Simulation and Inversion of Annual Light Curves of a Second Earth

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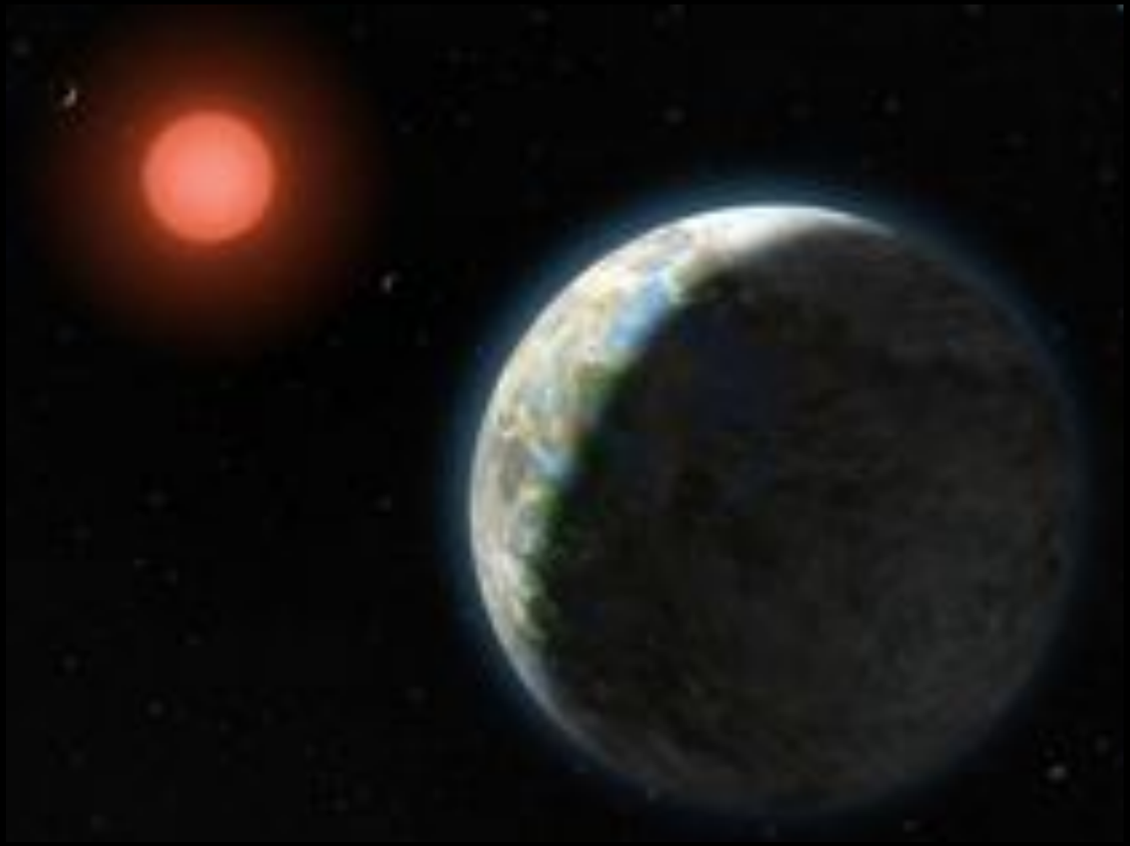

References:

Kawahara & Fujii, ApJ,720,1333 (2010)
Kawahara & Fujii, ApJL, 739, L62 (2011)
Fujii & Kawahara, in prep.

http://www.nasa.gov/topics/universe/features/Gliese_581.html

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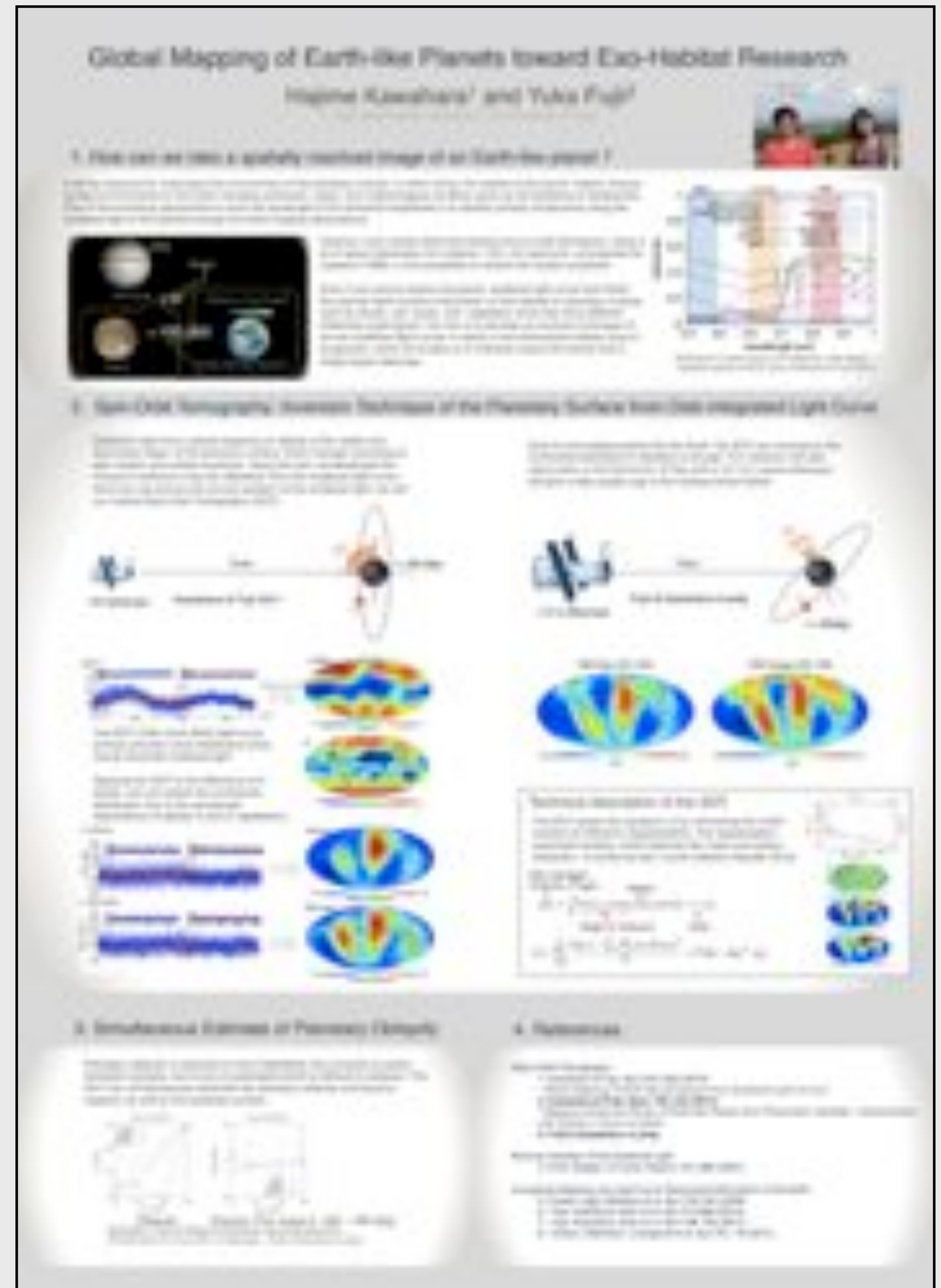


“Remote-Sensing” of Exoclimes

How can we observationally examine
the climates / habitat of such far HZ exoplanets?

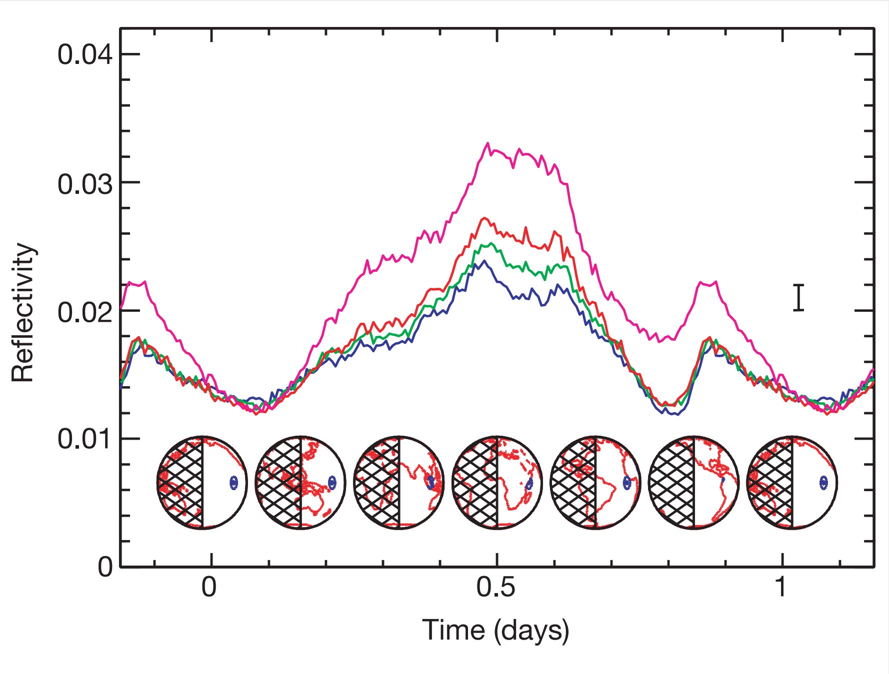
“Remote-Sensing” of Exoclimes

- Different reflection spectra (Colors)
- Non-uniform

Diurnal Variation of the Earth

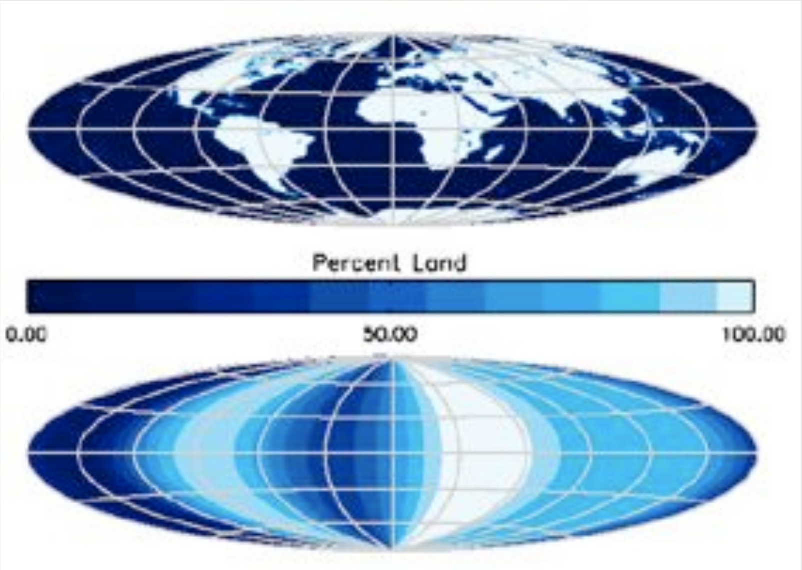
simulation (e.g.)
E. Ford, S. Seager & E. Turner, 2001

simulated daily variation of Earth (cloudless)



inversion (e.g.)
N. Cowan et al. 2009, 2011

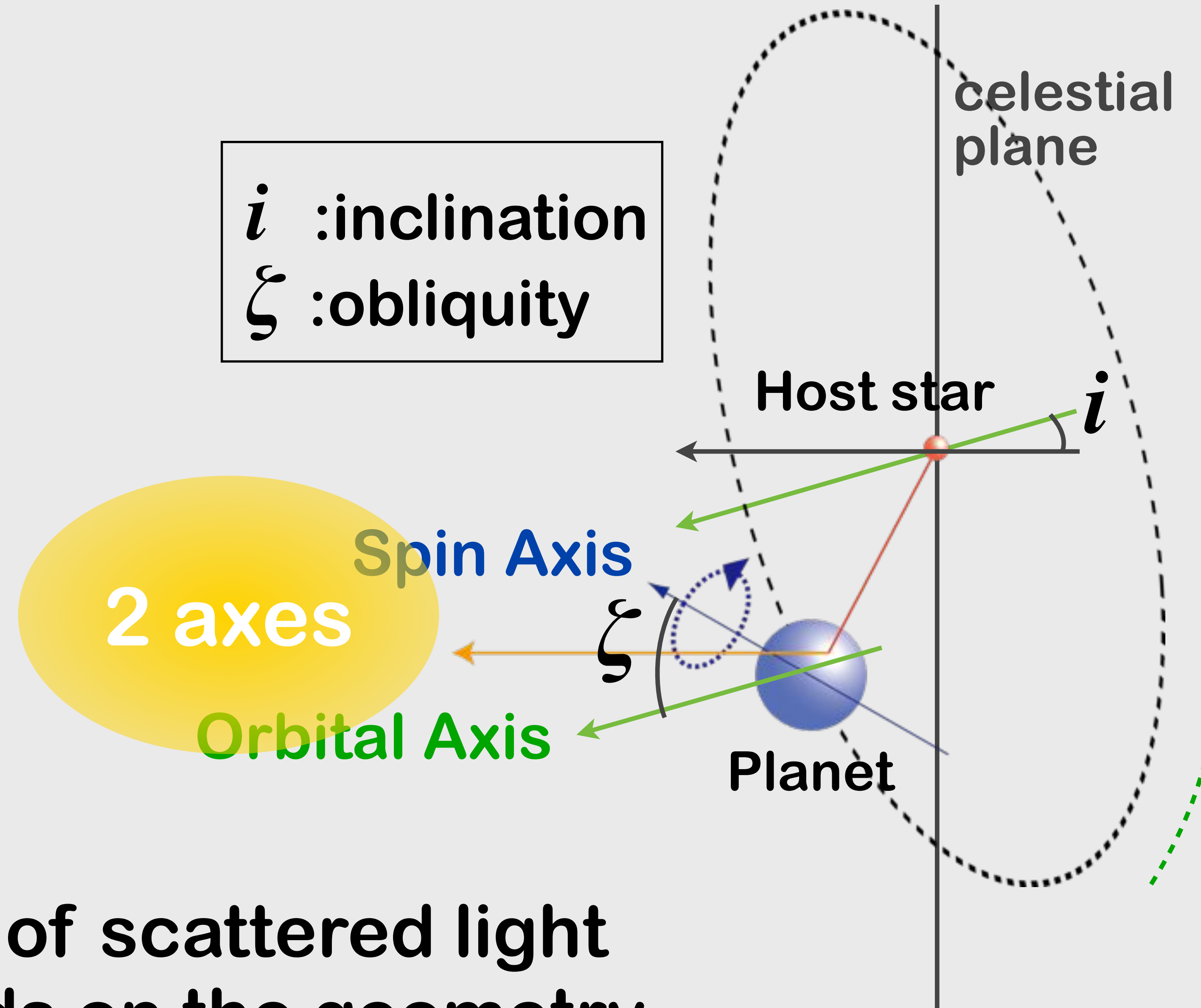
derived longitudinal map from observed diurnal variation of Earth



ref.)
P. H. H. Oakley & W. Cash, 2009
Y. Fujii, H. Kawahara, Y. Suto, et al. 2010, 2011

How we observe exoplanets

Planetary light
= Weighted sum of light
scattered at each pixel



Weight of contribution of scattered light from each pixel depends on the geometry among the pixel, host star, and observer

(e.g. no contribution from pixels not facing on the observer nor from those not being illuminated by the host star)

Formulation

Assuming Lambert scattering, reflectivity of planet is:

noise

$$d(t) = \int W(t, \phi, \theta; \mathbf{w})\, m(\phi, \theta)\, d\Omega + \epsilon$$

reflectivity (given) | weight function (design matrix) | albedo@(Φ,θ) (to be estimated)

Pixelization

$$d(t_i) \approx \sum W_j(t_i\,; \mathbf{w})\, m_j$$

- Fit light curves with this model with regularization

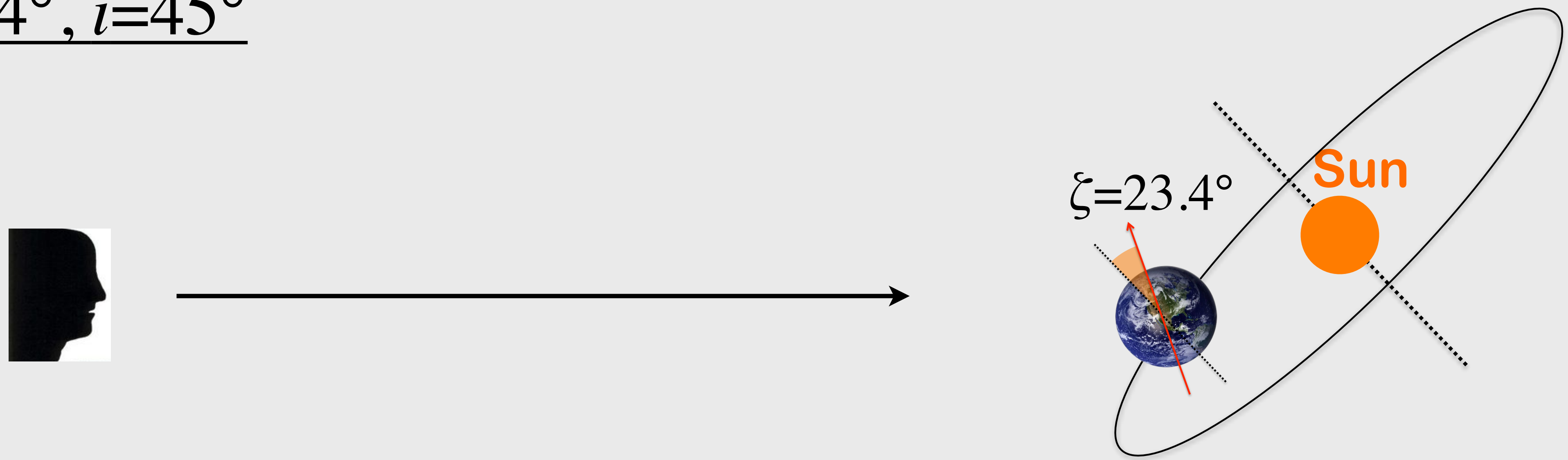
$$Q = \sum_{i=1}^{N} \frac{|d(t_i) - \sum_j W_j(t_i; \mathbf{w}) m_j|^2}{\sigma_i^2} + \lambda^2 |\mathbf{m} - \mathbf{m}_p|^2$$

χ^2 | regularization term

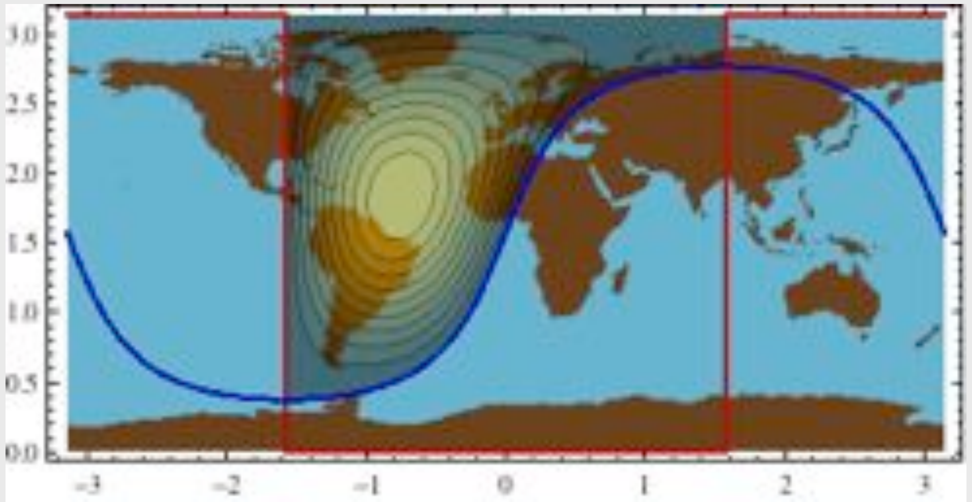
=> Spin-Orbit Tomography (SOT)

Behavior of Weight Function

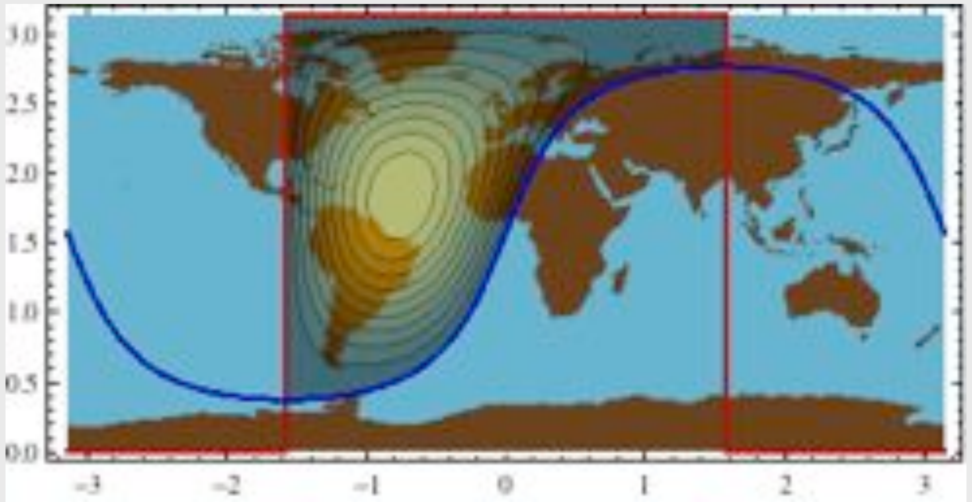
$\zeta=23.4°$, $i=45°$



Spin rotation



Orbital motion

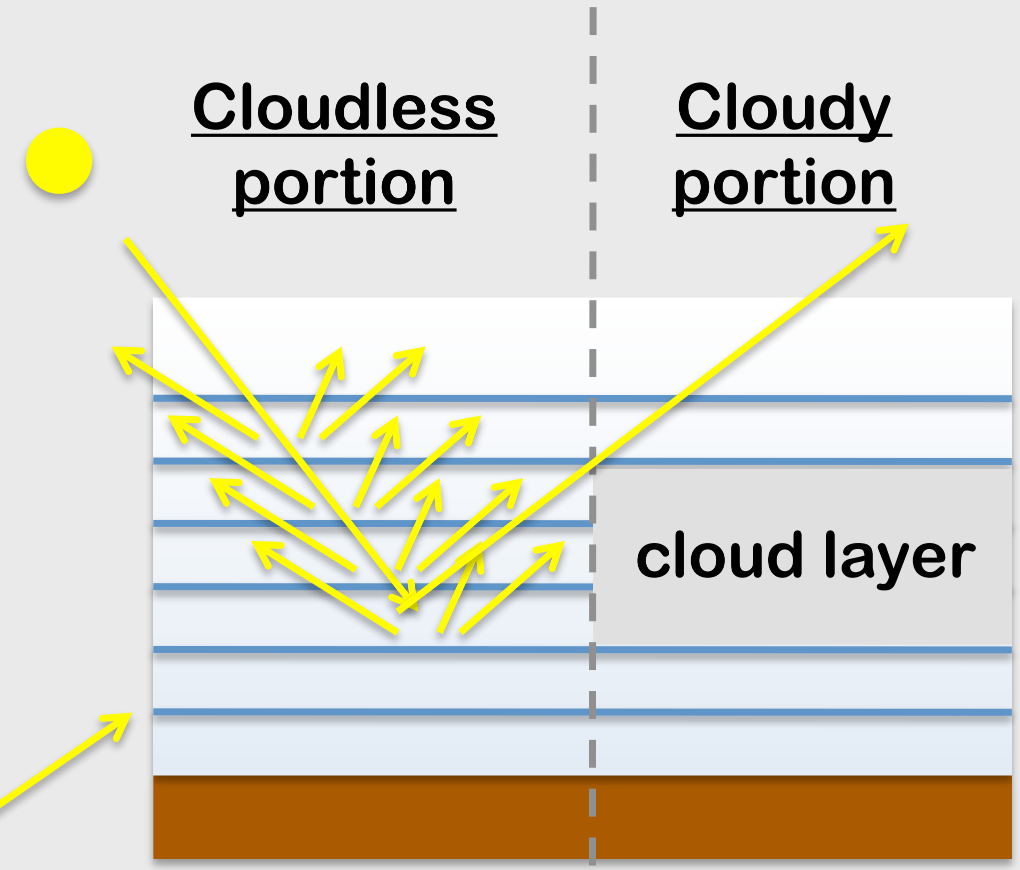


Testing SOT with Simulated light curves of our Earth

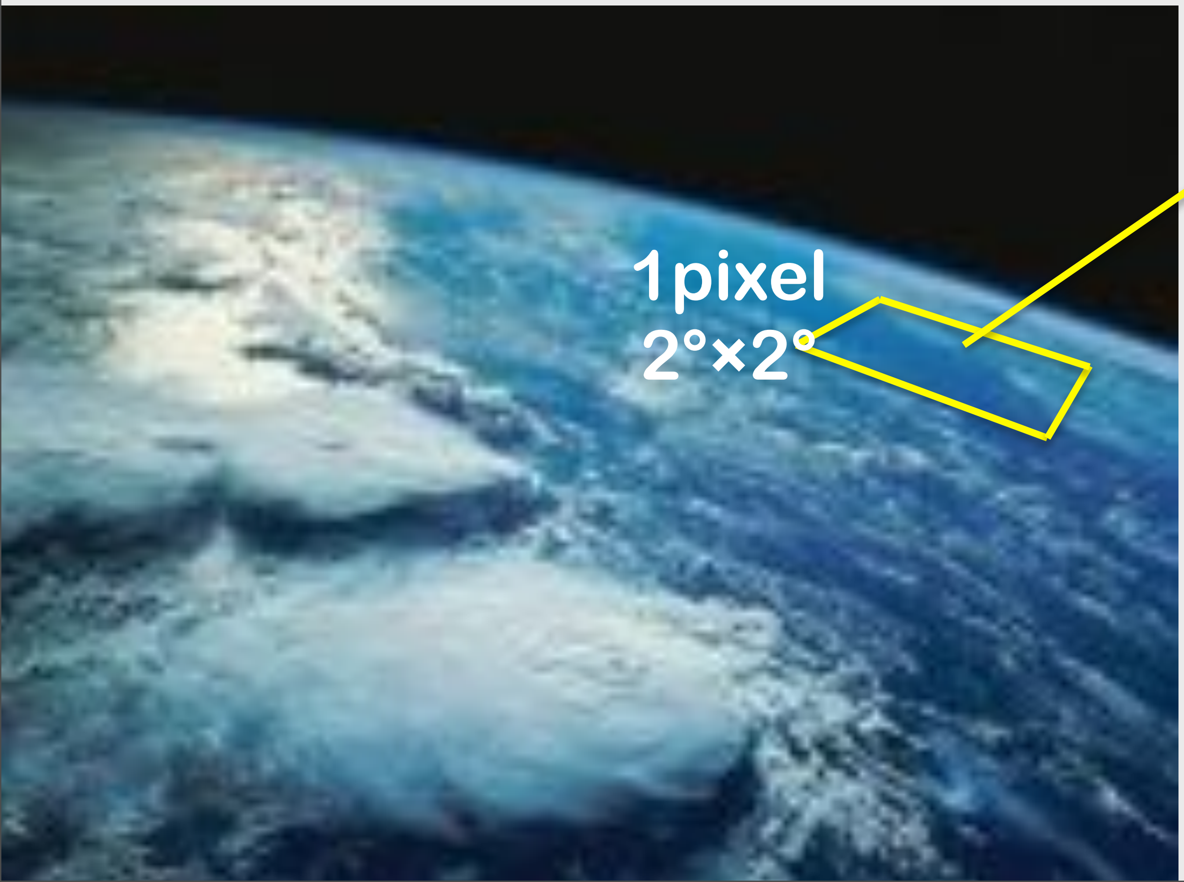
Simulation Scheme

(ref. Fujii+ 2011)

RSTAR6B calculates radiative transfer in the atmosphere



the Earth

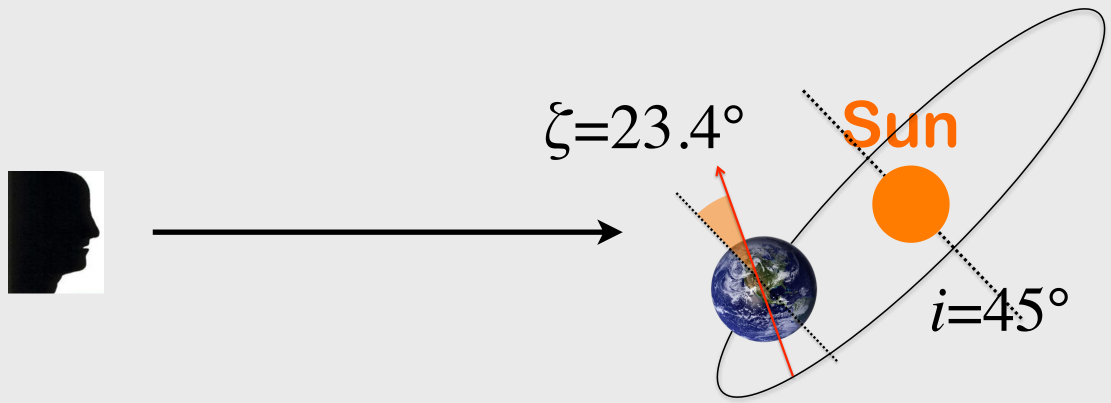


INPUT DATA at each pixel:

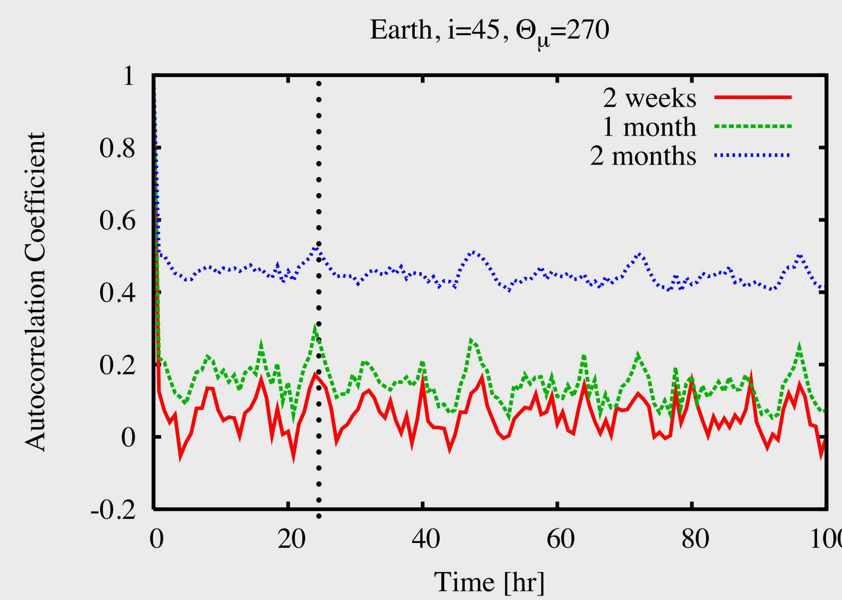
- Cloud Coverage (daily)
- Cloud Optical Thickness (daily)
- Surface Reflectivity (monthly)
- Snow Coverage (monthly)

from MODIS dataset

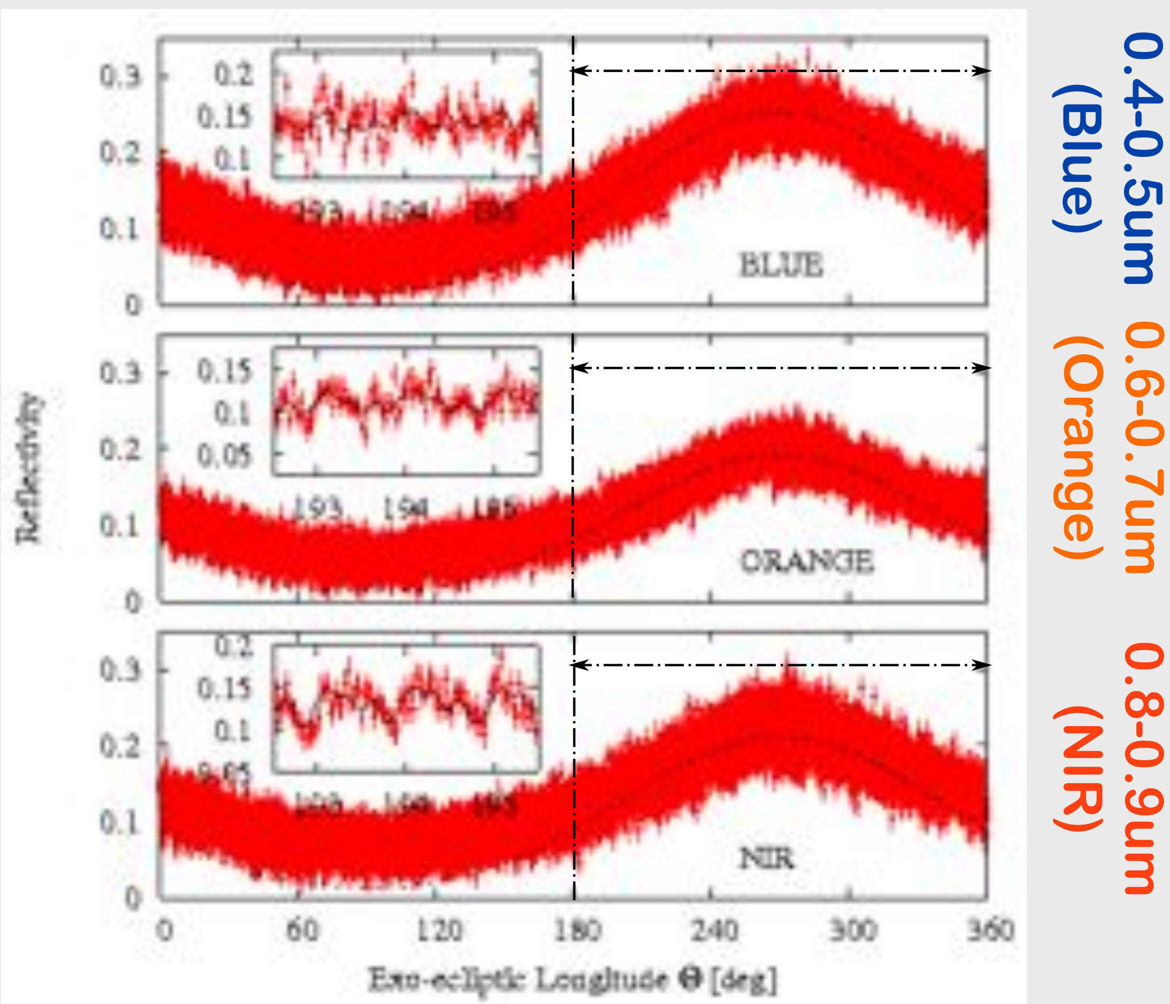
Annual Light Curves



- **Rotation period** (ref. Pallé et al. 2008)



exposure: 24/30 hr, SN~8 per frame



Assumptions

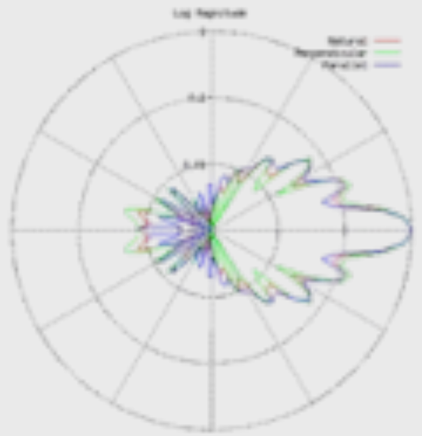
- **no starlight leakage**
- **readout noise, dark noise, exozodi**
- **sharpness ~ 0.08**
- **throughput*QE ~ 0.5**
- **@10pc, R=Rearth**

SN ~ 8/frame ⇔ D ~ 5m

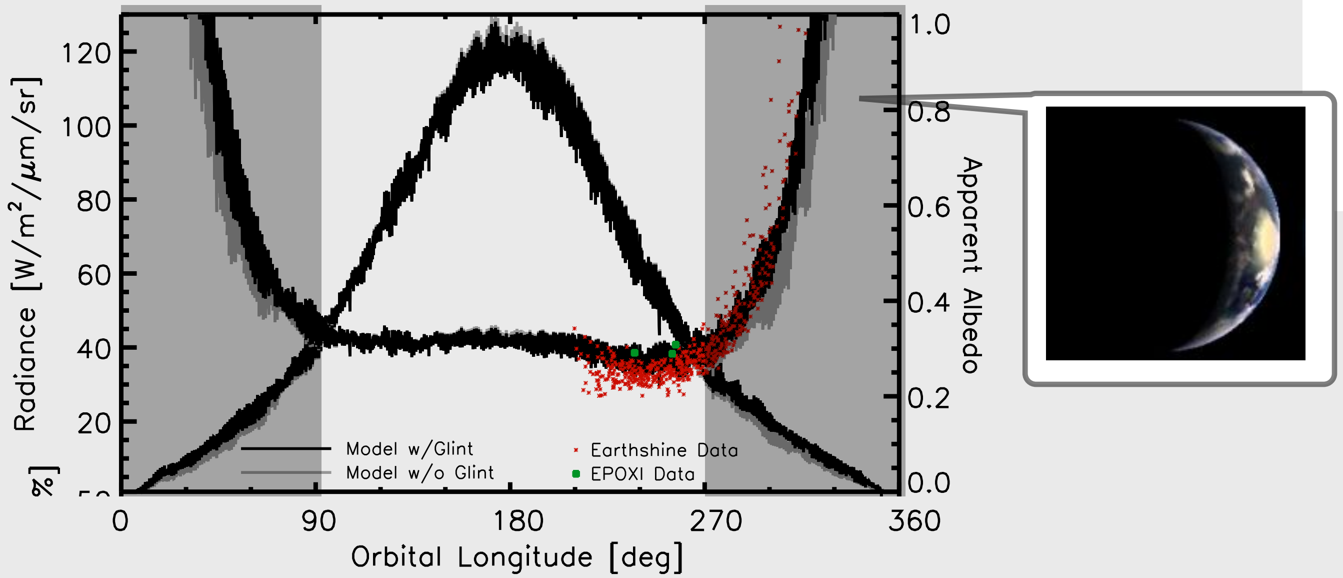
Effect of Anisotropic Scattering

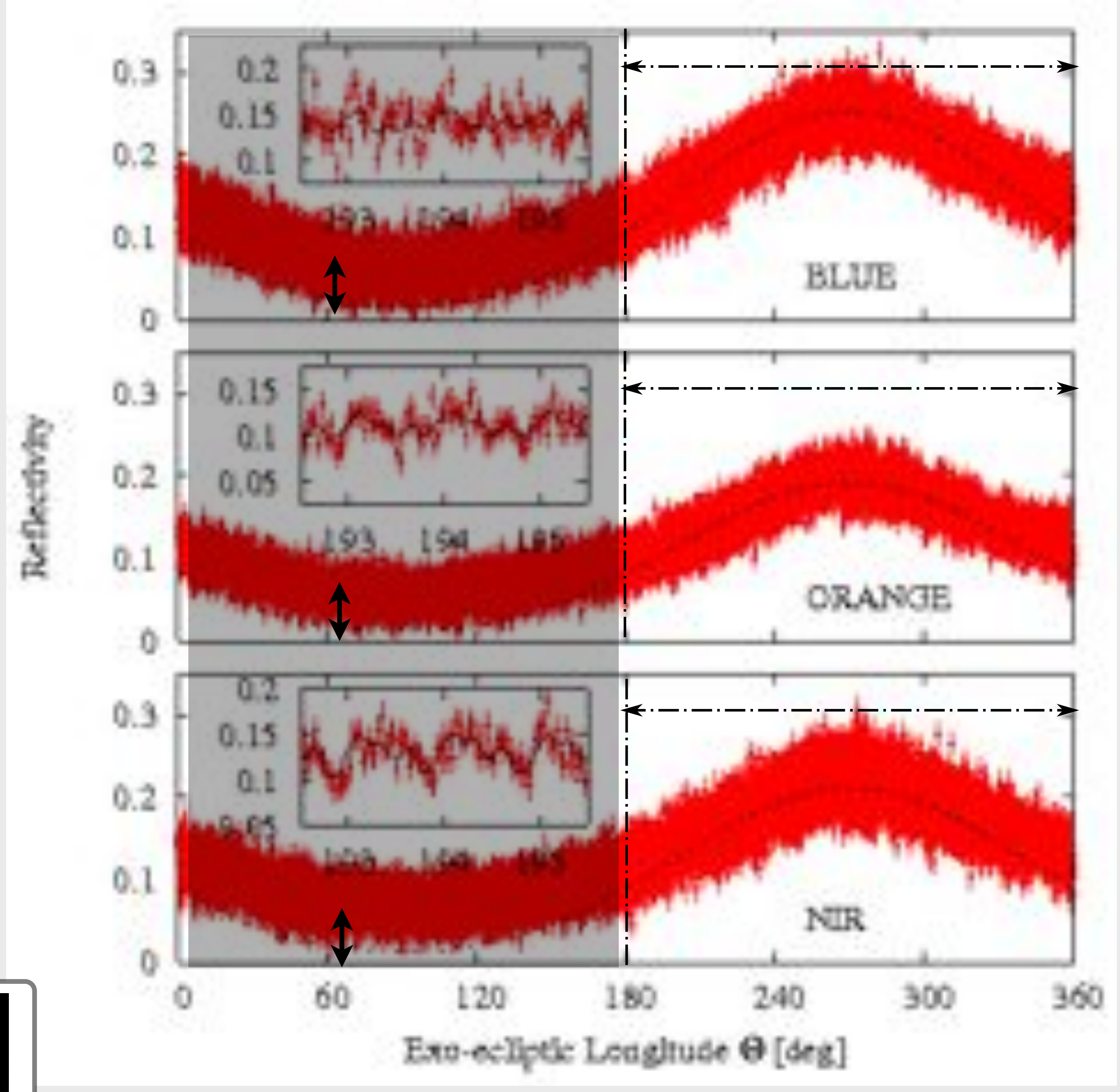
Phase function of Mie scattering

http://omlc.ogi.edu/calc/mie_calc.html

Back←  →Forward

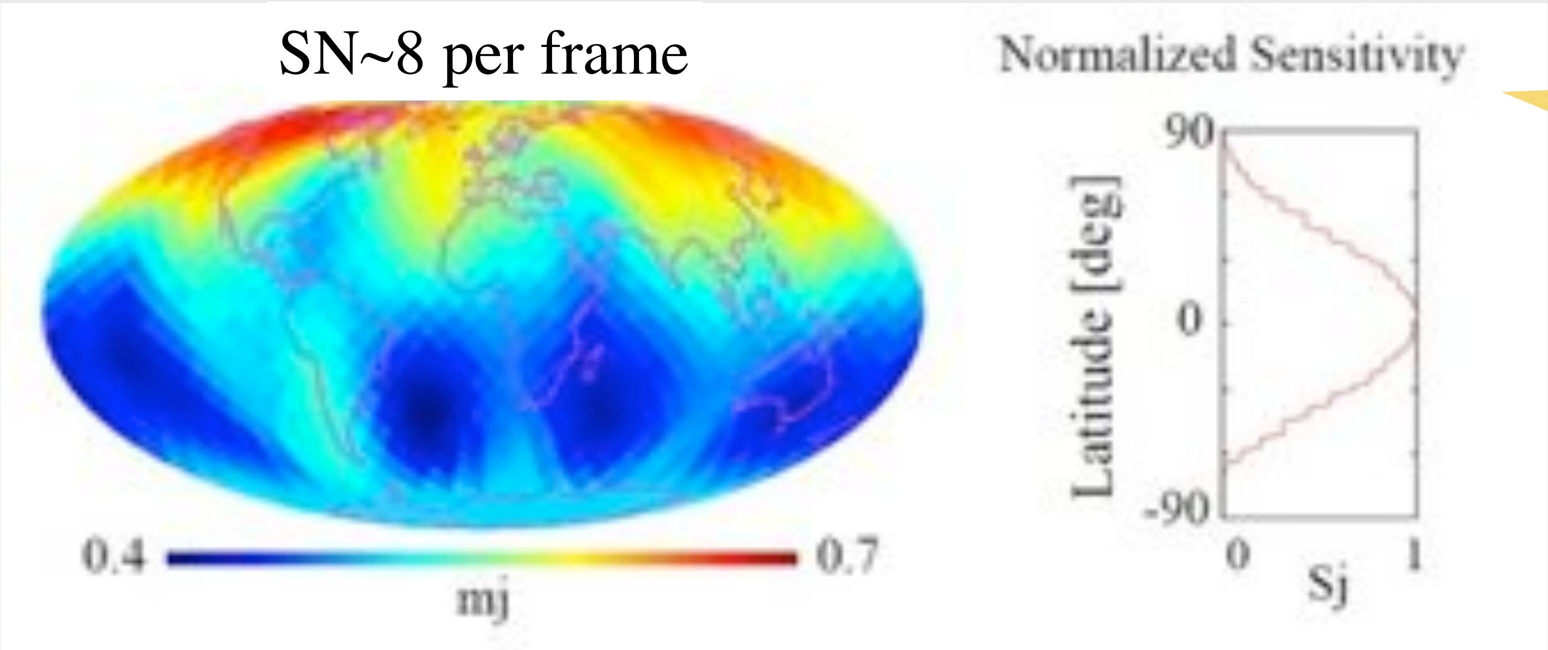
Ref.) Robinson et al. 2010 phase curve of the Earth





Data@phase angle>90° are used

Single-band Mapping



Sensitivity

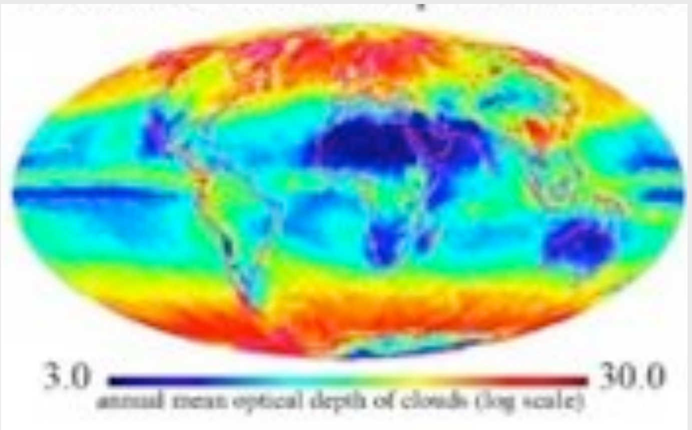
$$S(\theta_j) \propto \sqrt{\sum_{i=1}^{N} W_j^2(t_i;\mathbf{w})}$$

$$d(t_i) \approx \sum W_j(t_i\,;\mathbf{w})\,m_j$$

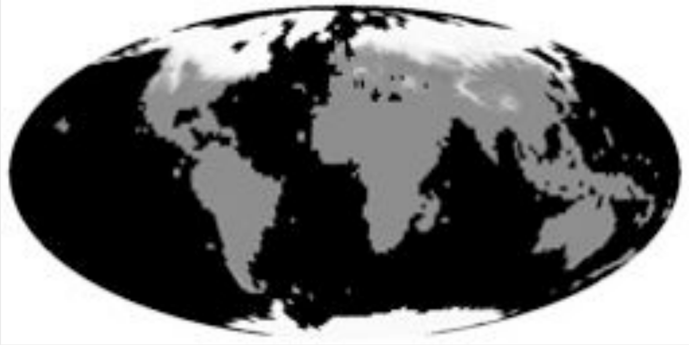
Single-band mapping traces components with high albedo

⇒ Clouds, Snow

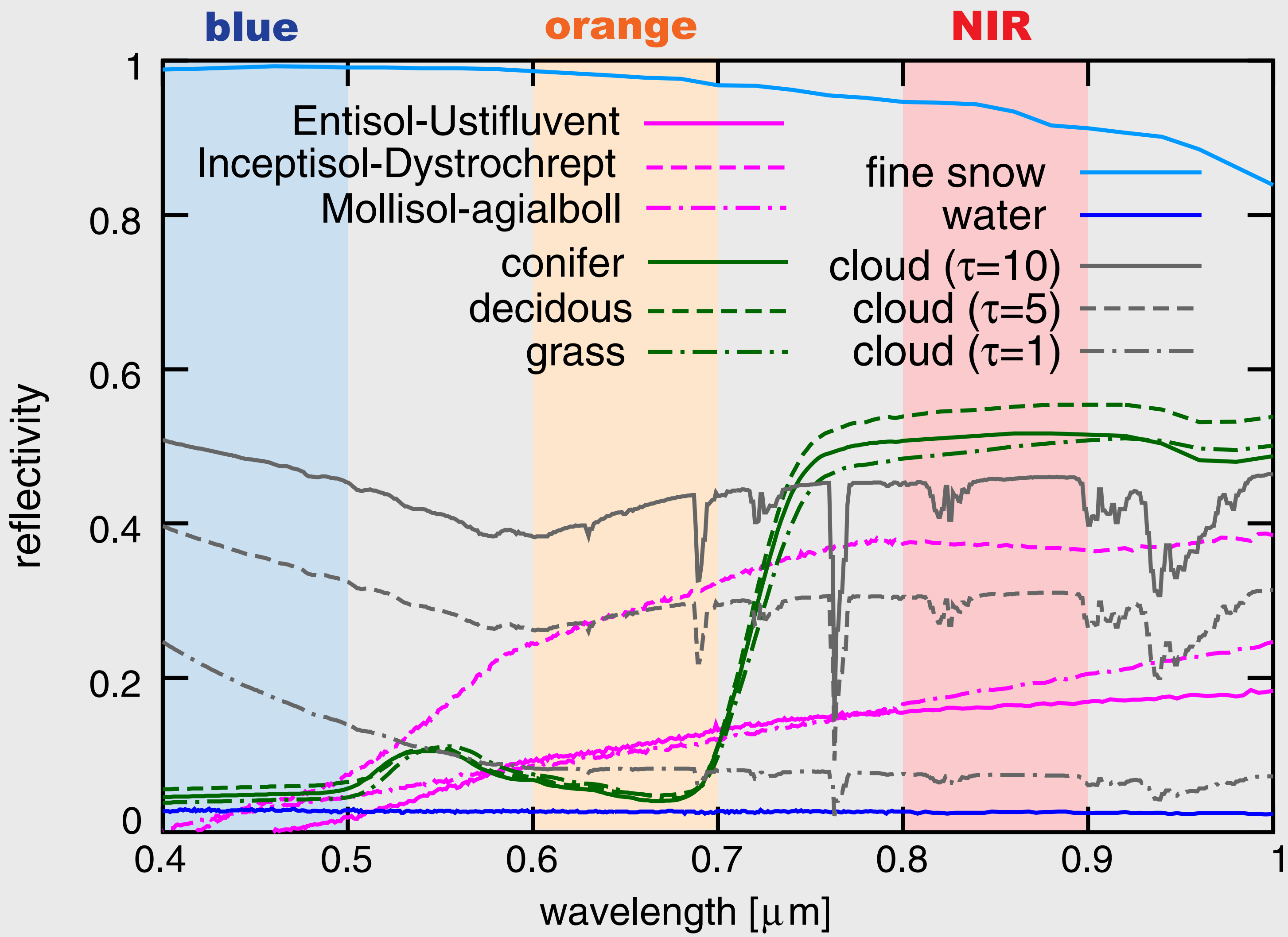
Cloud map



Snow map @March

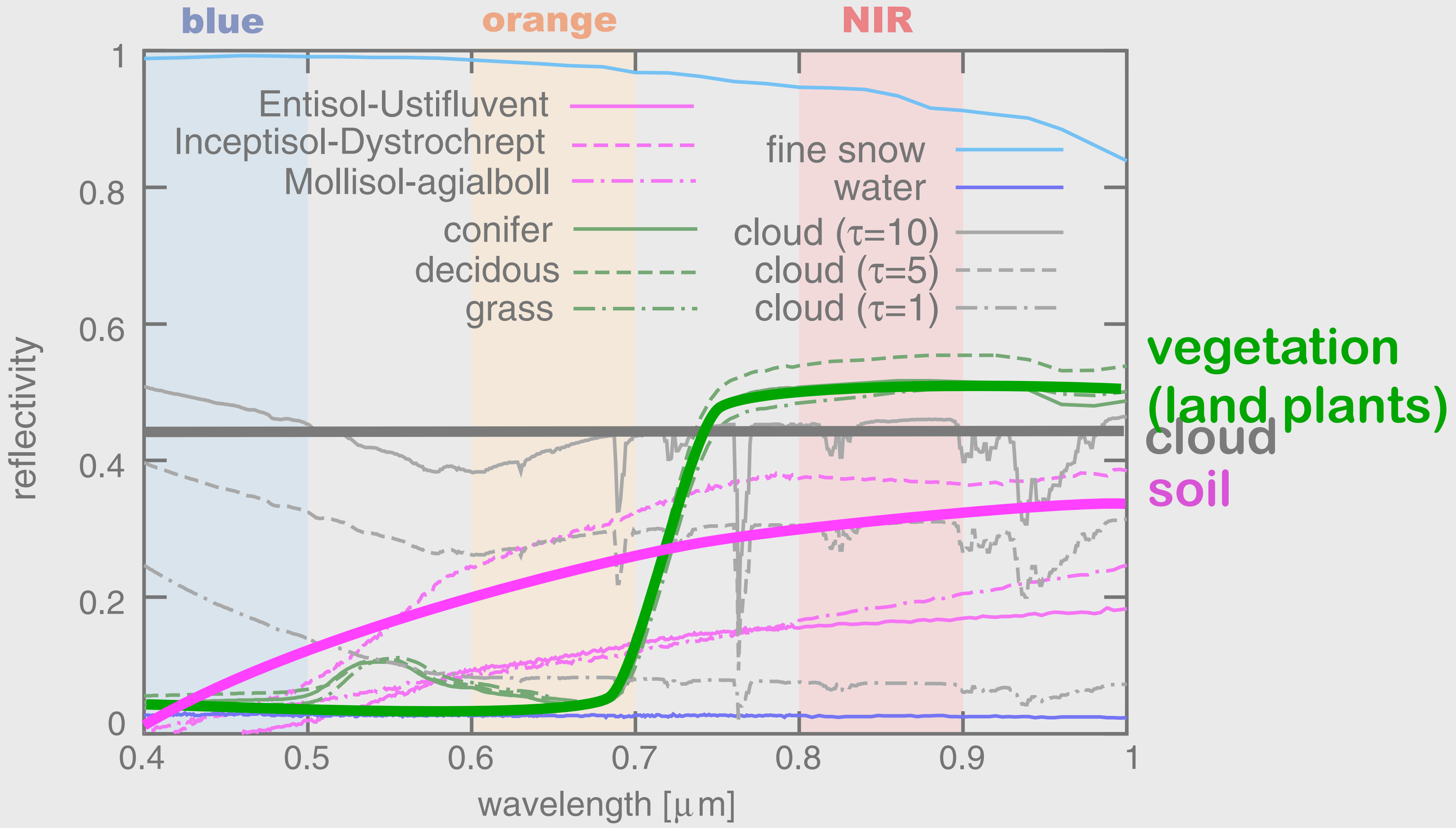


Surface Inhomogeneity



From Aster Spectral Libarary
http://speclib.jpl.nasa.gov/

Surface Inhomogeneity



From Aster Spectral Libarary
http://speclib.jpl.nasa.gov/

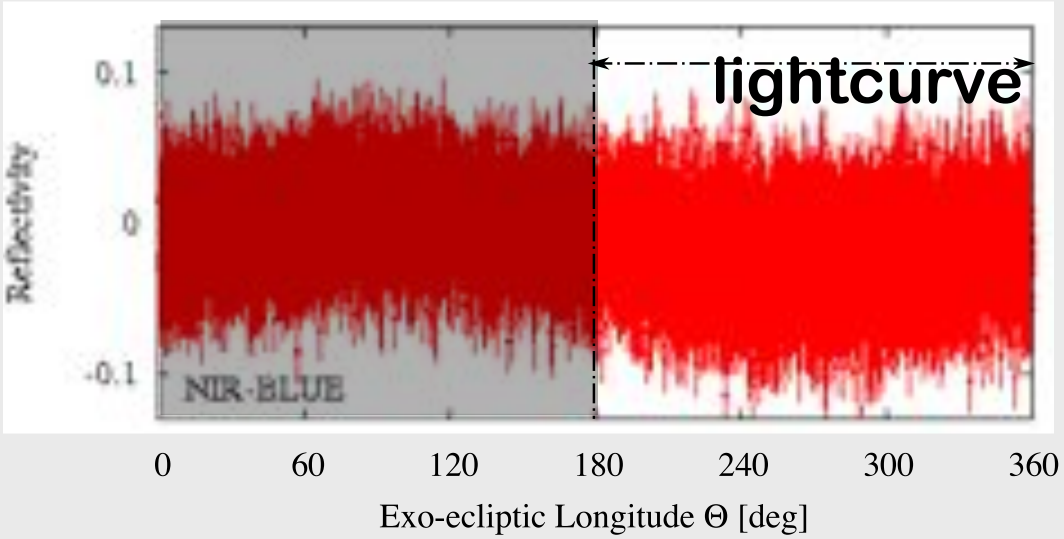
Differential Mapping

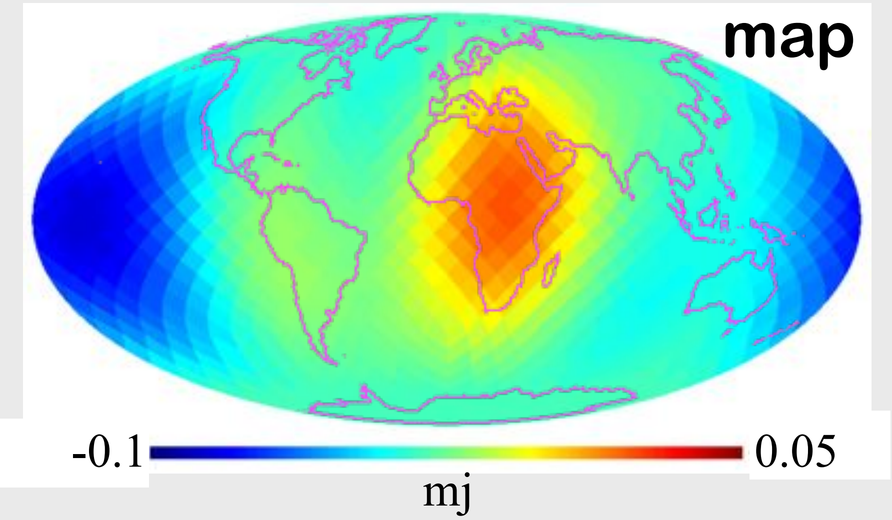
(SN~8 /frame)

D ~ 5m

NIR-Blue

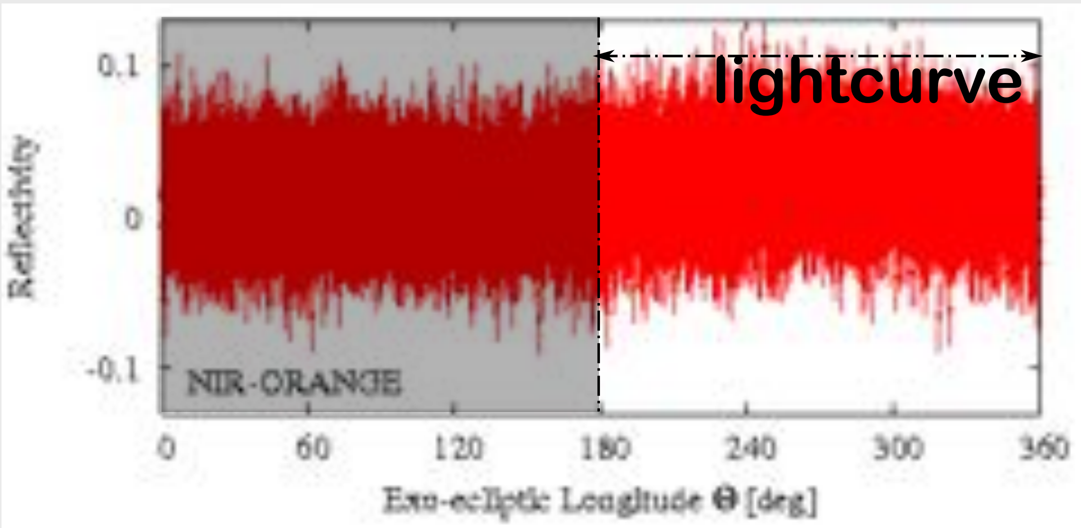
~ Soil proxy

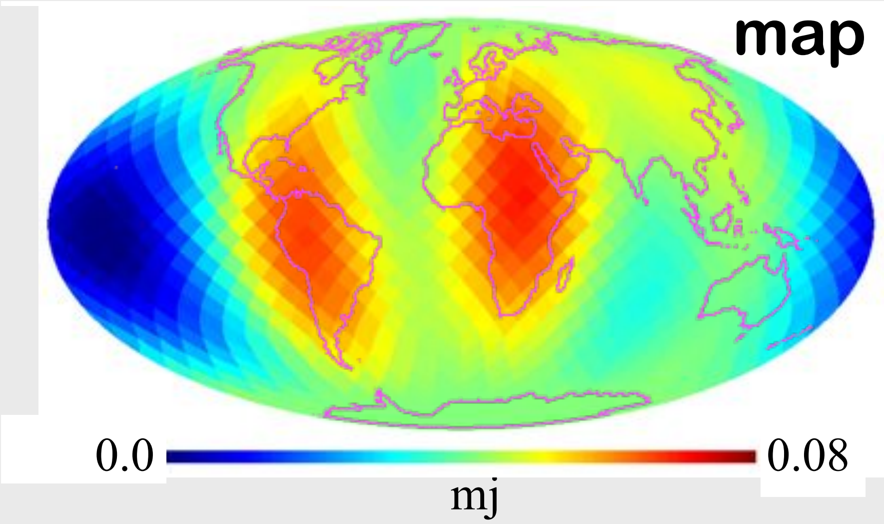




NIR-Orange

~ Vegetation proxy





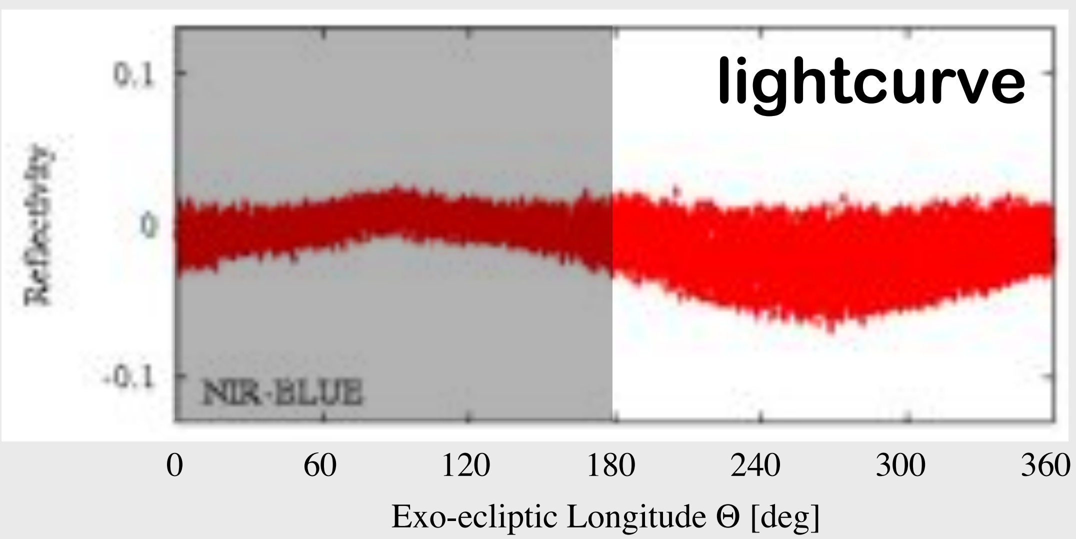
Differential Mapping

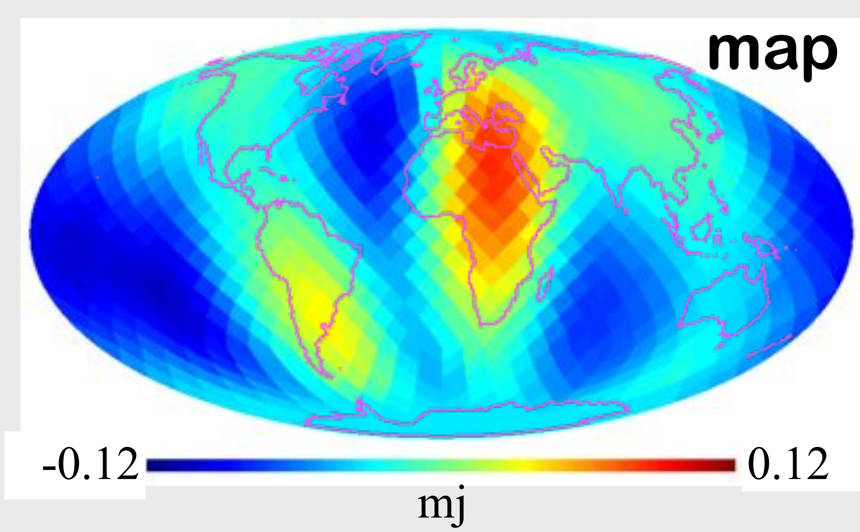
(SN~40 /frame)

D ~ 15m

NIR-Blue

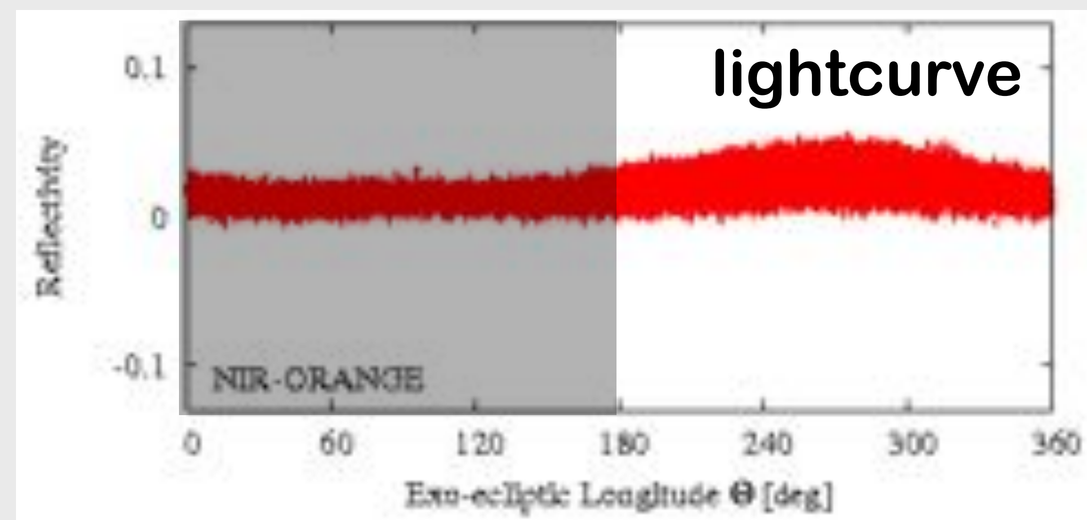
~ Soil proxy

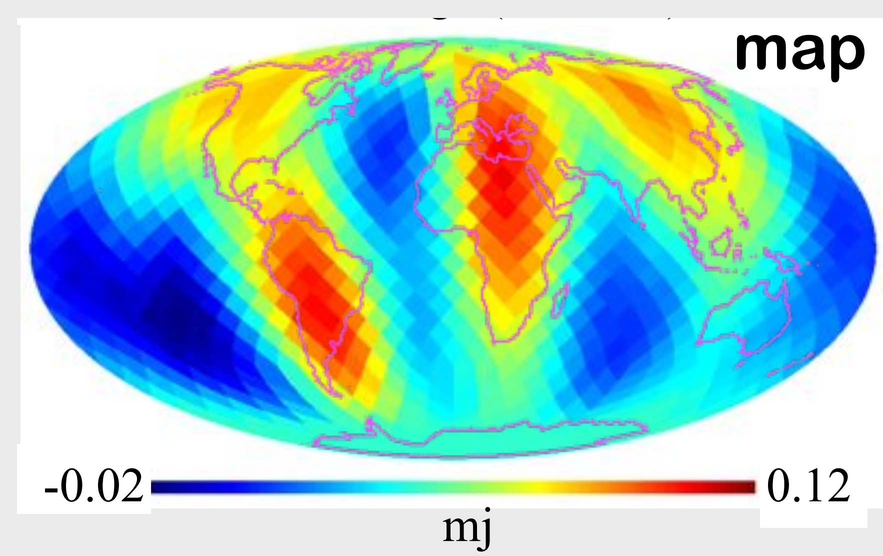




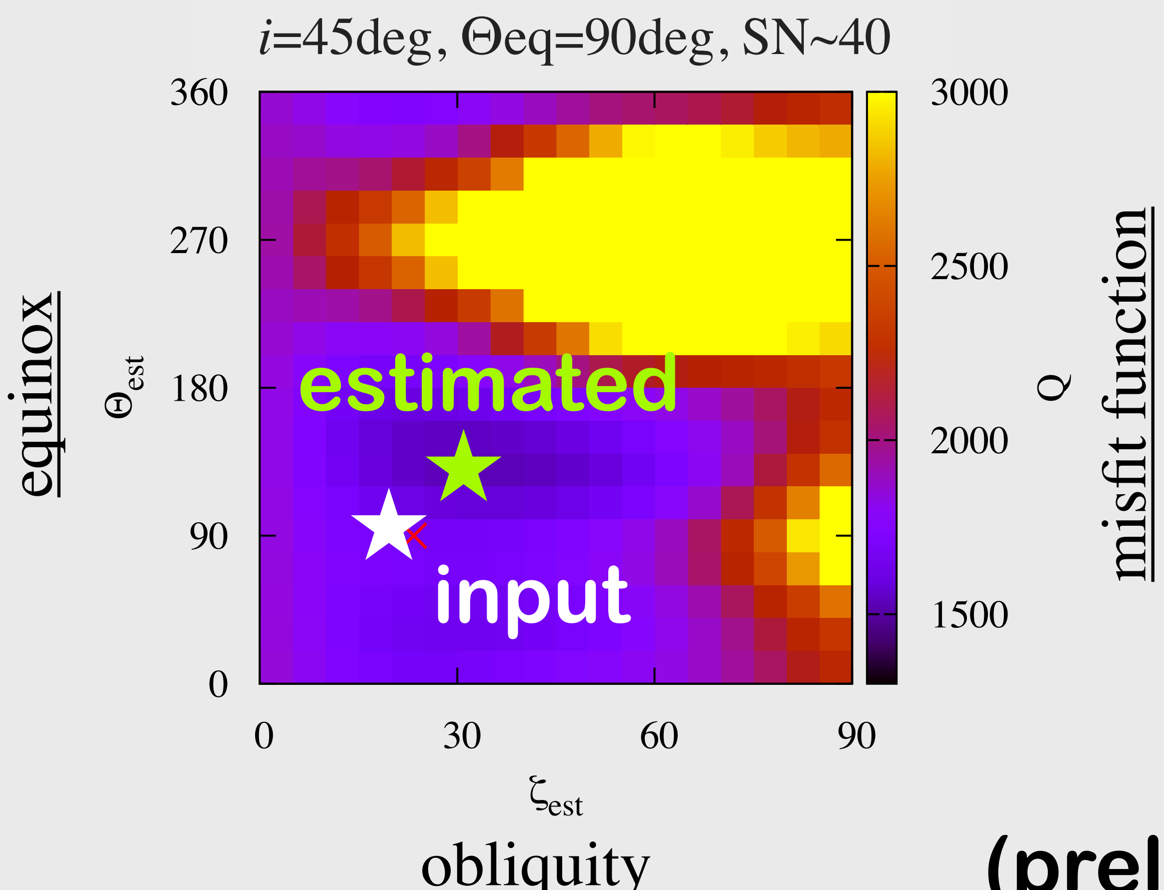
NIR-Orange

~ Vegetation proxy

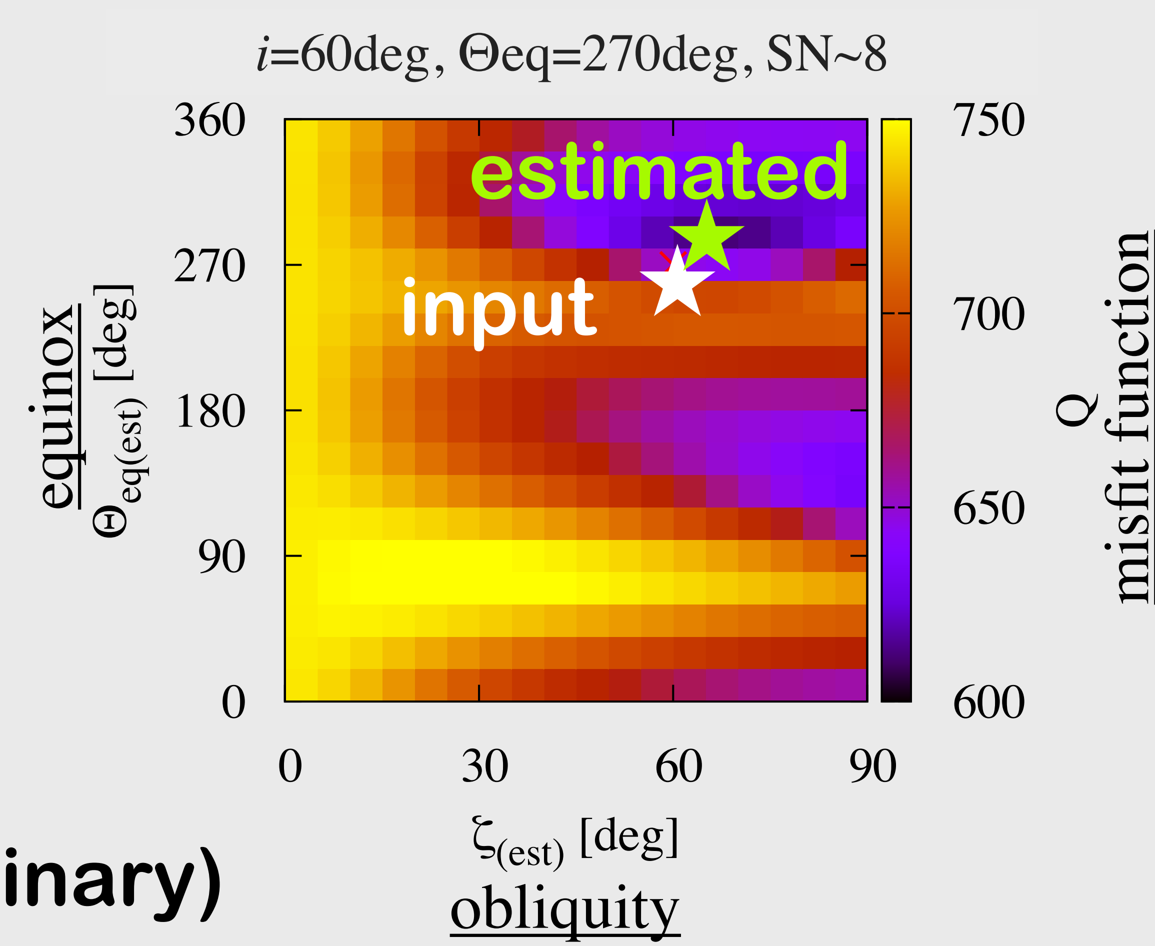




Obliquity Measurement



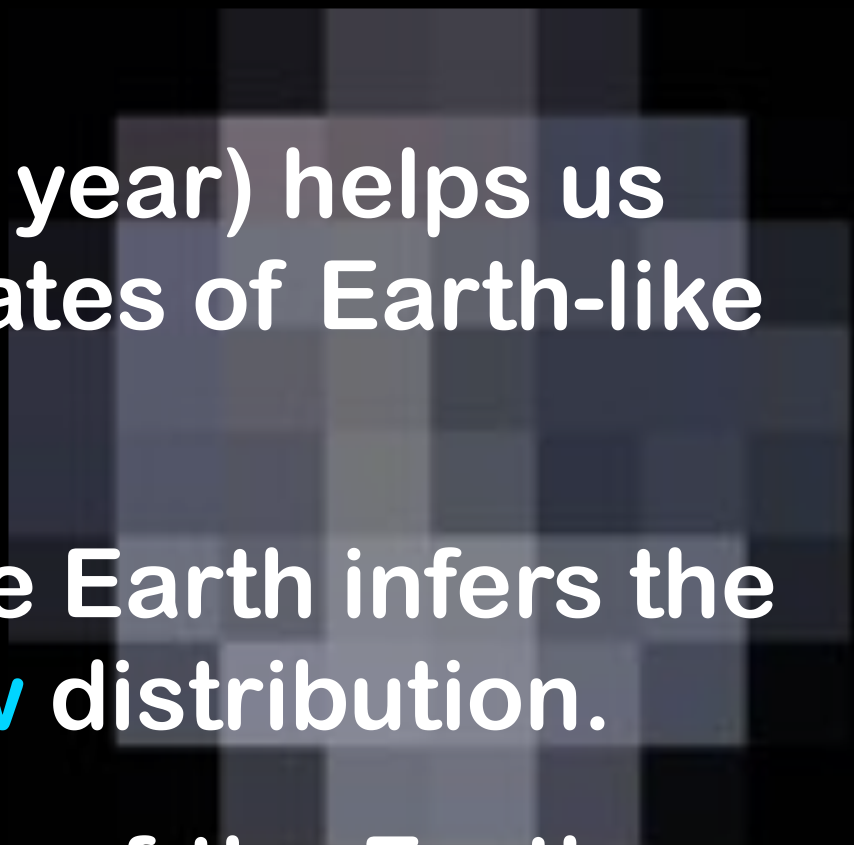
(preliminary)

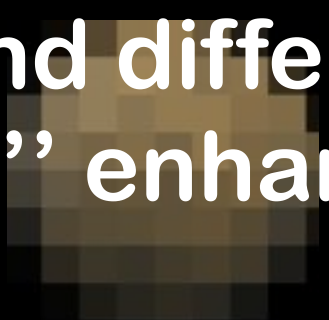


Planetary obliquity can be also estimated

Obliquity is an essential parameter which controls seasonality

Summary





<u>Spin-Orbit tomography</u>
Continuous observation (~1/2 year) helps us understand non-uniform climates of Earth-like exoplanets

- Single-band mapping of the Earth infers the annual mean of cloud/snow distribution.
- 2-band differential mapping of the Earth reveals the land distribution
- 2-band differential mapping bracketing “red-edge’’ enhances vegetation area