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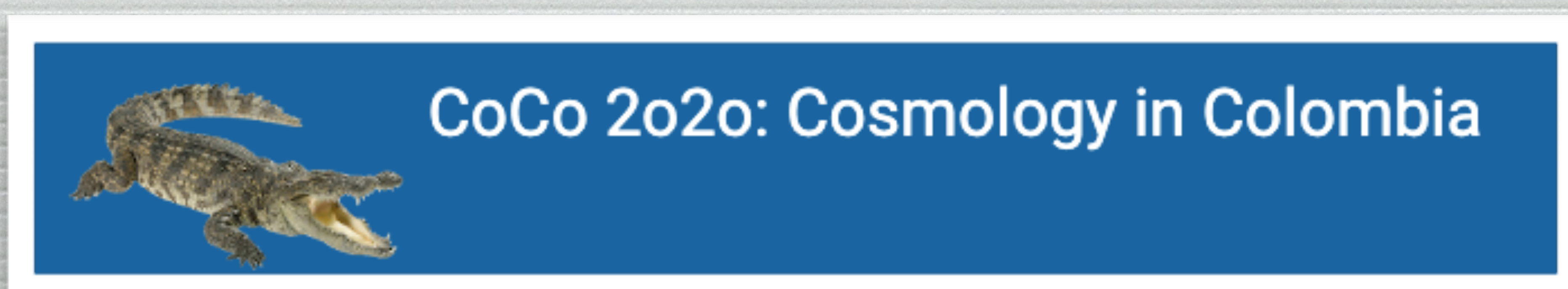
Cosmological Evolution of Scalar Field Dark Matter with an Axion-like Potential

Francisco Xavier Linares Cedeño

Based on: https://arxiv.org/abs/1703.10180 **and** https://arxiv.org/abs/2006.05037

In collaboration with
Alma Xóchitl González Morales
Luis Arturo Ureña López



Ultralight DM boson Cosmology

Basic Ingredients:

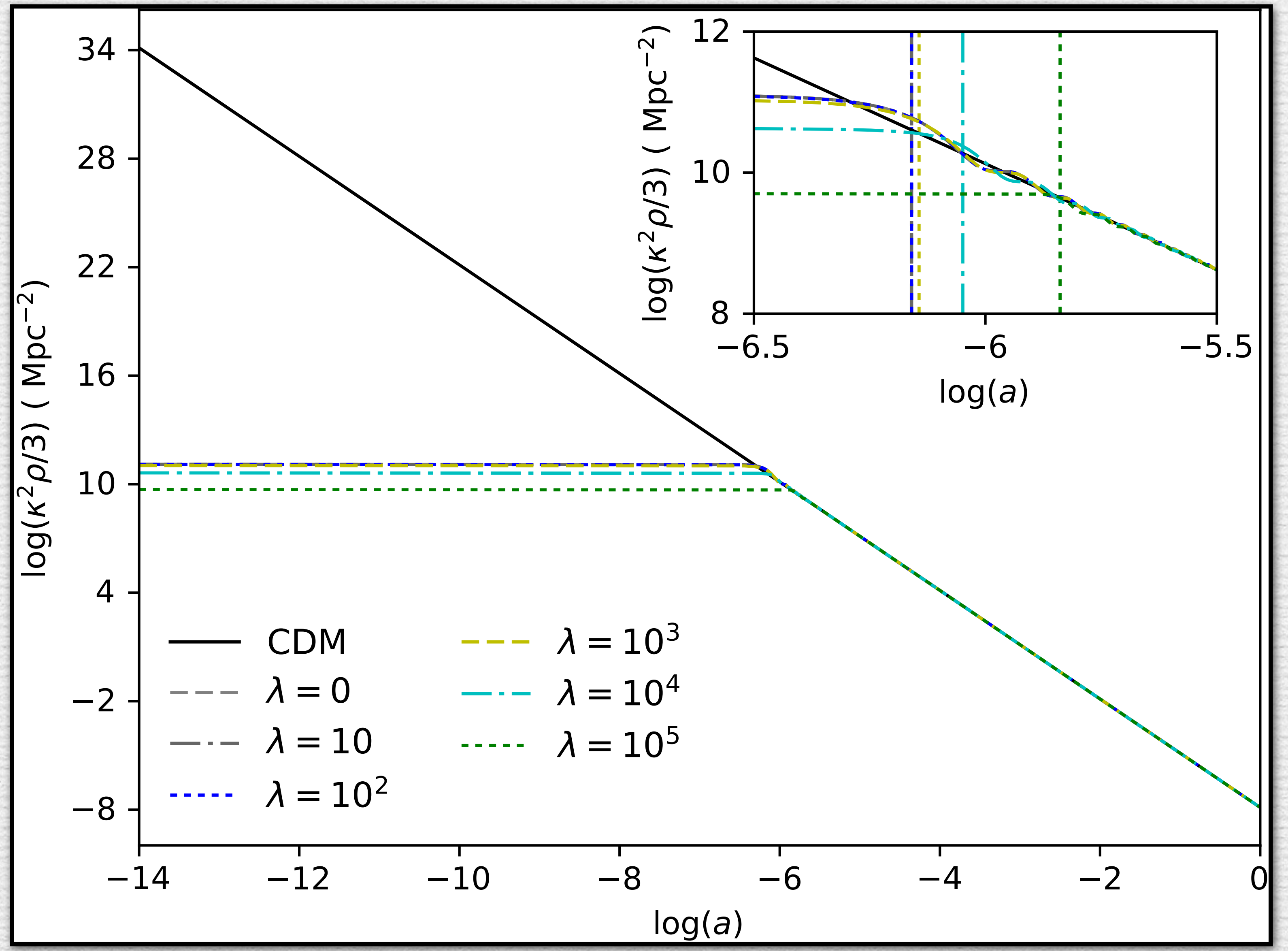
- General Relativity $G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa^2 \left(T^{SM}_{\mu\nu} + T^{\phi}_{\mu\nu} \right)$
- Spatially-flat (FRW) Universe $ds^2 = -dt^2 + a^2(t)\delta_{ij}dx^i dx^j$
- Ordinary Matter $\rho\,, p$
- Cosmological Constant Λ
- Scalar Field Dark Matter $\phi(t) \rightarrow \rho_\phi\,, p_\phi$
- Trigonometric Potential $V(\phi) = m_\phi^2 f^2 \left[1 + \cos\left(\frac{\phi}{f} \right) \right]$

Background Evolution

$$H^2 = \frac{\kappa^2}{3}\left(\sum_j \rho_j + \rho_\phi\right), \dot{H} = -\frac{\kappa^2}{2}\left[\sum_j \left(\rho_j + p_j\right) + \left(\rho_\phi + p_\phi\right)\right], \dot{\rho}_j = -3H\left(\rho_j + p_j\right), \ddot{\phi} = -3H\dot{\phi} - m_\phi^2 f \sin\left(\frac{\phi}{f}\right),$$

$$x \equiv \frac{\kappa\dot{\phi}}{\sqrt{6}H} = \Omega_\phi^{1/2}\sin(\theta/2), \quad y \equiv \frac{\kappa V^{1/2}}{\sqrt{3}H} = \Omega_\phi^{1/2}\cos(\theta/2), \quad y_1 \equiv -\frac{2\sqrt{2}}{H}\partial_\phi V^{1/2}, \quad y_2 \equiv -\frac{4\sqrt{3}}{H\kappa}\partial_\phi^2 V^{1/2}.$$

$$\theta' = -3\sin\theta + y_1, \quad y_1' = \frac{3}{2}\left(1+\omega_{tot}\right)y_1 + \frac{\lambda}{2}\Omega_\phi \sin\theta, \quad \Omega_\phi' = 3(\omega_{tot} - \omega_\phi)\Omega_\phi.$$



$$\lambda = \frac{3}{\kappa^2 f^2}$$

$$m_\phi = 10^{-22}\text{eV}$$

Linear Perturbations

$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j\,, \quad \phi(\overrightarrow{x}, t) = \phi(t) + \varphi(\overrightarrow{x}, t)\,,$$

$$\ddot{\varphi}(\overrightarrow{k}, t) = -3H\dot{\varphi}(\overrightarrow{k}, t) - \left(\frac{k^2}{a^2} + \frac{\partial^2 V(\phi)}{\partial \phi^2}\right)\varphi(\overrightarrow{k}, t) - \frac{1}{2}\dot{\phi}\dot{\bar{h}}\,,$$

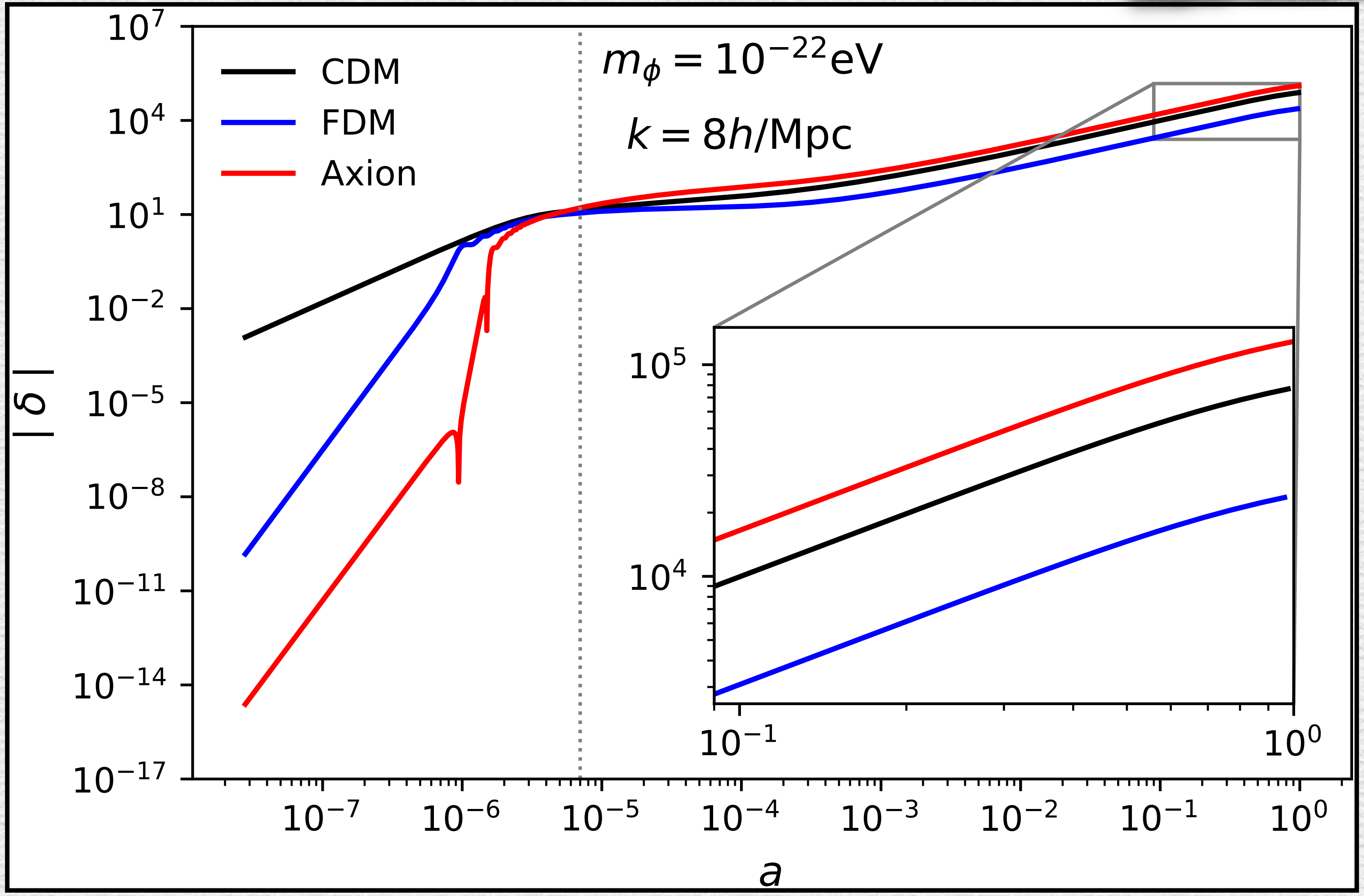
$$\delta_0' = \left[-3\sin\theta - \frac{k^2}{k_J^2}(1-\cos\theta)\right]\delta_1 + \frac{k^2}{k_J^2}\sin\theta\,\delta_0 - \frac{\bar{h}'}{2}(1-\cos\theta)\,,$$

$$\delta_1' = \left[-3\cos\theta - \frac{k_{eff}^2}{k_J^2}\sin\theta\right]\delta_1 + \frac{k_{eff}^2}{k_J^2}(1+\cos\theta)\,\delta_0 - \frac{\bar{h}'}{2}\sin\theta\,,$$

Boltzmann Code CLASS

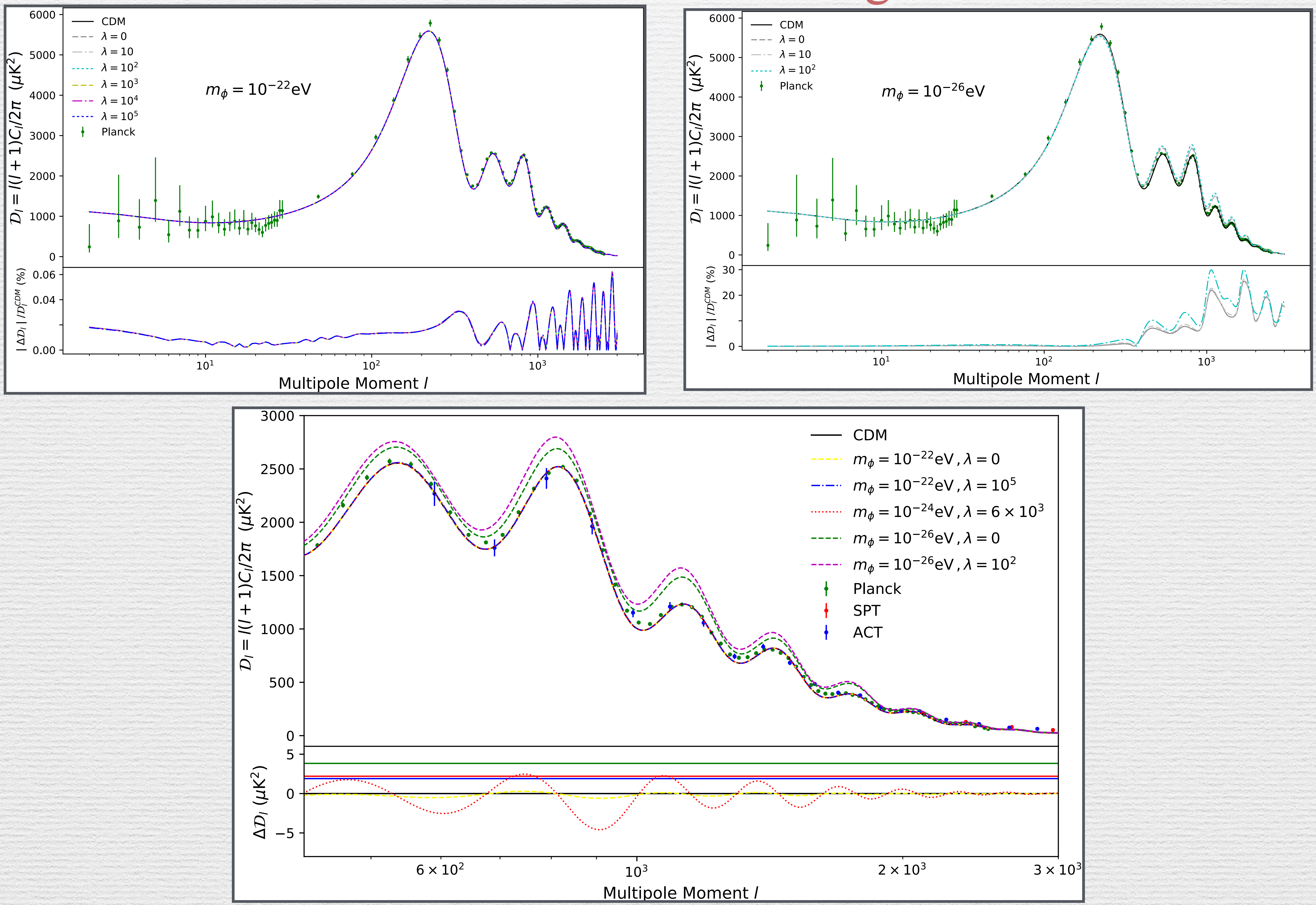
(Cosmic Linear Anisotropy Solving System)

Lesgourgues, Júlien . "The Cosmic Linear Anisotropy Solving System (CLASS) I: Overview ", 2011. https://arxiv.org/abs/1104.2932



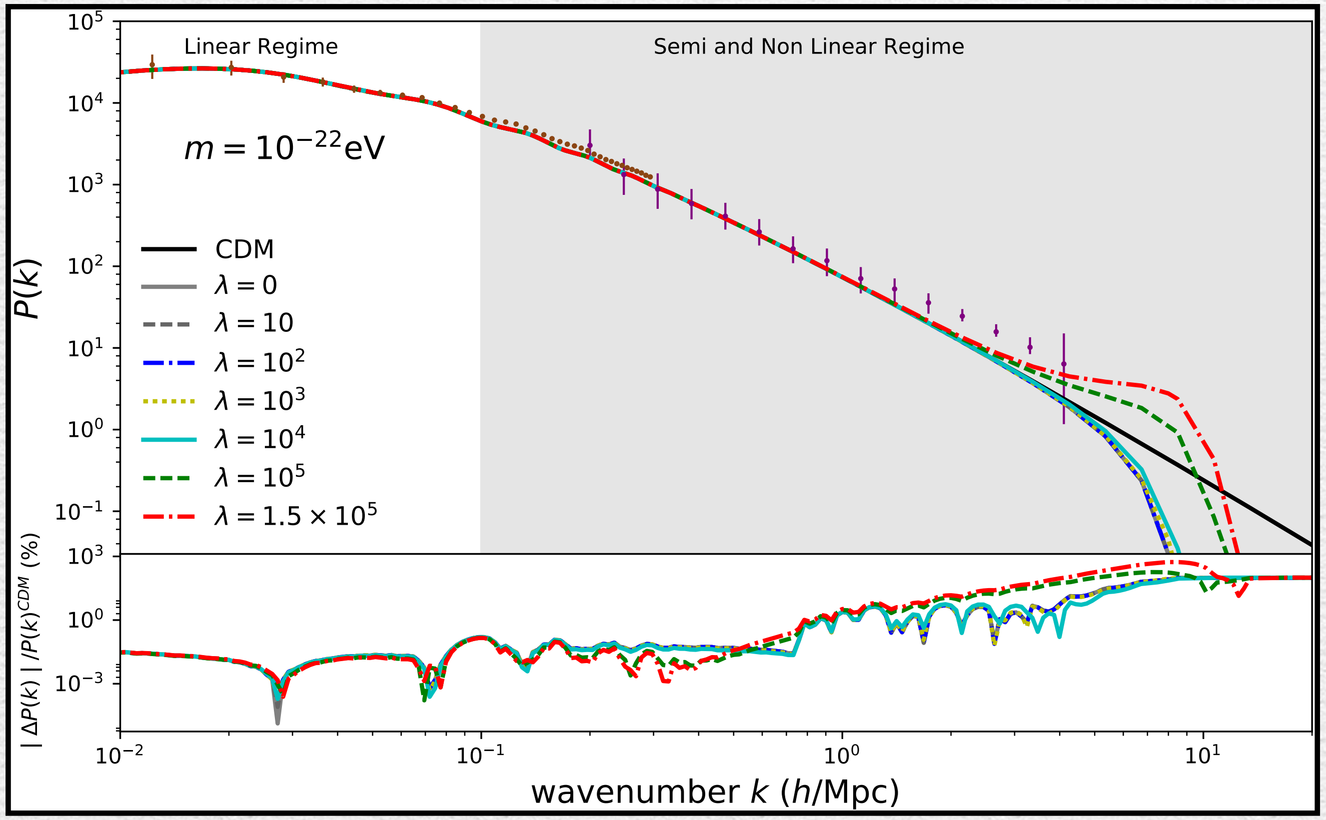
Cosmological Observables

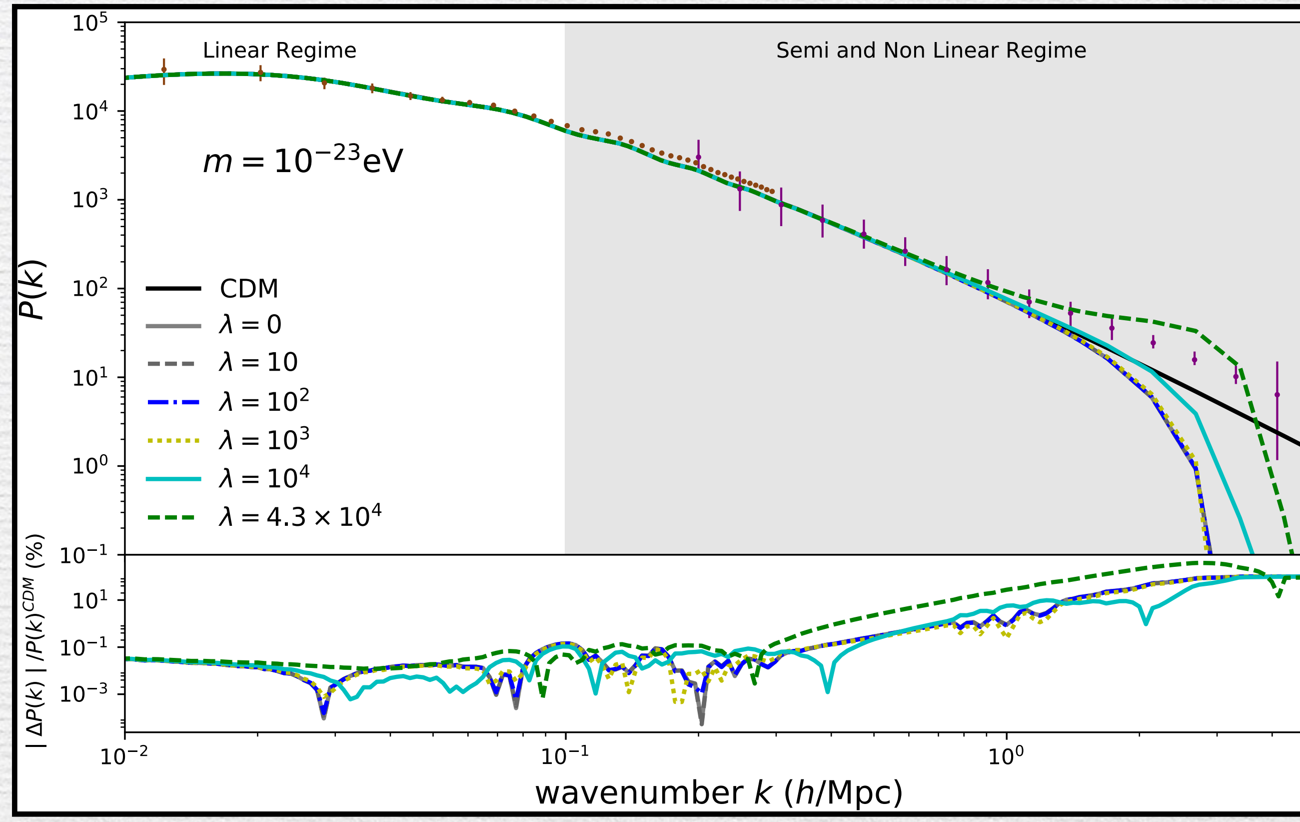
Cosmic Microwave Background



Cosmological Observables

3D & 1D Matter Power Spectrum





Transmitted Flux

$$F = e^{-\tau} \simeq e^{-A(1+\delta)^2}$$

Flux Contrast

$$\delta_F = \frac{F - \bar{F}}{\bar{F}}$$

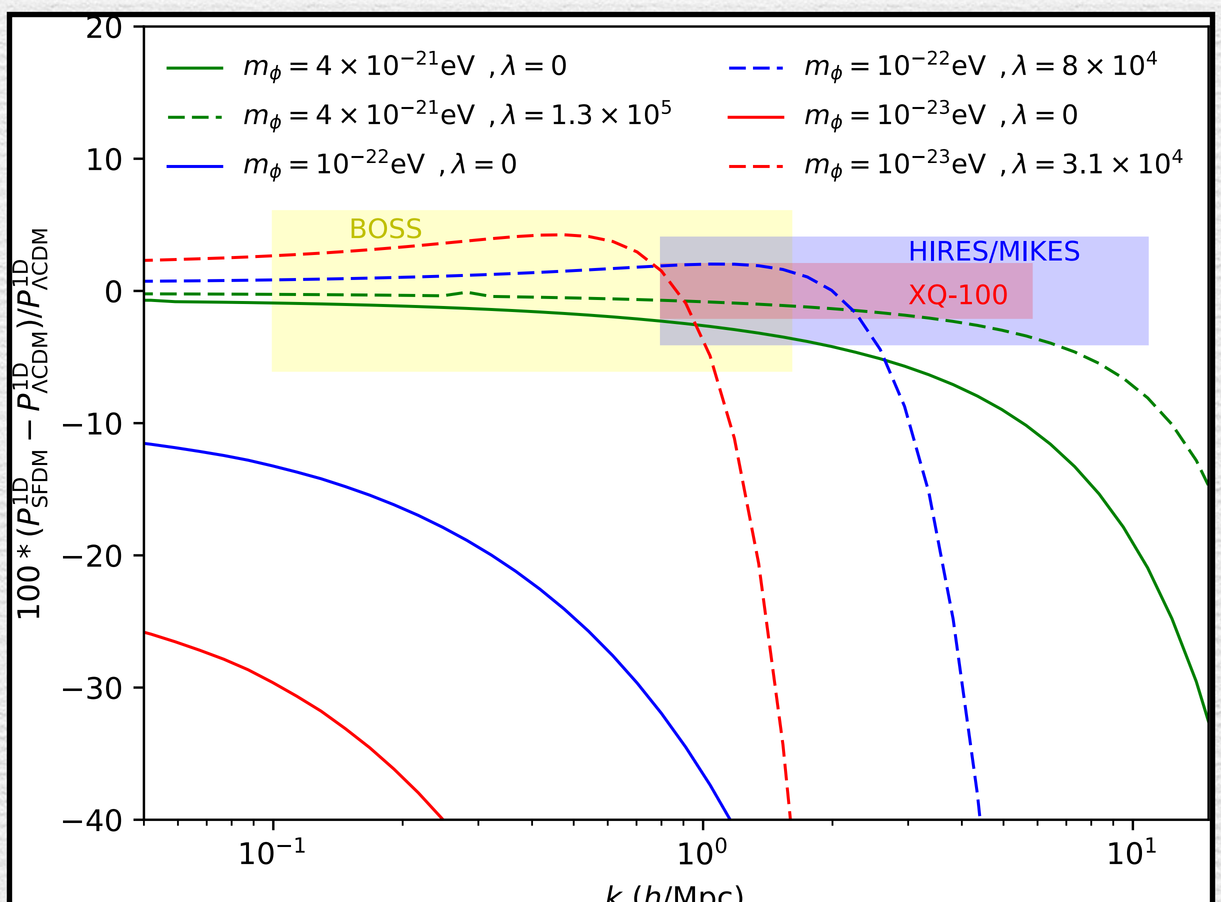
2-PCF

$$\xi_F = < \delta_F \delta_F' >$$

$$\xi_F \propto \xi^{1D}$$

$$\therefore$$

$$\mathscr{P}_F(k) \propto \mathscr{P}^{1D}(k_\parallel)$$

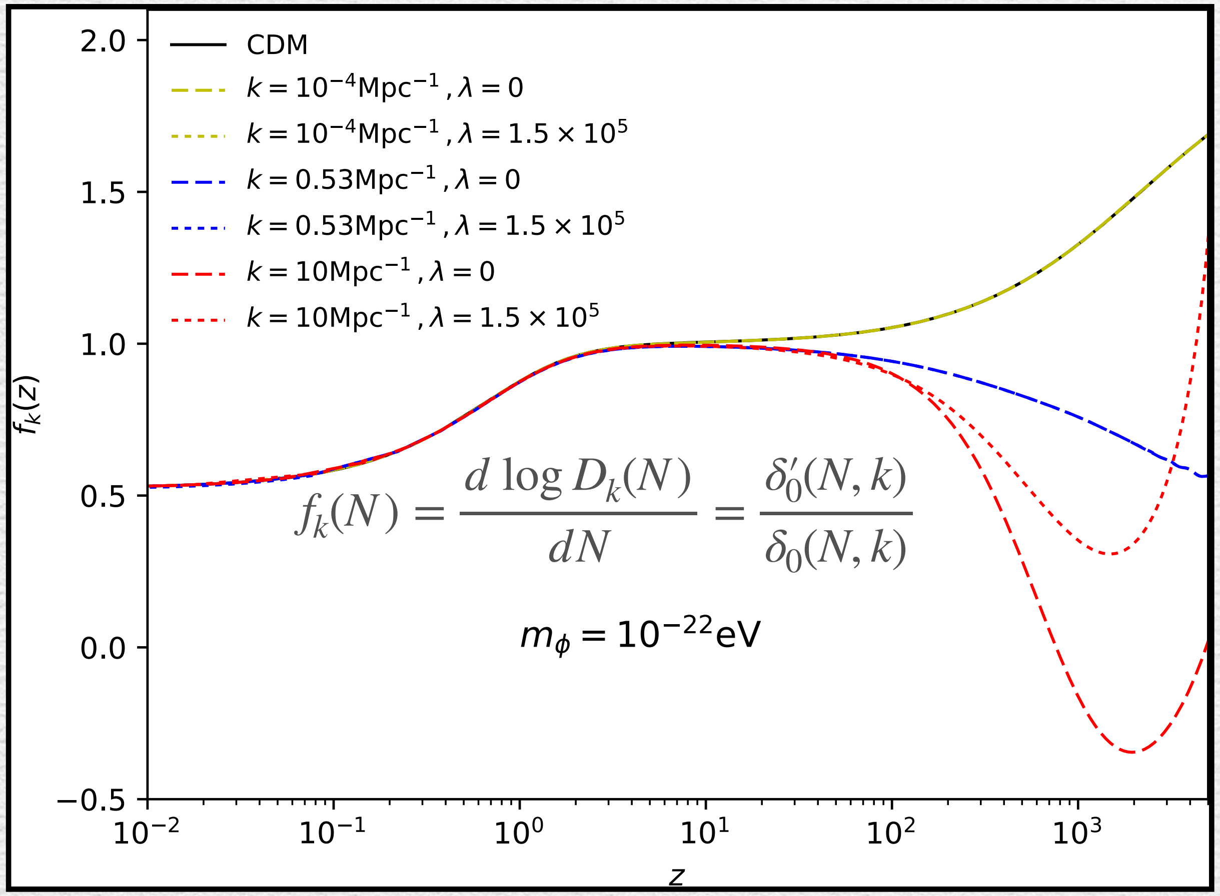


$$\mathscr{P}^{1D}(k_\parallel) = \frac{1}{2\pi} \int k_\perp \mathscr{P}^{3D}(k) dk_\perp$$

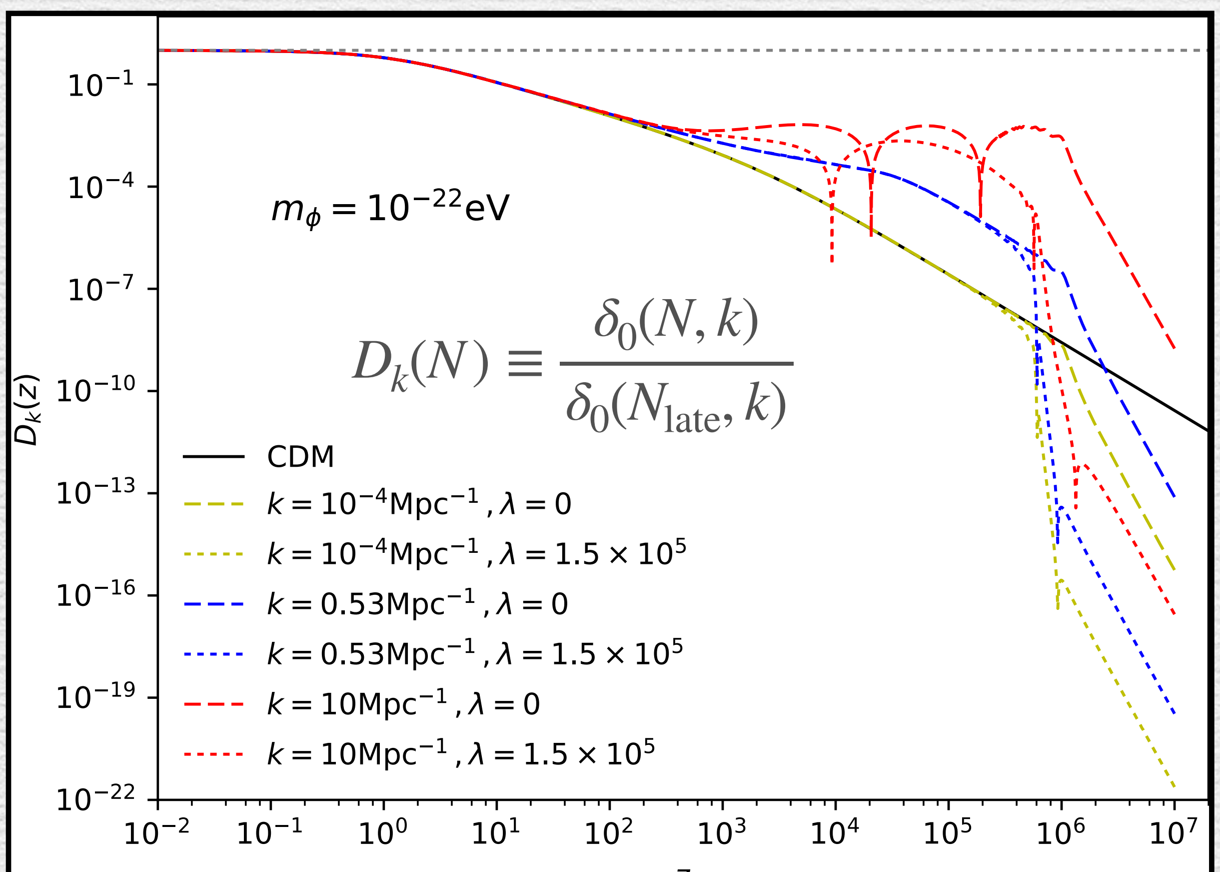
$$k = \sqrt{k_\perp^2 + k_\parallel^2}\,.$$

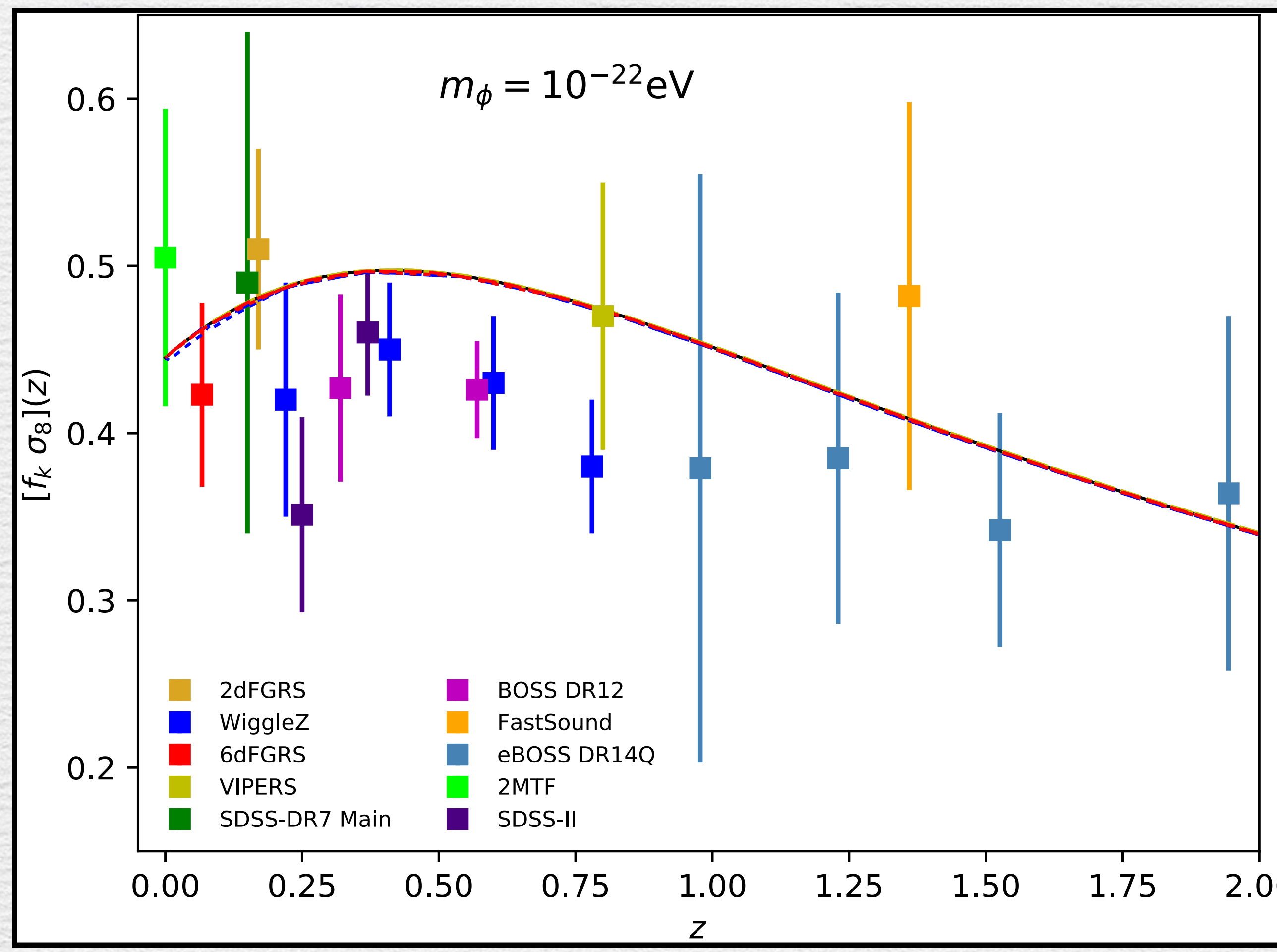
Cosmological Observables

Growth Factor and Velocity Growth Factor



$$\delta_0''(N) + \left(\frac{k k_{eff}}{k_J^2}\right)^2 \delta_0(N) = -\frac{\bar{h}''}{2} + 2\frac{k^2}{k_J^2}\frac{k_J'}{k_J}\delta_1(N)$$



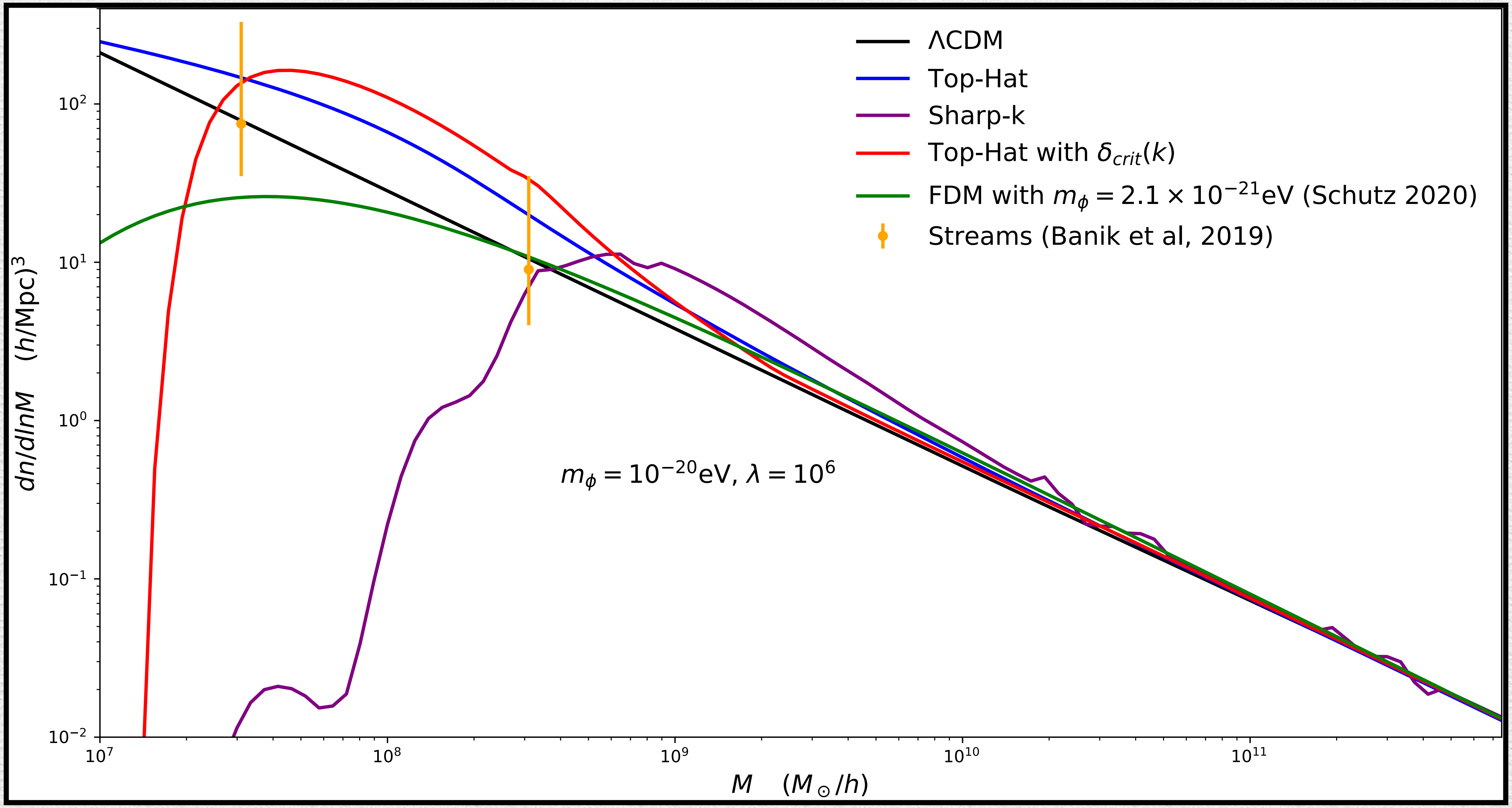


Cosmological Observables

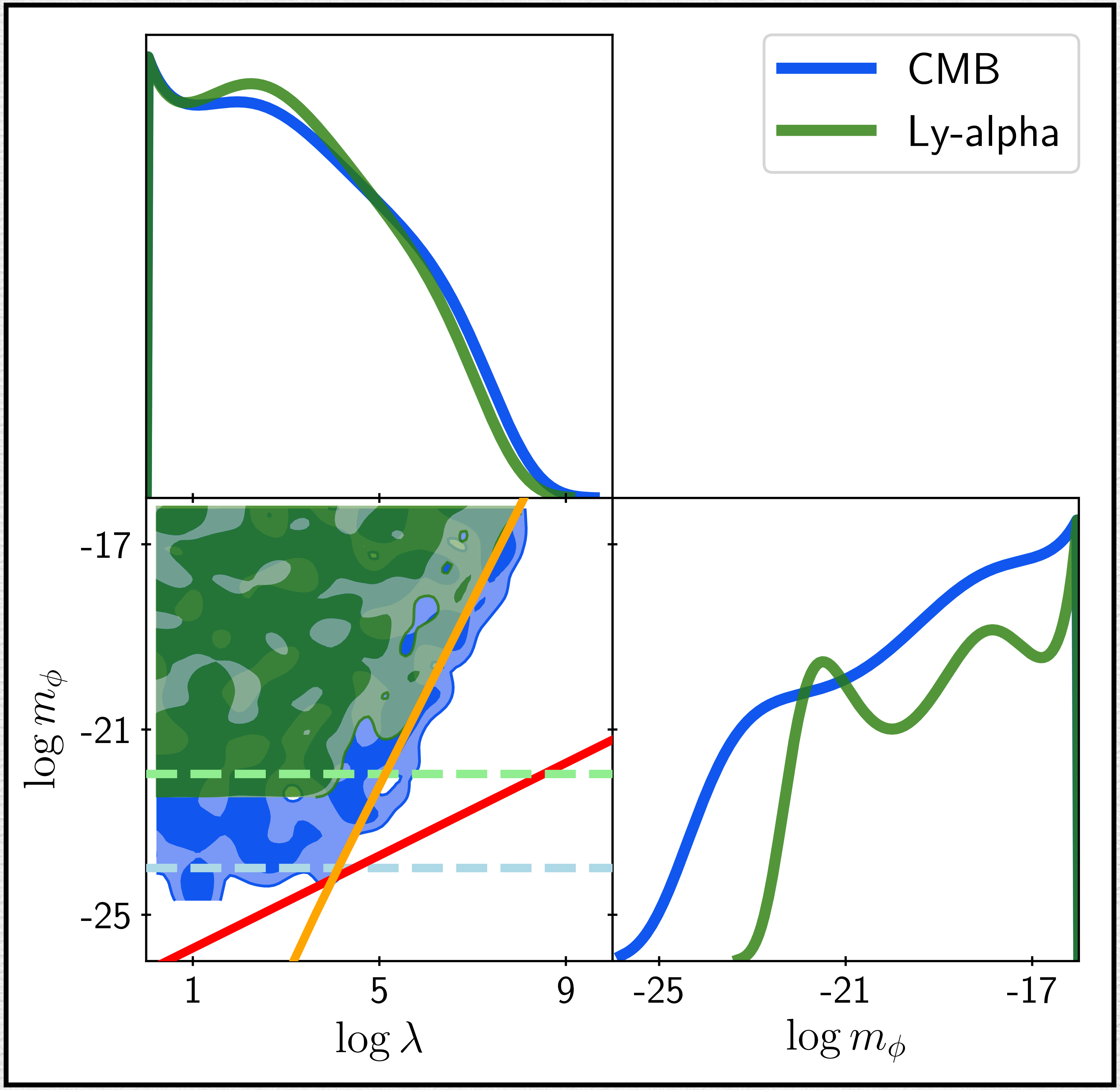
Semi-analytical Halo Mass Function

Window functions: $W_{TH}(kr) = \frac{3}{(kr)^3}\left[\sin(kr) - kr\cos(kr)\right]\,, \quad W_{SK}(kr) = \Theta(2\pi - kr)\,.$

Critical overdensity: $\delta_{crit} = 1.686\frac{D_{\rm CDM}(z=0)}{D_{\rm CDM}(z)}\,, \quad \delta_{crit}(k) = 1.686\frac{\delta_{\rm CDM}}{\delta_0(N,k)}\,.$



Statistical Analysis



Cosmological Parameter Estimator

MONTE PYTHON

(Monte Carlo code written in python)

Audren, Benjamin et al. "**Conservative Constraints on Early Cosmology: an illustration of the Monte Python cosmological parameter inference code**", 2013. https://arxiv.org/abs/1210.7183

Lower bound (CMB)

$\log m_\phi \geq -23.99$

Lower bound (Ly-α)

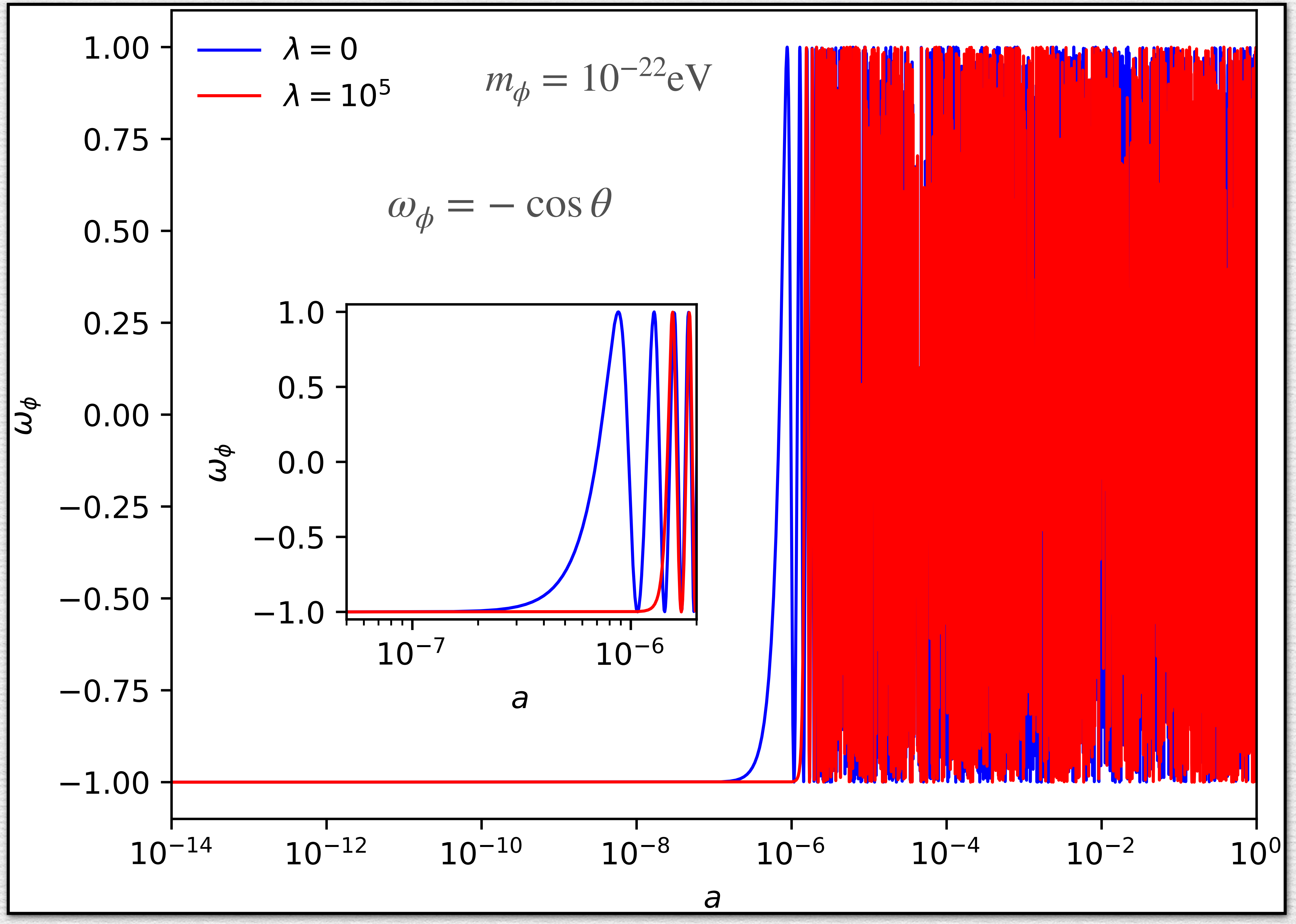
$\log m_\phi \geq -21.96$

Gracias!!!

Thank you!!!

¿Questions?

Background Evolution



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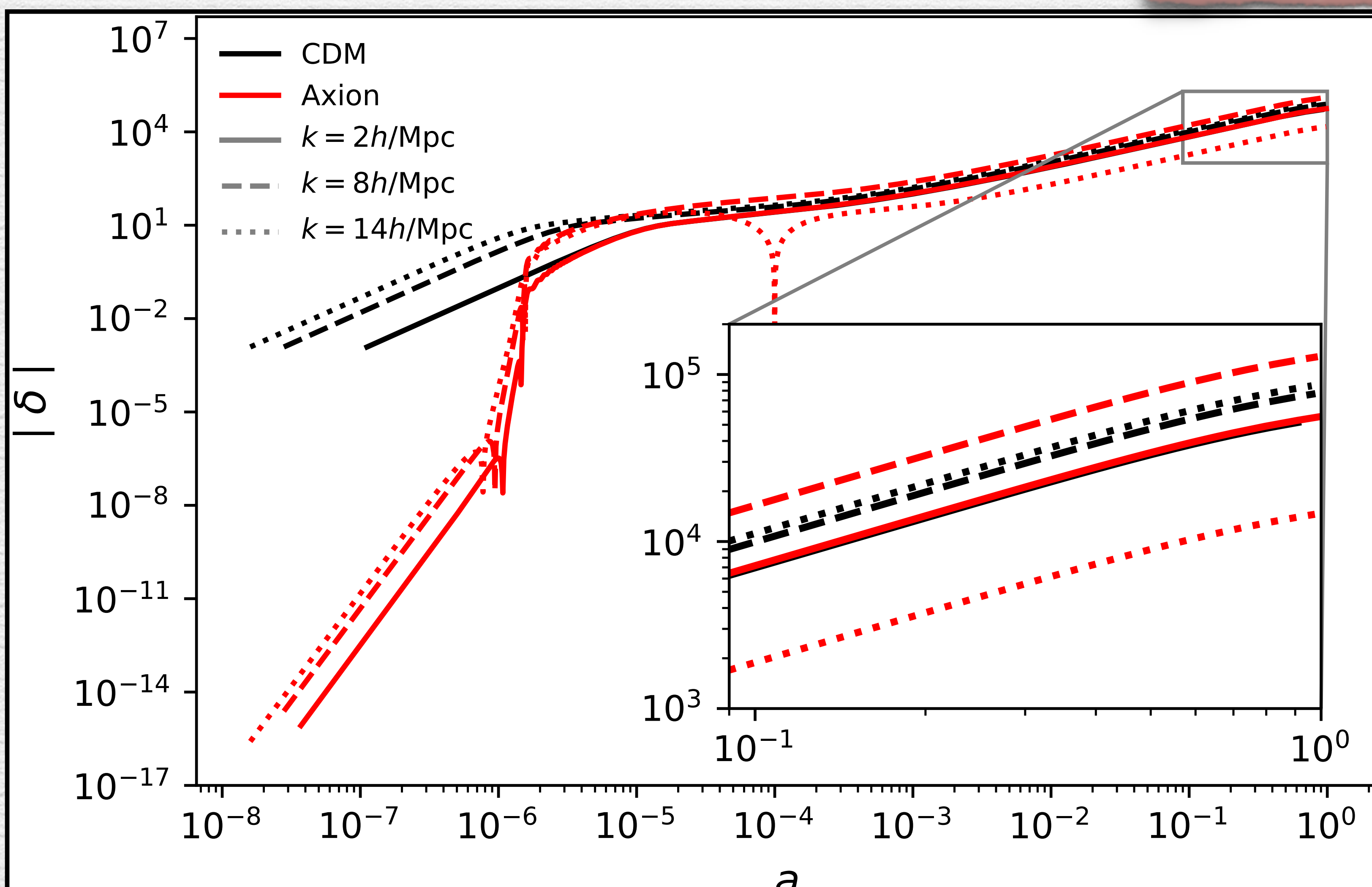

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