Solar Oblateness and SunSketcher*

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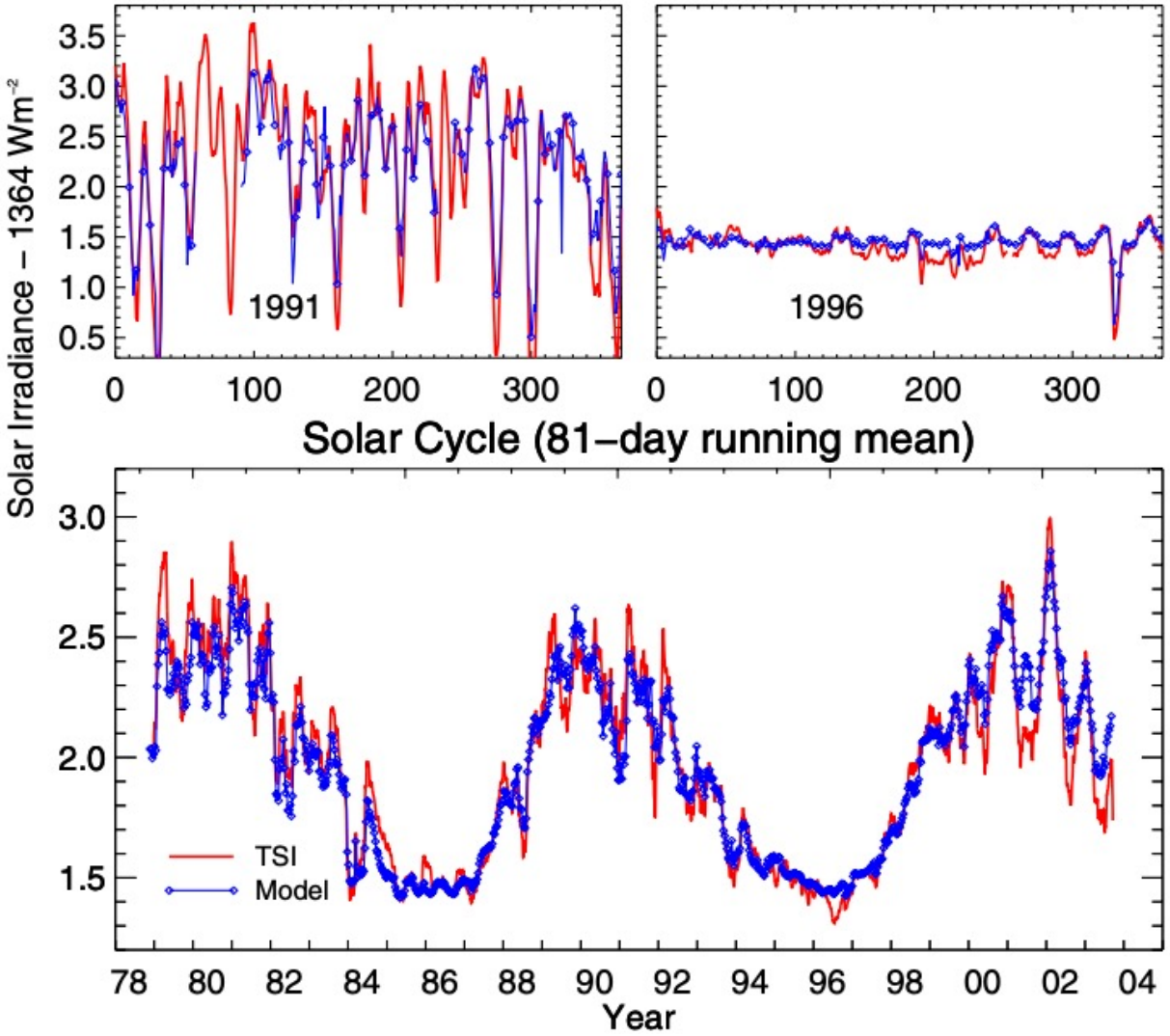
***The SunSketcher Team: Gordon Emslie, Greg Arbuckle, Jeff Galloway with a diverse and talented team of WKU undergraduate students*

*Two themes of my research since 1978:
How bright is the Sun?
How round is the Sun?

Basic Solar Astronomy

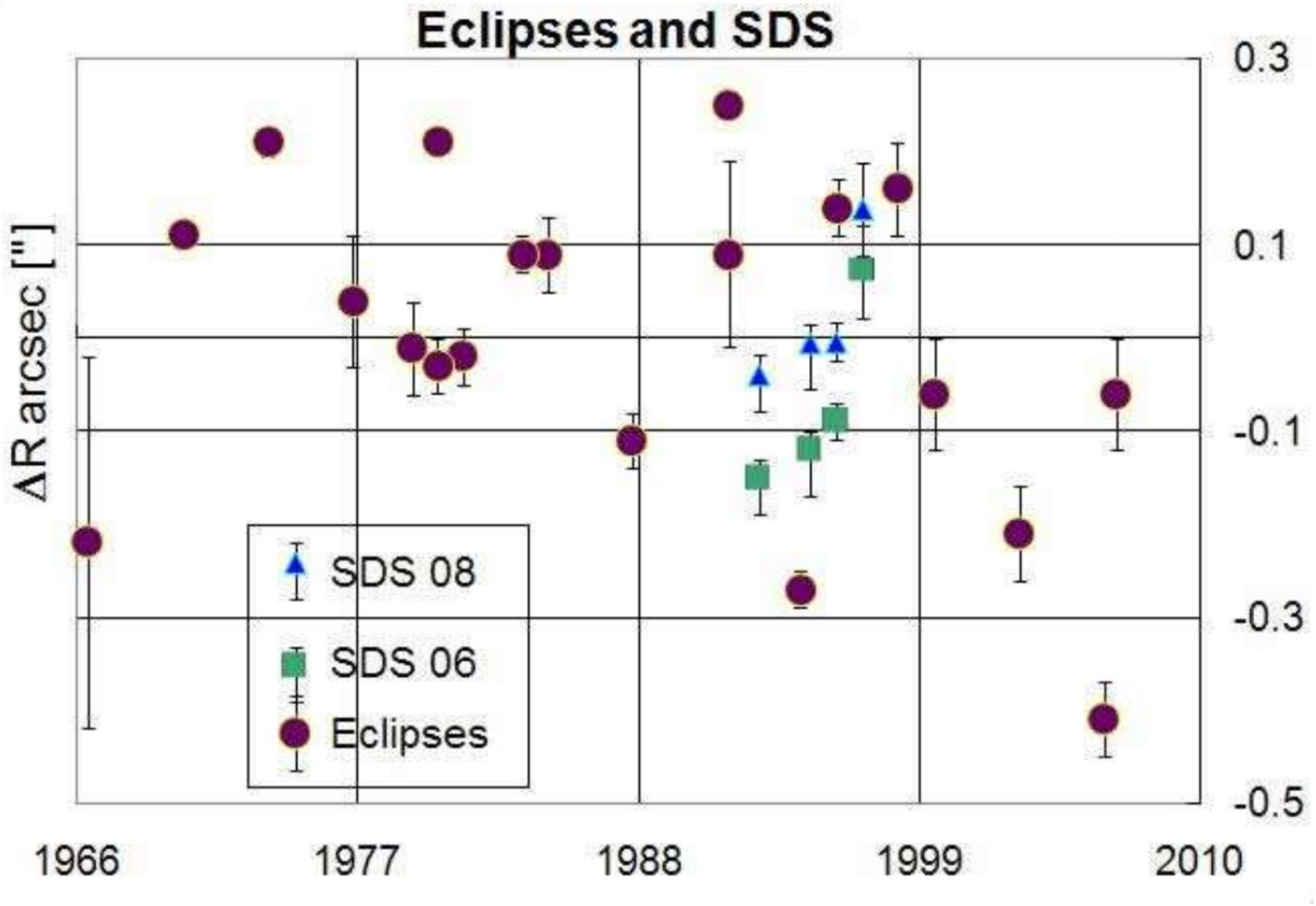
- From early times, at low angular resolution:
  - The solar radius (Aristarchus, 250 BC?)
  - The solar spectrum (Newton; Fraunhofer…)
  - The solar constant (1980s research)
  - Helioseismology (Woodard, 1987)
  - The shape of the Sun (SunSketcher)
- These are Sun-as-a-star research areas

The “solar constant” varies



Fröhlich-Lean 2005

The solar radius varies??



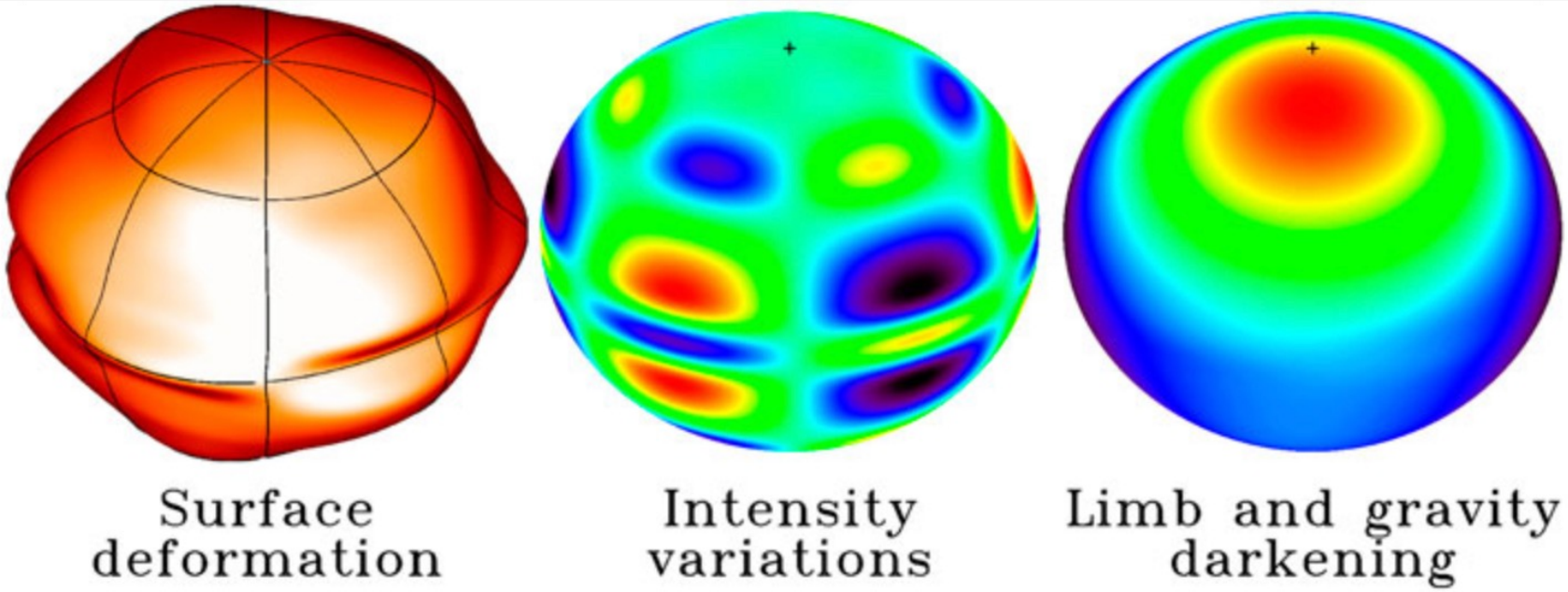
Meftah *et al.* 2015

Why should the Sun *not* be round, and so what if it isn't?

1) Rotation
2) Pulsation
3) Convection
4) Magnetic fields

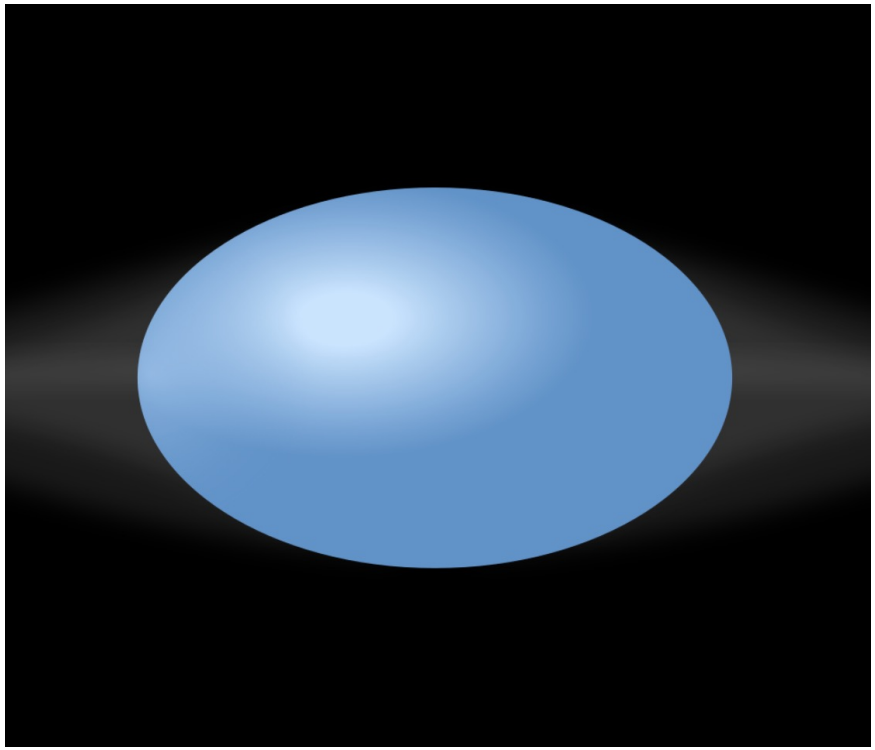
The solar surface reflects internal processes, which we otherwise know about via neutrinos, "helioseismology," and maybe theory.

Odd stellar shapes



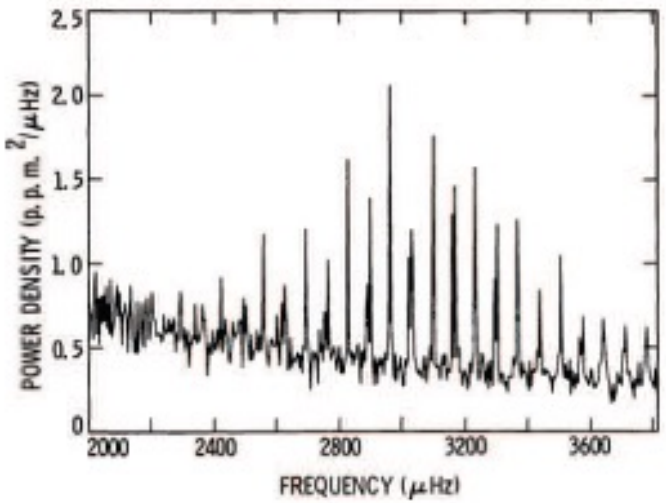
- The reason this is interesting is that the surface shape reflects internal dynamics, supplementing “asteroseismology”

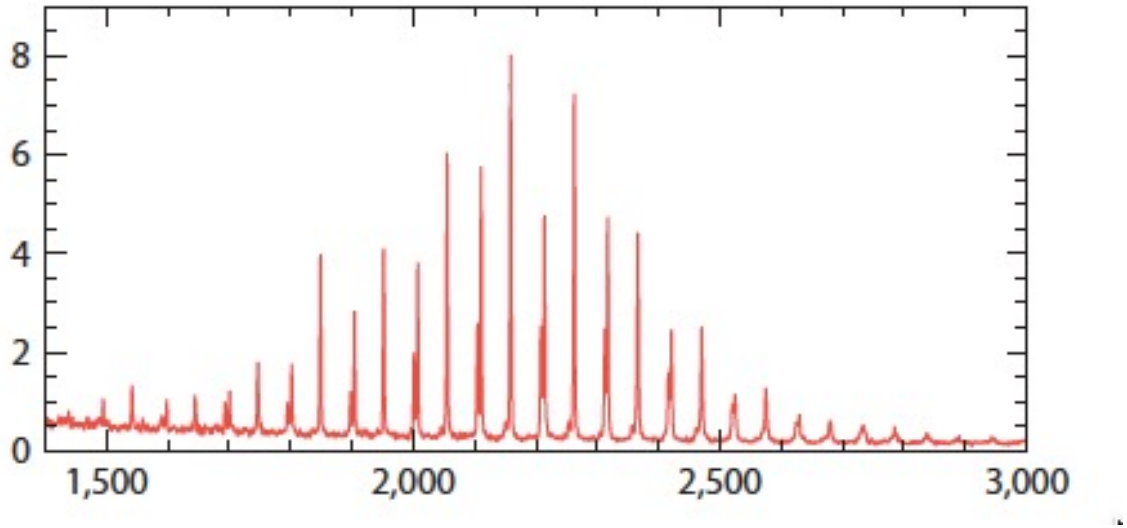
Achernar



• Alpha Eri, a rapidly rotating star with mean radius about 8x solar. It's a good illustration of "rotational darkening" and Von Zeipel's theorem. Roughly to scale.

Digression on “Asteroseismology” - standing waves at specific frequencies





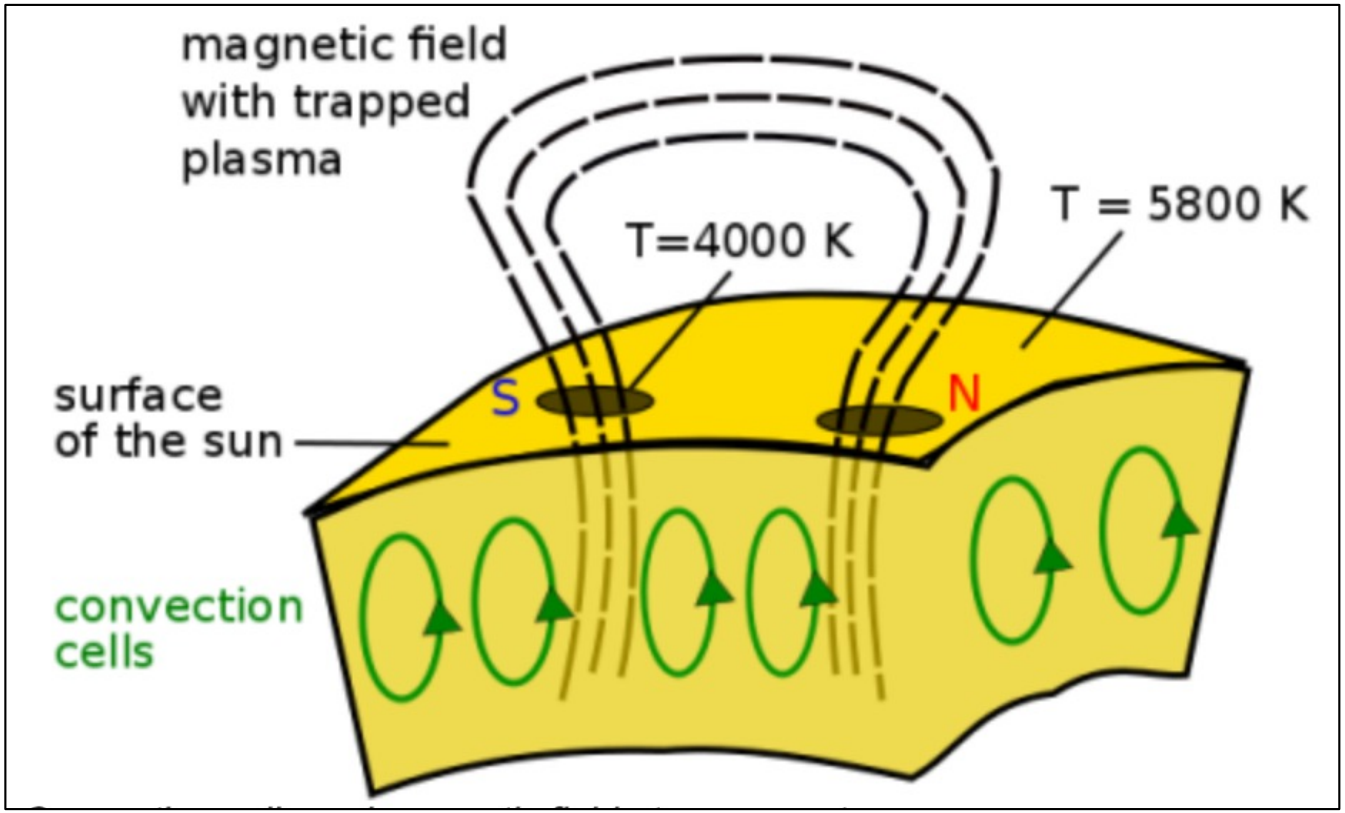
The Sun (Woodard, 1987)

- solar-type
- period ~27 d
- 4.85 x 10^{-6} pc
- magnitude -27

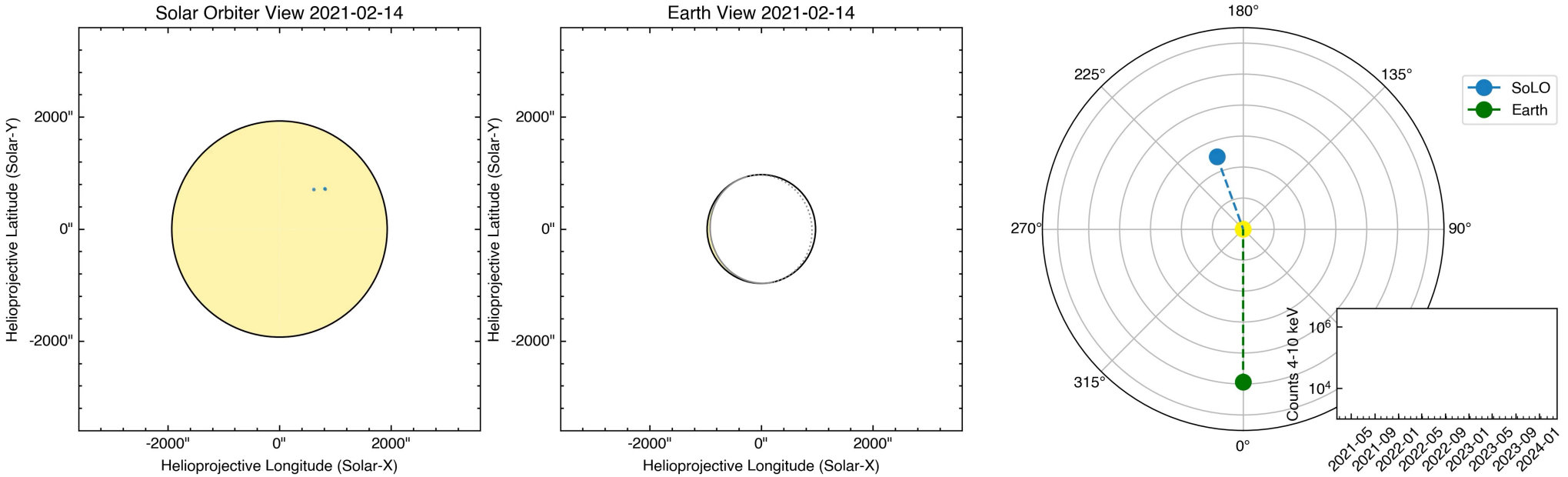
16 Cyg A (Chaplin & Miglio, 2013)

- solar-type
- period 24 d
- 21 pc
- magnitude 6

Solar Magnetic Activity



Solar Magnetic Activity: Flares

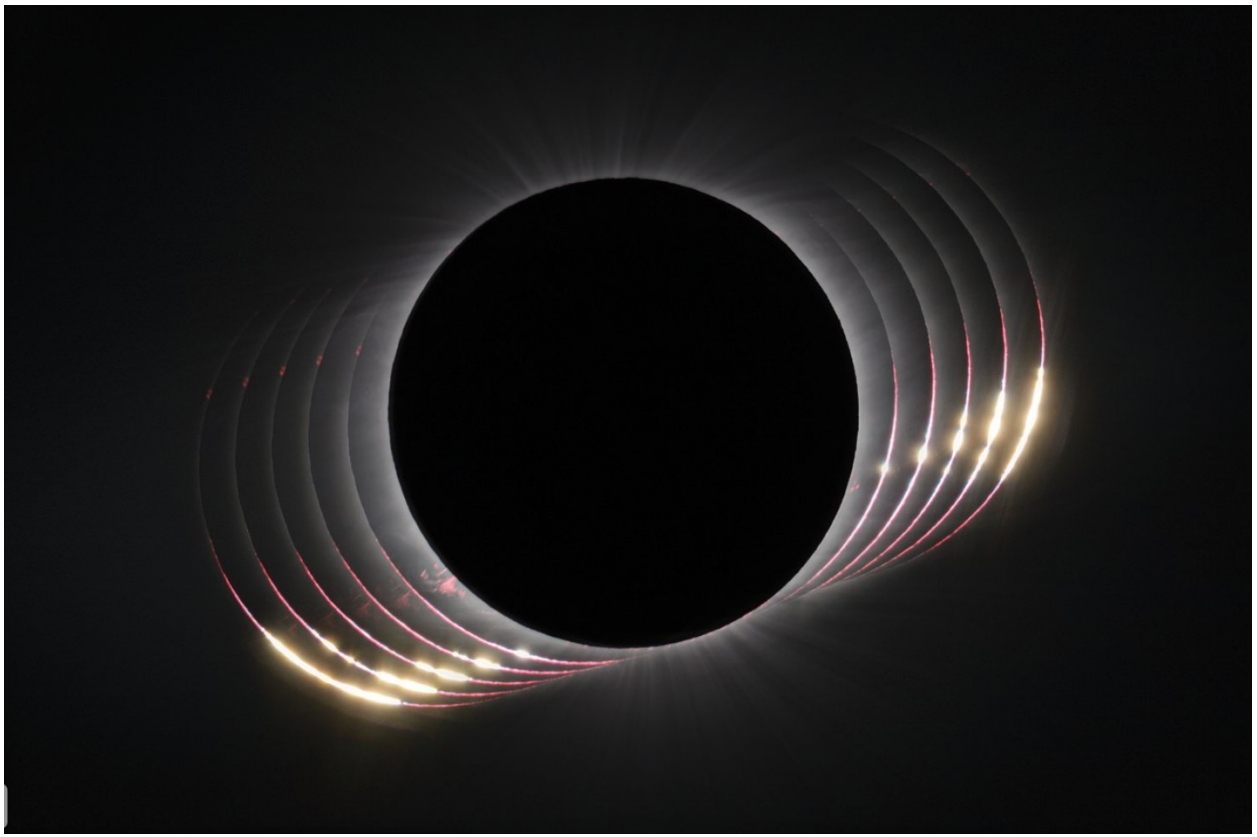


Solar Orbiter/ STIX movie courtesy of Laura Hayes and Hannah Collier (STIX team)

SunSketcher!

Hurray for Western Kentucky University!

Diamond Rings and Baily's Beads



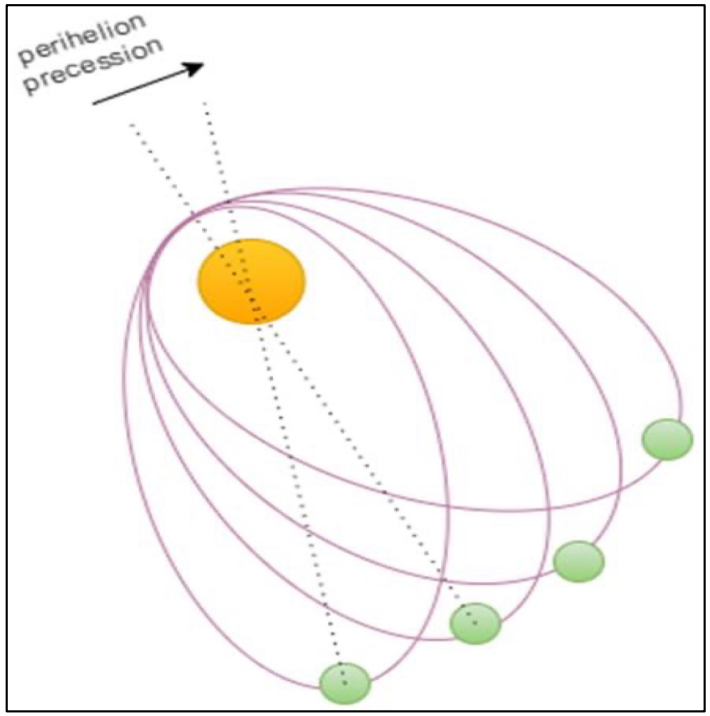
The 2019 eclipse from La Silla
Courtesy ESA and Petr Horálek

Francis Baily (bef. 1841)

The relativity connection

- Einstein's three decisive tests of general relativity:
  - The perihelion precession of Mercury
  - The gravitational deflection of starlight
  - The gravitational redshift

Precession of Perihelion



How much precession is there, in arcsec/century?

532.3035” (torques from other planets
0.0286” (torque from solar oblateness)
42.9799” (general relativity)
575.31” (total predicted)

574.10” ± 0.65” (observed)

The amazing thing (to me) is that this was a well-known anomaly in the mid-19th century!

- These numbers say that there’s a 2σ discrepancy, and that it implies an excess oblateness

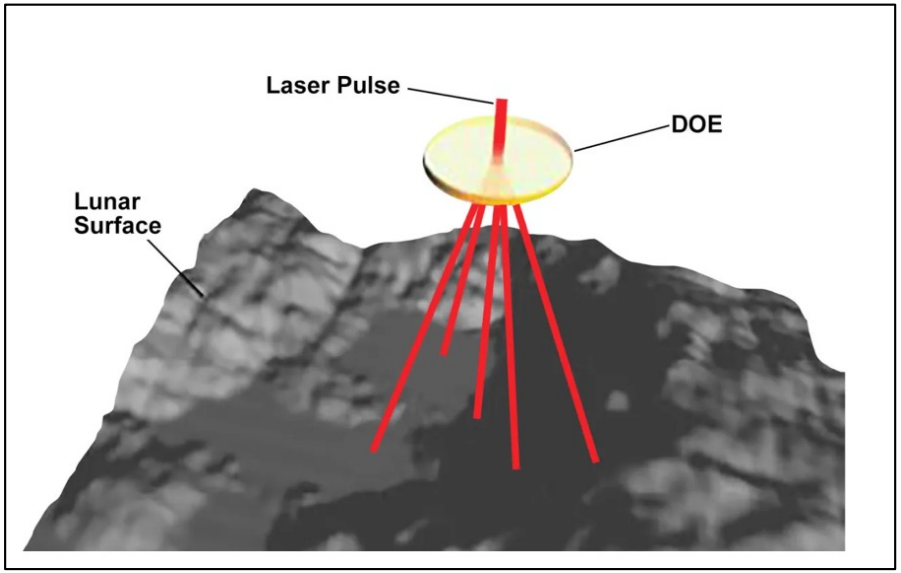
Tribute to R.H. Dicke

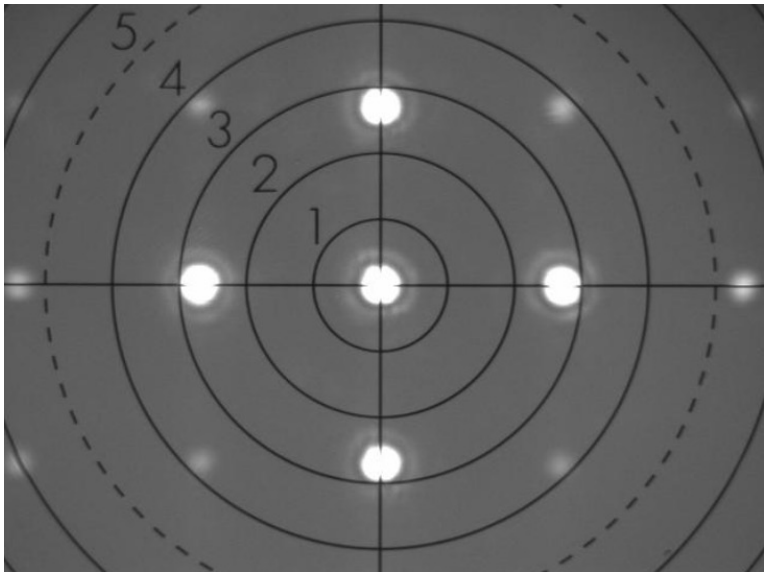
- The Brans-Dicke alternative relativity
- Brilliant but erroneous experimental work reported by Goldenburg & Dicke, 1974
- Better brilliant experimental work at SCLERA (Henry Hill), alas, cleared up the discrepancy
- A great inspiration!

How SunSketcher works

- A free smartphone app records the timing of the eclipse automatically, with GPS precision
- GPS plus LOLA (Lunar Reconnaissance Orbiter) makes this sophisticated astrometry accessible to… Everybody!
- Essentially, SunSketcher uses the Moon as an astrometric reference

LOLA: The Lunar Orbiter Laser Altimeter



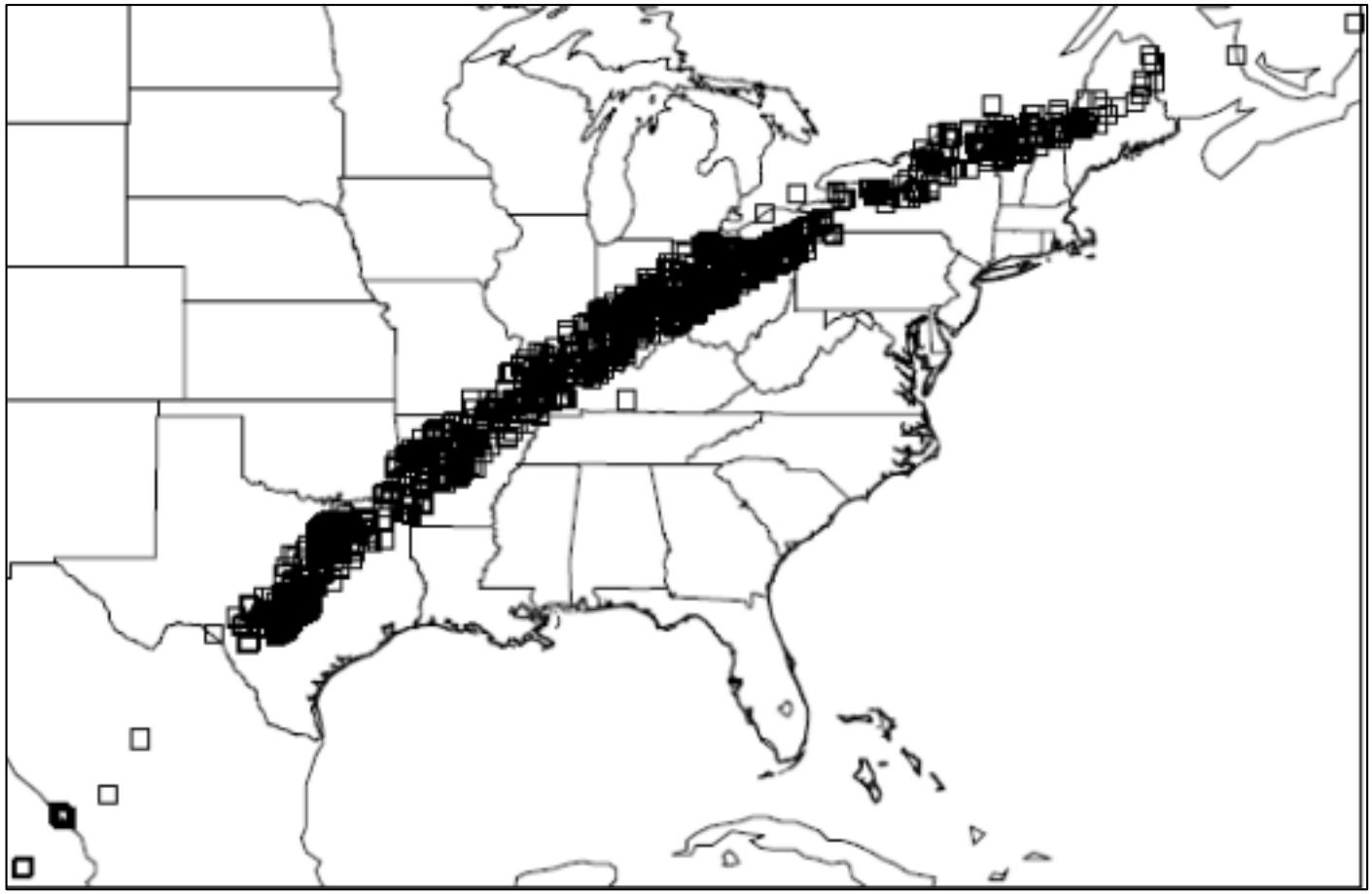


- In lunar polar orbit, 50 km altititude, LOLA “pings” the surface and develops a 3D map with 5 m precision
- LOLA contains a diffractive optic that forms five beams

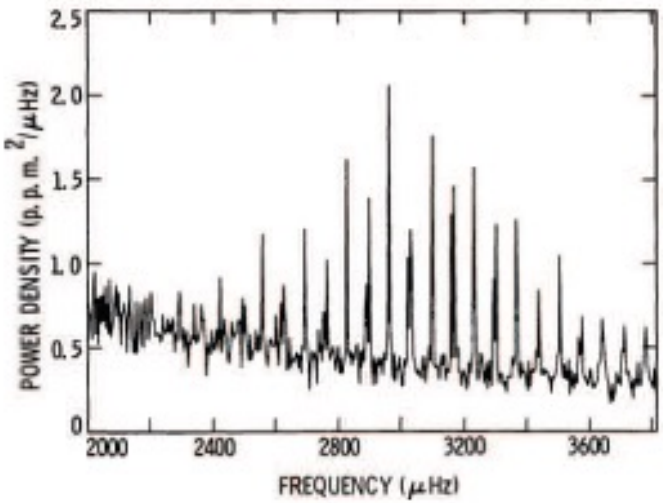
What actually happened

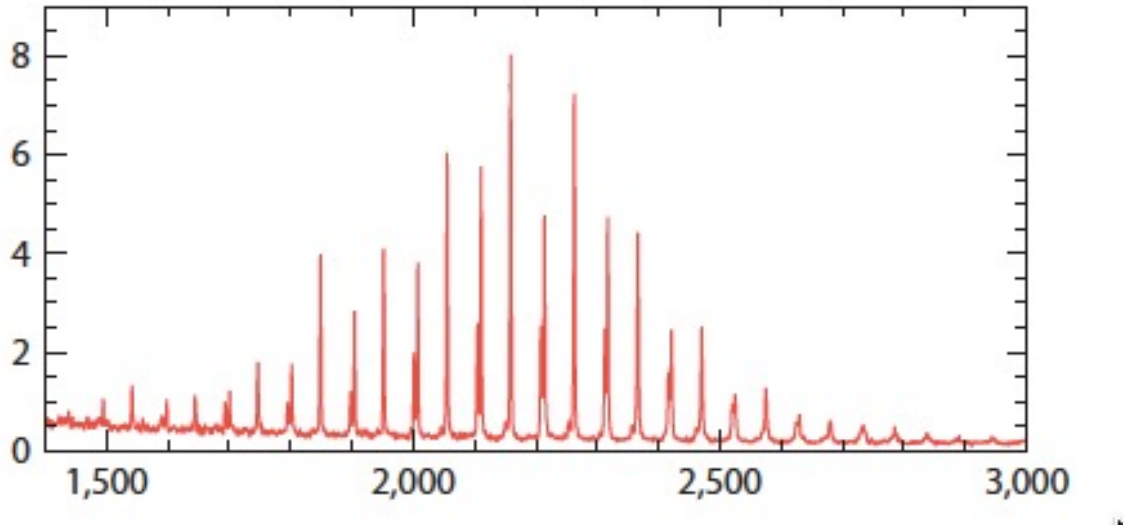
- A very diverse group of undergraduate students at Western Kentucky University built the app and other infrastructure
- We did a “beta-test” in 2023 (Odessa, TX USA), about 100 participants; some success achieved
- We did a full-up operation in 2024, gaining about 40,000 participants
- Data analysis is under way

Distribution of Observers 2024



Solar and stellar p-modes





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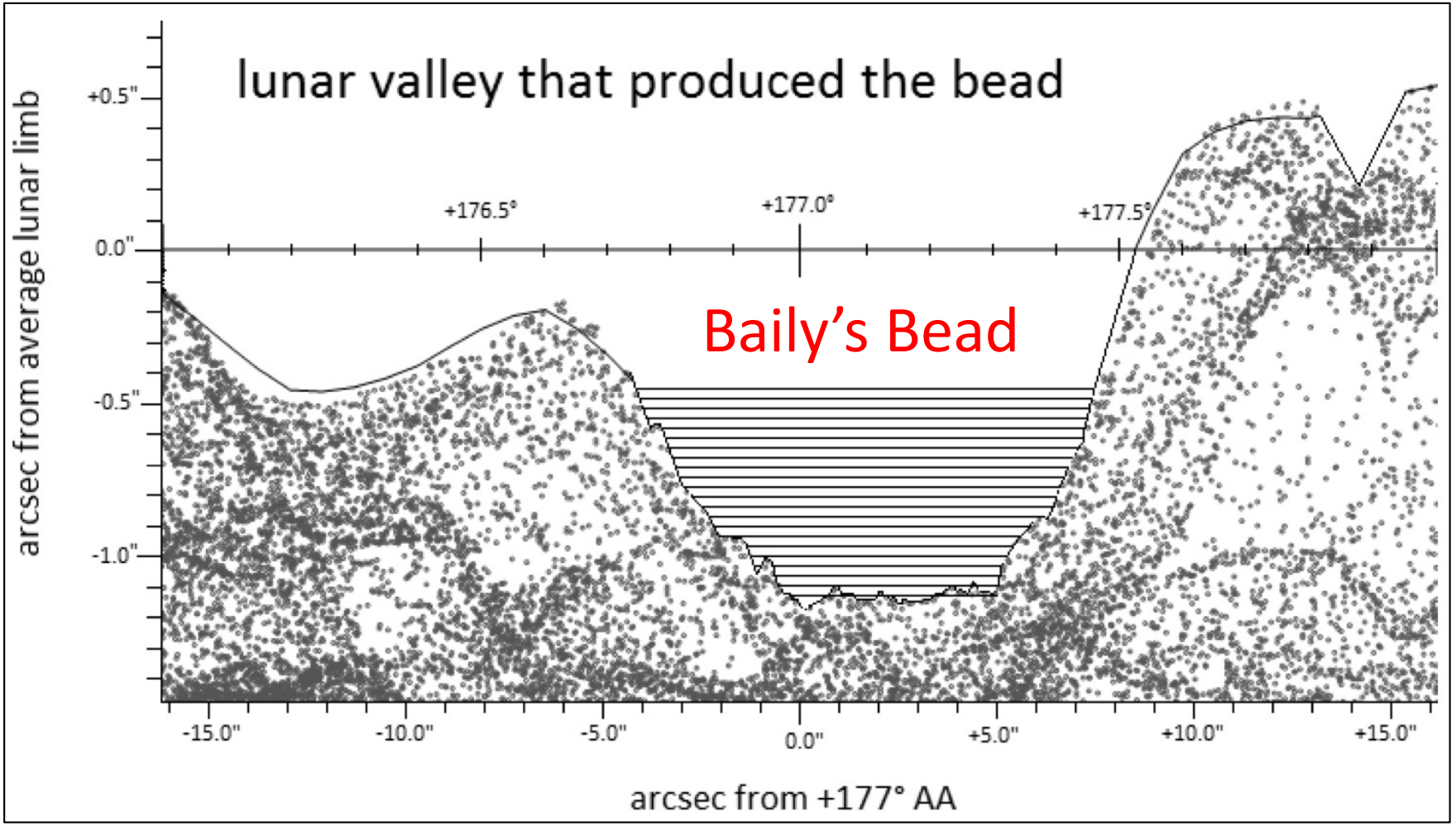
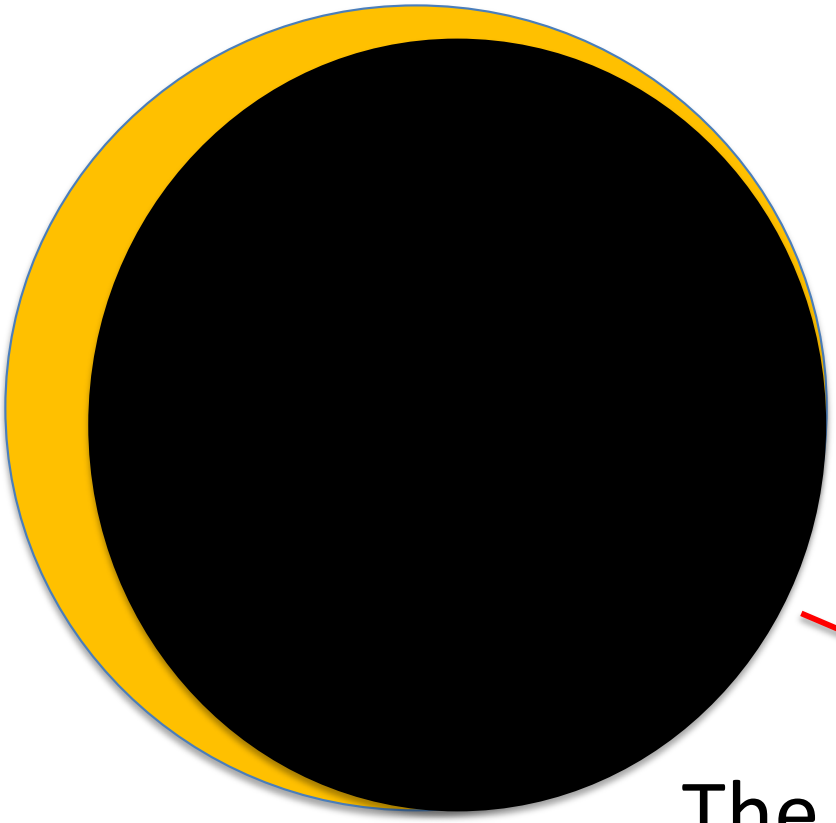
Lunar valleys



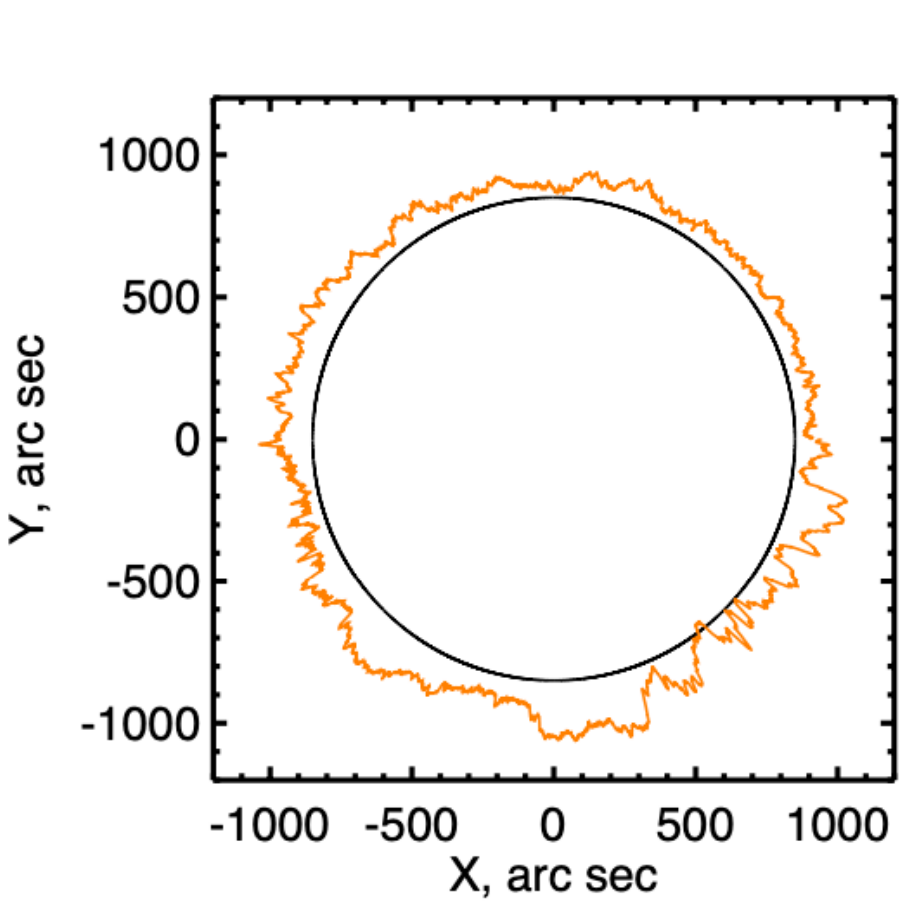
Sigismondi et al. 2012

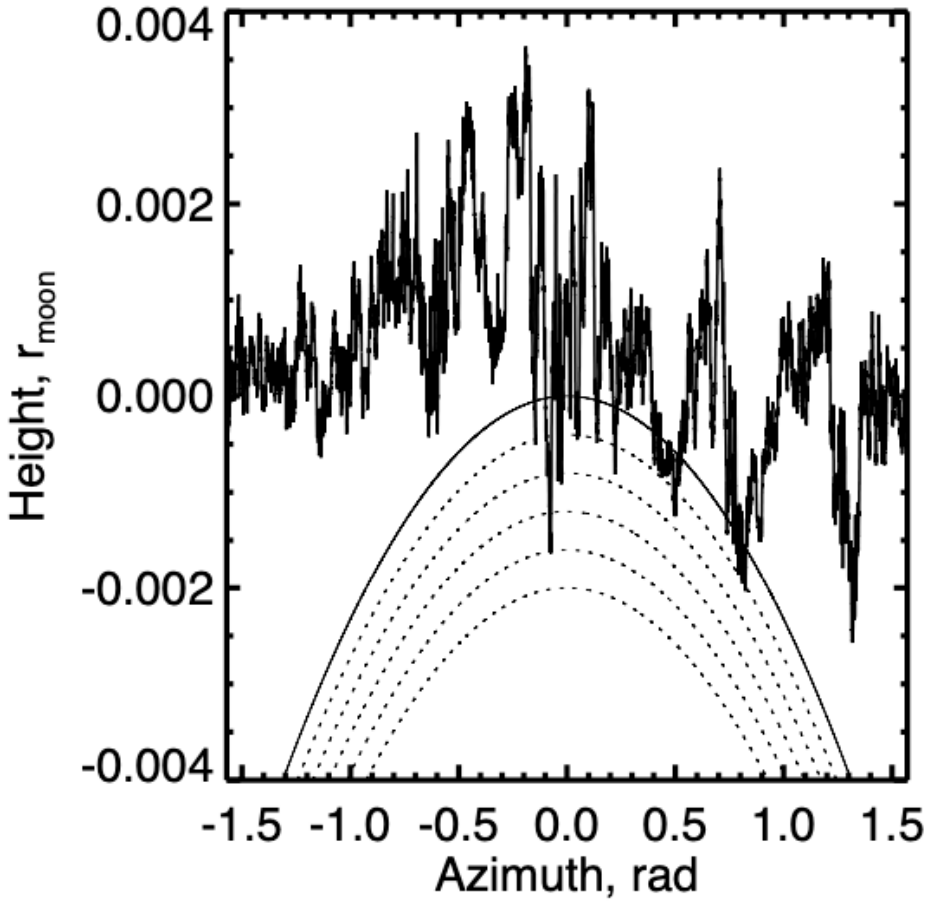
SunSketcher's Measurement



The exact time this happens!

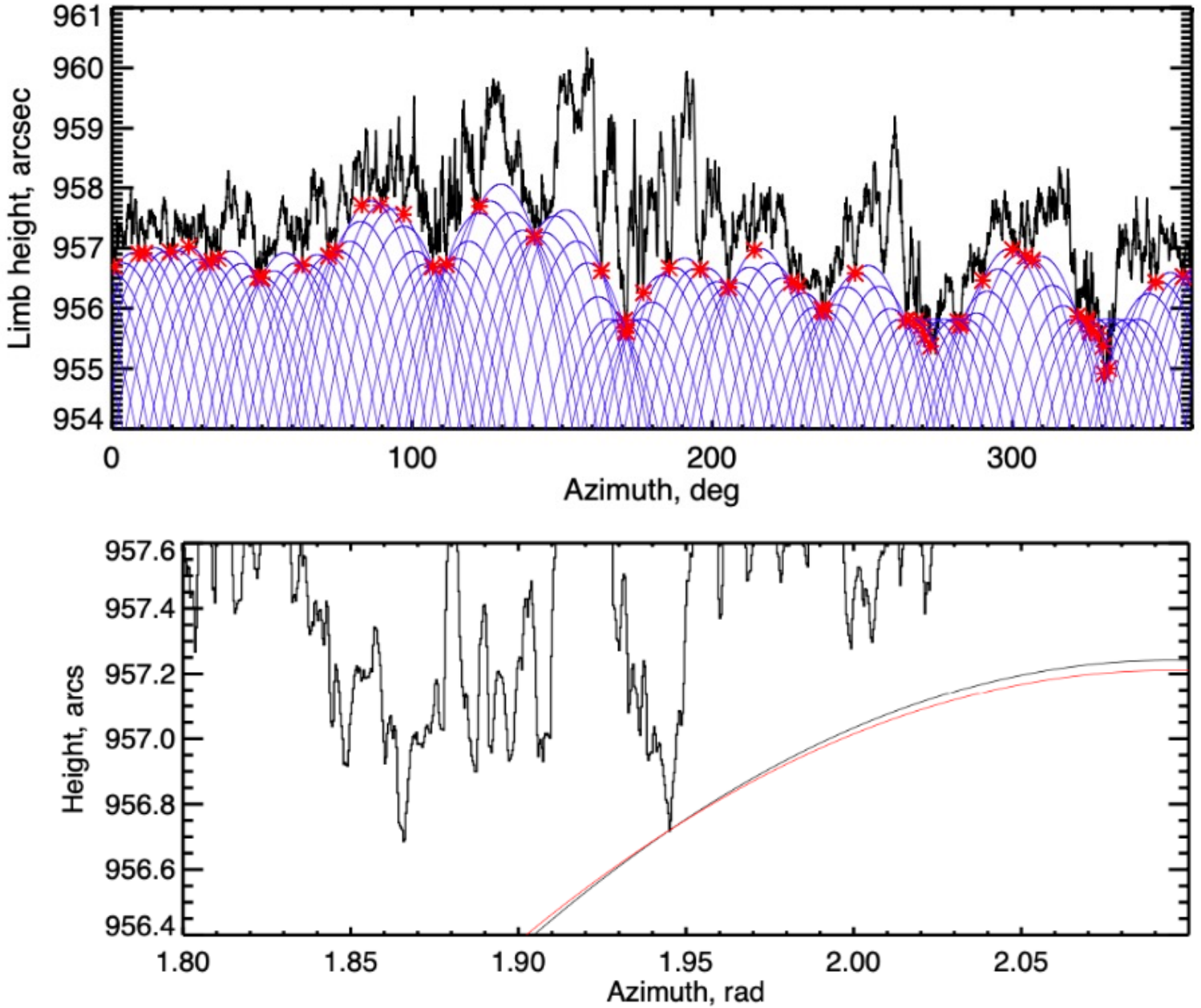
Modeling Bead formation I





The LOLA lunar limb data: circular and rectilinear coordinates

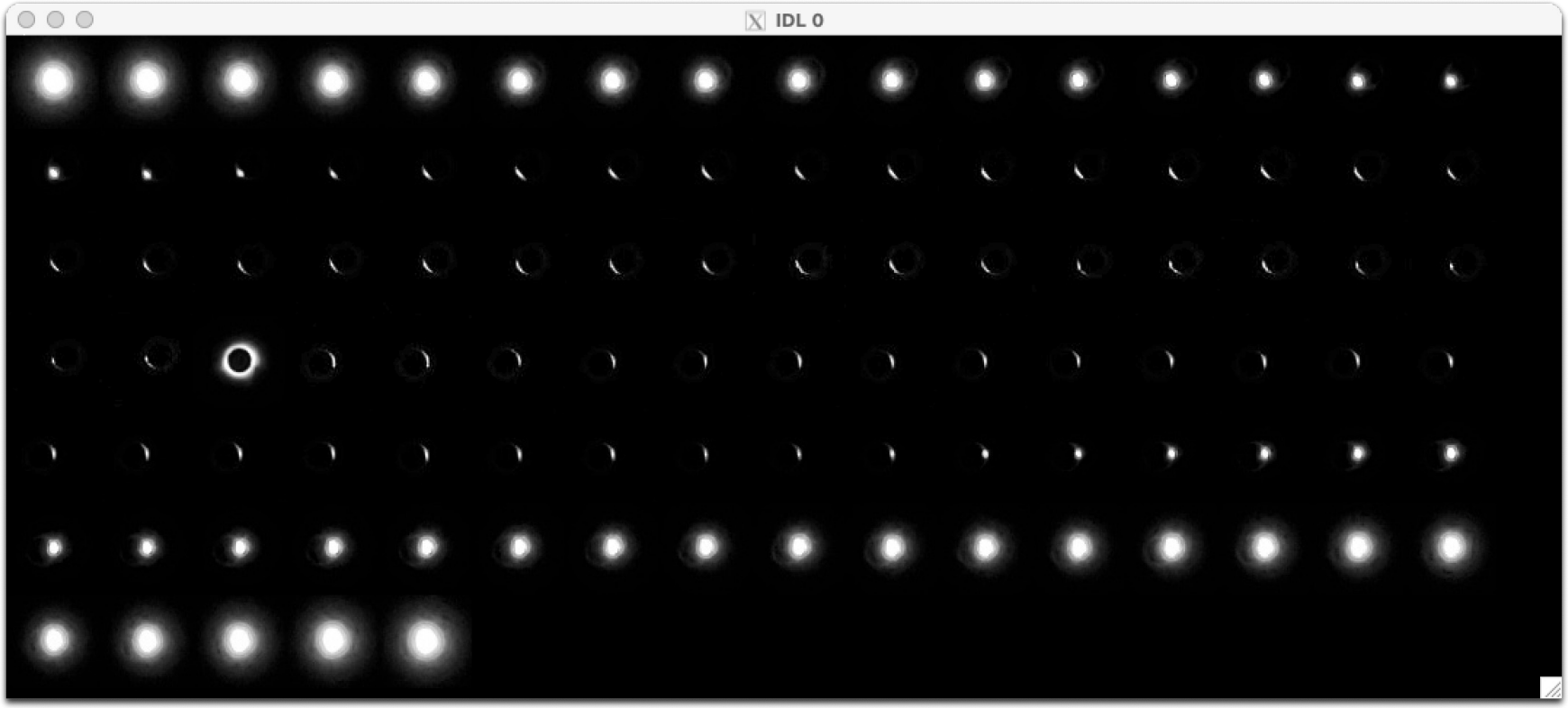
Modeling Bead formation II



The image pattern

- 101 images per set:
  - 50 at 2nd contact
  - 1 at totality
  - 50 at 3rd contact
- Non-linear time array compressed to 20 s

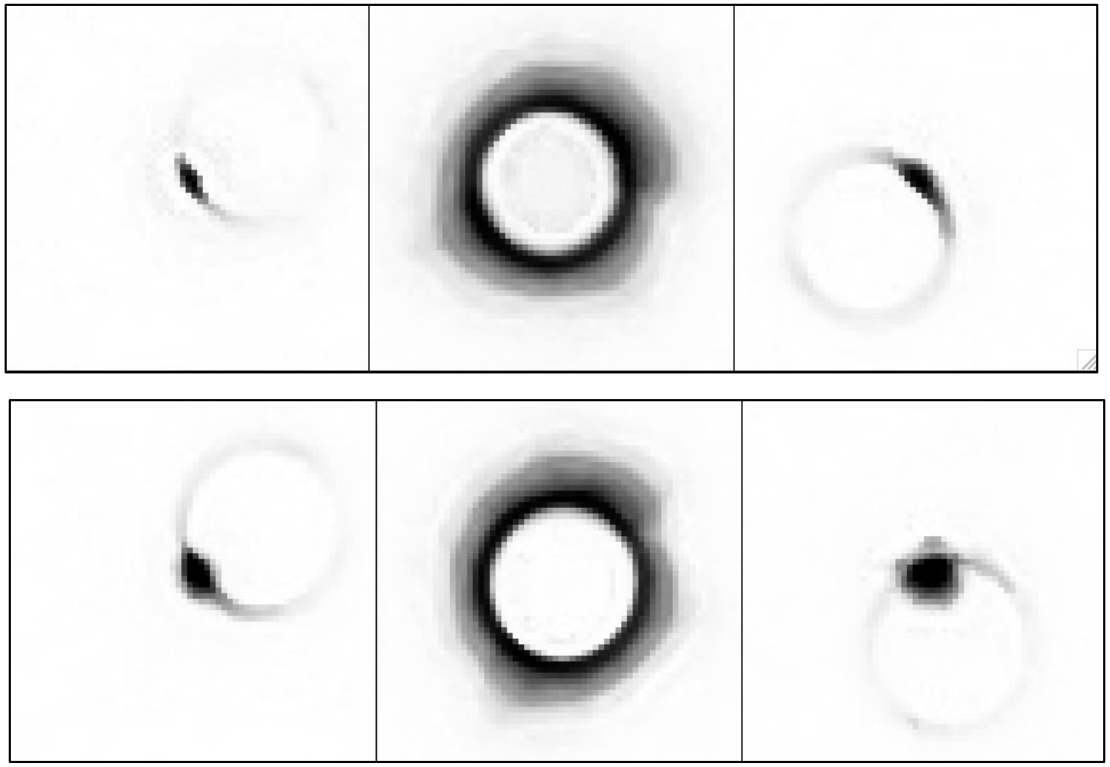
Some actual data



- This is user ID977

```
UNIXT           STRING    '08-Apr-24 19:27:01.488'
LAT             DOUBLE          44.978008
LON             DOUBLE         -72.150322
HEIGHT          DOUBLE          0.37919998
```

Some actual data



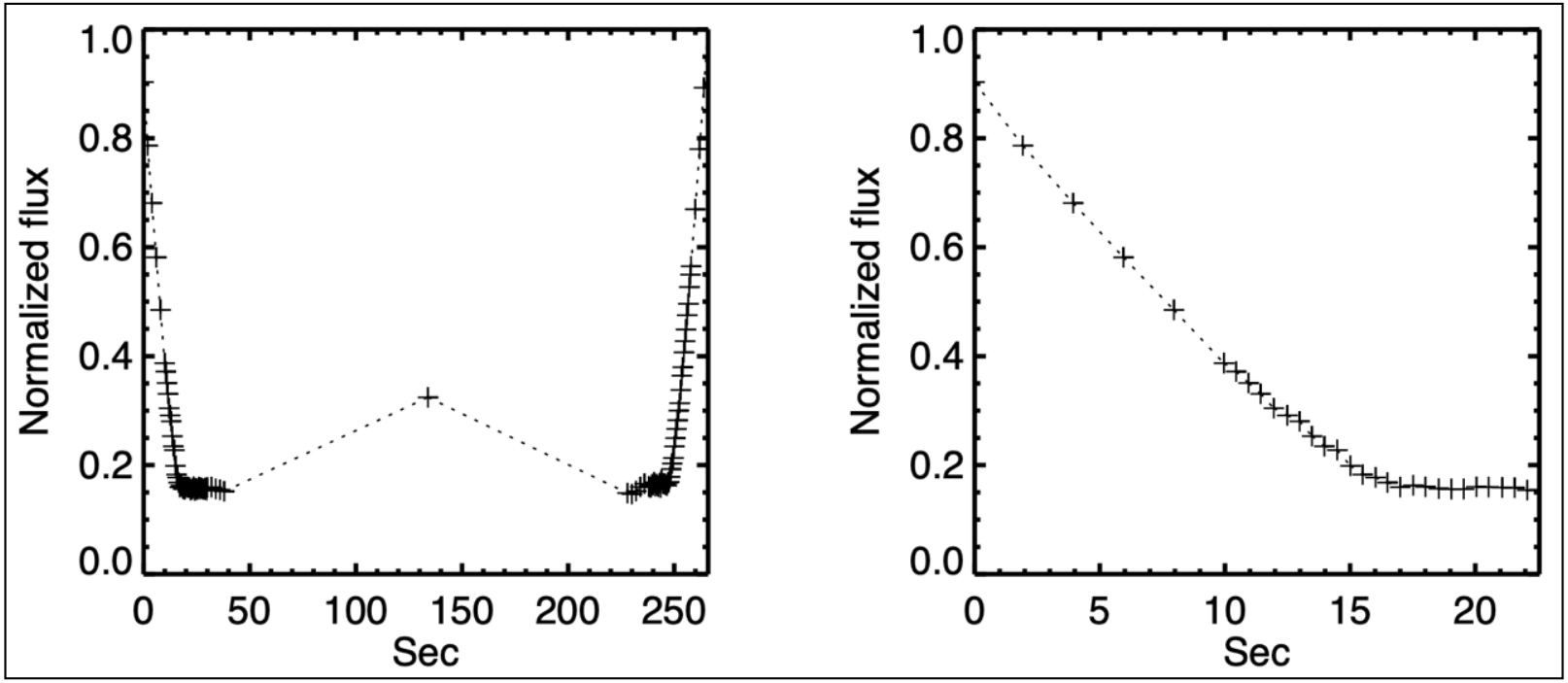
User ID 1024

User ID 1033

Analysis is not easy

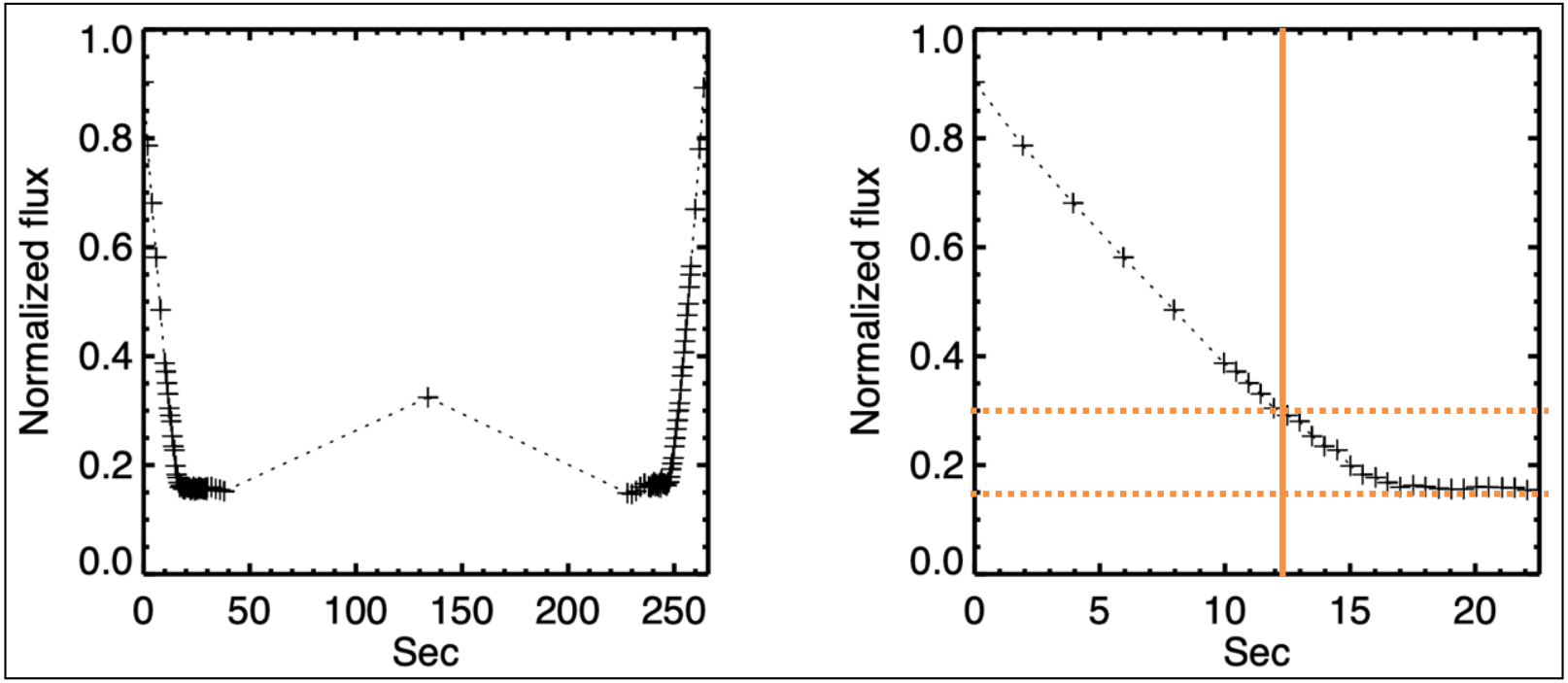
- The images have excellent timing and geolocation
- But the images are *really* low resolution
- Can root N statistics defeat various problems?
  - Image orientation
  - Seeing
  - JPG format
  - Reference time (where is the actual Bead?)
  - Solar magnetic lump interference

How to anchor the time series?



- Each data set has two timeseries of Bead brightness. We need a reference.
- A first idea: find the time of doubled coronal brightness…

How to anchor the time series?



- Each data set has two timeseries of Bead brightness. Each needs a reference.
- A first idea: find the time of doubled coronal brightness… ideas welcome!

Conclusions

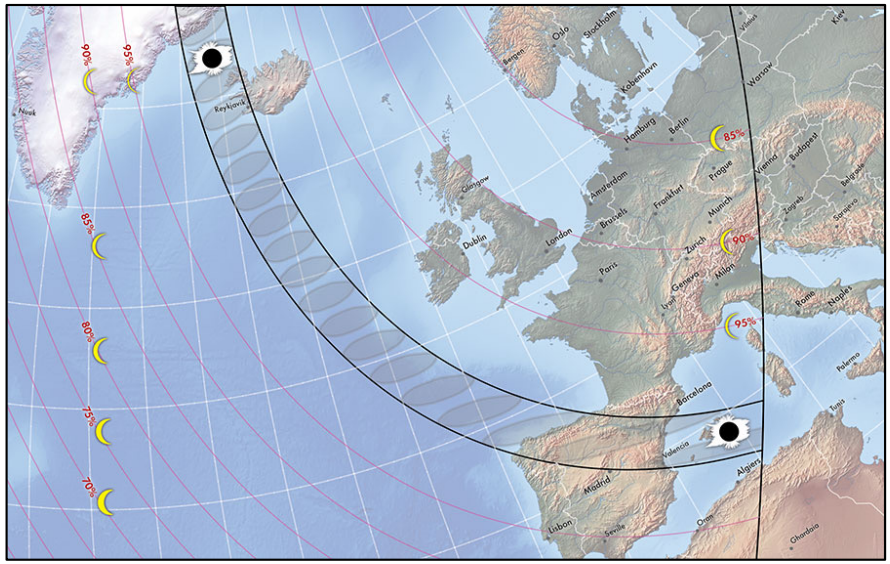
- We study the Sun to aid in understanding stars, especially for exobiology and threats to astronauts and things in space
- The exact shape of the Sun may give important clues to its interior structure
- We've been able to address this question with the aid of many volunteers with smartphones
- But we're not finished yet

Thoughts about outreach

- SunSketcher has been a great experience, working with a very diverse group of WKU undergraduates
- The outreach to our user group was hands-off for legal reasons, a bit unfortunate

The next really good total eclipses

2026 !



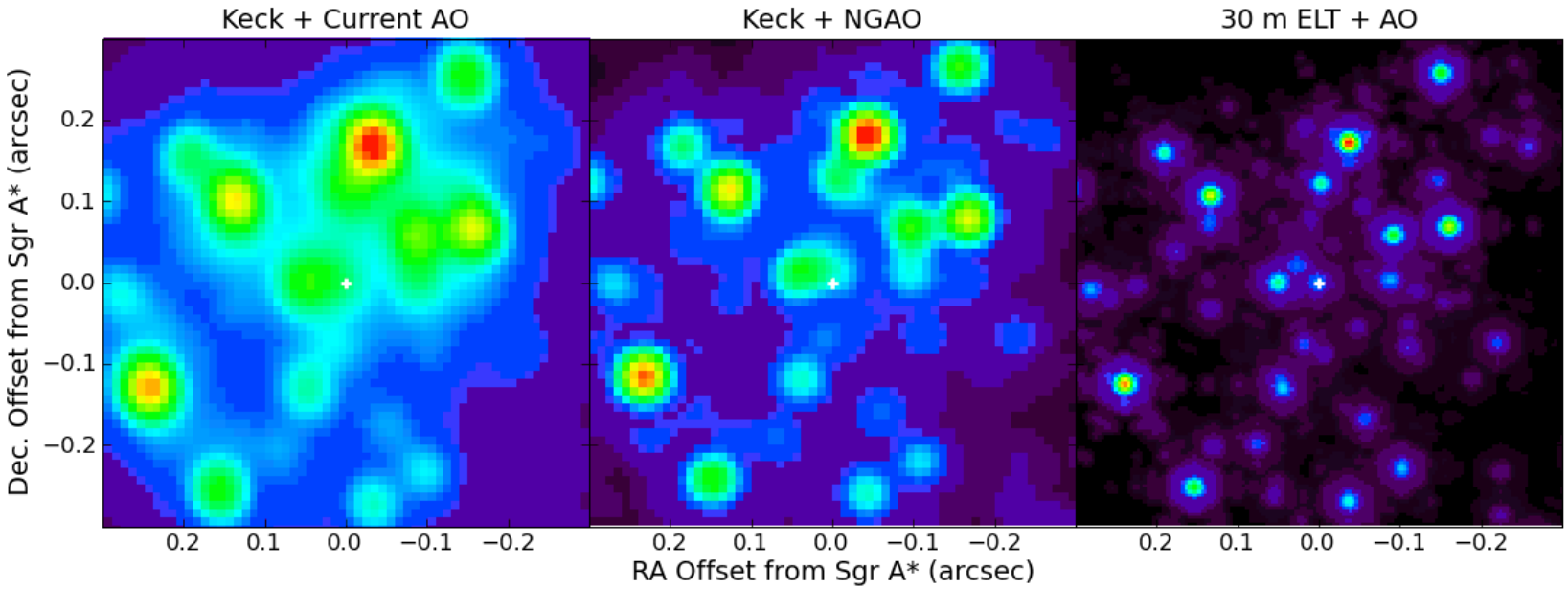
Algjör myrkvi! Vinsamlegast hjálpið!
Eklipse osoa! Mesedez, lagundu!
¡Eclipse total! ¡Por favor ayuda!
Un eclipsi total! Si us plau, ajuda!

2027 !!

A total eclipse! Please help!
Tayect s lekmal-is! Ttxil, ɛawen!
Dayax madoobaad guud! Fadlan caawi!
كسوف كلي! الرجاء المساعدة!

The end, thanks

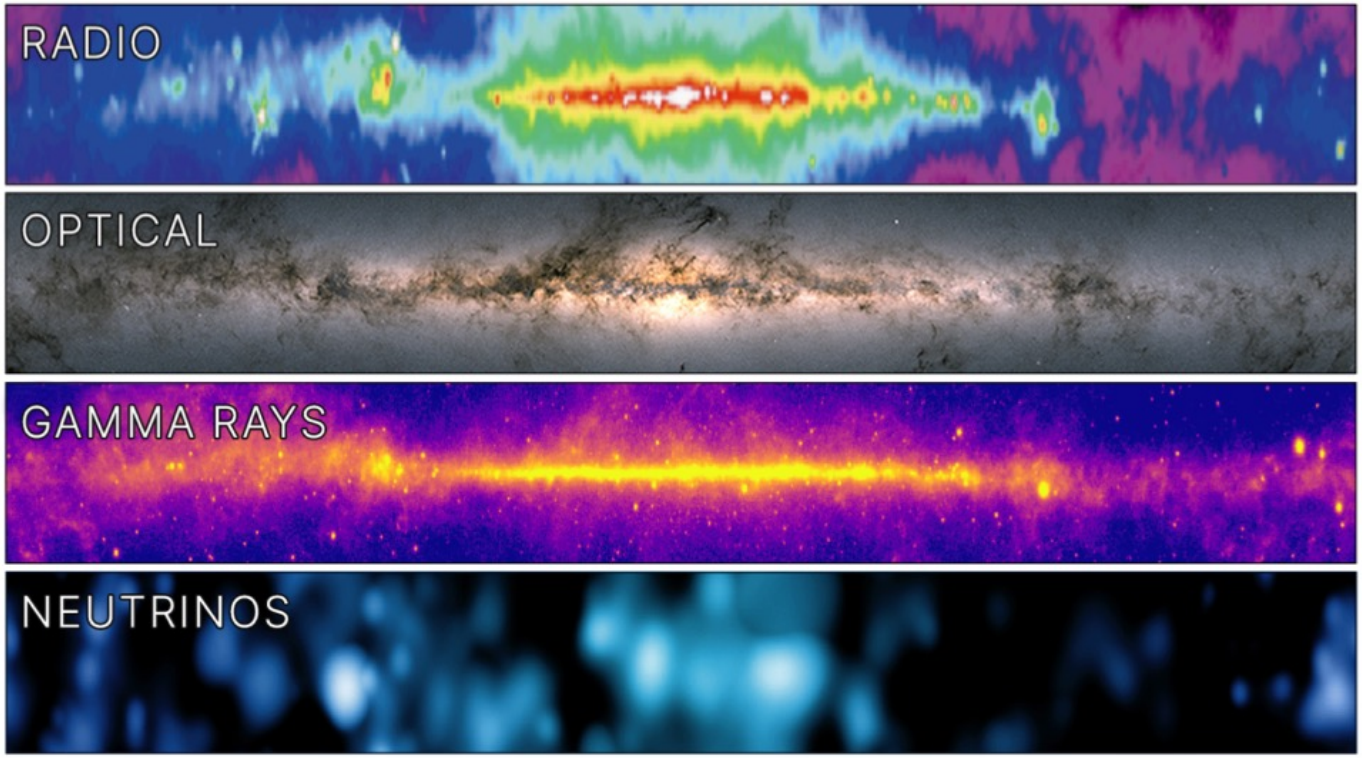
Time-domain astronomy



http://www.astro.ucla.edu/~ghezgroup/gc/pictures/Future_GCorbits.shtml

- The innermost square arcsec of the Galaxy consists entirely of objects orbiting our black hole
- This is new, but time-domain solar and planetary astronomy have been mainstream since Galileo

Multi-messenger astronomy*



IceCube Collaboration

*Note that solar multi-messenger astronomy probably began with George Graham (a London clockmaker) in 1772, also an early Sun-as-a-star result.