Santa Fe Cosmology Workshop 07

Mapping Dark Inhomogeneities to the CMB and LSS

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Goal:

To probe the nature of dark sectors
by all accessible dark properties,
including those of **inhomogeneous** dark kinetics

- Probed dark sectors:

  Dark energy, dark matter, neutrinos

- Why dark inhomogeneities are important:

  - Information additional to background $\Omega_{\text{dark}}h^2$ and $w(z)$
  - The inhomogeneous dynamics is very specific to models of dark microscopic kinetics and interactions
  - Some signatures of perturbations of dark species are less degenerate than the species' background signatures

Parameterizing Dark Properties: (focus on scalar perturbations)

a) Metric

$$\delta g_{\mu\nu}(z,k)$$

$$\mathcal{H}(z) \equiv \frac{\dot{a}}{a}; \quad \Phi(z,\boldsymbol{k}), \quad \Psi(z,\boldsymbol{k})$$

Any convenient fixed gauge will do

Use the Newtonian gauge

Mukhanov 92; Ma, Bertschinger 95

$$ds^2 = a^2[-(1+2\Phi)d\tau^2 + (1-2\Psi)\,d\boldsymbol{x}^2]$$

b) Densities and stresses

$$\mathrm{G}_{\mu\nu} = 8\pi G\,\mathbf{T}_{\mu\nu}$$

$$\rho_a(z); \quad \delta_a^{(c)}(z,\boldsymbol{k}), \quad \sigma_a(z,\boldsymbol{k})$$

$$\mathcal{H}^2 = \frac{8\pi G a^2}{3}\sum_a \rho_a \quad (+\text{ curv.})$$

$$\nabla^2\Psi = 4\pi G a^2 \sum_a (\rho_a + p_a)\,\delta_a^{(c)},$$

$$\Phi = \Psi - 8\pi G a^2 \sum_a (\rho_a + p_a)\,\sigma_a$$

c) Dynamics (kinetics)

$$w_a(z) \equiv p/\rho;$$

$$c^2_{\mathrm{eff},a}(z,\boldsymbol{k}) \equiv \frac{\delta p^{(c)}}{\delta\rho^{(c)}}, \quad \sigma_a(z,\boldsymbol{k})$$

$$\dot{\rho} = -3\mathcal{H}(1+w)\rho,$$

Hu 98

$$\dot{d} + \partial_i \mathrm{v}^i = -3\mathcal{H}\left(c^2_{\mathrm{eff}} - \frac{\dot{p}}{\dot{\rho}}\right)\delta^{(c)},$$

$$\dot{\mathrm{v}}^i + \mathcal{H}\mathrm{v}^i = -\partial_i\Phi - c^2_{\mathrm{eff}}\partial_i\delta^{(c)} + \frac{2}{3}\partial_i\nabla^2\sigma$$

Observables

Probes

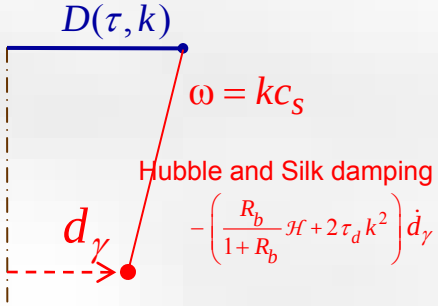
$$\left(d \equiv \frac{\delta\rho}{\rho + p} - 3\Psi = \frac{\delta n_{\rm coo}}{n_{\rm coo}} \right)$$

- **CMB**

$$\ddot{d}_\gamma + \frac{R_b}{1+R_b}\mathcal{H}\dot{d}_\gamma + c_s^2 k^2 (d_\gamma - D) = 0,$$

$$D(\tau,k) = -3(\Phi + \Psi + R_b \Phi)$$

$$\dot{\iota}_\gamma + n_i \nabla_i \iota_\gamma = -4 n_i \nabla_i (\Phi + \Psi) + C_T$$



- **LSS (Matter)**

$$\dot{d}_c + \partial_i v_c^i = 0, \qquad \dot{v}_c^i + \mathcal{H} v_c^i = -\partial_i \Phi$$

$$d_c = d_{c,in} - k^2 \int_0^\tau u_c \, d\tau, \qquad u_c = \frac{1}{a}\int_0^\tau (a\Phi)\, d\tau$$

These equations remain valid during **horizon entry**

Horizon Entry must be addressed

$$\mathcal{H}(z_{\rm ent}) \equiv \frac{\dot{a}}{a} \sim k$$

$$(R_{\rm Hubble} \sim \lambda_{\rm pert})$$

- Dark perturbations with $p \sim \rho$, including dark energy and radiation, leave their imprints only at $z_{\rm ent}$

$$\Phi \sim -\frac{4\pi G a^2 \delta\rho}{k^2} \sim -\left(\frac{\mathcal{H}}{k}\right)^2 \frac{\delta\rho}{\rho}$$

- Fluctuations of the CMB are affected by any dark species mostly at $z_{\rm ent}$

General-relativistic description is essential

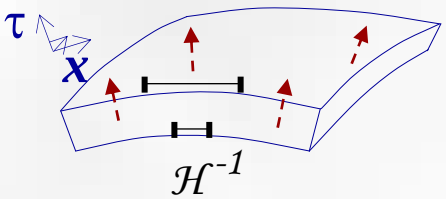
Conserved (Canonical) Density Perturbations

- (In any gauge without shear, i.e. where $\delta g_{ij} = -2a^2 \delta_{ij} \Psi$) d_a describes the perturbation of the **coordinate** density of a conserved number

$$\frac{\delta\rho}{\rho + p} = \frac{\delta n_{\rm pr}}{n_{\rm pr}}$$

$$\frac{n_{\rm coo}}{n_{\rm pr}} = \frac{V_{\rm pr}}{V_{\rm coo}} = a^3 (1 - 3\Psi)$$

$$\Longrightarrow \quad \boxed{d_a \equiv \frac{\delta\rho_a}{\rho_a + p_a} - 3\Psi = \frac{\delta n_{a\,\rm coo}}{n_{a\,\rm coo}}}$$



- Connected to – canonical $f(x^i, P_i)$: $$d(x^i) \equiv \frac{\int d^3 P_i \, P_0 \, \delta f(x^i, P_i)}{a^4 (\rho + p)}$$

  – the canonical pert. of radiation intensity: $$d(x^i) = \frac{3}{4} \left\langle \imath(x^i, n_i) \right\rangle_{n_i}$$

- The canonical d, $\delta f(x^i, P_i)$, $\imath(x^i, n_i)$
  - are conserved on superhorizon scales for (internally) adiabatic perturbations
  - match to the corresponding unambiguous perturbations in FRW

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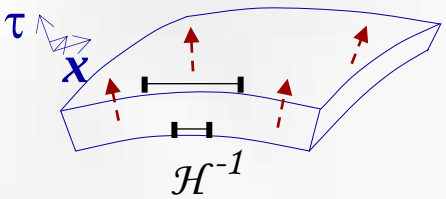


All such generalizations of a perturbation measure coincide in the **superhorizon** limit in linear theory

SB 06

- The canonical $d,\ \delta f(x^i, P_i),\ \iota(x^i, n_i)$
  - are conserved on superhorizon scales for (internally) adiabatic perturbations
  - match to the corresponding unambiguous perturbations in FRW

Dark Properties → Observables

Property	Quantified by	Important for	Effect on the CMB	Effect on Matter
Anisotropic Stress	σ $[\Phi - \Psi]$	Early stage of horizon entry	Amplitude (Suppressed by σ from streaming)	Minor on power (Enhanced by σ from streaming)
Stiffness	$c^2_{\rm eff} \equiv \frac{\delta p^{(c)}}{\delta \rho^{(c)}}$	Late stage of horizon entry	Amplitude (Enhanced by tracking quintessence)	Medium on power (Suppressed by tracking quintessence)
Velocity of a perturbation front	c_p	Features local in real space	Phase of the acoustic peaks	Phase of baryonic oscillations
Self-clustering	Φ, $\Phi + \Psi$	Horizon entry (CMB) and subhorizon evolution (LSS)	Significant suppression of power C_l	Primary driving of the structure growth

SB, arXiv:0707.0692

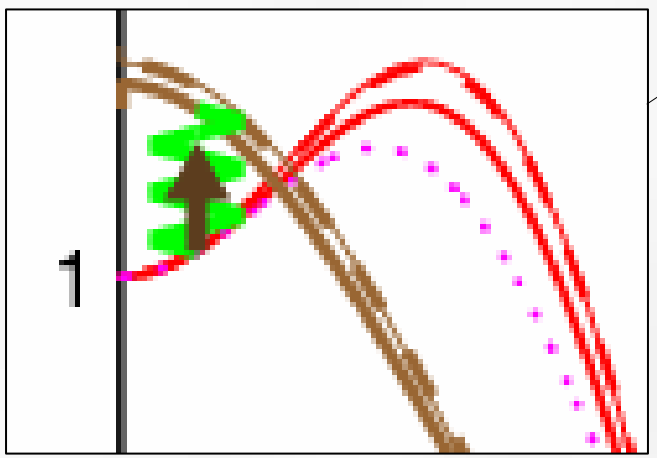
1. Anisotropic stress σ (of streaming neutrinos)
$\rightarrow$ Suppresses the amplitude of the CMB oscillations

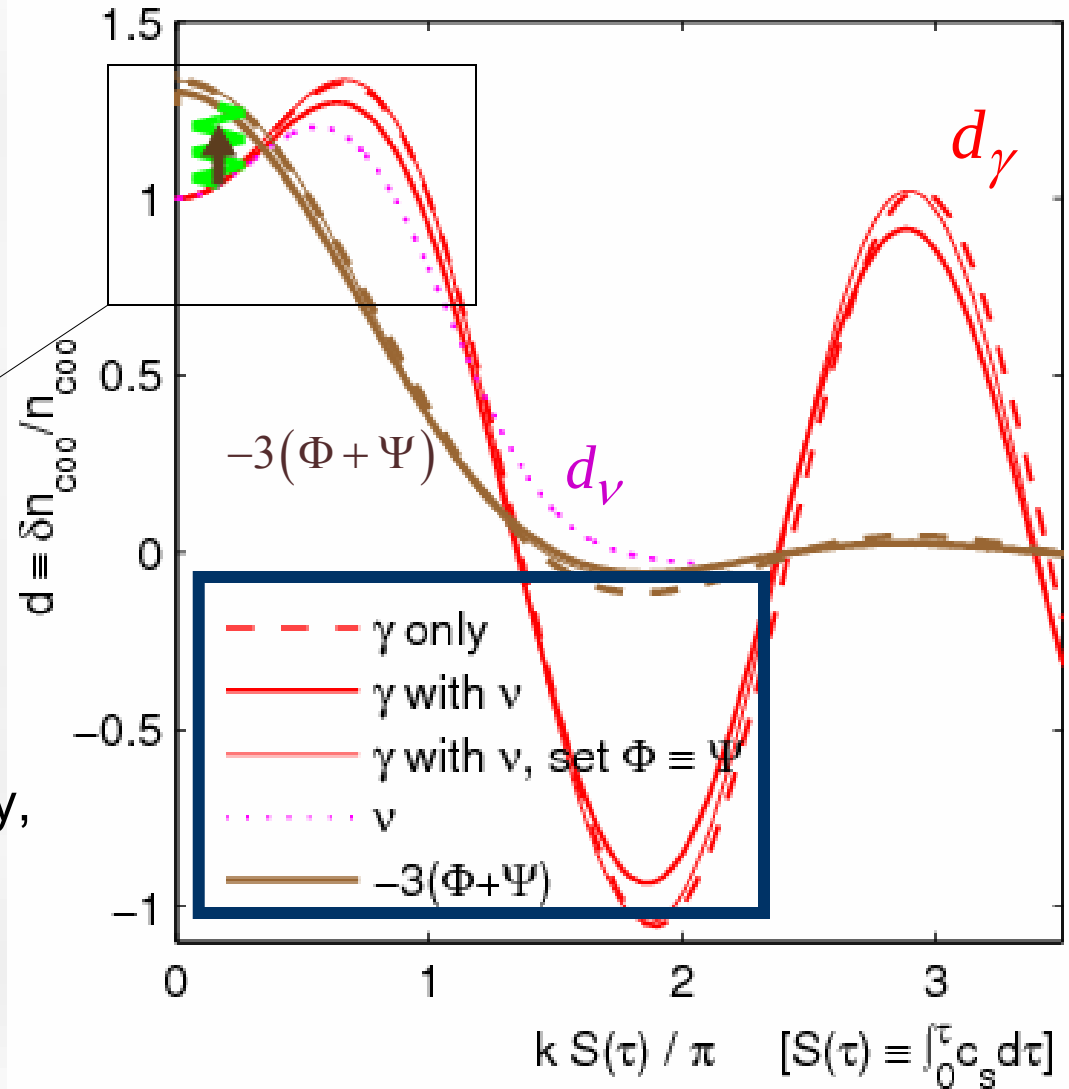
$$\Phi = \Psi - 8\pi G a^2 (\rho + p)\sigma$$

$$\ddot{d}_\gamma + c_s^2 k^2 (d_\gamma - D) = 0, \quad D = -3(\Phi + \Psi)$$

$$\frac{A_\gamma}{A_\gamma(\rho_\nu \to 0)} \approx \left(1 + \frac{4\rho_\nu}{15\rho_{\rm tot}}\right)^{-1}$$

Hu, Sugiyama 96
analytic eq. in SB, Seljak 04





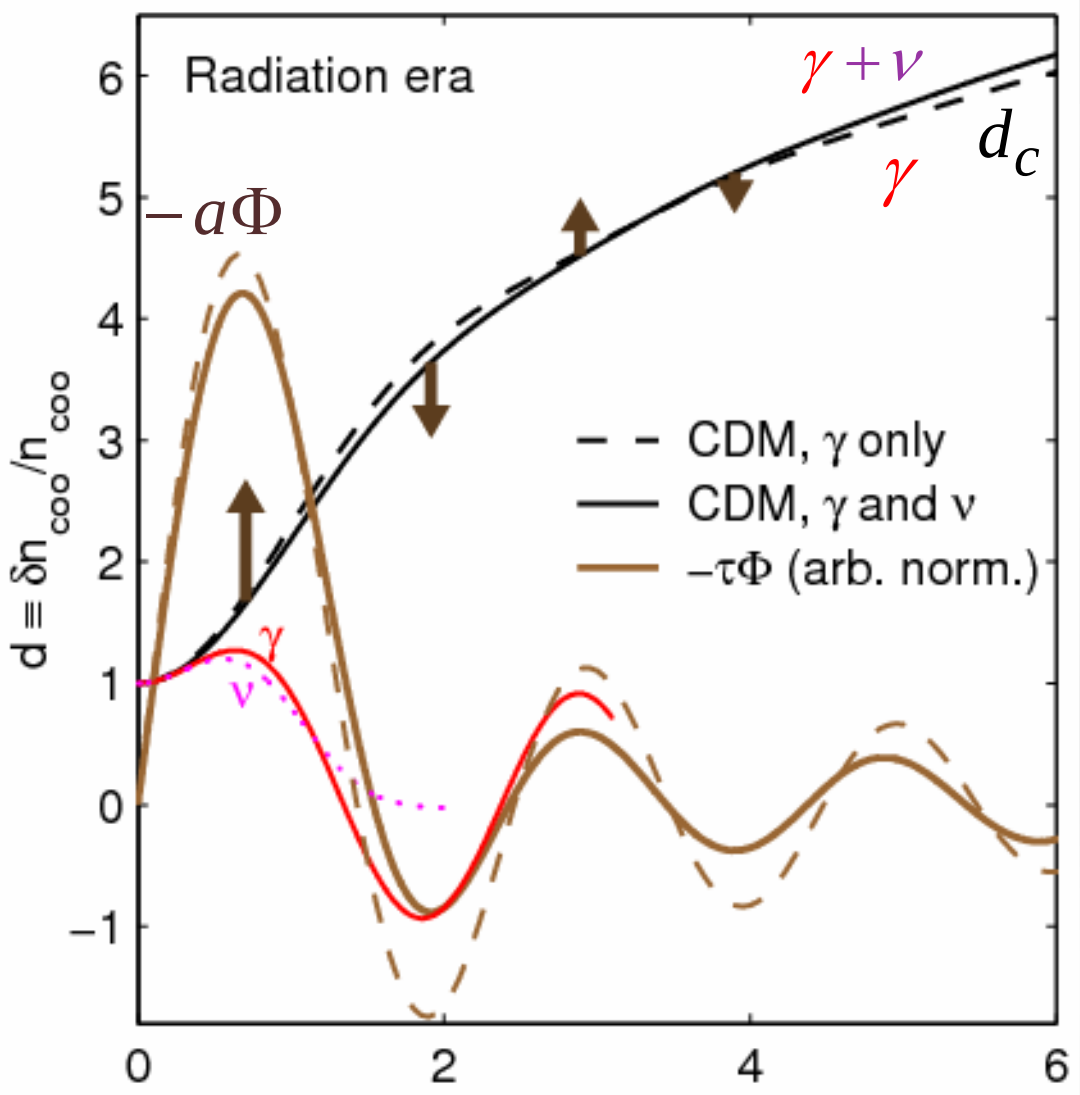
Caused by σ sourcing gravity, not by neutrino viscosity

Test: Remove σ as a source of $R_{\mu\nu}$

1. Anisotropic stress σ (of neutrinos)
→ Somewhat boosts the CDM transfer function

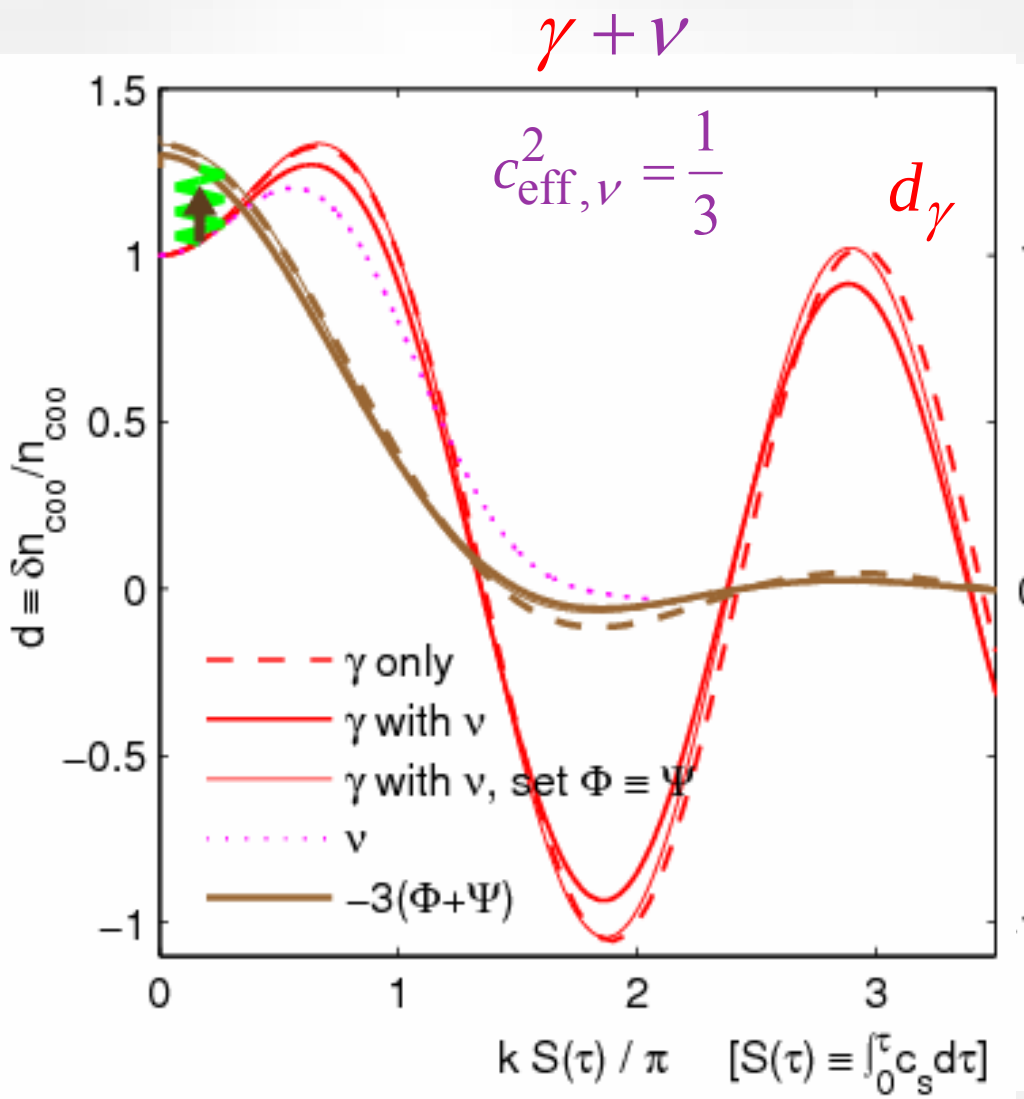
$$u_c = \frac{1}{a}\int_0^{\tau} (a\Phi)\, d\tau$$

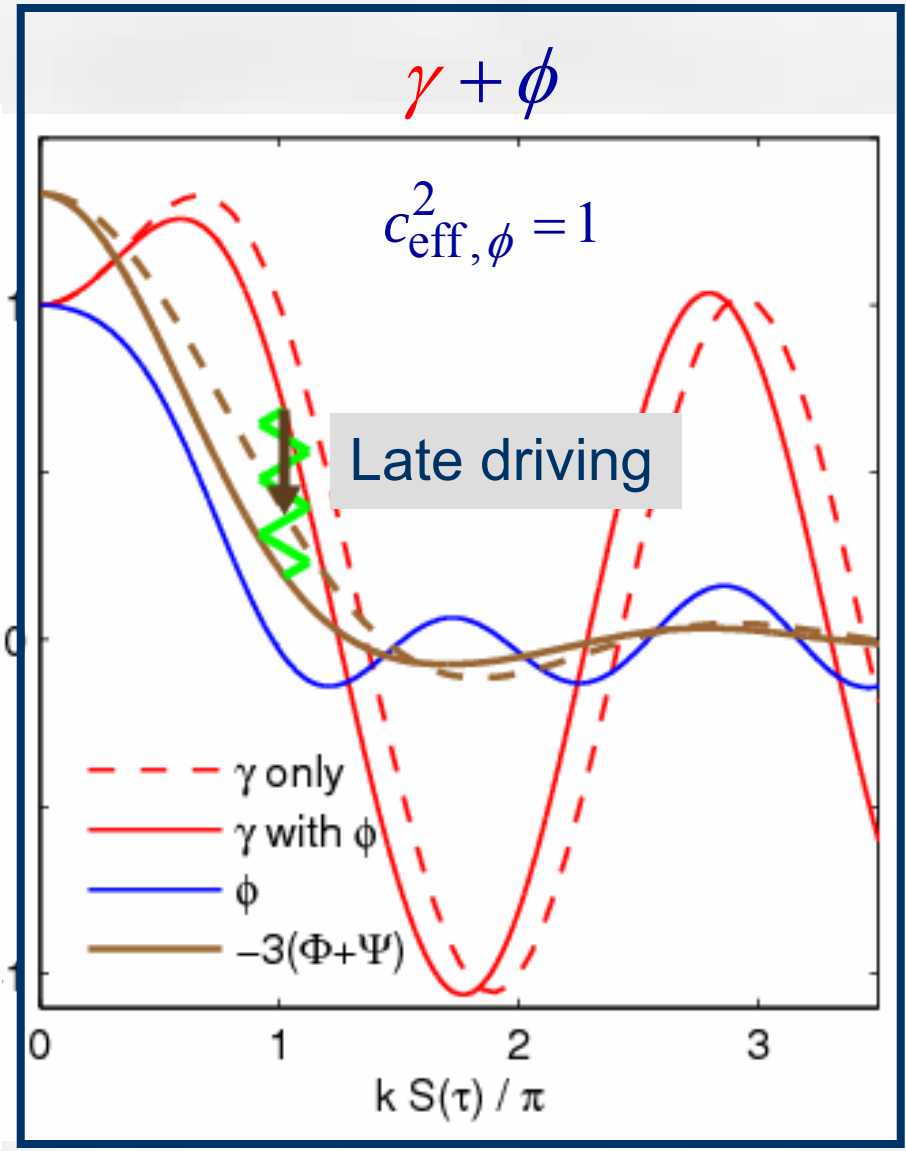
$$d_c = d_{init} - k^2 \int_0^{\tau} u_c \, d\tau$$



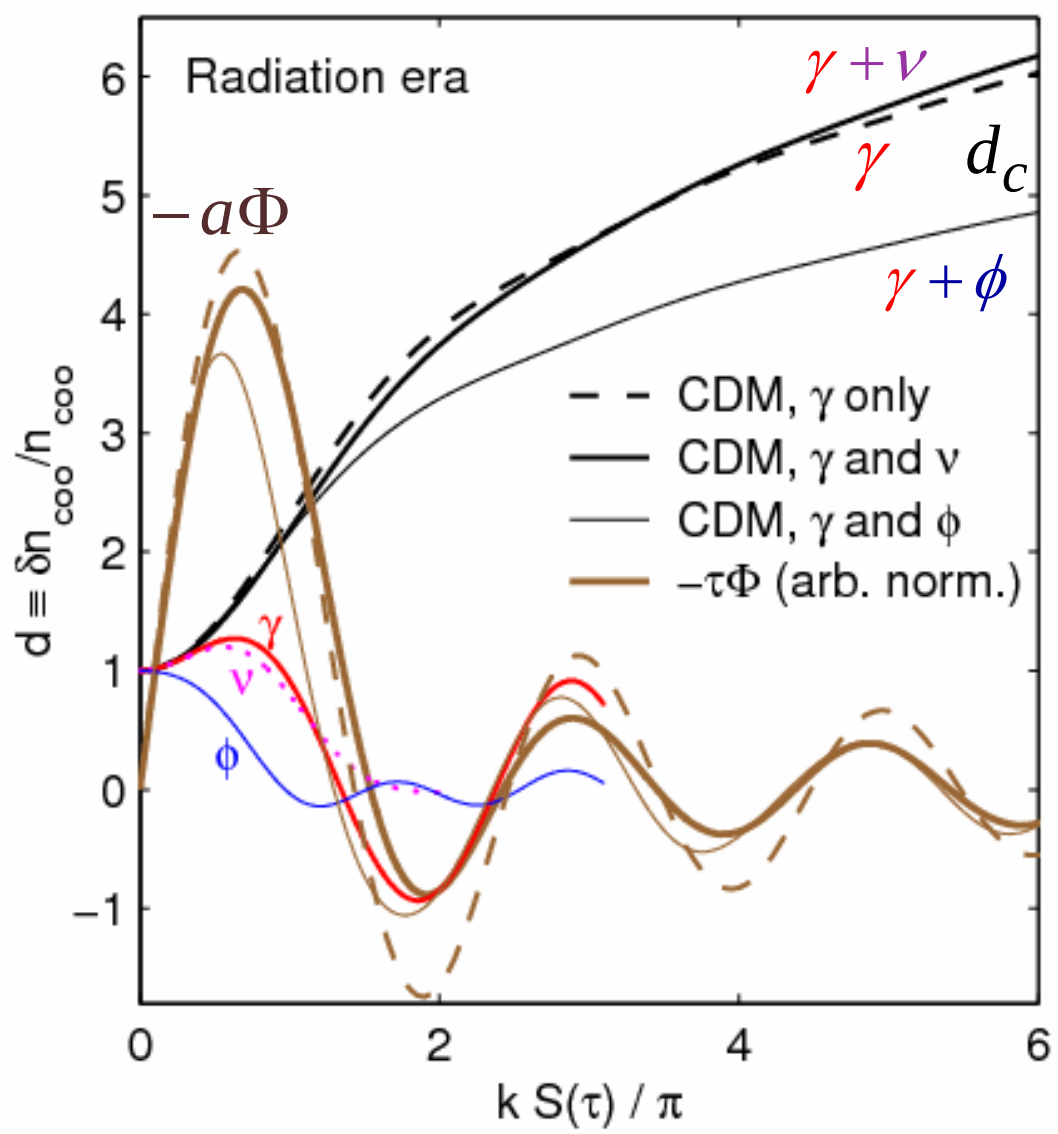
2. Stiffness $c^2_{\rm eff}$ (of tracking quintessence)

→ a. Somewhat boosts the CMB amplitude





2. Stiffness $c^2_{\rm eff}$ (of tracking quintessence)
→ b. Noticeably suppresses CDM perturbations



Late driving →
Reduced Hubble drag

$$\dot{v}^i_c + \mathcal{H} v^i_c = -\partial_i \Phi$$

$$\Delta\left(\frac{\delta\rho_c}{\rho_c}\right)_{\tau'>>\tau} = \Delta d(\tau')$$

$$\sim -k^2 \Phi(\tau)\, \tau\, \Delta\tau$$

LSS+CMB distinguish nonstandard $c^2_{\rm eff}$ from σ

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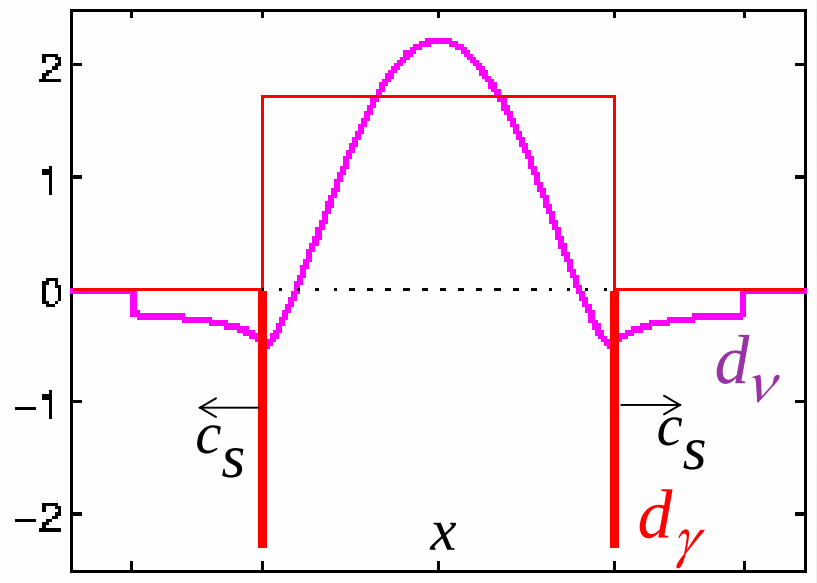
Self-clustering	Φ, $\Phi + \Psi$	Horizon entry (CMB) and subhorizon evolution (LSS)	Significant suppression of power C_l	Primary driving of the structure growth

3. Propagation velocity c_p
$\rightarrow$ Shifts the acoustic phase of the CMB

Real-space propagation of inhomogeneities:

$$d(k) = \int_{-\infty}^{\infty} dx\, e^{-ikx} d(x)$$

SB, Bertschinger 01, 02



$$d_\gamma(k) \rightarrow A_\gamma \cos\left(kc_s\tau\right) - \pi\sqrt{3}\,(\Phi+\Psi)\big|_{x=c_s\tau} \sin\left(kc_s\tau\right)$$

The acoustic **phase** is **shifted** $\Leftrightarrow$ $(\Phi+\Psi)\big|_{x=c_s\tau} \neq 0$

$\Leftrightarrow$ some perturbations propagate **faster than** $c_s = 1/\sqrt{3}$

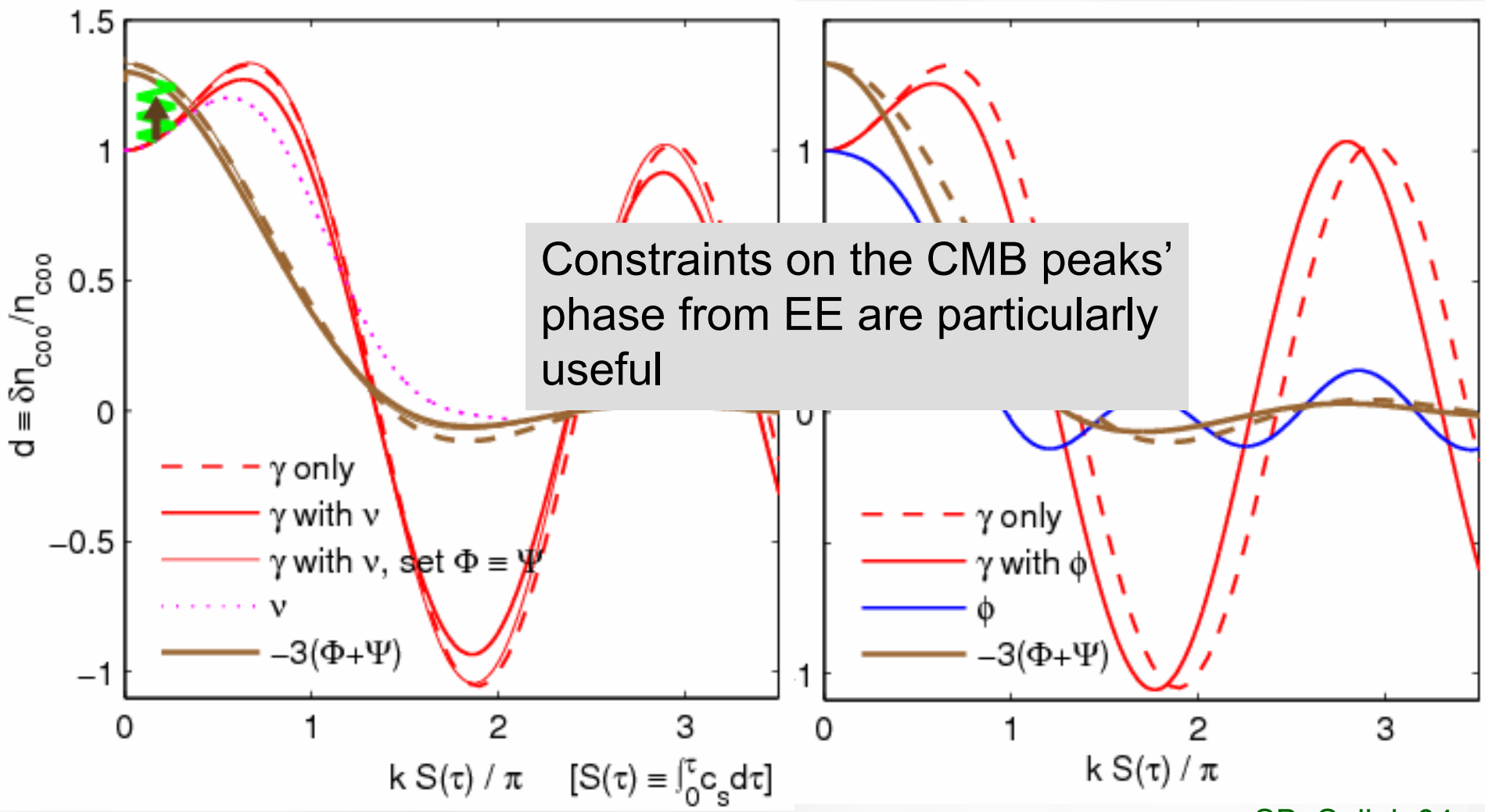
SB, Seljak 04

3. Propagation velocity c_p

→ Shifts the acoustic phase of the CMB

$\gamma + \nu$ $\delta l \approx -3.4\ \delta N_\nu$

$\gamma + \phi$ $\delta l \approx -11\ \delta N_\phi$



Constraints on the CMB peaks' phase from EE are particularly useful

SB, Seljak 04

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Probing $\Phi + \Psi$ by the CMB

$$C_l = 4\pi \int \frac{dk}{k} \Delta_\varsigma^2(k) \left| \int_0^{\tau_0} d\tau \, S(\tau,k) \, j_l\big(k(\tau_0 - \tau)\big) \right|^2$$

$$S = \left(e^{-\kappa}\right)^{\cdot} \left(\underbrace{\frac{1}{3} d_\gamma + \Phi + \Psi}_{} - \mathrm{v}_b^i n_i + Q^{ij} n_i n_j \right) + e^{-\kappa} \left(\dot{\Phi} + \dot{\Psi} \right)$$

(Traditional form $\dfrac{\delta T_\gamma^{(\mathrm{Newt})}}{T_\gamma} + \Phi$)

- For the modes that were **superhorizon at the last scattering**

$$S \approx \frac{\partial}{\partial \tau} \left[e^{-\kappa} \left(\frac{1}{3} d_{\gamma,\mathrm{init}} + \Phi + \Psi \right) \right]$$

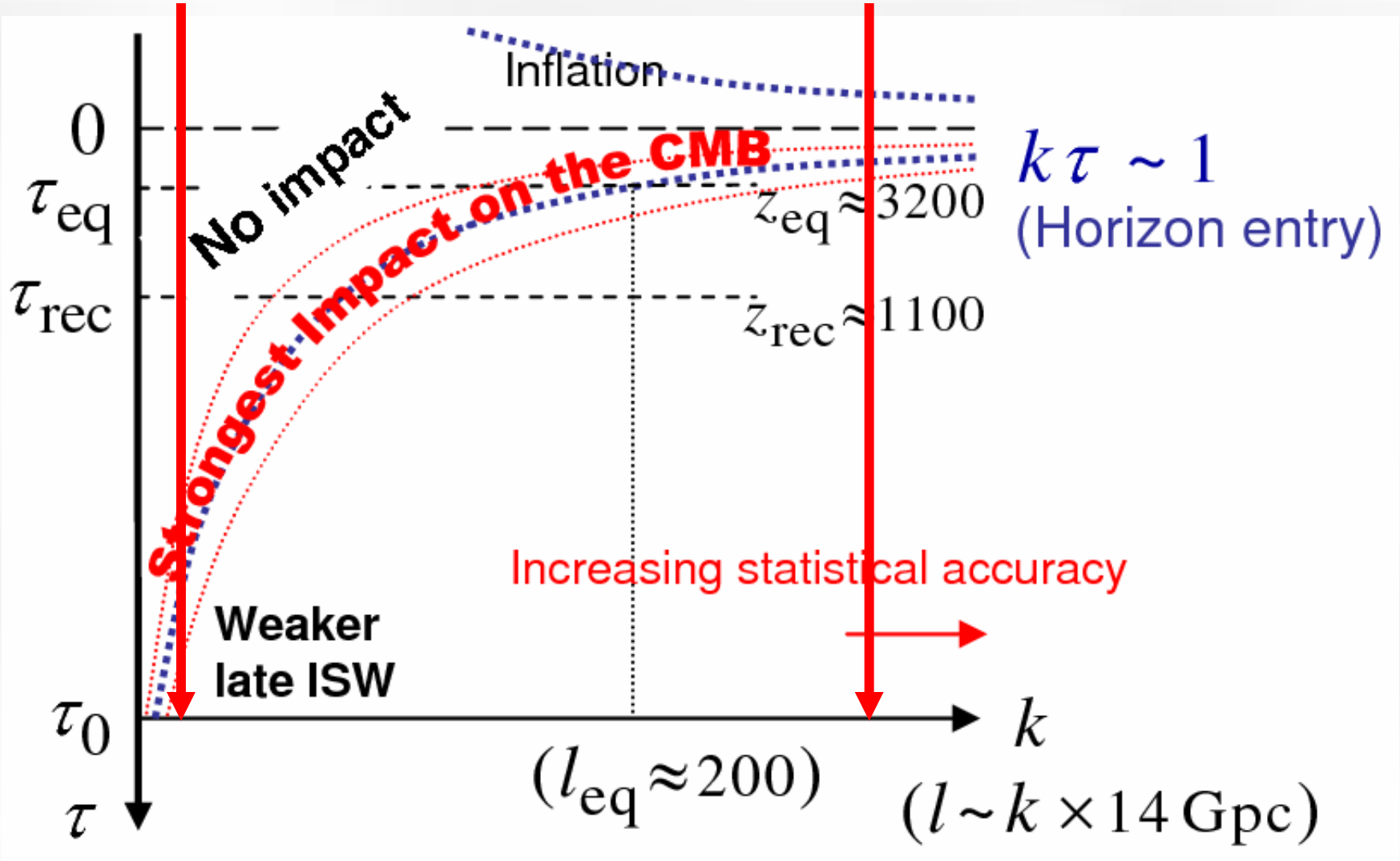
use time-independence of $d_\gamma = d_{\gamma,\mathrm{init}}$ on superhorizon scales

$$\delta C_l^{(\mathrm{entry})} = 4\pi \int \frac{dk}{k} \Delta_\varsigma^2(k) \, j_l\big(k(\tau_0 - \tau_{\mathrm{ent}})\big) \left| e^{-\kappa} \left(\frac{1}{3} d_{\gamma,\mathrm{init}} + \Phi + \Psi \right) \right|_{\mathrm{entry}}^2$$

$$\approx \frac{2\pi \, \Delta_\varsigma^2(l / r_{\mathrm{ent}})}{l(l+1)} \left| e^{-\kappa} \left(\frac{1}{3} d_{\gamma,\mathrm{init}} + \Phi + \Psi \right) \right|_{\mathrm{entry}}^2$$

- For either small or large scales, $\Phi + \Psi$ affects the CMB most of all during horizon entry, not at recombination or low redshift

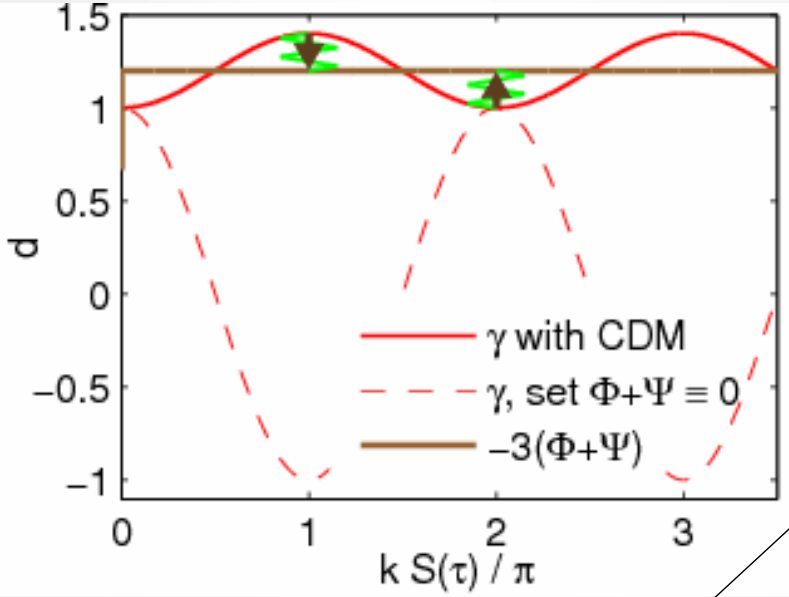
Probing $\Phi + \Psi$ by the CMB



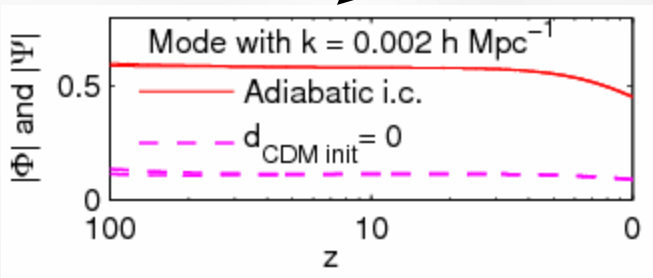
For modes that enter in the radiation era $z \sim 20l$

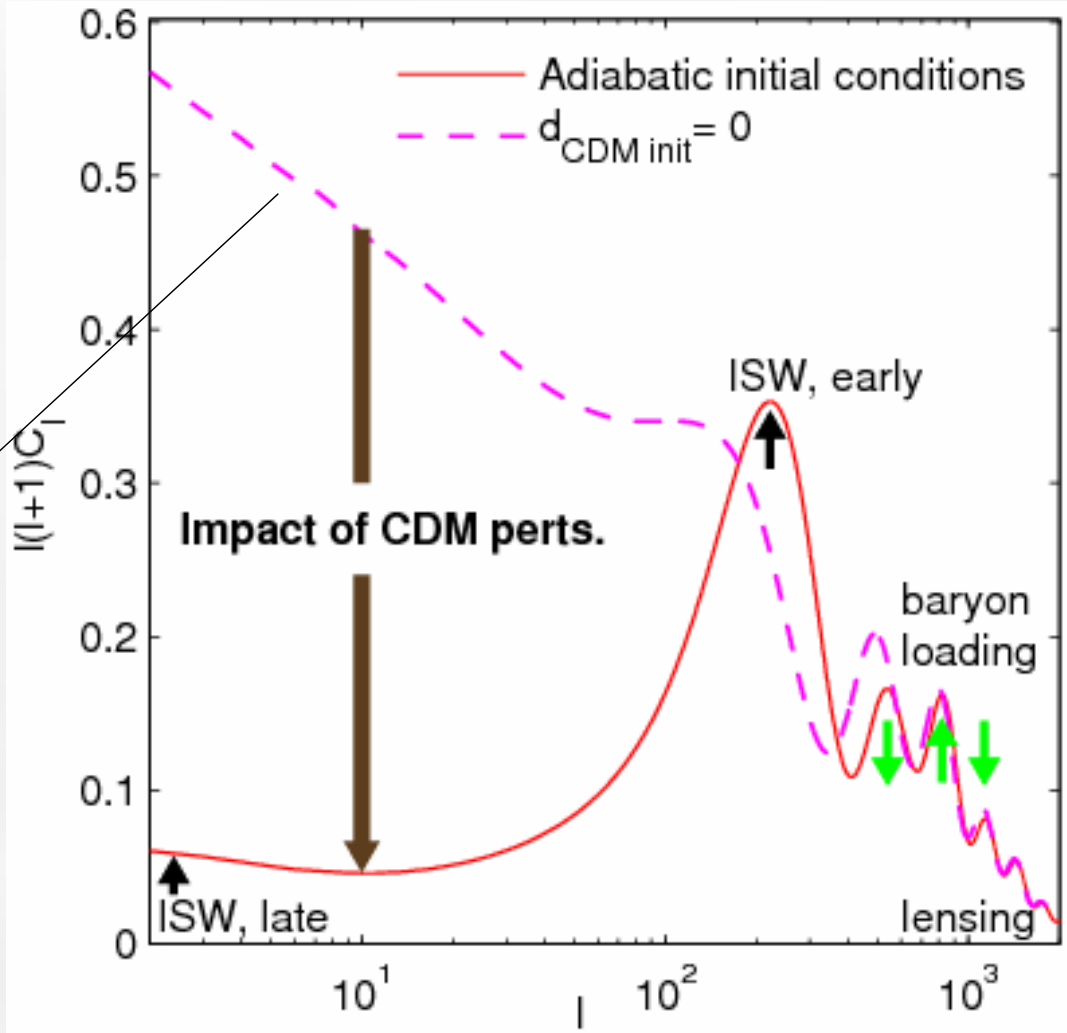
Dark clustering → Significantly suppresses C_l^{TT}

The suppression is 25-fold for the modes that enter during the domination of pressureless matter



Metric is less perturbed.
Cannot be ISW!





Dark clustering → Affects the growth of structure

$$u_c = \frac{1}{a}\int_0^{\tau} (a\Phi)\, d\tau$$

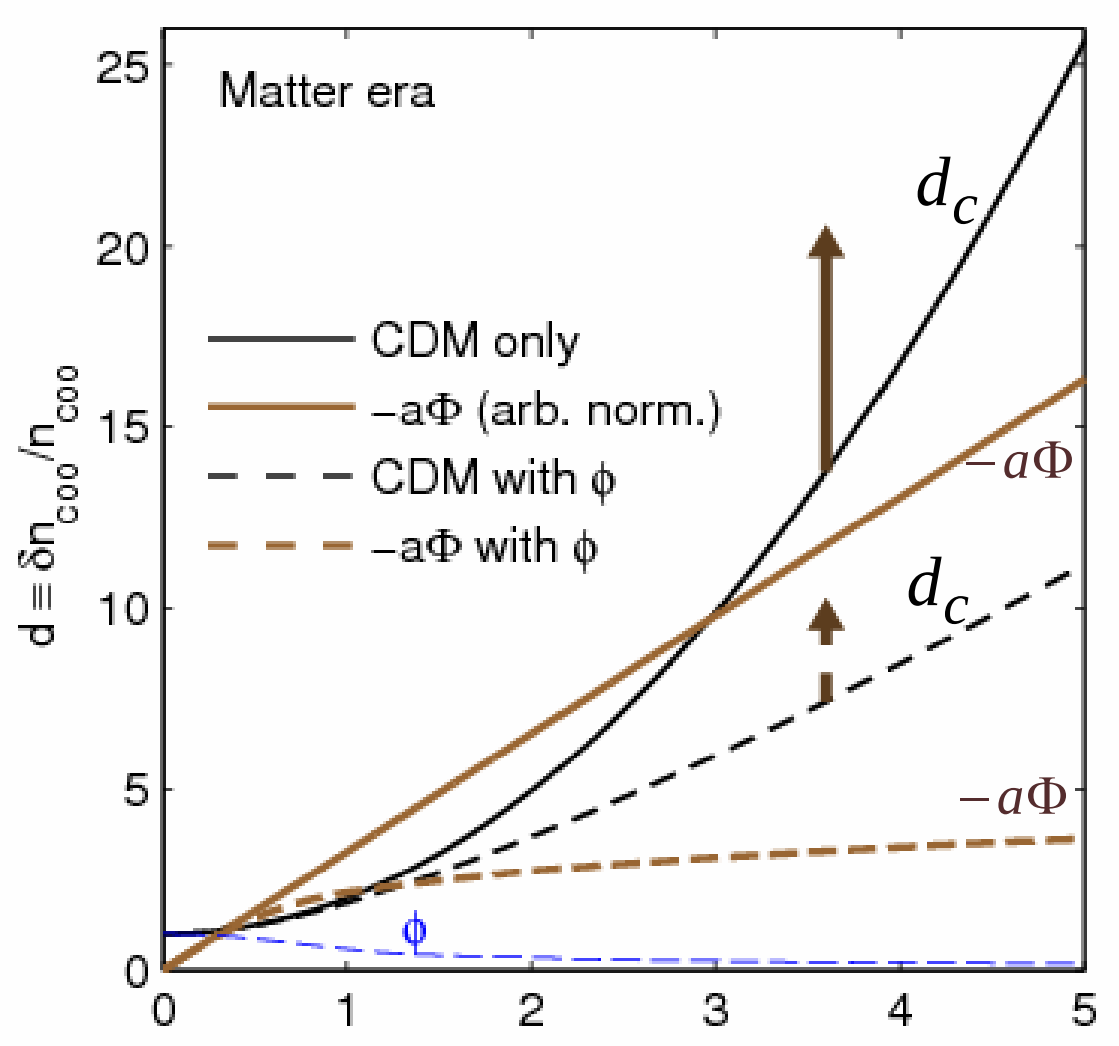
$$d_c = d_{init} - k^2 \int_0^{\tau} u_c \, d\tau$$

$$\Delta\left(\frac{\delta\rho_c}{\rho_c}\right)_{\tau' >> \tau} = \Delta d(\tau')$$

$$\sim -k^2 \Phi(\tau)\, \tau\, \Delta\tau$$

Expect non-standard growth for:

- modified gravity
- k-essence
- interacting DM



Conclusions

- Cosmological signatures of **dark inhomogeneities** encode plentiful information about the dark sectors (dark energy, dark matter, neutrinos, laws of gravity).

- Its decoding from horizon-scale dynamics is considerably more **direct and tractable** with **the canonical variables** for the species' perturbations.

- The dark perturbations can be probed by the **CMB** during horizon entry over all $z \sim 1\text{–}10^5$, better for higher z. (The sensitivity of **LSS**, on the other hand, increases toward low z).

- **Dark** σ, c^2_{eff}, c_{p}, and gravitational potentials Φ and $\Phi + \Psi$ are reflected by specific and distinct observable features in LSS and the CMB.