GeoSphere

Geosynchronous **Spher**ical Scattering Target
for Century-long Monitoring of Solar Irradiance

Judge & Egeland 2015, MNRAS Letters

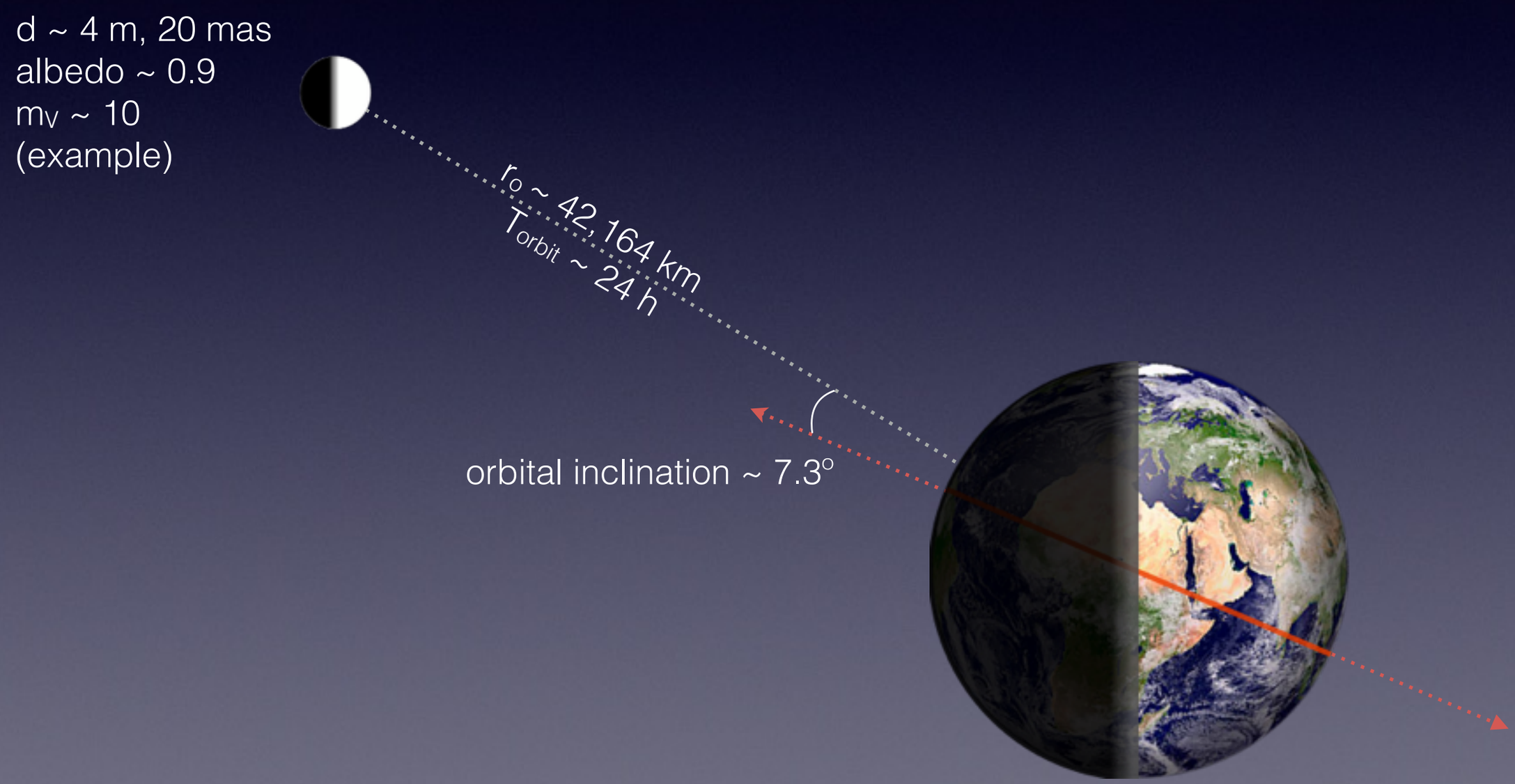
Ricky Egeland
Montana State University / HAO Newkirk Fellow

SORCE 2015 Meeting – Savannah
November 13, 2015

How does the irradiance of the Sun vary on century-long timescales?

GeoSphere: The Sun as Star

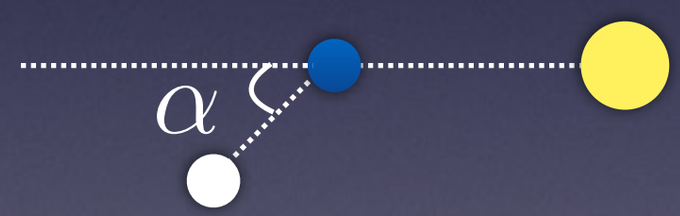
Geosynchronous **Spher**ical Scattering Target



Size Constraints

$$m_V(\alpha) \approx m_{V,\odot} - 2.5 \log_{10} \left(\frac{r_s^2}{(r_o - r_\oplus)^2} \frac{a}{q} \phi(\alpha) \right)$$

$$\phi(\alpha) = \left[\sin\alpha + (\pi - \alpha)\cos\alpha \right] / \pi$$



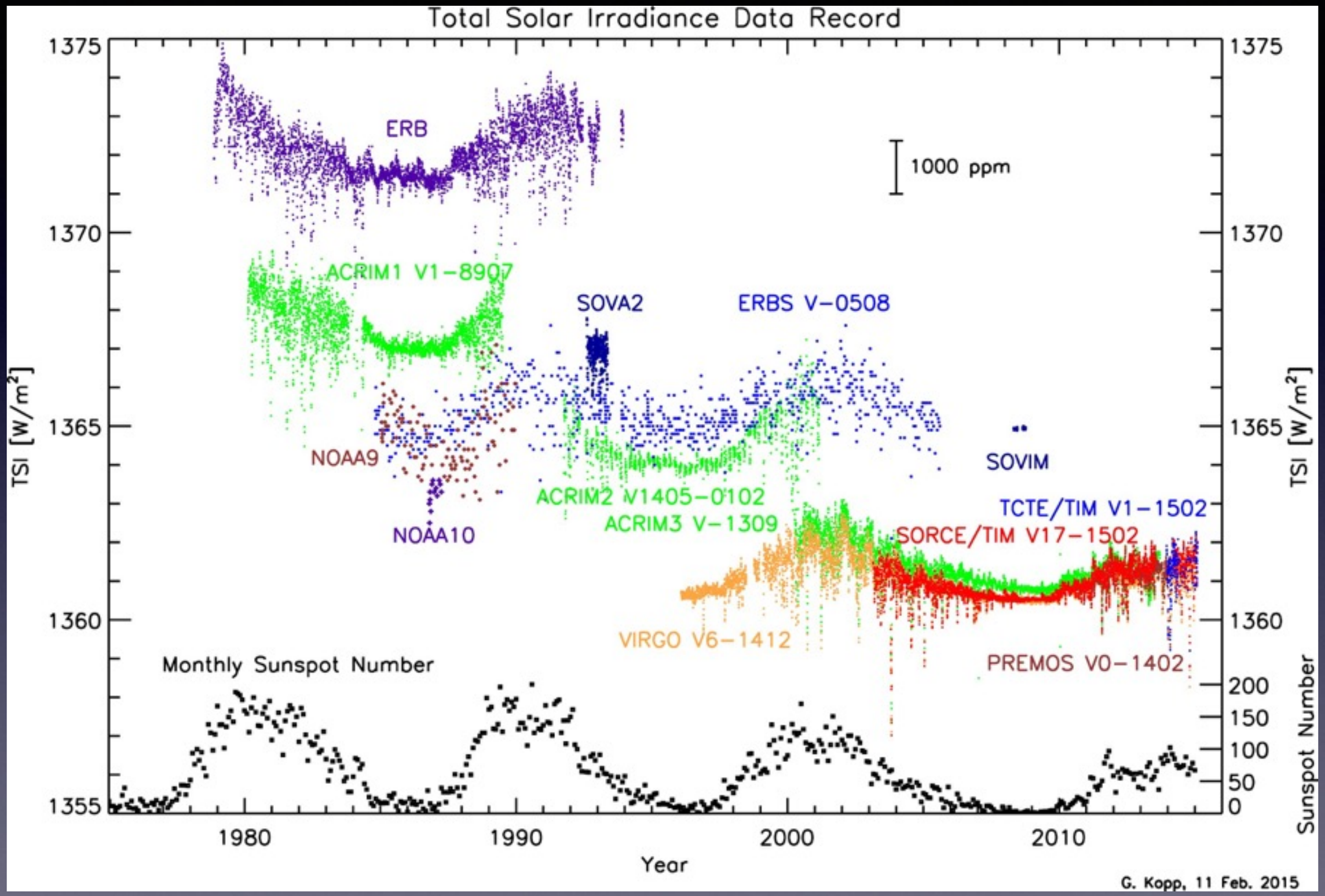
Assuming 0.05% rms photon noise, integration time < 100 s:

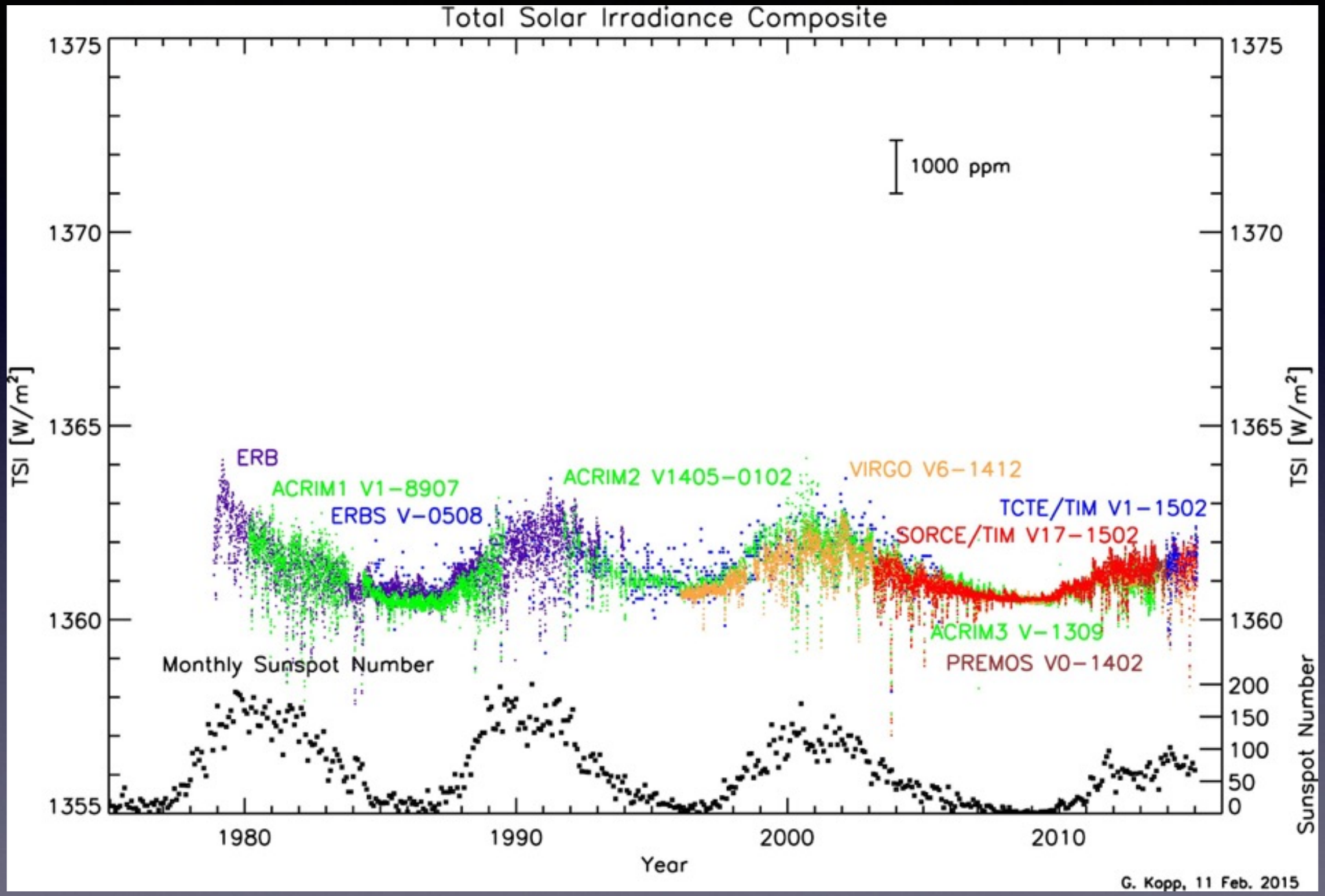
$$(d_s D)^2 \gtrsim 5800/\Delta\lambda \, \mathrm{m}^4$$

Assuming Strömgren *by* bands:

$$(d_s D)^2 \gtrsim 36 \, \mathrm{m}^4$$

“What a stupid idea. Anyway, we’re already making these measurements!”


Total Solar Irradiance Data Record
ERB
1000 ppm
ACRIM1 V1−8907
SOVA2
ERBS V−0508
NOAA9
NOAA10
ACRIM2 V1405−0102
ACRIM3 V−1309
SOVIM
TCTE/TIM V1−1502
SORCE/TIM V17−1502
VIRGO V6−1412
PREMOS V0−1402
Monthly Sunspot Number
TSI [W/m²]
Sunspot Number
Year
1375
1370
1365
1360
1355
200
150
100
50
0
1980
1990
2000
2010
G. Kopp, 11 Feb. 2015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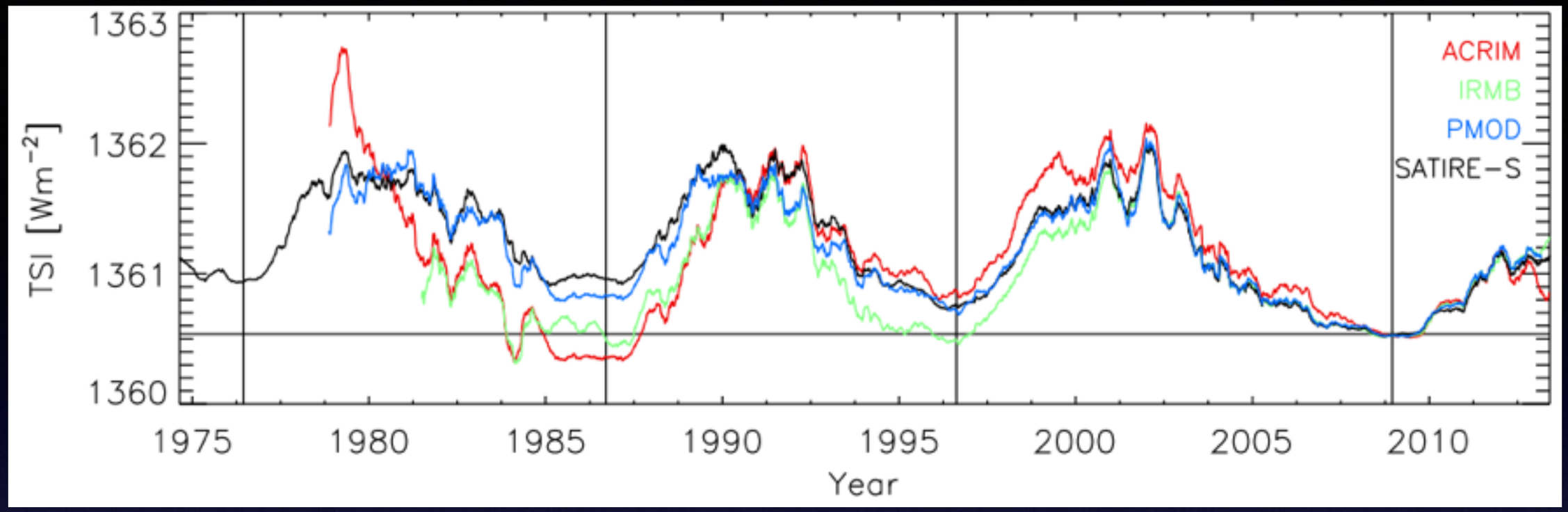
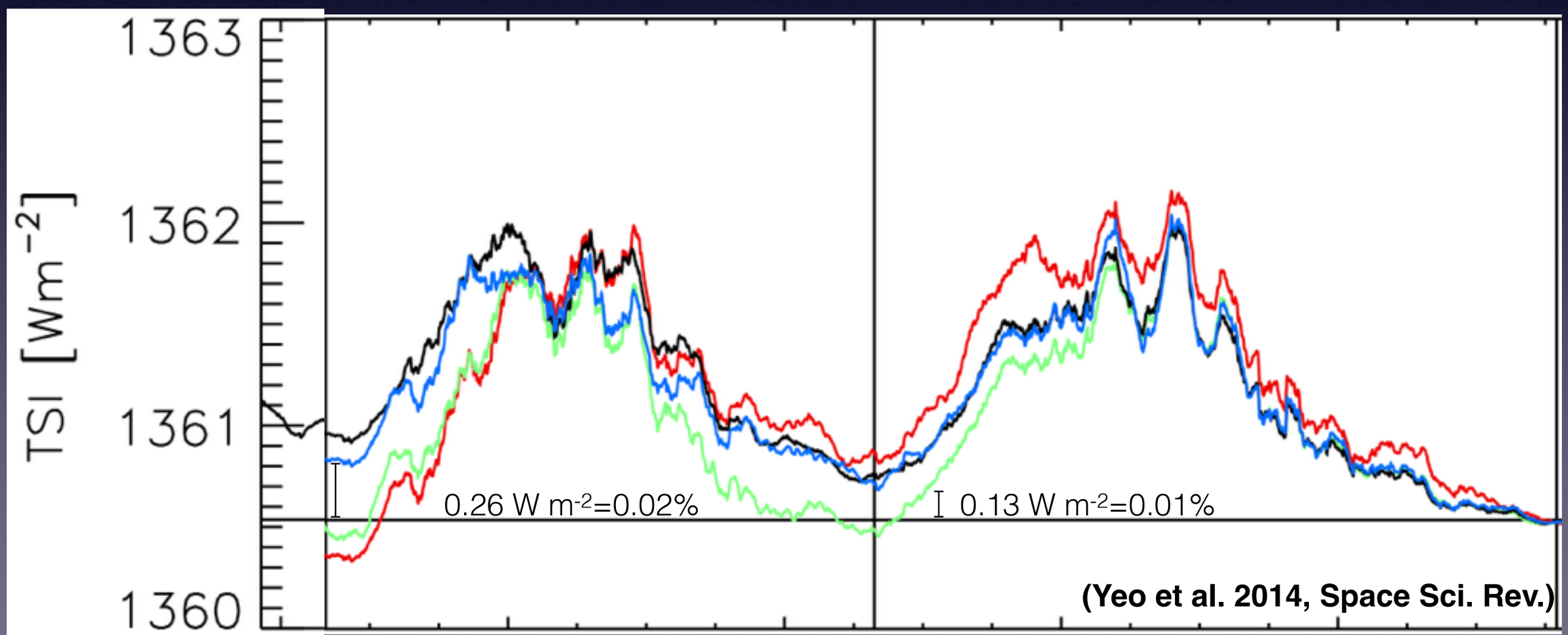
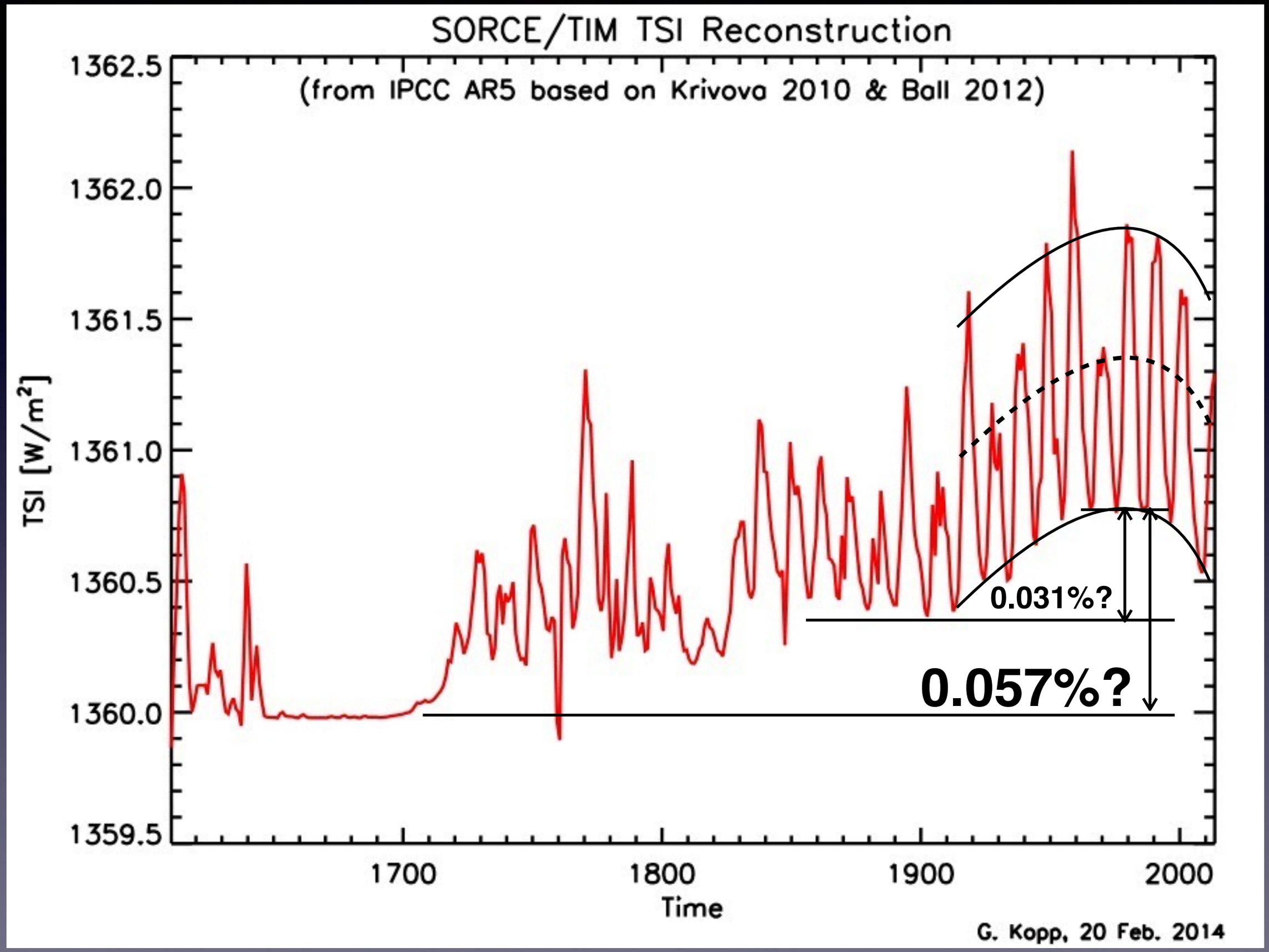
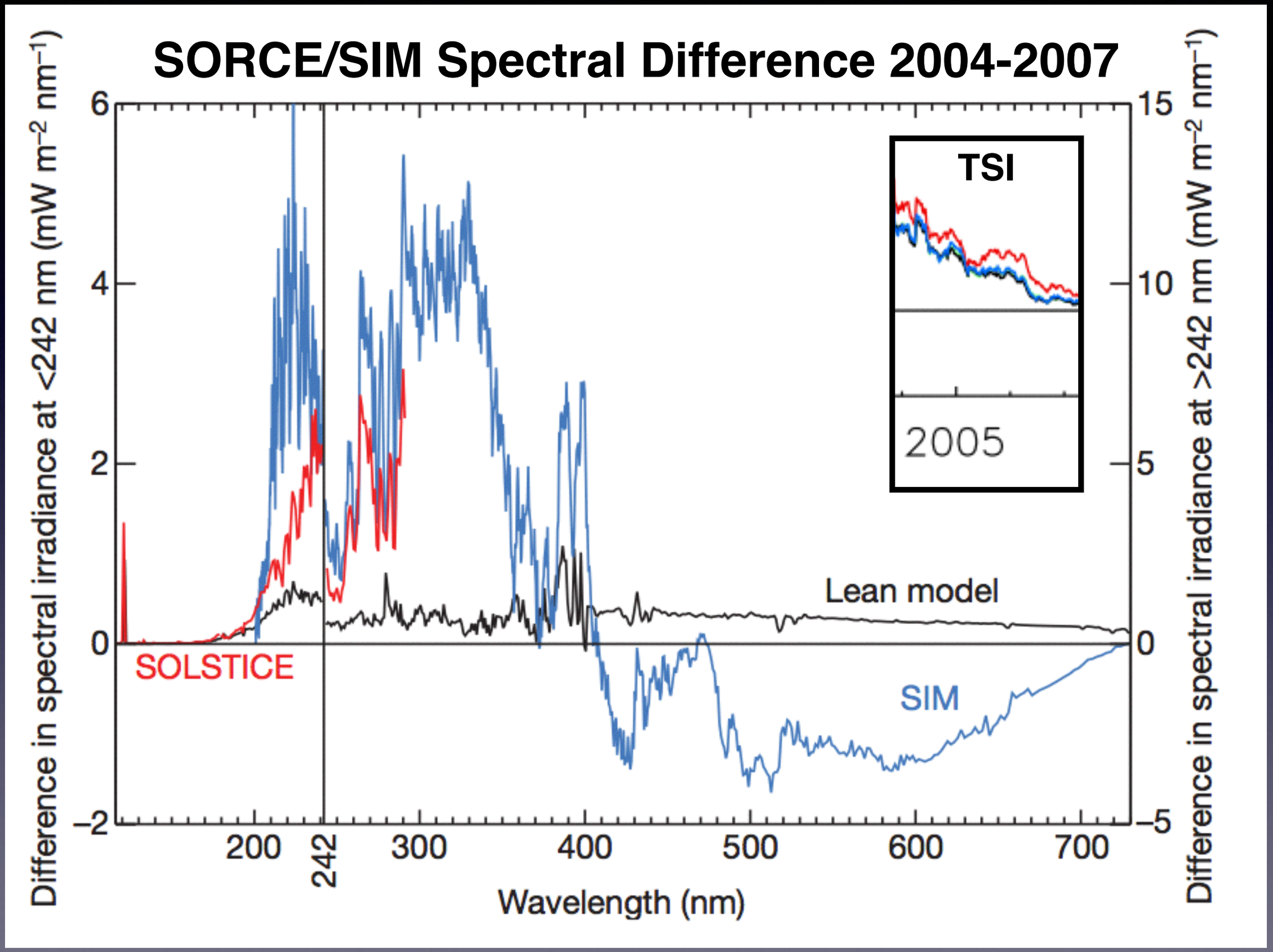




(Yeo et al. 2014, Space Sci. Rev.)

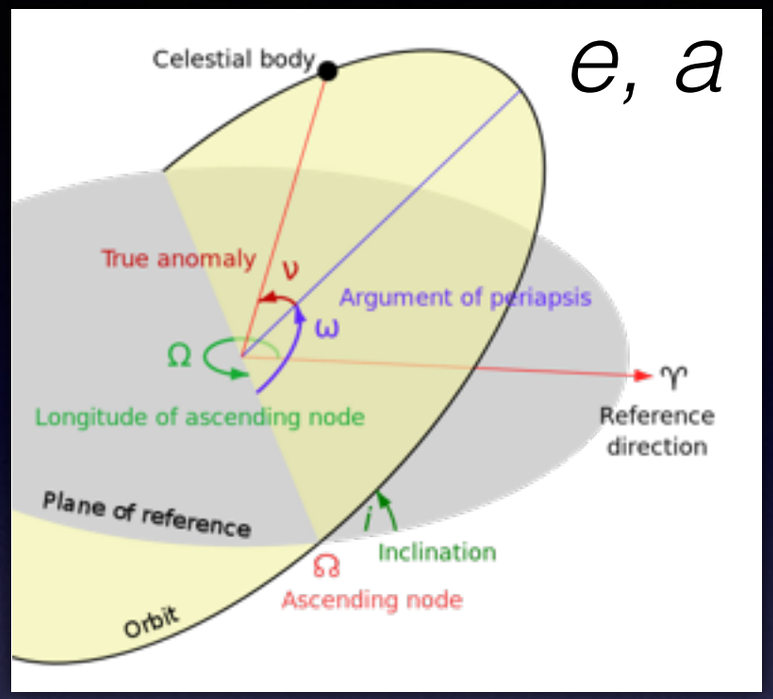

SORCE/TIM TSI Reconstruction
(from IPCC AR5 based on Krivova 2010 & Ball 2012)
TSI [W/m²]
1362.5
1362.0
1361.5
1361.0
1360.5
1360.0
1359.5
1700
1800
1900
2000
Time
0.031%?
0.057%?
G. Kopp, 20 Feb. 2014

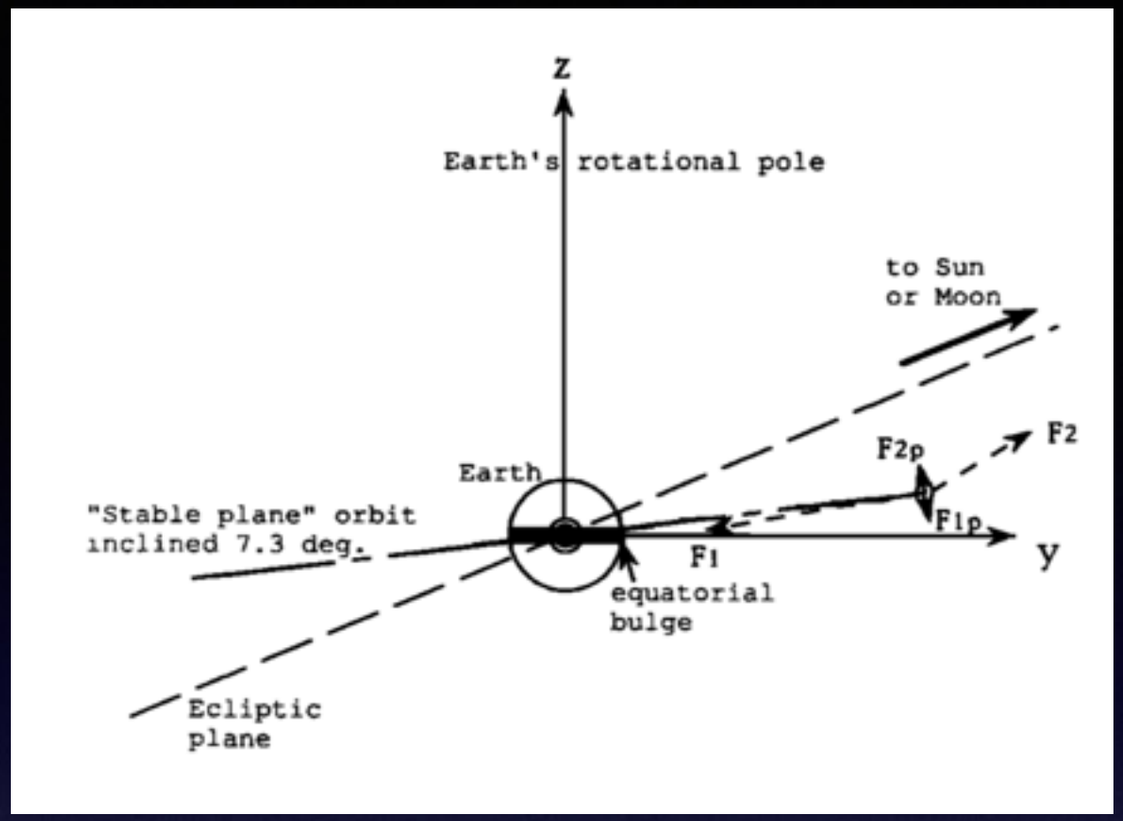


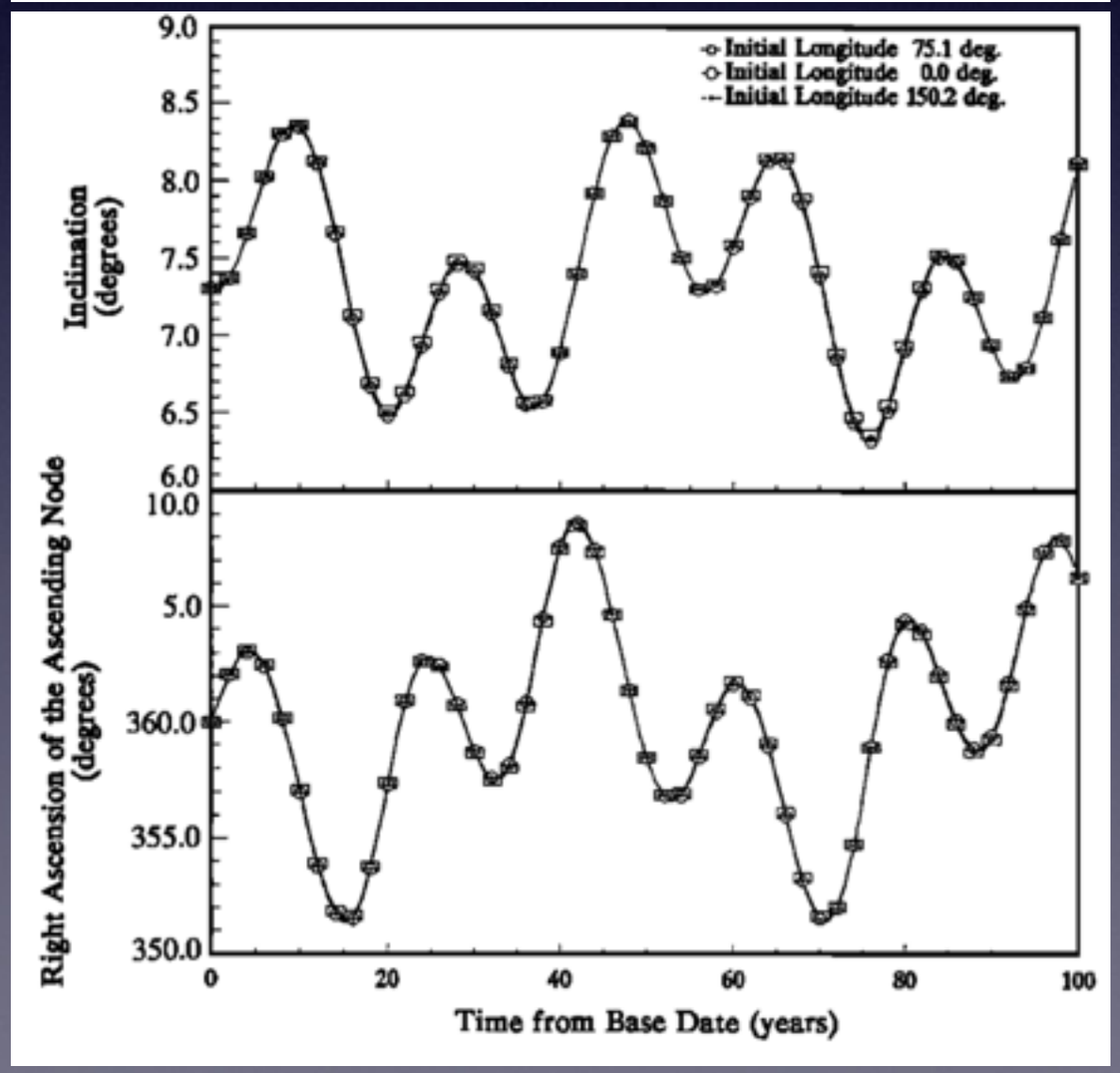
(Haigh et al. 2010)

“There’s no such thing as a stable orbit.”

Stable Orbits



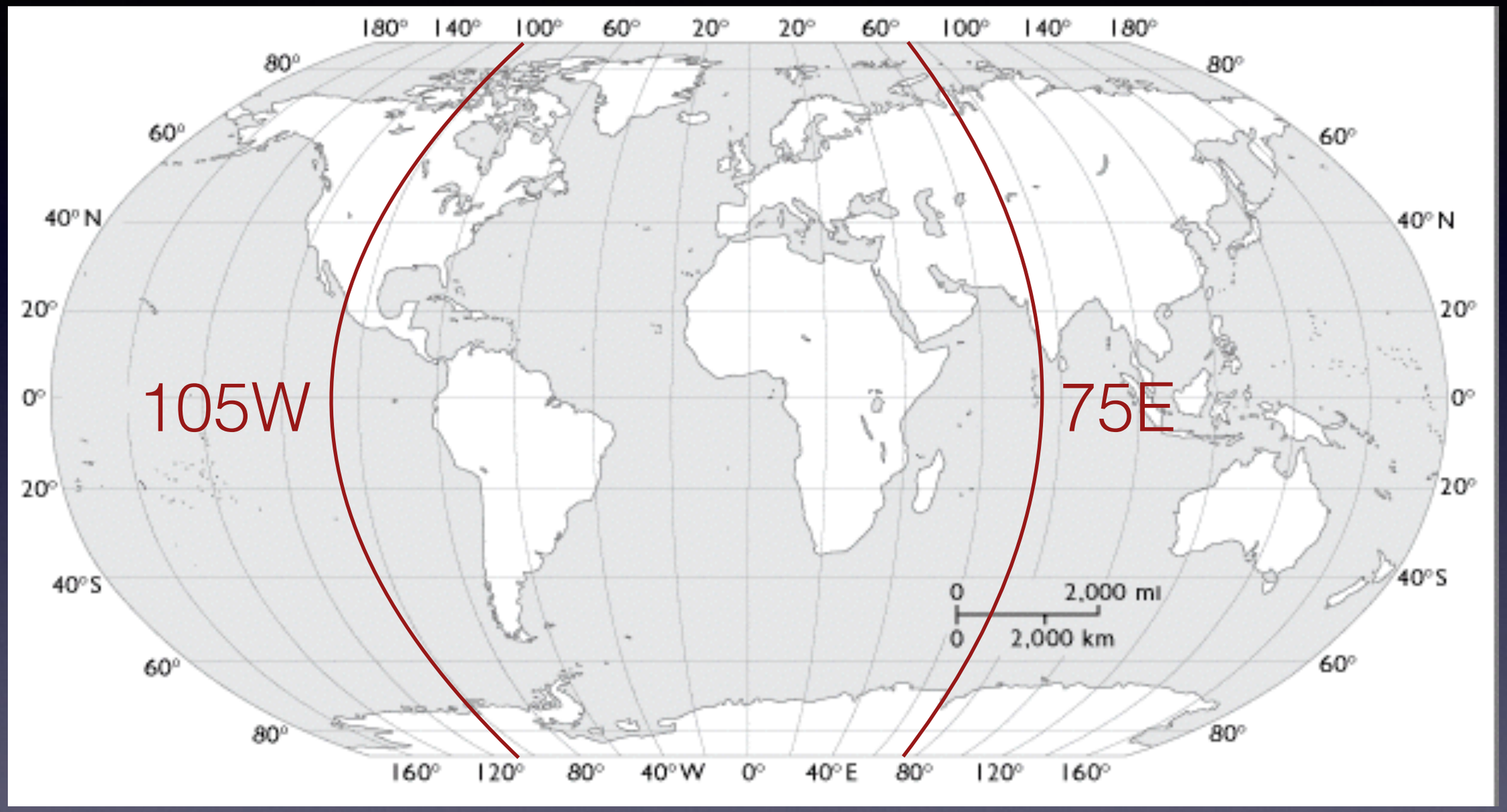




(Freisen et al. 1992)

- See Freisen et al. 1992
- Two stable longitudes: 105°W and 75°E
- "stable plane" exists at 7.3° inclination which has a reduced amplitude of orbital plane excursions
- Proposed as a better alternative for "graveyard orbits" (Rosengren et al. 2013)

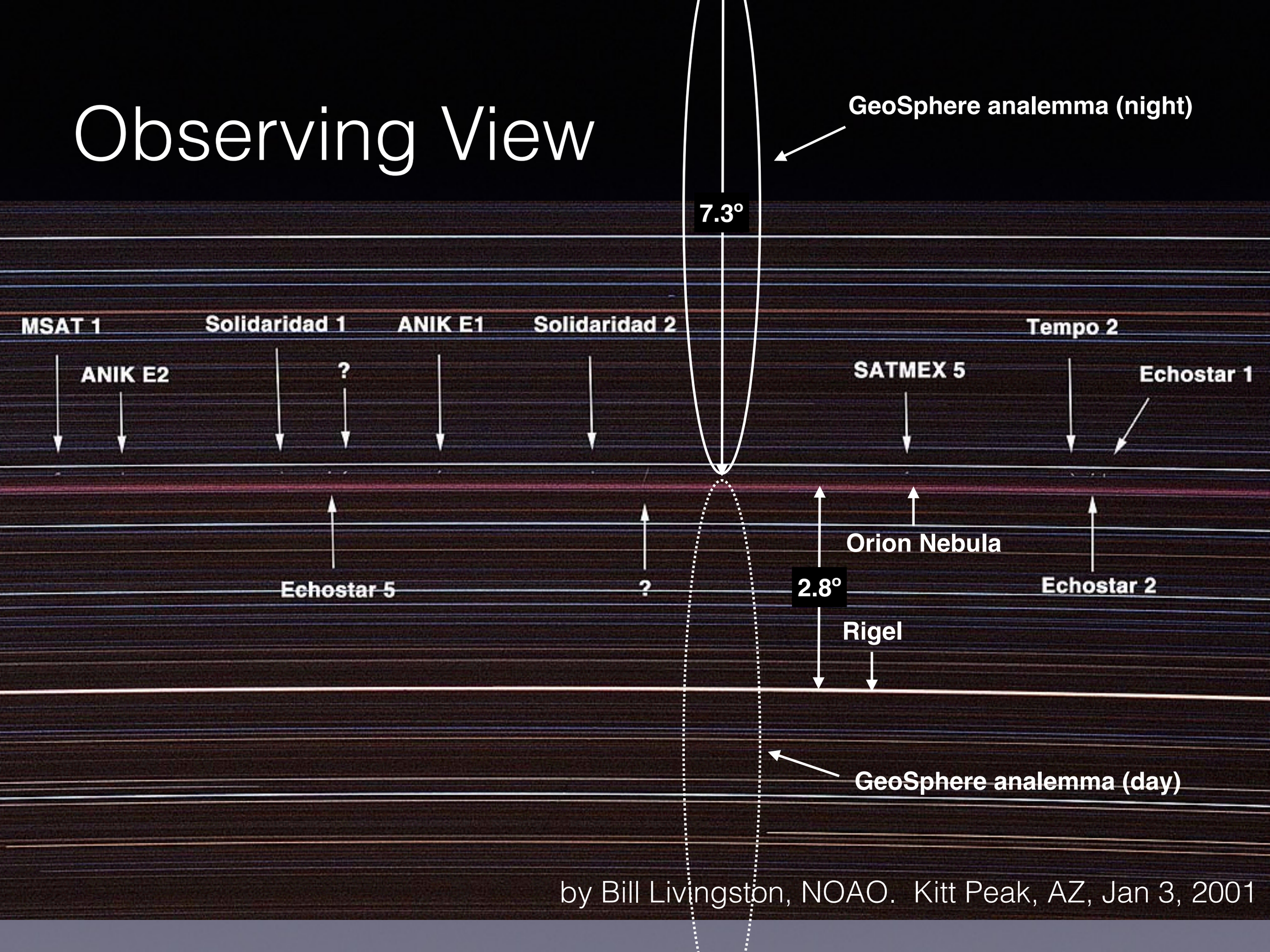
Stable Longitude Observatories



Boulder, CO; Apache Point, NM 105°W
Fairborn Obs., AZ; OAGH, Mexico 110°W
Lowell Observatory AZ; Kitt Peak, AZ 112°W
OAN, Mexico 115°W
CTIO, Chile 70°W

Indian Astronomical Observatory 78°E
Xinjiang Astronomical Observatory, China 87°E
Yunnan Astronomical Observatory, China 102°E

Observing View



by Bill Livingston, NOAO. Kitt Peak, AZ, Jan 3, 2001

“That kind of precision is impossible from the ground”

Robotic photometry 1993-Today

4 telescopes measure 300 Sun-like stars

Lou Boyd, input

Greg Henry, output

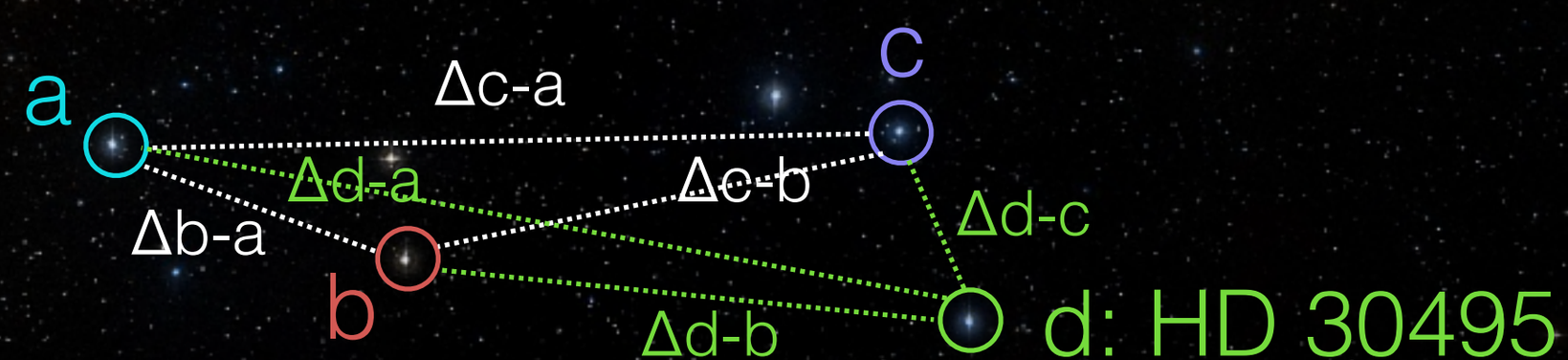
Tennessee State Univ. telescopes at Fairborn Observatory

Automated Photometric Telescopes (APTs)

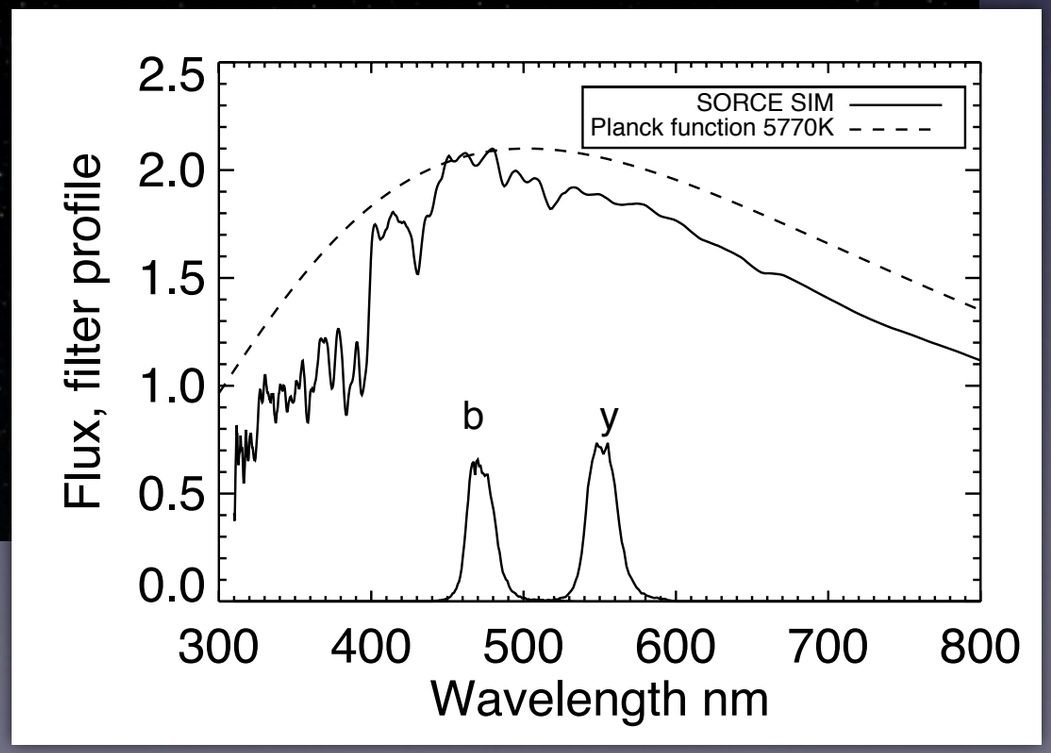
APT Group Observations

<u>Observations</u>

a, b, c, d,
a, sky_a,
b, sky_b,
c, sky_c,
d, sky_d,
a, b, c, d



20-30 s integrations per (*b*, *y*) band
~13 min per group

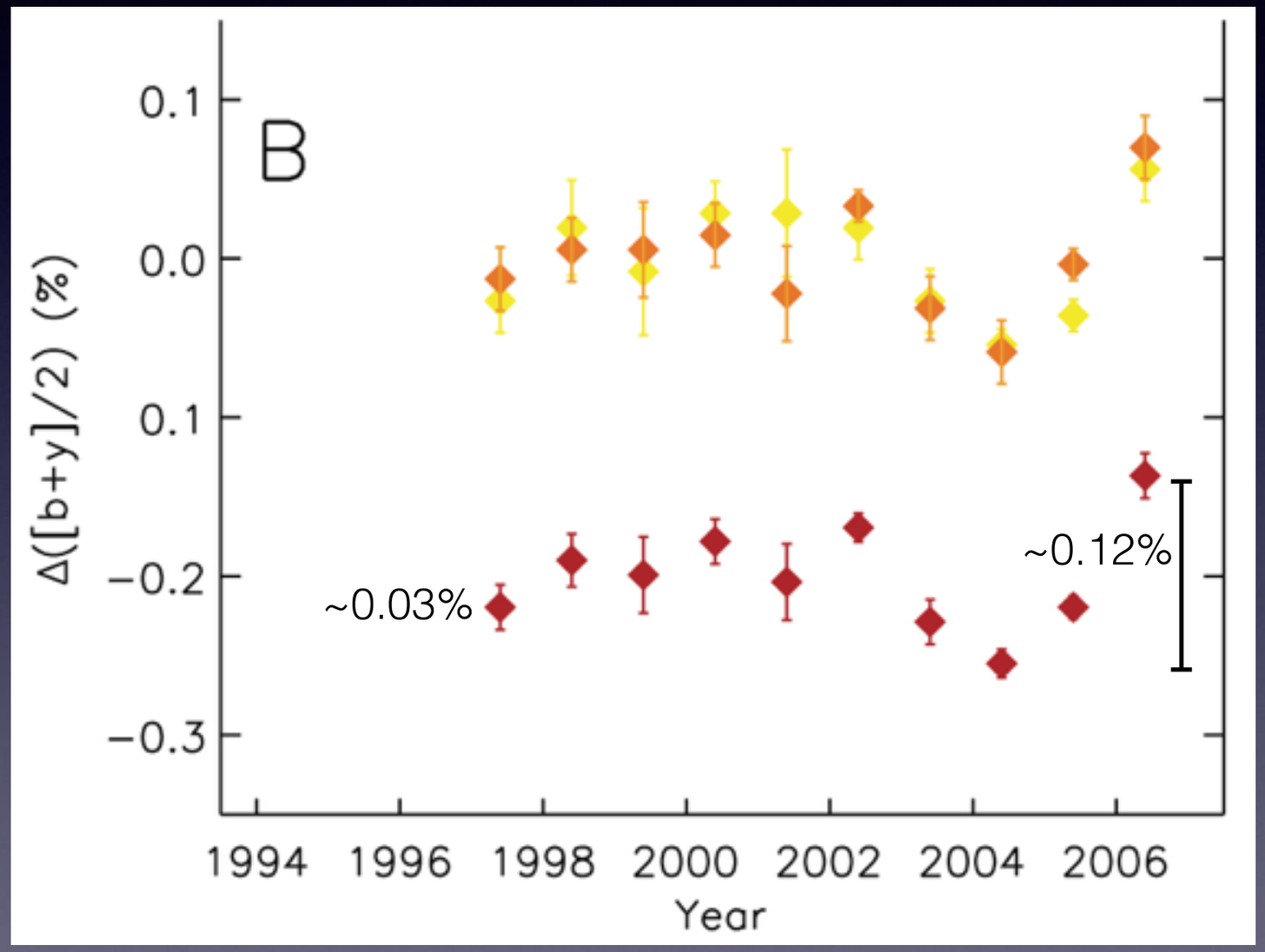


Could the APT program detect solar cycle variation?

~0.07% TSI → ~0.0010 mag *b, y* → ~0.1% *b, y*
(Lockwood 2007)

Yes!, e.g. "solar twin" 18 Sco with comparison star scatter ~0.02%

(Hall et al. 2007)



Achieving Precision

Every night:

Single difference: $x = t - c$

Repeated measurements: $\sigma_x^2 = \sigma_t^2 + \sigma_c^2$

Group of *N* comparisons: $\langle c \rangle_N = \frac{1}{N}\sum_{i=1}^{N} c_i \quad \sigma^2_{\langle c \rangle_N} = \frac{1}{N^2}\sum_{i=1}^{N} \sigma_i^2 \approx \frac{1}{N}\sigma_c^2$

Group difference: $x_N = t - \langle c \rangle_N, \qquad \sigma_x^2 = \sigma_t^2 + \frac{1}{N}\sigma_c^2$

Repeat *M* group meas.:

$$\langle x \rangle_{NM} = \frac{1}{M}\sum_{j=1,M} \left(t_M - \langle c \rangle\right),$$

$$\sigma^2_{\langle x \rangle_{NM}} = \frac{1}{M}\left(\sigma_t^2 + \frac{1}{N}\sigma_c^2\right)$$

Example *N* = 10, *M* = 5; 100 s integrations → 1.4 h

Achieving Precision

With one good group and *n* good nights in a year:

$$\sigma_{\langle c \rangle_{NMn}} \approx \sqrt{\frac{1}{nMN}} \sigma_c$$

with:

N ~ 10 (atmosphere, slew time)

M ~ 5 (integration time)

n ~ 50 (yearly revolution, weather)

σ_C ~ 0.001 mag (comparison variability)

$$\sigma \approx 2 \times 10^{-5} \text{ mag} \approx 0.002\%$$

“GeoSphere will reflect light from the Earth and Moon, too.”

GeoSphere Flux Ratios

$$\mathcal{F}_{\oplus,90^\circ}/\mathcal{F}_\odot \approx 4\times10^{-3}$$

$$\mathcal{F}_{\oplus,20^\circ}/\mathcal{F}_\odot \approx 5\times10^{-5}$$

$$\mathcal{F}_{\mathrm{Moon}}/\mathcal{F}_\odot \approx 3\times10^{-6}$$

Forward Model

$$\mathcal{F}_G = \mathcal{F}_{\odot G}(r_{oG}, r_{\odot G}, \alpha, \mathcal{F}_\odot, a_G)$$

$$+\mathcal{F}_{\oplus,\mathrm{refl}}(r_{oG}, r_{\odot G}, \alpha, a_\oplus, \mathcal{F}_\odot, a_G)$$

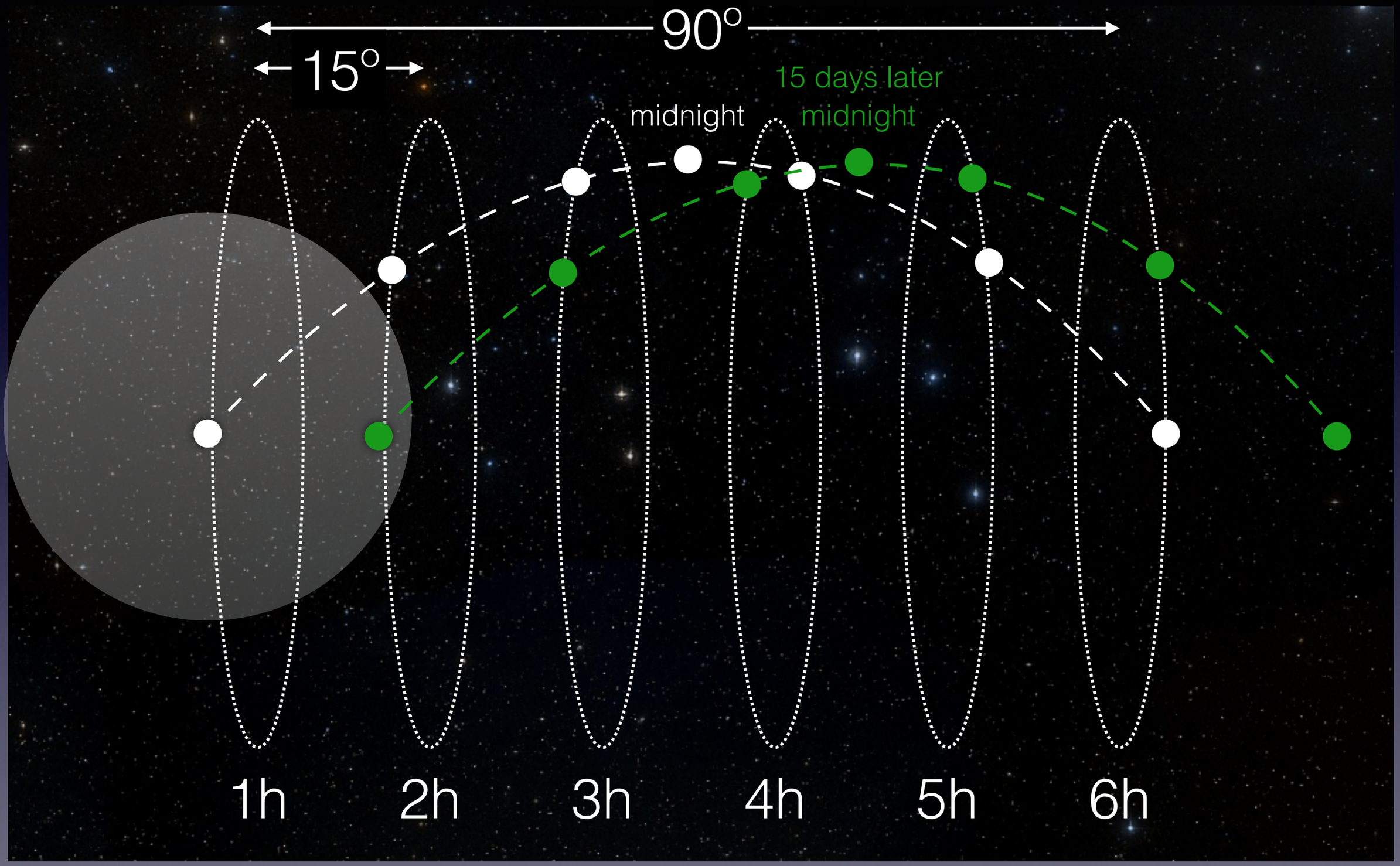
$$+\mathcal{F}_{\oplus,\mathrm{refr}}(r_{oG}, r_{\odot G}, \alpha, T_\oplus, \mathcal{F}_\odot, a_G)$$

Inverse Problem

$$\{\mathcal{F}_G, r_{oG}, r_{\odot G}, \alpha, a_G\} \rightarrow \{\mathcal{F}_\odot, a_\oplus, T_\oplus\}$$

“GeoSphere would move with respect to the background sky throughout the year… comparison stars won’t stay close by.”

GeoSphere Group Observations



“If your basis of comparison is always changing, observational errors will constantly *add*”

Achieving Precision

Continuous Measurement Throughout Year

$$d_4 = (\overbrace{c_4 - c_3} + \overbrace{c_3 - c_2} + \overbrace{c_2 - c_1}), \quad \sigma^2_{d_4} = (\sigma_4^2 + 2\sigma_3^2 + 2\sigma_2^2 + \sigma_1^2)$$

$$d_j = (c_j - \ldots - c_1), \quad \sigma^2_{d_j} = (\sigma_j^2 + \Sigma + \sigma_1^2)$$

$$\sigma^2_{d_j} = 2(j-1)\sigma_c^2$$

For *L* longitude bands of *N* stars over *n* nights:

$$\langle d \rangle_L = \frac{1}{L}\sum_{j=1}^{L} d_j, \quad \sigma^2(\langle d \rangle_L) = \frac{1}{L}\sum_{j=1}^{L} \sigma^2_{d_j} = (L-2)\sigma_c^2 \rightarrow \frac{(L-2)}{nN}\sigma_c^2$$

e.g. $L = 25, N = 10, n = 50,\ \sigma^2(\langle d \rangle_L) \approx 0.046\sigma_c^2.$

$$\sigma_c \approx 0.001 \rightarrow \sigma \approx 2 \times 10^{-4}\ \mathrm{mag} \approx 0.02\%$$

Average over many years for a 1/√Y reduction

“Space isn’t empty – the GeoSphere will *degrade*”

GeoSphere Albedo Stability

- Oxidation: Negligible ~1-10 O/cm^3 at 42,000 km
- Micrometeorite cratering: Extrapolating from LEO measurements, ~0.45% area/century
  - $a(t) = a_0 - kt(a_0 - b)$
  - Pre-crater before launch? ($b \rightarrow a_0$)
- Photochemical changes?
  - Use **simple** material: metal, alloy, or crystalline material?
  - Characterize/pre-burn before launch?
- **In-situ monitoring via ground-based lasers during eclipses?**

“It is just too expensive to launch something that big into such a high orbit.”

Engineering Considerations

- Materials?
- How to launch a *d*-meter inert object into a specific orbit?
- Expandable?
  - ~~Inflatable?~~
  - Hokkaidō Hoberman Sphere, 1.4→5.9 m
  - NRL PERCS design 1→10 m
- Piggyback mission as a 2nd faring?

“It’s still too expensive. You will never get funding for a century-long program.”

Conclusions

- The GeoSphere program could provide a measurement of spectral irradiance variations in visible wavelengths with sufficient precision to monitor secular variations above ~0.002% (sparse series) or ~0.02% (continuous series)
- Stable orbit allows ground-based observation *indefinitely.*
- Needs work investigating suitable materials, degradation, and deployment strategy.

see Judge & Egeland 2015, MNRAS Letters

“There aren’t enough stable comparison stars in the sky”

Stable Comparison Abundance

PERCENTAGE OF STARS WITH LONG-TERM VARIABILITY ($\sigma_{long} \geq 0.0005$ mag) AS A FUNCTION OF $B-V$

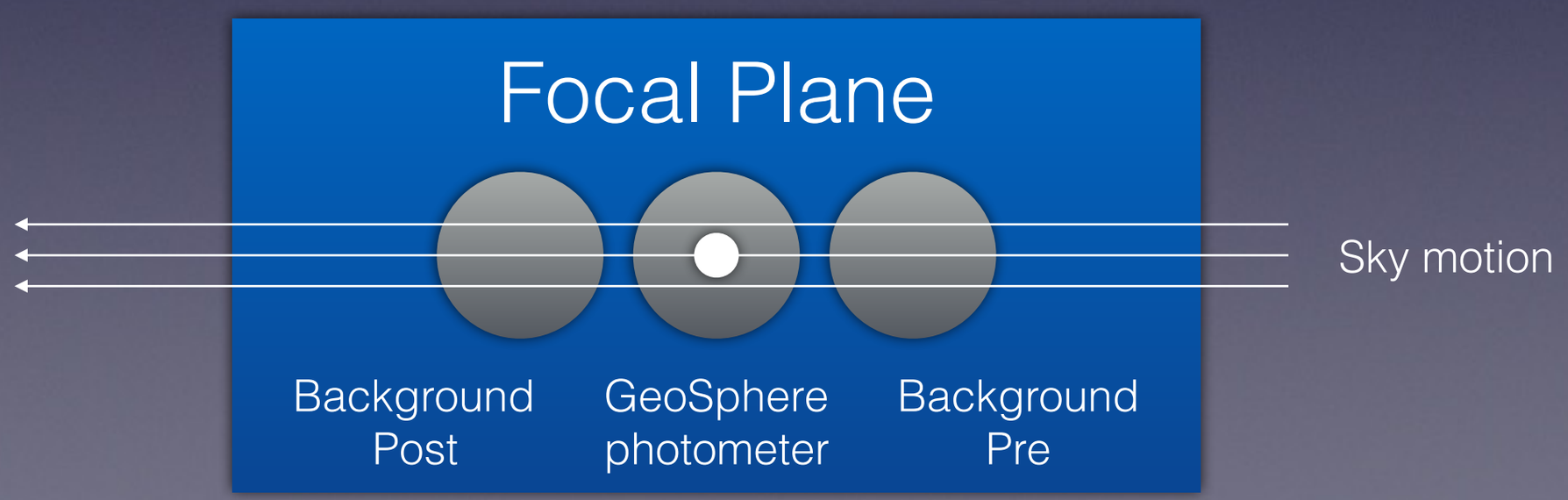
$B-V$ Range (mag) (1)	Main-Sequence Spectral Type (2)	N_{stars} (3)	Percentage Variable (4)
0.1–0.2 ……	A4–A7	4	0.0
0.2–0.3 ……	A8–A9	8	12.5
0.3–0.4 ……	F0–F3	30	36.7
0.4–0.5 ……	F4–F7	76	57.9
0.5–0.6 ……	F8–G0	61	59.0
0.6–0.7 ……	G1–G6	38	65.8
0.7–0.8 ……	G7–G9	14	57.1
0.8–0.9 ……	K0–K1	21	81.0
0.9–1.0 ……	K2–K3	17	70.6
1.0–1.1 ……	K4	9	33.3
1.1–1.2 ……	K5	9	66.7
1.2–1.3 ……	K7	2	100.0

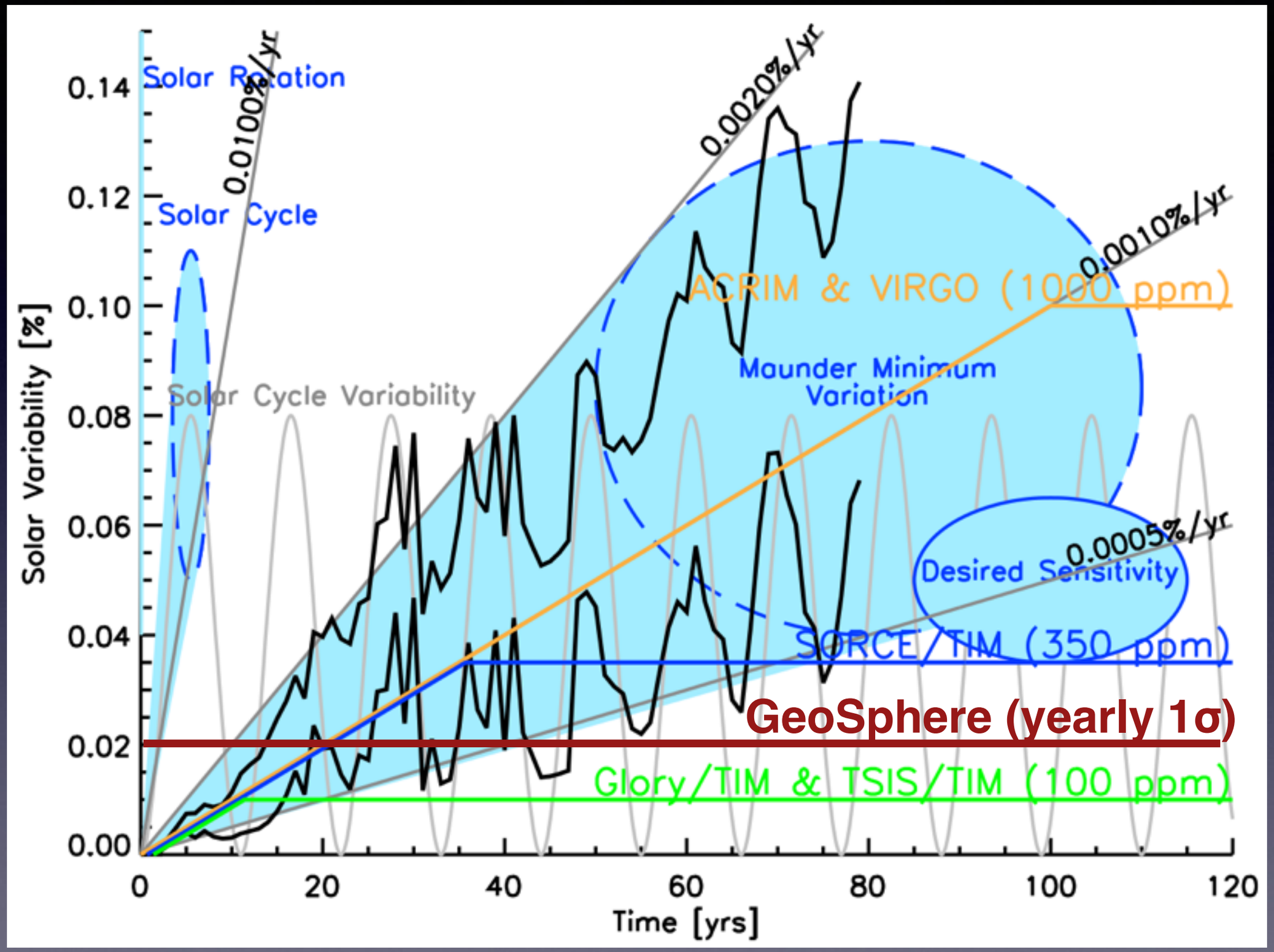
(Henry 1999)

“GeoSphere would *move* with respect to the stars! – your data would be polluted by background stars”

Stellar Noise

- Background stars pass behind GeoSphere moving at 15″ · cosδ · t, creating photometric noise for observations
- e.g. 5″ aperture, mag 10 GeoSphere, 100 s integrations: 1 in 100 integrations contain object of comparable magnitude
- Therefore, one needs to measure flux of these passing stars to subtract from the signal





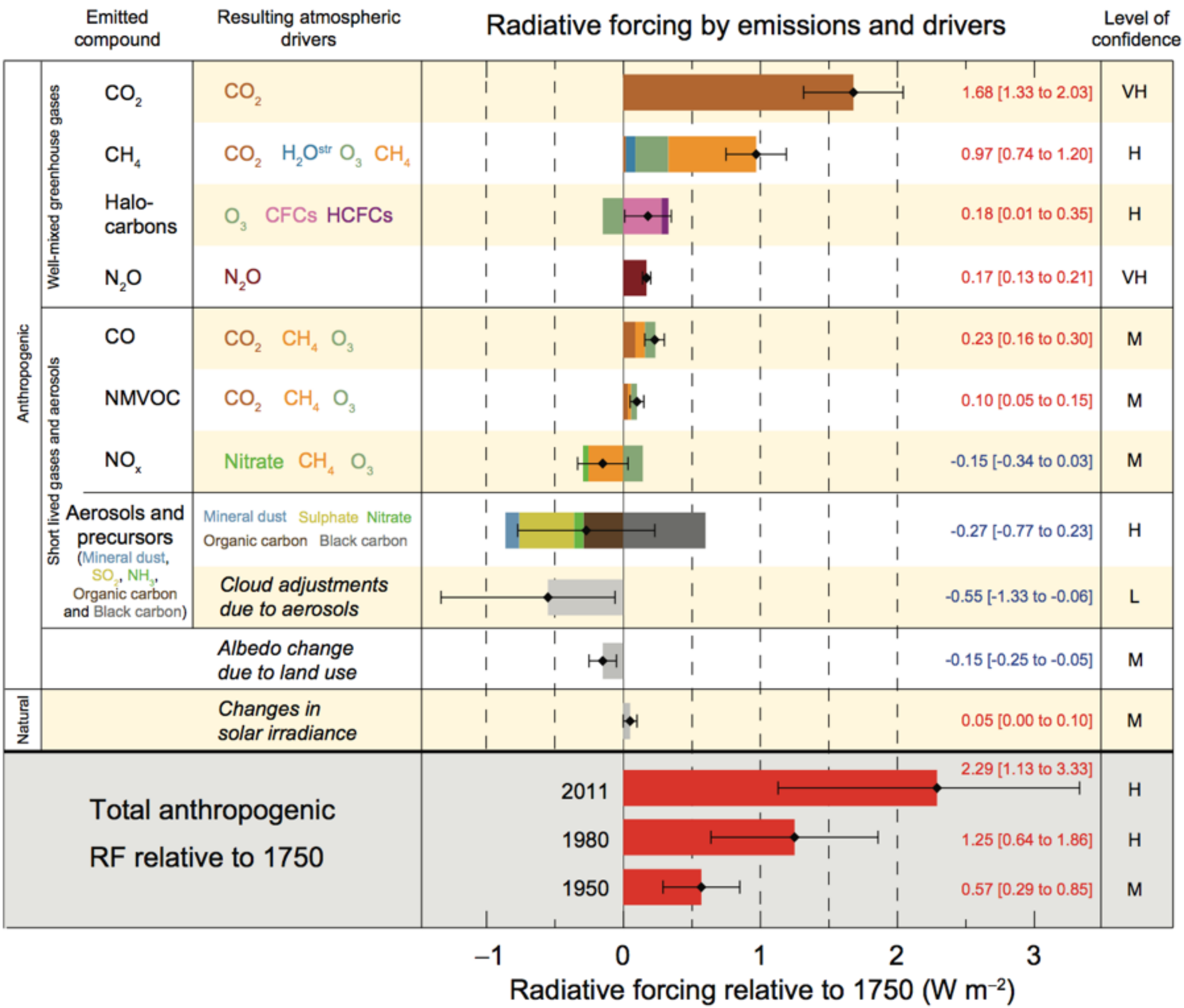
(Kopp & Lean 2011)
(Lean et al. 2005)

Other Applications

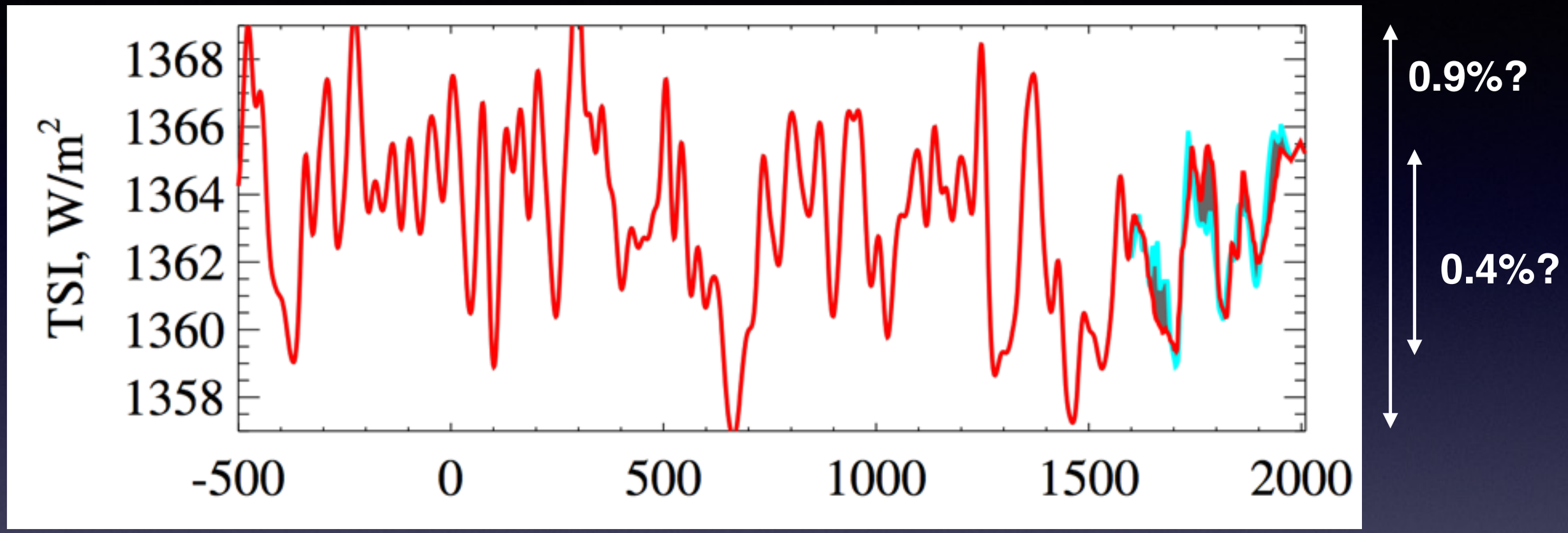
- Earth albedo variations
- Measure *uy* variations to check spectral cycle phase relationships
- Radar/Laser calibration sphere (c.f. PERCS, Bernhardt et al. 2008)
- $(B\text{-}V)_{Sun}$; Sun as a calibration “standard star”
- Large catalog of flat-activity stars

Observation Program

- In a 6h night, GeoSphere moves 6h in RA across the celestial sphere
- Its position at local midnight moves ~1 deg/day, or ~1/15 h RA/day
- Therefore, GeoSphere can be observed in conjunction with an object for about 6·15=90 days
- APT stars have one group of comparison stars; GeoSphere must have many groups; a large ensemble

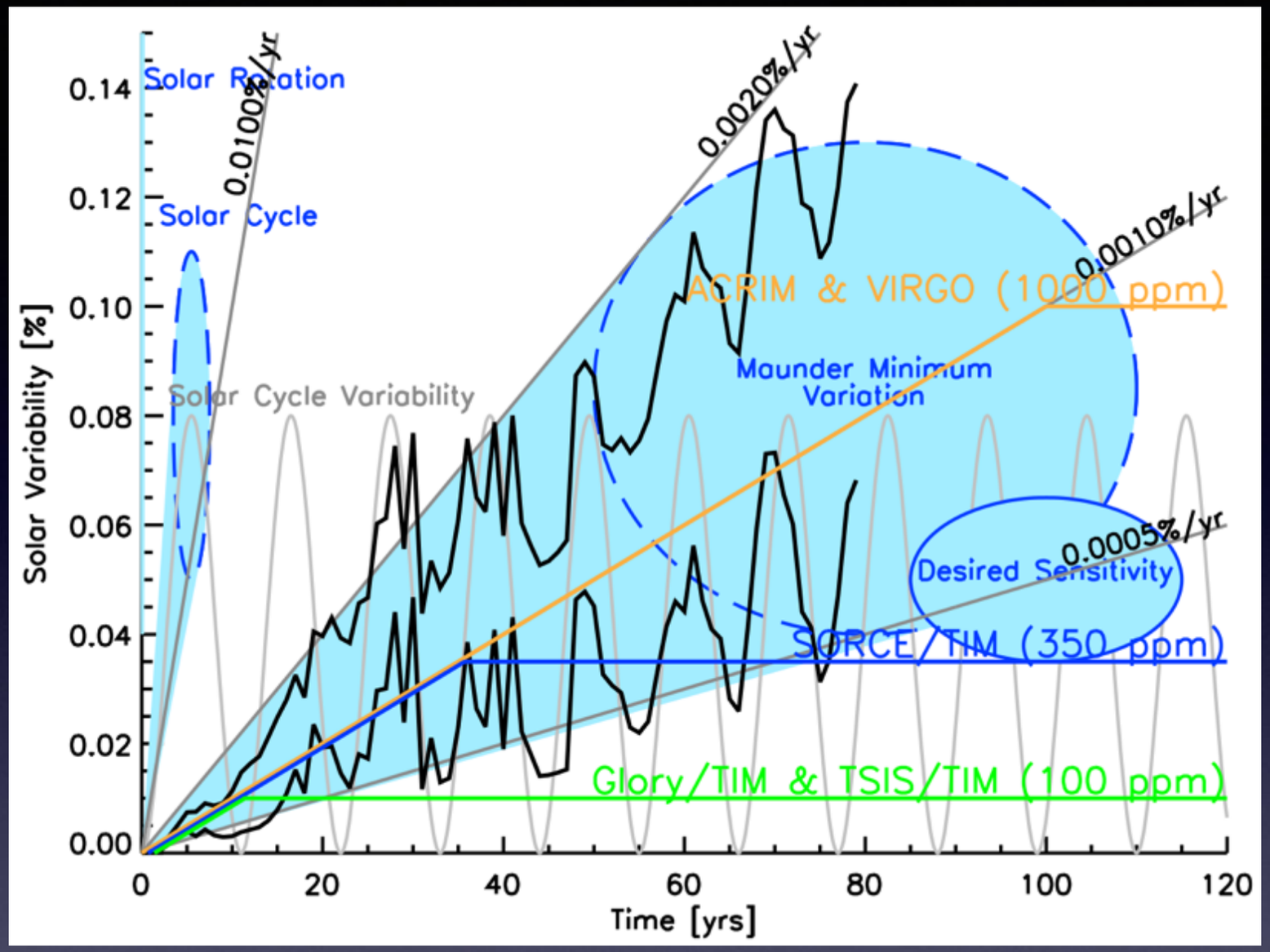


(Fig. SPM.5, IPCC 5th Assessment Report, 2013)



(Shapiro et al. 2011)

"… the observational data do not allow to select and favor one of the proposed reconstructions. Therefore, until new evidence becomes available, we are in a situation where different approaches and hypothesis yield different solar forcing values."



"Directly detecting [Maunder Minima-like] changes requires 1) instrument stabilities <0.001%/year and **measurement continuity**, and/or 2) measurements having **absolute accuracy** uncertainties <0.01%, as intended for the Glory/TIM and TSIS/TIM instruments, so that measurements separated by several decades could detect secular changes."

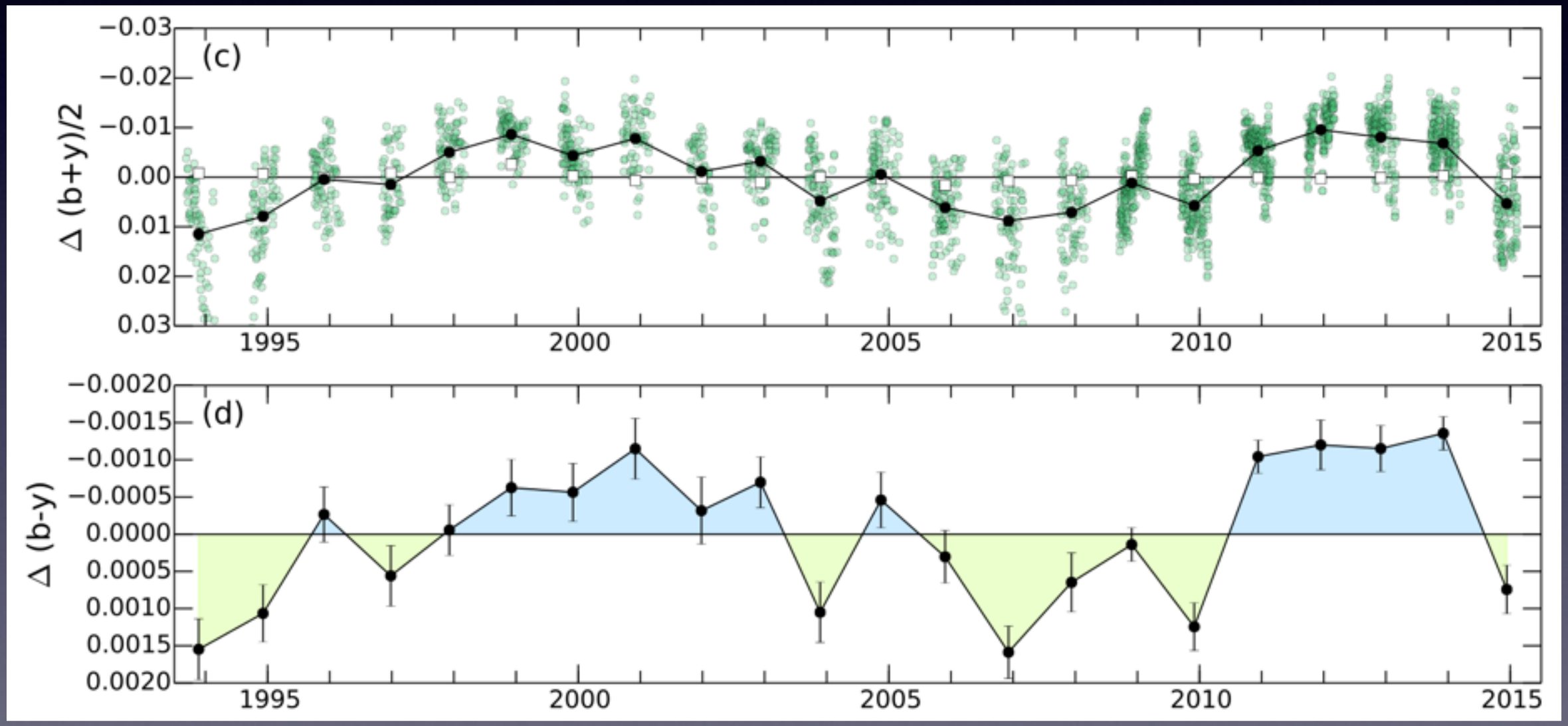
(Kopp & Lean 2011)

0.001 mag change ≈ 0.1%

HD 30495 variability

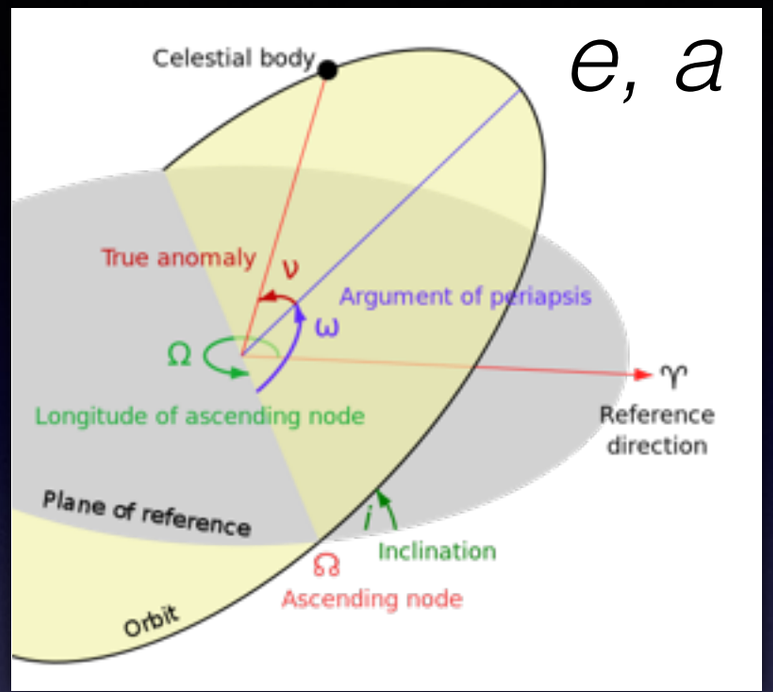
target amplitude ~ 0.02 mag ~ 1.8%
target uncertainty ~ 0.0006 mag ~ 0.059%

comp. yr-yr scatter ~ 0.0008 mag ~ 0.073%
comp. uncertainty ~ 0.0002 mag ~ 0.018%

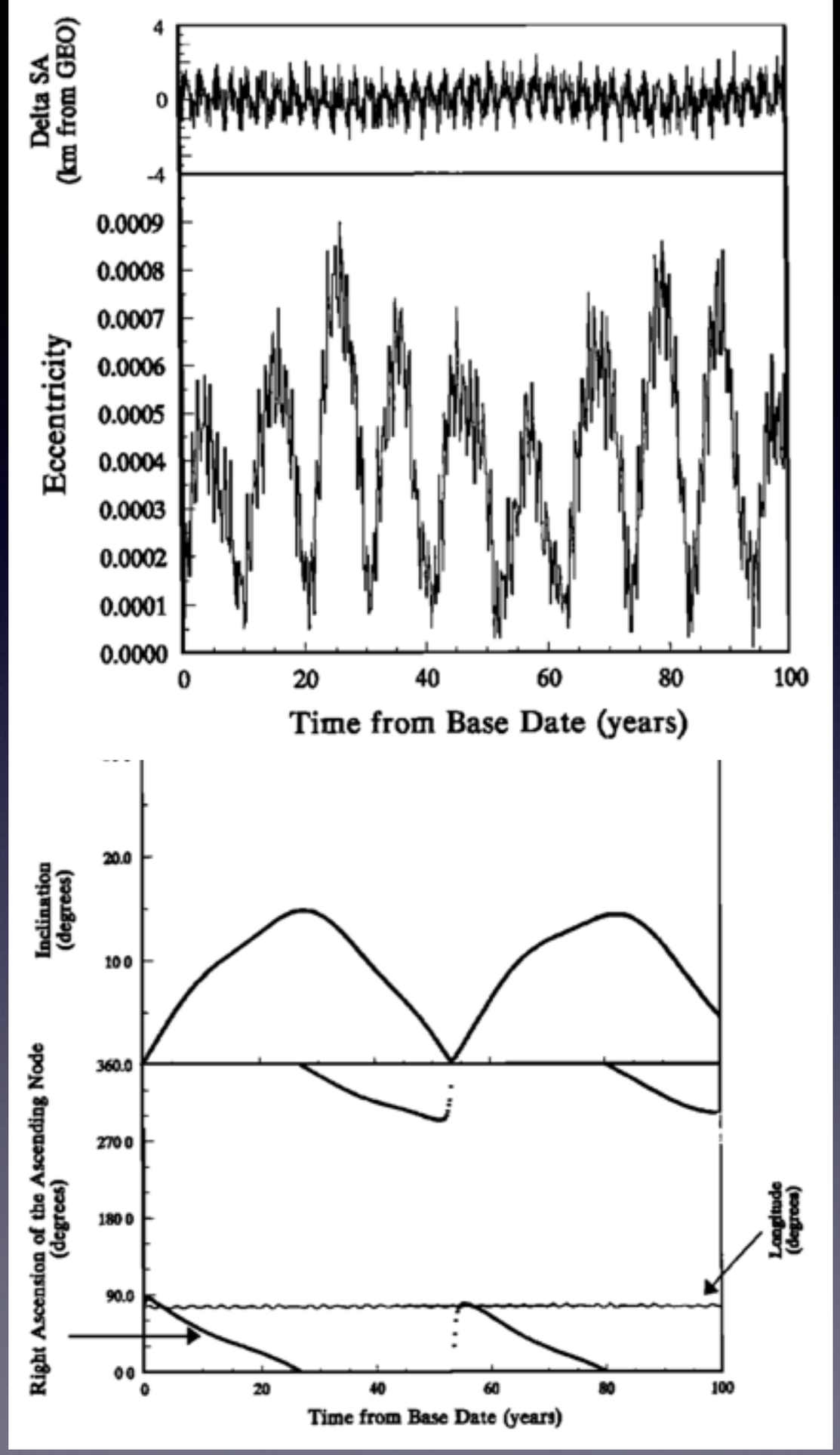


target amplitude ~ 0.003 mag ~ 0.28%
target uncertainty ~ 0.0003 mag ~ 0.027%

Stable Orbits



- Freisen et al. 1992 numerically simulated unpowered geosynchronous orbits on century time scales
- "worst case" radii excursions of up to 50 km for all near-geosynchronous orbits
  - ~1 mmag variation ⇒ in situ tracking needed
  - Observations: INTELSAT, abandoned 1969
- "Stable longitudes" exist at 75E and 105W about which orbits oscillate



(Freisen et al. 1992)