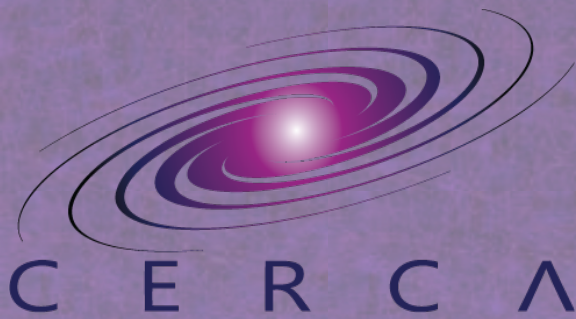


CMB SPECTRAL DISTORTIONS FROM COOLING MACROSCOPIC DARK MATTER

arXiv: 1804.08601

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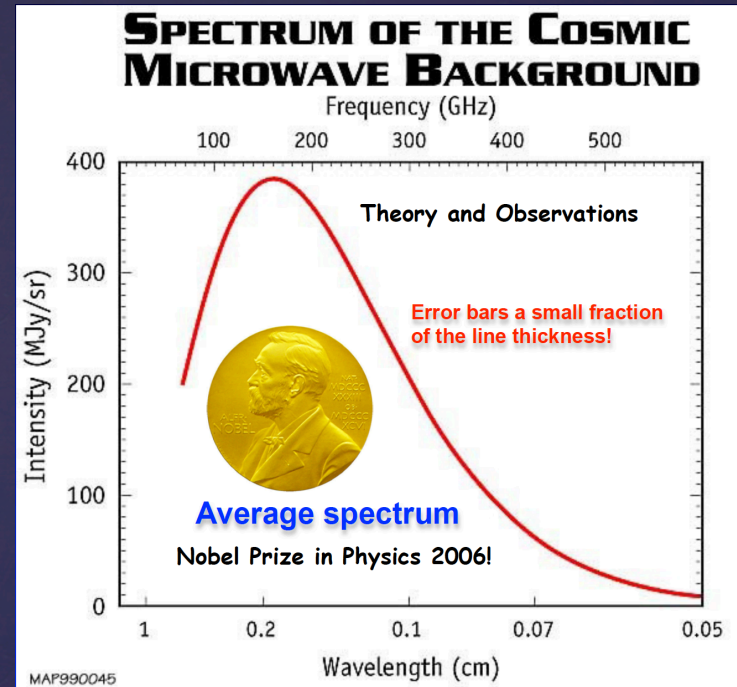
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OUTLINE

1. Introduction to CMB spectral distortions (SDs).
2. Energy release from Macro dark matter (DM).
3. Results & future work.

CURRENT UNDERSTANDING

- CMB is perfect blackbody (BB) (as measured by COBE-FIRAS), 1 part in 10^5 .
- Imperfect Thermodynamic Equilibrium \Rightarrow Distortions from BB.
- Proposed CMB Experiments:
 - PIXIE (NASA): 10^{-8} at 5σ .
 - PRISM (ESA): 10^{-9} .



$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/(k_B T)} - 1}$$

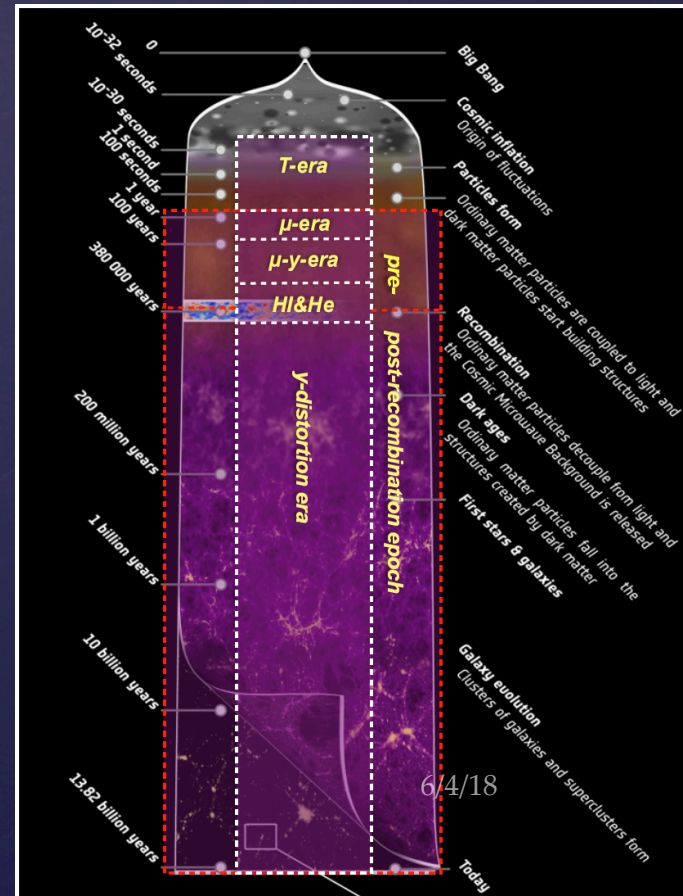
FUTURE GOALS

- **Expectations** (*Tashiro, PTEP 2014*)
 - Primordial Curvature Perturbations (Small Scale)
 - Non-Gaussianities
 - Recombination
 - Reionization & Structure Formation

- **Surprises** (*Tashiro, PTEP 2014*)
 - Primordial Magnetic Fields
 - Primordial Black Holes
 - Cosmic Strings

- **Dark Matter** (*Ali-Hamoud+, PRL 2015*)
(*SK, E. Dimastrogiovanni, G. Starkman, C. Copi, B. Lynn, 1804.08601*)

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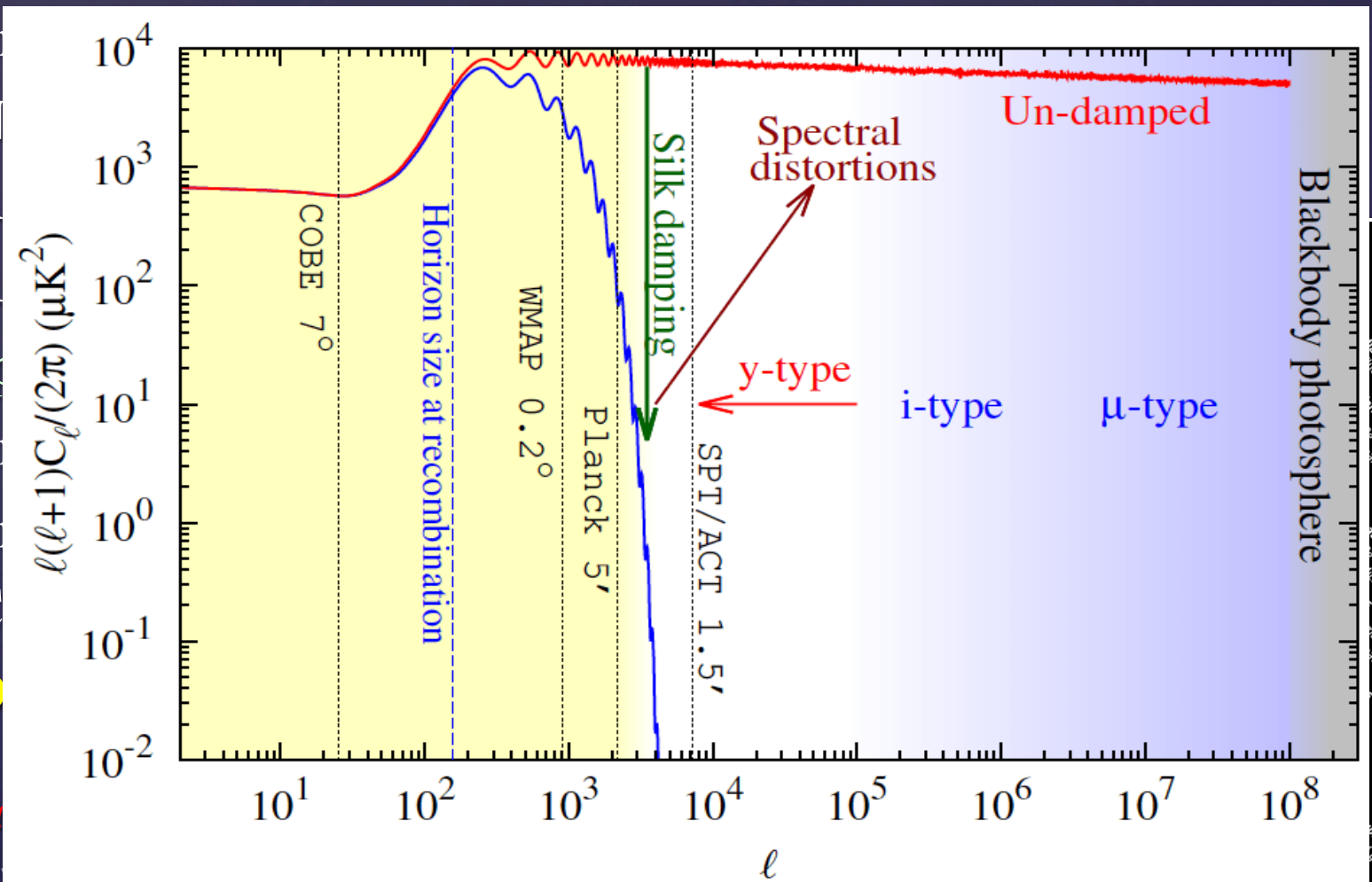


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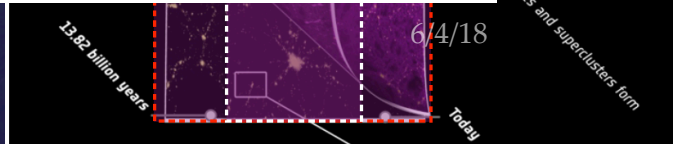
FUTURE GOALS

- Expectations (*Tashiro, PTEP 2014*)

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atter particles are coupled to light and
particles start building structures
ion
matter particles decouple from light and
Background is released
ion
matter particles fall into the
6 galaxies
olution
galaxies and superclusters form
Today



THERMAL ENVIRONMENT OF THE EARLY UNIVERSE

(Tashiro PTEP 2014, Chluba CUSO Lectures 2014)

- Energy Injection/Absorption Mechanisms
 - Blackbody mixing
 - Adiabatic Cooling of Baryonic Plasma
- Scattering/Thermalization Mechanisms
 - Compton Scattering (Energy Redistribution): $e(p) + \gamma(k) \leftrightarrow e(p') + \gamma(k')$
 - Double Compton Scattering (Photon Addition/Subtraction):
$$e(p) + \gamma(k) \leftrightarrow e(p') + \gamma(k') + \gamma(k_2)$$
 - Bremsstrahlung (Photon Addition/Subtraction): $e(p) + H^+(h) \leftrightarrow e(p') + H^+(h') + \gamma(k)$

TYPES OF DISTORTIONS

- μ

- High frequencies.

- $f_{\text{PI}} = \frac{1}{e^x - 1} \rightarrow \frac{1}{e^{x+\mu(x)} - 1}$ $\mu = \text{Chemical Potential}$

- y

- $y = \text{Compton parameter, } y = \int dt x_e n_e \sigma_T \frac{T_e}{m_e}$

$$\delta f = f_{\text{BB}} y \frac{x e^x}{e^x - 1} \left[x \left(\frac{e^x + 1}{e^x - 1} - 4 \right) \right] \quad x = \frac{h\nu}{kT_e}$$

EPOCHS OF DISTORTIONS

(Khatri & Sunyaev, JCAP 2012, Fig. 1)

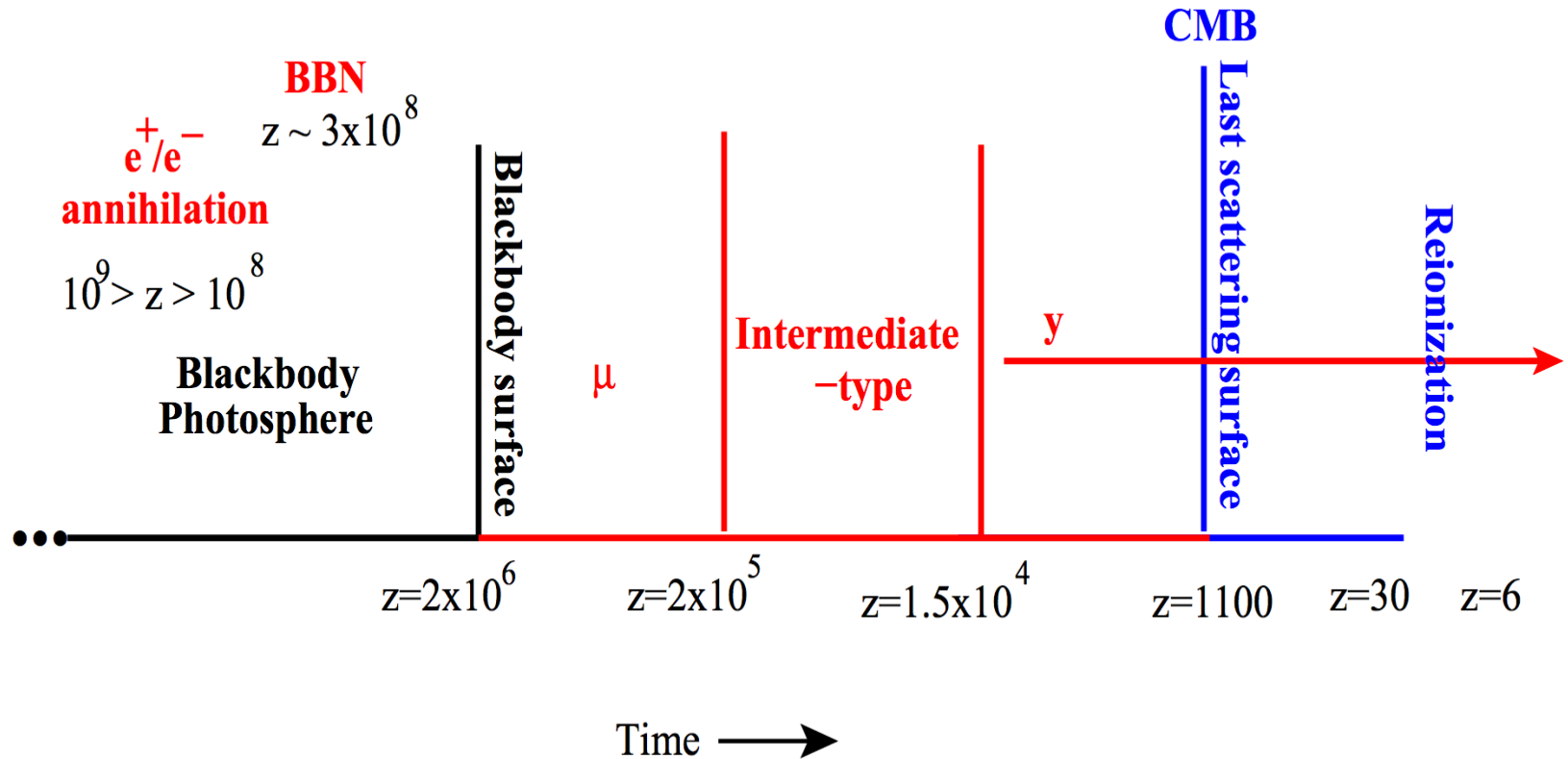


Figure 1. Important epochs related to the creation and evolution of the CMB spectrum.

ANALYTICAL FORMULAS FOR SDs

(Chluba, MNRAS 2013)

$$\mu \approx 1.4 \int \mathcal{J}_{\text{bb}} \mathcal{J}_{\mu} \frac{1}{c^2 \rho_{\gamma}} \frac{dQ}{dt} dt$$

$$y \approx \frac{1}{4} \int \mathcal{J}_{\text{bb}} \mathcal{J}_y \frac{1}{c^2 \rho_{\gamma}} \frac{dQ}{dt} dt$$

$$\mathcal{J}_{\text{bb}}(z) = \exp \left[-(z/z_{\mu})^{5/2} \right]$$

$$\mathcal{J}_y(z) = \left[1 + \left(\frac{1+z}{6.0 \times 10^4} \right)^{2.58} \right]^{-1}$$

$$\mathcal{J}_{\mu}(z) \approx 1 - \mathcal{J}_y(z)$$

$$z_{\mu} = 2 \times 10^6$$

CMB SDs FROM COOLING MACROSCOPIC DM: I. FRAMEWORK

MACRO DM: VIABILITY?

- Leading DM candidate, WIMP, hasn't been detected yet.
- WIMPs plausibly arise from Supersymmetry, absent in LHC.
- Macros behave as Cold DM (CDM) and no new elementary particles are required.

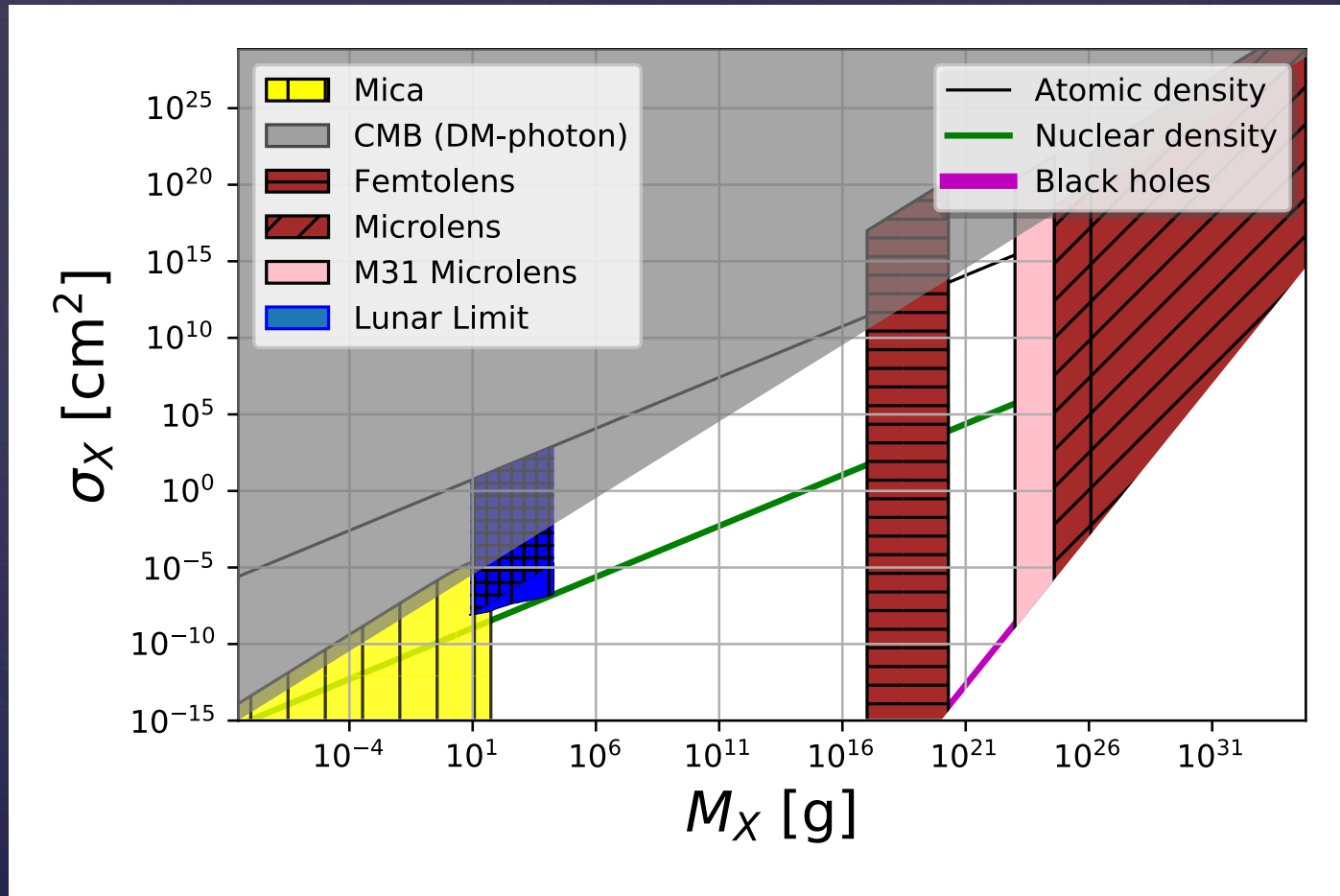
WEAKLY INTERACTING?

(Jacobs+, MNRAS 2015)

- Interaction/collision Frequency, $\Gamma = \sigma_x v n_x$
- Conventional DM: σ_x is small \Rightarrow DM-Baryons interact weakly.
- Macro DM: $n_x = \rho_x / M_x$: M_x is large & σ_x / M_x is small \Rightarrow DM-Baryons interact weakly!

MACRO DM: ALLOWED PARAMETER SPACE

(Jacobs+, MNRAS 2015, Fig. 3)



MACRO DM COOLING: BASIC PRINCIPLES

- DM formed Macros at t_{QCD} ($z \sim 10^{12}$), with $T = 3 \times 10^{12}$ K.
- Macros \sim Nuclear Density, $\rho_{\text{N}} = 2.8 \times 10^{14}$ g cm $^{-3}$.
- Neutron Stars (NS) serve as proxy for macros.
 - We will borrow NS cooling mechanisms.
- NS have:
 - Degenerate, isothermal core: npe plasma.
 - Non-degenerate atmosphere: insulates the hot interior.
- *Assumption: Thermal Equilibrium with CNB until $T = 10^9$ K.*

COOLING MECHANISMS:

1. ν EMISSION:

- Direct URCA:



- Most luminous/rapid cooling process. *(Lattimer+, PRL 1991)*
- Dominates at high temperatures.
- *Requires a critical proton fraction, $n_c \approx 1/9$.*

- Modified URCA:



- Slow process. *(Friman+, ApJ 1979)*
- Dominates at high temperatures.

- Cooper Pair Formation:



- Rapid but transient process. *(Yakovlev+, Astron. Astrophys 1999)*
- Dominates at high temperatures.
- Slows down MURCA & DURCA.

COOLING MECHANISMS:

2. γ EMISSION

(Shapiro & Teukolsky, Wiley-Interscience 1983)

- Surface emission.
- Slow process.
- Dominates at low temperatures.

ENERGY INJECTION IN CMB

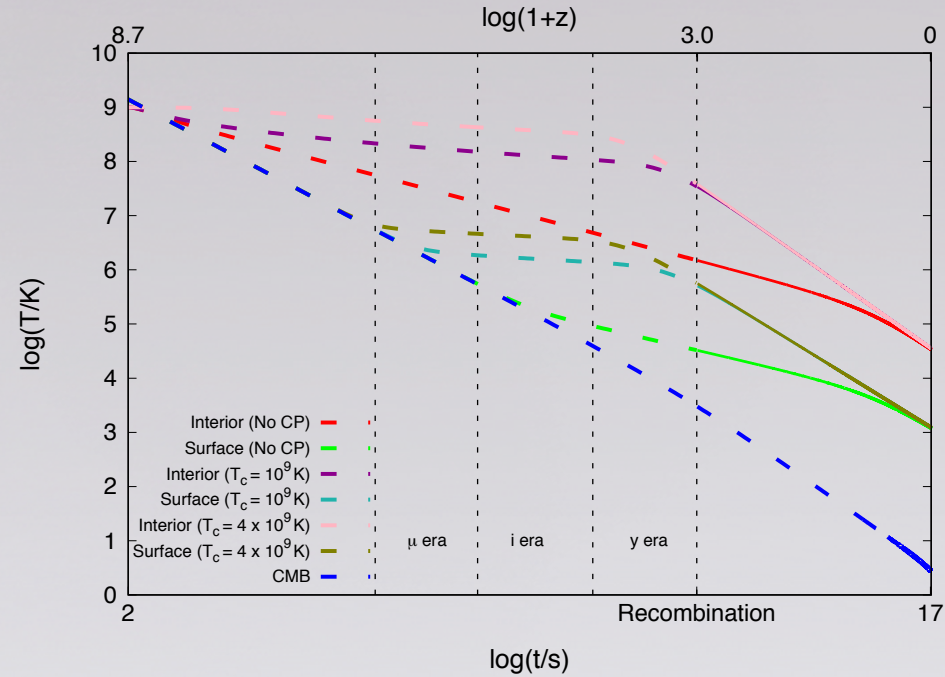
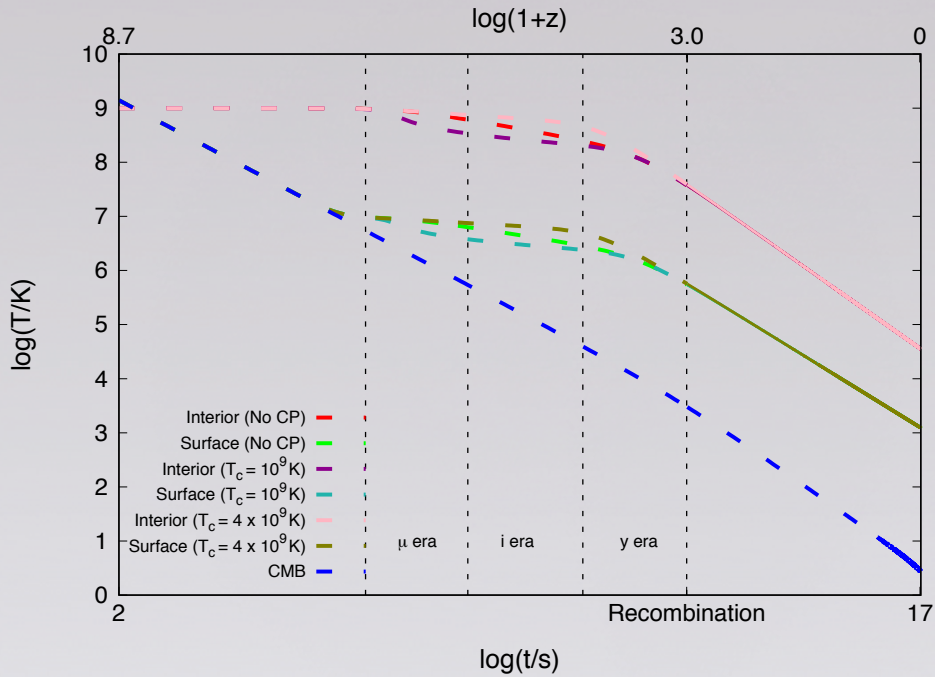
- Early degenerate phase: Macro interior cools through ν emission.
- At lower temperature: Macro cools through γ emission.
- During both the phases above, we calculate rate of γ energy emitted by the surface, L_γ .

FREE PARAMETERS

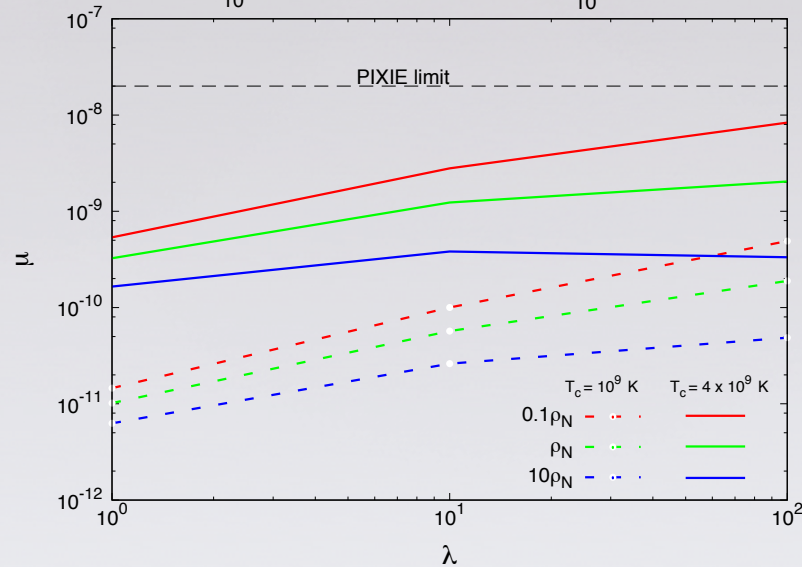
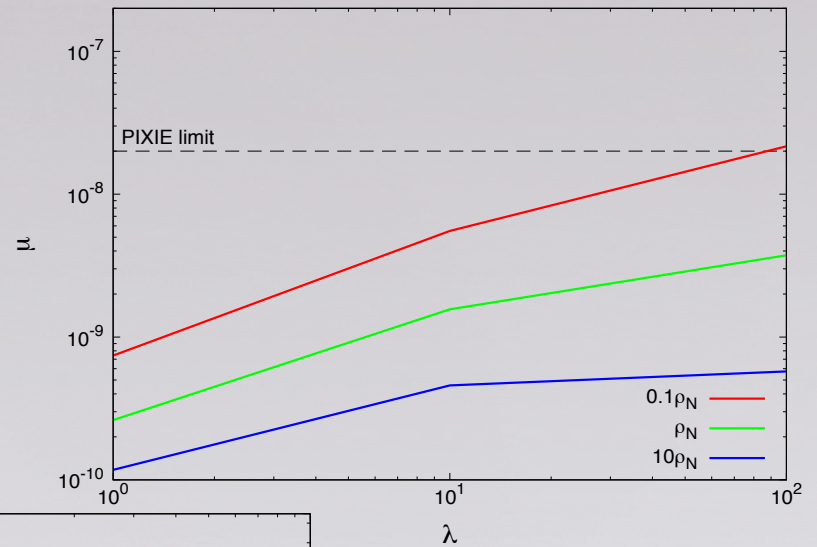
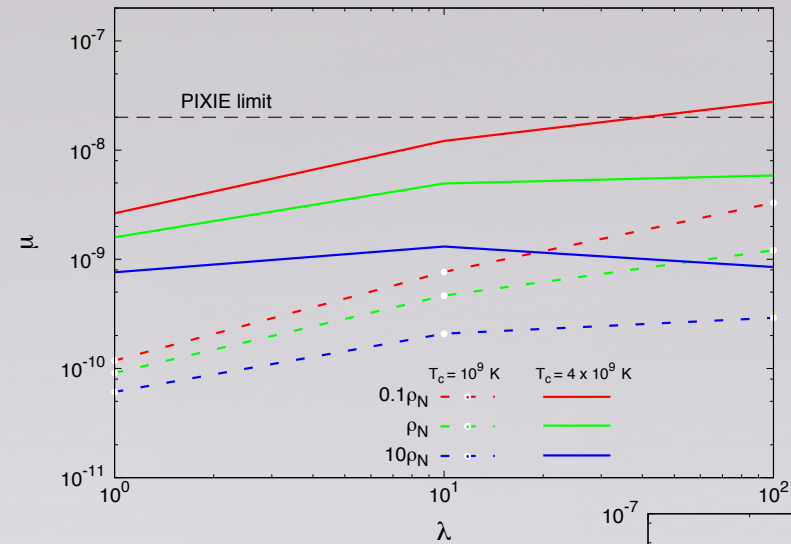
- $0.1\rho_N \leq \rho \leq 10\rho_N$
- Surface/atmospheric composition, λ
 - Metallic: $\lambda \approx 0.9$, opaque.
 - H/He: $\lambda \gg 1$, transparent.

CMB SDs FROM COOLING MACROSCOPIC DM: II. RESULTS

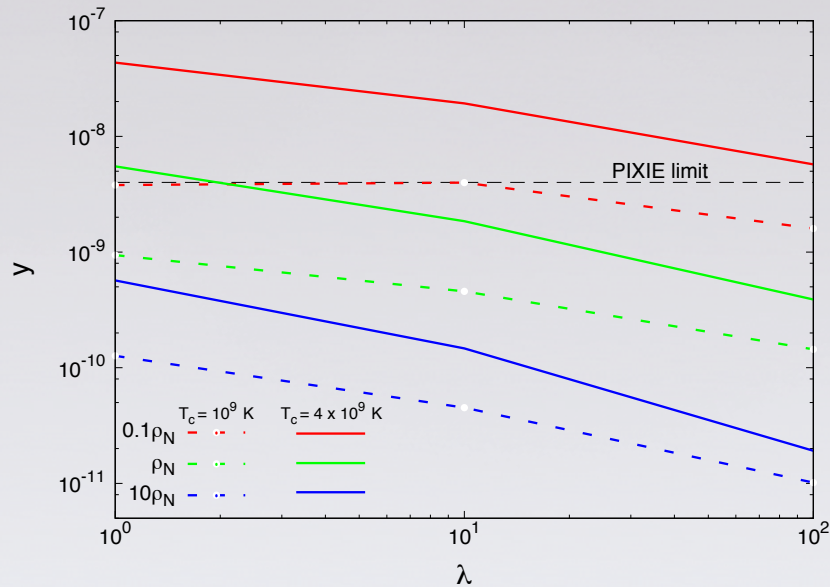
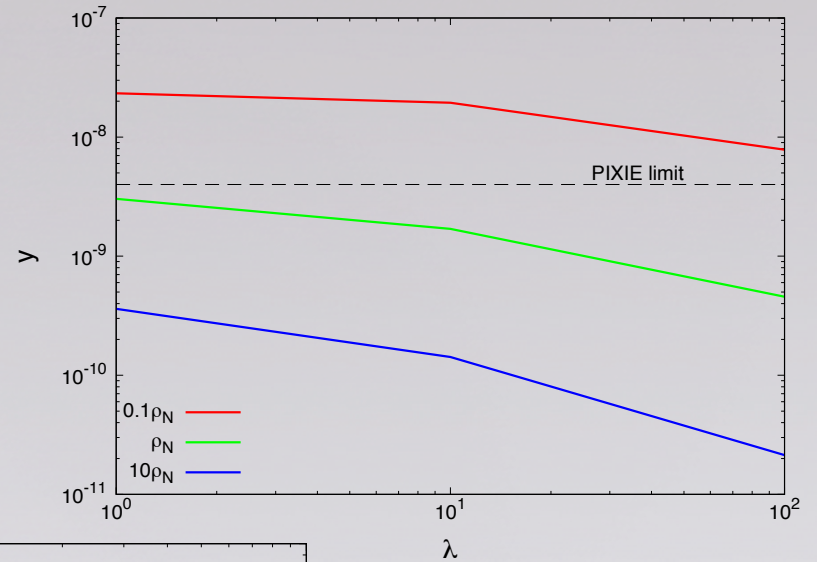
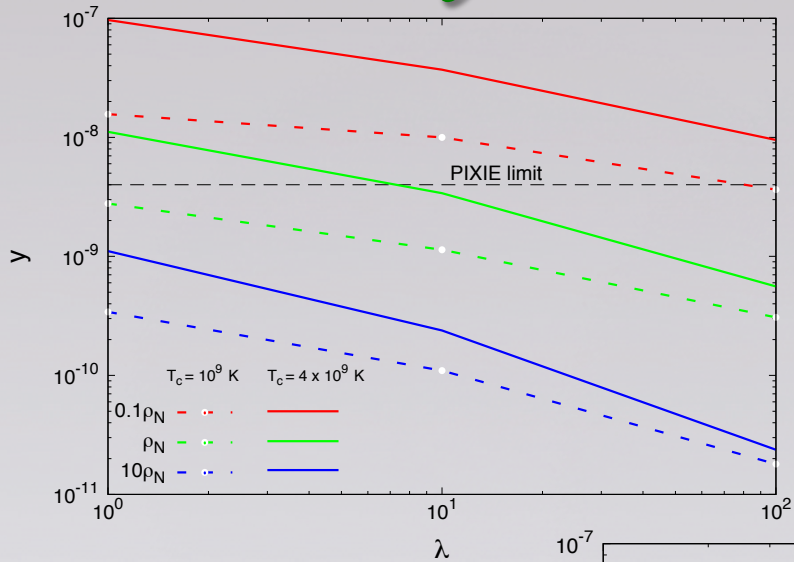
RESULTS: T vs. z



RESULTS: μ DISTORTIONS



RESULTS: γ DISTORTIONS



CONCLUSIONS & FUTURE WORK

- SDs are a probe of the Universe at small scales.
- Macros are alternative DM candidates.
- Hot macros can cause *detectable* SDs through surface emission of photons.
- Production of nuclei with a wide range of masses (including heavy nuclei) through a variety of mechanisms, and at a range of cosmological epochs.
- Formation of binary macros, with potential gravitational-wave and electromagnetic signals.
- Enhanced thermal and dynamical coupling of DM to baryons and photons.