Cosmological Constraints on SuperWIMPs

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BSM and DM at the LHC

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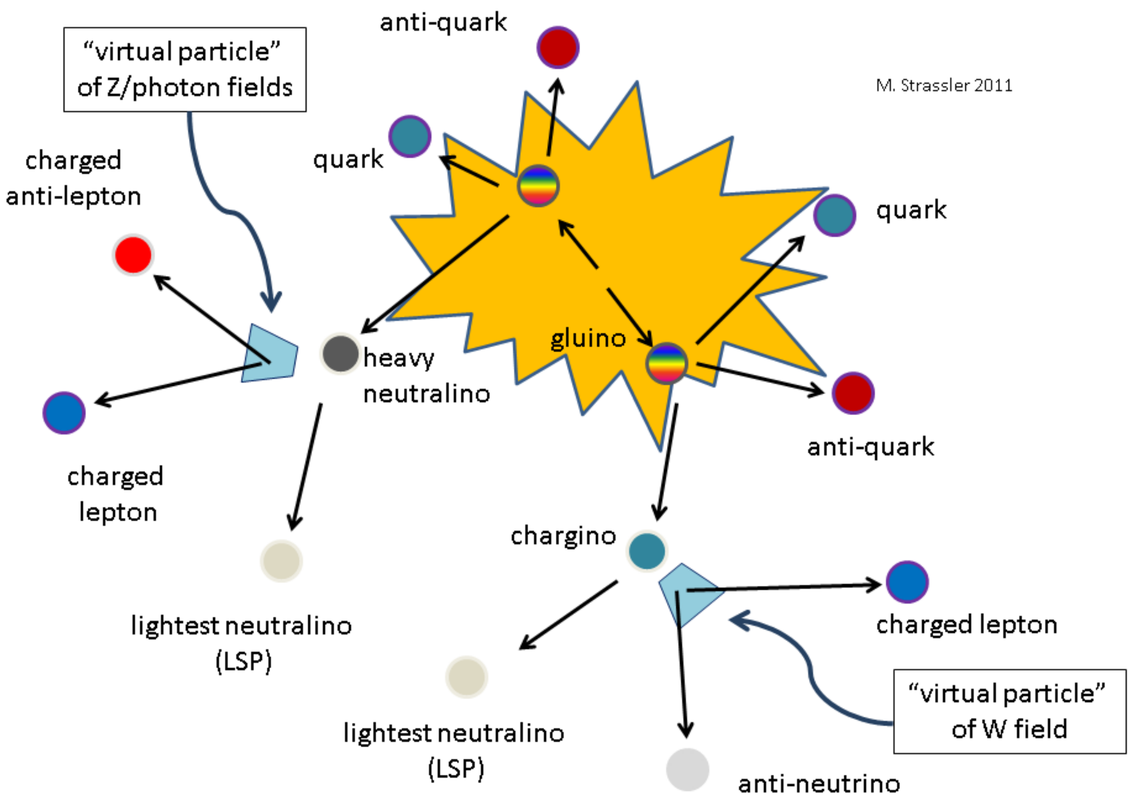

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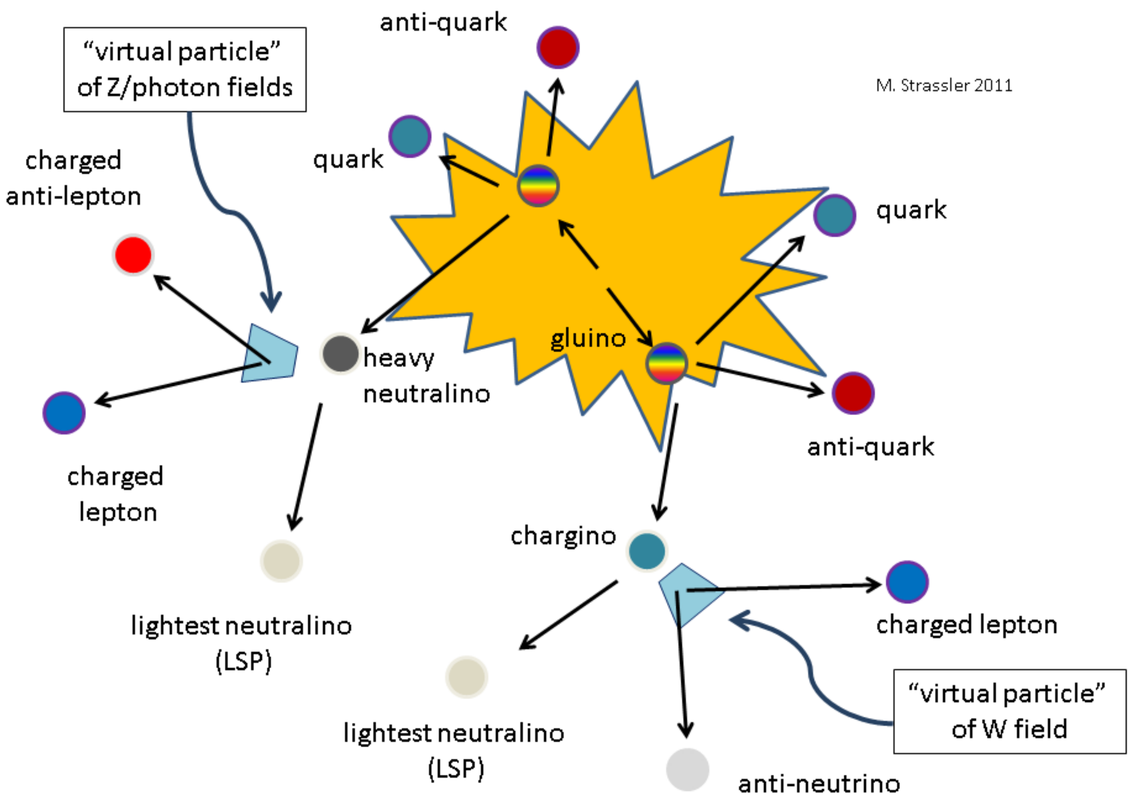

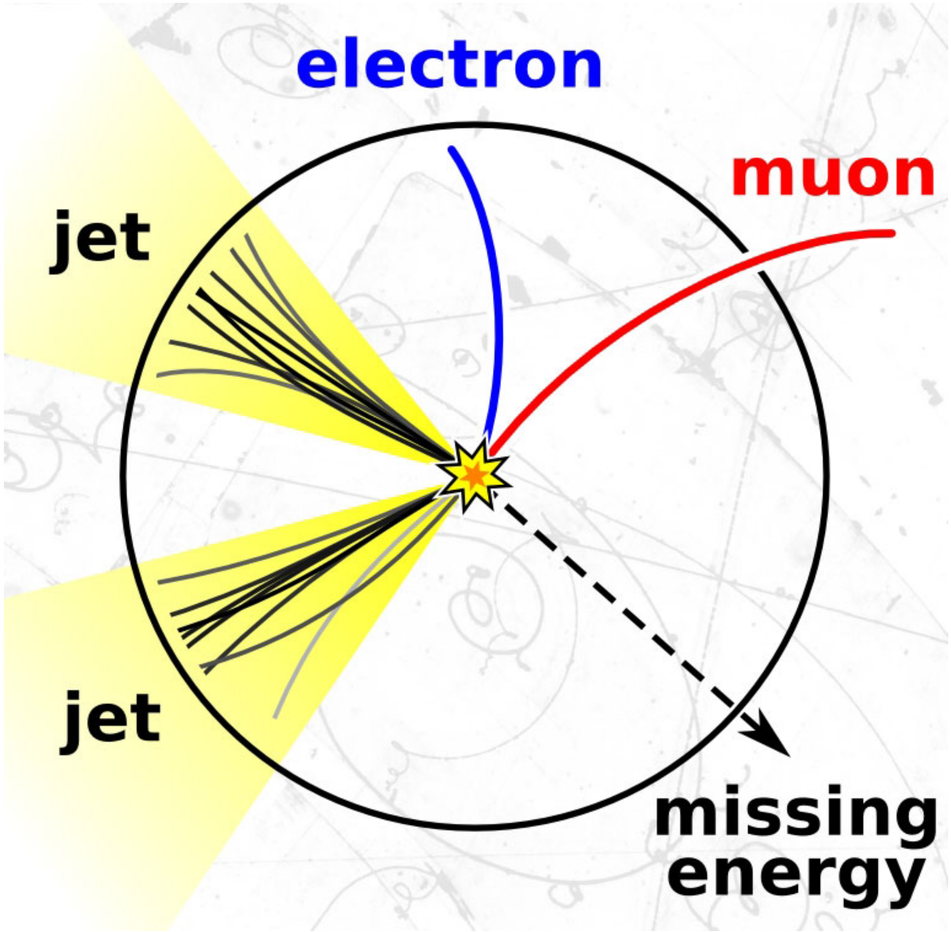

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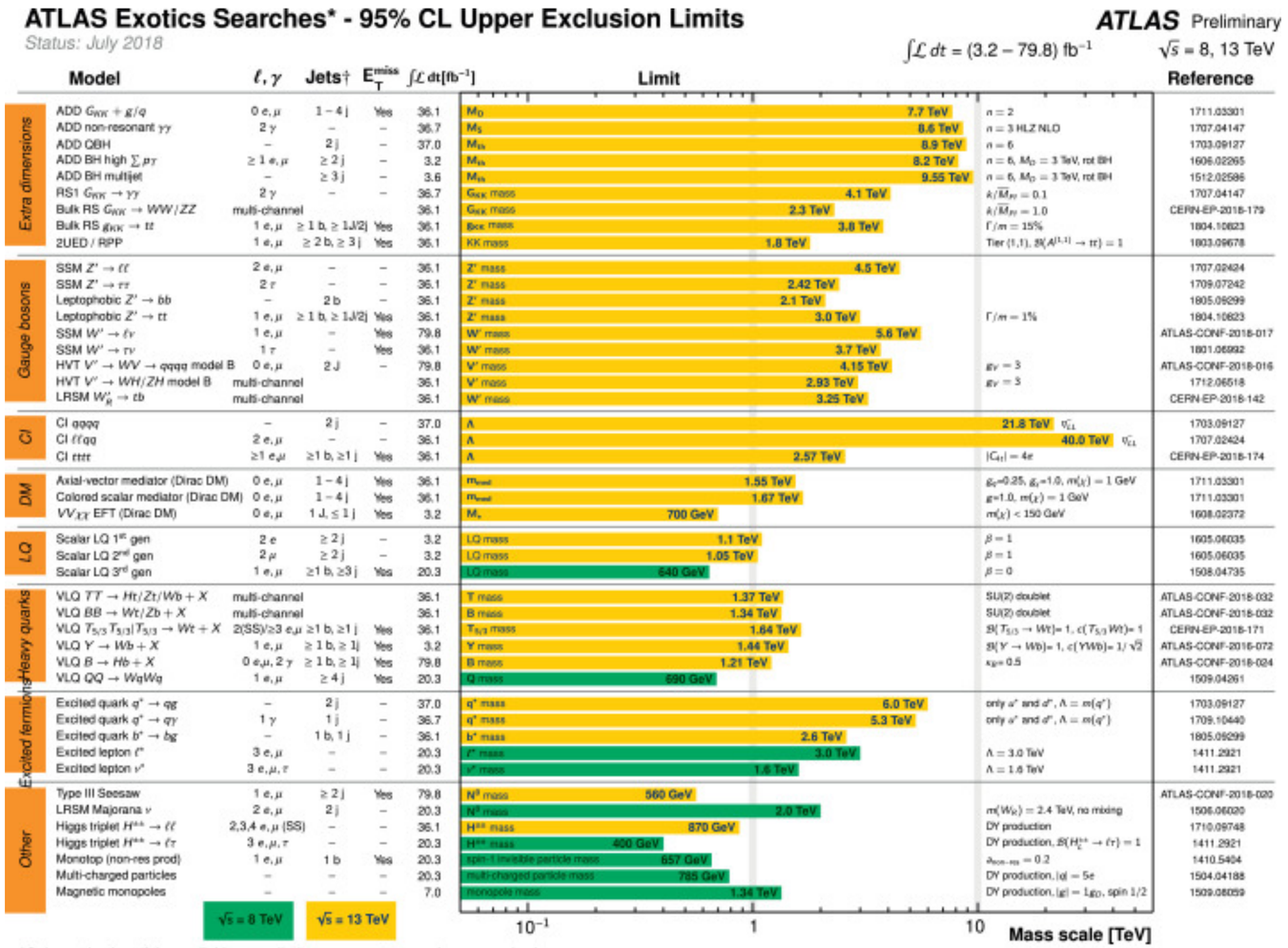

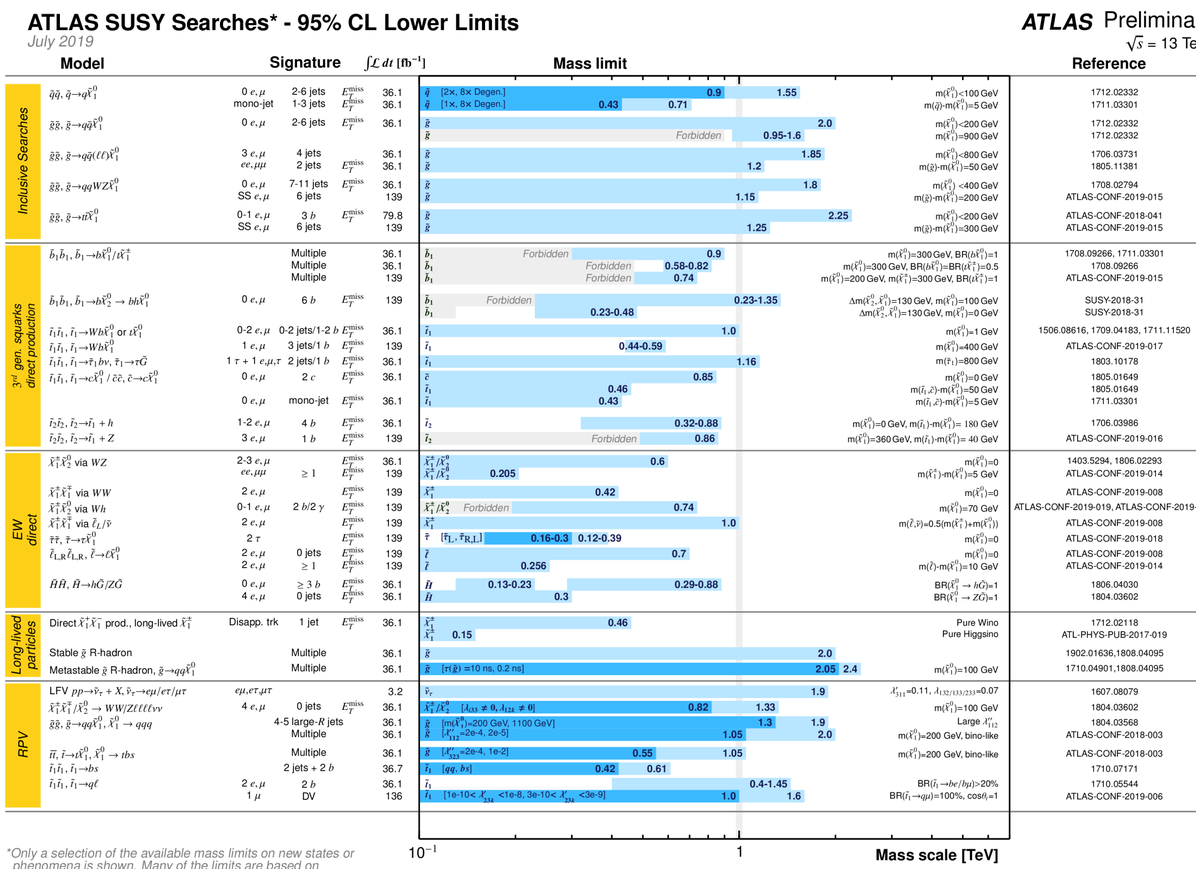

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What if BSM was very weakly coupled : Decay lengths upto ~ 100 m

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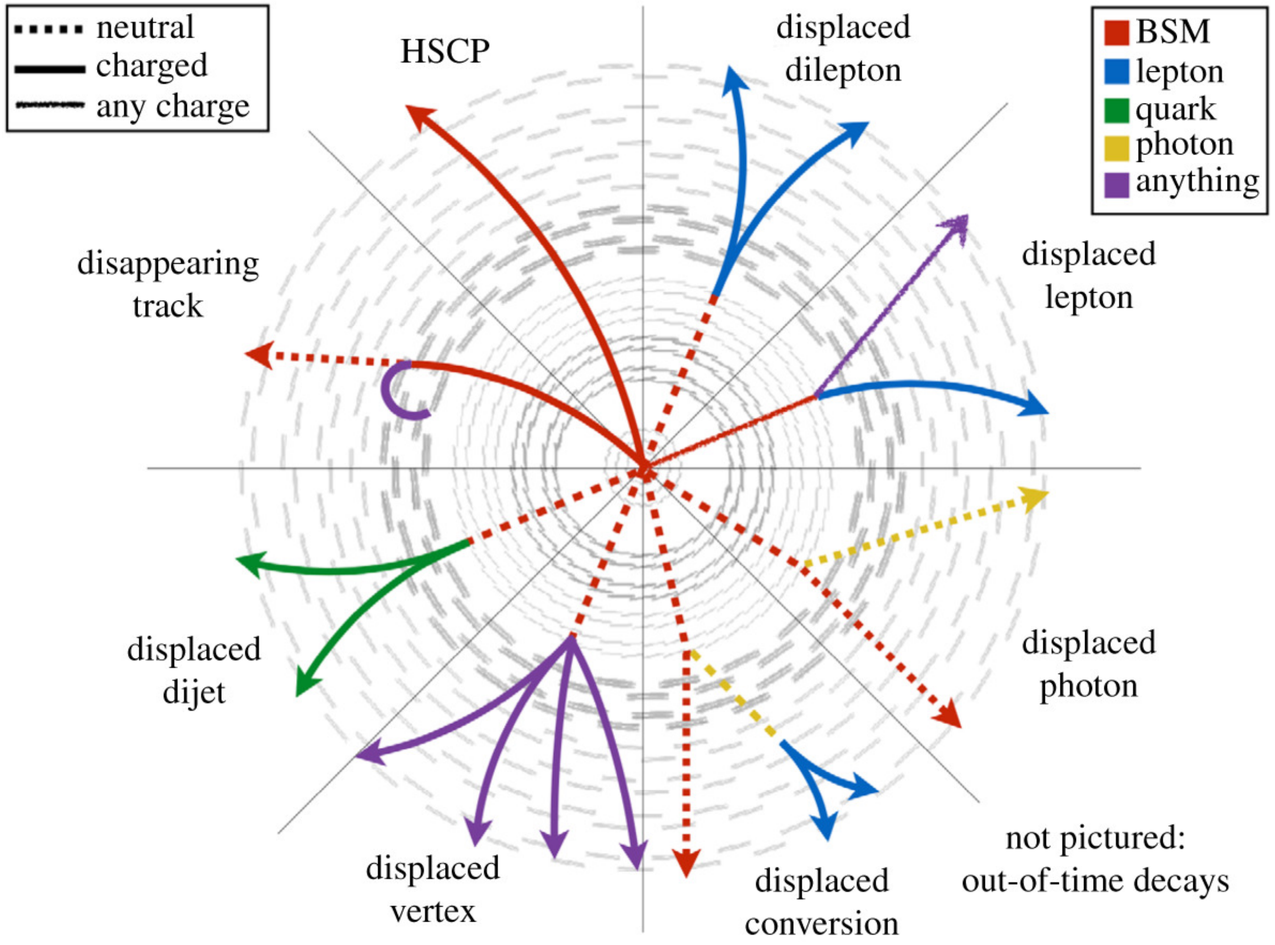

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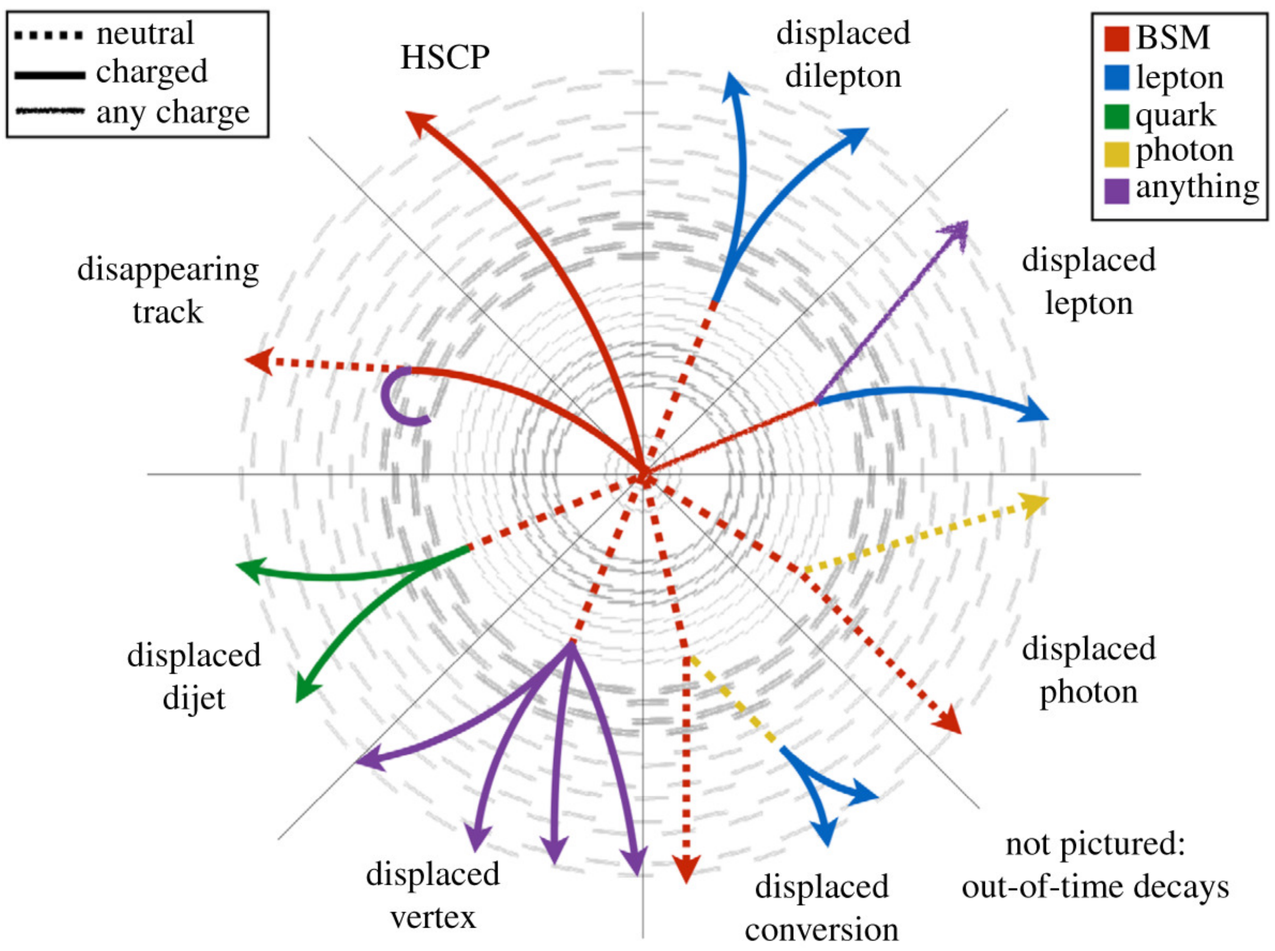

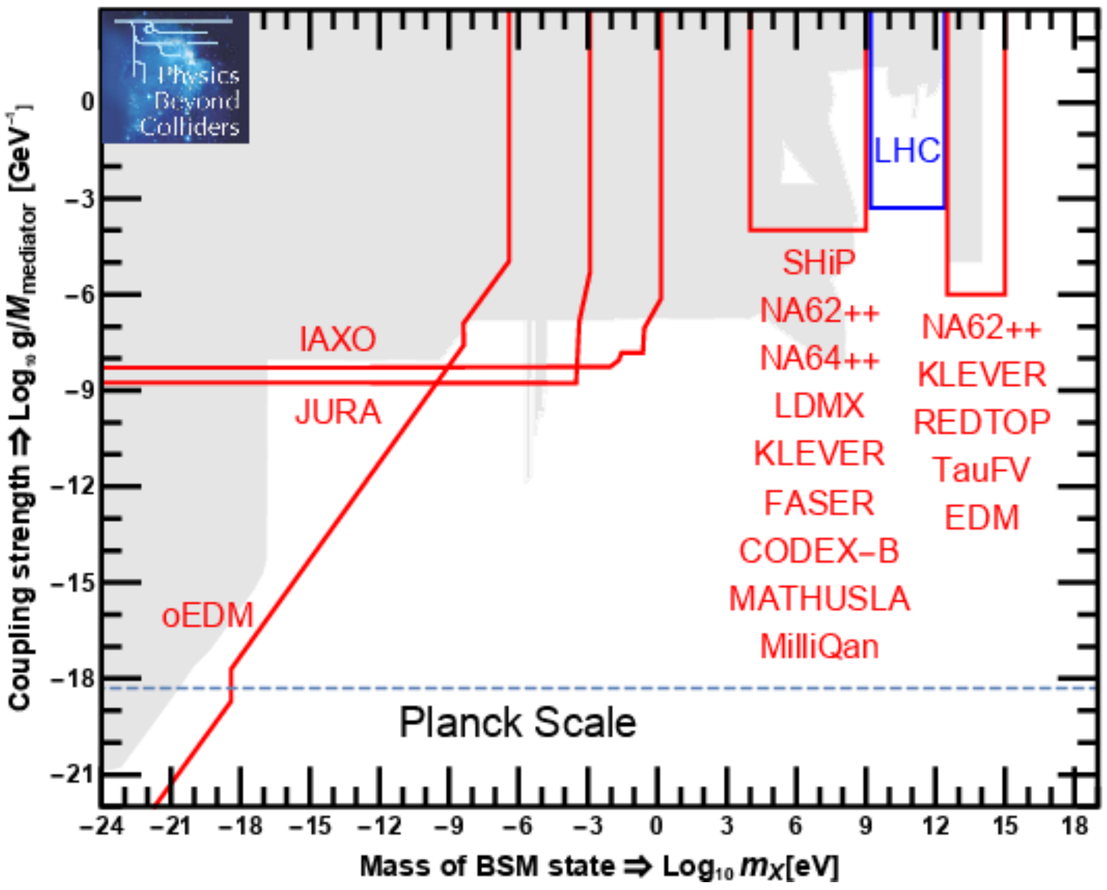

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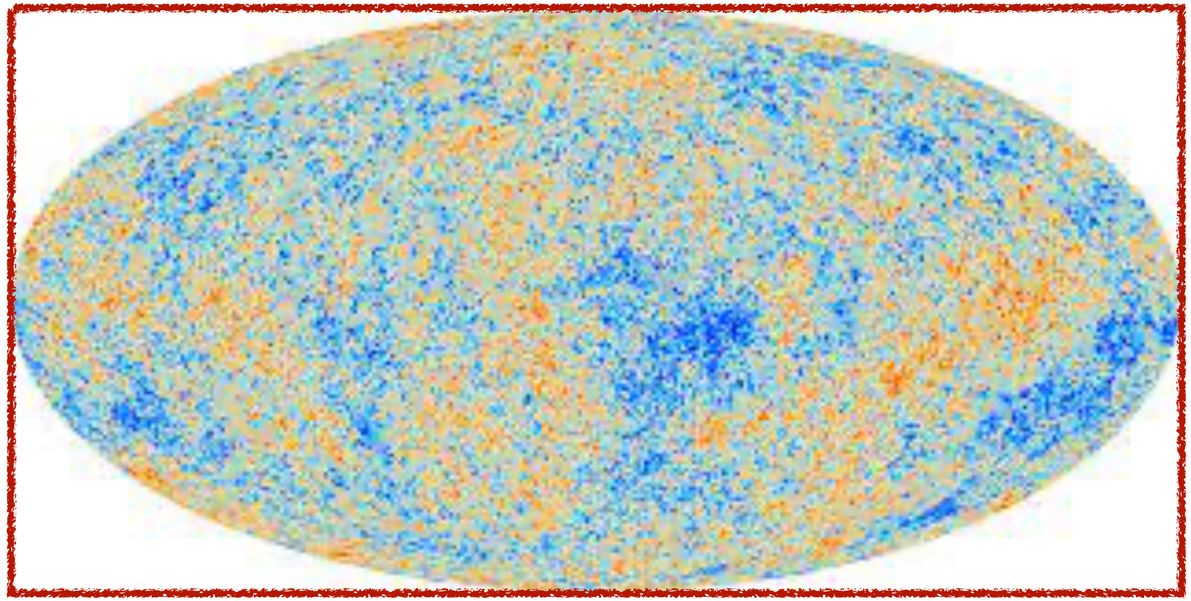

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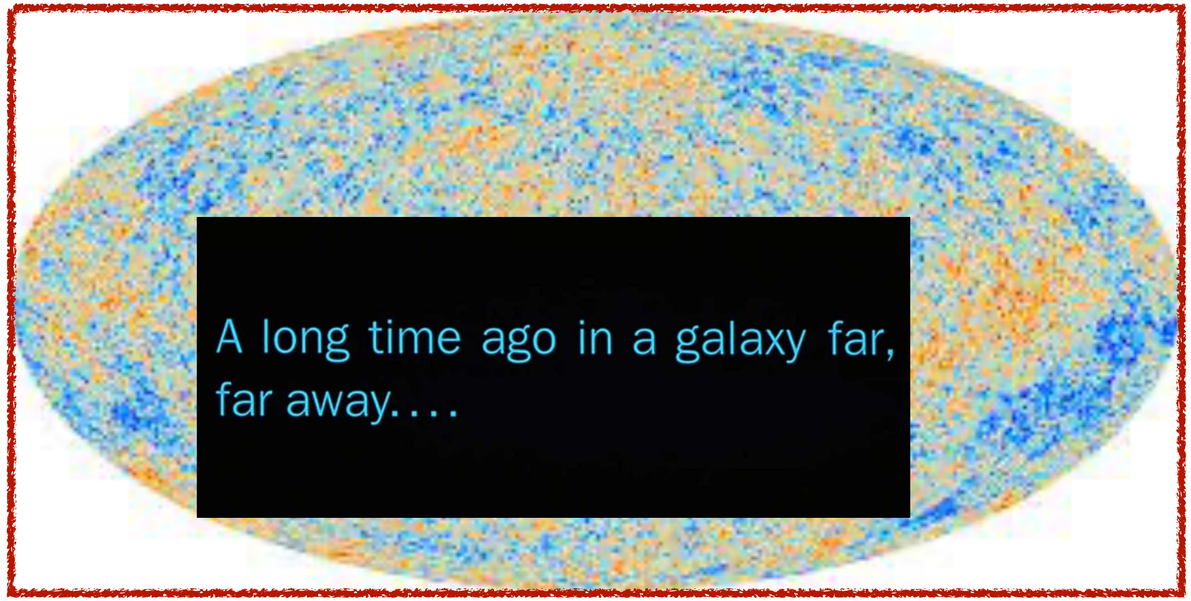

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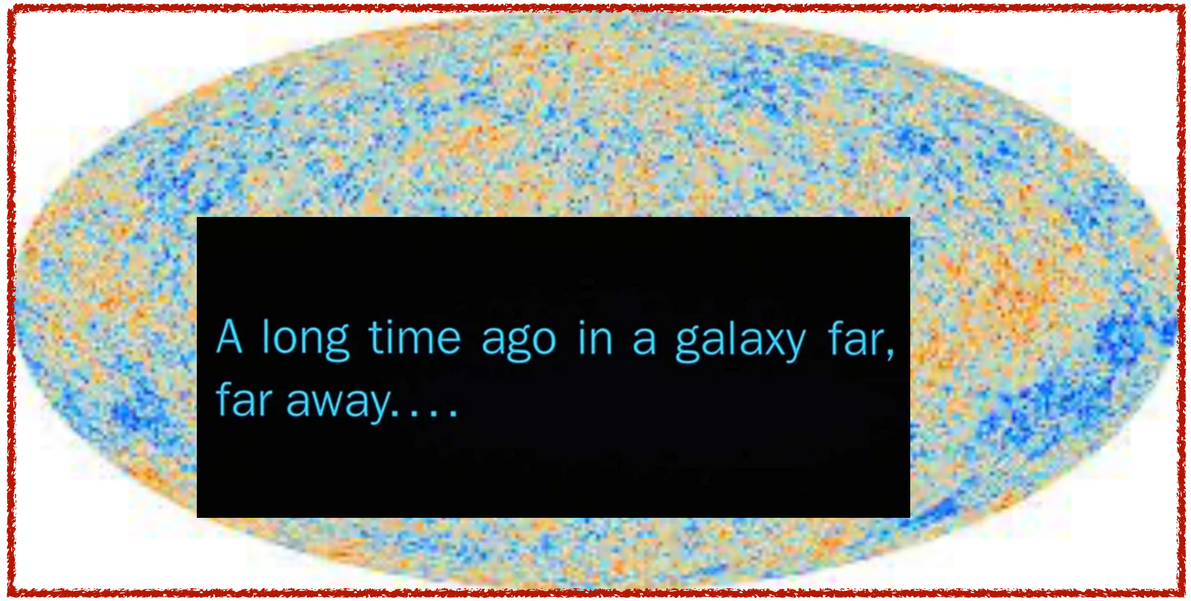

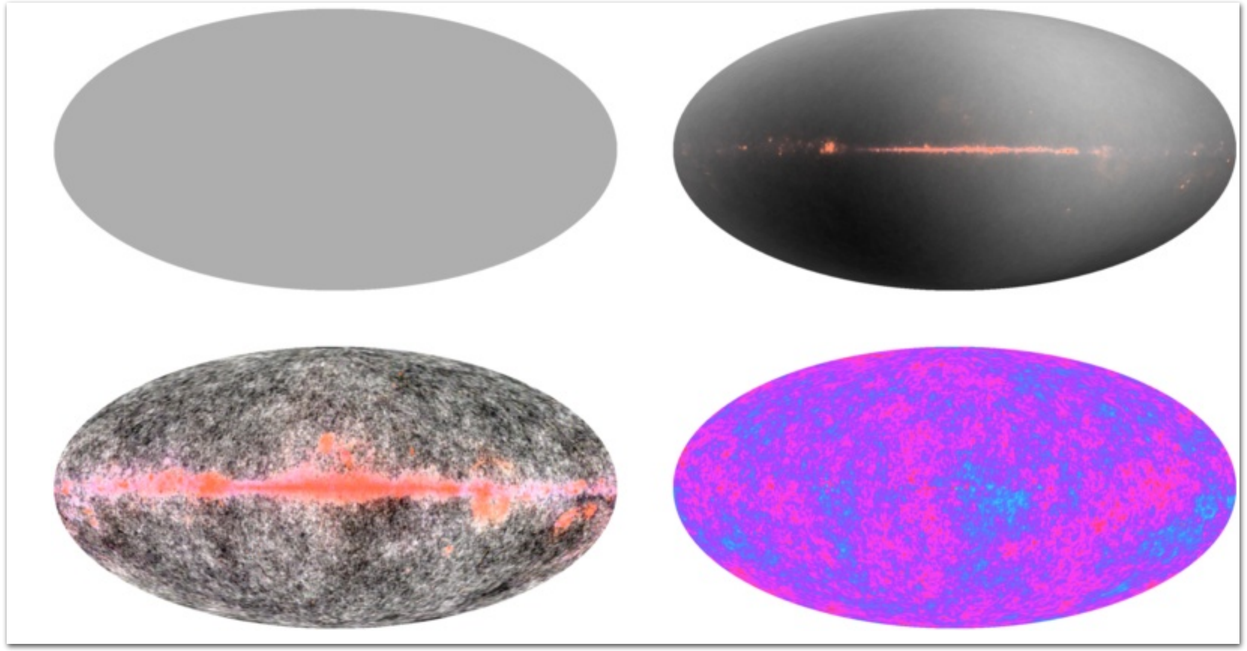

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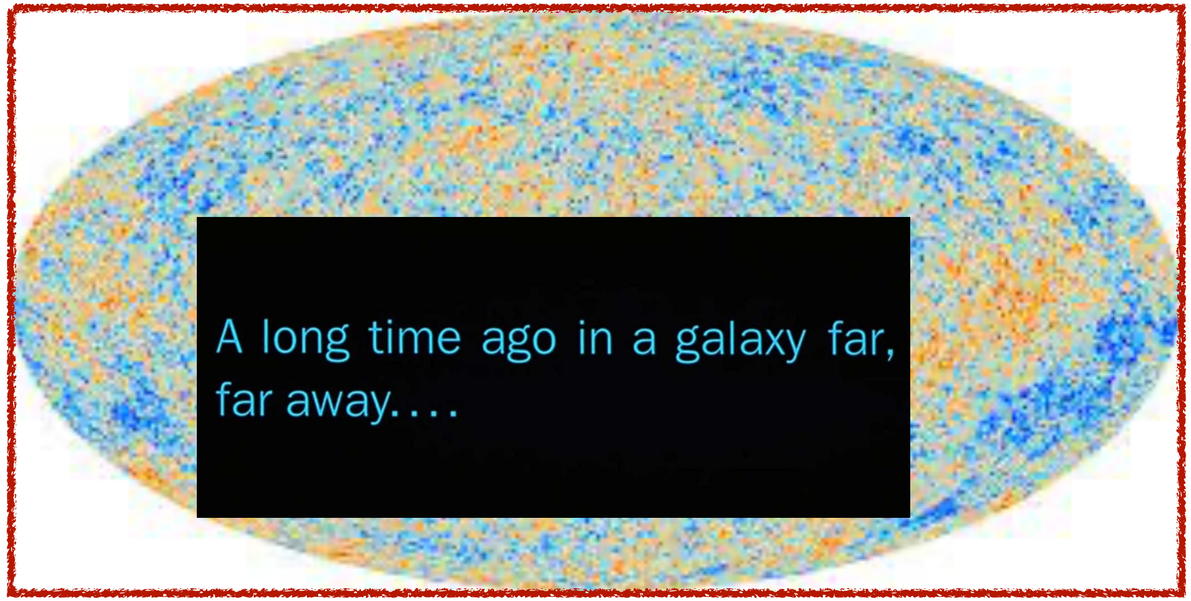

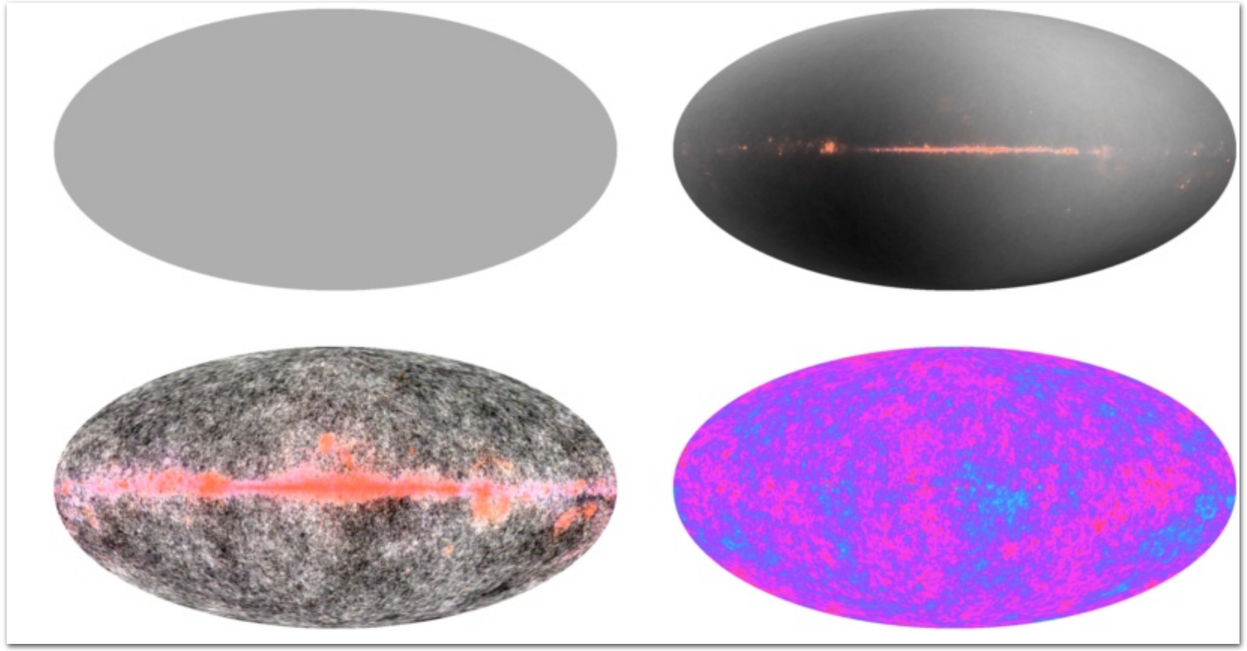

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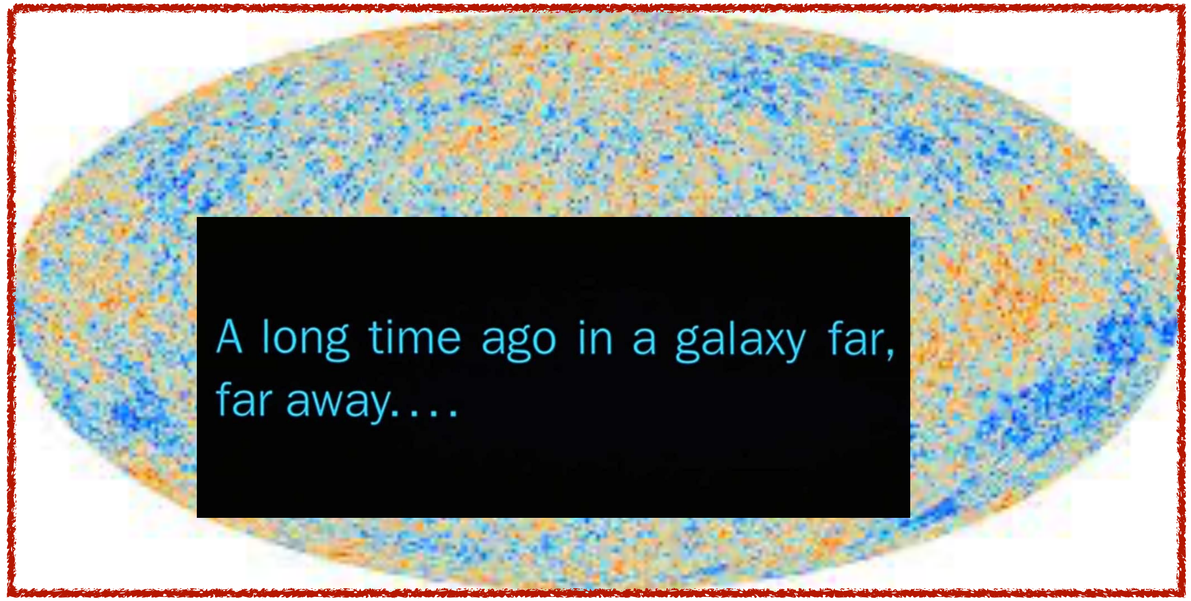

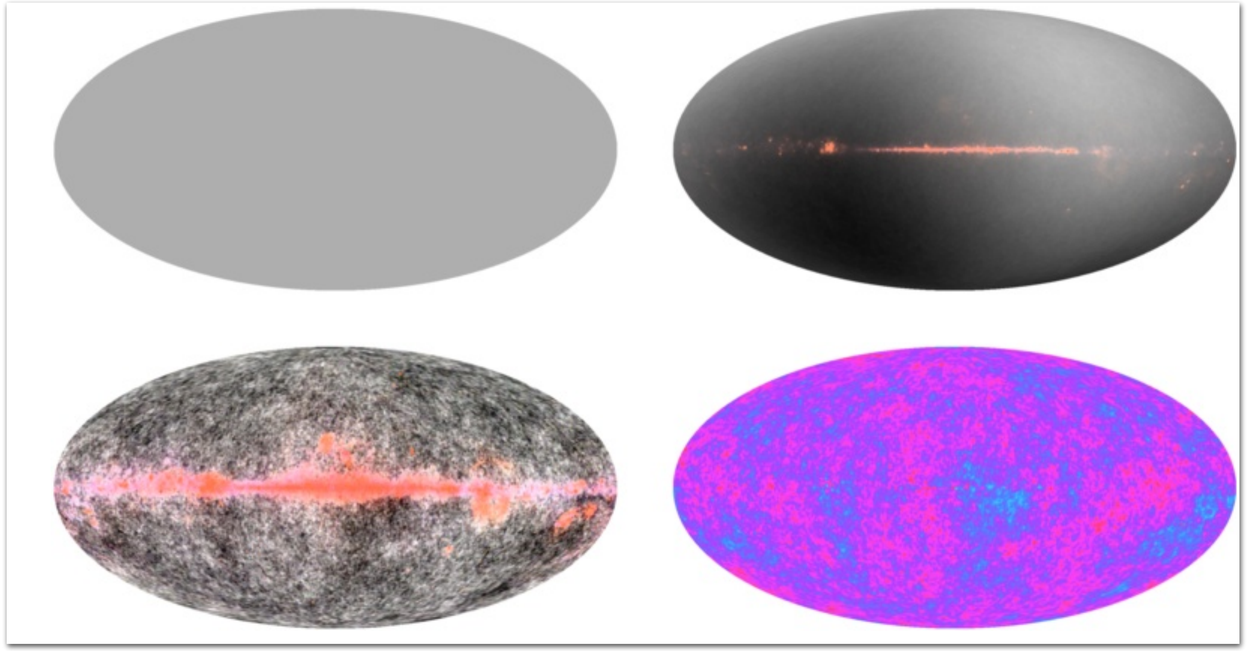

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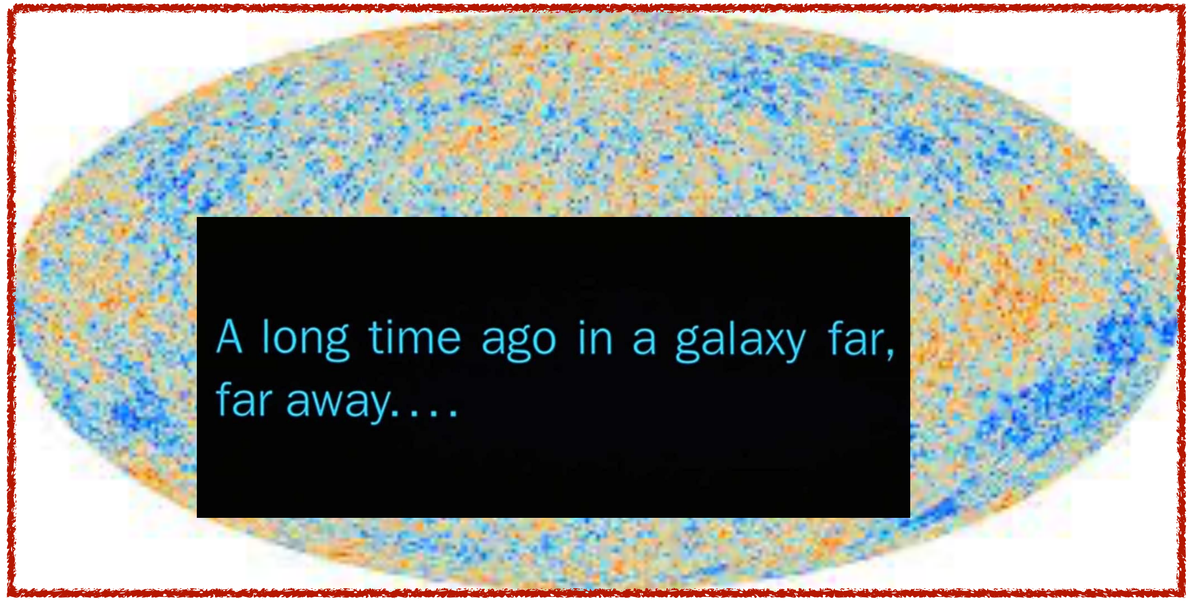

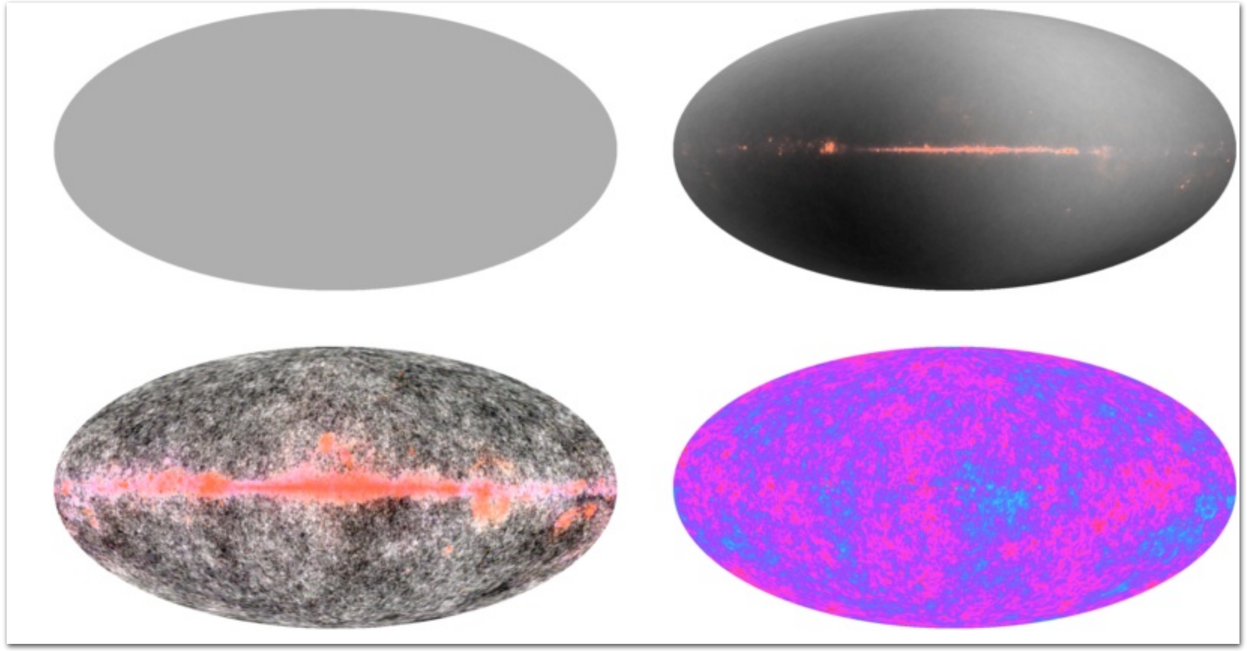

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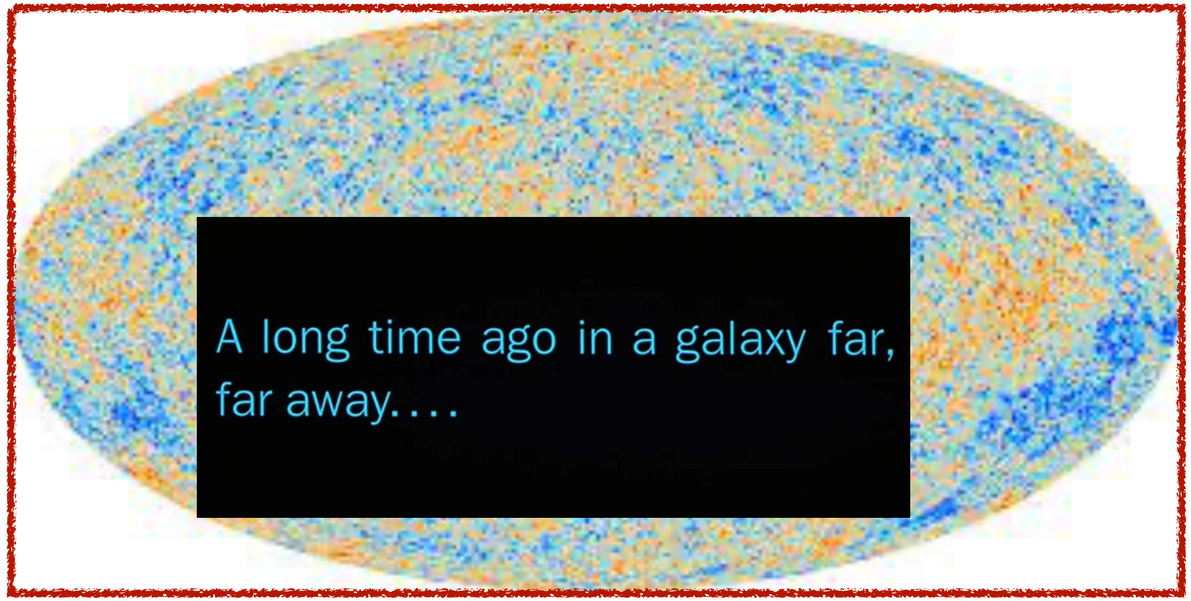

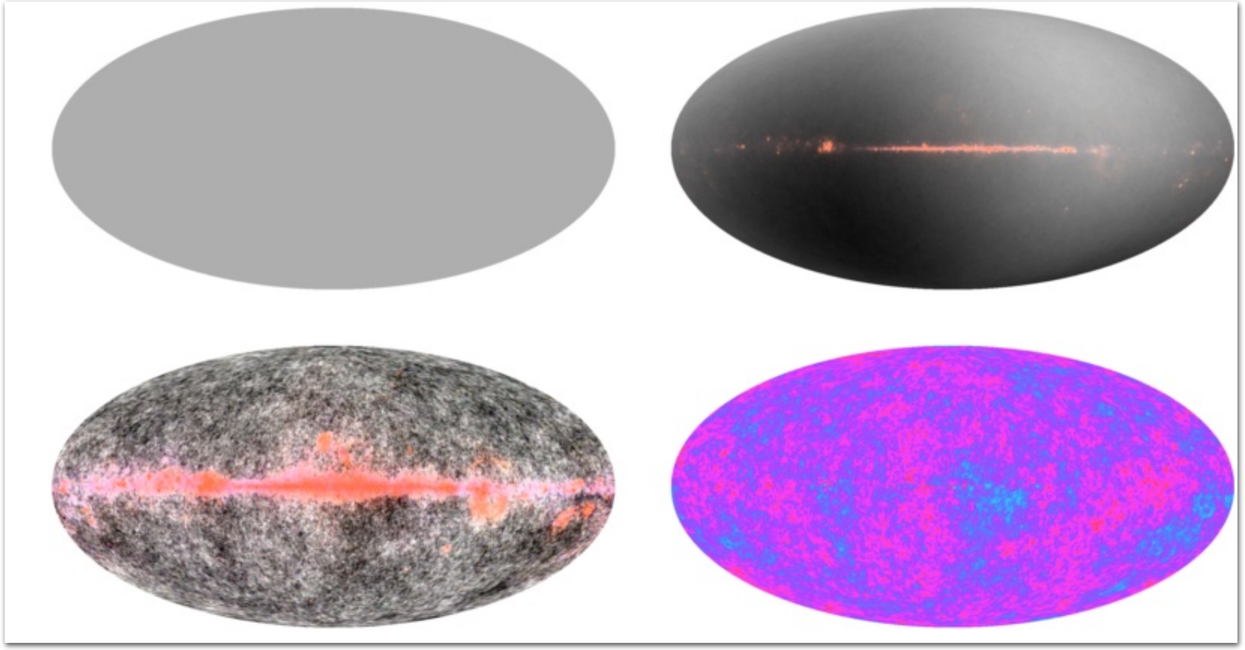

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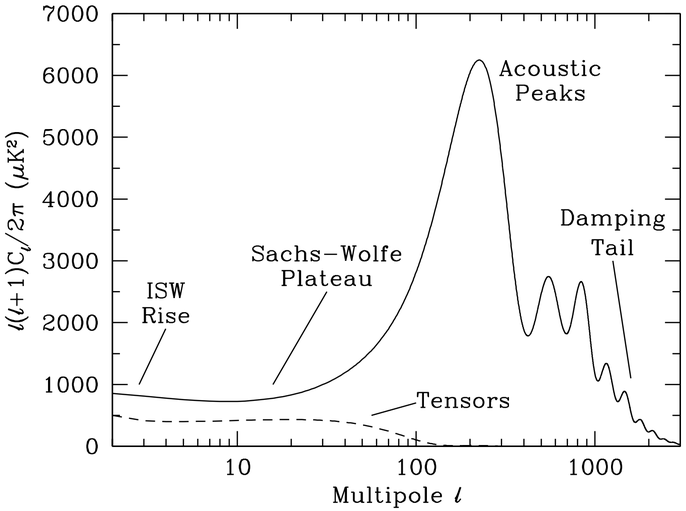

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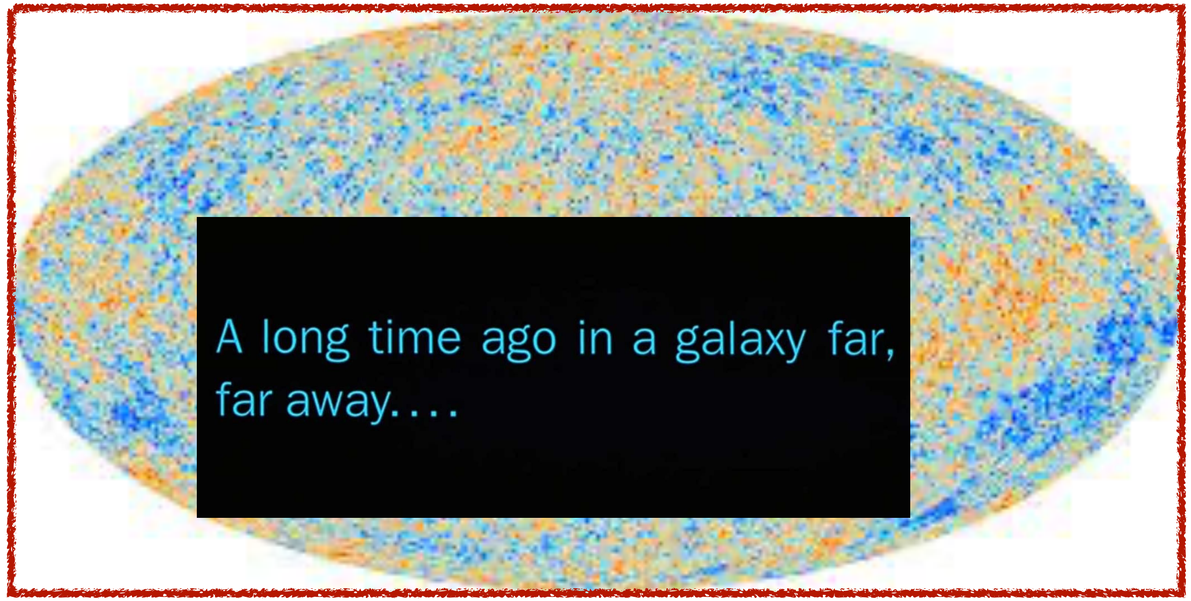

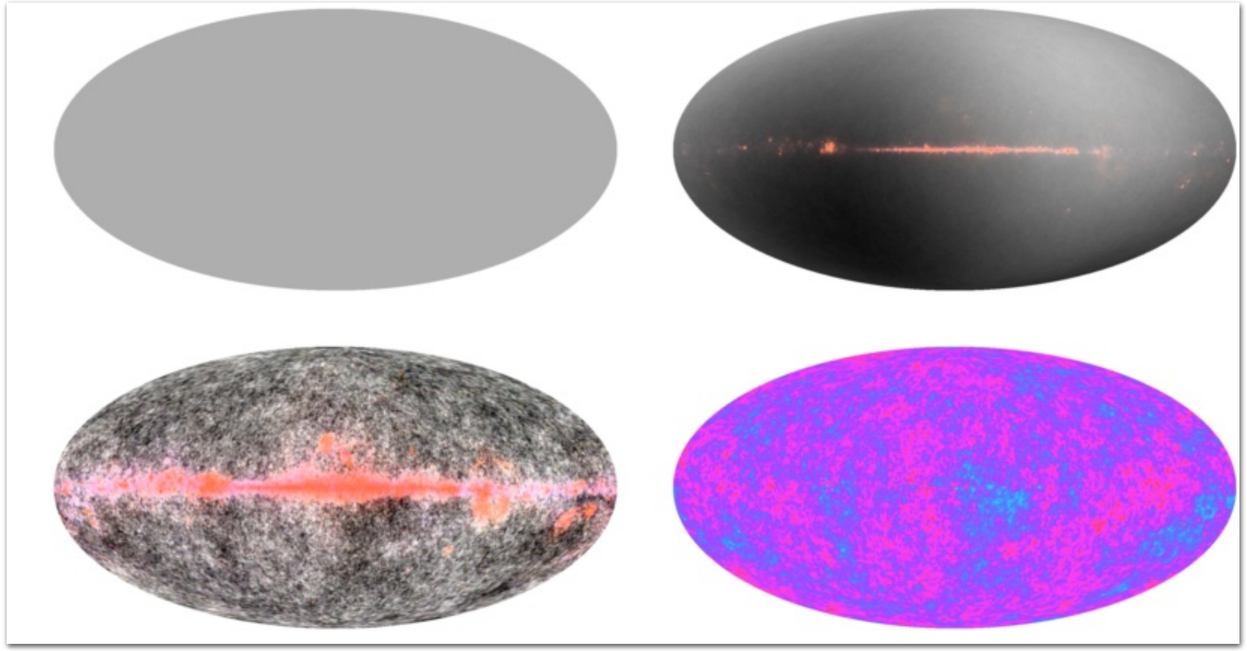

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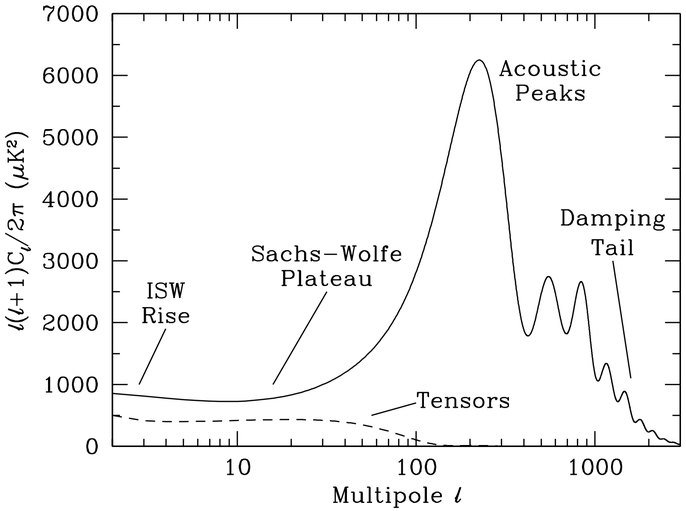

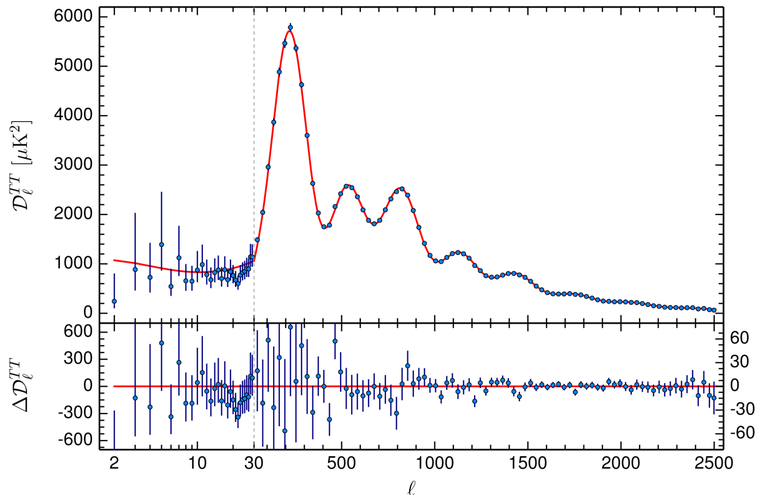

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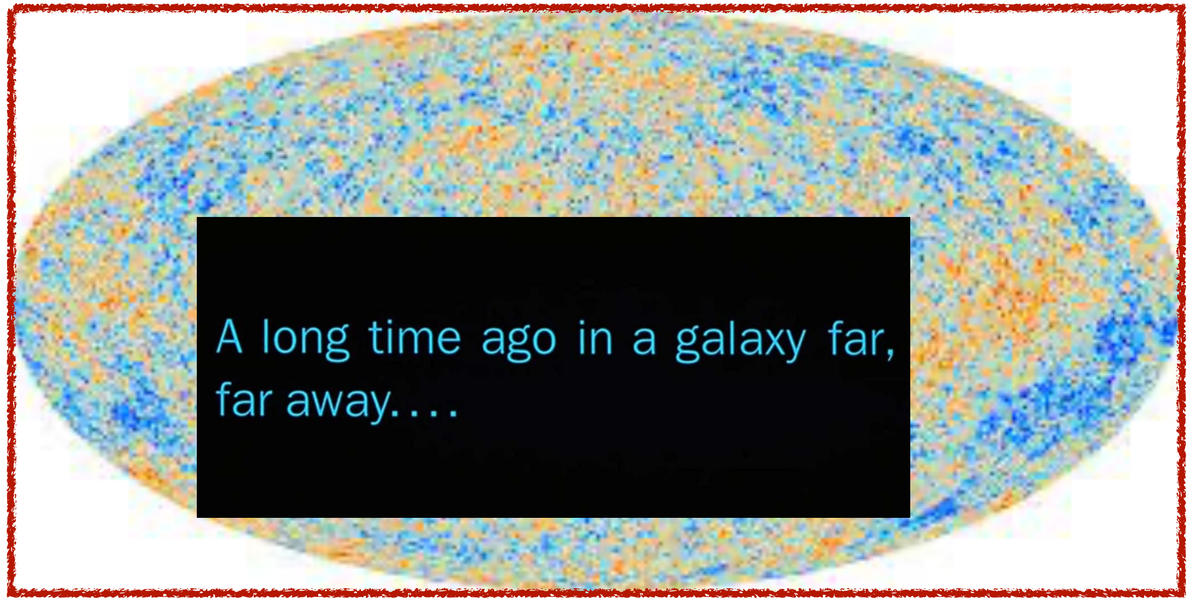

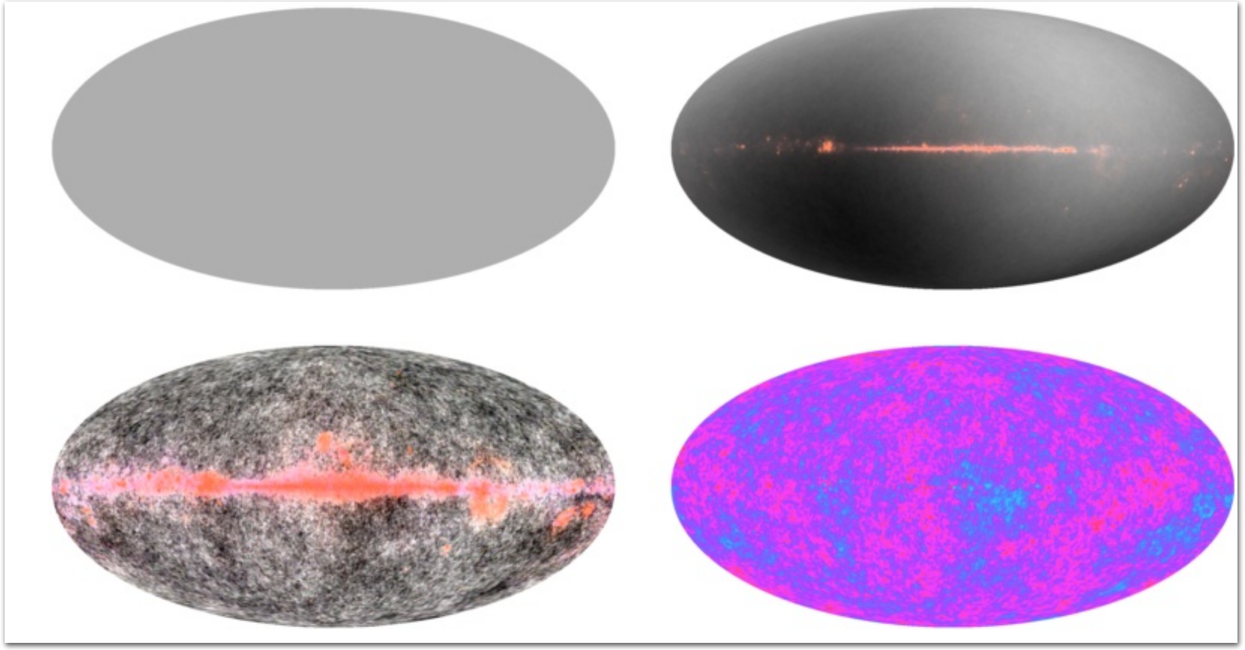

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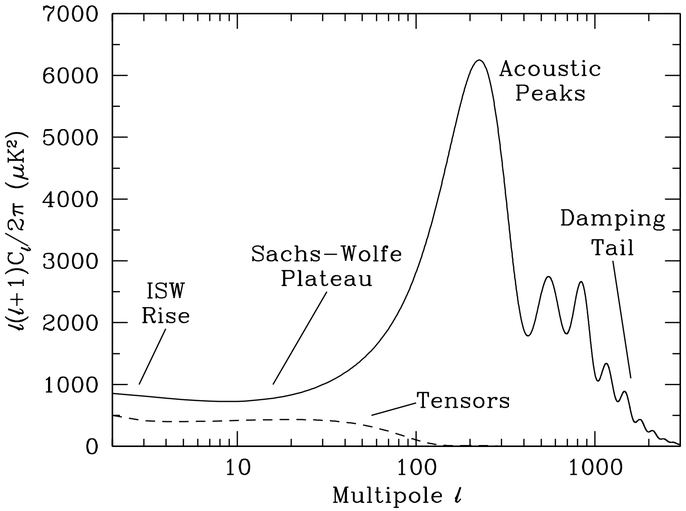

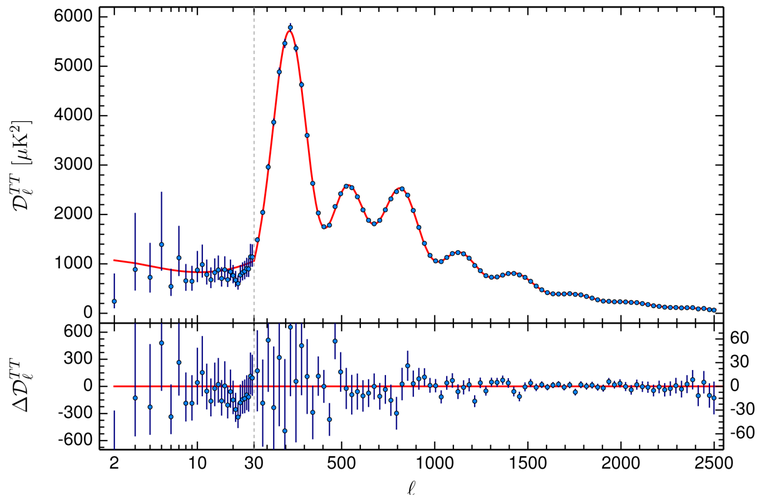

Power spectrum dominated by accoustic oscillations
and
Diffusion damping

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- Both Standard and non-standard processes

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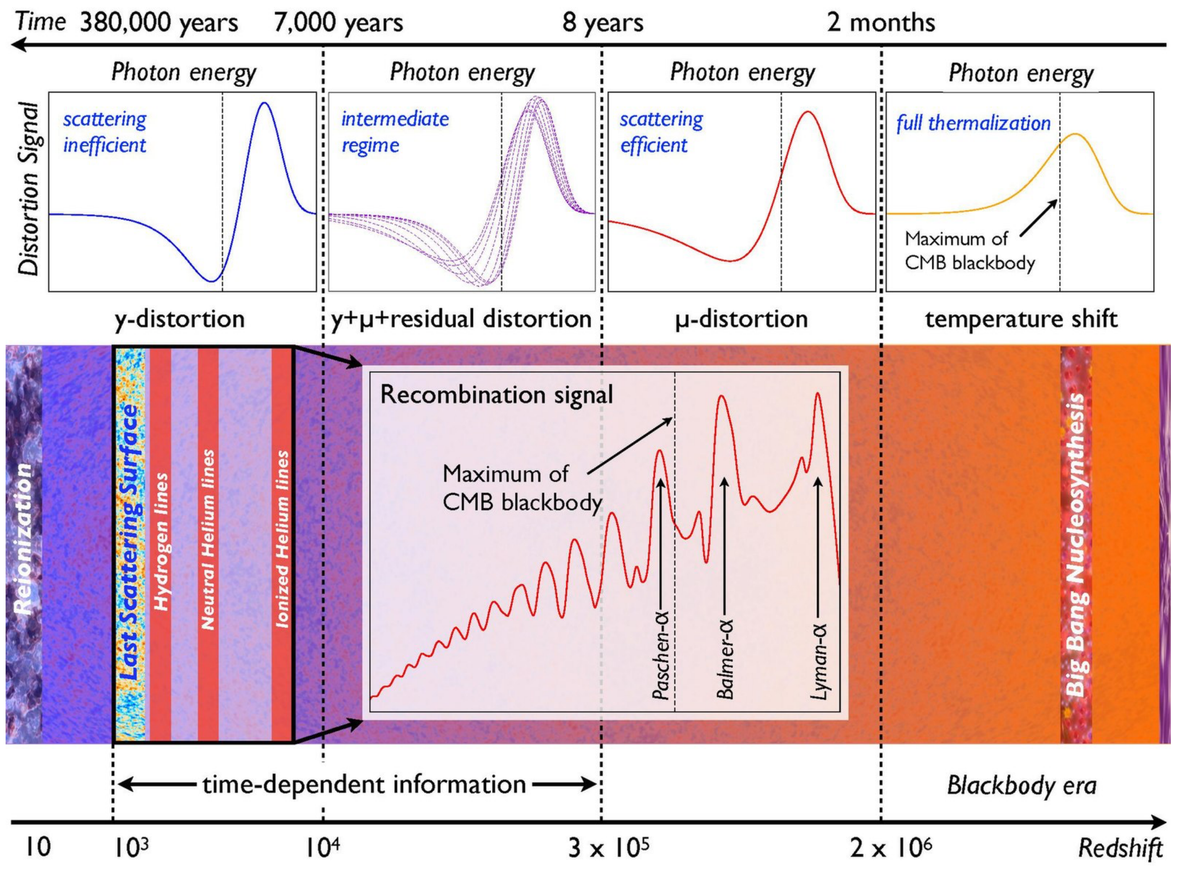

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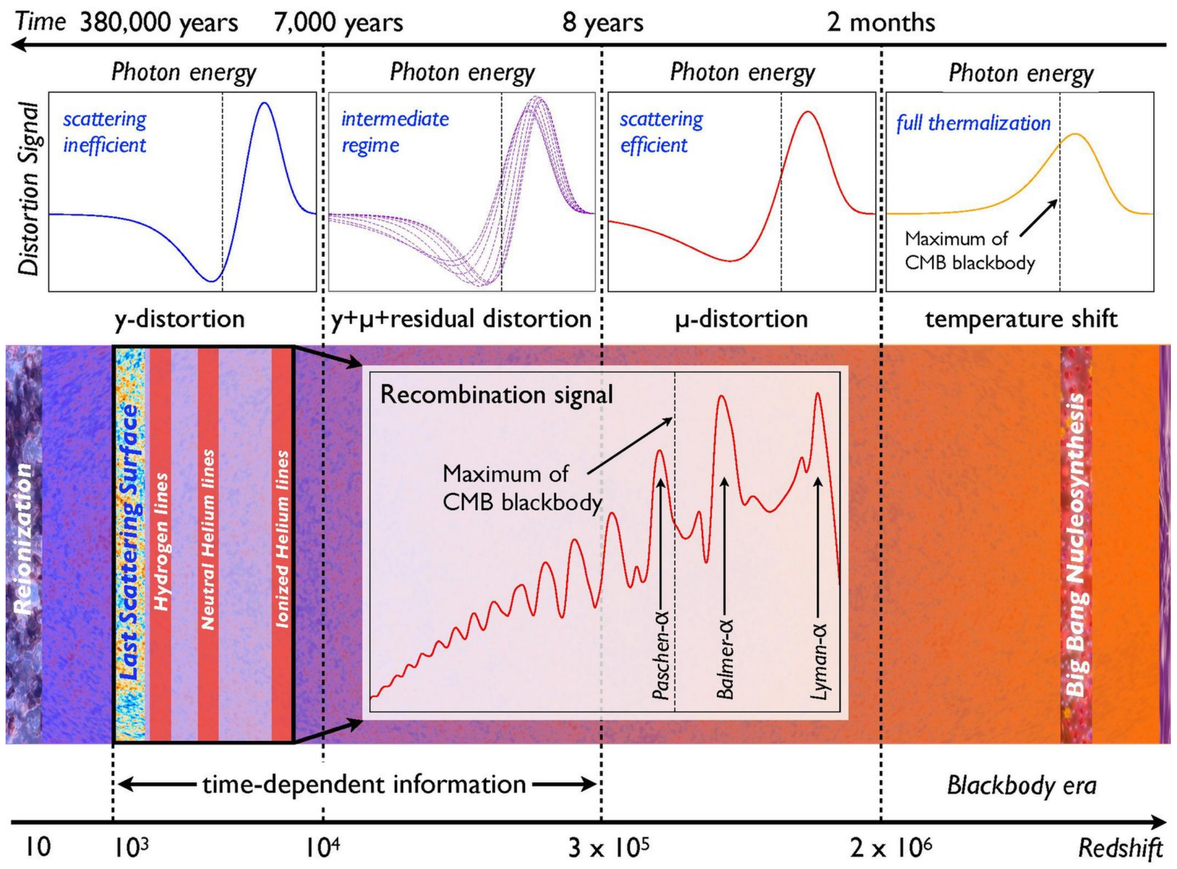

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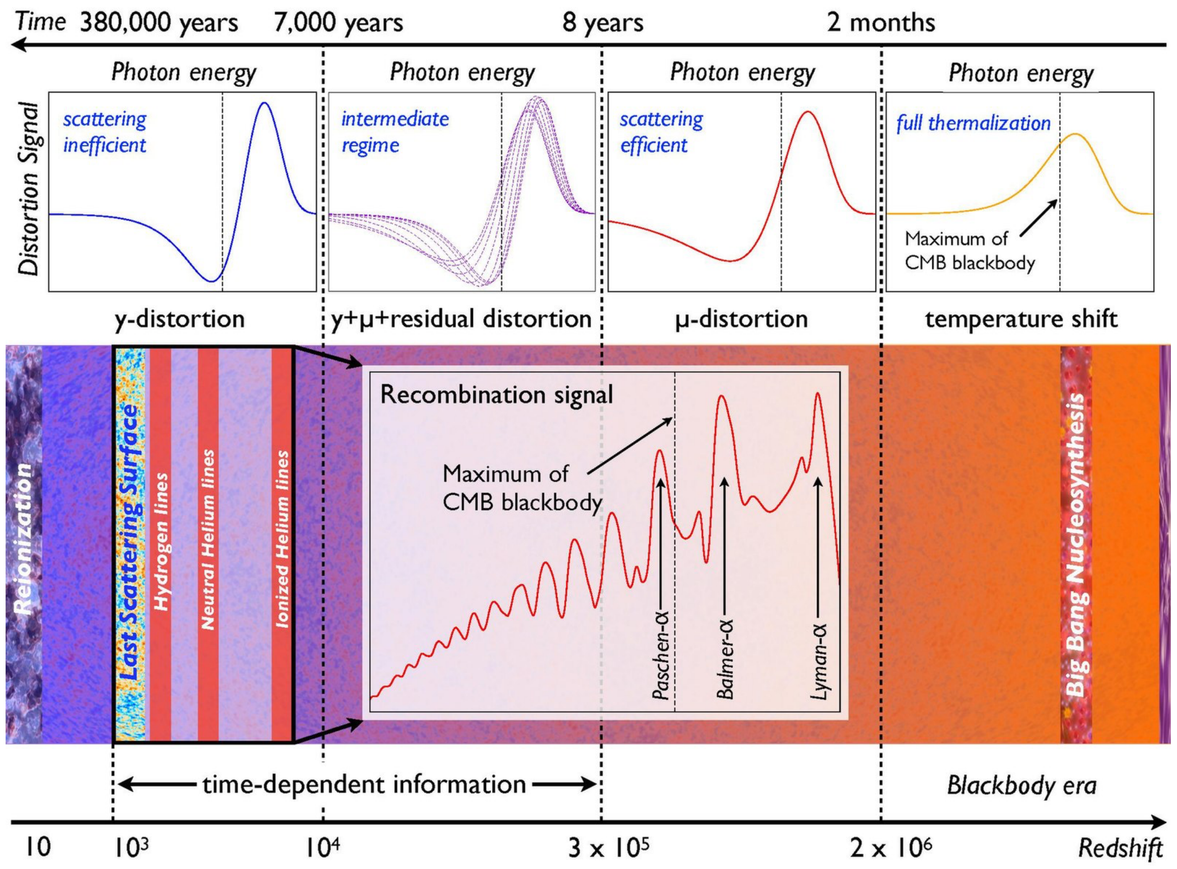

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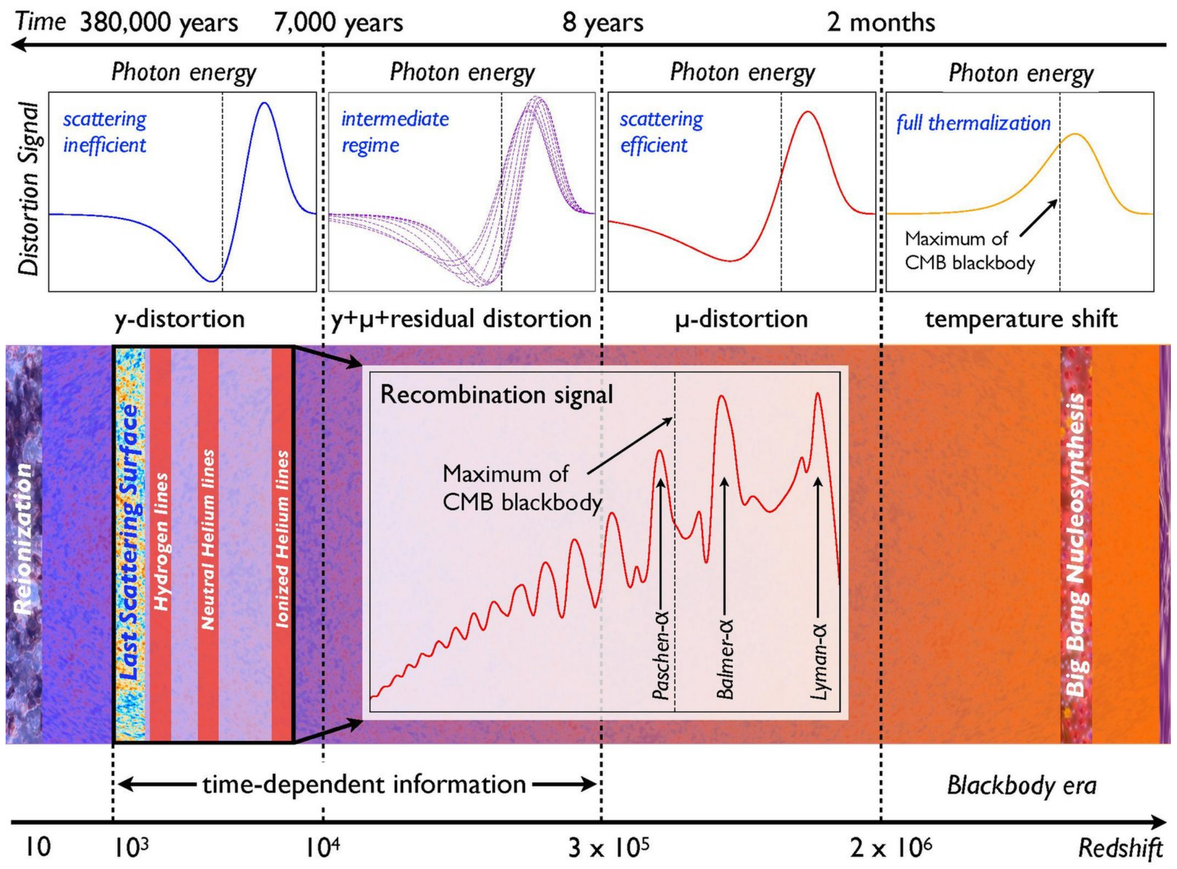

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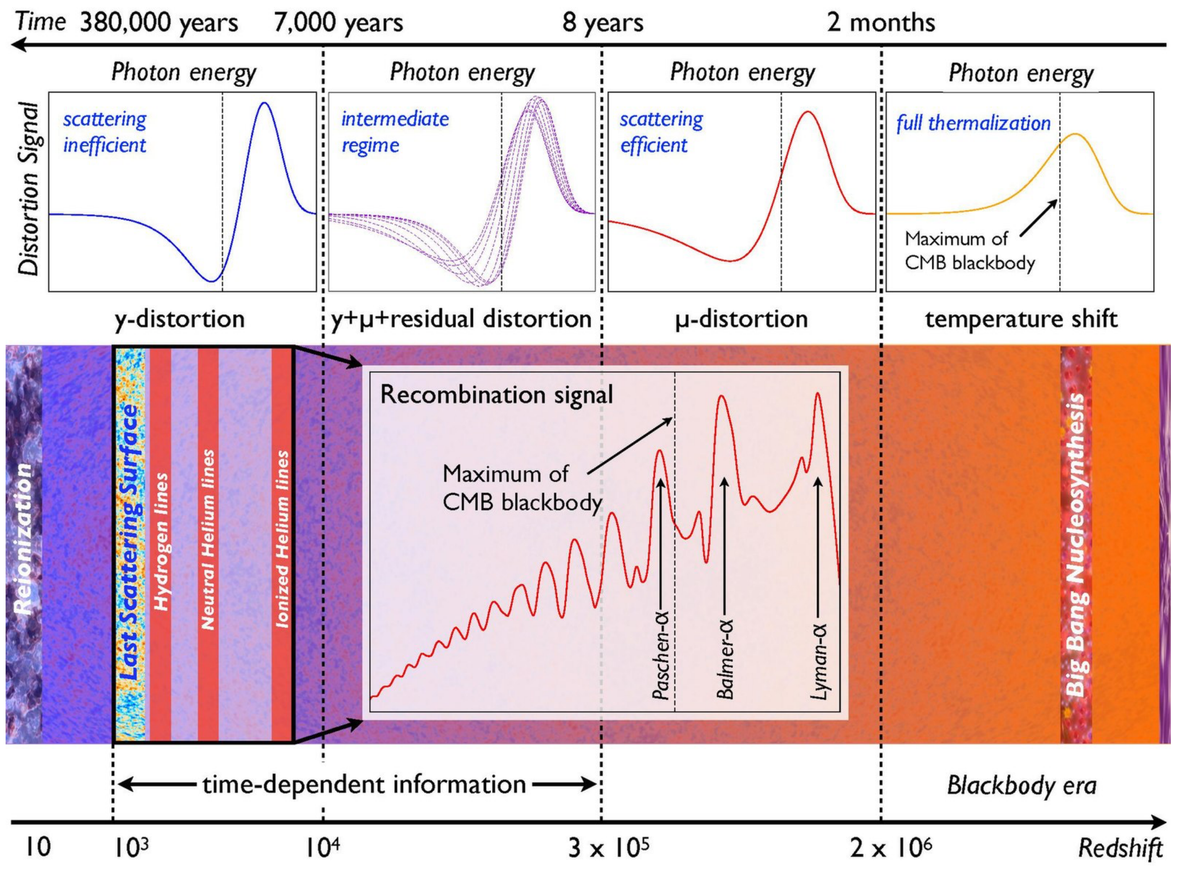

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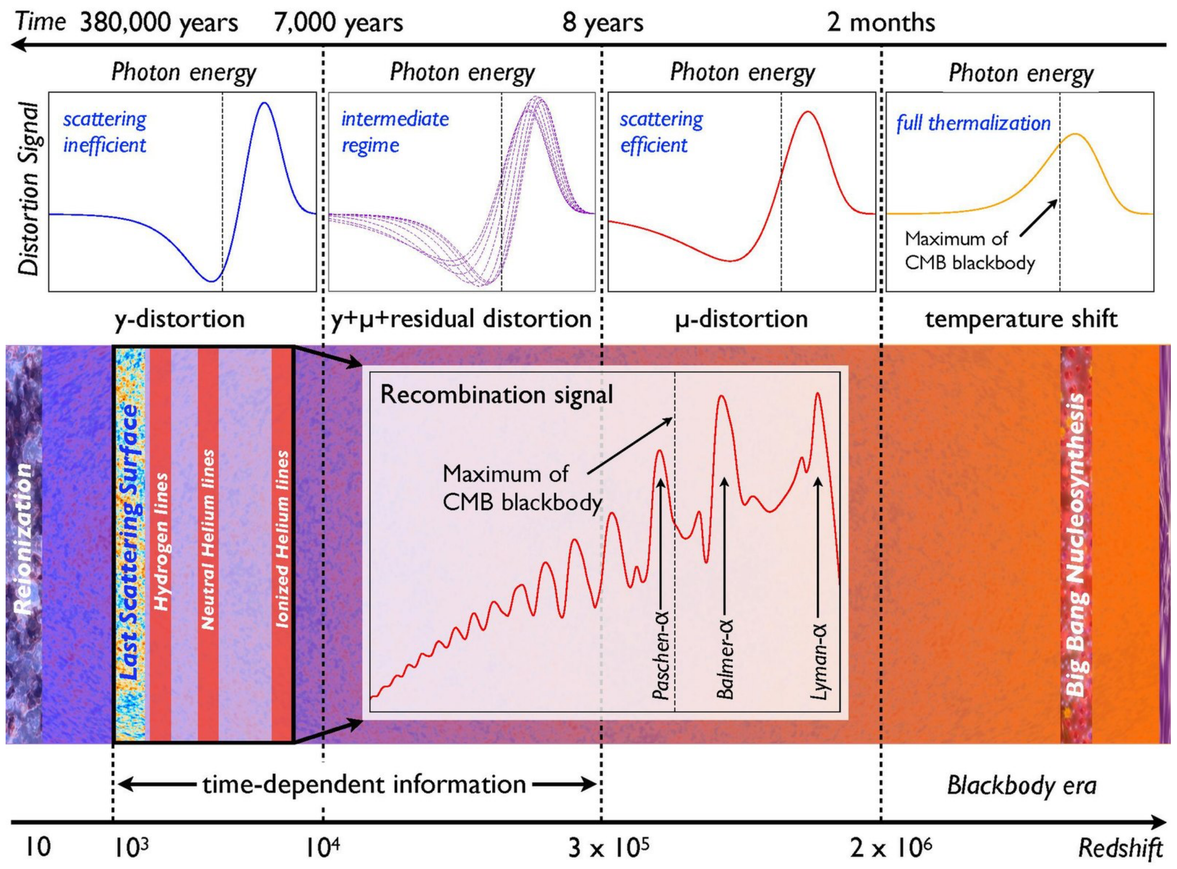

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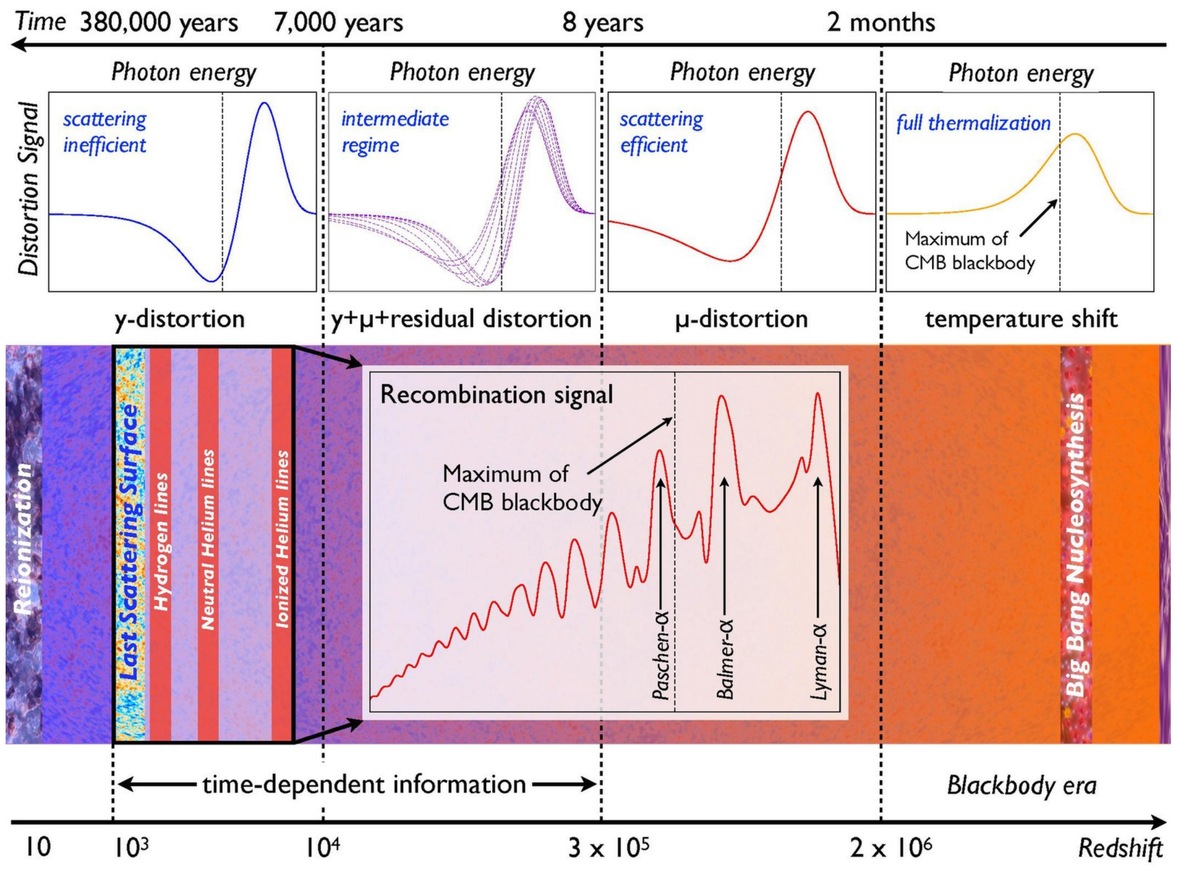

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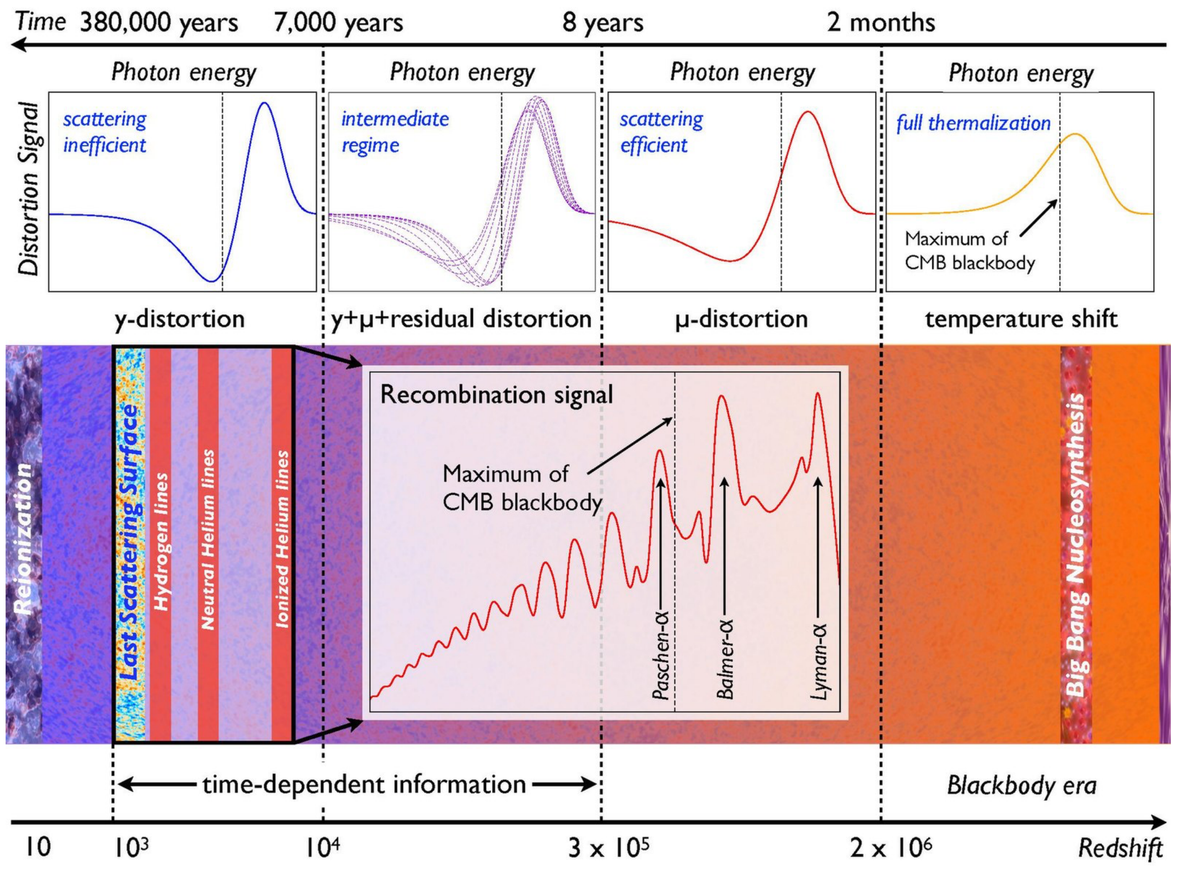

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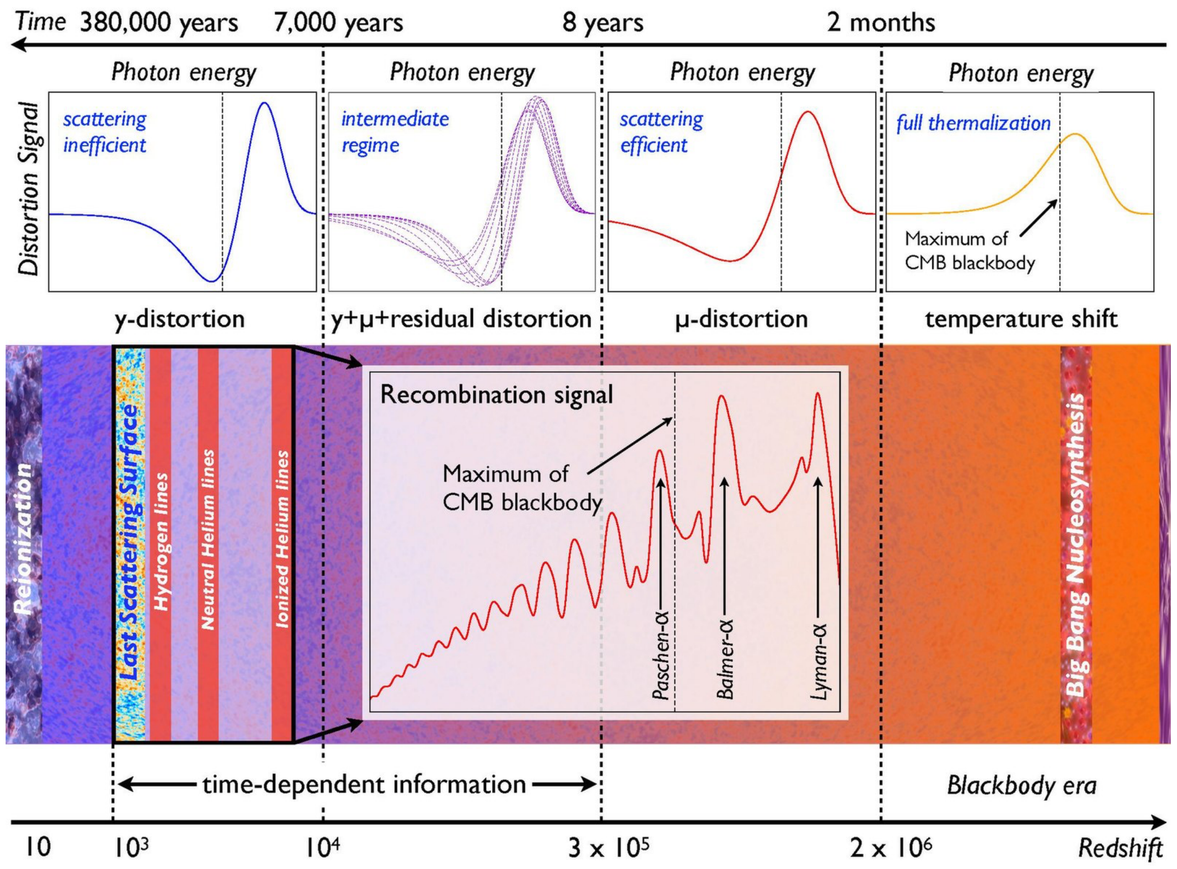

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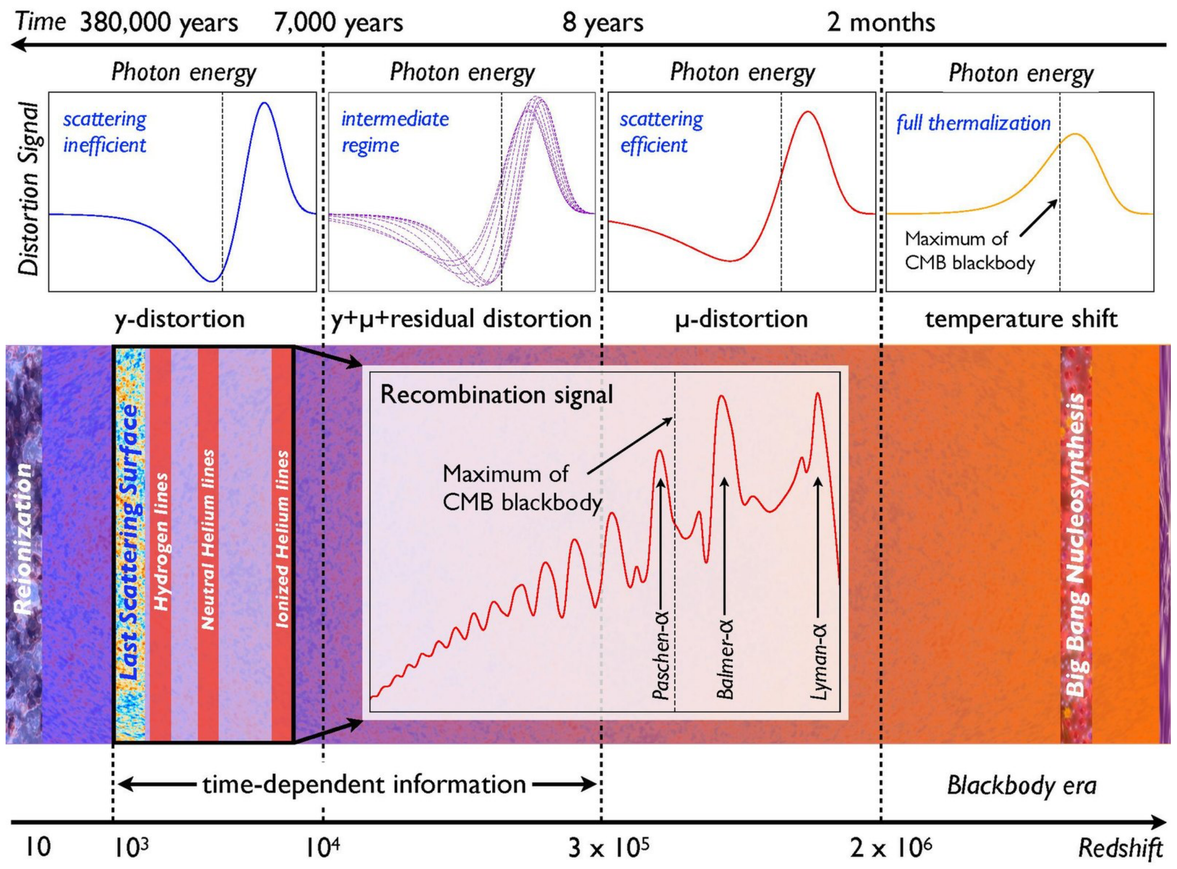
- Z < 10^4 : Compton scattering becomes inefficient,
- CMB photons boosted via non-relativistic scattering



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COBE/Firas measurement

$$|\mu| < 9 \times 10^{-5} \qquad |y| < 1.5 \times 10^{-5}$$

Constrains Cosmological models with exotic energy injection at the level $\Delta\rho_\gamma/\rho_\gamma < 6 \times 10^{-5}$

Any excess EM energy dumped by late decaying particles will be severely constrained by the above observations

Energy Injection rates

Decay

$$\dot{\mathcal{Q}} = \rho_{\rm cdm} f_{\rm frac} f_{\rm eff} \Gamma_{\rm dec} e^{-\Gamma_{\rm dec} t}$$

Annihilation

$$\dot{\mathcal{Q}} = \rho_{\rm cdm}^2 f_{\rm frac} f_{\rm eff} \frac{\langle \sigma v \rangle}{\mathrm{M}_\chi} \equiv \rho_{\rm cdm}^2 p_{\rm ann}$$

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$$\boxed{\dot{\mathcal{Q}} = \rho_{\rm cdm}^2 f_{\rm frac} f_{\rm eff} \frac{\langle \sigma v \rangle}{\mathrm{M}_\chi} \equiv \rho_{\rm cdm}^2 p_{\rm ann}}$$

Can Cosmology tell us more about BSM/Dark Matter

BBN Constraints

Production of light elements D, He-3/4, Li-7
A small amount of Be-9, B-10/11 via CNO processes

Characterized by the Baryon-Photon ratio $\eta = n_b/n_\gamma$ $\eta_{CMB} = 6.10 \pm 0.04$ (Ade et al., 2016)

Measurements of Abundances of other light elements

$D/H = (2.527 \pm 0.03)\ 10^{-5}$ High Redshift low metallicty H clouds (Cooke et al., 2017)

Any excess energy injection at late times can alter the predictions of BBN, primarily by photodissociation of light elements

$Li/H = (1.58 \pm 0.31)\ 10^{-10}$ Population II stars in the spheroid of the galaxy : factor 3 off from standard estimates (Sbordone et al. (2010))

$Y_p = 0{,}245 \pm 0{,}003$ He-4 primordial mass fraction (Particle Data group 2019))

Lyman-alpha Constraints

If a relativistic relic is produced deep in radiation dominated epoch ⟶ Denisty perturbations of these particles suppresed for scales below Their free streaming length

SuperWIMPS

Models of SuperWIMPS

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Feng, Rajaraman, Takayama 2003, Feng++ 2004, 2005
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Most previous constraints primarily concerns BBN, lifetimes between 10^4 -10^6

SuperWIMPS

SuperWIMPS

Example II :Axinos

SuperWIMPS

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$$A = (s + ia)/\sqrt{2} + \sqrt{2}\theta a + \theta^2 F$$

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Axino-gaugino-gauge boson interactions

SuperWIMPS

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$$\mathcal{L}_{\tilde{a}\lambda A} = i\frac{\alpha_Y C_{aYY}}{16\pi\,(f_a/N)}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\widetilde{B}B_{\mu\nu} + i\frac{\alpha_s}{16\pi\,(f_a/N)}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\widetilde{g}^b F^b_{\mu\nu}$$

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Additional freedom in the Peccei-Quinn scale

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Low PQ scales constrained by colliders while
PQ scales constrained by cosmology

CMB and BBN constraints on gravitino SWIMP

A slightly modified version of Exoclass

6+2 extension of the standard ΛCDM

$$\{h, \omega_{\rm b}, \omega_{\rm cdm}, n_s, A_s, z_{\rm reio}\} + \{\log_{10} f_{\rm frac}, \log_{10} \tau_{\rm dec}\}$$

Slow Monte-Carlo Convergence

Spectral distortion dominated exclusion region

$10^5 {\rm s} < \tau_{\rm dec} < 10^{13} {\rm s}$

CMB anisotropy dominated exclusion region > 10^{12} s

BBN most sensitive upto 10^{12} s

Needs CMBS4 + Prism to extend the reach

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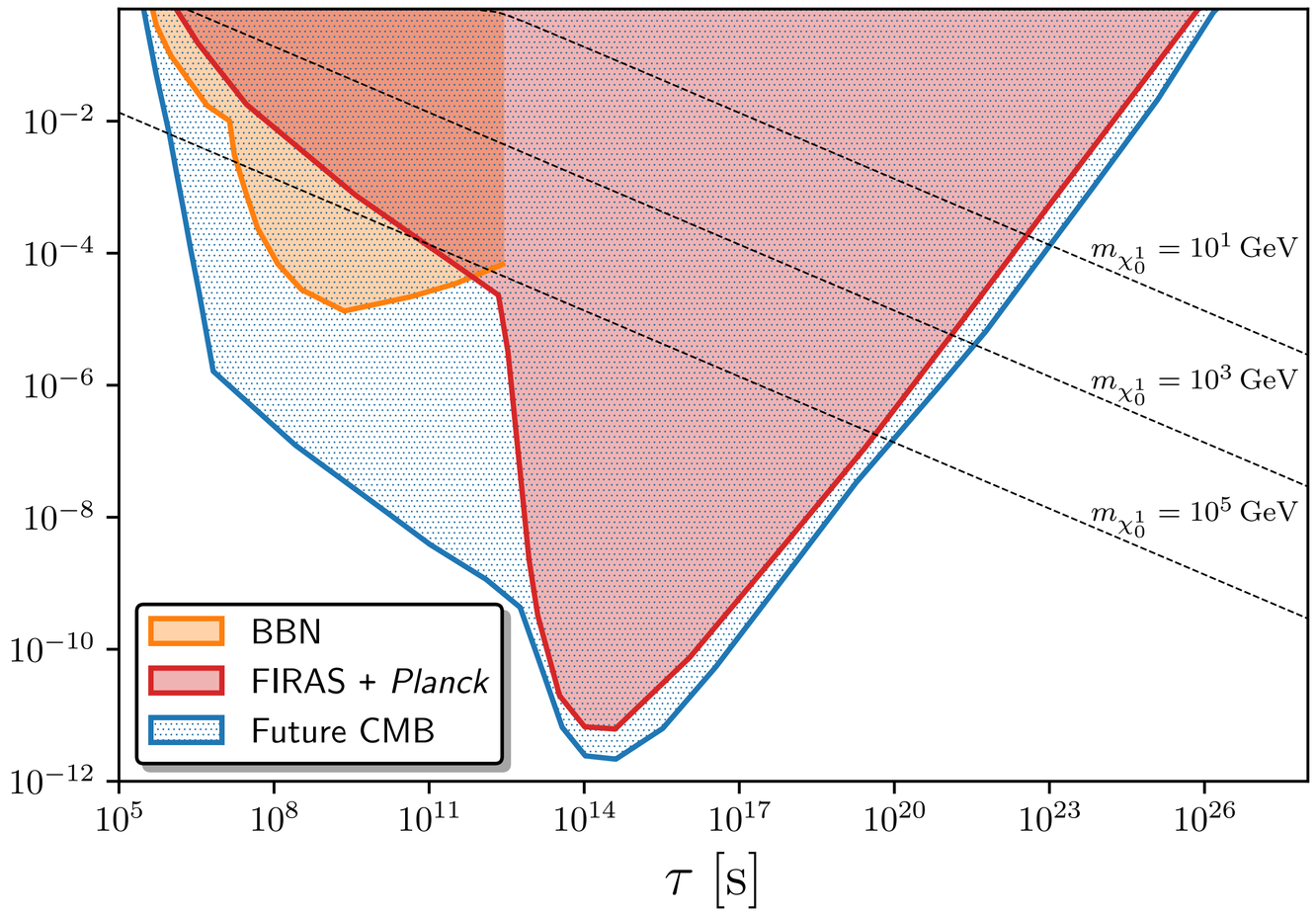

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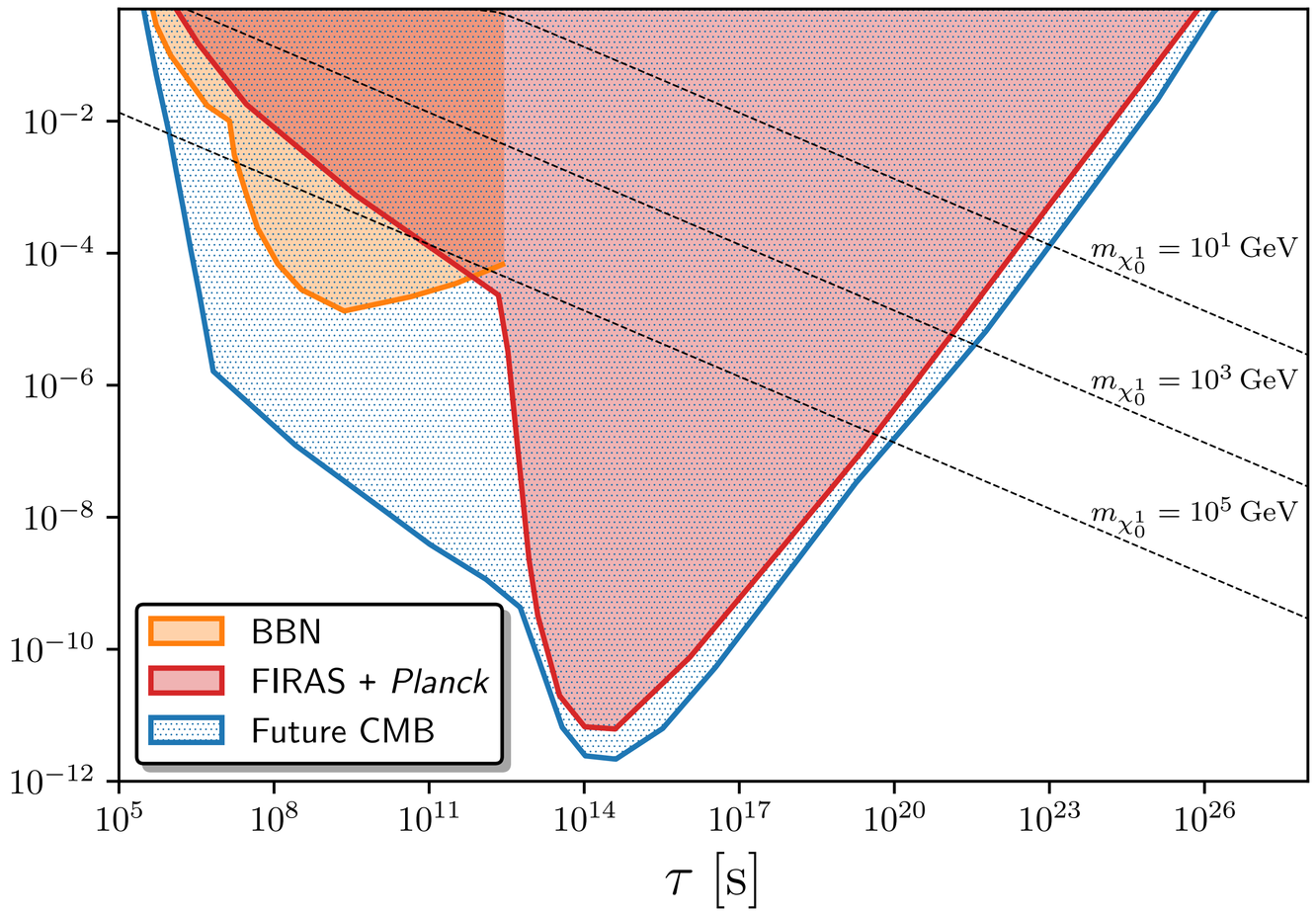

A slightly modified version of Exoclass

6+2 extension of the standard ΛCDM

$$\{h, \omega_{\rm b}, \omega_{\rm cdm}, n_s, A_s, z_{\rm reio}\} + \{\log_{10} f_{\rm frac}, \log_{10} \tau_{\rm dec}\}$$

Slow Monte-Carlo Convergence

Spectral distortion dominated exclusion region

$10^5 {\rm s} < \tau_{\rm dec} < 10^{13} {\rm s}$

CMB anisotropy dominated exclusion region > 10^{12} s

BBN most sensitive upto 10^{12} s

Needs CMBS4 + Prism to extend the reach

Used Exoclass [Stocker,Kramer,Lesgourgues, Poulin 2018], a tool to analyze spectral distortion
Present within the current Class [Lesgourgues 2011] version 3.

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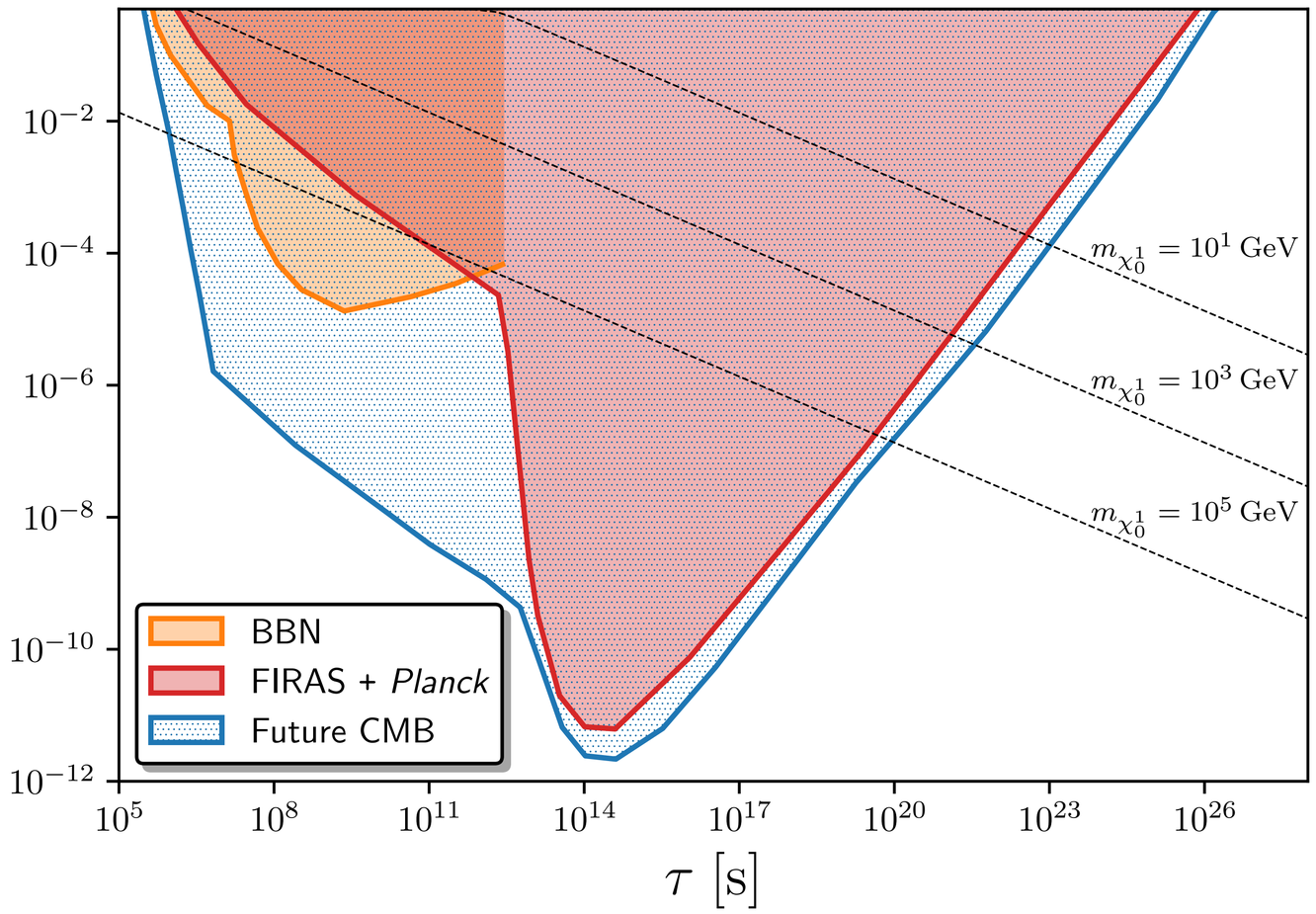

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Result consistent with Hooper, Lucca, Lesgorugues, Schoneberg : 1910.04619

Combined constraints

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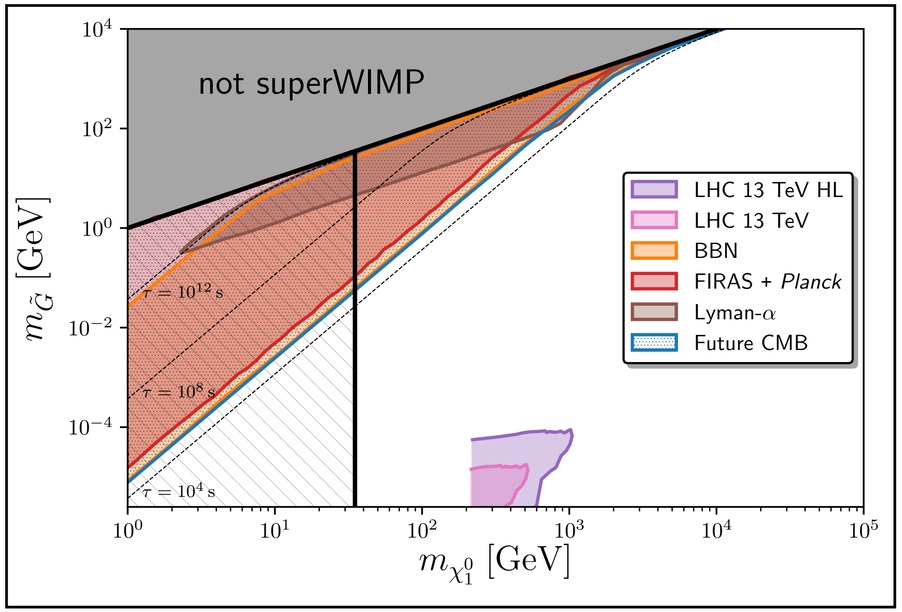

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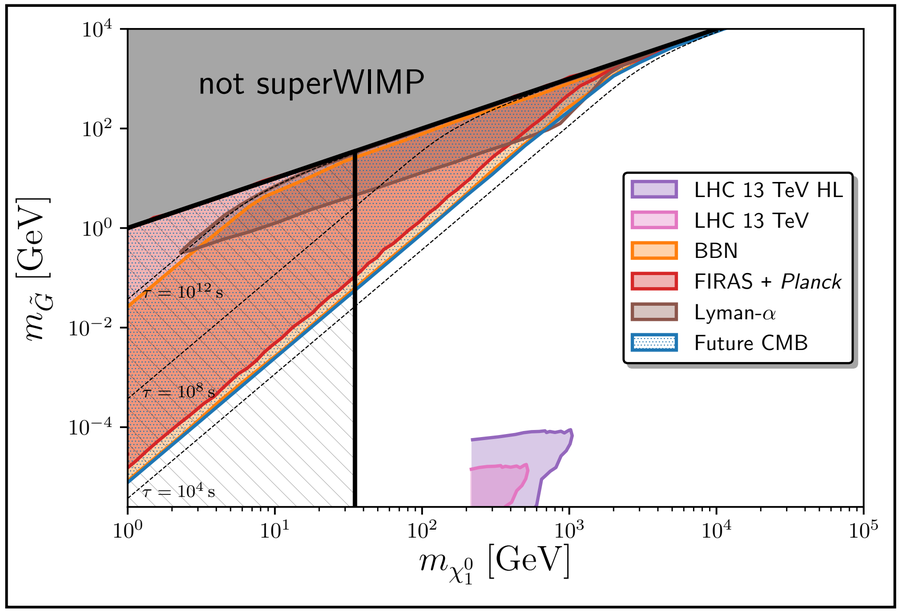

The light bino like thermal neutralino is ruled out below 34 GeV

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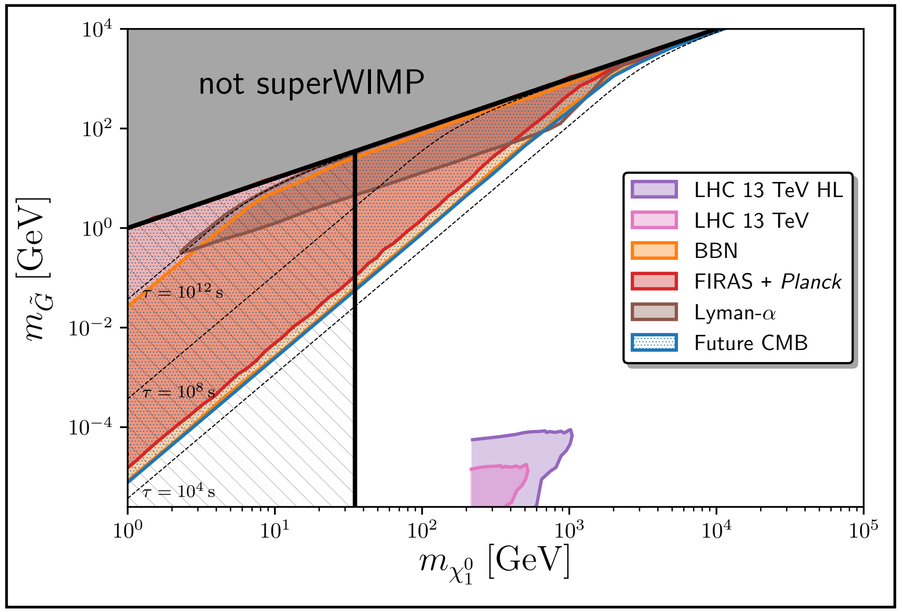

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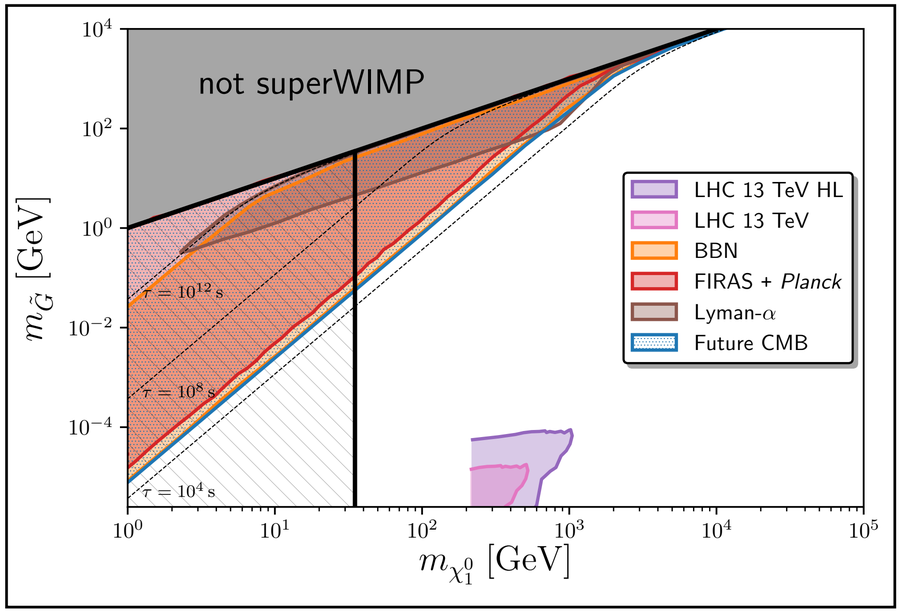

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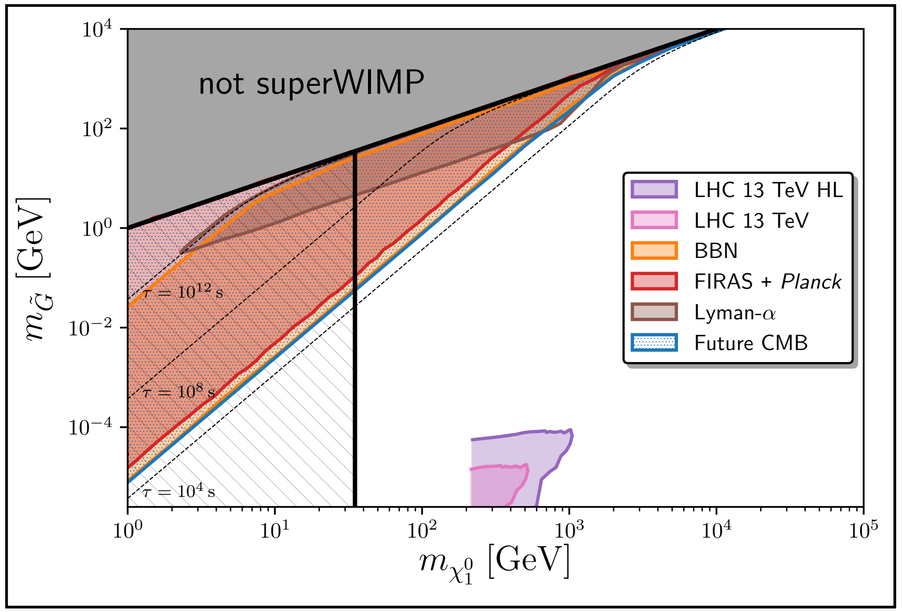

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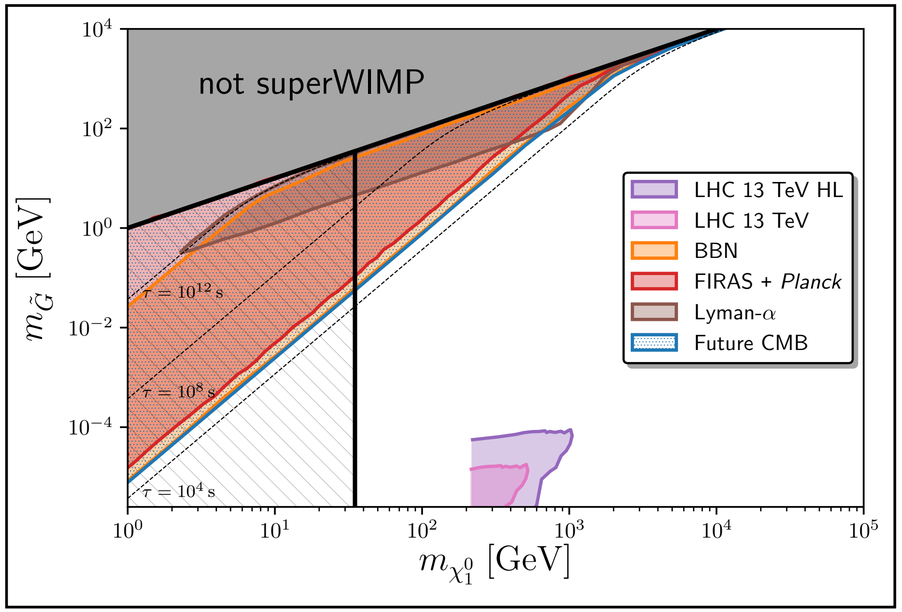

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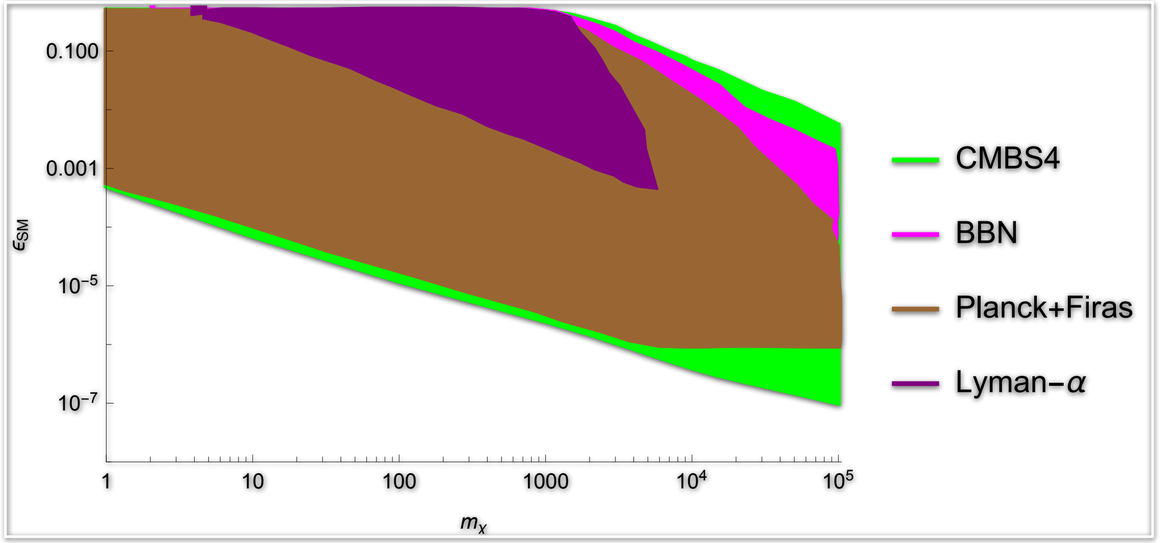

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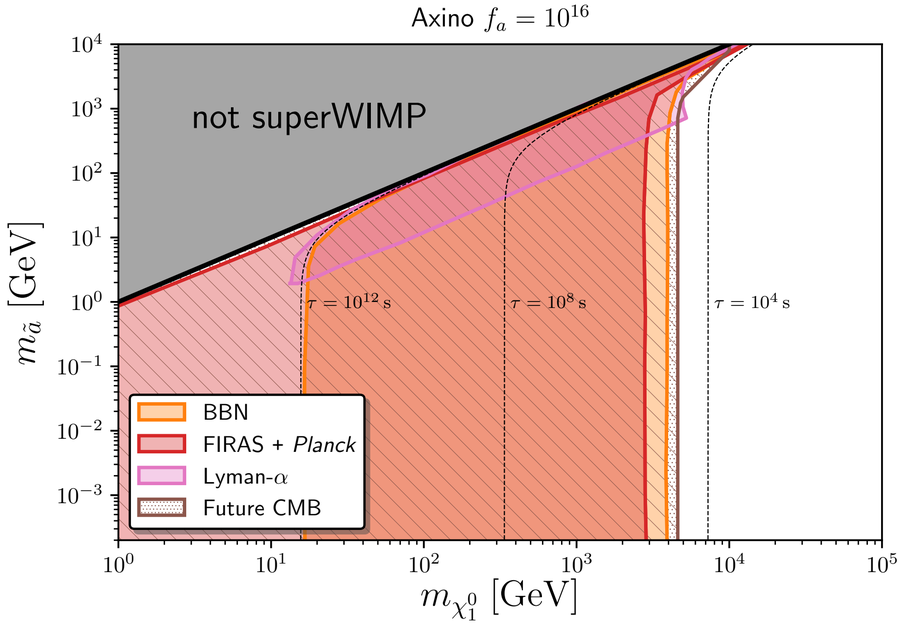

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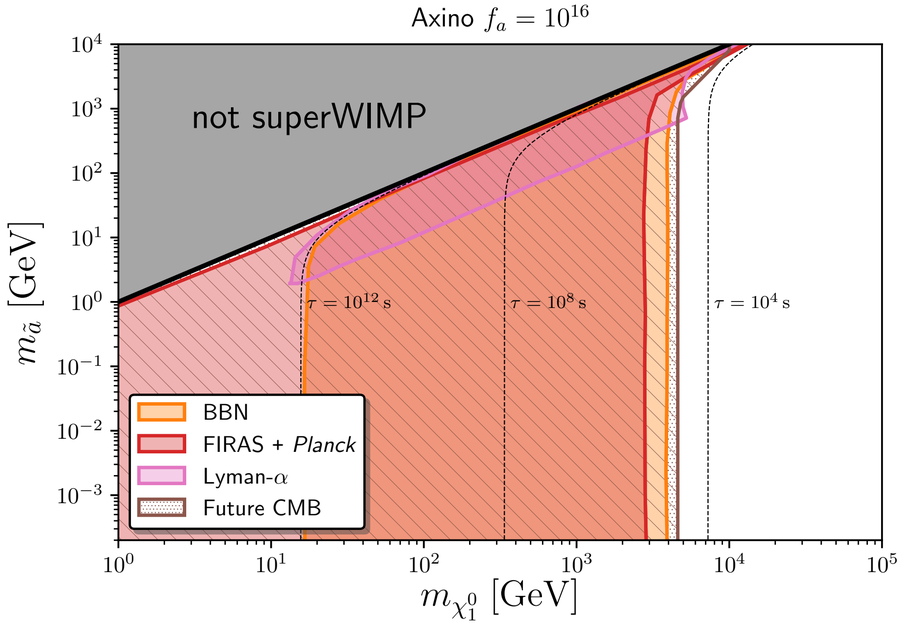

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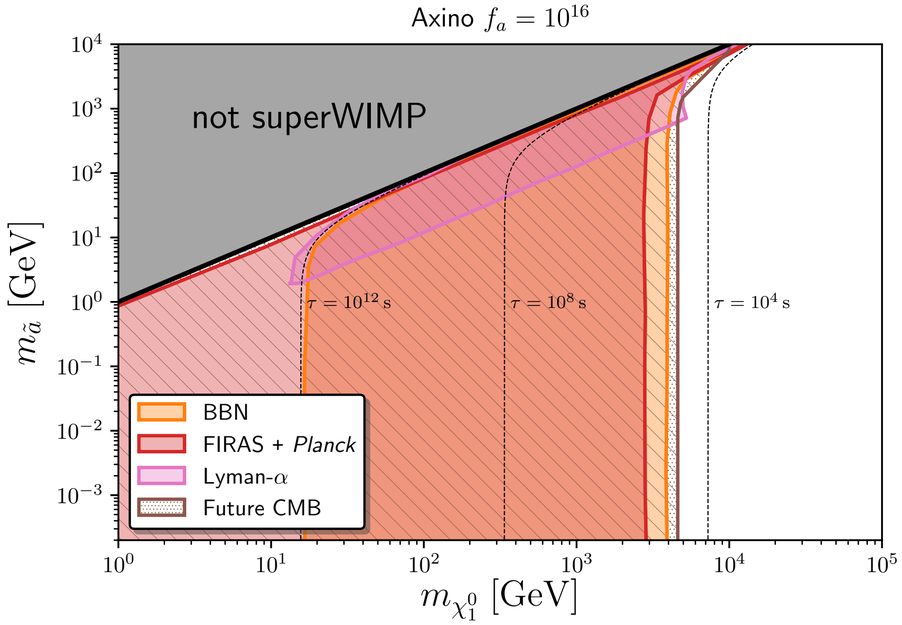

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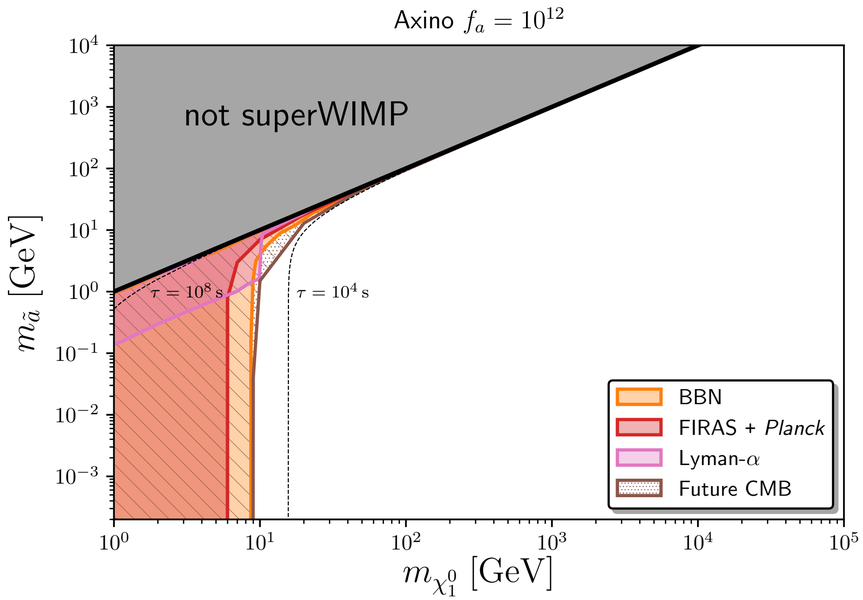

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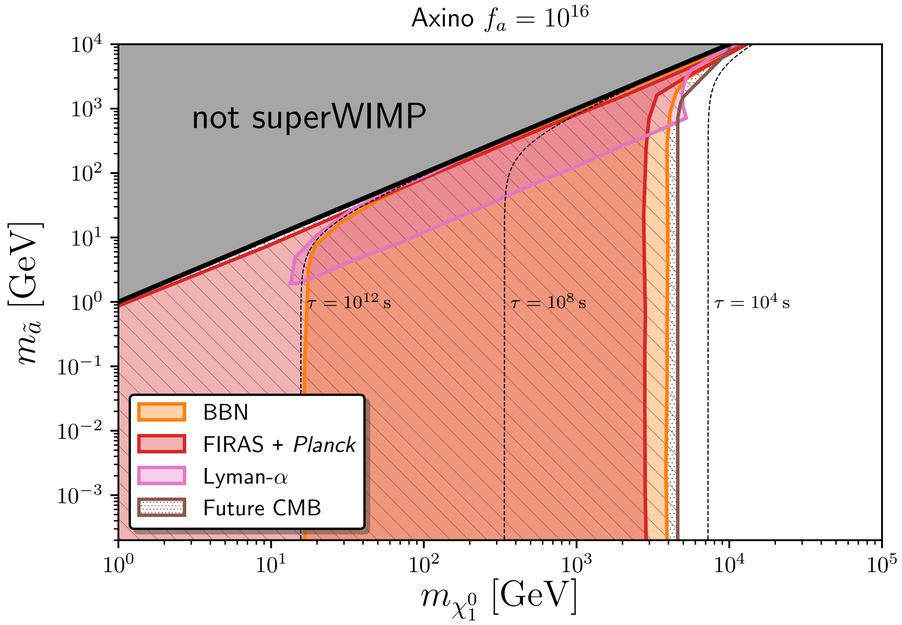

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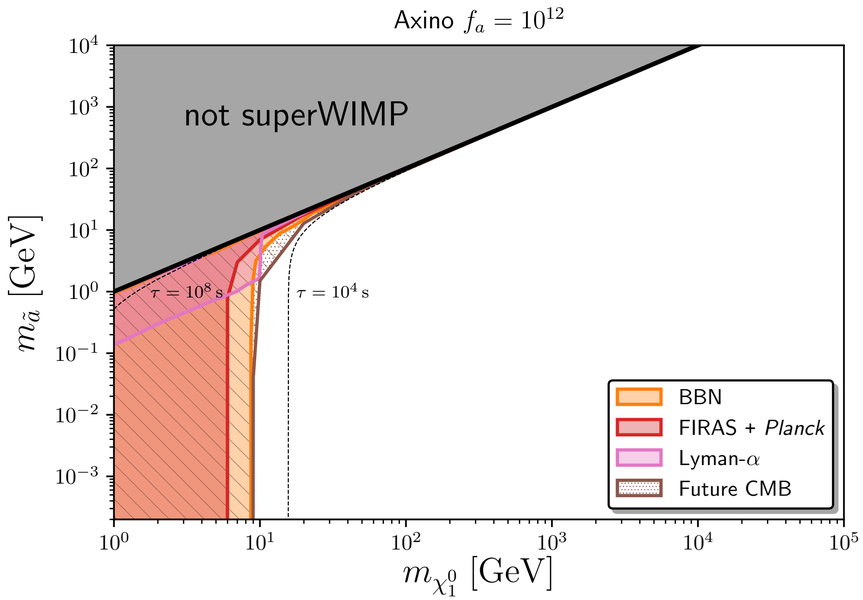

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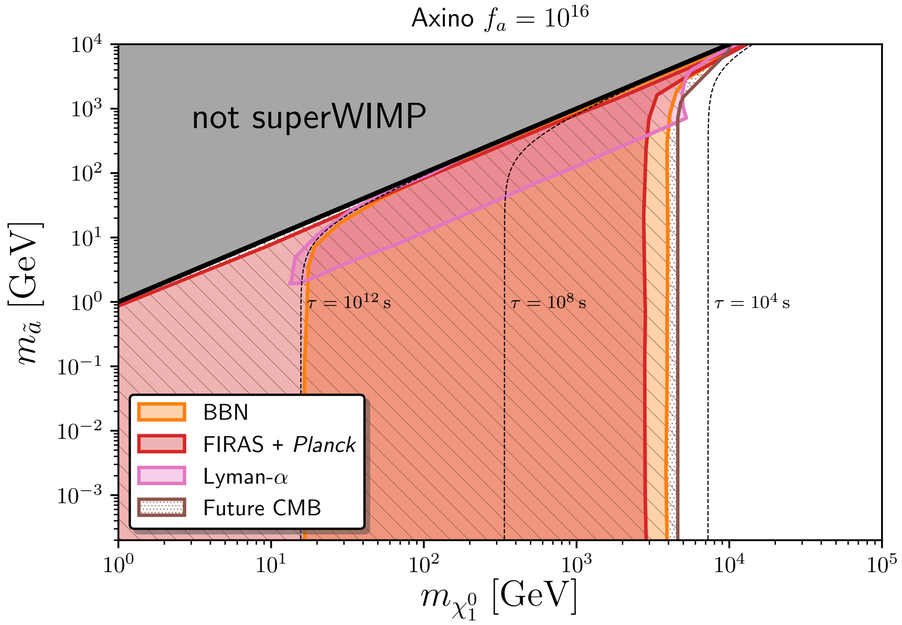

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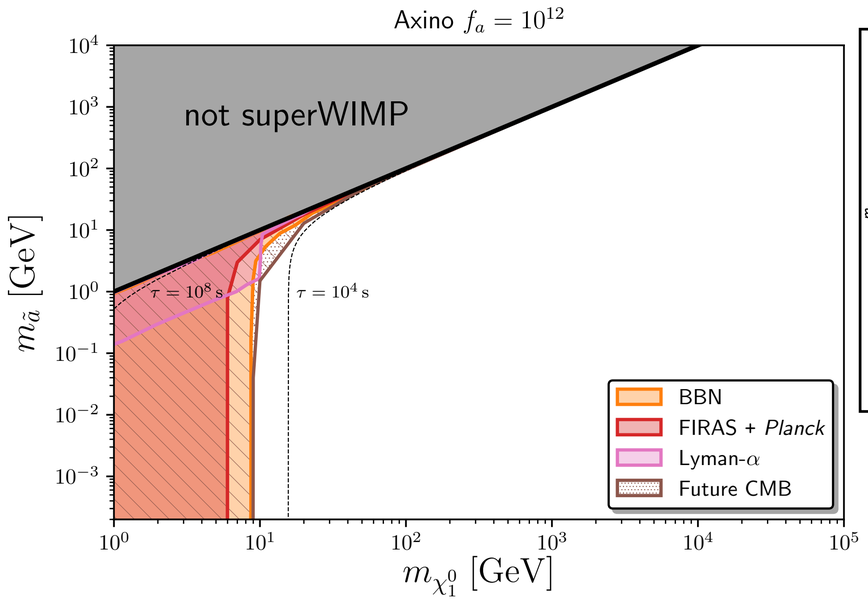

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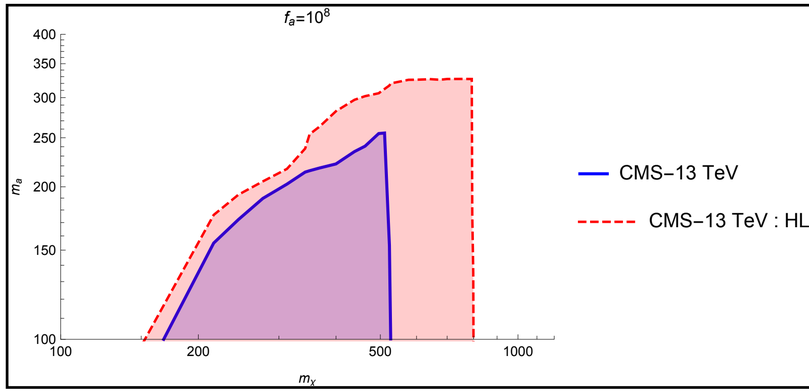

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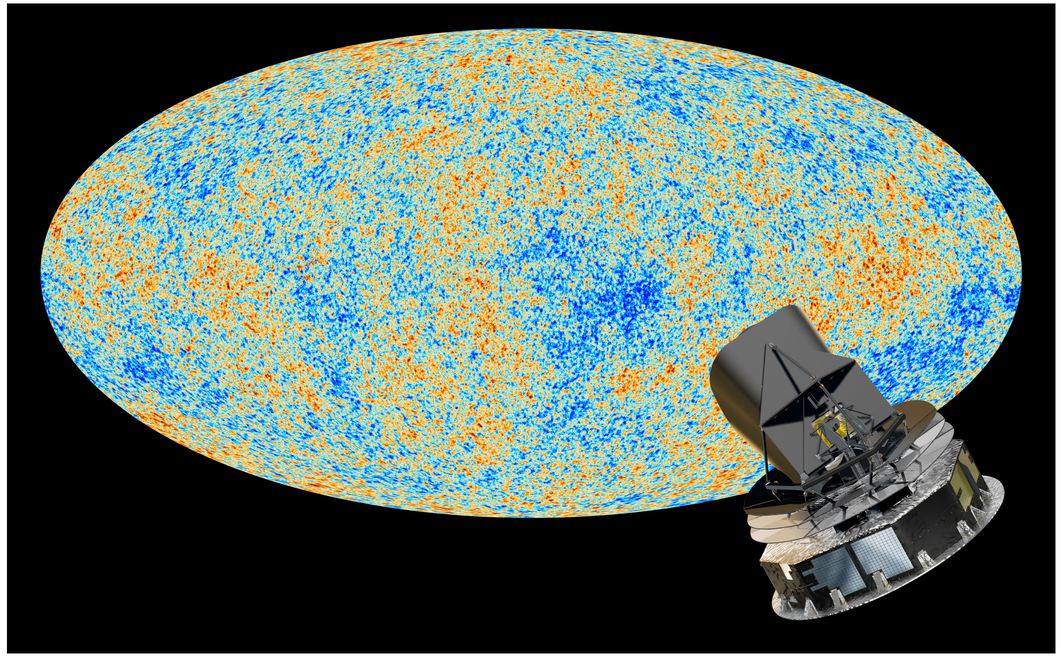


Kompaneets equation and PPSD

Modification of photon bath by Compton scattering

$$C[f]|_{\rm CS} = \dot{\tau}\frac{T_e}{m_e}\frac{1}{x^2}\frac{\partial}{\partial x}\left(x^4\left[\frac{\partial f}{\partial x} + \frac{T_z}{T_e}f(1+f)\right]\right)$$

$$\dot{\tau} = n_e\sigma_T$$
$$T_z \equiv T_0(1+z)$$

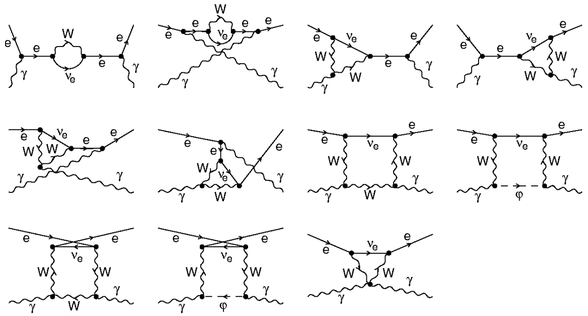
If CS is efficient, above moves towards an equillibrium solution

$$0 = \left[\frac{\partial f}{\partial x} + \frac{T_z}{T_e}f(1+f)\right] \longrightarrow f(x) = \frac{1}{\exp(\tilde{x}+C)-1}$$

BE equation with $\tilde{x} = x\,T_z/T_e = p/T_e$

Compton Scaterring conserves the number of photons in the bath and generates a non-zero chemical potential

Double Compton Scaterring + Brehmstralung generates a zero chemical potential $n\gamma \longleftrightarrow m\gamma$ with $n \neq m$



$$\frac{\partial f}{\partial \tau} = \frac{T_e}{m_e}\frac{1}{x^2}\frac{\partial}{\partial x}\left(x^4\left[\frac{\partial f}{\partial x} + \frac{T_z}{T_e}f(1+f)\right]\right) + \frac{K_{\rm BR}e^{-\tilde{x}}}{\tilde{x}^3}\mathcal{F} + \frac{K_{\rm DC}e^{-2x}}{x^3}\mathcal{F}$$

$$\mathrm{d}\tau = \sigma_T n_e \mathrm{d}t$$

See ...Hooper, Lucca, Lesgorugues, Schoneberg : 1910.04619
Chluba, Lesgourgues 2011

Spectral Distortions

Temperature Shifts

$$f(t,x) = B(x) + \Delta f(t,x)$$

$\Delta f(t,x)$ a distortion of the spectrum

$$\Delta f(x) = G(x)\frac{\Delta T}{T_z}$$

$$G(x) = -x\frac{\partial B(x)}{\partial x} = \frac{xe^x}{(e^x-1)^2}$$

Chemical potential μ distortion

$$f(x) = B(x+\mu) = \frac{1}{e^{x+\mu}-1} \approx \frac{1}{e^x-1} - \mu\frac{G(x)}{x} = B(x) - \mu\frac{G(x)}{x}$$

$$\Delta f(x) = -\mu\frac{G(x)}{x}$$

Compton y distortion

Kompaneets eqn without equillibrium

$$\frac{\Delta f}{\Delta\tau} \approx \frac{T_e}{m_e}\frac{1}{x^2}\frac{\partial}{\partial x}\left(x^4\left[\frac{\partial B(x)}{\partial x} + \frac{T_z}{T_e}B(x)(1+B(x))\right]\right) = \frac{T_z - T_e}{m_e}\frac{\frac{\partial}{\partial x}(x^3G(x))}{x^2}$$

$$\Delta f(x) \approx \Delta\tau\frac{T_e - T_z}{m_e}Y(x)$$

$$Y(x) \equiv -\frac{\frac{\partial}{\partial x}(x^3G(x))}{x^2} = G(x)\left[x\frac{e^x+1}{e^x-1} - 4\right]$$

Heating Sources

Injection and deposition

Energy Injection into IGM

$$\boxed{\text{deposition } \textit{function } f_c(z)}$$

Fraction of injected energy in channel c at redshift z

$$\boxed{\left.\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\right|_{\mathrm{dep,c}} = \left.\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\right|_{\mathrm{inj}} f_{\mathrm{c}} = \left.\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\right|_{\mathrm{inj}} f_{\mathrm{eff}}\ \chi_c \equiv \dot{\mathcal{Q}}\,\chi_c}$$

Use on-the spot approximation

$$\boxed{\dot{Q} = \left.\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\right|_{\mathrm{dep},h} + \dot{Q}_{\mathrm{non-inj}} = \dot{\mathcal{Q}}\,\chi_h + \dot{Q}_{\mathrm{non-inj}}}$$

Energy Deposition into heat

Lyman alpha

Estimate the Co-moving Free Streaming Scale

$$\lambda_{\rm FS}(t) \simeq \int_{t_{\rm prod}}^{t} \frac{{\rm d}t'}{a(t')} v(t')$$

Depends on the particle mass and cosmological parameters

$$\lambda_{\rm FS,WDM}(z=2) \simeq \int_0^t \frac{{\rm d}t'}{a(t')} \frac{p}{E}(t'),$$
$$\simeq \frac{1}{H_0}\sqrt{\frac{a_{\rm eq}}{\Omega_m}} \int_0^{a/a_{\rm eq}} \frac{{\rm d}y}{\sqrt{(1+y)(1+b^2y^2)}},$$

Value at z=0 should correspond to the thermal (WDM) transfer function

$$T(k) = \left[1 + (\alpha k)^{2\nu}\right]^{-5\nu}$$

Found by fitting the function to the actual transfer function from CLASS or CAMB

$$\alpha = a m_X^b \left(\frac{\omega_X}{0.12}\right)^{\eta} \left(\frac{h}{0.6736}\right)^{\theta} h^{-1}\,{\rm Mpc}$$

$$\alpha = 0.24 \left(\frac{m_x/T_x}{1\ {\rm keV}/T_\nu}\right)^{-0.83} \left(\frac{\omega_x}{0.12}\right)^{-0.16}\ {\rm Mpc}$$

With for a thermal WDM

$$\omega_x = \left(\frac{T_x}{T_\nu}\right)^3 \left(\frac{m_x}{94\ {\rm eV}}\right),$$