Partially Acoustic Dark Matter & Large Scale Structure

Yuhsin Tsai
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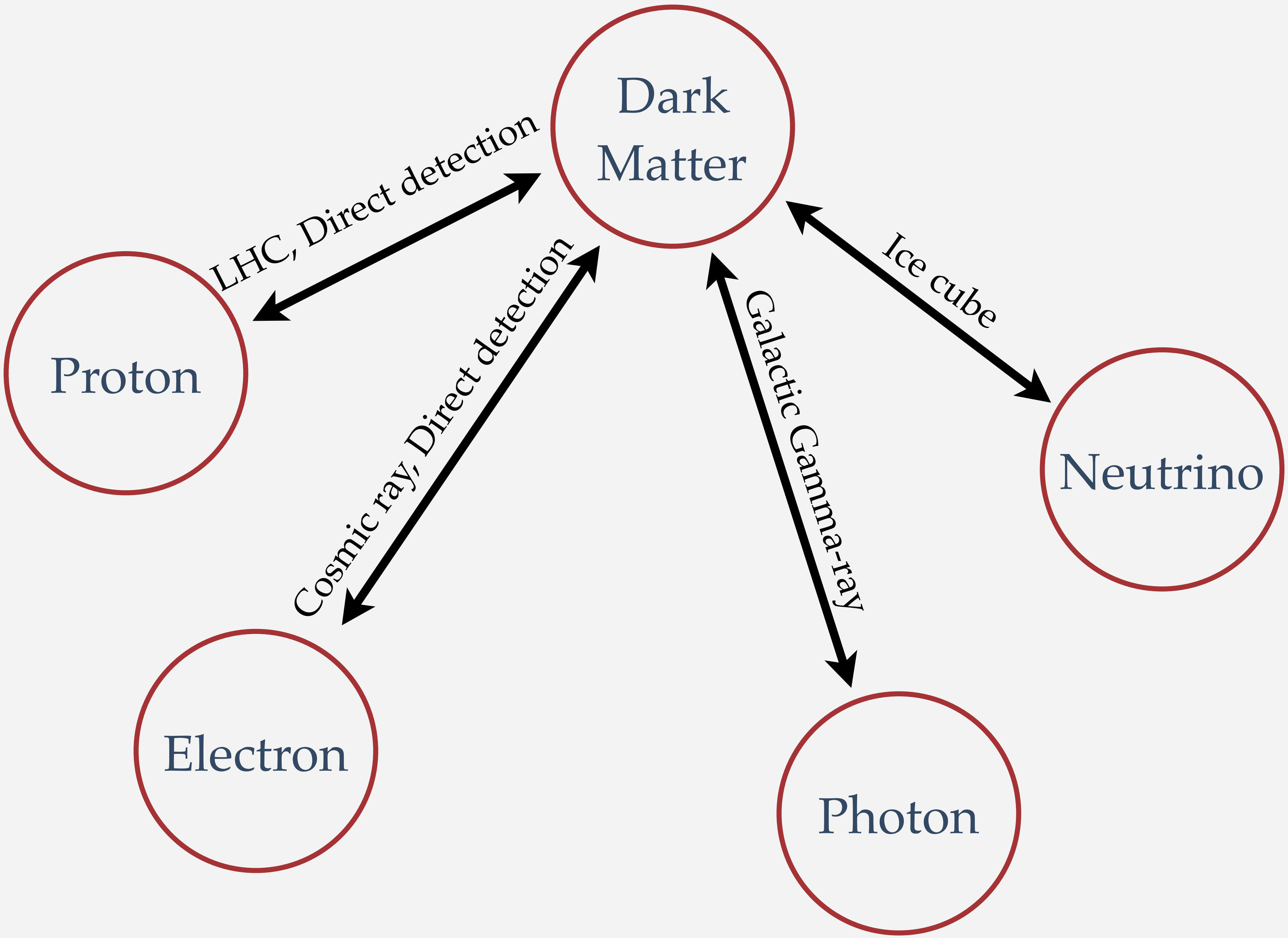
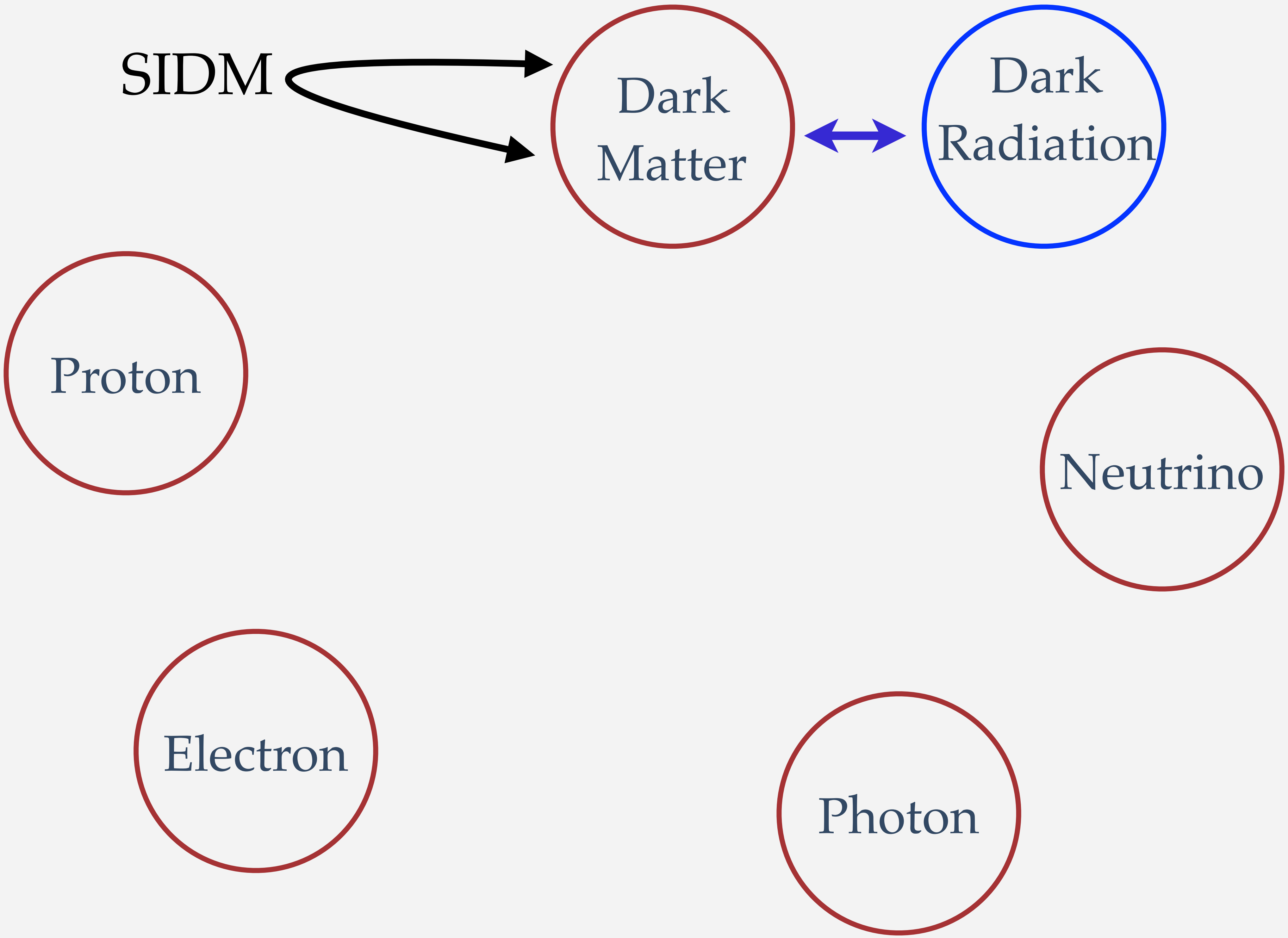
JHEP1612(2016)108, Zackaria Chacko, Yanou Cui, Sungwoo Hong, and Takemichi Okui, YT
arXiv: 1611.05879, Valentina Prilepina and YT

DM+DE+M / Anti-M asymmetry, NCTS, Dec 31 2016

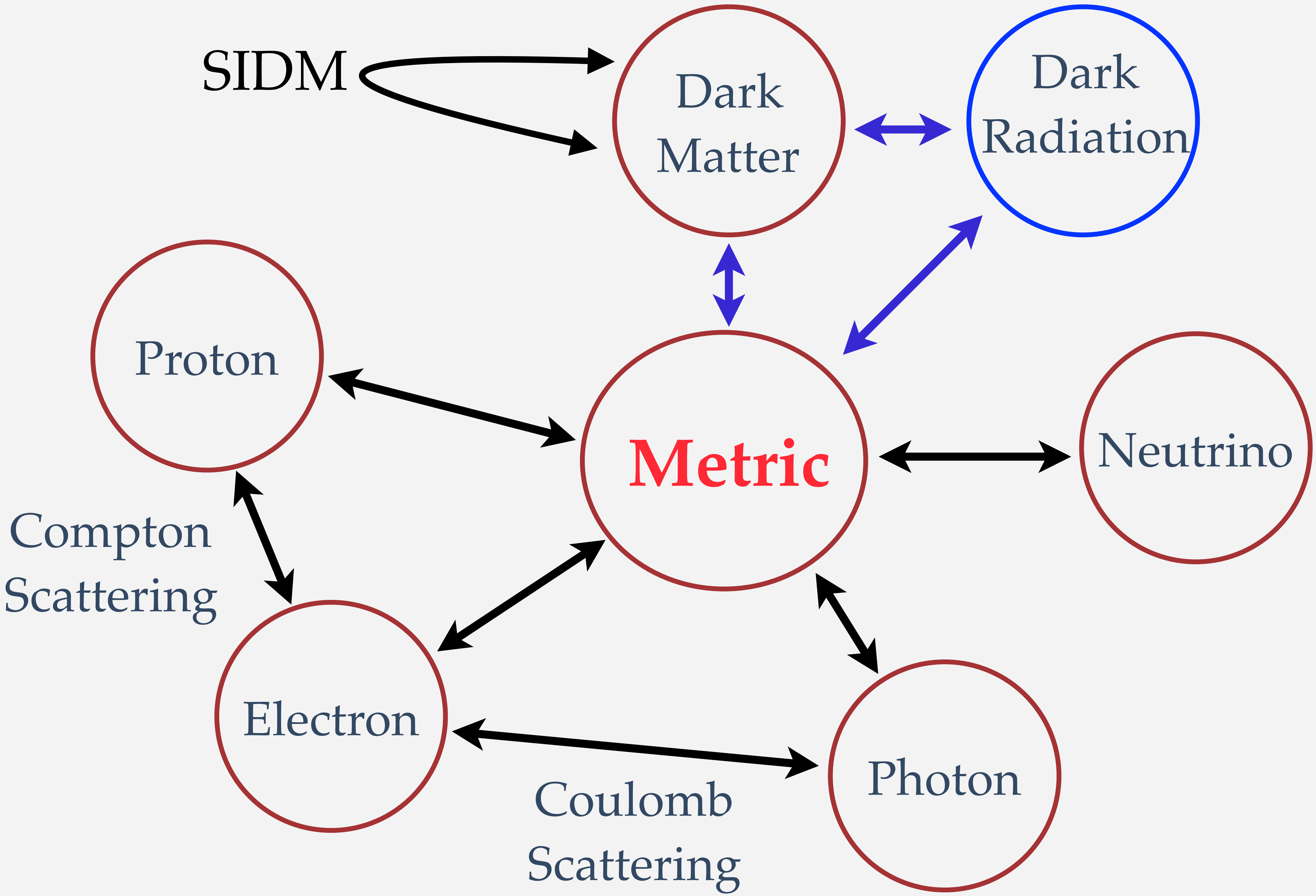
We've been trying very hard to see DM



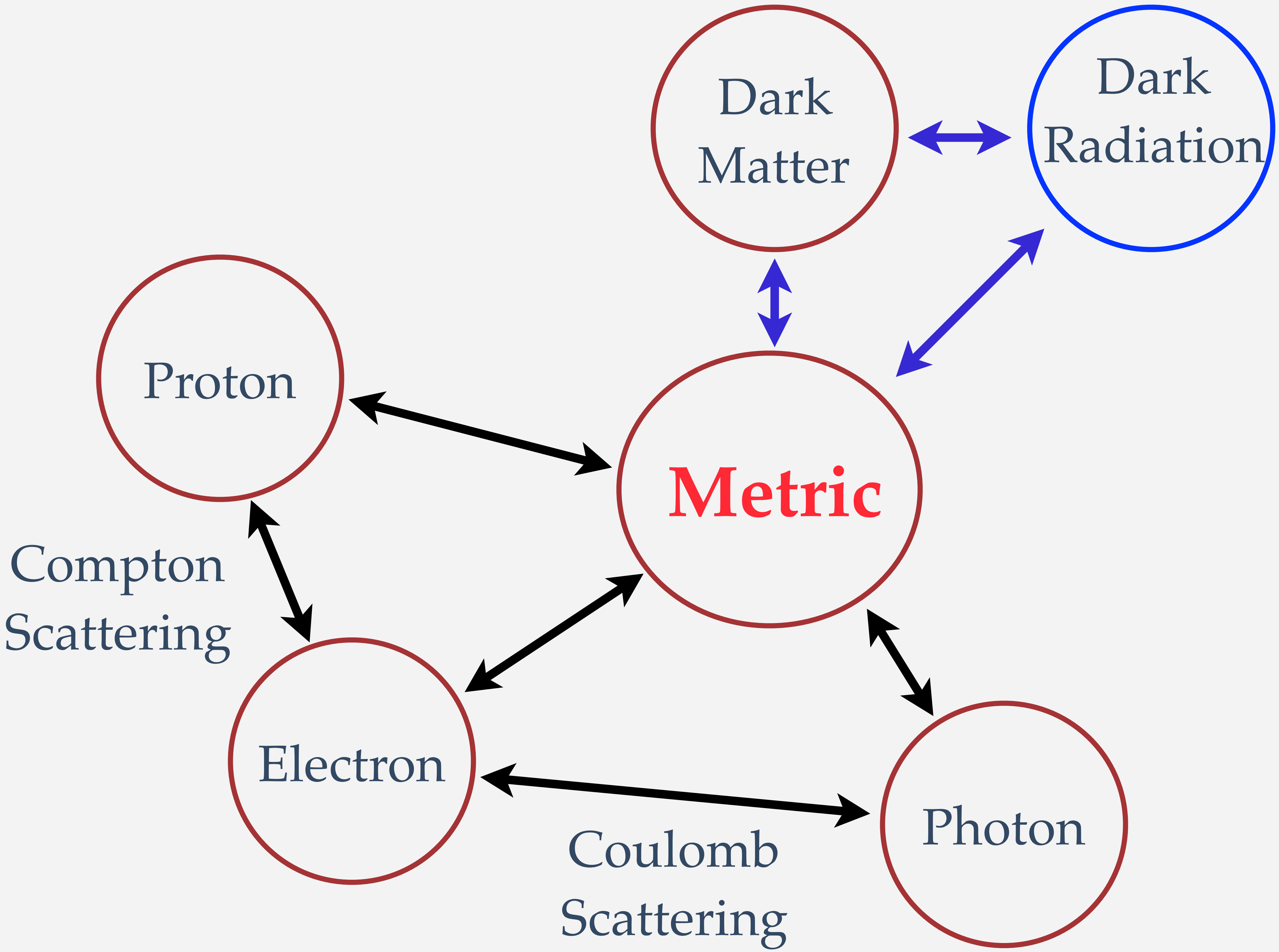
Maybe DM just doesn't couple to SM?



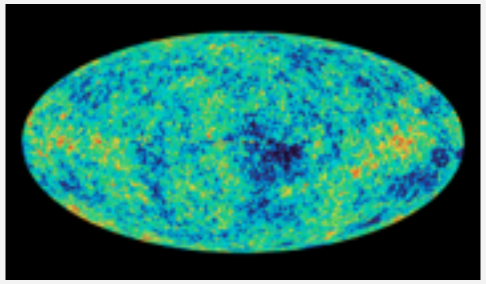
No, everything couples to gravity



Dark sector in Large Scale Structure physics

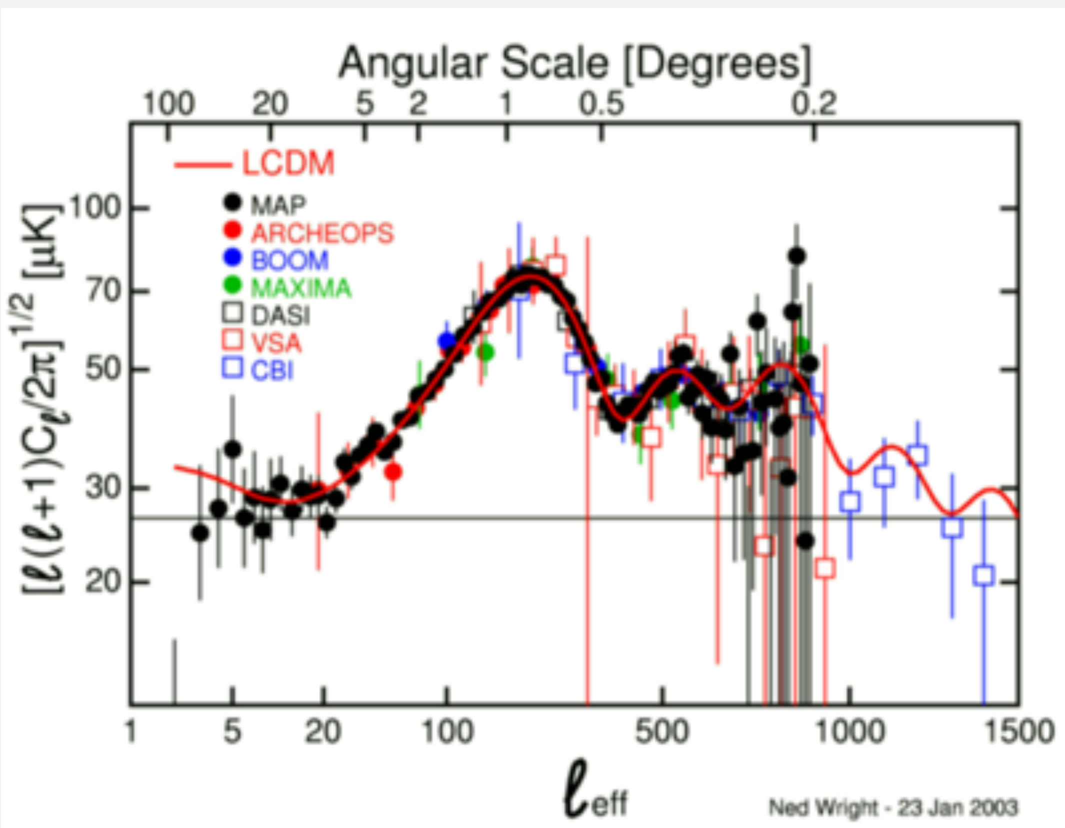


Precision measurement in cosmology

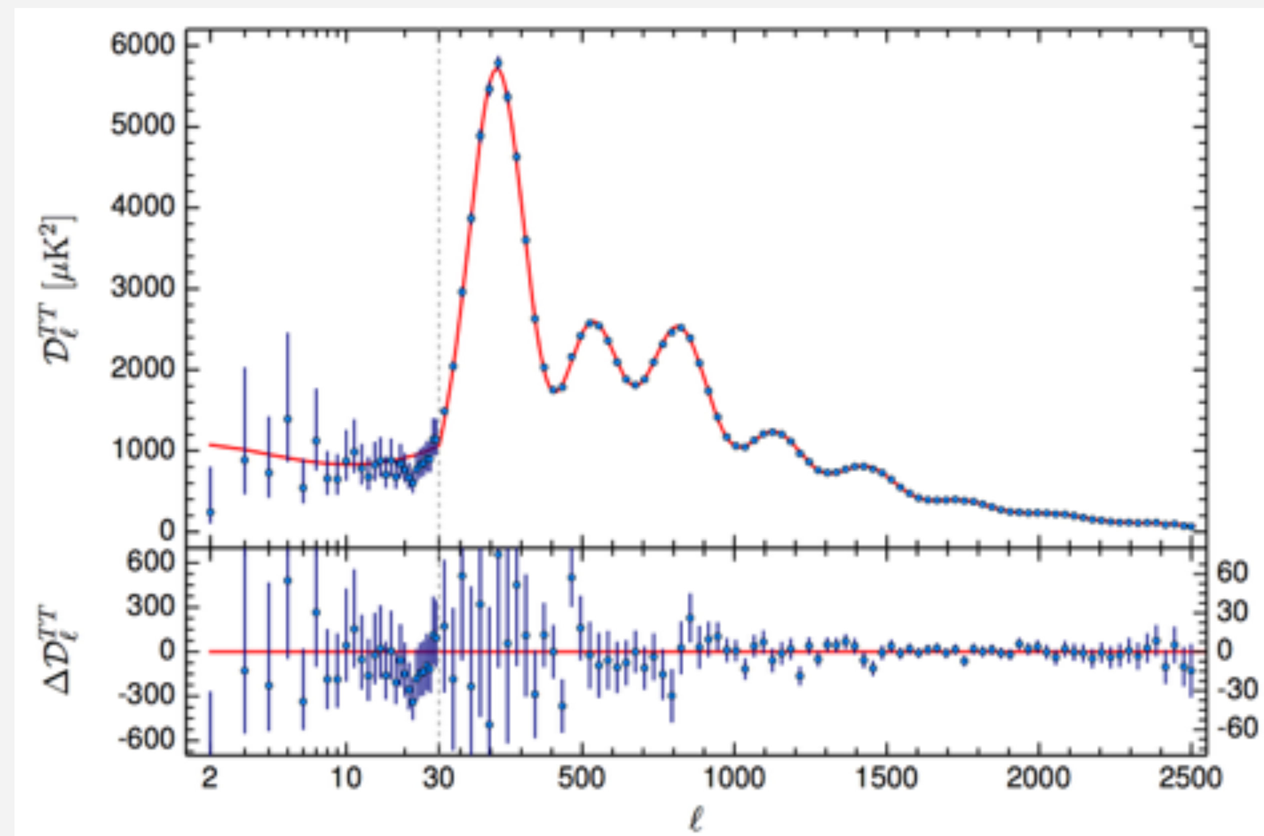


CMB Spectrum

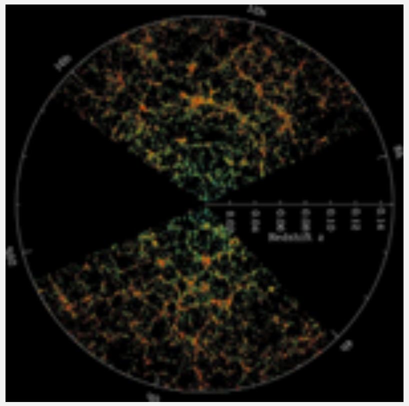
2003



2015



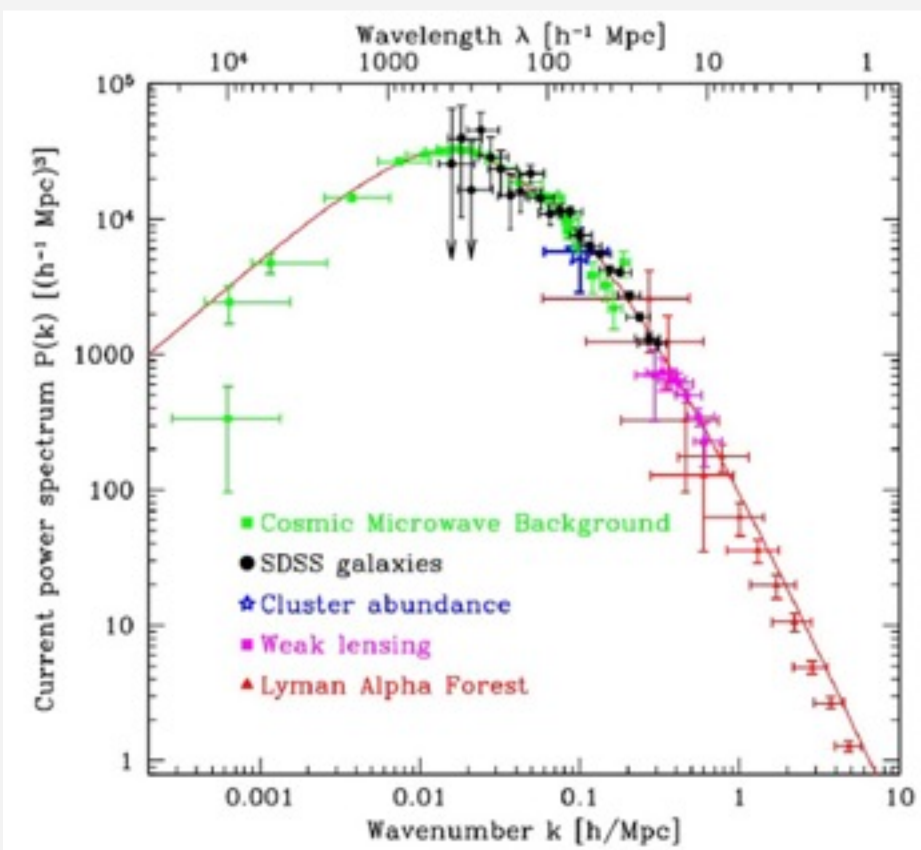
Precision measurement in cosmology



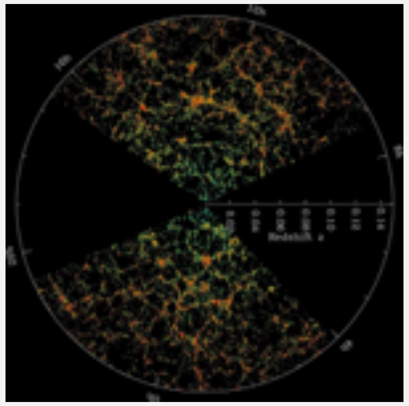
Matter Power Spectrum

Three ways to measure the spectrum

2004



Precision measurement in cosmology



Matter Power Spectrum

Three ways to measure the spectrum

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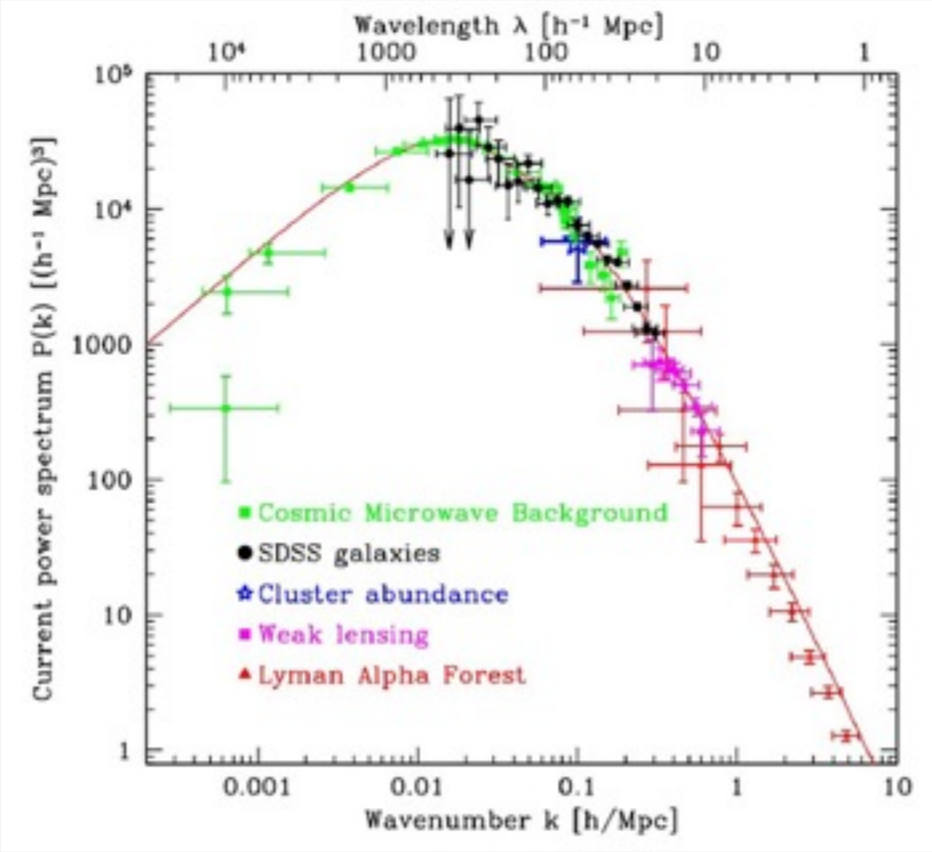
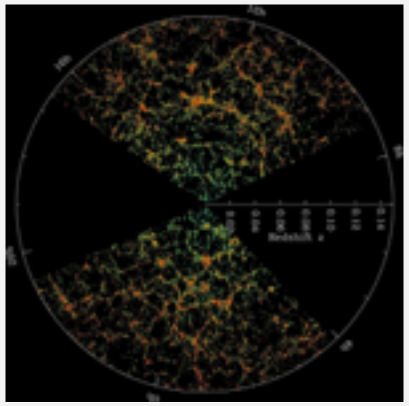


Assuming a DM model (ΛCDM), fix the parameters using CMB, predict the power spectrum today

Precision measurement in cosmology



Matter Power Spectrum

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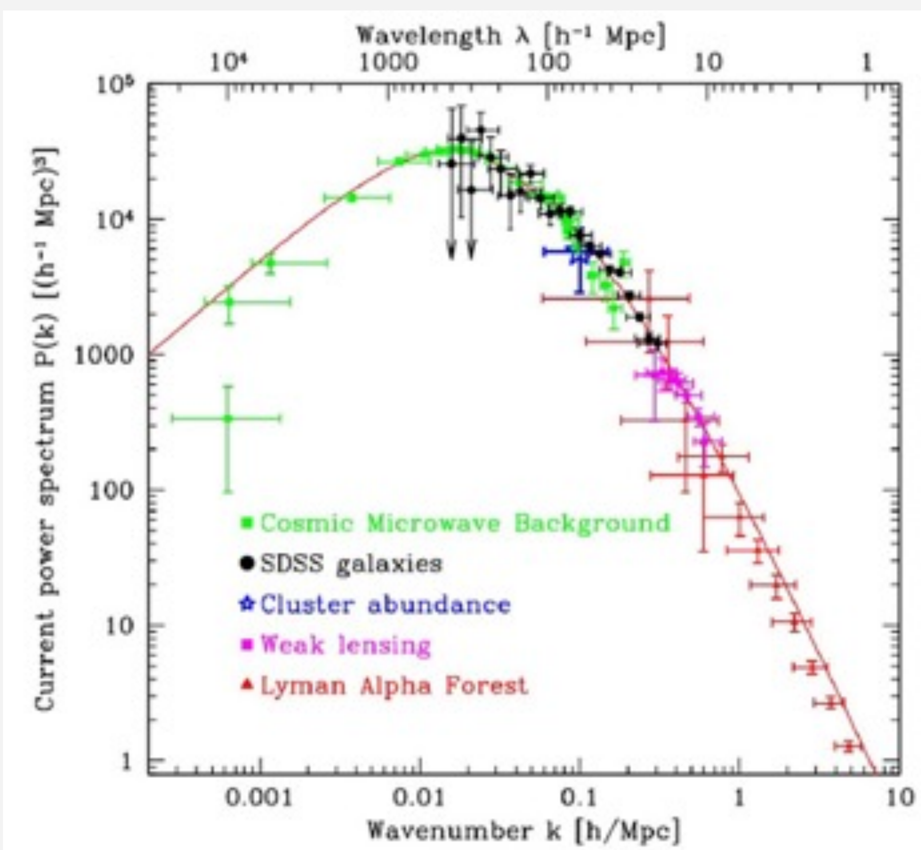
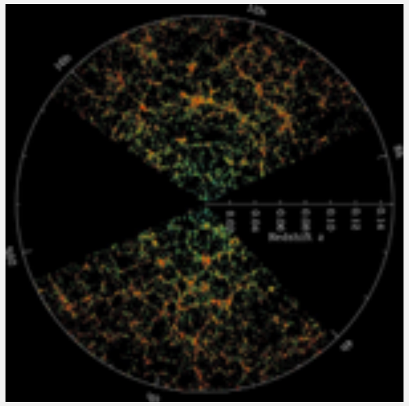


Three ways to measure the spectrum

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

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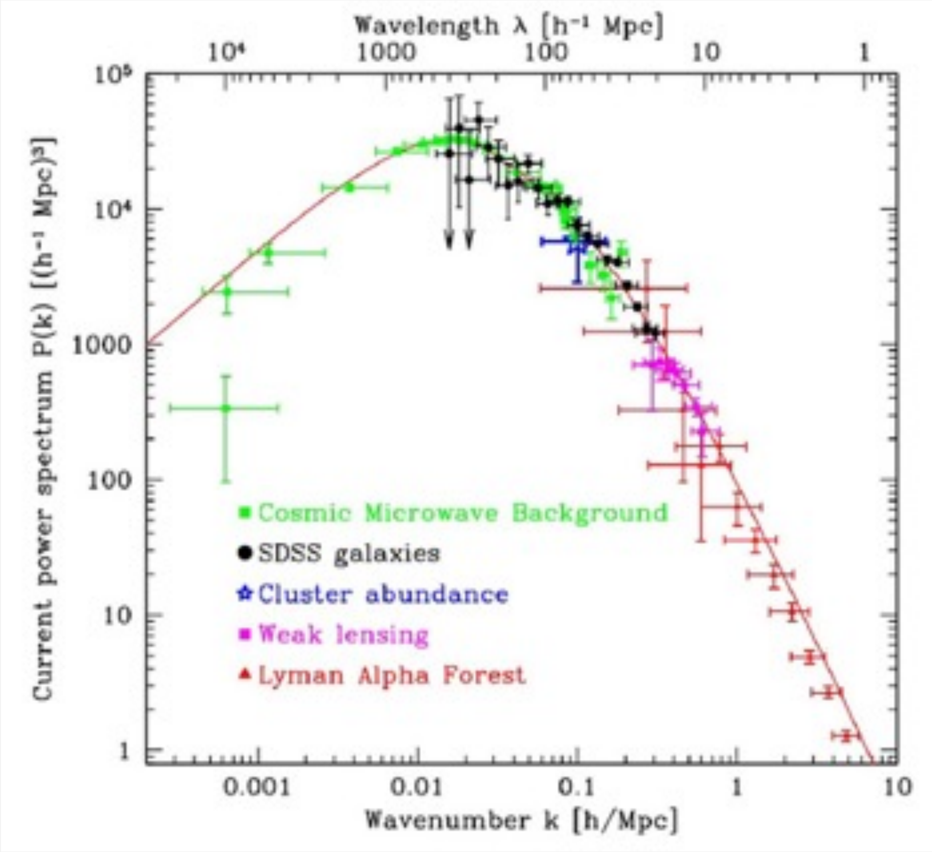


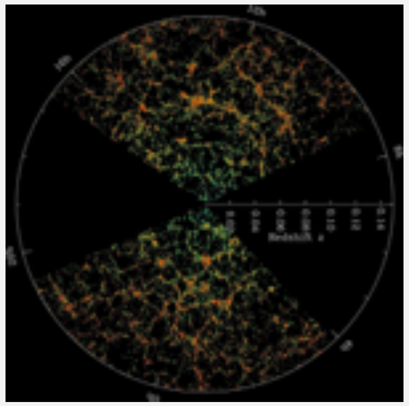
Three ways to measure the spectrum

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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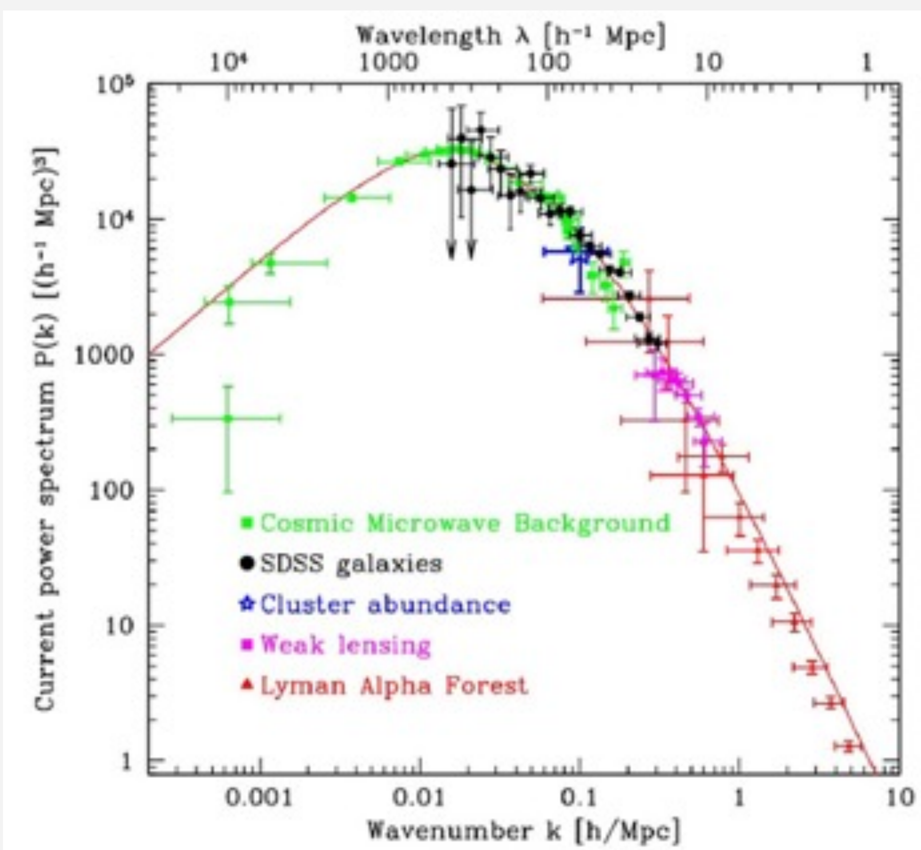
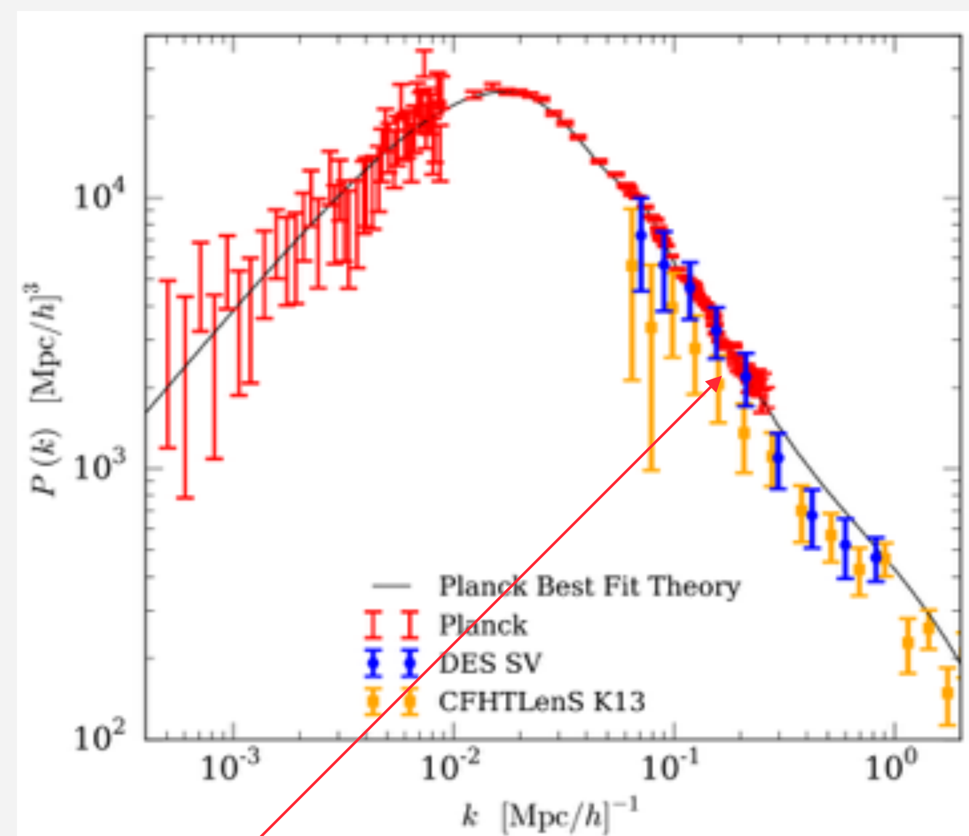
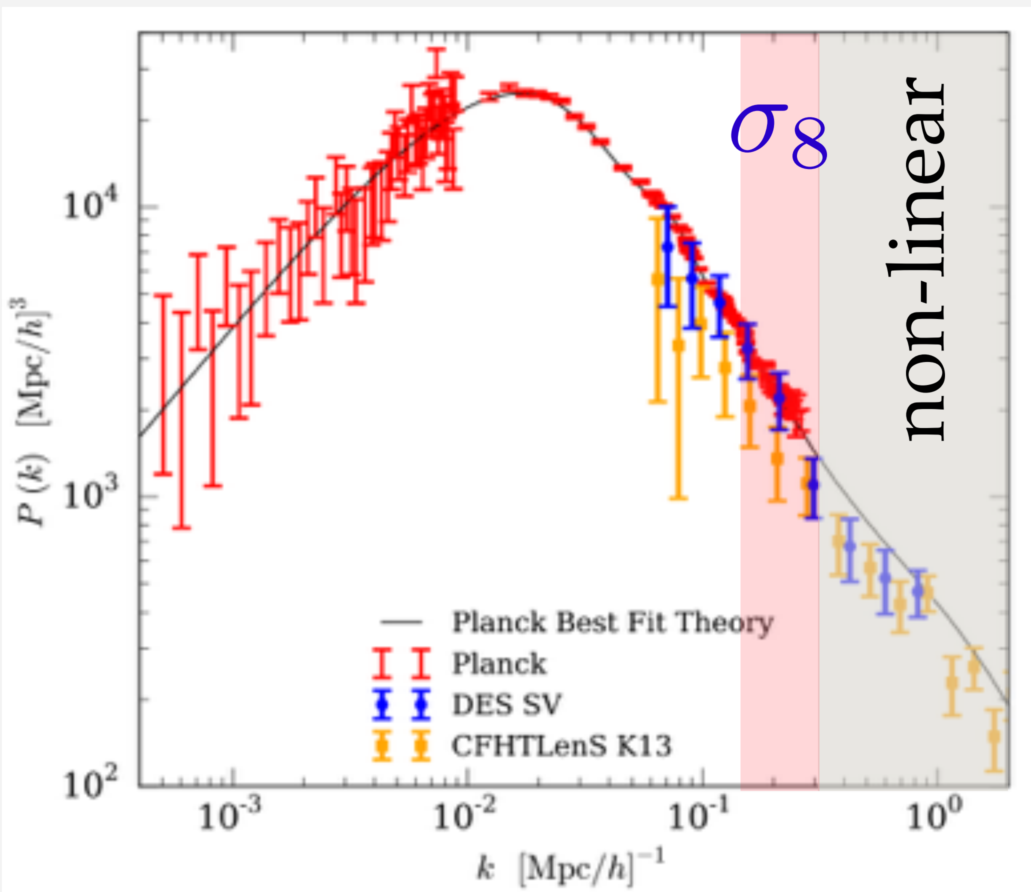


2015



Can start to cross check the CMB & WL results

The Sigma8 problem



DES: 1507.05552

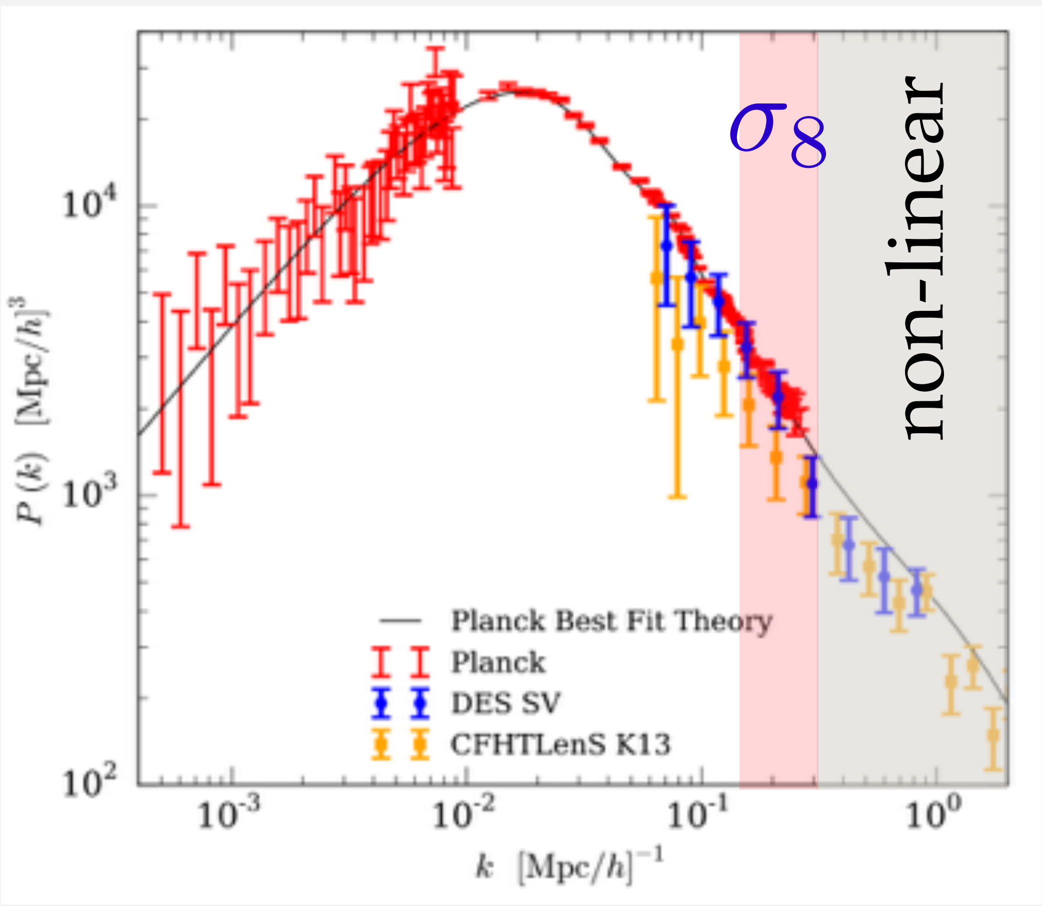
σ_8

~ 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



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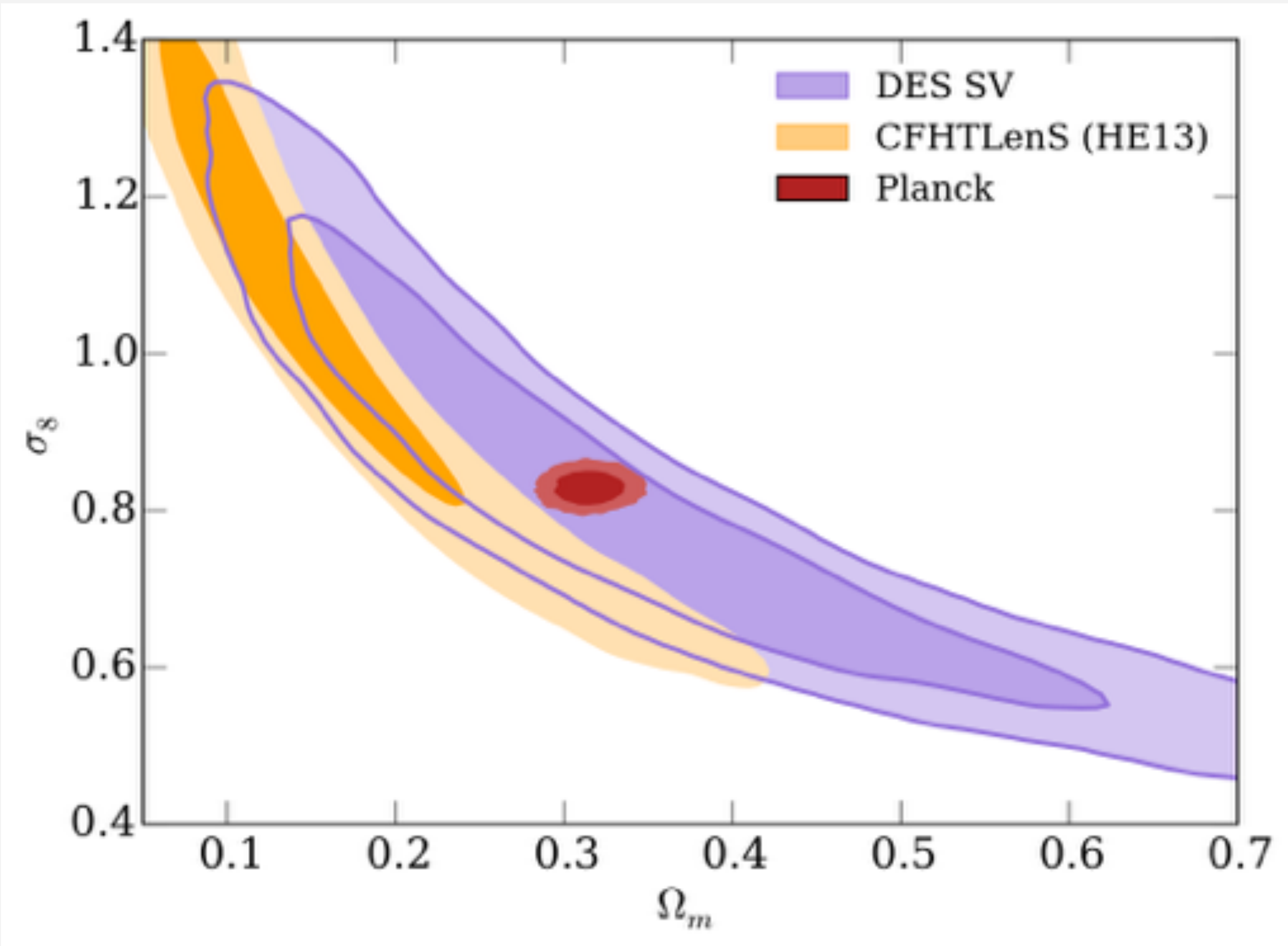
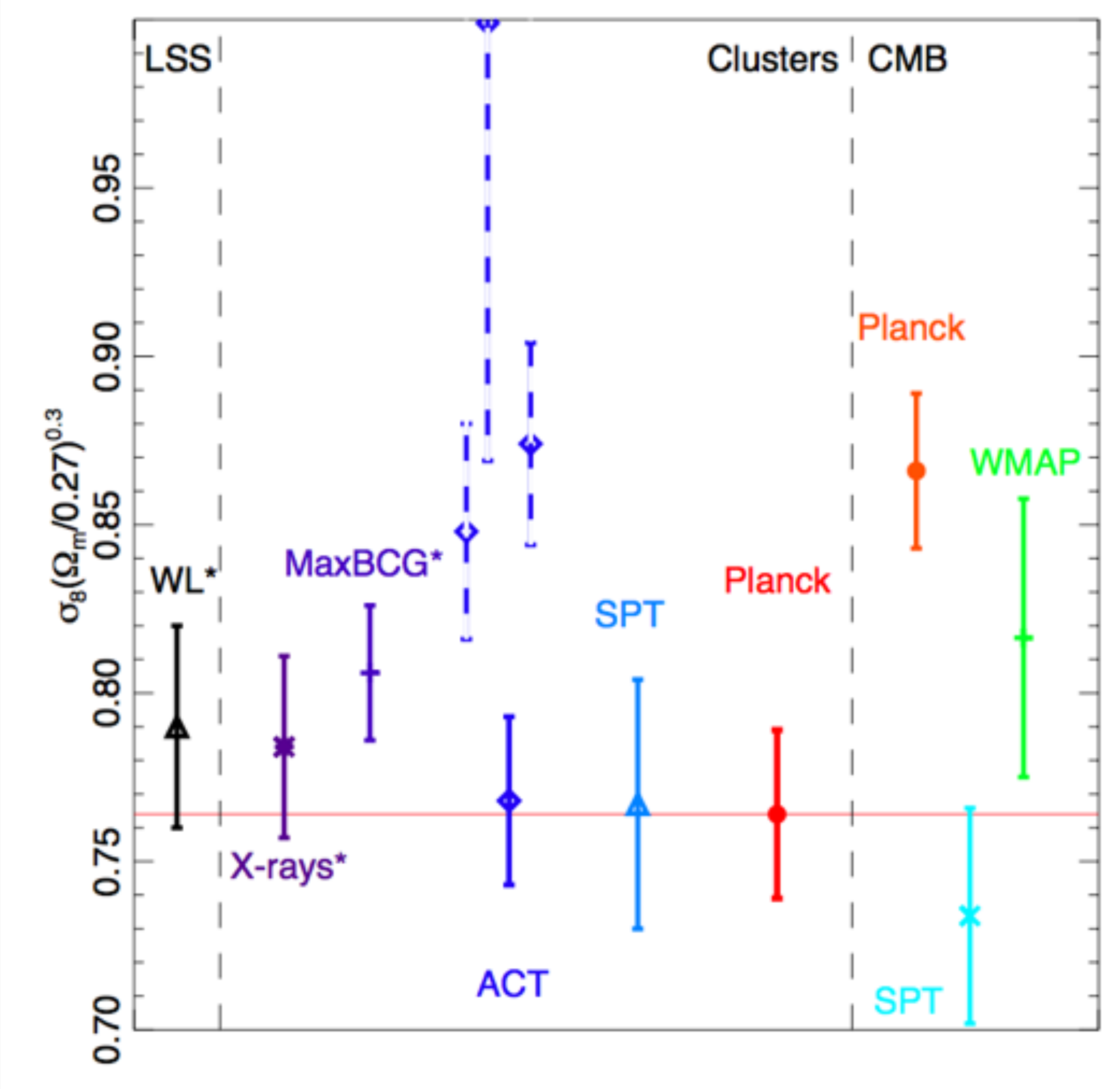


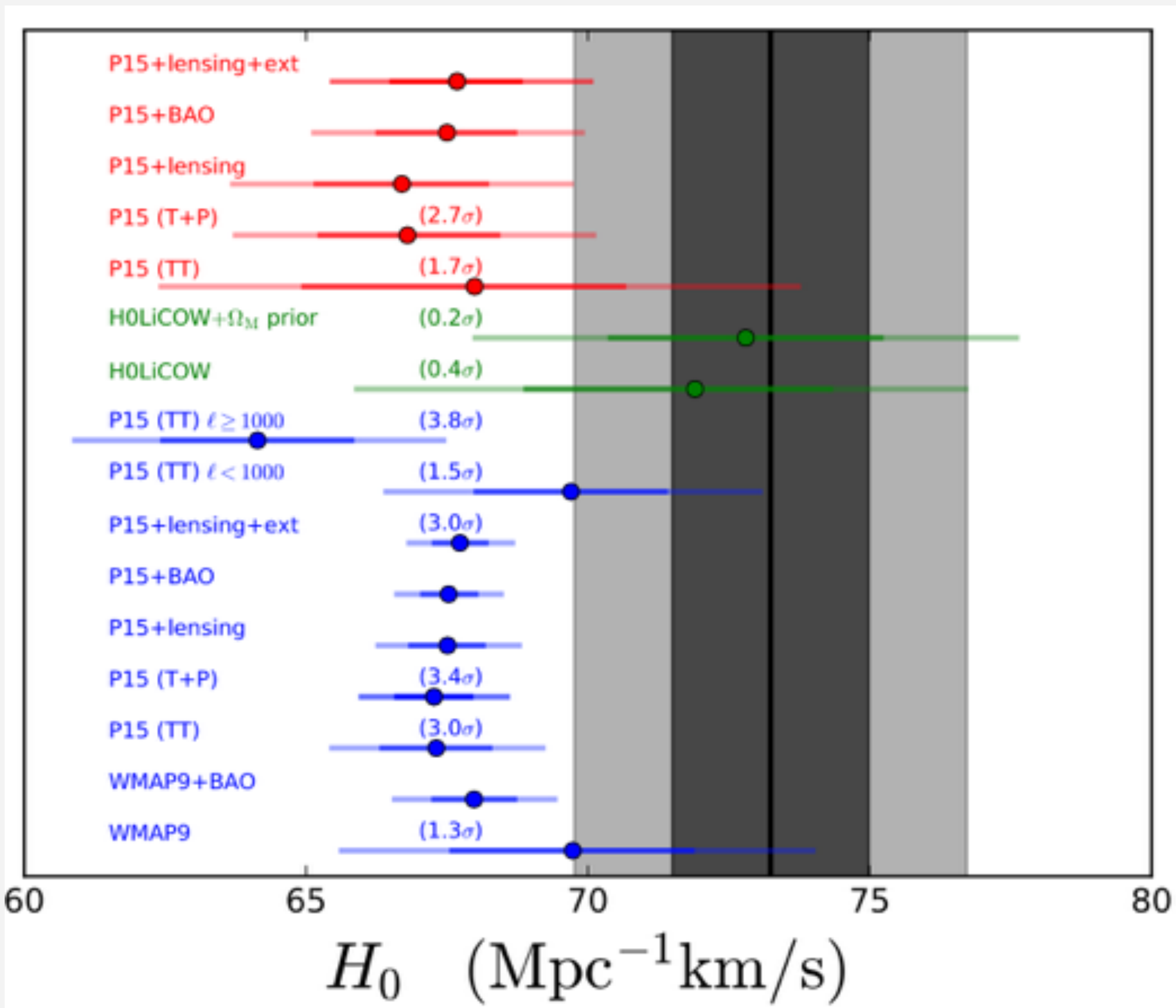
The CFHTLenS & CMB results deviate by ~ $2-3\sigma$.

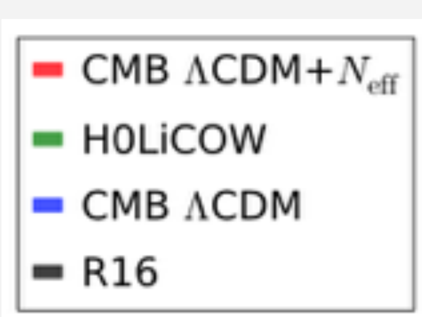
Results from galaxy counts

Planck 1303.5080



H0 problem





Bernal et. al. 1607.05617

Two H0 measurements

CMB + ΛCDM .

vs.

Local Measurements

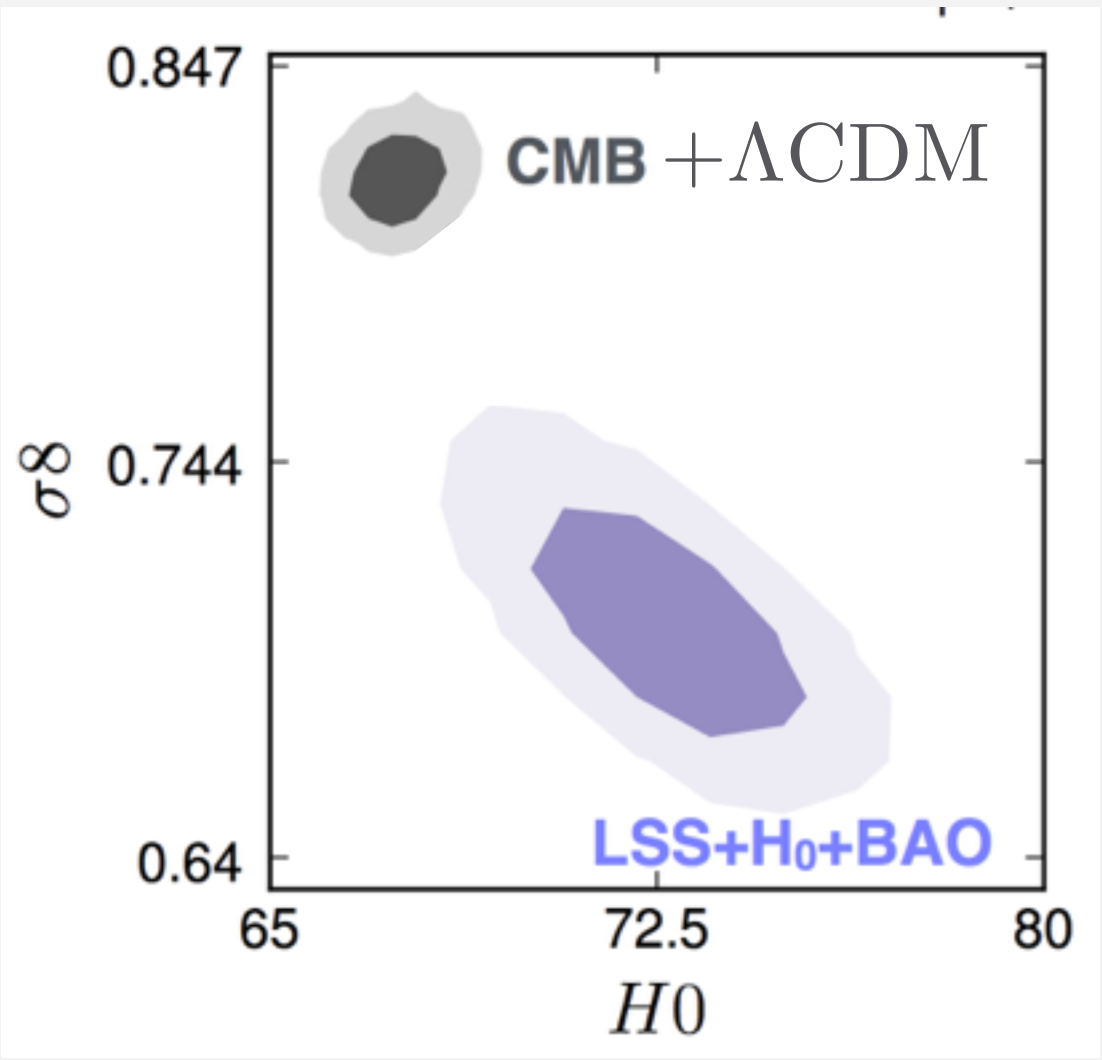
$$H_0^{\mathrm{Planck}} = 67.3 \pm 0.7\,\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$$

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

$> 3\sigma$ Discrepancy

Puzzles of Large Scale Structure

Poulin et. al. 1606.02073



Comparing to LCDM model,
we want to obtain a

Smaller density perturbation

Larger Hubble expansion

at the late time universe

Puzzles of Large Scale Structure

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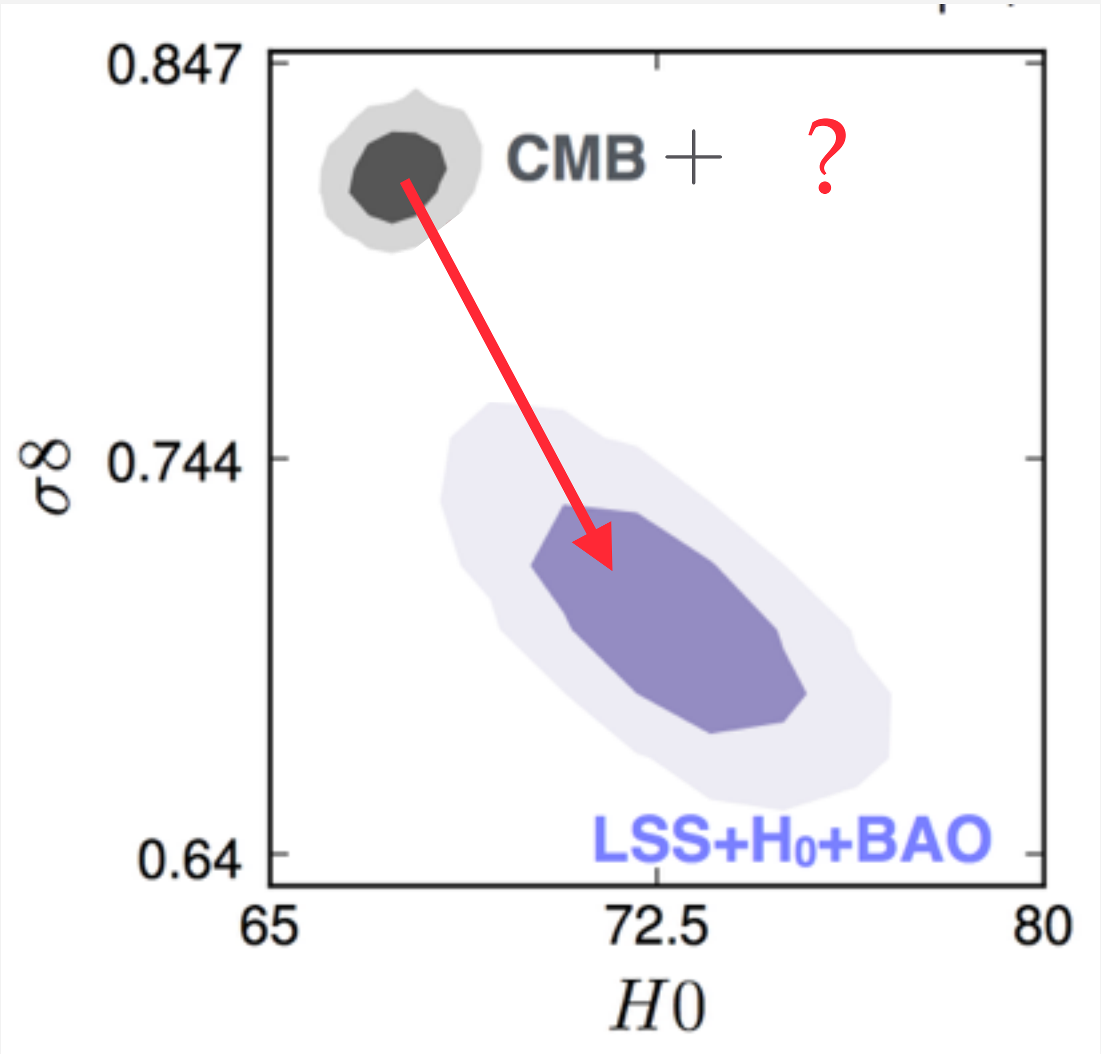

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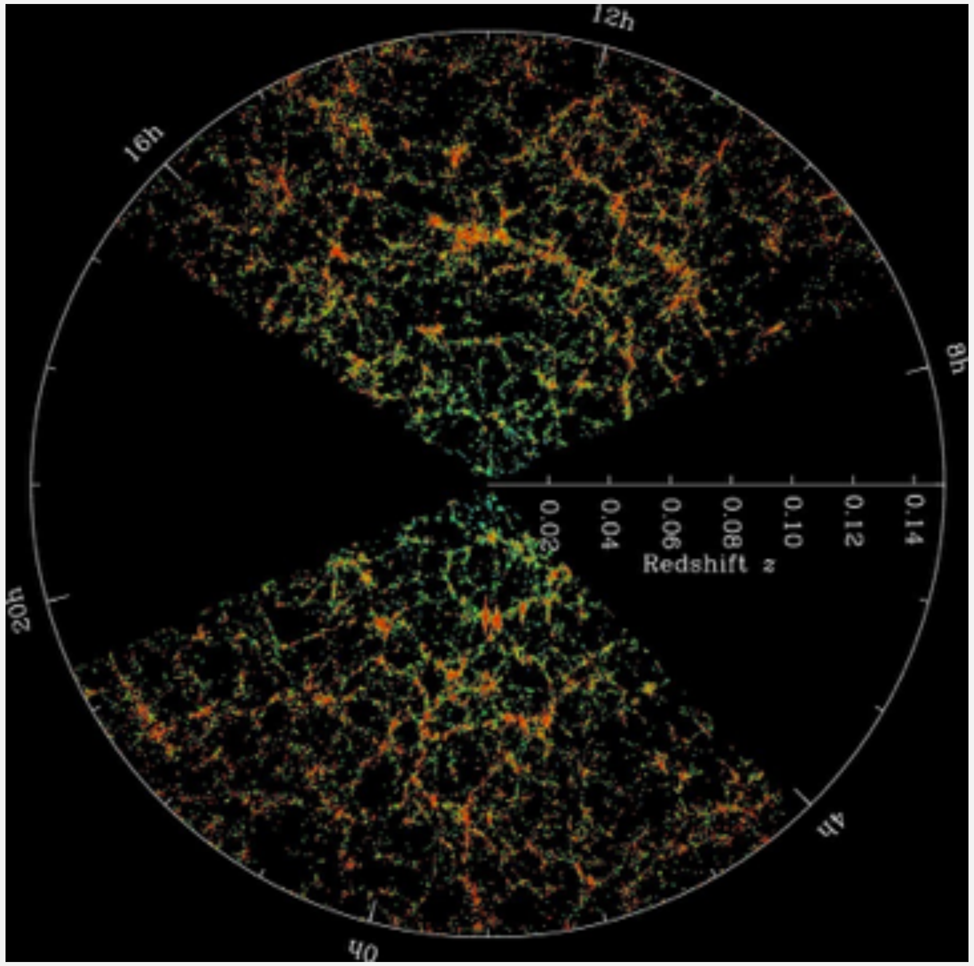
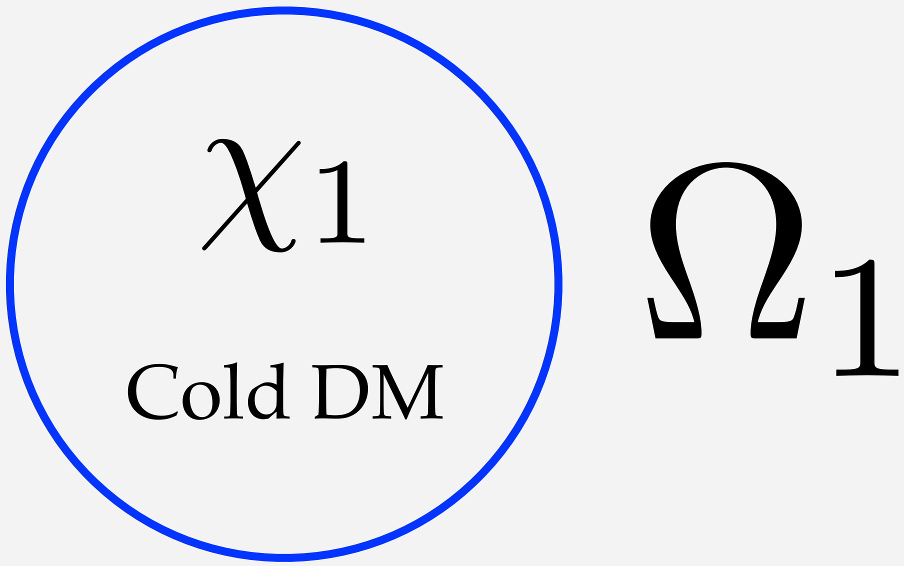
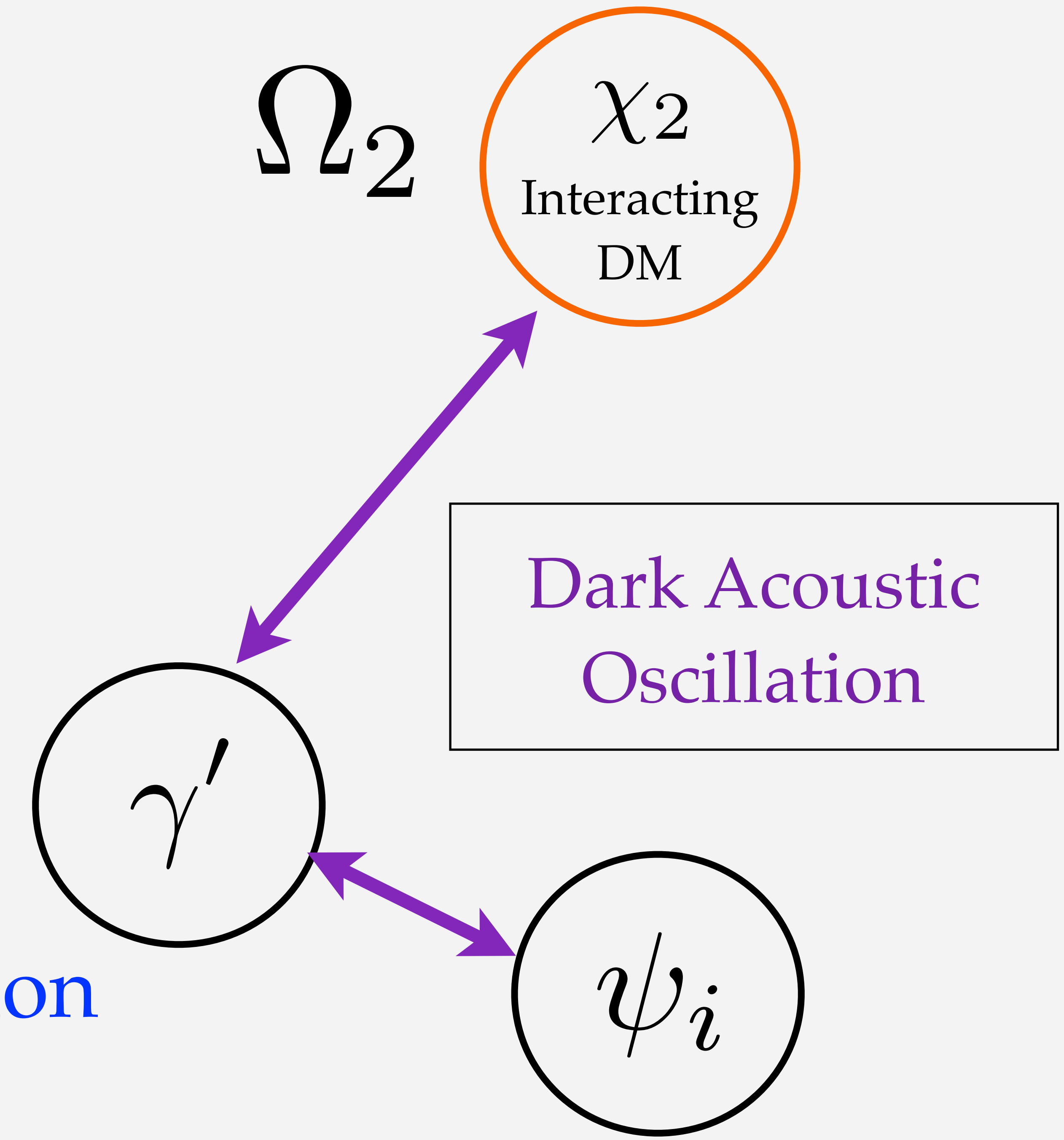
One solution: Partially Acoustic DM



DISTRIBUTION OF GALAXIES IN OUR UNIVERSE. CREDIT: SDSS

Consider a non-minimal dark sector





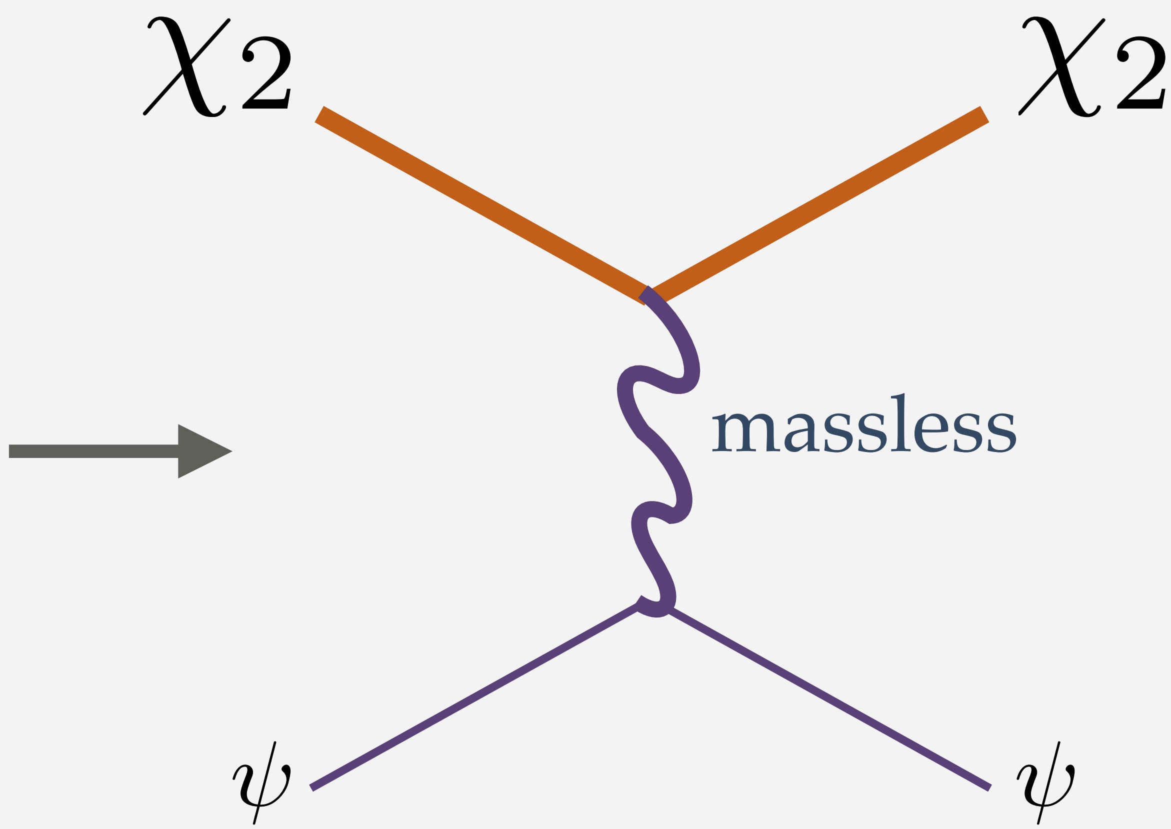
$$r \equiv \Omega_2/\Omega_{\rm DM}$$

$$r < 1$$

Partially Acoustic Oscillation
(PAcDM)

For the acoustic oscillation to exist

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



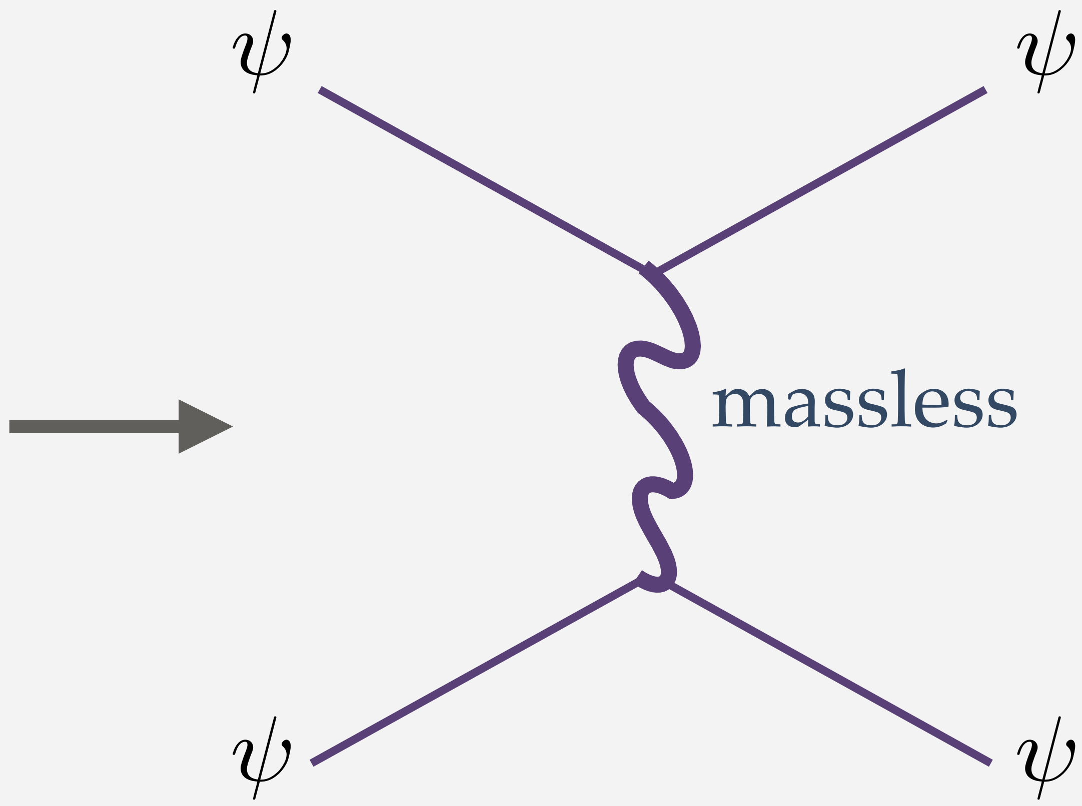
$$\Gamma \simeq \hat{\alpha}^2 \ln(\hat{\alpha}^{-1}) \frac{T_D^2}{m_{\rm DM}}$$

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

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

Tightly coupled dark radiation

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

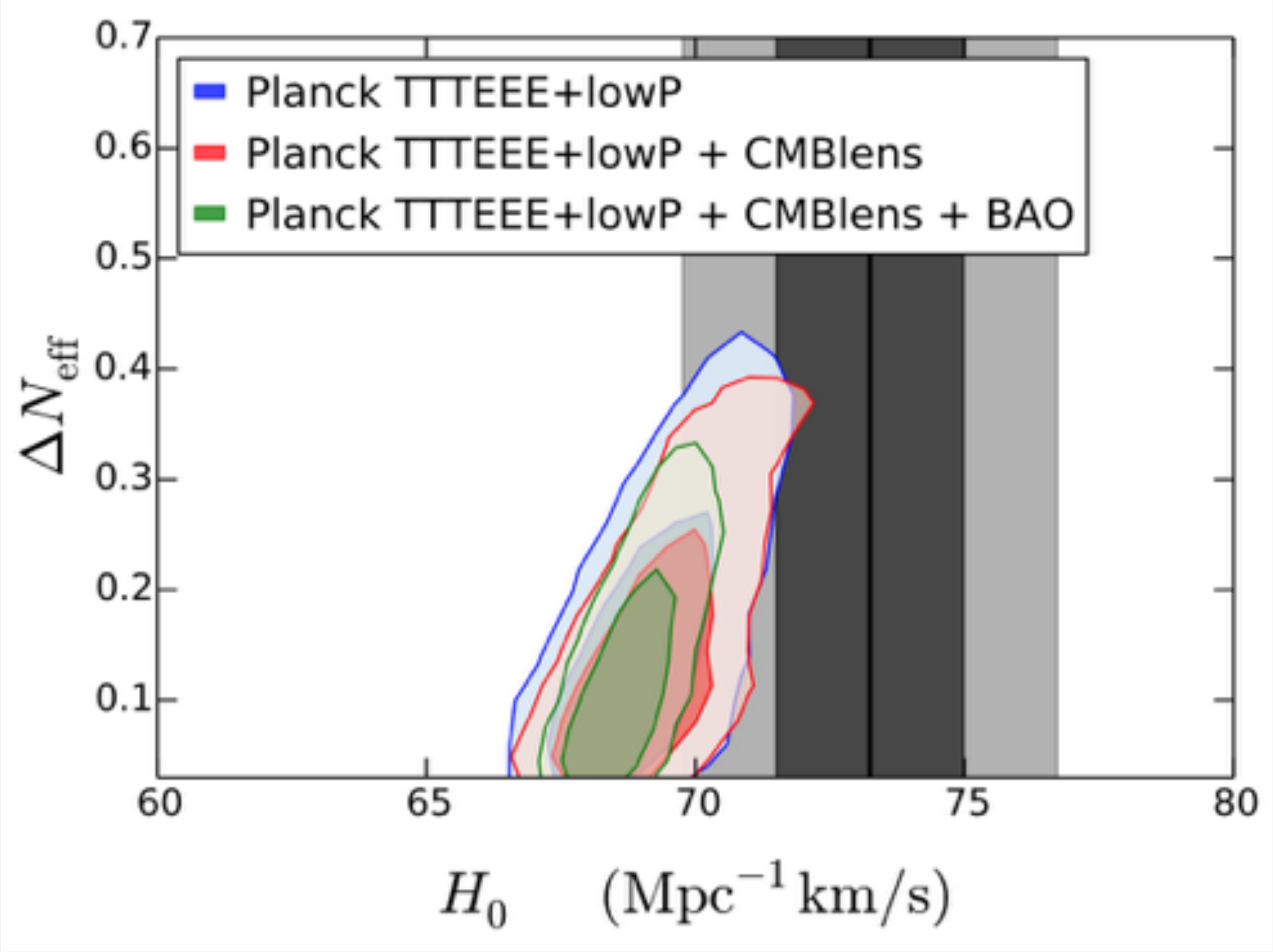


$$\Gamma \simeq \hat{\alpha}^2 \ln(\hat{\alpha}^{-1}) T_D$$

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

Solving H0 problem with extra dark radiation

Bernal et. al. 1607.05617

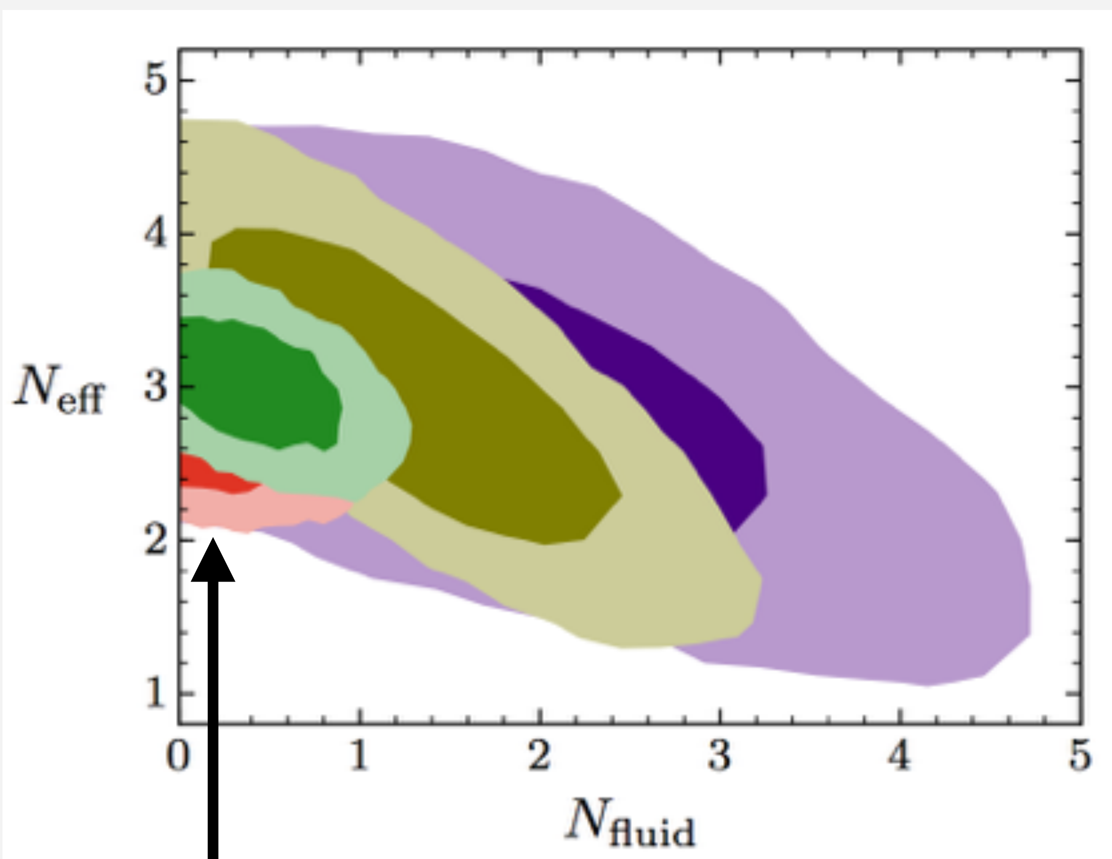


Can explain the larger H_0 by including $\Delta N_{\rm eff} > 0.4$ dark radiation

Adam Riess et.al. 1604.01424

Dark fluid is better than FS-radiation

Baumann et. al. 1508.06342



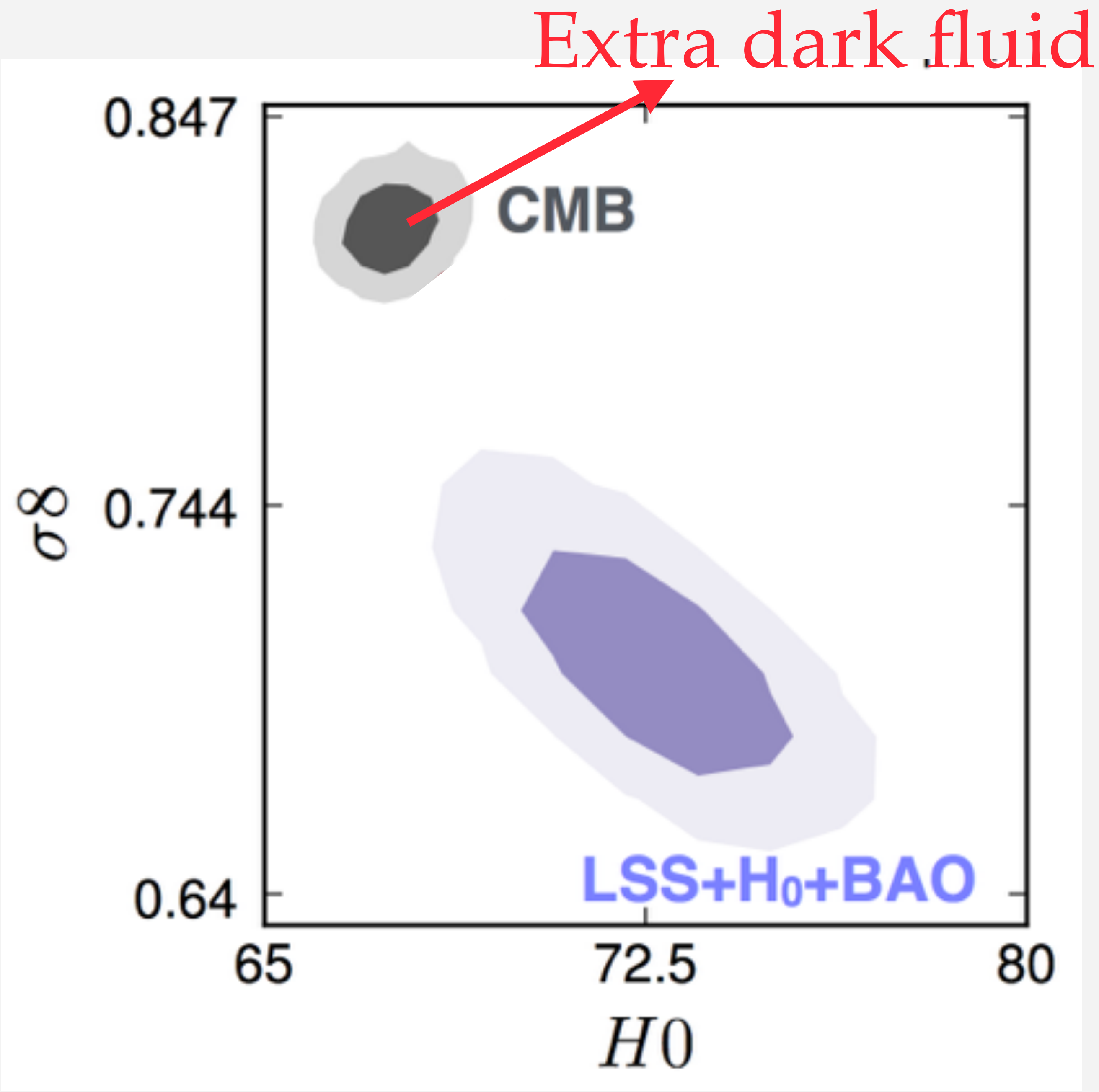
Planck TT, TE, and EE likelihoods

$\Delta N_{\rm eff}$ 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



Increase radiation density

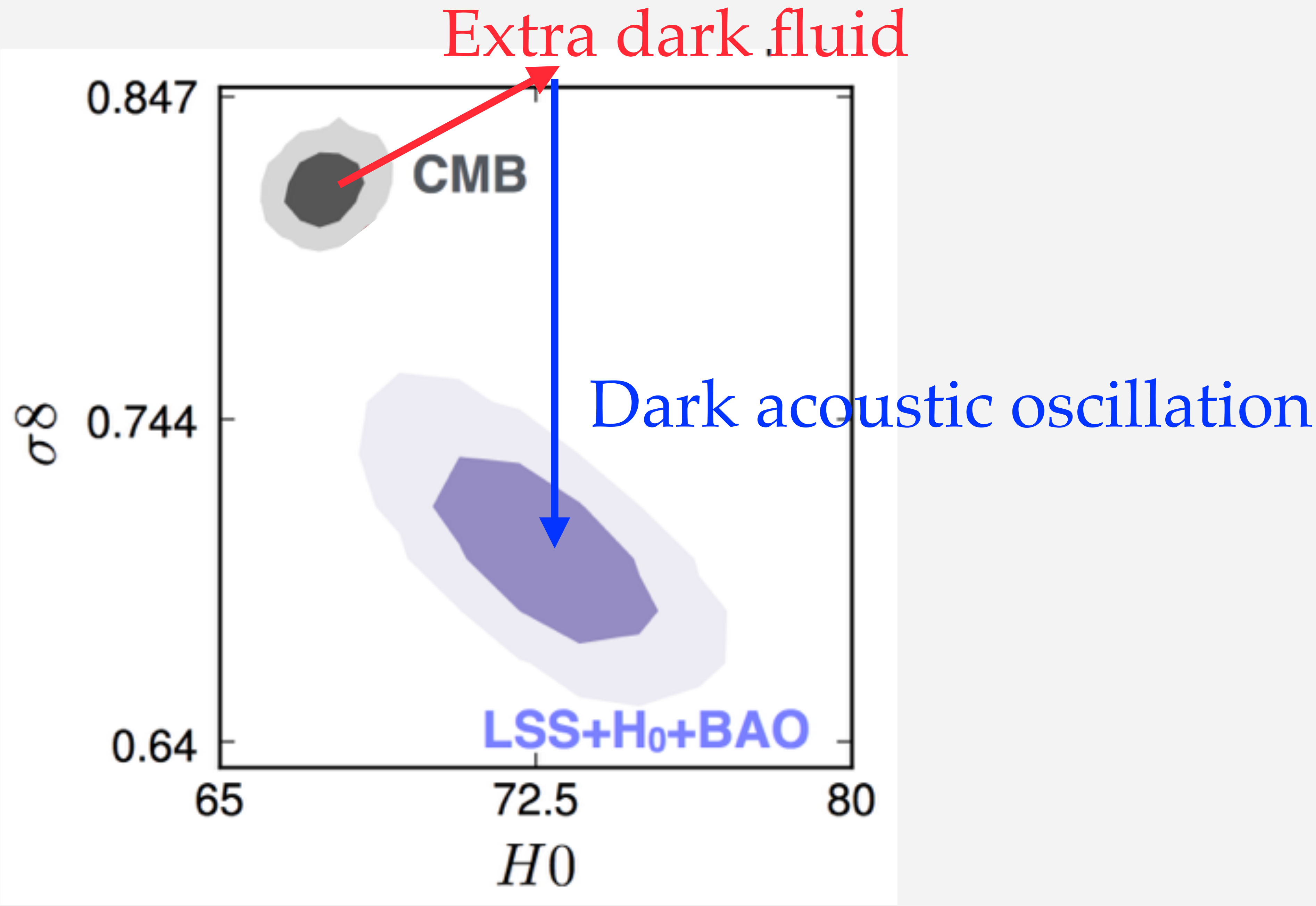
↓

Increase matter density

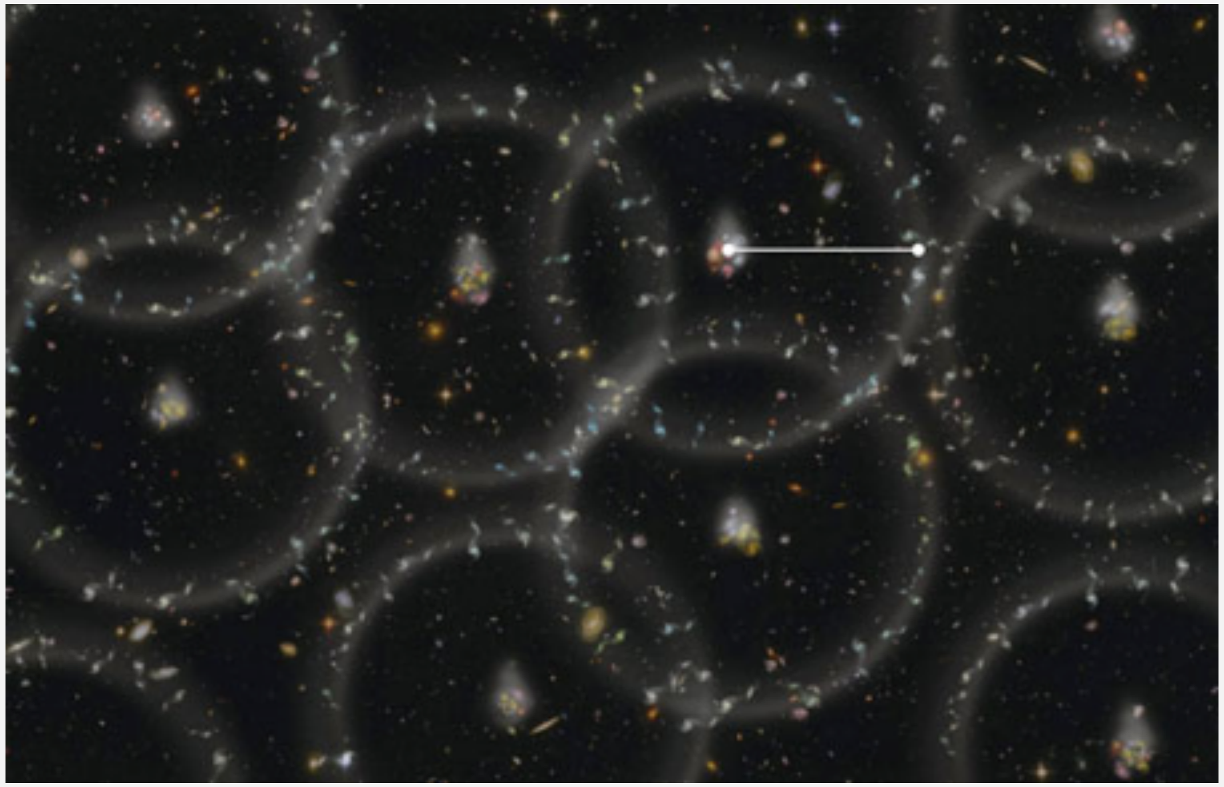
↓

Increase density perturbation

DM-DR scattering suppresses Sigma8

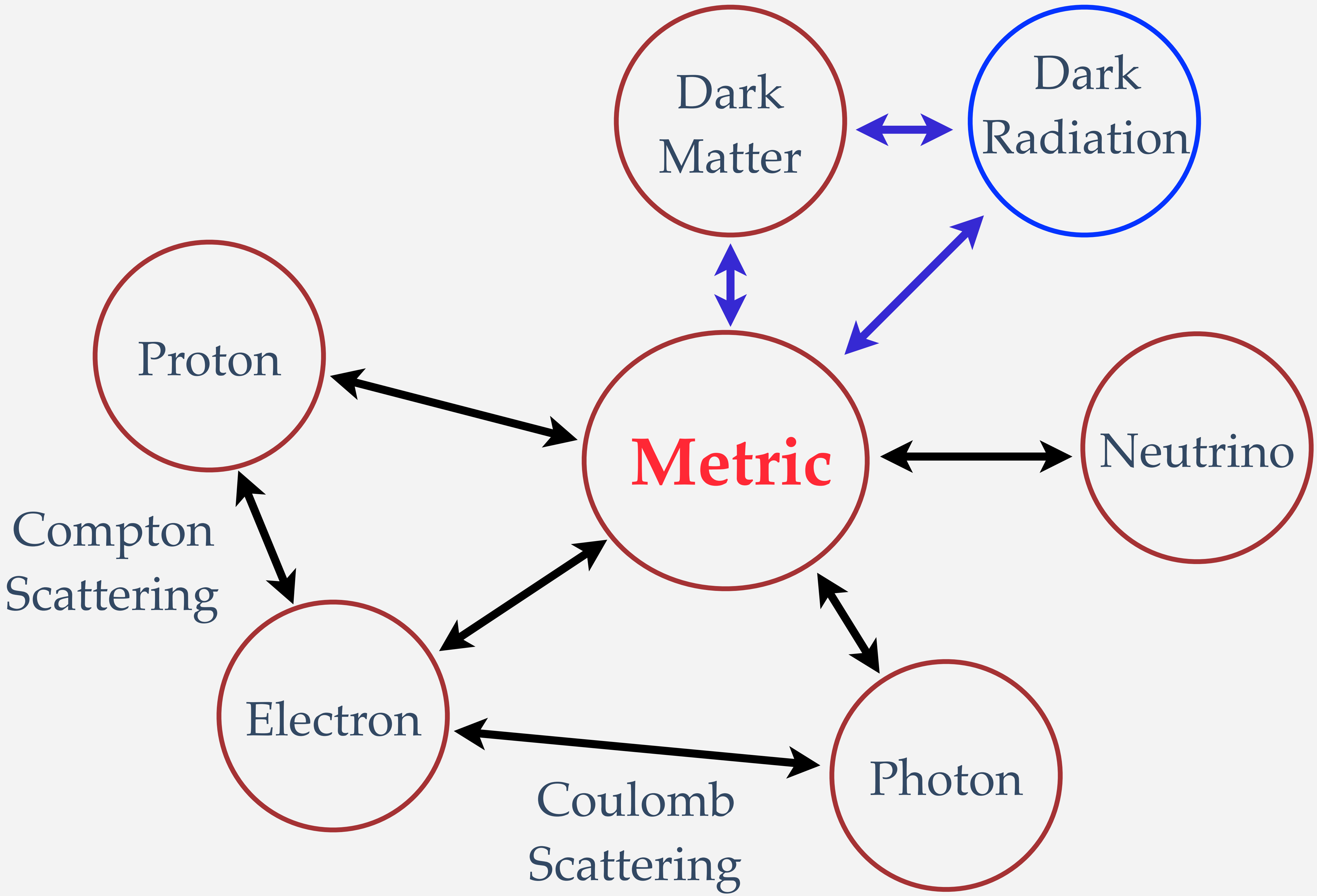


Structure Formation with DAO



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

Evolution of the Large Scale Structures



In the tightly coupled DM-DR limit

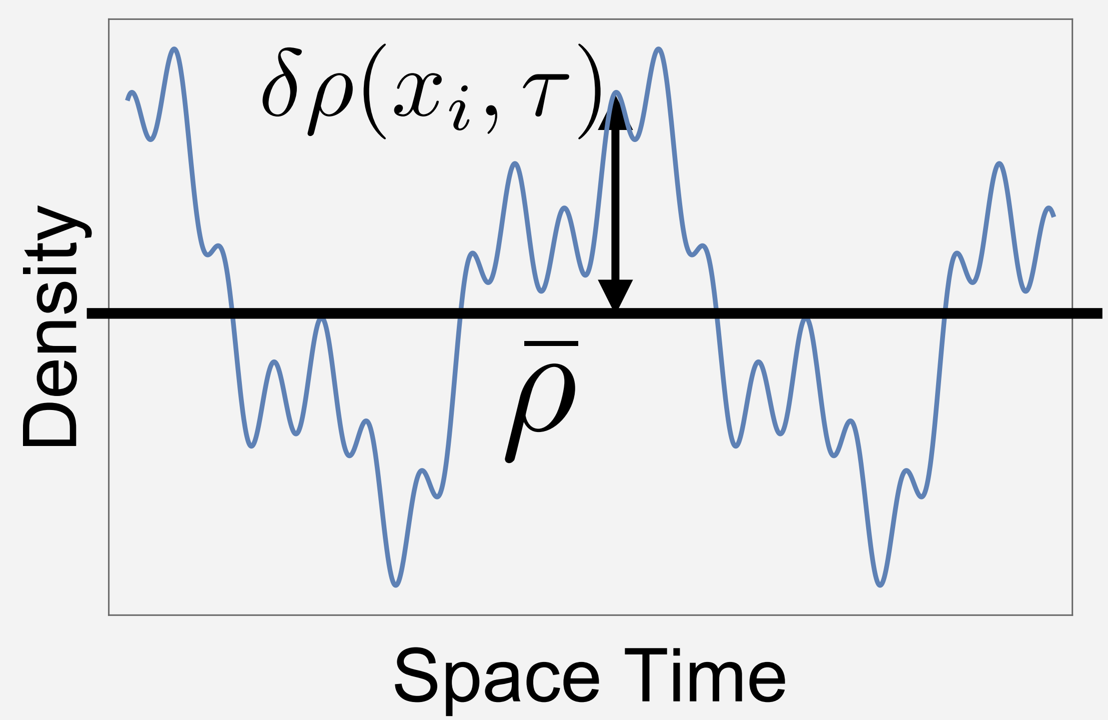
We can simplify the evolution of DM perturbation

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

metric perturbation

Density Perturbation

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



$$P(k)_s \propto k^{-3}\langle\delta_s(k,a)^2\rangle$$

In the tightly coupled DM-DR limit

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

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

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

Parametrize the ``mass" of DM-DR fluid

$$P(k)_s \propto k^{-3}\langle\delta_s(k,a)^2\rangle$$

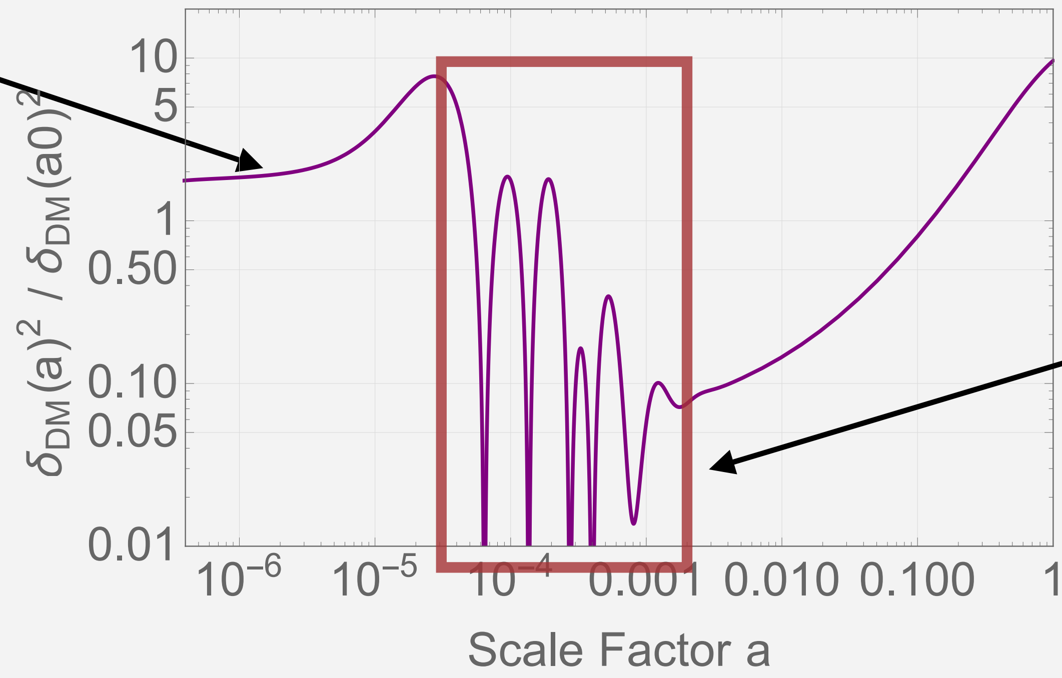
Radiation Domination , R << 1

Density perturbation oscillates => No structure grows

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

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

Enters horizon



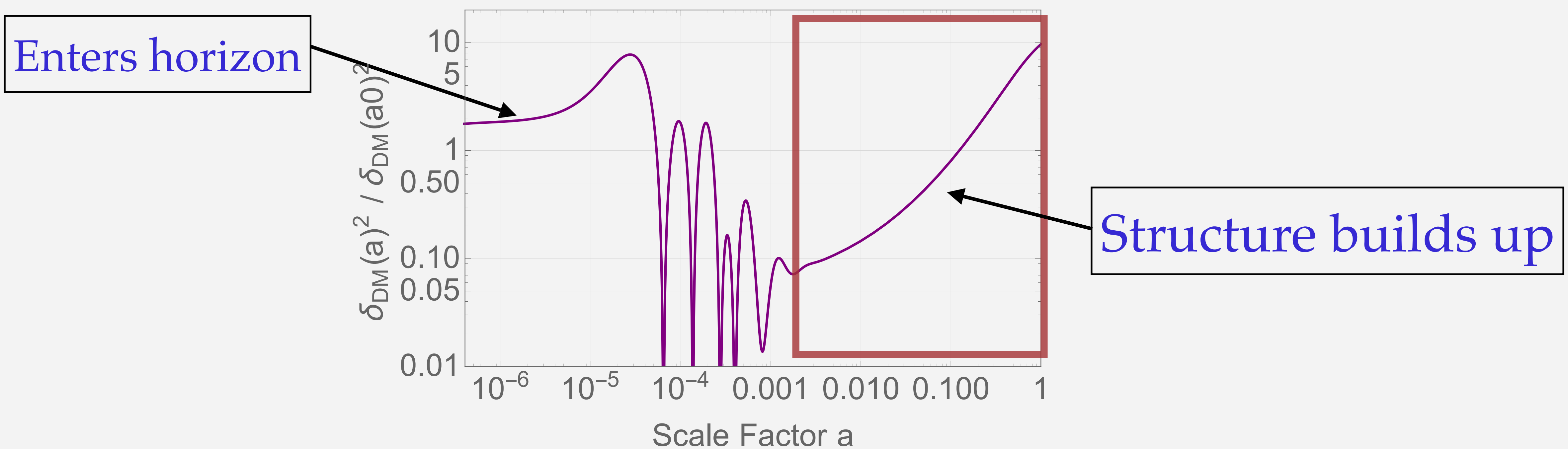
Structure does not grow!

Matter Domination , R >> 1

No oscillation => Linear growth

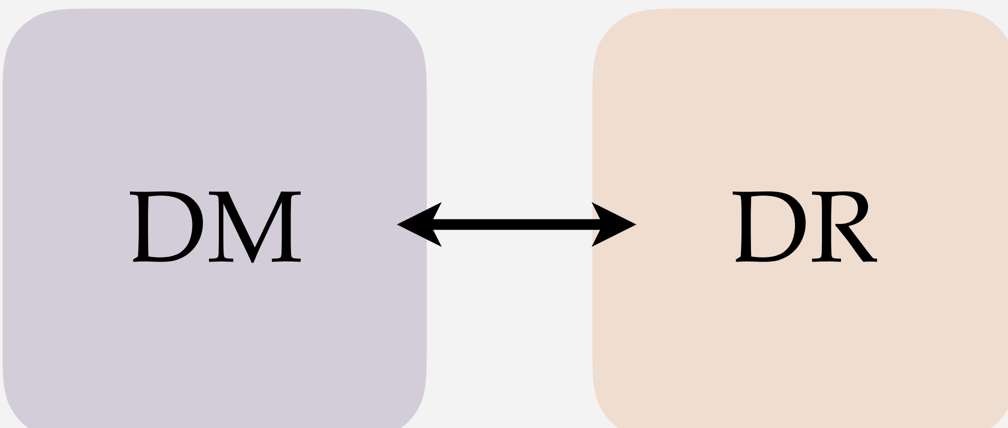
$$\ddot{\delta}_D + \frac{\dot{a}}{a}\frac{R}{1+R}\dot{\delta}_D + \frac{k^2}{3(1+R)}\delta_D \simeq -k^2\psi$$

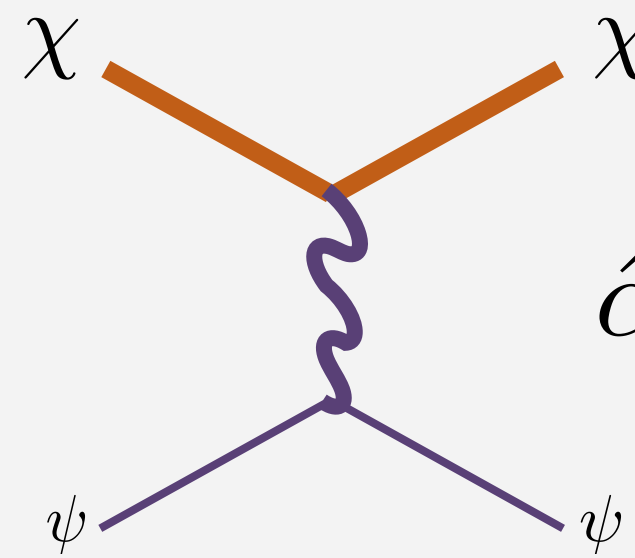
No oscillation, no damping from the DR scattering
Same structure formation as cold DM



Quasi-Acoustic Dark Matter

We need a small DM coupling for the right σ_8 suppression



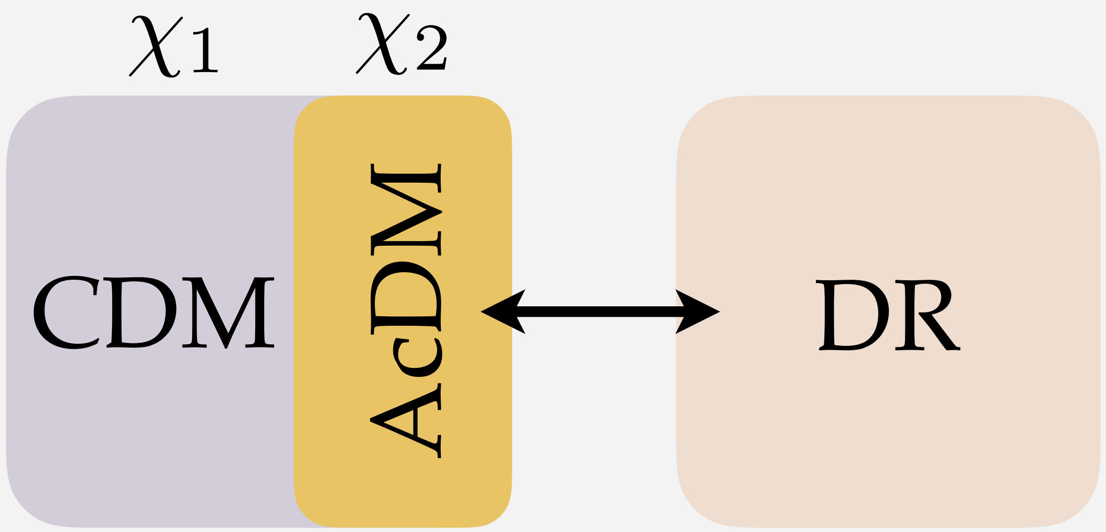


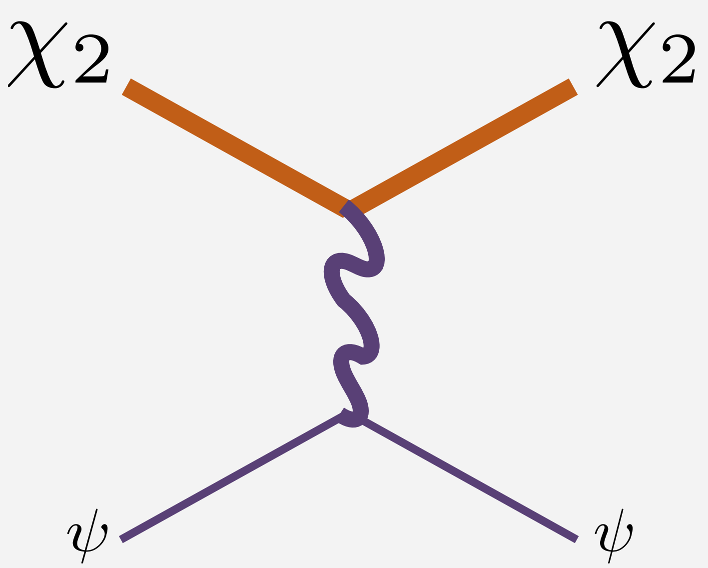
$$\hat{\alpha} \sim 10^{-8.5}$$

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

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

Partially-Acoustic Dark Matter





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

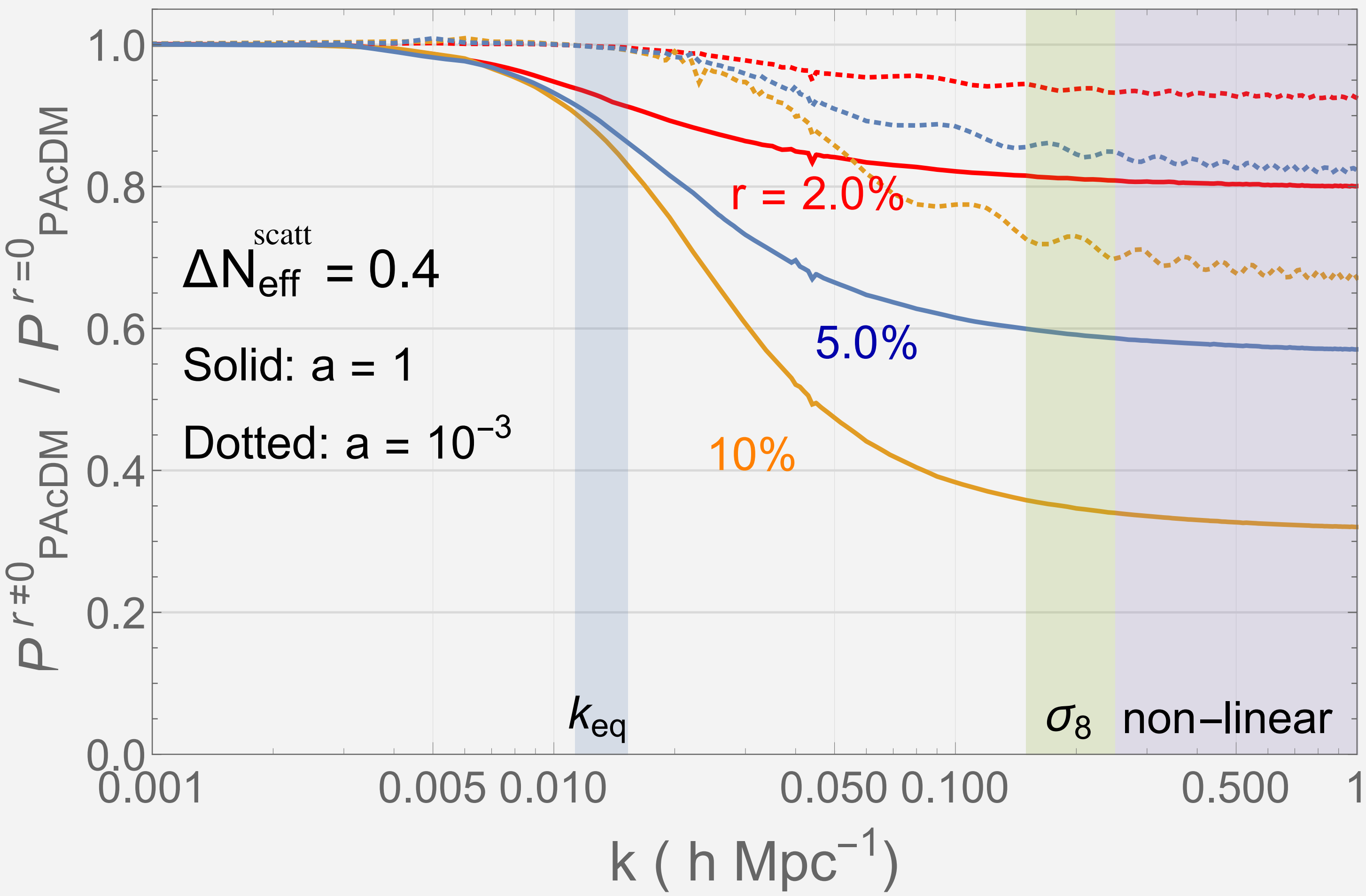
Allows an analytical study

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

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

Solving Sigma8 problem with PAcDM

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



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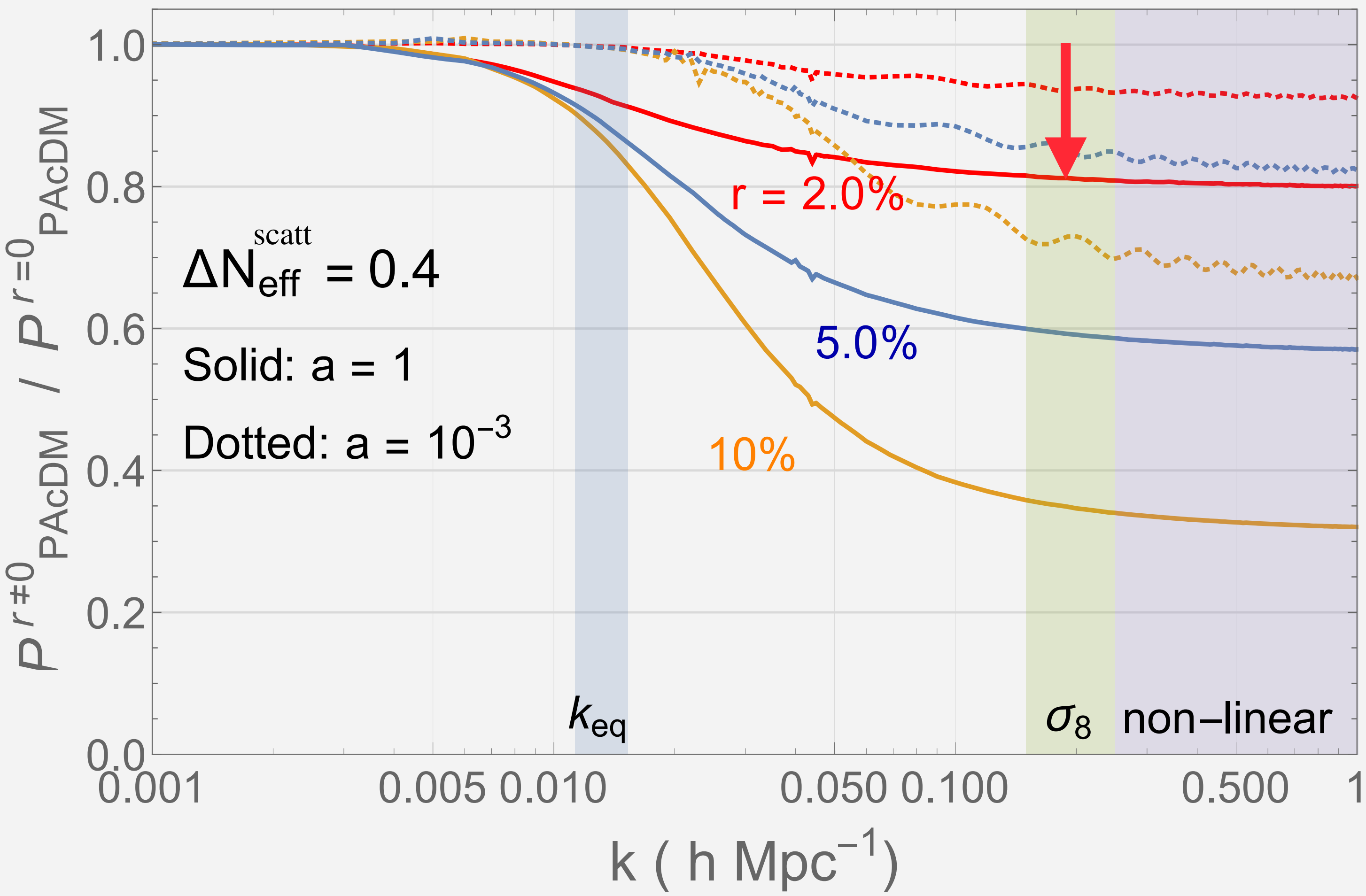


Need ~2% acoustic DM to solve the σ_8 problem

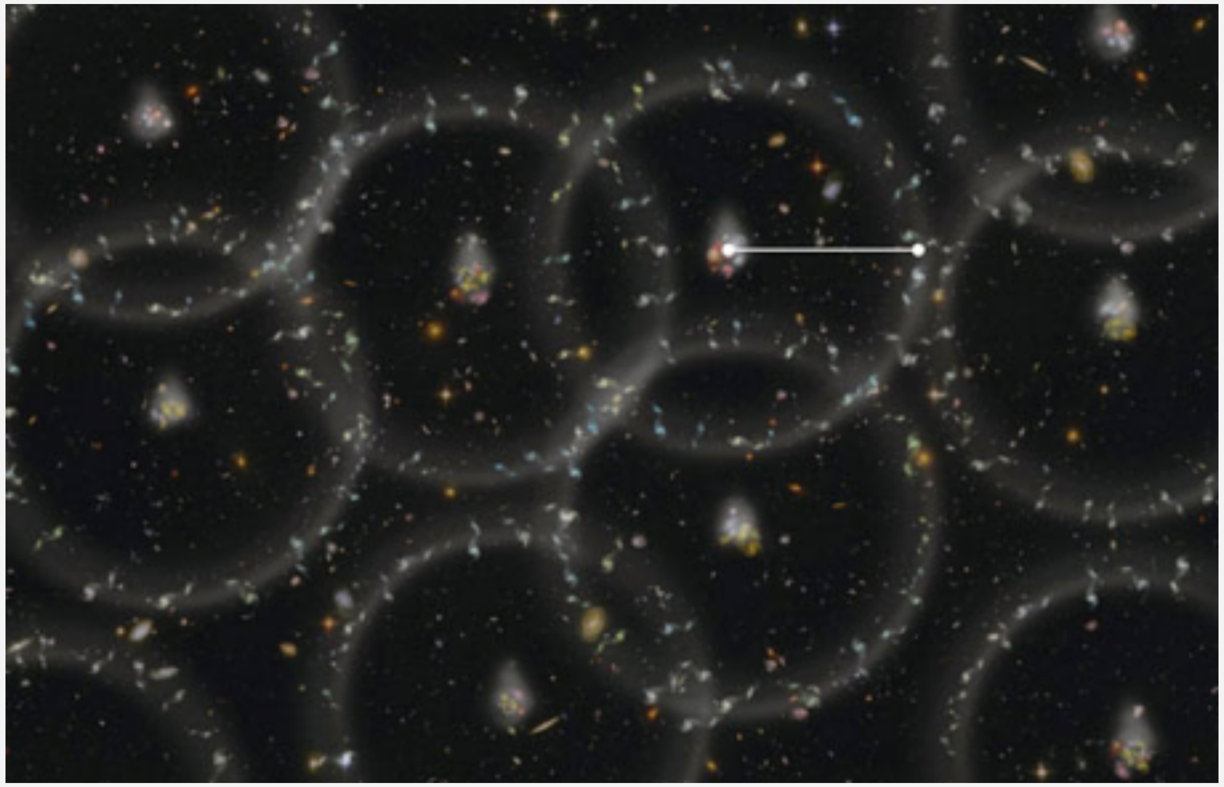
2% density is easy to obtained

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

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

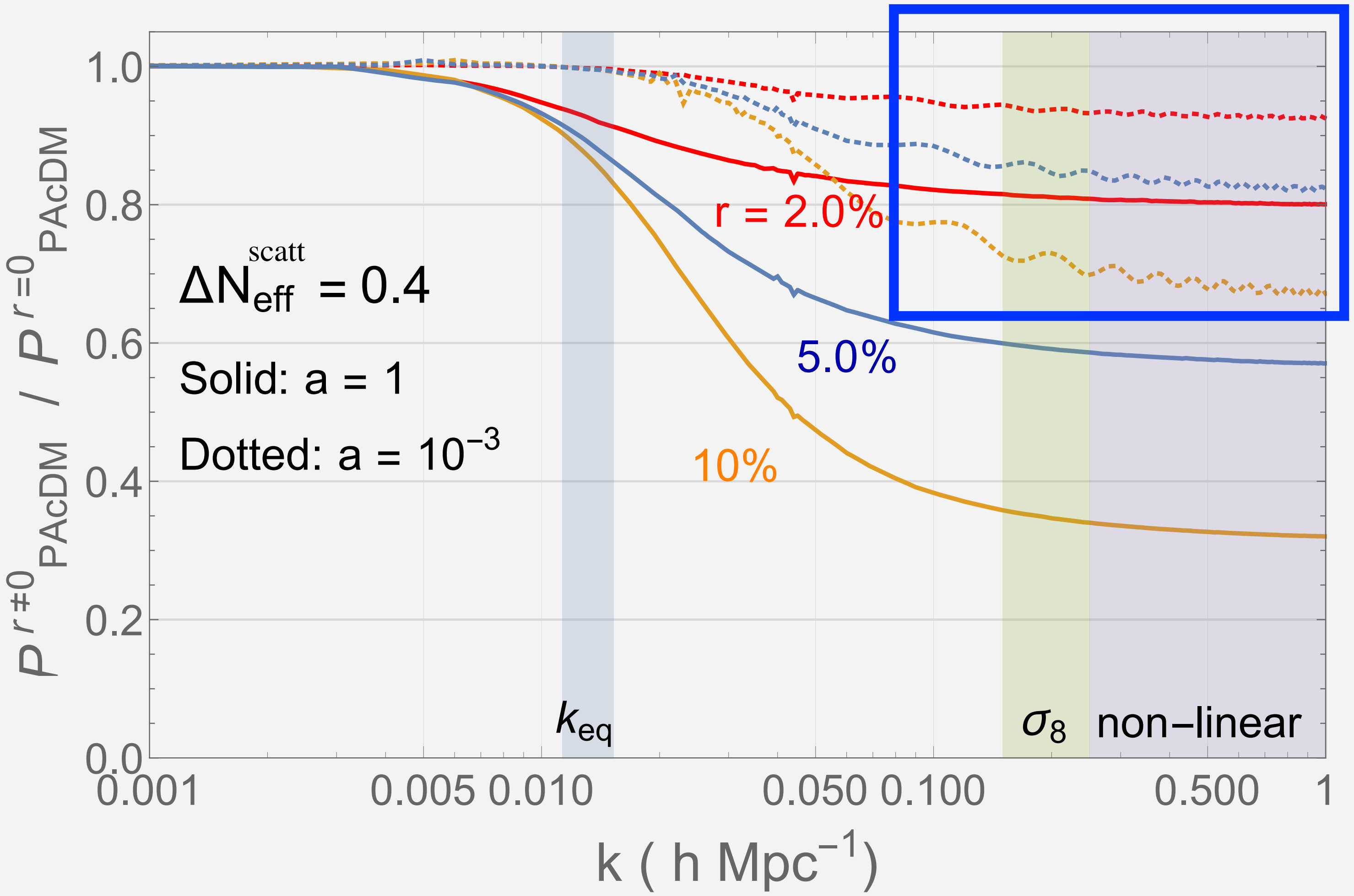
Only need $m_1 \simeq 7\, m_2$ to obtain the 2% ratio (assuming equal couplings)

Slowing Down the Structure Formation



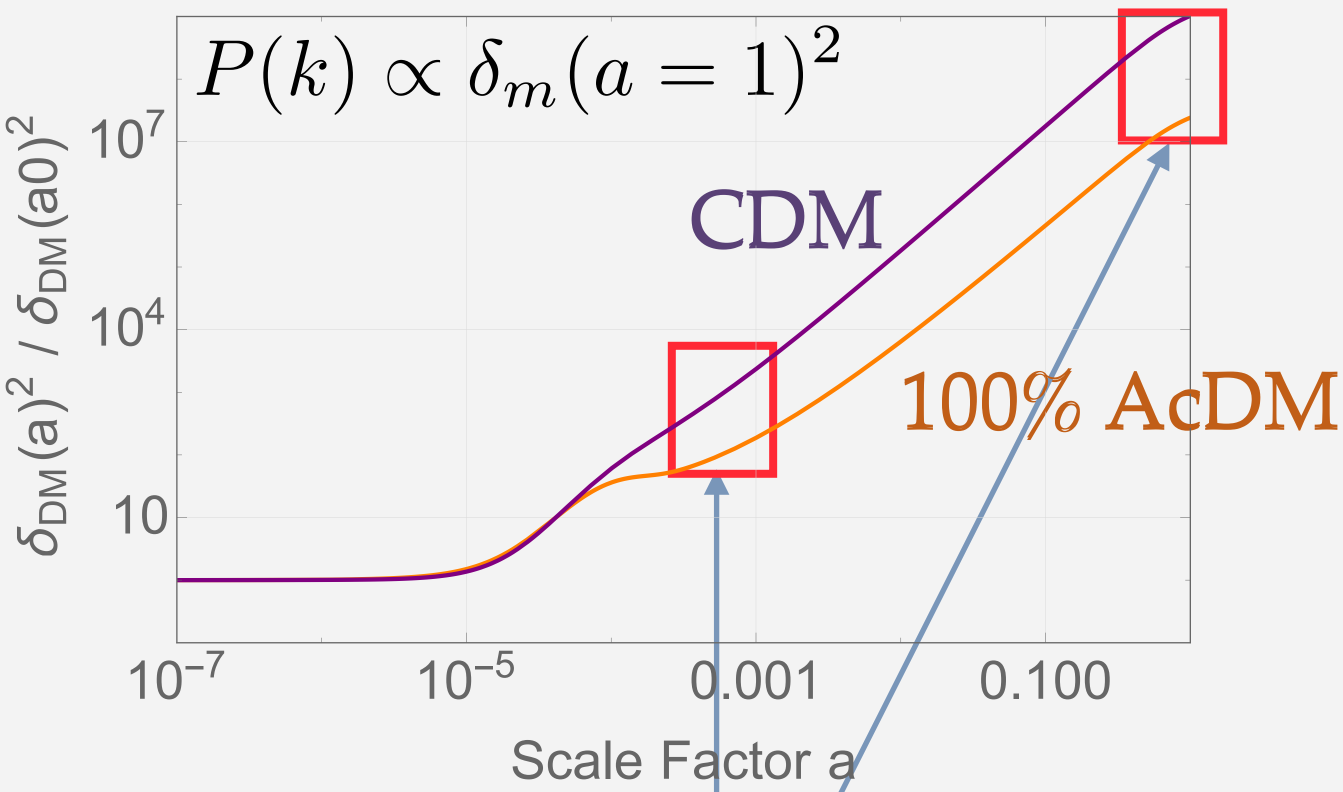
A cartoon produced by the BOSS project showing the spheres of baryons around the initial dark matter clumps

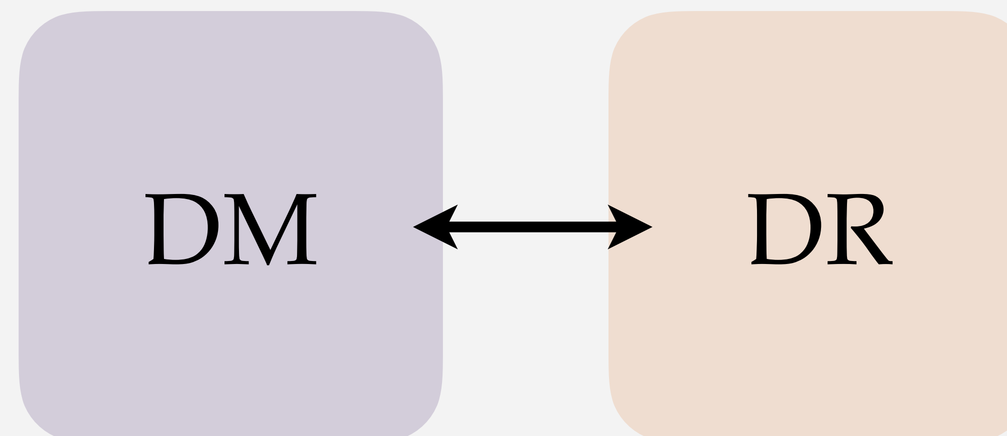
Smaller suppression at the CMB time



Correction to the power spectrum is smaller during the CMB time. Why?

In the Quasi-Acoustic Oscillation case



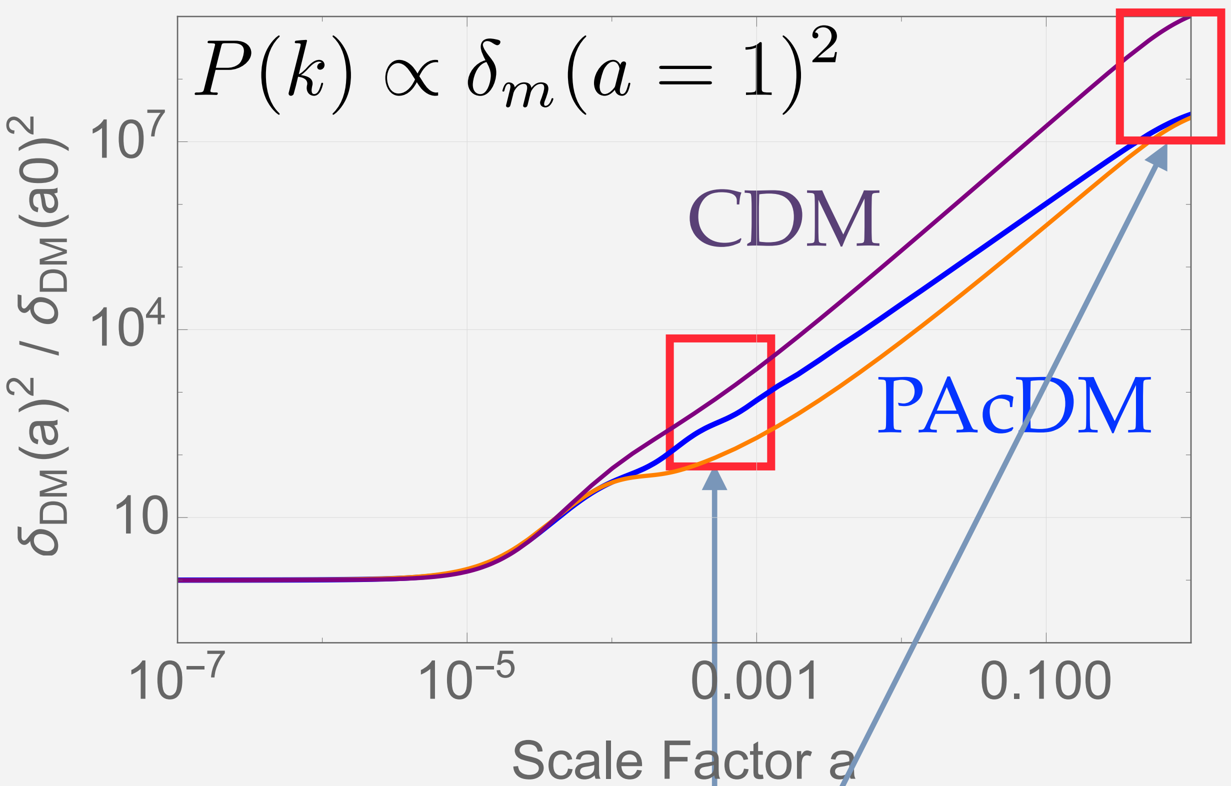


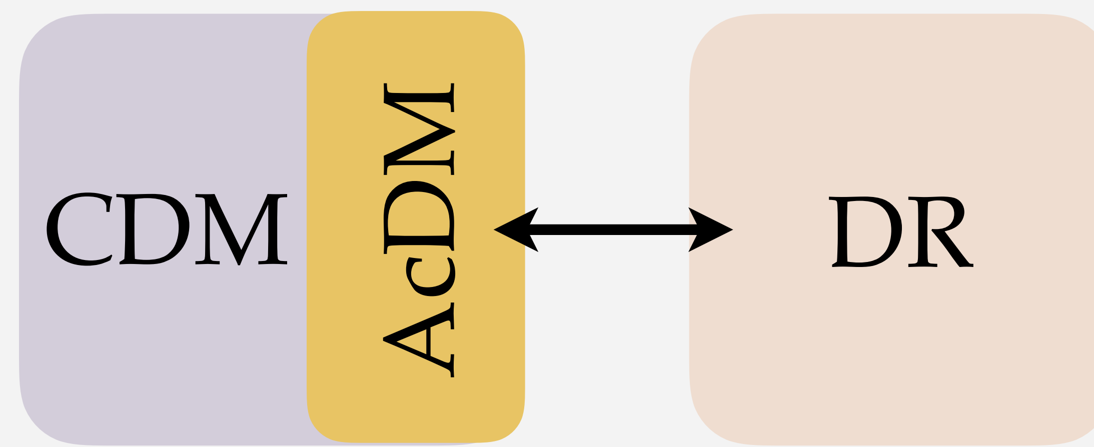
For TeV scale DM

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

Similar damping between today / CMB time

In the Partially-Acoustic Oscillation case



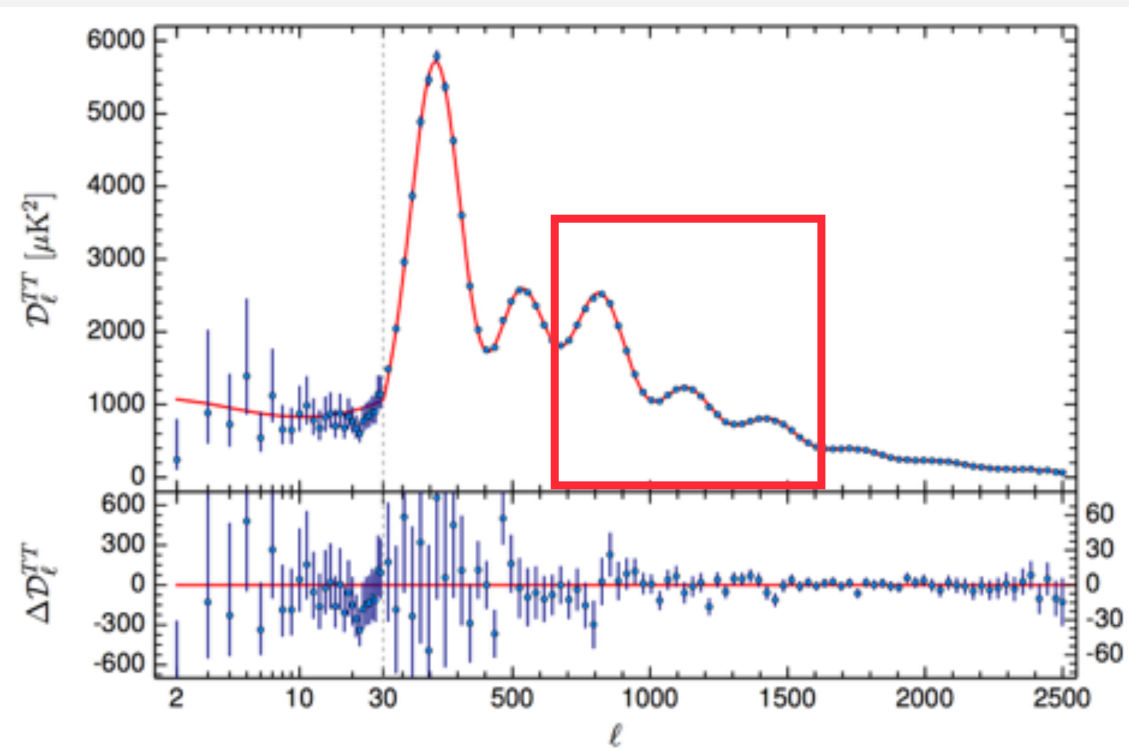


$$\frac{P(r)}{P(0)} \simeq (1-2r)\left(\frac{a}{a_{\rm eq}}\right)^{-1.2r}$$

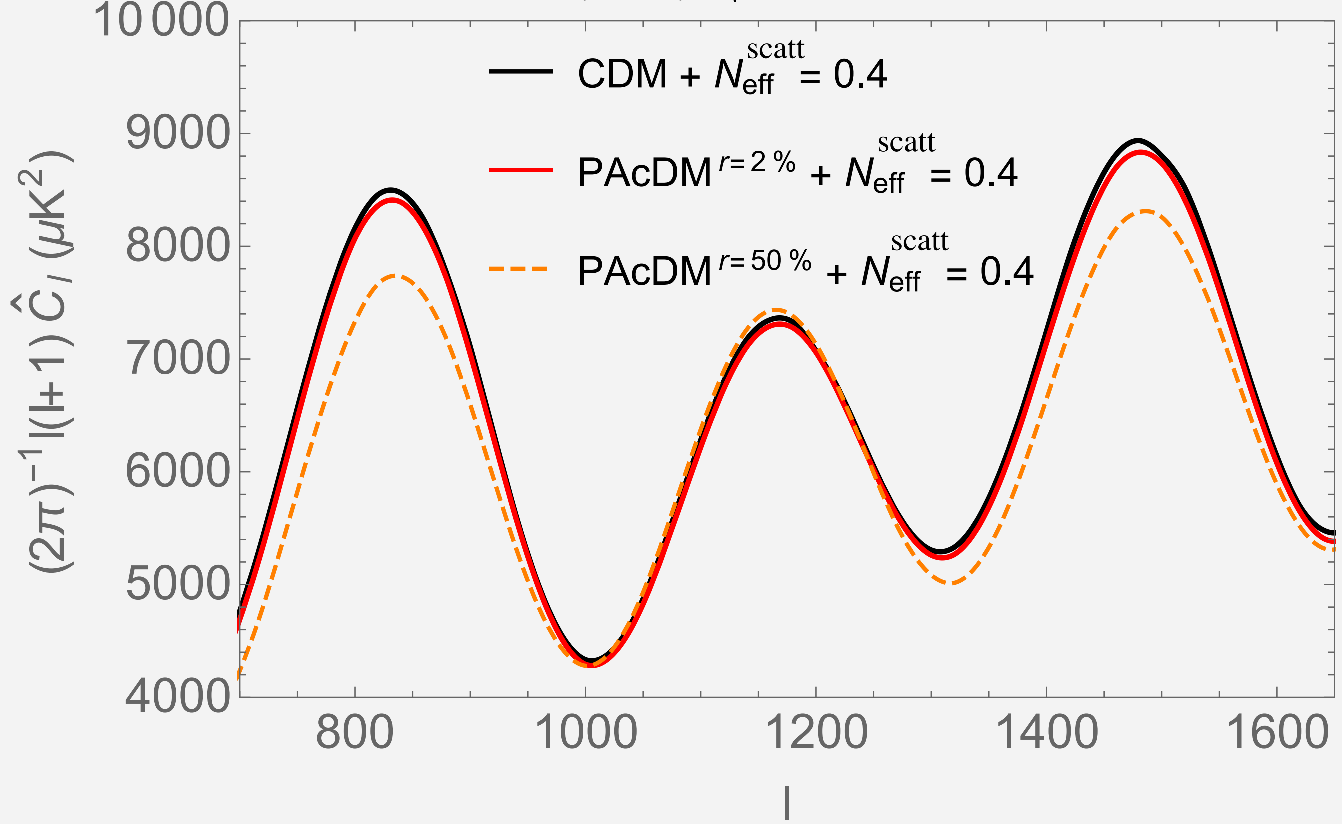
Structure grows slower comparing to CDM
Smaller correction to the CMB spectrum

Correction to the CMB spectrum

Planck 1502.01589



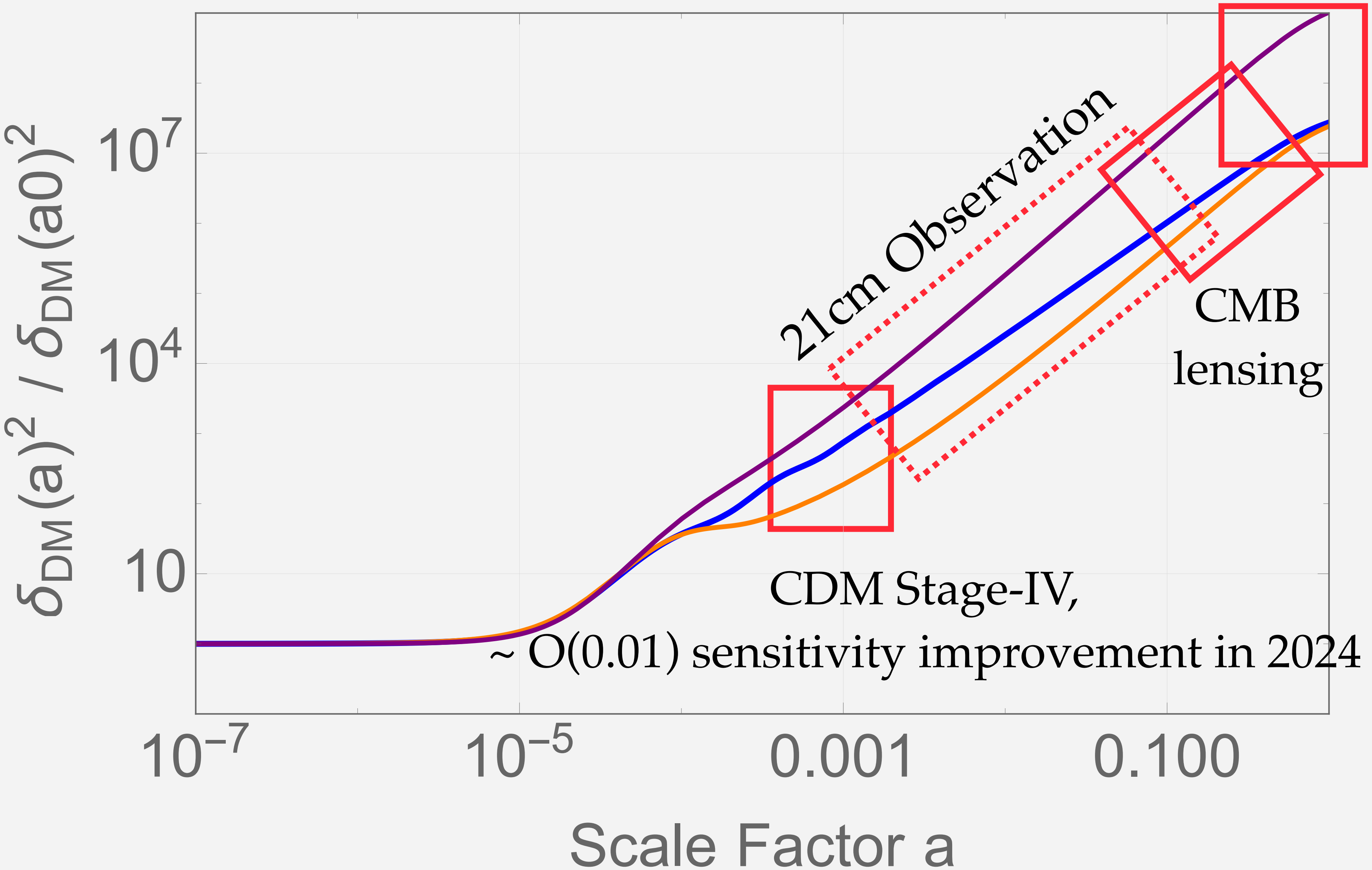
$$\left(\frac{\delta T}{T}\right)_* \equiv \frac{\delta_\gamma}{4} + \psi$$



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

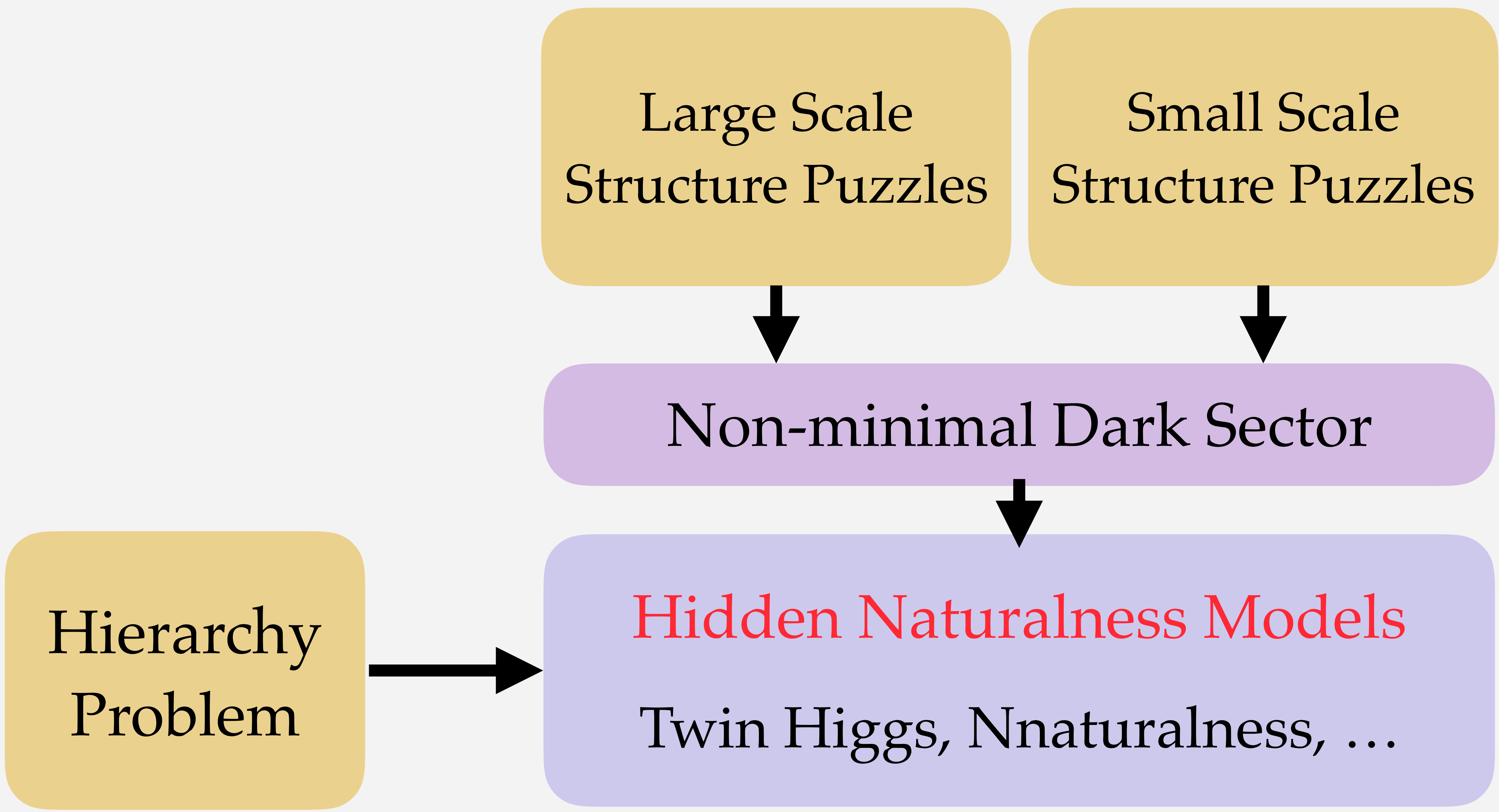
When r = 2%, the correction to CMB is less then ~ 2%, smaller then > 5% error bar in Planck result

Clear answer from future experiments



DES data
Weak Lensing
Experiments

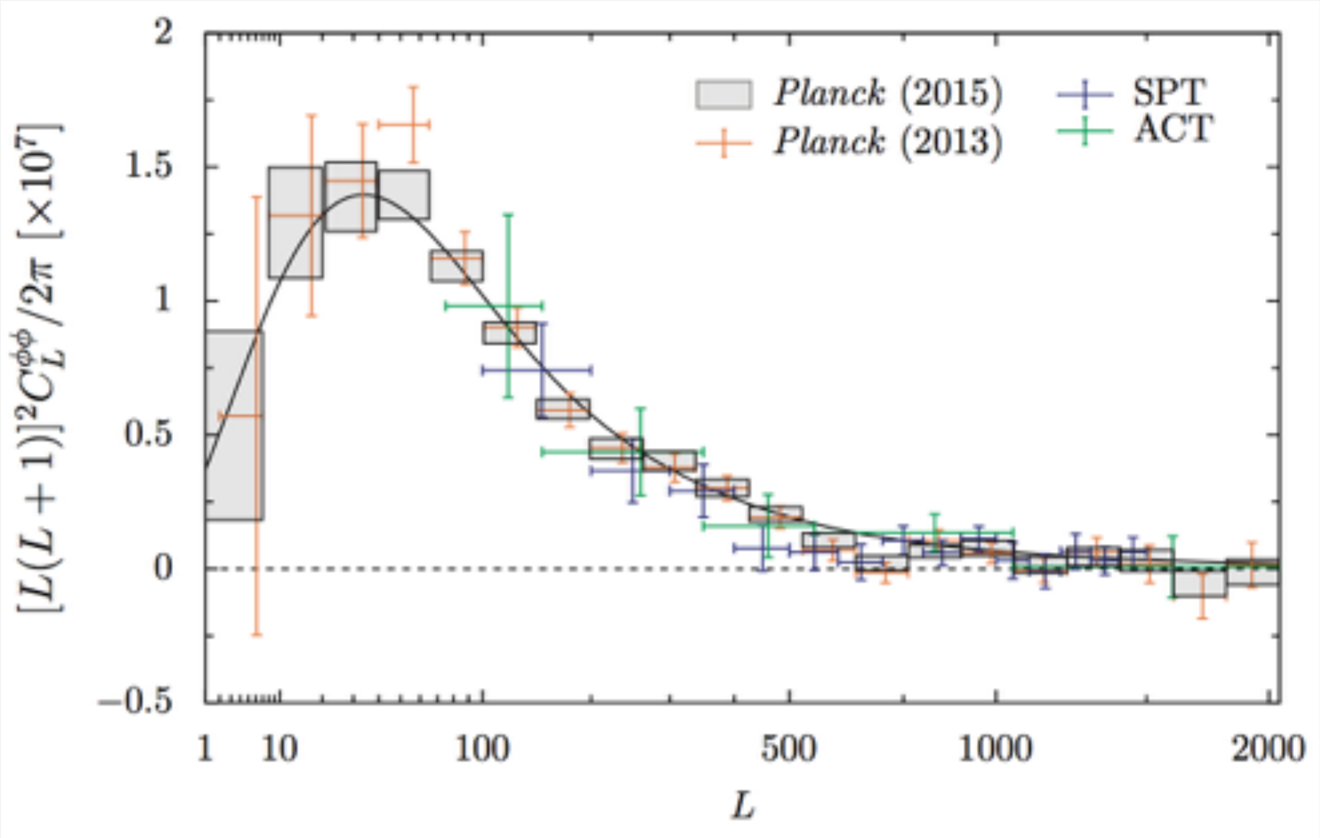
A clue to even deeper physics?



arXiv: 1611.05879, Valentina Prilepina and YT

CMB Lensing

Planck. 1502.01591



$$\ell^4 C_\ell^{\phi\phi} \propto \int_0^{\chi_*} d\chi\ (1-\chi/\chi_*)^2\ k\phi^2(k,a)\, g^2(\chi)$$

The smallest error bar (Planck) is 5% at L~150

PAcDM gives a ~2.5% correction when r = 2%

Conclusion

Large Scale Structure is sensitive to the dark sector dynamics

Acoustic Dark Oscillation
suppresses the matter power spectrum

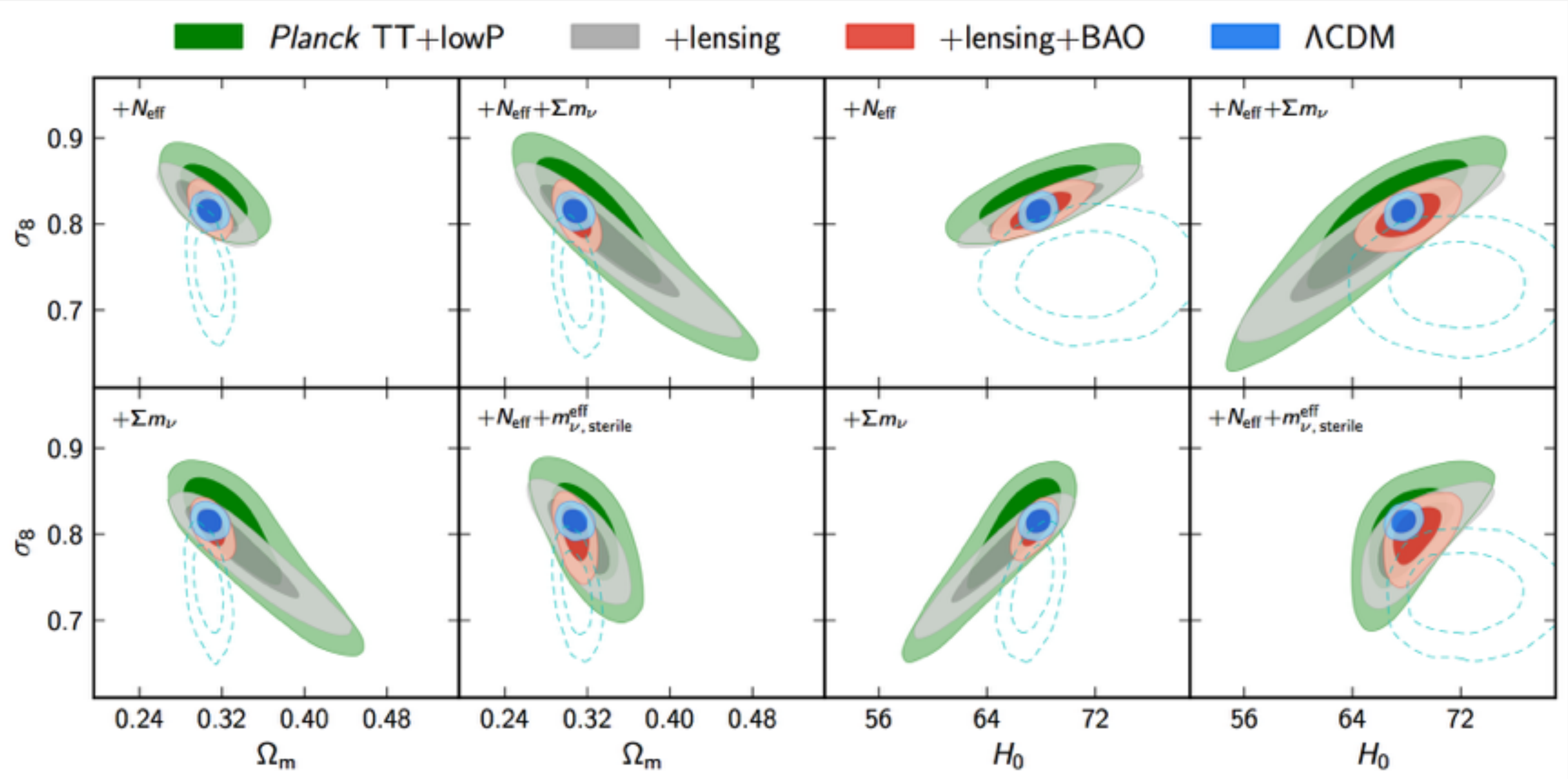
A smaller ratio of Cold DM
change the power-law growth of matter density spectrum

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

May also change the small scale structure

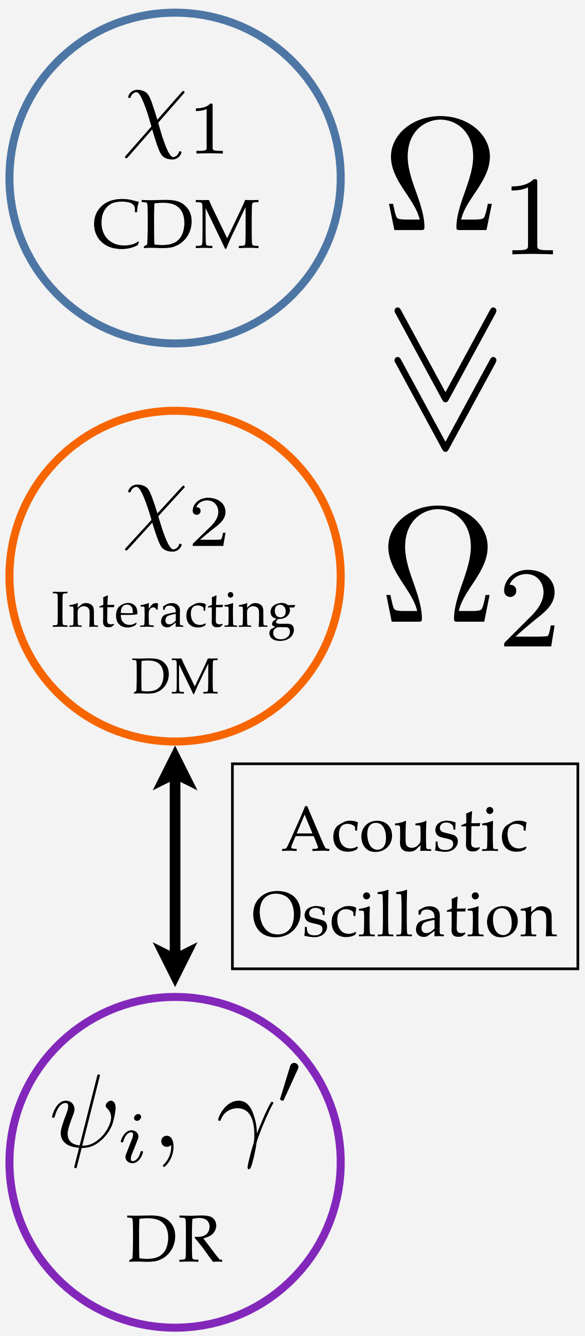
Working on it now, stay tuned!

Backup Slides



Planck TT+lowP
+lensing
+lensing+BAO
ΛCDM
+N_eff
+N_eff+Σm_ν
+Σm_ν
+N_eff+m^eff_ν, sterile
σ_8
0.9
0.8
0.7
0.24
0.32
0.40
0.48
Ω_m
56
64
72
H_0

In the partially acoustic case



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

DM density contrast is determined by χ_1

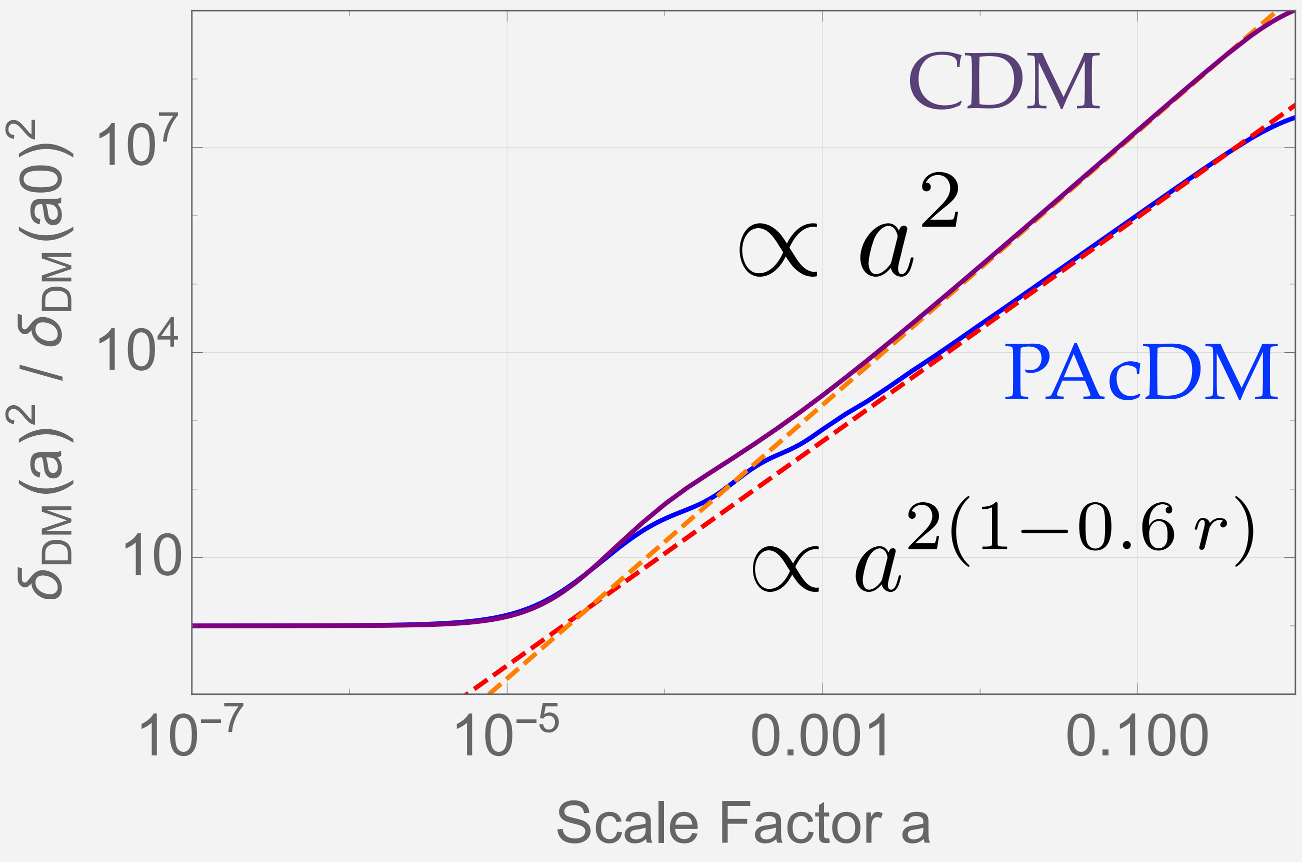
$$\ddot{\delta}_1 + \frac{2}{\tau}\dot{\delta}_1 = -k^2\phi$$

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

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

The < 100% CDM case

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



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 => $\boxed{\phi = \psi}$

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

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

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

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