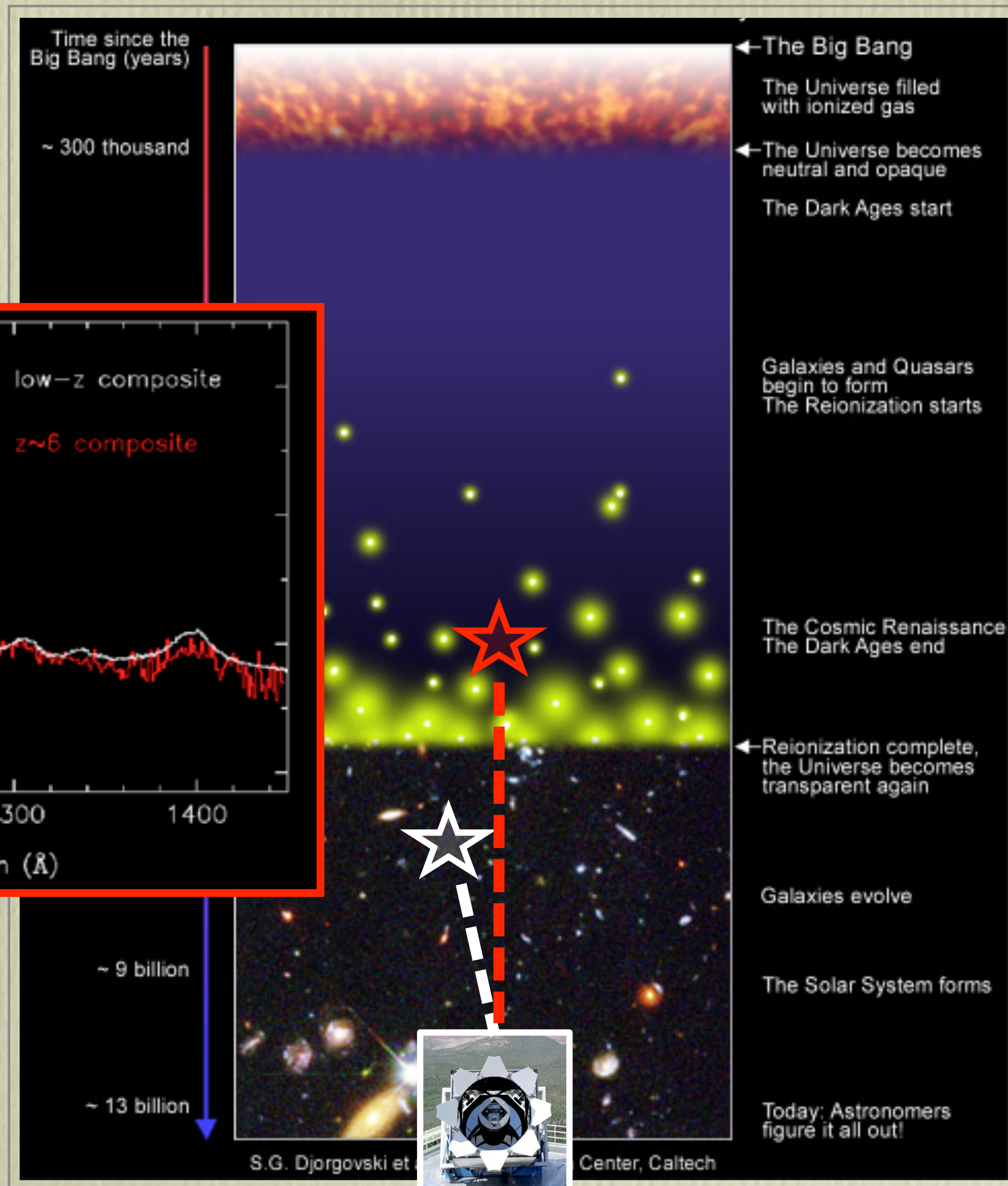
{MNRAS 425, 2988 (2012)}

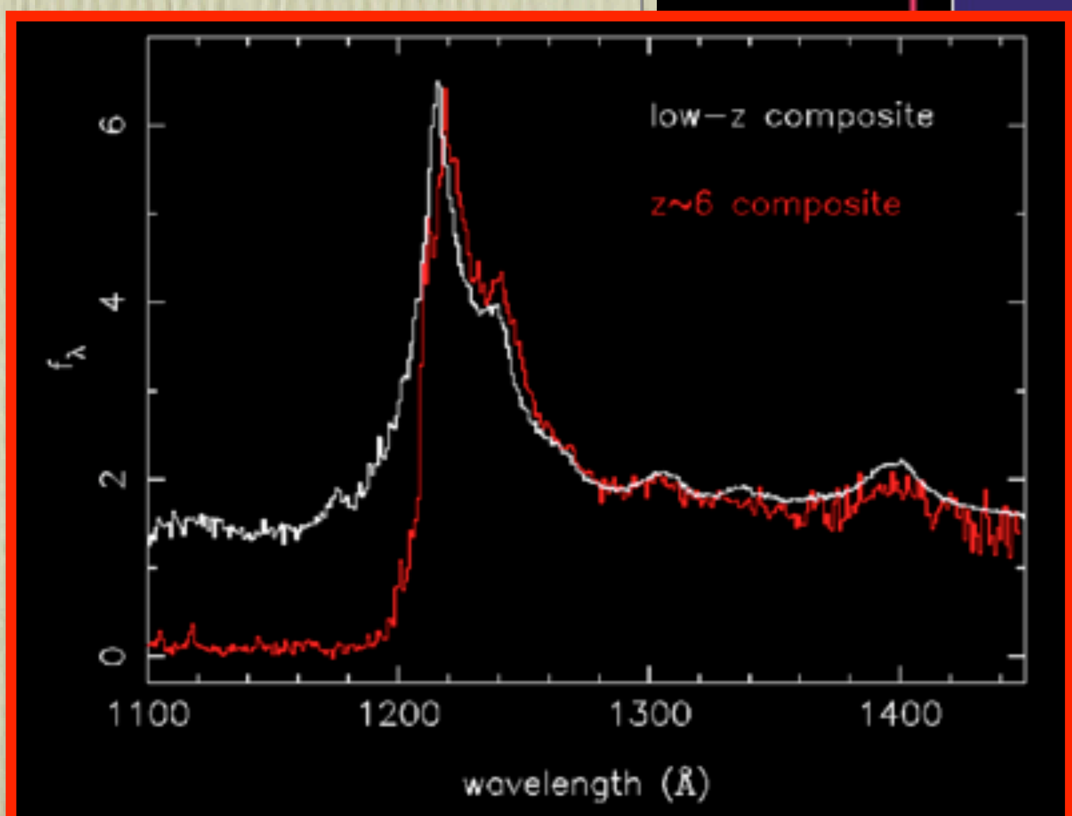
The 21cm Forest

Katie Mack
(University of Melbourne)
with Stuart Wyithe (University of Melbourne)

Forests

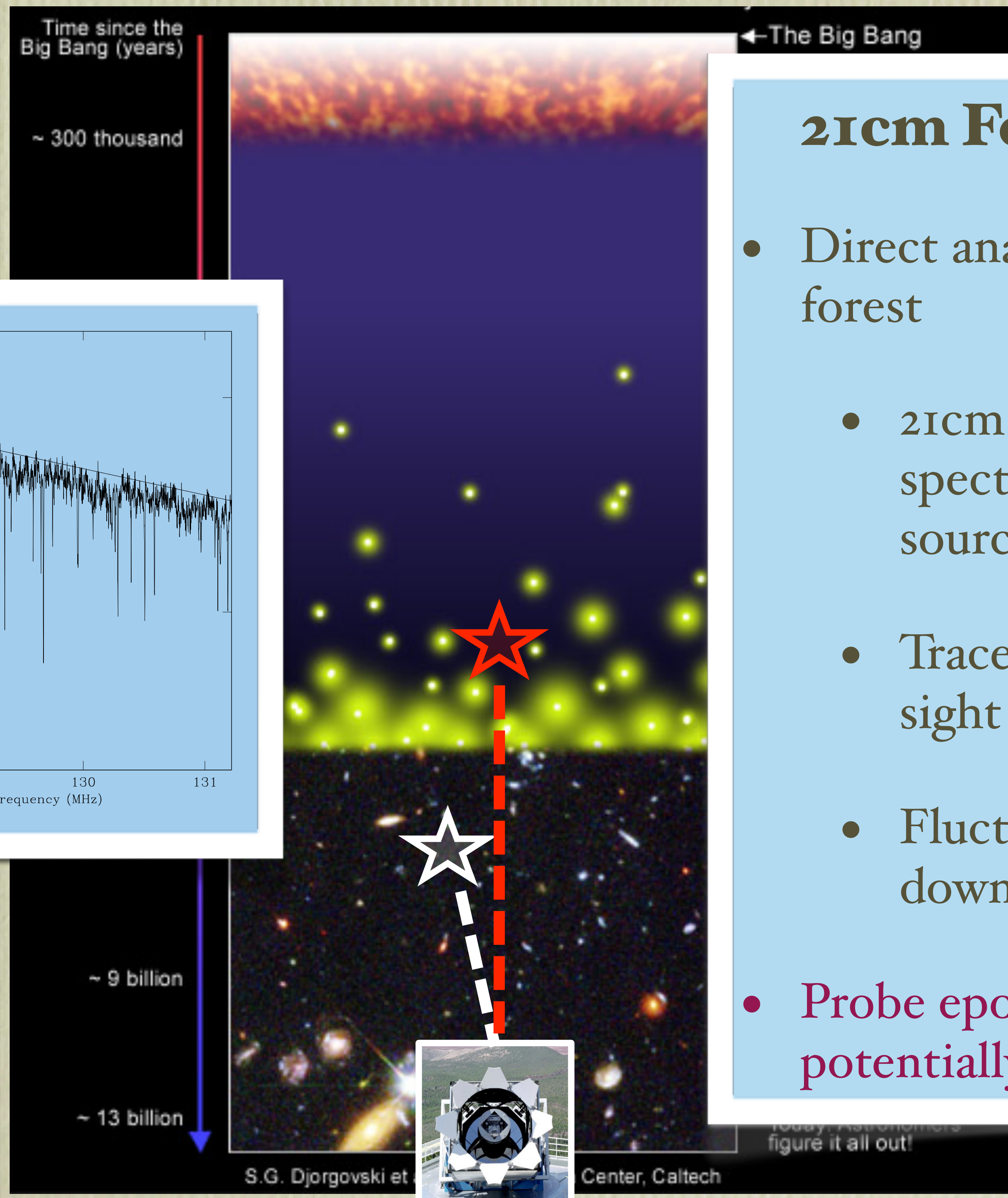


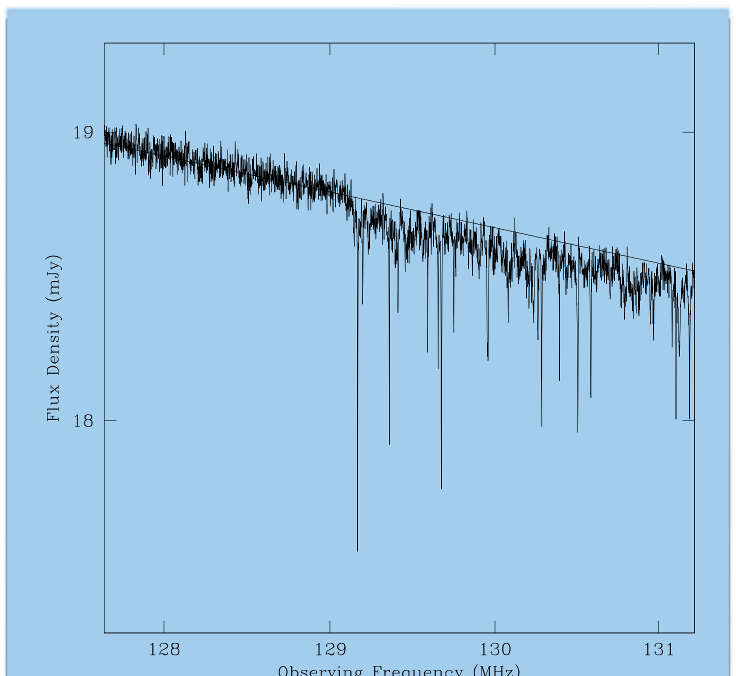
Time since the Big Bang (years)
~ 300 thousand
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et
Center, Caltech



low−z composite
z~6 composite
f_λ
0
2
4
6
1100
1200
1300
1400
wavelength (Å)

Forests





Carilli et al. 2002

21cm Forest

- Direct analog of Lyman-alpha forest
  - 21cm absorption in spectrum of bright radio source at high redshift
  - Trace HI along line of sight
  - Fluctuations on scales down to tens of kpc
- Probe epoch of reionization, potentially even dark ages

21cm Optical Depth

$$\tau_{\nu_0}(z) = \frac{3}{32\pi}\frac{h_p c^3 A_{10}}{k_B \nu_0^2}\frac{x_{HI} n_H(z)}{T_S(1+z)(\mathrm{d}v_\parallel/\mathrm{d}r_\parallel)}$$

peculiar velocities

$$\approx 0.009(1+\delta)(1+z)^{3/2}\frac{x_{HI}}{T_S}\left[\frac{H(z)/(1+z)}{\mathrm{d}v_\parallel/\mathrm{d}r_\parallel}\right]$$

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overdensity

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redshift

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overdensity

redshift

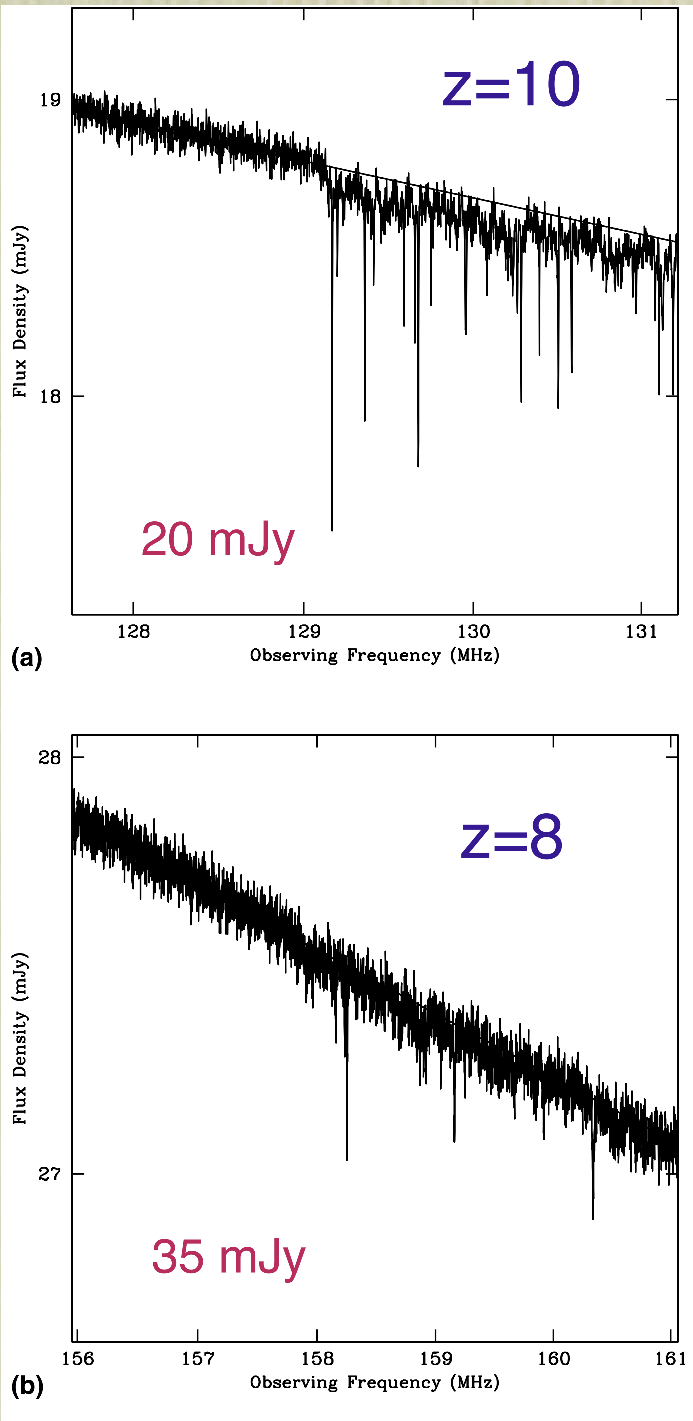
neutral fraction

spin temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_c^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

Signal Predictions

- Absorption due to IGM and minihalos (Carilli et al. 2004)
    - Looking for progenitors of Ly-alpha forest features (deep, narrow lines, τ~0.1%-few %)
    - Expect increase in noise level at onset of 21cm absorption
    - Need very bright source if looking at z<10

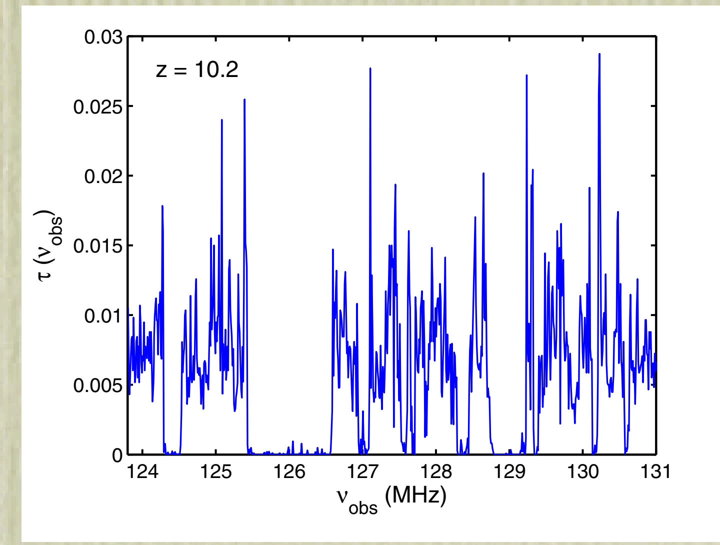


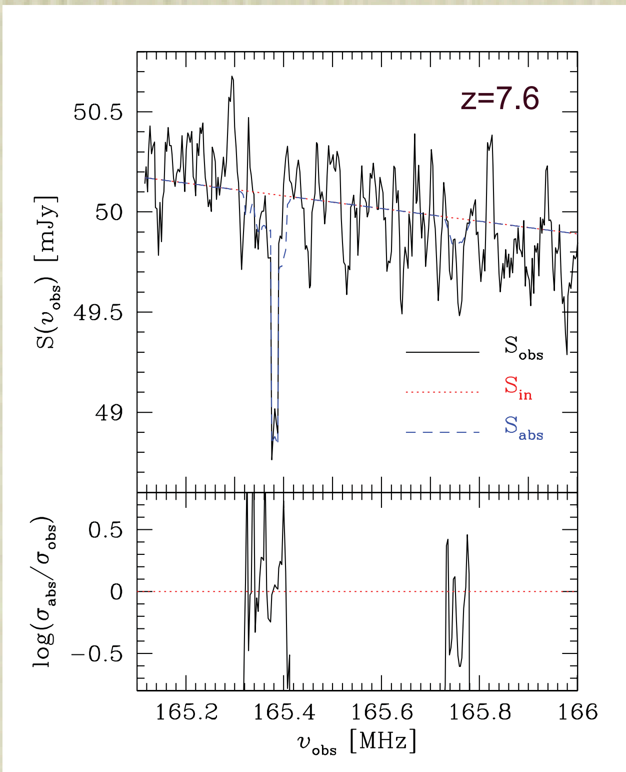
Signal Predictions

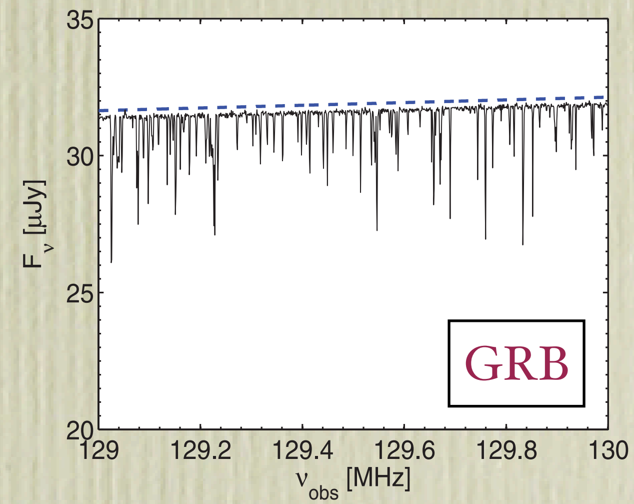
- Structures along line of sight (Xu et al. 2009, 2010; Ciardi et al. 2013)

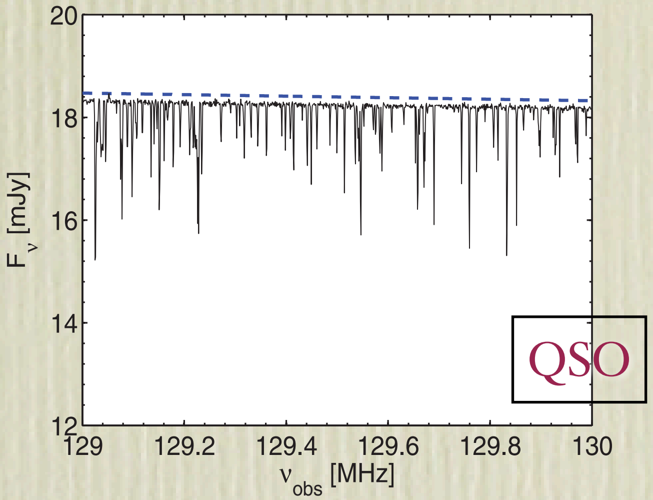
- Dwarfs and minihalos against QSOs and GRBs (Xu et al. 2010)

- GRBs could be used as background sources if extremely bright (e.g., from first stars)









X-Ray Efficiency f_X

Expected optical depth depends strongly on assumptions about x-ray efficiency

$$L_X = 3.4 \times 10^{40} f_X \left(\frac{\mathrm{SFR}}{1\ \mathrm{M_\odot yr^{-1}}} \right)\ \mathrm{erg\ s^{-1}}$$

X-ray luminosity from 0.2 to 10 keV extrapolated to high redshift (Furlanetto, Oh & Briggs 2006)

Observability

- Observing the 21cm forest requires bright radio sources in the background
- Lower optical depths require brighter sources

$$S_{min} = 160\ \mathrm{mJy} \left(\frac{S/N}{5} \frac{10^{-3}}{\tau} \frac{10^{6}\ \mathrm{m}^2}{A_{eff}} \frac{T_{sys}}{400\ \mathrm{K}} \right) \left(\frac{1\ \mathrm{kHz}}{\Delta\nu_{ch}} \frac{1\ \mathrm{week}}{t_{int}} \right)^{1/2}$$

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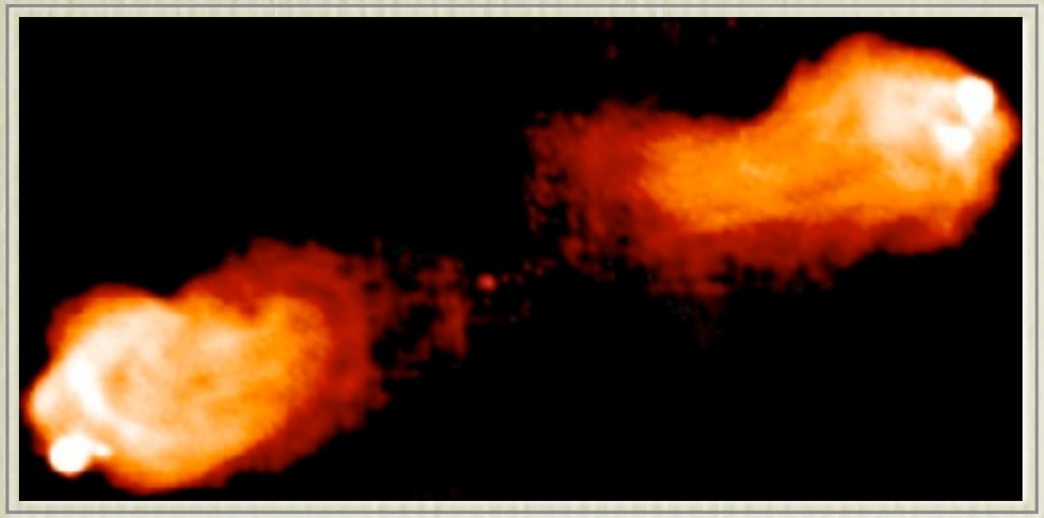
- At z=10, Cygnus A would have S ≤ 20 mJy (Carilli et al. 2002)



Cygnus A (via J. Conway and P. Blanco, VLA)

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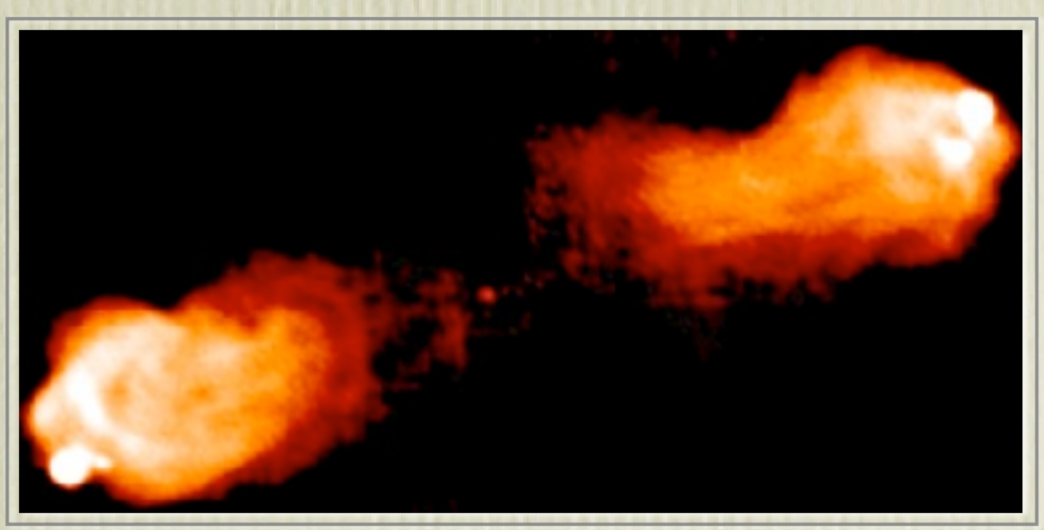
- **Question: Can we find such bright sources at high redshift?**



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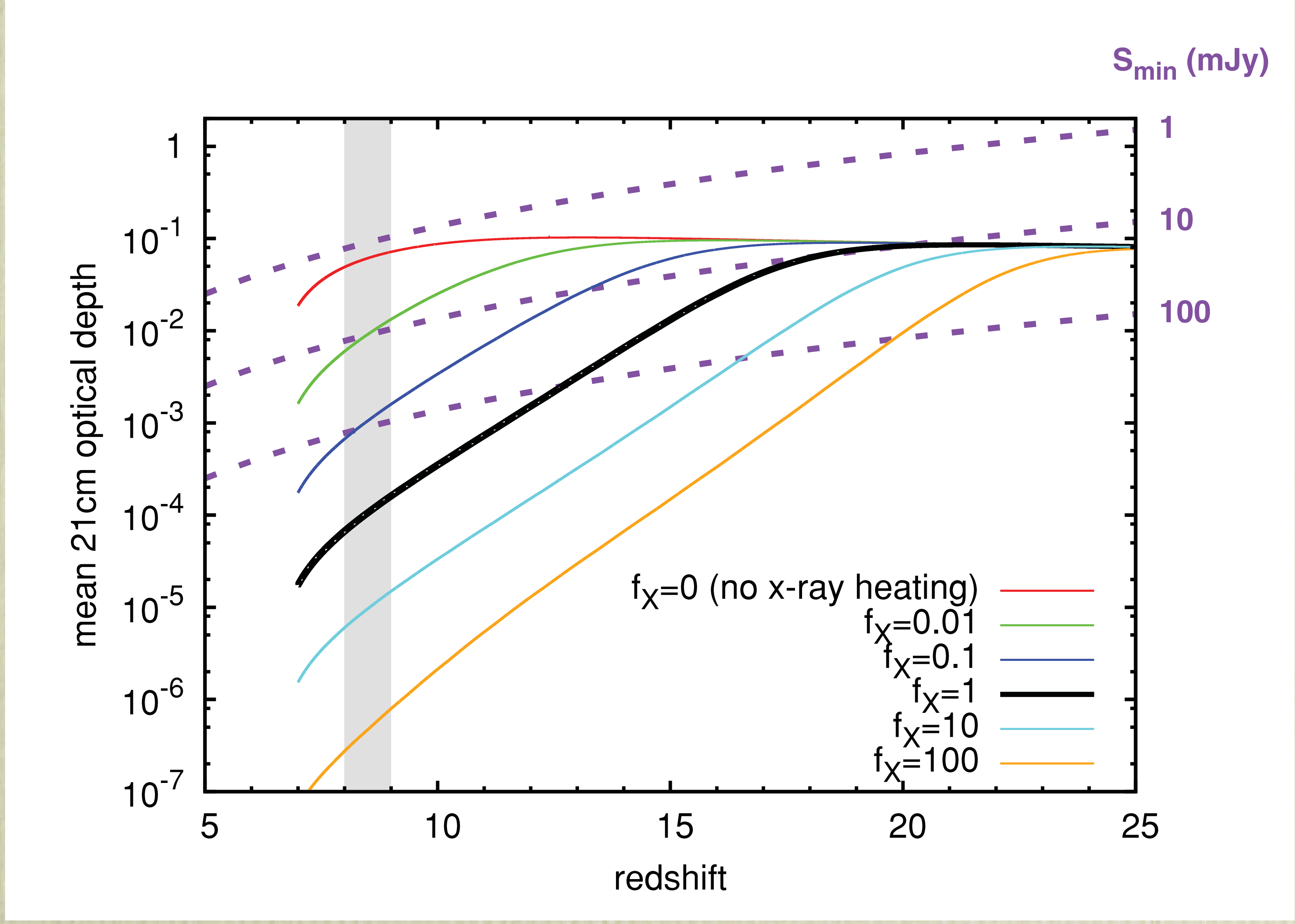

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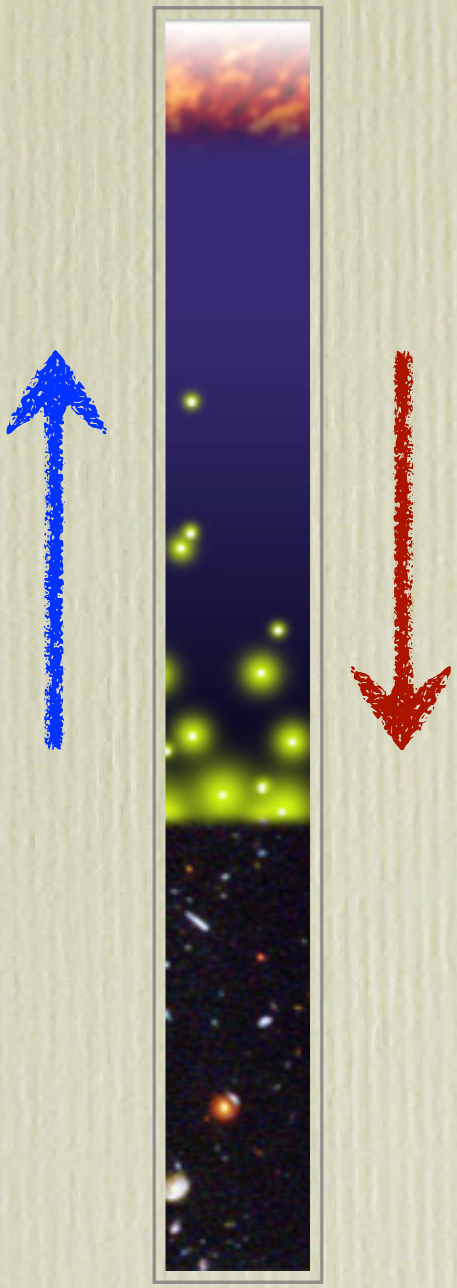
Catch-21cm

- For a detectable 21cm forest, require *both*:
  - High optical depth (high x_{HI}, low T_S)
  - Numerous bright sources (which heat and ionize the IGM)



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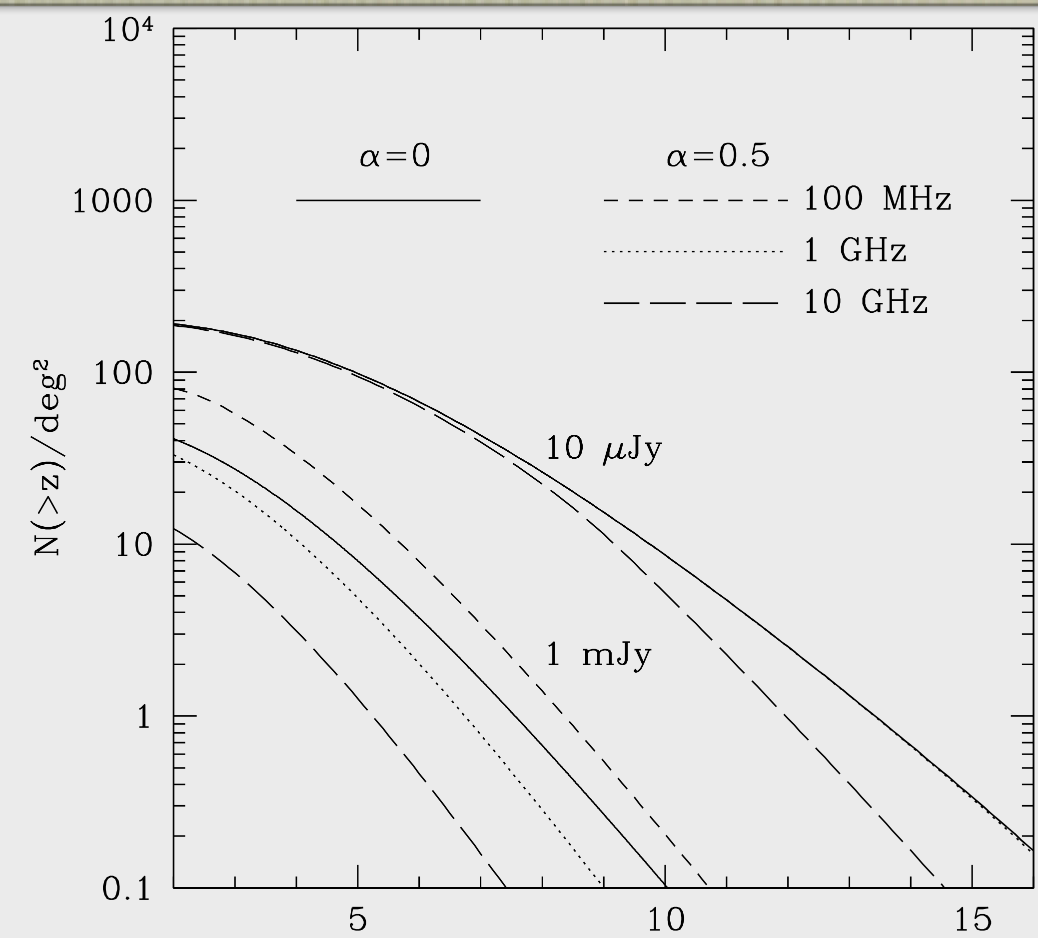

FIG. 6.—Sensitivity of our predictions for the 10 μJy and 1 mJy counts to the assumed spectral slope α of the radio spectrum $F_\nu \propto \nu^{-\alpha}$. The counts for $\alpha = 0$ are independent of frequency. When $\alpha = 0.5$ is assumed, however, the counts increase with decreasing frequency, as shown by comparing the predictions at 100 MHz (*short-dashed curve*), 1 GHz (*dotted curve*), and 10 GHz (*long-dashed curve*).

Haiman, Quataert, & Bower (2004)

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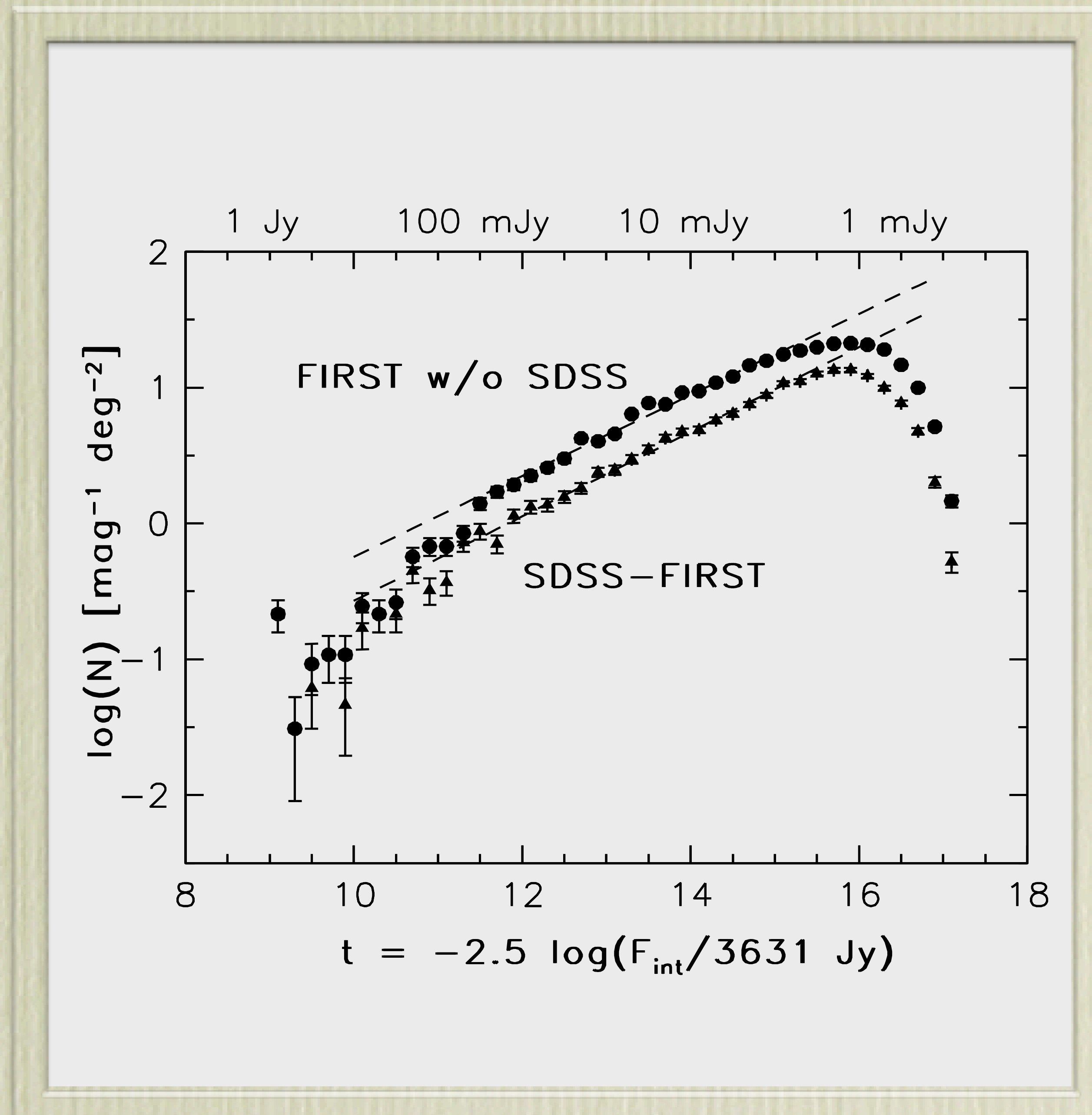
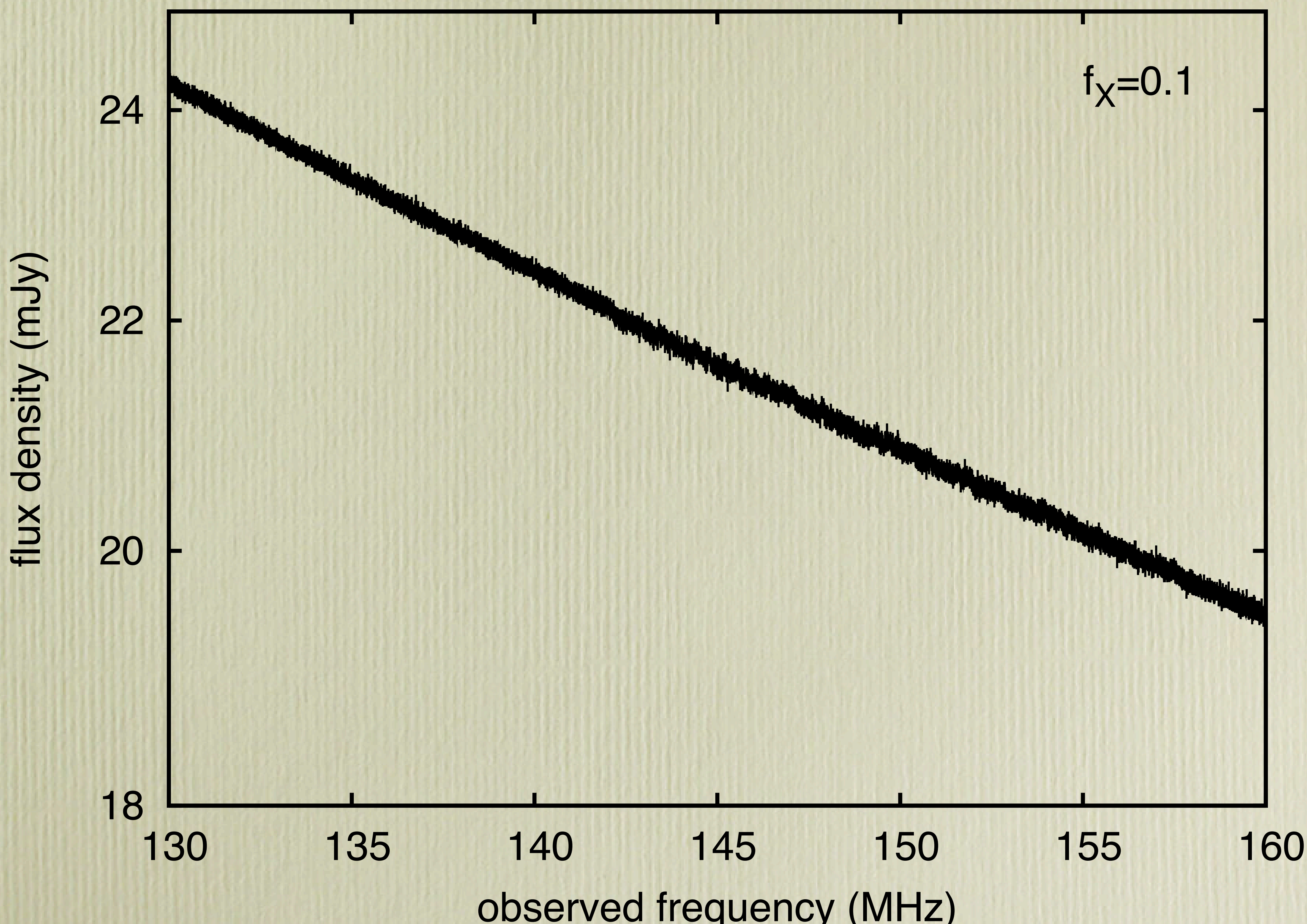
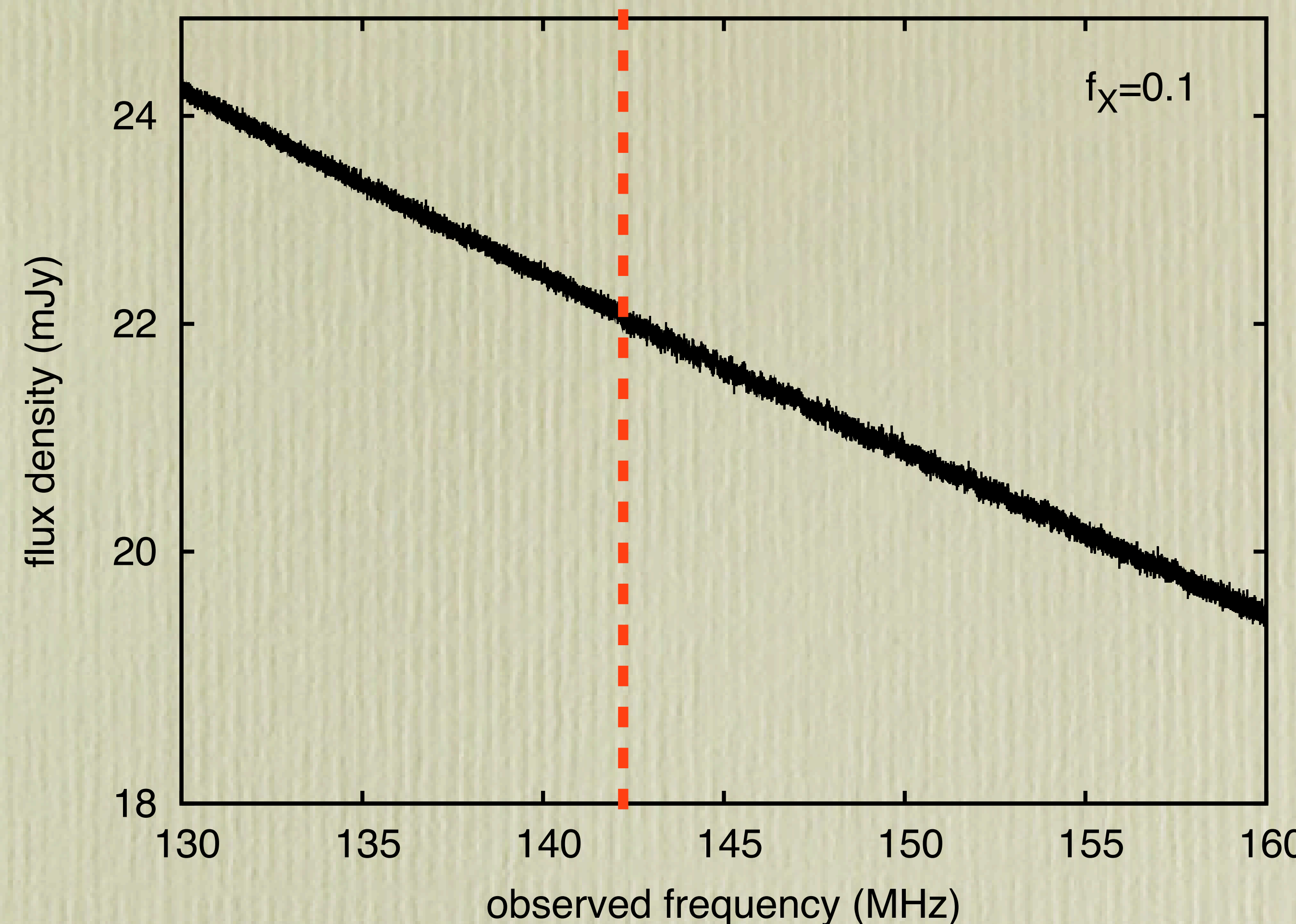


Ivezic et al. (2002)



f_X=0.1
24
22
20
18
flux density (mJy)
130
135
140
145
150
155
160
observed frequency (MHz)



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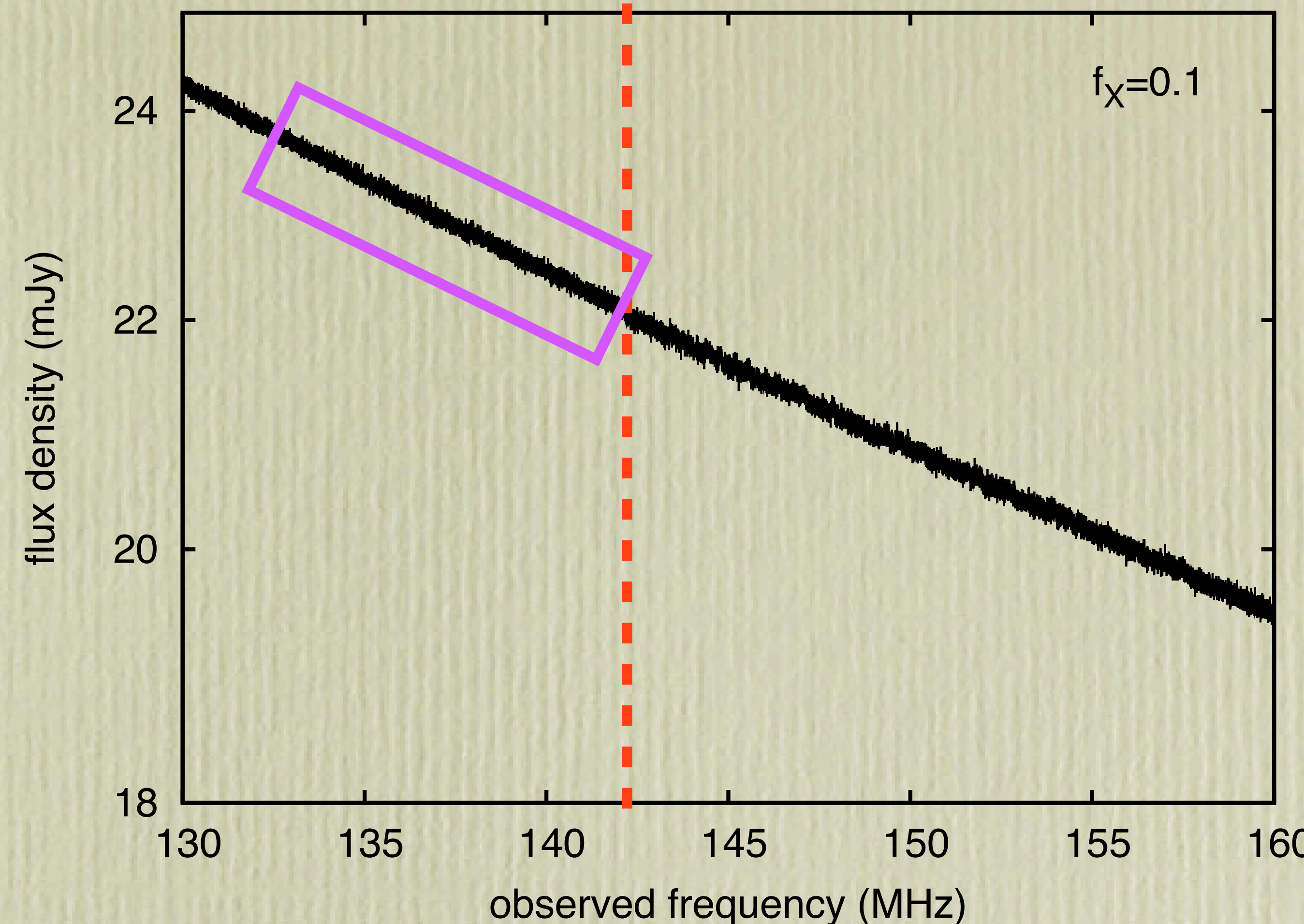

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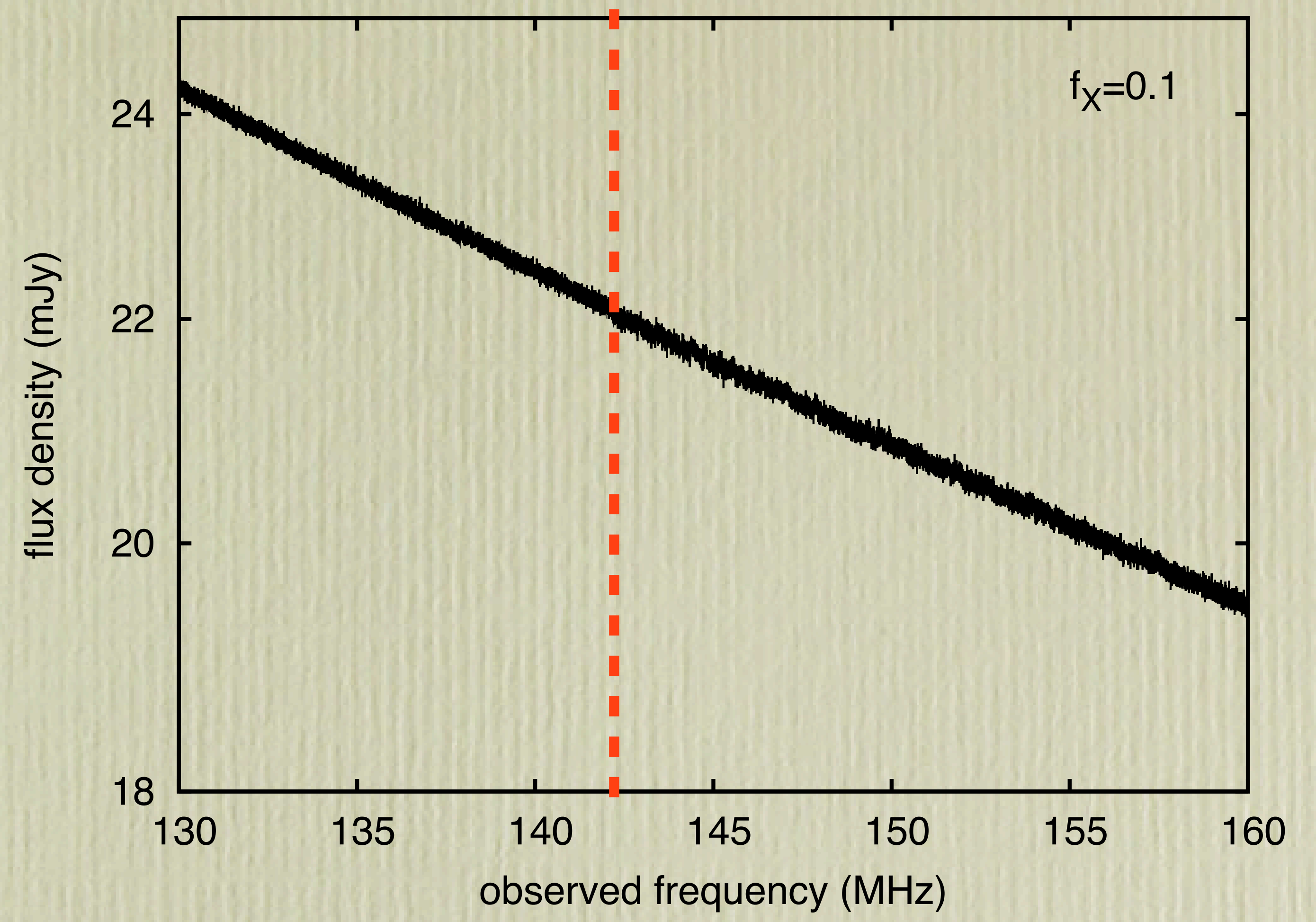

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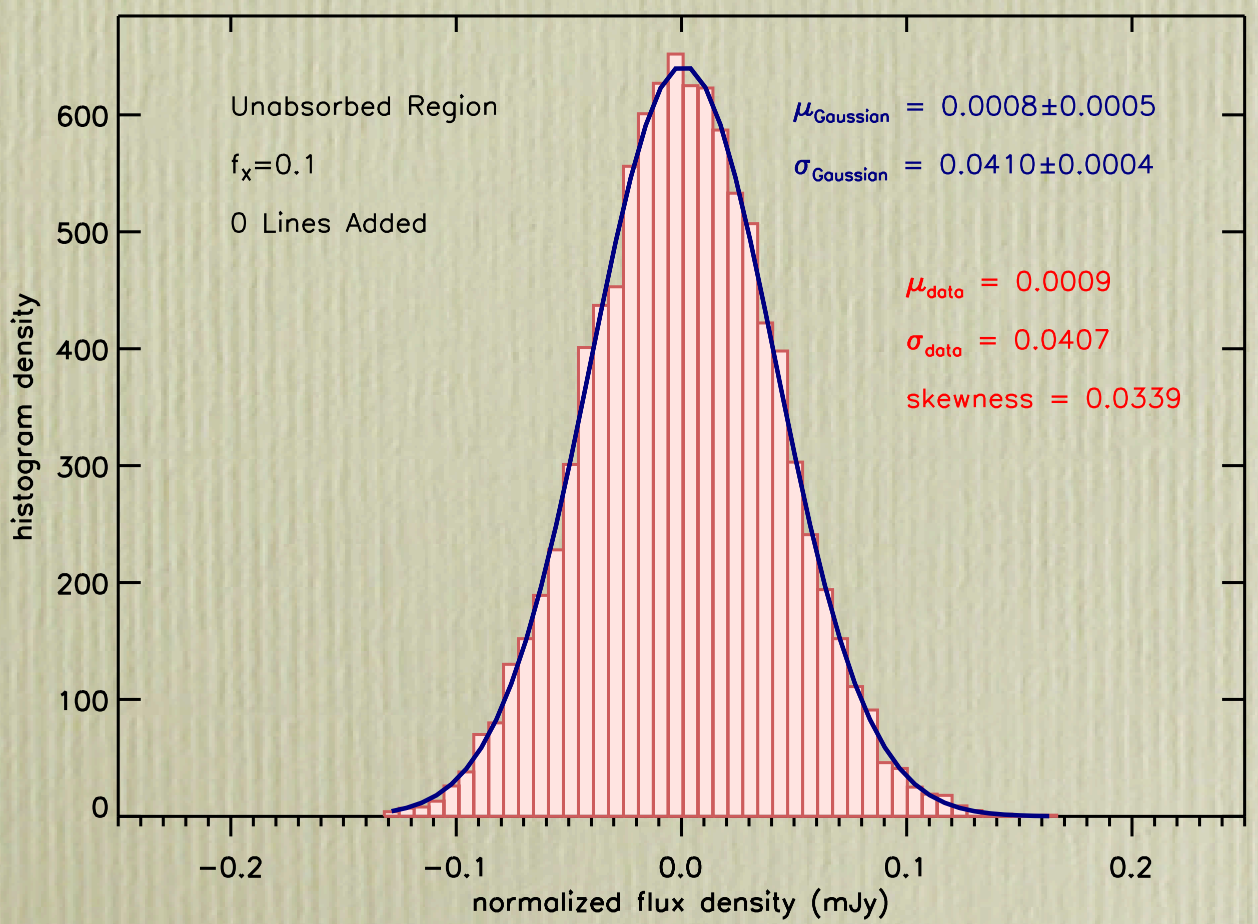
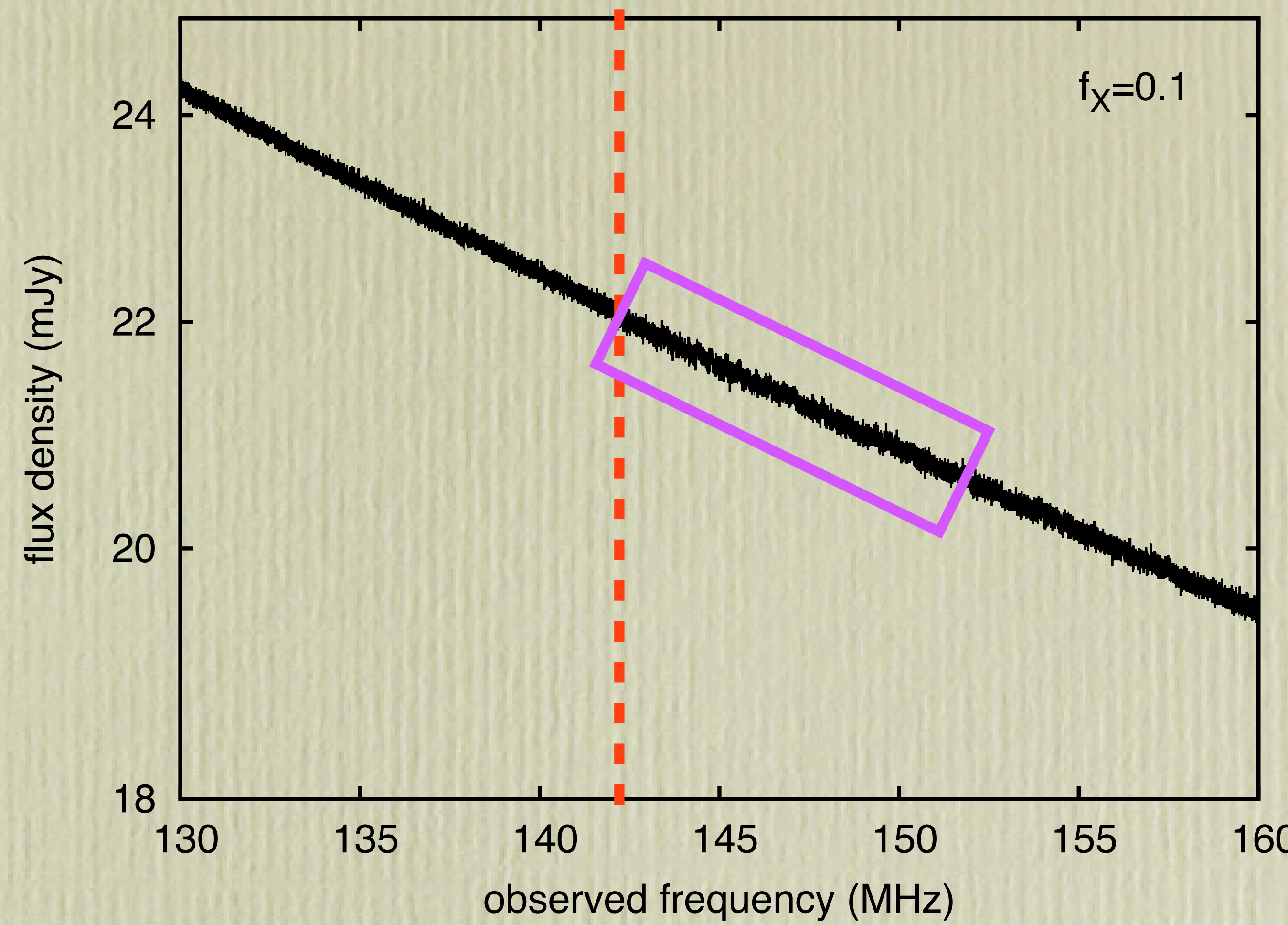


Unabsorbed Region
f_x=0.1
0 Lines Added
$\mu_{Gaussian}$ = 0.0008±0.0005
$\sigma_{Gaussian}$ = 0.0410±0.0004
μ_{data} = 0.0009
σ_{data} = 0.0407
skewness = 0.0339
histogram density
600
500
400
300
200
100
0
−0.2
−0.1
0.0
0.1
0.2
normalized flux density (mJy)



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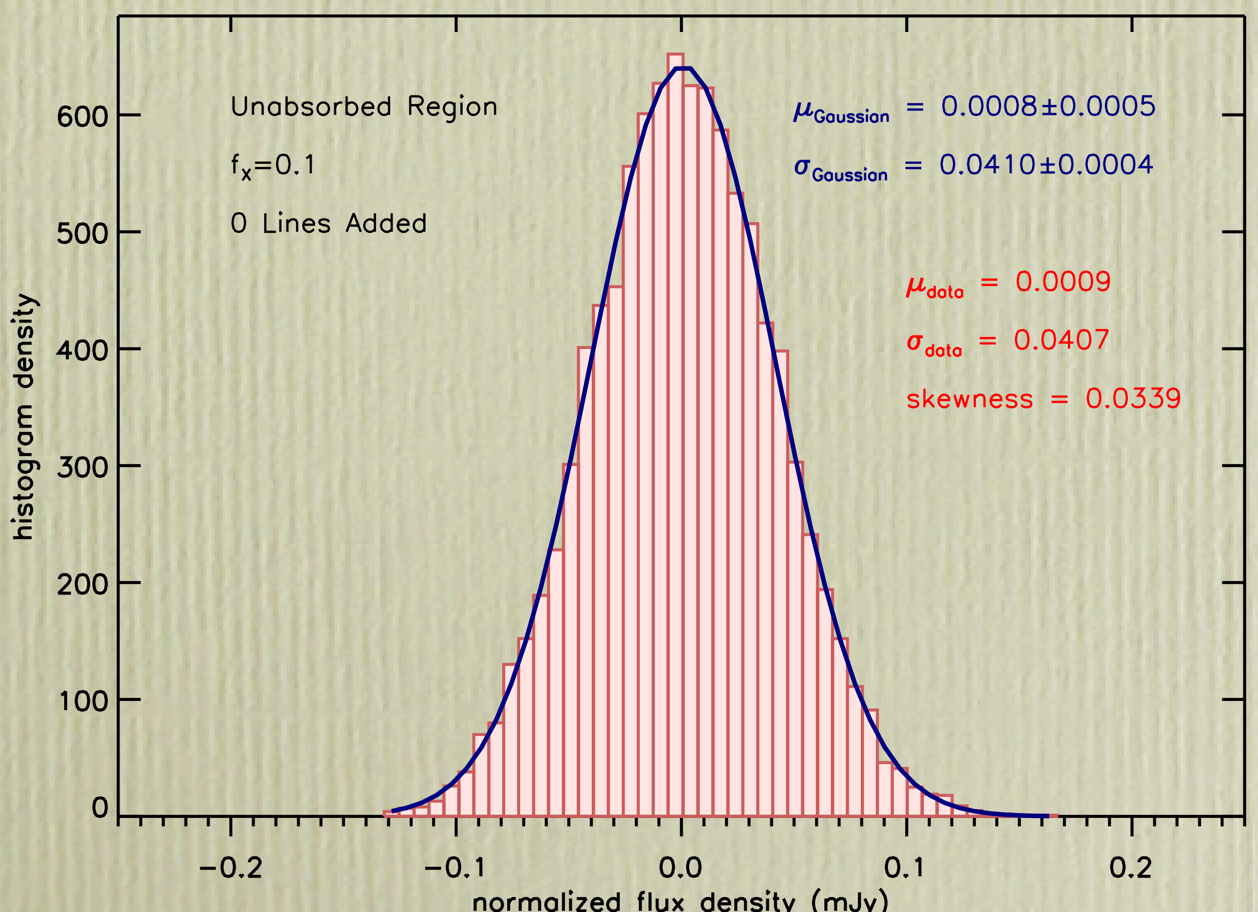

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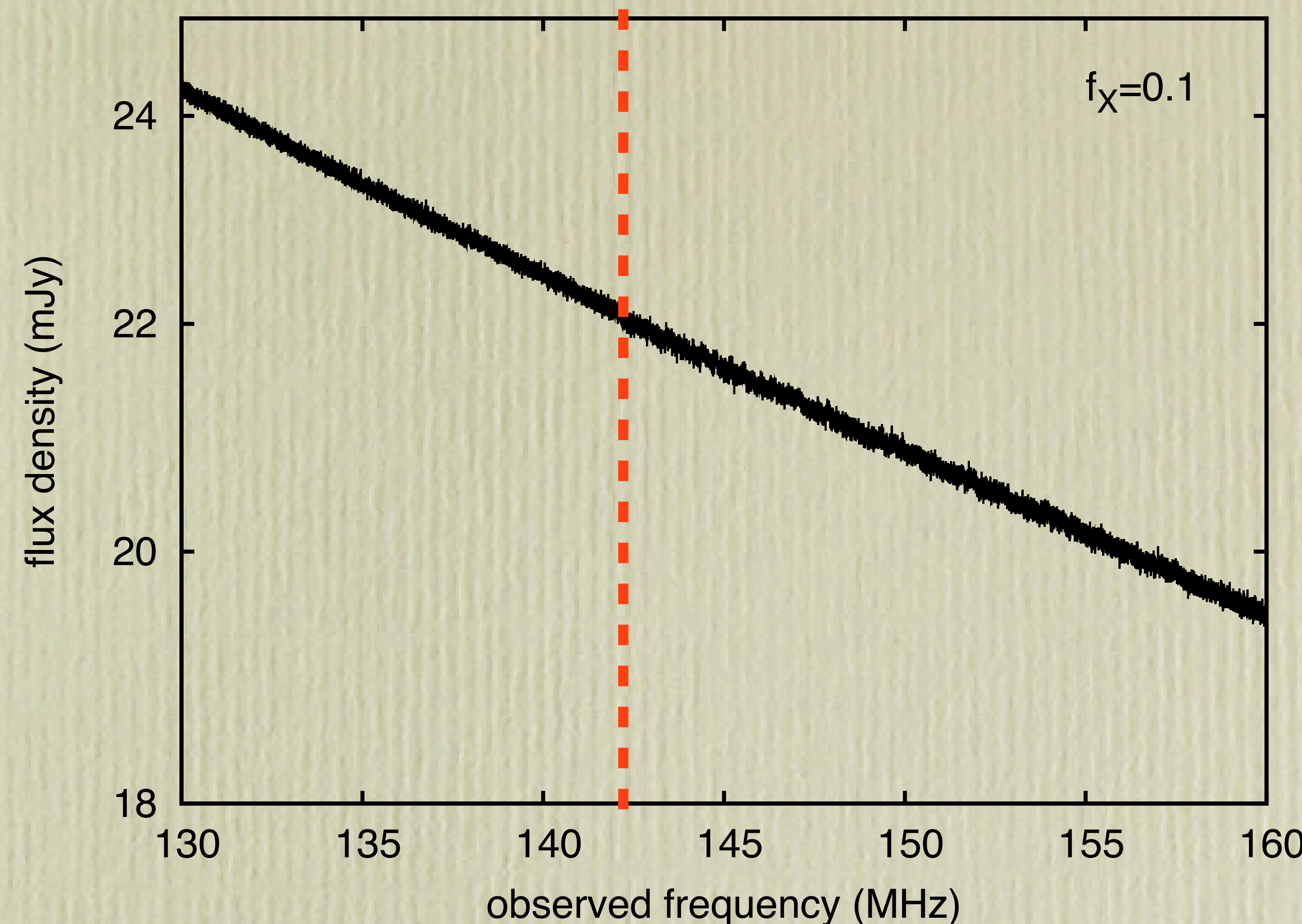
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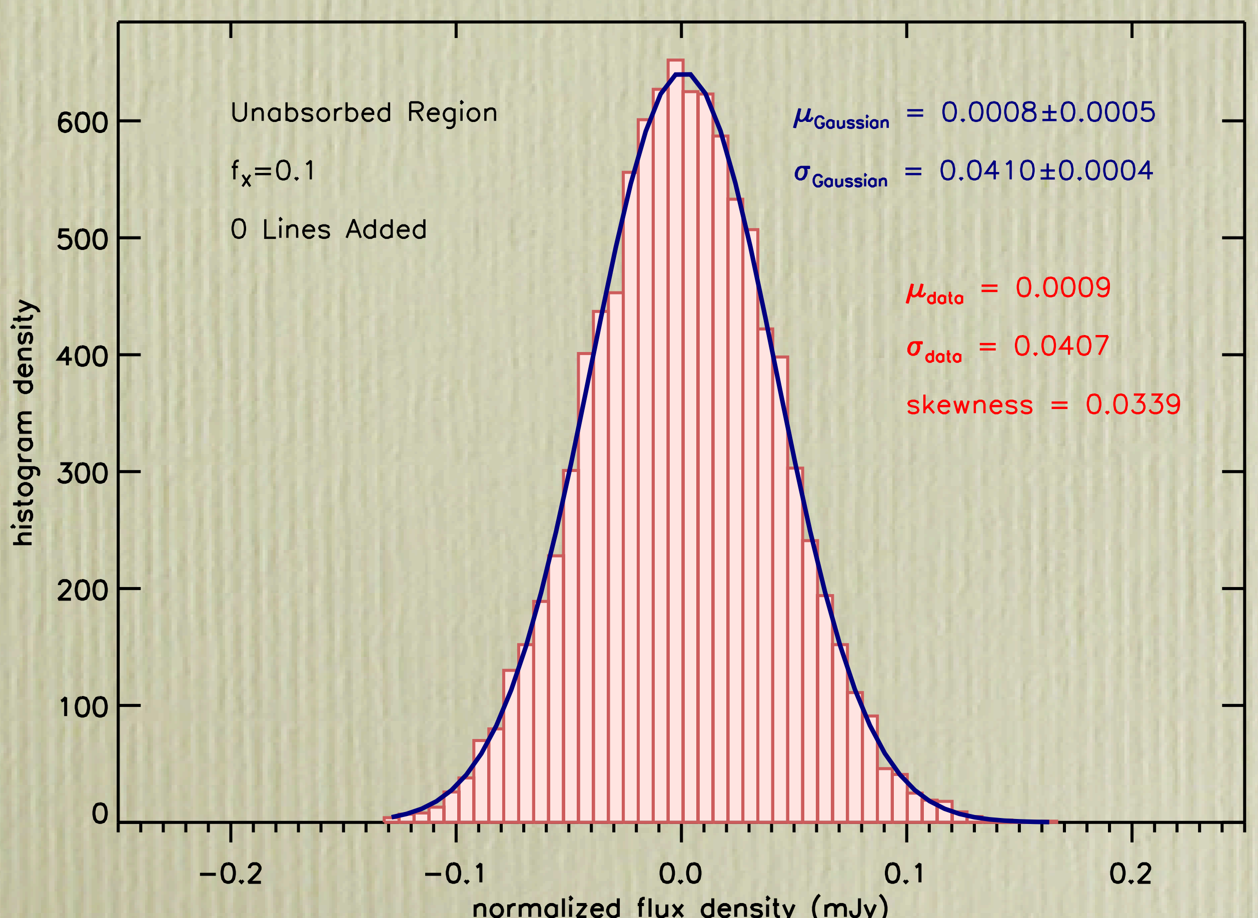
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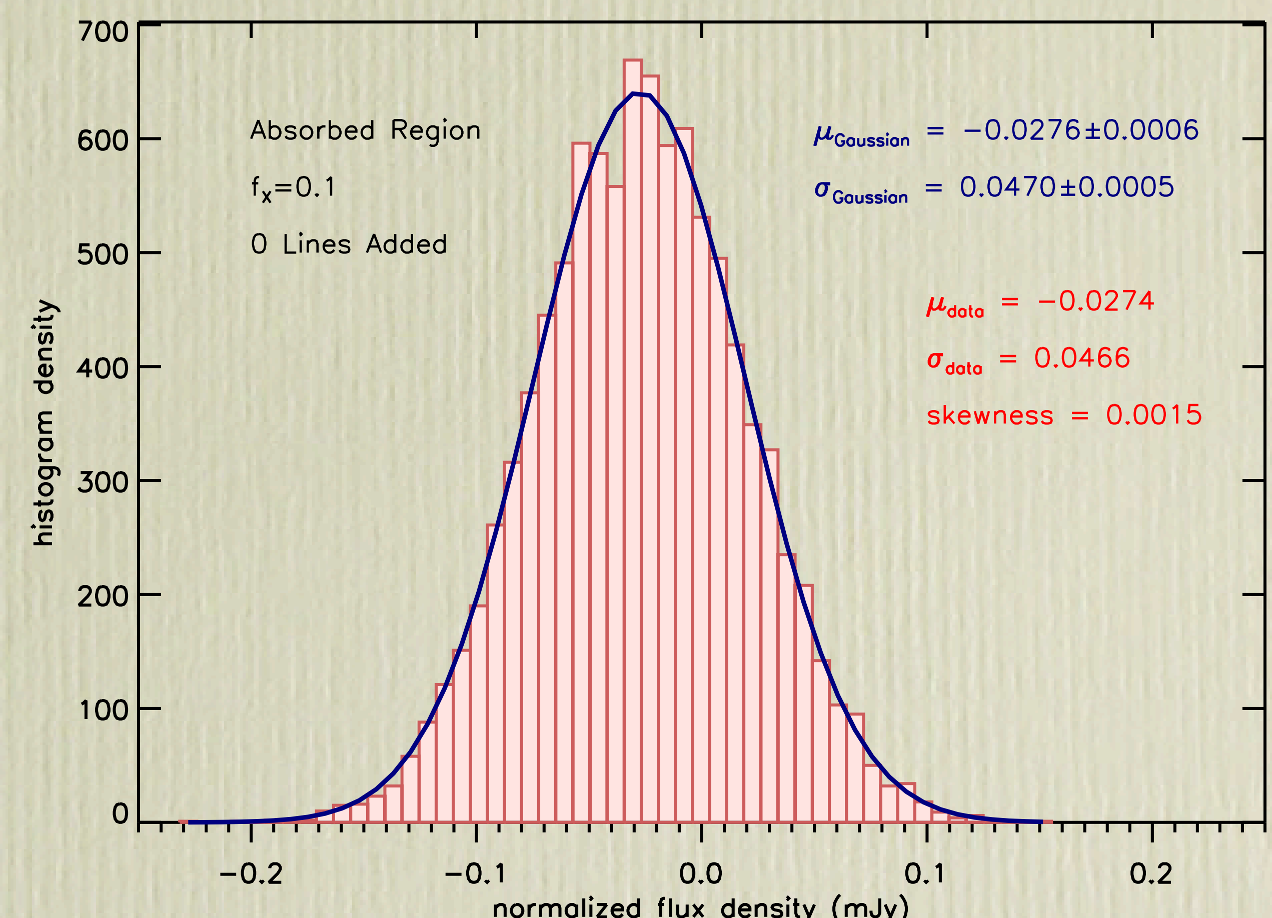
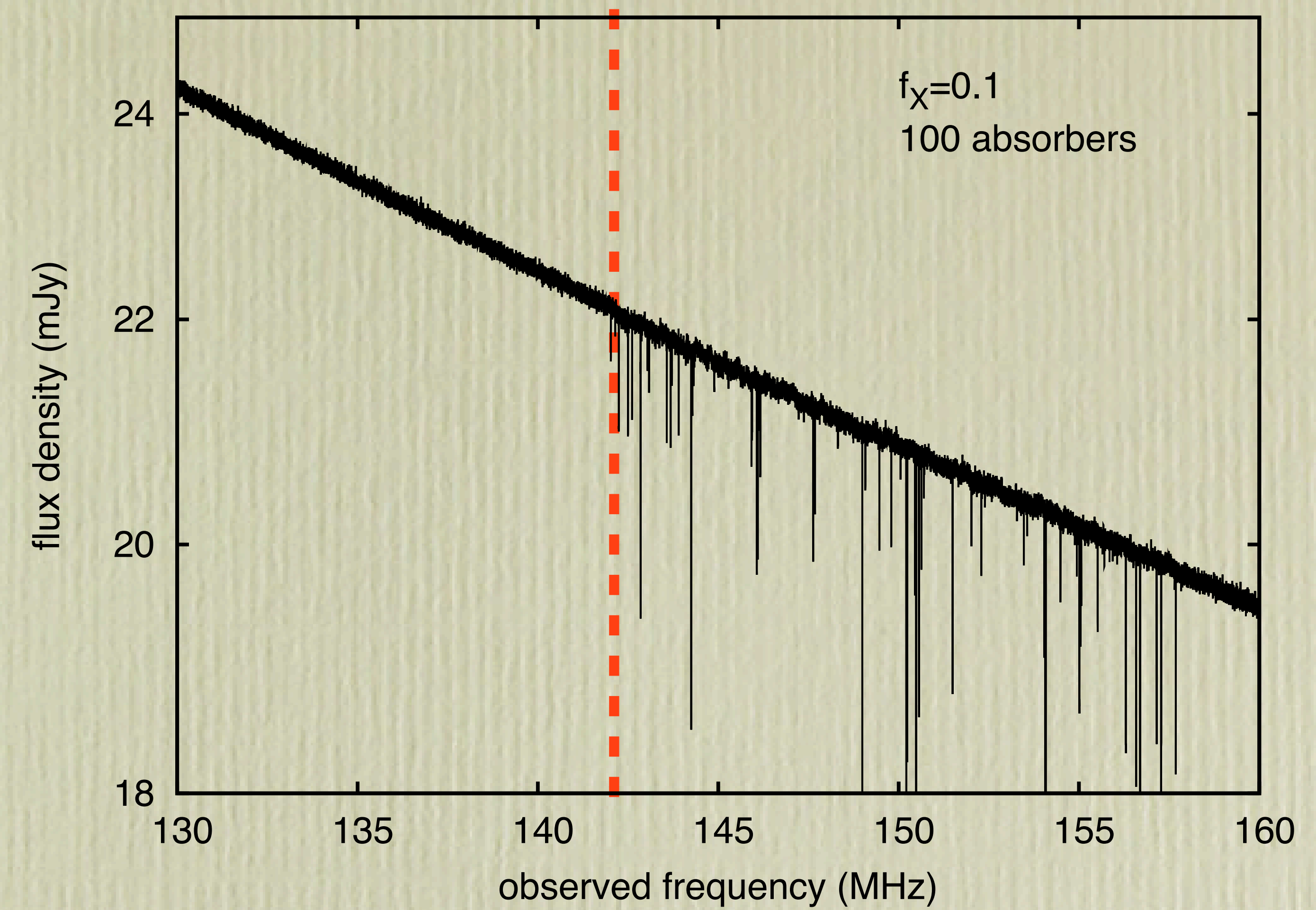
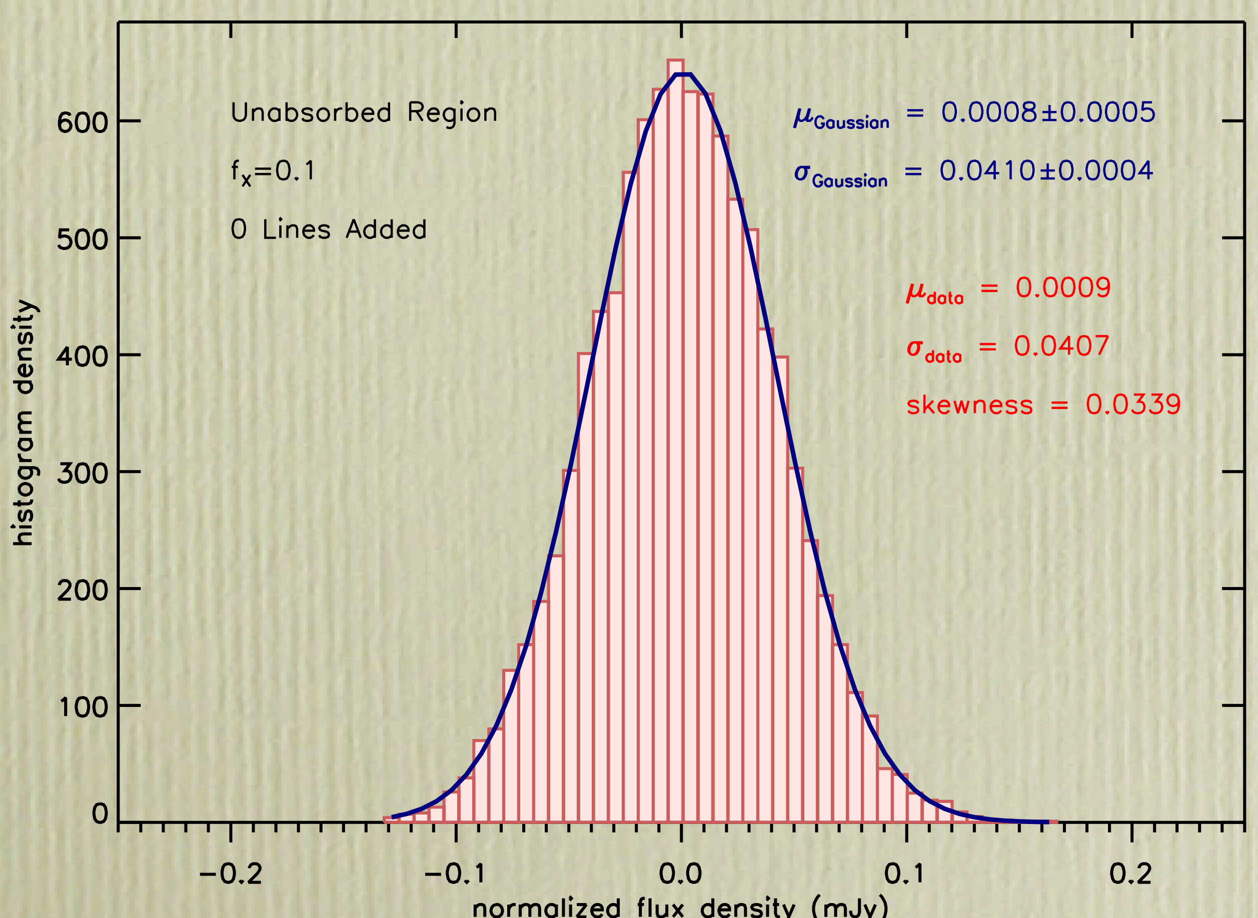

Absorbed Region
f_x=0.1
0 Lines Added
μ_Gaussian = −0.0276±0.0006
σ_Gaussian = 0.0470±0.0005
μ_data = −0.0274
σ_data = 0.0466
skewness = 0.0015
histogram density
normalized flux density (mJy)



f_X=0.1
100 absorbers
flux density (mJy)
observed frequency (MHz)



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histogram density
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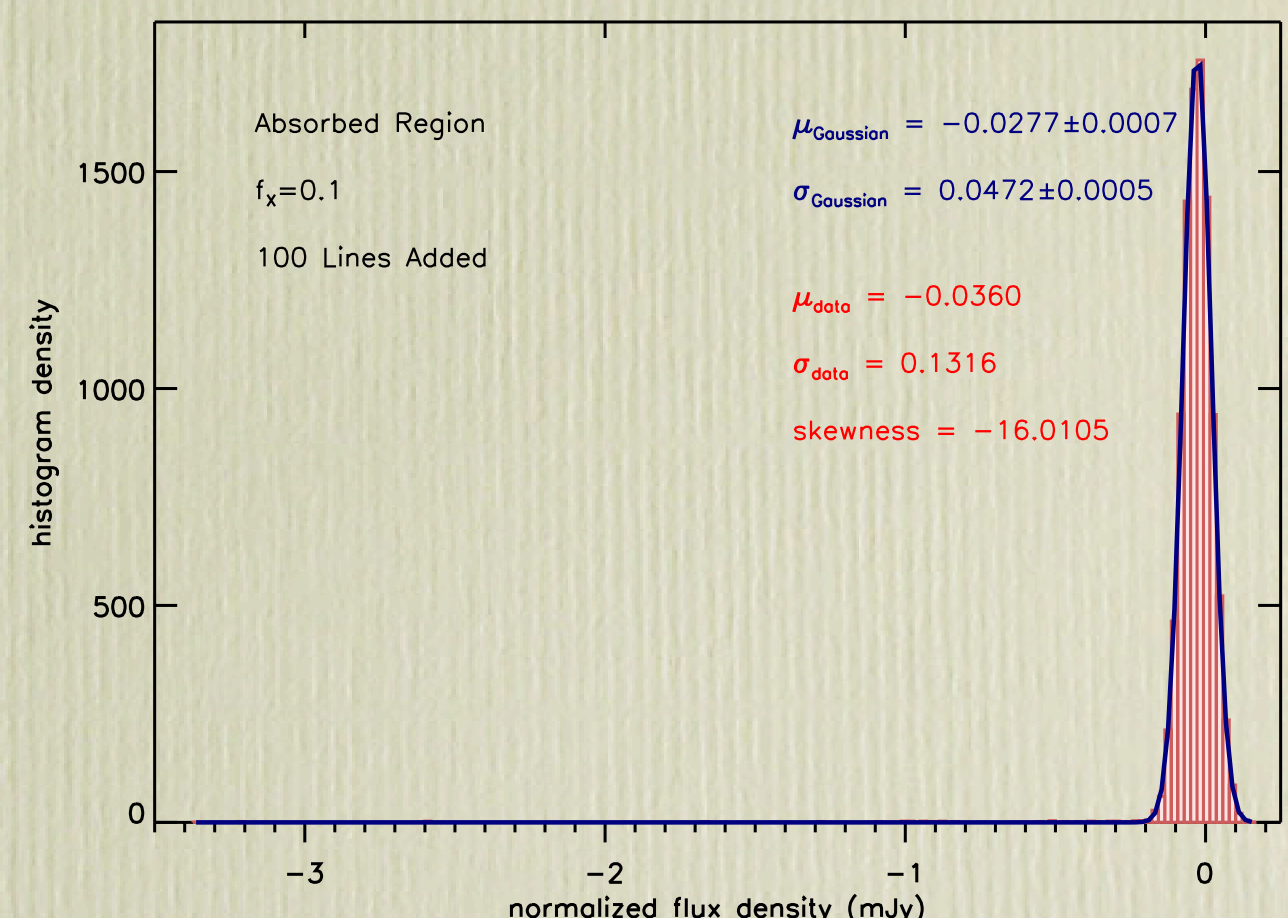
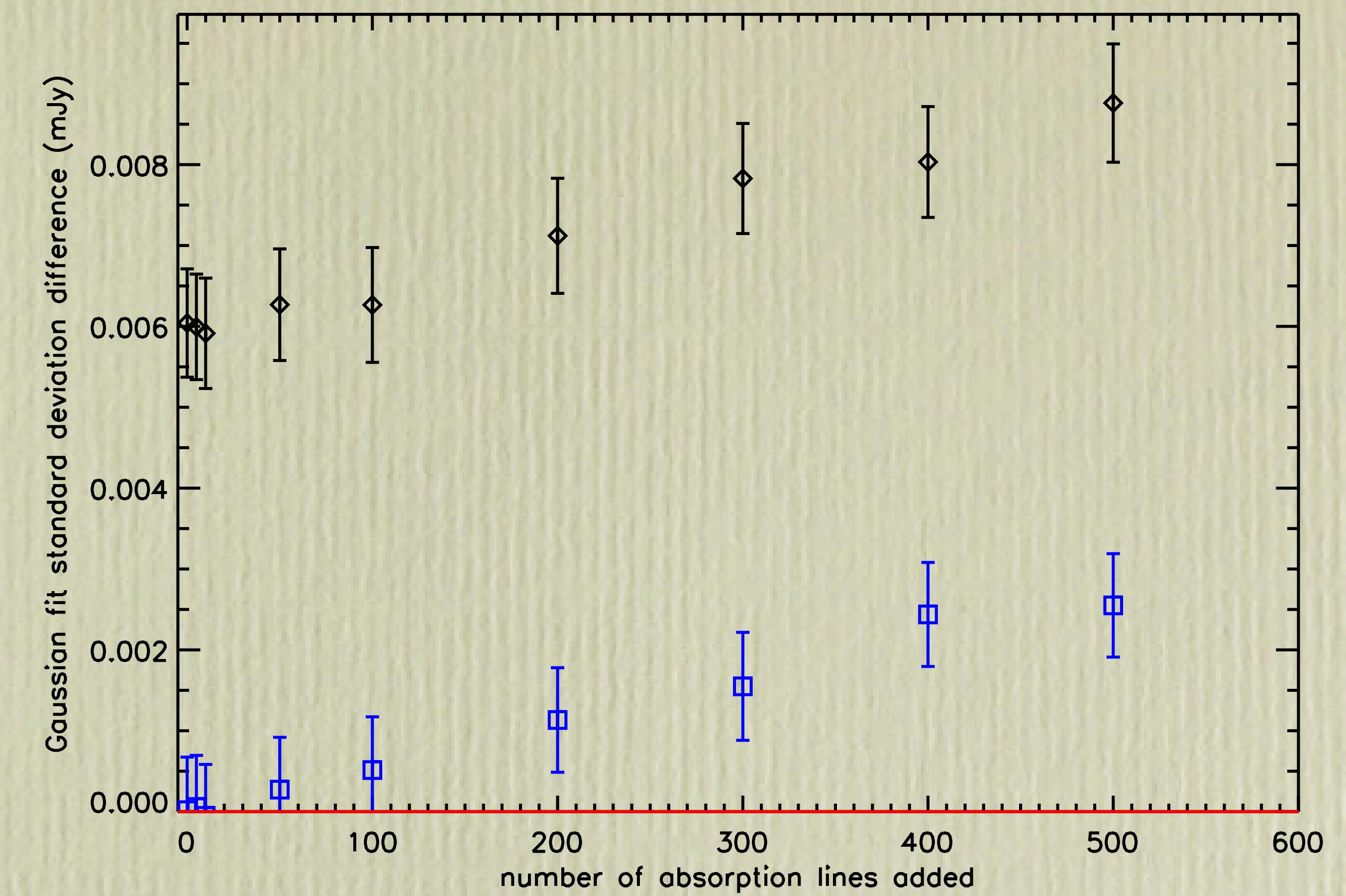
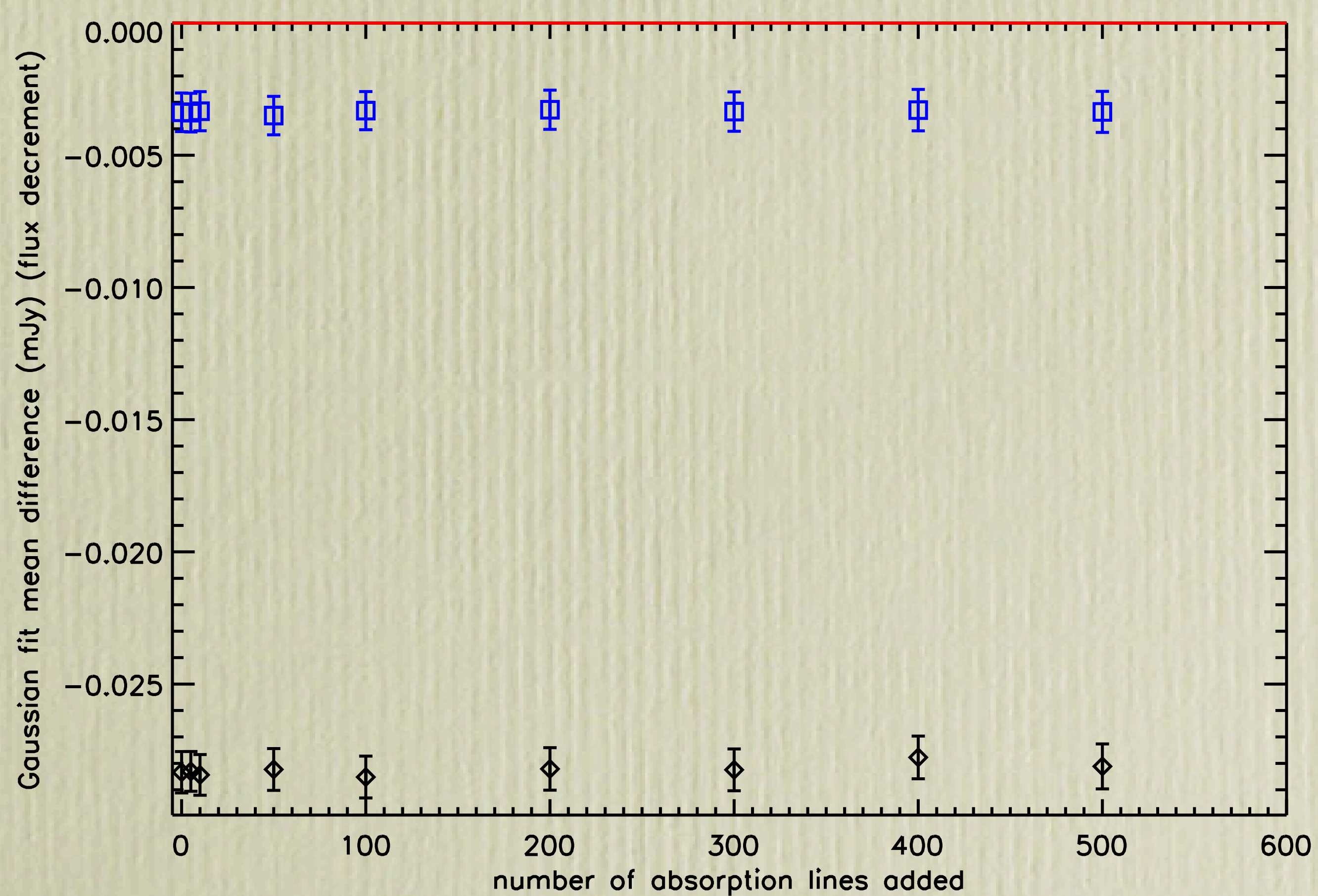


Absorbed Region
f_x=0.1
100 Lines Added
$\mu_{Gaussian}$ = −0.0277±0.0007
$\sigma_{Gaussian}$ = 0.0472±0.0005
μ_{data} = −0.0360
σ_{data} = 0.1316
skewness = −16.0105
histogram density
normalized flux density (mJy)

$\sigma_{G,Right} - \sigma_{G,Left}$



$\mu_{G,Right} - \mu_{G,Left}$



Challenges & Uncertainties

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  - f_X largely unconstrained at high z
  - Observations of 21cm forest could place strong constraints on f_X, thermal history

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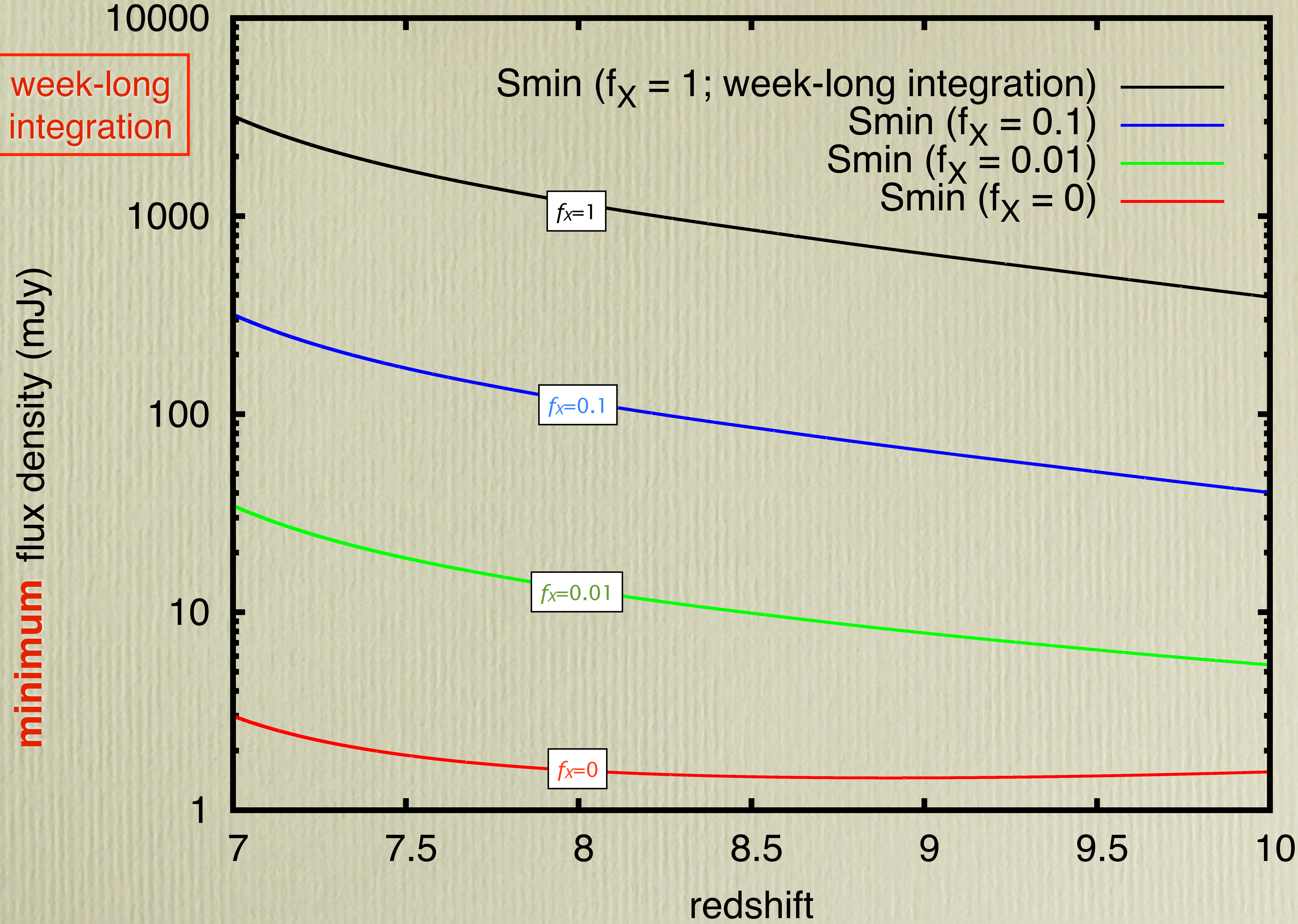
  - f_X largely unconstrained at high z
  - Observations of 21cm forest could place strong constraints on f_X, thermal history
- Observations: High-redshift radio sources
  - Number of radio-loud sources at high z unknown
  - Sources may be in radio catalogs but not identified
  - Even a few sightlines would be useful
  - EUCLID / WFIRST might identify potential sources

week-long integration



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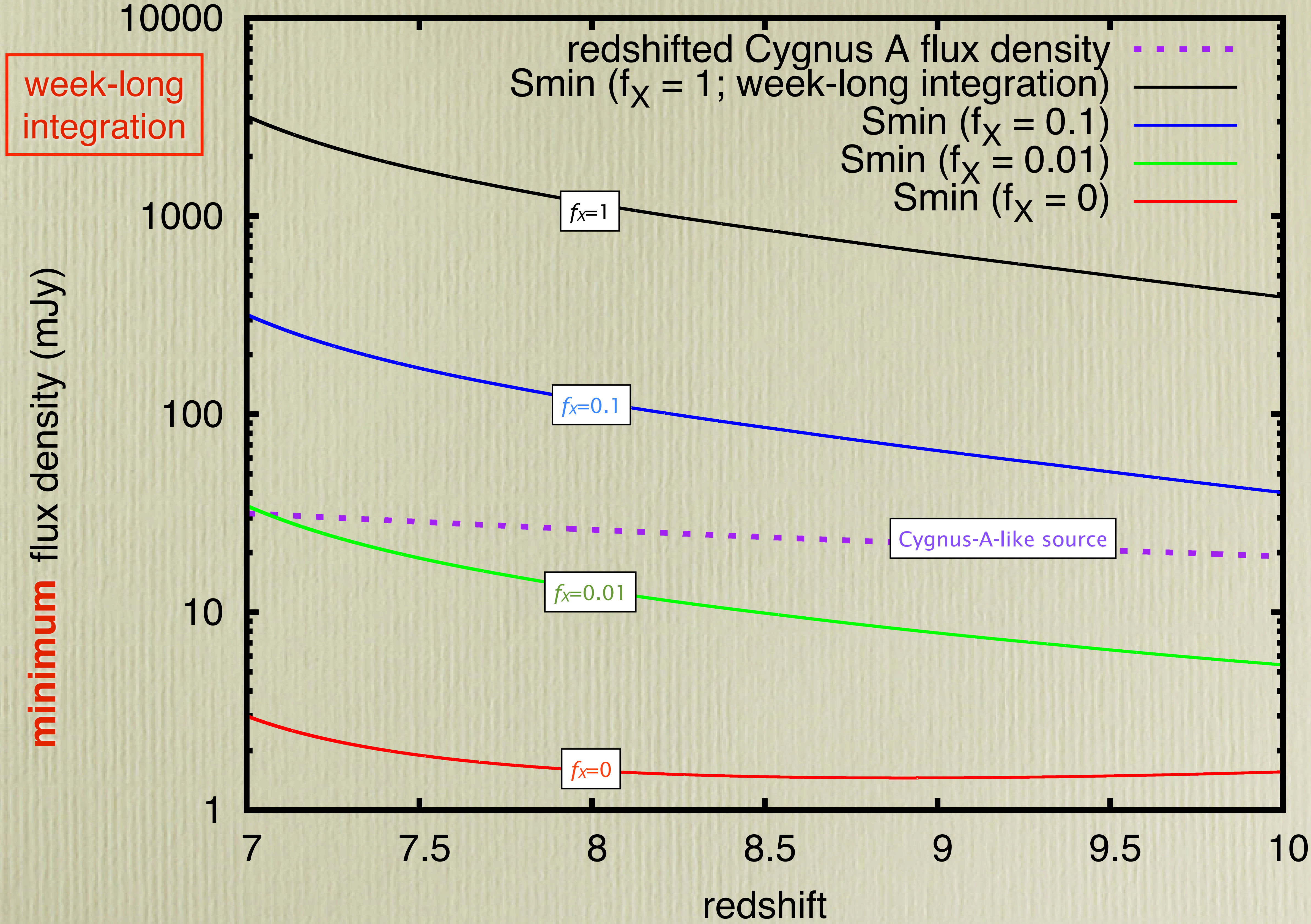

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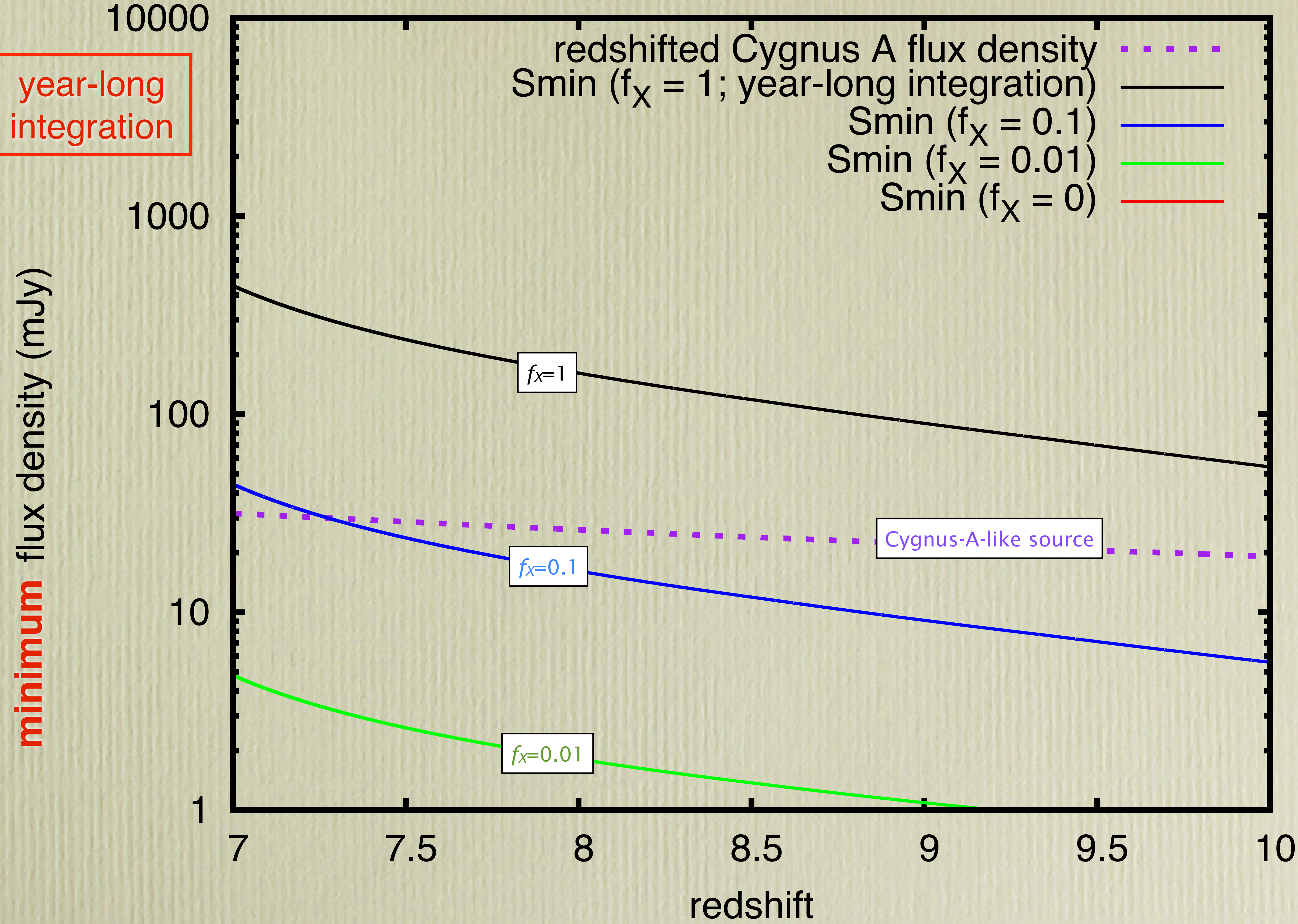
year-long integration



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