WMAP Reionization: Implications

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Caltech

Daniel Chalonge 8th Paris Cosmology Colloquium

WMAP Reionization

I. The case for early star-formation

II. First-star signatures in Infrared

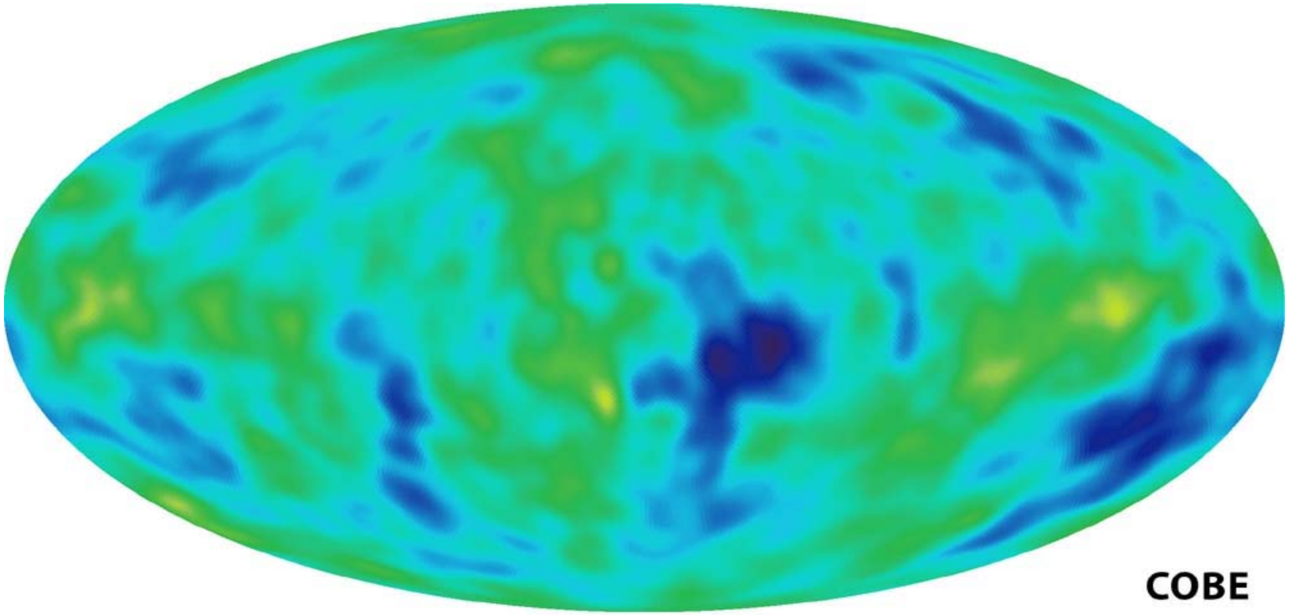
III. First-supernovae signature in small scale CMB via SZ

IV. A Complete Picture: (II) and (III) together and why?

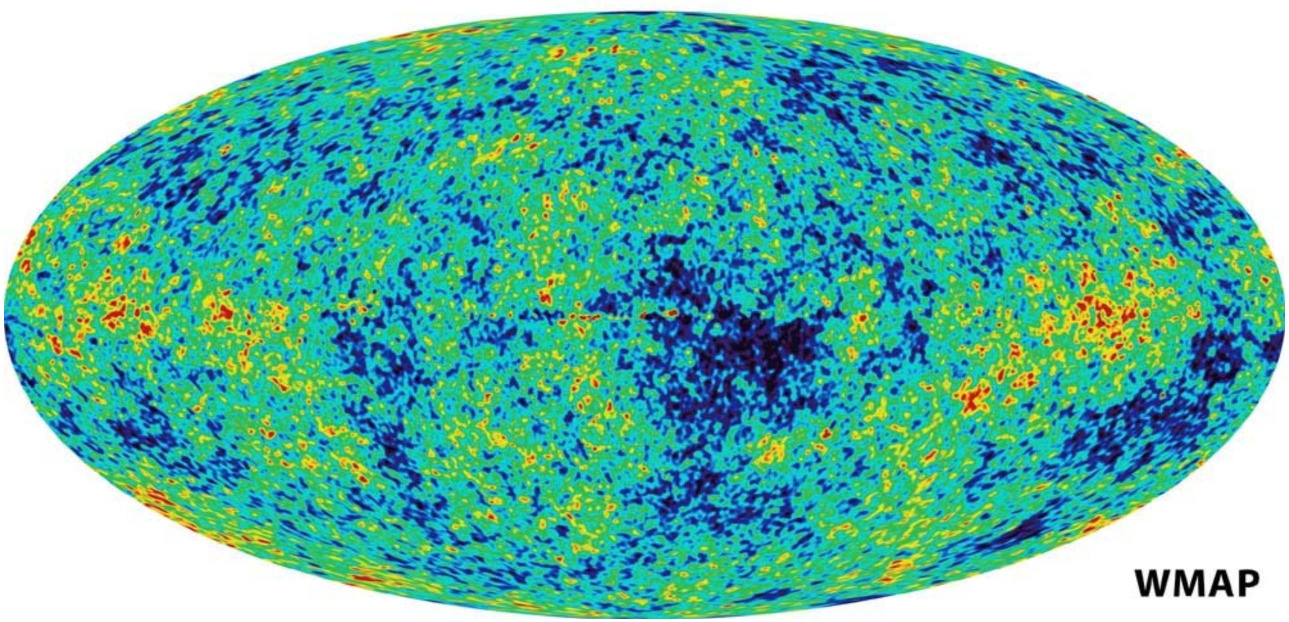
Cooray, Bock, Keating, Lange & Matsumoto 2004 ApJ, in press

Oh, Cooray & Kamionkowski 2003, MNRAS

Cooray 2004, PRD in press

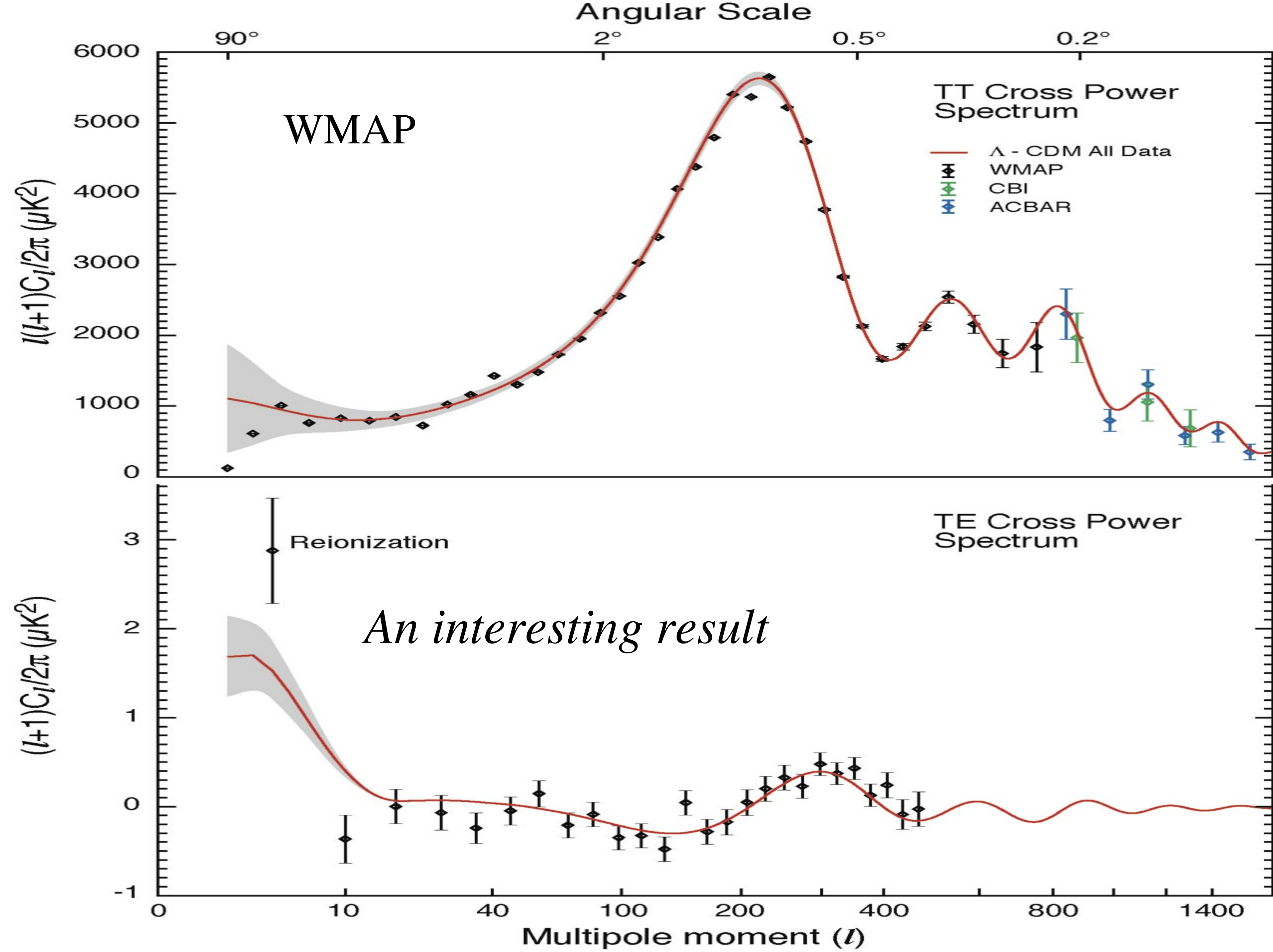


COBE

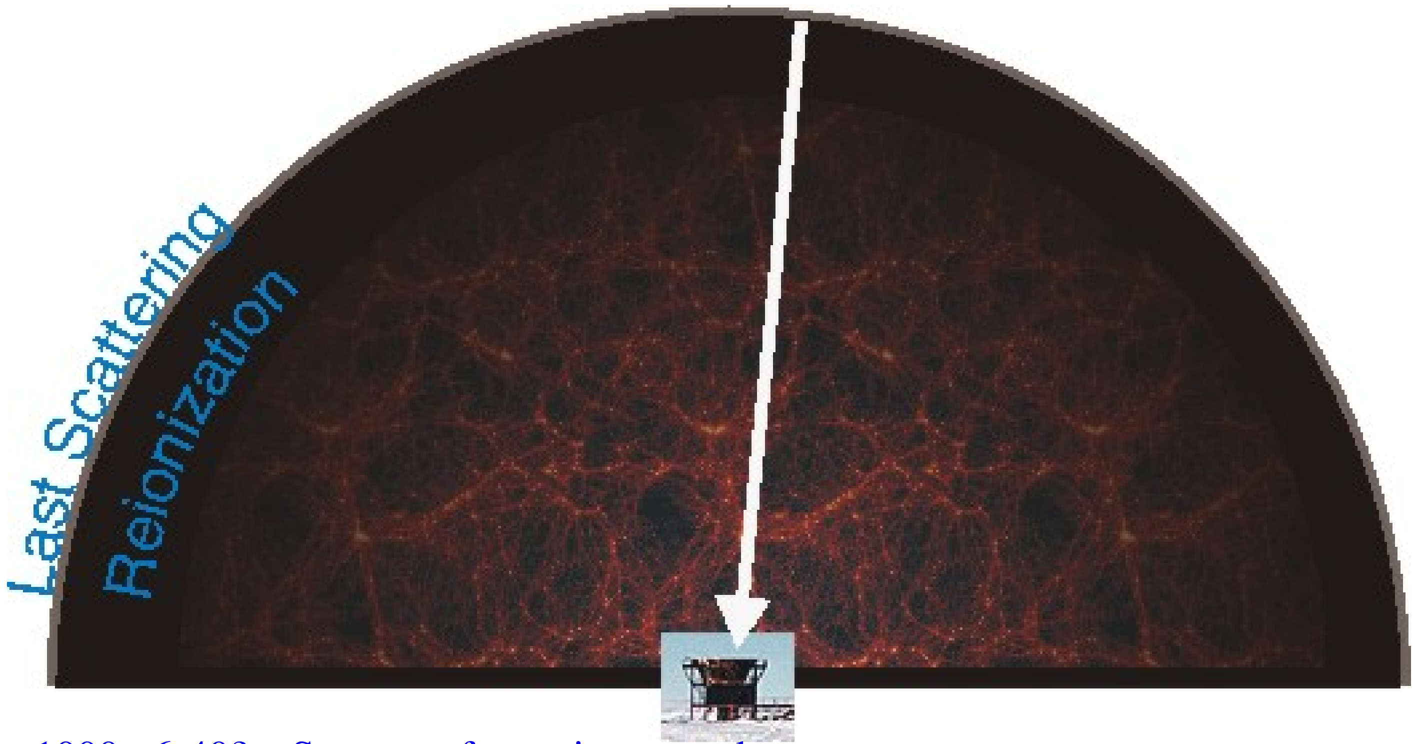


WMAP

http://map.gsfc.nasa.gov


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
WMAP
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
l(l+1)C_l/2π (μK²)
3
2
1
0
-1
Reionization
An interesting result
TE Cross Power Spectrum
(l+1)C_l/2π (μK²)
0
10
40
100
200
400
800
1400
Multipole moment (l)

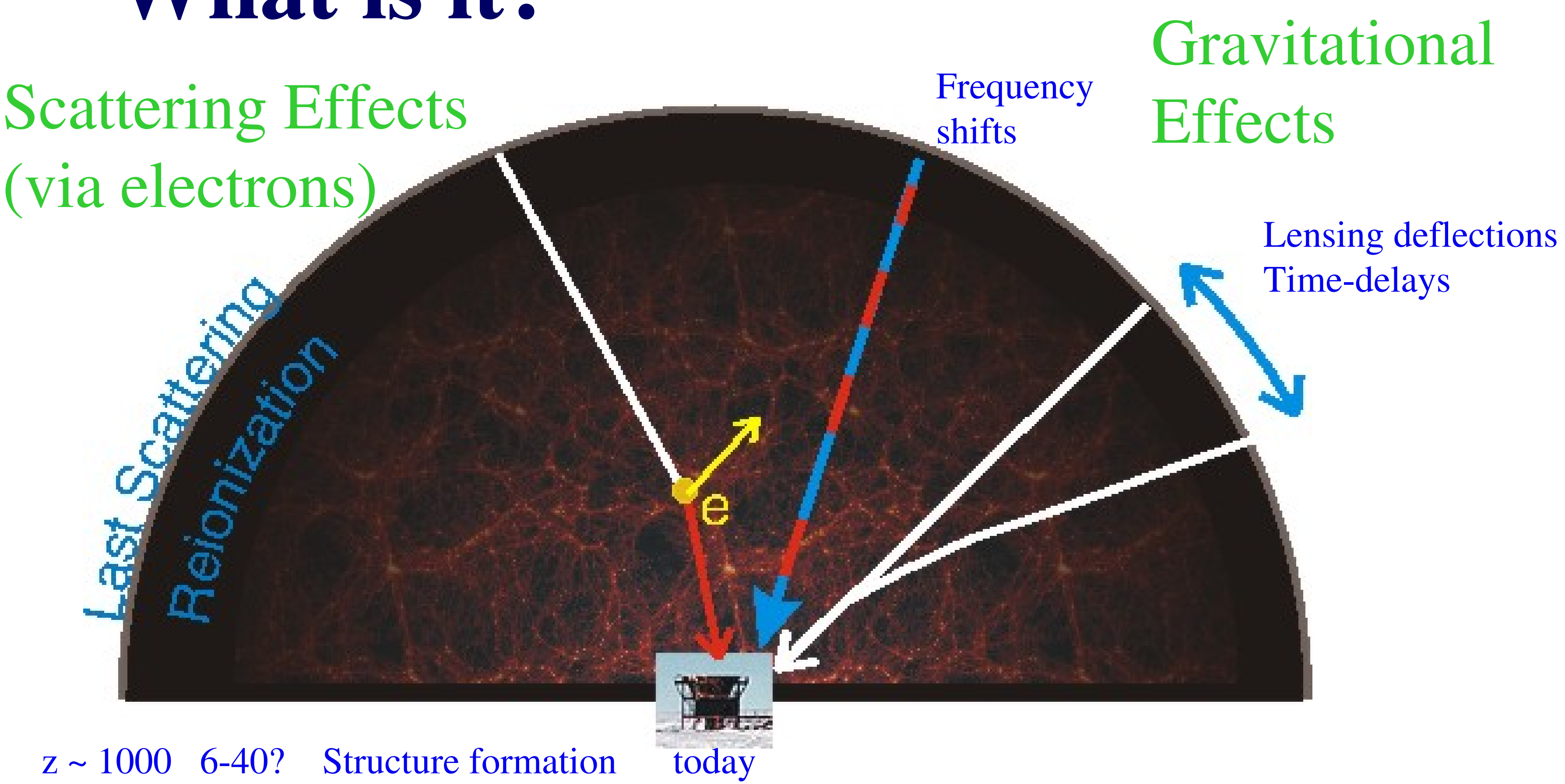
What is it?



z ~ 1000 6-40? Structure formation today

- last scattering: linear physics. Interesting signatures such as acoustic peaks.

What is it?



Simple but an Important fact: changes to CMB from the local universe

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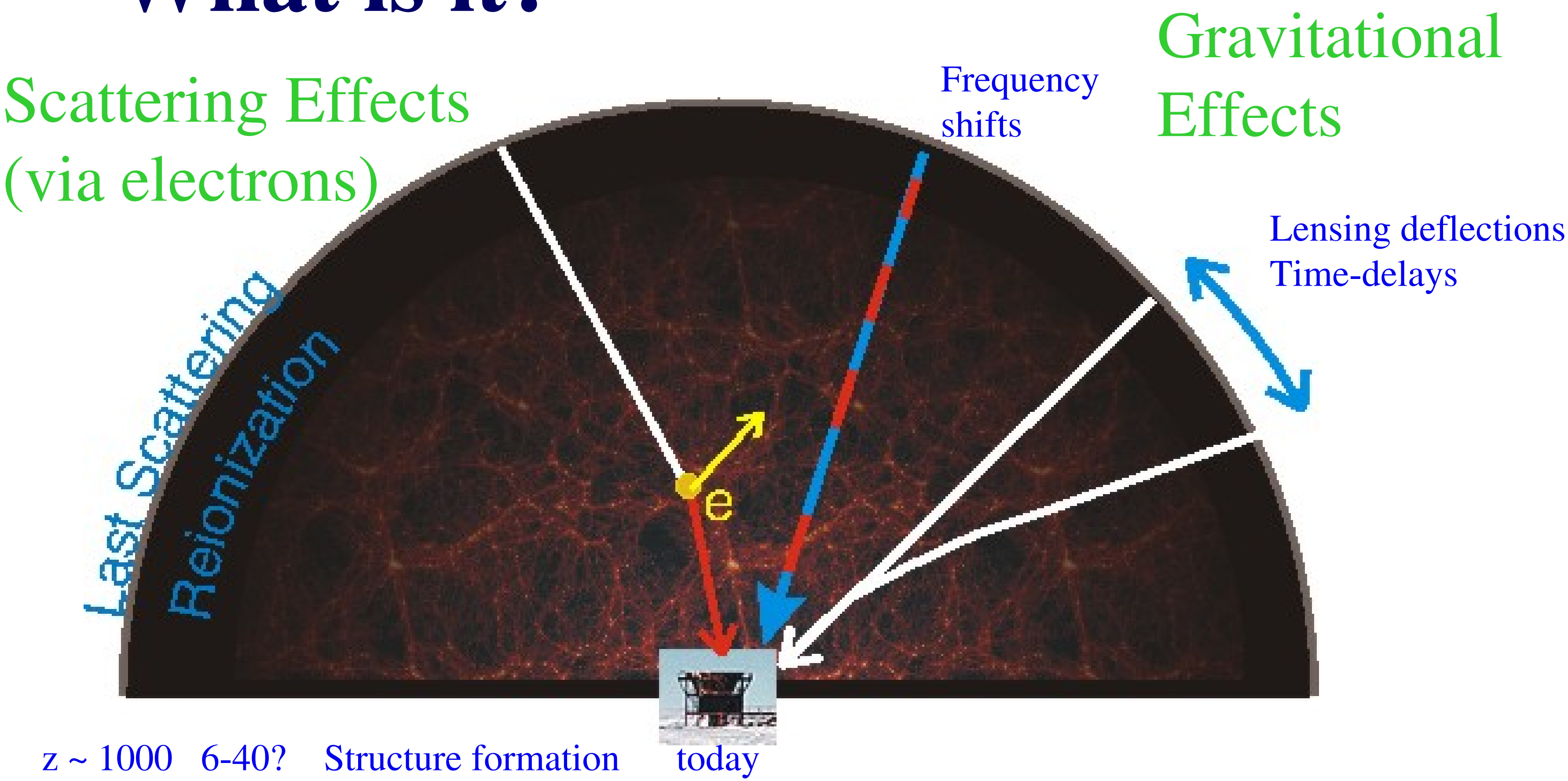
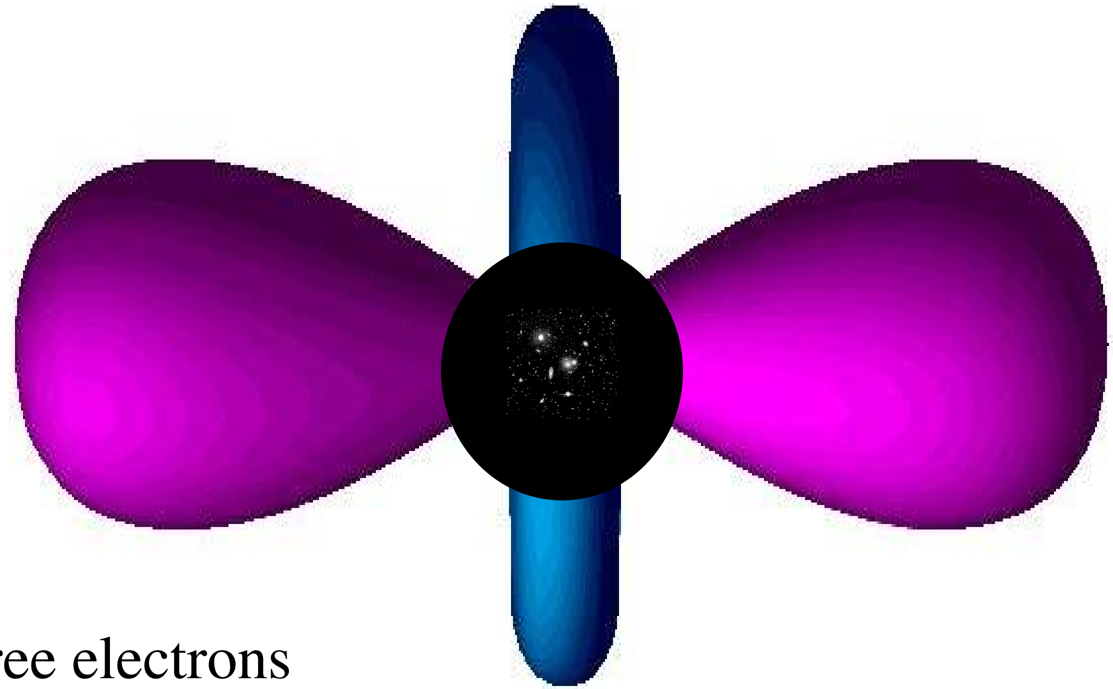


Simple but an Important fact: changes to CMB from the local universe

Strong evidence for early reionization!!

Reionized Signature: Scattering of CMB Quadrupole Produces Polarization



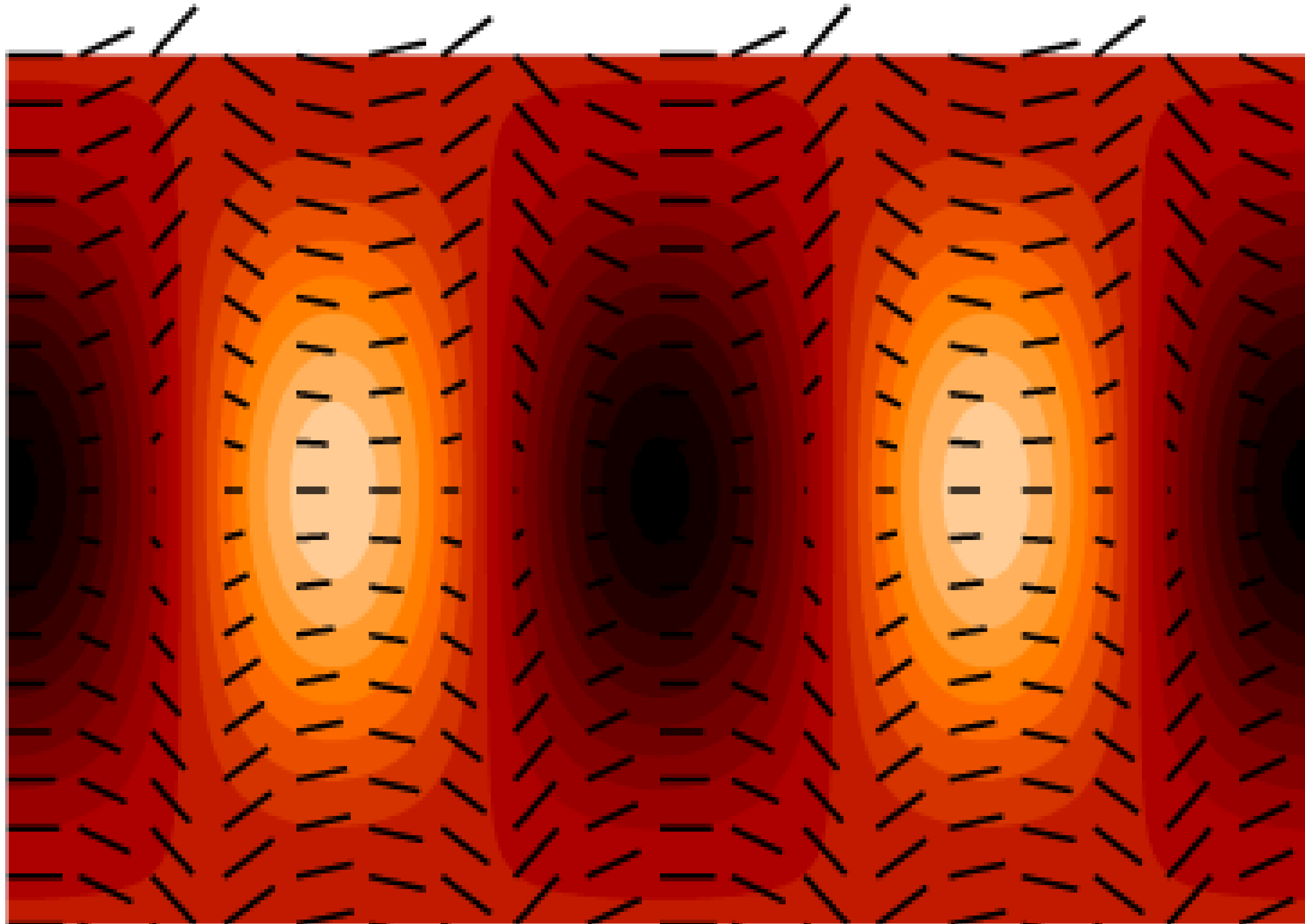
Reionization $\Rightarrow$ Free electrons

Compton scattering of any local quadrupole by electrons lead to polarizatior

When primordial CMB anisotropies are projected

$$P_{\mathrm{Pr}\,im} \propto \tau\, Q^{rms}(z) \propto \sqrt{C_2(z)}$$

Grad: Reionization



Polarization

Reionization $\Rightarrow$ Free electrons

Compton scattering of any local quadrupole by electrons lead to polarization

When primordial CMB anisotropies are projected

$$P_{\mathrm{Pr}\,im} \propto \tau\, Q^{rms}(z) \propto \sqrt{C_2(z)}$$

*G*alaxy Clusters $\Rightarrow$ Tons of Free electrons

Compton scattering of the quadrupole lead to SZ polarizatior

When primordial CMB anisotropies are projected

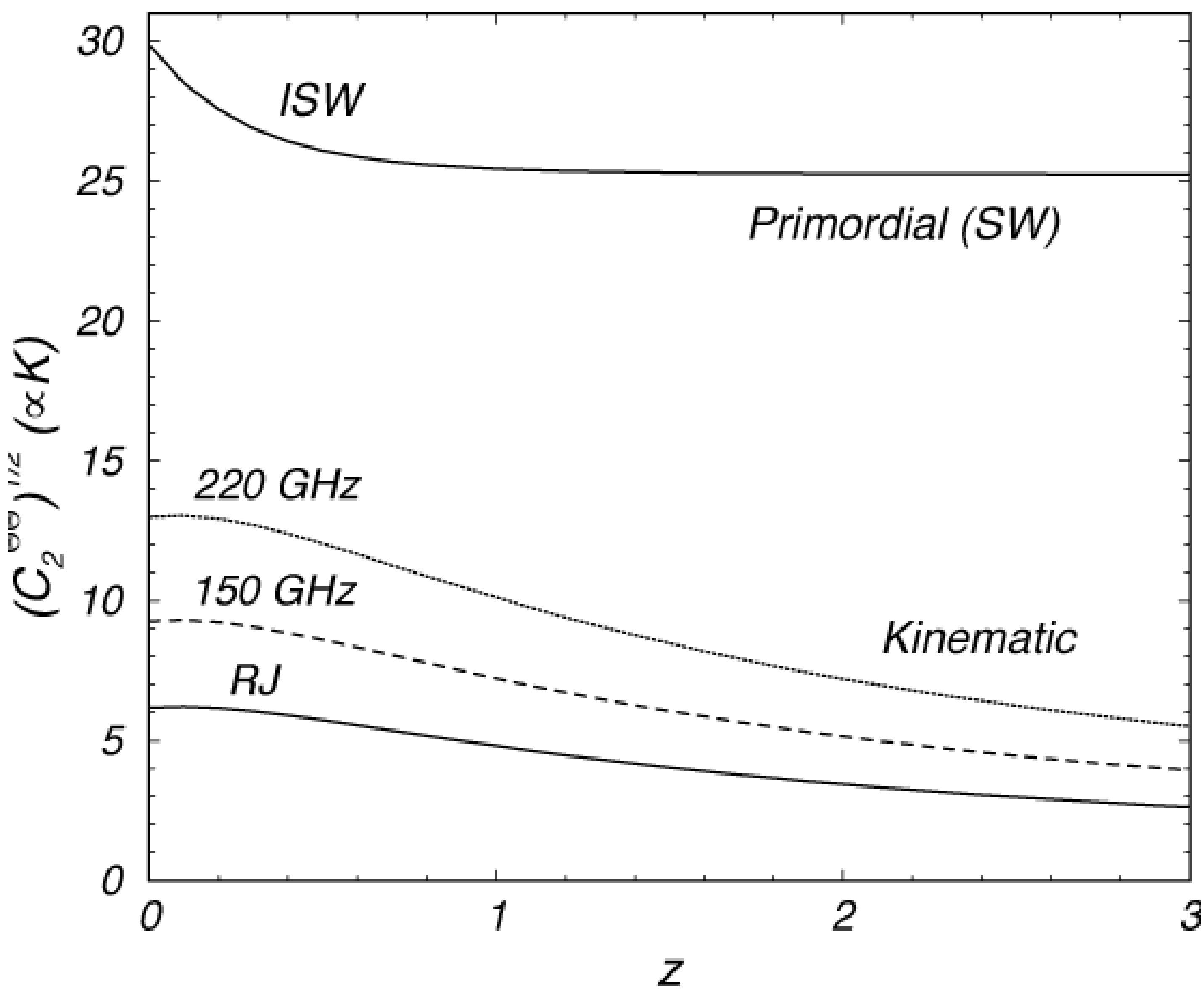
$$P_{\mathrm{Pr}\,im} \propto \tau\, Q^{rms}(z) \propto \sqrt{C_2(z)}$$

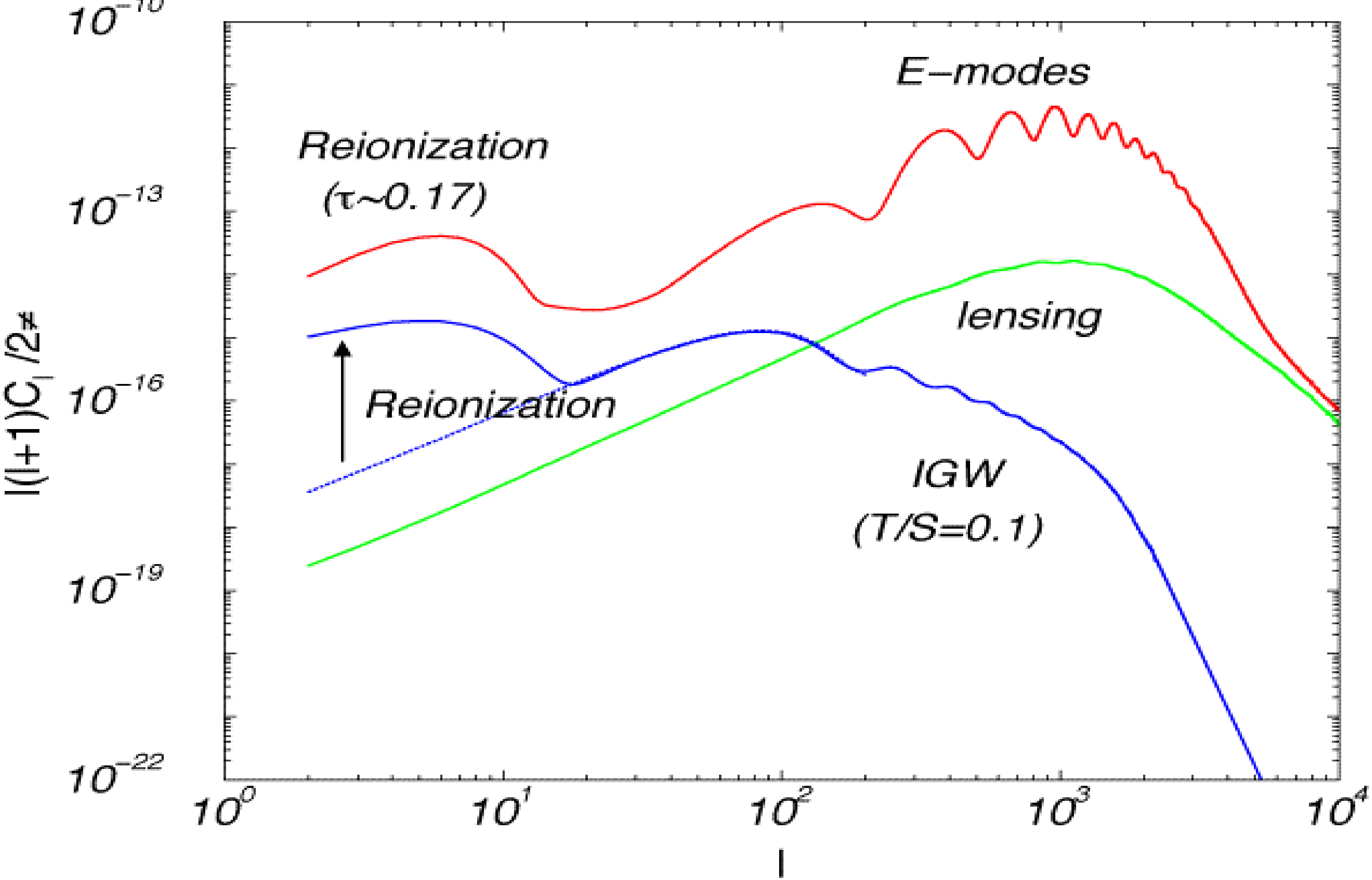
Cosmologically Important contribution

At large scales, two sources of contribution to $C_{l=2}(z)$

$$\frac{\Delta T}{T} = \left.\frac{\Phi}{3}\right|_{z=LSS} + 2\int d\eta \frac{d\Phi}{d\eta}$$

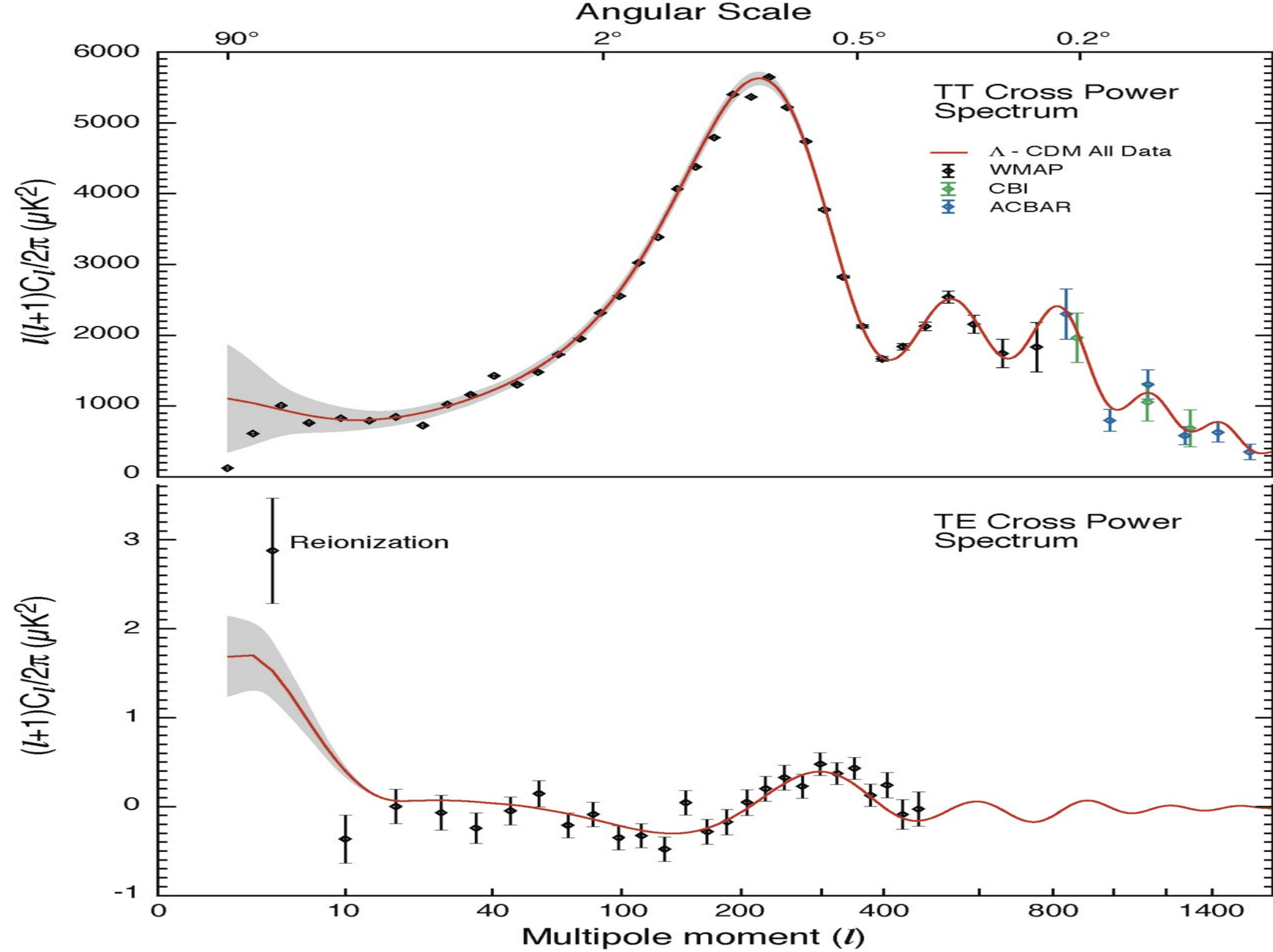
SW ISW


ISW
Primordial (SW)
220 GHz
150 GHz
Kinematic
RJ
30
25
20
15
10
5
0
0
1
2
3
z



(Reionization aids detection of Gravitational Waves)

Cooray 2002



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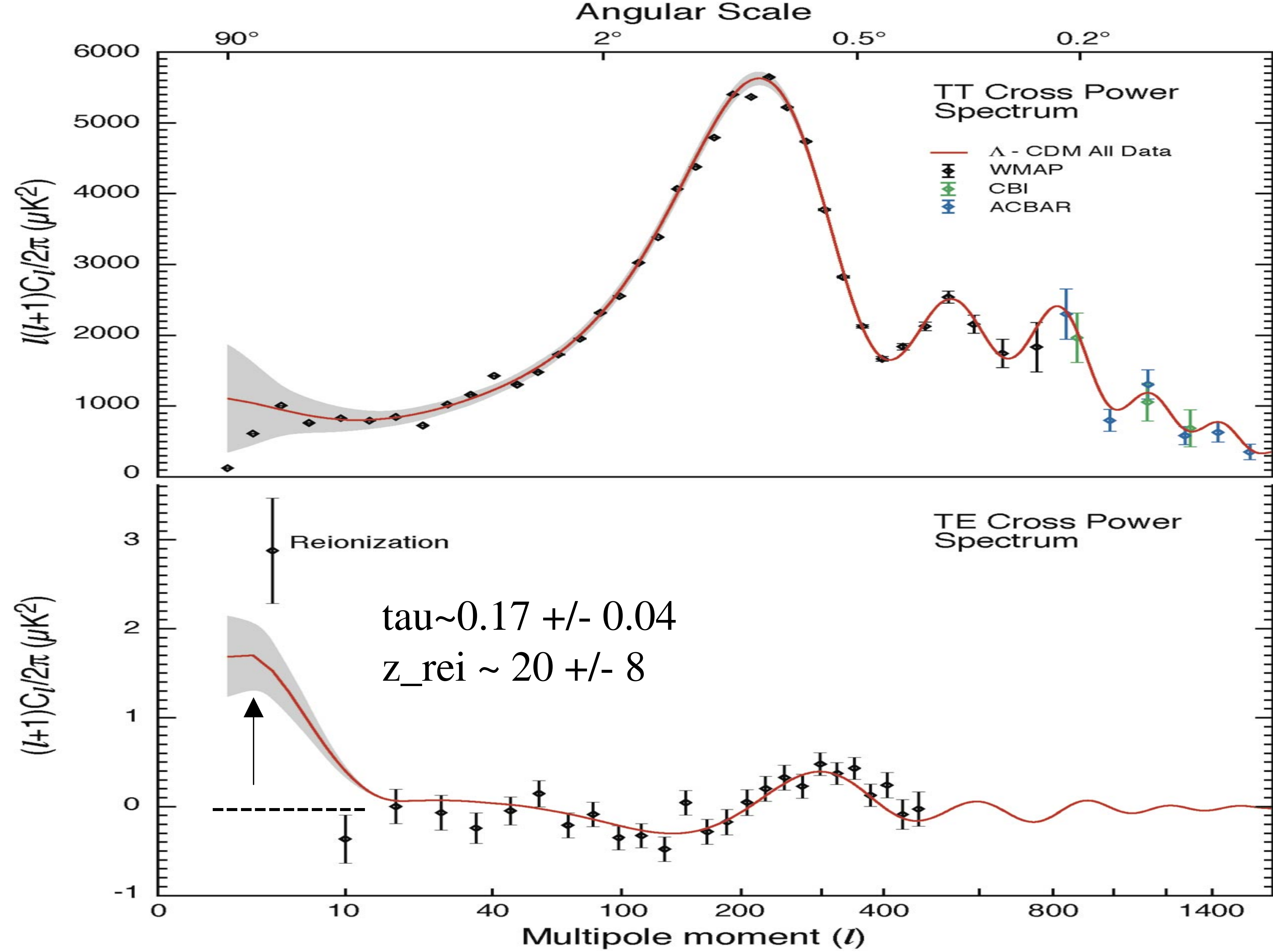

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z_rei ~ 20 +/- 8
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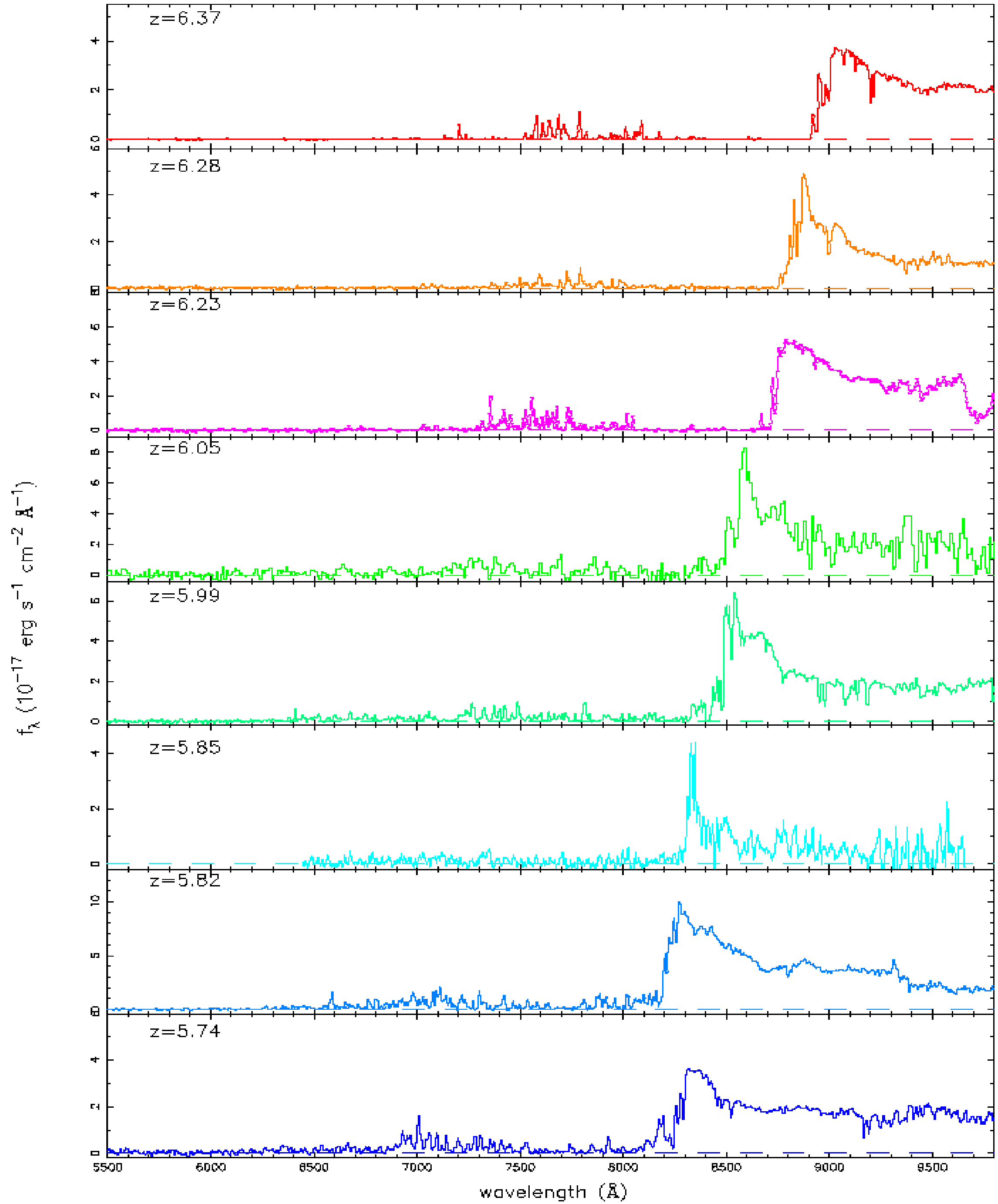
Why the reionization history may not be uniform?

Evidence from the Sloan Survey

(Fan et al. 2001)



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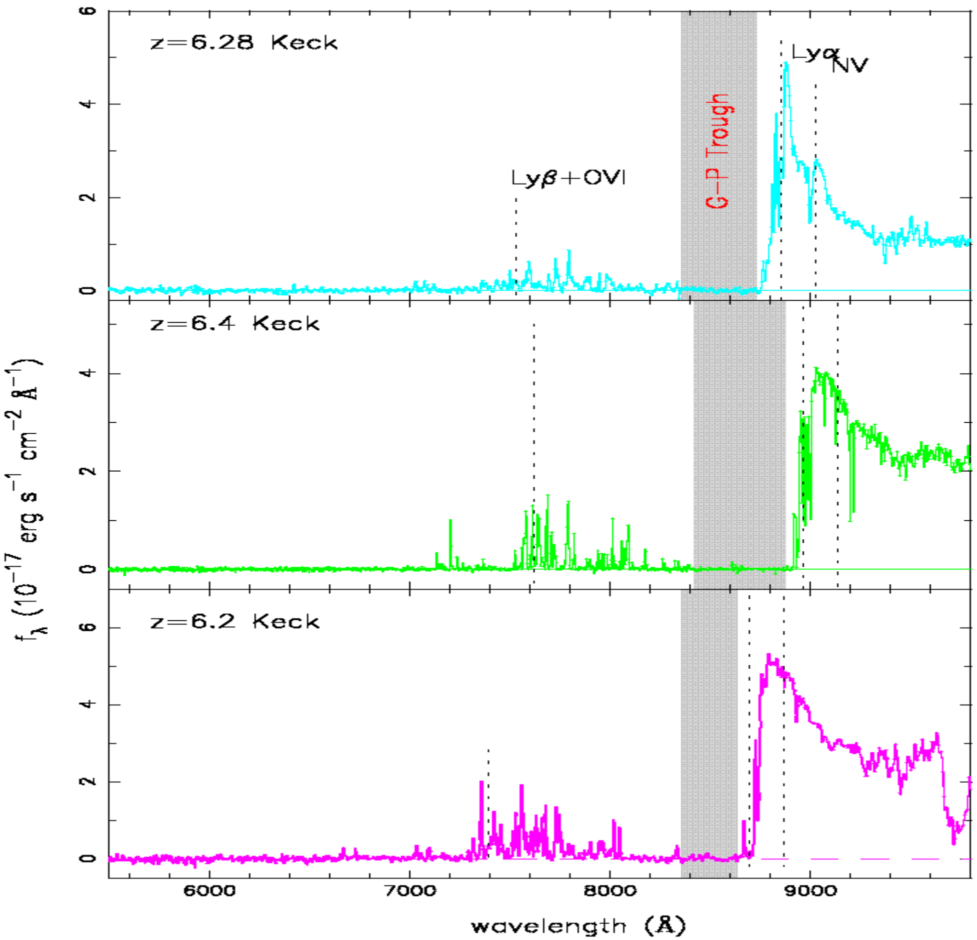

Gunn-Peterson troughs

-> Absorption by neutral Hydrogen

What reionized the universe?

Leading candidates

1. UV radiation from stars

Most likely

2. UV radiation from AGNs

(not enough)

3. The exotics
   decaying dark matter
   decaying neutrinos

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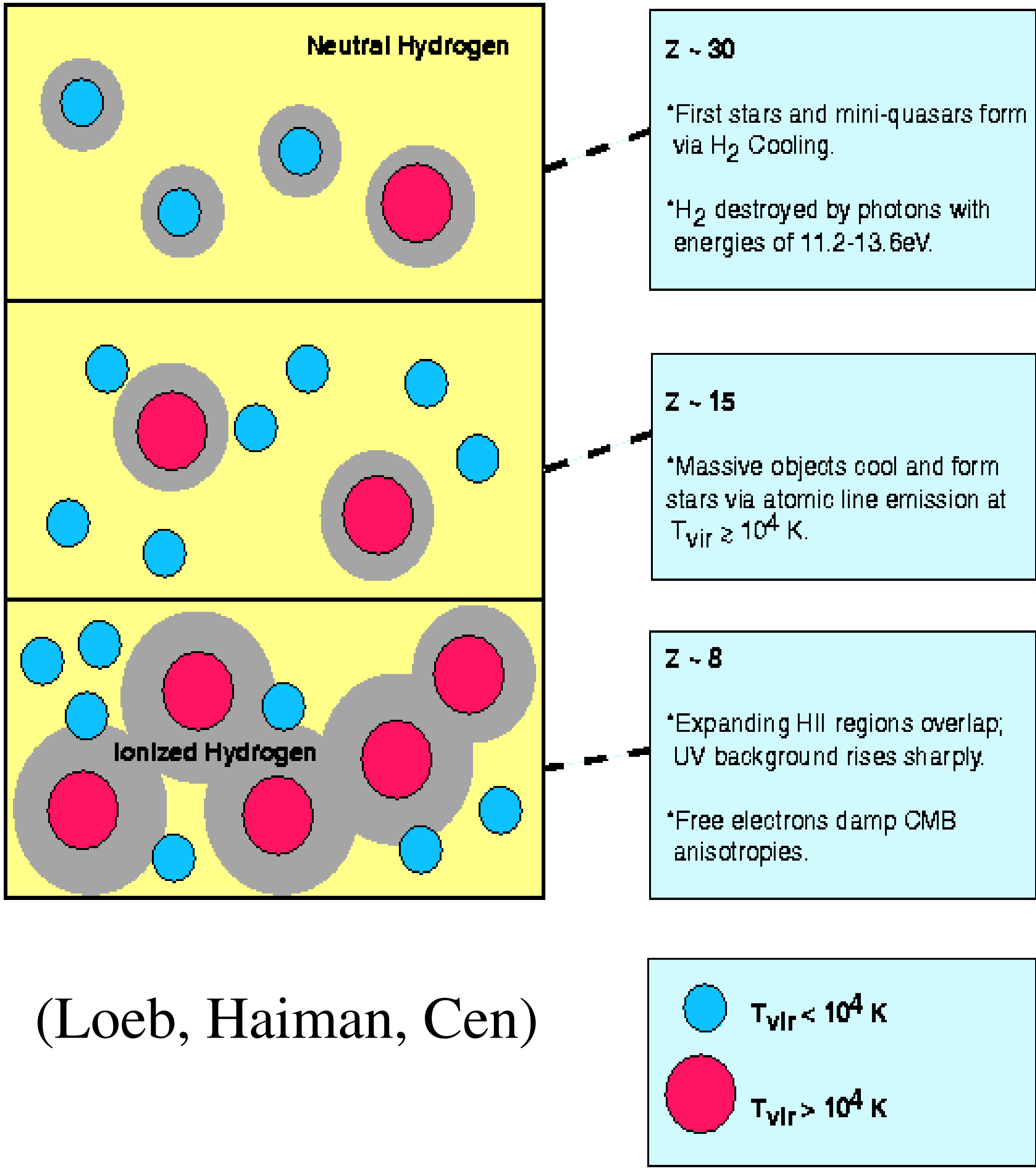
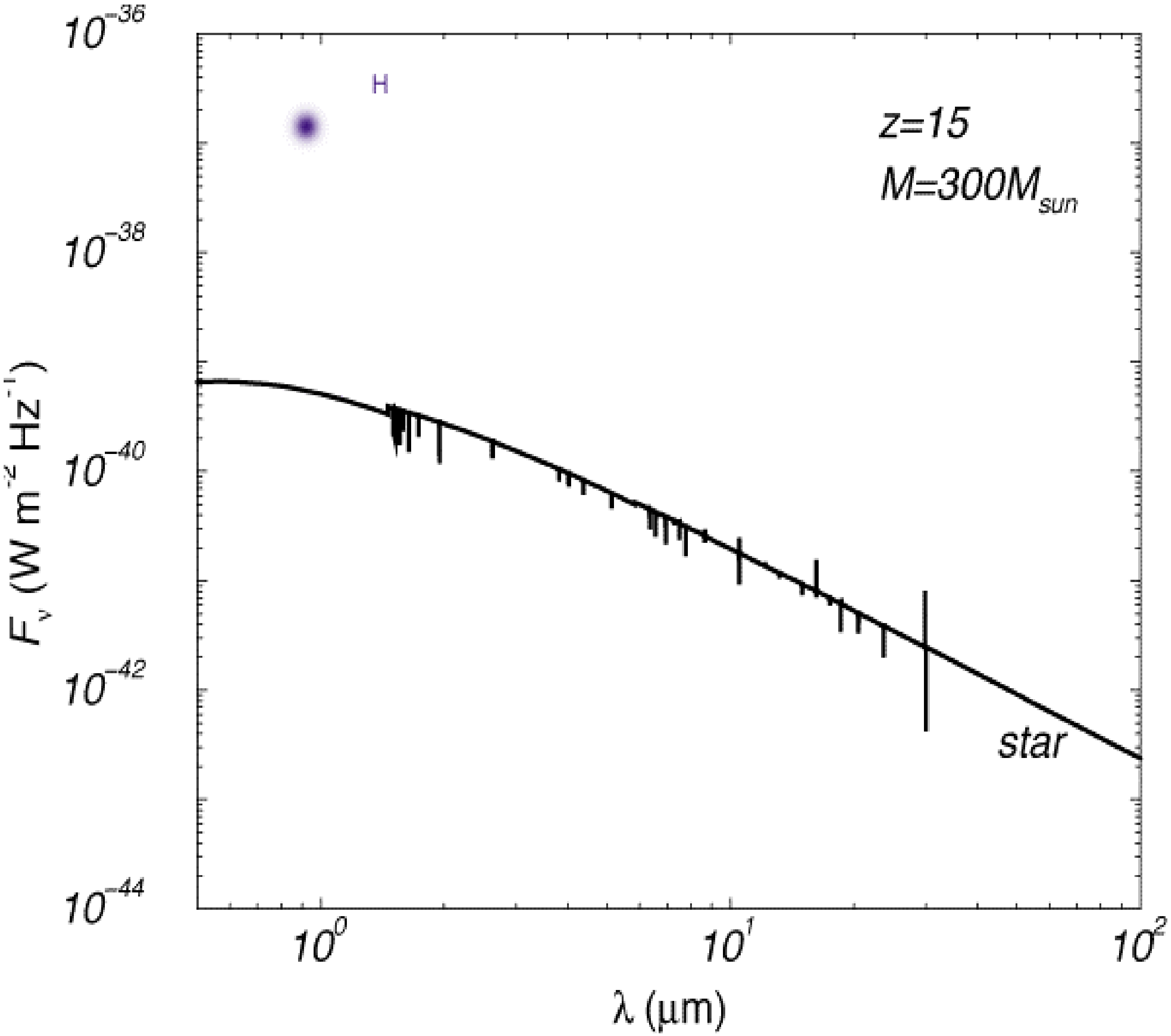


(Loeb, Haiman, Cen)

Can we detect the signature of first stars directly?



First star spectrum

Black body

T~$10^{4.8 \text{ to } 5}$ K

L~10^{38} M/M_{solar} ergs sec^{-1} <~ L_{edd}

t_{life}~10^6 years

(Scherrer 2002; Bromm et al. 2002; Santos et al. 2001)

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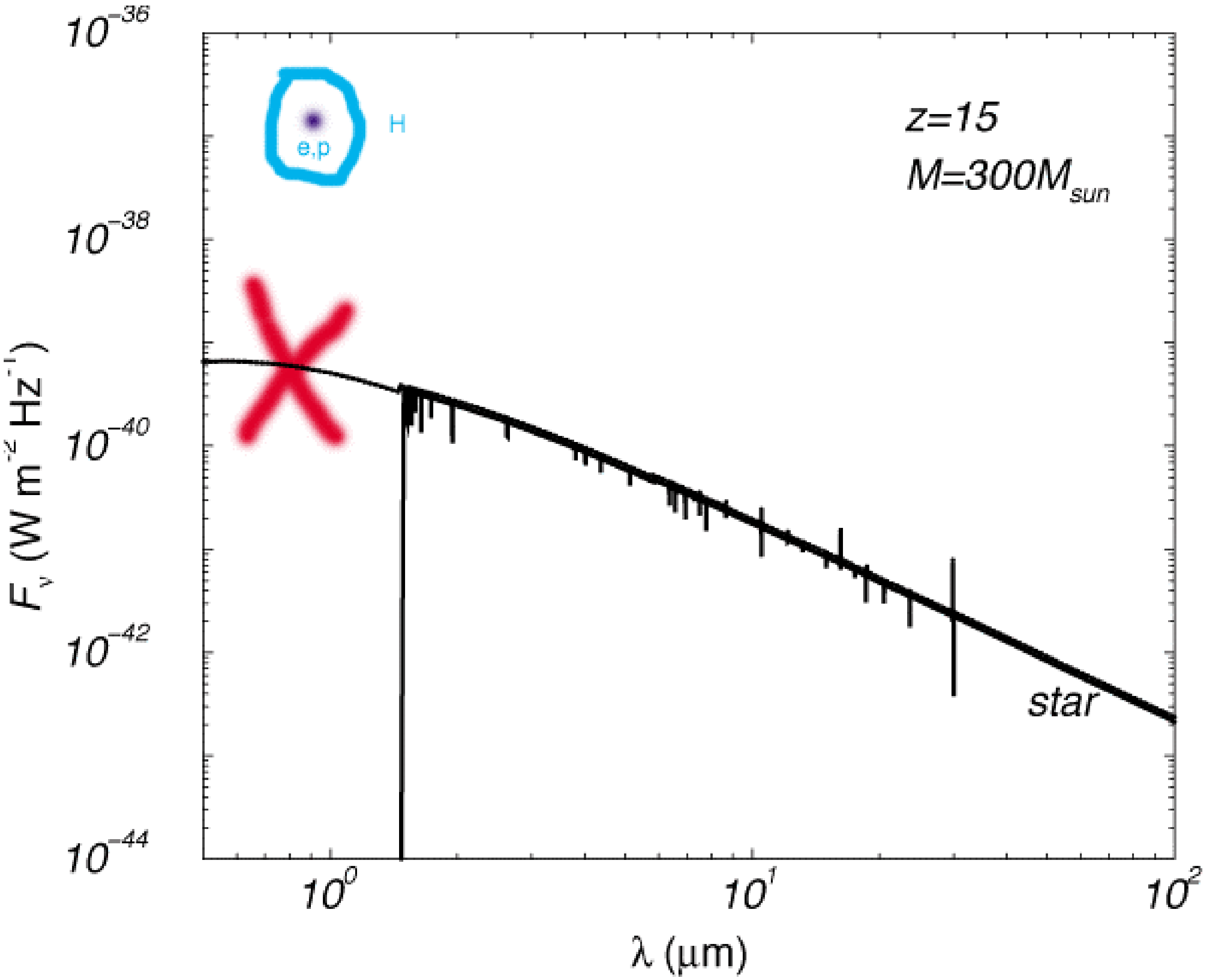

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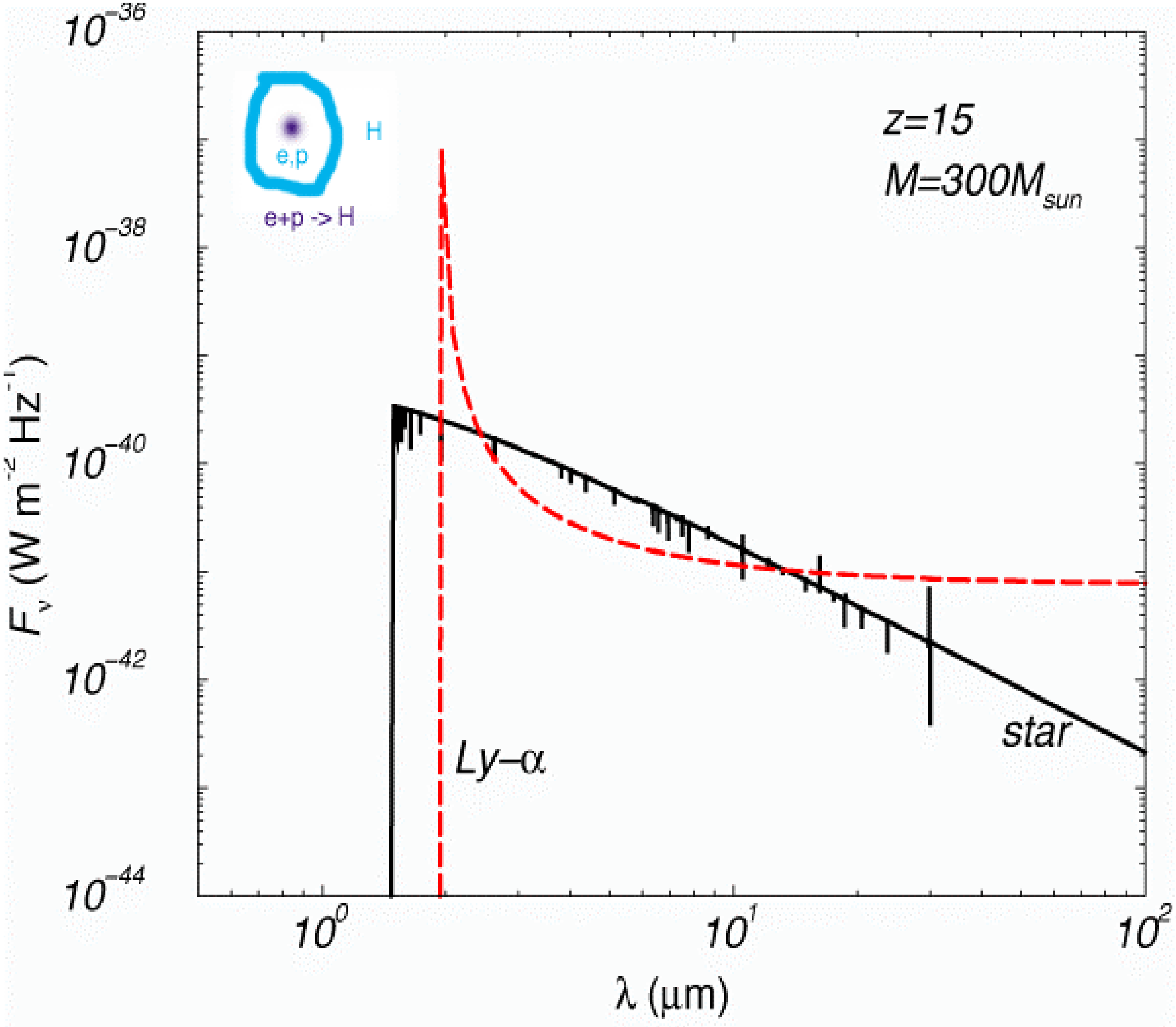

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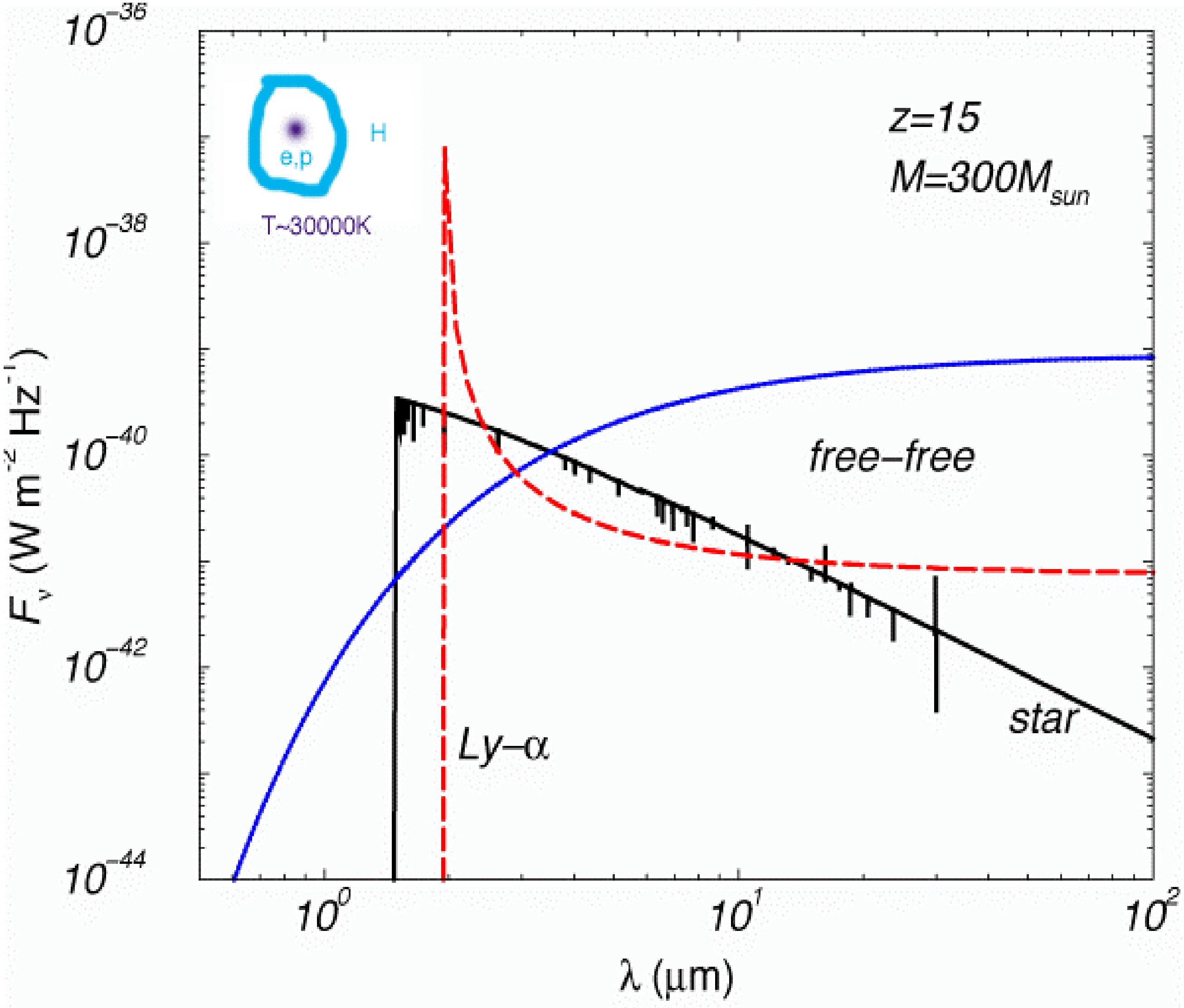

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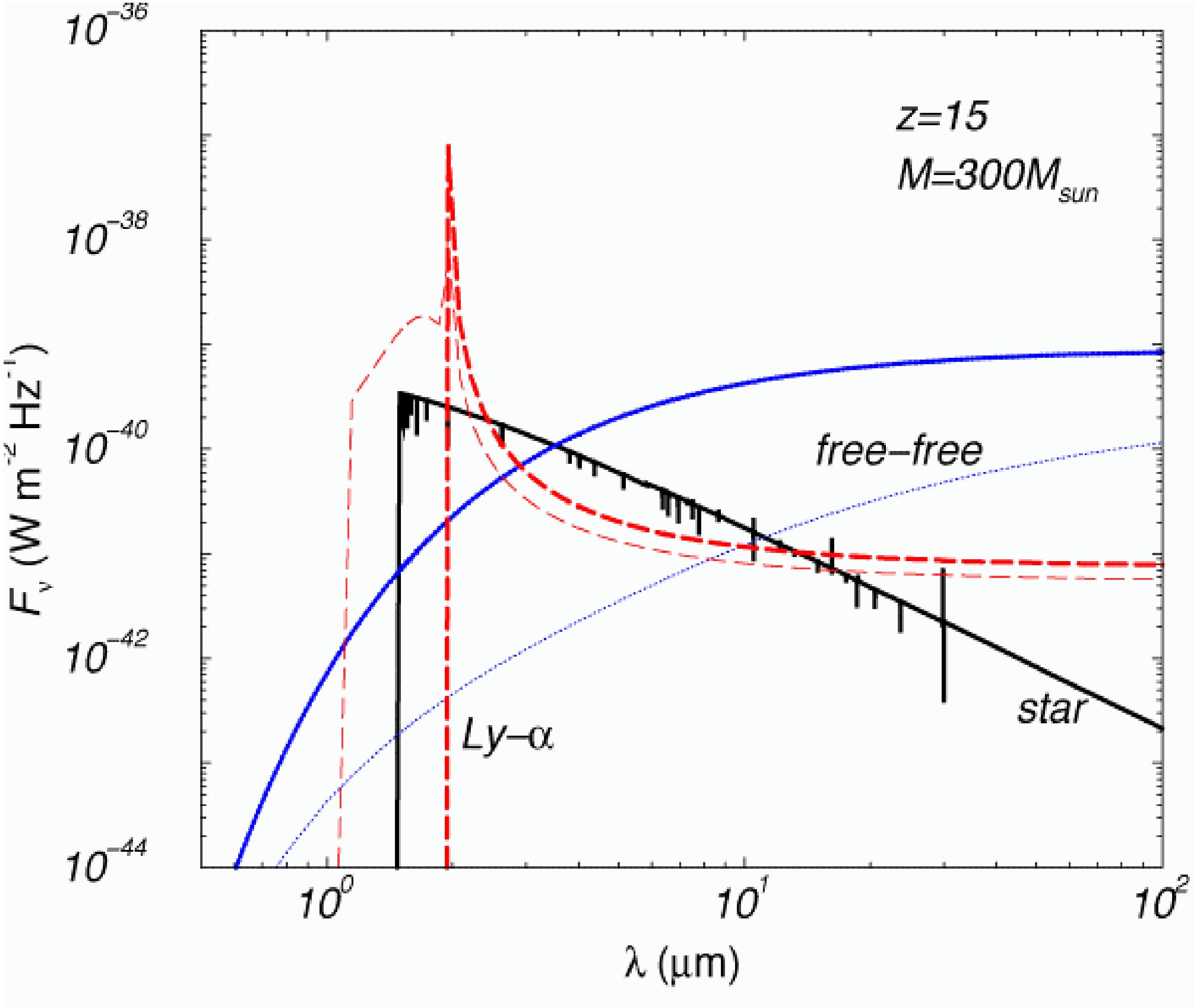

First star spectrum

Model uncertainties but the black-body spectrum of the star alone is more reliable

(Scherrer 2002; Bromm et al. 2002; Santos et al. 2001)

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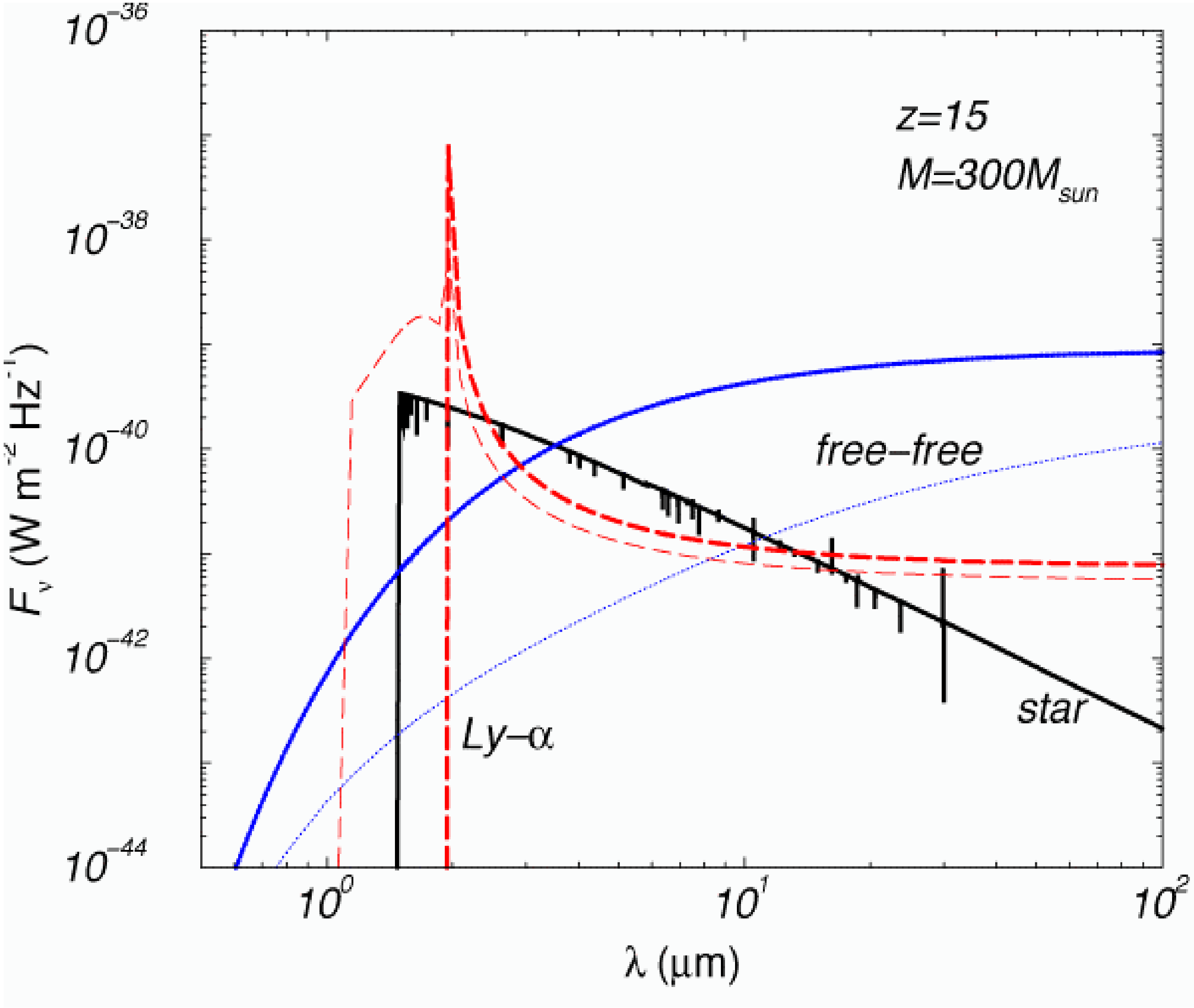


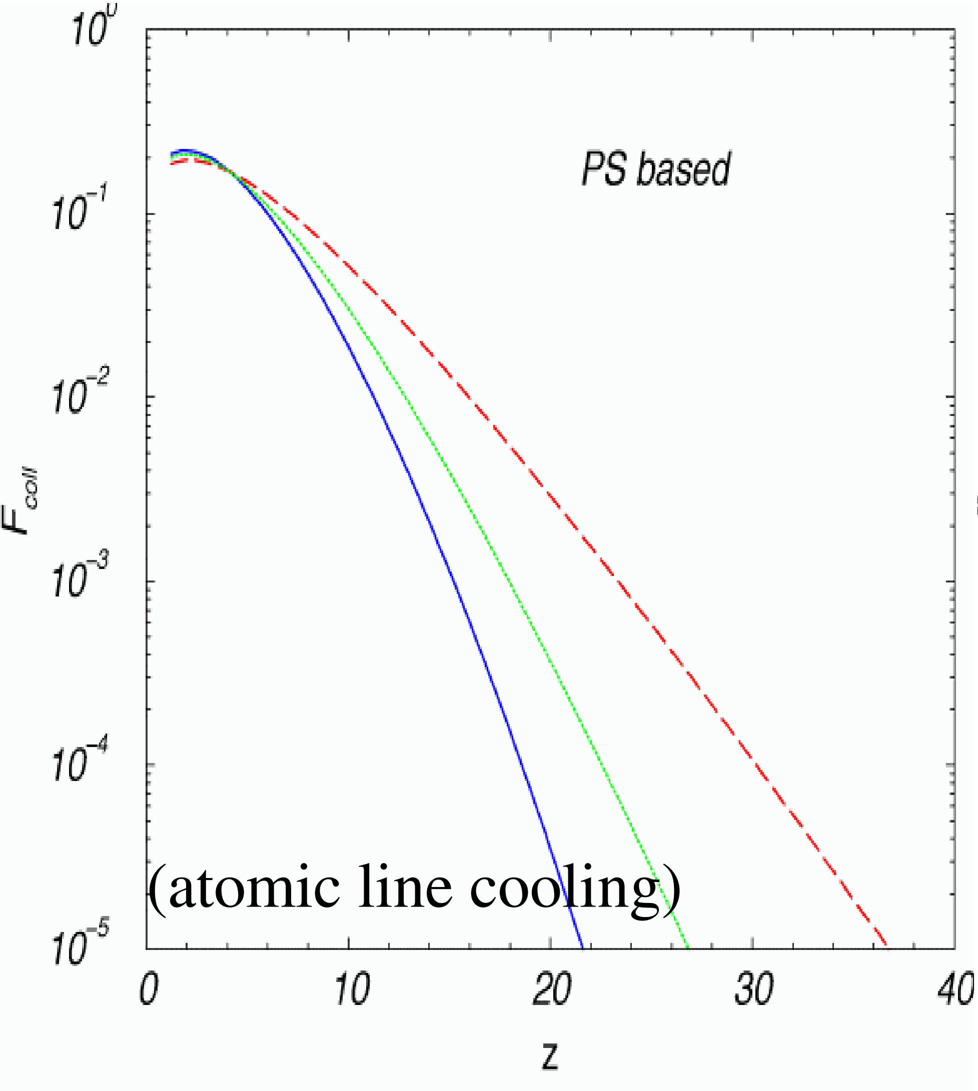
A 300 Msun first star at z~15, K-band mag 33 (unlikey to be detectable)

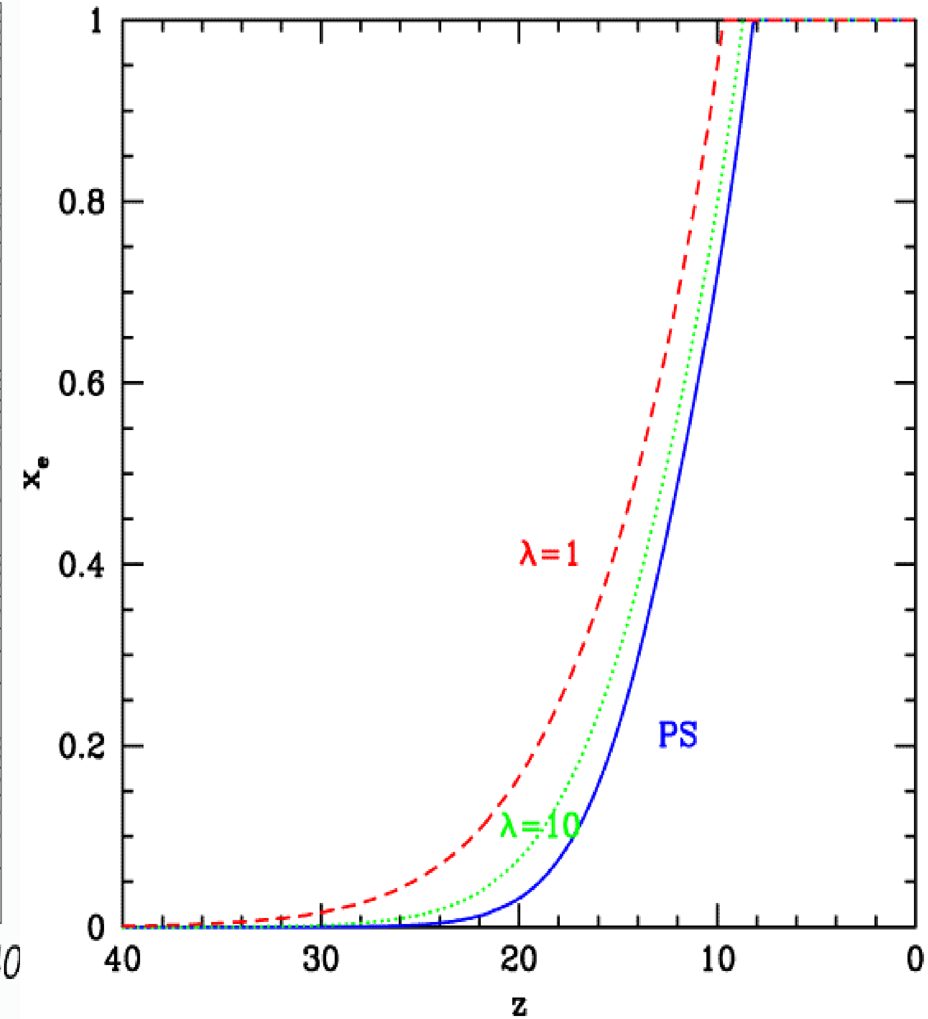
First proto-galaxies can contain as many as 10^5 stars.

(Still not detectable)

(Scherrer 2002; Bromm et al. 2002; Santos et al. 2001)

Reionized by Stars: Reionization is not sudden





Theoretical expectation: Structure formation at high redshift is natural and the slow reionization follows naturally.

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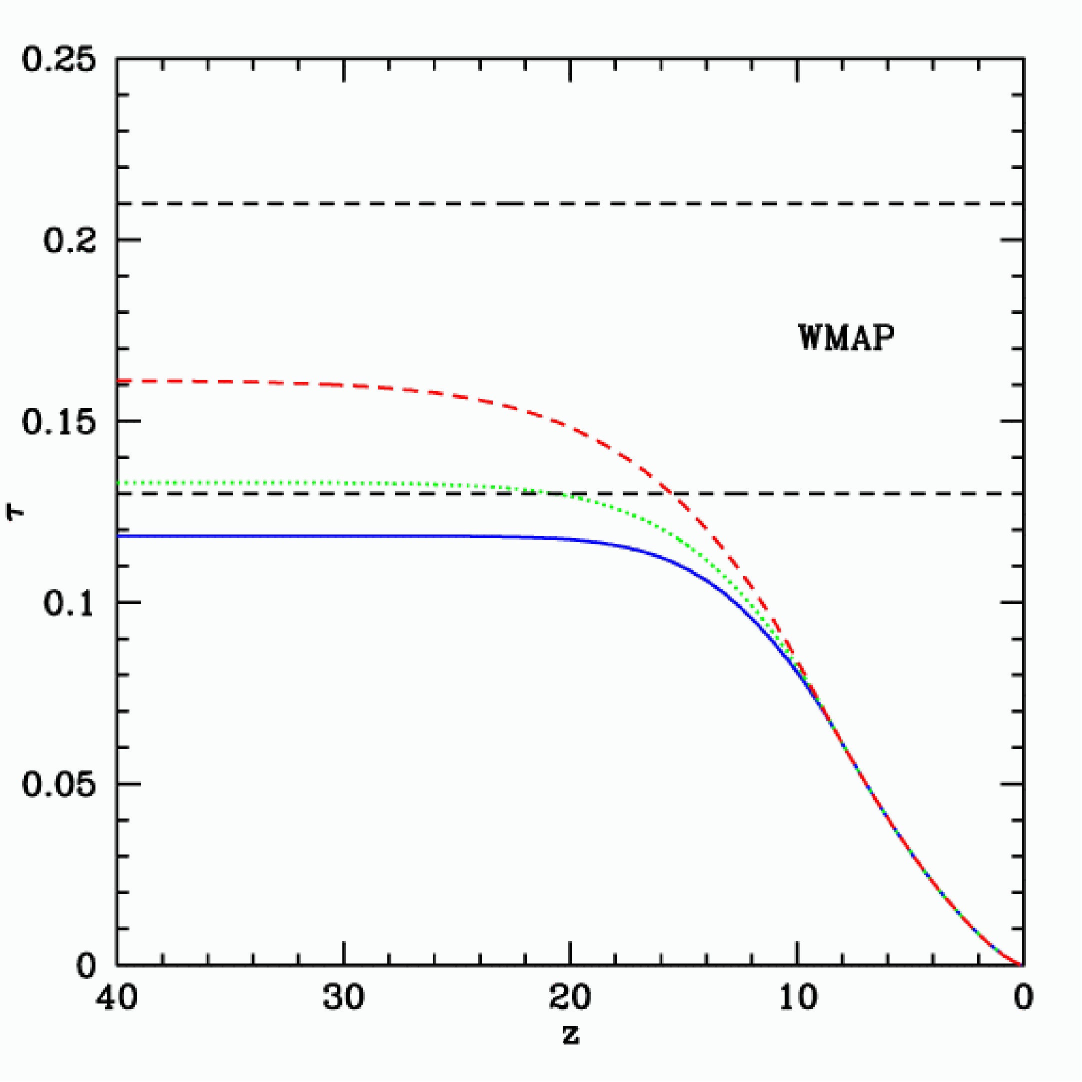


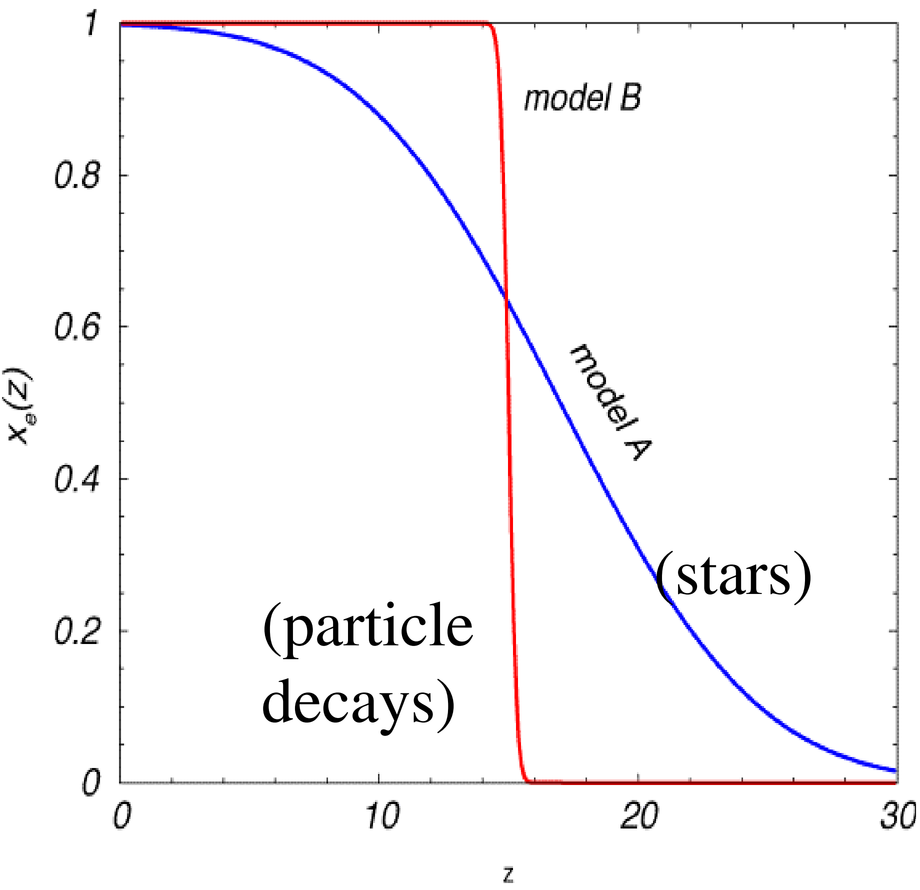
To reionize the universe:

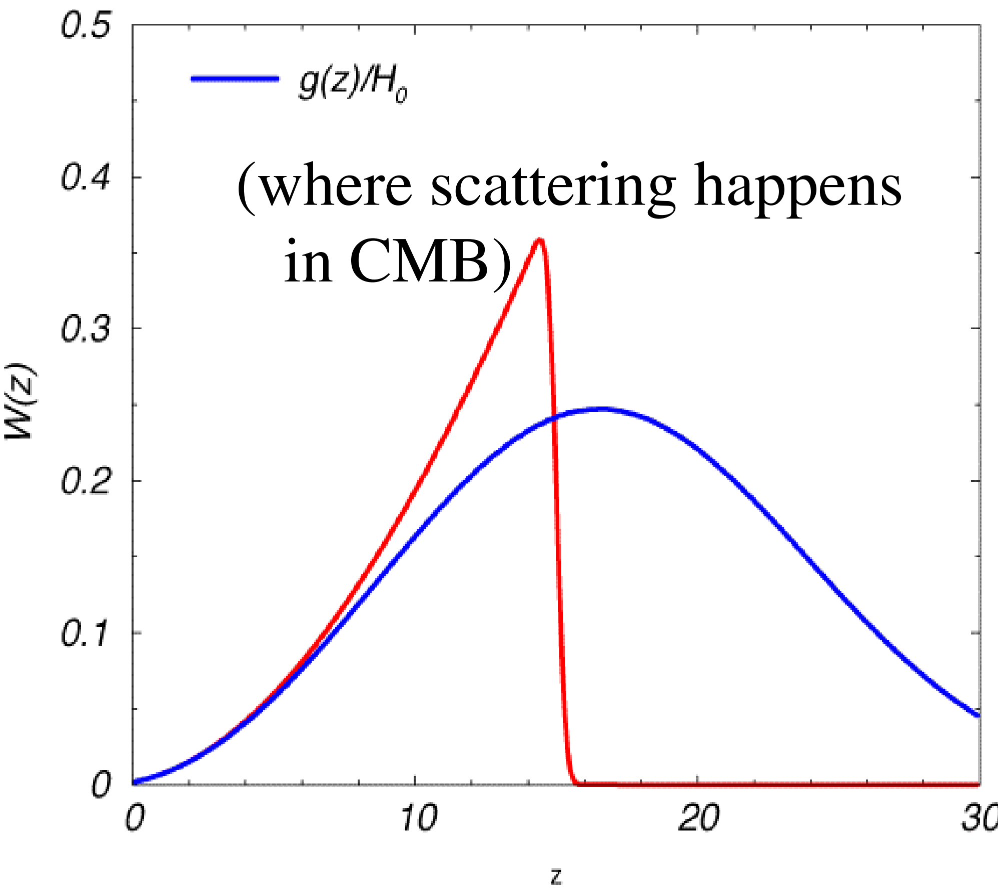
A generation of stars
(Pop IIIs, Pop IIs or II 1/2s)
at z >> 20

If Pop III, top-heavy mass
function => massive stars

If Pop II, star-formation
efficiency must be high
(ie. relatively more stars)

But, how (and even if stars, when)?





Both models give the same optical depth to scattering, but large scale CMB polarization bump cannot be used to separate them precisely

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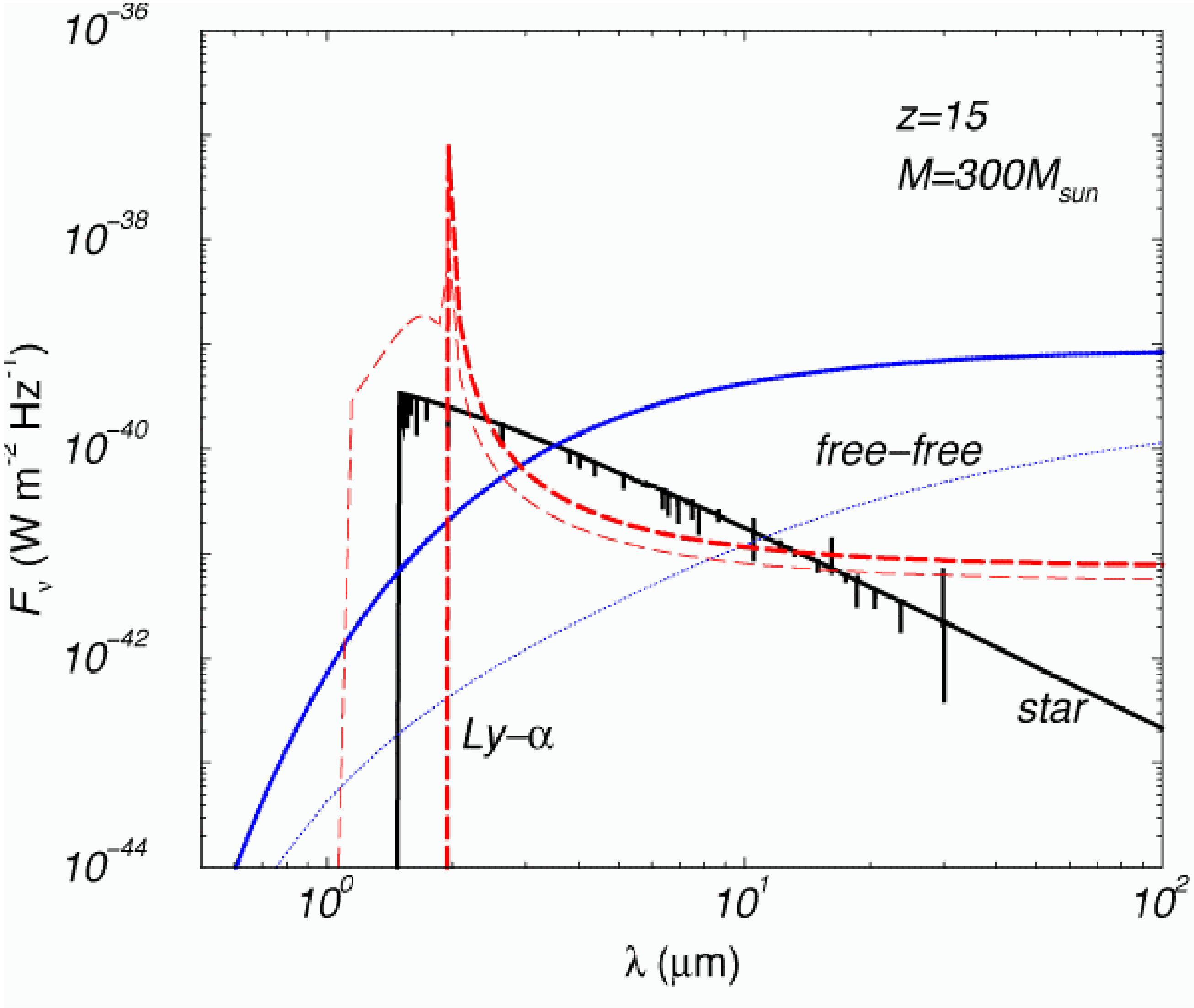

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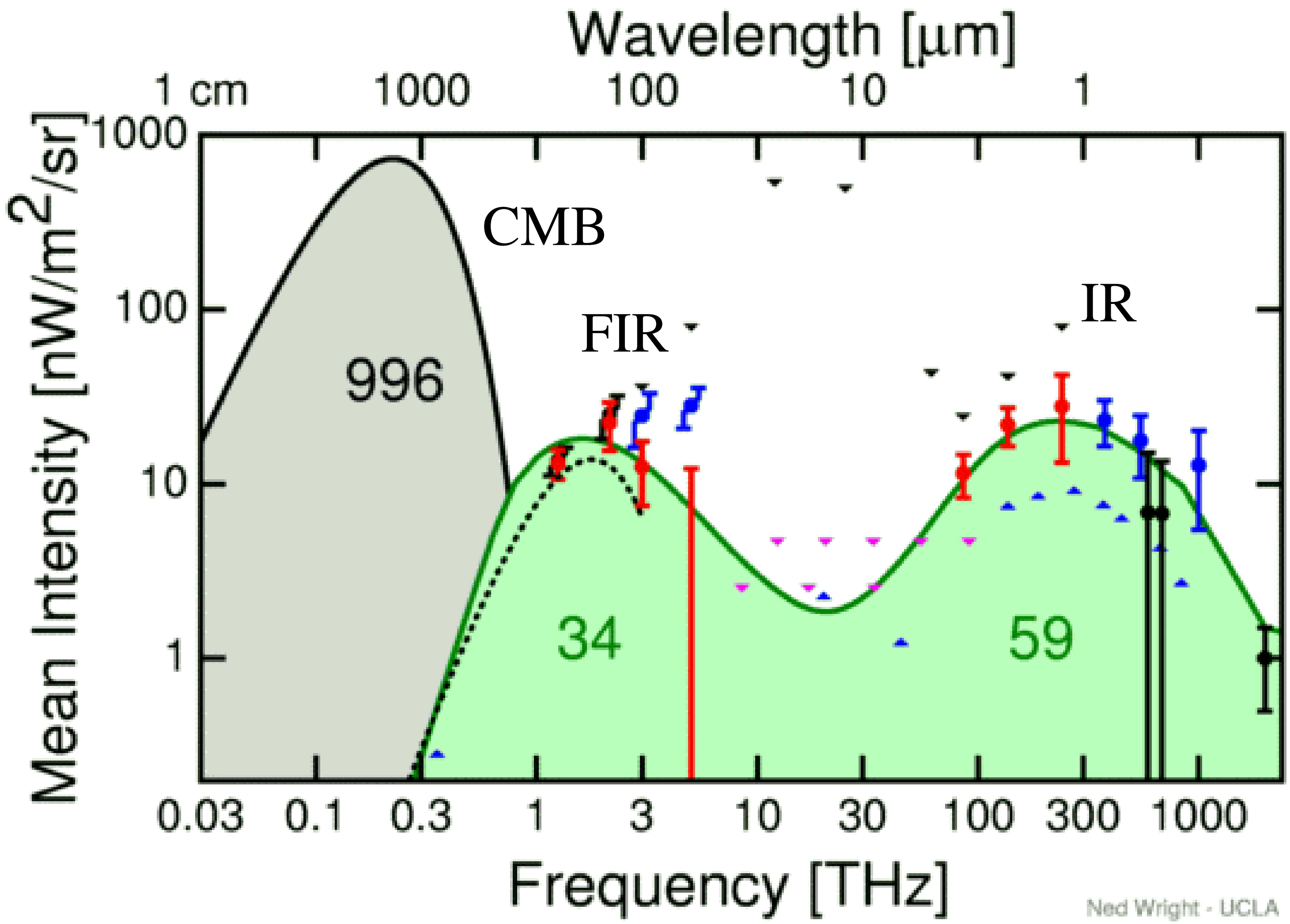
Interesting wavelength range is 1 to 3 microns!!

Lessons in IR: Observational realities



(Ned Wright)

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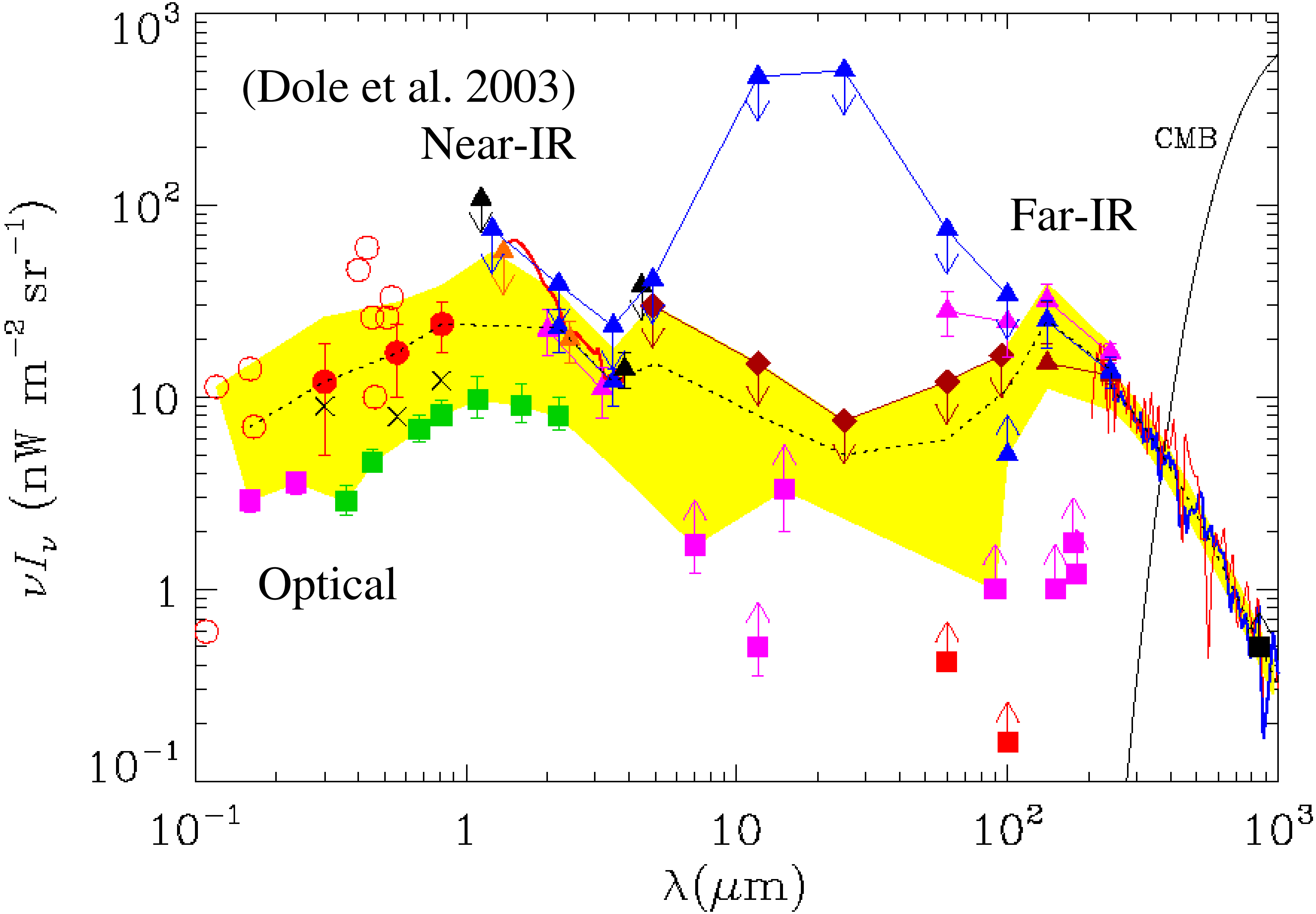
Lessons in IR: Absolute background Measured?



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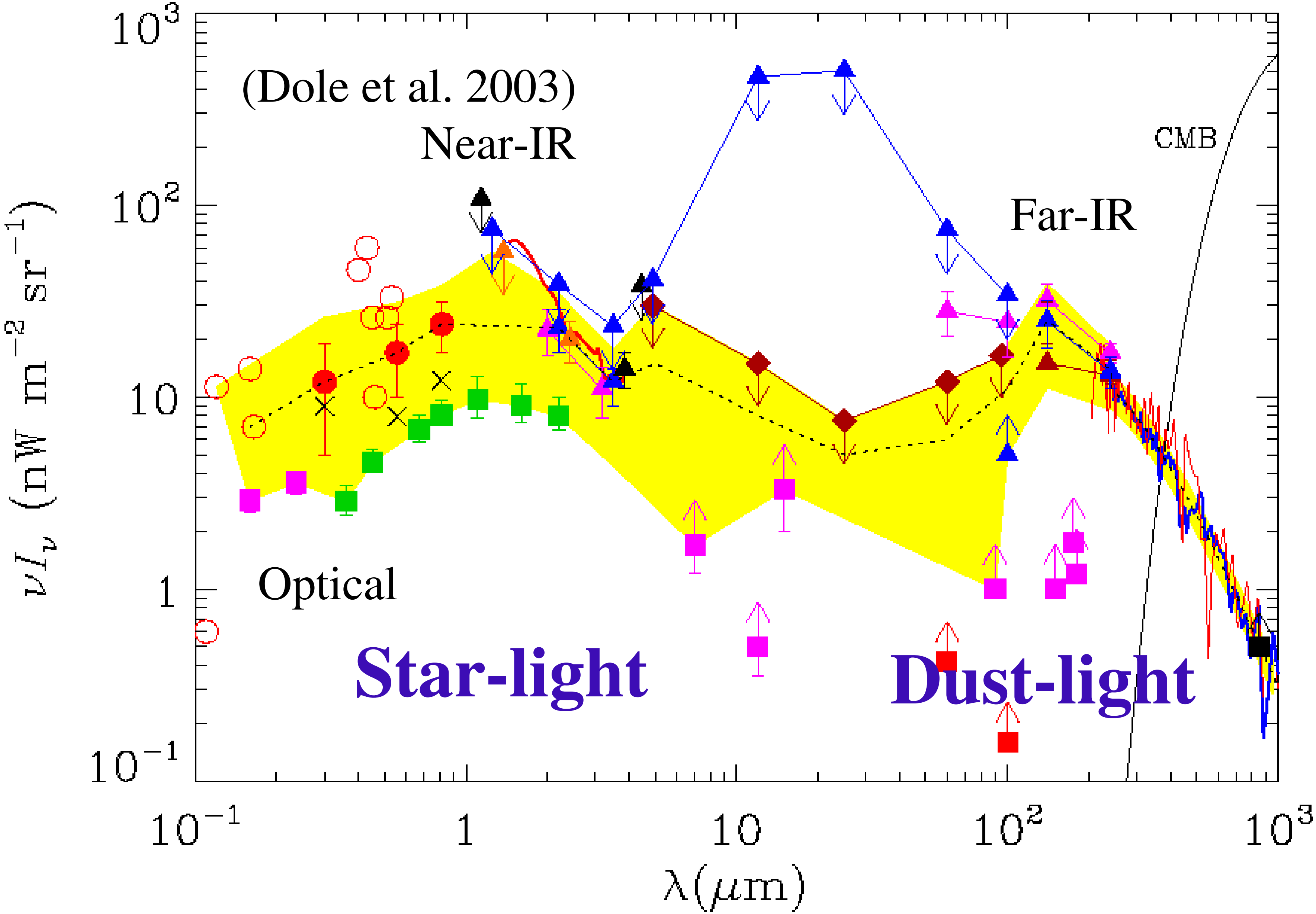
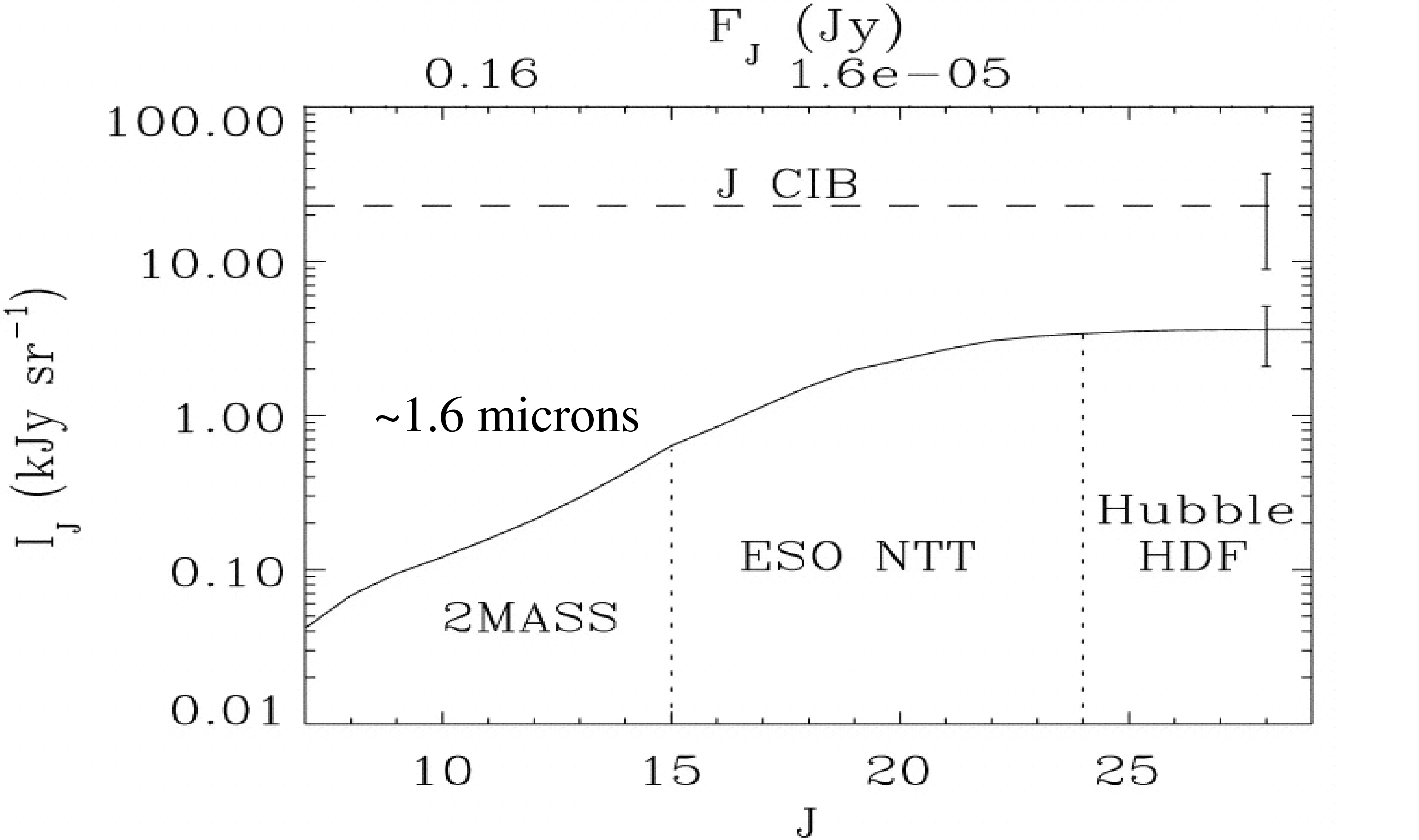


Problems in IR: Not enough stars at low redshifts?



The total near-IR absolute background cannot easily be explained with galaxy counts alone. (Cambresy et al. 2001 and many others)

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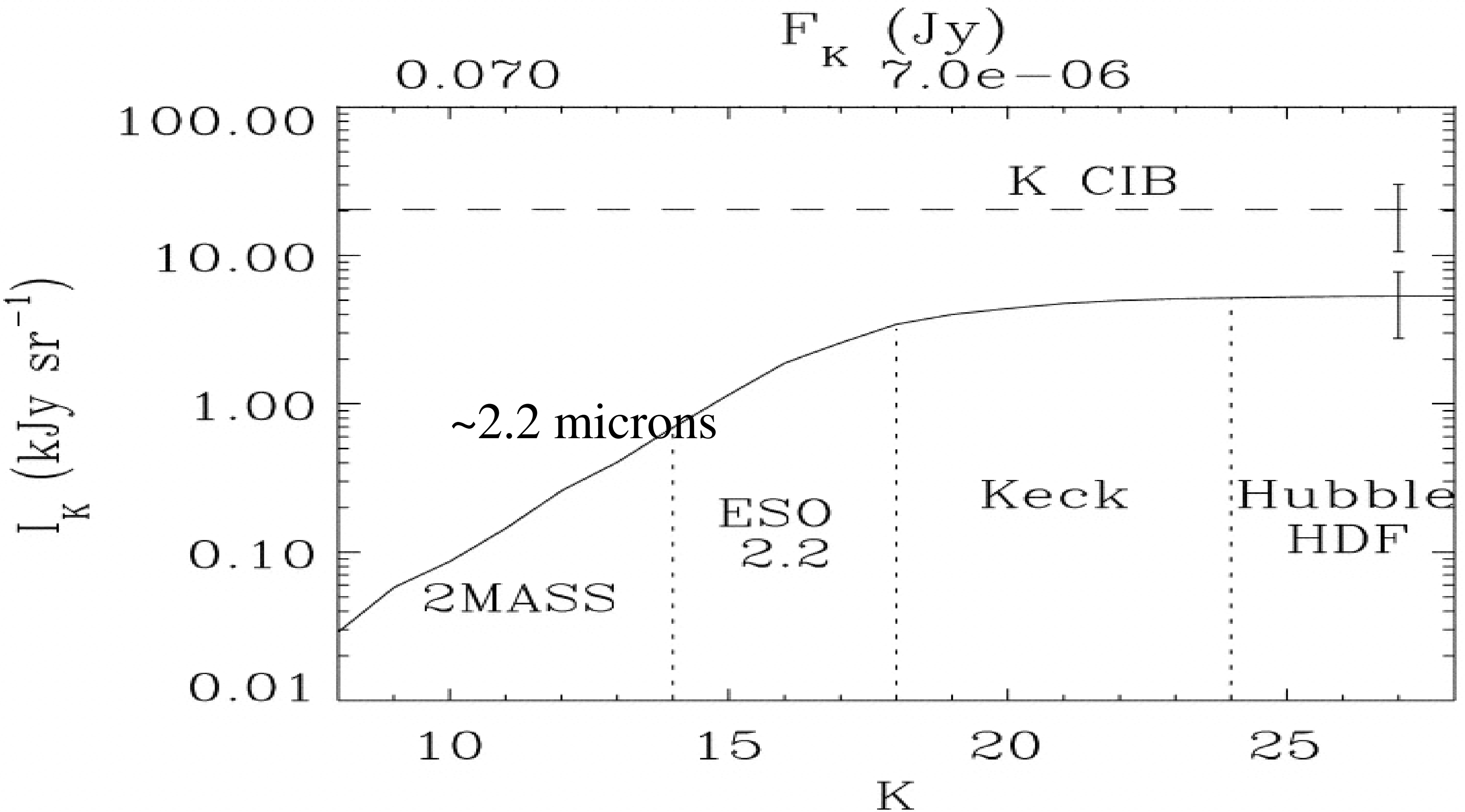

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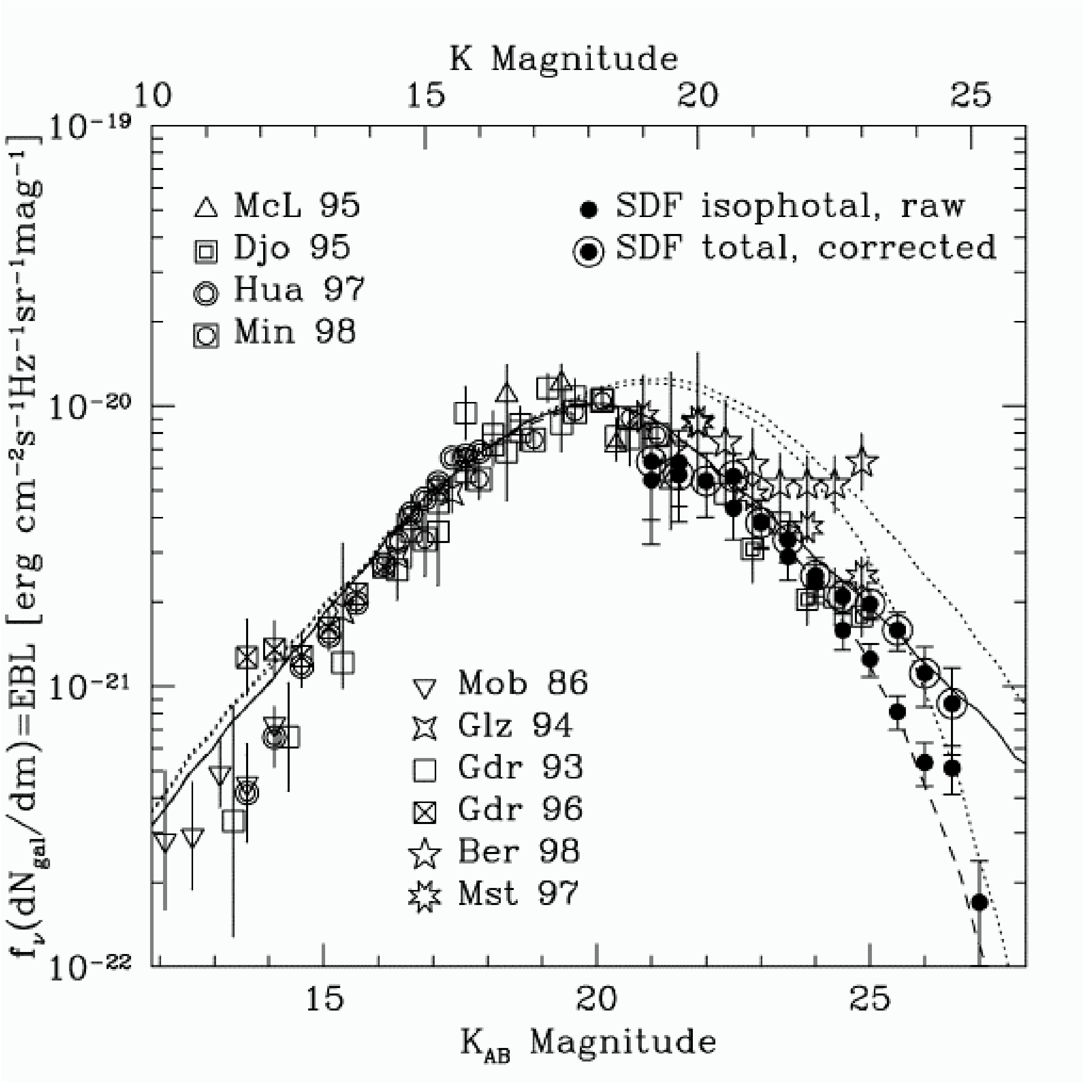


(With ISO, > 7.5 micron backgrounds may be explained with extrapolated counts)

Galaxy counts turnover at the faint end

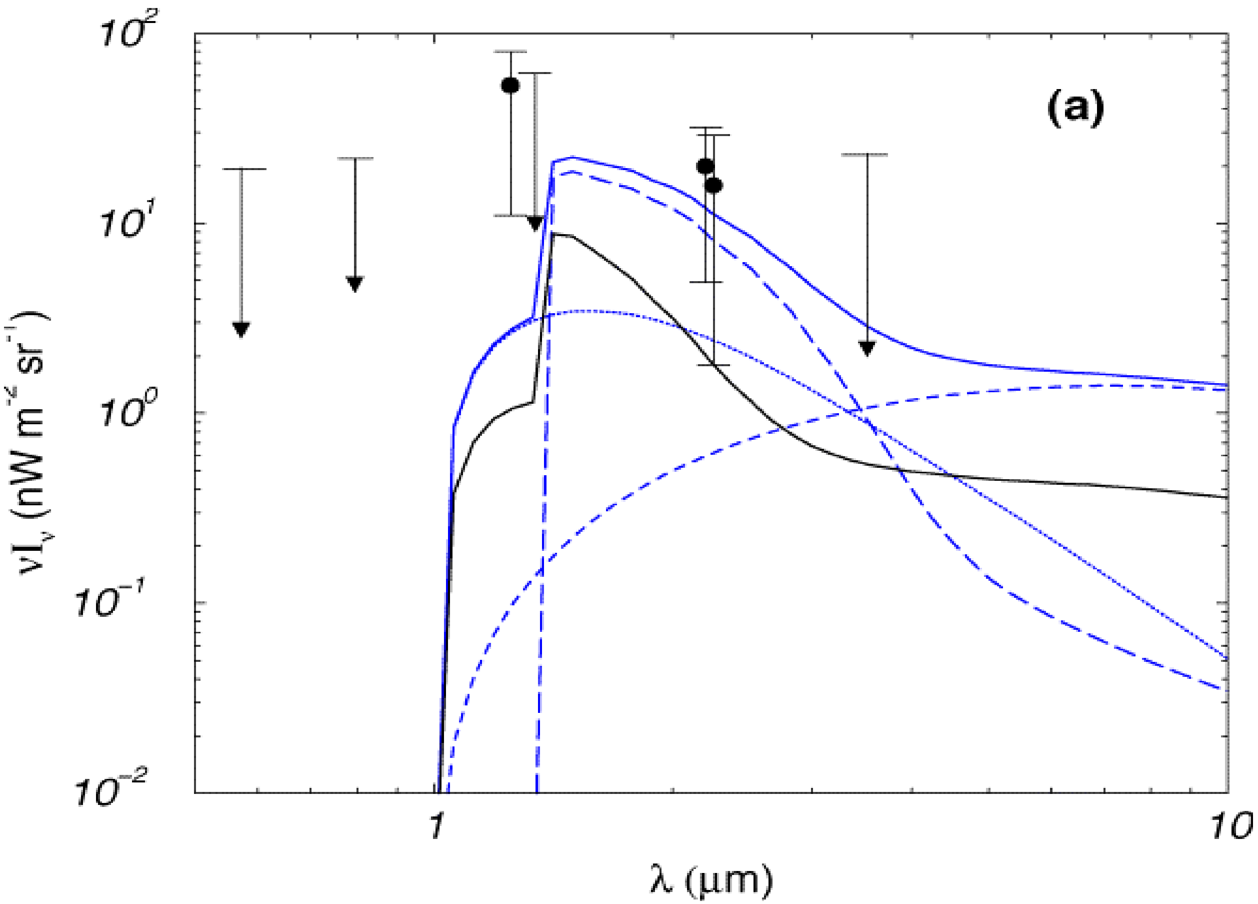
(SUBARU: Totani et al. 01)

⇒ The way out:

Background measurements are wrong (unlikely, given several independent sets of data)

Diffuse emissions (low-z low-surface brightness galaxies or high-z first-galaxy population)

Solutions in IR: First stars explain missing CIB?



First stars out to redshift of ~ 10

First stars
(either Pop III,
Pop II 1/2
or Pop IIs)
can explain the
missing amount

(Easier with Pop III)

Santos, Bromm & Kamionkowski 2001

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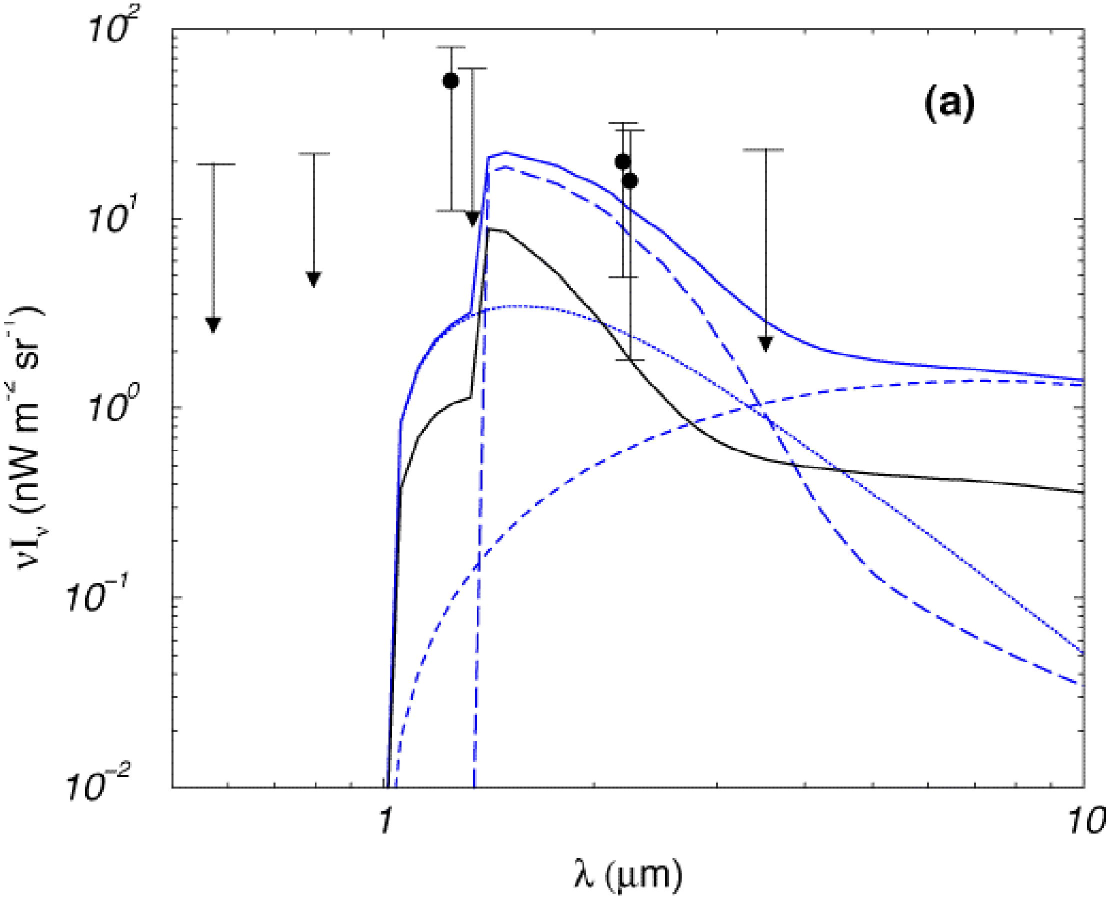

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First stars out to redshift of ~ 10

Many unknowns, a messy subject.

Cooray & Yoshida 2004

Can we detect the signature of first stars directly?

Evidence in the absolute background for a missing contribution not related to local galaxies.

The search of first stars cannot be done with absolute background measurements alone.

First star proto-galaxies will not be directly detectable with current instruments, but expectations are these will be with JWST.

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Can we at least look for a potential hint of significant star-formation at higher redshifts?

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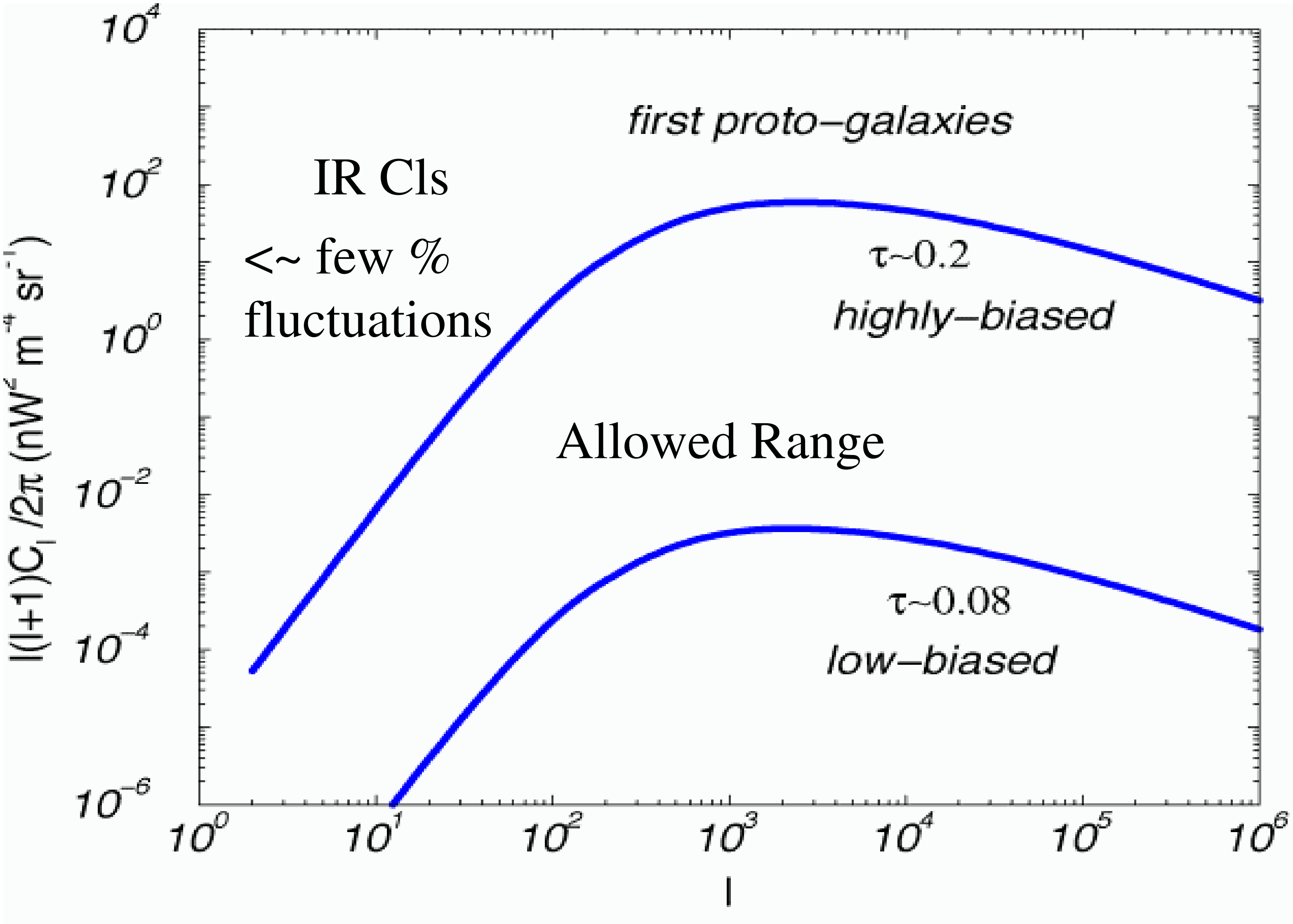
Consider spatial fluctuations in the unresolved IR background

(after removing most resolved foreground galaxies down to very deep magnitudes)

(essentially, do a CMB anisotropy type experiment in IR)

Spatial fluctuations (captures how first-stars are clustered)



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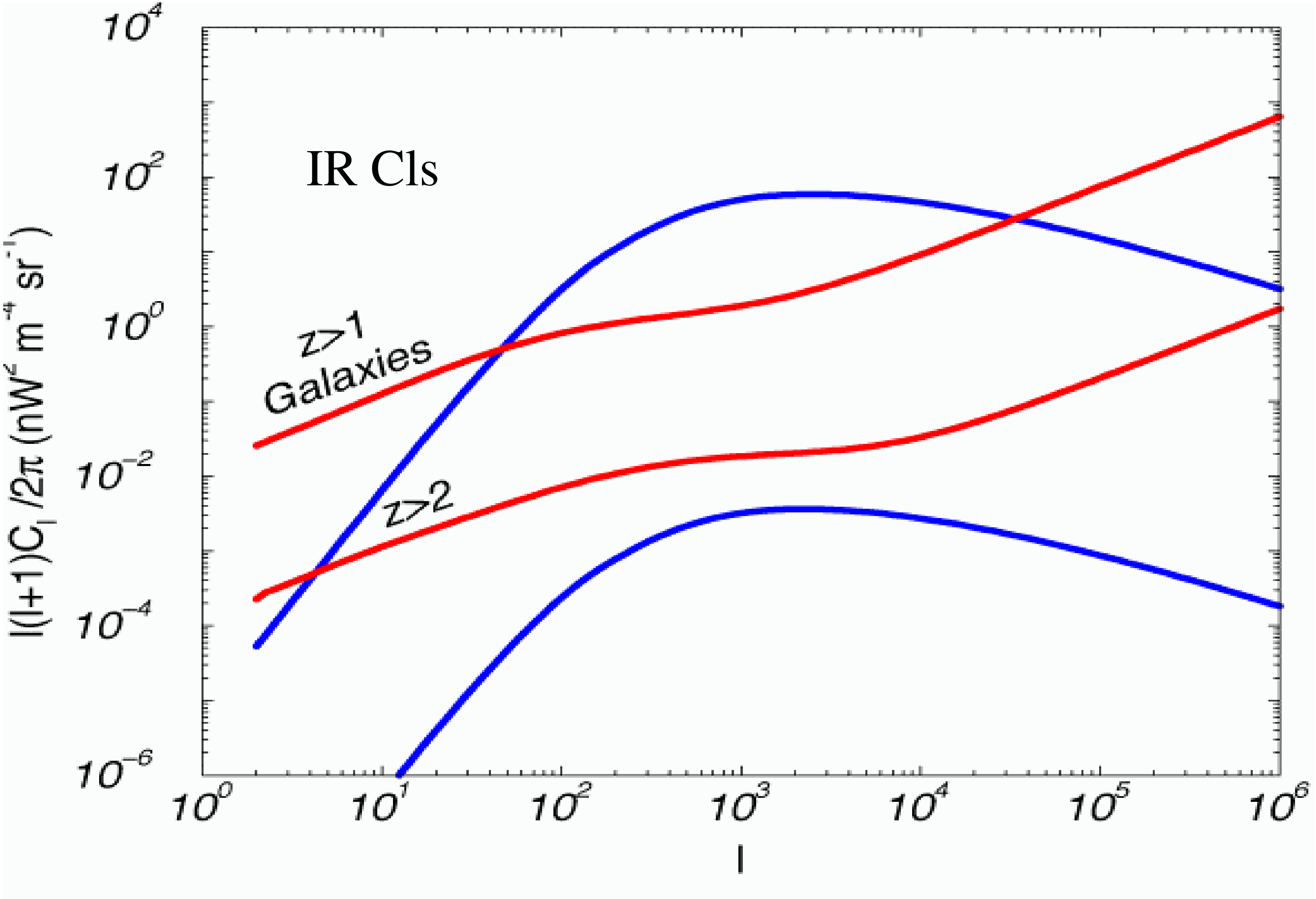
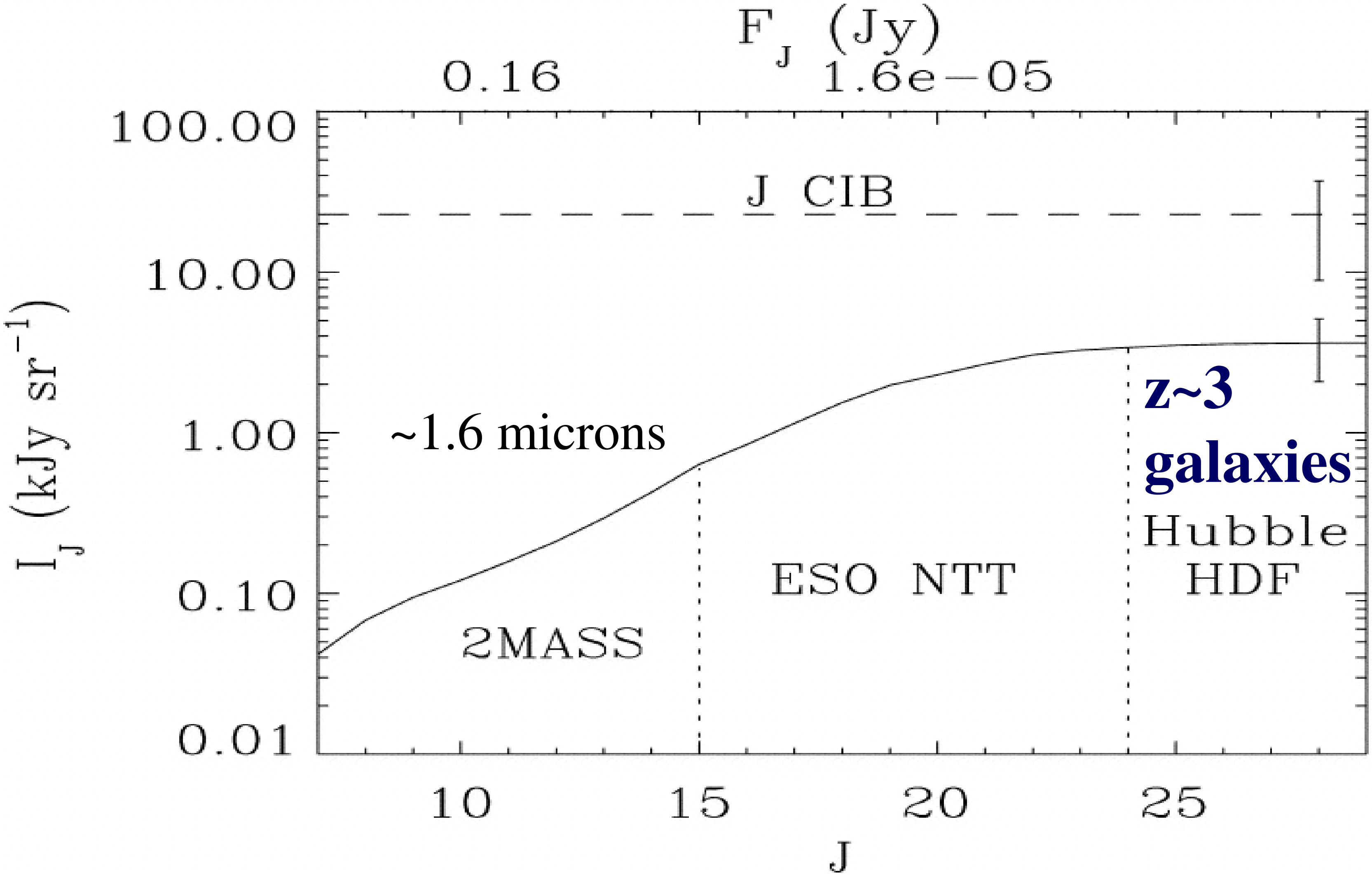


Not just first-objects: the mess in between

But faint z~3, galaxies may not be a problem



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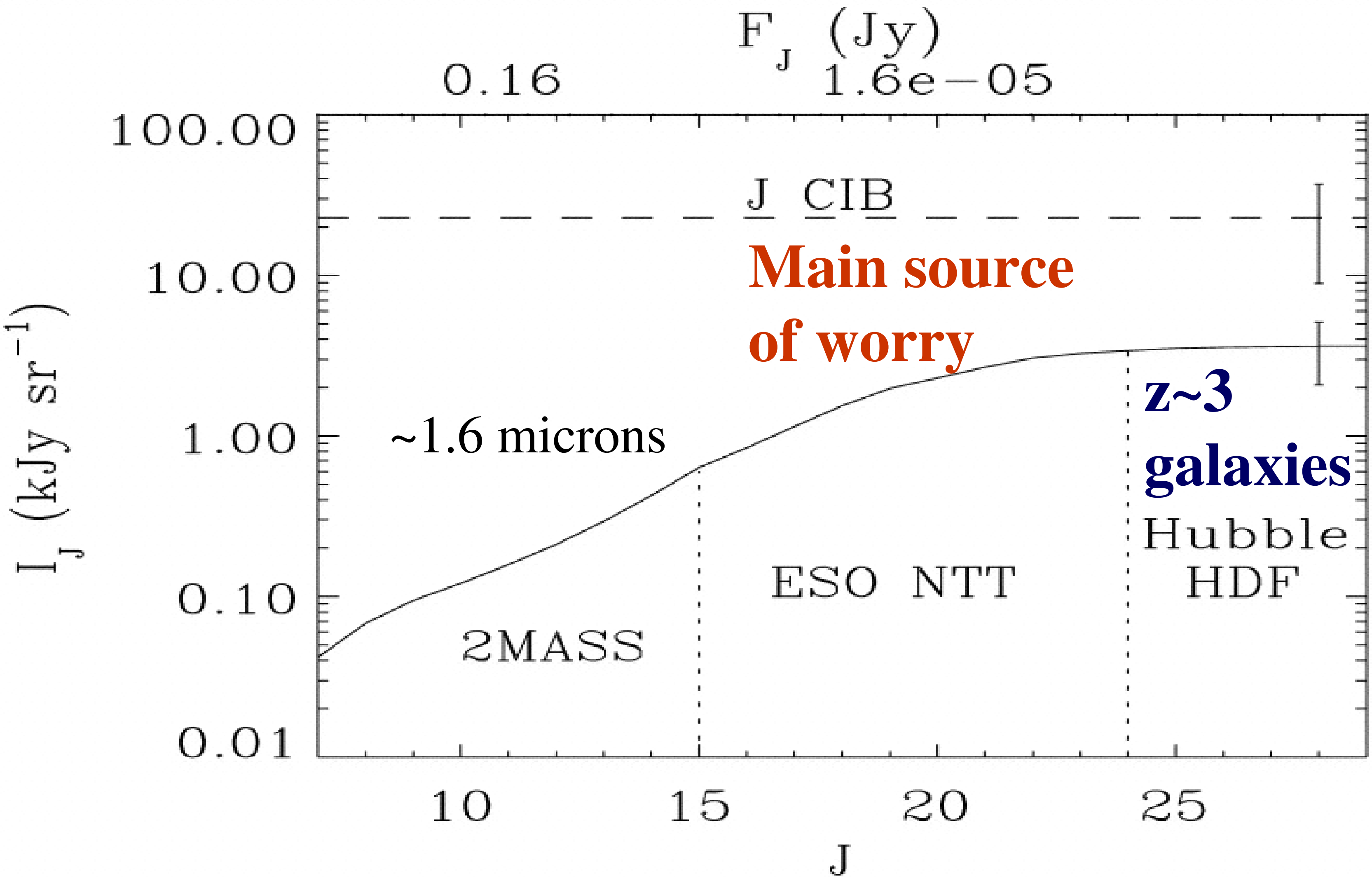

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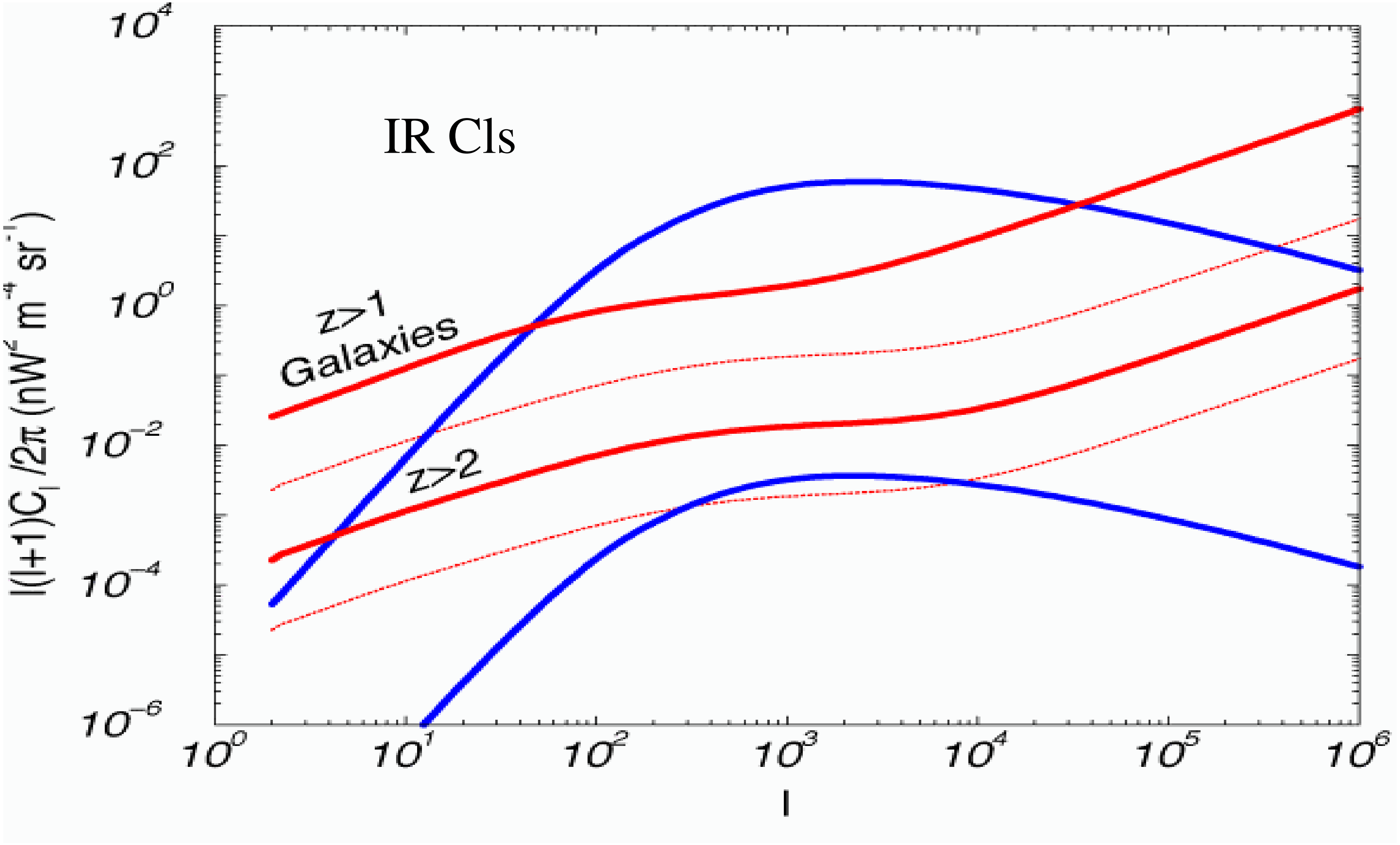
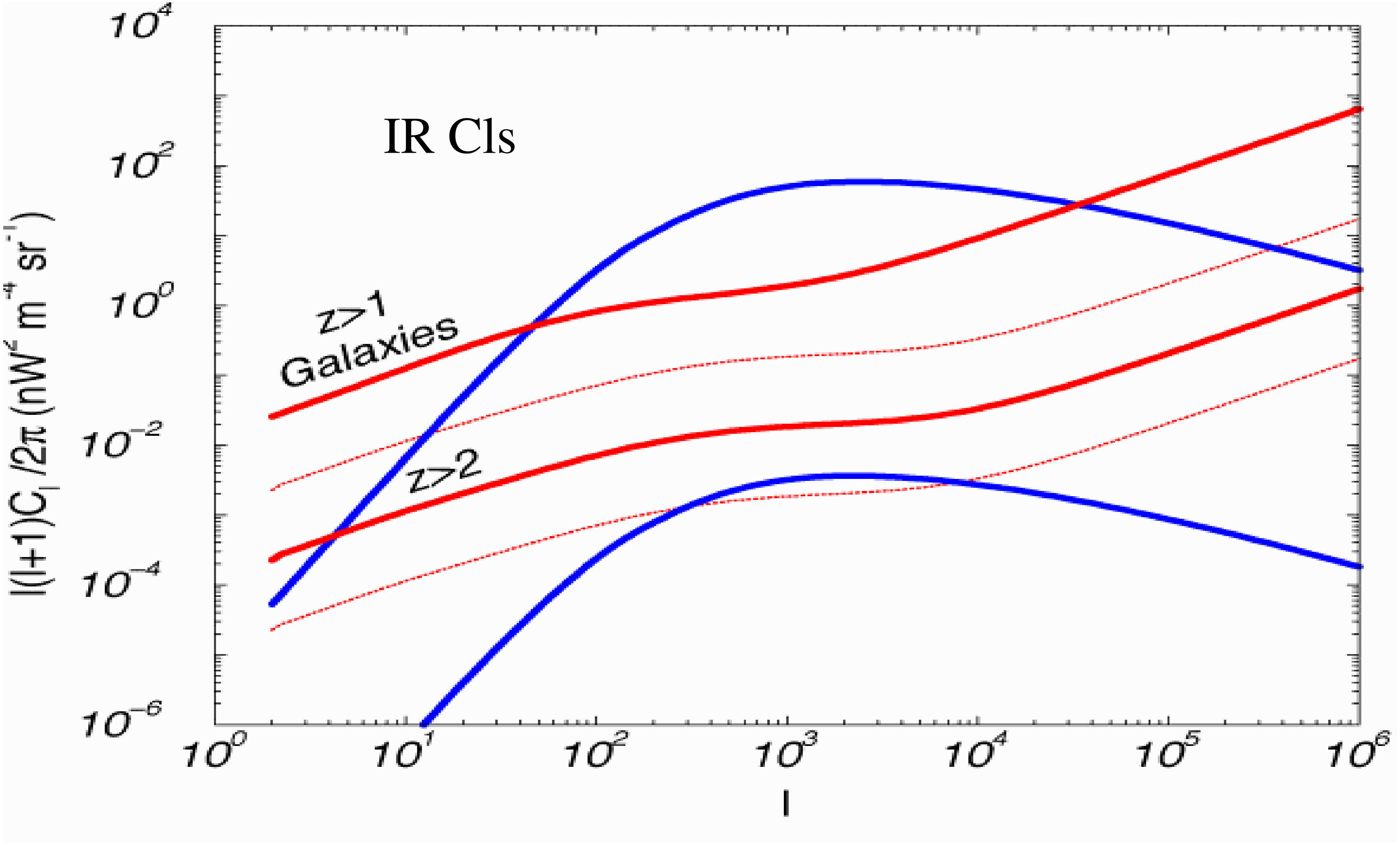


The real problem would the clustering of flluctuations from unresolved galaxies between z~ 1 to 2 (or K-band magnitides between 17 to 22)

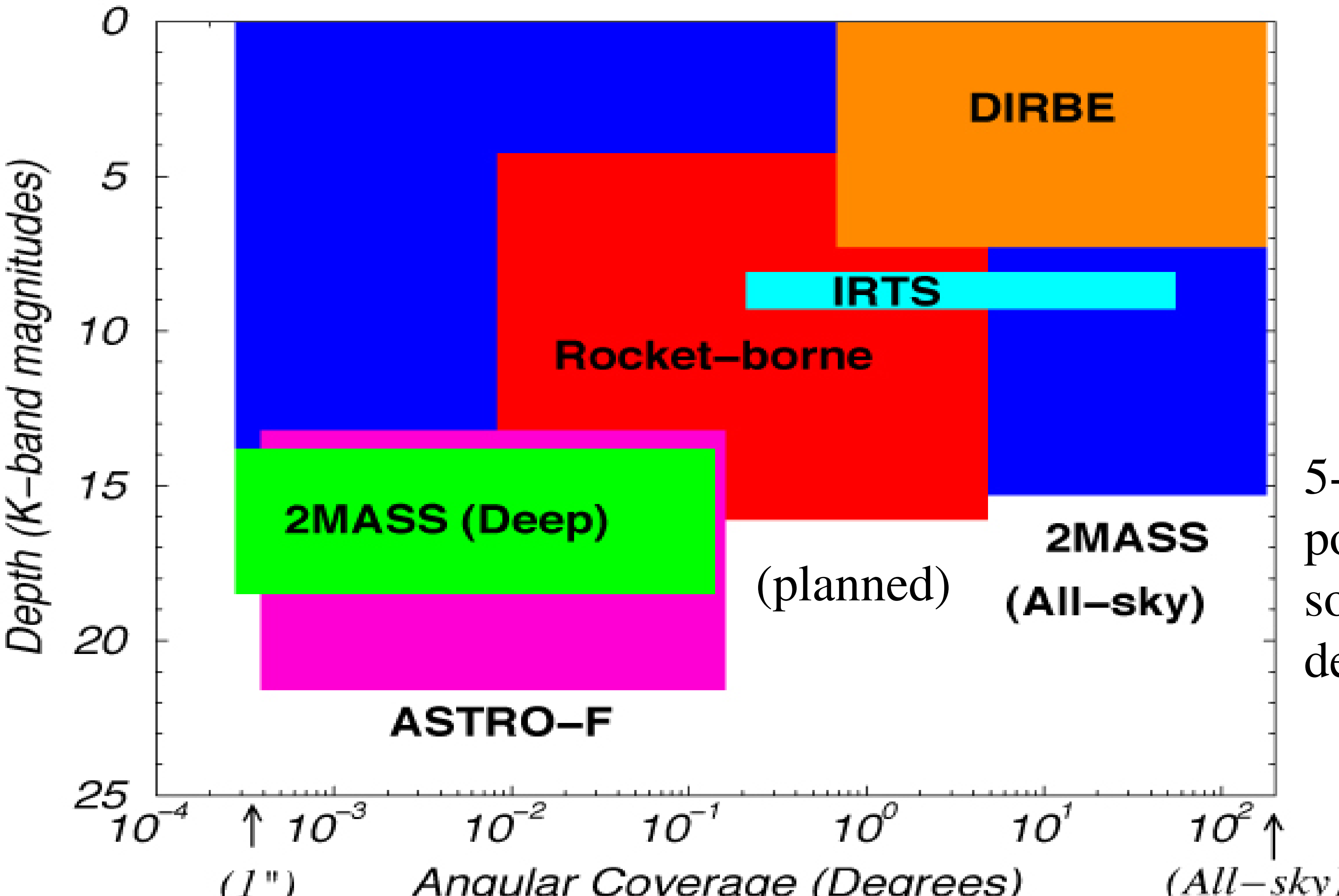
Spatial fluctuations (captures how first-stars are clustered)



Requirements: Large sky area (>10 square degrees.)

high resolution and sensitivity (to resolve foreground galaxies)

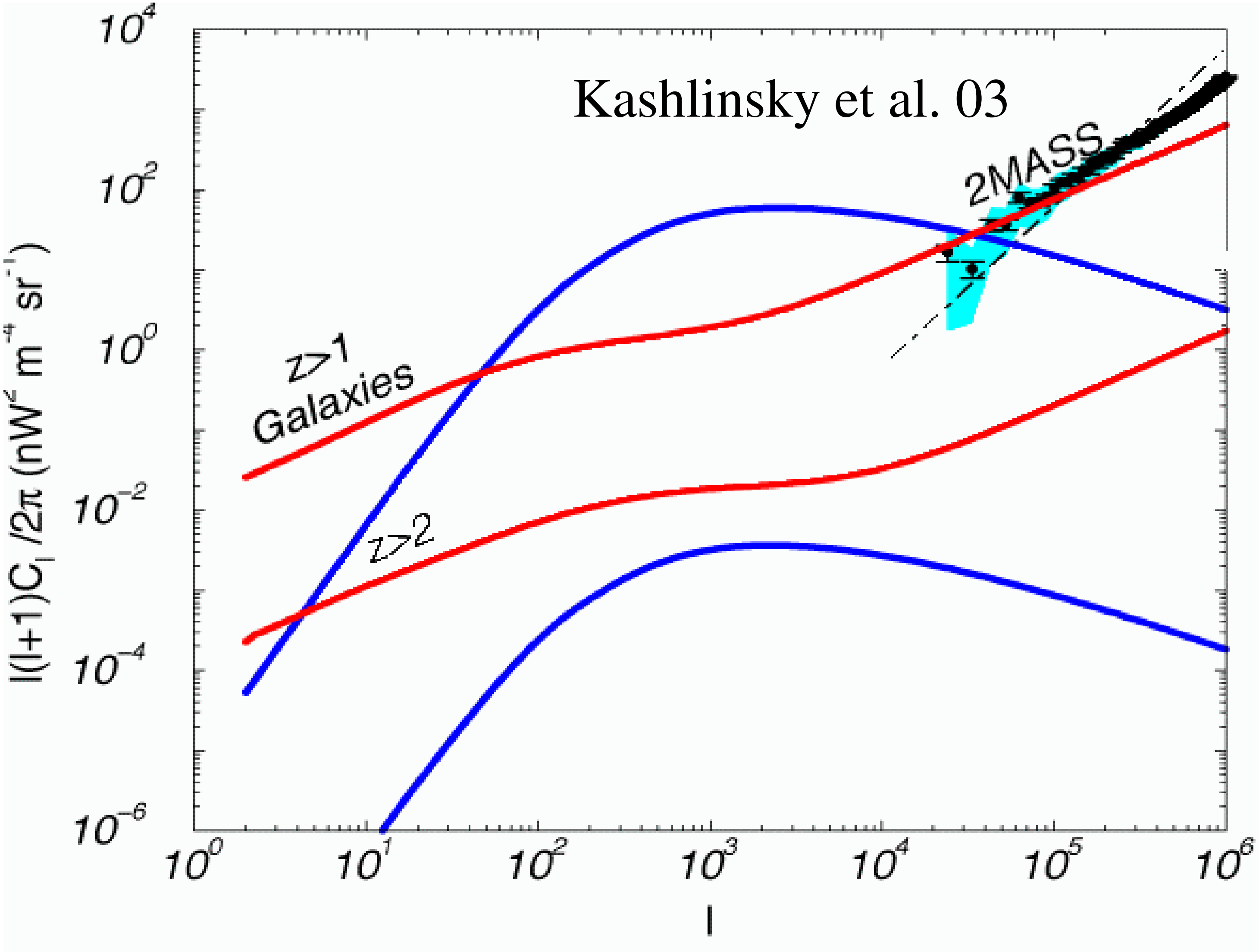
Theory to Reality: Near-IR wide-field surveys



5-sigma point source detection

(experiments at this end are preferred)

Fluctuation studies so far: 2MASS



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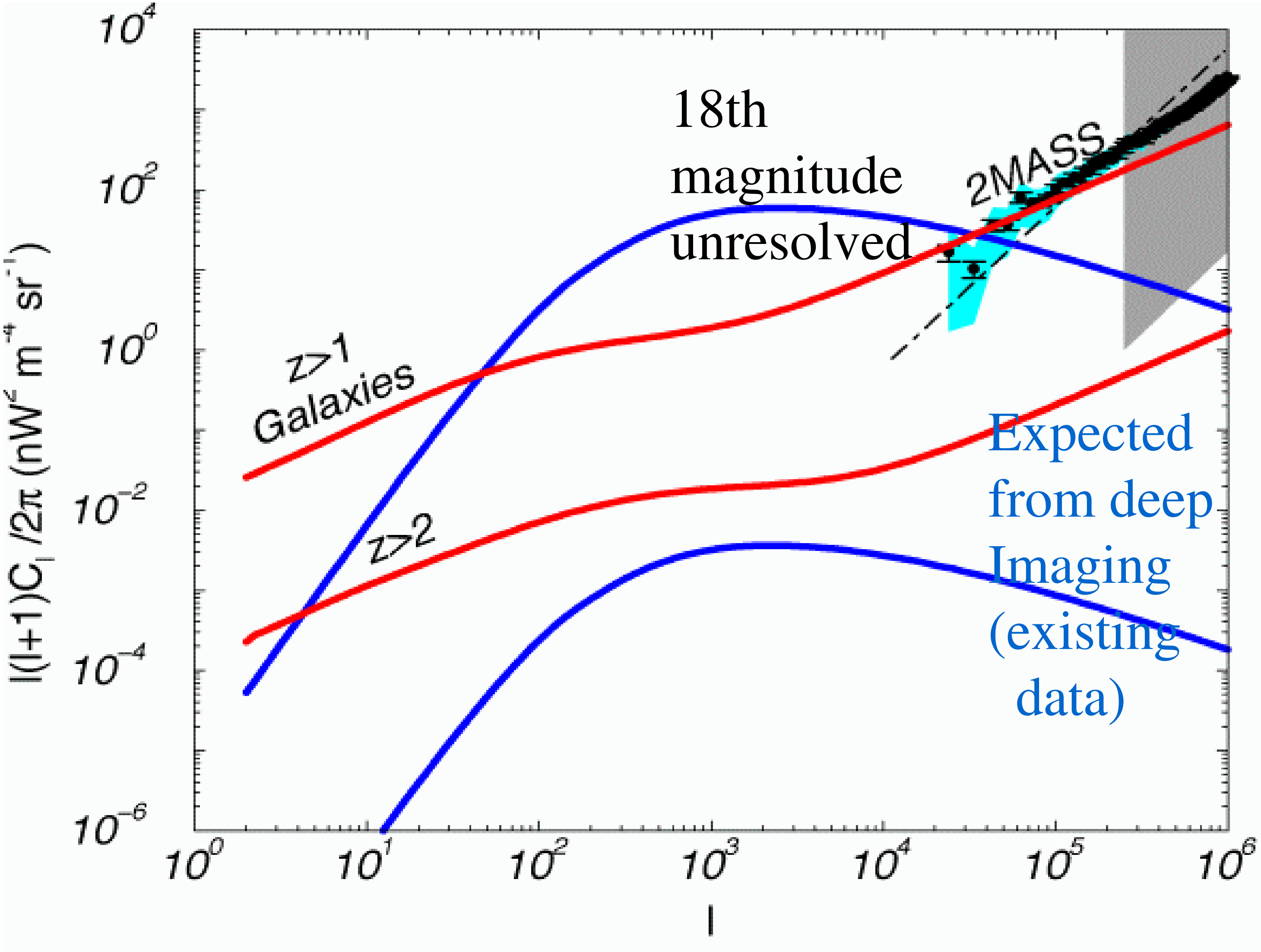


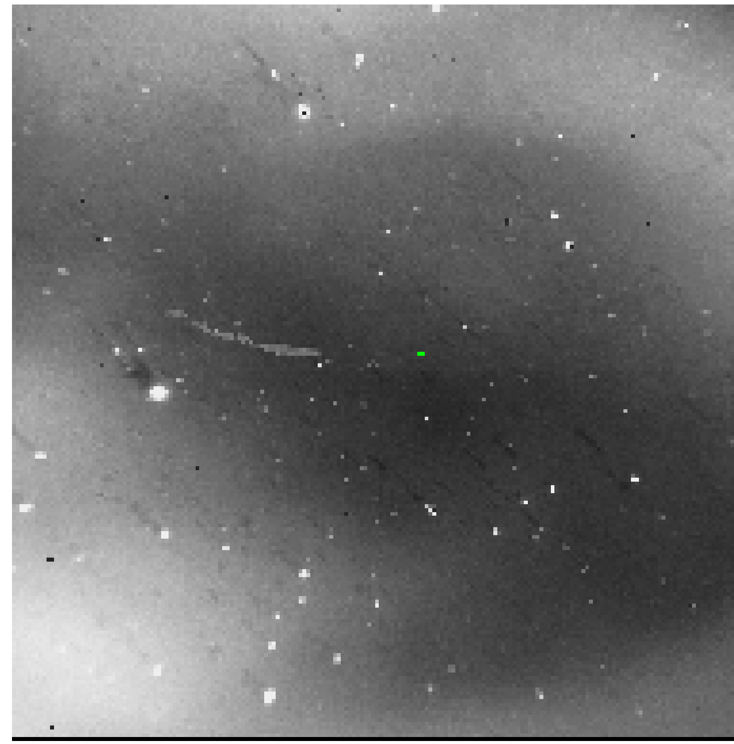
Some argue 2MASS may have already detected first stars (Magliocchetti et al. 2003)

(probably not)

(Excess fluctuations at arcminute to few arcminute scales, where first stars cluster)

Why ground-based data are not good for fluctuation measurements?

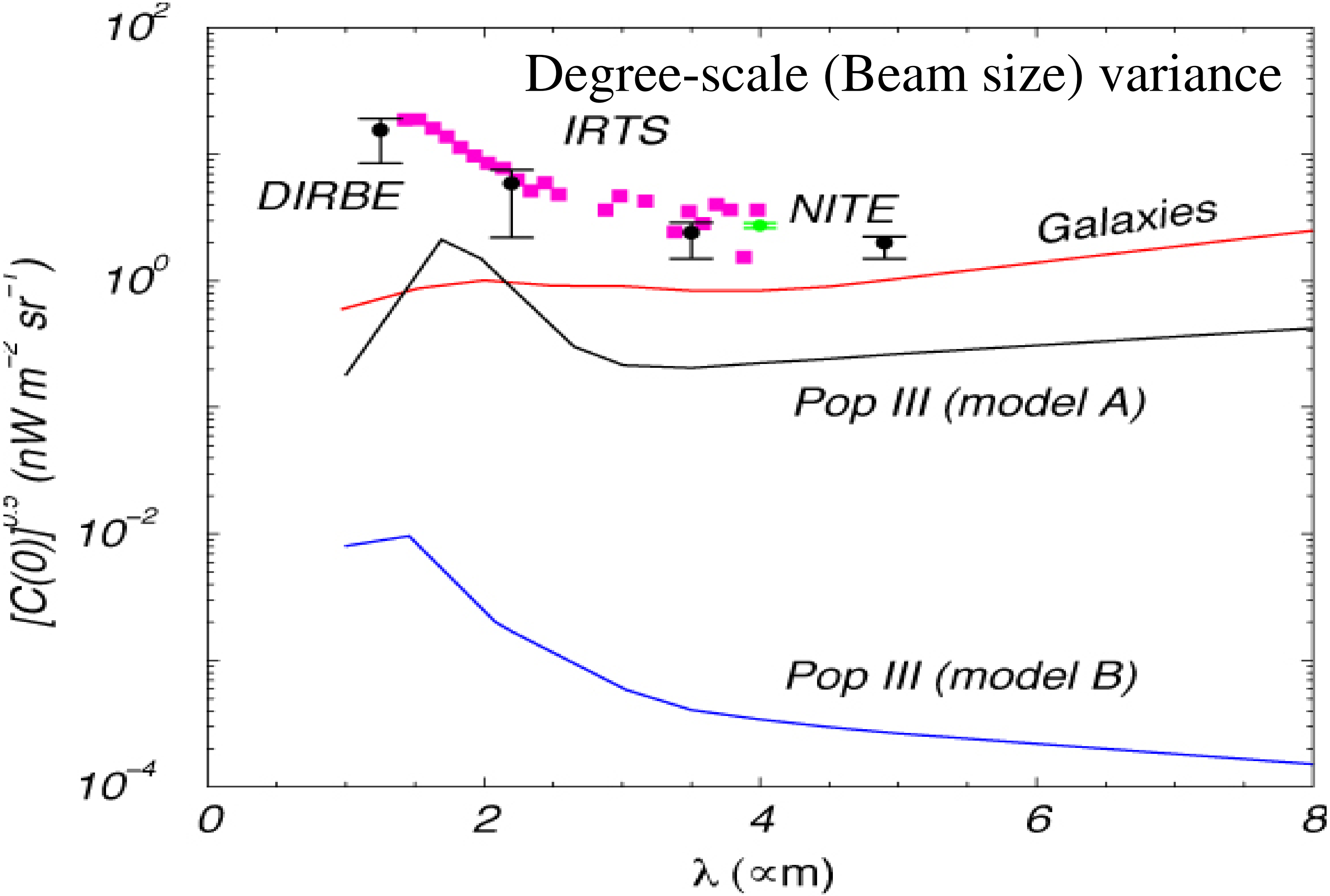
(thanks to Jamie)



H-band, same field (9 degrees), images separated by 7 minutes

Airglow dominates - fluctuations at degree scales

Fluctuation studies so far: DIRBE etc. (all-sky/poor resolution)



Current clustering studies dominated by systematics and foregrounds

(A substantial foreground zoadical light from the Solar system dust)

CIBER
(Cosmic Infrared Background ExploRer)

The upcoming rocket experiment
(Optimized for spatial fluctuations and first stars)

2 bands between 1 to 3 microns
15” or so resolution
~16 sqr. deg. field of view
(Useful to get about ~ 48 sqr. degrees in 3 flights)

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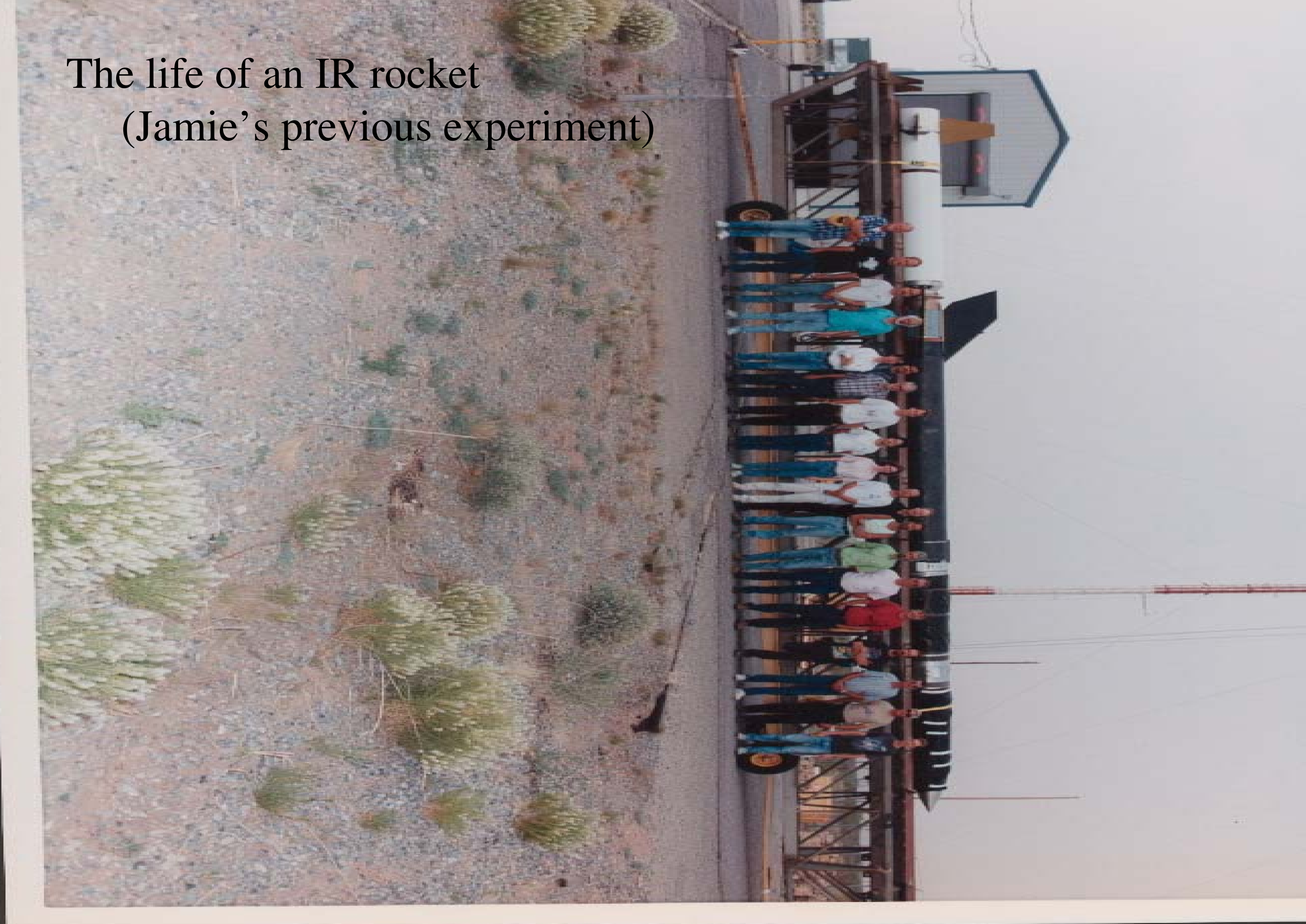
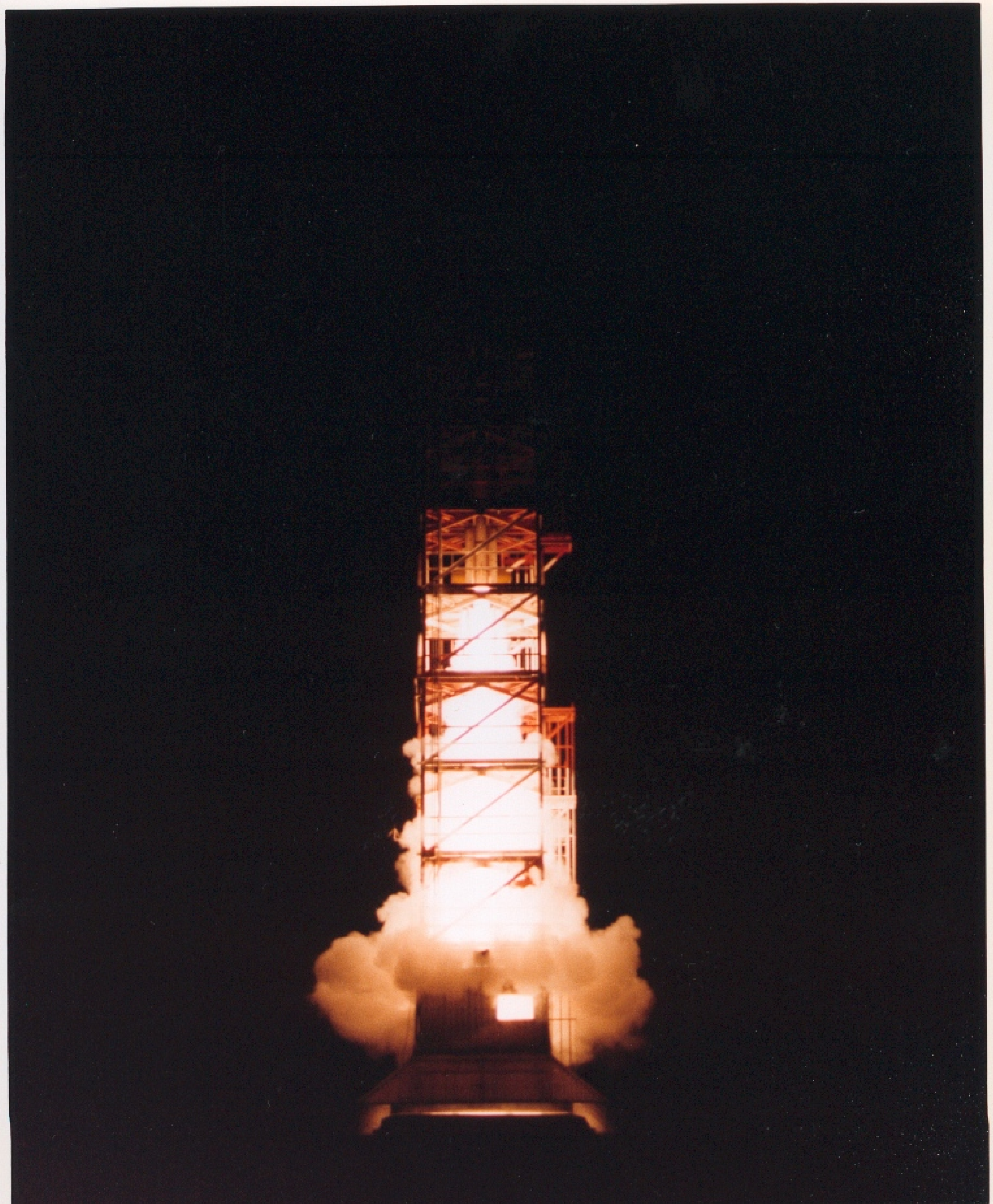
Main collaboration:
Caltech: Asantha Cooray, Andrew Lange
JPL: Jamie Bock **UCSD:** Brian Keating
ISAS Japan: Toshio Matsumoto

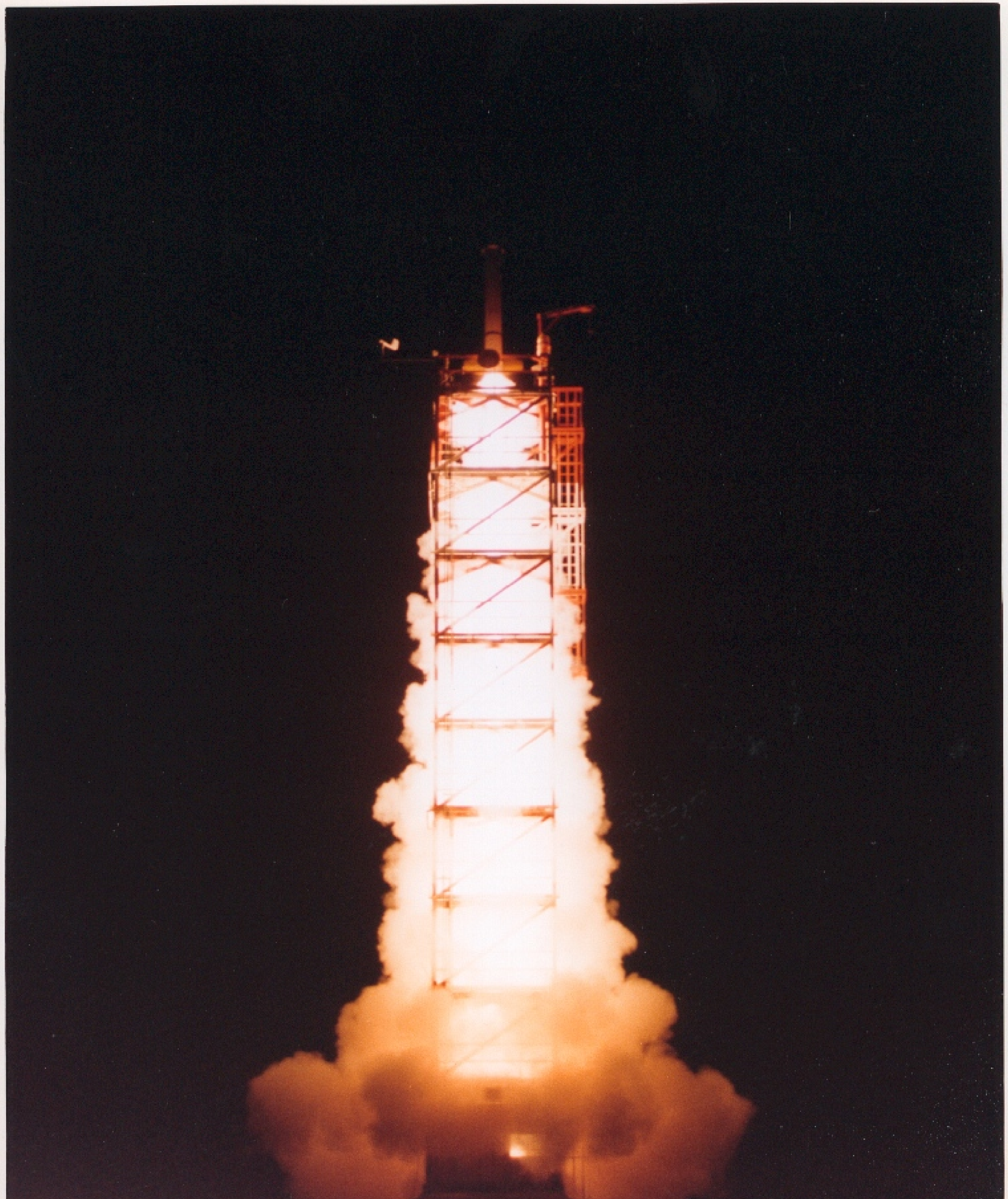
The life of an IR rocket

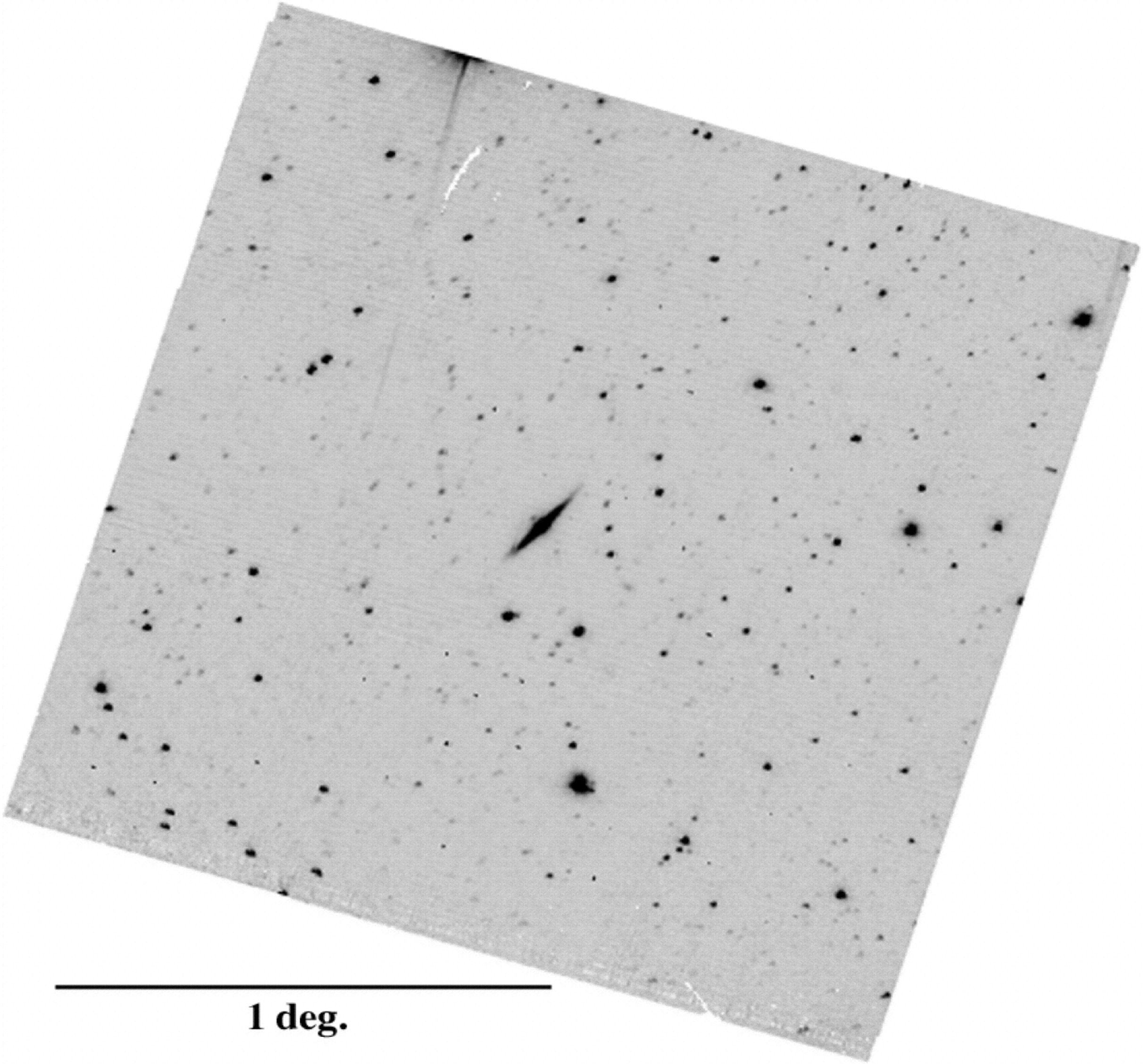
(Jamie's previous experiment)



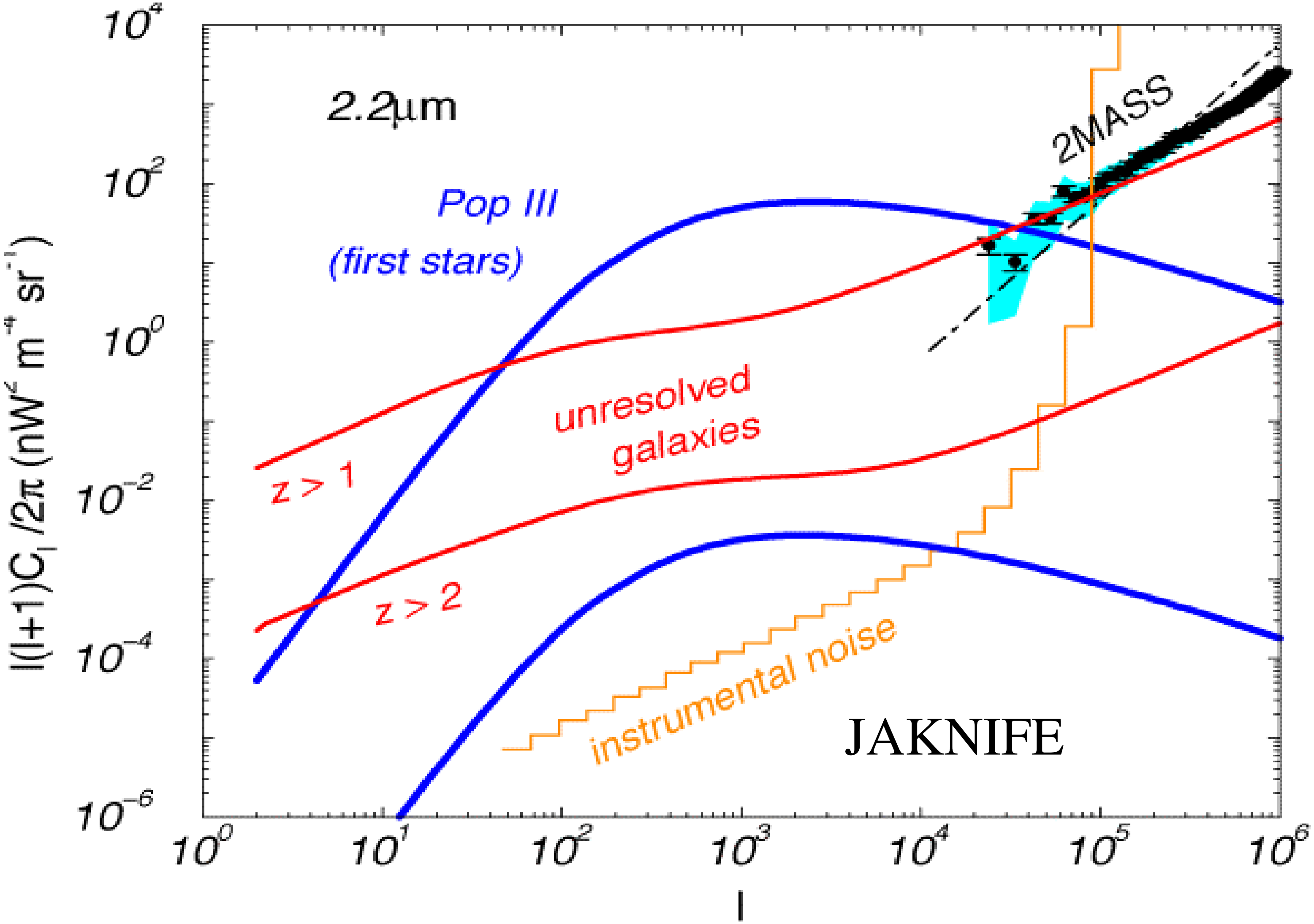

EXIT





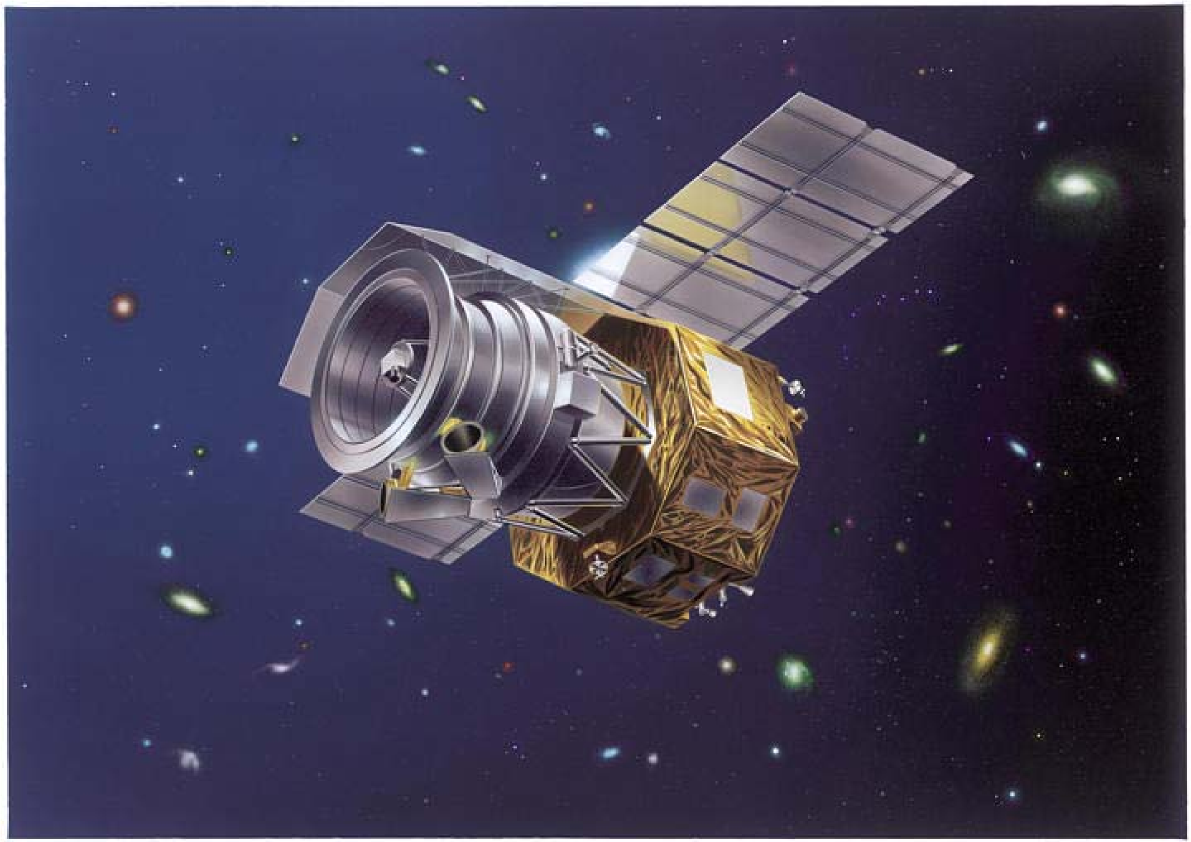


(A previous rocket data at ~4 microns;
not optimized for first stars, but background
measured in Xu et al. 2003)



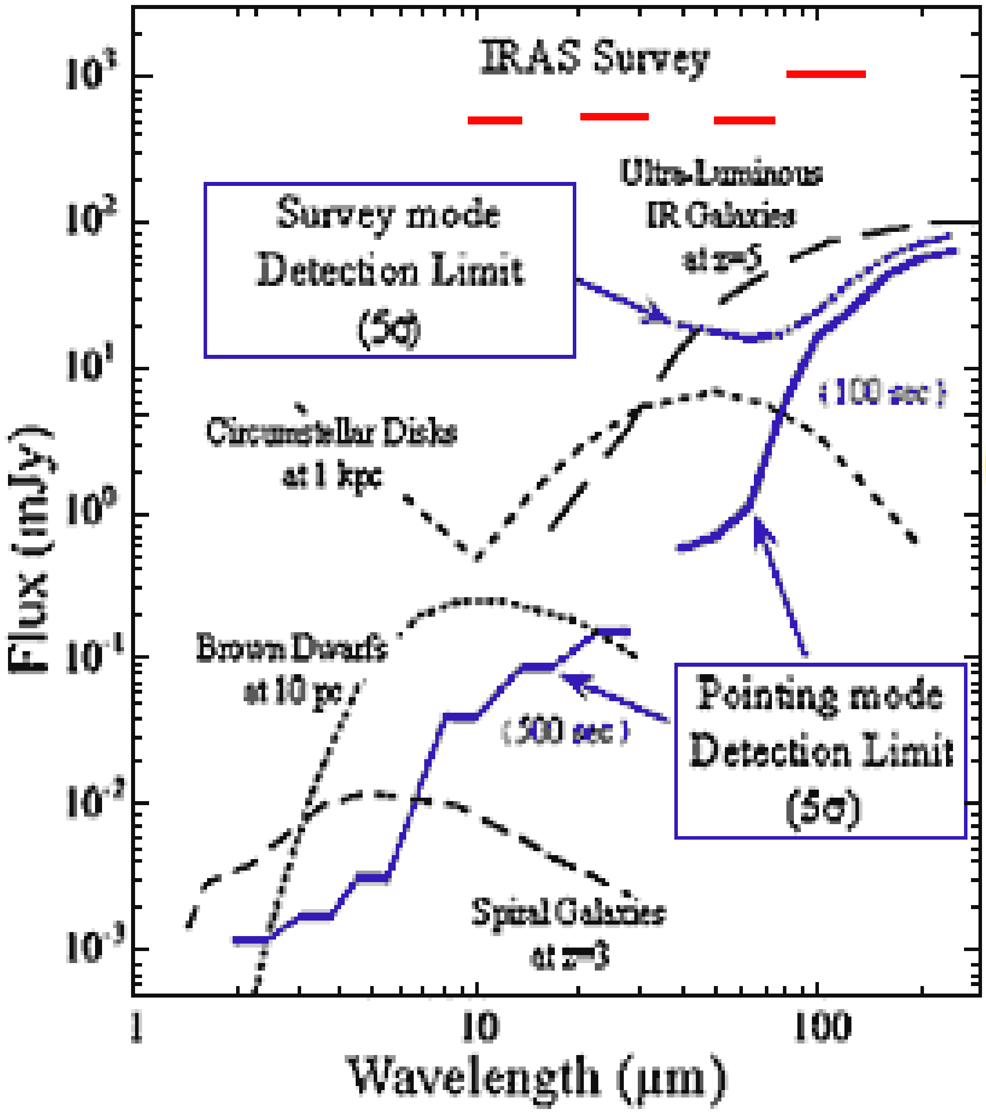
We can do the definitive experiment, but unknown related to foregrounds (zodiacal light!) is a major source of uncertainty

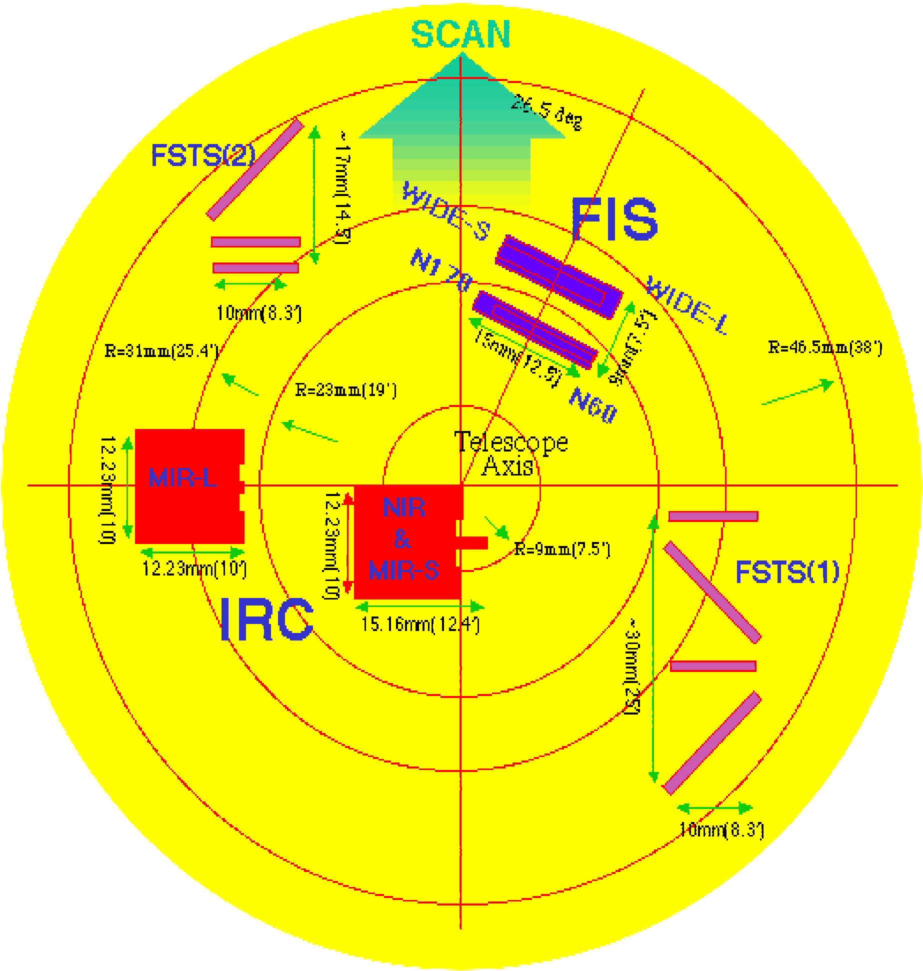
Beyond JAKNIFE: ASTRO-F



(aka IRIS: Infrared Imaging Survey)

Beyond JAKNIFE: ASTRO-F



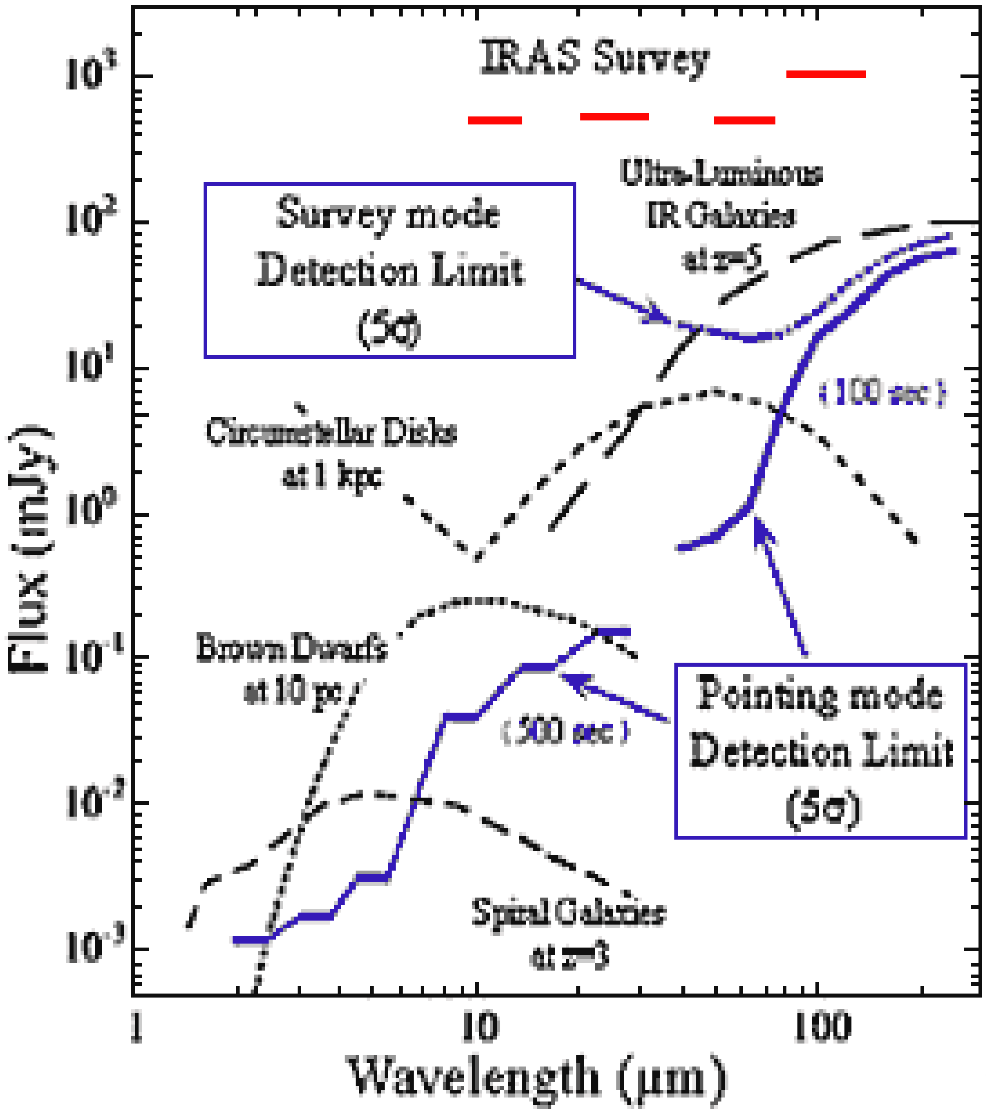


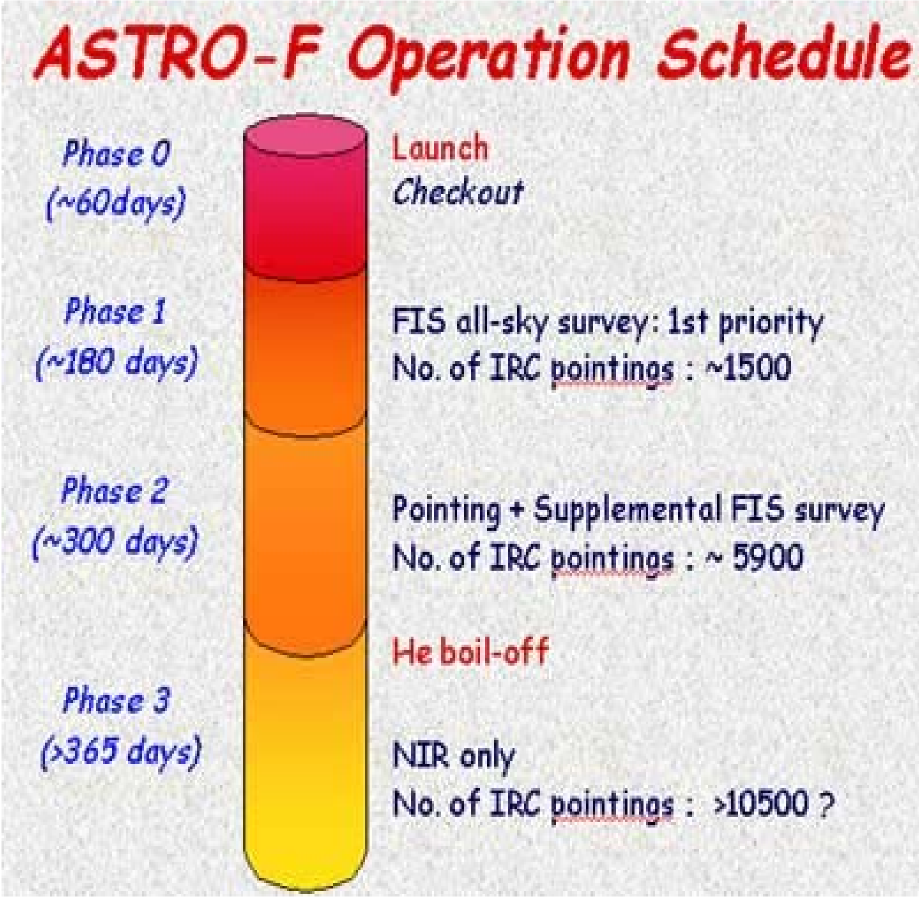
Two cameras: Far-IR and Near-IR

FIR imaging done first

Beyond NIFE: ASTRO-F

(launched > Feb 2005)





Two cameras: Far-IR and Near-IR

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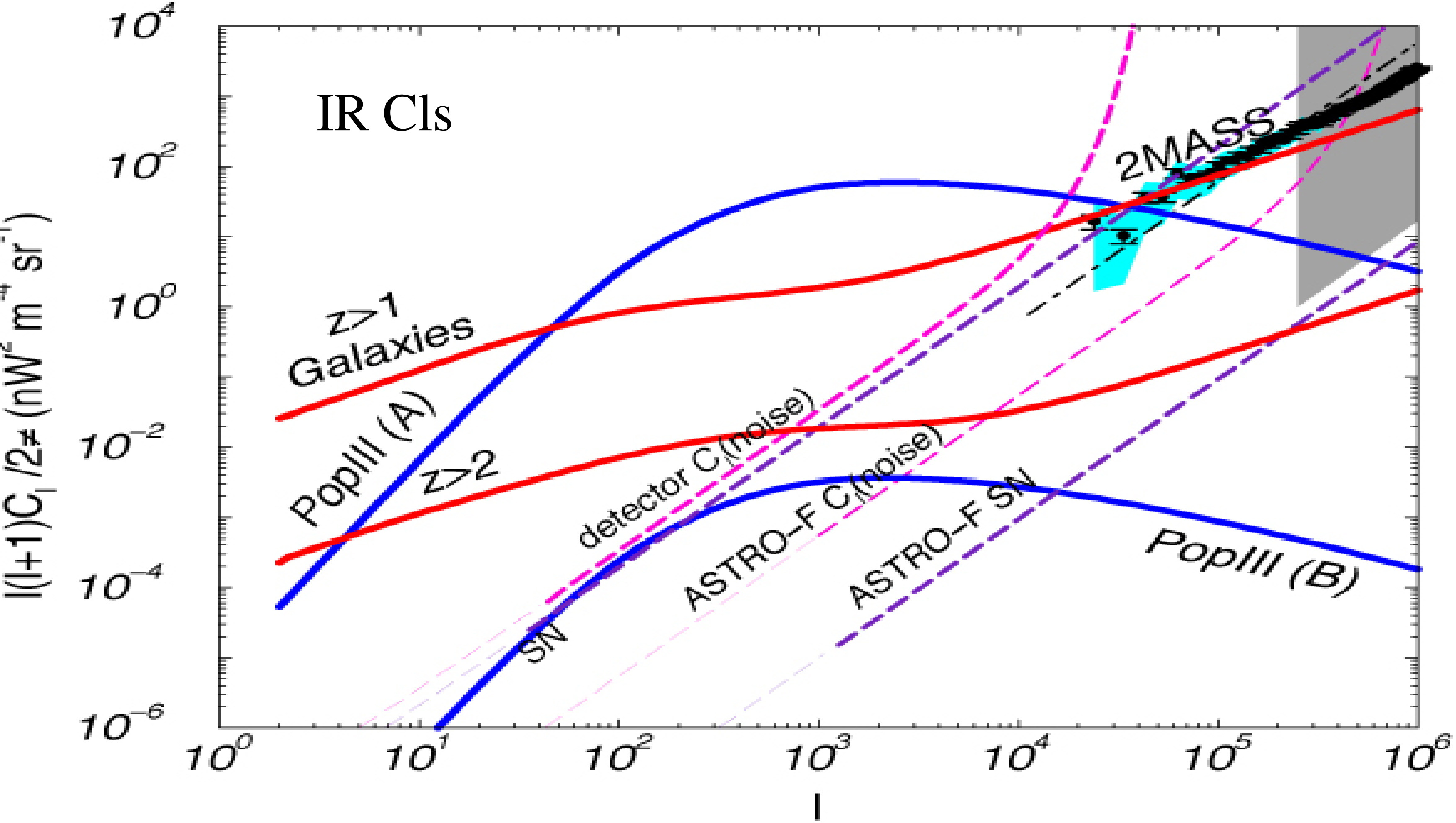
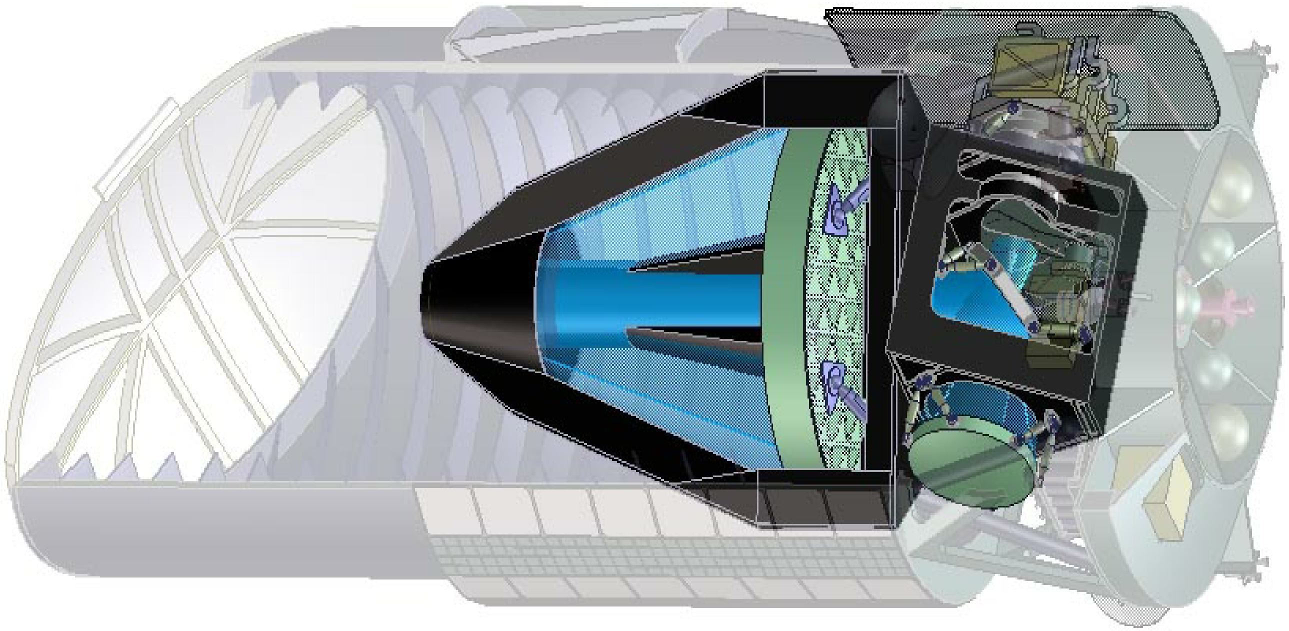
ASTRO-F (with 500 sec integrations)



High resolution: amazing abaility to resolve and remove foreground galactic stars and galaxies.

Near-IR observation details still to be worked out.

Filling the gaps: SNAP



Imaging data from the weak lensing survey can be used for IR fluctuation studies.

SNAP J-band can fill the gap below 2.5 microns of ASTRO-F!!!

First Stars

I. The case for early star-formation

II. First-star signatures in IR?

III. First-supernovae signature in small scale CMB via SZ?

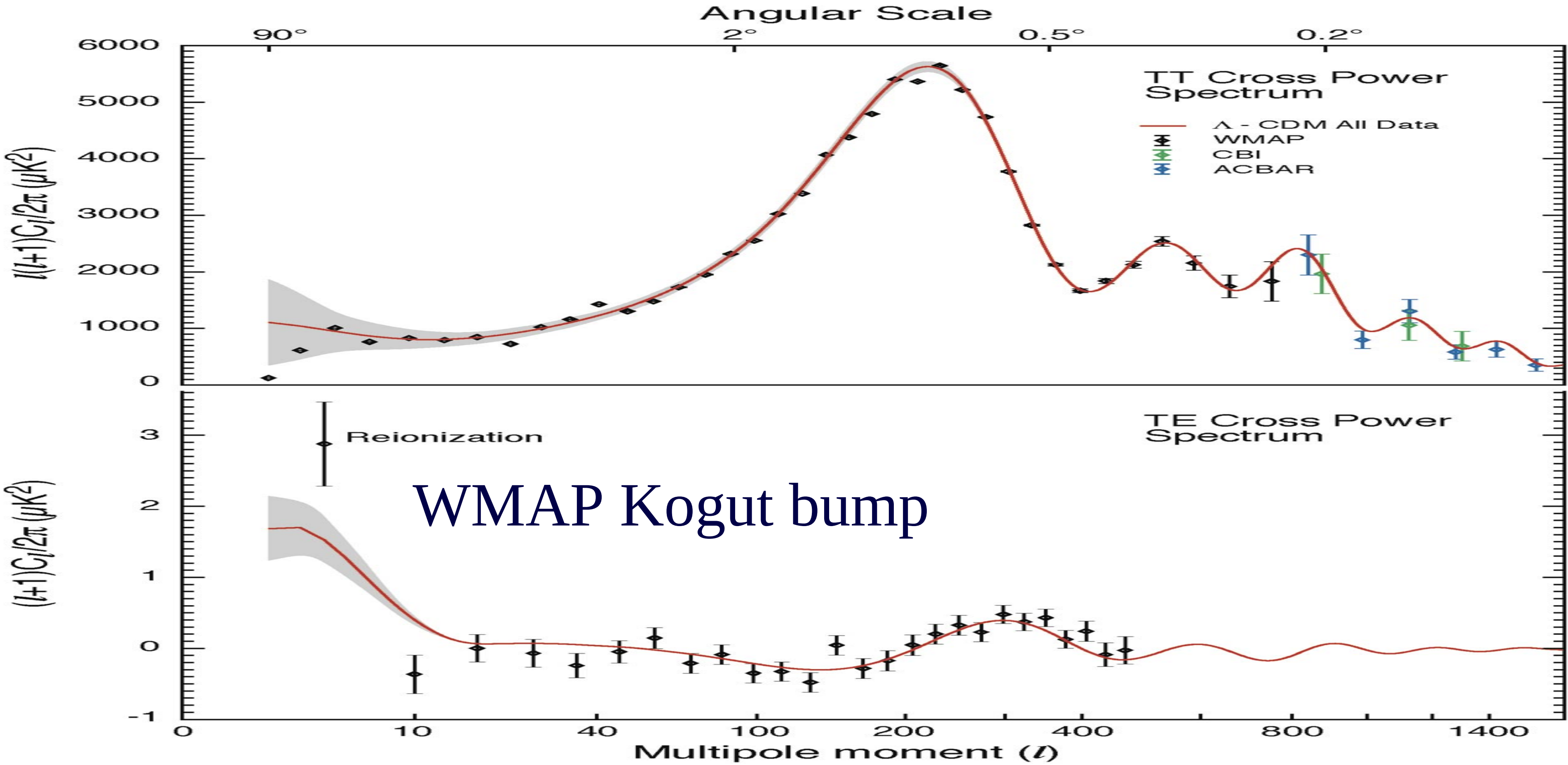
IV. Final battle: Putting II and III together and why?

Cooray, Bock, Keating, Lange & Matsumoto 2003

Oh, Cooray & Kamionkowski 2003

Interesting Facts and Suggestions

1. From WMAP TE-correlation: $\tau \sim 0.17 \pm 0.04 \quad z_{ri} \sim 17 \pm 5$



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2. An absolute minimum-y distortion for the universe

(photoionized gas: 1eV)

$$y = \sigma_T \int dz \frac{dt}{dz} n_e \frac{k_B T_e}{m_e c^2} \sim \tau \frac{k_B T_e}{m_e c^2}$$

$$y \sim 2 \times 10^{-7} \qquad (\text{FIRAS - y} < 1.5 \times 10^{-5})$$

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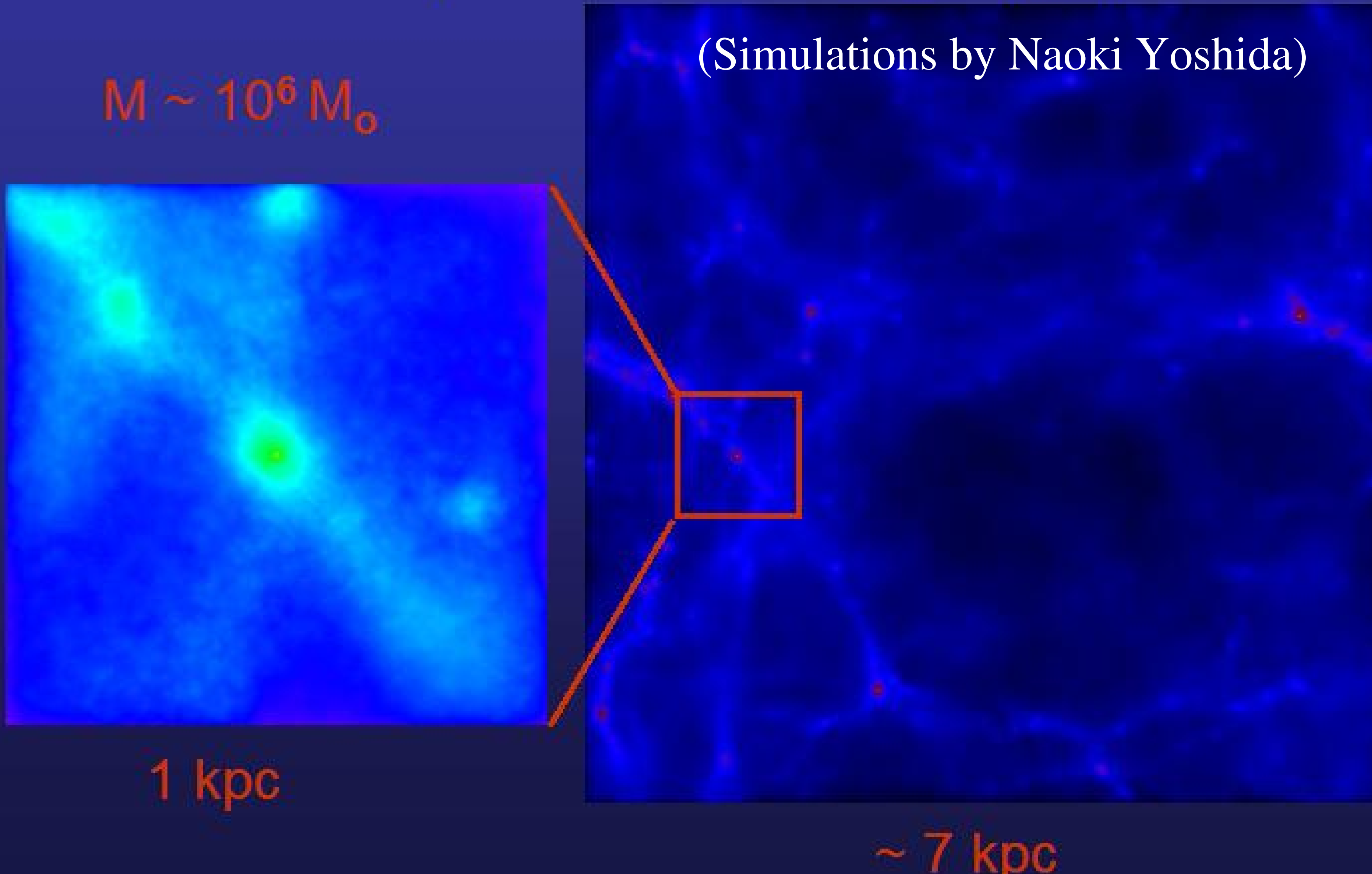
4. First generation of SNe =>

$$\text{Taylor - Sedov Expansion: R} \sim 2 \text{ kpc} \left(\frac{\text{E}_{\text{SN}}}{10^{53} erg}\right)^{1/5} \left(\frac{1+z}{20}\right)^{-11/5} \quad (1'')$$

$$t \sim t_{Compton} \approx 10^7 \text{yrs} \left(\frac{1+z}{20}\right)^{-4} \text{ and } S_{SZ} \sim 2 \text{ nJy} \left(\frac{\text{E}_{\text{SN}}}{10^{53} erg}\right) \left(\frac{1+z}{20}\right) \left(\frac{\varepsilon}{0.5}\right)$$

ε => Fractional energy transferred to CMB

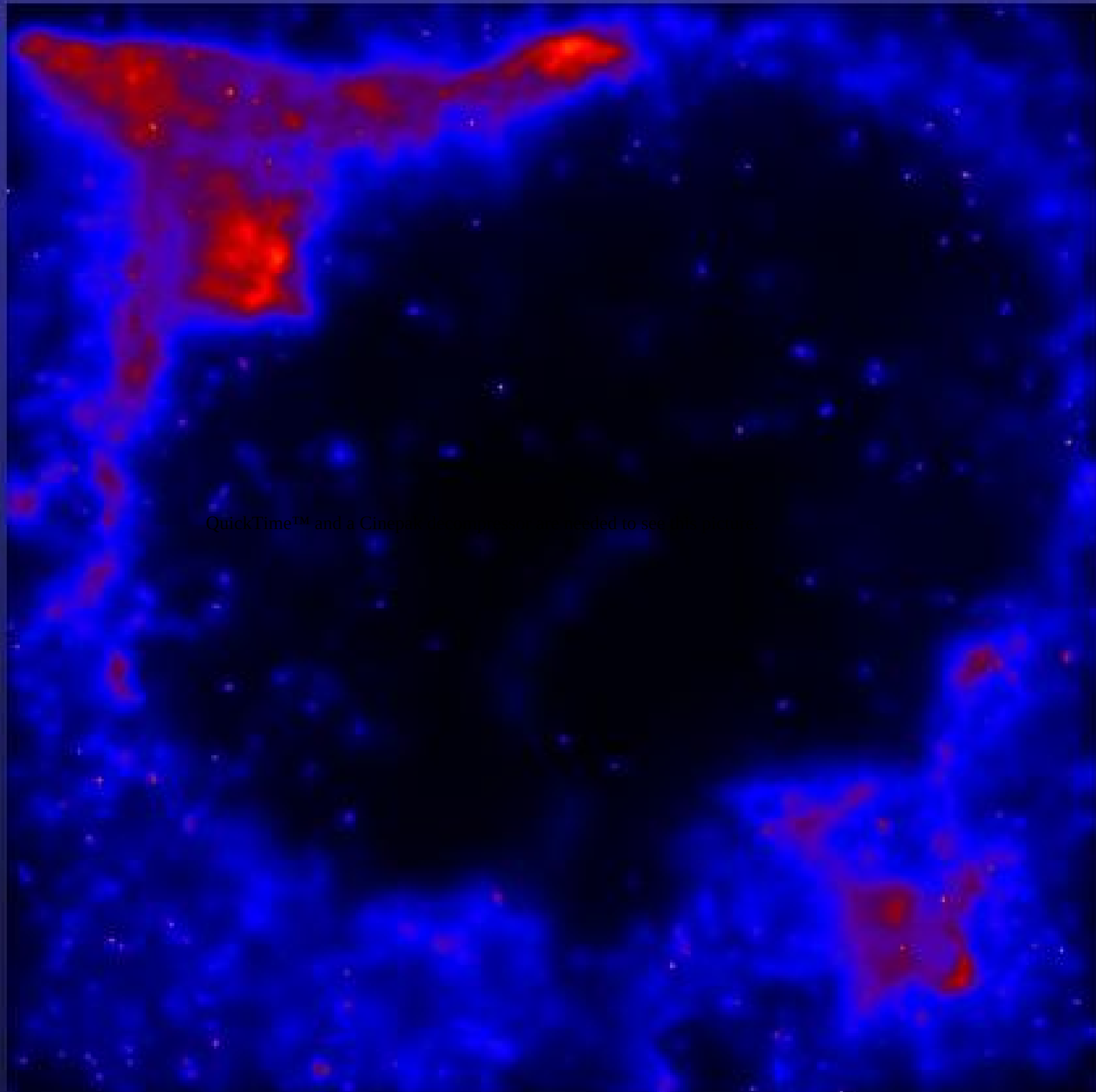
First Supernovae



The First Supernova-Explosion

Gas density

~ 1 kpc



- $E_{SN} \sim 10^{53}$ergs
- Complete Disruption (PISN)

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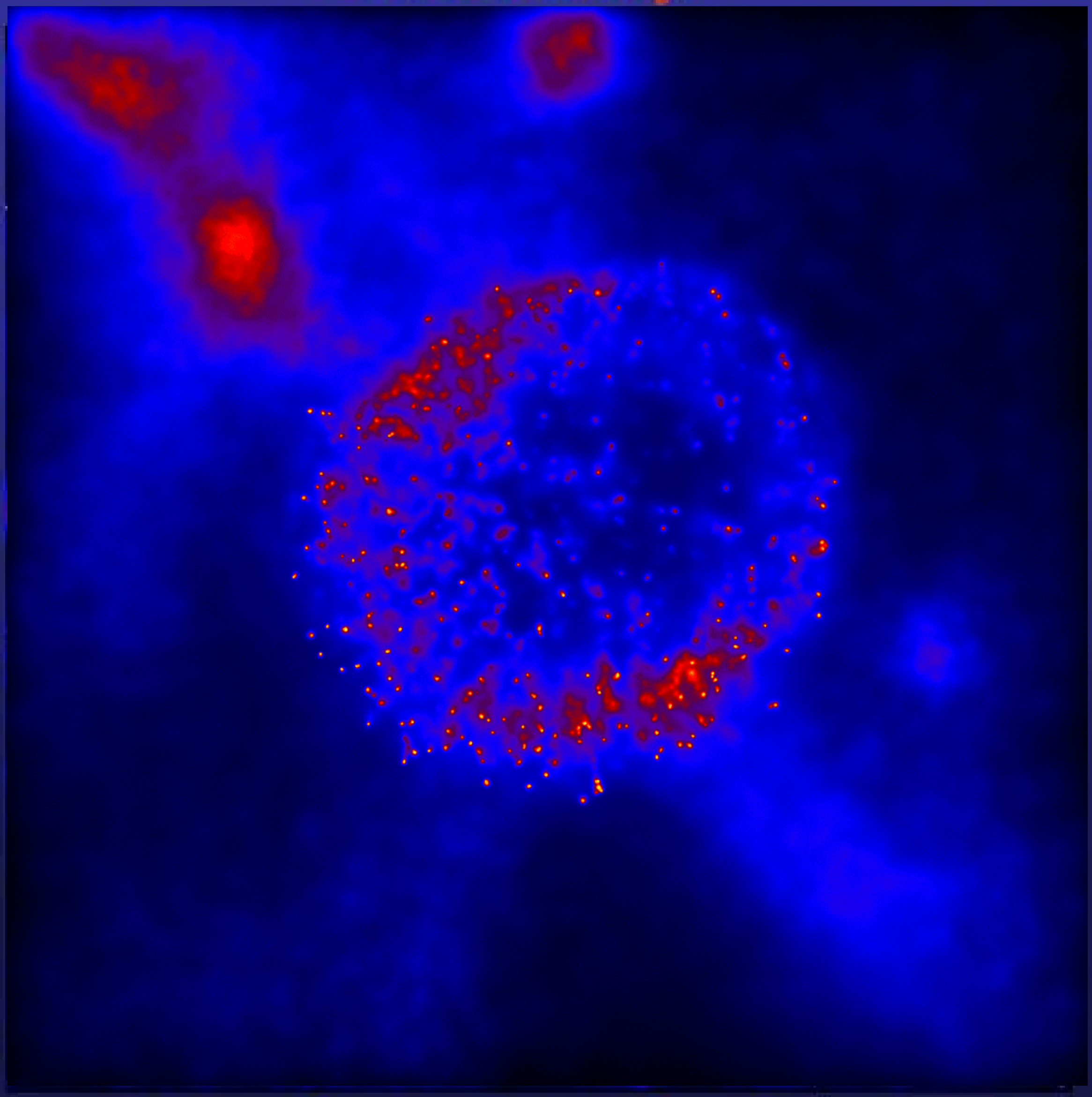

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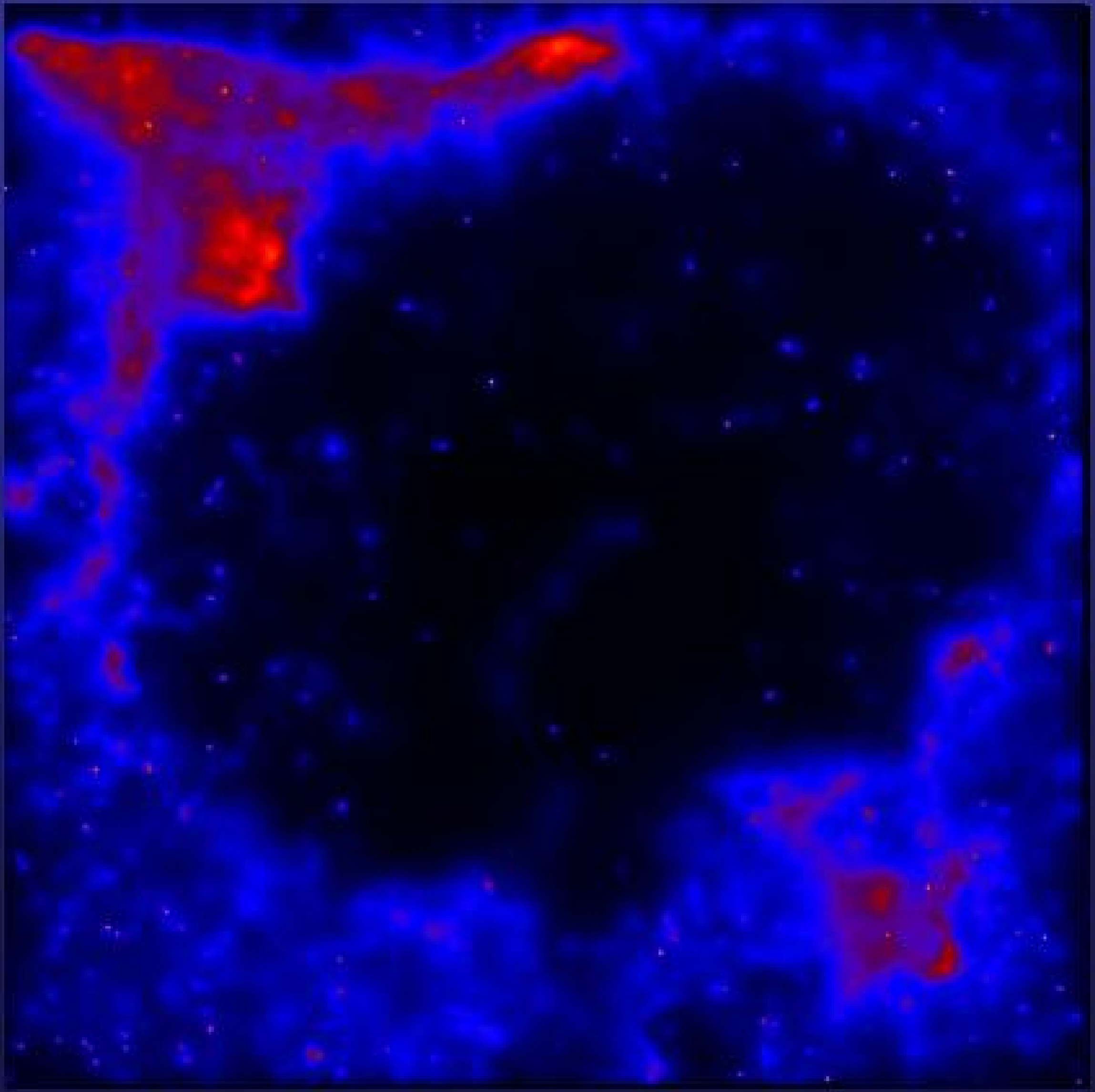

~ 1 kpc

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Reionized by First Stars

1. If massive

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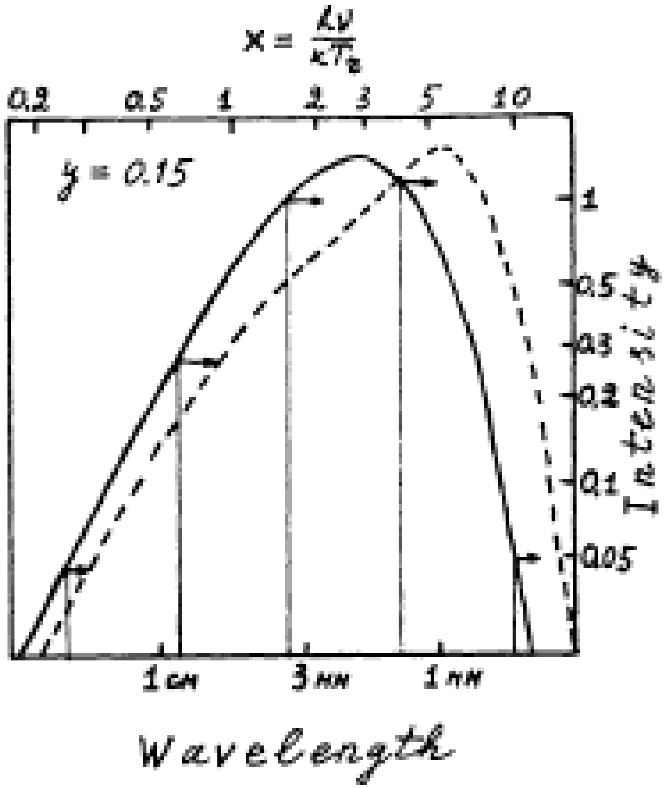
ε => Fractional energy transferred to CMB

Main cooling mechanism is through cooling off of CMB via inverse-Compton scattering

Compton Cooling

⇒ *Scattering moves photons from low frequencies (RJ part of the frequency spectrum) to high frequencies (Wien regime)*

From Sunyaev-Zel'dovich (1980):



Frequency shift the CMB blackbody

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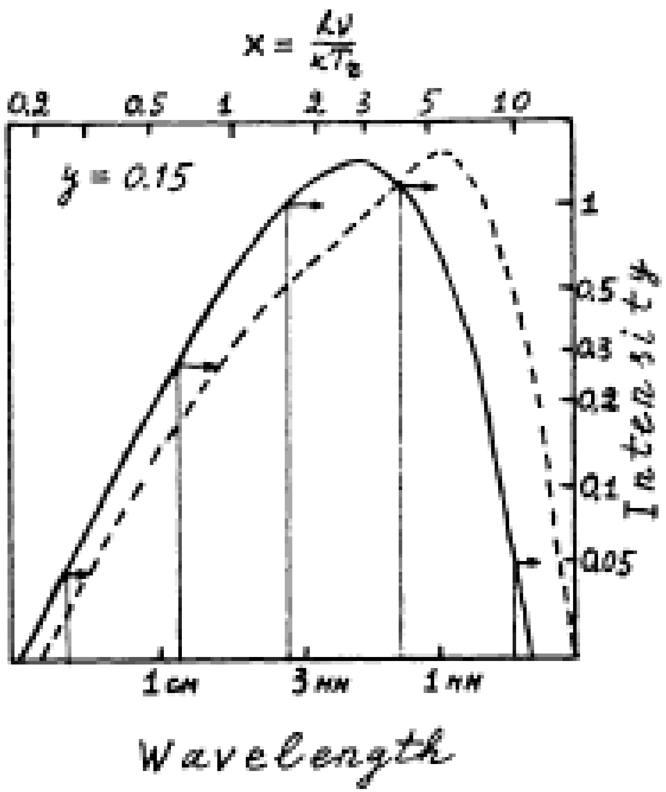
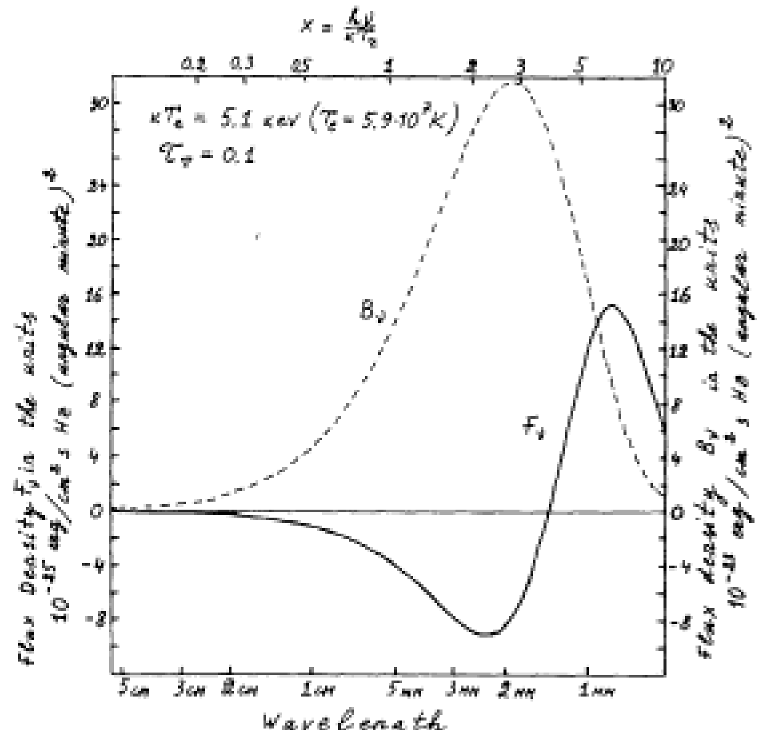


Frequency shift the CMB blackbody



and the difference (wrt to CMB)

Reionized by First stars

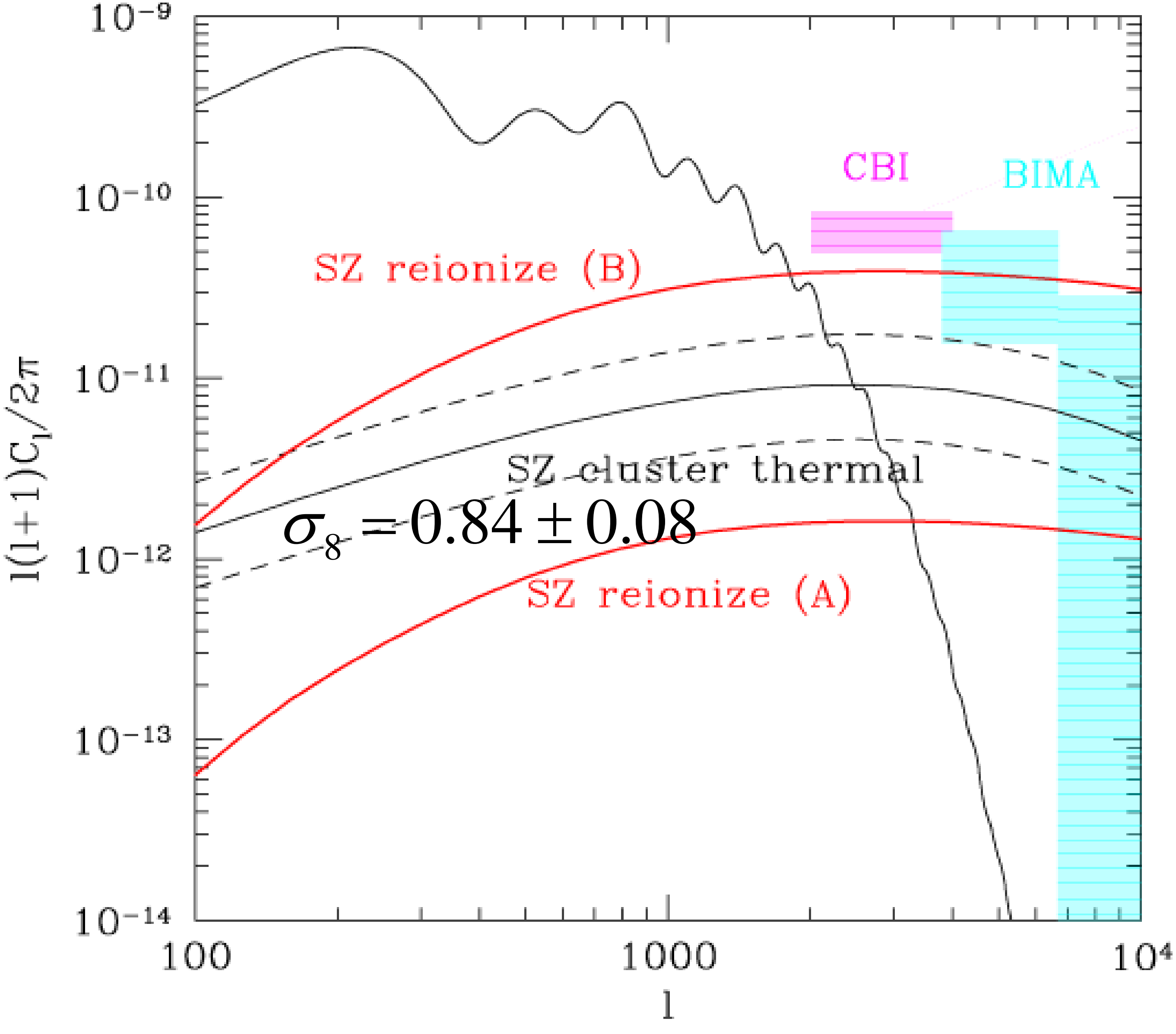
The effect is similar to the one due to hot-electrons in galaxy clusters and now observed at arcminute scales (e.g., Carlstrom et al.)

Departure from CMB black-body due to first SNe:

$$y \sim 4 \times 10^{-6} \left(\frac{E}{100eV} \right) \left(\frac{15}{1+z} \right)$$

(Still below the FIRAS - y limit of 10^{-5})

But, fluctuations are not small since halos in which first stars form are highly biased and strongly clustered!!

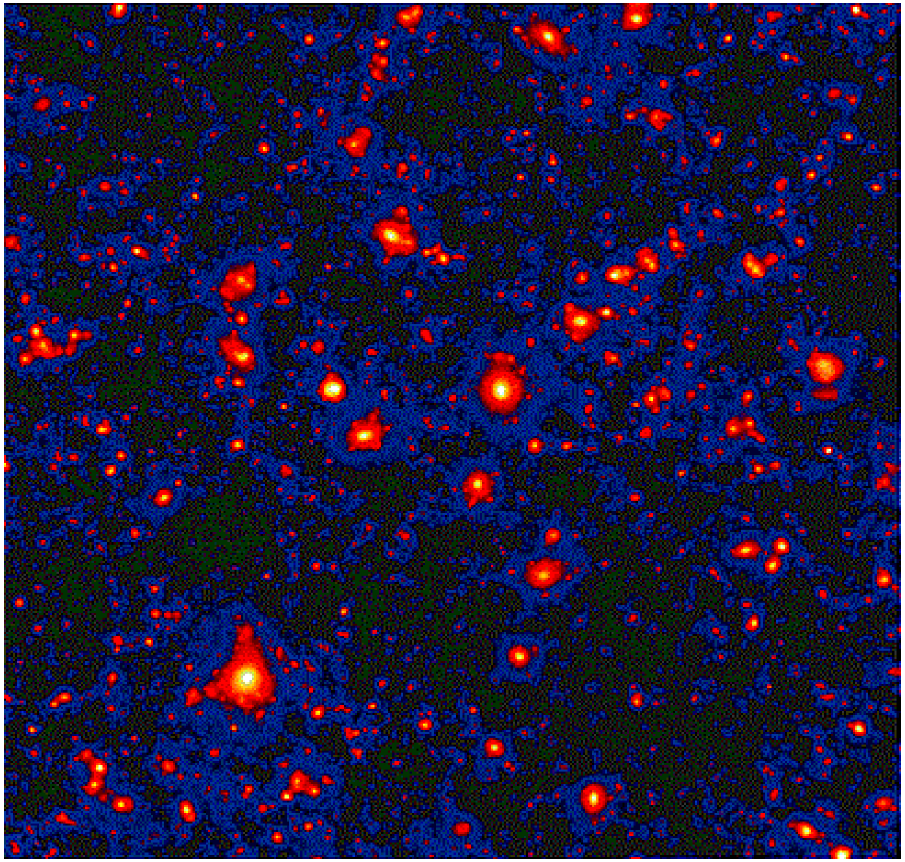


First stars in $10^5 K$ halos ($y \sim 10^{-5}$)

Oh, Cooray, Kamionkowski 2003, MNRAS

Cluster SZ Effect: Dominated by Massive Halos

(Springel et al. 2000)



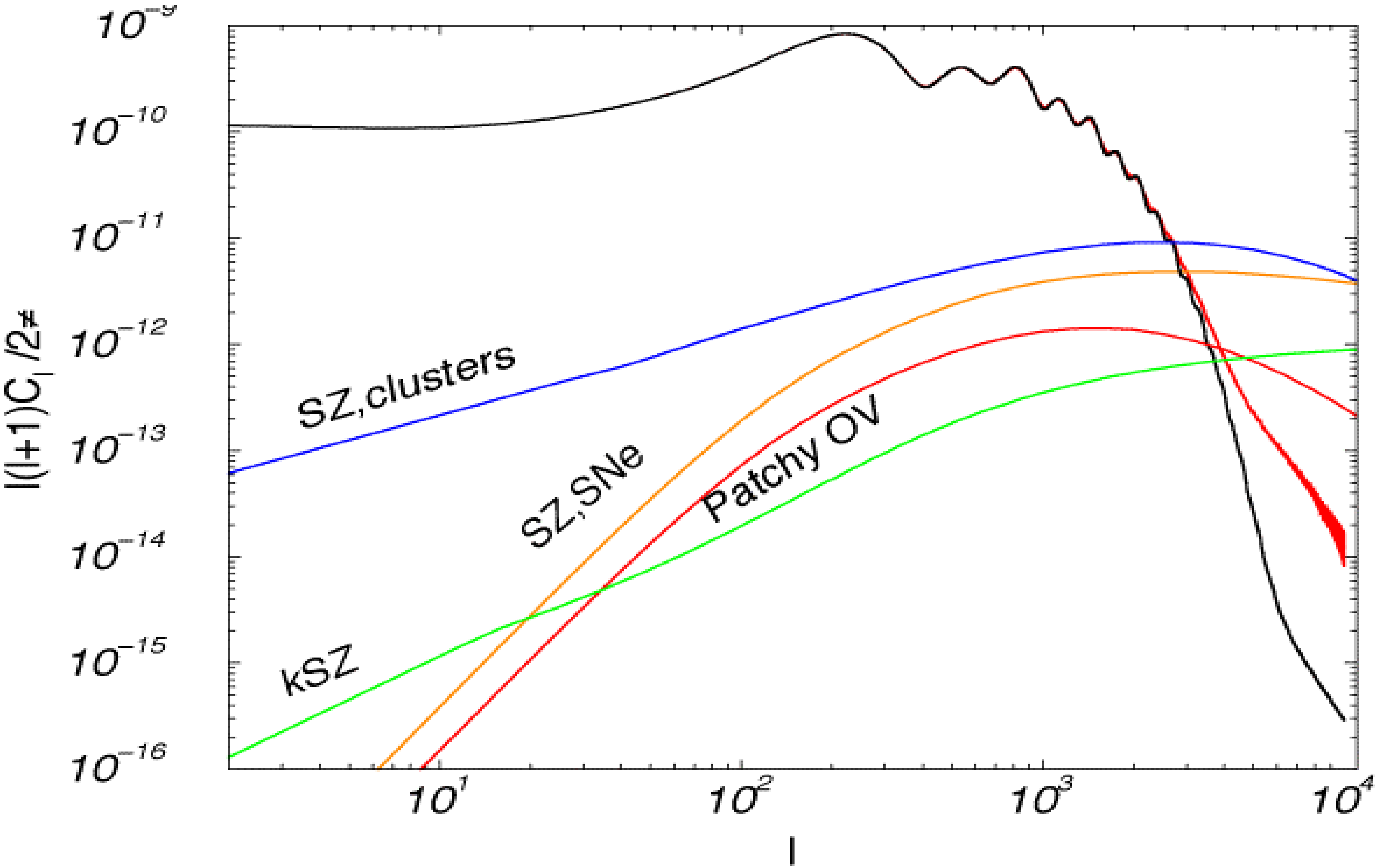
SZ: dominated by individual clusters where as SNe produce a smooth diffuse distribution

(small angular scale CMB experiments, with multifrequency information)

Reionized by Massive stars:

How to detect First SNe fluctuations?

CMB small angular scale fluctuations are confusing
(too many contributions)



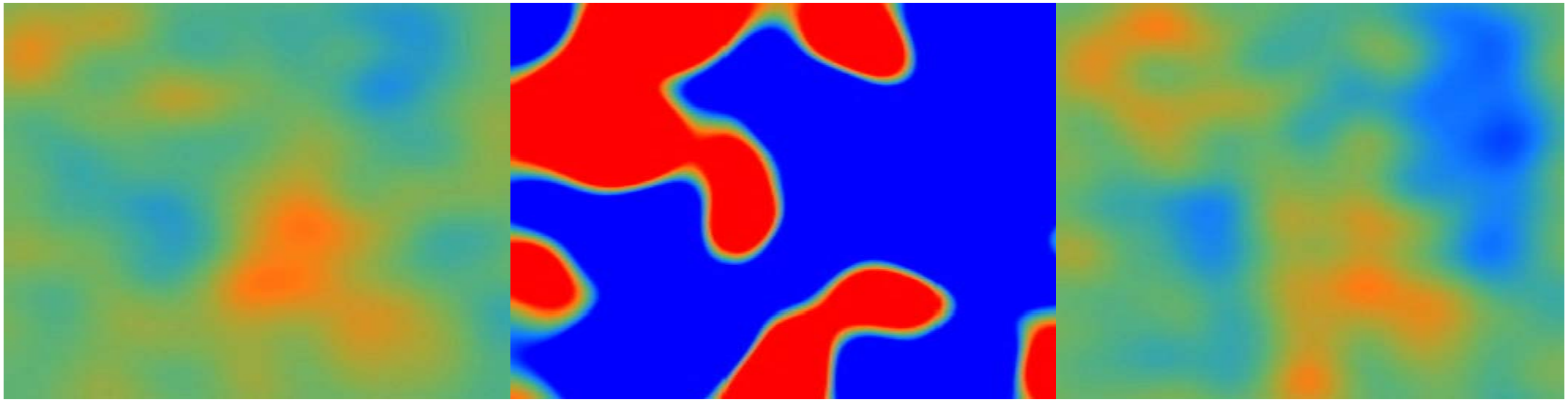
But there is hope: frequency separation

Separation of SZ thermal from CMB and rest in upcoming/present data

$\Rightarrow$ *combine experiments + known properties of foregrounds*

With Planck sensitivity:

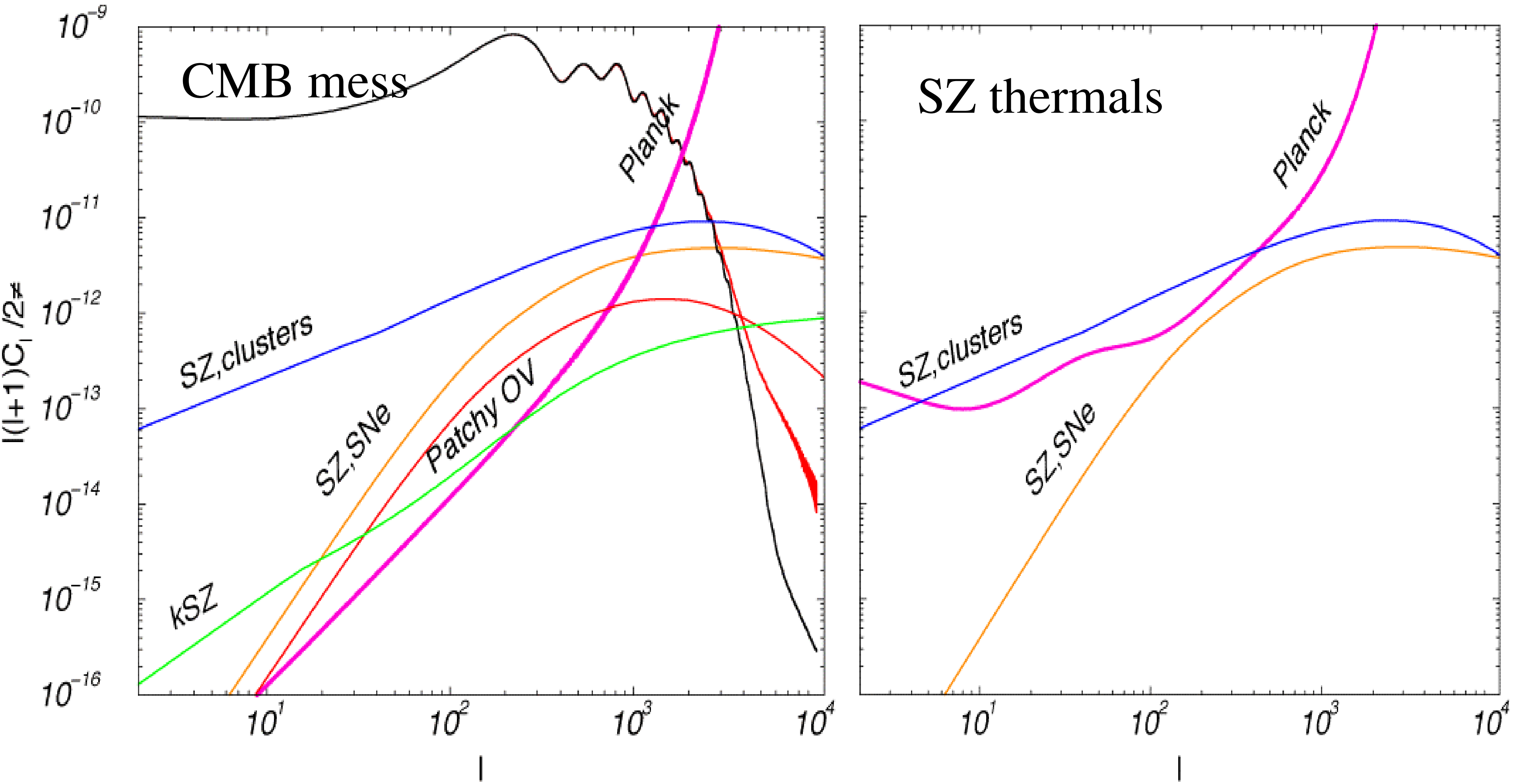
Input SZ   SZ+CMB+Foregrounds   Recovered SZ



(In real life, this is what we observe)

Cooray, Hu & Tegmark 2000

SZ separated in Multi-Frequency Data



Cooray, Hu & Tegmark 2000;

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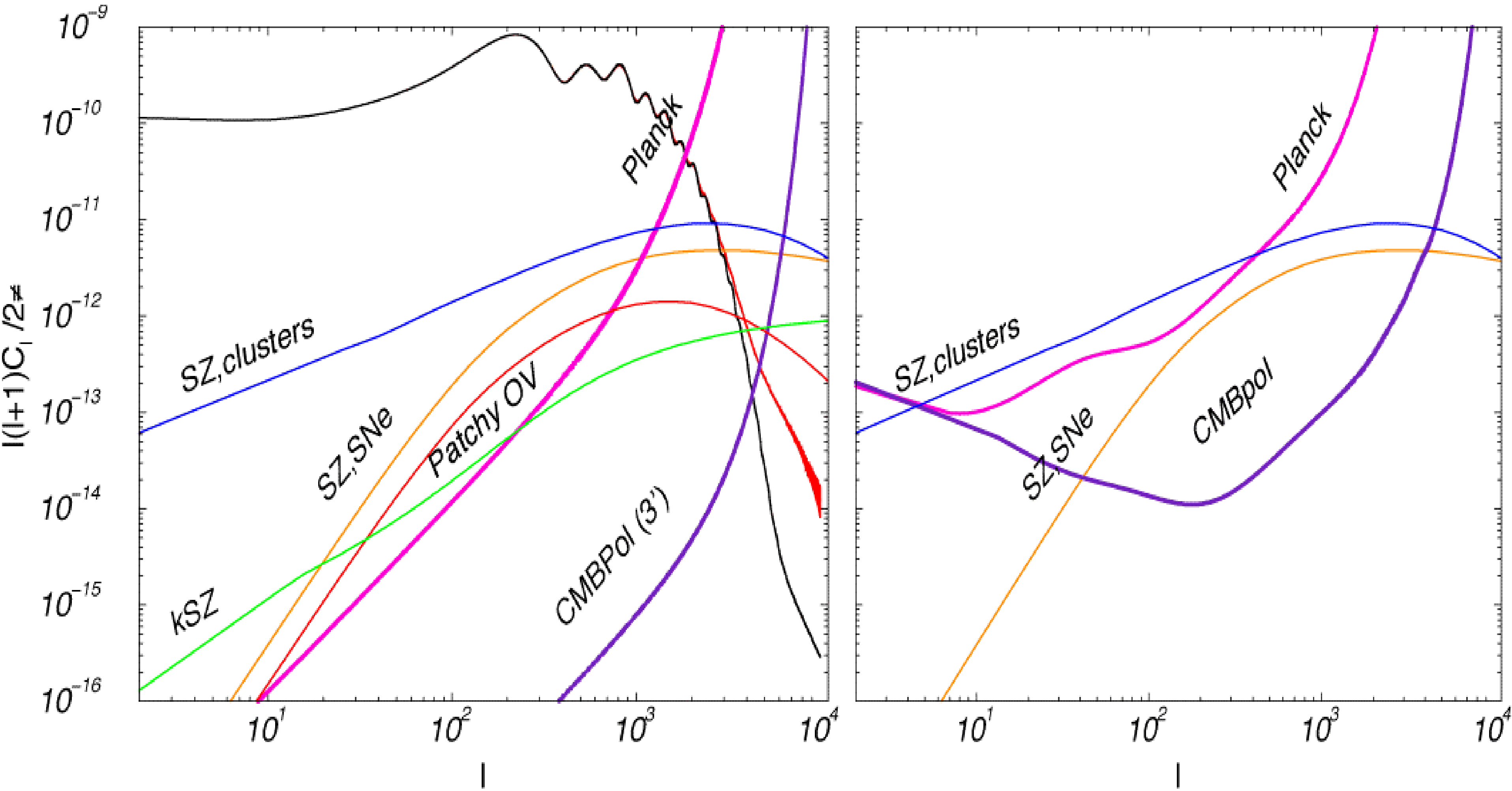

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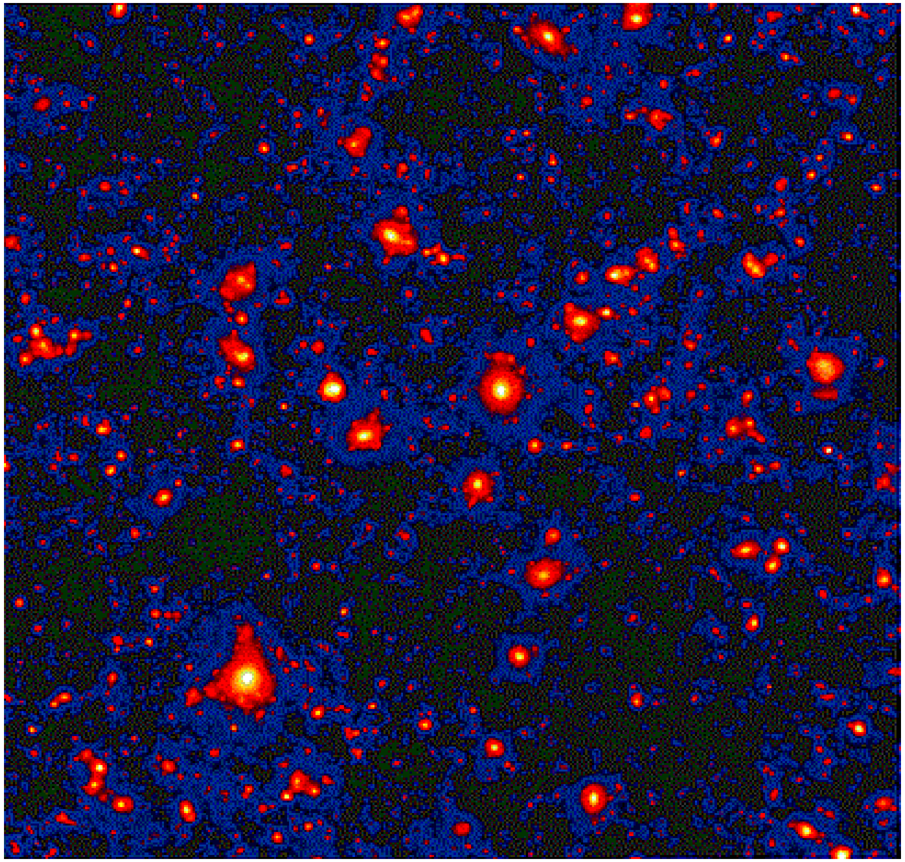
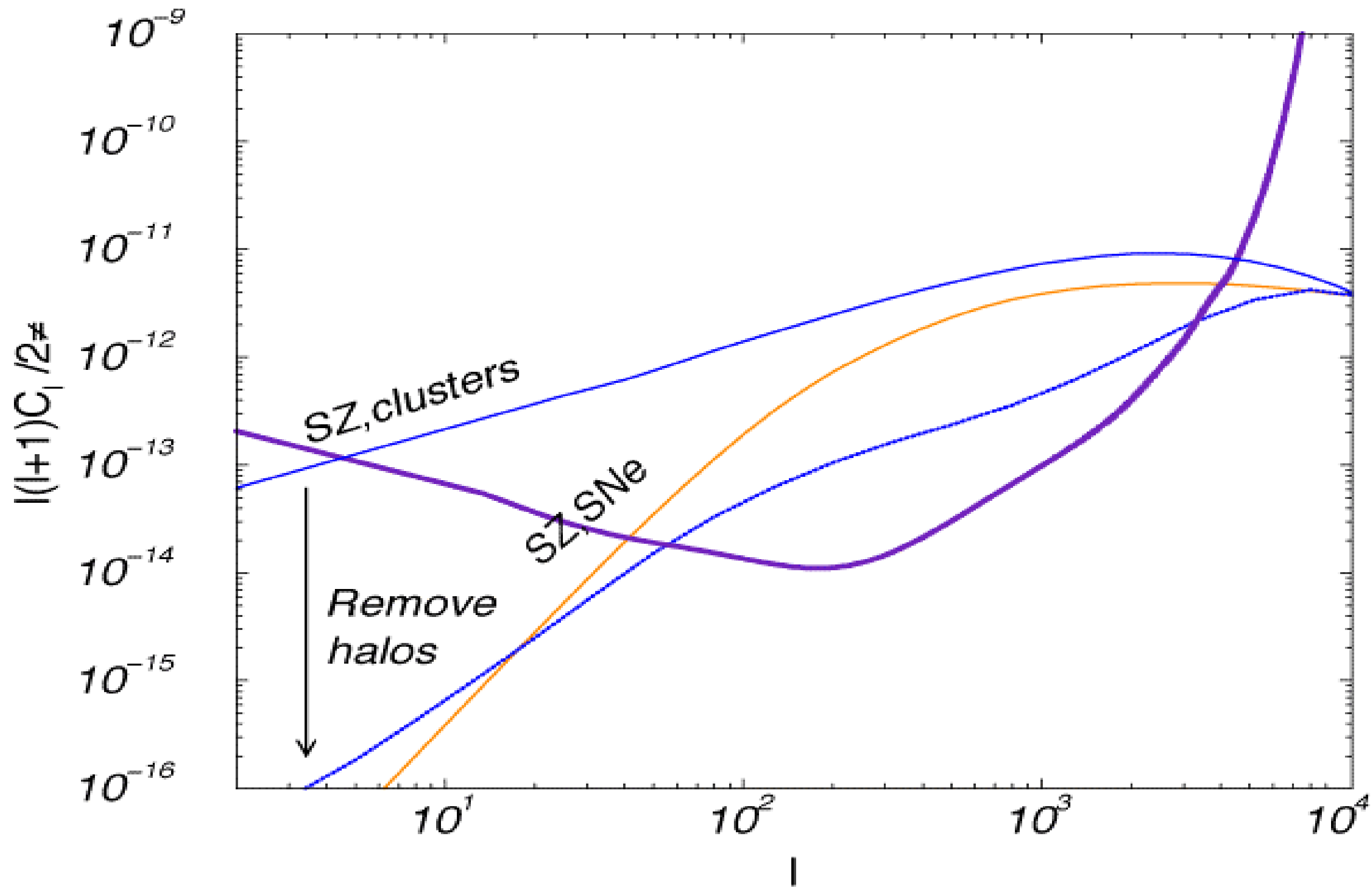


SZ thermal: dominated by individual clusters

SZ can also be separated out in multifrequency data!

Pop III SNe Sunyaev-Zel'dovich Effect

SZ contributions from clusters which are resolved



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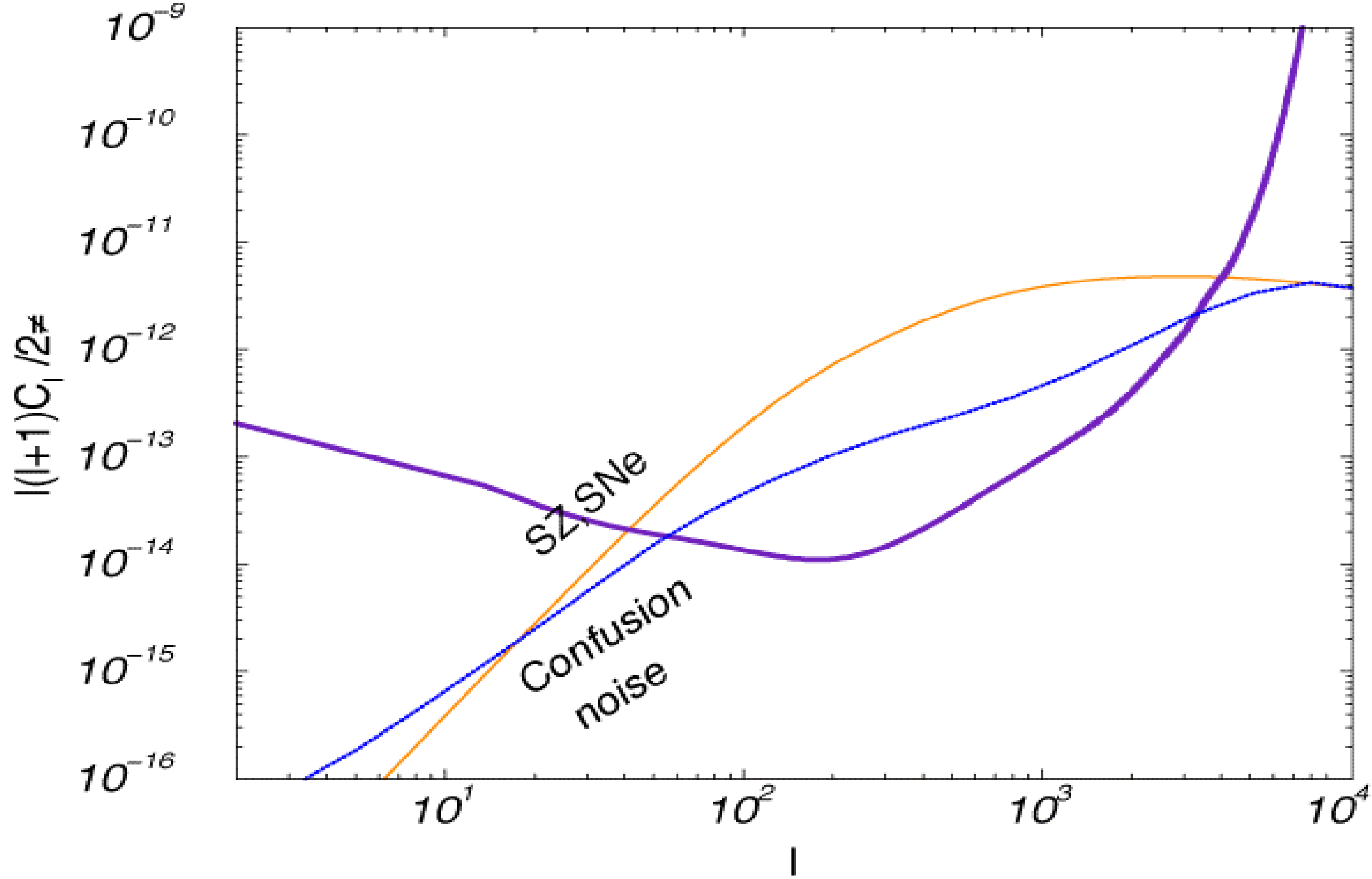

Who can do this? e.g., South Pole Telescope - 4000 sqr. degree map Atacama Cosmology Telescope

Putting all together: High-z probes of reionization

I. Large scale CMB polarization
II. Fluctuations in the Cosmic IR Background
III. Small scale CMB fluctuations - supernovae

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Unfortunately, (II) and (III) alone are not *clean* probes of early starformation and (I) measures optical depth.

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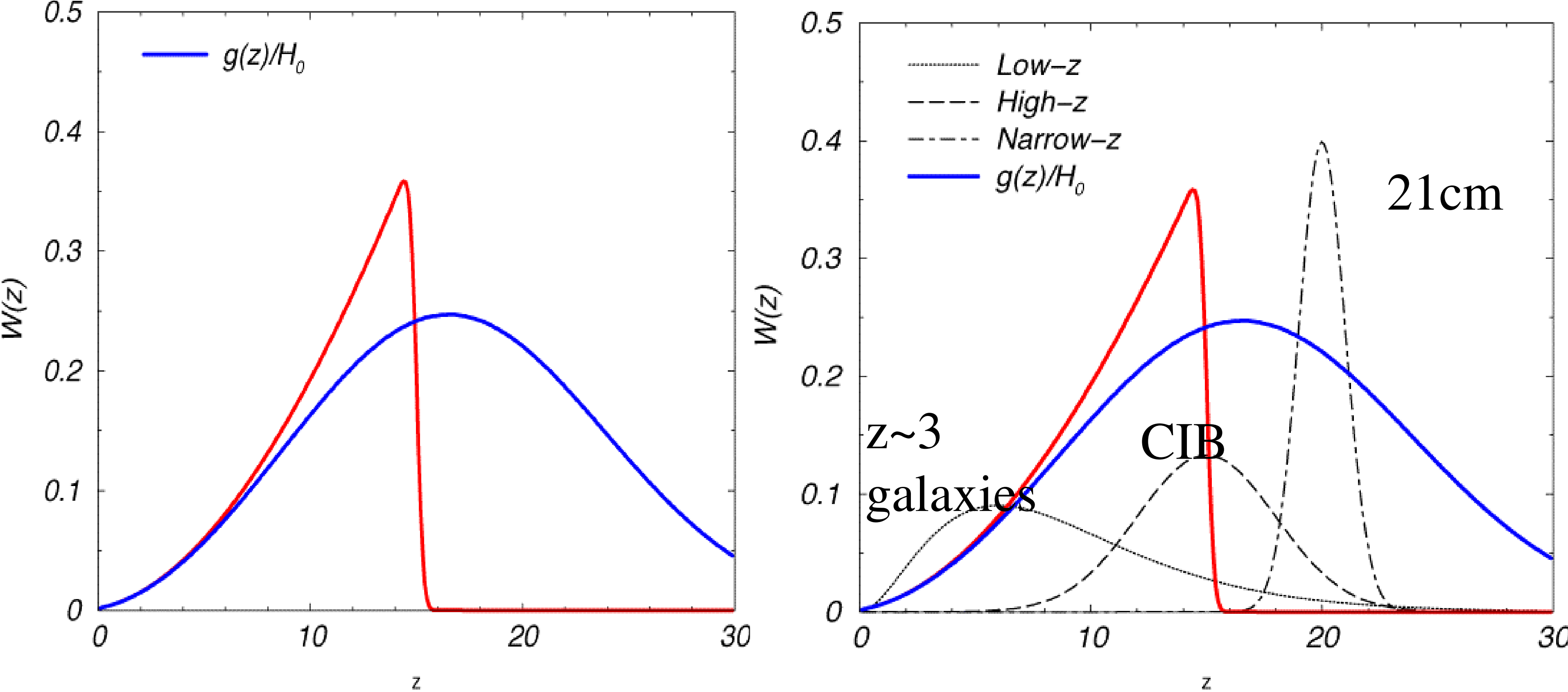
One can extract a whole lot of information from cross-correlations between these.

We already have WMAP Polarization maps, JAKNIFE will get a first map of IR fluctuations



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Polarization

Reionization $\Rightarrow$ Free electrons

Compton scattering of any local quadrupole by electrons lead to polarizatior

When primordial CMB anisotropies are projected

$$P_{\mathrm{Pr}\,im} \propto \tau\, Q^{rms}(z) \propto \sqrt{C_2(z)}$$

Electron motions generate a kinematic quadrupole

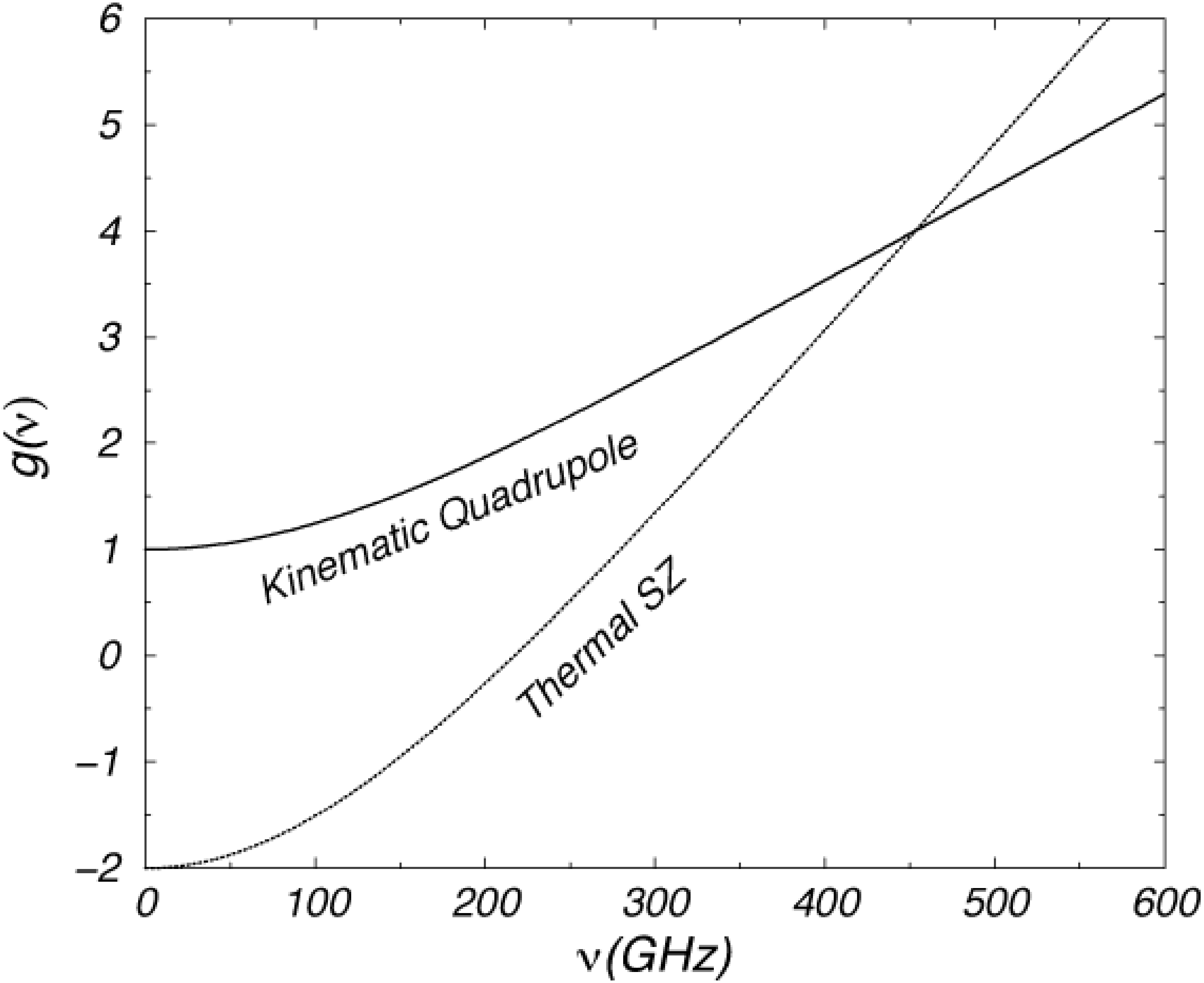
$$P_{Kin} \propto g(x)\,\tau\,\beta_{\mathrm{t}}^{2}$$

(To understand this,

$$I_\nu = C\frac{x^3}{e^{x\gamma(1+\beta\mu)}-1}$$

when expanded

$$I_\nu = C\frac{x^3}{e^x-1}\left[I_0 + I_1\mu + g(x)\beta^2\left(\mu^2-\frac{1}{3}\right)+\ldots\right]$$



6
5
4
3
2
1
0
−1
−2
g(ν)
0
100
200
300
400
500
600
ν (GHz)
Kinematic Quadrupole
Thermal SZ

*G*alaxy Clusters $\Rightarrow$ Tons of Free electrons

Compton scattering of the quadrupole lead to SZ polarization

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Double scattering effects (Intrinsic Quadrupole)

(First scattering produces a quadrupole which is scattered again to produce polarization)

$$P_{\mathrm{int}} \propto \tau^{2}\left(\beta_{t} + \mathrm{f(x)}\frac{\mathrm{k_B}T_{e}}{\mathrm{m_e}c^{2}}\right)$$

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Very small

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SZ thermal related pol. is not always small, but can be separated through f(x)

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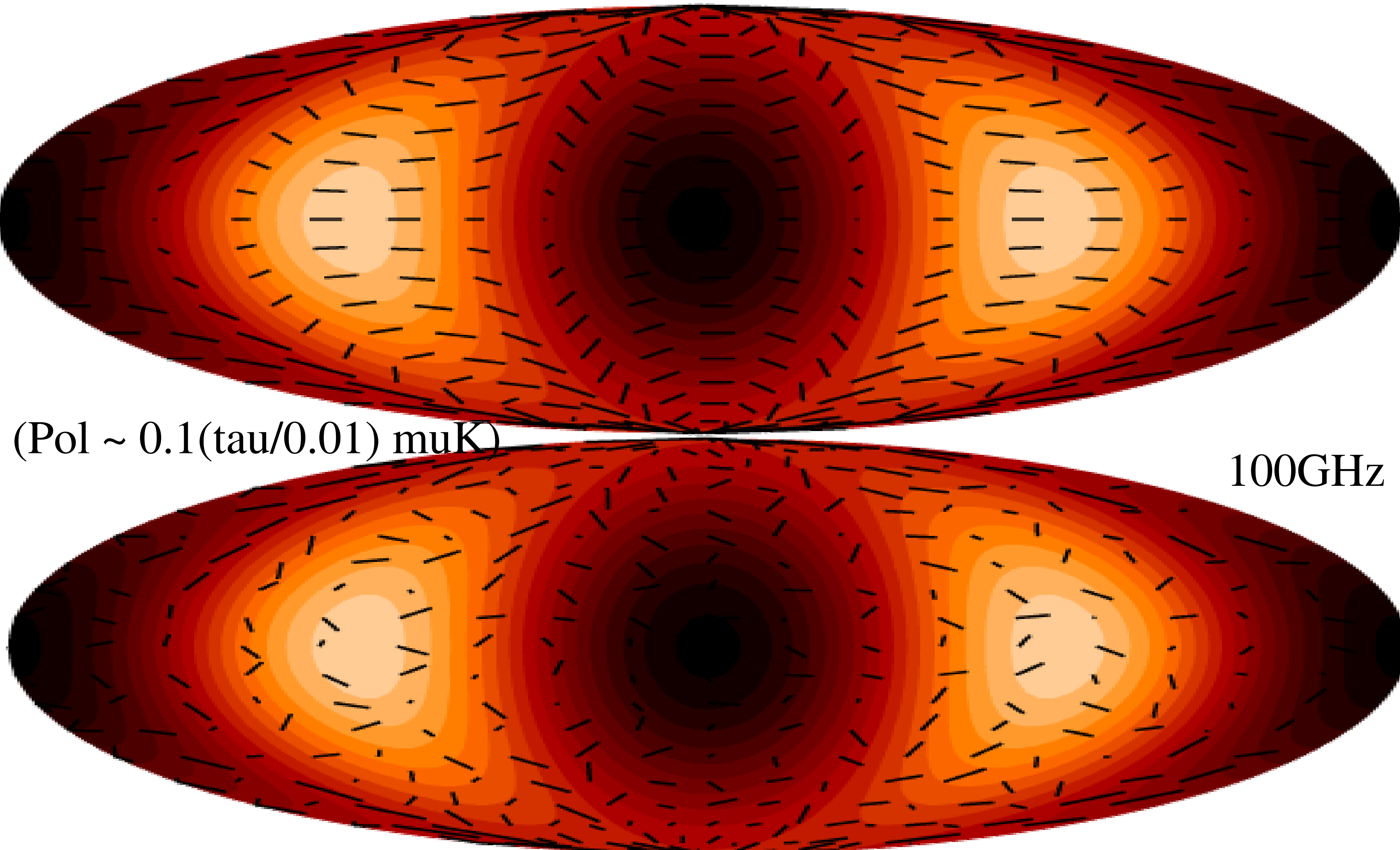
Combine with SZ thermal to measure cluster gas temperature profile

Clusters in CMB Polarization maps



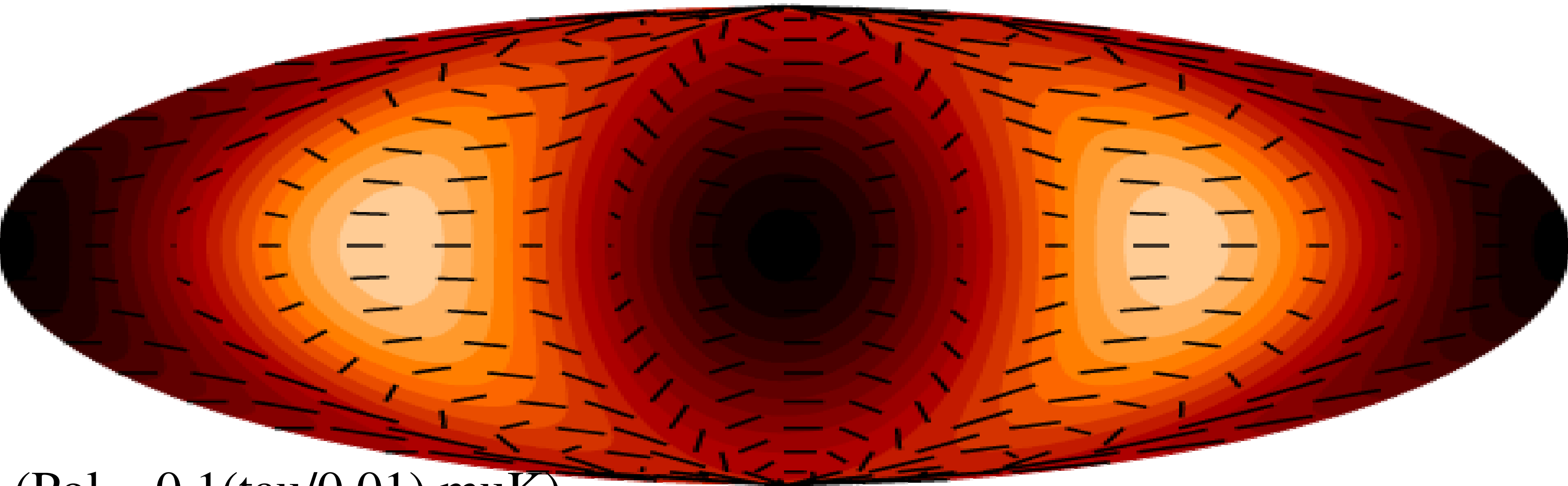
(Pol ~ 0.1(tau/0.01) muK)

100GHz

600GHz

(100 x kinematic to show randomness of velocities)

Clusters in CMB Polarization maps



(Pol ~ 0.1(tau/0.01) muK)

100GHz

At each redshift, spatial distribution of polarization is uniform.

=> One can average over large samples of clusters to determine a sample averaged polarization at each redshift.
=> This can be converted to estimate the quadrupole at that redshift

(Sunyaev & Sazonov 2002; Cooray & Baumann 2003)

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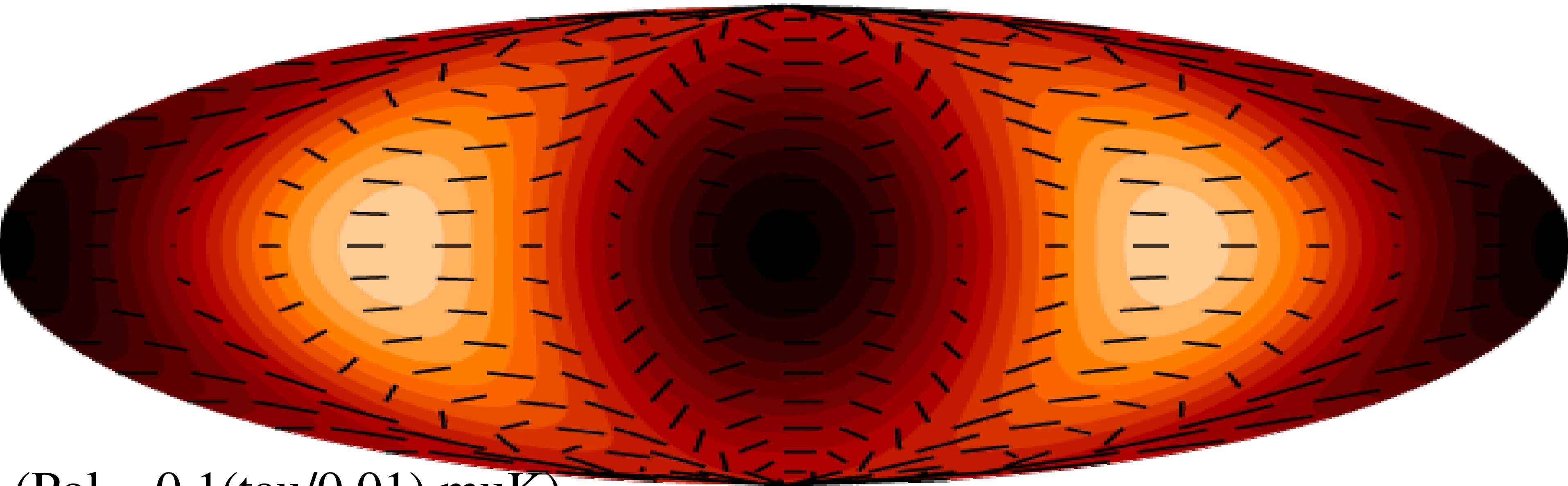

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This looks like hard. So, why bother?

Astrophysical measurements of dark energy

Fundamental structure:

If dark energy is smooth and homogeneous, dark energy only modifies the expansion rate:

$$H(z) \sim f(\text{cosmology})$$
$$\propto f(\Omega_m, \Omega_X, \Omega_c, w, z)$$

All observables in the universe are functions of the expansion rate

For e.g., distance out to some z:

$$r(z) = \int_0^z \frac{dz}{H(z)}$$

Integrations reduce sensitivity to parameters in the function "f"

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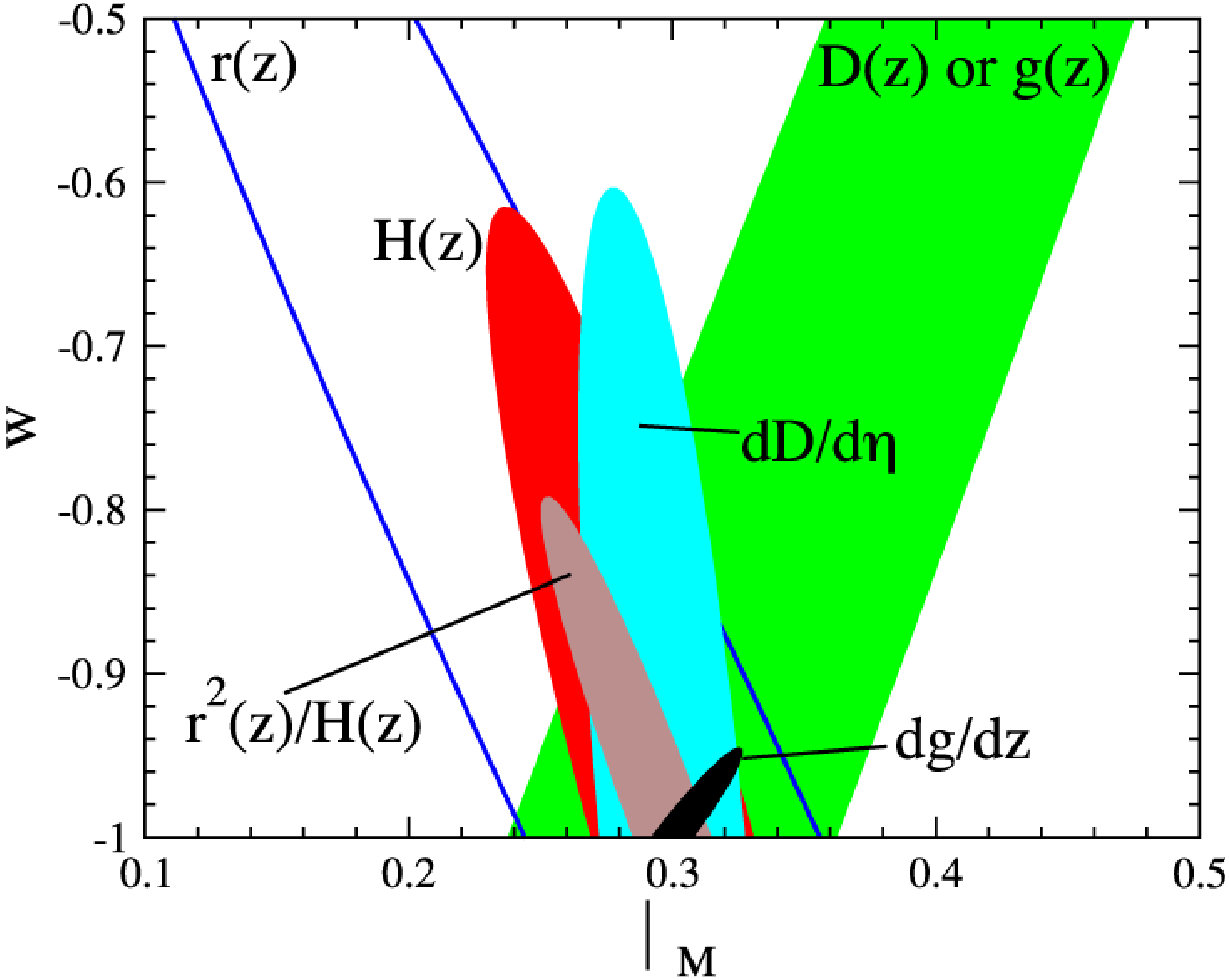
Better to probe derivatives, ie. dr(z)/dz directly. This is usually hard in practice.

In terms of cosmology (ie. Dark energy), this is an amazing measurement



10% errors
at z=0.1 … 2
at steps of 0.1
for each quantity

Different Probes compared equally.

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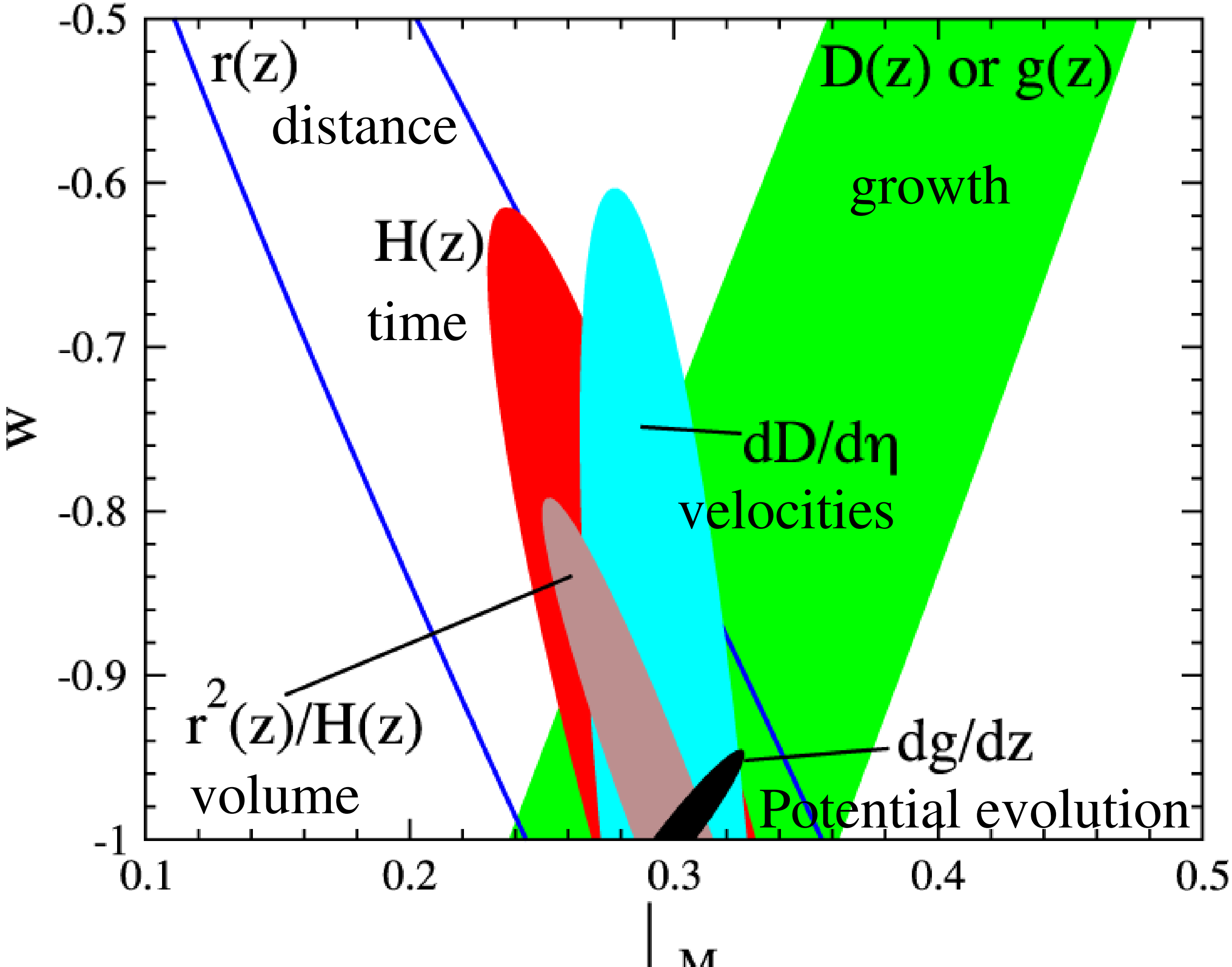

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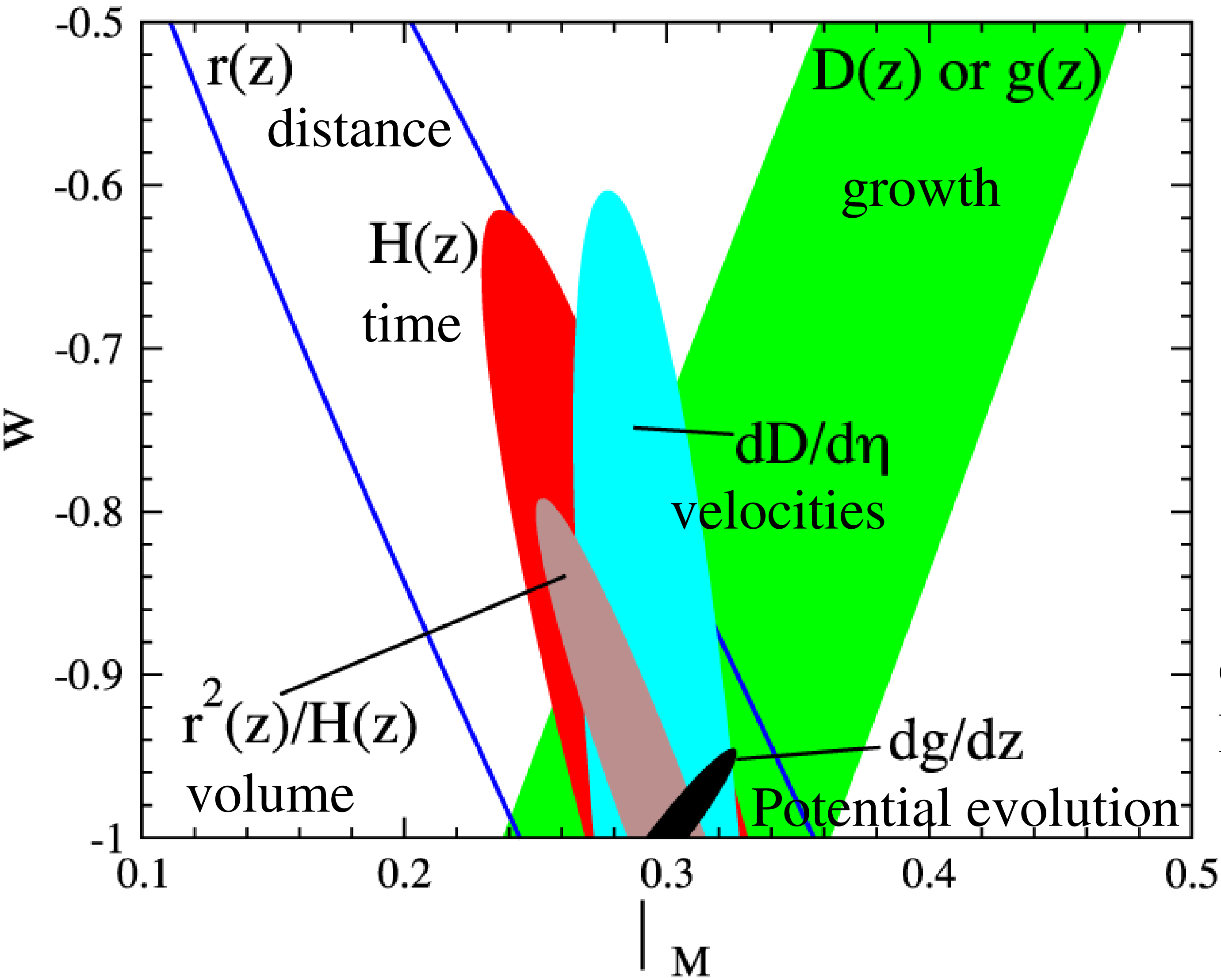
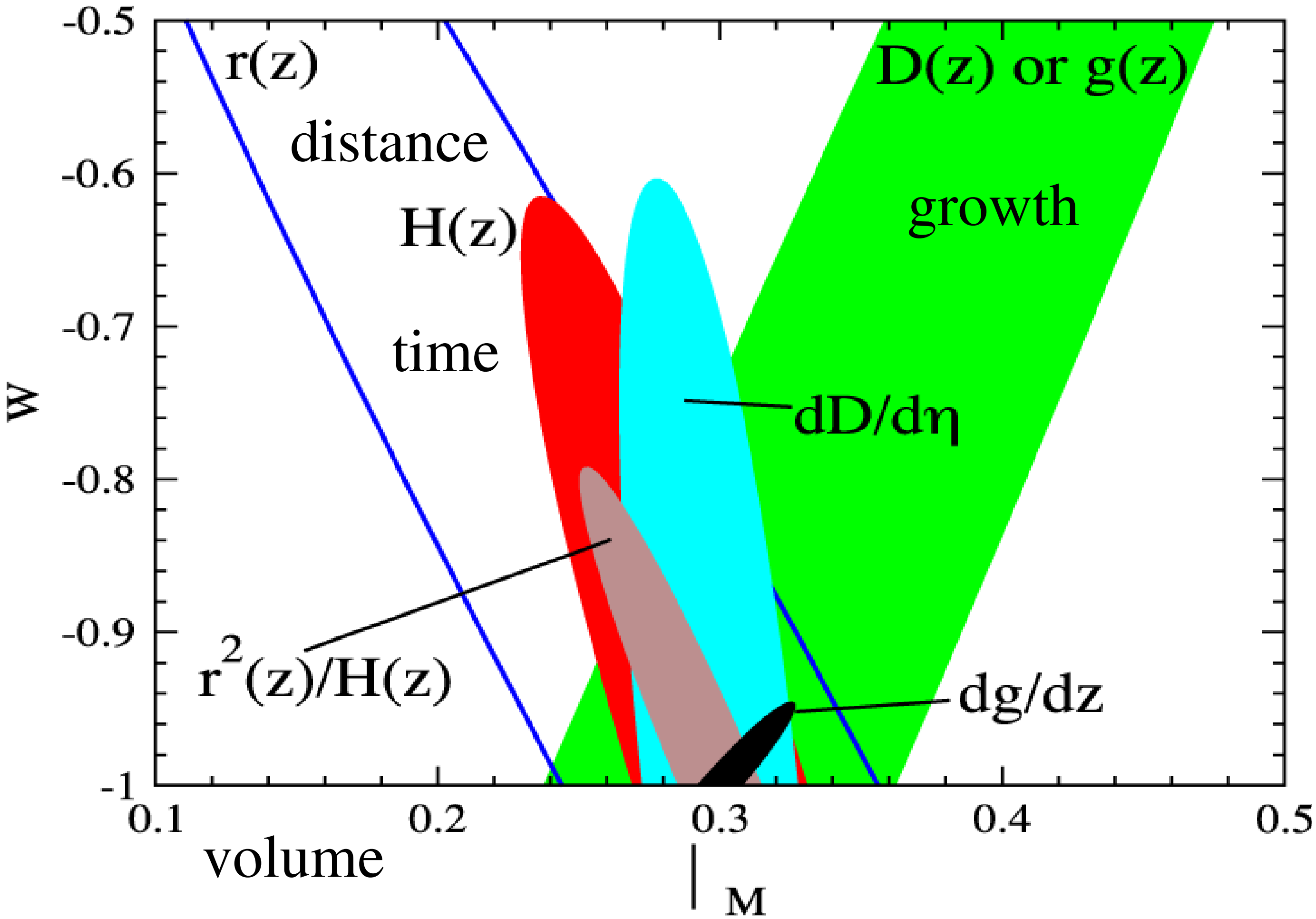


10% errors
at z=0.1 … 2
at steps of 0.1
for each quantity

dg/dz determines ISW effect in CMB (ie. The exact quadrupole at low redshifts)

Different Probes compared equally.

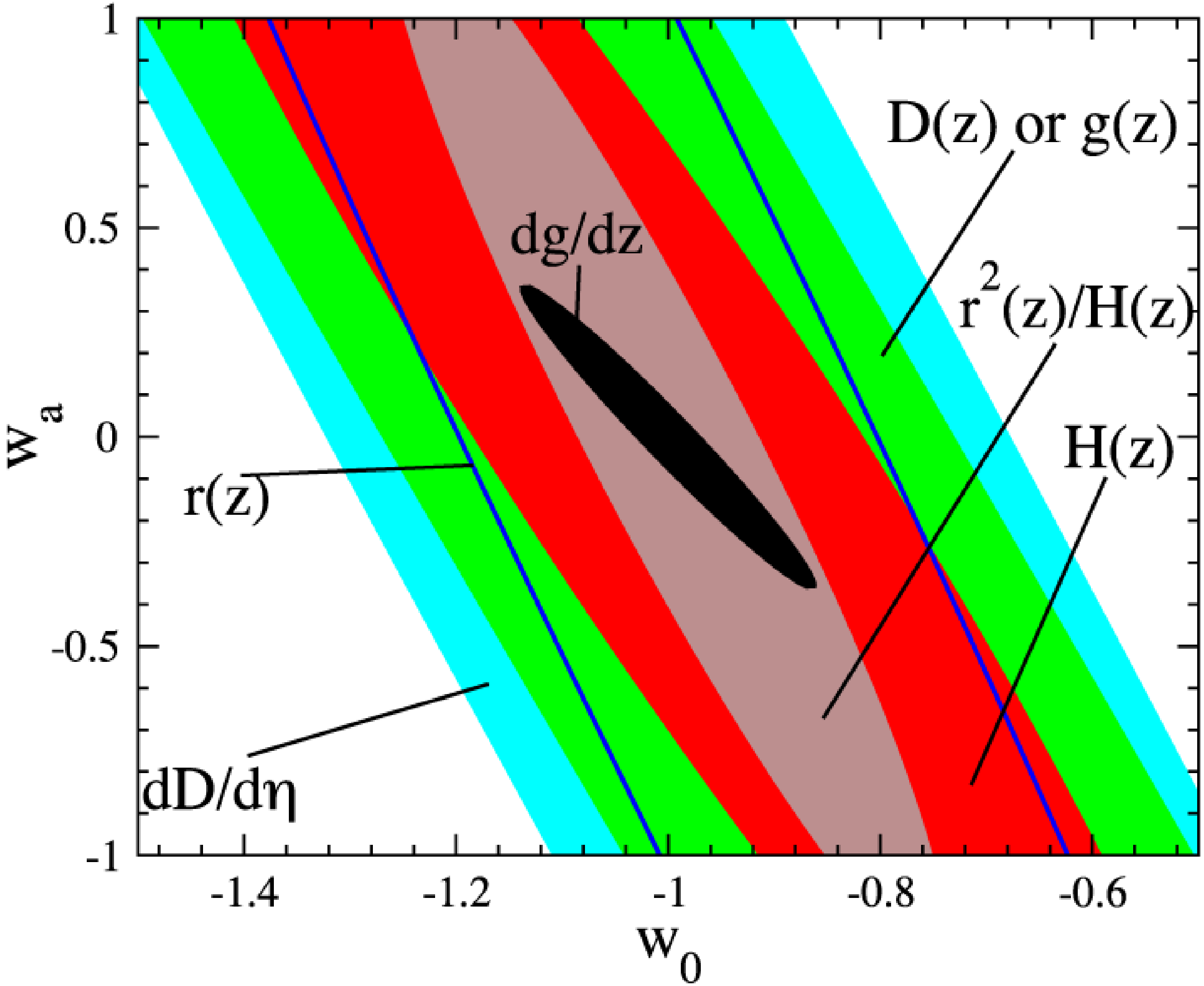
In terms of cosmology (ie. Dark energy), this is an amazing measurement



10% errors
at z=0.1 … 2
at steps of 0.1
for each quantity

Better to measure probes which are time/redshift derivatives directly!!!! This is why dg/dz gives@20 times better than d(z)

Same goes for redshift varying w(z)

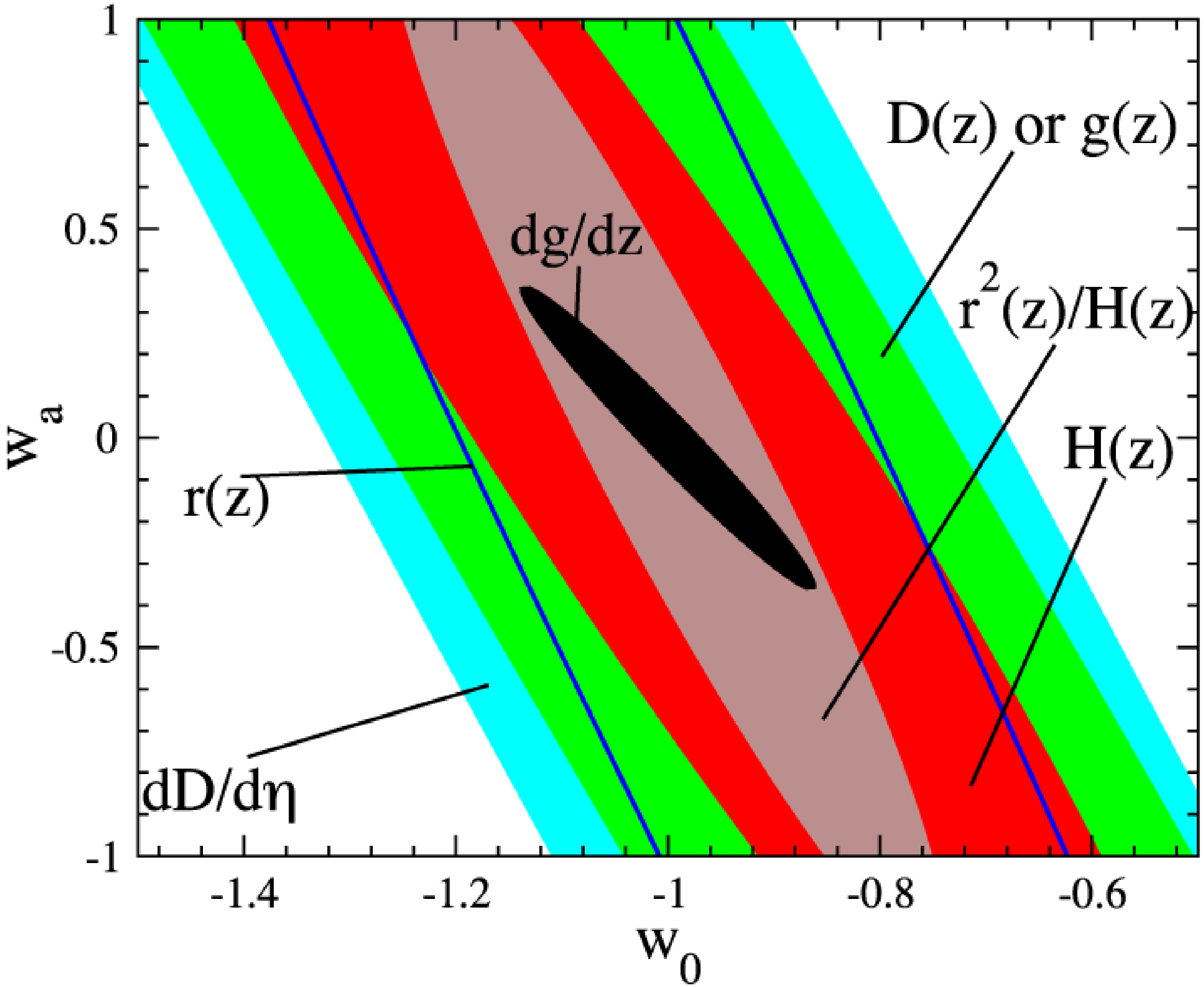


10% errors
at z=0.1 … 2
at steps of 0.1

dg/dz determines ISW effect in CMB (ie. The exact quadrupole at low redshifts)

Different Probes compared equally.

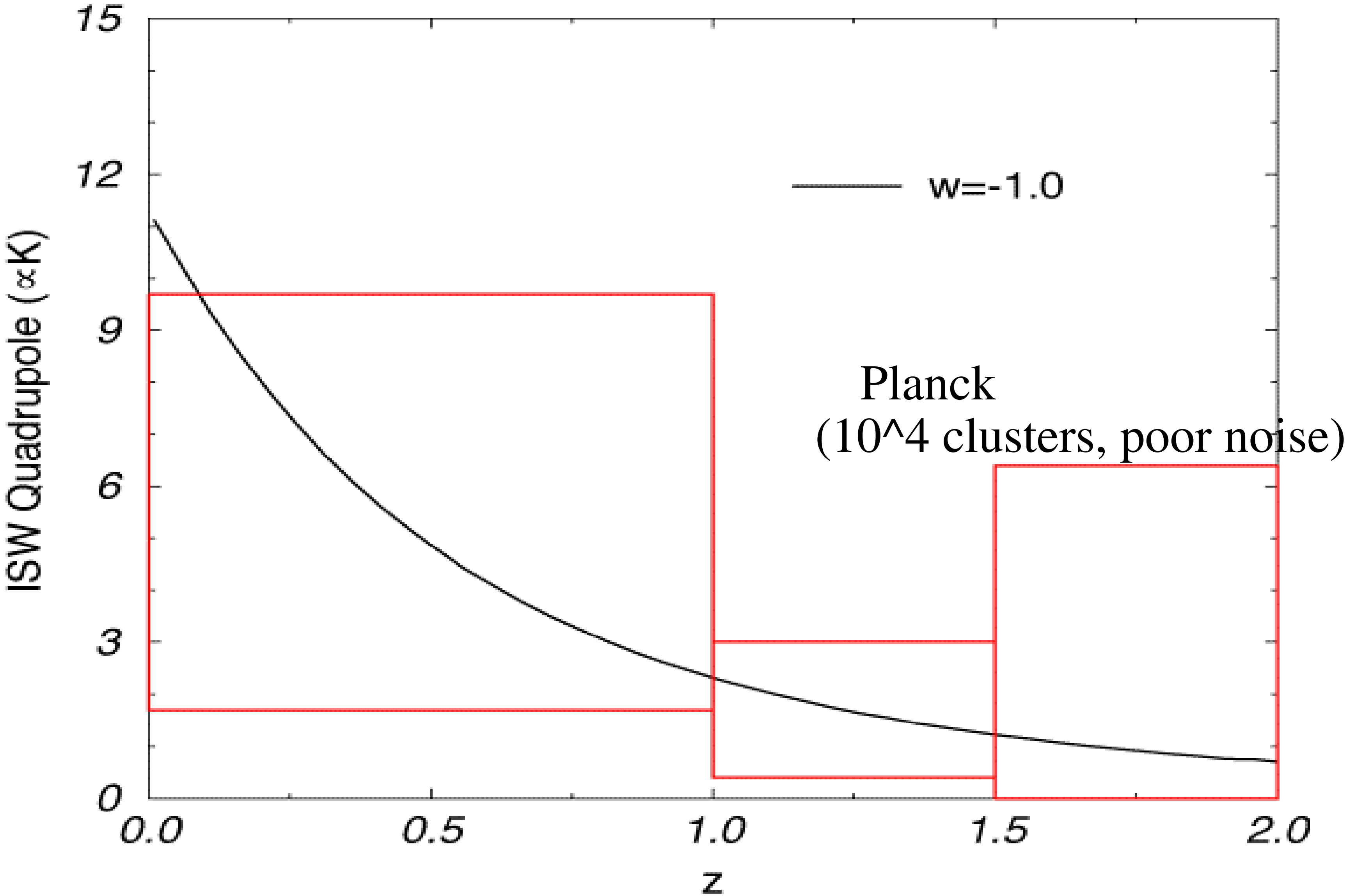
In terms of cosmology (ie. Dark energy), this is an amazing measurement



10% errors
at z=0.1 … 2
at steps of 0.1

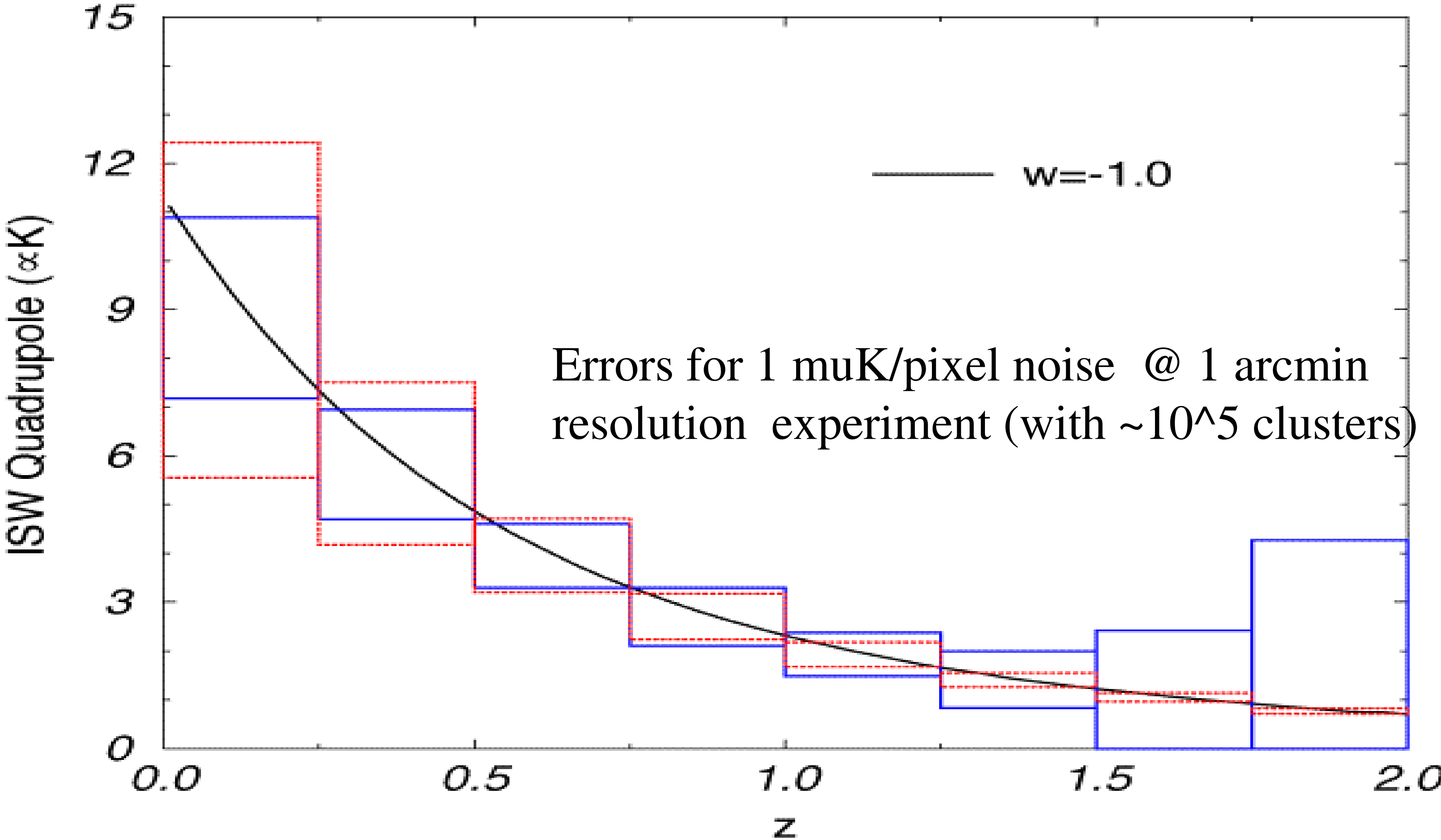
Compared to SNAP, 20 times worse fractional measurement gives equal constraining power with respect to dark energy

Useful?

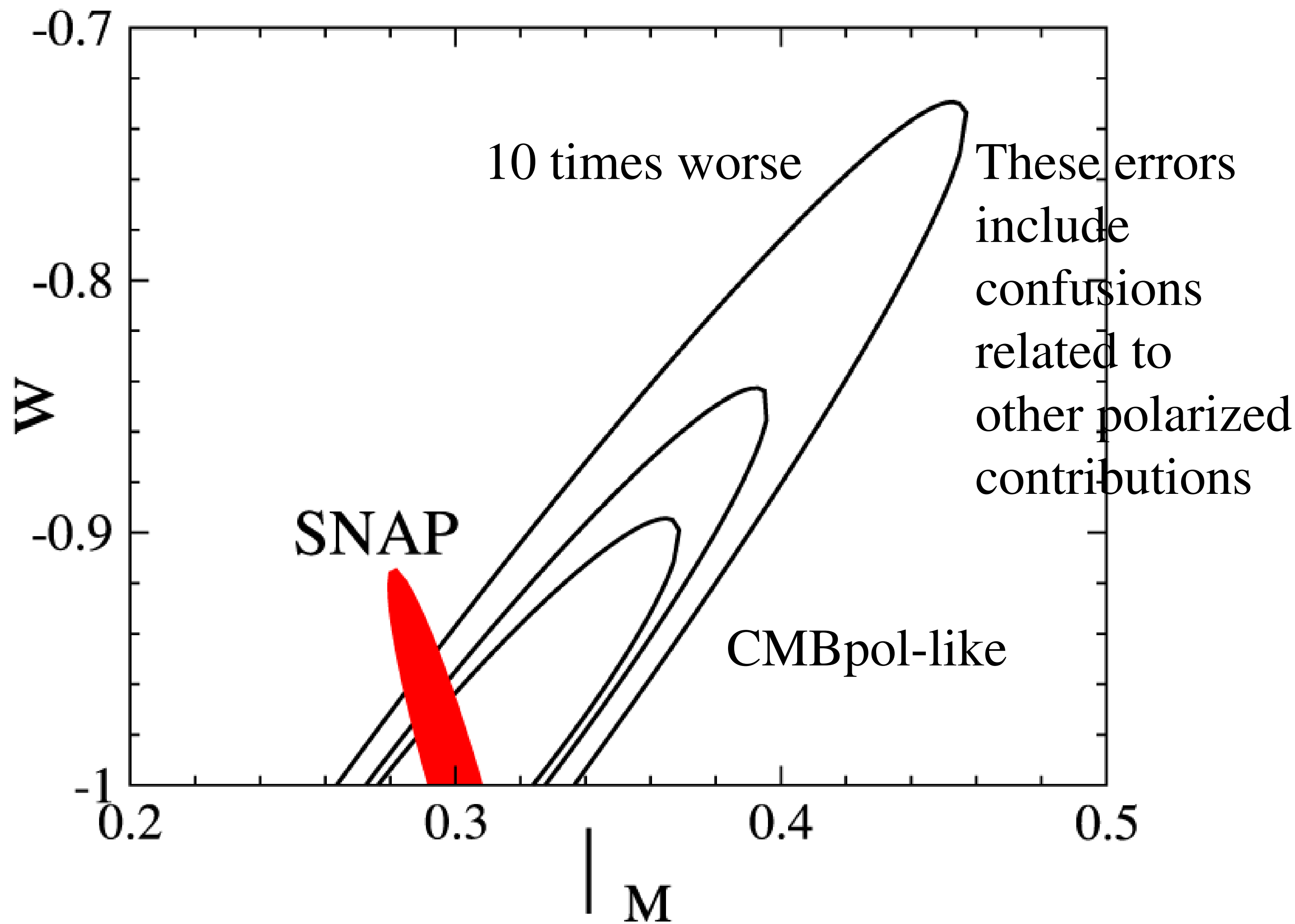


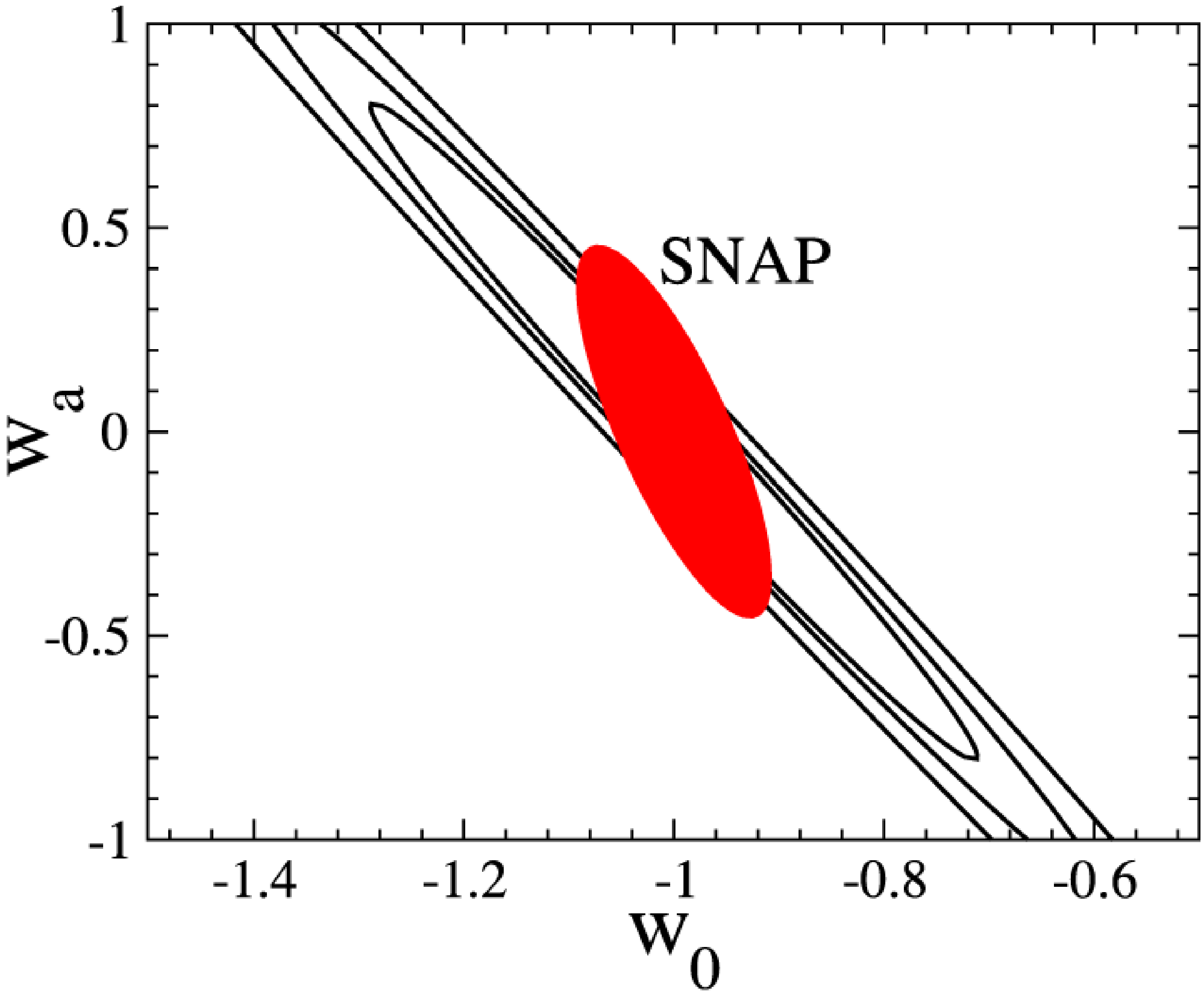
(Reconstruct the quadrupole as a function of redshift)

Beyond Planck…. Cluster Polarization in CMBpol era



(Reconstruct the quadrupole as a function of redshift)


-0.7
-0.8
-0.9
-1
0.2
0.3
0.4
0.5
w
M
10 times worse
These errors
include
confusions
related to
other polarized
contributions
SNAP
CMBpol-like



SNAP
1
0.5
0
-0.5
-1
-1.4
-1.2
-1
-0.8
-0.6
w_a
w_0

Summary

- ➢ WMAP optical depth to reionization is very interesting and suggest high-z starformation
- ➢IR background cannot be easily explained with galaxies
- ➢ Spatial fluctuations may provide useful clues to the presence of first stars.
- ➢ CIBER flights in 2005
- ➢ Significant improvements with ASTRO-F (~2007 with NIRC observations)
- ➢ Cross-correlation studies with CMB polarization a must!!
- ➢ Individual detections with JWST (> 2012)
- ➢ Cluster polarization => useful probe of dark energy

for more details visit http://www.cooray.org