Fundamental physics with CMB: anomalies, new particles, primordial black holes

Rishi Khatri
Speculations before 20th century

Universe = Milky Way

Image Credit: ESO/Yuri Beletsky
The year 2020 marks the 100 years since the great debate between Harlow Shapley and Heber Curtis (See Trimble 2013, arXiv:1307.2289 for an interesting analysis of the 1920 debate)

https://apod.nasa.gov/diamond_jubilee/debate20.html

How to measure astronomical distances?

I. Standard candles
i.e. objects with known luminosity

\[
\text{Flux (energy/time/area)} = \frac{\text{Luminosity (energy/time)}}{4\pi \text{distance}^2}
\]

Measure flux and solve for distance!

Andromeda Image credit: GALEX/NASA/JPL/Caltech
1912: Henrietta Leavitt discovered that Cepheid variable stars, massive young stars exhibiting radial oscillations, can be standard candles (Leavitt law)

Small Magellanic Cloud

Image Credit: ESA/Hubble and Digitized Sky Survey

Acknowledgements: Davide De Martin (ESA/Hubble)
The metric of the homogeneous isotropic Universe

Friedmann metric

\[ ds^2 = -dt^2 + a(t)^2 \left( \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin \theta^2 d\phi^2 \right) \]

Proper Distance \( R = a(t) r \), \( a(t) \): scale factor

Hubble parameter:

\[ H(t) = \frac{1}{a} \frac{da}{dt} \]

Velocity-distance relation today (\( t = t_0 \))

\[ V = \frac{dR}{dt} = H_0 R \]

Hubble parameter \( H(z) = H_0 \sqrt{\Omega_r (1 + z)^4 + \Omega_m (1 + z)^3 + \Omega_{\Lambda}} \)
(Friedmann equation)
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.
Hubble diagram in 1998: Discovery of dark energy

\[ \frac{d^2a}{dt^2} > 0 \Rightarrow \]

Accelerated expansion

Redshift \( 1 + z = \frac{1}{a} \)

Magnitude

\[ m - M = 5(\log D - 1) \]

Riess et al. 1998
Tremendous progress in CMB anisotropies after COBE
CMB spectrum experiment is long overdue

1948: Prediction of 5K thermal radiation by Alpher and Herman following up on the idea of Gamow
1965: Discovery of CMB
1960s-1990s: Numerous ground based and rocket based attempts to measure CMB spectrum and anisotropies
1990: COBE measures spectrum (blackbody) and anisotropies almost simultaneous measurement of blackbody spectrum by Canadian rocket experiment COBRA
2000-2015: WMAP,Planck,SPT,ACT,Boomerang... etc - tremendous increase in precision
Bicep2,SPT,ACT - First measurements of (lensing) B-mode polarization
2030: Primordial B-modes? CMB spectrum?
The culmination of observational and theoretical efforts of last 100 years is the standard $\Lambda$CDM cosmological model

$$\text{Standard } \Lambda\text{CDM} = \text{Standard model of particle physics}$$

$$+ \text{ general relativity}$$

$$+ \text{cosmological principle}$$

$$+ \text{flatness}$$

$$+ \text{single field inflation (2 parameters)}$$

$$+ \text{cold dark matter (1 parameter)}$$

$$+ \text{cosmological constant (1 parameter)}$$

$$+ \text{baryogenesis } (10^9 \text{ photons for every baryon})$$

(2 additional parameters: Hubble constant and optical depth to reionization can be fixed from other observations)

The 6-parameter model may fail in future as precision improves $\rightarrow$ anomalies or inconsistencies between different cosmological datasets $\rightarrow$ discovery of new physics
CMB is directly affected by new physics at $z \lesssim 2 \times 10^6$
Picture of Universe @ 380000 Years

The extreme simplicity of the early Universe before recombination and very weak interaction of the CMB photons with matter after recombination make precision science with CMB possible.

*Planck Collaboration 2015*
Decompose the observed CMB blackbody intensity on the sphere into spherical harmonics

Fluctuations about average CMB with intensity from $\bar{T} = 2.725$ K

$$\Theta(\theta, \phi) \equiv \frac{\Delta T(\theta, \phi)}{\bar{T}} = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi), \quad C_\ell = \sum_m a_{\ell m} a_{\ell m}^*$$
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Amplitude of each Fourier mode $\Theta_0(k)$ in tightly coupled photon-baryon plasma satisfies a forced damped harmonic oscillator equation

Average CMB temperature fluctuation at a point in space-time or Fourier mode $(k)$, $\Theta_0(k, \eta) = (1/4)\Delta \rho / \rho$ satisfies a forced harmonic oscillator equation

$$\frac{d^2 \Theta_0}{d\eta^2} + \frac{1}{a} \frac{da}{d\eta} \left( \frac{R}{1+R} \right) \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R)$$

$$R = \frac{3}{4} \frac{\rho_b}{\rho_\gamma}, \quad c_s = \sqrt{\frac{1}{3(1+R)}}$$

c_s = \text{Sound speed}, \quad \phi, \psi = \text{gravitational potentials}

Baryon loading $(R)$ damps the oscillations, Gravity from all components of the Universe modifies the oscillations.
Amplitude of each Fourier mode $\Theta_0(k)$ in tightly coupled photon-baryon plasma satisfies a forced damped harmonic oscillator equation

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$$R = \frac{3}{4} \frac{\rho_b}{\rho_\gamma}, \quad c_s = \sqrt{\frac{1}{3(1+R)}}$$

The amplitude of each Fourier mode oscillates. Adiabatic boundary conditions $\rightarrow \Theta_0(x, \eta) \propto \cos(kc_s \eta)e^{ik \cdot x} \rightarrow$ standing sound waves with temporal frequency $\omega = kc_s$ (sine mode absent)
Numerous ways for new physics to modify each of the terms

\[
\frac{d^2\Theta_0}{d\eta^2} + \frac{1}{a} \frac{da}{d\eta} \frac{R}{1 + R} \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R)
\]

Change in Hubble expansion or \( R \) modifies the damping term: e.g. charged dark matter will contribute to \( R \).
Numerous ways for new physics to modify each of the terms

\[ \frac{d^2 \Theta_0}{d\eta^2} + \frac{1}{a} \frac{da}{d\eta} \frac{R}{1 + R} \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R) \]

Interactions of dark matter or dark radiation with baryons or photons will modify the sound speed
Numerous ways for new physics to modify each of the terms

\[
\frac{d^2 \Theta_0}{d\eta^2} + \frac{1}{a \, d\eta} \frac{R}{1 + R} \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R)
\]

Any physics that modified the perturbations in any fluid affects CMB gravitationally through the forcing term
e.g. stopping neutrino free streaming by introducing new interaction between neutrino and dark matter
Gravity of dark matter, baryons, neutrinos modifies the acoustic oscillations

\[
\frac{d^2 \Theta_0}{d\eta^2} + \frac{1}{a} \frac{da}{d\eta} \frac{R}{1 + R} \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R)
\]

Dark matter: Constant gravity \((F)\) - shift the zero of oscillations
\[
\Theta_0 \propto \cos(kc_s \eta) - \psi
\]
Observed anisotropy: \(\Theta_0 + \psi \propto \cos(kc_s \eta)\)
\(\psi = \text{gravitational redshift}\)
Gravity of dark matter, baryons, neutrinos modifies the acoustic oscillations

\[
\frac{d^2 \Theta_0}{d\eta^2} + \frac{1}{a} \frac{da}{d\eta} \frac{R}{1 + R} \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R)
\]

Baryons: Resonant forcing term - amplification of oscillations
Gravity of dark matter, baryons, neutrinos modifies the acoustic oscillations

\[
\frac{d^2 \Theta_0}{d\eta^2} + \frac{1}{a} \frac{da}{d\eta} \frac{R}{1+R} \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R)
\]

Dark matter + Baryons: small shift in zero of oscillations → Asymmetry in odd-even peaks
\[
\Theta_0 + \psi \approx [\Theta_0(0) + \psi(0)(1 + R)] \cos(kc_s\eta) - \psi R
\]
No dark matter or No baryons ⇒ No asymmetry
Amplitude and asymmetry tell us how much dark matter ($\Omega_{dm}$) and baryons ($\Omega_b$) are there.
Gravity of decaying Neutrinos perturbations introduces phase-shift

\[ \frac{d^2 \Theta_0}{d \eta^2} + \frac{1}{a \, d\eta} \frac{R}{1 + R} \frac{d \Theta_0}{d \eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R) \]

Neutrinos are free streaming at speed of light
Gravity of decaying Neutrinos perturbations introduces phase-shift

\[
\frac{d^2 \Theta_0}{d\eta^2} + \frac{1}{a} \frac{da}{d\eta} \frac{R}{1 + R} \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R)
\]

At time $\eta$, they erase perturbations on scales $\lambda / 2\pi \lesssim \eta, k \gtrsim 1/\eta$ i.e. a mode decays on entering the horizon
Gravity of decaying Neutrinos perturbations introduces phase-shift

\[
\frac{d^2 \Theta_0}{d\eta^2} + \frac{1}{a} \frac{da}{d\eta} \frac{R}{1 + R} \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R)
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Perturbations in neutrinos decay faster than plasma can respond (sound speed) \(\rightarrow\) fast step function like contribution to \(F \rightarrow\) phase shift in acoustic oscillations

\[\Theta_0 + \psi \propto \cos(kr_s + \phi_\nu), \quad r_s = \int_0^\eta d\eta c_s(\eta)\]
Gravity of decaying Neutrinos perturbations introduces phase-shift

\[
\frac{d^2 \Theta_0}{d\eta^2} + \frac{1}{a} \frac{da}{d\eta} \frac{R}{1 + R} \frac{d\Theta_0}{d\eta} + k^2 c_s^2 \Theta_0 = F(\phi, \psi, R)
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Perturbations in neutrinos decay faster than plasma can respond (sound speed) \( \rightarrow \) fast step function like contribution to \( F \rightarrow \) phase shift in acoustic oscillations

\( \Theta_0 + \psi \propto \cos(k r_s + \phi_v), \quad r_s = \int_0^\eta d\eta c_s(\eta) \)

We observe this pattern of oscillations as it exists at the time of recombination.
We observe a 2-D spherical projection of the 3-D CMB field at recombination: \( r_s = r_*, z = z_* \approx 1100 \)

\[
C_\ell \sim \frac{2}{\pi} \int dk \, k^2 P_A(k) j_\ell^2[k(\eta_0 - \eta_*)] \left[ \Theta_0(k, \eta_*) + \psi(k, \eta_*) \right]^2
\]

Spherical Bessel projects mode \( k \) to \( \ell \approx k(\eta_0 - \eta_*) \equiv kD_A \)
CMB provides a standard ruler to measure the distance to the last scattering surface.

\[ \Theta = \frac{r_s}{\Delta A} \]

Angular mode \( l = \frac{1}{\Theta} = \frac{\Delta A}{r_s} \)
CMB peak positions are sensitive to the Hubble constant

Acoustic peaks correspond to extrema of \( \cos(kr_* + \phi_\nu) \)
\[
\rightarrow kr_* + \phi_\nu = m\pi, m \in \text{Integers}, m \geq 1
\]

\[
\ell_{\text{peak}} \approx k_{\text{peak}}D_A = (m\pi - \phi_\nu) \frac{D_A}{r_*}
\]

Angular diameter distance to lss \( D_A = \int_0^{z_*} \frac{dz}{H(z)} \)

Sound horizon at recombination \( r_* = \int_{z_*}^{\infty} \frac{dz}{c_s(z)} \frac{dz}{H(z)} \)

Hubble parameter \( H(z) = H_0 \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda} \)
(Friedmann equation)
$H_0$ measured by CMB is in tension with local measurement

CMB: $67.5 \pm 0.6 \text{ kms}^{-1}\text{Mpc}^{-1}$ *Planck Collaboration 2018*

SH0ES: $74.03 \pm 1.42 \text{ kms}^{-1}\text{Mpc}^{-1}$ *Riess et al, 2019*
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$\sim 4\sigma$ discrepancy
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$\sim 4\sigma$ discrepancy

With Planck, CMB is so precise that even when we fit 6 or more parameters of the cosmological model together, the $H_0$ from the CMB is more precise than the local measurement
Increasing the $H_0$ while keeping energy densities in matter and radiation fixed gives a constant change in $H(z)$

_Ghosh, Khatri, Roy 2019_

Keeping fixed the physical densities of matter and radiation $\Omega_r H_0^2$ and $\Omega_m H_0^2$ along with flatness ($\Omega_r + \Omega_m + \Omega_\Lambda = 1$) we want to increase $H_0$

\[
H_0^2 \rightarrow H_0^2 + \delta(H_0^2)
\]

\[
\Rightarrow H(z)^2 \rightarrow H(z)^2 + \delta(H_0^2)
\]
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$Ghosh, Khatri, Roy$ 2019

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$$H_0^2 \rightarrow H_0^2 + \delta(H_0^2)$$

$$\Rightarrow H(z)^2 \rightarrow H(z)^2 + \delta(H_0^2)$$

$H(z)$ is larger at higher redshifts. So importance of constant shift decreases at large $z$. 
Increasing the $H_0$ while keeping energy densities in matter and radiation fixed gives a constant change in $H(z)$

Ghosh, Khatri, Roy 2019

Keeping fixed the physical densities of matter and radiation $\Omega_r H_0^2$ and $\Omega_m H_0^2$ along with flatness ($\Omega_r + \Omega_m + \Omega_\Lambda = 1$) we want to increase $H_0$

\[ H_0^2 \rightarrow H_0^2 + \delta(H_0^2) \]
\[ \Rightarrow H(z)^2 \rightarrow H(z)^2 + \delta(H_0^2) \]

$D_A \rightarrow D_A + \delta D_A$, $\delta D_A < 0$, $r_*$ remains unchanged.
Increasing the $H_0$ while keeping energy densities in matter and radiation fixed gives a constant change in $H(z)$

$\text{Ghosh, Khatri, Roy 2019}$

Keeping fixed the physical densities of matter and radiation $\Omega_r H_0^2$ and $\Omega_m H_0^2$ along with flatness ($\Omega_r + \Omega_m + \Omega_\Lambda = 1$) we want to increase $H_0$

$$H_0^2 \rightarrow H_0^2 + \delta(H_0^2)$$

$$\Rightarrow H(z)^2 \rightarrow H(z)^2 + \delta(H_0^2)$$

Peak positions shift to smaller $\ell$ contradicting CMB observations,

$$\ell_{\text{peak}} \approx (m\pi - \phi_v) \frac{D_A}{r_*}$$
Solution: undo the decrease in $D_A$, or decrease $r_*$ to compensate or modify $\phi_v$ to compensate

Undoing the change in $D_A$ by modifying late time expansion history of the Universe by fine tuning evolution of dark energy
Compensate the change in $D_A$ by modifying early time expansion history of the Universe or by change in $r_*$
e.g. Early dark energy or introduce new relativistic particles
Solution: undo the decrease in $D_A$, or decrease $r_\ast$ to compensate or modify $\phi_\nu$ to compensate

*Ghosh, Khatri, Roy 2019*

For compensation by phase shift, $\phi_\nu$,

$$
\delta \ell_{\text{peak}} = \frac{\delta D_A}{D_A} - \frac{\delta \phi_m}{m \pi - \phi} = 0
$$

$$
\delta \phi_m \approx m \pi \frac{\delta D_A}{D_A}
$$
Solution: undo the decrease in $D_A$, or decrease $r_*$ to compensate or modify $\phi_\nu$ to compensate

*Ghosh, Khatri, Roy 2019*

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$$\delta \ell_{\text{peak}} = \frac{\delta D_A}{D_A} - \frac{\delta \phi_m}{m\pi - \phi} = 0$$

$$\delta \phi_m \approx m\pi \frac{\delta D_A}{D_A}$$

If we stop neutrinos from free streaming we get almost the right $\delta \phi_m$, scale ($m$) dependent phase-shift
Implement by introducing a new interaction of neutrinos with a fraction of dark matter

Ghosh, Khatri, Roy 2019
MCMC analysis including galaxy power spectrum from WiggleZ survey shows reduction in tension to $2.1\sigma$

\[ u = \frac{\sigma_{v\chi}}{\sigma_T} \frac{100 \text{ GeV}}{m_\chi} \]

\( f = \text{fraction of interacting dark matter} \)

W1 - \( k \leq 0.1h\text{Mpc}^{-1} \)
Joint analysis with SH0ES shows improvement in $\chi^2$ for one additional effective parameter ($f = 10^{-3}$)

Ghosh, Khatri, Roy 2019

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\Lambda$CDM</th>
<th>DNI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_0$ (km/s/Mpc)(bf)</td>
<td>$68.89^{+0.58}_{-0.59}$ (68.86)</td>
<td>$70.25^{+0.63}_{-0.61}$ (70.37)</td>
</tr>
<tr>
<td>$f u$ (bf)</td>
<td>0</td>
<td>0.02321$^{+0.0065}_{-0.012}$ (0.01874)</td>
</tr>
<tr>
<td>$100 \omega_b$</td>
<td>$2.243^{+0.015}_{-0.015}$</td>
<td>2.251$^{+0.015}_{-0.015}$</td>
</tr>
<tr>
<td>$\omega_{DM}$</td>
<td>$0.1176^{+0.0013}_{-0.0013}$</td>
<td>0.1181$^{+0.0013}_{-0.0013}$</td>
</tr>
<tr>
<td>$\ln 10^{10} A_s$</td>
<td>$3.07^{+0.024}_{-0.025}$</td>
<td>3.005$^{+0.025}_{-0.026}$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9709^{+0.0045}_{-0.0046}$</td>
<td>0.9492$^{+0.0047}_{-0.0048}$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.8283^{+0.0088}_{-0.009}$</td>
<td>0.831$^{+0.0091}_{-0.0092}$</td>
</tr>
<tr>
<td>$100 \theta_*$ (bf)</td>
<td>$1.04201^{+0.00030}_{-0.00030}$</td>
<td>1.04643$^{+0.00094}_{-0.00078}$ (+14.7$\sigma$)</td>
</tr>
<tr>
<td>$r_*$ (Mpc),bf</td>
<td>145.07</td>
<td>1.04614 (+0.4%)</td>
</tr>
<tr>
<td>$D_A$ (Mpc),bf</td>
<td>12.78</td>
<td>144.93 (-0.1%)</td>
</tr>
<tr>
<td>$\Delta \chi^2$</td>
<td>0</td>
<td>-9.08</td>
</tr>
</tbody>
</table>
Predict enhancement of B-mode power spectrum and matter power spectrum testable by future experiments

Ghosh, Khatri, Roy 2018, Ghosh, Khatri, Roy 2019
We may have discovered a new dark interaction (non-standard behaviour) of neutrinos in Hubble tension
Looking for anomalies in CMB spectrum
Standard model predicts distortions other than Sunyaev-Zeldovich effect at the level of $10^{-8}$ and SZ effect at level of $10^{-6}$.
No deviations from a Planck spectrum at $\sim 10^{-4}$

*Fixsen et al. 1996, Fixsen and Mather 2002*
Planck spectrum

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

Relativistic invariant occupation number/phase space density

\[ n(\nu) \equiv \frac{c^2}{2h\nu^3} I_\nu \]

\[ n(x) = \frac{1}{e^x - 1} \quad , \quad x = \frac{h\nu}{k_B T} \]
$y$-type (Sunyaev-Zeldovich effect) from clusters/reionization

$$y \gamma \ll 1 , \ T_e \sim 10^4$$

$$y = (\tau_{\text{reionization}}) \frac{k_B T_e}{m_e c^2} \sim (0.06)(1.6 \times 10^{-6}) \sim 10^{-7}$$

![DMR 53 GHz Maps](image)

$T = 2.725 \text{K}$

![Blackbody](image)

$y$-distortion

$T = 2.728 \text{ K}$

$\nu$ (GHz)

$I_\nu (\text{W m}^{-2} \text{ Hz}^{-1} \text{ Sr}^{-1})$
Efficiency of energy exchange between electrons and photons

Recoil:

\[ y_\gamma = \int dt \sigma T n_e \frac{k_B T_\gamma}{m_e c^2}, \quad T_\gamma = 2.725 (1 + z) \]

Doppler effect:

\[ y_e = \int dt \sigma T n_e \frac{k_B T_e}{m_e c^2} \]

In early Universe \( y_\gamma \approx y_e \)

\( y \): Amplitude of distortion

\[ y = \int dt \sigma T n_e \frac{k_B (T_e - T_\gamma)}{m_e c^2} \]
Efficiency of energy exchange between electrons and photons

Recoil:

\[ y_\gamma = \int dt c \sigma_T n_e \frac{k_B T_\gamma}{m_e c^2}, \quad T_\gamma = 2.725(1 + z) \]

No. of scatterings

Doppler effect:

\[ y_e = \int dt c \sigma_T n_e \frac{k_B T_e}{m_e c^2} \]

In early Universe \( y_\gamma \approx y_e \)

\( y \): Amplitude of distortion

\[ y = \int dt c \sigma_T n_e \frac{k_B (T_e - T_\gamma)}{m_e c^2} \]
Efficiency of energy exchange between electrons and photons

Recoil:

\[ y_{\gamma} = \int dt \sigma T n_e \frac{k_B T_{\gamma}}{m_e c^2}, \quad T_{\gamma} = 2.725(1 + z) \]

No. of scatterings \quad Energy transfer per scattering

Doppler effect:

\[ y_e = \int dt \sigma T n_e \frac{k_B T_e}{m_e c^2} \]

In early Universe \( y_{\gamma} \approx y_e \)

\( y \): Amplitude of distortion

\[ y = \int dt \sigma T n_e \frac{k_B (T_e - T_{\gamma})}{m_e c^2} \]
Intermediate-type distortions (Khatri and Sunyaev 2012b)

Solve Kompaneets equation with initial condition of $y$–type solution.

$$\frac{\partial n}{\partial y_\gamma} = \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \left( n + n^2 + \frac{T_e}{T} \frac{\partial n}{\partial x} \right), \quad \frac{T_e}{T} = \frac{\int (n + n^2) x^4 dx}{4 \int nx^3 dx}$$
Many processes in the early Universe inject relativistic particles. So far these have been studied assuming non-relativistic $y$-type distortions.

- **Particle decay:** $\frac{dQ}{dz} \propto e^{- \left( \frac{1+z_{\text{decay}}}{1+z} \right)^2} \left( \frac{1+z_{\text{decay}}}{1+z} \right)^4$
  
  *(Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)*

- **Cosmic strings:** $\frac{dQ}{dz} \propto \text{constant}$
  
  *Tashiro, Sabancilar, Vachaspati 2012*

- **Primordial Black holes (PBH):** Depends on the mass function
  
  *Tashiro and Sugiyama 2008, Carr et al. 2010*

  $\rightarrow$ non-trivial new physics during inflation to create $\mathcal{O}(1)$ fluctuations necessary to produce PBH
Particle cascades $\Rightarrow$ Non-Thermal Relativistic Distortions

Electromagnetic cascade

High Energy $e^-$

Background $e^- \gamma$ $H$ $H^* e^-$

$e^- e^-\gamma$ $H e^- \gamma$ $H^+$ $e^- e^-$

$e^- \gamma \gamma \gamma$ $e^- e^+$

Boosted CMB Photons

$\gamma \gamma \gamma \gamma \gamma \gamma \gamma \gamma$ 

Non-Thermal Relativistic Spectral Distortion
At $z \lesssim 10^5$ the shape of the CMB distortion depends on the spectrum of injected particles

*Acharya and Khatri 2019a*
New COBE constraints on decaying dark matter: upto a factor of 5 correction

electron-positron channel Acharya and Khatri 2019b
New COBE constraints on decaying dark matter: upto a factor of 5 correction

photon channel Acharya and Khatri 2019b

\[ f_X (95\% \text{ limit}) \]

\[ 10^{-4} \quad 10^{-3} \]

\[ 10^4 \quad 10^5 \]

\[ \text{DM} \rightarrow \gamma\gamma \]

\[ \text{yim approx.} \]

\[ 3 \text{ MeV} \]

\[ 30 \text{ MeV} \]

\[ 20 \text{ GeV} \]

\[ 20 \text{ keV} \]
CMB spectral distortions are sensitive to the mass of decaying particle as well as the lifetime.

**COBE Constraints Acharya and Khatri 2019b**

- **electron-positron channel**
- **photon channel**
Energy injection changes the recombination history/residual electron fraction after recombination

Acharya and Khatri 2019c

Lifetime = $10^{14}$ s

![Graph showing the effect of energy injection on the recombination history/residual electron fraction. The x-axis represents redshift (z) ranging from 100 to 1000, and the y-axis represents the electron fraction ($x_e$) ranging from $10^{-6}$ to $10^{-3}$. Different lines represent different energy injection scenarios, including no DM, 1 TeV $\gamma\gamma$, 100 MeV $e^-e^+$, 100 keV $e^-e^+$, 10 keV $\gamma\gamma$, and 1 MeV $\gamma\gamma$. Each line shows a distinct increase in $x_e$ with decreasing redshift.]
Scattering of quadrupole polarization

Hot

Cold

e−

E

B
CMB E-mode polarization is enhanced from extra scatterings.

\[ \frac{\ell(\ell+1)C_{\ell}(EE)}{2\pi} (\mu K^2) \]

- no DM
- 1 TeV $\gamma\gamma$
- 100 MeV $e^- e^+$
- 100 keV $e^- e^+$
- 10 keV $\gamma\gamma$
- 1 MeV $\gamma\gamma$
High energy photons can dissociate light elements produced in the BBN

*Acharya and Khatri 2019c*

<table>
<thead>
<tr>
<th>Reactions</th>
<th>photo-dissociation threshold (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2\text{H} + \gamma \rightarrow \text{n} + \text{p}$</td>
<td>2.22</td>
</tr>
<tr>
<td>$^3\text{He} + \gamma \rightarrow ^2\text{H} + \text{p}$</td>
<td>5.49</td>
</tr>
<tr>
<td>$^3\text{He} + \gamma \rightarrow \text{n} + \text{p} + \text{p}$</td>
<td>7.718</td>
</tr>
<tr>
<td>$^4\text{He} + \gamma \rightarrow ^3\text{H} + \text{p}, ^3\text{H} \rightarrow ^3\text{He} + e^- + \nu_e$</td>
<td>19.81</td>
</tr>
<tr>
<td>$^4\text{He} + \gamma \rightarrow ^3\text{He} + \text{n}$</td>
<td>20.58</td>
</tr>
<tr>
<td>$^4\text{He} + \gamma \rightarrow ^2\text{H} + ^2\text{H}$</td>
<td>23.85</td>
</tr>
<tr>
<td>$^4\text{He} + \gamma \rightarrow ^2\text{H} + \text{n} + \text{p}$</td>
<td>26.07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elements</th>
<th>theoretical value($1\sigma$)</th>
<th>observational value($1\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_2\text{H}/n_\text{H}$</td>
<td>$(2.58 \pm 0.13) \times 10^{-5}$ [75]</td>
<td>$(2.53 \pm 0.04) \times 10^{-5}$ [75]</td>
</tr>
<tr>
<td>$Y_p$</td>
<td>$0.24709 \pm 0.00025$ [75]</td>
<td>$0.2449 \pm 0.0040$ [76]</td>
</tr>
<tr>
<td>$n_3\text{He}/n_\text{H}$</td>
<td>$(10.039 \pm 0.090) \times 10^{-6}$ [75]</td>
<td>$1.5 \times 10^{-5}$ (2$\sigma$ upper limit) [77]</td>
</tr>
</tbody>
</table>
CMB anisotropy, spectral distortions and BBN constraints on long lived unstable particles

Acharya and Khatri 2019c
Primordial black holes can emit all standard model particles if they are hot enough

Acharya and Khatri 2019d
CMB and BBN constraints on primordial black holes

Acharya and Khatri 2019d

![Graph showing constraints on primordial black hole mass and fraction. The graph includes data from COBE-FIRAS, PIXIE, and various studies such as Lucca et al., Stocker et al., Poulter et al., BBN (Carr et al.), and BBN (this work). The constraints are represented on a log-log scale with axes for $f_{BH}$ and $M_{BH}$. The graph also includes lines for 21 cm global, Gamma rays, Cosmic rays, and Galactic 511 keV line.]
PBH constraints translate into constraints on primordial power spectrum

Probing 40 e-folds of inflation!
Injection of high energy neutrinos can change relative energy density of neutrinos and photons ($N_{\text{eff}}$): constraints beyond $z = 2 \times 10^6$

Neutrinos carry information from $z \gtrsim 2 \times 10^6$ and hand it over to photons at $z \lesssim 2 \times 10^6$ \textit{Acharya & Khatri 2020}

$$\Delta N_{\text{eff}} = N_{\text{eff}} \left( \frac{\Delta \rho_\nu}{\rho_\nu} - \frac{\Delta \rho_{\text{CMB}}}{\rho_{\text{CMB}}} \right)$$
High energy photons produced in neutrino cascade can destroy BBN elements
The future: Falsifying $\Lambda$CDM

Next decade will see a deluge of data from CMB as well as large scale structure experiments, Confronting the standard cosmological model Vera Rubin Observatory https://www.lsst.org/
The future: Falsifying $\Lambda$CDM

Next decade will see a deluge of data from CMB as well as large scale structure experiments, Confronting the standard cosmological model Vera Rubin Observatory https://www.lsst.org/

New ways of measuring the Hubble constant will test Hubble anomaly and confirm or deny it

Lensing time delay experiments $H0LiCOW$ series of experiments

Tip of the Red Giant Branch (TRGB) based calibration of Supernovae Freedman et al. 2019 - Carnegie-Chicago Hubble program
Discovery Space for the next CMB mission

Discovery

Precision measurement
(of things already discovered)

Primordial B-modes
(Gravitons)

Lensing B-modes
Spectral Distortions
E-modes

Discovery

17 e-folds of inflation, Nature of Dark Sector,
Primordial Black Holes, Topological Defects,
New interactions, particles
CMB space mission proposals

Spectral distortions (Absolute Calibration)  B-modes

Low resolution
PRISTINE (ESA)  LITEBIRD (JAXA)
PIXIE (NASA)
ECHO (ISRO)?

High resolution
CORE (ESA)
PICO (NASA)
ECHO (ISRO)
PRISM (ESA)
CMB-BHARAT mission presents an unique opportunity for India to take the lead on prized quests in fundamental science in a field that has proved to be a spectacular success, while simultaneously gaining valuable expertise in cutting-edge technology for space capability through global cooperation.
Thus the explorations of space end on a note of uncertainty. And necessarily so. We are, by definition, in the very center of the observable region. We know our immediate neighborhood rather intimately. With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary—the utmost limits of our telescopes. There, we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial.

The search will continue. Not until the empirical resources are exhausted, need we pass on to the dreamy realms of speculation.

*Edwin Hubble, The Realm of the Nebulae, 1936*