Title: Primordial black holes in the dark ages

Date: Sep 13, 2007 12:00 PM

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Abstract: We investigate the effect of evaporating primordial black holes on the ionization history of the universe, with emphasis on limits derivable from the CMB and future 21-cm observations of high-redshift neutral hydrogen.

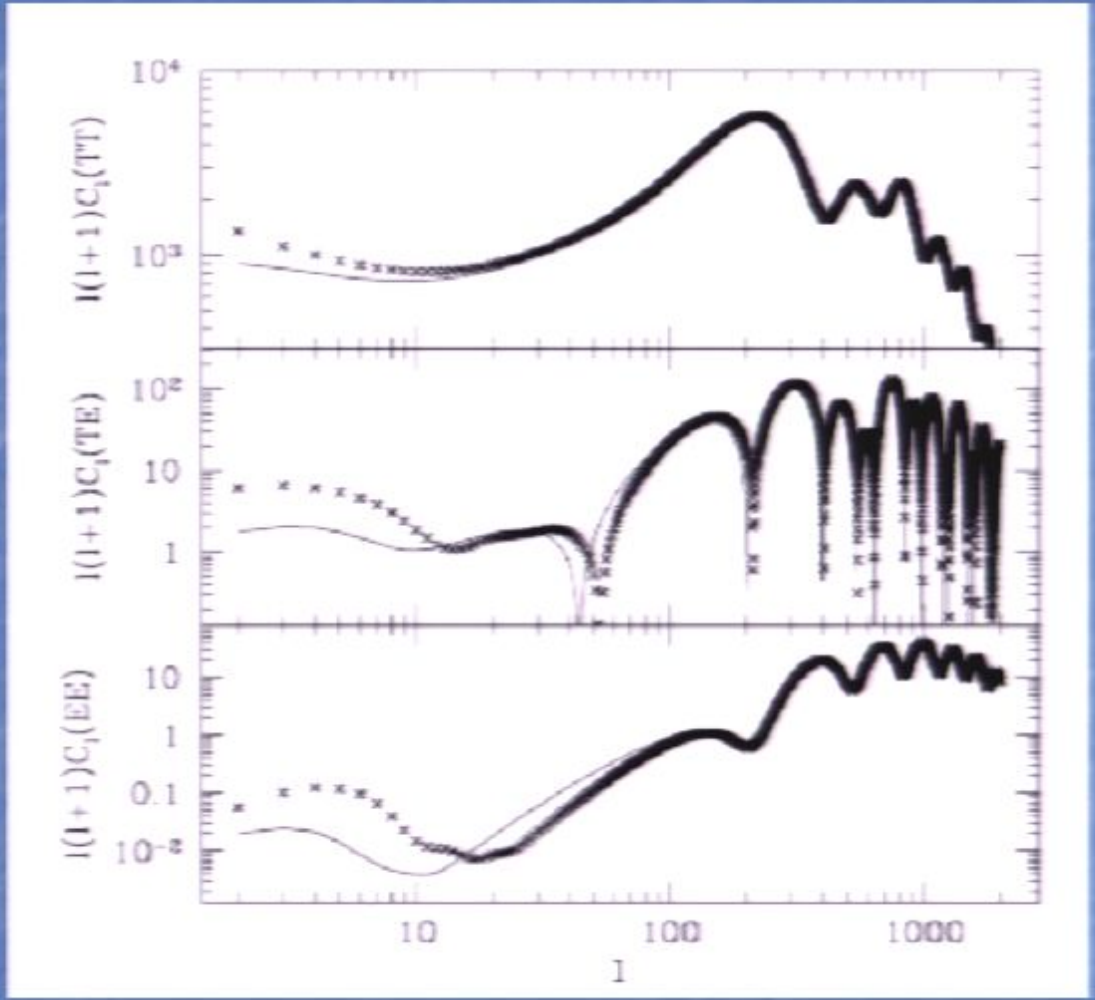
Primordial black holes

- Pre-stellar black holes – many proposed formation mechanisms
- Two regimes of interest:
  - evaporating: inject energy into IGM through Hawking radiation
  - accreting: X-ray radiation from accretion disks

Accreting PBHs

(Ricotti, Ostriker & Mack 2007)

- X-rays ionize IGM at high redshift
- Ionization increases τ – see with CMB polarization
- Polarization signal distinct from that of early reionization; may lead to parameter misestimation


10^4
10^3
$l(l+1)C_l(TT)$
10^2
10
1
$l(l+1)C_l(TE)$
10
1
0.1
10^{-2}
$l(l+1)C_l(EE)$
10
100
1000
l

Evaporating PBHs

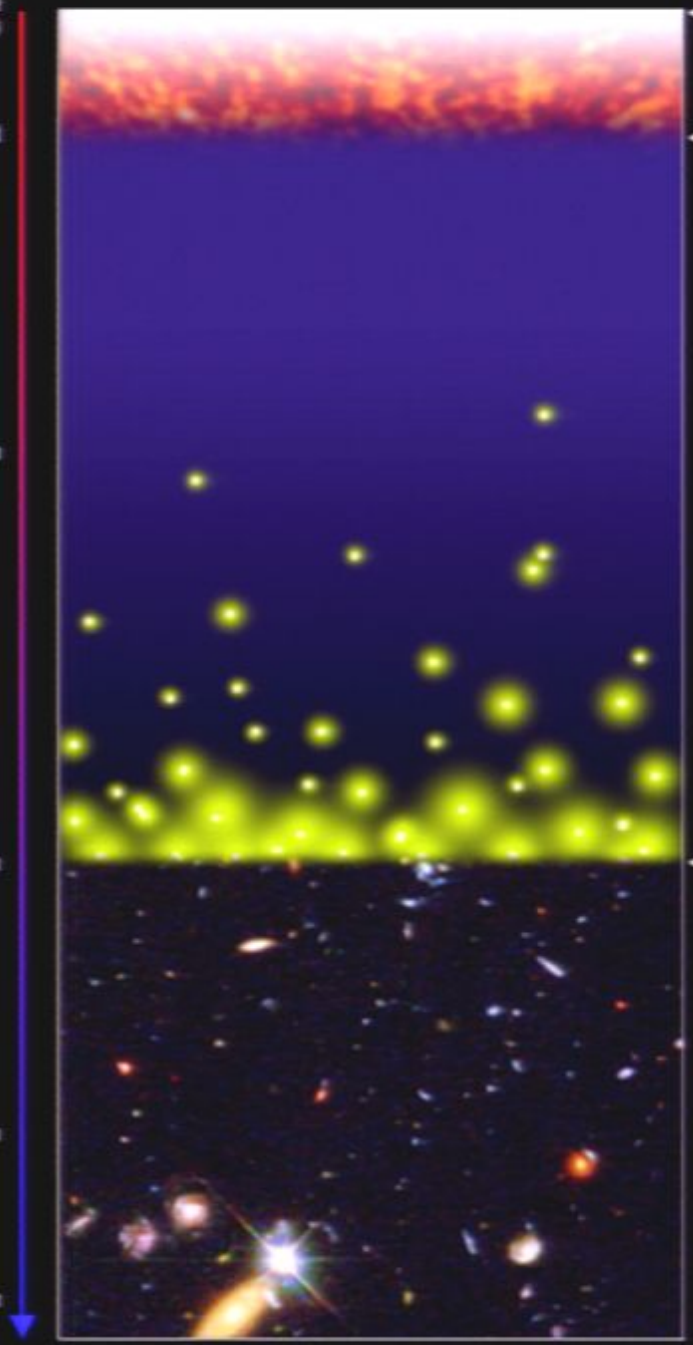
- Hawking radiation heats and ionizes IGM
- May produce strong signal at moment of evaporation
- Best constraints currently from gamma-ray background
- At $M = 10^{15}$ g, limit is $\Omega_{PBH} \sim 10^{-10}$

This talk: the overall gist

- Primordial black holes (PBHs) may have formed in the early universe
- Evaporation (or accretion) of PBHs injects energy into the intergalactic medium
- Energy injection affects ionization and temperature of IGM
- The redshifted 21cm line of neutral hydrogen is sensitive to changes in both – very good probe of exotic physics

What is the Reionization Era?

A Schematic Outline of the Cosmic History



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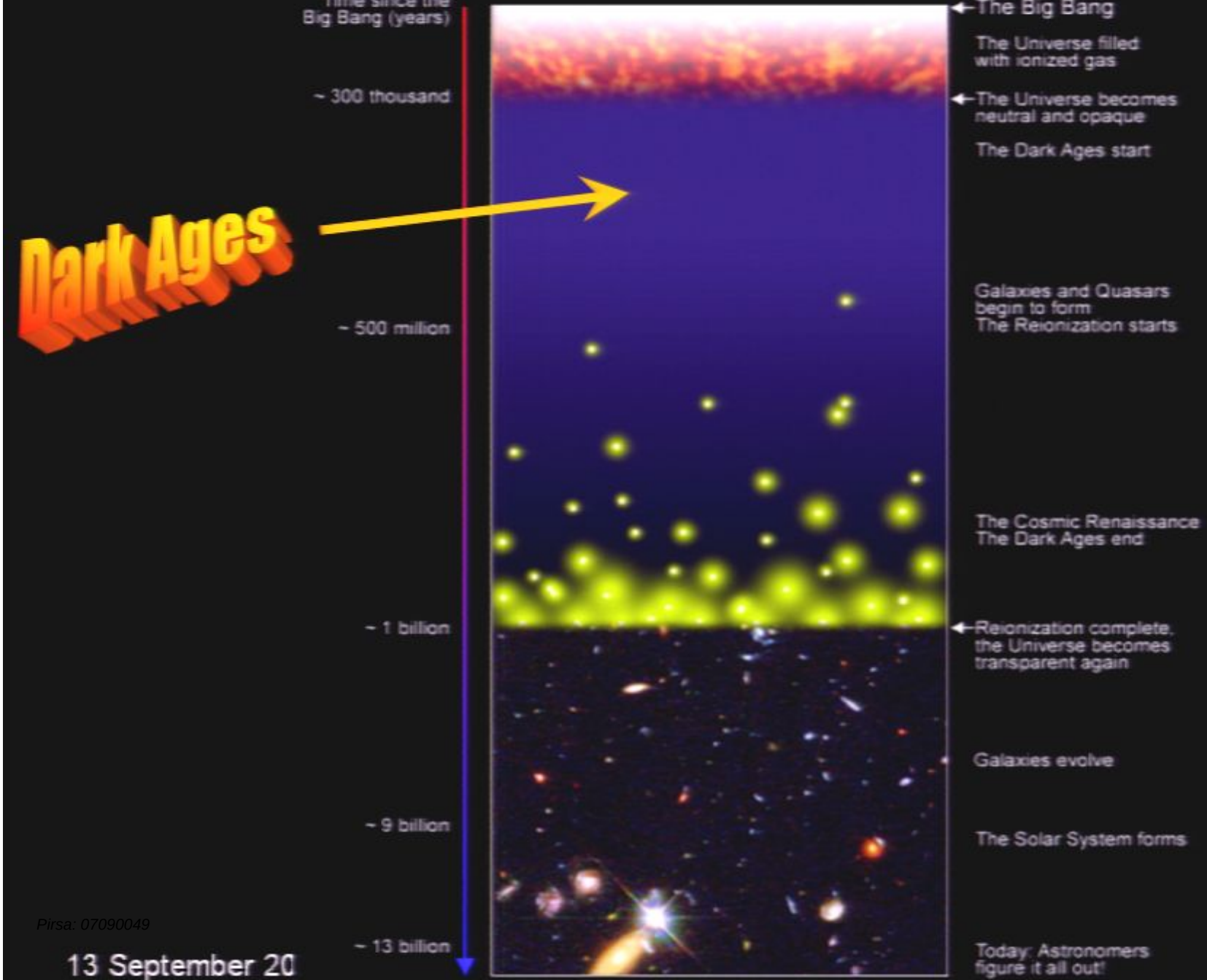

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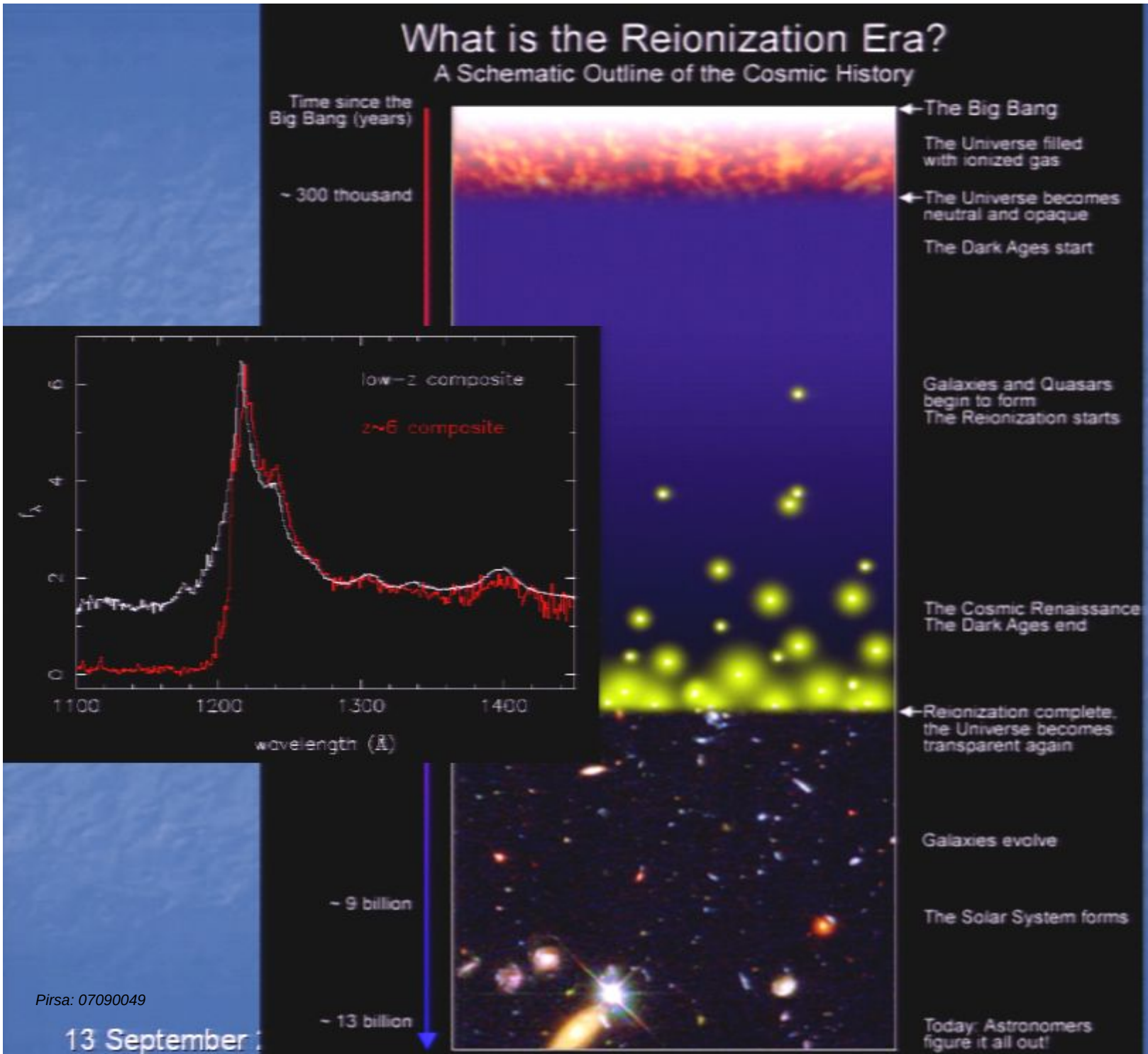
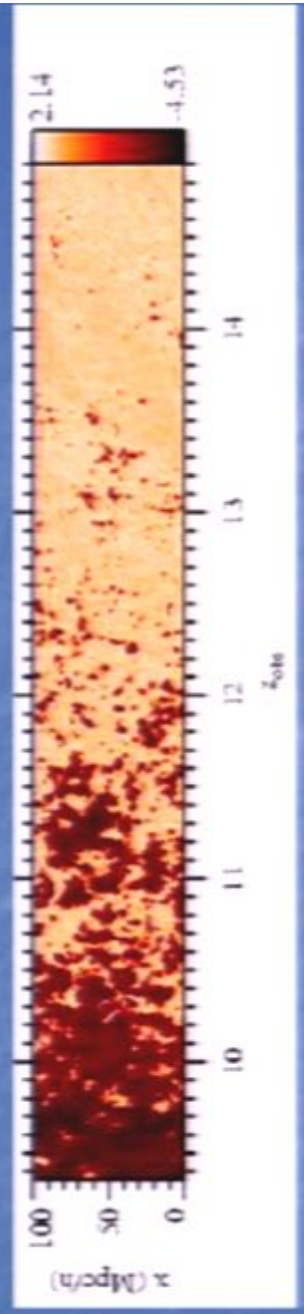
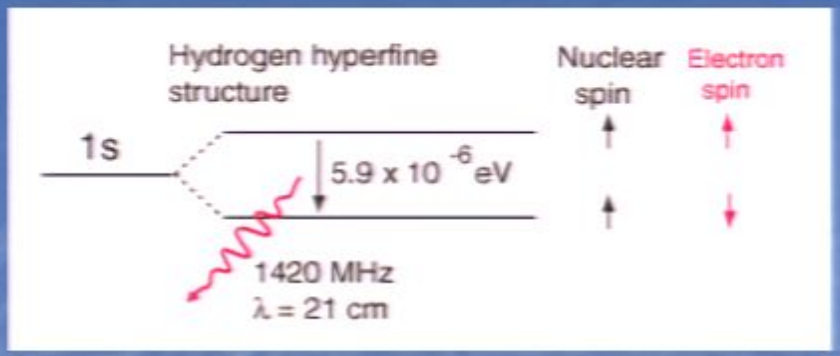


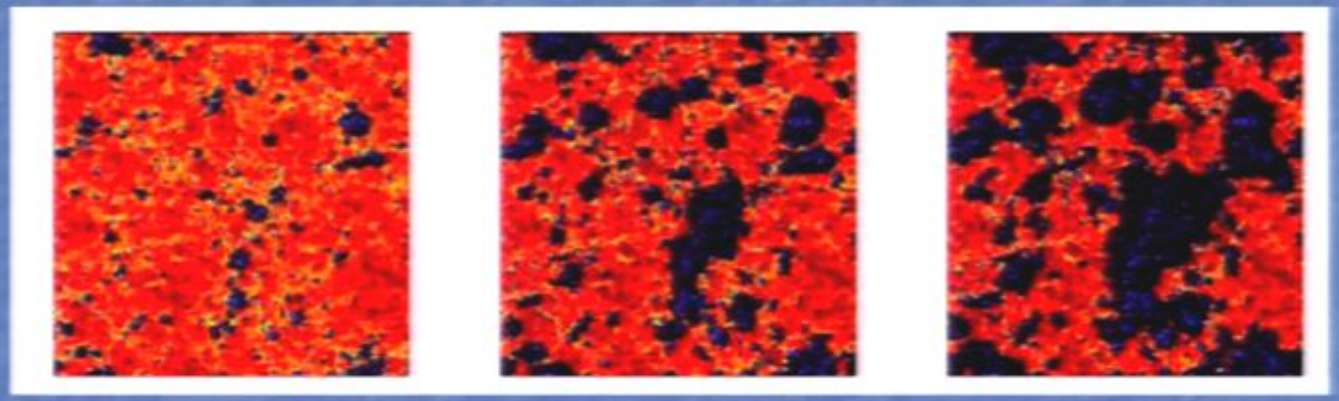


21cm signal



- During Dark Ages, universe mostly cold neutral hydrogen, and visible/UV light immediately absorbed
- Use the hyperfine splitting line of hydrogen:
  - in radio wavelengths, unabsorbed
  - requires little energy to excite

21cm tomography

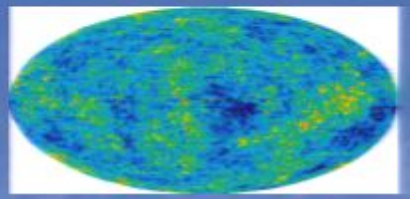


z=8.16 z=7.68 z=6.89

Zahn et al 2006

Observing with 21cm

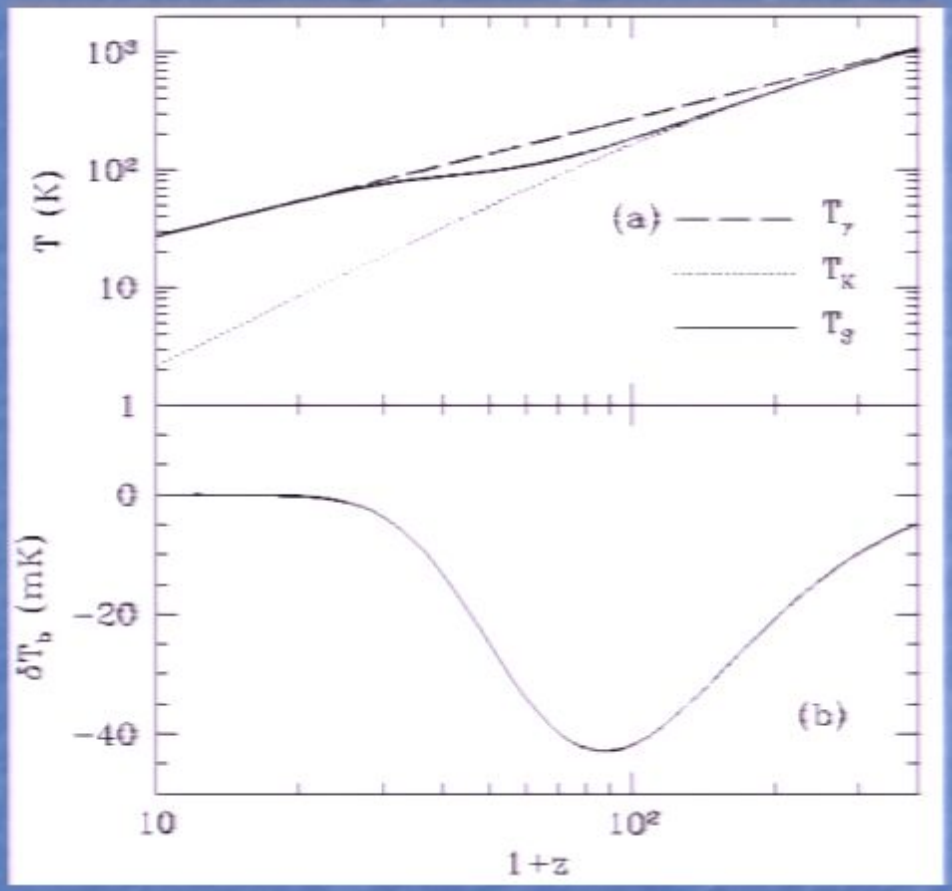
21cm vs. CMB



- More information in 21cm tomography
  - temperature + ionization of gas
  - many redshifts (not an integrated signal)

- Example: constraining dark matter annihilation (measuring energy injection)
  - CMBPol: $(dE/dt)/vol < 10^{-16}$ eV/s/m^3 (Padmanabhan & Finkbeiner 2005)
  - Future 21cm obs: $(dE/dt)/vol < 10^{-18}$ eV/s/m^3 (Furlanetto, Oh & Pierpaoli 2006)

Spin and brightness temps



The spin temperature determines the relative occupancy of the hyperfine levels

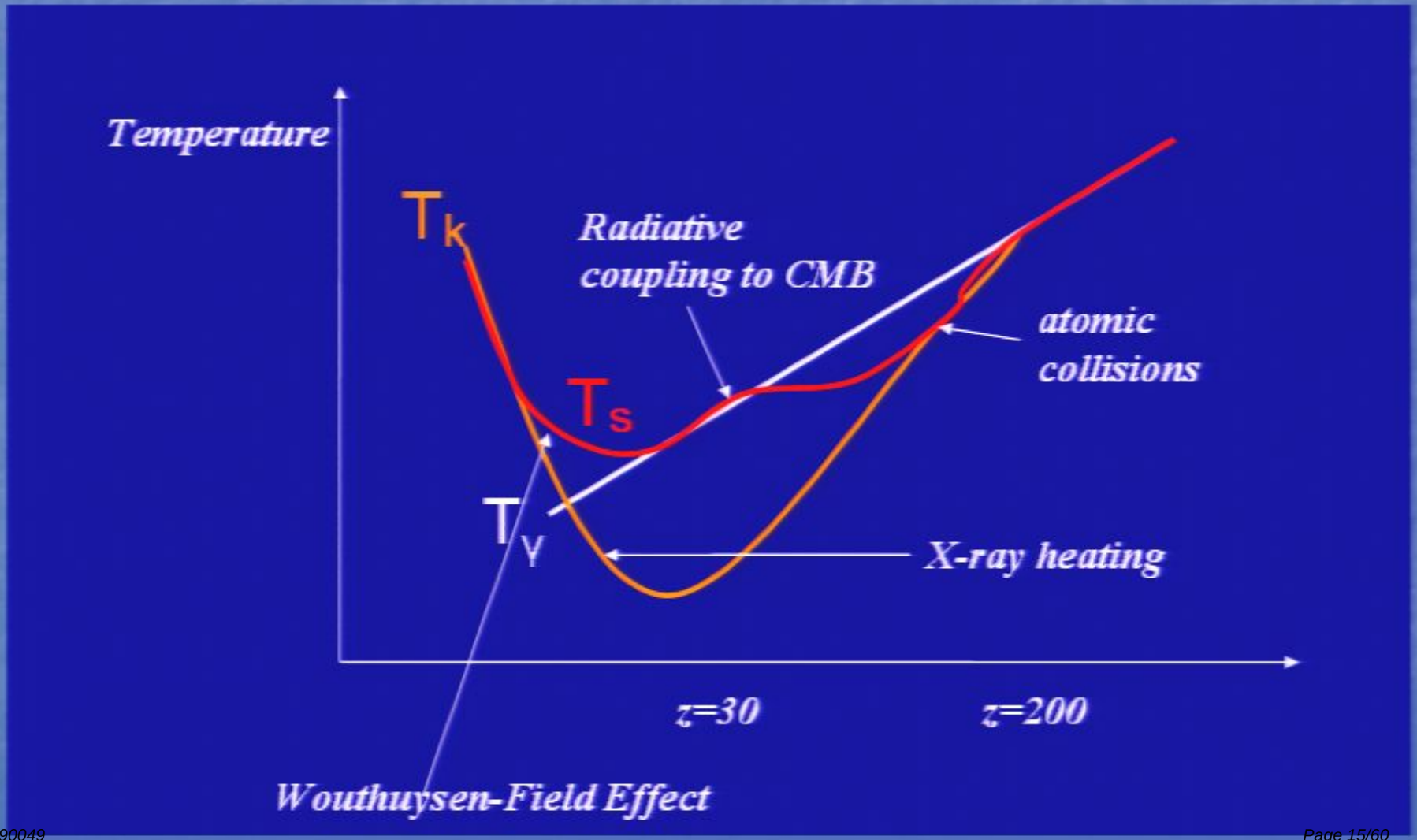
$$\frac{n_1}{n_0} = 3 \exp\left\{-\frac{T_*}{T_S}\right\}$$

$$T_S = \frac{T_{\rm CMB} T_k (1 + x_{\rm tot})}{T_k + T_{\rm CMB} x_{\rm tot}}$$

The brightness temperature measured by observations is determined by the spin temperature's coupling to the CMB

$$T_b = (1+z)^{-1}(T_S - T_{\rm CMB})(1 - e^{-\tau})$$

Spin and brightness temps



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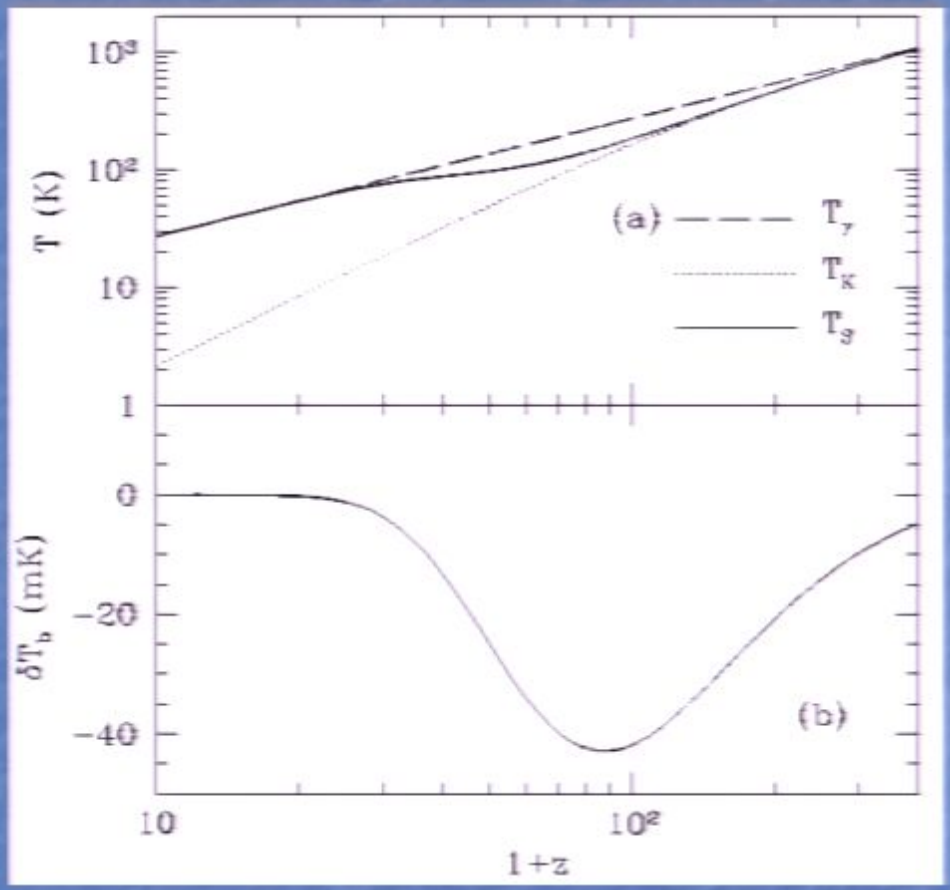

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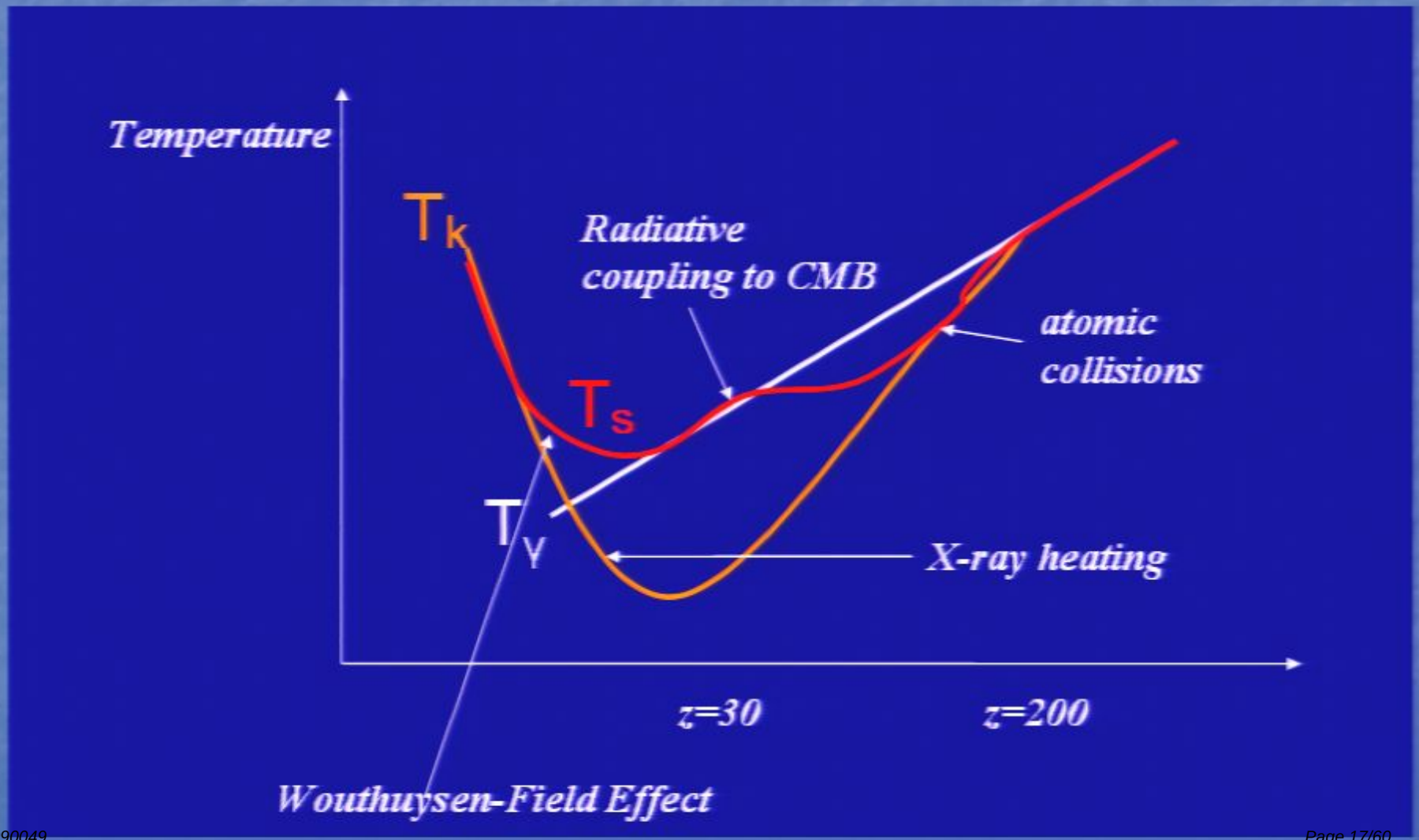
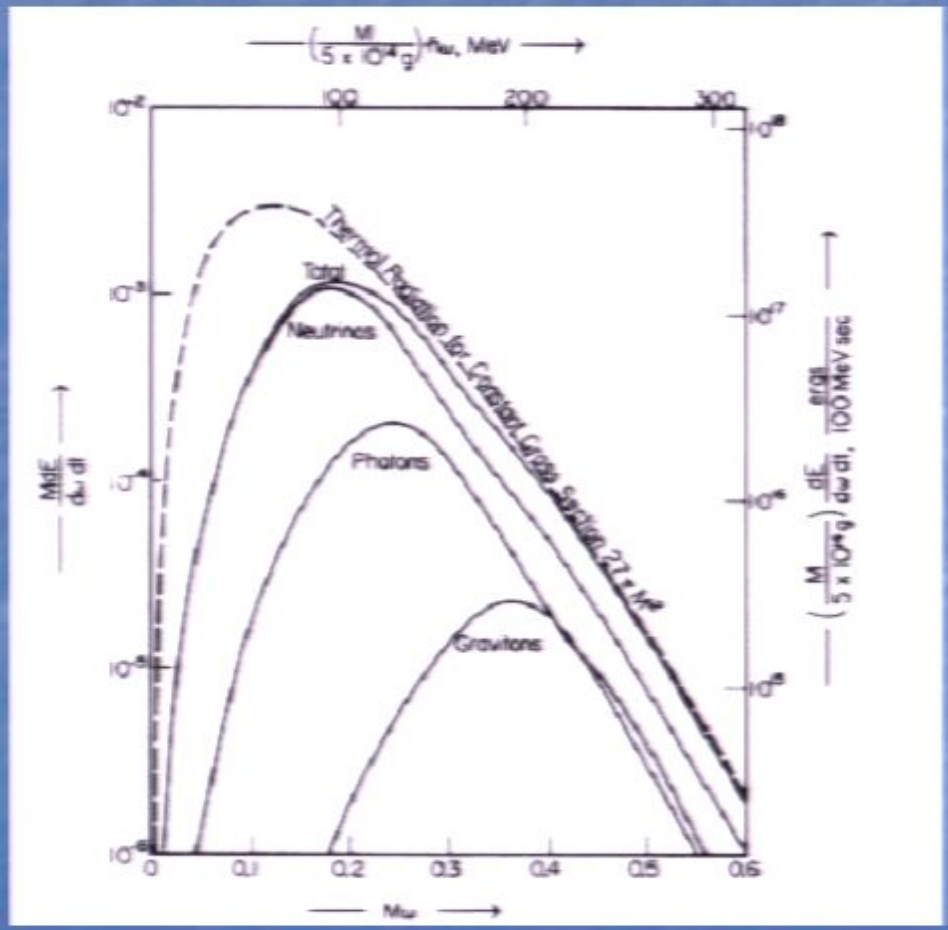


Hawking radiation

- PBHs emit particles in a roughly blackbody spectral distribution
- Temperature ~ M^{-1}
- Power ~ M^{-2}
- Lifetime ~ M^{3}
- PBH evaporation injects energy into the IGM



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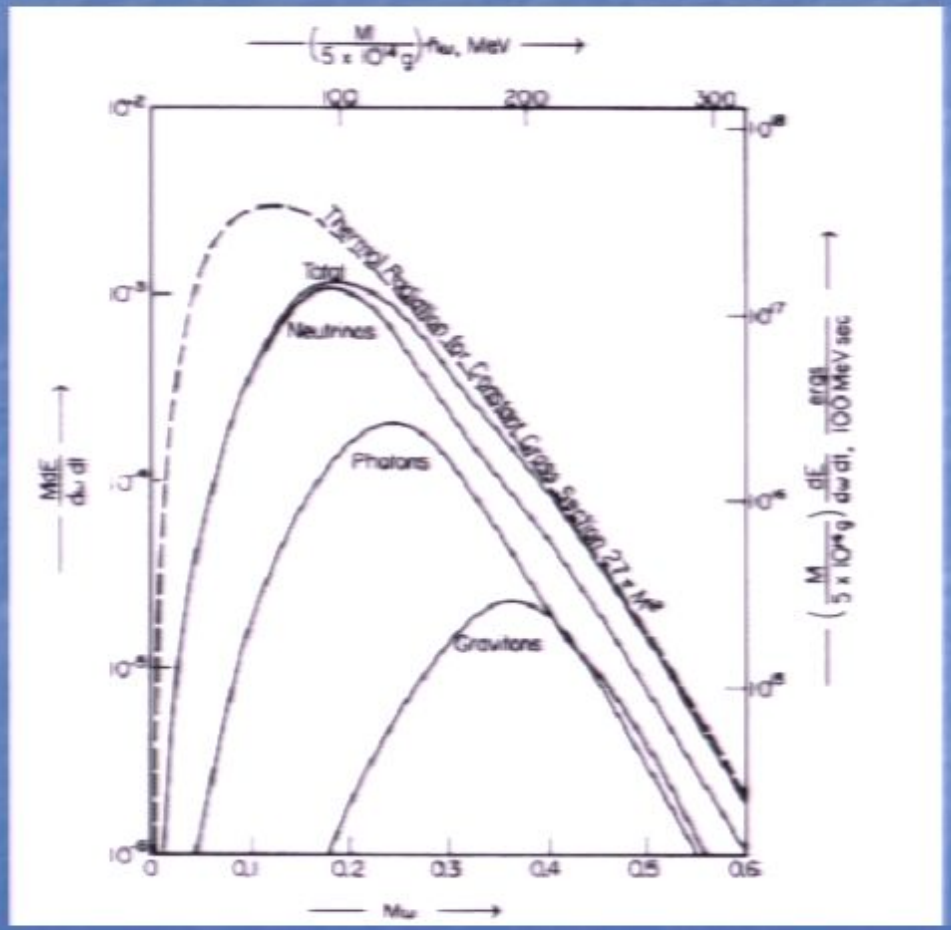

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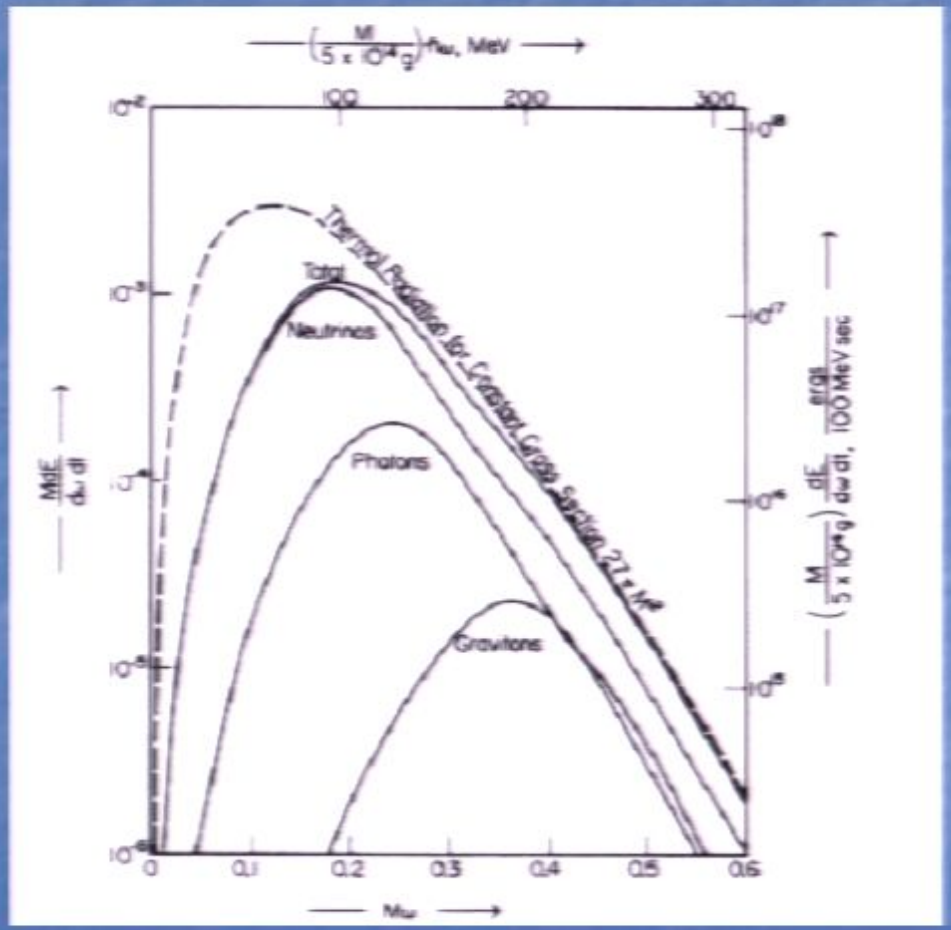
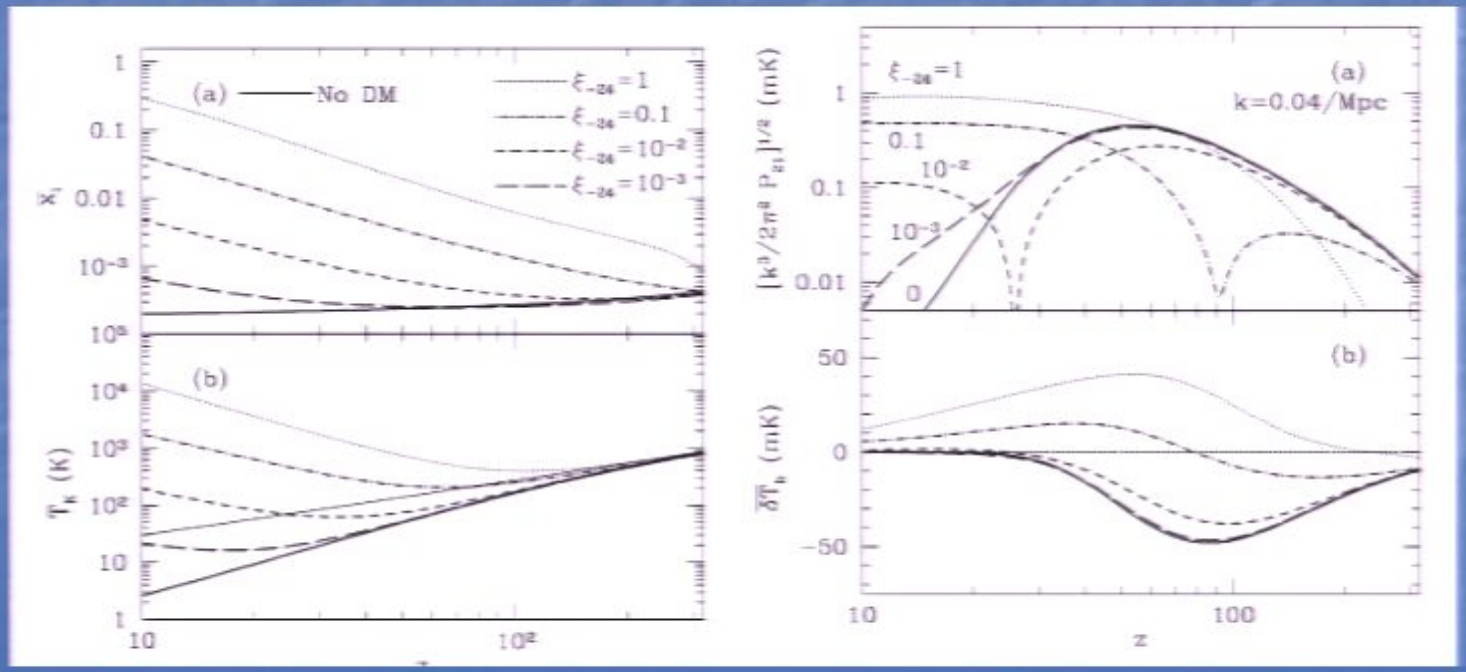


Analogy with decaying dark matter

- Furlanetto, Oh & Pierpaoli (hereafter FOP)
  - Energy injection from decaying DM in the dark ages
  - Implications for 21cm observations
- Claim: 21cm can detect 10^{-24} eV/cm^3/s
- Hypothesis: PBH evaporation should look similar to decaying DM



Simple order-of-magnitude estimate

- Assume:
  - Constant comoving number density n_{PBH}
  - Uniformly distributed PBHs
  - Constant energy injection rate
- Find (dE/dt)/volume for $M=10^{11}$ kg PBHs:

$P \approx 2e\text{-}4 * \hbar * c^6 / (G * M)^2 = 3.4e11$ W

Limit: 10^{-24} eV/cm^3/s = 1.6e-37 J/m^3/s

$\Rightarrow n_{PBH} < 4.7e\text{-}49$ m^{-3} $\Rightarrow$ $\Omega_{PBH} < 4.7e\text{-}12$

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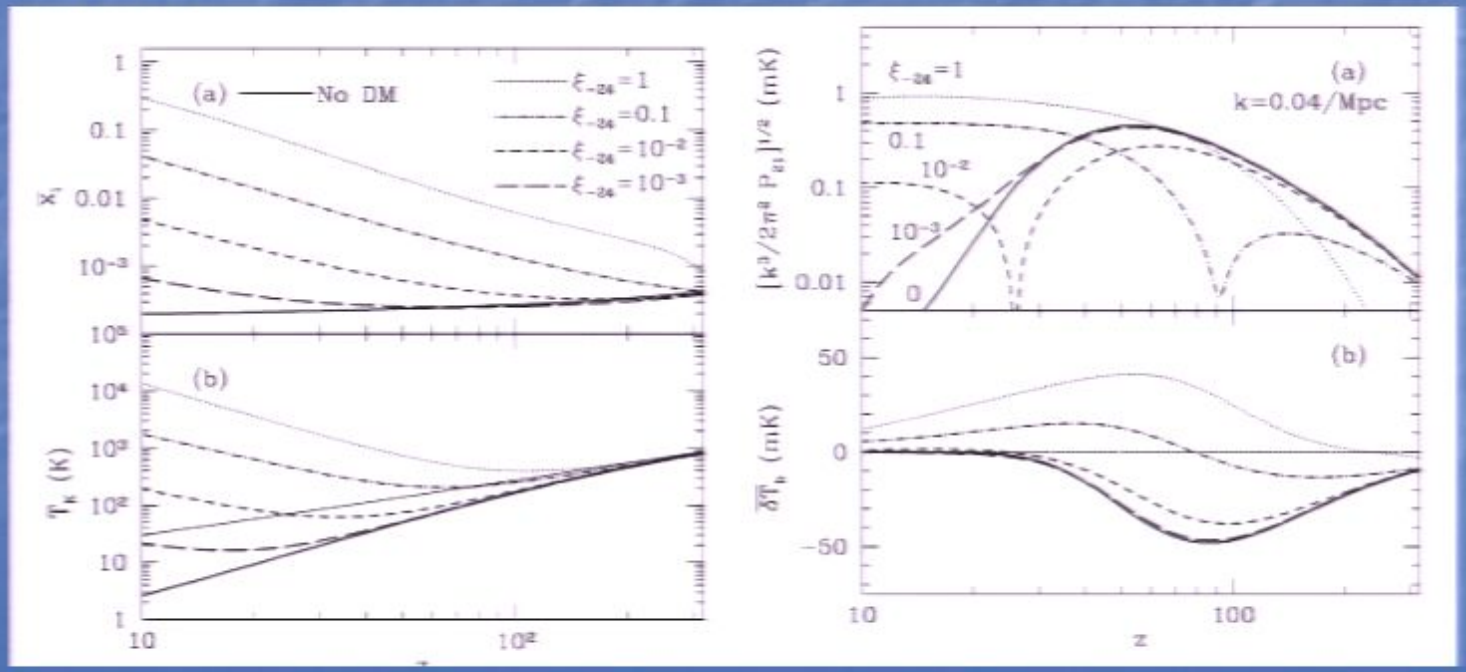

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Method

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1. Simulate Hawking radiation
   - Produce spectrum (with graybody factors)
   - Track photon energies with redshift
2. Allow for absorption by IGM
   - photoionization, Compton scattering, pair production (off atoms, free ions and the CMB), scattering off CMB photons
3. Find total energy injection into IGM over course of PBH evolution
4. Track temperature and ionization of IGM (pre- and post-recombination)
5. Track 21cm brightness temperature
6. Compute 21cm power spectrum

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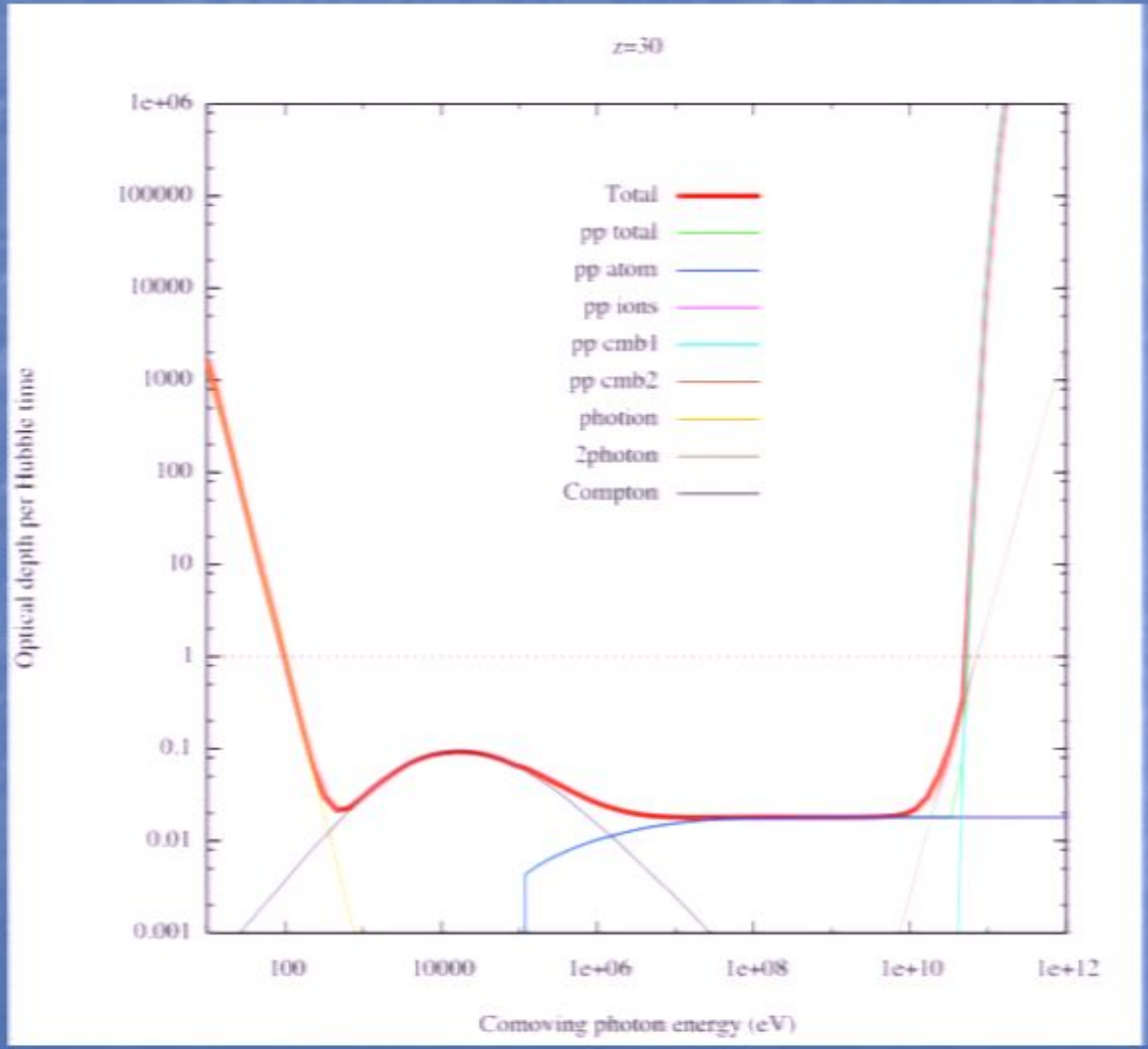
Transparency window



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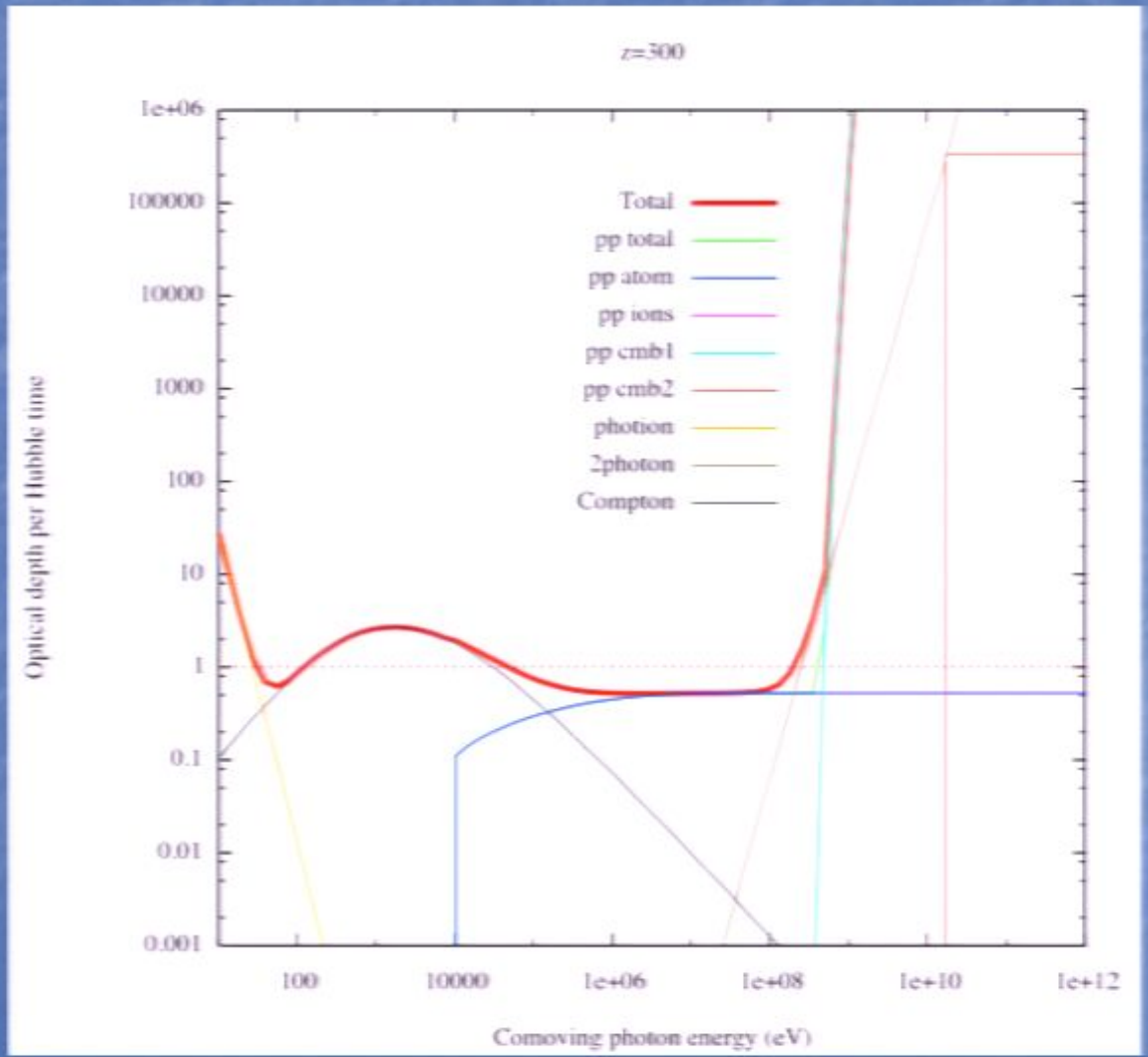

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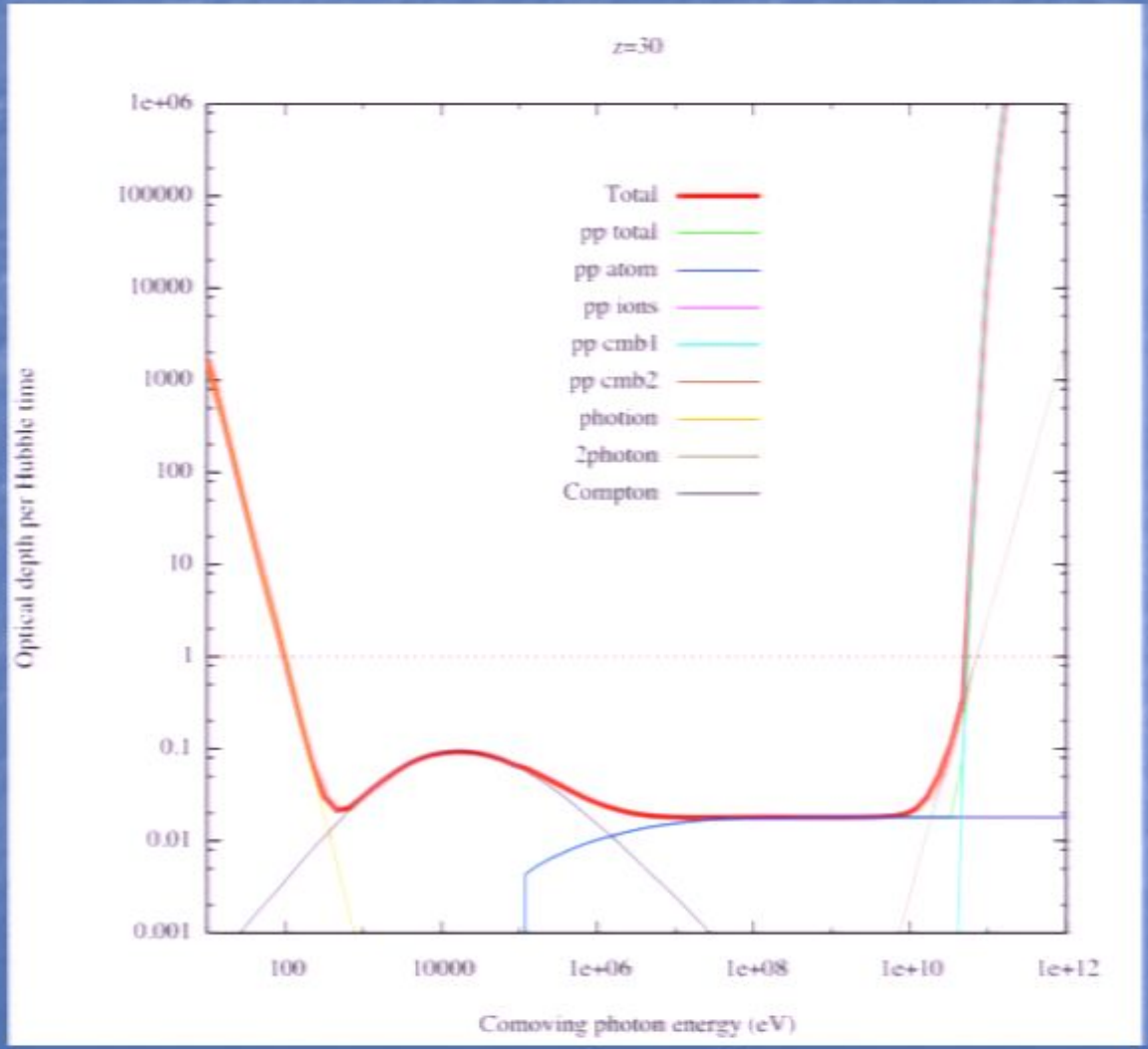

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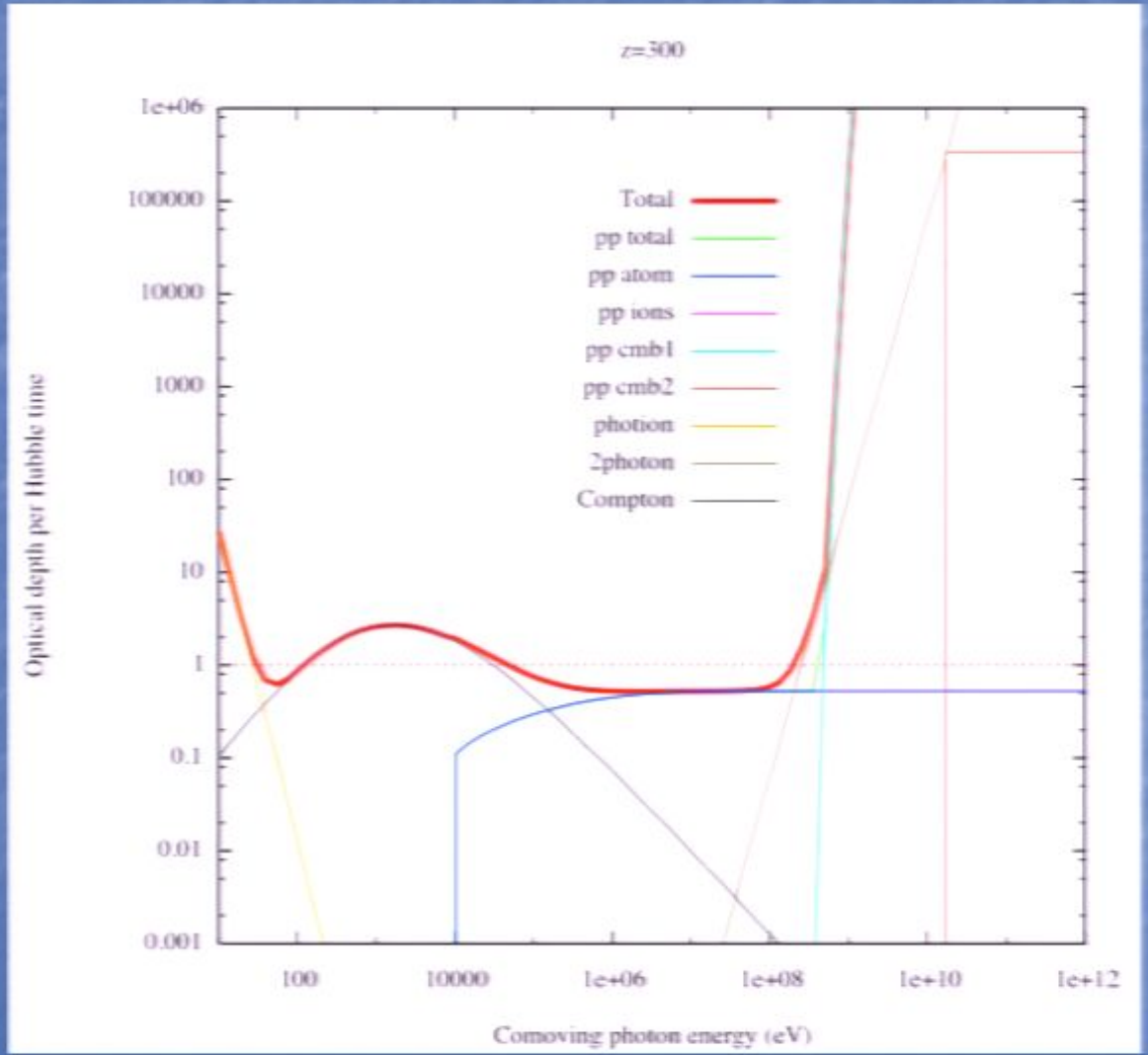

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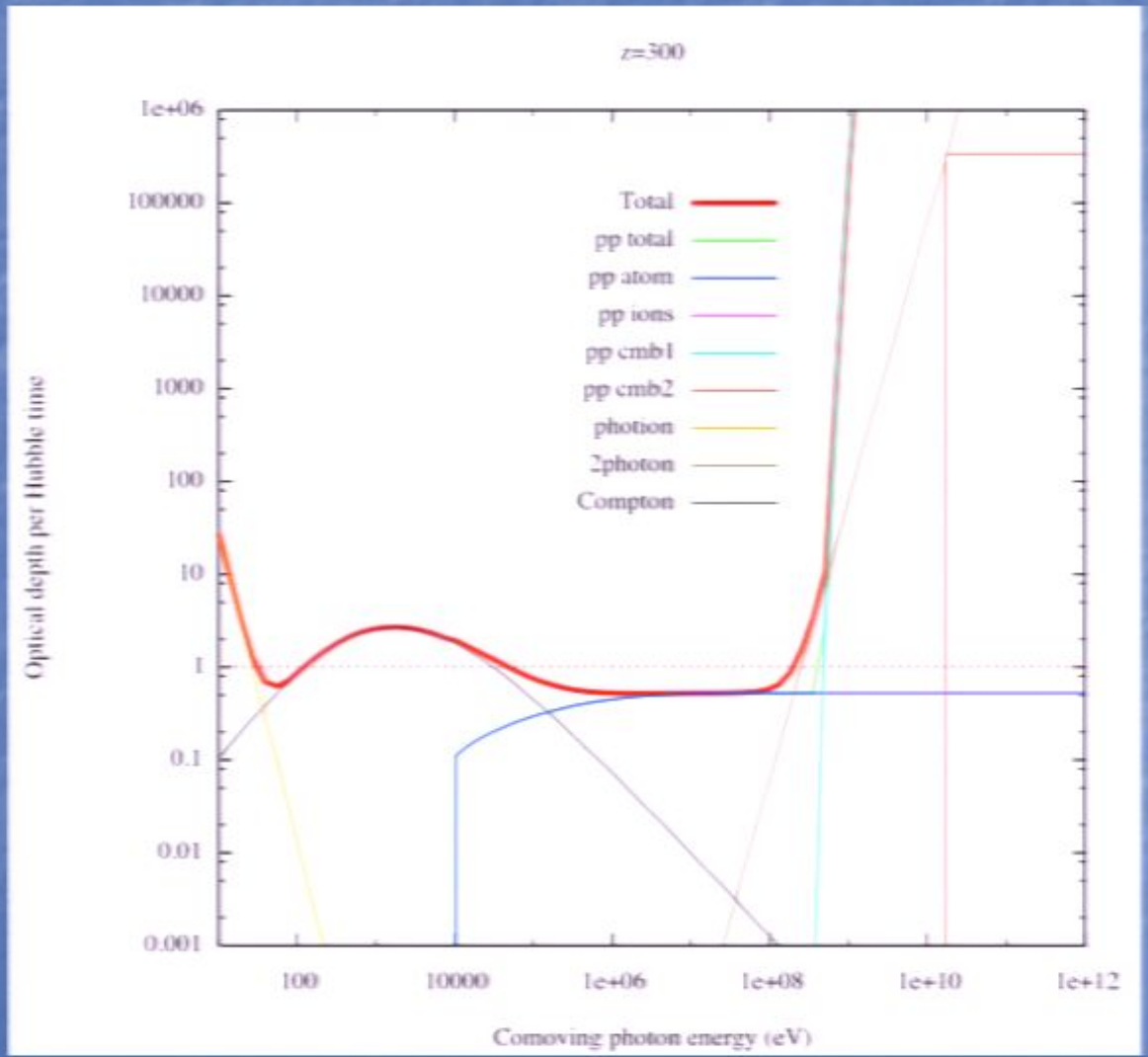

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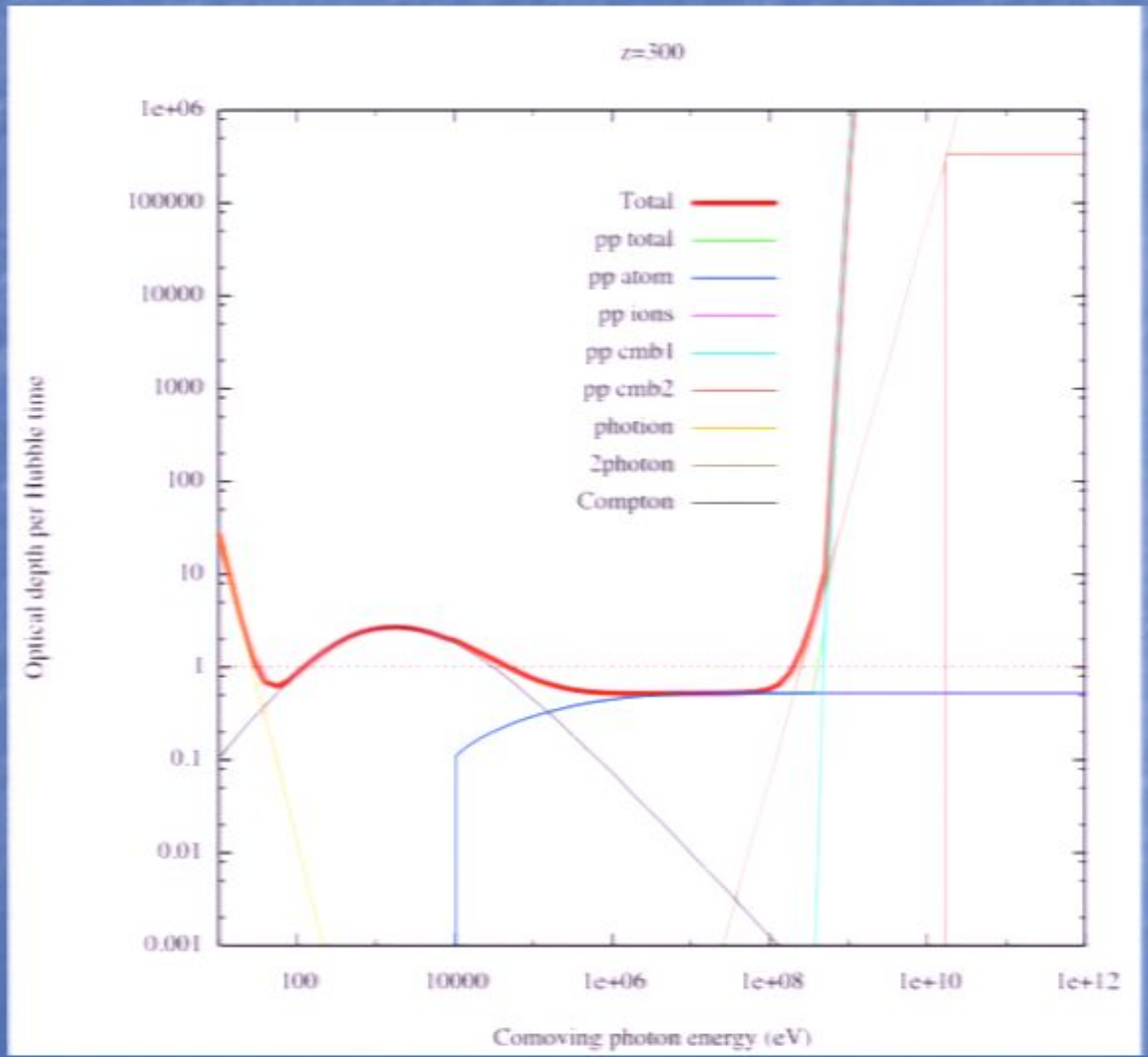
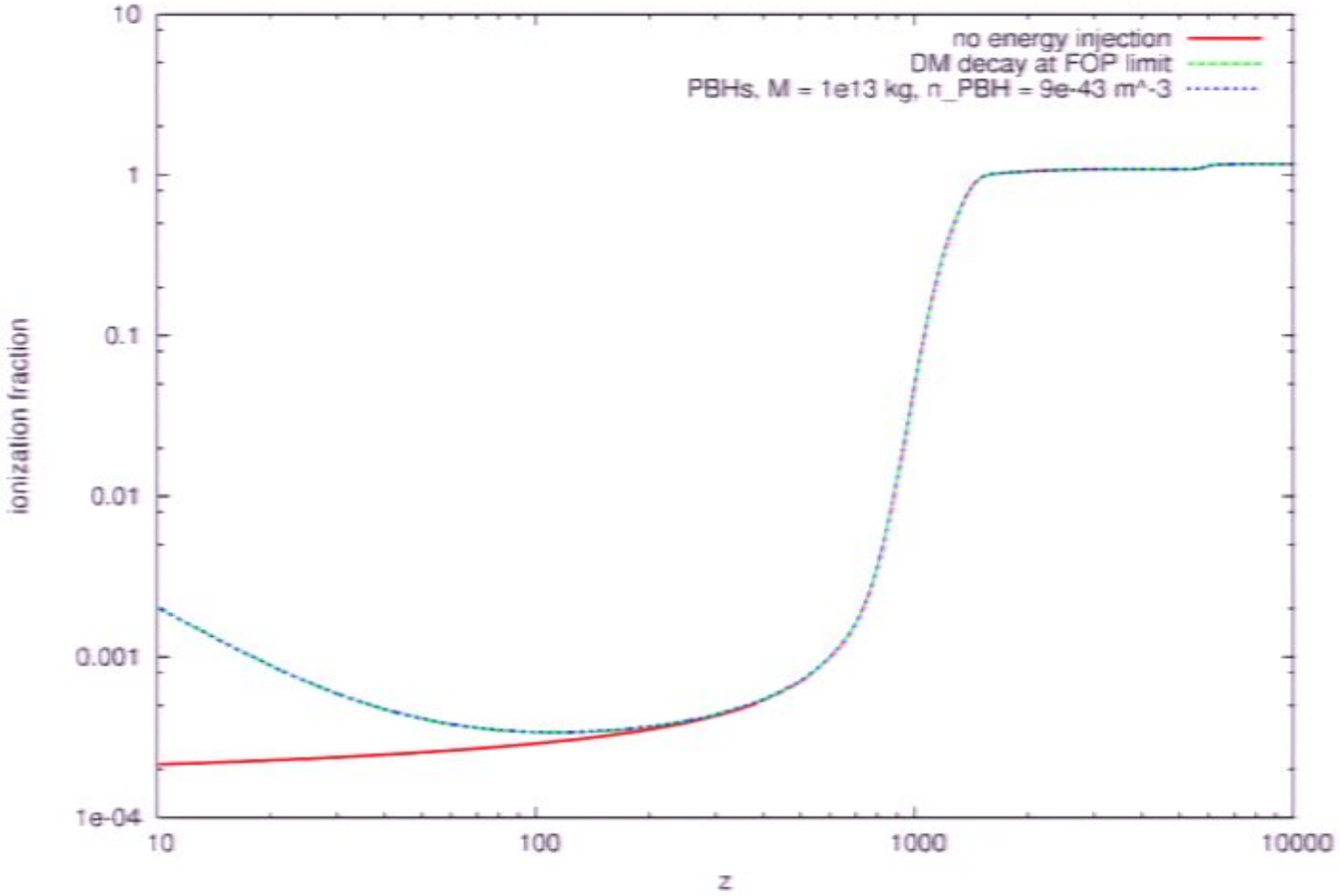


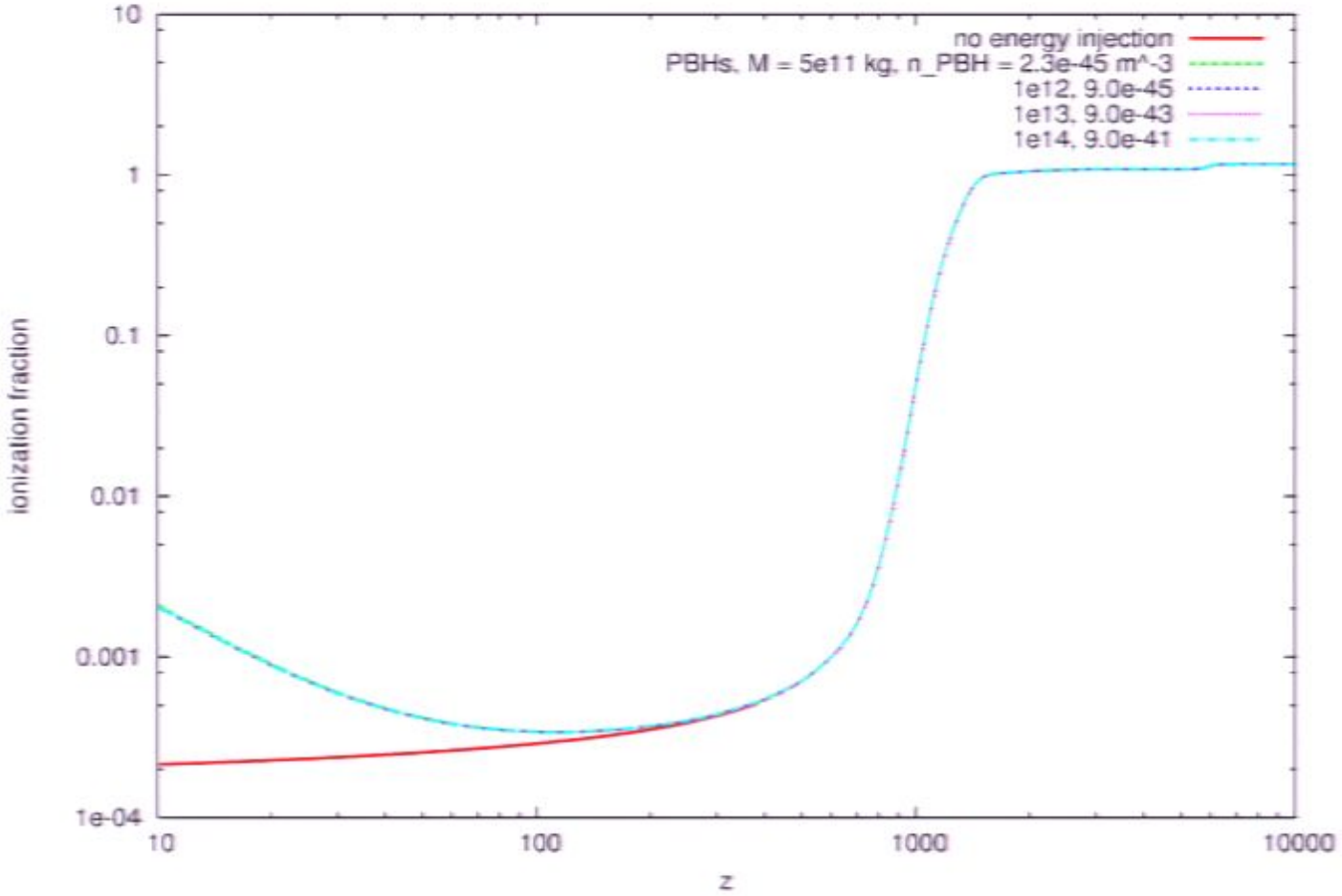
Results – ionization history

PBHs and decaying DM



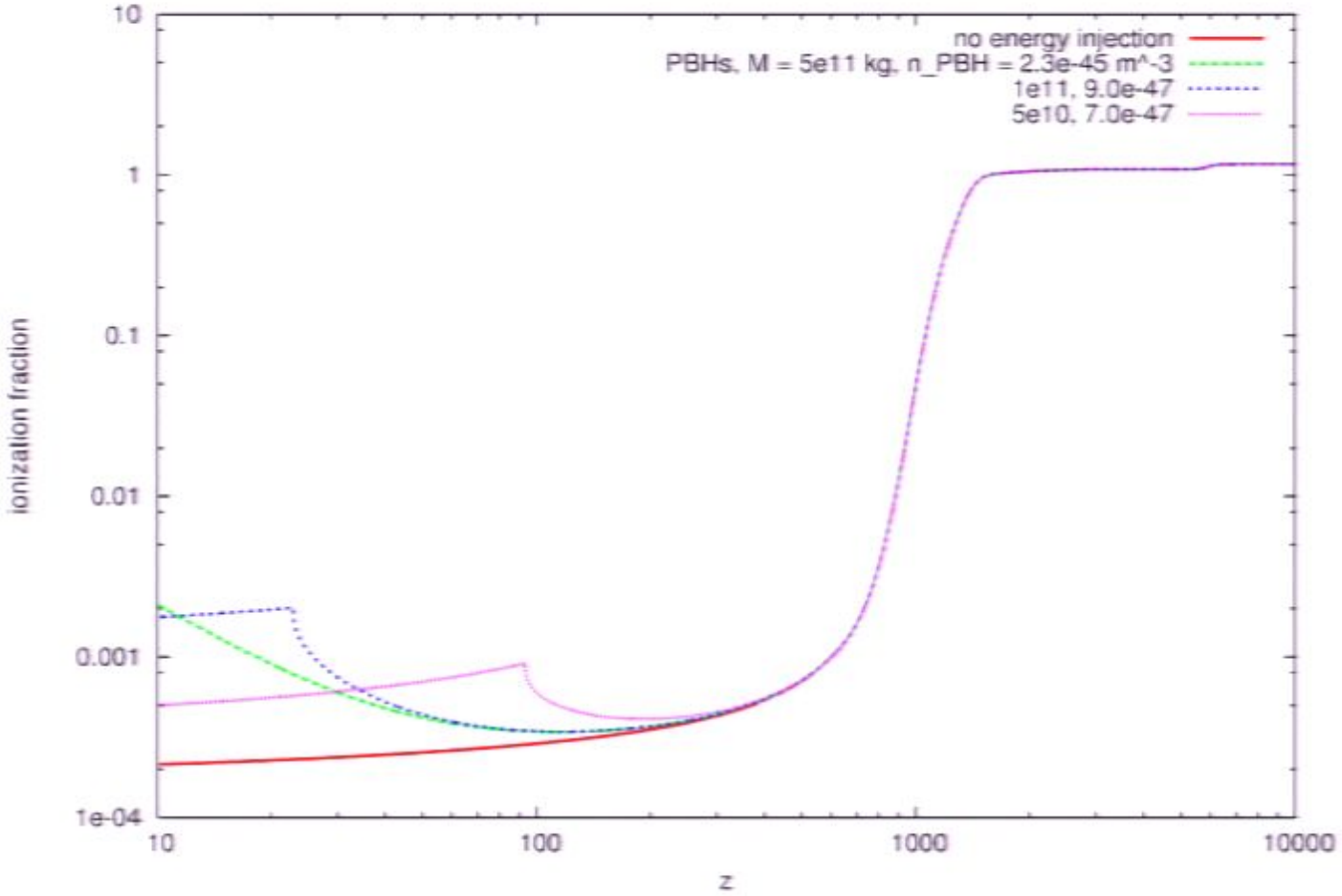
Results – ionization history

late-evaporating PBHs



Results – ionization history

early-evaporating PBHs



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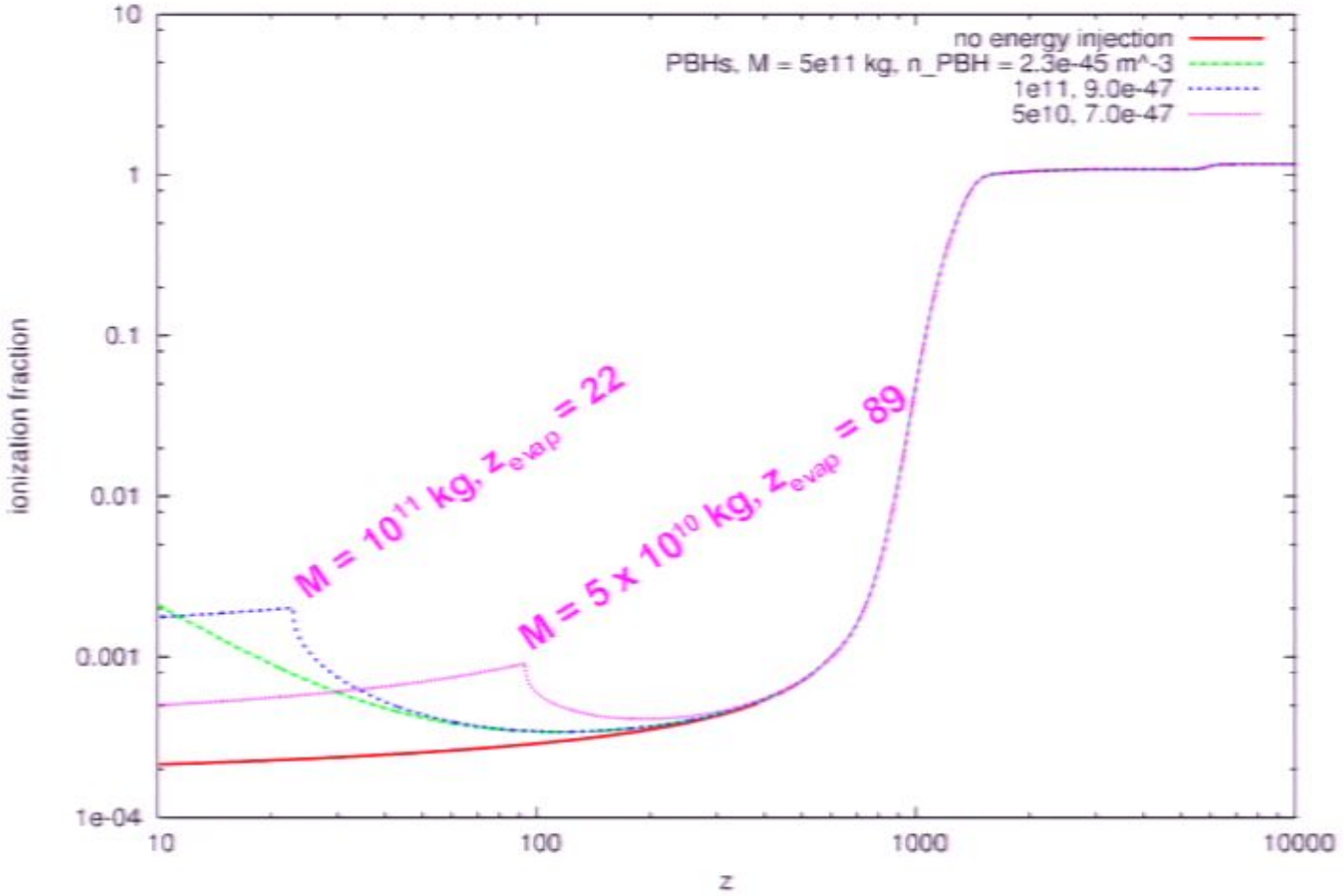
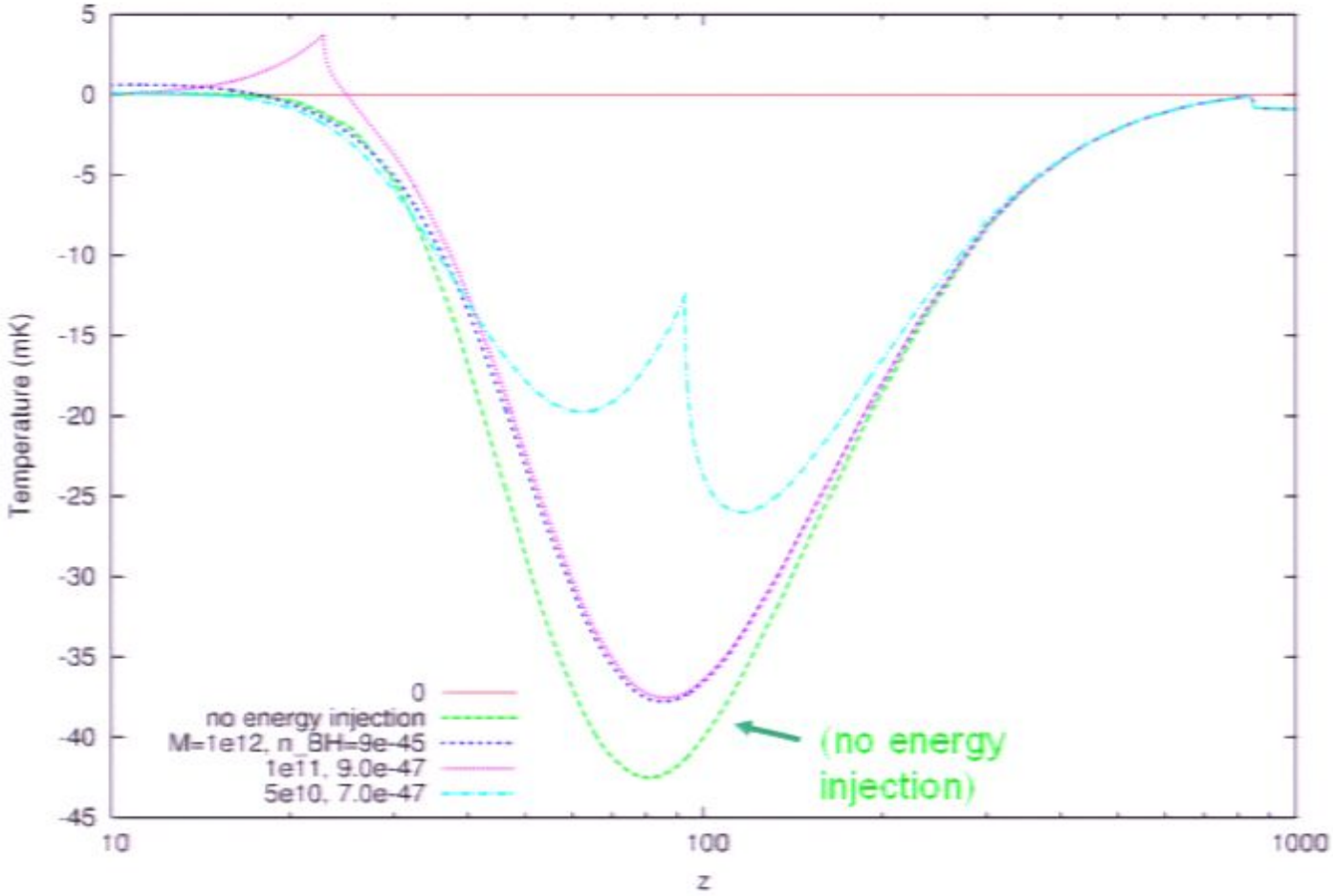


Results – brightness temperature



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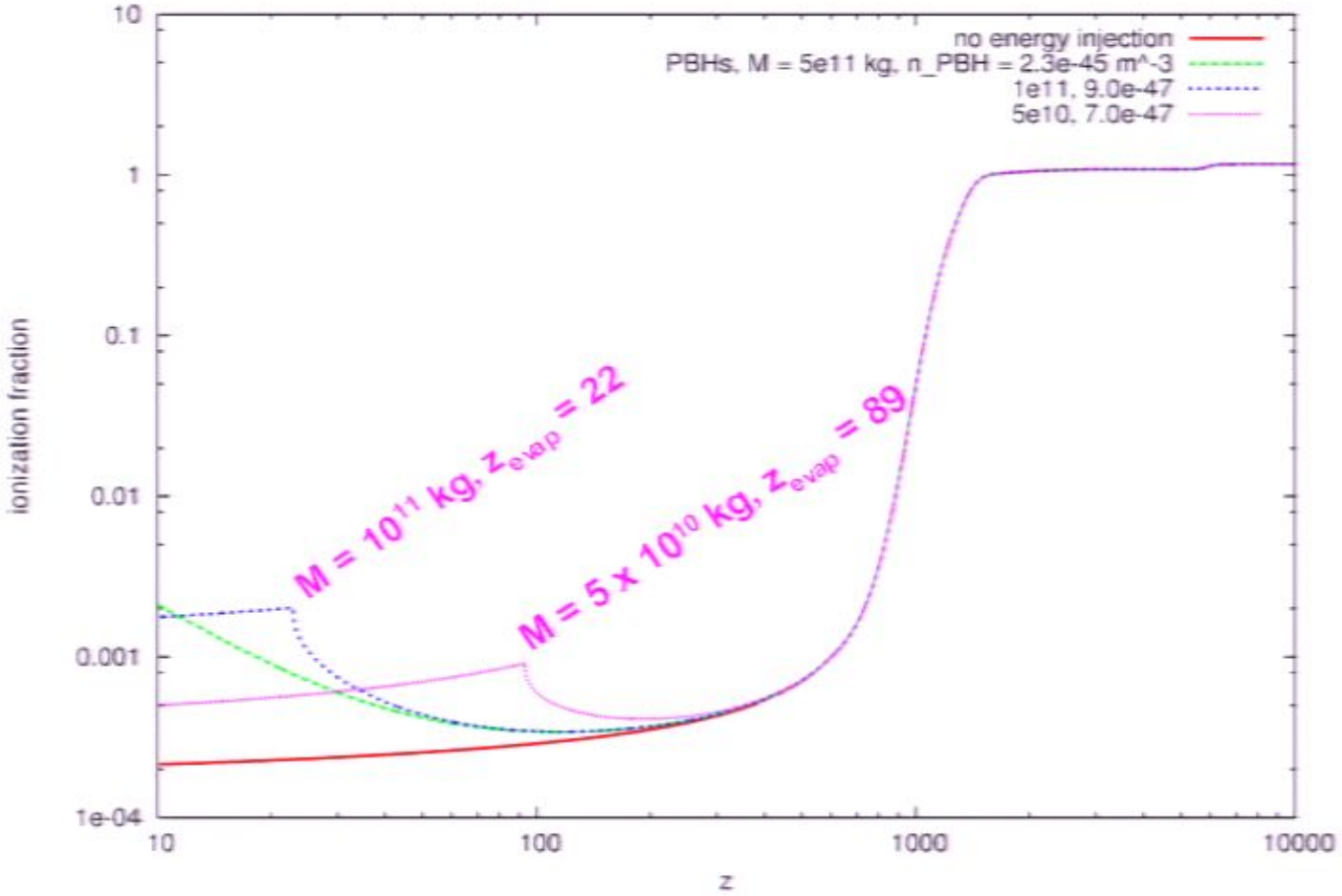

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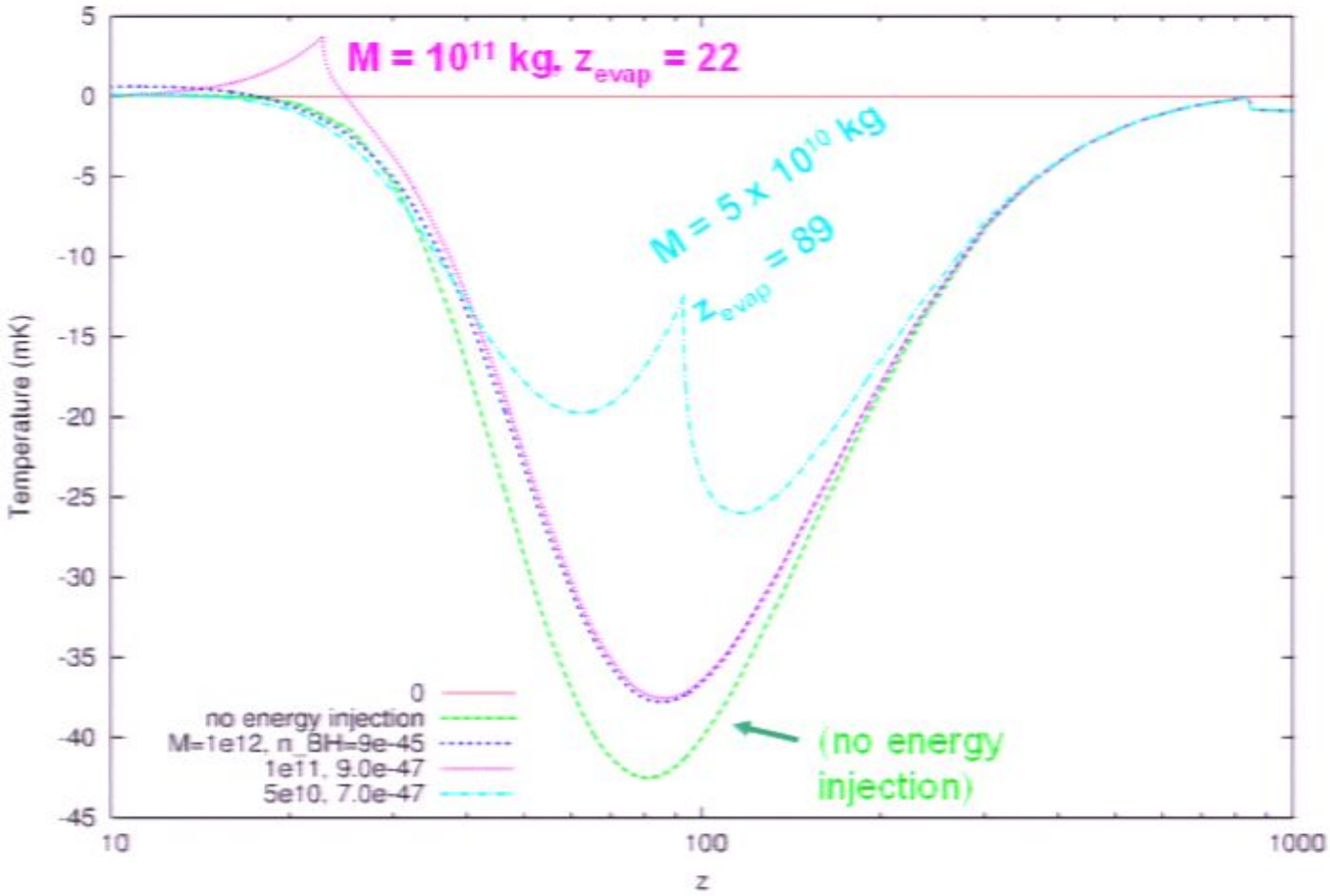
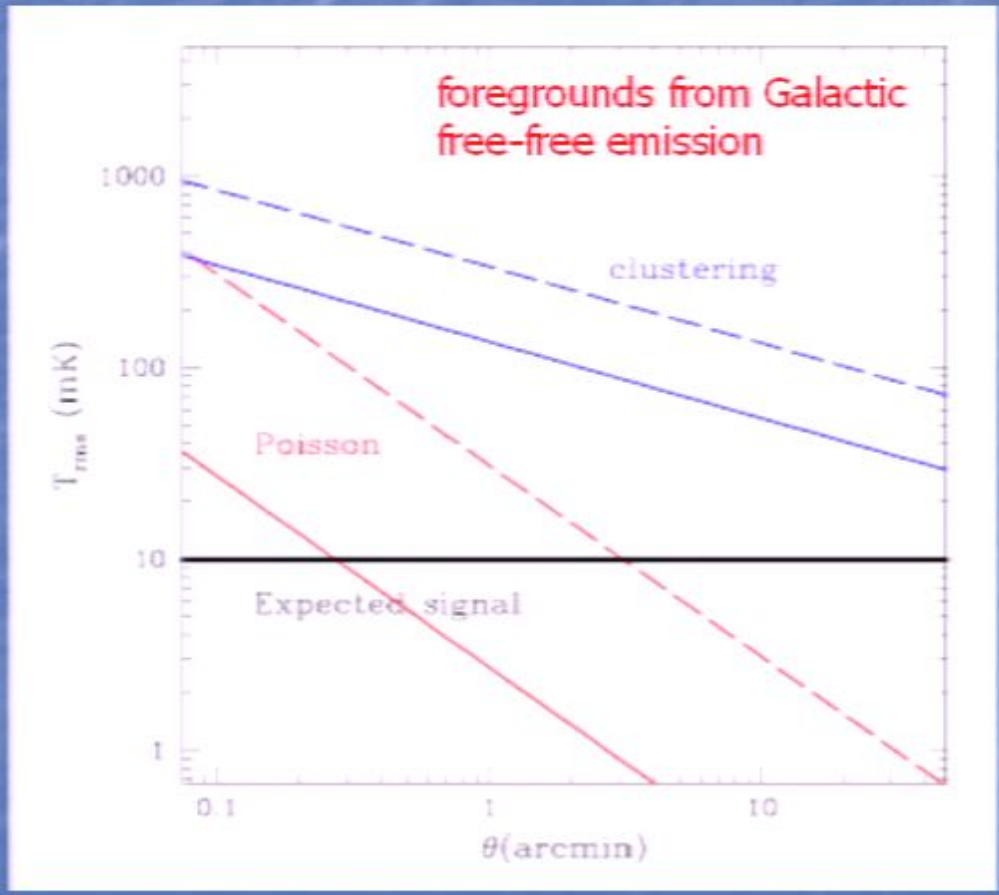


Foregrounds

- Main problem is foregrounds (galactic, extragalactic, terrestrial)
- Frequency information may help



Oh & Mack 2003

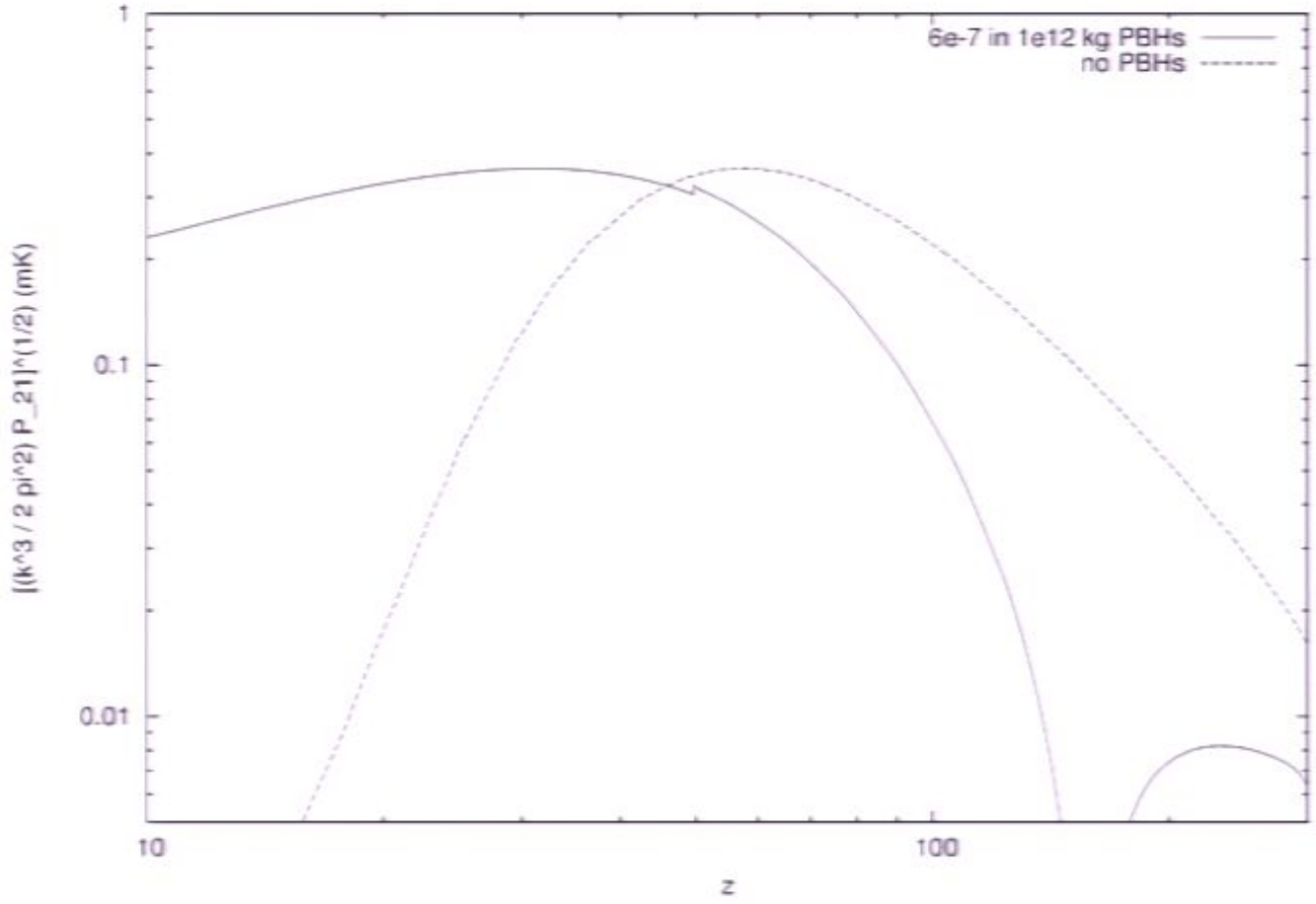
21cm power spectrum

- Foregrounds make 21cm fluctuation maps difficult to obtain
- Statistical detection (through the power spectrum) is more attainable

$$P_{21}(k,\mu) = \delta\bar{T}_b^2(\beta' + \mu^2)P_{\delta\delta}(k),$$

$$\sqrt{\frac{k^3\delta P_{21}}{2\pi^2}} \sim \frac{0.1\ \mathrm{mK}}{\epsilon^{1/4} f_{\mathrm{cov}}}\left(\frac{k}{0.04\ \mathrm{Mpc}^{-1}}\right)^{3/4}\left(\frac{T_{\mathrm{sky}}}{10^4\ \mathrm{K}}\frac{2\ \mathrm{km}}{R_{\mathrm{max}}}\right) \times \left(\frac{10\ \mathrm{MHz}}{B}\right)^{1/4}\left(\frac{1000\ \mathrm{hr}}{t_{\mathrm{int}}}\right)^{1/2}\left(\frac{1+z}{50}\right),$$

21cm power spectrum



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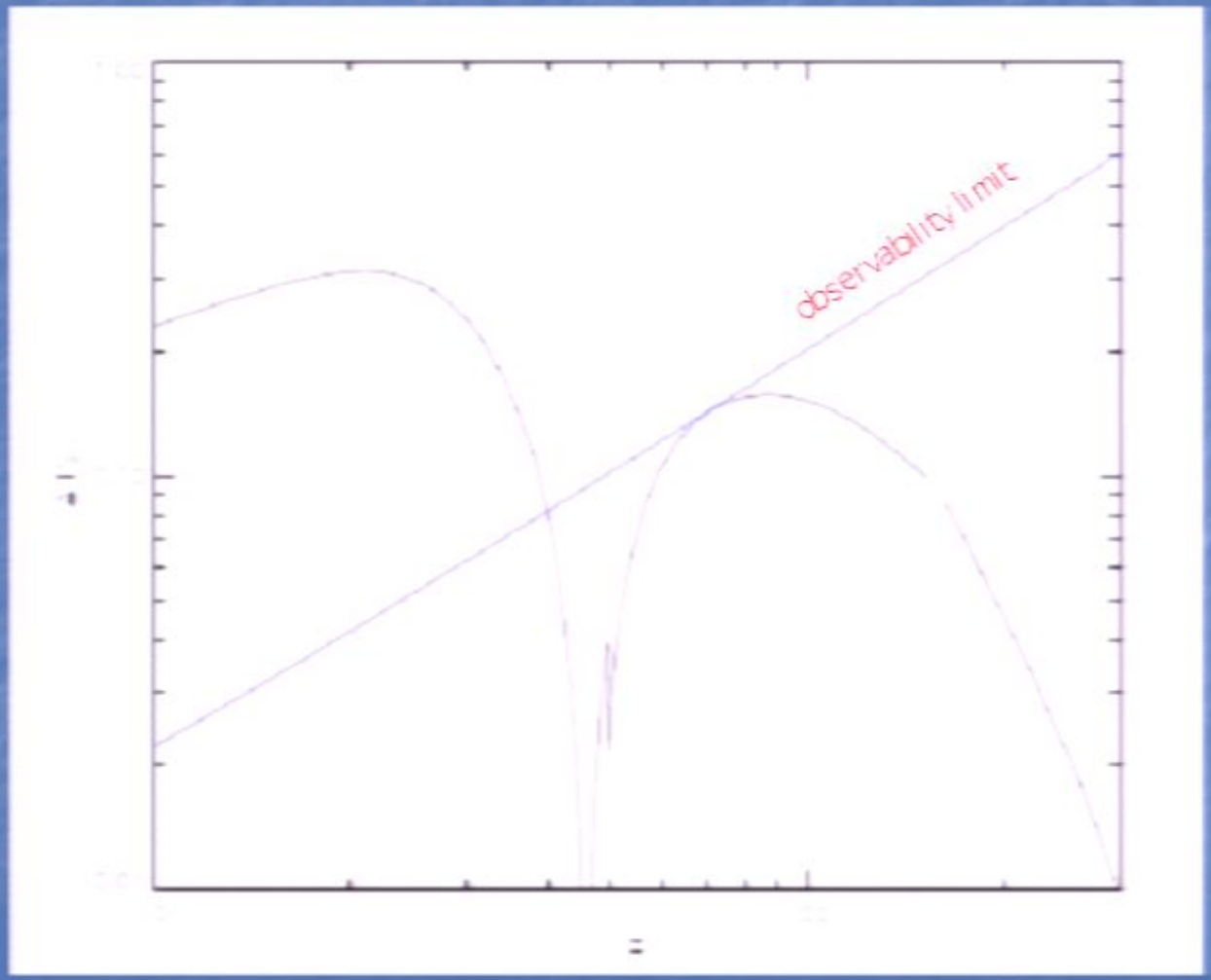
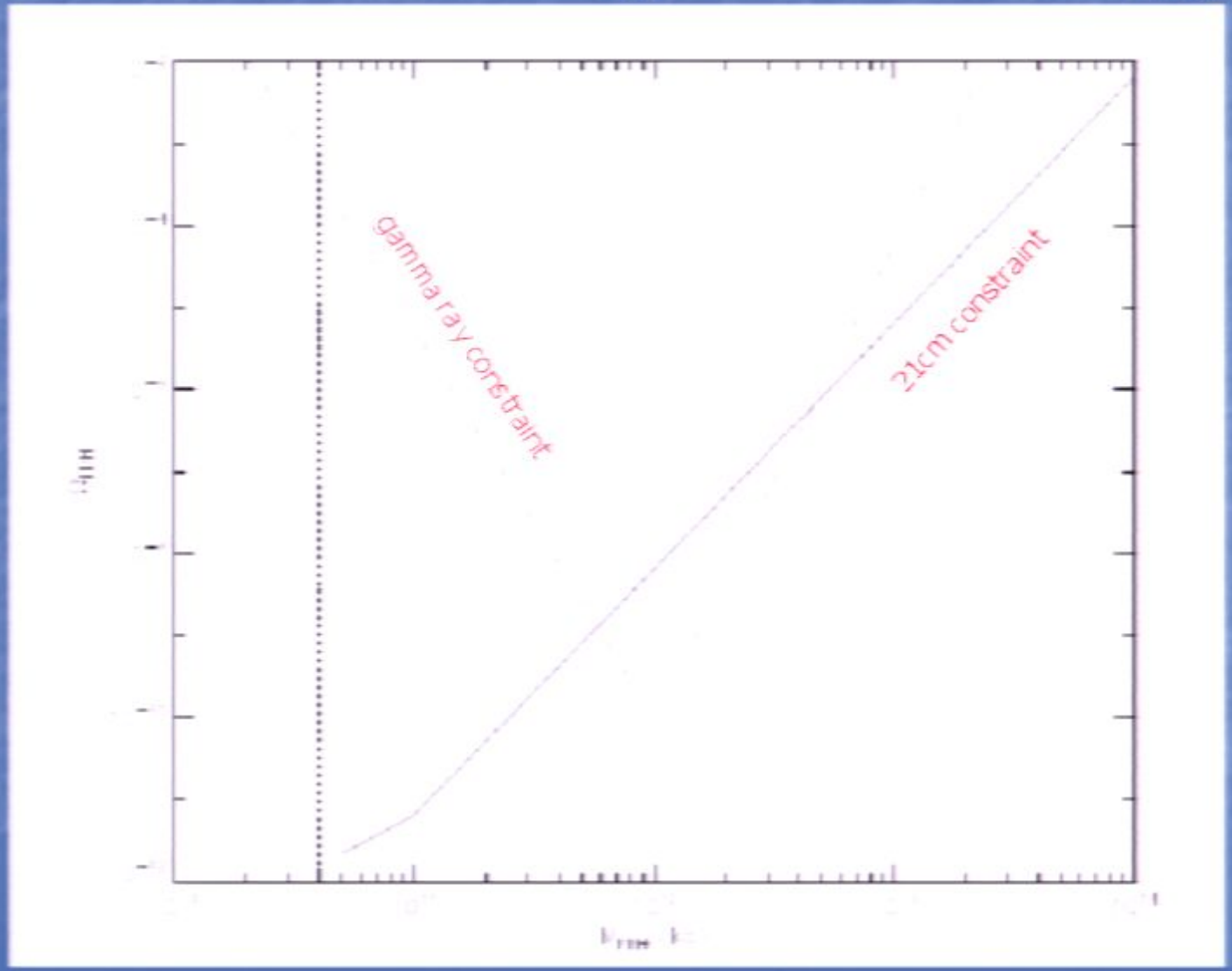
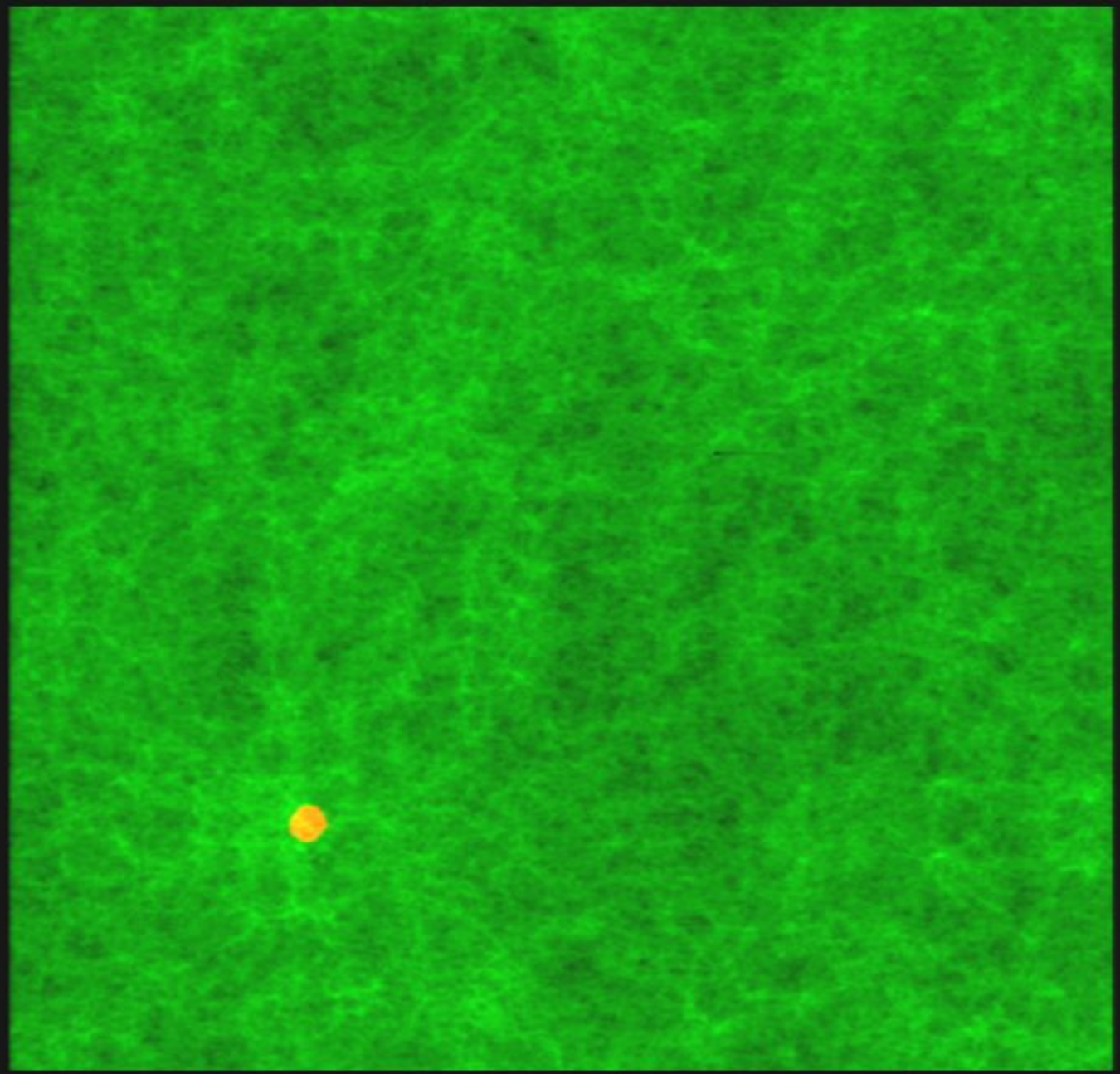


Constraints (preliminary)

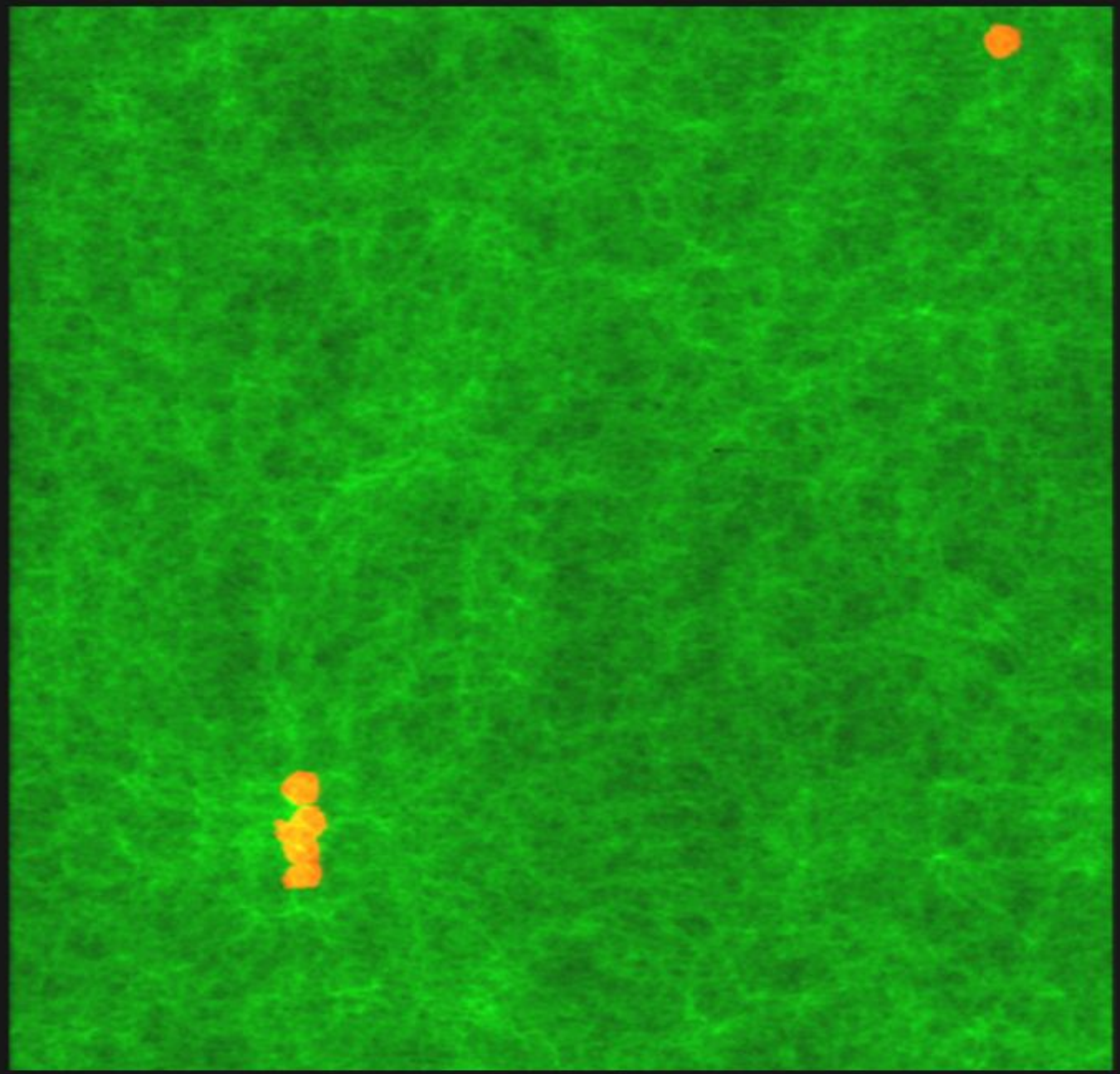


Conclusions & future work

- 21cm observations can detect exotic sources of energy injection in the dark ages
- Limits on PBH evaporation from 21cm can improve upon existing limits
- Future work:
  - Use 21cm for other exotic physics



35 h^{-1} Mpc (Iliev, Mellema, Shapiro & Pen 2007)



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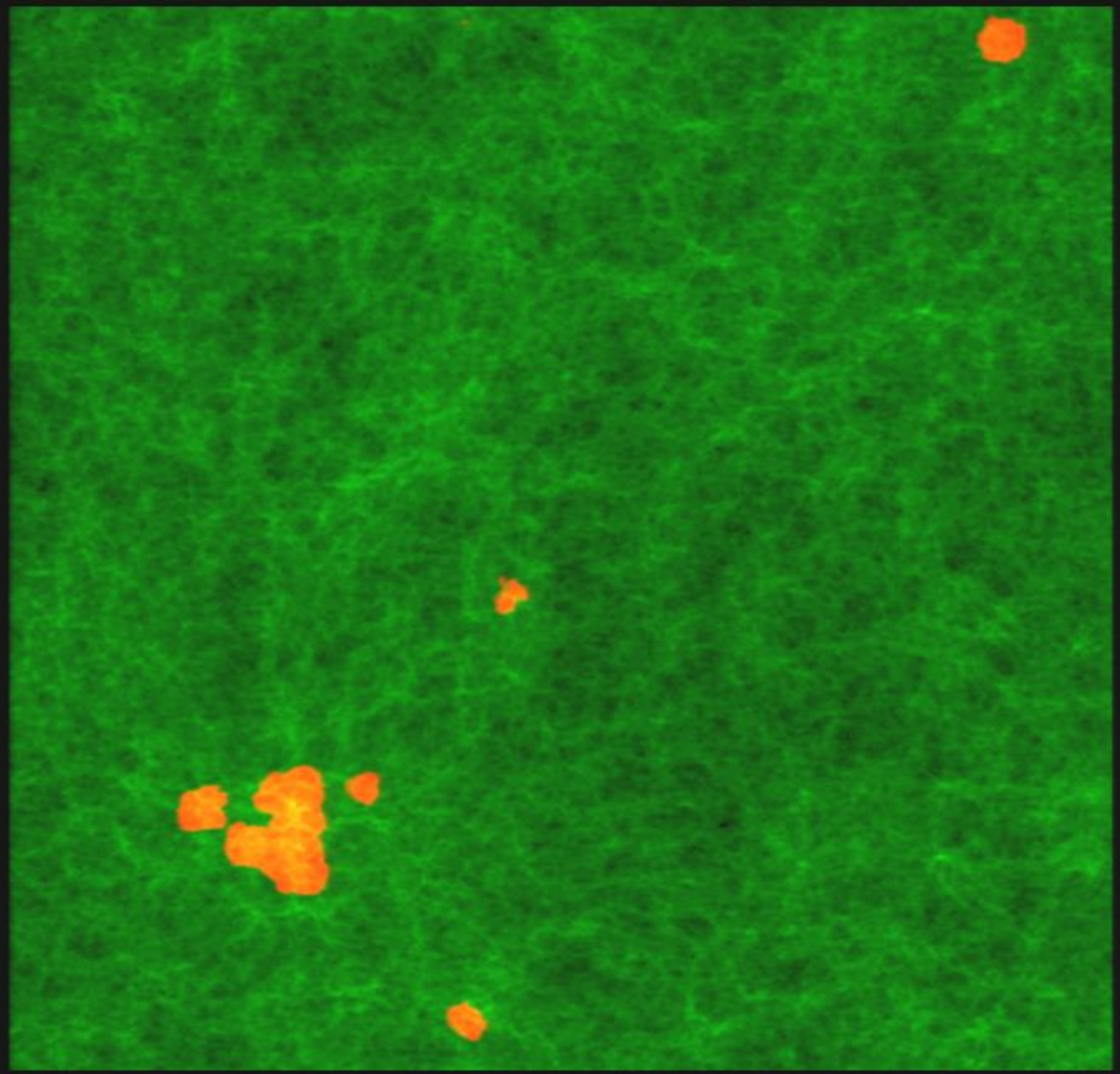

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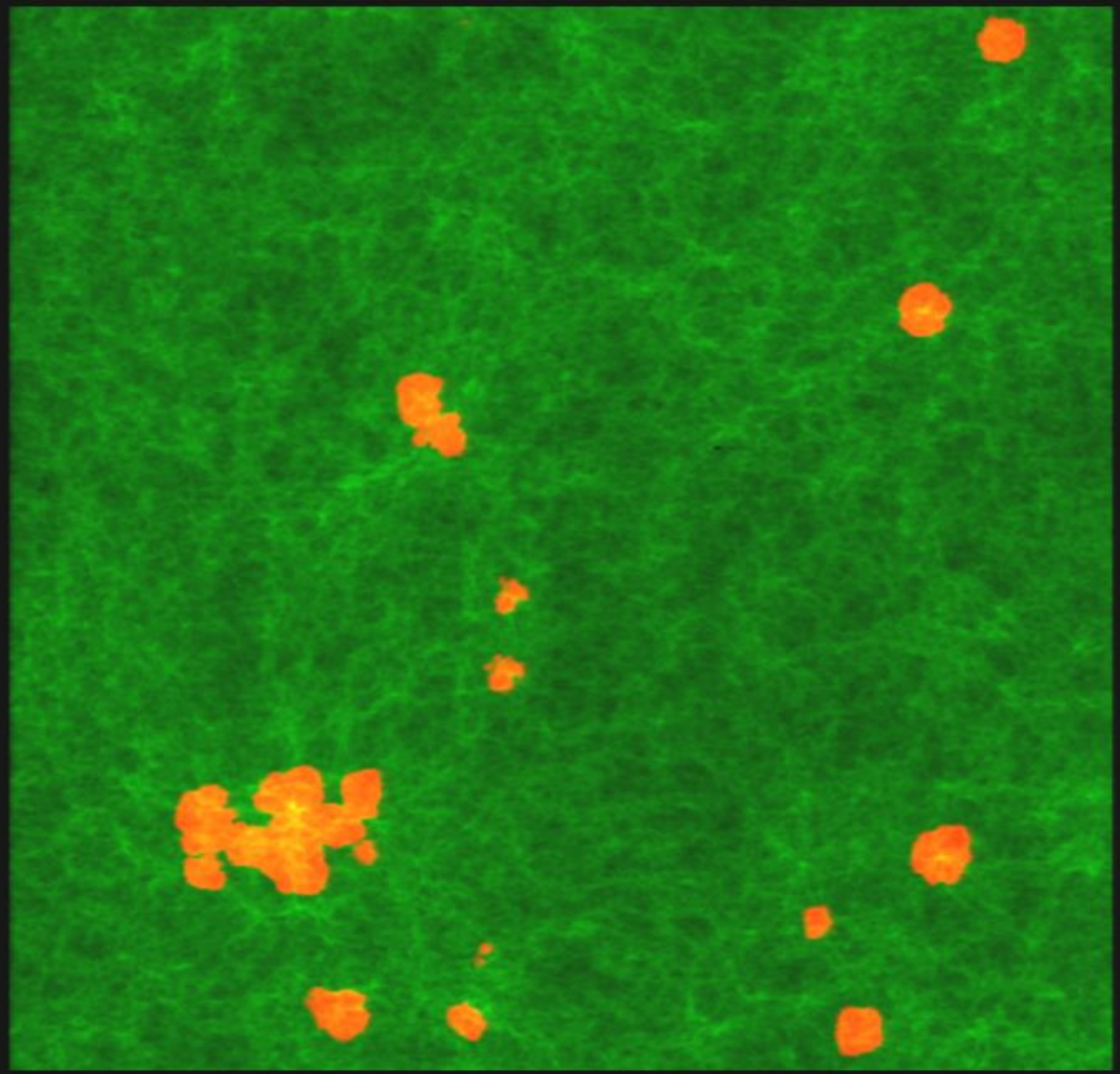

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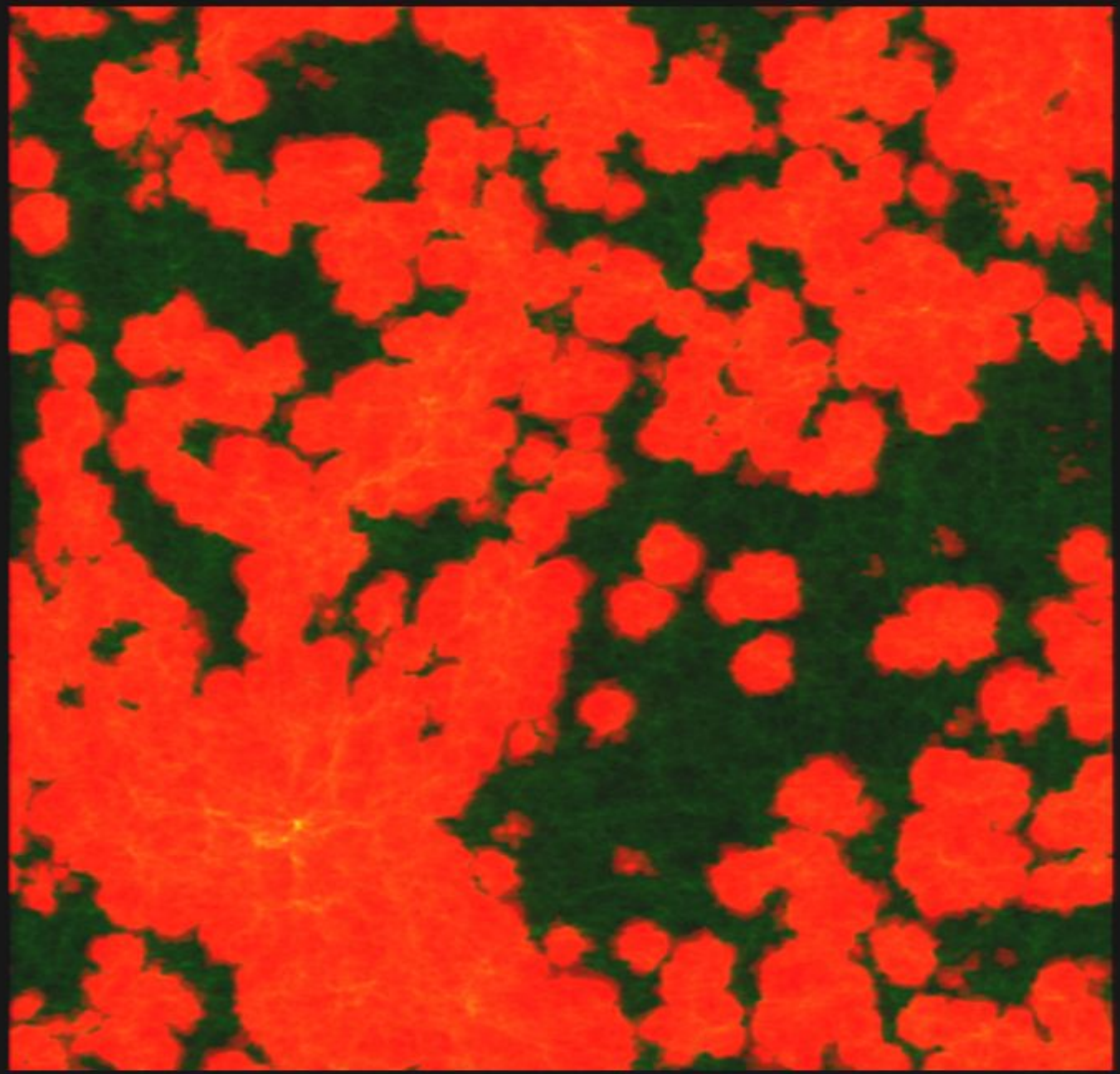

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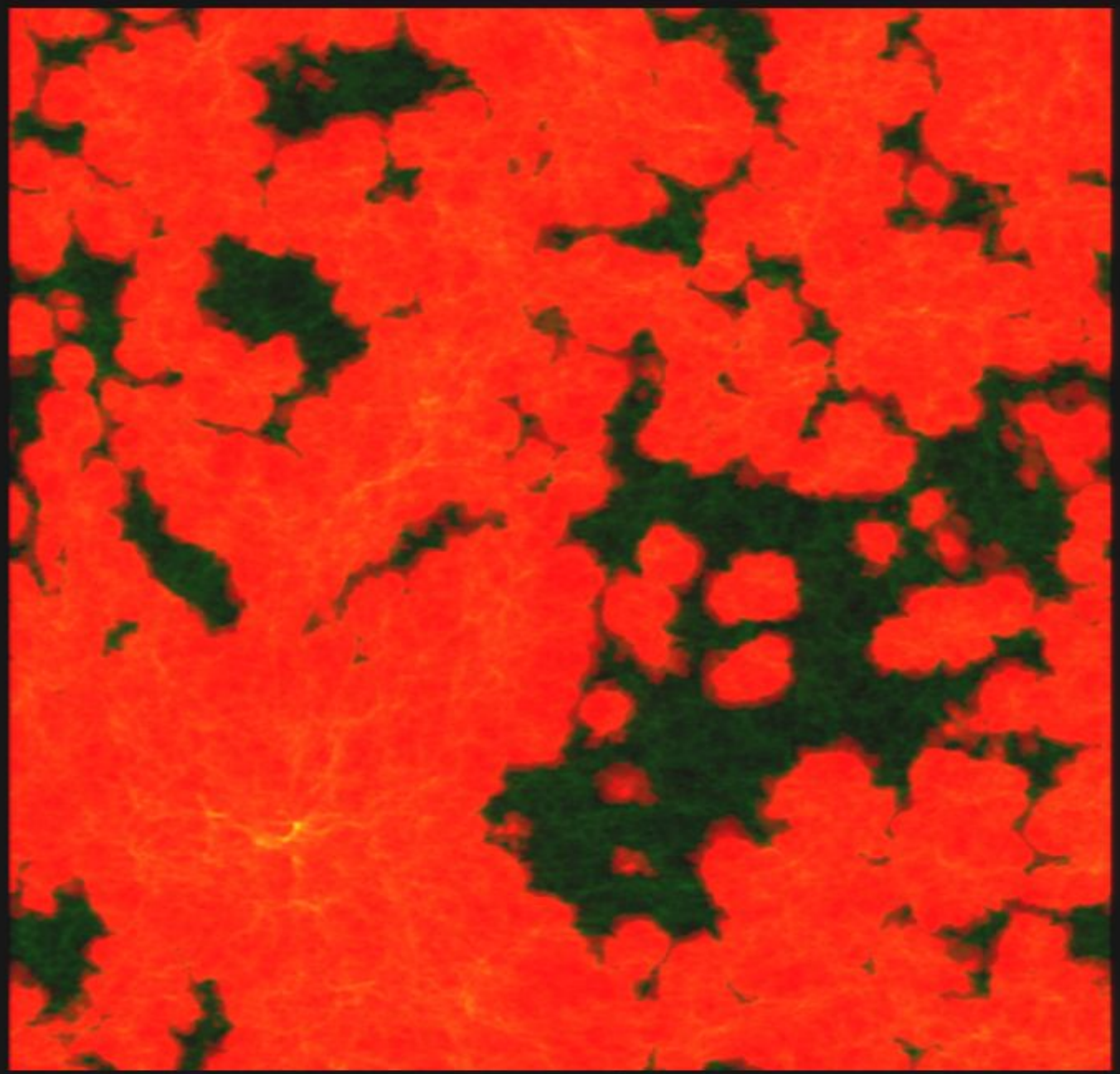
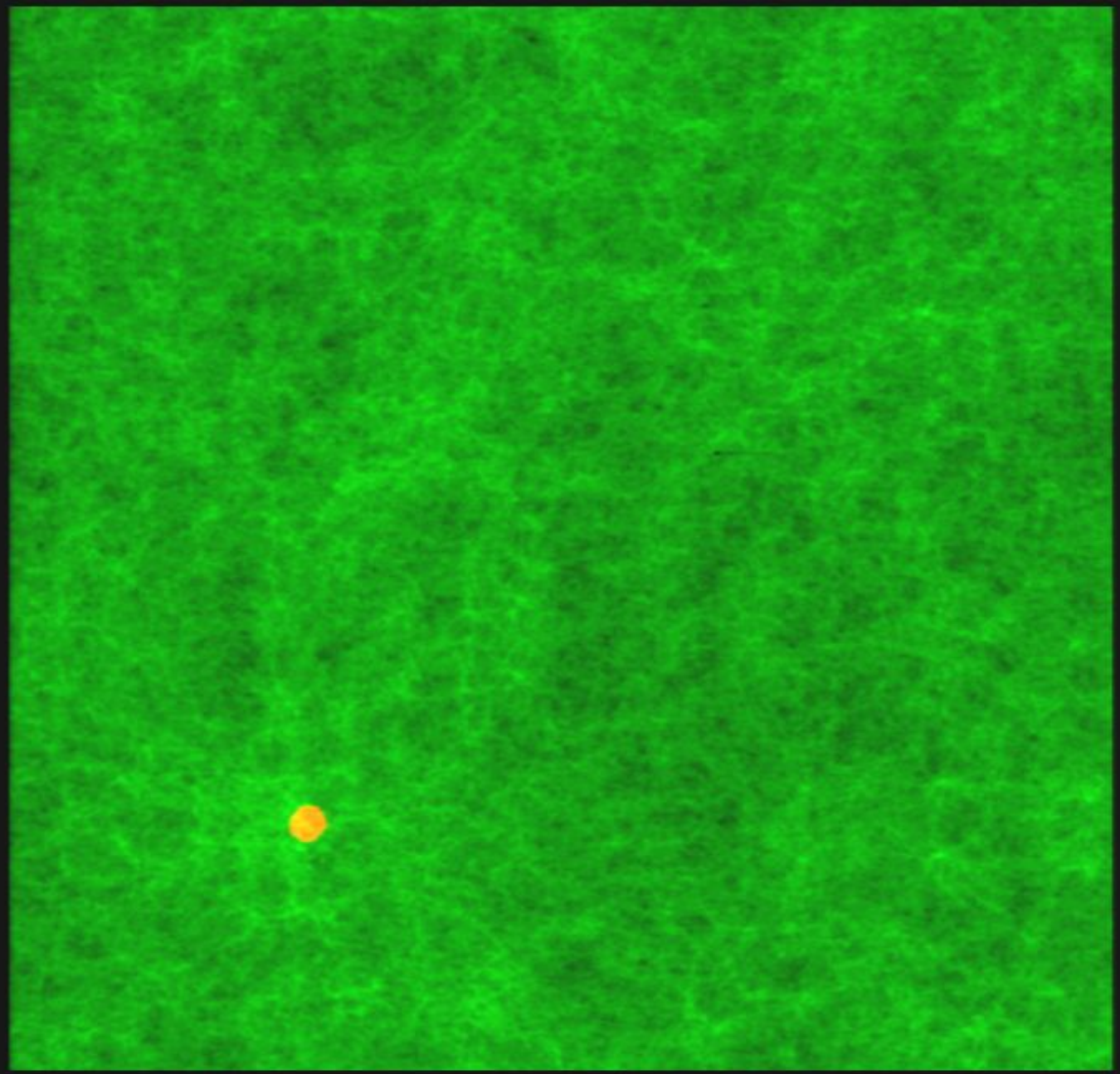
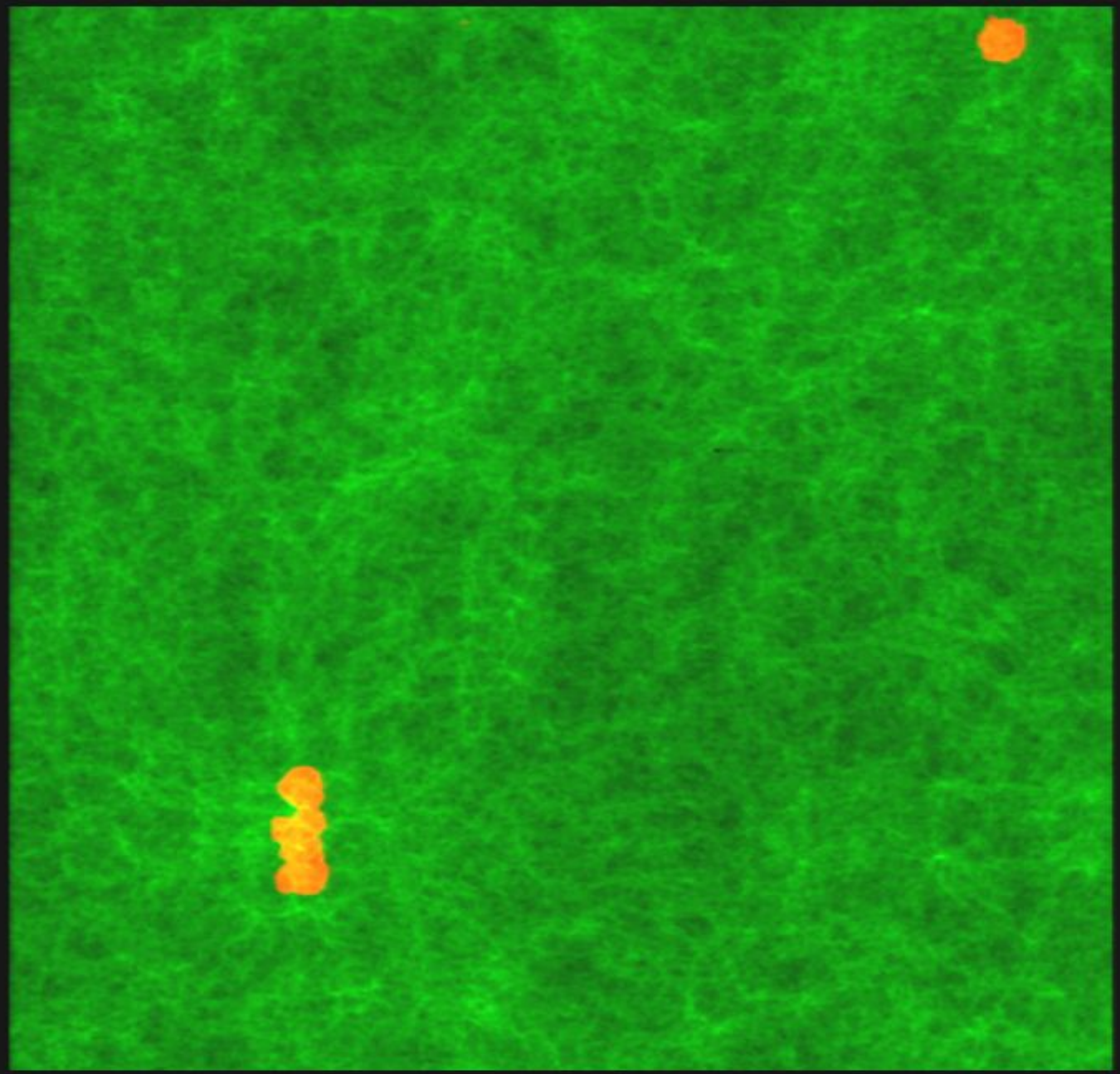


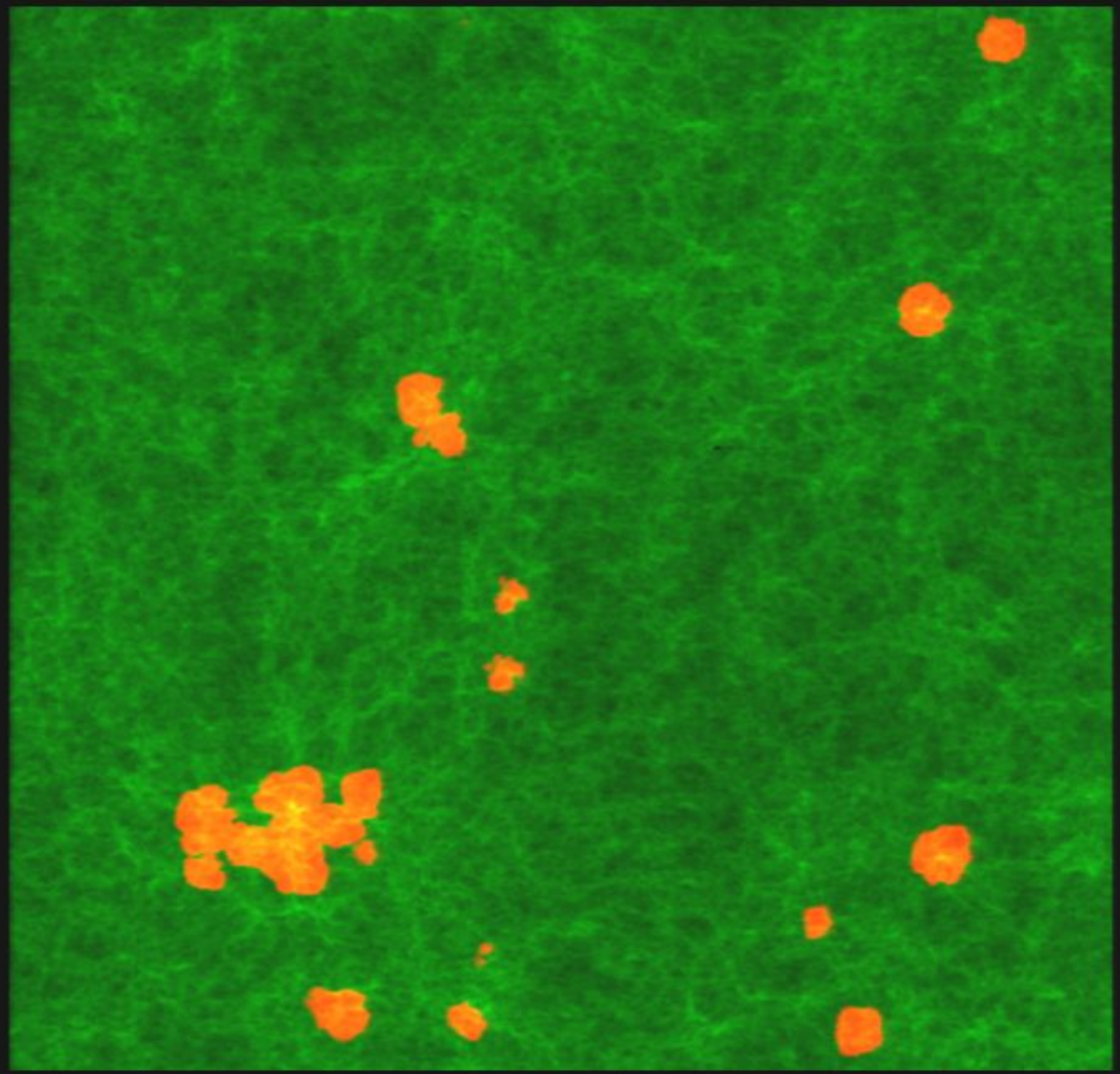
35 h^{-1} Mpc (Iliev, Mellema, Shapiro & Pen 2007)



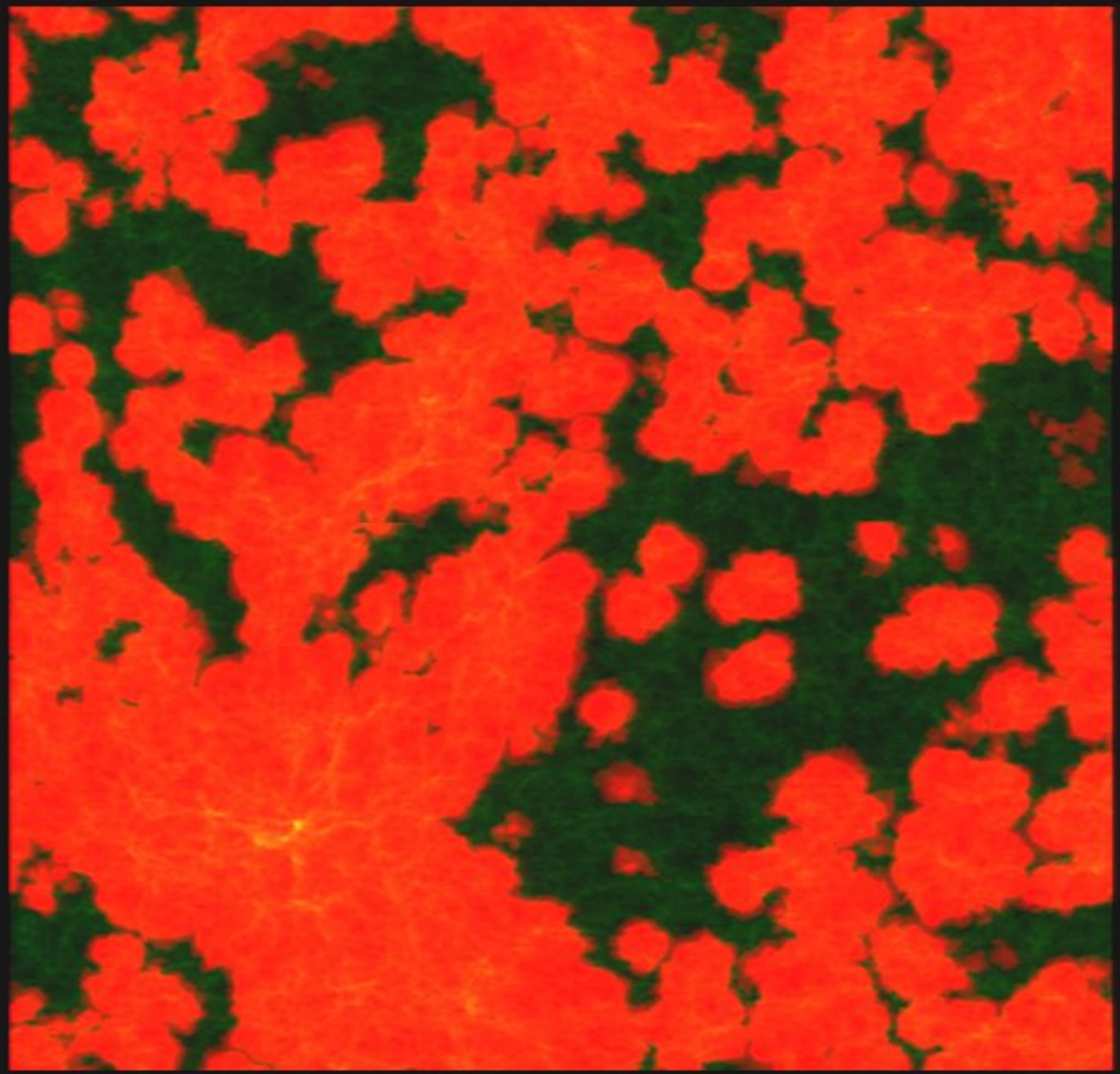
35 h^{-1} Mpc (Iliev, Mellema, Shapiro & Pen 2007)



35 h^{-1} Mpc (Iliev, Mellema, Shapiro & Pen 2007)



35 h^{-1} Mpc (Iliev, Mellema, Shapiro & Pen 2007)



35 h^{-1} Mpc (Iliev, Mellema, Shapiro & Pen 2007)