The Extragalactic Background Light: Implications for The Cosmic Star Formation History

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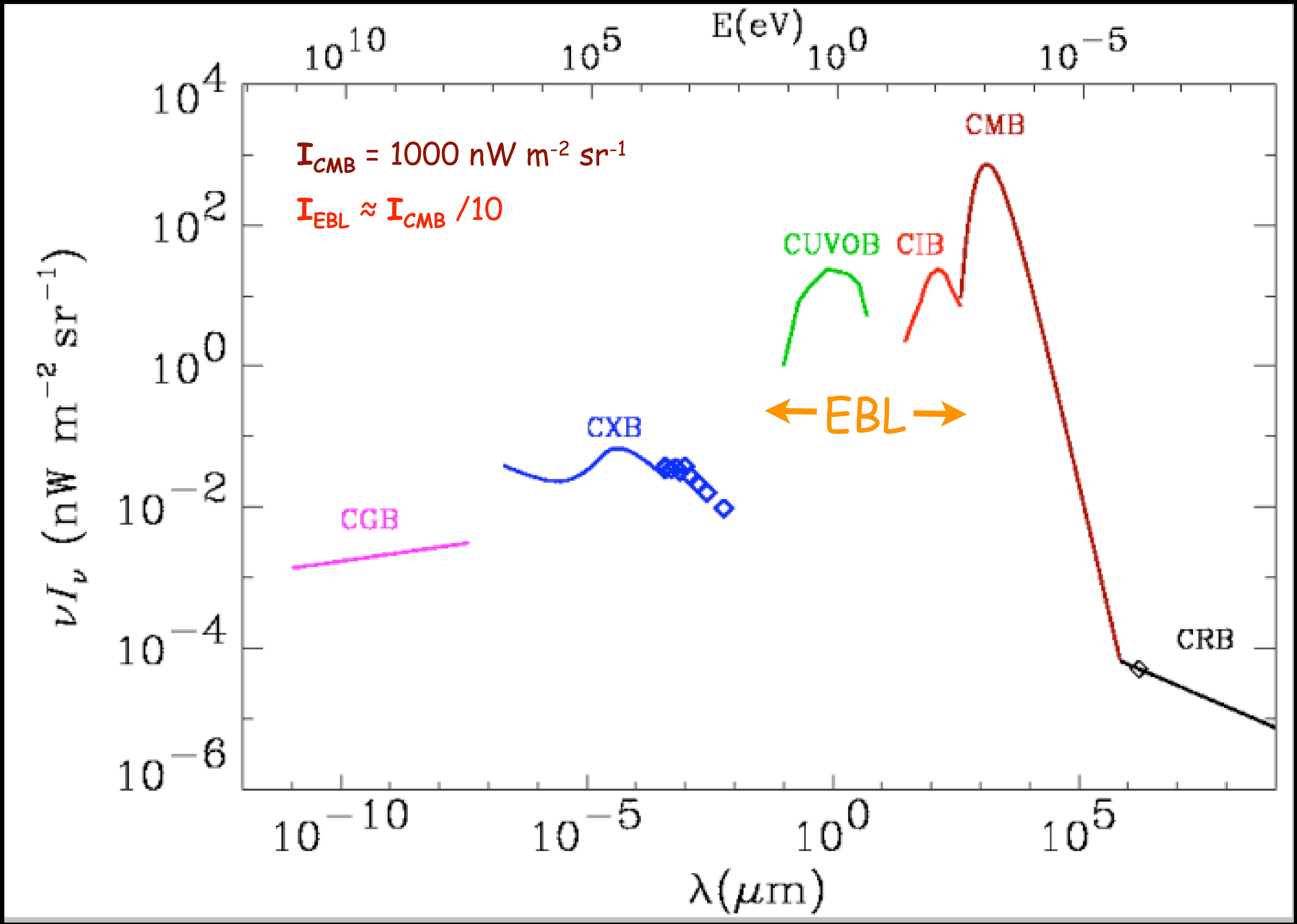
Hauser & Dwek 2001, ARA&A, 39, 249-307
Dwek & Krennrich 2005, ApJ, 618, 657
Dwek & Arendt 2005, in preparation

Lecture Outline

- The extragalactic background light (EBL):
  - What is it, how do we measure it, methods of determination, problems
- The subtraction of foreground emissions
  - zodiacal light, Galactic stars and ISM
- The nature of the near-IR EBL (NEBL)
  - residual zodi or extragalactic?
- Population III spectral imprint on the NEBL
- Is there any evidence for the Xgalactic nature of the EBL in the observed TeV spectra of blazars?
- Summary

The Extragalactic Background Light (EBL) in Context of Other Backgrounds



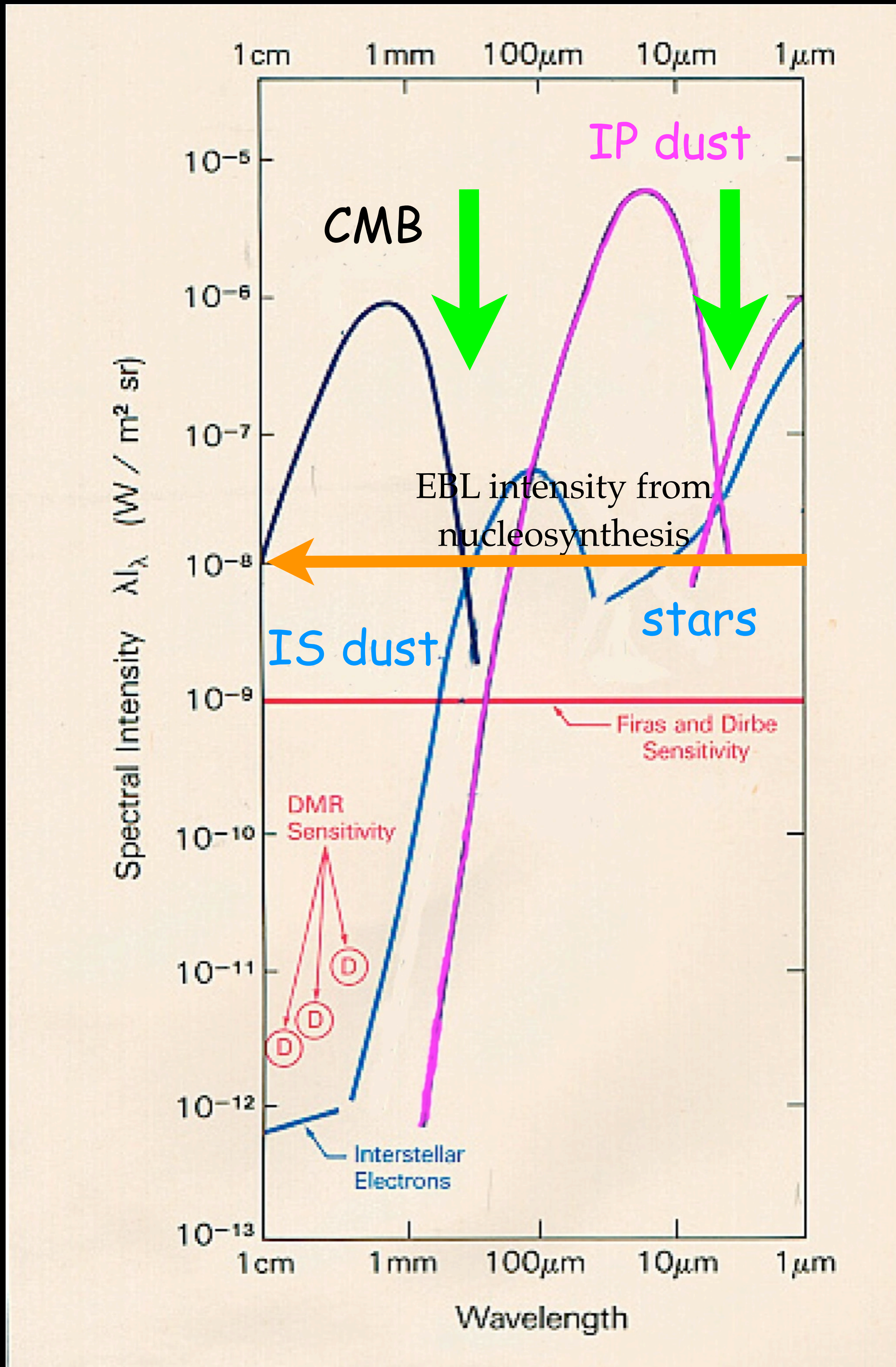
Sources Contributing to the EBL

The EBL consists of the cumulative radiation emitted by all energy sources since the epoch of recombination

- Exotic Sources
  - decaying particles, primordial black holes, exploding stars, Pop III stars
- Active Galactic Nuclei
  - powered by gravitational energy release
- Starlight
  - powered by the release of nuclear energy

The Importance of the EBL

- It contains information on:
  - cosmic star/BH formation history
  - cosmic history of metal production
  - thermalization of X-rays & starlight by dust
- Opacity source for TeV photons
- Causal relation to X-ray and radio backgrounds
- Constrains the existence/evolution of exotic sources



Difficulties in EBL Measurements

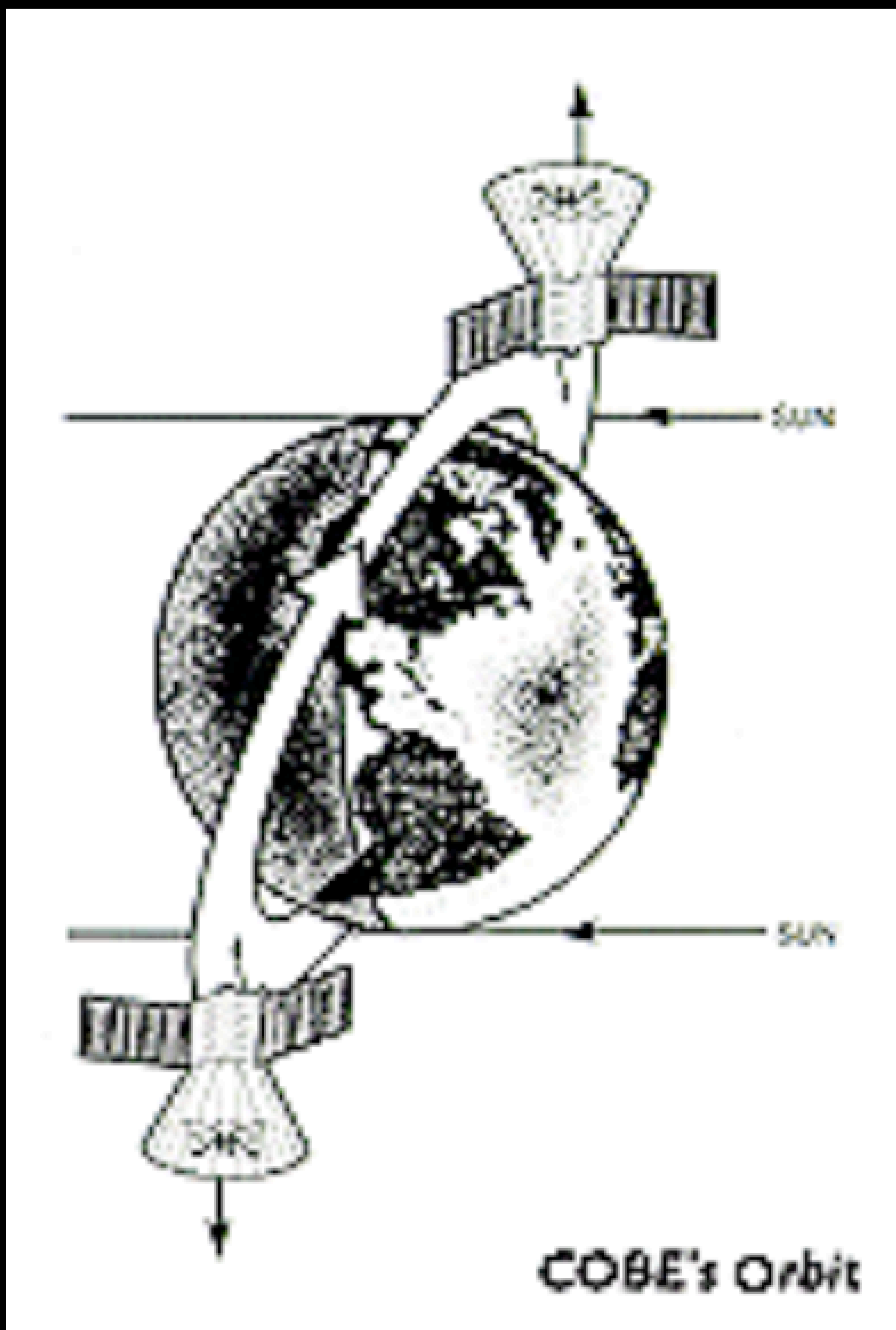
- No unique spectral characteristics
- Strong foreground emission
  - Interplanetary dust
    - reflected sunlight
    - thermal emission
  - Interstellar dust
  - Galactic starlight
- Spectral windows at ~ 5 and 300 μm

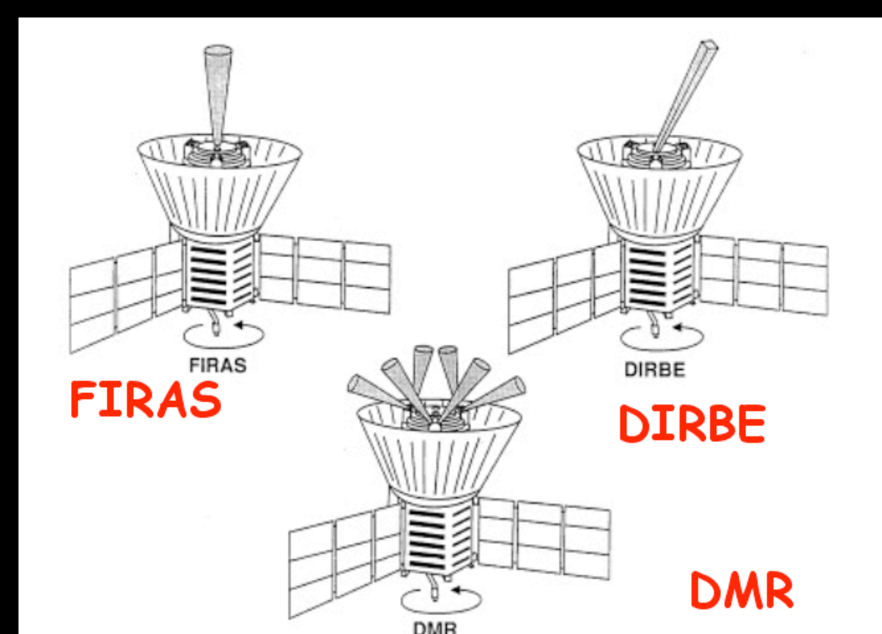
Measuring the EBL

- Direct diffuse sky measurements
  - Absolute calibration (IUE, DIRBE, IRTS, HST)
  - Excellent stray light rejection
  - Removal of foreground emission
- Source counts
  - Lower limit on EBL
  - Converge to EBL intensity
- Fluctuation analysis
  - Requires knowledge of $dI(z)/dz$
- Search for absorption in the spectra of TeV blazars
  - Requires knowledge of the intrinsic blazar spectrum

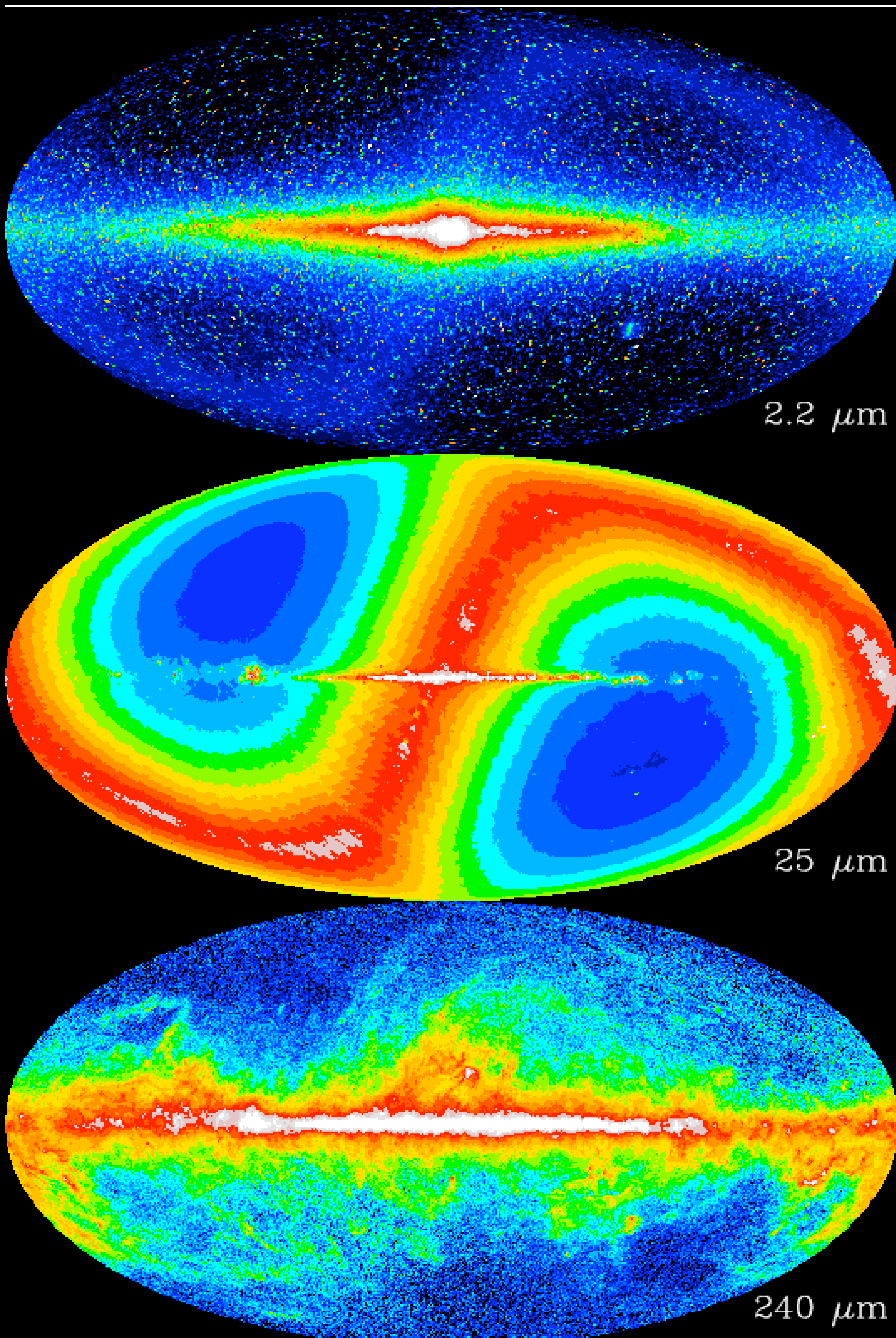
COBE Orbit Characteristics

- Sun-synchronous 900 km orbit with a 103 min. period
  - 99° inclination causes the orbit to precess by 1°/day
  - scans 1/2 sky each day
- Data was collected over a 10 moth period





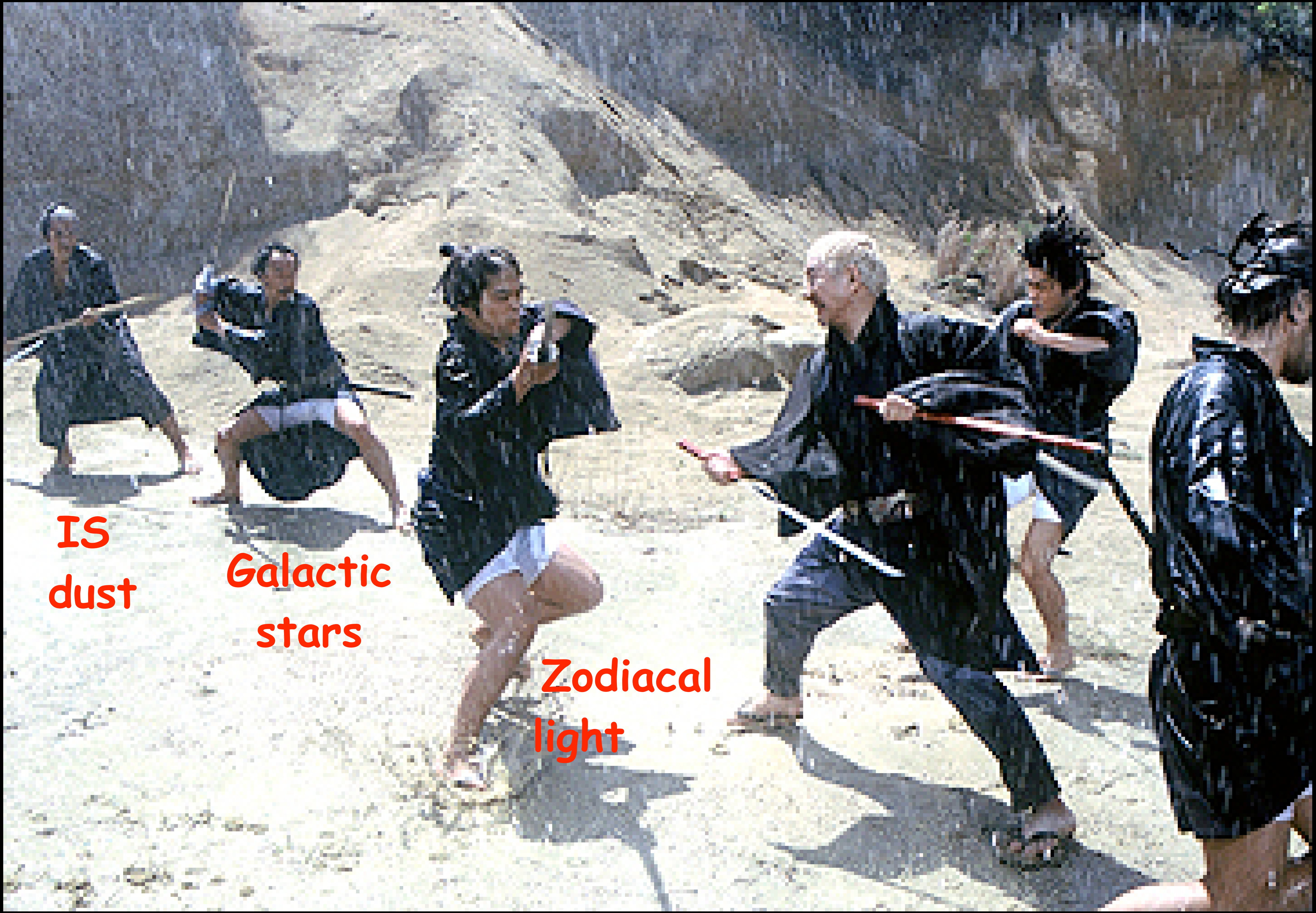
Scan modes of COBE Instruments



DIRBE Observed Sky

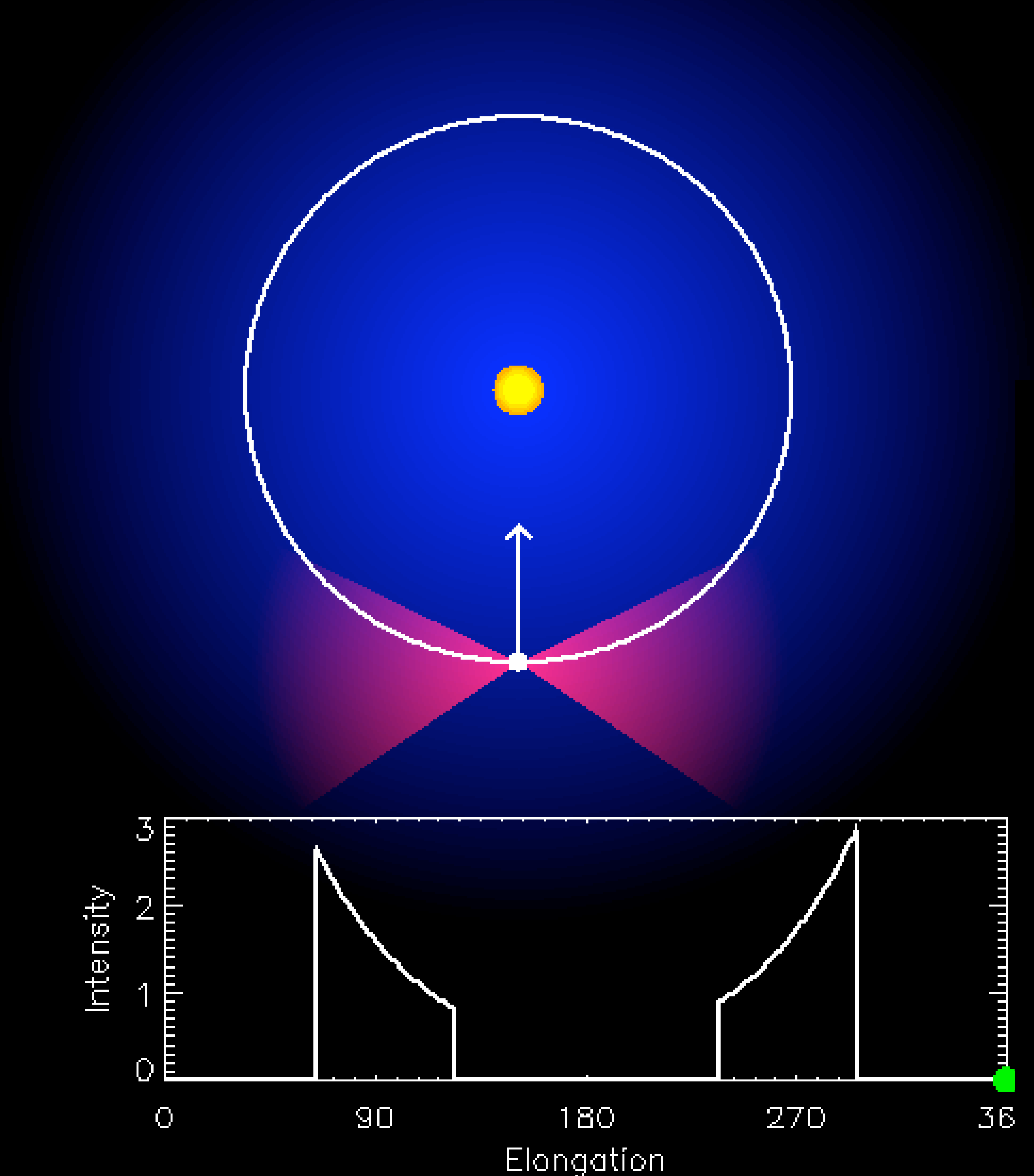
- 2.2 μm sky
  - starlight, IPD emission, LMC, SMC
- 25 μm sky
  - IPD emisison (Zodiacal light) Galactic ISM
- 240 μm sky
  - Interstellar Dust emission, LMC, SMC

Taking out the "Gang" of Foreground Emission Components

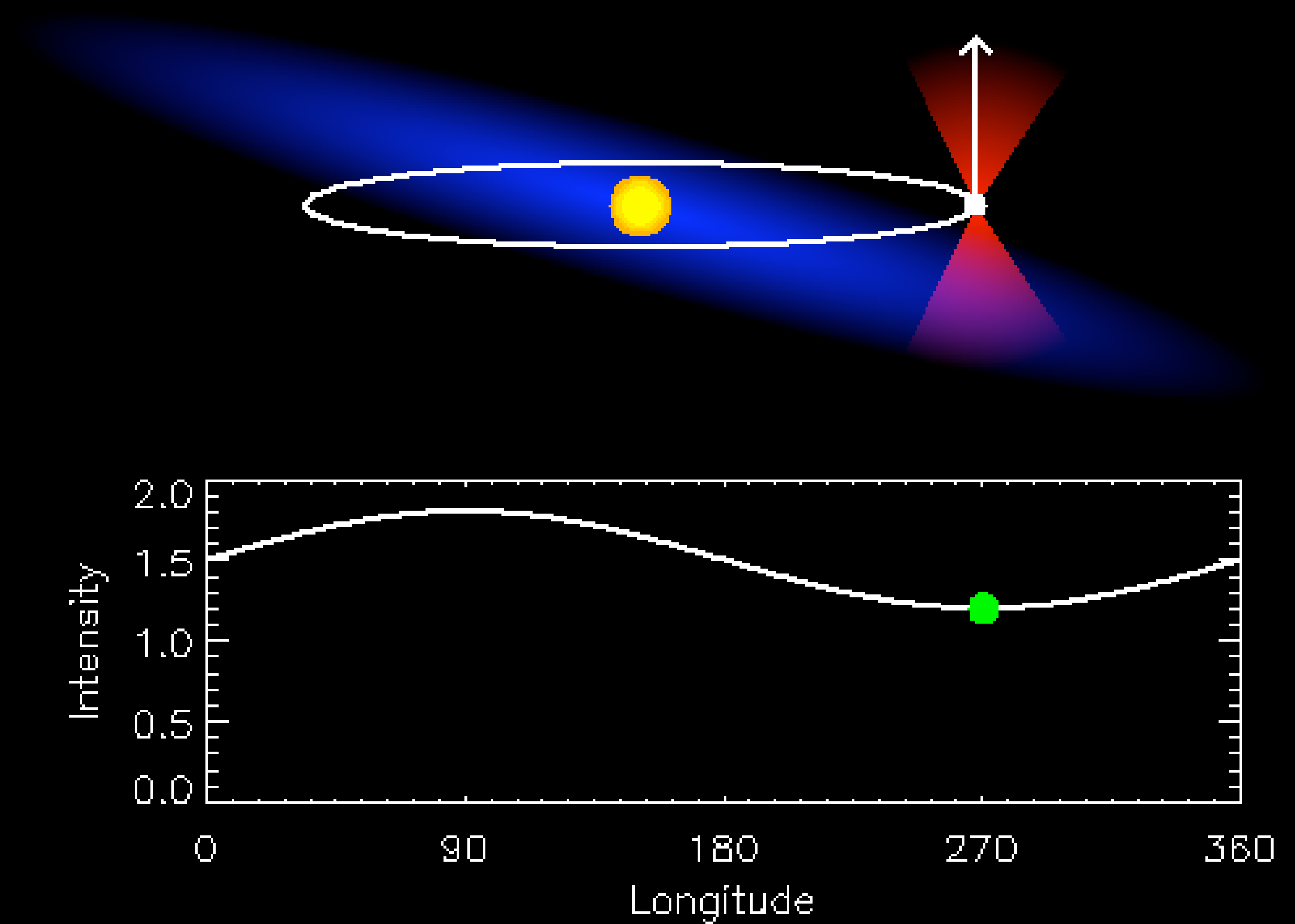


Zodi Light Variation

(1) Towards the ecliptic plane

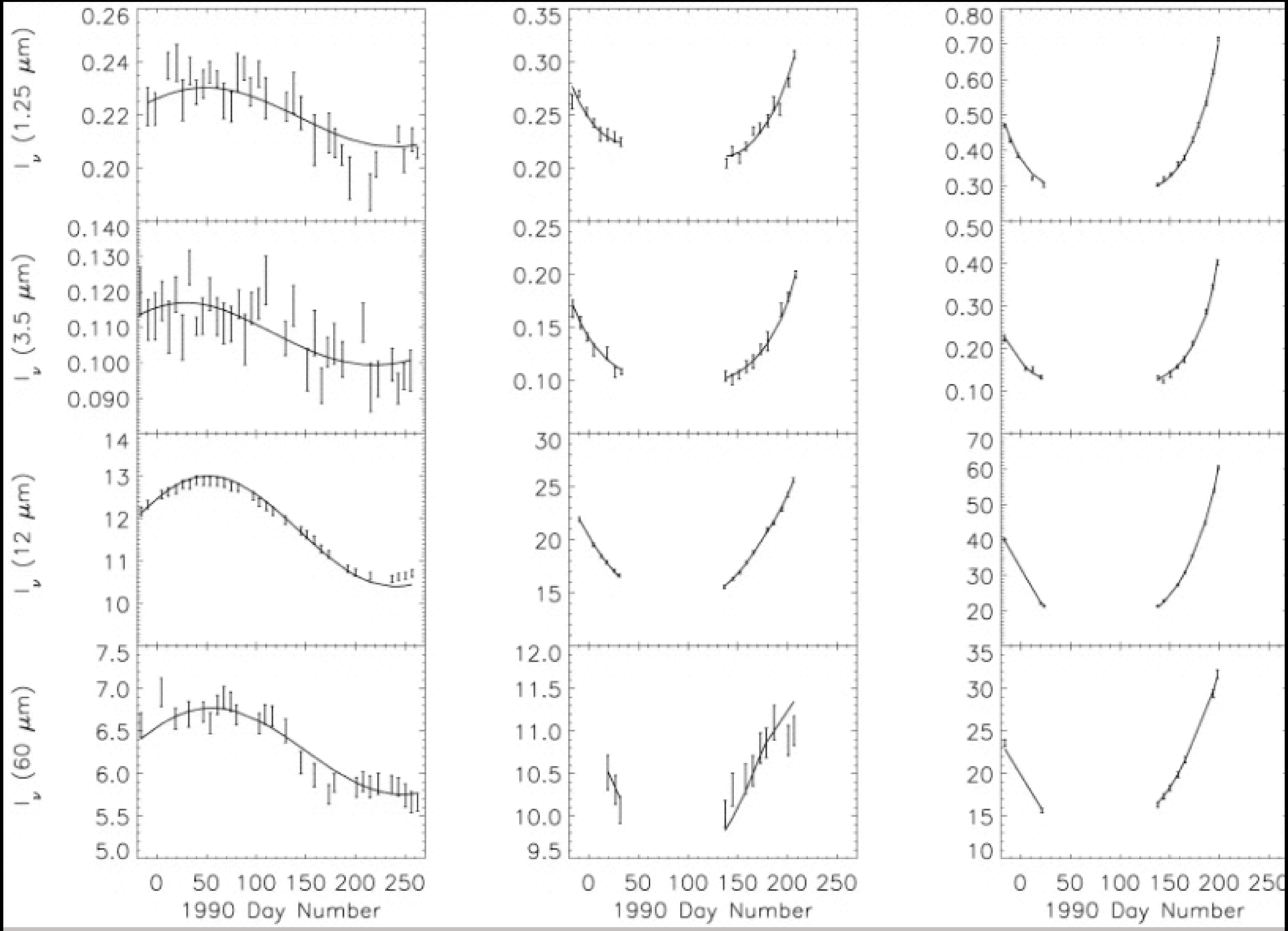


(2) Towards the ecliptic pole



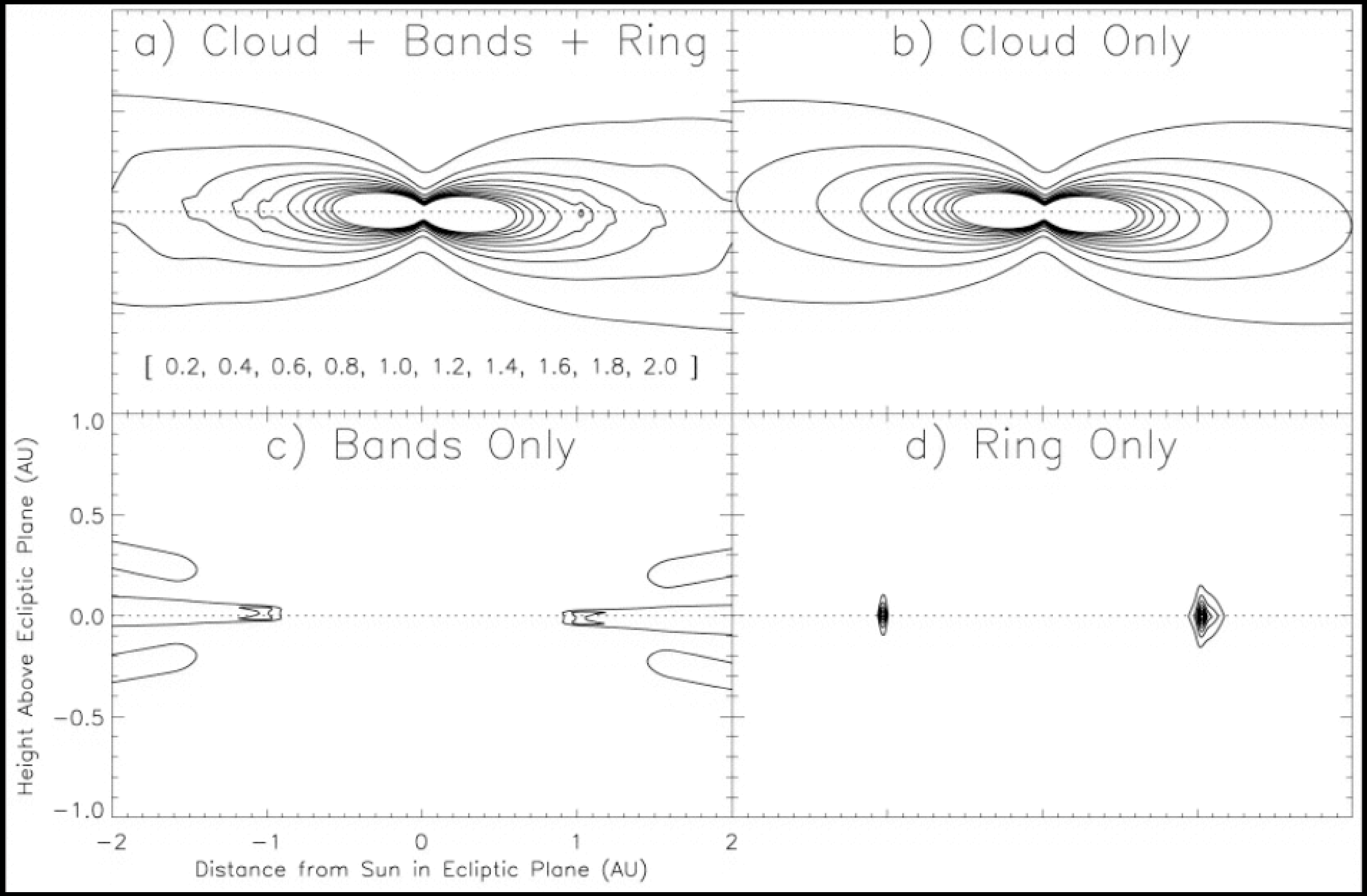
Observed Signatures of Zodiacal Light Emisison

high ecliptic latitudes | mid ecliptic latitudes | low ecliptic latitudes



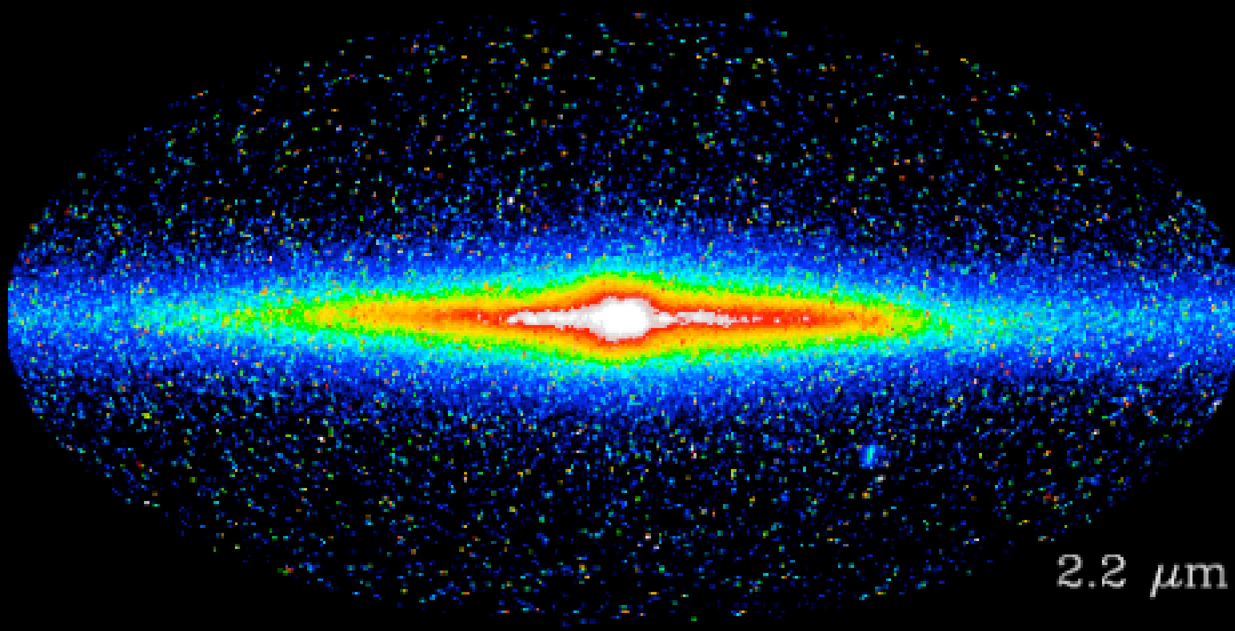
Components of the Zodiacal Dust Model

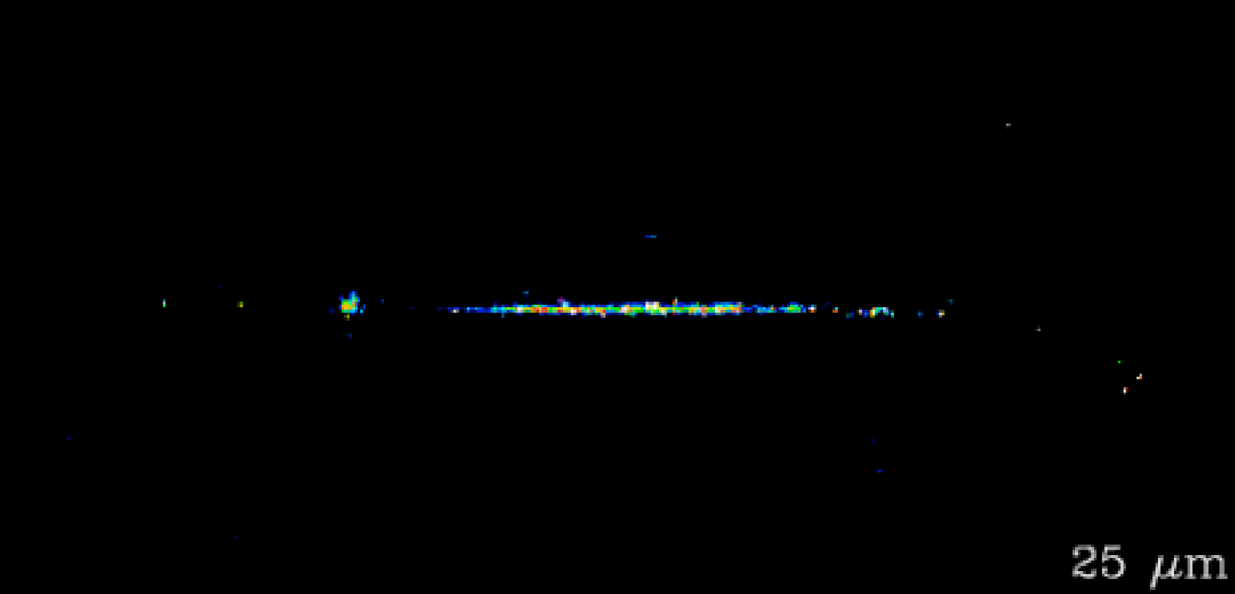
Kelsall et al. 1998

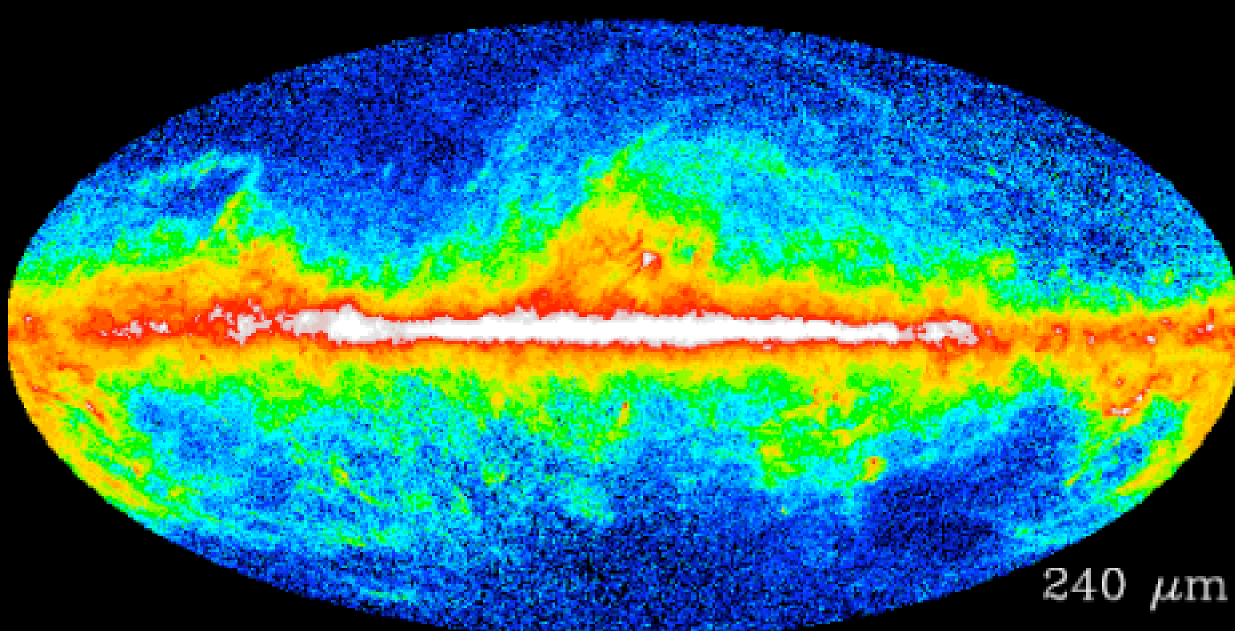


- Smooth dust cloud
  - asteroidal cometary collisions
    5 different models
- Interplanetary dust bands
  - asteroidal breakup
    - toroidal band model
    - migrating band model
- Circumsolar ring
  - Inward flowing dust particles, resonantly trapped in earth's orbit

Zodi Subtracted Sky

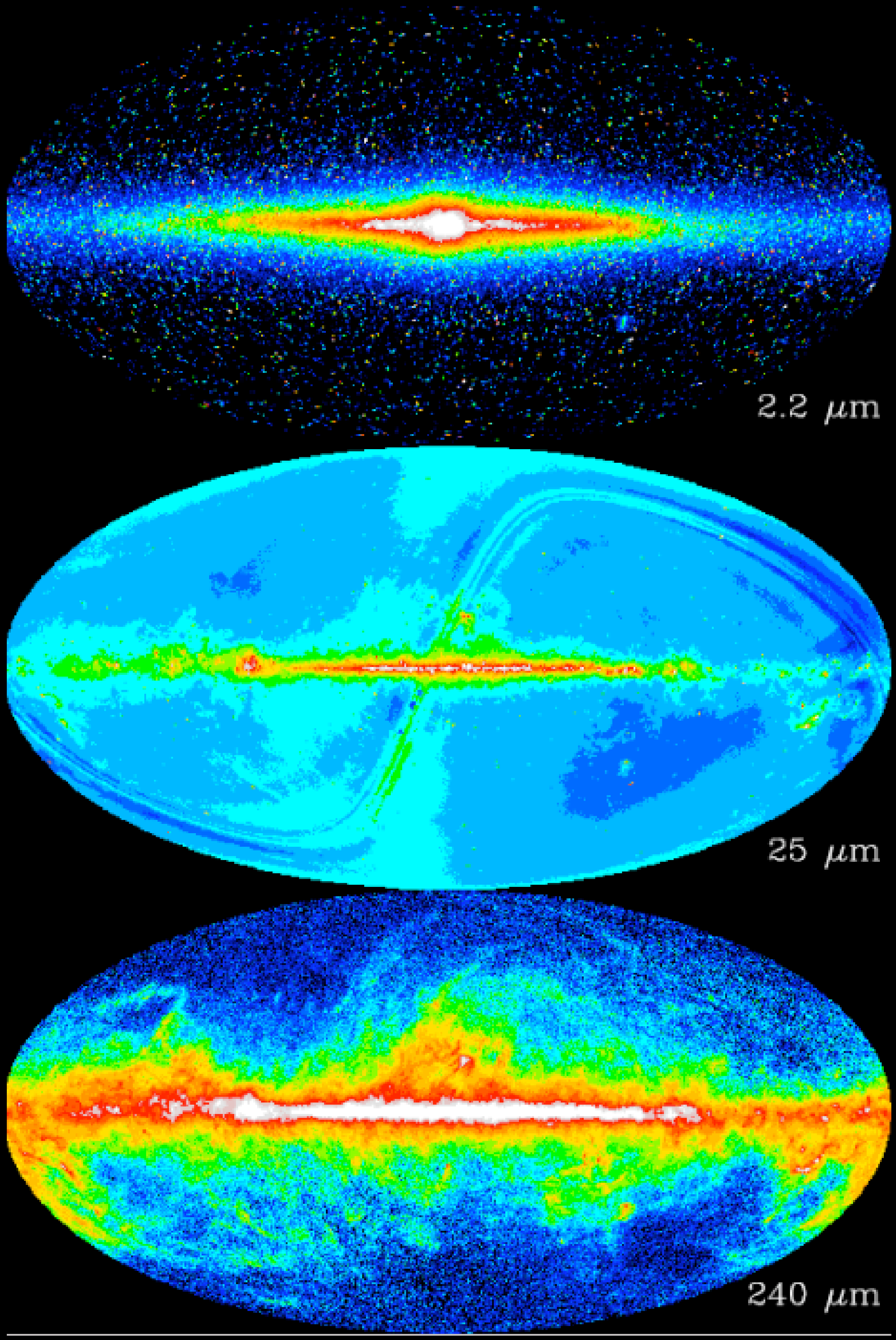






- 2.2 μm sky
  - starlight, LMC, SMC
- 25 μm sky
  - Galactic ISM
- 240 μm sky
  - Interstellar Dust emission, LMC, SMC

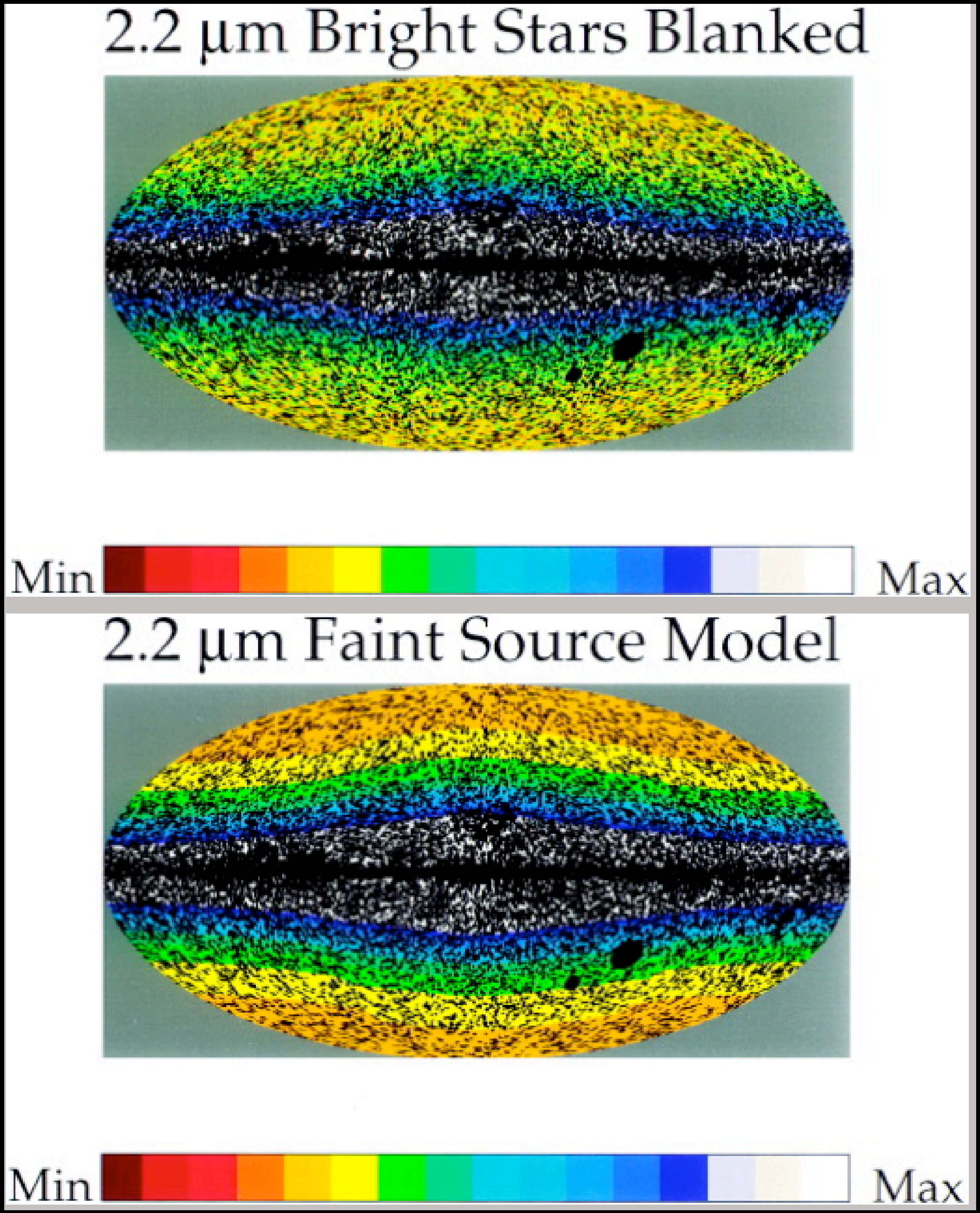
Zodi Subtracted Sky



- 2.2 μm sky
  - starlight, LMC, SMC
- 25 μm sky
  - Galactic ISM
  - 2% of previous level
- 240 μm sky
  - Interstellar Dust emission, LMC, SMC

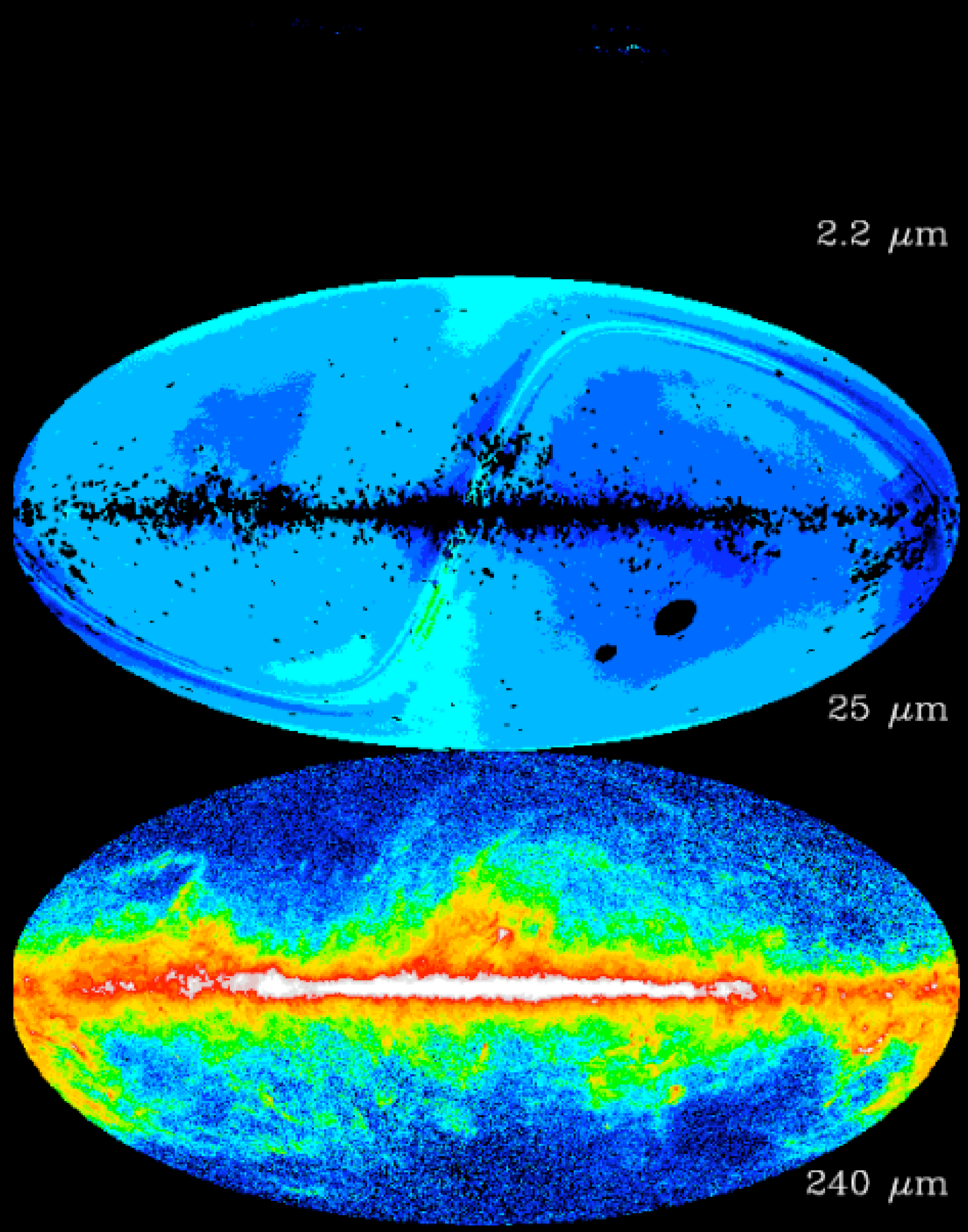
Starlight Model

Arendt et al. 1998

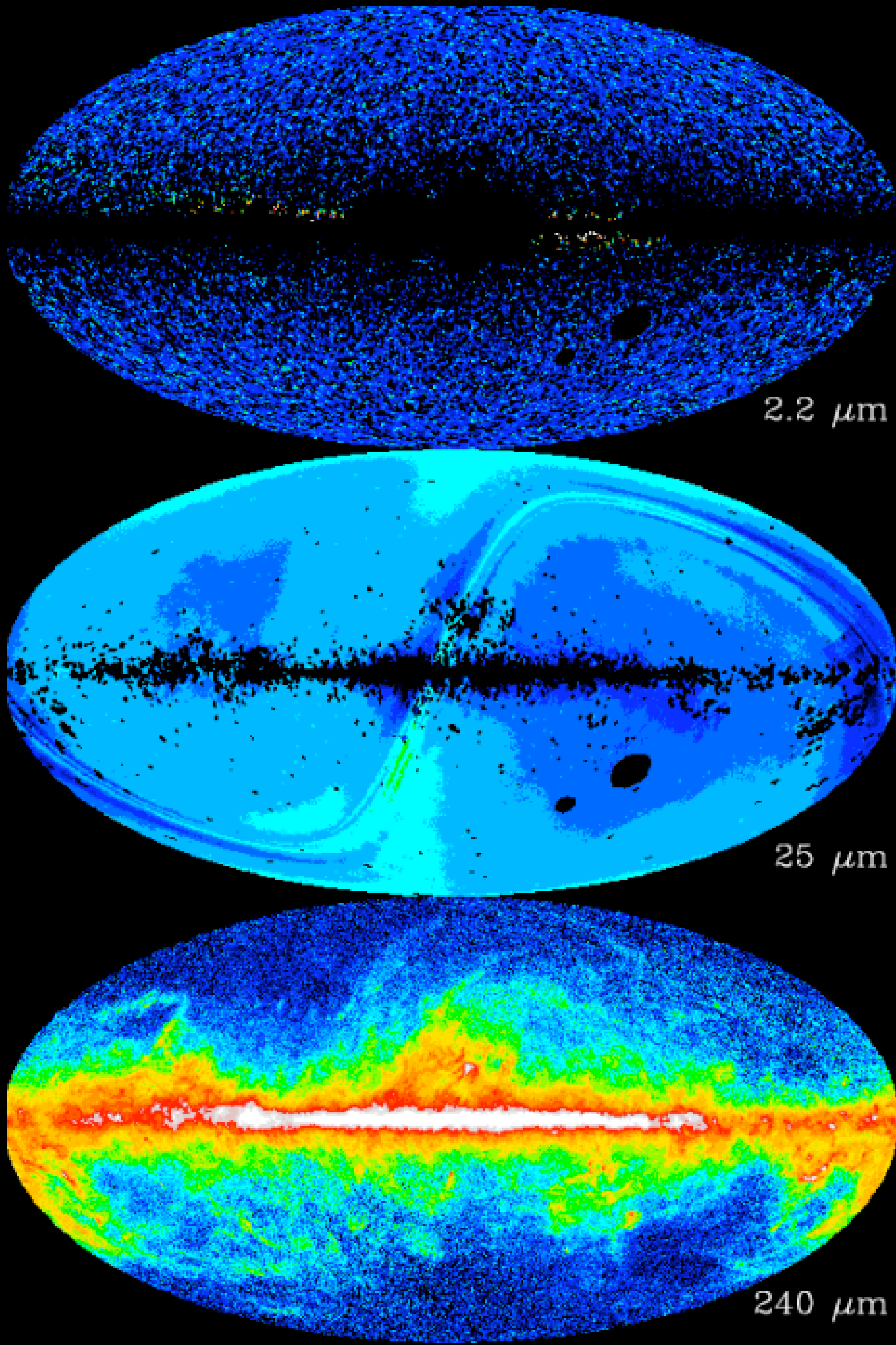


- Observed 2.2 μm sky
  - Zodi subtracted
  - bright sources blanketed
- Faint source model
  - Exponential disk
  - Spiral arms
  - Molecular ring
  - Stellar halo
  - Bulge

Satrlight Subtracted Sky



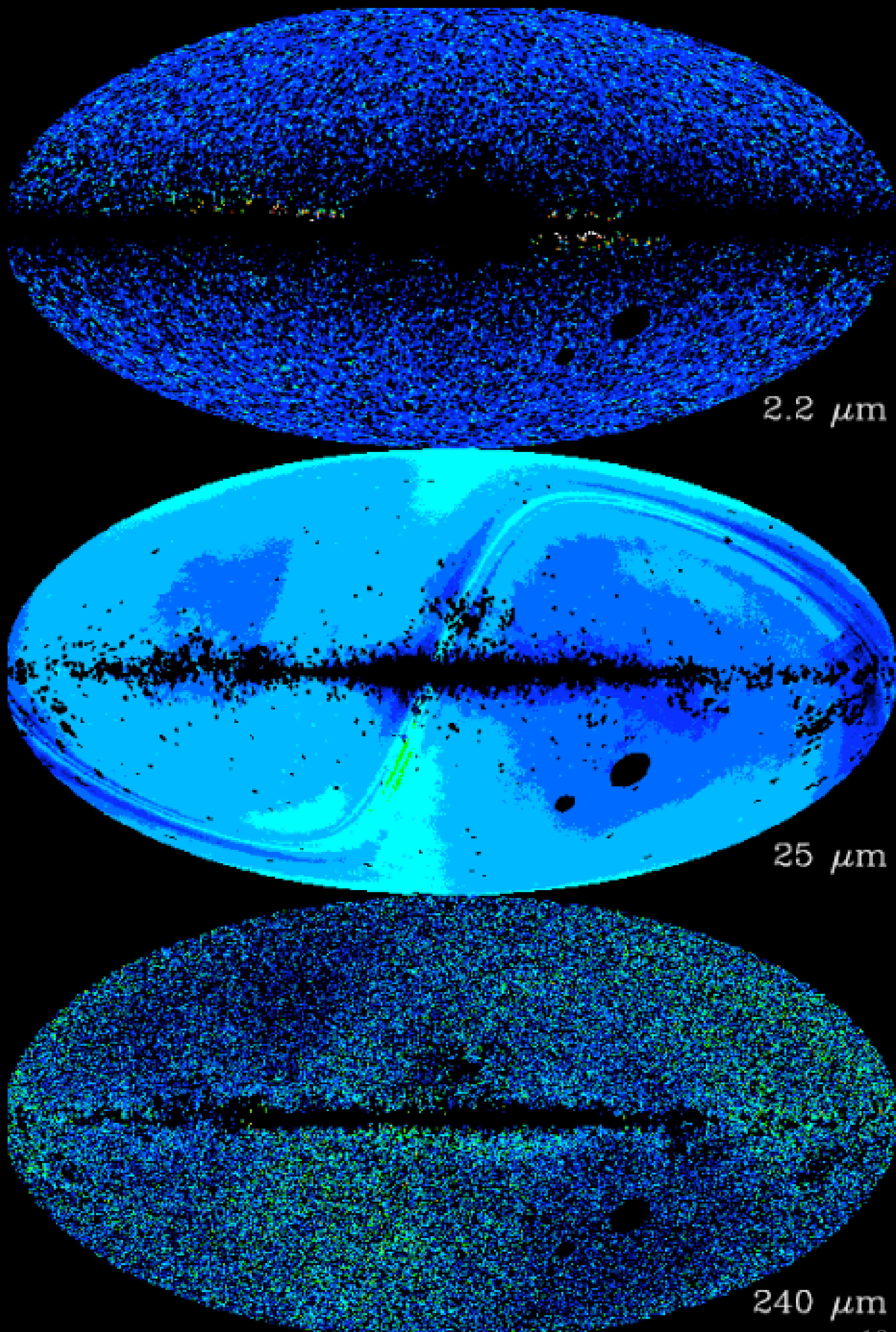
- 2.2 μm sky
  - bright and faint stars subtracted
- 25 μm sky
  - Dominated by Galactic ISM
  - 2% of previous level
- 240 μm sky
  - Interstellar Dust emission, LMC, SMC



Starlight Subtracted Sky

- 2.2 μm sky
  - bright and faint stars subtracted
  - linear scale
- 25 μm sky
  - Dominated by Galactic ISM
- 240 μm sky
  - Interstellar Dust emission, LMC, SMC

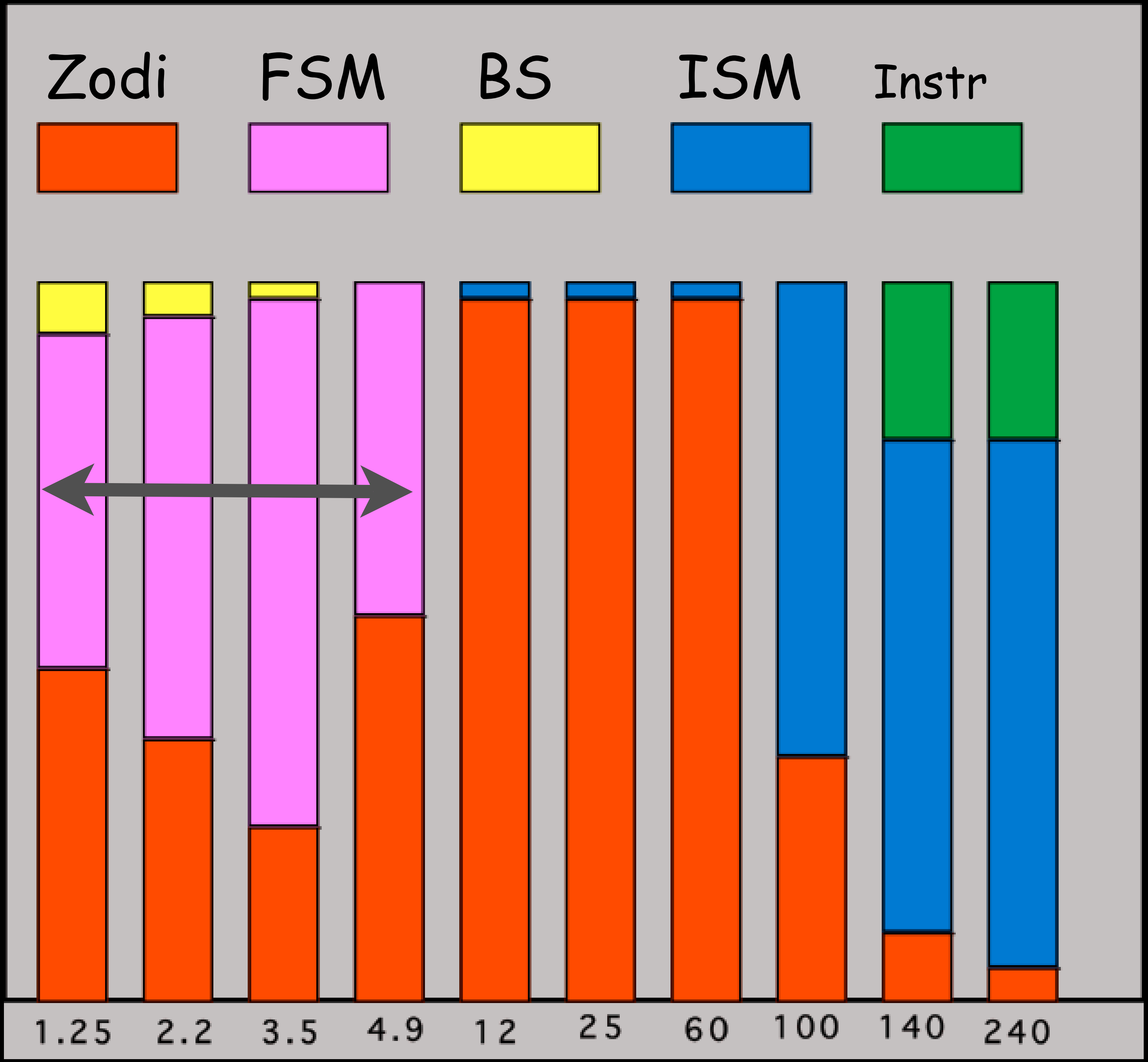
Residual Sky after ISM Subtraction



- 2.2 μm sky
- 25 μm sky
- 240 μm sky

Residual = EBL if it is positive AND isotropic

Systematic Uncertainties

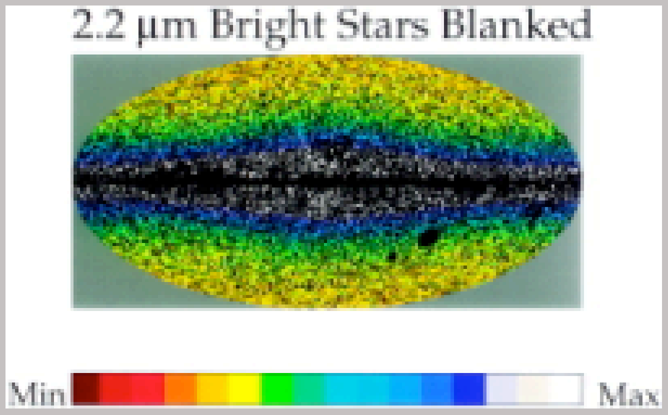


1.25	33±21
2.2	15±12
3.5	11±6
4.9	25±8
12	190±140
25	190±160
60	21±27
100	22±6
140	25±7
240	14±3

positive but not isotropic

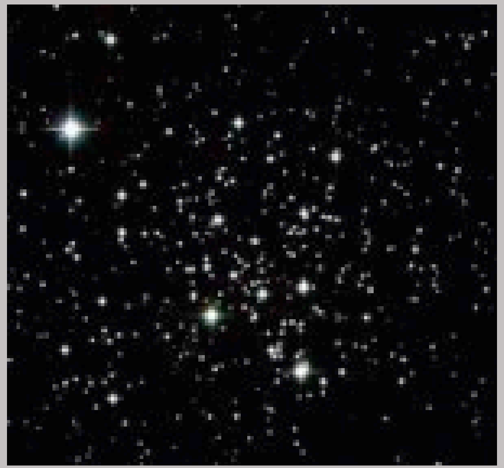
positive AND isotropic

Recent Detections and Limits on the EBL at the Near-IR Wavelengths



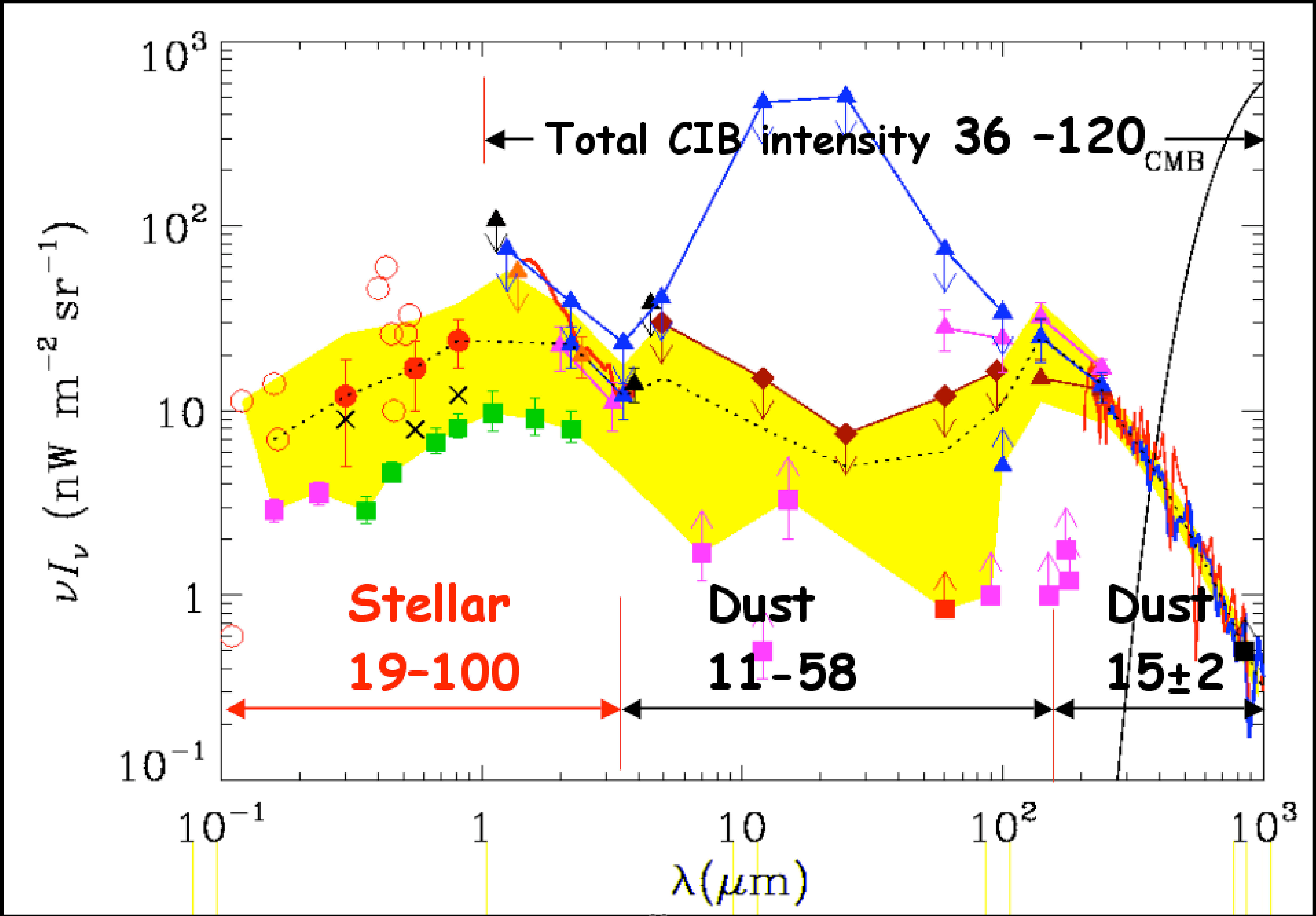
- **Dwek & Arendt (1998)**
  - 2.2 µm DIRBE stellar template + Kelsall zodi model
- **Gorjian, Wright, & Chary (2000)**
  - Subtracted stars brighter than 9 mag
  - extrapolated SKY model (the star count model of Wainscoat et al. 1992)
  - Subtracted a Kelsall-based zodi model using the strong no-zodi principle
- **Wright & Rees (2000)**
  - Compared the histogram of the DIRBE pixel intensities to SKY model
  - Wright zodi model
- **Wright (2001)**
  - 2MASS (the Two Micron All Sky Survey) data to remove resolved Galactic stars + SKY to remove the unresoloved stars
  - Wright zodi model
- **Cambresy et al (2001)**
  - 2MASS + Kelsall zodi model
- **Arendt & Dwek (2002)**
  - Multi-color DIRBE stellar template + Kelsall zodi model

2MASS image (16 mag)



Limits and Detections of the EBL

(Hauser & Dwek 2001)

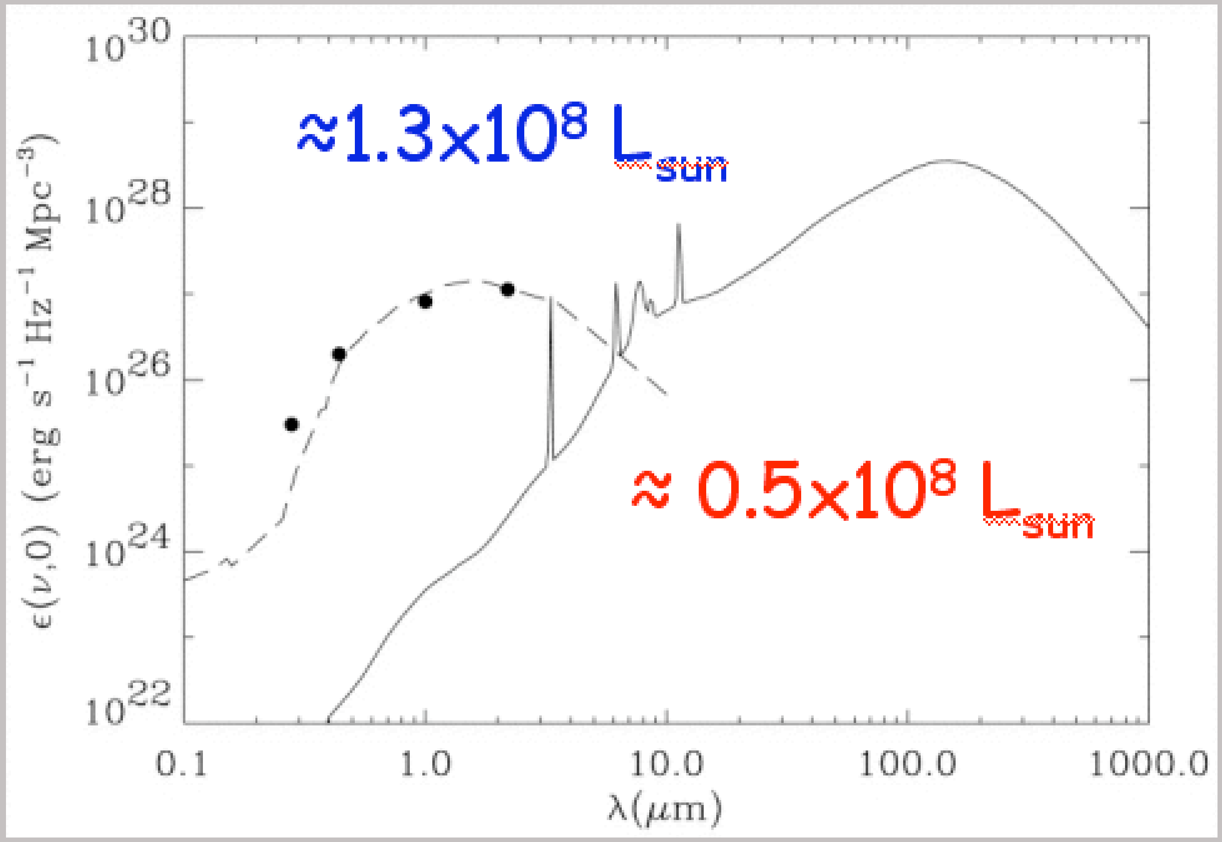


Galaxies were more Opaque in the Past

The luminosity density in the local universe

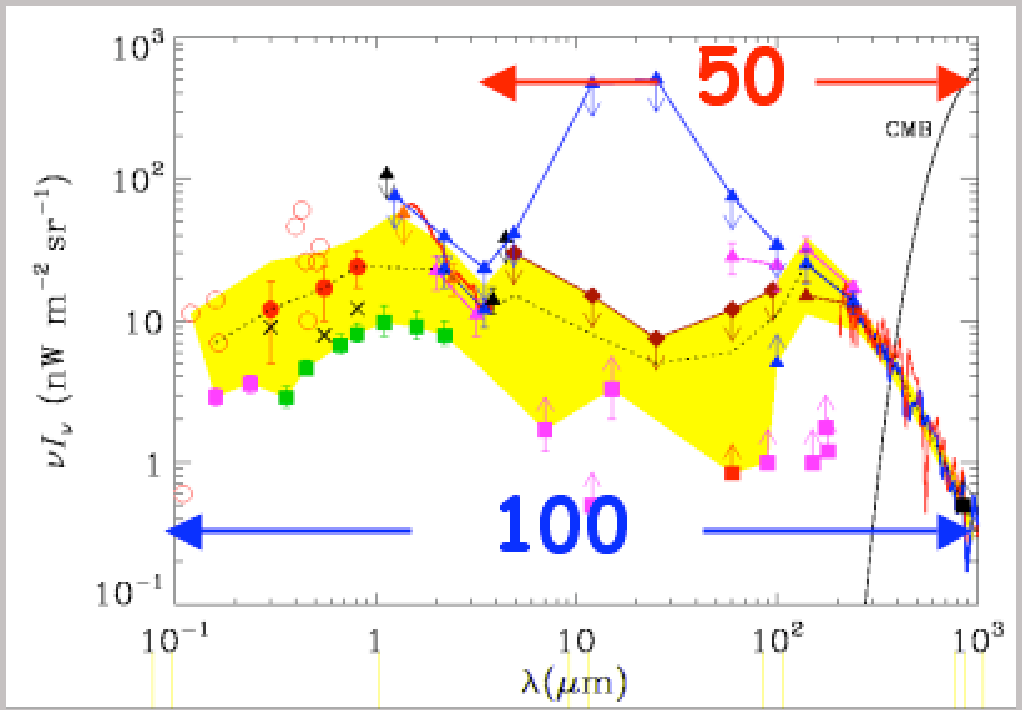
(Dwek et al. 1998)

$L_{IR}/L_{tot} \approx 0.30$

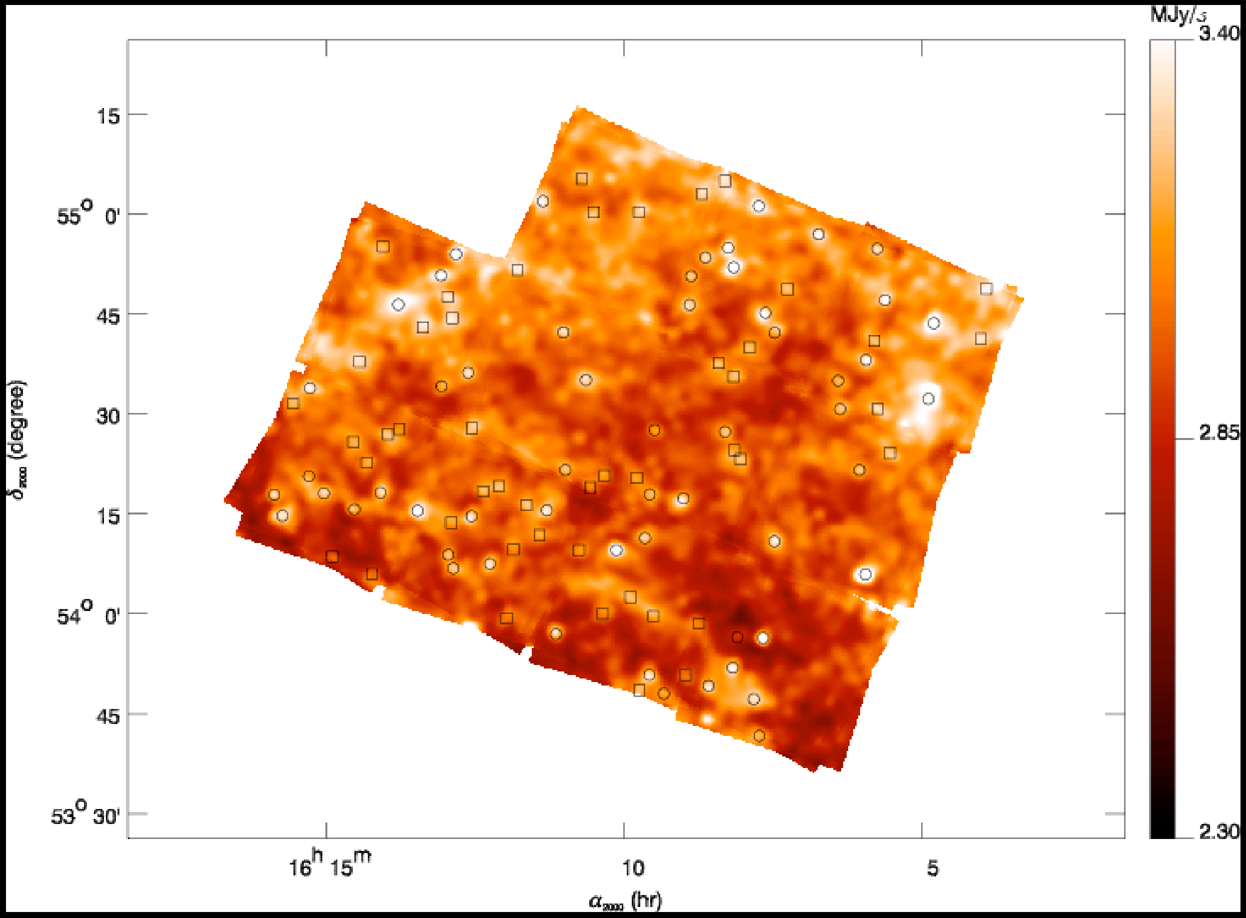


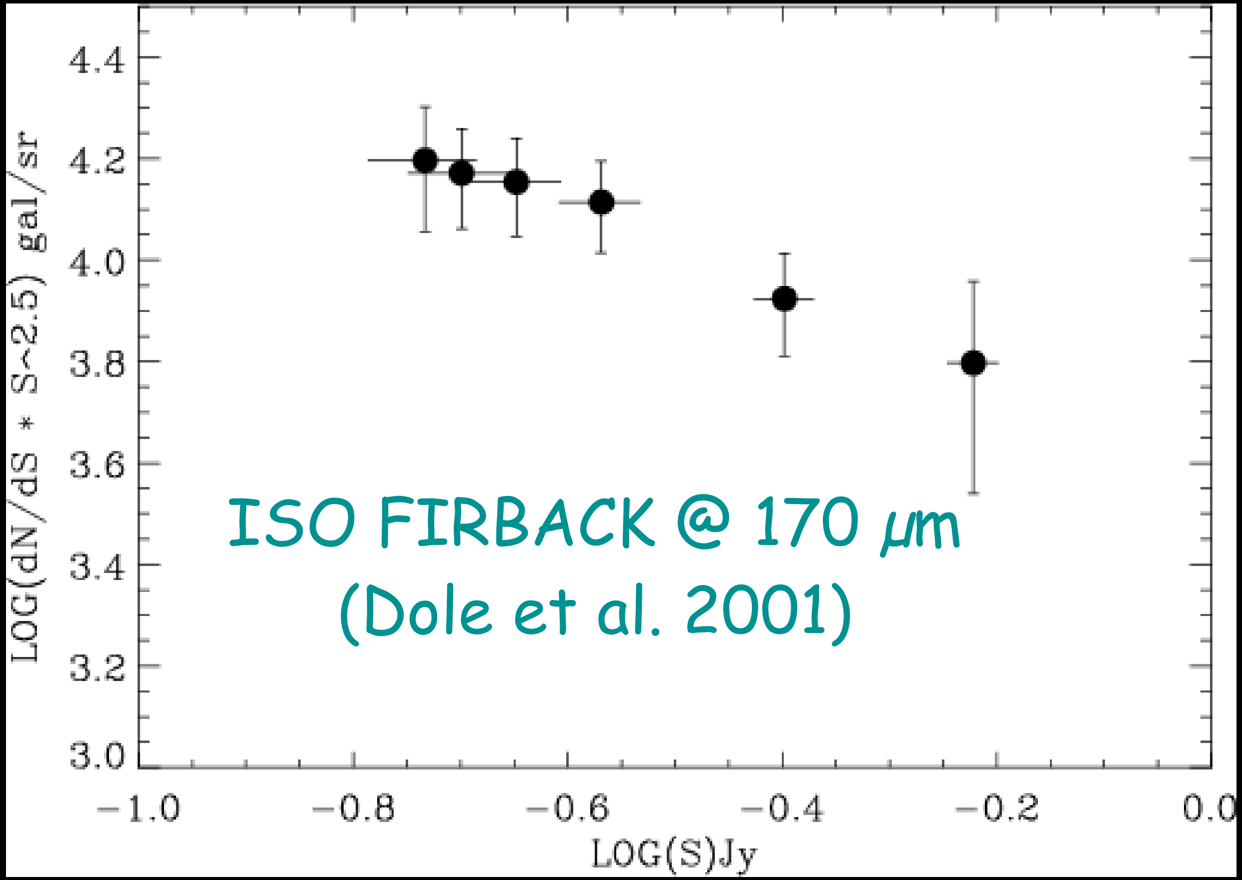
For the EBL

$L_{IR}/L_{tot} \approx 50/100 \approx 0.5$



EBL Determination from Galaxy Number Counts

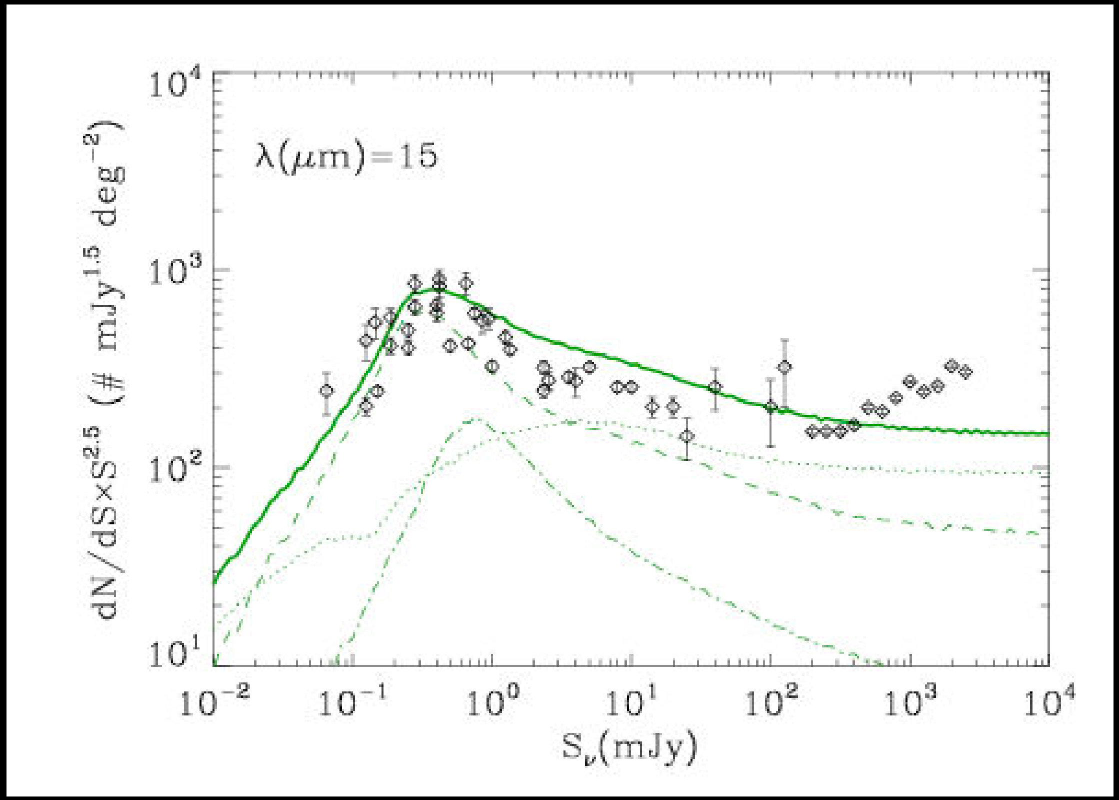


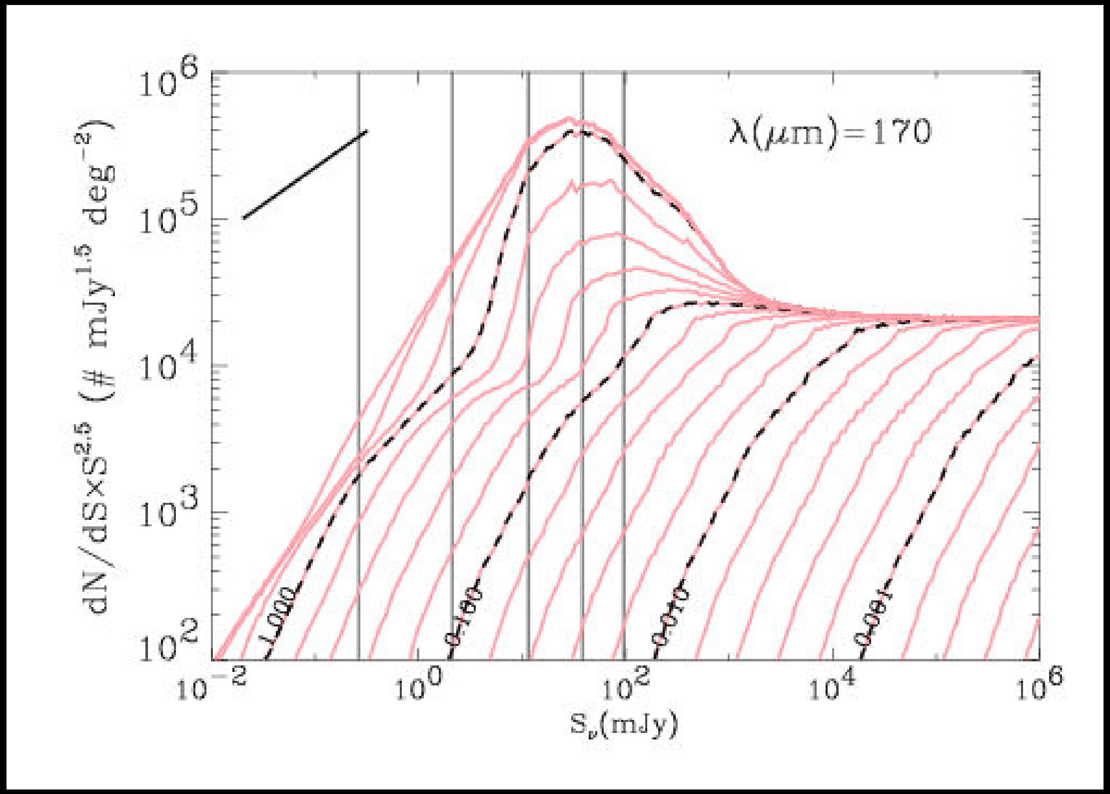


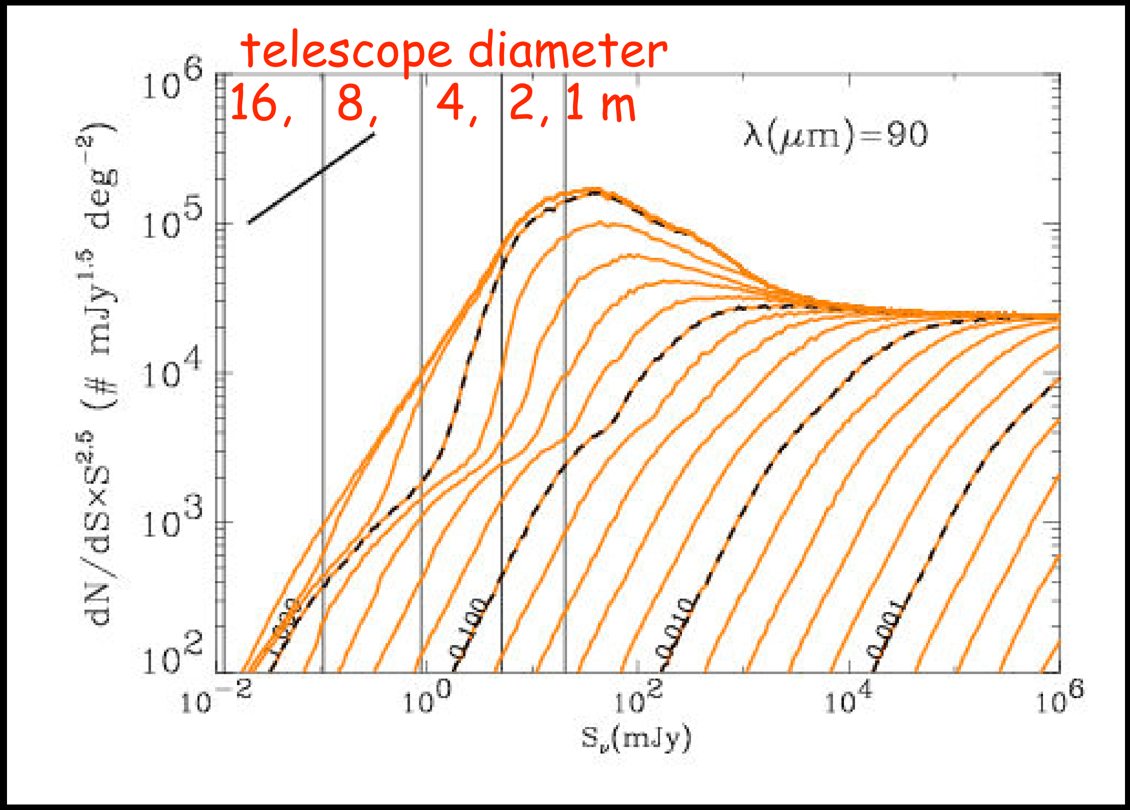
- Provide the EBL intensity from resolved galaxies
- Incomplete: low surface brightness galaxies may be missed
- Overlapping low-surface wings from galaxies can create a truly diffuse background
- Sensitivity and confusion limits
- Number counts provide useful limits on EBL

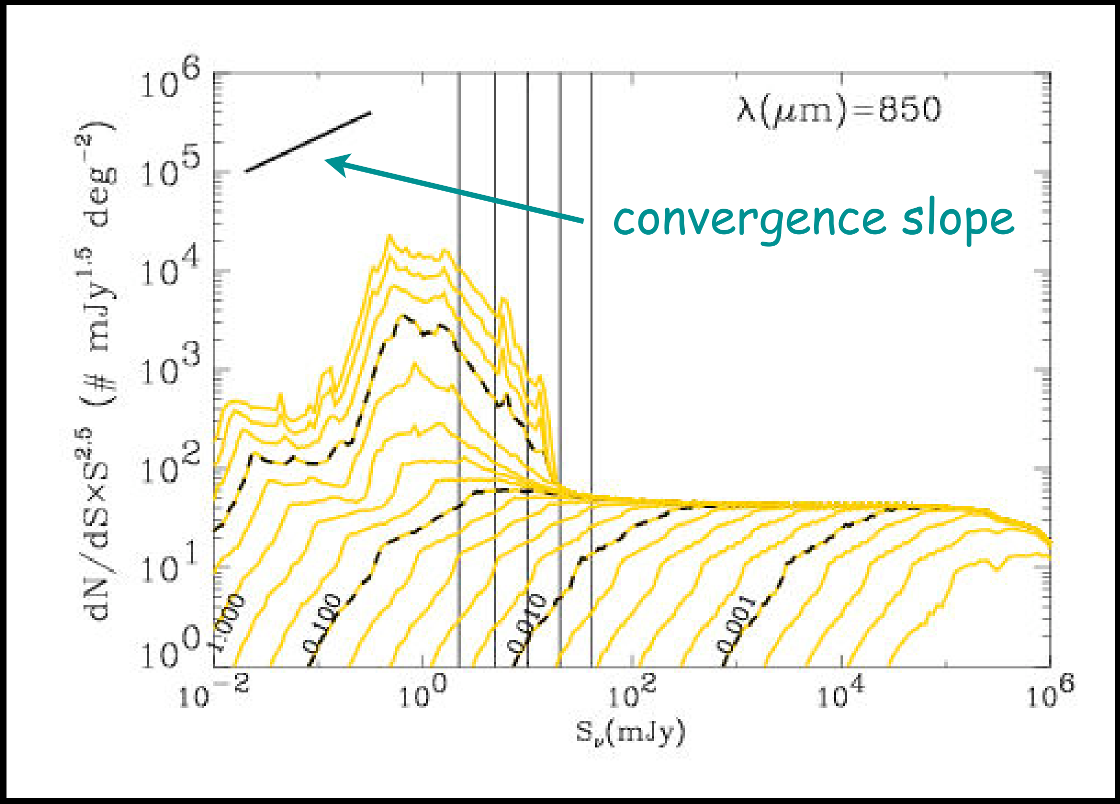
Building Up Galaxy Number Counts

(Dwek et al. 2002, using Chary & Elbaz (2001) galactic SEDs and input parameters)



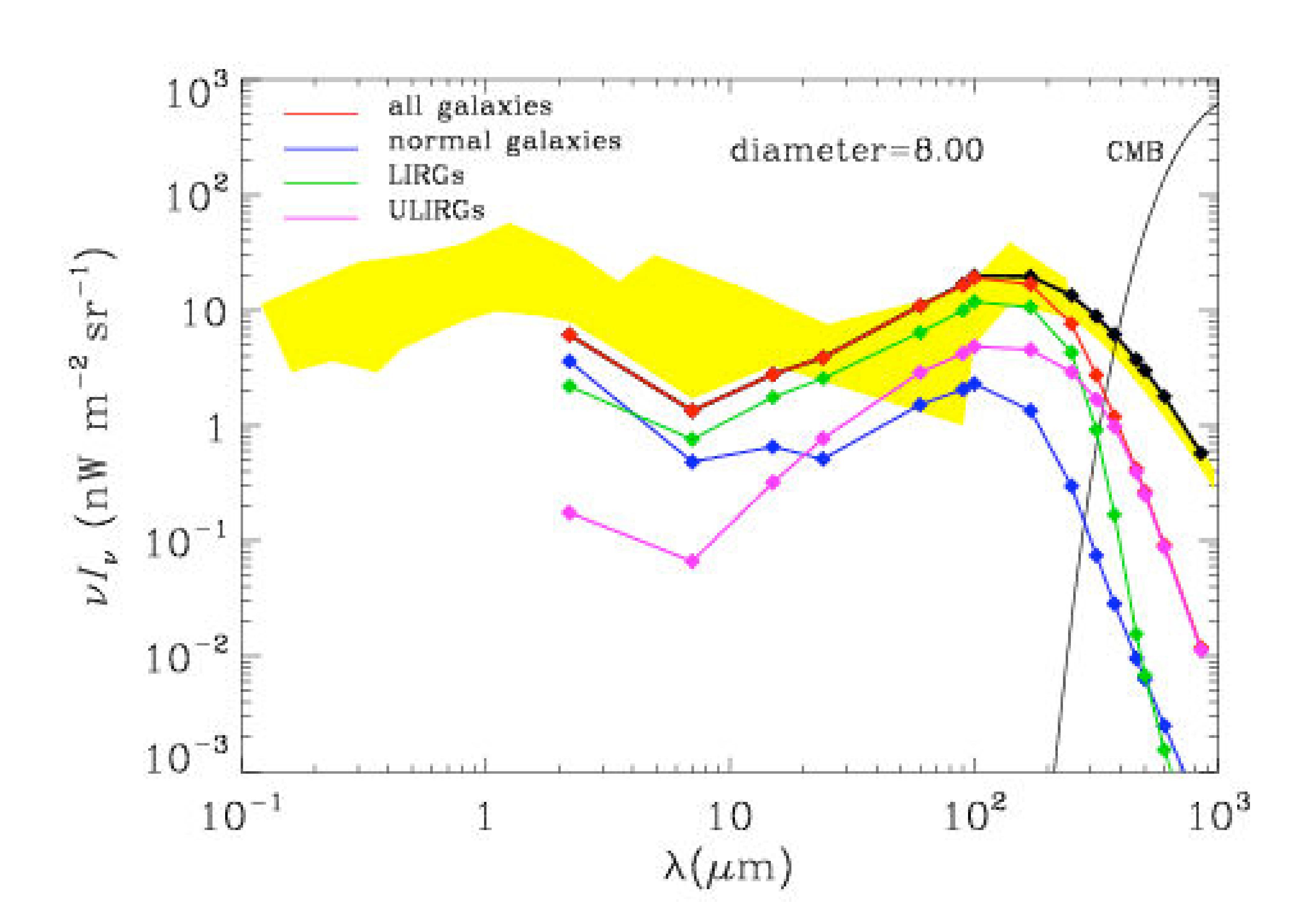






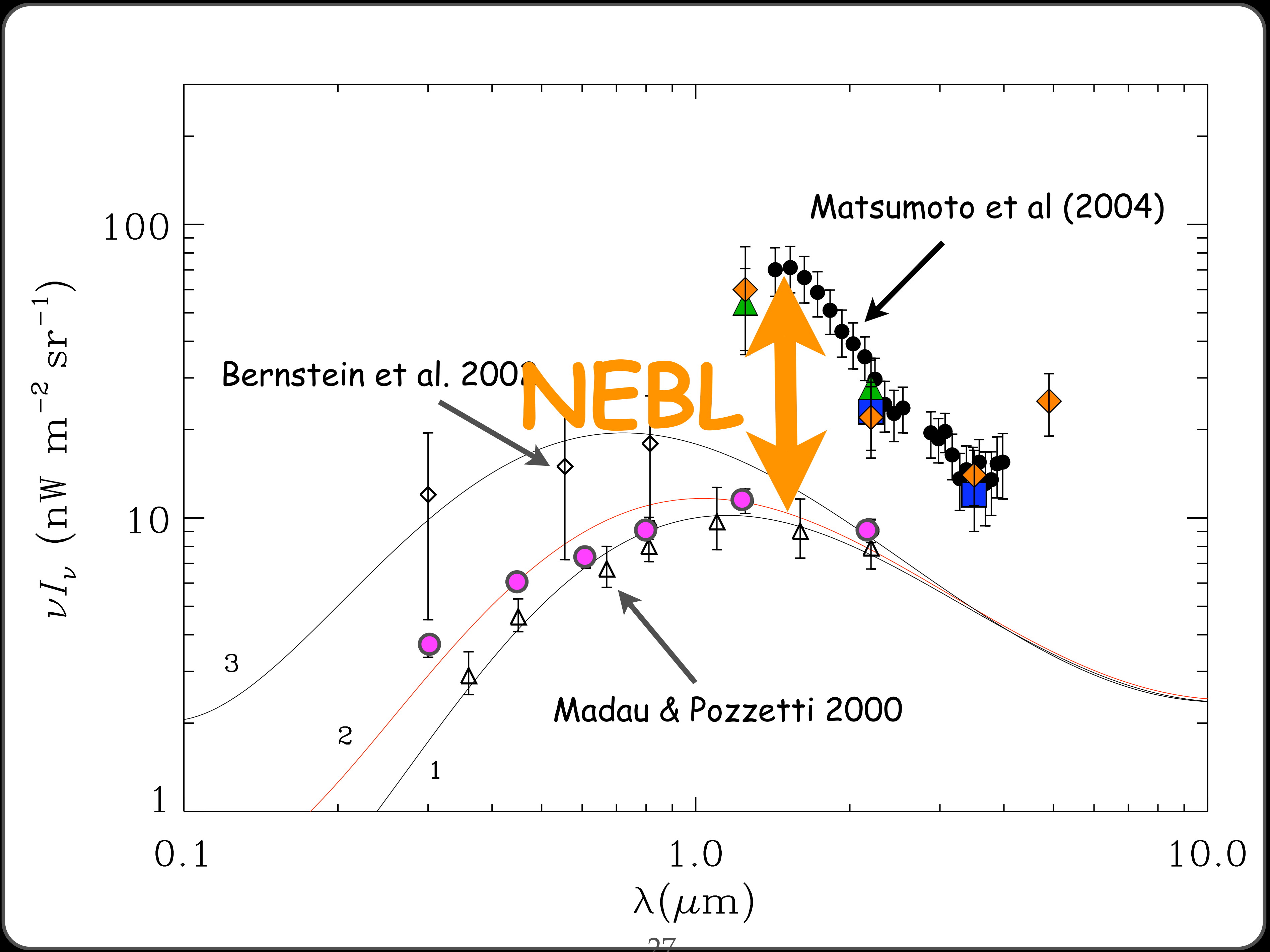
EBL Intensity Due to Resolved Galaxies

(8 m diameter telescope)



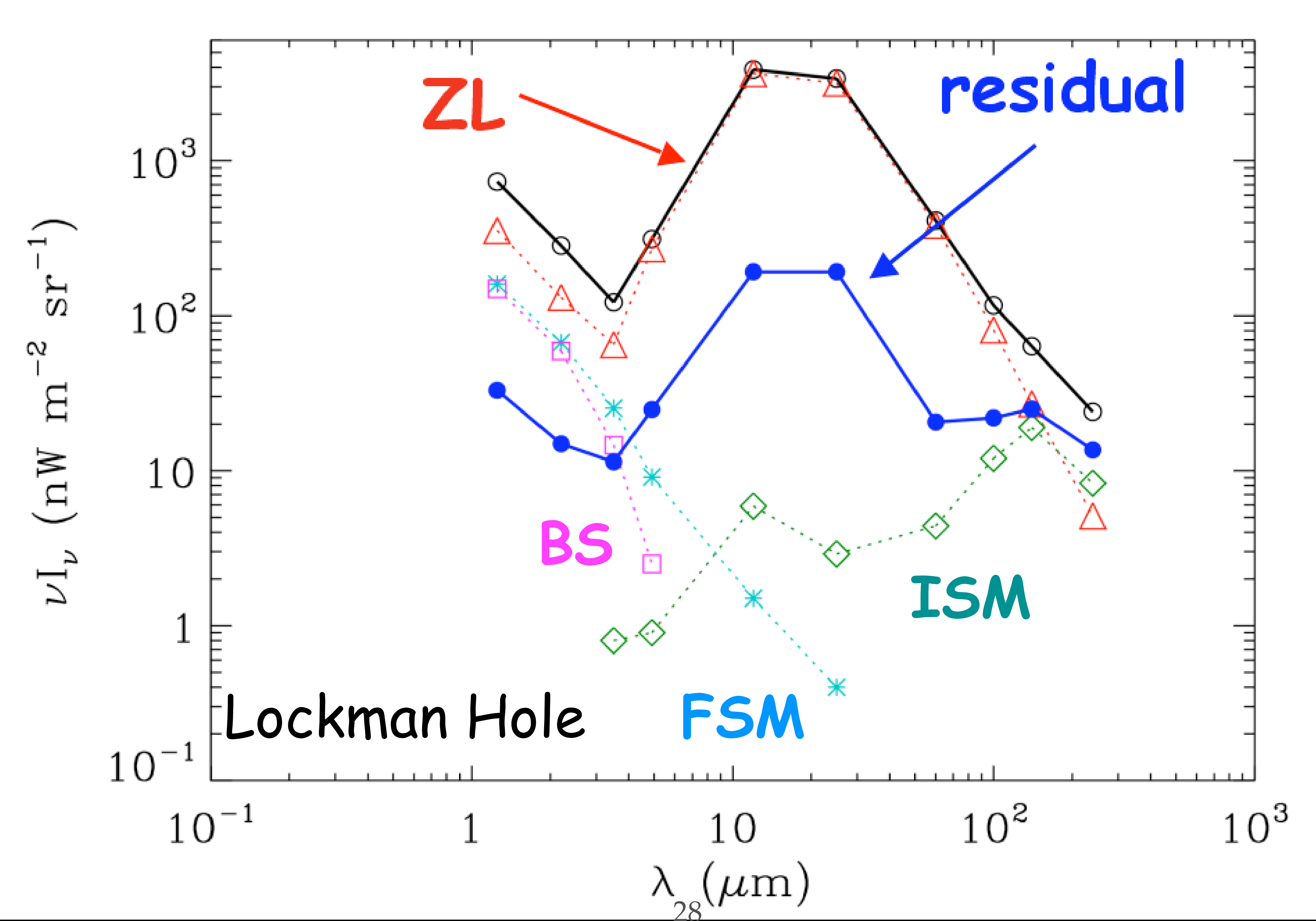
The EBL at Near-IR Wavelengths (NEBL)

Totani et al. 2001
Cambresy et al. 2001
Arendt & Dwek 2003
Wright 2001

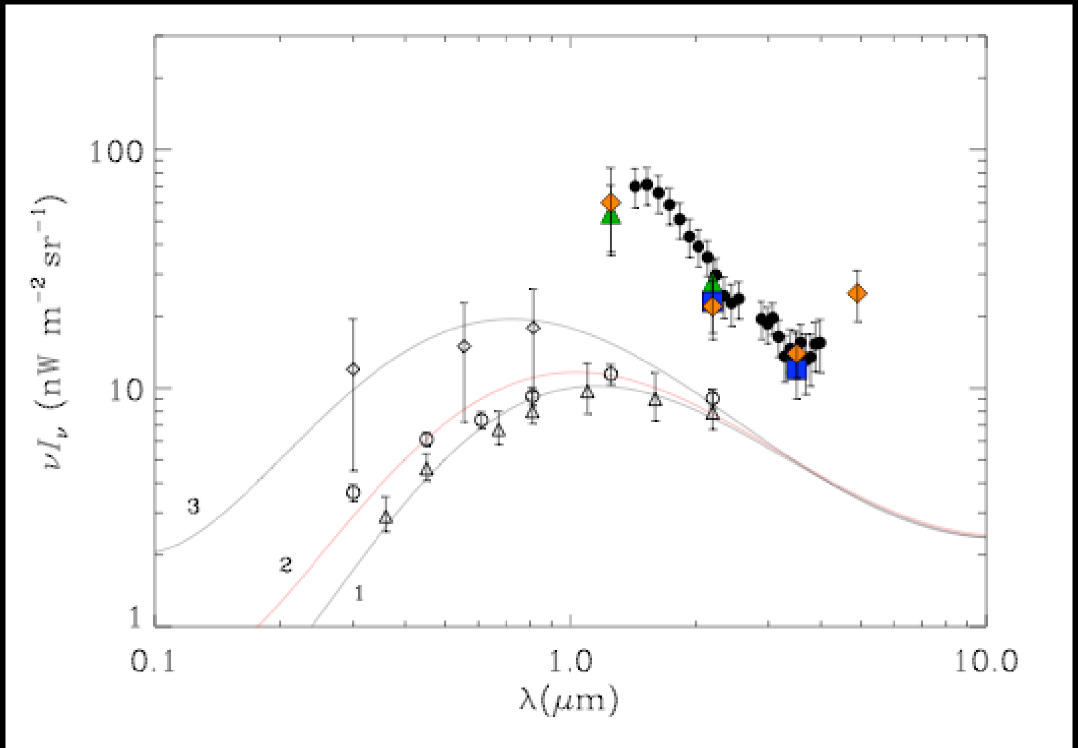


The Strong No-Zodi Principle (Wright 2002)

- The 5 - 60 μm residual spectrum is very similar to that of the zodi
- It cannot be the EBL, otherwise we wouldn't see any Xgal TeV sources
- Constrain zodi models to produce zero 25 μm flux at the ecliptic pole



The Nature of the 1-5 μm Excess Emission

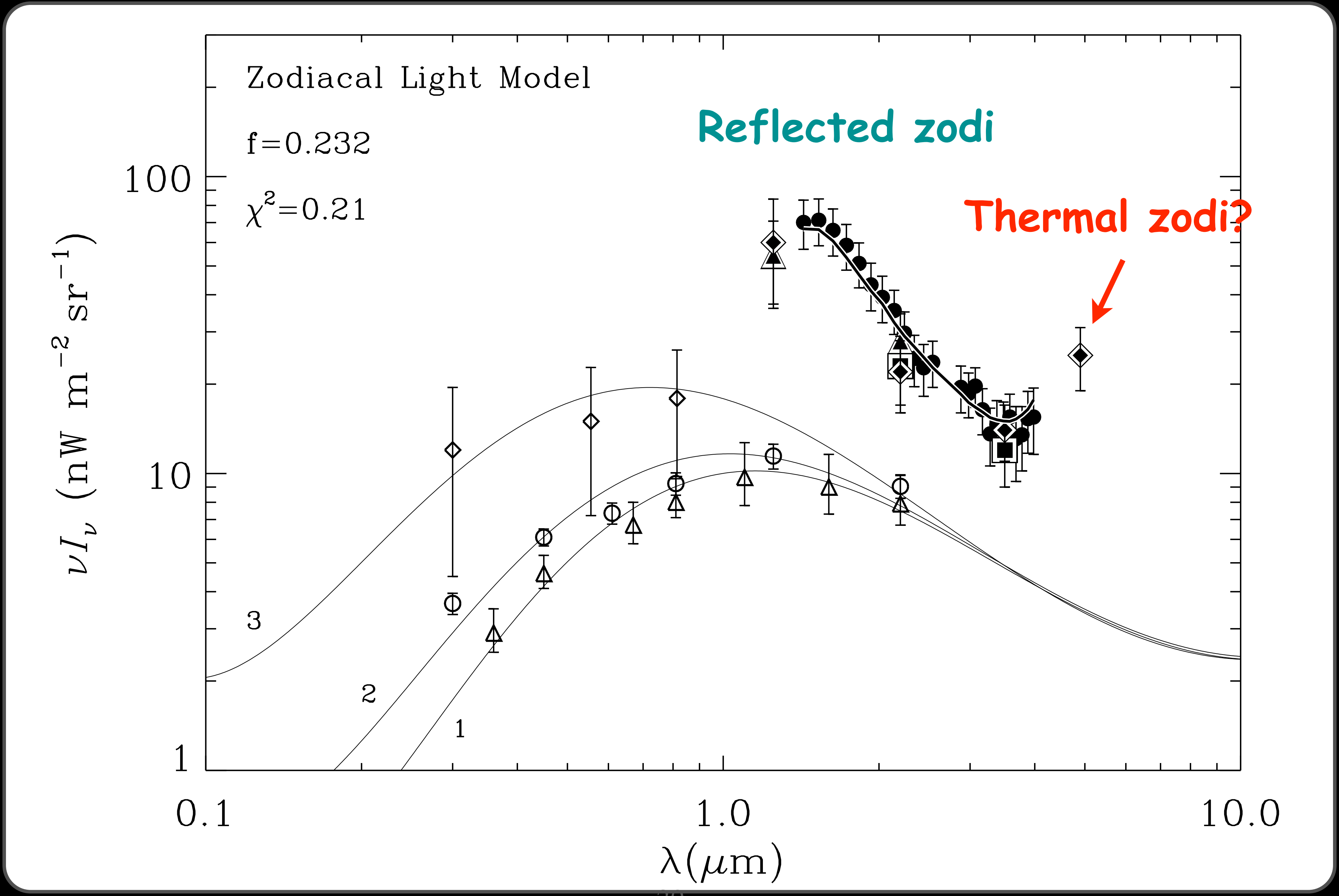


- Zodiacal Light
  - an isotropic component could have escaped the DIRBE detection
- Cosmological
  - red-shifted galaxy (z ≈ 8)
    - luminosities too high
    - large CSFR
    - overproduction of metals
  - distinct spectral component (Pop III stars?)

The NEBL has a Zodi spectrum!

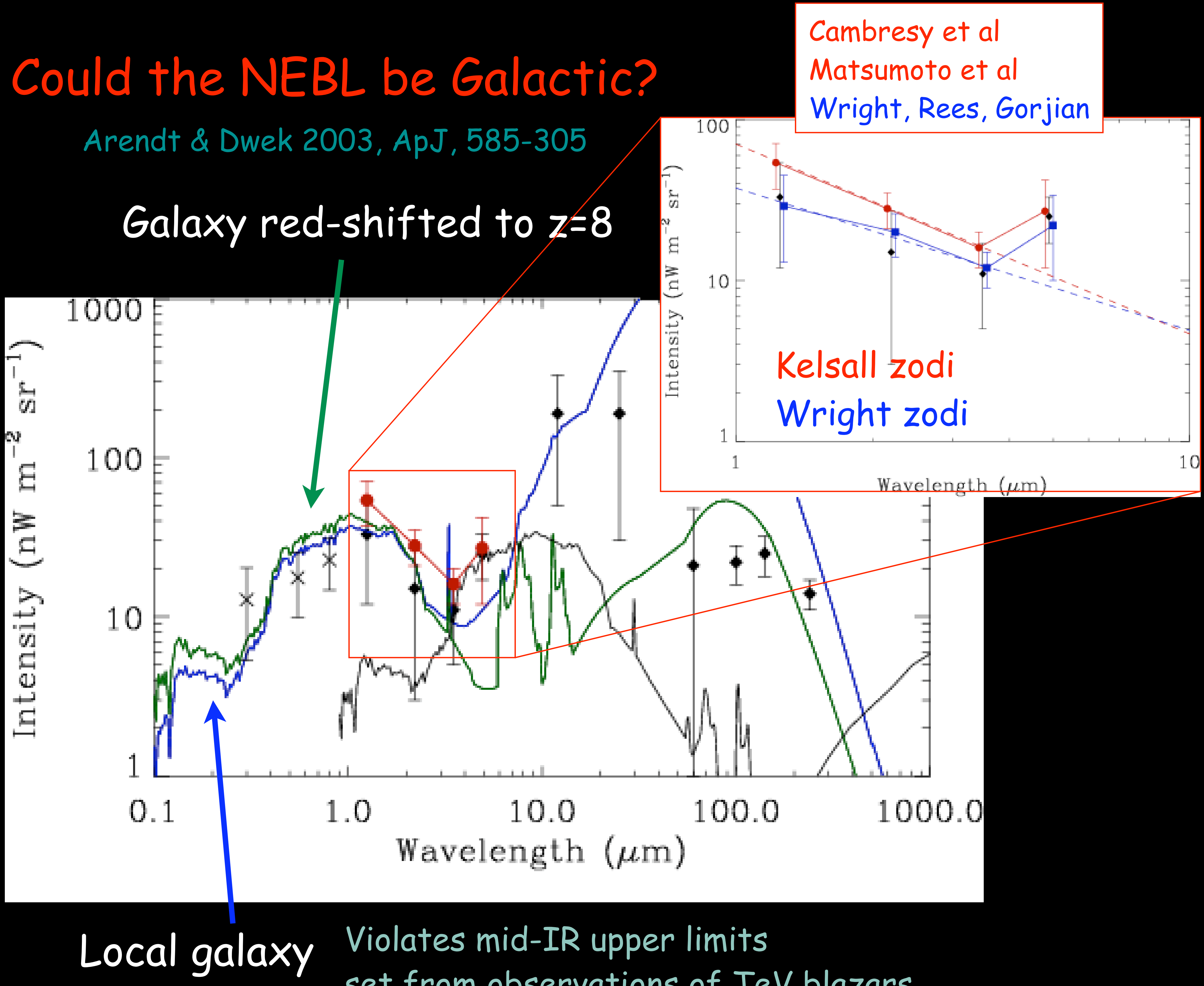
Requires 23% of the Zodi light to be in an isotropic (undetected by DIRBE) component. This isotropic component will also affect the thermal component of the zodiacal light.

Fluctuation analysis (Matsumoto et al. 2004) suggests it is not isotropic, and similar to the excess EBL (Kashlinsky & Odenwald 2000)



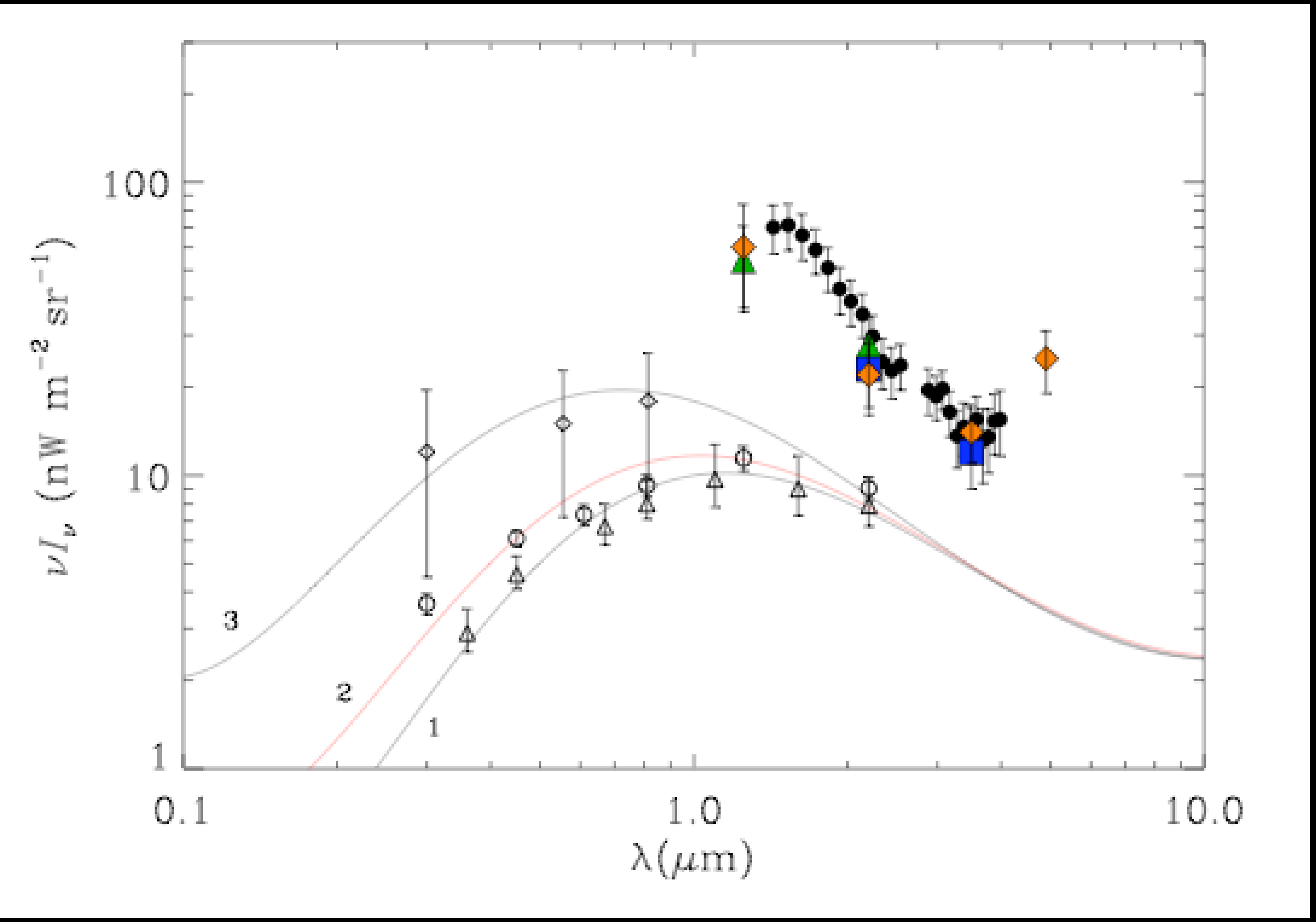
Could the NEBL be Galactic?

Arendt & Dwek 2003, ApJ, 585-305



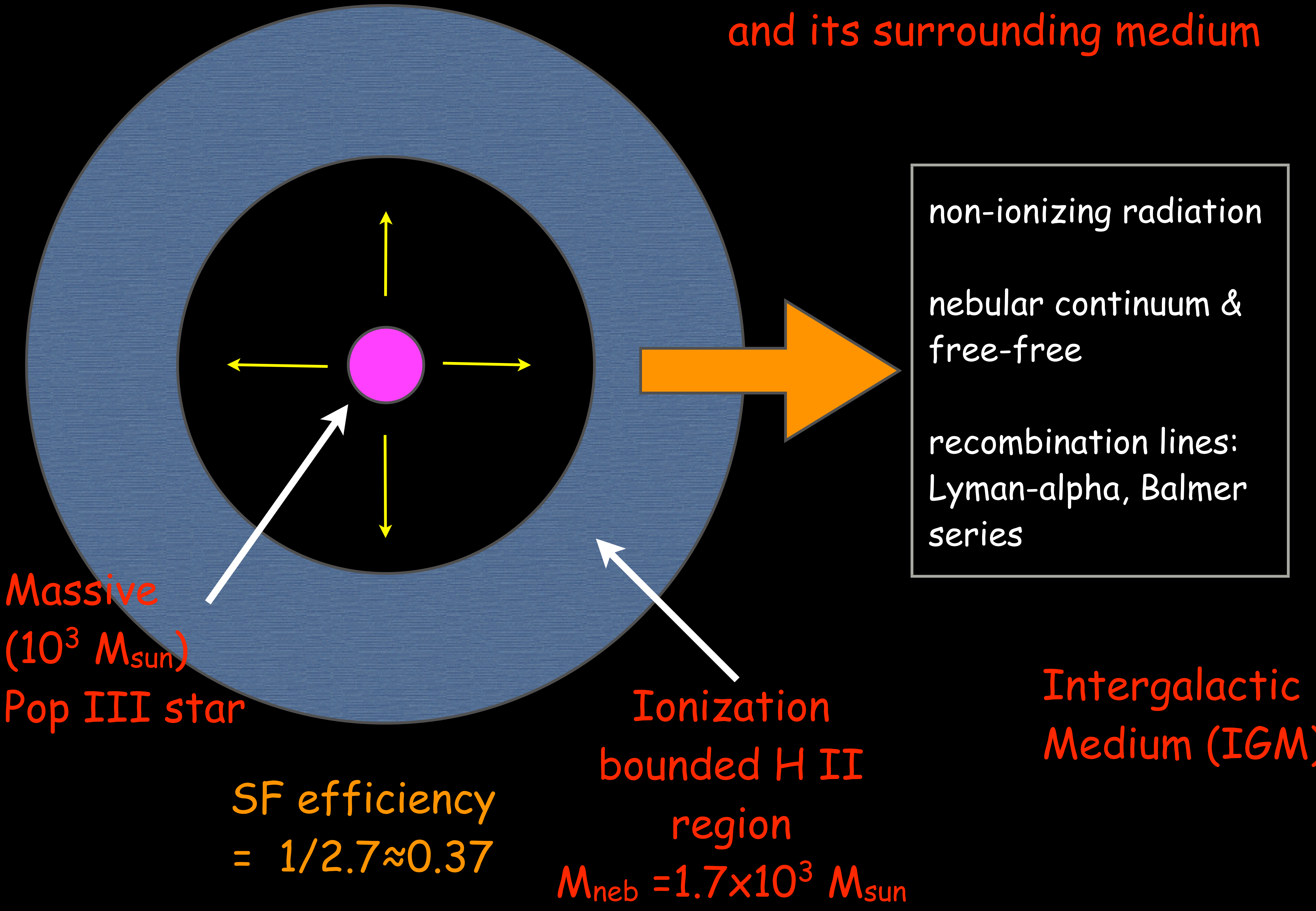
Violates mid-IR upper limits
set from observations of TeV blazars

The NEBL Could be the Spectral Signature of the First Stars that Formed out of the Primordial Gas



- The NEBL could be produced by the first stars that formed out of the primordial gas (Pop III stars)
- Originally suggested by Bond, Carr, Hogan, Arnett to close the universe with baryonic matter
- Currently invoked as the source of photons needed to re-ionize the universe prior to z ≈ 8

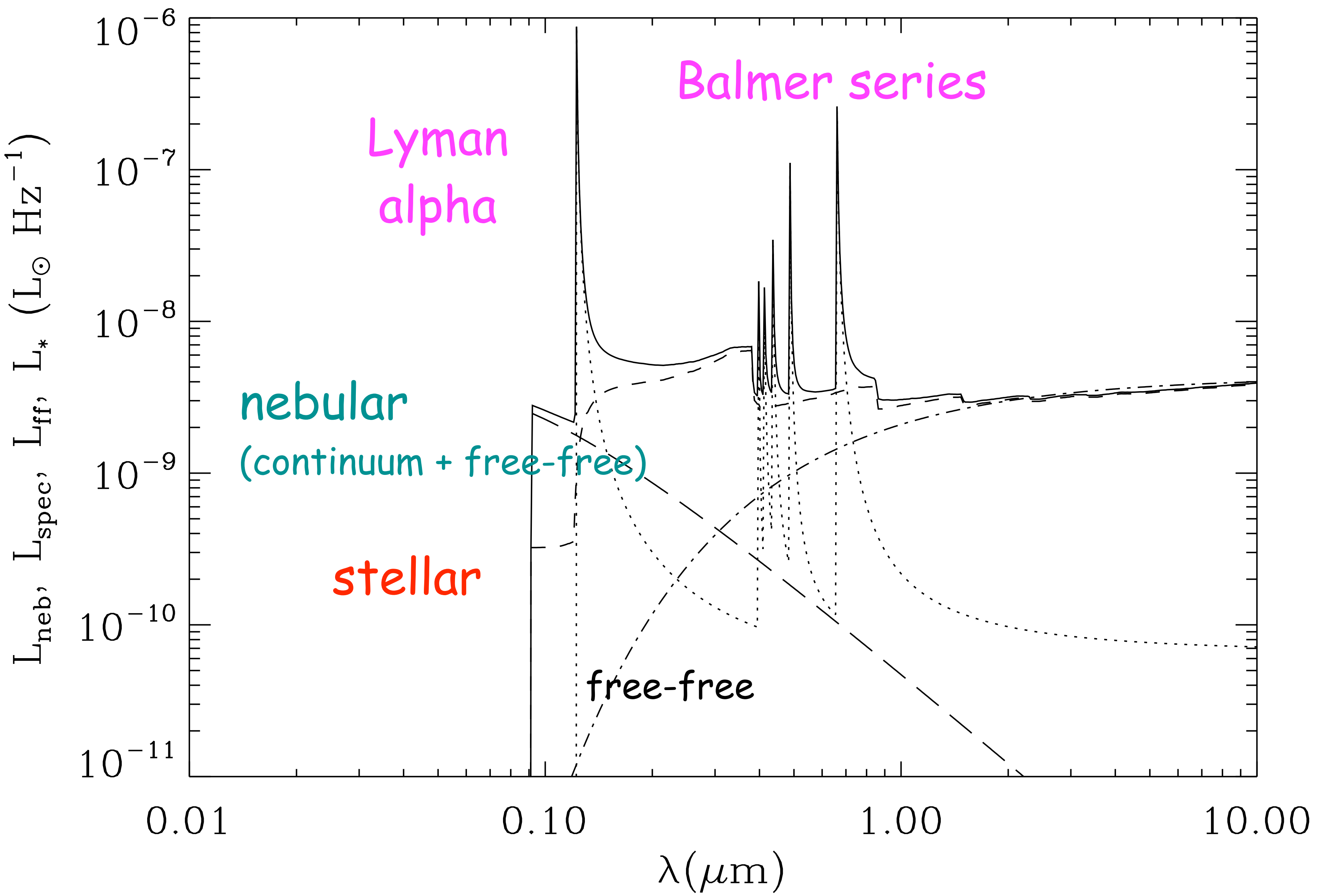
Schematics of Population III star and its surrounding medium



Population III Source Spectrum

$M_* = 1000\ M_{sun}$ $T_* = 10^5$ K

$L_* = L_{edd} \times M_* = 3.3\text{x}10^7\ L_{sun}$ $t_* = 0.007\ L_*/M_*c^2 = 2\text{x}10^6$ yr



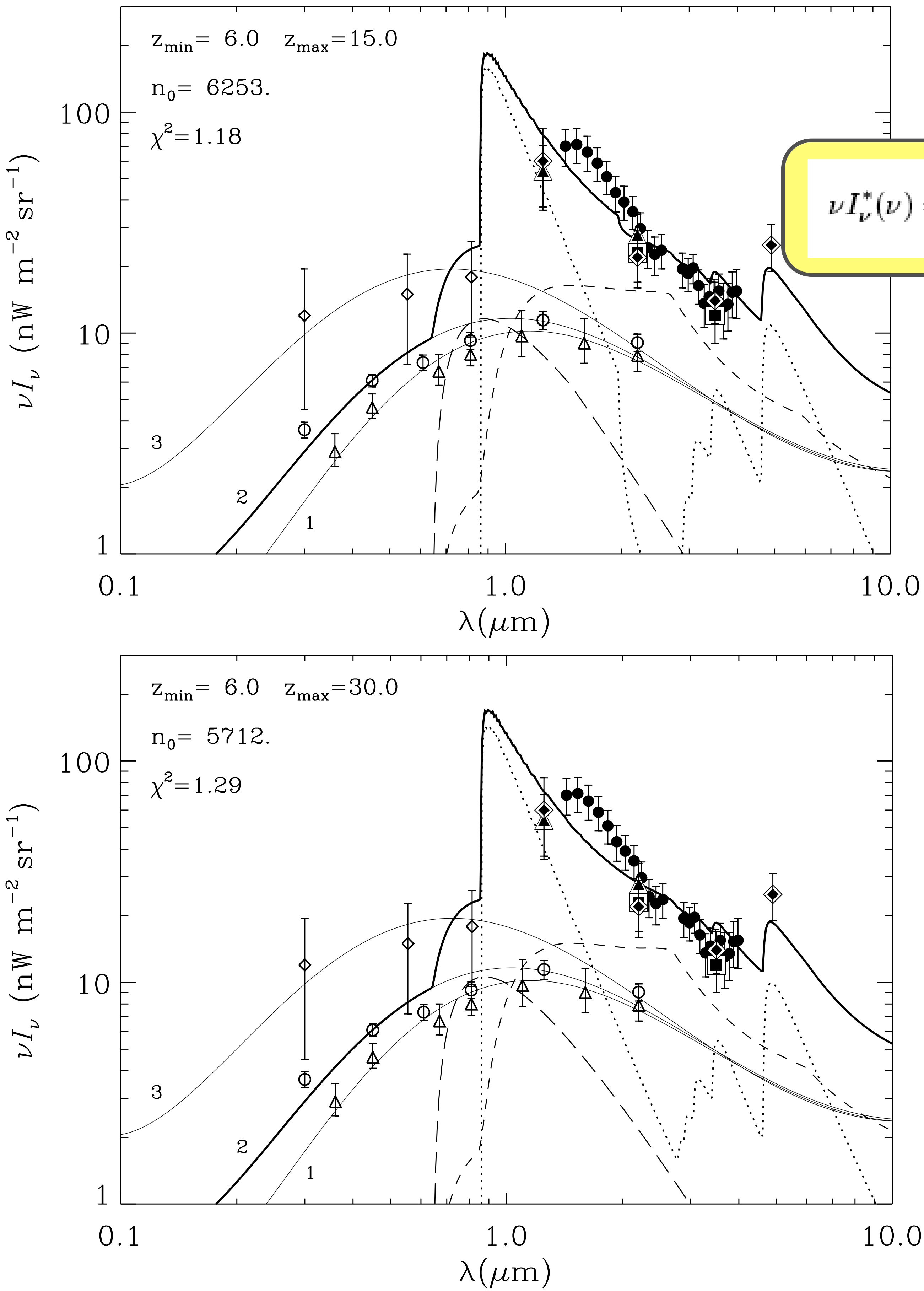
Stellar and nebular Energetics

(results of CLOUDY run)

Total luminosity = 10^3 L_{Edd} = 3.3×10^7 L_{sun}

Emission component	Fraction of total Lum
Escaping stellar non-ionizing radiation	11%
Nebular emission	29%
continuum recomb	24%
free-free	5%
Recombination lines	60%
Lyman alpha	51%
Balmer series	9%

NEBL Created by Population III Stars



$$\nu I^{*}_{\nu}(\nu) = \left(\frac{c}{4\pi}\right) \int_{z_{min}}^{z_{max}} n_{*}(z) \left[L^{*}_{\nu}(\nu',z) + L^{ff}_{\nu}(\nu',z) + L^{lines}_{\nu}(\nu',z)\right] \left|\frac{dt}{dz}\right| dz$$

$$\left|\frac{dt}{dz}\right| = H_0^{-1}\left[(1+z)E(z)\right]^{-1}$$

$$E(z) \equiv \left[\Omega_{\Lambda} + (1+z)^3\Omega_m\right]^{\frac{1}{2}}$$

$$n_{*}(z) = n_0\left(\frac{1+z}{1+z_{min}}\right)^{\alpha}$$

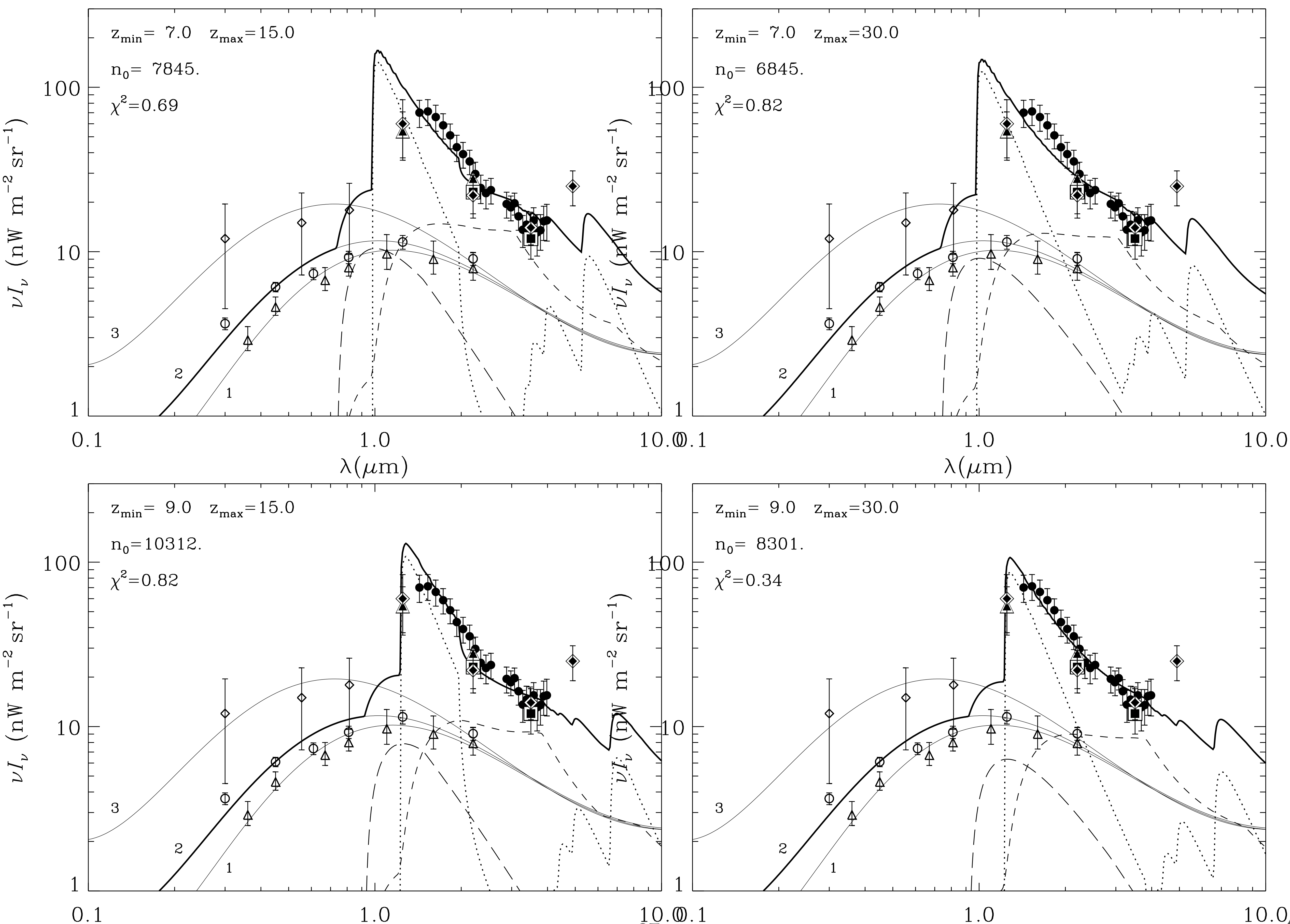
$\Omega_m = 0.27$ $\Omega_L=0.73$ $H_0=70$

no LOS absorption

alpha= - 2.0

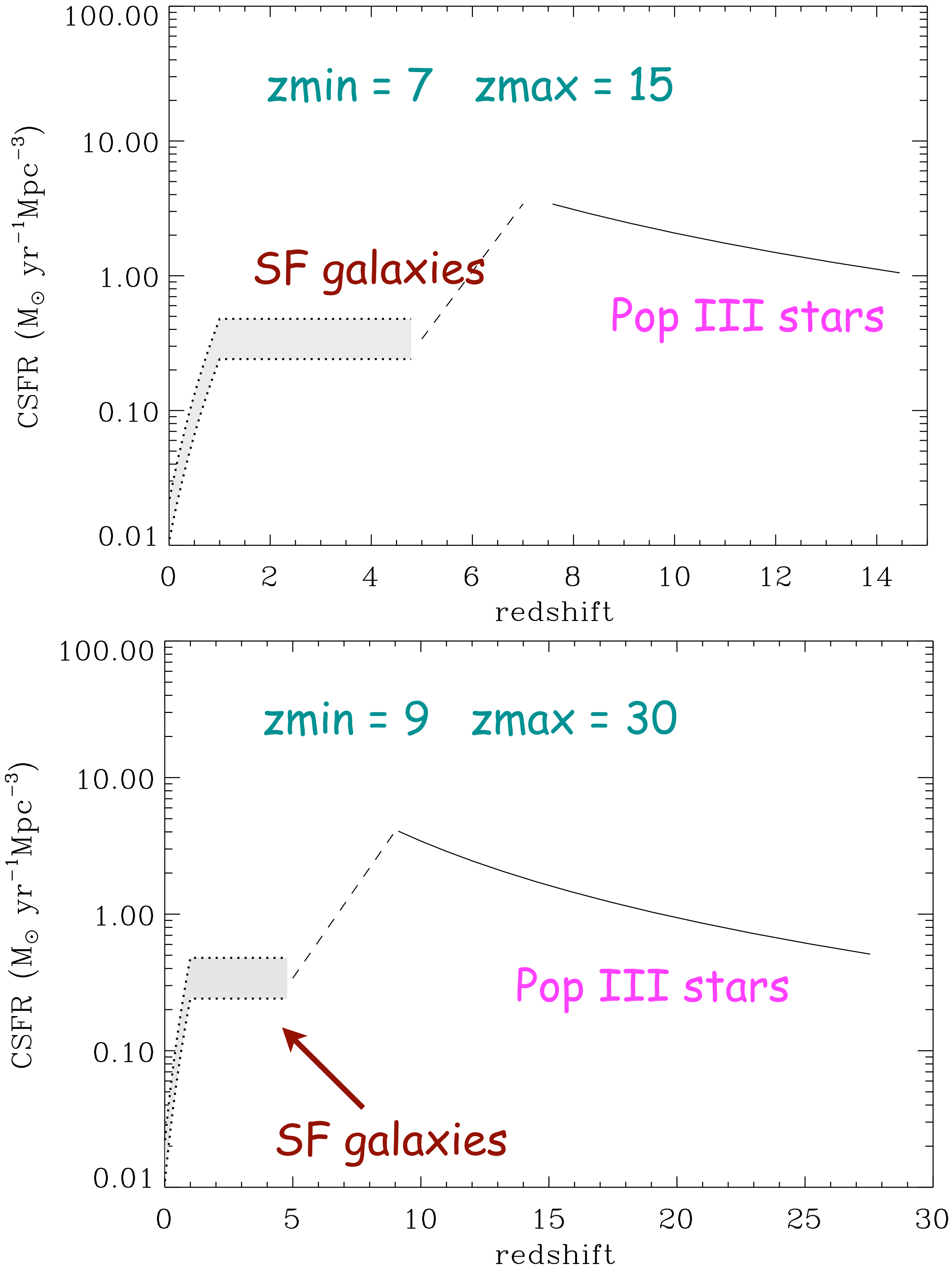
z_{min} = 6

H_{alpha} contributes to 4.9 μm flux



z_min= 7.0 z_max=15.0
n_0= 7845.
χ^2=0.69
z_min= 7.0 z_max=30.0
n_0= 6845.
χ^2=0.82
z_min= 9.0 z_max=15.0
n_0=10312.
χ^2=0.82
z_min= 9.0 z_max=30.0
n_0= 8301.
χ^2=0.34
νI_ν (nW m^-2 sr^-1)
λ(μm)
0.1
1.0
10.0
1
10
100
1
2
3

The Cosmic Star Formation rate



$$CSFR = n_* M_*/t_*$$

$$\sim (1 + z)^{-2}$$

Important implications for:

(1) collapse rate of dark matter (DM) haloes

(2) re-ionization

Is there any evidence for

absorption in the observed

gamma-ray spectrum

of TeV blazars?

TeV Blazars as Probes of the EBL Intensity

- TeV gamma-rays are attenuated by the EBL
- Allow for the determination of EBL in a wavelength region (5 – 60 μm) dominated by emission from interplanetary dust
- Problem: Intrinsic source spectrum is unknown

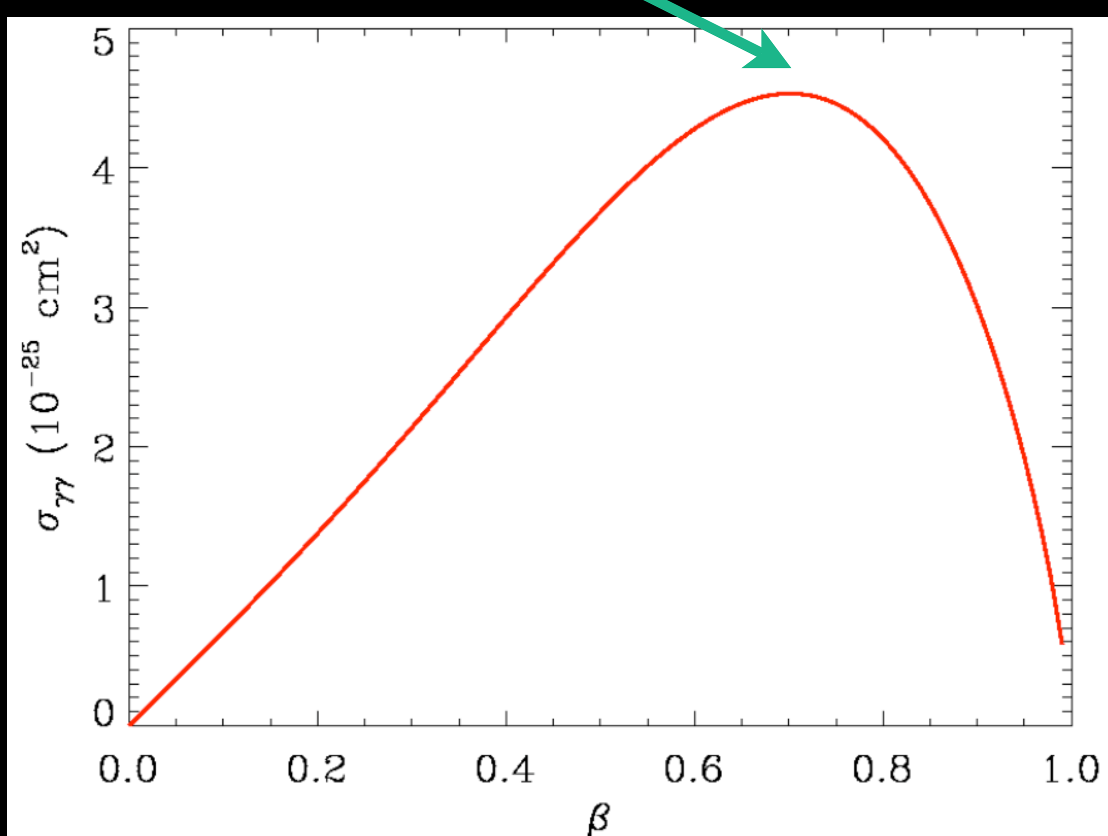
Peak cross section at energies:

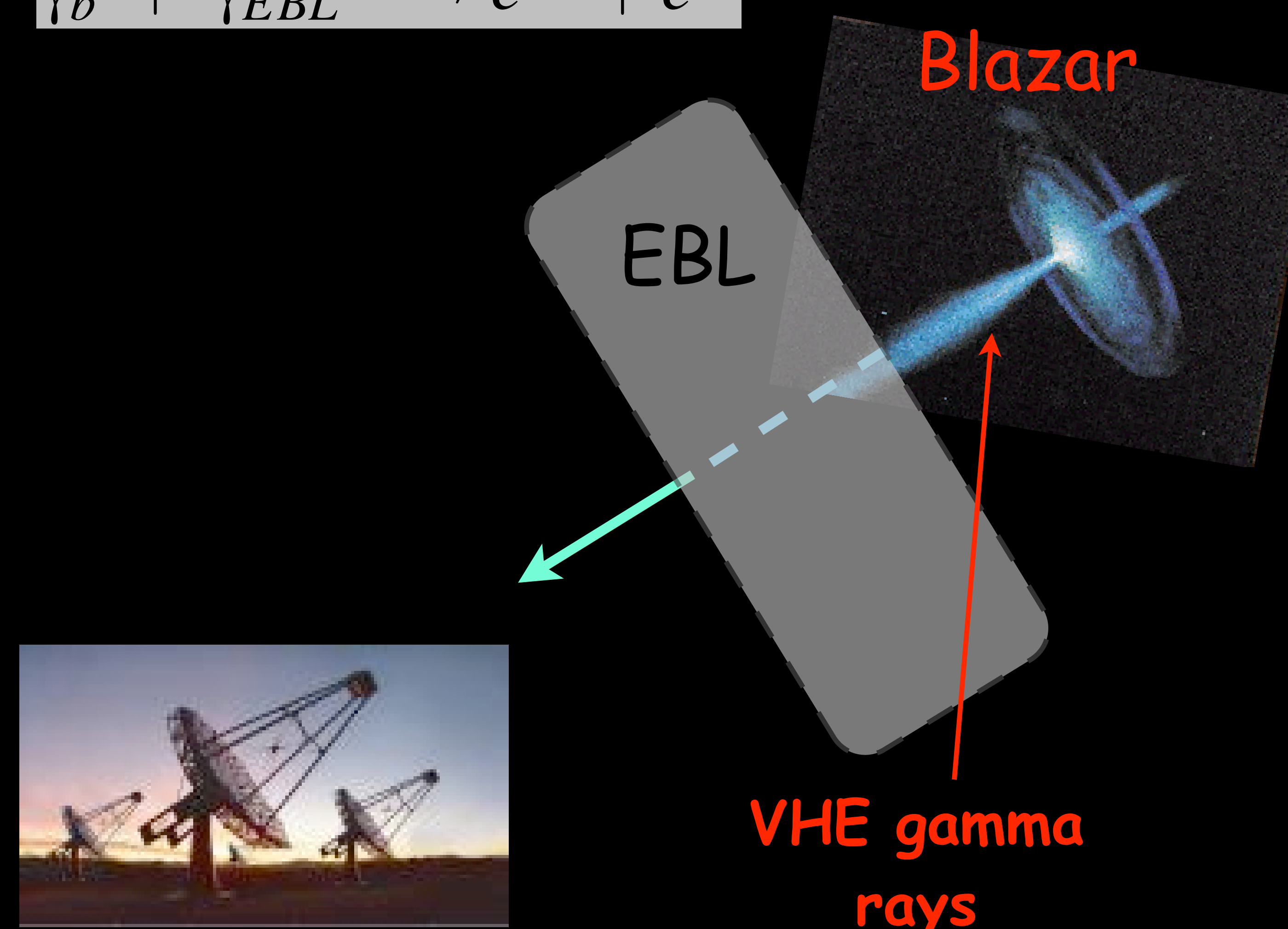
$E_\gamma(\text{TeV})\varepsilon_b(\text{eV}) \approx 1\ \text{MeV}^2$

or

$\lambda_b(\mu\text{m}) \approx 1.24\ E_\gamma(\text{TeV})$

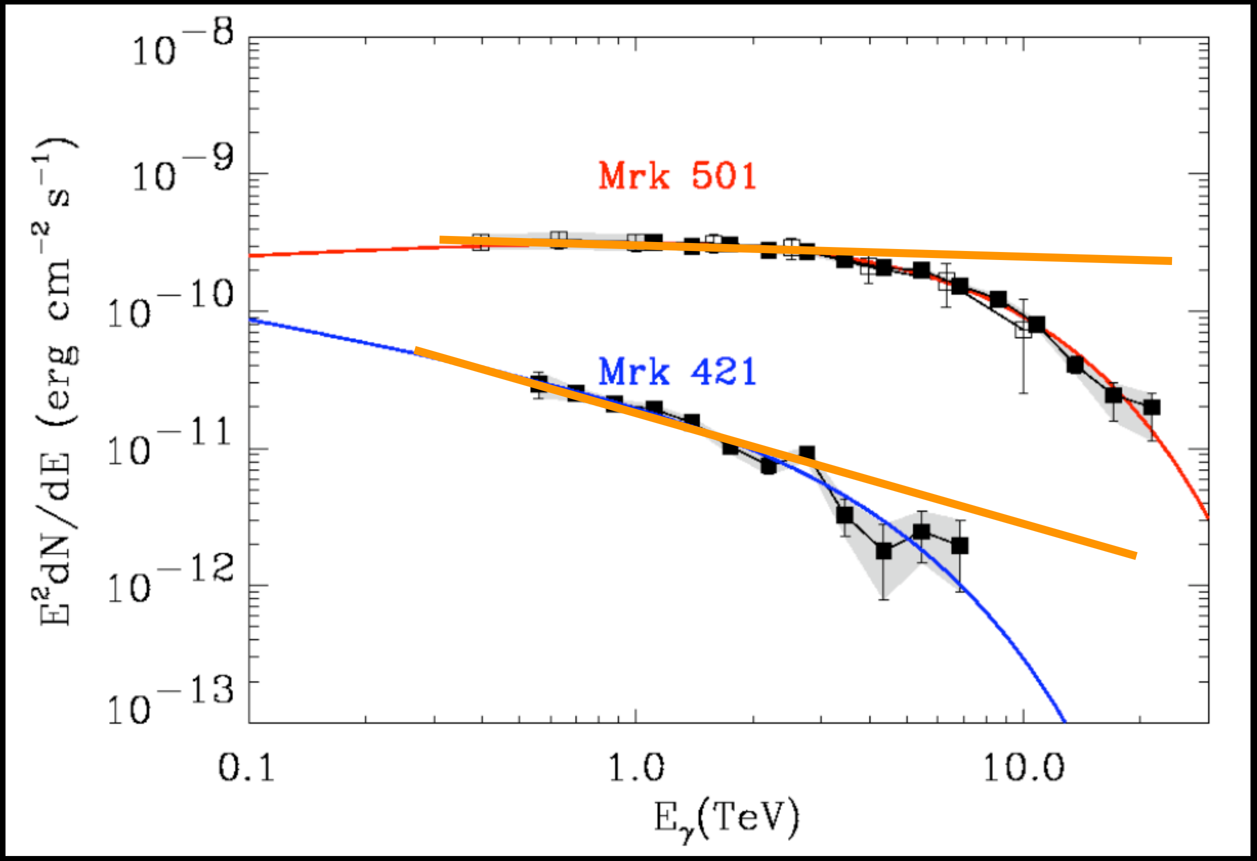
$$\gamma_b + \gamma_{EBL} \longrightarrow e^+ + e^-$$



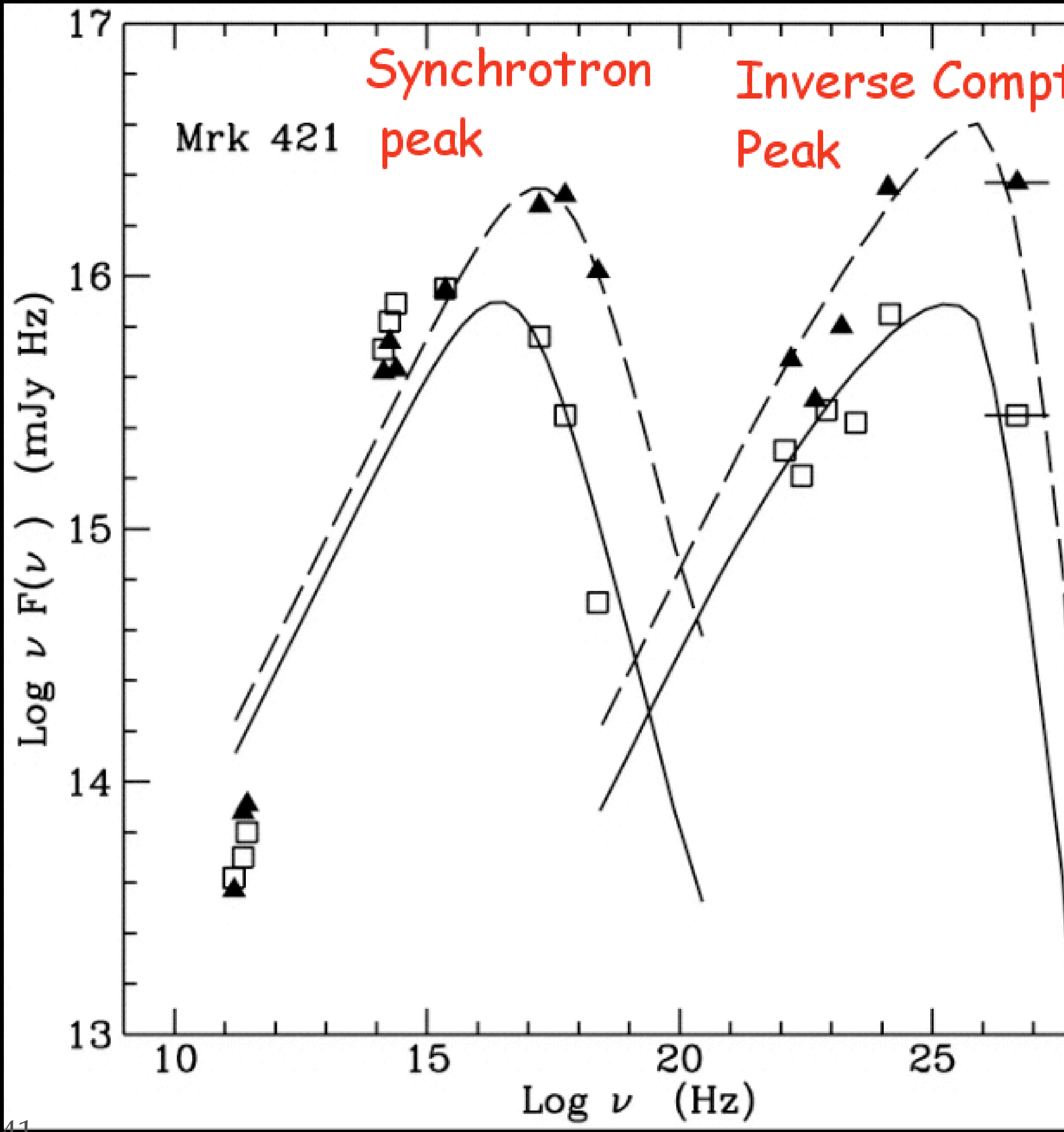


What is the Intrinsic blazar Spectrum?

Assume intrinsic spectrum is a power law
Search for a "break in the spectrum

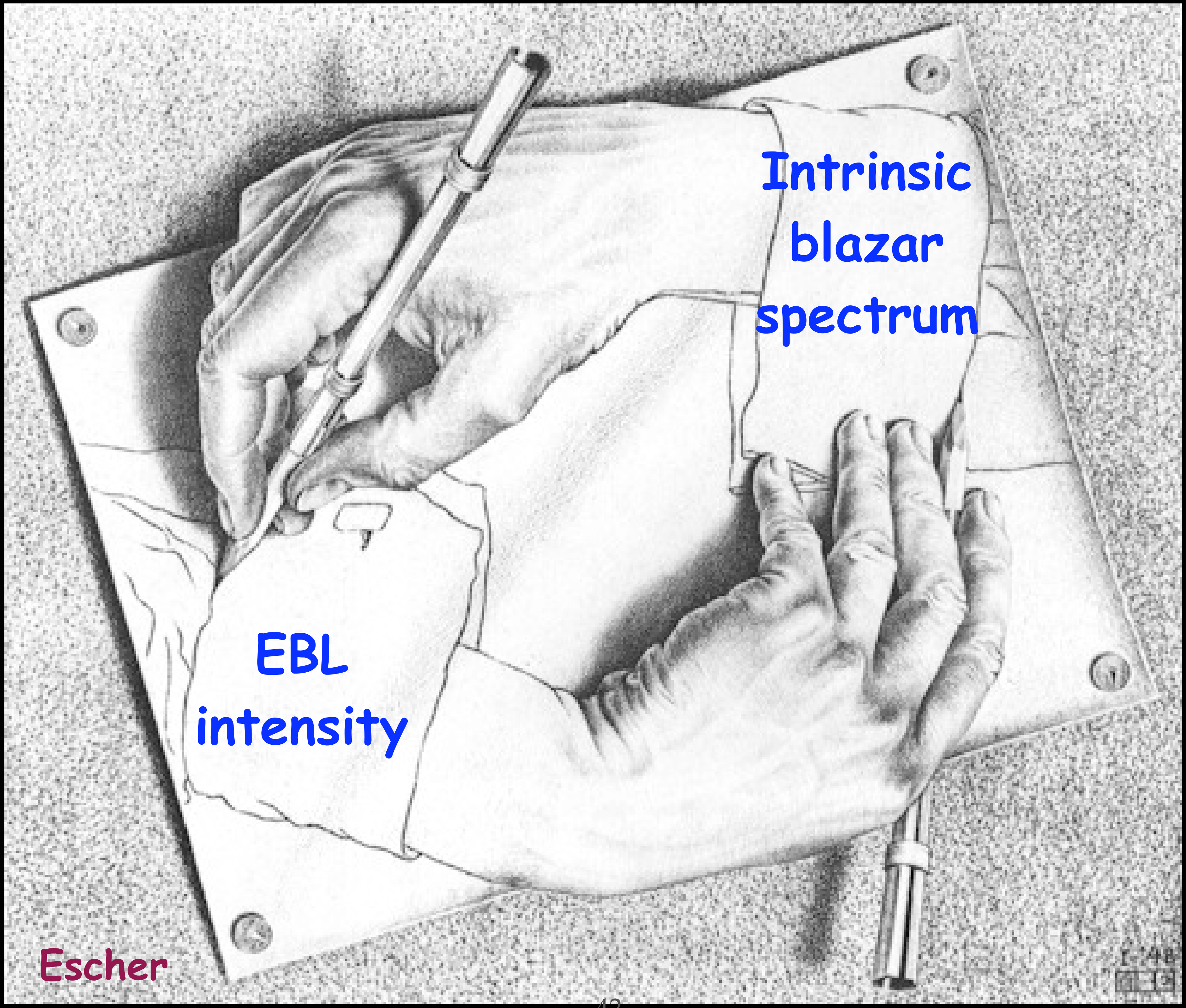


Intrinsic blazar spectrum is much more complex



- Intrinsic spectrum is NOT a simple power law
- Spectrum can be explained with a Synchrotron Self-Compton model

Determining the Blazar Spectrum for the EBL intensity and visa versa

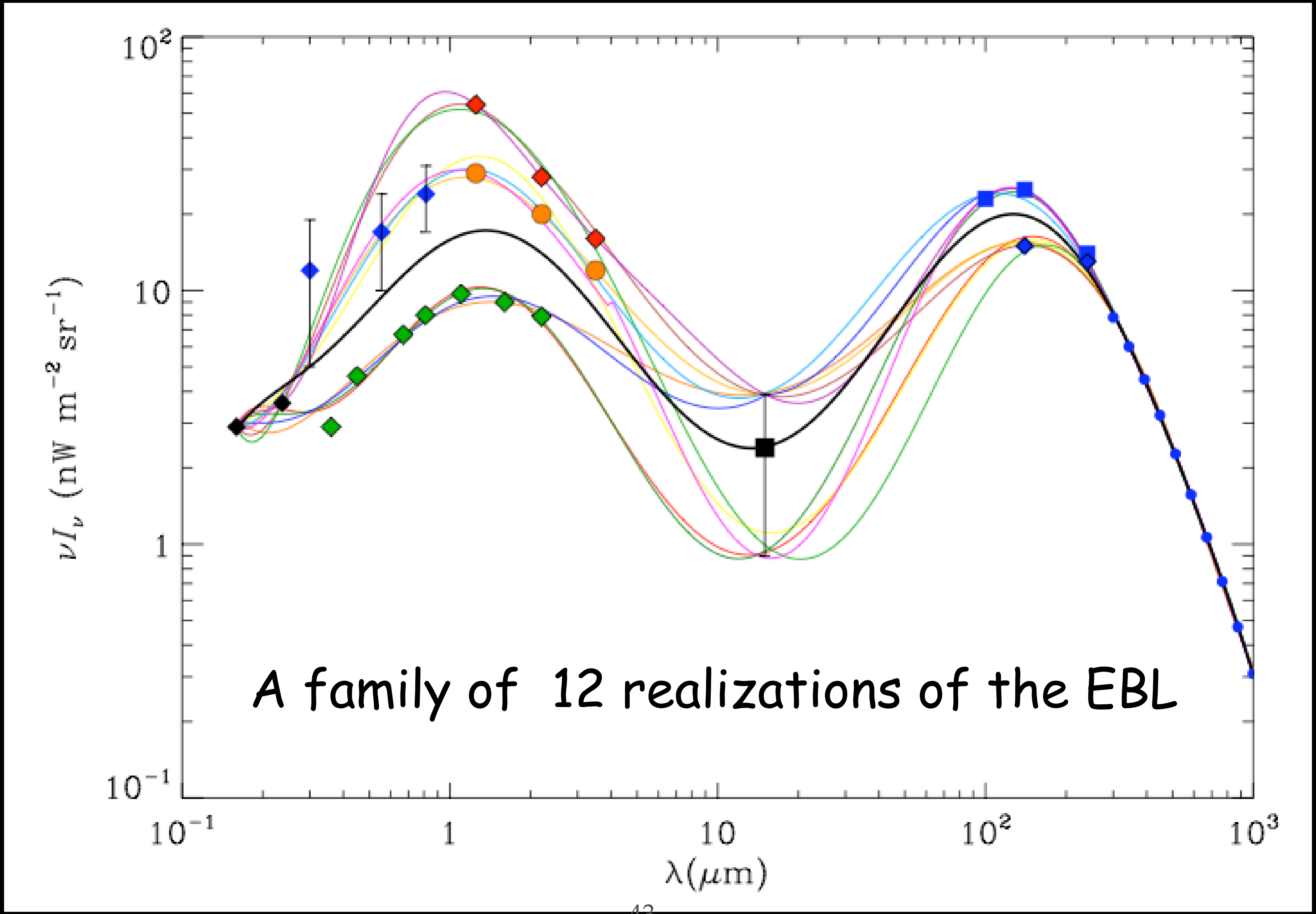


What EBL to Use? (Dwek & Krennrich 2004)

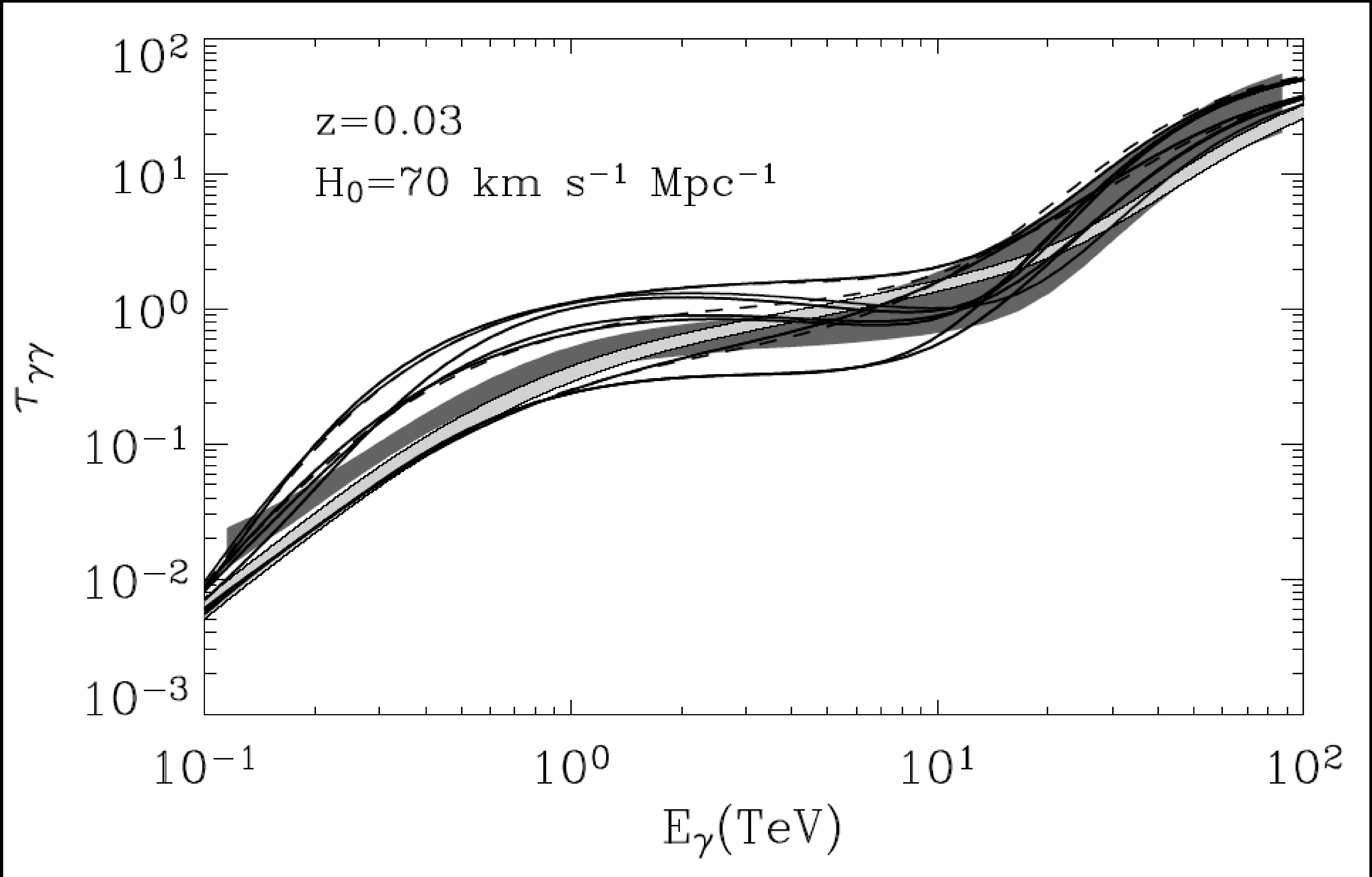
UV/opt
high, mid, low

near-IR
high, low

far-IR:
high, low



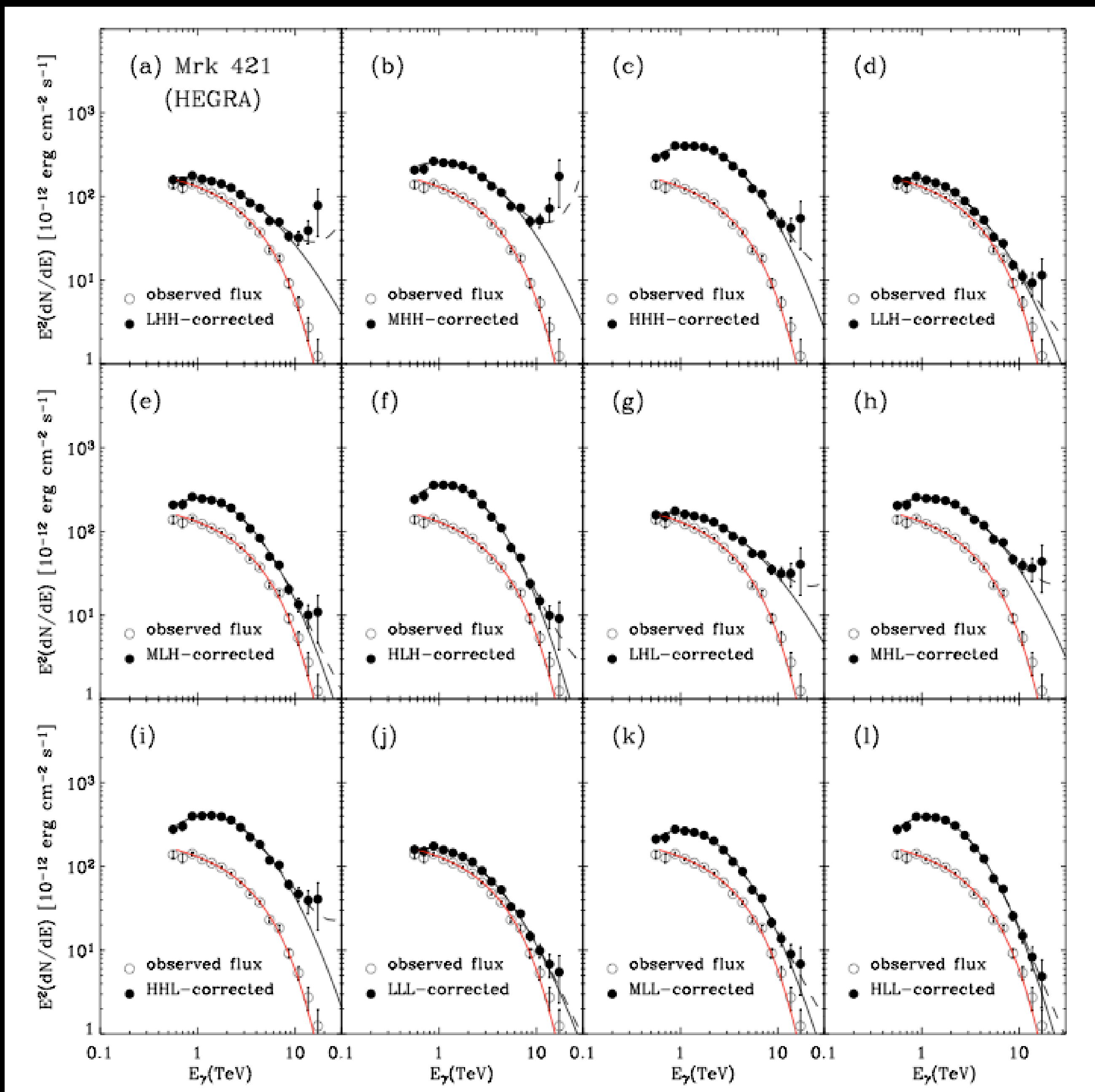
The Optical Depth due to all EBL Realizations

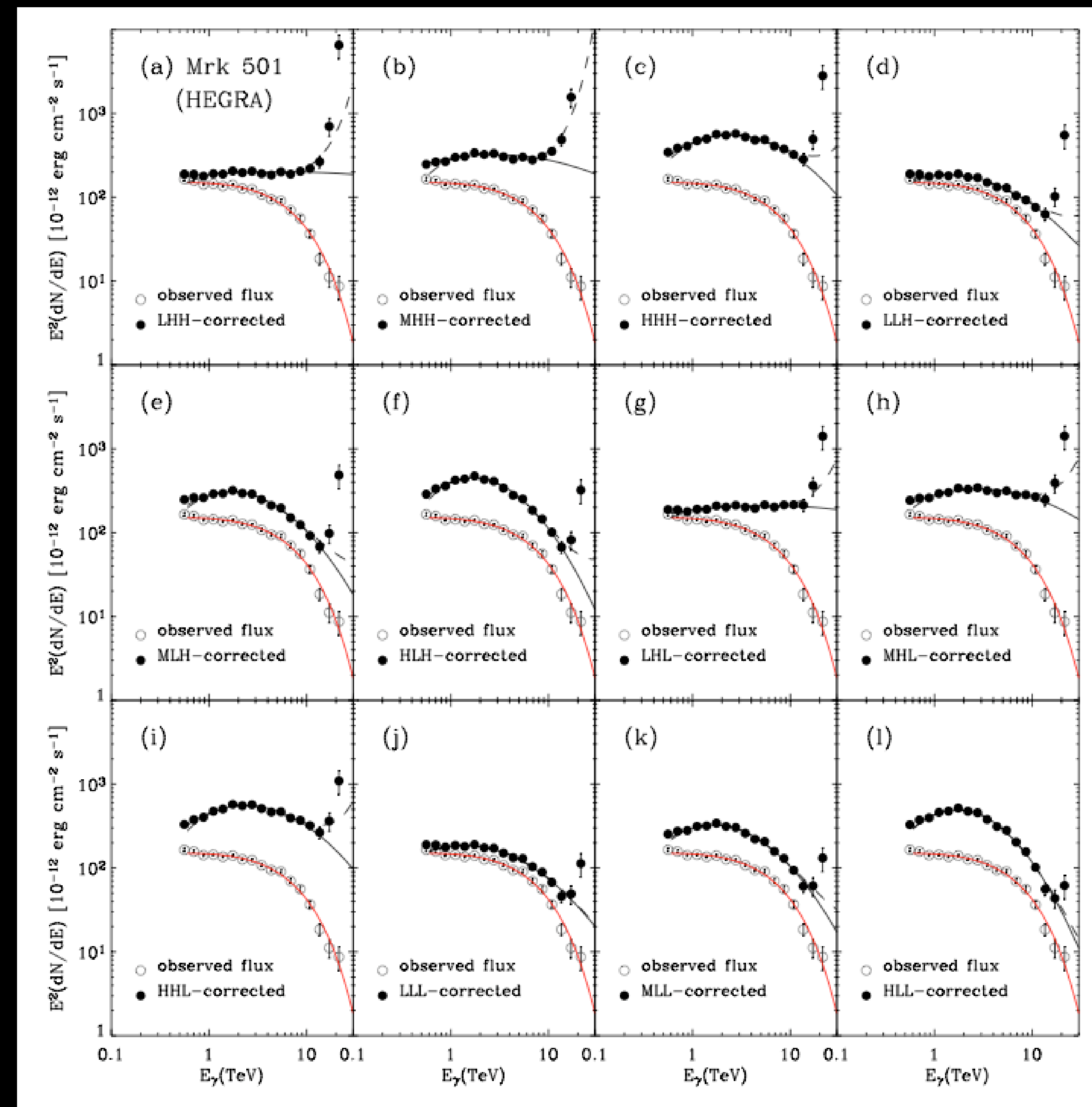


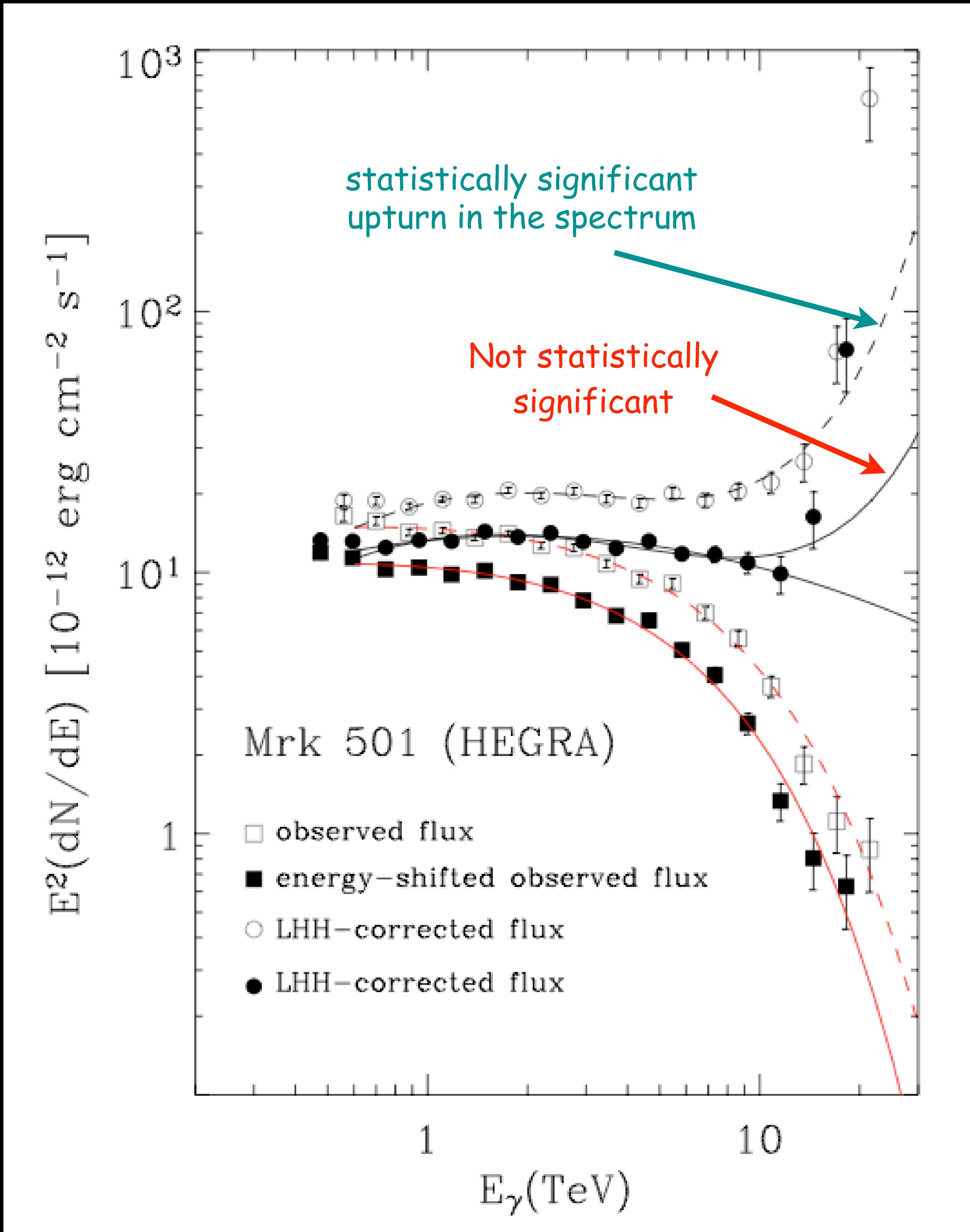
Intrinsic Blazar Spectra for EBL Realizations

(Dwek & Krennrich 2004)

Some spectra show an "unphysical" upturn





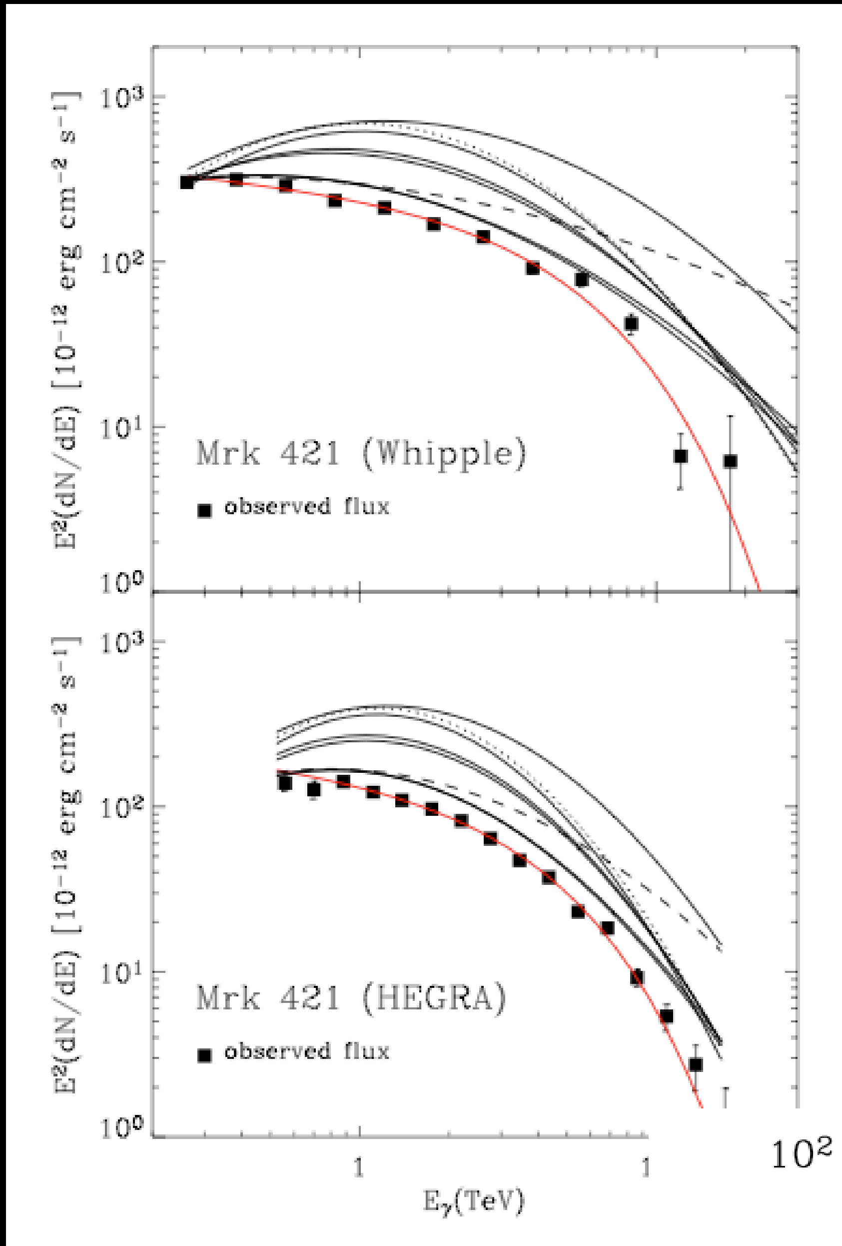


An "Unphysical Upturn in the Intrinsic Spectrum of Mrk 501

$$\left(\frac{dN}{dE}\right)_i = \Phi E^{-\alpha-\beta * log(E)}$$

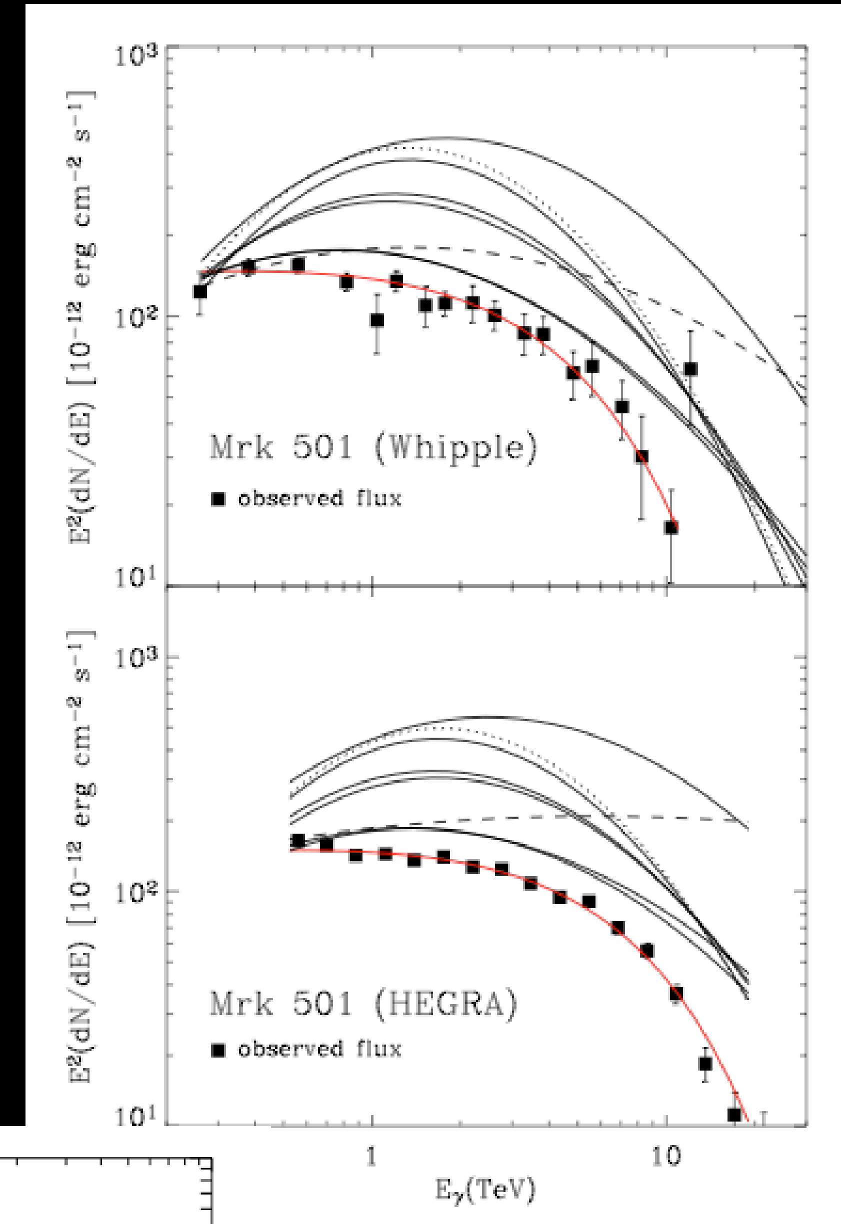
$$\left(\frac{dN}{dE}\right)_i = \Phi E^{-\alpha-\beta * log(E)} \times exp[E/E_0]$$

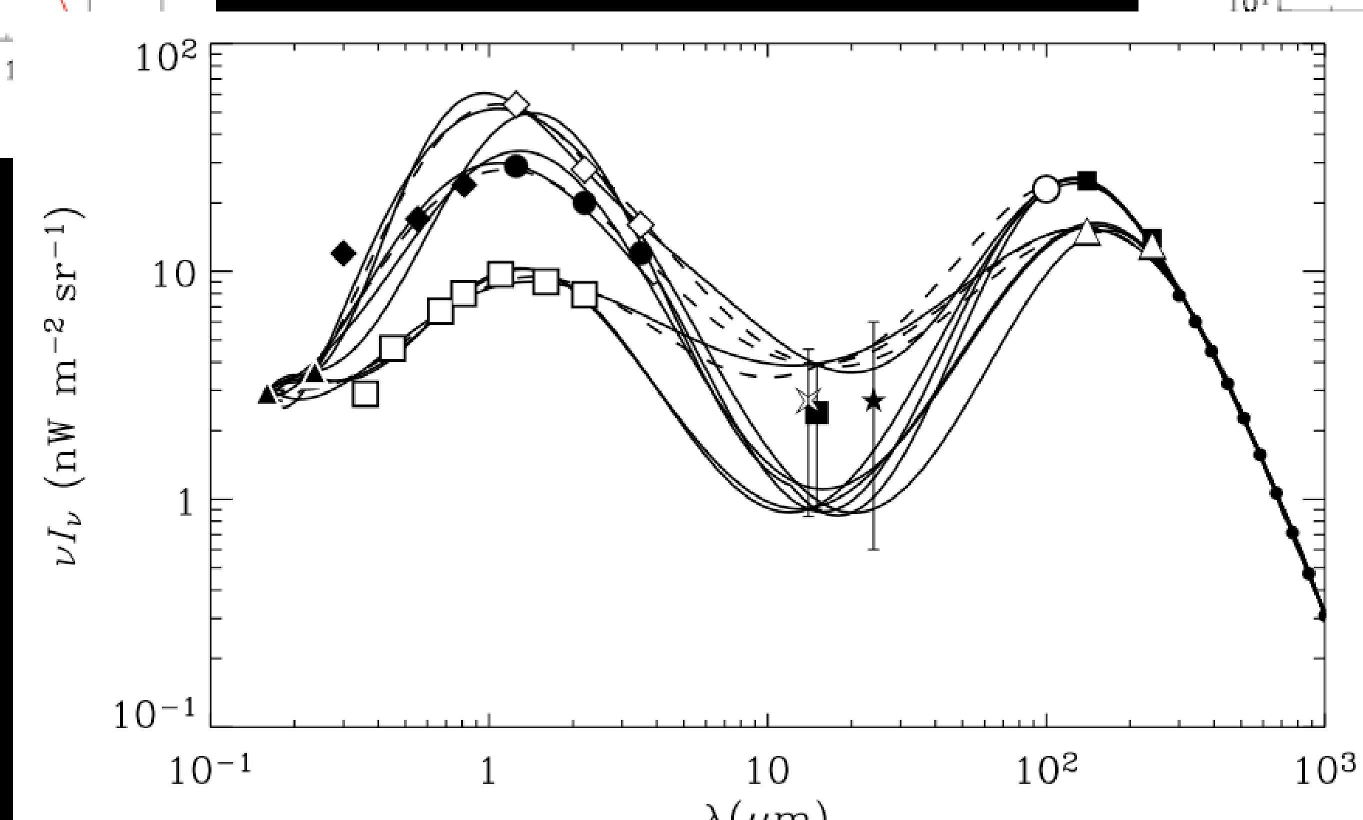
- The statistical F-test was applied to examine the significance of the upturn
- Significance of upturn depends on the uncertainty in the determination of the gamma-ray energy



Viable Intrinsic Blazar and EBL Spectra

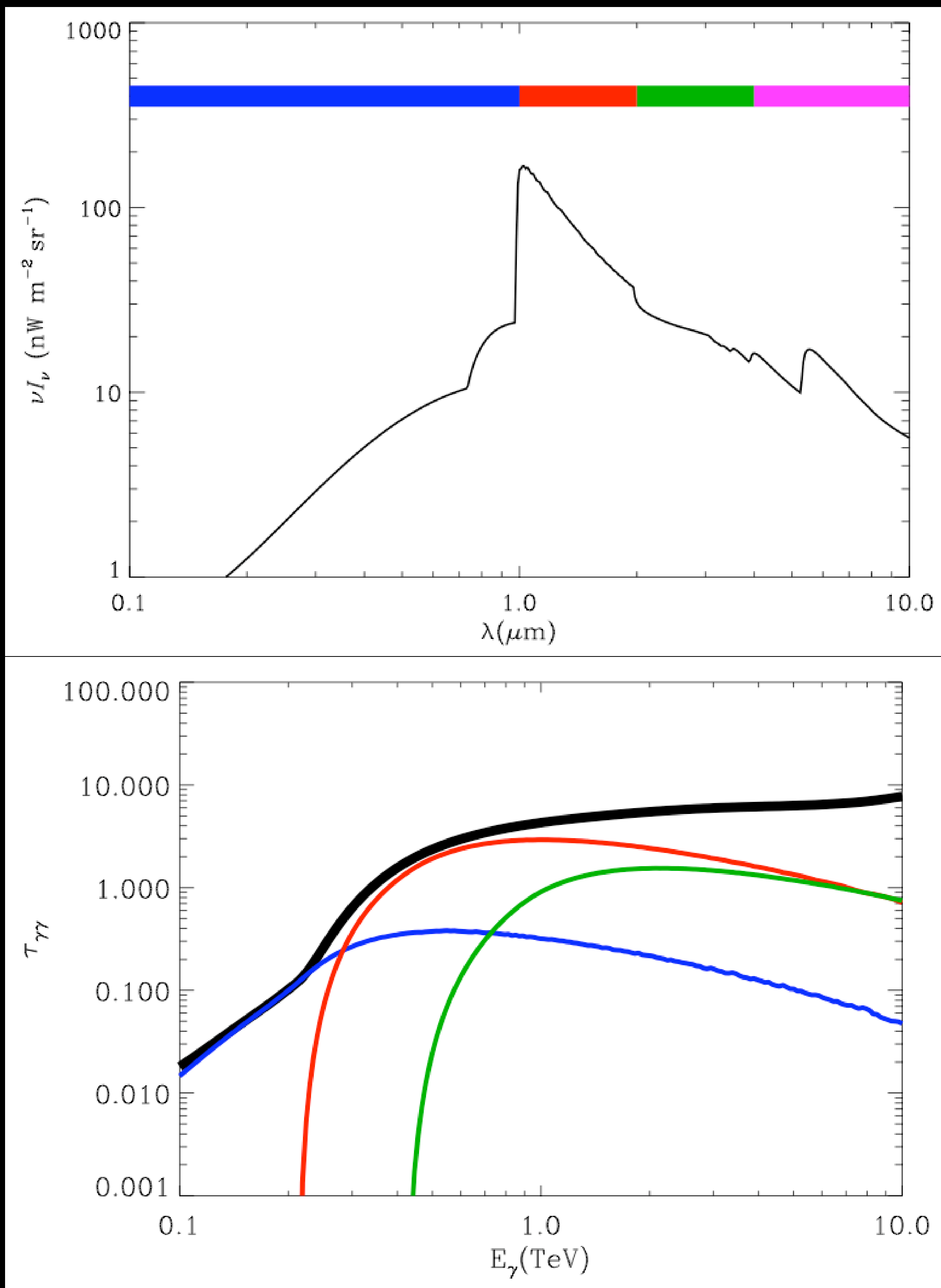
Constraints on gamma-ray production mechanisms



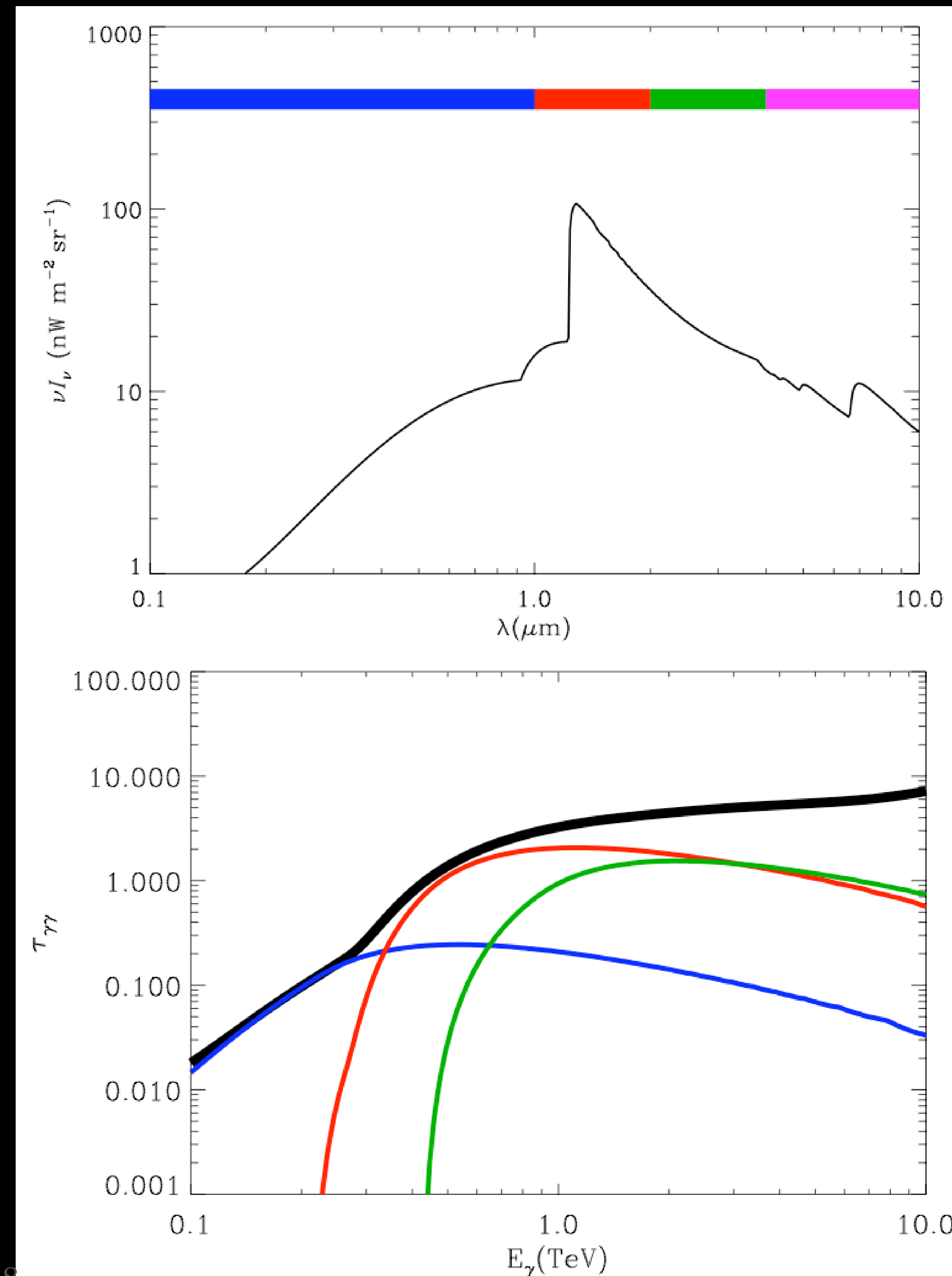


TeV Opacity due to the NEBL

Z_{min} = 7, Z_{max} = 15

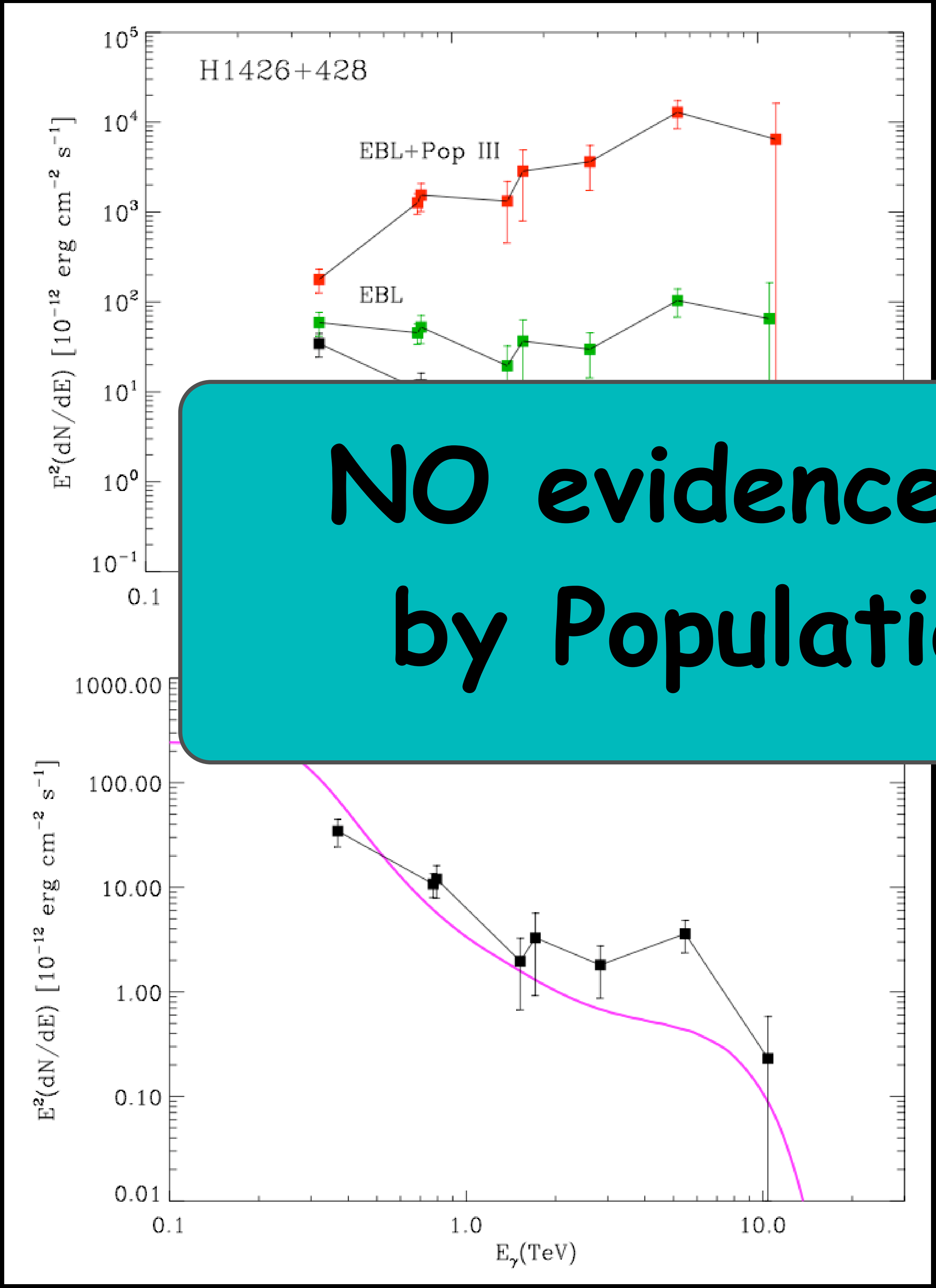


Z_{min} = 9, Z_{max} = 30

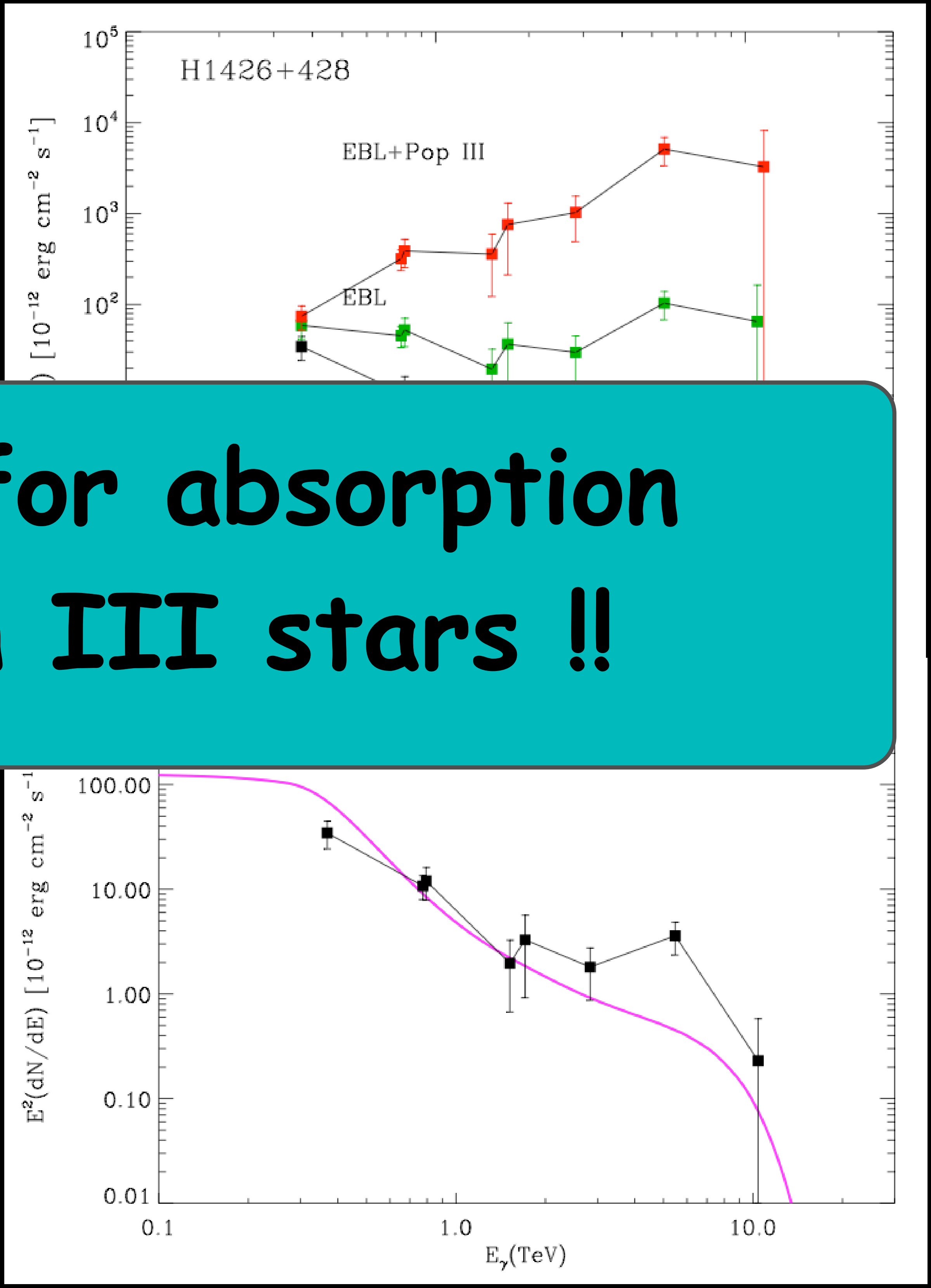


Intrinsic Spectrum of H1426+428 (z=0.129)

$Z_{min} = 7, \quad Z_{max} = 15$



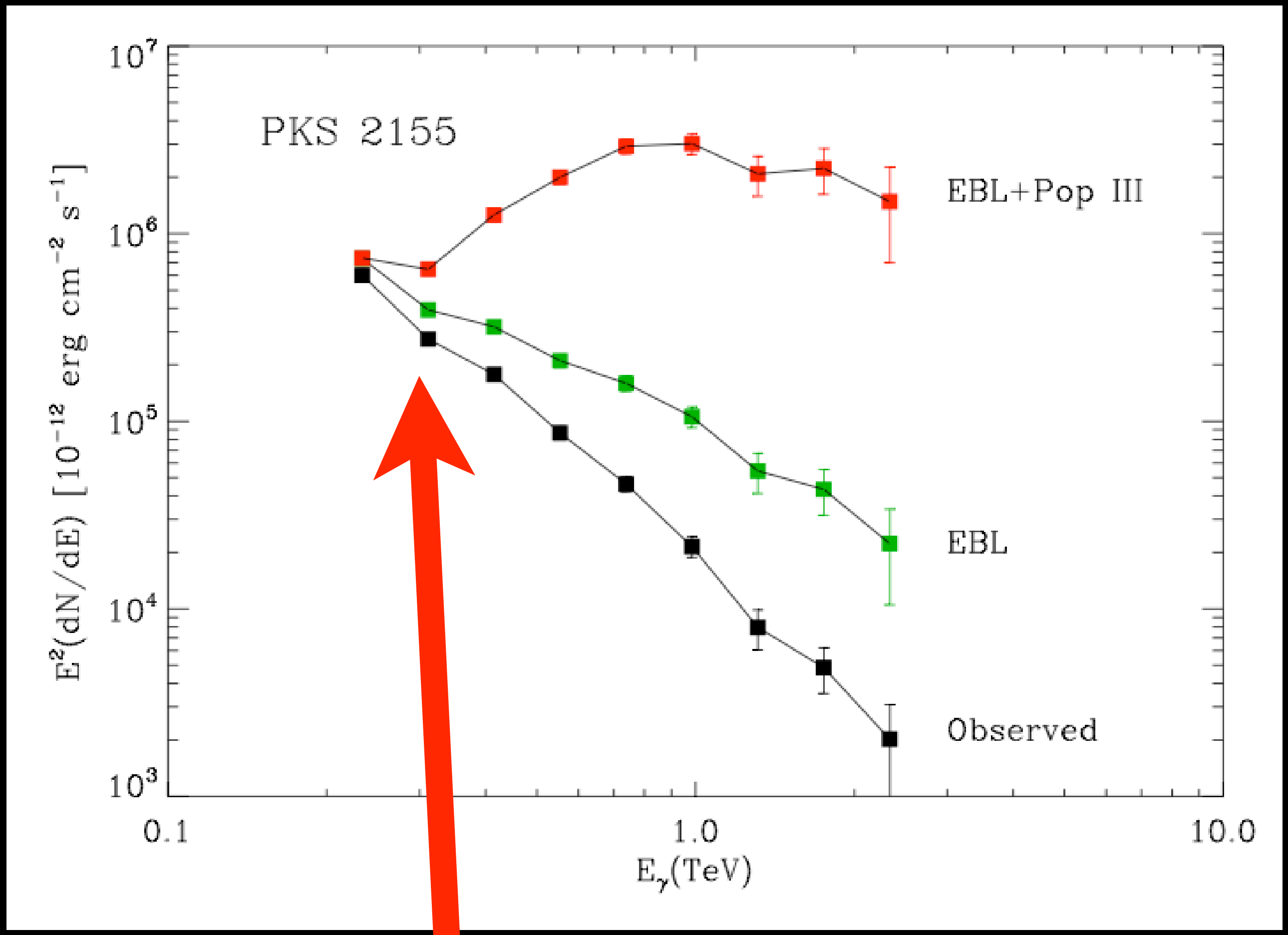
$Z_{min} = 9, \quad Z_{max} = 30$



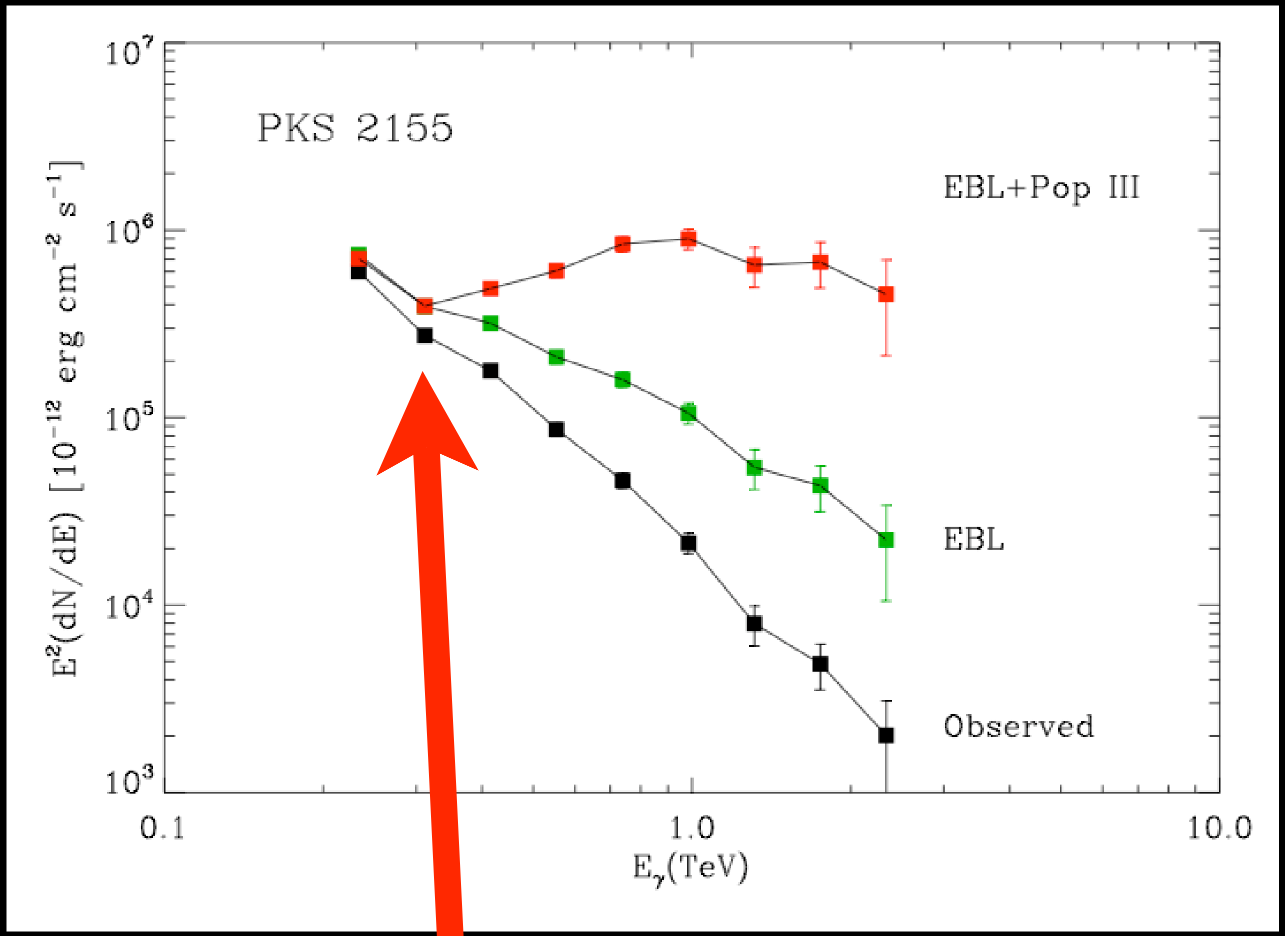
NO evidence for absorption by Population III stars !!

Intrinsic Spectrum of PKS 2155 (z=0.13)

$Z_{min} = 7, \quad Z_{max} = 15$



$Z_{min} = 9, \quad Z_{max} = 30$



- Population III stars create an interesting break in the intrinsic source spectrum
- Need 120 GeV datum point to confirm trend
- Can acceleration models explain a spectral break at 300 GeV?

Summary

- The NIRS and DIRBE data show a definite excess in the diffuse sky emission over that expected from normal star-forming galaxies
- The excess is best explained by residual zodi emission that escaped detection by DIRBE - however, fluctuation suggests its Xgal
- HOWEVER, the excess emission could also be extragalactic in origin (NEBL)
- If so, the most likely candidates are Pop III stars that started forming at $z \approx 15$-30, and stopped forming at $z \approx 7$-9
- The SFR needed is about 10x larger than that associated with normal galaxies
- NO evidence for NEBL signature in the intrinsic spectrum of blazars - HOWEVER, PKS 2155 is an exciting object that needs further studies at lower energies (≈ 100 GeV)


The END
Thank you very much
for listening

A spherical cow may be a good representation of reality, provided you have a sufficiently limited point of view