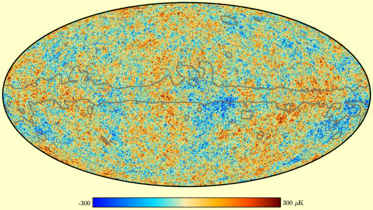

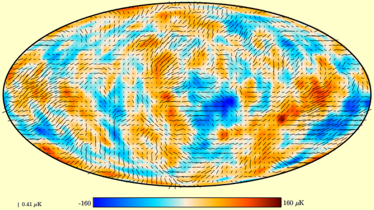

Phenomenology of the CMB

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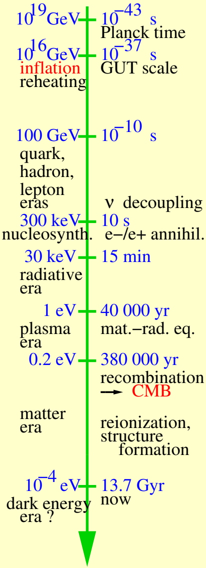
Conseil Scientifique de l'IN2P3
3 July 2023

Outline

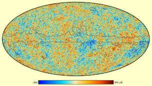
1. **The CMB** — introduction, power spectrum, E & B polarization, cosmological parameters & current status, reionization, gravitational lensing
2. **Inflation** — introduction, fluctuations, primordial power spectrum & observables, predictions & constraints, isocurvature, non-Gaussianity
3. **Other observables** — number of light species, neutrino masses, SZ effect, spectral distortions
4. **Conclusions & Targets**



1. The CMB

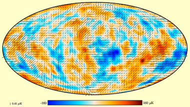
The **CMB** (Cosmic Microwave Background):

- Formed when universe became transparent at **recombination** of p^+ and e^- into neutral hydrogen.
- Very isotropic 2.73 K black-body radiation.
- Tiny fluctuations $\mathcal{O}(10^{-5}$ K):

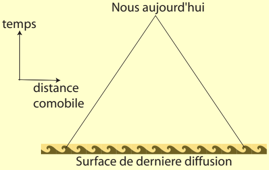


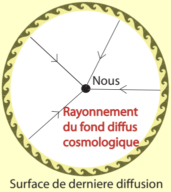
Planck 2018 T map

- Linearly **polarized** because of Thomson scattering at recombination:



Planck 2018 pol. map

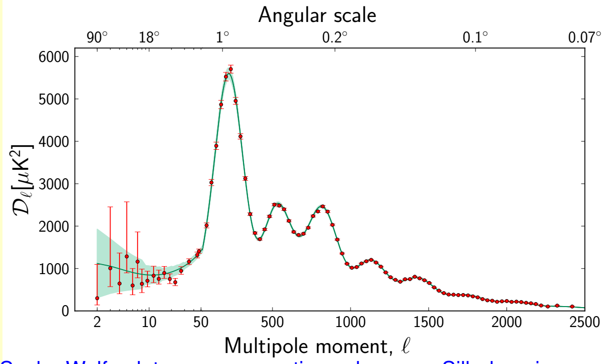




To describe temperature fluctuations in CMB:

2-point correlator $\langle T(\Omega_1) T(\Omega_2) \rangle$ $\Rightarrow$ **Power spectrum** C_ℓ^{TT}

$$T(\Omega) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m}^T Y_{\ell m}(\Omega); \qquad C_\ell^{TT} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{+\ell} |a_{\ell m}^T|^2$$



$\theta = 180^\circ/\ell$

$$D_\ell = \frac{\ell(\ell+1)C_\ell}{2\pi}$$

Planck temperature power spectrum

Sachs-Wolfe plateau acoustic peaks Silk damping

Cosmic variance: statistical error due to having only one sky to measure. Important at low ℓ where there are few $a_{\ell m}$ per ℓ.

Sachs-Wolfe plateau	Scales still super-horizon at recombination $\Rightarrow$ just primordial spectrum, **without evolution** (except ISW). Cosmic variance is large here, however.
Acoustic peaks	**Oscillations in baryon-photon plasma** before recomb. due to opposing forces gravity and radiation pressure. Snapshot at recomb.: certain λ at max or min of oscillation.
Silk damping	Recombination not instantaneous and initial mean free path photons $\neq 0 \Rightarrow$ photons diffuse out of overdensities on small scales and **smear out fluctuations**.

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Exact shape of C_ℓ depends on matter content of universe and other parameters
$\Rightarrow$ **precise determination of ΛCDM cosmological parameters**.

Examples: • position first peak $\rightarrow$ spatial curvature Ω_K,
• height second and third peaks $\rightarrow$ amount of baryons Ω_b & cold dark matter Ω_c.

$$\boldsymbol{\Omega_K} = 0.001 \pm 0.002, \quad \boldsymbol{\Omega_b h^2} = 0.0224 \pm 0.0001 \ (\mathbf{0.7\%}),$$
$$\boldsymbol{\Omega_c h^2} = 0.120 \pm 0.001 \ (\mathbf{1.0\%})$$
$$\Rightarrow \quad \boldsymbol{\Omega_m} \equiv \Omega_b + \Omega_c = 0.315 \pm 0.007, \quad \boldsymbol{\Omega_\Lambda} = 0.685 \pm 0.007.$$
$$\boldsymbol{h} \equiv H_0/100 = 0.674 \pm 0.005 \ (\mathbf{0.8\%}), \quad \textbf{Age} = 13.80 \pm 0.02 \text{ Gyr}.$$

[Planck 2018, 1807.06209]

CMB polarization

Consider for simplicity monochromatic EM plane wave propagating in z direction:

$$\vec{E}(t,\vec{x}) = \begin{pmatrix} a_1 e^{i\theta_1} \\ a_2 e^{i\theta_2} \\ 0 \end{pmatrix} e^{i(\omega t - kz)}.$$

Instead of $a_1, a_2, \theta_1, \theta_2$ we can use 4 Stokes parameters I, Q, U, V:

$$I = {a_1}^2 + {a_2}^2, \quad Q = {a_1}^2 - {a_2}^2, \quad U = 2a_1 a_2 \cos(\theta_1 - \theta_2), \quad V = 2a_1 a_2 \sin(\theta_1 - \theta_2).$$

- $I \rightarrow$ total intensity, $V \rightarrow$ left/right-handed circular polarization,
- $Q \rightarrow$ horizontal/vertical linear polarization, $U \rightarrow \pm 45^\circ$ linear polarization.

V is not produced by Thomson scattering and is **absent in CMB**.
Of course CMB is not monochromatic plane wave $\Rightarrow$ I, Q, U depend on $\vec{x}$ and ω.

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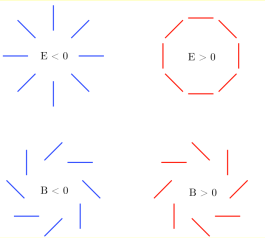
Of course CMB is not monochromatic plane wave $\Rightarrow$ I, Q, U depend on $\vec{x}$ and ω.

I (and V) invariant under rotations, not Q and U.
$\Rightarrow$ **Use E (gradient) and B (curl)** to describe **linear polarization** instead (invar. but non-local):

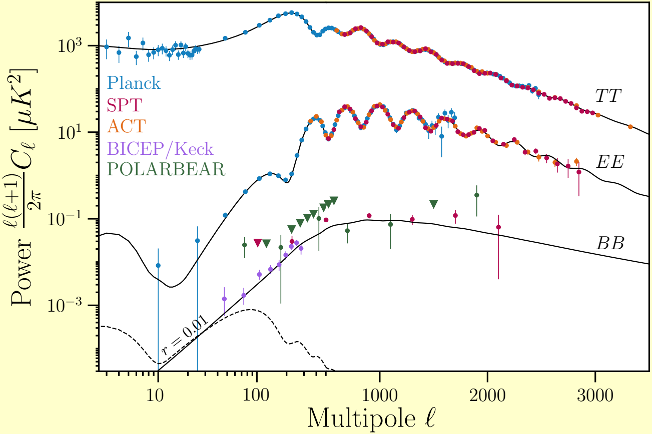
$$Q \pm iU = -\sum_{\ell,m} (E_{\ell m} \pm iB_{\ell m}) \ {}_{\pm 2}Y_{\ell m}$$

with ${}_{\pm 2}Y_{\ell m}$ spherical harmonics of spin ± 2.

Finally, $E = \sum_{\ell,m} E_{\ell m} Y_{\ell m}$ and $B = \sum_{\ell,m} B_{\ell m} Y_{\ell m}$.



Status current measurements of C_ℓ^{TT}, C_ℓ^{EE}, C_ℓ^{BB}: (not shown: TE cross spectrum)



Complementarity between satellite experiments (large scales) and ground-based experiments (small scales).

[Chang et al., 2203.07638]

- TT: we have **perfect measurements** (cosmic variance limited).
- EE: measured, but **to be improved** with next generation (especially low-ℓ).
- BB: unmeasured (primordial), **holy grail** for next generation of experiments.

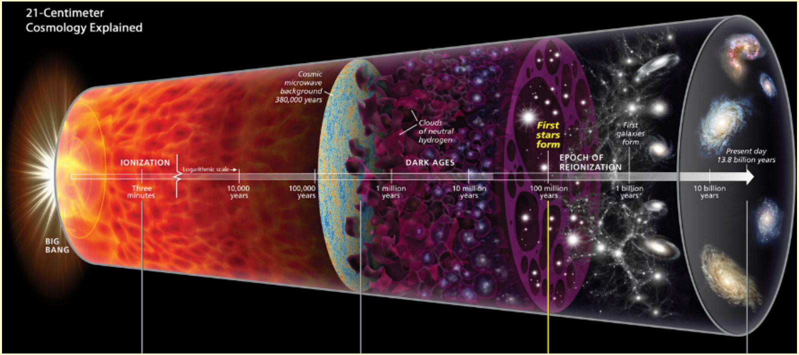


Image credit: Roen Kelly/Discover magazine

After recombination: universe no longer ionized. But star formation partially **reionizes** universe $\Rightarrow$ rescattering of CMB photons.

- **Reduces** existing CMB power spectrum $\propto e^{-\tau}$.
- **Polarizes** CMB through Thomson scattering $\rightarrow$ "reionization bump".

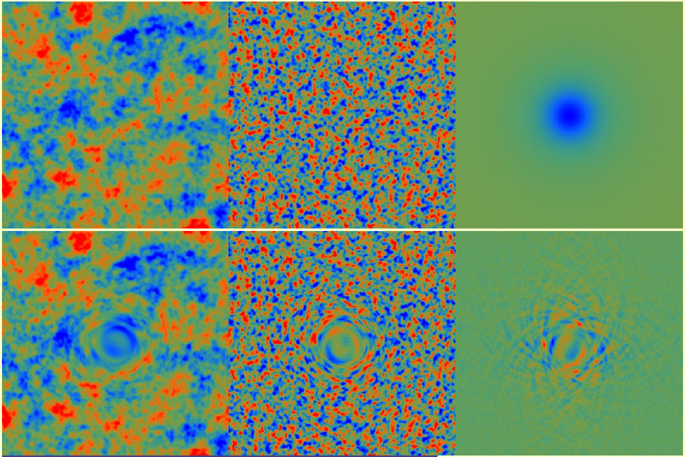
Optical depth to reionization $\tau = \int_{t_{\text{reion}}}^{t_0} \sigma_T n_e(t)\, c\, dt$ determines both.

$\tau = 0.054 \pm 0.007$ (**13%**) *[Planck 2018, 1807.06209]* τ larger $\leftrightarrow$ first stars formed earlier.

Gravitational lensing

Matter distribution in late universe has impact on CMB via **gravitational lensing**.

- + Allows determination total matter distribution.
- – Contamination of CMB spectrum (reduction peaks by smoothing).
- – **Creates B-polarization** from E, much larger than primordial B.



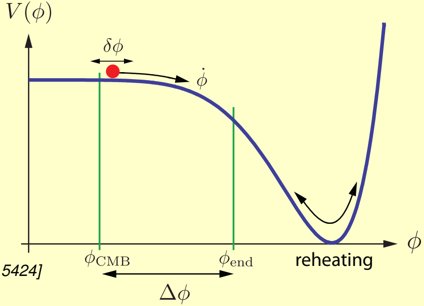
Unlensed:
(1) Temperature
(2) E-polarization
(3) Lensing potential

Lensed:
(1) Temperature
(2) E-polarization
(3) B-polarization

[Hu & Okamoto, astro-ph/0111606]

2. Inflation

Inflation = very rapid expansion driven by almost constant potential energy of **slowly rolling scalar field**.



[Baumann, 0907.5424]

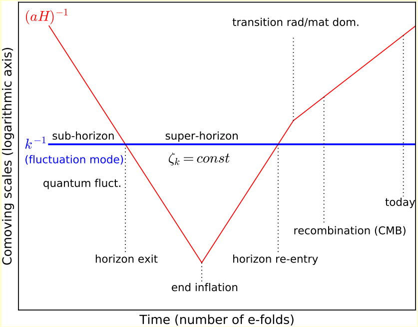
⇒ **Solves horizon & flatness** problems and **creates seeds** for structure formation:

1. Very rapid expansion: actual horizon much larger than observable universe;
2. Quantum fluctuations inflated to macroscopic classical perturbations.

Constraints on inflation models:

- Ad 1. At least 60 e-folds of inflation;
- Ad 2. Inflationary fluctuation properties have to match CMB observations.

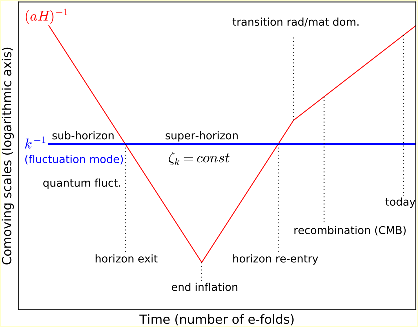
⇒ Observational constraints on underlying high-energy theories.



Quantum fluctuations completely change behaviour when inflated to $\lambda \gtrsim (aH)^{-1}$ (comoving Hubble length):

instead of oscillations → **growing** (or constant) and **decaying** mode.

When decaying mode negligible → fluctuations **classical** (squeezing).



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Single-field slow-roll inflation:

Scalar (∼ energy density) **fluctuations**: power spectrum $P_s(k) = A_s(k/k_0)^{n_s - 1}$

with **amplitude** $A_s = \dfrac{\hbar G}{\pi c^5} \dfrac{H_{k_0}^2}{\epsilon_{k_0}}$ and **spectral index** $n_s - 1 = -6\epsilon_{k_0} + 2\eta_{k_0}$

- $H_{k_0}^2 \approx \frac{8\pi G}{3c^2} V_{k_0}$ energy scale of inflation (at horizon exit of CMB pivot scale k_0),
- $\epsilon_{k_0} \approx \frac{c^4}{16\pi G}(V'/V)^2_{k_0}$, $\eta_{k_0} \approx \frac{c^4}{8\pi G}(V''/V)_{k_0}$ slow-roll parameters $\ll 1$.

A_s and n_s well measured, but degeneracy because **two** observables depend on **three** inflationary variables.

Tensor (gravitational wave) **fluctuations**: power spectrum $P_t(k) = A_t(k/k_0)^{n_t}$

with **amplitude** $\boxed{A_t = \frac{16\hbar G}{\pi c^5} H_{k_0}^2}$ and **spectral index** $\boxed{n_t = -2\epsilon_{k_0}}$

Instead of A_t we use r, **tensor-to-scalar ratio**: $\boxed{r \equiv A_t/A_s = 16\epsilon_{k_0} = -8n_t}$

Scalar fluctuations cannot create B-polarization, only tensor fluctuations can.

$\Rightarrow$ **If we can measure primordial B-modes, we will know *r*.**

This breaks degeneracy so that we learn

- **energy scale** of inflation (at horizon exit of CMB pivot scale),
- **first** and **second derivatives** of inflaton potential there (if single field).

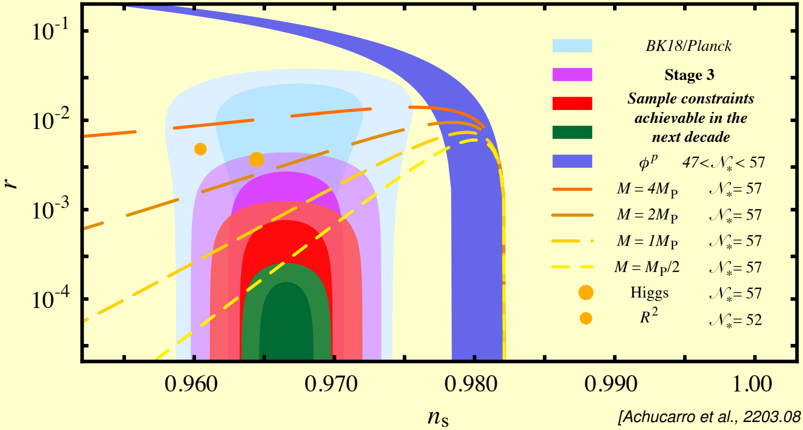
- In many models r directly gives lower bound on field excursion ("Lyth bound"): $\Delta\phi/M_P \gtrsim 10\sqrt{r}\,\sqrt{c^3/\hbar}$. *[Lyth, hep-ph/9606387]*
- If we can also measure n_t we will test single-field slow-roll consistency relat.

Current constraints:

$$\ln(10^{10} A_s) = 3.04 \pm 0.01\ (\mathbf{0.5\%}), \qquad n_s = 0.965 \pm 0.004\ (\mathbf{0.4\%}),$$
$$r < 0.032\ (95\%\ \mathrm{CL})$$

[Planck 2018, 1807.06209] and for r [Tristram et al., 2112.07961]

Forecasts and predictions for *r*:



[Achucarro et al., 2203.08128]

While *r* could be much smaller, there are **important targets** in region $r \gtrsim 0.001$:

- Popular Starobinsky R^2/Higgs inflation models;
- More generally, any single-field **monomial/plateau/hilltop** potential with **super-Planckian** characteristic scale/field excursion.

Isocurvature

If multiple-field inflation $\rightarrow$ possibility of **relative fluctuations** between components: **isocurvature modes**, parametrized by $\boxed{\beta_{\text{iso}} = A_{\text{iso}}/A_s}$. **Current constraints**:

$$\beta_{\text{iso}}(\text{CDM}) < 0.039, \quad \beta_{\text{iso}}(\nu \text{ density}) < 0.089, \quad \beta_{\text{iso}}(\nu \text{ velocity}) < 0.058 \text{ (95\% CL)}$$

[Montandon et al., 2007.05457]

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Non-Gaussianity

Since gravity **non-linear**, fluctuations not exactly Gaussian ⇒ information beyond power spectrum in higher correlators like **bispectrum** $B(k_1, k_2, k_3)$ (3-point corr.).

- Parametrized by $f_{\text{NL}} \sim B/P_s^2$ (different f_{NL} for different bispectrum shapes).
- Single-field slow-roll inflation: $f_{\text{NL}} \sim 0.01$.
  Other models predict larger f_{NL}; important **observational target:** $\boldsymbol{f_{\text{NL}} \sim 1}$.
- Multiple-field inflation: local bispectrum template;
  Single-field with non-standard kinetic terms: equilateral & orthogonal.

Current constraints:

$f_{\text{NL}}^{\text{loc}} = -0.9 \pm 5.1$, $f_{\text{NL}}^{\text{equ}} = -26 \pm 47$, $f_{\text{NL}}^{\text{ort}} = -38 \pm 24$ *[Planck 2018, 1905.05697]*

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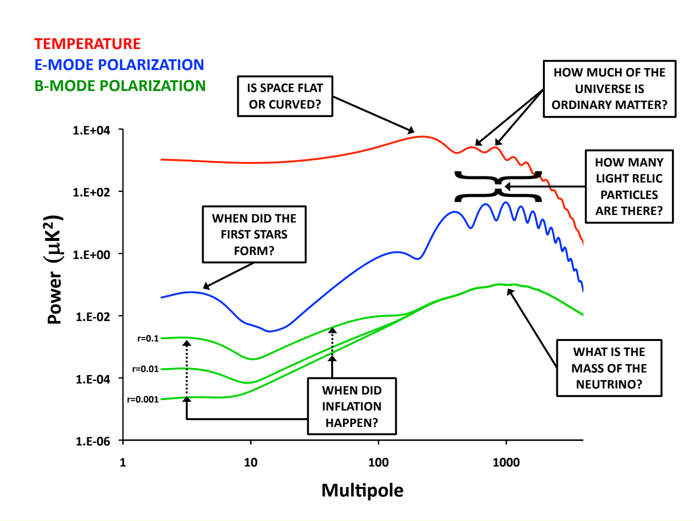
[Planck 2018, 1905.05697]

Features

Some inflation models predict **features** (like oscillations) correlated between power spectrum (T+E) and bispectrum. *See e.g. [Achucarro et al., 2203.08128]*

3. Other observables



[Chang et al., 2203.07638]

Number of light species

Energy density relativistic species: $\rho_R = \left(1 + N_{\text{eff}} \frac{7}{8} \left(\frac{4}{11}\right)^{4/3}\right) \rho_\gamma$

- If 3 neutrinos fully decoupled before electron-positron annihilation: $N_{\text{eff}} = 3$.
- In fact not fully decoupled, hence **SM prediction**: $\boldsymbol{N_{\text{eff}} = 3.046}$.
- **Other light particles**, like sterile neutrinos or axions, would increase N_{eff}
  $\Rightarrow$ change expansion history, transition radiation to matter domination
  $\Rightarrow$ impact on evolution CMB high-ℓ modes that reentered horizon early.

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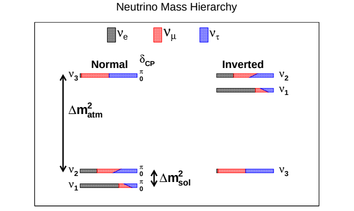
Neutrino masses

What is $\sum m_\nu$? Normal or inverted **hierarchy**?
Normal: $\sum m_\nu \geq 0.06$, inverted: $\sum m_\nu \geq 0.10$ eV.

Free-streaming **neutrinos do not cluster** on small scales to form structure.
Hence if $\sum m_\nu \uparrow \Rightarrow \Omega_\nu \uparrow$
$\Rightarrow$ larger suppression of small-scale structure
$\Rightarrow$ impact on gravitational lensing of CMB.



[Qian & Vogel, 1505.01891]

Current constraints: [Di Valentino et al., 2207.05167]

$N_{\text{eff}} = 3.08 \pm 0.17$ (**5.5%**), $\sum m_\nu < 0.13$ eV (95% CL)

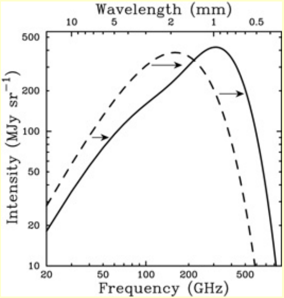
Sunyaev-Zel'dovich effect

Thermal SZ effect: Inverse Compton scattering of CMB photons by hot electrons in **galaxy clusters** distorts CMB frequency spectrum non-thermally, conserving photon number density.

$\Delta T_{\text{TSZ}}(\nu)/T_{\text{CMB}} = g(\nu)y$
with Compton parameter $y = \int \sigma_T n_e \frac{k_B T_e}{m_e c^2} dl$

and $g(\nu) \begin{cases} < 0 & \text{if } \nu < 217 \text{ GHz} \\ > 0 & \text{if } \nu > 217 \text{ GHz} \end{cases}$

$\Rightarrow$ Used to identify clusters, study cluster physics and galaxy formation.



[Carlstrom et al., astro-ph/0208192]

Kinetic SZ effect: Additional thermal distortion due to peculiar velocities of galaxy clusters (Doppler effect) $\Rightarrow$ Determine cluster velocities.

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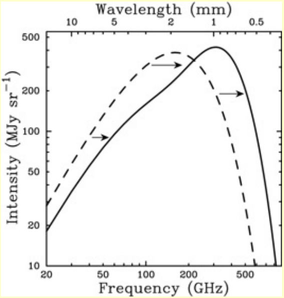

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Spectral distortions

Many other sources of spectral distortions exist, both before and after recomb.

- ***y*-type**: distortions similar to thermal SZ (conserve n_γ).
- **μ-type**: early energy injections, partially thermalized $\rightarrow$ behave like chem. pot.

Huge discovery potential: information not probed in other ways, and no new measurements since COBE satellite. *See e.g. [Chluba et al., 1903.04218]*

4. Conclusions & Targets

- There is a wealth of information in the CMB.
- The temperature power spectrum has been well measured, but upcoming experiments will improve measurements of **E-polarization** and **B-polarization**, and hopefully detect the primordial B-modes.
- **Scientific CMB-related targets for the next 15 years**:
  - Measure (or constrain) r to learn more about **inflation**.
  - Improve constraints on (or detect!) other inflationary observables: f_{NL}, β_{iso}, oscillations.
  - Improve error bars on τ and learn more about **reionization**/first stars.
  - Improve knowledge of **neutrino**/light particle sector: N_{eff}, $\sum m_\nu$.
  - Improve error bars on all **cosmological parameters**.
  - Reconstruct **matter distribution** through lensing: growth of structure.
  - Better measurements **SZ effects**: cluster physics, galaxy formation.
  - Learn more about **dark matter** and **dark energy** through the above.
  - Discovery potential **beyond-SM physics** (cosmic birefringence, . . .).
- Other targets CMB missions: **galactic science**, **mapping microwave sky**.
- Scientific CMB targets for later: n_t, spectral distortions, . . .