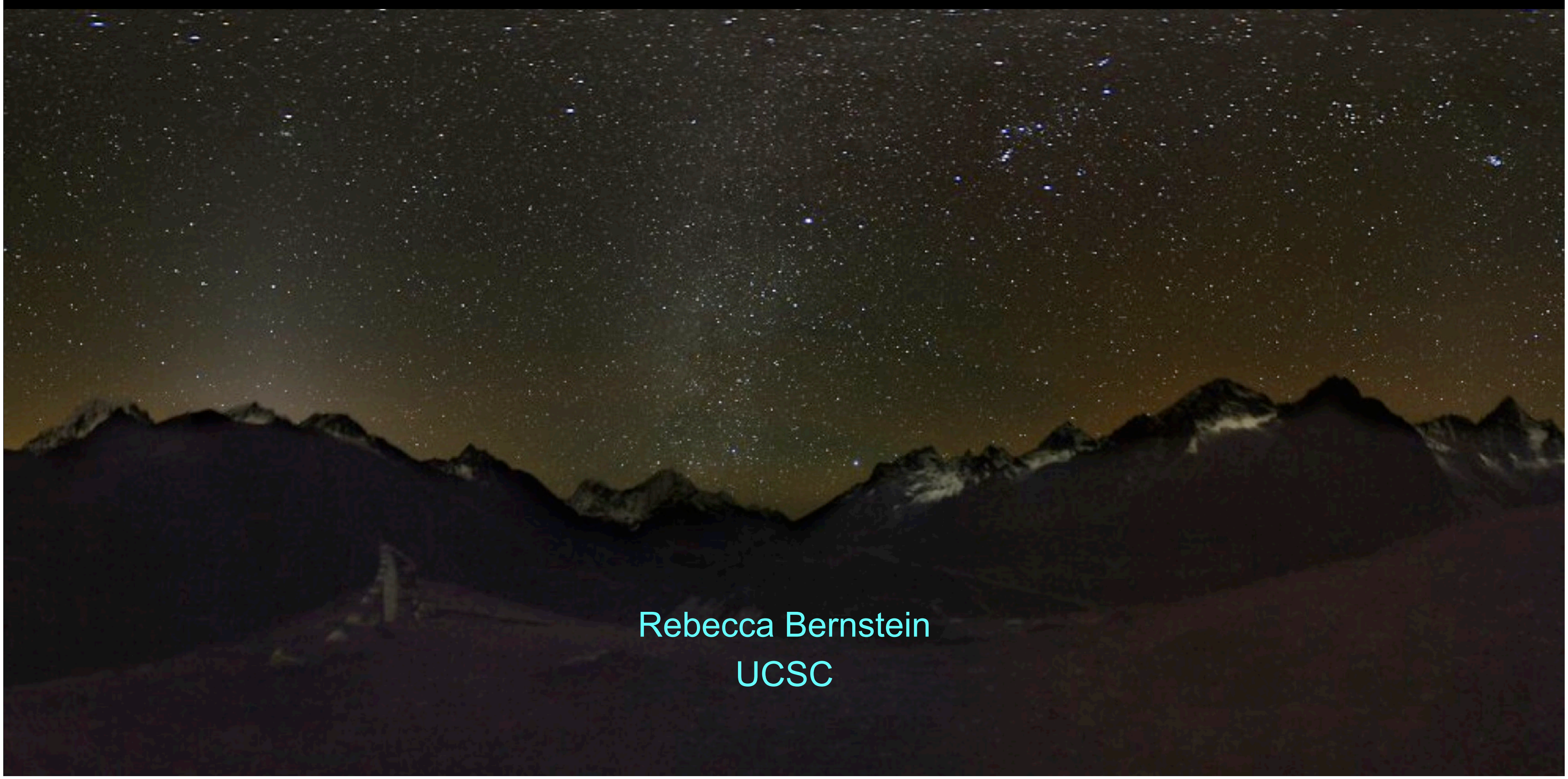
Absolute surface spectrophotometry of Zodiacal Light:

measurement of optical diffuse backgrounds



Rebecca Bernstein
UCSC

Outline

1. Zodiacal light: basics
   – Scattering geometry
   – Brightness (ballpark)
   – Variation (spatial, temporal)
   – Spectrum

2. Separation of Diffuse Galactic Light (DGL) from Zodiacal Light (ZL)
   – Source & scattering geometry
   – Spectrum

3. Calibration of diffuse background measurements
   – Instrumental backgrounds
   – Absolute,
   – … surface,
   – … … spectrophotometry,
   – … … … with multiple instruments

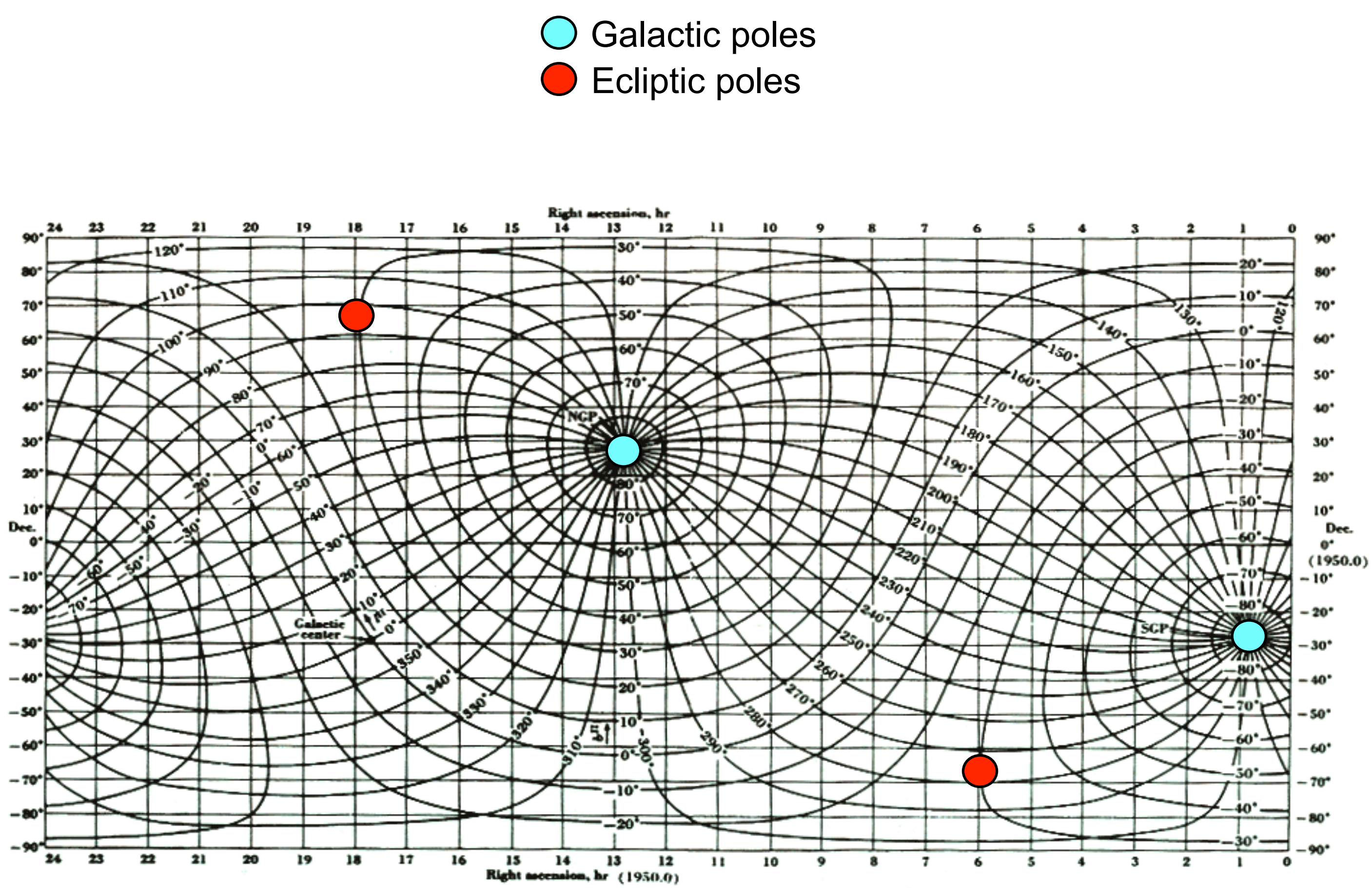
4. Complications near Earth
   – Airglow
   – Tropospheric & ground scattering
   – Earth-orbiting telescopes

5. Summary: recipes for happiness (happier-ness)

Based on: coordinated HST-/Ground-based program to measure the EBL (Bernstein, Freedman, & Madore 2002a,b,c, 2005; Bernstein 2007)

Zodiacal light — basics

- Geometry:



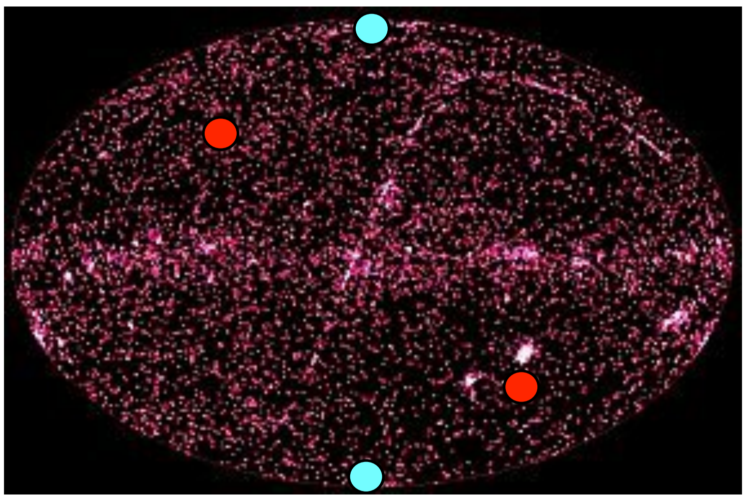
Equatorial Coordinates

Zodiacal light — basics

- Geometry:

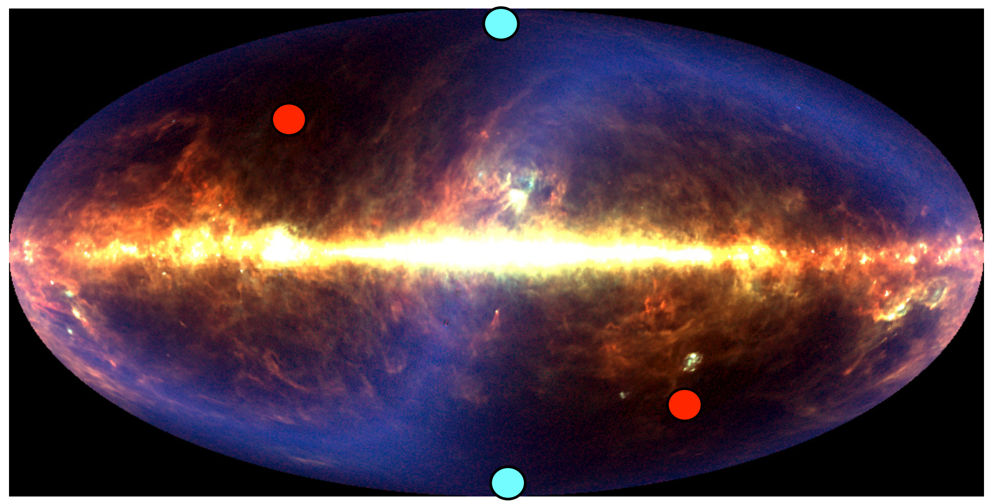
Galactic poles
Ecliptic poles

λ ≤ 3 μm   scattered sunlight



UV

λ > 2 μm thermal emission



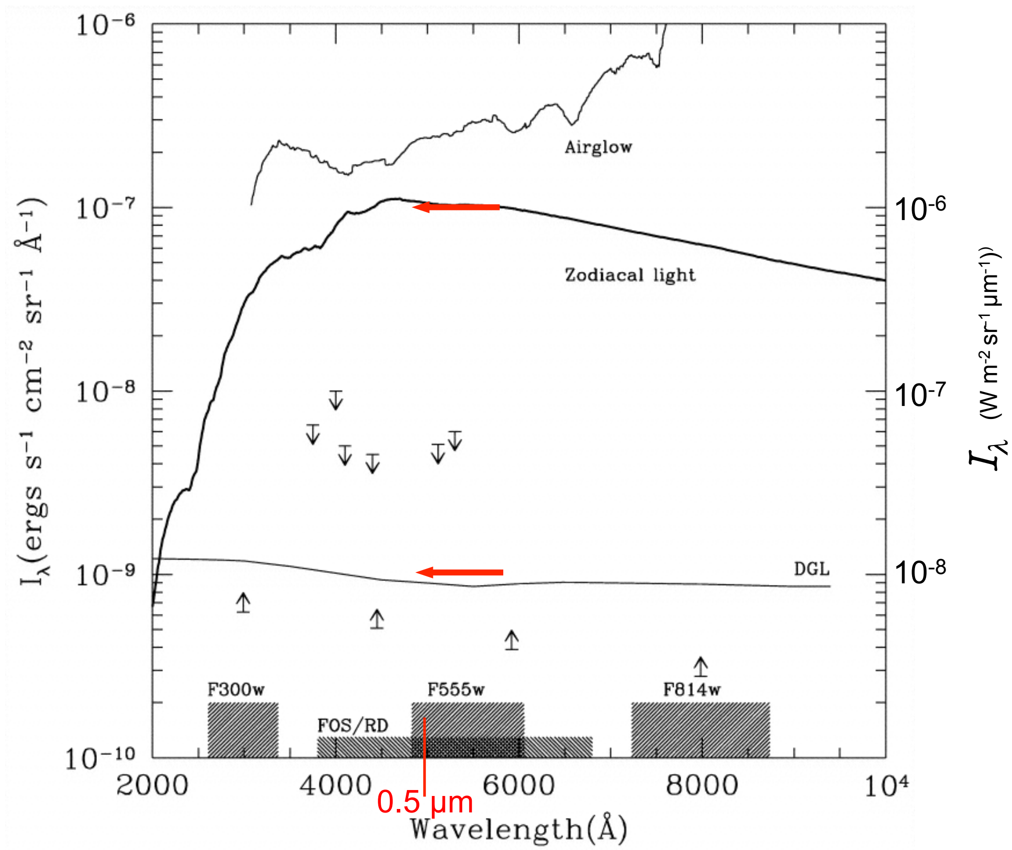
IR

Galactic Coordinates

Zodiacal light — basics (λ ~ 0.5 μm)

- Relative flux of backgrounds:

note: ZL ~ 100 x EBL
ZL ~ 10-100 x DGL
ZL ~ Airglow (from ground)

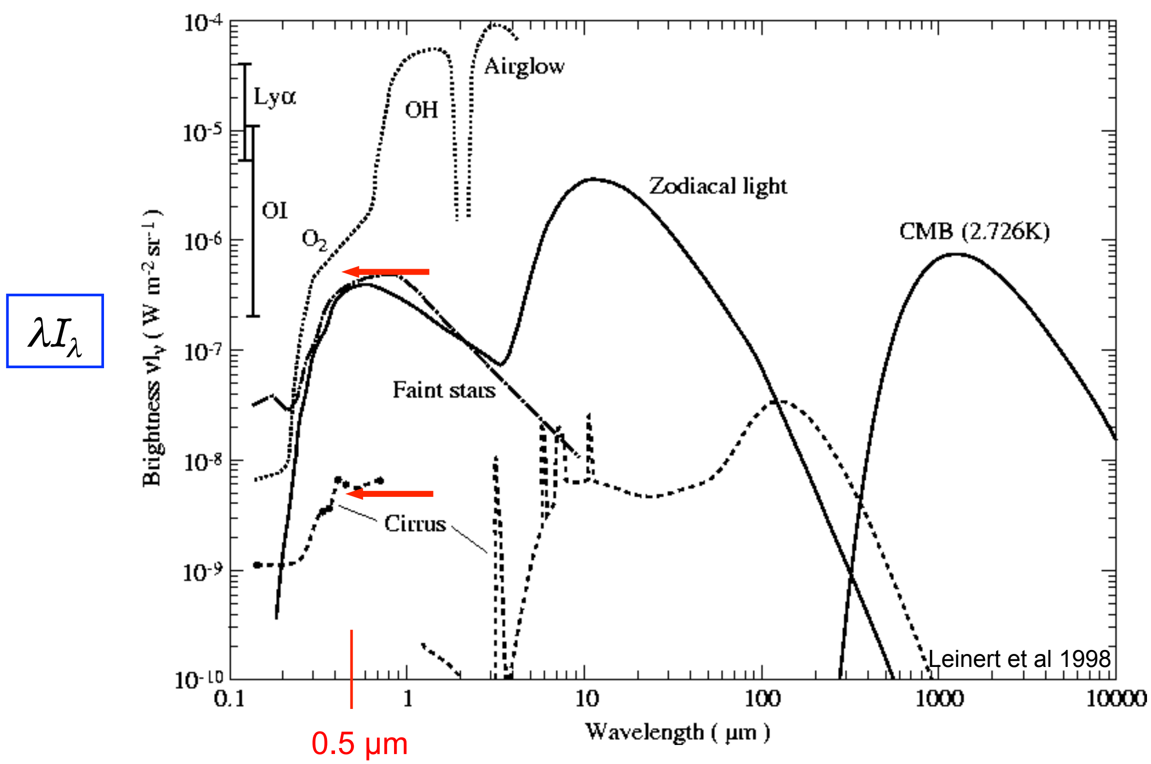


Zodiacal light — basics

- Relative flux of backgrounds:

Optical = scattered sunlight
Infrared = thermal emission

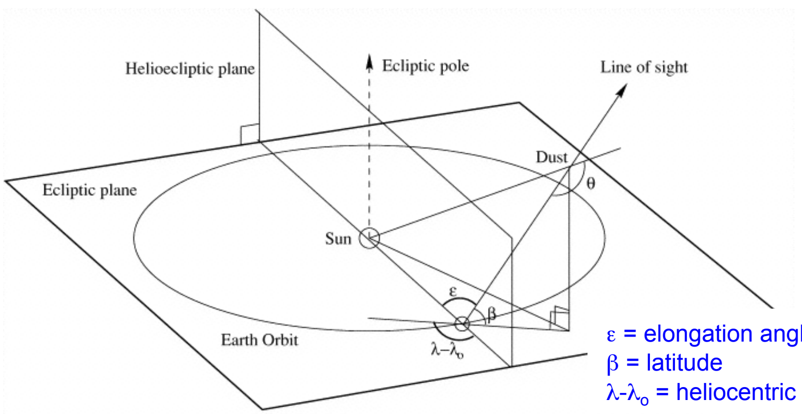
Scattered flux at λ ~ 0.5 μm does not accurately predict thermal flux at λ > 2 μm



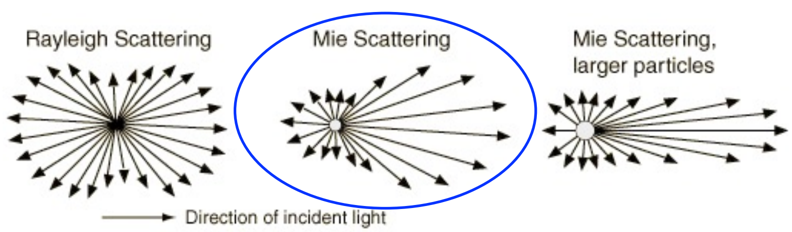
Zodiacal light — basics ($\lambda \sim 0.5\ \mu m$)

- Flux:
  - Stable w/ solar cycle (at $\varepsilon \geq 30^o$)
  - Seasonal variation: view w/r/t mid-plane of dust (e.g. Helios probe)
  - Structure: dust bands, cometary trails, earth trailing structures, etc, etc

Must be measured contemporaneously for accurate removal.



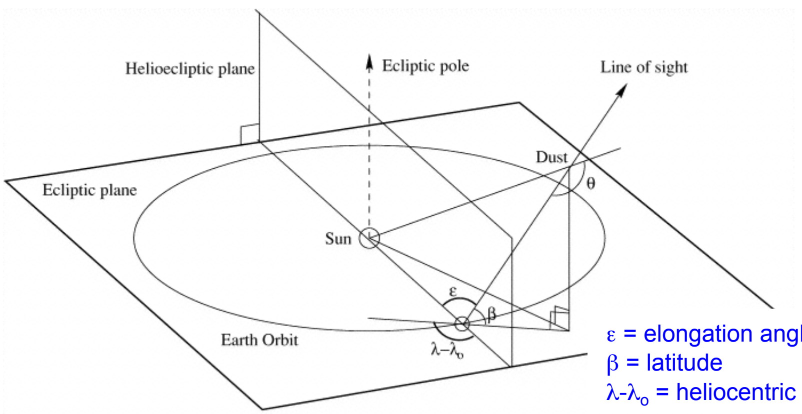
ε = elongation angle
β = latitude
λ-λ_o = heliocentric longitude



Zodiacal light — basics (λ ~ 0.5 μm)

- Flux:
  - Stable w/ solar cycle (at ε ≥ 30°)
  - Seasonal variation: view w/r/t mid-plane of dust (e.g. Helios probe)
  - Structure: dust bands, cometary trails, earth trailing structure

Must be measured contemporaneously for accurate removal.



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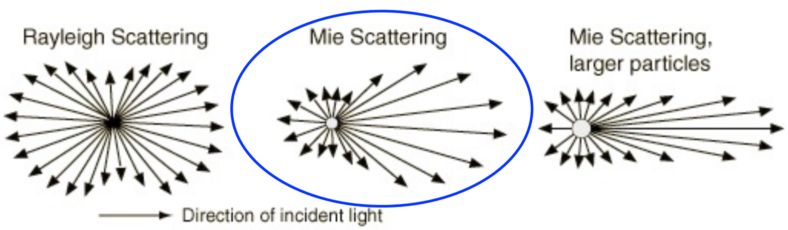
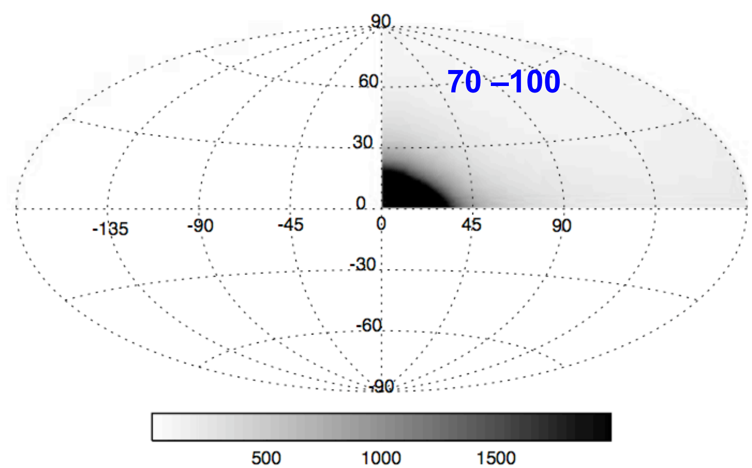


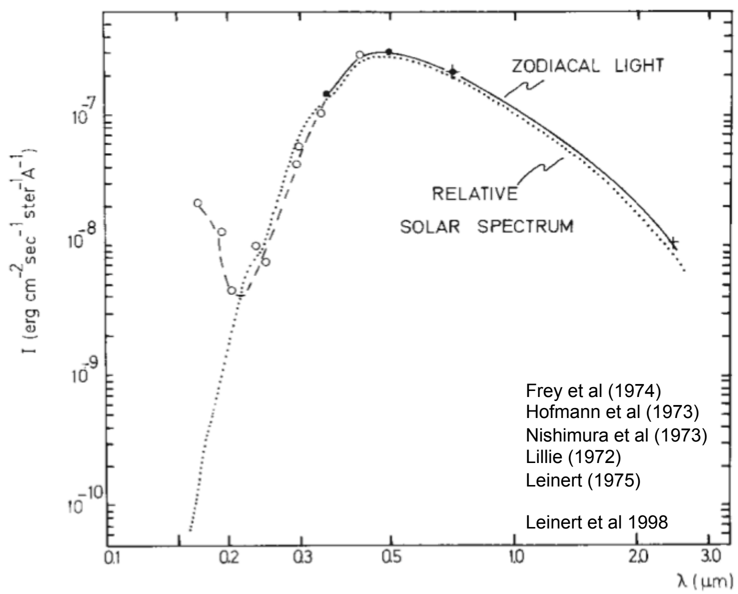


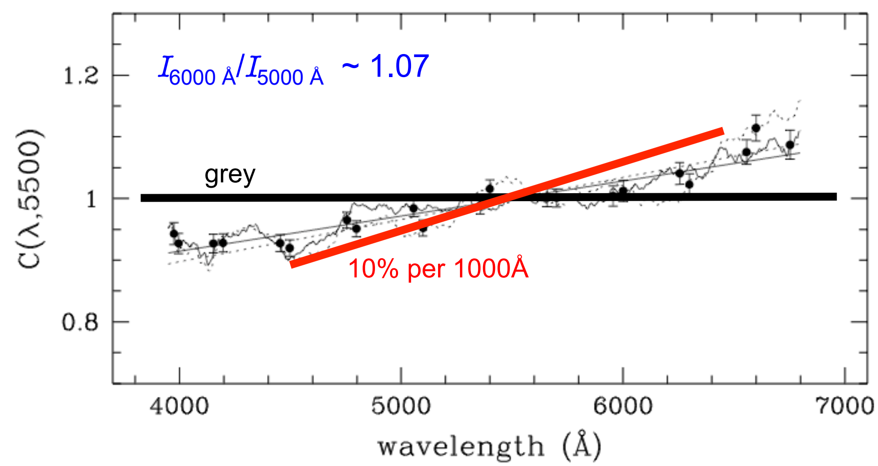
x10^{-9} ergs s^{-1} cm^{-2} sr^{-1} Å^{-1} = x10^{-8} W m^{-2} sr^{-1} μm^{-11}

~ 100 x optical EBL
~ 50-100 x optical DGL near poles

Zodiacal light — basics (λ ~ 0.5 μm)

- Spectrum:
  - solar
  - slightly reddened, depending on ε angle

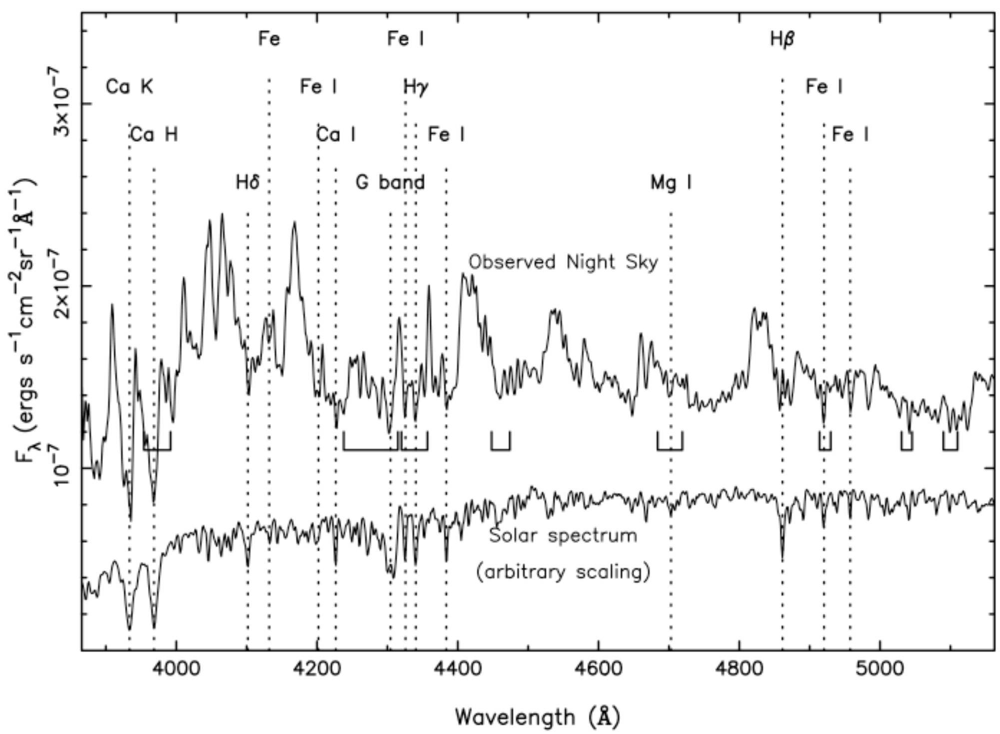




HST/FOS, $\lambda-\lambda_o$~ 130°,150°, β = 31°,35° (Δtime ~3 weeks)

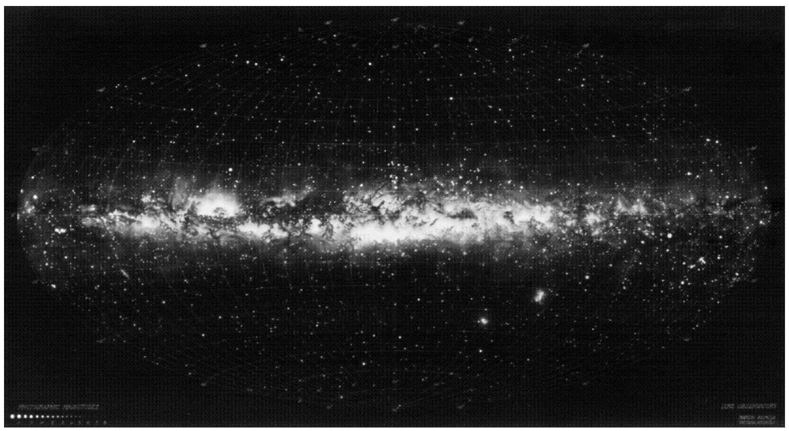
Zodiacal light — basics (λ ~ 0.5 μm)

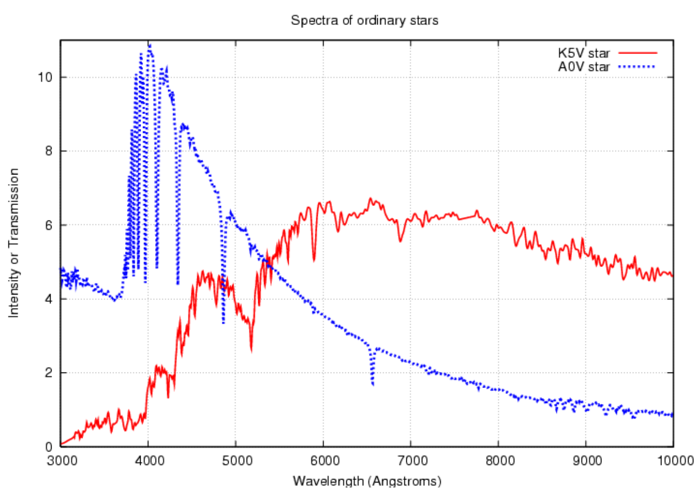
- Spectrum:
  - solar
  - slightly reddened, depending on ε angle
  - spectral features are well preserved
    - » flux can be measured from Fraunhoffer line strength (correlation, EW measurement, etc)
    - » better resolution is better (limited only by sensitivity)



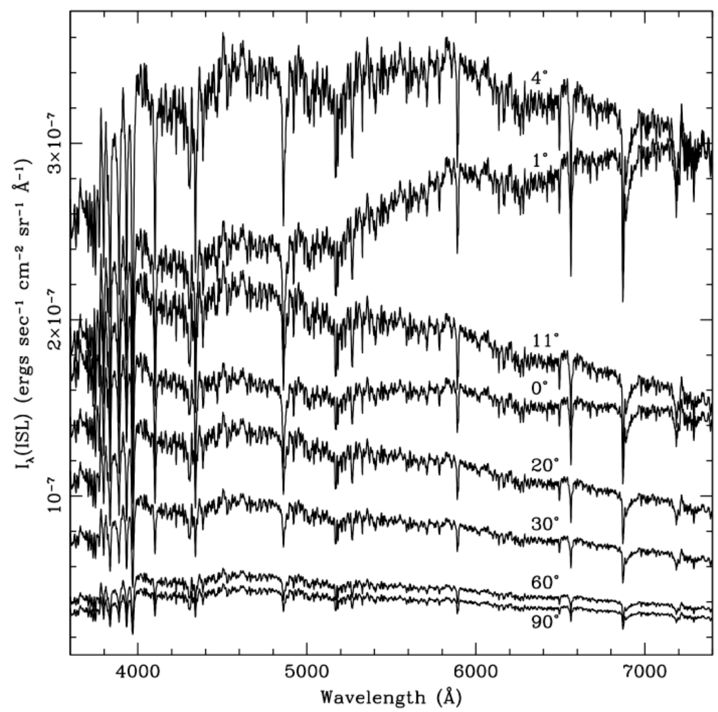
Diffuse Galactic Light

- Source: Integrated Star Light (ISL), known stellar types





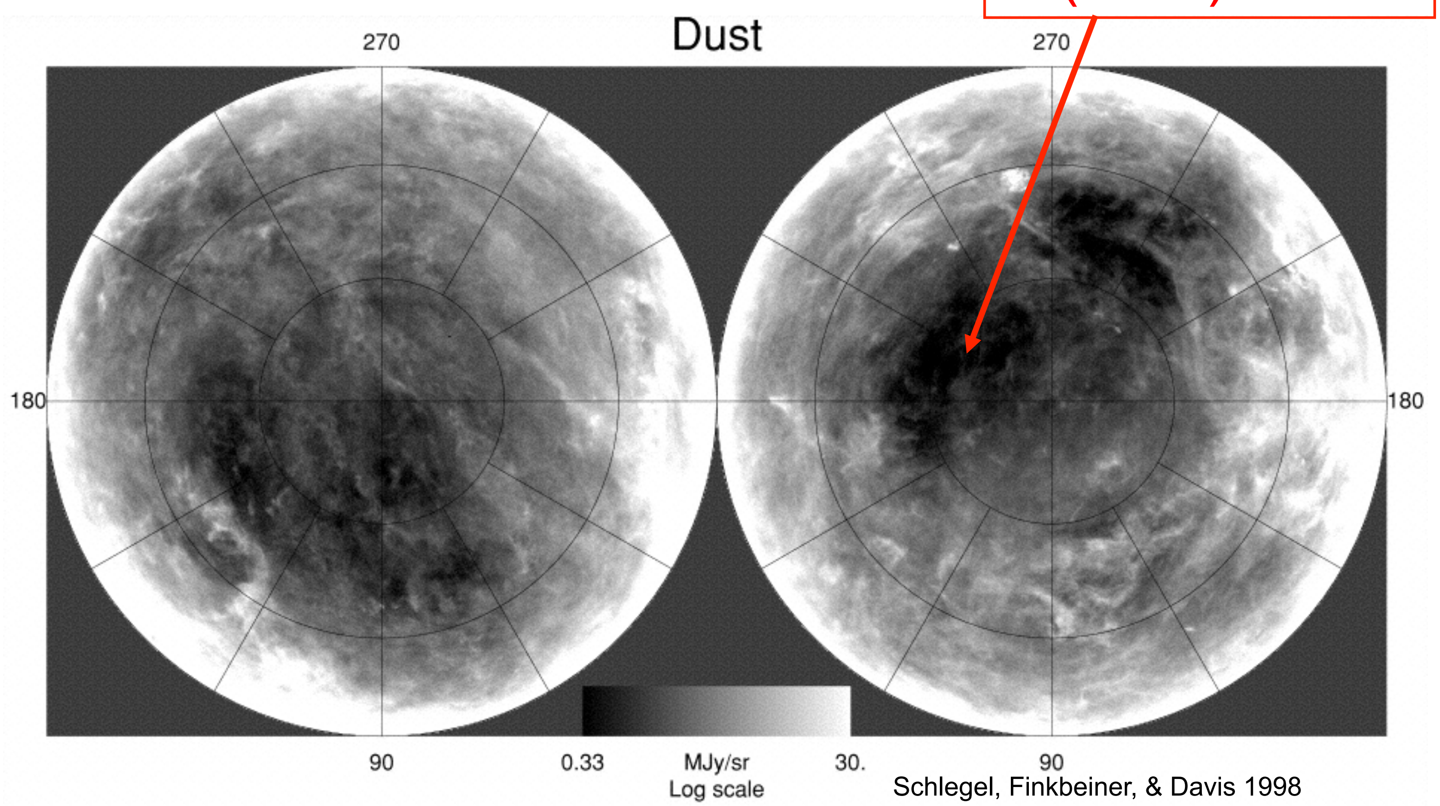
Integrated starlight at given Galactic Latitude:



Diffuse Galactic Light

- Source: Integrated Star Light (ISL), known stellar types
- Scattering: dust is spatially variable (on very small scales, 10's of arcsec)
  » Mean DGL flux can be estimated from simple scattering models using
    dust (or H) column density,
    ISL intensity along L.o.S, and
    observed extinction properties of galactic dust

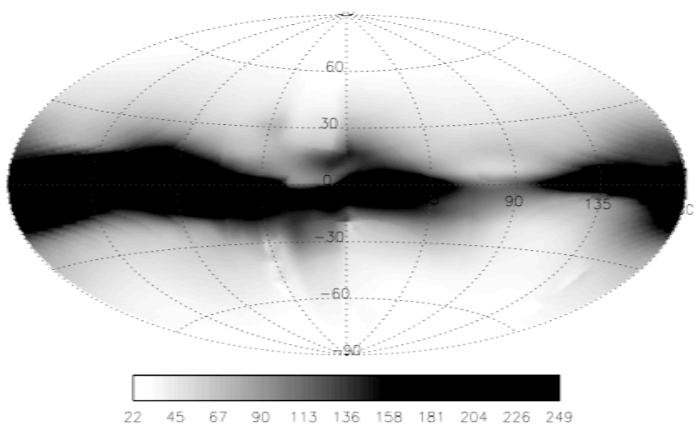
~ (1-10) x EBL



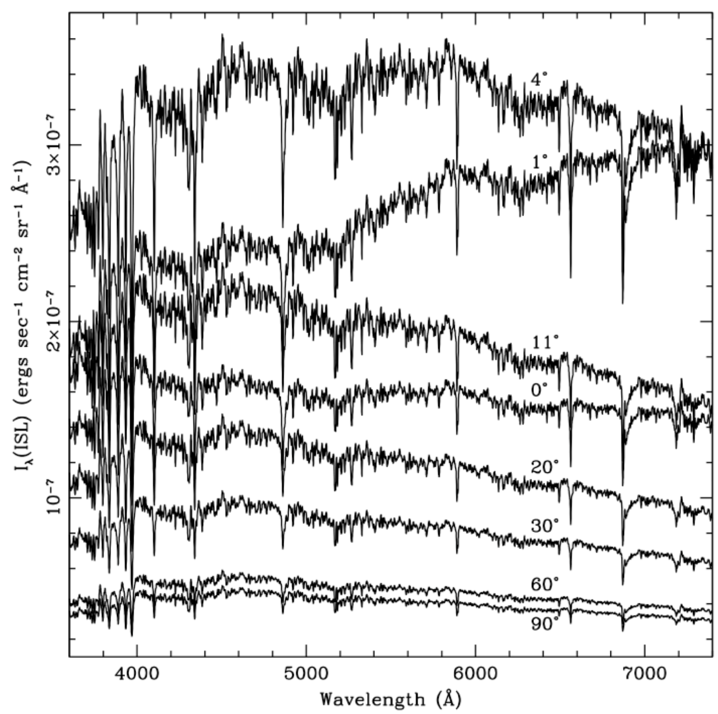
Schlegel, Finkbeiner, & Davis 1998

Diffuse Galactic Light

- Source: Integrated Star Light (ISL), known stellar types
- Scattering: dust is spatially variable (on very small scales)
  - » Mean DGL flux can be estimated from simple scattering models
- If poor spatial resolution, ISL is a direct contribution.
  - » Any solar-type spectrum will be removed as ZL if spectral features are used

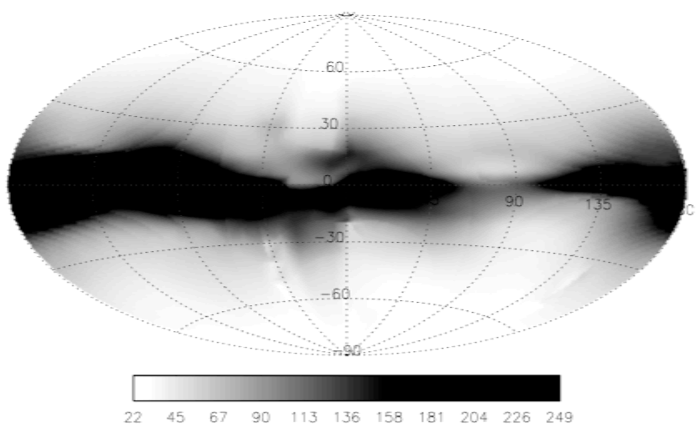


Integrated starlight at given Galactic Latitude:

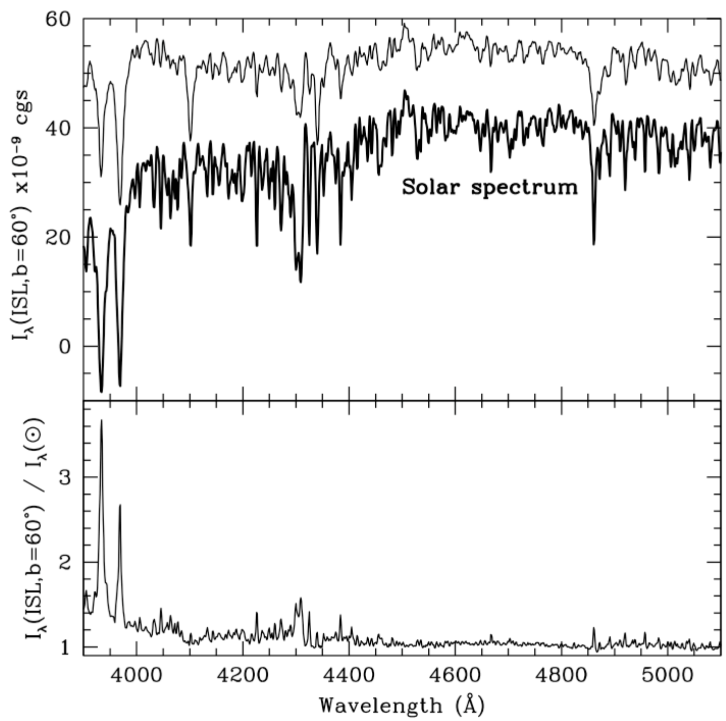


Diffuse Galactic Light

- Source: Integrated Star Light (ISL), known stellar types
- Scattering: dust is spatially variable (on very small scales)
    - » Mean DGL flux can be estimated from simple scattering models
- If poor spatial resolution, ISL is a direct contribution.
    - » Any solar-type spectrum will be removed as ZL if spectral features are used
    - » Other stellar mix can be identified by line ratios and correlated/removed simultaneously.

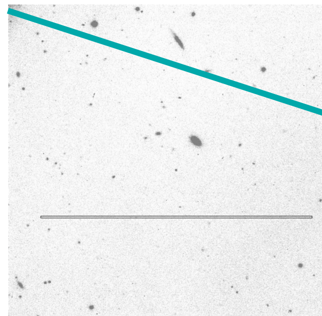


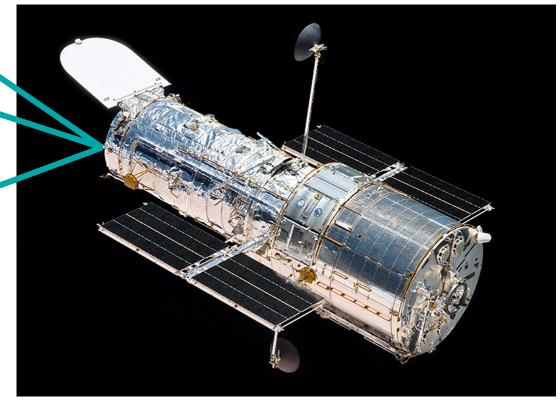
Compared to solar.

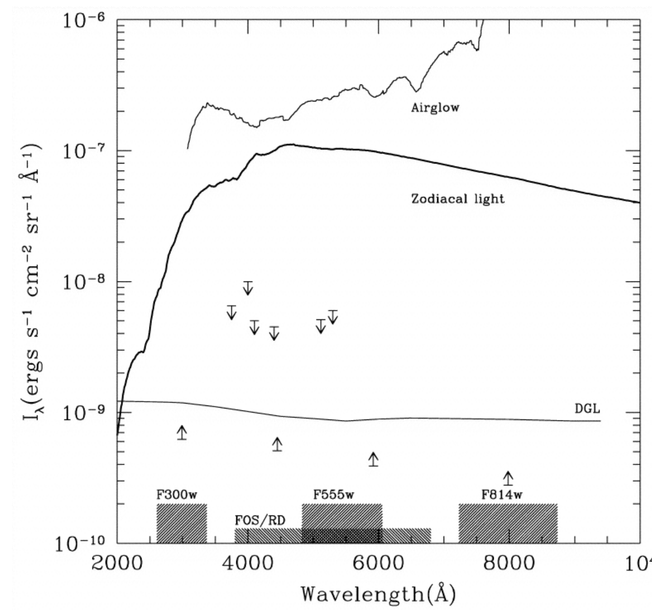


Calibration of measurement of diffuse backgrounds

- Case study: EBL measured with HST



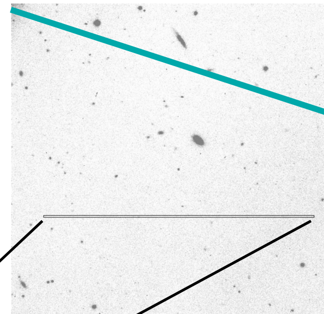


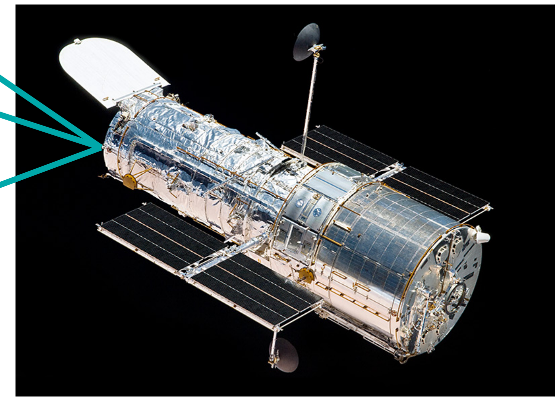


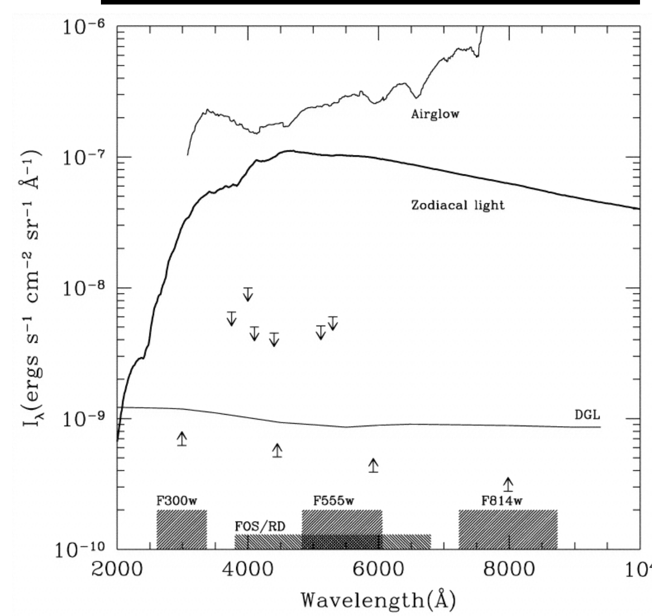
* [(Observed flux) - ZL - DGL - Inst] DN/s/pix = EBL DN/s/pix

Calibration of measurement of diffuse backgrounds

- Case study: EBL measured with HST+ LCO in an HST field of view





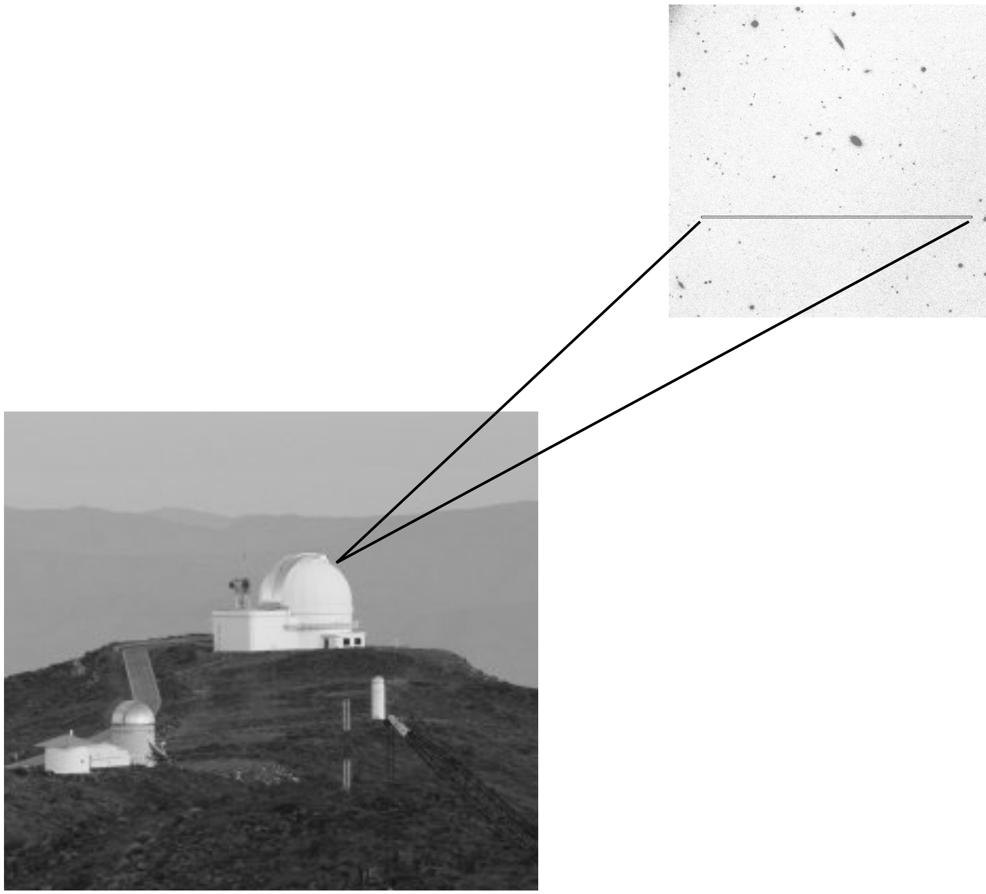


* HST/FOS turned out not to be sensitive enough to allow a ZL measurement

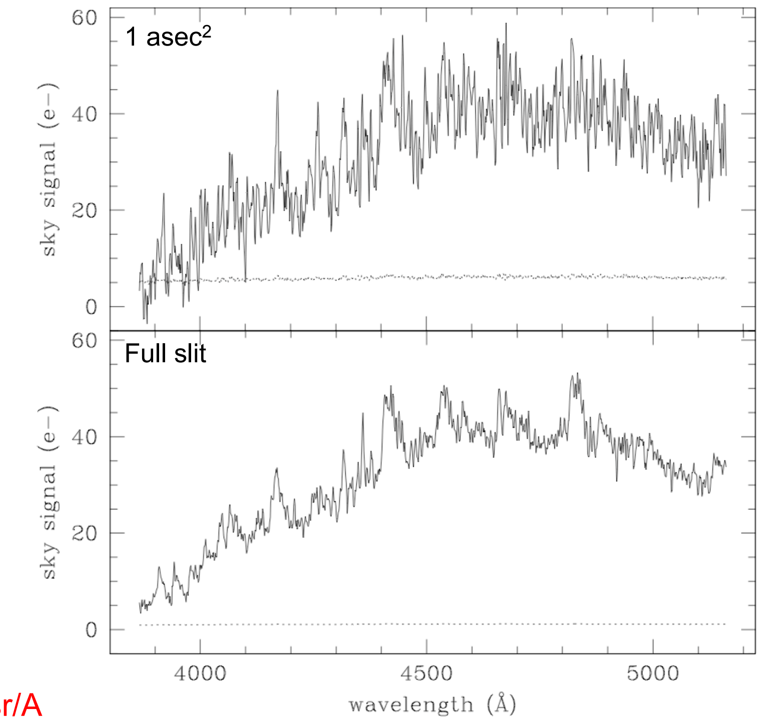
* [(Observed flux) - ZL - DGL - Inst] ers/s/cm^2/sr/A = EBL ers/s/cm^2/sr/A

Calibration of measurement of diffuse backgrounds

- Case study: EBL measured with HST+ LCO in an HST field of view



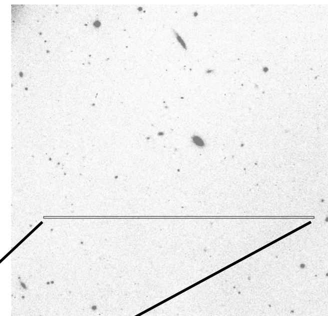
Raw spectrum:



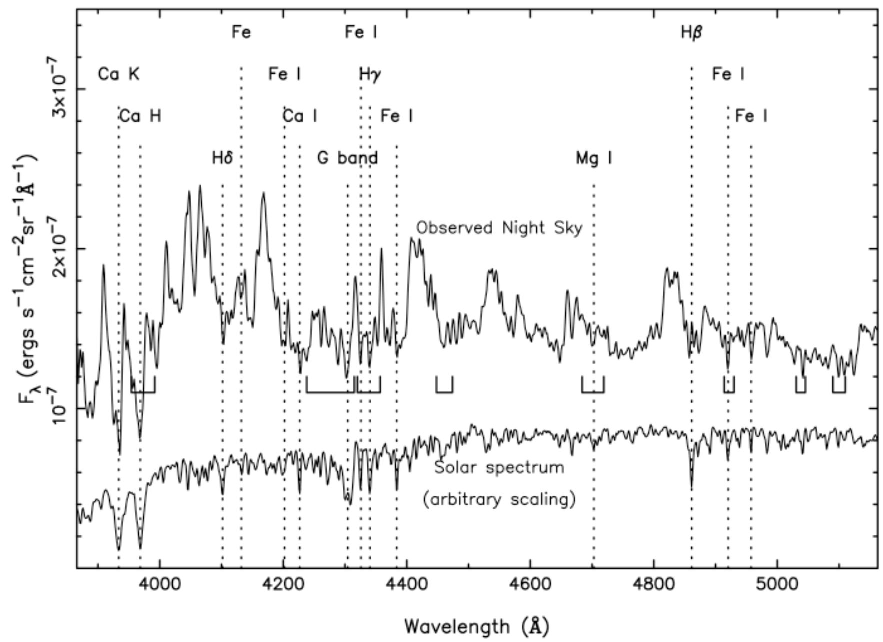
* [(Observed flux) - ZL - DGL - Inst] ers/s/cm^2/sr/A = EBL ers/s/cm^2/sr/A

Calibration of measurement of diffuse backgrounds

- Case study: EBL measured with HST+ LCO in an HST field of view



Calibrated spectrum:



* [(Observed flux) - ZL - DGL - Inst] ers/s/cm^2/sr/A = EBL ers/s/cm^2/sr/A

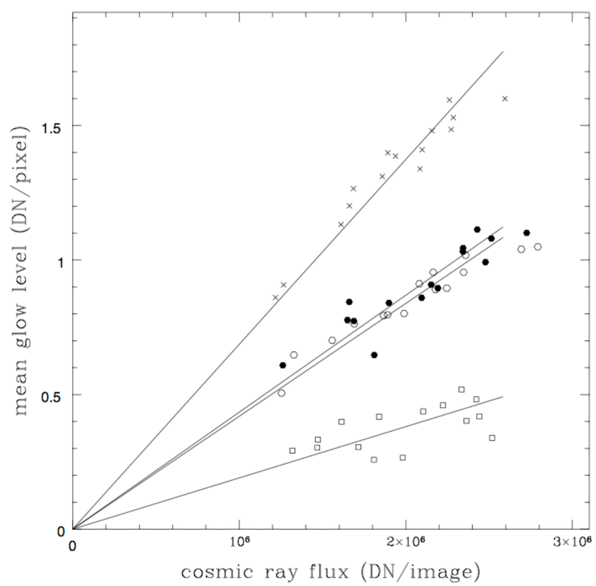
Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds: unpredictable!
  - Absolute …
  - Absolute surface ….
  - Absolute surface spectrophotometry

TABLE 1
ERROR BUDGET FOR ZODIACAL LIGHT FLUX

Step	Statistical Uncertainty (%)	Systematic Uncertainty (%)
Bias level removal (§ 3.2)	<0.01	...
Dark current removal (§ 3.3)	<0.01	...
Pixel-to-pixel flat-fielding (§ 3.4)	<0.01	...
Slit illumination (§ 3.4)	...	<0.1
Point-source flux calibration (§ 3.6.1)	...	0.6
Aperture correction (§ 3.6.2)	...	0.2

Unknown unknowns:** Dark "glow" from the MgF_2 (A/R coating) of window over CCDs



** - e^- traps at low light levels
- charge diffusion
- flux calibration drift
- uncertain psf corrections
- uncertain scattering properties in instrument
- radioctive glasses (BK7)
- etc etc etc

Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute [flux of a star vs uniform source]
  - Absolute surface ….
  - Absolute surface spectrophotometry

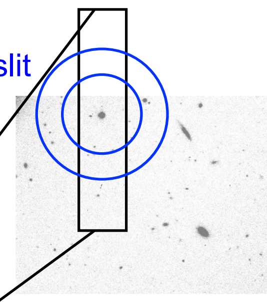
TABLE 1

ERROR BUDGET FOR ZODIACAL LIGHT FLUX

Step	Statistical Uncertainty (%)	Systematic Uncertainty (%)
Bias level removal (§ 3.2)	<0.01	. . .
Dark current removal (§ 3.3)	<0.01	. . .
Pixel-to-pixel flat-fielding (§ 3.4)..................	<0.01	. . .
Slit illumination (§ 3.4)..[slit jaw uniformity]	. . .	<0.1
Point-source flux calibration (§ 3.6.1)...........	. . .	0.6
Aperture correction (§ 3.6.2)	. . .	0.2

DN/s/pix ⇒ ergs/s/cm2/sr/A
vs
DN/s/ STAR ⇒ ergs/s/cm2/A

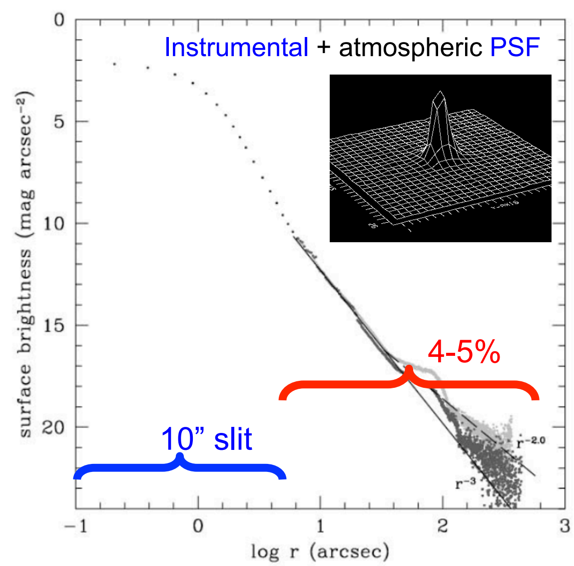
10" slit10" slit



How much **flux/star…**

… got into the slit? ~94-96%
… got to the CCD once in? ~97%

ALL of the **flux/area** will get in from a uniform background source.



Calibration of measurement of diffuse backgrounds

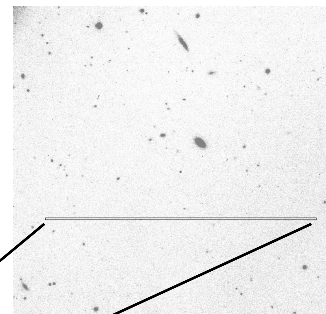
- Case study:
  - Instrumental backgrounds
  - Absolute …
  - Absolute surface ….
  - Absolute surface spectrophotometry

TABLE 1
ERROR BUDGET FOR ZODIACAL LIGHT FLUX

Step	Statistical Uncertainty (%)	Systematic Uncertainty (%)
Bias level removal (§ 3.2)	<0.01	...
Dark current removal (§ 3.3)	<0.01	...
Pixel-to-pixel flat-fielding (§ 3.4)	<0.01	...
Slit illumination (§ 3.4) [slit jaw uniformity]	...	<0.1
Point-source flux calibration (§ 3.6.1)	...	0.6
Aperture correction (§ 3.6.2)	...	0.2
Solid angle (§ 3.6.3)	...	0.6

How wide WAS that slit?

Matters you need to know **flux/*area*.**



Related questions:

- What is the telescope plate scale?
- What is the spectrograph plate scale?
- Is the grating tilted (x-y plate distortion)
- Is there optical distortion?
- Are the slit jaws parallel? uniform?
- etc etc etc

Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute …
  - Absolute surface ….
  - Absolute surface spectrophotometry

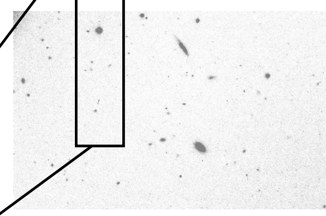
TABLE 1

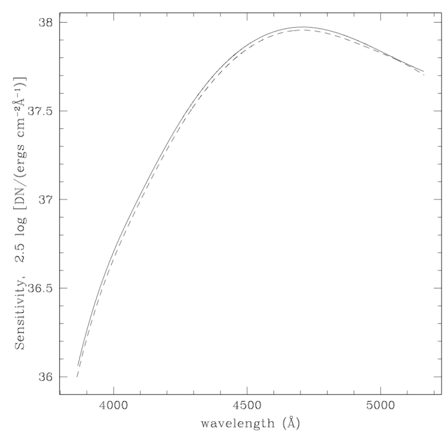
Error Budget for Zodiacal Light Flux

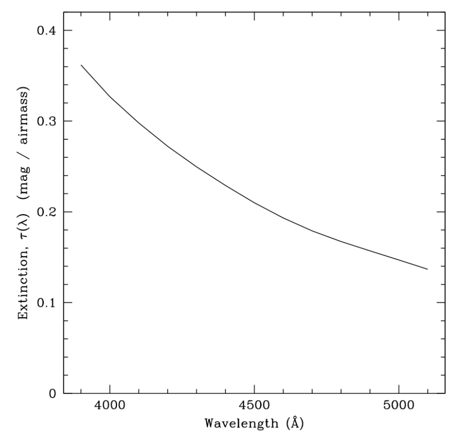
Step	Statistical Uncertainty (%)	Systematic Uncertainty (%)
Bias level removal (§ 3.2)	<0.01	. . .
Dark current removal (§ 3.3)	<0.01	. . .
Pixel-to-pixel flat-fielding (§ 3.4)...................	<0.01	. . .
Slit illumination (§ 3.4)................................	. . .	<0.1
Point-source flux calibration (§ 3.6.1)...........	. . .	0.6
Aperture correction (§ 3.6.2)	. . .	0.2
Solid angle (§ 3.6.3)	. . .	0.6

Sensitivity function
Extinction function

… atmospheric stability
… instrumental stability
… charge transfer, conservation, diffusion …

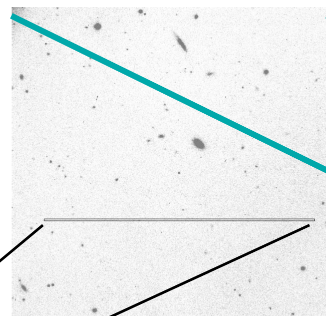


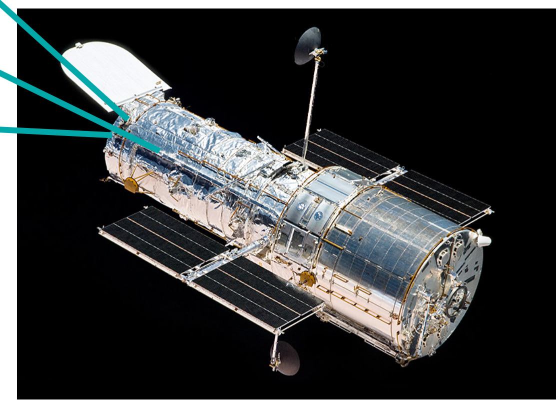




Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute …
  - Absolute surface ….
  - Absolute surface spectrophotometry
  - *With multiple instruments — measurements must be calibrated on an absolute scale.*

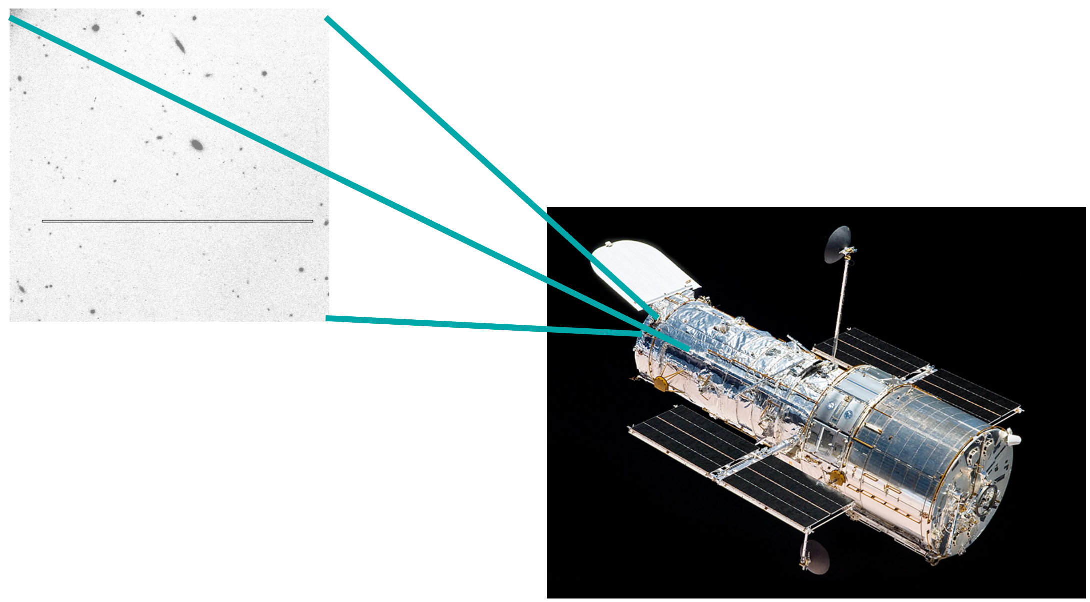




If backgrounds (100x EBL) are subtracted *after* calibration,
a ~5% calibration error becomes a ~500% uncertainty in the EBL.

Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute …
  - Absolute surface ….
  - Absolute surface spectrophotometry
  - *With one instrument — measurement becomes relative, not absolute.*

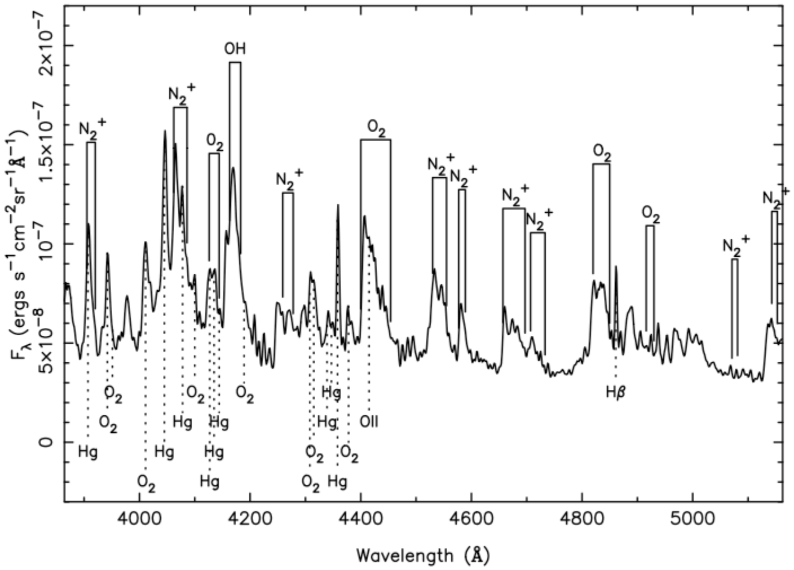


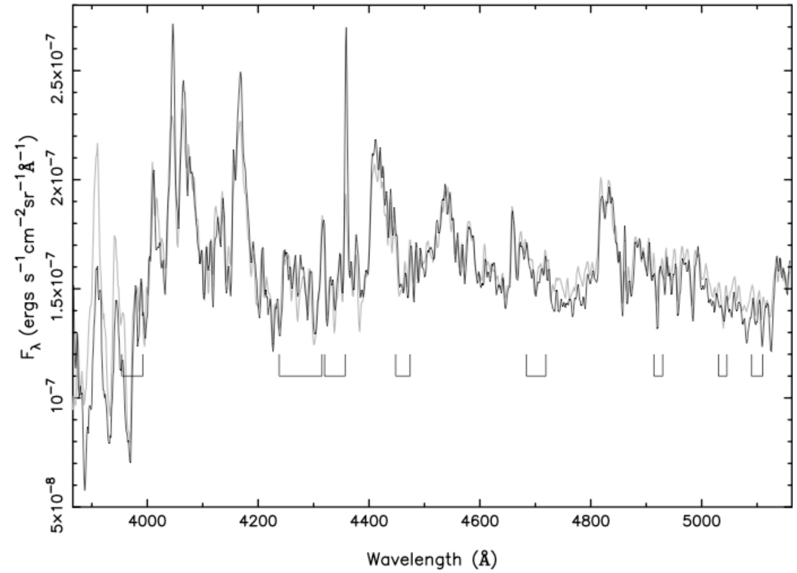
If backgrounds (100x EBL) are subtracted *before* calibration,
a ~5% calibration error becomes a ~5% uncertainty in the EBL.*

*(Unknown instrumental backgrounds are still a problem)

Measurements from/near the Earth

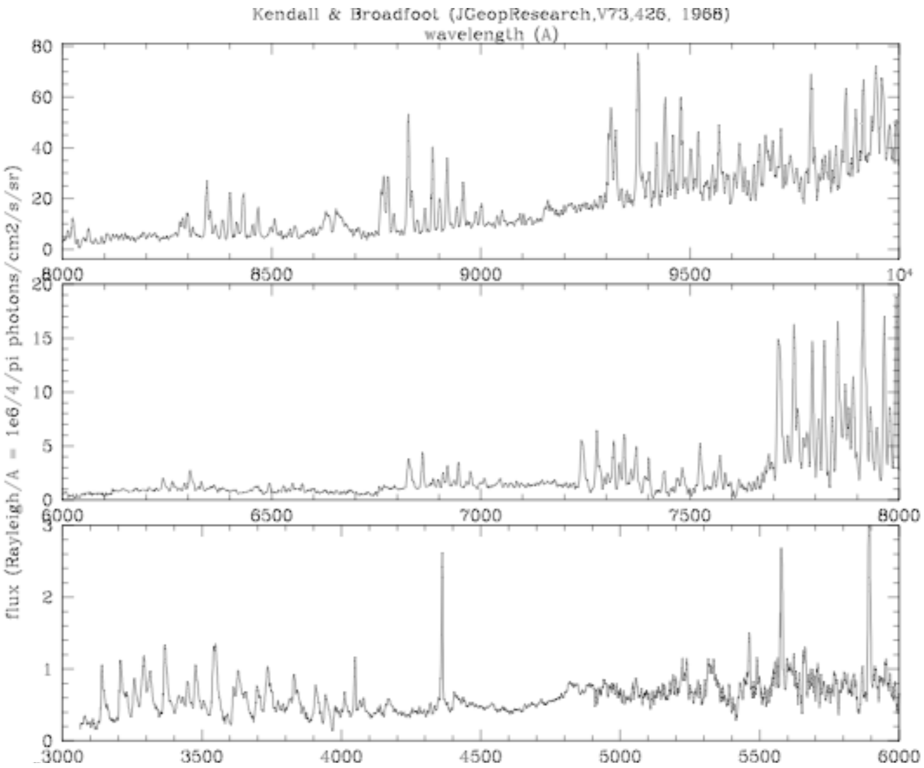
- Airglow in the optical
  - Particularly variable within ~2 hrs sunset/sunrise
  - Variability also due to scattering (see next slides)





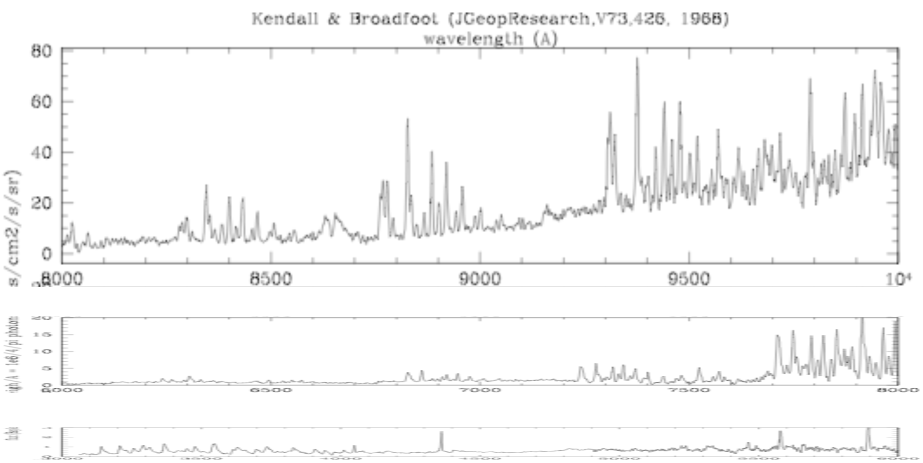
Measurements from/near the Earth

- Airglow in the near IR
  - Particularly variable
  - Bright



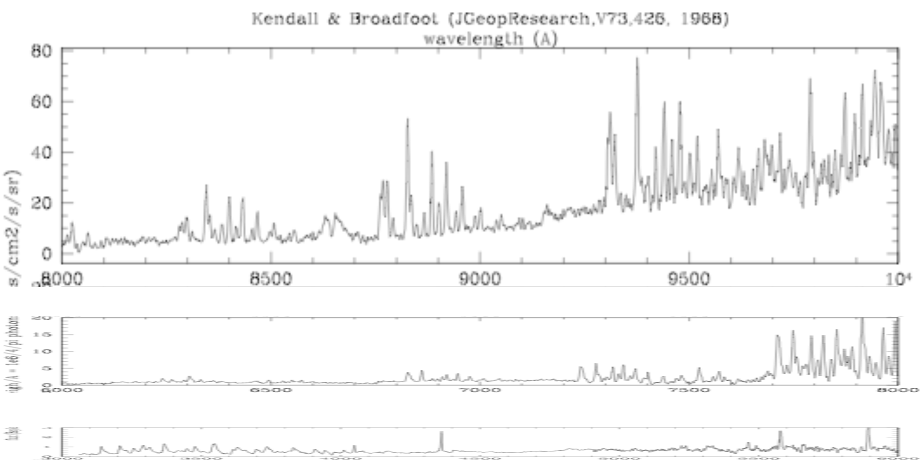
Measurements from/near the Earth

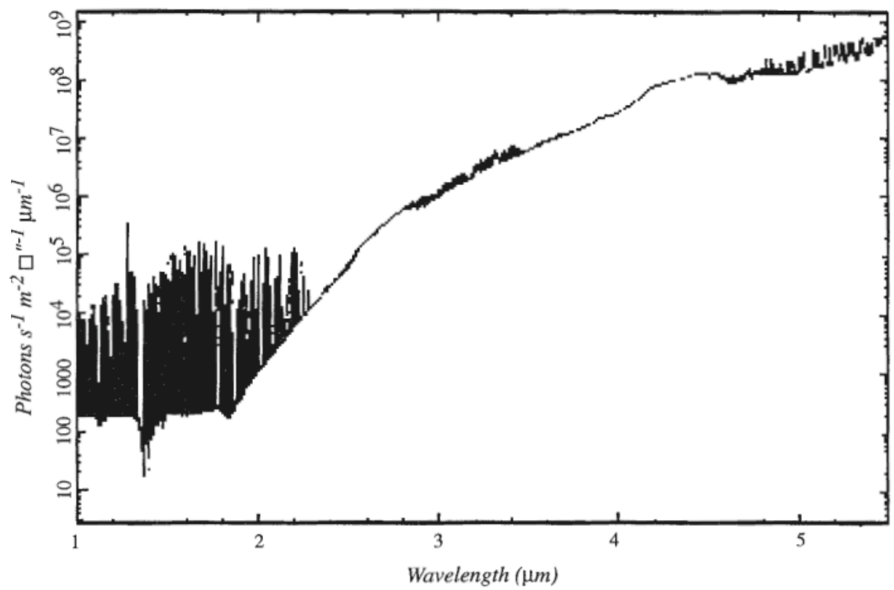
- Airglow in the near IR
  - Particularly variable
  - Bright



Measurements from/near the Earth

- Airglow in the near IR
  - Particularly variable
  - Bright





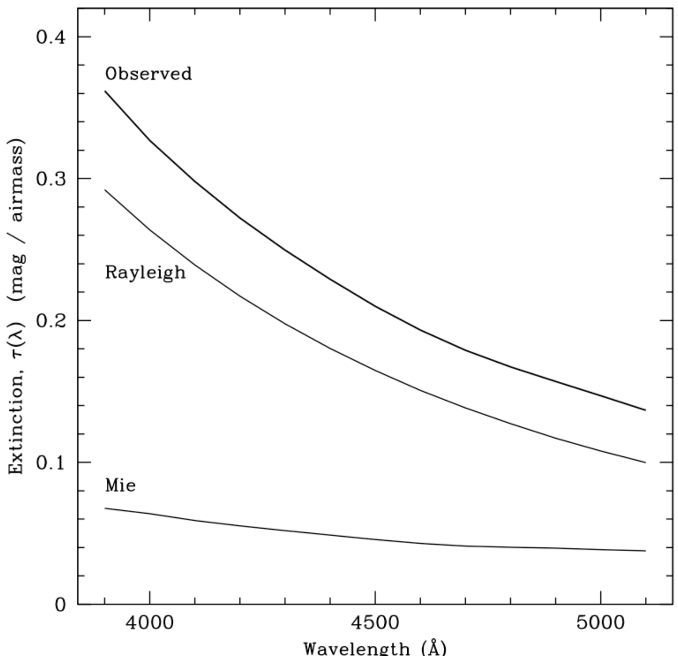
Measurements from/near the Earth

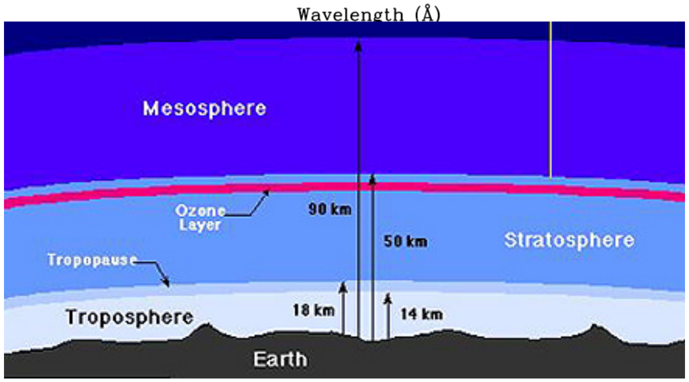
- Shuttle “glow” — emission from atmosphere in direction of line of sight
- “Earth shine”

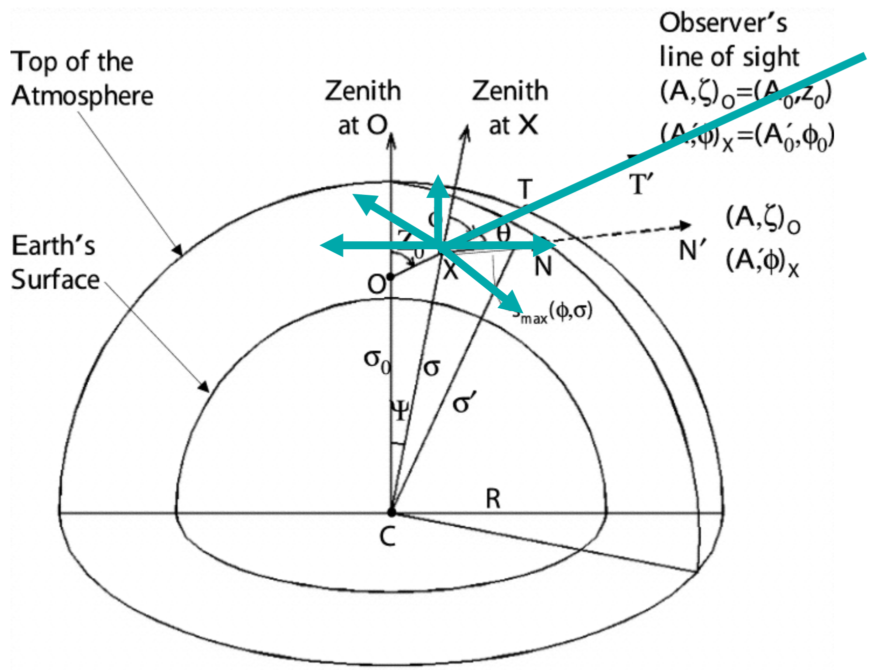
- These sources further complicated by
  - Radioactive windows (MgF_2, BK7, etc), which respond to radiation
  - Scattering in the telescope
  - Extended PSF of off-axis sources due to mirrors (micro-ripple, dust, etc)
  - etc etc etc

Measurements from/near the Earth

- Tropospheric scattering:
  - sources include [ZL, DGL, EBL] + [Moonlight, Integrated star light]
  - Can be modeled, but not at the 1% level.







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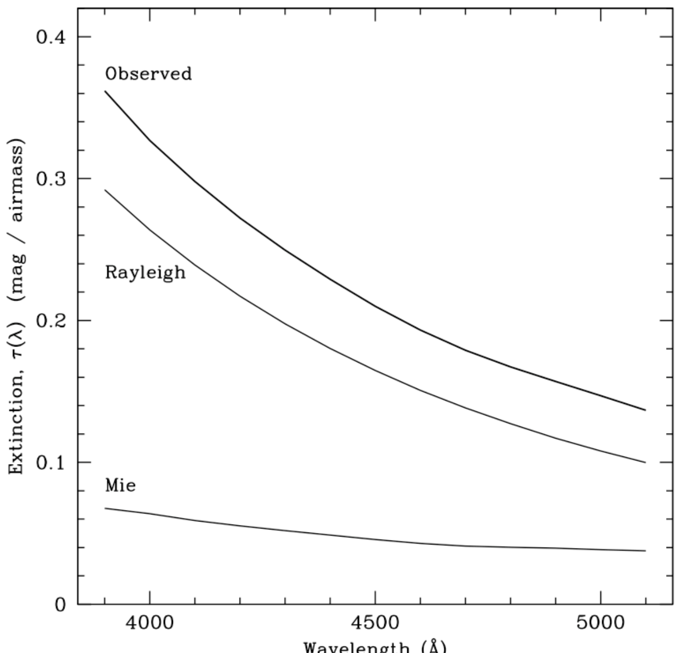

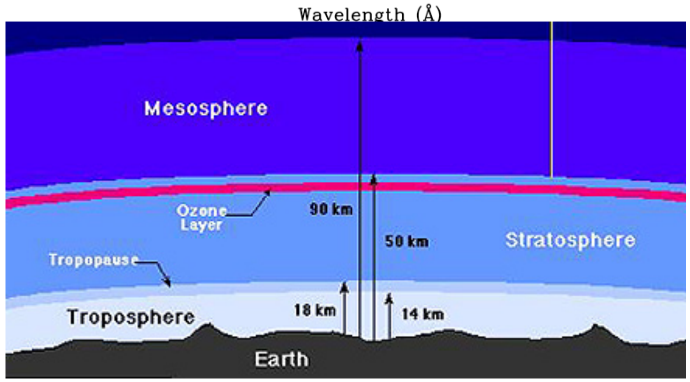

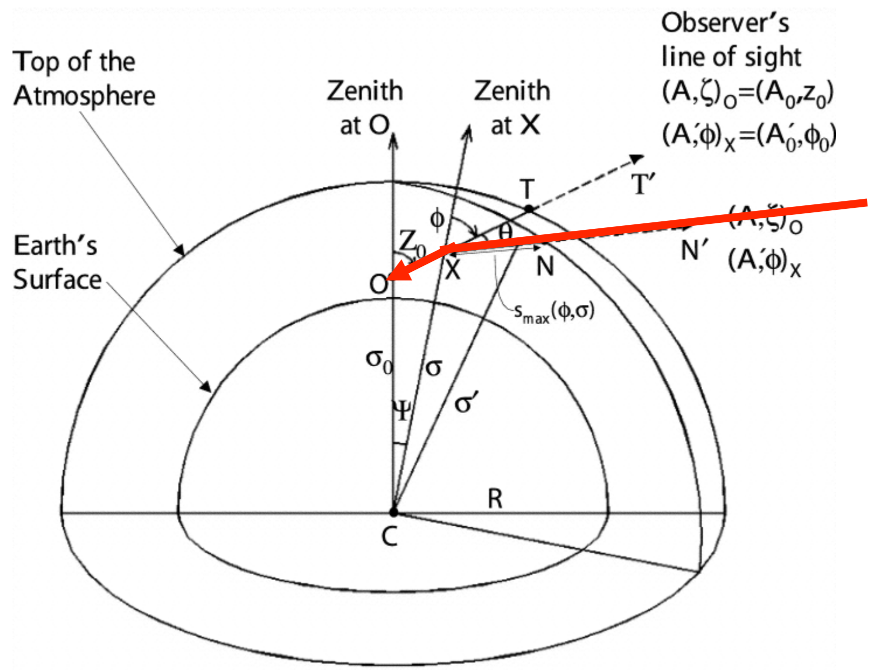

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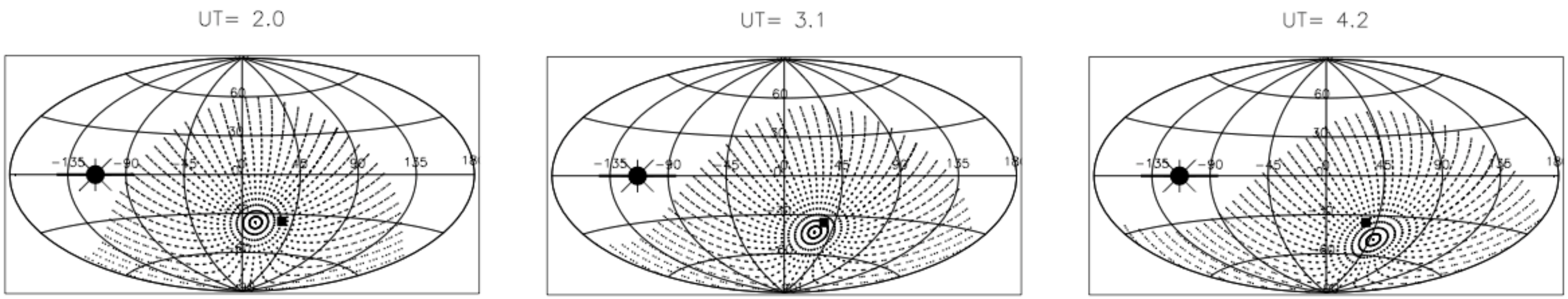
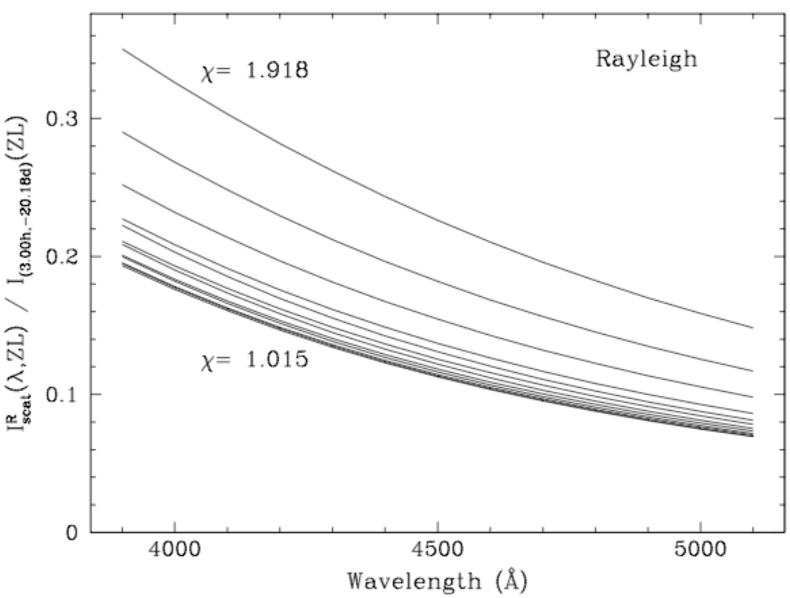
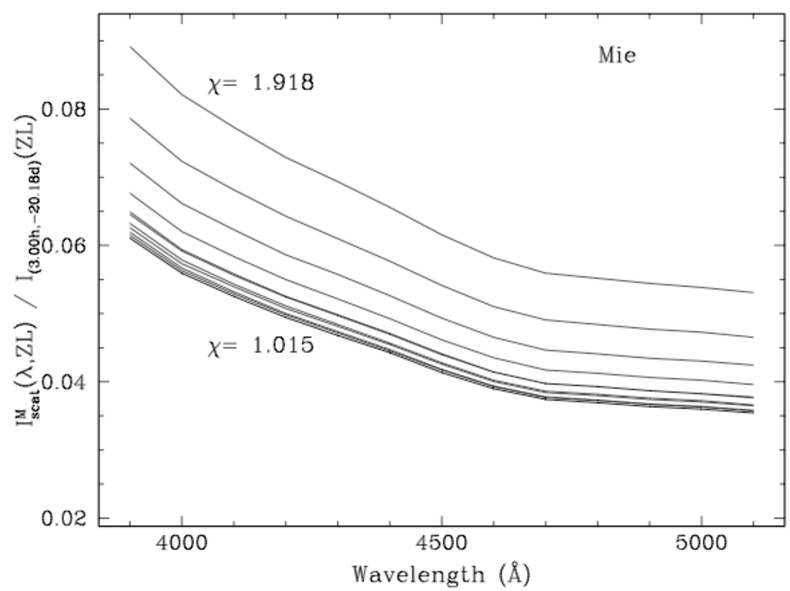
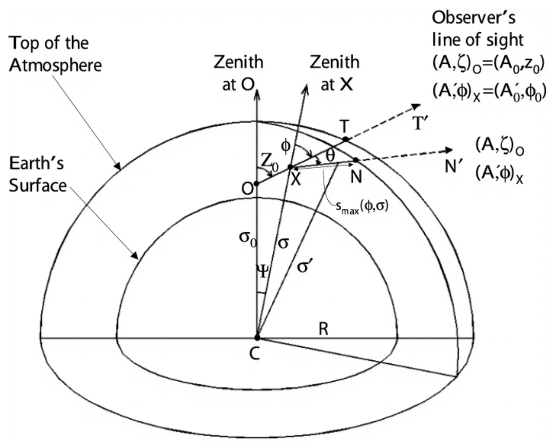


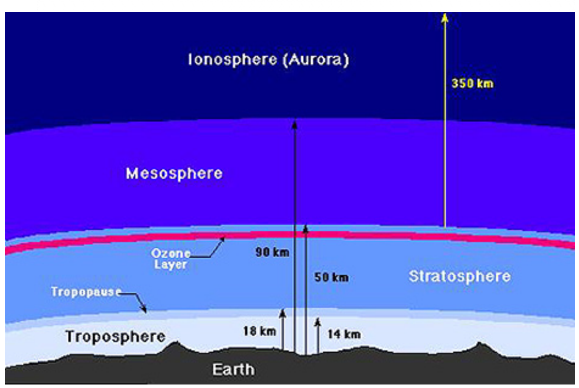


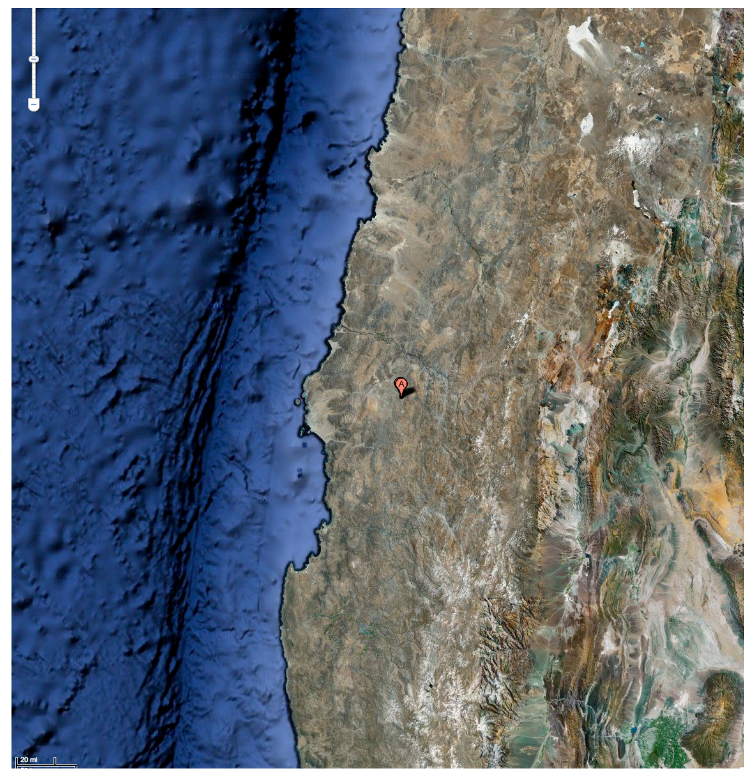


Measurements from/near the Earth

- Tropospheric scattering:
  - sources include [ZL, DGL, EBL] + [Moonlight, Integrated star light]
  - Can be modeled, but not at the 1% level.
- Ground scattering:
  - Albedo of soil, vegetation, etc within 100 km can contribute ~5%
  - Sources: [ZL, DGL, EBL] + [Moonlight, Integrated star light]
  - Can be modeled, but not at the 1% level.

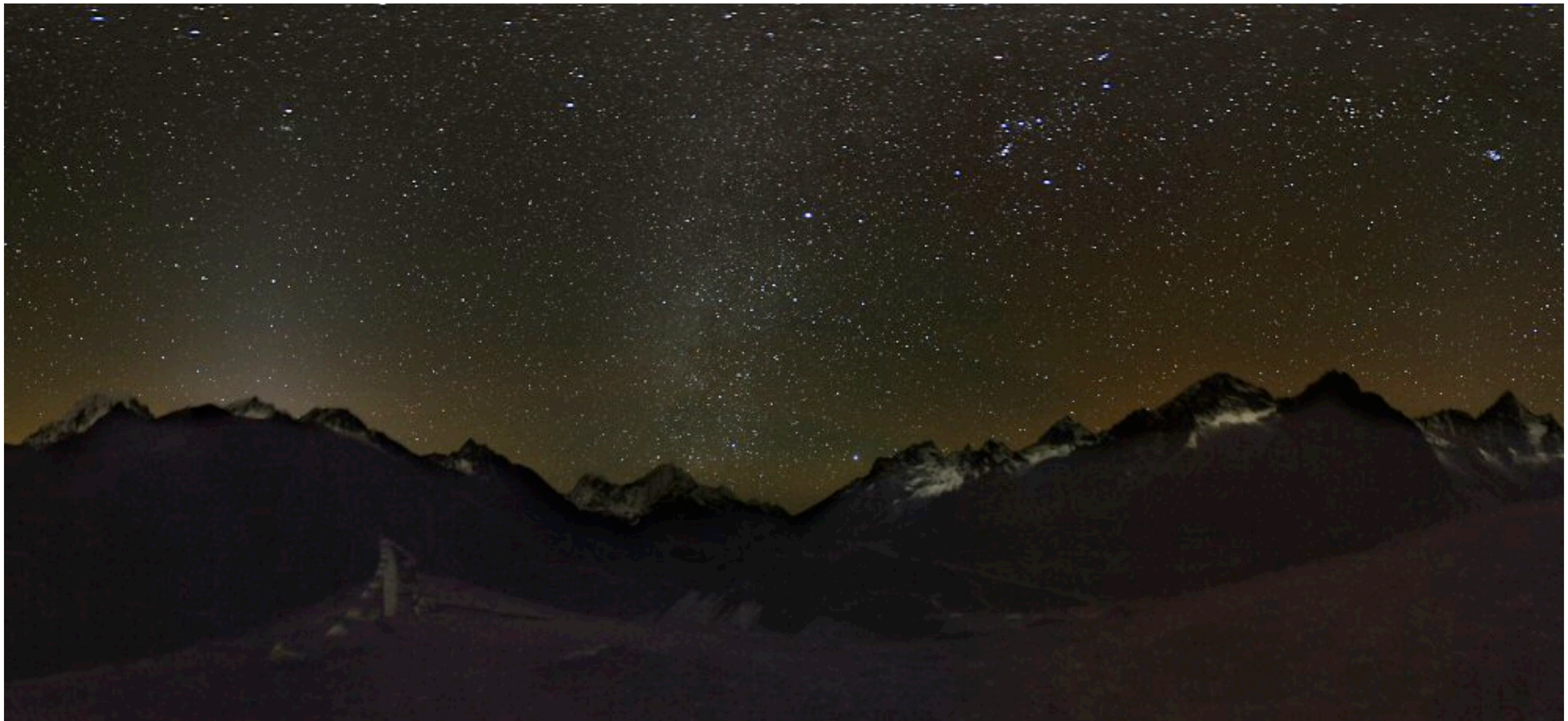






Recipe for happier-ness includes*

- Minimize backgrounds (line of sight, location of telescope)
- Above the Earth's atmosphere (or 5 AU, or *possibly* in the IR where atmospheric scattering is low)
- Use 1 instrument (for all diffuse and resolved backgrounds)
- Minimize in-instrument scatter (minimal # of optics)
- High spatial resolution (remove point source stars at ~22 AB mag V?)
- High spectral resolution (≤ 1Å)
- Avoid polarization-dependent instrumental effects (multiple mirrors)
- Include surface brightness tests prior to launch (charge transfer, trapping, instrument glow, etc)



* in measurement of diffuse backgrounds, only.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Reality and measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute [flux calibration]
  - Absolute surface ….
  - Absolute surface spectrophotometry

TABLE 1
ERROR BUDGET FOR ZODIACAL LIGHT FLUX

Step	Statistical Uncertainty (%)	Systematic Uncertainty (%)
Bias level removal (§ 3.2)	<0.01	...
Dark current removal (§ 3.3)	<0.01	...
Pixel-to-pixel flat-fielding (§ 3.4)....................	<0.01	...
Slit illumination (§ 3.4) ..[slit jaw uniformity]	...	<0.1
Point-source flux calibration (§ 3.6.1)...........	...	0.6
Aperture correction (§ 3.6.2)	...	0.2

How much light…

1. Got into the slit?
2. Got to the CCD once in?

from the (point source) standard star
vs your uniform background source