Using the Cosmic Infrared Background to Deduce Properties of High Redshift Stars

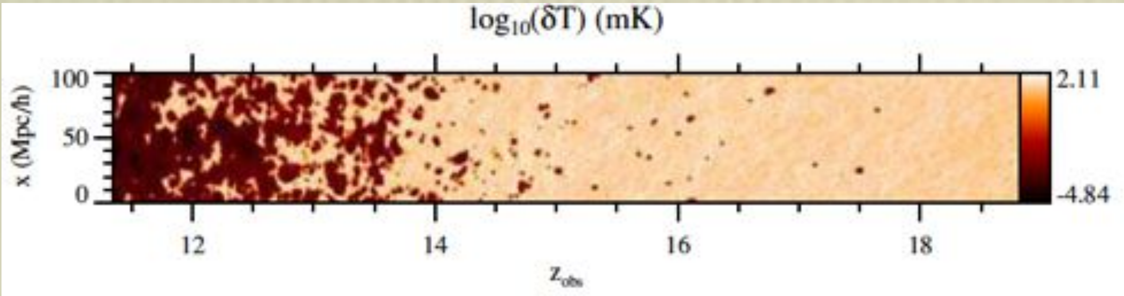
Elizabeth Fernandez
Institut d'Astrophysique Spatiale

with Eiichiro Komatsu (U. Texas / MPA), Paul Shapiro (U. Texas), Ilian Iliev (U. Sussex), Hervé Dole (IAS)

Stars at High Redshift

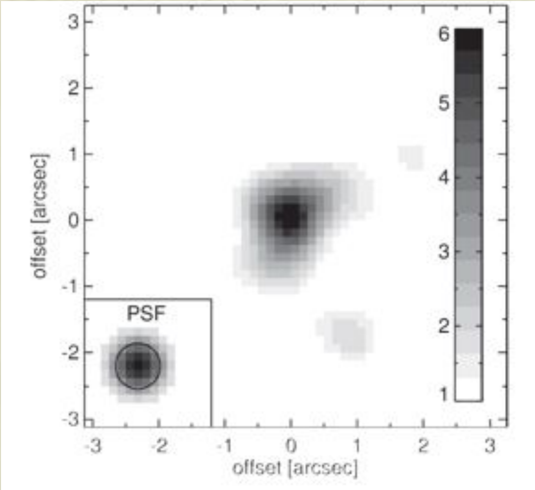
- How are stellar populations different than what we see today? (Pop III to Pop II)
- What are high redshift galaxies like?
- Why are they are important?
  - Understand reionization history
  - Understand metal enrichment

How to Observe the EoR



Mellema et al. 2006

- 21 cm line -
    - Great probe for pre-reionization
    - 3D map of neutral hydrogen
- High redshift galaxy surveys
    - Direct observation of galaxies
    - Biased - small fraction of bright, common objects



LAE at z~8.6, Lehnert et al. 2010

The Cosmic Infrared Background

- Integrated light from all of high redshift star formation
- A complimentary observable
  - Complimentary to the 21 cm line - probes later stages of reionization
  - Complimentary to high redshift galaxy surveys - probes the population as a whole

Dissecting the CIB

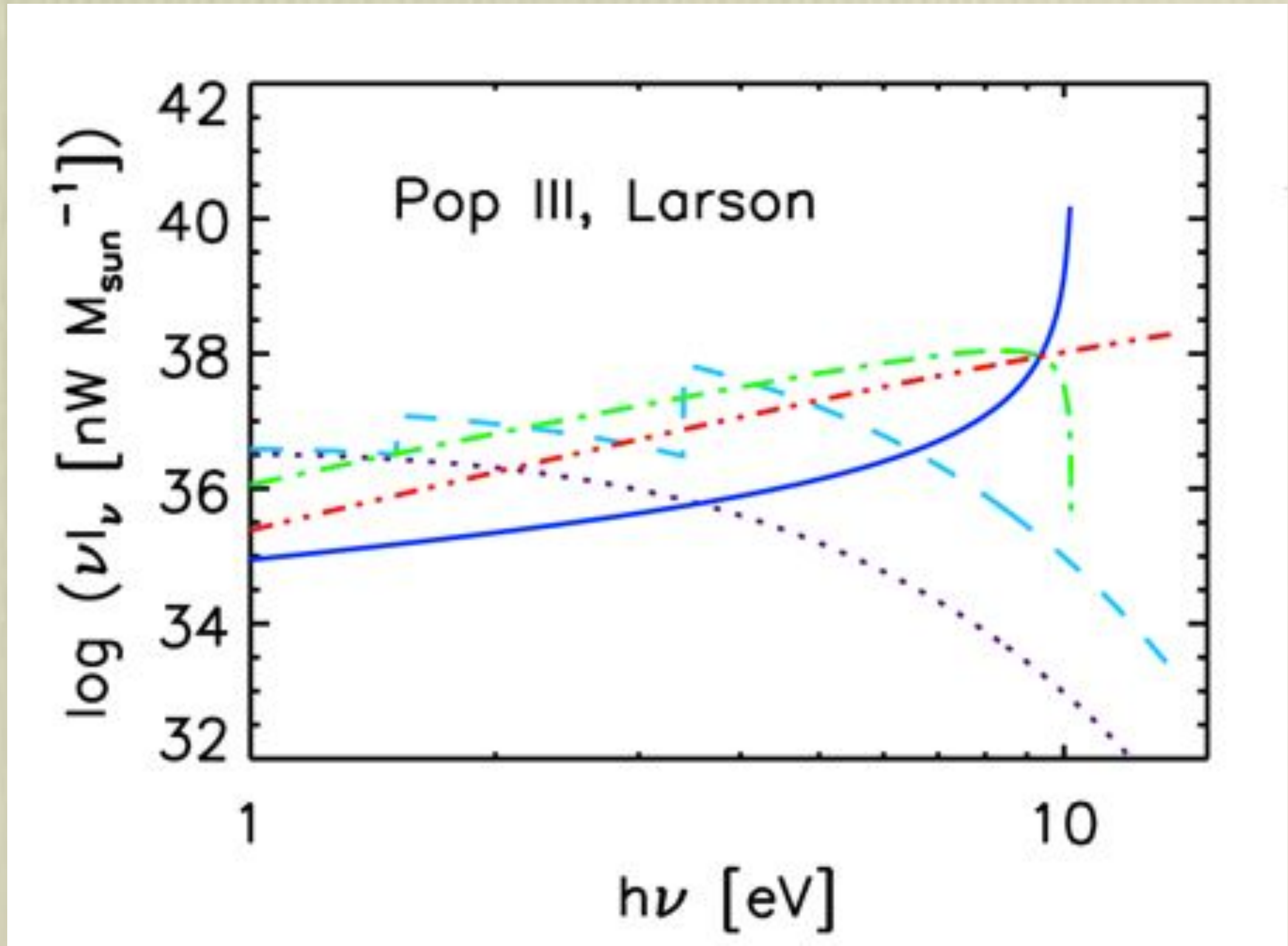
- The pieces
  - The properties of STARS themselves
  - The properties of GALAXIES
  - The NUMBER of stars forming
  - WHERE the light is reprocessed
  - HOW the light is reprocessed

The Tools

- Analytical formulae

Stellar Properties:

- Mass
- Metallicity



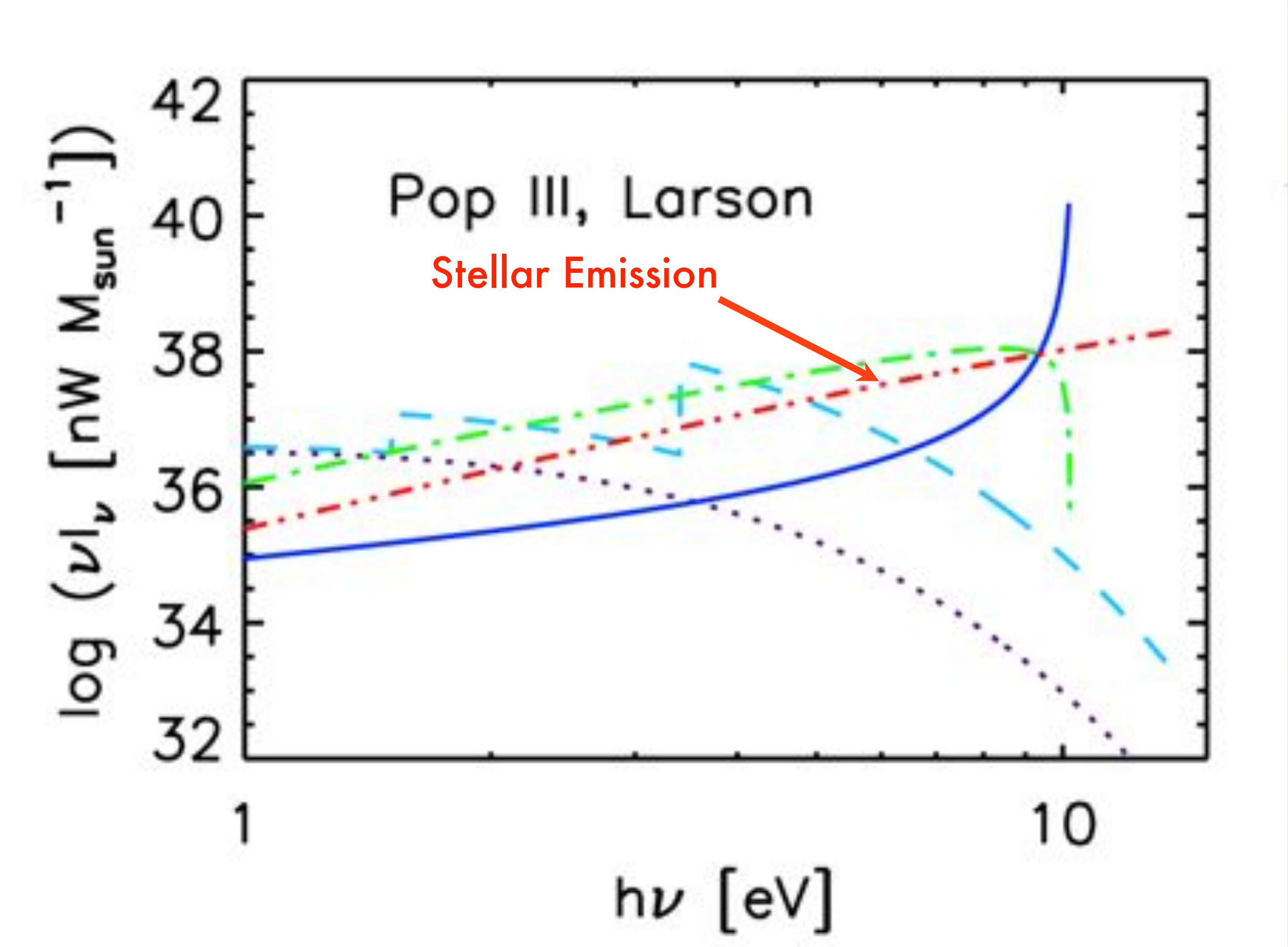
Fernandez et al 2010

The Tools

- Analytical formulae

Stellar Properties:

- Mass
- Metallicity



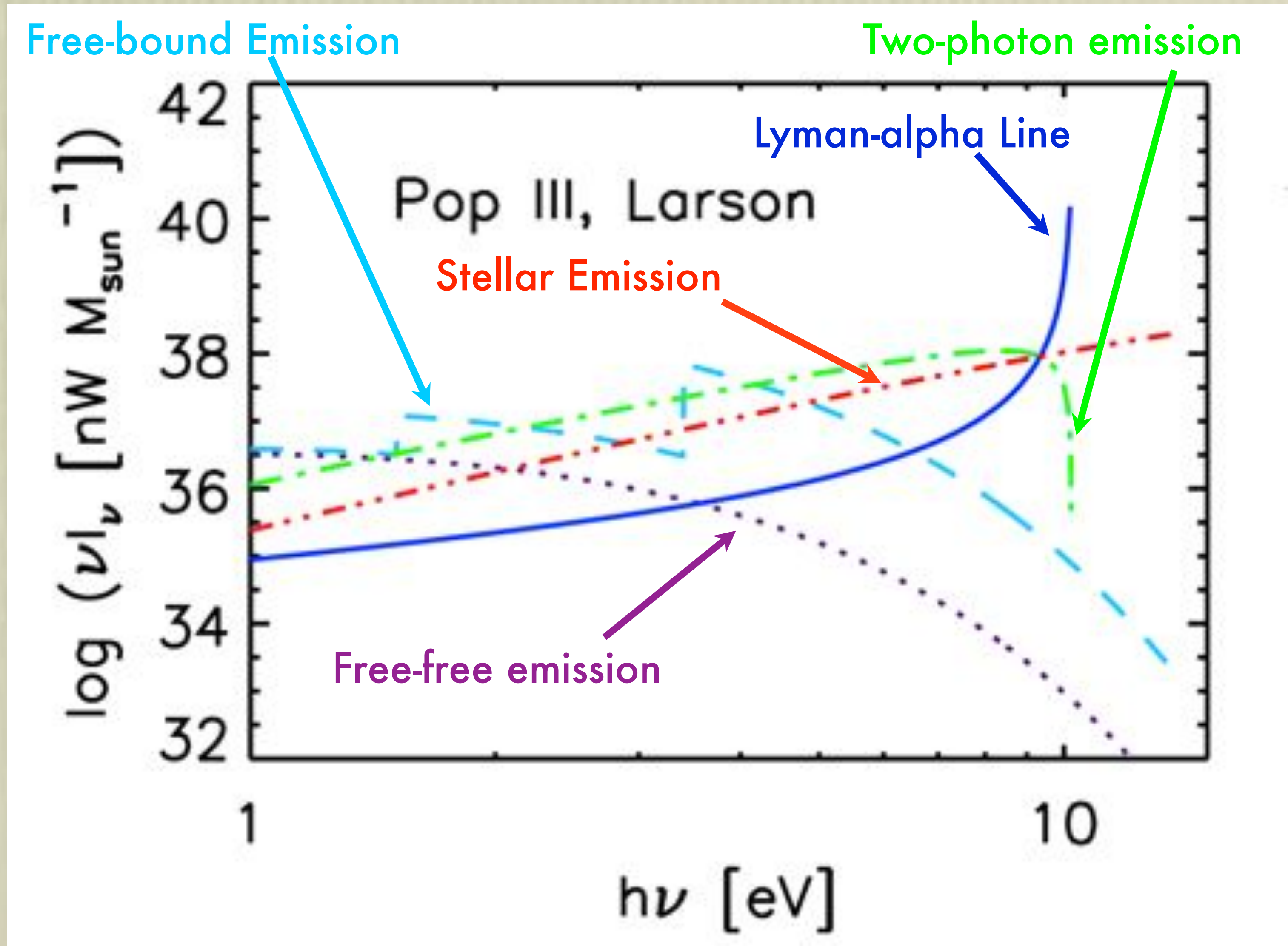
Fernandez et al 2010

The Tools

- Analytical formulae

Stellar Properties:

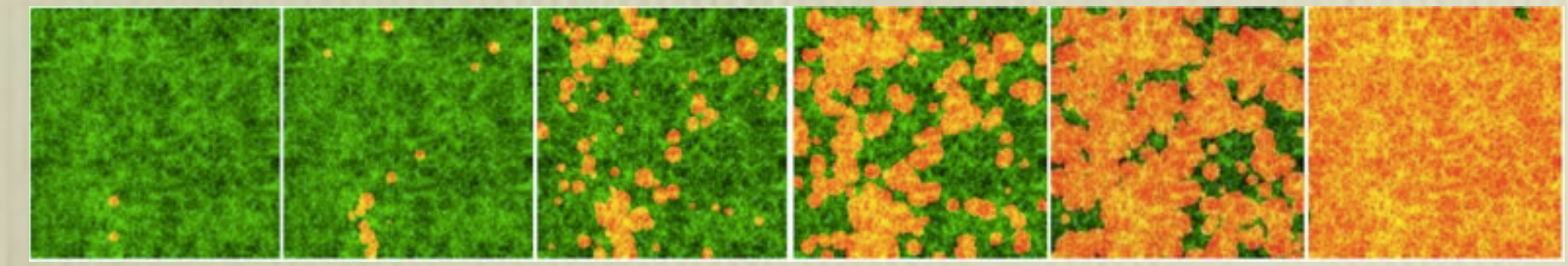
- Mass
- Metallicity



Fernandez et al 2010

The Tools

- Analytical formulae
- The simulations
  - N-body code with radiative transfer (Iliev et al. 2006, 2007, 2011)
  - Two simulations (M_{min} = 2 x 10^9 or 10^8 $M_\odot$)



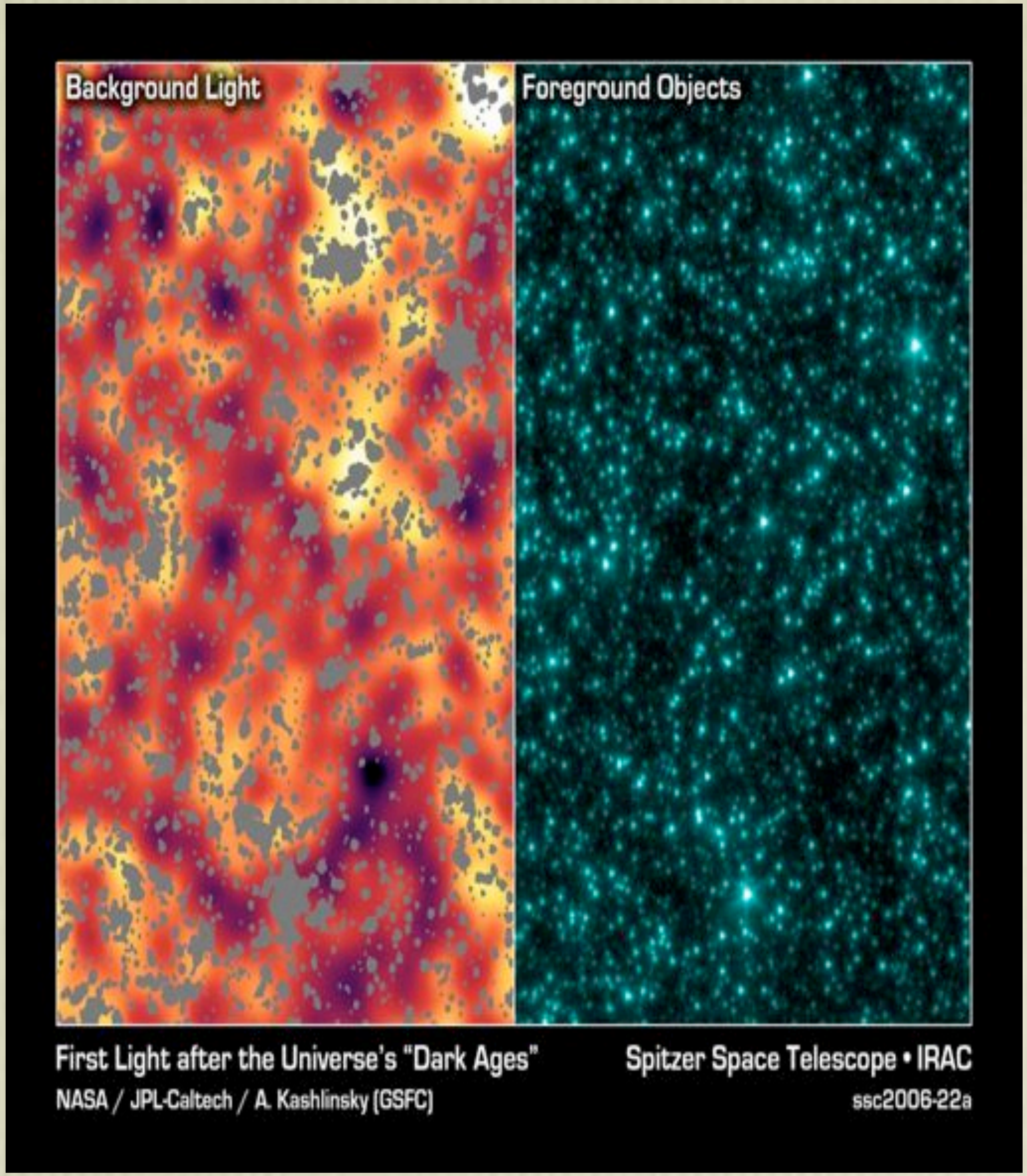
Modeling the Observables

- Mean CIB
  - Luminosity independent of location

$$I = \frac{c}{4\pi}\left(f_* \frac{\Omega_b}{\Omega_m}\right) \int \frac{dz}{H(z)(1+z)} \bar{\rho}_M^{halo}(z) \times \left[\bar{l}^*(z) + \bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

- Fluctuation power
  - Information on structures

$$C_l = \frac{c}{(4\pi)^2}\left(f_* \frac{\Omega_b}{\Omega_m}\right)^2 \int \frac{dz}{H(z) r^2(z)(1+z)^4} \times \left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z) + (1 - f_{\mathrm{esc}})\bar{L}(z)\right\}\right]^2 \times b_{eff}^2\left(k = \frac{l}{r(z)}, z\right) P_{\mathrm{lin}}\left(k = \frac{l}{r(z)}, z\right)$$



Modeling the Observables

- Mean CIB
    - Luminosity independent of location

$$I = \frac{c}{4\pi}\left(f_* \frac{\Omega_b}{\Omega_m}\right)\int \frac{dz}{H(z)(1+z)} \bar{\rho}_M^{halo}(z) \times \left[\bar{l}^*(z) + \bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

- Fluctuation power
    - Information on structures

$$C_l = \frac{c}{(4\pi)^2}\left(f_* \frac{\Omega_b}{\Omega_m}\right)^2 \int \frac{dz}{H(z) r^2(z)(1+z)^4} \times \left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z) + (1-f_{\mathrm{esc}})\bar{L}(z)\right\}\right]^2 \times b_{eff}^2\left(k = \frac{l}{r(z)}, z\right) P_{\mathrm{lin}}\left(k = \frac{l}{r(z)}, z\right)$$

- The pieces
    - The properties of STARS themselves
    - The properties of GALAXIES
    - The NUMBER of stars forming
    - WHERE the light is reprocessed
    - HOW the light is reprocessed

Modeling the Observables

- Mean CIB
  - Luminosity independent of location

$$I = \frac{c}{4\pi}\left(f_*\frac{\Omega_b}{\Omega_m}\right)\int \frac{dz}{H(z)(1+z)}\bar{\rho}_M^{halo}(z) \times \left[\bar{l}^*(z) + \bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

- Fluctuation power
  - Information on structures

$$C_l = \frac{c}{(4\pi)^2}\left(f_*\frac{\Omega_b}{\Omega_m}\right)^2\int \frac{dz}{H(z)r^2(z)(1+z)^4} \times \left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z) + (1-f_{\mathrm{esc}})\bar{L}(z)\right\}\right]^2 \times b_{eff}^2\left(k=\frac{l}{r(z)},z\right)P_{\mathrm{lin}}\left(k=\frac{l}{r(z)},z\right)$$

- The pieces
  - The properties of STARS themselves
  - The properties of GALAXIES
  - The NUMBER of stars forming
  - WHERE the light is reprocessed
  - HOW the light is reprocessed

Modeling the Observables

- Mean CIB
  - Luminosity independent of location

$$I = \frac{c}{4\pi}\left(f_*\frac{\Omega_b}{\Omega_m}\right)\int \frac{dz}{H(z)(1+z)}\bar{\rho}_M^{halo}(z) \times \left[\bar{l}^*(z) + \bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

- Fluctuation power
  - Information on structures

$$C_l = \frac{c}{(4\pi)^2}\left(f_*\frac{\Omega_b}{\Omega_m}\right)^2\int \frac{dz}{H(z)r^2(z)(1+z)^4} \times \left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z) + (1-f_{\mathrm{esc}})\bar{L}(z)\right\}\right]^2 \times b_{eff}^2\left(k=\frac{l}{r(z)}, z\right) P_{\mathrm{lin}}\left(k=\frac{l}{r(z)}, z\right)$$

- The pieces
  - The properties of STARS themselves
  - The properties of GALAXIES
  - The NUMBER of stars forming
  - WHERE the light is reprocessed
  - HOW the light is reprocessed

Modeling the Observables

- Mean CIB
    - Luminosity independent of location

$$I = \frac{c}{4\pi}\left(f_* \frac{\Omega_b}{\Omega_m}\right) \int \frac{dz}{H(z)(1+z)} \bar{\rho}_M^{halo}(z) \times \left[\bar{l}^*(z) + \bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

- Fluctuation power
    - Information on structures

$$C_l = \frac{c}{(4\pi)^2}\left(f_* \frac{\Omega_b}{\Omega_m}\right)^2 \int \frac{dz}{H(z) r^2(z)(1+z)^4} \times \left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z) + (1-f_{\mathrm{esc}})\bar{L}(z)\right\}\right]^2 \times b_{eff}^2\left(k = \frac{l}{r(z)}, z\right) P_{\mathrm{lin}}\left(k = \frac{l}{r(z)}, z\right)$$

- The pieces
    - The properties of STARS themselves
    - The properties of GALAXIES
    - The NUMBER of stars forming
    - WHERE the light is reprocessed
    - HOW the light is reprocessed

Stellar properties

Population II
stars

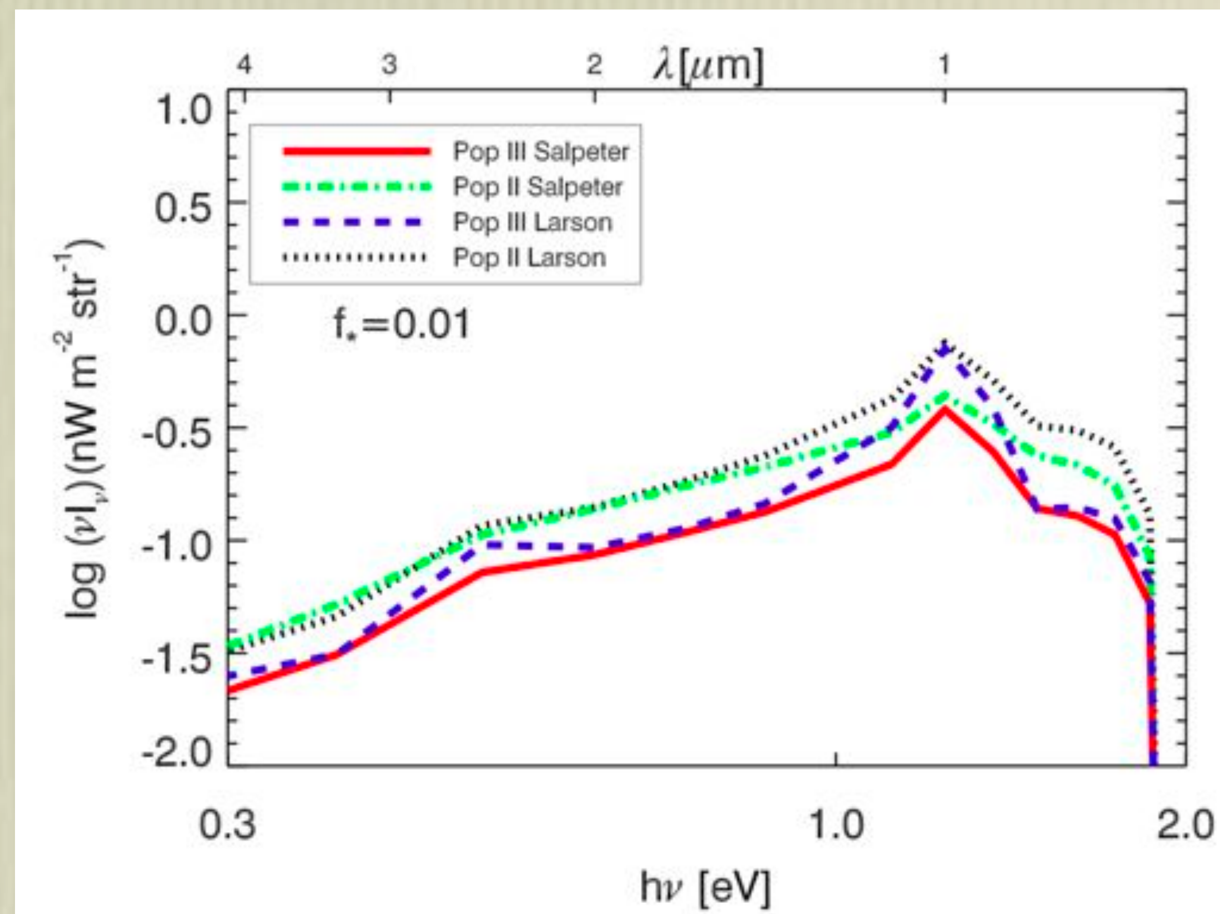
“Normal”
Salpeter IMF

Stellar properties

Population II stars

“Normal” Salpeter IMF

- Mean CIB
  - Shape changes only slightly
  - Conservation of energy! (Pop III heavy stars have more ionizing photons => more nebular emission, but less stellar emission



Fernandez, Komatsu, Iliev, Shapiro 2010

$$I = \frac{c}{4\pi}\left(f_* \frac{\Omega_b}{\Omega_m}\right) \int \frac{dz}{H(z)(1+z)} \bar{\rho}_M^{halo}(z) \times \left[\bar{l}^*(z) + \bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

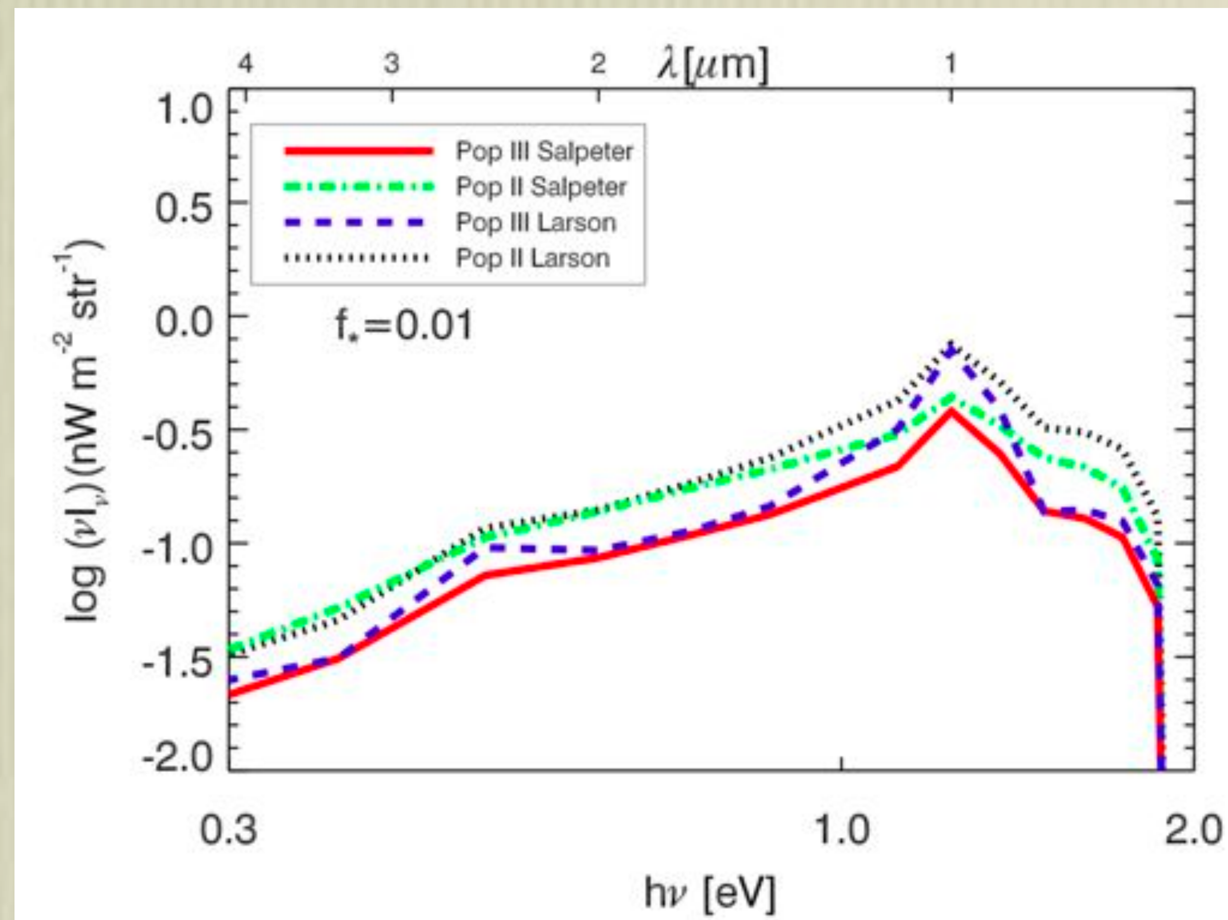
Stellar properties

Population II
stars

“Normal”
Salpeter IMF

- Mean CIB does not depend strongly on our assumptions of stellar properties

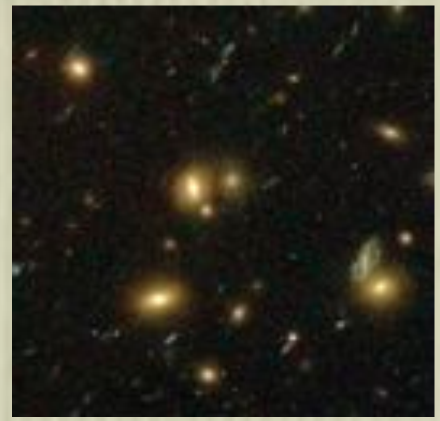
- Fluctuation analysis is degenerate with respect to stellar properties



Fernandez, Komatsu, Iliev, Shapiro 2010

Galactic properties

Massive Galaxies Only (> 10^9 $M_\odot$)

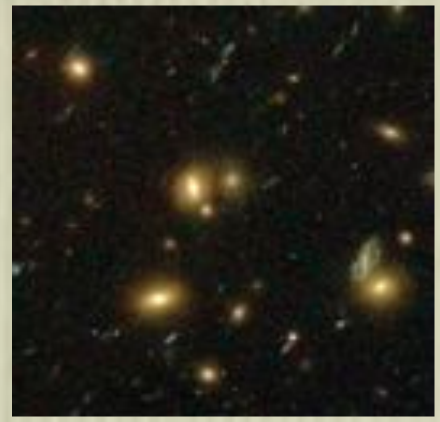


Small & Large Galaxies (> 10^8 $M_\odot$)

Small Galaxies Suppressed

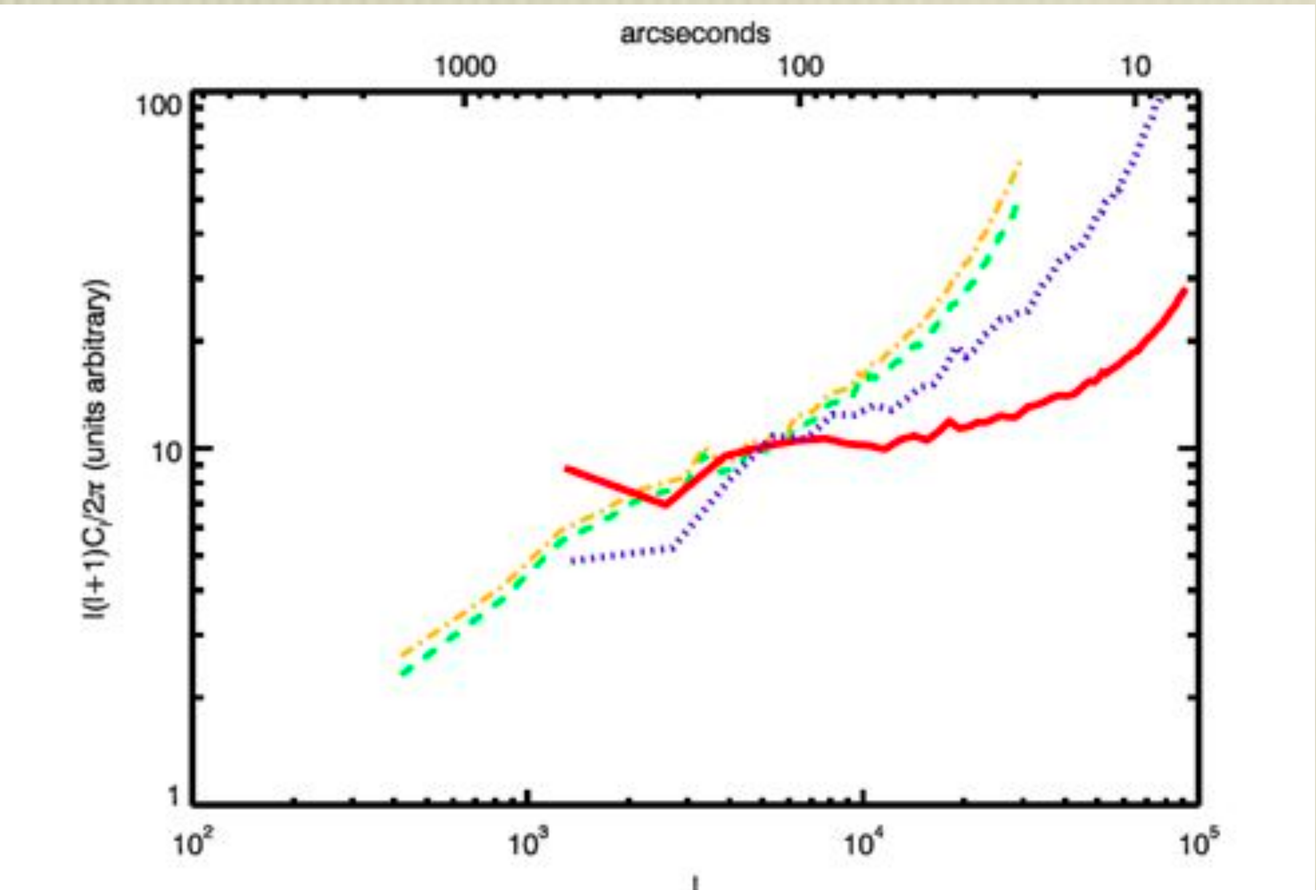
Galactic properties

Massive Galaxies Only (> 10^9 $M_\odot$)



Small & Large Galaxies (> 10^8 $M_\odot$)

Small Galaxies Suppressed

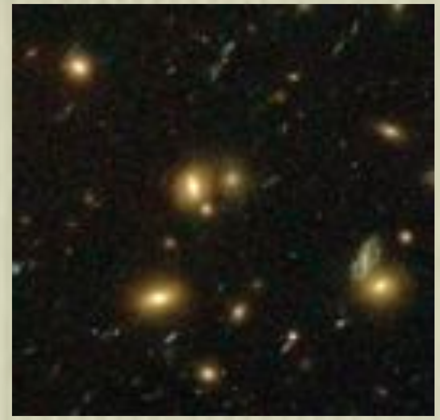


$$C_l = \frac{c}{(4\pi)^2}\left(f_*\frac{\Omega_b}{\Omega_m}\right)^2 \int \frac{dz}{H(z)r^2(z)(1+z)^4} \times \left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z) + (1-f_{\rm esc})\bar{L}(z)\right\}\right]^2 \times b_{eff}^2\left(k=\frac{l}{r(z)}, z\right) P_{\rm lin}\left(k=\frac{l}{r(z)}, z\right)$$

Fernandez, Iliev, Komatsu, Shapiro 2012

Galactic properties

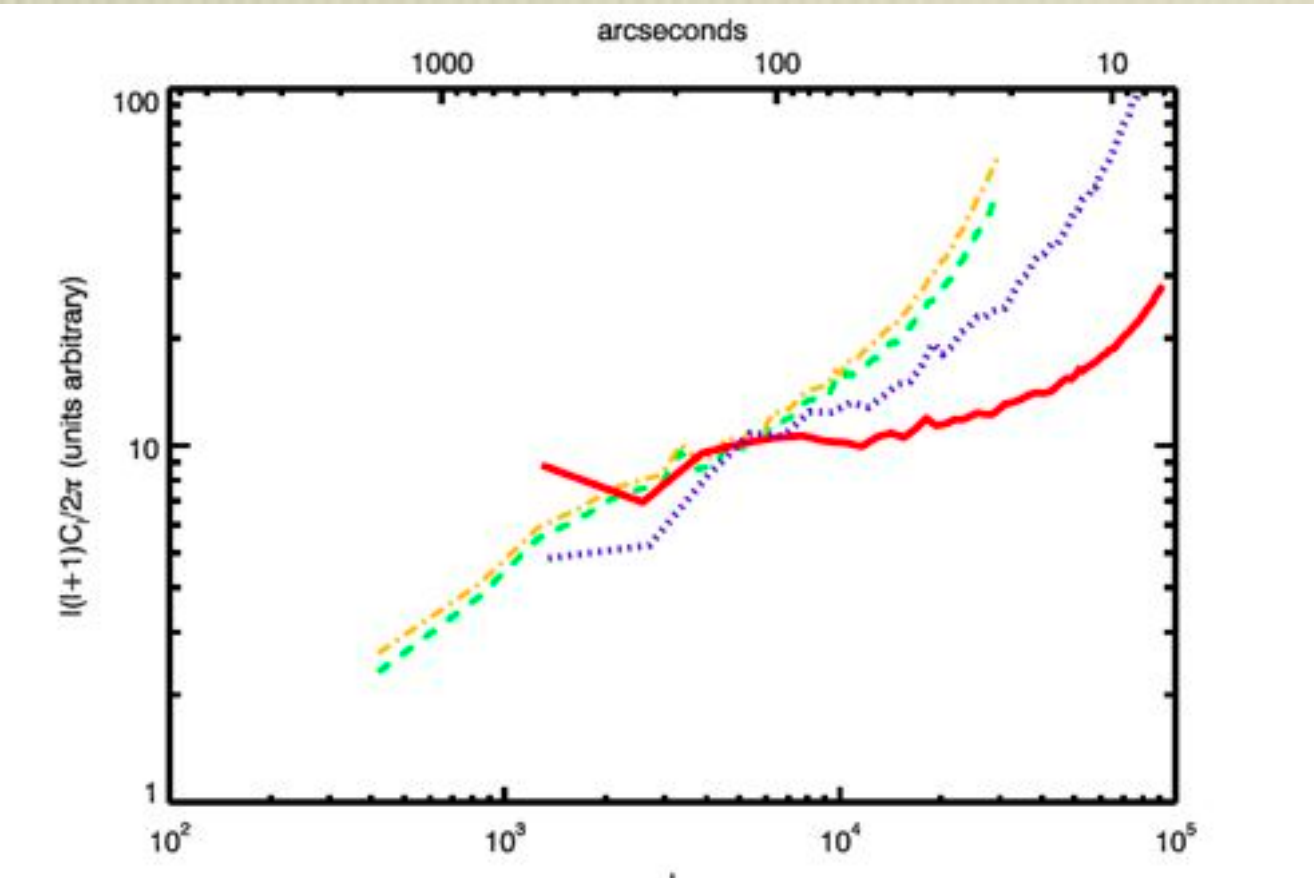
Massive Galaxies Only (> 10^9 $M_\odot$)



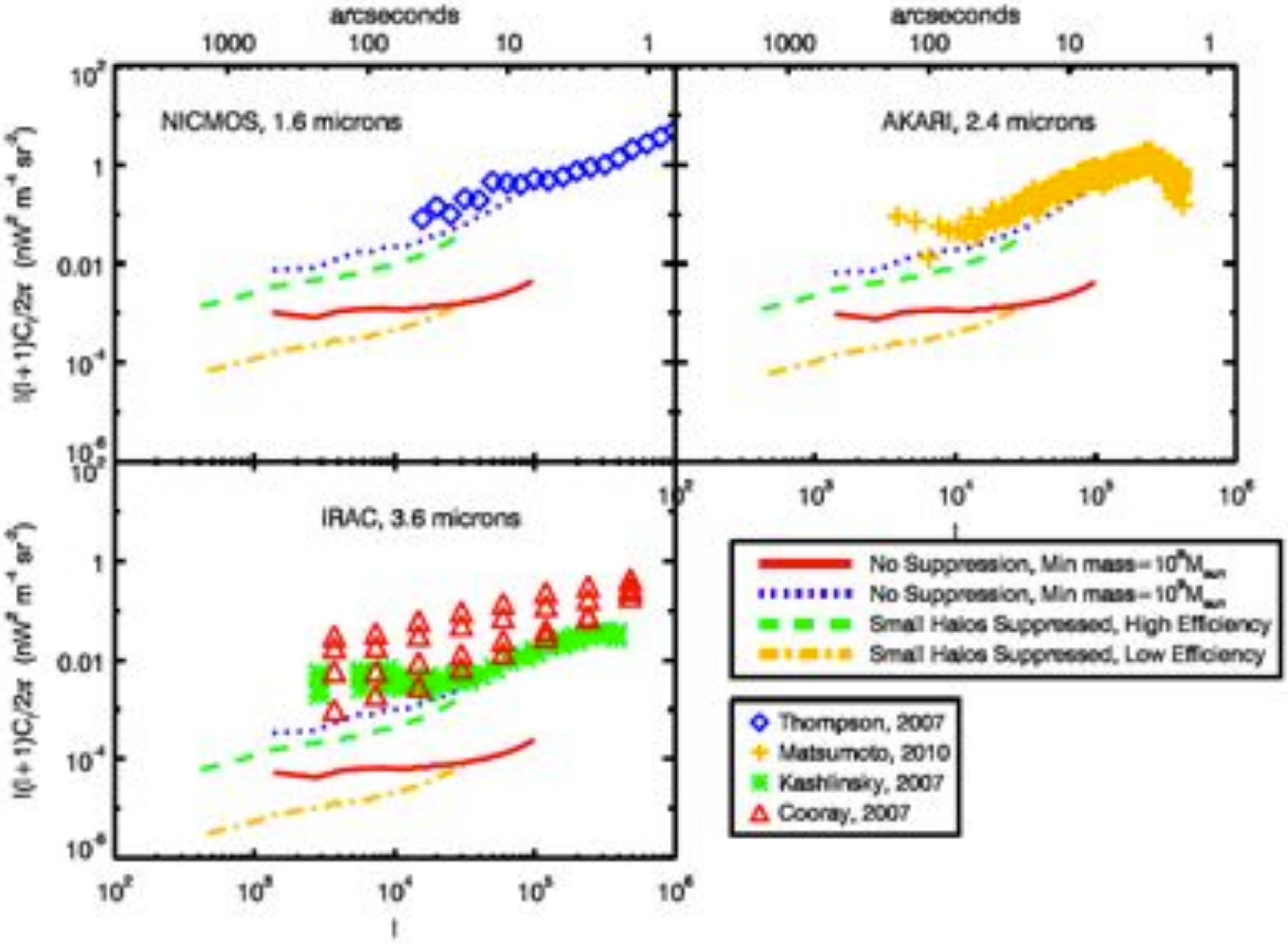
Small & Large Galaxies (> 10^8 to 10^9 $M_\odot$)

Small Galaxies Suppressed

- Bias is strongly dependent on minimum halo mass and suppression history
- Non-linear bias is very large at large l!
- Steepest for high minimum mass, suppression
- We never see a turnover

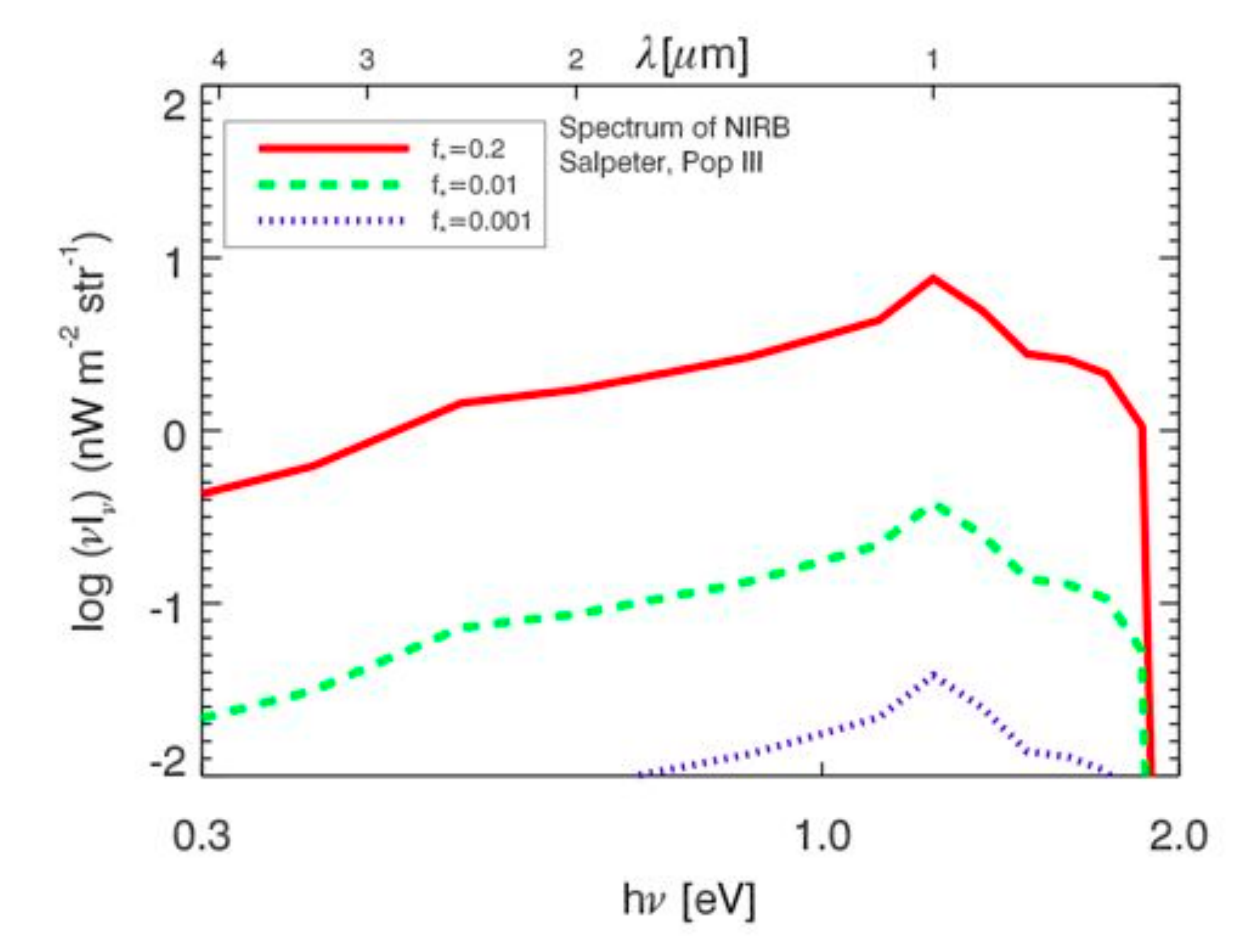


Fernandez, Iliev, Komatsu, Shapiro 2012


arcseconds
1000
100
10
1
NICMOS, 1.6 microns
AKARI, 2.4 microns
IRAC, 3.6 microns
$l(l+1)C_l/2\pi$ (nW^2 m^{-4} sr^{-2})
10^2
1
0.01
10^{-4}
10^{-6}
10^3
10^4
10^5
10^6
l
No Suppression, Min mass=10^8M$_{sun}$
No Suppression, Min mass=10^5M$_{sun}$
Small Halos Suppressed, High Efficiency
Small Halos Suppressed, Low Efficiency
Thompson, 2007
Matsumoto, 2010
Kashlinsky, 2007
Cooray, 2007

Star Formation Rate

- Mean very sensitive to f_*
- Current observations can rule out large values of f_*
- Fluctuations don't add much - dependence on f_* degenerate



Fernandez, Komatsu, Iliev, Shapiro 2010

$$I = \frac{c}{4\pi}\left(f_*\frac{\Omega_b}{\Omega_m}\right)\int \frac{dz}{H(z)(1+z)}\bar{\rho}_M^{halo}(z)$$
$$\times\left[\bar{l}^*(z)+\bar{l}^{ff}(z)+\bar{l}^{fb}(z)+\bar{l}^{2\gamma}(z)+\bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

Extracting More Information

The Mean CIB

$$I = \frac{c}{4\pi}\left(f_*\frac{\Omega_b}{\Omega_m}\right)\int \frac{dz}{H(z)(1+z)}\bar{\rho}_M^{halo}(z) \times \left[\bar{l}^*(z) + \bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

The Fluctuations of the CIB

$$C_l = \frac{c}{(4\pi)^2}\left(f_*\frac{\Omega_b}{\Omega_m}\right)^2\int \frac{dz}{H(z)r^2(z)(1+z)^4} \times \left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z) + (1-f_{\mathrm{esc}})\bar{L}(z)\right\}\right]^2 \times b_{eff}^2\left(k=\frac{l}{r(z)},z\right)P_{\mathrm{lin}}\left(k=\frac{l}{r(z)},z\right)$$

Extracting More Information

The Mean CIB

$$I = \frac{c}{4\pi}\left(f_*\frac{\Omega_b}{\Omega_m}\right)\int \frac{dz}{H(z)(1+z)}\bar{\rho}_M^{halo}(z)$$
$$\times\left[\bar{l}^*(z)+\bar{l}^{ff}(z)+\bar{l}^{fb}(z)+\bar{l}^{2\gamma}(z)+\bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

The Fluctuations of the CIB

$$C_l = \frac{c}{(4\pi)^2}\left(f_*\frac{\Omega_b}{\Omega_m}\right)^2\int \frac{dz}{H(z)r^2(z)(1+z)^4}$$
$$\times\left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z)+(1-f_{\mathrm{esc}})\bar{L}(z)\right\}\right]^2$$
$$\times b_{eff}^2\left(k=\frac{l}{r(z)},z\right)P_{\mathrm{lin}}\left(k=\frac{l}{r(z)},z\right)$$

Both depend on:
f_*
Luminosity

Extracting More Information

The Mean CIB

$$I = \frac{c}{4\pi}\left(f_*\frac{\Omega_b}{\Omega_m}\right)\int \frac{dz}{H(z)(1+z)}\bar{\rho}_M^{halo}(z)$$
$$\times\left[\bar{l}^*(z)+\bar{l}^{ff}(z)+\bar{l}^{fb}(z)+\bar{l}^{2\gamma}(z)+\bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

The Fluctuations of the CIB

$$C_l = \frac{c}{(4\pi)^2}\left(f_*\frac{\Omega_b}{\Omega_m}\right)^2\int \frac{dz}{H(z)r^2(z)(1+z)^4}$$
$$\times\left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z)+(1-f_{\mathrm{esc}})\bar{L}(z)\right\}\right]^2$$
$$\times b_{eff}^2\left(k=\frac{l}{r(z)},z\right)P_{\mathrm{lin}}\left(k=\frac{l}{r(z)},z\right)$$

Both depend on:
f_*
Luminosity

$$\delta I/I \equiv \sqrt{l(l+1)C_l/(2\pi I^2)}$$

Find the Fractional Anisotropy

Extracting More Information

The Mean CIB

$$I = \frac{c}{4\pi}\left(f_* \frac{\Omega_b}{\Omega_m}\right) \int \frac{dz}{H(z)(1+z)} \bar{\rho}_M^{halo}(z) \times \left[\bar{l}^*(z) + \bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\mathrm{Ly}\alpha}(z)\right]$$

The Fluctuations of the CIB

$$C_l = \frac{c}{(4\pi)^2}\left(f_* \frac{\Omega_b}{\Omega_m}\right)^2 \int \frac{dz}{H(z) r^2(z)(1+z)^4} \times \left[\bar{\rho}_M^{halo}(z)\left\{\bar{l}^*(z) + (1 - f_{\mathrm{esc}})\bar{L}(z)\right\}\right]^2 \times b_{eff}^2\left(k = \frac{l}{r(z)}, z\right) P_{\mathrm{lin}}\left(k = \frac{l}{r(z)}, z\right)$$

Both depend on:
f_*
Luminosity

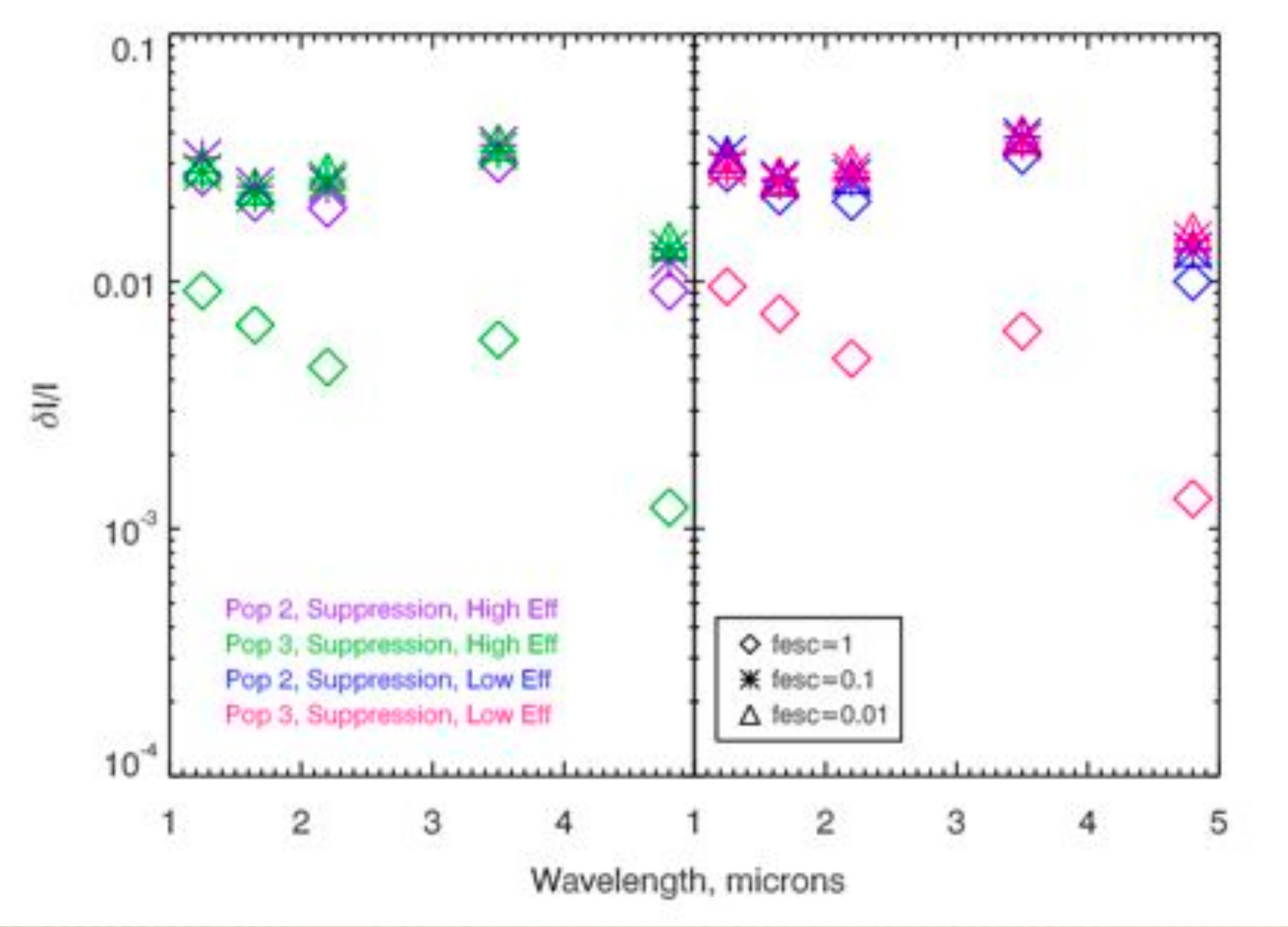
$$\delta I / I \equiv \sqrt{l(l+1) C_l / (2\pi I^2)}$$

Find the Fractional Anisotropy

Everything but f_{esc} nearly cancels out

The Escape Fraction

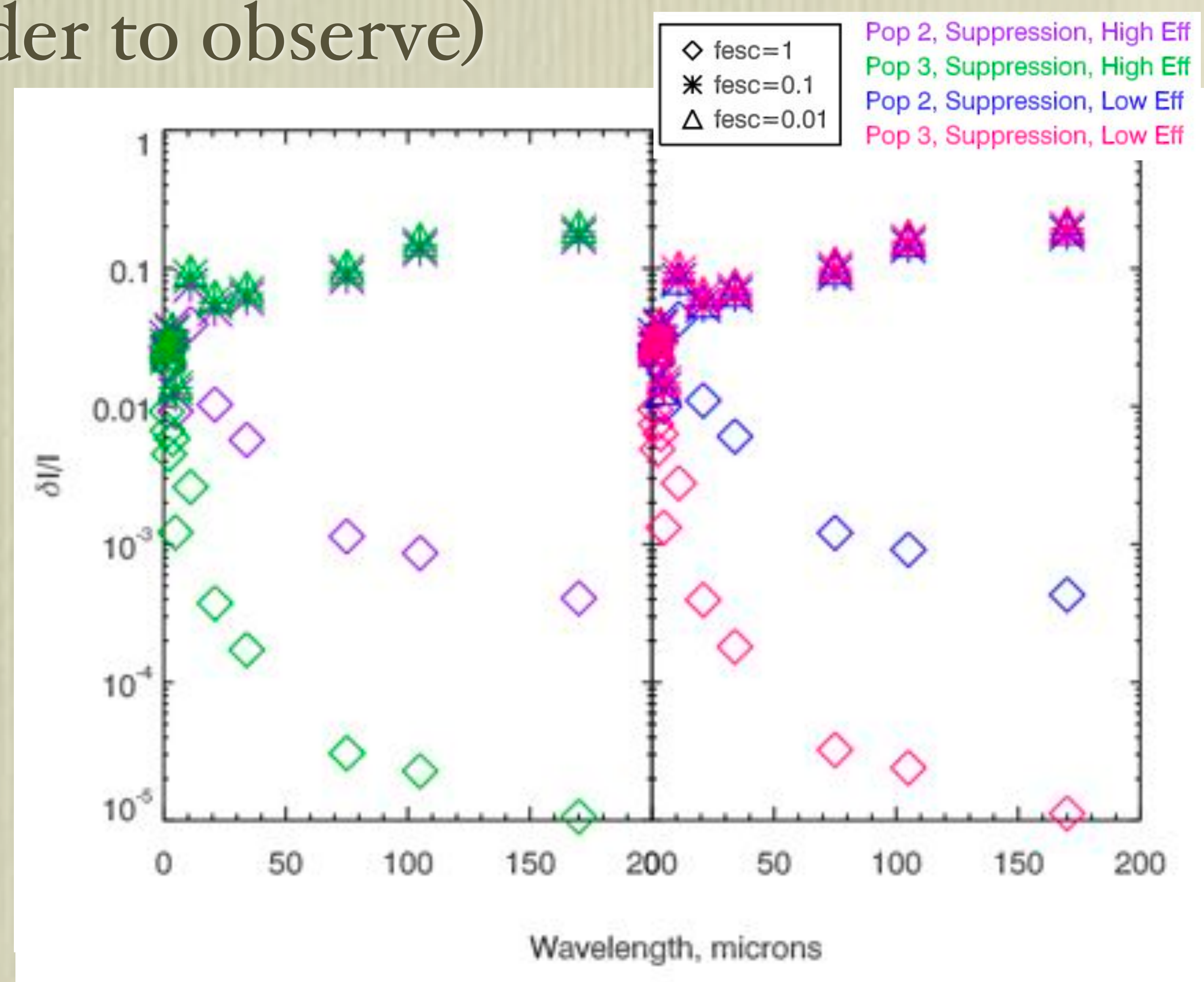
- Fractional Anisotropy taken at l-3000 (non-linear bias is not a factor between galactic populations)
- High values of the escape fraction with Pop III stars lead to lower values of δI/I



Fernandez, Dole, Iliev 2012

The Escape Fraction

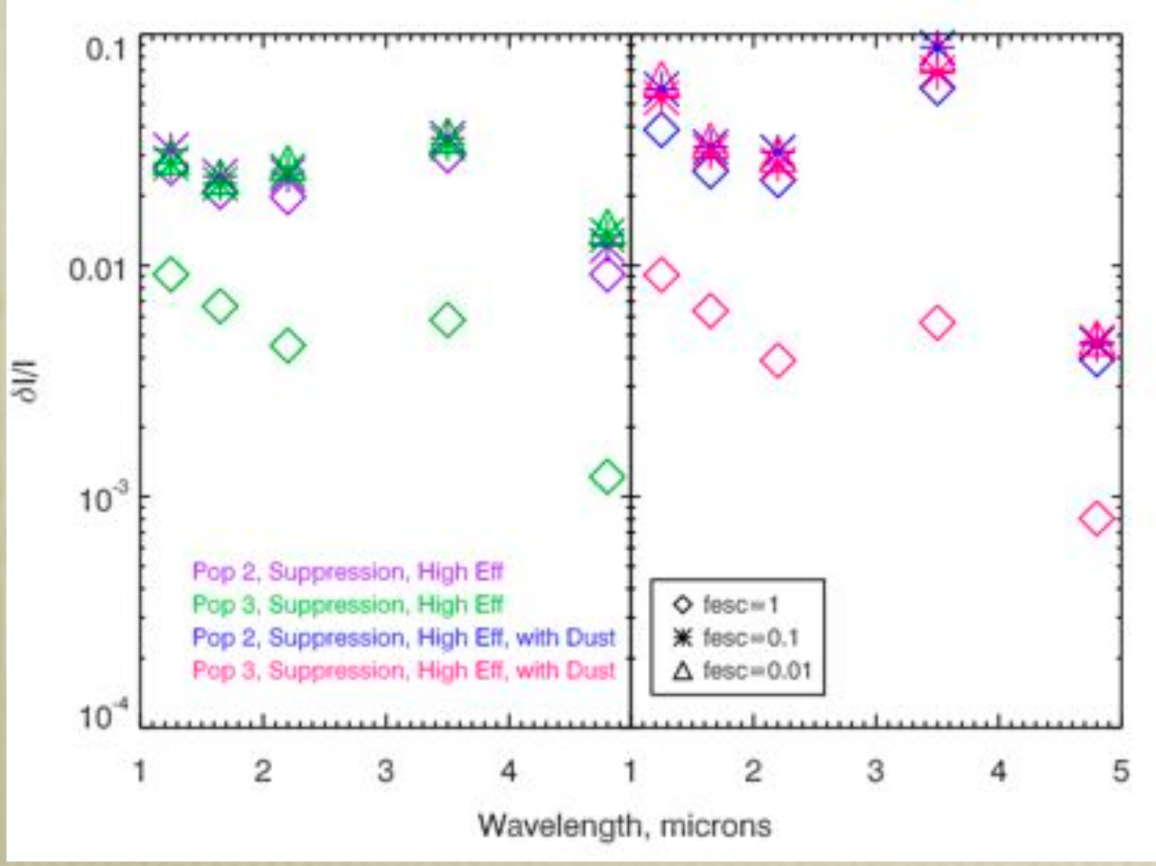
- This is seen more clearly at longer wavelengths (even though harder to observe)
- High values of the escape fraction with any population lead to lower values of δI/I

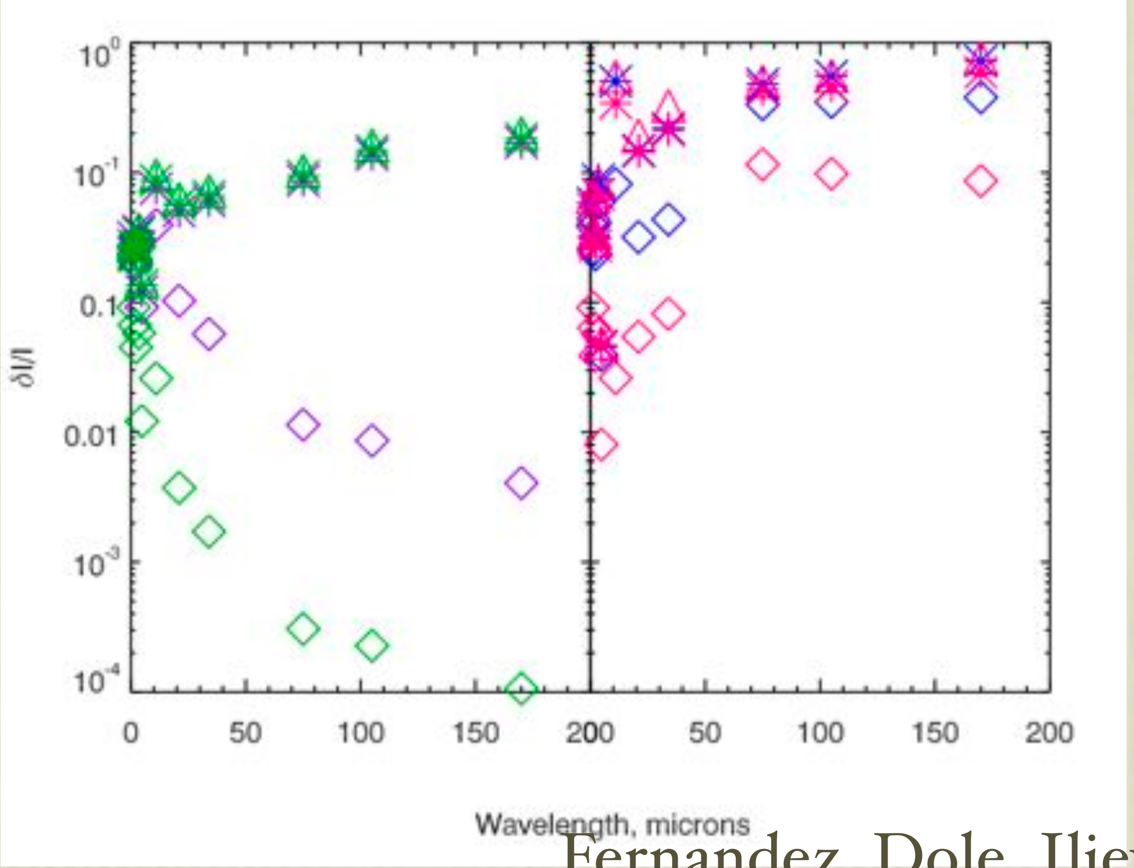


Fernandez, Dole, Iliev 2012

The Addition of Dust

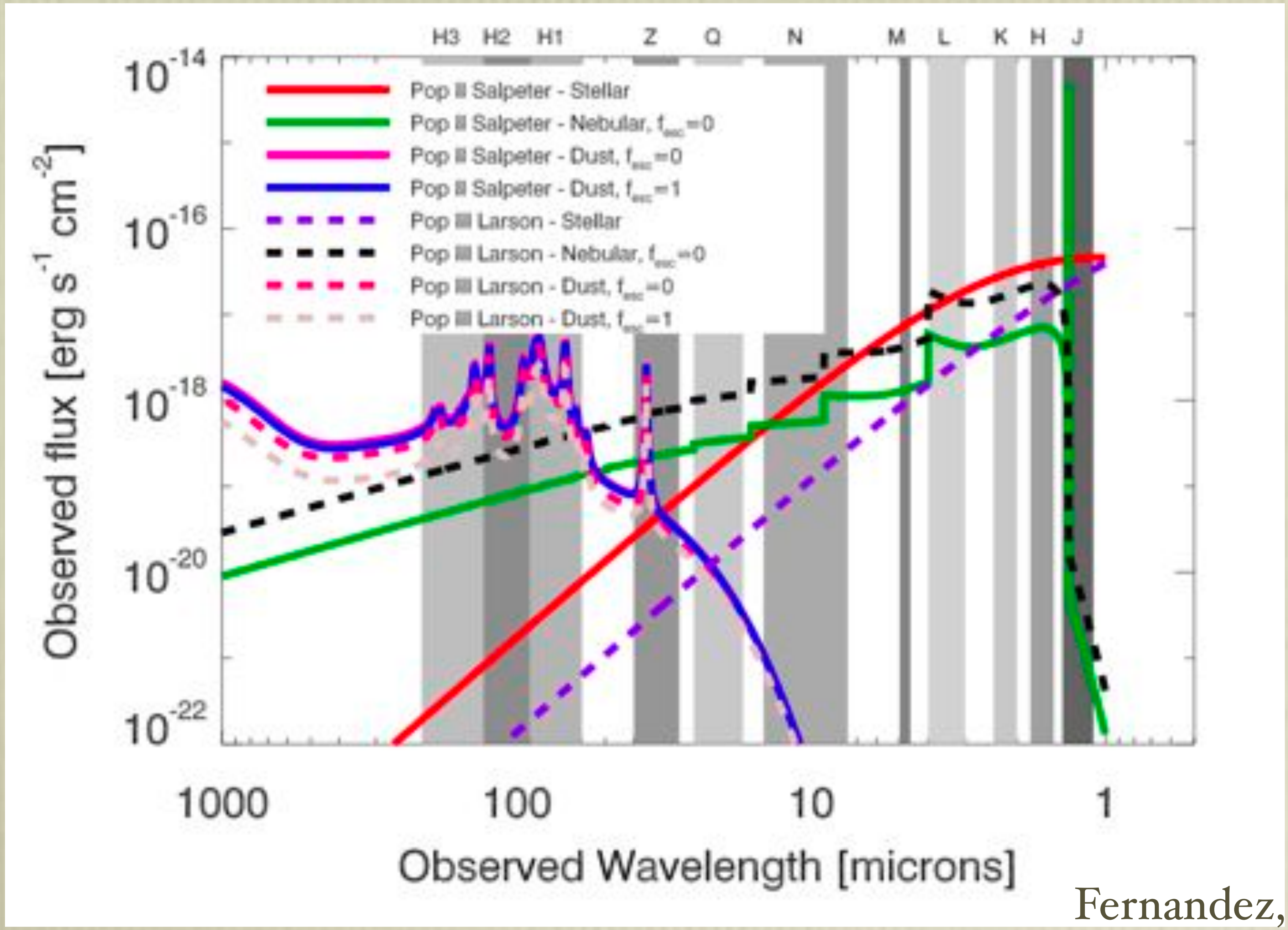
- Dust further changes the picture
  - Higher δI/I at long λ
  - Leaves its own distinct signature





Fernandez, Dole, Iliev 2012

- When f_{esc} low, nebular emission present within the halo at long wavelengths (that will affect the angular power spectrum)
- If f_{esc} high, nebular component disappears
- Dust adds emission at long wavelengths, mostly unaffected by f_{esc}
- Mean does not change with f_{esc}



Fernandez, Dole, Iliev 2012

Conclusions

- The pieces
  - The properties of STARS themselves - Hard to discern from both the mean or fluctuations
  - The properties of GALAXIES - The mass and suppression history is reflected in the angular power spectrum - a direct result of non-linear bias
  - The NUMBER of stars forming - The star formation rate is reflected in the amplitude of the mean CIB
  - WHERE the light is reprocessed - The escape fraction is revealed in the fractional anisotropy, since the amplitude of the fluctuations depend on the escape fraction, while the mean does not
  - HOW the light is reprocessed - Dust emission can change the signature of the fractional anisotropy through increased emission at longer wavelengths