The Extragalactic Background Light: Measurements and Cosmological Implications

(Hauser & Dwek 2001, ARA&A 39, 249-307)

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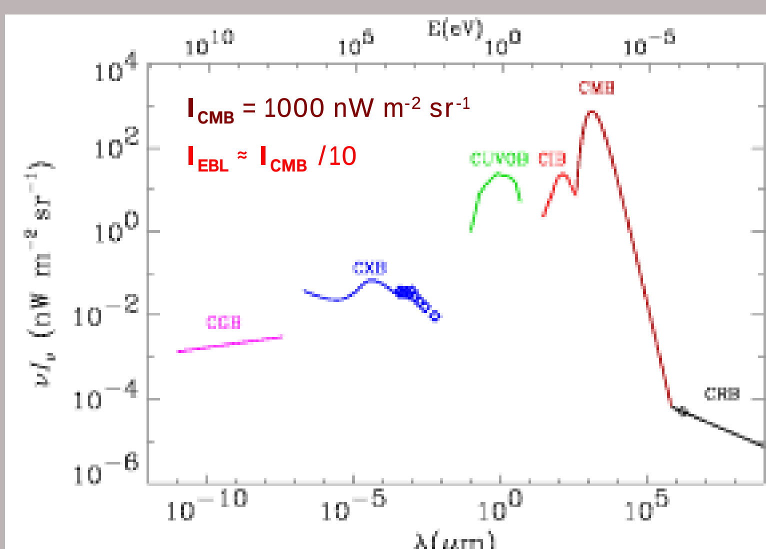
The Diffuse Background Radiation Spectrum



Units for EBL Measurements

$$\nu I_\nu(nW\ m^{-2}\ sr^{-1}) = \frac{3000}{\lambda(\mu\mathrm{m})} I_\nu(MJy\ sr^{-1})$$

$$= 3817\ \varepsilon^2 \mathrm{n}_\varepsilon (eV\ cm^{-3})$$

$$1\ Jy = 10^{-23}\ erg\ s^{-1}\ cm^{-2}\ Hz^{-1}$$

$$= 10^{-26}\ W\ m^{-2}\ Hz^{-1}$$

$$\varepsilon^2 \mathrm{n}_\varepsilon (eV\ cm^{-3}) = 2.62x10^{-4}\ \ \nu I_\nu(nW\ m^{-2}\ sr^{-1})$$

Sources Contributing to the EBL

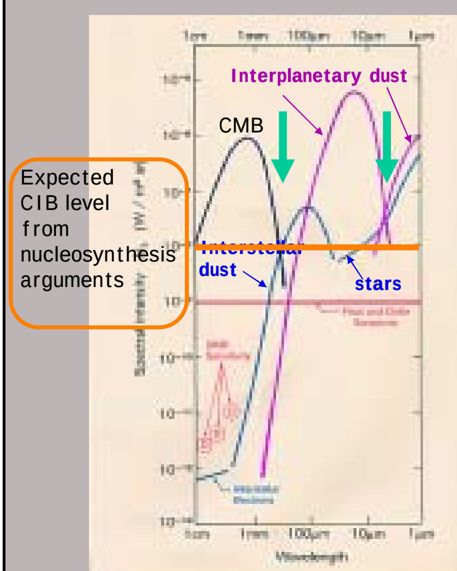
The EBL consists of the cumulative radiation from all energy sources since the epoch of recombination

- *Exotic sources*: decaying particles, primordial black holes, exploding stars, very massive objects, brown dwarfs
- *Active Galactic Nuclei (AGNs):* gravitational energy powered
- *Starlight*: nuclear energy powered sources

The Importance of the CIB

- It contains information on:
  - Cosmic star formation (black hole formation) history
  - Cosmic history of metal and dust production
  - Thermalization of X-UV-Optical photons by dust
- Opacity source for TeV photons
- Causal relation to X–ray and radio backgrounds
- Constrains the existence/evolution of exotic sources

Difficulties in CIB Measurements



- No unique spectral characteristics
- Strong foreground emissions
  - Interplanetary dust
  - Galactic stellar emission
  - Interstellar dust emission
- Spectral “Windows” at ~ 5 and 300 μm

Measuring the EBL

1) **Direct diffuse sky measurements**
   - Absolute calibration
   - Excellent stray light rejection
   - Removal of foreground emissions
2) **Source counts**
   - Provides lower limits on the EBL
   - Should convergence to EBL intensity
3) **Fluctuation analysis**
   - Requires knowledge of d /(z)/dz
4) **Search for absorption in the spectra of TeV γ–ray sources**
   - Requires knowledge of the intrinsic source spectrum

1) Diffuse Sky Measurements of the CIB

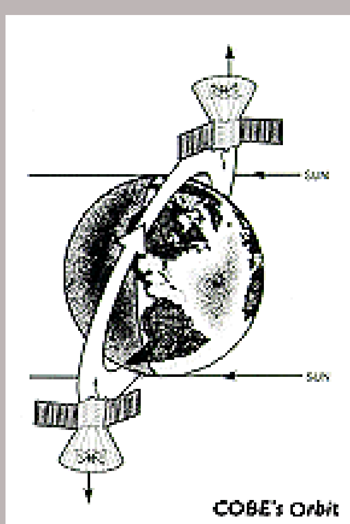
- **Measure absolute sky brightness**
- **Subtract foreground emission sources**
  - Interplanetary dust (**reflected, thermal**)
  - Discrete Galactic & extra–galactic sources
    - **Stars, star forming regions, LMC, SMC**
  - Diffuse emission from Galactic interstellar dust
- **Determine random & systematic uncertainties**
- **Examine residuals for**
  - **Positivity** and **isotropy**
- **Are there local contribution to the isotropic residual**
  - Dust shell in the solar system, a Galactic dust halo

The Cosmic Background Explorer (COBE) Satellite

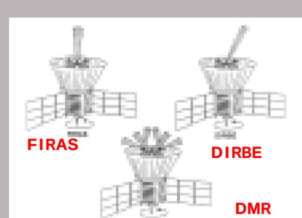
(Boggess et al. 1992, ApJ, 397, 420)

- **Diffuse Infrared Background Experiment (DIRBE) -**
  PI: M. G. Hauser
  - 1.25 2.2 3.5 4.9 µm
  - 12 25 60 100 140 240 µm
- **Far-Infrared Absolute Spectrophotometer (FIRAS)**
  PI: J. C. Mather
  - ≈ 100 – 1000 µm
- **Differential Microwave Radiometers (DMR) –**
  PI: G. Smoot

COBE Orbit Characteristics



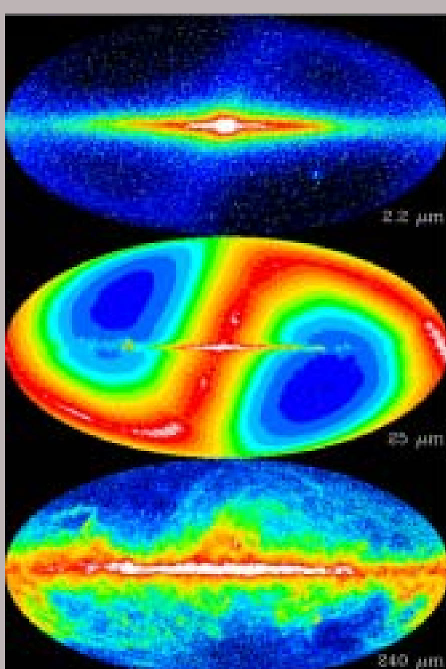
- **Sun-synchronous 900 km orbit with a 103 min period**
  - 99^0 inclination causes the orbit to precess by 1^0/day
  - Scans 1/2 sky each day
- **Data was collected over a 10 month period**



Sky scan Modes of The COBE instruments

Foreground Emission Components

- The Solar System - zodiacal light
  - Interplanetary dust particles
    - Reflected sunlight (1.25 – 3.5 μm)
    - Thermal dust emission @ T≈260 K
- The Galaxy
  - Stellar sources (discrete & unresolved)
  - Star-forming regions, molecular clouds
  - Thermal dust emission from the ISM
- Extragalactic sources: LMC and SMC



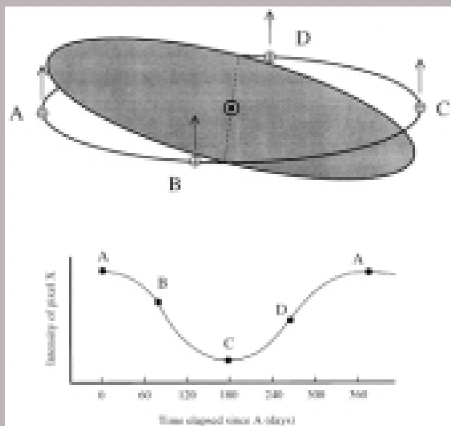
DIRBE Observed Sky

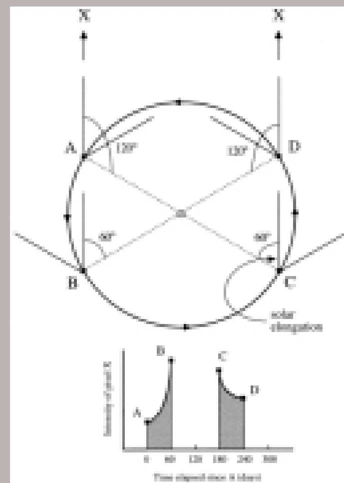
(Mollweide projection Galactic coordinates)

- 2.2 μm sky
  - IPD emission
  - Galactic starlight
  - LMC, SMC
- 25 μm sky
  - Dominated by IPD emission
- 240 μm sky
  - Dominated by ISM emission
  - LMC, SMC

Temporal Signature of the Interplanetary Dust Emission

The ZL emission is modulated because of the motion of the COBE satellite through the IPD cloud and the DIRBE scan pattern





Variations in Sky Brightness

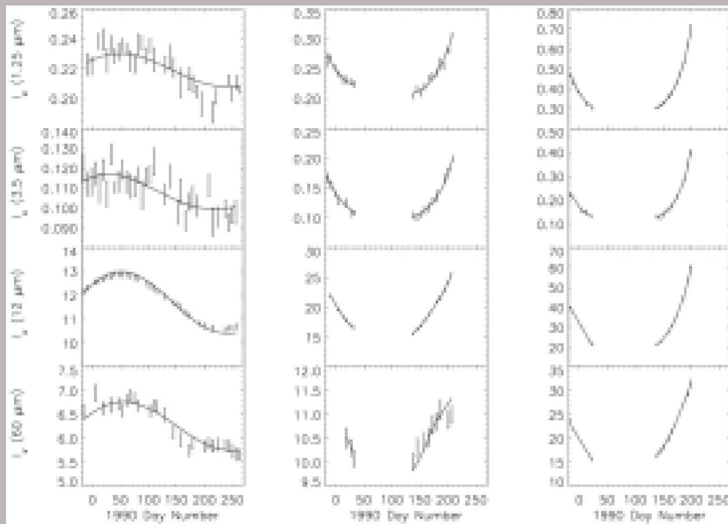
Towards the ecliptic plane

Towards the ecliptic pole

ANIMATION: RICK ARENDT

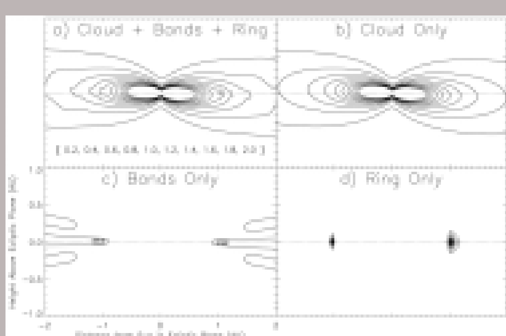
Observed Signatures of the IPD Emission

High eclip. lat. Mid eclip. lat. Low eclip. lat.

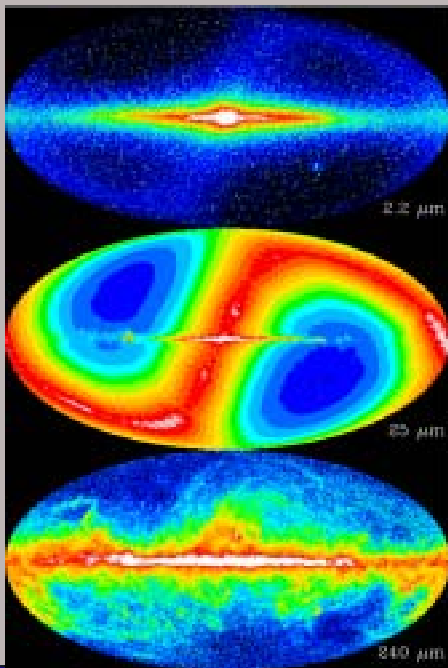


Zodi light model

(Kelsall et al. 1998)



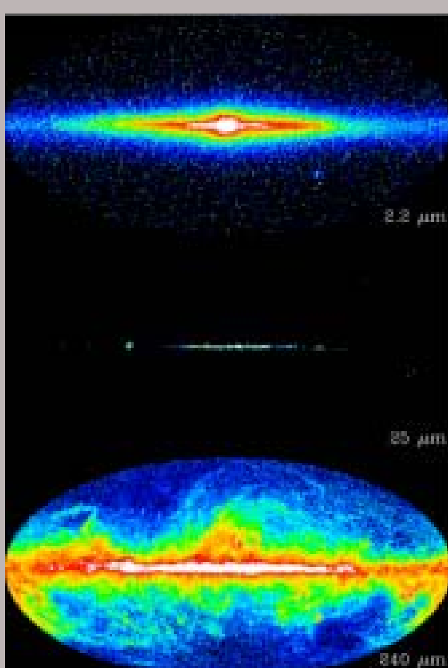
- **Smooth Dust Cloud**
  - Asteroidal, cometary collisions
    - 5 different models
- **Interplanetary Dust bands**
  - Asteroidal breakup
    - Toroidal band model *(Sykes 1990)*
    - Migrating band model *(Reach 1992)*
- **Circumsolar Ring**
  - Inward flowing dust particles, resonantly trapped in Earth's orbit *(Dermot et al. 1994)*



DIRBE Observed Sky

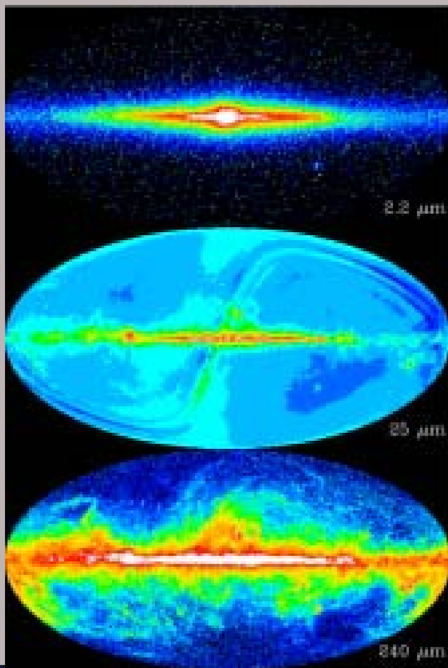
(Mollweide projection Galactic coordinates)

- **2.2 µm sky**
  - IPD emission
  - Galactic starlight
  - LMC, SMC
- **25 µm sky**
  - Dominated by IPD emission
- **240 µm sky**
  - Dominated by ISM emission
  - LMC, SMC



DIRBE Zodi Subtracted Sky

- **2.2 µm sky**
  - Galactic starlight
  - LMC, SMC
- **25 µm sky**
  - Dominated by Galactic ISM
- **240 µm sky**
  - Dominated by ISM emission
  - LMC, SMC



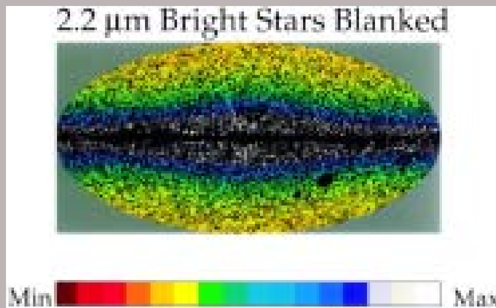
DIRBE Zodi Subtracted Sky

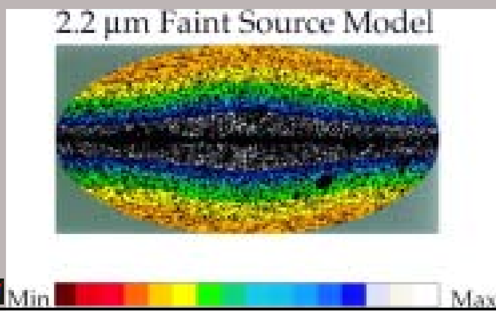
- 2.2 µm sky
  - Galactic starlight
  - LMC, SMC
- 25 µm sky
  - Dominated by Galactic ISM - 2% of previous level
- 240 µm sky
  - Dominated by ISM emission
  - LMC, SMC

Galactic Foreground Emissions

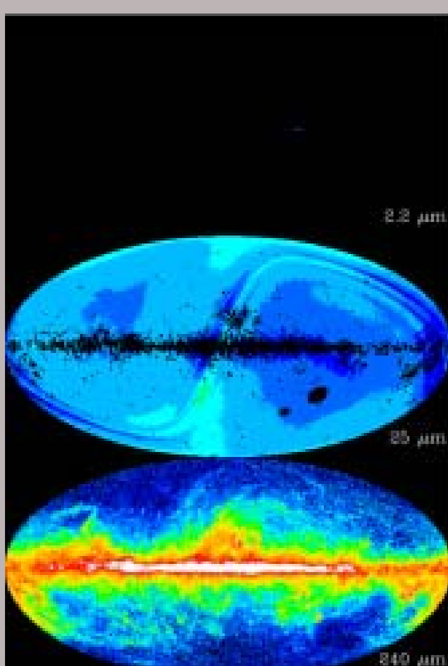
- **Bright resolved sources**
  - Stars at 1.25 to 25 µm
  - Star forming regions at 100 µm
  - LMC, SMC
- **Faint unresolved sources**
  - Primarily stars at 1.25 to 25 µm
  - Removed using a Faint Source Model (Arendt et al. 1998), based on the source count model of Wainscoat et al. 1992, Cohen et al. (1993, 1994, 1995)
- **Interstellar dust emission**
  - Need Galactic template that correlates with the dust emission

Removal of Foreground Stellar Emisison



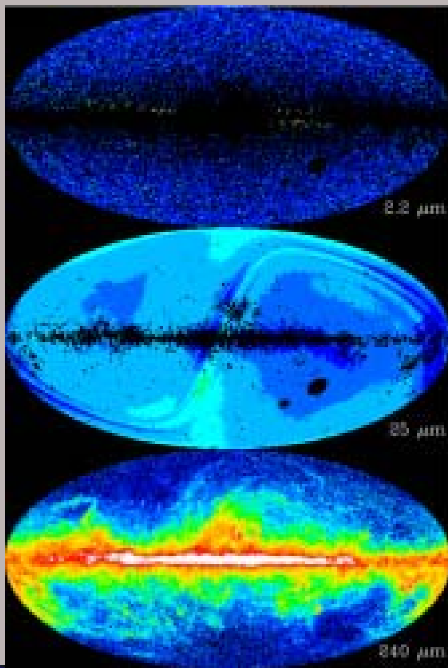


- **Observed 2.2 µm sky:**
  - Zodi subtracted
  - Bright sources blanked
- **Faint source model** (Arendt et al. 1998)
  - Exponential disk
  - Spiral arms
  - Molecular ring
  - Stellar halo
  - Bulge



DIRBE Star Subtracted Sky

- **2.2 µm sky**
  - Bright and faint stars subtracted
- **25 µm sky**
  - Dominated by Galactic ISM
- **240 µm sky**
  - Dominated by ISM emission
  - LMC, SMC



DIRBE Star Subtracted Sky

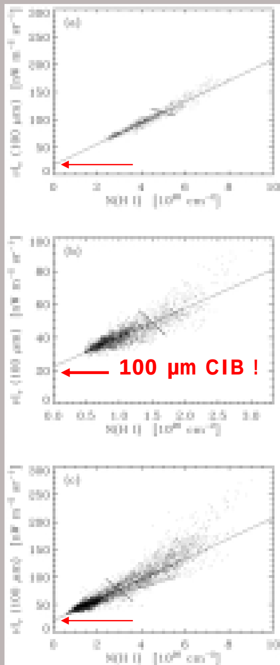
- 2.2 μm sky
  - Bright and faint stars subtracted

    (Linear Scale)
- 25 μm sky
  - Dominated by Galactic ISM
- 240 μm sky
  - Dominated by ISM emission
  - LMC, SMC

Interstellar Dust Emisison Component

- Adopt spatial template $T(l,b)$ for ISM
- Assume that for each DIRBE band:

  $$I(\lambda, l, b) = R(\lambda)\ T(l,b)$$
- Template requirement:
  - Only ISM
  - Similar angular scale as the DIRBE
  - Good S/N ratio
- Chosen templates:
  - Bell Labs HI map
  - DIRBE 100 μm map

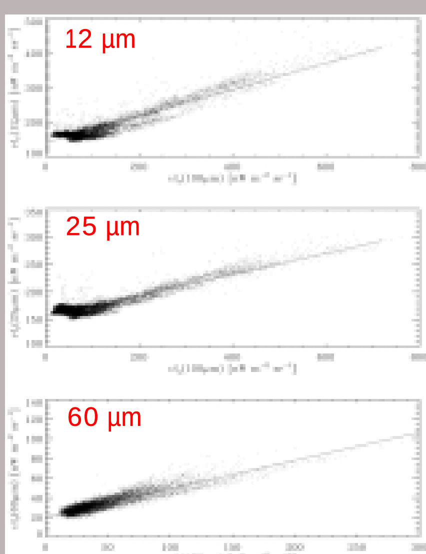


The Creation of an ISM Template

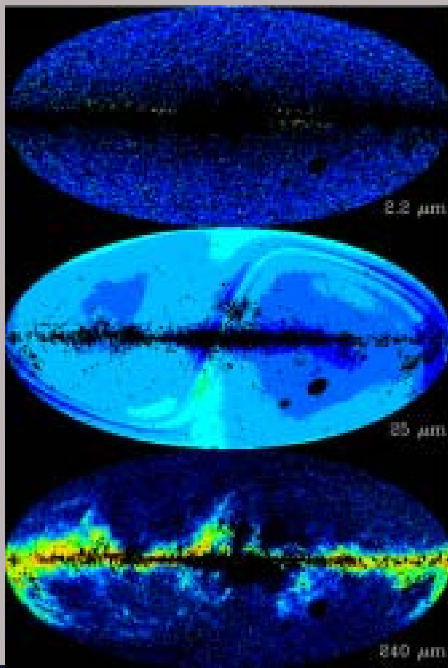
- The DIRBE ISM emission correlates best with the 100 µm DIRBE band
- To use the 100 µm band as an ISM template we need to subtract the extragalactic component
- Zero level of 100 µm template determined from 100 µm–H I correlation at the LH and NEP

- **DANGER!**
  - Extrapolation to N(H I)=0 can lead to erroneous results
  - There may be IR emission from an H II emission component

The Extragalactic component in the Various DIRBE band

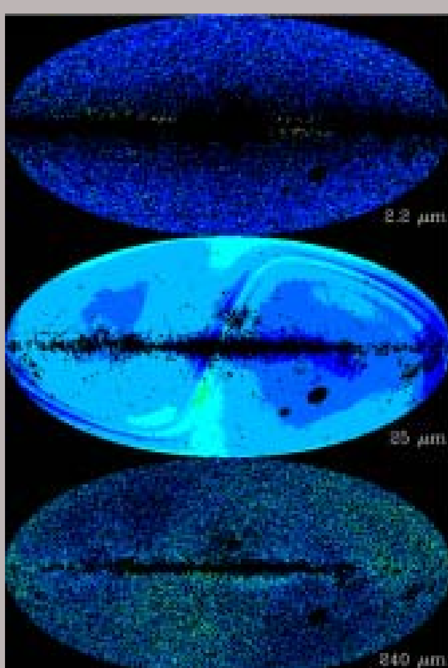


- The ISM 100 µm template was used to determine the color (spectrum) of the interstellar dust in all DIRBE bands
- Scaled 100 µm maps were subtracted from the other DIRBE bands to determine the CIB in select regions
- The CIB in all other bands depends on the 100 µm CIB



DIRBE ISM Subtracted Sky

- 2.2 μm sky
  - Bright and faint stars subtracted (Linear scale)
- 25 μm sky
  - ISM subtracted
- 240 μm sky
  - ISM subtracted sky
  - LMC, SMC blanked



DIRBE ISM Subtracted Sky

- 2.2 μm sky
  - Bright and faint stars subtracted (Linear scale)
- 25 μm sky
  - ISM subtracted
- 240 μm sky
  - 2-component ISM model subtracted (combination of 100 & 140 μm templates)
  - LMC, SMC blanked

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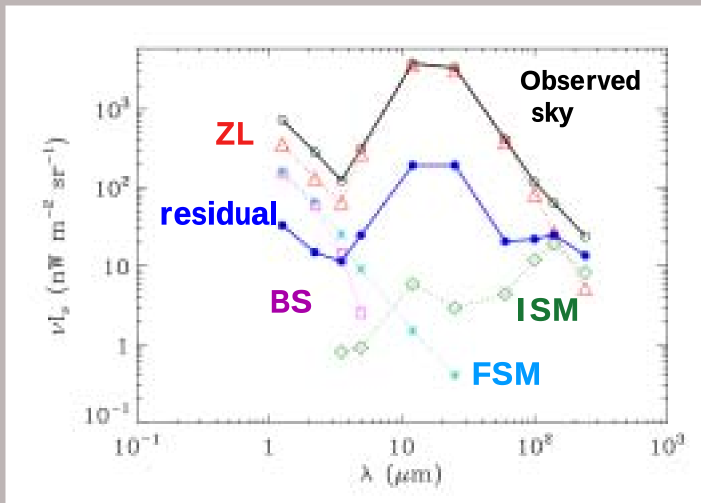
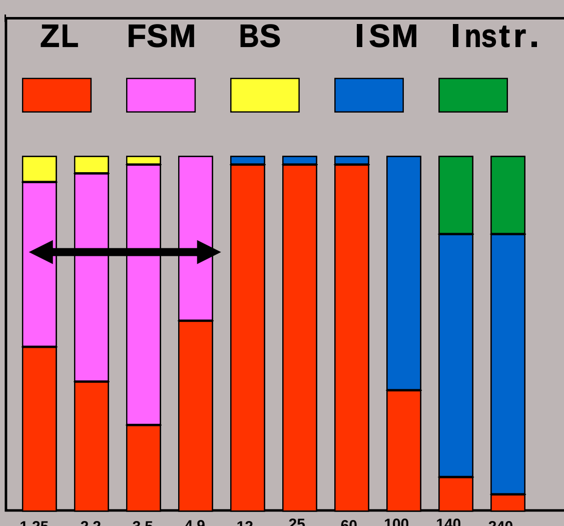
Spectral Decomposition of the Emission Towards the Lockman Hole



Systematic Uncertainties



Background

- 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!

Isotropic ????

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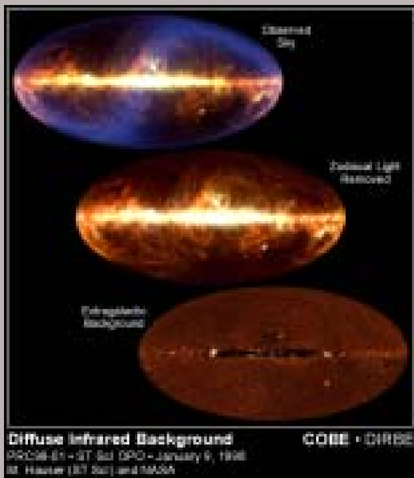
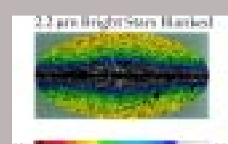
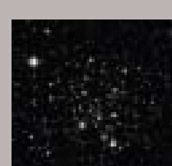
DIRBE Detects the CIB at 140 and 240 µm!



Recent Detections and Limits on the CIB
Detections in the Near-IR



- **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 unresolved stars
  - Wright zodi model
- **Cambresy et al (2001)**
  - 2MASS + Kelsall zodi model
- **Arendt & Dwek (2002)**
  - Multi-color DIRBE stellar template + Kelsall zodi model

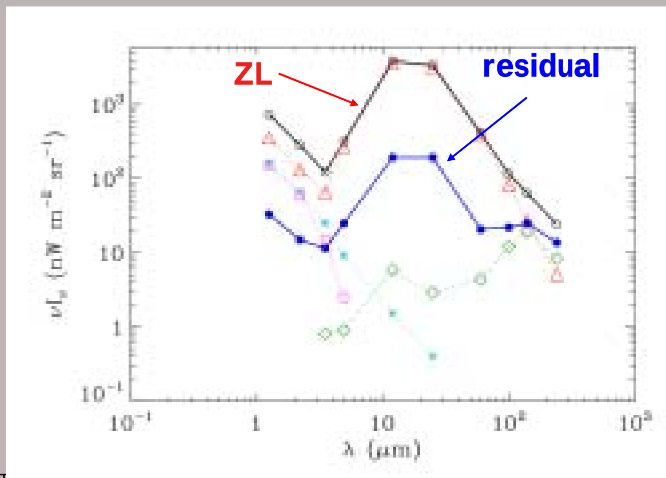


2MASS image (16 mag)

The Strong No-Zodi Principle

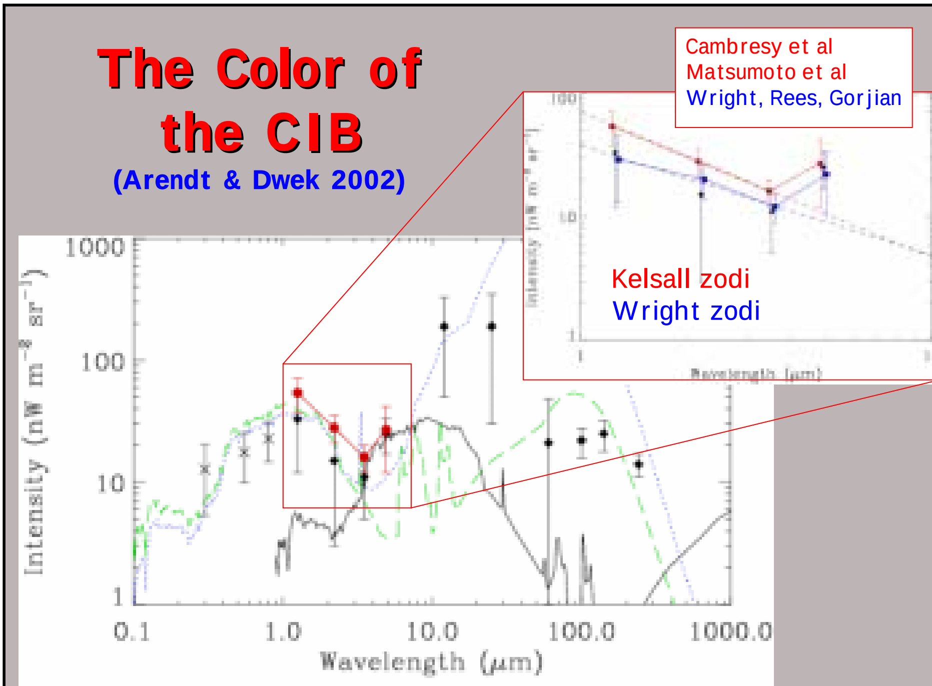
(Wright 2002)

The 5 – 60 µm Residual Spectrum is Very Similar to that of the Zodiacal Light

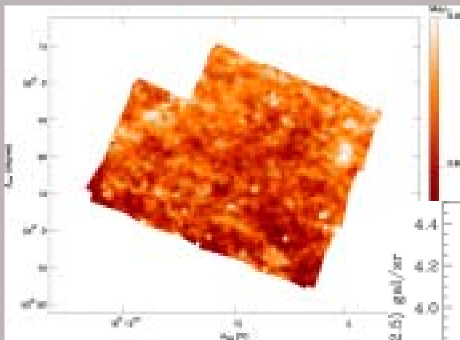


The Color of the CIB

(Arendt & Dwek 2002)

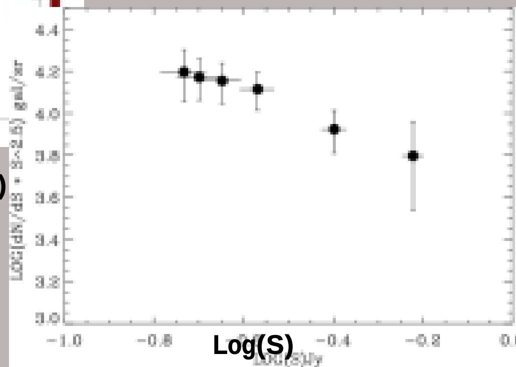


2) Galaxy Number Counts



ISO **FIRBACK @ 170 µm**
(Dole et al. 2001)

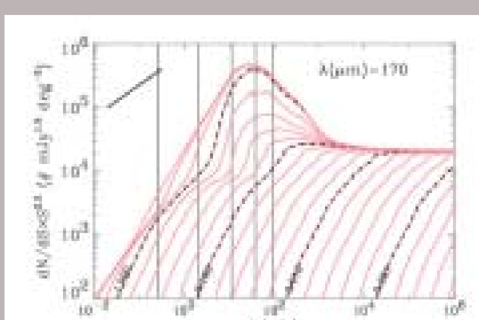
Log(dN/dS)



Log(S)

Problems With Number Counts

0) Convergence

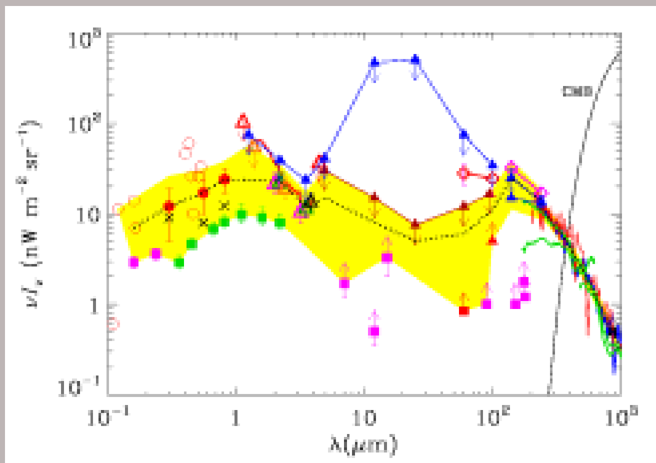


Dwek et al. 2002 with Chary & Elbaz (2001) input parameters

1) Low surface brightness galaxies can be missed

2) There may be a truly diffuse background from overlapping wings of resolved galaxies

Summary of EBL Detections and Limits



- CIB
- IRAS
- ISO
- SCUBA
- UV-Opt
- UV-Opt
- ………… nominal EBL limits

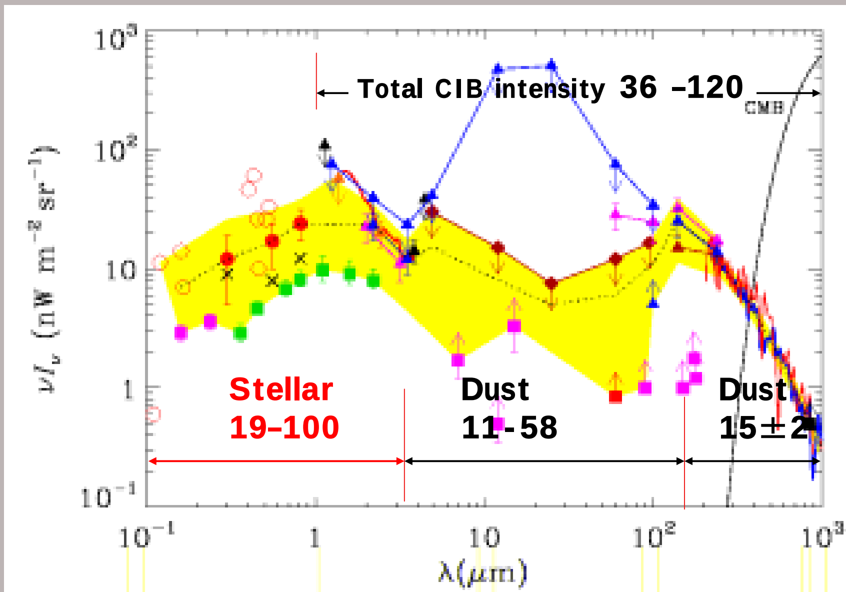
Cosmological Implications

1) EBL and CIB intensities

2) TeV opacity

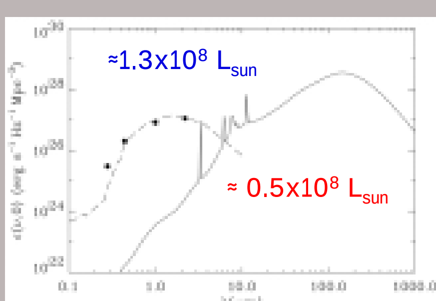
3) Models for the EBL

Total EBL Intensity 45–170 nW m^{-2} sr^{-1}

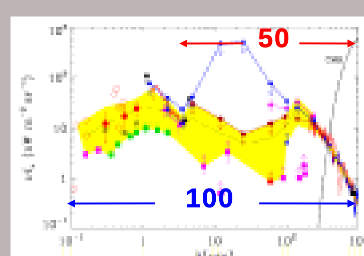


We Live in a Universe With Dusty Galaxies

The luminosity density in the local universe
(Dwek et al. 1998)
$L_{IR}/L_{tot} \approx 0.30$



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



Galaxies were more opaque in the past (high z) !

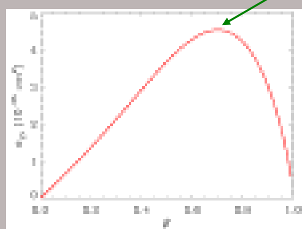
Mid–IR Limits on the CIB

Most difficult to probe because of the strong foreground emission from the interplanetary (IPD) dust cloud

High energy photons can be attenuated by $\gamma + \gamma_b \longrightarrow e^+ + e^-$ **interactions**

(Nikishov 1962)

Cross section for γ–γ interactions



Peak cross section at energies:

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

or

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

1 – 100 TeV photons can be readily attenuated by 1 – 100 µm CIB photons

IR Background–TeV γ–ray "Crisis"

The optical depth to TeV γ–rays:

$$\tau_{\gamma\gamma}(E) = n(\varepsilon)\ \sigma_{\gamma\gamma}(E,\varepsilon)\ L$$

$I_{CIB} = 28\ \mathrm{nW\ m^{-2}\ sr^{-1}}$ **at 60 µm** **(Finkbeiner et al. 2000)**

mfp(17 TeV photon) ≈ 14 Mpc

Distance to Mrk 421, 501 ≈ 160 Mpc

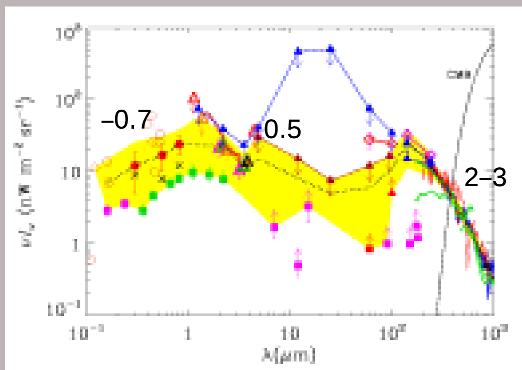
the intrinsic 17 TeV flux from these sources should be enhanced by a factor of:

≈ *exp*(12) ≈10^5 over the observed flux

IR Background–TeV γ–ray "crisis"!!!

(Protheroe & Meyer 2000)

Energy Dependence of TeV Opacity Depends on the Slope of the CIB



if

$\nu I_\nu \sim \nu^k \sim \lambda^{-k}$

or

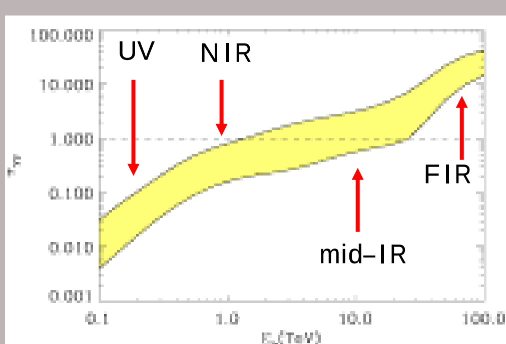
$n_\varepsilon(\varepsilon)\, \varepsilon^2 \sim \varepsilon^{2-k}$

then

$\tau_{\gamma\gamma}(E_\gamma) \sim E_\gamma^{\ 1-k}$

The TeV Opacity of the Universe

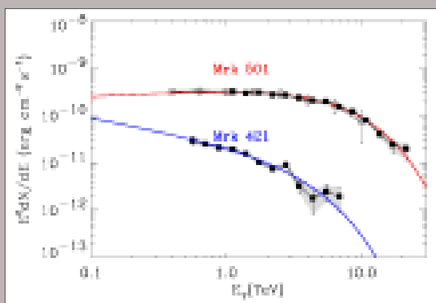
(z = 0.03, H_0=100, Ω_M=1)



- **The local universe (z<0.03) reaches unit optical depth for 20 TeV photons**
- **There is no TeV-IR "crisis"**

TeV γ-ray Probes of the CIB

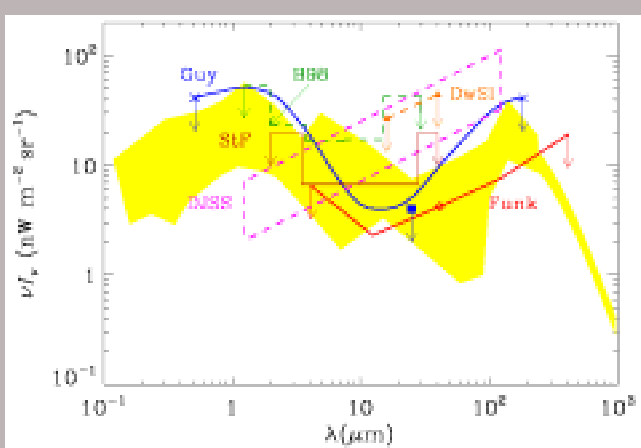
Mrk 501 (z = 0.034)
Mrk 421 (z = 0.031)
(Catanese & Weekes 1999 for a review)



- **Search for evidence for absorption in the source spectrum**
- **Early work assumed an intrinsic power-law spectrum**
  (Stecker, De Jager & Salamon 1992, Dwek & Slavin 1994)
- **PROBLEMS**
  - The intrinsic source spectrum is unknown
  - Possible internal absorption
  - Photon detection in the highest energy bin is uncertain

CIB Limits from TeV Observations

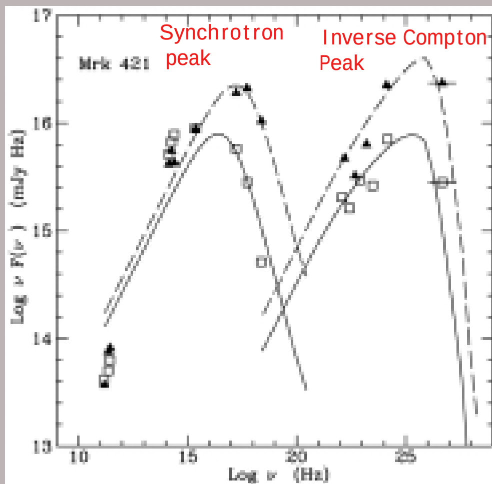
(Hauser & Dwek 2001)



- **All models (except Guy et al 2000) assume a simple power law for the source spectrum and assumed the high–E rollover is due to absorption**
- **Guy et al. Assumed an SSC model**

----- Mrk 421 limits,
___ Mrk 501 limits

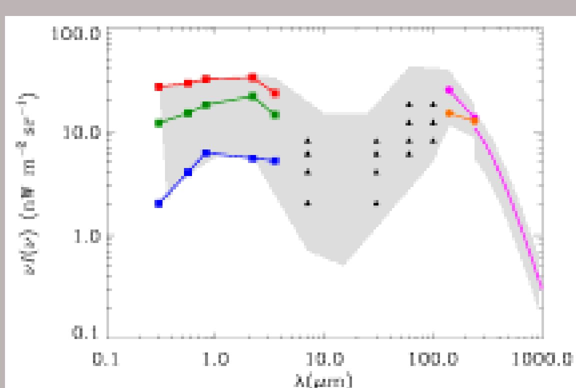
The Intrinsic Spectrum of TeV γ-ray Blazars



- Simultaneous X-ray and γ-ray observations of Mrk 421 and 501 show variability in both energy regimes
  (Catanese & Weekes 1999)
- Readily explained in the framework of the homogeneous synchrotron self-Compton (SSC) model
- Intrinsic spectrum is not a simple power law.
- Comlicates any inference of absorption

Determining the EBL With the Aid of TeV Astronomy

The optical and near-IR spectrum of the EBL is important for determining the location and intensity of the inverse Compton peak in the source spectrum
Guy et al. 2000, A&A, 359, 419



To find the location of the IC peak, one needs to simulate the EBL Spectrum
Dwek & de Jager(2001)

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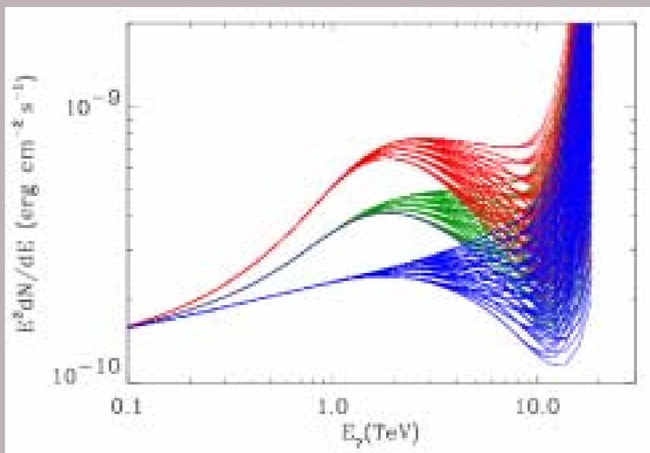
Intrinsic Source Spectra

Intrinsic Mrk 501 spectra calculated for various EBL spectra (Dwek & de Jager 2001)

(H_0 = 70 km/sec/Mpc)



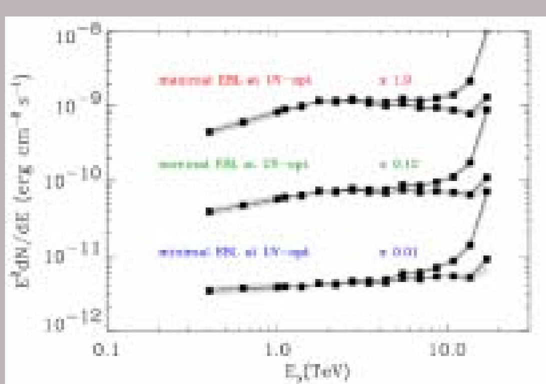
Maximal EBL

Minimal EBL

Nominal EBL

Searching for Allowable CIB Spectra

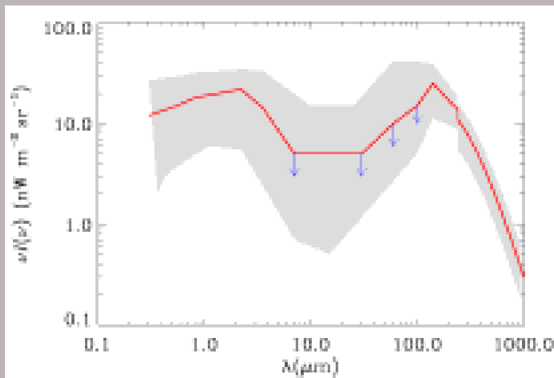
- **Requirement is that the intrinsic source spectrum should not rise beyond a few TeV**
- **This constraints on allowable CIB spectra**



Upper curves were calculated for mid-IR intensities of 6, 6, & 25 nW m^{-2} sr^{-1} at 7, 30, & 60 µm They are regarded as "unphysical".

Lower curves are physically "acceptable" and were calculated for mid-IR intensities of 4, 4, and 10 nW m^{-2} sr^{-1} at 7, 30, and 60 µm

Tentative TeV constraints on the CIB

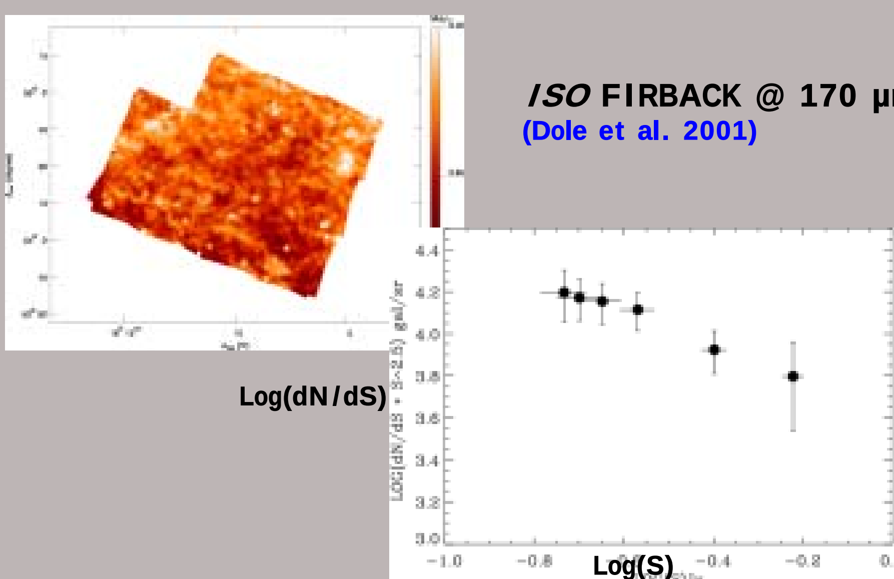


- $\nu I_\nu <$ 4 nW m^{-2} sr^{-1} between 5 - 30 μm
- $\nu I_\nu <$ 8 nW m^{-2} sr^{-1} at ~60 μm

Finkbeiner et al. 60–100 μm residuals are too large to be extragalactic !

Galaxy Number Counts

ISO **FIRBACK @ 170 μm**
(Dole et al. 2001)

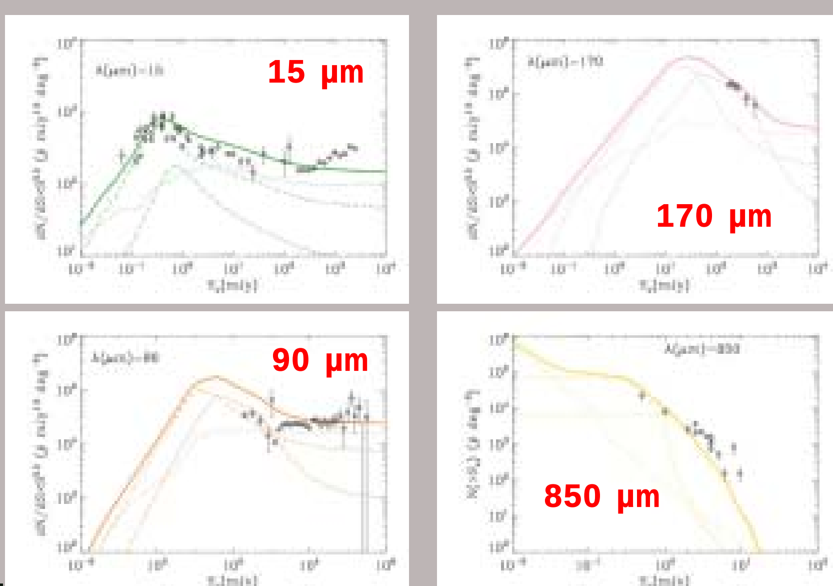


Backward Evolution Models

Extrapolate spectral properties **(SED)** and number densities of galaxies **(luminosity function)** in the local universe to higher redshift using some parametric form for their evolution

The Contribution of Galaxy "Types" to Observed # Counts

(……normal $L < 10^{11} L_{sun}$ ------ LIRGs $L \approx 10^{11-12} L_{sun}$ - . - . - . ULIRGs $L > 10^{12} L_{sun}$)



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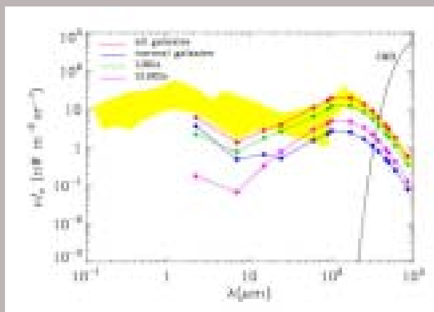
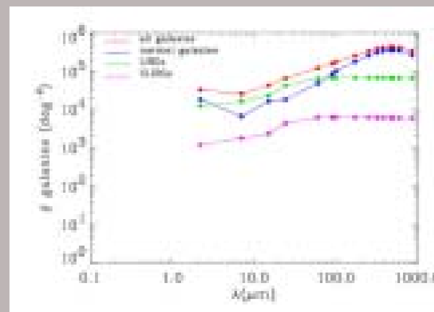
The contribution of various galaxy types to the cosmic IR background (CIB) and galaxy number counts

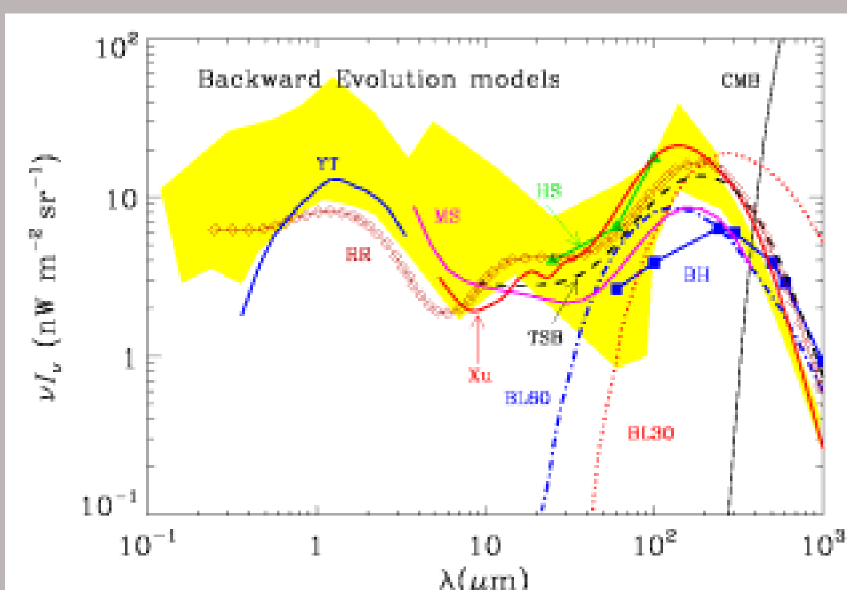
CIB limits and detections from Hauser & Dwek (2001, ARA&A, 39, 249)

Calculations assume that all galaxies in the universe are resolved and contribute to the number counts

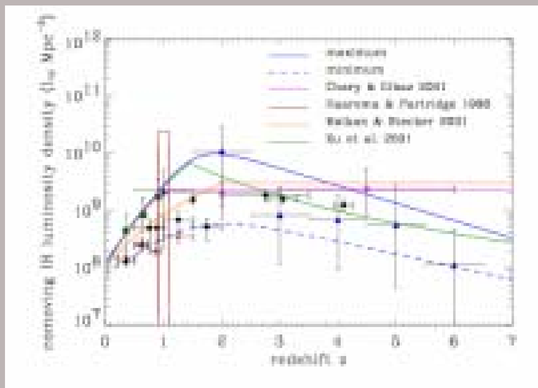




Backwards Evolution Models



Comoving IR Luminosity Density as a Function of Redshift



(Figure 4)

Chary & Elbaz 2001, ApJ, 556, 562

Haarsma & Partridge, 1998, ApJ, 508, L5

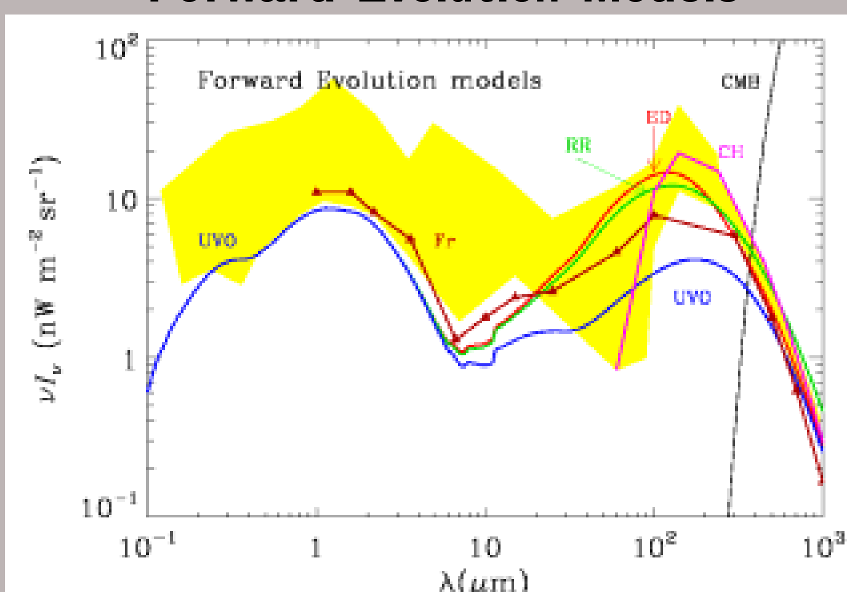
Malkan & Stecker 2001, ApJ, 555,641

Xu et al. 2001, astro-ph/0009220

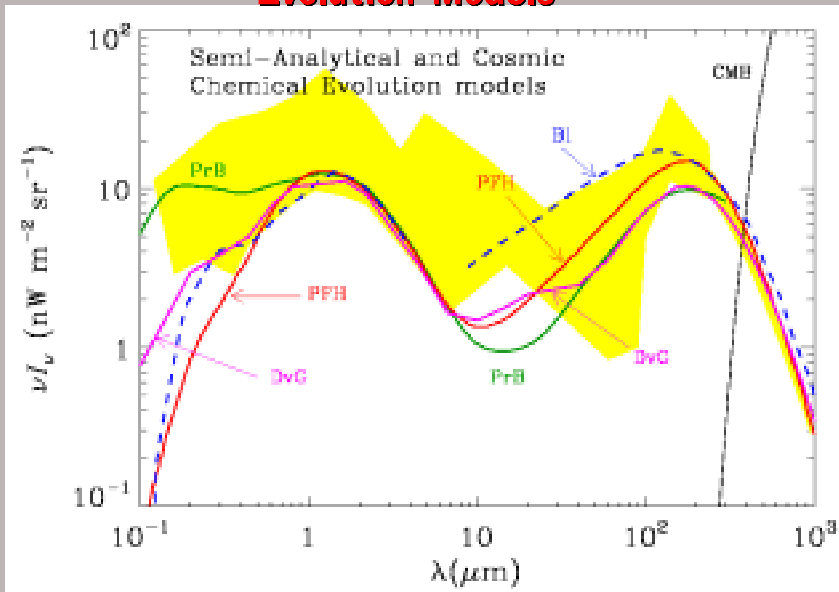
The comoving luminosity density for different cosmic star formation histories is compared to observed cosmic star formation rates (CSFR).

The observed CSFR, ρ_*, was converted to luminosity density, L, using the relation: $L(L_o\ Mpc^{-3}) = 1\times10^{10}\ \rho_*(M_o\ yr^{-1}\ Mpc^{-3})$

Forward Evolution Models



Semi-Analytical and Cosmic Chemical Evolution Models



SUMMARY

- EBL detected at FIR, NIR and UV/opt (?)
- EBL intensity ≈ 100 nW m^{-2} sr^{-1} consistent with the processing of 2–6% of baryonic matter to elements heavier than H
- Galaxies were more dust enshrouded at hi-z
- TeV currently best probe of CIB at mid-IR
- SCUBA resolves about 30–50% of CIB @ 850 μm
- CIB acounts for 50% of the CRB

A tribute to a dusty universe

With apologies to Charles E. Shultz