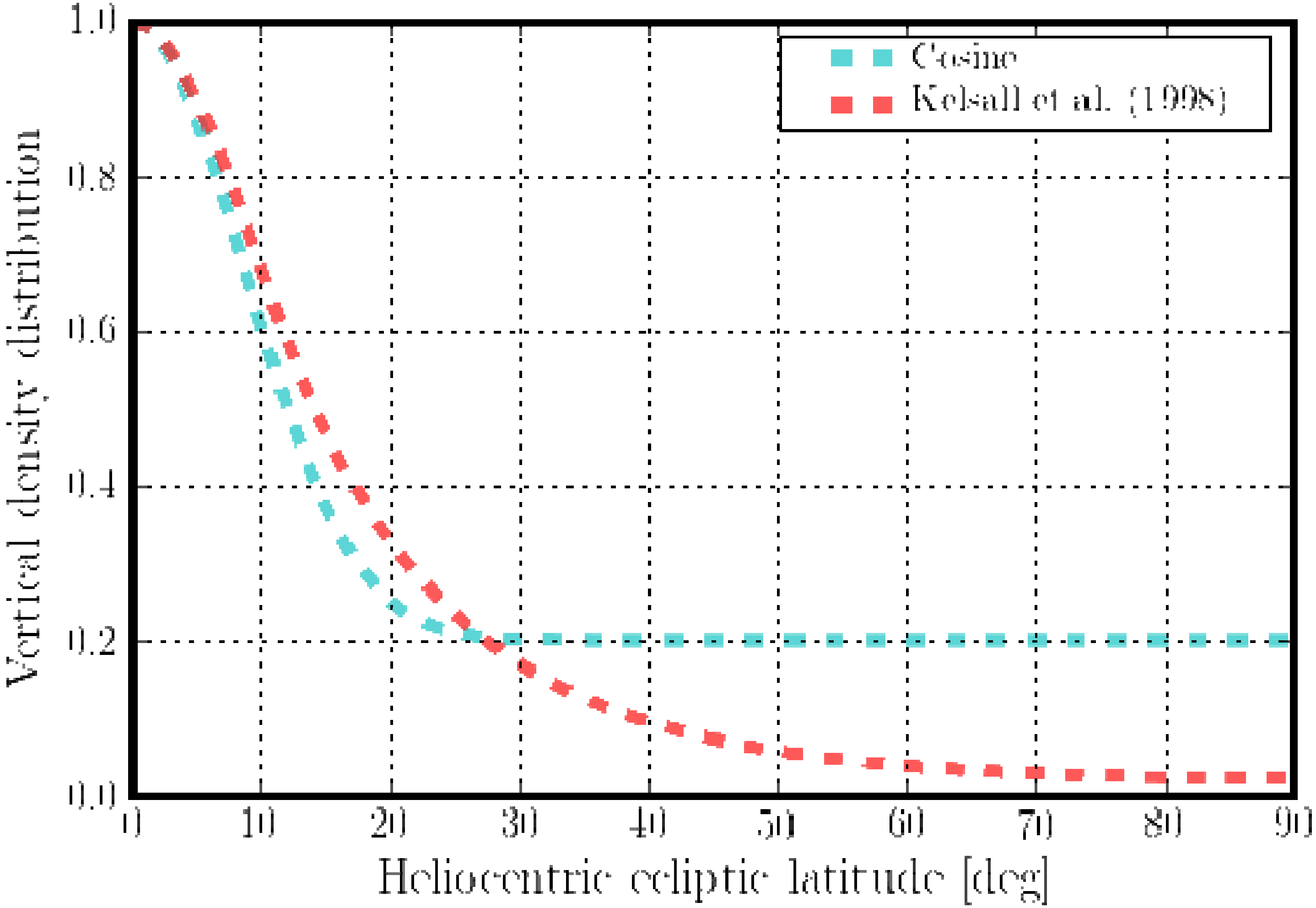
Pyo et al. (2009), submitted

3) RESULTS AND COMPARISON



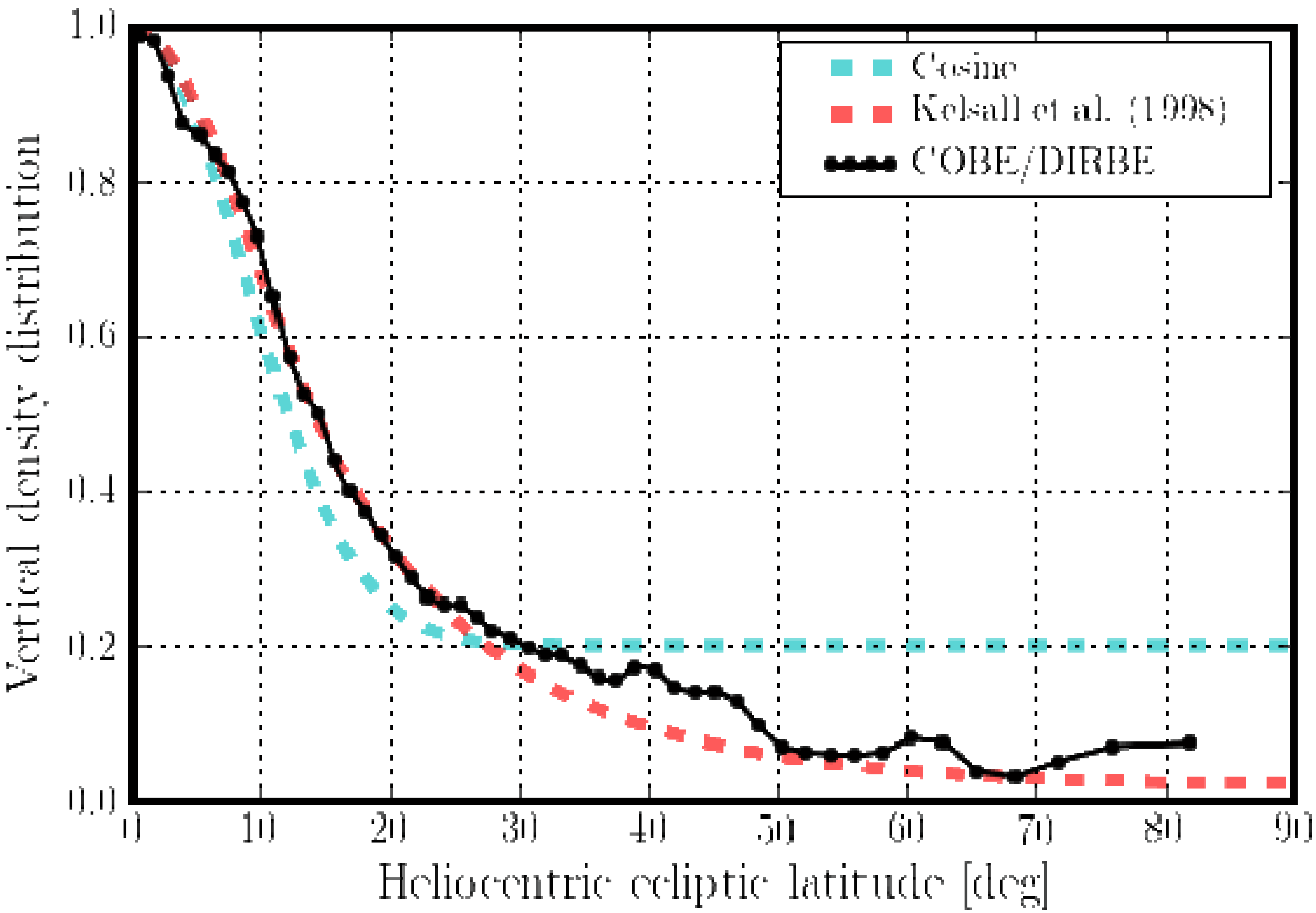
Pyo et al. (2009), submitted

3) RESULTS AND COMPARISON



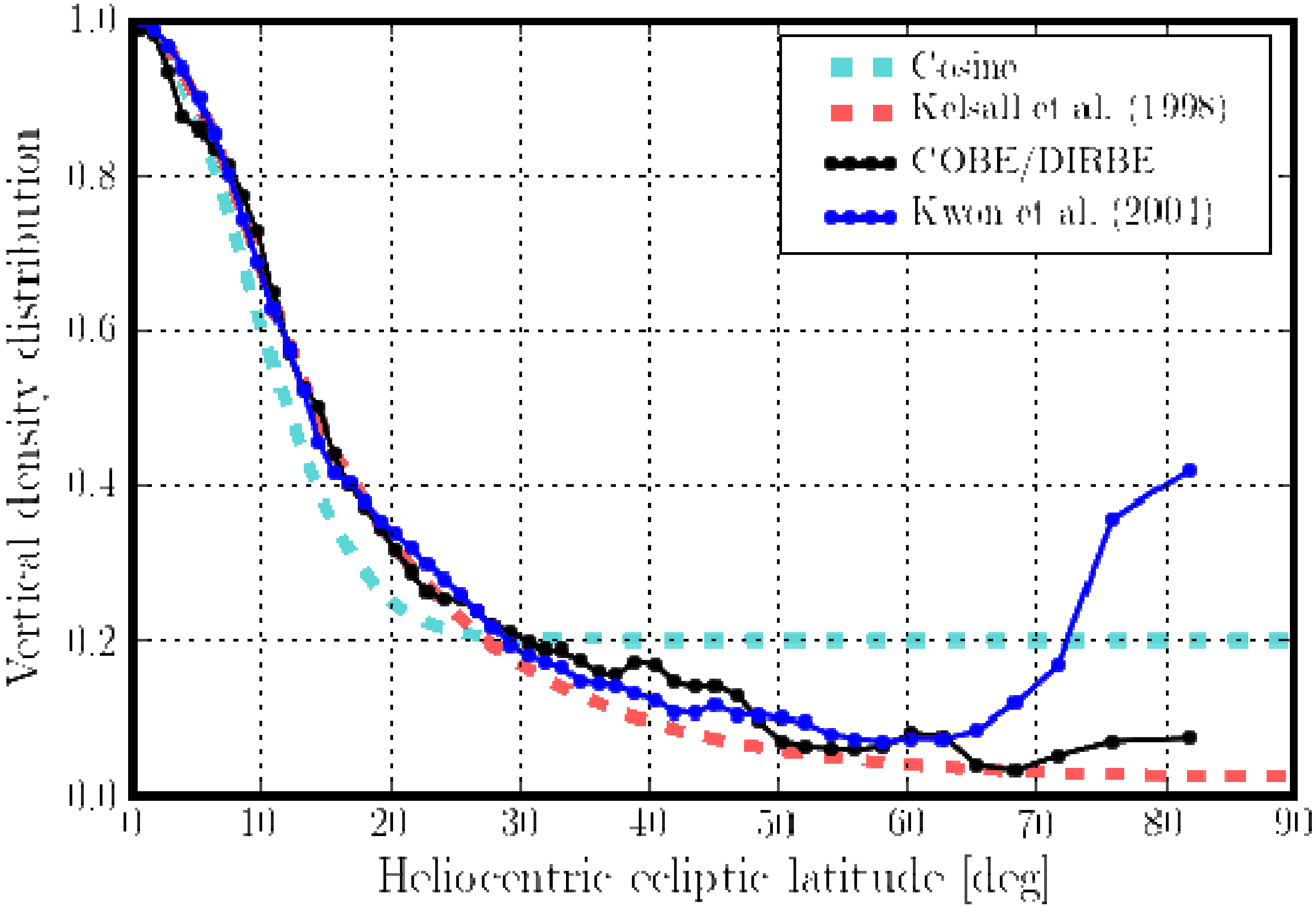
Pyo et al. (2009), submitted

3) RESULTS AND COMPARISON



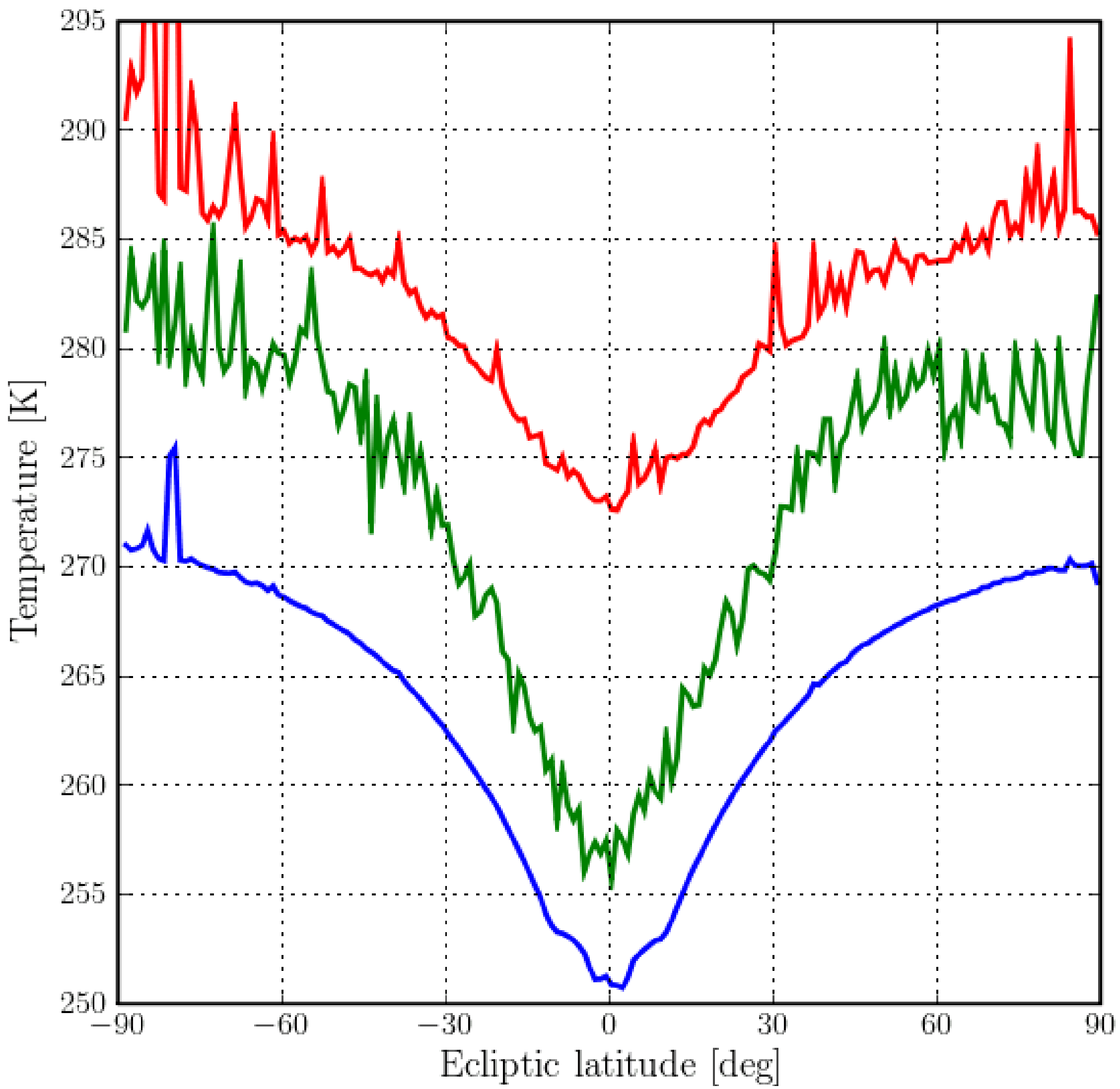
Pyo et al. (2009), submitted

3) RESULTS AND COMPARISON



Pyo et al. (2009), submitted

4) COLOR PROFILE OF ZE OVER LATITUDE Beta



COBE/ DIRBE

4.9 μm - 12 μm

AKARI/ IRC

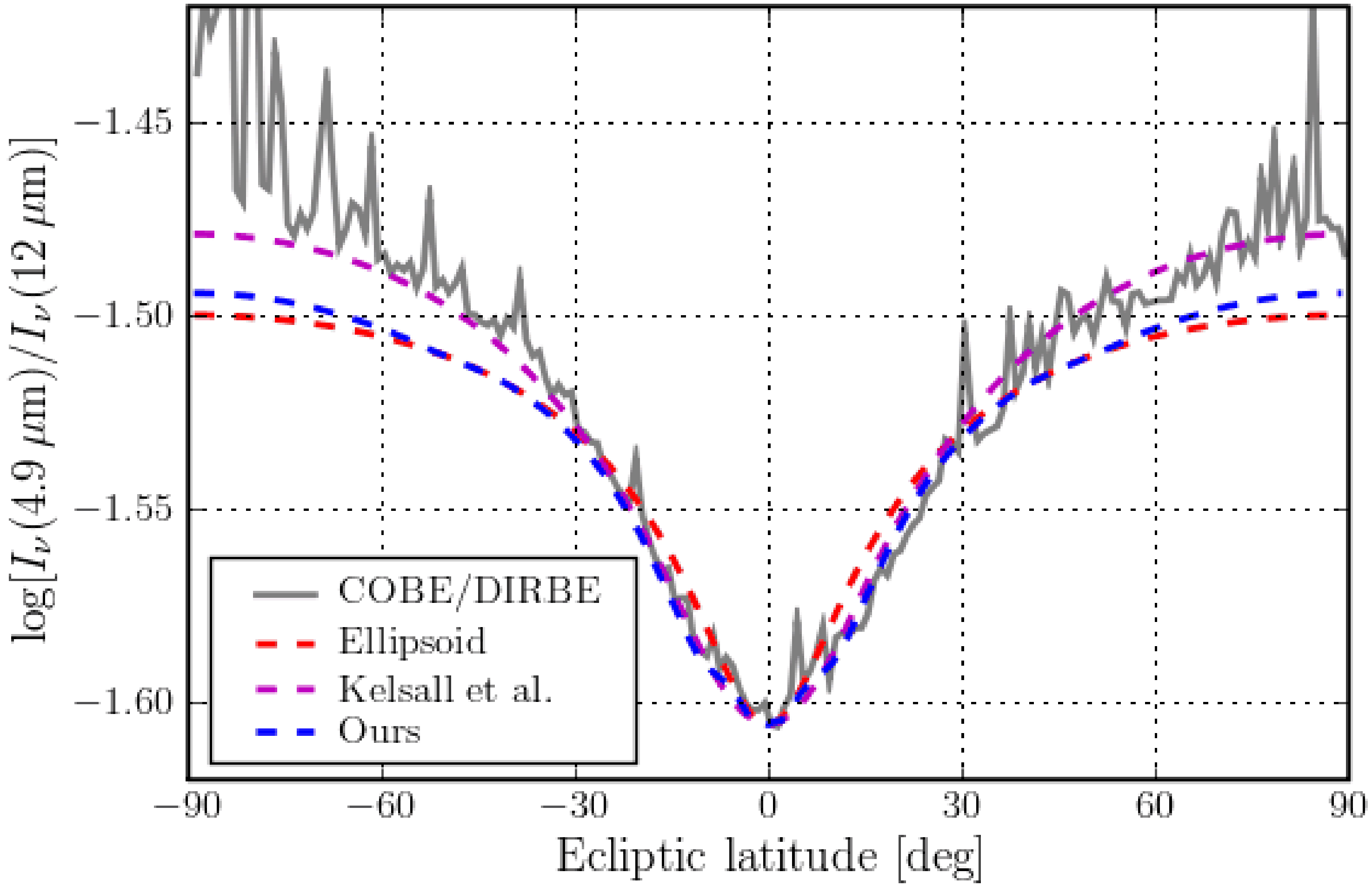
9 μm - 18 μm

COBE/ DIRBE

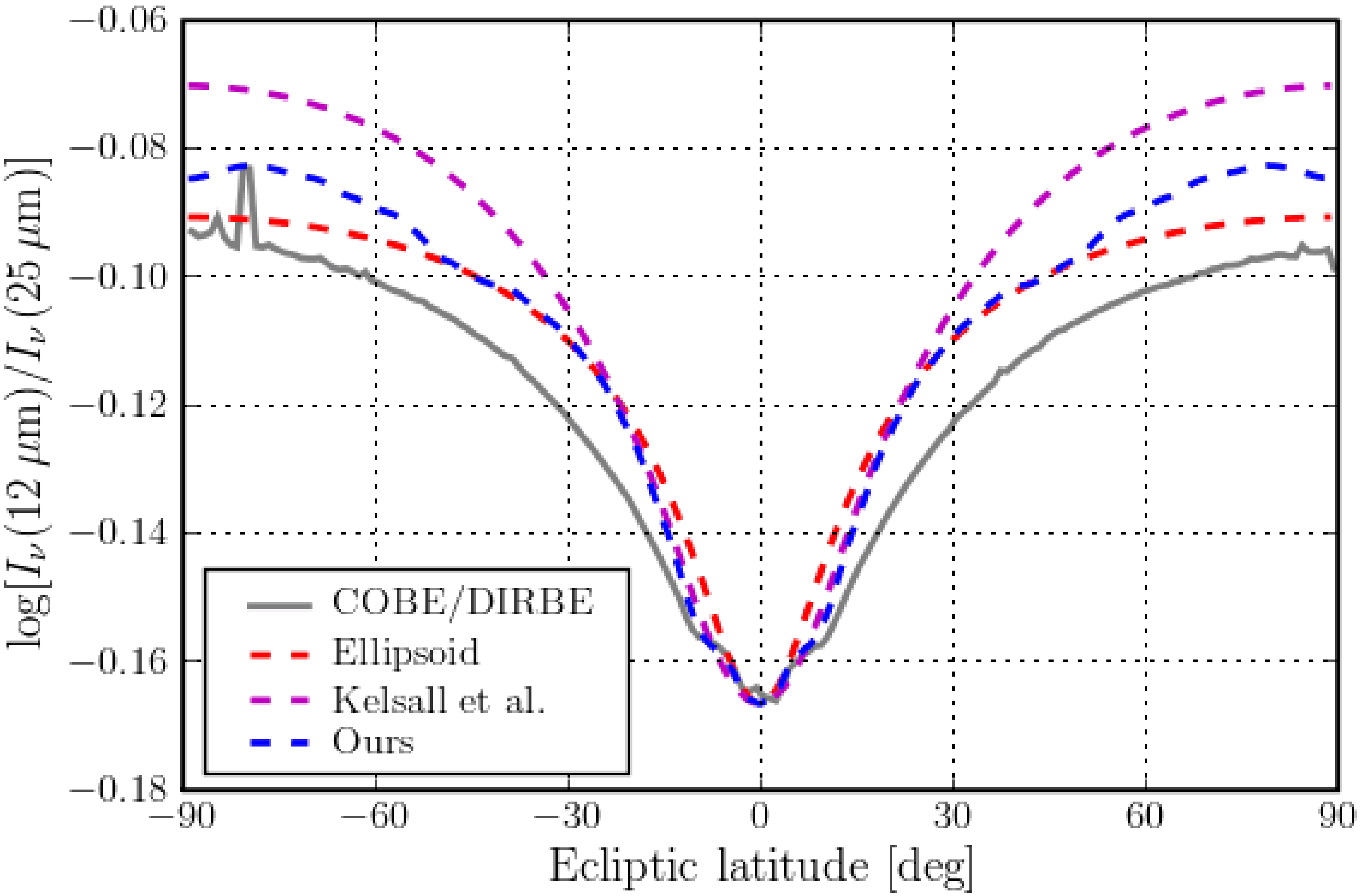
12 μm - 25 μm

Pyo et al. (2009), submitted

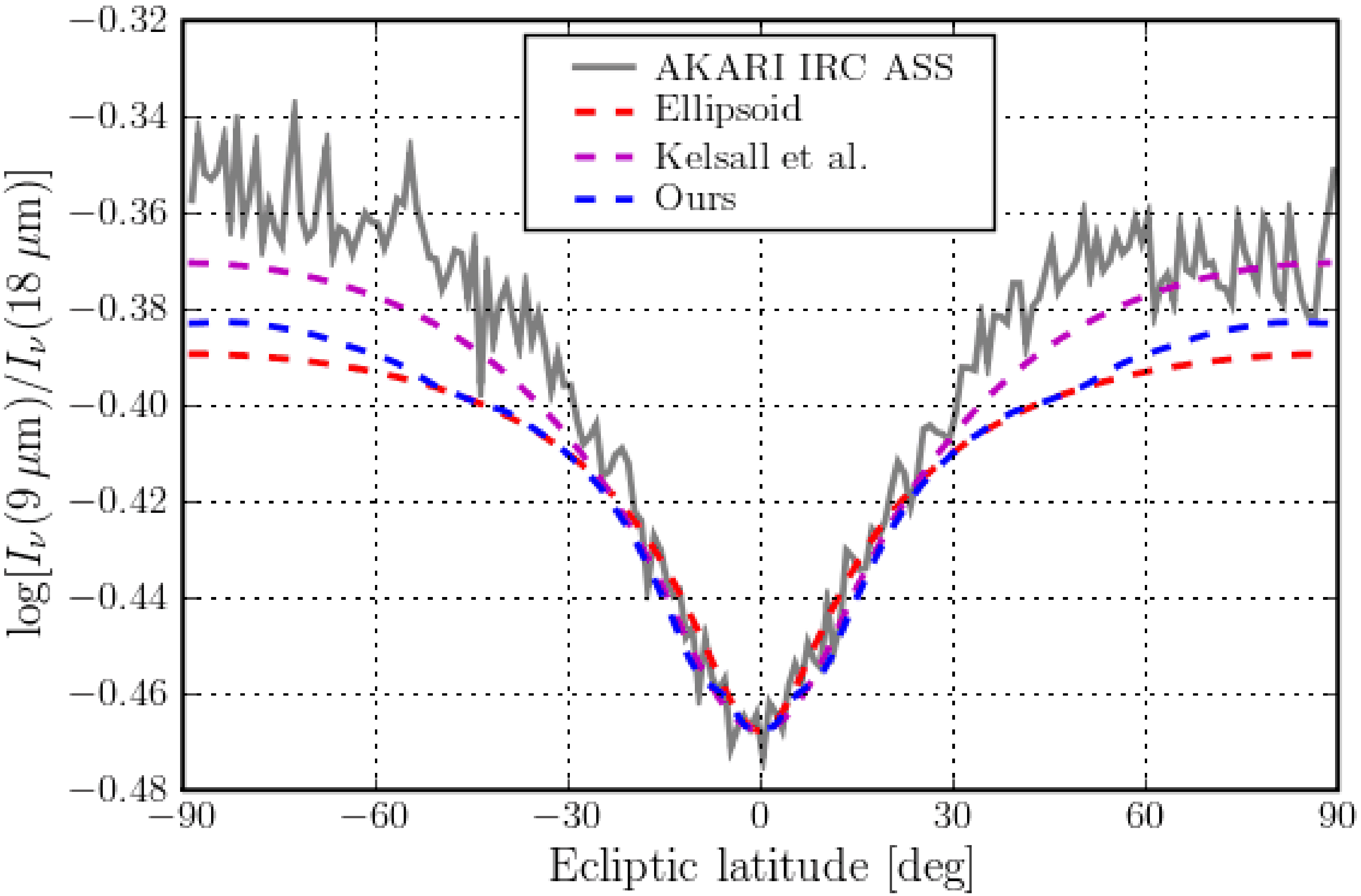
⇒ **Can we understand the beta-dependence of color temperature with the single component model ?**



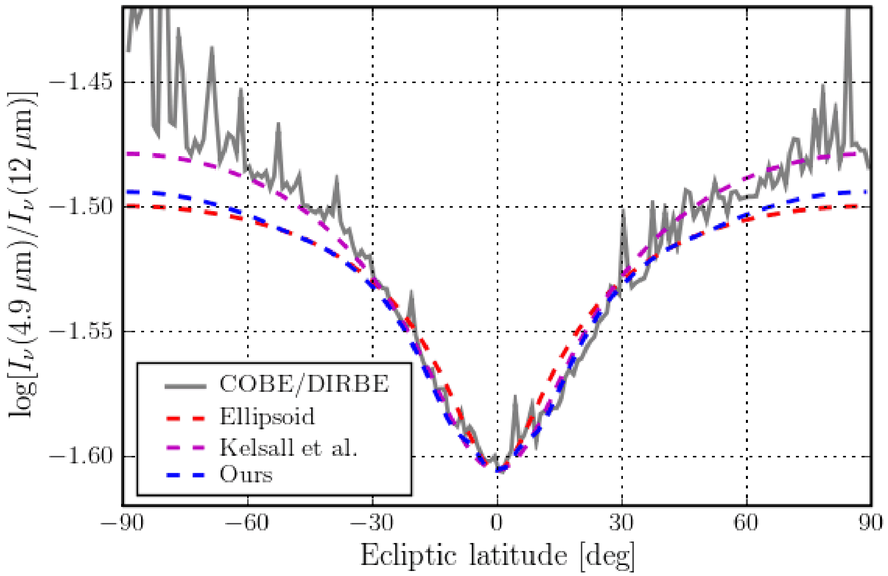
Pyo et al. (2009), submitted

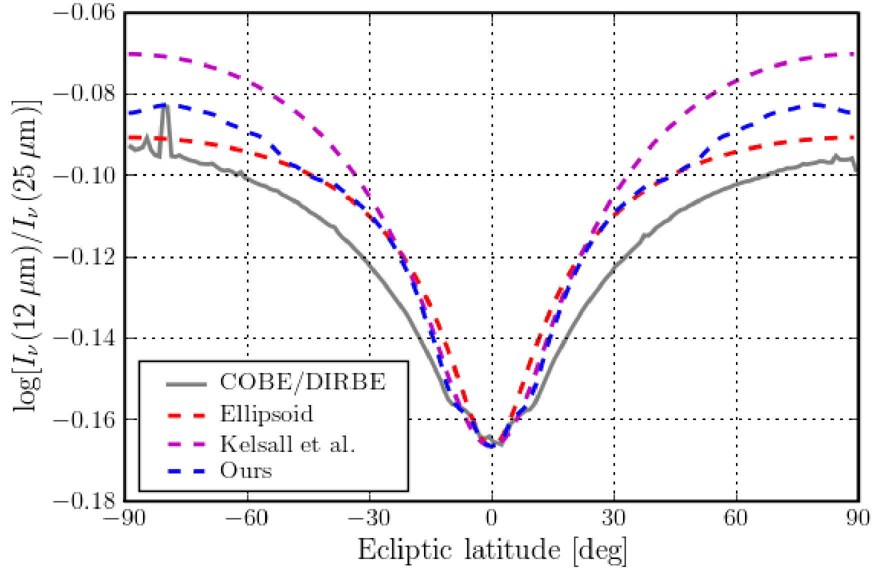


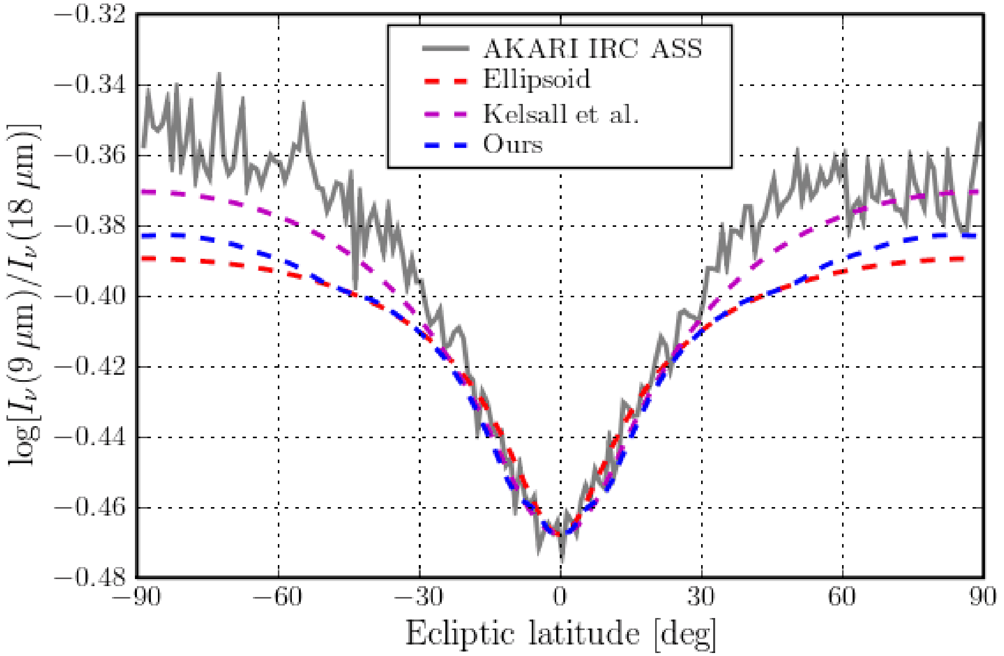
Pyo et al. (2009), submitted



Pyo et al. (2009), submitted







Pyo et al. (2009), submitted

The single component model has failed to reproduce the observed color profile of ZE over ecliptic latitude. This is an example of its many failures though.

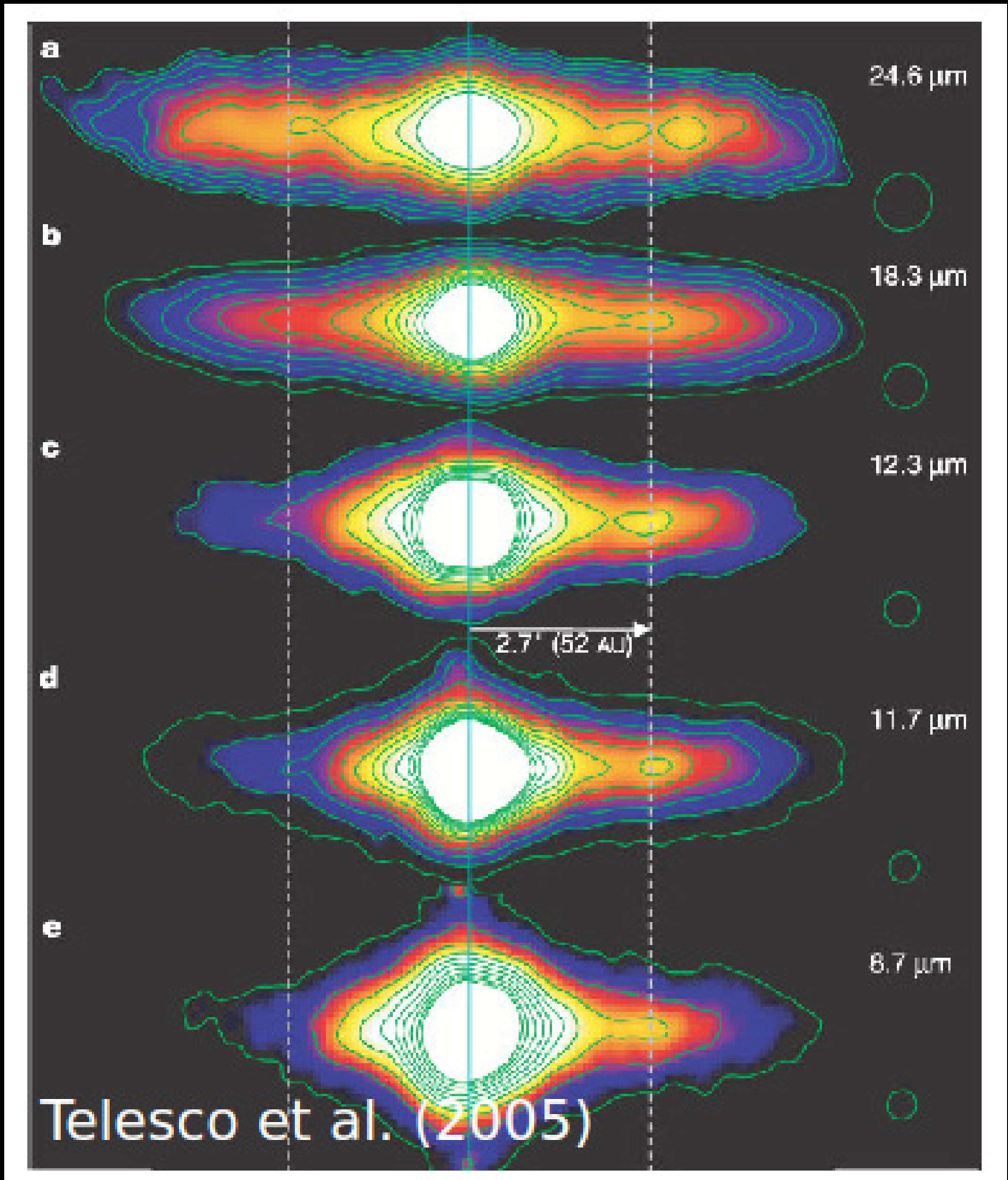
5) HOW DOES THE IPD CLOUD LOOK LIKE?

It does depend on the wavelength used.

- **The IPD cloud revealed by ZL in the optical happens to be similar to the one by ZE in 60 micro-meters.**
- **This is a limit of the brightness integral ; one may needs help from dynamical model, laboratory measurements of dust optical properties, etc.**

Why does the IPD cloud look different from wavelength to wavelength?

Beta Pic answers the question very well.



Chap 5. IN RETROSPECT

ON-AIR by Atta Kim

100 Countries/ 100 Men

References

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- Pyo, J., et al. 2009, EPS, submitted
- Telesco, C. M., et al. 2005, Nature, 433, 133