Partially Acoustic Dark Matter, Interacting Dark Radiation, & Large Scale Structure

Yuhsin Tsai
University of Maryland

in collaboration with
Zackaria Chacko, Yanou Cui, Sungwoo Hong, and Takemichi Okui

KICP Seminar, Oct 14 2016

Explaining (σ_8, H_0) Discrepancies using Non-Minimal Dark Sector

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Non-minimal Dark Sector and LSS

I'll focus on the solution of LSS ``puzzles" through DM-DR scattering

Z. Chacko, Y. Cui, S. Hong, T. Okui, YT (2016)

M. Buen-Abad, G. Marques-Tavares, and M. Schmaltz (2015)

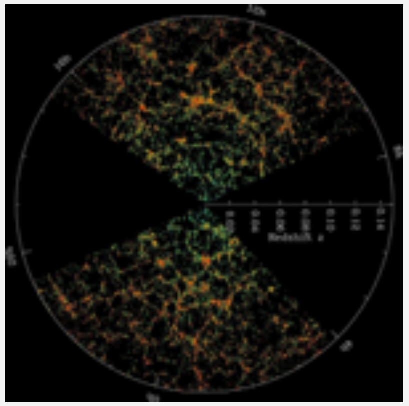
J. Lesgourgues, G. Marques-Tavares, and M. Schmaltz (2015)

P. Ko and Y. Tang (2016)

Other proposal

Decaying DM, Massive neutrinos, Dark energy models, …

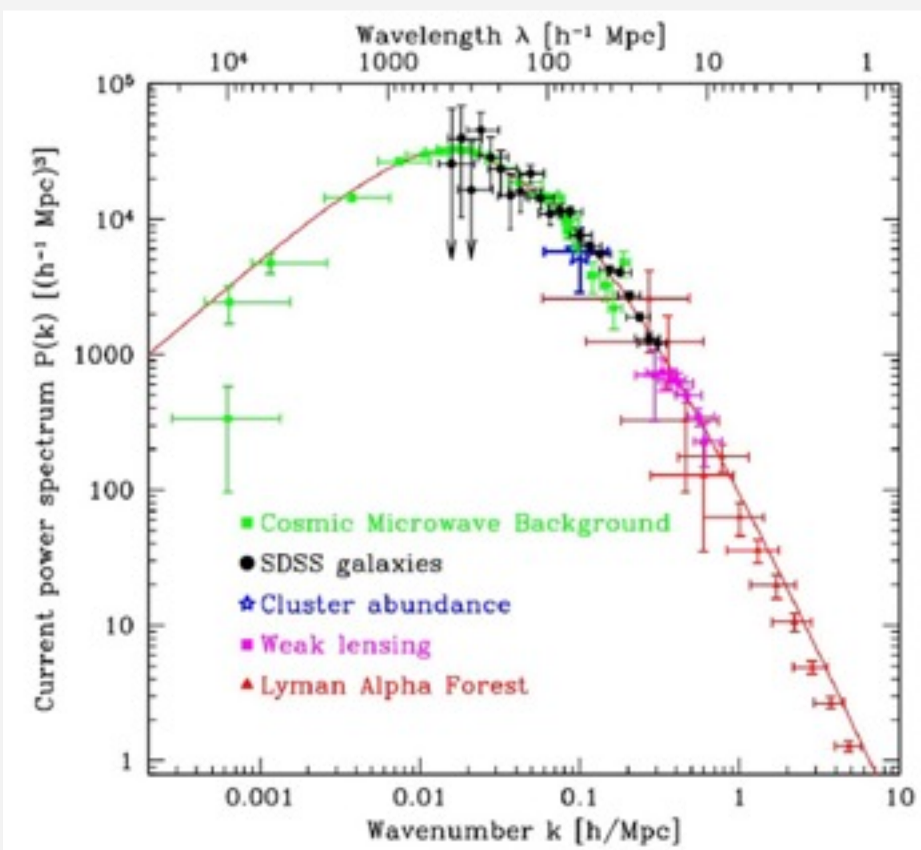
Precision measurement in cosmology



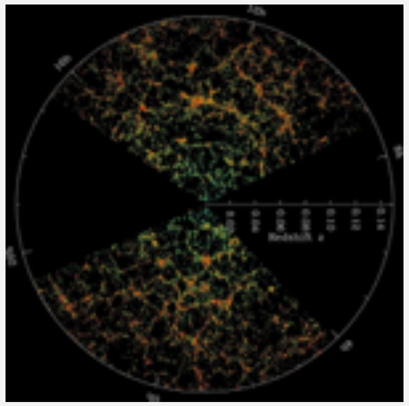
Matter Power Spectrum

Three ways to measure the spectrum

2004



Precision measurement in cosmology



Matter Power Spectrum

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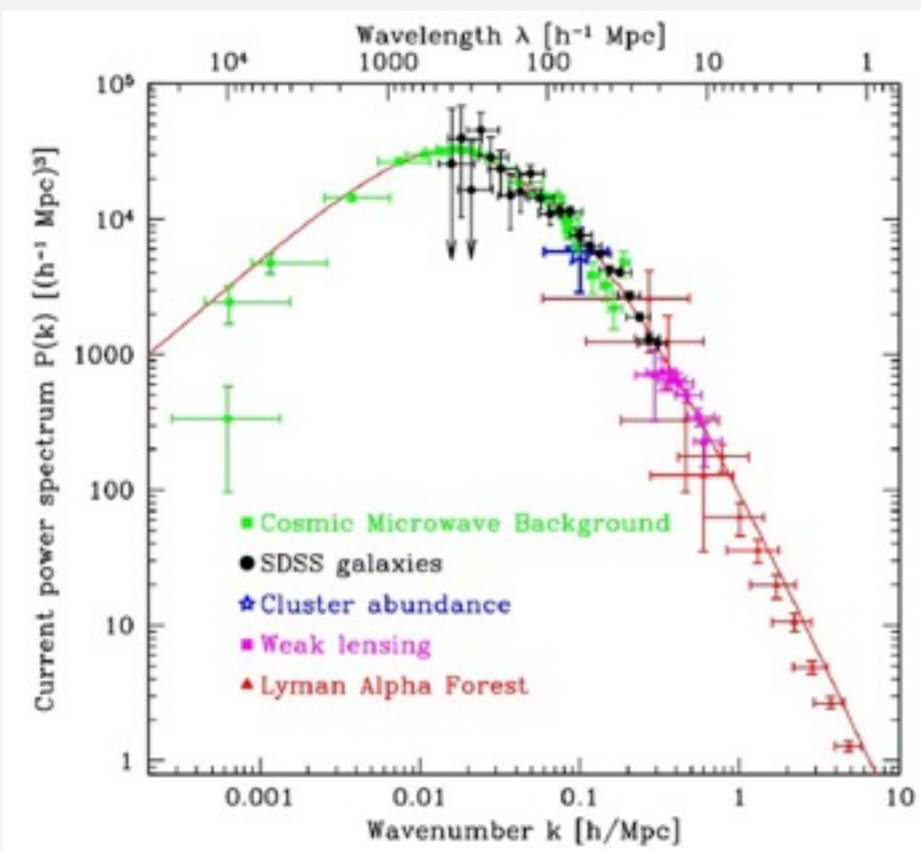
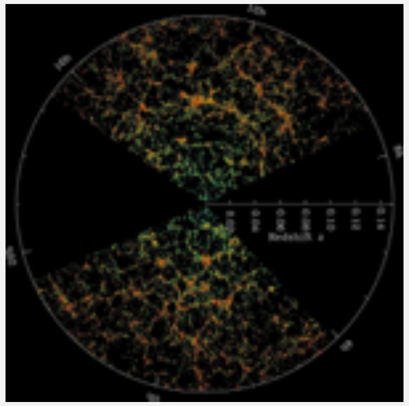


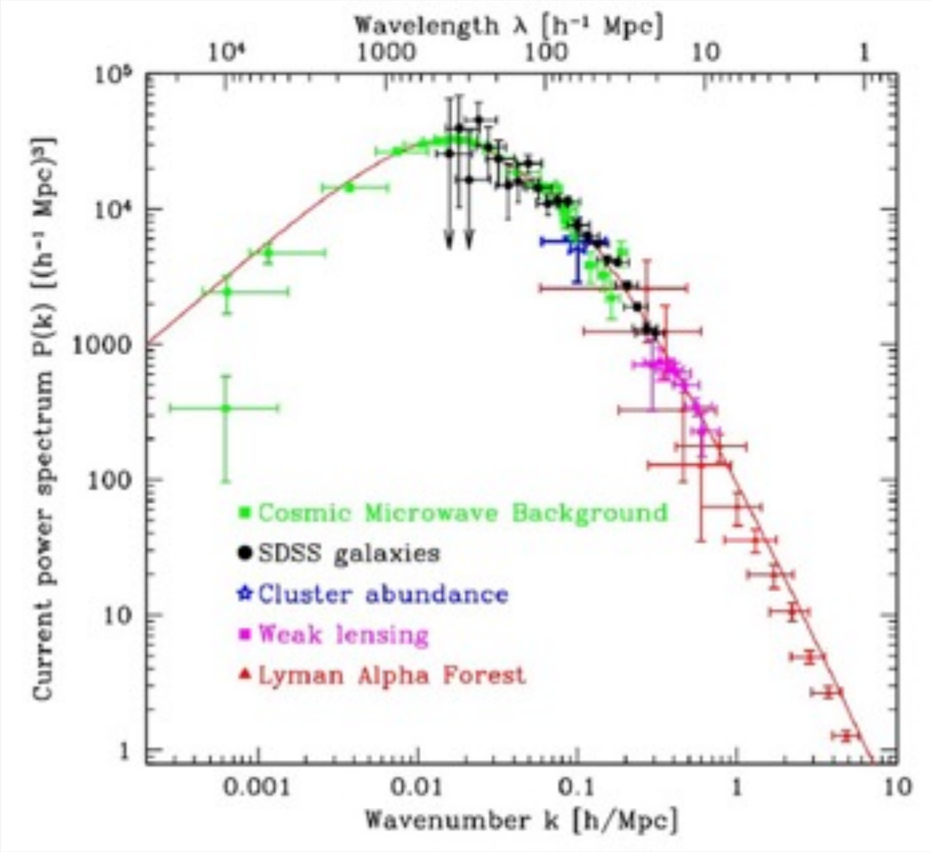
Assuming a DM model (ΛCDM), fix the parameters using CMB, predict the power spectrum today

Precision measurement in cosmology



Matter Power Spectrum

2004

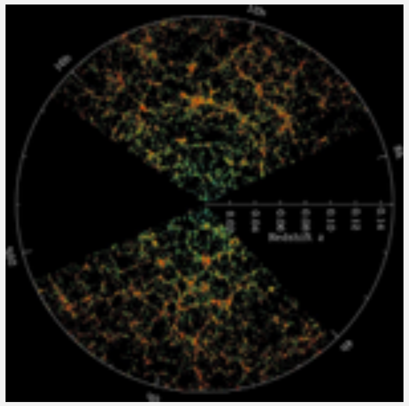


Three ways to measure the spectrum

Assuming a DM model (ΛCDM), fix the parameters using CMB, predict the power spectrum today

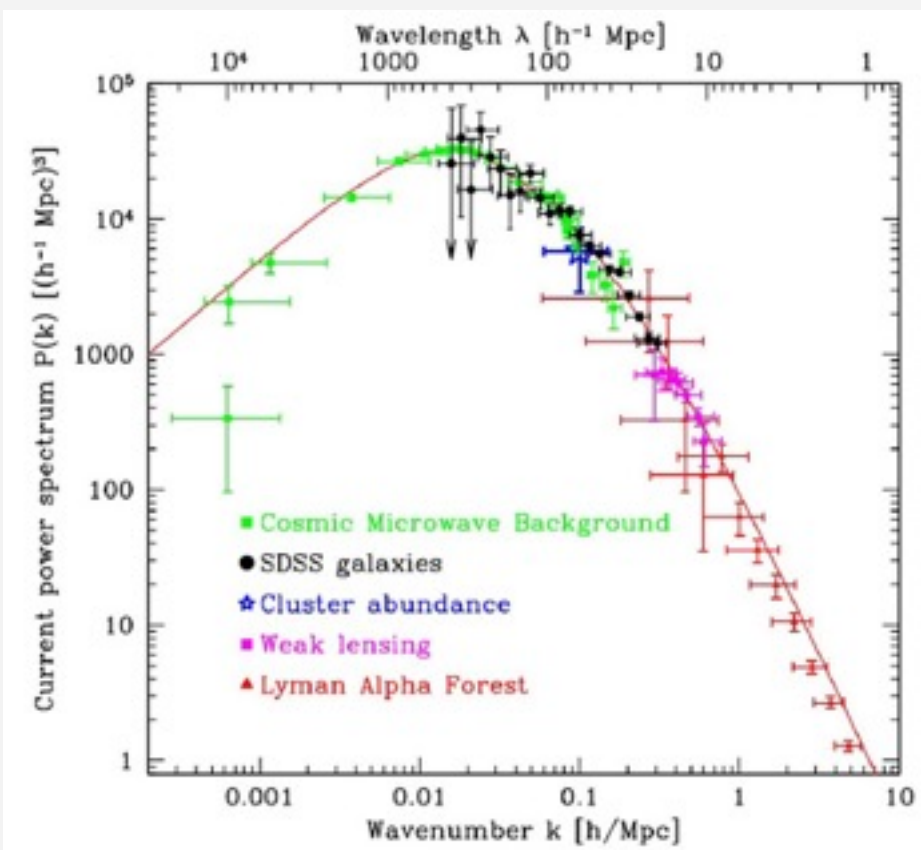
Map the galaxy distribution, then fit the DM distribution

Precision measurement in cosmology



Matter Power Spectrum

2004



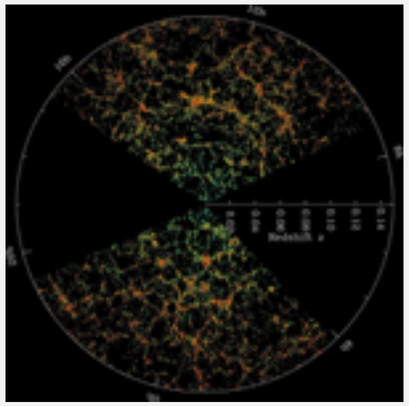
Three ways to measure the spectrum

Assuming a DM model (ΛCDM), fix the parameters using CMB, predict the power spectrum today

Map the galaxy distribution, then fit the DM distribution

Map the DM distribution directly using weak lensing experiments

Precision measurement in cosmology



Matter Power Spectrum

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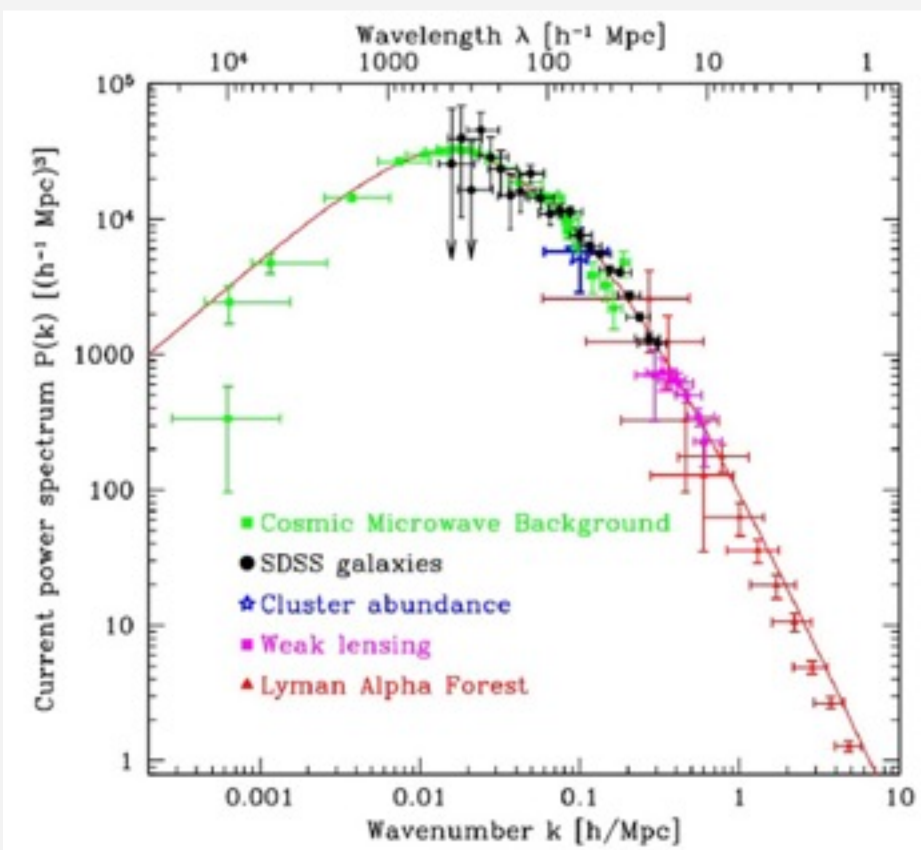
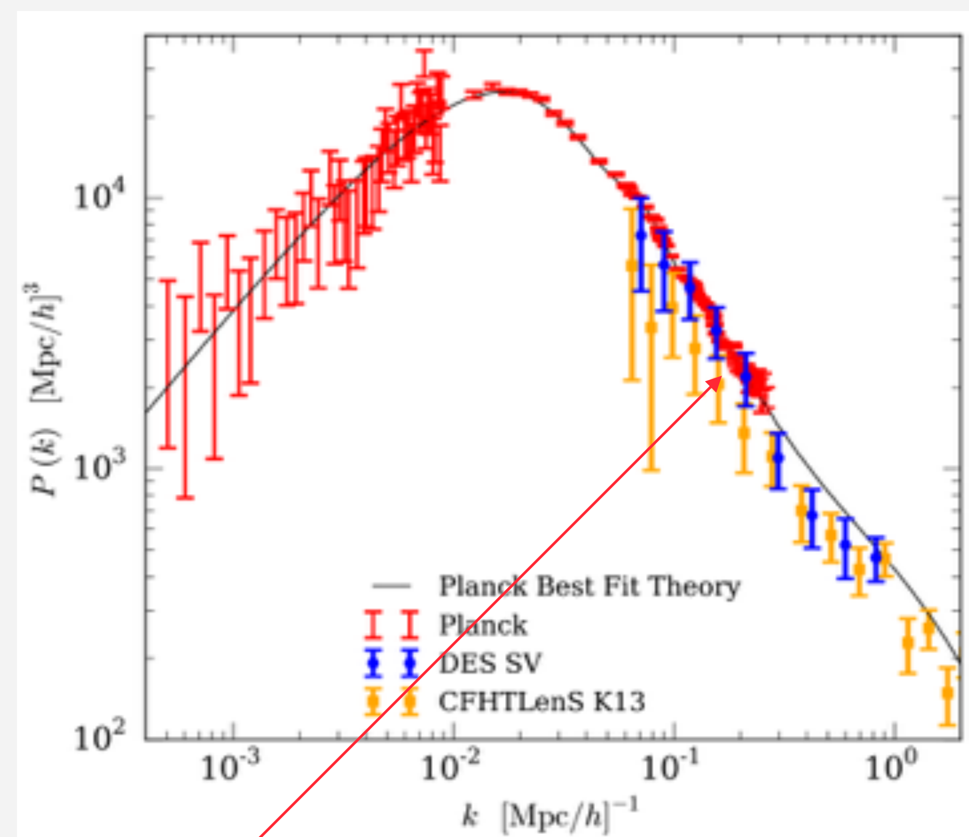
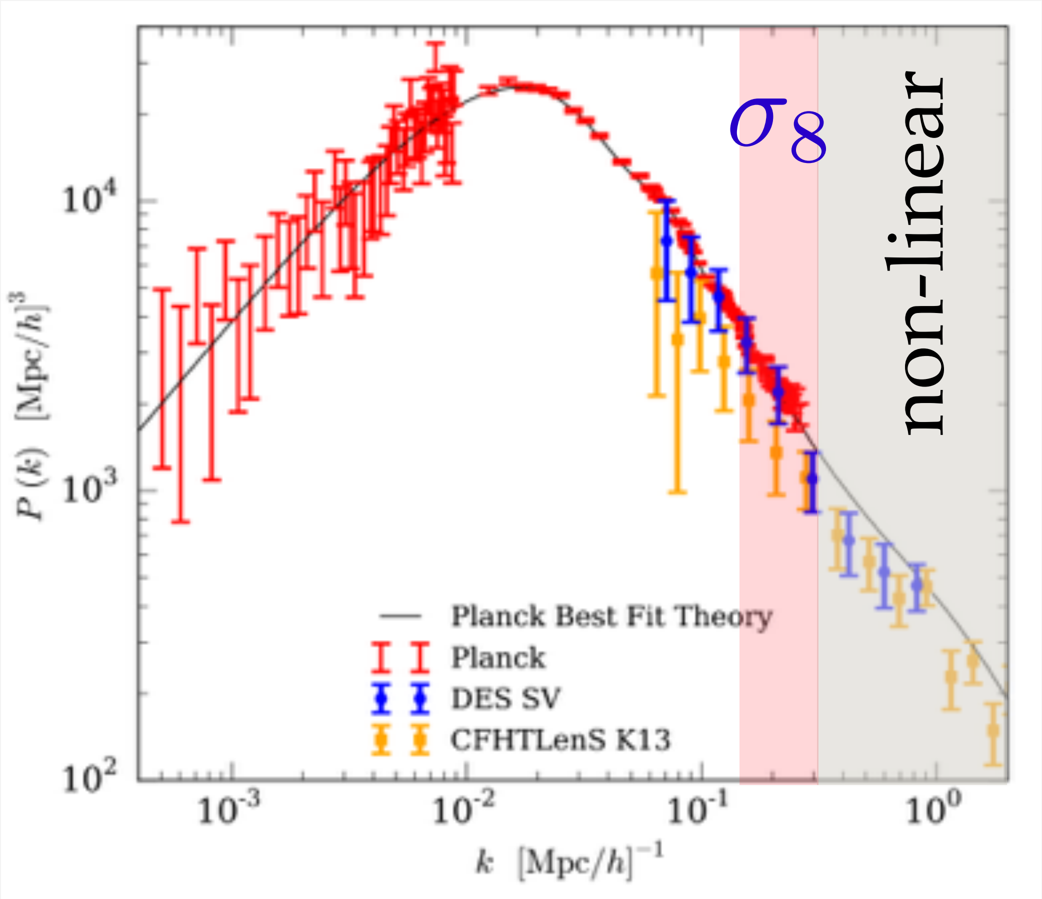


DES: 1507.05552



Can start to cross check the CMB & WL results

The Sigma8 problem



DES: 1507.05552

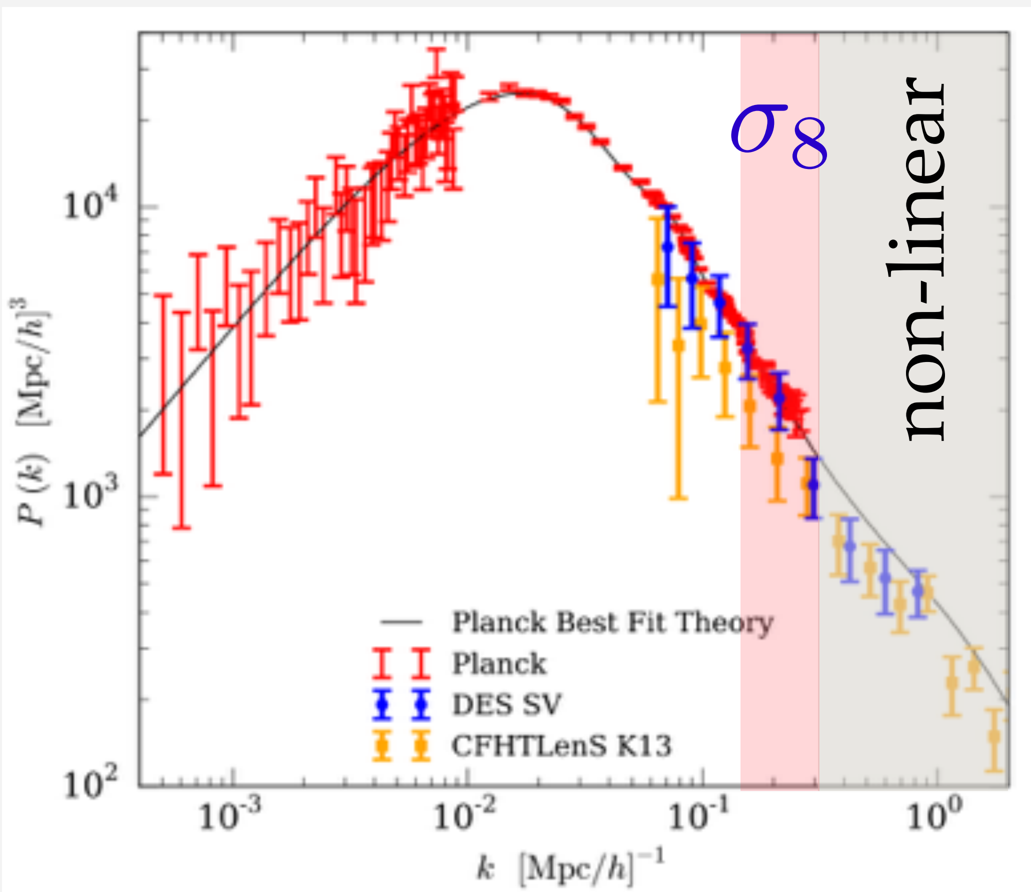
σ_8

~ amplitude of matter fluctuation on the scale of $8\,h^{-1}\mathrm{Mpc}$.

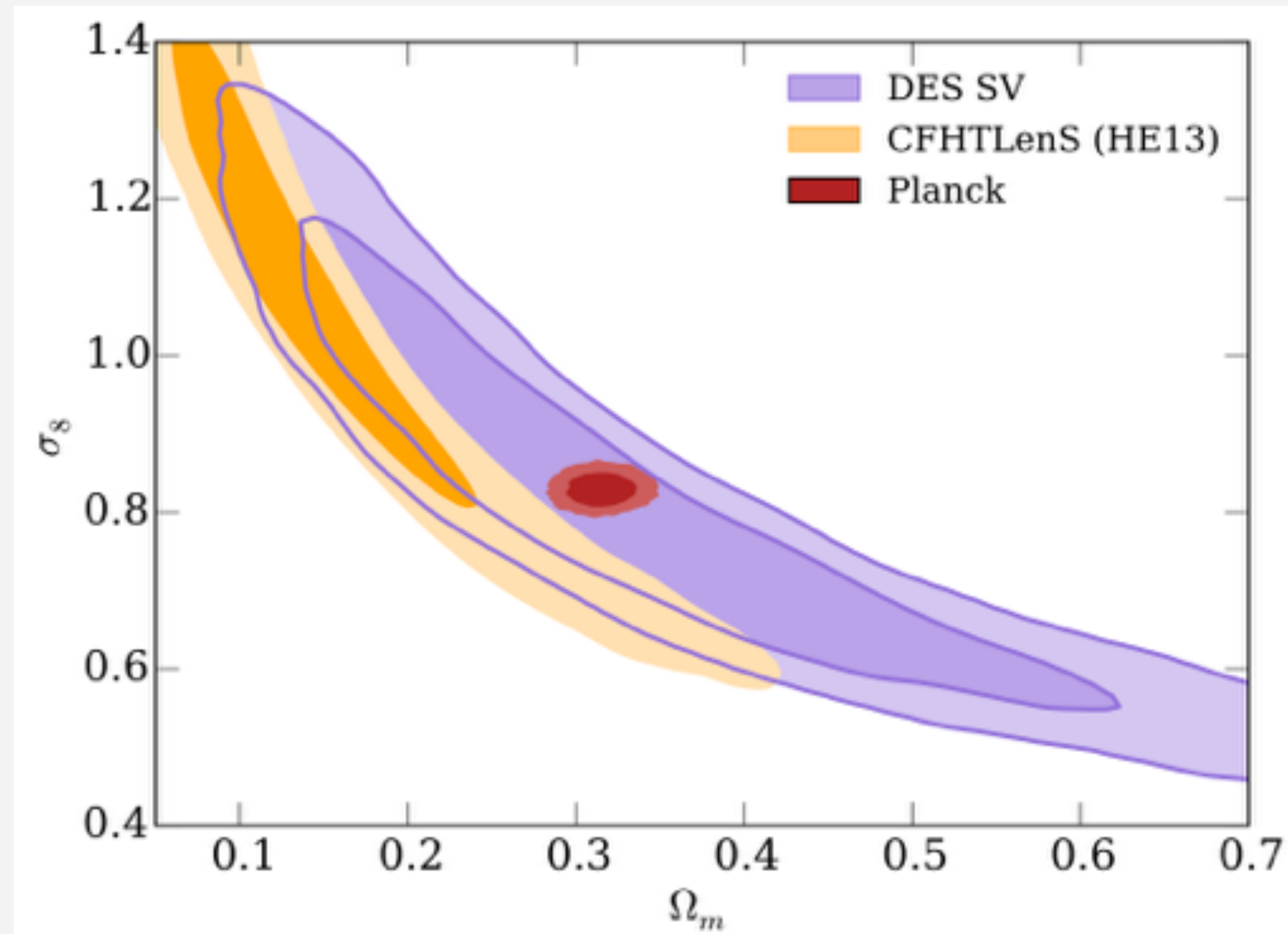
The smallest structure to study without significant non-linearity effects

The Sigma8 problem

Two σ_8 measurements: CMB + ΛCDM vs. Weak Lensing

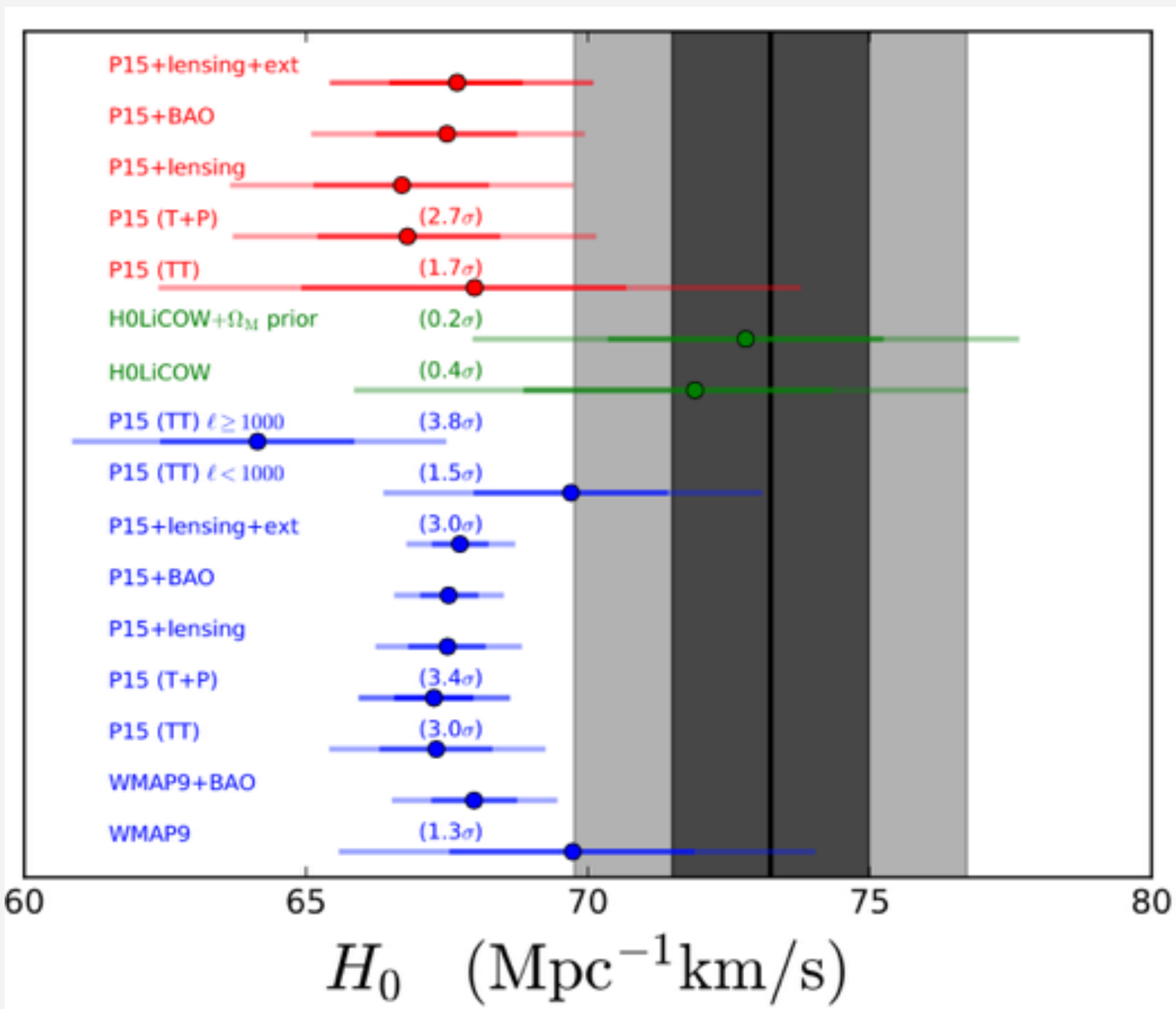


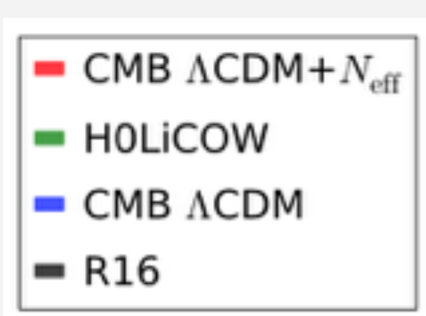
DES: 1507.05552



The CFHTLenS & CMB results deviate by ~ $2-3\sigma$.

H0 problem





Bernal et. al. 1607.05617

Two H0 measurements

CMB + ΛCDM .

vs.

Local Measurements

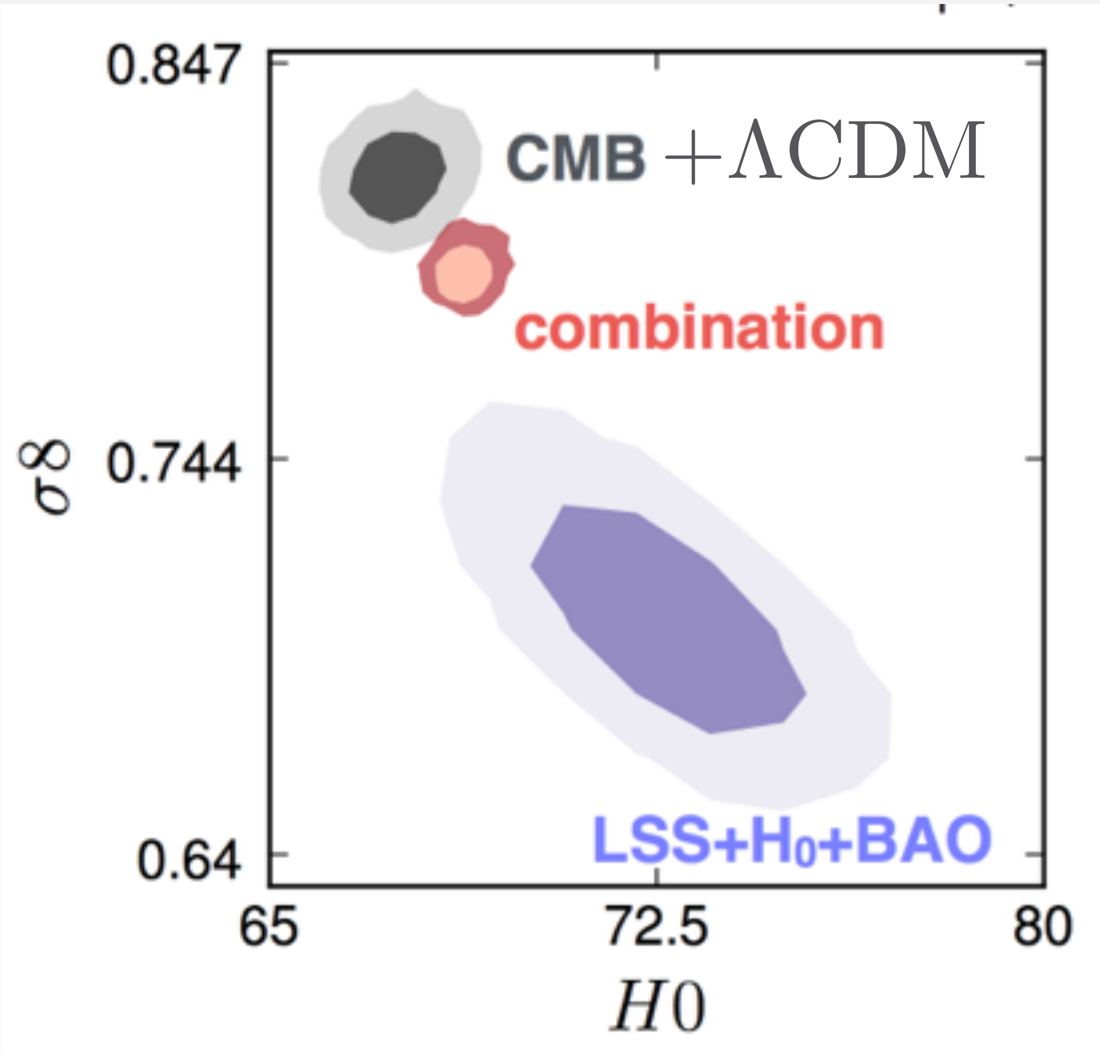
$$H_0^{\mathrm{Planck}} = 67.3 \pm 0.7\,\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$$

$$H_0^{\mathrm{HST}} = 73.02 \pm 1.79\,\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$$

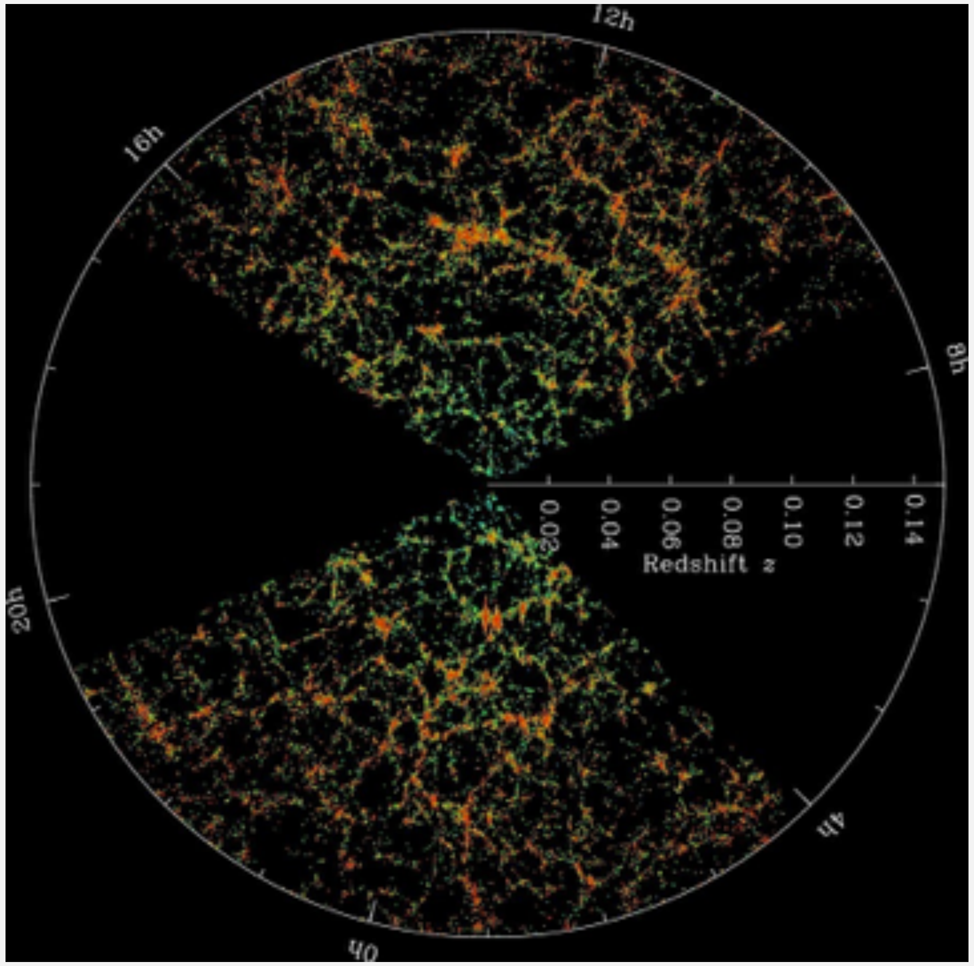
$> 3\sigma$ Discrepancy

Large Scale Structure problem

Poulin et. al. 1606.02073 : an illustration

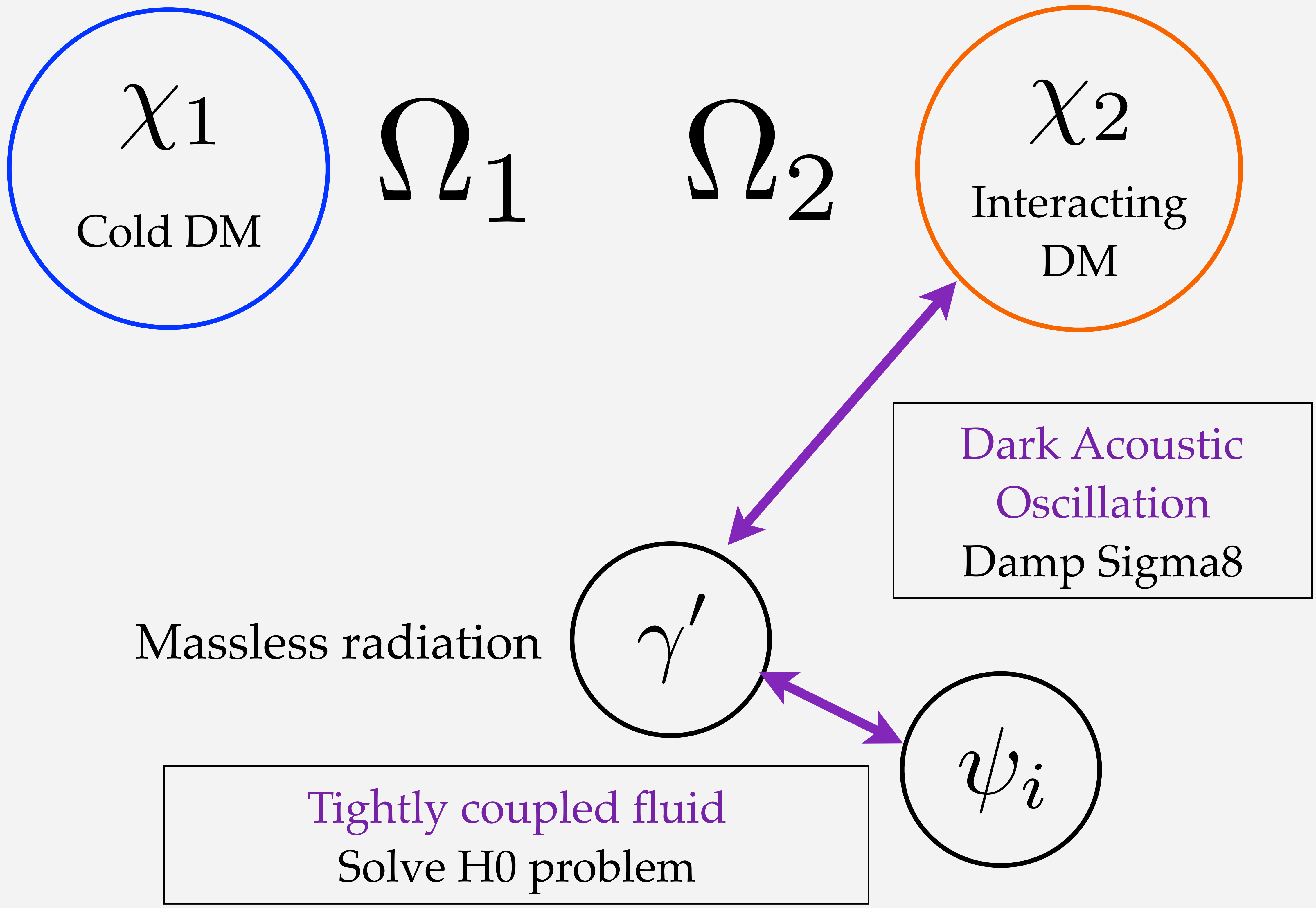


One solution: Partially Acoustic DM



DISTRIBUTION OF GALAXIES IN OUR UNIVERSE. CREDIT: SDSS

Consider a non-minimal dark sector



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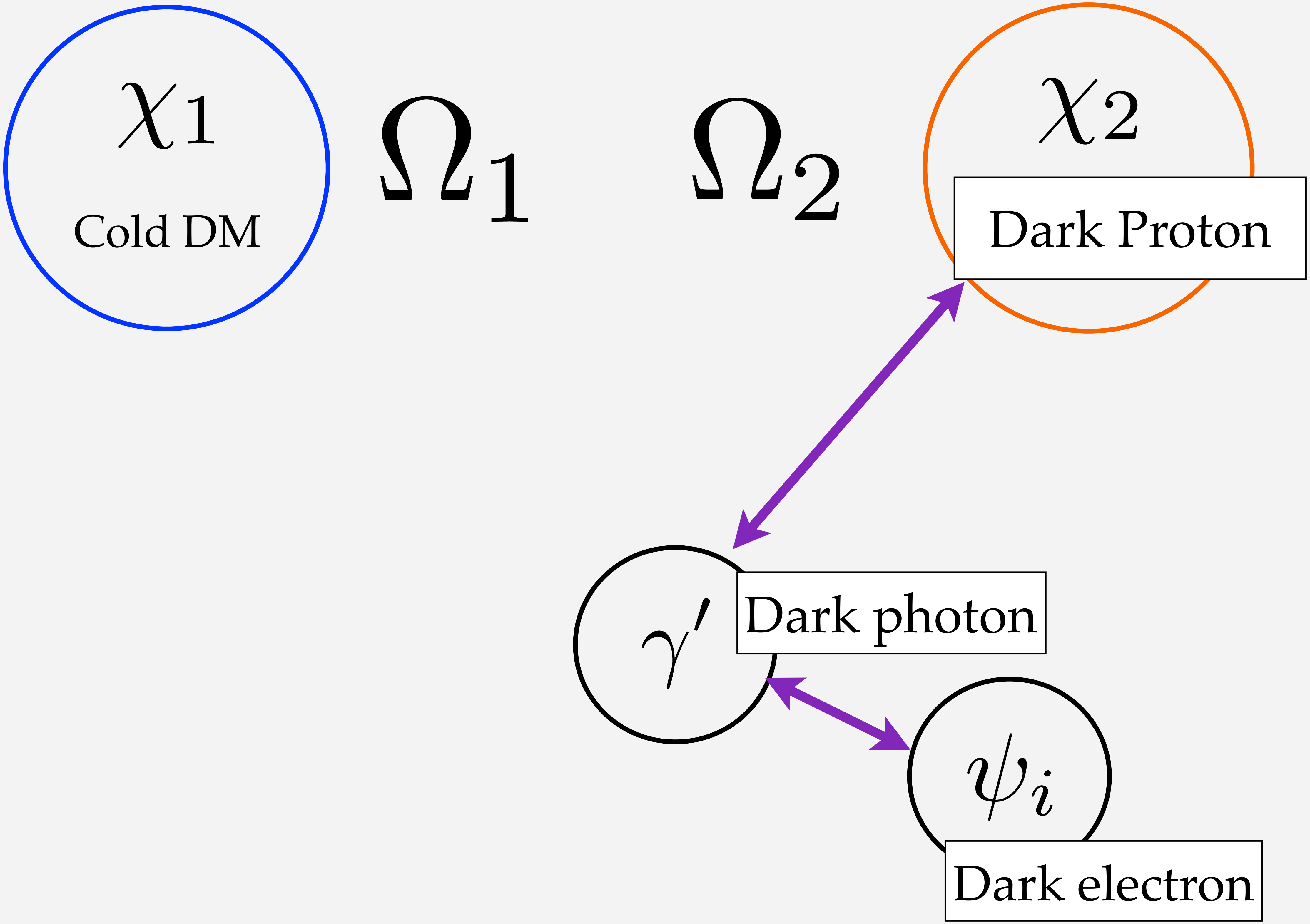
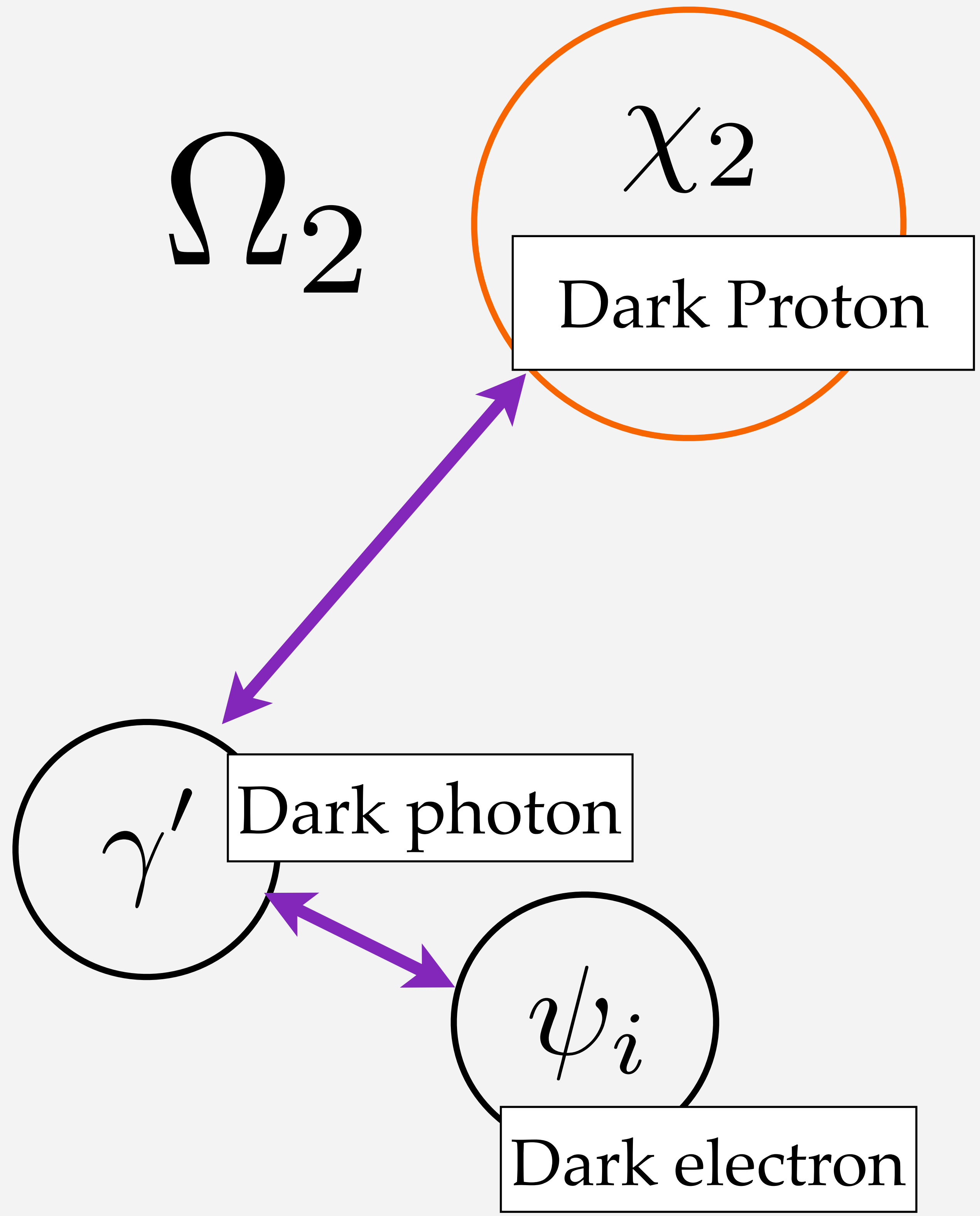


Consider a non-minimal dark sector

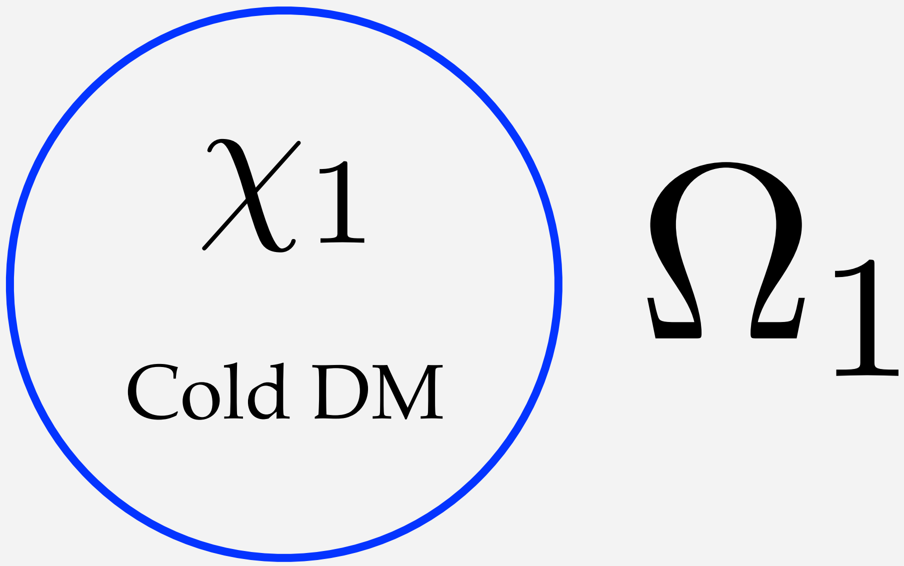


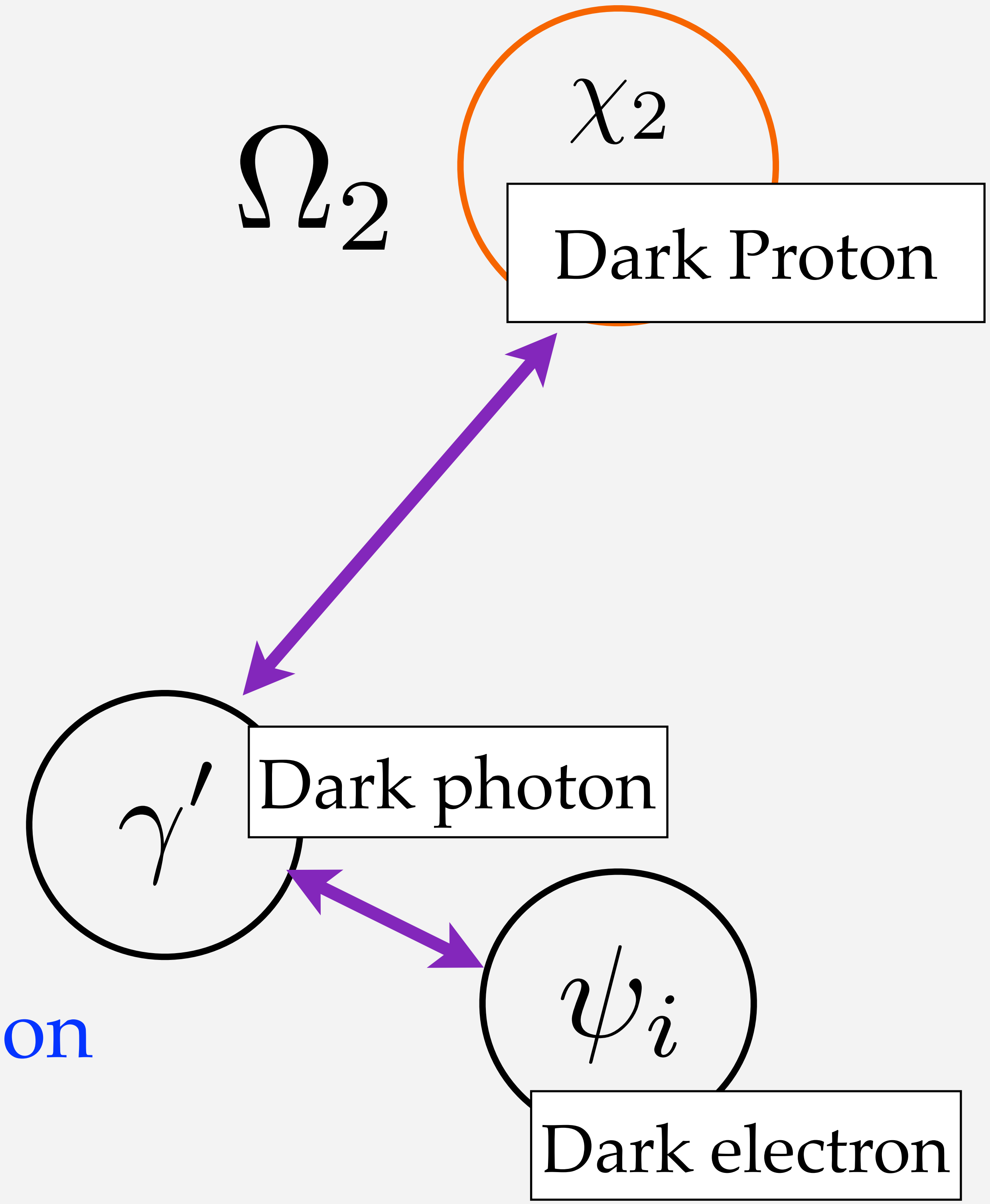
$$r \equiv \Omega_2/\Omega_{\rm DM}$$

$$r = 1$$

Fully Acoustic Oscillation

Consider a non-minimal dark sector





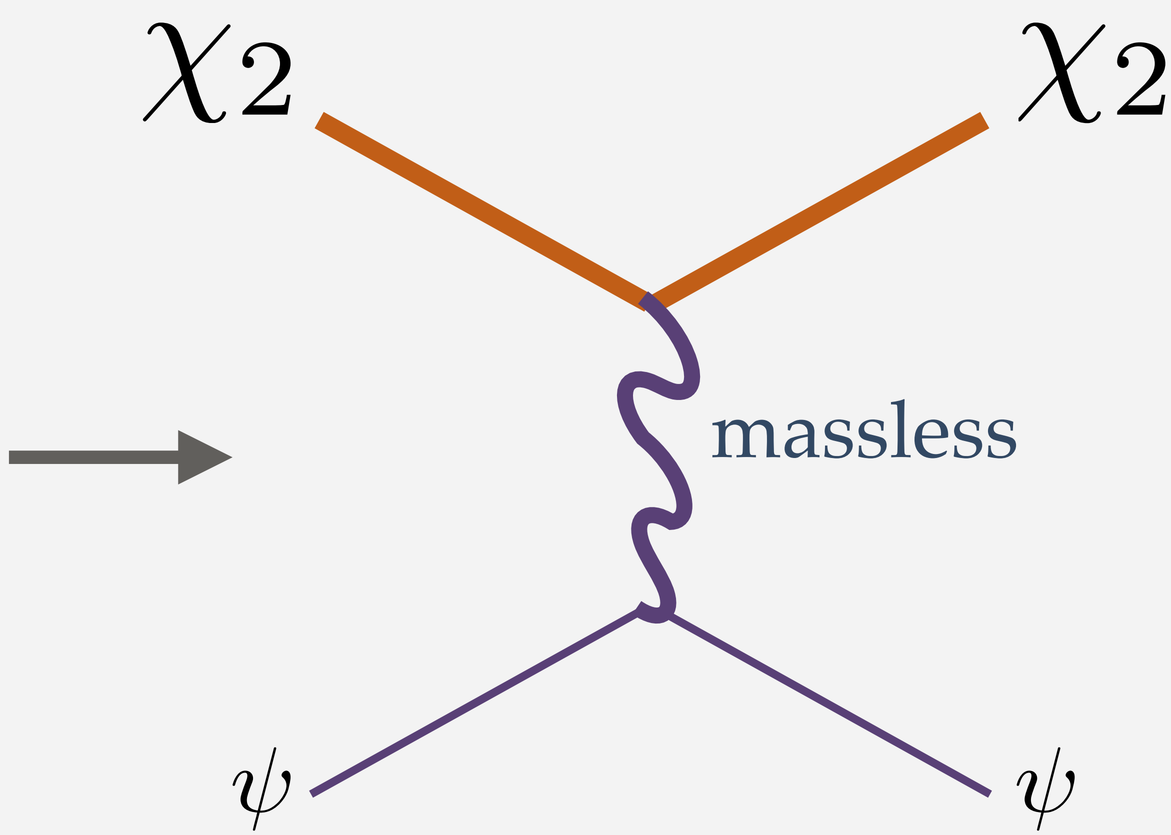
$$r \equiv \Omega_2/\Omega_{\rm DM}$$

$$r < 1$$

Partially Acoustic Oscillation

For the acoustic oscillation to exist

We need the DM-DR scattering to remain non-decoupled



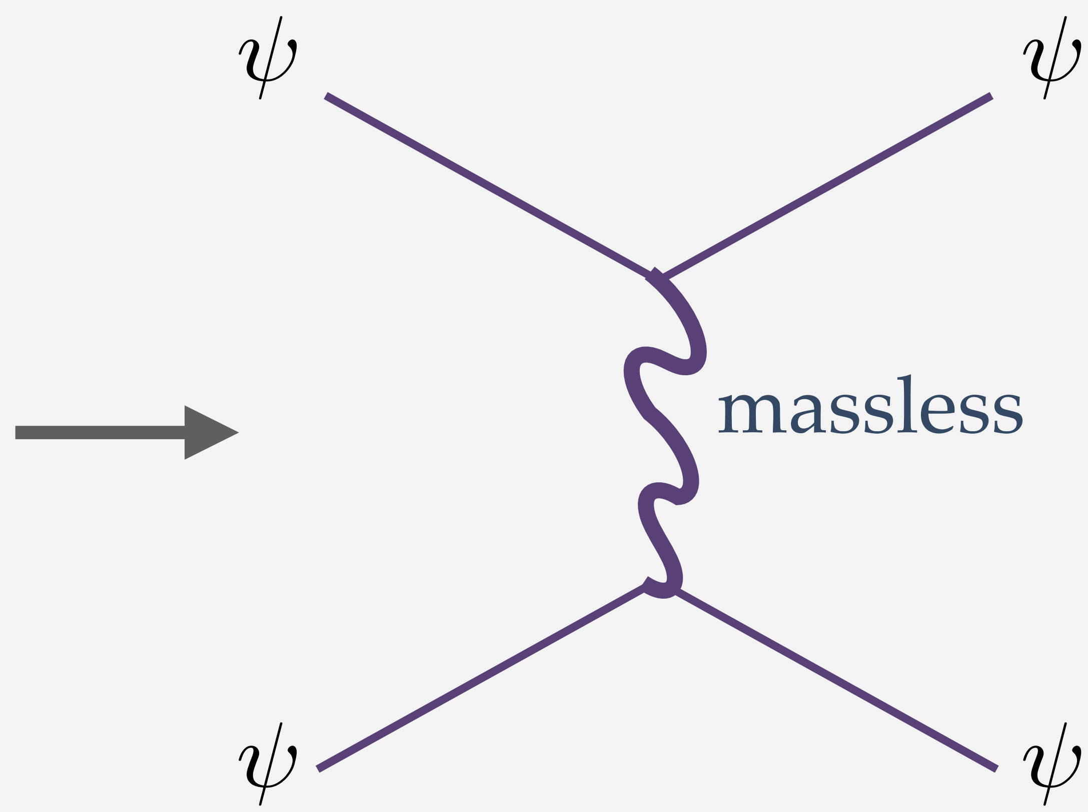
$$\Gamma \simeq \hat{\alpha}^2 \ln(\hat{\alpha}^{-1}) \frac{T_D^2}{m_{\rm DM}}$$

Same temp-dependence as Hubble in the radiation-dominant era

Easy to keep $\Gamma \gg H$ all the time, if $\hat{\alpha} \gg 10^{-8} \sqrt{\dfrac{m_{\chi_2}}{10\,\mathrm{GeV}}}$

Tightly coupled dark radiation

We need the DM-DR scattering to remain non-decoupled

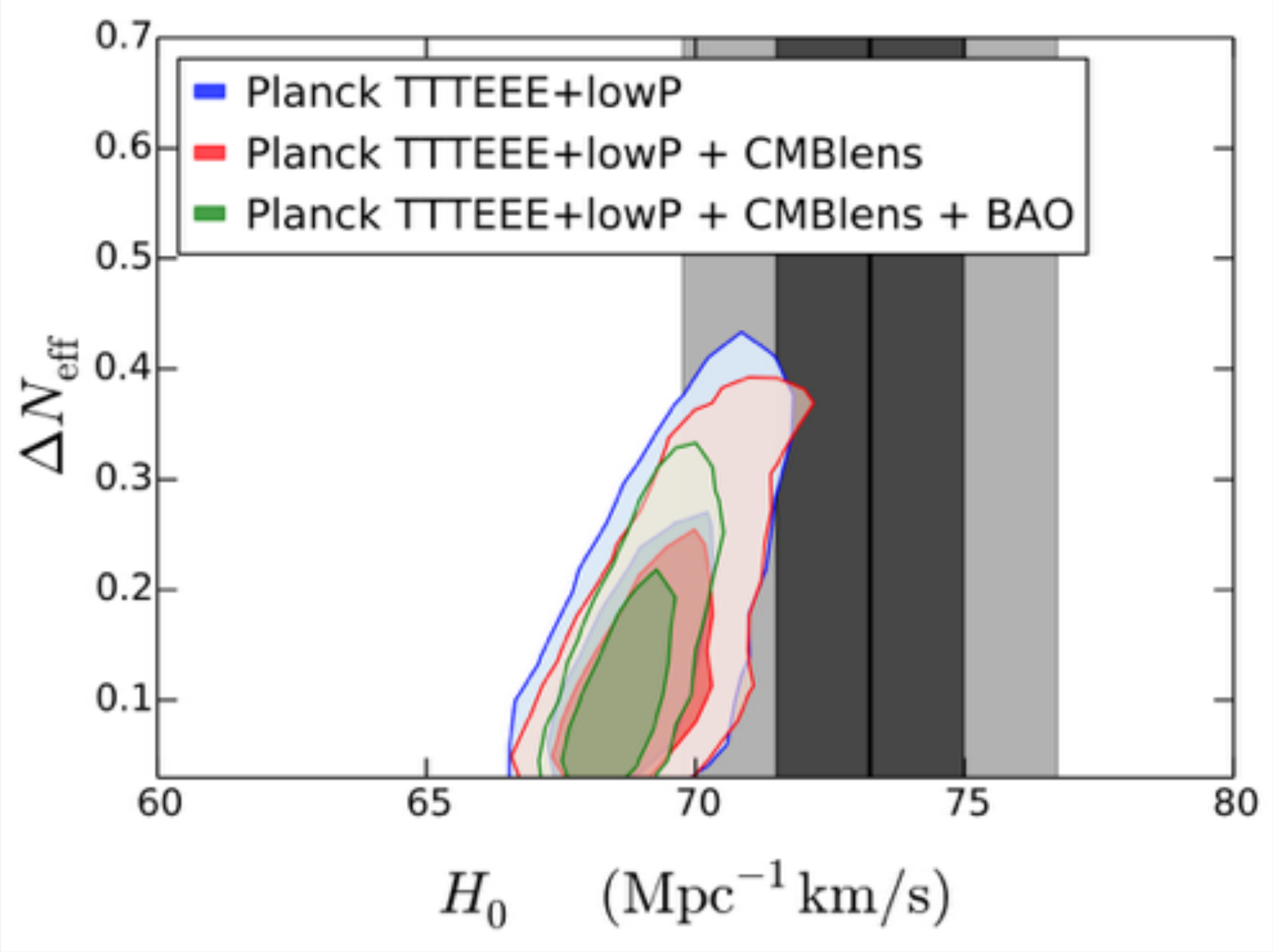


$$\Gamma \simeq \hat{\alpha}^2 \ln(\hat{\alpha}^{-1}) T_D$$

The same coupling keeps dark fermions/photon a tightly coupled fluid

Solving H0 problem with extra dark radiation

Bernal et. al. 1607.05617

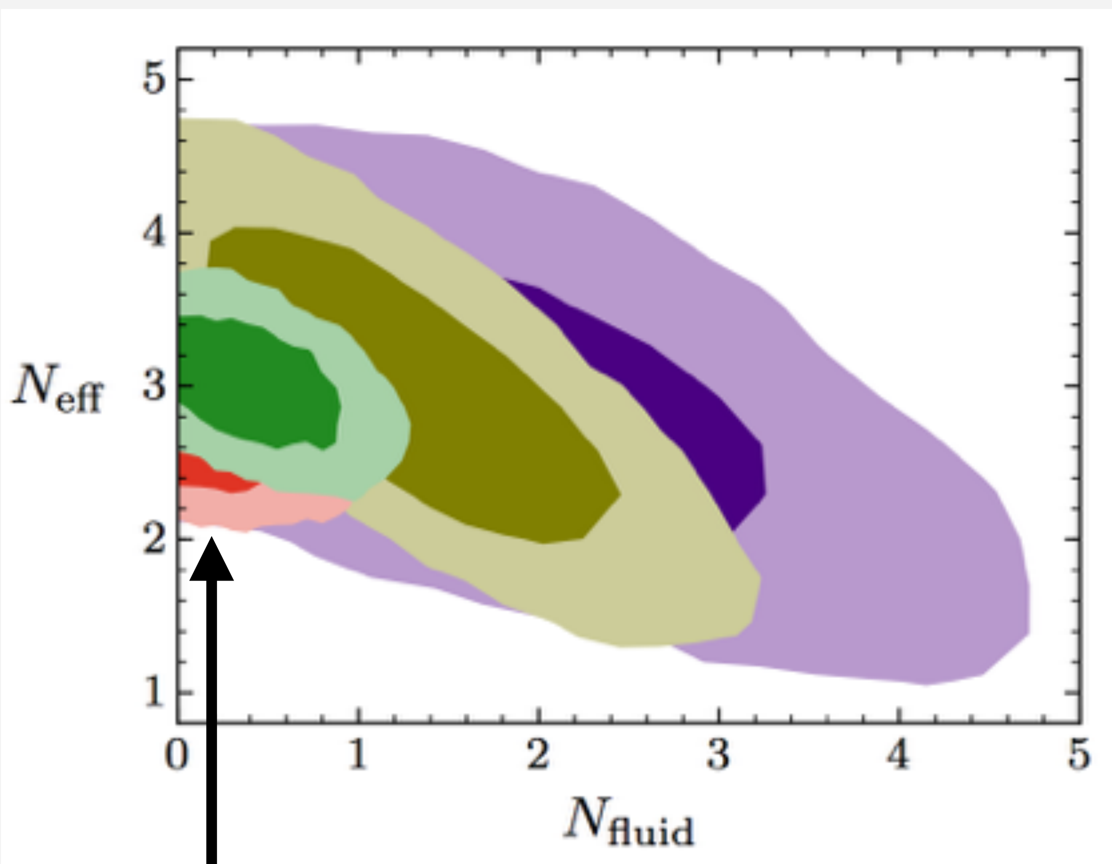


Can explain the larger H_0 by including $\Delta N_{\rm eff} > 0.4$ dark radiation

Adam Riess et.al. 1604.01424

Dark fluid is better than FS-radiation

Baumann et. al. 1508.06342



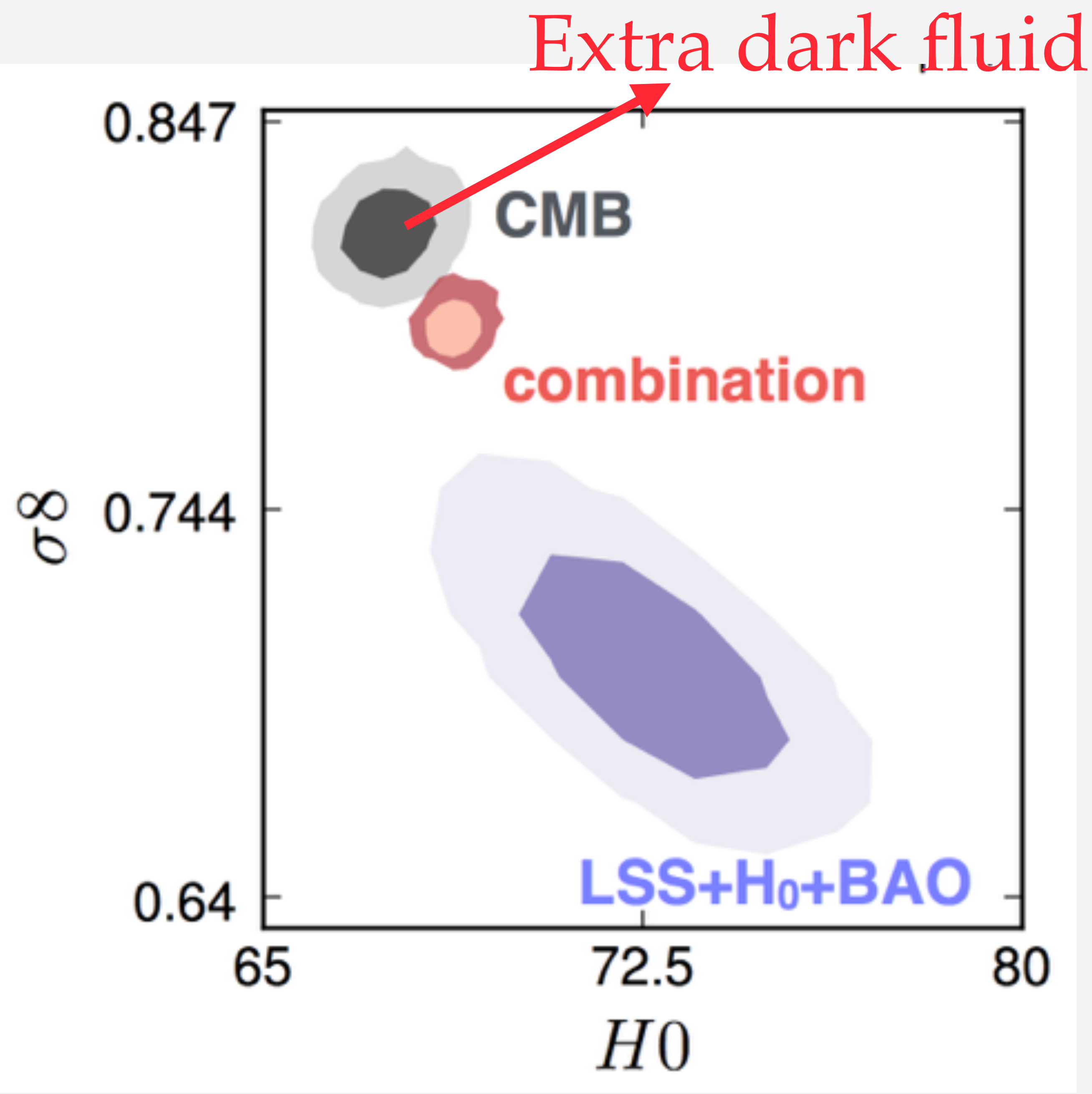
Planck TT, TE, and EE likelihoods

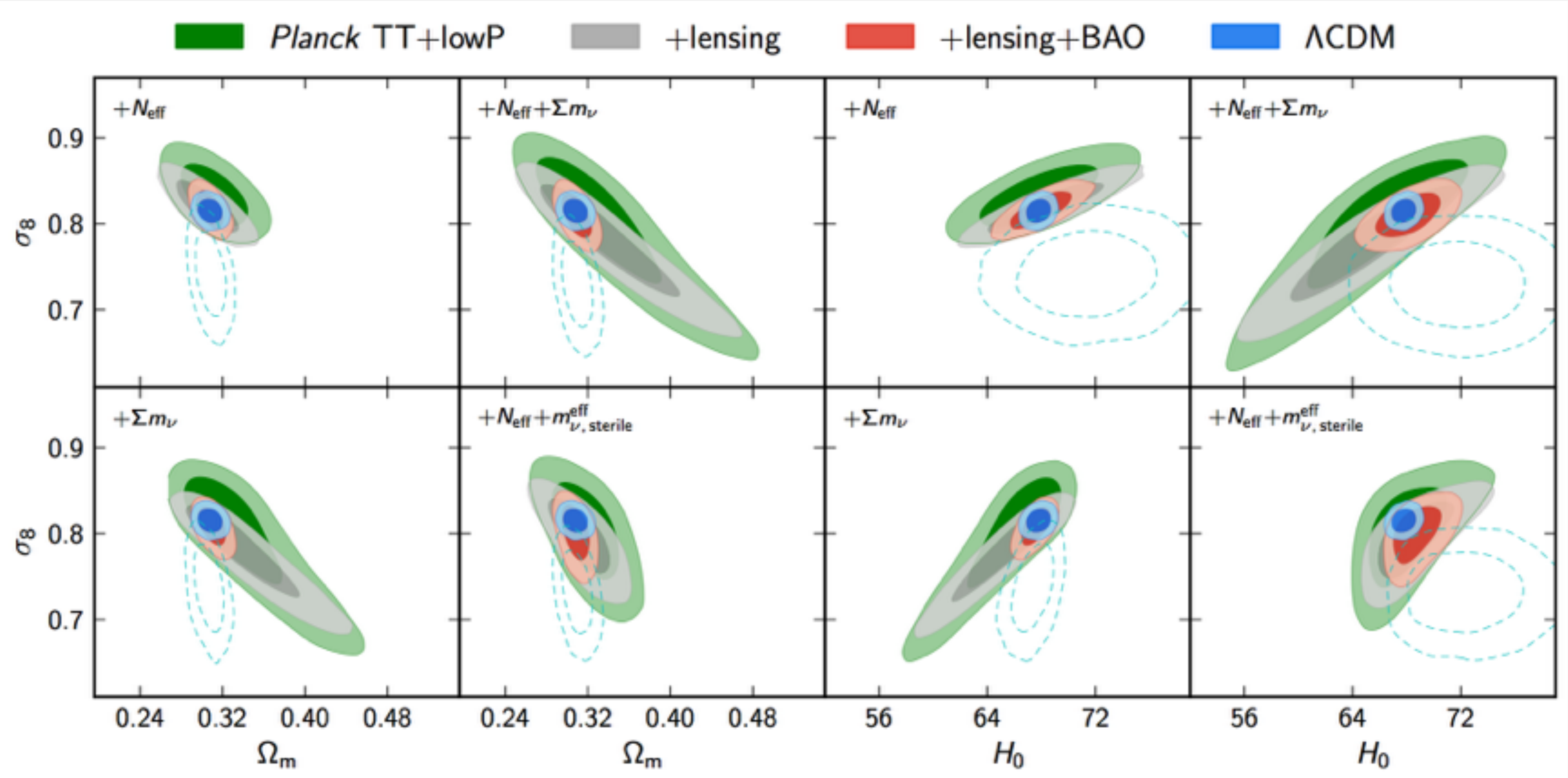
$\Delta N_{\rm eff}$ bound on a tightly coupled fluid is weaker

	TT, TE, EE		TT-only	
	varying Y_p	fixed Y_p	varying Y_p	fixed Y_p
$N_{\rm eff}$	$2.78^{+0.30}_{-0.35}$	$2.99^{+0.30}_{-0.29}$	$2.87^{+0.76}_{-0.74}$	$2.94^{+0.71}_{-0.69}$
$N_{\rm fluid}$	< 0.88	< 1.06	< 3.93	< 2.65

(2σ)

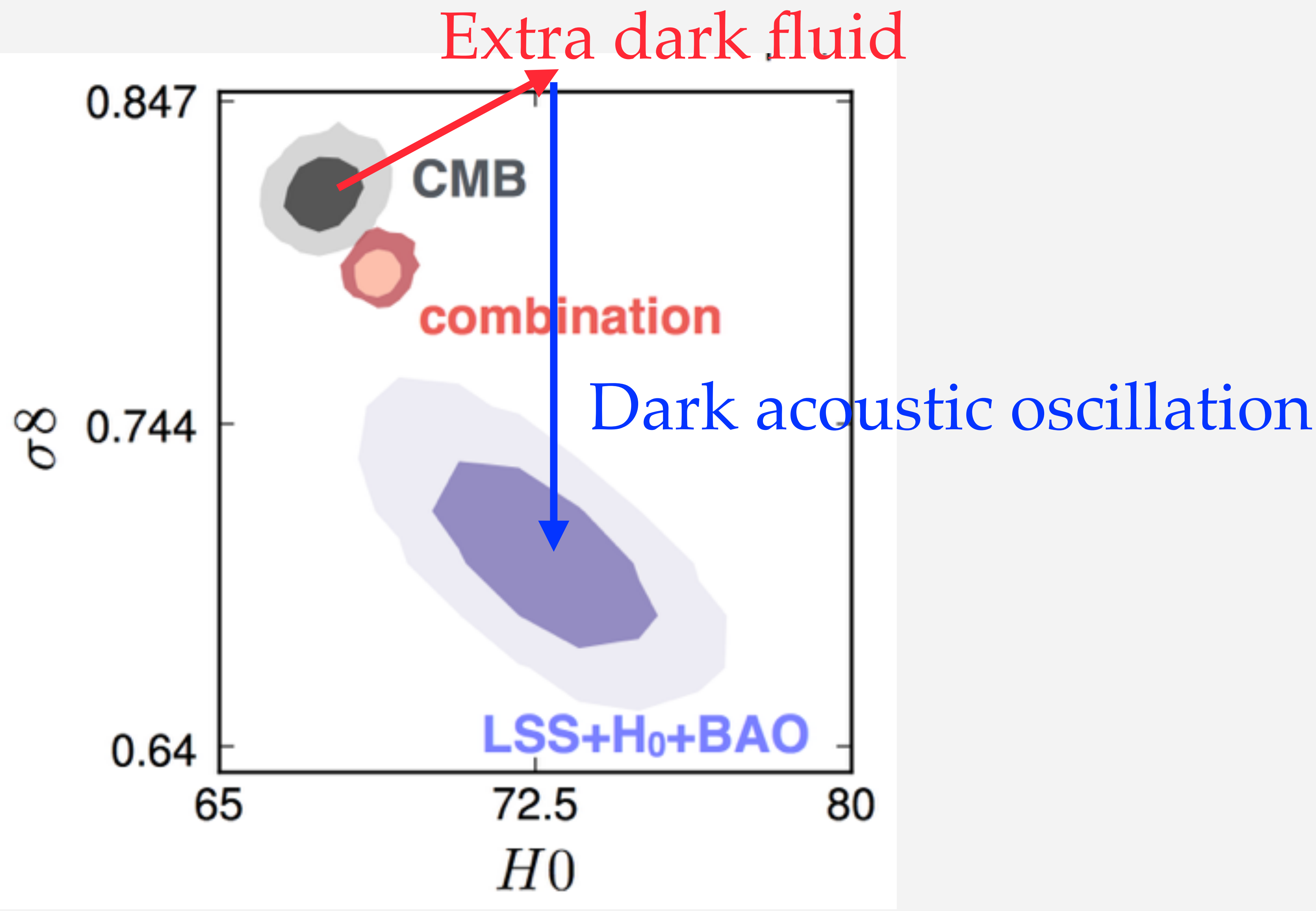
Reconcile H0, but makes sigma8 worse



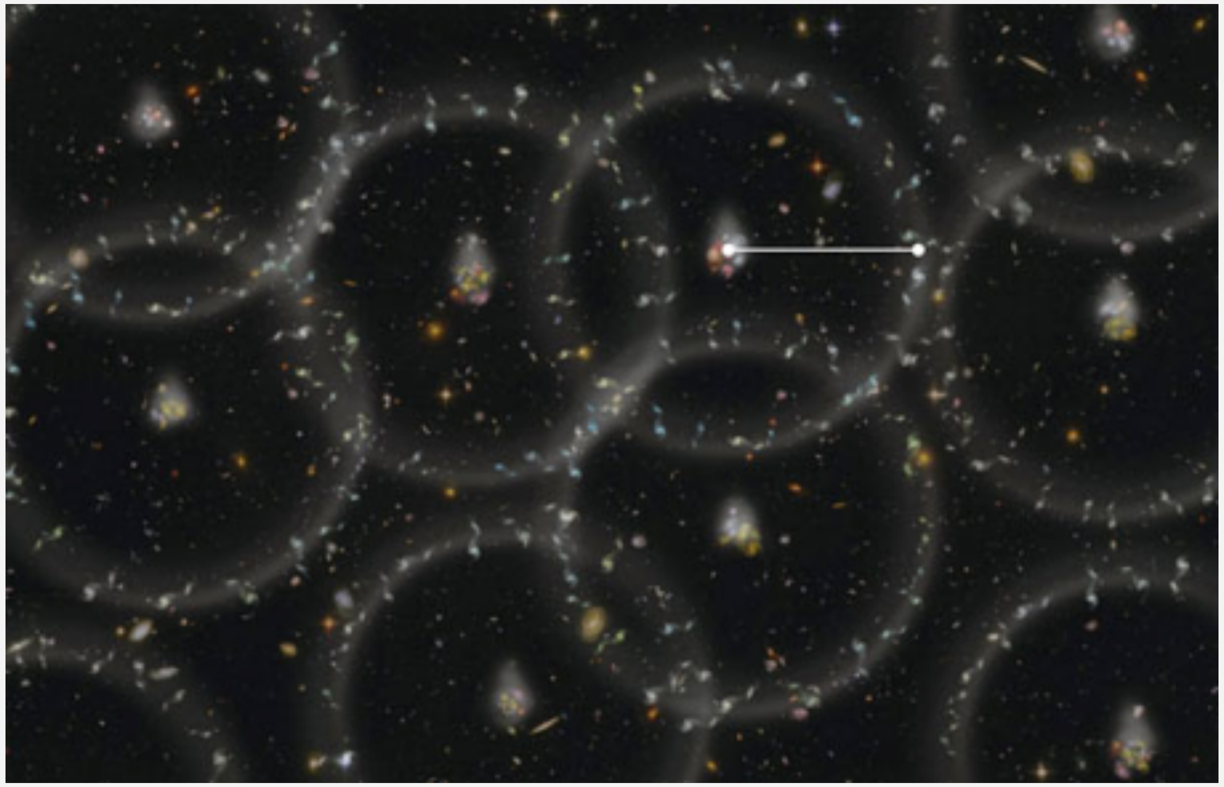


Planck TT+lowP
+lensing
+lensing+BAO
ΛCDM
+N_{eff}
+N_{eff}+Σm_ν
+Σm_ν
+N_{eff}+$m^{eff}_{\nu,\,sterile}$
σ_8
0.9
0.8
0.7
0.24
0.32
0.40
0.48
Ω_m
56
64
72
H_0

DM-DR scattering suppresses Sigma8

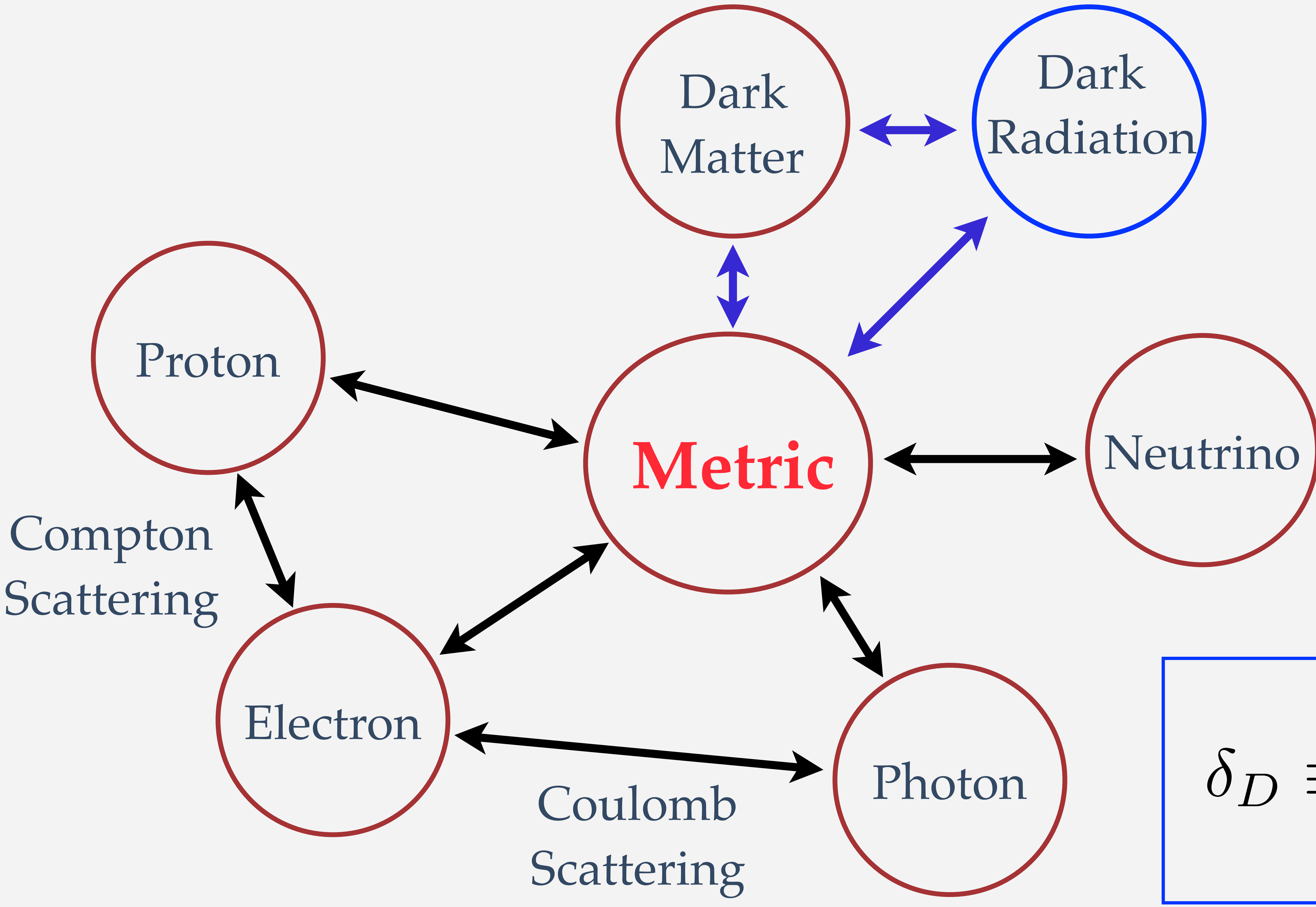


Structure Formation with Acoustic DM



A cartoon produced by the BOSS project showing the spheres of baryons around the initial dark matter clumps

Evolution of the Large Scale Structures



$$\delta_D \equiv \frac{\delta\rho_D}{\bar{\rho}_D}$$

Boltzmann Equation in Conformal Newtonian Gauge

$$\dot{\delta}_D = -\theta_D + 3\dot{\psi} \qquad \left(\frac{d\rho}{dt} = -\rho\nabla\cdot\vec{v}\right)$$

$$\dot{\theta}_D = -\frac{\dot{a}}{a}\theta_D + k^2\psi + \underline{a\Gamma(\theta_R - \theta_D)} \qquad \Gamma \equiv \frac{1}{\langle p_D^2\rangle}\frac{d\langle \delta p_D^2\rangle}{dt}$$

$$\dot{\delta}_R = -\frac{4}{3}\theta_R + 4\dot{\psi}$$

$$\dot{\theta}_R = \frac{k^2}{4}\delta_R + k^2\psi + \underline{R\,a\Gamma(\theta_D - \theta_R)}$$

$\theta_s \equiv \partial_i v_s^i$ Velocity Divergent

Metric Perturbation

$$ds^2 = a^2(\tau)[-(1+2\psi)d\tau^2 + (1-2\phi)\delta_{ij}dx^i dx^j]$$

No free-streaming particle => $\phi = \psi$

Boltzmann Equation in Conformal Newtonian Gauge

$$\dot{\delta}_D = -\theta_D + 3\dot{\psi} \qquad \left(\frac{d\rho}{dt} = -\rho\nabla\cdot\vec{v}\right)$$

$$\Gamma \equiv \frac{1}{\langle p_D^2\rangle}\frac{d\langle\delta p_D^2\rangle}{dt}$$

$$\dot{\theta}_D = -\frac{\dot{a}}{a}\theta_D + k^2\psi + \underline{a\Gamma(\theta_R - \theta_D)}$$

vanishes for cold DM, similar expression for SM baryon

$$\dot{\delta}_R = -\frac{4}{3}\theta_R + 4\dot{\psi}$$

$$\dot{\theta}_R = \frac{k^2}{4}\delta_R + k^2\psi + \underline{R\,a\Gamma(\theta_D - \theta_R)}$$

similar expression for SM photon

Tightly coupled DM-DR (similar to the baryon-photon system):

$$\Gamma \gg H \quad \Rightarrow \quad a\Gamma \gg \tau^{-1}$$

In the tightly coupled DM-DR limit

We can simplify the evolution of DM perturbation

$$\ddot{\delta}_D + \frac{\dot{a}}{a}\frac{R}{1+R}\dot{\delta}_D + \frac{k^2}{3(1+R)}\delta_D \simeq -k^2\phi$$

$$R \equiv \frac{3\rho_D}{4\rho_R}$$

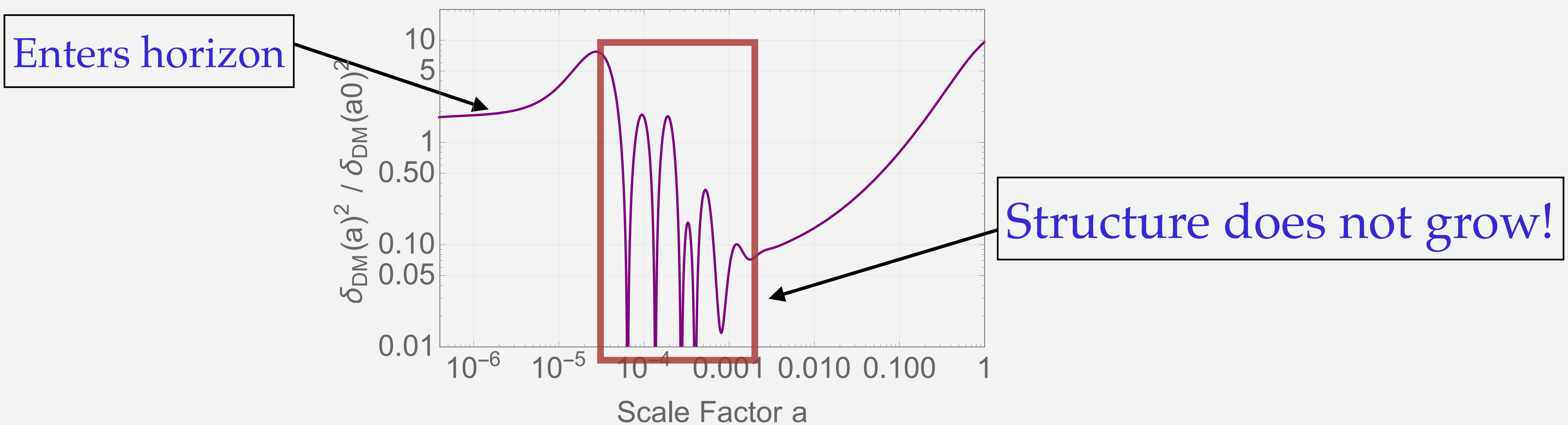
Parametrize the ``mass'' of DM-DR fluid

Radiation Domination , R << 1

Density perturbation oscillates => No structure grows

$$\ddot{\delta}_D + \frac{\dot{a}}{a}\frac{R}{1+R}\dot{\delta}_D + \frac{k^2}{3(1+R)}\delta_D \simeq -k^2\phi$$

The density perturbation oscillates as a harmonic oscillator!
Same physics as the baryon acoustic oscillation

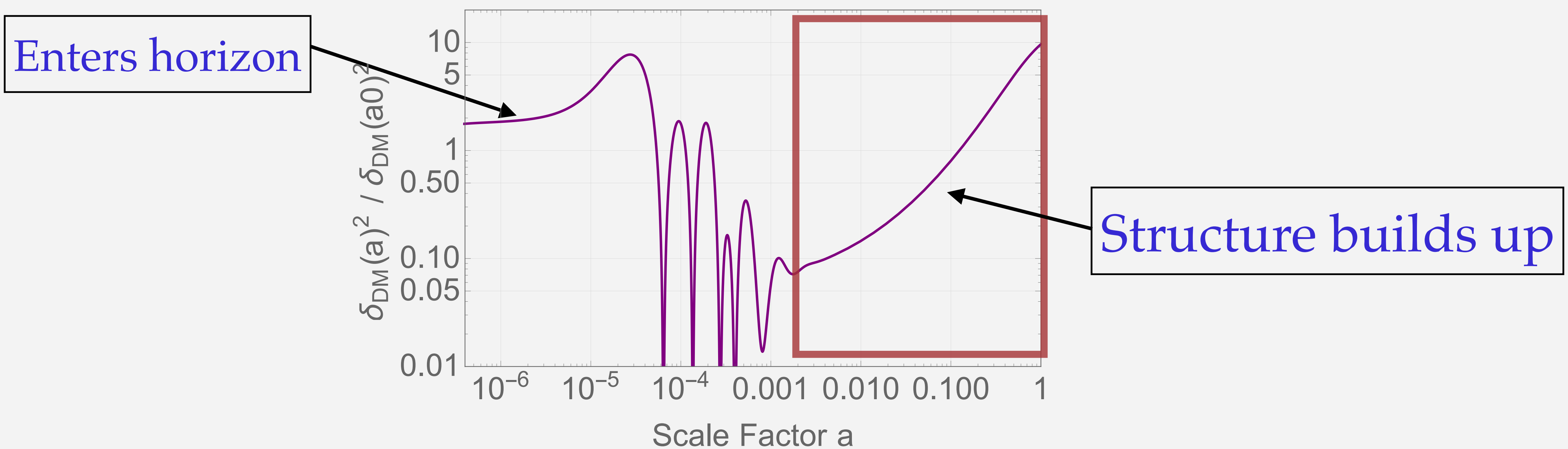


Matter Domination , R >> 1

No oscillation => Linear growth

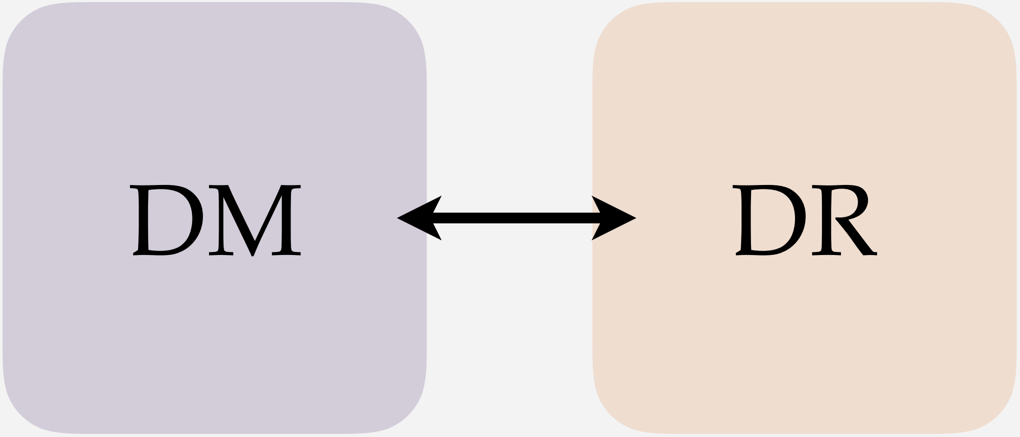
$$\ddot{\delta}_D + \frac{\dot{a}}{a}\frac{R}{1+R}\dot{\delta}_D + \frac{k^2}{3(1+R)}\delta_D \simeq -k^2\phi$$

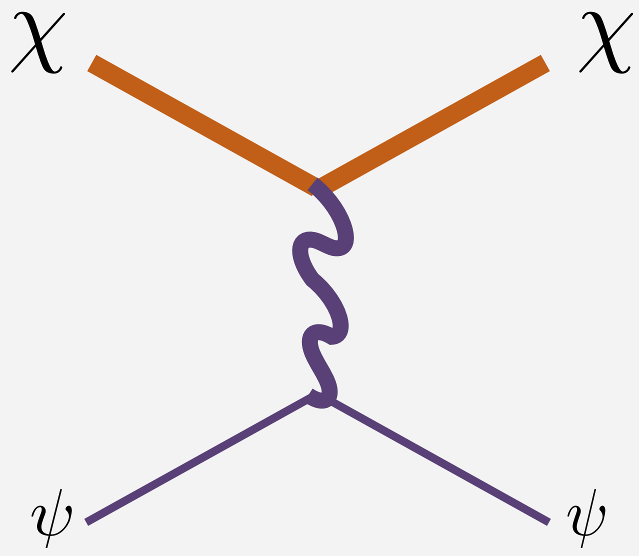
No oscillation, no damping from the DR scattering
Same structure formation as cold DM



If all the DM particles oscillate with DR

We need a small DM coupling for the right σ_8 suppression



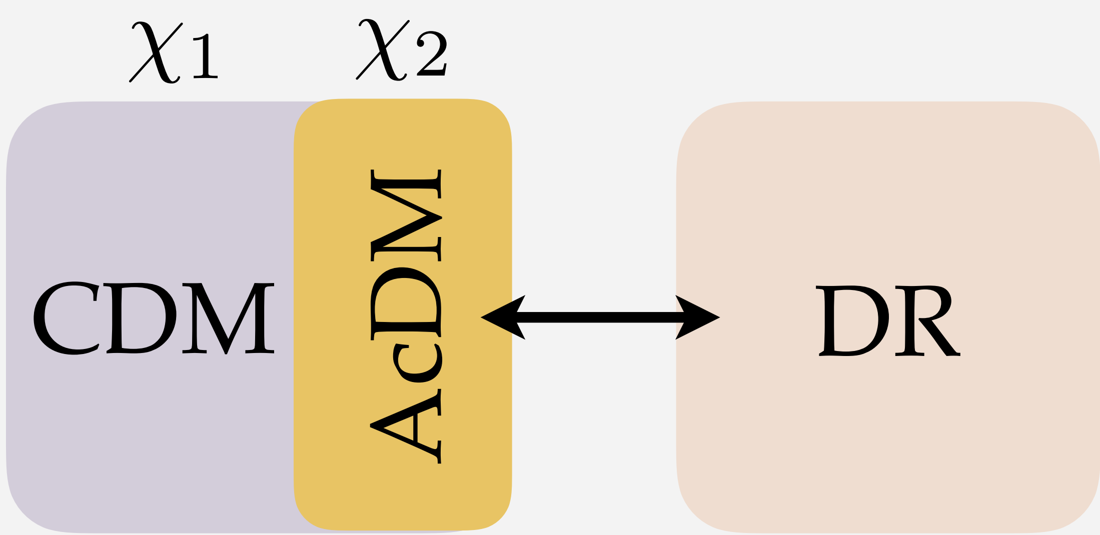


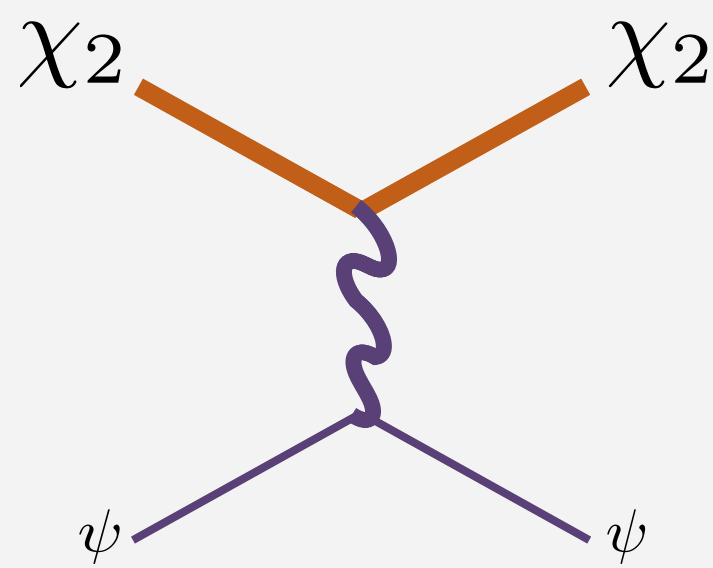
$$\hat{\alpha} \sim 10^{-8.5}$$

Manuel A. Buen-Abad, Gustavo Marques-Tavares, and Martin Schmaltz (2015)

Julien Lesgourgues, Gustavo Marques-Tavares, and Martin Schmaltz (2015)

How about only a fraction of DM particles having the acoustic oscillation?



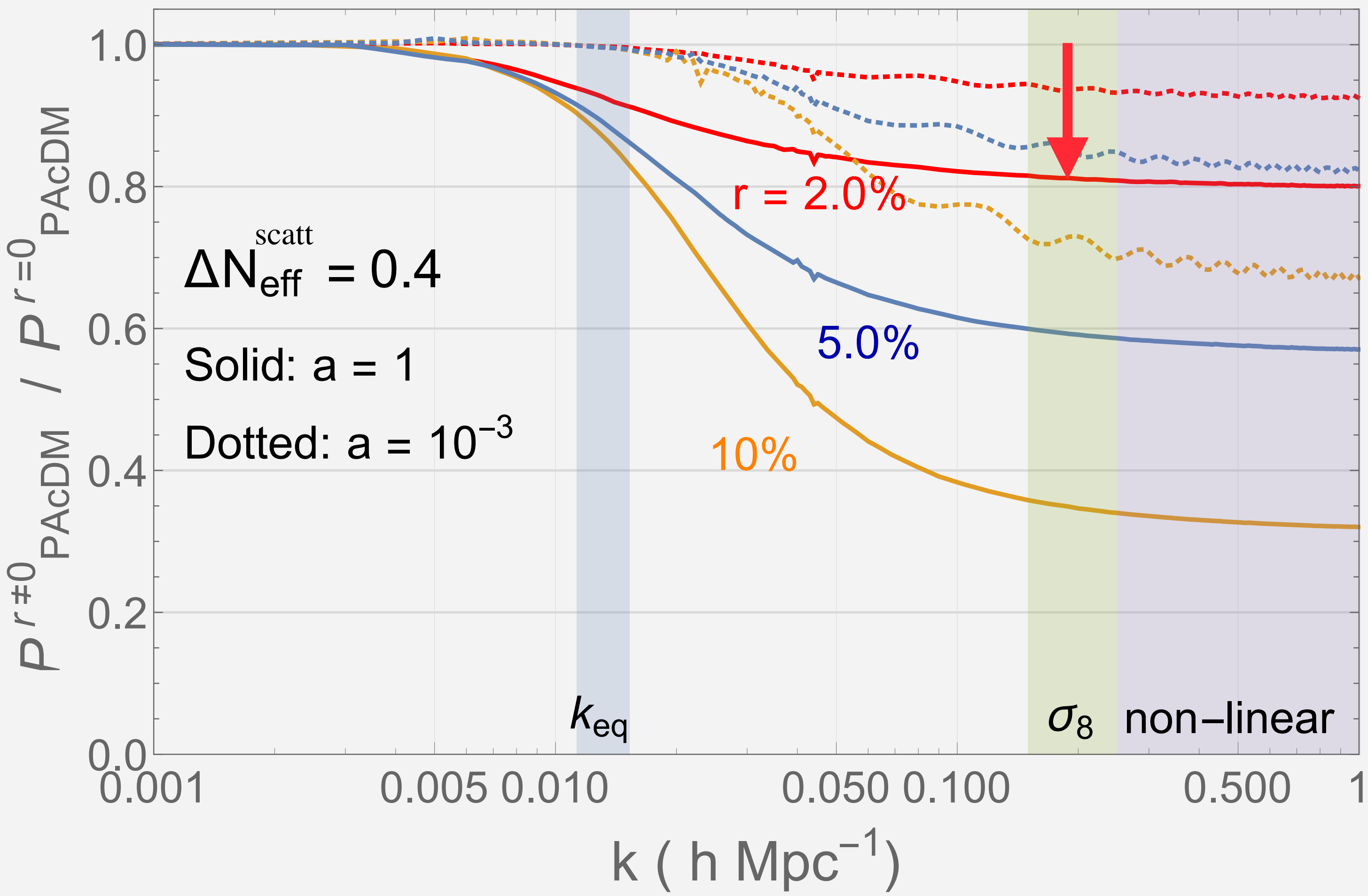


$$\Gamma \gg H(T)$$

If only a small component DM has the acoustic oscillation,
we can allow DM-DR to be tightly coupled (remain equilibrium)
and solve DM perturbation analytically

Solving Sigma8 problem with PAcDM

$$\left[\frac{\sigma_8(\Lambda\mathrm{CDM})}{\sigma_8(\mathrm{PAcDM})}\right]^2 \sim$$

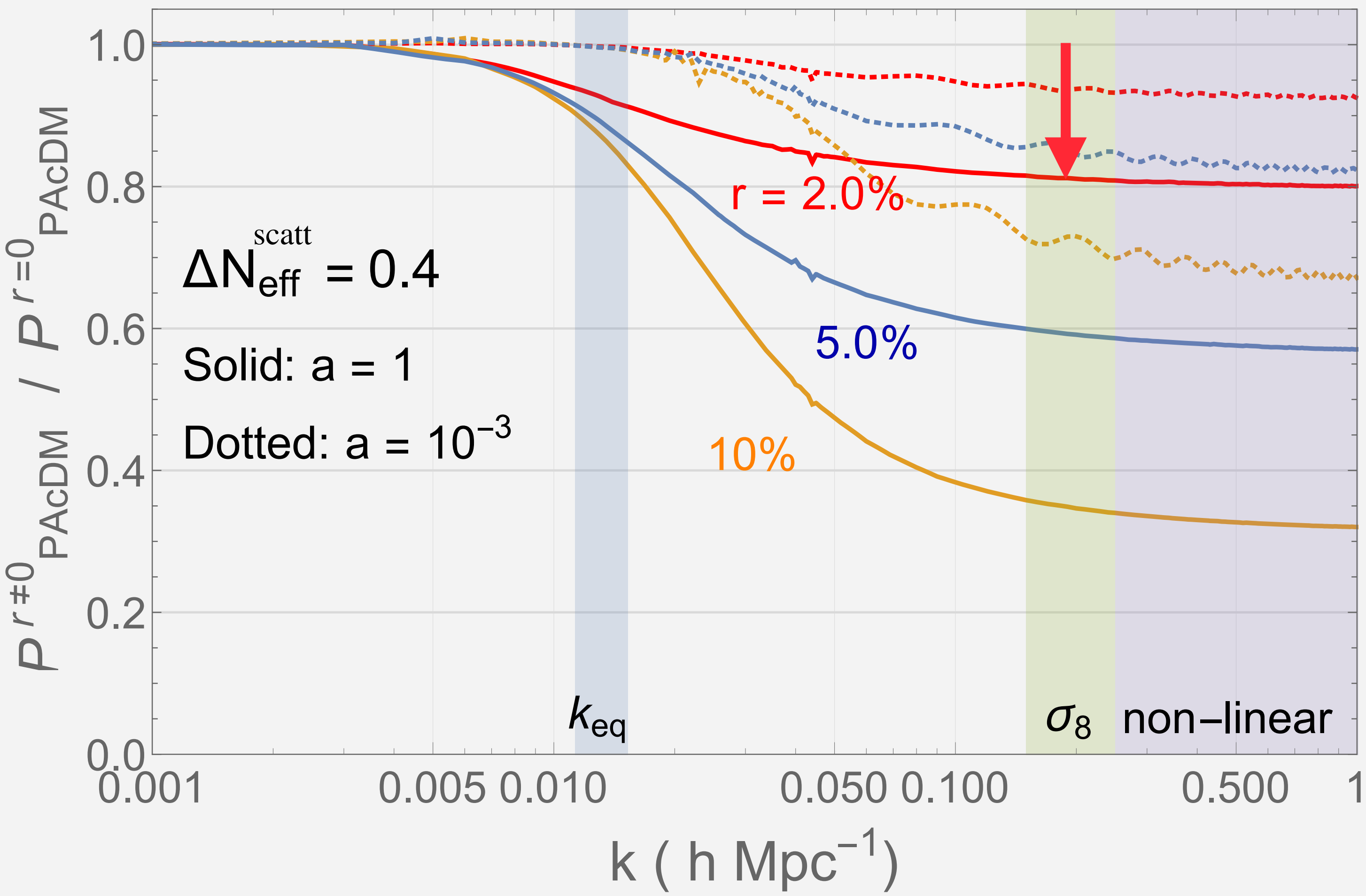


A simple analytical result

$$\frac{P(r)}{P(0)} \simeq (1-2r)\left(\frac{a}{a_{\mathrm{eq}}}\right)^{-1.2r} \qquad r \equiv \Omega_2/\Omega_{\mathrm{DM}}$$

Solving Sigma8 problem with PAcDM

$$\left[\frac{\sigma_8(\Lambda\text{CDM})}{\sigma_8(\text{PAcDM})}\right]^2 \sim$$



Need ~2% acoustic DM to solve the σ_8 problem

2% density is easy to obtained

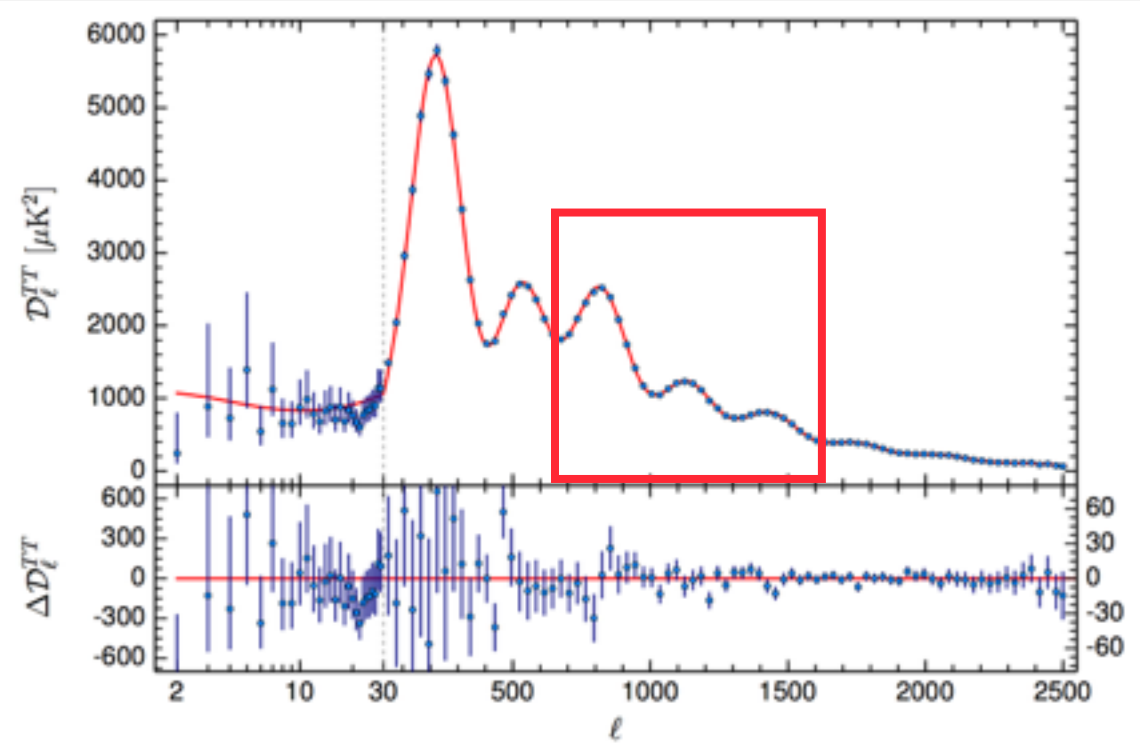
When both DM particles are WIMP-like and having thermal freeze out through a heavy mediator

$$\frac{\Omega_2}{\Omega_1} \simeq \left(\frac{m_2}{m_1}\right)^2$$

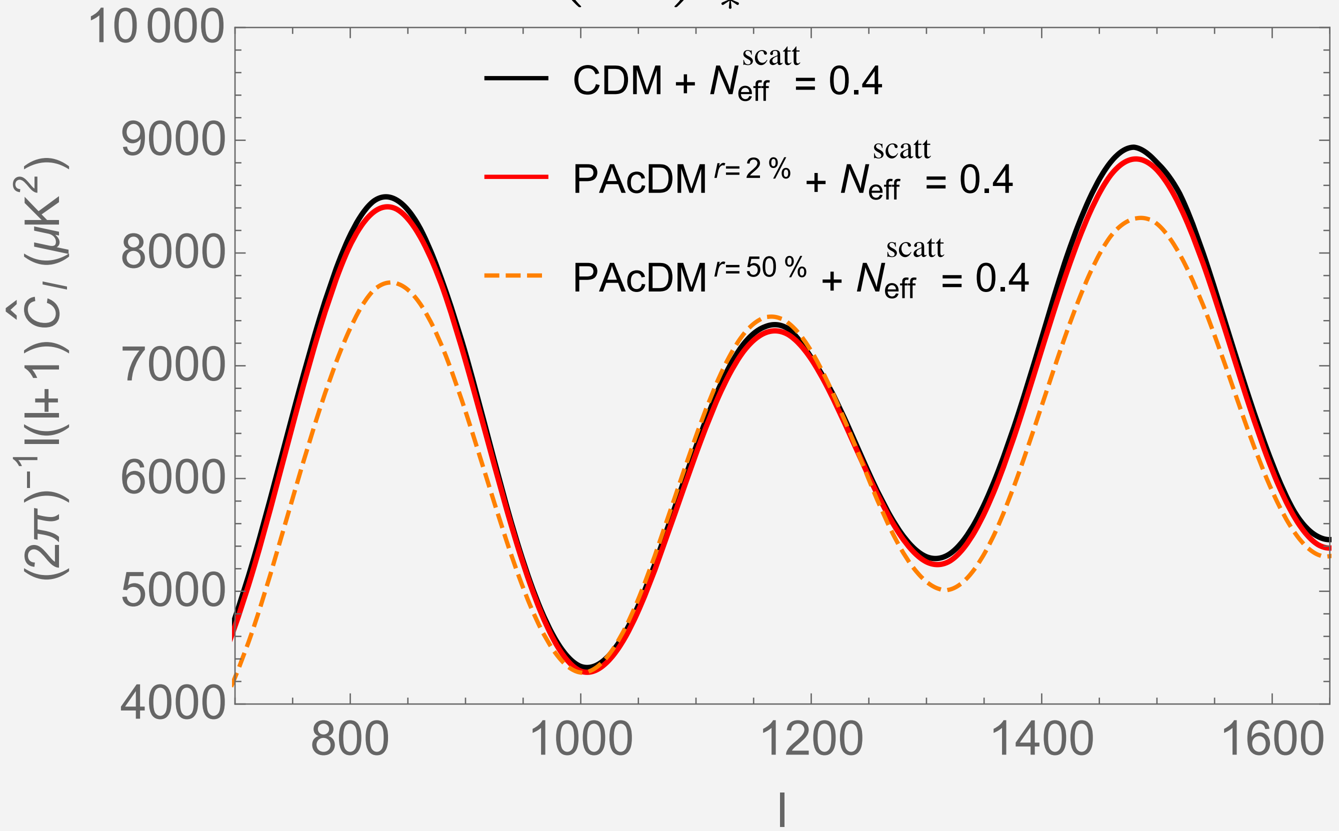
Only need $m_1 \simeq 7\, m_2$ to obtain the 2% ratio (assuming equal couplings)

Correction to the CMB spectrum

Planck 1502.01589



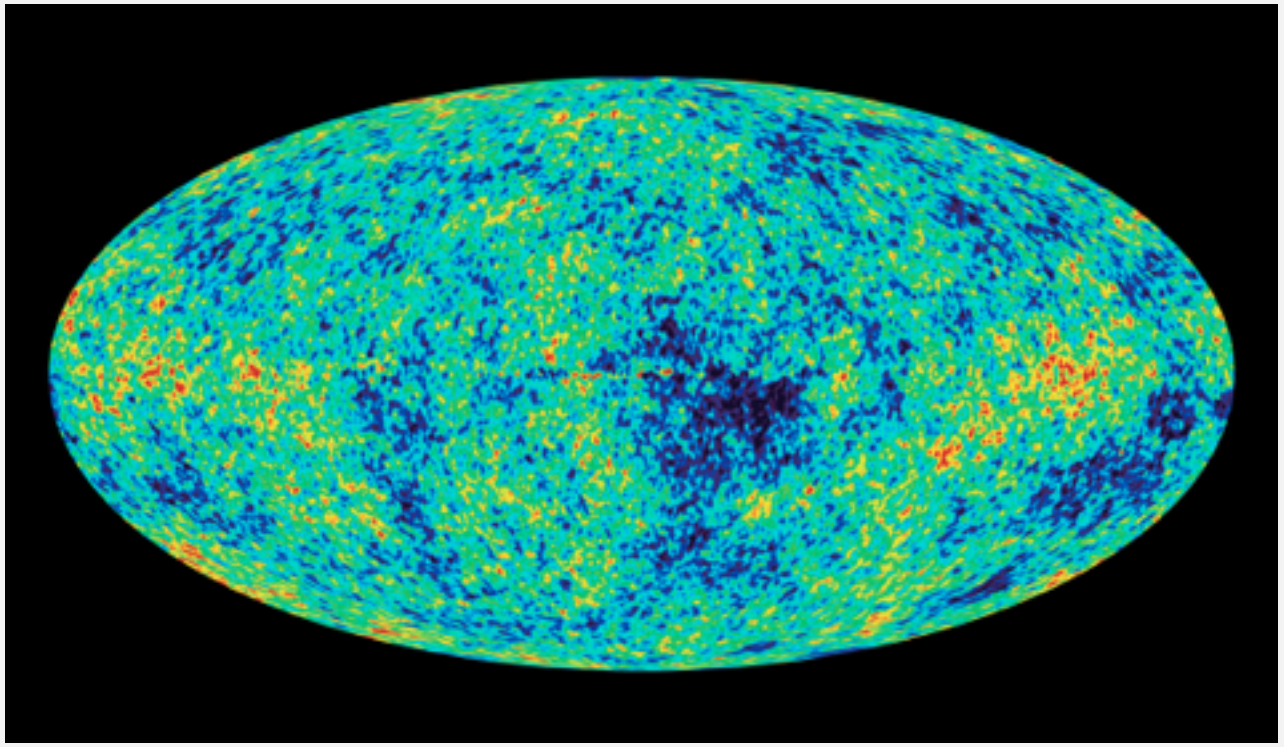
$$\left(\frac{\delta T}{T}\right)_* \equiv \frac{\delta_\gamma}{4} + \psi$$



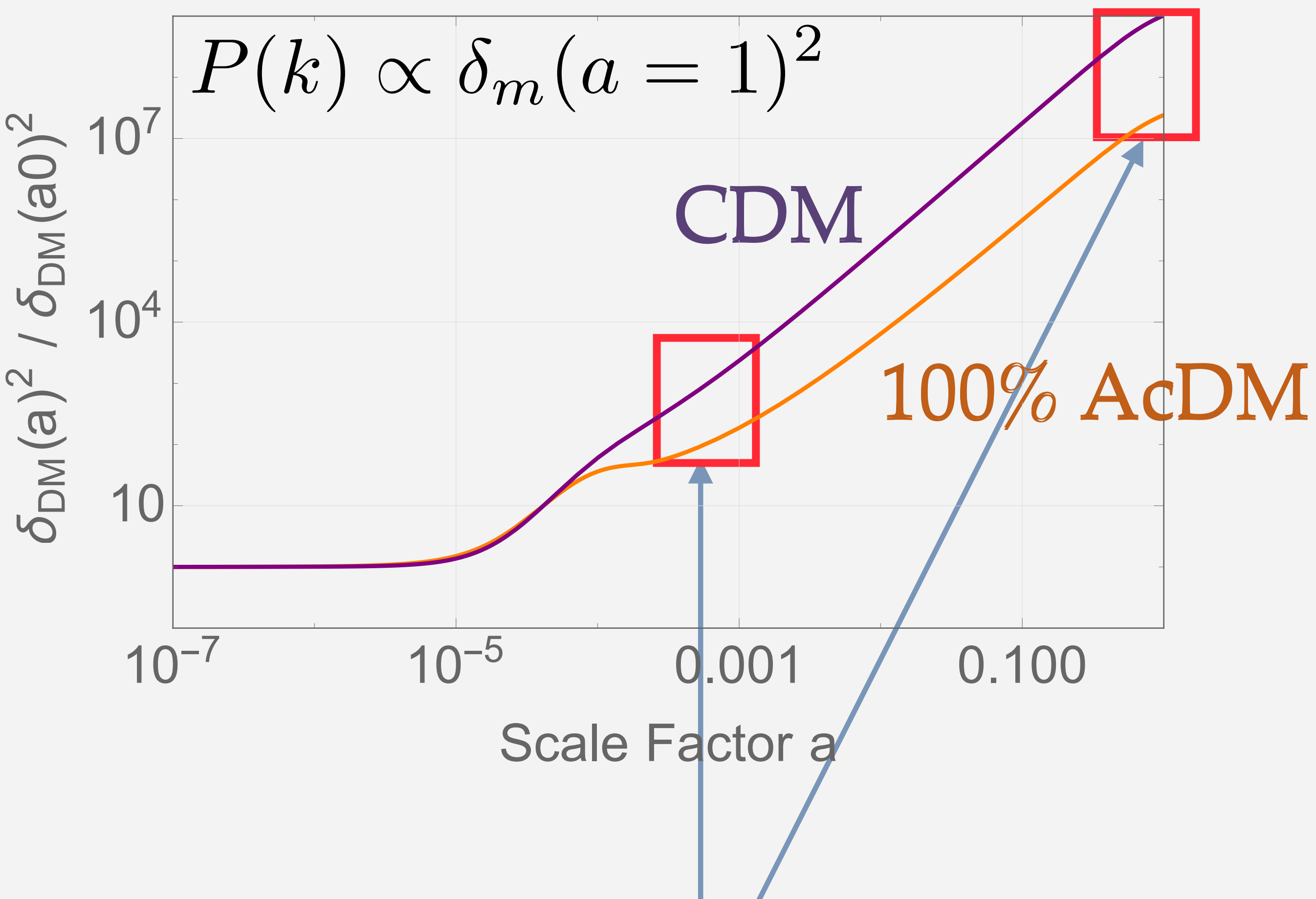
The pressure from dark fluid suppresses the compression peaks and enhances the expansion peaks

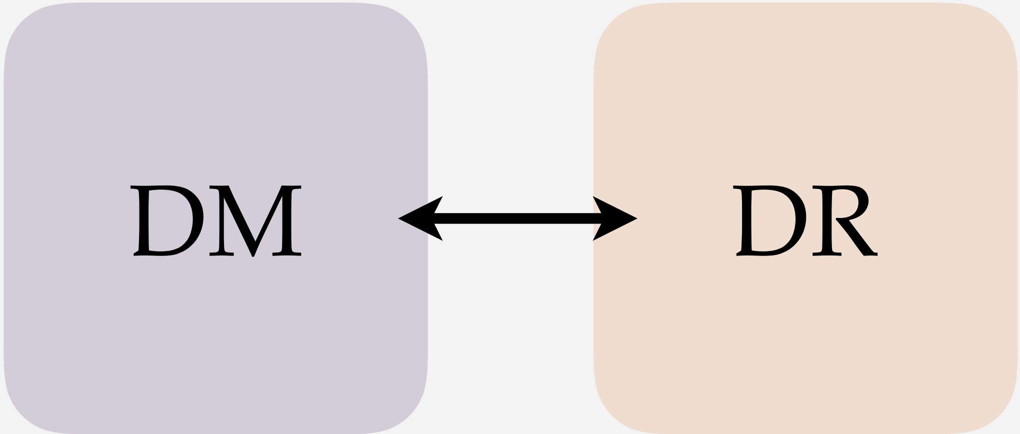
When r = 2%, the correction to CMB is less then ~ 2%, smaller then > 5% error bar in Planck result

Why is the CMB correction so small in the Partially Acoustic DM case?



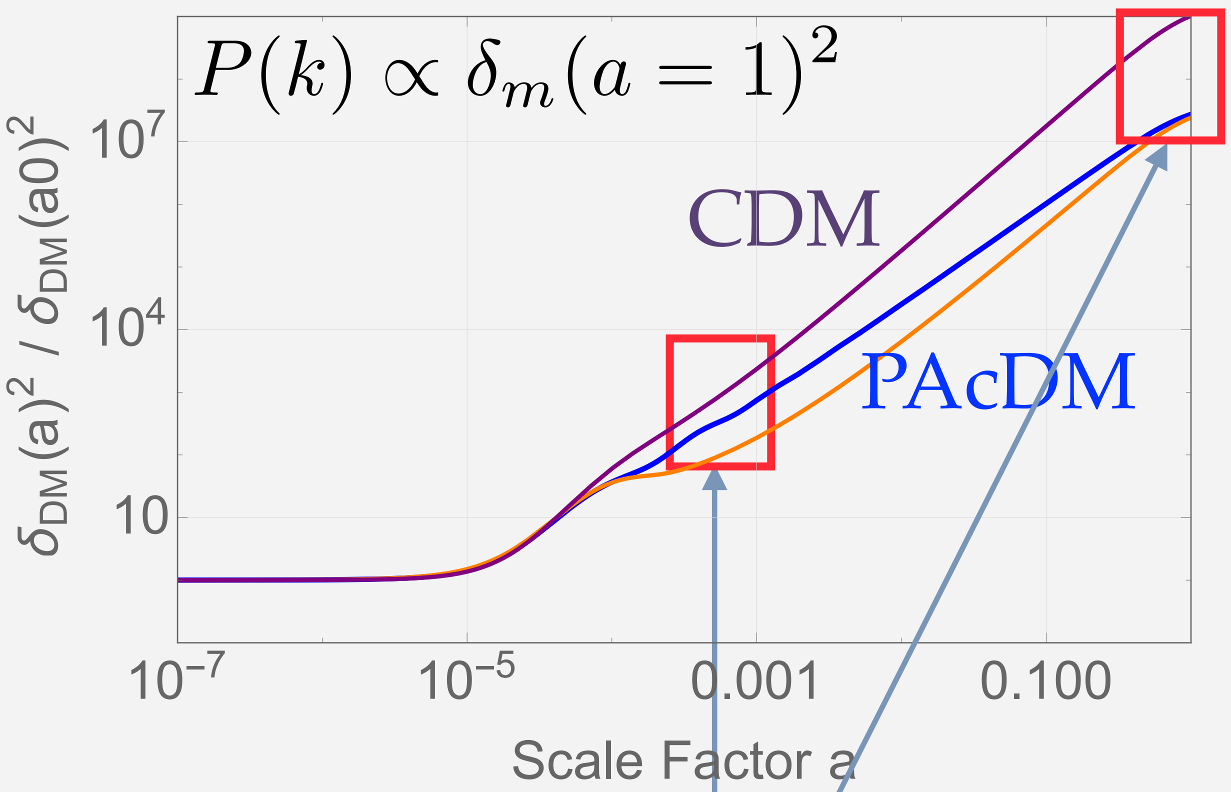
In the fully acoustic oscillation case

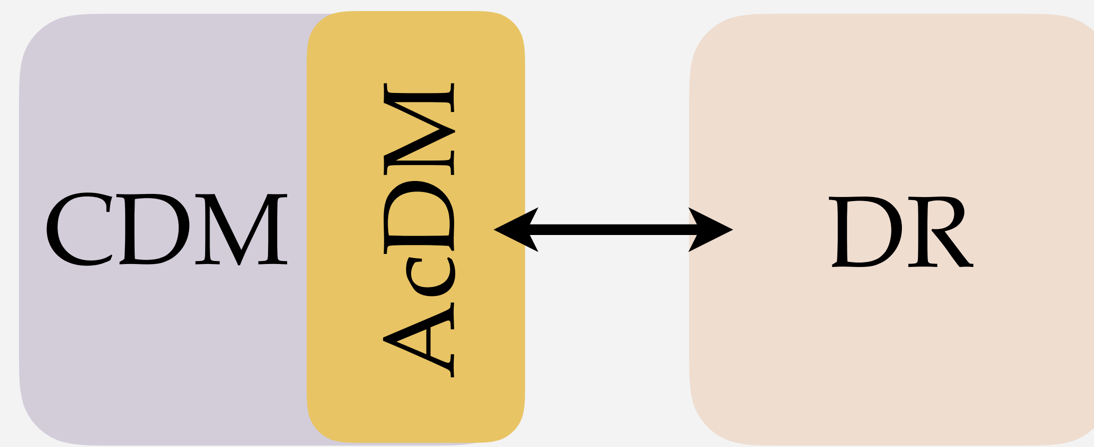




Similar damping between today / CMB time

In the partially acoustic oscillation case





$$\frac{P(r)}{P(0)} \simeq (1-2r)\left(\frac{a}{a_{\rm eq}}\right)^{-1.2r}$$

Structure grows slower comparing to CDM

Smaller correction to the CMB spectrum

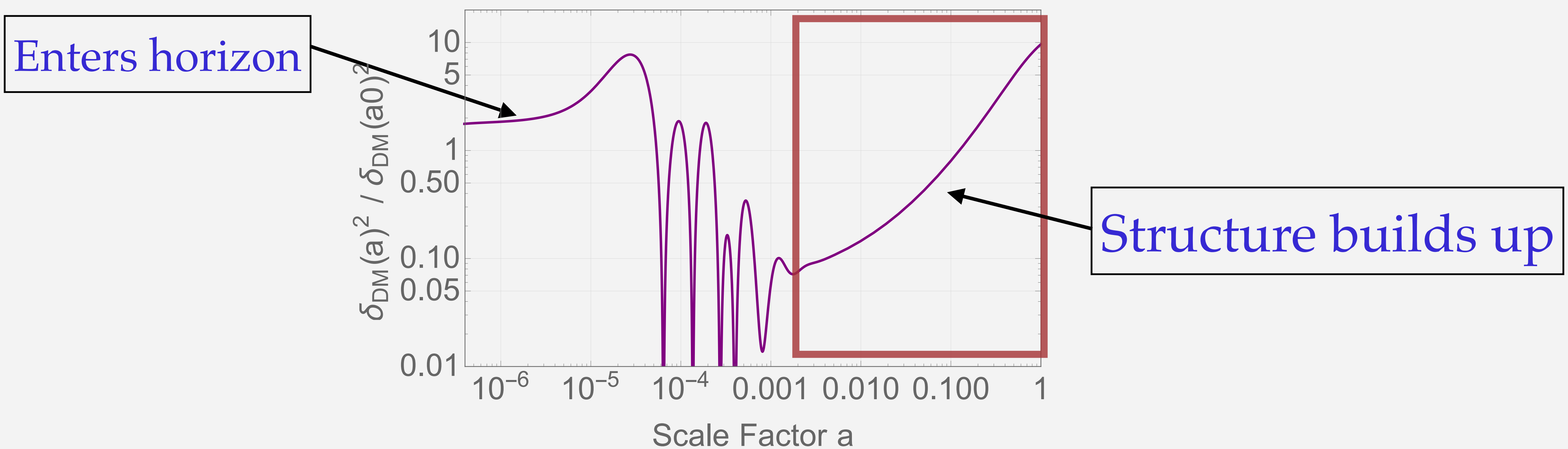
Matter Domination , R >> 1

No oscillation => Linear growth

$$\ddot{\delta}_D + \frac{2}{\tau}\dot{\delta}_D = -k^2\phi$$

No oscillation, no damping from the DR scattering

Same structure formation as cold DM



Matter Domination , R >> 1

No oscillation => Linear growth

$$\ddot{\delta}_D + \frac{2}{\tau}\dot{\delta}_D = -k^2\phi$$

$$k^2\phi = -4\pi G a^2 \sum_s \delta_s \rho_s \simeq -4\pi G a^2 \delta_D \rho_D$$

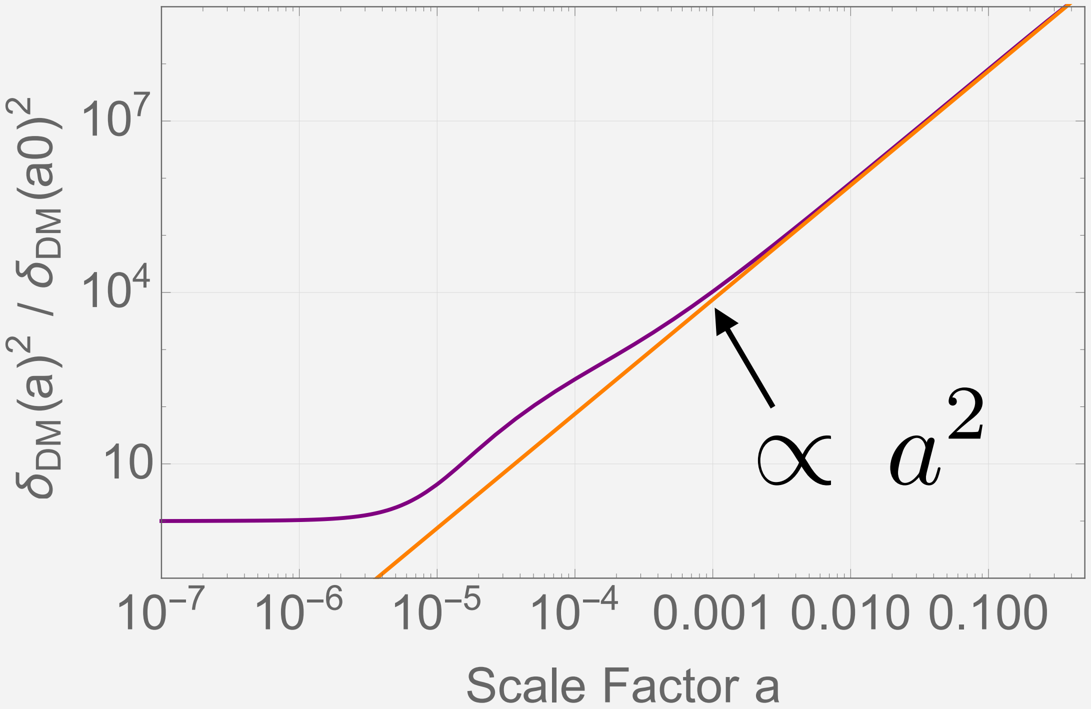
Einstein equation

$$= -\frac{6}{\tau}\,\delta_D$$

($\nabla^2\phi = 4\pi G\rho$ Poisson's eq. for gravity)

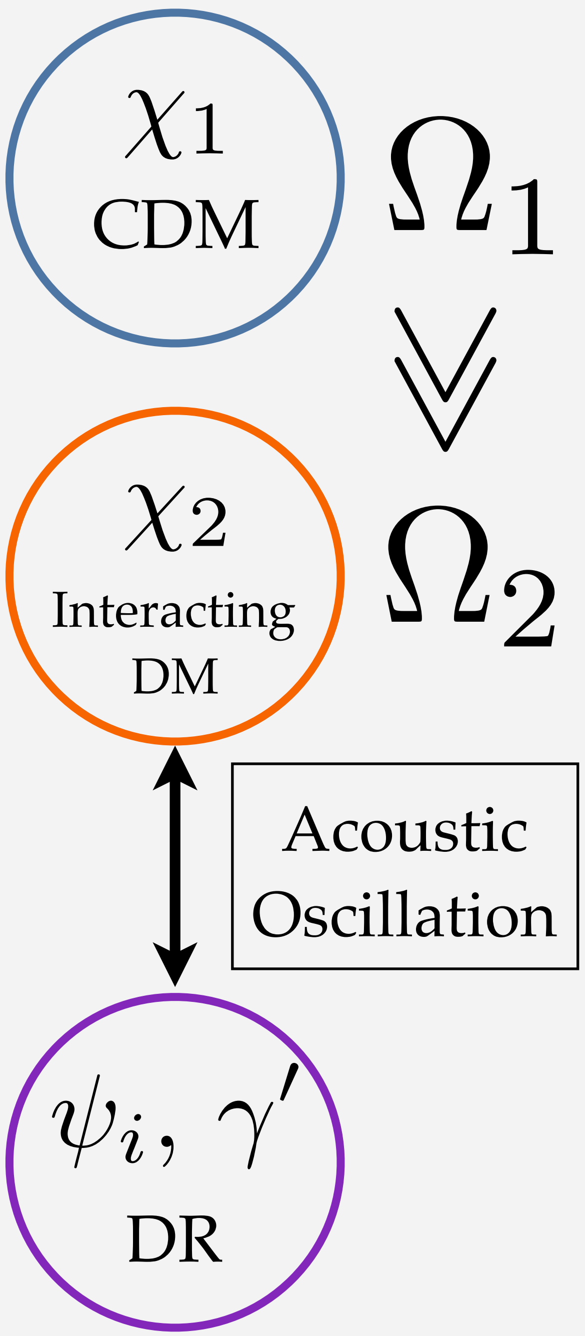
Linear growth of CDM

$$\ddot{\delta}_D + \frac{2}{\tau}\dot{\delta}_D = \frac{6}{\tau}\delta_D \quad \Rightarrow \quad \delta_D \propto \left(\frac{\tau}{\tau_{eq}}\right)^2 = \left(\frac{a}{a_{eq}}\right)^1$$



Density contrast in Cold DM case grows linearly in the deep matter-dominated era

In the partially acoustic case



Acoustic Oscillation $\Rightarrow \delta_1 \gg \delta_2$

DM density contrast is determined by χ_1

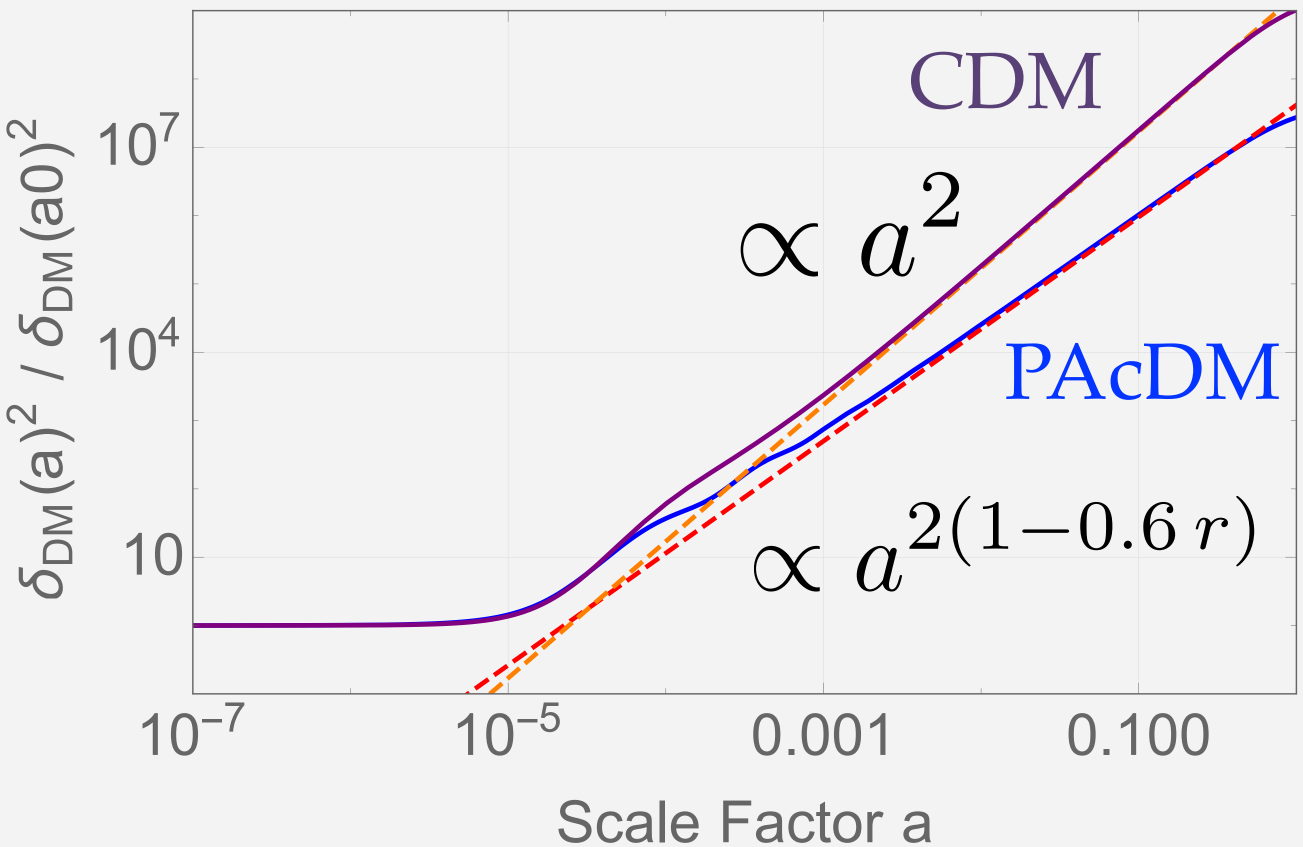
$$\ddot{\delta}_1 + \frac{2}{\tau}\dot{\delta}_1 = -k^2\phi$$

$$k^2\phi \simeq -4\pi G a^2(\delta_1\rho_1 + \delta_2\rho_2)$$

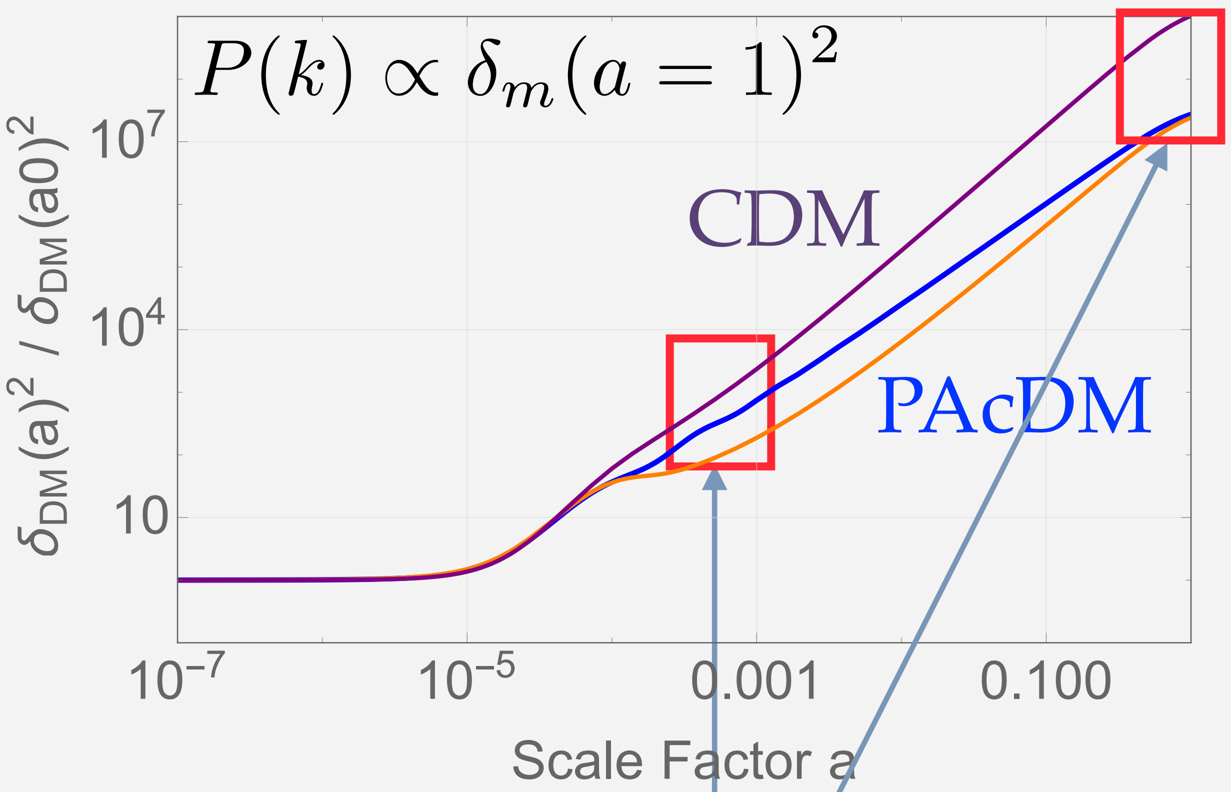
$$= -\frac{6}{\tau}(1-r)\delta_1 \qquad r \equiv \frac{\rho_2}{\rho_{DM}}$$

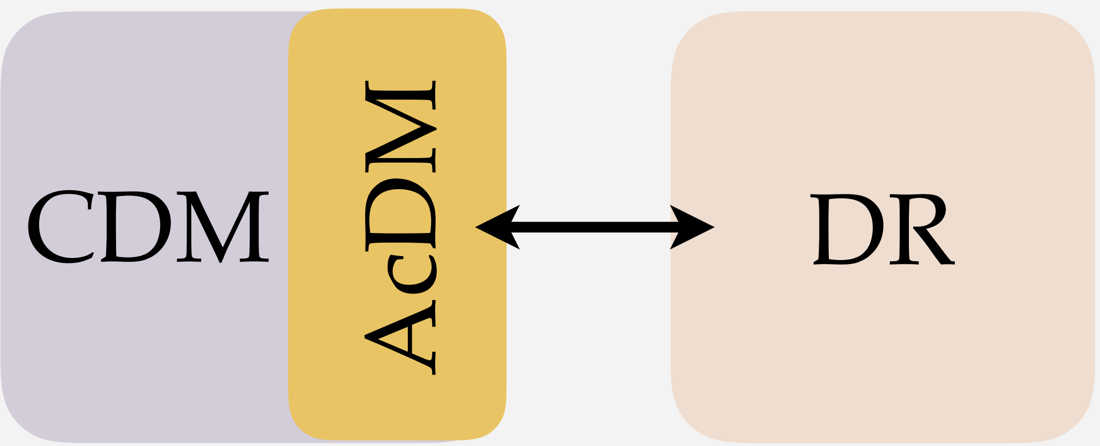
The < 100% CDM case

$$\ddot{\delta}_1 + \frac{2}{\tau}\dot{\delta}_1 = \frac{6}{\tau}(1-r)\delta_1 \quad \Rightarrow \delta_1 \propto \left(\frac{a}{a_{eq}}\right)^{1-0.6\,r+\mathcal{O}(r^2)}$$



How about only a fraction of DM particles having the acoustic oscillation?





$$\frac{P(r)}{P(0)} \simeq (1-2r)\left(\frac{a}{a_{\rm eq}}\right)^{-1.2r}$$

Structure grows slower comparing to CDM

Smaller correction to the CMB spectrum

Conclusion

Large Scale Structure is sensitive to the dark sector dynamics

A smaller ratio of Cold DM

change the power-law growth of matter density spectrum

Acoustic Dark Oscillation

suppresses the matter power spectrum

Having Dark Radiation

change the expansion, different effects on CMB between free-streaming/self-scattering

May also change the small scale structure

Working on it now, stay tuned!