Observational Clues of Stars at High Redshifts

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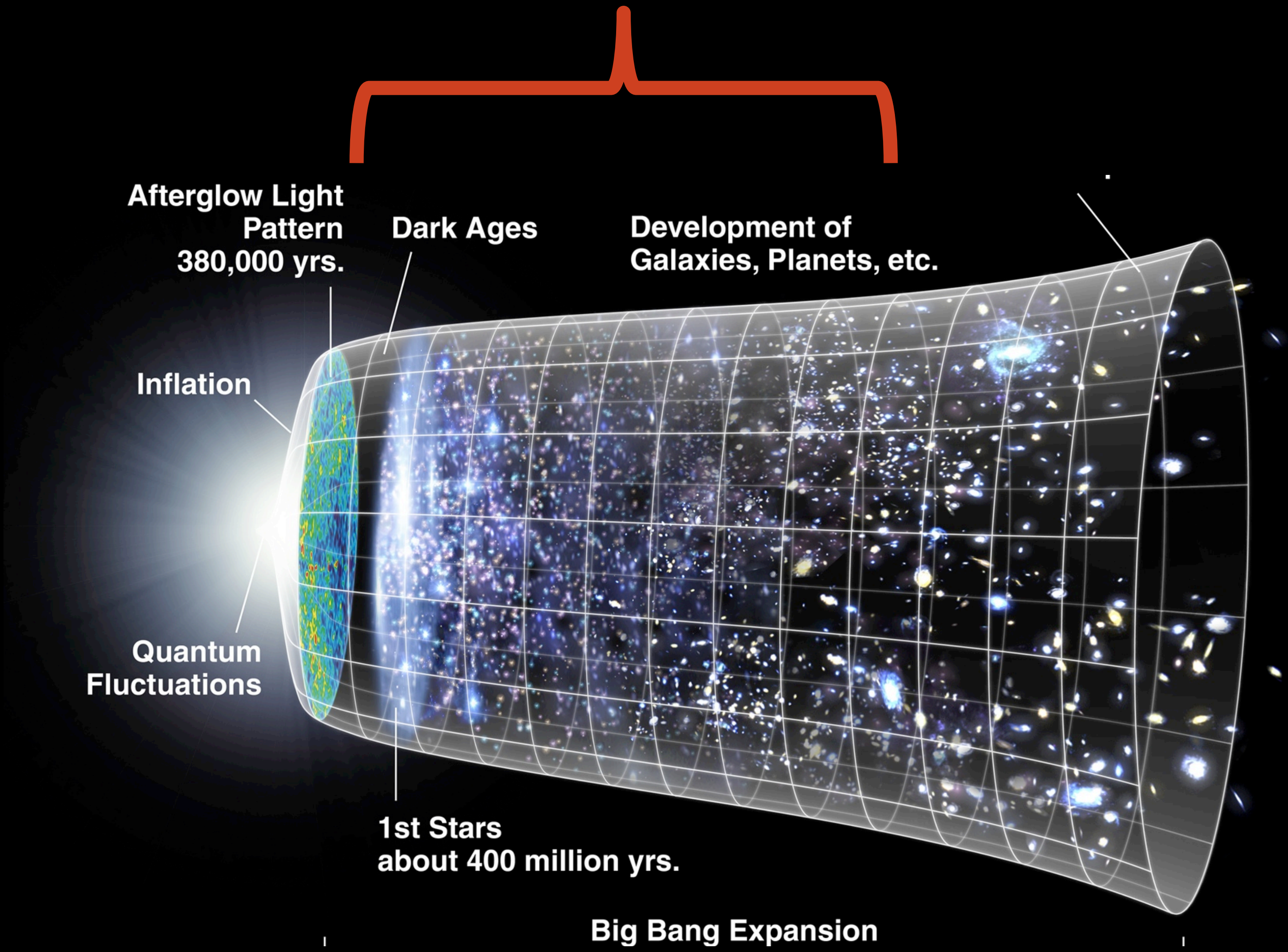
The First Generations of Stars
Development of Structure Formation
Metal Enrichment of the Universe
Reionizaton

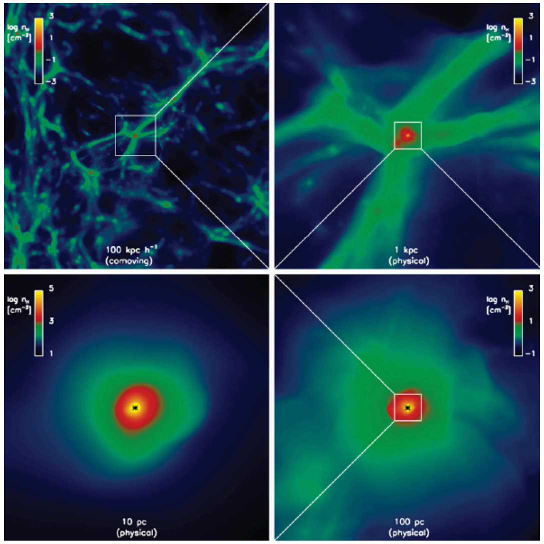


Four Fundamental Topics

The First Generations of Stars
Development of Structure Formation
Metal Enrichment
Reionization

The First Generations of Stars

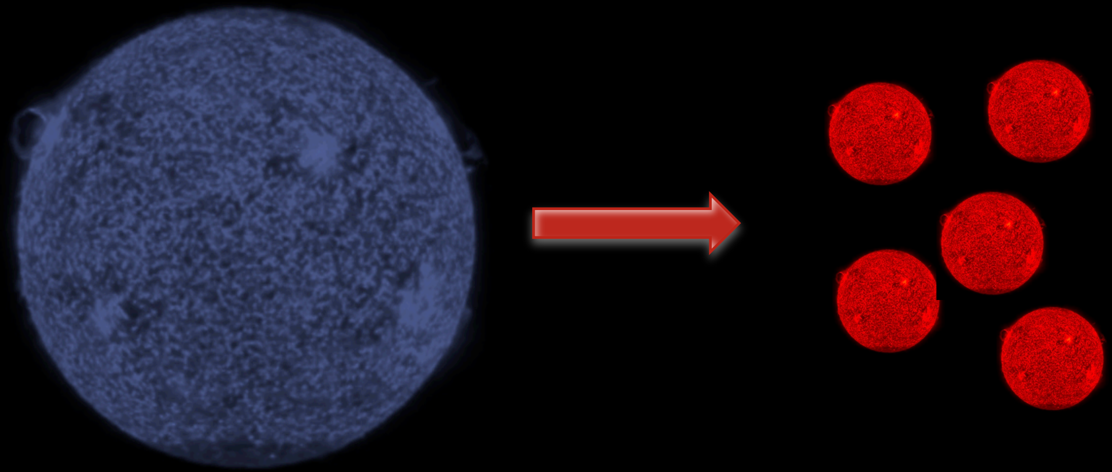
- First generations of stars could have been fundamentally different than stars we observe at lower redshifts
- No metallicity – Population III stars
- Could be massive (10s to 100s $M_{\odot}$)



Stacy et al 2010

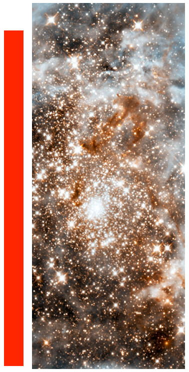
Metal Enrichment

- Population III stars eventually die and enrich the IGM
  - How many metals are released?
    - Dependent on stellar mass – black hole, supernova, other remnant
    - Mixing
- Critical metallicity reached & Population II stars form



Development of Structure Formation

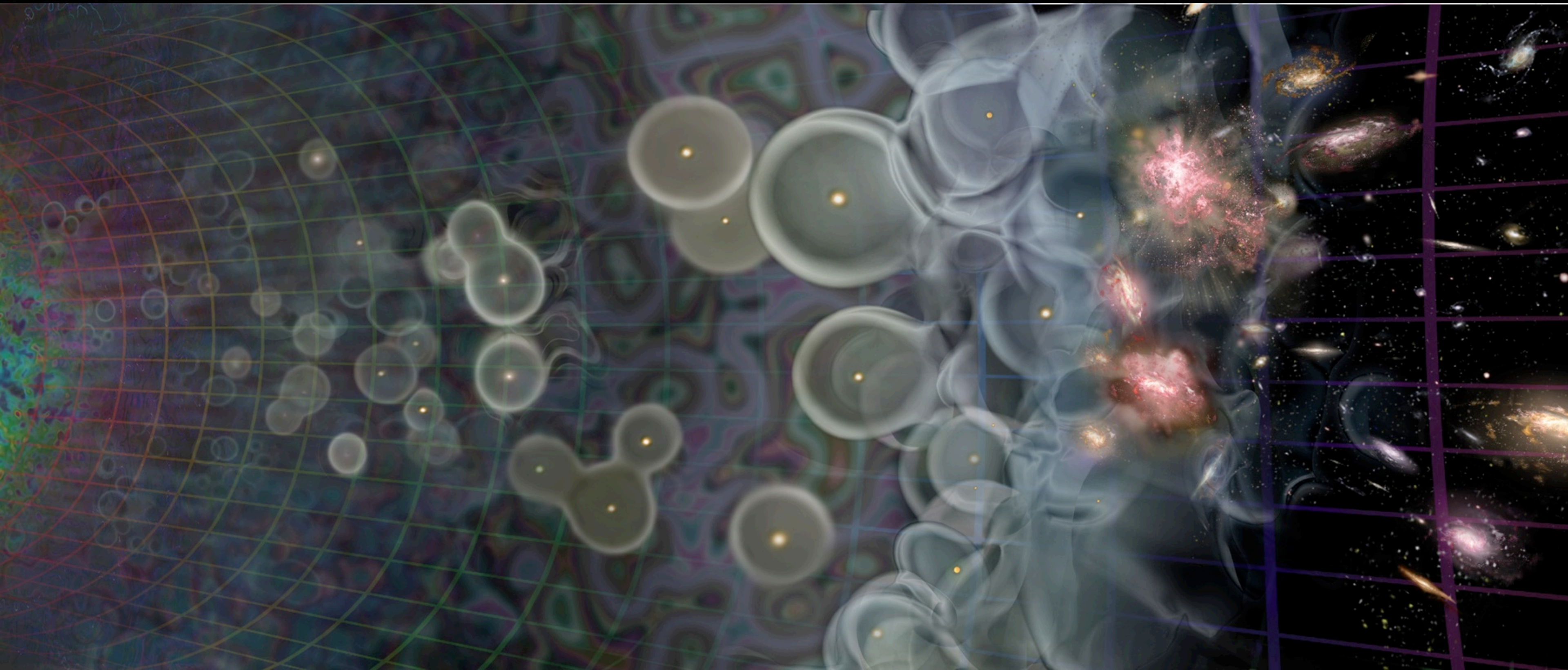
- When do stars start forming into galaxies?
- What are the masses of the galaxies formed?
- What is the mass of galaxies doing the ionizing?
- How they are these galaxies clustered in space?



Reionization

- We know that the universe was reionized early
  - If it was instantaneous, equivalent to $z \sim 11$
- Were stars responsible?
- Understanding reionization gives us information on:
  - Structures at high redshift
  - How many ionizing photons are being produced
  - How easily these photons enter the IGM ⟶ Escape Fraction
  - Shape and size of HII bubbles

What can be Observed?



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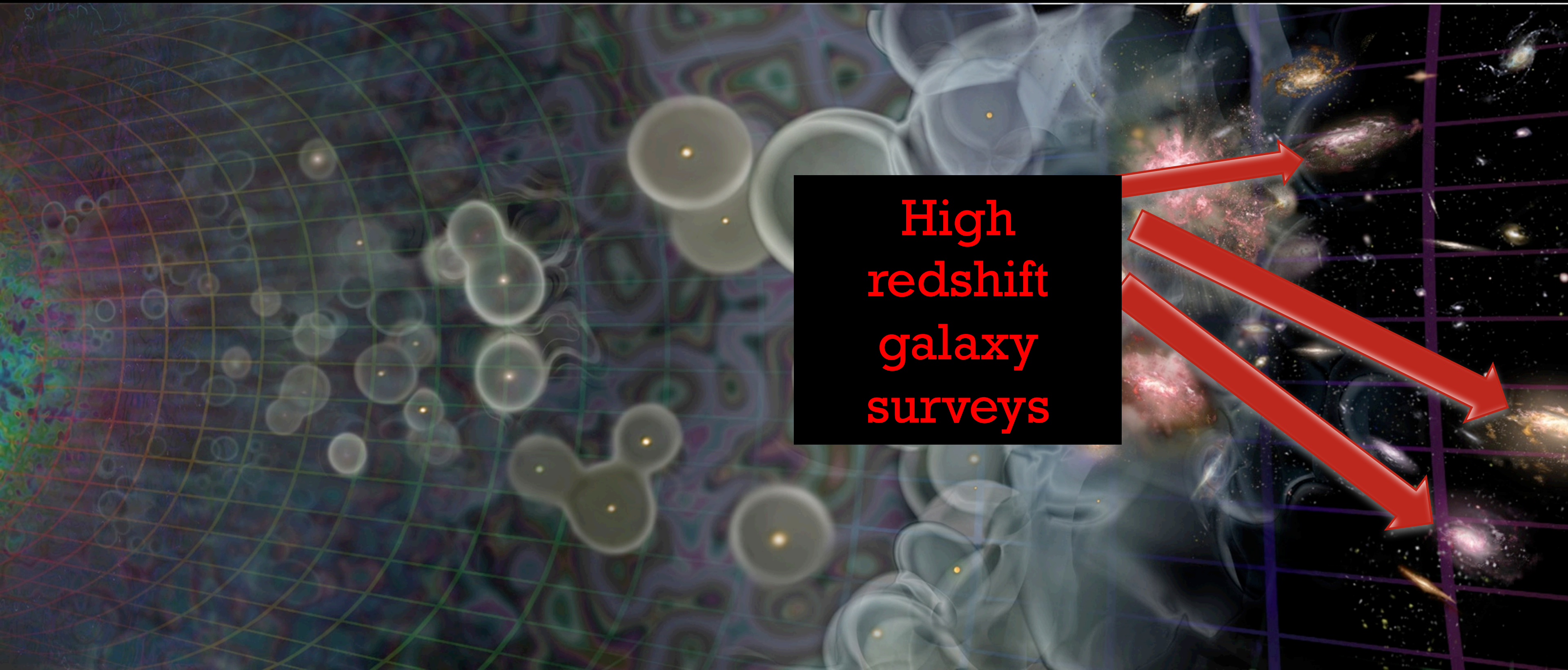

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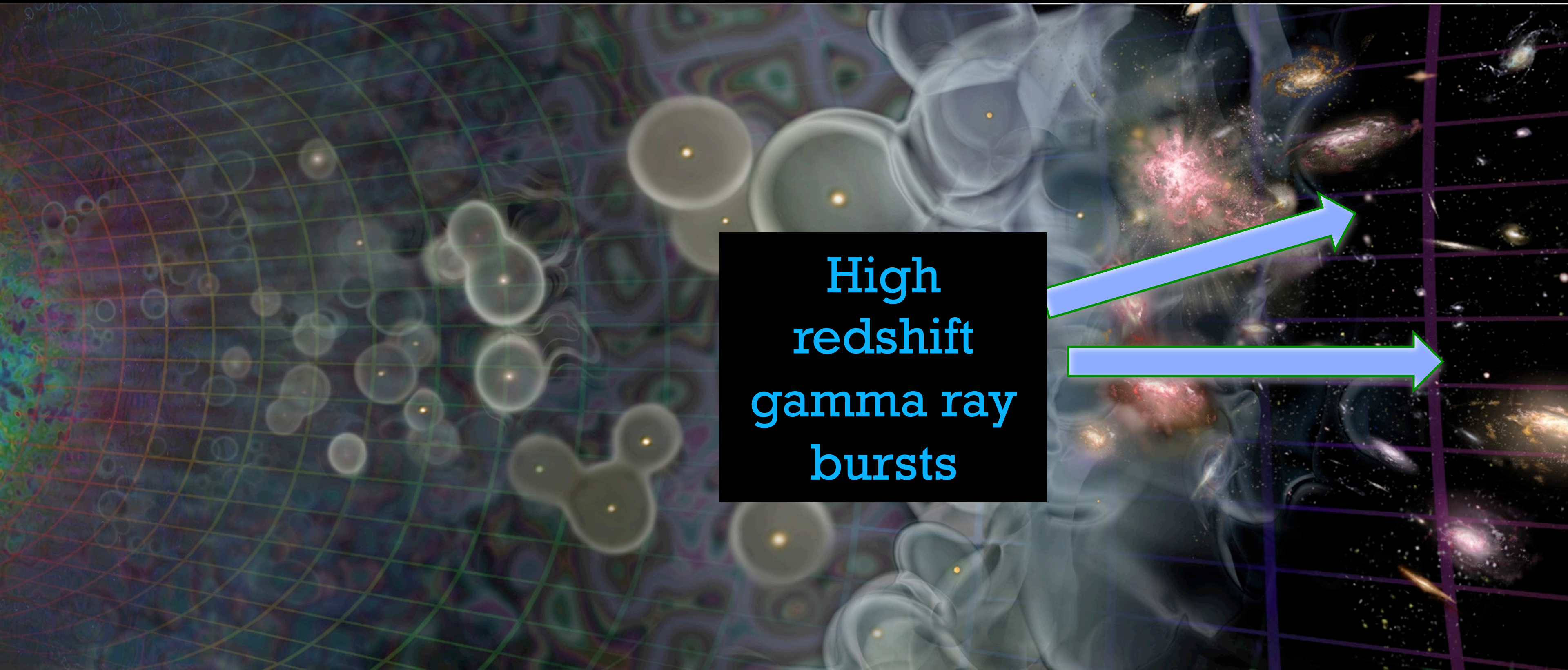

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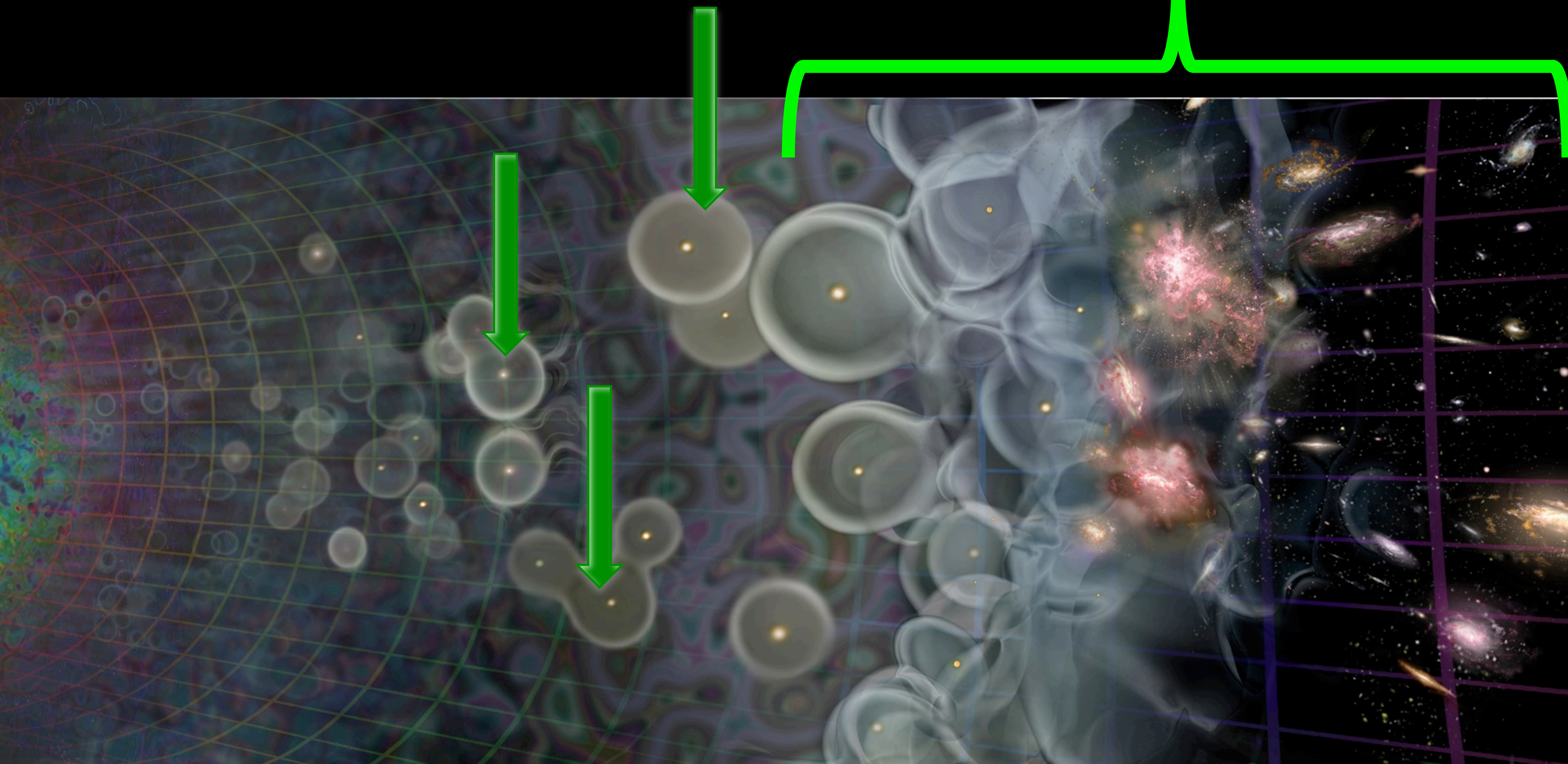

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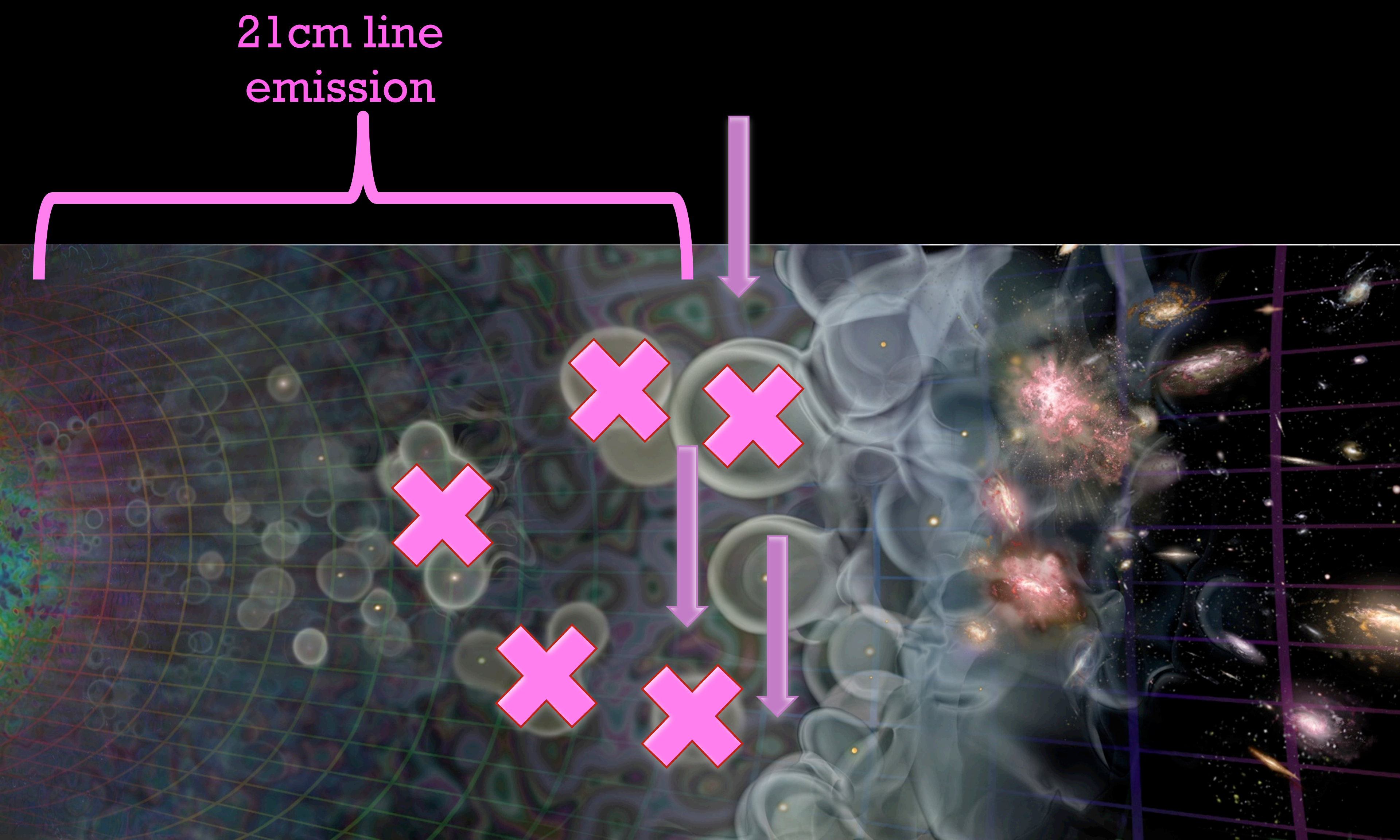


Emission from High Redshifts

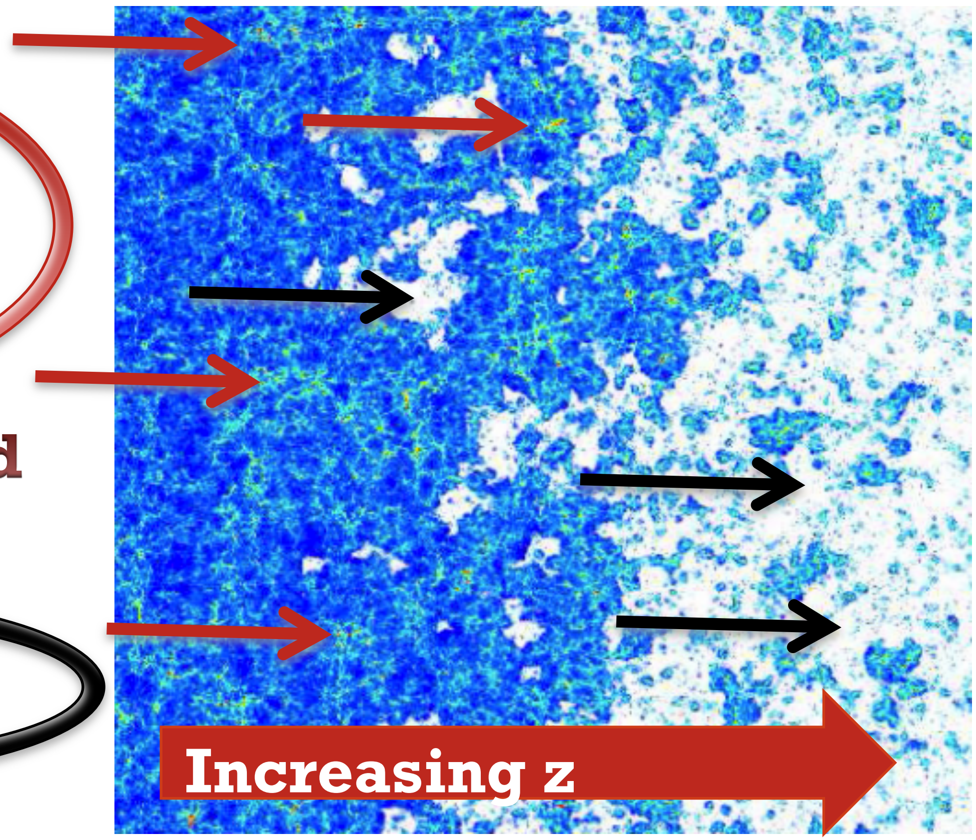
Galaxies

Ionized HII bubbles

The Near Infrared Background

Neutral Regions

21 cm line

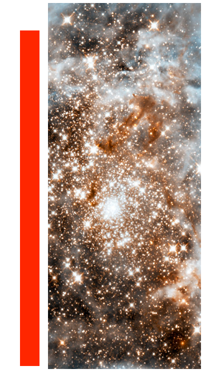


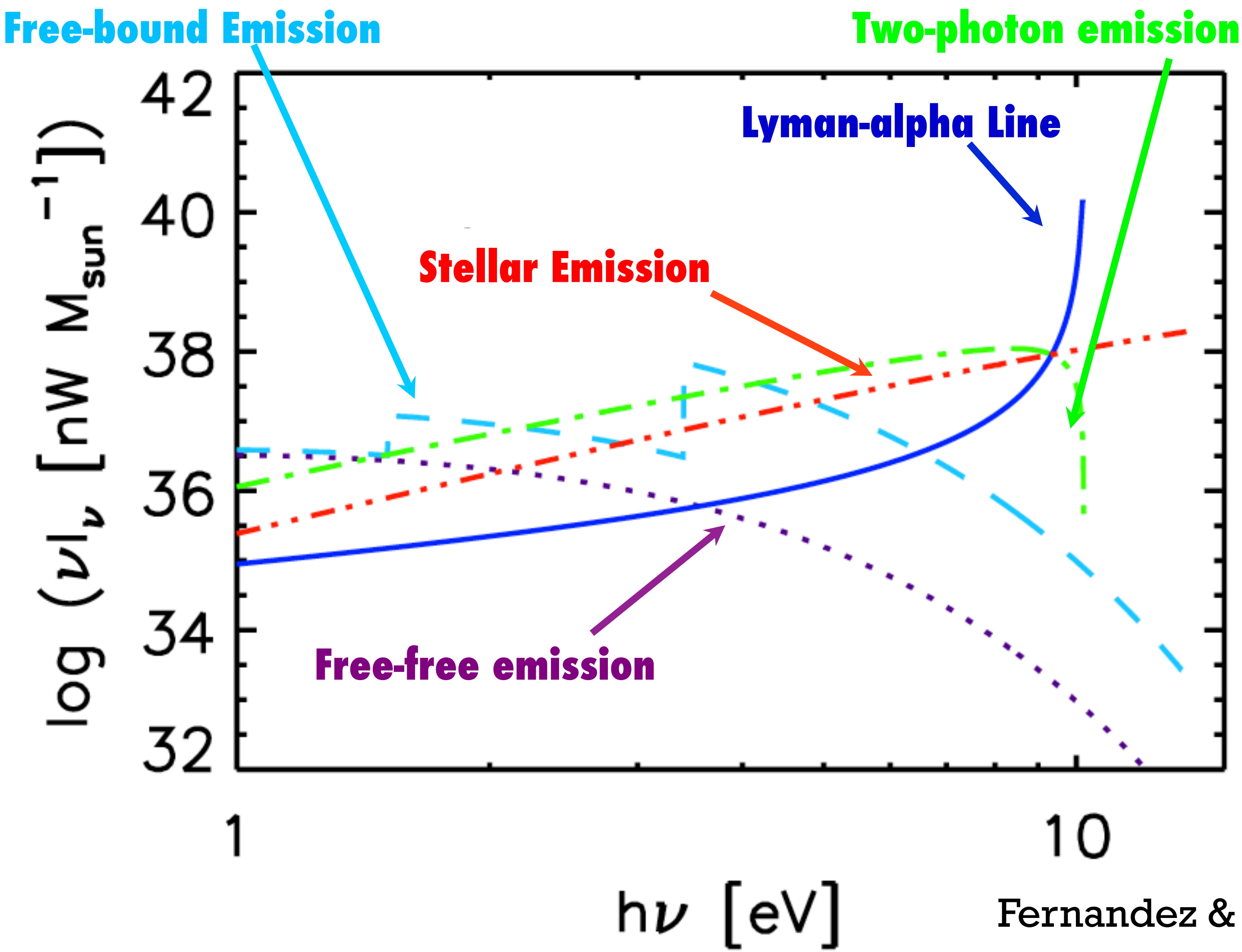
The simulation – 425/h Mpc
Park et al 2013

Mapping the Near Infrared Background Emission at High Redshift

the theory

Emission from Galaxies

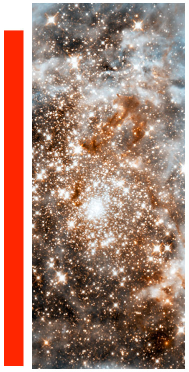




Rest frame spectrum

Fernandez & Komatsu 2008

Emission from Galaxies



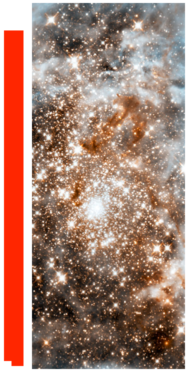
Redshifted to 1-4 microns

The infrared sky *must* hold clues

The Near Infrared Background

the predictions

The Mean Intensity of the NIRB



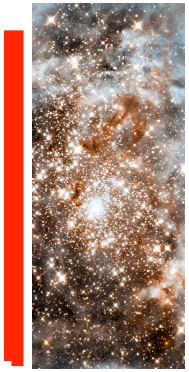
- The First Generations of Stars
- Development of Structure Formation
- Metal Enrichment of the Universe
- Reionizaton

$$I_\nu = \frac{c}{4\pi} \int dz \, \frac{p((1+z)\nu, z)}{H(z)(1+z)}$$

$$p(\nu, z) = \dot{\rho}_*(z) c^2 \sum_\alpha \langle \epsilon_\nu^\alpha \rangle$$

$$\langle \epsilon_\nu^\alpha \rangle \equiv \frac{1}{m_*} \int dm \, m \, f(m) \left[\frac{\overline{L}_\nu^\alpha(m) \tau(m)}{mc^2} \right]$$

The Mean Intensity of the NIRB



Mass of the first stars

- The First Generations of Stars
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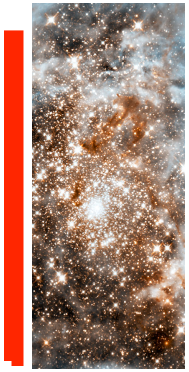

Luminosity, Age – depend on the mass and metallicity of the stars

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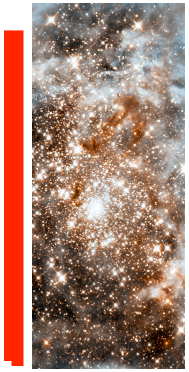

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Star formation efficiency – star formation rate

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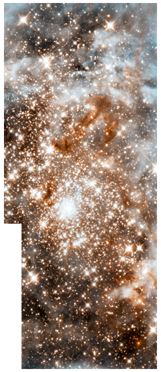
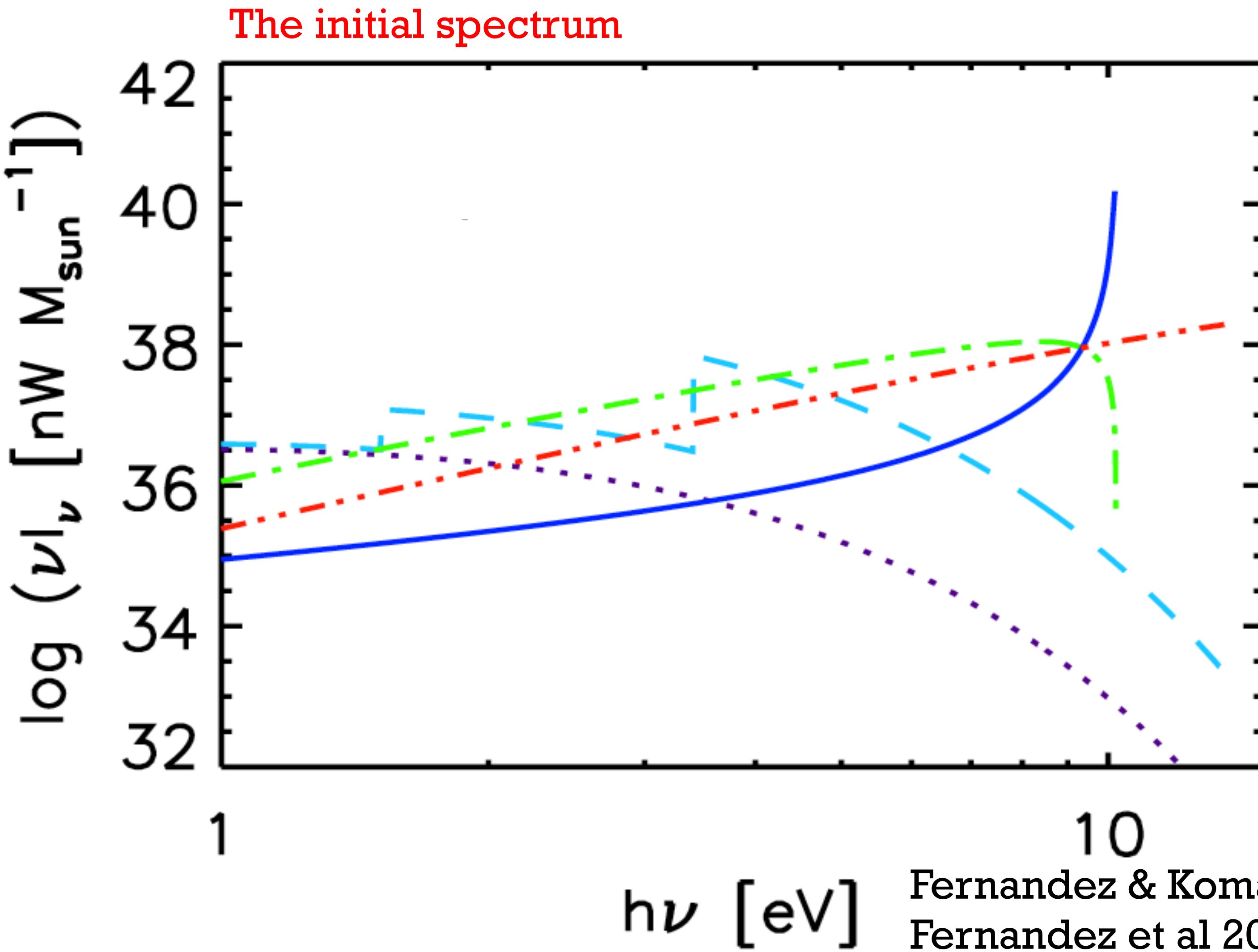
The Observable NIRB





Fernandez & Komatsu 2008,
Fernandez et al 2010

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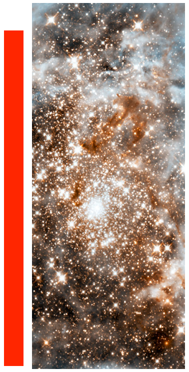
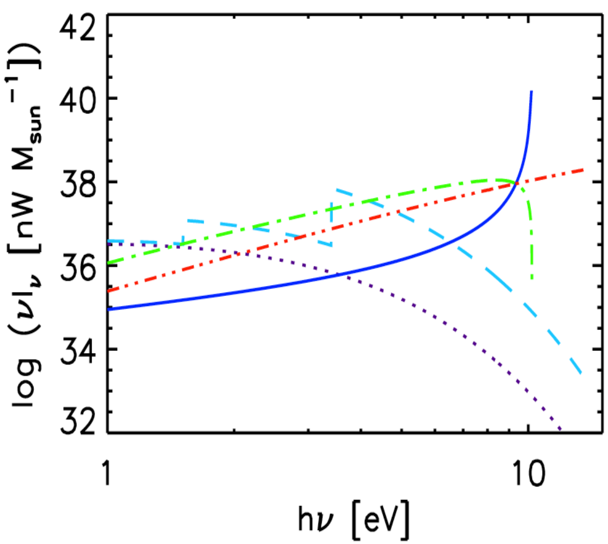
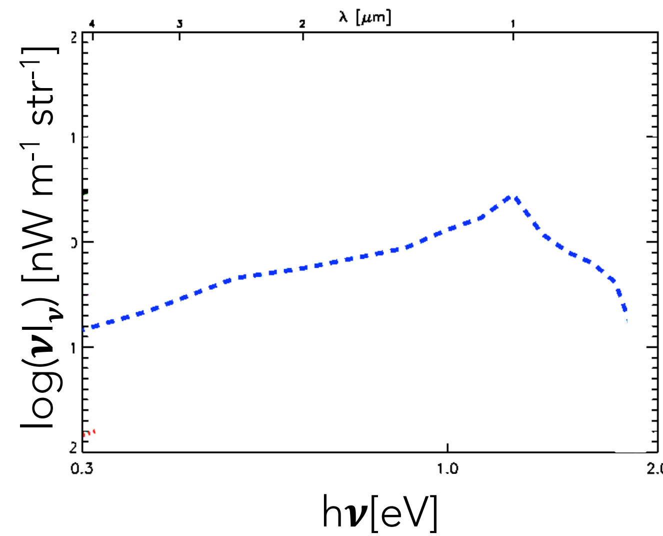


The initial spectrum



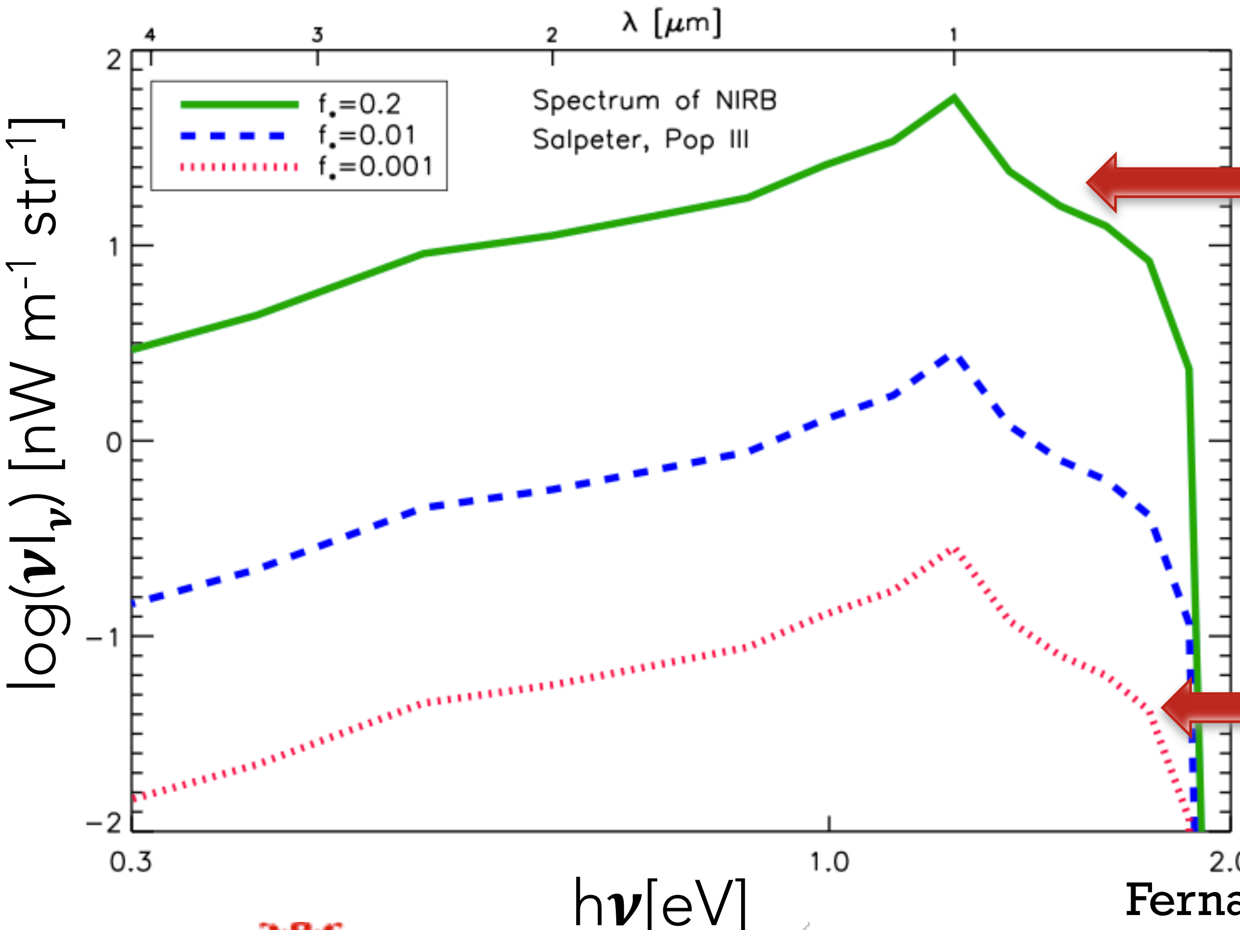
Integrate, redshift



Fernandez & Komatsu 2008,
Fernandez et al 2010

The Star Formation Efficiency

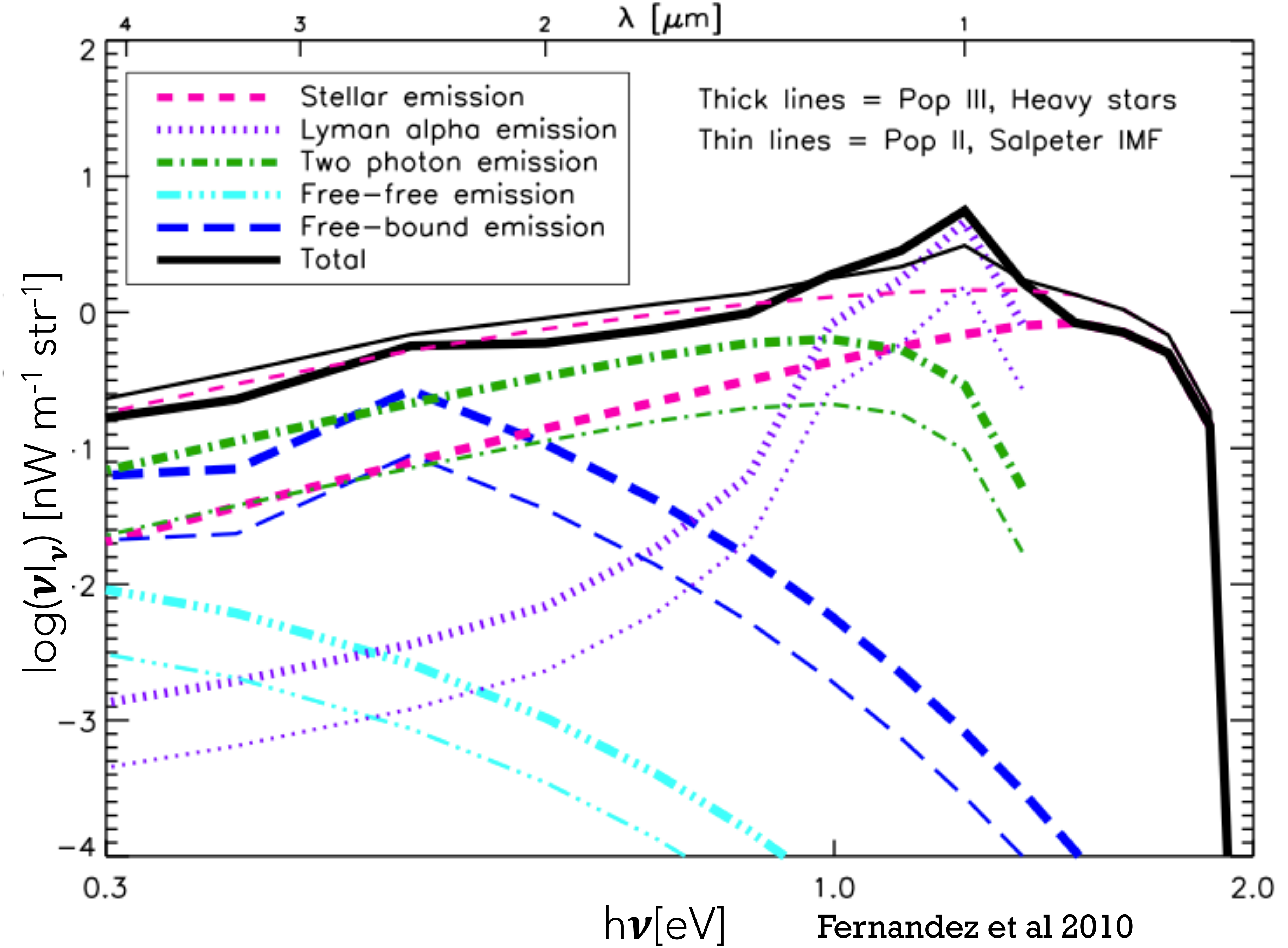
Amplitude depends directly on f_*



Ruled out by current observations

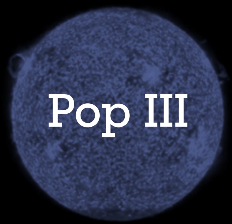
Too small to be detected by current observations

Fernandez et al 2010

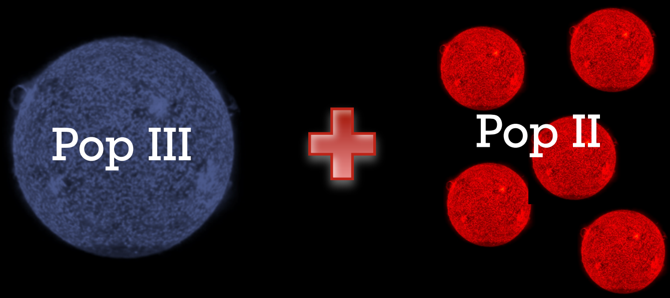


Fernandez et al 2010

What happens when we transfer from



To



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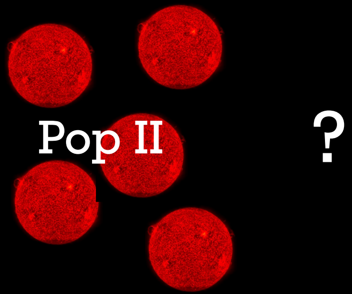
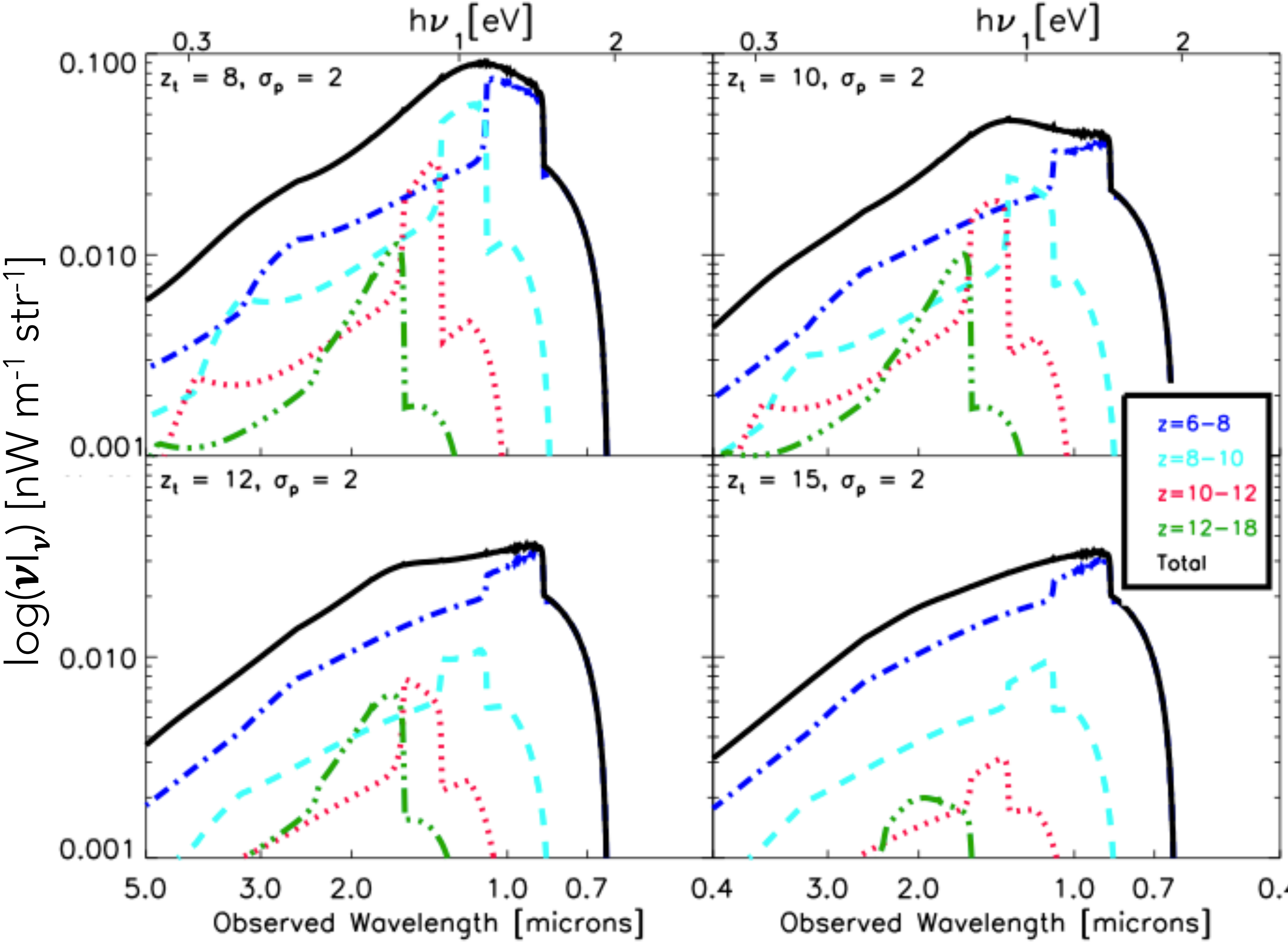
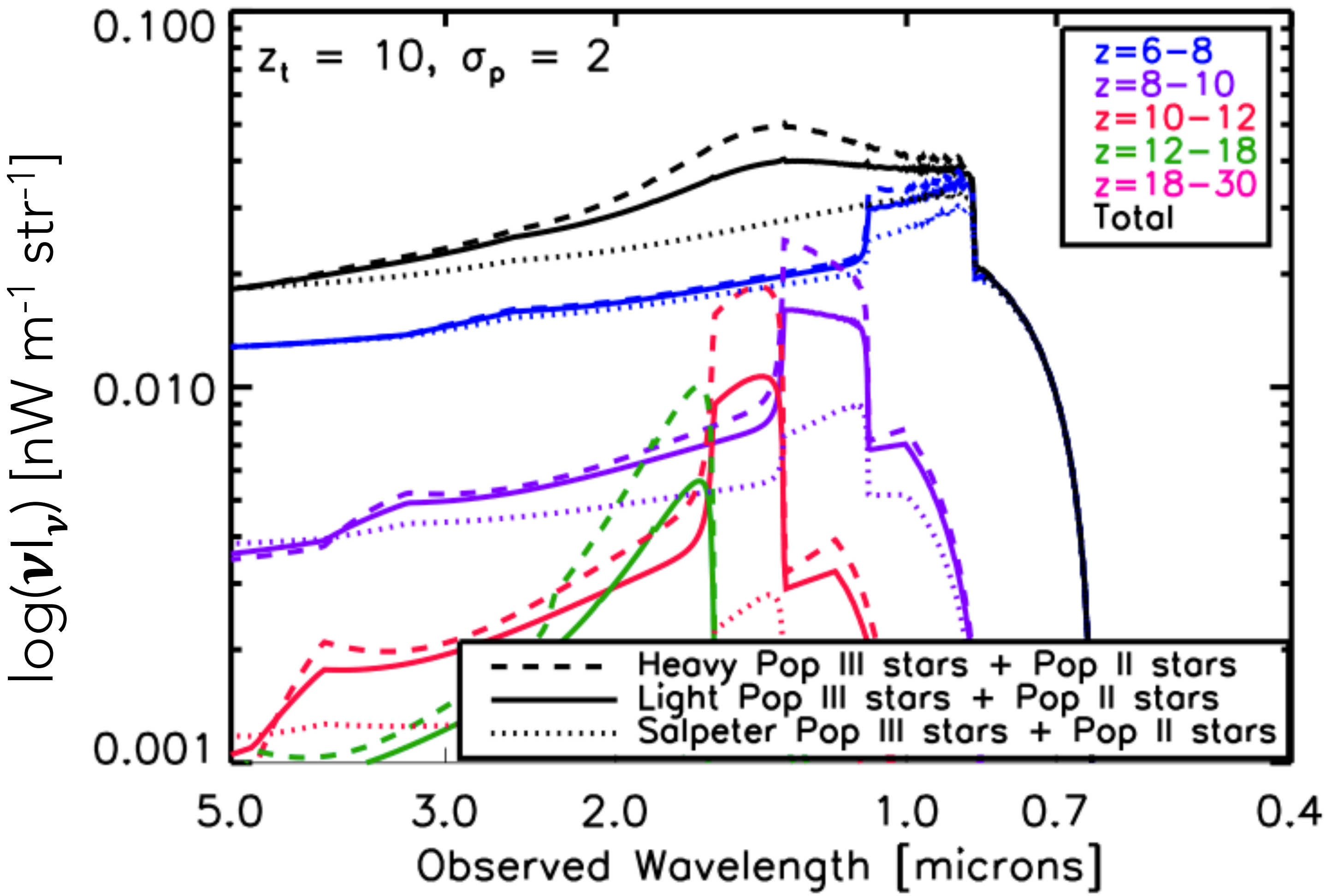




Fernandez & Zaroubi 2013

Mass of Population III Stars



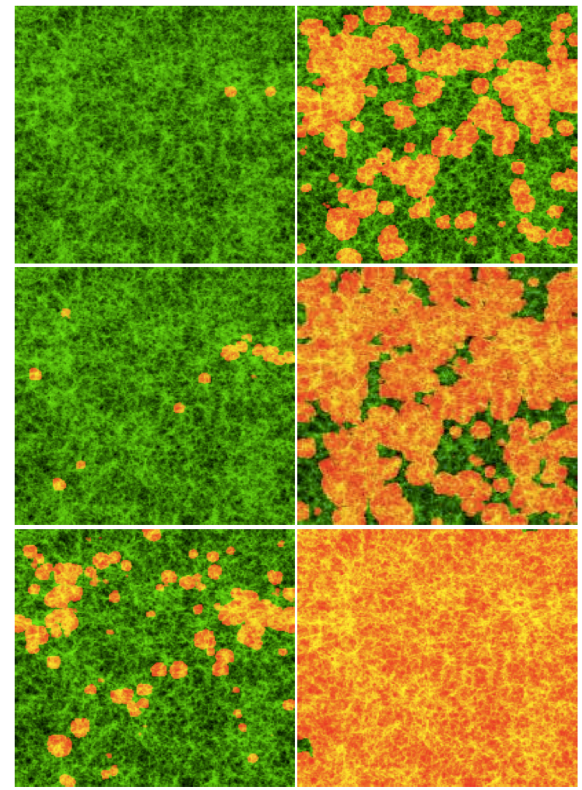
Fernandez & Zaroubi 2013

Why Study Fluctuations?

- Information about first structures – galaxies, HII regions
- Information on primordial density field
- Easier to interpret the data than looking at the mean intensity alone!

Structure Formation through Simulations

- N-body code with radiative transfer (Ilian et al 2006, 2007, 2011, 2013)
  - $M_{min} = 2x10^9$ or $10^8\ M_{sun}$
  - Various box sizes: $(425/h\ Mpc)^3$,$(114/h\ Mpc)^3$, $(37/h\ Mpc)^3$
- Various suppression histories
- Combine with predicted galaxy luminosities



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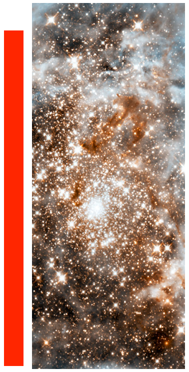

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$$f_\gamma = f_* f_{\rm esc} N_i$$

Escape fraction

% baryons in stars

Number of

Constant OR dependent on mass of halo

Making Predictions

- Assume a stellar population
  - Metallicity
    - Pop III
    - Pop II
  - Mass
    - Heavy (Larson mass spectrum, ~ 200 $M_\odot$)
    - Normal IMF (Salpeter)
  - Escape fraction
  - Star formation efficiency

$$f_\gamma = f_* f_{\rm esc} N_i$$

% baryons in stars

Escape fraction

Number of ionizing photons produced

The Angular Power Spectrum

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

The Angular Power Spectrum

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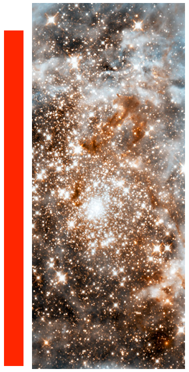

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The Angular Power Spectrum

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Linear Power Spectrum

Bias – depends on structure formation – how biased halos are

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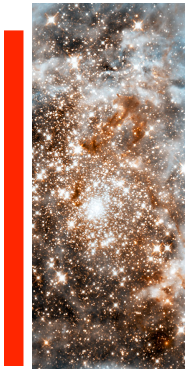
The Angular Power Spectrum



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The Angular Power Spectrum

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Escape fraction gives details on reionization

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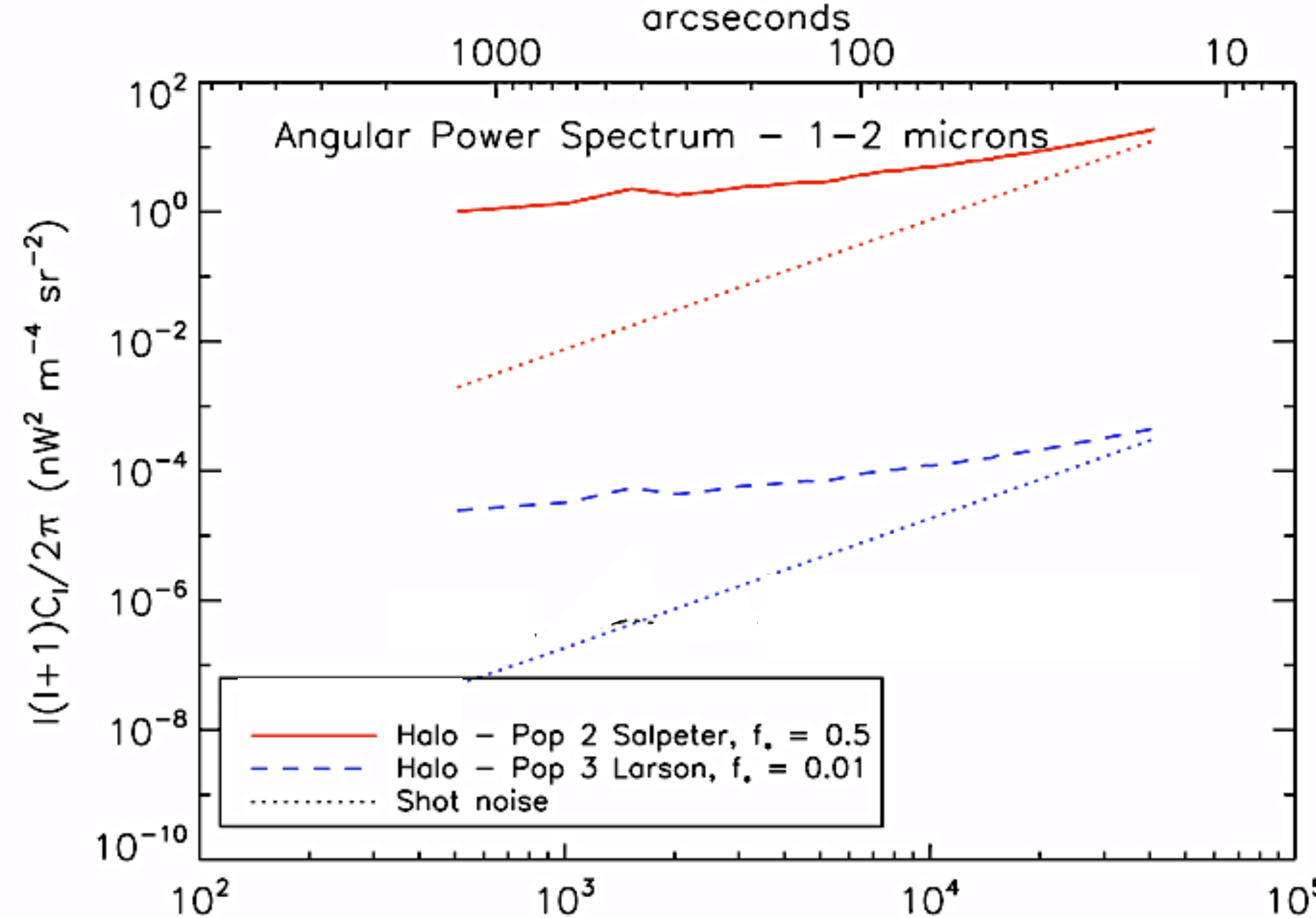
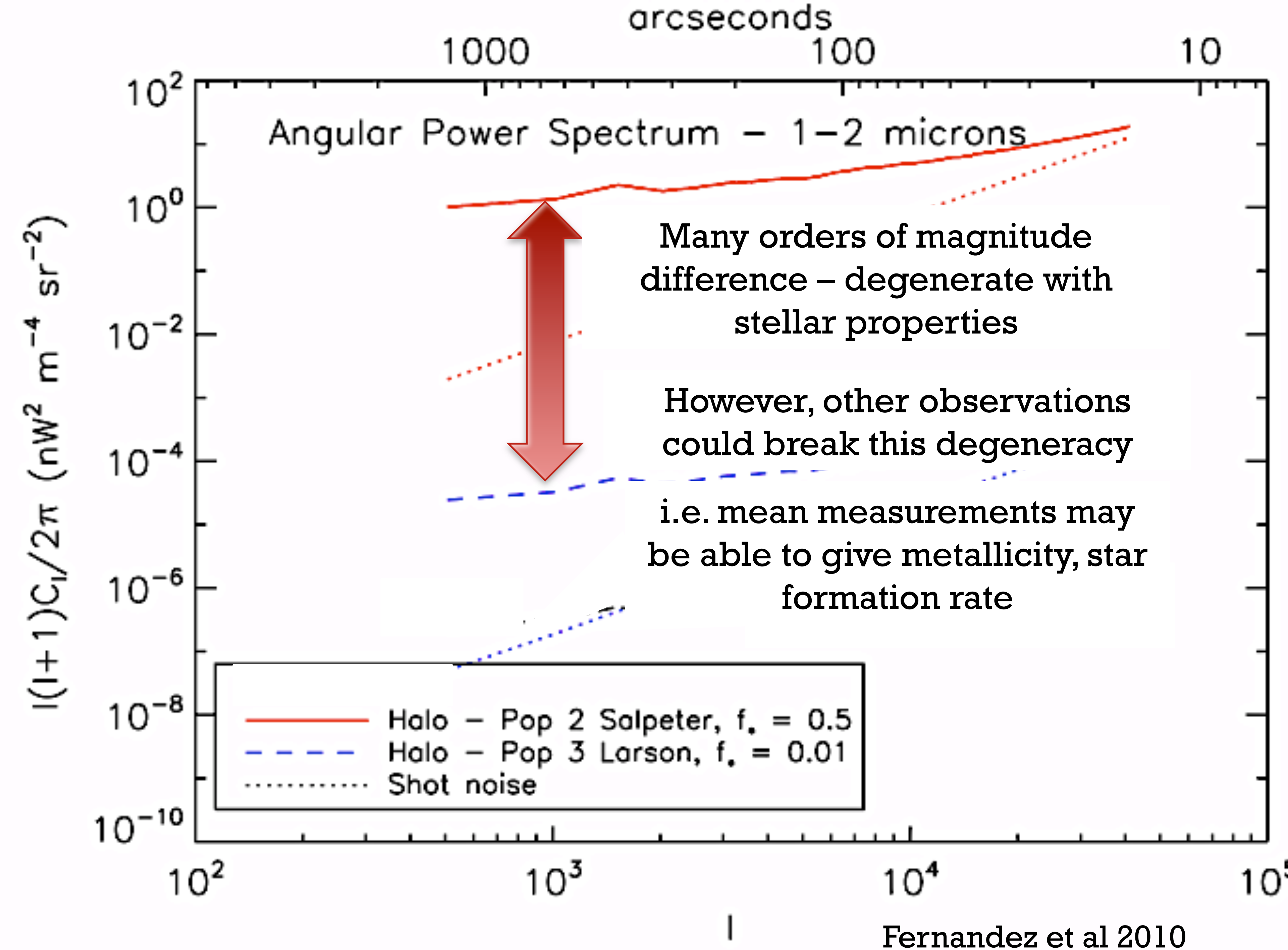
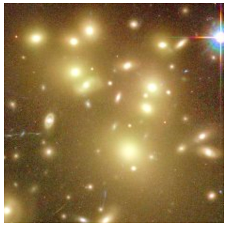


Fernandez et al 2010

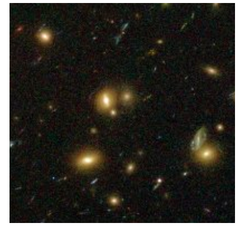


Fernandez et al 2010

Galactic Properties



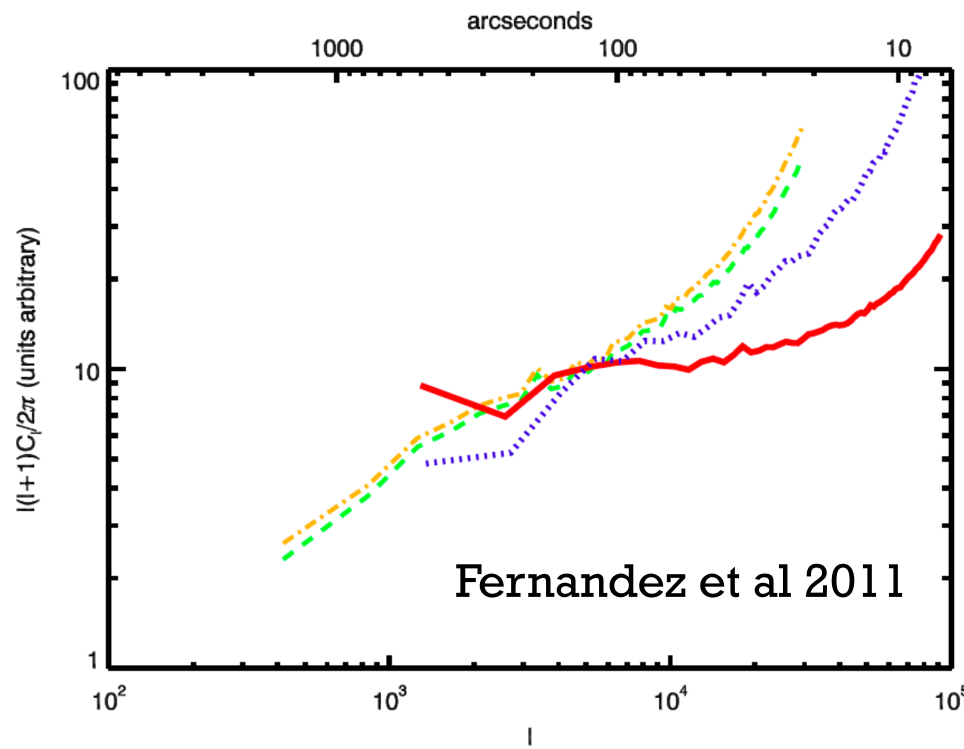
Massive Galaxies Only ($> 10^9 M_\odot$)



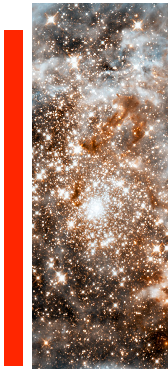
Small & Large Galaxies ($> 10^8 M_\odot$)

Small Galaxies Suppressed

- Mostly depends on bias
- Bias is strongly dependent on mass of halo and suppression history



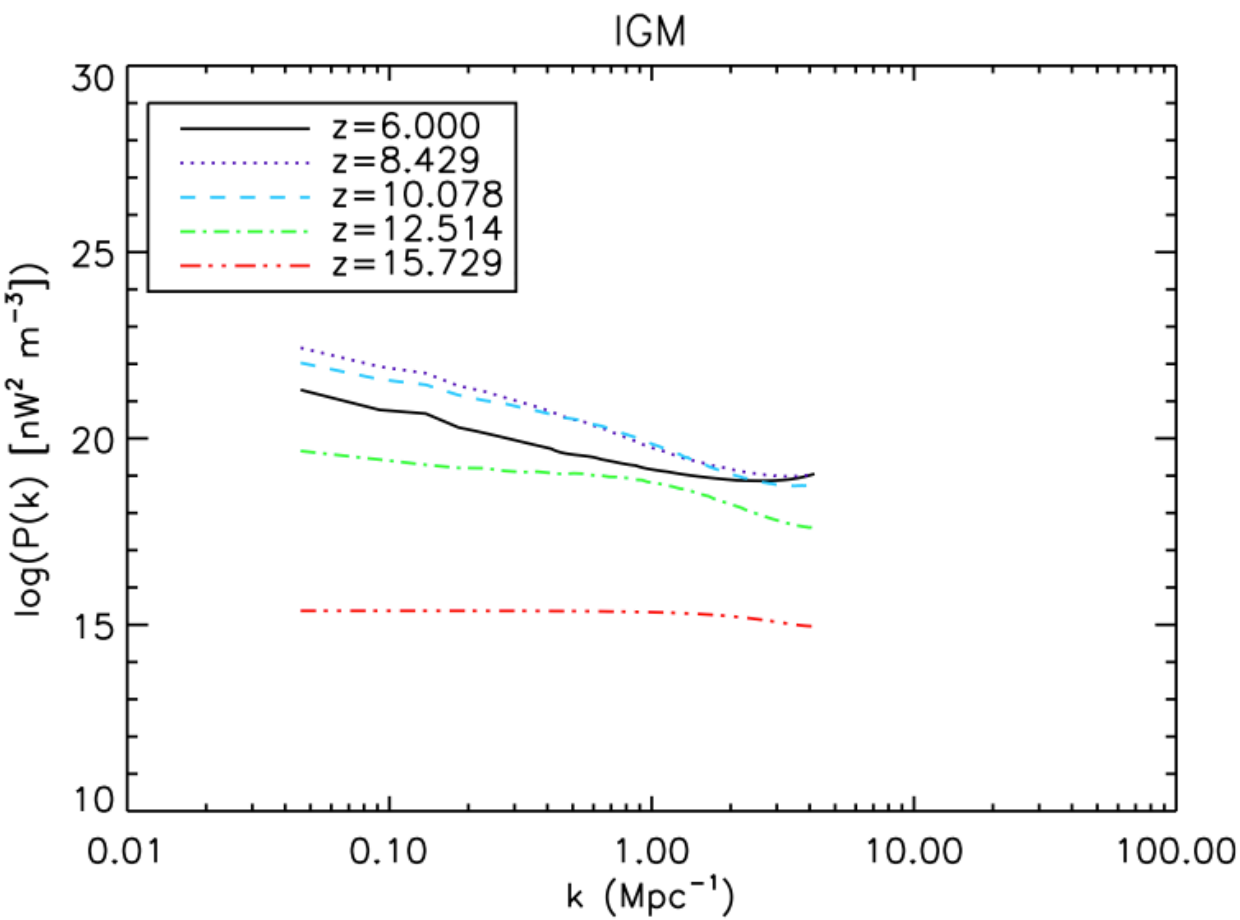
university groningen



Curious About Reionization? Look to the IGM

- Simulations have radiative transfer
  - Number of ionizing photons produced consistent with reionization
- HII bubble size, shape

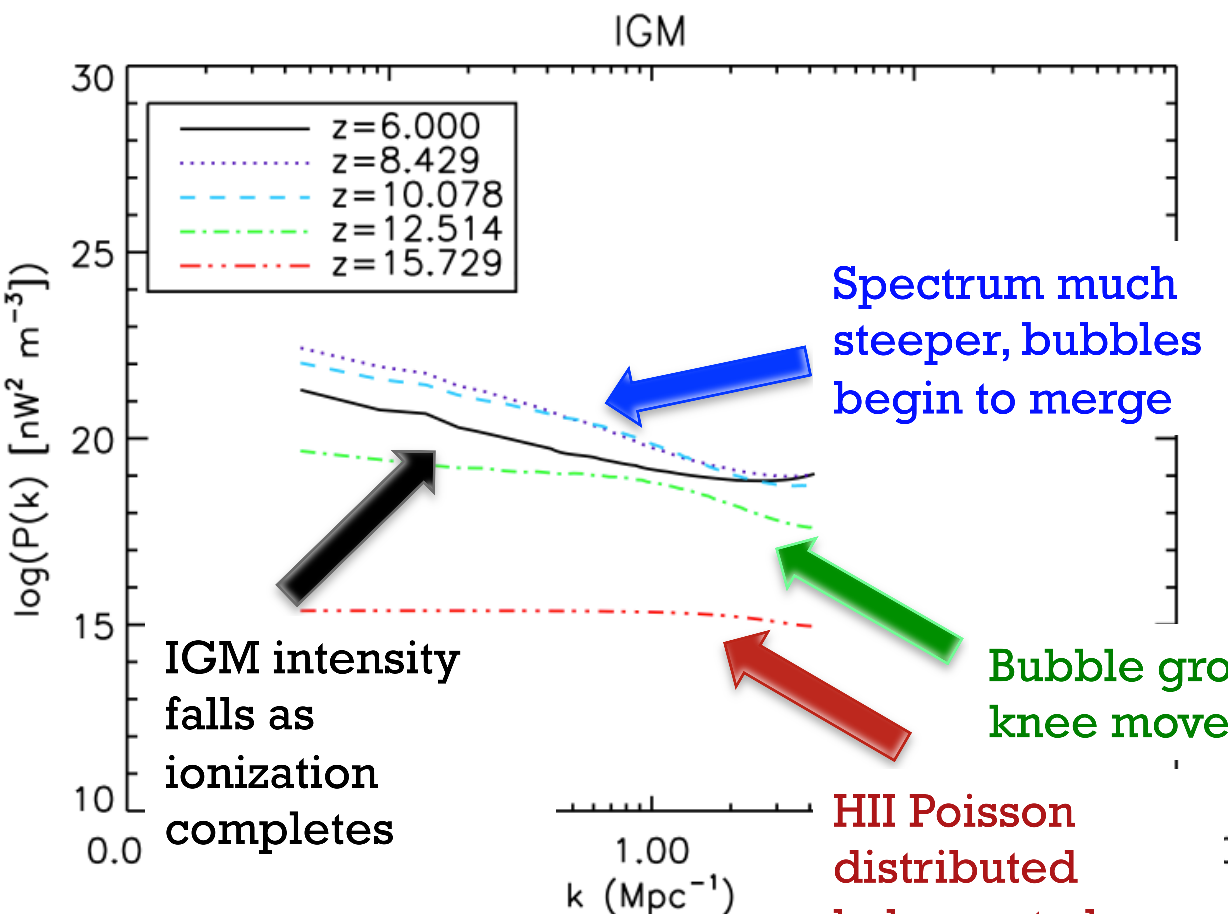
HII Bubbles



- Power spectrum of the IGM = information on HII bubbles
- "Knee" wavenumber inversely proportional to bubble size – see bubbles "grow"
- Difficult to observe!

Fernandez et al 2010

HII Bubbles

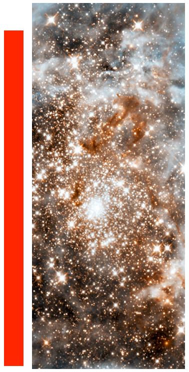


Spectrum much steeper, bubbles begin to merge

IGM intensity falls as ionization completes

Bubble grows, knee moves left

HII Poisson distributed halos up to knee



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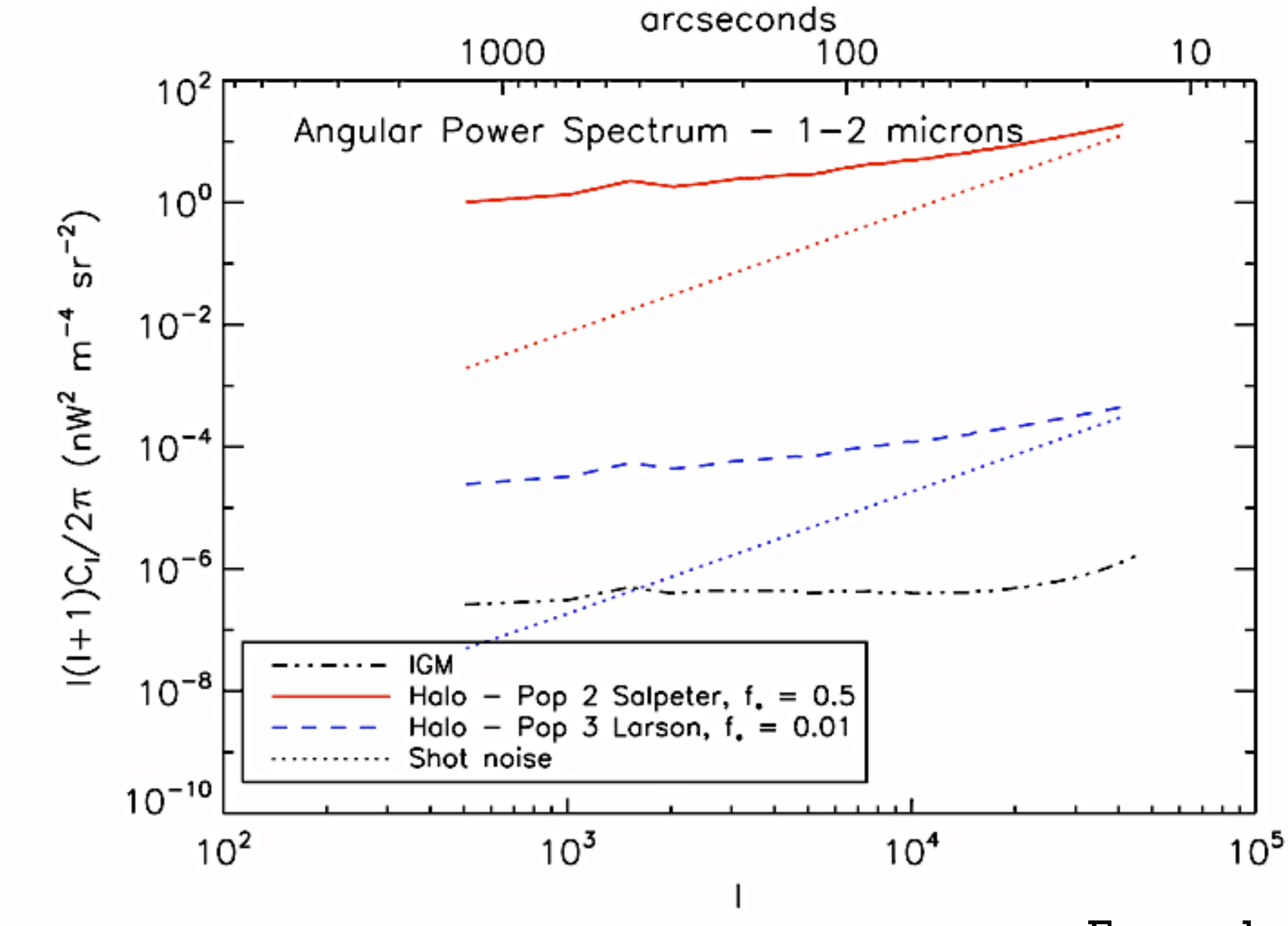
The Illusive IGM



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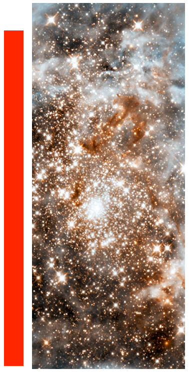
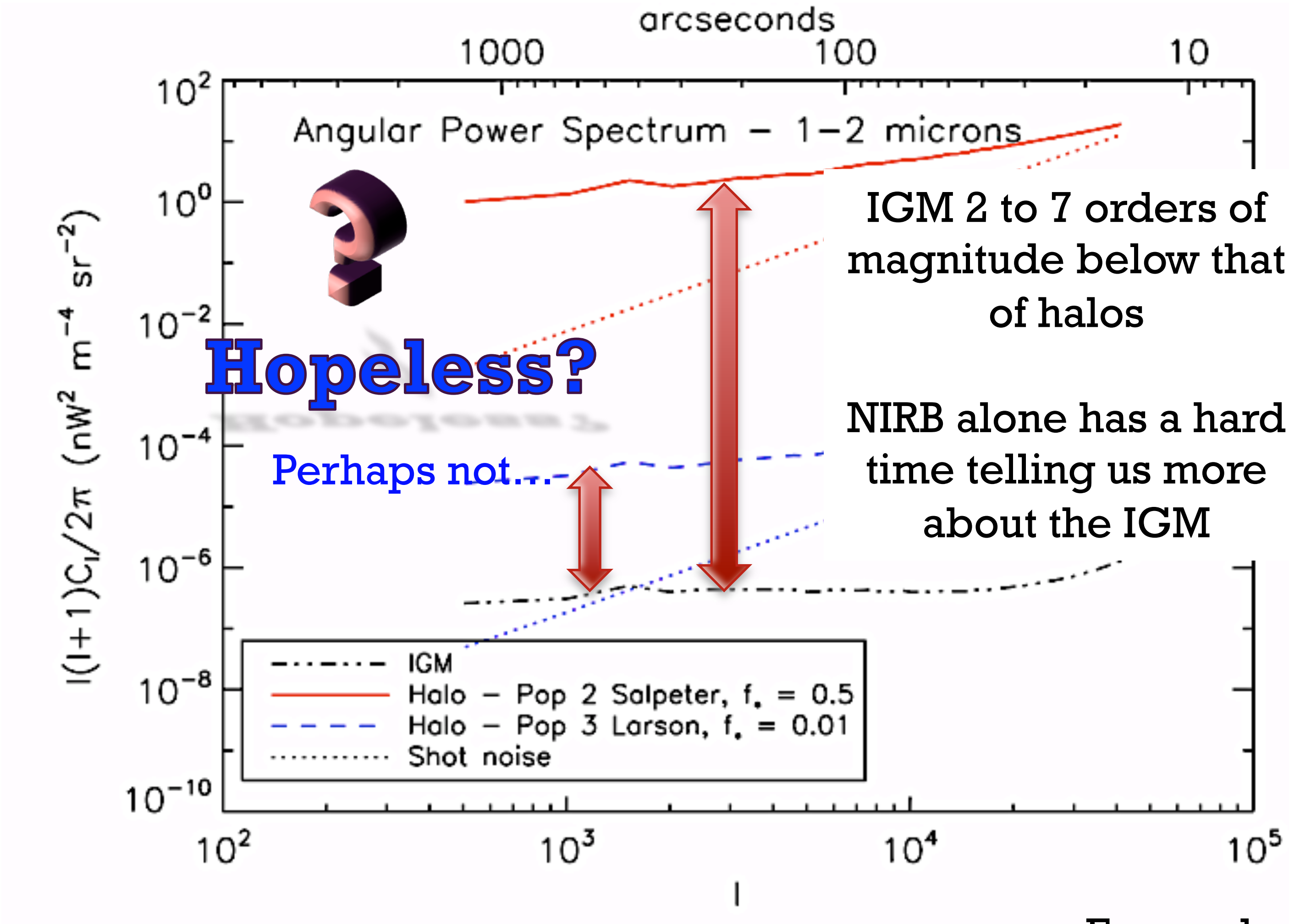




IGM 2 to 7 orders of magnitude below that of halos

NIRB alone has a hard time telling us more about the IGM

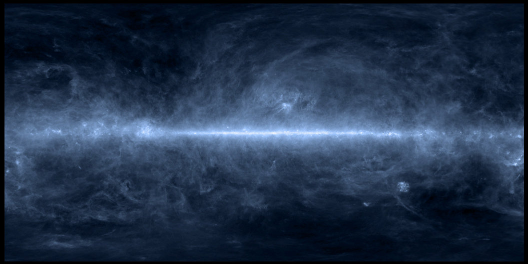
Fernandez et al 2010

The Near Infrared Background

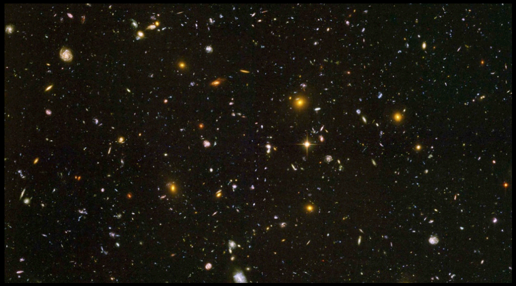
the observations

It's not that Easy to Observe…

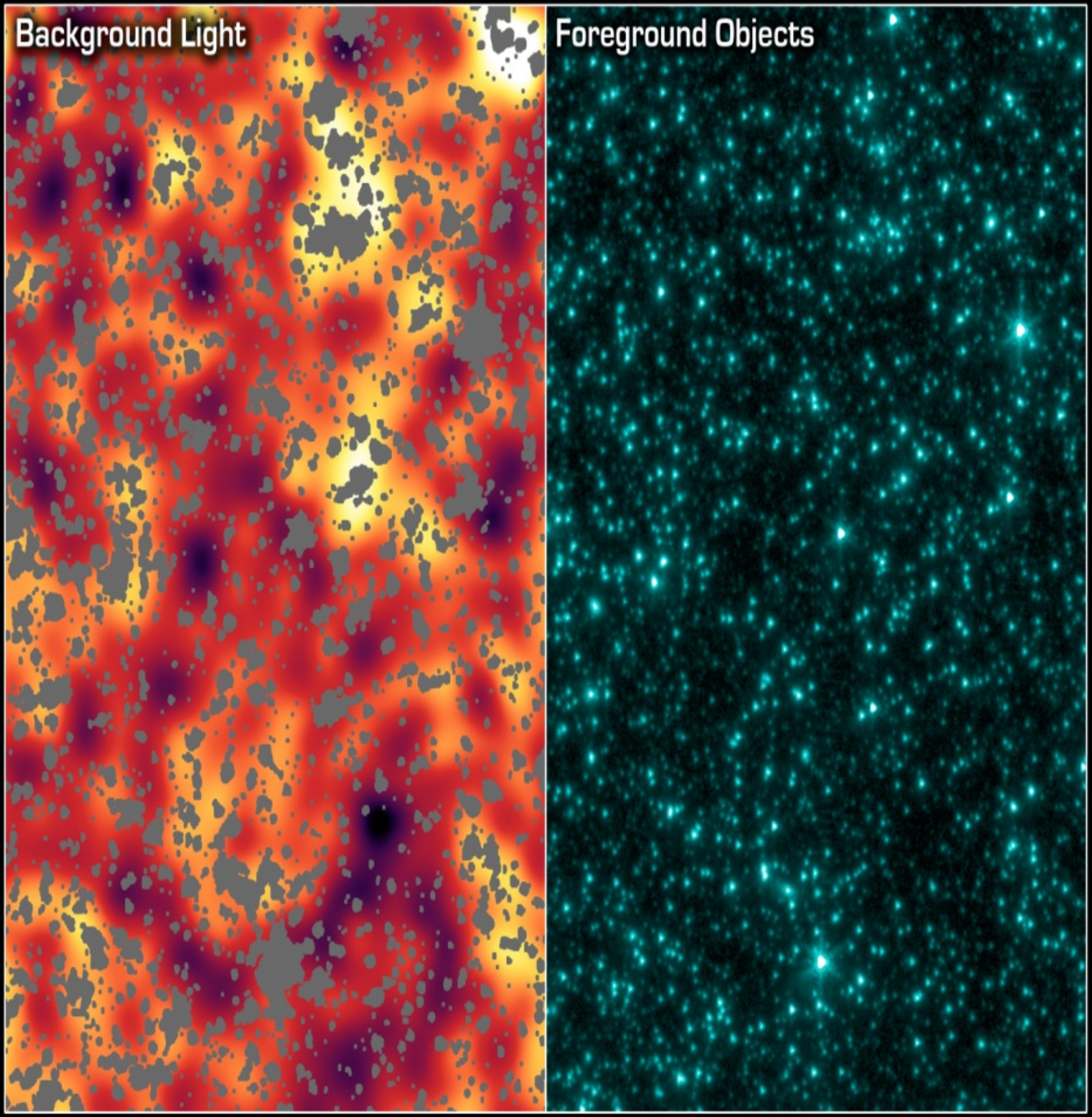
Zodiacal Light



Our Galaxy



Foreground galaxies



First Light after the Universe's "Dark Ages"

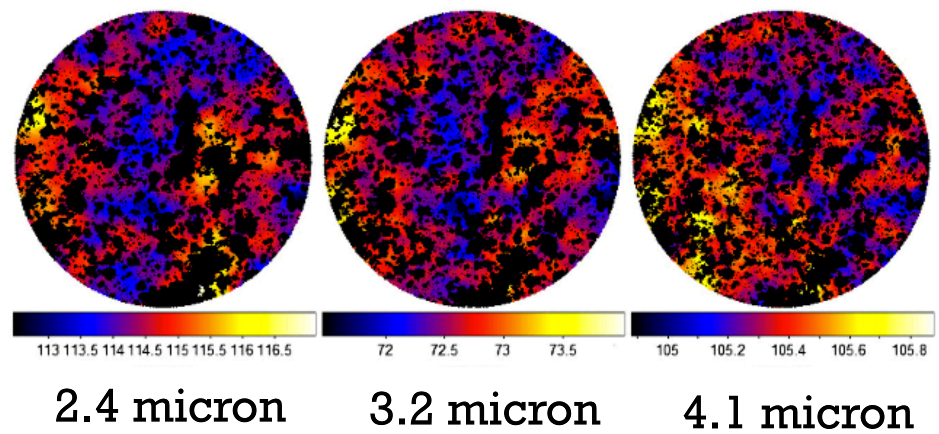
Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / A. Kashlinsky (GSFC)

ssc2006-22a

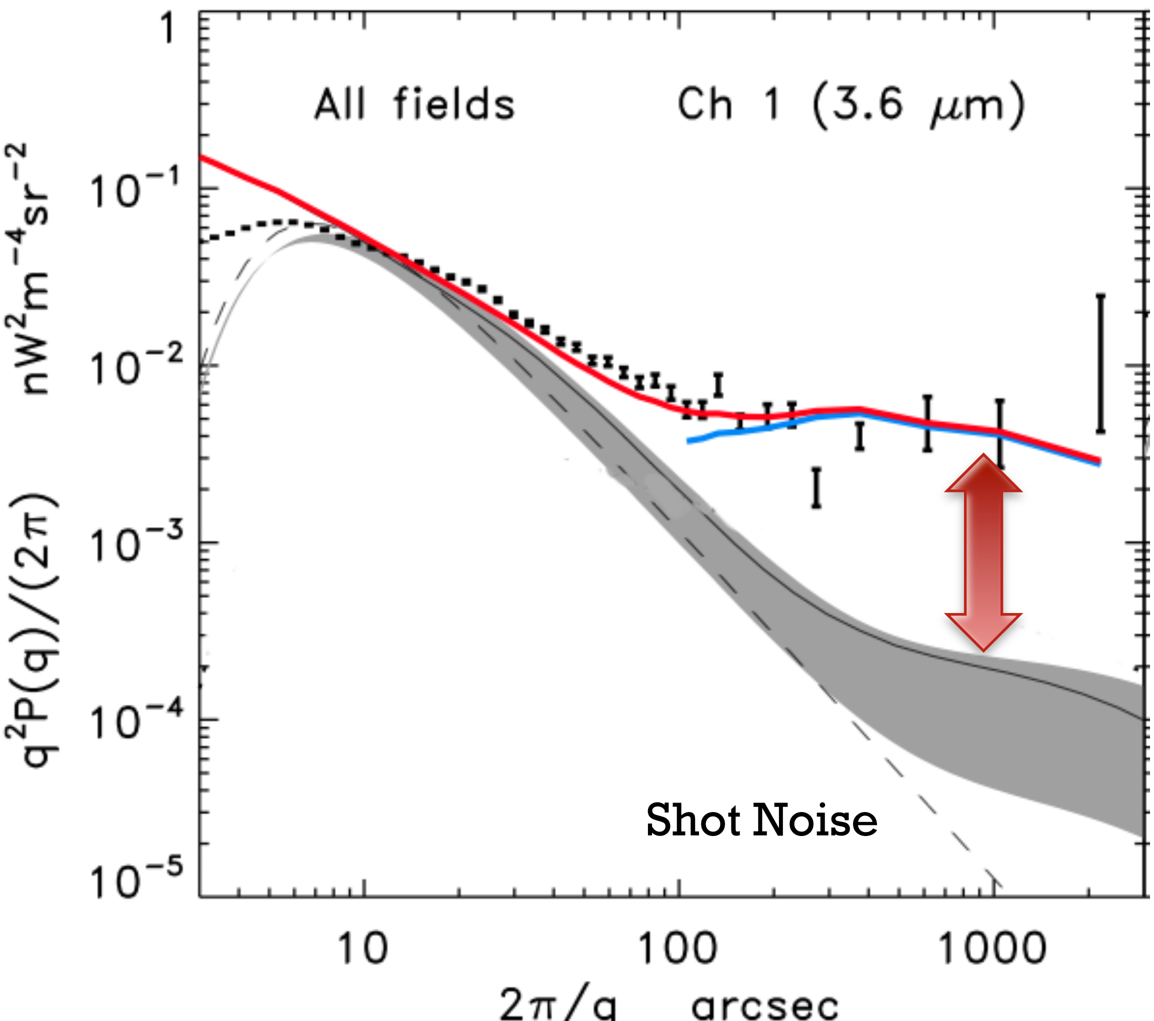
Fluctuations Measured by AKARI

- Observations are very difficult to make
- Mask out foreground sources
  - Bright pixels
  - Known galaxies
- Smooth images
  - Structures on ~ few hundred arcsec
  - Similar structure at all wavelengths



Matsumoto et al 2011

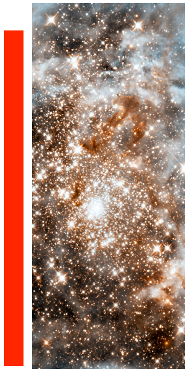
The High Redshift Component

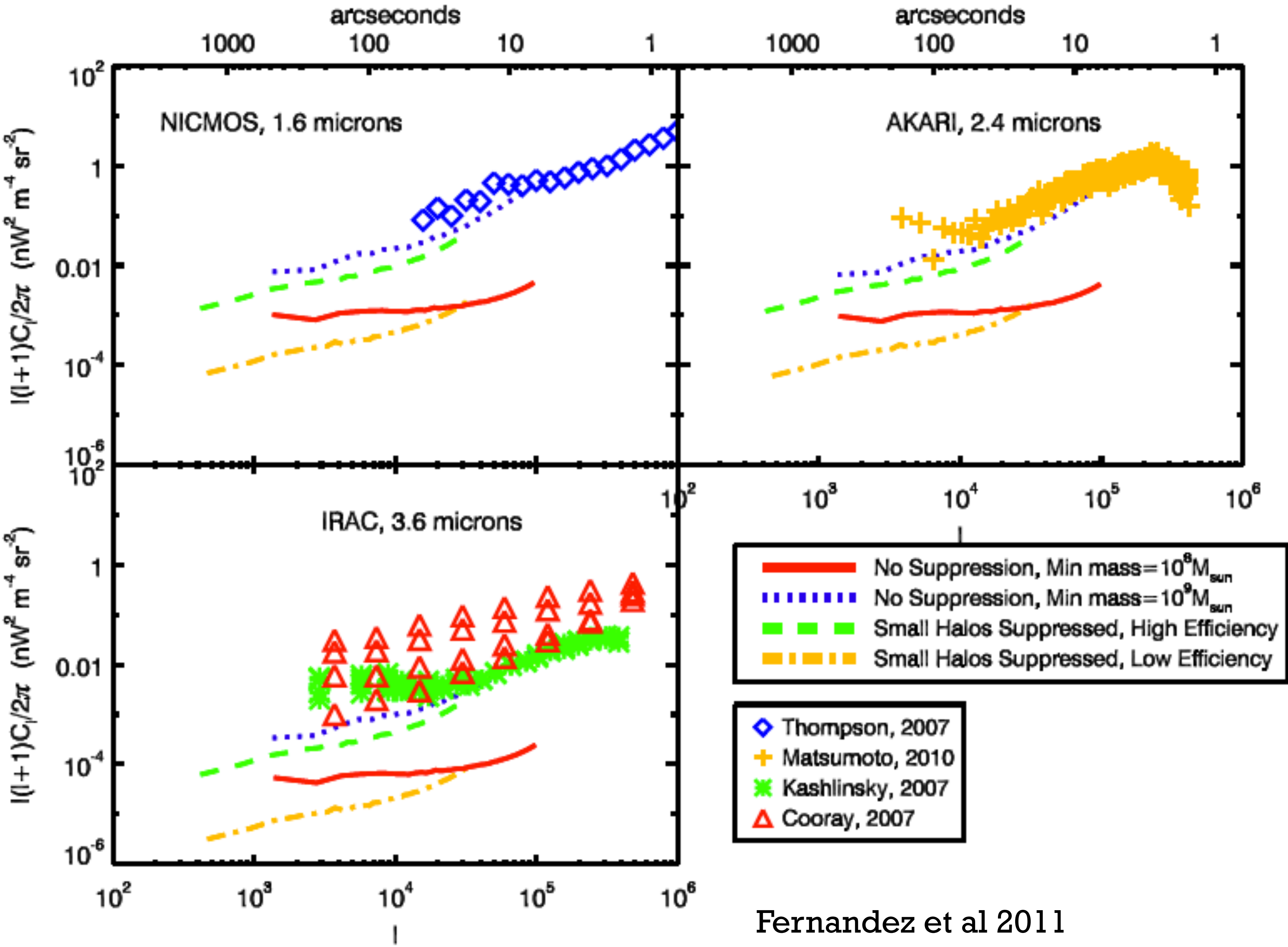


High Redshift Galaxies?

Low-z Galaxies

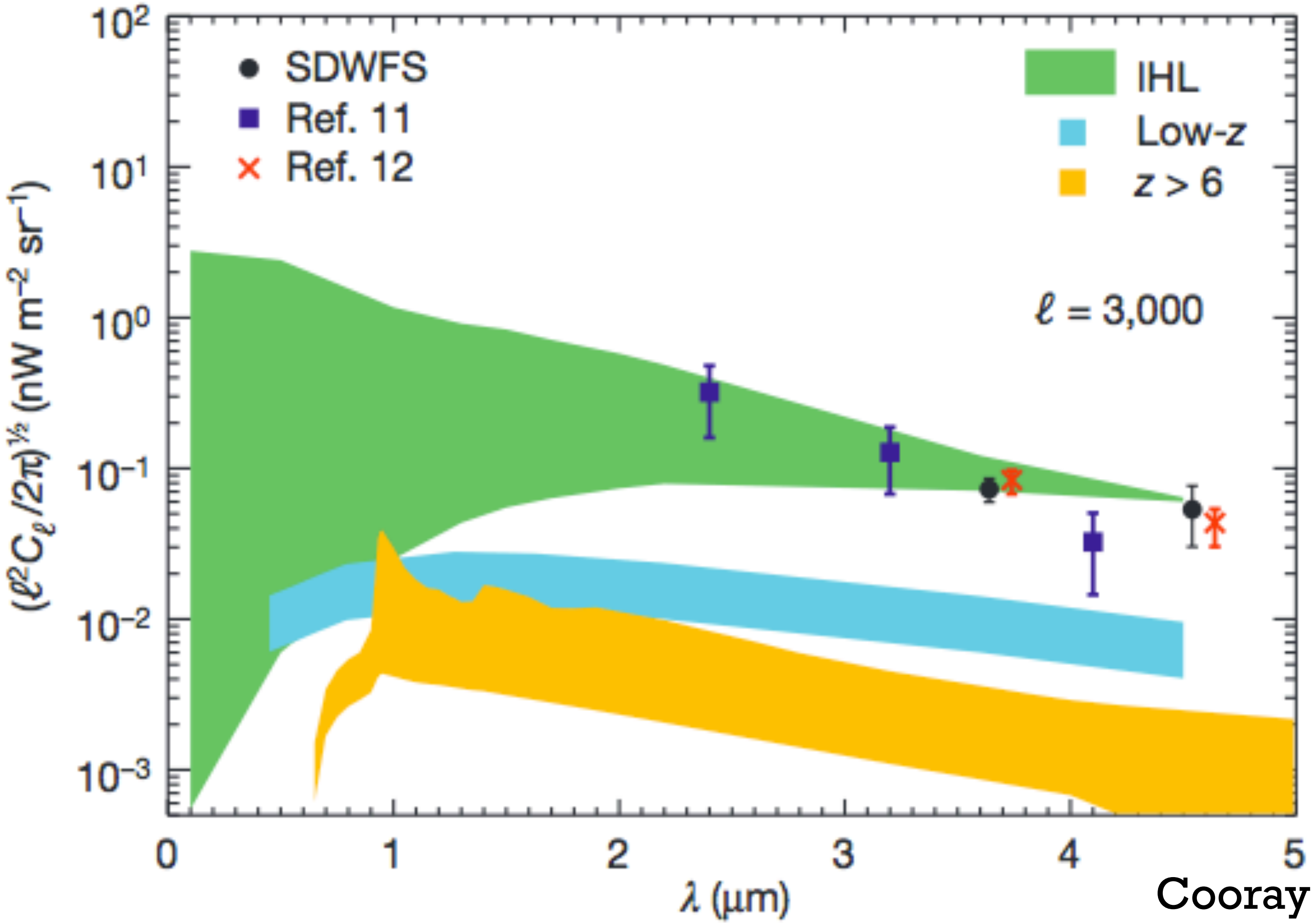
Kashlinsky et al 2012





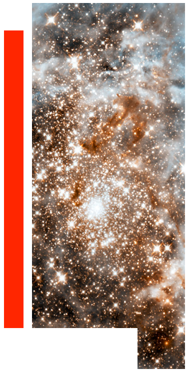
Fernandez et al 2011

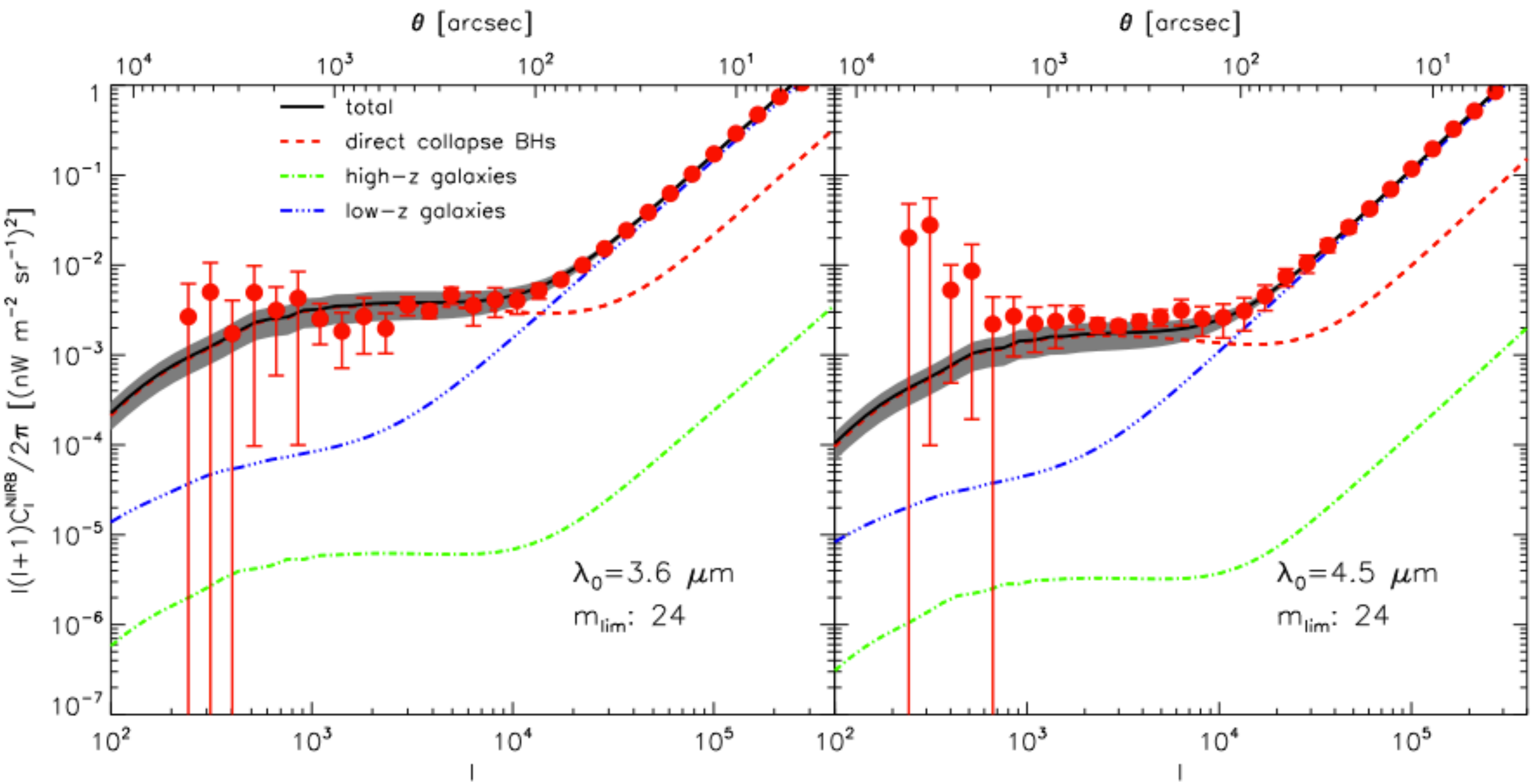
Intrahalo Stars



Cooray et al 2012

Another Possibility – Direct Collapse Black Holes





Yue et al 2013

Improving Observations

- AKARI
  - 13 bands, 2-160 microns
- CIBER (Cosmic Infrared Background Experiment)
  - Rocket borne
  - 7" to 2 degrees
  - Two wide field imagers, 0.8 an 1.6 microns

Fluctuations of the NIRB

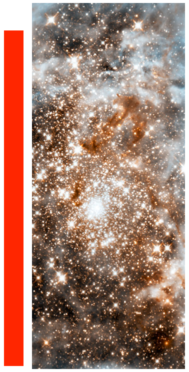
- Fluctuations are a promising method to observe high redshift stars
- Shape of spectra can give information on structures and mass of halos
- Very hard to get information on:
  - Metallicity and mass of stars
  - Star formation time scale
  - Any information about the IGM

- But all is not lost!
- Other observables to break degeneracy
- There's still hope for the IGM…

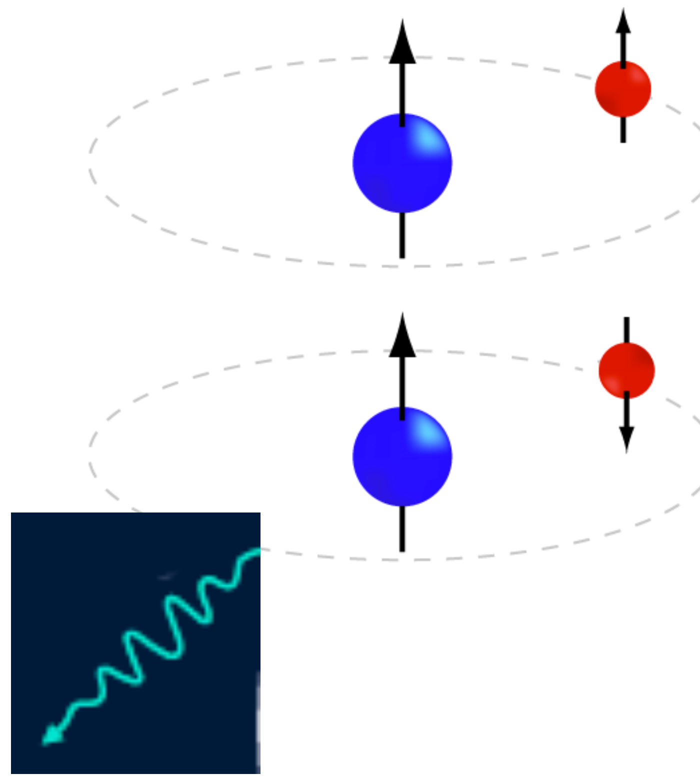
The 21cm Background

a closer look at the IGM

A Quick Intro to the 21 cm Line



- Results from the transition between hyperfine energy levels in neutral H
- Maps where star formation is not occurring
- Good for pre-reionization
- Line emission = direct redshift information



LOFAR

- Epoch of Reionization team – identify 21 cm line

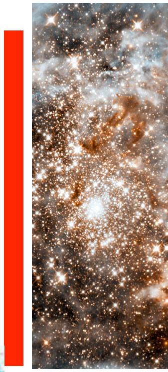
- And map reionization!

Cross Correlating for More Information

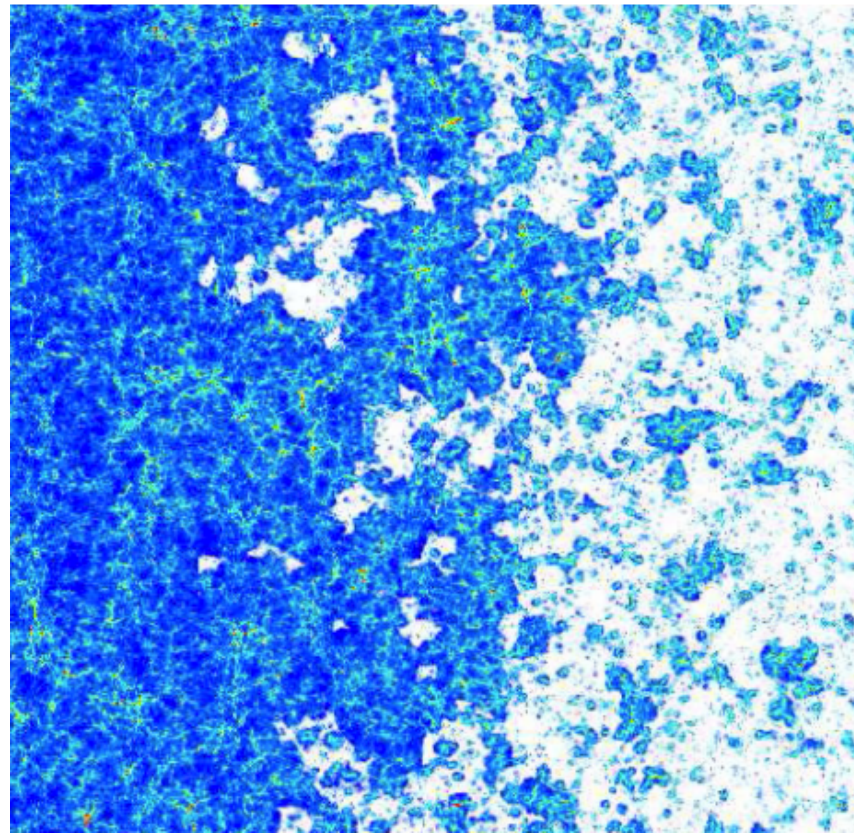
Cross-correlations

- Region dependent
  - 21 cm -> IGM -> Ionization
  - NIRB -> Galaxies -> Stars doing the ionizing
- The 21 cm line gives redshift information
  - This is not given by the NIRB measurements
- The NIRB and the 21cm line are fundamentally linked

In General…

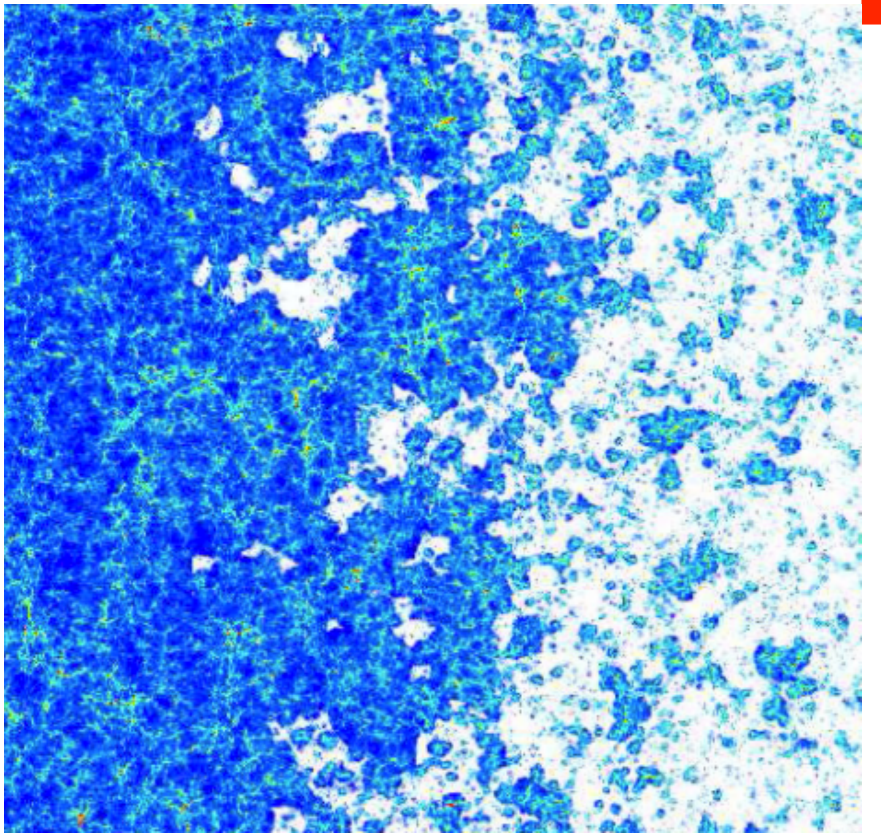


- Regions that are neutral don't have many galaxies to ionize them
- Areas that are bright in the 21cm will be dim in the infrared

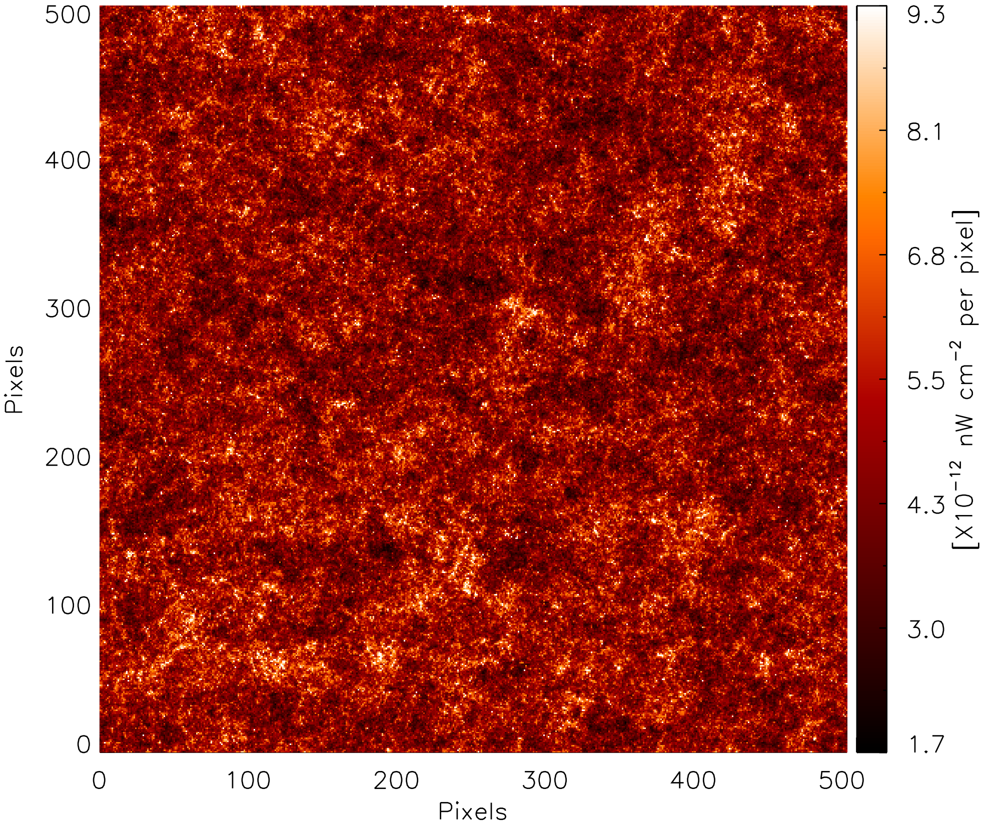


…therefore

- Emission in the infrared and emission in the 21 cm background should be anti-correlated

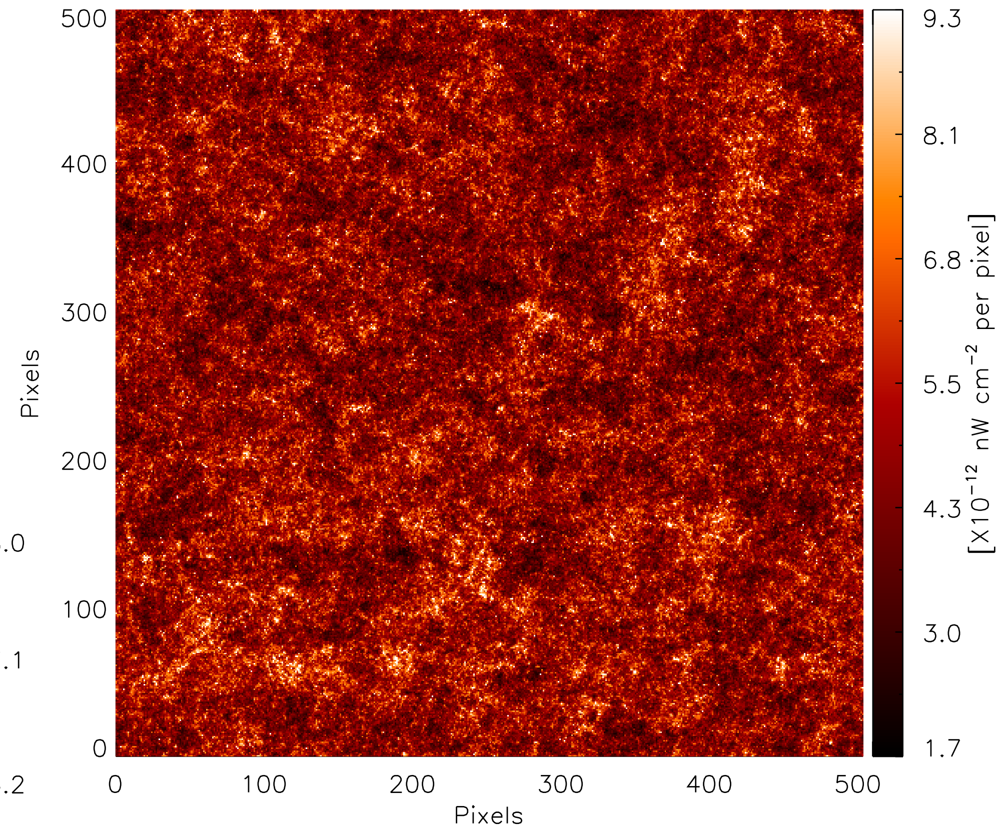


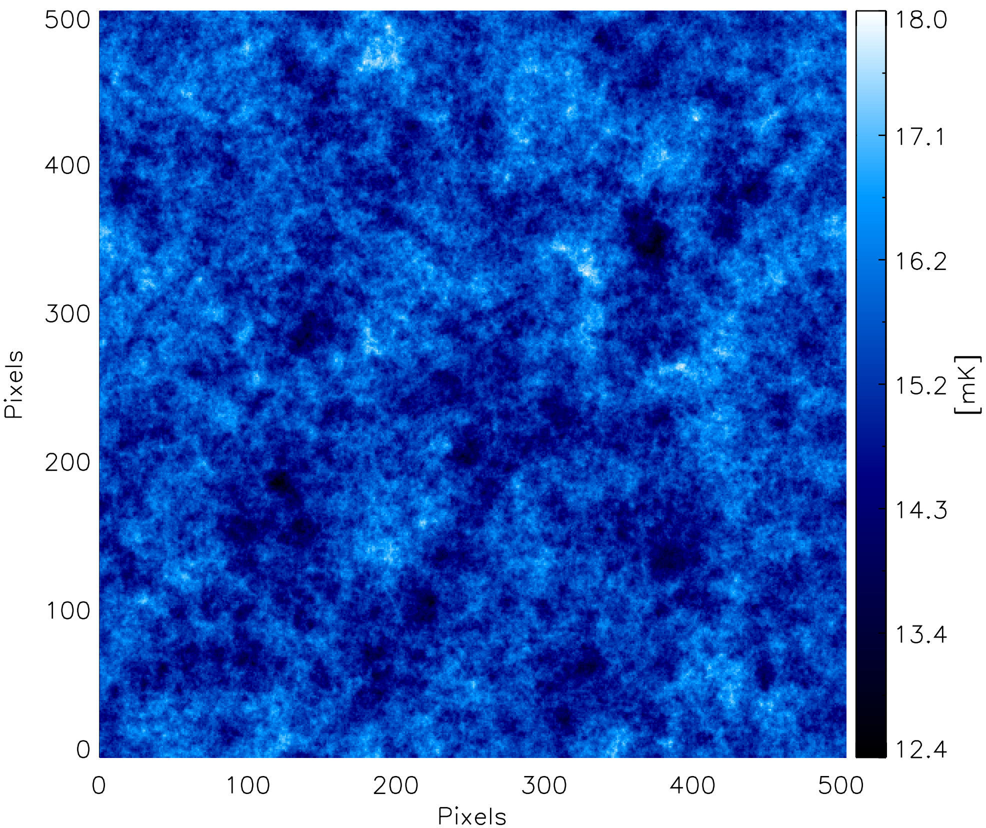
Raw NIRB map



500
400
300
200
100
0
Pixels
0
100
200
300
400
500
Pixels
9.3
8.1
6.8
5.5
4.3
3.0
1.7
[X10^{-12} nW cm^{-2} per pixel]

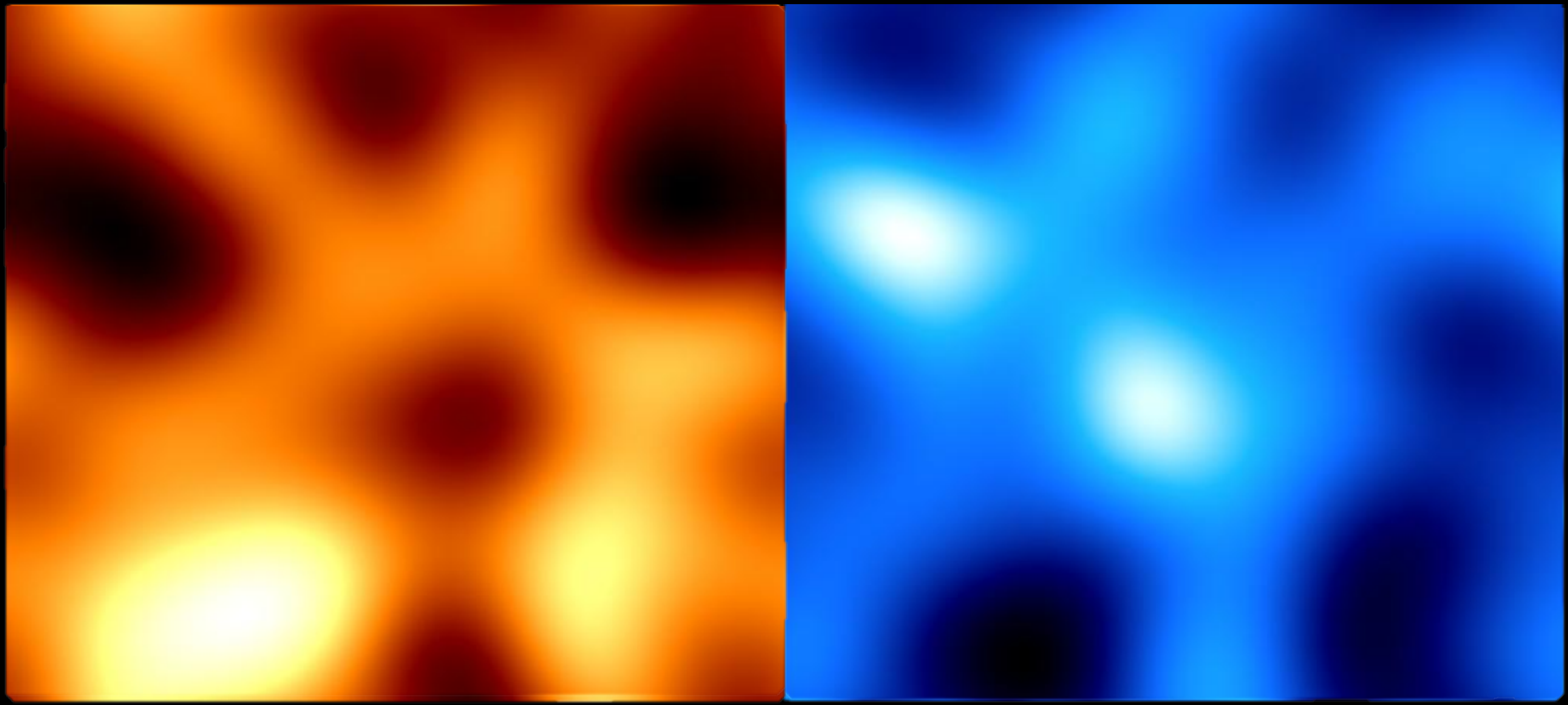
Raw NIRB map

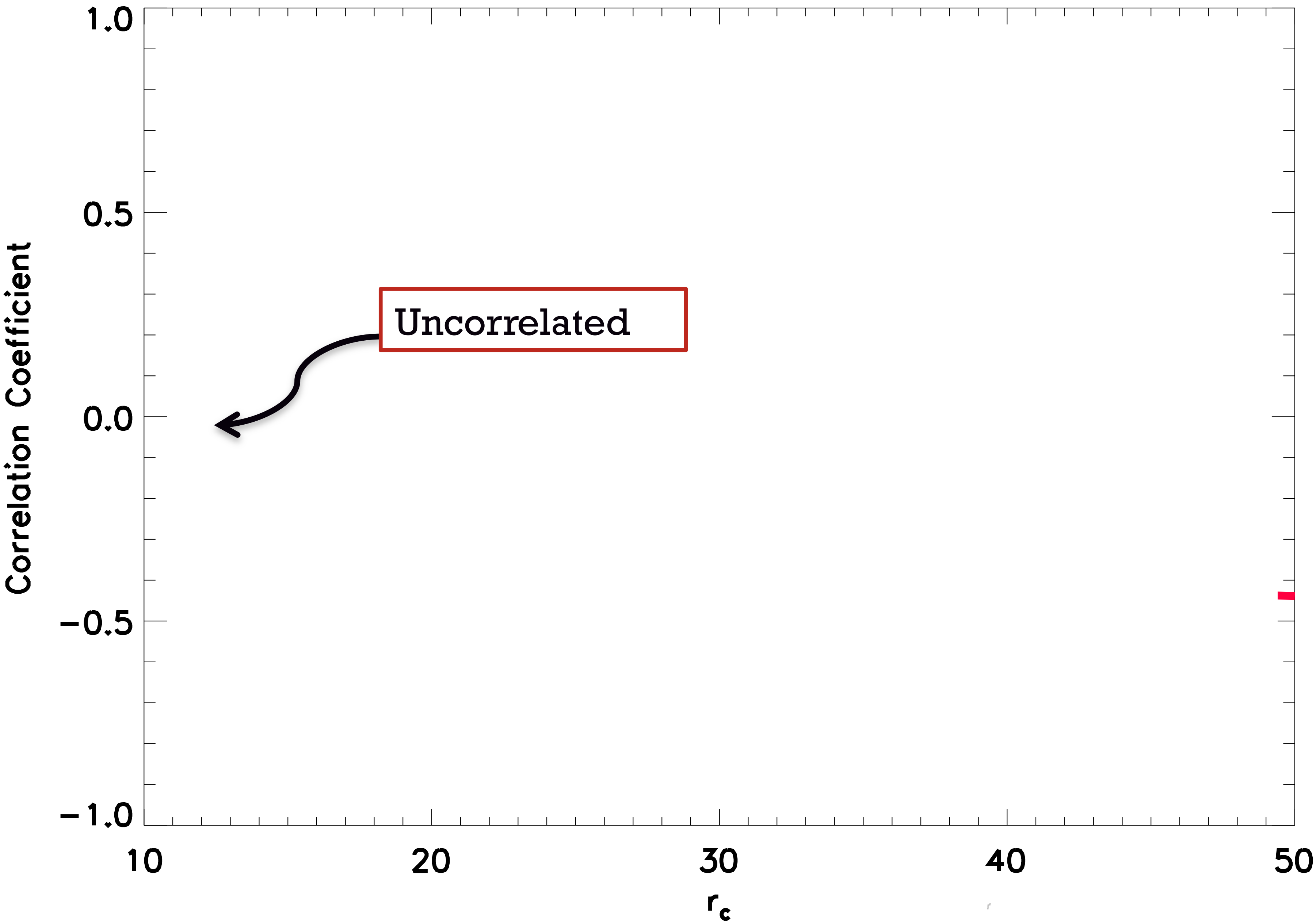




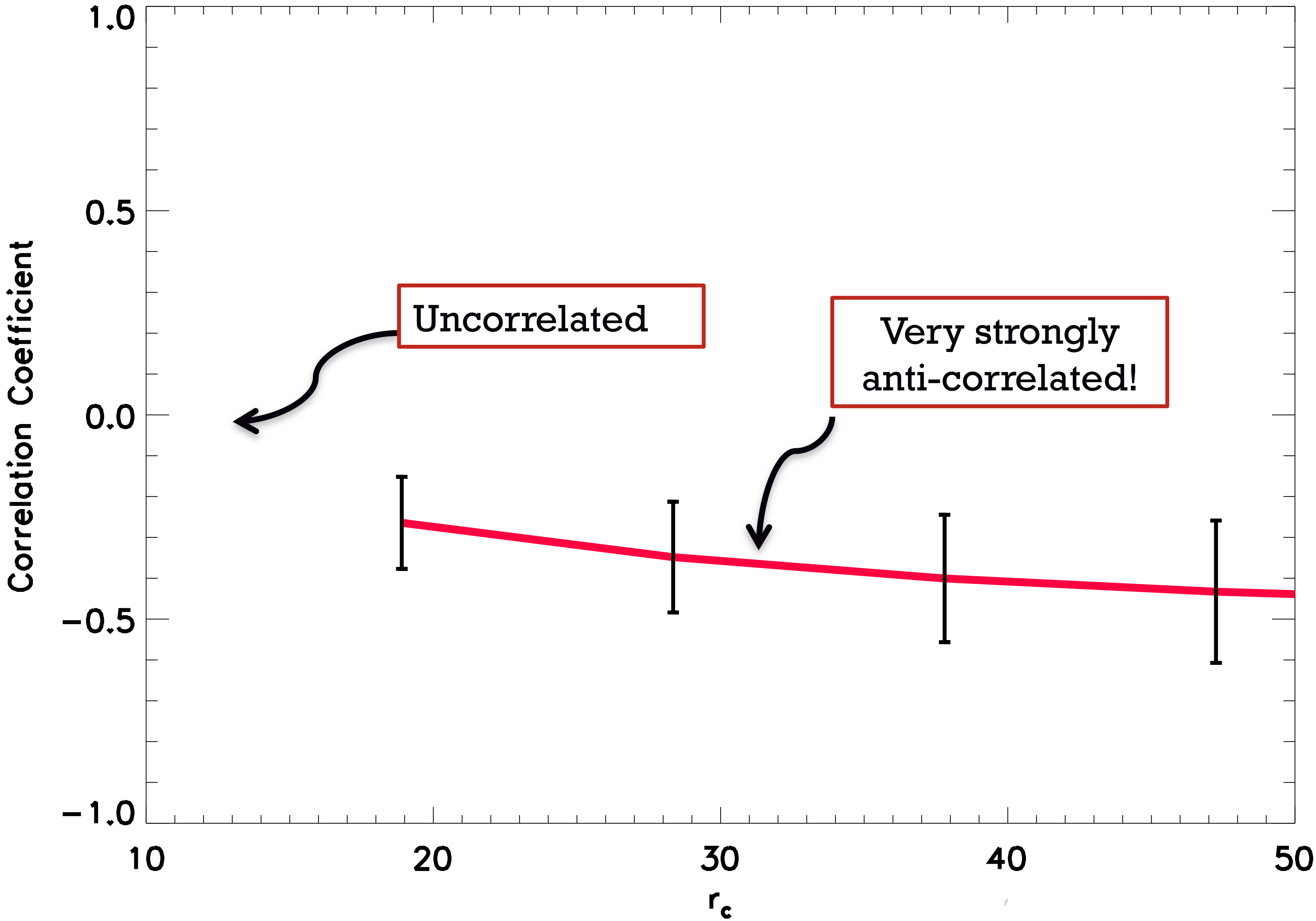
Raw LOFAR map

Perform Gaussian Smoothing

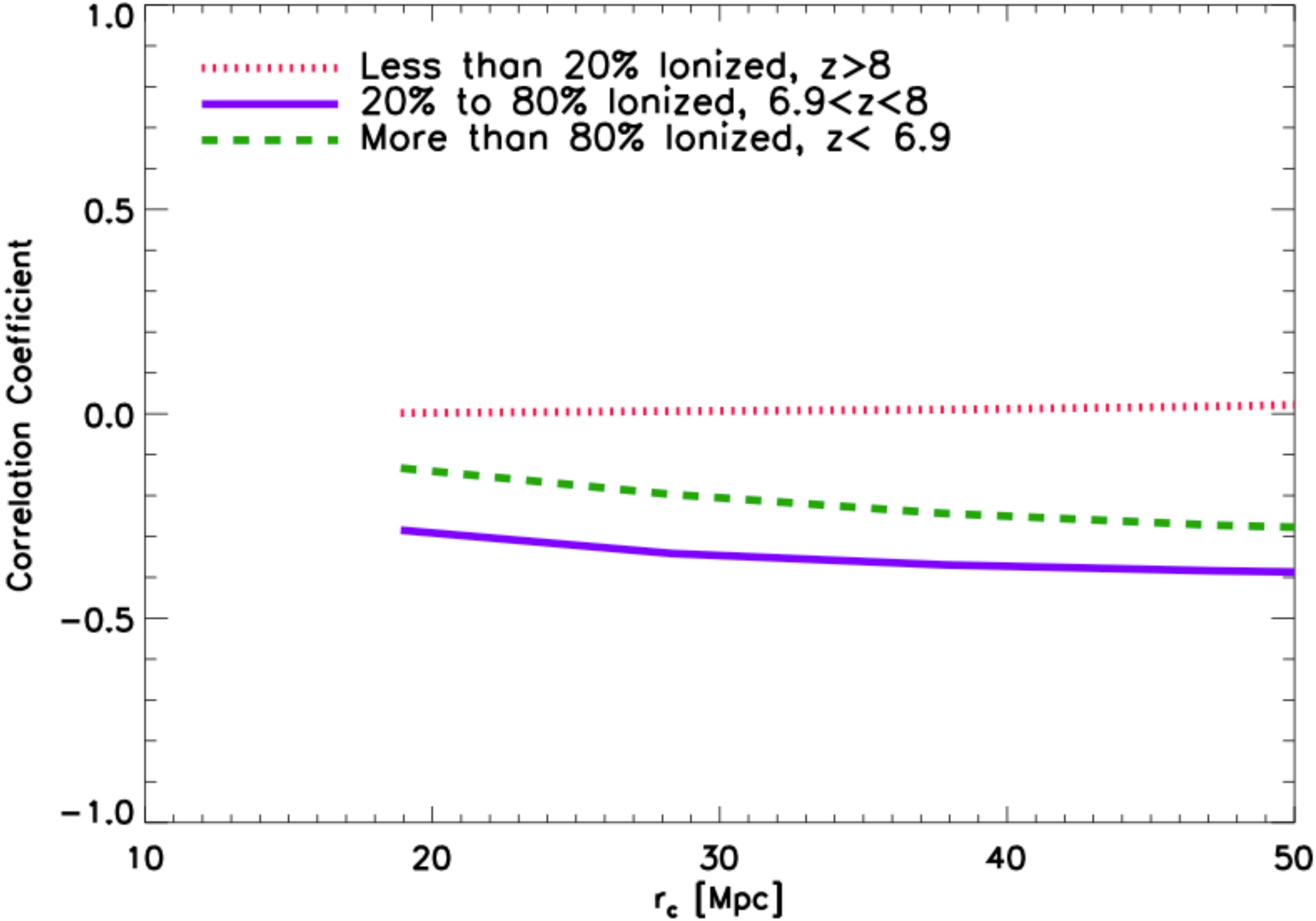




Fernandez et al 2013



Fernandez et al 2013



Fernandez et al 2013

The 21 cm background
and the NIRB
https://www.youtube.com/watch?
v=mbzHn5aMpz4

Learning about the First Generations of Stars Using Observations + Theory

- Properties of Early Stars
  - Star formation rate reflected in amplitude of NIRB.
  - Mass may be reflected in the shape of the spectra of the NIRB
- Development of Structure Formation – seen in shape of NIRB angular power spectrum
  - Can observe masses of galaxies that are emitting
  - Can infer suppression history
  - Anti-correlated with 21cm emission
- Metal Enrichment – be reflected in the shape of the spectra of the NIRB
- Reionization – Cross correlation between NIRB and 21cm background