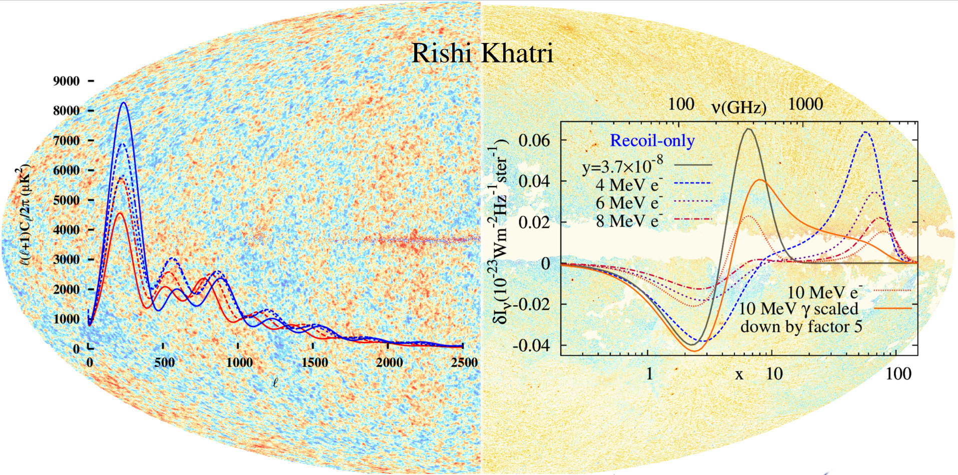
Fundamental physics with CMB: anomalies, new particles, primordial black holes

Rishi Khatri



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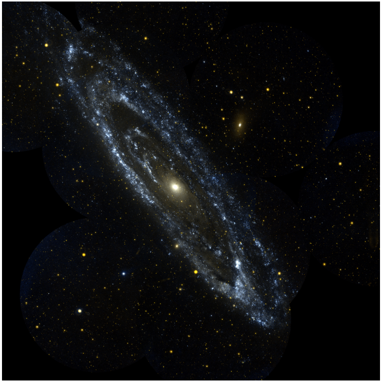
The year 2020 marks the 100 years since the great debate between Harlow Shapley and Heber Curtis

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



Andromeda Image credit: GALEX/NASA/JPL/Caltech

The Shapley - Curtis Debate in 1920

Harlow Shapley

Heber D. Curtis

The Scale of the Universe

1924: Hubble resolved ’Cepheid variable stars’ in Andromeda

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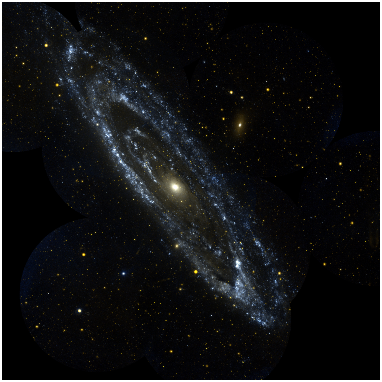

Andromeda Image credit: GALEX/NASA/JPL/Caltech

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1924: Hubble resolved 'Cepheid variable stars' in Andromeda

1922-1924: Friedmann - Expanding Universe

1927: Lemaitre - connection to Slipher's velocities of galaxies

1929: Hubble - distances to galaxies using Cepheids, Hubble diagram

Trimble 2013, arXiv:1307.2289

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 ?

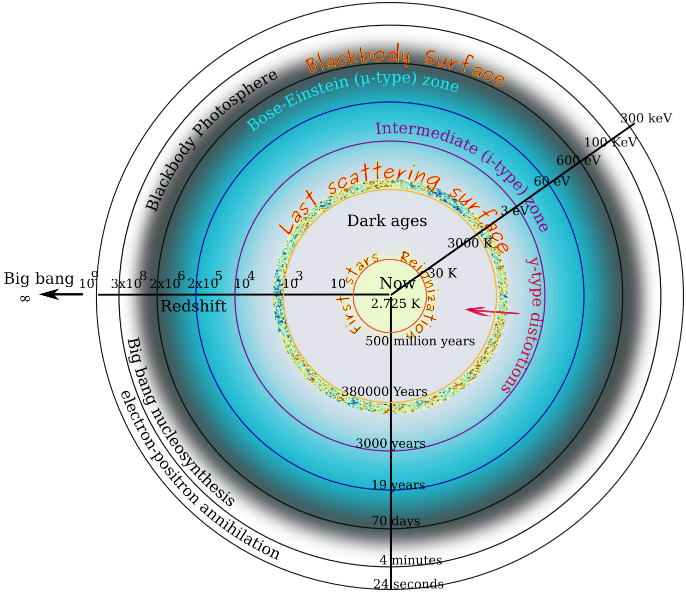
The culmination of observational and theoretical efforts of last 100 years is the standard ΛCDM cosmological model

Standard ΛCDM = Standard model of particle physics
+ general relativity
+ cosmological principle
+ flatness
+ single field inflation (2 parameters)
+ cold dark matter (1 parameter)
+ cosmological constant (1 parameter)
+ baryogenesis

(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 $\longrightarrow$ anomalies or inconsistencies between different cosmological datasets $\rightarrow$ discovery of new physics

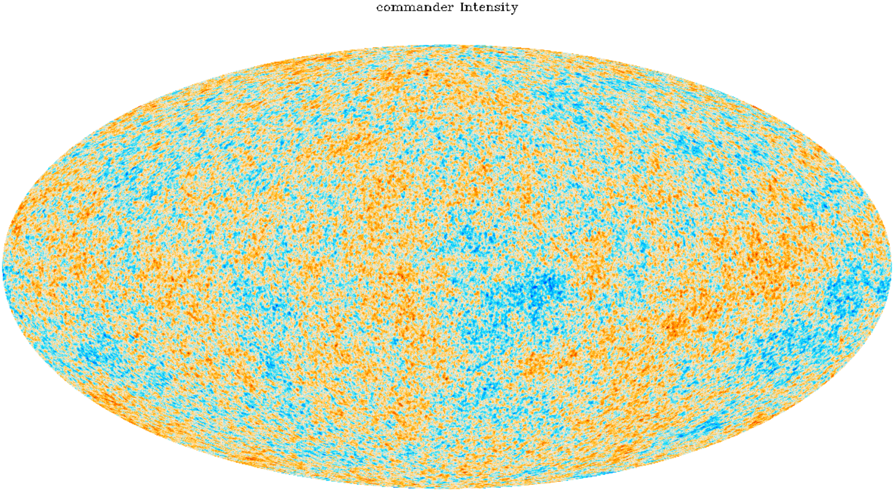
CMB is directly affected by new physics at $z \lesssim 2 \times 10^6$



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

$$\Theta(\theta,\phi) \equiv \frac{\Delta T(\theta,\phi)}{\bar{T}} = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi), \; C_\ell = \sum_m a_{\ell m} a^*_{\ell m}$$

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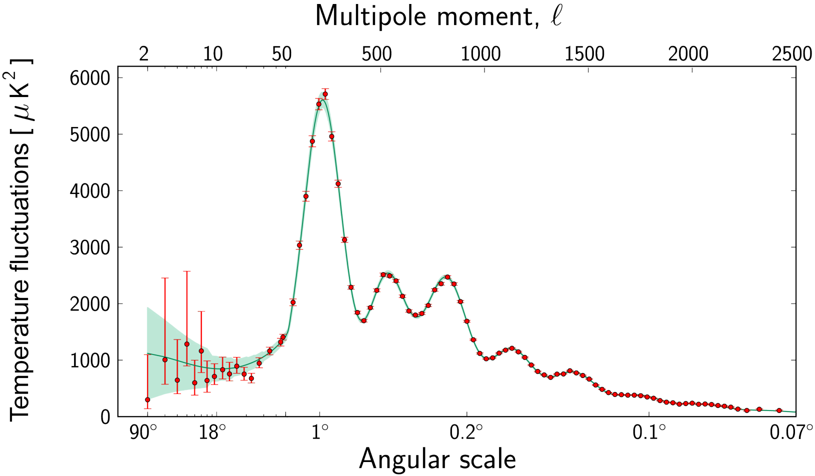

Amplitude of each Fourier mode Θ_0 in tightly coupled photon-baryon plasma satisfies a forced damped harmonic oscillator equation

Average CMB temperature fluctuation at point in space-time,
$\Theta_0(\mathbf{k}, \eta) = (1/4)\Delta\rho/\rho$

$$\frac{\mathrm{d}^2\Theta_0}{\mathrm{d}\eta^2} + \frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}\eta}\frac{R}{1+R}\frac{\mathrm{d}\Theta_0}{\mathrm{d}\eta} + k^2 c_\mathrm{s}^2 \Theta_0 = F(\phi, \psi, R)$$

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

c_s =Sound speed , ϕ, ψ=gravitational potentials
Baryon loading (R) damps the oscillations, Gravity from all components of the Universe modifies the oscillations

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$$R = \frac{3}{4}\frac{\rho_b}{\rho_\gamma}, \;\; c_\mathrm{s} = \sqrt{\frac{1}{3(1+R)}}$$

The amplitude of each Fourier mode oscillates. Adiabatic boundary conditions $\rightarrow \Theta_0 \propto \cos(kc_\mathrm{s}\eta)e^{i\mathbf{k}.\mathbf{x}} \rightarrow$ standing sound waves with temporal frequency $\omega = kc_\mathrm{s}$ (sine mode absent)

Numerous ways for new physics to modify each of the terms

$$\frac{\mathrm{d}^2\Theta_0}{\mathrm{d}\eta^2} + \frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}\eta}\frac{R}{1+R}\frac{\mathrm{d}\Theta_0}{\mathrm{d}\eta} + k^2 c_\mathrm{s}^2 \Theta_0 = F(\phi, \psi, R)$$

Change in Hubble expansion or R modifies the damping term: e.g. charged dark matter will contribute to R.

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Interactions of dark matter or dark radiation with baryons or photons will modify the sound speed

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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

$\Theta_0 \propto \cos(k c_s \eta) - \psi$

Observed anisotropy: $\Theta_0 + \psi \propto \cos(k c_s \eta)$

ψ =gravitational redshift

Gravity of dark matter, baryons, neutrinos modifies the acoustic oscillations

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Baryons: Resonant forcing term - amplification of oscillations

Gravity of dark matter, baryons, neutrinos modifies the acoustic oscillations

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Dark matter + Baryons: small shift in zero of oscillations $\rightarrow$ Asymmetry in odd-even peaks

$\Theta_0 + \psi \approx [\Theta_0(0) + \psi(0)(1+R)]\cos(kc_{\mathrm{s}}\eta) - \psi R$

Gravity of decaying Neutrinos perturbations introduces phase-shift

$$\frac{\mathrm{d}^2\Theta_0}{\mathrm{d}\eta^2} + \frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}\eta}\frac{R}{1+R}\frac{\mathrm{d}\Theta_0}{\mathrm{d}\eta} + k^2 c_\mathrm{s}^2 \Theta_0 = F(\phi, \psi, R)$$

Neutrinos are free streaming at speed of light

Gravity of decaying Neutrinos perturbations introduces phase-shift

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At time η, they erase perturbations on scales $\lambda/2\pi \lesssim \eta, k \gtrsim 1/\eta$ i.e. a mode decays on entering the horizon

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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

$\Theta_0 + \psi \propto \cos(k r_s + \phi_\nu), r_s = \int_0^\eta d\eta\, c_s(\eta)$

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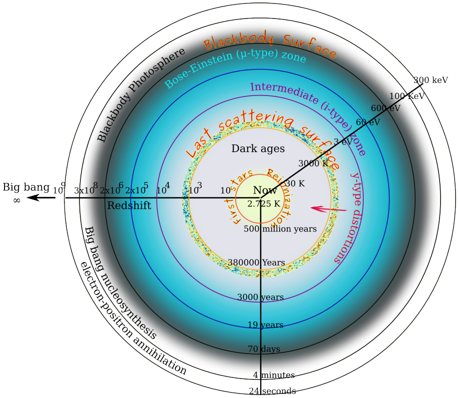
We observe this pattern of oscillations as it exists at the time of recombination.

We observe a 2-D spherical projection of the 3-D CMB field at recombination: $r_{\mathrm{s}} = r_*, z = z_* \approx 1100$

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



Spherical Bessel projects mode k to $\ell \approx k(\eta_0 - \eta_*) \equiv k D_A$

CMB peak positions are sensitive to the Hubble constant

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

$$\ell_{\rm peak} \approx k_{\rm peak} D_A = (m\pi - \phi_\nu)\frac{D_A}{r_*}$$

$$\text{angular diameter distance to lss } D_A = \int_0^{z_*} \mathrm{d}z \frac{1}{H(z)}$$

$$\text{sound horizon at recombination } r_* = \int_{z_*}^{\infty} \mathrm{d}z \frac{c_{\rm s}(z)}{H(z)}$$

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

H_0 measured by CMB is in tension with local measurement

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

SH0ES: $74.03 \pm 1.42\ \mathrm{kms^{-1}Mpc^{-1}}$ *Riess et al, 2019*

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$\sim 4\sigma$ discrepancy

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

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

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

$H(z)$ is larger at higher redshifts. So importance of constant shift decreases at large z

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

$D_A \to D_A + \delta D_A,\ \delta D_A < 0,$
r_* remains unchanged.

Increasing the H_0 while keeping energy densities in matter and radiation fixed gives a constant change in $H(z)$

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$H_0^2 \rightarrow H_0^2 + \delta(H_0^2)$
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Peak positions shift to smaller ℓ contradicting CMB observations,
$\ell_{\rm peak} \approx (m\pi - \phi_\nu)\frac{D_A}{r_*}$

Solution: undo the decrease in D_A, or decrease r_* to compensate or modify ϕ_ν to compensate

Ghosh,Khatri,Roy 2019

For compensation by phase shift, ϕ_ν,

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

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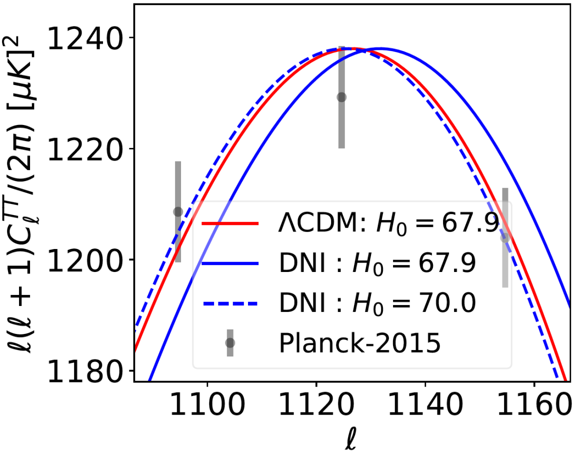
$$\delta\phi_m \approx m\pi\frac{\delta D_A}{D_A}$$

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



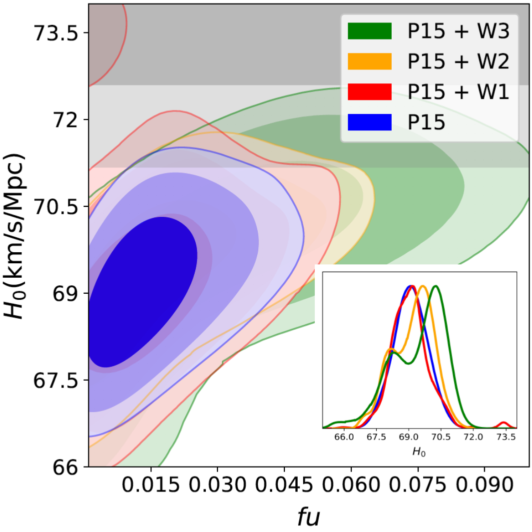
MCMC analysis including galaxy power spectrum from WiggleZ survey shows reduction in tension to 2.1σ

Ghosh,Khatri,Roy 2019

$u = \frac{\sigma_{\nu\chi}}{\sigma_T} \frac{100 \text{ GeV}}{m_\chi}$

f = fraction of interacting dark matter

W1 - $k \leq 0.1 h\text{Mpc}^{-1}$



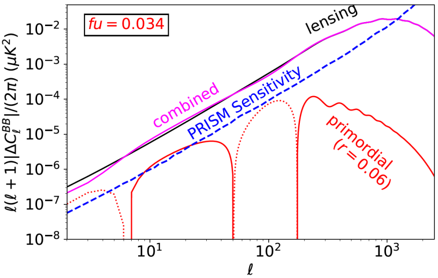
Joint analysis with SH0ES shows improvement in χ^2 for one additional effective parameter ($f = 10^{-3}$)

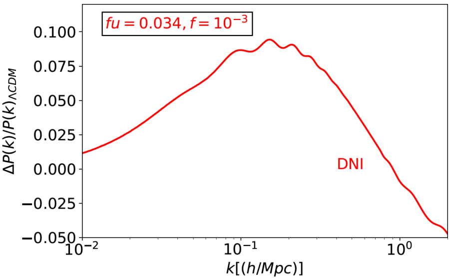
Ghosh,Khatri,Roy 2019

	P15+W1+SH0ES	
	ΛCDM	DNI
H_0 (km/s/Mpc)(bf)	$68.89^{+0.58}_{-0.59}$ (68.86)	$70.25^{+0.63}_{-0.61}$ (70.37)
fu (bf)	0	$0.02321^{+0.0065}_{-0.012}$(0.01874)
$100\ \omega_b$	$2.243^{+0.015}_{-0.015}$	$2.251^{+0.015}_{-0.015}$
$\omega_{\rm DM}$	$0.1176^{+0.0013}_{-0.0013}$	$0.1181^{+0.0013}_{-0.0013}$
$ln10^{10}A_s$	$3.07^{+0.024}_{-0.025}$	$3.005^{+0.025}_{-0.026}$
n_s	$0.9709^{+0.0045}_{-0.0046}$	$0.9492^{+0.0047}_{-0.0048}$
σ_8	$0.8283^{+0.0088}_{-0.009}$	$0.831^{+0.0091}_{-0.0092}$
$100\theta_*$	$1.04201^{+0.00030}_{-0.00030}$	$1.04643^{+0.00094}_{-0.00078}$($+14.7\sigma$)
bf	1.04205	1.04614(+0.4%)
r_*(Mpc),bf	145.07	144.93 (−0.1%)
$D_{\rm A}$(Mpc),bf	12.78	12.71 (−0.5%)
$\Delta\chi^2$	0	−9.08

Predict enhancement of B-mode power spectrum and matter power spectrum testable by future experiments

Ghosh,Khatri,Roy 2018, Ghosh,Khatri,Roy 2019





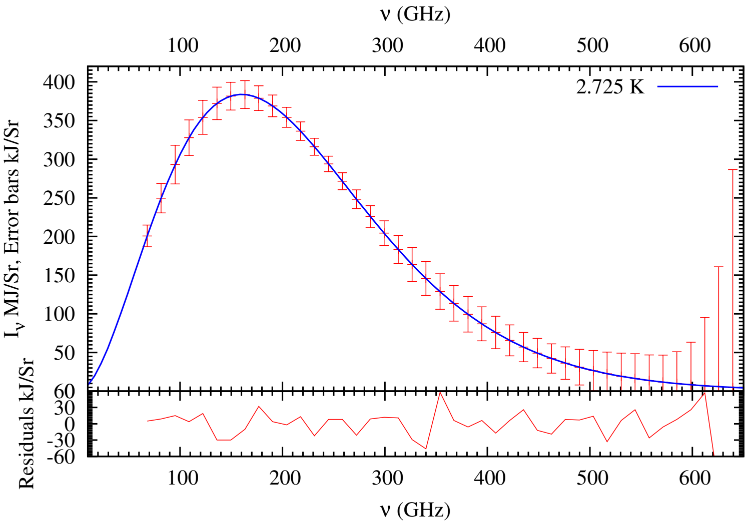
We may have discovered a new dark interaction (non-standard behaviour) of neutrinos in Hubble tension

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

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

Relativistic invariant occupation number/phase space density

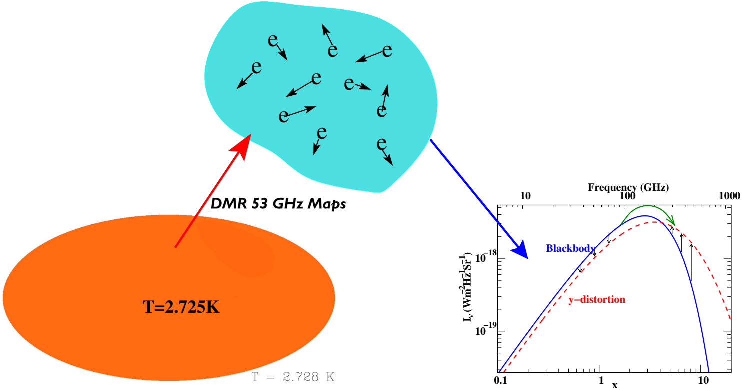
$$n(\nu) \equiv \frac{c^2}{2h\nu^3} I_\nu$$

$$n(x) = \frac{1}{e^x - 1} \quad , \quad x = \frac{h\nu}{k_\mathrm{B}T}$$

y-type (Sunyaev-Zeldovich effect) from clusters/reionization

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

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



Efficiency of energy exchange between electrons and photons

Recoil:

$$y_\gamma = \int \mathrm{d}t\, c\sigma_{\mathrm{T}} n_{\mathrm{e}} \frac{k_{\mathrm{B}} T_\gamma}{m_{\mathrm{e}} c^2}, \qquad T_\gamma = 2.725(1+z)$$

Doppler effect:

$$y_e = \int \mathrm{d}t\, c\sigma_{\mathrm{T}} n_{\mathrm{e}} \frac{k_{\mathrm{B}} T_{\mathrm{e}}}{m_{\mathrm{e}} c^2}$$

In early Universe $y_\gamma \approx y_{\mathrm{e}}$

y: Amplitude of distortion

$$y = \int \mathrm{d}t\, c\sigma_{\mathrm{T}} n_{\mathrm{e}} \frac{k_{\mathrm{B}} \left(T_{\mathrm{e}} - T_\gamma\right)}{m_{\mathrm{e}} c^2}$$

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No. of scatterings

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No. of scatterings   Energy transfer per scattering

Doppler effect:

$$y_e = \int \mathrm{d}t c \sigma_\mathrm{T} n_\mathrm{e} \frac{k_\mathrm{B} T_\mathrm{e}}{m_\mathrm{e} c^2}$$

In early Universe $y_\gamma \approx y_\mathrm{e}$

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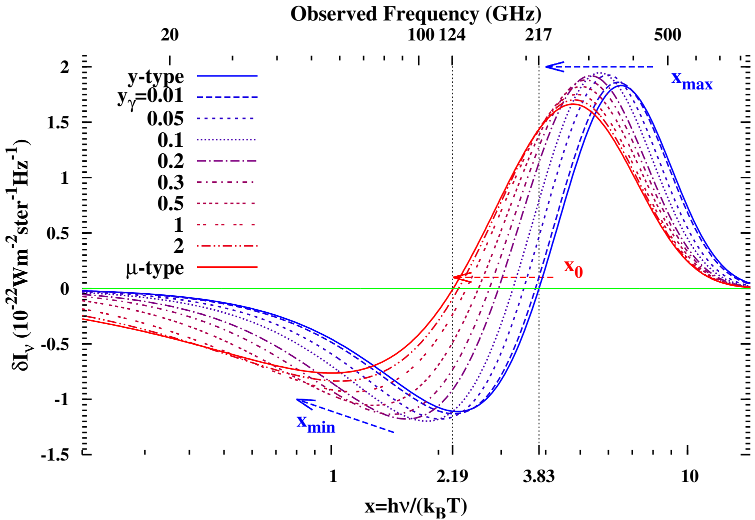
$$y = \int \mathrm{d}t c \sigma_\mathrm{T} n_\mathrm{e} \frac{k_\mathrm{B} \left(T_\mathrm{e} - T_\gamma\right)}{m_\mathrm{e} c^2}$$

Intermediate-type distortions *(Khatri and Sunyaev 2012b)*

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

$$\frac{\partial n}{\partial y_\gamma} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(n+n^2+\frac{T_e}{T}\frac{\partial n}{\partial x}\right),\quad \frac{T_e}{T} = \frac{\int (n+n^2)x^4dx}{4\int nx^3dx}$$

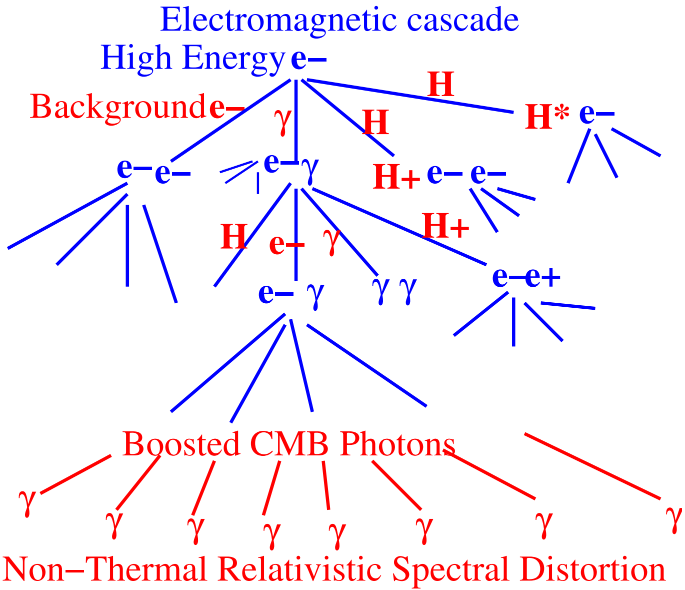


y and i-type distortions are non-relativistic solutions

Many processes in the early Universe inject relativistic particles. So far these have been studied assuming non-relativistic y-type distortions.

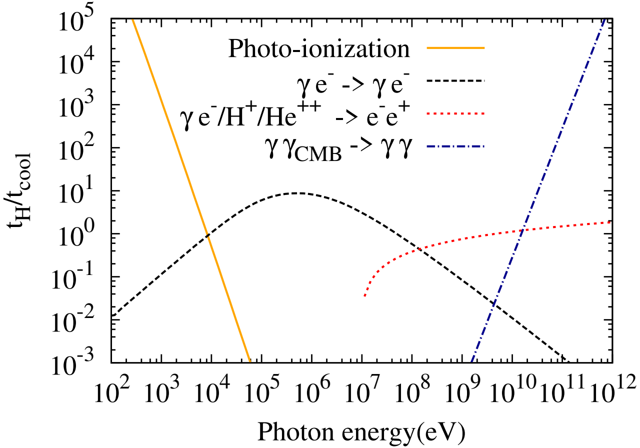
- Particle decay: $\frac{dQ}{dz} \propto \frac{e^{-\left(\frac{1+z_{\rm decay}}{1+z}\right)^2}}{(1+z)^4}$
  (Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)
- Cosmic strings: $\frac{dQ}{dz} \propto$ constant
  Tashiro, Sabancilar, Vachaspati 2012
- Primordial Black holes (PBH): 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 ⇒ Non-Thermal Relativistic Distortions



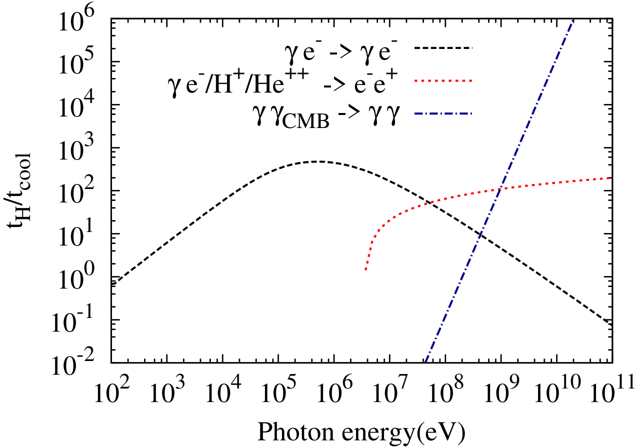
Photons lose energy slowly and must be evolved taking expansion into account

Photons injected at $z = 1000$.

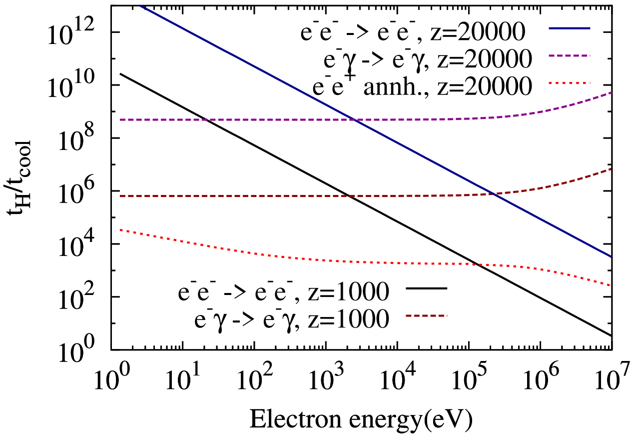


Photons lose energy slowly and must be evolved taking expansion into account

Photons injected at $z = 20000$.



Electrons lose energy fast compared to the expansion of the Universe



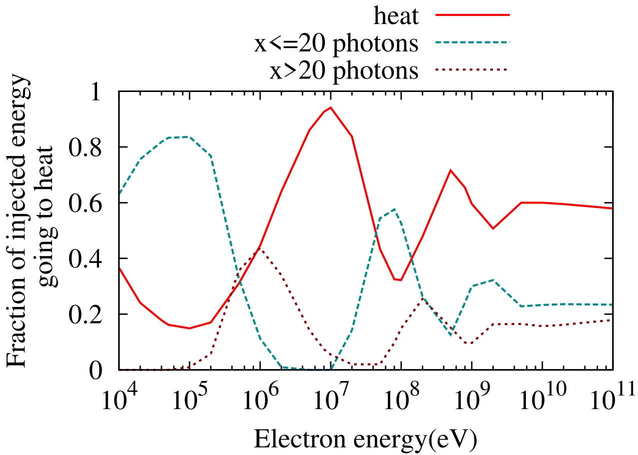
Recursive solution to the evolution of particle cascades

Divide the energy range from 1eV to 10 GeV in logarithmic energy bins

At each time step particles in the shower will cascade down from high energy to low energy bins ⇒ Recursive solution starting from lowest energy bins

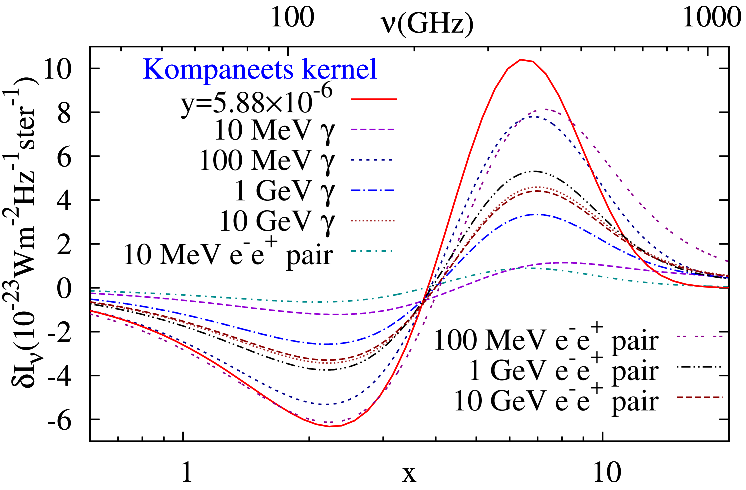
$$\Delta N_s^\beta = \sum_{\alpha=e^-,e^+,\gamma}\left(-\sum_{j<s}P^{\beta\alpha}(E_s,E_j)N_s^\beta+\sum_{j>s}P^{\alpha\beta}(E_j,E_s)N_j^\alpha+S^\beta(E_s)\right),$$

Fraction of energy going into spectral distortions is a function of energy



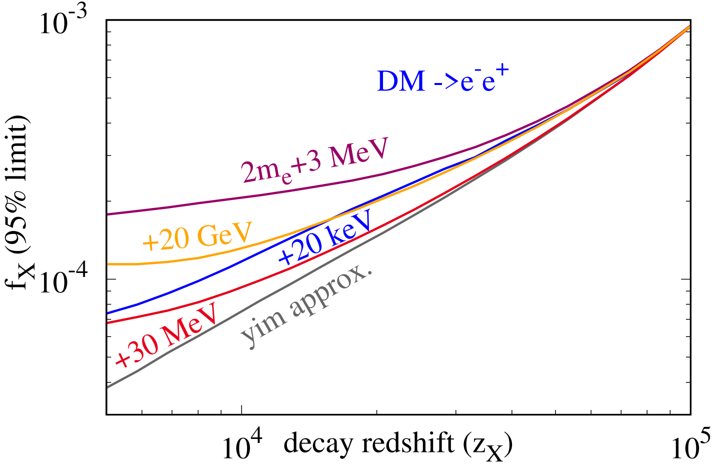
At $z \lesssim 10^5$ the shape of the CMB distortion depends on the spectrum of injected particles

Acharya and Khatri 2019a



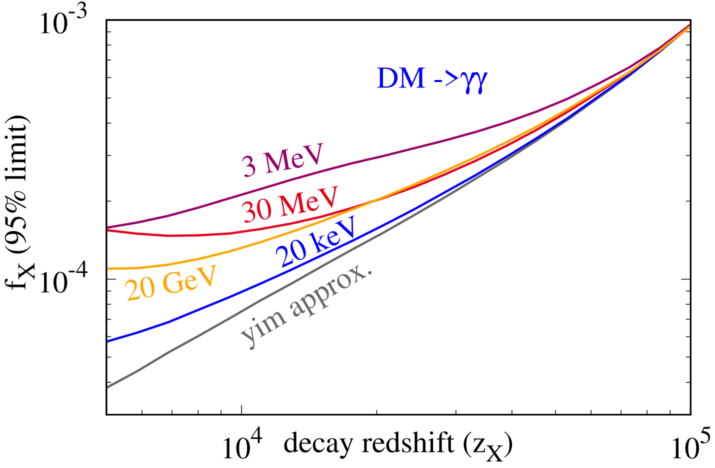
New COBE constraints on decaying dark matter: upto a factor of 5 correction

electron-positron channel *Acharya and Khatri 2019b*



New COBE constraints on decaying dark matter: upto a factor of 5 correction

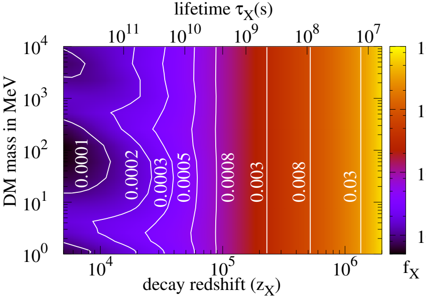
photon channel *Acharya and Khatri 2019b*



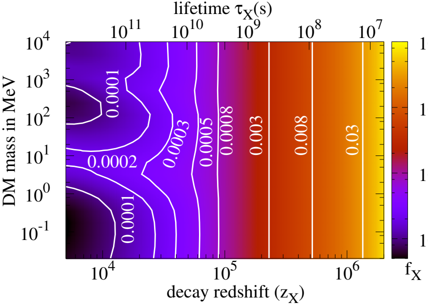
CMB spectral distortions are sensitive to the mass of decaying particle as well as the lifetime

COBE Constraints *Acharya and Khatri 2019b*

electron-positron channel



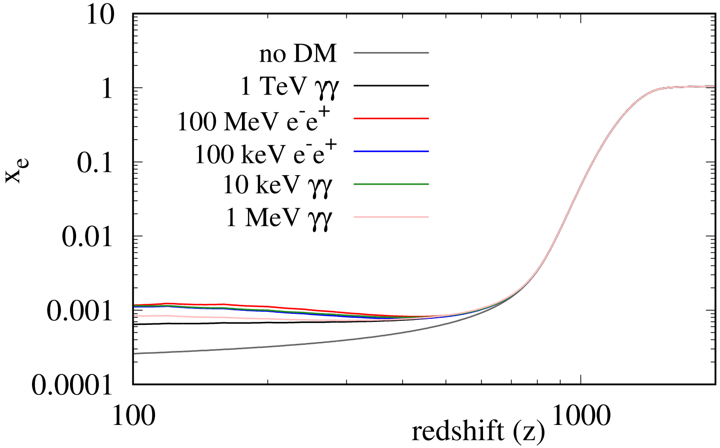
photon channel

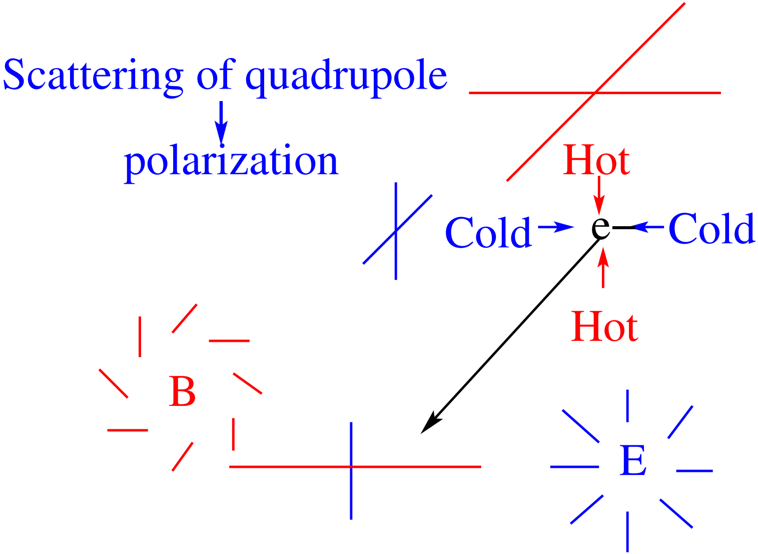


Energy injection changes the recombination history/residual electron fraction after recombination

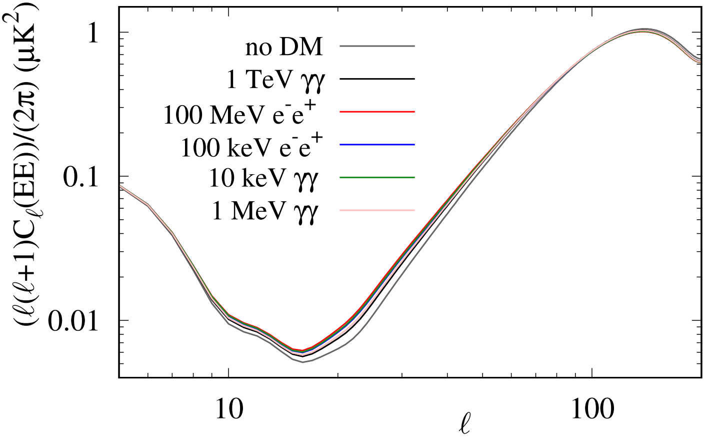
Acharya and Khatri 2019c

Lifetime = 10^{14} s




Scattering of quadrupole
polarization
Hot
Cold
e
Cold
Hot
B
E

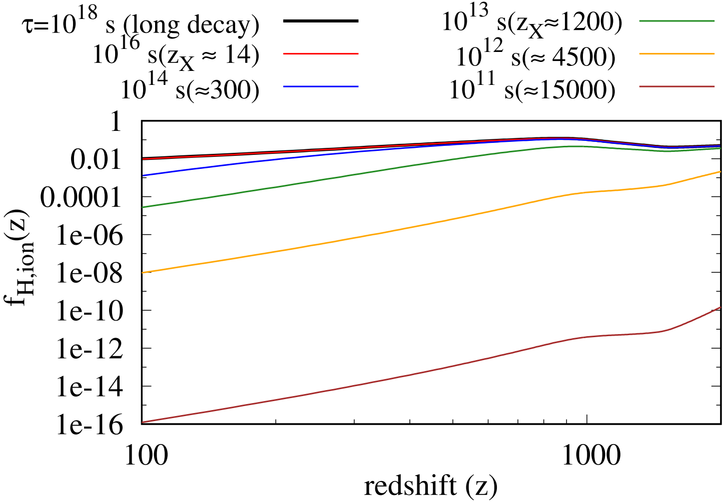
CMB E-mode polarization is enhanced from extra scatterings



A fraction of energy injected before recombination survives until after recombination

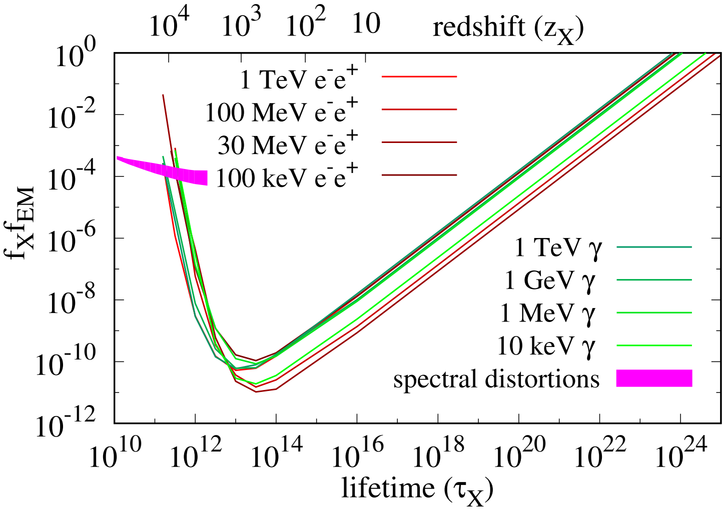
Acharya and Khatri 2019c

200 GeV dark matter decaying to electron-positron pairs



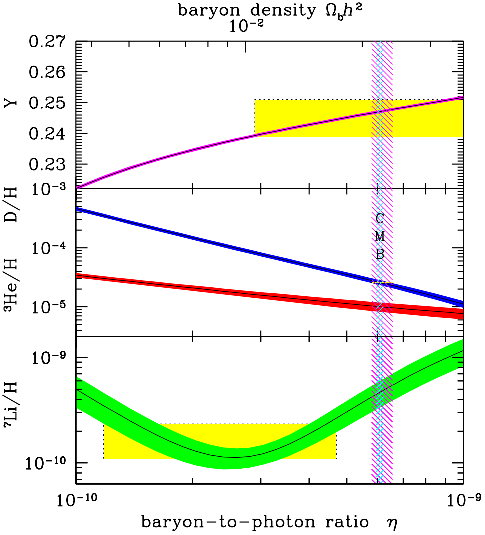
CMB anisotropies give strongest constraints for energy injection upto $z \approx 10000$!

Acharya and Khatri 2019c



Big bang nucleosynthesis

Fields, Molaro and Sarkar 2019, Particle Data Group



High energy photons can dissociate light elements produced in the BBN

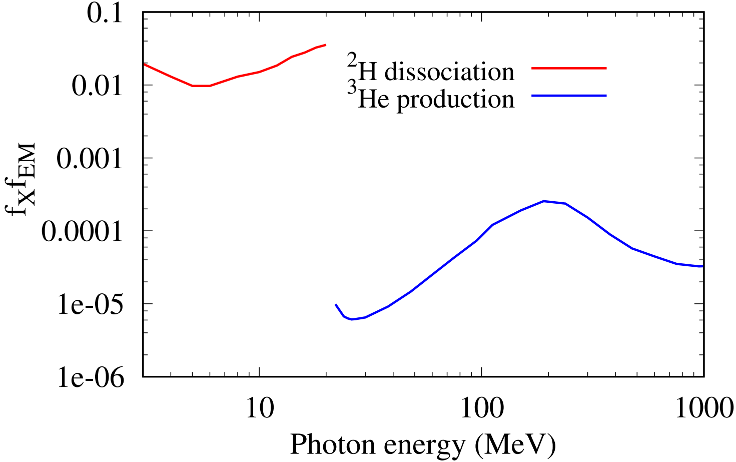
Acharya and Khatri 2019c

Reactions	photo-dissociation threshold (MeV)
^{2}H+$\gamma \rightarrow$ n+p	2.22
^{3}He+$\gamma \rightarrow$ ^{2}H+p	5.49
^{3}He+$\gamma \rightarrow$ n+p+p	7.718
^{4}He+$\gamma \rightarrow$ ^{3}H+p, ^{3}H $\rightarrow^3$ He + e^- + ν_e	19.81
^{4}He+$\gamma \rightarrow$ ^{3}He+n	20.58
^{4}He+$\gamma \rightarrow$ ^{2}H+^{2}H	23.85
^{4}He+$\gamma \rightarrow$ ^{2}H+n+p	26.07

Elements	theoretical value(1σ)	observational value(1σ)
$n_{^2\mathrm{H}}/n_\mathrm{H}$	$(2.58 \pm 0.13) \times 10^{-5}$ [75]	$(2.53 \pm 0.04) \times 10^{-5}$ [75]
Y_p	0.24709 ± 0.00025 [75]	0.2449 ± 0.0040 [76]
$n_{^3\mathrm{He}}/n_\mathrm{H}$	$(10.039 \pm 0.090) \times 10^{-6}$ [75]	1.5×10^{-5} (2σ upper limit) [77]

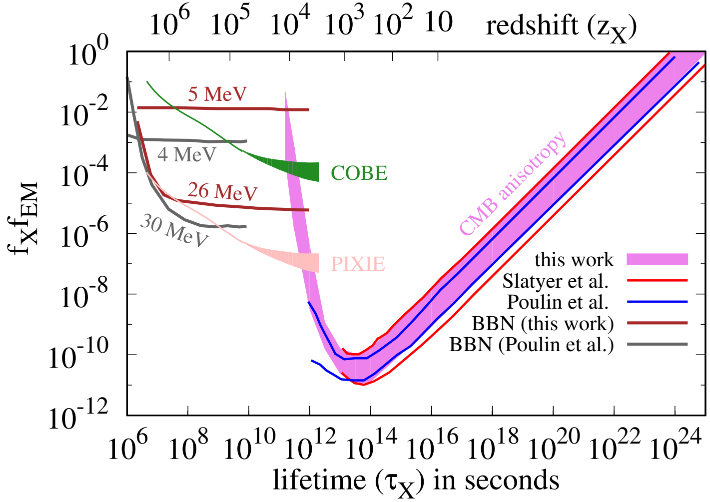
Strongest constraints come from deuterium destruction and He-3 over-production.

Acharya and Khatri 2019c



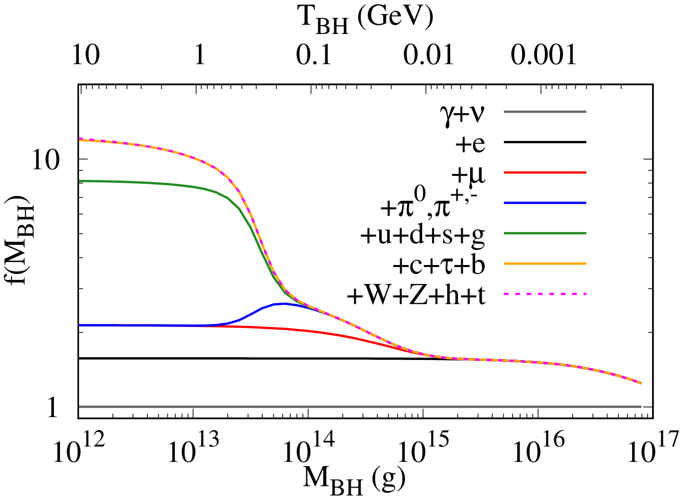
CMB anisotropy, spectral distortions and BBN constraints on long lived unstable particles

Acharya and Khatri 2019c



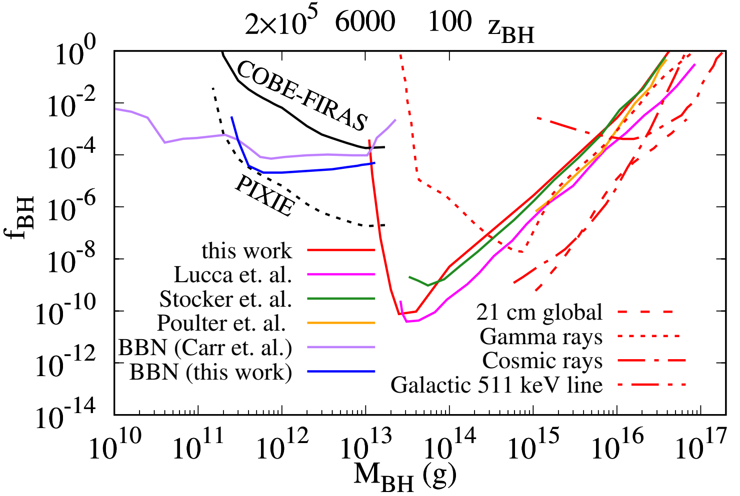
Primordial black holes can emit all standard model particles if they are hot enough

Acharya and Khatri 2019d



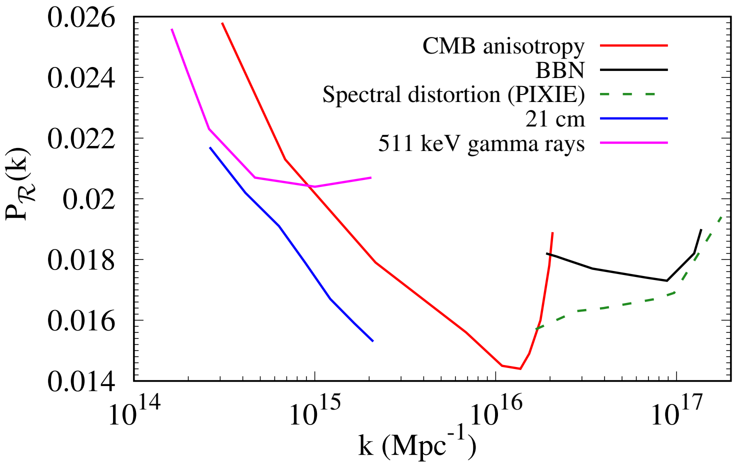
CMB and BBN constraints on primordial black holes

Acharya and Khatri 2019d



PBH constraints translate into constraints on primordial power spectrum

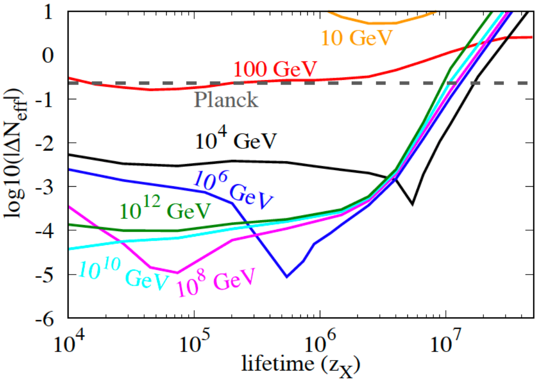
Probing 40 e-folds of inflation!



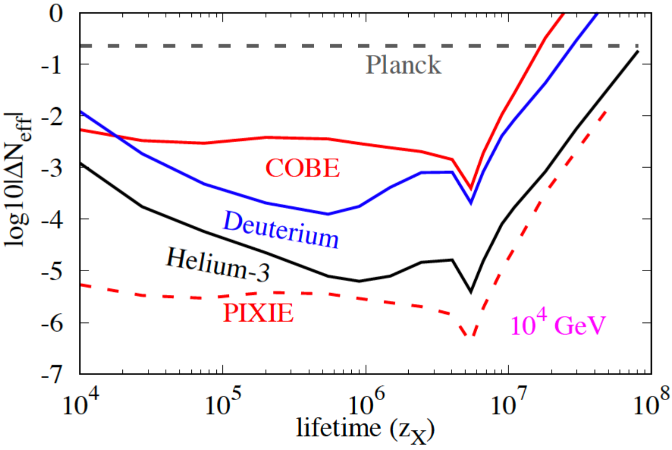
Injection of high energy neutrinos can change relative energy density of neutrinos and photons ($N_{\rm eff}$): constraints beyond $z = 2 \times 10^6$

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

$$\Delta N_{\rm eff} = N_{\rm eff}\left(\frac{\Delta\rho_\nu}{\rho_\nu} - \frac{\Delta\rho_{\rm CMB}}{\rho_{\rm CMB}}\right)$$



High energy photons produced in neutrino cascade can destroy BBN elements



The future: Falsifying ΛCDM

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/`

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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

Primordial B-modes
(Gravitons)

Precision measurement
(of things already discovered)

Lensing B-modes
Spectral Distortions
E-modes

Discovery
17 e-folds of inflation, Nature of Dark Sector,
Primodial 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)?

CORE (ESA)
PICO (NASA)
ECHO (ISRO)

High resolution

PRISM (ESA)

Planck launch 2009

Next (to next ?) Gen CMB mission ?

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