



UNIVERSITÀ  
DEGLI STUDI  
FIRENZE



# Evolving Dark Matter

## Coupled Dark Sector in Light of DESI Data

Lorenzo La Penna

University of Florence

December 18, 2025

*In collaboration with: A. Notari, M. Redi  
TPPC 2025 theory retreat*

Evolving Dark  
Matter

Lorenzo La Penna

Introduction

Tension in Light of  
New Data

Scalar Field  
Dynamics

Dark Degeneracy

Time Varying DM  
mass

Background  
Cosmology

Linear Cosmology

Conclusion

# Effective Description of Fluid in Cosmology

- The Universe on large scales ( $d \gtrsim \mathcal{O}(10 \text{ Mpc})$ ) is **homogeneous** and **isotropic**

$$ds^2 = [-dt^2 + a^2(t)\delta_{ij}dx^i dx^j] \quad \text{FLRW}$$

- Expansion determined by its constituent, described as **barotropic fluids**:

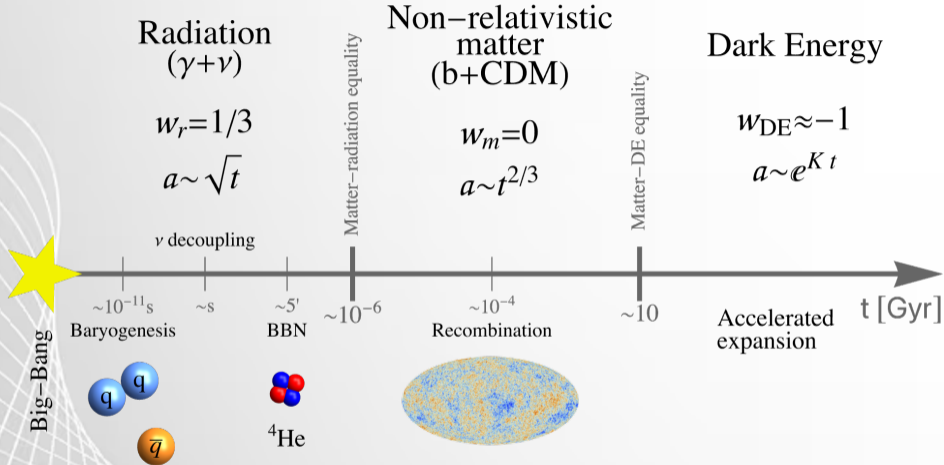
$$\left. \begin{array}{l} \text{Energy density} \quad \rho_I(t) \\ \text{Pressure} \quad \quad \quad p_I(t) \end{array} \right\}$$

## Equation of State

$$p_I(t) = w_I(t)\rho_I(t)$$

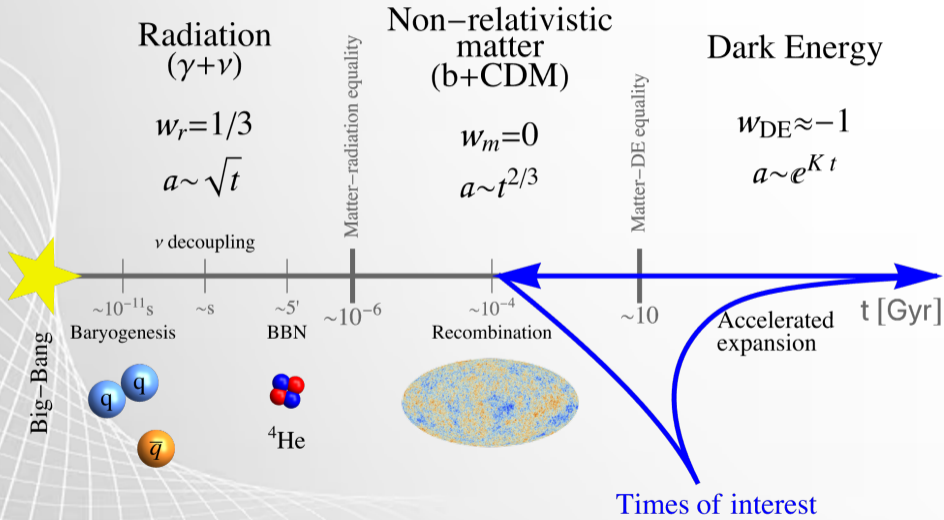
$$\left. \begin{array}{l} H^2 \equiv \left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{a^2(t)}{3M_p^2} \sum_I \rho_I(t) \\ \dot{\rho}_I(t) + 3H(1 + w_I(t))\rho_I(t) = 0 \end{array} \right\} w_I(t) \text{ determines the dynamics}$$

# Cosmic History



- Introduction
- Tension in Light of New Data
- Scalar Field Dynamics
- Dark Degeneracy
- Time Varying DM mass
- Background Cosmology
- Linear Cosmology
- Conclusion

# Cosmic History

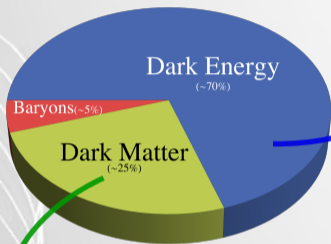


Times of interest

# The Invisible Universe and $\Lambda$ CDM:

What are dark matter and dark energy?

Today's Energy Budget



- **Dark Energy:**

Cosmological Constant  $\Lambda$

$$w_{\Lambda} = -1 \quad (p_{\Lambda} = -\rho_{\Lambda})$$

**No additional degrees of freedom!**

- **Dark Matter:**

Non-relativistic, collisionless perfect fluid **CDM**

$$w_{\text{DM}} = 0 \quad (p_{\text{DM}} = 0) \quad \delta p_{\text{DM}} = 0$$

} Structure formation

# Observations with BAO & Supernovae

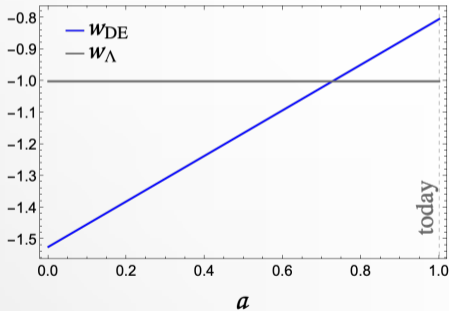


## DES+DESI+CMB

$w_0$	$w_a$	$\sigma$
$-0.803 \pm 0.054$	$-0.72 \pm 0.21$	$3.2\sigma$

## CPL form

$$w_{\text{DE}}(a) = w_0 + w_a(1 - a)$$



# Observations with BAO & Supernovae



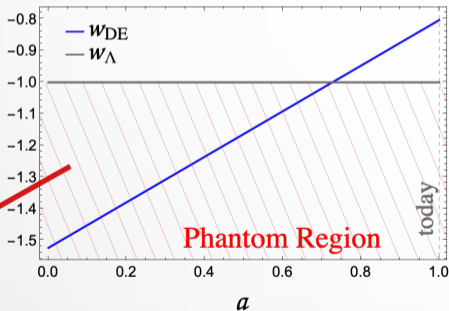
## CPL form

$$w_{\text{DE}}(a) = w_0 + w_a(1 - a)$$

## DES+DESI+CMB

$w_0$	$w_a$	$\sigma$
$-0.803 \pm 0.054$	$-0.72 \pm 0.21$	$3.2\sigma$

**No canonical degrees of freedom can propagate in the phantom region!**





So is there a consistent description of  $w_0w_a$ CDM?

### $w_0w_a$ CDM

- Decoupled dark components

$$S = \underline{S_{\text{DE}}} + S_{\text{DM}} \quad !$$

- $\dot{\rho}_{\text{tot}} + 3H(1 + w_{\text{tot}})\rho_{\text{tot}} = 0$

with:

$$\rho_{\text{tot}} = \rho_{\text{DM}} + \rho_{\text{DE}}$$

$$w_{\text{tot}} = w_{\text{CPL}} \frac{\rho_{\text{DE}}}{\rho_{\text{tot}}} > -1$$

- $\dot{\rho}_{\text{DE}} + 3H(1 + w_{\text{CPL}})\rho_{\text{DE}} = 0$   
 $\dot{\rho}_{\text{DM}} + 3H\rho_{\text{DM}} = 0$

### Coupled Dark Sector

- Interacting dark components

$$S = S_{\varphi+\chi}$$

- $\dot{\rho}_{\text{tot}} + 3H(1 + w_{\text{tot}})\rho_{\text{tot}} = 0$

with:

$$\rho_{\text{tot}} = \rho_{\chi} + \rho_{\varphi}$$

$$w_{\text{tot}} = w_{\varphi} \frac{\rho_{\varphi}}{\rho_{\text{tot}}}$$

- $\dot{\rho}_{\varphi} + 3H(1 + w_{\varphi})\rho_{\varphi} = -Q$   
 $\dot{\rho}_{\chi} + 3H\rho_{\chi} = Q$

So is there a consistent description of  $w_0w_a$ CDM?

### $w_0w_a$ CDM

- Decoupled dark components

$$S = \underline{S_{DE}} + S_{DM} !$$

- $\dot{\rho}_{\text{tot}} + 3H(1 + w_{\text{tot}})\rho_{\text{tot}} = 0$

with:

$$\rho_{\text{tot}} = \rho_{DM} + \rho_{DE}$$

$$w_{\text{tot}} = w_{CPL} \frac{\rho_{DE}}{\rho_{\text{tot}}} > -1$$

- $\dot{\rho}_{DE} + 3H(1 + w_{CPL})\rho_{DE} = 0$   
 $\dot{\rho}_{DM} + 3H\rho_{DM} = 0$

### Coupled Dark Sector

- Interacting dark components

$$S = S_{\varphi+\chi}$$

- $\dot{\rho}_{\text{tot}} + 3H(1 + w_{\text{tot}})\rho_{\text{tot}} = 0$

with:

$$\rho_{\text{tot}} = \rho_{\chi} + \rho_{\varphi}$$

$$w_{\text{tot}} = w_{\varphi} \frac{\rho_{\varphi}}{\rho_{\text{tot}}}$$

- $\dot{\rho}_{\varphi} + 3H(1 + w_{\varphi})\rho_{\varphi} = -Q$   
 $\dot{\rho}_{\chi} + 3H\rho_{\chi} = Q$

Same  
Background,  
Dark  
Degeneracy

# Time Varying Dark Matter Mass

The mass of DM is sourced by the quintessence field

$$S_{\text{dark}} = - \int d^4x \sqrt{-g} \left[ \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi + V(\varphi) - \mathcal{L}_\chi(\chi, \varphi) \right]$$

with DM being still **non-relativistic**:

World-line action  
of massive particle

$$\begin{aligned} S_\chi &= - \int d\tau m(\varphi) \sqrt{-g_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau}} \\ &= - \int d\tau m_\star \sqrt{-\tilde{g}_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau}} \end{aligned}$$

$$\tilde{g}_{\mu\nu} = \left( \frac{m(\varphi)}{m_\star} \right)^2 g_{\mu\nu}$$

# Time Varying Dark Matter Mass

The mass of DM is sourced by the quintessence field

$$S_{\text{dark}} = - \int d^4x \sqrt{-g} \left[ \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi + V(\varphi) - \mathcal{L}_\chi(\chi, \varphi) \right]$$

with DM being still **non-relativistic**:

World-line action  
of massive particle

$$\begin{aligned} S_\chi &= - \int d\tau m(\varphi) \sqrt{-g_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau}} \\ &= - \int d\tau m_\star \sqrt{-\tilde{g}_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau}} \end{aligned}$$

$$\tilde{g}_{\mu\nu} = \left( \frac{m(\varphi)}{m_\star} \right)^2 g_{\mu\nu}$$

**We do not need the UV theory of DM (i.e. Boson or Fermion)**

**We only need to assume the time dependence**  
 $m(t) = m(\varphi(t))$

# Construct the new dark sector from the isolated one (i.e. $w_0 w_a$ CDM)

$$\nabla_\mu T_{\nu, \chi}^\mu = \frac{1}{m} \frac{\partial m}{\partial \varphi} \partial_\nu \varphi T_\chi \quad \nabla_\mu T_{\nu, \varphi}^\mu = -\nabla_\mu T_{\nu, \chi}^\mu$$

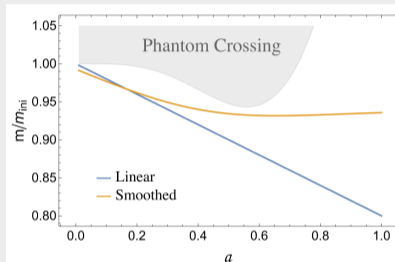
$$\rho_{DM} \rightarrow \rho_\chi = \rho_{DM} \frac{m}{m_{ini}}$$

$$\rho_{DE} \rightarrow \rho_\varphi = \rho_{DE} + \rho_{DM} \left( 1 - \frac{m}{m_{ini}} \right)$$

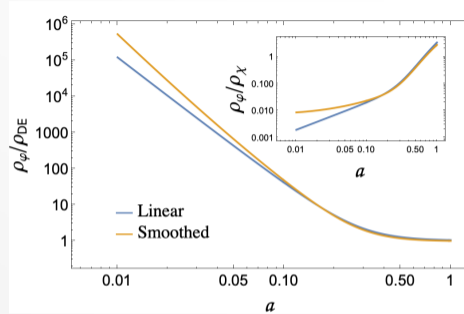
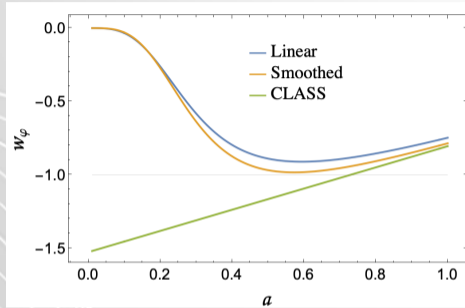
$$w_{DE} \rightarrow w_\varphi = \frac{w_{DE}}{1 + \frac{\rho_{DM}}{\rho_{DE}} \left( 1 - \frac{m}{m_{ini}} \right)}$$

$$m(\varphi(a)) = \begin{cases} m_{ini}(1 - \alpha a) & \text{Linear} \\ m_{ini} \{ 1 - [\alpha a (1 - S_\Delta(a - a_s)) + \alpha a_s S_\Delta(a - a_s)] \} & \text{Smoothed} \end{cases}$$

$$\text{with: } S_\Delta(x) = \frac{1}{2} \left( 1 + \tanh \left( \frac{x}{\Delta} \right) \right)$$

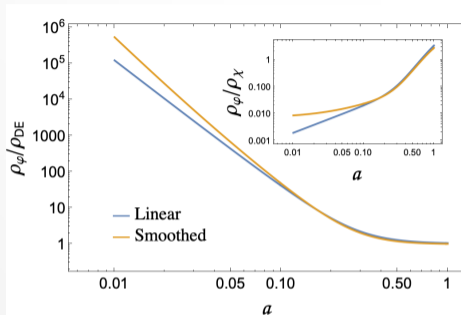
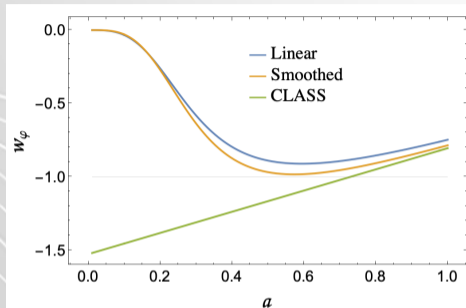


# Coupled Background



**CLASS** stands for the isolated picture  
obtained with the cosmological Boltzmann code CLASS

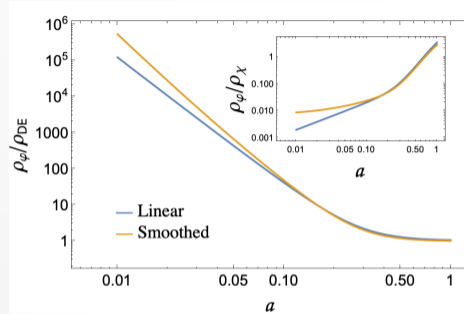
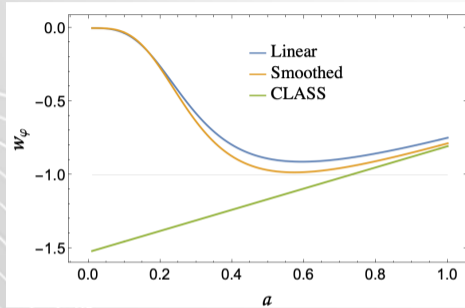
# Coupled Background



**Stable  
Quintessence**

**CLASS** stands for the isolated picture  
obtained with the cosmological Boltzmann code CLASS

# Coupled Background



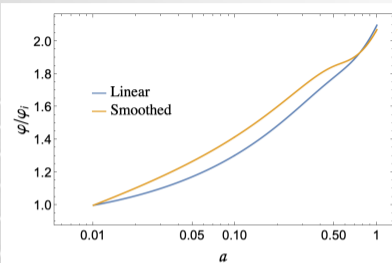
**Stable  
Quintessence**

**Strong energy injection  
towards DE at early times,  
but still a CDM dominated epoch.**

**CLASS** stands for the isolated picture

obtained with the cosmological Boltzmann code CLASS

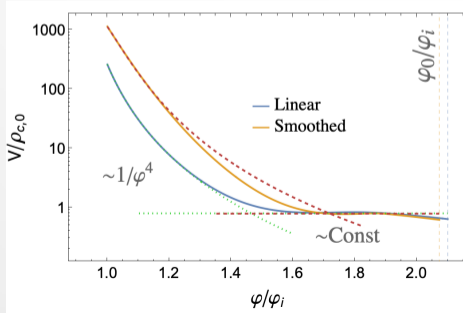
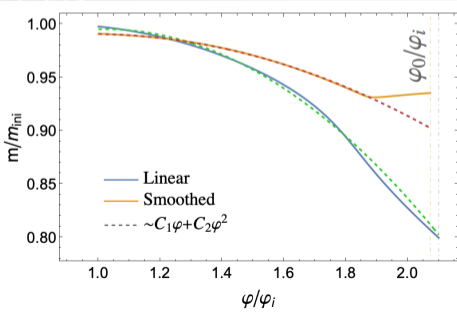
# Coupled Background



The field is moving also at early times differently from standard Thawing Quintessence

$$\frac{d\varphi}{da} = \frac{1}{H} \sqrt{\rho_\varphi(1 + w_\varphi)}$$

$$V(\varphi) = \frac{1}{2} \rho_\varphi(a(\varphi)) [1 - w_\varphi(a(\varphi))]$$



# Linear Order Cosmology

- Dark degeneracy broken at linear order

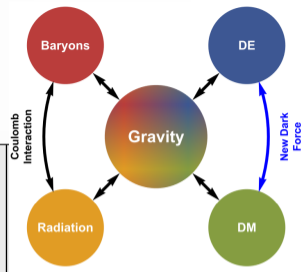
$$ds^2 = a^2 \left[ -(1 + 2\Psi)d\eta^2 + \delta_{ij}(1 - 2\Phi)dx^i dx^j \right]$$

$\Phi(\eta, \vec{x})$  Gravitational Potential

$$\delta_I = \delta\rho_I/\rho_I \quad \theta_I = \partial_i v_I^i \quad dt = a d\eta \quad \Psi \approx \Phi$$

$$\delta'_I + (1 + w_I)(\theta_I - 3\Phi') - 3\mathcal{H} \left( \frac{\delta p_I}{\delta\rho_I} - w_I \right) \delta_I = Q_1[m, \delta_J, \theta_J]$$

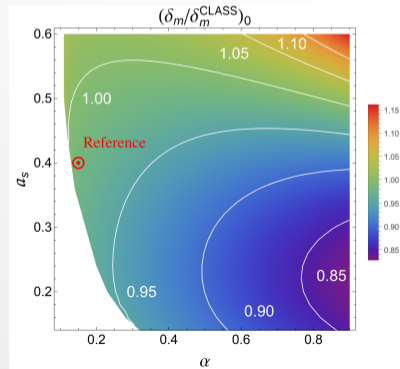
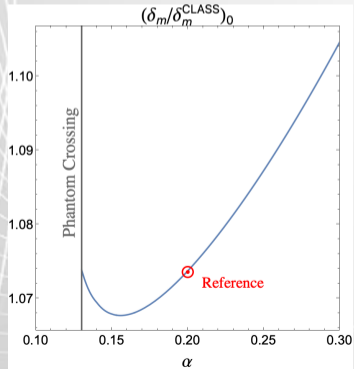
$$\theta'_I + \mathcal{H}(1 - 3w_I)\theta_I + \frac{w'_I}{1 + w_I}\theta_I - \frac{k^2}{1 + w_I} \frac{\delta p_I}{\delta\rho_I} \delta_I - k^2\Psi = Q_2[m, \delta_J, \theta_J]$$



# Sub-Horizon limit & Clustering of matter

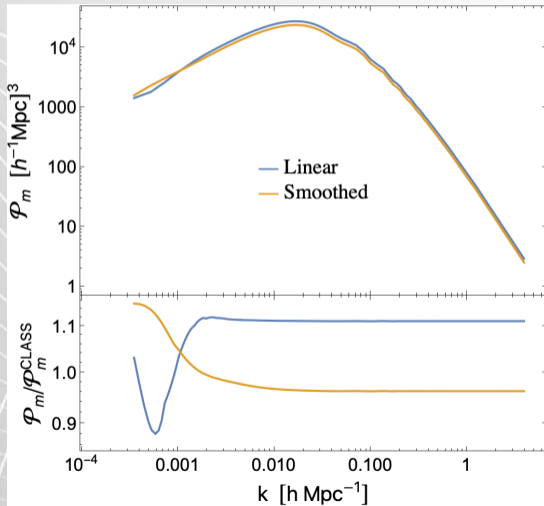
$$k \gg \mathcal{H} \quad \begin{cases} \delta''_{\varphi} + k^2 \delta_{\varphi} \approx 0 & \varphi \text{ never clusters efficiently and can be neglected} \\ \delta''_m + (\mathcal{H} + \mathcal{M})\delta'_m - \left[ \frac{3\mathcal{H}^2}{2\rho_{\text{tot}}} \rho_m + \mathcal{M}^2 \frac{\rho_{\chi}}{\rho_{\varphi}(1+w_{\varphi})} \right] \delta_{\chi} \approx 0 \end{cases}$$

$\mathcal{M} = \log(m)'$  < 0 less friction vs more/less gravitational collapse



# Total matter power spectrum

$$\langle \delta_m(\eta, \vec{k}) \delta_m(\eta, \vec{k}') \rangle = (2\pi)^3 \delta^{(3)}(\vec{k} + \vec{k}') \mathcal{P}_m(\eta, k)$$



non-relativistic matter ( $b+\chi$ )

Both enhanced and reduced power

Possible to tune parameters

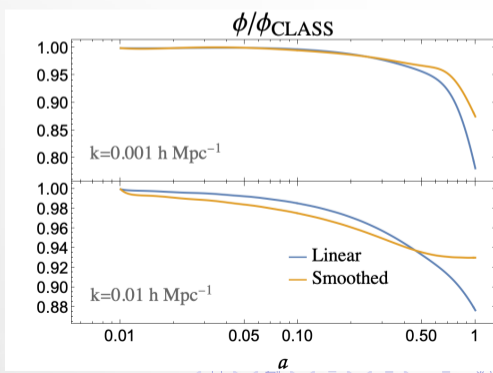
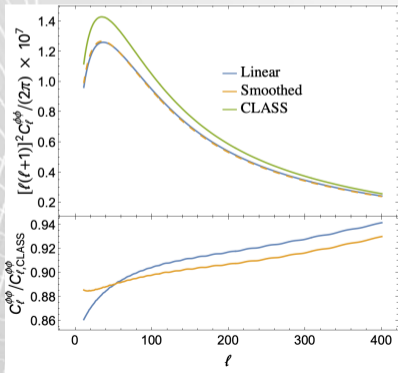
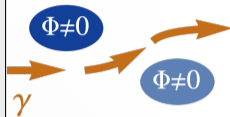
in order to reproduce the

isolated scenario

# Lensing power spectrum

$$C_\ell^{\phi\phi} = 16\pi \int_0^\infty \frac{dk}{k} \Delta_\zeta(k) \left[ \int_{\eta_i}^{\eta_0} d\eta T_{\Phi} j_\ell(k(\eta_0 - \eta)) W(\eta) \right]^2$$

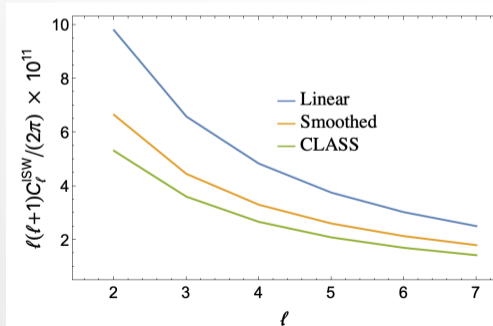
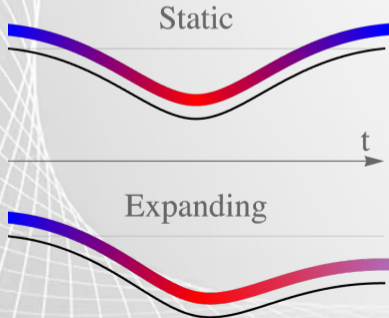
$$W(\eta) = \frac{\eta - \eta_i}{(\eta_0 - \eta)(\eta_0 - \eta_i)} \quad k^2 \Phi \approx -\frac{3\mathcal{H}^2}{2\rho_{\text{tot}}} \rho_m \delta_m \quad \text{suppression } \gamma$$



# Integrated Sachs-Wolfe Effect

$$\left(\frac{\Delta T}{T}\right)_\ell(k) \equiv \Theta_\ell(k) = \Theta_\ell^{(\delta)} + \Theta_\ell^{(SW)} + \Theta_\ell^{(Dop)} + \Theta_\ell^{(ISW)}$$

$$C_\ell^{TT} \supset C_\ell^{ISW} = 16\pi \int_0^\infty \frac{dk}{k} \Delta_\zeta(k) \left[ \int_{\eta_i}^{\eta_0} d\eta \frac{dT_\Phi}{d\eta} j_\ell(k(\eta_0 - \eta)) W(\eta) \right]^2$$









UNIVERSITÀ  
DEGLI STUDI  
FIRENZE



*Thank you for your attention*

- 👍 M. Archidiacono and others, *"Unveiling dark fifth forces with linear cosmology"*,10.1088/1475-7516/2022/10/074
- 👍 J. Khoury and others, *"Apparent  $w < -1$  and a Lower  $S_8$  from Dark Axion and Dark Baryons Interactions"*,10.1103/w4qb-plk8
- 👍 DES collaboration, *"The Dark Energy Survey Supernova Program: A Reanalysis Of Cosmology Results And Evidence For Evolving Dark Energy With An Updated Type Ia Supernova Calibration"*,2511.07517
- 👍 DESI collaboration, *"DESI DR2 results. II. Measurements of baryon acoustic oscillations and cosmological constraints"*,10.1103/tr6y-kpc6